BSM Targets at a Target-less DUNE

Snowmass Community Summer Study Workshop

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Northwestern University

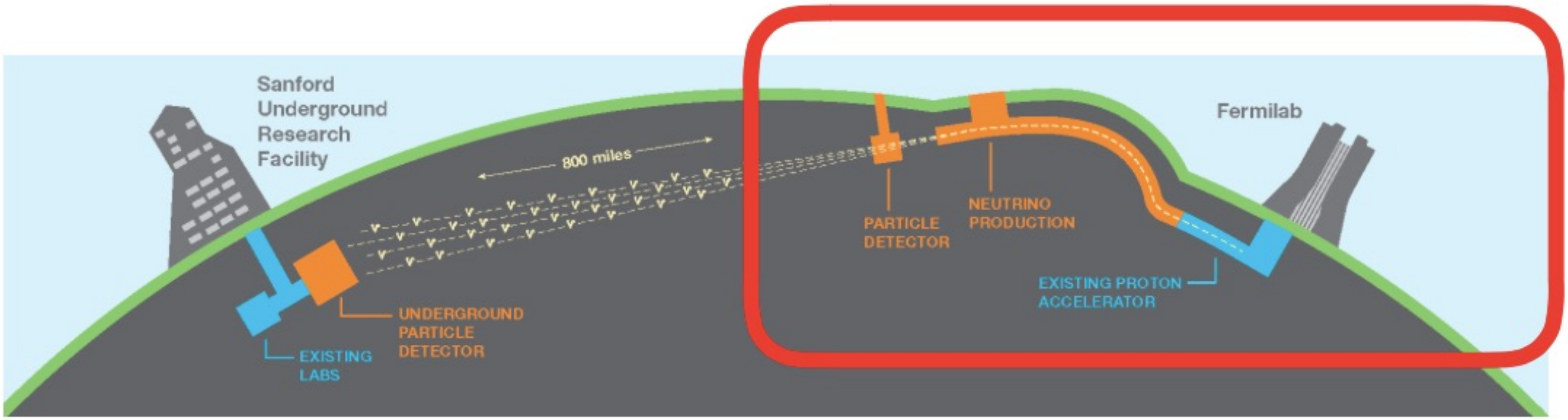
Physics goals of near detectors:

Primary role: Understanding Systematic Uncertainties

High beam luminosity + Large fiducial mass → Ideal to investigate **rare/new** neutrino interactions

$\sigma < 10^{-44}\ \mathrm{cm}^2$

- Test SM predictions
- Search for BSM physics

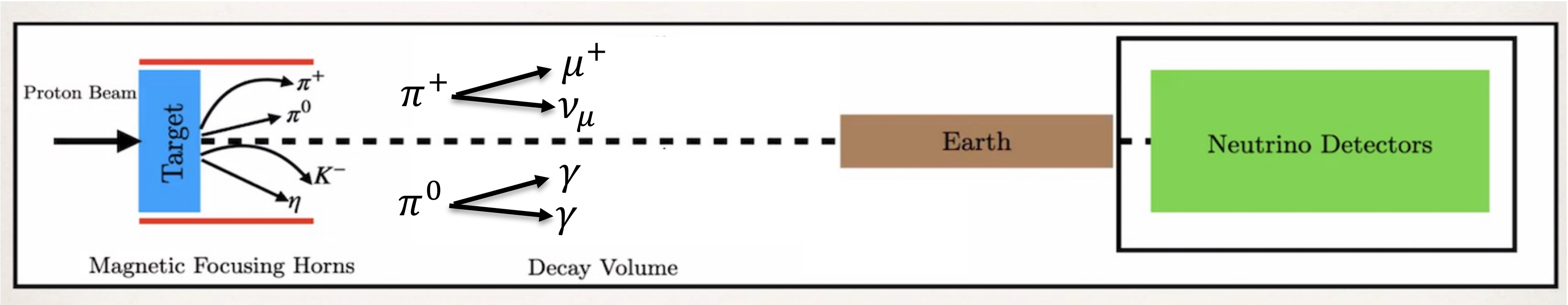


Question:

- **How can we fully leverage DUNE to search for New Physics?**

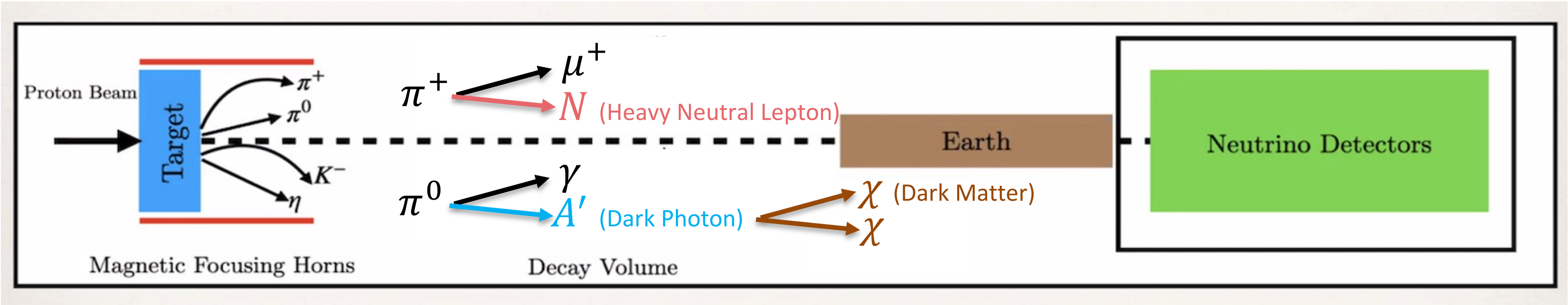
- **Can DUNE probe compelling new physics beyond the reach of high energy colliders?**

Neutrino Experiments as Dark Sector factories!



Credit: Kevin Kelly

The huge fluxes of neutrinos and photos can be used for BSM searches



- **Heavy Neutral Leptons, Dark Photon, light DM, etc**

Berryman et al, PRD (2018)
Breitbach et al, JHEP (2022)
De Romeri et al, PRD (2019)
Magill et al, PRL (2019)

- **Direct Search of Dark Sectors:**
  - Light Dark Matter
  - Axion-Like Particles
- **Conclusion**

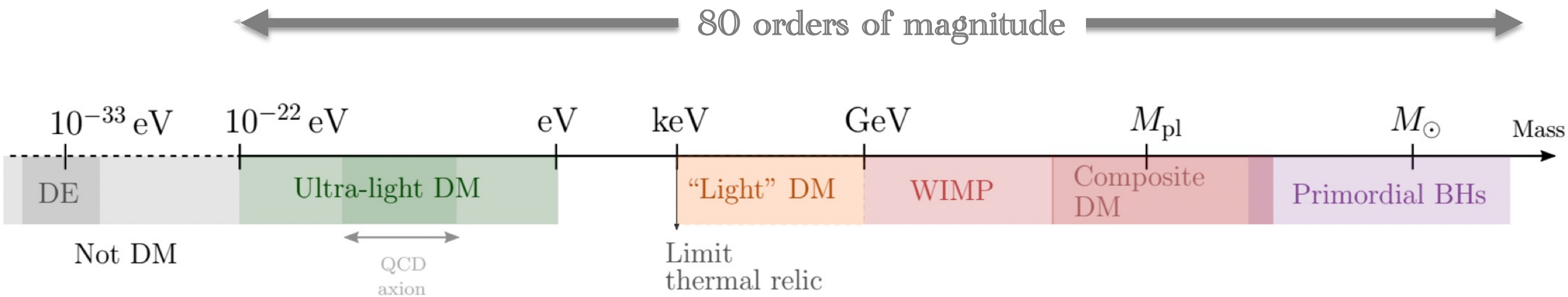
"What is Dark Matter?"

