New Directions for Axion Searches at Reactor Neutrino Experiments

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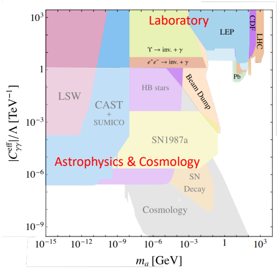
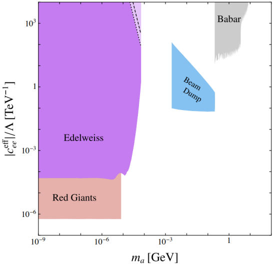
Axion-like-particles (ALP)

- ALPs are well motivated
- ALPs are typically searched from their conversions into gamma in helioscopes and haloscopes or their decays into two photons in beam dump experiments
- In this talk, I will present a new direction to probe ALPs at the low-energy, high intensity frontier through their production via the Primakoff process or Compton-like scattering off of electrons or nuclei at a nuclear reactor.
- The ALP signal at the detector emerges from their decays and inverse Primakoff and Compton scattering





Bauer, Neubert, Thamm (2017)

Production Mechanisms

$$\mathcal{L}_{\rm int} \supset -\frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu}\tilde{F}^{\mu\nu} + g_{aee} a\bar{\psi}\gamma^5\psi \tag{1}$$

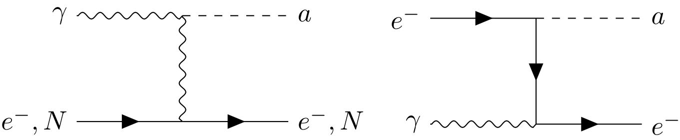


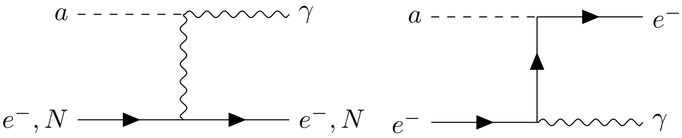
Figure: Primakoff (left) and Compton-like (right) processes for axion-photon and axion-electron conversion, respectively.

Primakoff process: Coherent conversion $\gamma \to a$ with Z^2 enhancement.

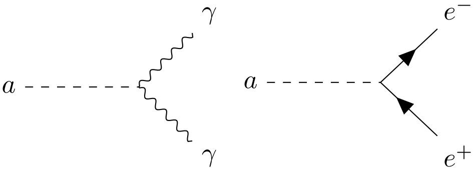
$$\sigma_{\gamma\to a} \approx \frac{9}{4} g_{a\gamma\gamma}^2 Z^2 \alpha \quad \text{(Primakoff)} \tag{2}$$

We utilize this Z^2 dependence for enhanced ALP production
see also Tsai, '86, Brodsky, *et. al.* '86

Detection Mechanisms



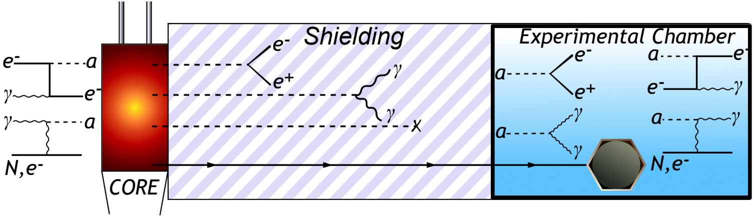
Tree-level axion detection through the Primakoff channel (left) and the Compton channel (right). Again we enjoy a Z^2-dependence in the Primakoff channel and a Z-dependence in the Compton channel. Avignone, *et. al.* '88



Axions may decay to $\gamma\gamma$ and e^+e^-;

$$\Gamma(a \to \gamma\gamma) = \frac{g_{a\gamma\gamma}^2 m_a^3}{64\pi}, \quad \Gamma(a \to e^+e^-) = \frac{g_{aee}^2 m_a}{8\pi}\sqrt{1 - \frac{4m_e^2}{m_a^2}} \tag{3}$$

