PROCEEDINGS OF SCIENCE

High-Energy Astrophysics above 10 MeV

Aldo Morselli*
INFN Roma Tor Vergata, Italy
E-mail: aldo.morselli@roma2.infn.it

High-energy phenomena in the cosmos, and in particular processes leading to the emission of gamma- rays in the energy range 10 MeV - 100 GeV, play a very special role in the understanding of our Universe. This energy range is indeed associated with non-thermal phenomena and challenging particle acceleration processes. The Universe can be thought as a context where fundamental physics, relativistic processes, strong gravity regimes, and plasma instabilities can be explored in a way that is not possible to reproduce in our laboratories. High-energy astrophysics and atmospheric plasma physics are indeed not esoteric subjects, but are strongly linked with our daily life. Understanding cosmic high-energy processes has a large impact on our theories and laboratories applications. The technology involved in detecting gamma-rays is challenging and drives our ability to develop improved instruments for a large variety of applications.

The energy range between 1 and 100 MeV is an experimentally very difficult range and remained uncovered since the time of COMPTEL. New instruments can address all astrophysics issues left open by the current generation of instruments. In particular, the breakthrough angular resolution in the energy range 10 MeV - 1 GeV is crucial to resolve patchy and complex features of diffuse sources in the Galaxy and in the Galactic Centre as well as increasing the point source sensitivity. This instrument addresses scientific topics of great interest to the community, with particular emphasis on multifrequency correlation studies involving radio, optical, IR, X-ray, soft gamma-ray and TeV emission. The possibility to study not only the pair production regime but also the Compton regime with this kind of detectors is currently under investigation and it is another possible very interesting breaktrought.

One of the most important goal is the detection of gamma rays and cosmic rays from the annihilation or decay of dark matter particles. This is a promising method for identifying dark matter, understanding its intrinsic properties, and mapping its distribution in the universe. Based on N-body simulations the largest γ-ray signal from DM annihilation is expected from the centre of the Galaxy. In the same region a large γ-ray background is produced by bright discrete sources and the cosmic-rays interacting with the interstellar gas and the photons fields but the DM-induced gamma-ray emission is expected to be so large there that the search is still worthwhile. A good angular resolution below 100 MeV is crucial and I will review the effort in this direction.

XI Multifrequency Behaviour of High Energy Cosmic Sources Workshop
25-30 May 2015
Palermo, Italy

*Speaker.

PoS(MULTIF15)032

Astrophysical searches for dark matter (DM) are a fundamental part of the experimental efforts to explore the dark sector. The strategy is to search for DM annihilation products in preferred regions of the sky, i.e., those with the highest expected DM concentrations and still close enough to yield high DM-induced fluxes at the Earth. For that reason, the Galactic Center (GC), nearby dwarf spheroidal galaxy (dSphs) satellites of the Milky Way, as well as local galaxy clusters are thought to be among the most promising objects for DM searches. In particular, dSphs represent very attractive targets because they are highly DM-dominated systems and are expected to be free from any other astrophysical gamma-ray emitters that might contaminate any potential DM signal. Although the expected signal cannot be as large as that from the GC, dSphs may produce a larger signal-to-noise (S/N) ratio. This fact allows us to place very competitive upper limits on the gamma-ray signal from DM annihilation [1, 2, 3], using data collected by the Large Area Telescope (LAT) onboard the Fermi gamma-ray observatory [4]. These are often referred to as the most stringent limits on DM annihilation cross-section obtained so far.

Despite these interesting limits derived from dSphs, the GC is still expected to be the brightest source of DM annihilations in the gamma-ray sky by several orders of magnitude. Although several astrophysical processes at work in the crowded GC region make it extremely difficult to disentangle the DM signal from conventional emissions, the DM-induced gamma-ray emission is expected to be so large there that the search is still worthwhile. Furthermore, the DM density in the GC may be larger than what is typically obtained in N-body cosmological simulations. Ordinary matter (baryons) dominates the central region of our Galaxy [5]. Thus, baryons may significantly affect the DM distribution. As baryons collapse and move to the center they increase the gravitational potential, which in turn forces the DM to contract and increase its density. This is a known and qualitatively well understood physical process [6, 8, 9]. It is also observed in many cosmological simulations that include hydrodynamics and star formation [10, 11, 12, 13, 14, 15]. If this is the only effect of baryons, then the expected annihilation signal will substantially increase [5, 7].

