Search for Dark Matter ALPs Through Photon Couplings in Atomic Systems

Reference : *PHYS. REV. D 108, 043029 (2023)*

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Based on

PHYSICAL REVIEW D **108**, 043029 (2023)

Inverse Primakoff scattering for axionlike particle couplings

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(Received 14 June 2022; revised 29 June 2023; accepted 3 August 2023; published 25 August 2023)

Axionlike particles (ALPs) can be produced in the Sun and are considered viable candidates for the cosmological dark matter (DM). It can decay into two photons or interact with matter. We identify new inelastic channels of inverse Primakoff processes due to atomic excitation and ionization. Their cross sections are derived by incorporating full electromagnetic fields of atomic charge and current densities, and computed by well-benchmarked atomic many-body methods. Complementing data from the underground XENONnT and surface TEXONO experiments are analyzed. Event rates and sensitivity reaches are evaluated with respect to solar- and DM-ALPs. New parameter space in ALP couplings with the photons versus ALP masses in (1 eV–10 keV) not previously accessible to laboratory experiments are probed and excluded with solar-ALPs. However, at regions where DM-ALPs have already decayed, there would be no ALP-flux and hence, no interactions at the detectors in direct search experiments. No physics constraints can be derived. Future projects would be able to evade the stability bound and open new observable windows in (100 eV–1 MeV) for DM-ALPs.

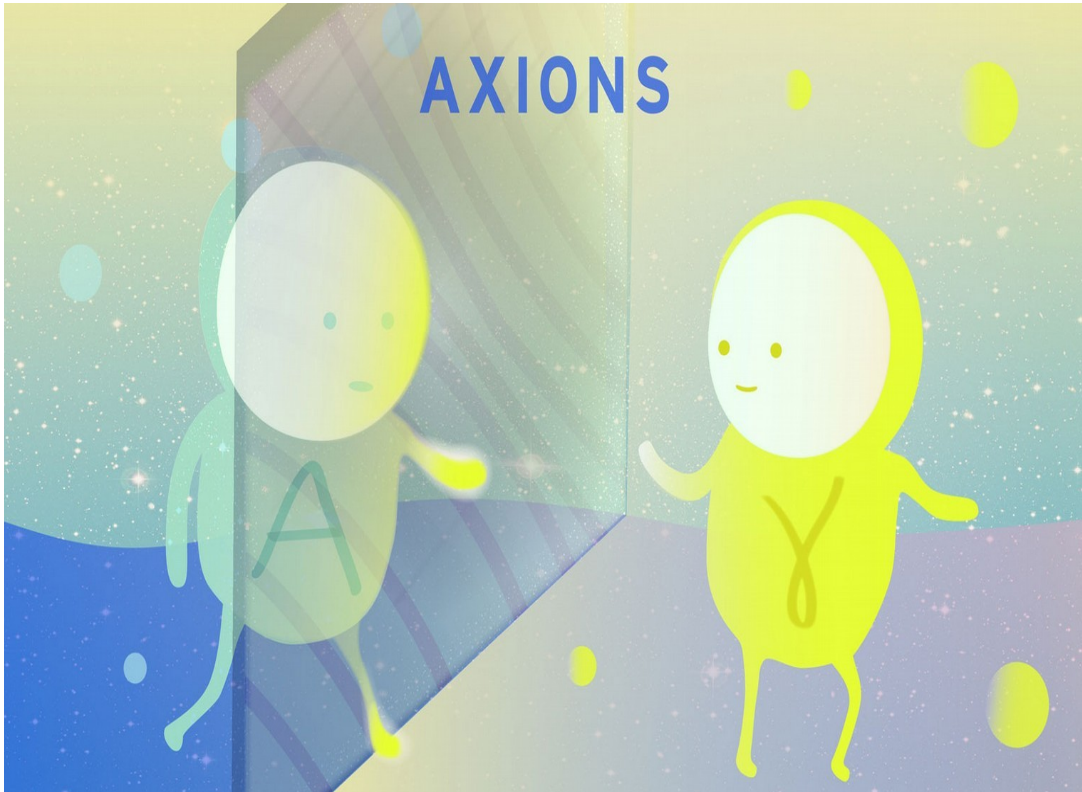
DOI: 10.1103/PhysRevD.108.043029

Outline

- Introduction
- Interaction Channels
- Dark Matter ALPs
- Analysis and Results
- Summary & Future Prospects

