



New Directions for Axion Searches at Reactor Neutrino Experiments



TEXAS A&M UNIVERSITY

Physics & Astronomy

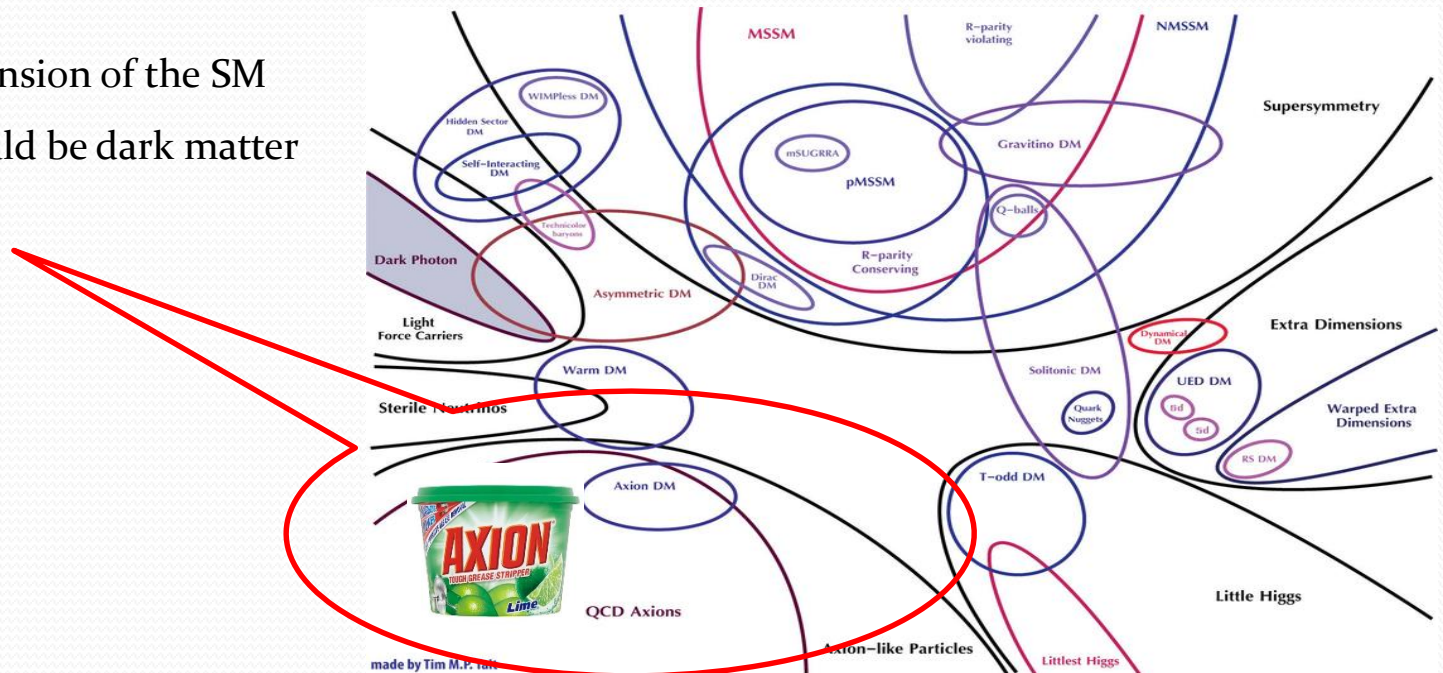
Doojin Kim

Future Prospects for Particle Physics, Astro-particle Physics and Cosmology
HKUST, January 9th, 2020

In collaboration with J. Dent, B. Dutta, S. Liao, R. Mahapatra, K. Sinha, and A. Thompson
[arXiv:1912.05733, PRL under review]

Motivation for Axion-like Particle Searches

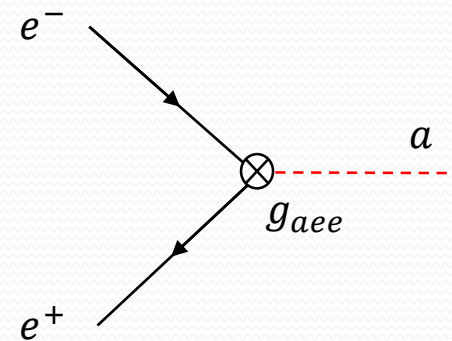
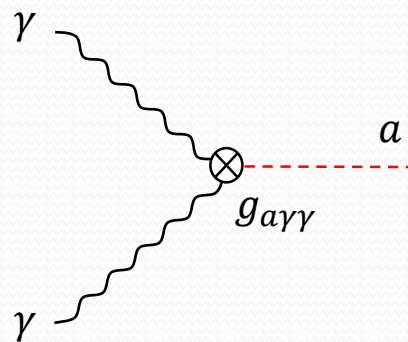
- QCD axion for solving dynamically the strong CP problem [Peccei and Quinn (1977); Weinberg (1978); Wilczek (1978)], more general pseudo-scalar axion-like particles (ALPs) which share similar properties/pheno. with QCD axion, both of which are ubiquitous also in string theory [Arvntaki, Dimopoulos, Dubovsky, Kaloper, March-Russell (2010); Cicoli, Goodsell, Ringwald (2012)]
- A plausible extension of the SM
- Axion/ALPs could be dark matter candidates.



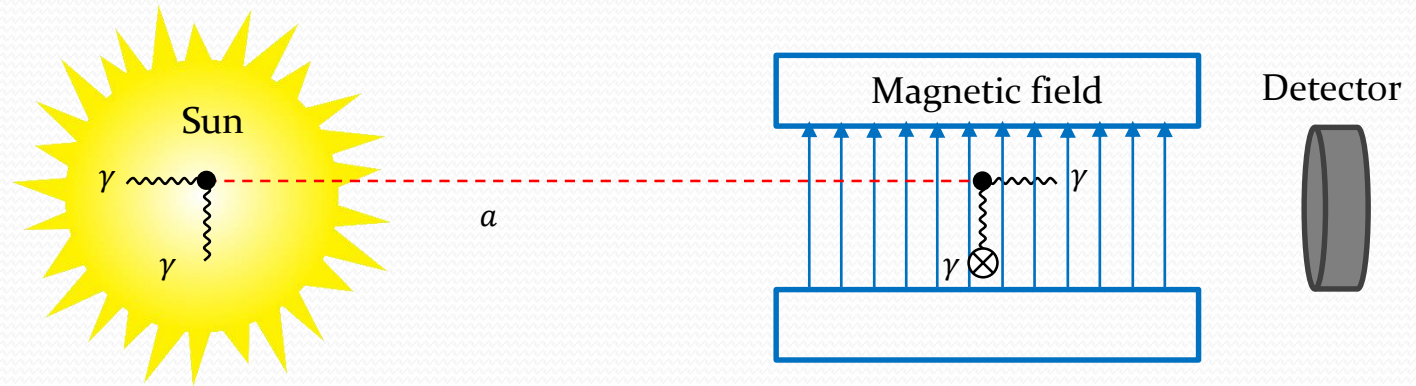
Axion-like Particle Searches

- ❑ Axion/ALP searches in the **low-energy frontier of particle physics** (vs. new (heavy) particle searches at the LHC in the (high-)energy frontier of particle physics)
- ❑ Many experimental search techniques are based on the **ALP-photon coupling**.
- ❑ Other couplings of ALP are also equally interesting and worth investigating, e.g., **ALP-electron coupling**.

