XIX Mexican Workshop on Particles and Fields 2025

Cinvestav

Searching for Axion-like particles with short-baseline reactor neutrino experiments

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Introduction

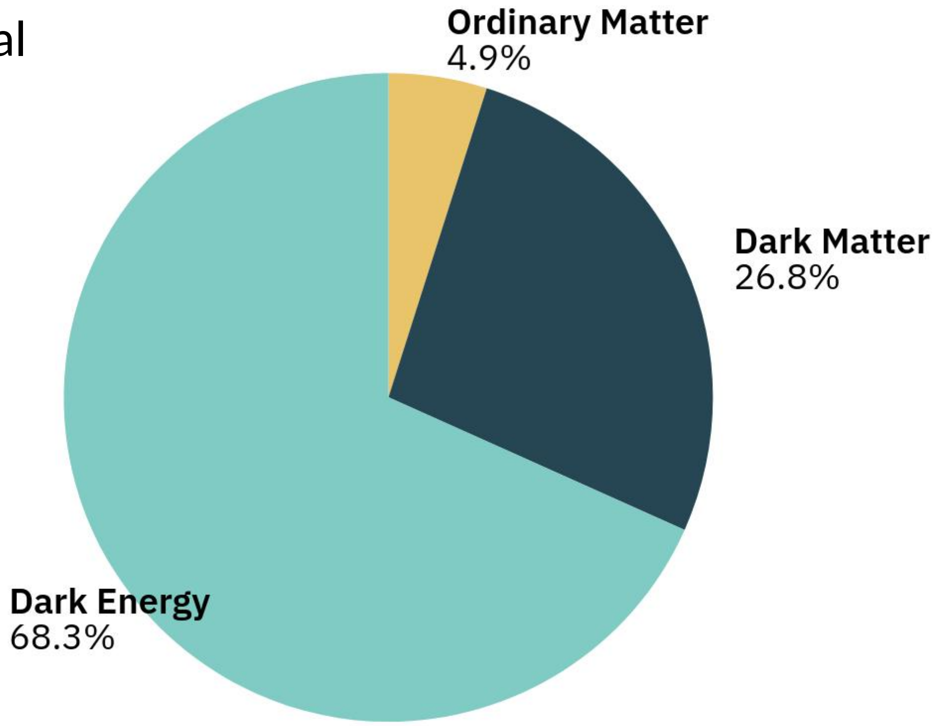
Particles beyond the Standard Model

The Standard Model describes all visible matter, but this only accounts for ~5% of the universe.

- This "dark sector" implies a fundamental problem:

  - Is our theory of particles incomplete?

- **Key Question:** What is Dark Matter made of?
- **Some Candidates:** WIMPs, Sterile Neutrinos, Axions, and Axion-like particles.

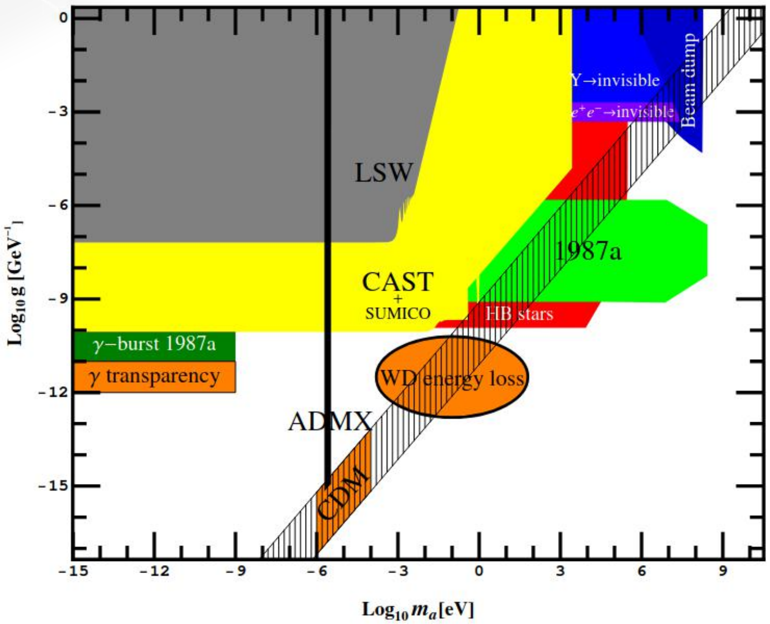


Axion-Like Particles (ALPs)

ALPs are pseudoscalar Nambu-Goldstone bosons from the spontaneous breaking of a global U(1) symmetry.

