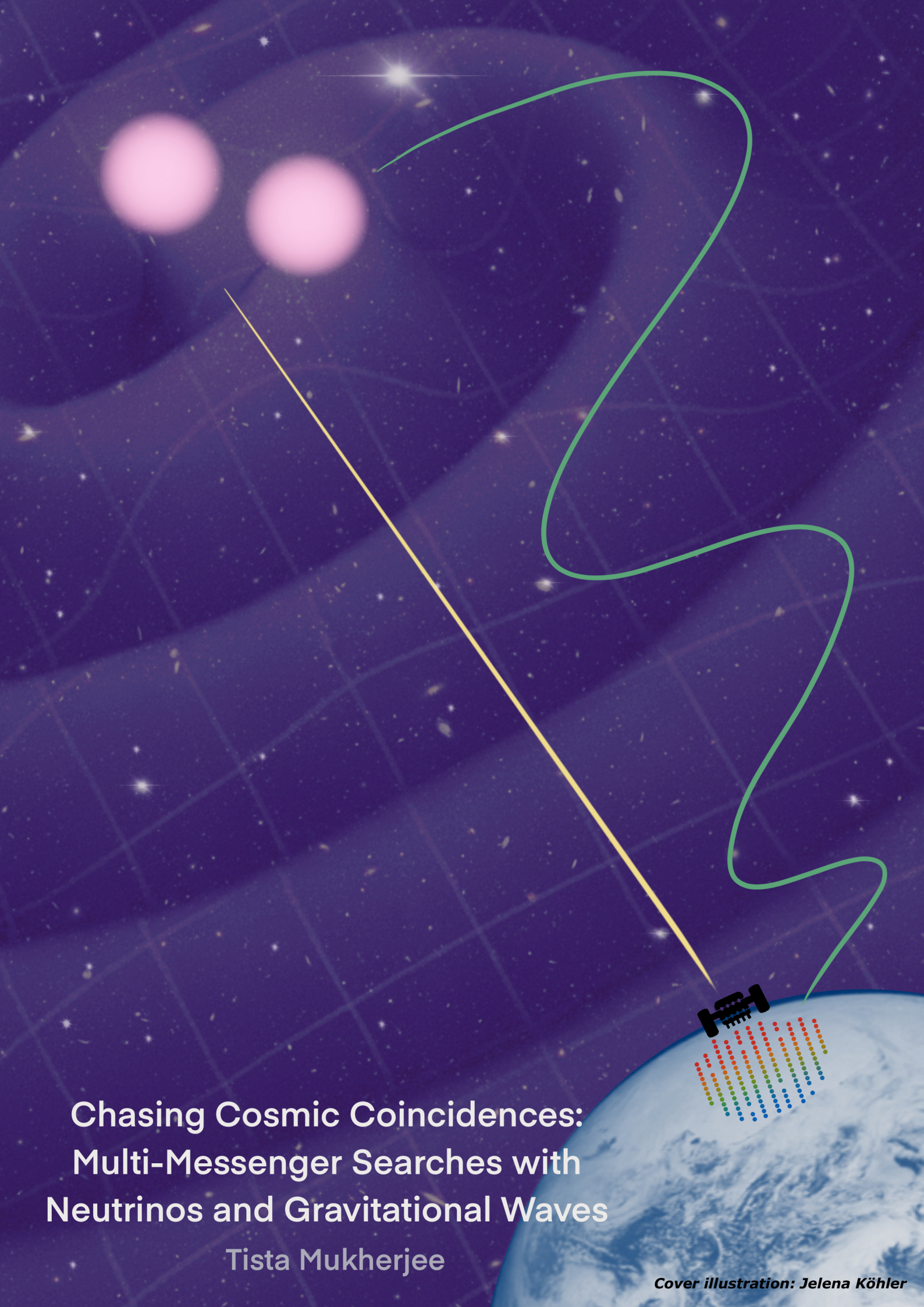


The background is a deep purple space filled with stars and distant galaxies. A large, faint, glowing green spiral or wave pattern dominates the upper half. A bright yellow line starts from a small satellite-like object on the Earth's horizon and extends diagonally upwards towards two bright pinkish-white spheres. The Earth's horizon is visible at the bottom right, showing blue oceans and white clouds. The satellite has a black body with several colorful dots (red, orange, yellow, green, blue) trailing behind it.

Chasing Cosmic Coincidences: Multi-Messenger Searches with Neutrinos and Gravitational Waves

Tista Mukherjee

Cover illustration: Jelena Köhler

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Statutory Declaration

I declare that I have developed and written the enclosed doctoral thesis completely by myself, and have not used sources or means without declaration in the text. The doctoral thesis was not used in the same or in a similar version to achieve an academic grading or is being published elsewhere.

Date

Tista Mukherjee

*To my parents,
my first teachers, whose lessons I carry with me,
from whom I continue to learn every day.*

*To my grandfather,
with whom I first discovered the joy of problem solving,
who encouraged me to pursue scientific research.*

*To the Govt. of West Bengal (2000-2011),
who ensured the right to quality education for all,
even for people coming from the most humble background.*

Abstract

The detection of astrophysical neutrinos and gravitational waves (GW) has ushered in a new era of multi-messenger astroparticle physics, offering unique opportunities to explore the non-thermal Universe. While coincident detections of GW and neutrinos alongside electromagnetic signals have already been achieved in separate instances, no common source of GW and neutrinos has yet been identified. Such a discovery will provide unprecedented insight into the processes that accelerate cosmic rays to extreme energies and the physics of compact objects.

To advance these ongoing search efforts, this thesis presents a systematic search for joint GW-neutrino emission, based on the largest sample of archival GW events from the third observation run of the LIGO–Virgo–KAGRA collaboration, publicly available since 2021. The analysis employs the all-flavour, sub-TeV neutrino sample from the IceCube Neutrino Observatory, motivated by scenarios in which off-axis jets produce Doppler de-boosted neutrino spectra below the TeV energy range. For the first time, these two datasets are combined within a joint framework, employing an unbinned maximum-likelihood method to assess the statistical significance of spatial and temporal coincidences. From the GW catalogues, 103 promising candidates of different source classes are identified, followed by blind sensitivity studies using neutrino events with scrambled right ascension and a catalogue search with unblinded data for correlated neutrinos within a 1000 s time window. No statistically significant coincidences are found, and upper limits are estimated on the time-integrated, energy-scaled, per-flavour neutrino flux, $E^2 F_{\nu+\bar{\nu}}$. The upper limits are found to be in the range between 1 - 10 GeV cm^{-2} within $\mathcal{O}(10\text{--}100)$ GeV neutrino energy range.

To address the implications of non-detection, the thesis also investigates the prospects for identifying common GW-neutrino sources with next-generation facilities, particularly the Einstein Telescope and IceCube-Gen2. Binary black hole mergers in active galactic nuclei disks are investigated as promising candidates for powering relativistic jets. For Northern Hemisphere sources, the expected neutrino background in the $10^3\text{--}10^7$ GeV range is estimated per declination bin, and the detection significance is quantified for both individual mergers that ET could observe and their populations, as well as for individual neutrino detectors and their networks. It is found that, even with improved sensitivity of next-generation detectors, catalogue searches remain limited in potential. In contrast, stacking analyses offer a viable path to uncovering a population of common GW-neutrino sources in the future.

Zusammenfassung

Auf der Spur Kosmischer Koinzidenzen: Multi-Messenger-Suche mit Neutrinos und Gravitationswellen

Die Entdeckung astrophysikalischer Neutrinos und Gravitationswellen (GW) hat eine neue Ära der Multi-Messenger-Astroteilchenphysik eingeläutet und bietet einzigartige Möglichkeiten zur Erforschung des nicht-thermischen Universums. Während die gleichzeitige Detektion von GW und Neutrinos zusammen mit elektromagnetischen Signalen bereits in einzelnen Fällen gelungen ist, wurde bislang noch keine gemeinsame Quelle für GW und Neutrinos identifiziert. Eine solche Entdeckung würde beispiellose Einblicke sowohl in die Prozesse liefern, die kosmische Strahlung auf extreme Energien beschleunigen, als auch generell in die Physik kompakter Objekte.

Um die laufenden Suchbemühungen voranzutreiben, präsentiert diese Arbeit eine systematische Suche nach gemeinsamer GW-Neutrino-Emission, basierend auf der größten Stichprobe von archivierten GW-Ereignissen aus der dritten Beobachtungsphase der LIGO-Virgo-KAGRA-Kollaboration, die seit 2021 öffentlich zugänglich ist. Die Analyse nutzt die All-Flavour-Sub-TeV-Neutrino-Messungen des IceCube-Neutrino-Observatoriums, motiviert durch Szenarien, in denen außeraxiale Jets Doppler-entzerrte Neutrino-Spektren im Sub-TeV-Energiebereich liefern. Zum ersten Mal werden diese beiden Datensätze in einer Analyse kombiniert, wobei eine Blind-Maximum-Likelihood-Methode ohne Binning verwendet wird, um die statistische Signifikanz räumlicher und zeitlicher Übereinstimmungen zu bewerten. Aus den GW-Katalogen werden 103 vielversprechende Kandidaten verschiedener Quellenklassen identifiziert, gefolgt von Sensitivitätsstudien mit in der Rektaszension verschmierten Neutrinos und anschließender Katalogsuche nach korrelierten Neutrinos innerhalb eines Zeitfensters von 1000 s. Es wurden für keines der Ereignisse statistisch signifikante Koinzidenzen gefunden. Daher wurden Obergrenzen für den zeitintegrierten, energieskalierten Neutrinofluss pro Flavour für Neutrinoenergien von $\mathcal{O}(10\text{-}100)$ GeV berechnet. Dieses Limit liegt für alle Ereignisse im Bereich $E^2 F_{\nu+\bar{\nu}} = 1\text{--}10 \text{ GeV cm}^{-2}$.

Um die Auswirkungen der Nichtdetektion zu untersuchen, befasst sich die Arbeit auch mit den Aussichten für die Identifizierung gemeinsamer GW-Neutrino-Quellen mit Observatorien der nächsten Generation, insbesondere dem Einstein-Teleskop (ET) und IceCube-Gen2. Ver-

schmelzungen von binären schwarzen Löchern in aktiven galaktischen Kernen werden als vielversprechende Kandidaten untersucht, da sie das Potenzial haben, relativistische Jets anzutreiben. Für Quellen der nördlichen Hemisphäre wurde der erwartete Neutrino-Hintergrund im Bereich von 10^3 - 10^7 GeV pro Deklinationsbin bestimmt und die Nachweissignifikanz sowohl für einzelne Verschmelzungen, die von ET beobachtet werden können, als auch für deren Populationen unter Einzel-Detektor- und Netzwerk-Szenarien von Neutrino Observatorien quantifiziert. Es zeigt sich, dass selbst mit verbesserter Empfindlichkeit der Detektoren der nächsten Generation die Möglichkeiten der Katalogsuche auf Basis von Einzelereignissen begrenzt bleiben. Im Gegensatz dazu bieten Stacking-Analysen einen gangbaren Weg, um in Zukunft eine Population gemeinsamer GW-Neutrino-Quellen aufzudecken.

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Chapter 1. Introduction

"Nothing in life is to be feared; it is only to be understood. Now is the time to understand more, so that we may fear less."

- Marie Curie

The most energetic phenomena in the Universe remain among the most puzzling and least understood ones to this date. For over a century, cosmic rays (CR) and photons in a broad band of wavelengths have been considered as our primary messengers from such high-energy, non-thermal astrophysical sources. However, both come with inherent fundamental limitations, as photons are absorbed and CR are deflected during their journey towards the Earth. Consequently, the source of these high-energy messengers remains hidden, leaving us with fundamental questions regarding the mechanisms that naturally empower such energetic phenomena in the Universe and how they accelerate particles to the highest energies ever observed.

To overcome these challenges, new messengers were needed which could travel vast cosmic distances without any alteration. Astrophysical neutrinos perfectly fit the scenario as they are produced alongside CR via hadronic interactions in similar astrophysical environments. But being neutral and weakly interacting particles, they reach Earth unscathed. As a result, they carry unique information about the processes driving CR acceleration. A breakthrough in this direction was recorded in 2013, when IceCube, a neutrino observatory located in Antarctica, reported 28 high-energy neutrino event candidates in the energy range of 30 - 1200 TeV [1], revealing the presence of a diffuse high-energy neutrino flux of extraterrestrial origin. This opened a new window to the high-energy Universe. Just two years after that, the LIGO detector's direct observation of gravitational waves (GW) from a binary black hole merger, GW150914 [2], occurring ~ 410 Mpc away from the Earth, established GW as a new astrophysical messenger.

Following this, the first observation of a multi-messenger source was achieved through the coincident detections of GW and electromagnetic (EM) radiation from a binary neutron star merger, GW170817 [3]. It confirmed the association of short gamma-ray bursts and the subsequent kilonova with the merger of compact binary objects, specifically consisting of neutron stars. This marked the beginning of the era of 'multi-messenger astroparticle physics'. Since then, multi-messenger observations have allowed us to study cosmic sources by combining observations from different astrophysical messengers originating in the non-thermal Universe. Evidence of joint sources of EM radiation and neutrinos is continuing to emerge [4–6], pointing to promising hadronic interaction sites that serve as CR accelerators. Even the absence of coincident signals provides meaningful constraints, contributing to a richer and more comprehensive understanding of the most energetic and exotic environments of the Universe.

To obtain a complete picture, a common source of GW and neutrinos is yet to be identified, as shown in Fig. 1.1, despite several promising candidates currently under investigation. Such a detection would open a unique window into the innermost, densest regions of hadronic accelerators, which are otherwise inaccessible. To address this challenge, the IceCube Neutrino Observatory is playing an active role, both in real-time and archival follow-ups of high-significance GW alerts issued by the LIGO-Virgo-KAGRA (LVK) collaboration [7–13], employing diverse neutrino data samples spanning a wide energy range of neutrinos.

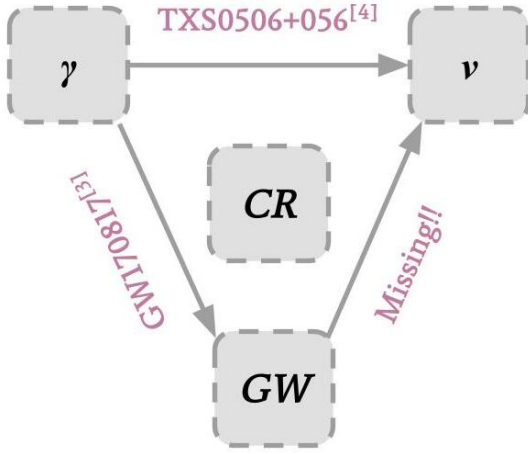


Figure 1.1.: The overall multi-messenger link. So far, coincident detections of Gravitational Waves (GW) and photons (γ) [3] and of neutrinos (ν) and γ [4] have been observed, while joint emission of GW and ν is still being searched for. Cosmic rays (CR), being deflected by magnetic fields, can not be directly correlated with other messengers.

However, the absence of confirmed joint GW-neutrino detections from these targeted follow-ups emphasises the need for more comprehensive and extensive searches. This thesis addresses that requirement by presenting a systematic study based on an extensive set of archival GW events, which have been publicly available since 2021. While these GW events passed only a less stringent detection criterion compared to that of the highly significant events, a coincident detection with neutrinos will boost their astrophysical relevance [14]. To enable such a search in the frame of this thesis, IceCube’s sub-TeV neutrino data sample is employed, since many potential joint GW-neutrino sources are expected to produce off-axis jets. In these scenarios, the higher-energy neutrino flux detectable at Earth gets Doppler de-boosted to sub-TeV energies [15], explaining the non-observation of high-energy neutrino counterparts.

This thesis also explores the prospects of identifying a common astrophysical source of GW and neutrinos with future detectors. In this context, binary black hole mergers are considered as prospective source candidates, since they represent the most abundant class of compact binary mergers that emit GW in the most sensitive frequency range for the terrestrial detectors. Under the assumption of the binary black hole system being embedded in an active galactic nucleus disk, post-merger, their remnants can launch relativistic jets. For such jets oriented toward Earth, and GW sources located in the Northern Hemisphere, the potential detection of TeV-PeV neutrinos from both individual sources and a population of GW-emitting binary black hole mergers is quantified, using detection capabilities of individual neutrino detectors, as well as their global networks. The detection significance for these configurations is quoted with the help of a robust background estimation. To this end, the layout of this thesis is as follows:

- **Chapter 2:** Introduces the framework of multi-messenger studies, while providing a brief overview of the individual messengers, and highlighting promising multi-messenger

sources, which could themselves emit or host astrophysical sources emitting GW and neutrinos in coincidence.

- **Chapters 3 and 4:** Describe the state-of-the-art techniques for GW and neutrino detection, respectively, together with the observations and data samples used in this thesis.
- **Chapter 5:** Presents the statistical analysis method applied for identifying significant coincidences between GW and neutrinos.
- **Chapter 6:** Discusses the selection of GW source candidates and the outcome of sensitivity studies performed with the ‘blind’ sub-TeV IceCube data sample, scrambled in right ascension.
- **Chapter 7:** Reports the results of the unblinded follow-up searches for coincidences between shortlisted GW events and IceCube-detected neutrinos.
- **Chapter 8:** Estimates the background in the Northern Hemisphere to explore the prospects for detecting joint GW-neutrino emission with enhanced future generations of detectors, focusing on binary black holes embedded in the disks of active galactic nuclei.
- **Chapter 9:** Concludes with a summary of the main insights gained from this work and their implications for future multi-messenger searches.

Chapter 2. Multi-messenger Astroparticle Physics: Concepts and Motivation

"Science is about connecting things. And that's what makes it beautiful."
— Donna Strickland

Astroparticle physics is an interdisciplinary research topic at the intersection of particle physics, astrophysics, and cosmology [16]. Currently, it is a thriving research discipline which tries to address the fundamental questions about highly energetic cosmic rays (CR), multi-wavelength photons, neutrinos, as well as gravitational waves (GW), coming from distant astrophysical sources. They are labelled as ‘messengers’, as all of them carry unique information about their respective astrophysical sources. Together, they provide unique insights into the high-energy universe, where they are naturally accelerated to energies far beyond the reach of terrestrial colliders [17].

Over the last few decades, this field has been further revolutionised as it was experimentally demonstrated [3, 4] how combining the information from the individual messengers can maximise the insight we can gain about the astrophysical environment they have experienced before reaching us. This marked the birth of ‘multi-messenger astroparticle physics’, which is a rapidly evolving field of research. As a part of this thesis, we will use this technique to search for common sources of GW and neutrinos, to enrich our understanding of such joint emission scenarios and possible sources. Before that, the individual messengers will be introduced and discussed in depth as a part of this chapter.

2.1. Cosmic Rays

The initiation of the field of astroparticle physics can be attributed to the first detection of CR. It all started with Theodore Wulf’s pioneering measurements of atmospheric ionisation at the base and summit of the Eiffel Tower. Wulf observed significantly higher ionisation levels at the top, which could not be explained by terrestrial radiation sources [18]. A decisive breakthrough came with the works of Domenico Pacini [19], Victor Hess [20], and Werner Kohlhörster [21], who unanimously confirmed the existence of charged particles of extra-terrestrial origin from their measurements. These particles, later labelled as ‘cosmic rays’, were found to be the cause behind the increasing ionisation with altitude.

At present, we know that CR constantly bombard Earth’s atmosphere from all directions. They can reach energies up to 10^{11} GeV due to acceleration at their sources, which is roughly 7 orders of magnitude higher than the Large Hadron Collider’s (LHC) current performance [17]. Observations suggest that they are composed of protons, alpha particles and heavier nuclei.

However, their exact proportion in the CR composition at different energies is still under investigation. After production, these CR particles propagate through galactic and extragalactic magnetic fields. Along the way, they get deflected and can lose energy through interactions with background photons.

After entering Earth's atmosphere, primary CR particles collide with air nuclei and can produce a shower of secondary particles, which comprises charged particles like mesons and leptons, as well as neutral particles like neutrinos and photons. A detailed discussion about CR induced air showers can be found in [17, 18]. However, in this section, we will mostly concentrate on the source properties to understand how they can achieve considerably high energies.

2.1.1. Observed Cosmic Ray Energy Spectrum

Multiple experiments, both via direct and indirect observations, have measured the CR energy spectrum, as shown in Fig. 2.1¹. It is spread across many orders of magnitude in energy and flux. In the energy scale around 1 GeV, we can expect to detect one particle per m² per s. But the flux falls steeply with increasing energy, and we end up with 1 particle per km² per century around 10¹¹ GeV. We can explain the CR flux across the entire energy range with a power-law as shown in Eq. 2.1.

$$\frac{dN}{dE dA dt d\Omega} \propto E^{-\gamma} \quad (2.1)$$

Here, N is the number of CR particles detected on Earth, E is its energy, A is the detector's surface area, and Ω is the solid angle. The power-law behaviour of the spectrum provides strong evidence that non-thermal processes govern CR acceleration [17]. The exponent γ is the spectral index, and its value varies at different points across the energy range, marking visible spectral features. The estimated best-fit values for the whole energy range are given in Eq. 2.2, following [17].

$$\frac{dN}{dE}(E) \propto \begin{cases} E^{-2.7}, & (E \lesssim 10^{6-7} \text{ GeV}) \\ E^{-3.1}, & (10^{6-7} \text{ GeV} \lesssim E \lesssim 10^{9.5} \text{ GeV}) \\ E^{-2.6}, & (10^{9.5} \text{ GeV} \lesssim E \lesssim 10^{11.5} \text{ GeV}) \end{cases} \quad (2.2)$$

As shown in Eq. 2.2, while the flux falls rapidly with energy, the spectrum starts steepening around 10⁶ GeV, known as the 'knee', as the spectrum softens from $\gamma = 2.7$ to 3.1 around 3×10^6 GeV. This feature is commonly interpreted as the gradual cutoff of galactic CR [17], with the maximum cutoff energy, $E_c = R_c \times Ze$, where R_c is the corresponding magnetic rigidity, and Ze is the total charge of a nucleus with atomic number Z , according to the Peters Cycle [24, 25]. It was experimentally supported by the data obtained by the KASCADE experiment [26]. Latest results show that there are more structures of individual mass spectra in this region, hinting towards different source populations [27–30].

¹GitHub repository: https://github.com/carmeloevoli/The_CR_Spectrum?tab=readme-ov-file

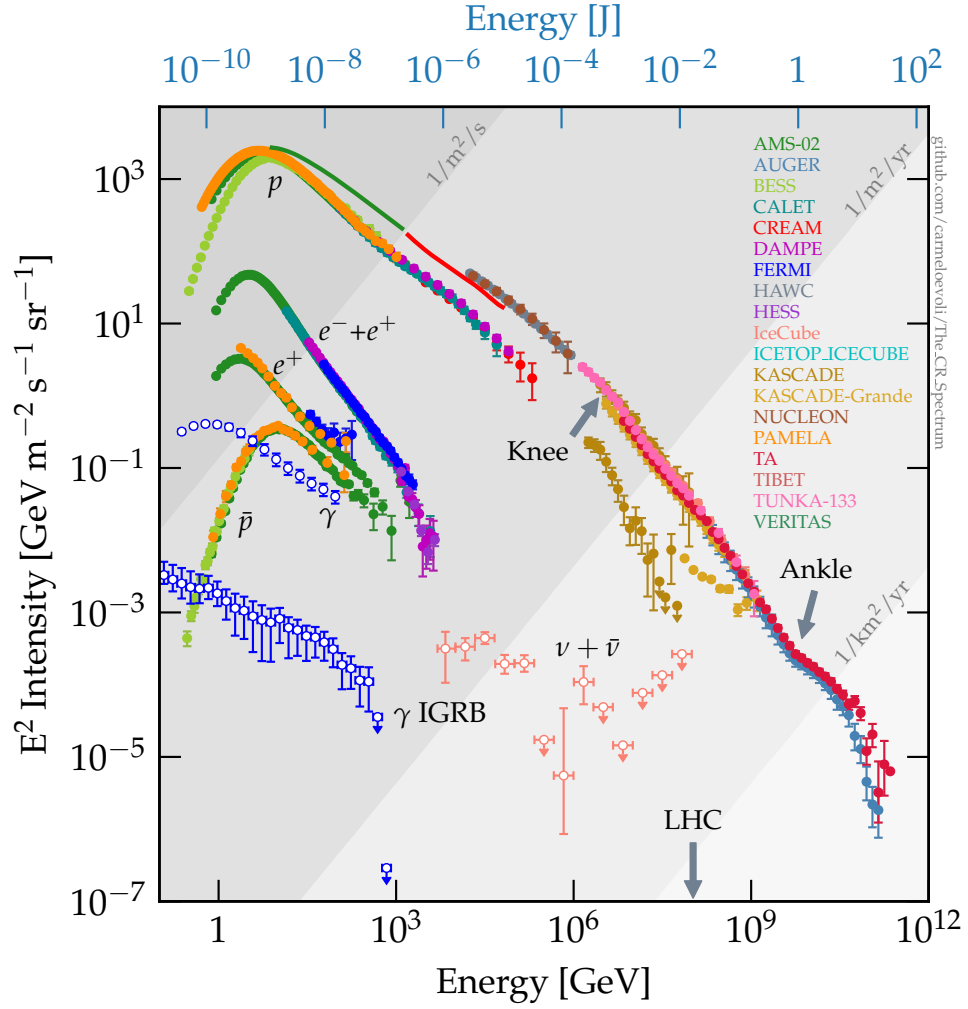


Figure 2.1.: The CR energy spectrum, as measured by several direct and indirect observations. The spectral features are pointed out on the plot, with the event detection rate. It also points out the required CR energy ($\approx 10^8$ GeV) to achieve a centre of mass energy similar to what the LHC produces ($\approx 1.4 \times 10^4$ GeV). Also, the diffuse high-energy neutrino (tracks + cascades) and the isotropic gamma-ray background (IGRB) spectrum are pointed out for comparison. Figure obtained from [22], produced by Carmelo Evoli, using the data available at [23].

Referring back to Eq. 2.2, the CR spectrum further hardens and starts flattening out as γ changes again from 3.1 to 2.6 till 3×10^9 GeV. It is known as the ‘ankle’. It is interpreted as the flux associated with the CR of extragalactic origin. This region is well measured by the Pierre Auger Observatory [31, 32] and the Telescope Array [33, 34]. Above this energy range, the spectrum further softens before it diminishes beyond 10^{11} GeV. According to Greisen [35], Zatsepin and Kuzmin [36], initially it was believed that the cut-off can be caused by the possible interaction between the CMB photons (γ_{CMB}), and the very high-energy protons (p^+), if they

are the dominating component at the end of the CR spectrum. This would initiate photo-pion production following a single pion channel as shown in Eq. 2.3, before they reach the Earth.

$$\begin{aligned} \gamma_{\text{CMB}} + p^+ &\rightarrow \Delta^+ \rightarrow n + \pi^+ \rightarrow n + \mu^+ + \nu_\mu \rightarrow n + e^+ + \nu_e + \bar{\nu}_\mu + \nu_\mu \\ &\rightarrow p + \pi^0 \rightarrow p + \gamma + \gamma \end{aligned} \quad (2.3)$$

The resultant neutrinos could be detectable on Earth, given a sufficient event rate ensured by a very large detector volume. They are known as the cosmogenic neutrinos, which are yet to be detected [37]. Additionally, recent results from the Pierre Auger Observatory suggest that the CR composition gets heavier near the suppression energy. For such a scenario, the observed spectral cut-off might originate from the limited acceleration power of the astrophysical sources [17, 38, 39].

2.1.2. Arrival Direction of Cosmic Rays

As CRs are charged particles, they are deflected by galactic and extragalactic magnetic fields as they propagate towards Earth. In the presence of a static magnetic field $\vec{B}$, a moving CR particle of charge Ze , mass m , velocity $\vec{v}$, and Lorentz factor Γ will experience a Lorentz force $\vec{F}_L$ being exerted on it, which could be quantified as,

$$\vec{F}_L = \Gamma m \frac{d\vec{v}}{dt} = \frac{Ze}{c} (\vec{v} \times \vec{B}). \quad (2.4)$$

As visible in Eq. 2.4, the particle will not be propagating in a straight line, but rather will undergo a helicoidal motion along the direction of $\vec{B}$ [40]. The associated Larmor radius for ultra-relativistic cases could be evaluated as,

$$r_L = \frac{E_{\text{CR}}}{ZeB} \sim \text{kpc} \times \frac{1}{Z} \times \frac{E_{\text{CR}}}{10^{18.5} \text{ eV}} \times \frac{3 \mu\text{G}}{B}. \quad (2.5)$$

From Eq. 2.5, it is evident that the deflection of CR particles should decrease with increasing energy, as magnetic rigidity ($R \simeq \frac{E_{\text{CR}}}{Ze}$) increases. Also, the CR particles of $E_{\text{CR}} \sim 1 \text{ PeV}$ should be well confined in our Galaxy [41, 42], for a typical value of the Galactic magnetic field $B \sim 3 \mu\text{G}$, in our vicinity. However, for CR particles of energy $\gtrsim 10^{18.5} \text{ eV}$, the Larmor radius is much larger compared to the size of our Galactic disk ($r_L \gtrsim 30 \text{ kpc}$). Thus, their origin must be extragalactic.

2.1.3. Cosmic Ray Accelerators

The astrophysical sources which can accelerate CR particles to extremely high energies must produce a CR flux that replicates the observed spectral shape of CR. To identify the sources, the underlying CR acceleration mechanism must first be understood.

One of the proposed mechanisms is diffusive shock acceleration, introduced by Enrico Fermi [17, 18]. In this process, a fast plasma collides with a slower surrounding material, leading towards the formation of shock fronts. Charged particles with initial energy E_0 repeatedly cross these non-relativistic shock fronts in a collisionless plasma. They gain energy through successive ‘head-on collisions’ with the approaching plasma flow. After each collision, the resultant energy of the i^{th} charge particle would be $E_i = \beta E_0$. In this case $\beta = \frac{v}{c}$, where v is the shock speed. After ‘ k ’ collisions, the final energy of the particle would be $E_i = \beta^k E_0$. It could be shown that the resulting fractional energy gain scales as $\frac{\Delta E}{E} \propto \beta$, leading to a source spectrum of $\frac{dN}{dE} \propto E^{-2}$ for the ideal diffusive shock acceleration. The source spectrum, when modified by propagation effects can somewhat account for the observed CR spectrum. This mechanism is famously known as the first-order Fermi acceleration, as $\frac{\Delta E}{E}$ has a linear dependence on β .

However, in his first attempt to explain CR acceleration, Fermi suggested that charged particles gain energy through repeated scattering in a turbulent plasma, with randomly moving magnetic clouds [43]. It involves particles scattering elastically off these magnetic irregularities, much like bouncing between ‘magnetic mirrors’. Because the mirrors are moving randomly, collisions with an approaching mirror make the particle gain some energy. In reverse, if the mirror is receding, the particles lose energy. In Fermi’s argument, he suggested that the probability of particles colliding with the mirrors moving towards them is higher. This would result in overall energy gain due to head-on collisions quantified as $\frac{\Delta E}{E} \propto \beta^2$, giving it the name ‘second-order Fermi acceleration’. This implies that the particle acceleration is less efficient in this case, compared to first-order Fermi acceleration.

The acceleration continues until the CR particle reaches a maximum energy (E_{max}) and escapes the acceleration environment once it has a Larmor radius $r_L > R_{\text{source}}$, which is the characteristic length scale of the source. E_{max} can be quantified following the Hillas criteria [38], which states the maximum attainable energy for acceleration in a shock with velocity β is $E_{\text{max}} = \beta q B R_{\text{source}}$, where $q = Ze$, the charge of the CR particle and B is the magnetic field strength at the source. The quantity β here is the velocity of the shock waves accelerating CR particles.

Following this relation, only a few sources can accelerate a CR particle of a given charge to higher energies. Also, given the B and R_{source} values associated with any source, the E_{max} value can be constrained, as visualised in Fig. 2.2. In addition to following the Hillas criteria, they should also satisfy the population criteria, i.e., the number density of the sources should be in agreement with the energy budget of UHECR, which is found to be $\sim 5 \times 10^{44} \text{ erg Mpc}^{-3} \text{ yr}^{-1}$ on Earth [45]. So, they can either be very populous but dim sources or scarce but bright sources. It is represented in Fig. 2.3, which is obtained from [44], where more details are available. Furthermore, the potential sources should also be capable of producing neutrinos in the TeV-PeV range, which is possible in a calorimetric environment which can trap CR protons with $E < 100 \text{ PeV}$ [46].

2.1.4. Limitations as a Messenger

Backtracking the CR path to identify their astrophysical sources is not straightforward, as charged particles suffer from massive deflection in the galactic and extragalactic magnetic field

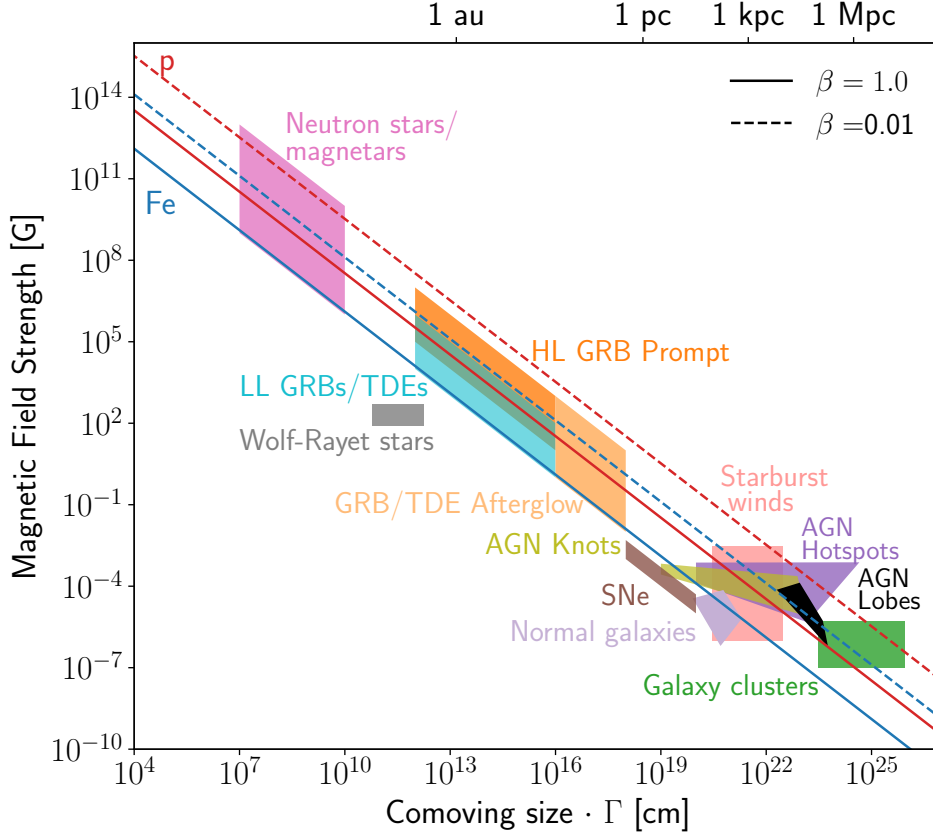


Figure 2.2.: Hillas diagram for a CR particle with energy 10^{20} eV, showing the limiting cases of proton and iron nuclei. Solid and dashed lines correspond to assumed shock speeds (β), corresponding to galactic ($\beta = 0.01$) and extragalactic ($\beta = 1$) sources. Details on the source classes are provided in [44], from which this plot is adapted.

while propagating towards us. For protons, the scale of deflection (θ) is quantified in Eq. 2.6, where E is the energy of the high-energy CR particle of extragalactic origin, B is the strength of the extragalactic magnetic field, and D is the distance of the source from Earth [47].

$$\theta = 3^\circ \frac{100 \text{ EeV}}{E} \times \frac{B}{\text{nG}} \times \frac{D}{100 \text{ Mpc}}. \quad (2.6)$$

Additionally, their deflection also causes a time delay for their arrival on Earth. In the Galactic scale, it is ~ 100 years, but it could be several thousand years for CR propagation through the extragalactic magnetic field [48]. Hence, direct correlation analysis can not be performed to identify the sources. Furthermore, the UHECR particles interact with CMB and the low-energy photon fields in the intergalactic medium, eventually losing energy before reaching the Earth. For all the above-mentioned reasons, it is more practical to rely on messengers created in the environments where CRs are accelerated, or on neutral secondaries produced at the sources, to identify potential UHECR origins. The following sections discuss these messengers in detail.

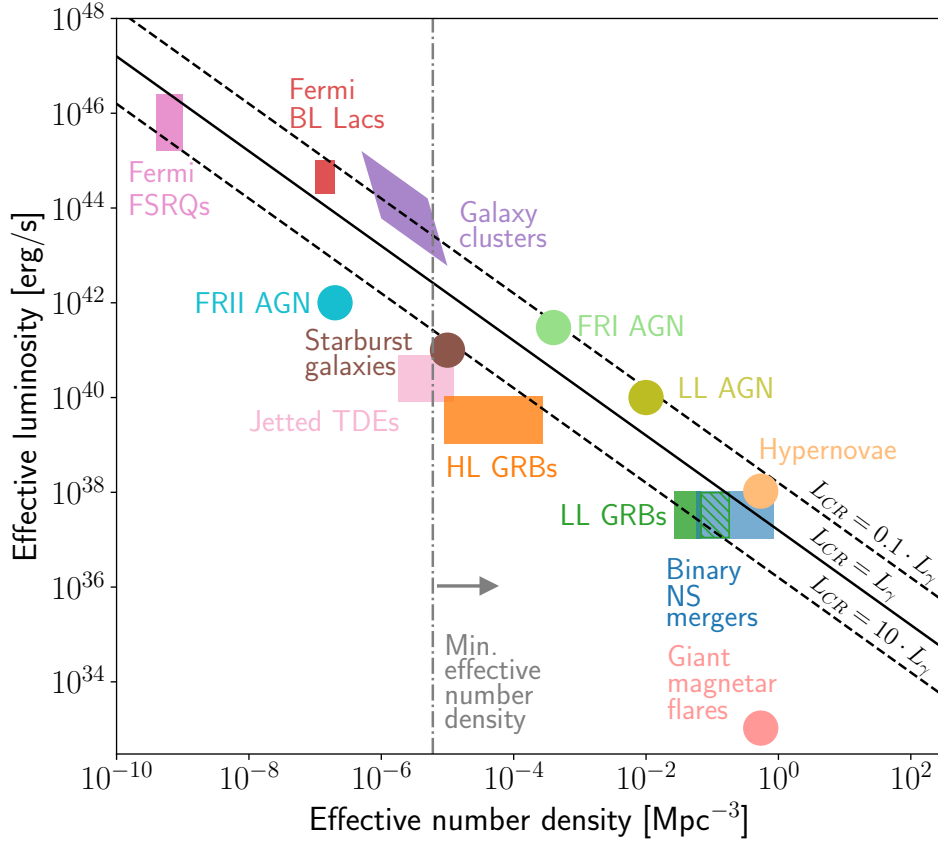


Figure 2.3.: Populations of candidate CR sources, obtained from [44]. The solid black line indicates those capable of supplying the required cosmic-ray energy budget of $5 \times 10^{44} \text{ erg Mpc}^{-3} \text{ yr}^{-1}$. Source luminosities shown here are inferred from photon observations. Further details are provided in [44]. Source classes lying to the left of the grey dashed line are considered too rare. To fit in, they need to be too bright, which would violate the observed CR flux threshold.

2.2. Photons

Historically, photons in the visible spectrum have served as the primary messenger for exploring the Universe. Today, they remain the most extensively studied messenger, observed across multiple wavelengths that probe different energy ranges.

2.2.1. Production Mechanisms

Photons span a wide range of wavelengths, from radio, infrared (IR), optical, ultraviolet (UV), to X-rays and gamma-rays. Typically, the radio waves, with wavelength, $\lambda \sim 1 \text{ mm} - \text{km}$, can have energy as low as 10^6 eV , whereas very high-energy gamma rays can reach up to $10^{12} - 10^{15} \text{ eV}$ [18]. Photons with different wavelengths are often associated with different physical processes and source environments, which in turn help classify the astronomical objects accordingly. Being electrically neutral particles, their paths are not deflected by magnetic fields. This

allows them to point directly back to their astrophysical sources, typically with good angular resolution.

Photons across multiple wavelengths can originate from various leptonic radiative processes involving high-energy electrons, such as synchrotron emission, bremsstrahlung, and (inverse) Compton scattering. A detailed discussion on this could be found in [49]. At the highest energies, particularly in the gamma-ray band (energies $\gtrsim 10^3$ eV), photons can also be produced via hadronic interactions, following the decay of neutral pions [50] created in CR interactions with matter (pp interaction) or ambient lower-energy photons ($p\gamma$ interaction) [50].

Both interactions are represented below in Eq. 2.7.

$$\begin{aligned}
p + p &\rightarrow \pi^{0/\pm} + X \\
p + \gamma &\rightarrow p(n) + \pi^{0(\pm)} \\
\pi^0 &\rightarrow \gamma + \gamma \\
\pi^+ &\rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \nu_e + \bar{\nu}_\mu + \nu_\mu \\
\pi^- &\rightarrow \mu^- + \bar{\nu}_\mu \rightarrow e^- + \bar{\nu}_e + \nu_\mu + \bar{\nu}_\mu
\end{aligned} \tag{2.7}$$

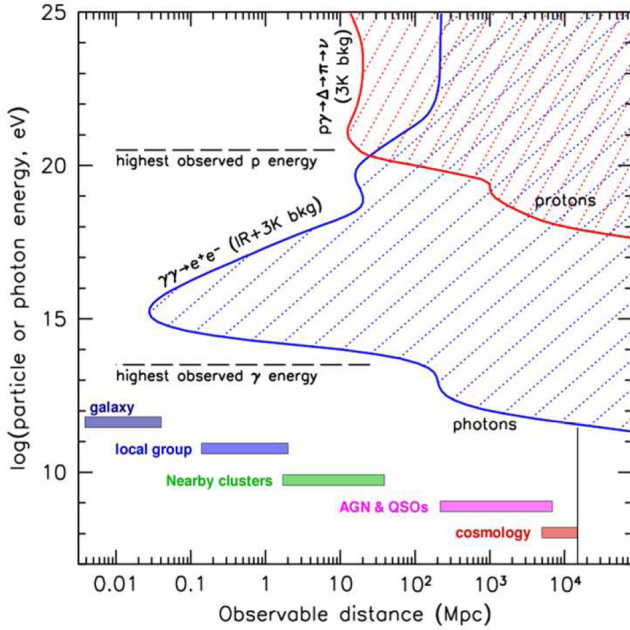


Figure 2.4.: CR proton and photon energy vs the distance within which they are detectable. Photons are affected by absorption in the infrared and CMB. The blue shaded area represents, for any given energy, the distance range a photon cannot reach. Protons, besides undergoing deflection due to magnetic fields, are also affected by the GZK cut-off as explained in Sec. 2.1.1. The red shaded area gives the distance range a proton cannot reach at a given energy. The figure is obtained from [51].

Thus, gamma-rays are being extensively used to identify CR accelerator candidates using the large number of gamma-ray telescopes observing the sky. Under the assumption that the secondary leptons produced in Eq. 2.7 share equal parts of the initial pion energy, and $\langle \frac{E_\pi}{E_p} \rangle \simeq 0.2$, the energy of gamma-rays produced (E_γ) is typically about 10% of the initial proton's energy (E_p) [46].

$$E_\gamma \approx \frac{E_p}{10}. \tag{2.8}$$

The interaction of UHECR with the CMB and the low-energy photon fields in the intergalactic medium produces ‘cosmogenic’ or ultra-high-energy photons, following the mechanism shown in Eq. 2.3. Their flux is sensitive to the composition of UHECRs, as a lighter composition would lead to the production of UHE photons. They can cascade down to lower energies, and their contribution to the isotropic gamma-ray background can be constrained by Fermi-

LAT. Thus, related studies can test models of CR sources, constrain their composition, and the physics governing their acceleration and propagation over vast cosmic distances.

2.2.2. Limitations as a Messenger

Despite the possibility of their origin in cosmic accelerators, high-energy gamma rays come with their own limitations as messengers. The ambiguity between leptonic² and hadronic production mechanisms also makes it difficult to definitively identify CR accelerators using photons alone. Furthermore, they are attenuated by interactions with ambient background radiation, particularly the extragalactic background light (EBL) and the CMB, and produce electron-positron (e^+e^-) pairs, as shown in Eq. 2.9.

$$\gamma + \gamma_{\text{CMB}} = e^+ + e^- \quad (2.9)$$

This effect imposes a photon horizon, significantly limiting the observable distance for very-high-energy (VHE) gamma rays, as shown in Fig. 2.4. As photons also interact with matter, CR sources could also be opaque to photons, as they can be absorbed and attenuated by dense clouds of matter surrounding the CR accelerator.

2.3. Neutrinos

Neutrinos (the "little neutral one") are neutral leptons in the Standard Model of particle physics [53, 54]. They come in three 'flavours', namely electron neutrino (ν_e) [55], muon neutrino (ν_μ) [56] and tau neutrino (ν_τ) [57], all companion neutral leptons for each of the charged leptons, which are electron (e^-), muon (μ^-), and tau (τ^-). ν_e and its anti-particle $\bar{\nu}_e$ were first proposed by Wolfgang Pauli to explain the continuous nature of the electron spectrum originating from β decay. Later, Enrico Fermi incorporated it into his theory of β^- decay [58], which successfully explained the entire phenomenon of radioactive decay, providing a firm theoretical foundation for neutrinos.

In the 1980s, the phenomenon of neutrino oscillation was observed, where neutrinos transform from one flavour to another because neutrino mass eigenstate and flavour eigenstate are different [59–63]. It predicts that neutrinos have non-zero rest mass, which is not permitted in the Standard Model. From cosmological evidence, a current upper bound has been predicted for neutrino mass (m_ν) for all neutrino species to be $m_\nu < 0.12$ eV [64], and from direct measurements for electron neutrinos, the current upper bound is $m_{\nu_e} < 0.45$ eV, as reported by the KATRIN collaboration [65].

Although many of their fundamental particle properties are elusive, neutrinos are ideal cosmic messengers. They are not deflected by magnetic fields and interact very rarely with matter or radiation. This allows neutrinos to travel virtually unimpeded from their sources to Earth, even from dense, radiation-opaque regions. Thus, from Earth we can observe the 'neutrino sky'

²In leptonic processes, they are produced via inverse Compton scattering [49]

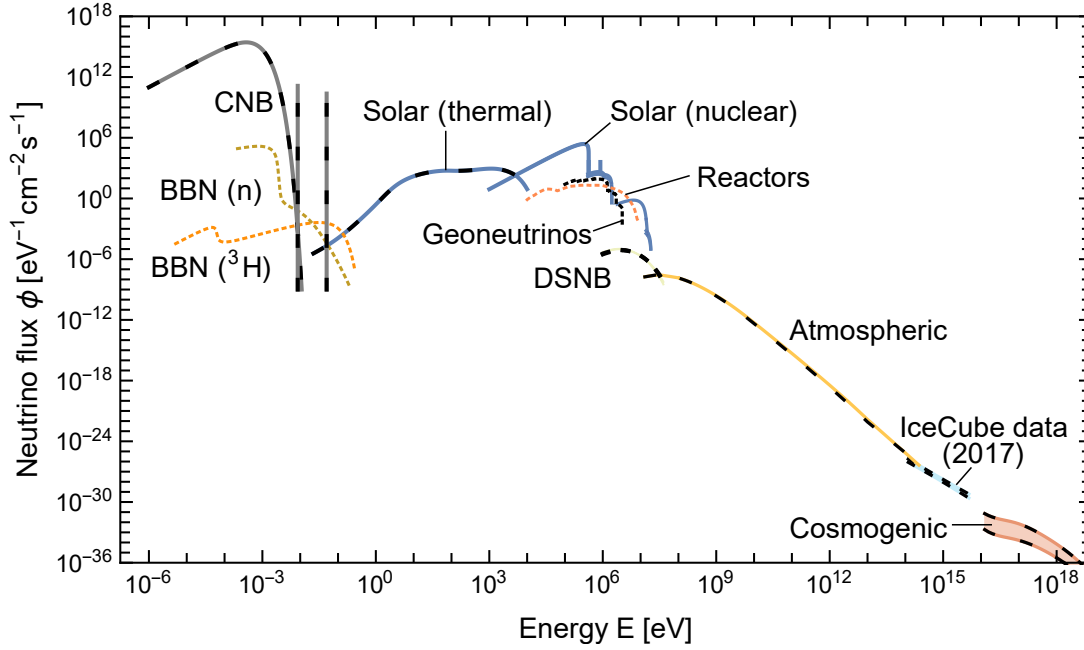


Figure 2.5.: A ‘grand unified neutrino spectrum’, coming from different source classes, as observable from Earth. The flux is integrated over zenith angle and summed over all flavours. In the figure, solid lines are for neutrinos and dashed lines are for anti-neutrinos. CNB is the cosmic neutrino background. BBN stands for big bang nucleosynthesis, and DSNB for diffuse supernova neutrino background. Cosmogenic neutrinos are produced from the interaction of ultra-high-energy cosmic rays with the cosmic microwave background. Figure and details obtained from [52].

spread over a wide range of energy, as depicted in Fig. 2.5, starting from neutrinos with meV energies, produced at different cosmological epochs, to the highest energy neutrinos related to CR interactions.

2.3.1. Production Mechanism of Cosmic Neutrinos

High-energy neutrinos are products of CR interactions with ambient matter or radiation at astrophysical sources. They are produced in astrophysical environments and are exclusively produced via hadronic processes, both via photo-hadronic ($p\gamma$) and hadronuclear (pp) interactions while the charged pions decay, as shown in Eq. 2.7. This makes them a ‘smoking gun’ signature for hadronic acceleration of CR. It is to be noted that for pp interaction, the ratio of the production of charged to neutral pions is $K_\pi = \frac{N_\pi^\pm}{N_\pi^0} \approx 2$. But for $p\gamma$ interaction, the non-resonant pion production makes $K_\pi \approx 1$ [66]. Following the calculations shown in Eq. 2.8, the energy of produced neutrinos (E_ν) is typically about 5% of the initial proton’s energy (E_p)

$$E_\nu \approx \frac{E_p}{20}. \quad (2.10)$$

In the calculations shown in Eq. 2.10, the parent CR particle is assumed to be a proton. For heavier CR nuclei, $E_\nu \simeq \frac{0.05 E_{\text{CR}}}{A}$, where A is the mass number of the CR nuclei of energy E_{CR} [46].

Whether the secondary pions, neutrons and muons decay, lose energy, or undergo further interactions depends strongly on the density of matter and radiation fields in the source environment. These processes shape both the intensity and the flavour composition of the neutrino flux that ultimately escapes. At the point of production, the expectation for neutrino and antineutrino flavour ratio is $\nu_e : \nu_\mu : \nu_\tau = 1:2:0$. Due to flavour oscillation, while traversing a large distance from the source to the detector on Earth, the final flavour ratio on Earth for astrophysical high-energy neutrinos should turn out to be $1:1:1$ ³ [69, 70].

2.3.2. Diffuse Flux of Astrophysical Neutrinos

The first detection of an isotropic flux of astrophysical HEN took place in 2013 [1] by the IceCube collaboration. The diffuse flux above ~ 100 TeV is broadly consistent with the Waxman-Bahcall (WB) bound [71], as shown in Fig. 2.6.

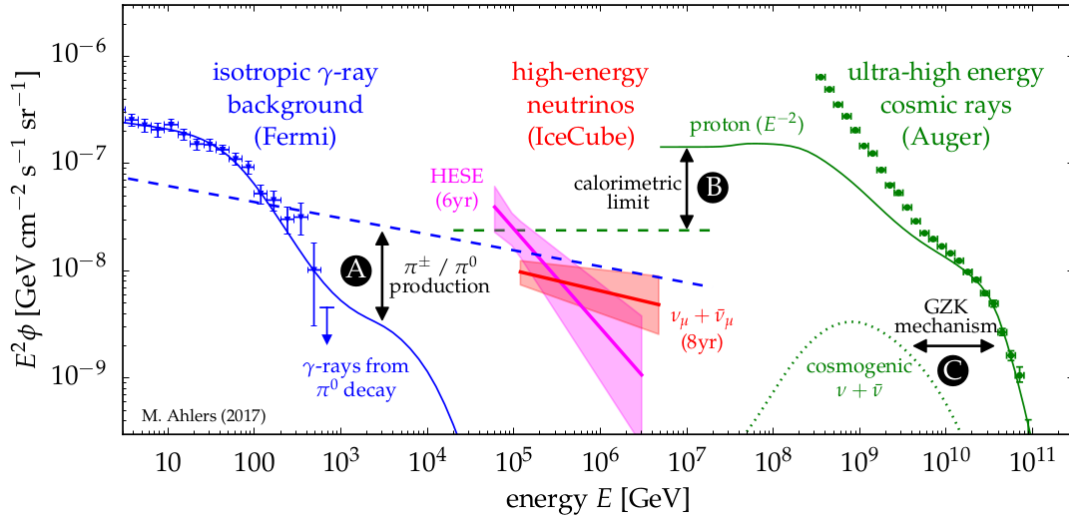


Figure 2.6.: Energy budget of extragalactic photons (blue), neutrinos (pink and red) and CR (green). The dashed lines illustrate expectations based on interconnections between these messengers. Their consistency with observations suggests a common origin. For instance, the blue dashed line reflects the link between neutrinos and gamma rays via pion decay, while the green dashed line corresponds to the Waxman–Bahcall limit on neutrinos inferred from CR data. Figure and details obtained from [72].

³A recent IceCube study favoured a muon-damped scenario, yielding a flavour composition $f_{\nu_e} : f_{\nu_\mu} : f_{\nu_\tau} = 0.19^{+0.26}_{-0.15} : 0.43^{+0.27}_{-0.17} : 0.38^{+0.37}_{-0.24}$, with 68% uncertainties. However, this can also hint towards a limitation in current reconstruction methods for the tau neutrino classifier [67]. With a better classifier, different event selection, and broken power law flux assumption, new result seems to favour the standard pion decay scenario, with best-fit $f_{\nu_e} : f_{\nu_\mu} : f_{\nu_\tau} = 0.30 : 0.37 : 0.33$, with 68% uncertainties. However, the muon-damped scenario is still within the 68% CL contour [68].

This bound was formulated in 1998, well before the discovery of high-energy neutrinos, and is based on the observed flux of UHECR above 10^{19} eV. The derivation assumes that UHECRs are extragalactic protons injected with a spectrum proportional to E_{CR}^{-2} , as expected from first-order Fermi acceleration (see Sec. 2.1.3), before modifications from propagation effects.

From the initial measurement of UHECR flux by Fly's Eye and AGASA⁴, and accounting for energy losses during propagation, the energy generation rate of extragalactic CR was estimated to be about $4.5 \times 10^{44} \text{ erg Mpc}^{-3} \text{ yr}^{-1}$ [45]. Expressed as the "energy per logarithmic particle energy interval", this budget remains approximately constant between 10^{19} and 10^{21} eV, and is also valid for lower-energy protons if they abide by the E_{CR}^{-2} injection spectrum for CR particles. On this basis, the WB bound predicts an upper limit (UL) for the per flavour diffuse extragalactic neutrino flux, $\Phi_{\nu+\bar{\nu}} \sim 10^{-8} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$. The agreement of IceCube's measurements with WB UL provided the first strong indication that the detected astrophysical HEN are extragalactic in origin, and served as an observational proof between the HEN production and extragalactic CR flux.

2.3.3. Limitations as a Messenger

An intrinsic limitation stems from the effectively unlimited horizon of neutrinos. Since they interact only weakly, astrophysical neutrinos can traverse cosmological distances essentially unimpeded, unlike photons, as shown in Fig. 2.4. Although it appears advantageous for the neutrinos, it also complicates source identification, since the detected flux may contain contributions from both very distant and relatively nearby sources, without an obvious way to disentangle them.

Additionally, the tiny interaction cross-section of neutrinos makes their detection notoriously difficult, requiring very large detectors (More in Ch. 4) to identify a sufficient flux of astrophysical neutrinos. On top of that, the astrophysical neutrino detectors on Earth also compete with the large atmospheric neutrino and muon flux, which serves as a 'background'. The atmospheric muons and neutrinos are produced as a result of CR interaction in our atmosphere. The CR interaction with the atmospheric nuclei initiates a hadronic shower, producing secondaries like pions ($\pi^{\pm}$), kaons ($K^{\pm}$) and D-mesons. The pions and kaons are short-lived particles which decay to muons and neutrinos/antineutrinos. The atmospheric neutrinos produced from the pion and kaon decays are labelled as 'conventional' flux [73, 74]. Alternatively, the heavier D-mesons decay first to charmed mesons, which further decay to produce the 'prompt' flux of atmospheric neutrinos [75]. These atmospheric muons and neutrinos can also travel all the way to reach the detector volume and mimic the exact signature that the astrophysical neutrinos leave after detection. To deal with the enormous background, all the astrophysical neutrino detectors employ various strategies which differ depending on the energy and arrival direction of the astrophysical neutrinos. It is discussed in detail in Sec. 4.2.2.

⁴Now we also have modified measurements from Pierre Auger and Telescope Array observatories.

2.4. Gravitational Waves

Gravitational waves (GW) were first formalised by Albert Einstein in 1916 as a consequence of his general theory of relativity (GR) [76]. In GR, gravity is described as the distortion of spacetime caused by the presence of energy and matter. The dynamics of the gravitational field and its coupling with matter are described by Einstein's field equations (EFE). It relates spacetime curvature to the energy and momentum density of matter in the following way,

$$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R = \frac{8\pi G}{c^4}T_{\mu\nu}. \quad (2.11)$$

Here, $R_{\mu\nu}$ is the Ricci curvature tensor, R is the Ricci scalar, $g_{\mu\nu}$ is the metric tensor, and $T_{\mu\nu}$ is the stress-energy tensor. G is the Gravitational constant, and c is the speed of light in vacuum.

2.4.1. Production, Propagation and Properties of Gravitational Waves

For systems far from a gravitating object, where the gravitational field is weak, spacetime can be considered nearly flat. In this context, $g_{\mu\nu}$ is expressed as a small perturbation ($h_{\mu\nu}$) around $\eta_{\mu\nu}$, which is the Minkowskian flat metric (diag(-1,1,1,1)). This implies, $g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$, where $|h_{\mu\nu}| \ll 1$. This approximation is known as linearised gravity.

Applying this to Eq. 2.11 and keeping only first-order terms in $h_{\mu\nu}$, one arrives at the linearised Einstein equations. In a vacuum, when $T_{\mu\nu} = 0$, it reduces to,

$$\square \bar{h}_{\mu\nu} = 0. \quad (2.12)$$

Here, $\square$ is the D'Alembertian operator and $\bar{h}_{\mu\nu} = h_{\mu\nu} - \frac{1}{2}\eta_{\mu\nu}h$, the trace-reversed perturbation (for each component of $\bar{h}_{\mu\nu}$, $\bar{h} = -h$). As implied by Eq. 2.12, which is a wave equation, perturbations $\bar{h}_{\mu\nu}$ in spacetime propagate as waves at the speed of light in vacuum. These are GW.

Under the far-field approximation for a slowly-moving source, the transverse, traceless, metric perturbation caused by a time-varying mass-energy distribution, denoted as h_{ij}^{TT} (generally referred to as the GW strain), is given by,

$$h_{ij}^{TT} = \frac{2G}{c^4 r} \frac{d^2 Q_{ij}^{TT}}{dt^2}. \quad (2.13)$$

Here Q_{ij} is the quadrupole tensor and Q_{ij}^{TT} is the transverse traceless Q_{ij} , obtained by using projection operators. The quantity ' r ' is the distance between the source and the observer. Eq. 2.13 states that accelerating mass distributions with a time-varying, non-zero quadrupole moment emit GW. The simplest example of such a system is a binary composed of two compact objects, such as black holes or neutron stars, orbiting each other. These systems produce a strong, continuously varying quadrupole moment arising from their asymmetric mass distribution and

orbital motion. This basic theoretical model underpins all confirmed GW observations to date, which involve the mergers of compact binaries. More on this is discussed in detail in Ch. 3. Unlike EM radiation, but similar to neutrinos, GWs interact extremely weakly with matter. They also do not scatter while propagating through the astrophysical media. This allows them to traverse vast cosmological distances with minimal distortion, at the speed of light. So, they can carry useful information about the bulk mass motion of the innermost and densest region of the astrophysical source. This unique property makes them powerful messengers of the whispers from the furthest, most extreme, and otherwise obscured regions of the Universe, and also about Gravity itself.

2.4.2. Limitations as a Messenger

Due to the small physical distortions they cause, current GW detectors have a comparatively closer horizon for detecting astrophysical transients⁵. However, it is expected to improve with future observation runs by increasing detector sensitivity and with next-generation observatories. Also, localisation of the GW sources is typically worse compared to what is obtained via photons and neutrinos. That is why identifying neutrino and EM counterparts of the GW emission helps us to better constrain the source location and study the source surroundings better.

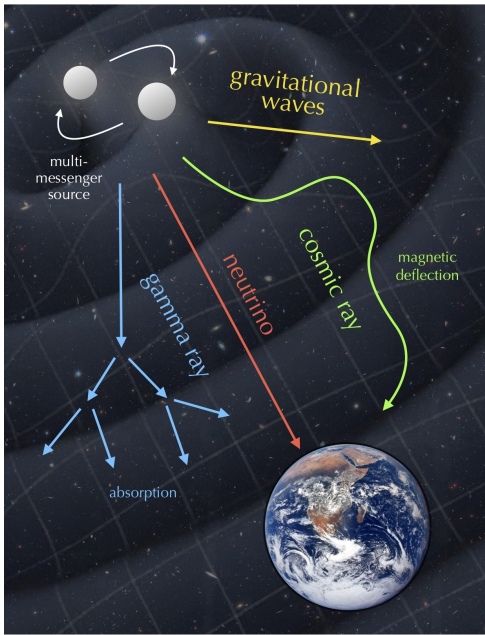


Figure 2.7.: The multi-messenger connection. Credit: Markus Ahlers. Source: [NBI](#)

An EM counterpart of a GW source has been confirmed [3], which also serves as the first coordinated real-time multi-messenger follow-up campaign. However, the joint emission of neutrinos and GW is yet to be determined, which establishes the main motivation of this thesis work.

2.5. The Multi-messenger Picture

As discussed above, so far, CRs are the most energetic particles ever detected. Over the last hundred years, they have been studied rigorously to earn insights about their Galactic and extragalactic sources. But the fundamental question about their origin remains poorly understood. One of the key challenges in localising their sources is the deflections they experience as they travel towards Earth. As the nature of the galactic and extragalactic magnetic fields is still not precisely known, simulating the CR trajectory yields imprecise results. However, the environment that supports CR production also produces secondary messengers, such as photons

⁵For example, the LVK horizon falls within 190 Mpc, depending on the detector, for binary neutron star mergers [77]

and neutrinos, as discussed before. The comparable energy densities observed in CRs, neutrinos, and photons across a wide energy range strongly suggest a common origin [71].

The WB bound, derived from observations of CR, provides an upper limit on the astrophysical neutrino flux, which is largely consistent with current neutrino observations [72]. In certain volatile source environments, GW may also accompany photons and neutrinos, produced by accelerating mass distributions with a time-varying quadrupole moment. The detection of such a multi-messenger signal would provide direct insight into the central engine driving the CR acceleration, which is often inaccessible via EM observations alone [78]. By combining the complementary information carried by different messengers, one can overcome the individual limitations and project a more complete understanding of the high-energy Universe, as depicted in Fig. 2.7.

2.6. Candidates for Multi-messenger Sources

On the Galactic scale, supernovae [79, 80] and the galactic plane [81] itself pose as multi-messenger sources of photons and neutrinos. Supernova remnants [82] and pulsar wind nebulae [83] are widely considered as plausible CR accelerators. Even core-collapse supernovae⁶ are expected to produce bursts of GW. However, the predicted amplitude is too small to be confidently detected with the sensitivity of current terrestrial GW detectors [84]. Nevertheless, more relevant to the scope of this thesis are the extragalactic sources, described below in more detail.

Active Galactic Nuclei

Among the extragalactic sources, Active Galactic Nuclei (AGN) are one of the most studied multi-messenger source candidates. It has a central supermassive black hole (SMBH) at the centre of the galaxy, known as the ‘core’. These are usually very bright, emitting a significant amount of radiation across the EM spectrum, powered by accretion of matter onto the SMBH. This intense energy output is not caused by nuclear reactions like those in stars, but rather by the accretion of matter onto a supermassive black hole (SMBH) at the galaxy’s centre. AGNs are sometimes accompanied by a relativistic jet that provides favourable conditions for hadronic acceleration [85, 86]. When such a jet is oriented towards Earth, the source appears exceptionally luminous and is classified as a ‘blazar’ [87]. Even AGN without jets, or those with misaligned jets, can still serve as CR source candidates [44, 86, 88]. Various propositions have been developed to explain CR acceleration that can occur in different parts of AGN [89–92]. Some of the most promising scenarios are discussed in [93–97]. Interestingly, evidence of neutrino emission has also been emerging from different source classes of AGN [4, 5, 98].

⁶The famous supernova SN 1987A is an example of a core-collapse or Type II supernova, from which both photons and neutrinos were observed.

Star Burst Galaxies

Another prominent class of multi-messenger sources are Star-Burst Galaxies (SBG) [88, 99], which host dense gas environments, powerful magnetised winds and elevated rates of star formation and supernovae. These conditions not only allow in-situ particle acceleration but can also facilitate scattering of ambient CR from other extragalactic sources, making SBGs compelling CR point-source candidates. Combining the data from Pierre Auger and Telescope Array observatories, SBG has been posing a favourable UHECR source candidate [94]. It is interesting as NGC1068 is not only a Seyfert galaxy. It also harbours substantial starburst activity in its circumnuclear region. [5, 100]. Furthermore, observation of radio emission [101] and gamma-rays from SBGs [102] indicates its candidature as an efficient CR accelerator.

Tidal Disruption Events

Tidal disruption events are transient phenomena caused by a star getting so close to an SMBH that it gets ripped apart by the SMBH's tidal forces. To date, they have been observed across a wide band of the EM spectrum, alongside a few instances of neutrino coincidences [103, 104]. They are also expected to emit GW caused by the stellar disruption. However, the frequency of emitted GW is much lower with respect to the current sensitivity range of terrestrial GW detectors [105]. With space-borne GW detectors under consideration, they would provide a unique opportunity to observe such events with multiple messengers and verify their credibility as CR accelerators.

Gamma Ray Bursts

Other than AGN and SBG, Gamma Ray Bursts (GRB) are also prominent multi-messenger sources. They are known to be the most energetic, bright, transient sources in the Universe. Their typical apparent luminosity can be 10^{52} erg s⁻¹. GRBs are observed to be isotropically distributed over the sky. This validates their extragalactic origin. Their EM spectra show evidence in favour of a broken power law, which suggests non-thermal particle production [106]. GRB burst duration has a bi-modal distribution, based on which further GRB subclasses are created. If a GRB is triggered by a compact binary merger, after emission of GW, the 'prompt' phase (T_{90}) lasts for less than 2 s [106–108]. It is labelled as a short GRB (sGRB). A central compact object is formed within this time, accompanied by a relativistic jet. There, non-thermal charged particles are accelerated in the presence of a strong magnetic field in the jet. This leads to sudden bursts of low-energy gamma-rays, which could also be accompanied by X-ray emission. The GRBs lasting for a longer timescale, with $T_{90} \sim \mathcal{O}(100)$ s, are generally connected to the catastrophic deaths of a massive star, collapsing into a black hole, also believed to produce a burst of GW. It is usually termed as the 'collapsar', which also creates a central compact object and relativistic jets as described above. A schematic diagram of GRB is shown in Fig. 2.8

In the presence of a relativistic jet, the accelerated protons in and around the jet actively participate in hadronic interactions. Accelerated protons in these jets must interact with the strong

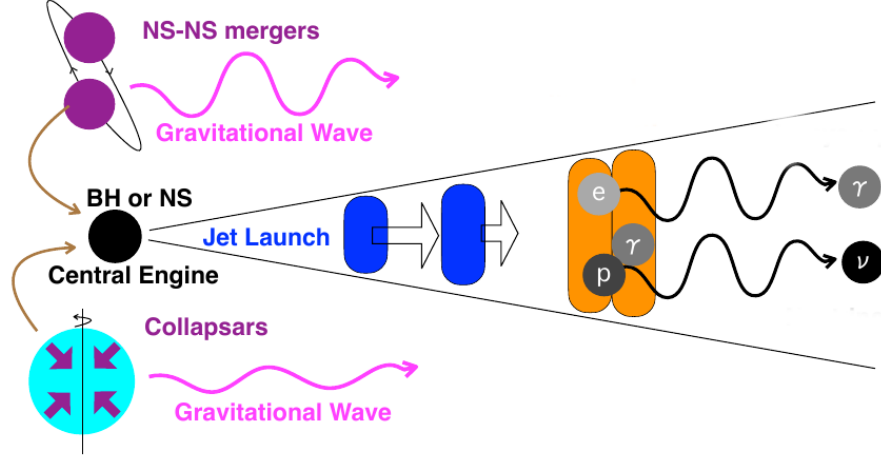


Figure 2.8.: Schematic diagram of a GRB, obtained from [106], and further modified.

photon fields in the relativistic jet. The $p\gamma$ interaction produces high-energy neutrinos as a secondary particle, via charged pion decay. It is worth mentioning that high-energy neutrinos can also be produced via pp interaction. However, it gives a conservative approximation of the observed neutrino flux, which certain GRB models could still favour with highly matter-dense jets. Despite all these strong hints from theoretical modelling of GRBs and decade-long observational efforts, coincident detection of high-energy neutrinos from GRBs is still missing [109–111], which has led towards meaningful constraints on the baryonic loading factor, for example. However, observation of very-high-energy gamma-rays from GRBs has kept the debate ongoing [112, 113].

Compact Binary Coalescences

Compact binary coalescences (CBC) are closely related to GW emission. Furthermore, they can also be embedded in the AGN environment [114–117] and can be hosted by an SBG, which already comes with a high amount of massive stars as well as a high rate of core-collapse supernovae [118]. Also, it is already observed that they can trigger GRBs [3]. In that process, mergers of compact objects, particularly binary neutron star (BNS) mergers, are theorised to produce powerful, relativistic jets. These jets are nearly identical due to the narrow range of BNS masses. This provides a compelling explanation for the observed narrow rigidity range ($\frac{E}{Ze}$) of UHECRs, a long-standing puzzle [119]. Efficient CR acceleration can also occur in long-lived, highly magnetised outflows outside the main jet, where turbulent magnetic fields can transfer up to half of the dissipated energy to CRs, making them overall potential UHECR sources [119].

It is also possible for a Binary Black Hole (BBH) remnant to have relativistic jets [120], if a BBH merger occurs in an AGN disk [116, 117]. The dense, gaseous environment of the AGN disk allows the remnant BH to accrete matter. The accretion of matter can power EM radiation. On the other hand, if the remnant BH acquires high spins and enhanced accretion

rates, it can lead to the launch of powerful jets. These jets are ejected from the remnant BH and propagate into the surrounding dense AGN disk atmosphere, where they collide with disk materials. The interaction between the jet and the AGN disk medium generates various types of shocks, responsible for accelerating CR protons to high energies. The accelerated CR protons can interact with the disk gas and ambient photon fields, and hadronically produce photons and neutrinos, as shown in Eq. 2.7, which strengthens the multi-messenger connection [115].

Despite all these promising scenarios, the ‘smoking gun’ signature of high-energy neutrino observation from CBC is yet to be confirmed [7–12, 121, 122]. Nevertheless, CBC has already been established as an interesting multi-messenger source as depicted in Fig. 2.7, presenting multiple promising avenues for CR acceleration and connecting GW, CR, photons, and neutrinos within a unified framework. This thesis is therefore driven by the search for such multi-messenger associations, with a focus on identifying potential neutrino counterparts to GW detections, as it is still a missing link. To this end, the next chapters introduce the methods and resources employed in this investigation, summarise the results and investigate prospects of joint detection of GW and neutrino emission from common astrophysical sources.

Chapter 3. Detecting Gravitational Waves: Instruments and Data

"Matter tells spacetime how to curve. Spacetime tells matter how to move."
- John Wheeler

Gravitational waves (GW) are ripples in the fabric of spacetime, caused by massive accelerating objects, as presented in Sec. 2.4. The first indirect evidence of GW emission came from the observation of the Hulse-Taylor binary system PSR 1913+16 [123] in 1975. It was observed that the ‘periastron’, i.e., the point of closest approach in a binary star system, was shifting closer. This implies that the rotational period is decreasing over time. The reason is the energy loss due to GW radiation. Decades after the indirect detection of GW, direct observation was achieved in 2015 [2]. This marked the beginning of a new era in observational astrophysics. Since then, a growing network of GW detectors has enabled the detection of 90 confirmed GW sources till April 2020 [124–126], which is now updated to over 200, accounting for detections till January 2024¹ [127].

This chapter illustrates the key ingredients for GW data analysis, which will become relevant in Ch. 6 and 7. Beginning with discussing the principles for direct detection of GW signals from astrophysical sources, current GW detectors and the basics of data processing are presented. Finally, the known sources of GW, along with related information inferred from the publicly available data, are discussed.

3.1. Direct Detection of Gravitational Waves

The very first direct detection of GW from distant astrophysical sources was associated with a stellar-mass ($36^{+5}_{-4}M_{\odot}$ and $29^{+4}_{-4}M_{\odot}$) binary black hole (BBH) merger, which occurred ~ 410 Mpc away [2]. The associated time-frequency plot for this pivotal discovery is shown in Fig. 3.1. It presents multiple complementary views of the signal in both time and time–frequency space for the Hanford and Livingston detectors. More details are discussed in Sec. 3.1.1.

Since this landmark detection, binary neutron star (BNS) and neutron star–black hole (NSBH) systems were also identified as GW emitters. The component masses of all detected GW sources till O3 are illustrated in Fig. 3.2. These discoveries have provided unprecedented insights into the astrophysical population and dynamics of compact binaries (see discussion in Sec. 3.5), often beyond the reach of other terrestrial experiments and messengers like photons.

To understand how such faint signals originating $\mathcal{O}(100)$ Mpc away can be captured with high confidence, it is essential to examine the fundamental working principles of GW detectors.

¹Latest report from GWTC-4.0 [127], from August 2025. It is mentioned here for completeness, but for analysis purposes relevant to this thesis, I will stick to the events detected till 2020.

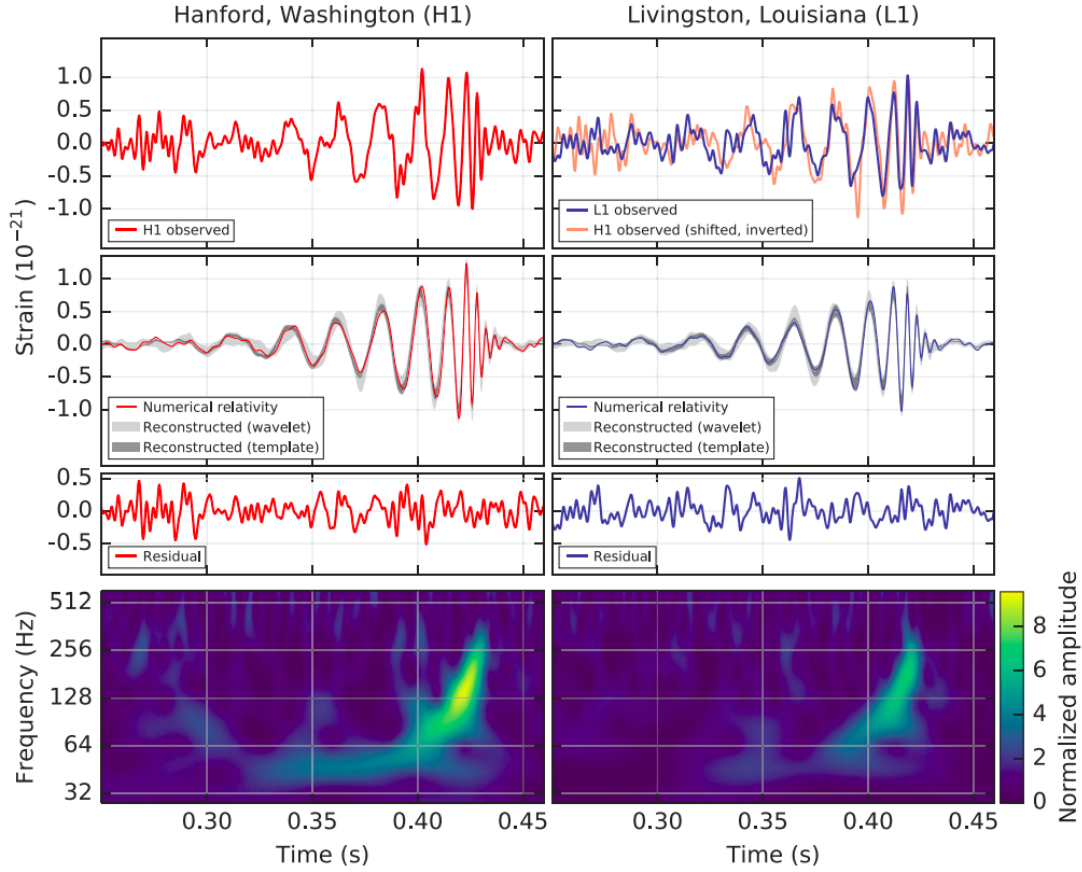


Figure 3.1.: (Top panel) Time-domain and (bottom panel) time-frequency representation of the GW150914 signal as recorded by the two LIGO detectors: Hanford (H1, left) and Livingston (L1, right), obtained from [2]. See text for details.

3.1.1. Detection Principle

As mentioned previously, GW signals are produced by massive objects when they are accelerated, similar to the emission of EM radiation due to accelerated electric charges. The propagating GW signal causes spacetime to alternately stretch and compress in directions perpendicular to its direction of travel, as it propagates outward at the speed of light. The strain produced by a passing GW is defined as the fractional change in length, $h(t) = \frac{\Delta L}{L}$, between free-falling test masses.

Direct detection of GW requires building an extremely sensitive detector that can unambiguously identify the length variations (ΔL) caused by the propagation of GW. According to Eq. 2.13, this strain is directly proportional to the second time derivative of the mass quadrupole moment of the source. However, the numerical value of $h(t)$ associated with cataclysmic astrophysical phenomena, such as compact binary coalescences (CBCs), is minimal. At a representative distance of 200 Mpc, the $h(t) \sim 10^{-21}$ [128]. It corresponds to a length change $\Delta L \sim 10^{-18}$ m for an interferometer with an arm length, $L = 1$ km.

