PROCEEDINGS OF SCIENCE

PoS(DSU2015)020

Dark matter signatures in a mostly unexplored gamma-ray energy window

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The energy range 0.3 MeV - 100 MeV between Compton and pair production regimes is unique for studying matter evolution, antimatter generation, very energetic phenomena in compact objects and massive black holes, and for resolving the Galactic Center region, still expected to be the brightest source of dark matter annihilations in the gamma-ray sky. Until now, instruments in this energy range lacked the sensitivity for a breakthrough that would require an efficient instrument working both in the Compton scattering regime, and in the electron-positron pair production regime at higher energies, with excellent background subtraction capability. The e-ASTROGAM Mission (M. Tavani, V. Tatischeff et al.) to be proposed to the 2016 ESA M5 Call for a medium-size mission will add the as yet unexplored MeV - GeV range to dark matter investigations with excellent angular resolution and exposure. Models will be tested in a spectral range not currently studied in order to disentangle the possible dark matter contribution from the diffuse background, the point sources contribution and the other possible explanations.

The 11th International Workshop Dark Side of the Universe 2015
14-18 December 2015
Kyoto, Japan

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1. Introduction

The medium-energy gamma-ray domain between Compton and pair production regimes is associated with the thermal/non-thermal transition in a variety of cosmic sources, jet launching and challenging particle acceleration processes, yet it has remained largely unexplored, see figure 1.

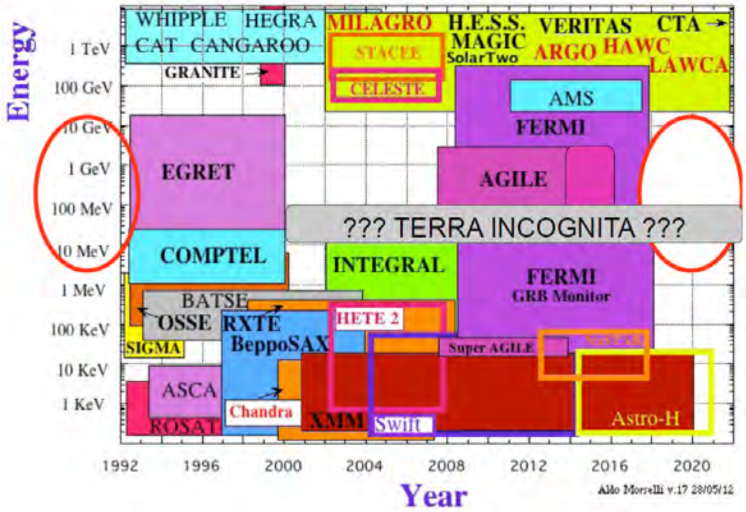

Figure 1: Energy range covered by past, present and future high-energy X and gamma-ray missions over the years.

Despite the recent important results and progress in space-based gamma-ray astrophysics achieved by AGILE and Fermi satellites, current gamma-ray experiments are leaving crucial unresolved issues in the energy range 0.3 MeV - 100 MeV. Over three-quarters of the gamma-ray sources from the third Fermi Large Area Telescope (3FGL) catalog [1], including many unidentified sources, have measured power-law spectra at photon energies $E_\gamma > 100$ MeV steeper than E_γ^{-2}, implying that they radiate most of their energy below 100 MeV. Furthermore, this energy range is known to feature a characteristic spectral turn-over associated to hadronic emission from pion decay (the pion bump), and is thus crucial to learn about the nature of the radiating, nonthermal particles. The 0.3 - 10 MeV range is also the domain of gamma-ray line emission from nuclear processes independent of the often uncertain thermodynamic state of the ambient gas. Besides, at the electron rest-mass energy of 0.511 MeV the annihilation of electron-positron pairs can be studied in various high-energy sources, in particular the narrow line component of the e+/e- annihilation radiation from the Galactic Center region, whose origin is still a mystery after more than 40 years of observations. In the inner region of the Milky Way a better angular resolution with respect to AGILE and Fermi is needed in the energy range below 100 MeV in order to disentangle the possible dark matter contribution from the diffuse background and the point sources.