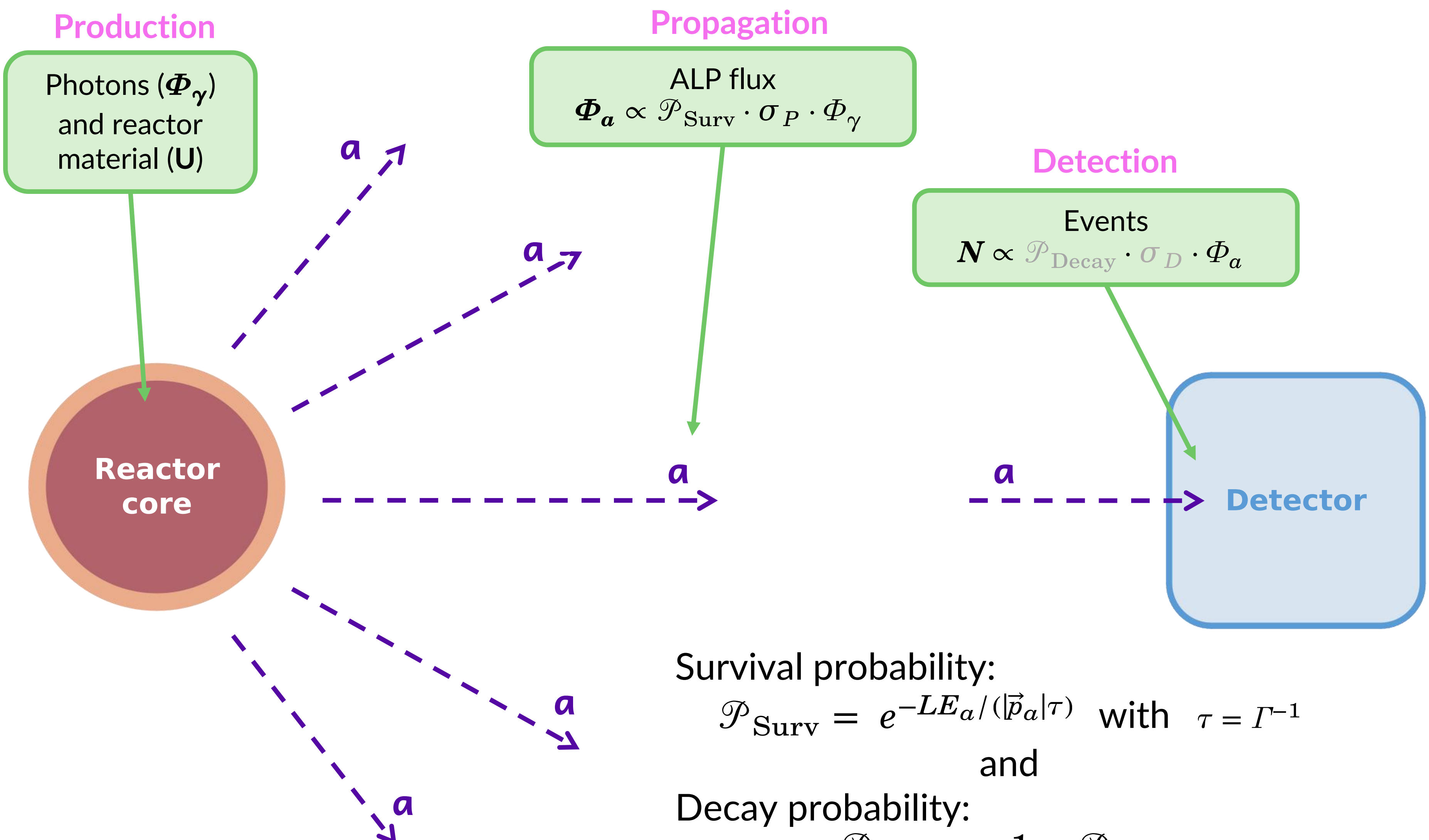
- Well-motivated by the QCD Axion, the leading solution to the Strong CP Problem.
- A compelling cold dark matter candidate.
- Arise naturally in many Beyond the Standard Model (BSM) theories, such as string theory.

Unlike the QCD Axion, ALP mass (m_a) and couplings (e.g., $g_{a\gamma\gamma}$) are independent parameters.



J Jaeckel and A. Ringwald, Ann.Rev.Nucl.Part.Sci. 60 (2010) 405-437

ALPs production at reactors and detection processes



Survival probability:

$$\mathscr{P}_{\text{Surv}} = e^{-LE_a/(|\vec{p}_a|\tau)} \quad \text{with} \quad \tau = \Gamma^{-1}$$

