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Direct Detection Constraints on Axion-photon-photon Coupling via Inverse Primakoff Scattering

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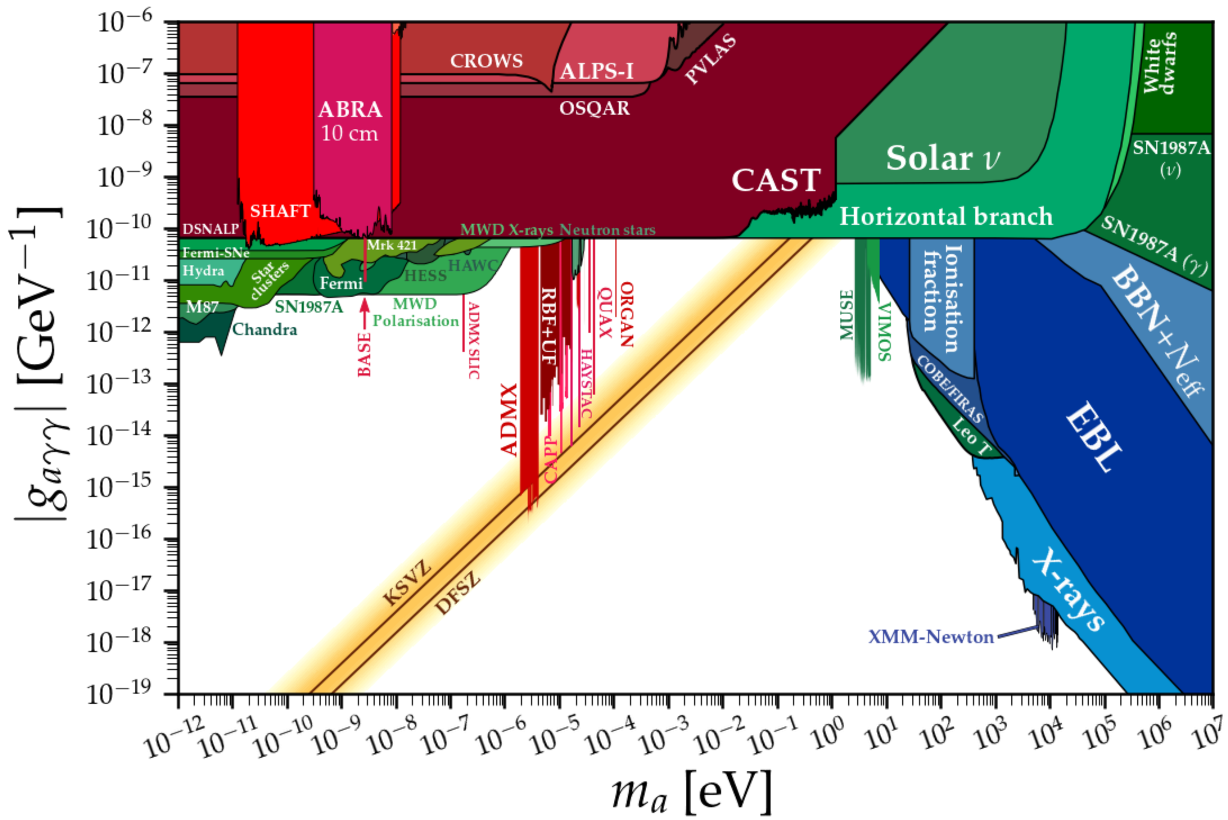
Reference: arXiv: 2206.07878

Portal to New Physics: Axions & ALPs

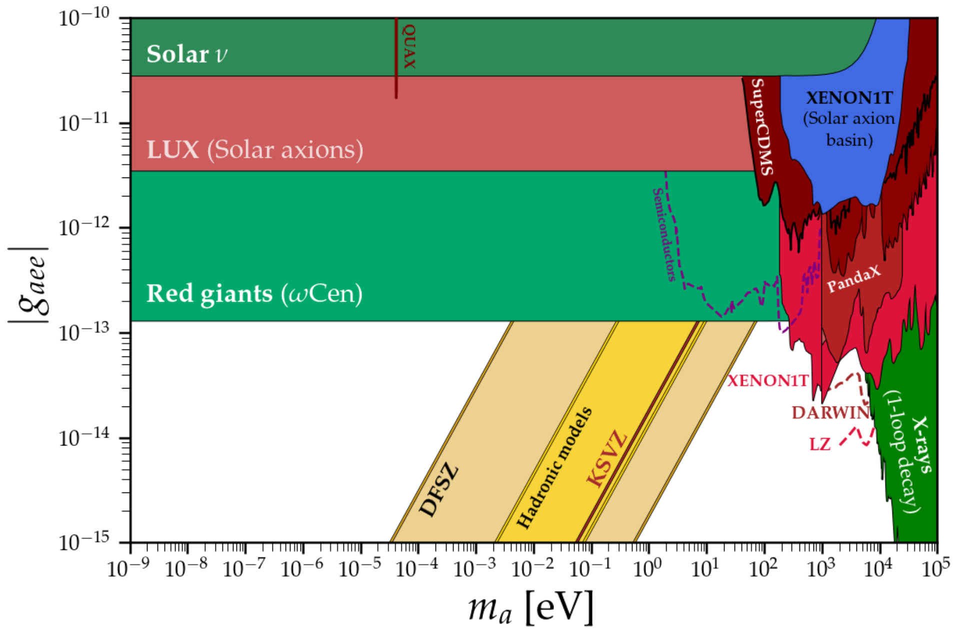
- Physics should be the same for every time, space, and observer.
- Gauge invariant $\longrightarrow$ symmetries $\longrightarrow$ SM gauge theory
- Some phenomena cannot be explained with current SM
  - Strong CP problem
  - The existence of DM
- QCD axion mass $m_a \simeq m_\pi \frac{f_\pi}{f_a}$, coupling $\sim 1/f_a$. Other axions $m_{ALP} \sim \frac{\Lambda^2}{f_a}$ is nearly arbitrary.
- Interaction Lagrangian $\mathcal{L}_I = -\frac{g_{a\gamma\gamma}}{4}\phi_a F_{\mu\nu}\widetilde{F}^{\mu\nu} - \sum_f \frac{g_{aff}}{2m_f}\partial_\mu \phi_a \overline{\Psi}_f(\gamma^\mu\gamma_5)\Psi_f$

