The Future is Flavourful

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Probing Axion-like Particles: Novel Detection Channels and Expanding Experimental Sensitivity for Dark Matter and Solar ALPs

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Outline

- **Introduction**
- **Interactions**
- **Dark Matter ALPs**
- **Solar 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
- ✔ For QCD axions, axion-photon coupling ~ $1/f_a$, $m_a \sim 1/f_a$.

  For ALPs, $m_{ALP} \sim \Lambda^2 / f_a$ is nearly arbitrary .
- ✔ Sources of ALPs:
  - (a) Dark Matter
  - (b) Sun

Coupling of ALPs to photons (g_{agg}) - chances to explore and understand the physics beyond SM

Interactions

Lagrangian:

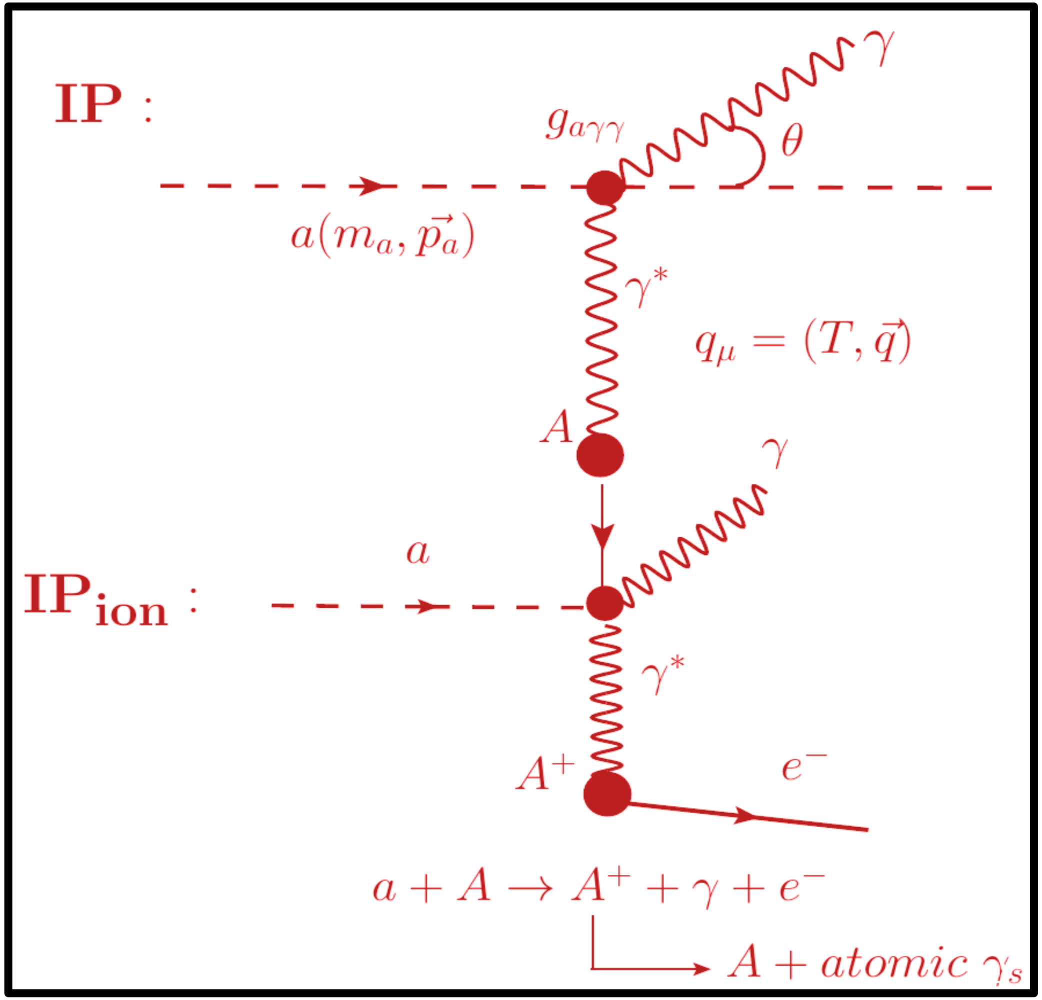
$$\mathcal{L}_I = -\frac{g_{a\gamma\gamma}}{4}\phi_a F_{\mu\nu}\widetilde{F}^{\mu\nu} - \sum_f \frac{g_{aff}}{2m_f}\partial_\mu\phi_a\overline{\Psi}_f(\gamma^\mu\gamma_5)\Psi_f$$

Vacuum Decay,

$$a \rightarrow \gamma_1 + \gamma_2$$

Three Inverse Primakoff (IP) interactions are:

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



Double-pole Enhancement for IP$_{ion}$

Differential cross section of the ALP IP processes:

$$\frac{d^2\sigma}{dT d\Omega} = \frac{\alpha_{em} g^2_{a\gamma\gamma}}{16\pi} \frac{E_a - T}{v_a E_a} \left(\frac{V_L}{(q^2)^2} \mathscr{R}_L + \boxed{\frac{V_T}{(Q^2)^2}} \mathscr{R}_T \right)$$

$$\mathscr{R}_{L/T} = \sum \overline{\sum} |\langle F | \rho / \vec{j}_\perp | I \rangle|^2 \, \delta (E_I - E_F - T)$$

$$V_L = 2 \left[E_a^2 - m_a^2 + (E_a - T)^2\right] q^2 - (q^2)^2 - (T^2 - 2E_a T + m_a^2)^2 \, ,$$

$$V_T = \boxed{m_a^4} + \frac{Q^2}{2q^2} \left[(m_a^4 - 4m_a^2 E_a T) + (2m_a^2 + 4E_a^2 - 4E_a T + 2T^2) \, Q^2 - (Q^2)^2 \right]$$