We don't know!

There could be several kinds, making up a whole "dark sector"

"Where is Dark Matter?"

We don't know!

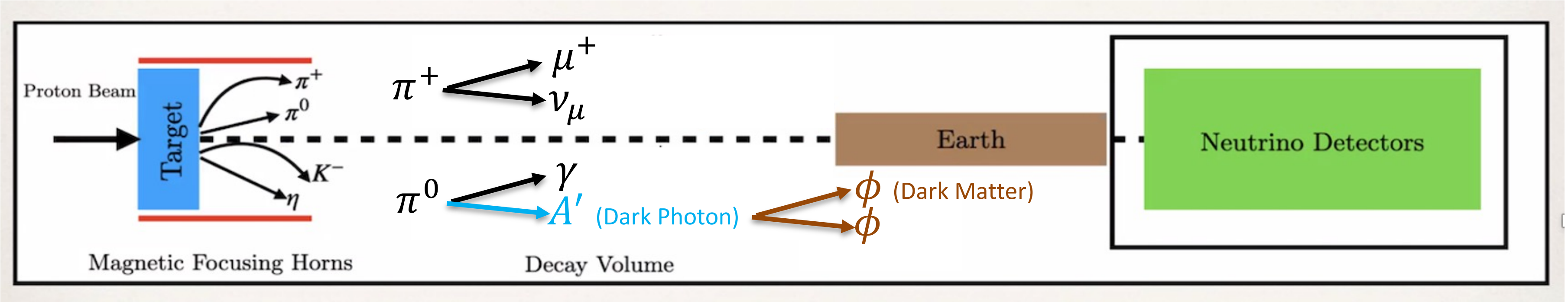


Elisa G. M. Ferreira, arXiv:2005.03254

“How is Dark Matter?”

TOM GAULD for NEW SCIENTIST

Light Dark Matter

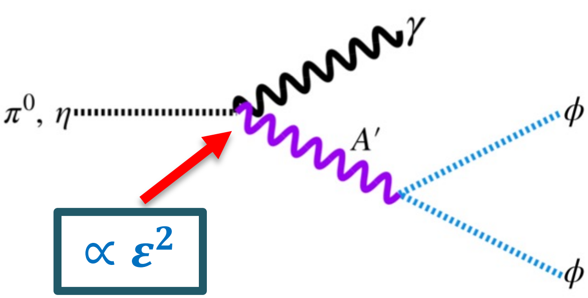


Photons at the target kinetically produce Dark Photons, which decay into dark matter:

$$\mathcal{L} \supset -\frac{\varepsilon}{2} F^{\mu\nu} F'_{\mu\nu} + \frac{M^2_{A'}}{2} A'_\mu A'^\mu + |D_\mu \phi|^2 - M^2_\phi |\phi|^2$$

$$\boxed{D_\mu = \partial_\mu - i g_D A'_\mu, \quad g_D = \sqrt{4\pi\alpha_D}}$$

DM production

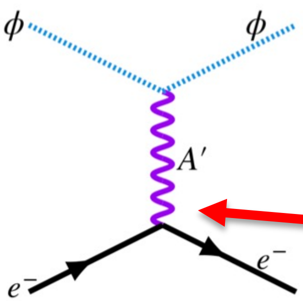


$\boxed{\propto \varepsilon^2}$

De Romeri, Kelly, Machado, PRD (2019)

(also Beam bremsstrahlung and Resonance production)

DM detection

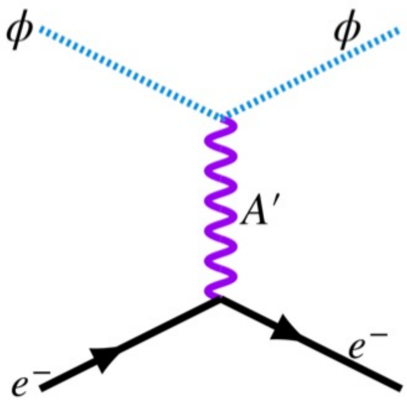


$\boxed{\propto \varepsilon^2}$

$\boxed{\text{DM event rate} \sim \varepsilon^4 \alpha_D}$

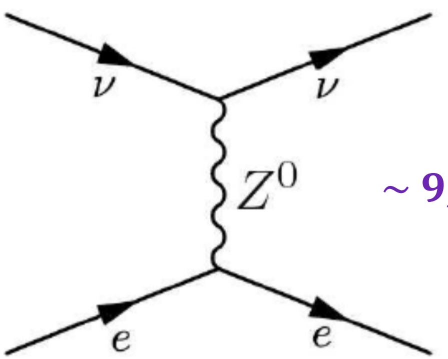
Light Dark Matter

DM signal: elastic scattering on electrons



How can we get rid of neutrinos in a neutrino detector?

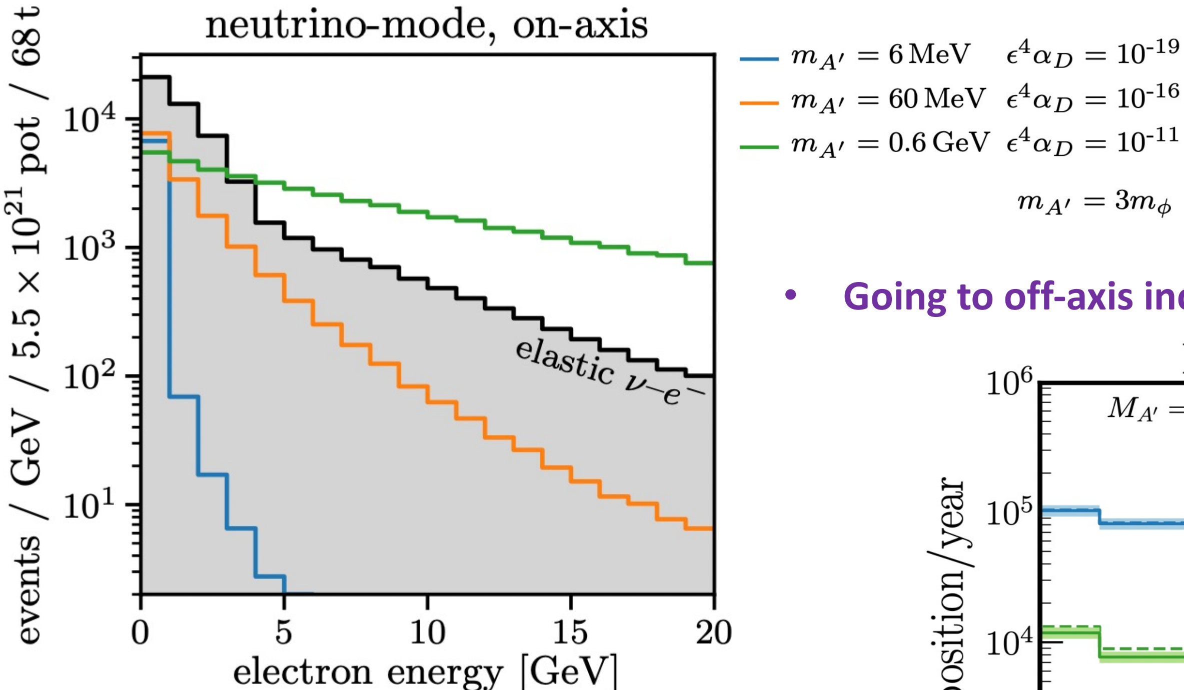
But so do neutrinos!