$$\mathcal{L}_{\text{int}} \supset -\frac{1}{4}g_{a\gamma\gamma}aF_{\mu\nu}\tilde{F}^{\mu\nu} - g_{aee}a\bar{\psi}_e\gamma_5\psi_e$$



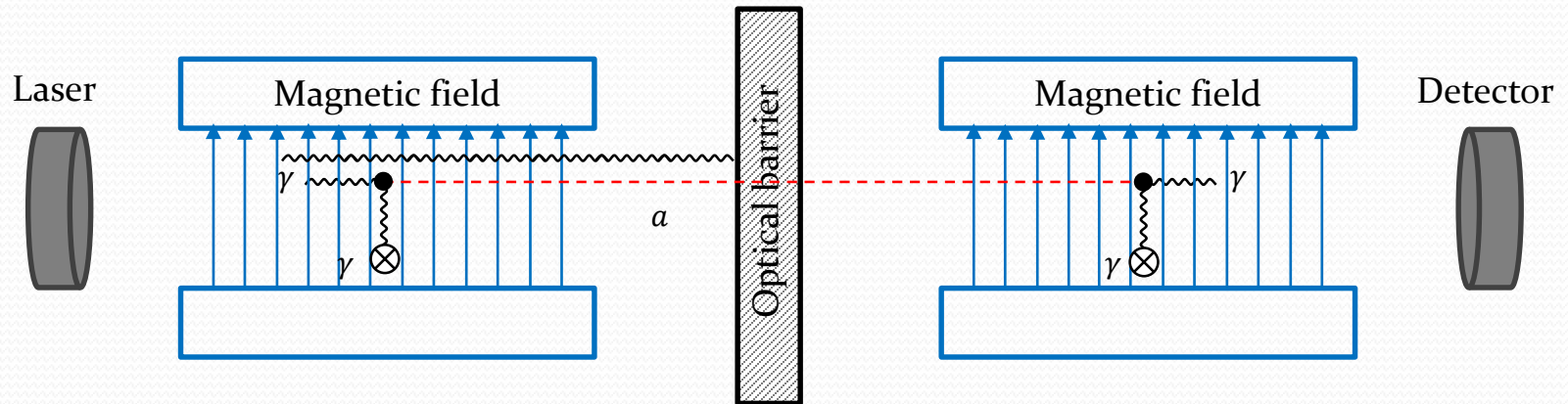
ALP Searches: CAST



- ☐ Plenty of photons inside the Sun
⇒ Large signal flux expected



ALP Searches: Light-Shining-through-Wall (LSW)

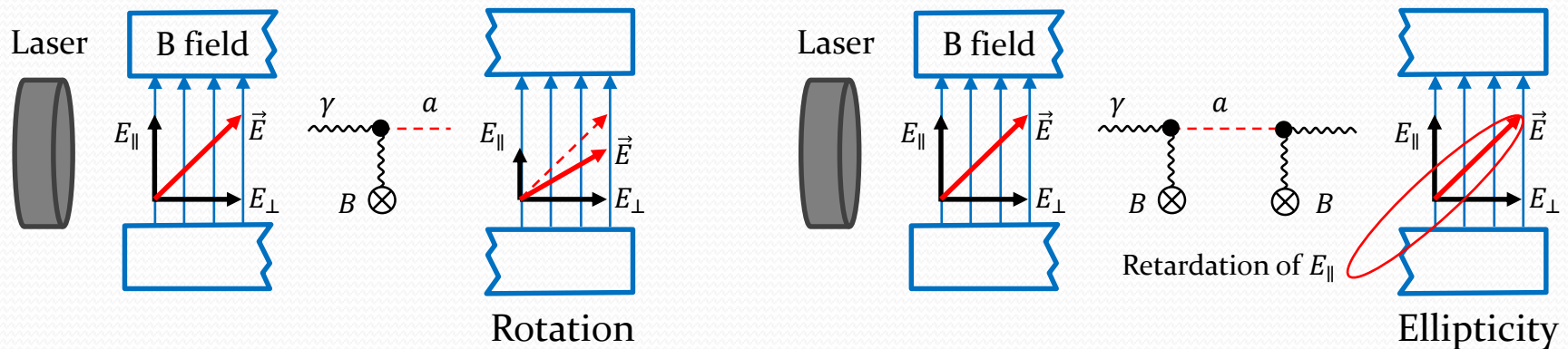


- ❑ Lab-produced ALP search, i.e., direct probe
- ❑ High intensity laser beam available
 - ⇒ Large signal flux expected
- ❑ Accessible mass range set by the energy of the laser

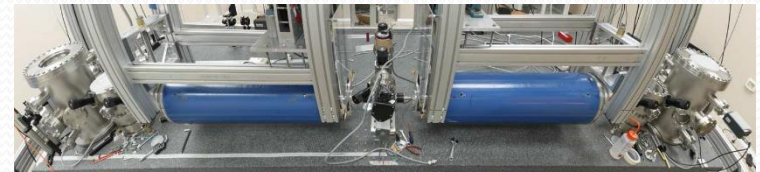


[ALPS experiment]

ALP Searches: Polarization Experiments

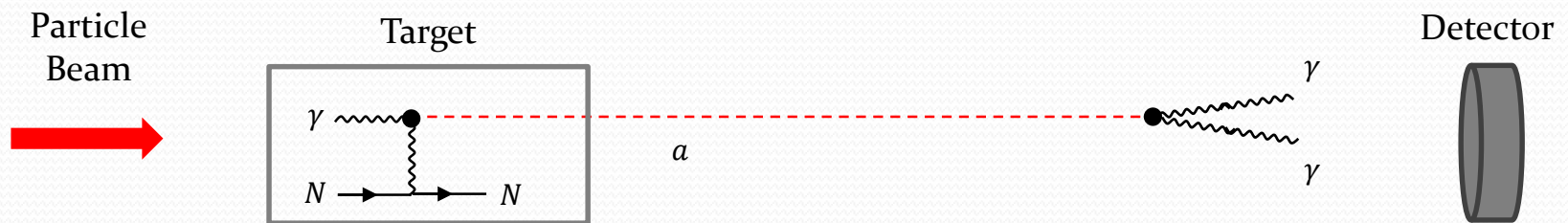


- ❑ Lab-produced ALP search, i.e., direct probe
- ❑ Due to $g_{a\gamma\gamma} a \vec{B} \cdot \vec{E}$, a laser beam with its E-field polarized will have its E_{\parallel} depleted (by $\gamma \rightarrow a$ conversion) and phase delayed (due to $\gamma \rightarrow a \rightarrow \gamma$), resulting in sizable rotation and ellipticity, respectively.

