

TAsP: Theoretical Astroparticle Physics

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Main scientific activities and achievements of the IS TAsP during the year 2025.

Axion Physics:

- **High-quality Peccei-Quinn symmetry.**

In ¹⁾, We explore a class of axion models where an accidental U(1) Peccei-Quinn (PQ) symmetry automatically emerges from the interplay of vertical (grand-unified) and horizontal (flavor) gauge symmetries. A distinctive feature of the vertical-horizontal setup is the presence of parametrically light fermions, known as anomalons, which are introduced to cancel the gauge anomalies of the flavor symmetry. A high-quality axion may be obtained instead in the post-inflationary scenario, with axion mass $m_a \gtrsim 0.01$ eV (as highlight in Fig. 1), and anomalon masses predicted below the eV scale.

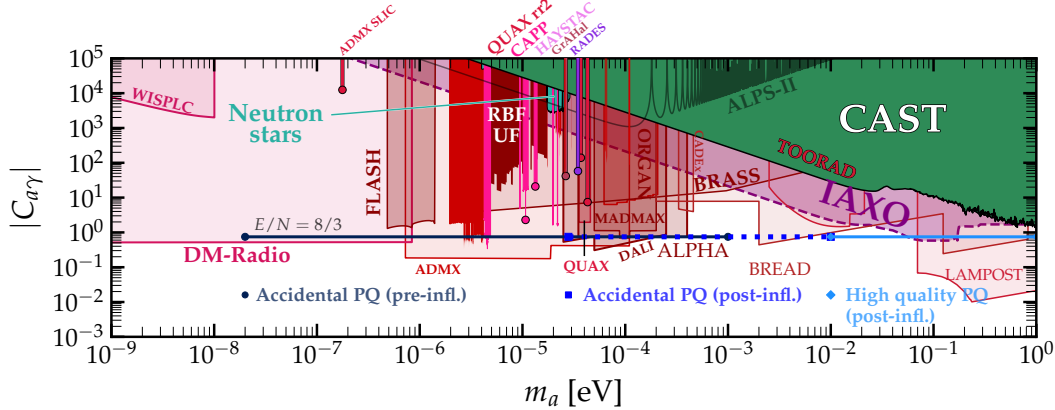


Figure 1: Axion-photon coupling as a function of the axion mass. Current limits and future sensitivities are represented by filled and shaded regions, respectively. A high-quality PQ symmetry is obtained for $m_a \gtrsim 0.01$ eV (light blue line) in the post-inflationary PQ-breaking scenario. An accidental PQ symmetry (not addressing the PQ-quality problem) corresponds to the intervals $m_a \in [2 \times 10^{-8}, 10^{-3}]$ eV in the pre-inflationary PQ-breaking scenario (black line) and $m_a \in [2.8 \times 10^{-5}, 0.01]$ eV in the post-inflationary PQ-breaking scenario (blue/dashed line).

- **Fresh look at the diffuse ALP background from supernovae.**

In ²⁾, proton-neutron stars formed in core-collapse supernovae (SNe) are efficient sources of axion-like particles (ALPs), produced mainly through nucleon–nucleon bremsstrahlung and pion conversion, yielding spectra peaked at $\mathcal{O}(100)$ MeV. We revisit the diffuse ALP background from all past

SNe and update the corresponding Fermi-LAT constraints. Assuming the maximal ALP–nucleon coupling allowed by SN 1987A cooling, we obtain an upper limit $g_{a\gamma\gamma} \leq 2 \times 10^{-13} \text{ GeV}^{-1}$ for $m_a \leq 10^{-10} \text{ eV}$, improving previous bounds by roughly a factor two improvement with respect to the existing bounds.

Physics of dark sectors:

• Axion-Like Electrophilic Portal for Pion Dark Matter.

In ³⁾ we investigate a scenario in which Strongly Interacting Massive Particle (SIMP) dark matter interacts with an axion-like particle (ALP) that couples exclusively to electrons. This minimal setup provides interactions that enforce thermal equilibrium between dark matter and the Standard Model (SM) in the early Universe. We analyze the cosmological evolution of the dark sector and the constraints arising from dark matter annihilations, ALP laboratory searches, and astrophysical observations. Our results show that the allowed parameter space is wider than in previous studies, and an ALP with mass $m_a \sim \mathcal{O}(10) \text{ MeV}$ can act as a viable portal between the visible and dark sectors. Interestingly, this mass range overlaps with the parameter space suggested by the reported X_{17} anomaly. Furthermore, introducing a non-vanishing θ -angle in the dark sector opens up the parameter space to heavier ALP masses.

