New Directions for ALP Searches Combining Nuclear Reactors and Haloscopes

based on arXiv:2310.03631 (PRL 2024)
in collaboration with F. Arias-Aragón and J. Quevillon

Vedran Brdar

Motivation: Strong CP Problem and Axion

- take QCD with 1 quark

$$\tilde{m} = e^{i\gamma_5\phi}$$

$$\mathcal{L}_{\not{C}\not{P}} \supset \frac{\theta}{32\pi^2}\epsilon_{\mu\nu\rho\sigma} G_a^{\mu\nu} G_a^{\rho\sigma} - \bar{\psi}\tilde{m}\psi$$

- under chiral rotation $\psi' = \psi e^{\frac{i\alpha\gamma_5}{2}}$
  $\phi \to \phi' = \phi + \alpha,\ \theta \to \theta' = \theta - \alpha$
- $\bar{\theta} \equiv \theta + \phi$ is invariant and we can not rotate away the CP violation terms in the strong sector
- neutron electric dipole moment $\simeq 10^{-14}\bar{\theta}$ e cm and measurements give $|d_n| < 1.8 \times 10^{-26}$e cm
- $\bar{\theta} \lesssim 10^{-12}$ (strong CP problem)

- introduce $U(1)_{\mathrm{PQ}}$ symmetry which is spontaneously broken and generates axion

$$\mathcal{L}_a \supset \frac{a}{f_a}\frac{1}{32\pi^2}\epsilon_{\mu\nu\rho\sigma} G_a^{\mu\nu} G_a^{\rho\sigma}$$

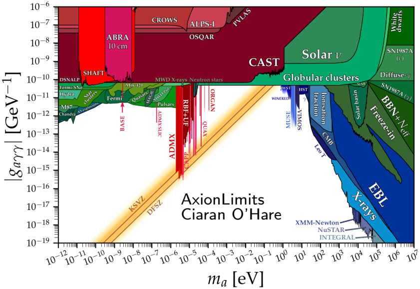
- from the axion potential we find that its VEV is $\langle a \rangle = -\bar{\theta} f_a$
- redefine $a_p = a - \langle a \rangle$; $\langle a_p \rangle = 0$
- we got $\mathcal{L}_a \supset -\bar{\theta}\frac{1}{32\pi^2}\epsilon_{\mu\nu\rho\sigma} G_a^{\mu\nu} G_a^{\rho\sigma}$ which cancels $\not{C}\not{P}$ term in QCD $\mathcal{L}$
- in addition to solving the strong CP problem, axion is also a viable dark matter (DM) candidate

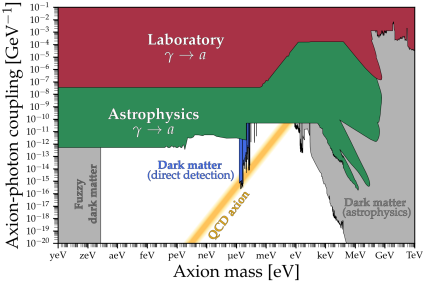
Axion-Photon Interaction

- axion's two-photon interaction plays a key role in the majority of the experimental searches

$$\mathcal{L} \supset -\frac{1}{4}\, g_{a\gamma\gamma}\, a\, F^{\mu\nu}\, \tilde{F}_{\mu\nu} = g_{a\gamma\gamma} \vec{E} \cdot \vec{B}$$

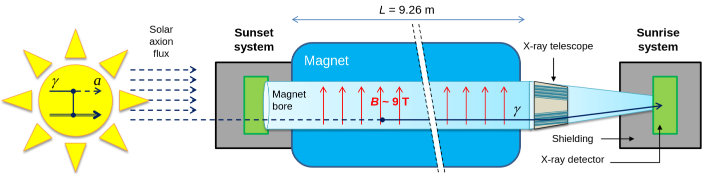
- here, $g_{a\gamma\gamma} \propto f_a^{-1}$ and $m_a f_a \approx m_\pi f_\pi \sim (100\,\mathrm{MeV})^2$
- fo the case of axion-like particles (ALPs), particle's mass and its decay constant are treated as independent parameters



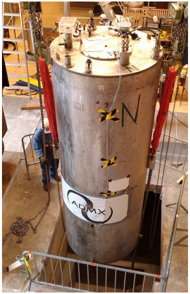


Detection via Axion/ALP Conversion in Magnetic Field

- Helioscope searches with CAST experiment: ALPs are produced in the Sun by Primakoff scattering and converted back to X-rays in the B-field



