Axion-like Particle Searches at Next-Generation Neutrino Experiments: from Decay to Conversion

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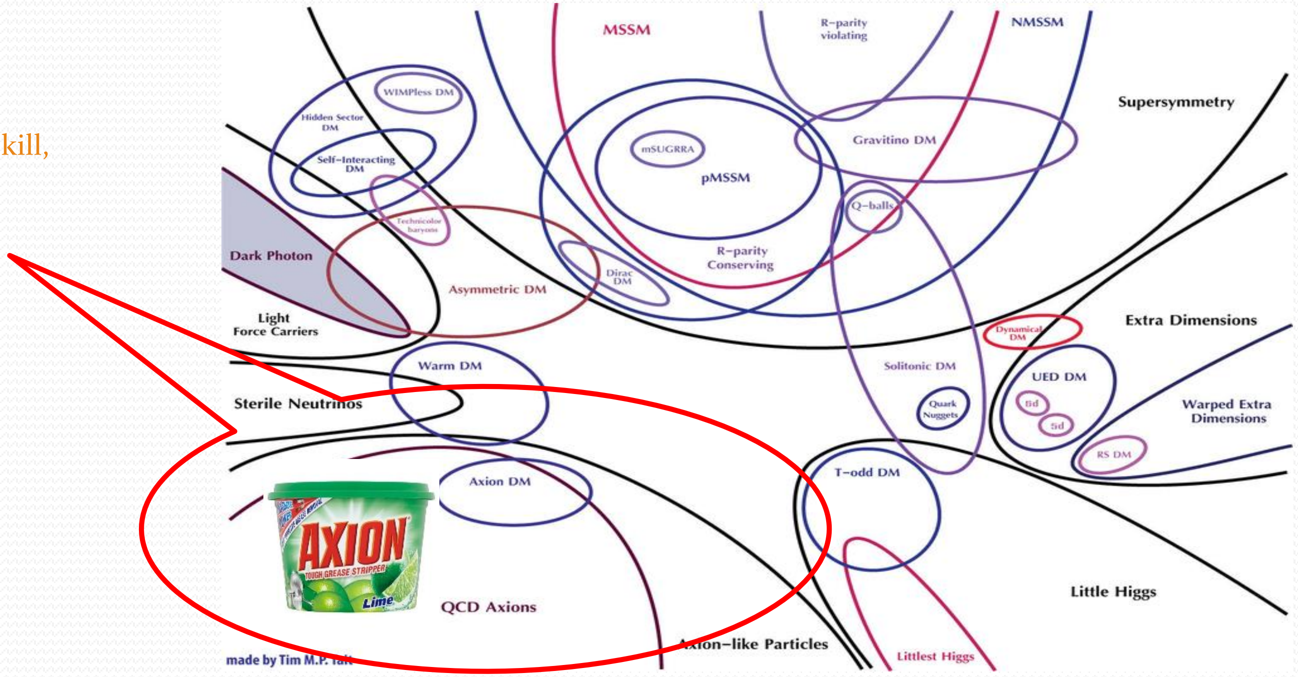
Motivations for Axion-like Particle Searches

- ❑ QCD axion for solving dynamically the strong CP problem [Weinberg (1978); Wilczek (1978); Peccei and Quinn (1977)]
- ❑ More general pseudo-scalar axion-like particles (ALPs) which share similar properties/ pheno. wiith QCD axion, both of which are ubiquitous also in string theory [Arvnitaki, Dimopoulous, Dubovsky, Kaloper, March-Russell (2010); Cicoli, Goodsell, Ringwald (2012)]

- ❑ A plausible extension of the SM
- ❑ Axion/ALPs could be dark matter candidates [Preskill, Wise, Wilczek (1983); Abbott, Sikivie (1983); Dine, Fischler (1983)].

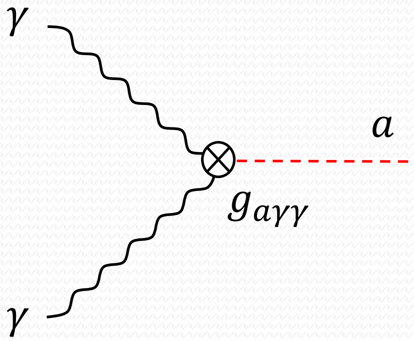


Motivations for Axion-like Particle Searches

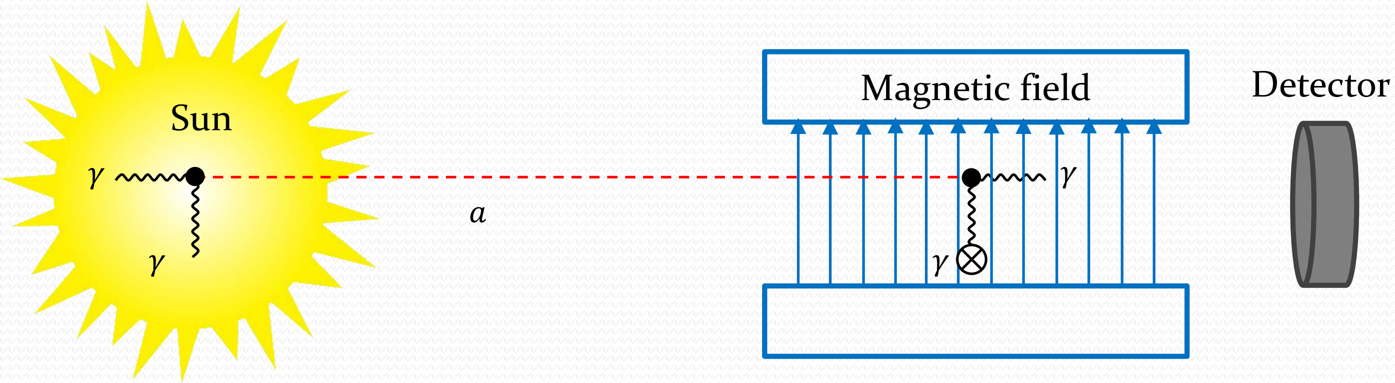
- Axion/ALP searches in the **low-energy frontier of particle physics** (vs. new physics searches at the LHC in the (high-)energy frontier of particle physics) ⇒ Axion/ALP searches in the **intensity frontier of particle physics**

- 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, ALP-gluon coupling, ALP-nucleon coupling.

$$\mathcal{L}_{\rm int} \supset -\frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$



ALP Searches: Helioscopes

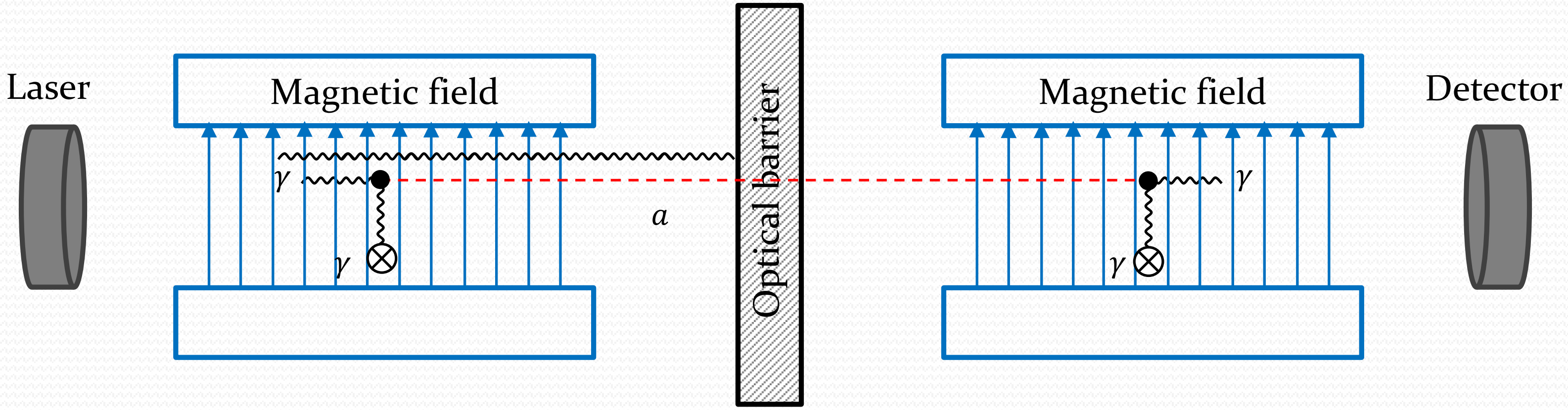


❑ Plenty of photons inside the Sun

$\Rightarrow$ Large signal flux expected

[CAST experiment]

