newASTROGAM – The New MeV to GeV Gamma-ray Observatory

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newASTROGAM is a breakthrough mission concept for the study of the non-thermal Universe from space with γ-rays in the energy range from 15 keV to 3 GeV. It is based on advanced space-proven detector technologies, which will achieve unprecedented sensitivity, angular and energy resolution combined with polarimetric capability. Since the MeV γ-ray energy range is the most under-explored electromagnetic window to the Universe, a mission in this energy range can for the first time sensitively address fundamental astrophysics questions connected to the physics of compact objects and merger events, jets and their environments, supernovae and the origin of the elements, potentially constrain the nature of dark matter and many more science objectives. The mission will detect and follow-up many of the key sources of multi-messenger astronomy in the 2040s.

newASTROGAM provides an unprecedentedly broad energy coverage from keV to GeV energies. They payload concept consists of a Silicon tracker combined with a crystal calorimeter. Both detectors are surrounded by an anti-coincidence detector to reject charged cosmic rays. In addition, a thin X-ray coded mask provides very good imaging capabilities. Such a mission can uniquely detect γ-rays via the photoelectric effect, Compton scattering and electron-positron pair production. newASTROGAM is proposed to the ESA call for medium-class mission ideas (M8).

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1. Introduction

The γ-ray sky at MeV and GeV energies provides unique and crucial information on the most energetic and intriguing phenomena of our Universe. Photons in this range provide fundamental insights into the physics of nucleosynthesis, accretion, particle acceleration, strong magnetic fields, and extreme-gravity environments [1]. Observing the sky at these energies with a large field of view (FoV) and unprecedentedly high sensitivity is of paramount importance in the era of multi-messenger astronomy, as clearly underlined in the Voyage 2050 program and Astro2020 Decadal Survey report.

newASTROGAM[1] is designed as a unique multi-purpose observatory with scanning and pointing capability, enabling imaging, polarimetry, line and continuum spectroscopy, sub-millisecond timing, and fast transient detection in the MeV-GeV energy domain. It will be the first instrument with adequate sensitivity in the MeV range and simultaneous GeV coverage, thus ensuring the broad-band information needed to unravel many fundamental physical processes. *newASTROGAM* is *new* because a hard-X-ray imager with arcminute source localization capability has been added to the original design. This addition broadens the purpose of the mission, which will not only complement data from, but also provide trigger information to, prominent facilities such as SKA, ALMA, Roman Space Telescope, ELT, newAthena, CTAO, SWGO, LISA, the Einstein Telescope, IceCube-Gen2, KM3NeT.

While the mission will contribute to many science topics of interest for a broad and diverse community, *newASTROGAM* promises major breakthroughs in the following areas:

- physics of extreme cosmic accelerators from within the Galaxy to Cosmic Dawn;
- nucleosynthesis, supernova explosions, chemical evolution of the Interstellar Medium (ISM);
- Cosmic Ray (CR) sources and feedback;
- the extreme Universe in the era of multi-messenger astronomy;
- fundamental physics.

2. Science

With its large FoV ($\sim 1/3$ of the sky), all-sky scanning mode, and arcmin localization capability, *newASTROGAM* will study the activity of thousands of cosmic accelerators such as pulsars, stellar and supermassive black holes (SMBHs), γ-ray bursts (GRBs), magnetars, supernovae (SNe), and kilonovae. With its unprecedented sensitivity (see Fig. 1), it will provide the deepest all-sky mapping of the MeV emission produced by the radioactive decay of newly synthesized nuclei, CR interactions, $e^{\pm}$ pairs, and decisively search the MeV–GeV sky for dark-matter (DM) signatures. Finally, it will help identify electromagnetic counterparts to gravitational-wave (GW) and high-energy neutrino sources, expanding the pioneering role of the *Fermi* satellite.

Insights into Extreme Acceleration Processes

MeV-GeV variability studies of relativistic jets can be conducted with *newASTROGAM* on timescales of seconds to hours for GRBs and from minutes to years for AGN. For AGN jets they will provide