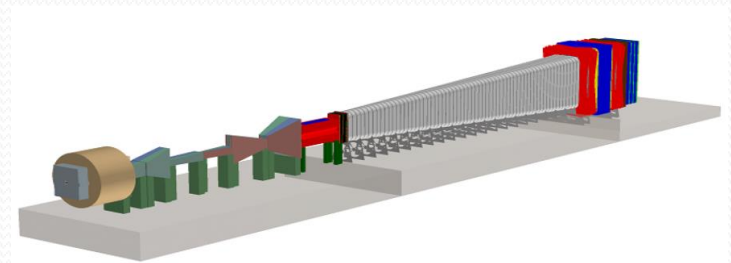


[PVLAS experiment]

ALP Searches: Beam-Dump Experiments

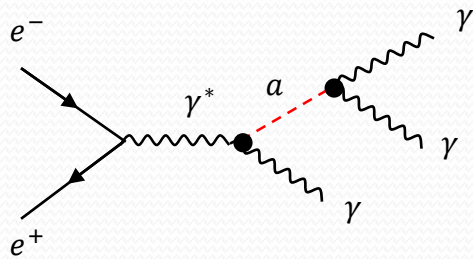


- ❑ Lab-produced ALP search, i.e., direct probe
- ❑ High intensity particle beams available
 - ⇒ Large signal flux expected (photons from bremsstrahlung and meson decays)
- ❑ Heavier ALPs are preferred, as they can decay within detector complex

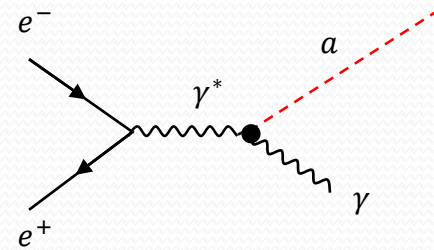


[SHiP experiment]

ALP Searches: Lepton Colliders

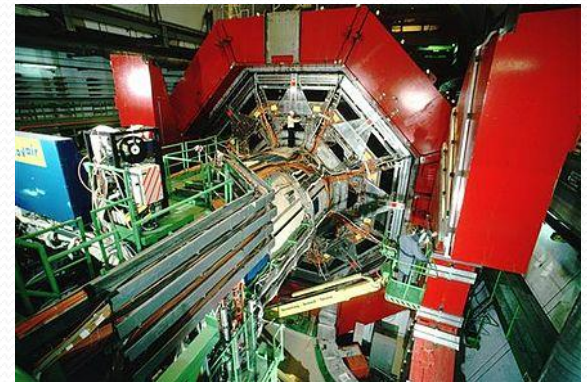


$$e^- e^+ \rightarrow \gamma^* \rightarrow \gamma a, a \rightarrow \gamma\gamma$$



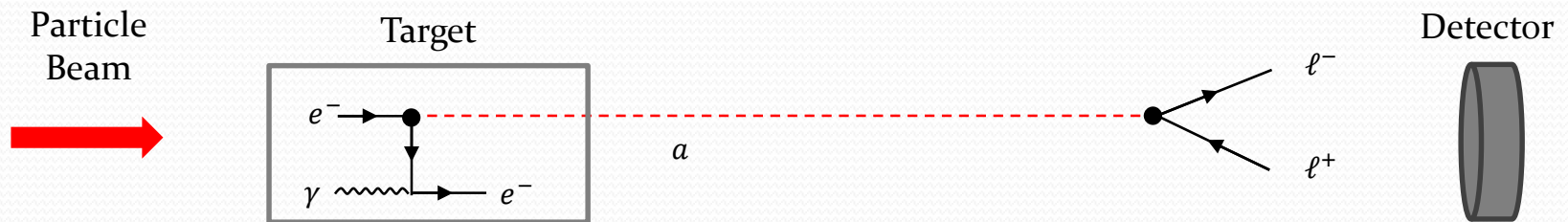
$$e^- e^+ \rightarrow \gamma^* \rightarrow \gamma a \text{ with } a \text{ being stable or invisibly decaying}$$

- ❑ Lab-produced ALP search, i.e., direct probe
- ❑ The three photon channel (e.g., Babar data [Dolan, Ferber, Hearty, Kahlhoefer, Schmidt-Hoberg (2017)]) and the single photon + missing energy channel (e.g., LEP data [Mimasu, Sanz (2014)]) can be reinterpreted.

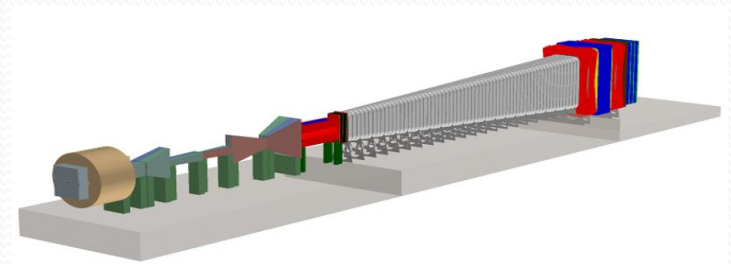


[L3 experiment]

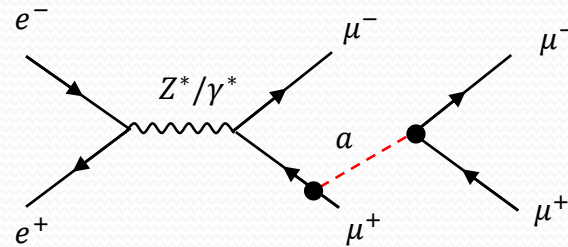
ALP Searches: Beam-Dump Experiments



- ❑ Lab-produced ALP search, i.e., direct probe
- ❑ High intensity particle beams available
 - ⇒ Large signal flux expected (photons from bremsstrahlung and meson decays)
- ❑ Sensitivity reaches are restricted by kinematics, i.e.,
 $m_a > 2m_\ell$

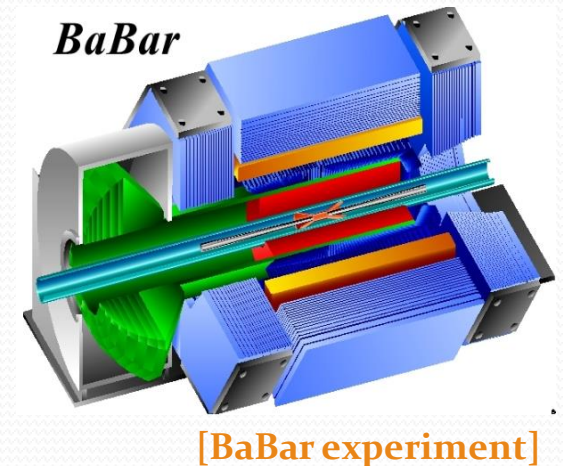


ALP Searches: Lepton Colliders



$$e^- e^+ \rightarrow Z^* / \gamma^* \rightarrow \mu^- \mu^+ a, a \rightarrow \mu^- \mu^+$$

- ❑ Lab-produced ALP search, i.e., direct probe
- ❑ Under the assumption of flavor-universal coupling of ALP, muonic dark force searches in the four muon channel can be reinterpreted (e.g., Babar data [Bauer, Neubert, Thamm (2017)])