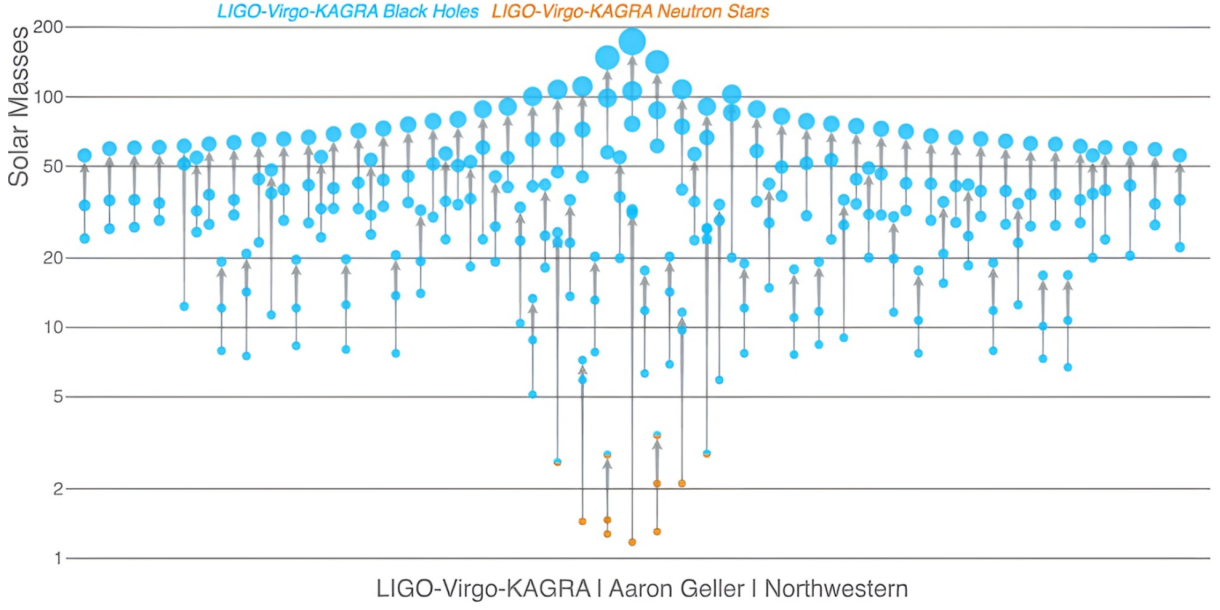


Figure 3.2.: The astrophysical sources of the 90 GW signals confidently detected till the third observation run (O3). All of them are associated with compact binary mergers, such as BBH, BNS and NSBH mergers. The masses of the corresponding components of each binary system are also depicted. Credit: [Aron Geller/U-Chicago](#).

Additionally, the strain amplitude at the detector scales inversely with distance from the source, as evident from Eq. 2.13. Thus, despite originating from some of the most energetic events in the Universe, the resulting strain on terrestrial detectors remains extremely small. As a consequence, detecting such signals requires exquisitely sensitive instruments capable of measuring length changes many orders of magnitude smaller than the radius of an atomic nucleus ($\sim 10^{-15}$ m).

Precision laser interferometry using suspended test masses has long been recognised as a viable technique for detecting such geodesic deviations caused by extragalactic GW sources [129]. Based on this, first-generation (1G) ground-based interferometers, such as GEO600 [130] in Germany, the French-Italian Virgo project [131], and the initial LIGO detectors [132] in the U.S., played a crucial role in pioneering this technology and refining key design principles.

While these initial instruments did not make detections, the breakthrough came with the second-generation (2G) GW detector, the Advanced Laser Interferometric Gravitational Wave Observatory (aLIGO) [133]. It was built and became operational in September 2015. It is an enormous L-shaped Michelson interferometer with perpendicular arms stretching 4 km in each direction. It was further equipped with much better noise reduction techniques, which enhanced its sensitivity (see Sec. 3.1.2). A schematic diagram of the interferometer framework is shown in Fig. 3.3.

According to [133], a multi-stage Nd:YAG laser (wavelength, $\lambda = 1064$ nm), with an output power up to 180 W, is used as a light source [134]. A beam splitter is introduced in the middle to divide the main beam of light into two beams, travelling along the two perpendicular inter-

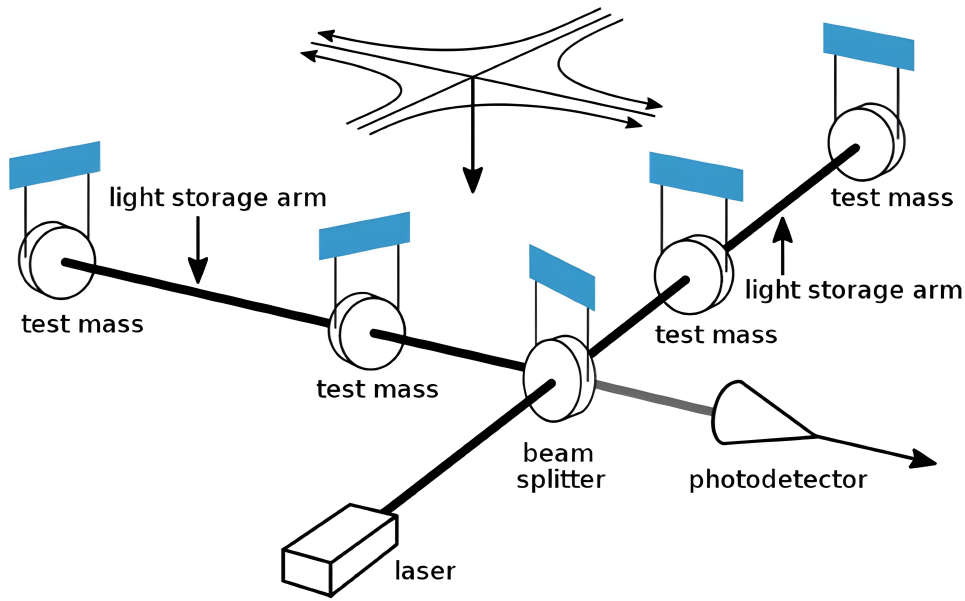


Figure 3.3.: Diagram of the LIGO interferometer. The basic design and principle are explained in the text. Image courtesy: [LIGO Laboratory](#)

ferometer arms, towards the mirrors at the end². The two beams reflect within a cavity and eventually recombine. They superpose within a photodetector to create an interference pattern. The interferometer is set up such that there is a phase difference of 180° upon recombination. As a result, there should be complete destructive interference and no light signal in the detector, in the absence of a GW signal.

The passing of GW translates to a differential change in the lengths of the interferometer's arms. This differential length change causes a relative phase shift between the light beams returning from the arms. This phase shift, even if minute, alters the interference pattern of the recombined light, leading to a change in the intensity of light detected at a photodiode. The change in the photodiode's output current is directly proportional to the GW strain, $h(t)$. Interferometers like LIGO are designed to measure these minute changes, which lead to the strain data.

An example is shown in Fig. 3.1 for GW150914. The top panels display the raw strain data, with the Hanford trace shifted and inverted to match the Livingston signal for clarity. The second row overlays the observed strain with theoretical predictions from numerical relativity, wavelet reconstruction, and template waveforms, demonstrating their close agreement. The third row shows the residuals obtained by subtracting the best-fit waveform from the data, indicating that the measured noise is consistent with the detector background. Finally, the bottom panels present spectrograms of the data, revealing the characteristic 'chirp' signature of a compact binary merger, which is characterised by an increase in frequency and amplitude as the two black holes spiral together and merge [2].

²These are the 'freely-falling test masses', as they are isolated from external forces as much as possible, apart from the suspension system keeping them in place. So, their motion reflects only the influence of spacetime distortions caused by GW.

3.1.2. Noise Mitigation

To keep the detectors operational, the main challenge has been to maintain a sufficiently low noise level in the system, allowing for the confident measurement of even the smallest changes. For this sensitivity, many noise sources become relevant, such as seismic vibrations that are dominant in the low-frequency range [135], thermal vibrations of the strings carrying the mirrors [136], and vibrations of the mirror surfaces [137]. Due to the quantised nature of light, photons in the laser beam arrive at irregular intervals, following a Poisson distribution. This leads to two quantum noise effects:

- Fluctuations in the detected optical power, known as photon shot noise [138].
- Fluctuating radiation pressure on the mirrors, causing a jitter in the position of the mirrors [139].

To counter various noise sources, the state-of-the-art technique utilises Fabry-Pérot cavities in the interferometer arms. They effectively multiply the length of the arms by storing the laser light for many round trips. Hence, this configuration amplifies the GW-induced phase change. Additionally, power-recycling mirrors have been implemented to sharpen the interference fringes [140], and squeezed light is used to mitigate the quantum noise [141, 142]. Furthermore, sophisticated vibration-dampening technology has been used to suppress terrestrial noise in the 2G detector configuration [143]. Looking ahead in the future, to enhance sensitivity to even fainter GW signals, cryogenic cooling has already been tested with KAGRA [144] and will be implemented in the future third-generation (3G) detectors for reducing thermal noise.

3.2. Gravitational Wave Detection Network

Despite the event discoveries made by aLIGO, a single detector alone cannot provide complete information about a GW event. The faintness of the signal and the variety of noise sources make it difficult to confidently determine the signal's origin, direction and properties using just one instrument. This is where a global network of GW detectors is highly beneficial. By operating in coordination, these detectors can rapidly triangulate the location of a GW source through slight differences in the time at which the wave arrives at each site. This not only improves sky localisation but also increases sky coverage and confidence in the detection by ruling out local noise artefacts. Furthermore, different orientations and sensitivities of the GW network enable more accurate parameter estimation for the GW signal, such as its polarisation and amplitude [145].

Currently, there are five operating GW detectors on Earth. Two of them are the aLIGO detectors in the United States, in Hanford, Washington, and Livingston, Louisiana [133] which have been operational since 2015. Its configuration has already been mentioned in Sec. 3.1.1.

There is also the Advanced Virgo (AdVirgo) detector in Cascina, Italy [146]. It joined the LIGO detectors from their second observation run (O2), creating the LV network. It was active during the detection of GW170817, the first GW signal associated with a BNS merger that occurred in

the galaxy NGC 4993 [3]. It is historically significant since GW170817 was the first GW source to be followed up via multi-messenger campaigns. The observation of EM transients from GW170817 revealed a plethora of new information beyond the scope of what either messenger could have provided individually. Interpretation of the complementary information carried by photons and GW, originating from a single source, has revealed new insights into mysteries like the origins of short gamma-ray bursts and the production of heavy elements in the Universe. This has also enabled independent probes of cosmological expansion and high-precision tests of fundamental physics. The prospects of more such detections further add to the potential of GW observations from CBCs to be unique and powerful probes of fundamental physics.

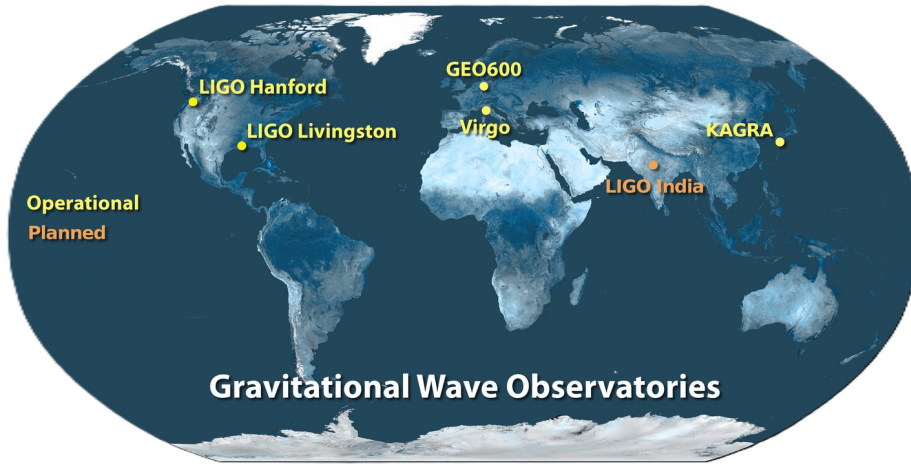


Figure 3.4.: Location of the current (LIGO, Virgo, KAGRA, GEO600) and future (LIGO-India) GW detectors. Source: **LIGO**

During the third observation run (O3), Kamioka Gravitational Wave Detector (KAGRA), joined the existing LV network [144]. It is situated in Hida, Japan. Like AdVirgo, KAGRA also has 3 km-long arms. Unlike other detectors, it utilises cryogenic mirrors to reduce the coating noise of the mirrors. However, KAGRA hasn't reached its estimated sensitivity after its commissioning. So far, it acts as a calibration device. By the end of O3, all the GW detections have been detected with the aLIGO and AdVirgo detectors. Finally, there is also the GEO600 detector in Hannover, Germany [130]. It has 600 m long arms. Though the shorter arm length limits its sensitivity, it played a key role in developing the mirror suspension techniques and interferometers [136]. There is also a planned installation of another aLIGO detector in India [147, 148]. Fig. 3.4 shows the respective positions of all the current and planned detectors on the world map.

Prospects with Third Generation Detectors

The Einstein Telescope [149] (ET) is a prospective third-generation (3G) ground-based GW detector poised to be operational by the mid-2030s. It will be accompanied by Cosmic Explorer [150] (CE), another future 3G detector, foreseen to be active in the 2040s.

ET, a proposed European project, will feature a triangular (10 km arms each) or 2L (15 km arms each) configuration. It will be an underground GW detector, which enhances its sensitivity, par-

ticularly at lower frequencies, compared to 2G detectors. CE represents the U.S. community's effort in 3G detection, considering arm lengths of 40 km and 20 km. These proposed observatories aim to achieve an order of magnitude better sensitivity and a wider accessible frequency band than 2G detectors, such as aLIGO and AdVirgo. This leap in capability will allow for the detection of an immense number of CBCs, with ET alone expected to detect $10^5 - 10^6$ BBH mergers per year, reaching cosmological redshift up to $z \sim 20$, and BNS mergers at rates of around 7×10^4 per year, extending to $z \sim 2-3$ [151].

When operating as a network, ET and CE can complement each other. ET excels at low frequencies due to its underground placement, while CE offers slightly better sensitivity in the 10 - 100 Hz range due to its large arm length [152]. Their combined efforts will significantly improve source localisation and parameter estimation, which is crucial for advancing multi-messenger astrophysics through joint GW, neutrino, and EM observations [153].

3.3. Identifying Gravitational Waves from Astrophysical Sources

During the data-taking runs, information recorded by each detector is processed to identify GW signals using the 'matched filtering' technique [154]. In this method, the GW signal is 'matched' with a collection of template waveforms to identify potential signal candidates in the presence of additive Gaussian noise. This is achieved by maximising the 'signal-to-noise ratio' (SNR). It is an optimal detection statistic for a signal as it is directly related to the likelihood ratio to determine the signal's strength, modelled as a known waveform, relative to the additive Gaussian noise [155, 156].

3.3.1. Signal-to-Noise Ratio

In the matched filtering framework, instead of directly calculating the SNR (ρ), the power SNR (ρ^2), which represents the square of the amplitude SNR (ρ), and is an additive quantity for a network of detectors, is evaluated in the time domain.

$$\rho^2(t) = \int_{-\infty}^{\infty} \frac{H^*(f)W(f)}{S_n(f)} e^{-i2\pi ft} df. \quad (3.1)$$

As shown in Eq. 3.1, $H^*(f)$ is the complex conjugate of the Fourier transform of $h(t)$, which represents the GW strain data. It consists of the GW signal waveform with unknown amplitude and arrival time, embedded within the noisy data. The data is modelled as $\omega(t) = \alpha h(t - t_0) + n(t)$, for which $W(f)$ is the Fourier transform. Here, α is an amplitude scaling factor, t_0 is the signal arrival time, and $n(t)$ is the detector noise. $S_n(f)$ is the two-sided power spectral density (PSD) of noise $n(t)$ [155].

In the context of a GW detector network, as a first step, (ρ_i^2) is calculated for individual detectors. If $\rho_i^2(t_d)$ exceeds the predetermined SNR threshold ρ_{th}^2 , for individual detectors, candidate detection is recorded, subject to the associated false alarm probability. However, high SNR values can also arise from non-stationary noise artefacts or glitches [157]. Therefore, SNR

alone is usually not the optimal choice for ranking GW candidates. To mitigate this, additional signal-consistency tests are applied: Two main methods are defined below:

- χ^2 signal consistency test: It evaluates whether the time-frequency distribution of power within detected data aligns with the expected power (ρ^2) distribution of a matching GW template. A true GW signal is expected to distribute its power consistently across all frequency bands, leading to a low χ^2 . In contrast, noise transients often produce high total SNR, but their power is typically concentrated in only a few frequency bands. This inconsistent power distribution results in a large χ^2 value, indicating that the event is likely a glitch [158].
- ξ^2 signal consistency test: It compares the SNR time series of a detected event to the auto-correlation of the template waveform time series, indicating how closely the data matches the expected GW signal, ideally being zero for an exact match and one for a noise transient [159].

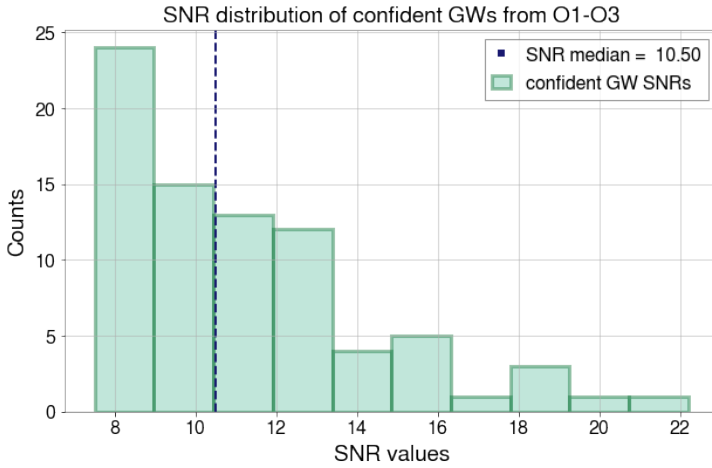


Figure 3.5.: SNR distribution of all the 90 significant GW events starting from the first to the third observation run of LIGO-Virgo-KAGRA (LVK).

Using ρ_i , χ^2 , or ξ^2 , and other information, such as the signal arrival time and phase at different detectors, various search statistics are constructed for ‘ranking’ GW candidates according to their statistical significance or likelihood of being a potential astrophysical signal [160]. In this process, triggers from different detectors that hail from the same template are clustered across a time window for coincidence formation. Even though single-detector triggers are not extremely uncommon, they are down-weighted in the ranking.

For events passing these checks, the network SNR is reported as the quadrature sum of individual detector SNRs, as given in Eq. 3.2.

$$\rho_{\text{net}} = \sqrt{\rho_i^2}. \quad (3.2)$$

Commonly, a network SNR threshold $\rho_{\text{th}} \approx 8$ is used [124]. However, this value is not a hard cutoff and is influenced by factors such as the number of detectors operating, their respective sensitivities, and the conditions of the observing run [124–126].

The SNR distribution for the GW events detected with high significance during O1-O3 is shown in Fig. 3.5. It includes SNR values for the 90 CBCs detected with high confidence. The minimum SNR value was found to be 7.5 for GW200220_061928, an event detected during

O3b [126], proving the previous statement that there is no strict lower bound on the SNR required for a confident detection.

3.3.2. False Alarm Rate

Although SNR remains strongly correlated with the detection significance after applying data-quality vetoes and glitch removal, to come up with a more robust statistic, the false alarm rate (FAR) is introduced.

The mathematical definition of FAR is given as,

$$FAR = \frac{N_{\text{bkg}}}{T_{\text{obs}}}. \quad (3.3)$$

Here, N_{bkg} is the number of detected background noise events having a similar or greater SNR. T_{obs} is the total duration of the background data. It is determined by conditioning the probability distribution on the noise-only hypothesis to assess the rate at which noise artefacts can produce a trigger of the same rank [161].

A common approach involves generating a background (N_{bkg}) via ‘time-sliding’. The assumption underlying this method is that noise

transients in different detectors are uncorrelated and that true GW signals are sparse within the dataset. So, the trigger time associated with the data streams from different detectors could be shifted by time intervals longer than any astrophysical time delay, to generate a background-only dataset. The minimum time shift applied for each pipeline is selected to exceed the coincidence window used to identify consistent signals across the detector network [126]. This time-shifting procedure is then repeated many times over a sufficiently long duration (T_{obs}) of input data. The technique is conceptually similar to background scrambling used in neutrino analyses (see Ch. 5).

Once a large background dataset is obtained, the FAR for any given candidate event is determined by comparing its ranking statistic (e.g., SNR, likelihood ratio) to the distribution of ranking statistics observed in the background [124]. The p-value, which indicates the statistical significance, is then calculated based on this count, the observation time, and the total background time. The procedure is explained in detail in [162].

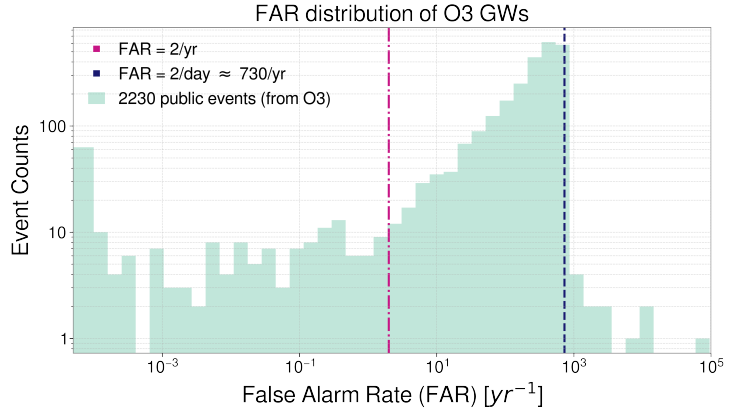


Figure 3.6.: The raw FAR distribution of O3 events released as part of [125] and [126], from GW signal search pipelines. Unique CBC signals with $FAR \leq 2 \text{ yr}^{-1}$ are sent as real-time alerts to the community as ‘confident’ detections. However, signals with $FAR \leq 2 \text{ day}^{-1}$ are part of the archival data release, considered for further analysis, according to [126]. Few events with $FAR > 2 \text{ day}^{-1}$ are visible in the plot, but bear no physical importance.

3.3.3. Probability of astrophysical origin



Figure 3.7.: The p_{astro} distribution of all the 90 confidently detected GW events starting from the first to the third observation run (O1-O3) of LIGO-Virgo-KAGRA (LVK).

Matched filtering pipelines also estimate the candidate's probability of astrophysical origin (p_{astro}). It is crucial information as the likelihood of an event being astrophysical at a given FAR varies across different regions of the CBC parameter space, depending on how frequently such events occur [156]. It is essentially estimated as a Bayesian posterior of detecting a GW signal coming from a CBC-like source. Mathematically, we can express it as,

$$p_{\text{astro}} = p_{\text{BBH}} + p_{\text{BNS}} + p_{\text{NSBH}}. \quad (3.4)$$

Here, p_{BBH} , p_{BNS} , and p_{NSBH} are the probabilities for detecting the GW signal from a BBH, BNS, and NSBH-like source, respectively.

Thus, the probability of the GW signal being associated with terrestrial noise is $p_{\text{terr}} = 1 - p_{\text{astro}}$. This distinction predominantly guides the low-latency alerts sent by LVK during the observation runs [77, 163]. Decisions are made by the astronomical community on which GW candidates are worth following up for multi-messenger counterparts. Generally, BNS mergers have higher priorities, followed by NSBH and BBH merger-like events. The p_{astro} distribution of the 90 GW events during O1-O3 is shown in Fig. 3.7.

Matched-filtering pipelines estimate p_{astro} based on a Poisson mixture model of signal and noise events [164, 165]. After the triggers are ordered according to the ranking statistics, and FAR estimation takes place, as explained in Sec. 3.3.1, 3.3.2, a signal model is constructed describing the expected distribution of ranking statistics for true astrophysical signals. It is generally obtained via signal injections based on fiducial astrophysical population distributions (e.g., masses, spins, redshift, etc.) and injected onto the background. For this step, the 'sensitive hypervolume' ($\langle VT \rangle$) is a key component. It is defined as,

$$\langle VT \rangle = \frac{N_{\text{obs}}}{R}. \quad (3.5)$$

where, rate of coalescence is R and N_{obs} is the expected number of observed GW signals [166] in time T .

From population assumptions, it represents the detector network's sensitivity to signals from a given population of CBCs.

$$\langle VT \rangle = \int dz d\theta \frac{dV_c}{dz} \frac{1}{1+z} p_{\text{pop}}(\theta) f(z, \theta) T. \quad (3.6)$$

Here, $\frac{dV_c}{dz}$ denotes the differential comoving volume. $p_{\text{pop}}(\theta)$ represents the distribution of source parameters in the astrophysical population, and $f(z, \theta)$ is the detection probability for the fraction of simulated events that are recovered above the detection threshold with parameters θ at redshift z . The factor $\frac{1}{1+z}$ in the denominator accounts for the time dilation of the intrinsic event rate due to cosmic expansion.

Similarly, a noise model describes the distribution of ranking statistics for noise events. It is primarily derived from time-shifted analyses, explained in Sec. 3.3.2. Finally, p_{astro} for an event is calculated by considering the ratio of the likelihood of the event being astrophysical versus background, weighted by the expected rates of CBC mergers and background events [124–126]. However, it should be noted that the possibility of the detected GW signal being burst-like is not accounted for in the framework. Hence, no p_{astro} estimation is provided by a burst search pipeline for public use. Apart from this, there is always a finite probability of a GW signal getting low p_{astro} because of imperfect merger rate estimations, which always come with huge uncertainties [167]. Therefore, having $p_{\text{terr}} > p_{\text{astro}}$ does not necessarily rule out the possibility that the GW signal is coming from an astrophysical origin.

3.3.4. Parameter estimation

Estimating the source parameters from an individual GW signal is the next vital process. The goal is to constrain both intrinsic and extrinsic parameters of CBC systems. The intrinsic parameters are inherent properties of the binary system, such as component masses (m_1, m_2), dimensionless spin vectors ($\vec{\chi}_1, \vec{\chi}_2$), effective inspiral spin (χ_{eff}), etc. The extrinsic parameters are related to the system's position and orientation relative to Earth. A few examples of this kind are: sky location (right ascension α and declination δ), luminosity distance (d_L), inclination angle (θ_N) between total angular momentum and line-of-sight, time of merger (t_c), reference phase (ϕ), polarization angle (ψ), etc.

Parameter estimation is performed after a GW signal is identified as a signal candidate, after data quality checks and after mitigating ‘glitches’. It primarily relies on Bayesian inference [168], implemented in software packages like LALInference [169], BILBY [170, 171], and RIFT [172]. These frameworks compute the posterior probability distribution of the parameters conditioned on the observed data. Using Bayes’ theorem, it is expressed as:

$$p(\theta|d, F) \propto p(d|\theta, F)p(\theta|F). \quad (3.7)$$

Here, $p(\theta|d, F)$ is the posterior probability distribution of the CBC parameters (θ) mentioned above, given the detector strain data (d) and the signal hypothesis (F). $p(d|\theta, F)$ is the likelihood function, which represents the probability of observing the data given specific parameter values. $p(\theta|F)$ is the prior probability distribution, reflecting any a priori knowledge or assumptions about the parameters before observing the data. The strain data, d , is the raw output from GW detectors, which is a noisy time series where GW signals might be present.

For signal modelling, theoretical models of GW waveforms are used, characterising the inspiral, merger, and ringdown phases. These models vary depending on the CBC parameters. The

noise in the detectors is typically assumed to be stationary and Gaussian distributed. The likelihood, $p(d|\theta, F)$, searches for signals of known shape in noisy data. For CBC searches, priors ($p(\theta|F)$) represent initial beliefs about the parameters, which are ‘population-informed’, i.e., based on astrophysical expectations or previous observations. The choice of prior can significantly impact the posterior distribution, especially for parameters that are not well-measured by the data. That is why, for burst searches, broad, uninformative priors are used to allow the data to dominate the inference.

The process of parameter estimation is computationally intensive due to the evaluation of waveform models across a high-dimensional parameter space. Because of this, traditional parameter estimation pipelines can potentially take weeks per event. So, it is typically performed in real-time for GW candidates that are deemed highly significant. An initial estimation is often conducted shortly after it is identified to roughly infer component masses and other properties relevant for follow-up searches. This is followed by a more exhaustive set of parameter estimation to produce final, high-accuracy results. During the offline parameter estimation of archival strain data, we benefit from improved background statistics, extensive data calibration, and vetting. The results from these offline analyses are used to create Gravitational Wave Transient Catalogues (GWTC) [124–127, 173].

3.4. Astrophysical Sources of Gravitational Waves

After GW signals are identified and an initial idea about the source parameters is obtained, they are investigated with the primary aim of understanding the astrophysical origin of the recorded GW signals. As compact binaries inspiral, the frequency and amplitude of the GW increase, as the GW radiation by the orbital motion causes the orbit to shrink. This phenomenon is known as ‘chirping’. This inspiral phase and chirping do not continue forever. For a binary system, as the compact objects spiral closer, their separation eventually reaches a critical limit. It is approximately $\frac{6G(m_1+m_2)}{c^2}$, where m_1 and m_2 are the masses of the compact objects. Beyond this separation, the orbital dynamics of the system significantly change, and they rapidly plunge towards each other and merge. This limit is known as the innermost stable circular orbit (ISCO) [174]. The frequency of GW emitted at this point is inversely proportional to the total mass $M = m_1 + m_2$ of the binary, as shown in Eq. 3.8

$$f_{\text{ISCO}} = \frac{c^3}{6^{2/3}\pi G(m_1 + m_2)}. \quad (3.8)$$

Currently operational ground-based GW detectors are the most sensitive when $10 < f_{\text{ISCO}} \leq 1000$ Hz. Below or above this range, the detector performance is hindered due to the overwhelming presence of noise [137]. Following the frequency-mass relationship from Eq. 3.8, it is evident that the 2G ground-based detectors, i.e. LVK, are primarily sensitive to stellar-mass compact objects of mass $4 \lesssim M < 200 M_\odot$.

Several interesting astrophysical sources fall within this mass range. Some of them are listed here [128, 174]:

- CBCs, such as BBH, BNS, and NSBH mergers with $M < 200 M_{\odot}$ in distant galaxies, are the most well-understood sources within this frequency range.
- If the stellar collapse to a neutron star or black hole in our Galaxy and distant galaxies is sufficiently non-spherical, which sometimes triggers supernovae, it can produce a burst of GW within this frequency range.
- The rotation and vibration of pulsars in our Galaxy can produce continuous and almost monochromatic GW due to non-axisymmetric deformations or internal instabilities.
- Low-mass X-ray Binaries, where neutron stars are accreting mass, are also considered potential long-lived sources of continuous emission of GW.
- Stochastic GW background that could originate from the superposition of countless distant, individually unresolvable astrophysical sources or fundamental processes in the very early Universe, such as phase transitions and the Big Bang, is also a sought-after source within this frequency range. Although observationally very weak, LVK attempts to set stronger limits for these backgrounds by cross-correlating data from multiple detectors [175].

From the above-mentioned list, LVK has only observed GW signals associated with astrophysical CBCs, and continues to search for GW-burst-like events [127]. To find out such associations, ‘online’ searches are carried out concurrently with observation runs to send low-latency alerts of CBCs detected with high confidence, with initial parameter estimation performed. ‘Offline’ searches are conducted after each observation run ends, to perform computationally intensive, deeper searches for comprehensive event characterisation. These archival searches can be further categorised into two main methods: template-based and non-template-based searches.

3.4.1. Template-based Searches

Template-based searches primarily focus on detecting GW emitted from CBCs. For these transient sources, the anticipated GW emissions are sufficiently modelled across most of their parameter space. Therefore, robust inference frameworks based on the matched filtering method are used. It involves correlating the detector’s output with a waveform template. There are currently four such GW detection pipelines provided and used by the LVK community:

- **GstLAL (Gstreamer and the LIGO Algorithm Library):** GstLAL performs matched filtering using multi-rate signal processing, optimised for low-latency analysis [176]. The template waveforms are available for the range of redshifted total mass of $2 \leq M \leq 758 M_{\odot}$, with a minimum component mass of $1 M_{\odot}$. Triggers are generated by maximising the SNR (ρ) over 1 s time windows, if $\rho > 4$ for the LIGO detectors and $\rho > 3.5$ for Virgo [124]. It is also the only pipeline that considers single-detector triggers for further processing.

- **MBTA (Multi-Band Template Analysis):** MBTA is also a low-latency pipeline that is being used from O3. It decomposes each waveform template into low- and high-frequency components using a multi-band approach, thereby reducing computational cost [177]. The templates cover redshifted component masses from 1 - 195 $M_{\odot}$, assuming aligned spins. Triggers above an SNR threshold of 4.8 for BBH/NSBH, and 4.5 for BNS, are considered for time coincidences, only if at least two detectors record them within a time window of the light-travel delay. It can also create ‘pseudo-triple’ events from double events with sub-threshold signals in a third detector to improve sky localisation.
- **PyCBC:** PyCBC performs offline analysis using time-domain templates. It utilises a stochastic template bank covering a redshifted total mass range of 2 to 500 $M_{\odot}$ with spin-aligned waveform models. Coincidences require matched templates and time delays within allowed light-travel windows.
- **PyCBC-Highmass:** A modified version of the standard PyCBC pipeline optimised for higher-mass compact binaries, with a template bank specifically covering higher total masses (25 - 400 $M_{\odot}$). The search configuration is tuned for better sensitivity to short-duration, high-mass signals, including allowance for larger spin magnitudes and mass ratios [178].

Using multiple independent template-based pipelines ensures the robustness of GW searches and makes them comprehensive. As each pipeline is optimised for different scientific priorities and computational strategies, they provide essential cross-validation of results. GstLAL and MBTA emphasise low-latency searches for rapid alerts, whereas PyCBC and PyCBC-Highmass focus on offline, high-significance analyses with broader parameter coverage. Thus, more GW signals are picked out by these two pipelines. They also have different sensitivities to different source classes (e.g., light BNS, high-mass BBH, precessing systems). But as they operate on the same strain data, sometimes a single event could also be double-counted by multiple pipelines, which the analysers need to be aware of while dealing with the raw catalogues.

3.4.2. Non-template-based Searches

In contrast to the CBC searches, there are plausible sources of short or long-duration GW emissions, which are poorly modelled or even unknown. These sources include core-collapse supernovae, long-duration gamma-ray bursts, soft gamma repeaters, etc. For these cases, traditional matched filtering techniques are ineffective due to the lack of accurate waveform templates. Therefore, general transient-finding methods with minimal assumptions about signal morphology are utilised. Thus, non-template-based search pipelines also offer the potential to identify unforeseen astrophysical sources of GW. The GW burst search pipeline available within the LVK collaboration is known as the ‘Coherent Wave Burst’ (cWB)-allSky search [179].

The data from the completely unmodelled version of cWB-allSky is not publicly available. However, a CBC-optimised version of cWB-allSky is also used. After the completion of O3b, the results obtained from this pipeline during the entire O3 period became available. The events from this particular version of cWB-allSky are referred to as ‘cWBs’ from here on in this thesis.

CBC-optimised cWB-allSky Search

Unlike CBC searches that rely on specific waveform templates, the burst-search algorithm identifies ‘clusters’ of excess energy above the baseline detector noise [180–182]. For a GW signal, it typically expects a chirping time-frequency pattern, with increasing frequency and power over time. The detection statistic is based on the coherent energy (E_c), which is derived from cross-correlating reconstructed signal waveforms from multiple detectors. This is proportional to the coherent network SNR. Candidates are ranked using this statistic [183]. The SNR for each detector is estimated from the reconstructed waveforms and then combined to calculate the network SNR, as discussed in Sec. 3.3.1. To distinguish genuine GW events from glitches, the pipeline checks the network correlation coefficient (CC), defined as $\frac{E_c}{(E_c + E_n)}$, where E_n is the residual noise energy. Genuine GW events are expected to have $CC \sim eq\ 1$, while noise events (glitches) have $CC \ll 1$. The estimation for FAR is derived from time-shifted data, similar to what has been explained in Sec. 3.3.2. Only cWBs identified by this minimally modelled search pipeline can have p_{astro} estimation. That is provided by modelling signal and noise event rates using standard Poisson mixture formalism (see Sec. 3.3.3), where only BBH merger rates are considered for the signal assumption. cWB can work with arbitrary detector networks. But during O3, it was often restricted to pairs of detectors (e.g., HL, HV, LV) rather than the full HLV network, as the full network did not improve significance at the time.

3.5. Catalogue of Gravitational Wave Events

During the data-taking runs, LVK shares information publicly in real-time on GW detections after performing all the steps mentioned in Sec. 3.3 to facilitate follow-up searches by the astronomical community. These follow-up alerts, from LVK’s first three observation runs (O1–O3), correspond to GW events detected with high confidence with a $FAR < 2\text{ yr}^{-1}$, depending on background activity around the GW signal detection time [124–126]. They are labelled as ‘highly significant’ detections. They are also included in the event catalogue release following an extensive archival search to obtain more robust parameter estimation on an event-by-event basis. These catalogues are generally known as ‘Gravitational Wave Transient Catalogues’ (GWTC).

3.5.1. High-significance Events till O3

O1 started on September 12, 2015, and went on till to January 19, 2016. From November 30, 2016, to August 25, 2017, the O2 data-taking campaign was active. After the completion of both O1 and O2, GWTC-1 was released [124]. It contained detailed information about the 11 highly significant events from these two observation runs. They are also colloquially known as ‘confidently detected’ or ‘confident’ events. Among these 11 events, there are 10 BBH mergers and 1 BNS merger.

GWTC-2 was made publicly available, containing information on 39 confident events from the first half of the third observational run (O3a), which went on from April 1, 2019, 15:00 UTC to

October 1, 2019, 15:00 UTC [173]. It was further updated, and GWTC-2.1 was released with 44 events [125]. The events in this updated catalogue were highly likely to be associated with CBCs (i.e., $p_{\text{astro}} > 0.5$ from at least one detection pipeline), even though they had $\text{FAR} > 2 \text{ yr}^{-1}$. Similarly, 35 confident CBC events were added to the GWTC-3 catalogue [126]. They were detected during the second half of the third observation run (O3b), between November 1, 2019, 15:00 UTC, and March 27, 2020, 17:00 UTC. So, till the end of O3, there are 90 confidently detected events. The entire community has extensively followed up on them to detect multi-messenger emissions. Details of some of the interesting candidates are mentioned below.

GW150914

This event marked the first direct observation of gravitational waves by aLIGO on September 14, 2015 [2]. It was identified as a BBH merger, a phenomenon whose existence had been postulated but never observationally verified before. GW150914 remains one of the highest SNR CBCs from O1 and O2, with $\text{SNR} = 24.4$ (see Fig. 3.1).

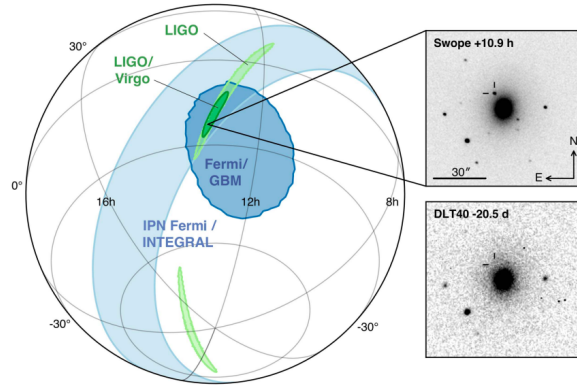


Figure 3.8.: localisation of GW170817. (Left) 90% credible regions from LIGO–Virgo. IPN triangulation from Fermi and INTEGRAL (light blue), and Fermi-GBM (dark blue). (Inset) optical counterpart in the Swope discovery image 10.9 hr after the merger (top right) and the DLT40 pre-discovery image 20.5 days earlier (bottom right). The reticle marks the transient. Figure and details from [3].

GW170817

Observed on August 17, 2017, this was the first detection of GW from a BNS merger by the LV network [3]. It was also detected with the highest SNR ($\text{SNR} = 33$) among the events listed in GWTC-1. Additionally, it was the most precisely detected GW events with a 90% containment area on the sky ($\Delta\Omega_{90}$) of 16 deg^2 . Crucially, it was also accompanied by EM counterparts, including a short gamma-ray burst and a kilonova, as represented in Fig. 3.8). This ushered in a new era of multi-messenger astronomy. GW170817 provided unprecedented constraints on the properties of matter in extreme environments, particularly the neutron star Equation of State (EoS). It also enabled a GW-based cosmological measurement of the Hubble constant.

GW190814

This event involved a $23 M_{\odot}$ black hole coalescing with a $2.6 M_{\odot}$ compact object [125]. The nature of the lighter object is uncertain. It falls into the ‘lower mass gap’ between neutron stars and black holes. It could be either the most massive neutron star or the lightest black hole ever observed.

GW190521

GW190521 was a BBH merger with a total mass of $150 M_{\odot}$, and a remnant mass of $147.4^{+40.0}_{-16.0} M_{\odot}$, making it the highest mass BBH in GWTC-2.1. Its primary component mass fell within the pair-instability mass gap, a region where black hole formation was theoretically challenging. This event garnered significant interest due to a possible association with an observed flare from an AGN (See Fig. 3.9), suggesting new avenues for multi-messenger astronomy with BBHs [184].

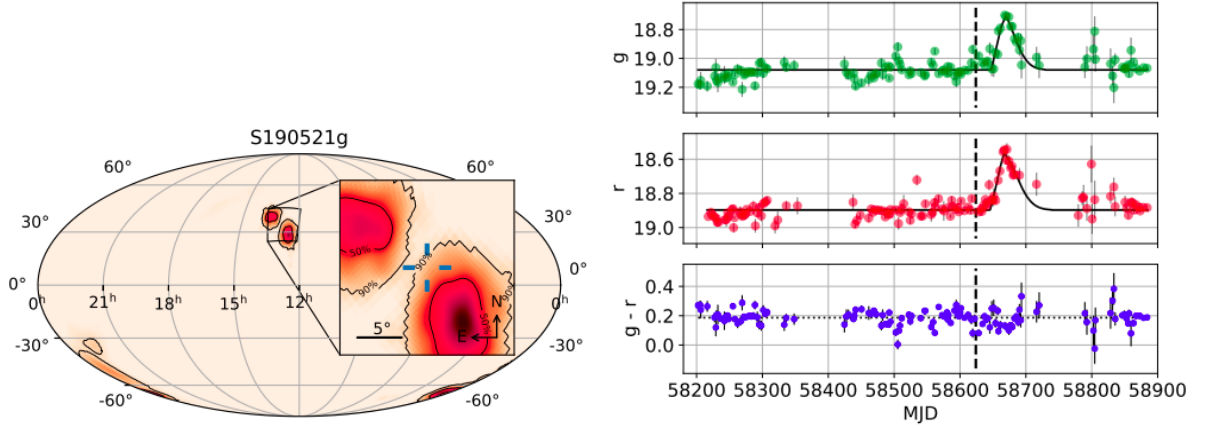


Figure 3.9.: (Left) The skymap associated with GW190521 depicting the 50% and 90% LIGO localisation regions. The location of ZTF19abannhr is marked and falls within the 78% contour. (Right) ZTF g-band photometry, r-band photometry, and g-r colour for J1249+3449 over the past 25 months, before the flare-up. The flare beginning around MJD ~ 58650 is compared with a dashed vertical line, which corresponds to the GW190521 trigger time. Figures and details obtained from [184].

BNS and NSBHs detected during O3

GW190425 was the only significant BNS event detected during O3a. Notably, it was observed by Livingston (L1) and Virgo (V1) and identified by only the GstLAL search pipeline. The O3b candidates included the first confident observations of NSBH mergers: GW191219_163120 and GW200115_042309. GW200115_042309 was the lowest total mass binary from O3b, and its secondary component mass ($m_2 = 1.44^{+0.85}_{-0.29} M_{\odot}$) is consistent with known Galactic neutron stars. GW200210_092254 from O3b is notable because its less massive component's mass ($m_2 = 2.83^{+0.47}_{-0.42} M_{\odot}$) spans the range for both possible neutron stars and black holes, making its classification as NSBH or BBH uncertain from GW data alone.

3.5.2. Low-significance Events from O3

After the completion of O3, LVK publicly released the archival information about more than 2200 low-significance or ‘sub-threshold’ GW from the entire O3. They have slightly higher FAR values, as identified by CBC and also CBC-optimised cWB search pipelines. According

to the definition valid till O3b, they should have $\text{FAR} \leq 2 \text{ day}^{-1}$, and $p_{\text{astro}} < 0.5$. 1201 of them were detected during O3, and were included in GWTC-2.1³ [125]. The remaining 1048 candidates were detected during O3b and are found in GWTC-3⁴ [126]. None of them was released in real-time during O3.

It is important to note here that the sub-threshold classification does not necessarily imply that these events are convincingly linked to terrestrial origin. They have passed the signal consistency checks mentioned in Sec. 3.3. But many of these events were detected during periods of reduced GW detector sensitivity, which resulted in higher background rates at the time of observation. Furthermore, the assigned p_{astro} value for these events is highly dependent on population assumptions and waveform models used by the search pipelines mentioned in 3.4, as it is a Bayesian posterior estimate. So, these low-significance GW remain compelling source candidates for multi-messenger follow-up campaigns that can also attest to the validity of their astrophysical origin. Consequently, they are interesting source candidates for archival neutrino follow-up studies. Identifying temporally and spatially coincident neutrinos could not only enhance the credibility of the GW detection [14] but also improve its sky localisation. Such multi-messenger coincidences could, in turn, prompt more efficient EM follow-up efforts for interesting GW source candidates in general.

Finding possible multi-messenger counterparts for these sub-threshold GW from archival studies would also verify our current understanding of the ‘threshold’ we currently set on parameters FAR, p_{astro} , and SNR to claim a GW detection and trigger a follow-up search. That will allow us to better judge their significance. It is even more relevant considering the wealth of information we will be getting from the 3G GW detectors. Having a better insight into the ‘significance’ of GW events will help us to efficiently identify interesting GW alerts for real-time follow-ups, which will be crucial soon.

Hence, for this thesis, the main focus is to identify plausible neutrino counterparts for sub-threshold GW, which were not followed up on in real-time by the astronomical community, and verify their astrophysical significance. Recently, a search has been carried out to look for their high-energy ($\mathcal{O}(10\text{-}100)$ TeV) neutrino counterpart [185]. A search in IceCube for sub-TeV neutrinos [122] is conducted in the analysis relevant to this thesis, discussed in Ch. 7.

³For public O3a catalogue: <https://zenodo.org/records/5117762>

⁴For public O3b catalogue: <https://zenodo.org/records/5546665>

Chapter 4. Detecting Neutrinos: Instruments and Data

"The Universe is full of magical things patiently waiting for our wits to grow sharper."

— Eden Phillpotts

Historically, one of the main challenges regarding experimental studies of neutrinos has been their poor detection prospects, since they have an extremely tiny interaction cross-section. A breakthrough occurred when anti-neutrinos were first experimentally confirmed in 1956 by Cowan and Reines [55] through an inverse beta decay procedure. Shortly afterwards, the concept of using astrophysical neutrinos as potential probes for studying the Universe was recognised by Markov [186]. He first discussed the idea of installing detectors deep in a lake or sea to determine the direction of charged particles originating from neutrino interactions in the detector medium, using Cherenkov radiation, which would allow neutrinos to serve as a probe into stellar atmospheres.

The first experimental endeavour in this direction was the Deep Underwater Muon and Neutrino Detector (DUMAND) project [187] in the 1980s. It aimed to construct prototype strings of photomultipliers in the Pacific Ocean off the coast of Hawaii at a depth of 5 km. Although DUMAND was ultimately unsuccessful due to technical difficulties, it was a pioneering experiment that laid the groundwork for future large-scale neutrino observatories underwater in the early 2000s, like the Baikal detector [188] in Lake Baikal, Siberia, and the Astronomy with a Neutrino Telescope and Abyss environmental RESearch project (ANTARES) [189] in the Mediterranean Sea. As a complementary approach, the idea of using Antarctic ice as a neutrino detection medium arose. Although photons in water are less scattered than in ice, the clear and compressed ice at the South Pole has a longer mean absorption length of photons. It also has no radioactivity. This motivated the Antarctic Muon and Neutrino Detector Array (AMANDA)[190] to be initiated in the late 1990s. The initial encouraging results motivated further endeavours to build an even bigger detector for extra-terrestrial neutrinos, which paved the way for the IceCube Neutrino Observatory [191].

4.1. IceCube: The Detector

The IceCube Neutrino Observatory is a cubic-kilometre detector located under the Antarctic ice at the geographic South Pole. Completed in 2013, its primary objective is to detect neutrinos originating from distant astrophysical sources. However, due to the already mentioned small cross-section and low fluxes of astrophysical neutrinos reaching Earth, achieving a statistically significant detection requires an instrumented volume on the order of at least $\sim 1 \text{ km}^3$ to observe

a few extragalactic neutrinos at PeV energies per year [72, 192], which justifies IceCube’s large volume.

4.1.1. Detection Mechanism

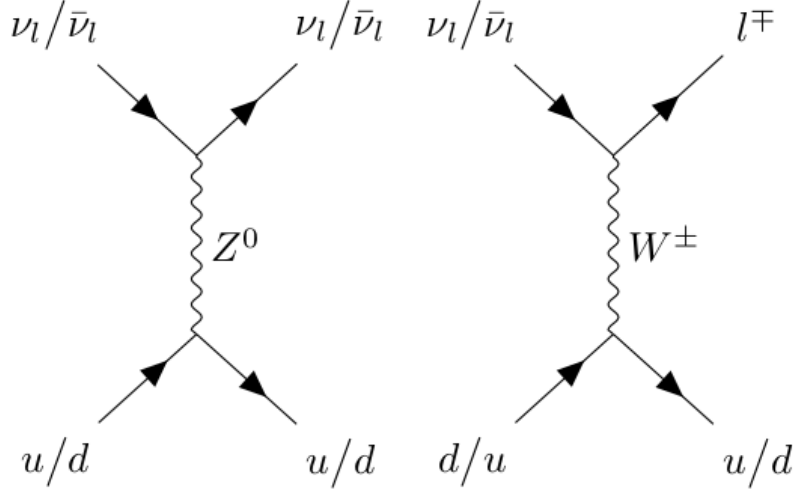


Figure 4.1.: Feynman diagram for deep inelastic scattering of neutrinos. (Left) Neutral current interaction (Right) Charged current interaction. Reproduced from [193].

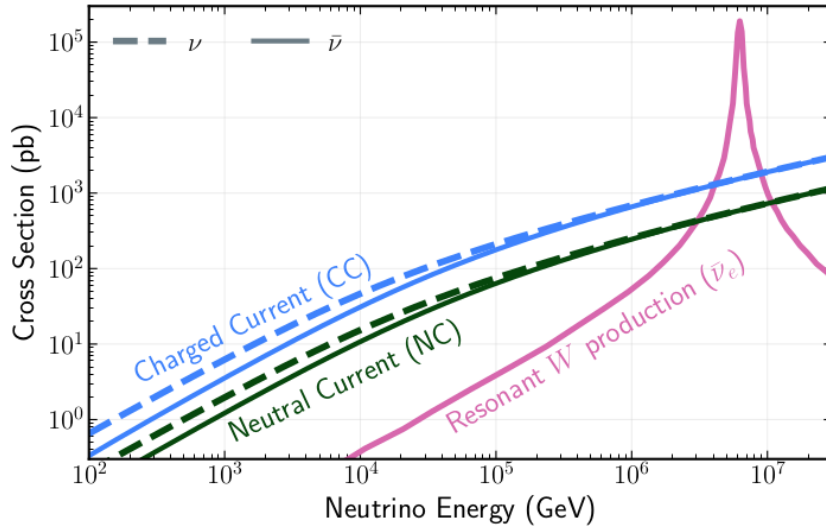


Figure 4.2.: The neutrino-nucleon interaction cross sections with respect to energy of the interacting neutrino/anti-neutrino, considering neutral current [194], charge current [195], and Glashow resonance [196, 197]. Figure and details obtained from [198].

IceCube detects neutrinos indirectly by observing the Cherenkov light emitted by charged secondary particles produced in neutrino interactions within the ice. The nature of the primary

interaction type is deep inelastic scattering [199], for which the associated Feynman diagram is shown in Fig. 4.1.

It could be either a neutral current interaction or a charge current. The cross-section associated with each interaction is shown in Fig. 4.2. As a result of the scattering, charged secondary particles (e^- , μ^- , τ^-) are produced. When the interacting neutrino is energetic enough, the velocity of the charged leptons exceeds the speed of light in that ice, which is a dielectric medium. This phenomenon results in an emission of blue light (350-600 nm), which is known as Cherenkov radiation [201]. It is emitted at an angle θ_c with respect to the direction of the charged lepton, as shown in Fig 4.3, Mathematically, the emission angle,

$$\cos \theta_c = \frac{1}{n\beta}. \quad (4.1)$$

Here ‘n’ is the refractive index of the medium, which is ice in this case, and has $n \approx 1.31$ ¹.

The quantity $\beta = \frac{v}{c}$, where v is the velocity of the charged lepton and c is the speed of light in vacuum. For ice (and also water), $\theta_c \approx 41^\circ$ [193]. The sensors in the detection units are fine-tuned to detect this Cherenkov light, as elaborated on in the next section.

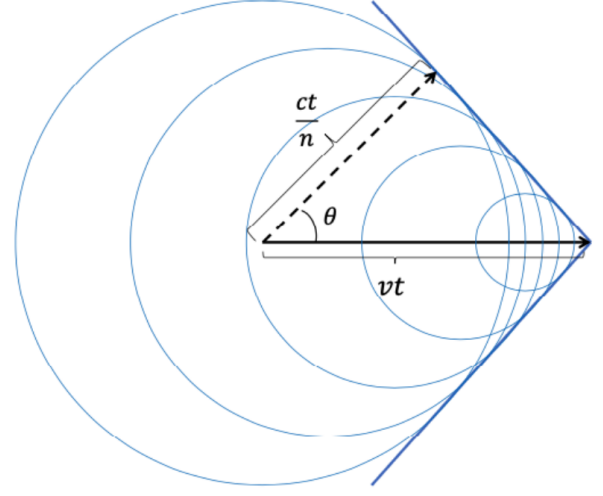


Figure 4.3.: Schematic diagram of Cherenkov radiation, obtained from [200]. It is shown here that the associated photons are emitted at a characteristic angle θ_c , which is determined by the dielectric detection medium. See text for details.

4.1.2. The Detection Unit: Digital Optical Modules

The fundamental building block of the IceCube instrumentation is the Digital Optical Module (DOM). The DOM collects the Cherenkov light emitted as a result of the neutrino interaction in the surrounding medium. They are robust devices designed to function in a predominantly autonomous manner, in the extreme temperature and pressure conditions of the South Pole. They provide precise charge measurements with nanosecond time resolution [204].

Each DOM is a spherical optical detecting unit containing a 10-inch Hamamatsu R7081-02 PMT [205, 206] which is typically downward-facing to optimise the detection of up-going neutrino events [207]. Standard PMTs have a peak quantum efficiency of approximately 25% at 390 nm. The PMTs operate at a gain of 10^7 and are sensitive to wavelengths between 300-650 nm [204]. A μ -metal cage surrounds the PMT bulb to reduce the influence of Earth’s magnetic field, improving collection efficiency and reducing gain variations [208, 209]. Each PMT has a high voltage divider circuit, with a maximum capability of 2047 V. A main-

¹ $n \approx 1.31$ is an average behaviour. The refractive index of ice varies with wavelength. More details on the ice properties could be found in [202, 203]

board acts as the central DAQ unit for each DOM, integrating various components for high voltage power supply control, data acquisition, digitisation, calibration, and communication.

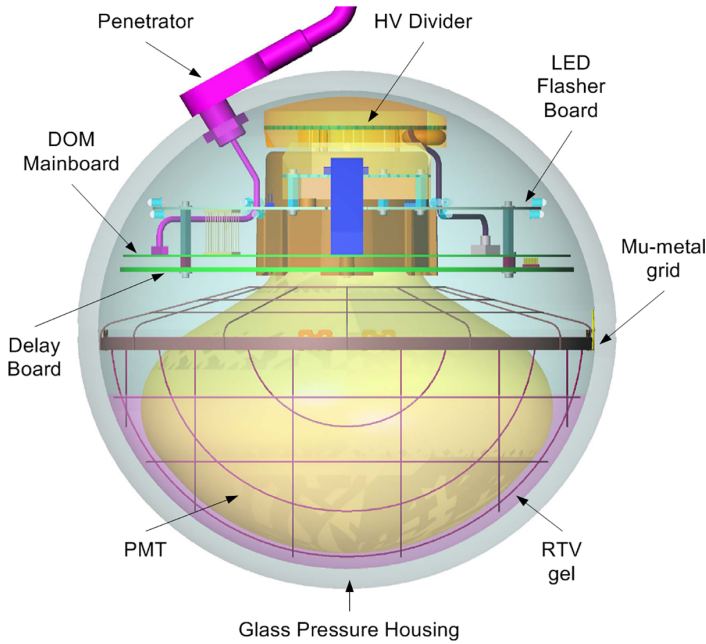


Figure 4.4.: Schematic diagram of the Digital Optical Modules (DOM) used in IceCube. Source: [IceCube gallery](#).

Laboratory (ICL) on the surface. The other two pairs connect to the DOMs directly above and below, enabling local coincidence checks.

Most DOMs include a flasher board with 12 single-coloured LEDs, primarily for calibration purposes and measuring ice properties [210, 211]. These LEDs can emit controlled flashes, detectable by neighbouring DOMs, to calibrate charge and time response, improve DOM localisation, and study ice optical properties. The spherical housing is a pressure-resistant borosilicate glass container (outer diameter ≈ 13 inches, thickness ≈ 0.5 inches) designed to withstand the immense pressure of refreezing in ice. Three wire pairs extend from the DOM. One pair provides power and a bidirectional digital communication pathway to the IceCube

4.1.3. Detector Geometry

To capture the neutrino detection signature in-ice and distinguish astrophysical neutrinos from background, the IceCube detector is equipped with three complementary detector components, which are also pointed out in Fig. 4.5.

- **In-ice array:** This is the primary component for detecting high-energy astrophysical neutrinos. It has a detection threshold of 100 GeV. It comprises 86 strings containing 5160 DOMs in total drilled into the Antarctic ice [204]. The instrumentation starts at a depth of 1450 m and continues to 2450 m, where the ice is very clear, which facilitates the capture of Cherenkov radiation optimally. The in-ice array is segmented into two parts by a dust layer. The whole configuration is optimised for detecting events in the TeV-PeV energy range. Most strings (78 out of 86) are arranged in a hexagonal pattern with an average spacing of 125 m. The DOMs on these strings are typically spaced 17 m apart. As the high-energy neutrinos typically light up a large volume in the detector, a sparse configuration allows for a cost-effective setup. With this configuration, IceCube has achieved sub-degree precision in the direction reconstruction of astrophysical neutrinos [213].

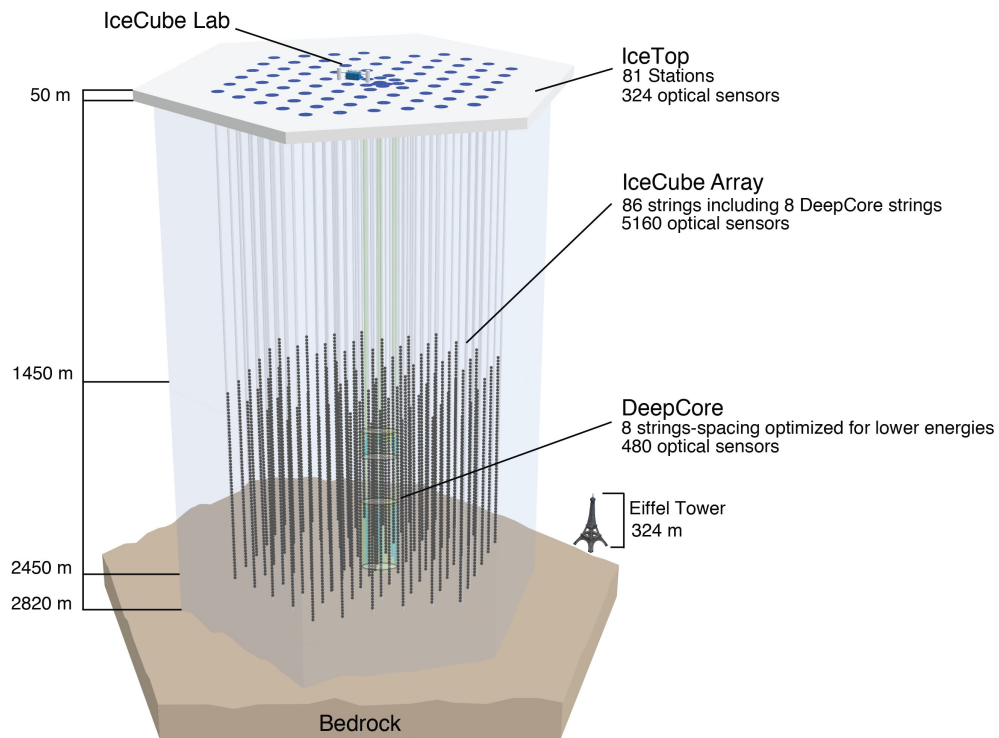


Figure 4.5.: Schematic diagram of the IceCube Neutrino Observatory. Source: [IceCube gallery](#)

- **DeepCore:** This is a denser sub-array of 8 strings located at the centre of the main in-ice detector [212]. It contains seven standard IceCube strings within its fiducial region. The instrumentation starts at depths between 2100 m and 2450 m below the dust layer, which places the DOMs in the clearest ice of the detector. The sub-array itself is segmented into two parts by the dust layer. A subset of 10 DOMs deployed above the DeepCore region, within the depths of 1750-1850 m, forms a ‘veto cap’. It can identify and reject atmospheric muons, especially the ones coming vertically. This significantly reduces the background rate for DeepCore events. Furthermore, the larger IceCube array surrounding DeepCore also acts as an active veto. A schematic diagram of the DeepCore installation is shown in Fig. 4.6, where each of the above-mentioned components is identified².

The primary purpose of DeepCore is to lower the neutrino detection energy threshold to approximately 10 GeV. To achieve this, the strings are more closely spaced, with a mean spacing of 70 - 72 m. The spacing between the DOMs is also less here. It comes with 7 m spacing between 2100 m and 2450 m depth, 10 m spacing in the veto region [214]. DeepCore DOMs also feature a newer PMT model (R7081MOD) with higher quantum efficiency (around 34%) than the main IceCube strings [215].

- **IceTop:** This is a cosmic ray (CR) detector array located on the surface of the ice directly above the in-ice detector [216]. It consists of 162 ice-filled Cherenkov tanks arranged

²For a light reading, refer to: [IceCube DeepCore](#)

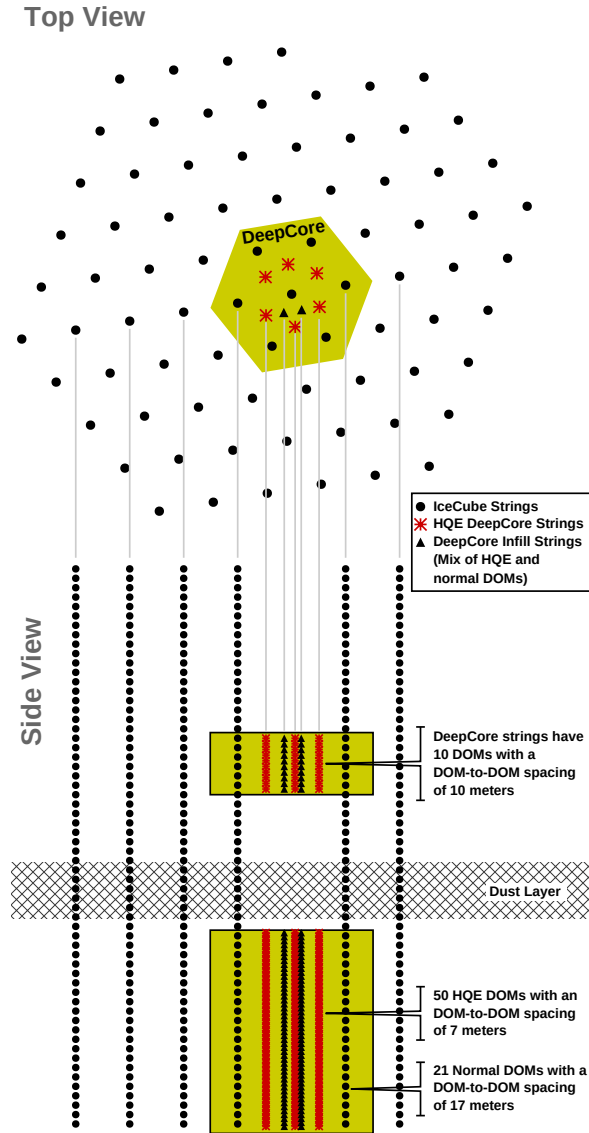


Figure 4.6.: A schematic diagram of the full DeepCore configuration, obtained from [212].
 Courtesy: [IceCube research news](#).

in 81 pairs, each separated by 10 m. Each tank contains two IceCube DOMs (high-gain and low-gain). IceTop measures air showers from CR and primarily focuses on studying CR around the ‘knee’ (PeV-EeV). It also serves as a veto against the atmospheric muons for the in-ice neutrino detectors. IceTop’s veto capability begins at energies around 300 GeV [217]. Non-uniform snow accumulation on top of the tanks affects the veto capabilities due to an increase in the detection threshold and uncertainties. To counter these effects, in addition to dedicated studies to model the snow effects [218], a major effort to enhance the surface array with hybrid detector stations comprising elevated radio antennas and scintillation detectors is planned and currently in deployment [219–221].

4.2. From Interaction to Inference

As neutrinos interact within IceCube’s detector volume, and the DOMs capture the resultant light from the interactions, the raw data is transferred to the IceCube Laboratory (ICL) on the surface, which serves as the central control system for the observatory. The DAQ system applies trigger criteria to perform data reduction in real-time by looking for local coincidences before giving an event output. These events are then forwarded to the ‘Processing and Filtering’ (PnF) stage. Here, further filters are applied to identify interesting events, which consequently reduces the data volume. Daily ~ 100 GB data is thus transmitted via satellite [204].

4.2.1. Event Topologies

Using the Level 2 data following the PnF stage, one of the key challenges to navigate is identifying the flavour of individual events, which end up in the final selection. It is identified by looking at the signatures the charged leptons leave after an individual neutrino’s interaction in ice.

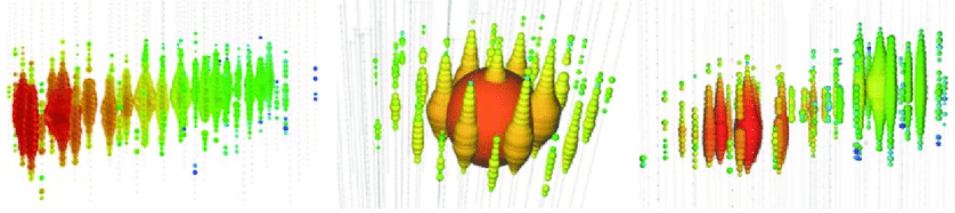


Figure 4.7.: Typical event topologies observed by IceCube. (Left) Tracks, caused by CC interaction of ν_μ , (centre) cascades, caused by CC interaction of ν_e , ν_τ , and NC interaction of all flavours, (right) double bang, exclusively associated with ν_τ . Hit DOMs are shown as coloured dots, where the colour encodes the relative detection time (red = earlier, green = later) and the dot size indicates the amount of detected Cherenkov light. Figure and details obtained from [222].

Tracks

If the parent neutrino is a muon-neutrino (ν_μ), the secondary muon produced via CC interaction (more details in Sec. 4.1.1) can travel long distances before it further loses its energy via radiative processes like Bremsstrahlung or ionisation. As these muons scatter less in ice, they look like they have travelled in a long, straight path, which is referred to as ‘tracks’ [223]. The more energetic the muon neutrinos are, the longer and distinct the track is. They also maintain exceptional directionality and the angular resolution roughly scales with the neutrino energy (E_ν) as, $\Delta\Psi \approx 0.7^\circ (\frac{E_\nu}{\text{TeV}})^{-0.7}$ [207]. However, for tracks, it is difficult to have an accurate energy estimation due to Cherenkov effects, and also because the tracks can start outside of the detector’s fiducial volume. An example event is shown in the left panel of Fig. 4.7.

Cascades

For an electron neutrino (ν_e), the resultant electron produces an electromagnetic shower in the local detector volume. A similar effect could be obtained from CC interaction of tau neutrinos (ν_τ) and NC interaction of all flavours [191]. The Cherenkov light signal observed due to the shower-like particles is more spherical than being track-like. So the angular resolution is poorer than that of tracks ($\Delta\Psi \sim \mathcal{O}(10^\circ)$) [224]. However, as the interaction is initiated only within the detector volume, the light is well-contained within the detector. Though the light pattern spreads out within the distance of a few metres, this length scale is proportional to $\log_{10}(E_\nu)$. So the energy resolution of these events is much superior. An example event is shown in the middle panel of Fig. 4.7.

Double Bangs

This is an exclusive signature associated with ν_τ . The secondary tau initiates an initial cascade before travelling approximately 50 m per PeV energy and decaying. A second cascade follows because of the tau decay [225]. However, below a few PeV energy, the ν_τ can only travel a very short distance before decaying. So the resultant signature becomes difficult to distinguish from that of a cascade. Although, simulated event example is shown in the right panel of Fig. 4.7 [222], IceCube has now reported observation of ν_τ in the TeV-PeV energy range [67, 226].

4.2.2. Data Samples

Once neutrino events have passed through triggering and filtering, and some idea about the event topology is obtained, the events are organised into specialised data sets for a certain time period, tailored for different physics goals. All of them aim to provide information about the arrival direction and energy of the events contained in the datasets. Each sample is produced with dedicated selection criteria, optimised reconstruction methods, and targeted background rejection strategies. As a result, neither a single data set exists, nor does a ‘universal’ strategy for preparing datasets. In the context of this thesis, one high-energy and one low-energy sample, each with tailored event reconstruction, selections and background suppression strategies, are of particular relevance and will be discussed in detail below.

High-energy Neutrinos in IceCube

While IceCube seeks to detect rare high-energy astrophysical neutrino events, they are outnumbered by an overwhelming background of atmospheric muons and neutrinos, which look exactly like the astrophysical neutrino in the detector. Every second, IceCube detects 3000 atmospheric muons [204], and 275 atmospheric neutrinos are detected daily, whereas the detection rate of astrophysical neutrinos is 1-2 per month [227]. To deal with the enormous background, IceCube has to employ various strategies which differ depending on the energy of the neutrino and the specific sub-detector array being utilised.

- **Background suppression techniques:** Generally, for neutrinos in the energy range of TeV - PeV, the primary IceCube detector uses several methods to mitigate background. As it is buried deep within the Antarctic ice, that naturally provides a shielding against atmospheric muons. IceTop also has veto capabilities. In-ice events with energies above 300 GeV that are accompanied by a coincident air-shower signal in IceTop are flagged as likely originating from atmospheric muons [217]. Also, a part of the detector itself can serve as an "outer veto layer". Events that produce their first light in this outer layer are discarded, ensuring that only neutrino interactions with vertices well-contained within the detector are considered [228–231]. This is a powerful technique for reducing the atmospheric muon background. Furthermore, for events originating specifically from the Northern Hemisphere (NH), known as up-going events, the Earth itself acts as a shield, absorbing nearly all atmospheric muons [232, 233]. This makes the northern sky significantly more sensitive to astrophysical neutrinos, with atmospheric neutrinos being the dominant remaining background. That can be managed by making energy cuts, as the atmospheric neutrinos follow a $E^{-3.7}$ spectrum, which is much softer than that of the astrophysical neutrinos [234], following presumably a $\sim E^{-2}$ spectrum³, as discussed in Ch. 2.
- **Event reconstruction:** The high-energy neutrino sample relevant for a part of this thesis work (see Ch. 8) is the publicly available all-sky dataset of selected tracks, covering 10 years of IceCube data (2008–2018). It is known in the community as the 10-year Point Source Track (PSTrack) dataset⁴. The reconstruction discussion here is therefore restricted to PSTrack only. Other high-energy event selections, both tracks and cascades, rely on different reconstruction techniques, for which comprehensive overviews are available in [193, 224, 228–231, 233]

To detect high-energy track-like events at the DAQ level (Level-1), the Simple Multiplicity Trigger (SMT)-8 trigger is employed, which requires a minimum of 8 DOMs with HLC hits within a $5 \mu\text{s}$ time window. Further data reduction occurs at the PnF stage (Level-2), specifically using the Muon Filter by executing quick reconstructions. At this stage, the poorly reconstructed triggers are mostly removed, and the resultant data is transmitted to the North. There, the data undergoes more sophisticated online processing to maximise astrophysical neutrino events, minimise background contamination, and ensure high-quality direction reconstructions [193, 207, 235].

Initially, fast algorithms such as LineFit [236, 237] provide quick estimates of the event direction. It identifies a best-fit track following the least-squares minimisation method [238] for the χ^2 quantity defined below.

$$\chi^2 = \sum_{i=0}^{N_{\text{hit}}} \phi(\rho), \quad \phi(\rho) = \begin{cases} \rho^2, & \text{if } \rho < \mu, \\ \mu(2\rho - \mu), & \text{if } \rho \geq \mu \end{cases} \quad (4.2)$$

³The current best-fit single power law estimate for the spectral index is $2.58^{+0.10}_{-0.09}$ [229].

⁴Check out: [Data release](#)

In Eq. 4.2, $\rho = |\vec{v}(t_i - t_0) + \vec{r}_0 - \vec{r}_i|$. The muon velocity is $\vec{v}$, $\vec{r}_i$ is the position of the i^{th} hit at time t_i , $\vec{r}_0$ is the point of the track at time t_0 and N_{hit} is the number of hits. $\phi(\rho)$ is known as the Huber penalty function [239].

This output track estimate is further used by a more sophisticated, likelihood-based Multi Photoelectron (MPE) approach [237], called SplineMPE, to obtain a more refined track reconstruction. The Paraboloid method is used to estimate the angular uncertainty of track reconstructions using the paraboloid sigma (σ) as a proxy [240], given in Eq. 4.3.

$$\sigma = \sqrt{\frac{\sigma_1^2 + \sigma_2^2}{2}}. \quad (4.3)$$

Here, σ_1 and σ_2 are the scales of the axes of the ellipse, which is fit around the global minima of the SplineMPE likelihood map.

The energy reconstruction is achieved via another likelihood-based algorithm called MuEx [241]. It estimates the reconstructed energy by exploiting the linearity between the total number of photons produced (η) and the deposited energy (E):

$$\eta = \Lambda E + \kappa. \quad (4.4)$$

In Eq. 4.4, κ is the expected number of noise photons. Λ is the number of photons per unit energy and is derived from simulations for the exact muon track hypothesis employed.

Following this stage, the Muon Filter Level 3 [242] is used for offline processing, to significantly reduce the rate of atmospheric muons while retaining most neutrinos. It removes low-energy, misreconstructed events using criteria such as total charge collected, $Q_{\text{tot}} \geq 100$ PE, and the average-charge-weighted DOM distance to the track, $d_{\text{Qavg}} \leq 90$ m. Before moving to the next stage, the SplineMPE algorithm is applied again, using the results of the first as a seed and incorporating energy estimation to improve angular resolution. Finally, Boosted Decision Trees (BDT) are used to improve data sample purity by rejecting atmospheric muons and misreconstructed cascade events [193, 207, 235].

Low-energy Neutrinos in IceCube

The DeepCore subarray is designed to detect lower-energy neutrinos in the sub-TeV regime. It deals with similar backgrounds as mentioned for the high-energy neutrinos, but at a much higher rate. So, its strategies for background suppression are more complicated and tailored to deal with high background rates at lower energies.

- **Background suppression for low-energy neutrinos:** While the surrounding main IceCube array acts as an active veto for DeepCore, it uses further kinematic cuts based on ‘effective velocities’ calculated from hit timing and location. Events with effective velocities between 0.25-0.4 m/ns, characteristic of atmospheric muons originating outside

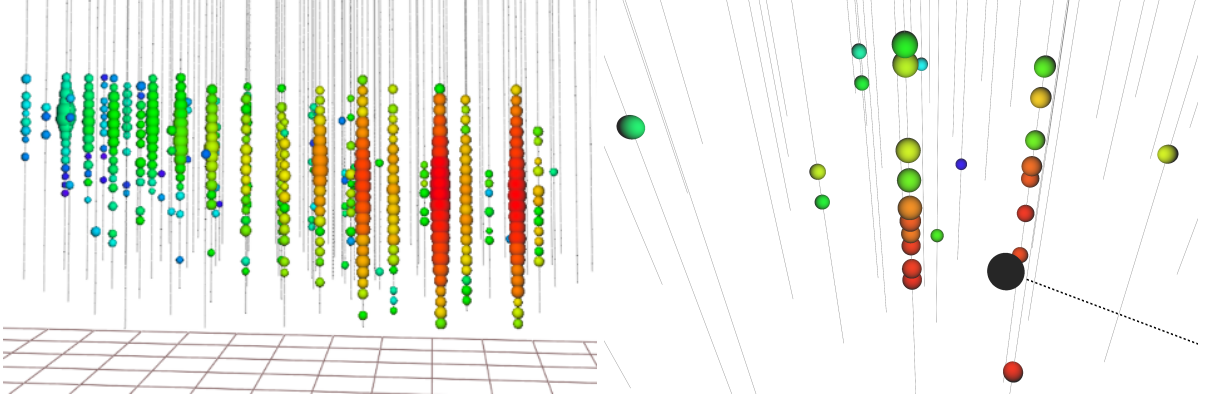


Figure 4.8.: (Left) An example high-energy neutrino event (IceCube-170922A) detected by IceCube, associated to the TXS blazar flare on 22nd September, 2017. It has an estimated energy of 290 TeV. (Right) A simulated low-energy neutrino event in DeepCore, with an energy of 25 GeV. The black dashed line and the black round marker show the direction and interaction point of the incoming neutrino. Figure and details obtained from [243]. Courtesy: [IceCube research news](#).

DeepCore, are disregarded [212]. This method retains 99.4% of neutrino events while significantly reducing atmospheric muon contamination.

- **Event reconstruction:** As a part of this thesis (see Ch. 6 and 7), the low-energy dataset which has been used is known as ‘GRECO Online’. GRECO stands for ‘GeV Reconstructed Events with Containment for Oscillations’. It was originally developed for an analysis regarding tau neutrino appearance [244]. For details of the initial event selection, refer to [214].

At Level-1, DeepCore has a distinct condition known as Simple Multiplicity Trigger (SMT)-3, which requires at least 3 HLC hits within a $2.5 \mu s$ time window, enabling the detection of lower-energy events. At Level-2, the DeepCore Filter is used to identify the promising sub-TeV events for further offline processing [215]. However, the main shortcoming of GRECO, like any low-energy neutrino dataset, is that, unlike higher-energy IceCube events, which exhibit distinct track or cascade topologies, DeepCore events at $\mathcal{O}(10)$ GeV often do not show clear topological separation due to the short muon tracks, as evident in Fig. 4.8.