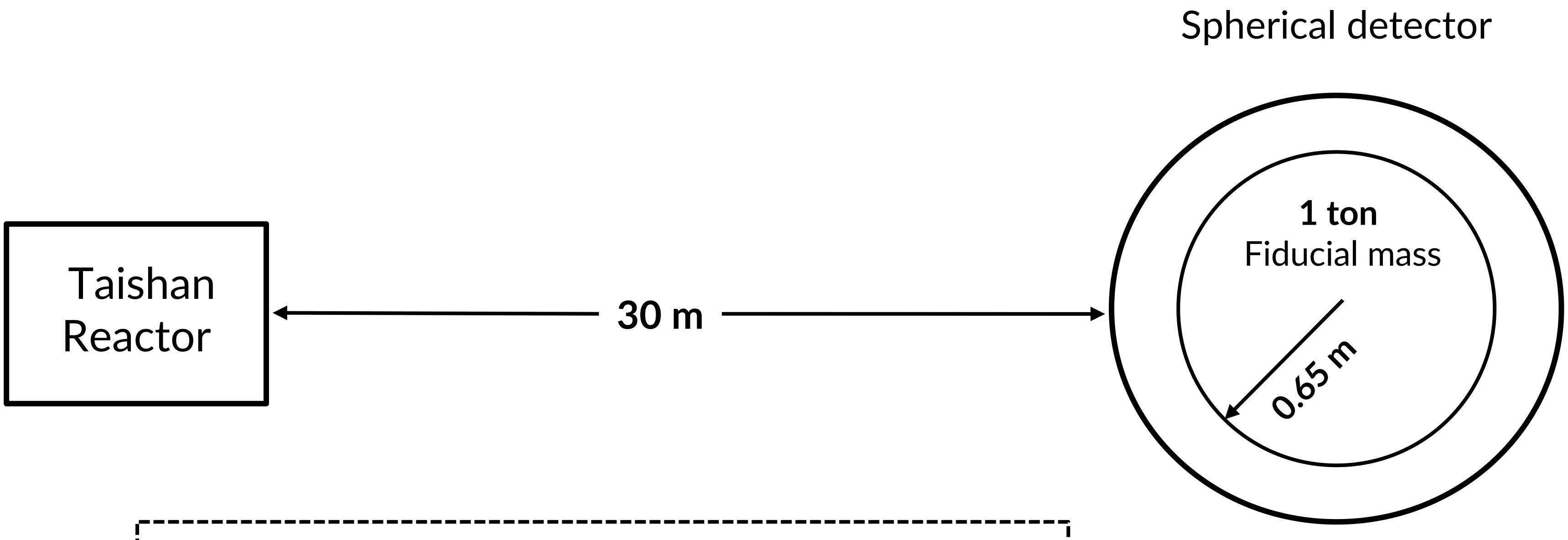
and

Decay probability:

$$\mathscr{P}_{\text{Decay}} = 1 - \mathscr{P}_{\text{Surv}}$$

JUNO-TAO like experiment

The Taishan Antineutrino Observatory (TAO) $\longrightarrow$ Satellite experiment of the Jiangmen Underground Neutrino Observatory (JUNO).



Principal background:
Singles from radioactivity ~ 3×10^9 events/year

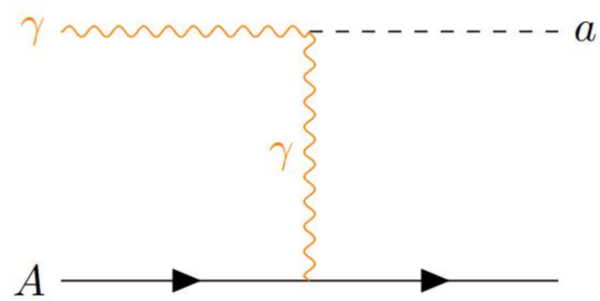
Gadolinium doped liquid scintillator (LAB - Linear Alkylbenzene)

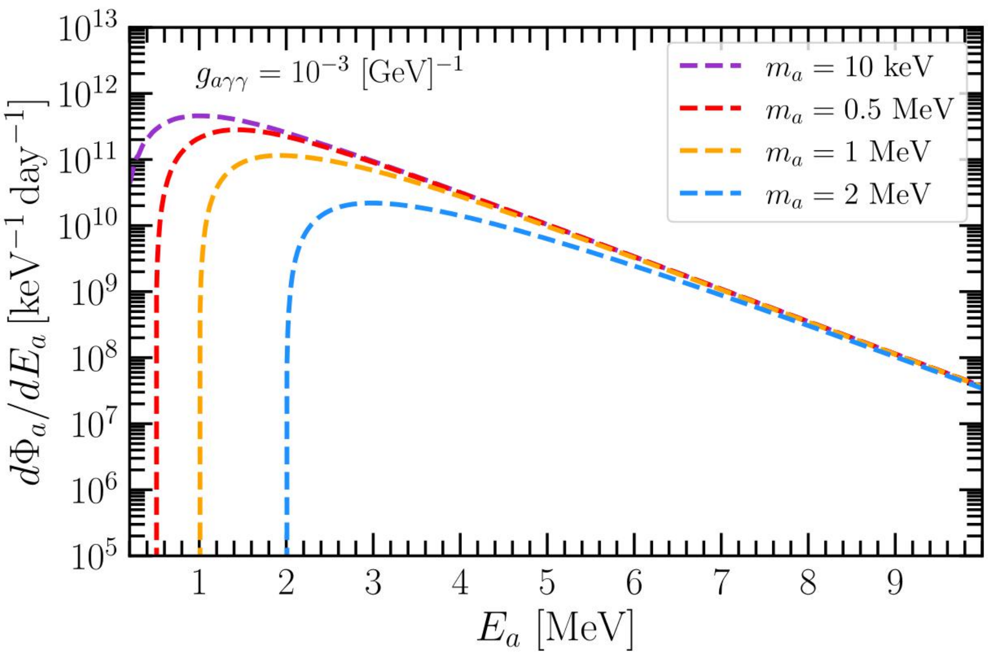
JUNO Collaboration, arXiv:2005.08745 (2020)

Production and detection through ALP-photon coupling

Production through $g_{a\gamma\gamma}$ couplings

Primakoff photon-ALP conversion





Resulting ALP Flux:

$$\frac{d\Phi_a^P}{dE_a} = \mathscr{P}_{\text{Surv}} \frac{\sigma_P^P}{\sigma_{\text{Tot}}} \frac{d\Phi_\gamma}{dE_\gamma}\bigg|_{E_\gamma = E_a}$$

(Survival probability) x (Production Probability) x (Initial Photon Flux)

