Contribution Prospectives 2020 – GT06 and GT04

Indirect searches for dark matter in a multimessenger context

Principal author/s:
Francesca Calore, LAPTh-Annecy-le-Vieux– francesca.calore@lapth.cnrs.fr
Céline Combet, LPSC-Grenoble– celine.combet@lpsc.in2p3.fr
Laurent Derome, LPSC-Grenoble– laurent.derome@lpsc.in2p3.fr
Julien Lavalle, LUPM-Montpellier– lavalle@in2p3.fr
David Maurin*, LPSC-Grenoble– david.maurin@lpsc.in2p3.fr
Vivian Poulin, LUPM-Montpellier– vivian.poulin@umontpellier.fr
Pierre Salati*, LAPTh-Annecy– salati@lapth.cnrs.fr
Pasquale Serpico, LAPTh-Annecy– serpico@lapth.cnrs.fr

Co-author/s:
Johann Cohen Tanugi, LUPM-Montpellier– johann.cohen-tanugi@umontpellier.fr

October 1, 2019

Abstract

Highly energetic astrophysical messengers such as γ-rays or cosmic ray antimatter are a powerful way to look for dark matter annihilation or decay in the sky. These channels are among the leading ones for discovering dark matter in the form of weakly-interacting massive particles (WIMPs), which are still very appealing candidates owing to the simplicity of their production mechanism in the early universe. In this contribution, we highlight the most promising theoretical and phenomenological developments that should accompany the observation program of the leading experiments in the field, as well as some perspectives for future observatories. The synergies of different probes will also be emphasized.

1 Introduction

The identification of dark matter (DM) is one of the major endeavours of particle physics and cosmology of the XXIst century. Despite the outstanding growth of gravitational evidence for DM (notably from cosmological data (1)), and the important theoretical and experimental efforts deployed to detect DM particles, the nature of this elusive form of matter remains unknown. The weakly interacting massive particle (WIMP) hypothesis is definitely the most scrutinised model for cold DM so far (2), but searches for DM particle candidates at the weak scale have been unsuccessful with current instruments, on ground and in space. At this stage, it is unclear if the WIMP paradigm has to be revised in favour of alternative DM models, or it is broadly correct, but for instance kinematically outside the bulk of the range explored. While a diversity of strategies involving in particular cosmological and gravitational probes [see relevant contributions] is the most promising way to collect evidence of alternative scenarios, indirect WIMP searches with antiparticles and gamma-ray photons (3) currently provide some among the strongest limits. They have significant margins of improvements, due to methodological advances and, for the latter, also due to the forthcoming generation of gamma-ray telescopes, notably the Cherenkov Telescope Array, CTA (4). Alone, these arguments justify a prominent place of both observational campaigns and theoretical/phenomenological DM analyses within

---

*Corresponding authors.

the IN2P3 activities of the forthcoming decade. A few strategies that appear promising to us in this direction are detailed in Sec. 2 for gamma-rays, and in Sec. 3 for cosmic-ray antimatter. Perhaps, more important is to fully exploit the information collected by different observations in different channels and energy ranges, which requires a vision and analysis that goes beyond what achievable by a single experimental collaboration. In Sec. 4, besides summarizing the bright perspectives of the field, we illustrate a couple of examples of this multimessenger approach, where theorists have an even more important role to play.

2 Some perspectives on DM searches via gamma-rays

Very often, constraints on the WIMP parameter space are based upon unsatisfactory astrophysical background models, i.e. models that are not able to provide a good fit to the data at the Poisson noise level, and therefore lead to upper limits on the additional DM component which are largely affected by systematic errors, difficult to be properly accounted for in the limit setting procedure [see an example in (5)].

This is particularly severe in the inner region of the Galaxy, where the gamma-ray emission is dominated by the interactions of cosmic rays with the interstellar matter and fields (Galactic diffuse emission). "Cleaner" and, in this respect, more promising targets for DM identification are dwarf galaxies, optically faint galaxies whose dynamics has been proved to be dominated by large haloes of DM (6). The faintest detectable galaxies and their "dark haloes" counterparts represent very promising targets to probe the WIMP paradigm with several, multi wavelength, observations: from optical to gamma rays [see, for example, (7; 8; 9)].

