Axion-like Particle Searches at Rare Nuclear Isotope Accelerator Facilities

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In collaboration with W. Jang, K. Kong, Y. Kwon, J.-C. Park, M. S. Ryu, S. Shin, U.-K. Yang, and J. Yu, in progress

Axions and Axion-like Particles

QCD axion for solving dynamically the strong CP problem

[Peccei, Quinn, PRL (1977); Weinberg, PRL (1978); Wilczek, PRL (1978)]

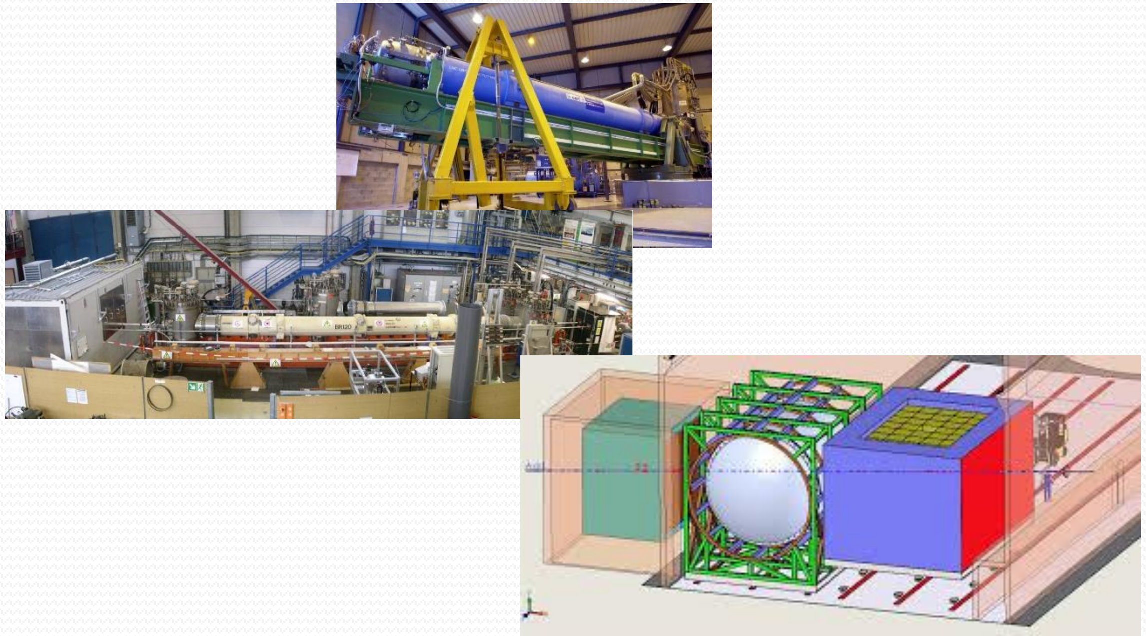
⇒ Extended to more general pseudo-scalar **axion-like particles** (ALPs) which share similar properties/pheno. wiith QCD axion

[Arvanitaki, Dimopoulos, Dubovsky, Kaloper, March-Russell, PRD (2010); Cicoli, Goodsell, Ringwald, JHEP (2012)]