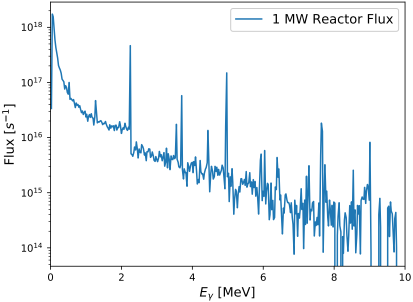
ALPs at Reactor Neutrino Experiments



- Nuclear reactors are high intensity low energy γ sources
- γ are produced in the core in large amounts
- scattering off high-Z material in the core ($^{235}_{92}$U, $^{231}_{90}$Th, etc.) → convert to ALPs via Primakoff or Compton channels. Large Z^2 and Z enhancement, respectively.
- ALPs travel through shielding (where they may decay and not be seen)
- Detected via the inverse Compton and Primakoff channels, as well as decays, inside detector housing

Reactor Photon Spectrum

- MCNP core simulation + GEANT4 to calculate γ spectrum at 1 MW MINER reactor Agnolet et. al., '16
- 10^{23} γ per day at 1 MW
- γ rate scales linearly with reactor power



Backgrounds

- $\mathcal{O}(100)$ DRU (counts/kg/keV/day) in the region of interest for reactor neutrino experiments
- Nearly background-free beyond 2.6 MeV endpoint for radiochemical backgrounds
- Photon veto (as in the case of MINER) can substantially reduce these backgrounds (ALP signal is $invisible \to \gamma(e^-)$'s)
- Exact background shapes unknown and require a more dedicated analysis; motivates a single-bin analysis for this study

Existing & Proposed Experiments

- MINER (NSC at Texas A&M) - 1609.02066
- CONNIE (Angra 2 reactor, Brazil) - 1608.01565
- CONUS - (Brokdorf plant) J.Phys.Conf.Ser. 1342 (2020) 1, 012094
- ν-cleus (Chooz) - 1704.04320

We give conservative background estimates:

Experiment	Core Thermal Power	Core Proximity (m)	Bkg Rate in ROI (DRU)	Exposure (kg·days)
MINER (Ge)	1 MW	2.25	100	4000
ν-cleus ($CaWO_4$)	4 GW	40	100	10
CONNIE (Si CCD)	4 GW	30	700	100
CONUS (Ge PPC)	4 GW	17	100	4000

Exposures are based on 1000 days run time with nominal detector masses as seen in proposals / design reports.

Analysis

All γ's are fully absorbed in the core or convert into ALPs via branching ratio:

$$BR = \frac{\sigma_{\gamma \to a}}{\sigma_{\gamma \to a} + \sigma_{SM}} \tag{4}$$

They may survive and scatter or decay inside the fid. detector volume:

$$P_{surv} = e^{-\ell / \tau_{lab} v_a} \tag{5}$$

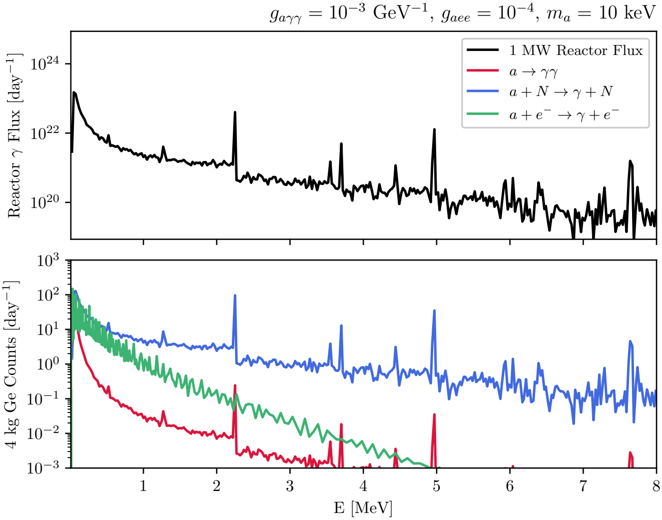
$$P_{decay} = e^{-\ell / \tau_{lab} v_a} \left(1 - e^{-\Delta \ell / \tau_{lab} v_a}\right), \tag{6}$$