[1]**Mission homepage:** https://www.new-astrogam.eu

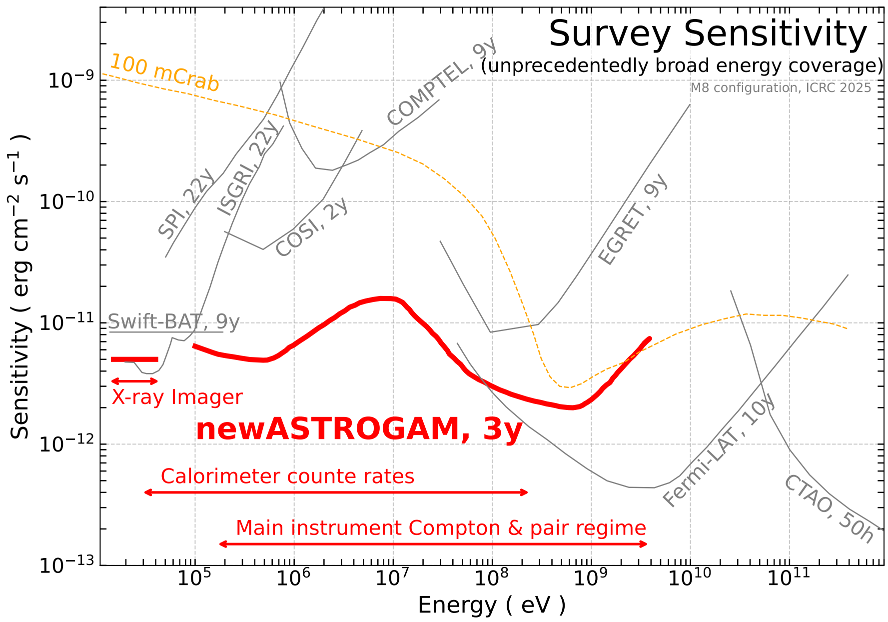

Figure 1: Point-source (extra-galactic) continuum sensitivity of different X- and γ-ray instruments.

crucial information on the size and location of the acceleration site, and on the Lorentz factor and any precession of the jet. The detailed shape of the emission spectrum around the MeV peak places important constraints on acceleration and radiation mechanisms, and maximum particle energy [2]. *newASTROGAM* data will also constrain the lepton/baryon content and magnetization of the jets, whose knowledge is fundamental to assessing their energetics, the microphysics of particle acceleration, and the impact on their surroundings. Analogous constraints on the sites and mechanisms of particle acceleration will be placed on black-hole (BH) and neutron-star (NS) X-ray binaries, recently probed by INTEGRAL and *Fermi* as high-energy emitters, with the MeV band providing the missing link [3, 4].

γ-ray polarimetry [5] is a young field with a large discovery potential. Polarisation changes between X-rays and γ-rays can probe the location and evolution of relativistic particle outflows. *newASTROGAM* will enable polarimetric measurements for tens of Galactic sources with sensitivity to variations in time. For accreting BHs, measurements of the polarisation and the MeV cutoff energy can firmly establish the nature of the observed MeV tail, disentangling its origin between the jet and the disk corona.

Current observations of TeV-to-PeV neutrinos suggest the existence of both a Galactic and an extragalactic population of hadronic PeVatrons (PeV ion accelerators) mostly hidden to GeV-TeV γ-ray telescopes due to strong γ-ray absorption in the source. A handful of temporal associations between neutrinos and γ-ray flares suggest AGN jets and Galactic γ-ray binaries as promising PeVatrons [6]. Some steady neutrino sources [7] are claimed to be associated with AGN coronae. The accompanying cascade radiation would preferentially appear in the MeV band [8], making *newASTROGAM*'s role decisive to decipher the processes of PeV particle acceleration, both in Seyfert galaxies [9] and in blazars [10].

newASTROGAM will shed light on BH activity in the early Universe. The most luminous AGN, powered by accretion onto a SMBH of about $10^9\,M_\odot$, are most abundant at redshifts $z \gtrsim 3$ [11], before the cosmic noon in star-formation history. The jet emission peaks in the MeV-GeV band, and largely dominates the radiative output when the jet points in our direction (blazar). *newASTROGAM* can characterise the jet activity of hundreds of objects, both in quiescence and during flares. MeV blazars can be detected up to redshift $z \sim 6-7$ [11], though most of the detected sources will have redshifts $z < 4$. The opportunity is unique to shed light on the physics of this source class, the cosmological evolution of SMBHs, the environment of their growth, and the extent to which AGN jets influence galaxy evolution [12]. This topic is also identified as a Voyage 2050 priority.