Exclusion Plot for $g_{a\gamma\gamma}$



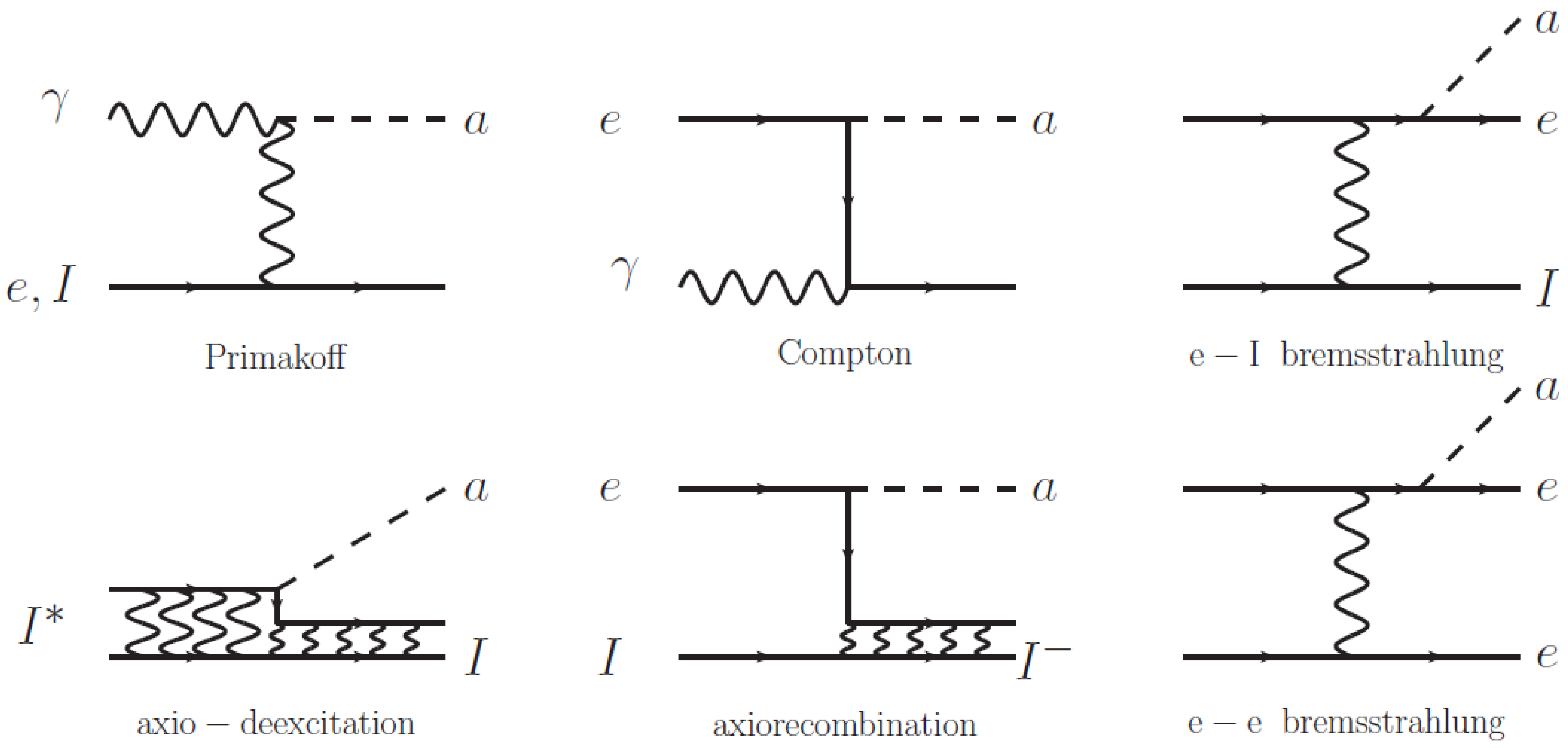
Ciaran O'Hare, doi.org/10.5281/zenodo.3932430

g_{aee} is constrained by DM detectors already!



