Potential Physics Topics at DAMSA

TEXAS A&M UNIVERSITY
Physics & Astronomy

Doojin Kim (doojin.kim@tamu.edu)

Physics Opportunities at Beam Dump Facility in PIP-II and Beyond

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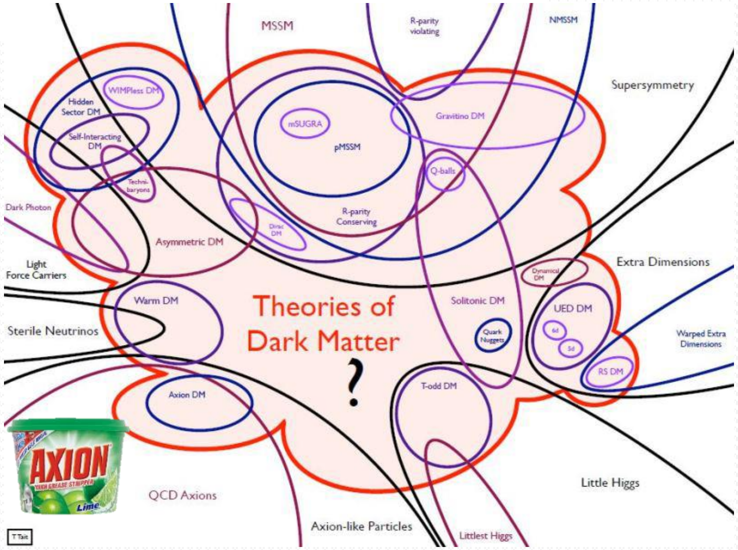
Axions and Axion-like Particles

QCD axion for solving dynamically the strong CP problem

[Peccei, Quinn, PRL (1977); Weinberg, PRL (1978); Wilczek, PRL (1978); Kim, PRL (1979); Shifman, Vainshtein, Zakharov, NPB (1980); Dine, Fischler, Srednicki, PLB (1981); Zhitnitsky, SJNP (1980)]

$$\mathcal{L} = \theta \frac{1}{16\pi^2} F^a_{\mu\nu} \tilde{F}^{\mu\nu a}$$



$\Rightarrow$ Extended to more general pseudo-scalar **axion-like particles** (ALPs) which share similar properties/pheno. wiith QCD axion [Arvanitaki, Dimopoulos, Dubovsky, Kaloper, March-Russell, PRD (2010); Cicoli, Goodsell, Ringwald, JHEP (2012)]