Explosive Nucleosynthesis and Chemical Evolution of Galaxies

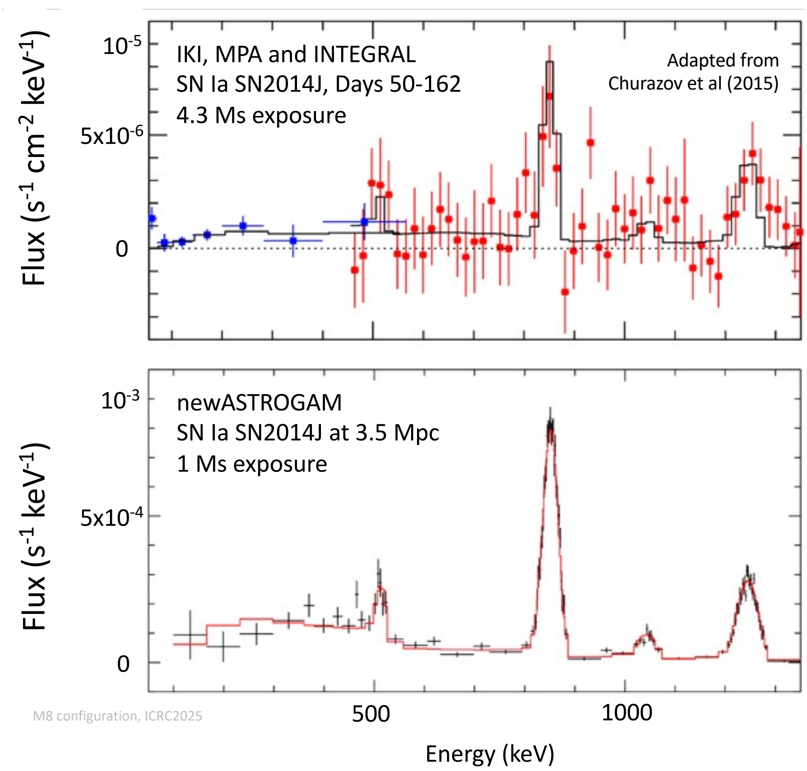

Figure 2: Improvement over INTEGRAL (top, [13]) for a type-Ia SN. Lines from the ^{56}Ni decay chain will clearly be resolved (bottom), yielding the radioactive and total ejecta masses, a characteristic of the progenitors.

Interstellar enrichment in heavy nuclei is driven by asymptotic-giant-branch stars, core-collapse supernovae (SNe), white-dwarf explosions, and NS mergers (kilonovae), but their relative contributions are not established at all [14]. *newASTROGAM* can detect important nuclear decay lines with unprecedented sensitivity and, for nominal mission lifetimes, improve over the upcoming COSI mission [15] by factors 2.5 to 30, depending on the line.

The large FoV will help detecting γ-rays, the earliest photons to escape explosion sites, before the optical peak, for optimal constraints on the nature and mass of the progenitor and on the explosion itself [16]. The detection of type-Ia SNe out to a distance of 30 Mpc will enable precise measurements of the total mass of ^{56}Ni/^{56}Co in the ejecta (see Fig. 2), probing the progenitors and also testing the calibration of the cosmological distance determination with SNe Ia [17]. γ-rays from the ^{44}Ti/^{44}Sc decay chain can be detected in most of the young Galactic supernova remnants and in SN1987A, providing information on the degree of asymmetry and clumpiness of the ejecta of core-collapse SNe [1].

newASTROGAM can detect line emission from kilonovae up to 12 Mpc away and measure the mass of nuclei synthesised by rapid neutron capture. In the Milky Way, it can uncover the remnant of a kilonova up to 10–100 kyr old through long-lived radioisotopes such as ^{126}Sn and their fission products [18–20]. *newASTROGAM* will map the positron annihilation line at 511 keV with unprecedented quality and may even obtain the first point-source detection. It can detect the 2.2-MeV neutron-capture line from accreting neutron stars. It can also map the long-lived ^{26}Al and ^{60}Fe radioisotopes, shedding new light on stellar nucleosynthesis and on the subsequent mixing of the high-metallicity ejecta into the ISM [21]. Finally, it may provide the first unambiguous estimate of the ^{22}Na and ^{7}Be (see ref. [22] for INTEGRAL hints of the latter) yield in a nova, and thus gauge the nova contribution to the Galactic enrichment in ^{7}Li.

Cosmic Ray Sources and Feedback on Galaxy Evolution

newASTROGAM data will be crucial to resolve important CR puzzles. Observations of CR accelerators below 1 GeV will be decisive for disentangling the emission of accelerated ions and electrons, and that of freshly accelerated versus re-accelerated CRs, and will allow studying CR feedback on the sources. *newASTROGAM* will provide the first precise measurement of the “Pion Bump” below 500 MeV, a direct probe of hadronic emission [23]. MeV-band spectra of CR sources will probe the initial acceleration of CR electrons and hence the connection between CRs and quasi-thermal plasma [24], while nuclear de-excitation lines will provide otherwise inaccessible information on CR ions below 200 MeV/nucleon.