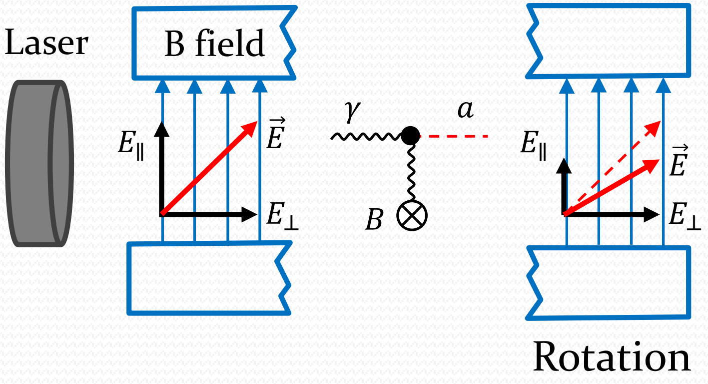
ALP Searches: Light-Shining-through-Wall (LSW)



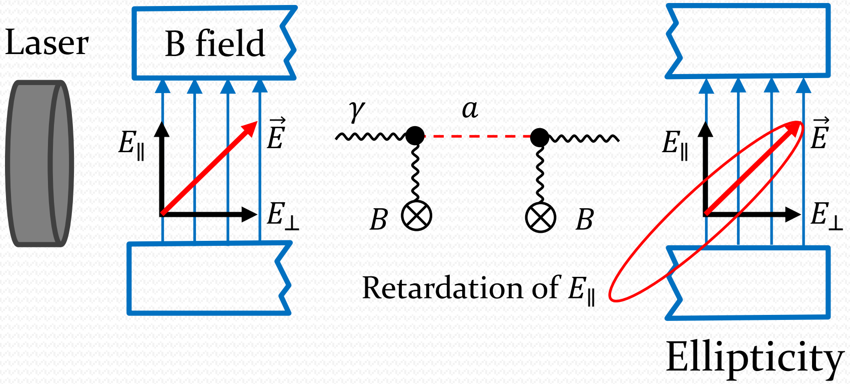
- ☐ Lab-produced ALP search, i.e., direct probe
- ☐ High intensity laser beam available
  - ⇒ Large signal flux expected
- ☐ Accessible mass range set by the energy of the laser

[ALPS experiment]

ALP Searches: Polarization Experiments

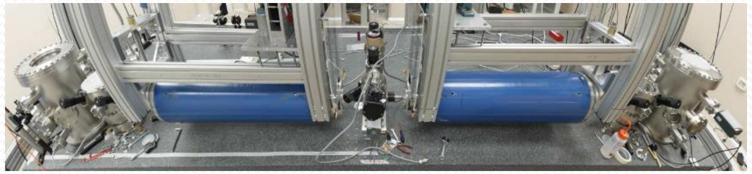


Rotation



Ellipticity

- ☐ 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 $\gamma \to a$ conversion) and phase delayed (due to $\gamma \to a \to \gamma$), resulting in sizable rotation and ellipticity, respectively.



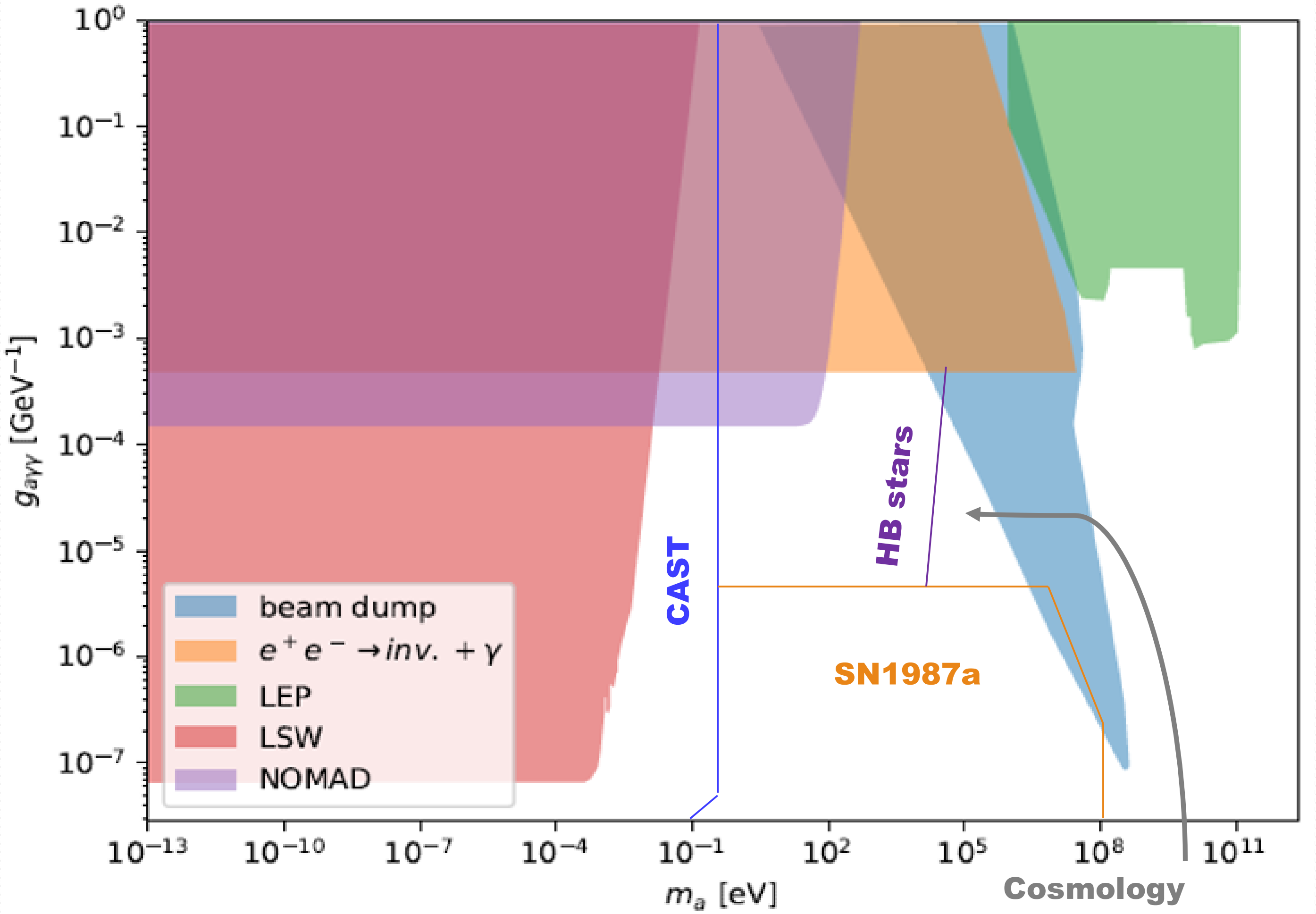
[PVLAS experiment]

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!