Axion/Axion-like Particle Searches

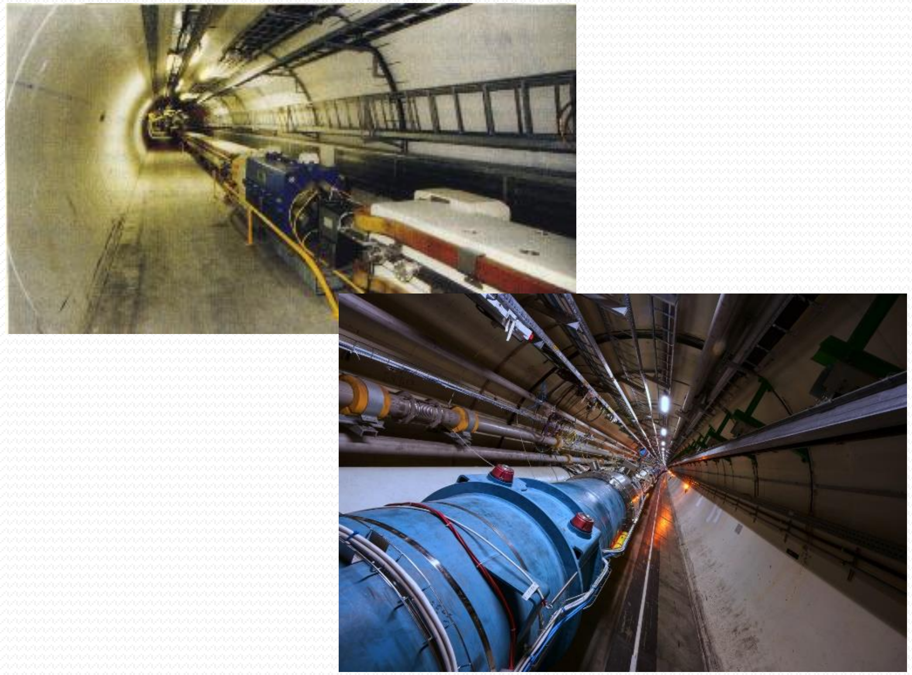
Low-energy & **intensity** frontier

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



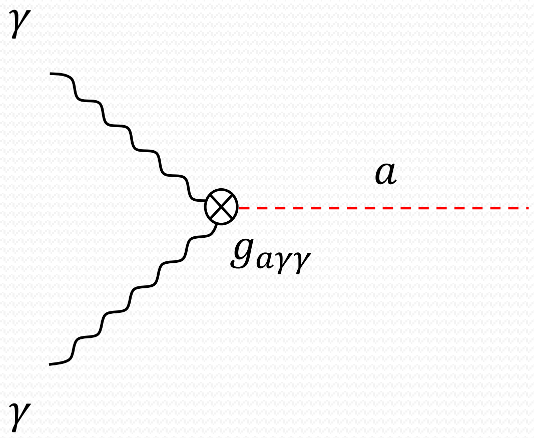
High-energy frontier

E.g. Heavy resonance searches

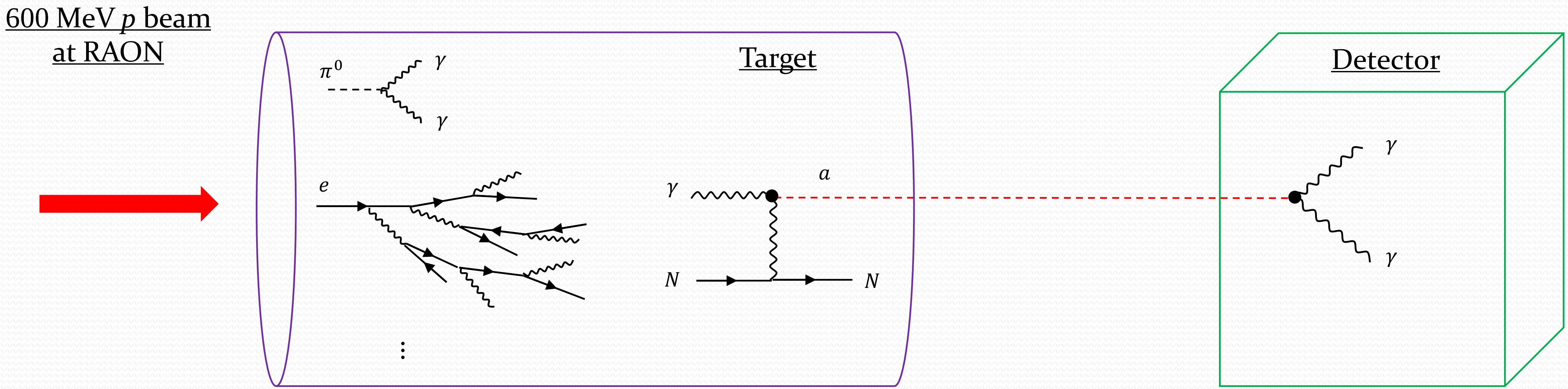