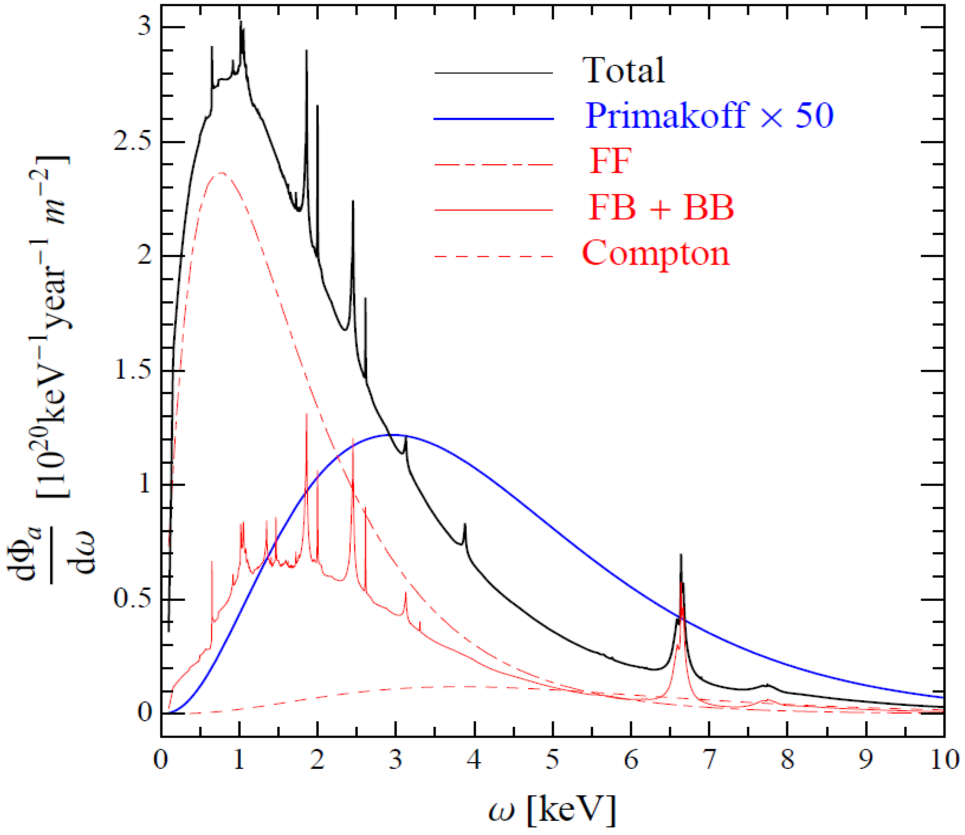
- Haloscopes
- Helioscopes/LSW
- Astro bounds
- Cosmology
- Our proposal: dark matter (DM) detectors

Primakoff and ABC Reaction



Javier Redondo, JCAP **12** (2013) 008, arXiv:1310.0823

Sources of Axions & ALPs – Solar



Solar axion luminosity should fellow stellar energy-loss limits

$$\Phi_a = g_{10}^2\, 3.75 \times 10^{11}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}\,,$$
$$L_a = g_{10}^2\, 1.85 \times 10^{-3} L_\odot\,,$$
$$\langle E \rangle = 4.20\ \mathrm{keV}\,,$$
$$\langle E^2 \rangle = 22.7\ \mathrm{keV}^2\,,$$

Fitting Formula:

$$\frac{d\Phi_a}{dE} = 6.02 \times 10^{10}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{keV}^{-1}\, g_{10}^2\, E^{2.481} e^{-E/1.205}$$

Javier Redondo, JCAP **12** (2013) 008, arXiv:1310.0823.
S. Andriamonje *et al* (CAST Collaboration), JCAP **04** (2007) 010, arXiv:hep-ex/0702006.

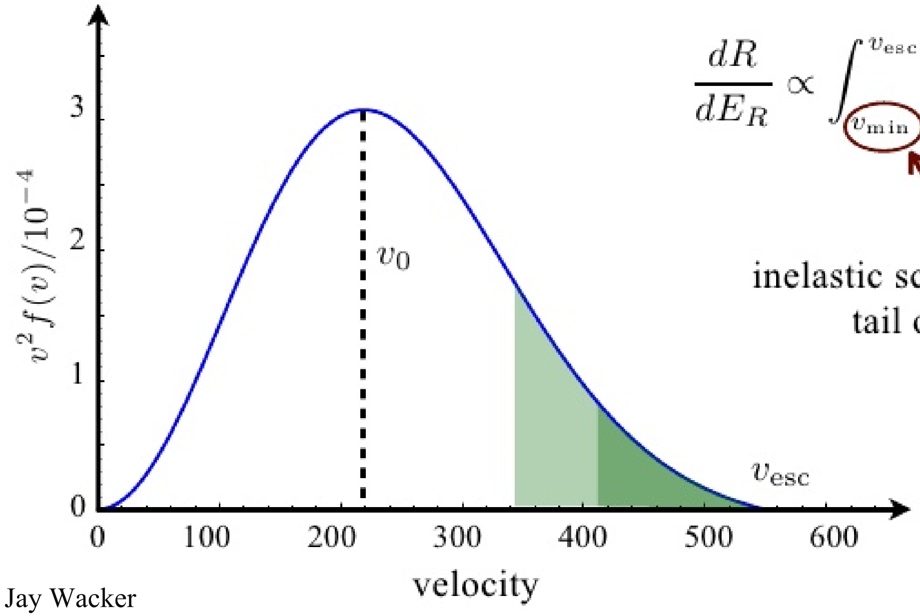
Sources of Axions & ALPs – Dark Matters

Standard Halo Model

Scattering rate depends on halo profile

$$\frac{dR}{dE_R} \propto \int_{v_{\min}}^{v_{\rm esc}} d^3v\, f(v)\, v \frac{d\sigma}{dE_R}$$