The technology involved in detecting gamma-rays in the 0.3 MeV - 100 MeV energy range is challenging, and until now instruments lacked the sensitivity for a breakthrough. The e-ASTROGAM Mission (M. Tavani, V. Tatischeff et al.) to be proposed to the 2016 ESA M5 Call for a medium-size mission will address all astrophysics issues left open by the current generation of instruments and it will open an entirely new observational window.

2. The e-ASTROGAM Project

The e-ASTROGAM space mission wiil be a wide-field observatory for the MeV / sub-GeV energy band. Proposed to the 2014 ESA M4 Call for a medium-size mission opportunity under the name ASTROGAM (with a payload designed to be only 300 kg following ESA guidelines for M4), e-ASTROGAM is the enhanced version under study to be submitted to the 2016 ESA M5 call. It is a unified proposal from the entire gamma-ray community, merging the ASTROMEV (0.3 - 10 MeV) with the GAMMA-LIGHT (10 MeV - 10 GeV) concepts to a single instrument for a complete coverage of the spaceborne gamma-ray domain. Based on the AGILE, Fermi, PAMELA and AMS heritage, and ingeniously combining the two well-mastered detection techniques of Compton scattering and pair tracking, e-ASTROGAM will be dedicated to the observation of the Universe with unprecedented sensitivity in the mostly unexplored energy range 0.3 MeV - 100 MeV extending up to GeV energies. The mission science drivers can be grouped into three main themes:

- Theme-1: Matter and antimatter in our Galaxy and beyond
- Theme-2: Accelerators in the nearby and distant Universe
- Theme-3: Fundamental Physics and new messengers

One of the main scientific goal in Theme-3 is to answer the open question about the nature of Dark Matter. For a complete description of the ASTROGAM Mission and its scientific objectives we refer to (M. Tavani, V. Tatischeff et al.) citetavani-tati ASTROGAM Collaboration website: *http://astrogam.iaps.inaf.it/*.

3. The Instrument and Scientific Performance

Interactions of photons with matter in the e-ASTROGAM energy range is dominated by Compton scattering from 0.1 MeV up to about 15 MeV in silicon, and by electron-positron pair production in the field of a target nucleus at higher energies. e-ASTROGAM maximizes its efficiency for imaging and spectroscopy of energetic gamma rays by using both processes. The e-ASTROGAM instrument is based on double-sided Silicon detectors coupled to front-end-electronics capable of acquiring analog information on energy deposition in the range 20-1000 keV with high efficiency and high signal-to-noise. Both Compton events induced by photons in the range 0.3-30 MeV and pair production events in the 30 MeV - 30 GeV range can be detected by the e-ASTROGAM Tracker equipped with a Calorimeter and an Anticoincidence system. Figure 2 shows representative topologies for Compton and pair events.

For Compton events, point interactions of the gamma ray in tracker and calorimeter produce spatially resolved energy deposits, which have to be reconstructed in sequence using the redundant kinematic information from multiple interactions. Once the sequence is established, two sets of information are used for imaging: the total energy and the energy deposit in the first interaction measure the first Compton scatter angle. The combination with the direction of the scattered photon

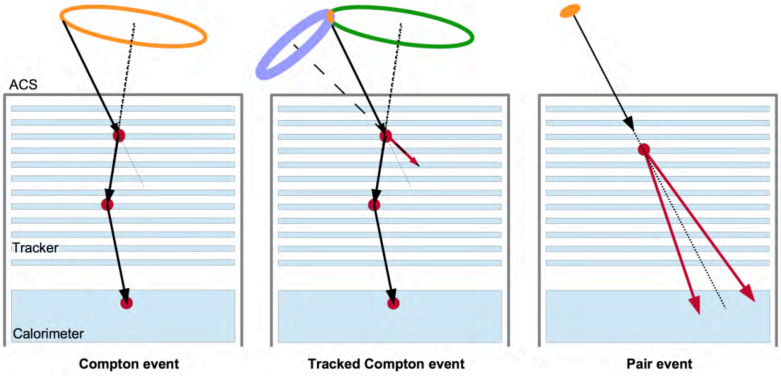

Figure 2: Representative event topologies for Compton events without (left) and with electron tracking (center) and for a pair event (right panel) inside the e-ASTROGAM detector.