$\sim 9,400\ \nu - e$ events / year!

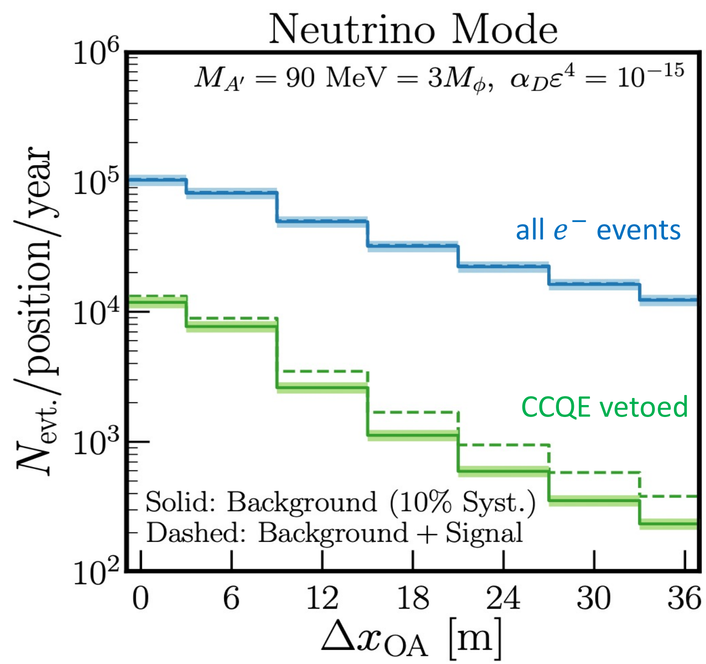
Light Dark Matter

- **Challenge: elastic neutrino-electron scattering is a huge background!**



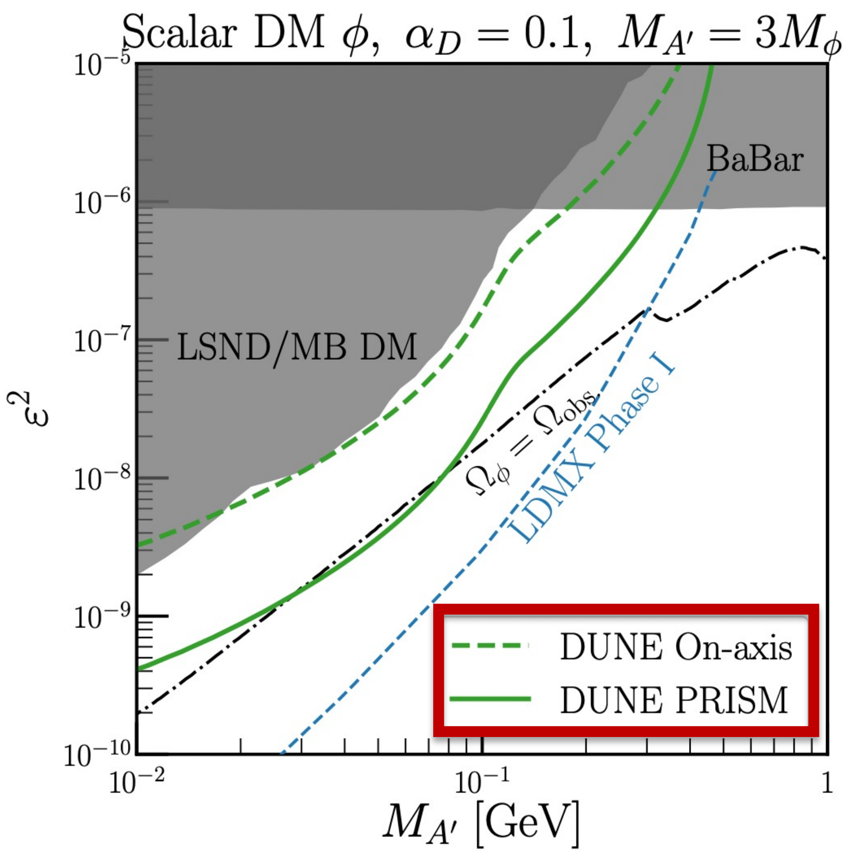
Breitbach, Buonocore, Frugiuele, Kopp, Mittnacht, JHEP (2022)

- **Going to off-axis increases DM signal/background**



De Romeri, Kelly, Machado, PRD (2019)