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

For regulating the photon pole: $\frac{1}{(Q^2)^2} \to \frac{1}{(Q^2 - \Lambda_T^2/4)^2 + T^2 \Lambda_T^2}$ $\quad \Lambda_T \equiv n_A \sigma_\gamma(T)$

Double-pole Enhancement for IP_{ion}

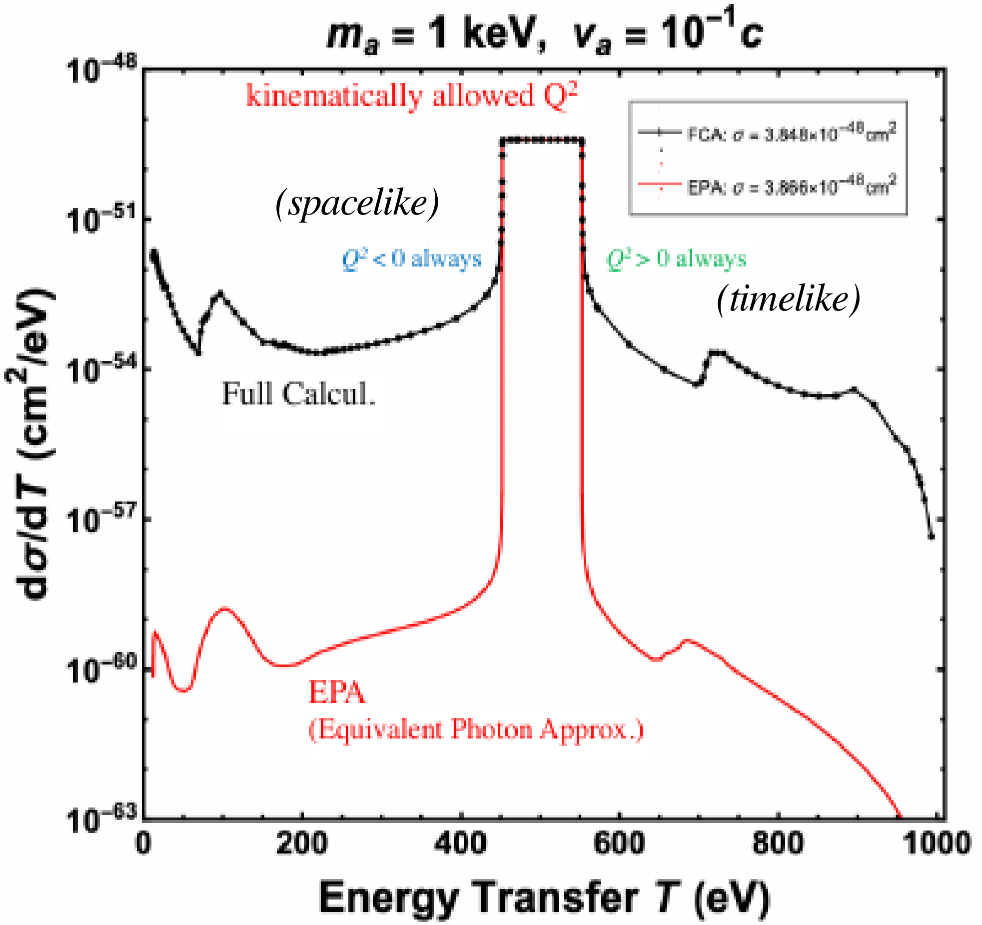
From kinematics:

$$Q^2 = m_a^2 - 2E_a(E_a - T)(1 - v_a \cos\theta)$$

◆ **For Non-Relativistic ALP ($E_a \approx m_a$), IP_{ion} has double pole enhancement near $T \approx m_a/2$**

➢ EPA is a good approximation in $Q^2 = 0$ region

$$\text{EPA}: \ \mathcal{R}_L = 0\,, \ \mathcal{R}_T = \frac{T}{2\pi^2\alpha}\sigma_\gamma(T)$$



Dark Matter ALPs

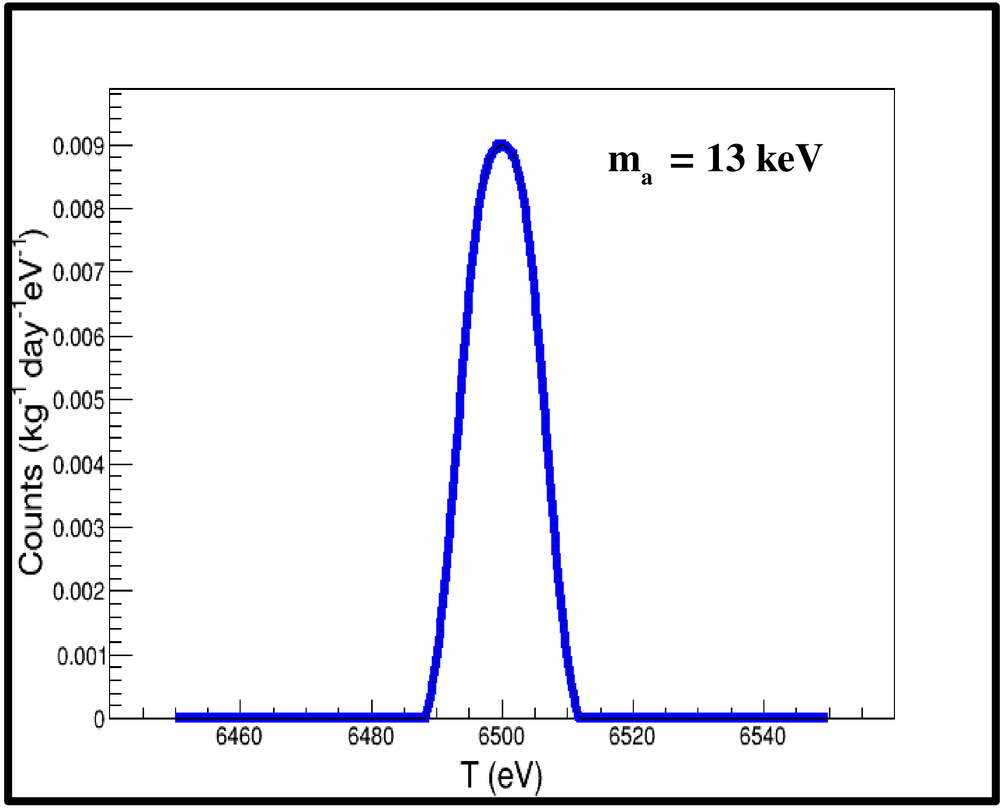
Inverse Primakoff Ionization (IP_{ion})