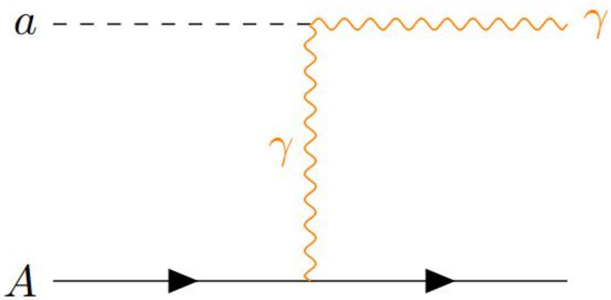
where $\sigma_{\text{Tot}} = \sigma_{\text{SM}} + \sigma_a^P$

ALP decay width (determine lifetime $\tau = \Gamma^{-1}$) :

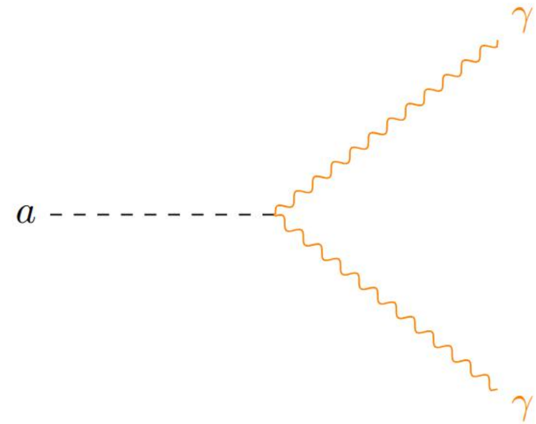
$$\boxed{\Gamma(a \to \gamma\gamma) = g_{a\gamma\gamma}^2 \frac{m_a^3}{64\pi}}$$

Detection through $g_{a\gamma\gamma}$ couplings

Inverse Primakoff



Decay into a γ-pair



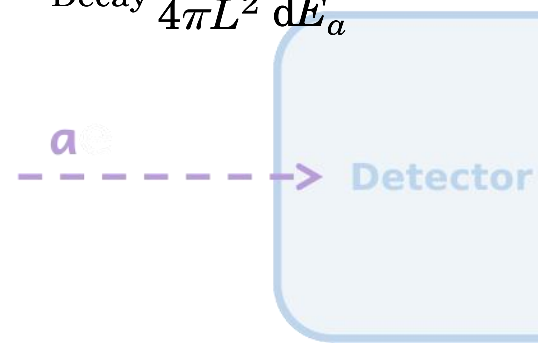
Event Rate from ALP Conversion

$$\left(\frac{\mathrm{d}N}{\mathrm{d}E_a}\right)_{IP} = \frac{m_{\mathrm{det}}}{2\pi L^2} N_A \sigma_D^P(E_a) \frac{\mathrm{d}\Phi_a^P}{\mathrm{d}E_a}$$

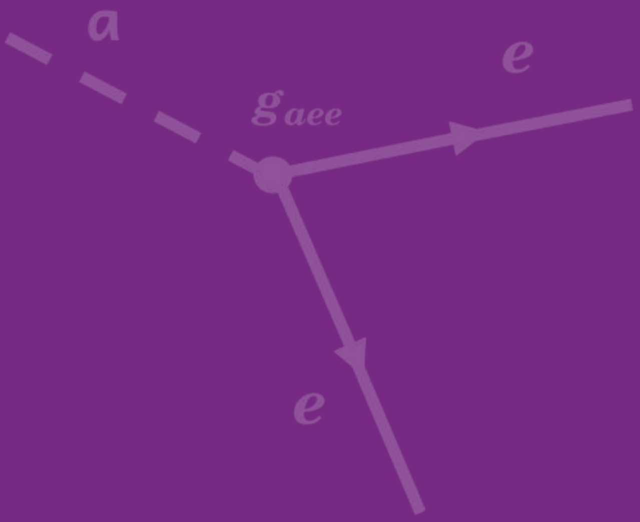
Event Rate from ALP Decay

$$\left(\frac{\mathrm{d}N}{\mathrm{d}E_a}\right)_{\mathrm{Decay}} = \mathscr{P}_{\mathrm{Decay}} \frac{A}{4\pi L^2} \frac{\mathrm{d}\Phi_a^P}{\mathrm{d}E_a}$$

$$\boxed{\left(\frac{\mathrm{d}N}{\mathrm{d}E_a}\right)_{\mathrm{Total}} = \left(\frac{\mathrm{d}N}{\mathrm{d}E_a}\right)_{IP} + \left(\frac{\mathrm{d}N}{\mathrm{d}E_a}\right)_{Decay}}$$