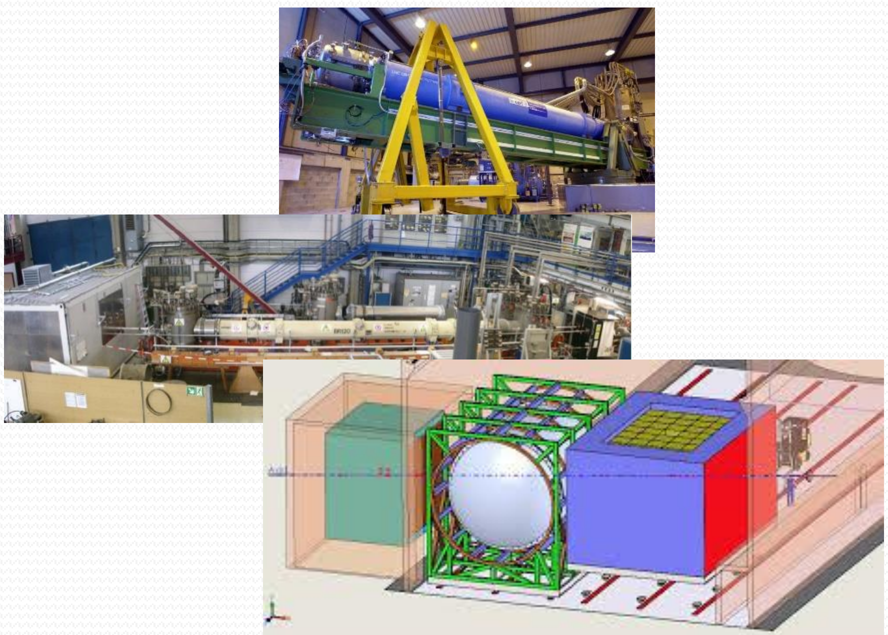
Axion/Axion-like Particle Searches

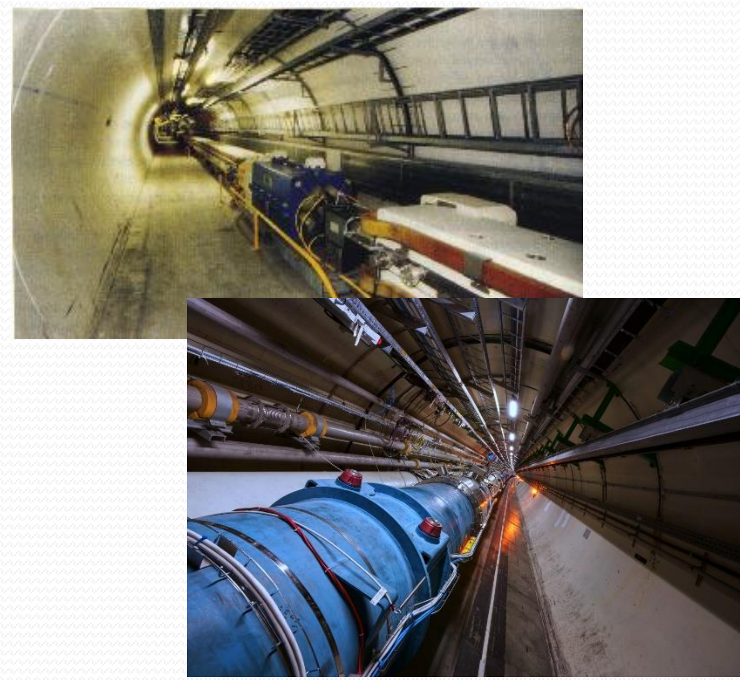
Low-energy & **intensity** frontier

High-energy frontier

Axion/ALP searches (e.g., DAMSA)

