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Indirect search for dark matter with cosmic-ray antinuclei: the GAPS experiment

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Abstract. The General Antiparticle Spectrometer (GAPS) is a balloon-borne experiment designed to perform low-energy cosmic-ray antinuclei measurements to search for indirect signatures of dark matter annihilation or decay. A wide range of well-motivated dark matter models predicts antinuclei fluxes about two orders of magnitude above the expected astrophysical background below 250 MeV/n. The study of this unexplored low-energy region allows GAPS to achieve an unprecedented sensitivity for antideuteron and antihelium nuclei fluxes. GAPS will collect high statistics of low-energy antiprotons, extending the measurement of the antiproton spectrum to the unexplored region below 100 MeV. The GAPS experiment will perform three long-duration balloon flights over Antarctica, the first of which is planned for the 2024/2025 Austral summer. The experimental apparatus consists of a Si(Li) tracker surrounded by a time-of-flight system made of plastic scintillator paddles. GAPS uses a novel identification technique based on the formation of an exotic atom and its de-excitation and decay. This contribution will first illustrate the scientific potential of the GAPS experiment and its impact on indirect dark matter searches. It will then describe the experimental apparatus and the detection technique exploited to identify antinuclei events. The expected sensitivity for antinuclei, based on detailed instrument simulations, will be then discussed. Finally, the status of payload integration and testing before the first flight will be summarized.

1 Introduction

The General AntiParticle Spectrometer (GAPS) [1, 2] is the first experiment optimized for the detection of low-energy antinuclei, operating in the energy region below 0.25 GeV/n. Several beyond-the-Standard Model theories predict that dark matter annihilation or decay will produce a flux of antideuteron and antihelium nuclei several orders of magnitude higher than the astrophysical background in the energy region below a few GeV/n [3, 4]. Consequently, GAPS will operate in an almost background-free energy range. The experiment employs a novel identification technique that involves the formation of an exotic atom and the observation of its decay and annihilation products. GAPS will perform such measurements using long-duration balloon (LDB) flights over Antarctica. The first of three planned flights is expected to be performed in the 2024/25 austral summer. During its lifetime, GAPS will achieve a leading sensitivity for antideuteron and antihelium nuclei detection [5, 6]. Moreover, the geometrical acceptance of ~ 10 $\mathrm{m^2sr}$ will allow GAPS to collect large statistics of antiprotons and light nuclei below 250 MeV/n. In Section 2 the experimental apparatus is described, while the detection principle and the reconstruction algorithm are introduced in Section 3. Then in Sections 4 and 5 the measurement capabilities of the experiment for antideuterons, antihelium, antiprotons and light nuclei are presented. Finally, the status of the integration of GAPS science payload will be summarized in Section 6.

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2 The GAPS experiment

The GAPS experimental apparatus consists of a time-of-flight (ToF) surrounding a tracker system. The ToF is arranged in an outer and an inner ToF systems made of Eljen EJ-200 plastic scintillator paddles [7, 8, 9]. The outer ToF if made of and horizontal plane above the rest of the detector (named "umbrella") and of four lateral vertical walls (named "cortina"). The inner ToF is a cube that surrounds the tracker system on top, bottom and lateral sides. All scintillators are 6.35 mm thick and 16 cm wide, with a length between 1.1 and 1.8 m. Each paddle is read out with silicon photomultipliers (Hamamatsu S13360-6050VE) on both ends. This system provides the measurement of energy depositions and time, and is able to measure the longitudinal position along its longest dimension. The tracker systems is made of 1008 Si(Li) detectors arranged in 7 planes evenly spaced by 10 cm [10, 11, 12, 13, 14, 15]. A tracker plane is made of 6×6 modules, where each module contains 2×2 detectors. Each detector has a cylindrical shape of $\sim$10 cm diameter and 2.5 mm thickness and it is segmented into eight strips of equal area. The required operational temperature of $\sim$-40° is achieved with an oscillating heat pipe system [16, 17, 18, 19]. The readout is performed with a dedicated application specific integrated circuit (ASIC) which provides the required dynamic range between $\sim$10 keV and $\sim$100 MeV [20, 21, 22]. The resulting energy resolution of the Si(Li) detectors is better than 4 keV at 60 keV, fulfilling the requirement for X-ray discrimination. A schematic view of the instrument is shown in Figure 1.