inelastic scattering sensitive to tail of distribution



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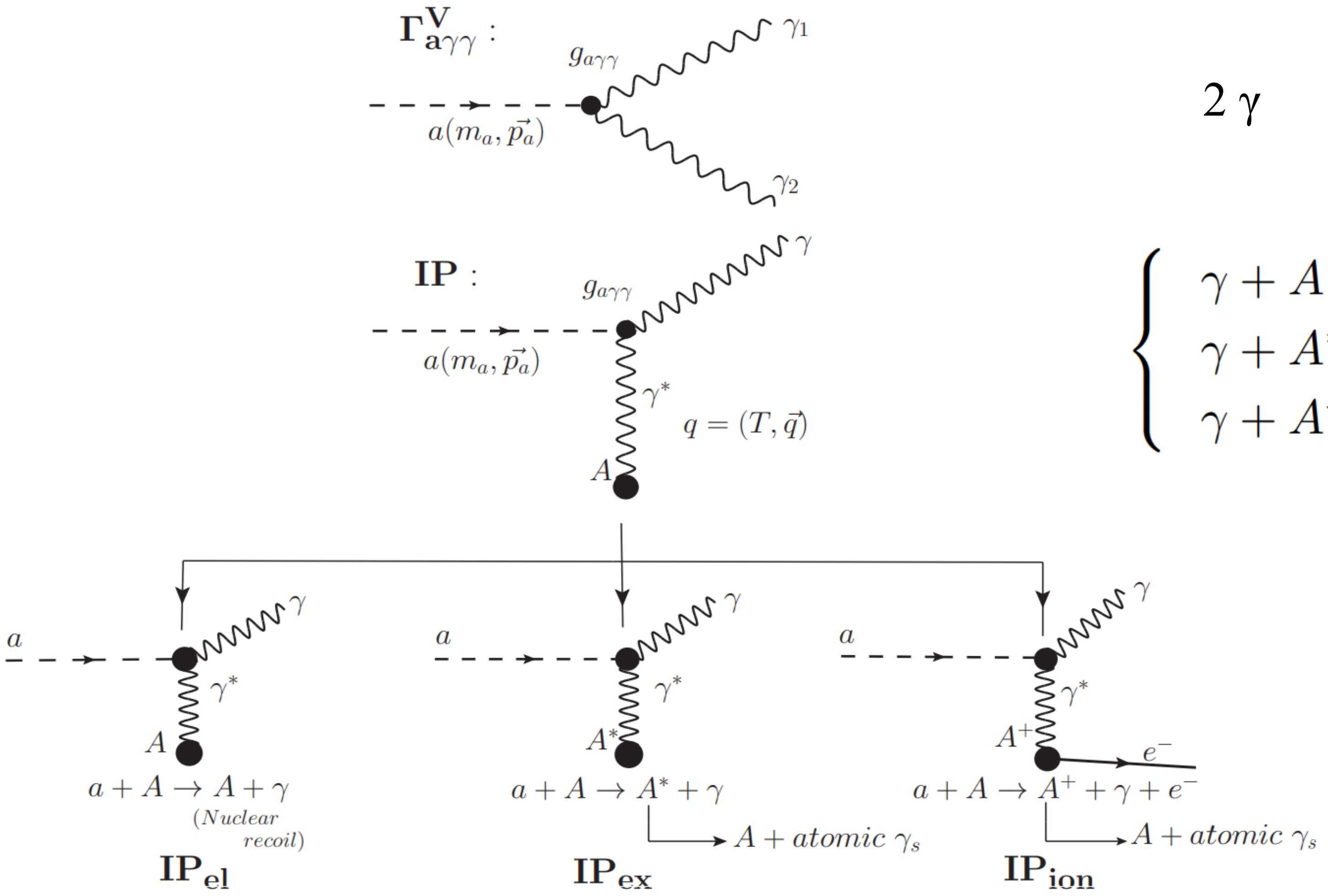
$$\frac{dR}{dT} = \frac{\rho_\chi N_T}{m_\chi} \frac{d\langle \sigma v_\chi \rangle}{dT}$$

$$\frac{d\langle \sigma v_\chi \rangle}{dT} = \int_{v_{\min}}^{v_{\max}} d^3 v_\chi f(\vec{v}_\chi) v_\chi \frac{d\sigma}{dT}$$

$$f(\vec{v}_\chi) = \frac{1}{K} e^{-\frac{|\vec{v}_\chi + \vec{v}_E|^2}{v_0^2}} \Theta(v_{\rm esc} - |\vec{v}_\chi + \vec{v}_E|)$$

v_0 = 220 km/s ~ 10^{-3} c
v_E = 232 km/s
v_{esc} = 544 km/s

2γ Decay v.s. Inverse Primakoff (IP)