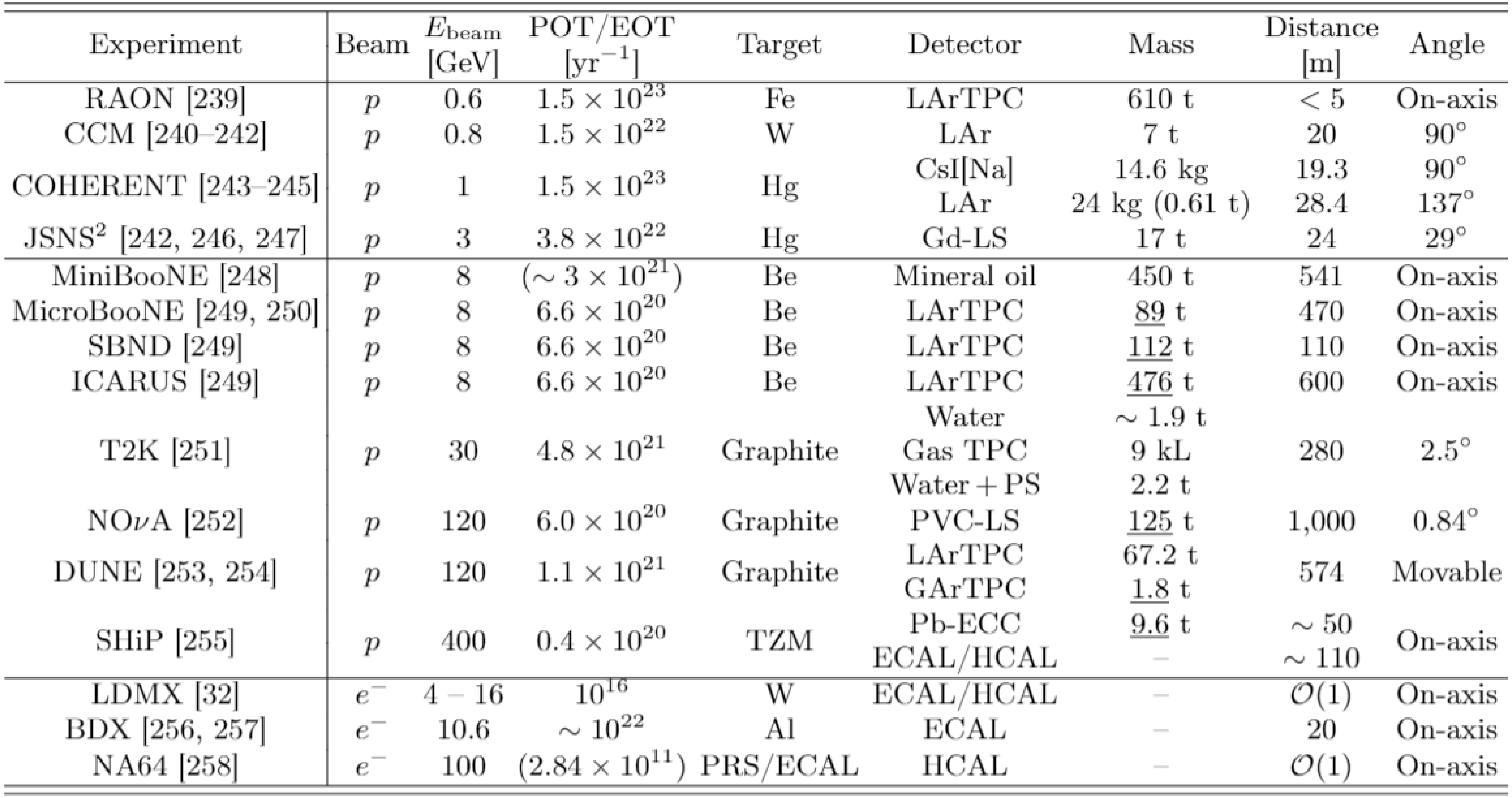
Current Limits from Lab-Produced ALP Searches



Why Neutrino Experiments?

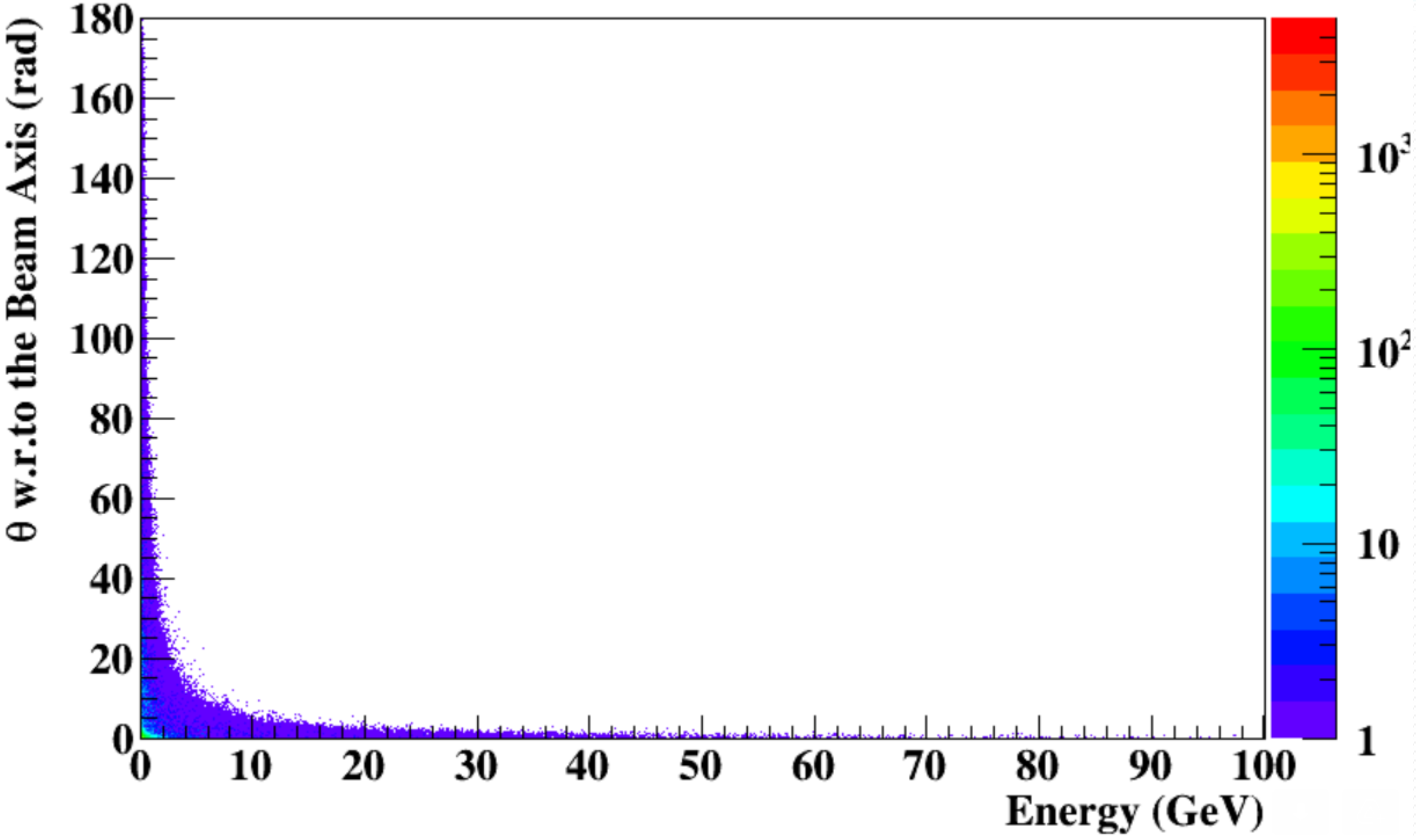
- ✓ **High Intensity**: Not only neutrinos but also photons, which may create axion/ ALP, are copiously produced.
- ✓ **“Bonus” Physics Case**: The same experimental setup is used for studying neutrino-sector physics (e.g., neutrino oscillations, CEvNS) and ALP physics.
- ✓ **Complementarity**: The ALP searches at neutrino experiments can provide complementary information in exploring relevant parameter space.