Axions & ALPs : Portal to New Physics

- ✔ Some phenomena cannot be explained with current SM:
  - a. Strong CP problem
  - b. The existence of DM
- ✔ Axion - first introduced in 1970s as a solution to the strong CP problem in QCD
- ✔ Axionlike Particles (ALPs) – Variants of QCD axions – not necessarily solutions to the strong CP problem
- ✔ Sources of ALPs:
  - (a) Dark Matter
  - (b) Sun



(Sandbox Studio, Chicago, Symmetry Magazine/Fermilab and SLAC)

Coupling of ALPs to photons, $g_{a\gamma\gamma}$ - chances to explore and understand the physics beyond SM

Interaction Channels

Lagrangian:

$$\mathcal{L}_I = -\frac{g_{a\gamma\gamma}}{4}\phi_a F_{\mu\nu}\widetilde{F}^{\mu\nu} - \sum_f \frac{g_{aff}}{2m_f}\partial_\mu\phi_a\overline{\Psi}_f(\gamma^\mu\gamma_5)\Psi_f$$

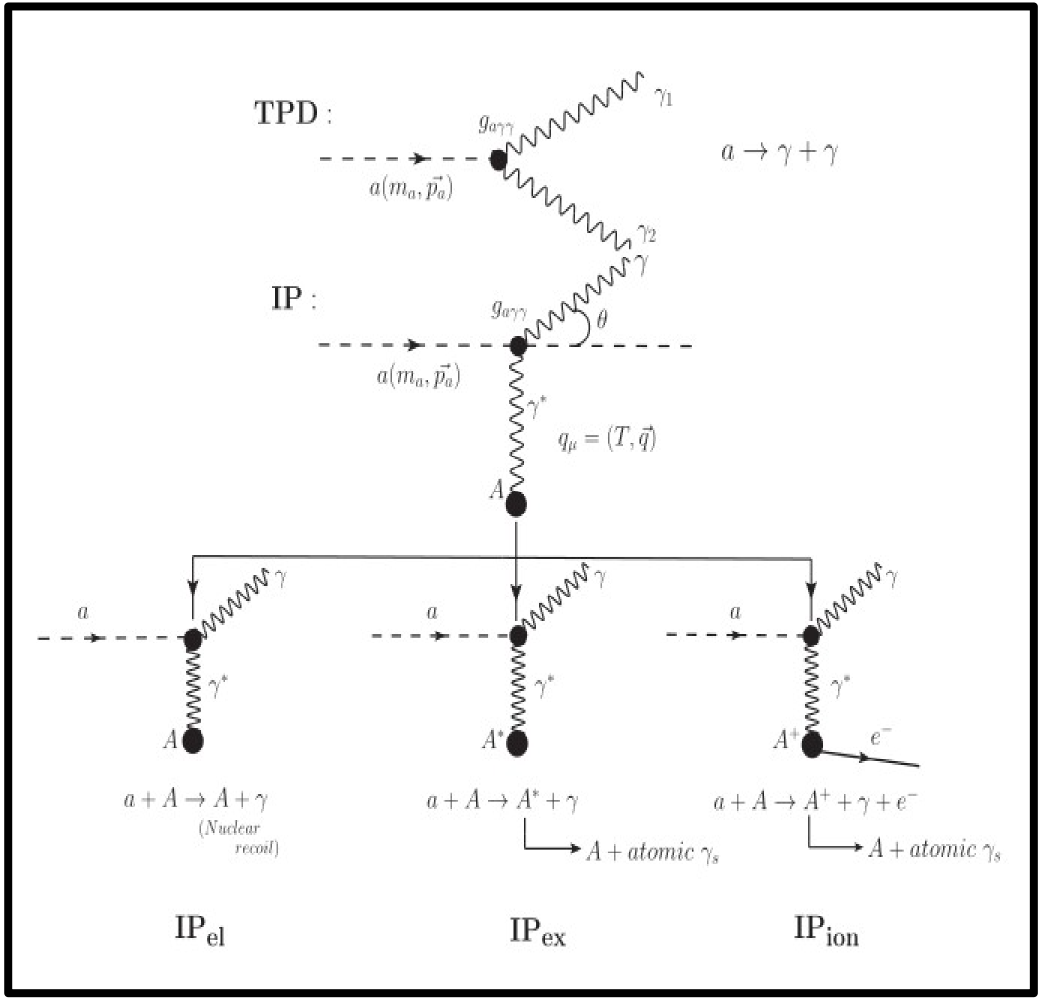
- **We have focussed only on the processes resulting from a finite $g_{a\gamma\gamma}$**

Vacuum Decay (Two-Photon Decay – TPD):

$$a \to \gamma_1 + \gamma_2$$

Inverse Primakoff (IP) interactions:

$$a + A \to \begin{cases} \gamma + A & \text{IP}_{el} : \text{elastic scattering} \\ \gamma + A^* & \text{IP}_{ex} : \text{atomic excitation} \\ \gamma + A^+ + e^- & \text{IP}_{ion} : \text{atomic ionization} \end{cases}$$