Lab-Based Searches vs. Non-Lab-Based Searches

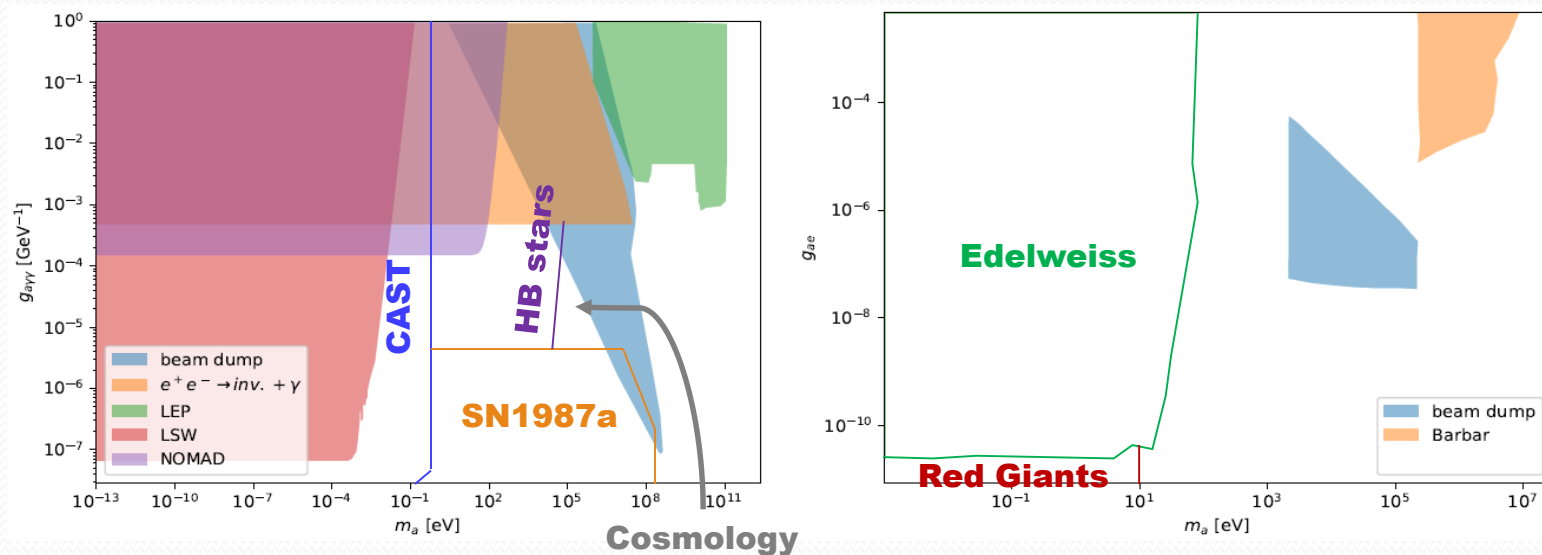
- ❑ The PVLAS Collaboration (a polarization experiment and a lab-produced ALP search) claimed an anomaly [Zavattini et al., PRL 96 (2006) 110406] (which was later identified as a spurious effect of unknown systematics [Zavattini et al., PRD 77 (2008) 032006]) which would be explained by the oscillation of photons into ALPs.
- ❑ The preferred values for the ALP mass and the coupling were **inconsistent with the astrophysical bounds** (e.g., CAST), motivating a number of theoretical speculations to make the ALPs compatible with them [E.g., Jaeckel, Masso, Redondo, Ringwald, Takahashi (2006); Ahlers, Gies, Jaeckel, Ringwald (2007); Brax, van de Bruck, Davis (2007)].
- ❑ The coupling or the ALP mass can **depend on a host of environmental parameters**, such as the temperature, matter density, or plasma frequency, as well as the momentum transfer at the ALP-photon vertex.

Lab-based searches:

Not only **complementary** to astrophysical searches but also more **conservative!**

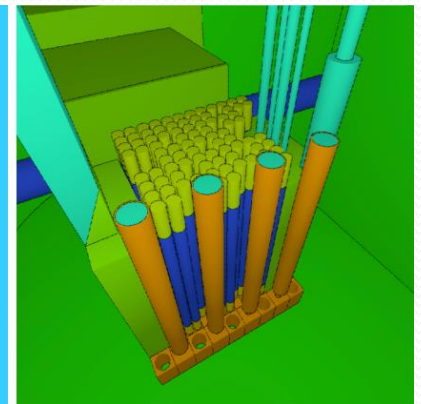
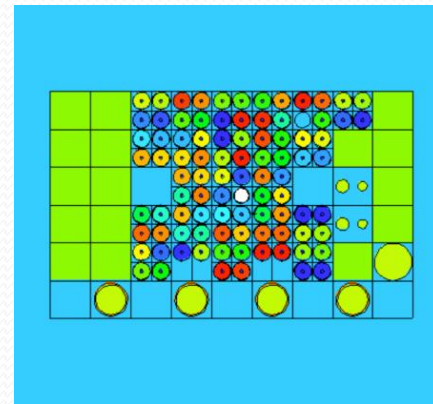
Current Constraints from Lab-Based Experiments

- Existing lab-based constraints for the ALP-photon coupling (left panel) and the ALP-electron coupling (right panel) with other couplings assumed negligible.





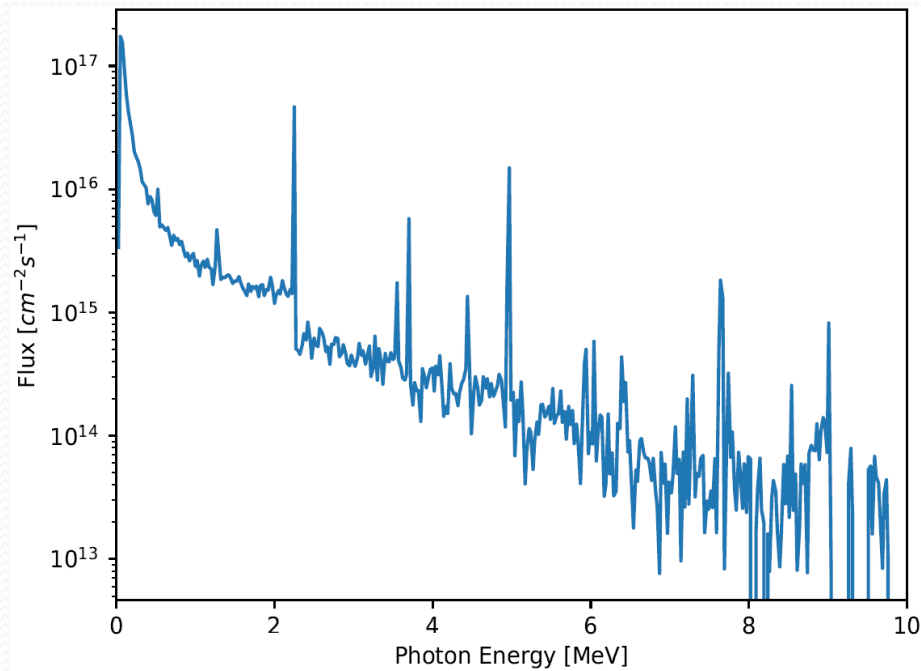
ALP Search at Reactor



Why Reactors?

- ✓ **High Intensity**: The number of photons, which may create axion/ALP, are enormous.
- ✓ **Relatively Low Cost**: Existing reactors and/or experimental facilities can be used and/or readily redesigned.
- ✓ **“Bonus” Physics Case**: The same experimental setup is used for studying CEvNS events and ALP events.
- ✓ **Complementarity**: The reactor ALP searches can provide complementary information in exploring relevant parameter space.

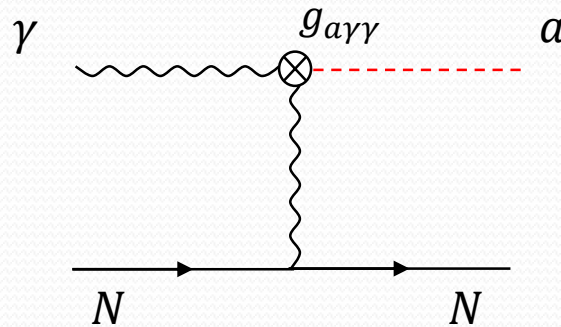
Photon Flux at the MINER Reactor



- ❑ Expected photon flux based on a GEANT simulation for a M watt reactor (10^{19} photons/s).
- ❑ Cascade photons, photons from isotope decays etc included.