A preliminary analysis of *Fermi* LAT observations of the GC region was presented in [20], [21].

These results produced a lot of activity outside the Fermi collaboration with claims of evidence for dark matter in the Galactic Center (i.e. [22] [23] and references therein) but there are other possible explanations for this excess, e.g., past activity of the Galactic Center ([24] [25]) or a population of millisecond pulsars around the Galactic Center [26].

So, how to discriminate between different hypotesis ?

Are we seeing dark matter with the Fermi-LAT in a region around the Milky Way center? Maybe yes, but we can't be sure as far as we don't understand the background at the level needed for disentangle a DM-induced γ-ray flux in this interesting region. It would be really important to have a new experiment with better angular resolution at energies below 100 MeV that can point to the Galactic Center for a relevant fraction of time.

In [27] for example we analyze in detail the constraints that can be obtained for generic DM candidates from *Fermi*-LAT inner Galaxy gamma-ray measurements assuming some specific (and well motivated) DM distributions. The approach is conservative, requiring simply that the expected DM signal does not exceed the gamma-ray emission observed by the *Fermi*-LAT in an optimized region around the GC. The region is chosen in such a way that the S/N ratio is maximized. This kind of analysis, without modeling of the astrophysical background, was also carried out by the

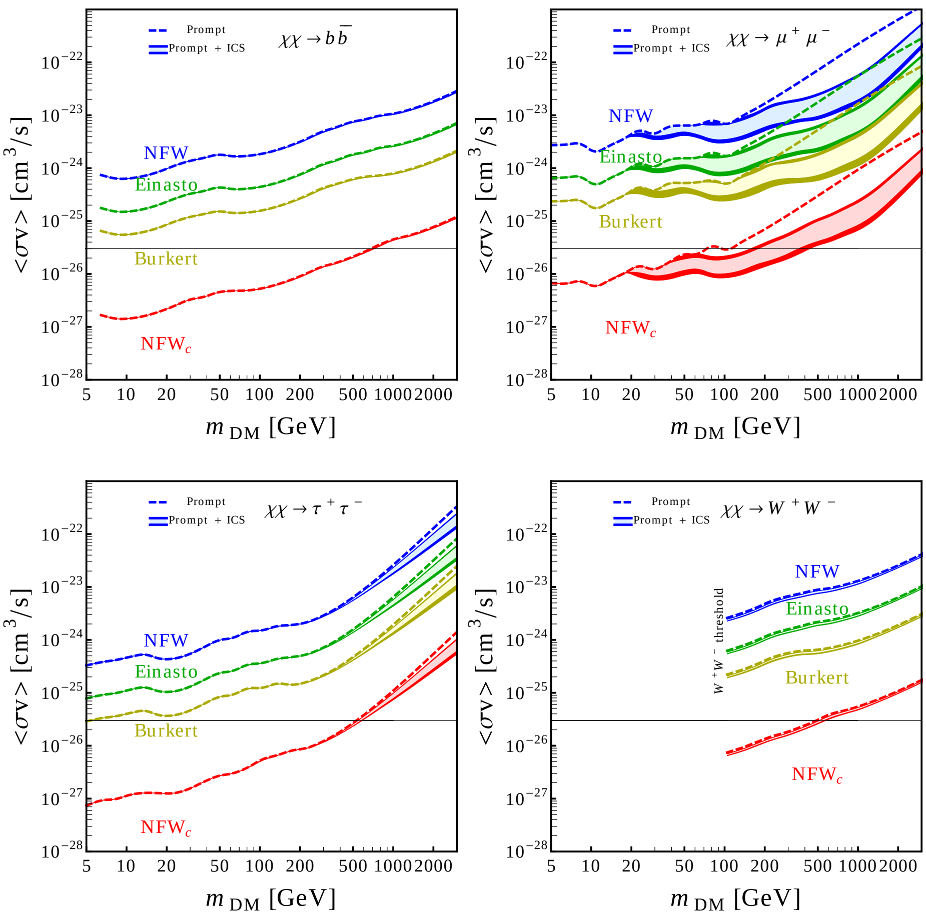

Figure 1: 3σ upper limits on the annihilation cross-section of models in which DM annihilates into $b\bar{b}$, $\mu^+\mu^-$ (upper panel), $\tau^+\tau^-$ or W^+W^- (lower panel), for the four DM density profiles discussed in the text. Upper limits set without including the Inverse Compton Scattering (ICS) component in the computation are also given as dashed curves (prompt) for comparison. The uncertainty in the diffusion model is shown as the thickness of the solid curves (from top to bottom: MIN, MED, MAX) while the lighter shaded regions represent the impact of the different strengths of the Galactic magnetic field with lower(higher) values of the cross-section corresponding to $B_0 = 1$ μG($B_0 = 10$ μG). The horizontal line corresponds to the expected value of the thermal cross-section for a generic WIMP candidate.

Fermi-LAT collaboration to constrain DM models from Galactic halo observations [28].