2 γ

$$\Gamma^{V}_{a\gamma\gamma} = \frac{1}{64\pi} g^2_{a\gamma\gamma} m_a^3$$

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

$$\mathcal{L}_I = -\frac{g_{a\gamma\gamma}}{4} \phi_a F_{\mu\nu} \widetilde{F}^{\mu\nu}$$

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

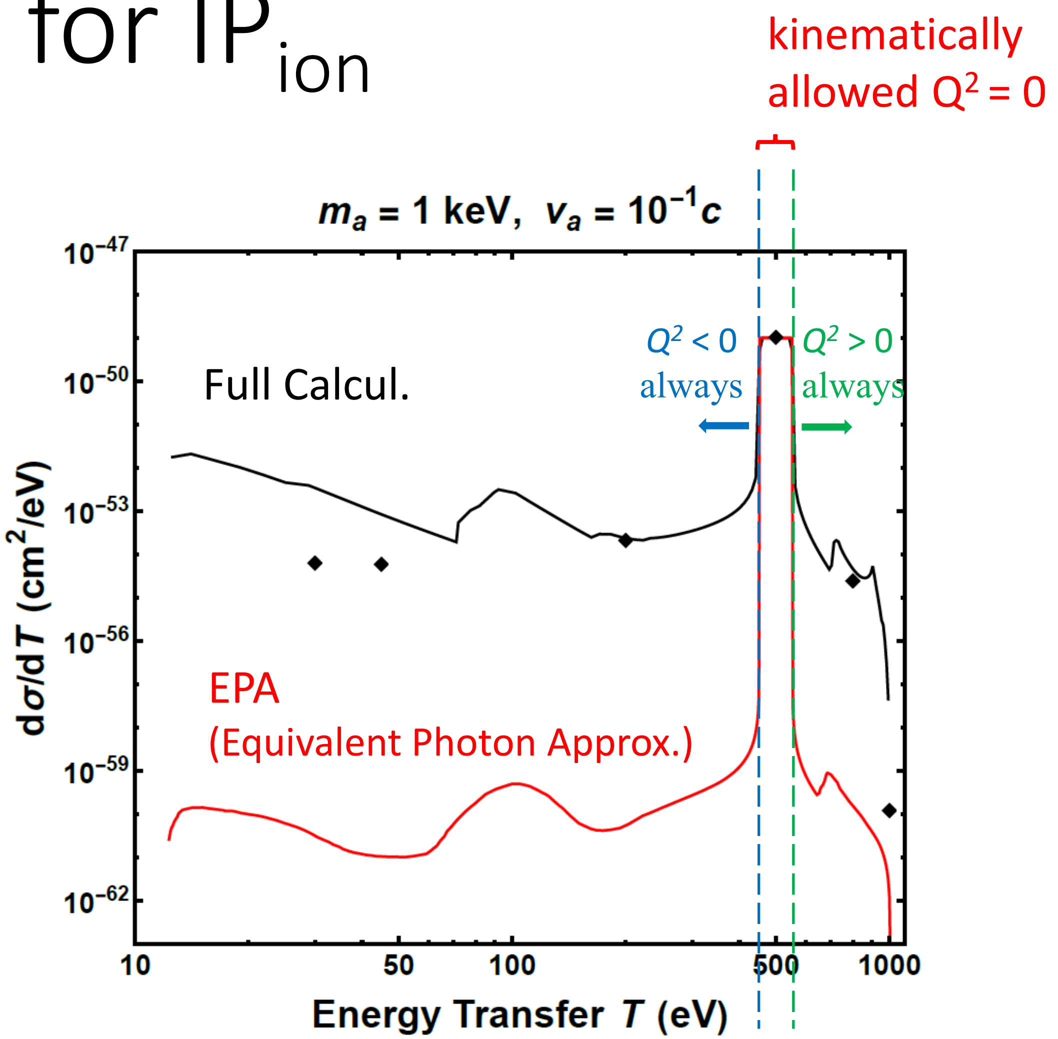
$$\frac{d^2\sigma}{dT\,d\Omega} = \frac{\alpha_{em} g_{a\gamma\gamma}^2}{16\pi}\,\frac{E_a - T}{v_a E_a}\left(\frac{V_L}{(q^2)^2}\mathscr{R}_L + \frac{V_T}{(Q^2)^2}\mathscr{R}_T\right)$$

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

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

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

$$\frac{1}{(Q^2)^2} \to \frac{1}{(Q^2 - \Lambda_T^2/4)^2 + T^2\Lambda_T^2} \qquad \Lambda_T \equiv n_A \sigma_\gamma(T)$$