A List of Beam-Dump Experiments



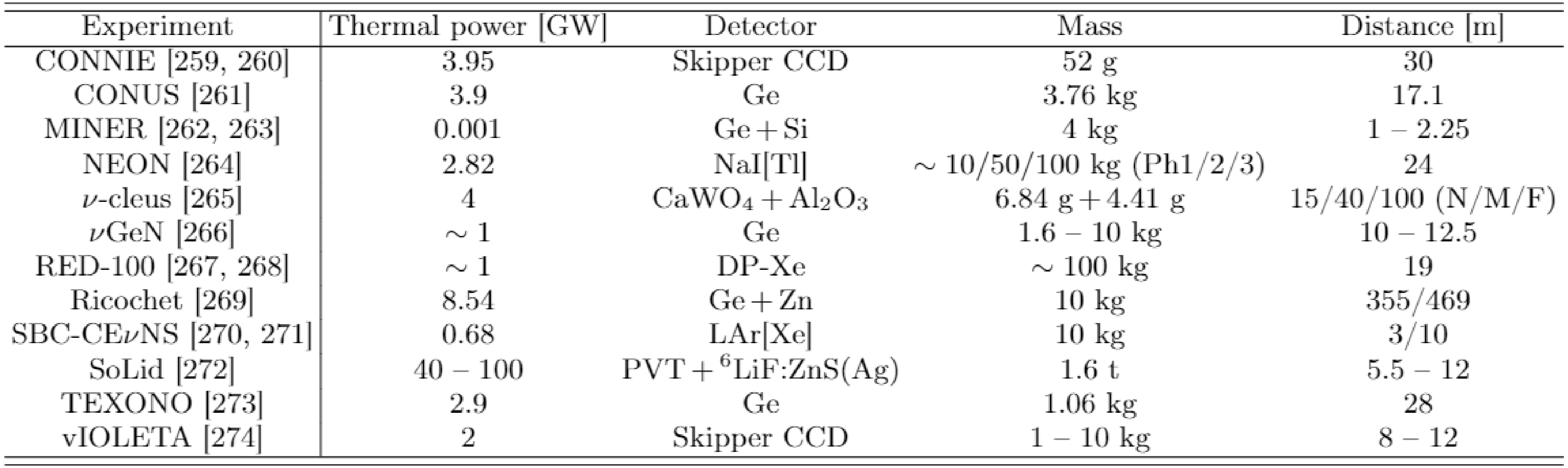
Experiment	Beam	E_{beam} [GeV]	POT/EOT [yr^{-1}]	Target	Detector	Mass	Distance [m]	Angle
RAON [239]	p	0.6	1.5×10^{23}	Fe	LArTPC	610 t	< 5	On-axis
CCM [240–242]	p	0.8	1.5×10^{22}	W	LAr	7 t	20	90°
COHERENT [243–245]	p	1	1.5×10^{23}	Hg	CsI[Na] LAr	14.6 kg 24 kg (0.61 t)	19.3 28.4	90° 137°
JSNS^2 [242, 246, 247]	p	3	3.8×10^{22}	Hg	Gd-LS	17 t	24	29°
MiniBooNE [248]	p	8	$(\sim 3 \times 10^{21})$	Be	Mineral oil	450 t	541	On-axis
MicroBooNE [249, 250]	p	8	6.6×10^{20}	Be	LArTPC	89 t	470	On-axis
SBND [249]	p	8	6.6×10^{20}	Be	LArTPC	112 t	110	On-axis
ICARUS [249]	p	8	6.6×10^{20}	Be	LArTPC	476 t	600	On-axis
T2K [251]	p	30	4.8×10^{21}	Graphite	Water Gas TPC Water + PS	~ 1.9 t 9 kL 2.2 t	280	2.5°
NOνA [252]	p	120	6.0×10^{20}	Graphite	PVC-LS	125 t	1,000	0.84°
DUNE [253, 254]	p	120	1.1×10^{21}	Graphite	LArTPC GArTPC	67.2 t 1.8 t	574	Movable
SHiP [255]	p	400	0.4×10^{20}	TZM	Pb-ECC ECAL/HCAL	9.6 t –	~ 50 ~ 110	On-axis
LDMX [32]	e^-	4 – 16	10^{16}	W	ECAL/HCAL	–	$\mathcal{O}(1)$	On-axis
BDX [256, 257]	e^-	10.6	$\sim 10^{22}$	Al	ECAL	–	20	On-axis
NA64 [258]	e^-	100	(2.84×10^{11})	PRS/ECAL	HCAL	–	$\mathcal{O}(1)$	On-axis

Photon Flux as Neutrino Experiments



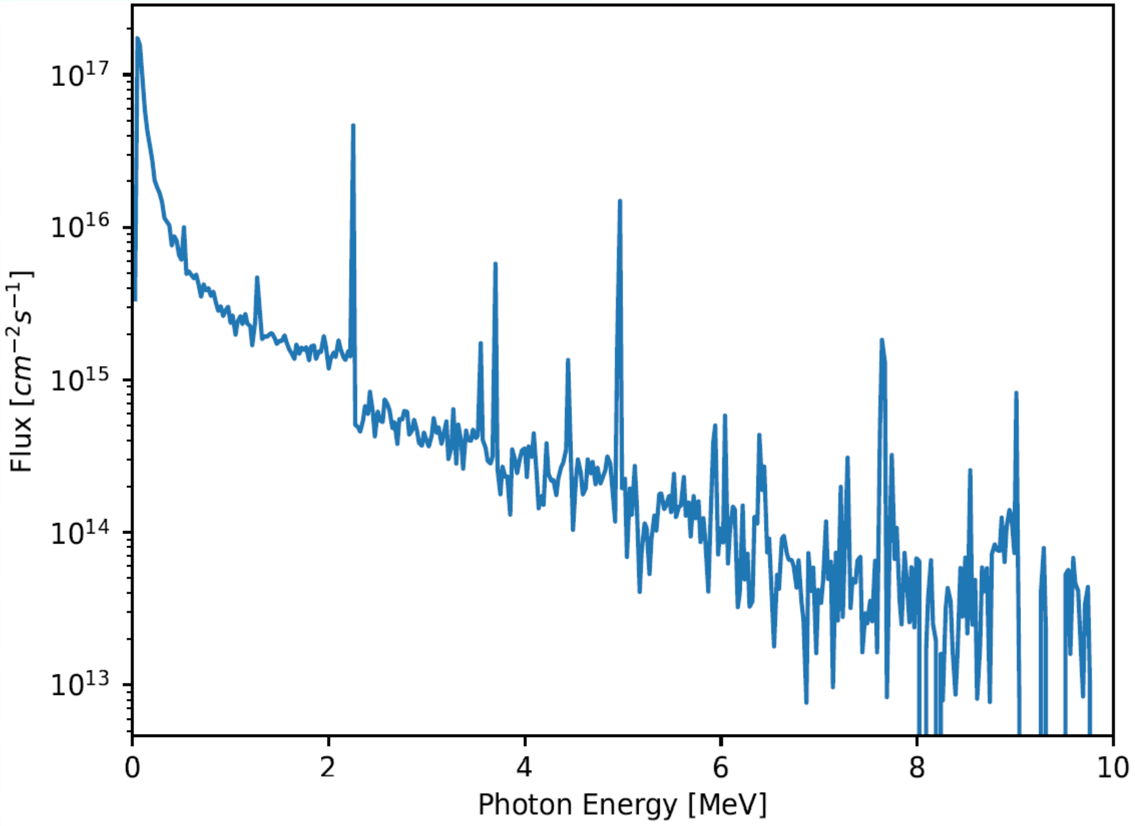
- ☐ Expected photon flux based on a GEANT simulation for a MW DUNE-like experiment: $\sim 10^{23}$ photons/yr.
- ☐ Cascade photons, photons from meson decays etc included.