The results are presented in Figure 1, where the constraints obtained are shown for different final states. There we also illustrate the case $\langle\sigma v\rangle = 3\times10^{-26}$ cm^3 s^{-1}, which corresponds to the value of the annihilation cross-section associated to the correct thermal relic abundance for a Weakly Interacting Massive Particle (WIMP) whose annihilation is dominated by the s-wave (velocity-independent) contribution and thus, $\Omega_{DM}\,h^2 \approx 3\times10^{-27}$ cm^3 s^{-1} $\langle\sigma v\rangle^{-1} \approx 0.1$ [30]. For comparison, the constraints are given considering only the contribution from prompt gamma rays and the total contribution from prompt plus ICS gamma rays.

First, it is worth noting that if the DM density follows an Einasto, NFW or Burkert profile, the upper limits on the annihilation cross section are above the value of the thermal cross-section for any annihilation channel. Nevertheless, the situation is drastically different when we consider the DM compression due to baryonic infall in the inner region of the Galaxy. As pointed out in Ref. [5], the effect of the baryonic adiabatic compression might be crucial for indirect DM searches, as it increases by several orders of magnitude the gamma-ray flux from DM annihilation in the inner regions, and therefore the DM detectability. Indeed, by adopting the NFW$_c$ profile and for a $b\bar{b}$, $\tau^+\tau^-$ and W^+W^- channel, the thermal annihilation cross-section is already reached for a DM mass of 680, 530 and 490 GeV, respectively. For the $\mu^+\mu^-$ channel the effect of the prompt gamma rays is less important since generally fewer photons are produced in the FSR compared to the hadronic decays of the other channels. (For the W^+W^- which is open when $m_{DM} \gtrsim 90$ GeV, the $W^\pm$ decays produce a large number of photons, especially at high energy). Notice that the lower bound associated with prompt gamma rays for $\mu^+\mu^-$ is 100 GeV compared to about 500–700 GeV in the other channels. Thus the ICS is important in this case, also due to the relatively harder $e^\pm$ spectrum [29]. We can see that for $B_0 = 1\ \mu$G the lower bound on the DM mass turns out to be 358 GeV and for $B_0 = 10\ \mu$G the bound is 157 GeV, using the MIN diffusion model. For MED and MAX diffusion models the values turn out to be 404, 171 GeV and 439, 179 GeV, respectively. As discussed in [27], when the magnetic field is stronger the energy of the injected $e^\pm$ is more efficiently liberated in the form of microwaves, resulting in a softer gamma-ray spectrum, and producing therefore lower constraints . Therefore, we have shown that in those cases in which the ICS component is dominant (for heavy WIMP masses in general), the variation of the magnetic field can significantly alter the expected gamma-ray fluxes from the inner regions of the Galaxy.

