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# Multimessenger NuEM Alerts with AMON

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The Astrophysical Multimessenger Observatory Network (AMON), has developed a real-time multi-messenger alert system. The system performs coincidence analyses of datasets from gamma-ray and neutrino detectors, making the Neutrino-Electromagnetic (NuEM) alert channel. For these analyses, AMON takes advantage of sub-threshold events, i.e., events that by themselves are not significant in the individual detectors. The main purpose of this channel is to search for gamma-ray counterparts of neutrino events. We will describe the different analyses that make-up this channel and present a selection of recent results.

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## 1. Multi-messenger Astrophysics

The study of the Universe has been benefited by the improvement of our technology and analysis techniques. Recently, this has allowed us to combine the information available from different observations that focus on individual components of the physical phenomena. The most important results in the past lustrum are the detection of gravitational waves and electromagnetic radiation from the merger of a binary neutron star [1], together with the detection of high-energy neutrinos and gamma-rays from the blazar TXS 0506-056 [2].

The information given by each individual messenger — cosmic rays, electromagnetic radiation, neutrinos, and gravitational waves — help us get a general picture about the acceleration mechanisms and identification of sources that produce cosmic-rays, gamma-ray bursts, the nature of dark matter and other unsolved questions in astrophysics [See for example 3, 4].

In these contribution we present an overview of the Neutrino-Electromagnetic (NuEM) channel of the Astrophysical Multimessenger Observatory Network. This effort is based on the new paradigm of multi-messenger astrophysics, which aims at coordination between different observatories and combining independent datasets into a coincidence analysis.

## 2. AMON

The Astrophysical Multimessenger Observatory Network (AMON) is a program developed at the Pennsylvania State University. Its primary objective is to perform real-time coincidence searches of sub-threshold events of different observatories. Any statistically significant coincidence is then reported to the astrophysical community through Gamma-ray Coordinates Network (GCN, also known as the Transient Astronomy Network). AMON also stores events into its database to perform archival coincidence searches. It broadcasts individual events to GCN if the observatories providing the events consider them to be of interest to the astrophysical community. And finally, it aims to be a framework that facilitates the interaction between observatories trying to combine their datasets [5]. A list of participants can be found in the AMON webpage[1].

The AMON alert system started sending alerts in 2016. Currently, AMON provides the following public alerts:

- IceCube Gold, Bronze and Cascade alerts,
- HAWC Burst-like alerts,
- NuEM channel alerts.

The notices of these alerts can be found in the GCN webpage[2]. The webpage also includes the now decomissioned IceCube HESE and EHE alerts.

[1] https://www.amon.psu.edu/amon-participants/
[2] https://gcn.gsfc.nasa.gov/amon.html



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## 3. The NuEM Channel

The AMON NuEM channel focuses on neutrino and high-energy photon coincidences by using sub-threshold data[3] from different observatories. The main objective of this channel is to search for the sources of high-energy neutrinos with the help of high-energy gamma rays.

This search can be performed since there are physical processes where neutrinos and gamma rays are produced together. It is known that accelerated cosmic rays interact with radiation fields or interstellar matter surrounding the region around astrophysical sources. These interactions produce secondary charged and neutral pions. Charged pions mainly decay via $\pi^+ \rightarrow \mu^+ + \nu_\mu$, followed by the decay of the muon as $\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$ and a similar process with the charge conjugate. Neutral pions decay into two gamma-ray photons, $\pi^0 \rightarrow \gamma + \gamma$. A photohadronic interaction, i.e. a collision between a cosmic ray and a photon, will produce charged and neutral pions with probabilities of one-third and two-thirds. If the interaction is just hadronic, then the probability of producing charged and neutral pions is one-third for each type of pion [6].

The NuEM channel receives data from the IceCube [7], ANTARES [8], HAWC [9], and *Fermi*-LAT [10] observatories. We have performed archival coincidences analysis between: *Fermi*-ANTARES [11], HAWC-IceCube [12], *Fermi*-IceCube [13] and HAWC-ANTARES, which preliminary results are shown in this contribution.

The general algorithm used in AMON to find and rank coincidences is as follows:

1. Set a criteria to select events which conform a coincidence. The criteria can be:
   - A time window where events can arrive.
   - A maximum angular distance between events.
2. Calculate a ranking statistic for the coincidence. This usually includes:
   - A likelihood calculation, $\lambda(\boldsymbol{x})$, quantifying the overlap between events. Maximizing the likelihood, $\lambda_{\text{max}}$, gives an estimate of the position of the coincidence $\boldsymbol{x}_{\text{max}}$.
   - A combination of p-values using Fisher's method [14]. The p-values can be, for example, how likely the individual event is from background, or how likely is the overlap between events just random.
3. Calculate the false-alarm rate of the coincidence as a function of the ranking statistic.

The false-alarm rate (FAR) is built by simulating random coincidences and generating a distribution of the ranking statistic. The analysis *Fermi*-ANTARES [11] and HAWC-IceCube [12] are, at the time of writing, running in real-time. The latency of these analyses are in the order of hours: 1 to 12 hours when data is downlinked from the *Fermi*-LAT instrument, and 3 to 7 hours when the data is collected by the HAWC Observatory (which corresponds to the time a point in the sky transits the detector's field of view). The calculation of the ranking statistic and the alert sending time is less than a minute. For the public real-time system we have set, with an agreement between the observatories, a threshold of FAR $<$ 4 per year to send alerts. Alerts are sent as notices and circulars through GCN[4].