Hence, more recently, GRECO has been optimised to enhance sensitivity to transient astrophysical neutrino sources by improving its effective area across the sky, especially around the energy range of $\mathcal{O}(100)$ GeV [245]. To achieve this, the event selection combines efficient cuts and a boosted decision tree (BDT) to suppress noise triggers and atmospheric backgrounds. After applying all the event selection cuts, the events are reconstructed using ‘PegLeg’ [246], which is a low-energy reconstruction algorithm, specifically used for the GRECO selection. It is very time-consuming, taking approximately 10 minutes to reconstruct each event [215]. However, it can reconstruct both tracks and cascades, and including the cascade-like events in the dataset improves A_{eff} by a factor of

~ 3 [198]. Pegleg provides eight reconstructed parameters as outputs, which are the hit position (x, y, z), hit time (t), direction (θ, ϕ), track length (l) and total deposited energy (E_{tot}). The resulting sample is an all-sky, all-flavour dataset, which can roughly contain 60% of atmospheric neutrinos [215]. It is an example of a high-statistics/low-purity sample⁵, which also includes astrophysical neutrinos. Thus, it is well-suited for transient follow-up in a shorter time window (typically ~ 1000 s), where the background could be suppressed by the incoming flux of astrophysical signal neutrinos, and has already been used in several analyses [10, 247, 248]. Further details on the cuts and reconstruction methods employed for the GRECO Online dataset could be found in [215].

4.3. Science Goals of IceCube

Exploiting the final level data selection, the IceCube collaboration provides the opportunity to the scientific community to perform astroparticle physics research in multiple frontiers. Some of them are discussed below.

- **Neutrino Physics:** IceCube performs precise measurements of atmospheric neutrino oscillations [214, 249–251], including tau neutrino appearance [244] and muon neutrino disappearance [252]. Studies to better understand the neutrino mass ordering are also performed [246]. The DeepCore sub-detector is particularly optimised for these low-energy analyses. IceCube also allows us to measure neutrino-nucleon cross-sections at high energies [253]. A breakthrough was the detection of the Glashow resonance [197], which occurs when a high-energy electron antineutrino interacts with an electron (see Fig. 4.2).
- **Beyond Standard Model Physics:** IceCube looks for neutrinos produced from dark matter decay or annihilation, for a large amount of dark matter accumulation in the core of Earth itself [254], or in celestial bodies like the Sun [255, 256], the Galactic Centre [257], and in galaxy clusters [258] using DeepCore data. It also allows us to search for sterile neutrinos [259, 260], magnetic monopoles [261], quantum gravity effects [262], and Lorentz symmetry violation [263].
- **Cosmic Ray Studies:** Icecube tries to understand the elemental composition of CRs using signals from extensive air showers (EAS) detected by IceTop and in-ice components [30, 264, 265]. Using the data, we can study high-energy CR, especially in the ‘knee’ region (PeV - EeV), which represents the transition from Galactic to extragalactic origins. Furthermore, we can test phenomenological models that describe hadronic interactions of CRs with atmospheric nuclei [266–269]. Additionally, using the data, there are ongoing efforts to identify mass composition sensitive parameters [270]. Investigating the arrival directions of CRs to understand their distribution and potential sources is also one of the analysis motives [271, 272].

⁵In contrast, IceCube also provides low-statistics/high-purity samples, such as the starting track selections [228], where most of the events have a high probability of being astrophysical.

- **Diffuse Studies with Astrophysical Neutrinos:** IceCube addresses several key aspects regarding the diffuse measurement of astrophysical neutrino flux. It already confirmed the detection of astrophysical neutrinos in 2013 [1]. Since then, efforts are ongoing to understand its characteristics, including the energy spectrum. Recently a strong evidence in favour of a broken power law spectrum of astrophysical neutrinos has emerged [230, 231]. While trying to understand its flavour composition, a pion decay scenario is currently favoured [68]. However, a muon-damped source scenario is also under investigation [67].

Among its other objectives are the measurement of the astrophysical neutrino–antineutrino ratio [273], the characterisation of the diffuse neutrino flux originating from the Galactic Plane [274–276], and the search for cosmogenic neutrinos at extremely high energies [37]. Furthermore, IceCube contributes to the identification of astrophysical tau neutrinos [277] and to a detailed understanding of the astrophysical muon neutrino spectrum [278].

- **Neutrino Astronomy:** A core objective for IceCube is to locate the sources of high-energy neutrinos, which can provide invaluable information about the origin of CR. IceCube provides this complementary view of the sky using different event selections. This involves looking for individual or populations of neutrino sources that are either steady [234], transient [279], or flaring [280]. Using the data, we can perform continuous, unbiased searches across the entire sky for neutrino flares or clusters, even without relying on pre-defined source lists.

IceCube also sends real-time alerts with a latency of a few seconds on the interesting high-energy tracks and cascades with high astrophysical purity via the GCN notice system in machine-readable format to facilitate autonomous follow-ups [213, 281, 282]. All these alerts are also released in the form of catalogues, and used for neutrino source identification [283, 284]. A cluster alert system [285] to identify potential flaring neutrino sources [286] in real-time has also been developed, and communication is in place for triggered electromagnetic (EM) follow-up searches via a memorandum of understanding. There is also another work ongoing for the development of a real-time alert system based on identifying multiplets of neutrino events coming from the same location within 30 days to trigger optical follow-up searches [287].

In addition to performing neutrino astronomy with high-energy events, DeepCore data is also used for systematic studies to identify transient sources emitting sub-TeV neutrinos [215, 245, 288]. While solar neutrinos are typically below IceCube’s primary detection range, the observatory contributes to identifying neutrino coincidences with solar flares [289].

- **Multi-messenger Follow-ups:** Other than identifying high-energy neutrino candidates with a high probability of astrophysical origin and issuing rapid alerts to the broader astronomical community, IceCube also follows up on alerts from Gravitational Wave (GW) and EM (e.g., optical, X-ray, gamma-ray) community, enabling timely multi-messenger follow-up searches in coordination with other telescopes [290, 291]. It also actively

searches for neutrinos from various transient astrophysical sources, including Gamma-Ray Bursts [109–111, 247], Fast Radio Bursts [292], and novae, with a focus on sub-TeV neutrino emission [248, 293]. Association of high-energy IceCube neutrinos with two tidal disruption events [103, 104] has led to further studies [294], but no counterpart was found. GW events are also regularly followed up via both real-time searches using high-energy tracks [9, 13] and archival searches using neutrino events across a broad neutrino energy range, from MeV-PeV [7, 8, 10–12, 122, 295]. Currently, there is no statistically significant coincidence reported. Additionally, IceCube has conducted both catalogue and stacking searches to identify neutrinos coming from the vicinity of detected ultra-high-energy cosmic ray events by combining data obtained from multiple neutrino and CR observatories, resulting in upper limits on neutrino flux for each ultra-high-energy CR event [118, 296].

IceCube also has estimated upper limits for core-collapse supernovae [297, 298], specifically from high-energy neutrinos. It has also followed up on a recent core collapse supernova, SN2023ixf, which occurred 6.4 Mpc away from the Earth. Because of the supernova’s location at $RA = 210.9^\circ$ and $\delta = 54.3^\circ$, high-energy neutrino tracks specifically from the Northern Hemisphere were used for the follow-up, but no evidence of correlated neutrino emission was observed [299]. DeepCore can also potentially help to detect neutrinos coming from an upcoming Galactic supernova [300]. Searches for bursts of MeV neutrinos from nearby supernovae are also performed continuously in real time, and any detections are automatically announced within the SNEWS network [295]. Thus, DeepCore’s integration within the larger IceCube observatory allows for a multi-faceted approach to neutrino astronomy, enabling detailed studies across a broad energy range.

IceCube has been dedicatedly searching for neutrinos coming from different active galactic nuclei subclasses by looking into the data obtained from different EM telescopes, such as Fermi-LAT-detected blazars [301, 302], X-ray bright Seyfert galaxies [303], hard X-ray AGNs [98], to name a few. A dedicated study has been performed to detect neutrinos from AGN core [304]. Already in 2017, TXS 0506+056 was identified as the first hadronic accelerator during its flaring state, which was observed by MAGIC, H.E.S.S., and VERITAS, Fermi-LAT, AGILE, Swift XRT, ASAS-SN, Kiso/KWFC, Kanata/HONIR, OVRO and VLA, across the whole electromagnetic spectrum [4]. Eventually, an AGN-starburst composite galaxy NGC1068 [5] has also emerged as a steady emitter of high-energy neutrinos, with 4.2σ . A softer evidence of neutrino emission with 2.9σ has been reported from the direction of NGC4151 [98]. Finally, in 2023, IceCube also announced detection of high-energy cascades from the Galactic Plane [81], which has now been probed further using multiple combined datasets and analysis techniques [305, 306].

IceCube also allows us to study the optical properties of ice [307–313], dust concentration [314], snow accumulation [218], and other characteristics [315, 316] of the Antarctic ice. These studies not only help us to better understand the systematic uncertainties, but also facilitate conducting diverse scientific research.

4.4. Future of IceCube

Given all these exciting achievements, IceCube is preparing for future enhancements, focusing on IceCube-Gen2 project and an immediate IceCube-Upgrade.

4.4.1. IceCube-Upgrade

The IceCube-Upgrade [317], planned to be deployed for the 2025-2026 season, will provide several new strings within the DeepCore sub-array region. This will further increase DOM density and include different types of PMTs facing multiple directions, significantly improving angular uncertainty for southern sky events and enhancing sensitivity at low energies, between 1 GeV to 1 TeV [318]. This improved reconstruction will enable neutrino source searches at sub-TeV energies [319]. This enhancement is also critical for more precise atmospheric neutrino oscillation measurements [320] and low-energy neutrino-aided dark matter searches [321, 322]. The data and experience gained from the upgrade will also contribute to better calibration [323] and ice models [313], which are crucial for future progress.

Key Components

The IceCube Upgrade will test new optical sensors, such as mDOM (Multi-PMT Digital Optical Module) [324] and D-Egg [325], for IceCube-Gen2. mDOMs will have 24 smaller 3-inch PMTs, each pointing in almost all directions, thereby increasing the photocathode area by a factor of 2.2. D-Eggs will use two 8-inch PMTs facing up and down, offering lower power consumption and requiring smaller boreholes. A redesigned version of the standard IceCube DOMs, referred to as pDOMs, will be deployed in the calibration region to enhance the characterisation of their in-situ response [326].

4.4.2. IceCube-Gen2

IceCube-Gen2 [327] is envisioned as the successor to the current IceCube detector, designed to serve as a "window to the extreme Universe". It is planned to be fully operational by 2033. It aims to significantly increase the detector volume to 8 km^3 ($\sim 10^{2/3}$ times of IceCube) and extend the sensitivity beyond 10^{18} eV . The event rate should increase by an order of magnitude for all neutrino flavours in the $10^{14} \text{ eV} - 10^{16} \text{ eV}$ energy range, with improved flavour identification and point-source sensitivity at least five times better than the current detector. The Gen-2 configuration will facilitate near real-time reconstruction with $\lesssim 1^\circ$ resolution for rapid multi-messenger follow-ups with EM and GW observatories. It will also help identify dominant populations of neutrino sources, probe the diffuse astrophysical neutrino flux, and address open questions about CR physics and fundamental neutrino properties.

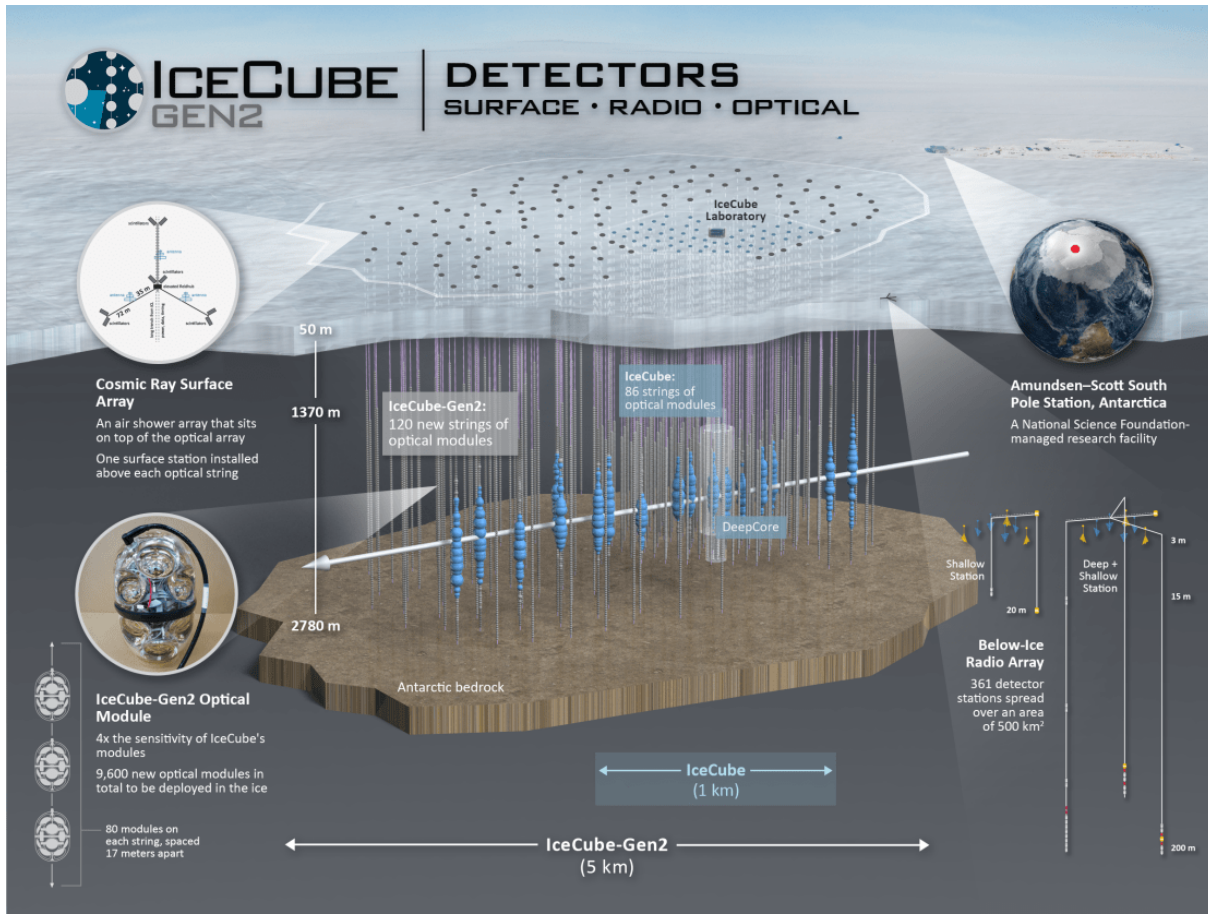


Figure 4.9.: IceCube Gen-2 schematic diagram. Credit: [WIPAC/ICEHEP](#)

Key Components

IceCube-Gen2 will add new components to the existing IceCube infrastructure. The current in-ice optical array will be expanded with 120 new strings of mDOMs and D-Eggs, spaced about 240 m apart, instrumenting a total volume of 8 km³, with new optical sensors of enhanced detection capabilities. A large surface array to accompany the in-ice array will also be an intrinsic part of the whole configuration, to veto the atmospheric background to detect astrophysical neutrino events. It will consist of scintillators and radio antennas to mitigate snow effects on IceTop, lower the air-shower detection threshold, improve composition measurements, and enable PeV γ -ray searches from the Galactic Centre. In addition, a ~ 500 km² in-ice radio array with 313 stations will extend sensitivity to neutrinos in the $10^{16} - 10^{18}$ eV range via Askaryan emission, providing unprecedented reach for transient astrophysical events and strengthening multi-messenger capabilities [328].

The Fig. 4.9 shows an overall schematic diagram of the planned extension. As a part of this thesis, the prospect of transient source search in the era of Gen-2 has been explored. But before that, the general neutrino source search methods need to be discussed, which are highlighted in Ch. 5.

Chapter 5. Search for Co-incidences: Unbinned Maximum Likelihood Analysis

"The most important questions of life are, for the most part, really only problems of probability."

- Pierre-Simon Laplace

For this thesis work, the primary objective is to identify potential astrophysical sources of neutrinos. Any analysis developed to identify neutrino sources aims to distinguish neutrinos originating from astrophysical sources, which are referred to as ‘signals’, from the dominant atmospheric and diffuse astrophysical neutrino ‘background’. To this end, statistical methods based on likelihood ratio tests are employed. These tests evaluate the compatibility of the observed data with contrasting hypotheses: one assuming the presence of signal neutrinos, and the other representing a background-only scenario.

In this chapter, the method used to perform the analysis relevant to this thesis, as well as many other analyses with neutrino data, is discussed. It starts by outlining the key components of the hypothesis-testing approach, followed by a description of the signal and background models represented by different likelihoods. Finally, the overall structure of the analysis, including its practical implementation and interpretation of results, is outlined. Elements of the framework have previously been presented in a proceeding [329].

5.1. Hypothesis Testing

To search for signal neutrinos in the data, two case scenarios are considered. The data can represent two competing hypotheses:

- **Null hypothesis** ($\mathcal{H}_0$): We only have background neutrino events in our data.
- **Signal hypothesis** ($\mathcal{H}_s$): We inject some signal neutrinos correlated with a specific astrophysical source, along with background events.

These hypotheses are constructed in a way that incorporates all relevant information from the data into the analysis, but they represent two contradictory scenarios. For mathematical representation [235], let us assume a multi-dimensional space Θ . There belongs some set of parameters (θ) which can efficiently discriminate between $\mathcal{H}_s$ and $\mathcal{H}_0$. To specify the scenarios representing $\mathcal{H}_0$, we rely on a subset of Θ , Θ_0 ($\Theta_0 \subset \Theta$), and the alternative scenario $\mathcal{H}_s$ is represented by the complementary subset Θ_0^c . To summarise,

$$\mathcal{H}_0 : \theta \in \Theta_0, \quad \mathcal{H}_s : \theta \in \Theta_0^c \quad (5.1)$$

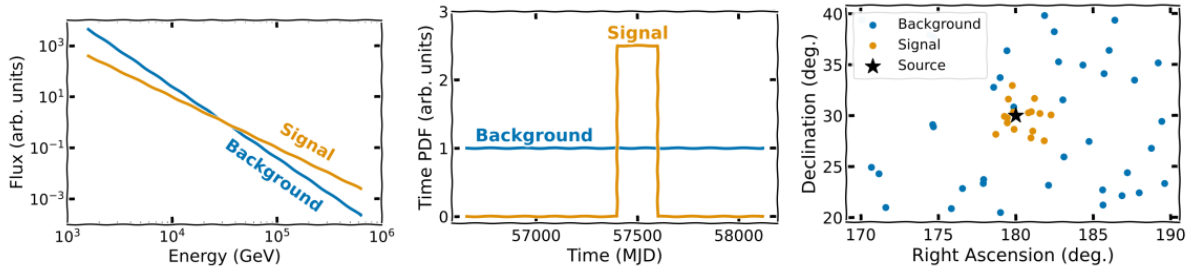


Figure 5.1.: Illustration of the (left) spectral, (centre) temporal, and (right) spatial features of the signal and background hypotheses. Adapted from [198].

The main distinguishing features between the signal and background neutrinos are discussed below and represented in Fig. 5.1.

- **Spatial feature:** The signal neutrinos are expected to be clustered around the source spatially and temporally. The spread of the cluster is dictated by the detector's angular resolution around the true direction. In contrast, the background events are isotropically distributed [198, 330].
- **Spectral feature:** The signal neutrinos are expected to follow a E^{-2} spectrum, following Fermi acceleration mechanisms. In contrast, the atmospheric neutrinos from extensive air showers (EAS) follow a power law of $\sim E^{-3.7}$ below ~ 1 TeV. It further steepens to $\sim E^{-4}$ (till 100 TeV) in higher energies above due to meson re-interactions [17, 331].
- **Temporal feature:** If the signal neutrino emission is time-dependent (periodic, flares, one-time bursts), the events coming from the astrophysical neutrinos should be emitted within a certain time window. In contrast, atmospheric neutrinos form a time-independent background, unrelated to the source activity. However, their rate fluctuates seasonally due to variations in the atmospheric pressure and temperature. Warmer temperatures cause the atmosphere to expand, thus lowering its density. This results in increasing the mean free path for pions and kaons, which enhances their decay probability. Eventually, this raises the background rate. Cooler temperatures compress the atmosphere, leading to more meson interactions and a lower neutrino flux [198, 332, 333].

To incorporate all the above-mentioned information, we search for neutrino events coming from a sky location $\vec{x}_s$, and they follow a certain spectral shape $E^{-\gamma}$. For time-dependent emission, the search is conducted within a time window of t_w , which is chosen around the time of source activity. All these together represent the signal hypothesis. The background hypothesis is that when the events are spatially and temporally not influenced by the astrophysical source and follow a different spectral shape altogether.

5.2. Likelihood

Once the signal ($\mathcal{H}_s$) and background ($\mathcal{H}_0$) hypotheses are defined, statistical testing is required to evaluate which is better supported by the data. The likelihood-ratio test is the standard method used for this purpose. According to the Neymann-Pearson lemma, it is the most powerful test to distinguish between the two competing hypotheses. However, before conducting a likelihood ratio test, we first need to define the likelihood functions describing the contrasting hypotheses. Suppose $p(X | \theta)$ denotes the probability of obtaining observation ‘ X_i ’ given a particular set of parameters θ . The general representation of the likelihood function would be [235],

$$\mathcal{L} = \prod_i p(X_i | \theta) \quad (5.2)$$

Our goal is to estimate the parameters that best describe the potential source. By maximising the likelihood $\mathcal{L}$, we can obtain the best-fit parameters $\hat{\theta}$ in the parameter space of Θ that describe the observations (X_i) we have. So,

$$\mathcal{L}(\hat{\theta} | X) = \max_{\theta \in \Theta} \mathcal{L}(\theta | X). \quad (5.3)$$

This forms the foundation of the maximum likelihood estimation (MLE) method. There are two main approaches to performing MLE using neutrino data.

- **Binned MLE:** In this approach, the entire data is binned into histograms. It is much simpler to implement, but it loses some information in the binning process. It is often used when data volume is high or binning is unavoidable (e.g., detector resolution limitations)
- **Unbinned MLE:** This method uses individual event information directly. It is more rigorous, especially for low-statistics regimes. It is commonly used in particle physics and neutrino astronomy.

5.2.1. Unbinned Maximum Likelihood

For neutrino source searches, the standard analysis method is based on unbinned maximum likelihood (UML) estimation. In this case, each event contributes individually to the total likelihood. This approach optimally utilises event-level observables, including reconstructed direction, time, and energy.

The likelihood function evaluates the probability that a given set of observed neutrino events $\vec{x}_i$ originates from a point-like astrophysical source located at $\vec{x}_s$. The likelihood is formulated as a Bernoulli trial, where each event is assumed to either be produced by a source (following the signal hypothesis) or arise due to background.

The Point Source Likelihood

Assume we have a well-localised, ‘point-like’ astrophysical source of neutrinos, whose angular size is much smaller than the detector’s angular resolution. In that case, the likelihood takes the following form [198]:

$$\mathcal{L}_{\text{PS}}(n_s(\gamma)) = \prod_{i=1}^N \left(\frac{n_s S_i}{n_s + n_b} + \frac{n_b B_i}{n_s + n_b} \right). \quad (5.4)$$

In Eq. 5.4

- N is the total number of events observed in the sky.
- n_s is the number of signal neutrinos.
- n_b is the expected number of background events
- S_i represents the signal probability density (PDF)
- B_i represents background PDF

As among N events, n_s are signal events, $n_b = N - n_s$. So, $\frac{n_b}{n_s + n_b} = (1 - \frac{n_s}{N})$. The index i runs over each of the N candidate neutrino events.

The signal hypothesis S_i incorporates both spatial and energy information, typically modelled based on the reconstructed event observables $\vec{x}_i$, and $\phi_v(\vec{x}_s, \gamma)$, which represents the spectral hypothesis for the point source. The source spectrum is usually assumed to follow a power-law.

$$\phi_v(\vec{x}_s, \gamma) = \frac{dN}{dE dA dt} = \phi_0 \left(\frac{E}{E_0} \right)^{-\gamma} \quad (5.5)$$

In Eq. 5.5,

- ϕ_0 is the flux normalisation, with the units of $\text{GeV cm}^{-2} \text{s}^{-1}$
- E_0 is a reference energy
- γ is the spectral index

Both n_s and γ could be treated as free parameters, for which the likelihood is maximised [10]. In certain analyses, however, γ is fixed to a physically motivated value, leaving only n_s as a free parameter to simplify the optimisation [12]. The background PDF B_i is typically estimated from scrambled datasets, by randomly reassigning the right ascension or time of individual events, assuming an isotropic distribution.

5.2.2. Binned vs unbinned MLE for source searches

The entire framework explained above could have been implemented using a binned MLE as well. However, several limitations make the UML more favourable for neutrino source searches, as previously discussed in [332].

In a binned analysis, a fixed angular bin is typically chosen to match the detector's angular resolution. It could be used to select events near the source direction. A statistically significant excess of events within this bin, above the expected atmospheric background, could indicate a potential source. Additional event selection criteria, such as energy or time cuts, may be applied to improve sensitivity, especially for transient signals, by reducing background contamination within the chosen time window.

However, the binned approach simplifies each event into a binary decision: either it falls within the selected bin and counts toward the signal, or it does not. This binary treatment discards valuable information that could help distinguish signal-like events from the background. For example:

- Events near the edge of the search bin contribute equally to those near the centre, despite being less compatible with a point source hypothesis.
- Energetic events that are much more likely to originate from an astrophysical source following a harder spectrum of E^{-2} , versus the atmospheric background following a spectrum of $E^{-3.7}$, are not given additional weight beyond the energy cuts.
- The effectiveness of a binned analysis depends on how well the selection cuts match the assumed signal model. Cuts optimised for one spectral or spatial hypothesis may perform poorly for others [334]. There is often a trade-off between maximising sensitivity and maximising discovery potential.

To overcome these challenges, I follow the UML method for the analyses performed as a part of this thesis, which was introduced in [330]. This approach incorporates angular and energy information on an event-by-event basis. By retaining full event-level information and allowing flexible modelling of signal hypotheses, the unbinned MLE provides improved sensitivity and discovery potential for both steady and transient neutrino sources. This method was first developed for the AMANDA detector [190] and has since been refined and widely adopted in IceCube analyses. Similar techniques [335] have also been applied to data from other neutrino observatories, such as ANTARES.

5.2.3. The Extended Point Source Likelihood

If the source is transient, an additional Poissonian term $\frac{(n_s+n_b)^N}{N!}e^{-(n_s+n_b)}$ is included in the likelihood [8, 247]. It encodes whether we observe an excess beyond the expected background. If the probability of observing N events is based on an expectation of having $n_s + n_b$ events, where n_b is the expected number of background events, the final likelihood takes the following form:

$$\mathcal{L}_{\text{ext}}(n_s(\gamma)) = \frac{(n_s + n_b)^N}{N!} e^{-(n_s+n_b)} \prod_{i=1}^N \left(\frac{n_s S_i}{n_s + n_b} + \frac{n_b B_i}{n_s + n_b} \right). \quad (5.6)$$

This is the form of likelihood that is relevant to this thesis, and has been implemented in the analysis discussed in Ch. 7 for the sub-threshold GW follow-up search. To test the hypotheses

for transient sources which are not point-like (here, GW sources), on the sky, further spatial information is included in the test statistics, which is discussed in Sec. 5.4. But before that, the PDFs employed to represent $\mathcal{H}_i$ and $\mathcal{H}_s$ need to be discussed.

5.3. Signal and Background Probability Distribution Functions

As discussed before, the PDFs S_i and B_i in Eq. 5.6 are multi-dimensional, incorporating information related to spatial reconstruction, energy estimation, and event timing of each observed neutrino event. Despite the inherent multidimensionality, these components can be treated separately, as the variables are independent of each other. A detailed description of their construction and functional forms, including all subcomponents, is provided in this section. The discussion here is mostly based on [198, 330], if not mentioned otherwise.

5.3.1. Signal PDF

The Signal PDF (S_i) has three main components: spatial (S_{sp}), spectral (S_E), and temporal (S_{tmp}). So,

$$S(\vec{x}_i, \phi_v(\vec{x}_s, \gamma)) = S(\vec{x}_i, \vec{x}_s, \sigma_i, E_i, t_i, t_s, \Delta t, \gamma) \quad (5.7)$$

$$= S_{sp}(\vec{x}_i | \vec{x}_s, \sigma_i; E_i, \gamma) \times S_E(\sigma_i, E_i, \vec{x}_s, \gamma) \times S_{tmp}(t_i, t_s, \Delta t). \quad (5.8)$$

Here, each event is characterised by an estimated energy E_i and a reconstructed direction $\vec{x}_i$. Each of them also includes the angular uncertainty on this position σ_i . As mentioned before, $\vec{x}_s$ is the source position and γ is the spectral index.

Spatial Component

In reality, the spatial term S_{sp} depends on both the reconstructed energy (E_i) and the assumed spectral index (γ), since the angular resolution for point-like sources improves with increasing energy and can vary slightly with γ . However, for practical purposes, this dependence is often neglected [198]. Hence, the spatial term can be approximated as, $S_{sp}(\vec{x}_i | \vec{x}_s, \sigma_i; E_i, \gamma) \approx S_{sp}(\vec{x}_i | \vec{x}_s, \sigma_i)$.

While the explicit energy dependence is omitted in this simplified form of the spatial PDF, the angular uncertainty σ_i is typically calibrated through a procedure known as pull correction [336]. This process relates the reconstructed angular error to the true opening angle between the actual and reconstructed event directions as a function of the reconstructed energy. The calibration is spectrum-dependent and is usually performed for a fixed spectral index, most often $\gamma = 2$. Furthermore, the angular reconstruction uncertainties are typically treated as radially symmetric. It implies that the resolution is assumed to be the same in azimuth and zenith. Under this assumption, S_{sp} depends only on the angular separation ψ_i between the reconstructed event direction and the source position. So, finally, $S_{sp}(\vec{x}_i | \vec{x}_s, \sigma_i) \approx S_{sp}(\psi_i, \sigma_i)$. To model S_{sp} ,

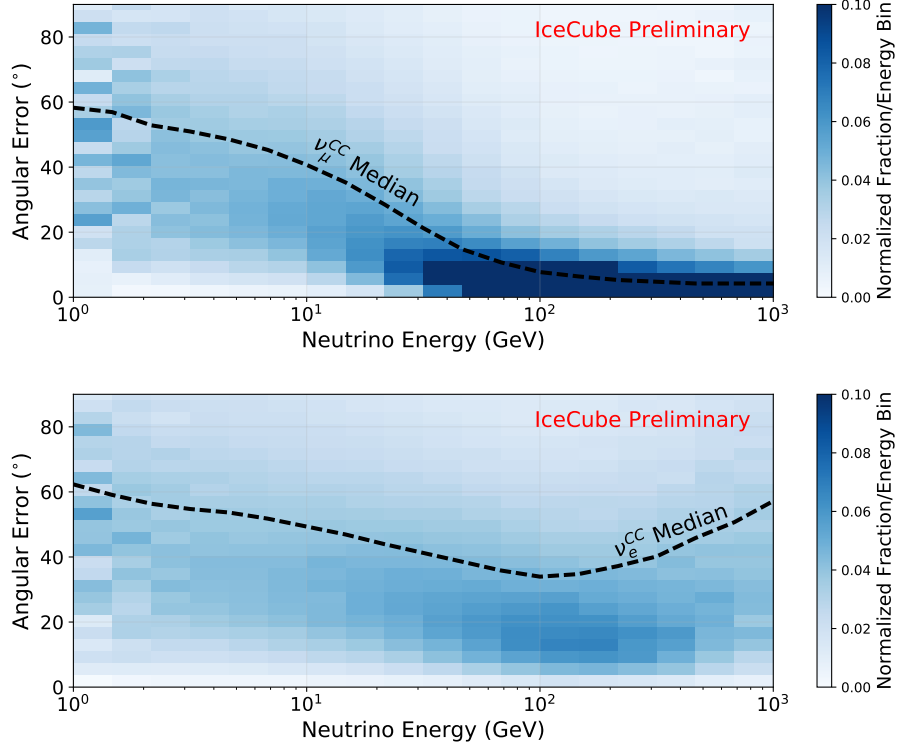


Figure 5.2.: Angular uncertainty for GRECO tracks and cascades with respect to energy. Figure obtained from [245].

we often rely on a two-dimensional (2D) Gaussian function with a characteristic width given by σ_i .

$$S_{\text{sp}}(\psi_i, \sigma_i) = \frac{1}{2\pi\sigma_i^2} e^{-\frac{\Delta\psi_i^2}{2\sigma_i^2}} \quad (5.9)$$

As defined above, here $\psi_i = |\vec{x}_i - \vec{x}_s|$.

Because S_{sp} is defined on the surface of a sphere, its formulation must account for its curvature. The effect becomes particularly dominant for events with large σ_i . Such cases are common in cascade-like events [224] or low-energy samples [245], as seen in Fig. 5.2 for the GRECO sample. When σ_i exceeds approximately 7° , the standard two-dimensional Gaussian approximation no longer provides an accurate description. In these situations, the spatial term is more appropriately modelled using a von Mises–Fisher distribution [337] which is well-suited for probability distributions on a spherical surface.

Spectral Component

The second term in Eq. 5.8 represents the spectral component of the signal PDF. It helps to distinguish the background from the source spectrum, given a spectral index of γ . Other than that, reconstructed energy (E_i) and declination (δ_i) serve as the key variables in this context.

In this formulation, dependencies on angular uncertainty are omitted, as was also done for the spatial component [198]. So, the energy PDF can be typically expressed as,

$$S_E(E_i, \delta_i | \gamma) \propto A_{\text{eff}}(E_i, \delta_i) \times E_i^{-\gamma} \quad (5.10)$$

The normalisation factor is chosen so that S_E integrates to 1 over the entire energy of the neutrino dataset in concern, for each fixed value of γ . In Eq. 5.10, an additional term is shown, which is known as the effective area (A_{eff}) of the detector. It acts as a bridge between the detector level quantities, such as the number of signal events (n_s), and the source spectral assumption ϕ_v as shown in Eq. 5.5, in the following way:

$$n_s = \Delta t \int \phi_s(\vec{x}_s, \gamma) \times A_{\text{eff}}(E_i, \delta_i) dE \quad (5.11)$$

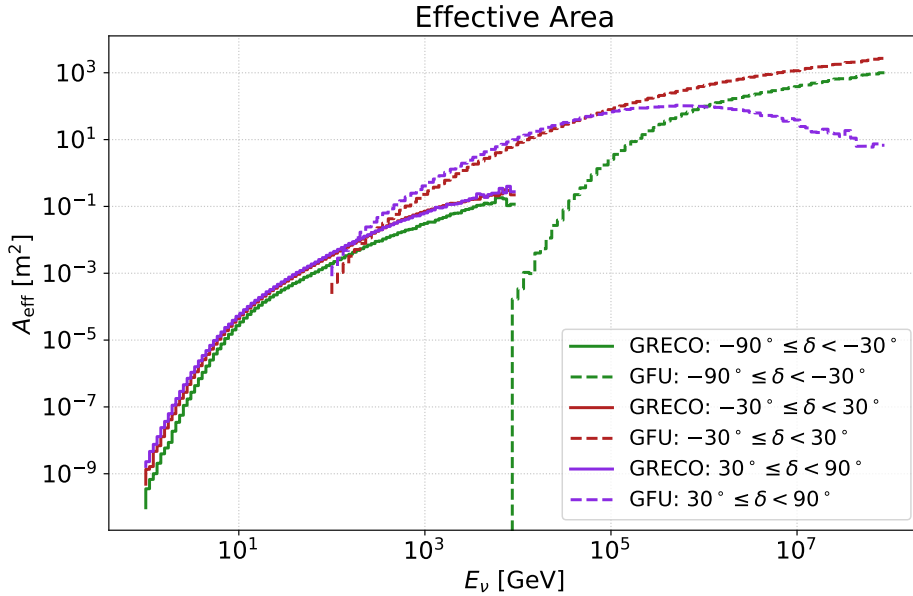


Figure 5.3.: The effective area (A_{eff}) of IceCube low-energy all-flavour neutrinos compared to that of the high-energy tracks, as a function of neutrino energy. The low-energy event selection is the most sensitive in the $\mathcal{O}(10\text{--}100)$ GeV energy range. It has nearly uniform coverage across the whole sky. On the other hand, the high-energy tracks are optimised for use in the TeV-PeV energy range. The A_{eff} suffers comparatively more in the Southern Hemisphere due to a higher background of atmospheric muons.

Mathematically, for a given flavour of neutrino,

$$A_{\text{eff}} = \varepsilon(E_{\text{th}}, \theta) \times A(\theta) \times P_v(E_v, E_{\text{th}}) \times e^{-[\sigma_v(E_v) N_A X(\theta)]} \quad (5.12)$$

Here, $A(\theta) = A \cos(\theta) = A \sin(90^\circ - \theta) = A \sin(\delta)$ is the projected area of the neutrino detector perpendicular to the neutrino coming from a zenith angle (θ) or declination (δ). $P_v(E_v, E_{\text{th}})$

is the interaction probability of the neutrinos, and the exponential term in Eq. 5.12 is the absorption coefficient of the Earth. $\varepsilon(E_{\text{th}}, \theta)$ is the detector efficiency term which accounts for the reconstruction of the secondary lepton above the energy threshold E_{th} [17]. Physically, A_{eff} represents the size of an ideal detector with perfect detection efficiency ($\varepsilon = 1$), that would yield the same response as the actual detector and the applied analysis cuts [198].

A representation of IceCube's A_{eff} in high- and low-energies could be found in Fig. 5.3. A_{eff} increases with energy because both the neutrino interaction cross section grows and higher-energy secondary particles travel further, making them easier to detect within the detector. However, for upward-going neutrinos ($\delta > 0$), A_{eff} declines at the highest energies since the Earth becomes increasingly opaque to these neutrinos (see Fig. 4.2). In the Southern Hemisphere, A_{eff} remains considerably smaller across most energies compared to the Northern Hemisphere, as stricter event selection is necessary to suppress the larger atmospheric background present there. These trends are naturally reflected in the signal energy PDF because of its dependence on A_{eff} , as indicated in Eq. 5.10

To maximise sensitivity across a range of possible astrophysical sources, γ can be allowed to vary, typically $1 \leq \gamma \leq 4$ [207]. For a chosen γ value within this range, neutrino events are simulated following Eq. 5.5. These events are used to build S_E as a 2D histogram in E_i and δ_i . The histogram spans the full range of E_i and 30 equally spaced bins for γ . This signal PDF is then divided by the corresponding fixed background PDF, giving a 2D map of relative signal strength across E_i and δ_i values. Maps are computed for $1 \leq \gamma \leq 4$, and the likelihood fit interpolates between them to determine the best value¹ [235].

Temporal Component

The third and final term in Eq. 5.8 represents the temporal component of a signal PDF. It is a critical element if the astrophysical neutrino source has time-dependent emission. An example of such a case is the GW sources discussed in Ch. 3, which are well-known examples of transient sources.

The main goal of incorporating time information is to achieve better signal-to-background discrimination, especially for short-duration flares where the background is significantly reduced. Some common temporal models are discussed below

- **Gaussian profile:** It assumes a smooth, bell-shaped temporal distribution of neutrino arrivals [235, 245]. It is defined by a central time (t_s), which is defined by the source observation time and flare duration t_w . Mathematically, it is represented as

$$S_{\text{tmp}}(t_i, t_s, \Delta t) \propto e^{-\frac{(t_i - t_s)^2}{2\Delta t^2}} \quad (5.13)$$

¹The best-fit γ is the one that maximises the combined spatial and energy likelihood for all events near the source.

It is often normalised with respect to the uptime of each IceCube data-taking season. However, previous analyses which have used Gaussian profiles have not reported significantly improved results [4] compared to a box time profile, which is described below.

- **Box profile:** This model assumes a constant probability within a defined time window (Δt), and is zero elsewhere. It is also defined by a start time (t_s), which is the transient event observation time and a duration (Δt). The mathematical form is shown below:

$$S_{\text{imp}}(t_i; t_s, \Delta t) = \begin{cases} \frac{1}{\Delta t}, & \text{if } t_s - \Delta t/2 \leq t_i \leq t_s + \Delta t/2 \\ 0, & \text{otherwise} \end{cases} \quad (5.14)$$

It is considered more suitable for online triggered follow-up searches because its start and end are well-defined, allowing it to be aligned with the end of a dataset [213]. Thus, it effectively acts as a mask, selecting events within the specified time window. This is the model that has been used for the GW follow-up analysis described in Ch. 6 and 7.

In some cases, for the signal assumption, S_{imp} could be set to mirror light curves from EM observations [4], or the parameters describing the temporal PDF ($t_s, \Delta t$) can be treated as free parameters to be fitted by the likelihood maximisation [215, 235]. Furthermore, for transient sources, the likelihood function itself needs to be modified, as shown in Eq. 5.6, on top of adding a temporal term in the signal PDF, which is implemented in the analyses presented in Ch. 6 and 7.

5.3.2. Background PDF

The background PDF (B_i) consists mostly of atmospheric muons and neutrinos. Like the signal (S_i), it is also composed of spatial and spectral components. The explicit form is shown below:

$$\begin{aligned} B &= B_{\text{sp}}(\delta_i | \Phi_{\text{bkg}}) \times B_{\text{E}}(E_i | \delta_i, \Phi_{\text{bkg}}) \\ &= \frac{1}{2\pi} P_{\text{B}}(\sin(\delta_i)) \times E_{\text{B}}(E_i, \delta_i) \end{aligned} \quad (5.15)$$

Here, the background neutrino flux is represented by Φ_{bkg} . To construct the background PDF, we follow a data-driven approach. Both P_{B} and E_{B} are derived from data, as PDFs of the dataset as a function of declination. Calculating the PDFs using the actual dataset is a realistic and valid approach because the vast majority of events in the dataset are believed not to be from astrophysical sources.

For transient sources, the background temporal PDF is generally assumed to be uniform across the examined time window. However, it's acknowledged that atmospheric backgrounds have a seasonal modulation (around 4-10%) due to temperature and pressure changes affecting atmospheric lepton production rates. While some analyses neglect this for simplicity, others address it by taking into account the local event rate in time or by using off-time windows near the on-time window [336]. For the analysis presented in Ch. 6 and 7, an off-time window of ± 5

days is considered [329], as within that off-time window we have enough events which can be scrambled to produce a background-like dataset, while being computationally efficient.

5.4. Test Statistics

For a point source, following the UML method, the likelihood ($\mathcal{L}$) defined in Eq. 5.6 is maximised for the best-fit values of n_s and γ , as shown in Eq. 5.3. It is then compared against the likelihood of the background-only hypothesis (implied by $n_s = 0$). For representation, the background likelihood could be written as $\mathcal{L}(\theta_0 | X)$ where $\theta_0 \in \Theta_0$, as introduced in Eq. 5.1. Now the likelihood ratio λ could be defined as the ratio of the maximised likelihood over the background-only likelihood [235].

$$\lambda = \frac{\mathcal{L}(\theta | X)}{\mathcal{L}(\theta_0 | X)} \quad (5.16)$$

Finally, the test statistic (TS) is introduced to measure how consistent the observed data are with the null hypothesis.

$$TS = 2 \log \lambda \quad (5.17)$$

Using the point-source likelihood shown in Eq. 5.6, TS is defined as [8],

$$TS = 2 \ln \left(\frac{\mathcal{L}_{\text{PS}}(\hat{n}_s(\hat{\gamma}))}{\mathcal{L}_{\text{PS}}(n_s = 0)} \right) \quad (5.18)$$

Here, $\hat{n}_s$ and $\hat{\gamma}$ are the best-fit values for the number of signal neutrino n_s and γ which maximise $\mathcal{L}$ in Eq. 5.4. Similar representation can be obtained using Eq. 5.6. Now, for $n_s = 0$, the denominator is only driven by the background PDF. Modifying Eq. 5.6, we have:

$$\mathcal{L}(n_s = 0) = \prod_{i=1}^N B_i(E_i, \delta_i) \quad (5.19)$$

Here, ‘i’ denotes the index representing the total number of neutrinos on the sky. So essentially, for each event, the energy E_i and declination δ_i are well-known. Hence, Eq. 5.19 has no free parameters [198]. In practice, TS_{PS} is computed by directly maximising Eq. 5.18 for n_s and γ . It is more straightforward than first maximising the likelihood and then forming the log-likelihood ratio. They are not only mathematically equivalent but also computationally more stable.

Test Statistic with spatial prior

In many cases, the astrophysical sources we are concerned about are not point sources. This is true, in particular for the analyses described in Chap. 6 and 7. For extended sources like GW skymaps, as it is shown in the left panel of Fig. 5.4, one must take into account the localisation uncertainty of the progenitors. So, they are considered a combination of multiple point sources. This technique was first introduced in an analysis searching for joint sources of neutrinos and UHECRs [118].

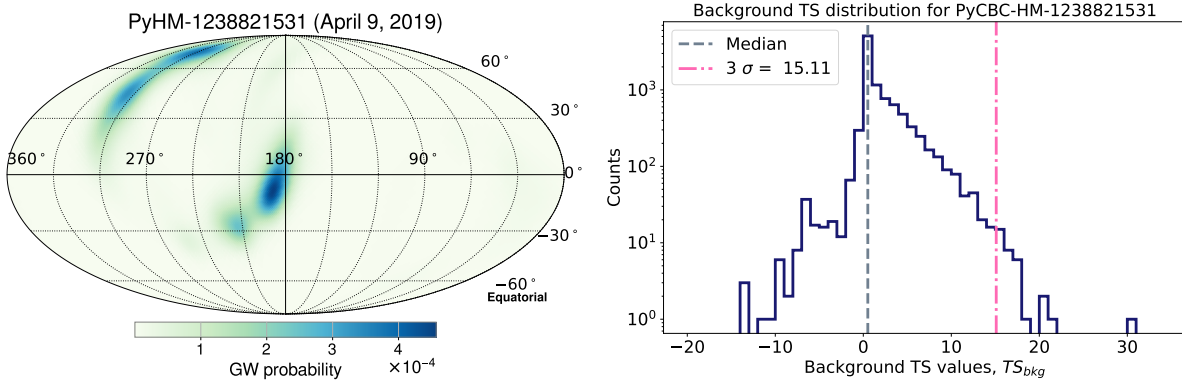


Figure 5.4.: (Left) An example GW skymap, as a typical example of astrophysical sources extended skymaps, due to poor localisation information from the respective detectors. (Right) Corresponding BGTS distribution. The BGTS median and 3σ deviations from the median are highlighted on the plot.

To include the localisation information of the extended sources, their respective skymaps are used as input. The skymaps are probability distributions on the sky. They contain the probability of finding the point source for each pixel in the sky, at a location $\vec{x}_s$. For example, for GW skymaps, the probability distribution is P_{GW} . So, the joint likelihood would be:

$$\mathcal{L}_{\text{ext}}(\vec{x}_s, n_s, \gamma) = \mathcal{L}_{\text{PS}}(\vec{x}_s, n_s, \gamma) \times P_{\text{GW}}(\vec{x}_s) \quad (5.20)$$

When taking the log likelihood ratio, the skymap term and the point source term are separated into a sum, and the final TS is found by finding the maximum of this sum across the whole sky.

$$\begin{aligned} TS &= 2 \ln \left(\frac{\mathcal{L}_k(\hat{n}_s(\hat{\gamma})) \cdot P_{\text{GW}}}{\mathcal{L}_k(n_s = 0)} \right) \\ &= 2 \ln \left(\frac{\mathcal{L}_k(\hat{n}_s(\hat{\gamma}))}{\mathcal{L}_k(n_s = 0)} \right) + 2 \ln \left(\frac{(P_{\text{GW}})_k}{P_{\text{GW}}^{\text{max}}} \right) \\ &= TS_{\text{PS}} + 2 \ln(\omega_k). \end{aligned} \quad (5.21)$$

Here, k denotes each pixel where a point source could be located. This information is obtained from the source skymap. $P_{\text{GW}}^{\text{max}}$ represents the maximum probability of finding a source at a given pixel on the sky, according to the skymap. To implement this in practice, the point-source TS is calculated at every single location on the sky. For each pixel, we calculate ω_k as $\frac{(P_{\text{GW}})_k}{P_{\text{GW}}^{\text{max}}}$ where $(P_{\text{GW}})_k$ is the probability of having a GW source in the k^{th} pixel. So, the maximum value of $2 \ln(\omega_k)$ is 0 for the best-fit GW source location. It is increasingly negative for the pixels where the GW source is less likely to be located. Thus, it acts as a spatial penalty term depending on the GW skymap. Thus, the TS_{PS} map is ‘penalised’ by the term ω_k , which contains the spatial information for each pixel ‘ k ’. Then, the final TS of the analysis is the maximum value from the sum of the point-source only value and the skymap-only maps.

5.5. Sensitivity, Evidence and Discovery Potential

After calculating the TS for individual sources, it is important to interpret the obtained TS values to interpret the results of hypothesis testing. For that, as a first step, we need to know how the TS behaves for the null hypothesis ($\mathcal{H}_0$), i.e., the background-like case. This serves as a benchmark against which we compare our results with signal injection, or actual data, which represents our signal hypothesis ($\mathcal{H}_s$).

5.5.1. The Background Test Statistic

To represent the background-like hypothesis, the TS value (with or without spatial penalty) for each source candidate is estimated without any signal injection, which means $n_s = 0$. This is done by generating background datasets through time-scrambling [329, 333, 338]. In this method, the recorded arrival times of individual neutrino events are randomly altered. Because of Earth's rotation, altering the event time is equivalent to shifting the reconstructed right ascension. Thus, an event detected at a different time would appear to arrive from a different right ascension while retaining the same declination. This process is repeated typically $10^4 - 10^5$ times, each representing a 'pseudo-experiment' or independent trial. The resulting dataset would be uniformly distributed in right ascension, as expected for background events. But it will have the original declination distribution preserved, which is closely related to A_{eff} , as discussed in Sec. 5.3.

These scrambled neutrino events are now treated as our background events (n_b), while computing the background TS value for each trial (TS_{bkg}). The TS_{bkg} values are collected for all trials, which correspond to the background TS (BGTS) distribution for individual source candidates. An example background TS distribution is shown in the right panel of Fig. 5.4. For other specific source scenarios, the BGTS distributions could be found in Fig. 6.18, in Ch. 6 and also in Appendix A.

5.5.2. Signal Injection

After obtaining a robust background estimation, we aim to evaluate the expected results of our analysis for a specific signal strength that can be observed. It also helps us to assess the sensitivity of our analysis. To perform this signal injection step, simulated neutrino events are selected from a Monte Carlo dataset with an assumed spectral index γ . Then they are added to the scrambled dataset and injected onto a $1^\circ \times 1^\circ$ box around a potential source location [333].

Sensitivity and Discovery Potential

From these injections, we calculate the 90% sensitivity, which is reported for each source candidate. This sensitivity estimate provides a benchmark for the detection capabilities of our analysis.

The 90% sensitivity is defined as the flux for which the TS value after signal injection is greater than the median of the BGTS distribution for 90% of the trials [329, 333, 338]. To perform

sensitivity studies, we inject an increasing number of n_s , following a spectrum with a preferred γ value, into the source skymap. The injected n_s values are scaled to account for the detector's acceptance, allowing us to relate each n_s to a specific flux level, as shown in Eq. 5.11. This procedure is also repeated across multiple trials for each source candidate. For each injected n_s value, we need to calculate the fraction of TS values obtained after signal injection which is greater than the threshold defined based on the BGTS distribution. This is defined as 'passing fraction' estimation.

The 90% sensitivity is defined as the flux at which the TS exceeds the median of the BGTS distribution in 90% of the trials, corresponding to $\text{PF} = 0.9$. Similarly, 3σ / 5σ discovery potential (DP) is defined as the flux level at which the TS exceeds the threshold corresponding to a 3σ / 5σ (single-sided) fluctuation above the background in 90% of trials ($\text{PF} = 0.9$) [329, 333, 338].

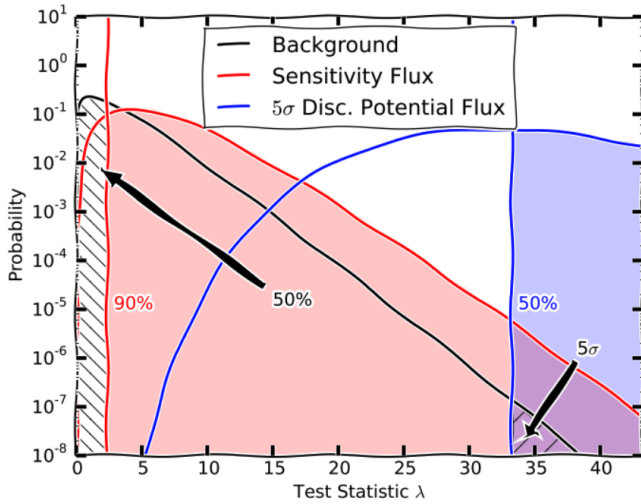


Figure 5.5.: Diagram to depict sensitivity and DP in terms of the signal and BGTS distributions. On the plot, the 90% CL sensitivity and the 50% CL 5σ DP are indicated. However, it should be pointed out that the chosen CLs and significance threshold for discovery are analysis-specific choices. For example, for the analysis presented in Ch. 6 and 7, the threshold of 90% sensitivity and 3σ evidence potential for 90% C.L. is followed. Figure and details obtained from [339].

Fig. 5.5 shows a schematic diagram of sensitivity and DP in terms of background and signal TS distributions. Notably, in most of the neutrino point-source searches, and also for the analysis relevant for this thesis (See Ch. 6), a 90% CL is adopted for the definitions of both sensitivity and DP. With this threshold, the background discrimination is expected to be stronger, which is advantageous in the sub-TeV energy range. However, this is not a universal choice. Other studies may employ different CLs, such as 50%. Unless specified otherwise, all sensitivity estimates, discovery potentials, and upper limits presented in this thesis are evaluated at the 90% CL.

Signal Recovery Tests

In addition to evaluating the TS distribution for signal-injected datasets, it is important to examine the best-fit values of the free parameters in the likelihood, specifically n_s and γ . This is typically done through bias tests, where known values of n_s and γ are injected into the analysis, and the corresponding distributions of the recovered $\hat{n}_s$ and $\hat{\gamma}$ are studied.

In an ideal case, the fit should recover the injected values, i.e., $N_{\text{fit}} = N_{\text{inj}}$ and γ_{fit} should be equal to the assumed spectral index value γ_{inj} . Significant deviations from the injected values indicate bias in the parameter estimation. A bias toward lower or higher values of N_{fit} and γ_{fit} would suggest under-fitting or over-fitting, respectively.

For extended sources in particular, under-fitting of n_s is more likely. This arises because injected neutrino signals, when distributed according to the source skymap, are spread over a large number of pixels due to the typically broad spatial uncertainty associated with individual source candidates. As a result, the signal becomes diluted, making it more difficult for the likelihood to correctly identify the true number of signal events.

5.5.3. Significance and Trial Correction

Significance

After completing the background and sensitivity studies, we can quantify the significance of an observation we have obtained using real data by comparing the observed TS value (TS_{obs}) with the background distribution to compute a p -value. The p -value quantifies the likelihood of obtaining a TS value at least as large as the one observed, solely caused by background fluctuations. Smaller p -values correspond to a lower probability of obtaining TS_{obs} from background fluctuation, and therefore represent stronger evidence of an event associated with a real astrophysical signal. It is common to express p -values in terms of the number of standard deviations (X_{sig}) from the mean of a Gaussian distribution. The mapping between p -value and X_{sig} can be derived by integrating the Gaussian PDF, leading to

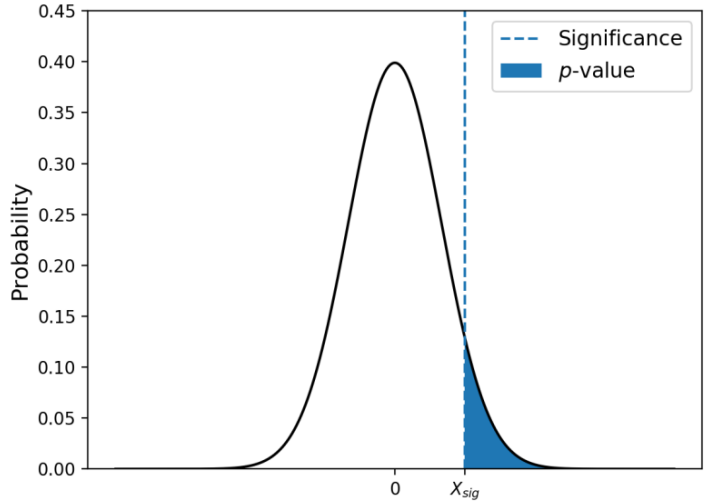


Figure 5.6.: A plot showing the relation between statistical significance (X_{sig}) and p -value, in the context of a Gaussian distribution. Figure obtained from [333].

$$X_{\text{sig}} = \sqrt{2} \operatorname{erf}^{-1} (1 - 2p) \quad (5.22)$$

Here, erf^{-1} denotes the inverse error function [333]. Fig. 5.6 illustrates the relation between significance and p -value. As reference values, a 3σ deviation from background expectation corresponds to $p \approx 1.35 \times 10^{-3}$. This is often regarded as moderate evidence, while 5σ ($p \approx 2.87 \times 10^{-5}$) is the conventional threshold for a discovery claim.

Trial correction

As mentioned in Sec. 5.5, we need to carry out multiple searches or trials within the same analysis, using the same dataset. In that case, the probability of observing a significant result purely by chance increases. This phenomenon is known as the ‘look-elsewhere’ effect. To account for this, a statistical correction is applied to obtain the post-trial p -value from the pre-trial one. In this work, the Šidák correction [340] is used, under the assumption that each trial is statistically independent. The corrected value is given below:

$$p_{\text{post}} = 1 - (1 - p_{\text{pre}})^N \quad (5.23)$$

Here, N is the number of independent trials performed. Figure 5.7 shows how the relation between p_{pre} and p_{post} changes with increasing N . It is clear that the more trials performed, the smaller the pre-trial p -value must be to remain significant after correction.

This expression can also be interpreted in terms of false positives (FP). If the probability of FP in a single trial is p_{pre} , then the probability of not having a FP is $1 - p_{\text{pre}}$. For N number of trials, the same would be $(1 - p_{\text{pre}})^N$. Then, the probability of observing at least one FP across all N trials is $1 - (1 - p_{\text{pre}})^N$, which gives us the corrected, post-trial p -value. It is implemented in the results described in Ch. 7.

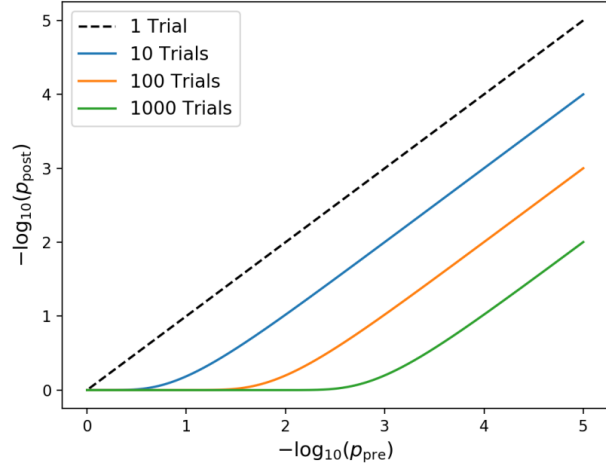


Figure 5.7.: A plot showing the relation between pre-trial and post-trial p -values, for different numbers of trials. Figure obtained from [333].

Chapter 6. Event Selection and Sensitivity Studies: GW follow-up with Neutrinos

"Somewhere, something incredible is waiting to be known."

— Maria Mitchell

Previously, in Ch. 3, the ‘low-significance’ or sub-threshold GW events have been introduced (see Sec. 3.5.2), and the motivation for initiating multi-messenger studies of these events with neutrinos was briefly discussed. However, they were not subjected to real-time neutrino follow-ups during the third observation run (O3) of the LIGO-Virgo-KAGRA (LVK) GW detection network, as their event data became publicly available only after the catalogue releases.

The first systematic effort in initiating multi-messenger studies with archival sub-threshold GWs and neutrinos involved a Bayesian follow-up analysis using the Low Latency Algorithm for Multi-messenger Analysis (LLAMA) pipeline [341]. This approach aimed to identify possible high-energy neutrino counterparts to individual sub-threshold GW events. A key limitation of such analyses is that they solely focus on identifying high-energy neutrino counterparts. However, given the majority of the prospective common astrophysical sources of GW and neutrinos are believed to have off-axis jets, such sources are expected to produce neutrinos in the sub-TeV energy range due to Doppler de-boosting effects [15].

Another shortcoming of the previous analysis was its strong dependence on the accuracy of waveform modelling and population-based priors, particularly the posterior estimates of the GW source distance (d_{GW}) and the astrophysical probability (p_{astro}) associated with the GW detection. These quantities are derived using Bayesian parameter estimation methods employed by the LVK collaboration and are highly sensitive to the choice of prior assumptions, as discussed in Sec 3.3. In particular, the p_{astro} values vary significantly across different search pipelines, owing to differences in assumed source population models, merger rates as functions of compact binary coalescence (CBC) masses and redshift, which already comes with a large uncertainty, and the specific waveform templates used [126]. As a result, a model-independent follow-up strategy driven solely by event-by-event GW and neutrino information becomes valuable for a robust interpretation of sub-threshold GWs. Therefore, a complementary search for sub-TeV neutrino counterparts to the sub-threshold GW candidates is essential.

To this end, as a part of this thesis, an unbinned maximum likelihood (UML) framework is adopted for conducting the sub-TeV neutrino follow-up. This method does not rely on prior model assumptions for the GW source population. Hence, it offers a complementary and more agnostic approach to the Bayesian analyses. The UML framework itself is described in detail in Chapter 5. In this chapter, the focus will be on the preparation to carry out an archival search using this method. The selection of sub-threshold GWs from GWTC-2.1 and -3, the sub-TeV neutrino dataset used to perform the search and the results obtained from sensitivity

studies will be discussed in this chapter. The contents discussed here were previously presented in [329, 338].

6.1. Sub-threshold Gravitational Waves

In this section, an overview of the sub-threshold GWs is provided to demonstrate the procedure used to filter and identify the most significant candidates from the full catalogue. These short-listed events serve as the targets for the archival sub-TeV neutrino follow-up search, for which the estimated sensitivities are included in this chapter.

6.1.1. Sub-threshold Event Selection

After the completion of the first half of O3 (O3a), detailed information on 1201 sub-threshold GW candidates was made public with the release of GWTC-2.1¹ [125]. They were identified through four distinct CBC search pipelines developed by the LVK collaboration, namely GstLAL [176], MBTA [177], PyCBC [162], and PyCBC-HM [178].

Similarly, 1048 sub-threshold candidates were included in the GWTC-3 catalogue² [126]. It includes information on cWBs detected during the entire O3, alongside CBCs from the second half of O3 (O3b). To estimate p_{astro} for cWBs, the pipeline relies on population information from BBH mergers. These cWBs should not be confused with GW burst-like candidates detected by another fully unmodelled pipeline. The latter events are not publicly released. For further details, see Sec. 3.4.

To systematically identify sub-threshold CBC and cWB candidates for this study, the following selection criteria, based on the false alarm rate (FAR) and p_{astro} values, are employed:

$$2 \text{ yr}^{-1} \leq \text{FAR} < 2 \text{ day}^{-1} \quad (6.1)$$

$$p_{\text{astro}} < 0.5 \quad (6.2)$$

The following section describes the implementation of this filtering strategy and the resulting dataset used for follow-up analysis.

Selection based on FAR

To identify sub-threshold candidates from GWTC-2.1 and 3, the first step is to perform a selection based on the given FAR. The distributions of FAR values for all CBCs aggregated from four independent pipelines, and for cWBs from O3, are shown in Fig. 6.1.

The first bin in each histogram corresponds to events with $\text{FAR} < 10^{-4} \text{ yr}^{-1}$. On the other end, events with $\text{FAR} \geq 2 \text{ day}^{-1}$ are also present in both catalogues. But these carry negligible astrophysical significance. Hence, such events are excluded.

¹<https://zenodo.org/records/5117762>

²<https://zenodo.org/records/5546665>

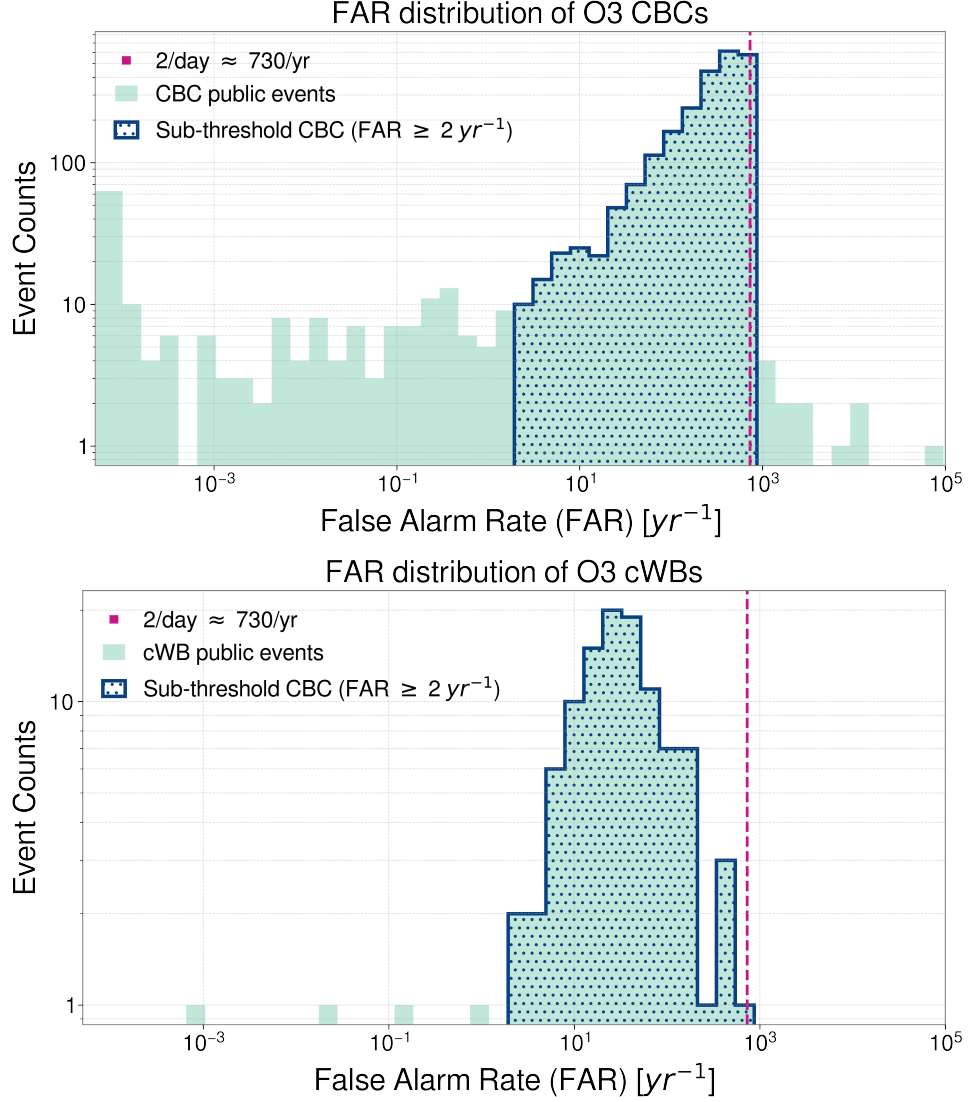


Figure 6.1.: False Alarm Rate (FAR) distributions for CBCs (top) and cWBs (bottom) from O3. Four template-based pipelines identified CBC candidates during the O3 period. Among them, those having $\text{FAR} < 2 \text{ yr}^{-1}$ are classified as confident detections. The cWB pipeline performs a minimally modelled search for burst-like GW events. In both panels, the dotted region marks sub-threshold events with $2 \text{ yr}^{-1} \leq \text{FAR} < 2 \text{ day}^{-1}$, which are the focus of this study. Events above this range (right of the dashed line) are excluded. cWBs with $\text{FAR} < 2 \text{ yr}^{-1}$, those not confirmed by CBC searches, remain scientifically interesting. Three of them were selected in this analysis for neutrino follow-up.

The GWTC-2.1 and GWTC-3 catalogues include all CBC and cWB candidates with $\text{FAR} < 2 \text{ day}^{-1}$ ($\sim 730 \text{ yr}^{-1}$). This range encompasses both confident and sub-threshold detections. As a result, confident GW events with $\text{FAR} < 2 \text{ yr}^{-1}$ also appear alongside lower-significance candidates. To isolate only the sub-threshold population of interest, we apply the selection criterion described in Eq. 6.1. The dotted regions in Fig. 6.1 highlight the sub-threshold GWs satisfying this criterion. This selection step removes highly significant GW events that have already been

the subject of follow-up studies using both high- and low-energy neutrinos from IceCube [9, 10], allowing the analysis to focus exclusively on the sub-threshold GWs that constitute the primary targets considered in this work.

Selection based on p_{astro}

After applying the selection condition from Eq. 6.1, the p_{astro} distribution for the sub-threshold GWs from GWTC-2.1 and -3 is shown in Fig. 6.2. Here again, candidates from all GW search pipelines have been considered altogether.

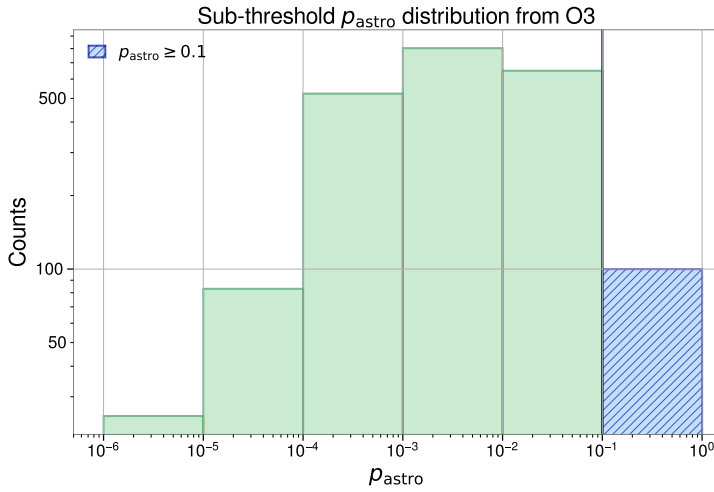


Figure 6.2.: Distribution of p_{astro} values for all sub-threshold GWs with $2 \text{ yr}^{-1} \leq \text{FAR} < 2 \text{ day}^{-1}$. It includes both CBCs and cWBs detected during the O3. The last bin, highlighted in pale blue with hatching, includes events with $p_{\text{astro}} \geq 0.1$. These are selected for the archival neutrino counterpart search presented in this work.

According to Eq. 6.2, there are no sub-threshold GWs with $p_{\text{astro}} > 0.5$, as they were designated as ‘confident events’ while updating catalogues. It is important to note that a given sub-threshold GW can be reported by multiple pipelines, potentially with differing p_{astro} values. In such cases, the version of the candidate associated with the highest p_{astro} is retained for further analysis to ensure that each event is represented by its most astrophysically favourable characterisation.

In Fig. 6.2, the distribution shows that the vast majority of candidates (approximately 96%) have $p_{\text{astro}} \simeq 0$. They could be more influenced by terrestrial noise or instrumental artefacts noted as glitches. To improve the reliability of the selected sample for follow-up analysis, an additional criterion is imposed by selecting only those events with $p_{\text{astro}} \geq 0.1$, from both catalogues. After applying this selection, 45 sub-threshold CBCs are identified from O3a and O3b each, resulting in a total of 90 CBCs.

The selection of cWB events from O3 deserves a dedicated explanation, even though the overall treatment mimics that of the CBC events. Many of the cWBs overlap with CBCs. From the O3a observing period, information on 51 cWB events was made publicly available. Among these, 17 events overlap with confident CBC detections from the same run. These overlapping cases are highlighted in the left panel of Fig. 6.3. Similarly, from O3b, among the 83 cWBs listed, 9 candidates coincide with 9 confident, BBH-like O3b events. They are pointed out in the right panel of Fig. 6.3.

The selection of cWB events from O3 deserves a dedicated explanation, even though the overall treatment mimics that of the CBC events. Many of the cWBs overlap with CBCs. From the O3a observing period, information on 51 cWB events was made publicly available. Among these, 17 events overlap with confident CBC detections from the same run. These overlapping cases are highlighted in the left panel of Fig. 6.3. Similarly, from O3b, among the 83 cWBs listed, 9 candidates coincide with 9 confident, BBH-like O3b events. They are pointed out in the right panel of Fig. 6.3.

The coincidence between cWB detections and template-based CBC signals likely stems from the partial dependence of the cWB pipeline on BBH population models for calculating p_{astro} .

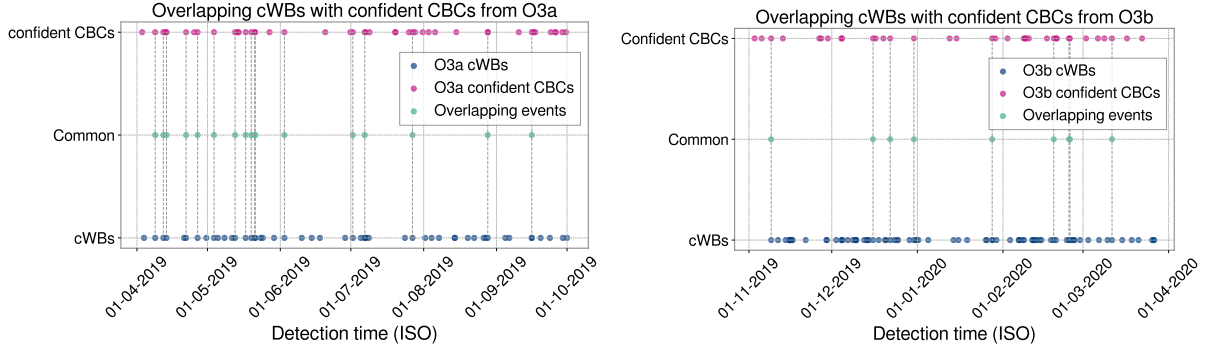


Figure 6.3.: Common detections between cWB and CBC search pipelines from (left) O3a and (right) O3b. 17 common detections were identified from O3a, all labelled as ‘confidently detected CBCs’, with $\text{FAR} < 2 \text{ yr}^{-1}$. Similarly, 9 cWBs overlap with confident CBC detections from O3b.

As a result, certain events may appear in both template and non-template based search pipelines, sometimes with relatively higher p_{astro} values for the non-template searches.

For the unique 34 cWBs from O3a, the FAR distribution is shown in the right panel of Fig. 6.1. Only three of them were found to have $p_{\text{astro}} \geq 0.1$ after satisfying the selection criteria from Eq. 6.1. These sub-threshold candidates are identified as cWB-1246523564 ($p_{\text{astro}} = 0.16$), cWB-1250939932 ($p_{\text{astro}} = 0.45$), and cWB-1253293503 ($p_{\text{astro}} = 0.36$). The skymaps for these events are shown in Fig. 6.4.

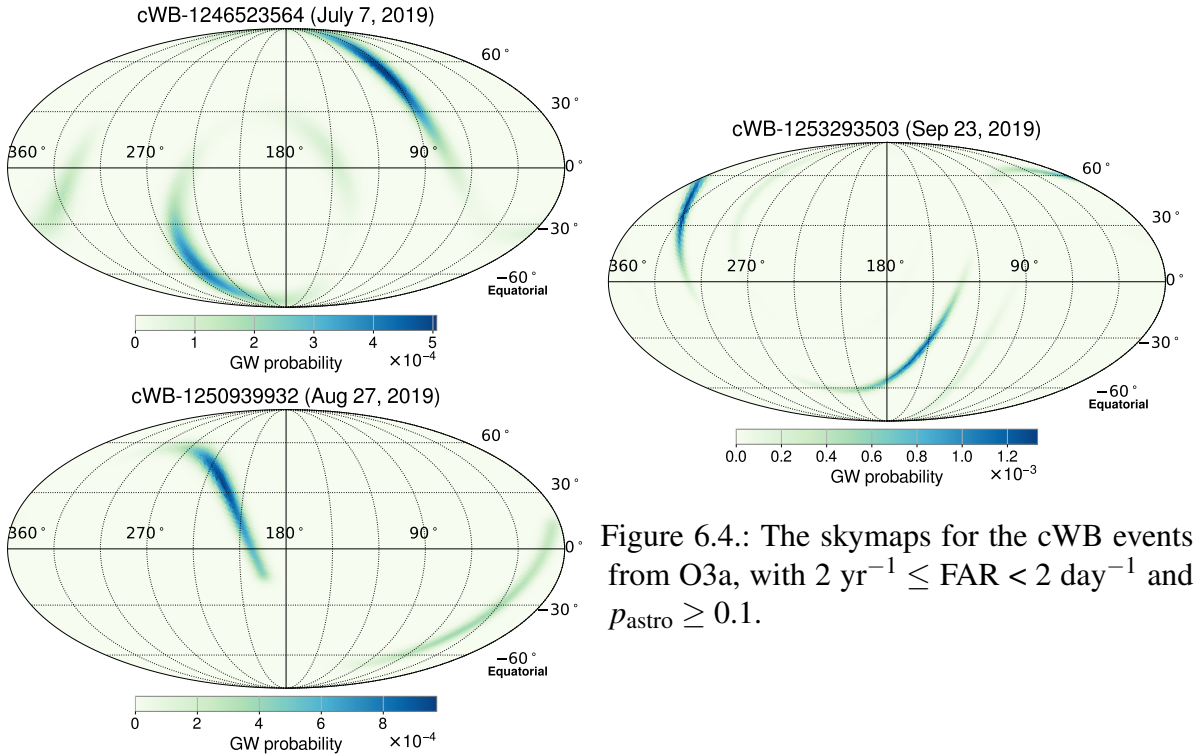


Figure 6.4.: The skymaps for the cWB events from O3a, with $2 \text{ yr}^{-1} \leq \text{FAR} < 2 \text{ day}^{-1}$ and $p_{\text{astro}} \geq 0.1$.

Similarly, for the unique 74 cWBs from O3b, predominantly they have $p_{\text{astro}} < 0.1$, and therefore are excluded from further analysis. Finally, 7 sub-threshold GWs with $2 \text{ yr}^{-1} \leq \text{FAR} < 2 \text{ day}^{-1}$ and $p_{\text{astro}} \geq 0.1$ were retained.

Thus, finally, a total of 10 cWBs from O3a and O3b satisfied the selection conditions. The p_{astro} distribution for them is shown in the left panel of Fig. 6.5.

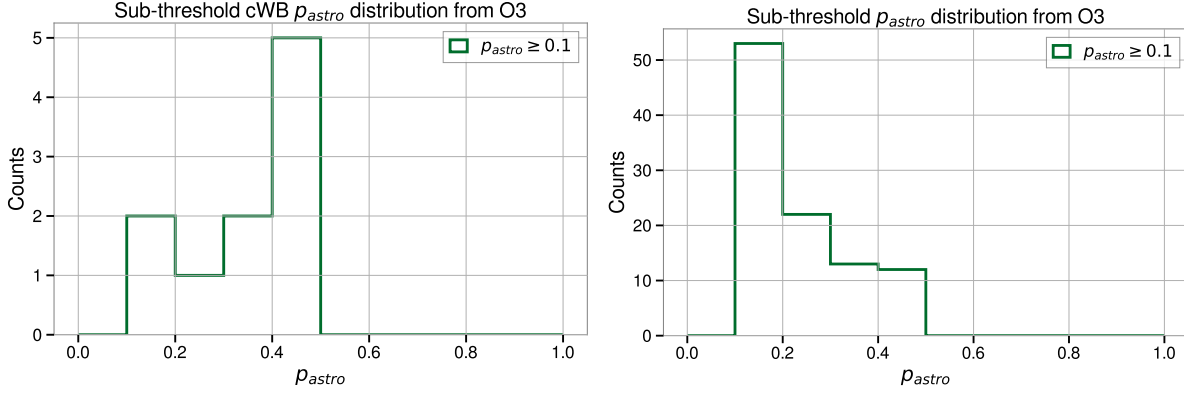


Figure 6.5.: The p_{astro} distribution for (left) cWB events from O3, and (right) the total 100 shortlisted sub-threshold CBCs and cWBs, with $2 \text{ yr}^{-1} \leq \text{FAR} < 2 \text{ day}^{-1}$ and $0.1 \leq p_{\text{astro}} \leq 0.5$. No events with $p_{\text{astro}} \geq 0.5$ are present in this sample, consistent with the sub-threshold classification defined in [126].