Search for ALPs Interacting with Photons

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



ALP Search in DAMSA at RAON



- Meson decays
- E&M showers
- …

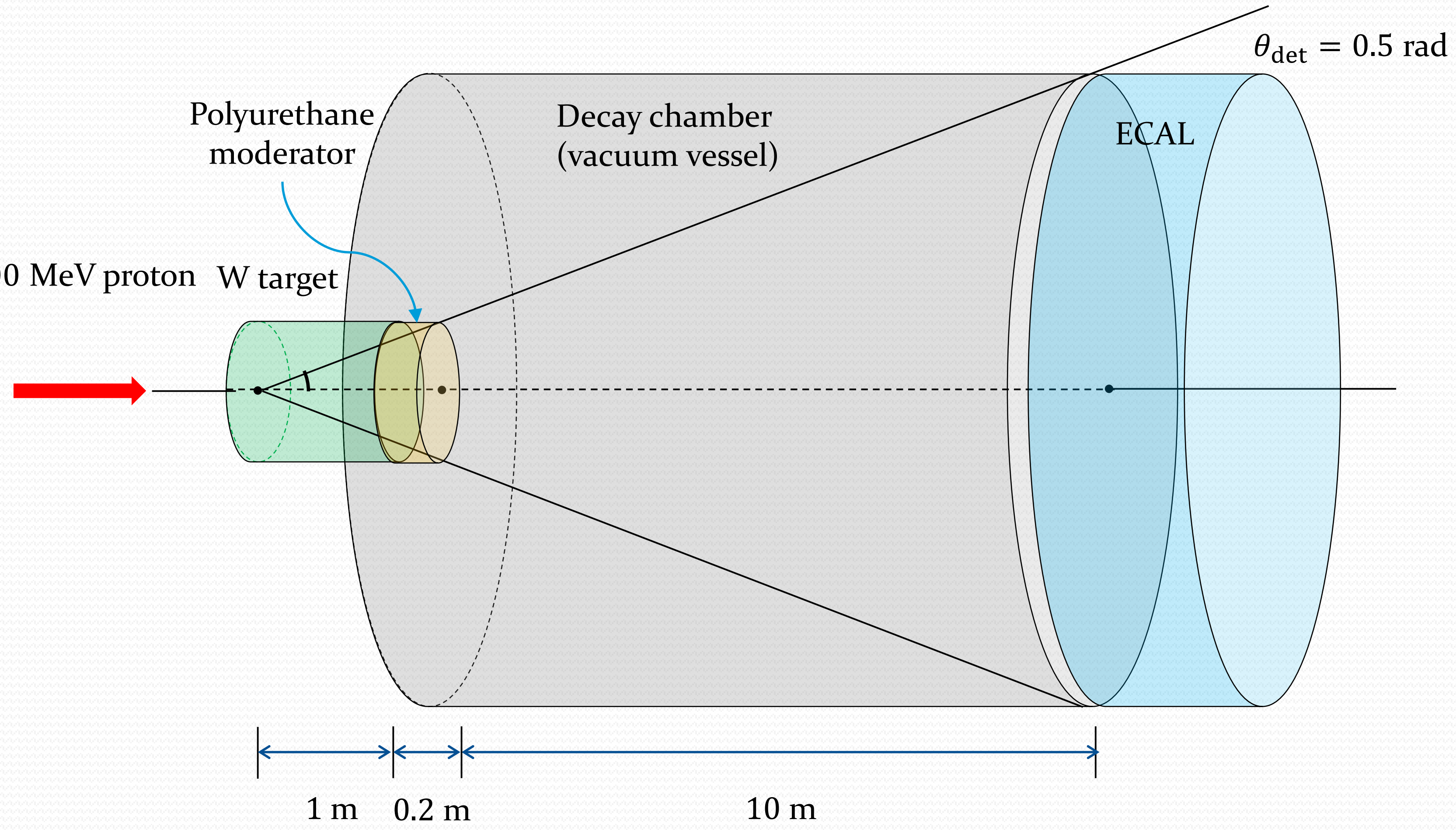
Production of photons

ALP production by Primakoff process

ALP detection by its decay to two photons