[3] The numerical definition of a sub-threshold event is set by each individual observatory.

[4] The NuEM notices are found in `https://gcn.gsfc.nasa.gov/gcn/amon_nu_em_coinc_events.html`



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## 4. Results

Table 1 shows the public alerts that appear in GCN, as well as the results of the archival coincidence searches performed so far. For the archival coincidences we show the ones that have a FAR < 1 per year.

| Name | R.A. [°] | Decl. [°] | $\delta\theta$ [°] | FAR [$yr^{-1}$] | Time UTC |
|---|---|---|---|---|---|
| Real-time alerts | | | | | |
| NuEM-210515A | 93.64 | 14.66 | 0.15 | 3.93 | 2021-05-15 00:20:43 |
| NuEM-210515B | 93.93 | 12.51 | 0.20 | 1.90 | 2021-05-15 00:19:27 |
| NuEM-210111A | 162.34 | 19.46 | 0.37 | 3.85 | 2021-01-11 13:06:41 |
| NuEM-201124A | 134.99 | 7.74 | 0.23 | 2.96 | 2020-11-24 14:13:37 |
| NuEM-201107A | 140.20 | 29.76 | 0.15 | 3.49 | 2020-11-07 15:55:31 |
| ANTARES-Fermi 200704A | 255.42 | -34.48 | 0.43 | 0.98 | 2020-07-04 15:53:48 |
| NuEM-200202A | 200.30 | 12.71 | 0.17 | 1.39 | 2020-02-02 14:07:52 |
| ANTARES-Fermi 191011A | 49.96 | 18.80 | 0.40 | 1.21 | 2019-10-11 15:54:32 |
| Archival Coincidences | | | | | |
| ANTARES-Fermi | 248.00 | -7.7 | 0.07 | 0.09 | 2012-11-21 20:19:52 |
| ANTARES-Fermi | 279.68 | -5.05 | 0.10 | 0.09 | 2014-08-05 11:13:33 |
| HAWC-IceCube | 4.93 | 2.96 | 0.16 | 0.99 | 2016-12-12 04:38:41 |
| HAWC-IceCube | 173.99 | 2.27 | 0.53 | 0.026 | 2018-04-12 07:54:51 |
| HAWC-ANTARES | 25.6 | 25.0 | 0.2 | 0.7 | 2016-01-08 04:39:38 |
| HAWC-ANTARES | 222.8 | -0.8 | 0.2 | 0.87 | 2017-09-07 01:21:22 |
| HAWC-ANTARES | 85.4 | 3.4 | 0.2 | 0.41 | 2019-03-29 03:01:18 |

**Table 1:** Real-time and Archival coincidences in the AMON NuEM channel. Real-time alerts are sent when the FAR is less than 4 per year. Archival coincidences have a FAR of less than 1 per year. Although the ANTARES-Fermi alerts are part of the AMON NuEM channel, the alerts are currently sent via GCN circulars instead of notices.

Follow-up observations of the real-time alerts have been made by a couple of observatories. Table 2 shows some of the instruments that submitted GCN circulars of their follow-up observations.

We have also looked at the Fermi All-sky Variability Analysis (FAVA)[5] as well as the SIMBAD[6] and NED[7] catalogs, but no counterpart has been found so far for any of the coincidence alerts.

## 5. Summary

The multi-messenger approach has become a new paradigm to study astrophysical objects. Its advantages are that we can have a better understanding of different phenomena in the universe, such as sources of high-energy cosmic rays and neutrinos, the processes leading to gamma-ray bursts and the nature of dark matter. However, the tasks are challenging and require development of new

[5] https://fermi.gsfc.nasa.gov/ssc/data/access/lat/FAVA/
[6] http://simbad.u-strasbg.fr/simbad/
[7] http://ned.ipac.caltech.edu/



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| Name | Followed by |
| --- | --- |
| NuEM-210515A/B | ANTARES |
| NuEM-210111A | ANTARES, INTEGRAL,MAXI |
| NuEM-201124A | ANTARES |
| NuEM-201107A | *Fermi*-LAT |
| NuEM-200202A | MASTER, ANTARES |
| FERMI-ANTARES-191011A | MASTER |

**Table 2:** Follow-up observations of the NuEM alerts published as GCN Circulars. No counterpart was found in these observations. If seen online, each alert has a link to their respective circular.

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techniques as well as the cooperation between different collaborations. AMON is a framework that aims to help with these issues. As an example, we have shown here the NuEM channel, a channel that performs coincidence analyses between neutrino data and gamma-ray data. The datasets used are diverse since they come from observatories such as IceCube, ANTARES, HAWC and Fermi-LAT. The AMON-NuEM channel has been sending alerts to the astrophysical community since 2019. The channel is still growing, with new coincidences planned to be added to it such as the HAWC-ANTARES analysis.

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