Differential Cross-section,

$$\left.\frac{d\sigma}{dT}\right|_{EPA} = \frac{g_{a\gamma\gamma}^2}{8}\left[\frac{1}{{E_A}^2 - {M_A}^2}\right]\frac{{M_A}^4}{4\pi n}$$

Vacuum decay rate

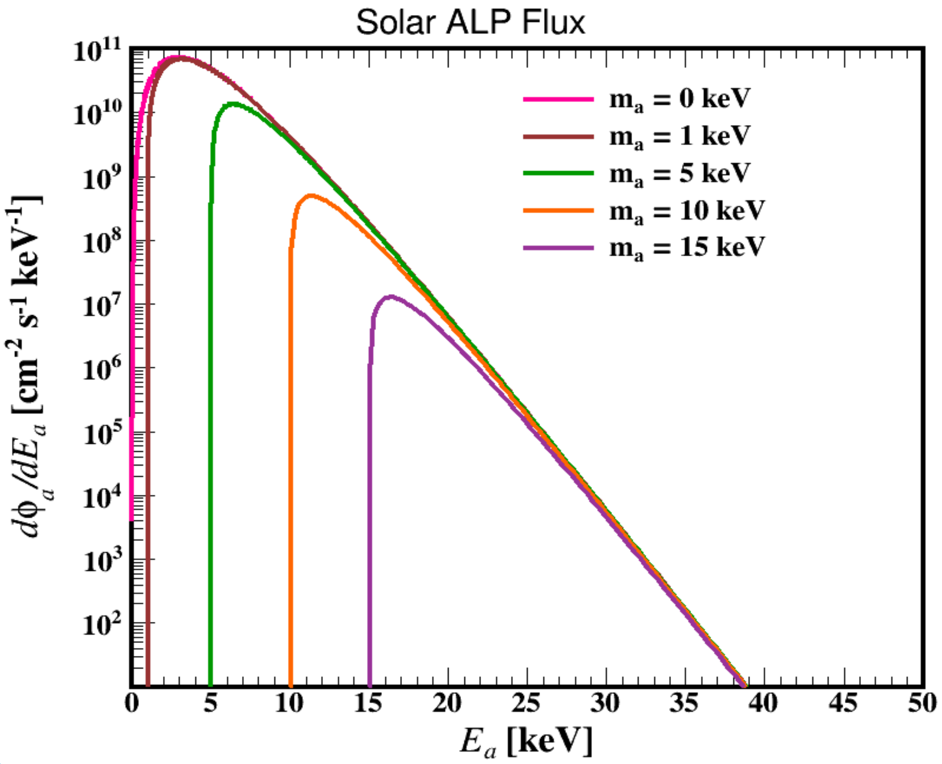
$$\Gamma_{a\gamma\gamma}^{V} = \frac{1}{64\pi} g_{a\gamma\gamma}^2 m_a^3$$



Solar ALPs

- Relatively of low mass - can travel in relativistic speed
- Dominant interaction channel - IP_{el}

Flux of solar axions:



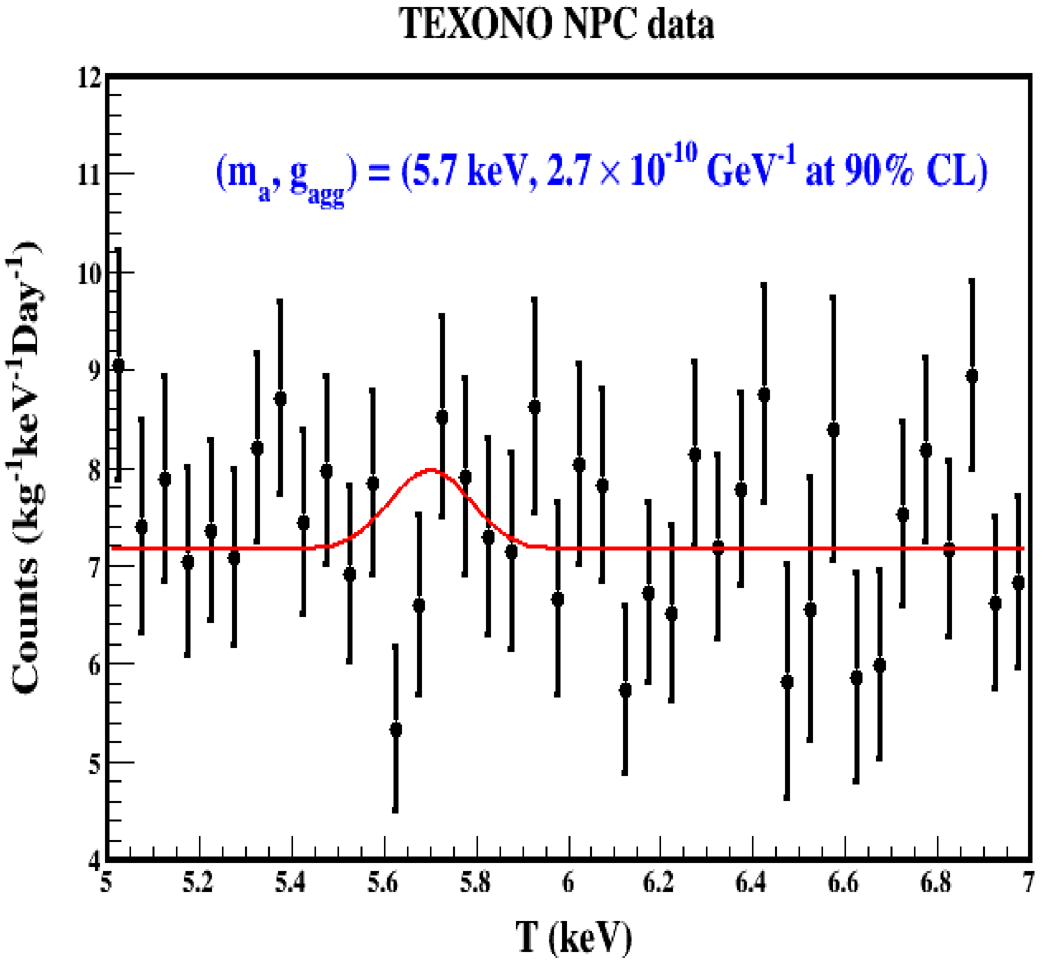
Analysis and Results

TEXONO

(a) Low energy data with point-contact germanium detector at **300 eV** to 12 keV_{ee}

(b) High-Purity Germanium detector data at 12 keV_{ee} to 3000 keV_{ee}
(1.98 keV_{ee} at 1 MeV_{ee})

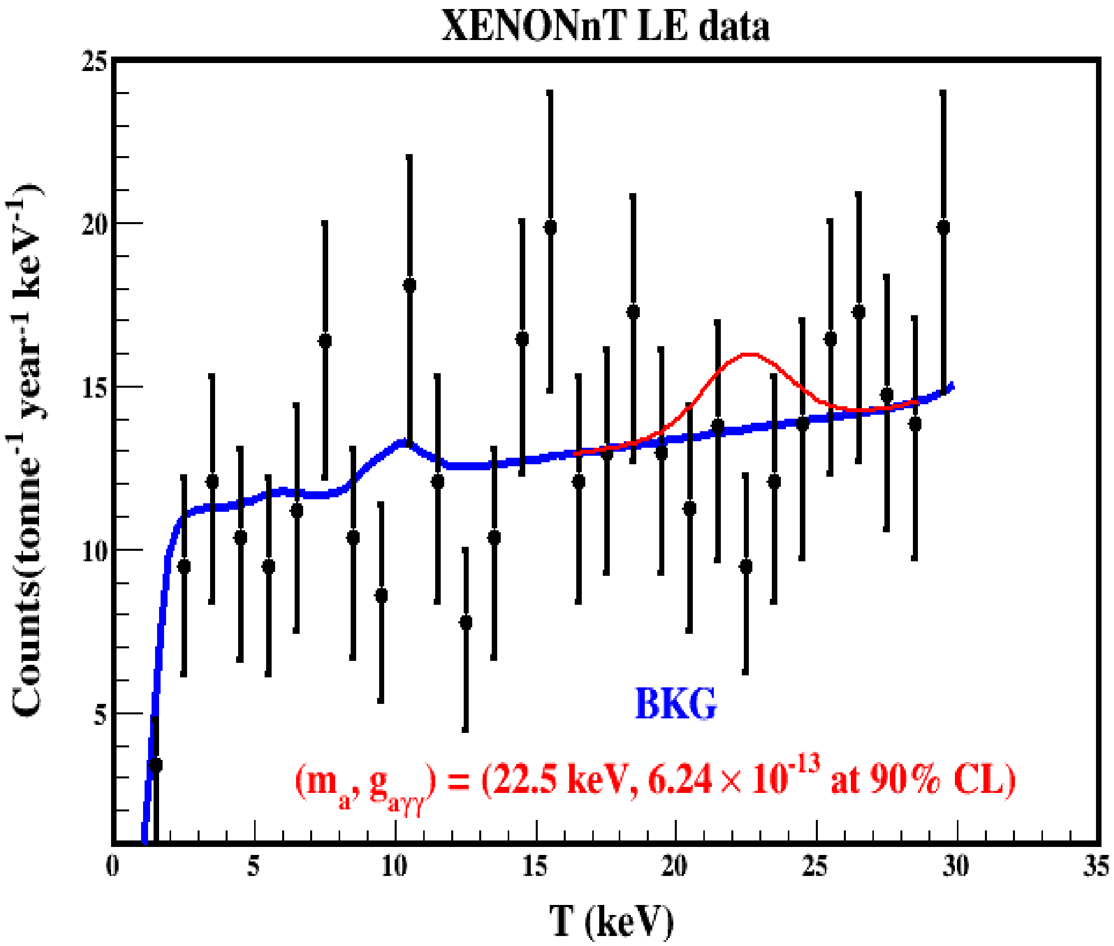
- low threshold & excellent energy resolution