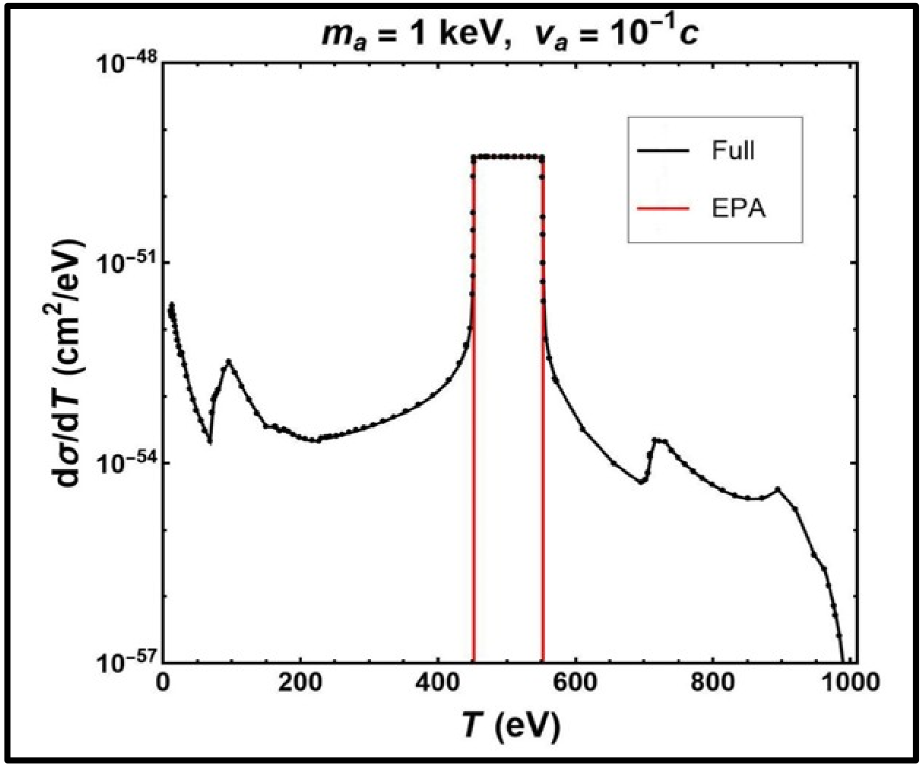


Double-pole Enhancement for IP_{ion}

Differential cross section of the ALP IP processes:

$$\frac{d\sigma_{\rm IP}}{dT\,d\Omega} = \frac{\alpha g_{a\gamma\gamma}^2}{16\pi}\left(\frac{E_a - T}{v_a E_a}\right)\left[\frac{V_L}{(q^2)^2}\mathscr{R}_L + \frac{V_T}{(Q^2)^2}\mathscr{R}_T\right]$$

Exhibit a double pole structure at $Q^2 = 0$ and for $m_a \neq 0$



- Full calculation: Atomic wave functions using FCA
- EPA is a good approximation in $Q^2 = 0$ region

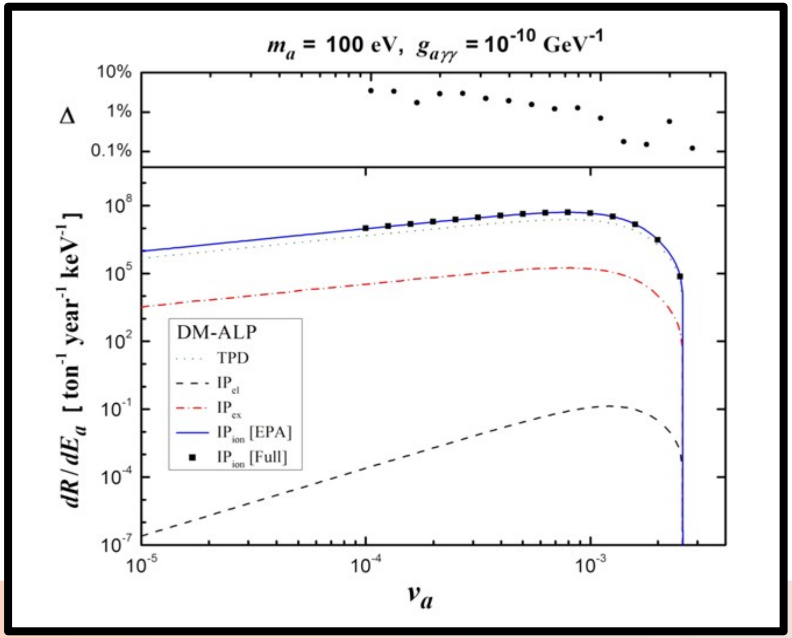
For NR ALPs, IP_{ion} has double pole enhancement near $T \approx m_a/2$

