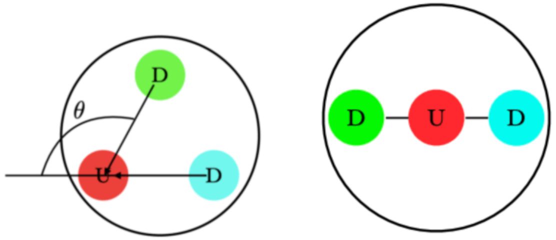
ALP Searches at Neutrino and Dark Matter Frontier Experiments

Adrian Thompson

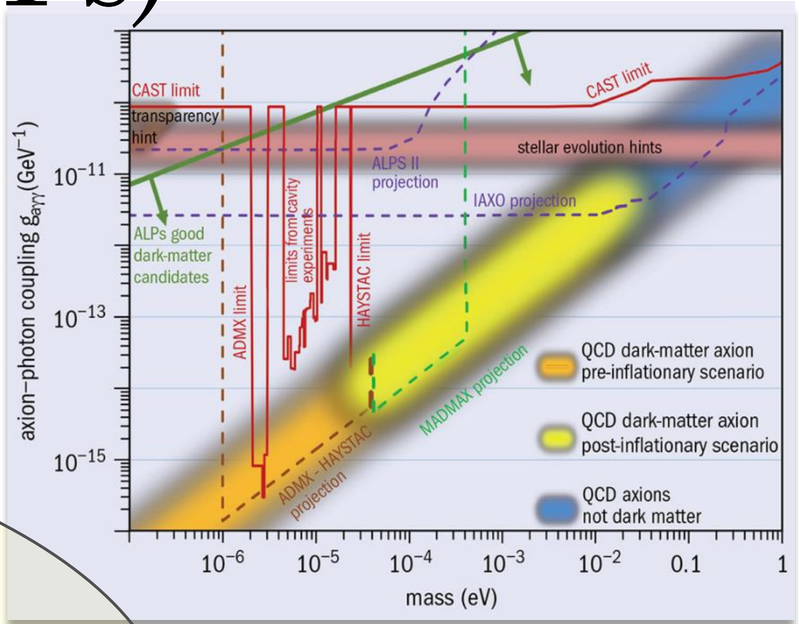
Phenomenology 2021 Symposium

Axion-like Particles (ALPs)



Hook, 1812.02669

- Strong CP
- Stringy CP-odd operators
- Dark Matter
- Heavy axions and High-quality axions



Majorovits 2018

$$\frac{1}{4} g_{a\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$

$$i g_{al} a \bar{\ell} \gamma^5 \ell$$

$$\frac{1}{4} g_{aGG} a G_{\mu\nu} \tilde{G}^{\mu\nu}$$

$$i g_{aN} a \bar{N} \gamma^5 N$$

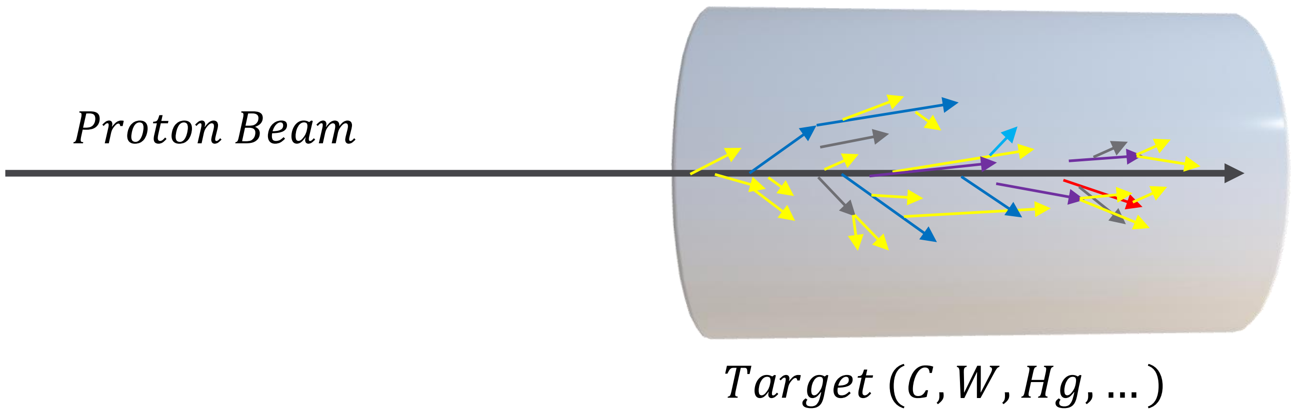
$$\frac{1}{4} g_{aZ} a Z_{\mu\nu} \tilde{Z}^{\mu\nu}$$

$$\frac{1}{4} g_{aW} a W_{\mu\nu} \tilde{W}^{\mu\nu}$$

$$\frac{1}{4} g_{a\gamma Z} a F_{\mu\nu} \tilde{Z}^{\mu\nu}$$

....