The impact of CRs is a highly uncertain feedback factor in galaxy evolution. The pressure gradient of GeV CRs can drive galactic outflows, whereas low-energy ($<$ 100 MeV) CRs are the main source of ionisation and heating in dark clouds, with direct impact on star formation. *newASTROGAM* observations will advance our poor understanding of the propagation of these two important CR populations, probing their spectra at different locations in the disk, near their sources, in the “quiet” ISM and in the highly turbulent medium of starburst regions, where re-acceleration can occur [25, 26]. Mapping their large-scale distribution will measure beyond the Galactic disk the imprint of star-forming regions [27].

In the Galactic center region, *newASTROGAM* will improve the spatial and spectral characterisation of the puzzling γ-ray excess, to elucidate its debated origin between DM annihilation, an excess of CRs, or a population of unresolved millisecond pulsars [28]. On larger scales, the angular resolution and energy band of the instrument are ideal to study the morphology and ion/lepton composition of the Fermi bubbles, and help assess their origin as a CR-driven wind or as jets powered by the central BH, Sgr A* [29, 30].

Deciphering the Energetic Transient Sky

The sensitivity, FoV, and spectral range of *newASTROGAM* will allow the MeV/GeV-band detection of hundreds of long (see Fig. 3) and short GRBs. The latter, counterparts to binary NS mergers, will

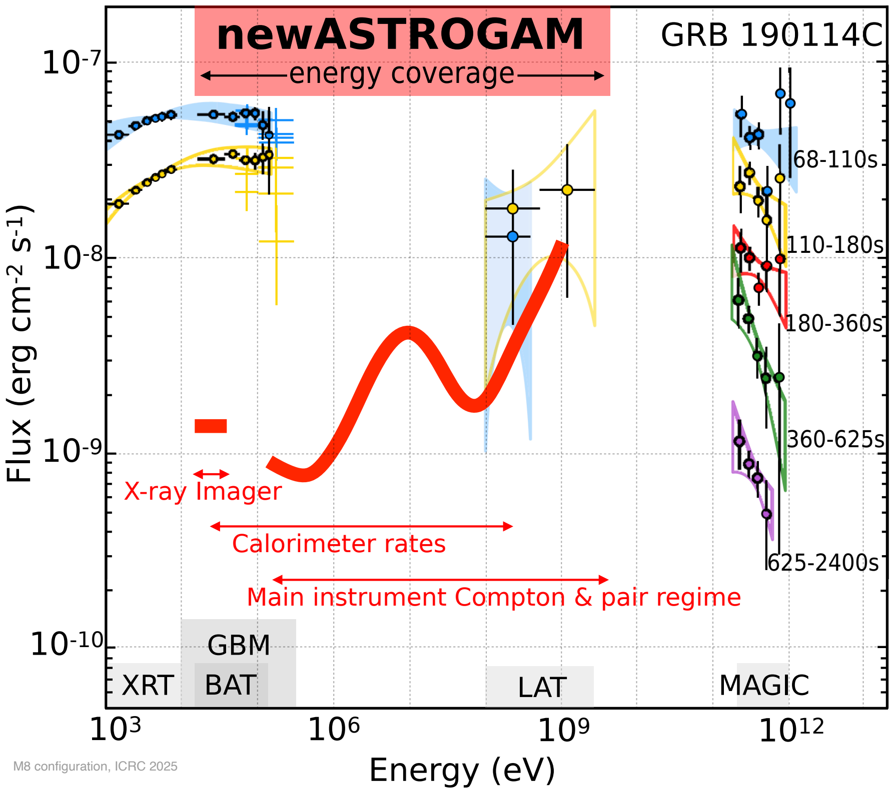

Figure 3: X- and γ-ray afterglow spectrum of a long GRB [31]. *newASTROGAM* probes the poorly covered transition region, its sensitivity is shown in red here for 600 s exposure.

be detected at a rate of several tens per year, ensuring synergy with GW detectors. For the former, the mission will not only see the bright prompt emission, but can uniquely follow the afterglow and determine the radiation process and the spectrum of the radiating particles.