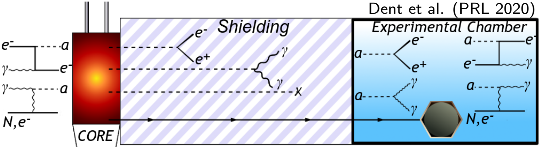
- Haloscopes: A microwave cavity is in a magnetic field, allowing the conversion of DM axions into photons. If the axion's mass matches the resonance frequency of the cavity, the power output experiences amplification



Axion/ALP Production at Nuclear Reactors

- Primakoff scattering of copiously produced photons in the reactor core generates ALP flux
- ALPs decay or scatter in nearby neutrino experiments (e.g. CONNIE, CONUS, MINER, TEXONO)

Dent et al. (PRL 2020)



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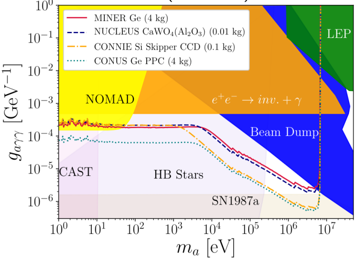
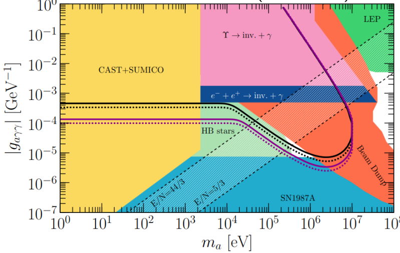


Aristizabal Sierra et al. (JHEP 2021)



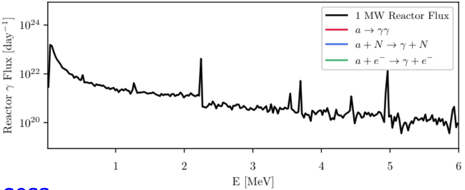
Axion Reactoscope

- Axions/ALPs are produced in the reactor core via Primakoff scattering of photons chiefly off U^{235}
- Axions/ALPs are converted in the B-field to detectable $\mathcal{O}(\text{MeV})$ photons

Photon Flux

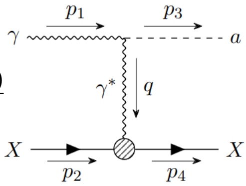
$$\frac{d\Phi_\gamma}{dE_\gamma} = \frac{0.58\times 10^{21}}{\text{MeV s}} \left(\frac{P}{\text{GW}}\right) e^{-1.1\frac{E_\gamma}{\text{MeV}}}$$

Dent et al. (PRL 2020)



ALP Production via Primakoff process

$$\frac{d\Phi_a^0}{dE_a} = \frac{\sigma_{\text{Prim}}(E_a)}{\sigma_{\text{tot}}(E_a)} \frac{d\Phi_\gamma(E_a)}{dE_a}$$



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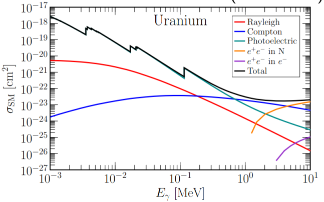
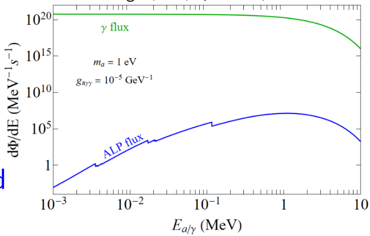


Axion Reactoscope

- ALP flux at the distance D from the core

$$\frac{d\Phi_a}{dE_a} = \frac{\text{Exp}[-D/(c\tau)]}{4\pi D^2} \, \frac{\sigma_{\text{Prim}}(E_a)}{\sigma_{\text{tot}}(E_a)} \, \frac{d\Phi_\gamma}{dE_a}$$

Arias-Aragón, VB, Quevillon, 2310.03631



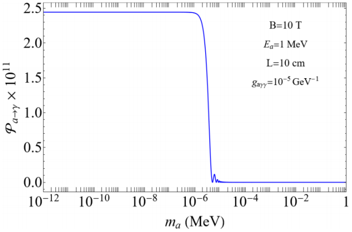
$a \to \gamma$ conversion across distance L in B-field