A List of Reactor Neutrino Experiments



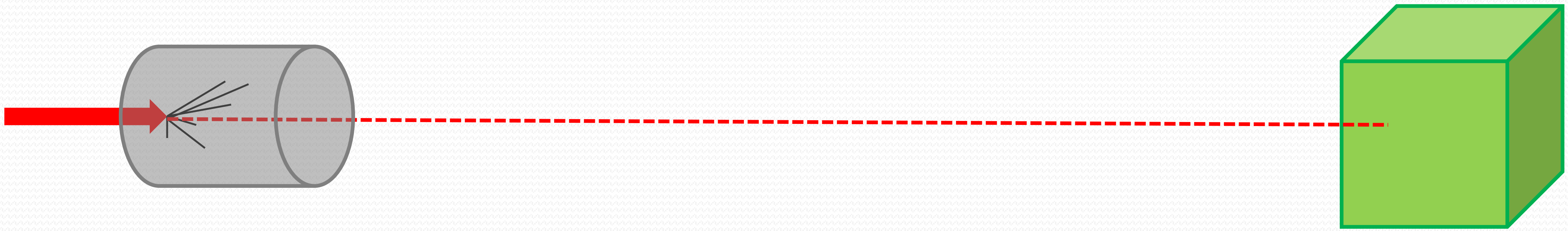
Experiment	Thermal power [GW]	Detector	Mass	Distance [m]
CONNIE [259, 260]	3.95	Skipper CCD	52 g	30
CONUS [261]	3.9	Ge	3.76 kg	17.1
MINER [262, 263]	0.001	Ge + Si	4 kg	1 – 2.25
NEON [264]	2.82	NaI[Tl]	$\sim$ 10/50/100 kg (Ph1/2/3)	24
ν-cleus [265]	4	CaWO$_4$ + Al$_2$O$_3$	6.84 g + 4.41 g	15/40/100 (N/M/F)
νGeN [266]	$\sim$ 1	Ge	1.6 – 10 kg	10 – 12.5
RED-100 [267, 268]	$\sim$ 1	DP-Xe	$\sim$ 100 kg	19
Ricochet [269]	8.54	Ge + Zn	10 kg	355/469
SBC-CEνNS [270, 271]	0.68	LAr[Xe]	10 kg	3/10
SoLid [272]	40 – 100	PVT + ^{6}LiF:ZnS(Ag)	1.6 t	5.5 – 12
TEXONO [273]	2.9	Ge	1.06 kg	28
vIOLETA [274]	2	Skipper CCD	1 – 10 kg	8 – 12

Photon Flux at Reactors



- ❑ Expected photon flux based on a GEANT simulation for a MW MINER-like reactor: ~10^{19} photons/s.
- ❑ Cascade photons, photons from isotope decays etc included.

ALP: Production to Detection



ALP production

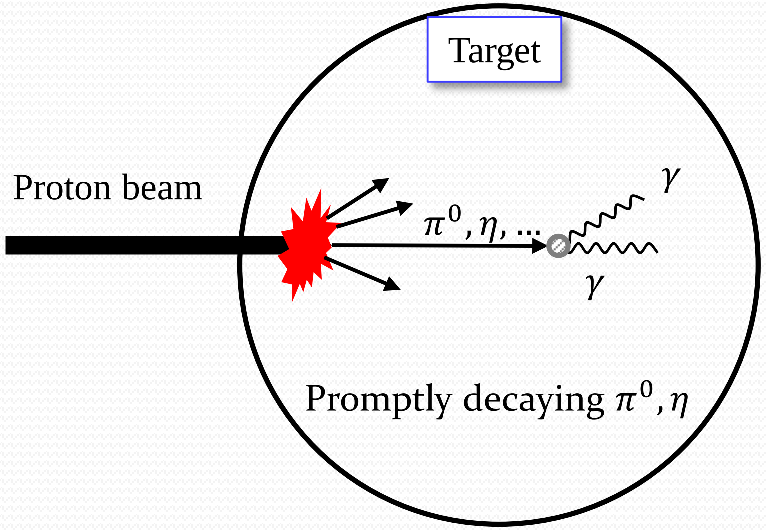
ALP transportation

ALP detection

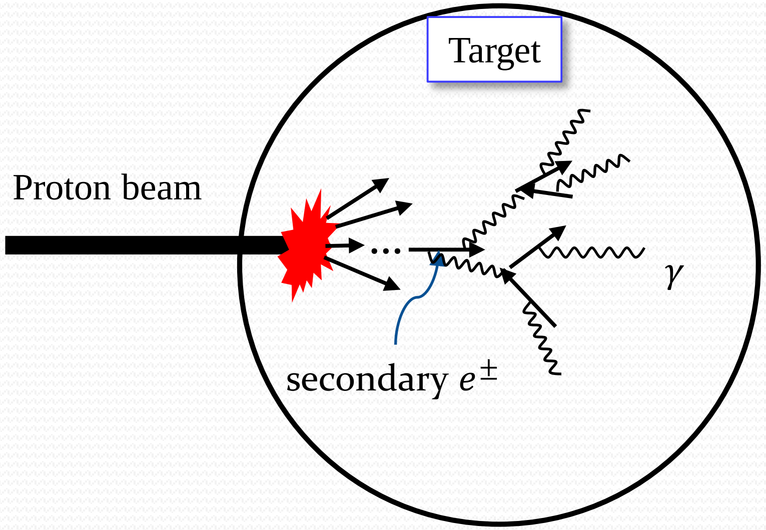
$$P_{\text{prod}} \quad \times \quad P_{\text{tran}} \quad \times \quad P_{\text{det}}$$

Production of ALP: Sources of Photons

Meson decays



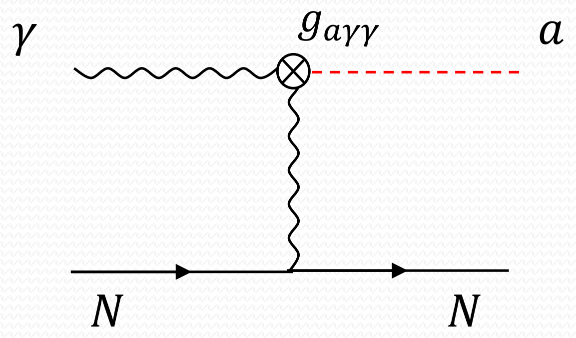
Cascade photons



- **Dedicated simulation using e.g., GEANT** is needed to **describe the production of cascade photons** inside the target material while standard event generators, e.g., PYTHIA, can describe the production of mesons.
- See also [Verbinski, Weber, and Sund, PRC **7**, 1173] for photons at reactors.

Production of ALP: 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!

$$\frac{d\sigma_P^p}{d\cos\theta} = \frac{1}{4} g_{a\gamma\gamma}^2 \alpha Z^2 F^2(t) \frac{|\vec{p}_a|^4 \sin^2\theta}{t^2} \qquad t = (p_1 - k_1)^2 = m_a^2 + E_\gamma(E_a - |\vec{p}_a|\cos\theta)$$

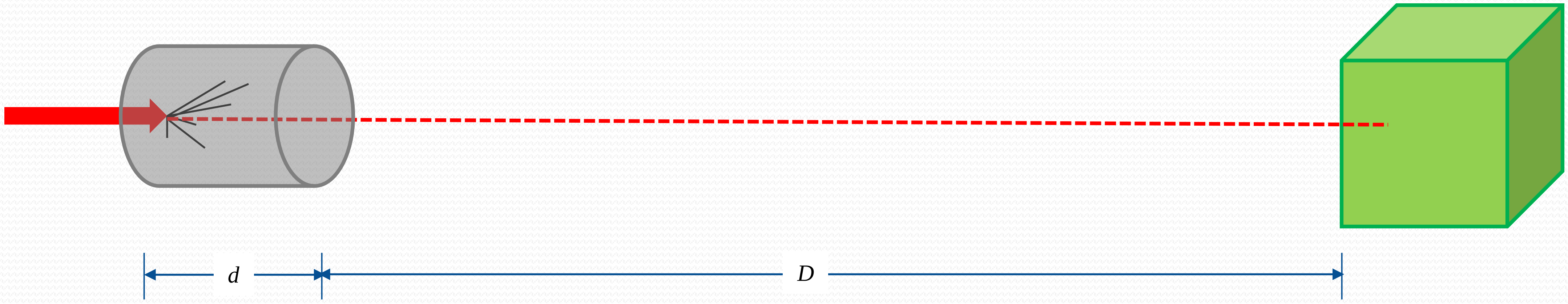
Z: atomic number, α: fine structure constant, $F(t)$: form factor, E_γ: incident photon energy,
$|\vec{p}_a|$: magnitude of the outgoing three-momentum of the ALP at the angle θ relative to the incident photon momentum

$$P_{\rm prod} = \frac{\sigma_{\rm prod}^{\rm fid}}{\sigma_{\rm SM} + \sigma_{\rm prod}^{\rm tot}}$$

- $\sigma_{\rm prod}^{\rm fid}$: production cross-section of ALPs moving toward the detector
- $\sigma_{\rm prod}^{\rm tot}$: total production cross-section of ALPs
- $\sigma_{\rm SM}$: cross-section of photon standard interactions (e.g., pair conversion)

Transportation of ALP

- ❑ ALP should neither interact in the target/dump or reactor core nor decay before reaching the detector of interest.