The X-ray Coded Mask will yield arcmin localisation, guiding multi-wavelength follow-up observations of the source environment and of the development of the kilonova as softer light emerges hours and days later. Moreover, *newASTROGAM* will measure intermediate X- to γ-rays in a special burst event mode (*calorimeter count rates*) and provide polarimetry for the brightest events, key to identifying the radiation process and constrain the magnetic and kinetic profile of the jet [32]. Time-domain surveys conducted by SKA in the radio, Roman in the infrared, and Rubin in the optical, will revolutionise our knowledge of the transient sky: *newASTROGAM* will add the fundamental MeV-GeV band to this revolution, covering many source classes beyond the well-studied micro-quasars, AGN and GRB transients, including magnetars [33] and Fast Blue Optical Transients [34]. All detected transient signals will be rapidly disseminated with arcminute localization in hard X-rays.

Fundamental and New Physics

newASTROGAM will explore fundamental physics. It will access the MeV to GeV mass scale of DM, where direct searches are insensitive and collider searches are highly model dependent, and offer multiple angles for detections [35, 36]: its angular resolution allows DM signals from subhalos and the inner Galaxy to be better identified than with *Fermi*, it offers unprecedented details of DM models explaining the 511 keV line [37, 38], and can differentiate pulsar and DM interpretations of the Galactic-center excess [35]. Weakly Interacting Sub-eV Particles, e.g. axions and axion-like particles (ALP) [39], would produce spectral signatures in the MeV band [40] or could be probed by ALP-induced GRBs from extragalactic SNe [41, 42]. Polarimetry of bright GRBs will address fundamental questions related to vacuum birefringence and Lorentz-invariance violation [43]. Finally, *newASTROGAM* will be highly sensitive to photon emission from primordial BHs in the mass range 10^{15-17} g, which peaks at 1-30 MeV [44, 45].

3. *newASTROGAM* Mission Configuration

To achieve a breakthrough sensitivity, *newASTROGAM* will be launched in an equatorial low-Earth orbit of inclination $< 2.5°$, eccentricity < 0.01, and altitude $550 - 600$ km. Such an orbit is only marginally affected by the South Atlantic Anomaly therefore minimising instrumental particle backgrounds, ideal for high-energy observations [46]. Alerts for new transient sources detected onboard with arcminute accuracy will be instantly transmitted to the ground. The mission will mostly do survey observations covering with its large FoV the entire sky in one day. In addition, occasional target-of-opportunity observations can be performed by a nearly inertial pointing to focus on a particular region. The nominal mission duration is planned to be three years.

The payload consists of a single instrument operating over five orders of magnitude in photon energy (15 keV–3 GeV), detecting photons via the photoelectric effect, Compton scattering, and $e^{\pm}$ pair production. To veto cosmic rays, the outermost Anti-Coincidence (AC) system is composed of segmented panels of plastic scintillators covering the top and the lateral sides of the roughly quadratic payload (≈120 cm across). The AC vetoes more than 99.99% of the penetrating charged particles and is based on heritage of the *AGILE* and *Fermi* missions. Within the AC and 14 cm before the first Silicon Tracker layer is a thin Coded Mask to image X-rays in the ∼15–40 keV energy range with an angular resolution of ∼15', providing a localisation capability of a few arcminutes for bright sources. The mask consists of a tungsten sheet with a pseudo-random pattern (open fraction 50%). The mask mechanical support is also provided by an X-ray collimator of carbon fibre walls. The FoV of the X-ray coded mask monitor is 4.06 sr (half coded).

The instrument's heart is a Silicon microstrip Tracker. Such strips are already employed for γ-ray detection in space (e.g. for *DAMPE*). The Tracker measures hard X-rays that have passed the Coded Mask and γ-rays that undergo Compton scattering or pair conversion. The baseline design has double-sided detectors (DSSDs) read out by low-noise and low-power electronics with self-triggering capability. The Tracker is supported by a very light carbon fibre mechanical structure. 9 DSSDs are wire bonded strip to strip to form a 2-D ladder. Alternatively, CMOS pixels [47, 48] will be assessed and compared to the baseline DSSDs during the study phase.

The Calorimeter is a pixelated detector made of a high-Z scintillation material (such as CsI(Tl)) for efficient absorption of γ-rays and $e^{\pm}$ pairs. It consists of an array of parallelepiped crystal bars read out by silicon drift detectors or silicon photomultipliers. The depth of interaction in each crystal is measured from the difference of recorded scintillation signals at both ends. The Calorimeter architecture is based on the heritage of instruments like for example *INTEGRAL*/PICsIT or *POLAR-2*.

4. Conclusions

newASTROGAM is a proposed MeV to GeV observatory with exceptionally large energy coverage. Planned to orbit the earth in the 2040's as a medium-class ESA mission, *newASTROGAM* promises major breakthroughs via measurements in an otherwise under-covered wavelength regime.

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