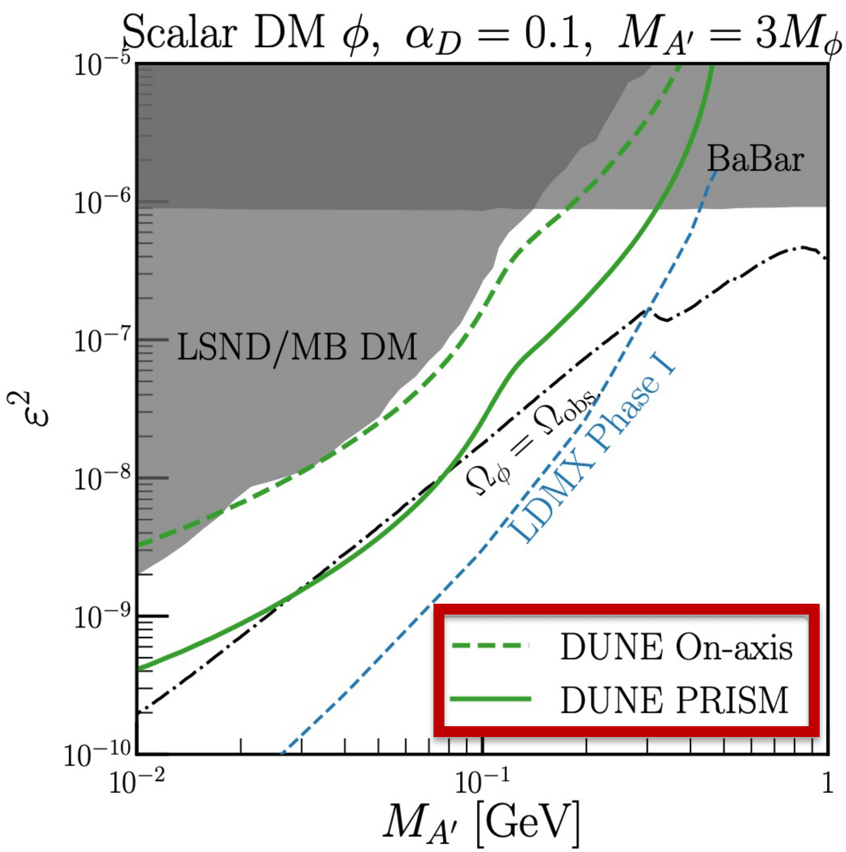
Light Dark Matter



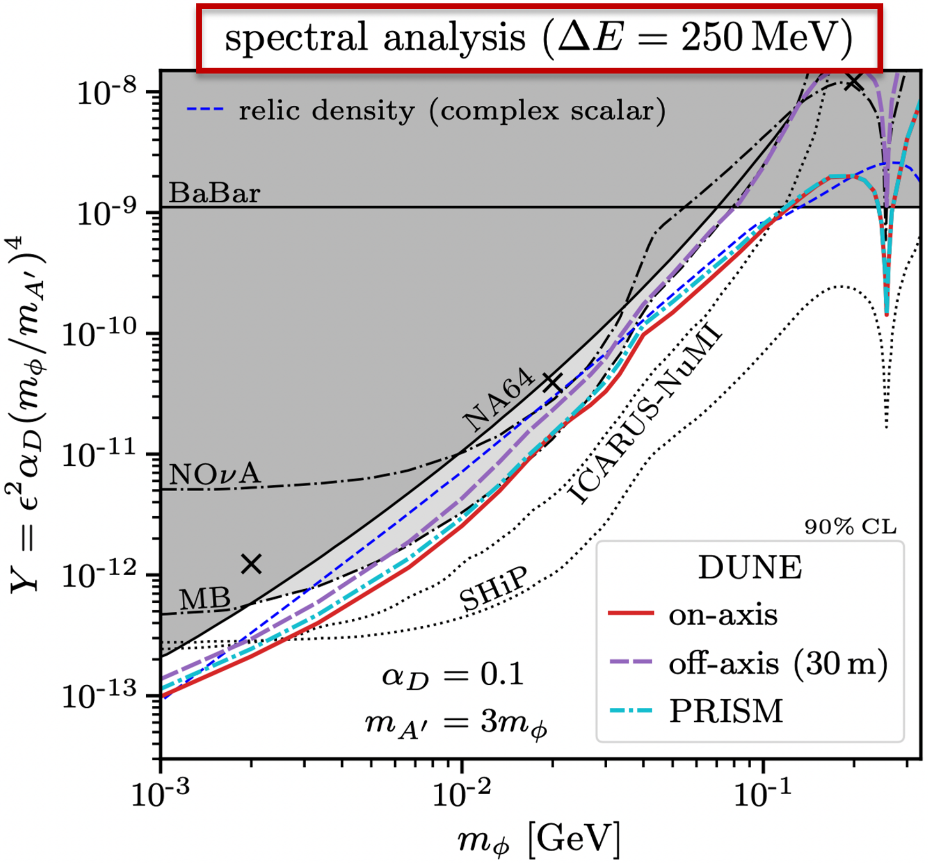
De Romeri, Kelly, Machado, PRD (2019)

See talk by Kevin Kelly

Light Dark Matter



De Romeri, Kelly, Machado, PRD (2019)



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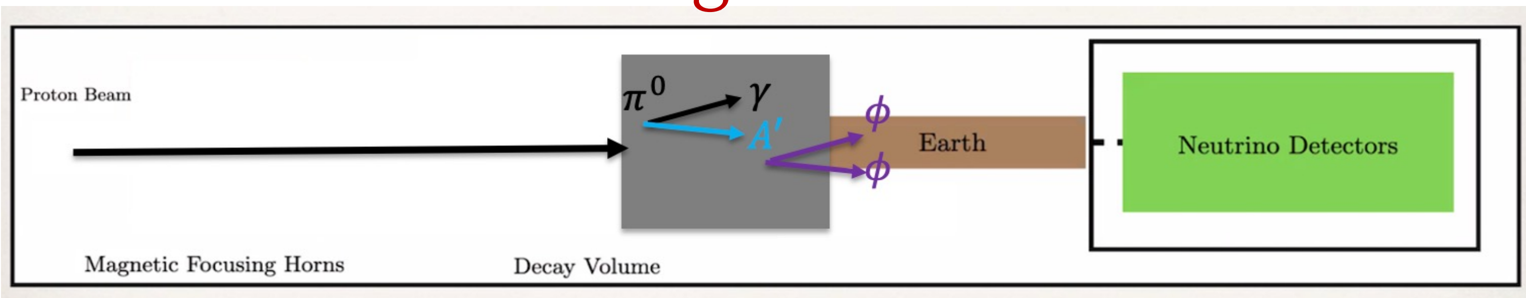
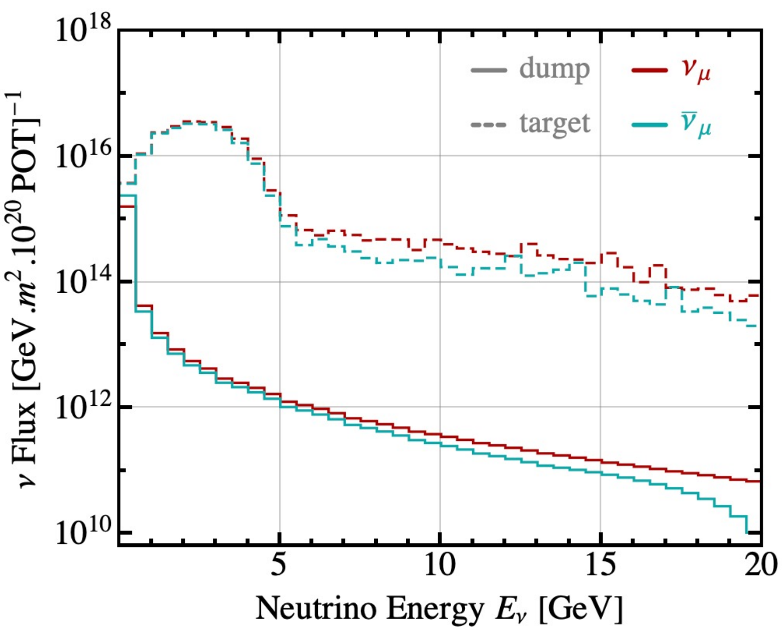
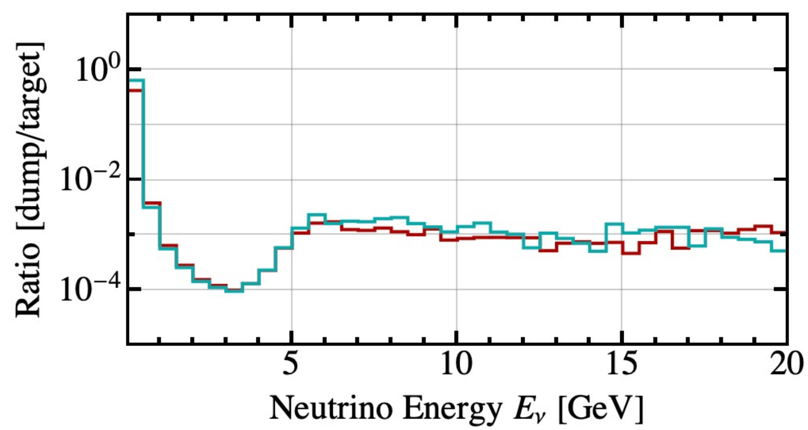
Light Dark Matter at Target-less DUNE



- Impinging protons directly to the dump area;
- Shorter distance between the source point and the detector → more DM signal;
- Charged mesons absorbed in the Al beam dump before decay;
- **The ν flux decreases by 3 orders of magnitude → Only 0.5 ν-e background in 3 mo-0.6 MW!**