from the vertices of the first and second interactions generates a ring on the sky containing the source direction. Multiple photons from the same source enable a full deconvolution of the image, using probabilistic techniques. For energetic Compton scatters (above 1 MeV), measurement of the track of the scattered electron becomes possible, resulting in a reduction of the event ring to an arc, hence further improving event reconstruction. Compton scattering depends on polarization of the incoming photon, hence careful statistical analysis of the photons for a strong (e.g., transient) source yields a measurement of the degree of polarization of its high-energy emission. Pair events produce two main tracks from the electron and positron at small opening angle. Tracking of the initial opening angle and the plane spanned by electron and positron enables direct back-projection of the source. Multiple scattering in the tracker material (or any intervening passive materials) leads to broadening of the tracks and limits the angular resolution at low energies. The nuclear recoil taking up an unmeasured momentum results in a small uncertainty, usually negligible compared to instrumental effects. The energy of the gamma ray is measured using the calorimeter. Polarization information in the pair domain is given by the azimuthal orientation of the electron-positron plane.

The Point Spread Function of e-ASTROGAM is shown in figure 3 , and the sensitivity is shown in figure 4 is for an effective exposure of 1 year of a high Galactic latitude source. Sensitivities above 30 MeV are given at the 5-sigma confidence level, whereas those below 10 MeV (30 MeV for COMPTEL) are at 3-sigma. The curves for Chandra/ACIS-S, Suzaku/HXD (PIN, GSO), INTEGRAL/IBIS and ASTRO-H (HXI, SGD) are given for an observing time T_{obs} = 100 ks. The COMPTEL and EGRET sensitivities are given for the observing time accumulated during the whole duration of the CGRO mission ($T_{obs} \sim 9$ years). The Fermi-LAT sensitivity is for a high Galactic latitude source and T_{obs} = 1 year . For MAGIC, H.E.S.S. and CTA the sensitivities are given for T_{obs} = 50 hours. The scientific performances of the e-ASTROGAM instrument were

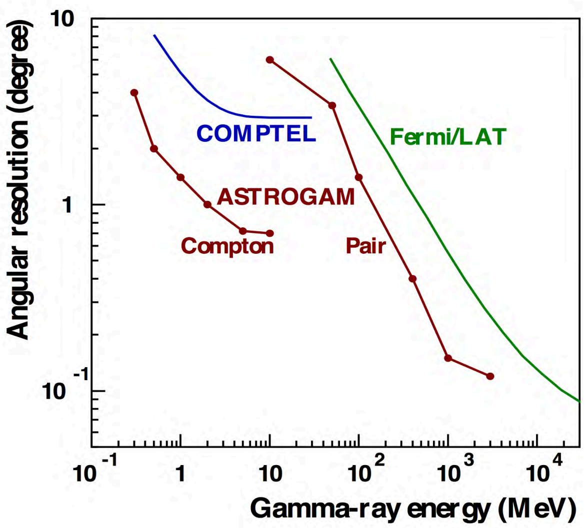

Figure 3: Point Spread Function (PSF, 68% containment radius) of the e-ASTROGAM gamma-ray detector. For comparison, we show the Fermi-LAT Pass7 PSF and the COMPTEL instrument. In the Compton domain, the performance of e-ASTROGAM and COMPTEL is the FWHM of the angular resolution measure (ARM) .

evaluated by detailed numerical simulations, using two different sets of software tools: MEGAlib and Bogemms.

4. Dark Matter Studies in the MeV - GeV domain

One of the major scientific objectives of e-ASTROGAM is the search for dark matter (DM) by means of the production of secondary gamma-rays after the annihilation or decay of the DM particle candidates. The importance of e-ASTROGAM for DM searches can be seen in figure 5 where the differential γ-ray energy spectra per annihilation of WIMP are plotted [2]. As one can see the bulk of the emission even for high WIMP masses is in the energy range 5 MeV - 100 MeV. Decaying DM can also produce a detectable line in the e-ASTROGAM energy range that might be detectable out of the continuum. Together with Fermi and CTA, e-ASTROGAM will probe most of the space of WIMP models with thermal relic annihilation cross section.