Neutrino and Dark Matter Frontier: Beam Target Physics



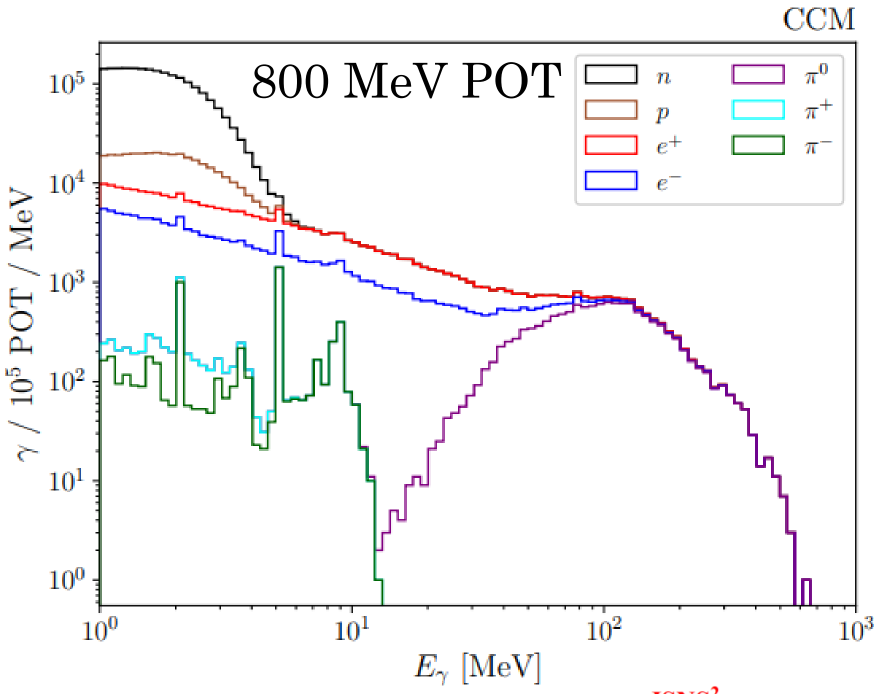
Not just for neutrino/neutron production:

- Proton bremsstrahlung
- Meson production and subsequent decay $(\pi^0, \pi^\pm, K, \rho, \ldots)$
- e^+/e^- production, bremsstrahlung and annihilation
- Neutron scattering and capture
- …and more subprocesses

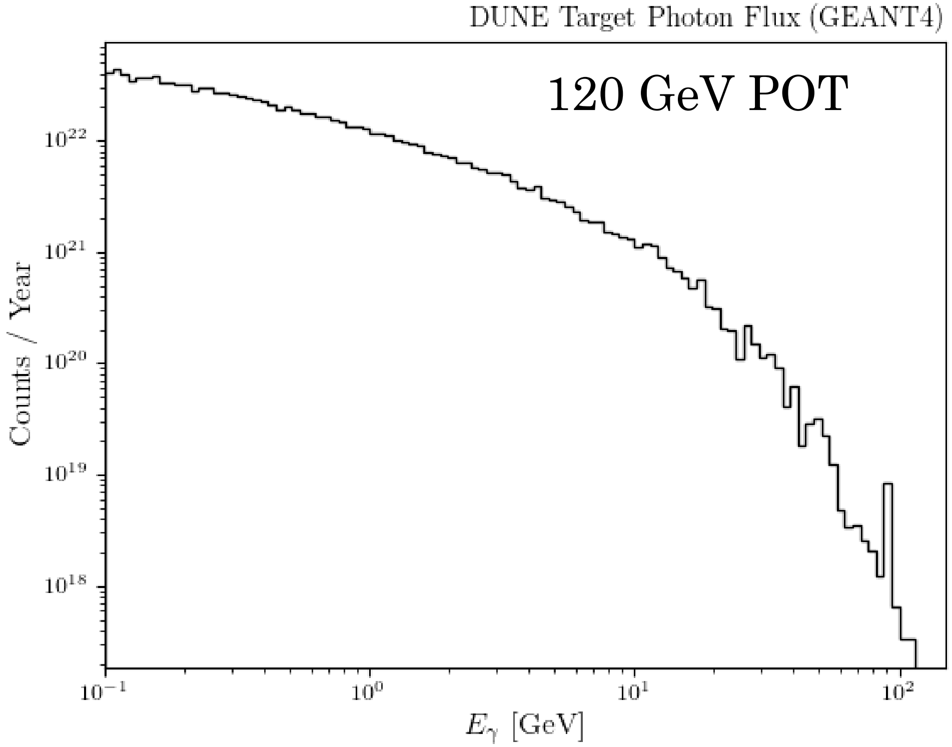
This is a $p + A$ collider!