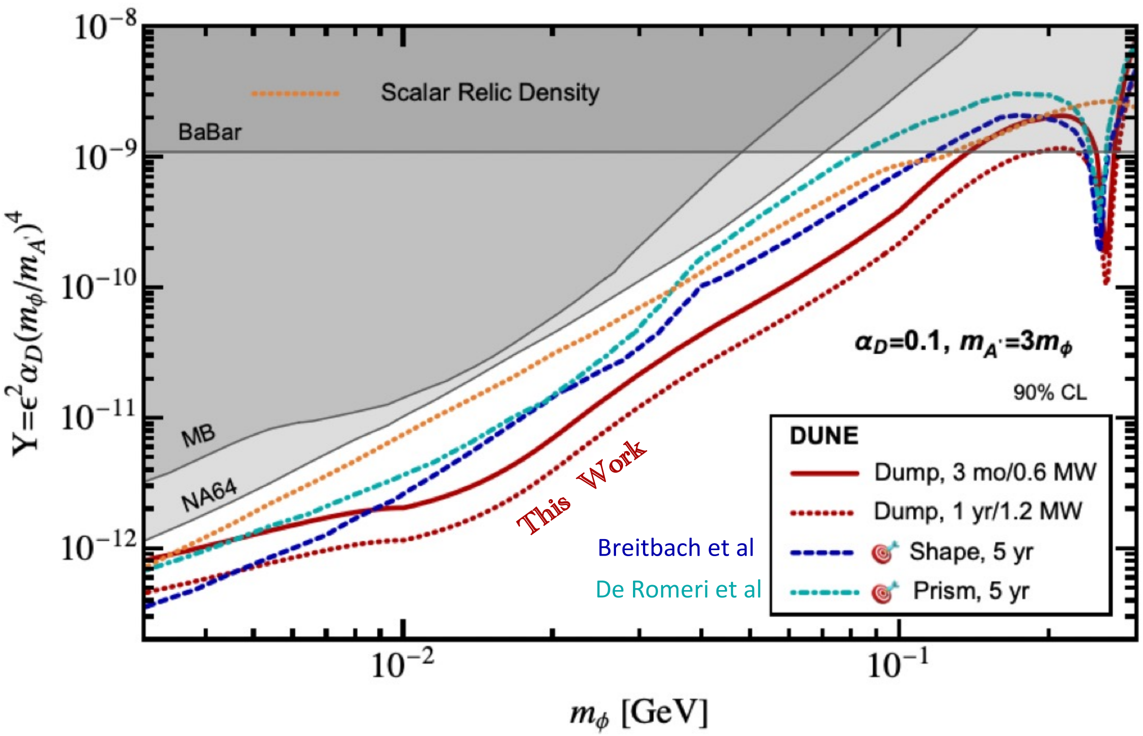
See talk by Wooyoun Jang





Brdar, Dutta, Jang, Kim, Shoemaker, ZT, Thompson, Yu
arXiv: 2206.06380

Light Dark Matter at Target-less DUNE



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Target-less DUNE can probe the parameter space for thermal relic DM in only 3 months!

Axion-Like Particles (ALPs)

- (pseudo)scalars, strongly motivated by theory and cosmology;
- Why is CP conserved in QCD? Solution to the strong CP problem (QCD axion);
- DM candidates;

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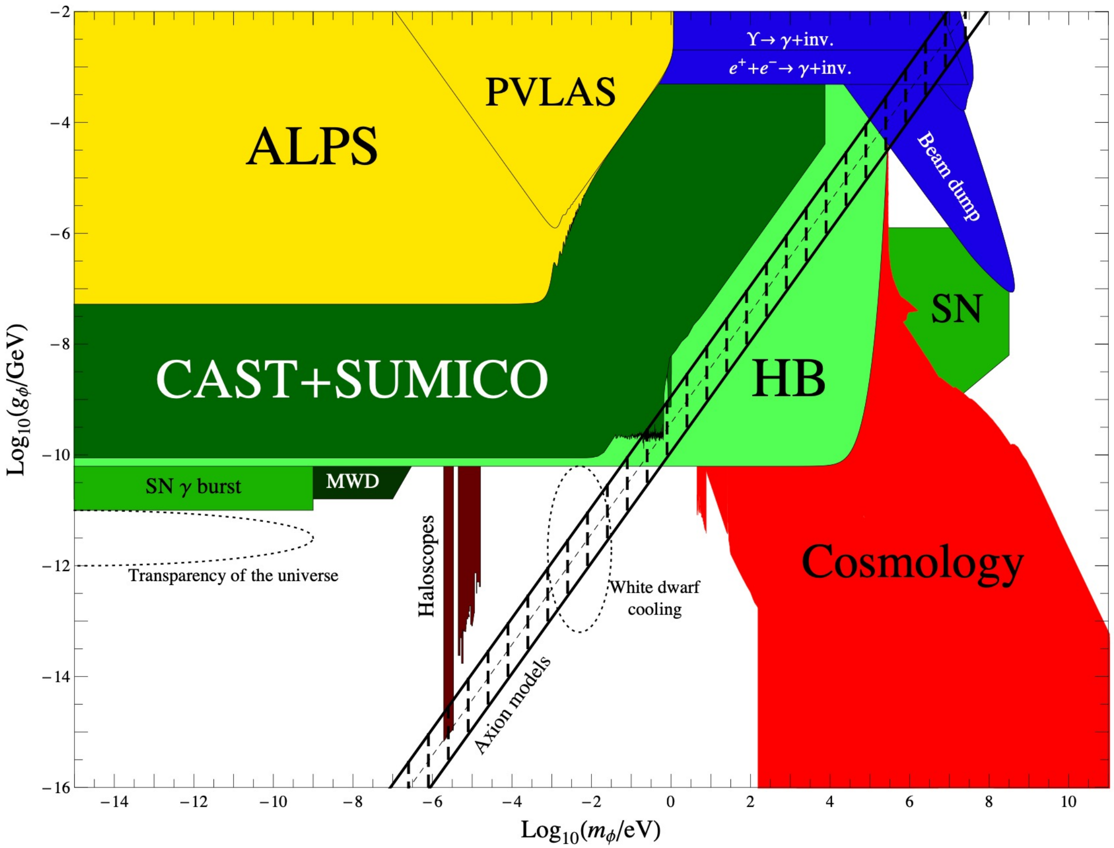