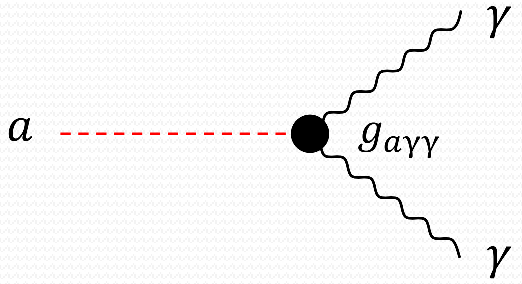
$$P_{\text{tran}} = \underbrace{\exp(-\rho_T\, \sigma_{\text{prod}}^{\text{tot}} d)}_{\approx 1 \text{ in most experiments}} \exp\left(-\frac{D}{\bar{\ell}_a^{\text{lab}}}\right)$$

- ρ_T: scattering target number density in the target/dump or reactor core
- $\sigma_{\text{scat}}^{\text{tot}}$: ALP scattering cross-section in the target/dump or reactor core
- d: thickness of target/dump or reactor core
- D: distance to the detector of interest
- $\bar{\ell}_a^{\text{lab}}$: lab-frame mean decay length of ALP

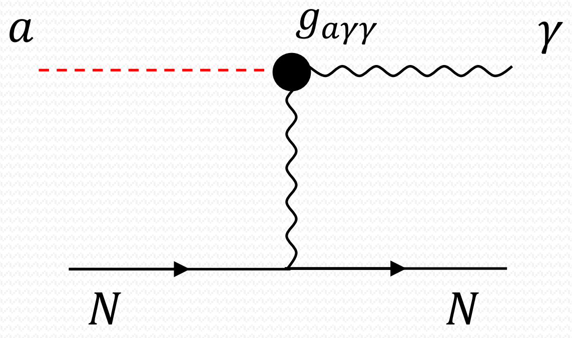
Detection of ALP

- (Broadly speaking) three channels available

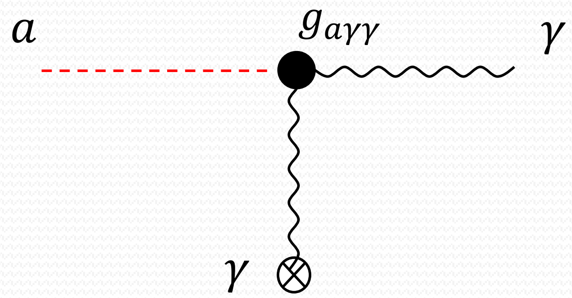
Decay



Scattering

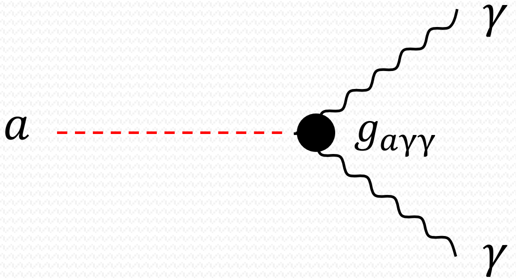


Conversion



Detection of ALP: Decay

- ☐ ALP decays in flight to a couple of photons which can be detected at detectors.



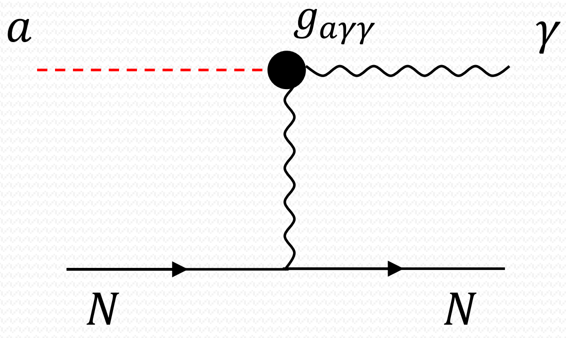
$$\Gamma(a \to \gamma\gamma) = \frac{g_{a\gamma\gamma}^2 m_a^3}{64\pi}$$

$$P_{\text{det}}^{\text{decay}} = 1 - \exp\left(-\frac{L_{\text{det}}}{\bar{\ell}_a^{\text{lab}}}\right)$$

- $\bar{\ell}_a^{\text{lab}}$: lab-frame mean decay length of ALP
- L_{det}: length of detector

Detection of ALP: Scattering

- ☐ ALP can interact with a nucleus via the inverse Primakoff process, $a + N \to \gamma + N$ [Dent, Dutta, **DK**, Liao, Mahapatra, Sinha, Thompson (2019); Brdar, Dutta, Jang, **DK**, Shoemaker, Tabrizi, Thompson, Yu (2020)]



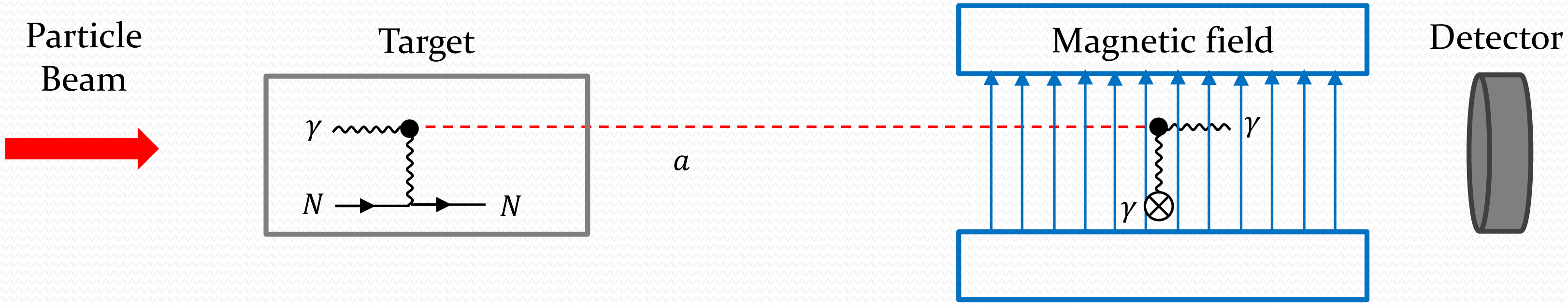
$$\frac{d\sigma^{s}_{\rm det}}{d\cos\theta} = \frac{1}{2} g^2_{a\gamma\gamma} \alpha Z^2 F^2(t) \frac{|\vec{p}_a|^4 \sin^2\theta}{t^2}$$

$$P^{\rm scat}_{\rm det} = n_T \, \sigma^{\rm fid}_{\rm det} \, L_{\rm det}$$

- n_T: scattering target number density
- $\sigma^{\rm fid}_{\rm det}$: fiducial ALP scattering cross-section
- $L_{\rm det}$: length of magnetic field region

- ☐ Useful in probing lighter ALPs whose decay rarely happen.

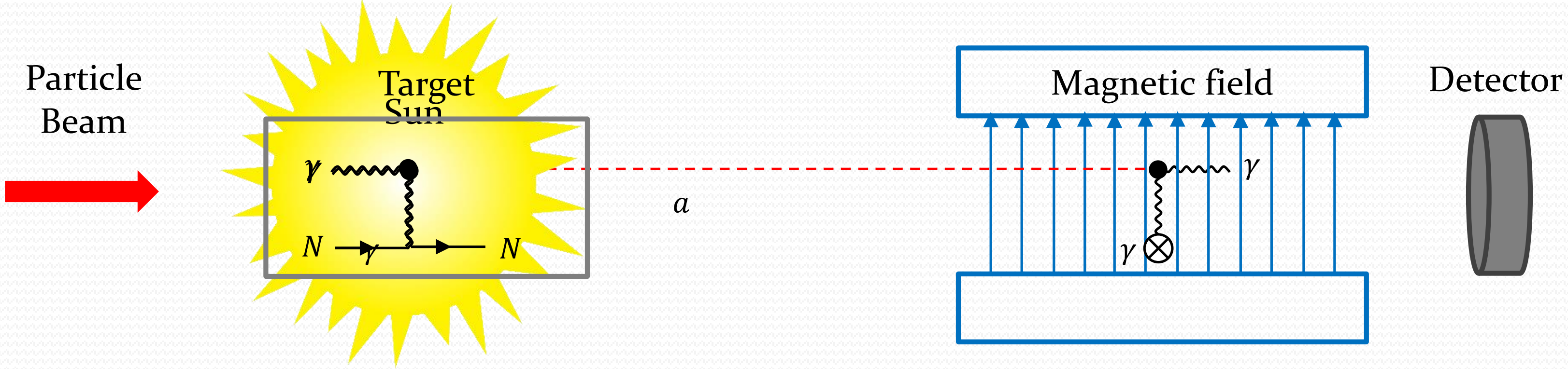
Detection of ALP: PASSAT – Main Idea



- ☐ Particle Accelerator helioScopes for Slim Axion-like-particle deTection (PASSAT): Utilizing the principle of the axion helioscope but replaces ALPs produced in the Sun with those produced in a target material. [Bonivento, **DK**, Sinha (2019)]