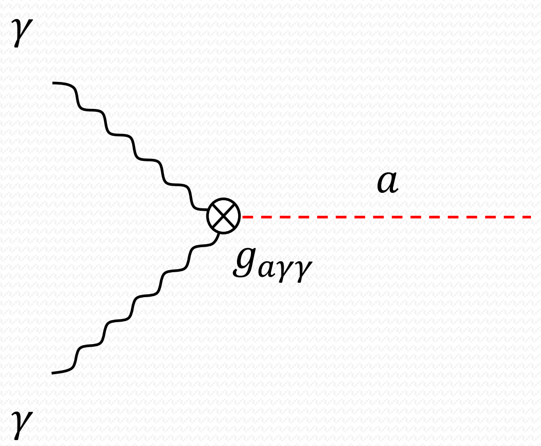
E.g. Heavy resonance searches



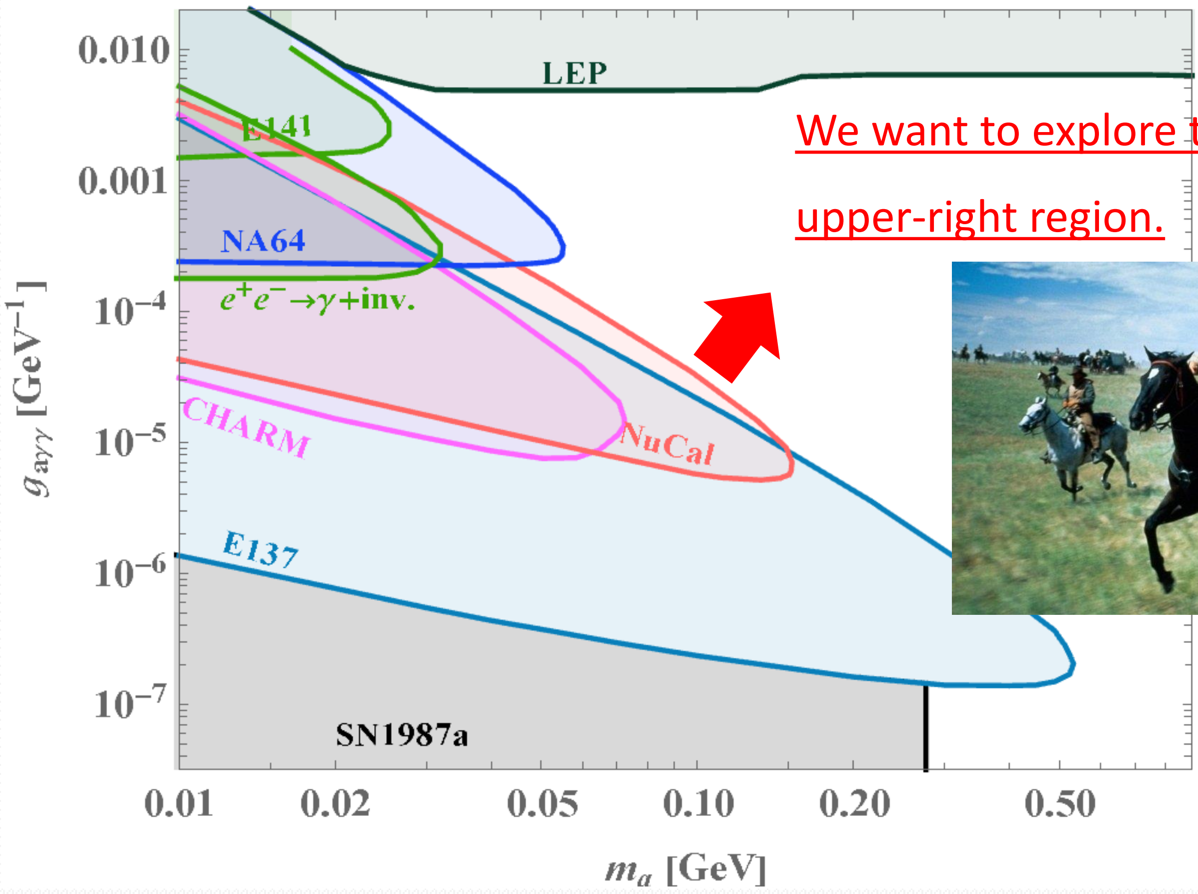


Search for ALPs Interacting with Photons

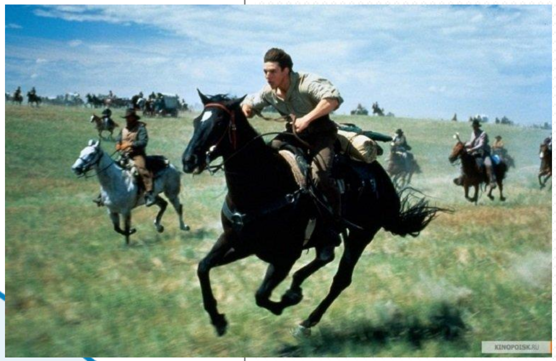
$$\mathcal{L}_{\rm int} \supset -\frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$



Existing Efforts in the Search for ALPs



We want to explore toward the upper-right region.



[E.g., A review on axions/ALPs, Fortin, Guo, Harris, **DK**, Sinha, Sun, arXiv:2102.12503]

Basic Strategies and Challenges

The upper-right region features larger coupling and larger mass.

⬇

ALPs in this region tends to decay rather promptly (unless significantly boosted).

⬇

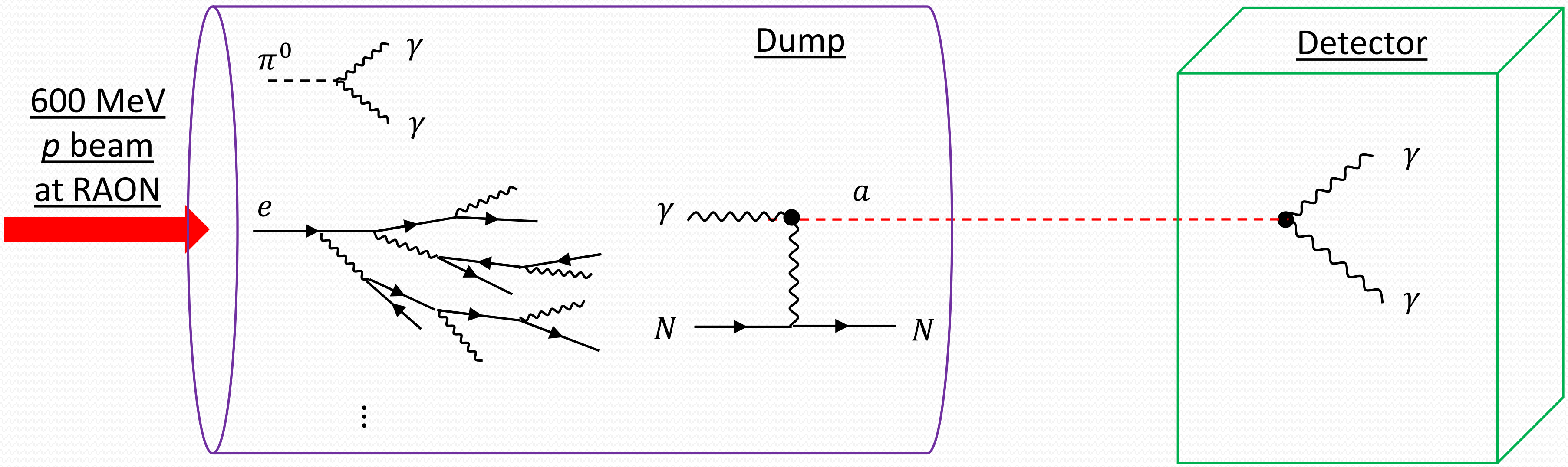
Most of ALPs decay away before reaching the detector area.

⬇

Our proposed strategies

- Placing the detector system close to the source point $\Rightarrow$ Neutron-induced backgrounds? vs. featureful signal
- Lower beam energy $\Rightarrow$ Suppressed ν-induced backgrounds
- Intense beam $\Rightarrow$ Copious signal production