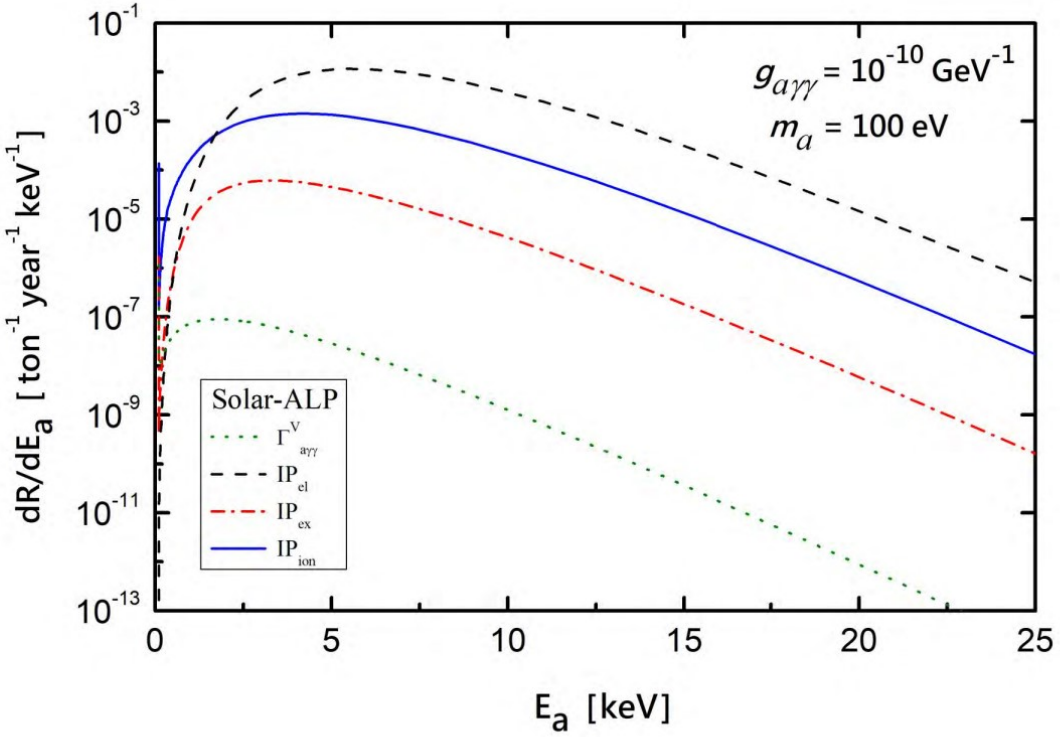


$$\mathrm{EPA}:\ \mathcal{R}_L = 0\,,\ \mathcal{R}_T = \frac{T}{2\pi^2\alpha}\,\sigma_\gamma(T)$$

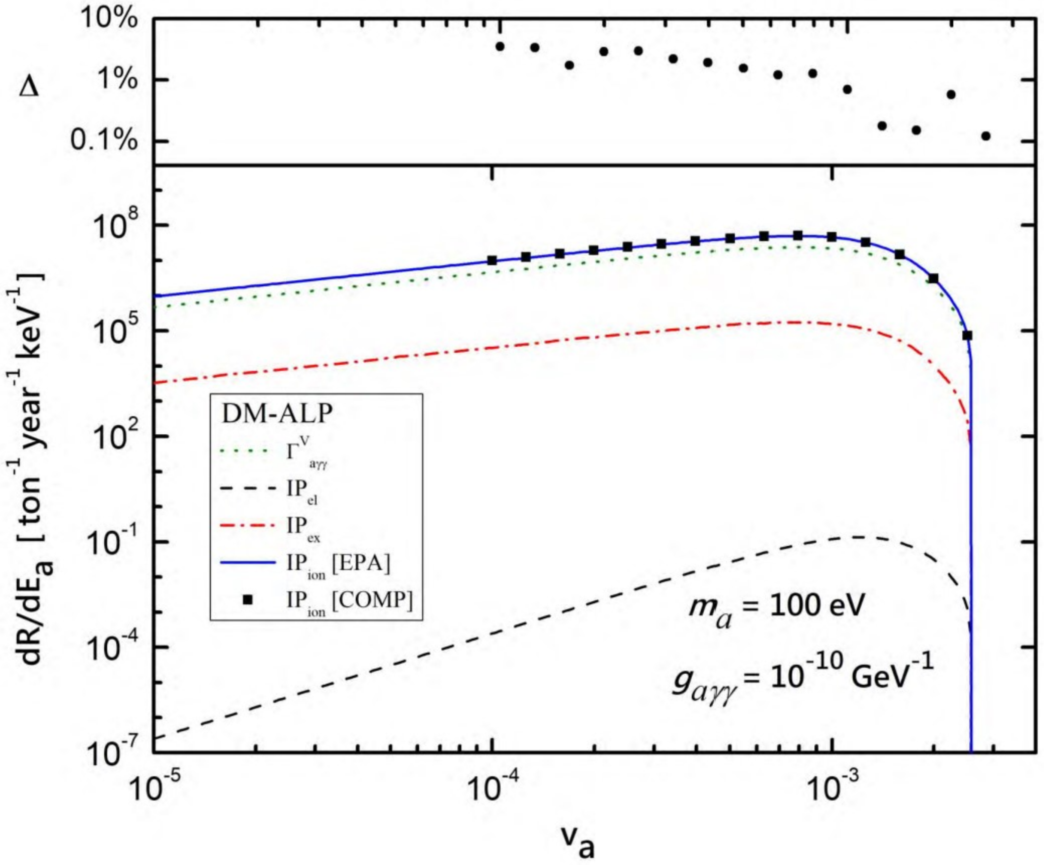
Differential Event Rates

$$\frac{dR}{dE_a} \propto \sigma \frac{d\phi}{dE_a} \equiv \Gamma \frac{dn}{dE_a}$$