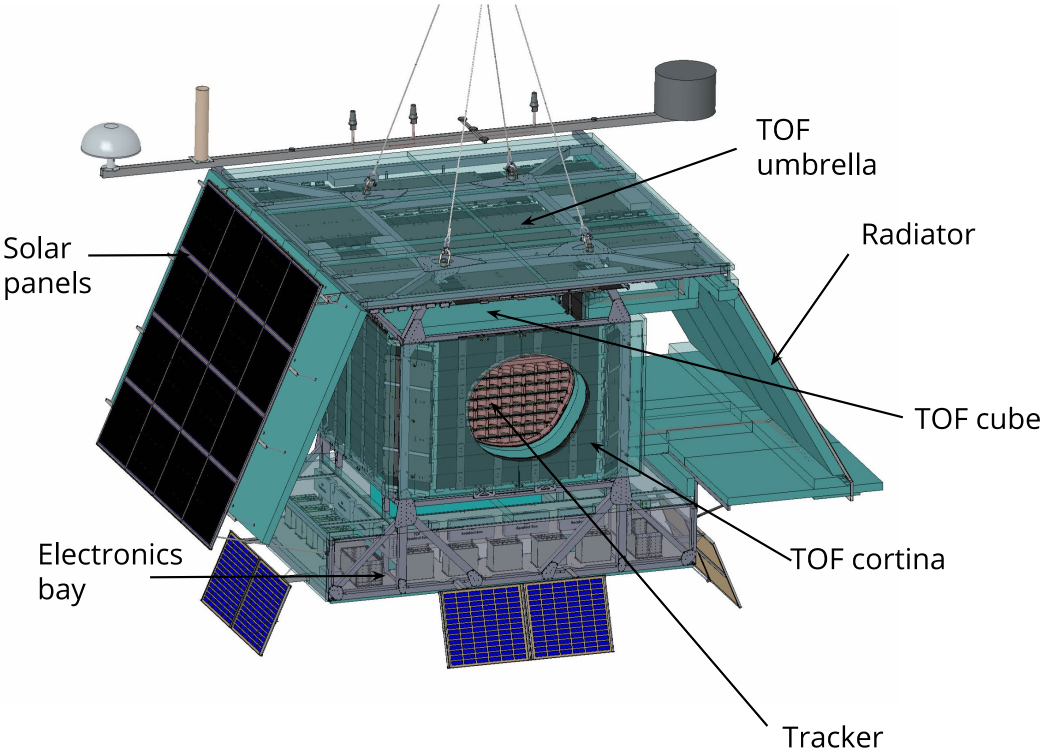

Figure 1: Schematic view of the GAPS experimental apparatus.

3 Detection principle

The detection principle relies on observing the annihilation products of the incoming antinucleus (hereafter called "primary"). After being slowed down by ionization losses, the primary can substitute an atomic electron (most often in a silicon detector or in the aluminum frame), forming an exotic atom. This exotic atom decays through a series of atomic transitions, emitting characteristic X-rays, and the antinucleus eventually annihilates with the target nucleus producing several secondary particles, mainly pions and protons, from a common vertex [5]. This concept was validated with a beam test with antiprotons at KEK accelerator where the X-rays from the exotic atom were detected [23]. To distinguish antiproton nuclei from the cosmic ray background, a rejection power of at least 10^6 is required, considering the relative particle abundances. Additionally, to measure a potential antideuteron component, an extra rejection factor of 10^5 is necessary to also eliminate antiproton background [24]. A precise reconstruction of the event topology is required to achieve these discrimination performances.

A custom reconstruction algorithm was developed to reconstruct the track of the primary particle, to identify the secondary particles produced in the annihilation, and to determine the position of the annihilation vertex [25]. Initially, the primary track is identified from the first two hits in the ToF. Next, a scan along the primary track is conducted to identify the best track candidates for the annihilation products. The annihilation vertex is then determined as the point that minimizes its distance from all tracks. This method is iterated a second time after removing spurious hits and tracks. The algorithm exhibits a 90% reconstruction efficiency, and the annihilation vertex is reconstructed with a precision of less than 10 cm (68% containment). A reconstructed annihilation event of a simulated antideuteron with $\beta = 0.28$ is shown in Figure 2, illustrating that the event was well reconstructed.