Photon Spectra

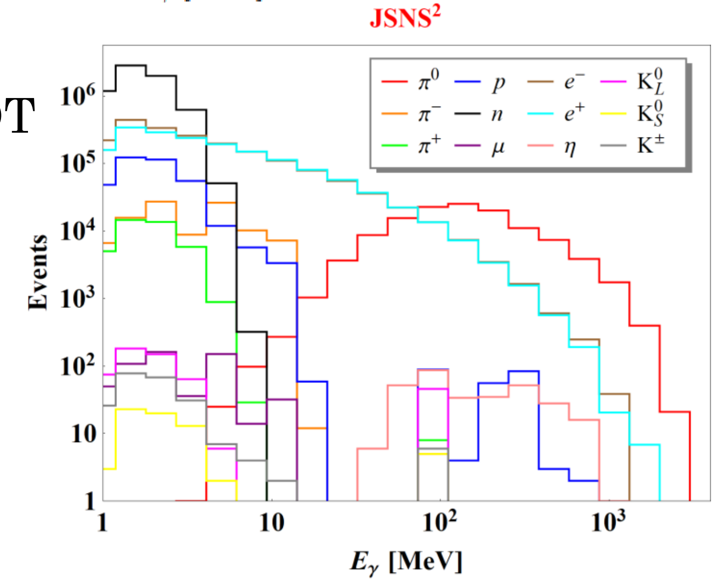
800 MeV POT



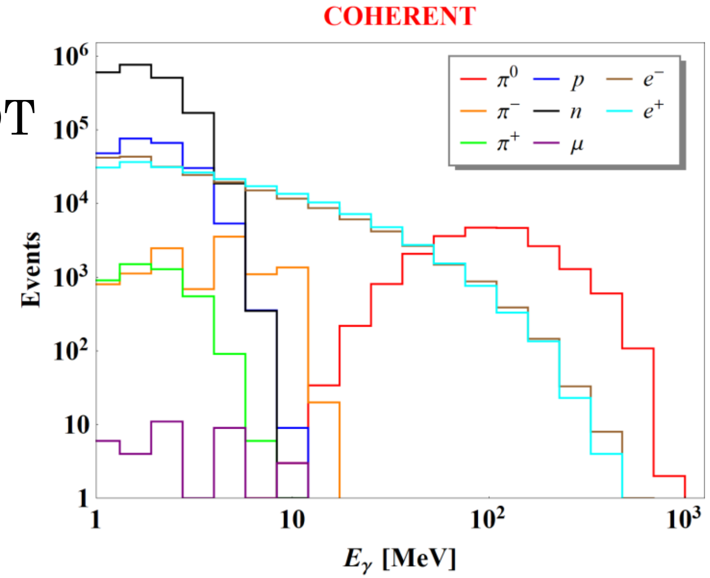
120 GeV POT



3 GeV POT

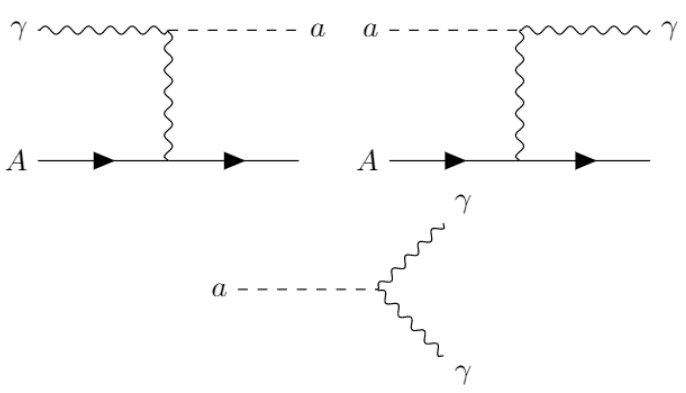


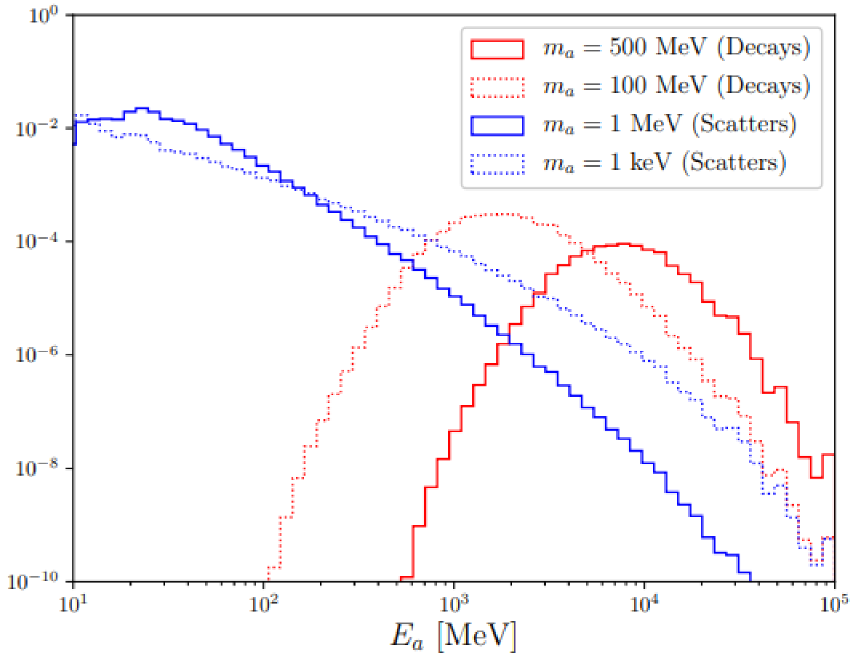
1 GeV POT



ALP-photon Coupling

$$\mathcal{L} = \frac{1}{4} g_{a\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$



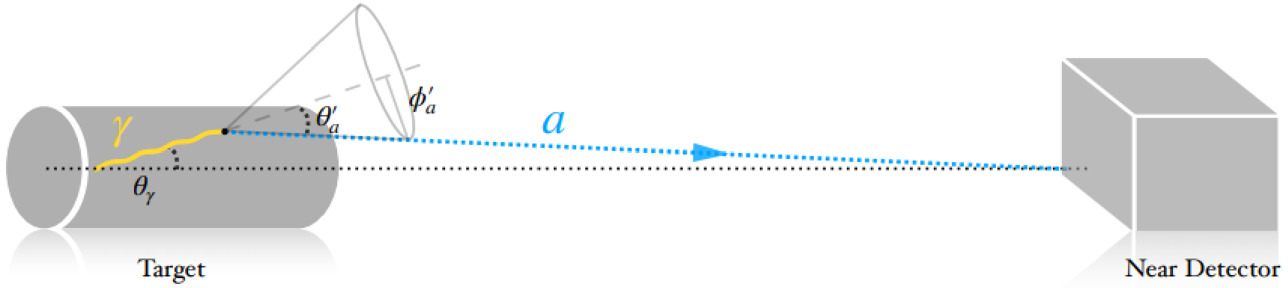


Production Mechanism

- Primakoff Scattering
  - Coherent ($\propto Z^2$)
  - Very forward for $m_a \ll E_\gamma$