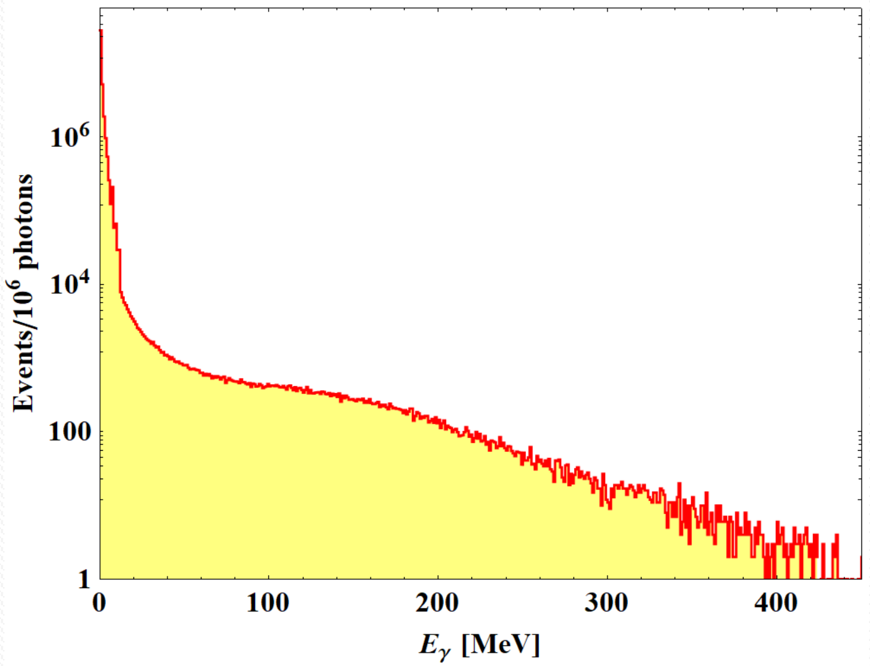
[DAMSA: **D**ump-produced **A**boriginal **M**atter **S**earches at an **A**ccelerator, see also back-up slides.]

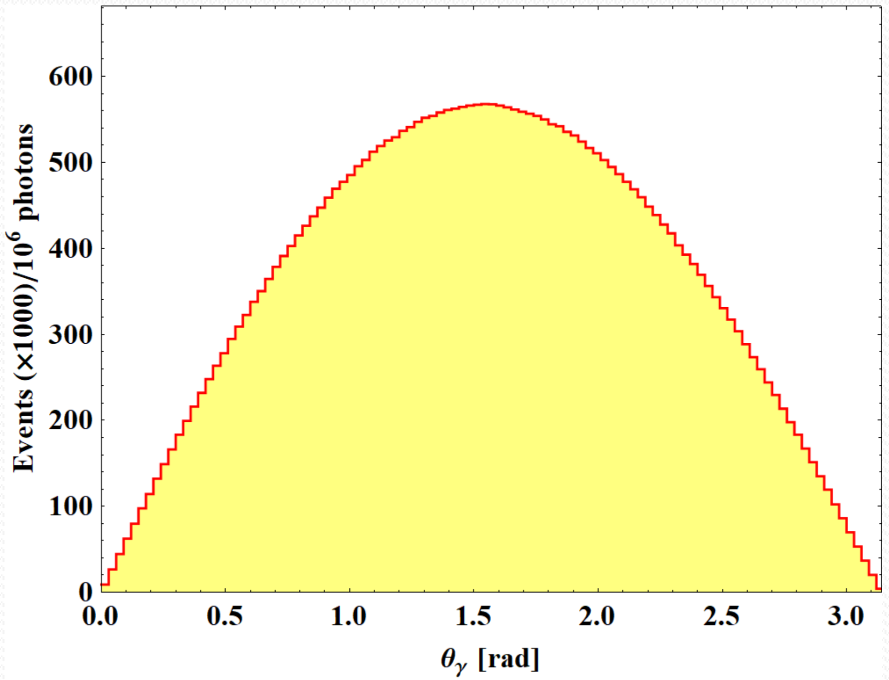
Schematic Design of the DAMSA Experiment



ECAL with precision position and timing resolution
(see Wooyoung Jang's talk)