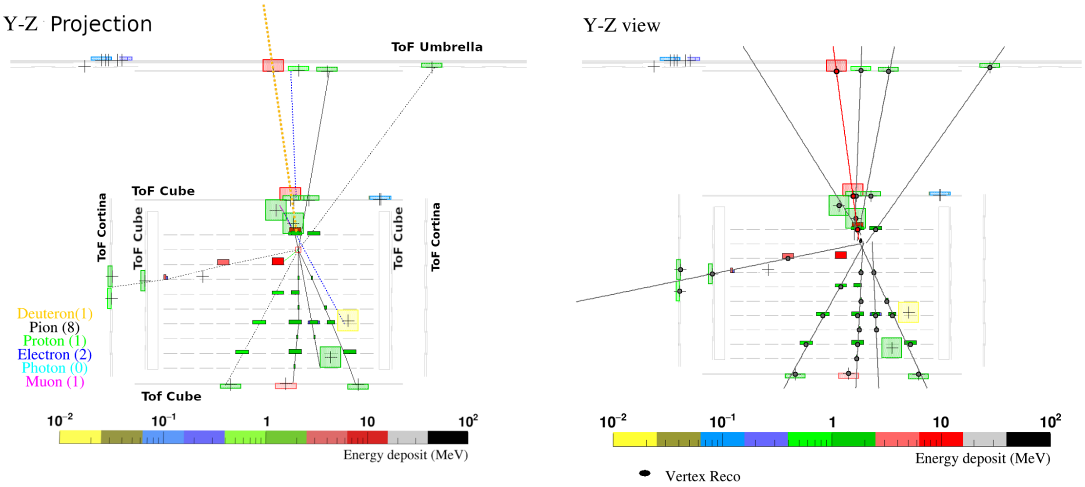

Figure 2: Schematic view of a simulated antideuteron annihilation event (side view). Gray boxes represent the active parts of the detector. On the left side, the simulated tracks are drawn, with a different color for each particle species (solid lines for particles, dashed lines for antiparticles). Each colored box represents a hit, where the color indicates the amount of the energy deposition. On the right side, the reconstructed tracks and the associated hits are shown as gray lines/points (red for the primary) The small black ellipse represents the 95% confidence interval of the fitted annihilation vertex.

4 Sensitivity to antinuclei

Antideuteron nuclei have never been observed in cosmic rays, so any detection would be an indication of new physics. As shown in Figure 3, the predicted flux of a generic 70-GeV WIMP annihilating via the $b\bar{b}$ channel is at least two orders of magnitude higher than the astrophysical background in the energy range covered by GAPS [26]. The GAPS sensitivity in the 0.10.25 GeV/n region is expected to improve the previous upper limit set by BESS by a factor ∼30 [5, 27]. Additionally, the experiment will be sensitive to other dark matter models, such as right-handed Kaluza-Klein neutrinos (from extra-dimensional grand unified theories), decaying LSP gravitinos, the next-to-minimal supersymmetric model (NMSSM), dark photon models, and heavy dark matter models with Sommerfeld enhancement.

The flux of antihelium nuclei predicted by various dark matter models is shown in Figure 4. After three long-duration balloon (LDB) flights, GAPS has the potential to investigate dark matter models annihilating via the W^+W^- channel [6]. Although the AMS-02 collaboration has reported a few antihelium candidates, detailed information about these events has not yet been published. The GAPS experiment