ALP Production: Primakoff Process

- Primakoff process, $\gamma(p_1) + N(p_2) \rightarrow a(k_1) + N(k_2)$



- The production cross section is enhanced by the coherency factor Z^2 !

$$\frac{d\sigma_P^p}{d\cos\theta} = \frac{1}{4} g_{a\gamma\gamma}^2 \alpha Z^2 F^2(t) \frac{|\vec{p}_a|^4 \sin^2\theta}{t^2}$$

$$t = (p_1 - k_1)^2 = m_a^2 + E_\gamma(E_a - |\vec{p}_a| \cos\theta)$$

Z : atomic number,

α : fine structure constant

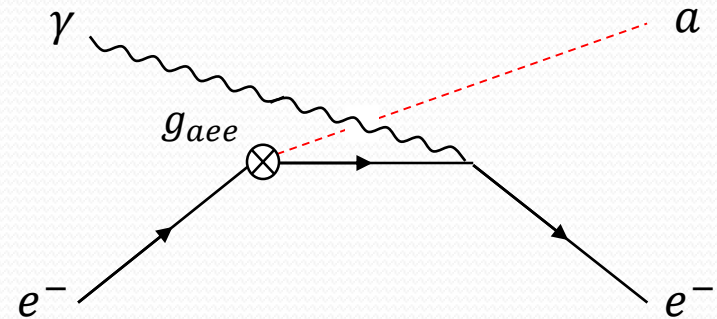
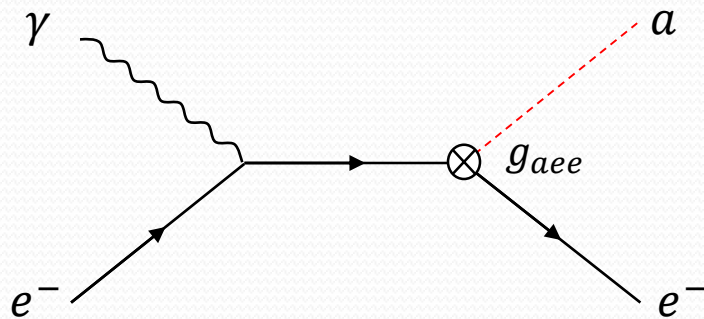
$F(t)$: form factor

$|\vec{p}_a|$: magnitude of the outgoing three-momentum of the ALP at the angle θ relative to the incident photon momentum

E_γ : incident photon energy

ALP Production: Compton-like Process

- Compton-like process, $\gamma + e^- \rightarrow a + e^-$



- The production cross section is enhanced by Z !

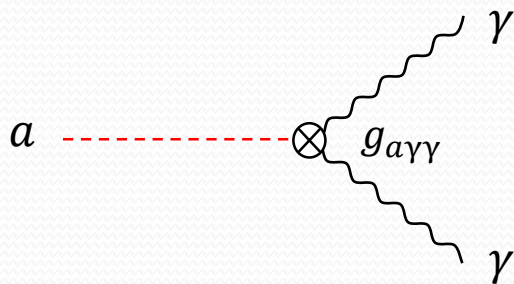
$$\frac{d\sigma_C^p}{dx} = \frac{Z\pi g_{aee}^2 \alpha x}{4\pi(s - m_e^2)(1 - x)} \left[x - \frac{2m_a^2 s}{(s - m_e^2)^2} + \frac{2m_a^2}{(s - m_e^2)^2} \left(\frac{m_e^2}{1 - x} + \frac{m_a^2}{x} \right) \right]$$

$$x = 1 - \frac{E_a}{E_\gamma} + \frac{m_a^2}{2E_\gamma m_e}$$

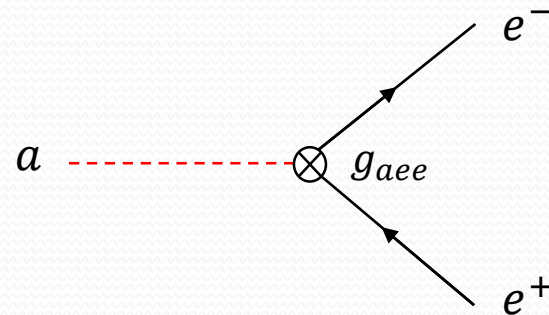
s : usual Mandelstam variable

ALP Detection: ALP Decay

- ALP decays in flight to a couple of photons or a electron-positron pair which are detected by the (MINER) detector.



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

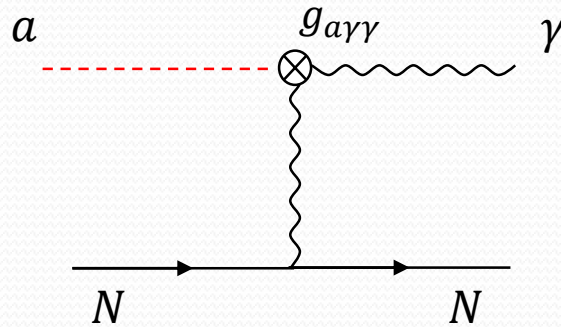


$$\Gamma(a \rightarrow e^+e^-) = \frac{g_{aee}^2 m_a}{8\pi} \sqrt{1 - \frac{4m_e^2}{m_a^2}}$$

- E.g., with $E_a = 20$ MeV, $m_a = 1$ MeV and $g_{a\gamma\gamma} = 10^{-5}$ MeV $^{-1}$, the mean decay length is 7.9 meters.

ALP Detection: ALP Scattering

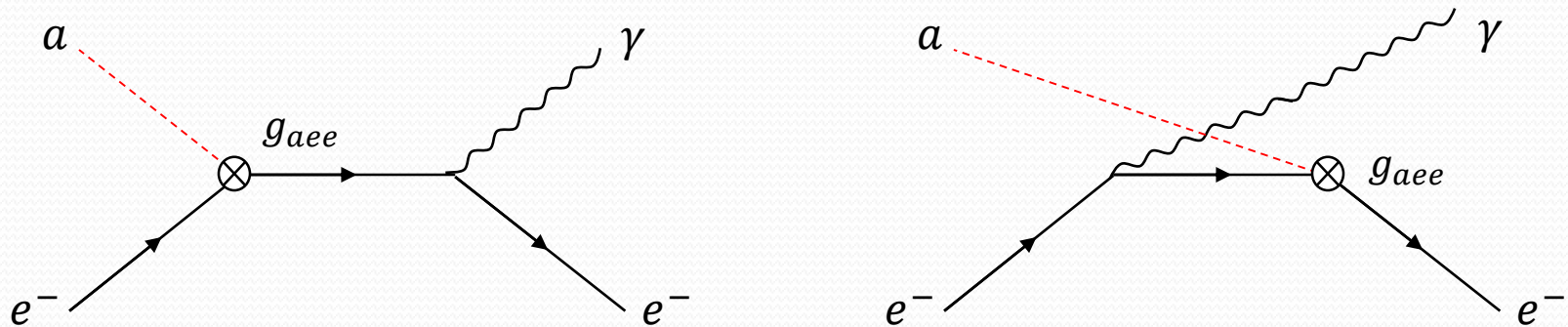
- ALP can interact with a nucleus via the inverse Primakoff process, $a + N \rightarrow \gamma + N$



$$\frac{d\sigma_P^p}{d\cos\theta} = \frac{1}{2} g_{a\gamma\gamma}^2 \alpha Z^2 F^2(t) \frac{|\vec{p}_a|^4 \sin^2\theta}{t^2}$$