Dark Matter ALPs

- IP_{ion} and TPD are dominant channels

- The percentage deviations between Full calculation and EPA are < 3% in the double pole region

- Event rate ∝ $(g_{a\gamma\gamma})^2$

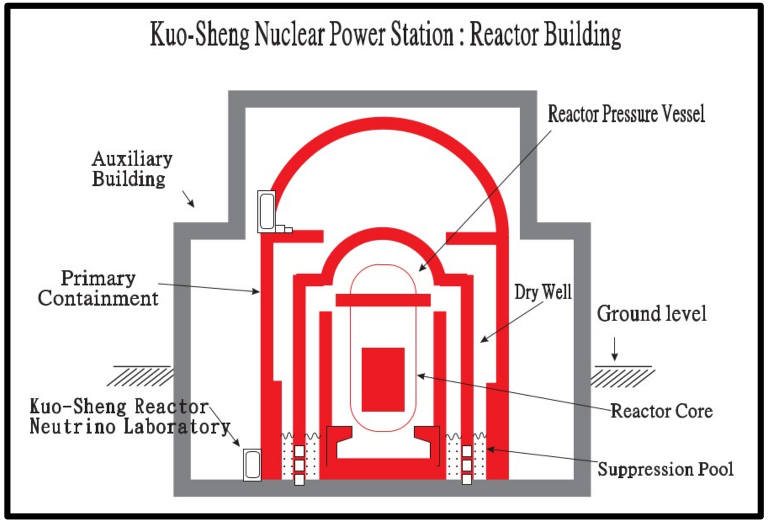


(Illustration by Sandbox Studio, Chicago with Ana Kova)

Analysis and Results

TEXONO (Taiwan EXperiment On NeutrinO)

- Point Contact Ge detector technology
- Low threshold – 300 eV_{ee}
- Excellent Energy Resolution
- Spans a large energy range – from 300 eV_{ee} to 3 MeV_{ee}



(Taiwan EXperiment On NeutrinO – History, Status and Prospects, THE UNIVERSE, Vol. 3, No. 4, 22-37)

Analysis and Results

TEXONO (Taiwan EXperiment On NeutrinO)