Solar, relativistic



DM, non-relativistic



Expected Event Rates

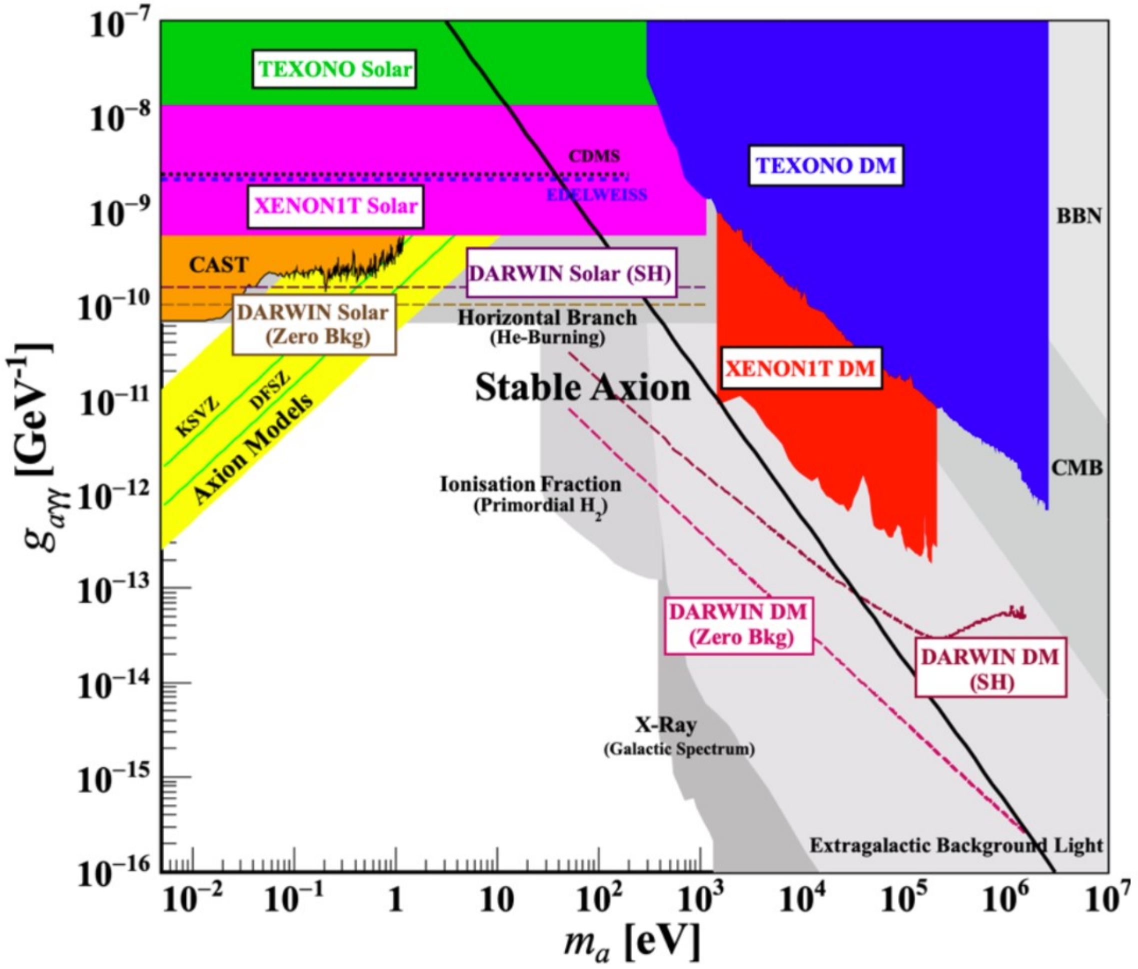
		Event Rates ($ton^{-1}year^{-1}$)		
		Detection Channels		
m_a	$\Gamma^V_{a\gamma\gamma}$	IP_{el}	IP_{ex}	IP_{ion}
		DM-ALP		
1 eV	2.5×10^{-4}	$\mathcal{O}(10^{-14})$	0	0
1 keV	250	1.7×10^{-5}	1.6×10^{-3}	500
1 MeV	2.5×10^{8}	9.9×10^{-5}	2.2×10^{-10}	5.0×10^{8}
		solar-ALP		
1 meV	$\mathcal{O}(10^{-27})$	7.0×10^{-2}	2.9×10^{-4}	8.1×10^{-3}
1 eV	$\mathcal{O}(10^{-15})$	7.0×10^{-2}	2.9×10^{-4}	8.1×10^{-3}
1 keV	3.9×10^{-3}	7.0×10^{-2}	2.9×10^{-4}	1.6×10^{-2}