ALP Search in DAMSA at RAON



- Meson decays
- E&M showers
- …

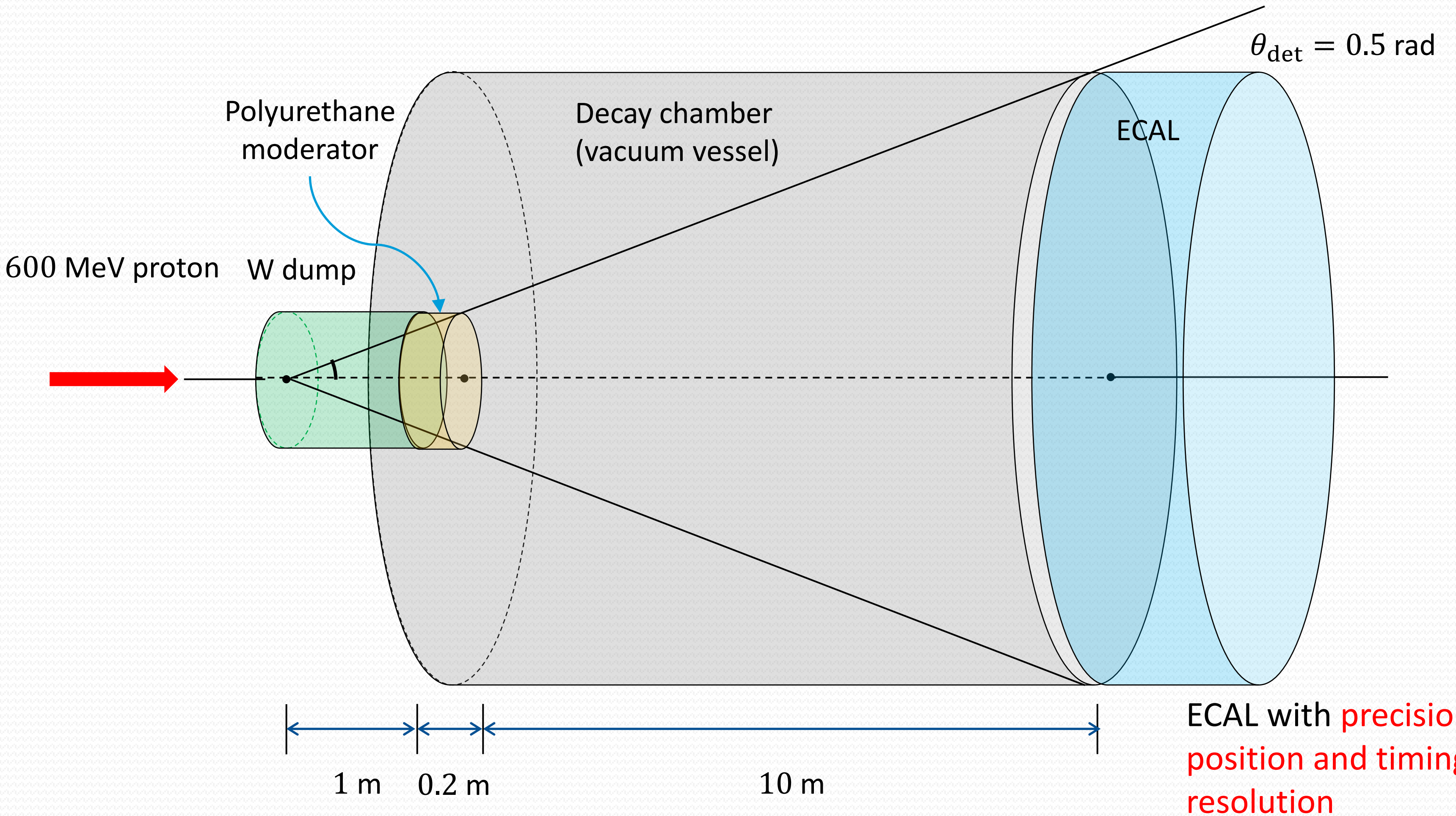
Production of photons

ALP production by Primakoff process

ALP detection by its decay to two photons

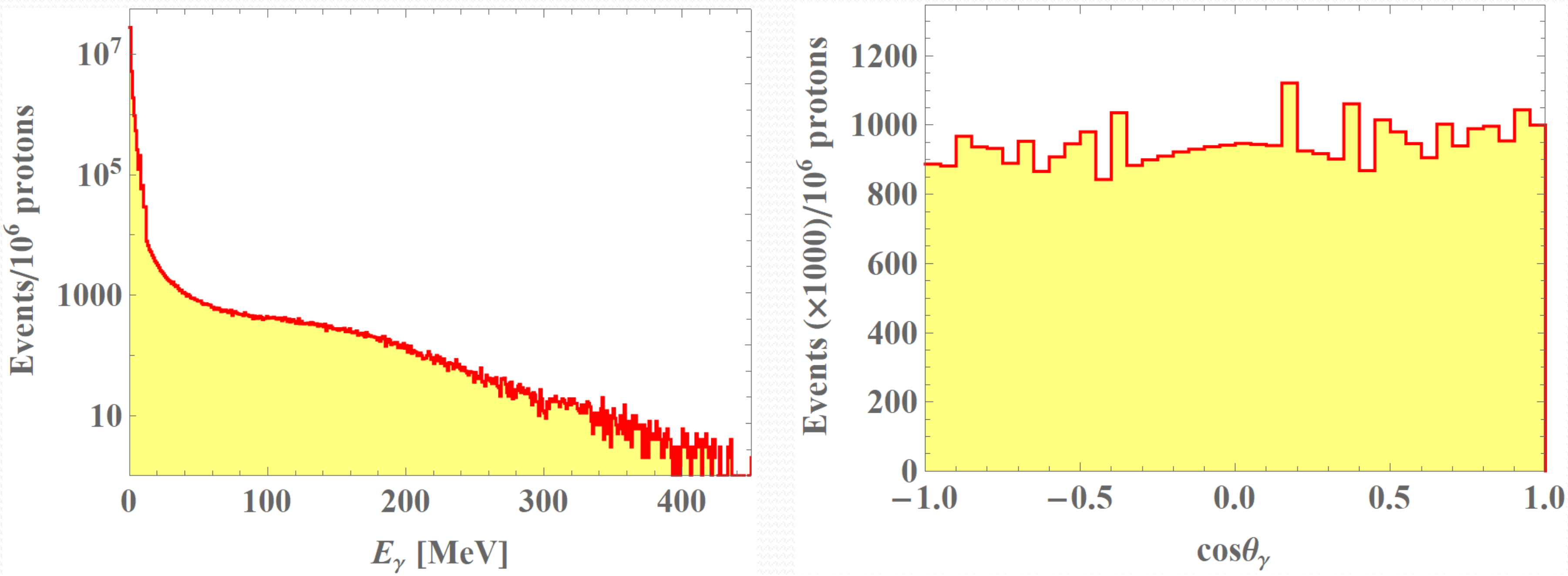
DAMSA: **D**ump-produced **A**boriginal **M**atter **S**earches at an **A**ccelerator