Photon Flux at the DAMSA Target

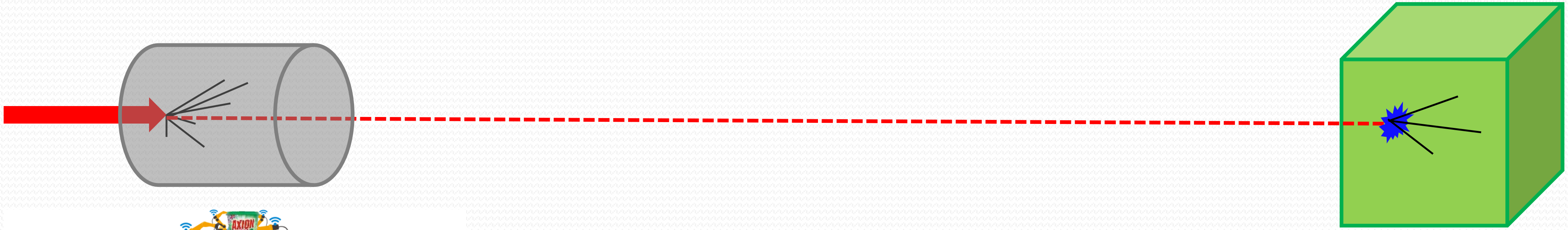




- GEANT4 simulation with QGSP_BIC and 1M protons injected on a cylindrical ($d \times l = 1\text{m} \times 1\text{m}$) W target ⇒ ~38 photons/proton
- Expected annual protons on target: $\sim 1.5 \times 10^{23}$ ⇒ $\sim 5.7 \times 10^{24}$ photons/year

ALP: Production to Detection

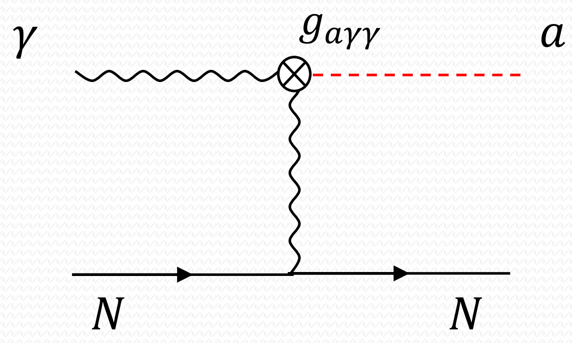
ALP production | ALP transportation | ALP detection



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

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!

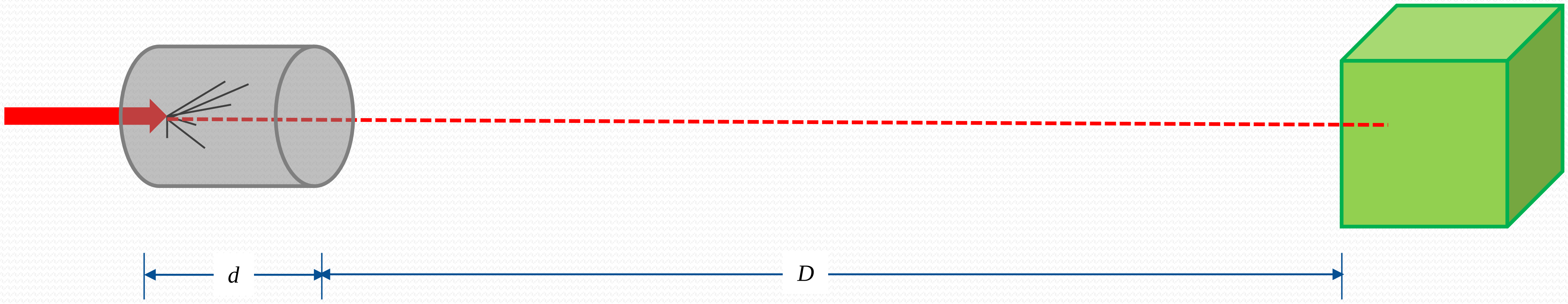
$$\frac{d\sigma_P^p}{d\cos\theta} = \frac{1}{4} g_{a\gamma\gamma}^2 \alpha Z^2 F^2(t) \frac{|\vec{p}_a|^4 \sin^2\theta}{t^2}$$