These, together with 90 sub-threshold CBC events identified earlier, yield a final sample of 100 sub-threshold GWs across the full O3 run. Together, they represent the top 4% of the sub-threshold population in terms of p_{astro} . The p_{astro} distribution for all the shortlisted 100 sub-threshold GWs from O3 is shown in the right panel of Fig. 6.5. They form the main cluster of the shortlisted dataset for subsequent neutrino correlation studies.

Final catalogue of sub-threshold GWs

Now that 100 sub-threshold GWs from O3 have been identified, it makes sense to have a closer look at the selected candidates. As discussed in chapter 3.3, some of the most interesting parameters associated with individual GW signals for this analysis are, for example, their SNR, FAR, p_{astro} , sky area coverage, source type, and detector configuration. Some of these are also relevant for evaluating the ‘signalness’ of a GW event candidate. Precisely, candidates are more signal-like if they have:

- Detected by at least two detectors in time coincidence within the GW detector network.
- High SNR. To set a bar, the SNR distribution of the shortlisted 100 sub-threshold GWs is compared with that of the confidently detected GW event.
- Lower FAR (compared to other shortlisted candidates)
- High p_{astro} (compared to other shortlisted candidates)

In that order, the detector configuration for the shortlisted 100 sub-threshold GWs is shown in Fig. 6.6.

In general, we expect a ‘real’ GW signal to be detected by more than one GW detector, given that multiple detectors are in the data-taking process together. A sub-threshold candidate being detected by three different detectors altogether, satisfying the SNR threshold for the local detector, is less likely to be of noise origin. From Fig. 6.6, it is visible that there are 25 such candidates in the list. Most of the other candidates were detected by the H1L1 detectors jointly. This is simply because Virgo was not optimally active in some phases. There is one candidate that was detected by only the Livingston (L1)³ detector, due to an hour-long observational downtime of Hanford around the detection time. It is the GstLAL-1240164426 event, detected by the GstLAL [176], which is the only LVK matched filtering pipeline accepting single-detector triggers. The corresponding skymap is provided in the left panel of Fig. 6.7.

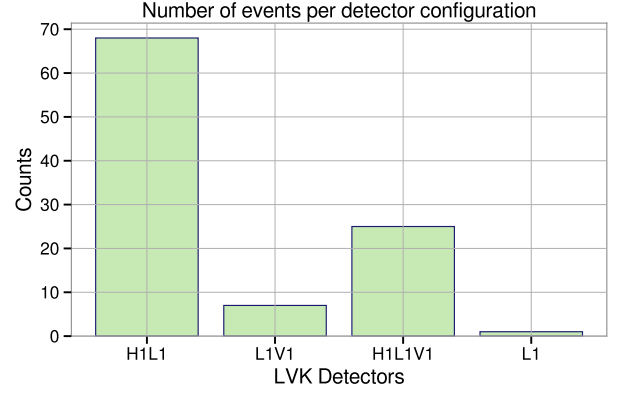


Figure 6.6.: Detectors configuration for the shortlisted 100 sub-threshold GW from O3, 99 of them were detected by more than one GW detector with an acceptable SNR value.

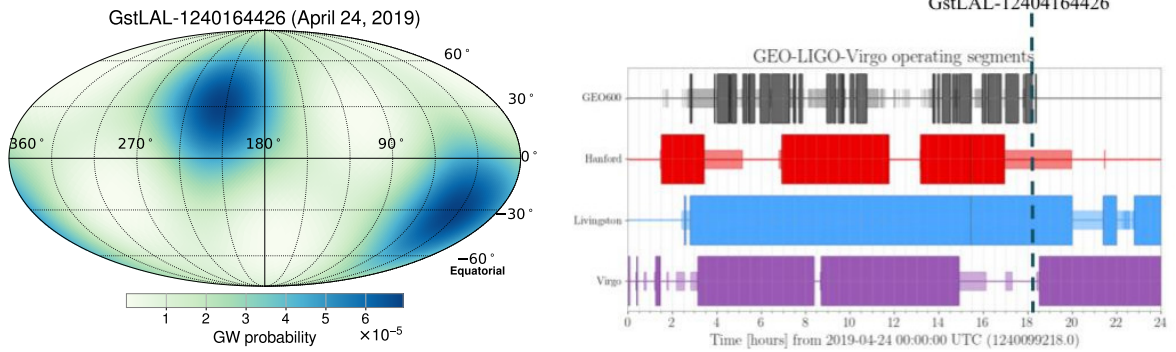


Figure 6.7.: GstLAL-1240164426 is the only shortlisted sub-threshold GW that was identified by only one GW detector (Livingston), but satisfied the SNR threshold. The skymap is shown in the left figure. The event was detected on April 24, 2019, at 18:06:48, with $\text{FAR} \sim 9 \text{ yr}^{-1}$ and $p_{\text{astro}} = 0.12$. At that time, both Hanford and Virgo were experiencing observation downtime. It is evident from the figure on the right, obtained from the [GWOSC website](#). The event detection time is marked on the plot.

As it was detected by only one active detector, it has the worst localisation. However, it has quite a low FAR ($\sim 9 \text{ yr}^{-1}$) compared to most of the other candidates, which can have $\text{FAR} >$

³Originally, Hanford had two interferometers on the same site (H1 and H2). To distinguish them, the numbering was introduced. Even after H2 was retired, the convention stayed. Till now, all individual detectors in each site are marked as H1, L1, and V1, depicting that these are the first detectors to be active in each site.

100 yr^{-1} . Also, the $p_{\text{astro}} > 0.1$. So it is considered for the neutrino follow-up search in this analysis.

As the next step, the distribution of the SNR of all shortlisted 100 events is studied and compared with that of the 79 high-significance GWs from the same observing run, as illustrated in Fig. 6.8. It is important to note that all sub-threshold events from O3 within $2 \text{ yr}^{-1} \leq \text{FAR} < 2 \text{ day}^{-1}$

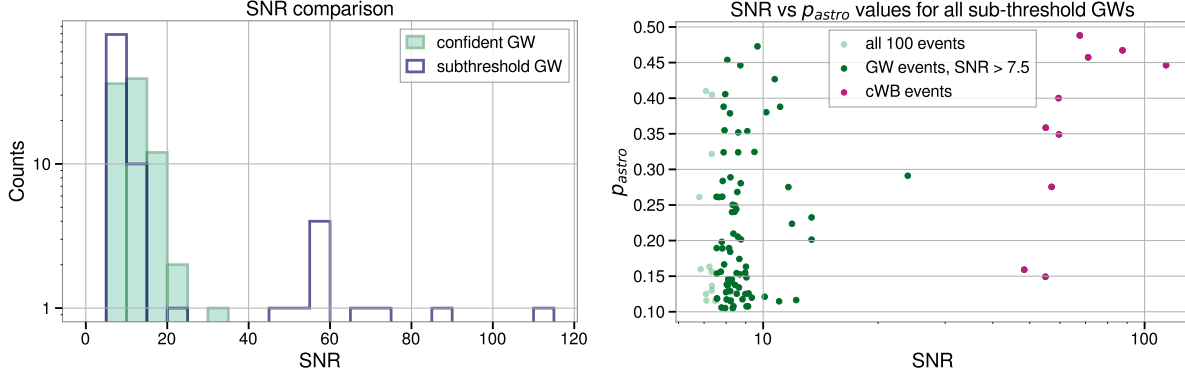


Figure 6.8.: (Left) The SNR distribution of the 100 shortlisted sub-threshold GWs from O3. A comparison is shown with the SNR distribution of the 79 confidently detected GWs during O3. (Right) The SNR values are compared to the corresponding p_{astro} values for individual GWs. There is no evident correlation between them, which is also expected as SNR is the true measure of signalness, whereas p_{astro} is a Bayesian posterior probability, which depends on signal model assumptions.

satisfy the SNR thresholds required by each detector at the time of their observation. This condition also applies to the highly-significant detections with $\text{FAR} < 2 \text{ yr}^{-1}$, ensuring that all candidates are evaluated under consistent detection criteria.

From Fig. 6.8, it is evident that despite their classification as ‘sub-threshold’ GWs, all of the 100 shortlisted candidates exhibit SNR values comparable to those of confidently detected events. This suggests that the low significance assigned to these events is not due to their intrinsic weakness as signals. Rather, it is likely due to their signal morphology deviating from the typical CBC waveforms, which results in higher FAR in template-based searches. Such mismatches can arise if the signals originate from unconventional sources or are affected by instrumental artefacts, for example, that hinder the template matching process.

In particular, a subset demonstrates notably high SNRs, exceeding $\text{SNR} = 40$. All of them are associated with the shortlisted cWBs, as depicted in the right panel of Fig. 6.8. It is also evident that there is no correlation between event candidates having high SNR and those having high p_{astro} . SNR measures directly come from the matched filtering techniques. In contrast, the p_{astro} values are the Bayesian posteriors influenced by the signal model assumptions preferred by the modelled or minimally modelled search pipelines.

To highlight candidates with relatively high SNR, the minimum SNR value associated with any confidently detected GW event is used as a reference point, that is, 7.5. Almost all the shortlisted GW events have an SNR value higher than that. Although no further SNR-based cuts are applied in this analysis, this comparison helps to distinguish stronger signals within the

sub-threshold sample. Among the 100 events, 21 have SNR values exceeding 10, of which 15 also exhibit $p_{\text{astro}} > 0.3$.

The next relevant quantities are FAR and p_{astro} for the shortlisted sub-threshold GWs. Given the individual distributions shown in Fig. 6.1, and 6.5, here it is verified if there is any inter-dependence between these two quantities for the sub-threshold GWs, for the 100 shortlisted candidates. This will give us an estimate of how many of them have lower FAR and higher p_{astro} at the same time. It is shown in the 2D histogram in Fig. 6.9.

11 candidates have $p_{\text{astro}} > 0.4$, for which $\text{FAR} < 20 \text{ yr}^{-1}$. However, most of the low FAR candidates have $0.2 < p_{\text{astro}} < 0.3$.

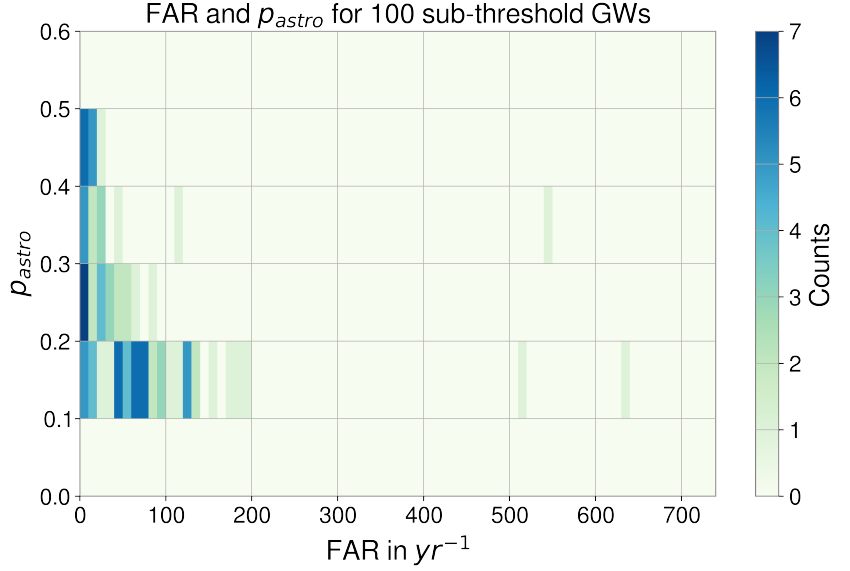


Figure 6.9.: The p_{astro} values for the 100 shortlisted sub-threshold GWs, shown corresponding to their FAR values. There is no correlation between high FAR and high p_{astro} values, which is expected given the discussion presented in Sec. 3.3.

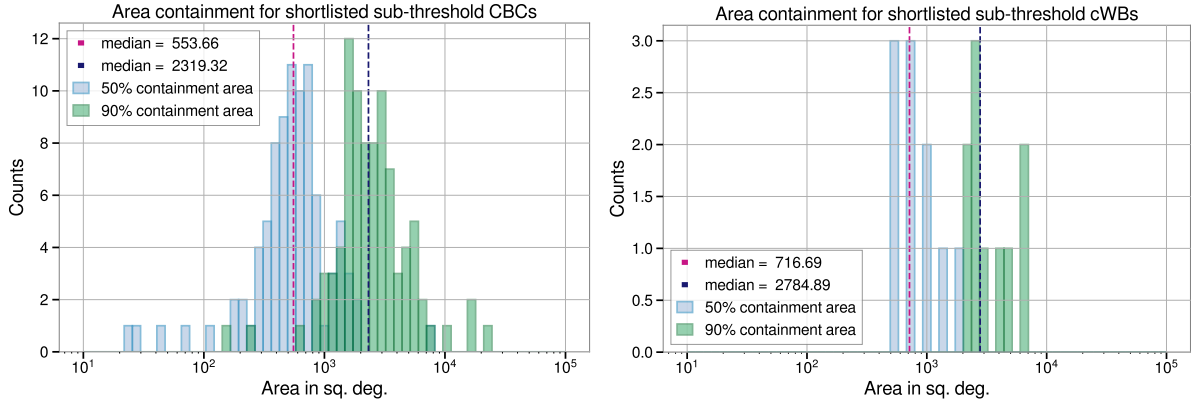


Figure 6.10.: The 50% and 90% containment areas from the 100 shortlisted sub-threshold GW skymaps, for (left) 90 CBCs and (right) 10 cWBs from the entire O3. Although cWBs tend to have worse localisation on the sky, no drastic difference is observed for the shortlisted events.

To gain an understanding of the localisation of individual events, the 50% and 90% containment areas from the skymaps of these sub-threshold GWs are also shown in Fig. 6.10. It is already evident from these plots that the majority of the sub-threshold GWs do not have good localisation. Finding probable neutrino counterparts can significantly decrease the localisation uncertainty for individual GW skymaps, which can make EM follow-up campaigns more efficient.

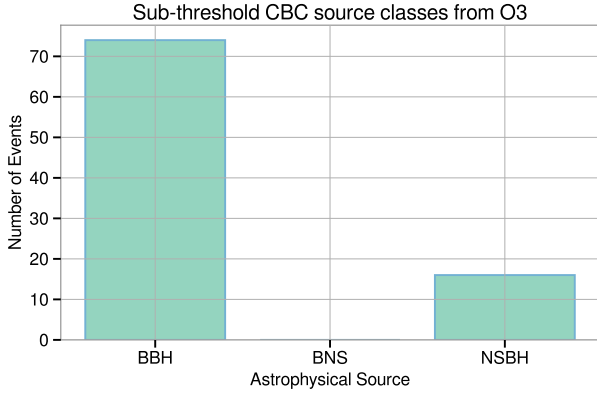


Figure 6.11.: The type of CBC sources we have in our sub-threshold GW shortlist. Most of them are BBH merger-like events. There are 16 NSBHs, and no BNS merger-like candidates.

Also, it is interesting to know the source type associated with each event. For the 100 short-listed events, 10 are cWBs. Among the 90 CBCs, there are 16 NSBH-like candidates. All of the rest are BBH-like events. The source classification is shown in Fig. 6.11. The entire list, along with details of individual candidates and their skymaps, is provided in Appendix A.

6.1.2. Additional Interesting GW Events

While scrutinising the FAR distribution for cWBs from O3, as shown in the lower panel of Fig. 6.1, it is noticeable that two events have $\text{FAR} < 2 \text{ yr}^{-1}$, each from O3a and O3b.

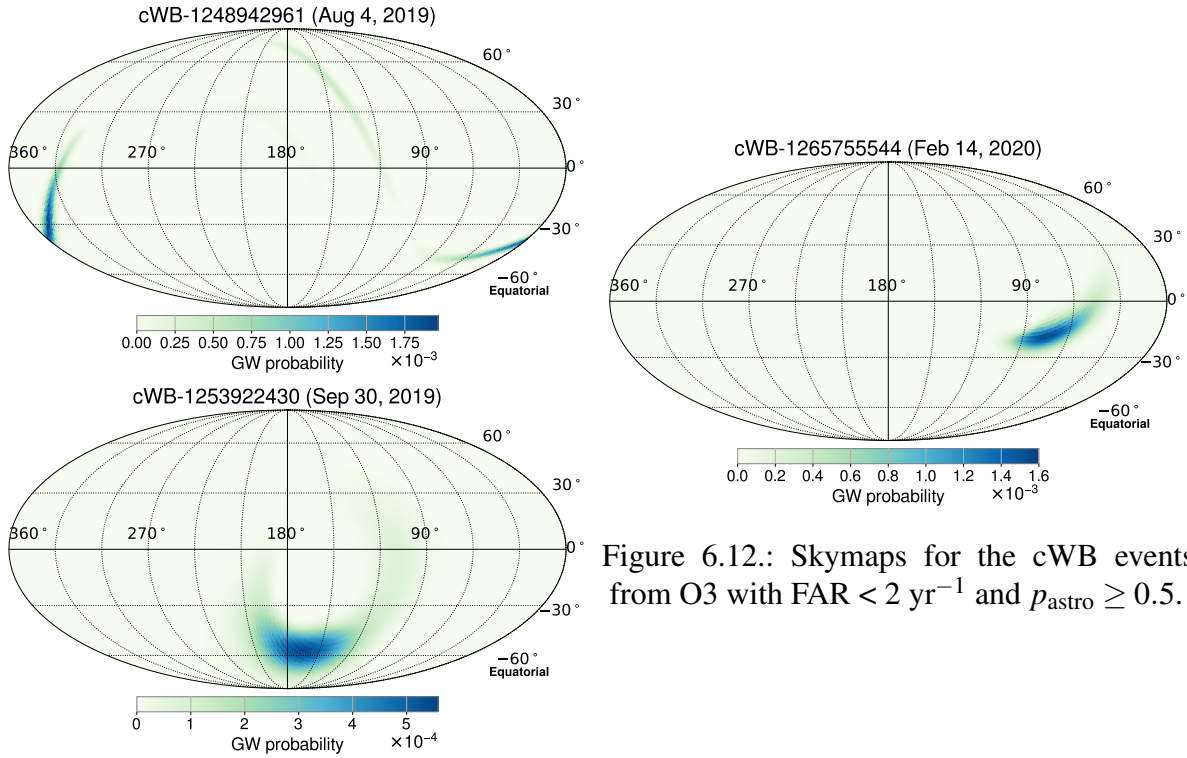


Figure 6.12.: Skymaps for the cWB events from O3 with $\text{FAR} < 2 \text{ yr}^{-1}$ and $p_{\text{astro}} \geq 0.5$.

From O3a, these two cWBs (cWB-1248942961, cWB-1253922430) have $\text{FAR} \lesssim 1 \text{ yr}^{-1}$ and $p_{\text{astro}} > 0.5$, but are not associated with any high-significance detection from O3a. None of them is listed as a confident event independently, because none of the CBC search pipeline identified them. All the 90 LVK confident events were primarily identified by one or more CBC search pipelines, which look for GW signals from BBH, BNS, or NSBH-like sources. It is also another requirement to label a GW signal as a confident detection.

Similarly, from O3b, two additional cWBs (cWB-1259514943, cWB-1265755544) were found to have $\text{FAR} < 1 \text{ yr}^{-1}$ and quite high p_{astro} , i.e., $p_{\text{astro}} > 0.9$. Interestingly, cWB-1259514943 was recorded just 1 s after the confident BBH-like candidate GW191204_171525. As a result, it was associated with a different GPS time and escaped the filtering for confident CBCs. However, it is strongly believed to be a manifestation of the CBC in the cWB analysis pipeline. So, only cWB-1265755544 ($p_{\text{astro}} \sim 0.9$) was found to be recorded independently by the minimally modelled cWB search pipeline.

So, in total, we end up with three cWB events, cWB-1248942961 ($p_{\text{astro}} = 0.98$), cWB-1253922430 ($p_{\text{astro}} = 0.64$), and cWB-1265755544 ($p_{\text{astro}} = 0.91$) of ‘high-significance’. They were found not to be associated with any confident CBC detection from O3. Nevertheless, due to their strong signal characteristics, they are included in this follow-up analysis. The corresponding skymaps are shown in Fig. 6.12. So, in total, 103 GWs will be considered for further analysis.

6.2. GRECO Data Sample

As mentioned before, this work focuses on the sub-TeV neutrinos detected by IceCube’s dense infill array, DeepCore [212]. As a part of this work, we use the reconstructed GRECO events from the dataset known as ‘GRECO-v002-p10b’. The events were recorded during the data-taking runs of 2012 to 2019, between 26th April, 2012, to 29th May, 2020. A general discussion on this particular event selection can be found in Sec. 4.2.2.

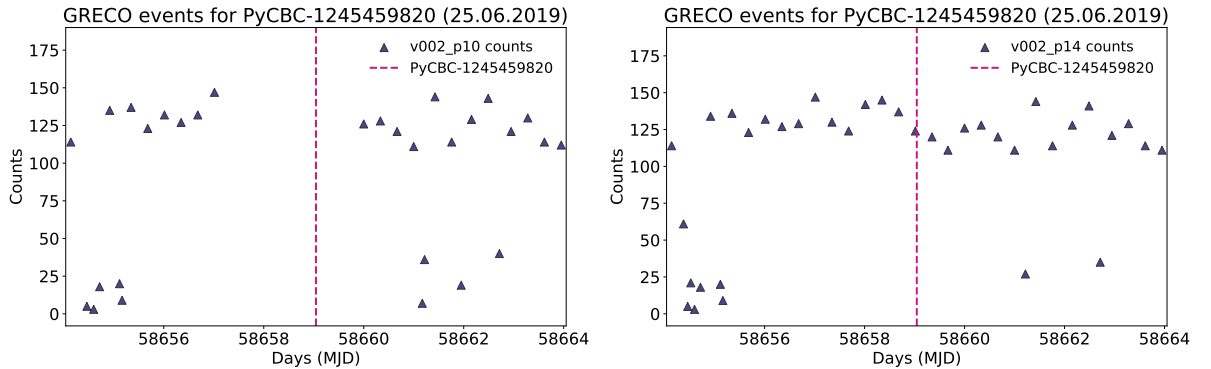


Figure 6.13.: (Left) The GRECO daily reconstructed event counts from GRECO-v002-p10 around the GW event PyCBC-1245459820. As it is visible that there are no reconstructed events available for 2 days, after 58657 MJD, to just before 58660 MJD. (Right) The daily event counts from the newly available dataset, including the missing events from GRECO-v002-p10.

GRECO-v002-p10b was an intermediate release, specifically to update GRECO-v002-p10, for the sub-threshold GW follow-up analysis. The reason behind that was having no reconstructed events for more than 2 days in GRECO-v002-p10, after MJD 58657 (23rd June, 2019). It is visible in the left panel of Fig. 6.13.

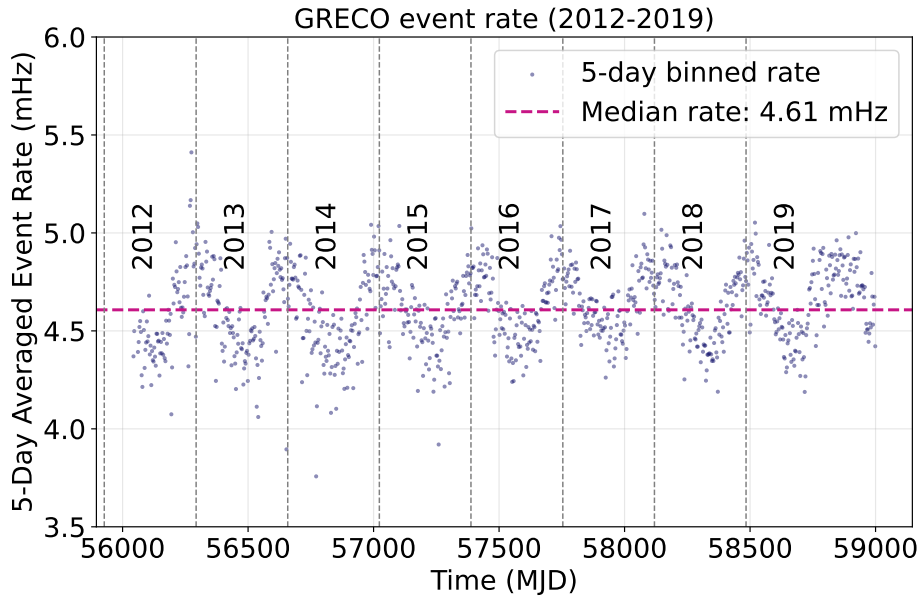


Figure 6.14.: The 5-day averaged GRECO rate for the years 2012-2019. The average event rate shows a sinusoidal behaviour due to the seasonal variations in the atmospheric neutrino flux, as mentioned before in Ch. 5. The median rate is 4.6 mHz, which is marked on the plot by the dashed line.

These events were necessary to follow up on an NSBH-merger-like event, which was detected by the PyCBC pipeline on 25th June, 2019. The reason for having no events available in GRECO-v002-p10 from the ‘good’ data taking runs⁴ (run no. 132735, 132736, 132737, 132751, 132752) between those days is a failure of the current reconstruction algorithm ‘Peg-Leg’ [246], which is currently implemented for GRECO. The reconstruction is usually slow and requires resubmission multiple times to the grid to obtain the final result. It takes even longer for higher energy events or if the likelihood parameter space is difficult to minimise. In that case, a chunk of events could go missing during reconstruction [342].

To solve this issue, Dr. Michael Larson decided to run the reconstruction separately to obtain reconstructed events from these good run lists (GRL) for the run IDs mentioned above, and included them in the latest versions of GRECO, v10b and v14. During the unblinding request, v14 was not available as it also comes with two more years of data (2012-2022), which required more processing time. So v10b was used for this work. The daily event counts from the final dataset with reconstructed events are shown in the right panel of Fig. 6.13 for a few days around the GW event time. From here on, the main GRECO features related to the likelihood analysis (See Ch. 5) to be performed are discussed.

⁴The requirements for a data-taking run to be listed as a ‘good’ run are that all strings are working properly which-energy neutrino taking data, at least 5030 DOMs are active during the entire run, no light is coming from LEDs or other calibration devices, and the run must be 7 to 9 hours long [215]. The list of all good runs, which is available internally in the collaboration, is known as ‘good run list’ (GRL).

Event rate

GRECO has a relatively stable event rate, which provides an estimate of the number of background events to expect across the entire sky within a specific time window. Fig. 6.14 presents the 5-day binned GRECO event rate from 2012 to 2022. The average expectation is ~ 4.6 events in 1000 s, which is also marked on the plot. It provides a robust background for transient searches. Roughly 60% of the background is expected to be associated with the atmospheric neutrinos, and the rest comes from atmospheric muons [215]. The observed sinusoidal modulation reflects seasonal variations in the atmospheric neutrino flux, as previously mentioned and discussed in Ch. 5. Although the background rate is quite high, it should be strongly suppressed while searching for short transients, as explained in Ch. 5.

Effective area

For short-duration transients, the main driving force that boosts sensitivity is effective area (A_{eff}).

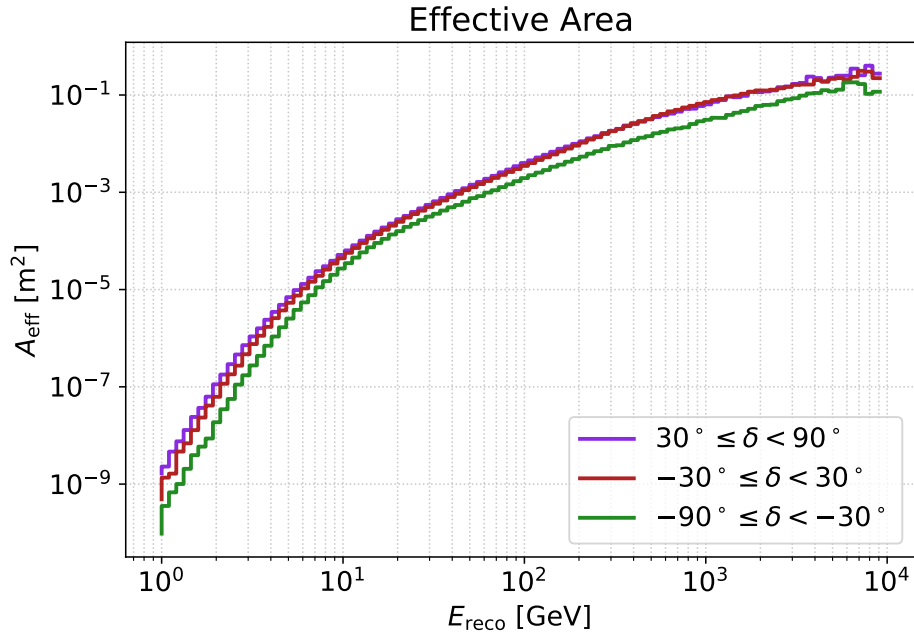


Figure 6.15.: All-flavour effective area for GRECO in the Southern Hemisphere, celestial horizon, and Northern Hemisphere. GRECO has comparable effective area coverage all over the sky in the energy range of $\mathcal{O}(10 - 100)$ GeV. This makes GRECO a good choice for searching for sub-TeV neutrino counterparts to GW sources.

As shown in Fig. 6.15, GRECO maintains a fairly uniform A_{eff} across all sky regions, including the Southern Hemisphere (SH), Northern Hemisphere (NH), and the celestial horizon. This contrasts with GFU (see Fig. 5.3), which primarily focuses on high-energy (sub-PeV) track events and comes with much enhanced A_{eff} coverage in the NH. For GFU, the A_{eff} suffers in the SH for

background suppression (for related discussion, see Ch. 4.2.2) [198, 213]. GRECO’s uniform sky coverage, specifically due to the inclusion of cascades [198], is particularly well-suited for following up on GW events, which often have broad and widely distributed localisation regions spanning both hemispheres.

Energy range and resolution

The GRECO dataset covers a reconstructed energy (E_{reco}) range of $\mathcal{O}(10\text{-}100)$ GeV, as seen in the left panel of Fig. 6.16. This energy range, in contrast to IceCube’s high-energy samples (such as GFU, sensitive to $\mathcal{O}(10\text{-}100)$ TeV), makes GRECO particularly valuable for identifying lower-energy neutrino counterparts to astrophysical transients.

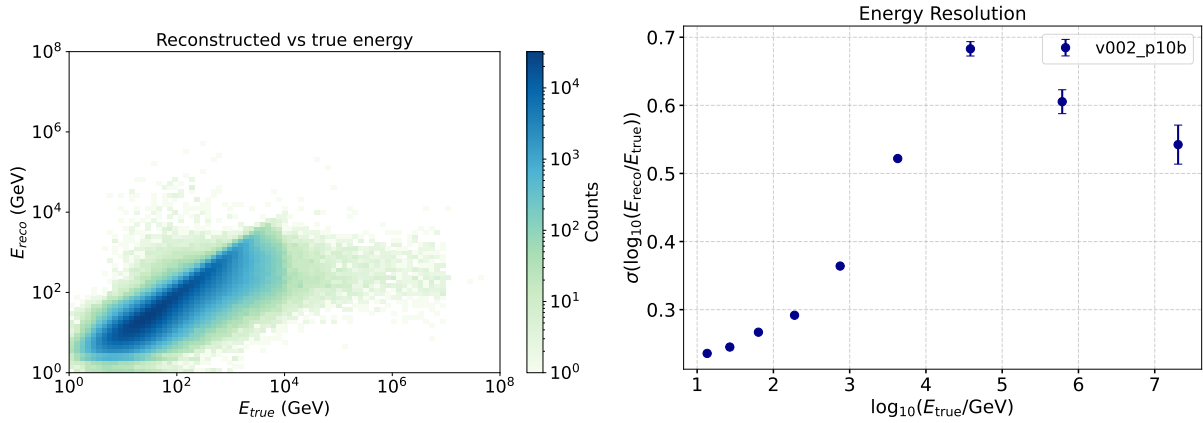


Figure 6.16.: GRECO energy distribution and energy resolution for GRECO-v002-p10b dataset.

Fig. 6.16 shows both the reconstructed energy distribution and the energy resolution. As seen in the plots, the energy reconstruction can perform poorly at higher energies, as the reconstruction algorithm is computationally expensive and sometimes stops too early, before converging to the global minimum [342]. The trend is visible in the left panel of the plot, where there are some poorly reconstructed events at high energies, which affect the resolution. As these poorly reconstructed events still appear in the final event selection, they make the energy resolution plot appear worse as energy increases.

In the newer datasets, a hard cut is applied for $\log(E_{\text{reco}}) = 3.5$, as beyond that, the linearity no longer exists, and a much lower E_{reco} value is assigned even for higher E_{true} . It helps us to achieve a flatter trend in the higher-energy end of the energy resolution plot. However, keeping those events in the dataset is also not alarming, as removing them reduces the A_{eff} and therefore the significance for short transients also gets suppressed. It can help if we are sure that we are removing significant background, but for short transients, the background within a limited time window is already low enough that it doesn’t matter [342].

Angular resolution

The GRECO sample initially did not come with an angular error (σ) estimate from PegLeg, as it is extremely computationally expensive. The angular uncertainty estimators, such as Paraboloid [240], which rely on sampling the reconstruction algorithm many times for different regions in the parameter space, cannot be used as part of it.

The angular uncertainties for the events were separately estimated and added to the version of GRECO Online, which is used for neutrino astronomy. It is derived from a random forest algorithm, which was trained on both charged-current and neutral-current interactions for neutrinos of all flavours [198]. Further details are available in [248].

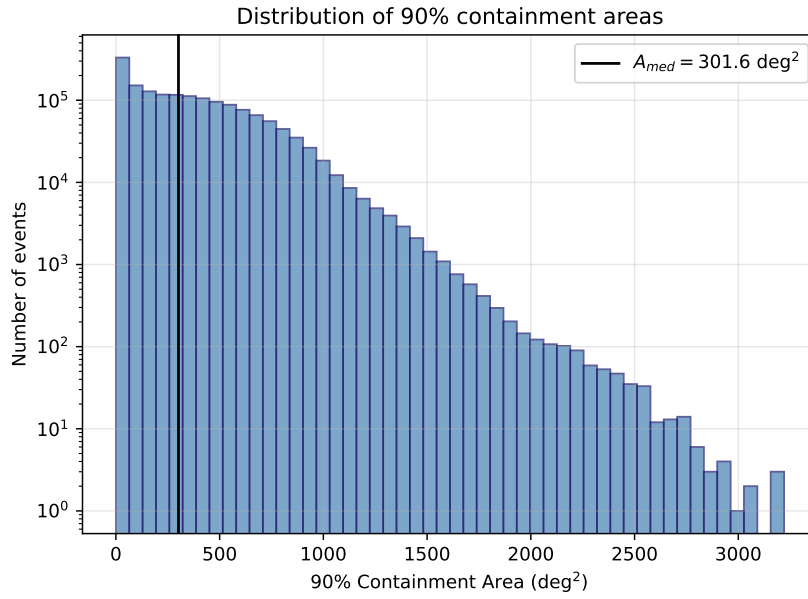


Figure 6.17.: The GRECO area containment (90% C.L.) corresponding to the uncertainty obtained from individual events. The median is also marked. For reference, for sub-threshold GWs, the median area from 90% containment region is $\gtrsim 2000 \text{ deg}^2$, as shown in Fig. 6.10.

The distribution of angular uncertainty with respect to reconstructed energy is shown in Fig. 5.2. It is observed that some higher-energy events may achieve resolutions as fine as 1° . However, typical cascade-like events have uncertainties around $O(10^\circ)$. This is always a problem for low-energy event selections, as less energy is lost by the charged leptons inside the detector volume, and this in turn leads to less deposited charge on the DOMs, which makes event reconstruction extremely hard. This is the main downside of using GRECO: the events exhibiting poorer angular resolution compared to high-energy tracks. This limits point-source sensitivity, effectively reducing such searches to counting experiments. However, this limitation is less critical for extended and transient sources like GW events. The related skymaps have much worse localisation, with a median 90% containment area $> 2000 \text{ deg}^2$ (see Fig. 6.10), which is most of the time an order more compared to the GRECO area containment, as seen in Fig 6.17. Therefore,

despite its coarse angular resolution, GRECO can help with constraining the location of GW sources.

6.3. Background and Sensitivity Studies

Previous studies (e.g., [10]) have used GRECO to investigate possible lower-energy neutrino counterparts to 90 confident GW events observed during the O1, O2, and O3 runs. as a part of this work, wI extend this approach by using GRECO to search for sub-TeV neutrino counterparts associated with selected sub-threshold GW candidates from the O3 run. Before performing the coincident search with GRECO data, the first step is to complete the background and sensitivity studies, considering individual shortlisted GW events to evaluate the analysis performance. To perform the background studies, scrambled data is used as described in Sec. 5.5.1. The results from these background studies are used to evaluate sensitivity for the individual shortlisted 103 GW events using sub-TeV neutrino simulations available within IceCube, as described in Sec. 5.5.

6.3.1. Background Studies

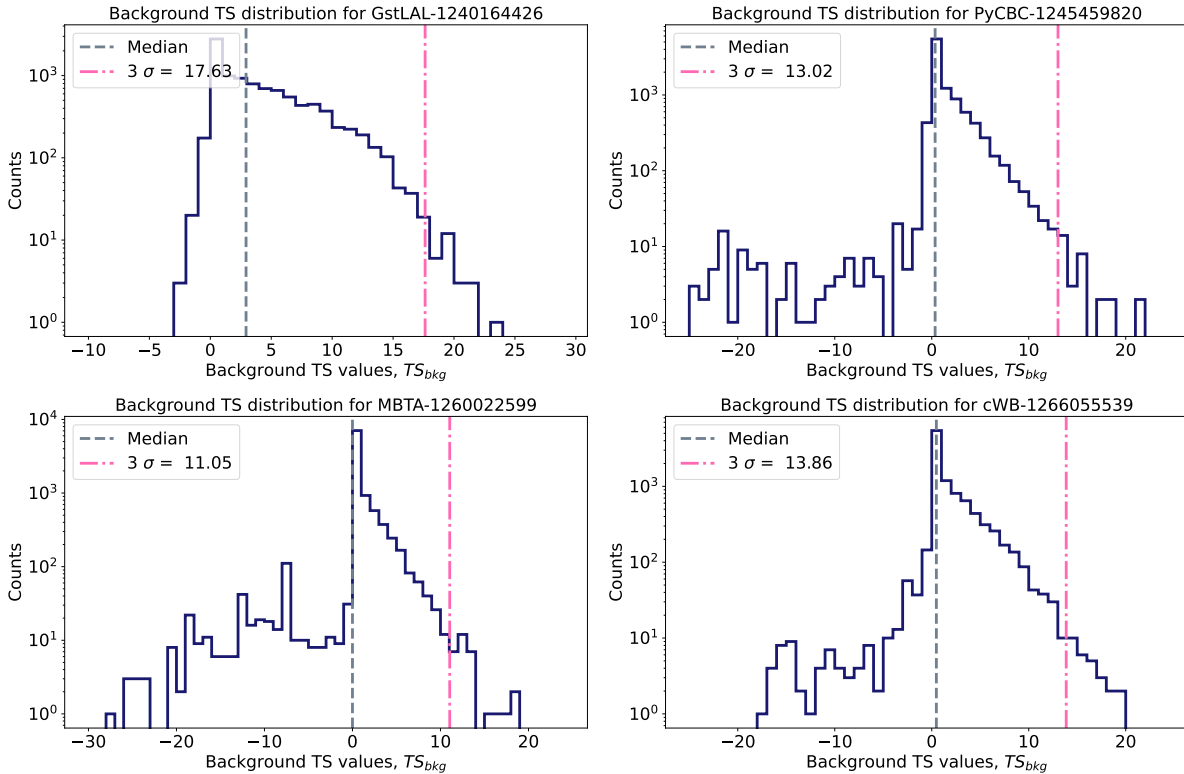


Figure 6.18.: Examples of background TS distributions for some of the shortlisted sub-threshold GWs. The corresponding skymaps are available in Appendix A. The median of each BGTS distribution is marked, alongside the 3σ deviation from the median.

Following the prescription from Ch. 5, the background TS (BGTS) distribution is constructed for each of the 103 shortlisted GWs from O3. This is achieved by randomly sampling the arrival times of each neutrino event detected within a ± 5 day off-time window around each GW detection time. This procedure is repeated 10,000 times, individually considered as an independent trial. The resulting BGTS distribution is then used as a reference for a background-like case.

In general, all BGTS distributions contain some dominant spatial features that they inherit from ω_k . They contain several negative TS values as the background neutrinos fall on the pixels belonging to the less-probable regions on the GW skymap. There, ω_k is much less than one, resulting in $2 \ln(\omega_k)$ to be significantly negative. It acts as a dominant spatial penalty term on the final TS value, as reflected in Eq. 5.21. The BGTS distribution of GstLAL-1240164426 is distinct in that aspect. Most of the TS values there are positive, with the $TS_{\text{med}} > 0$. The reason is a worse localisation of the GW source, and having the most probable source position spread across the two hemispheres, as visible in Fig. 6.7.

A few example BGTS distributions for some of the shortlisted GW events detected during O3 are shown in Fig. 6.18.

6.3.2. Studies with Signal Injection

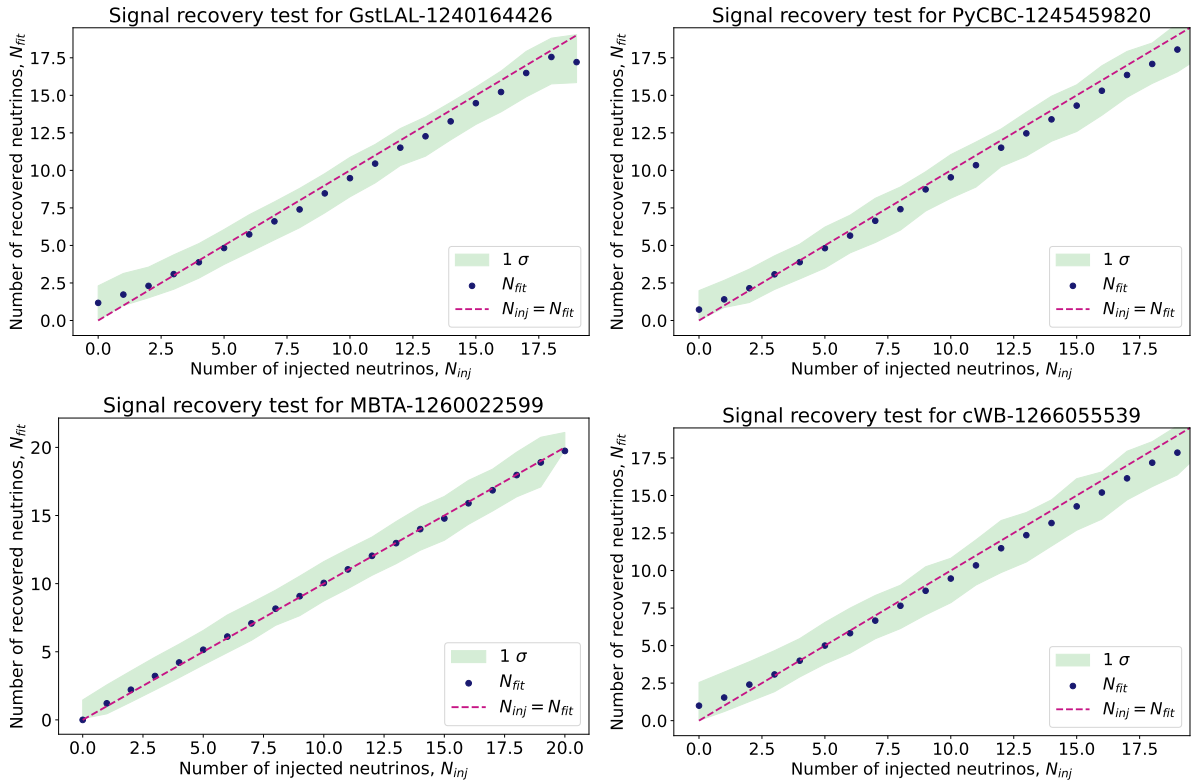


Figure 6.19.: Examples of signal recovery tests for some of the shortlisted sub-threshold GWs.

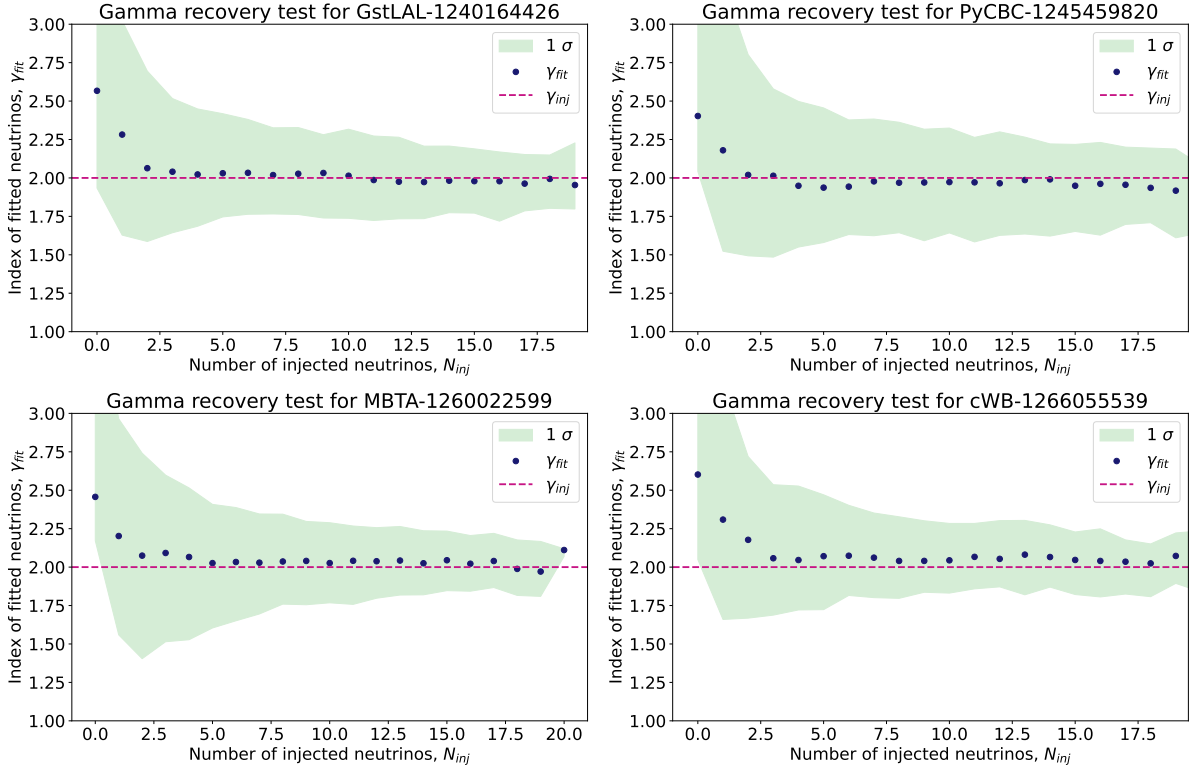


Figure 6.20.: Examples of spectral index recovery tests for some of the shortlisted sub-threshold GWs.

With signal injection, we perform sensitivity studies and signal recovery tests by injecting signal neutrinos following a $\gamma = 2$ spectrum. The method was outlined in Sec. 5.5.2.

Signal Recovery Tests

Some example bias plots for sub-threshold GW candidates from O3 are provided in Figs. 6.19 and 6.20. Here, we plot the number of neutrinos injected, N_{inj} , vs the recovered number of best-fit neutrinos, N_{fit} . We also check the bias on the spectral index γ of the fitted signal neutrinos recovered from the highest probable region of the GW skymap. As we inject neutrino events with $\gamma_{inj} = 2$, we compare that with the recovered γ values, noted as γ_{fit} .

For the best-case scenario, we are expected to get $N_{fit} = N_{inj}$. Similarly, we expect to retrieve $\gamma_{fit} = 2$. In the worst-case scenario, we will see a huge bias in the fit towards lower or higher values of N_{fit} and γ_{fit} . From that, we can infer that our setup is under-fitting or over-fitting, respectively. Especially, for the sub-threshold GWs, under-fitting of the number of signal neutrinos is more probable. However, with a larger number of signal injections, linearity is obtained, as seen in all the plots.

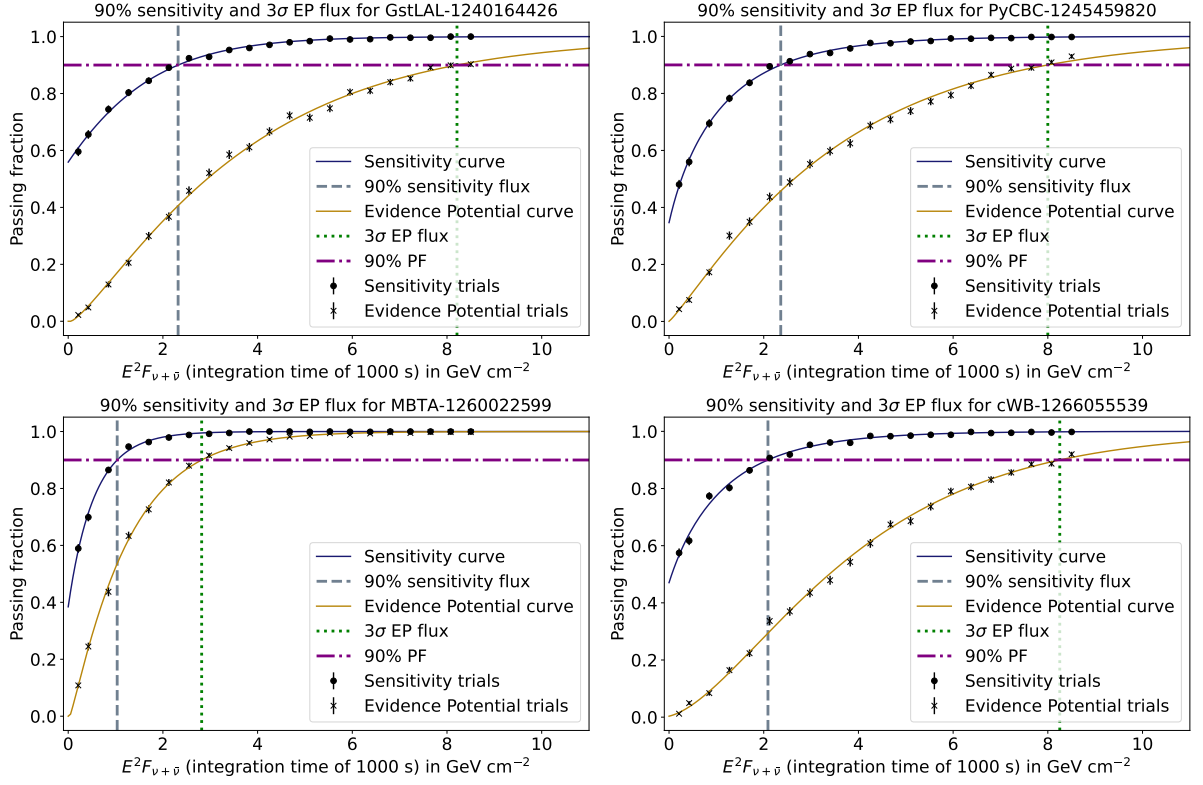


Figure 6.21.: Sensitivity and Evidence Potential (EP) curves shown for some of the shortlisted sub-threshold events from O3, for which the BGTS distribution is shown in Fig. 6.18. The 90% passing fraction is identified on the individual plots, and the corresponding time-integrated energy squared sensitivity and EP fluxes are highlighted.

Sensitivity Studies

To perform sensitivity studies, we inject an increasing number of n_s , following a spectrum with $\gamma=2$, into the GW skymap. For each injected n_s , we calculate the corresponding TS values and compare them with the BGTS distribution. Also, the flux level corresponding to each injected n_s value is noted. This procedure is repeated across multiple trials for each shortlisted GW to calculate the Passing Fraction (PF) for various flux levels. Then, 90% sensitivity and 3σ evidence potential (EP) is calculated according to the definition given in Sec. 5.5.

In Fig. 6.21, a few sample sensitivity and 3σ evidence potential (EP) plots are shown as an example. The overall sensitivity results obtained for all 103 shortlisted GW are tabulated in Table 6.1. Each column carries the information about the GW event ID, the detection time in UTC, the 90% sensitivity and 3σ EP flux, with corresponding n_s values.

Table 6.1.: 90% Sensitivity and 3σ Evidence Potential flux

GW ID	Time (UTC)	Sensitivity flux	n_s	EP flux	n_s
PyCBC-HM-1238423132	04.04.2019	1.91	2.79	8.14	11.76

Table 6.1 (continued)

GW ID	Time (UTC)	Sensitivity flux	n_s	EP flux	n_s
PyCBC-HM-1238442602	04.04.2019	2.38	2.98	8.45	10.44
PyCBC-1238582124	06.04.2019	1.77	2.61	7.42	10.90
PyCBC-HM-1238821531	09.04.2019	1.59	2.50	6.60	10.26
PyCBC-HM-1239092652	12.04.2019	1.14	2.34	3.31	6.70
PyCBC-HM-1239227262	13.04.2019	2.00	2.95	7.07	10.21
PyCBC-HM-1239632437	18.04.2019	1.27	2.37	4.24	7.81
GstLAL-1240164426	24.04.2019	2.32	3.34	8.14	11.61
MBTA-1240423628	27.04.2019	2.99	2.98	8.83	8.75
GstLAL-1241108686	05.05.2019	2.64	2.98	8.79	8.87
MBTA-1241324936	08.05.2019	2.96	3.02	8.55	8.58
PyCBC-HM-1241639735	11.05.2019	1.58	2.36	7.00	10.42
MBTA-1242280001	19.05.2019	3.29	3.20	9.08	8.81
PyCBC-HM-1242314274	19.05.2019	1.79	2.55	7.42	10.56
PyCBC-1243167760	29.05.2019	1.20	2.40	3.10	6.04
PyCBC-HM-1243220837	30.05.2019	1.70	2.91	5.42	9.29
PyCBC-HM-1243748255	05.06.2019	1.86	2.54	3.52	10.32
PyCBC-HM-1243985990	07.06.2019	1.93	2.87	7.82	11.57
PyCBC-HM-1244202953	10.06.2019	1.82	2.68	7.00	10.61
PyCBC-HM-1244278698	11.06.2019	1.78	2.64	7.71	11.33
PyCBC-HM-1244848599	11.06.2019	1.78	2.33	6.90	9.02
PyCBC-244375744	12.06.2019	3.04	3.13	7.18	8.00
PyCBC-HM-1244987689	19.06.2019	2.02	2.79	8.09	11.05
PyCBC-1245459820	25.06.2019	2.00	2.82	7.72	10.87
PyCBC-HM-1245839180	29.06.2019	2.00	2.68	8.46	11.10
PyCBC-1246272532	04.07.2019	3.18	2.90	7.98	7.22
cWB-1246523564	07.07.2019	1.98	2.84	8.08	11.36
GstLAL-1246849694	11.07.2019	1.68	2.80	6.00	9.90
MBTA-1247500937	18.07.2019	1.95	2.76	7.20	10.10
PyCBC-1248215122	26.07.2019	2.46	3.12	9.02	11.37
cWB-1248942961 ⁵	04.08.2019	2.35	2.92	7.68	9.40
MBTA-1249050626	05.08.2019	2.43	2.80	6.71	7.73
PyCBC-HM-1249097859	06.08.2019	2.15	2.93	7.74	10.56
PyCBC-1249416363	09.08.2019	2.18	2.63	8.85	10.67
GstLAL-1249479778	10.08.2019	3.20	2.98	8.23	7.57
PyCBC-HM-1249495257	10.08.2019	1.94	2.68	7.54	10.35
PyCBC-HM-1250026325	16.08.2019	2.91	2.68	7.90	7.27
PyCBC-HM-1250205962	18.08.2019	2.37	2.70	7.96	8.99
cWB-1250939932	27.08.2019	1.71	2.75	6.43	10.35

⁵cWB with $p_{\text{astro}} > 0.5$

Table 6.1 (continued)

GW ID	Time (UTC)	Sensitivity flux	n_s	EP flux	n_s
PyCBC-1251787804	06.09.2019	3.07	3.14	8.26	8.40
PyCBC-HM-1251890211	07.09.2019	2.38	2.59	8.96	9.61
GstLAL-1251926900	07.09.2019	2.26	2.96	7.51	9.68
PyCBC-1252064527	09.09.2019	1.82	2.66	7.54	10.94
PyCBC-HM-1252645611	16.09.2019	2.63	2.78	9.14	9.82
PyCBC-1252672417	16.09.2019	1.76	2.57	8.35	12.23
GstLAL-1252939489	19.09.2019	1.72	2.55	6.58	9.75
cWB-1253293503	23.09.2019	1.75	2.53	7.54	11.01
PyCBC-HM-1253402832	24.09.2019	1.95	3.00	8.41	12.81
MBTA-1253719269	28.09.2019	1.87	2.97	6.98	10.95
cWB-1253922430 ⁶	30.09.2019	2.71	2.60	9.50	9.16
MBTA-1257135715	07.11.2019	3.86	3.53	7.46	6.75
PyCBC-1257260006	08.11.2019	1.93	2.53	7.81	10.35
PyCBC-1258003304	17.11.2019	2.05	2.59	8.17	10.40
PyCBC-HM-1258674399	24.11.2019	1.52	2.46	6.35	10.23
PyCBC-HM-1258872800	27.11.2019	1.90	2.53	8.07	10.62
PyCBC-HM-1259379760	03.12.2019	1.94	2.70	7.60	10.54
MBTA-1259591721	05.12.2019	2.96	2.87	7.88	7.66
cWB-1259959714	09.12.2019	1.69	2.59	7.27	10.80
MBTA-1260022599	10.12.2019	1.03	2.12	2.82	5.76
cWB-1260301231	13.12.2019	2.16	2.64	8.84	10.61
PyCBC-HM-1260305408	13.12.2019	2.01	3.00	7.33	10.65
PyCBC-1260407000	15.12.2019	1.86	2.68	7.39	10.67
PyCBC-1261058247	22.12.2019	1.71	2.47	7.18	10.40
PyCBC-HM-1261146225	23.12.2019	1.90	2.74	7.99	11.48
PyCBC-HM-1261149025	23.12.2019	2.09	3.13	7.53	11.17
PyCBC-HM-1261197166	24.12.2019	1.91	2.85	7.38	11.23
PyCBC-HM-1261273562	25.12.2019	1.96	2.80	7.60	10.92
PyCBC-1261656171	29.12.2019	2.00	2.71	8.31	11.42
GstLAL-1261658694	29.12.2019	3.13	3.01	8.23	7.97
PyCBC-HM-1261717507	30.12.2019	1.94	2.78	8.22	11.52
GstLAL-1261725523	30.12.2019	2.33	2.77	8.59	10.21
PyCBC-1262314840	06.01.2020	1.94	2.76	7.38	10.68
PyCBC-1262321982	06.01.2020	1.81	2.61	7.41	10.56
PyCBC-1262657374	10.01.2020	2.26	2.90	9.14	11.58
PyCBC-1262800092	11.01.2020	1.41	2.63	4.41	8.02
PyCBC-HM-1262878298	12.01.2020	1.35	2.43	5.00	9.22
PyCBC-1262924523	13.01.2020	1.51	2.53	5.63	9.42

⁶cWB with $p_{\text{astro}} > 0.5$

Table 6.1 (continued)

GW ID	Time (UTC)	Sensitivity flux	n_s	EP flux	n_s
PyCBC-1263215647	16.01.2020	2.86	2.92	8.69	8.76
PyCBC-HM-1263748131	22.01.2020	1.90	2.77	8.88	12.54
cWB-1264014232	25.01.2020	2.34	2.88	9.78	11.63
cWB-1264222462	28.01.2020	2.19	2.90	8.97	11.73
PyCBC-HM-1264246793	28.01.2020	1.77	2.68	6.87	10.46
PyCBC-HM-1264333383	29.01.2020	1.95	2.88	7.76	11.61
PyCBC-HM-1264569708	01.02.2020	1.17	2.18	4.47	8.17
PyCBC-1264663254	02.02.2020	1.87	2.62	8.01	11.06
PyCBC-HM-1265364040	10.02.2020	1.63	2.46	7.57	11.37
MBTA-1265537921	12.02.2020	1.57	2.44	5.84	9.20
PyCBC-1265685461	14.02.2020	1.07	2.20	3.10	6.31
PyCBC-HM-1265754804	14.02.2020	1.32	2.33	4.75	8.64
cWB-1265755544 ⁷	14.02.2020	2.17	2.39	8.42	9.17
GstLAL-1266028677	18.02.2020	1.65	2.43	7.49	11.21
cWB-1266055539	18.02.2020	2.10	2.62	8.24	10.16
GstLAL-1266330503	21.02.2020	3.30	2.90	8.24	7.35
GstLAL-1266480585	23.02.2020	1.40	2.42	5.51	9.51
GstLAL-1266516436	23.02.2020	1.26	2.30	5.00	9.27
cWB-1266548742	24.02.2020	2.29	3.14	7.97	10.86
PyCBC-HM-1267131516	01.03.2020	1.74	2.73	7.05	11.17
PyCBC-HM-1267132237	01.03.2020	1.70	2.54	7.63	11.26
PyCBC-HM-1267485300	05.02.2020	1.71	2.76	5.68	9.18
PyCBC-HM-1268250455	14.03.2020	1.46	2.50	5.19	8.77
GstLAL-1268338066	15.03.2020	1.78	2.71	6.52	9.83
PyCBC-1268438406	16.03.2020	1.73	2.66	6.72	10.23
cWB-1269257119	26.03.2020	1.74	2.58	7.68	11.06

Declination-dependence of Sensitivity

Using the 90% sensitivity flux values tabulated in Table 6.1 obtained from the sensitivity studies, the declination dependence of per-flavour sensitivity of the sub-threshold GWs is also studied. We represent the sensitivities of the sub-threshold GWs separately, identified by different pipelines in Fig. 6.22. For demonstration, only GWs detected by GstLAL, MBTA, and cWB-all-sky-search pipelines are shown here. The plots corresponding to PyCBC and PyCBC-Highmass pipelines are shown in Fig. A.3. The 90% sensitivity flux for each event is plotted with respect to the best-fit declination, obtained from the corresponding GW skymap. Each point corre-

⁷cWB with $p_{\text{astro}} > 0.5$

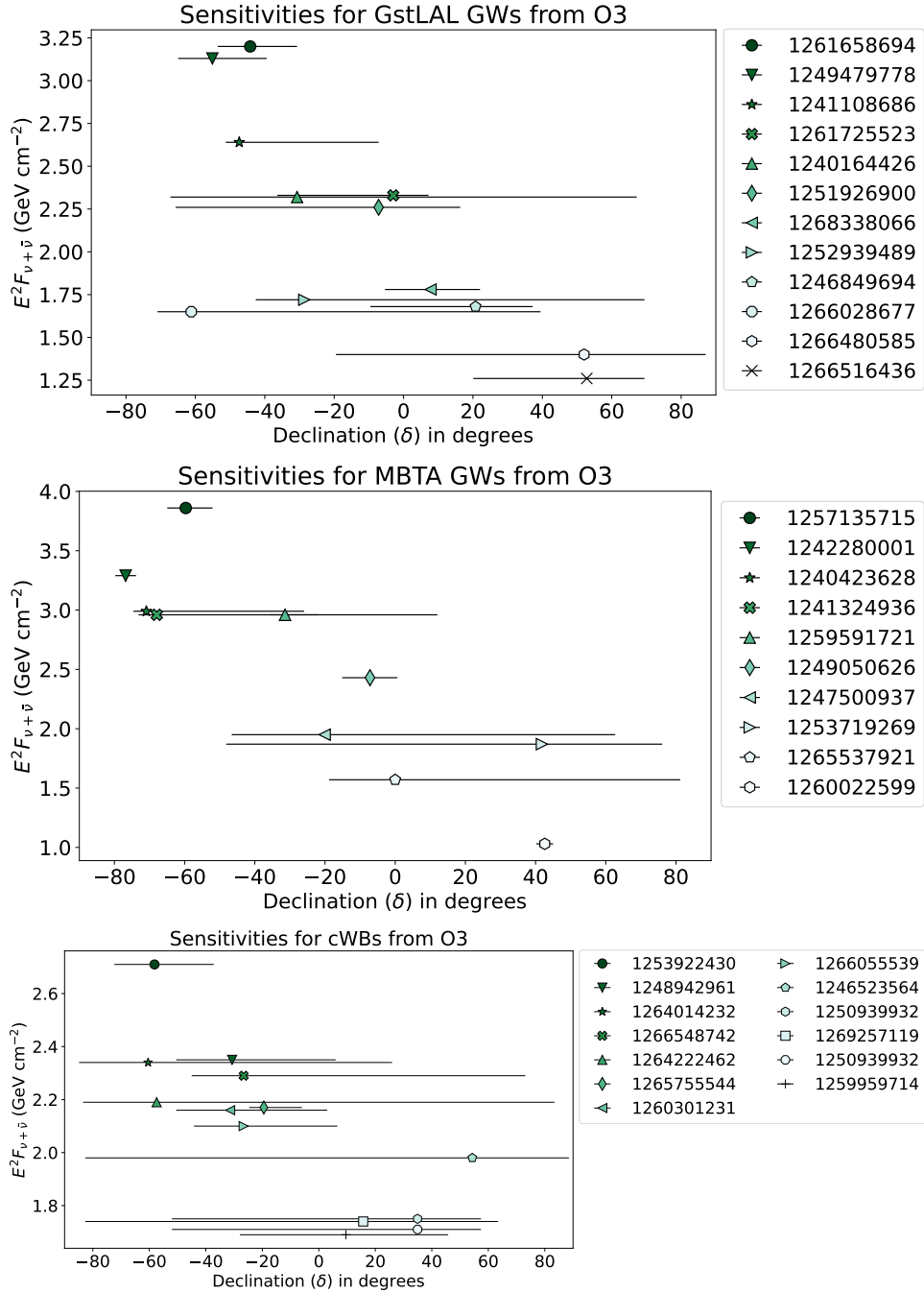


Figure 6.22.: Declination dependence of per-flavour sensitivity flux calculated at 1 GeV for the sub-threshold CBC and cWB candidates identified by GstLAL, MBTA, and cWB-all-sky pipelines during O3. The declination of the pixel containing the best-fit source location has been identified by a marker. Different GW candidates have been identified by different coloured markers. The horizontal spread across the markers covers the declination range for the 50% containment area from the respective GW skymap.

sponding to a different GW source candidate has been identified by a marker. The horizontal

spread across the markers covers the declination range for the 50% containment area for the respective GW skymap.

Each plot in Fig. 6.22 demonstrates slightly better sensitivities in the Northern Hemisphere (NH) than in the Southern Hemisphere (SH), which is caused by comparatively lower A_{eff} caused by enhanced cuts for atmospheric background suppression. This is a well-known feature of GRECO, which was also identified in a previous analysis [10]. Some events in the SH still appear to have better sensitivity. The reason for that is that those particular GW sources have a significant part of their skymaps located in the NH.

Also, it is notable that the LVK 50% containment region for most of the sub-threshold candidates is pretty large, ranging from the Northern to the Southern hemisphere. The main reason for this is a worse localisation of sub-threshold GWs compared to that of confident events by the GW detectors. However, this could be significantly improved if we can identify neutrino counterparts spatially and temporally correlated to these candidates.

6.4. Summary and Discussion

In this chapter, the detailed procedure of sub-threshold GW event selection for a catalogue search is outlined. For that, the publicly available LVK data from O3 is used. These events satisfy $2 \text{ yr}^{-1} \leq \text{FAR} < 2 \text{ day}^{-1}$ and $0.1 \leq p_{\text{astro}} < 0.5$. Among them, 90 are CBC candidates, including 16 NSBH merger-like events. In addition, 10 cWB events with $p_{\text{astro}} < 0.5$ and 3 cWB events with $p_{\text{astro}} < 0.5$ have been identified. The objective is to search for potential sub-TeV neutrino counterparts that are spatially and temporally coincident with these GW candidates. For each event, dedicated background and sensitivity studies have been carried out using scrambled GRECO data. Also, bias tests are performed. The corresponding results are summarised in Tab. 6.1, with representative example plots provided for demonstration.

The declination dependence of the per-flavour sensitivity has been demonstrated for candidates from three different pipelines. Notably, for some sub-threshold GWs, the localisation is particularly poor. Identifying coincident neutrino events would allow a better localisation of the GW-emitting sources. This would make future follow-ups of sub-threshold GW candidates more efficient, especially for electromagnetic follow-up searches. In that direction, with the conclusion of sensitivity studies, the next step is to unblind the GRECO data sample to search for sub-TeV neutrino emission correlated with the individual sub-threshold GW candidates. The procedure and results for that are discussed in Ch. 7.

Chapter 7. Results: Sub-threshold GW follow-up with Sub-TeV Neutrinos

“The thrill of unwrapping the unknown is the essence of discovery.” — Vera Rubin

To follow up on the sub-threshold GW candidates from O3, a selection criterion to identify promising source candidates is developed and applied to the whole source catalogue, as described in Ch. 6. The background trials and sensitivity studies have also been performed to evaluate the analysis performance, using the methods described in Ch. 5. The next logical step is to use the unscrambled IceCube GRECO dataset and search for sub-TeV neutrino coincidences with individual sub-threshold GW events. In IceCube terminology, this transition from scrambled data to the actual dataset is known as ‘unblinding’. Following this two-step procedure eliminates bias, preserves statistical rigour, and ensures that any claimed discovery is credible and reproducible, which are crucial for establishing trust in major discoveries. As a part of this chapter, the unblinding procedure employed for this analysis and the corresponding results are discussed. Some of the main results included here were first presented in [122].

7.1. Unblinding Plan

As part of this thesis work, the unblinding is carried out as a time-dependent catalogue search using the GRECO-v002-p10b dataset, as mentioned in Sec. 6.2. For each GW candidate, we look for neutrino events that are spatially and temporally coincident within a ± 500 s time window around the GW detection time. This search targets all the 103 shortlisted sub-threshold GW events identified in Sec. 6.1.

For each event, a pre-trial p -value is computed, quantifying how compatible the observed neutrino events within the time window are with the spatial and energy distribution described under the signal hypothesis. To assess the significance of neutrino observation from the most promising GW source candidate, a post-trial p -value is computed using the Šidák correction method [340] as explained in Sec. 5.5.3. If a neutrino counterpart is found with a trial-corrected significance of at least 3σ , the best-fit signal parameters will be reported, which are:

- The number of signal events n_s ,
- The joint best-fit source coordinates (right ascension, r.a. and declination, δ),
- The spectral index γ .

If no significant correlation is observed, we will instead place upper limits on the energy-scaled time-integrated flux for both neutrinos and anti-neutrinos ($\nu + \bar{\nu}$), $E^2 F_{\nu+\bar{\nu}}$, for individual GW

events. Here, the flux is defined as, $F_{\nu+\bar{\nu}} = \frac{dN}{dA dE}$, for an integration time of $\delta t = 1000$ s. These limits are calculated assuming a benchmark E^{-2} spectrum, as the neutrinos are being emitted by the source.

7.2. Unblinding Results

Following the plan described in Sec. 7.1, the unblinding has been performed on the 103 short-listed GW events. This section presents the results of that search, including the summary of pre-trial p -values and their overall distribution. Next, interesting GW+ ν coincidences are discussed, and the trial-corrected p -value for that event is reported. Finally, we present flux upper limits for the case where no significant association is found.

7.2.1. Estimation of pre-trial p -values

As a first step, the unscrambled neutrino data is used to identify neutrino events detected within a ± 500 s time window around each shortlisted GW candidate. For every GW event, the sky pixel is determined which contains the maximum test statistic (TS_{obs}) following the method outlined in Eq. 5.21, using the identified neutrino events. This pixel represents the joint best-fit source location for both the neutrino and GW signals. The observed TS_{obs} for each GW event is compared against the corresponding background TS (BGTS) distribution. It is then evaluated how many background trials yield a TS_{bkg} larger than TS_{obs} . The fraction of such trials, relative to the total number of pseudo-experiments, which is 10,000 for this analysis, defines the pre-trial p -value, p_{pre} . The resulting values for each source candidate are summarised in the Tab. 7.1.

7.2.2. Summary of unblinding results

Table 7.1.: Summary of unblinding results for the shortlisted 103 GW events. The events are arranged in the ascending order of the corresponding pre-trial p -value (p_{pre}). For each event, the GW event details, time of occurrence, observed TS value, pre-trial p -value, and flux upper limit $E^2 F_{\nu+\bar{\nu}}$ (for $\delta t = 1000$ s) are listed.