Although the above results can be interpreted in general as implying that vanilla WIMP models and contracted DM profiles are incompatible with the Fermi data, one should keep in mind that if one works in the framework of a specific particle physics model this conclusion might in principle be avoided in some regions of the parameter space. For example, the final state can be a combination of the annihilation channels presented here, as in supersymmetry where the lightest neutralino annihilation modes are 70% $\bar{b}b$ – 30%$\tau^+\tau^-$ for a Bino DM, and 100% W^+W^- for a Wino DM (or for a Higgs-portal model). More importantly, the value of the annihilation cross section in the Galactic halo might be smaller than 3×10^{-26} cm^3 s^{-1} for a DM candidate that is thermally produced. For example, in the early Universe coannihilation channels can also contribute to $\langle \sigma v \rangle$. Also, DM particles whose annihilation in the early Universe is dominated by p-wave (velocity-dependent) contributions would have a smaller value of $\langle \sigma v \rangle$ in the Galactic halo, where the DM velocity is much smaller than at the time of freeze-out, and can therefore escape the constraints presented here. These two effects can in fact occur in some regions of the parameter space of well motivated models for particle DM, such as the neutralino. In this sense, the results derived above for pure annihilation channels can be interpreted as limiting cases that give an idea of what can happen in realistic scenarios.

A new version of the event-level reconstruction and analysis framework (called Pass 8) is now implemented from the Fermi LAT collaboration. With this new analysis software we can increase the efficiency of the instrument at high energy and have a data set based on independent event analysis thus gaining a better control of the systematic effects [32].

A new analysis of the dSphs with the use of Pass 8 begin to constrain some of the preferred parameter space for a DM interpretation of a gamma-ray excess in the Galactic center region.

As shown in 2, for interpretations assuming a $\bar{b}b$ final state, the best-fit models lie in a region of parameter space slightly above the 95% CL upper limit from this analysis, with an annihilation

PoS(MULTIF15)032

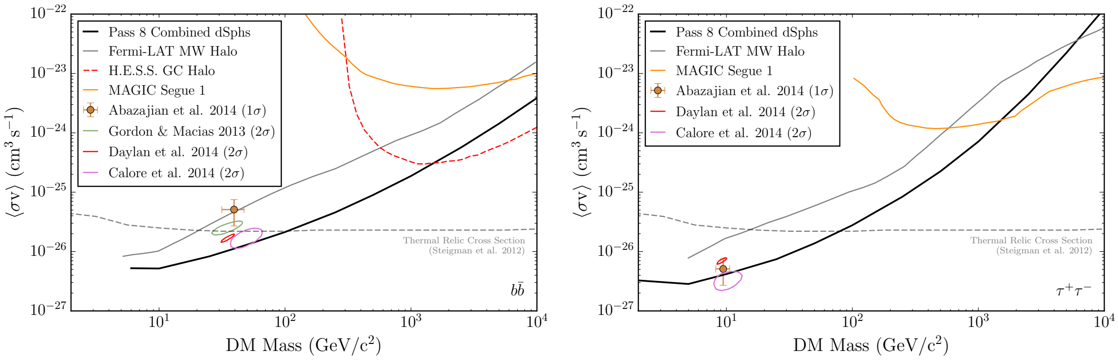

Figure 2: Comparison of constraints on the DM annihilation cross section for the $\bar{b}b(left)$ and $\bar{\tau}\tau$ (right) channels [33] with previously published constraints from LAT analysis of the Milky Way halo (3σ limit) [28], 112 hours of observations of the Galactic Center with H.E.S.S. [16], and 157.9 hours of observations of Segue 1 with MAGIC [17]. Closed contours and the marker with error bars show the best-fit cross section and mass from several interpretations of the Galactic center excess [22].