We convolve the detection rate with the reactor photon flux:

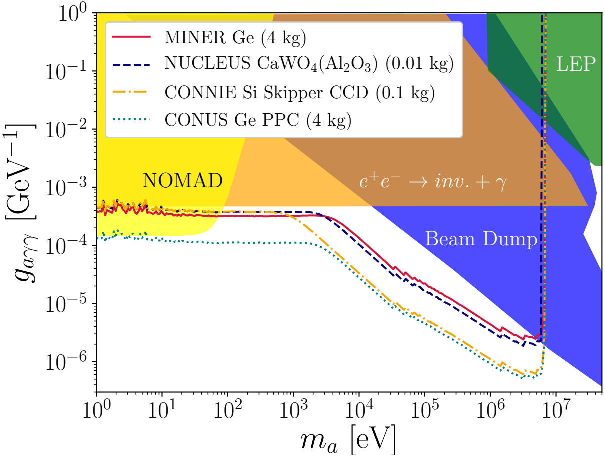
$$\boxed{dN_{scatter} = \mathcal{E} \sigma_{a \to \gamma} \frac{1}{4\pi\ell^2} \times \frac{d\Phi_\gamma(E_\gamma)}{dE_\gamma} \times BR \times P_{surv} dE_\gamma} \tag{7}$$

$$\boxed{dN_{decay} = T \frac{A}{4\pi\ell^2} \times \frac{d\Phi_\gamma(E_\gamma)}{dE_\gamma} \times BR \times P_{decay} dE_\gamma} \tag{8}$$

Axion Scattering and Decay Spectra

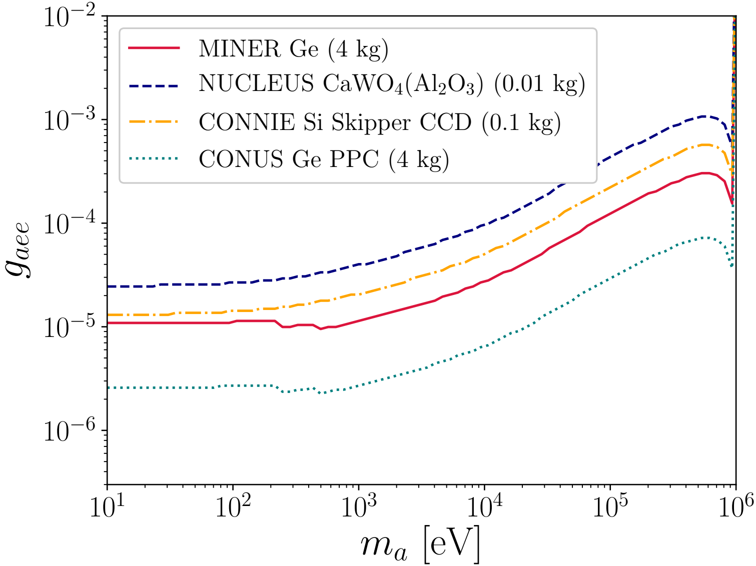


Limits on $g_{a\gamma\gamma}$: 1000 day exposures



- Scattering allows us to probe axion for any mass up to ∼ 1 MeV
- There also exist astrophysical and cosmological constraints which are model dependent (Jaeckel *et. al.* '06, Khoury & Weltman '04, Masso & Redondo '06, Mohapatra & Nasri '07, etc.)