GW ID	Time (UTC)	Catalogue	Event-type	TS_{obs}	p_{pre}	$E^2 F_{\nu+\bar{\nu}}$ [GeV cm ⁻²]
PyCBC-HM-1261717507	30.12.2019	GWTC-3	BBH	18.07	0.0004	9.65
PyCBC-HM-1244202953	10.06.2019	GWTC-2.1	BBH	9.70	0.014	6.05
PyCBC-HM-1265364040	10.02.2020	GWTC-3	BBH	7.53	0.033	5.22
cWB-1259959714	09.12.2019	GWTC-3	cWB	6.93	0.039	5.05
PyCBC-HM-1267132237	01.03.2020	GWTC-3	BBH	6.33	0.052	5.00
cWB-1260301231	13.12.2019	GWTC-3	cWB	6.61	0.057	5.73
GstLAL-1246849694	11.07.2019	GWTC-2.1	BBH	4.96	0.069	3.86

Table 7.1 (continued)

GW ID	Time (UTC)	Catalogue	Event-type	TS_{obs}	p_{pre}	$E^2 F_{\nu+\bar{\nu}}$ [GeV cm ⁻²]
GstLAL-1268338066	15.03.2020	GWTC-3	BBH	4.93	0.078	4.12
PyCBC-HM-1238442602	04.04.2019	GWTC-2.1	BBH	6.255	0.078	5.32
PyCBC-HM-1238423132	04.04.2019	GWTC-2.1	BBH	5.54	0.085	4.63
PyCBC-HM-1244278698	11.06.2019	GWTC-2.1	BBH	4.20	0.086	4.04
MBTA-1257135715	07.11.2019	GWTC-3	BBH	0.0	0.10	3.86
cWB-1248942961 ¹	04.08.2019	GWTC-3	cWB	2.21	0.13	3.99
PyCBC-HM-1253402832	24.09.2019	GWTC-2.1	BBH	5.63	0.135	4.07
cWB-1269257119	26.03.2020	GWTC-3	cWB	3.15	0.17	3.60
PyCBC-HM-1243748255	05.06.2019	GWTC-2.1	BBH	3.18	0.17	3.54
PyCBC-1252672417	16.09.2019	GWTC-2.1	BBH	3.10	0.17	3.72
PyCBC-HM-1264333383	29.01.2020	GWTC-3	BBH	4.01	0.17	3.57
cWB-1266548742	24.02.2020	GWTC-3	cWB	5.00	0.18	4.12
GstLAL-1252939489	19.09.2019	GWTC-2.1	BBH	2.13	0.196	3.04
PyCBC-1262657374	10.01.2020	GWTC-3	NSBH	3.44	0.21	3.88
PyCBC-1263215647	16.01.2020	GWTC-3	NSBH	0.91	0.21	3.86
cWB-1266055539	18.02.2020	GWTC-3	cWB	3.11	0.21	3.83
GstLAL-1266028677	18.02.2020	GWTC-3	BBH	1.74	0.22	2.99
PyCBC-1257260006	08.11.2019	GWTC-3	NSBH	2.121	0.2231	3.15
PyCBC-HM-1243220837	30.05.2019	GWTC-2.1	BBH	1.049	0.2488	2.28
PyCBC-HM-1239632437	18.04.2019	GWTC-2.1	BBH	1.395	0.249	1.74
PyCBC-1251787804	06.09.2019	GWTC-2.1	NSBH	0.067	0.254	3.07
PyCBC-1246272532	04.07.2019	GWTC-2.1	NSBH	0.26	0.26	3.54
PyCBC-HM-1264569708	01.02.2020	GWTC-3	BBH	1.67	0.27	1.88
cWB-1264222462	28.01.2020	GWTC-3	cWB	2.36	0.27	3.40
GstLAL-1251926900	07.09.2019	GWTC-2.1	BBH	0.35	0.27	2.72
MBTA-1241324936	08.05.2019	GWTC-2.1	BBH	0.50	0.28	3.62
PyCBC-HM-1238821531	09.04.2019	GWTC-2.1	BBH	2.35	0.28	2.57
GstLAL-1249479778	10.08.2019	GWTC-2.1	BBH	0.0	0.2867	3.20
PyCBC-1267485300	05.02.2020	GWTC-3	BBH	0.518	0.3016	2.07
GstLAL-1266330503	21.02.2020	GWTC-3	BBH	0.0	0.31	3.30
PyCBC-HM-1244848599	11.06.2019	GWTC-2.1	BBH	0.923	0.34	2.46

¹cWB with $p_{\text{astro}} > 0.5$

Table 7.1 (continued)

GW ID	Time (UTC)	Catalogue	Event-type	TS_{obs}	p_{pre}	$E^2 F_{\nu+\bar{\nu}}$ [GeV cm ⁻²]
cWB-1250939932	27.08.2019	GWTC-3	cWB	0.525	0.34	2.12
PyCBC-HM-1261149025	23.12.2019	GWTC-3	BBH	0.0	0.35	2.09
MBTA-1259591721	05.12.2019	GWTC-3	BBH	0.0	0.35	2.96
PyCBC-HM-1250026325	16.08.2019	GWTC-2.1	BBH	0.0	0.36	2.91
PyCBC-1262924523	13.01.2020	GWTC-3	NSBH	1.487	0.37	1.99
PyCBC-1262321982	06.01.2020	GWTC-3	NSBH	1.005	0.38	1.35
MBTA-1240423628	27.04.2019	GWTC-2.1	BBH	0.0	0.39	2.99
GstLAL-1241108686	05.05.2019	GWTC-2.1	BBH	0.0	0.40	2.75
PyCBC-HM-1252645611	16.09.2019	GWTC-2.1	BBH	0.745	0.4277	3.06
PyCBC-HM-1245839180	29.06.2019	GWTC-2.1	BBH	0.0	0.4292	2.00
PyCBC-HM-1251890211	07.09.2019	GWTC-2.1	BBH	0.0	0.433	2.40
PyCBC-1265685461	14.02.2020	GWTC-3	BBH	0.0	0.435	1.07
PyCBC-HM-1265754804	14.02.2020	GWTC-3	BBH	0.0	0.447	1.32
PyCBC-HM-1261197166	24.12.2019	GWTC-3	BBH	0.741	0.461	2.04
PyCBC-1261058247	22.12.2019	GWTC-3	NSBH	0.521	0.4651	1.84
cWB-1265755544 ²	14.02.2020	GWTC-3	cWB	0.096	0.4709	2.37
PyCBC-1249416363	09.08.2019	GWTC-2.1	NSBH	0.0	0.4876	2.18
PyCBC-HM-1258872800	27.11.2019	GWTC-3	BBH	0.219	0.4881	1.94
cWB-1253922430 ³	30.09.2019	GWTC-3	cWB	0.0	0.4963	2.71
PyCBC-1258003304	17.11.2019	GWTC-3	BBH	0.0	0.5065	2.05
PyCBC-HM-1242314274	19.05.2019	GWTC-2.1	BBH	0.0	0.5087	1.79
PyCBC-1264663254	02.02.2020	GWTC-3	NSBH	0.112	0.5105	1.87
GstLAL-1266480585	23.02.2020	GWTC-3	BBH	0.0	0.5114	1.40
cWB-1253293503	23.09.2019	GWTC-2.1	cWB	0.0	0.533	1.75
PyCBC-1238582124	06.04.2019	GWTC-2.1	NSBH	0.0	0.5385	1.77
PyCBC-HM-1264246793	28.01.2020	GWTC-3	BBH	0.688	0.5473	1.77
PyCBC-HM-1261146225	23.12.2019	GWTC-3	BBH	0.014	0.5676	1.90
PyCBC-1262314840	06.01.2020	GWTC-3	NSBH	0.397	0.5678	1.94
GstLAL-1266516436	23.02.2020	GWTC-3	BBH	0.13	0.5715	1.26
PyCBC-HM-1267131516	01.03.2020	GWTC-3	BBH	0.0	0.586	2.29
PyCBC-1261656171	29.12.2019	GWTC-3	BBH	0.0	0.615	2.00

²cWB with $p_{\text{astro}} > 0.5$ ³cWB with $p_{\text{astro}} > 0.5$

Table 7.1 (continued)

GW ID	Time (UTC)	Catalogue	Event-type	TS_{obs}	p_{pre}	$E^2 F_{\nu+\bar{\nu}}$ [GeV cm ⁻²]
PyCBC-HM-1263748131	22.01.2020	GWTC-3	BBH	0.0	0.6564	1.90
cWB-1264014232	25.01.2020	GWTC-3	cWB	0.0	0.6918	2.34
PyCBC-HM-1243985990	07.06.2019	GWTC-2.1	BBH	0.0	0.6995	1.93
GstLAL-1240164426	24.04.2019	GWTC-2.1	BBH	0.682	0.7215	2.32
PyCBC-HM-1261273562	25.12.2019	GWTC-3	BBH	0.0	0.8399	1.96
PyCBC-1262800092	11.01.2020	GWTC-3	BBH	0.0	0.8577	1.41
MBTA-1247500937	18.07.2019	GWTC-2.1	BBH	0.0	0.8711	1.95
PyCBC-1268438406	16.03.2020	GWTC-3	NSBH	0.0	0.8825	1.73
PyCBC-1244375744	12.06.2019	GWTC-2.1	NSBH	0.0	0.8884	3.04
PyCBC-HM-1250205962	18.08.2019	GWTC-2.1	BBH	0.0	0.898	2.36
PyCBC-HM-1241639735	11.05.2019	GWTC-2.1	BBH	0.0	0.90	1.60
MBTA-1249050626	05.08.2019	GWTC-2.1	BBH	0.0	0.90	2.43
PyCBC-1243167760	29.05.2019	GWTC-2.1	BBH	0.0	0.90	1.22
PyCBC-HM-1268250455	14.03.2020	GWTC-3	BBH	0.0	0.91	1.46
GstLAL-1261658694	29.12.2019	GWTC-3	BBH	0.0	0.91	3.12
PyCBC-HM-1260305408	13.12.2019	GWTC-3	BBH	0.0	0.91	2.00
PyCBC-HM-1258674399	24.11.2019	GWTC-3	BBH	0.085	0.92	1.52
PyCBC-HM-1239092652	12.04.2019	GWTC-2.1	BBH	0.0	0.92	1.14
PyCBC-1260407000	15.12.2019	GWTC-3	NSBH	0.0	0.93	1.88
PyCBC-HM-1239227262	13.04.2019	GWTC-2.1	BBH	0.0	0.93	2.00
cWB-1246523564	07.07.2019	GWTC-3	cWB	0.0	0.93	1.98
MBTA-1265537921	12.02.2020	GWTC-3	BBH	0.0	0.94	1.57
PyCBC-1245459820	25.06.2019	GWTC-2.1	NSBH	0.0	0.94	2.00
PyCBC-HM-1259379760	03.12.2019	GWTC-3	BBH	0.0	0.94	1.94
PyCBC-1252064527	09.09.2019	GWTC-2.1	BBH	0.0	0.94	1.07
PyCBC-HM-1249495257	10.08.2019	GWTC-2.1	BBH	0.0	0.94	1.94
MBTA-1253719269	28.09.2019	GWTC-2.1	BBH	0.0	0.95	1.87
GstLAL-1261725523	30.12.2019	GWTC-3	BBH	0.0	0.95	2.33
PyCBC-HM-1244987689	19.06.2019	GWTC-2.1	BBH	0.0	0.96	2.02
MBTA-1260022599	10.12.2019	GWTC-3	BBH	0.0	0.96	1.03
PyCBC-HM-1249097859	06.08.2019	GWTC-2.1	BBH	-8.031	0.96	2.15
MBTA-1242280001	19.05.2019	GWTC-2.1	BBH	-8.535	0.97	3.29
PyCBC-HM-1262878298	12.01.2020	GWTC-3	BBH	0.0	0.98	1.35

Table 7.1 (continued)

GW ID	Time (UTC)	Catalogue	Event-type	TS_{obs}	p_{pre}	$E^2 F_{\nu+\bar{\nu}}$ [GeV cm ⁻²]
PyCBC-1248215122	26.07.2019	GWTC-2.1	NSBH	-1.059	0.99	2.46

7.2.3. Joint GW + ν Skymaps

From the p_{pre} values tabulated above, it is evident that two BBH-merger-like events $p_{\text{pre}} \lesssim 0.01$, which signifies $\lesssim 1\%$ probability of chance coincidence. Their details are discussed below. For the unblinded GW + ν joint skymap of all the 103 shortlisted GW events, refer to Appendix B.

PyCBC-HM-1261717507

The most significant candidate is a sub-threshold BBH-like event. The GPS time of the event is 1261717507. It was detected by the PyCBC-Highmass pipeline on December 30, 2019, during O3b. The pre-trial p -value associated with this event is 0.0004 (3.35σ). However, after trial-correction using Eq. 5.23 for $N = 103$ events, the significance drops to 0.04 (1.76σ one-sided). The joint skymap for the GW and GRECO events detected within 1000 s by IceCube is shown in Fig. 7.1.

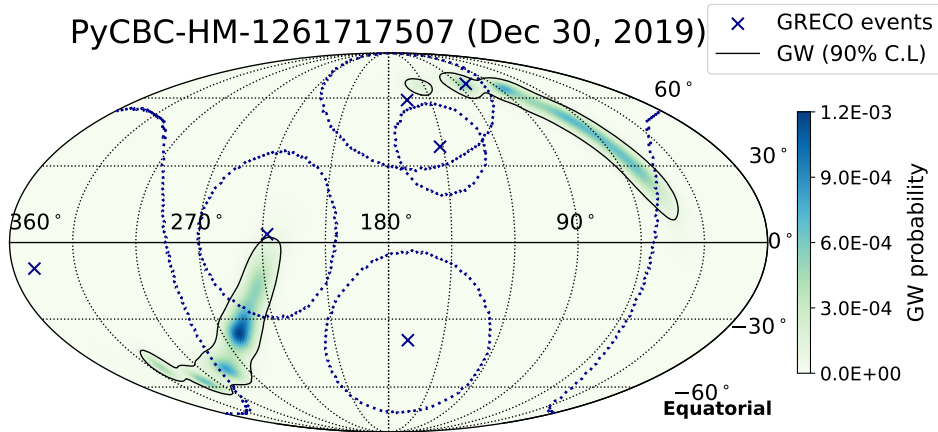


Figure 7.1.: Skymap of the most significant sub-threshold GW from the shortlisted 103 events. The GPS time for detection of the GW event is 1261717507, which corresponds to December 30, 2019. The p_{astro} value corresponding to this detection is 0.16. The neutrinos detected within 1000 s around the sub-threshold GW detection time are overlaid on top of the GW skymap. The probability of chance coincidence for this event is 0.04% (4% after trial correction).

In total, 6 GRECO events were detected within the 1000 s time-window. Referring to Table 6.1, one can compare the fitted number of signal neutrinos required to meet the 90% sensitivity

flux, which was 2.78. Examining the skymap closely, it is evident that neutrino 4 ($\delta > 60^\circ$) is primarily driving the TS values in this case. It was found to be emitted ~ 337 s after LVK detected the BBH merger. From BBH merger models, neutrino emission is expected to happen after the launching of jets from the remnant compact object, which is created only after the merger takes place. So, it fits well within the neutrino emission scenarios expected from BBH merger models (see Sec. 2.6). Two specific cases are discussed briefly in Ch. 8.

Fig. 7.2 shows the TS_{obs} for PyCBC-HM-1261717507, overlaid on the respective BGTS distributions derived from scrambled trials. The median and the 3σ deviation from the background are also marked for reference. It demonstrates the deviation from background expectation obtained with TS_{obs} .

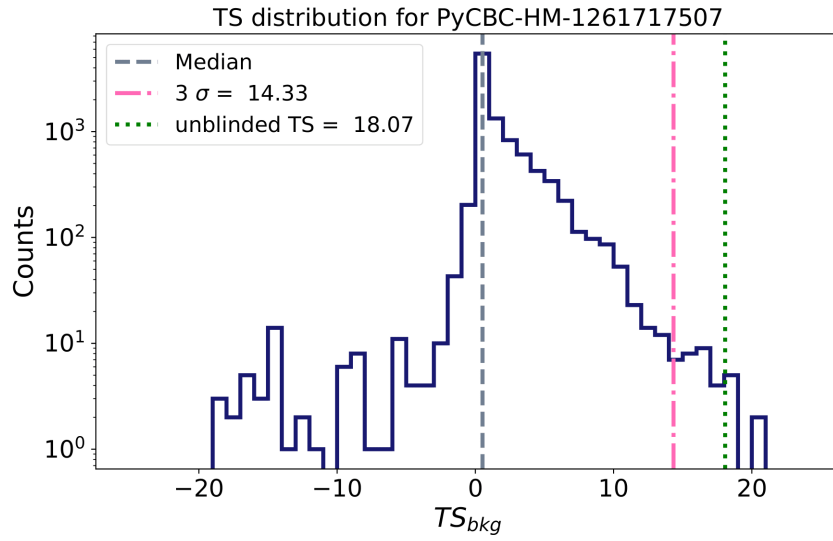


Figure 7.2.: The observed TS value for PyCBC-HM-1261717507 is shown here, overlaid on top of the corresponding background TS (BGTS) distribution. The median of the background distribution and 3σ deviation from it are also indicated.

The corresponding TS map, including the spatial penalty term (see Eq. 5.21), which was observed after unblinding, is shown in Fig. 7.3. Originally, the best-fit location for the GW emitting source was (r.a. = 260.86° , $\delta = -35.68^\circ$), where the skymap was spread out over both the Northern and Southern Hemisphere. However, influenced by the neutrino event, the joint GW + ν source position has shifted to the NH, which is marked by the position of TS_{obs} . For follow-up efforts, such as electromagnetic counterpart searches, this joint position would serve as a new focal point. This demonstrates one of the central motivations of this analysis: identifying coincidences with well-localised neutrino events can indeed improve our ability to highlight promising regions of the sky for extended sources like sub-threshold GWs, which can influence our decisions while triggering further follow-up studies.

Despite all the successes mentioned above, a joint detection of GW + ν from the pixel where TS_{obs} is located can't be claimed, as after trial correction, $p_{\text{post}} \simeq 0.04$ (1.76σ). This means that the probability of chance-coincidence is around 4%, which is non-negligible.

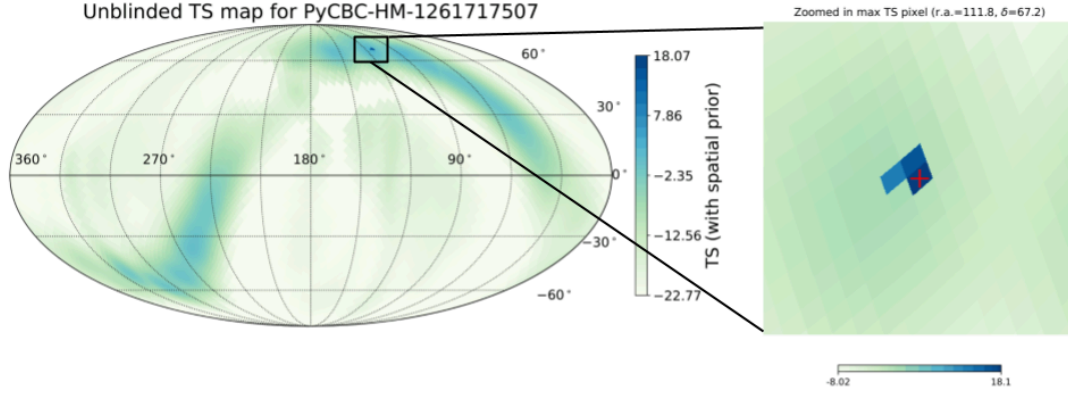


Figure 7.3.: (Left) The unblinded TS skymap for PyCBC-HM-1261717507 and (right) the zoomed-in view of the sky location corresponding to the maximum test statistic (TS) in the unblinded map, TS_{obs} . The colour scale indicates the local TS value, with the red cross marking the pixel of maximum significance, centred at $\text{r.a.} = 111.8^\circ$, $\delta = 67.2^\circ$.

PyCBC-HM-1244202953

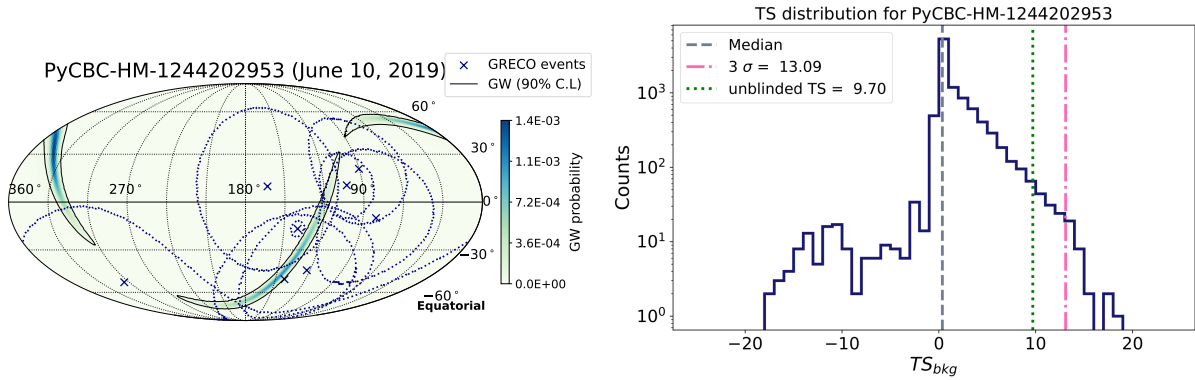


Figure 7.4.: (Left) Joint GW + ν skymap for a BBH merger like event, PyCBC-HM-1244202953, detected on June 10, 2019. Neutrinos detected within the 1000 s search window are overlaid on the GW skymap. The pre-trial p -value for this event is 0.014. (Right) The observed TS value is overlaid on the corresponding background TS distribution. The median and the 3σ range of the background are also indicated.

The next most significant source candidate is another sub-threshold BBH merger-like event, but detected during O3a, also by the PyCBC-Highmass pipeline. The signal was recorded on June 10, 2019, with a p_{astro} value of 0.14. As tabulated in Table 7.1, the observed p_{pre} for joint emission of GW + ν from this event is 0.014 (2.2σ one-sided), which is again not significant

enough. The joint GW + ν skymap is shown in left panel of Fig. 7.4. The right panel shows the corresponding BGTS distribution on which the TS_{obs} is marked.

Results obtained for cWBs and NSBH events

Among the 10 shortlisted cWBs, the most significant one has a GPS time of 1259959714. It was detected again during O3b, on December 9, 2019, solely by the CBC optimised GW burst search pipeline. The pre-trial p -value was found to be 0.038. The joint GW skymap with GRECO events detected within 1000 s by IceCube is shown in Fig. 7.5. The right panel shows the observed TS values for the most significant sub-threshold cWB event, overlaid on the respective background TS distributions derived from scrambled trials. The median and the 3σ deviation from the background are also marked for reference.

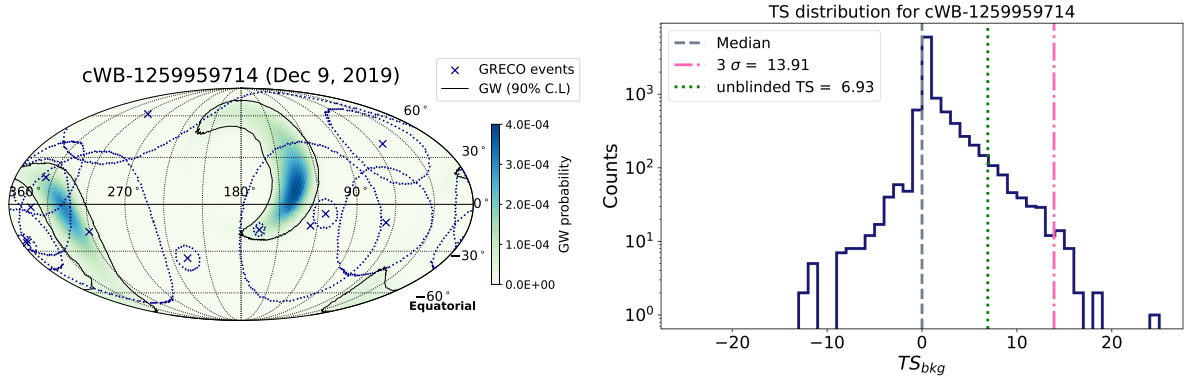


Figure 7.5.: (Left) Skymap of the most significant sub-threshold cWB from the shortlisted 103 events. The GPS time for detection of the GW event is 1259959714, which corresponds to December 9, 2019. The p_{astro} value for this detection is 0.28. Neutrinos detected within the 1000 s search window are overlaid on the GW skymap. The pre-trial p -value for this event is 0.038. (Right) The observed TS value is overlaid on the corresponding background TS distribution. The median and the 3σ range of the background are also indicated.

3 of the 10 cWBs had $p_{\text{astro}} > 0.5$, as mentioned in Sec. 6.1. None of them shows statistically significant neutrino correlations within the search time window. For example, the joint GW + ν is shown for cWB-1248942961 in Fig. 7.6, which had a $p_{\text{astro}} = 0.98$ while detection by LVK. Finally, among the 16 shortlisted NSBH-like shortlisted sub-threshold events, none show statistically significant neutrino correlations within the search time window of 1000 s. The lowest p_{pre} among them was found to be 0.21, for PyCBC-1262657374. For details and the joint GW + ν skymap, refer to Fig. 7.7.

From the Fig. 7.4, 7.5, 7.6 shown above, it is evident that the number of GRECO events recorded within the 1000 s time window was higher compared to what was necessary to fulfil the sensitivity expectations (see Table 6.1). Yet, sufficient evidence of joint emission is not possible to claim because of the larger angular uncertainties associated with promising coincident neutrino events. This effectively gives us a lower number of best-fit n_s corresponding to the TS_{obs} . That significantly affected the discovery prospect for the individual GW events.

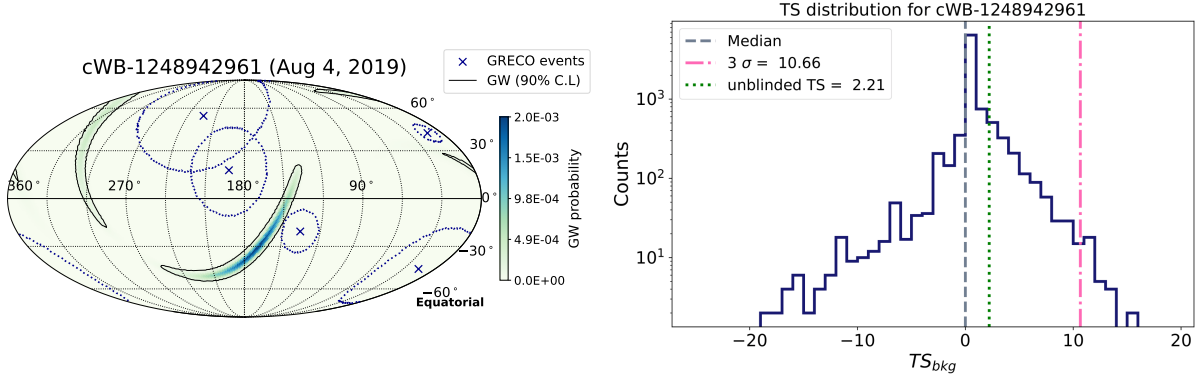


Figure 7.6.: (Left) Skymap of the cWB-1248942961, which was recorded on August 04, 2019. The p_{astro} corresponding to this detection is 0.98. Neutrinos detected within the 1000 s search window are overlaid on the GW skymap. The pre-trial p -value for this event is 0.13. (Right) The observed TS value is overlaid on the corresponding background TS distribution. The median and the 3σ range of the background are also indicated.

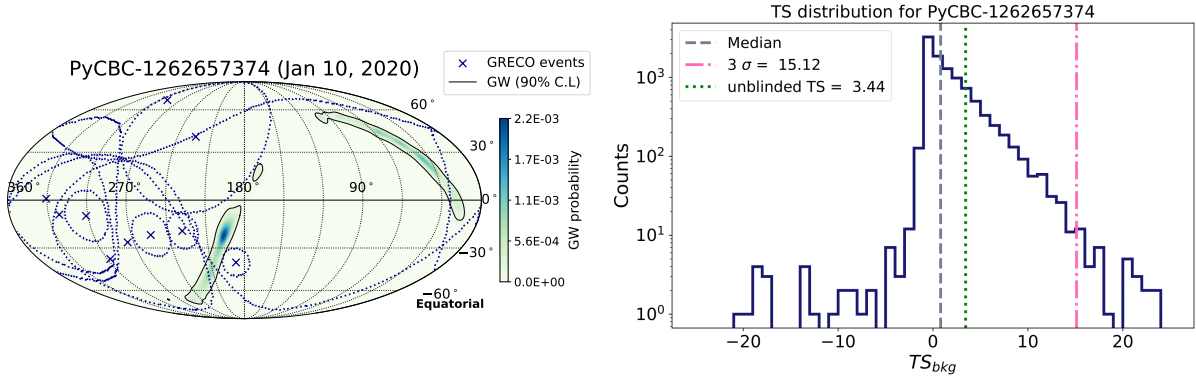


Figure 7.7.: (Left) Skymap of the NSBH candidate, which was recorded to have the lowest p_{pre} among the 16 shortlisted ones. The GPS time for detection of the GW event is 1262657374, which corresponds to January 10, 2020. Neutrinos detected within the 1000 s search window are overlaid on the GW skymap. The probability of chance coincidence was found to be 21%. (Right) The observed TS value is overlaid on the corresponding background TS distribution. The median and the 3σ range of the background are also indicated.

7.2.4. Pre-trial p -value distribution

As mentioned above, the p -value for each GW event quantifies the probability of obtaining a TS at least as large as TS_{obs} under the background hypothesis, based on the BGTS distribution. Referring to their values in Table 7.1, their overall distribution is next to be examined. To interpret whether this distribution is consistent with background expectations, a reference background distribution must be established for comparison.

Background expectation

To compare the p -values obtained from the UML search, we generate an expected background distribution by randomly sampling TS values from the BGTS of each GW event and converting them to p -values, in the same method as explained above. This sampling is repeated 10,000 times to build the distribution. The accumulated p -values are then binned, and the median count in each bin represents the expected number of background events with p -values in that range.

In principle, if the BGTS is continuous, which can be achieved with very well localised, high-energy tracks [8], the resulting p -values under the background hypothesis should be uniformly distributed between 0 and 1. A very few may give p -values close to 0, which represents rare, signal-like fluctuations. Otherwise, the p -value will be close to 1 for more common, background-like outcomes. When accumulated over many repetitions, the distribution of p -values should appear flat. However, with GRECO, we encounter a contrasting scenario, as the background expectation is non-uniform across $[0,1]$. This comes from the discrete nature of the BGTS, as seen before in Sec. 6.3.1. Since GW skymaps are extended, and GRECO events have relatively poor angular resolution compared to high-energy tracks, it is almost always possible to find some overlap between the two. In such situations, the BGTS effectively reduces to a counting experiment. So, the BGTS can only take a limited number of values depending on how many events fall inside the contour. Consequently, the p -values derived from this finite set of TS values are also limited to discrete points. When accumulated, the resulting p -value distribution develops features, for example, in-between plateaus and jumps instead of being smooth and uniform.

This behaviour is particularly pronounced near $p = 1.0$, where a majority of pseudo-experiments yield low TS values (e.g., $TS = 0$). As a result, many trials cluster at high p -values, producing a sharp pile-up, while bins near $p = 0$ remain sparsely populated. This step-like structure in the background expectation, shown in Sec. 6.3.1 and Fig. 7.8, reflects the limited resolution of the BGTS in the sub-TeV regime.

Comparison of background and observed p -values

After generating the background p -value expectation, marked with the magenta histogram in Fig. 7.8, the observed p -value distribution for the 103 shortlisted GW events obtained with the UML method is overlaid in the same figure as the green histogram. The corresponding σ distribution is included in Appendix B.

The observed distribution follows the general features of the background expectation, including the characteristic plateaus and jumps that arise from the discrete nature of the BGTS. One notable feature is the absence of events in the bin between 0.75 and 0.8. This empty bin is not specific to the observed data alone but also appears in the background expectation, which similarly shows no entries in that range. This consistency indicates that the gap originates from the structure of the background distribution itself.

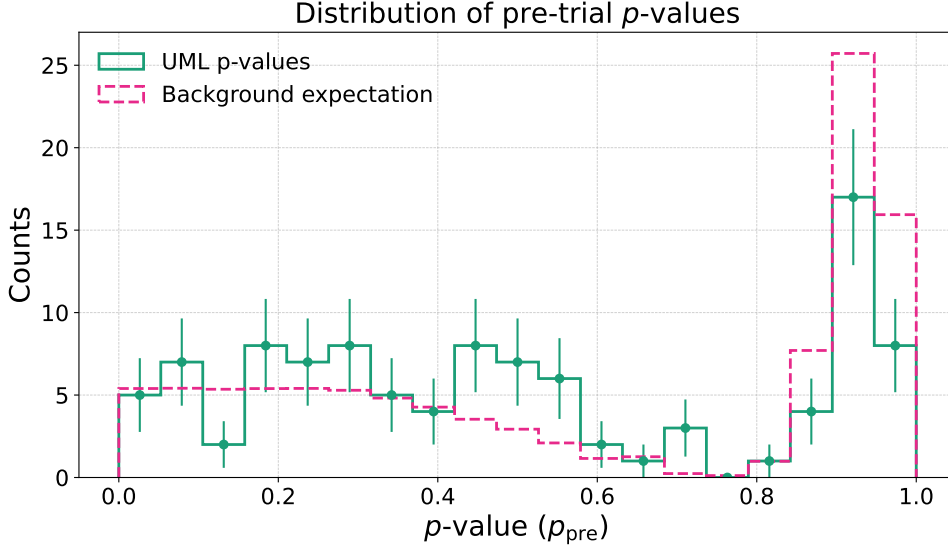


Figure 7.8.: Distribution of pre-trial p -values for the 103 shortlisted sub-threshold GW events from the O3 observing run. The green histogram with error bars displays the observed p -value distribution obtained using the UML method. It is compared with the expected background distribution, obtained by randomly sampling TS values from the background TS distribution for each GW event and calculating the corresponding p -values. This background sampling was repeated 10,000 times to construct the expectation. The observed distribution is consistent with the null hypothesis, and no significant excess is observed.

7.2.5. Kolmogorov-Smirnov Test

To quantitatively assess how much the observed p -value distribution is consistent with the background expectation, a Kolmogorov–Smirnov (KS) test is performed [333]. The KS statistic quantifies the vertical distance between the null distribution and the observed distribution by comparing their cumulative distribution functions (CDFs). In this case, a two-sample KS test is performed since there are two empirical distributions whose compatibility needs to be tested. One of them represents the observed p -value distribution, the other is the expected background p -value distribution, which is described above. The CDFs of each distribution are shown in Fig. 7.9.

In the plot, a plateau is visible for $0.75 < p\text{-value} \lesssim 0.8$ for the CDF representing the observed p -values. It appears exactly where a dip is visible in the observed p -value distribution in Fig. 7.8. Thus, it is not a plotting artefact but a genuine feature in the observed CDF of the p -values. With 103 discrete entries, a flat step like this typically reflects a gap in the available p -values, which is present in this case between 0.75 and 0.8, followed by several values clustered just above 0.8. This clustering produces a sharp rise in the CDF near the upper end, which also appears as the structure in Fig. 7.8. Such irregularities are expected when the CDF is built from a finite, discrete set of values.

The maximal difference between the CDFs of the two distributions is quantified as the KS statistic. In this case, the KS test yields a statistic, $D_{\text{obs}} = 0.167$, corresponding to the maximum

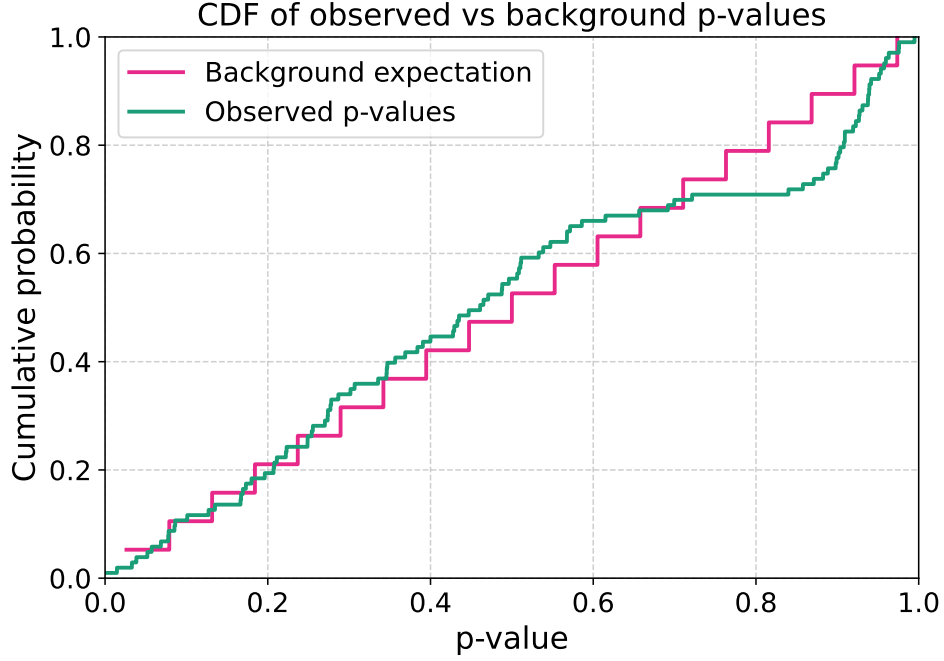


Figure 7.9.: The CDF distributions representing the observed and the null expectations

vertical distance between the observed CDF and the background expectation. This implies a $\sim 17\%$ probability difference at the point of largest discrepancy. However, the condition to reject the null hypothesis is,

$$D_{n,m} > \sqrt{-\ln\left(\frac{\alpha}{2}\right) \frac{1 + \frac{m}{n}}{2m}} \quad (7.1)$$

In Eq. 7.1, n and m are the sizes of the two empirical distributions ($n = m = 103$), and α is the CL at which the null hypothesis is preferred to be rejected. To reinstate, in this case, the null hypothesis is that the two distributions are consistent with each other. The alternative hypothesis is that there are inconsistencies between the two distributions, as the observed p -values are not completely background-like, and the 103 GWs may contain some signal-like cases.

For the 103 sources, and $\alpha = 0.01$, $D_{n,m} > 0.22$, which means a difference of at least 0.22 would be required to reject the null hypothesis with 99% CL. As $D_{\text{obs}} < D_{n,m}$, the observed deviation is therefore not sufficient for rejection. The KS test p -value is 0.696, meaning that under the null hypothesis, a discrepancy of this size or larger would arise in about 70% of realisations by chance. So, the KS test shows no significant deviation of the observed CDF from the background expectation.

7.2.6. Flux Upper Limits

As none of the shortlisted events has $> 3\sigma$ significance after trial correction, we report flux upper limits (ULs) (90% C.L.) for all of them, following the unblinding plan outlined in Sec. 7.1. These limits were calculated assuming an E^{-2} neutrino spectrum and a fixed 1000 s integration

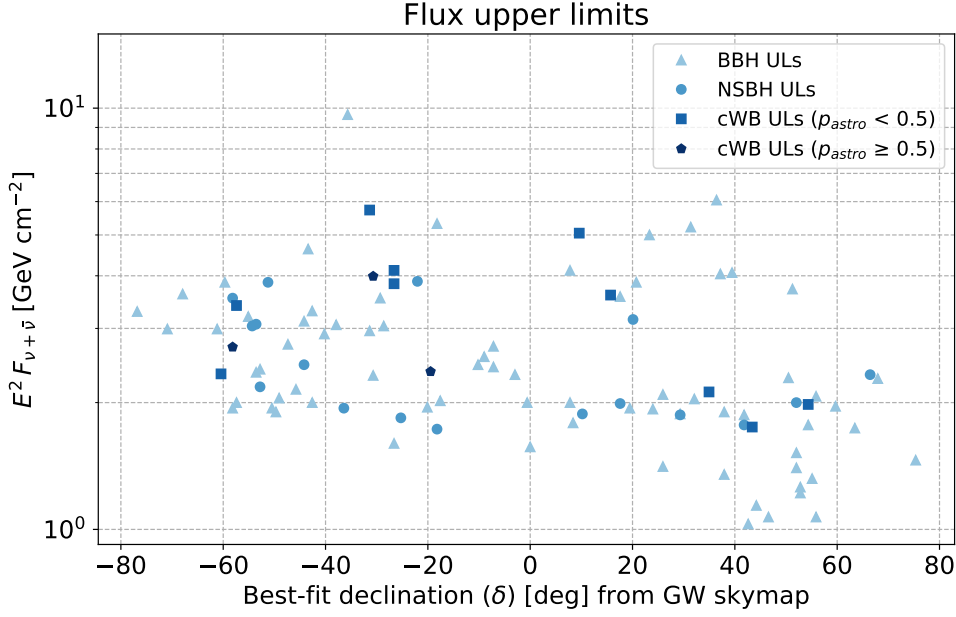


Figure 7.10.: 90% C.L. flux upper limits for neutrino emission associated with the 103 short-listed sub-threshold GW events. The calculation is performed assuming spectral index $\gamma = 2$ and a 1000-second integration time. The ULs obtained for different event-types, such as BBH mergers, NSBH mergers, cWBs with $p_{\text{astro}} < 0.5$, and cWBs with $p_{\text{astro}} \geq 0.5$ are marked separately.

time around each GW detection time. The flux ULs are plotted as a function of the best-fit declination obtained solely from the corresponding GW skymaps. The results are shown in Fig. 7.10, for different groups of events, separated as BBH-mergers, NSBH mergers, cWBs with $p_{\text{astro}} < 0.5$, and cWBs with $p_{\text{astro}} \geq 0.5$. It is visible in the plot that the most constraining ULs we have are coming from mostly BBH merger-like events, as pointed out in the Table 7.1. Furthermore, it is also visible that in the Northern Hemisphere (NH), the flux ULs are more constraining, due to having slightly better A_{eff} coverage.

Furthermore, we also include previously published ULs for 79 confident GW events from O3, obtained using both the GRECO and GFU datasets [9, 10], and compare the results with the ULs obtained in this work. The results are shown in Fig. 7.11. The comparison shows that the ULs with GRECO for sub-threshold GWs are of a similar order of magnitude to those for confident events, which is something we expect. It also follows the trend of the point-source sensitivity that GRECO has. The sensitivity across the entire sky is flatter compared to that of the high-energy track sample, as GRECO has complementary A_{eff} coverage across the whole sky. For both GRECO and GFU, the flux ULs are more constraining in the NH, compared to those of the Southern Hemisphere (SH). However, the limits obtained with GFU are more constraining, as expected, primarily due to improved angular resolution for high-energy tracks. It allows better suppression of background within a smaller search region. This enhances the signal-to-background separation and leads to better flux ULs.

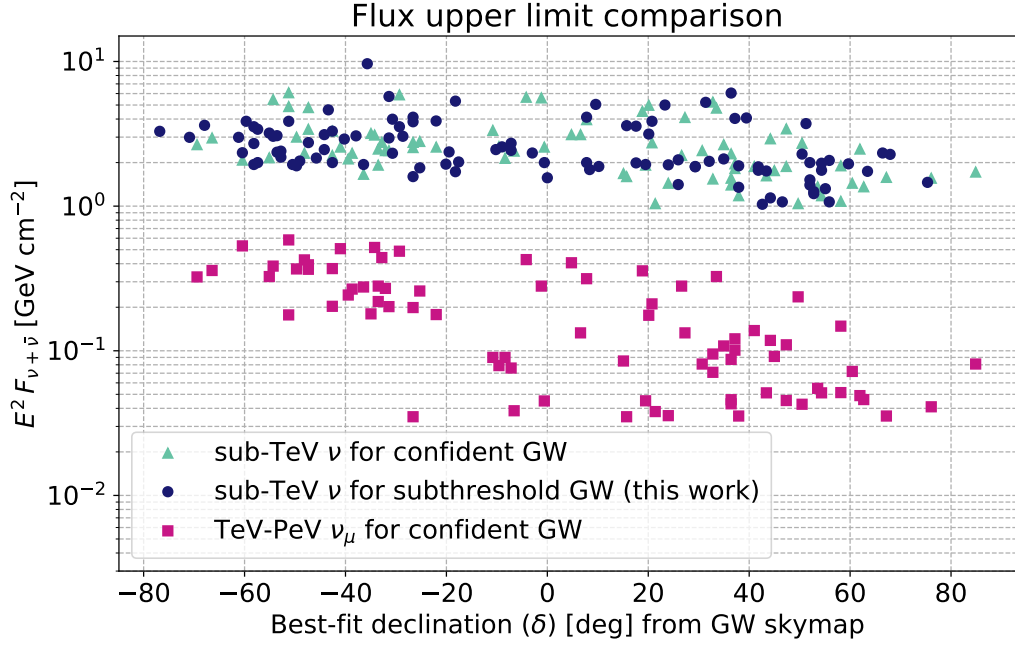


Figure 7.11.: 90% C.L. flux upper limits for neutrino emission associated with the 103 short-listed sub-threshold GW events. The calculation is performed assuming spectral index $\gamma = 2$ and a 1000-second integration time. Results are compared to previously published ULs for the 79 confident GW events from O3, using both sub-TeV all-flavour (GRECO) [10] and TeV-PeV tracks (GFU) data sample [9]. Each flux value is plotted against the best-fit declination from the corresponding GW skymap.

7.3. Summary and Discussion

In this chapter, the results obtained from the archival catalogue search performed following the UML method to identify temporally and spatially coincident sub-TeV neutrinos with 103 selected GW events are presented. Though lower in significance according to the GW detectors, they are still promising source candidates for joint emission of GW + ν , which are not yet well identified. For the sub-TeV neutrinos, GRECO-v002-p10b is used, which includes all-sky, all-flavour events detected with IceCube-DeepCore. The search time window is 1000 s centred around each GW detection time.

No statistically significant neutrino counterpart was identified from any individual GW event. Though a BBH merger-like candidate had $p_{\text{pre}} \sim 0.0004$, after accounting for trial factors, it is 1.76σ . Consequently, neutrino flux ULs were derived for each event. The limits presented here complement those from the high-energy and sub-TeV neutrino follow-ups.

With the increase in sub-threshold GW detection rates during the fourth observation run of LVK, and more similar observations expected with 3G detectors, similar follow-up search campaigns could be performed, providing us the opportunity to probe more possible cases of joint emission. A better localisation of the GW sources will also enhance such a search. With sub-threshold GW alerts now publicly available in real time during O4, this approach opens promising avenues for future real-time multi-messenger campaigns.

Overall, the detection prospects suffer because of the larger angular uncertainty associated with the majority of the sub-TeV neutrinos, as that affects the signal-to-background separation capabilities of individual events. Given that the flux ULs are less constraining, it does not allow us to effectively constrain or exclude source models. With improved reconstruction of the sub-TeV neutrinos with the use of more advanced methods, like using neural networks, the detection prospects could be further improved. There are already some efforts in this direction. In addition to this, the IceCube Upgrade [317] will provide a higher exposure at low energies and is expected to improve the localisation and energy determination capabilities of the detector in the sub-TeV energy range. This is also likely to improve the capabilities of the analysis presented in this chapter.

The analysis framework employed here can be readily extended to other IceCube data samples. An analysis using high-energy tracks is already under development and progressing towards unblinding.

Chapter 8. Future Prospects: Joint GW and Neutrino Detection

“We are Stardust brought to life, then empowered by the Universe to figure itself out. And we have only just begun.”

— Jocelyn Bell Burnell

After more than a decade of searches, common astrophysical sources of neutrinos and Gravitational Waves (GW) have not been observed. All GW detections with high significance by LIGO-Virgo-KAGRA (LVK) [8, 9, 12, 343], as well as interesting shortlisted sub-threshold GW [122], which are publicly available, have been investigated using various data samples covering a vast energy range, without yielding any statistically significant coincidence (see Ch. 7). To date, only neutrino flux upper limits (UL) have been obtained, since the current neutrino experiments are individually not sensitive enough to any neutrino flux coming from individual GW sources. Naturally, this raises the question of how fruitful future multi-messenger campaigns involving GW and neutrinos would be in the era of next-generation GW and neutrino detectors.

To this end, this chapter quantifies the prospects for detecting joint GW and neutrino emission from astrophysical sources, under certain benchmark model fluxes. It begins with a discussion of GW and neutrino detectors that could be available in the foreseeable future, with particular attention to their sensitivities and complementarities. For neutrino detectors, a dedicated background estimation is performed, providing the basis for evaluating the significance of neutrino detections. Both individual GW events and a population of GW sources are considered under specific neutrino emission models before moving on to assess if upcoming observatories can enhance the chances of a confirmed joint detection. Part of the discussion was briefly highlighted in [151].

8.1. Future GW and Neutrino Detectors

It has already been mentioned in Sec. 3.2 that by mid-2030s, third-generation (3G) GW detectors, like the Einstein Telescope (ET), should be operational, and would have much better sensitivity compared to LVK. In the neutrino front as well, we expect to have the IceCube-Upgrade [317] and IceCube-Gen2 [327] in the Southern Hemisphere (SH), improving our sensitivity in both low- and high-energy regimes respectively, as discussed in Ch. 4. A fully operational KM3NeT [345, 346] and Baikal-GVD [347] will be active in the Northern Hemisphere (NH). A group of other ambitious projects for TeV-PeV neutrino telescopes are also under discussion. P-ONE[348], currently at a prototypal stage, aims at the realisation of a 1 km³ array

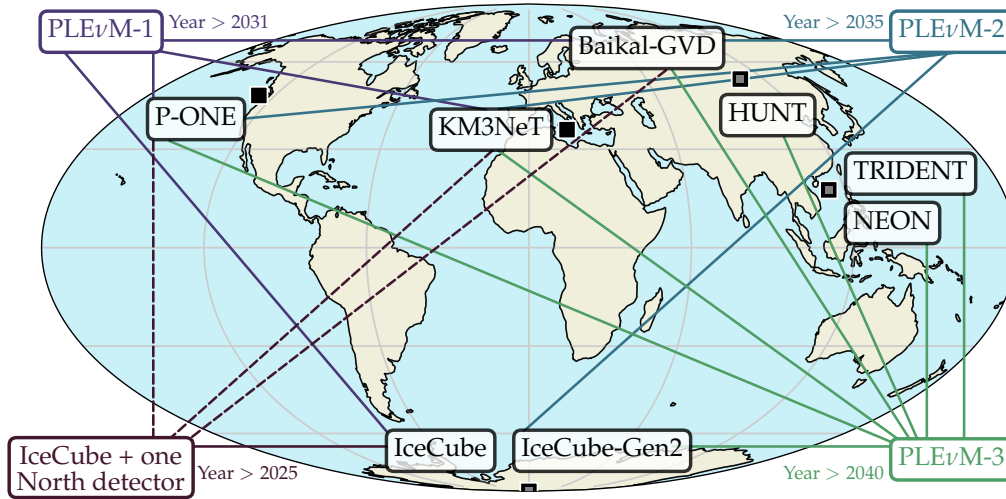


Figure 8.1.: High-energy neutrino detectors around the globe. Among them, IceCube is fully operational. Some are active but under construction (for example, KM3NeT and Baikal-GVD). Others are in the preparatory phase. They all contribute to different configurations of PLEνM, a global network of high-energy neutrino detectors. IceCube, along with other IceCube-sized detectors located in the sites of KM3NeT, Baikal-GVD, and P-ONE, is referred to as PLEνM-1. When IceCube is replaced by IceCube-Gen2, the global network is defined as PLEνM-2. These two configurations are the most relevant for this work. Additionally, combining the TRIDENT, NEON, and HUNT leads towards PLEνM-3. Figure obtained from [344].

of multi-PMT optical modules off Canada in the Pacific Ocean. The Chinese project TRIDENT [349] is studying the feasibility of a neutrino telescope in the South China Sea, aiming at an instrumented volume of 8 km^3 . In China, other ambitious projects are also under discussion, such as NEON [350] and HUNT [351]. Locations of these individual detectors are pointed out in Fig. 8.1.

In addition to the optical Cherenkov detectors discussed above, several radio-detection experiments, such as ARA [352], ARIANNA [353], RNO-G [354], and IceCube-Gen2 Radio [328], are targeting the detection of cosmogenic neutrinos at EeV energies. Complementary searches are also being pursued with extensive air-shower detectors, such as the Pierre Auger observatory [355, 356] and GRAND [357], which exploit Earth-skimming tau neutrinos (up-going) and neutrinos from inclined air showers (down-going). These experiments provide an essential eye in the highest-energy neutrino regime, though they are beyond the scope of the present work, which focuses on the TeV–PeV energy range accessible to optical Cherenkov detectors.

However, the discovery potential of any individual detector for high-energy neutrinos from GW sources, or any short-lived transient sources, so to speak, will suffer due to limited fluence during the flare-up period. Moreover, for a significant energy range (GeV–TeV) where the high-energy neutrino detectors have good sensitivity, they struggle because of a dominating atmospheric neutrino background, as explained in Sec. 4.2.2. Even though IceCube sees the whole sky in neutrinos all the time, its position at the South Pole and limited detection volume also act as additional constraints.

8.1.1. PLEvM and Combined Effective Area

A significant increase in the all-sky neutrino detection rate would immensely boost the sensitivity by a few factors compared to that achievable with a single-detector configuration. To enhance the full sky neutrino rate, multiple IceCube-like neutrino detectors, of similar or larger volume, are needed across the globe. When they are operating together, the combined effective area (A_{eff}) is expected to improve all over the sky. This combined configuration of a global neutrino telescope network is called ‘PLEvM-1’ [344], which represents the combined A_{eff} of IceCube, KM3NeT, Baikal-GVD and P-ONE, as shown in Fig. 8.1. An upgraded configuration, ‘PLEvM-2’, is also available in which IceCube’s A_{eff} is replaced by that of Gen-2, allowing us to examine how such an extension would influence the joint-detection landscape [344].

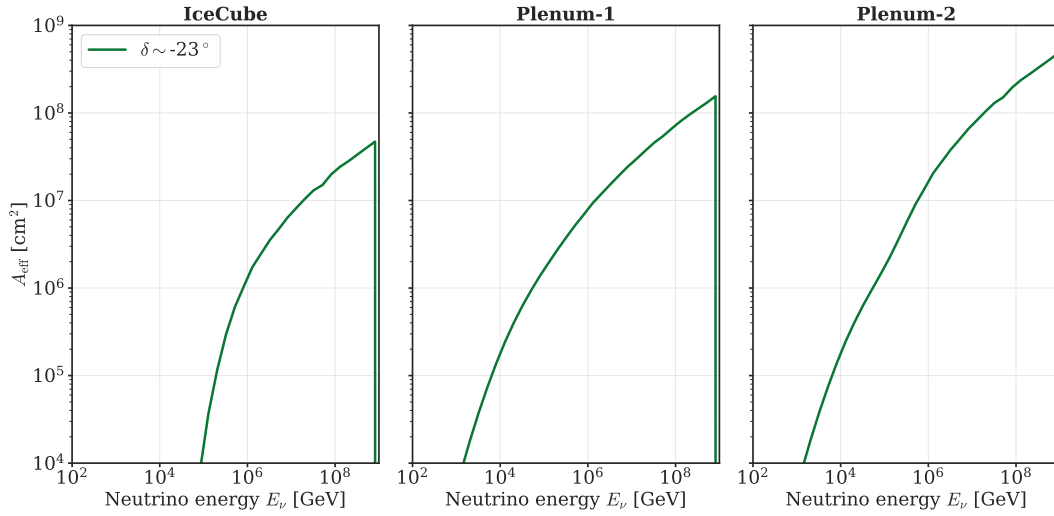


Figure 8.2.: Effective area for TeV-PeV neutrinos in IceCube, PLEvM-1 and PLEvM-2 detectors, for declination = -23° , addressing a source located in reference position of GW170817. One can see how, with the global network of neutrino detectors, the effective area increases by orders of magnitude. Obtained using the PLEvM code [358].

To demonstrate this, consider a GW170817-like source located at right ascension (r.a.) and declination (δ) $\sim [197^\circ, -23^\circ]$ [3]. Fig. 8.2 shows how the A_{eff} coverage is improved by orders of magnitude in that region of sky by considering the joint A_{eff} with PLEvM-1 and PLEvM-2, compared to single high-energy neutrino detectors. These configurations have already been considered to investigate the improvement in sensitivity to steady emitters of high-energy neutrinos [359]. As a part of this thesis, they are used to evaluate the sensitivity for transient sources, like compact binary coalescences (CBC).

8.2. Background Estimation

Before evaluating the prospects of GW follow-up searches, accurately quantifying the atmospheric neutrino background across the relevant energy range is crucial. Below ~ 10 TeV, this

atmospheric background can overwhelm the signal neutrinos coming from astrophysical sources of our interest [278, 360]. Quantifying the background neutrino contribution across different detectors, declinations, and energy ranges allows a more accurate assessment of signal detection significance.

8.2.1. Atmospheric Neutrino Flux

In the energy range of $10^2 - 10^7$ GeV, the dominant background for neutrinos coming from a particular astrophysical source is the atmospheric muons and neutrinos. However, specifically for up-going tracks, the atmospheric muons are not dominant as the Earth acts as a filter. So, only the atmospheric neutrinos can pass through and mimic signal-like events in any neutrino detector, as discussed in Ch. 4.

Atmospheric neutrino flux from MCEq

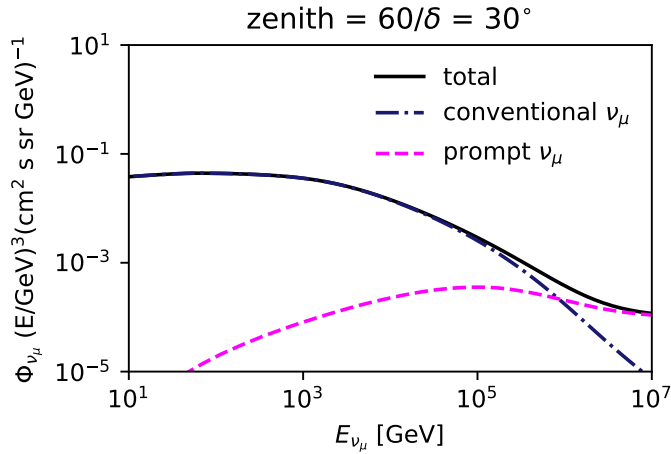


Figure 8.3.: The flux of $\nu_\mu + \bar{\nu}_\mu$ at the surface obtained as a solution of MCEq. An example result is shown here for zenith (θ) = 60° , $\delta = 30^\circ$. The magenta dashed line represents the contribution of the prompt $\nu_\mu + \bar{\nu}_\mu$ flux, and the blue dashed-dotted line shows the conventional flux contribution. Details on them were discussed in Sec. 4.2.2.

the column depth or interaction probability in atmosphere [17, 360].

To quantify the fluxes, the first step involves simulating the atmospheric neutrino flux, ϕ_v^{atm} , across the relevant energy range for various zenith angles (θ). This is achieved by solving the Matrix Cascade Equations (MCEq)¹ [361]. It is a numerical tool used to simulate the evolution of particle cascades as they propagate through the Earth's atmosphere. MCEq models the particle flux at the surface in discrete energy bins, providing differential spectra and total fluxes

The conventional atmospheric neutrino flux is strongly angle-dependent because the probability of meson decay versus interaction in the atmosphere varies with zenith angle. For near-vertical directions, mesons traverse a shorter path through the atmosphere before reaching the denser lower atmosphere. Thus, the likelihood of interaction is higher compared to decay, and that suppresses neutrino production. For near-horizontal directions, mesons travel a much longer path in the thinner upper atmosphere, enhancing the chance of decay into neutrinos. In contrast, prompt particles decay almost immediately, so their contribution is essentially not affected by the

¹GitHub repository: <https://github.com/mceq-project/MCEq>

using various models for particle interactions and atmospheric density profiles. For this work, the SIBYLL 2.3c hadronic interaction model [362] is used, in combination with the H3a cosmic ray (CR) flux model [363], which divides the CR energy spectrum into three source populations. Among them, the first one is around the knee region, typically attributed to Galactic supernova remnants (cut-off energy = 4 PeV). The second population is located at the knee region, originating from a different class of Galactic accelerators that extends the Galactic contribution to higher rigidity, filling the gap between the knee and ankle (cut-off energy = 30 PeV). The final population component is dominant above the ankle, and is a mix of the highest energy Galactic contribution and extragalactic components (cut-off energy = 2 EeV) [364].

The zenith angle (θ) values range from 90° to 180° , which corresponds to upward-going neutrinos (i.e., originating from the Northern Hemisphere from IceCube's perspective). The relationship between zenith angle (θ) and declination (δ) for a detector located at the South Pole is:

$$\theta = 90^\circ - \delta \quad (8.1)$$

Due to the spherical symmetry of the Earth and the atmosphere, this implies the following mapping between the Northern and Southern Hemispheres:

$$\theta_{\text{NH}} = 180^\circ - \theta_{\text{SH}} \quad (8.2)$$

In Fig. 8.3, an example case for $\theta = 60^\circ$, $\delta = 30^\circ$ is shown. The muon and anti-muon neutrino ($\nu_\mu + \bar{\nu}_\mu$) flux is plotted for the energy range of $10 - 10^7$ GeV. The detailed calculation for mapping between the zenith angles and declinations can be found in Appendix C. The total flux consists of the conventional and prompt particle fluxes, where the prompt is a dominant contribution for $E_\nu > 10^6$ GeV. For the background calculation, only $\nu_\mu + \bar{\nu}_\mu$ is considered, as the signal case is high-energy up-going tracks for this analysis.

8.2.2. Diffuse Astrophysical Background Neutrino flux

The next essential component for the background estimation is the diffuse astrophysical neutrino background, arising from numerous unresolved Galactic and extragalactic sources.

This background flux is typically modelled as:

$$\phi_{\text{astro}}^{\text{bkg}} = \phi_{\text{per-flavour}}^{\text{astro}} \left(\frac{E}{100 \text{ TeV}} \right)^{-\gamma_{\text{astro}}} \quad (8.3)$$

According to the published IceCube results [229], the astrophysical diffuse muon neutrino flux could be expressed as a single power law flux (SPL) with a best-fit spectral index of $\gamma_{\text{astro}} = 2.58^{+0.10}_{-0.09}$. The corresponding per-flavour normalisation at 100 TeV is given by

$$\phi_{\text{per-flavour}}^{\text{astro}} \stackrel{100 \text{ TeV}}{=} 1.68^{+0.19}_{-0.22} \text{ GeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \quad (8.4)$$

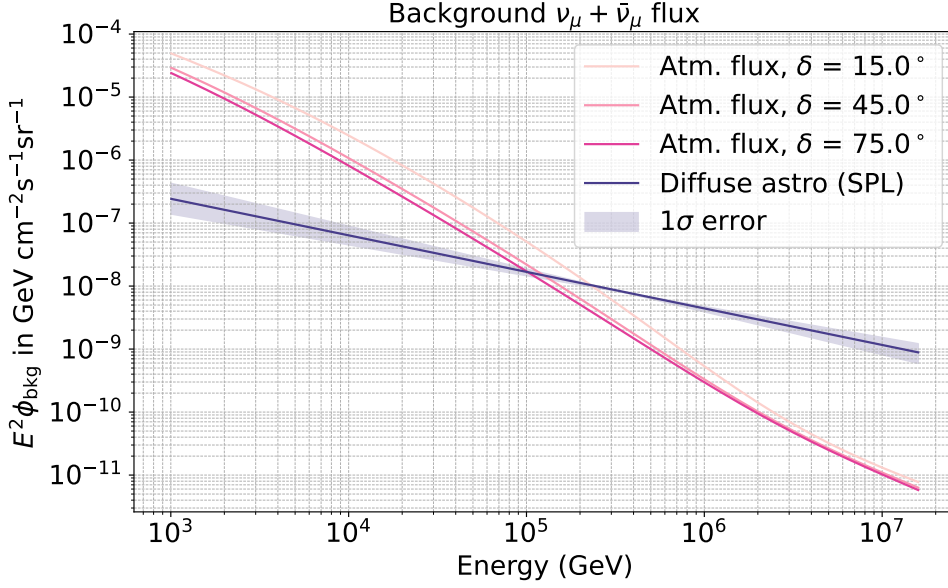


Figure 8.4.: The energy dependence of the atmospheric and diffuse astrophysical muon neutrino background is shown here. The atmospheric contribution for three distinct declinations in the Northern hemisphere is considered. The diffuse astrophysical flux falls off as a single power law of energy but has no zenith dependence. Beyond 5×10^5 GeV, it is the most dominant contribution as background neutrino flux.

More recently, analyses based on an all-sky sample of medium-energy starting events (tracks and cascades) have indicated a deviation from the SPL description, favouring a broken power-law parametrisation of the diffuse spectrum [230, 231] with 4.7σ significance. While this development is noteworthy, in the present work we restrict ourselves to the upgoing tracks and therefore stick to the earlier SPL estimate, as shown in Eq. 8.4.

The diffuse astrophysical background is independent of the zenith angle, unlike the atmospheric contribution, because astrophysical neutrinos arrive uniformly from all directions, without a horizon limiting their sources [228]. But the flux falls off with energy following the aforementioned power law, in Eq. 8.4. The overall variation of atmospheric and astrophysical background muon neutrino flux with energy is shown in Fig. 8.4.

8.2.3. Total Background Neutrino Flux

The total background of muon neutrinos ($N_{\nu_\mu + \bar{\nu}_\mu}^{\text{bkg}}$) in each energy bin is calculated by adding up the individual contributions from atmospheric and astrophysical diffuse muon neutrino flux. Hence, for each energy bin,

$$\phi_{\text{tot}}^{\text{bkg}} = \phi_{\text{astro}}^{\text{bkg}} + \phi_{\text{atm}}^{\text{bkg}} \quad (8.5)$$

The flux as shown in Eq. 8.5, multiplied by the declination-dependent A_{eff} of the detector (obtained using PLEvM code² [358]), gives the number of neutrinos in each energy bin. The evaluation of the background contribution, $N_{\nu_\mu + \bar{\nu}_\mu}^{\text{bkg}}$, finally utilises the chosen time window (Δt)

²GitHub repository: <https://github.com/PleNuM-group/Plenum>

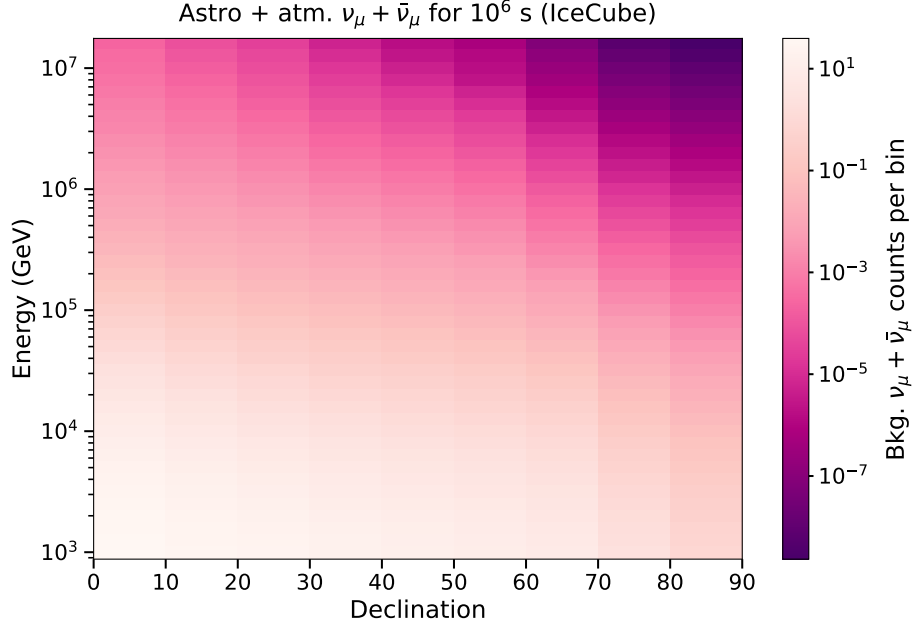


Figure 8.5.: The background neutrino count per energy bin considering both atmospheric and astrophysical background $\nu_\mu + \bar{\nu}_\mu$, for the IceCube detector, for 10^6 s.

within each declination bin ($\delta_1 \leq \delta \leq \delta_2$). Eq. 8.6 shows the final expression. For detailed calculation, check Eq. C.2.

$$N_{\nu_\mu + \bar{\nu}_\mu}^{\text{bkg}} = \Delta t \, 2\pi \sin(\delta_2 - \delta_1) \int_{E_{\min}}^{E_{\max}} dE \, \phi_{\text{tot}}^{\text{bkg}}(\theta, E) A_{\text{eff}}(\delta, E) \quad (8.6)$$

The estimated count for $N_{\nu_\mu + \bar{\nu}_\mu}^{\text{bkg}}$ per energy bin for 10^6 s is shown in Fig. 8.5, considering IceCube A_{eff} for upward-going, P8Track-10 year event selection [232] (see details in Sec. 4.2.2). The background counts for different values of Δt could be obtained further (see Appendix C), and must be compared to the signal models of our interest. For declination values, we stick to the Northern Hemisphere, and evaluate the background counts for 10° declination bins between $\delta = 0-90^\circ$. We only consider the A_{eff} for $E_{\min} \geq 1$ TeV, as below that the A_{eff} of the high-energy neutrino detector is not ideally optimised. $E_{\max}$ is set to 10^7 GeV, which is chosen according to the energy range obtained from MCEq solutions, shown in Fig. 8.3, beyond which we have a negligible background estimate for atmospheric neutrinos. Similar studies are performed for other IceCube-Gen2, PLEvM-1, and PLEvM-2, for which results are shown in Appendix C.

8.3. Prospects for Catalogue Search with Binary Black Hole Mergers

After quantifying the background, the neutrino signal from a BBH merger-like source for catalogue searches is estimated, considering diverse detector configurations. For the high-energy neutrino detectors, individual detectors like IceCube and IceCube-Gen2 are included, account-

ing for their optimal configuration, along with PLEvM-1 and PLEvM-2. For GW observations, we consider the detection horizon of current LVK detectors as well as the future ET³.

Among the CBC sources, BNS mergers are well-established as prime multi-messenger sources, especially after the landmark GW170817 event [3], which had clear electromagnetic (EM) counterparts. In contrast, BBH mergers are typically not expected to produce EM or neutrino counterparts as isolated objects. But, if some BBH systems are embedded in AGN disks, it offers an exciting scenario [114–117]. These disks are considered ‘promising factories’ to form compact object binaries, as there is a high density of stars and compact objects, which increases encounter probability and facilitates binary formation through dynamical interactions. After the occurrence of the BBH merger in the matter-dense environment of the AGN disk, a recent work has shown that the remnant BH can accrete matter and launch powerful jets [365], which can collide with disk materials. The interaction between the jet and the AGN disk accelerates protons to high energies, which can interact with the ambient photon fields and hadronically produce photons and neutrinos, as shown in Eq. 2.7. The potential of a BBH merger being a multi-messenger source in such a scenario is already discussed in Sec 2.6.

This particular scenario got even more interesting when an optical flare transient ZTF19abanrhr associated with AGN J124942.3+344929 was found as a plausible EM counterpart to a BBH merger event, GW190521 [184], detected by LVK during O3a [366] (also see Sec. 3.5). Although no neutrino counterpart was detected, IceCube has published flux upper limits [9, 10]. Several models [367, 368] predict that in future, such sources will be more common, especially with the 3G detectors. Thus, the prospect of identifying joint emission of GW and neutrinos based on benchmark models from such sources is evaluated, considering neutrino detectors that will be active during future observation runs of LVK and ET, for example.

8.3.1. High-energy Neutrino Fluence from BBH mergers

For signal estimation, neutrino emission models of an individual BBH merger embedded in an AGN disk need to be considered. The muon neutrino (ν_μ) fluence⁴ is reported in [116, 117], till 10^9 GeV. The corresponding flux ($\phi_{\nu_\mu}^{\text{BBH}}(E_\nu)$) is estimated for different source scenarios, which are discussed below.

- In [116], the authors consider a BBH system $10^3 R_g$ away from the AGN core. The unit R_g is the Schwarzschild radius, and is defined as,

$$R_g = \frac{GM_{\text{SMBH}}}{c^2} \quad (8.7)$$

M_{SMBH} is the mass of a supermassive BH at the AGN core. Distance of the BBH system from the BH, r_d , is set to $10^3 R_g$. The BBH merger has a total mass of $100 M_\odot$. They

³Cosmic Explorer (CE) or ET+CE configurations are not considered here, as this work is a simple proof of concept.

⁴By definition, fluence is the time-integrated flux. For a time window $[t_0, t_1]$, fluence = $\int_{t_0}^{t_1} \phi(E_\nu, t) dt$, where $\phi(E_\nu, t)$ is the differential flux with a unit of $\text{GeV}^{-1} \text{cm}^{-2} \text{s}^{-1}$.

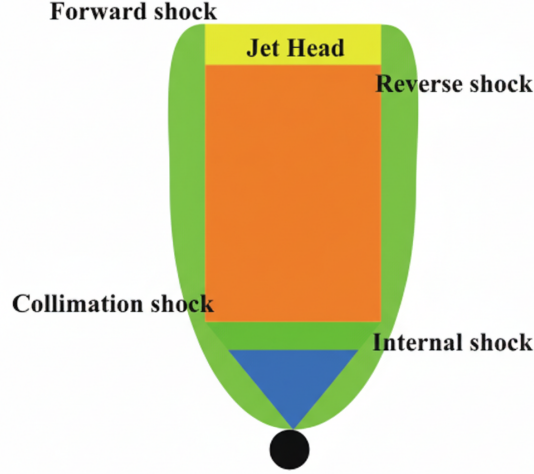


Figure 8.6.: Schematic diagram of an idealised jet, with four types of shocks. The shocks are located at the junction of each shock site. Figure reproduced from [116].

investigate neutrino emission from different shock sites, marked as the reverse shock (RS), collimation shock (CS), and internal shock (IS), which form during the created jet's interaction with the disk atmosphere [115]. A schematic diagram is shown in Fig. 8.6. For each of the shock sites, the accretion rate $\dot{m} = f_{\text{acc}}\dot{m}_{\text{BHL}}$ varies. Here, f_{acc} is the rate parameter and $\dot{m}_{\text{BHL}}$ is the accretion rate.

- On the other hand, in [117], neutrino fluence is estimated considering Forward Shock (FS) formation as the jet propagates within the disk atmosphere. In this case, f_{acc} is fixed to 15, but $\phi_{\nu_\mu}^{\text{BBH}}(E_\nu)$ varies for different r_d values. The source distance from the Earth is fixed at 5300 Mpc. The fluence values are provided based on different jet durations, depending on varying r_d values. While calculating the fluence, the authors here also assume a constant neutrino emission for the entire jet duration.

For both models, the fluence is reported assuming an SMBH at the AGN core with a mass of $10^8 M_\odot$. Neutrino bursts are expected to occur post-merger, after the GW emission, when a jet erupts from the remnant BH. In both studied scenarios, the resultant jet is pointing directly towards Earth, with an initial jet opening angle $\theta_j \sim 0.2$. It is, overall, a fairly idealised situation, which would enhance the neutrino fluence detectable on Earth [15]. For both models, pp interaction dominates neutrino production in the lower energies, while $p\gamma$ interaction contributes to producing neutrinos with energies above ~ 10 TeV [116, 117]. Additionally, a characteristic increase in the fluence is observed around $\sim$ PeV energies, as in lower energies, the neutrino fluence is suppressed due to Bethe-Heitler production.

The important source parameters for both of the models are tabulated in Tab. 8.1. The resultant fluence plots are shown in Fig. 8.7.

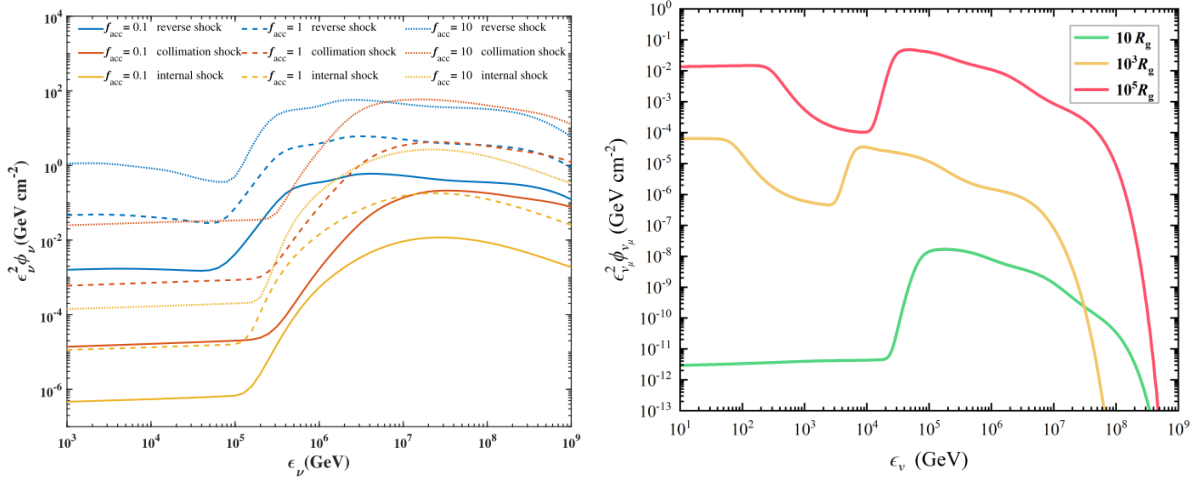


Figure 8.7.: The neutrino fluence obtained for BBH mergers in AGN disks, as presented in [116, 117]. (Left) The fluence is calculated for 5×10^6 s and the BBH merger is occurring at a distance from the AGN core fixed to $10^3 R_g$, where R_g is the Schwarzschild radius of the central SMBH. The source is ~ 100 Mpc away from the Earth [116]. Different fluence values are calculated for different shock acceleration scenarios and different accretion rates of the remnant black hole. (Right) The fluence is calculated for a BBH merger, which is ~ 5300 Mpc away from the Earth. The accretion rate of the remnant black hole is $f_{\text{acc}} = 15$. The different fluence values are estimated based on the jet duration, which depends on the distance of the BBH merger from the AGN core [117]. Figures obtained from the original articles.

Table 8.1.: Source parameters influencing the high-energy neutrino fluence from BBH mergers occurring in AGN disks. For each case [116, 117], the total mass of the BBH merger (M_{BBH}), its distance from Earth (d_L), as well as from the AGN core (r_d), accretion parameter of the remnant Black Hole (f_{acc}), and the jet duration for which fluence is calculated (t_j) with their corresponding units, are specified.

Ref.	M_{BBH} ($M_{\odot}$)	d_L (Mpc)	r_d (R_g)	f_{acc}	t_j (s)	E_{ν} (GeV)
[116]	100	100	10^3	0.1	5×10^6	$10^3 - 10^9$
				1		
				10		
[117]	150	5300	10	15	7×10^4	$1 - 10^9$
			10^3		10^4	
			10^5		8×10^5	

8.3.2. Simulating Signal Neutrinos from BBH Merger in AGN Disk

Considering the fluence given in [116, 117], the number of signal neutrinos, ($N_{\nu_\mu + \bar{\nu}_\mu}^{\text{BBH}}$) coming from an individual source candidate can be calculated in the following way:

$$N_{\nu_\mu + \bar{\nu}_\mu}^{\text{BBH}} = 2 \times \Delta t \int_{E_{\min}}^{E_{\max}} dE \phi_{\nu_\mu}^{\text{BBH}}(E_\nu) A_{\text{eff}}(\delta, E_\nu) \quad (8.8)$$

The factor of 2 is multiplied to account for both neutrinos and anti-neutrinos. $A_{\text{eff}}(\delta, E_\nu)$ is obtained for different detector configurations using the PLEvM code⁵. Δt is chosen based on the jet-duration (t_j) assigned to each scenario (see Tab. 8.1). The background estimation for each case also has a similar implementation (see associated plots in Appendix C). $E_{\min}$ is set as 1 TeV, for all detectors, in accordance with the background calculation performed in Sec. 8.2. Similarly, $E_{\max}$ is set to 10^7 GeV, as the background estimation is simulated only till this energy range.

Following the above prescription, the signal rate obtained for a BBH merger occurring at 100 Mpc is shown in Fig. 8.8, considering the most optimistic scenario with $f_{\text{acc}} = 10$. The corresponding flux, $\phi_{\nu_\mu}^{\text{BBH}}(E_\nu)$ for different shock sites is reproduced from the fluence provided in [116] (for $\Delta t = 5 \times 10^6$ s), which is shown in the left panel of Fig. 8.7. As expected, the signal rate is much higher for detector configurations such as Gen-2 and PLEvM-2, which provide the most extensive A_{eff} coverage in TeV - PeV energy range. The estimated signal rate is quite high for reverse and collimated shocks, as they facilitate more efficient CR proton acceleration, compared to internal shock [116].

However, it represents an unrealistic scenario. A source distance of 100 Mpc is too close for the distance assumption, where a GW detector like LVK is capable of detecting a BBH merger in an AGN disk. To this end, the results can be further optimised for a BBH merger located further away from the Earth. For standardisation, we need to estimate the nearest distance at which at least one BBH merger can occur in an AGN disk during the operation time of a GW detector. Given the current measured BBH merger rate per comoving volume, $R(d_L)$ at different luminosity distances can be parametrised as follows:

$$R(z) = R_0(1+z)^\kappa \quad (8.9)$$

Here, R_0 is the local merger rate at redshift $z = 0$. The estimated value from LVK O3 for R_0 is given as $18.4_{-8.3}^{+12.6} \text{Gpc}^{-3} \text{yr}^{-1}$. The best fit value for the evolution parameter, $\kappa = 2.9_{-1.8}^{+1.7}$ for $z \lesssim 1$ ($d_L \sim 6800$ Mpc) [167]. Thus, the number of expected BBH mergers occurring in AGN disks $n(d_L)$ is given below.

⁵GitHub repository: <https://github.com/PlenuM-group/Plenum>

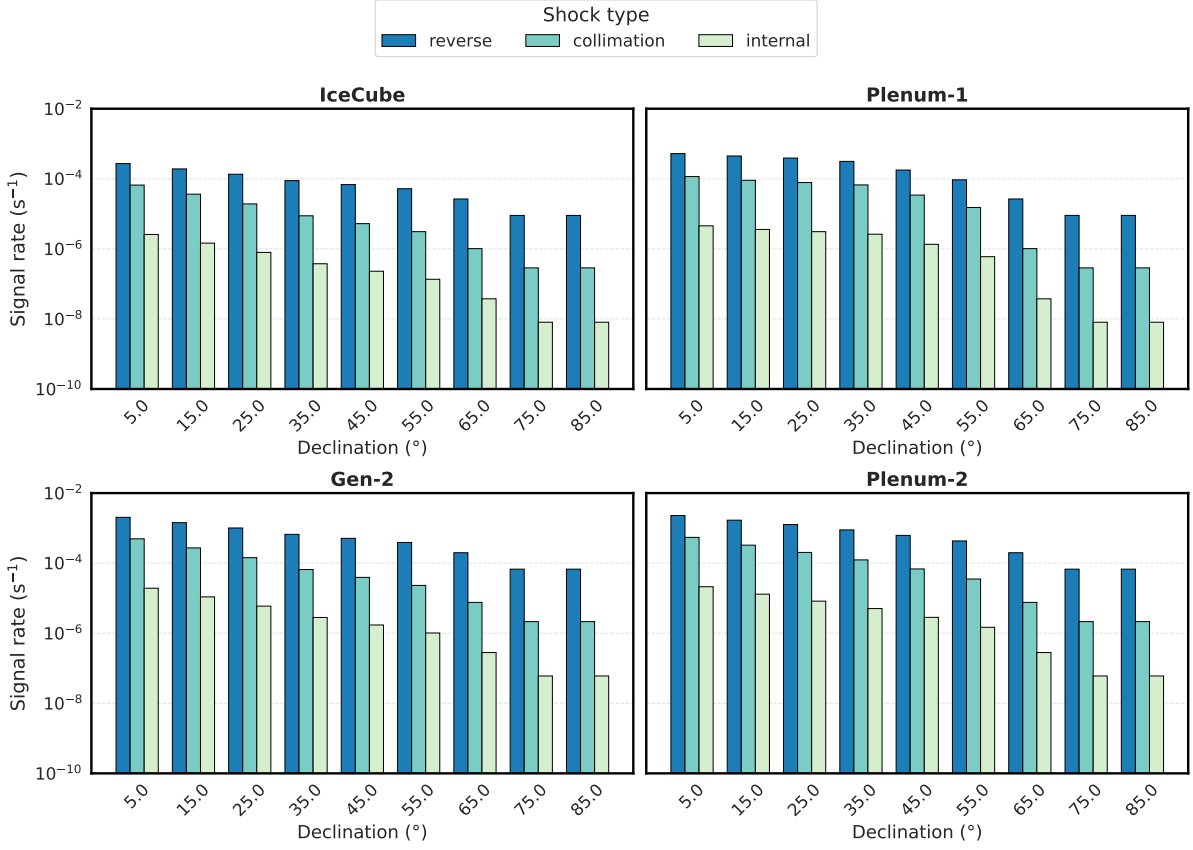


Figure 8.8.: The rate of signal events detected by IceCube, PLEvM-1, Gen-2, and PLEvM-2, for a source located at 100 Mpc away from the Earth. The fluence values correspond to $f_{\text{acc}} = 10$, $\Delta t = 5 \times 10^6$ s, and three different shock sites: internal (IS), collimated (CS), and reverse shocks (RS). Fluence obtained from [116]. The total number of signal events could be calculated by scaling the rate according to the desired time window (Δt).

$$\begin{aligned}
 n(d_L) &= R(d_L) \times V(d_L) \times T_{\text{obs}} \times P_{\text{AGN}} \\
 &\approx R(d_L) \times \frac{4}{3} \pi d_L^3 \times T_{\text{obs}} \times P_{\text{AGN}}
 \end{aligned} \tag{8.10}$$

The current best estimate for the probability of a BBH merger occurring at an AGN disk, $P_{\text{AGN}} \sim 0.2$ [369]. In $T_{\text{obs}} = 1$ year, to have $n(d_L) = 1$, $d_L \sim 400$ Mpc⁶. Similarly, for LVK, which is active for $T_{\text{obs}} = 10$ years, the chances of observing a BBH merger in AGN disk increase given the longer operation time. Thus, the nearest one could be detected around $d_L \sim 186$ Mpc. Modifying the fluence accordingly, as shown in Eq. 8.11, would allow us to predict $N_{\nu_\mu + \bar{\nu}_\mu}^{\text{BBH}}$.

$$\phi_{\nu_\mu}^{\text{BBH}} \propto \frac{1}{d_L^2} \tag{8.11}$$

⁶However, the chances of observing a BBH merger in AGN disk increase given the longer operation time.