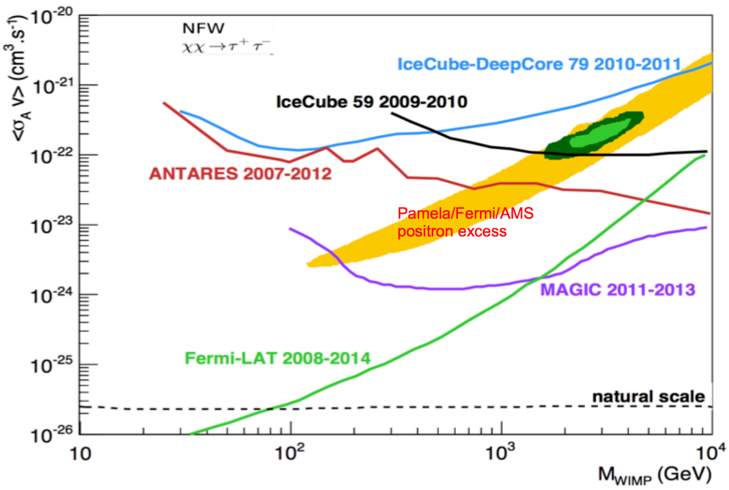

Figure 3: Comparison of constraints on the DM annihilation cross section for the $\bar{\tau}\tau$ channel [33] with Antares [18], IceCube-DeepCore [19] and MAGIC [17]

cross section in the range of $(1\text{–}3)\times10^{-26}$ cm^3 s^{-1} and m_{DM} between 25 and 50 GeV. However, uncertainties in the structure of the Galactic DM distribution can significantly enlarge the best-fit regions of $\langle\sigma v\rangle$ channel, and m_{DM}. Figure 3 shows a comparison of constraints on the DM annihilation cross section for the $\bar{\tau}\tau$ channel [33] with Antares [18], IceCube-DeepCore [19] and MAGIC [17]. One can see that the Fermi limits are the best limits below 2 TeV.

At lower energies a new instrument like Gamma-Light [34] , ASTROGAM [35] or Pangu [36] can really improve these results.

The 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

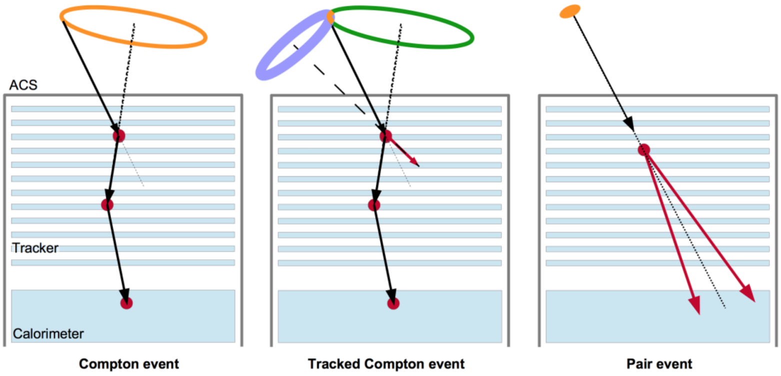

Figure 4: Representative event topologies for Compton events without (left) and with electron tracking (center) and for a pair event (right panel) inside ASTROGAM .

range 0.3-30 MeV and pair production events in the 30 MeV - 30 GeV range can be detected by the ASTROGAM Tracker equipped with a Calorimeter and an Anticoincidence system. Figure 4 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 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 ASTROGAM is shown in figure 5 , and the sensitivity is shown

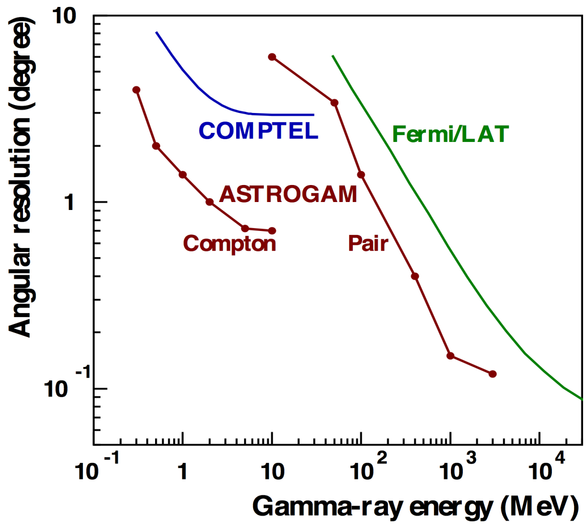

Figure 5: Point Spread Function (PSF, 68% containment radius) of the ASTROGAM gamma-ray detector. For comparison, we show the Fermi-LAT Pass7 PSF and the COMPTEL instrument. In the Compton domain, the performance of ASTROGAM and COMPTEL is the FWHM of the angular resolution measure (ARM) .