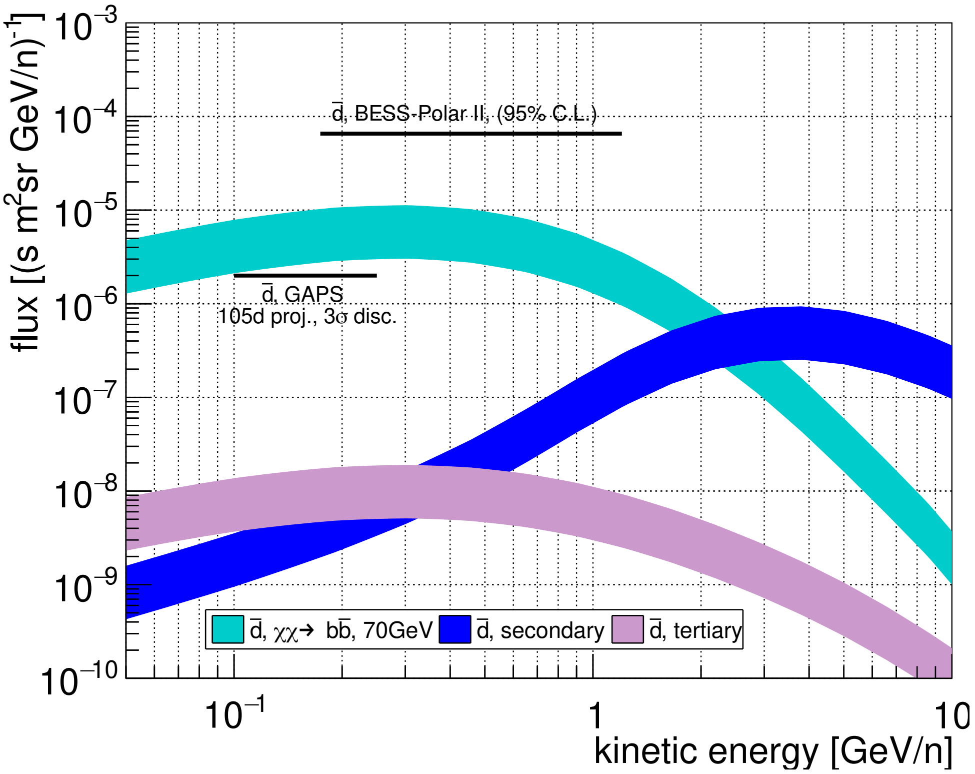

Figure 3: GAPS antideuteron sensitivity (black line) compared with the flux predicted by a generic 70 GeV WIMP (red band) and astrophysical background (cyan and green) models [5, 26]. BESS-Polar II upper limit for the antideuteron flux is also shown [27].

can test the presence of antihelium in cosmic rays through an orthogonal measurement in a lower energy range, using a completely different detection technique.

5 Antiprotons and light nuclei

In addition to searching for antideuteron and antihelium nuclei, GAPS will precisely measure the antiproton spectrum in the 0.10.21 GeV/n region. Since dark matter annihilation or decay processes that produce antideuterons also produce antiprotons, accurately measuring the antiproton spectrum will help constrain antideuteron production in dark matter models. In particular low-energy antiprotons are sensitive to models of light dark matter and primordial black holes [26]. This measurement will also provide detailed constraints on Galactic propagation models and will enhance our understanding of the attenuation and production of cosmic particles in the atmosphere. Furthermore, analyzing antiproton data from the first flight will allow for the validation of the exotic atom identification technique and will provide an accurate measurement of the background for heavier antinuclei studies. The projected antiproton flux with the predicted statistics from 3 LDB flights is shown in Figure 5.

Although the GAPS experiment is specifically designed to detect cosmic-ray antinuclei, measuring low-energy cosmic-ray nuclei is also feasible and highly beneficial for several reasons [29]. Nuclei measurements will improve our understanding of the propagation of cosmic-ray light nuclei, particularly in the Heliosphere. With the planned three flights, nuclei fluxes will be measured under different solar activity conditions, allowing for the testing and calibration of cosmic ray solar modulation models. Furthermore, models for secondary production in the atmosphere will be tested with precision within a few percent. Non-interacting nucleus events, without secondary tracks, allow the validation of reconstruction algorithm of primary particle. Conducting a high-statistics test of identification capabilities with protons and deuterons is also preparatory for the antiproton/antideuteron analysis.