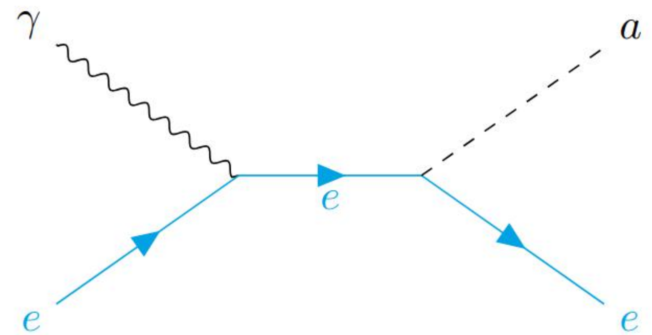


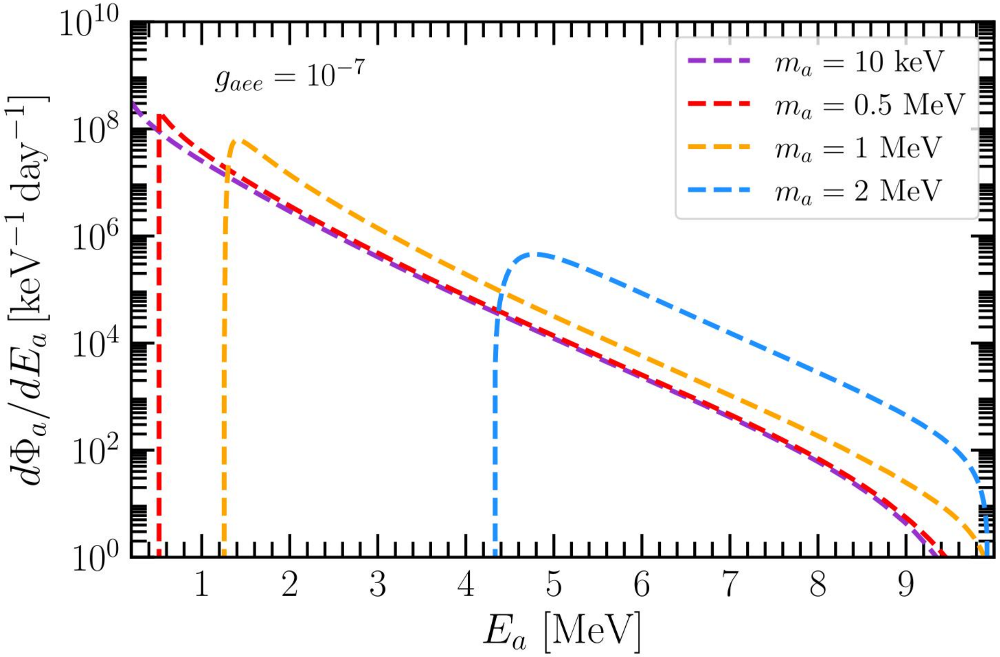
Production and detection through ALP-electron coupling



Production through $\mathbf{g_{aee}}$ couplings

Compton-like scattering





Resulting ALP Flux:

$$\frac{\mathrm{d}\Phi_a^C}{\mathrm{d}E_a} = \mathscr{P}_{\text{Surv}} \int \frac{1}{\sigma_{\text{Tot}}} \frac{\mathrm{d}\sigma_P^C}{\mathrm{d}E_a} \frac{\mathrm{d}\Phi_\gamma}{\mathrm{d}E_\gamma} dE_\gamma$$

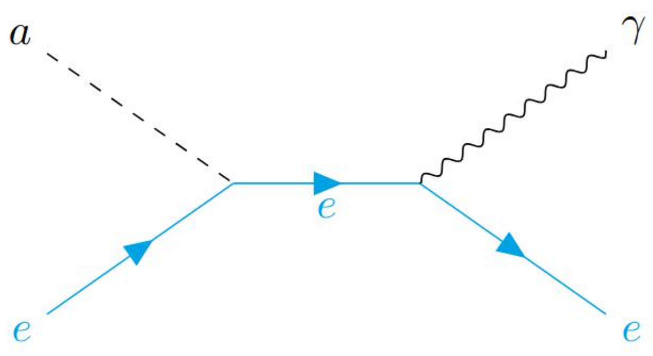
(Survival probability) x (Production Probability) x (Initial Photon Flux)

ALP decay width (determine lifetime $\tau = \Gamma^{-1}$) :

$$\boxed{\Gamma(a \to e^+e^-) = \frac{m_a g_{aee}^2}{64\pi} \sqrt{1 - 4\frac{m_e^2}{m_a^2}}}$$

Detection through g_{aee} couplings

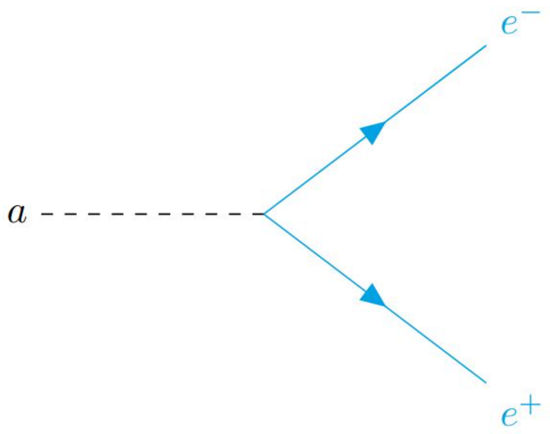
Inverse Compton-like scattering



Event Rate from Inverse Compton Scattering:

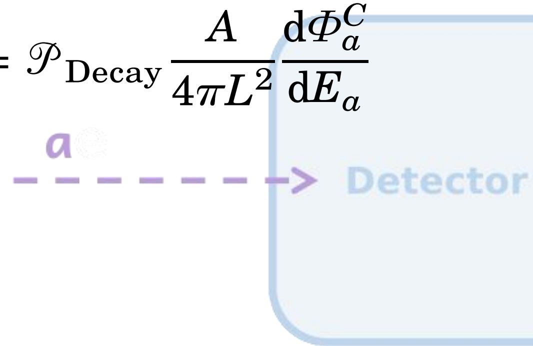
$$\left(\frac{\mathrm{d}N}{\mathrm{d}E_a}\right)_C = \frac{m_{\mathrm{det}}}{4\pi L^2} N_A \int \frac{d\sigma_D^C}{d\gamma}(E_\gamma, E_a)\frac{\mathrm{d}\Phi_a^C}{\mathrm{d}E_a} d\gamma$$

Decay into an electron-positron pair



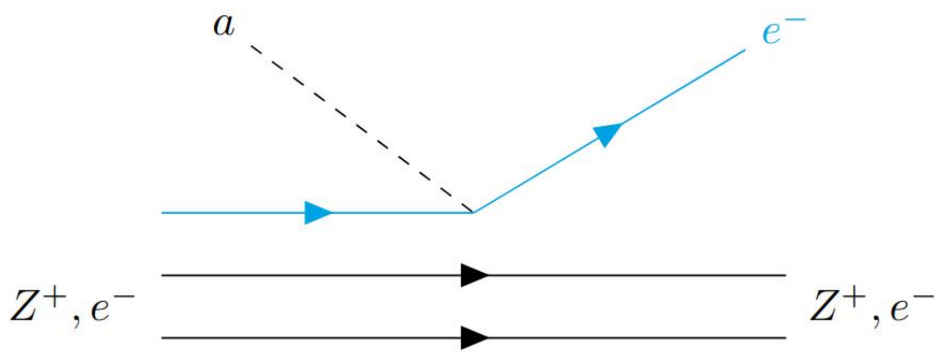
Event Rate from Decay

$$\left(\frac{\mathrm{d}N}{\mathrm{d}E_a}\right)_{\mathrm{Decay}} = \mathscr{P}_{\mathrm{Decay}}\frac{A}{4\pi L^2}\frac{\mathrm{d}\Phi_a^C}{\mathrm{d}E_a}$$