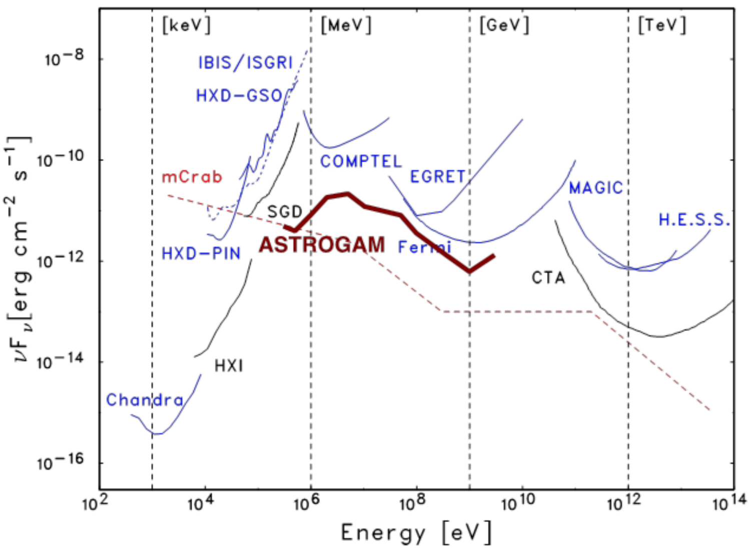

Figure 6: Point source continuum sensitivity of different X and γ-ray instruments compared with ASTROGAM.

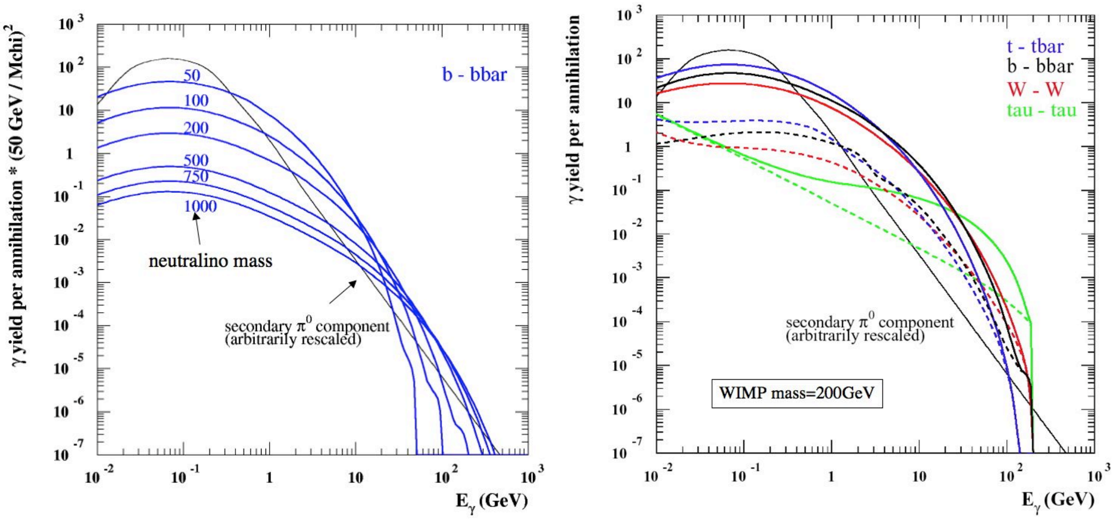

Figure 7: Differential energy spectra per annihilation for a few sample annihilation channels and a fixed WIMP mass (200 GeV) (left) and differential γ-ray energy spectra per annihilation for a fixed annihilation channel ($\bar{b}b(left)$) and for a few sample values of WIMP masses [31]. For comparison we also show the emissivity, with an arbitrarily rescaled normalization, from the interaction of primaries with the interstellar medium. The solid lines are the total yields, while the dashed lines are components not due to π^0 decays (right).