Schematic Design of the DAMSA Experiment



ECAL with precision position and timing resolution

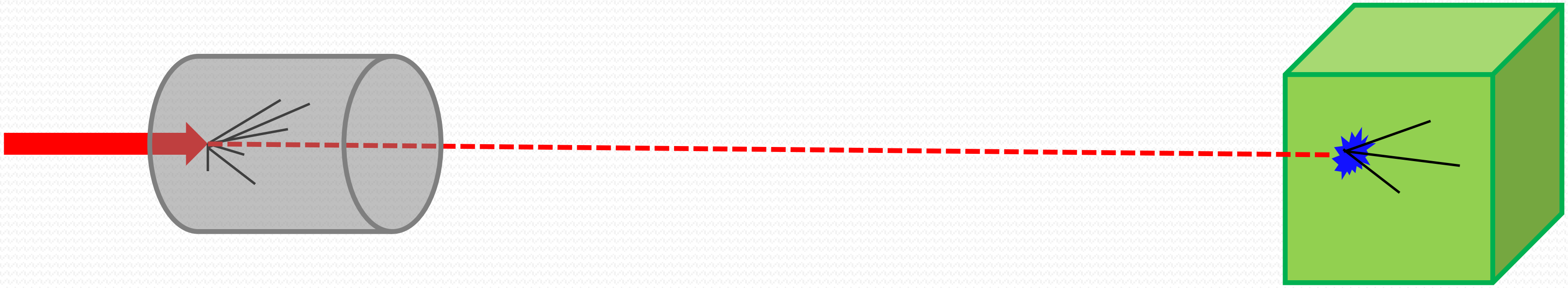
Photon Flux at the DAMSA Target



- GEANT4 simulation with QGSP_BIC and 1M protons injected on a cylindrical ($d \times l = 1\text{m} \times 1\text{m}$) tungsten dump $\Rightarrow$ $\sim$800 photons/proton
- Expected annual protons on dump: $\sim 1.5 \times 10^{23} \Rightarrow \sim 5.8 \times 10^{25}$ photons/year (with a 50% duty factor)