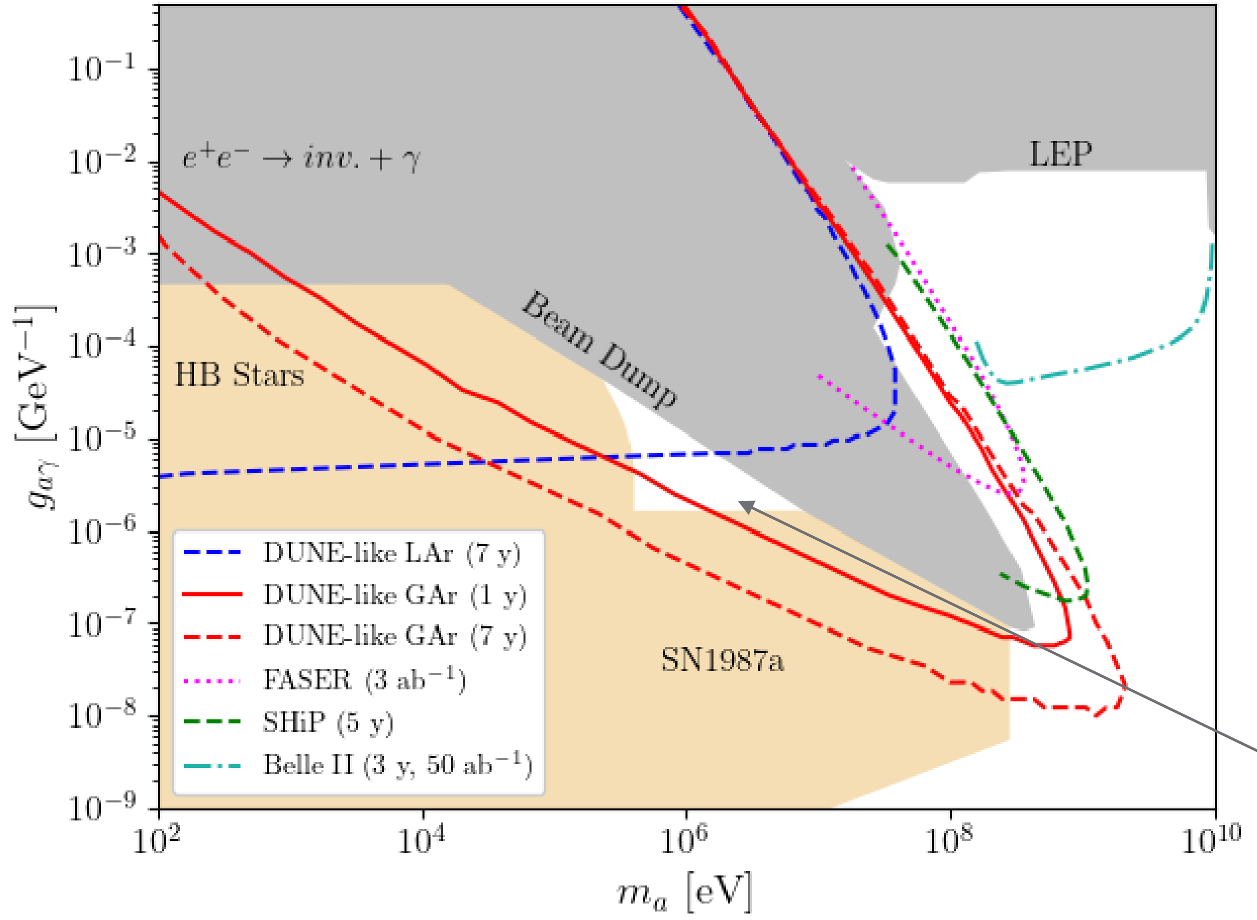
Detection Mechanisms

- Inverse Primakoff Scattering
- $a \to \gamma\gamma$ decays



ALP-photon Sensitivity (DUNE)

Vedran Brdar, Bhaskar Dutta, Wooyoung Jang, Doojin Kim, Ian M. Shoemaker, Zahra Tabrizi, **Adrian Thompson**, Jaehoon Yu *Phys.Rev.Lett.* 126 (2021) 20, 201801 (2011.07054)