We identify two main classes of limitations in setting robust (and trustable) upper limits on DM particle models:

- *Theoretical model limitations:* Indirect searches for WIMP DM, notably with gamma rays, are traditionally based on the assumption that the DM profile in the center of galaxies is cuspy (10). However, evidence from dynamical studies of the Milky Way (11), and the latest hydrodynamical simulations of galaxy formation challenge this longstanding paradigm by preferring more cored profiles (12). The same holds true for the DM distribution in dwarf spheroidal galaxies [see e.g. (13)]. Also, the distribution of sub-haloes in the Milky Way, was too approximately predicted in simulations (because of mass and spatial resolution limits). Semi-analytical models (14; 15) and simulations (16) , have shown that sub-haloes can be more resilient than what naively assumed. This implies that the number and distribution of detectable "dark" sub-haloes has to be revised in light of new modelling of the survival probability of sub-structures in the Galaxy (17). Also, globular clusters are traditionally believed not to contain a large fraction of DM. Nevertheless, Ref. (18) found significant gamma-ray emission that can be better explained by DM annihilating in the globular cluster Omega Centauri. Eventually, a better theoretical modelling of the DM distribution can tell us that the lamppost under which we were focusing our effort is not the brightest one, but that other targets are more promising; or, perhaps, that the limits on the WIMP parameter space are instead much weaker than what set so far.

- *Background model limitations*: The other class of limitations is related to the fact that for indirect searches with gamma rays we have not achieved yet a perfect description of the sky with astrophysical background models. The goodness of fit of background only (i.e. without DM) models is rather poor all over the sky and depends significantly on the models adopted, especially for the Galactic diffuse emission, which is the brightest source of background photons at low Galactic latitudes. The systematics affecting the fit often prevents to set meaningful upper limits of the DM parameter space. This severely affects analyses from the GC region (19; 20), but background modelling uncertainties have shown to be significant also for constraining DM from the direction of dSphs (8).

Thus, we estimate that both strategies will be crucial in pushing down the sensitivity to WIMP models, especially in synergy with information from other messengers (see Sec. 4.)

3 Cosmic Ray Antimatter

3.1 Recent past and current status

In 2008, the PAMELA satellite (21) detected a clear excess of cosmic ray positrons above a few GeV. This anomaly triggered a hectic activity in the field and also raised the hope that the long awaited indirect signal of the presence of DM species was eventually found. Ten years later, we know that DM cannot be the only source of the positron anomaly (22) and that mundane possibilities such as pulsars (23) could also provide very convincing explanations. But the hunt for an anomaly in the anti-matter cosmic radiation is still going on.

The interest is now focused on antiprotons. Contrary to positrons, these species are not sourced by known astrophysical objects. They are produced by the spallation of interstellar gas by high-energy primary cosmic rays, i.e. protons and helium nuclei (24). Calculations of the corresponding flux at the Earth have been carried out for two decades in France (25; 26; 27; 28) and have been the driving force of the cosmic ray alpine collaboration (CRAC), a research group which has been set up in Annecy and Grenoble (later extended to Montpellier) to look for DM induced anomalies in anti-matter cosmic rays (29). The group has also been involved in the modeling of cosmic ray propagation inside the magnetic halo of the Galaxy (30). It has recently published many comprehensive analyses of the AMS-02 results (31; 32), showing for instance that the positron anomaly cannot be explained solely by DM and secondary production (33). Quite recently, David Maurin has published USINE (34), a public code to compute the yields of cosmic ray species at the Earth. The USINE code has been used in the CRAC investigations of the B/C ratio. New tools (35) have been devised to cope with the high level of accuracy of the new generation of cosmic ray experiments.

A few studies (36; 37; 38; 39; 40)have recently pointed toward a possible excess in the antiproton flux measured by AMS-02. There seems to be an excess at a few GeV which could be explained by adding DM. The CRAC has investigated the question. By refining the treatment of theoretical errors and introducing a covariance matrix of errors, no anomaly is found. Notice that no fit is performed. The measurements are in perfect agreement with a pure secondary production (41).

3.2 Expected improvements

We plan to further explore if adding a DM component would improve significantly the previous agreement. Several tests need to be performed, using either a frequentist or a Bayesian approach. Strong limits will also be put on the DM properties. As a preliminary step, a study of the nuclear cosmic ray component published by AMS-02 is needed in order to constrain further parameters of the propagation scenario (such as the propagation halo size) needed to sharpen the prediction of the flux due to DM.