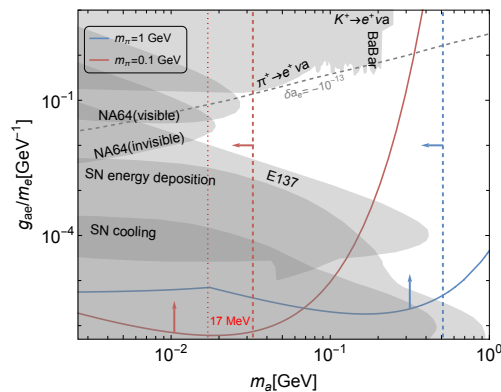


Figure 2: Summary of the constraints for different choices of dark matter mass. Thermalization between the ALPs and the SM is efficient above the solid lines. The maximal value of m_a allowed by CMB and indirect detection constraints is shown as a dashed line. The gray region is excluded by laboratory searches and SN1987A. The available parameter space corresponds to the white region above the solid line and to the left of the dashed line, as shown by the arrows.

• Atoms as Electron Accelerators for New Physics Searches.

In fixed-target experiments, atoms can effectively act as electron accelerators, increasing the centre-of-mass energy in collisions with beam particles. In Ref. ⁴⁾, we leverage this effect to explore its potential for new physics searches. We consider positrons from beams of various energies annihilating with atomic electrons in a ^{74}W fixed target. We estimate the sensitivity for detecting these new particles using the positron beam at the Beam Test Facility linac at the Laboratori Nazionali di Frascati, the H4 beamline in the CERN North Area, and the proposed Continuous Electron Beam Accelerator Facility of Jefferson Laboratory.

• Blind unblinding procedure for the PADME X17 data sample.

Ref. ⁵⁾ includes the fundamental contributions of theorists to shape the analysis of the LNF

PADME experiment.

- **X_{17} Boson After PADME Results on Resonant Production in Positron Annihilation.**

PADME as reported an excess of e^+e^- final-state events from positron annihilation on fixed-target atomic electrons. Although the global significance is modest (1.8σ), the excess appears at $\sqrt{s} \sim 17$ MeV, coinciding with the invariant mass at which anomalous e^+e^- pair production has previously been observed in nuclear transitions of ^8Be , ^4He , and ^{12}C . This alignment strengthens the case for a common origin, potentially involving a new X_{17} boson. In Ref. ⁶⁾, we discuss the implications of this independent accelerator-based evidence and, combining it with existing nuclear results, obtain an updated mass determination of $m_{X_{17}} = 16.88 \pm 0.05$ MeV, reducing the uncertainty from nuclear data alone by more than a factor of two.

- **Unveiling atomic electron motion effects in e^+e^- high-energy collisions at NA64.**

In ⁷⁾, atomic electron motion is known to produce well-studied effects in low-energy (MeV-scale) processes. Recently, this phenomenon has attracted renewed interest in the high-energy physics community due to its potential to significantly enhance the center-of-mass energy in fixed-target experiments. However, direct experimental evidence of this effect in high-energy collisions has not yet been observed. We argue that a striking manifestation of atomic electron momenta could be revealed by the NA64 experiment at CERN during the proposed run with a 40 GeV positron beam. At this energy, $\mu^+\mu^-$ production via positron annihilation on electrons at rest is kinematically forbidden. The observation of $\mu^+\mu^-$ pairs from this channel would therefore constitute direct evidence of a center-of-mass energy increase induced by atomic electron motion. We also examine the expected signatures for the proposed 60 GeV run, as well as for the data already collected at 70 GeV. Intriguingly, in both cases, the predicted number of $\mu^+\mu^-$ pairs from positron annihilation is reduced relative to the electron-at-rest approximation.

Physics Beyond the Standard Model:

- **Dark Matter and Minimal Flavor Violation framework.**

In ⁸⁾ Minimal Flavor Violation (MFV) provides a compelling framework for exploring physics beyond the Standard Model, in which new QCD-singlet fields transforming under the global $\text{SU}(3)^3$ quark flavor symmetry can naturally be stable and serve as dark matter (DM) candidates. We show that the DM–MFV framework can accommodate the excess observed in either $K^+ \rightarrow \pi^+\nu\bar{\nu}$ or $B^+ \rightarrow K^+\nu\bar{\nu}$, although a unified explanation of both channels cannot be achieved within a minimal setup containing only a single dark matter multiplet with nearly degenerate masses. Overall, our findings highlight the intricate interplay between MFV-based model building, flavored dark matter scenarios, and precision flavor experiments, emphasizing that flavored dark matter remains both theoretically robust and experimentally testable.

- **A new perspective on the CMSSM.**

In ⁹⁾, we investigate the implications of third-family Yukawa unification ($t-b-\tau$), as expected when SM fermions are embedded in **16**-plets of an $\text{SO}(10)$ GUT, for the SUSY scale, the neutralino dark-matter candidate, and its relic abundance. The extra MSSM Higgs bosons lie at 2–3 TeV, potentially observable at the HL-LHC, while stops and gluinos near $\mathcal{O}(10)$ TeV would require an FCC-hh. The neutralino is a bino heavier than 2.5 TeV, overproducing dark matter and remaining undetectable in planned searches. Matching the observed relic density requires a dilution factor $10 < \mathcal{D} < 1000$, pointing to non-standard cosmology with possible gravitational-wave signatures.

References

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