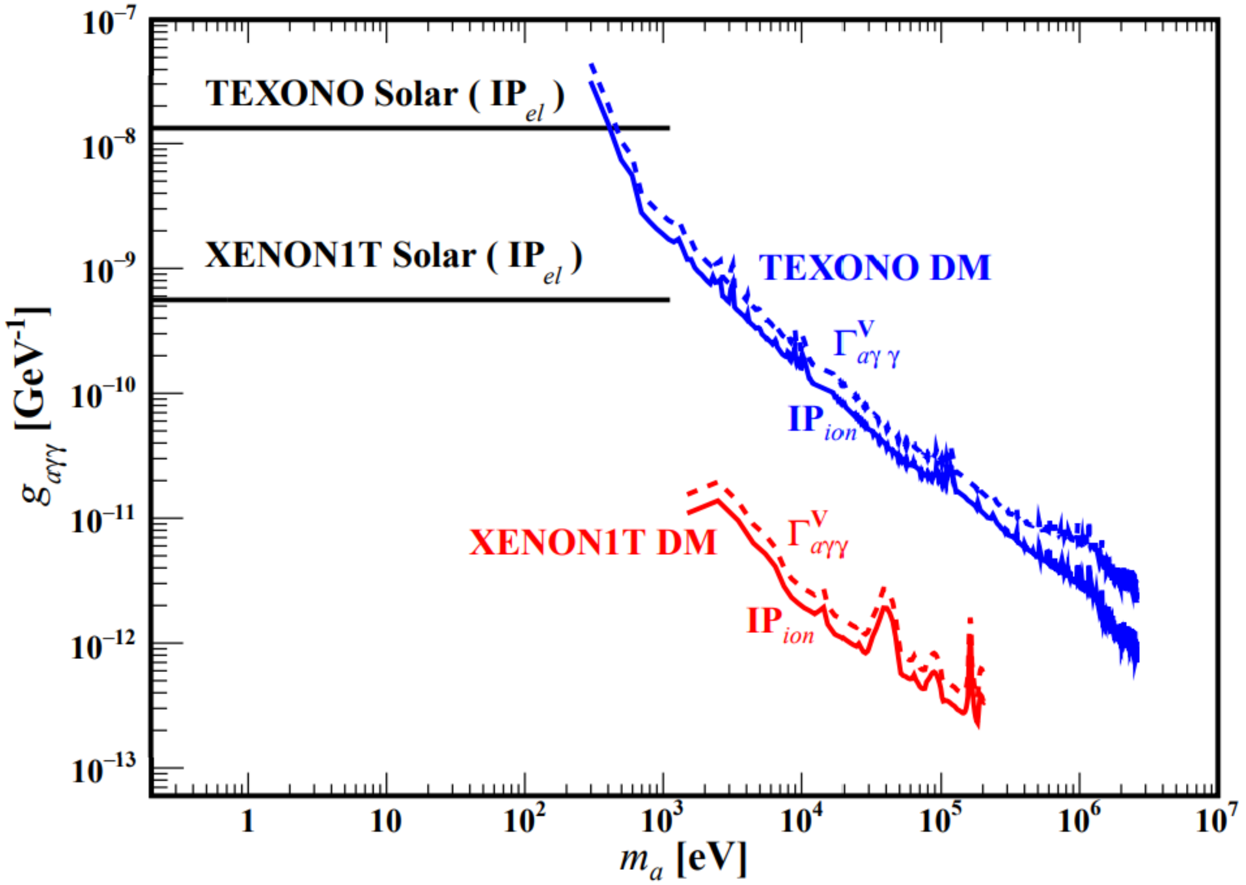
$g_{a\gamma\gamma} = 10^{-10}\,\mathrm{GeV}^{-1}$

DM-ALP: $R \propto g^2_{a\gamma\gamma}$

solar-ALP: $R \propto g^4_{a\gamma\gamma}$

New Limits on Exclusion Plot





Summary

- Axions and ALPs are well-motivated “portals” to new physics, and their laboratory (direct) constraints can be expanded and improved with current (& future) DM detectors.
- We advance further in this work by systematically studying the 3 inverse-Primakoff (IP) channels via well-benchmarked atomic many-body calculations, and comparing with 2γ-decay process to constrain axion-photon-photon coupling.

Reference:

C.-P. Wu *et al.*, arXiv:2206.07878 [hep-ph].

Jiunn-Wei Chen *et al.*, Phys. Rev. D 93, 093012 (2016), arXiv:1601.07257 [hep-ph].

Thanks for your attention!

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Equivalent Photon Approx. (EPA)

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

$$\left[\frac{d\sigma}{dT}\right]^{\text{IP}_{ion}}_{\text{EPA}} = \frac{g^2_{a\gamma\gamma}}{32\pi^2}\frac{\sigma_\gamma}{\Lambda_T}\frac{m_a^4}{v_a^2 E_a^2}\tan^{-1}\left[\frac{Q^2-\Lambda_T^2/4}{T\Lambda_T}\right]\Bigg|^{Q^2_{\max}}_{Q^2_{\min}}$$

$$R^{\text{IP}_{ion}}_{\text{EPA}} = n_A v_a \sigma^{\text{IP}_{ion}}_{\text{EPA}} = \frac{g^2_{a\gamma\gamma} m_a^3}{32\pi}\frac{m_a}{E_a} = \frac{2}{\gamma}\Gamma^V_{a\gamma\gamma}$$

- Cross sections depend on the target
- Rates are independent on the target