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

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

Transportation of ALP

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

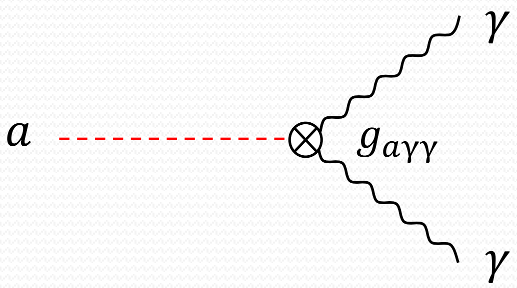


$$P_{\rm tran} = \underbrace{\exp(-\rho_T\, \sigma_{\rm prod}^{\rm tot} d)}_{\approx 1 \text{ in most experiments}} \exp\left(-\frac{D}{\bar{\ell}_a^{\rm lab}}\right)$$

- ρ_T: scattering target number density in the target
- $\sigma_{\rm scat}^{\rm tot}$: ALP scattering cross-section in the target
- d: thickness of target
- D: distance to the detector
- $\bar{\ell}_a^{\rm lab}$: 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 $g_{a\gamma\gamma} = 10^{-5}$ GeV^{-1}, the mean decay length is 1.1 meters.

Calculating Signal Detection Rate

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

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 = target-detector distance)

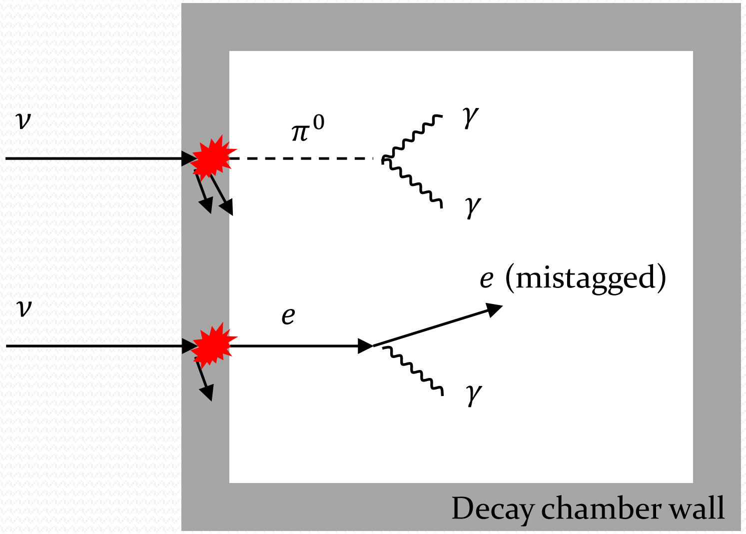
Probability of decay inside the detector volume