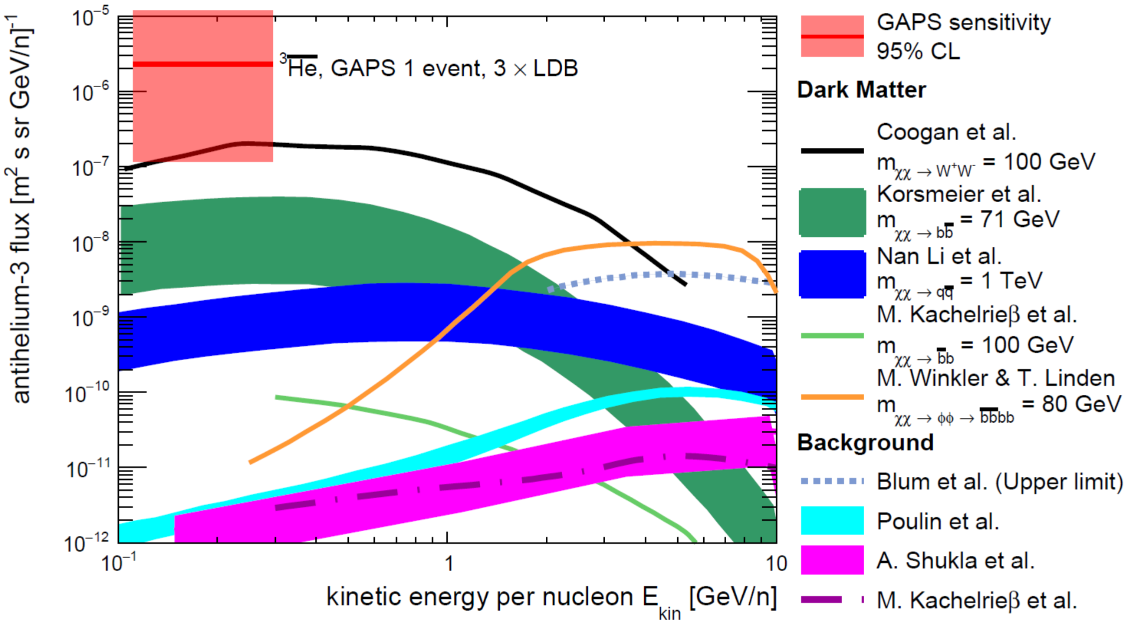

Figure 4: GAPS antihelium sensitivity (red line, with 95% C.L.) compared with the flux predicted by different dark matter and astrophysical background models [6].

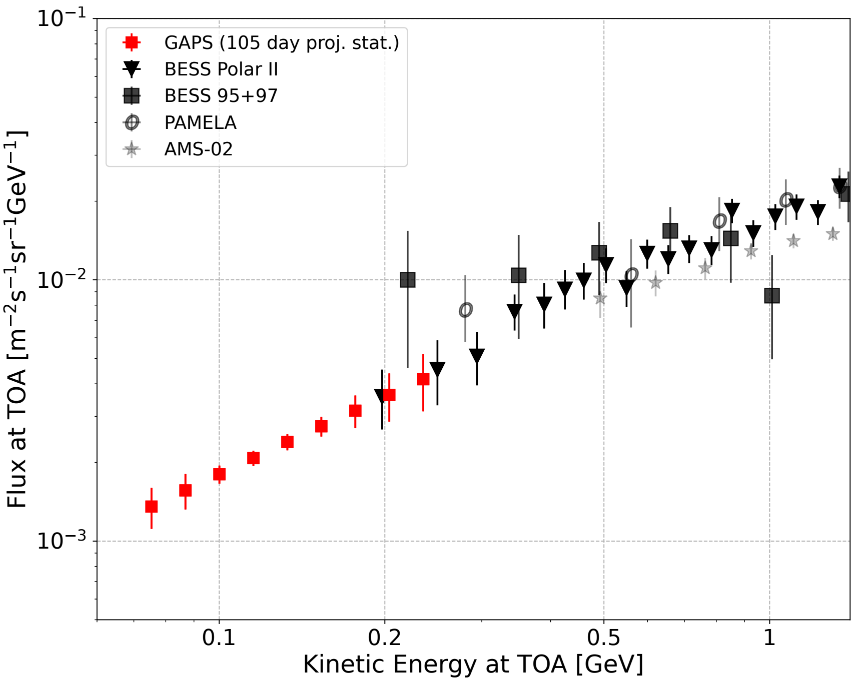

Figure 5: Projected GAPS cosmic antiproton spectrum at the top of the atmosphere with the statistics expected from three 35-day flights (red) compared with the results of other experiments (black) [28].

6 GAPS timeline

As for July 2024, the integration of the GAPS scientific payload have been completed and the compatibility and hang tests were successfully completed at the Columbia Scientific Balloon Facility in Palestine, Texas (US). Figure 6 show the payload during the hang tests. The GAPS timeline from the beginning of integration until the first flight is summarized below.

- Fall 2021 - February 2022: construction and test of GAPS Functional Prototype at MIT Bates Laboratory.
- March 2022 - May 2023: payload integration and tests with cosmic muons at MIT and Berkley Space Science Laboratory.
- June 2023: thermal-vacuum test at NTS El Segundo.
- July 2023 - May 2024: re-build of payload, calibration and test with cosmic muons at Columbia Nevis Laboratory.
- July 2024: compatibility and hang tests at Columbia Scientific Balloon Facility, Palestine.
- Fall 2024: payload shipped to McMurdo station in Antarctica.
- December 2024: First flight from McMurdo station.