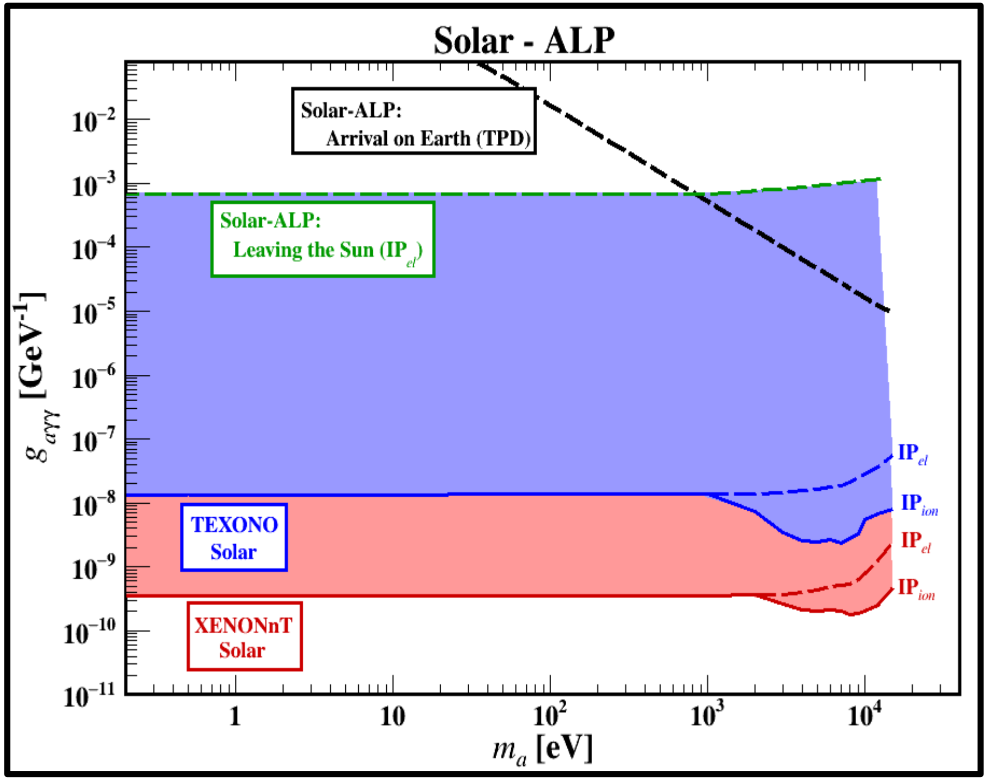
Analysis and Results

XENONnT

XENONnT data with liquid xenon at 1 keV_{ee} to 140 keV_{ee} - **large exposure** while having low threshold and background.