- Point Contact Ge detector technology
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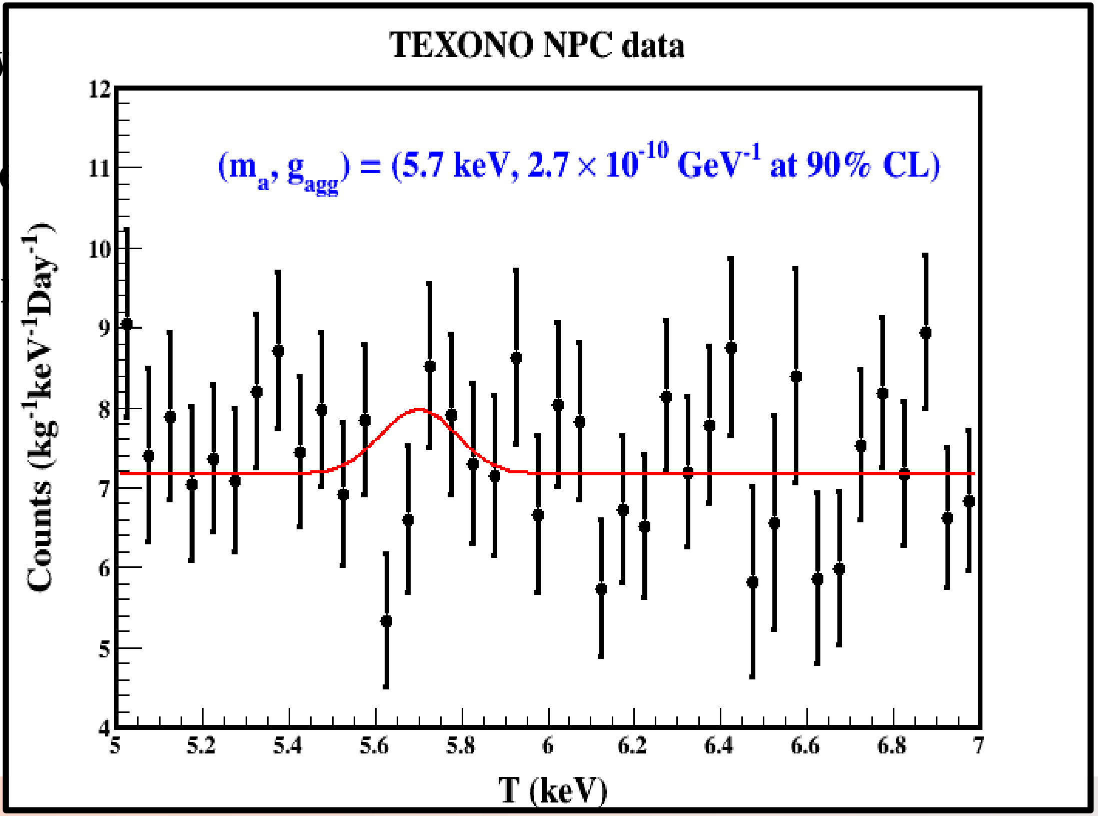
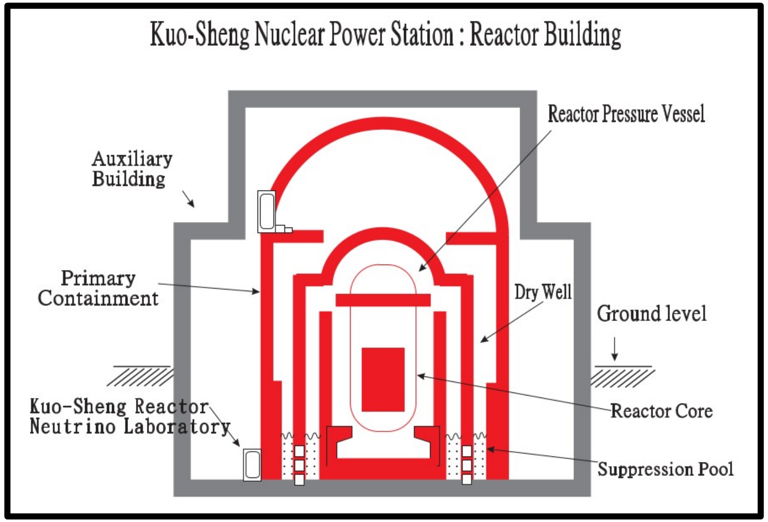
- Exc
- Spa





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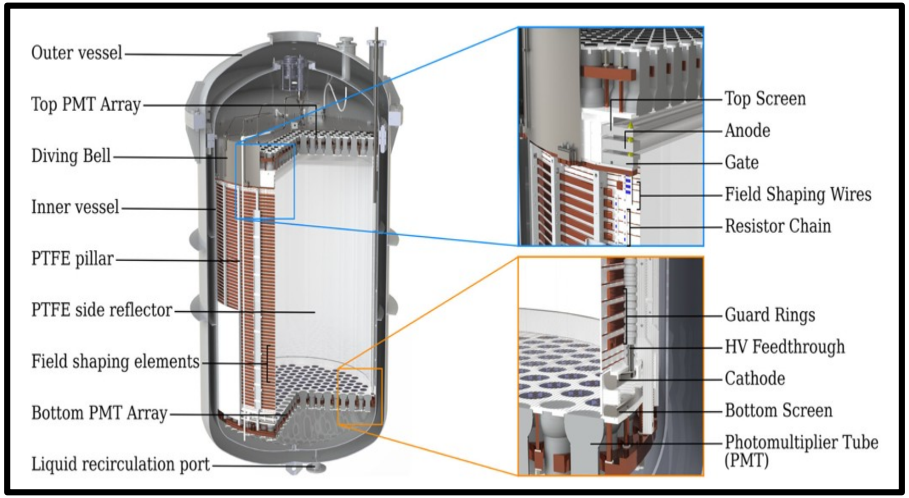
XENONnT

- Liquid Xe as target – Tonne scale detector
- Energy range – from 1 keV_{ee} to 140 keV_{ee}
- Large Exposure