Following Eq. 8.11, $\phi_{\nu\mu}^{\text{BBH}}$ is calculated for a single BBH-merger located at $d_L = 400$ Mpc. Using it, the signal rate estimates are shown in Fig. 8.9. Clearly, the signal rate has decreased significantly from what was obtained in Fig. 8.8.

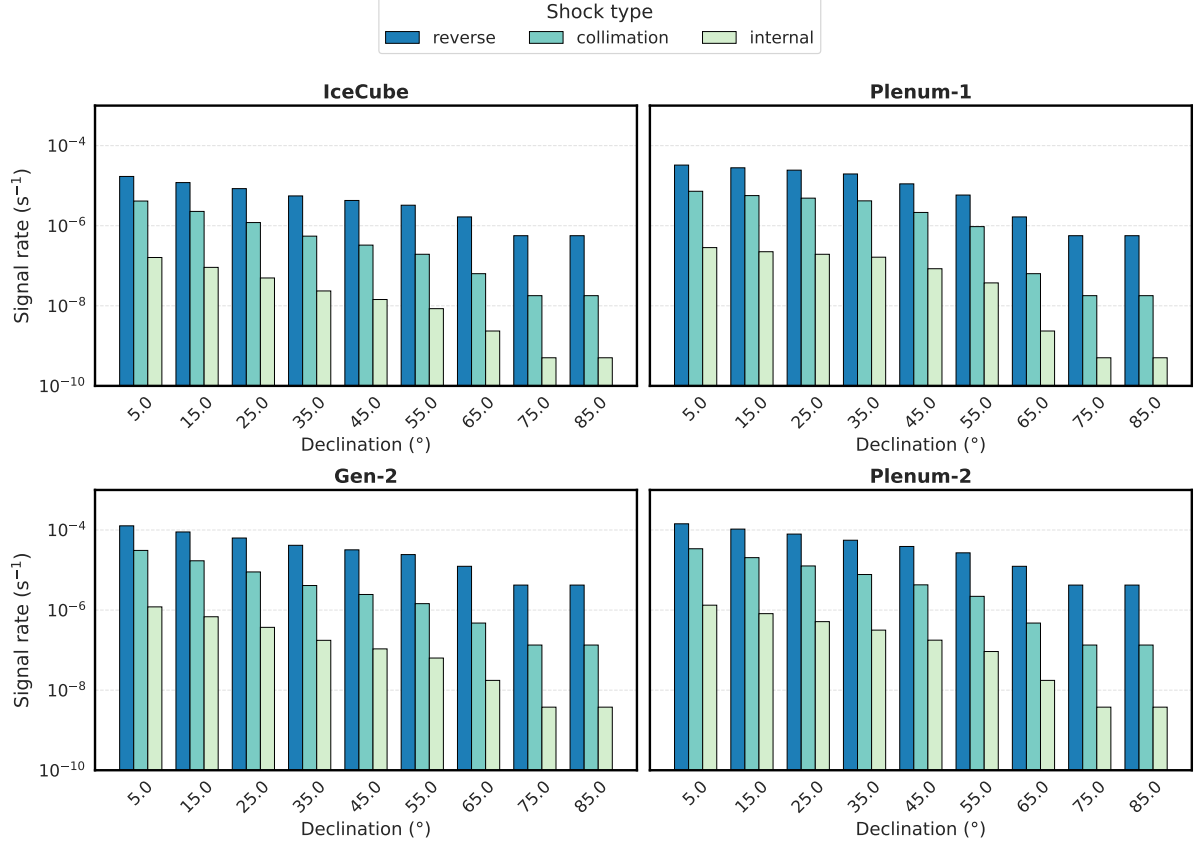


Figure 8.9.: The rate of signal events detected by IceCube, PLEvM-1, Gen-2, and PLEvM-2, for a source located at 400 Mpc away from the Earth. The fluence values correspond to $f_{\text{acc}} = 10$, $\Delta t = 5 \times 10^6$ s, and three different shock sites: internal (IS), collimated (CS), and reverse shocks (RS). Fluence obtained from [116]. The total number of signal events could be calculated further by scaling the rate according to the desired time window (Δt).

The result can be further optimised by accounting for the time variation of neutrino emission from the individual sources. In this work, a constant emission is assumed for 5×10^6 s, which roughly accounts for two months. However, it is not a realistic scenario. Although a higher emission is expected after the collimation of the jet, which happens 100 s after the jet launch [116], it should subsequently decline rather than remain steady. As the jet expands, both the photon density and baryon density decrease, which will incorporate time variation in high-energy neutrino emission. But a time profile quantifying that for similar sources is unavailable, so it was not possible to deviate from this rate estimate.

A more realistic case is represented by [117], where $\phi_{\nu\mu}^{\text{BBH}}(E_\nu)$ is calculated for a source located at 5300 Mpc, comparable to the distance where ZTF19abnrhr was observed [117, 184]. The signal rate obtained for this scenario using Eq. 8.8 is shown in Fig. 8.10. The signal rate here also benefits from the higher A_{eff} coverage for Gen-2 and PLEvM-2 in the considered energy

range, what was also seen in Fig. 8.9. For different values of r_d , the rate varies, and $r_d = 10^5 R_g$ offers the most optimistic scenario as it is located furthest away from the AGN core. So, it benefits from the maximum density of the lower-energy photons, which can interact more efficiently with the high-energy protons to produce a higher fluence of high-energy neutrinos.

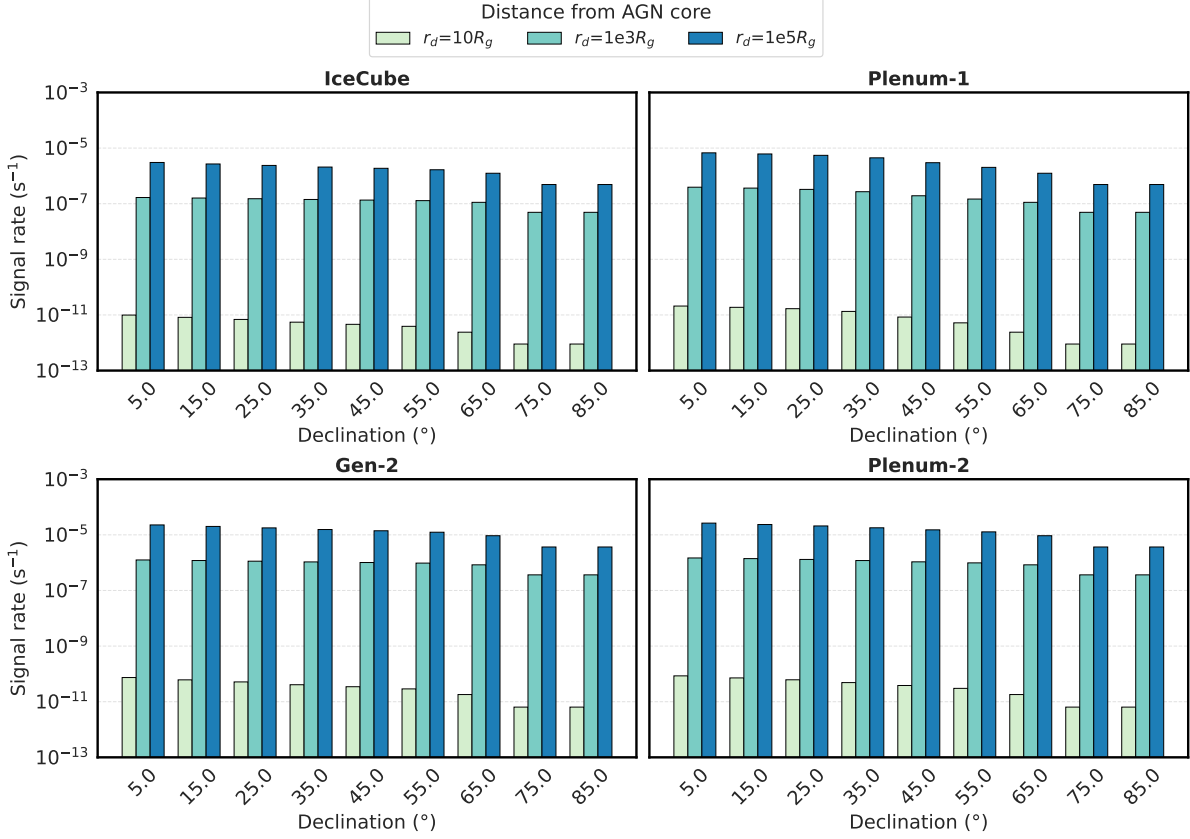


Figure 8.10.: The rate of signal event detection for a source located at 5300 Mpc, for different r_d values from the AGN core. Fluence obtained from [117], only accounting for forward shock (FS) acceleration. $f_{\text{acc}} = 15$ for all given r_d values. Fluence is calculated for the corresponding jet duration shown in Tab. 8.1. The total number of signal events could be calculated by scaling the rate according to the desired time window (Δt).

Significance Calculation

As Fig. 8.10 presents a more realistic scenario, the significance of the observed neutrino detection is calculated considering the $N_{\nu_\mu + \bar{\nu}_\mu}^{\text{BBH}}$ counts for different Δt values, as tabulated in Tab. 8.1 for various r_d values, and comparing them with the corresponding background estimates. The relevant background estimations are included in Appendix C. The detailed derivation for significant calculation is also included in Appendix. D. Following Eq. D.9, the significance of the

detection (σ_{det}) of a joint-emission of neutrino and GW from their common astrophysical source is defined as,

$$\begin{aligned}\sigma_{\text{det}} &= \frac{N_{\nu_{\mu}+\bar{\nu}_{\mu}}^{\text{BBH}}}{\sqrt{N_{\nu_{\mu}+\bar{\nu}_{\mu}}^{\text{BBH}} + N_{\nu_{\mu}+\bar{\nu}_{\mu}}^{\text{bkg}}}} \\ &= \frac{R_{\text{sig}} \times \sqrt{\Delta t}}{\sqrt{R_{\text{sig}} + R_{\text{bkg}}}}\end{aligned}\quad (8.12)$$

Here, $N_{\nu_{\mu}+\bar{\nu}_{\mu}}^{\text{BBH}}$ and $N_{\nu_{\mu}+\bar{\nu}_{\mu}}^{\text{bkg}}$ are respectively the number of signal and background neutrinos detected within a considered time window (Δt). R_{sig} and R_{bkg} are the corresponding signal and background event rates.

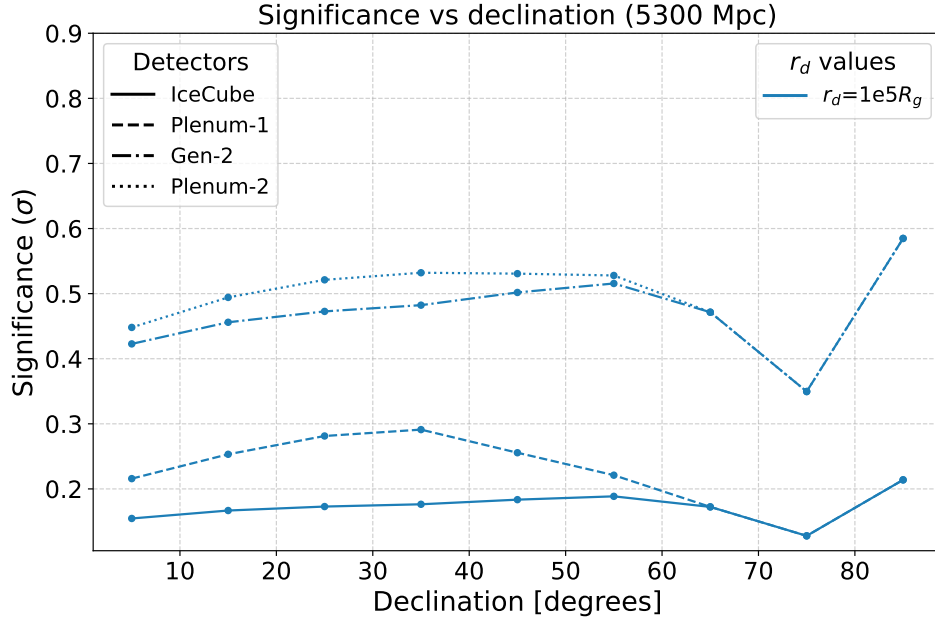


Figure 8.11.: The detection significance quantified for a source located at 5300 Mpc, referring to the scenario presented in Fig. 8.10, specifically $10^5 R_g$ away from the AGN core, and $\Delta t = 8 \times 10^5$ s. Different high-energy neutrino detector configurations are considered.

Following Eq. 8.12, the significance of a joint emission detection by different high-energy neutrino detectors, σ_{det} , for a BBH-merger located at $r_d = 10^5 R_g$, 5300 Mpc away from us is shown in Fig. 8.11, as it has the highest signal count for the longest time-window ($\Delta t = 8 \times 10^5$ s) among all the source scenarios considered for different r_d values, as tabulated in Tab. 8.1. Hence, σ_{det} is also the maximum, as $\sigma_{\text{det}} \propto \sqrt{\Delta t}$, as shown in Eq. 8.12.

For all considered source locations in the Northern Hemisphere, σ_{det} is almost constant and negligible for IceCube, within $\delta \lesssim 55 - 60^\circ$. It decreases a little while moving further away to the North, reaching a minimum around $70^\circ < \delta < 80^\circ$, for decreasing $N_{\nu_{\mu}+\bar{\nu}_{\mu}}^{\text{BBH}}$. But for $80^\circ < \delta < 90^\circ$, σ_{det} suddenly increases, caused by a sudden drop in background count in the last declination bin, which is more drastic than the decrease in signal count. This increasing

trend for σ_{det} near the pole with $\delta > 80^\circ$ is the same for all the detector configurations considered in this work, even though the signal is highest near the horizon for having a higher A_{eff} . But consequently, the background also overwhelms the signal the most there, as discussed and demonstrated in Sec. 8.2. Near the pole, the background becomes more manageable.

Overall, the joint emission detection prospect via catalogue search is non-significant for all considered detectors due to the weak neutrino fluence coming from an individual source located at 5300 Mpc. For other r_d values, the significance is, of course, worse for having lower Δt . Even with enhanced A_{eff} for Gen-2 and PLEvM-2, claiming evidence ($\sim 3\sigma$) of high-energy neutrino counterpart detection from a distant BBH merger occurring in AGN disk is unlikely. However, for very close source, for example, at $d_L = 400$ Mpc, the significance could be much more than 3σ , for the scenario presented in Fig. 8.10. The same was seen also for Fig. 8.9 ($d_L = 400$ Mpc). But such high significance can only be achieved considering an optimistic scenario with very high accretion rate ($f_{\text{acc}} = 10 - 15$), efficient reverse shock acceleration, and a detector with bigger A_{eff} coverage, such as PLEvM-1, Gen-2, or PLEvM-2. Associated plots could be found in Appendix D. Given this prediction, accumulating signal by stacking GW sources against the background emerges as the most promising strategy to achieve discovery. Therefore, the potential of such an approach with future detectors is examined next.

8.4. Prospects for Stacking Analysis

With significantly improved sensitivities anticipated from upcoming GW detectors such as ET, the detection horizon for CBCs will expand considerably. This extended reach opens the door to stacking analyses, where observation from multiple GW sources could be combined to obtain statistically significant neutrino signals. While detecting spatially and temporally coincident neutrinos from individual GW events would remain challenging, given a faint signal competing against a large background, stacking could be a promising tool.

As BBH sources are so far the most populous CBC sources of GW, for this work, we only predict the stacking prospects for them. Similar work for BNS sources has already been introduced [370].

In the era of ET, an enormous number of BBH mergers are expected to be detected on a daily basis. BBH mergers with total masses in the range of $20\text{--}100 M_\odot$ are expected to be detected up to redshifts of $z \sim 20$ [149]. This represents a substantial improvement over the 2G detectors, which are expected to reach a redshift of $z \sim 1$ as the final target sensitivity. If restricted within $z = 1$, ET is expected to detect nearly 100% of BBH mergers with signal-to-noise ratio (SNR) ≥ 12 [151].

Interestingly, for that redshift range, the merger rate increases with increasing distance, as shown in Eq. 8.9. Given the measured value of κ from LVK O3, $\kappa = 2.9_{-1.8}^{+1.7}$ for $z \lesssim 1$ [167]. Beyond this redshift range, no measurement of the redshift evolution of the BBH merger rate is available, as LVK has limited sensitivity. At very high redshift, only a few massive stars have formed, so the rate is likely to decrease beyond the peak of star formation at $z \sim 2$.

Given that BBH mergers will constitute the majority of CBC detections with ET, even a small fraction ($P_{\text{AGN}} \sim 0.1 - 0.3$) occurring in exotic environments of AGN disks would yield a sig-

nificant number of GW source candidates, making stacking a potentially powerful strategy to uncover otherwise hidden multi-messenger signals.

8.4.1. Redshift-dependent BBH merger rate

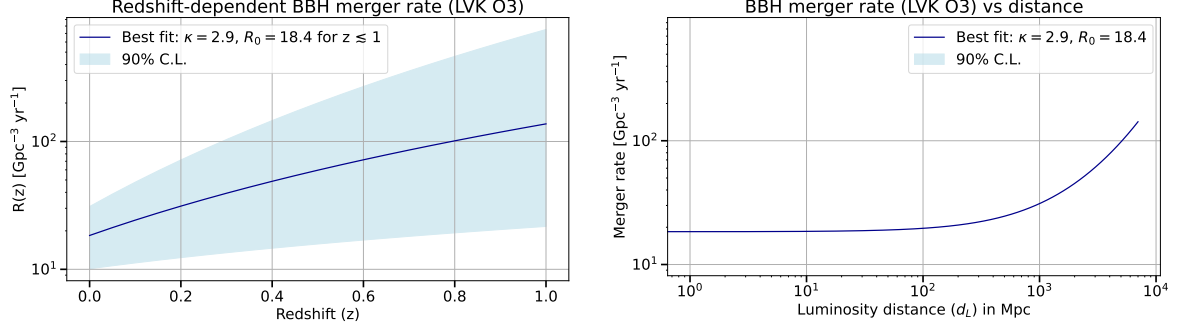


Figure 8.12.: (Left) The BBH merger rate evolution till $z = 1$. The current best estimate for $R_0 = 18.4^{+12.6}_{-8.3} \text{Gpc}^{-3} \text{yr}^{-1}$ is obtained from LVK O3. The best fit value for $\kappa = 2.9^{+1.7}_{-1.8}$, for $z \lesssim 1$. (Right) The rate variation for luminosity distance d_L .

To understand the potential of a stacking analysis in the era of ET, it is essential to comprehend the population of BBH mergers that ET can detect. For demonstration, we stick to $z \lesssim 1$ because within this range, κ is confirmed to be positive. Using Eq. 8.9, the BBH merger rate up to $z = 1$ is shown in the left panel of Fig. 8.12. The right panel demonstrates the variation of merger rate corresponding to luminosity distance d_L . For this, we exploit the relation between d_L and z , which is

$$d_L = (1 + z)d_C \quad (8.13)$$

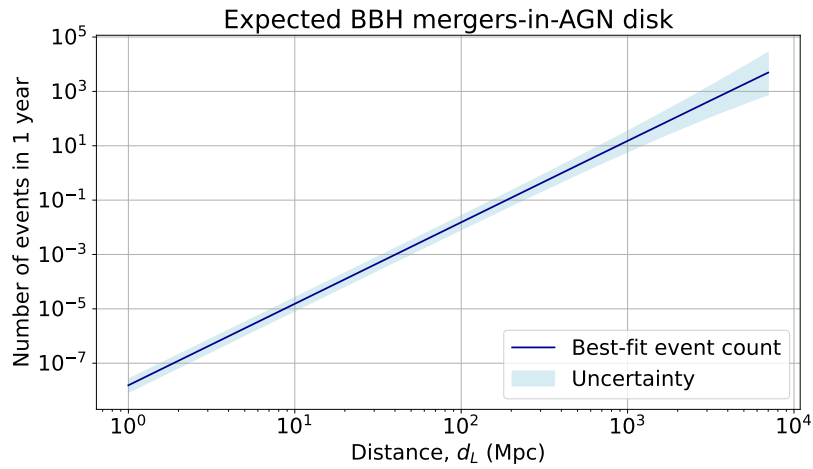


Figure 8.13.: Expected number of BBH mergers occurring in AGN disk, assuming $P_{\text{AGN}} = 0.2$, for $T_{\text{op}} = 1$ year.

Here, d_C is the comoving volume defined for a given redshift. It is plotted till $d_L \sim 7000$ Mpc, which corresponds to $z \sim 1$. The relevant cosmological model parameters are $\Omega_m = 0.315$, which is the matter density parameter. The Dark energy density parameter, $\Omega_\Lambda = 0.685$, and the Hubble constant, $H_0 = 67.66 \text{ km s}^{-1} \text{ Mpc}^{-1}$ [64].

Using this redshift-dependent BBH merger rate, the total number of expected BBH mergers occurring in AGN disks ($N_{\text{BBH}}^{\text{cum}}$) that ET can detect within one year of its operation time ($T_{\text{obs}} = 1$ year) for different d_L values could be calculated using Eq. 8.10. The result is shown in Fig. 8.13. P_{AGN} is the probability of the occurrence of a BBH merger in an AGN disk. It is set to 0.2, as an optimistic assumption [369]. At $d_L = 1$ Gpc, the estimated value for $N_{\text{BBH}} = 26.02^{+33.56}_{-15.70}$ in 1 year. For a longer operational time, it would increase multiplicatively.

8.4.2. Localisation Uncertainty with ET

Following the BBH merger rate, the predicted localisation uncertainty of ET needs to be studied to quantify the neutrino background we can get from the whole region while stacking. The variation of sky localisation uncertainty for the 90% containment region of a GW skymap ($\Delta\Omega_{90}$) with distance d_L is shown for ‘ET-triangle’ configuration (ET- Δ)⁷, in the left panel of Fig. 8.14.

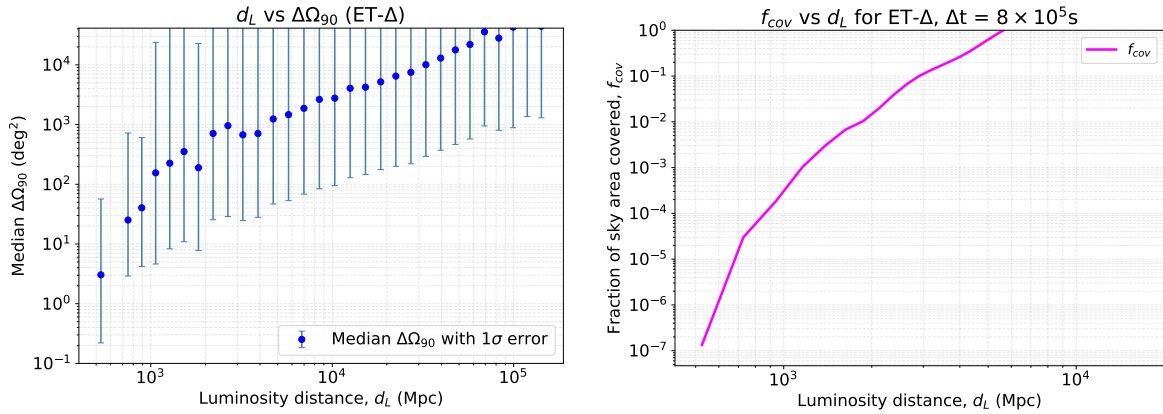


Figure 8.14.: (Left) The localisation uncertainty (90% containment region), $\Delta\Omega_{90}$ is plotted here against distance d_L , for ET- Δ . (Right) The fraction of sky area covered (f_{cov}) due to the localisation uncertainty ($\Delta\Omega_{90}$) of the GW events occurring within the neutrino observation time window (Δt). In this case, $\Delta t = 8 \times 10^5$ s. Using the best-fit $\Delta\Omega_{90}$ for each distance value d_L , f_{cov} is always saturated to 1 for $d_L > 5000$ Mpc.

As discussed before, with ET, BBH mergers occurring in distant galaxies could be detected with respectable significance. However, as we go to the depth of the Universe, $\Delta\Omega_{90}$ typically becomes worse with increasing distance (d_L), as evident from Fig. 8.14. That, combined with the frequent occurrences of BBH mergers with increasing luminosity distance, will result in an accumulated uncertainty region on the sky. It is quantified by f_{cov} , as given in Eq. 8.14 [370].

⁷ A possible 10 km long triangular GW detector configuration located near Maastricht, as mentioned in Sec. 3.2.

$$f_{\text{cov}}(d_{\text{GW}}^{\text{lim}}) = \int_0^{d_{\text{GW}}^{\text{lim}}} \frac{\Delta\Omega_{90}(d_L)}{4\pi} R(z) 4\pi d_C^2 \Delta t P_{\text{AGN}} d(d_C) \quad (8.14)$$

It estimates the fraction of sky area covered by the individual localisation uncertainty ($\Delta\Omega_{90}$) coming from all the BBH mergers detectable by ET within a given distance limit ($d_{\text{GW}}^{\text{lim}}$) and an observation time window (Δt). The comoving distance, d_C is defined in Eq. 8.13. Using the $\Delta\Omega_{90}(d_L)$ shown in the left panel of Fig. 8.14, $f_{\text{cov}}(d_L)$ is estimated for $\Delta t = 8 \times 10^5$ s, in accordance to the model presented in [117] ($r_d = 10^5 R_g$) and $P_{\text{AGN}} = 0.2$, at different d_L values shown in the right panel of Fig. 8.14.

As seen from the plot, for $d_L > 5$ Gpc, the individual error regions of the BBH mergers occurring within that distance limit in $\Delta t = 8 \times 10^5$ s are cumulatively covering the whole sky, resulting in $f_{\text{cov}} = 1$. This will increase the background neutrino estimation as well.

8.4.3. Stacking Significance with Distance

From Fig. 8.14, it is visible that for distant GW sources, the localisation would be worse. For a bigger uncertainty region on the sky, the cumulative number of background neutrinos ($N_{\nu+\bar{\nu}}^{\text{bkg,cum}}$) for the stacked signal would also be higher. Also, the neutrino flux decreases with d_L^2 , as shown in Eq. 8.11. So, the number of signal neutrinos coming from a single source also decreases if the GW source is further away from us. However, the cumulative number of signal neutrinos $N_{\text{sig}}^{\text{cum}}$ should always increase with distance. So, it makes sense to study exactly how the joint detection significance varies with d_L . The best case would be identifying a sweet spot, where $N_{\text{BBH}}^{\text{cum}}$ is sufficiently high, so that $N_{\text{sig}}^{\text{cum}}$ is higher or comparable to $N_{\nu+\bar{\nu}}^{\text{bkg,cum}}$ within a certain detection time window Δt , as that can provide significant detection.

To implement this, $N_{\text{BBH}}^{\text{cum}}(d_L)$ is calculated, as was done in Fig. 8.13, using Eq. 8.10. For each distance, $\phi_{\nu_\mu}^{\text{BBH}}(d_L)$ is scaled following the relation shown in Eq. 8.11. To demonstrate, we consider the neutrino fluence for the most realistic case as seen in Fig. 8.10, assuming $r_d = 10^5 R_g$, and $\Delta t = 8 \times 10^5$ s.

Assuming all BBH mergers are isotropically distributed in the sky, and are embedded in identical scenarios (i.e., all are located $10^5 R_g$ away from the AGN core in this case and emit a constant flux of neutrinos for 8×10^5 s around each of their merger time), the cumulative signal count for all sources, $N_{\text{sig}}^{\text{cum}}(d_L)$ in any declination bin ($\delta_1 \leq \delta \leq \delta_2$) is given by,

$$\begin{aligned} N_{\text{sig}}^{\text{cum}}(d_L) &= \sum_{d_L} N_{\text{BBH}}(d_L, T_{\text{op}}) \times N_{\nu_\mu+\bar{\nu}_\mu}^{\text{BBH}}(d_L, \Delta t) \times \frac{2\pi(\sin \delta_2 - \sin \delta_1)}{4\pi} \\ &= R(d_L) \times \frac{4}{3}\pi d_L^3 \times T_{\text{obs}} \times P_{\text{AGN}} \times N_{\nu_\mu+\bar{\nu}_\mu}^{\text{BBH}}(d_L, \Delta t) \times \frac{2\pi(\sin \delta_2 - \sin \delta_1)}{4\pi} \end{aligned} \quad (8.15)$$

Here, $N_{\nu_\mu+\bar{\nu}_\mu}^{\text{BBH}}(d_L, \Delta t)$ is the number of signal neutrinos coming within neutrino observation time window, Δt , from a single BBH merger source situated d_L away from the Earth. T_{op} is the GW detector's operation time. The luminosity distance is evaluated at the midpoint of each distance bin, $d_{L_1} \leq d_L \leq d_{L_2}$. It is computed using Eq. 8.8 and Eq. 8.11, for a given declination bin,

$\delta_1 \leq \delta \leq \delta_2$. The last term in Eq. 8.15 represents the fractional region of the sky confined within the declination bin.

Similarly, for background calculation, we assume f_{cov} is equally distributed in each declination bin considered in the Northern Hemisphere. Thus,

$$N_{\nu+\bar{\nu}}^{\text{bkg,cum}}(d_L) = R_{\nu+\bar{\nu}}^{\text{bkg,per sr}}(\delta, d_L) \times f_{\text{cov}} \times 4\pi \times \frac{2\pi(\sin \delta_2 - \sin \delta_1)}{4\pi} \times N_{\text{BBH}}(d_L, T_{\text{op}}) \times \Delta t \quad (8.16)$$

The first term is the background neutrino rate per steradian for the considered detector, given a declination bin. The term $N_{\text{BBH}}(d_L, T_{\text{op}})$ is the number of BBH mergers within the observation time in the distance bin, $d_{L1} \leq d_L \leq d_{L2}$. Summing over all such bins yields $N_{\text{BBH}}^{\text{cum}}(d_L)$, within a given distance limit of interest.

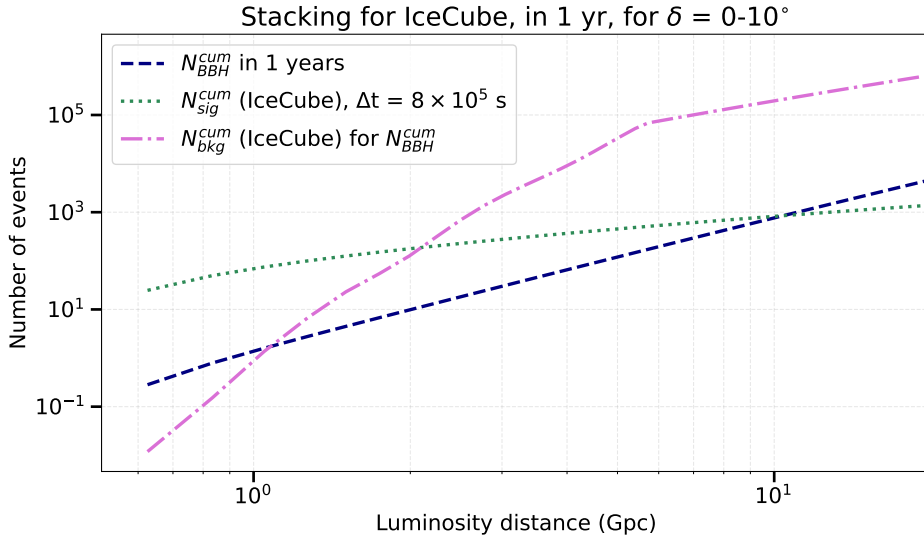


Figure 8.15.: The variation of the number of BBH mergers in AGN disks located within $0^\circ \leq \delta \leq 10^\circ$ detected by ET in 1 year of its operation time, with respect to luminosity distance (d_L). It is assumed that $P_{\text{AGN}} = 0.2$. The cumulative number of signal neutrinos ($N_{\text{sig}}^{\text{cum}}$) coming from these sources, within 8×10^5 s time window is also shown. All of the BBH mergers are considered to be independently occurring $10^5 R_g$ away from the AGN core, and the fluence compatible with that has been adopted from [117]. More details are tabulated in Tab. 8.1. The signal is compared with the cumulative number of background neutrinos ($N_{\nu}^{\text{bkg,cum}}$) IceCube will detect for all the GW sources occurring within 8×10^5 s time window is estimated using f_{cov} . The variation is shown up to 20 Gpc.

Although for signal estimation, $\Delta t = 8 \times 10^5$ s, for the background, the relevant integration time scales with the total number of BBH merger events included in the stacking for each distance bin. In this case, we assume each stacked event in a distance bin is identical, but independent and non-overlapping in time. Since the mergers do not occur simultaneously within the 8×10^5 s time window, but are distributed over the one-year GW observation period, the background in each 8×10^5 s time window contributes altogether while stacking. The total contribution is

then compared against the signal for the total observation time. The background count is finally integrated across the energy interval from $E_{\min} = 1$ TeV to $E_{\max} = 10^7$ GeV.

Using this framework, the variation of $N_{\text{BBH}}^{\text{cum}}(d_L)$, $N_{\text{sig}}^{\text{cum}}(d_L)$, and $N_{\nu+\bar{\nu}}^{\text{bkg,cum}}(d_L)$ are shown in Fig. 8.15, considering IceCube A_{eff} . Also, for the declination bin, $\delta_1 = 0^\circ$, $\delta_2 = 10^\circ$ are considered, as the background and signal count are maximum near the horizon. However, it could be implemented for any other declination band and detector configuration.

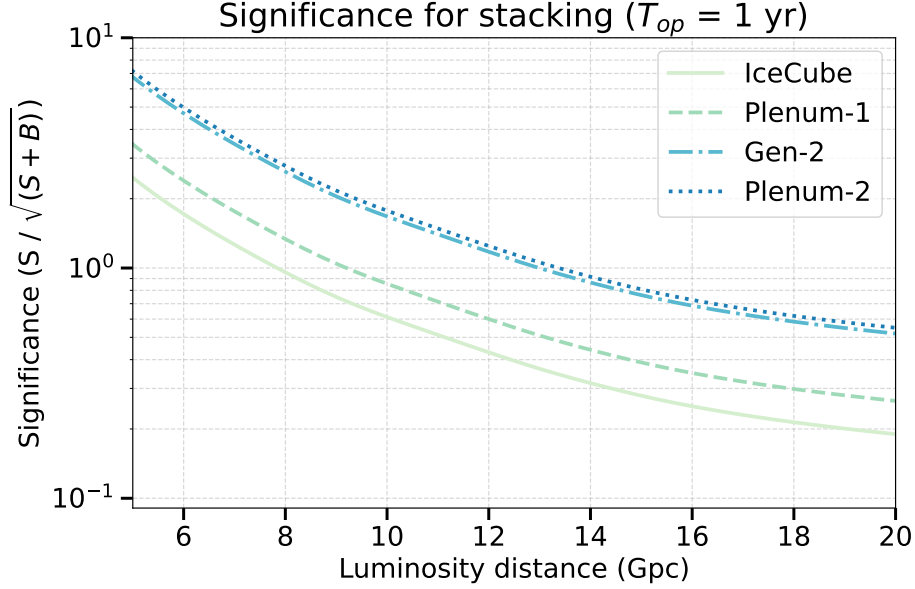


Figure 8.16.: The detection significance for stacking analysis, in distances $d_L > 5$ Gpc, which is heavily background dominated for IceCube, as seen in Fig. 8.15, considering ET operational time in 1 year. However, with the help of high-energy neutrino detector configurations with larger A_{eff} coverage, the detection significance via stacking continues to remain $\sim 3\sigma$ till 8 Gpc.

The distance, d_L is restricted to 20 Gpc, which roughly corresponds to $z \sim 2$, as within that the BBH merger rate density should be high⁸. It is visible that $N_{\text{sig}}^{\text{cum}}(d_L)$ is slowly increasing with distance, and dominates over the background till 2 Gpc. In this case, thus, 2 Gpc could be considered as the ‘sweet spot’, where the astrophysical stacked signal is dominating over the background, yielding detection significance $\geq 3\sigma$. This signal-dominance stems from very well-localised sources detected by ET within that distance, leading to smaller f_{cov} values, and minimum background accumulation within the considered time window. $N_{\nu+\bar{\nu}}^{\text{bkg,cum}}(d_L)$, however, increases more rapidly with distance, and overwhelms the signal accumulated by IceCube in the larger distances. The increment driven by f_{cov} stops beyond 5 Gpc, as f_{cov} saturates to 1, but it continues to increase driven by the increasing number of BBH mergers.

The evolution of $N_{\text{sig}}^{\text{cum}}$ and $N_{\nu+\bar{\nu}}^{\text{bkg,cum}}$ with distance is obtained for PLEvM-1, IceCube-Gen2, and PLEvM-2 as well, for $0^\circ \leq \delta \leq 10^\circ$. Using those results, the variation of joint-emission detection significance σ_{det} for stacking is inferred, modifying Eq. 8.12 accordingly with the

⁸The LVK O3 rate estimate previously stated in Eq. 8.9 is assumed to be applicable till $z \lesssim 2$.

cumulative counts for the whole energy range of $10^3 - 10^7$ GeV. From the results, it can be inferred that by stacking well-localised sources detected by ET and restricting the analysis to a signal-dominated regime (< 2 Gpc), a detection with $> 3\sigma$ could be achieved even with IceCube. If the considered BBH mergers are confined within $0^\circ \leq \delta \leq 10^\circ$, IceCube can continue to efficiently accumulate signal neutrinos from those well-localised sources with a detection significance of $\sim 2\sigma$ from the population of BBH mergers occurring within 2 - 5 Gpc. To extend the distance reach of the analysis, larger neutrino detection configurations with enhanced effective area would be useful. It is shown in Fig. 8.16. At $d_L > 5$ Gpc, with IceCube, $\sigma_{\text{det}} < 2\sigma$. But PLEvM-1, PLEvM-2, and Gen-2, are capable of claiming evidence of TeV-PeV neutrino emission from the population of BBH merger sources occurring within 8 Gpc, via stacking. To further enhance the detection prospect, selecting well-localised sources by setting a limit on f_{cov} to perform a distance-triggered stacking would be advantageous [370]. A work motivated by these results is currently under development.

8.5. Summary and Discussion

To summarise, this prospect study is developed to evaluate the future when an increasing number of BBH mergers will be detected by 3G GW detectors, like ET. Their occurrence in AGN disks offers a scenario where high-energy neutrino emission is possible. However, from individual GW sources, the prospect of identifying high-energy neutrino emission only with IceCube with high confidence remains no-optimistic. For that, a global network of high-energy neutrino detectors would be advantageous, as that offers uniform enhanced effective area coverage across the whole sky. Even for cases of non-detections, stringent upper limits could be obtained on the neutrino flux, allowing us to constrain source parameters of individual BBH mergers.

Although the detection prospects from a single source remain limited, stacking serves as an alternative. Within the distance limit of a high BBH merger rate, accumulating signal neutrinos from a population of BBH sources would allow us to overcome the background. That is more likely to be possible with ET, as it will confidently detect numerous well-localised BBH sources, during its operational time. With good GW event localisation, background neutrino events will be suppressed, and significant detections can be claimed. Thus, the logical step forward is identifying a distance limit where the cumulative localisation uncertainty coming from BBH merger sources is small enough to meet optimal detection criteria. Additionally, larger neutrino detectors, such as IceCube-Gen2, would be essential in the next decades as they will play a crucial role by detecting fainter signals coming from distant sources.

Looking ahead in the future, developing stacking analysis for GW sources thus seems to be timely. However, the study presented here is still limited by simple assumptions. The next step is to drift away from that and examine results by varying source specifications with redshift. Another limitation is the available models of high-energy neutrino emission from BBH mergers in AGN disks, which strongly influence results reported here. For more robust predictions, updated source modelling, improved population assumptions and precise information about the high-energy neutrino emission time profile are planned to be incorporated.

Chapter 9. Conclusion and Outlook

"You cannot hope to build a better world without improving individuals. To that end, each of us must work for our own improvement."

— Marie Curie

In the course of this thesis, I have explored the possibility of identifying a coincident emission of gravitational waves (GW) and neutrinos to identify their common sources. Motivated by the limitations of traditional messengers such as multi-wavelength photons and cosmic rays, the analysis aims to exploit the multi-messenger potential of GWs and neutrinos, as the two of them can escape from the innermost, dense regions of compact object mergers serving as cosmic accelerators.

To carry out the study, archival sub-threshold GW events from the third observing run (O3) of the LIGO–Virgo–KAGRA (LVK) collaboration and sub-TeV neutrino data from the IceCube Neutrino Observatory, known as ‘GRECO’, are used. It is the first analysis employing these two data sets in a joint framework using an unbinned maximum likelihood (UML) method to evaluate the statistical significance of potential spatial and temporal coincidences. To do that, promising GW events were carefully selected from an extensive list of ~ 2200 GW events, based on their probability of being a real GW signal, based on individual false alarm rate and p_{astro} values. These shortlisted sub-threshold GWs are not weak signals. Rather, they are comparable to the credibility of the confident GWs, which were shared in real time in O3. The final 103 shortlisted GW events belonged to the top 4% of events most likely to be of astrophysical origin. They consist of 74 binary black hole mergers, 16 neutron star-black hole mergers, 10 GW burst-like events with $p_{\text{astro}} < 0.5$, and the remaining 3 are also burst-like events but with $p_{\text{astro}} > 0.5$.

Sensitivity studies were subsequently carried out on this subset to quantify the detection prospects of the analysis, using the blind GRECO dataset with scrambled right ascension. As expected, the sensitivity was found to be better for events more confined in the Northern Hemisphere for slightly better effective area (A_{eff}) coverage there, compared to those in the Southern Hemisphere, because of IceCube’s location in the geographic South Pole.

Following the sensitivity studies, the GRECO dataset was unblinded. No statistically significant coincidences between GW events and IceCube sub-TeV neutrinos were observed within the 1000 s search time window. The lowest pre-trial p -value was found to be 0.04% (3.35σ), which is $< 3\sigma$ after trial correction. Consequently, upper limits (ULs) on the time-integrated, energy-scaled, per-flavour neutrino flux ($E^2 F_{\nu+\bar{\nu}}$) were derived for individual GW events, belonging to different ‘source classes’. The ULs lie in the range $1 - 10 \text{ GeV cm}^{-2}$, integrated within a 1000 s

time window, for neutrino energies between $\mathcal{O}(10\text{--}100)$ GeV. There was also no prominent difference observed in the ULs belonging to different source classes. The limits are generally more constraining for sources located in the Northern Hemisphere compared to those in the Southern Hemisphere, consistent with the sensitivity results. The ULs were further compared to the ULs in the sub-TeV energy range, also obtained via UML analysis, but associated with the 79 confidently detected GWs during O3. The two sets of limits were found to be comparable, supporting the conclusion that sub-threshold GWs are not intrinsically different in their source properties. But their designation as ‘sub-threshold’ is purely a detection-level effect. Altogether, with this work, we achieve the most comprehensive constraints in the sub-TeV energy range currently available for joint GW-neutrino emission scenarios. It is also inferred that although Doppler de-boosting can shift the neutrino spectral peak to lower energies, IceCube does not have exceptional sensitivity in this energy range given the current detector configuration, which is tuned to detect sources emitting neutrinos in the TeV - PeV energy range. With IceCube-Upgrade, that gap can be filled in. Also, given the current ULs, it seems to be unlikely that the detected GW emitters are exceptionally matter dense, which can aid in efficient pp interactions, boosting neutrino flux in the sub-TeV regime.

However, while comparing the GRECO ULs for sub-threshold GWs to the ULs coming from high-energy tracks (GFU) for confidently detected GWs, it is evident that the GFU results are more constraining. This is mainly because the high-energy tracks in the TeV–PeV range are the neutrino events for which IceCube has the maximum sensitivity, which offer superior directional reconstruction due to a larger number of in-ice hits, compared to lower-energy sub-TeV events. In addition, GFU achieves more effective background suppression by exploiting the higher energy of its events, leading to a larger overall A_{eff} than GRECO. This difference is especially pronounced in the Northern Hemisphere, where the rejection of background muons is more efficient. Motivated by these results, the exact analysis framework discussed as a part of this thesis has already been adapted to search for high-energy track counterparts in the TeV - PeV range. It is now close to unblinding as well, establishing the robustness of the developed analysis framework.

Overall, these results highlight the challenges of detecting common GW-neutrino sources in the lower-energy regime with current IceCube instrumentation. Further improvements are expected with better reconstruction of low-energy events. A new implementation aiming at that, based on machine learning algorithms, is currently under review in the collaboration. The reconstruction should particularly improve after the full deployment of IceCube-Upgrade, which will provide significantly increased sensitivity across the $1\text{--}10^3$ GeV energy range [318]. With its denser string configuration, the Upgrade will register more hits from faint, low-energy events, enabling more accurate sub-TeV event reconstruction. Additional improvements could be achieved through improved characterisation of neutrino point spread functions when defining the signal PDF, which would further strengthen sensitivity.

In the meantime, the developed methodology is robust enough to be readily adaptable and scalable for other data samples, such as high-energy tracks (analysis already under development) and cascades. While no coincident detections have yet been identified, the work presented in

this thesis underlines the importance of pursuing such multi-messenger searches using the most comprehensive set of publicly available GW events. Looking forward, several promising directions exist for future research and discovery. First of all, during the fourth observation run, a large number of real-time alerts from LVK were received in real-time, for both high- and low-significance events [127]. With the completion of subsequent observing runs, larger and more sensitive GW catalogues will become fully available. Together with continuous IceCube operations and complementary detectors such as KM3NeT, these will allow more inclusive searches, both in archival analyses and in real-time pipelines. Extending the present framework to incorporate additional neutrino data samples, along with machine-learning-based background rejection and reconstruction, holds further potential to improve sensitivity and advance the search for common GW-neutrino sources.

Another limitation of the archival follow-up searches is the high trial factor. Even when very well-localised neutrino events coincide with a GW skymap within the preferred time window, the pre-trial p -value may appear significant, but the post-trial p -value can still be largely penalised. To mitigate this problem, performing the analysis in real time is a promising strategy. This has already been employed for the highly significant GW events, using high-energy tracks (GFU). Starting with the LVK fourth observation run, the sub-threshold GW alerts are also shared within the community in real-time, enabling the LLAMA follow-up using GFU. Since LLAMA incorporates Bayesian posteriors from parameter estimation as priors in its odds ratio, the coincidence outcome is inherently model-dependent. To overcome this, a natural next step would therefore be to extend the UML follow-up of sub-threshold GWs into real time. Although could be readily implemented using GFU, a breakthrough will come with achieving reliable and prompt real-time reconstruction of GRECO as well. Parallel improvements are also underway in that direction, ensuring that sub-TeV data can be included in such pipelines in the very near future. This means the story is far from over for sub-TeV neutrino follow-up analyses of sub-threshold GWs.

With such frameworks, one can not only identify promising GW candidates in real time but also refine their localisation by combining high- and low-energy neutrino data, and even trigger electromagnetic follow-up campaigns for particularly interesting sources. The realisation of this vision requires a unified analysis framework capable of receiving, streaming, processing, and managing real-time alerts from different messengers. Sophisticated alert brokers such as AMPEL [371], originally developed for efficient optical follow-up surveys, already provide flexible infrastructures adaptable beyond their initial applications. Contributing to the development, improvement, and management of such multi-messenger platforms for enabling their use in neutrino correlation search would be an exciting and timely step forward.

Furthermore, the current non-detection of a common GW-neutrino source motivates assessing the discovery prospects with next-generation instruments. While IceCube continues to operate, upcoming facilities such as IceCube-Gen2, KM3NeT, P-ONE, and Baikal-GVD will greatly enhance sensitivity to TeV – PeV neutrinos, and the Einstein Telescope will be capable of extending the GW detection horizon out to $z \sim 20$ [151]. Together, these instruments will provide unprecedented opportunities to search for coincident GW–neutrino signals. The most

promising scenarios include either single, nearby, powerful GW sources or stacked populations of compact binary mergers embedded in dense environments. These prospects were investigated in the framework of this thesis.

Specifically, the focus is on binary black hole mergers, as they are the most abundant compact binary coalescences in the Universe and, when embedded in dense environments, may be capable of launching powerful relativistic jets. Within a catalogue search scenario, predictions appear promising only for binary black hole mergers occurring very nearby, within the declination bins of $0^\circ \leq \delta \leq 10^\circ$ or $\delta > 80^\circ$, with jets oriented towards the observer and highly accreting remnants located in dense, photon-rich regions farther from the core of an active galactic nucleus. For such favourable but realistic cases, the expected signal neutrino rate is of the order of $\sim 10^{-4}$ events per second. The exact number of detected neutrinos depends on the adopted search time window, but the time variability of the neutrino fluence is rather unclear. Furthermore, the number of signal neutrinos depends on the chosen detector configuration. Combining A_{eff} of operating detectors under a global network of distributed neutrino detectors yields the most optimistic predictions. Nevertheless, the detection significance for individual GW sources remains low under realistic assumptions, even with the global network of detectors, due to a more prominent background of atmospheric and diffuse astrophysical neutrinos in the $10^3 - 10^7$ GeV, which has been quantified as part of this thesis, in each energy and declination bin to ensure a robust significance prediction for different detectors and search time windows.

In contrast, stacking GW sources seems more promising, with the potential to provide the first evidence of a population of joint GW-neutrino emitters, if the GW sources are well-localised. In the era of Einstein Telescope, with its extended horizon for binary black hole mergers, it will be possible to detect joint emission of GW and neutrinos by stacking the precisely located GW events, and consequently reducing the neutrino background. IceCube can contribute significantly to detect stacked signals from well-localised binary black hole located within 2 Gpc. To push the detection capability close to 10 Gpc, IceCube-Gen2 would be crucial in the neutrino front, to identify faint signals from distant GW emitters. A global network of neutrino detectors would also be useful in that regard.

This brings us to the fact that, at the moment, no dedicated stacking framework exists for GW-neutrino searches, either at low or high energies. Developing such an algorithm addressing the existing LVK alerts, therefore, represents a logical next step forward. The analysis framework must be easily extended in future with the data from later LVK observation runs, as well as with future observatories. Specifically, implementing distance-triggered stacking analyses may not only improve discovery prospects but also provide means to efficiently utilise the enormous number of GW alerts expected in the coming years. In case of non-detections, stringent upper limits and population-level constraints will still advance our understanding regarding the source models and bring us closer to a discovery. To this end, it should be emphasised that the prospect to detect TeV - PeV neutrinos from single GW source or its population, as reported in this thesis, strongly depend on the currently available benchmark fluence models [116, 117], which has been adopted for this work. Predictions will be more precise once updated fluence expectation are available. Also, below the TeV – PeV regime, combining the A_{eff} of IceCube-Upgrade

and KM3NeT-ORCA to probe lower-energy neutrinos from GW sources is another compelling direction. Furthermore, broadening the scope to include binary neutron stars and neutron star-black hole mergers will diversify and strengthen future searches.

Given all these ongoing efforts and future endeavours, overall, we are moving slowly towards discovering the common sources of GW and neutrinos. Ultimately, the first confirmed detection of a common GW-neutrino source will be a landmark in astroparticle physics. Such a discovery will deliver unique insights into CR acceleration, relativistic jet formation, and the microphysics of compact objects, opening another unprecedented window into the most extreme environments of the Universe. With the important constraints on possible GW–neutrino sources achieved as a part of this work by performing the most extensive analysis to date, it lays a solid foundation for future searches. With the advent of more sensitive instruments, the refinement of existing methods, and the development of innovative analysis strategies, the prospects for discovering the long-sought common sources of GWs and neutrinos are brighter than ever.

Appendix

A. Shortlisted Sub-threshold GWs from O3

The sub-threshold GW events from GWTC-2.1 and GWTC-3 were shortlisted based on their FAR and p_{astro} values, as explained in Ch. 6. To begin with, events having $2 \text{ yr}^{-1} \leq \text{FAR} < 2 \text{ day}^{-1}$ are selected, which were not labelled as confident GWs during O3. It is to be noted that in the catalogues, the FAR values are given in $\text{Hz}(\text{s}^{-1})$.

$$\begin{aligned} 1 \text{ yr} &= 3600 \times 24 \times 365 \text{ s} \\ \Rightarrow 1 \text{ s}^{-1} &= 3.154 \times 10^7 \text{ yr}^{-1} \end{aligned} \tag{A.1}$$

Following Eq. A.1, the FAR values are converted to the unit of yr^{-1} . Finally, GW events with $0.1 \leq p_{\text{astro}} \leq 0.5$ are selected for the follow-up search. It is important to note that a given sub-threshold GW can be reported by multiple pipelines, potentially with differing p_{astro} values. In such cases, the version of the candidate associated with the highest p_{astro} is retained for further analysis to ensure that each event is represented by its most astrophysically favourable characterisation.

After this stage, it is rechecked if any event is double-counted by multiple pipelines. Thus, the identification of unique sub-threshold GW events is ensured, and we end up with 100 short-listed GWs, among which there are 90 CBCs and 10 cWBs. An additional 3 cWB events were identified with $p_{\text{astro}} > 0.5$, as they did not appear in the high-significance event list and were not recognised by any CBC search pipeline. Most of the CBC candidates are identified by the PyCBC [162] and PyCBC-Highmass [178] search pipelines, as they have a larger template bank, performs time-consuming but rigorous archival searches to pick out GW signals. None of these events has been followed up previously with the sub-TeV neutrinos. The details of all these 103 GWs are tabulated below in Tab. A.1.

The Shortlisted Gravitational Wave Events

Table A.1.: List of 103 short-listed sub-threshold GW events from O3. The FAR and p_{astro} values for individual GW events are given, with the detection time, event type, and active detectors which identified the GW signal.

GW ID	Time (UTC)	Event-type	Detectors	FAR[yr^{-1}]	p_{astro}
PyCBC-HM-1238423132	04.04.2019	BBH	H1V1	61.34	0.13
PyCBC-HM-1238442602	04.04.2019	BBH	L1V1	3.76	0.43
PyCBC-1238582124	06.04.2019	NSBH	H1L1V1	104.61	0.13

Table A.1 (continued)

GW ID	Time (UTC)	Event-type	Detectors	FAR[yr ⁻¹]	p _{astro}
PyCBC-HM-1238821531	09.04.2019	BBH	H1L1	51.46	0.16
PyCBC-HM-1239092652	12.04.2019	BBH	H1L1	18.36	0.38
PyCBC-HM-1239227262	13.04.2019	BBH	H1V1	3.98	0.36
PyCBC-HM-1239632437	18.04.2019	BBH	H1L1	68.29	0.12
GstLAL-1240164426	24.04.2019	BBH	L1	9.04	0.12
MBTA-1240423628	27.04.2019	BBH	H1L1V1	16.80	0.47
GstLAL-1241108686	05.05.2019	BBH	H1L1V1	16.96	0.11
MBTA-1241324936	08.05.2019	BBH	H1L1V1	630.59	0.12
PyCBC-HM-1241639735	11.05.2019	BBH	H1L1	97.82	0.11
MBTA-1242280001	19.05.2019	BBH	H1L1V1	518.17	0.16
PyCBC-HM-1242314274	19.05.2019	BBH	H1L1	45.41	0.19
PyCBC-1243167760	29.05.2019	BBH	H1L1	21.24	0.44
PyCBC-HM-1243220837	30.05.2019	BBH	H1L1	63.96	0.15
PyCBC-HM-1243748255	05.06.2019	BBH	H1L1	49.93	0.20
PyCBC-HM-1243985990	07.06.2019	BBH	H1L1	61.77	0.17
PyCBC-HM-1244202953	10.06.2019	BBH	H1L1	62.08	0.14
PyCBC-HM-1244278698	11.06.2019	BBH	H1L1	55.24	0.14
PyCBC-HM-1244848599	11.06.2019	BBH	H1L1	70.00	0.12
PyCBC-1244375744	12.06.2019	NSBH	H1L1V1	41.93	0.35
PyCBC-HM-1244987689	19.06.2019	BBH	H1L1	89.50	0.12
PyCBC-1245459820	25.06.2019	NSBH	H1L1V1	86.86	0.21
PyCBC-HM-1245839180	29.06.2019	BBH	H1L1	18.76	0.41
PyCBC-HM-1246272532	04.07.2019	NSBH	H1L1V1	72.10	0.18
cWB-1246523564	07.07.2019	cWB	H1L1	6.84	0.16
GstLAL-1246849694	11.07.2019	BBH	H1L1	2.69	0.35
MBTA-1247500937	18.07.2019	BBH	H1L1V1	47.43	0.15
PyCBC-1248215122	26.07.2019	BBH	H1L1V1	124.70	0.12
cWB-1248942961 ¹	04.08.2019	cWB	H1L1	0.02	0.98
MBTA-1249050626	05.08.2019	BBH	H1L1V1	26.21	0.28
PyCBC-HM-1249097859	06.08.2019	BBH	H1L1	24.45	0.26
PyCBC-1249416363	09.08.2019	NSBH	H1L1	56.25	0.21
GstLAL-1249479778	10.08.2019	BBH	H1L1V1	6.64	0.28
PyCBC-HM-1249495257	10.08.2019	BBH	H1L1	32.67	0.26

¹cWB with p_{astro} > 0.5

Table A.1 (continued)

GW ID	Time (UTC)	Event-type	Detectors	FAR[yr ⁻¹]	p _{astro}
PyCBC-HM-1250026325	16.08.2019	BBH	L1V1	4.30	0.38
PyCBC-HM-1250205962	18.08.2019	BBH	H1L1	16.65	0.41
cWB-1250939932	27.08.2019	cWB	H1L1	7.26	0.45
PyCBC-1251787804	06.09.2019	NSBH	H1L1V1	170.11	0.105
PyCBC-HM-1251890211	07.09.2019	BBH	H1L1	14.90	0.41
GstLAL-1251926900	07.09.2019	BBH	H1L1V1	10.11	0.24
PyCBC-1252064527	09.09.2019	BBH	H1L1	99.64	0.15
PyCBC-HM-1252645611	16.09.2019	BBH	H1L1V1	63.67	0.11
PyCBC-1252672417	16.09.2019	BBH	H1L1V1	119.52	0.13
GstLAL-1252939489	19.09.2019	BBH	H1L1V1	8.97	0.25
cWB-1253293503	23.09.2019	cWB	H1L1	5.82	0.36
PyCBC-HM-1253402832	24.09.2019	BBH	L1V1	21.48	0.12
MBTA-1253719269	28.09.2019	BBH	H1L1V1	185.78	0.13
cWB-1253922430 ²	30.09.2019	cWB	H1L1	1.02	0.64
MBTA-1257135715	07.11.2019	BBH	H1L1V1	113.75	0.32
PyCBC-1257260006	08.11.2019	NSBH	H1L1	75.74	0.18
PyCBC-1258003304	17.11.2019	BBH	H1L1	48.14	0.26
PyCBC-HM-1258674399	24.11.2023	BBH	H1L1	49.66	0.19
PyCBC-HM-1258872800	27.11.2019	BBH	H1L1	41.92	0.19
PyCBC-HM-1259379760	03.12.2019	BBH	H1L1	80.27	0.11
MBTA-1259591721	05.12.2019	BBH	L1V1	19.04	0.11
cWB-1259959714	09.12.2019	cWB	H1L1	8.10	0.28
MBTA-1260022599	10.12.2019	BBH	H1L1V1	542.23	0.39
cWB-1260301231	13.12.2019	cWB	H1L1	3.27	0.47
PyCBC-HM-1260305408	13.12.2019	BBH	H1L1	15.95	0.39
PyCBC-1260407000	15.12.2019	NSBH	H1L1	68.36	0.25
PyCBC-1261058247	22.12.2019	NSBH	H1L1	46.37	0.29
PyCBC-HM-1261146225	23.12.2019	BBH	H1L1	14.36	0.45
PyCBC-HM-1261149025	23.12.2019	BBH	H1L1	24.51	0.32
PyCBC-HM-1261197166	24.12.2019	BBH	H1L1	23.73	0.32
PyCBC-HM-1261273562	25.12.2019	BBH	H1L1	31.47	0.27
PyCBC-1261656171	29.12.2019	BBH	H1L1	131.61	0.12
GstLAL-1261658694	29.12.2019	BBH	H1L1V1	7.32	0.24

²cWB with p_{astro} > 0.5

Table A.1 (continued)

GW ID	Time (UTC)	Event-type	Detectors	FAR[yr ⁻¹]	p _{astro}
PyCBC-HM-1261717507	30.12.2019	BBH	H1L1	56.85	0.16
GstLAL-1261725523	30.12.2019	BBH	H1L1V1	3.54	0.12
PyCBC-1262314840	06.01.2020	NSBH	H1L1	199.16	0.11
PyCBC-1262321982	06.01.2020	NSBH	H1L1	122.79	0.14
PyCBC-1262657374	10.01.2020	NSBH	H1L1	129.64	0.14
PyCBC-1262800092	11.01.2020	BBH	L1V1	6.23	0.22
PyCBC-HM-1262878298	12.01.2020	BBH	V1L1	10.81	0.20
PyCBC-1262924523	13.01.2020	NSBH	H1L1	127.74	0.14
PyCBC-1263215647	16.01.2020	NSBH	H1L1	131.77	0.12
PyCBC-HM-1263748131	22.01.2020	BBH	H1L1	39.12	0.16
cWB-1264014232	25.01.2020	cWB	H1L1	8.19	0.25
cWB-1264222462	28.01.2020	cWB	H1L1	7.38	0.15
PyCBC-HM-1264246793	28.01.2020	BBH	H1L1	44.95	0.16
PyCBC-HM1264333383	29.01.2020	BBH	H1L1	72.22	0.12
PyCBC-HM-1264569708	01.02.2020	BBH	H1L1	72.96	0.12
PyCBC-1264663254	02.02.2020	NSBH	H1L1	37.88	0.28
PyCBC-HM-1265364040	10.02.2020	BBH	H1L1	24.12	0.32
MBTA-1265537921	12.02.2020	BBH	H1L1	151.96	0.16
PyCBC-1265685461	14.02.2020	BBH	H1L1	55.41	0.20
PyCBC-HM-1265754804	14.02.2020	BBH	H1L1	27.38	0.26
cWB-1265755544 ³	14.02.2020	cWB	H1L1	0.13	0.91
GstLAL-1266028677	18.02.2020	BBH	H1L1V1	11.70	0.13
cWB-1266055539	18.02.2020	cWB	H1L1	2.16	0.49
GstLAL-1266330503	21.02.2020	BBH	H1L1V1	8.44	0.29
GstLAL-1266480585	23.02.2020	BBH	H1L1	10.62	0.14
GstLAL-1266516436	23.02.2020	BBH	H1L1V1	4.81	0.23
cWB-1266548742	24.02.2020	cWB	H1L1	3.29	0.40
PyCBC-HM-1267131516	01.03.2020	BBH	H1L1	54.61	0.12
PyCBC-HM-1267132237	01.03.2020	BBH	H1L1	20.18	0.24
PyCBC-HM-1267485300	05.02.2020	BBH	H1L1	96.39	0.11
PyCBC-HM-1268250455	14.03.2020	BBH	H1L1	72.38	0.14
GstLAL-1268338066	15.03.2020	BBH	L1V1	9.08	0.15
PyCBC-1268438406	16.03.2020	NSBH	H1L1	129.26	0.14

³cWB with p_{astro} > 0.5

Table A.1 (continued)

GW ID	Time (UTC)	Event-type	Detectors	FAR[yr ⁻¹]	p _{astro}
cWB-1269257119	26.03.2020	cWB	H1L1	2.37	0.46

Gravitational Wave Skymaps

For these 103 GW events, the overall characteristics are discussed in Ch. 6. Here, their individual skymaps are included.

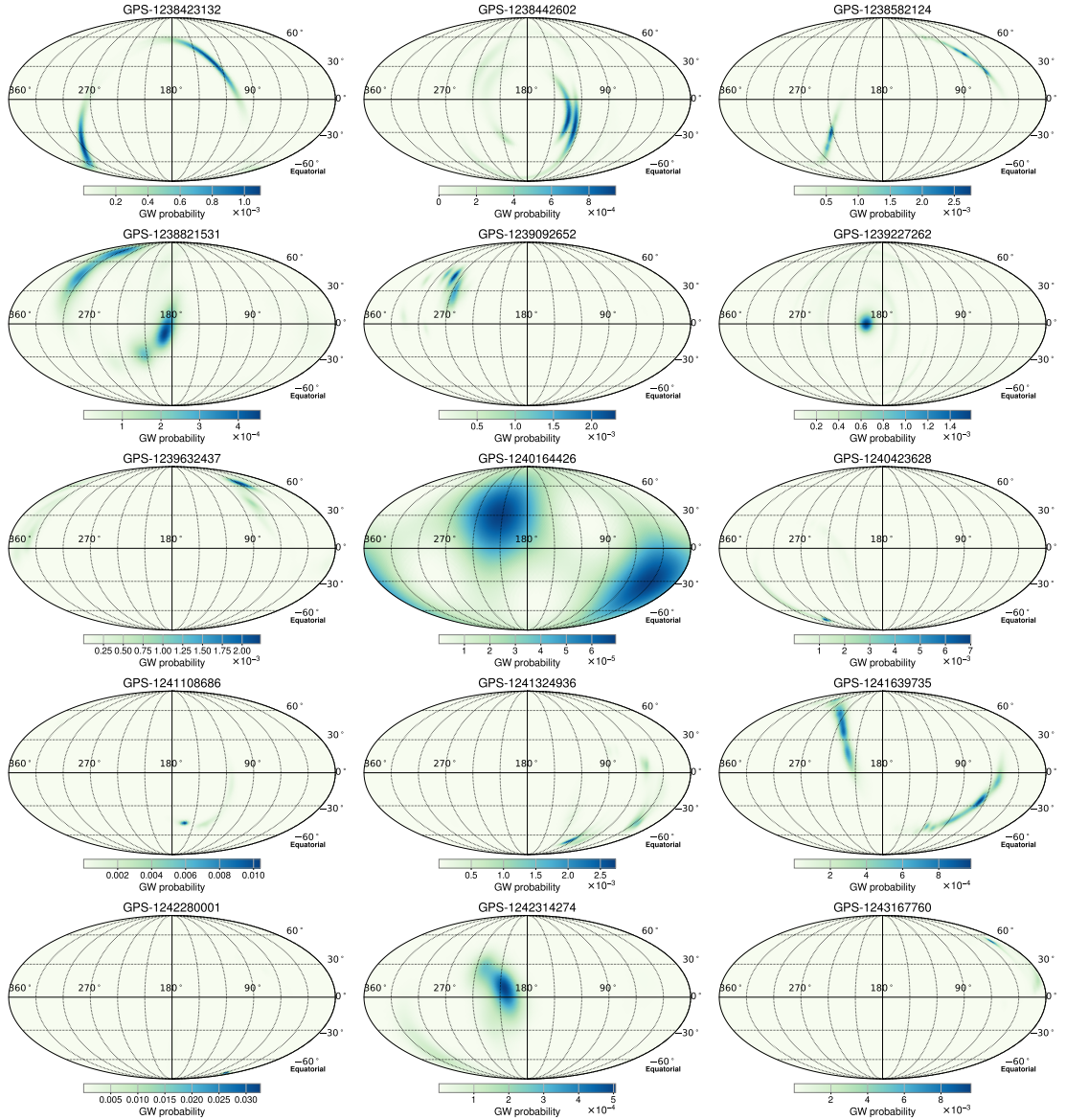


Figure A.1.: GW skymaps for shortlisted events from O3a (continued).

We can interpret the GW skymaps as a probability distribution map for possible source positions on the sky. It is typically plotted for RA = 0° - 360° and δ = -90° - 90°. The skymaps (Hier-

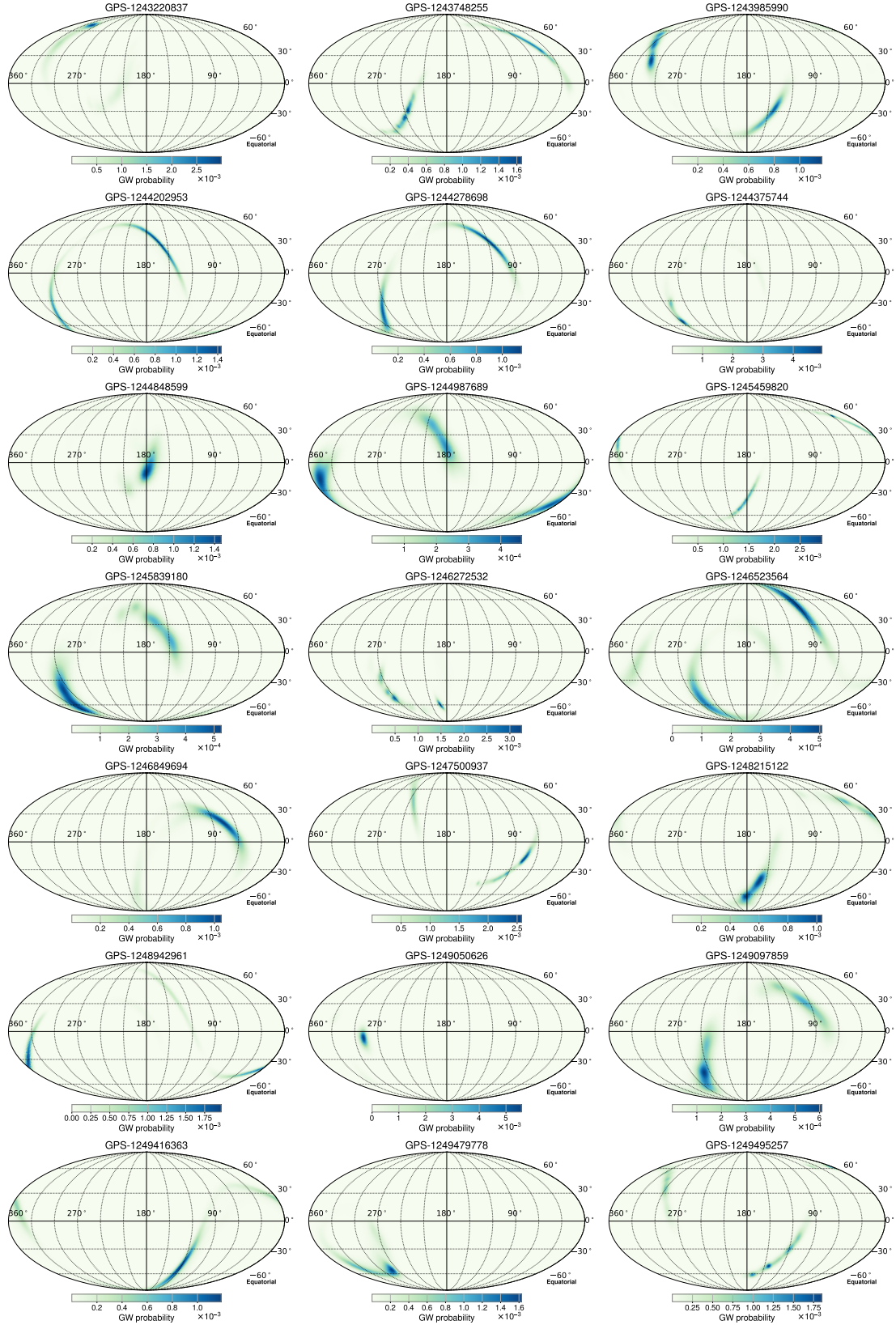


Figure A.1.: GW skymaps for shortlisted events from O3a (continued).

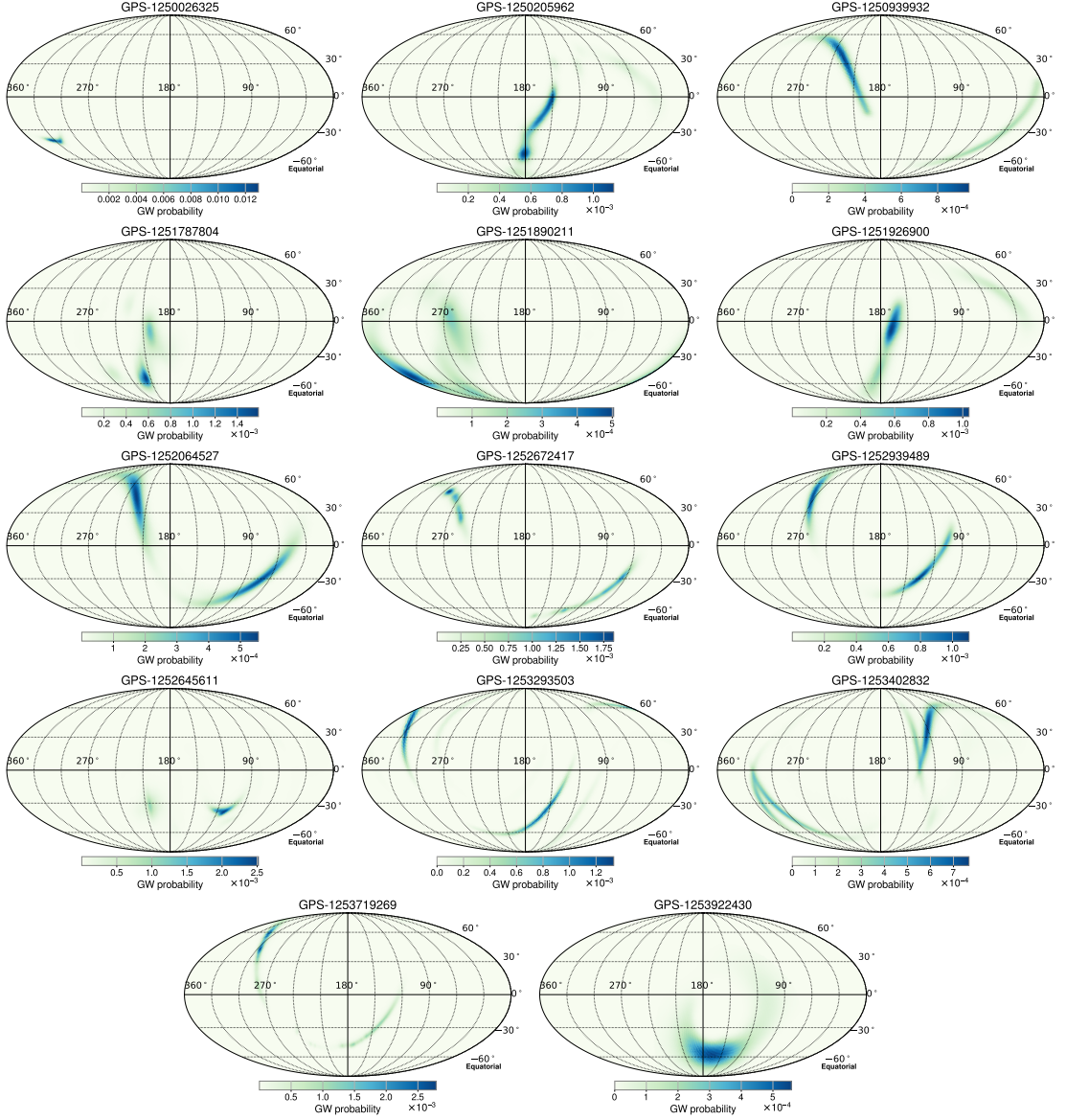


Figure A.1.: GW skymaps for shortlisted events from O3a.

archical Equal Area isoLatitude Pixelization of a sphere) are plotted in the form of a HEALPix map [372], to demonstrate their localisation. HEALPix divides the whole sky into pixels of equal area. The number of pixels, N_{pixel} is given as,

$$N_{\text{pixel}} = 12 \times N_{\text{side}}^2 \quad (\text{A.2})$$

where N_{side} is related to the solid angle of the pixel in the following way:

$$\Omega_{\text{pix}} = \frac{\pi}{3N_{\text{side}}^2} \quad (\text{A.3})$$

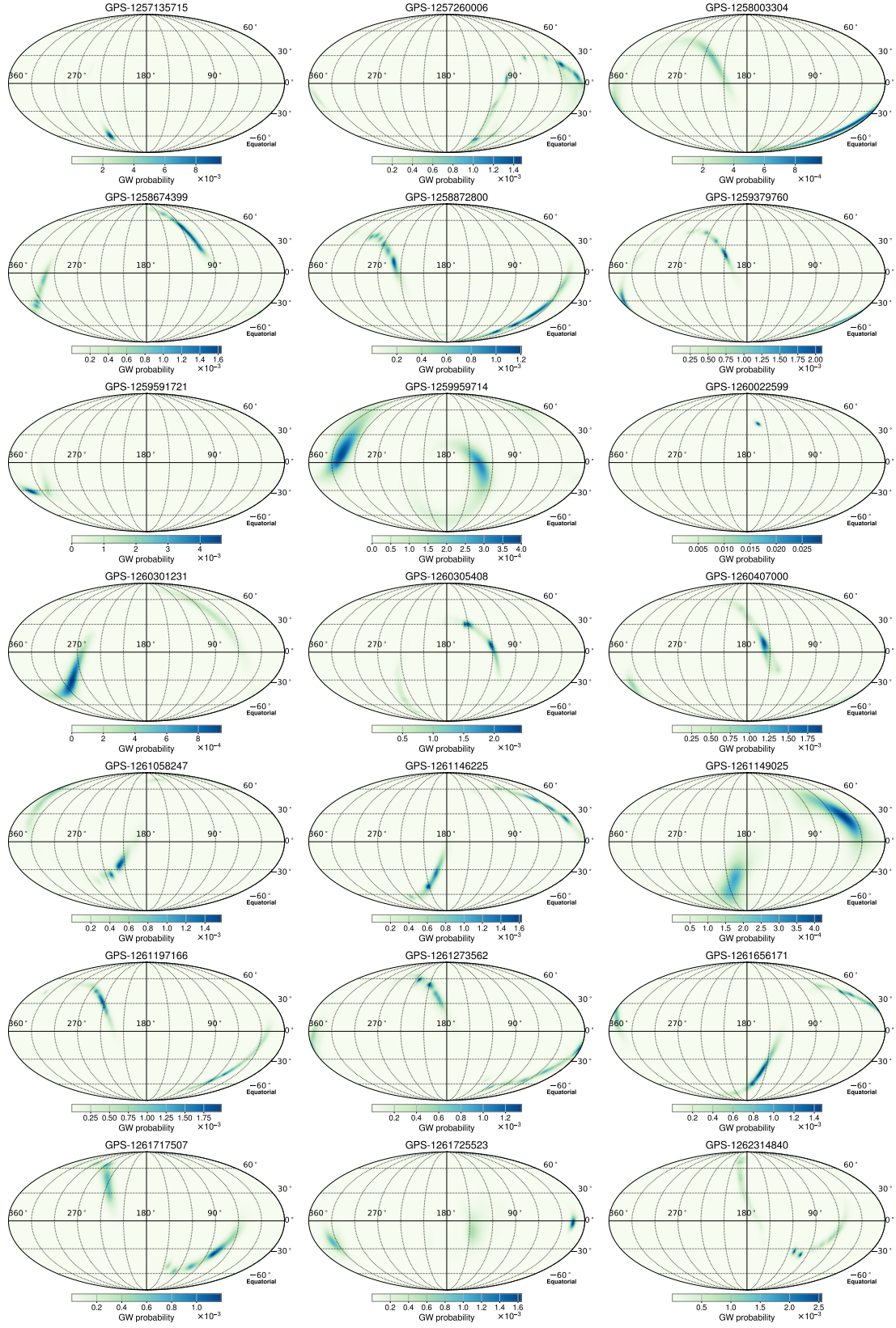


Figure A.1.: GW skymaps for shortlisted events from O3b (continued).