D. Cadamuro, 1210.3196 [hep-ph]

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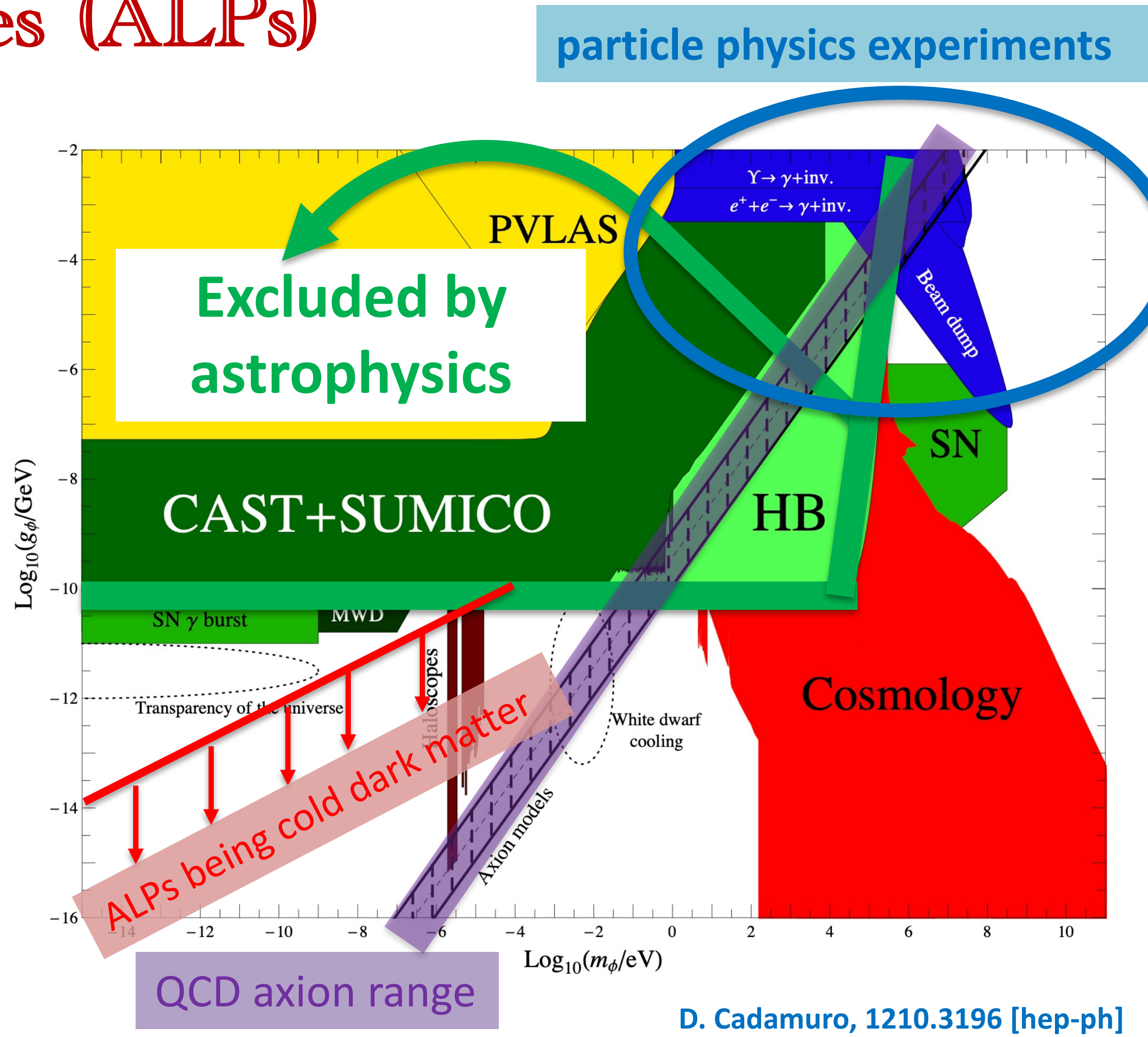
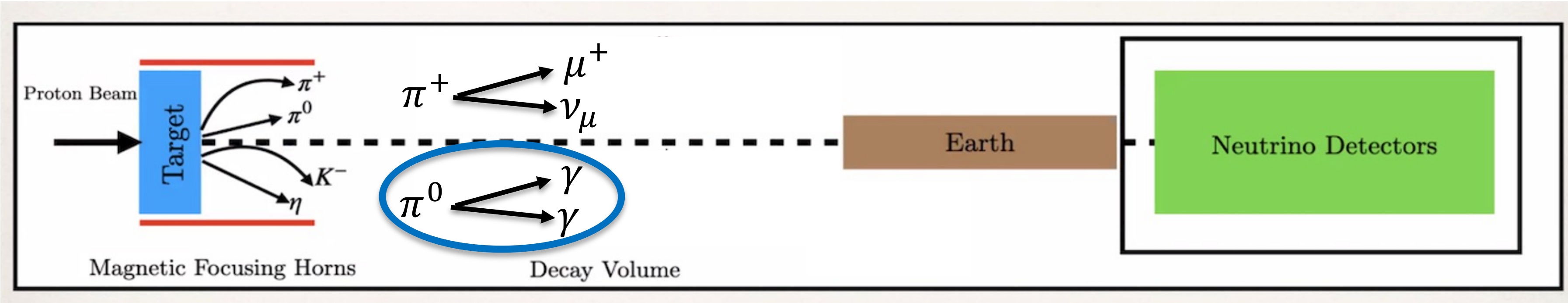


D. Cadamuro, 1210.3196 [hep-ph]

ALPs at Neutrino Experiments

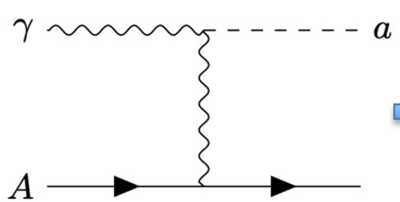


Credit: Kevin Kelly

Using photons to produce ALPs:

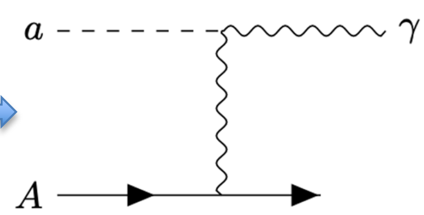
$$\mathcal{L}_{a\gamma\gamma} \supset -\frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$

ALP production

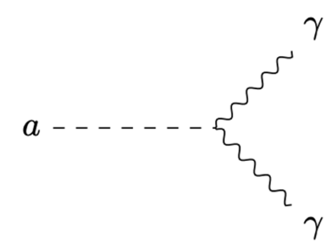


Primakoff scattering

ALP detection

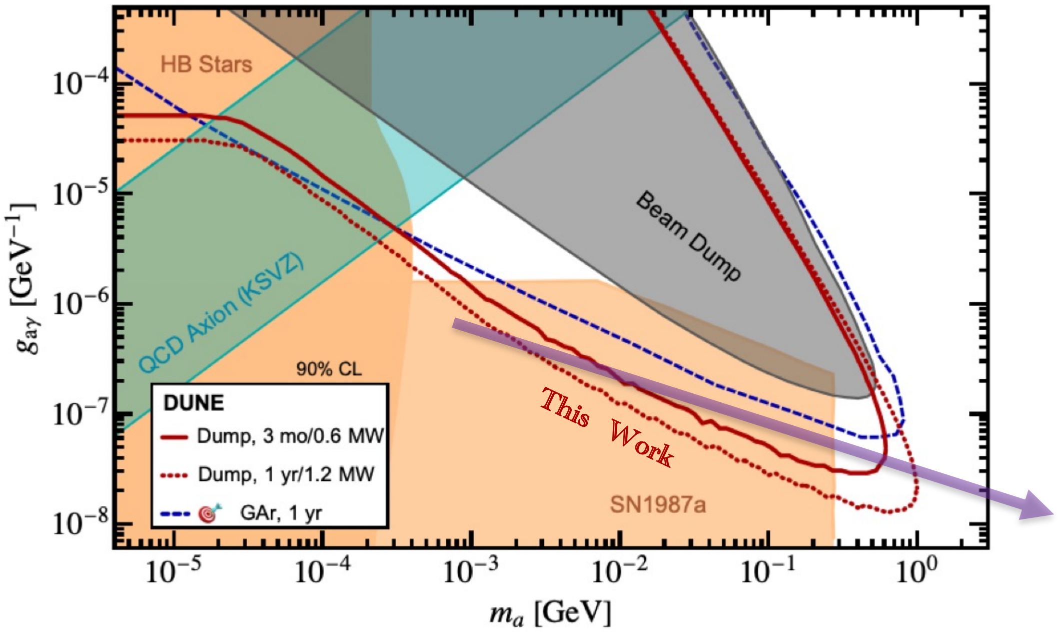


Inverse Primakoff scattering



ALP decay

ALPs at Target-less DUNE



- The only lab-based constraints!
- Can probe QCD-axion
- 3 months target-less DUNE can do better than 1 yr GAr

Brdar, Dutta, Jang, Kim, Shoemaker, *ZT*, Thompson, Yu
PRL (2021)