Raffelt, Stodolsky (PRD 1988)

$$\mathcal{P}_{a\to\gamma} = \left(\frac{g_{a\gamma\gamma}B}{q}\right)^2 \sin^2\left(\frac{qL}{2}\right) \qquad q = \sqrt{(m_a^2/(2E_a))^2 + (g_{a\gamma\gamma}B)^2}$$

for small $m_a, g_{a\gamma\gamma} \Rightarrow \quad \mathcal{P}_{a\to\gamma} \approx (g_{a\gamma\gamma}BL/2)^2$

Arias-Aragón, VB, Quevillon, 2310.03631



- Finally, number of γ produced in the magnetized region reads

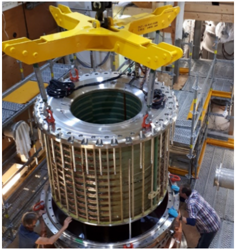
$$N_\gamma = T\pi R^2 \int \frac{d\Phi_a}{dE_a}(E_a)\mathcal{P}_{a\to\gamma}\, dE_a$$

Experimental Setup and Sensitivities

- For a successful measurement, a photon detection system should be placed behind the magnetized region
- Regarding detectors, there is an option to use inorganic scintillators, e.g. NaI[Tl], LaBr3(Ce) for the detection of $\mathcal{O}$(MeV) photons
- CAST also searched for MeV photons from ALP conversion (0904.2103) and based on that we made conservative background estimates of $\mathcal{O}(1)$ event per second
- for such case, $g_{a\gamma\gamma}$ sensitivity is weakened by 1 order of magnitude compared to the ideal case with no backgrounds
- reactor-related backgrounds can be removed with proper shielding

Experimental Setup and Sensitivities

- nuclear reactor (ILL) and the resonant cavity experiment (GrAHal) in close proximity to each other (700 m) exist in Grenoble, France



- "ILL+GrAHal Available": $B = 9.5$ T, $R = 40$ cm and L=80 cm
- "ILL+GrAHal High B": $B = 43$ T, $R = 1.7$ cm and L=3.4 cm

Experimental Setup and Sensitivities

- ALP production at ILL and detection with ILL magnets
- ALP production at Bugey and detection with CAST at CERN
- "Optimal": Kashiwazaki-Kariwa power plant ($P \sim 8.2$ GW) + BabyIAXO

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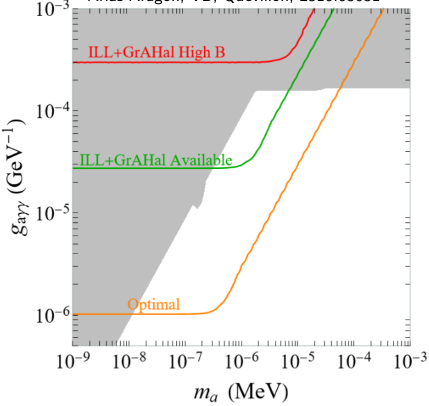
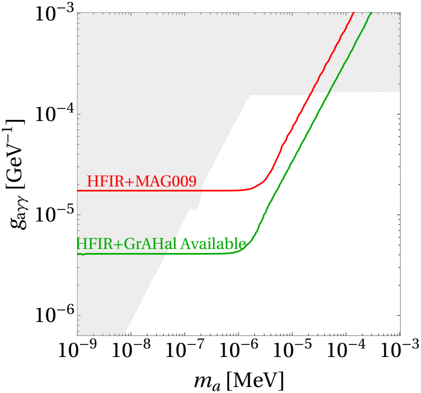


- a large portion of the yet uncovered parameter space can be probed
- astrophysical and cosmological constraints are not included
- astrophysical ALP production can be suppressed (see scenarios motivated by the old PVLAS anomaly)

Reactoscope Opportunities at ORNL



- "HFIR+MAG009": $B = 14$ T, $R = 2.1$ cm, L=20 cm

- magnet can be put at the distance of ~ 10 m from the reactor core
- e.g. PROSPECT $\bar{\nu}$ detector is at the distance of 6.5 m

Summary

- ALPs can be copiously produced in nuclear reactors provided there is an $g_{a\gamma\gamma}$ interaction
- Through the same interaction, ALPs can convert back to photons in a magnetic field
- The experimental setup features a nuclear reactor alongside the adjacent magnetic field, an essential component in axion haloscope experiments
- Appropriate locations for conducing the "Axion reactoscope" experiment include Grenoble (France) and Oak Ridge National Laboratory
- There are regions in the parameter space where sensitivity projections exceed the existing laboratory limits