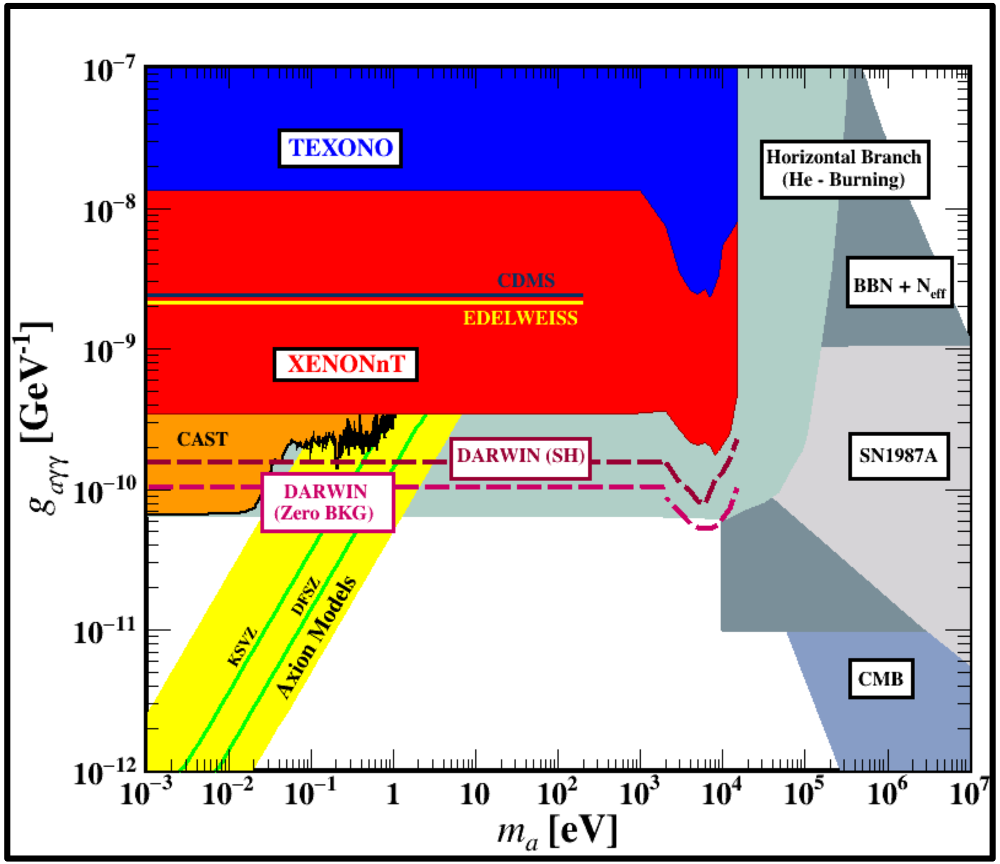


Exclusion Plots – Solar ALP

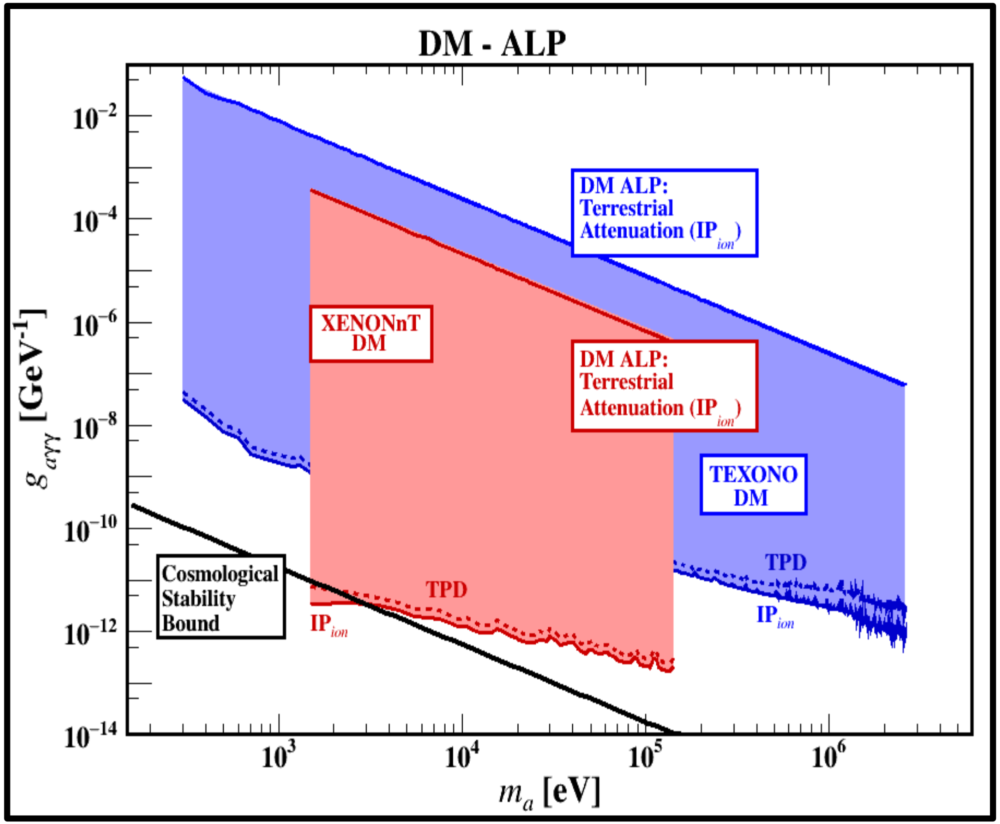


(a)

(b)