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

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

Background Considerations

Neutrino-originating

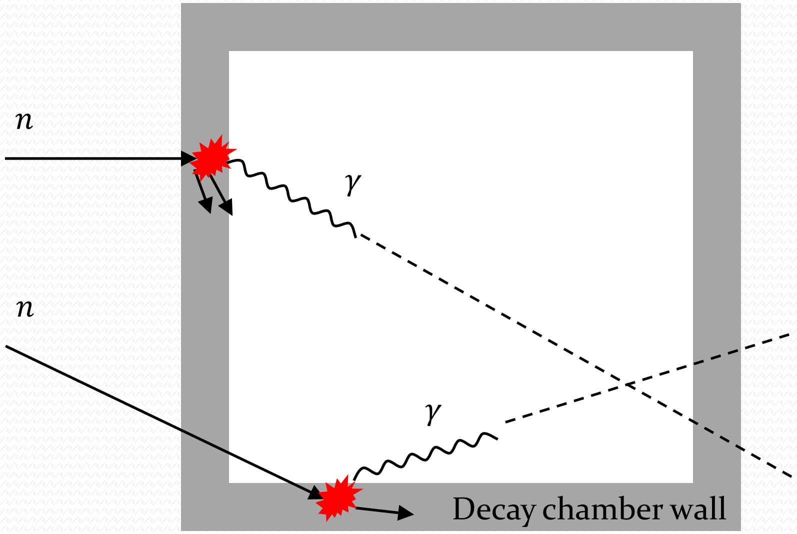


Beam energy as low as 600 MeV

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

⇒ **Negligible**

Neutron-originating



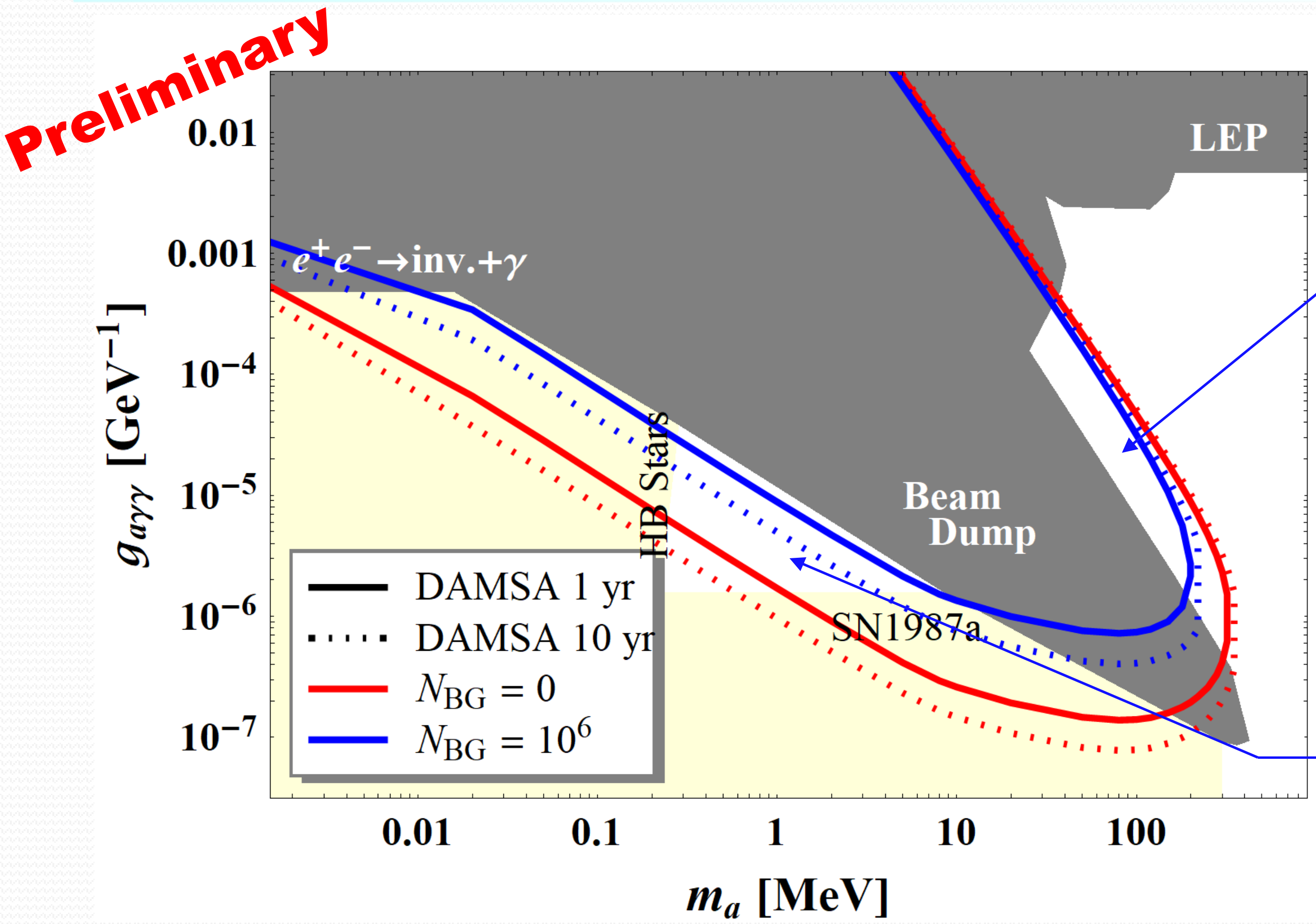
Any two photon tracks

- 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 target
- Invariant mass consistent with m_a of interest

⇒ **Reducible by more than 8-9 orders of magnitude**

(See Wooyoung Jang's talk for required detector capability)

Expected ALP Sensitivity Reach at DAMSA



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

DAMSA will cover part of the so-called "cosmological triangle" where only (standard) cosmology would constrain.