ALP: Production to Detection

ALP production | ALP transportation | ALP detection

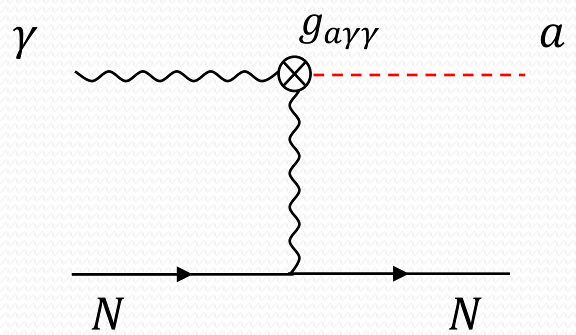


$$P_{\text{prod}} \times P_{\text{tran}} \times P_{\text{det}}$$

ALP Production: Primakoff Process

Primakoff process,

$$\gamma(p_1) + N(p_2) \to a(k_1) + N(k_2)$$



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

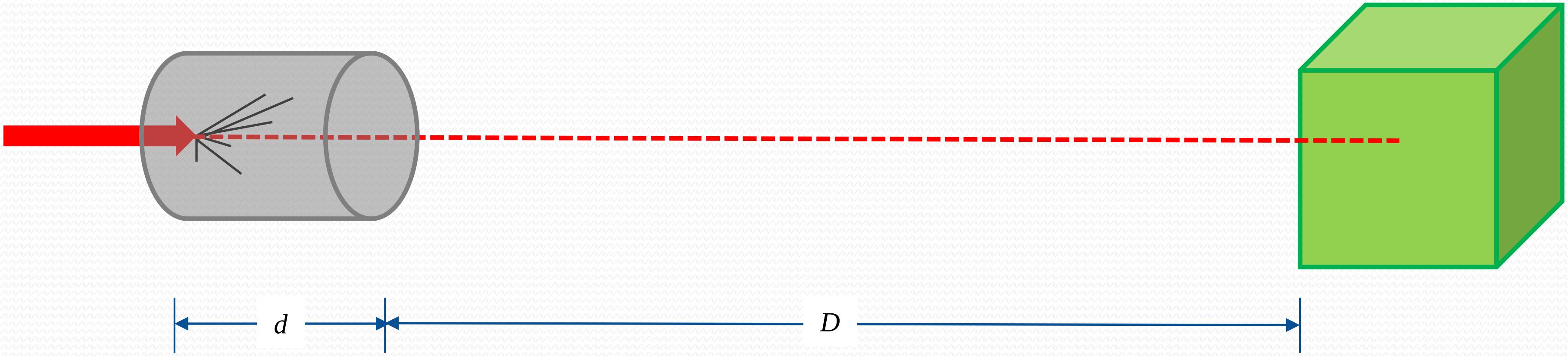
$$\frac{d\sigma_P^p}{d\cos\theta} = \frac{1}{4} g_{a\gamma\gamma}^2 \alpha Z^2 F^2(t) \frac{|\vec{p}_a|^4 \sin^2\theta}{t^2}$$

$$t = (p_1 - k_1)^2 = m_a^2 - 2E_\gamma(E_a - p_a \cos\theta_a)$$

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

Transportation of ALP

ALP should neither interact in the target nor decay before reaching the detector.



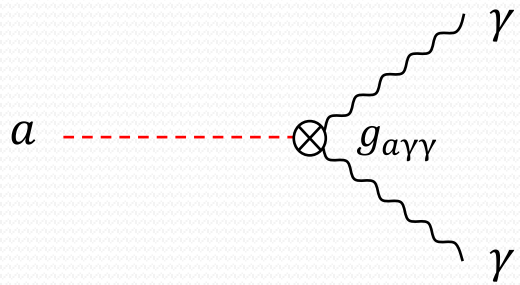
$$P_{\text{tran}} = \underbrace{\exp(-\rho_T\, \sigma_{\text{prod}}^{\text{tot}} d)}_{\approx 1 \text{ in most experiments}} \exp\left(-\frac{D}{\bar{\ell}_a^{\text{lab}}}\right)$$

≈ 1 in most experiments

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

ALP Detection: ALP Decay

ALP decays in flight to a couple of photons which are detected by the DAMSA detector.



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

E.g., with $E_a = 0.3$ GeV, $m_a = 0.1$ GeV and $g_{a\gamma\gamma} = 10^{-5}\ \mathrm{GeV}^{-1}$, the mean decay length is 1.1 meters.

Calculating Signal Detection Rate

$$S = \int dE_\gamma \frac{dN_\gamma}{dE_\gamma} \cdot \frac{\sigma_P^p}{\sigma_{SM} + \sigma_P^p} \cdot P_{\mathrm{surv}}^\gamma \cdot P_{\mathrm{decay}}^\gamma$$

ALP flux at the detector location

Number of photons moving toward the detector

Competition between Primakoff production and other SM processes

ALP survival probability

$$P_{surv}^\gamma = \exp\left(-\frac{\ell_d m_a}{p_a \tau_a^\gamma}\right)$$

(ℓ_d = dump-detector distance)

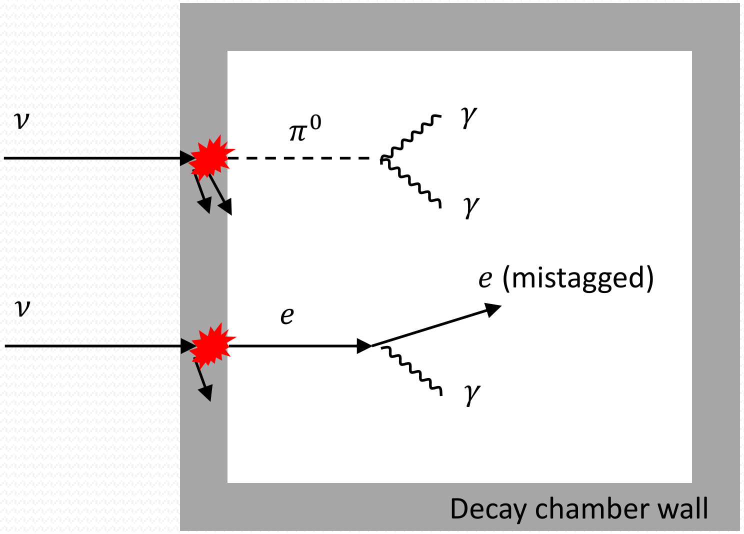
Probability of decay inside the detector volume

$$P_{\mathrm{decay}}^\gamma = 1 - \exp\left(-\frac{\Delta\ell\, m_a}{p_a \tau_a^\gamma}\right)$$