The next frontier is the search for anti-matter nuclei. An abnormal flux of anti-deuterons below a few GeV is expected in the case of DM (42) and provides a potentially clear signature. But detecting anti-deuterons is far from easy as they need to be disentangled from antiprotons. Efforts in that sense are being pursued with the AMS-02 collaboration as well as within the forthcoming GAPS experiment (`https://gaps1.astro.ucla.edu/gaps/`). A number of theoretical refinements in the treatment of the relevant coalescence cross section would also be welcome.

The detection of anti-helium nuclei seems easier as no know species carries a $Z = -2$ charge. It is then of paramount importance to update the calculations of the anti-He-3 flux expected from secondary production and also from DM (43; 44; 45; 46). Incidentally, AMS-02 has repeatedly shown at conferences preliminary analysis results with a few anti-He-3 and anti-He-4 candidates (47). Although these could be due to very tiny systematics, one should keep a close eye on the possibility that anti-helium has been found. Refined calculations of the corresponding secondary fluxes need to be performed (48). The standard lore in cosmology is based on an asymmetric Universe where CP and B are violated and where the baryon number has been produced during a very early stage of the Universe by a process going out of equilibrium. The discovery of a single anti-He-4 nucleus, should it be confirmed, would be an earthquake for cosmology as it would be a tantalizing indication for the presence of anti-stars within the Milky Way.

4 Conclusion

The search for anti-matter in cosmic rays has been a driving force in the indirect searches for DM, and has motivated new and refined experiments as well as a better modeling of Galactic transport of charged species. Currently, positron (49) and antiproton (50) data are among the most constraining channels for DM searches, although there are still important margins of improvements in the data analysis methodology which deserve to be developed. At the same time, the discovery of a few anti-helium events would be a very strong incentive for new developments in the field. Should recent hints by AMS-02 be confirmed, it would represent a major discovery with implication beyond DM searches, since it would drastically change our understanding of cosmology.

We have also briefly argued why we believe it is of utmost importance to scrutinise what is the space left for WIMP DM with current gamma-ray telescopes, by critically assessing theoretical model uncertainties on the DM distribution in galaxies and their substructures (for instance by evaluating the impact of stellar encounters and baryonic effects on the sub-halo survival probability) and by developing new gamma-ray data analysis techniques (including for instance unresolved point-source emission via techniques based on wavelet decomposition and pixel count statistics) to push down the sensitivity to DM signals.

These two lines of research have further margins of progress by adopting a broader picture, fully embracing a multimessenger approach beyond the analyses that can be performed within the perimeter of single experiments, with a crucial role played by theoretical teams. Let us illustrate this point with a couple of examples:

- Forthcoming surveys such as LSST promise a much better characterization of DM-rich systems, as well as the discovery of a large number of DM-rich Galactic substructures (dwarf spheroidals), which would boost by a factor of a few the DM constraining power of *already existing data*, such as the ones collected by Fermi-LAT. This is dealt with in more details in [gravitational contribution].

- It has recently become more and more clear that the gamma ray channel can foster WIMP DM searches also *indirectly*, by promoting a sharper understanding of the landscape of high-energy astrophysical systems, and improve the knowledge of “astrophysical backgrounds” for DM, which are actually interesting targets of investigation on their own. One example of this strategy, involving searches for the putative population responsible for the “Galactic Center excess” in Fermi-LAT data in gravitational waves, has been for instance explored in (51). One notable example is provided by the inverse Compton emission associated to Galactic leptonic accelerators such as pulsar wind nebulae (PWN). Current gamma data, notably by HAWC (52), suggest that the diffusion is much slower that the average Galactic value in extended “cocoons” around these objects. The characterization of these regions requires a synergy of Fermi-LAT, HAWC and Cherenkov data (with important perspectives for CTA), and is in turn crucial: 1) for assessing the contribution of PWN to the positron and electron flux measured in cosmic rays at Earth (notably by AMS-02); 2) to revisit the room for a DM contribution to the positron fraction, sharpening the sensitivity of this channel; 3) to meaningfully extend current cosmic ray propagation models to an inhomogeneous framework, with consequences for both points 1,2).