ALP Detection: ALP Scattering

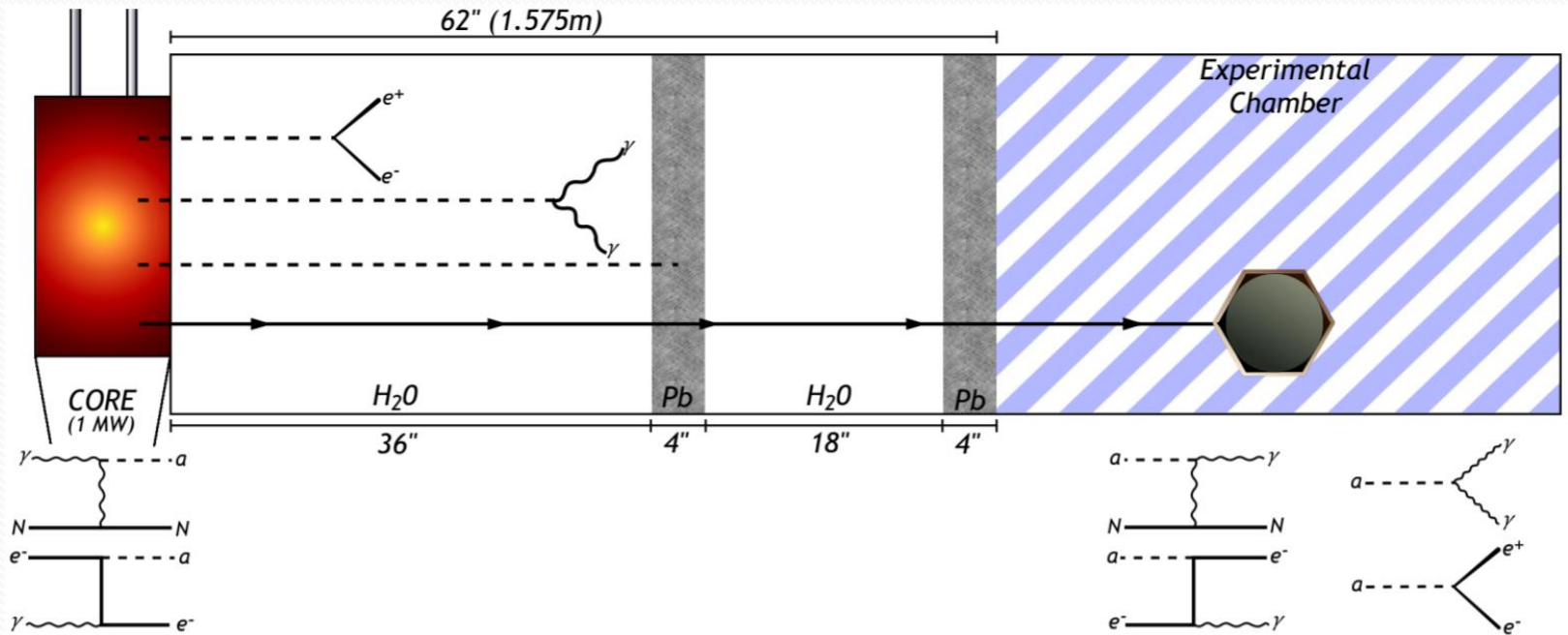
- ALP can interact with an electron via the Compton-like process, $a + e^- \rightarrow \gamma + e^-$



$$\frac{d\sigma_C^d}{d\Omega} = \frac{Zg_{aee}^2\alpha E_\gamma}{8\pi m_e^2 |\vec{p}_a|} \left(1 + \frac{4m_e^2 E_\gamma^2}{(2m_e E_a + m_a^2)^2} - \frac{4m_e E_\gamma}{(2m_e E_a + m_a^2)} - \frac{4m_a^2 |\vec{p}_a|^2 m_e E_\gamma \sin^2 \theta}{(2m_e E_a + m_a^2)^3} \right)$$

ALP Searches at MINER

- Schematic description of the proposed ALP search strategy at MINER. (Note the strategy is generic, hence applicable to other reactor-based experiments.)

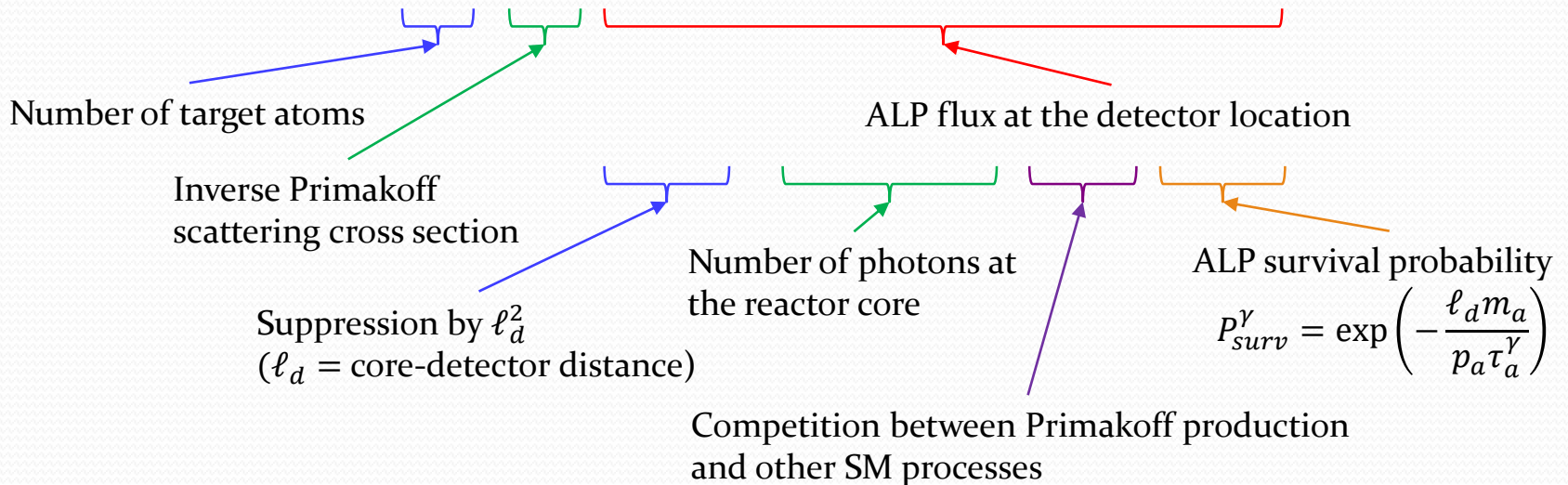


ALP production $\xrightarrow{\text{ALP transport}}$ ALP detection

Calculating Signal Detection Rate – Scattering Case

- Detection by the inverse Primakoff scattering process

$$S = N_T \cdot \sigma_P^d \cdot \frac{1}{4\pi\ell_d^2} \int dE_\gamma \frac{dN_\gamma}{dE_\gamma} \cdot \frac{\sigma_P^p}{\sigma_{SM}} \cdot P_{surv}^\gamma$$



- Detection by the Compton-like scattering process: $\sigma_P^d \rightarrow \sigma_C^d$, $\sigma_P^p \rightarrow \int dE_a \frac{d\sigma_C^p}{dE_a}$, $P_{surv}^\gamma \rightarrow P_{surv}^e$