Brdar, Dutta, Jang, Kim, Shoemaker, *ZT*, Thompson, Yu
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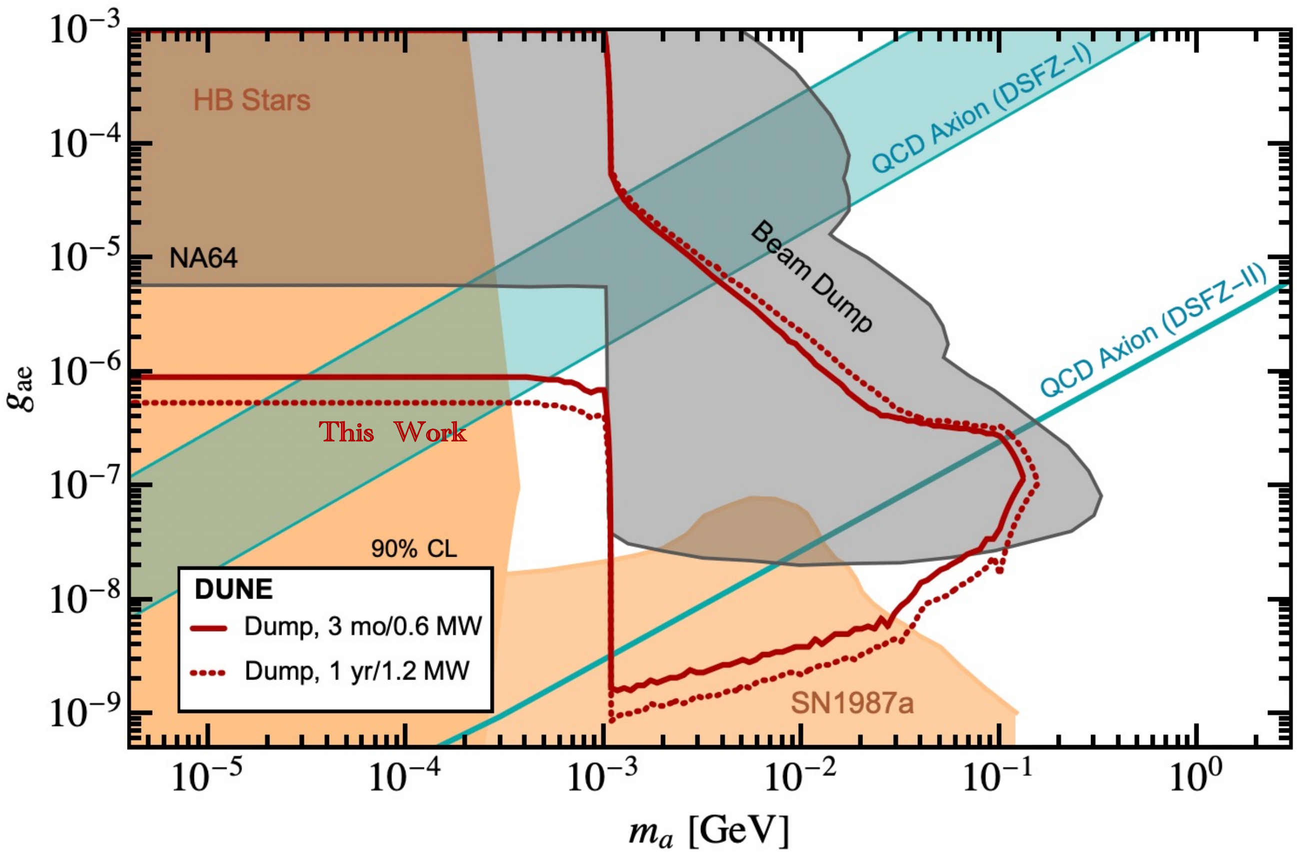
ALPs at Target-less DUNE



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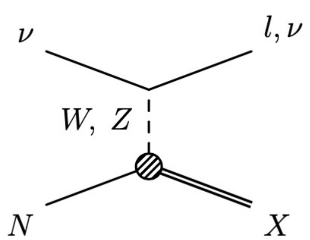
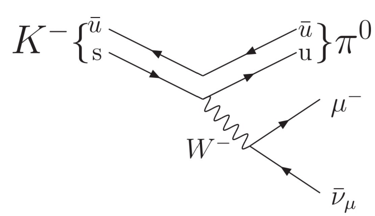
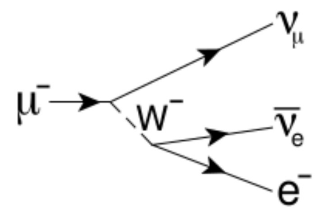
DIS: FASERν



Kaon/Muon decay: ISODAR, KDAR





Solar neutrinos: Borexino

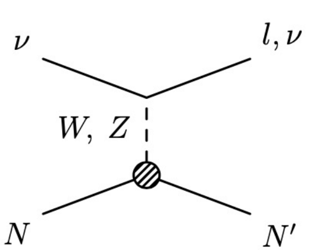
^{7}**Be** $\boxed{^7\mathrm{Be} + e^- \to {}^7\mathrm{Li} + \nu_e}$

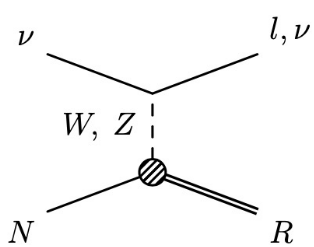
$\boxed{^3\mathrm{He} + p \to {}^4\mathrm{He} + e^+ + \nu_e}$ **hep**

(hep)

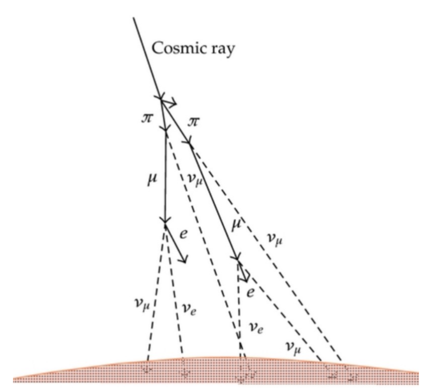
$\boxed{p + e^- + p \to {}^2\mathrm{H} + \nu_e}$ ***pep***