Last but not least, it is worth mentioning that the lower (i.e. <100 MeV) and higher energy range (> 100 TeV) of the gamma-ray band remain almost unexplored windows of parameter space, and offer a potential for serendipitous discoveries, including of more exotic types of DM candidates (for a couple of examples, see (53) and (54)). We encourage IN2P3 to promote efforts towards (respectively, space and ground-based) facilities exploring these windows, and to seize opportunities to join international efforts towards their realization. Advanced proposals for a MeV telescope exist (55), while the first (sub-)PeV gamma ray telescope is already under construction (56). They have both a broad multi-messenger and multi-wavelength program, fostering obvious synergies with existing IN2P3 programs.

References

[1] N. Aghanim *et al.*, “Planck 2018 results. VI. Cosmological parameters,” 2018.

[2] G. Bertone, D. Hooper, and J. Silk, "Particle dark matter: Evidence, candidates and constraints," *Phys. Rept.*, vol. 405, pp. 279–390, 2005.

[3] J. Lavalle and P. Salati, "Dark Matter Indirect Signatures," *Comptes Rendus Physique*, vol. 13, pp. 740–782, 2012.

[4] T. Bringmann and C. Weniger, "Gamma Ray Signals from Dark Matter: Concepts, Status and Prospects," *Phys. Dark Univ.*, vol. 1, pp. 194–217, 2012.

[5] H.-S. Zechlin, S. Manconi, and F. Donato, "Constraining Galactic dark matter with gamma-ray pixel counts statistics," *Phys. Rev.*, vol. D98, no. 8, p. 083022, 2018.

[6] L. E. Strigari, "Dark matter in dwarf spheroidal galaxies and indirect detection: a review," *Rept. Prog. Phys.*, vol. 81, no. 5, p. 056901, 2018.

[7] M. Ackermann *et al.*, "Searching for Dark Matter Annihilation from Milky Way Dwarf Spheroidal Galaxies with Six Years of Fermi Large Area Telescope Data," *Phys. Rev. Lett.*, vol. 115, no. 23, p. 231301, 2015.

[8] F. Calore, P. D. Serpico, and B. Zaldivar, "Dark matter constraints from dwarf galaxies: a data-driven analysis," *JCAP*, vol. 1810, no. 10, p. 029, 2018.

[9] F. Calore, V. De Romeri, M. Di Mauro, F. Donato, and F. Marinacci, "Realistic estimation for the detectability of dark matter sub-halos with Fermi-LAT," *Phys. Rev.*, vol. D96, no. 6, p. 063009, 2017.

[10] J. F. Navarro, C. S. Frenk, and S. D. M. White, "A Universal density profile from hierarchical clustering," *Astrophys. J.*, vol. 490, pp. 493–508, 1997.

[11] M. Portail, O. Gerhard, C. Wegg, and M. Ness, "Dynamical modelling of the galactic bulge and bar: the Milky Way's pattern speed, stellar and dark matter mass distribution," *Mon. Not. Roy. Astron. Soc.*, vol. 465, no. 2, pp. 1621–1644, 2017.

[12] F. Calore, N. Bozorgnia, M. Lovell, G. Bertone, M. Schaller, C. S. Frenk, R. A. Crain, J. Schaye, T. Theuns, and J. W. Trayford, "Simulated Milky Way analogues: implications for dark matter indirect searches," *JCAP*, vol. 1512, no. 12, p. 053, 2015.

[13] J. I. Read, M. G. Walker, and P. Steger, "Dark matter heats up in dwarf galaxies," *Mon. Not. Roy. Astron. Soc.*, vol. 484, no. 1, pp. 1401–1420, 2019.

[14] M. Stref, T. Lacroix, and J. Lavalle, "Remnants of Galactic subhalos and their impact on indirect dark matter searches," *Galaxies*, vol. 7, no. 2, p. 65, 2019.

[15] N. Hiroshima, S. Ando, and T. Ishiyama, "Modeling evolution of dark matter substructure and annihilation boost," *Phys. Rev.*, vol. D97, no. 12, p. 123002, 2018.

[16] F. C. van den Bosch, G. Ogiya, O. Hahn, and A. Burkert, "Disruption of Dark Matter Substructure: Fact or Fiction?," *Mon. Not. Roy. Astron. Soc.*, vol. 474, no. 3, pp. 3043–3066, 2018.

[17] M. Hutten, M. Stref, C. Combet, J. Lavalle, and D. Maurin, "γ-ray and ν Searches for Dark-Matter Subhalos in the Milky Way with a Baryonic Potential," *Galaxies*, vol. 7, no. 2, p. 60, 2019.