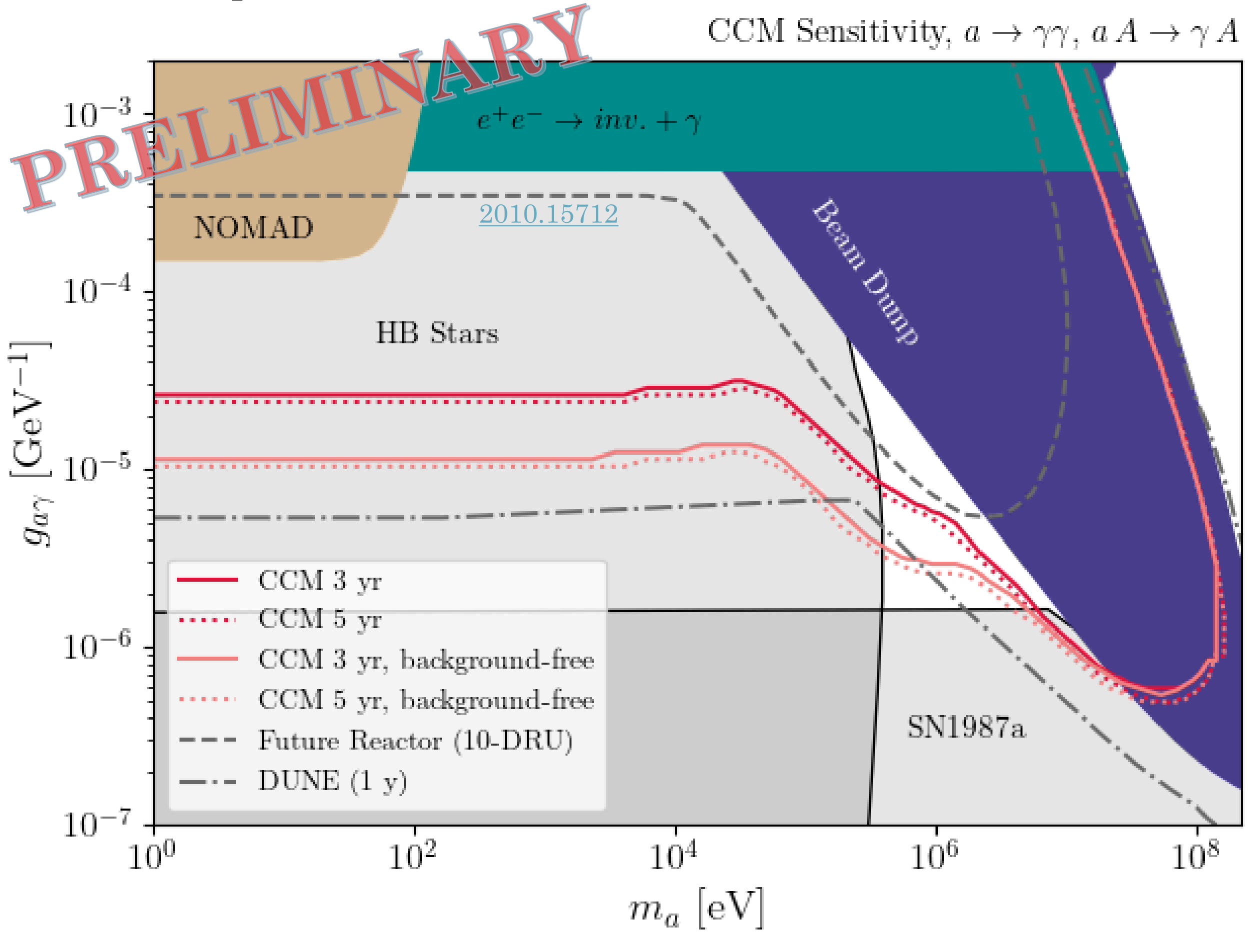


- DUNE:
  - 120 GeV beam, $1.1 \cdot 10^{21}$ POT/yr on 1.5m graphite target (GEANT4)
  - 574m target-to-detector complex
- Decays searched for in the GAr detector
  - Lower density gaseous Ar suppresses scattering backgrounds, while $\gamma\gamma$ final state has relatively high efficiency
- Scatters searched for in the LAr detector (50t fiducial)
  - Backgrounds can be reduced further by looking at γ angle w.r.t. beam line

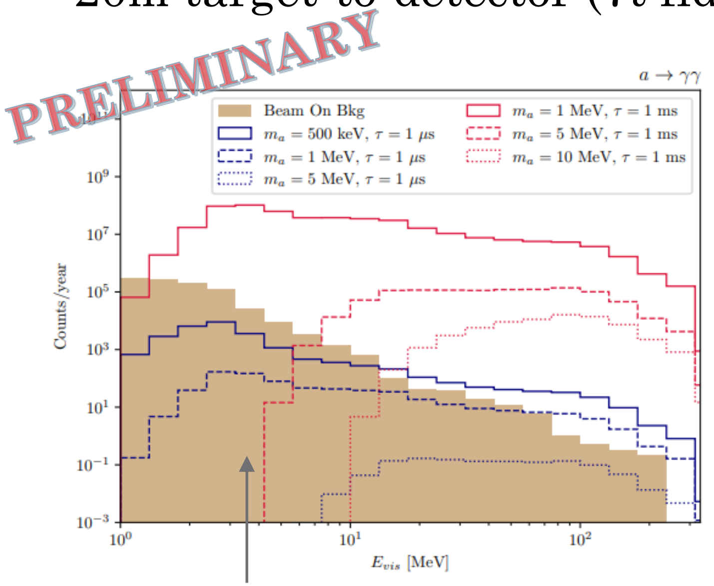
"Cosmological Triangle"

ALP-photon Sensitivity (CCM)

Dutta, **Thompson**, CCM Collaboration, 2021



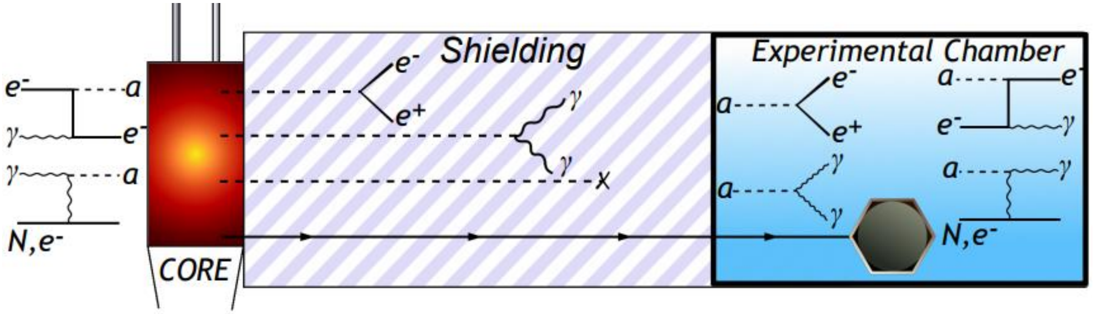
- CCM:
  - 800 MeV beam, $7.5 \cdot 10^{21}$ POT/yr on tungsten target
  - 20m target-to-detector (7t fiducial Lar)



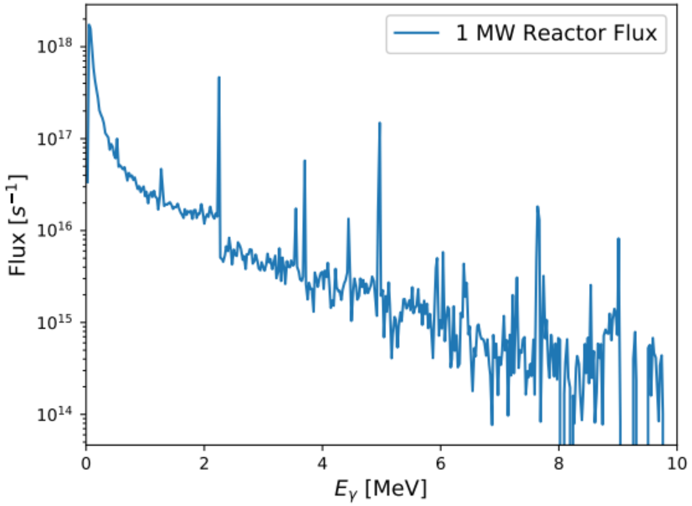
Work ongoing to reduce beam-on background