Resolving the inner region of our Galaxy at high-energies remains one of the outstanding problems of modern astrophysics. Despite several attempts, the origin of positrons currently annihilating at the rate of 2×10^{43} s^{-1} from the inner Galaxy is not accounted for by current models of star formation and compact object activities in the region. Recent data show that in addition to the central bulge also the inner disk is producing 511 keV emission. Candidate positron sources include: the central black hole activity, massive stars, Supernovae, compact binaries, pulsars, and possibly DM annihilation/de-excitation. The much improved e-ASTROGAM sensitivity at the electron-positron annihilation energy will be used for a high-resolution mapping of the mysterious 511 keV radiation. In the Fermi-LAT analysis of the Galactic Center the diffuse gamma-ray backgrounds and discrete sources, as we model them today, can account for the large majority of the

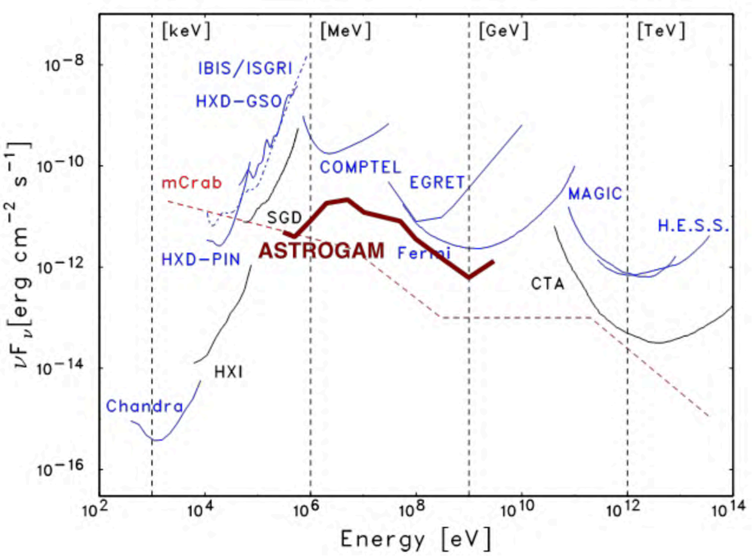

Figure 4: Point source continuum sensitivity of different X and γ-ray instruments compared with e-ASTROGAM.

detected gamma-ray emission from the Galactic Center. Nevertheless a residual emission is left, not accounted for by the above models of standard astrophysical phenomena. In the crowded Galactic Center region the analysis to disentangle a possible DM signal from conventional emissions has still large uncertainties due to the extremely difficult subtraction of the Galactic diffuse emission and the contribution of unresolved sources. The very good angular resolution of e-ASTROGAM at low energies will help to resolve sources in the galactic center region and to disentangle the possible DM contribution, see figure 6.

e-ASTROGAM will also perform indirect DM detection searches in dwarf spheroidal galaxies and put constraints on DM contribution to the largely unknown diffuse extragalactic gamma-ray background in the spectral range 0.3 - 100 MeV. Models will be tested in a spectral range not yet currently studied.

5. Conclusions

e-ASTROGAM will cover an energy interval not covered by any other past, present or future experiments opening a new astrophysical observational window. Dark Matter signatures in the Galactic Center region, dwarf spheroidal galaxies and in the diffuse extragalactic gamma-ray background will be explored in an unique way and in a mass range unachievable by other means.

References

[1] M. Tavani (Lead), V. Tatischeff (co-Lead) et al. [ASTROGAM Collaboration], ASTROGAM proposal submitted for the ESA M4 Mission Programme, Jan 15, 2015, *http://astrogam.iaps.inaf.it/*.