(Note than for the Primakoff case, $E_a \approx E_\gamma$)

Calculating Signal Detection Rate – Decay Case

- Detection by the ALP decay to two photons

$$S = \frac{\Delta\Omega}{4\pi\ell_d^2} \int dE_\gamma \frac{dN_\gamma}{dE_\gamma} \cdot \frac{\sigma_P^p}{\sigma_{SM}} \cdot P_{\text{surv}}^\gamma \cdot P_{\text{decay}}^\gamma$$

Number of ALPs reaching the detector

Probability of decay inside the detector volume

$$P_{\text{decay}}^\gamma = \exp\left(-\frac{\ell_s m_a}{p_a \tau_a^\gamma}\right) \left[1 - \exp\left(-\frac{\Delta\ell m_a}{p_a \tau_a^\gamma}\right)\right]$$

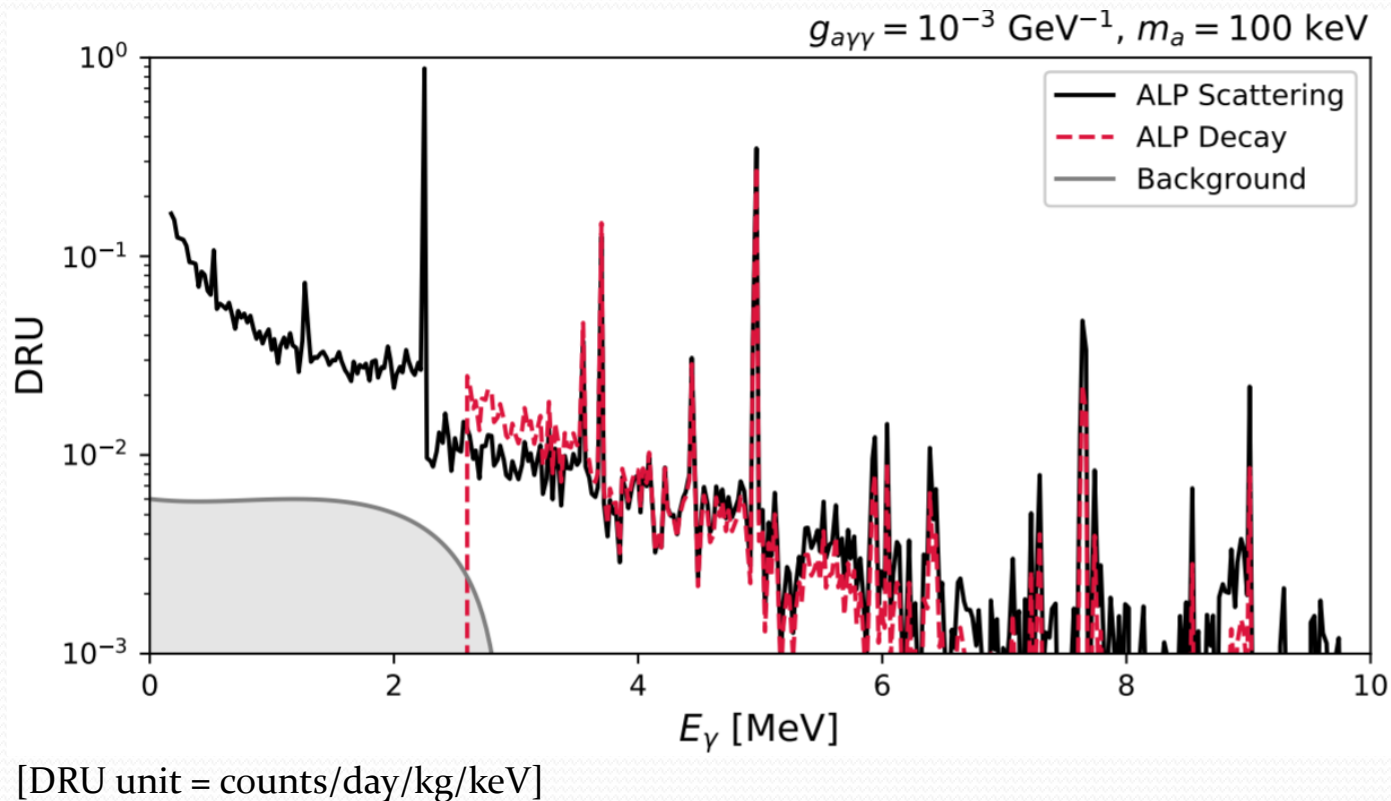
ℓ_s : the thickness of the detector shielding

$\Delta\ell$: detector length

- Detection by the ALP decay to an electron-positron pair : $\sigma_P^p \rightarrow \int dE_a \frac{d\sigma_C^p}{dE_a}$, $P_{\text{surv}}^\gamma \rightarrow P_{\text{surv}}^e$, $P_{\text{decay}}^\gamma \rightarrow$

P_{decay}^e

Expected Signal Photon Rates at MINER



- ❑ The backgrounds pictured stem from sources of radiochemical emission and are expected to remain flat and attenuate quickly by 2.6 MeV thalium endpoint.

Data Analysis

❑ Benchmark detectors

- 4 kg-Ge detector (ongoing), 200 kg-CsI detector (scheduled) and 2,000 kg-CsI detector (future)

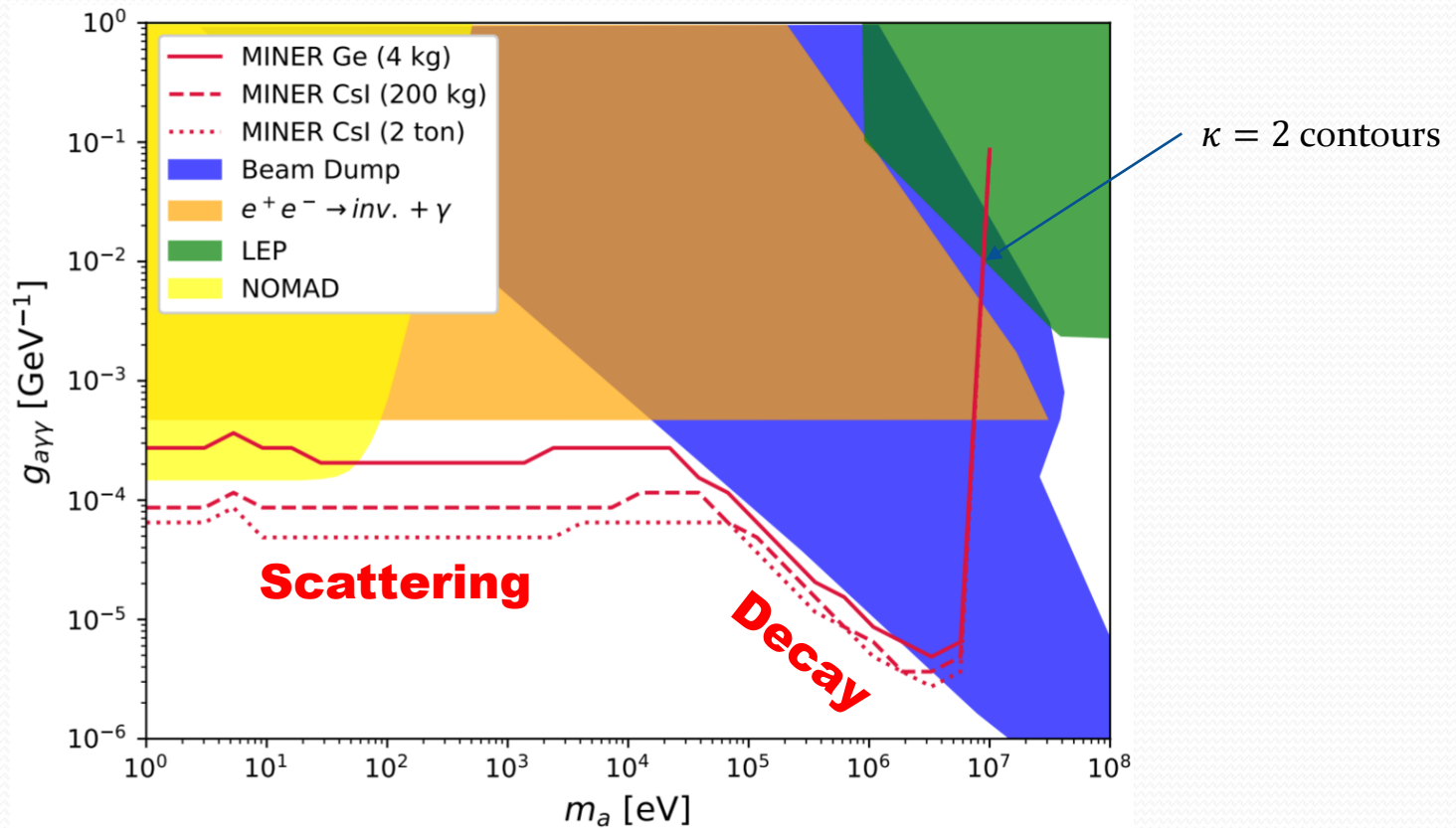
❑ As a conservative evaluation, we calculated the projected sensitivities via a single energy bin