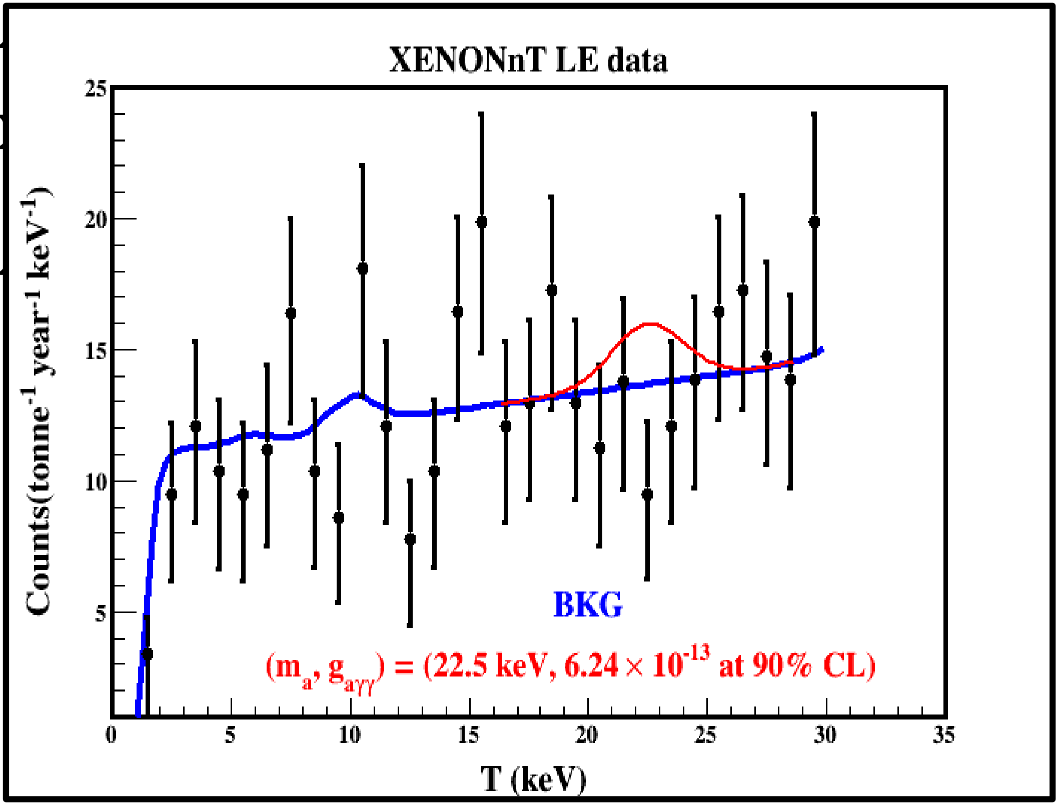


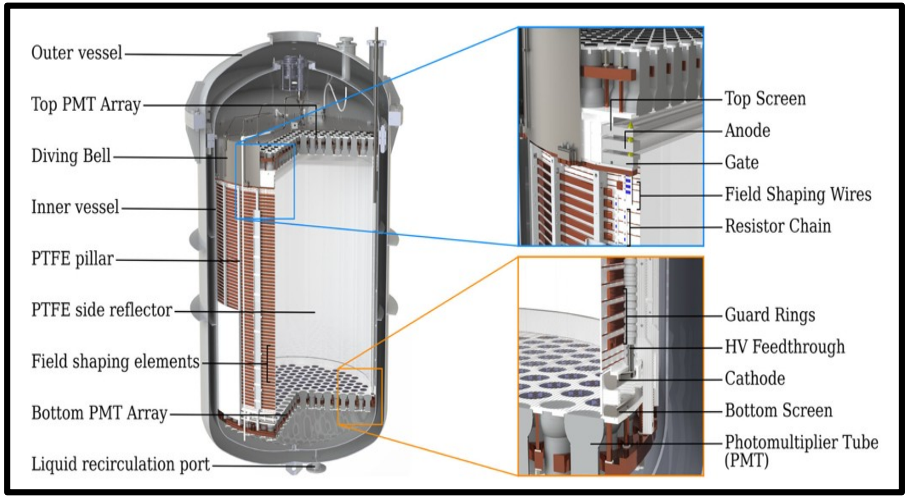
(Eur. Phys. J. C, 84(8):784, 2024)