($\Delta\ell$: decay chamber length)

Background Considerations

<u>Neutrino-originating</u>

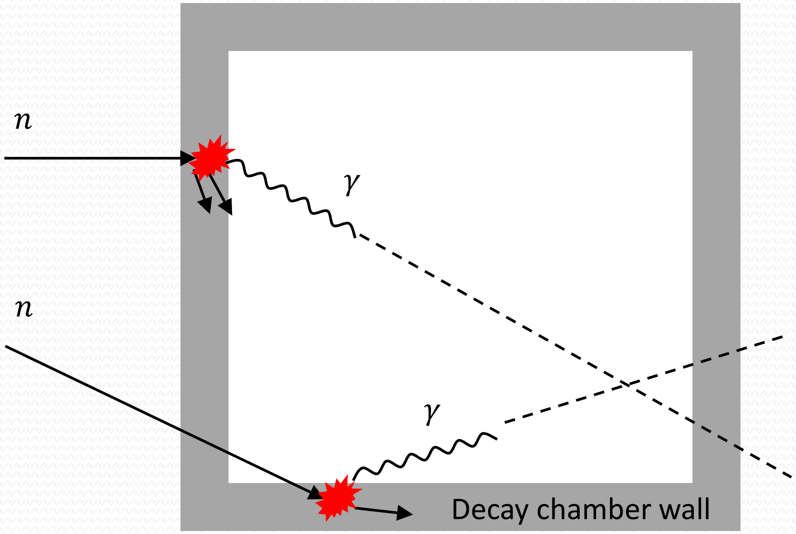


Beam energy: 600 MeV

- Suppressed production of charged pions
- Neutrinos from stopped pions and muons, resulting in an isotropic, i.e., dispersed, neutrino flux

$\Rightarrow$ **Negligible**

<u>Neutron-originating</u>



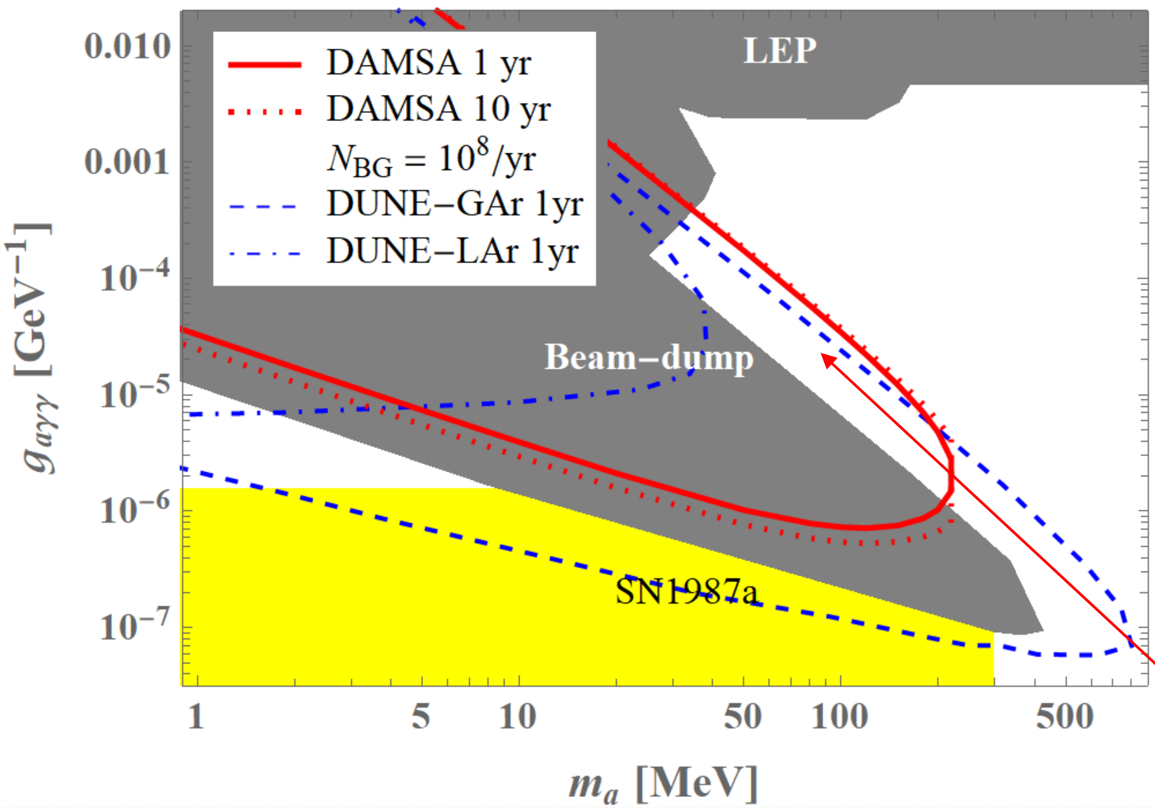
Any two photon tracks

- Accidentally crossing each other at a point in the decay chamber within detector position and timing resolutions, and
- Vector sum of their momenta traced back to the dump
- Invariant mass consistent with m_a of interest