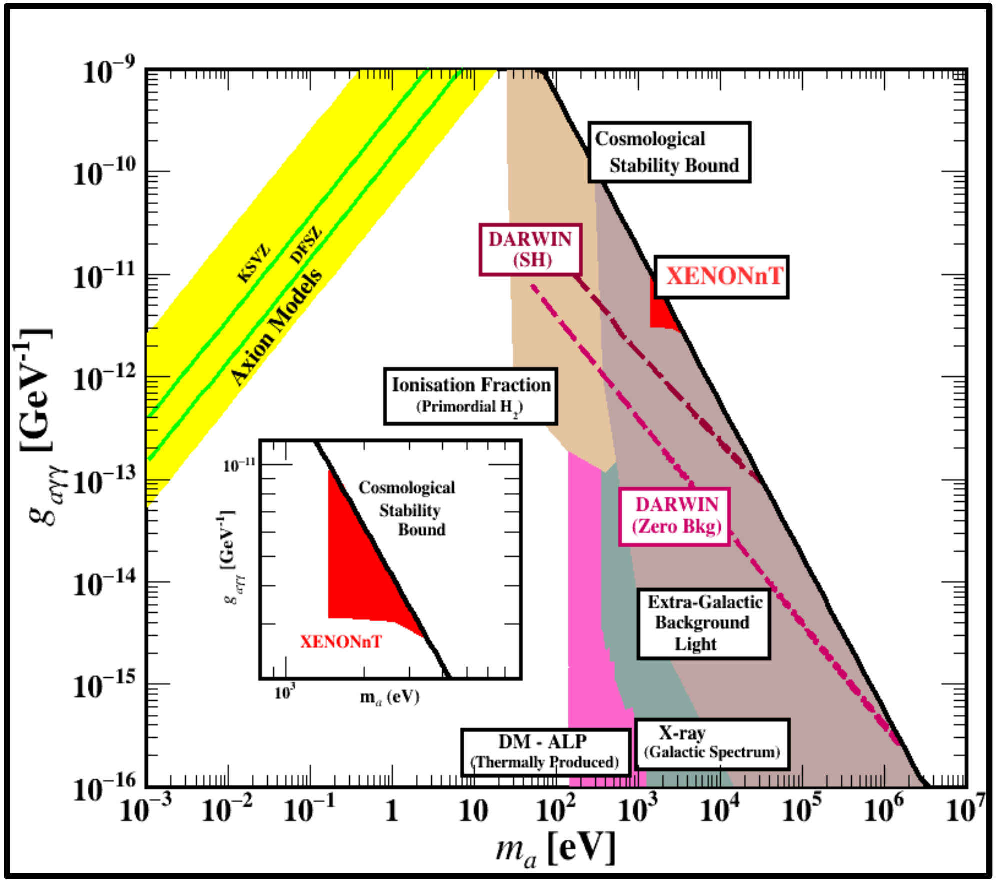


Exclusion Plots – DM ALP

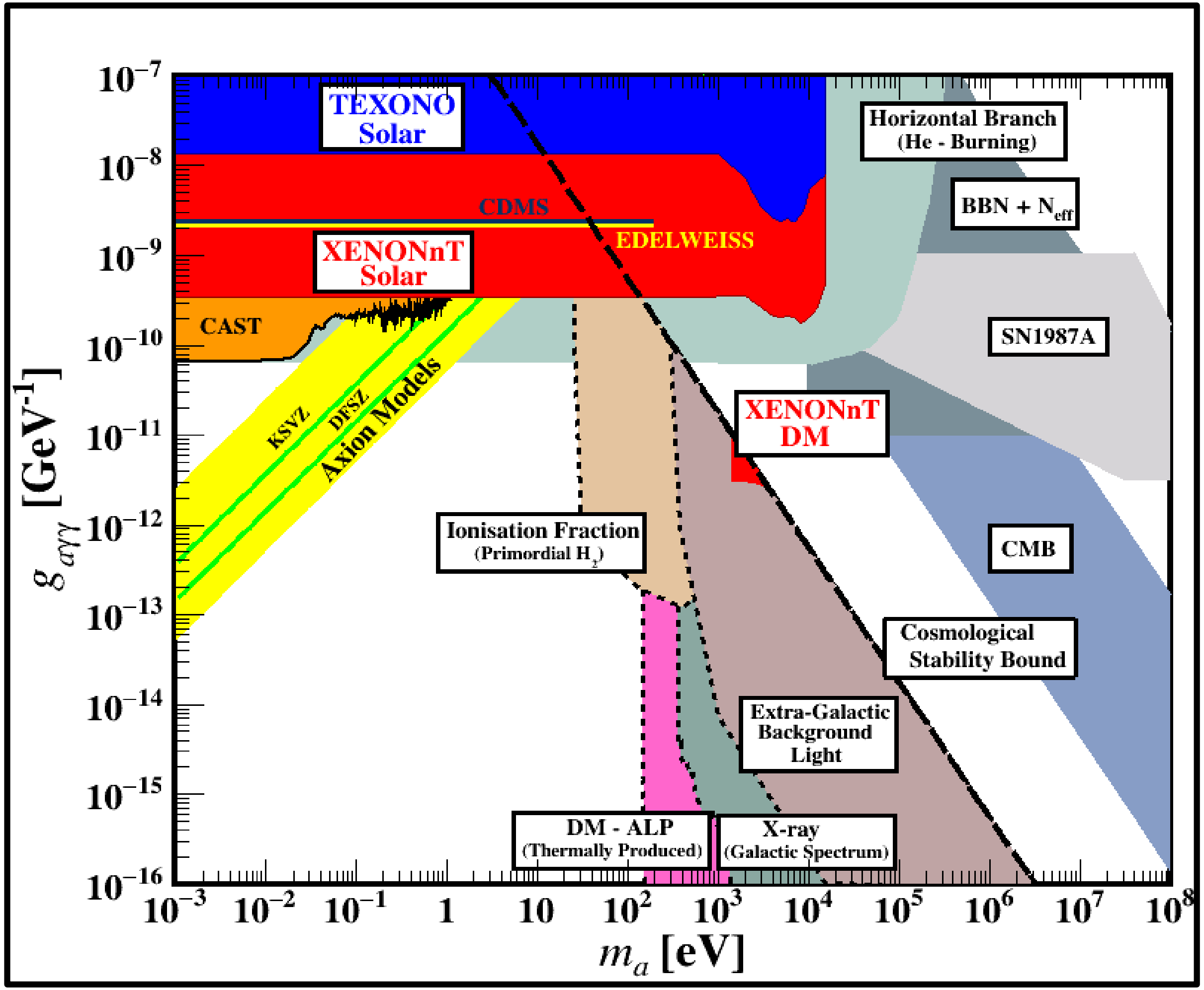


(a)

(b)