[18] A. M. Brown, R. Massey, T. Lacroix, L. E. Strigari, A. Fattahi, and C. Bœhm, "The glow of annihilating dark matter in Omega Centauri," 2019.

[19] E. Storm, C. Weniger, and F. Calore, "SkyFACT: High-dimensional modeling of gamma-ray emission with adaptive templates and penalized likelihoods," *JCAP*, vol. 1708, no. 08, p. 022, 2017.

[20] O. Macias, S. Horiuchi, M. Kaplinghat, C. Gordon, R. M. Crocker, and D. M. Nataf, "Strong Evidence that the Galactic Bulge is Shining in Gamma Rays," 2019.

[21] O. Adriani *et al.*, "A new measurement of the antiproton-to-proton flux ratio up to 100 GeV in the cosmic radiation," *Phys. Rev. Lett.*, vol. 102, p. 051101, 2009.

[22] M. Boudaud *et al.*, "A new look at the cosmic ray positron fraction," *Astron. Astrophys.*, vol. 575, p. A67, 2015.

[23] D. Hooper, P. Blasi, and P. D. Serpico, "Pulsars as the Sources of High Energy Cosmic Ray Positrons," *JCAP*, vol. 0901, p. 025, 2009.

[24] J. Silk and M. Srednicki, "Cosmic Ray anti-Protons as a Probe of a Photino Dominated Universe," *Phys. Rev. Lett.*, vol. 53, p. 624, 1984. [,269(1984)].

[25] F. Donato, D. Maurin, P. Salati, A. Barrau, G. Boudoul, and R. Taillet, "Anti-protons from spallations of cosmic rays on interstellar matter," *Astrophys. J.*, vol. 563, pp. 172–184, 2001.

[26] F. Donato, N. Fornengo, D. Maurin, and P. Salati, "Antiprotons in cosmic rays from neutralino annihilation," *Phys. Rev.*, vol. D69, p. 063501, 2004.

[27] F. Donato, D. Maurin, P. Brun, T. Delahaye, and P. Salati, "Constraints on WIMP Dark Matter from the High Energy PAMELA $\bar{p}/p$ data," *Phys. Rev. Lett.*, vol. 102, p. 071301, 2009.

[28] G. Giesen, M. Boudaud, Y. Génolini, V. Poulin, M. Cirelli, P. Salati, and P. D. Serpico, "AMS-02 antiprotons, at last! Secondary astrophysical component and immediate implications for Dark Matter," *JCAP*, vol. 1509, no. 09, p. 023, 2015.

[29] M. Boudaud, M. Cirelli, G. Giesen, and P. Salati, "A fussy revisitation of antiprotons as a tool for Dark Matter searches," *JCAP*, vol. 1505, no. 05, p. 013, 2015.

[30] D. Maurin, F. Donato, R. Taillet, and P. Salati, "Cosmic rays below z=30 in a diffusion model: new constraints on propagation parameters," *Astrophys. J.*, vol. 555, pp. 585–596, 2001.

[31] Y. Génolini *et al.*, "Indications for a high-rigidity break in the cosmic-ray diffusion coefficient," *Phys. Rev. Lett.*, vol. 119, no. 24, p. 241101, 2017.

[32] Y. Génolini *et al.*, "Cosmic-ray transport from AMS-02 boron to carbon ratio data: Benchmark models and interpretation," *Phys. Rev.*, vol. D99, no. 12, p. 123028, 2019.

[33] M. Boudaud, E. F. Bueno, S. Caroff, Y. Genolini, V. Poulin, V. Poireau, A. Putze, S. Rosier, P. Salati, and M. Vecchi, "The pinching method for Galactic cosmic ray positrons: implications in the light of precision measurements," *Astron. Astrophys.*, vol. 605, p. A17, 2017.

[34] D. Maurin, "USINE: semi-analytical models for Galactic cosmic-ray propagation," 2018.

[35] L. Derome, D. Maurin, P. Salati, M. Boudaud, Y. Génolini, and P. Kunzé, "Fitting B/C cosmic-ray data in the AMS-02 era: A cookbook," *Astron. Astrophys.*, vol. 627, p. A158, 2019.

[36] M.-Y. Cui, Q. Yuan, Y.-L. S. Tsai, and Y.-Z. Fan, "Possible dark matter annihilation signal in the AMS-02 antiproton data," *Phys. Rev. Lett.*, vol. 118, no. 19, p. 191101, 2017.