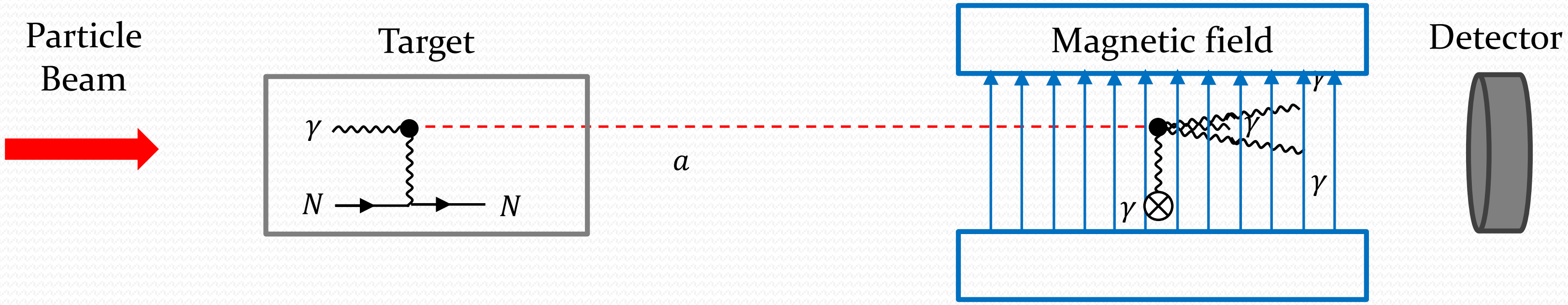
⇒ ALP-photon conversion: **Probing light (slim) ALPs** that are otherwise inaccessible to laboratory-based experiments which rely on ALP decay, and complements astrophysical probes that are more model-dependent.

PASSAT vs CAST



Sun is replaced by the **target material** as the source of ALPs.

PASSAT vs Beam-Dump Exp.

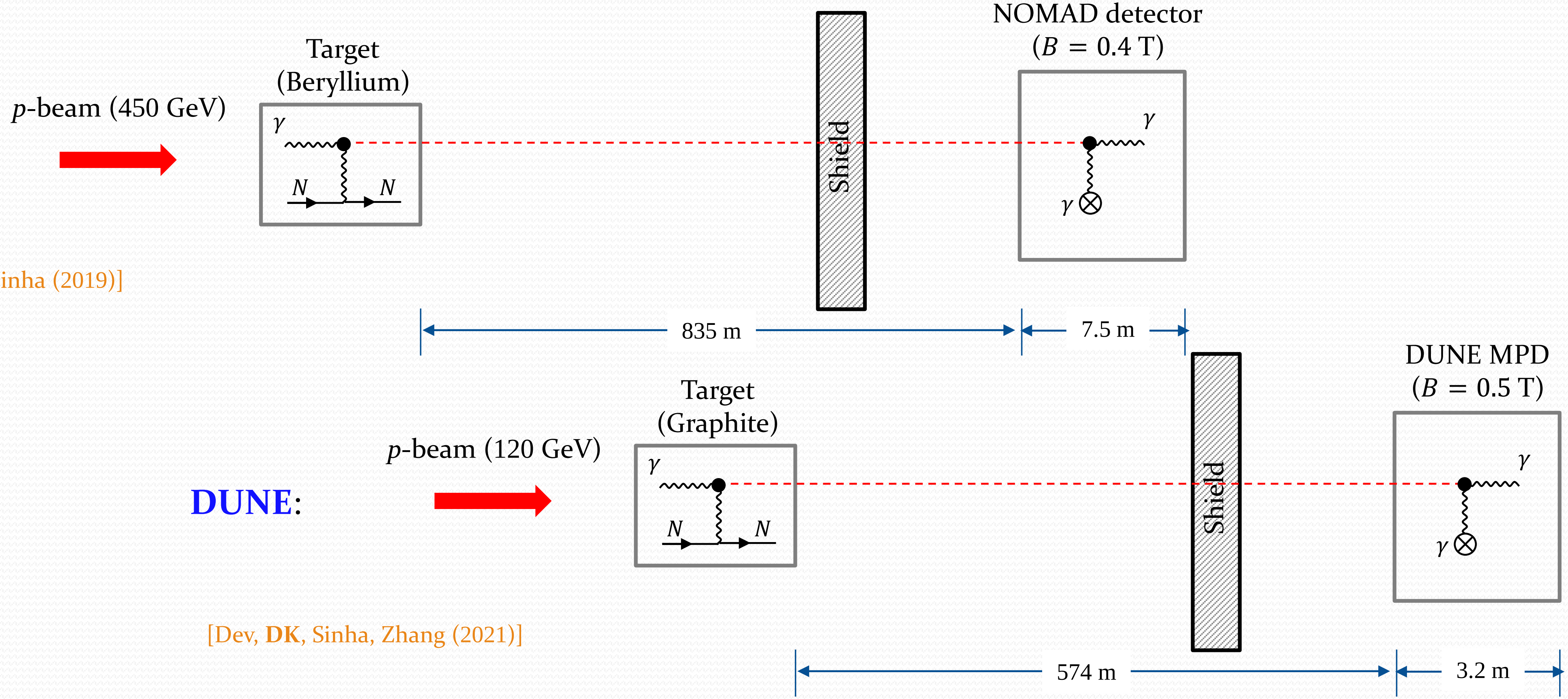


ALP decay process is replaced by the **ALP conversion process**.

Detection of ALP: Probability of Conversion

$$P_{\text{det}}^{\text{conv}} = \left(\frac{g_{a\gamma\gamma} B L_{\text{det}}}{2}\right)^2 \underbrace{\left(\frac{2}{q L_{\text{det}}}\right)^2 \sin^2\left(\frac{q L_{\text{det}}}{2}\right)}_{\text{Form factor reflecting the coherence of the conversion}} \quad \text{with} \quad q = 2\sqrt{\left(\frac{m_a^2}{4E_a}\right)^2 + \left(\frac{1}{2} g_{a\gamma\gamma} B\right)^2}.$$

Applications: NOMAD and DUNE MPD



NOMAD:

p-beam (450 GeV)

Target
(Beryllium)

Shield

NOMAD detector
(B = 0.4 T)

835 m

7.5 m

[Bonivento, **DK**, Sinha (2019)]

DUNE:

p-beam (120 GeV)

Target
(Graphite)

Shield

DUNE MPD
(B = 0.5 T)

574 m

3.2 m

[Dev, **DK**, Sinha, Zhang (2021)]

Event Rate Calculation

For a given photon (say, *i*th photon)