Detection through g_{aee} couplings

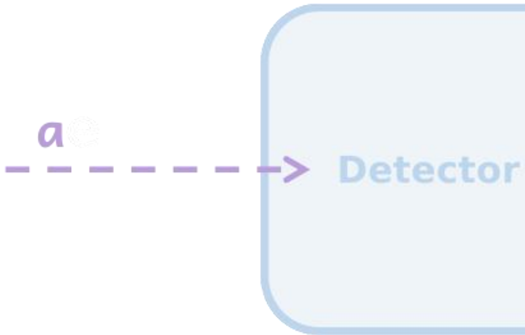
Axio-electric effect

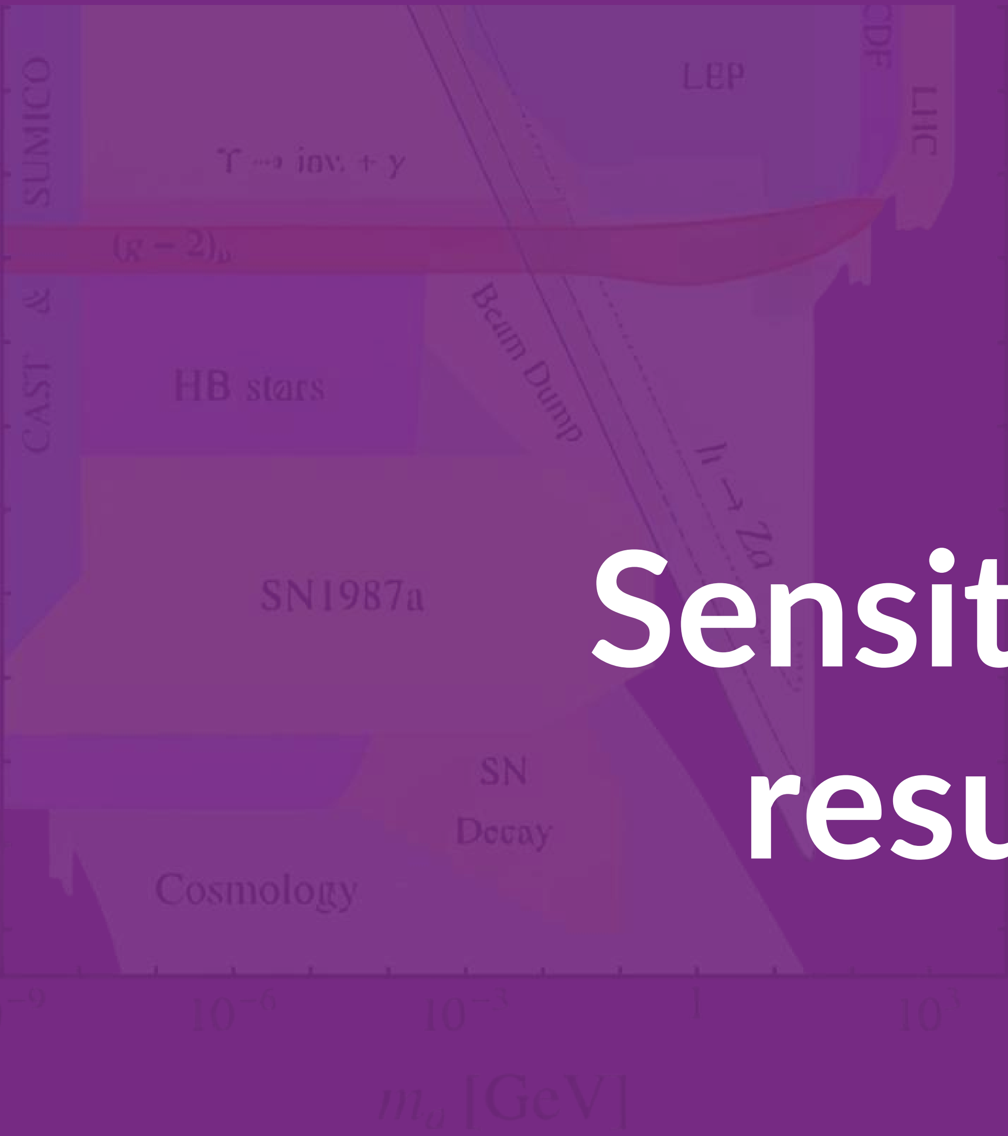


Event Rate from Axio-electric Effect

$$\left(\frac{\mathrm{d}N}{\mathrm{d}E_a}\right)_A = \frac{m_{\mathrm{det}}}{4\pi L^2} N_A \sigma_D^A \frac{\mathrm{d}\Phi_a^C}{\mathrm{d}E_a}$$

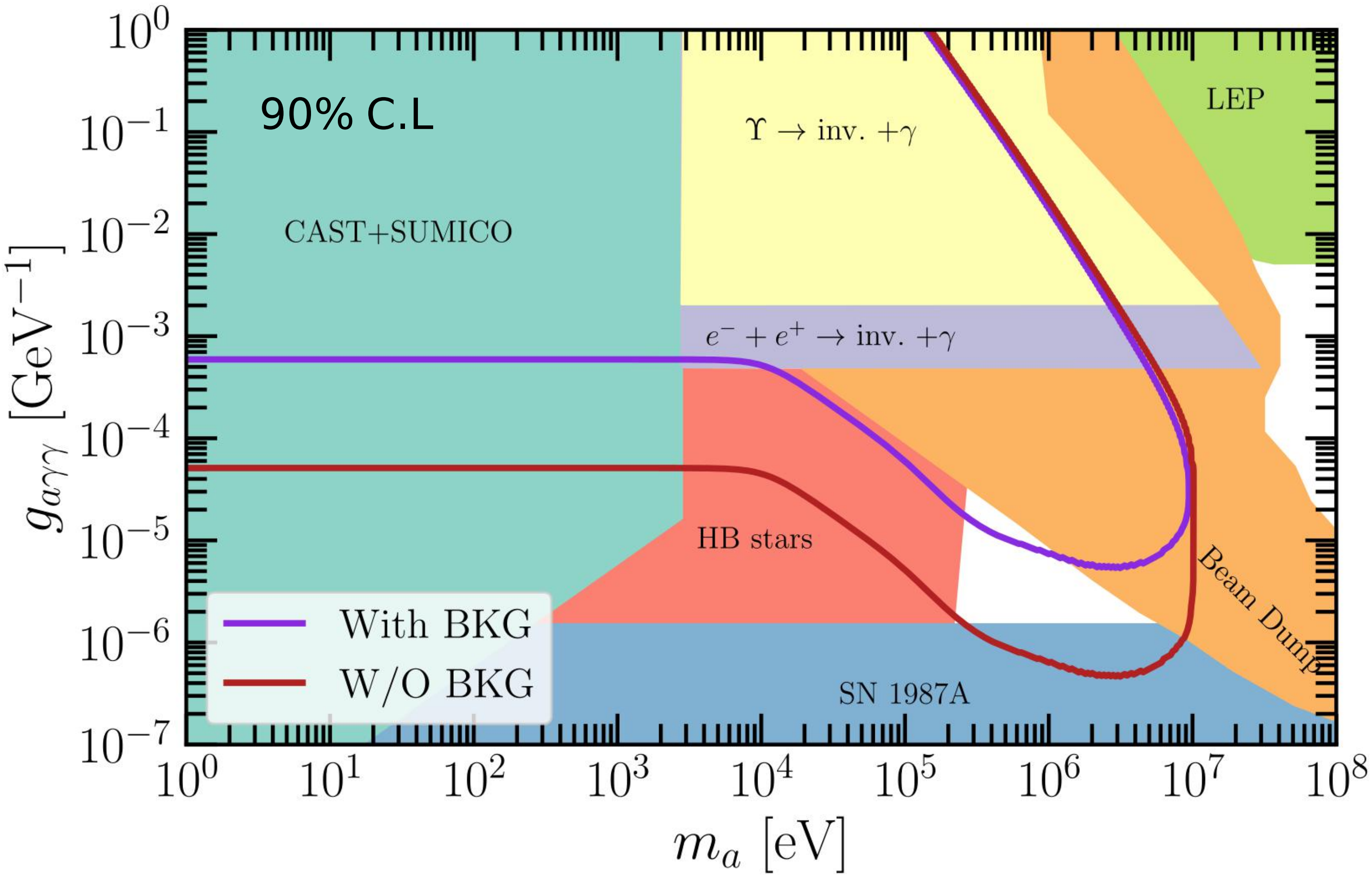
$$\boxed{\left(\frac{\mathrm{d}N}{\mathrm{d}E_a}\right)_{\mathrm{Total}} = \left(\frac{\mathrm{d}N}{\mathrm{d}E_a}\right)_C + \left(\frac{\mathrm{d}N}{\mathrm{d}E_a}\right)_A + \left(\frac{\mathrm{d}N}{\mathrm{d}E_a}\right)_{Decay}}$$