Analysis and Results

XENONnT

- L
- E
- L





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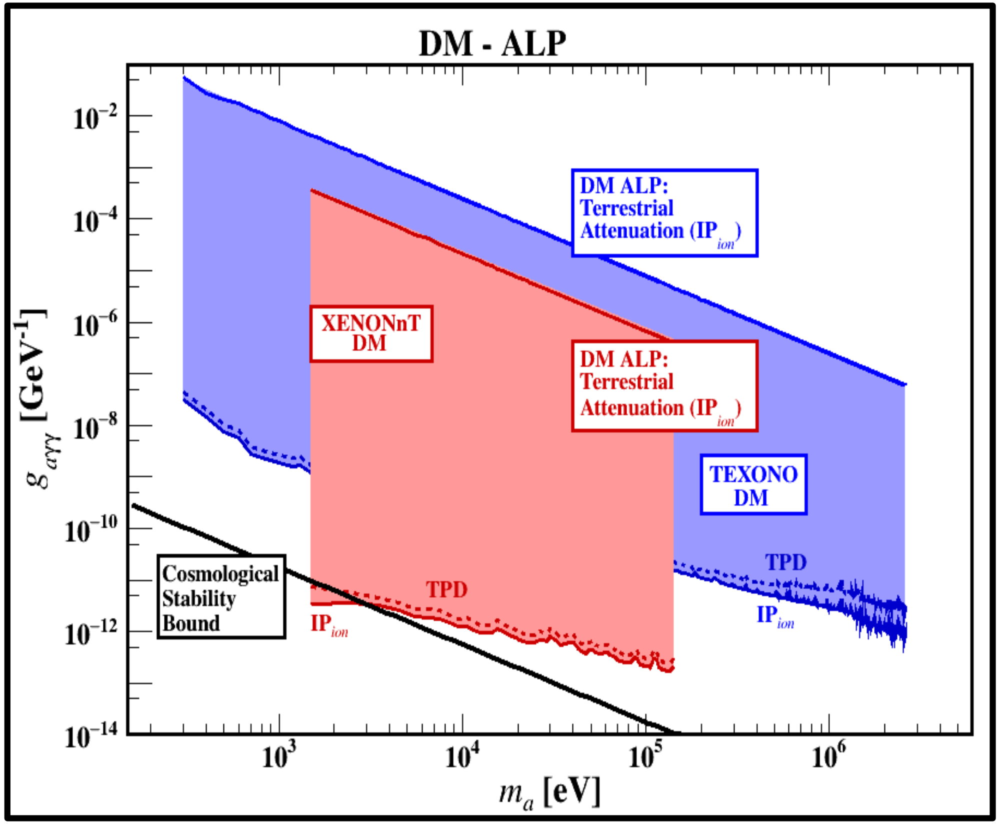
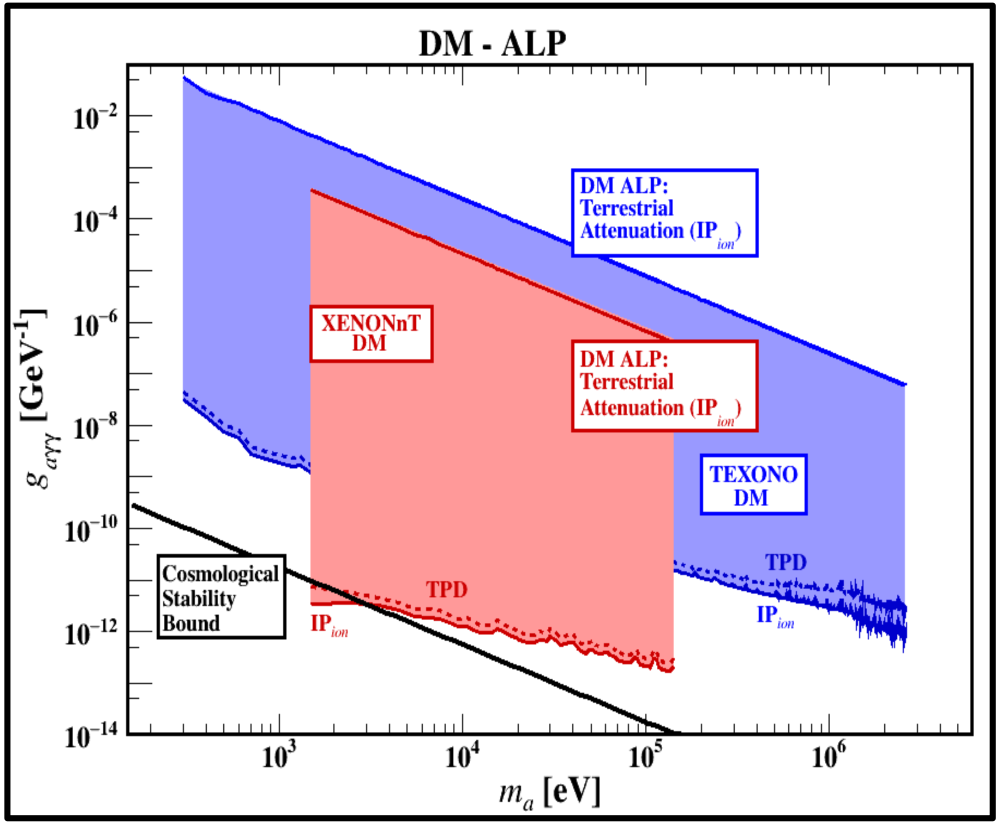
Exclusion Plots – DM ALP