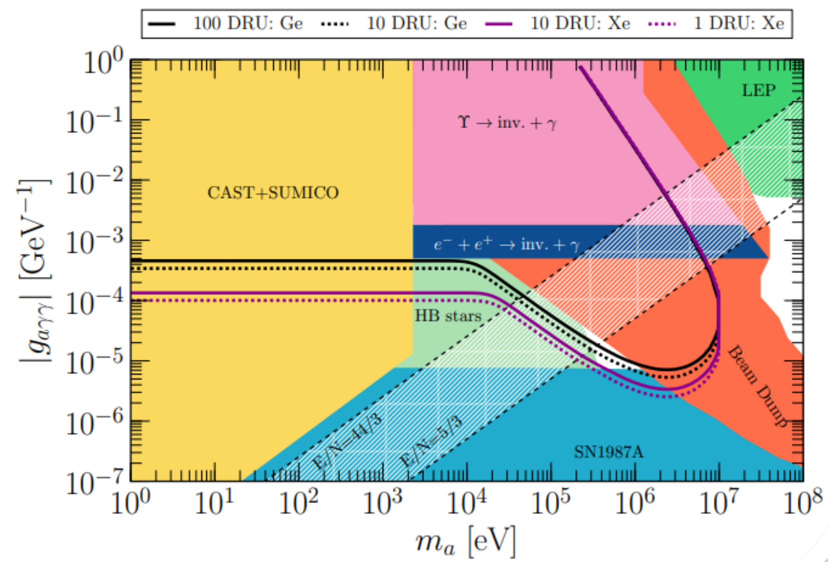
ALPs at Reactors

See Aristizabal Sierra, De Romeri, Flores, Papoulias (2010.15712) and Dent, Dutta, Kim, Mahapatra, Sinha, **Thompson** *et al* *Phys.Rev.Lett.* 124 (2020) 21, 211804 (1912.05733)



- Reactors also offer intense environments to produce ALPs in their cores
- Photon fluxes, electrons, and nuclear physics can source ALPs to probe several couplings, including the cosmological triangle in $g_{a\gamma}$





ALP-electron coupling

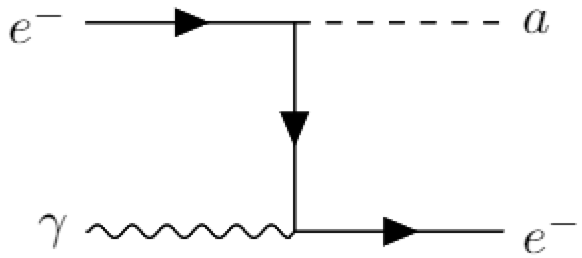
$$\mathcal{L} = i g_{ae} a \bar{e} \gamma^5 e$$

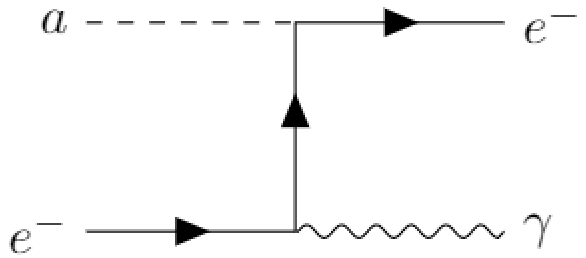
Production Mechanism:

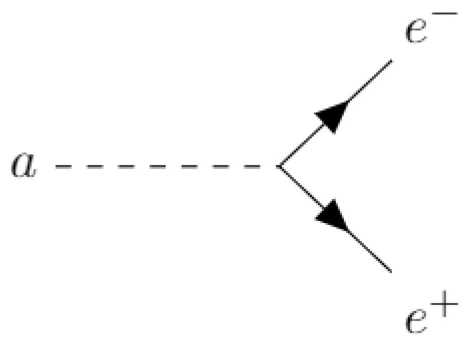
- Compton-like scattering $\gamma\, e^- \rightarrow a\, e^-$, sourced by the intense photon flux (GEANT4) induced by POT
- Additionally, e^+/e^- ALP-bremsstrahlung and resonance production are potentially strong channels (W.I.P.)

Detection Mechanisms:

- Inverse Compton scattering $a\, e^- \rightarrow \gamma\, e^-$
- ALP decays ($a \rightarrow e^+ e^-$)