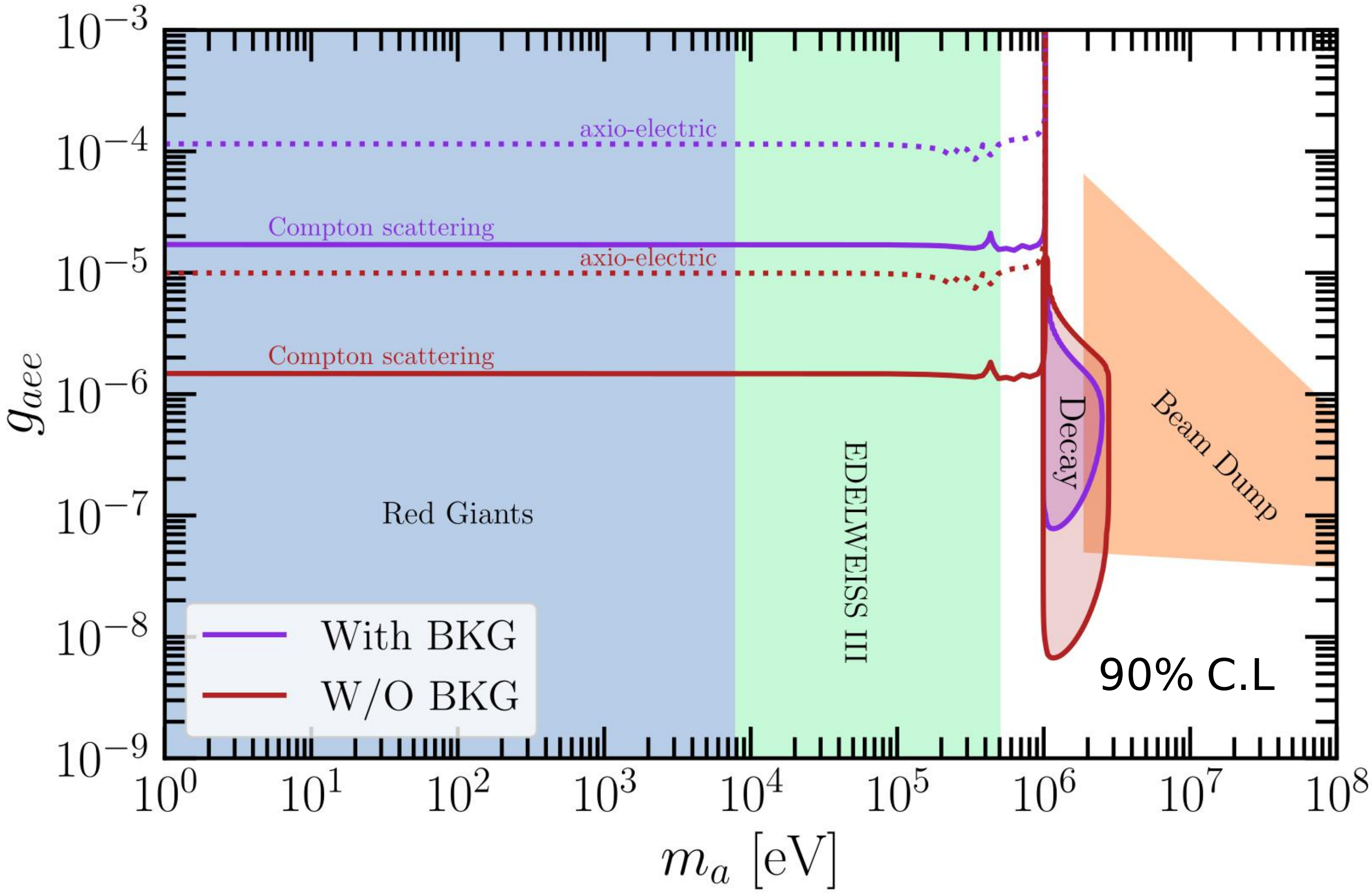


Sensitivity results

Photon-ALP coupling sensitivities



Electron-ALP coupling sensitivities



Conclusions

- Our work demonstrates that short-baseline reactor experiments such as JUNO-TAO are an effective new tool for searching for MeV-scale ALPs.
- Significant new sensitivity can be achieved for the ALP-photon coupling ($g_{a\gamma\gamma}$), probing a large, unexplored region in the MeV mass range.
- The search for the ALP-electron coupling (gaee) can be dramatically improved, with projected sensitivities reaching as low as $g_{aee} \approx 10^{-8}$.
- Reactor experiments are a key terrestrial tool in the worldwide effort to discover ALPs, highly complementary to existing searches.

Thank you!

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