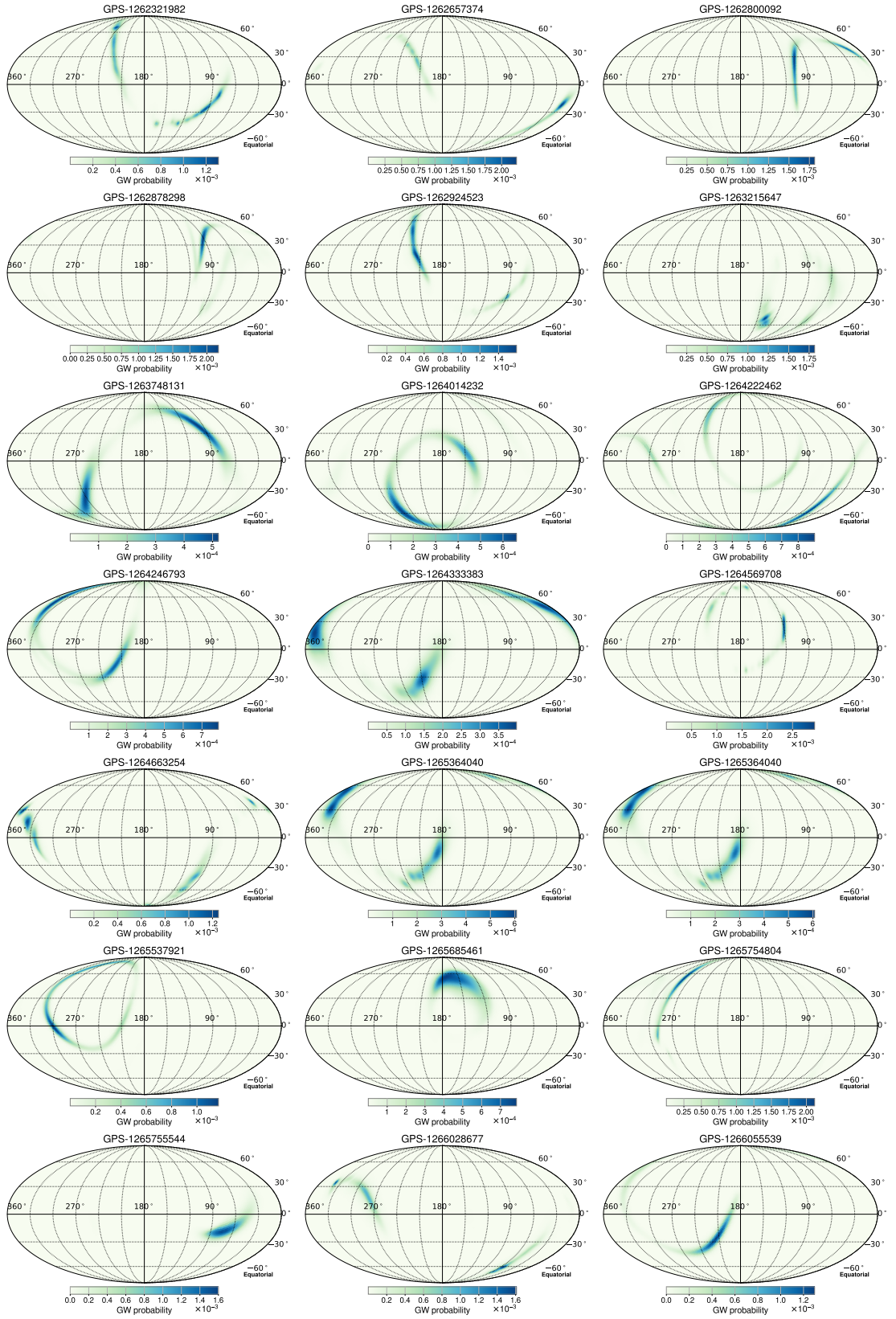


Figure A.1.: GW skymaps for shortlisted events from O3b (continued).

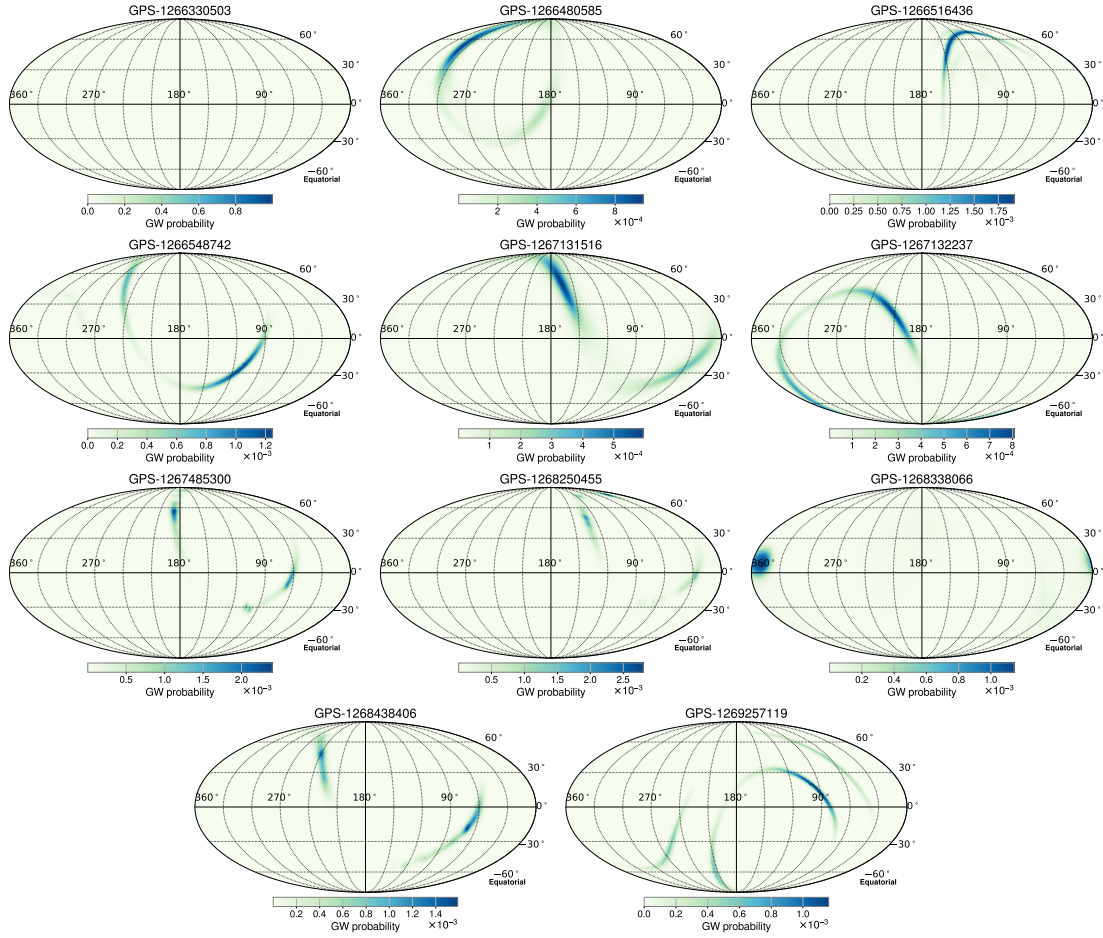


Figure A.2.: GW skymaps for shortlisted events from O3b.

The area of each pixel can further be calculated:

$$A_{\text{pixel}} = \Omega_{\text{pixel}} \times \left(\frac{180}{\pi} \right)^2 \quad (\text{A.4})$$

Reducing the N_{side} , thus reduces the number of pixels on the sky, which further increases the area per pixel. Overall, it lowers the angular resolution for each pixel.

Typically, the GW skymaps from LVK come with $N_{\text{side}} = 128$ or higher, as the skymaps have substructures finer than the GRECO angular resolution. Using the skymaps as it is would require a lot of computation time, especially for signal injection. Because the median angular uncertainty for GRECO events is not lower than 5° even if the event's reconstruction energy, $E_{\text{reco}} \gtrsim 100$ GeV, the skymaps can be converted to lower-resolution maps with $N_{\text{side}} = 64$. It corresponds to an angular resolution of $\sim 0.92^\circ$. This single step saves almost $3/4^{\text{th}}$ of the computation time and memory. In addition, a 99% quantile cut is applied to these maps, which forces the pixels where the GW localisation probability $\simeq 0$ to have zero probability. This further reduces N_{pixel} that actually needs to be considered for computation for sensitivity studies, and thus increases computation speed. It is a standard procedure usually adopted for neutrino source searches, as previously explained in [215].

However, decreasing the skymap resolution further (for example, $N_{\text{side}} = 8$, with angular resolution $\sim 7.3^\circ$) to match the GRECO angular resolution might over-smooth the GW probability maps, potentially losing useful spatial information, which we use to calculate the spatial prior. Thus, for this analysis, the N_{side} is fixed to 64.

Declination-dependence of Sensitivity

In Sec. 6.22, the declination dependence of sensitivity for the shortlisted sub-threshold GWs identified by the GstLAL, MBTA, and cWB-all-sky-search pipelines is shown. Here, in Fig. A.3, the results for the shortlisted sub-threshold GWs from the other two pipelines, which are PyCBC, and PyCBC-Highmass, are included.

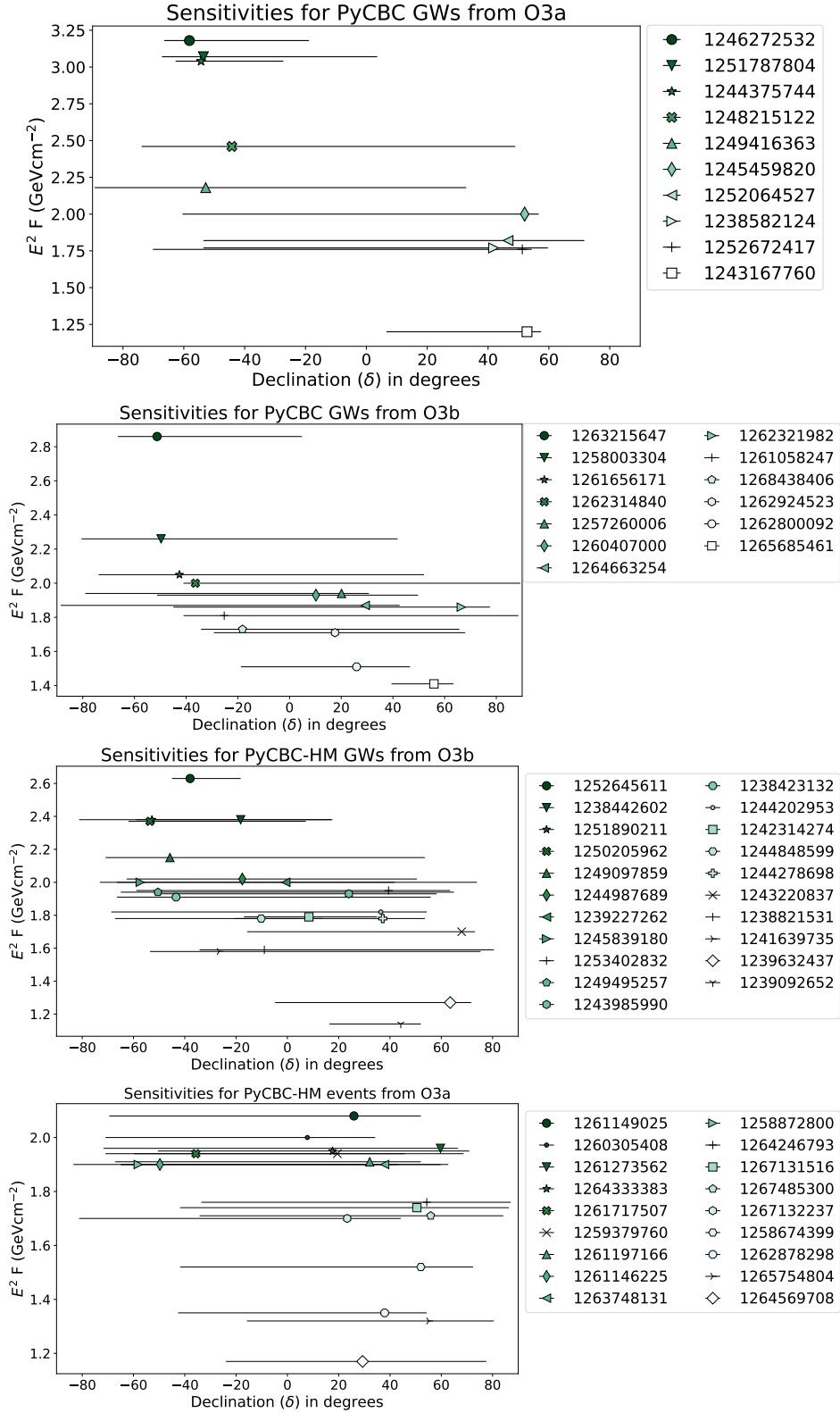


Figure A.3.: Declination dependence of per-flavour sensitivity flux calculated at 1 GeV for the sub-threshold CBC candidates identified by PyCBC and PyCBC-Highmass pipelines during O3. The declination of the pixel containing the best-fit source location has been identified by a marker. Different GW candidates have been identified by different coloured markers and the related GPS times when they were detected. The horizontal spread across the markers covers the declination range for the 50% containment area from the respective GW skymap.

B. Unblinded Skymaps

For each of the 103 shortlisted GW events tabulated in Tab. A.1, spatially and temporally correlated sub-TeV neutrinos are searched for within a 1000 s time window. The final results are obtained via unblinding, as described in Ch. 7. The main outcome has been highlighted and discussed in detail there. For completion, the joint skymaps for GW + neutrinos for all the events are provided here.

Joint GW and neutrino skymaps for O3

The joint GW + neutrino skymaps for all shortlisted GW events from LVK O3 are provided here.

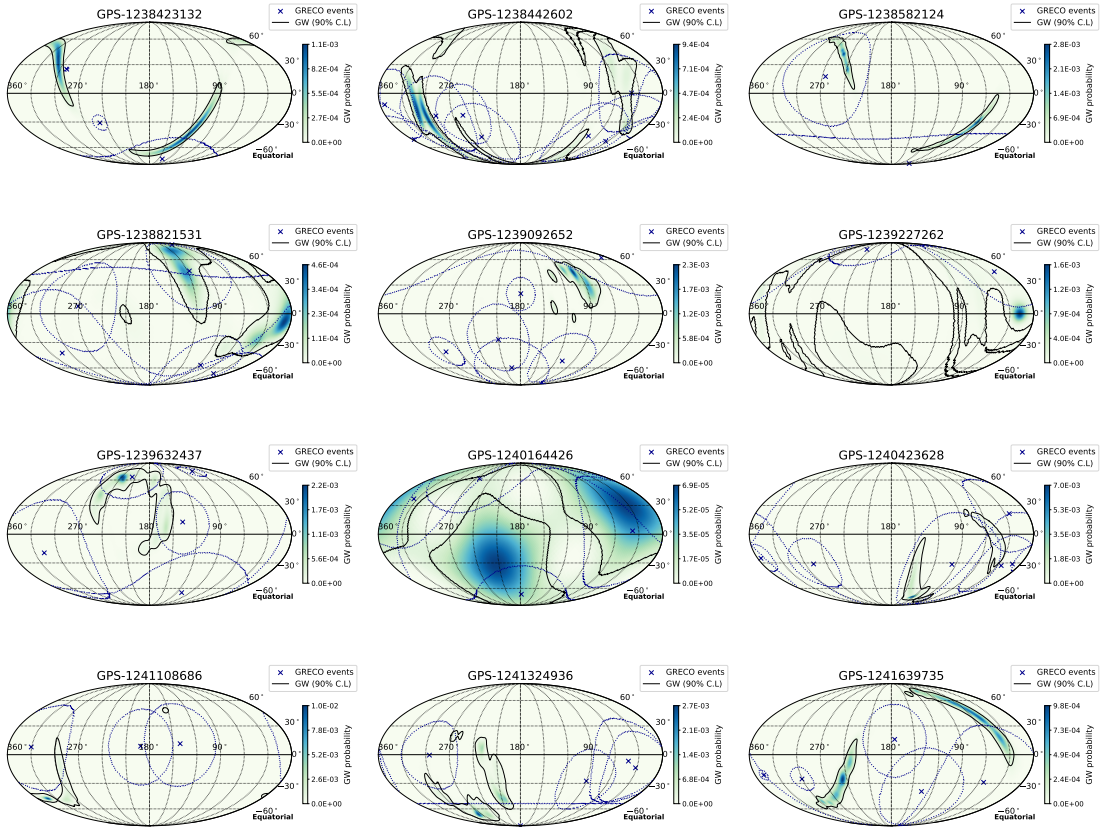


Figure B.1.: Joint GW + neutrino skymap for GWs shortlisted from O3a (continued).

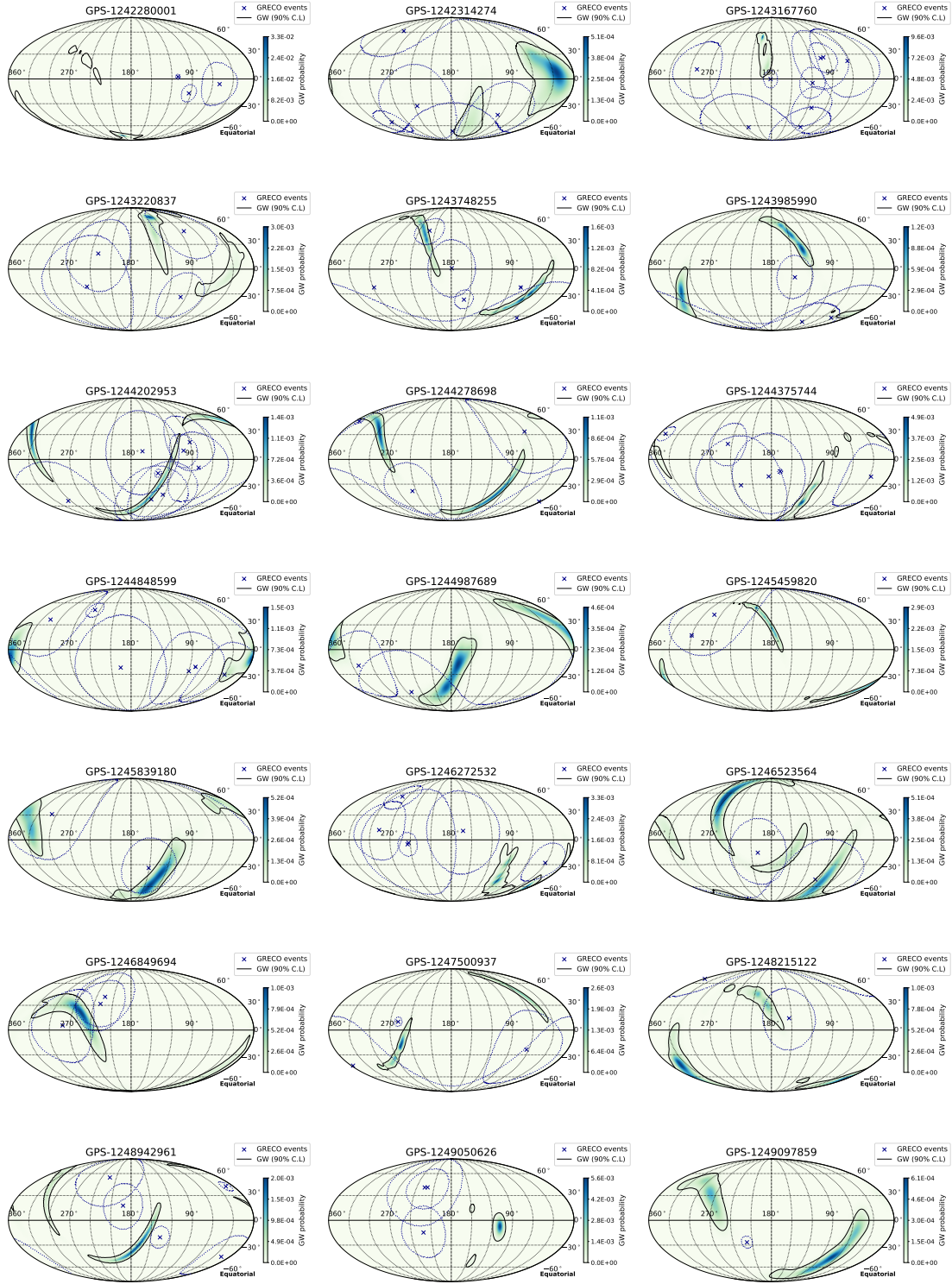


Figure B.1.: Joint GW + neutrino skymap for GWs shortlisted from O3a (continued).

Significance corresponding to p_{pre}

For each of the shortlisted GW, the observed p_{pre} -value is tabulated in Tab. 7.1. The corresponding significance is calculated following Eq. 5.6. The associated distribution for 103 GWs

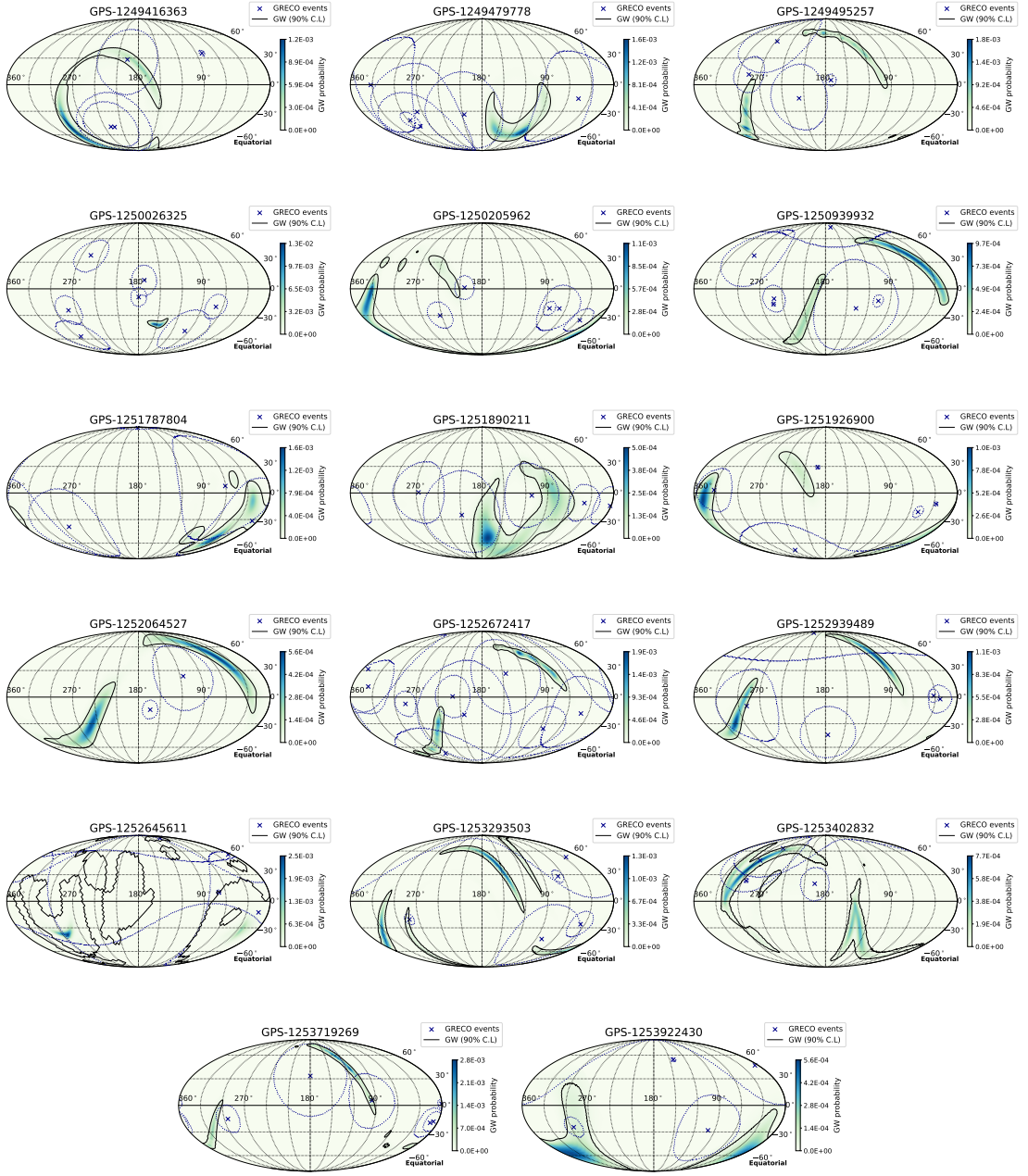


Figure B.1.: Joint GW + neutrino skymap for GWs shortlisted from O3a (continued).

is shown in Fig. B.2 for completeness. The one event with significance $> 3\sigma$ corresponds to PyCBC-HM-1261717507. After trial-correction, the significance drops to $< 2\sigma$.

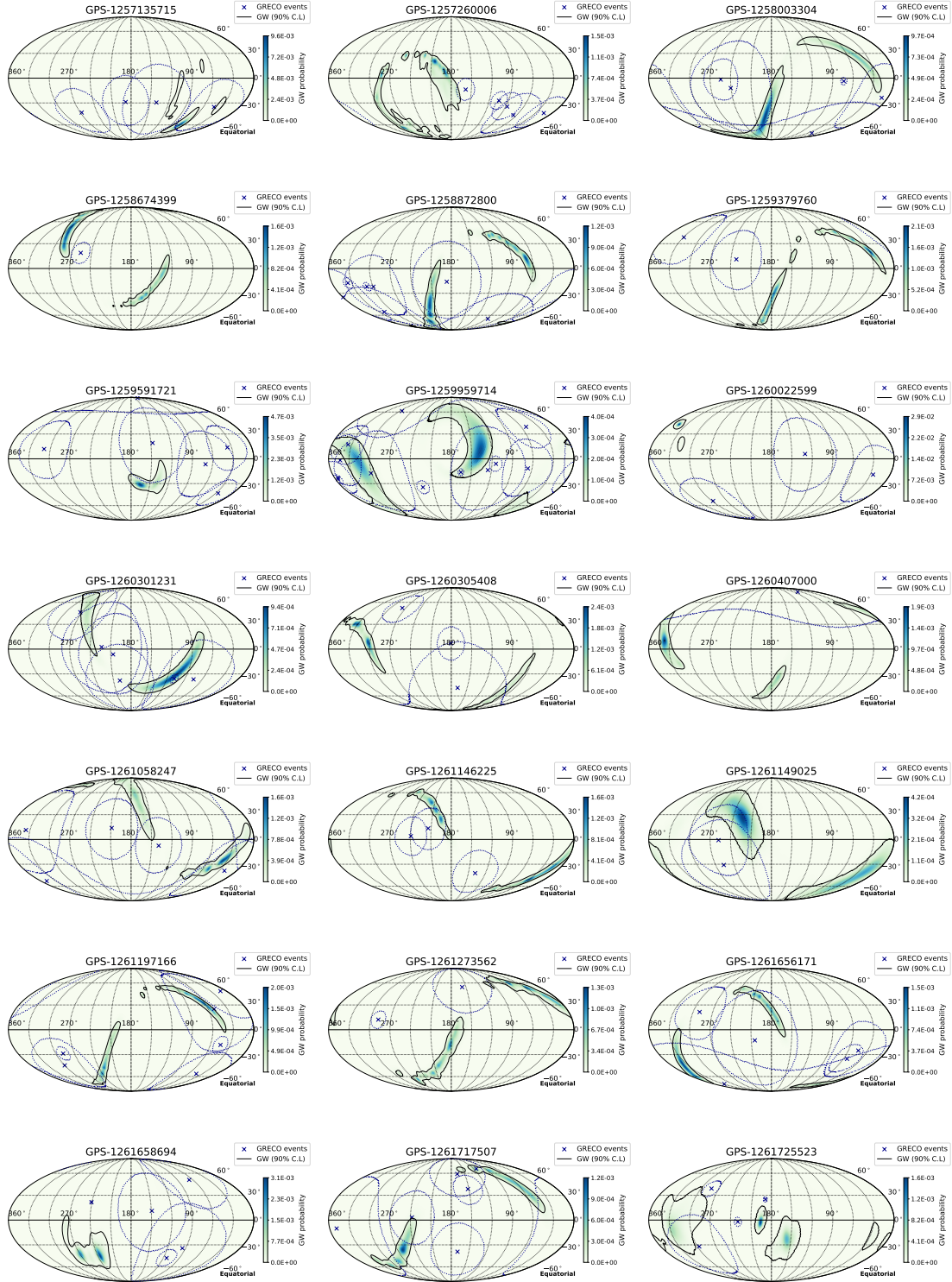


Figure B.1.: Joint GW + neutrino skymap for GWs shortlisted from O3b (continued).

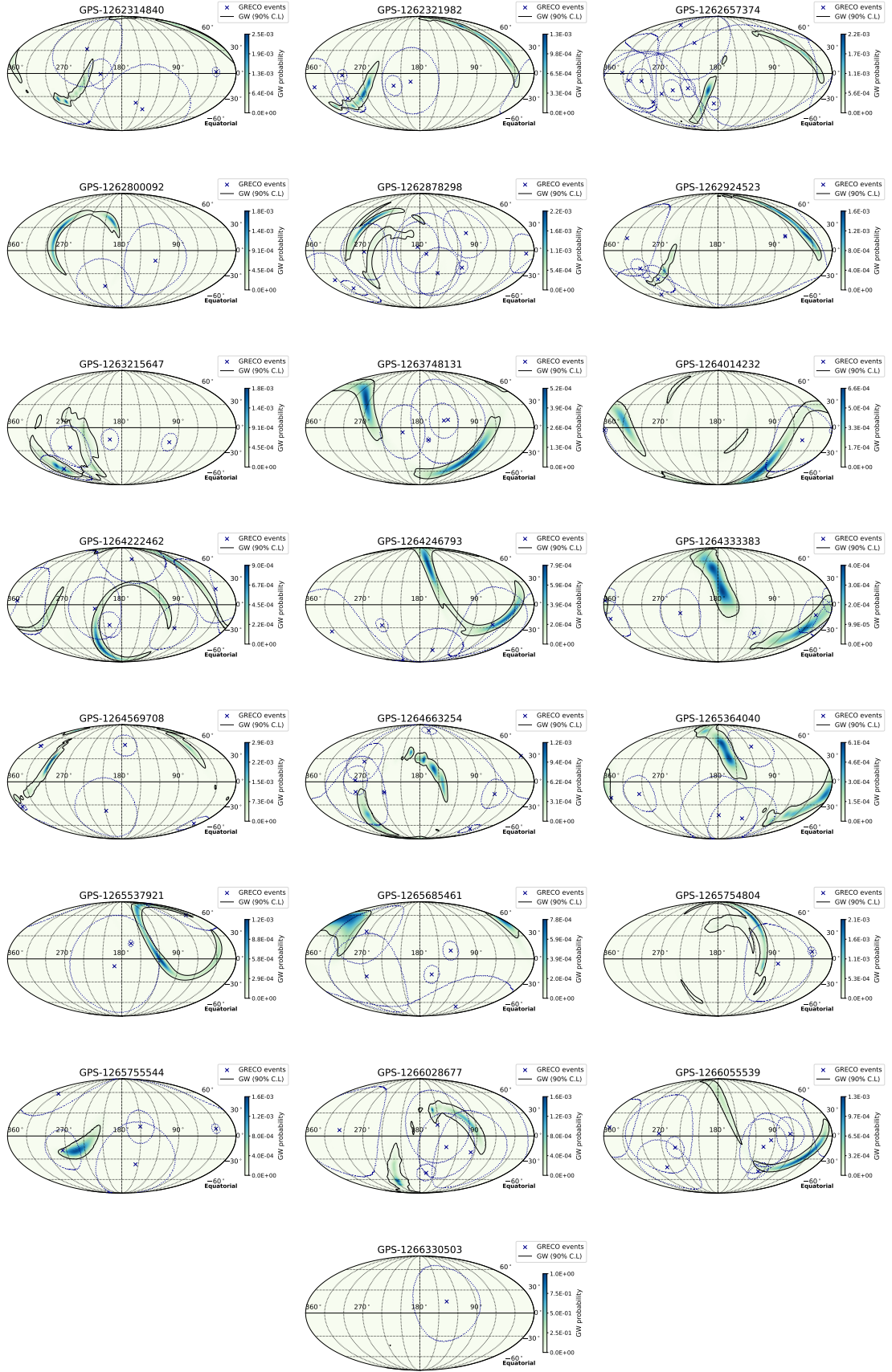


Figure B.1.: Joint GW + neutrino skymap for GWs shortlisted from O3b (continued).

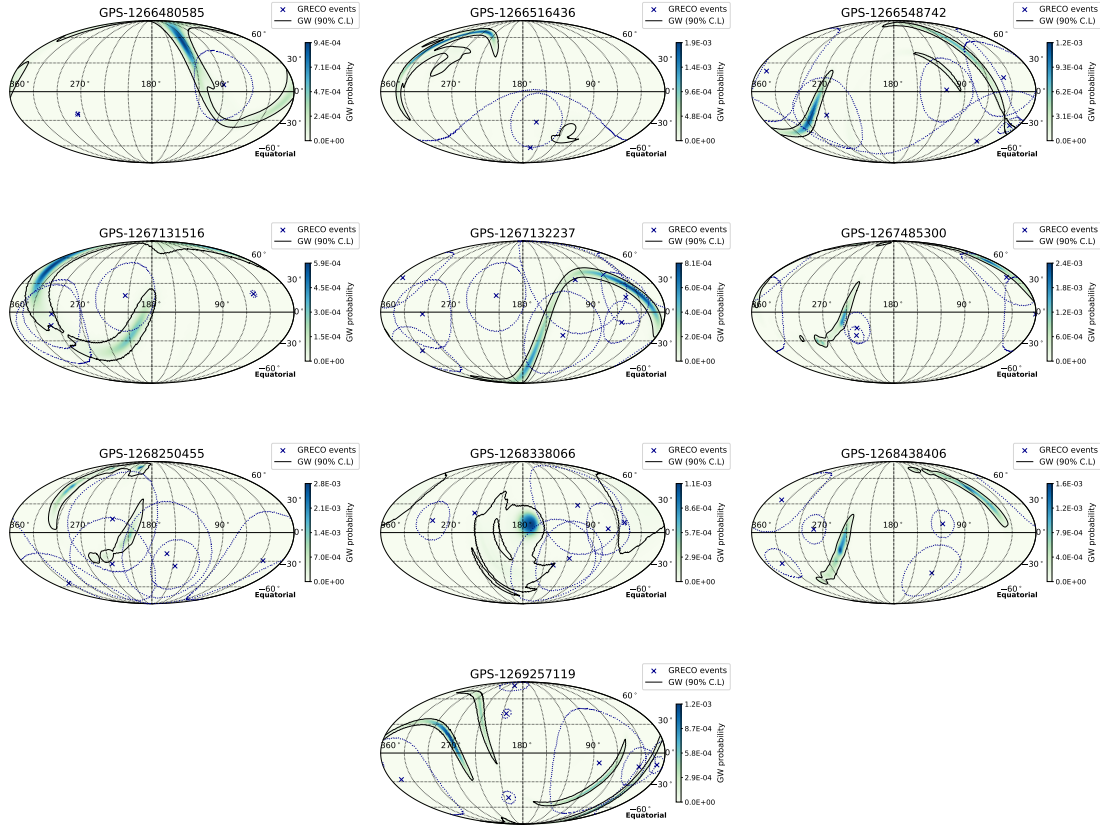


Figure B.1.: Joint GW + neutrino skymap for GWs shortlisted from O3b.

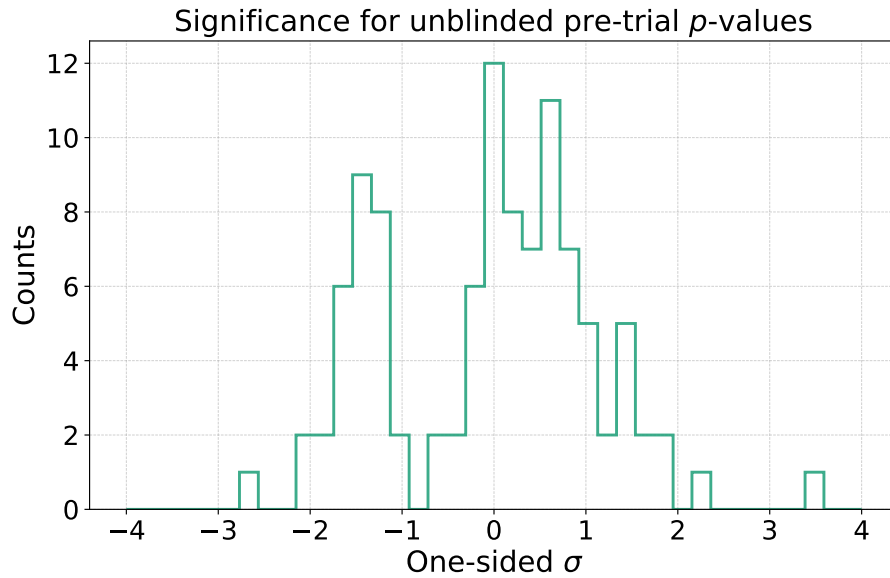


Figure B.2.: The one-sided sigma value corresponding to each unblinded pre-trial p -value. The one with significance $> 3\sigma$ corresponds to PyCBC-HM-1261717507.

C. Background Event Simulation

This appendix refers to Chapter 8. It contains additional plots and calculations on the background neutrino flux for different declinations and the effective area for different detectors, such as IceCube, PLEvM-1, IceCube-Gen2, and PLEvM-2.

Zenith and declination mapping for Northern Hemisphere

As a part of this work, zenith angle (θ) values ranging from 90° to 180° , which correspond to upward-going neutrinos (i.e., originating from the Northern Hemisphere from IceCube's perspective), are considered.

Following Eq. 8.1, for IceCube, $\theta = 90^\circ - \delta$. Due to the spherical symmetry of the Earth and the atmosphere, the atmospheric neutrino flux (ϕ_v^{atm}) satisfies the mirror symmetry:

$$\begin{aligned}\phi_v^{\text{atm}}(\cos \theta) &= \phi_v^{\text{atm}}(-\cos \theta) \\ &= \phi_v^{\text{atm}}(\cos(180^\circ - \theta)).\end{aligned}\tag{C.1}$$

This implies the following mapping between the NH and SH:

$$\theta_{\text{NH}} = 180^\circ - \theta_{\text{SH}}$$

So, for corresponding declinations, the atmospheric flux could be obtained in this manner, solving the MCEq [361]:

$$\begin{aligned}\phi_v^{\text{atm}}(\theta_{\text{NH}} = 0^\circ) &= \phi_v^{\text{atm}}(\theta_{\text{SH}} = 180^\circ), & \delta = 90^\circ \\ \phi_v^{\text{atm}}(\theta_{\text{NH}} = 10^\circ) &= \phi_v^{\text{atm}}(\theta_{\text{SH}} = 170^\circ), & \delta = 80^\circ \\ \phi_v^{\text{atm}}(\theta_{\text{NH}} = 20^\circ) &= \phi_v^{\text{atm}}(\theta_{\text{SH}} = 160^\circ), & \delta = 70^\circ \\ &\vdots \\ \phi_v^{\text{atm}}(\theta_{\text{NH}} = 80^\circ) &= \phi_v^{\text{atm}}(\theta_{\text{SH}} = 100^\circ), & \delta = 10^\circ\end{aligned}$$

At the horizon ($\delta = 0^\circ$), $\theta = 90^\circ$. So, $\phi_v^{\text{atm}}(\theta = 90^\circ)$ for $\delta = 0^\circ$.

The results for atmospheric muon neutrino background flux at different declination ranges, across a wide energy range of $10^3 - 10^7$ GeV is shown in Fig. C.1.

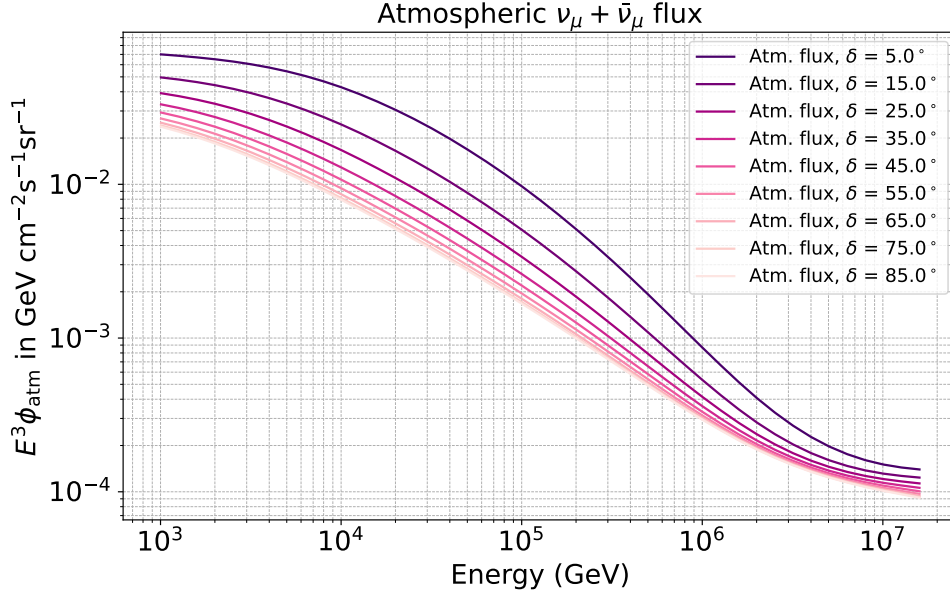


Figure C.1.: The energy dependence of the atmospheric muon neutrino background is shown here for nine distinct declination values. Obtained from the solution of MCEq.

Effective area for different configurations

To simulate the number of background events in the Northern Hemisphere for IceCube, PLEvM-1, Gen-2, and PLEvM-2, their corresponding effective area information is needed. It is obtained using the PLEvM code¹ [358]. The individual plots for each detector configuration is shown in Fig. C.2.

These effective area values for each energy and declination bin is used to compute the energy-dependent number of background events across the Northern Hemisphere, in 10° declination bins. The calculation for that is presented in the next section.

Background estimation

For all the source models considered, the observation time-windows (Δt) range between 1000 s to 5×10^6 s. For these values of Δt , the background counts ($N_{\nu_\mu}^{\text{bkg}}$) per energy and declination bin are quantified in the following manner, considering the total background neutrino of atmospheric muon neutrinos and the diffuse astrophysical muon neutrino flux.

¹GitHub repository: <https://github.com/PlaNuM-group/Plenum>

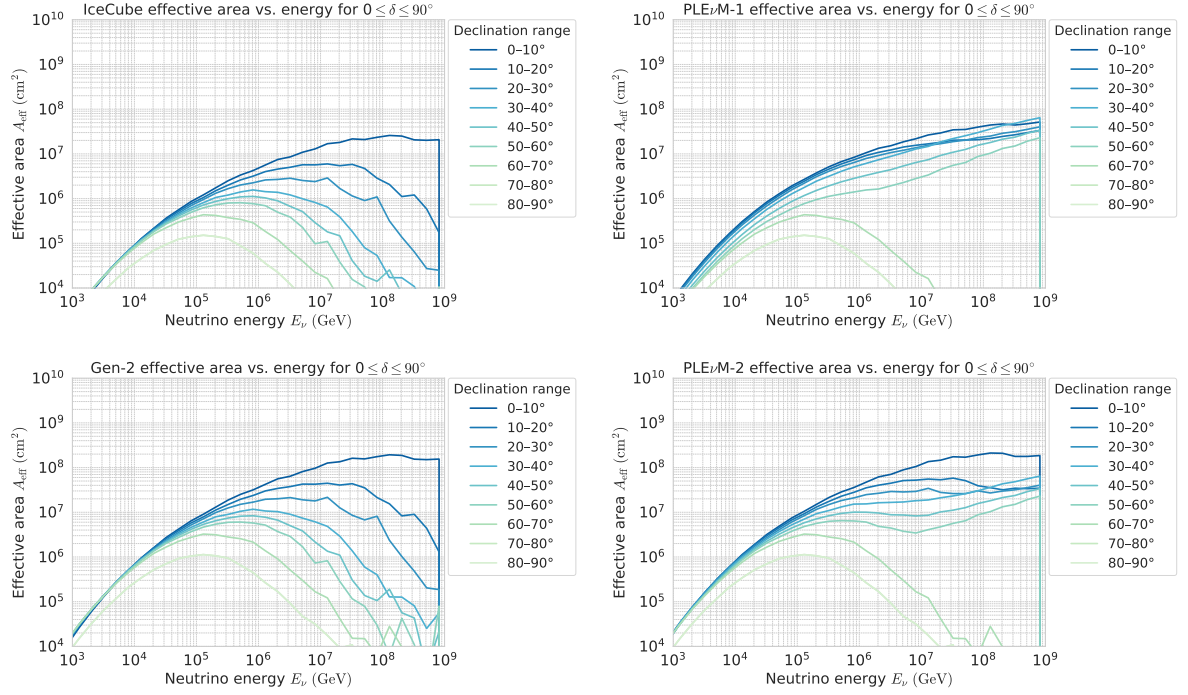


Figure C.2.: The effective area for IceCube, PLEvM-1, IceCube-Gen2, and PLEvM-2, in the energy range of $10^3 - 10^9$ GeV, in the Northern Hemisphere, in 10° declination bins.

$$\begin{aligned}
N_{\nu_\mu}^{\text{bkg}} &= \int_0^{\Delta t} dt \int d\Omega \int_{E_{\min}}^{E_{\max}} dE \phi_{\text{tot}}^{\text{bkg}}(\theta, E) A_{\text{eff}}(\delta, E) \\
&= \Delta t \int_0^{2\pi} d\phi \int_{\theta_1}^{\theta_2} \sin\theta d\theta \int_{E_{\min}}^{E_{\max}} dE \phi_{\text{tot}}^{\text{bkg}}(\theta, E) A_{\text{eff}}(\delta, E) \\
&= \Delta t 2\pi \int_{\delta_1}^{\delta_2} \cos\delta d\delta \int_{E_{\min}}^{E_{\max}} dE \phi_{\text{tot}}^{\text{bkg}}(\theta, E) A_{\text{eff}}(\delta, E) \\
&= \Delta t 2\pi \sin(\delta_2 - \delta_1) \int_{E_{\min}}^{E_{\max}} dE \phi_{\text{tot}}^{\text{bkg}}(\theta, E) A_{\text{eff}}(\delta, E) \quad (\text{C.2})
\end{aligned}$$

Following the relation described above, $N_{\nu_\mu}^{\text{bkg}}$ is quantified for IceCube, PLEvM-1, IceCube-Gen2, and PLEvM-2. For this step, their corresponding A_{eff} within $10^3 - 10^7$ GeV energy range, and $\Delta t = [1000, 10^4, 7 \times 10^4, 8 \times 10^5, 5 \times 10^6]$ s are considered. The choice of time duration for background estimation is influenced by the fluence estimations provided by the benchmark neutrino flux models from [116, 117, 373]. The results are included below.

Background estimation for different detectors and time-windows

For IceCube, the results are shown first. The background computed for 1000 s is used for the signal estimation for BNS merger-like events, as shown in Appendix D. Others are used to

quantify the detection significance of signal neutrinos coming from BBN-merger-like events in AGN disk, as shown in Sec. 8.3, 8.4.

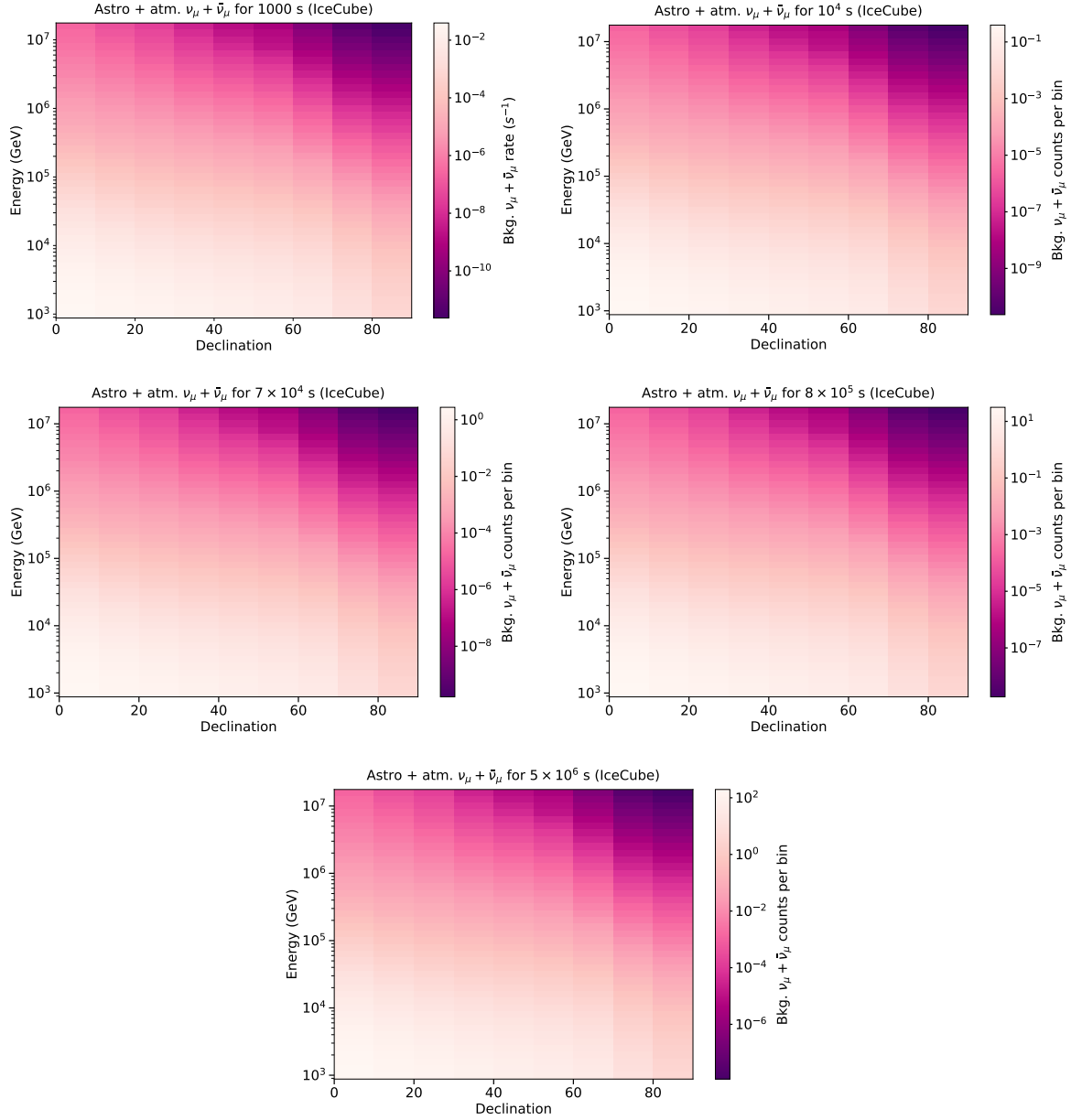


Figure C.3.: Background estimation using IceCube effective area, for various time windows, corresponding to different signal models.

For PLEvM-1, the results are shown next. The background computed for 1000 s is used for the signal estimation for BNS merger-like events, as shown in Appendix D. Others are used to quantify the detection significance of signal neutrinos coming from BBN-merger-like events in AGN disk, as shown in Sec. 8.3, 8.4.

For IceCube-Gen2, the results are shown here. The background computed for 1000 s is used for the signal estimation for BNS merger-like events, as shown in Appendix D. Others are used

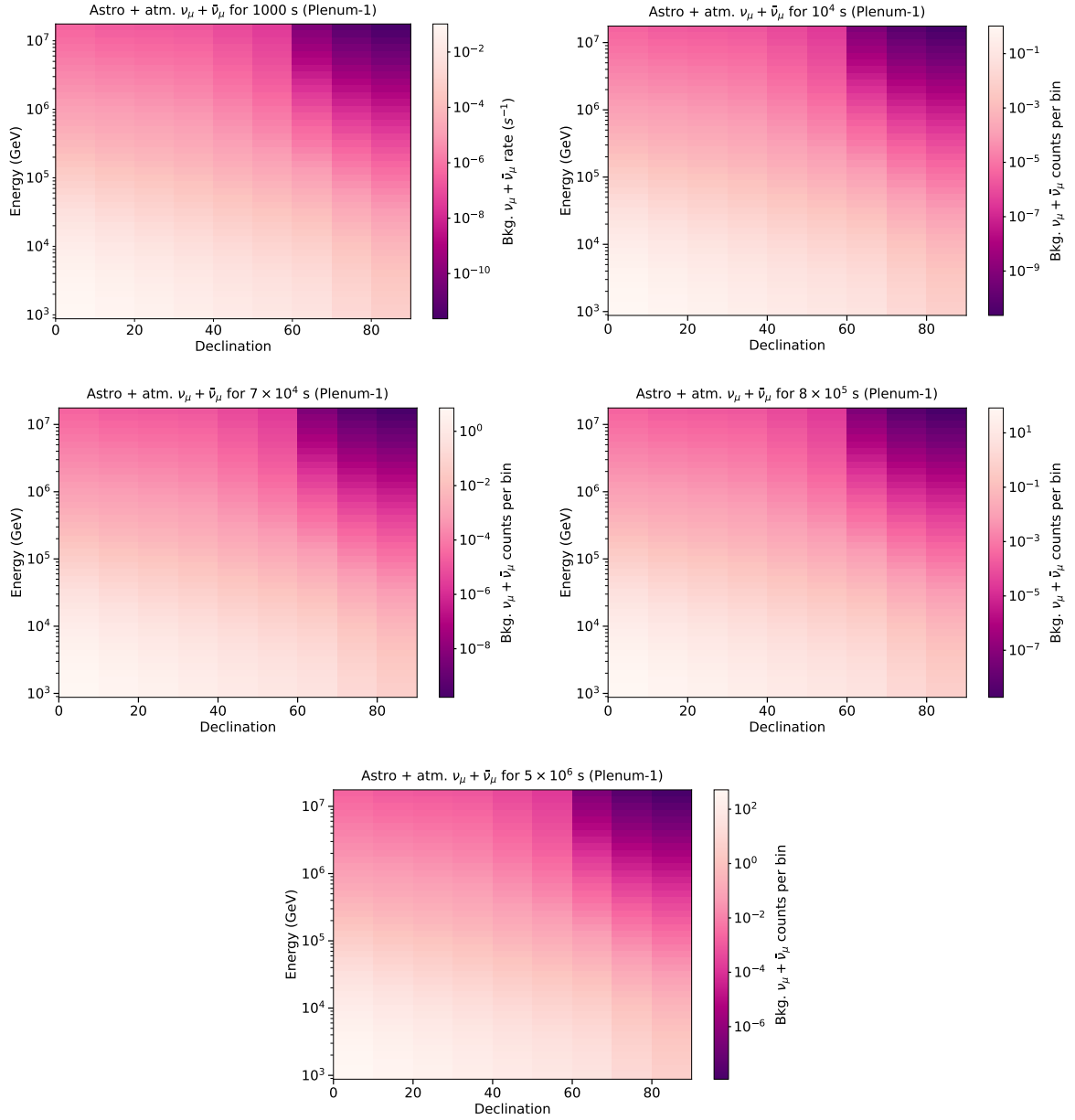


Figure C.4.: Background estimation using PlevM-1 effective area, for various time windows, corresponding to different signal models.

to quantify the detection significance of signal neutrinos coming from BBN-merger-like events in AGN disk, as shown in Sec. 8.3, 8.4.

Finally, for PLEvM-2, the results are shown here. The background computed for 1000 s is used for the signal estimation for BNS merger-like events, as shown in Appendix D. Others are used to quantify the detection significance of signal neutrinos coming from BBN-merger-like events in AGN disk, as shown in Sec. 8.3, 8.4.

For all these detectors, the computed background event numbers for different time windows is then used to quantify the significance of signal detection within the same time window, considering different source scenarios. One example is shown in Appendix D.

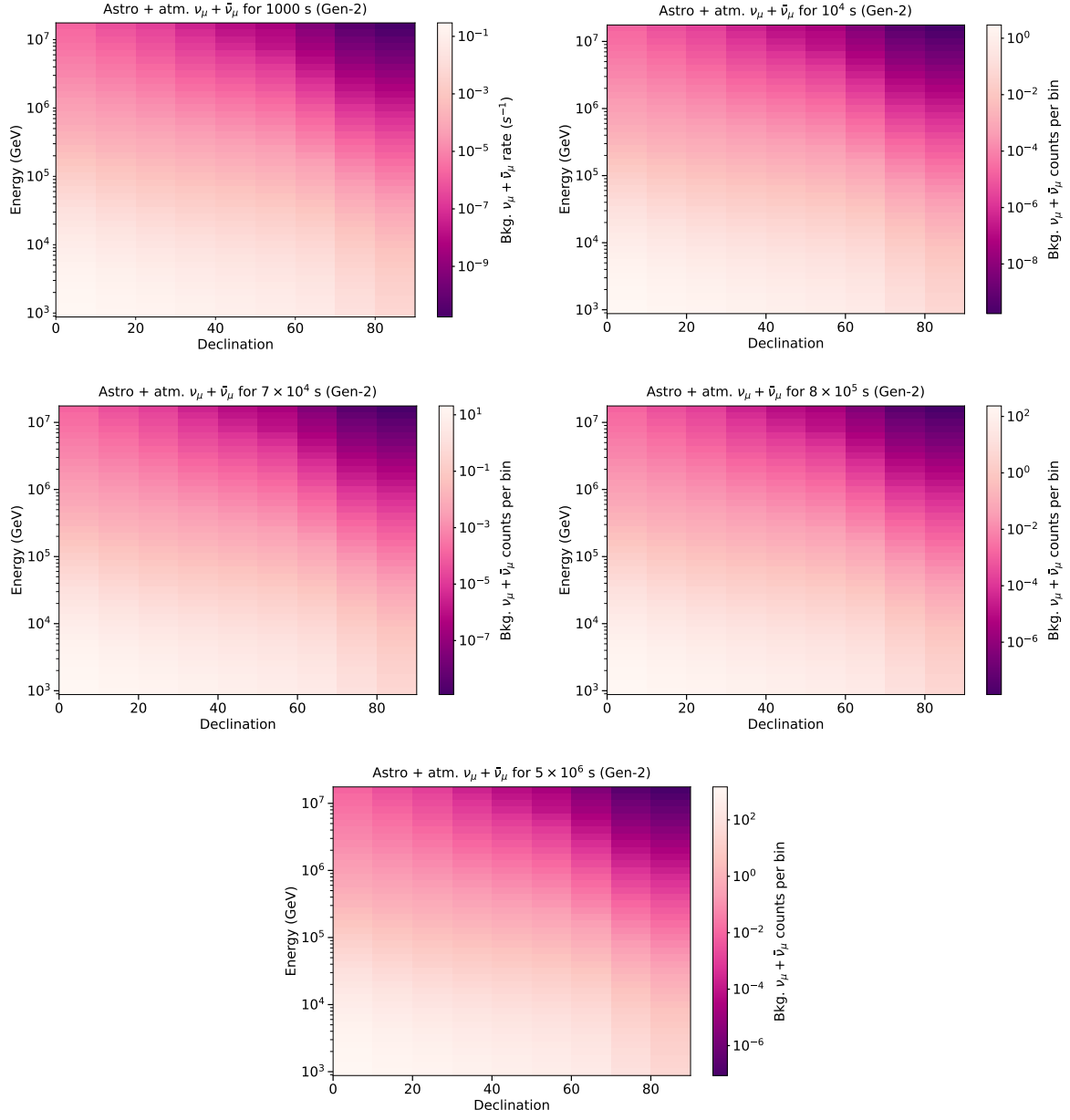


Figure C.5.: Background estimation using IceCube-Gen2 effective area, for various time windows, corresponding to different signal models.

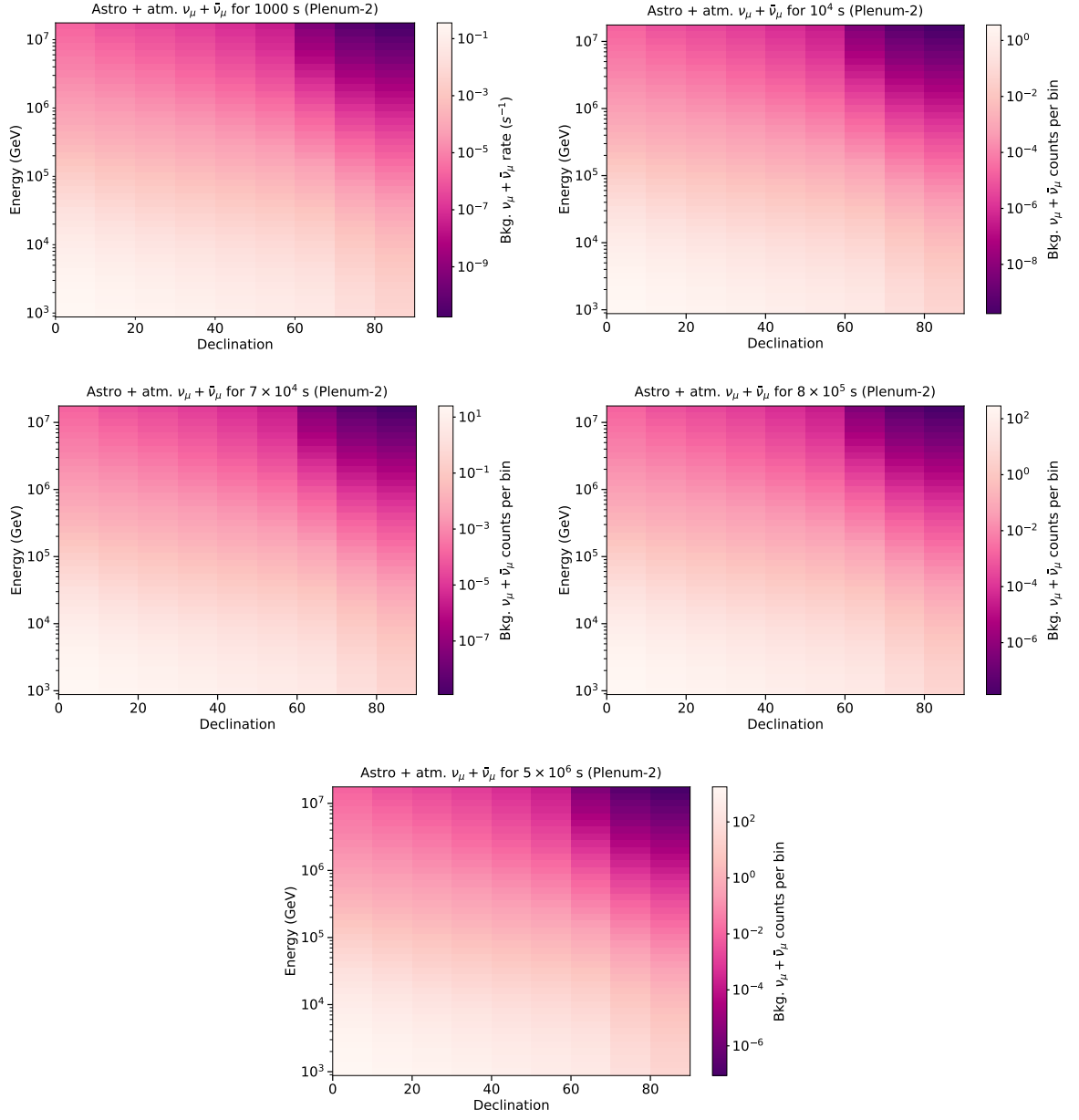


Figure C.6.: Background estimation using PlevM-2 effective area, for various time windows, corresponding to different signal models.

D. Search Prospect for Compact Binary Merger-like Sources

This appendix refers to Chapter 8. It contains results for the catalogue search prospects for individual Binary Neutron Star (BNS) merger sources, considering different neutrino detector configurations. We consider the BNS merger-like sources simply because they are the most promising and extensively studied multi-messenger GW sources, accompanied by precise theoretical modelling. The study was mainly performed for benchmarking the signal simulation method, which is later employed for BBH merger-like sources which suitable flux models, as shown in Sec. 8.3, 8.4.

High-energy neutrino emission from Binary Neutron Star mergers

In [373], for a BNS merger-like source, the authors estimate the HEN fluence for different phases of sGRBs, including prompt emission, EE, X-ray flares, and plateau emission. In the sGRB environment, the non-thermal protons, which eventually interact with the ambient photons, accelerate via diffusive shocks. On the other hand, they lose energy via photo-meson ($p\gamma$) cooling, adiabatic cooling and synchrotron radiation. The acceleration process continues until the acceleration timescale, t_{acc} is more than the cooling timescales. In these scenarios, the protons lose energy through cooling before being accelerated to a specific energy. The relevant acceleration and cooling timescales are given in Eq. D.2.

$$t_{\text{acc}} = \frac{\varepsilon_p}{ceB} \quad (\text{D.1})$$

$$t_{p\gamma} = \frac{c}{2\gamma_p^2} \int_{\bar{\varepsilon}_{th}}^{\infty} d\bar{\varepsilon}_\gamma \sigma_{p\gamma} \kappa_{p\gamma} \bar{\varepsilon} \int_{\bar{\varepsilon}/2\gamma}^{\infty} d\varepsilon_\gamma \varepsilon_\gamma^{-2} \frac{dn}{d\varepsilon_\gamma},$$

$$t_{\text{syn}} = \frac{6\pi m_i^4 c^3}{m_e^2 \sigma_T B^2 \varepsilon_i},$$

$$t_{\text{dyn}} = \frac{r_{\text{diss}}}{c\Gamma} \quad (\text{D.2})$$

In the above equations, other than the constants bearing their usual meaning, B is the magnetic field strength. $\gamma_p = \frac{\varepsilon_p}{m_p c^2}$, $\bar{\varepsilon}_{th} = 145$ MeV is the threshold for photomeson production. ε_γ is the photon energy in rest frame. $\sigma_{p\gamma}$ and $\kappa_{p\gamma}$ are respectively, the cross-section and inelasticity relevant to photomeson production. m_i and ε_i are respectively the mass and energy of particle species ‘i’, undergoing synchrotron cooling, and m_e is the mass of electron. σ_T is the Thompson scattering cross-section. The whole framework is detailed in [373]

Hence, the proton energy in the fluid rest frame for which $t_{\text{acc}} < (t_{\text{syn}}, t_{\text{dyn}}, t_{p\gamma})$, gives us the maximum proton energy $\epsilon_{p,\text{max}}$. In the observer's frame, we can define the maximum proton energy as

$$E_{p,\text{max}} = \Gamma \epsilon_{p,\text{max}} \quad (\text{D.3})$$

where Γ is the Lorentz factor. These protons then interact with the ambient photons and produce pions following the photo-meson production process. The pions decay and produce electron and muon neutrinos. Due to neutrino mixing, the neutrino flux on Earth is $(\nu_e : \nu_\mu : \nu_\tau) = (1:1:1)$, instead of $(1:2:0)$ at the source. The flux values are determined using a tri-bimaximal mixing matrix, given in [374].

To calculate the neutrino flux during the different GRB phases, such as prompt, plateau, extended emission, etc., standard values for the useful model parameters are considered. These values are tabulated in Tab. 1 in [373], and are observationally motivated [375–385]. As a part of this work, flux values are adopted directly from the paper. Given these flux values, the expected number of signal ν_μ events can be calculated as the number of up-going tracks for detectors like IceCube and its future extension, IceCube-Gen2. The number of ν_μ depends on the effective area of the chosen detector. As a part of this work, IceCube, PLEvM-1, IceCube-Gen2, and PLEvM-2 are considered, similar to what is done for Ch. 8.

Signal Calculation

Folding the effective area (A_{eff}) information, signal neutrino numbers could be calculated using Eq. D.4.

$$\begin{aligned} N_{\nu_\mu + \bar{\nu}_\mu}^{\text{BNS}} &= 2 \times \int_0^{\Delta t} dt \int_{E_{\text{min}}}^{E_{\text{max}}} dE \phi_{\nu_\mu}^{\text{BNS}}(E_\nu) A_{\text{eff}}(\delta, E_\nu) \\ &= 2 \times \Delta t \int_{E_{\text{min}}}^{E_{\text{max}}} dE \phi_{\nu_\mu}^{\text{BNS}}(E_\nu) A_{\text{eff}}(\delta, E_\nu) \end{aligned} \quad (\text{D.4})$$

Here, $\phi_{\nu_\mu}^{\text{BNS}}$ is the flux obtained from a single BNS merger located 300 Mpc away from the Earth, as provided in [373]. The time-window is chosen to be 1000 s. The results for four different detector configurations, i.e., IceCube, PLEvM-1, IceCube-Gen2, and PLEvM-2 are shown in Fig. D.1. The results are relevant for an optimistic case for the extended emission scenario. For all other cases, the signal count is too low and almost non-significant.

For the optimistic scenario considered for extended emission, the maximum number of signal events recorded by all detectors in 1000 s comes from near the horizon, where declination is $0^\circ \leq \delta \leq 10^\circ$. The signal count for IceCube matches lies in the same ballpark as predicted in [373]. It is further enhanced for PLEvM-1, IceCube-Gen2, and PLEvM-2 due to larger A_{eff} coverage all over the sky.

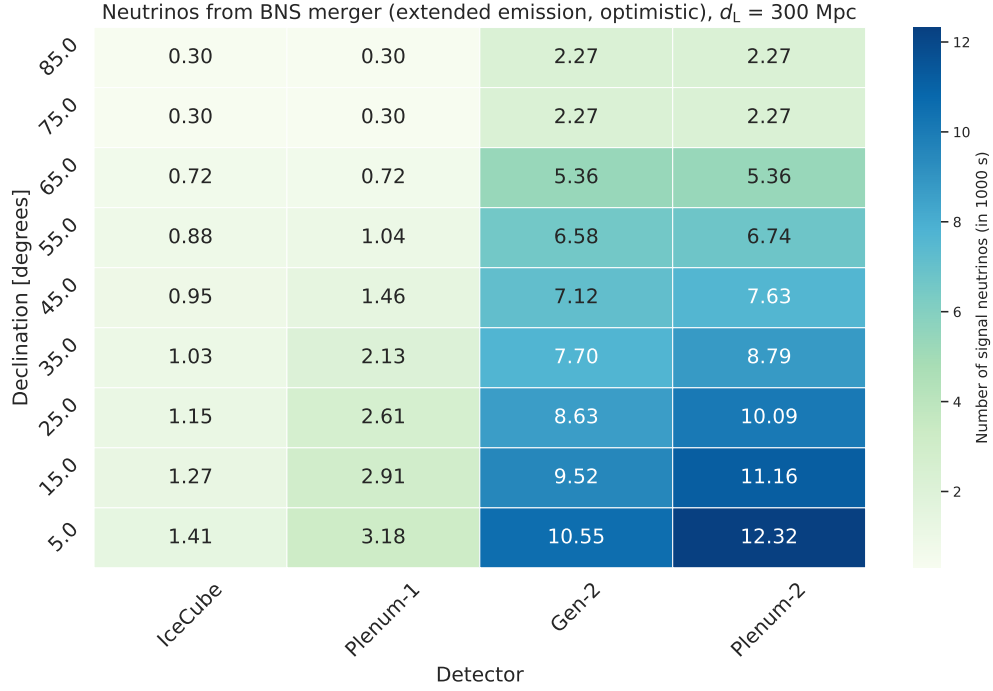


Figure D.1.: Number of signal neutrinos detected by different TeV-PeV neutrino detector configurations in 1000 s during the extended emission of a binary neutron star merger, located $d_L = 300$ Mpc away from Earth.

Significance Calculation

Using the signal count obtained previously, joint emission detection significance from a single source of BNS merger, located 300 Mpc away from the Earth is estimated.

To quantify the significance, suppose, the rate of signal neutrinos coming from our astrophysical sources as recorded by our detectors is R_{sig} . For a considered time window, Δt , the total number of signal neutrinos would be,

$$N_{\text{sig}} = R_{\text{sig}} \times \Delta t \quad (\text{D.5})$$

Similarly, if the background atmospheric neutrino detection rate for a detector is R_{bkg} , the total number of signal neutrinos for the same time-window Δt is,

$$N_{\text{bkg}} = R_{\text{bkg}} \times \Delta t \quad (\text{D.6})$$

Using Eq. D.5 and Eq. D.6, the total number of neutrinos that any neutrino detector would be the sum of the signal and background neutrinos detected during Δt . Hence, the total number of neutrinos (N_v) detected during Δt is,

$$\begin{aligned} N_v &= N_{\text{sig}} + N_{\text{bkg}} \\ &= (R_{\text{sig}} + R_{\text{bkg}}) \times \Delta t \end{aligned} \quad (\text{D.7})$$

Now, as per our definition, $N_{\text{sig}} = N_v - N_{\text{bkg}}$. So, the variance,

$$\sigma(N_{\text{sig}}) = \sqrt{N_v} \quad (\text{D.8})$$

Given, $\langle N_{\text{bkg}} \rangle = 0$

The associated significance is defined as $\frac{N_{\text{sig}}}{\sigma}$. It is given as follows:

$$\begin{aligned} \text{significance} &= \frac{N_{\text{sig}}}{\sigma} \\ &= \frac{N_{\text{sig}}}{\sqrt{N_v}} \\ &= \frac{N_{\text{sig}}}{\sqrt{N_{\text{sig}} + N_{\text{bkg}}}} \end{aligned} \quad (\text{D.9})$$

$$\begin{aligned} &= \frac{R_{\text{sig}} \times \Delta t}{\sqrt{(R_{\text{sig}} + R_{\text{bkg}}) \times \Delta t}} \\ &= \frac{R_{\text{sig}} \times \sqrt{\Delta t}}{\sqrt{(R_{\text{sig}} + R_{\text{bkg}})}} \end{aligned} \quad (\text{D.10})$$

Thus, $\text{significance} \propto \sqrt{\Delta t}$. As a consequence, for longer observation time-windows, detection significance would increase, as also seen for the results presented in Sec. 8.3.

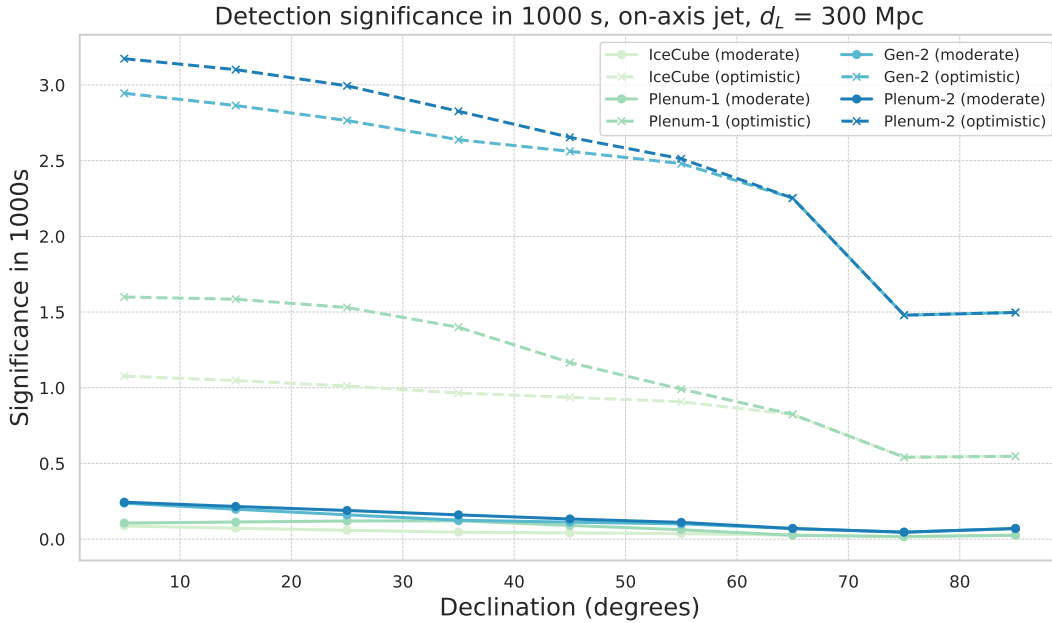


Figure D.2.: The detection significance within a time window of 1000 s, for detecting neutrinos during the extended emission of a BNS merger occurring 300 Mpc away from Earth.

Using Eq. D.9, we can directly calculate the significance of neutrino detection for $\Delta t = 1000$ s, for individual BNS mergers, inserting previously obtained $N_{\nu_\mu + \bar{\nu}_\mu}^{\text{BNS}}$ and $N_{\nu_\mu + \bar{\nu}_\mu}^{\text{bkg}}$ for signal and

background counts respectively. The background estimation for 1000 s time window is demonstrated in Appendix C. The corresponding results are shown in Fig. D.2.

It is observed that with IceCube, the detection prospect is non-significant, given the faint signal received during the 1000 s time-window in the TeV-PeV energy range, from the BNS merger source. PLEvM-2 also does not offer a huge advantage in the Northern Hemisphere. However, with IceCube-Gen2, and PLEvM-2's much enhanced A_{eff} coverage in the declination range considered for this work, the detection significance can reach 3σ near the horizon, overcoming the existing background in that energy range. The detection significance decreases as we go further away from the preferred declination bin with largest A_{eff} coverage, as the signal count decreases.