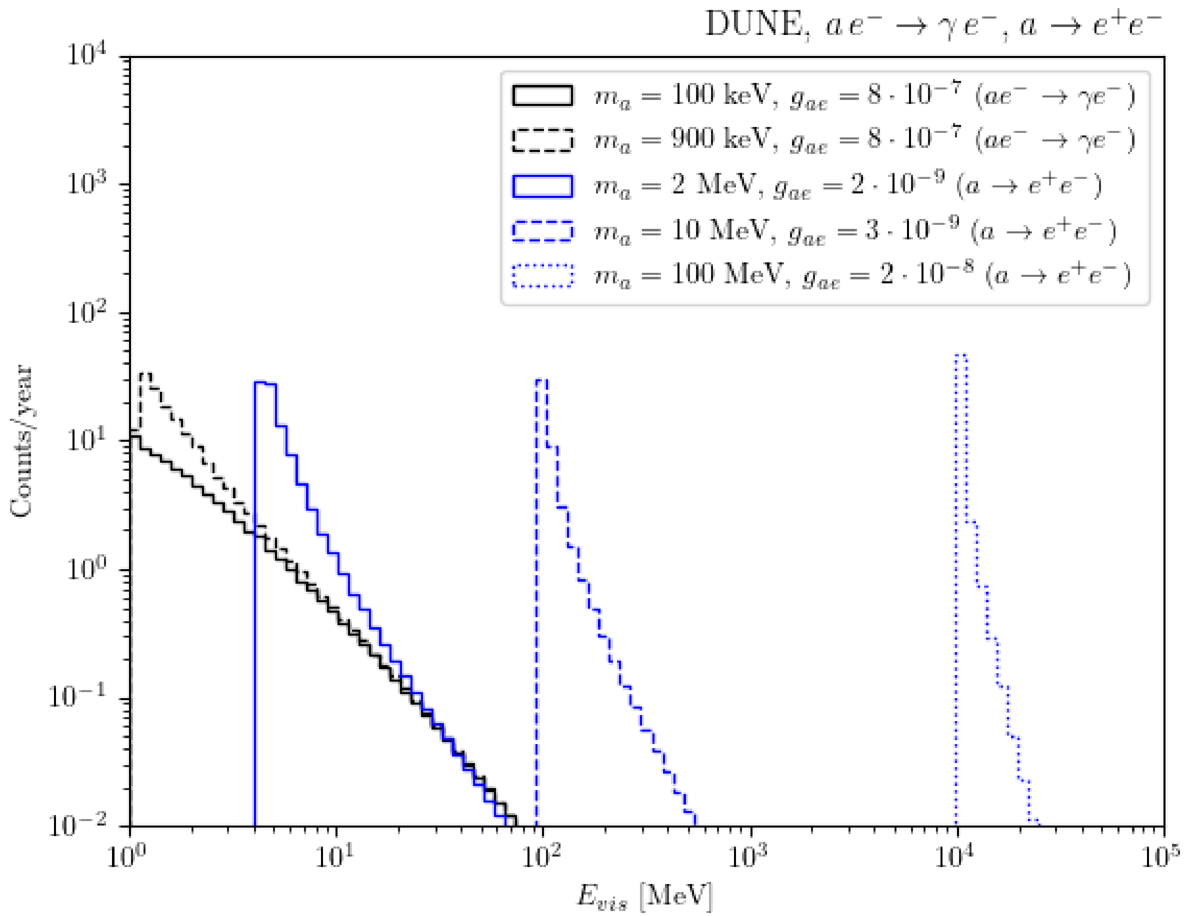


ALP Energy Spectra

- DUNE will be sensitive to both scattering and decays
- The Compton production channel has a threshold

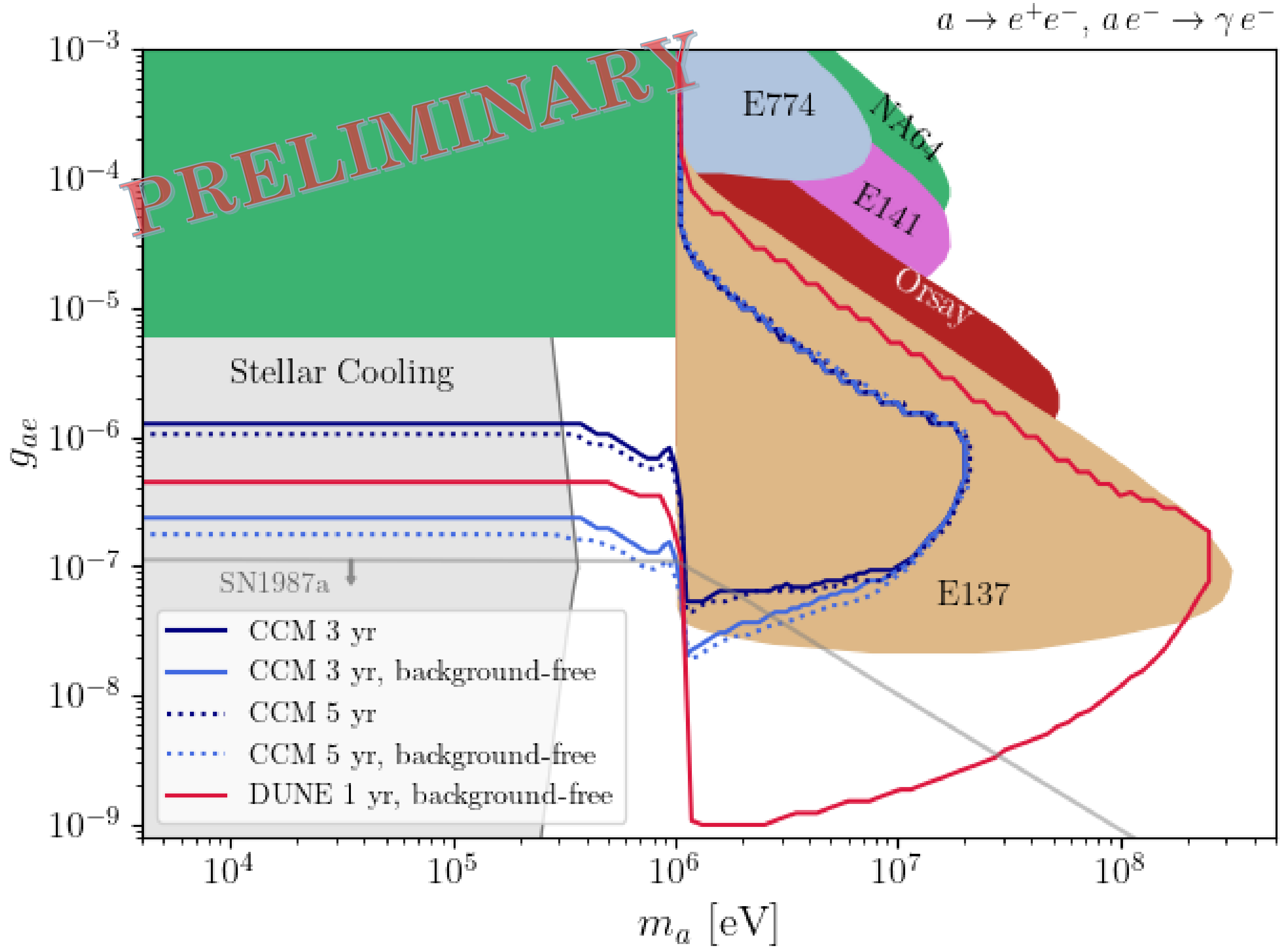
$$s > (m_a + m_e)^2,$$

  this implies $E_\gamma > \frac{m_a^2}{2\,m_e} + m_a$. We therefore detect a falling spectrum with a m_a-dependent starting point
  - e^+e^- final state
    - Dominant for $m_a > 2m_e$, high energy spectrum
  - γe^- final state
    - Dominant for $m_a < 2m_e$, low energy spectrum