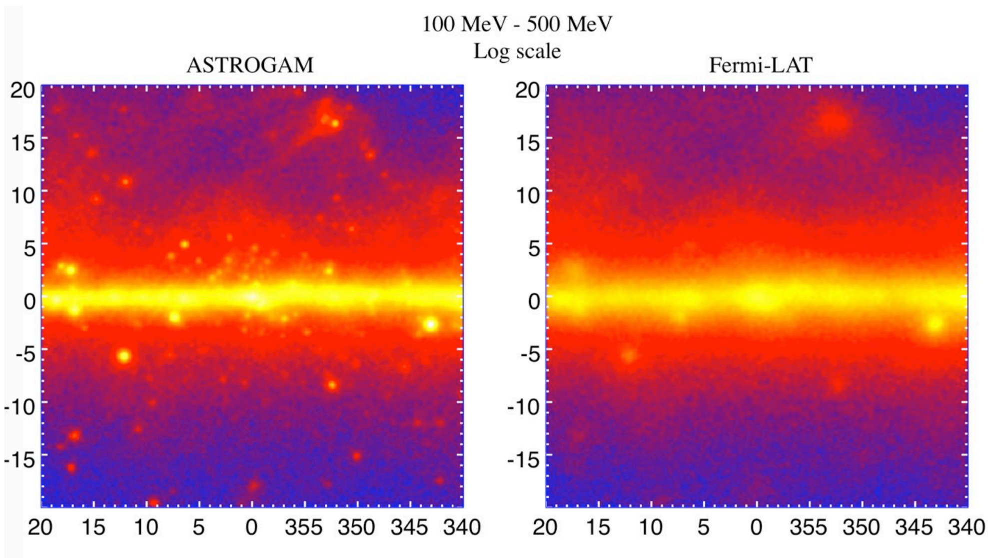

Figure 8: ASTROGAM view of the Galactic Center Region in the 100 MeV-500 MeV energy region compared with the Fermi view.

in figure 6 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 importance of ASTROGAM for Dark Matter searches can be seen in figure 7 where the differential γ-ray energy spectra per annihilation of WIMP are plotted [31]. As one can see the bulk of the emission even for high WIMP masses is in the energy range 5 MeV - 100 MeV.

The very good angular resolution at low energies will help to resolve sources in the galactic center region and to desentangle a possible dark matter contribution (see figure 8).

Conclusions

Detection of gamma rays from the annihilation or decay of dark matter particles is a promising method for identifying dark matter, understanding its intrinsic properties, and mapping its distribution in the universe (in synergy with the experiments at the LHC and in the underground laboratories). In the future it would be extremely important to extend the energy range of experiments at lower energies (compared to the Fermi energies) (ASTROGAM) and higher energies (HAWC, Dampe, HERD, Gamma-400, CTA, LHAASO)

References

[1] M. Ackermann *et al.* [Fermi-LAT Collaboration], Phys. Rev. Lett. **107** (2011) 241302 [arXiv:1108.3546 [astro-ph.HE]].

[2] A. A. Abdo *et al.* [Fermi-LAT Collaboration], Astrophys. J. **712** (2010) 147 [arXiv:1001.4531 [astro-ph.CO]].

[3] A. Geringer-Sameth and S.M. Koushiappas, Phys. Rev. Lett. **107** (2011) 241303 [arXiv:1108.2914 [astro-ph.CO]].

[4] W. B. Atwood *et al.* [Fermi-LAT Collaboration], Astrophys. J. **697** (2009) 1071 [arXiv:0902.1089 [astro-ph.IM]].

[5] F. Prada, A. Klypin, J. Flix Molina, M. Martinez and E. Simonneau, Phys. Rev. Lett. **93** (2004) 241301 [astro-ph/0401512].

[6] Ya. B. Zeldovich, A. A. Klypin, M. Yu. Khlopov and V. M. Chechetkin, Sov. J. Nucl. Phys. **31** (1980) 664.