7 Conclusions

The GAPS experiment aims to perform low-energy cosmic-ray antinuclei measurements in the region below 250 MeV/n searching for indirect signatures of dark matter. By utilizing a novel detection technique based on exotic atom formation and decay, GAPS will achieve unprecedented sensitivity in detecting antideuteron and antihelium nuclei, reaching the values of 2×10^{-6} $\mathrm{m^{-2}\ s^{-1}\ sr^{-1}\ (GeV}/n)^{-1}$ and 1.3×10^{-6} $\mathrm{m^{-2}\ s^{-1}\ sr^{-1}\ (GeV}/n)^{-1}$, respectively, after three long-duration balloon flights. GAPS will also perform a precision measurement of antiproton spectrum between 100 and 210 MeV/n. The instrument have already been assembled and tested at ground in Columbia Nevis laboratories and successfully performed compatibility and hang tests at the Columbia Scientific Balloon Facility in Palestine. The payload is now ready for his first flight that will take place in December 2024 from McMurdo station in Antarctica.

Figure 6: The GAPS scientific payload during the hang tests held at the Columbia Scientific Balloon Facility in Palestine.

References

[1] K. Mori, C.J. Hailey, E.A. Baltz, W.W. Craig, M. Kamionkowski, W.T. Serber and P. Ullio, *Astrophys. J.* **566** (2002) 604.

[2] C.J. Hailey, *New J. Phys.* **11** (2009) 105022.

[3] F. Donato, N. Fornengo and P. Salati, *Phys. Rev. D* **62** (2000) 043003.

[4] N. Fornengo, L. Maccione and A. Vittino, *JCAP* **09** (2013) 031.

[5] GAPS collaboration, *Astropart. Phys.* **74** (2016) 6.

[6] GAPS collaboration, *Astropart. Phys* **130** (2021) 102580.

[7] S. Quinn et al.„ *PoS* (ICRC2019) 128.

[8] S. Quinn et al., *PoS* (ICRC2021) 079.

[9] S. Feldman et al., *PoS* (ICRC2023) 120.

[10] K. Perez et al., *Nucl. Instrum. Meth. A* **905** (2018) 12.

[11] M. Kozai et al., *Nucl. Instrum. Meth. A* **947** (2019) 162695.

[12] F. Rogers and et al., *Journal of Instrumentation* **14** (2019) P10009.

[13] N. Saffold et al., *Nucl. Instrum. Meth. A* **997** (2021) 165015.

[14] M. Kozai et al., *Nucl. Instrum. Meth. A* **1034** (2022) 166820.

[15] M. Xiao et al., *IEEE Transactions on Nuclear Science* **70** no.8 (2023) 2125-2133.

[16] S. Okazaki, H. Fuke, Y. Miyazaki and H. Ogawa *J. Astron. Inst.* **3** (2014) 1440004.

[17] H. Fuke, S. Okazaki, H. Ogawa and Y. Miyazaki, *J. Astron. Inst.* **06** (2017) 1740006.

[18] S. Okazaki et al., *Applied Thermal Engineering* **141** (2018) 20.

[19] H. Fuke et al., *Nucl. Instrum. Meth. A* **1049** (2023) 168102.

[20] M. Manghisoni et al., *IEEE Transactions on Nuclear Science* **68** no.11 (2021) 2661-2669.

[21] V. Re et al., *Nucl. Instrum. Meth. A* **1045** (2023) 167617.

[22] M. Manghisoni et al., *IEEE Transactions on Nuclear Science* **71** no.1 (2024) 96-105.

[23] T. Aramaki et al., *Astroparticle Physics* **49** (2013) 52–62

[24] M. Boezio, R. Munini and P. Picozza, *Prog. Part. Nucl. Phys.* **112** (2020) 103765.

[25] R. Munini et al., *Astroparticle Physics* **133** (2021) 102640.

[26] P. von Doetinchem et al., *IOP Publishing* **2020** (2020) 035.

[27] K. Sakai et al., *Phys. Rev. Lett.* **132** (2024) 131001.

[28] F. Rogers et al., *Astroparticle Physics* **145** (2023) 102791.

[29] R. Munini, A. Lenni et al., *PoS* (ICRC2023) 179.