Preliminary Sensitivity

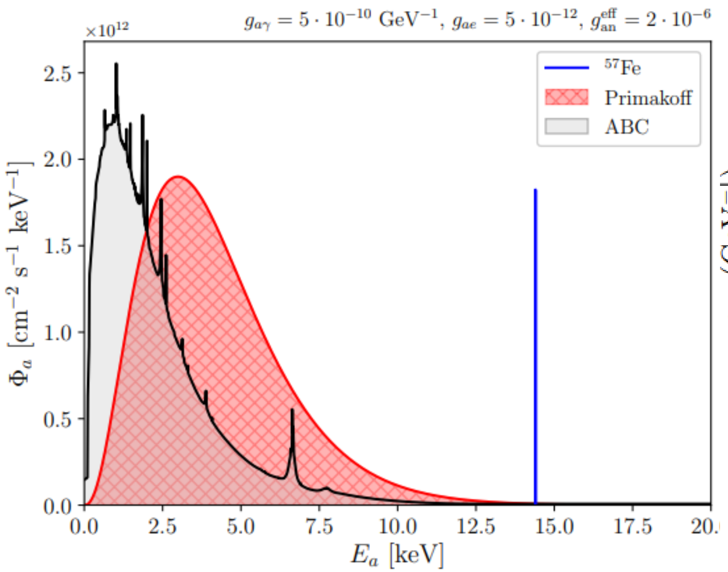
- DUNE 1 year exposure at LAr + GAr detectors
- CCM 3 and 5 year exposures
- Some bounds below $m_a = 1$ MeV are model-dependent;
  - Stellar cooling (RG, HB stars)
  - SN1987a (also subject to SN physics assumptions)
  - Constraints from loop-induced $a \to \gamma\gamma$ at beam dumps ignored
- Sensitivity should improve when bremsstrahlung and resonant production channels are modeled in

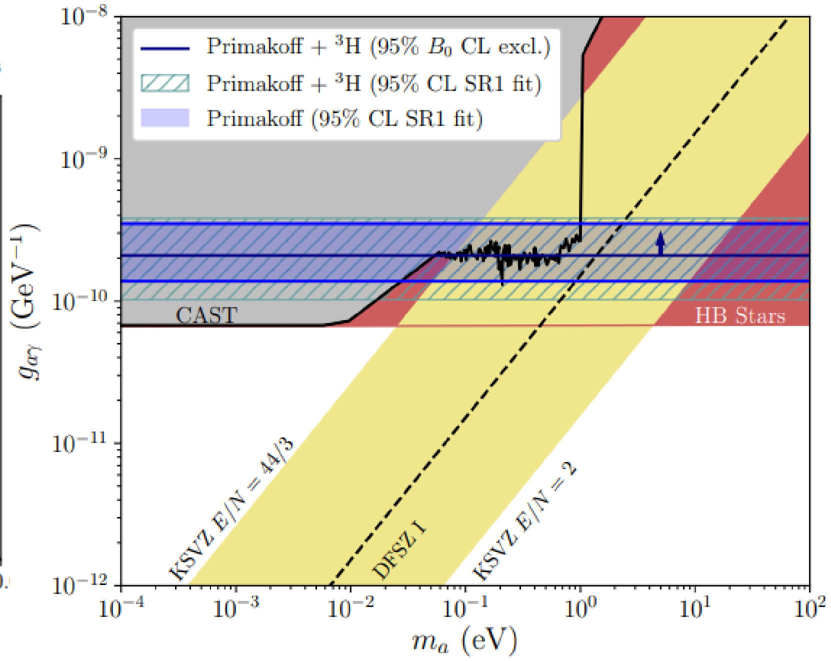


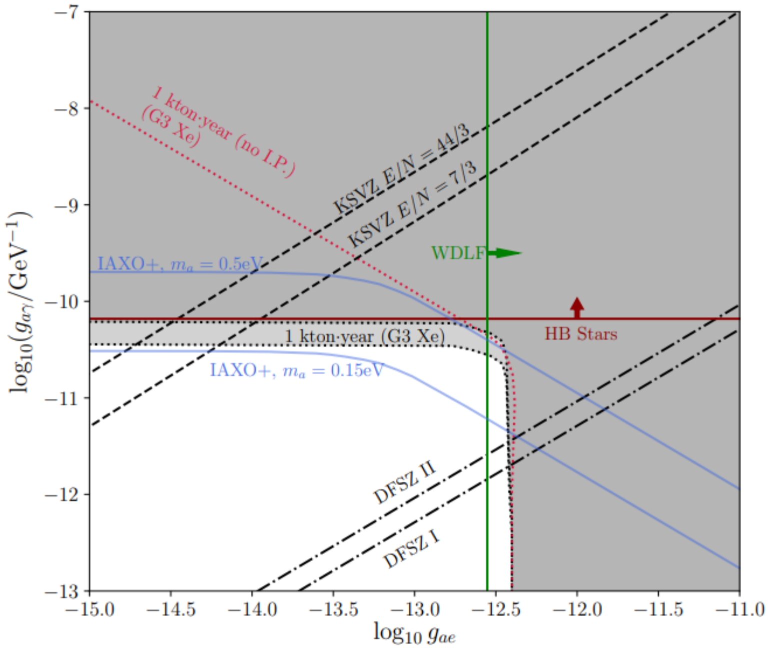
See also Gao *et al* (2006.14598)

Dark Matter Frontier: Solar Axion Searches

Dent, Dutta, Newstead, **Thompson**
Phys.Rev.Lett. 125 (2020) 13, 131805
(2006.15118)







ALPs sourced in the Sun via several channels (ionization, bremsstrahlung, Compton scattering, Primakoff, nuclear decays…)

XENON1T excess: ALP models fit to data and overlap with QCD axion parameter space, but excluded by stellar cooling

More generally, future Dark Matter Direct Detection experiments (e.g. third-gen Xe) can complement large scale ALP searches like IAXO in the heavier mass range

Going forward from here

- Experiments at the Neutrino and Dark Matter Frontier can set leading limits on MeV and heavy ALPs while also probing a broadband of ALP masses < MeV
- More possibilities open up when we include other couplings (gauge bosons, nuclear couplings)
- Understanding the particle spectra within these targets (photons, electrons,…) is crucial to seeing the full picture of phenomenological opportunities

Thank You!