[2] A. Cesarini, F. Fucito, A. Lionetto, A. Morselli, P. Ullio, Astropart. Phys. 21 (2004) 267 [astro-ph/0305075]

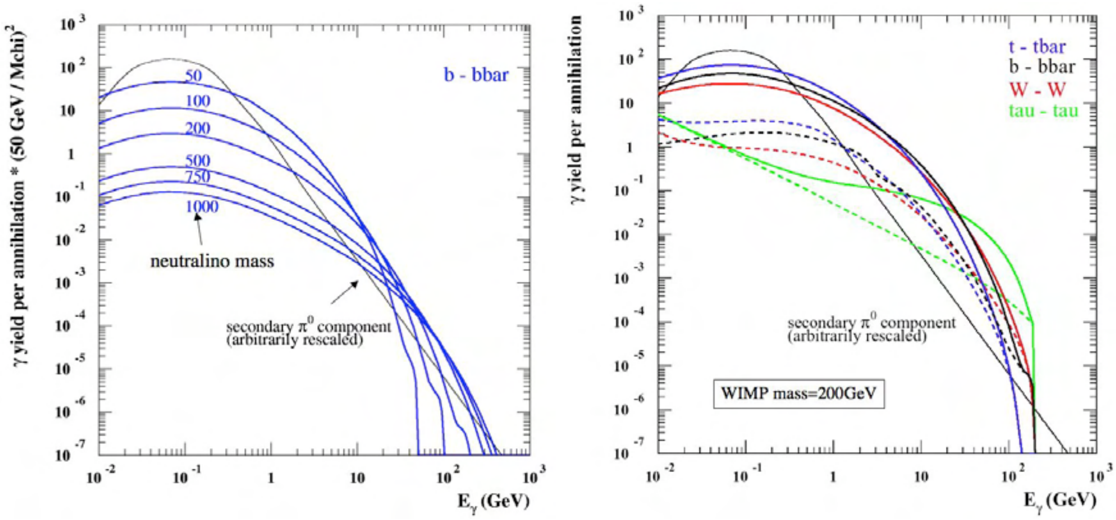

Figure 5: Left: differential energy spectra per annihilation for a few sample annihilation channels and a fixed WIMP mass (200 GeV) and differential γ-ray energy spectra per annihilation for a fixed annihilation channel ($b\bar{b}$) and for different values of WIMP masses [2]. For comparison we also show the emissivity, with an arbitrarily rescaled normalization, from the interaction of primaries with the interstellar medium. Right: The solid lines are the total yields for different annihilation channels, while the dashed lines are components not due to π^0 decays.

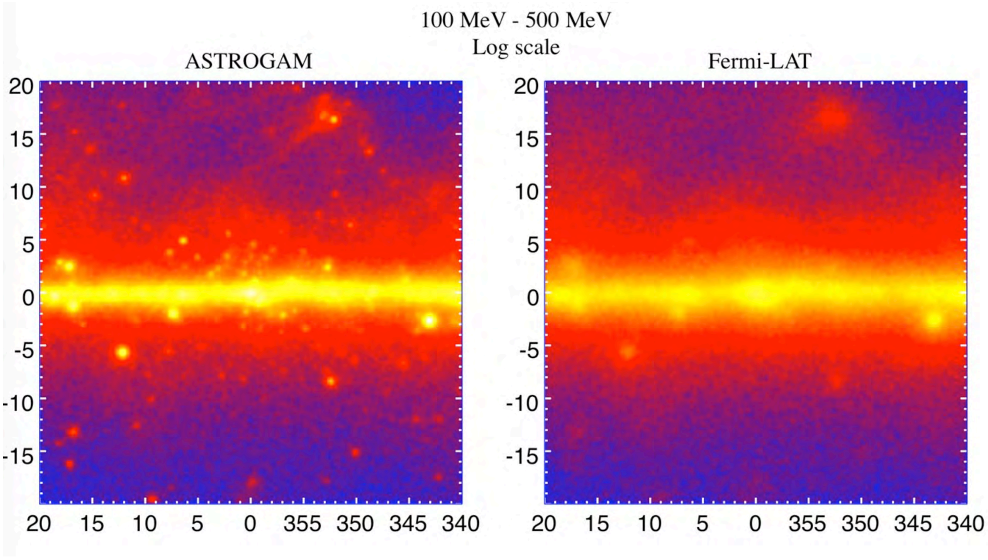

Figure 6: e-ASTROGAM simulated view of the Galactic Center Region in the 100 MeV-500 MeV energy region (left) compared with the Fermi view (right).