(a)

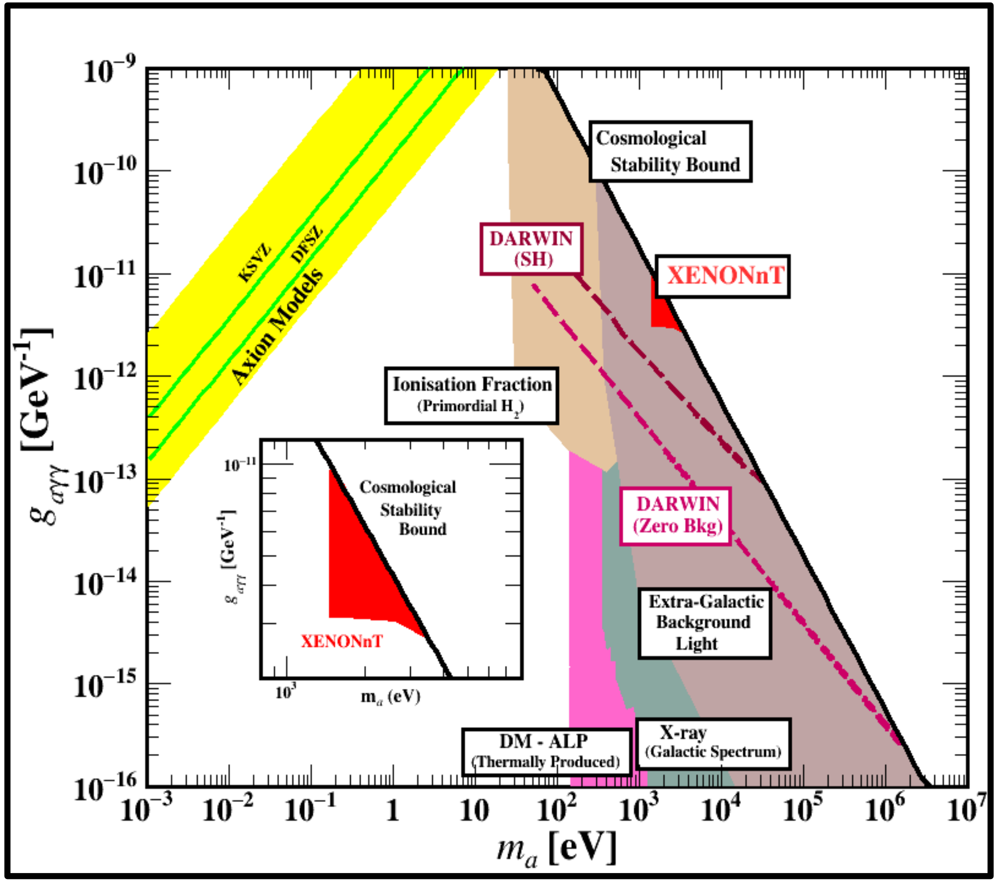
(b)

Exclusion Plots – DM ALP



(a)

(b)



Summary

- Identified **new detection channel (IP_{ion})** to probe $g_{a\gamma\gamma}$ for laboratory-based experimental searches.
- IP_{ion} channel has **discovery potential** for the search of ALPs.
- Developed **new sophisticated tool (FCA)** for calculating cross-section for many-body systems.
- New tools are good at calculating cross-section above 80eV within **5% error**.
- IP_{ion} sensitivities of future projects (**DARWIN**) would exceed the cosmological stability bound for DM-ALPs.

Future Prospects

- Comprehensive analysis of ALPs through a **global approach** considering the coupling between **ALPs and photons, as well as ALPs and electrons**.
- Exploring reactor ALPs via IP and decay processes.

Thank You!...

Backup

FCA, RRPA & MCRRPA

- **<u>Frozen Core Approximation (FCA)</u>**

  - In FCA, core electrons in the system are treated as "frozen" or inert, meaning their positions are fixed and do not participate in the calculation of the e^-- e^- interactions.

  - By freezing the core electrons, the e^-- e^- interactions are effectively treated as a perturbation on top of the frozen core.

- **<u>Relativistic Random Phase Approximation (RRPA)</u>**

  - For many-body systems RPA can be used to account for collective effects that influence the system's response to external perturbations.

- **<u>Multi-Configuration Relativistic Random Phase Approximation (MCRRPA)</u>**

  - MCRRPA is a theoretical framework used to calculate cross sections for nuclear reactions involving heavy nuclei, combining aspects of the multiconfiguration Dirac-Hartree-Fock (MCDHF) method with the RRPA to account for both relativistic effects and collective excitations.