[37] A. Cuoco, M. Krämer, and M. Korsmeier, "Novel Dark Matter Constraints from Antiprotons in Light of AMS-02," *Phys. Rev. Lett.*, vol. 118, no. 19, p. 191102, 2017.

[38] I. Cholis, T. Linden, and D. Hooper, "A Robust Excess in the Cosmic-Ray Antiproton Spectrum: Implications for Annihilating Dark Matter," *Phys. Rev.*, vol. D99, no. 10, p. 103026, 2019.

[39] A. Cuoco, J. Heisig, L. Klamt, M. Korsmeier, and M. Krämer, "Scrutinizing the evidence for dark matter in cosmic-ray antiprotons," *Phys. Rev.*, vol. D99, no. 10, p. 103014, 2019.

[40] S.-J. Lin, X.-J. Bi, and P.-F. Yin, "Investigating the dark matter signal in the cosmic ray antiproton flux with the machine learning method," 2019.

[41] M. Boudaud, Y. Génolini, L. Derome, J. Lavalle, D. Maurin, P. Salati, and P. D. Serpico, "AMS-02 antiprotons are consistent with a secondary astrophysical origin," 2019.

[42] F. Donato, N. Fornengo, and P. Salati, "Anti-deuterons as a signature of supersymmetric dark matter," *Phys. Rev.*, vol. D62, p. 043003, 2000.

[43] R. Duperray, B. Baret, D. Maurin, G. Boudoul, A. Barrau, L. Derome, K. Protasov, and M. Buenerd, "Flux of light antimatter nuclei near Earth, induced by cosmic rays in the Galaxy and in the atmosphere," *Phys. Rev.*, vol. D71, p. 083013, 2005.

[44] E. Carlson, A. Coogan, T. Linden, S. Profumo, A. Ibarra, and S. Wild, "Antihelium from Dark Matter," *Phys. Rev.*, vol. D89, no. 7, p. 076005, 2014.

[45] M. Cirelli, N. Fornengo, M. Taoso, and A. Vittino, "Anti-helium from Dark Matter annihilations," *JHEP*, vol. 08, p. 009, 2014.

[46] A. Coogan and S. Profumo, "Origin of the tentative AMS antihelium events," *Phys. Rev.*, vol. D96, no. 8, p. 083020, 2017.

[47] S. Ting, "Latest results from the AMS experiment," 2018.

[48] V. Poulin, P. Salati, I. Cholis, M. Kamionkowski, and J. Silk, "Where do the AMS-02 antihelium events come from?," *Phys. Rev.*, vol. D99, no. 2, p. 023016, 2019.

[49] L. Bergstrom, T. Bringmann, I. Cholis, D. Hooper, and C. Weniger, "New Limits on Dark Matter Annihilation from AMS Cosmic Ray Positron Data," *Phys. Rev. Lett.*, vol. 111, p. 171101, 2013.

[50] A. Reinert and M. W. Winkler, "A Precision Search for WIMPs with Charged Cosmic Rays," *JCAP*, vol. 1801, no. 01, p. 055, 2018.

[51] F. Calore, T. Regimbau, and P. D. Serpico, "Probing the Fermi-LAT GeV excess with gravitational waves," *Phys. Rev. Lett.*, vol. 122, no. 8, p. 081103, 2019.

[52] A. U. Abeysekara *et al.*, "Extended gamma-ray sources around pulsars constrain the origin of the positron flux at Earth," *Science*, vol. 358, no. 6365, pp. 911–914, 2017.

[53] F. D'Eramo and S. Profumo, "Sub-GeV Dark Matter Shining at Future MeV γ -Ray Telescopes," *Phys. Rev. Lett.*, vol. 121, no. 7, p. 071101, 2018.

[54] A. Esmaili and P. D. Serpico, "Gamma-ray bounds from EAS detectors and heavy decaying dark matter constraints," *JCAP*, vol. 1510, no. 10, p. 014, 2015.

[55] A. De Angelis *et al.*, "The e-ASTROGAM mission," *Exper. Astro.*, vol. 44, no. 1, pp. 25–82, 2017.

[56] X. Bai *et al.*, "The Large High Altitude Air Shower Observatory (LHAASO) Science White Paper," 2019.