analysis using $\kappa = \frac{N_s}{\sqrt{N_s + N_b}}$ with N_s , N_b being integrated signal and background events, restricting to > 25 keV in energy.

❑ Background consideration

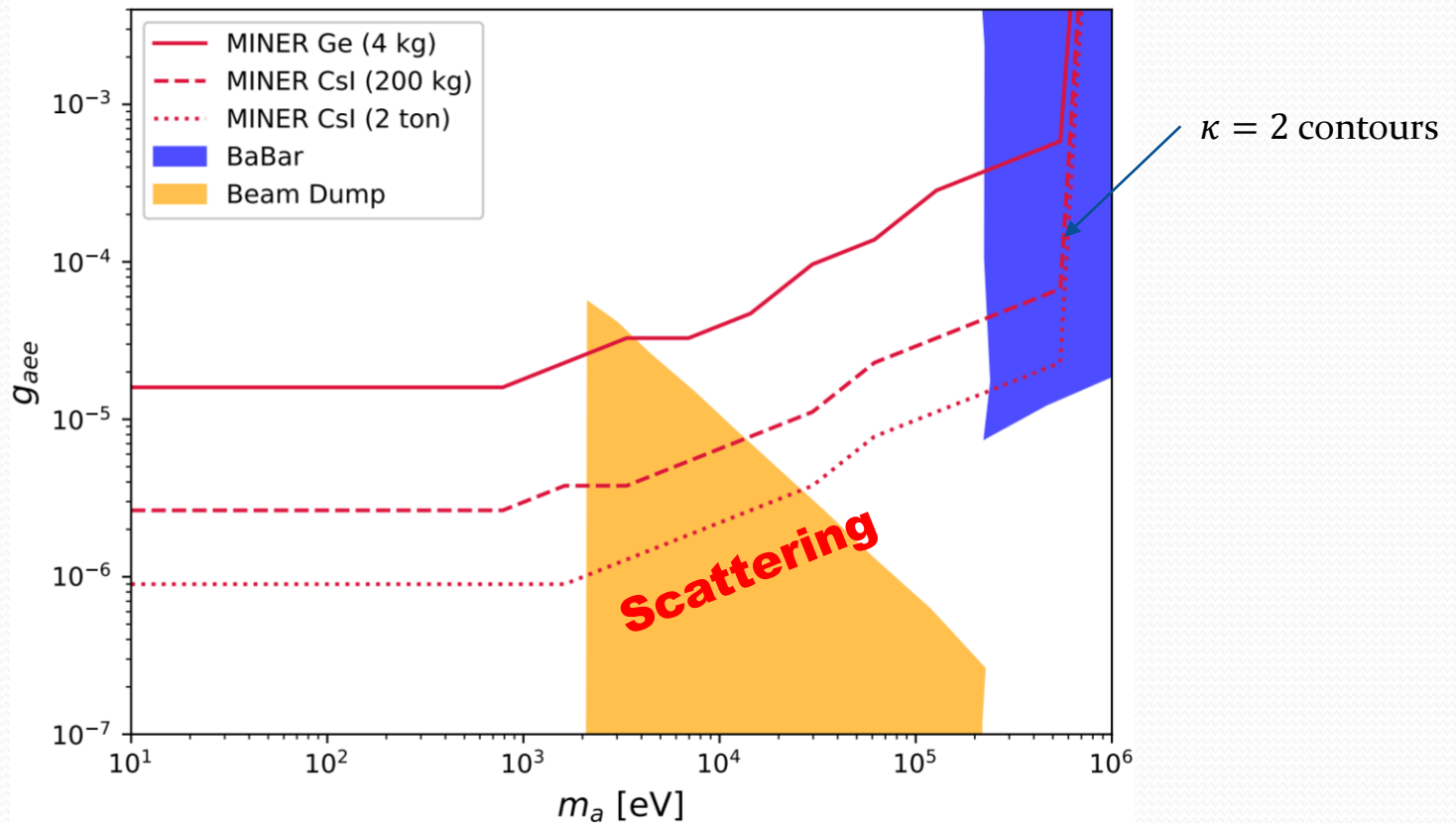
- For Ge detector, preliminary studies suggest **0.006 DRU**.
- For CsI detector, we take a reference value of **0.0033 DRU** as reported by the KIMS collaboration for their CsI setup [PRD 90, 052006 (2014)]
- For Compton-like ALP detection, the final state of $\gamma + e^-$ is readily identifiable and has reducible backgrounds, so we assume a **signal-only model**.

Expected Signal Sensitivity: ALP-Photon Coupling



- ❑ Only ALP-photon coupling turned on. The limit peaked at $m_a \sim 4$ MeV is set by the ALP decay rate which depends on the distance from the flux source and the ALP decay length.

Expected Signal Sensitivity: ALP-Electron Coupling



- ❑ Only ALP-electron coupling turned on. ALP-decay requires $m_a > 2m_e$, so decay contributions are not large enough.

Conclusions

- ❑ We have pointed out a **new experimental direction to search for ALPs** at reactor-based experiments.
- ❑ The results suggest that the proposed search strategy should allow us to **probe a wide range of parameter space** that none of the lab-produced ALP search experiments have ever explored.
- ❑ The expected experimental sensitivity for the ALP-photon coupling covers regions constrained by astrophysical searches, providing **conservative and complementary limits**.
- ❑ The expected experimental sensitivity for the ALP-electron coupling covers regions which are never constrained by existing searches, providing **new limits**.
- ❑ The proposed search strategies are **readily applicable to other reactor-based experiments** and they can “immediately beat” other lab-based ALP experiments.