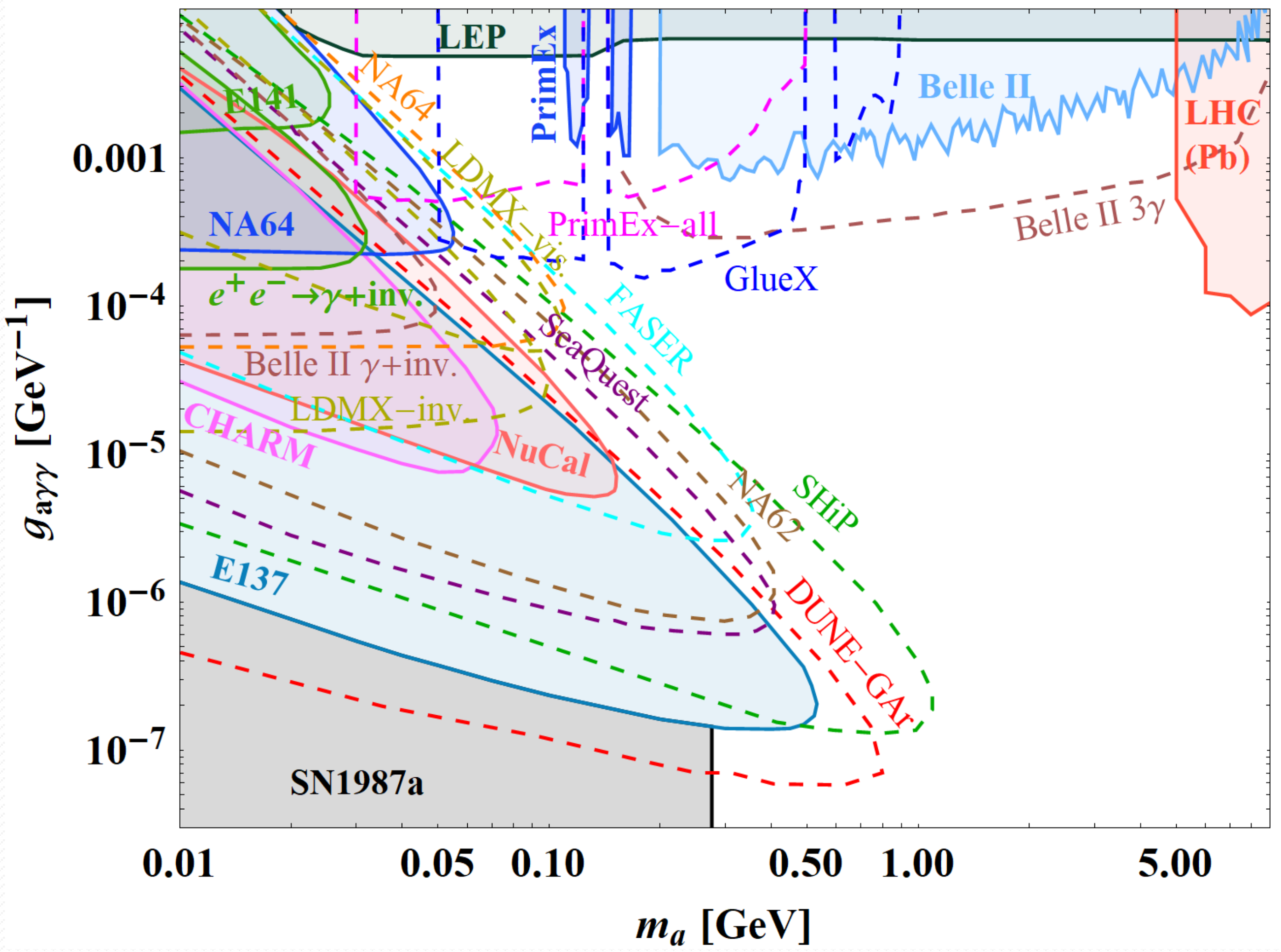
$$P_i = P_{\mathrm{prod},i} \times P_{\mathrm{tran},i} \times P_{\mathrm{det},i}$$

For a sufficiently large $N\gamma$

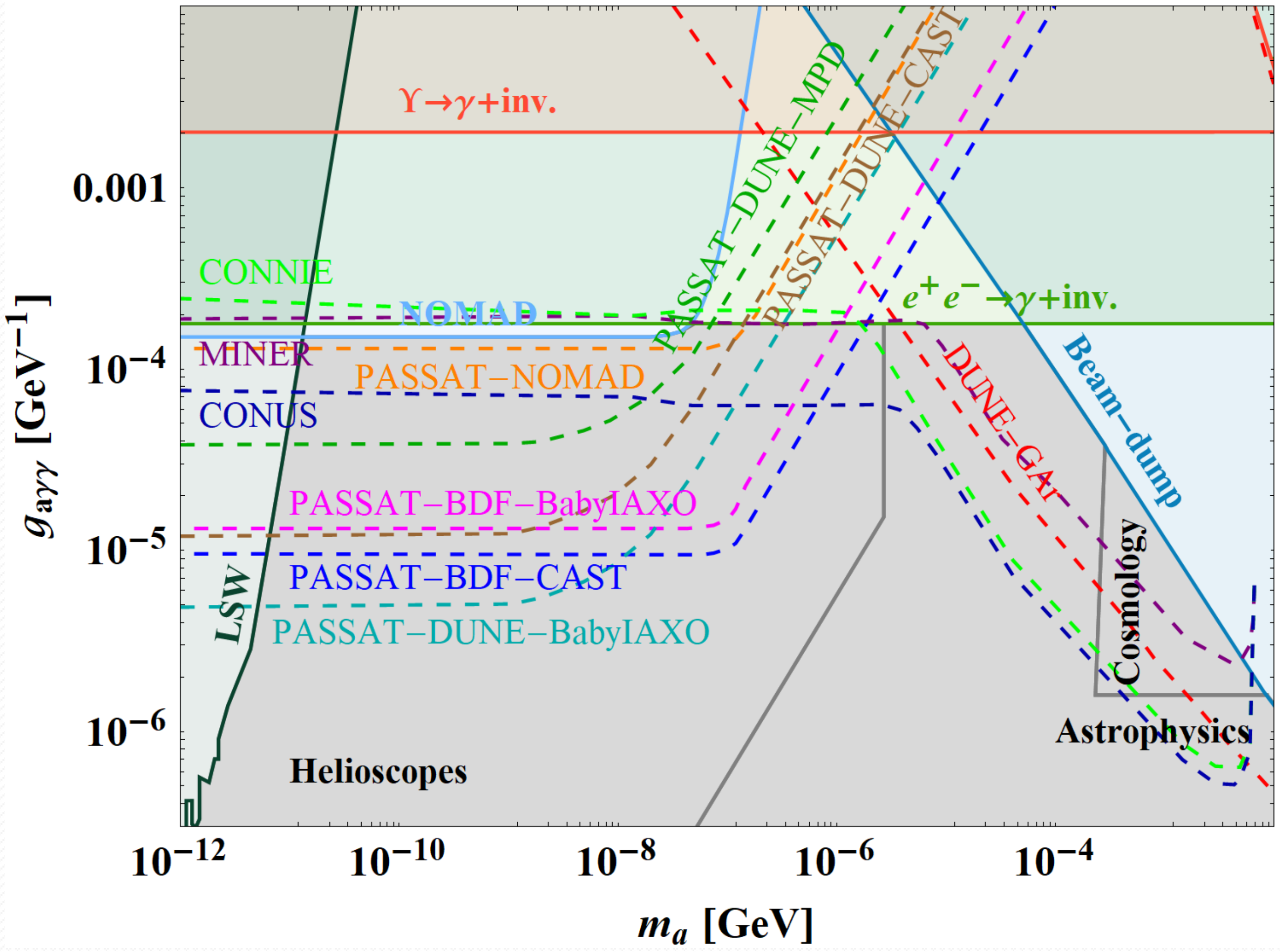
$$\langle P \rangle = \frac{1}{N_\gamma} \sum_{i=1}^{N_\gamma} P_i$$

$$N_{\mathrm{tot}} = N_{\mathrm{tot},\gamma} \langle P \rangle$$

Sensitivity Reaches: Decay Channel



Sensitivity Reaches: Scattering and Conversion Channels



Conclusions

- ☐ A more dedicated estimate of the photon flux in the target/dump or reactor core allows us to estimate ALP sensitivity reaches at neutrino experiments more precisely.
- ☐ The well-known ALP search in the decay channel and the proposed search strategies using ALP scattering and conversion should allow us to probe a wide range of parameter space that none of the lab-produced ALP search experiments have ever explored.
- ☐ The three channels are complementary to one another and are expected to provide a complete picture in investigating ALP parameter space.
- ☐ The expected experimental sensitivity for the ALP-photon coupling covers regions constrained by astrophysical searches, providing conservative and complementary limits.