[7] Y. Mambrini, C. Muñoz, E. Nezri and F. Prada, JCAP **01** (2006) 010 [hep-ph/0506204].

[8] G.R. Blumenthal, S.M. Faber, R. Flores and J.R. Primack, Astrophys. J. **301** (1986) 27.

[9] O. Y. Gnedin, A. V. Kravtsov, A. A. Klypin and D. Nagai, Astrophys. J. **616** (2004) 16 [astro-ph/0406247 [astro-ph]].

[10] M. Gustafsson, M. Fairbairn and J. Sommer-Larsen, Phys. Rev. D **74** (2006) 123522 [astro-ph/0608634 [astro-ph]].

[11] P. Colín, O. Valenzuela and A. A. Klypin, Astrophys. J. **644** (2006) 687 [astro-ph/0506627 [astro-ph]].

[12] P. B. Tissera, S. D. M. White, S. Pedrosa and C. Scannapieco, MNRAS **406** (2010) 922 [arXiv:0911.2316 [astro-ph.CO]].

[13] O. Y. Gnedin, D. Ceverino, N. Y. Gnedin, A. A. Klypin, A. V. Kravtsov, R. Levine, D. Nagai and G. Yepes, arXiv:1108.5736 [astro-ph.CO].

[14] M. Zemp, O. Y. Gnedin, N. Y. Gnedin and A. V. Kravtsov, Astrophys. J. **748** (2012) 54 [arXiv:1108.5384 [astro-ph.GA]].

[15] J. Sommer-Larsen and M. Limousin, MNRAS **408** (2010) 1998 [arXiv:0906.0573 [astro-ph.CO]].

[16] A. Abramowski et al. (H.E.S.S. Collaboration), Phys. Rev. Lett. 106, 161301 (2011) [arXiv:1103.3266]

[17] J. Aleksić et al. (MAGIC Collaboration), J. Cosmol. Astropart. Phys. 1402, 008 (2014) [arXiv:1312.1535]

[18] S. Adrían-Martínez et al. [Antares Coll.] arXiv:1505.04866

[19] M.G. Aartsen et al. [IceCube Collaboration] arXiv:1309.7007

[20] V. Vitale and A. Morselli for the Fermi/LAT Collaboration, 2009 Fermi Symposium, eConf Proceedings C091122 [arXiv:0912.3828]

[21] A. Morselli, B.Cañadas, V.Vitale, Il Nuovo Cimento **34** C, N. 3 (2011) [arXiv:1012.2292]

[22] F.Calore et al. arXiv:1409.0042

[23] T. Daylan et al., 2014, arXiv:1402.6703

[24] J. Petrovic et al., 2014, JCAP, 10, 052

[25] E.Carlson , S.Profumo , 2014, Phys. Rev. D, 90, 023015

[26] Lee et al. arXiv:1506.05124

[27] G.A.Gomez-Vargas *et al.* JCAP 10 (2013) 029 [arXiv:1308.3515]

[28] M. Ackermann *et al.* [Fermi LAT Collaboration], Astrophys. J. **761** (2012) 91 [arXiv:1205.6474 [astro-ph.CO]].

[29] A. Birkedal, K. T. Matchev, M. Perelstein and A. Spray, hep-ph/0507194.

[30] G. Jungman, M. Kamionkowski and K. Griest, Phys. Rep. **267** (1996) 195 [arXiv:hep-ph/9506380].

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

[32] M. Ackermann *et al.* [Fermi LAT Collaboration], Phys. Rev. D. 91, 122002 (2015) [arXiv:1506.00013]

[33] M. Ackermann *et al.* [Fermi LAT Collaboration], PRL Accepted [arXiv:1503.02641]

[34] A.Morselli et al., Nuclear Physics B - 239Ð240 (2013) 193-198 [arXiv:1406.1071]

[35] http://astrogam.iaps.inaf.it

[36] X.Wu et al. Proceedings of the XI Multifrequency Behaviour of High Energy Cosmic Sources Workshop, 25-30 May 2015, Palermo, Italy