$\Rightarrow$ **Reducible by more than 8-9 orders of magnitude**

(See Wooyoung and Jacob's talks)

Expected ALP Sensitivity Reach at DAMSA

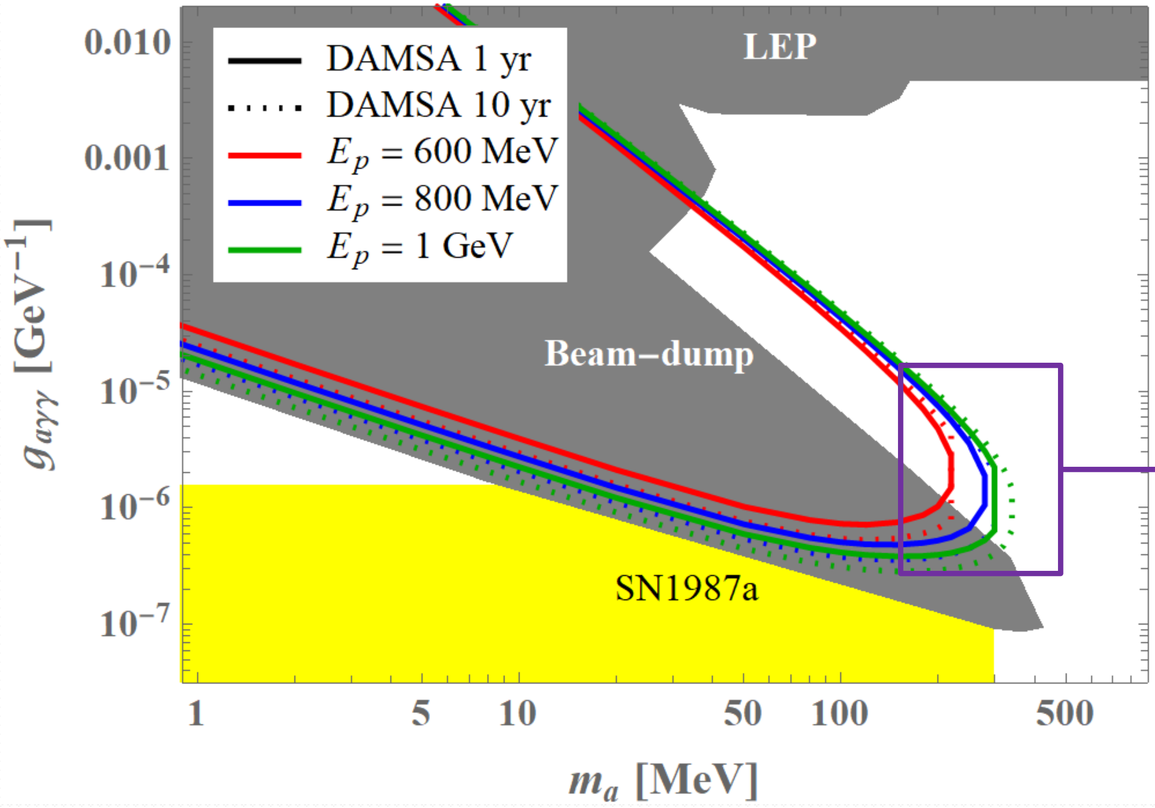


[Jang, **DK**, Kong, Kwon, Park, Ryu, Shin, Van De Water, Yang, Yu, PRD107, L031901]

- Beam energy: 600 MeV
- POTs: 1.5×10^{23} per year with a 50% duty factor
- # of BGs: 10^8 per year (see Wooyoung & Jacob's talks)
- DUNE sensitivity curves from [Brdar, Dutta, Jang, **DK**, Shoemaker, Tabrizi, Thompson, Yu, PRL126, 201801]

DAMSA can probe the ALP parameter region that has never been explored.

Expected ALP Sensitivity Reach with the PIP-II Beam



- Beam energy: 800 MeV and 1 GeV scenarios
- POTs: 1.5×10^{23} per year with a 50% duty factor for comparison purposes
- # of BGs: 10^8 per year for comparison purposes

Higher beam energies allow us to explore larger mass regions.

Conclusions

- The proton beam (at PIP-II) will **copiously produce photons** in the dump.
- An axion-like particle search was illustrated as an example physics case.
- Neutrino-origin backgrounds are **negligible** due to the low-energy beam, whereas enormous neutron-origin backgrounds can be **suppressed significantly** with the aid of a **high-capability** detector. (see also Wooyoung and Jacob's talks.)
- DAMSA can be sensitive to large-mass and large-coupling regions of ALP parameter space due to its **close proximity to the dump**.
- DAMSA at PIP-II can provide opportunities for exploring other physics cases.

Back-up

Other Planned Experiments