Seeing this promising trend for the next generation and larger neutrino detector configurations, now the framework is applied to estimate the detection prospects of high-energy neutrinos coming from BBH-merger sources, as discussed in Ch. 8. An additional plot on significance calculation is included here, relevant to the scenario presented in Sec. 8.3, Fig. 8.10.

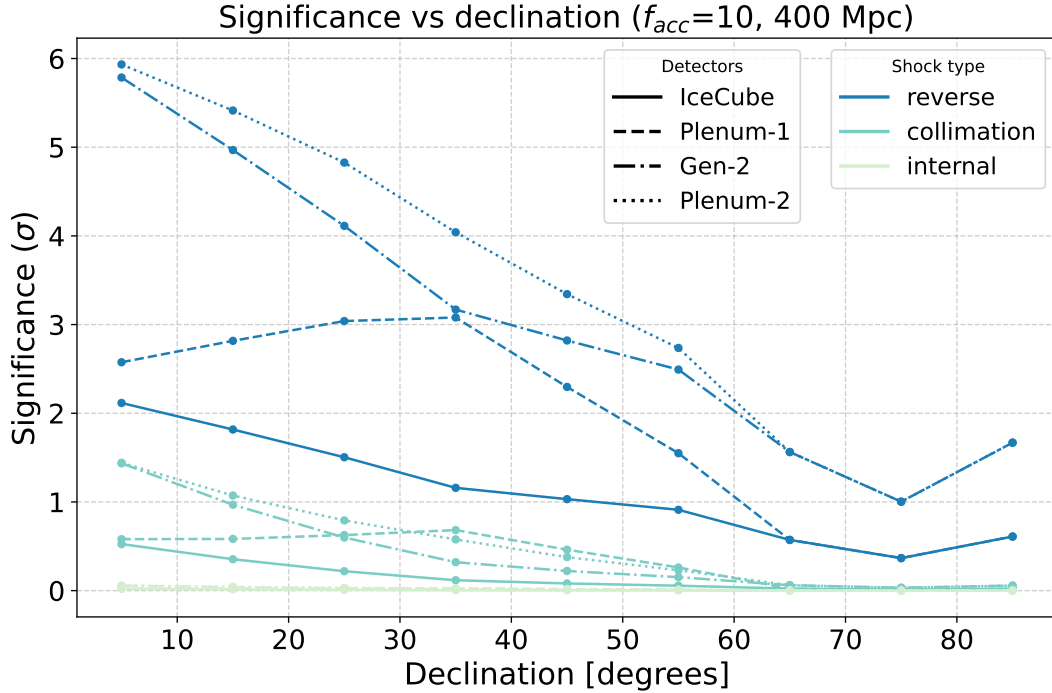


Figure D.3.: The detection significance quantified for a source located at 400 Mpc, referring to the scenario presented in Fig. 8.10, specifically $10^3 R_g$ away from the AGN core, $f_{\text{acc}} = 10$, and $\Delta t = 5 \times 10^6$ s, for reverse, internal, and collimated shocks. Different high-energy neutrino detector configurations are considered.

In this case, for very close source with $d_L = 400$ Mpc, reaching a detection significance of 3σ or higher could only be possible considering an optimistic scenario with high accretion rate ($f_{\text{acc}} = 10$), efficient reverse shock acceleration, and a detector with bigger A_{eff} coverage, such as PLEvM-1, Gen-2, or PLEvM-2.

Bibliography

- [1] ICECUBE collaboration, *Evidence for High-Energy Extraterrestrial Neutrinos at the IceCube Detector*, *Science* **342** (2013) 1242856 [1311.5238].
- [2] LIGO SCIENTIFIC, VIRGO collaboration, *Observation of Gravitational Waves from a Binary Black Hole Merger*, *Phys. Rev. Lett.* **116** (2016) 061102 [1602.03837].
- [3] LIGO SCIENTIFIC, VIRGO, FERMI GBM, INTEGRAL, ICECUBE, ASTROSAT CADMIUM ZINC TELLURIDE IMAGER TEAM, IPN, INSIGHT-HXMT, ANTARES, SWIFT, AGILE TEAM, 1M2H TEAM, DARK ENERGY CAMERA GW-EM, DES, DLT40, GRAWITA, FERMI-LAT, ATCA, ASKAP, LAS CUMBRES OBSERVATORY GROUP, OZGRAV, DWF (DEEPER WIDER FASTER PROGRAM), AST3, CAASTRO, VINROUGE, MASTER, J-GEM, GROWTH, JAGWAR, CALTECHNRAO, TTU-NRAO, NUSTAR, PAN-STARRS, MAXI TEAM, TZAC CONSORTIUM, KU, NORDIC OPTICAL TELESCOPE, EPESSTO, GROND, TEXAS TECH UNIVERSITY, SALT GROUP, TOROS, BOOTES, MWA, CALET, IKI-GW FOLLOW-UP, H.E.S.S., LOFAR, LWA, HAWC, PIERRE AUGER, ALMA, EURO VLBI TEAM, PI OF SKY, CHANDRA TEAM AT MCGILL UNIVERSITY, DFN, ATLAS TELESCOPES, HIGH TIME RESOLUTION UNIVERSE SURVEY, RIMAS, RATIR, SKA SOUTH AFRICA/MEERKAT collaboration, *Multi-messenger Observations of a Binary Neutron Star Merger*, *Astrophys. J. Lett.* **848** (2017) L12 [1710.05833].
- [4] ICECUBE collaboration, *Neutrino emission from the direction of the blazar TXS 0506+056 prior to the IceCube-170922A alert*, *Science* **361** (2018) 147 [1807.08794].
- [5] ICECUBE collaboration, *Evidence for neutrino emission from the nearby active galaxy NGC 1068*, *Science* **378** (2022) 538 [2211.09972].
- [6] ICECUBE collaboration, *Observation of high-energy neutrinos from the Galactic plane*, *Science* **380** (2023) adc9818 [2307.04427].
- [7] ANTARES, ICECUBE, PIERRE AUGER, LIGO SCIENTIFIC, VIRGO collaboration, *Search for High-energy Neutrinos from Binary Neutron Star Merger GW170817 with ANTARES, IceCube, and the Pierre Auger Observatory*, *Astrophys. J. Lett.* **850** (2017) L35 [1710.05839].
- [8] ICECUBE collaboration, *IceCube Search for Neutrinos Coincident with Compact Binary Mergers from LIGO-Virgo's First Gravitational-wave Transient Catalog*, *Astrophys. J. Lett.* **898** (2020) L10 [2004.02910].
- [9] ICECUBE collaboration, *IceCube Search for Neutrinos Coincident with Gravitational Wave Events from LIGO/Virgo Run O3*, *The Astrophysical Journal* **944** (2023) 80.
- [10] ICECUBE collaboration, *A Search for IceCube Sub-TeV Neutrinos Correlated with Gravitational-wave Events Detected By LIGO/Virgo*, *The Astrophysical Journal* **959**

- (2023) 96.
- [11] ICECUBE collaboration, *Searches for IceCube Neutrinos Coincident with Gravitational Wave Events*, *PoS ICRC2023* (2023) 1484.
 - [12] ICECUBE collaboration, *Multi-Energy and Multi-Sample Searches for IceCube Neutrinos from LIGO/Virgo/KAGRA Gravitational Wave Events*, *PoS ICRC2025* (2025) 915.
 - [13] Z. Marka, J. Thwaites, J. Vandenbroucke and D. Veske, *Results from IceCube Searches for High-energy Neutrinos Coincident with Gravitational-Wave Alerts in LVK O4*, *PoS ICRC2025* (2025) 1113 [2507.08131].
 - [14] D. Veske, A. Zhang, Z. Márka and S. Márka, *Enhancing the significance of astrophysical events with multimessenger coincidences*, *Phys. Rev. D* **111** (2025) 103013 [2407.08732].
 - [15] D. Biehl, J. Heinze and W. Winter, *Expected neutrino fluence from short Gamma-Ray Burst 170817A and off-axis angle constraints*, *Mon. Not. Roy. Astron. Soc.* **476** (2018) 1191 [1712.00449].
 - [16] V. Cirkel-Bartelt, *History of astroparticle physics and its components*, *Living Rev. Rel.* **11** (2008) 2.
 - [17] T.K. Gaisser, R. Engel and E. Resconi, *Cosmic rays and particle physics*, Cambridge University Press (2016).
 - [18] M.S. Longair, *High energy astrophysics*, Cambridge university press (2011).
 - [19] D. Pacini, *Penetrating Radiation at the Surface of and in Water*, *Nuovo Cim.* **8** (1912) 93 [1002.1810].
 - [20] V.F. Hess, *Über Beobachtungen der durchdringenden Strahlung bei sieben Freiballonfahrten*, *Phys. Z.* **13** (1912) 1084.
 - [21] W. Bothe and W. Kolhörster, *Das wesen der höhenstrahlung*, *Zeitschrift für Physik* **56** (1929) 751.
 - [22] C. Evoli, *The Cosmic-Ray Energy Spectrum*, Dec., 2020. 10.5281/zenodo.4396125.
 - [23] D. Maurin, M. Ahlers, H. Dembinski, A. Haungs, P.-S. Mangeard, F. Melot et al., *A cosmic-ray database update: CRDB v4.1*, *European Physical Journal C* **83** (2023) 971 [2306.08901].
 - [24] B. Peters, *Primary cosmic radiation and extensive air showers*, *Nuovo Cim.* **22** (1961) 800.
 - [25] T.K. Gaisser, *Spectrum of cosmic-ray nucleons, kaon production, and the atmospheric muon charge ratio*, *Astropart. Phys.* **35** (2012) 801 [1111.6675].
 - [26] KASCADE collaboration, *KASCADE measurements of energy spectra for elemental groups of cosmic rays: Results and open problems*, *Astropart. Phys.* **24** (2005) 1.
 - [27] KASCADE-GRANDE collaboration, *Kneelike Structure in the Spectrum of the Heavy Component of Cosmic Rays Observed with KASCADE-Grande*, *Phys. Rev. Lett.* **107** (2011) 171104.
 - [28] KASCADE-GRANDE collaboration, *Ankle-like feature in the energy spectrum of light elements of cosmic rays observed with KASCADE-Grande*, *Phys. Rev. D* **87** (2013) 081101.

- [29] GRAPES-3 collaboration, *Evidence of a Hardening in the Cosmic Ray Proton Spectrum at around 166 TeV Observed by the GRAPES-3 Experiment*, *Phys. Rev. Lett.* **132** (2024) 051002.
- [30] ICECUBE collaboration, *Spectrum of PeV Cosmic-Ray Protons and Helium Nuclei with IceCube*, in *39th International Cosmic Ray Conference*, 2025 [[2511.05284](#)].
- [31] PIERRE AUGER collaboration, *The Pierre Auger Cosmic Ray Observatory*, *Nucl. Instrum. Meth. A* **798** (2015) 172 [[1502.01323](#)].
- [32] PIERRE AUGER collaboration, *Interpreting the cosmic ray spectrum and composition measurements across the ankle and up to the highest energies with the data of the Pierre Auger Observatory*, *EPJ Web Conf.* **283** (2023) 02013.
- [33] TELESCOPE ARRAY collaboration, *The Cosmic Ray Energy Spectrum Observed with the Surface Detector of the Telescope Array Experiment*, *Astrophys. J. Lett.* **768** (2013) L1 [[1205.5067](#)].
- [34] TELESCOPE ARRAY collaboration, *Recent Results and Status of TA/TALE/TA $\times$ 4 Experiment*, *Moscow Univ. Phys. Bull.* **79** (2024) 375.
- [35] K. Greisen, *End to the cosmic ray spectrum?*, *Phys. Rev. Lett.* **16** (1966) 748.
- [36] G.T. Zatsepin and V.A. Kuzmin, *Upper limit of the spectrum of cosmic rays*, *JETP Lett.* **4** (1966) 78.
- [37] ICECUBE collaboration, *Search for Extremely-High-Energy Neutrinos and First Constraints on the Ultrahigh-Energy Cosmic-Ray Proton Fraction with IceCube*, *Phys. Rev. Lett.* **135** (2025) 031001 [[2502.01963](#)].
- [38] A.M. Hillas, *The Origin of Ultrahigh-Energy Cosmic Rays*, *Ann. Rev. Astron. Astrophys.* **22** (1984) 425.
- [39] PIERRE AUGER collaboration, *Constraining the sources of ultra-high-energy cosmic rays across and above the ankle with the spectrum and composition data measured at the Pierre Auger Observatory*, *JCAP* **05** (2023) 024 [[2211.02857](#)].
- [40] M. Spurio, *Particles and astrophysics*, Springer (2015).
- [41] R. Cowsik and L.W. Wilson, *Is the Resident Time of Cosmic Rays in the Galaxy Energy Dependent?*, in *13th International Cosmic Ray Conference*, 1973.
- [42] J. Ormes and P. Freier, *On the Propagation of Cosmic Rays in the Galaxy*, *Astrophys. J.* **222** (1978) 471.
- [43] E. Fermi, *On the Origin of the Cosmic Radiation*, *Phys. Rev.* **75** (1949) 1169.
- [44] R. Alves Batista et al., *Open Questions in Cosmic-Ray Research at Ultrahigh Energies*, *Front. Astron. Space Sci.* **6** (2019) 23 [[1903.06714](#)].
- [45] E. Waxman, *Cosmological origin for cosmic rays above 10^{19} eV*, *Astrophys. J. Lett.* **452** (1995) L1.
- [46] K. Murase and E. Waxman, *Constraining High-Energy Cosmic Neutrino Sources: Implications and Prospects*, *Phys. Rev. D* **94** (2016) 103006 [[1607.01601](#)].
- [47] F. Capel and D.J. Mortlock, *Impact of using the ultrahigh-energy cosmic ray arrival energies to constrain source associations*, *Mon. Not. Roy. Astron. Soc.* **484** (2019) 2324 [[1811.06464](#)].

- [48] P. Davoudifar, *Time Delays, Deflection Angels and the Possible Origin of The Highest Energy Cosmic Rays*, *PoS ICRC2025* (2011) 230.
- [49] G.B. Rybicki and A.P. Lightman, *Radiative processes in astrophysics*, John Wiley & Sons (2024).
- [50] Particle Data Group, P.A. Zyla et al., *Review of Particle Physics*, *Progress of Theoretical and Experimental Physics* **2020** (2020) 083C01.
- [51] P. Chen and K.D. Hoffman, *Origin and evolution of cosmic accelerators - the unique discovery potential of an UHE neutrino telescope: Astronomy Decadal Survey (2010-2020) Science White Paper*, 0902.3288.
- [52] E. Vitagliano, I. Tamborra and G. Raffelt, *Grand Unified Neutrino Spectrum at Earth: Sources and Spectral Components*, *Rev. Mod. Phys.* **92** (2020) 45006 [1910.11878].
- [53] S.L. Glashow, J. Iliopoulos and L. Maiani, *Weak Interactions with Lepton-Hadron Symmetry*, *Phys. Rev. D* **2** (1970) 1285.
- [54] H. Fritzsch, M. Gell-Mann and H. Leutwyler, *Advantages of the Color Octet Gluon Picture*, *Phys. Lett. B* **47** (1973) 365.
- [55] C.L. Cowan, F. Reines, F.B. Harrison, H.W. Kruse and A.D. McGuire, *Detection of the free neutrino: A Confirmation*, *Science* **124** (1956) 103.
- [56] G. Danby, J.M. Gaillard, K.A. Goulianos, L.M. Lederman, N.B. Mistry, M. Schwartz et al., *Observation of High-Energy Neutrino Reactions and the Existence of Two Kinds of Neutrinos*, *Phys. Rev. Lett.* **9** (1962) 36.
- [57] DONUT collaboration, *Observation of tau neutrino interactions*, *Physics Letters B* **504** (2001) 218.
- [58] E. Fermi, *Tentativo di una teoria dell'emissione dei raggi beta*, *Ric. Sci.* **4** (1933) 491.
- [59] SNO COLLABORATION collaboration, *Measurement of the Rate of $\nu_e + d \rightarrow p + p + e^-$ Interactions Produced by ^8B Solar Neutrinos at the Sudbury Neutrino Observatory*, *Phys. Rev. Lett.* **87** (2001) 071301.
- [60] Z. Maki, M. Nakagawa and S. Sakata, *Remarks on the unified model of elementary particles*, *Prog. Theor. Phys.* **28** (1962) 870.
- [61] L. Wolfenstein, *Neutrino Oscillations in Matter*, *Phys. Rev. D* **17** (1978) 2369.
- [62] S.P. Mikheyev and A.Y. Smirnov, *Resonance Amplification of Oscillations in Matter and Spectroscopy of Solar Neutrinos*, *Sov. J. Nucl. Phys.* **42** (1985) 913.
- [63] T. Kajita, *Atmospheric neutrino results from Super-Kamiokande and Kamiokande — Evidence for ν_μ oscillations*, *Nuclear Physics B - Proceedings Supplements* **77** (1999) 123.
- [64] PLANCK collaboration, *Planck 2018 results. VI. Cosmological parameters*, *Astron. Astrophys.* **641** (2020) A6 [1807.06209].
- [65] KATRIN collaboration, *Direct neutrino-mass measurement based on 259 days of KATRIN data*, *Science* **388** (2025) adq9592 [2406.13516].
- [66] F. Halzen, *High-energy neutrinos from the Cosmos*, *Annalen Phys.* **533** (2021) 2100309.
- [67] N. Lad, *Measurement of Astrophysical Neutrino flavour composition with Twelve Years of IceCube Data*, Ph.D. thesis, Humboldt-Universität zu Berlin, 2025.

- [68] ICECUBE collaboration, *Characterization of the Three-Flavor Composition of Cosmic Neutrinos with IceCube*, [2510.24957](#).
- [69] J.F. Beacom, N.F. Bell, D. Hooper, S. Pakvasa and T.J. Weiler, *Measuring Flavor Ratios of High-Energy Astrophysical Neutrinos*, *Phys. Rev. D* **68** (2003) 093005.
- [70] S. Palomares-Ruiz, O. Mena and A.C. Vincent, *On the flavor composition of the high-energy neutrinos in IceCube*, *Nucl. Part. Phys. Proc.* **273-275** (2016) 433 [[1411.2998](#)].
- [71] E. Waxman and J.N. Bahcall, *High-energy neutrinos from astrophysical sources: An upper bound*, *Phys. Rev. D* **59** (1999) 023002.
- [72] M. Ahlers and F. Halzen, *Opening a New Window onto the Universe with IceCube*, *Prog. Part. Nucl. Phys.* **102** (2018) 73 [[1805.11112](#)].
- [73] M. Honda, T. Kajita, K. Kasahara, S. Midorikawa and T. Sanuki, *Calculation of atmospheric neutrino flux using the interaction model calibrated with atmospheric muon data*, *Phys. Rev. D* **75** (2007) 043006.
- [74] A. Schukraft, *A view of prompt atmospheric neutrinos with icecube*, *Nuclear Physics B - Proceedings Supplements* **237-238** (2013) 266-268.
- [75] R. Enberg, M.H. Reno and I. Sarcevic, *Prompt neutrino fluxes from atmospheric charm*, *Physical Review D* **78** (2008) .
- [76] A. Einstein, *Über gravitationswellen*, *Sitzungsber. Preuss. Akad. Wiss. Berlin* **154** (1918) 1918.
- [77] KAGRA, LIGO SCIENTIFIC, VIRGO collaboration, *Prospects for observing and localizing gravitational-wave transients with Advanced LIGO, Advanced Virgo and KAGRA*, *Living Rev. Rel.* **19** (2016) 1 [[1304.0670](#)].
- [78] R. Perna, D. Lazzati and W. Farr, *Limits on electromagnetic counterparts of gravitational wave-detected binary black hole mergers*, *Astrophys. J.* **875** (2019) 49 [[1901.04522](#)].
- [79] KAMIOKANDE-II collaboration, *Observation of a Neutrino Burst from the Supernova SN 1987a*, *Phys. Rev. Lett.* **58** (1987) 1490.
- [80] R.M. Bionta et al., *Observation of a Neutrino Burst in Coincidence with Supernova SN 1987a in the Large Magellanic Cloud*, *Phys. Rev. Lett.* **58** (1987) 1494.
- [81] ICECUBE collaboration, *Observation of High-Energy Neutrinos from the Galactic Plane*, *PoS ICRC2023* (2023) 1108 [[2307.14842](#)].
- [82] I. Sushch, E. de Ona Wilhelmi, R. Brose, E. Mestre, Y. Su and R. Zanin, *SNR G39.2-0.3, an hadronic cosmic rays accelerator*, *Mon. Not. Roy. Astron. Soc.* **497** (2020) 3581 [[2007.04627](#)].
- [83] S.T. Spencer, A.M.W. Mitchell and B. Reville, *Hadronic emission from the environment of the Crab Pulsar Wind Nebula by re-accelerated particles*, *Astron. Astrophys.* **698** (2025) A131 [[2504.08432](#)].
- [84] D. Vartanyan, A. Burrows, T. Wang, M.S.B. Coleman and C.J. White, *Gravitational wave signature of core-collapse supernovae*, *Phys. Rev. D* **107** (2023) 103015 [[2302.07092](#)].

- [85] J. Matthews, A. Bell and K. Blundell, *Particle acceleration in astrophysical jets*, *New Astron. Rev.* **89** (2020) 101543 [2003.06587].
- [86] F.M. Rieger, *Active galactic nuclei as potential sources of ultra-high energy cosmic rays*, *Universe* **8** (2022) 607.
- [87] P. Padovani, D.M. Alexander, R.J. Assef, B. De Marco, P. Giommi, R.C. Hickox et al., *Active galactic nuclei: what's in a name?*, *The Astronomy and Astrophysics Review* **25** (2017) .
- [88] T. Bister, *Probing UHECR sources - Constraints from cosmic-ray measurements*, *PoS ICRC2025* (2025) 1387 [2508.20767].
- [89] D. Caprioli, *“Espresso” acceleration of ultra-high-energy cosmic rays*, *The Astrophysical Journal* **811** (2015) L38.
- [90] S.S. Kimura, K. Murase and B.T. Zhang, *Ultrahigh-energy Cosmic-ray Nuclei from Black Hole Jets: Recycling Galactic Cosmic Rays through Shear Acceleration*, *Phys. Rev. D* **97** (2018) 023026 [1705.05027].
- [91] J.H. Matthews, A.R. Bell, K.M. Blundell and A.T. Araudo, *Ultrahigh energy cosmic rays from shocks in the lobes of powerful radio galaxies*, *Mon. Not. Roy. Astron. Soc.* **482** (2019) 4303 [1810.12350].
- [92] D. Ehlert, F. Oikonomou and E. Peretti, *Ultra-high-energy cosmic rays from ultra-fast outflows of active galactic nuclei*, *Mon. Not. Roy. Astron. Soc.* **539** (2025) 2435 [2411.05667].
- [93] PIERRE AUGER collaboration, *An update on the arrival direction studies made with data from the Pierre Auger Observatory*, *PoS ICRC2023* (2023) 252.
- [94] PIERRE AUGER, TELESCOPE ARRAY collaboration, *New full-sky studies of the distribution of ultra-high-energy cosmic-ray arrival directions*, *PoS ICRC2025* (2025) 282 [2507.10441].
- [95] J.P. Lundquist, S. Vorobiov, L. Merten, A. Reimer, M. Boughelilba, P. Da Vela et al., *Combined Fit of Spectrum and Composition for FR0 Radio-galaxy-emitted Ultra-high energy Cosmic Rays with Resulting Secondary Photons and Neutrinos*, *Astrophys. J.* **978** (2025) 20 [2407.06961].
- [96] A. Partenheimer, K. Fang, R. Alves Batista and R. Menezes de Almeida, *Ultra-high-energy Cosmic-Ray Sources Can Be Gamma-Ray Dim*, *Astrophys. J. Lett.* **967** (2024) L15 [2404.17631].
- [97] R.C. Anjos and C.H. Coimbra-Araújo, *Central accumulation of magnetic flux in massive Seyfert galaxies as a possible engine to trigger ultrahigh energy cosmic rays*, *Phys. Rev. D* **96** (2017) 023008 [1803.02168].
- [98] ICECUBE collaboration, *Search for Neutrino Emission from Hard X-Ray AGN with IceCube*, *Astrophys. J.* **981** (2025) 131 [2406.06684].
- [99] A. Loeb and E. Waxman, *The cumulative background of high energy neutrinos from starburst galaxies*, *JCAP* **05** (2006) 003.
- [100] B. Eichmann, F. Oikonomou, S. Salvatore, R.-J. Dettmar and J. Becker Tjus, *Disentangling the multi-messenger puzzle of the AGN-starburst composite galaxy NGC 1068*, *PoS ICRC2023* (2023) 1453.

- [101] M.S. Yun, N.A. Reddy and J.J. Condon, *Radio properties of infrared selected galaxies in the IRAS 2 Jy sample*, *Astrophys. J.* **554** (2001) 803.
- [102] FERMI-LAT collaboration, *GeV Observations of Star-forming Galaxies with Fermi-LAT*, *Astrophys. J.* **755** (2012) 164 [1206.1346].
- [103] R. Stein et al., *A tidal disruption event coincident with a high-energy neutrino*, *Nature Astron.* **5** (2021) 510 [2005.05340].
- [104] S. Reusch et al., *Candidate Tidal Disruption Event AT2019fdr Coincident with a High-Energy Neutrino*, *Phys. Rev. Lett.* **128** (2022) 221101 [2111.09390].
- [105] M. Toscani, G. Lodato, D.J. Price and D. Liptai, *Gravitational Waves from tidal disruption events: an open and comprehensive catalog*, *Mon. Not. Roy. Astron. Soc.* **510** (2022) 992 [2111.05145].
- [106] G.G. Fazio, R. Barkana, S. Tsujikawa and J.E. Kim, *The Encyclopedia of Cosmology*, World Scientific (2023).
- [107] E. Waxman and J. Bahcall, *High energy neutrinos from cosmological gamma-ray burst fireballs*, *Phys. Rev. Lett.* **78** (1997) 2292.
- [108] M.J. Rees and P. Meszaros, *Unsteady outflow models for cosmological gamma-ray bursts*, *The Astrophysical Journal* **430** (1994) L93.
- [109] ICECUBE collaboration, *Extending the search for muon neutrinos coincident with gamma-ray bursts in IceCube data*, *Astrophys. J.* **843** (2017) 112 [1702.06868].
- [110] R. Abbasi et al., *Searches for Neutrinos from Gamma-Ray Bursts Using the IceCube Neutrino Observatory*, *Astrophys. J.* **939** (2022) 116 [2205.11410].
- [111] ICECUBE collaboration, *Limits on Neutrino Emission from GRB 221009A from MeV to PeV Using the IceCube Neutrino Observatory*, *Astrophys. J. Lett.* **946** (2023) L26 [2302.05459].
- [112] H. Abdalla, R. Adam, F. Aharonian, F. Ait Benkhali, E. Angüner, M. Arakawa et al., *A very-high-energy component deep in the γ -ray burst afterglow*, *Nature* **575** (2019) 464.
- [113] LHAASA, LHAASO collaboration, *Very high-energy gamma-ray emission beyond 10 TeV from GRB 221009A*, *Sci. Adv.* **9** (2023) adj2778 [2310.08845].
- [114] F. Antonini and F.A. Rasio, *Merging black hole binaries in galactic nuclei: implications for advanced-LIGO detections*, *Astrophys. J.* **831** (2016) 187 [1606.04889].
- [115] C. Yuan, K. Murase, S.S. Kimura and P. Mészáros, *High-energy neutrino emission subsequent to gravitational wave radiation from supermassive black hole mergers*, *Phys. Rev. D* **102** (2020) 083013 [2008.05616].
- [116] Z.-H. Zhou and K. Wang, *High-energy Neutrino Emission Associated with GWs from Binary Black Hole Mergers in AGN Accretion Disks*, *The Astrophysical Journal Letters* **958** (2023) L12.
- [117] J.-P. Zhu, *High-energy neutrinos from merging stellar-mass black holes in active galactic nuclei accretion disc*, *Mon. Not. Roy. Astron. Soc.* **528** (2023) L88 [2310.14255].
- [118] L.J. Schumacher, *Search for the common sources of high-energy cosmic neutrinos and ultra-high-energy cosmic rays*, Ph.D. thesis, RWTH Aachen U., 2021.

- [119] G.R. Farrar, *Binary Neutron Star Mergers as the Source of the Highest Energy Cosmic Rays*, *Phys. Rev. Lett.* **134** (2025) 081003 [2405.12004].
- [120] R.D. Blandford and R.L. Znajek, *Electromagnetic extractions of energy from Kerr black holes*, *Mon. Not. Roy. Astron. Soc.* **179** (1977) 433.
- [121] ANTARES, ICECUBE, LIGO, VIRGO collaboration, *Search for Multimessenger Sources of Gravitational Waves and High-energy Neutrinos with Advanced LIGO during Its First Observing Run, ANTARES, and IceCube*, *Astrophys. J.* **870** (2019) 134 [1810.10693].
- [122] T. Mukherjee, *Archival Search for IceCube Sub-TeV Neutrino Counterparts to Sub-Threshold Gravitational Wave Events from the Third Observing Run of the LIGO-Virgo-KAGRA*, *PoS ICRC2025* (2025) 954 [2509.13003].
- [123] R.A. Hulse and J.H. Taylor, *Discovery of a pulsar in a binary system*, *Astrophys. J. Lett.* **195** (1975) L51.
- [124] B. Abbott et al., *GWTC-1: A Gravitational-wave Transient Catalog of Compact Binary Mergers Observed by LIGO and Virgo During the First and Second Observing Runs*, *Physical Review X* **9** (2019) 031040.
- [125] LIGO SCIENTIFIC, VIRGO collaboration, *GWTC-2.1: Deep extended catalog of compact binary coalescences observed by LIGO and Virgo during the first half of the third observing run*, *Phys. Rev. D* **109** (2024) 022001 [2108.01045].
- [126] LIGO SCIENTIFIC, VIRGO, KAGRA collaboration, *GWTC-3: Compact Binary Coalescences Observed by LIGO and Virgo during the Second Part of the Third Observing Run*, *Phys. Rev. X* **13** (2023) 041039 [2111.03606].
- [127] LIGO SCIENTIFIC, VIRGO, KAGRA collaboration, *GWTC-4.0: Updating the Gravitational-Wave Transient Catalog with Observations from the First Part of the Fourth LIGO-Virgo-KAGRA Observing Run*, 2508.18082.
- [128] K.S. Thorne, *Gravitational waves*, [gr-qc/9506086](#).
- [129] R. Weiss, *Republication of: Electromagnetically coupled broadband gravitational antenna*, *Gen. Rel. Grav.* **54** (2022) 153.
- [130] K.L. Dooley et al., *GEO 600 and the GEO-HF upgrade program: successes and challenges*, *Class. Quant. Grav.* **33** (2016) 075009 [1510.00317].
- [131] F. Acernese et al., *Virgo status*, *Class. Quant. Grav.* **25** (2008) 184001.
- [132] LIGO SCIENTIFIC collaboration, *LIGO: The Laser interferometer gravitational-wave observatory*, *Rept. Prog. Phys.* **72** (2009) 076901 [0711.3041].
- [133] LIGO SCIENTIFIC collaboration, *Advanced LIGO*, *Class. Quant. Grav.* **32** (2015) 074001 [1411.4547].
- [134] J.H. Pöld, *Design, implementation and characterization of the advanced LIGO 200 W laser system*, Ph.D. thesis, Leibniz U., Hannover, 2014.
- [135] ADVANCED LIGO collaboration, *Environmental noise in advanced LIGO detectors*, *Class. Quant. Grav.* **38** (2021) 145001 [2101.09935].
- [136] S.M. Aston et al., *Update on quadruple suspension design for Advanced LIGO*, *Class. Quant. Grav.* **29** (2012) 235004.

- [137] ADVANCED LIGO collaboration, *Advanced ligo reference design, LIGO, Internal Technical Document M 60056* (2009) .
- [138] C.M. Caves, *Quantum Mechanical Noise in an Interferometer*, *Phys. Rev. D* **23** (1981) 1693.
- [139] C. Caves, *Quantum-Mechanical Radiation-Pressure Fluctuations in an Interferometer*, *Phys. Rev. Lett.* **45** (1980) 75.
- [140] B.J. Meers, *Recycling in Laser Interferometric Gravitational Wave Detectors*, *Phys. Rev. D* **38** (1988) 2317.
- [141] LIGO SCIENTIFIC collaboration, *Enhancing the sensitivity of the LIGO gravitational wave detector by using squeezed states of light*, *Nature Photon.* **7** (2013) 613 [1310.0383].
- [142] M. Tse et al., *Quantum-Enhanced Advanced LIGO Detectors in the Era of Gravitational-Wave Astronomy*, *Phys. Rev. Lett.* **123** (2019) 231107.
- [143] G. Hammond, S. Hild and M. Pitkin, *Advanced technologies for future ground-based, laser-interferometric gravitational wave detectors*, *J. Mod. Opt.* **61** (2014) 10 [1402.4616].
- [144] KAGRA collaboration, *Detector configuration of KAGRA—the Japanese cryogenic gravitational-wave detector*, *Classical and Quantum Gravity* **29** (2012) 124007.
- [145] S. Klimenko, G. Vedovato, M. Drago, G. Mazzolo, G. Mitselmakher, C. Pankow et al., *Localization of gravitational wave sources with networks of advanced detectors*, *Phys. Rev. D* **83** (2011) 102001 [1101.5408].
- [146] THE VIRGO collaboration, *Advanced Virgo: a second-generation interferometric gravitational wave detector*, *Classical and Quantum Gravity* **32** (2014) 024001.
- [147] C.S. Unnikrishnan, *IndIGO and LIGO-India: Scope and plans for gravitational wave research and precision metrology in India*, *International Journal of Modern Physics D* **22** (2013) 1341010.
- [148] S. Pandey, I. Gupta, K. Chandra and B.S. Sathyaprakash, *The Critical Role of LIGO-India in the Era of Next-generation Observatories*, *Astrophys. J. Lett.* **985** (2025) L17 [2411.10349].
- [149] ET collaboration, *Science Case for the Einstein Telescope*, *JCAP* **03** (2020) 050 [1912.02622].
- [150] M. Evans et al., *A Horizon Study for Cosmic Explorer: Science, Observatories, and Community*, **2109.09882**.
- [151] ET collaboration, *The Science of the Einstein Telescope*, *JCAP* **03** (2026) 081 [2503.12263].
- [152] M. Di Giovanni, *Einstein Telescope an Cosmic Explorer*, in *59th Rencontres de Moriond on Gravitation: Moriond 2025 Gravitation*, 2025 [2505.11033].
- [153] M.L. Chan, C. Messenger, I.S. Heng and M. Hendry, *Binary Neutron Star Mergers and Third Generation Detectors: Localization and Early Warning*, *Phys. Rev. D* **97** (2018) 123014 [1803.09680].
- [154] L.W. Couch, M. Kulkarni and U.S. Acharya, *Digital and analog communication systems*, vol. 8, Pearson Upper Saddle River (2013).

- [155] D. Veske, *Searching for new discoveries in binary black hole mergers and of multi-messenger detections with gravitational-waves*, Columbia University (2022).
- [156] A. Ray, *Astrophysics, cosmology, and fundamental interactions with Gravitational Waves*, Ph.D. thesis, The University of Wisconsin-Milwaukee, 2024.
- [157] J. Merritt, B. Farr, R. Hur, B. Edelman and Z. Doctor, *Transient glitch mitigation in Advanced LIGO data*, *Phys. Rev. D* **104** (2021) 102004 [2108.12044].
- [158] B. Allen, χ^2 time-frequency discriminator for gravitational wave detection, *Phys. Rev. D* **71** (2005) 062001.
- [159] C. Messick et al., *Analysis Framework for the Prompt Discovery of Compact Binary Mergers in Gravitational Wave Data*, *Phys. Rev. D* **95** (2017) 042001 [1604.04324].
- [160] L.S. Collaboration, V. Collaboration et al., *A guide to ligo–virgo detector noise and extraction of transient gravitational-wave signals*, *Classical and Quantum Gravity* **32** (2015) 074001 [1411.4547].
- [161] K. Cannon, C. Hanna and J. Peoples, *Likelihood-Ratio Ranking Statistic for Compact Binary Coalescence Candidates with Rate Estimation*, 1504.04632.
- [162] S.A. Usman et al., *The PyCBC Search for Gravitational Waves from Compact Binary Coalescence*, *Classical and Quantum Gravity* **33** (2016) 215004.
- [163] R.W. Kiendrebeogo et al., *Updated Observing Scenarios and Multimessenger Implications for the International Gravitational-wave Networks O4 and O5*, *Astrophys. J.* **958** (2023) 158 [2306.09234].
- [164] W.M. Farr, J.R. Gair, I. Mandel and C. Cutler, *Counting And Confusion: Bayesian Rate Estimation With Multiple Populations*, *Phys. Rev. D* **91** (2015) 023005 [1302.5341].
- [165] S.J. Kapadia et al., *A self-consistent method to estimate the rate of compact binary coalescences with a Poisson mixture model*, *Class. Quant. Grav.* **37** (2020) 045007 [1903.06881].
- [166] V. Tiwari, *Estimation of the Sensitive Volume for Gravitational-wave Source Populations Using Weighted Monte Carlo Integration*, *Class. Quant. Grav.* **35** (2018) 145009 [1712.00482].
- [167] LIGO-VIRGO-KAGRA COLLABORATION collaboration, *Population of merging compact binaries inferred using gravitational waves through GWTC-3*, *Physical Review X* **13** (2023) 011048.
- [168] E. Thrane and C. Talbot, *An introduction to Bayesian inference in gravitational-wave astronomy: parameter estimation, model selection, and hierarchical models*, *Publ. Astron. Soc. Austral.* **36** (2019) e010 [1809.02293].
- [169] J. Veitch et al., *Parameter estimation for compact binaries with ground-based gravitational-wave observations using the LALInference software library*, *Phys. Rev. D* **91** (2015) 042003 [1409.7215].
- [170] G. Ashton et al., *BILBY: A user-friendly Bayesian inference library for gravitational-wave astronomy*, *Astrophys. J. Suppl.* **241** (2019) 27 [1811.02042].
- [171] I.M. Romero-Shaw et al., *Bayesian inference for compact binary coalescences with bilby: validation and application to the first LIGO–Virgo gravitational-wave transient catalogue*, *Mon. Not. Roy. Astron. Soc.* **499** (2020) 3295 [2006.00714].

- [172] J. Wofford et al., *Improving performance for gravitational-wave parameter inference with an efficient and highly-parallelized algorithm*, *Phys. Rev. D* **107** (2023) 024040.
- [173] R. Abbott et al., *GWTC-2: Compact Binary Coalescences Observed by LIGO and Virgo During the First Half of the Third Observing Run*, *Physical Review X* **11** (2021) 021053.
- [174] B.S. Sathyaprakash and B.F. Schutz, *Physics, astrophysics and cosmology with gravitational waves*, *Living Reviews in Relativity* **12** (2009) .
- [175] KAGRA, VIRGO, LIGO SCIENTIFIC collaboration, *Upper limits on the isotropic gravitational-wave background from Advanced LIGO and Advanced Virgo's third observing run*, *Phys. Rev. D* **104** (2021) 022004 [2101.12130].
- [176] K. Cannon et al., *GstLAL: A Software Framework for Gravitational Wave Discovery*, *SoftwareX* **14** (2021) 100680.
- [177] F. Aubin et al., *The MBTA Pipeline for Detecting Compact Binary Coalescences in the Third LIGO–Virgo Observing Run*, *Classical and Quantum Gravity* **38** (2021) 095004.
- [178] A.H. Nitz, *Distinguishing short duration noise transients in LIGO data to improve the PyCBC search for gravitational waves from high mass binary black hole mergers*, *Classical and Quantum Gravity* **35** (2018) 035016.
- [179] S. Klimenko et al., *Method for Detection and Reconstruction of Gravitational Wave Transients with Networks of Advanced Detectors*, *Phys. Rev. D* **93** (2016) 042004.
- [180] LIGO SCIENTIFIC, VIRGO collaboration, *All-sky search for short gravitational-wave bursts in the first Advanced LIGO run*, *Phys. Rev. D* **95** (2017) 042003 [1611.02972].
- [181] LIGO SCIENTIFIC, VIRGO collaboration, *All-Sky Search for Short Gravitational-Wave Bursts in the Second Advanced LIGO and Advanced Virgo Run*, *Phys. Rev. D* **100** (2019) 024017 [1905.03457].
- [182] LIGO SCIENTIFIC, VIRGO, KAGRA collaboration, *All-sky search for short gravitational-wave bursts in the first part of the fourth LIGO–Virgo–KAGRA observing run*, 2507.12374.
- [183] S. Klimenko, I. Yakushin, A. Mercer and G. Mitselmakher, *Coherent method for detection of gravitational wave bursts*, *Class. Quant. Grav.* **25** (2008) 114029 [0802.3232].
- [184] M.J. Graham et al., *Candidate Electromagnetic Counterpart to the Binary Black Hole Merger Gravitational Wave Event S190521g*, *Phys. Rev. Lett.* **124** (2020) 251102 [2006.14122].
- [185] D. Veske, Z. Marka and A. Zhang, *Constraints on the Population of Common Sources of Gravitational Waves and High-Energy Neutrinos with IceCube During the Third Observing Run of the LIGO and Virgo Detectors*, in *39th International Cosmic Ray Conference*, 2025.
- [186] M.A. Markov, *On high energy neutrino physics*, in *10th International Conference on High Energy Physics*, pp. 578–581, 1960.
- [187] DUMAND collaboration, *Cosmic Ray Muons in the Deep Ocean*, *Phys. Rev. D* **42** (1990) 3613.
- [188] V. Balkanov, I. Belolaptikov, N. Budnev, L. Bezrukova, A. Chensky, D. Chernovd et al., *The baikal neutrino project: status report*, *Nuclear Physics B-Proceedings Supplements*

- 118** (2003) 363.
- [189] ANTARES collaboration, *ANTARES: the first undersea neutrino telescope*, *Nucl. Instrum. Meth. A* **656** (2011) 11 [1104.1607].
 - [190] E. Andres et al., *The AMANDA neutrino telescope: Principle of operation and first results*, *Astropart. Phys.* **13** (2000) 1.
 - [191] T. Gaisser and F. Halzen, *IceCube*, *Ann. Rev. Nucl. Part. Sci.* **64** (2014) 101.
 - [192] F. Halzen, *IceCube: From Oscillations to PeV Neutrino Events*, *Nucl. Phys. B Proc. Suppl.* **237-238** (2013) 211.
 - [193] W. Luszczak, *Every Flare, Everywhere: Untriggered Searches for Astrophysical Neutrino Transients Using Data from the IceCube Detector*, Ph.D. thesis, The University of Wisconsin-Madison, 2021.
 - [194] A. Cooper-Sarkar, P. Mertsch and S. Sarkar, *The high energy neutrino cross-section in the Standard Model and its uncertainty*, *JHEP* **08** (2011) 042 [1106.3723].
 - [195] R. Gandhi, C. Quigg, M.H. Reno and I. Sarcevic, *Ultra high-energy neutrino interactions*, *Astropart. Phys.* **5** (1996) 81.
 - [196] A. Loewy, S. Nussinov and S.L. Glashow, *The Effect of Doppler Broadening on the 6.3 PeV W^- Resonance in $\bar{\nu}_e e^-$ Collisions*, **1407.4415**.
 - [197] ICECUBE collaboration, *Detection of a particle shower at the Glashow resonance with IceCube*, *Nature* **591** (2021) 220 [2110.15051].
 - [198] A. Pizzuto, *Hunting for cosmic neutrino sources from giga- to exa-electronvolt with IceCube*, Ph.D. thesis, U. Wisconsin, Madison (main), 2022.
 - [199] J.A. Formaggio and G.P. Zeller, *From eV to EeV: Neutrino Cross Sections Across Energy Scales*, *Rev. Mod. Phys.* **84** (2012) 1307 [1305.7513].
 - [200] C.F. Tung, *A multimessenger approach to neutrino astronomy*, Ph.D. thesis, Georgia Institute of Technology, 2021.
 - [201] P.A. Cherenkov, *Visible radiation produced by electrons moving in a medium with velocities exceeding that of light*, *Phys. Rev.* **52** (1937) 378.
 - [202] ICECUBE collaboration, *In situ estimation of ice crystal properties at the South Pole using LED calibration data from the IceCube Neutrino Observatory*, *The Cryosphere* **18** (2024) 75.
 - [203] V.F. Petrenko and R.W. Whitworth, *Physics of ice*, OUP Oxford (1999).
 - [204] ICECUBE collaboration, *The IceCube Neutrino Observatory: Instrumentation and Online Systems*, *JINST* **12** (2017) P03012 [1612.05093].
 - [205] ICECUBE collaboration, *Calibration and Characterization of the IceCube Photomultiplier Tube*, *Nucl. Instrum. Meth. A* **618** (2010) 139 [1002.2442].
 - [206] Hamamatsu Photonics K.K., “S13360 series mppc datasheet.” https://www.hamamatsu.com/resources/pdf/ssd/s13360_series_kapd1052e.pdf, 2016.
 - [207] T. Carver, *Time integrated searches for astrophysical neutrino sources using the IceCube detector and gender in physics studies for the genera project*, Ph.D. thesis, University of Geneva, 2019.

- [208] A. Bernhard, *Origin of IceCube's astrophysical neutrinos: Autocorrelation, multi-point-source and time-structured searches*, Ph.D. thesis, Technical University of Munich, 2015.
- [209] ICECUBE collaboration, *IceCube: A Cubic Kilometer Radiation Detector*, *IEEE Trans. Nucl. Sci.* **56** (2009) 1141 [0807.0034].
- [210] ICECUBE collaboration, *IceCube performance with artificial light sources: The road to cascade analyses*, *PoS ICRC2007* (2007) 1233.
- [211] ICECUBE collaboration, *Measurement of South Pole ice transparency with the IceCube LED calibration system*, *Nucl. Instrum. Meth. A* **711** (2013) 73 [1301.5361].
- [212] ICECUBE collaboration, *The Design and Performance of IceCube DeepCore*, *Astroparticle physics* **35** (2012) 615.
- [213] T. Kintscher, *Rapid response to extraordinary events: transient neutrino sources with the IceCube experiment*, Ph.D. thesis, Humboldt Universitaet zu Berlin (Germany), 2020.
- [214] M.J. Larson, *A search for tau neutrino appearance with IceCube-DeepCore*, Ph.D. thesis, University of Copenhagen, Faculty of Science, Niels Bohr Institute, 2018.
- [215] C. Chen, *Search for astrophysical neutrino sources using IceCube low-energy neutrinos*, Ph.D. thesis, Georgia Tech, 2022.
- [216] ICECUBE collaboration, *IceTop: The surface component of IceCube*, *Nucl. Instrum. Meth. A* **700** (2013) 188 [1207.6326].
- [217] ICECUBE collaboration, *Cosmic Ray Composition and Energy Spectrum from 1-30 PeV Using the 40-String Configuration of IceTop and IceCube*, *Astropart. Phys.* **42** (2013) 15 [1207.3455].
- [218] L. Pyras, L. Paul, K. Rawlins, I. Reistroffer and A. Thakuri, *Advances in reconstructing the cosmic-ray energy spectrum with IceTop*, *PoS ICRC2025* (2025) 367 [2507.08691].
- [219] ICECUBE collaboration, *Status and plans for the instrumentation of the IceCube Surface Array Enhancement*, *PoS ICRC2023* (2023) 342 [2402.17854].
- [220] ICECUBE collaboration, *Performance of the Prototype Station of the IceCube Surface Array Enhancement*, *PoS ICRC2025* (2025) 394 [2510.14636].
- [221] S. Shefali, *Production, Calibration and Performance of the Scintillation Detectors for the IceCube Surface Array Enhancement*, Ph.D. thesis, Karlsruher Institut für Technologie (KIT), 2026.
- [222] ICECUBE collaboration, *Neutrino astronomy with IceCube and beyond*, *J. Phys. Conf. Ser.* **888** (2017) 012007.
- [223] ICECUBE collaboration, *A muon-track reconstruction exploiting stochastic losses for large-scale Cherenkov detectors*, *JINST* **16** (2021) P08034 [2103.16931].
- [224] ICECUBE collaboration, *A Convolutional Neural Network based Cascade Reconstruction for the IceCube Neutrino Observatory*, *JINST* **16** (2021) P07041 [2101.11589].
- [225] J.G. Learned and S. Pakvasa, *Detecting tau-neutrino oscillations at PeV energies*, *Astropart. Phys.* **3** (1995) 267.

- [226] ICECUBE collaboration, *Observation of Seven Astrophysical Tau Neutrino Candidates with IceCube*, *Phys. Rev. Lett.* **132** (2024) 151001 [2403.02516].
- [227] ICECUBE collaboration, *Atmospheric and astrophysical neutrinos above 1 TeV interacting in IceCube*, *Phys. Rev. D* **91** (2015) 022001 [1410.1749].
- [228] ICECUBE collaboration, *The IceCube high-energy starting event sample: Description and flux characterization with 7.5 years of data*, *Phys. Rev. D* **104** (2021) 022002 [2011.03545].
- [229] ICECUBE collaboration, *Characterization of the astrophysical diffuse neutrino flux using starting track events in IceCube*, *Phys. Rev. D* **110** (2024) 022001 [2402.18026].
- [230] ICECUBE collaboration, *Evidence for a Spectral Break or Curvature in the Spectrum of Astrophysical Neutrinos from 5 TeV–10 PeV*, *Phys. Rev. Lett.* **136** (2026) 121002 [2507.22233].
- [231] ICECUBE collaboration, *Improved measurements of the TeV-PeV extragalactic neutrino spectrum from joint analyses of IceCube tracks and cascades*, *Phys. Rev. D* **113** (2026) 062002 [2507.22234].
- [232] ICECUBE collaboration, *IceCube Data for Neutrino Point-Source Searches Years 2008-2018*, **2101.09836**.
- [233] ICECUBE collaboration, *Search for steady point-like sources in the astrophysical muon neutrino flux with 8 years of IceCube data*, *Eur. Phys. J. C* **79** (2019) 234 [1811.07979].
- [234] ICECUBE collaboration, *Time-Integrated Neutrino Source Searches with 10 Years of IceCube Data*, *Phys. Rev. Lett.* **124** (2020) 051103 [1910.08488].
- [235] F. Lucarelli, *Search for Transient Extragalactic Sources of Neutrinos with Ten Years of IceCube Data*, Ph.D. thesis, Geneva U., 2022.
- [236] V. Stenger, *Track fitting for Dumand-II octagon array*, University of Hawaii at Manoa (1990) .
- [237] AMANDA collaboration, *Muon track reconstruction and data selection techniques in AMANDA*, *Nucl. Instrum. Meth. A* **524** (2004) 169.
- [238] M.G. Aartsen et al., *Improvement in Fast Particle Track Reconstruction with Robust Statistics*, *Nucl. Instrum. Meth. A* **736** (2014) 143 [1308.5501].
- [239] S.P. Boyd and L. Vandenberghe, *Convex optimization*, Cambridge university press (2004).
- [240] T. Neunhoffer, *Estimating the angular resolution of tracks in neutrino telescopes based on a likelihood analysis*, *Astropart. Phys.* **25** (2006) 220.
- [241] ICECUBE collaboration, *Energy Reconstruction Methods in the IceCube Neutrino Telescope*, *JINST* **9** (2014) P03009 [1311.4767].
- [242] L. Rädcl, *Measurement of High-Energy Muon Neutrinos with the IceCube Neutrino Observatory*, Ph.D. thesis, RWTH Aachen U., 2017.
- [243] ICECUBE collaboration, *Low energy event reconstruction in IceCube DeepCore*, *Eur. Phys. J. C* **82** (2022) 807 [2203.02303].
- [244] ICECUBE collaboration, *Measurement of Atmospheric Tau Neutrino Appearance with IceCube DeepCore*, *Phys. Rev. D* **99** (2019) 032007 [1901.05366].

- [245] ICECUBE collaboration, *Searching for neutrino transients below 1 TeV with IceCube*, *PoS ICRC2021* (2021) 1131 [2108.01530].
- [246] M. Leuermann, *Testing the neutrino mass ordering with IceCube DeepCore*, Ph.D. thesis, RWTH Aachen University, 2018.
- [247] ICECUBE collaboration, *Search for 10–1000 GeV Neutrinos from Gamma-Ray Bursts with IceCube*, *Astrophys. J.* **964** (2024) 126 [2312.11515].
- [248] ICECUBE collaboration, *Search for sub-TeV Neutrino Emission from Novae with IceCube-DeepCore*, *Astrophys. J.* **953** (2023) 160 [2212.06810].
- [249] M.G. Aartsen et al., *Neutrino oscillation studies with IceCube-DeepCore*, *Nucl. Phys. B* **908** (2016) 161.
- [250] ICECUBE collaboration, *Measurement of Atmospheric Neutrino Oscillations at 6–56 GeV with IceCube DeepCore*, *Phys. Rev. Lett.* **120** (2018) 071801 [1707.07081].
- [251] K. Leonard DeHolton, *Measuring the atmospheric neutrino oscillation parameters with IceCube deepcore*, Ph.D. thesis, U. Wisconsin, Madison (main), University of Wisconsin Madison, 2022.
- [252] S. Yu, *Measurement of Atmospheric Muon Neutrino Disappearance Using CNN Reconstructions with IceCube*, *Phys. Sci. Forum* **8** (2023) 62.
- [253] ICECUBE collaboration, *Measurement of the high-energy all-flavor neutrino-nucleon cross section with IceCube*, *Phys. Rev. D* **104** (2020) 022001 [2011.03560].
- [254] ICECUBE collaboration, *Search for dark matter from the center of the Earth with 10 years of IceCube data*, *Eur. Phys. J. C* **85** (2025) 490 [2412.12972].
- [255] ICECUBE collaboration, *Search for GeV-scale dark matter annihilation in the Sun with IceCube DeepCore*, *Phys. Rev. D* **105** (2022) 062004 [2111.09970].
- [256] J. Lazar, *Limits on WIMP-Scattering Cross Sections using Solar Neutrinos with Ten Years of IceCube Data*, *PoS ICRC2025* (2025) 486 [2507.08519].
- [257] ICECUBE collaboration, *Indirect dark matter search in the Galactic Centre with IceCube*, *PoS ICRC2023* (2023) 1394 [2308.06729].
- [258] ICECUBE collaboration, *A search for neutrinos from decaying dark matter in galaxy clusters and galaxies with icecube*, *PoS ICRC2021* (2021) 506 [2107.11527].
- [259] ICECUBE COLLABORATION collaboration, *Search for Unstable Sterile Neutrinos with the IceCube Neutrino Observatory*, *Phys. Rev. Lett.* **129** (2022) 151801 [2204.00612].
- [260] ICECUBE collaboration, *Searching for eV-scale sterile neutrinos with eight years of atmospheric neutrinos at the IceCube Neutrino Telescope*, *Phys. Rev. D* **102** (2020) 052009 [2005.12943].
- [261] J. Häußler and N. Moller, *Search for Sub-Relativistic Magnetic Monopoles with the IceCube Neutrino Observatory*, *PoS ICRC2025* (2025) 492 [2507.05896].
- [262] ICECUBE collaboration, *Search for quantum gravity using astrophysical neutrino flavour with IceCube*, *Nature Phys.* **18** (2022) 1287 [2111.04654].
- [263] ICECUBE collaboration, *Neutrino Interferometry for High-Precision Tests of Lorentz Symmetry with IceCube*, *Nature Phys.* **14** (2018) 961 [1709.03434].
- [264] ICECUBE collaboration, *Study of mass composition of cosmic rays with IceTop and IceCube*, *PoS ICRC2021* (2021) 323 [2107.09626].

- [265] P. Koundal, *Elemental Composition of Cosmic Rays: Analysis of IceCube data using Graph Neural Networks*, Ph.D. thesis, Karlsruhe Institute of Technology, 2024.
- [266] EAS-MSU, ICECUBE, KASCADE-GRANDE, NEVOD-DECOR, PIERRE AUGER, SUGAR, TELESCOPE ARRAY, YAKUTSK EAS ARRAY collaboration, *Update on the Combined Analysis of Muon Measurements from Nine Air Shower Experiments*, *PoS ICRC2021* (2021) 349 [2108.08341].
- [267] ICECUBE collaboration, *Measurement of the mean number of muons with energies above 500 GeV in air showers detected with the IceCube Neutrino Observatory*, *Phys. Rev. D* **112** (2025) 082004 [2506.19241].
- [268] ICECUBE collaboration, *Investigation of Electromagnetic and Muonic Air-Shower Components using IceTop Simulations*, *PoS ICRC2025* (2025) 424 [2508.08478].
- [269] ICECUBE collaboration, *Muon number reconstruction with IceTop using a two-component lateral distribution function*, *PoS ICRC2025* (2025) 437 [2509.13002].
- [270] ICECUBE collaboration, *Studies of a muon-based mass sensitive parameter for the IceTop surface array*, *PoS ICRC2021* (2021) 312 [2109.02506].
- [271] ICECUBE collaboration, *Cosmic Ray Anisotropy with 11 Years of IceCube Data*, *PoS ICRC2023* (2023) 360 [2308.02331].
- [272] ICECUBE collaboration, *Observation of Cosmic-Ray Anisotropy in the Southern Hemisphere with 12 yr of Data Collected by the IceCube Neutrino Observatory*, *Astrophys. J.* **981** (2025) 182 [2412.05046].
- [273] B. Skrzypek and S. Klein, *Measuring the Astrophysical $\bar{\nu} : \nu$ Ratio with IceCube*, 2508.02795.
- [274] ICECUBE collaboration, *Analysis of the Galactic Astrophysical Flux with 12.1 Years of IceCube Starting Tracks, Throughgoing Tracks and Cascades*, *PoS ICRC2025* (2025) 1135.
- [275] O. Janik and C. Haack, *Using End-to-End Optimized Summary Statistics to Improve IceCube's Diffuse Galactic Fits*, *PoS ICRC2025* (2025) 1132 [2507.06666].
- [276] ICECUBE collaboration, *Combining IceCube Muon Tracks and Cascades to measure the Galactic Diffuse Neutrino Flux*, *PoS ICRC2025* (2025) 1056 [2507.06089].
- [277] ICECUBE collaboration, *Astrophysical neutrino flux measurement and search for tau neutrino induced cascades with 11 years of IceCube data*, *PoS ICRC2025* (2025) 1011 [2507.08421].
- [278] L. Kardum, *Unfolding the muon neutrino flux*, Ph.D. thesis, Tech. U., Dortmund (main), 2023.
- [279] ICECUBE collaboration, *All-flavor Time-dependent Search for Transient Neutrino Sources*, *PoS ICRC2025* (2025) 1007 [2507.08775].
- [280] ICECUBE collaboration, *Search for Multi-flare Neutrino Emissions in 10 yr of IceCube Data from a Catalog of Sources*, *Astrophys. J. Lett.* **920** (2021) L45 [2109.05818].
- [281] ICECUBE collaboration, *The IceCube Realtime Alert System*, *Astropart. Phys.* **92** (2017) 30 [1612.06028].
- [282] ICECUBE collaboration, *The Next Generation of IceCube Real-time Neutrino Alerts*, *PoS ICRC2019* (2020) 1021 [1908.04884].

- [283] ICECUBE collaboration, *IceCat-1: The IceCube Event Catalog of Alert Tracks*, *Astrophys. J. Suppl.* **269** (2023) 25 [2304.01174].
- [284] ICECUBE collaboration, *IceCat-2: Updated IceCube Event Catalog of Alert Tracks*, *PoS ICRC2025* (2025) 1224 [2507.06176].
- [285] ICECUBE collaboration, *New Public Neutrino Alerts for Clusters of IceCube Events*, *PoS ICRC2025* (2025) 949 [2507.07491].
- [286] ICECUBE collaboration, *An updated list of target sources for IceCube neutrino cluster alerts*, *PoS ICRC2025* (2025) 919 [2507.06312].
- [287] ICECUBE collaboration, *Development of an IceCube realtime alert using multiplet signal for optical follow-up*, *PoS ICRC2023* (2023) 1467.
- [288] ICECUBE collaboration, *First all-flavor search for transient neutrino emission using 3-years of IceCube DeepCore data*, *JCAP* **01** (2022) 027 [2011.05096].
- [289] ICECUBE collaboration, *Search for GeV neutrino emission during intense gamma-ray solar flares with the IceCube Neutrino Observatory*, *Phys. Rev. D* **103** (2021) 102001 [2101.00610].
- [290] ICECUBE collaboration, *Follow-up of Astrophysical Transients in Real Time with the IceCube Neutrino Observatory*, *Astrophys. J.* **910** (2021) 4 [2012.04577].
- [291] ICECUBE collaboration, *Low-latency neutrino follow-up combining diverse IceCube selections*, *PoS ICRC2025* (2025) 956 [2507.08748].
- [292] ICECUBE collaboration, *A Search for Coincident Neutrino Emission from Fast Radio Bursts with Seven Years of IceCube Cascade Events*, *Astrophys. J.* **946** (2023) 80 [2212.06702].
- [293] ICECUBE collaboration, *Search for GeV-PeV neutrinos from nova T Coronae Borealis with IceCube*, *PoS ICRC2025* (2025) 1200 [2507.07096].
- [294] ICECUBE collaboration, *Search for High-Energy Neutrinos from TDE-like Flares with IceCube*, *PoS ICRC2023* (2023) 1478 [2307.15531].
- [295] N. Valtonen-Mattila, *Searching for IceCube Neutrinos from the Death of Stars and Beyond: From MeV to PeV Energies*, Ph.D. thesis, Acta Universitatis Upsaliensis, 2024.
- [296] ANTARES, ICECUBE, TELESCOPE ARRAY collaboration, *Search for correlations of high-energy neutrinos and ultrahigh- energy cosmic rays*, *EPJ Web Conf.* **207** (2019) 02010 [1905.10111].
- [297] ICECUBE collaboration, *Constraining High-energy Neutrino Emission from Supernovae with IceCube*, *Astrophys. J. Lett.* **949** (2023) L12 [2303.03316].
- [298] ICECUBE collaboration, *Searching for high-energy neutrinos from shock-interaction powered supernovae with the IceCube Neutrino Observatory*, *PoS ICRC2023* (2023) 1105 [2308.01047].
- [299] ICECUBE collaboration, *Results from IceCube Follow-up of Nearby Supernova SN2023ixf*, *PoS ICRC2025* (2025) 1109 [2507.07097].
- [300] ICECUBE collaboration, *IceCube Sensitivity for Low-Energy Neutrinos from Nearby Supernovae*, *Astron. Astrophys.* **535** (2011) A109 [1108.0171].
- [301] ICECUBE collaboration, *Searches for steady neutrino emission from 3FHL blazars using eight years of IceCube data from the Northern hemisphere*, *PoS ICRC2019*

- (2020) 916 [1908.08458].
- [302] R. Abbasi et al., *Search for Astrophysical Neutrinos from 1FLE Blazars with IceCube*, *Astrophys. J.* **938** (2022) 38 [2207.04946].
- [303] ICECUBE collaboration, *IceCube Search for Neutrino Emission from X-Ray Bright Seyfert Galaxies*, *Astrophys. J.* **988** (2025) 141 [2406.07601].
- [304] ICECUBE collaboration, *Search for high-energy neutrinos from AGN cores*, *PoS ICRC2019* (2020) 845 [1908.05170].
- [305] ICECUBE collaboration, *Measuring the Astrophysical Galactic Plane Neutrino Flux and Searching for Galactic PeVatrons using the IceCube Multi-Flavor Astrophysical Neutrino Sample*, *PoS ICRC2025* (2025) 1193 [2507.08753].
- [306] ICECUBE collaboration, *Measuring the Neutrino Flux in Segments along the Galactic Plane with IceCube*, *PoS ICRC2025* (2025) 1130 [2507.08097].
- [307] M. Ackermann et al., *Optical properties of deep glacial ice at the South Pole*, *J. Geophys. Res.* **111** (2006) D13203.
- [308] ICECUBE collaboration, *Measurement of South Pole ice transparency with the IceCube LED calibration system*, *Nucl. Instrum. Meth. A* **711** (2013) 73 [1301.5361].
- [309] ICECUBE collaboration, *Evidence of optical anisotropy of the South Pole ice*, *PoS ICRC2013* (2013) 0580.
- [310] ICECUBE collaboration, *Light diffusion in birefringent polycrystals and the IceCube ice anisotropy*, *PoS ICRC2019* (2020) 854 [1908.07608].
- [311] ICECUBE collaboration, *A calibration study of local ice and optical sensor properties in IceCube*, *PoS ICRC2021* (2021) 1023 [2107.10435].
- [312] ICECUBE collaboration, *In situ estimation of ice crystal properties at the South Pole using LED calibration data from the IceCube Neutrino Observatory*, *The Cryosphere* **18** (2024) 75.
- [313] ICECUBE collaboration, *State of the Ice Model in IceCube Observatory*, *PoS ICRC2025* (2025) 1013 [2507.06341].
- [314] P.B. Price, K. Woschnagg and D. Chirkin, *Age vs depth of glacial ice at South Pole*, *Geophysical Research Letters* **27** (2000) 2129.
- [315] ICECUBE collaboration, *South Pole glacial climate reconstruction from multi-borehole laser particulate stratigraphy*, *J. Glaciol.* **59** (2013) 1117.
- [316] ICECUBE collaboration, *An improved mapping of ice layer undulations for the IceCube Neutrino Observatory*, *PoS ICRC2023* (2023) 975 [2307.13951].
- [317] ICECUBE collaboration, *The IceCube Upgrade - Design and Science Goals*, *PoS ICRC2019* (2021) 1031 [1908.09441].
- [318] Y. Kobayashi, *Prospects for GeV Neutrino Transient Searches with the IceCube Upgrade*, *PoS ICRC2025* (2025) 1076 [2507.16050].
- [319] A. Partenheimer, J. Thwaites, K. Fang, J. Vandenbroucke and B.D. Metzger, *Prospects for Observing Astrophysical Transients with Gigaelectronvolt Neutrinos*, *Astrophys. J.* **982** (2025) 94 [2412.05087].
- [320] ICECUBE collaboration, *Sensitivity of the IceCube Upgrade to Atmospheric Neutrino Oscillations*, *PoS ICRC2023* (2023) 1036 [2307.15295].

- [321] ICECUBE collaboration, *Prospective Sensitivity to Solar Dark Matter using the IceCube Upgrade*, *PoS ICRC2025* (2025) 486 [2507.14943].
- [322] D. Hooper and F. Vassallo, *Searching for dark matter annihilation in the Sun with the IceCube Upgrade*, *Phys. Rev. D* **112** (2025) 035014 [2505.06734].
- [323] ICECUBE collaboration, *Impact of Hole-ice Calibration on High Energy Event Reconstruction with the IceCube Upgrade*, *PoS ICRC2025* (2025) 1029 [2507.07062].
- [324] ICECUBE collaboration, *Design and performance of the multi-PMT optical module for IceCube Upgrade*, *PoS ICRC2021* (2021) 1070 [2107.11383].
- [325] ICECUBE collaboration, *D-Egg: a dual PMT optical module for IceCube*, *JINST* **18** (2023) P04014 [2212.14526].
- [326] ICECUBE collaboration, *Electronics Development for the New Photo-Detectors (PDOM and D-Egg) for IceCube-Upgrade*, *PoS ICRC2019* (2020) 966 [1908.11564].
- [327] ICECUBE-GEN2 collaboration, “IceCube-Gen2 Technical Design Report, Part I and II.” <https://icecube-gen2.wisc.edu/science/publications/tdr/>, 2023.
- [328] ICECUBE-GEN2 collaboration, *IceCube-Gen2: the window to the extreme Universe*, *J. Phys. G* **48** (2021) 060501 [2008.04323].
- [329] ICECUBE collaboration, *Searching for IceCube sub-TeV neutrino counterparts to sub-threshold Gravitational Wave events*, *PoS ICRC2023* (2023) 1504 [2308.06102].
- [330] J. Braun, J. Dumm, F. De Palma, C. Finley, A. Karle and T. Montaruli, *Methods for point source analysis in high energy neutrino telescopes*, *Astropart. Phys.* **29** (2008) 299 [0801.1604].
- [331] M. Honda, T. Kajita, K. Kasahara, S. Midorikawa and T. Sanuki, *Calculation of atmospheric neutrino flux using the interaction model calibrated with atmospheric muon data*, *Phys. Rev. D* **75** (2007) 043006.
- [332] J.R. Braun, *A Maximum-likelihood search for neutrino Point Sources with the AMANDA-II detector*, Ph.D. thesis, University of Wisconsin–Madison, 2009.
- [333] R. Hussain, *Searching for Neutrinos from Gravitational Wave Sources with IceCube*, Ph.D. thesis, The University of Wisconsin-Madison, 2021.
- [334] G.C. Hill and K. Rawlins, *Unbiased cut selection for optimal upper limits in neutrino detectors: The Model rejection potential technique*, *Astropart. Phys.* **19** (2003) 393 [astro-ph/0209350].
- [335] A. Heijboer, *Track reconstruction and point source searches with ANTARES*, Ph.D. thesis, Amsterdam U., 2004.
- [336] S.J. Fahey, *Searches for Neutrinos from Fast Radio Burst and Other Astrophysical Transients with IceCube*, Ph.D. thesis, The University of Wisconsin-Madison, 2018.
- [337] N.I. Fisher, *Statistical analysis of circular data*, cambridge university press (1995).
- [338] ICECUBE collaboration, *Searching for sub-TeV IceCube neutrinos correlated to sub-threshold GW events*, *28th European Cosmic Ray Symposium* (2025) [2506.09694].
- [339] R. Reimann, *Search for the sources of the astrophysical high-energy muon-neutrino flux with the IceCube neutrino observatory*, Ph.D. thesis, RWTH Aachen U., 2019.

- [340] Z. Šidák, *Rectangular confidence regions for the means of multivariate normal distributions*, *Journal of the American Statistical Association* **62** (1967) 626.
- [341] I. Bartos, D. Veske, A. Keivani, Z. Marka, S. Countryman, E. Blaufuss et al., *Bayesian Multi-Messenger Search Method for Common Sources of Gravitational Waves and High-Energy Neutrinos*, *Phys. Rev. D* **100** (2019) 083017 [1810.11467].
- [342] M. Larson, *Private communication*, 2023.
- [343] KM3NET collaboration, *Searches for neutrino counterparts of gravitational waves from the LIGO/Virgo third observing run with KM3NeT*, *JCAP* **04** (2024) 026 [2311.03804].
- [344] L.J. Schumacher, M. Bustamante, M. Agostini, F. Oikonomou and E. Resconi, *Beyond first light: Global monitoring for high-energy neutrino astronomy*, *Phys. Rev. D* **112** (2025) 083027.
- [345] U.F. Katz, *KM3NeT: Towards a km³ Mediterranean Neutrino Telescope*, *Nucl. Instrum. Meth. A* **567** (2006) 457 [astro-ph/0606068].
- [346] KM3NET collaboration, *Letter of intent for KM3NeT 2.0*, *J. Phys. G* **43** (2016) 084001 [1601.07459].
- [347] BAIKAL-GVD collaboration, *Overview of the Baikal-GVD neutrino telescope: 2024 status*, *EPJ Web Conf.* **319** (2025) 04002.
- [348] P-ONE collaboration, *The Pacific Ocean Neutrino Experiment*, *PoS ICRC2021* (2022) 024 [2111.13133].
- [349] TRIDENT collaboration, *A multi-cubic-kilometre neutrino telescope in the western Pacific Ocean*, *Nature Astron.* **7** (2023) 1497 [2207.04519].
- [350] H. Zhang, Y. Cui, Y. Huang, S. Lin, Y. Liu, Z. Qiu et al., *A proposed deep sea Neutrino Observatory in the Nanhai*, *Astropart. Phys.* **171** (2025) 103123 [2408.05122].
- [351] T. Huang et al., *Proposal for the High Energy Neutrino Telescope*, *PoS(ICRC2023)* (2023) .
- [352] ARA collaboration, *Askaryan Radio Array: searching for the highest energy neutrinos*, *Eur. Phys. J. ST* **234** (2025) 5065 [2411.01761].
- [353] ARIANNA collaboration, *Targeting ultra-high energy neutrinos with the ARIANNA experiment*, *Adv. Space Res.* **64** (2019) 2595 [1903.01609].
- [354] RNO-G collaboration, *Design and Sensitivity of the Radio Neutrino Observatory in Greenland (RNO-G)*, *JINST* **16** (2021) P03025 [2010.12279].
- [355] PIERRE AUGER collaboration, *Probing the origin of ultra-high-energy cosmic rays with neutrinos in the EeV energy range using the Pierre Auger Observatory*, *JCAP* **10** (2019) 022 [1906.07422].
- [356] PIERRE AUGER collaboration, *Search for Ultra-High-Energy Neutrinos at the Pierre Auger Observatory: New Triggers, Methods, and Constraints*, *PoS ICRC2025* (2025) 1170 [2507.10214].
- [357] GRAND collaboration, *The Giant Radio Array for Neutrino Detection (GRAND): Science and Design*, *Sci. China Phys. Mech. Astron.* **63** (2020) 219501 [1810.09994].
- [358] L.J. Schumacher, M. Huber and M. Bustamante, “PLEnuM software tools.”

- [359] M. Huber, *Multi-Messenger correlation study of Fermi-LAT blazars and high-energy neutrinos observed in IceCube*, Ph.D. thesis, Munich, Tech. U., 2020.
- [360] L. van Rootselaar, *Unfolding the Muon Neutrino Spectrum with Eleven Years of IceCube Data*, *PoS ICRC2025* (2025) 1199.
- [361] A. Fedynitch, R. Engel, T.K. Gaisser, F. Riehn and T. Stanev, *Calculation of conventional and prompt lepton fluxes at very high energy*, *EPJ Web Conf.* **99** (2015) 08001 [1503.00544].
- [362] F. Riehn, H.P. Dembinski, R. Engel, A. Fedynitch, T.K. Gaisser and T. Stanev, *The hadronic interaction model SIBYLL 2.3c and Feynman scaling*, *PoS ICRC2017* (2018) 301 [1709.07227].
- [363] T.K. Gaisser, *Spectrum of cosmic-ray nucleons, kaon production, and the atmospheric muon charge ratio*, *Astropart. Phys.* **35** (2012) 801 [1111.6675].
- [364] T.K. Gaisser, T. Stanev and S. Tilav, *Cosmic Ray Energy Spectrum from Measurements of Air Showers*, *Front. Phys. (Beijing)* **8** (2013) 748 [1303.3565].
- [365] R.K. Joshi, A. Bhake, B. Banerjee, B. Vaidya, M. Ruiz, A. Tsokaros et al., *Binary black holes in magnetized disks of active galactic nuclei*, *Astron. Astrophys.* **703** (2025) A304 [2509.16796].
- [366] LIGO SCIENTIFIC, VIRGO collaboration, *GW190521: A Binary Black Hole Merger with a Total Mass of $150M_{\odot}$* , *Phys. Rev. Lett.* **125** (2020) 101102 [2009.01075].
- [367] I. Bartos, Z. Haiman, Z. Marka, B.D. Metzger, N.C. Stone and S. Marka, *Gravitational-wave localization alone can probe origin of stellar-mass black hole mergers*, *Nature Commun.* **8** (2017) 831 [1701.02328].
- [368] K.E.S. Ford and B. McKernan, *Binary black hole merger rates in AGN discs versus nuclear star clusters: loud beats quiet*, *Mon. Not. Roy. Astron. Soc.* **517** (2022) 5827 [2109.03212].
- [369] W. Ishibashi and M. Gröbner, *Gravitational wave mergers of accreting binary black holes in AGN discs*, *Mon. Not. Roy. Astron. Soc.* **529** (2024) 883 [2412.01925].
- [370] M. Mukhopadhyay, S.S. Kimura and K. Murase, *Gravitational wave triggered searches for high-energy neutrinos from binary neutron star mergers: Prospects for next generation detectors*, *Phys. Rev. D* **109** (2024) 043053 [2310.16875].
- [371] J. Nordin et al., *Transient processing and analysis using AMPEL: alert management, photometry, and evaluation of light curves*, *Astron. Astrophys.* **631** (2019) A147 [1904.05922].
- [372] K.M. Górski, E. Hivon, A.J. Banday, B.D. Wandelt, F.K. Hansen, M. Reinecke et al., *HEALPix - A Framework for high resolution discretization, and fast analysis of data distributed on the sphere*, *Astrophys. J.* **622** (2005) 759 [astro-ph/0409513].
- [373] S.S. Kimura, K. Murase, P. Mészáros and K. Kiuchi, *High-Energy Neutrino Emission from Short Gamma-Ray Bursts: Prospects for Coincident Detection with Gravitational Waves*, *Astrophys. J. Lett.* **848** (2017) L4 [1708.07075].
- [374] P.F. Harrison, D.H. Perkins and W.G. Scott, *Tri-bimaximal mixing and the neutrino oscillation data*, *Phys. Lett. B* **530** (2002) 167 [hep-ph/0202074].

- [375] L. Nava, G. Ghirlanda, G. Ghisellini and A. Celotti, *Spectral properties of 438 GRBs detected by Fermi/GBM*, *Astron. Astrophys.* **530** (2011) A21 [[1012.2863](#)].
- [376] W.-f. Fong, E. Berger, R. Margutti and B.A. Zauderer, *A Decade of Short-duration Gamma-ray Burst Broadband Afterglows: Energetics, Circumburst Densities, and jet Opening Angles*, *Astrophys. J.* **815** (2015) 102 [[1509.02922](#)].
- [377] A. Lien et al., *The Third Swift Burst Alert Telescope Gamma-Ray Burst Catalog*, *PoS SWIFT10* (2015) 038.
- [378] T. Sakamoto et al., *The Second Swift BAT Gamma-Ray Burst Catalog*, *Astrophys. J. Suppl.* **195** (2011) 2 [[1104.4689](#)].
- [379] Y. Kagawa et al., *X-raying extended emission and rapid decay of short gamma-ray bursts*, *Astrophys. J.* **811** (2015) 4 [[1506.02359](#)].
- [380] Y. Kaneko, Z.F. Bostancı, E. Göğüş and L. Lin, *Short Gamma-Ray Bursts with Extended Emission Observed with Swift/BAT and Fermi/GBM*, *Mon. Not. Roy. Astron. Soc.* **452** (2015) 824 [[1506.05899](#)].
- [381] S. Kisaka, K. Ioka and T. Sakamoto, *Bimodal Long-Lasting Components in Short Gamma-Ray Bursts: Promising Electromagnetic Counterparts to Neutron Star Binary Mergers*, *Astrophys. J.* **846** (2017) 142 [[1707.00675](#)].
- [382] G. Chincarini et al., *Unveiling the origin of X-ray flares in Gamma-Ray Bursts*, *Mon. Not. Roy. Astron. Soc.* **406** (2010) 2113 [[1004.0901](#)].
- [383] R. Margutti et al., *X-ray flare candidates in short gamma-ray bursts*, *Mon. Not. Roy. Astron. Soc.* **417** (2011) 2144 [[1107.1740](#)].
- [384] P.A. Evans et al., *Methods and results of an automatic analysis of a complete sample of Swift-XRT observations of GRBs*, *Mon. Not. Roy. Astron. Soc.* **397** (2009) 1177 [[0812.3662](#)].
- [385] A. Rowlinson et al., *Signatures of magnetar central engines in short GRB lightcurves*, *Mon. Not. Roy. Astron. Soc.* **430** (2013) 1061 [[1301.0629](#)].

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