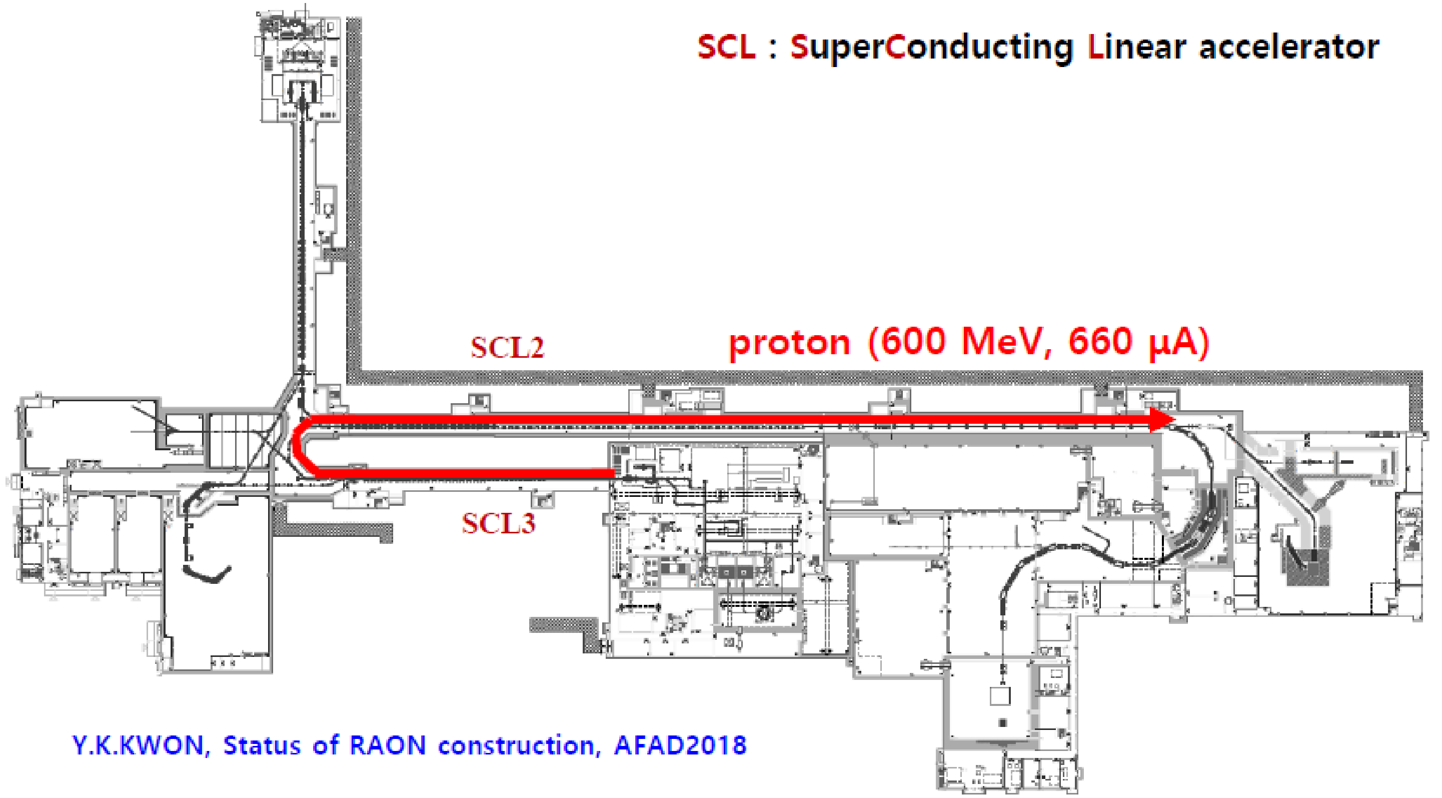
Conclusions

- RAON can conceive rich phenomenology of both new physics and Standard Model physics.
- The proton beam at RAON will copiously produce photons in the target.
- 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.
- DAMSA can be sensitive to large-mass and large-coupling regions of ALP parameter space due to its close proximity to the target.
- We encourage the exploration of other physics opportunities.

Bonus Slides

RAON Facility

RAON (Rare isotope Accelerator complex for ON-line experiments)



Y.K.KWON, Status of RAON construction, AFAD2018