Limits on g_{aee}: 1000 day exposures

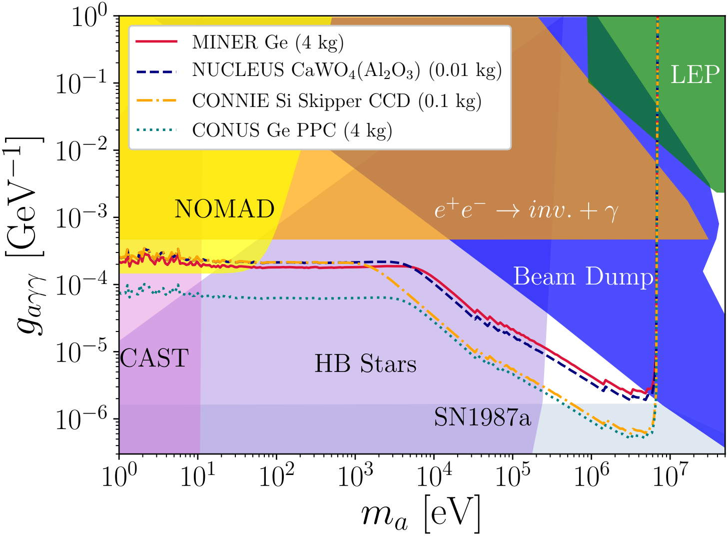


Conclusion

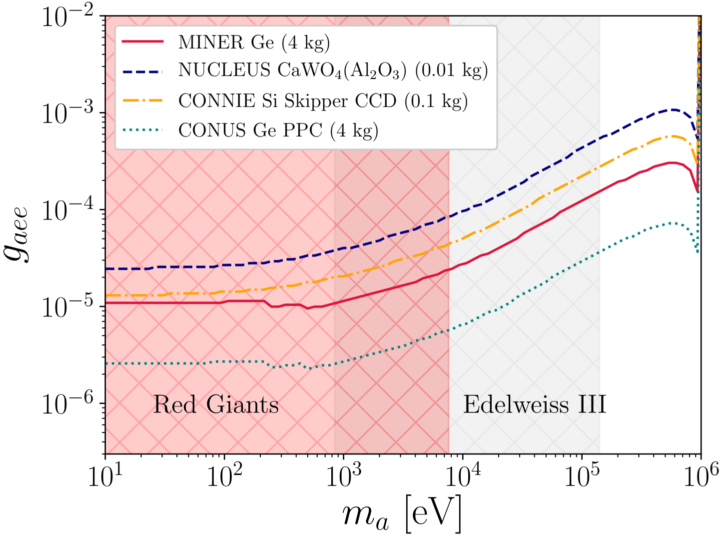
- A way forward to search for ALPs at the high-intensity frontier has been presented
- Photon-axion Primakoff (inverse), $\propto Z^2$, is utilized for axion production (detection via scattering) along with the axion decay to 2γ to probe photon-axion coupling. Similarly, Compton (inverse) production is utilized for axion production (detection via scattering).
- New parts of parameter space can readily be probed with existing experiments
- Stopped-pion sources, in addition to reactors, can also provide the intense γ flux needed to reach unexplored parts of the ALP parameter space

Thank You!

Backup


MINER Ge (4 kg)
NUCLEUS $CaWO_4(Al_2O_3)$ (0.01 kg)
CONNIE Si Skipper CCD (0.1 kg)
CONUS Ge PPC (4 kg)
NOMAD
$e^+e^- \to inv. + \gamma$
LEP
Beam Dump
CAST
HB Stars
SN1987a
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
$g_{a\gamma\gamma}$ [GeV−1]
10^0
10^1
10^2
10^3
10^4
10^5
10^6
10^7
m_a [eV]

Backup


MINER Ge (4 kg)
NUCLEUS $CaWO_4(Al_2O_3)$ (0.01 kg)
CONNIE Si Skipper CCD (0.1 kg)
CONUS Ge PPC (4 kg)
Red Giants
Edelweiss III
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
g_{aee}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
10^{6}
m_a [eV]