Global Exclusion Plot



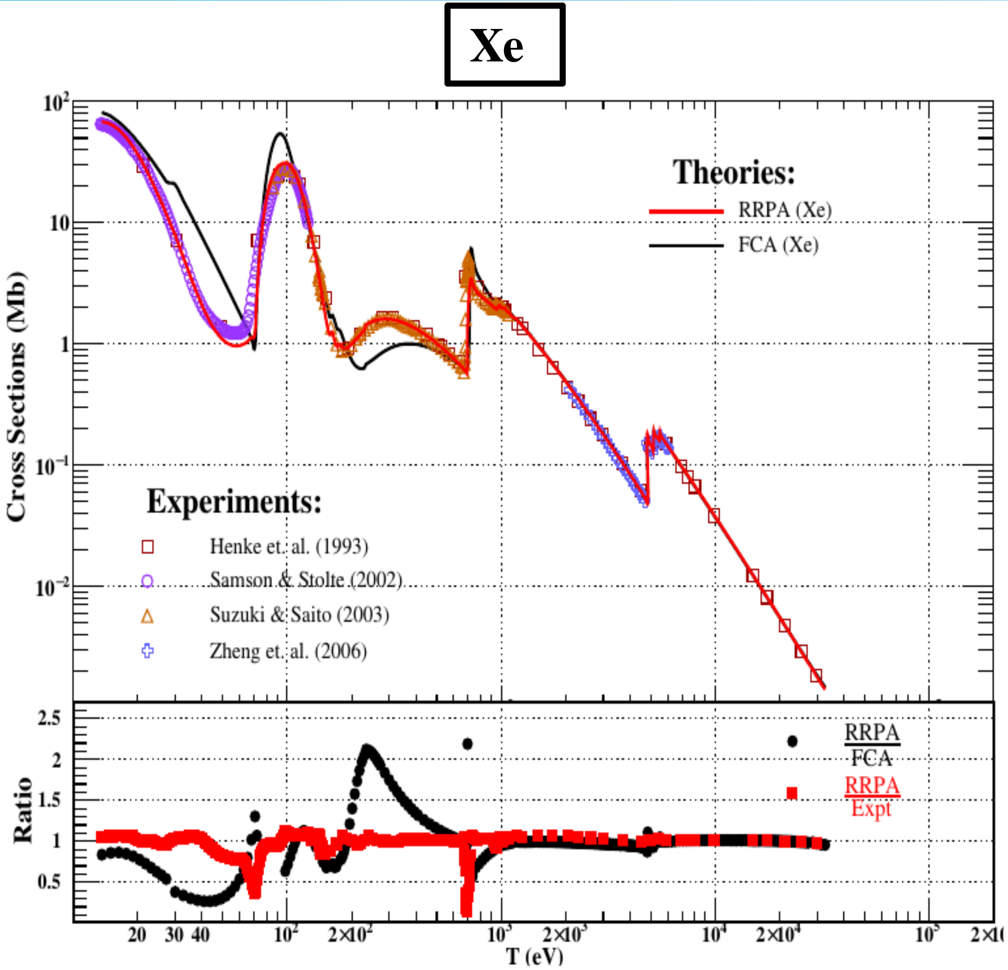
Summary & Future Prospects

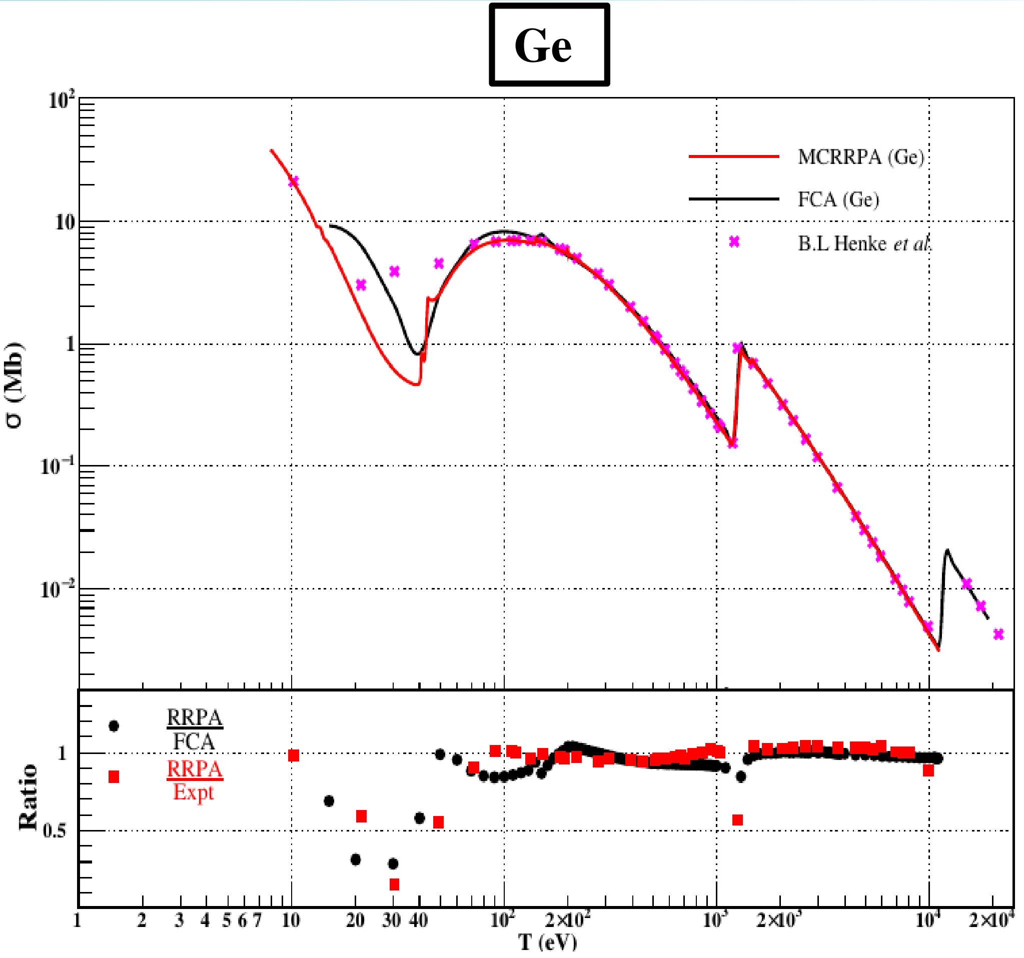
- Identified **new detection channel (IP_{ion})** to probe $g_{a\gamma\gamma}$ for laboratory-based experimental searches.
- Developed **new sophisticated tools (FCA, RRPA, MCRRPA)** for calculating cross-section for many-body systems.
- IP_{ion} channel has **discovery potential** for the search of ALPs.
- New tools are good at calculating cross-section above 80eV within **5% error**.
- Expanded the sensitivities of laboratory experiments in probing the m_a - $g_{a\gamma\gamma}$ parameter space.
- IP_{ion} sensitivities of future projects (**DARWIN**) would exceed the cosmological stability bound for DM-ALPs.
- Comprehensive analysis of ALPs through a **global approach** considering the coupling between ALPs and photons, as well as ALPs and electrons.
- Translating experimental constraints of IP effects of this work to bounds on g_{aee} based on **quantum loop effect**.

Thank You!...

Backup

Photoabsorption cross section





FCA, RRPA & MCRRPA

- **Frozen Core Approximation (FCA)**
  - 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.
- **Relativistic Random Phase Approximation (RRPA)**
  - For many-body systems RPA can be used to account for collective effects that influence the system's response to external perturbations.
- **Multi-Configuration Relativistic Random Phase Approximation (MCRRPA)**
  - 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.