QE, Resonances: MINOS, NOvA, DUNE

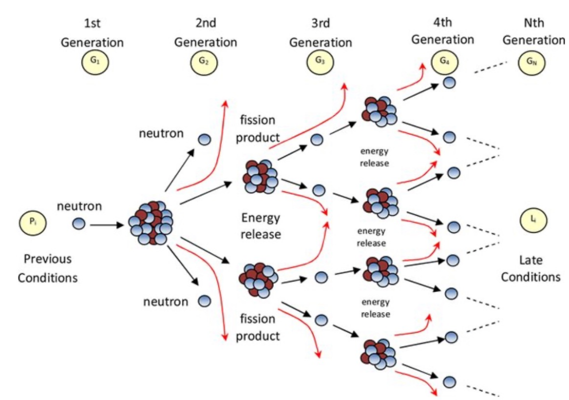




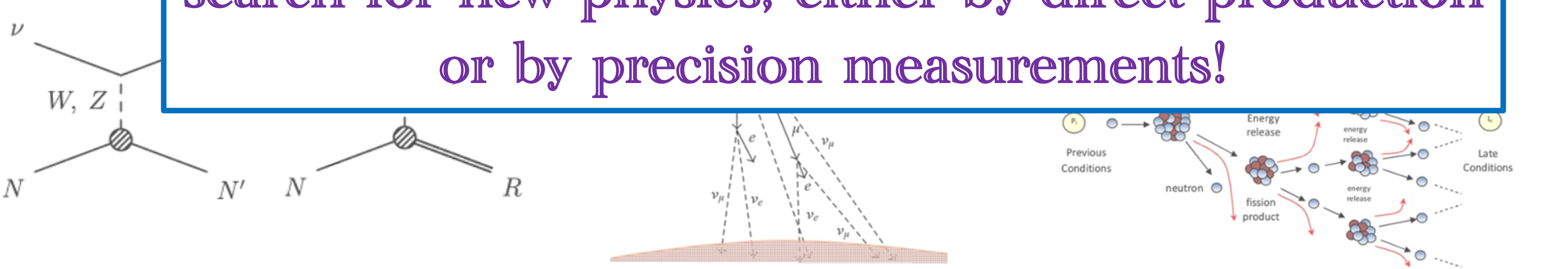
Atmospheric Neutrinos: IceCube



Beta decay and IBD: Reactor Experiments

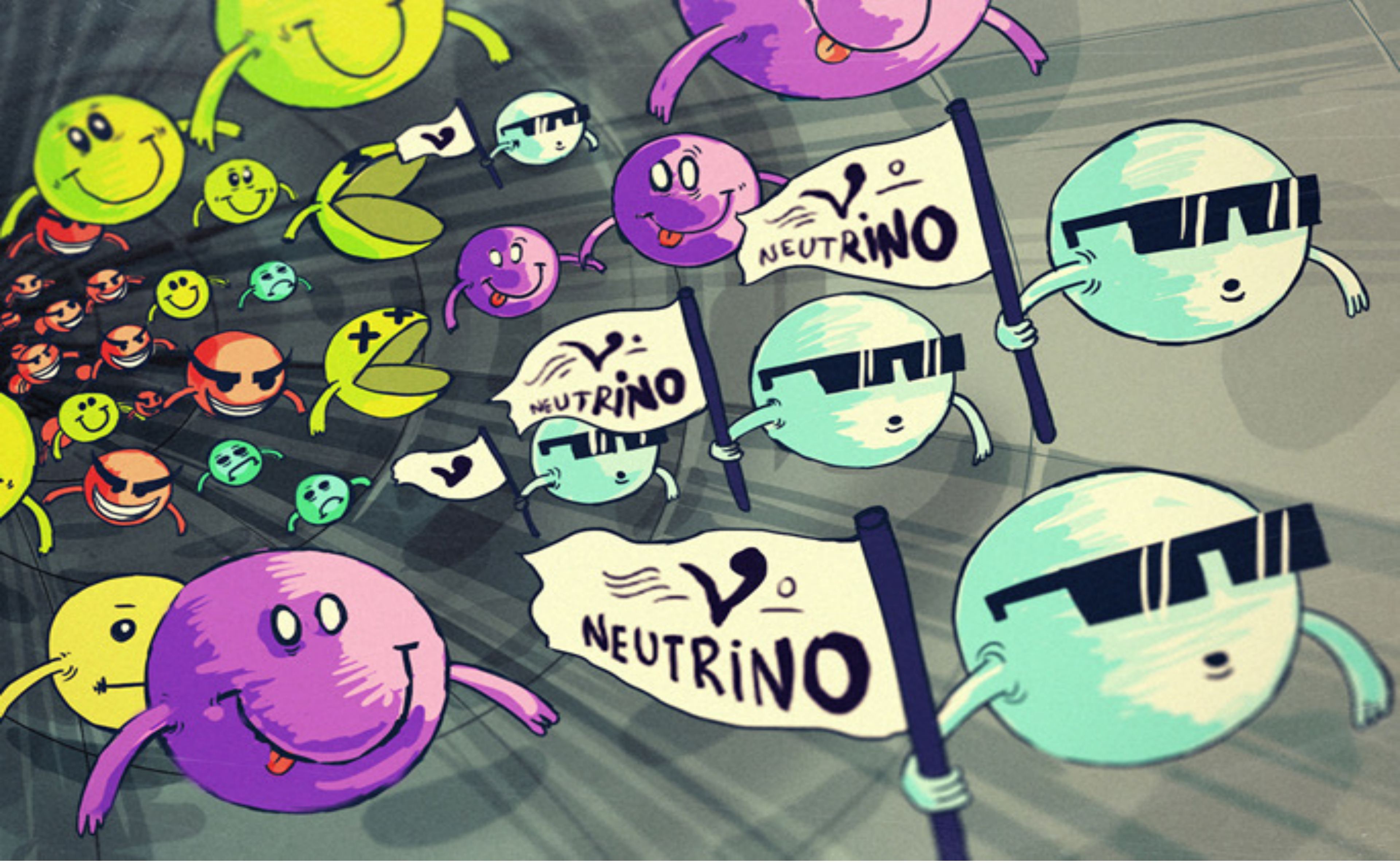


Neutrino experiments give us a powerful tool to search for new physics, either by direct production or by precision measurements!



Conclusion:

- New generation of neutrino experiments are being built to answer many unknowns in the neutrino sectors;
- We can use the near detectors to directly search for dark sector (e.g.: ALPs, light DM, etc.);
- For several BSM models, near detectors give the best constraints;
- We can remove most of the neutrino background by using the target-less configuration;
- Target-less DUNE can probe the parameter space for thermal relic DM in only 3 months!
- It can also probe the region for QCD axion, and give best lab-based constraint on the parameter space of ALPs

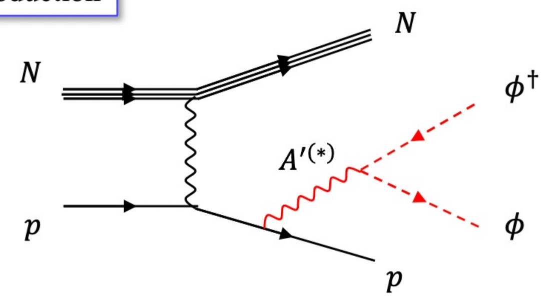


Thanks for your attention

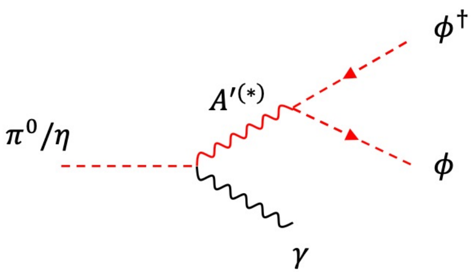
Back up Slides

Production and Detection of Dark Matter

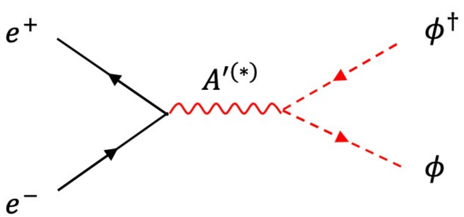
DM production



Beam bremsstrahlung

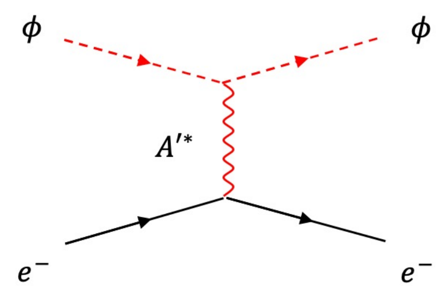


Neutral meson decays



Resonance production

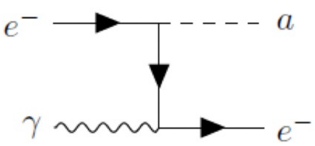
DM detection



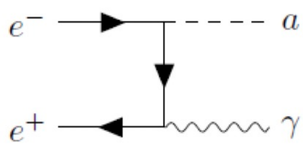
Elastic scattering with an electron

Production and Detection of ALPs

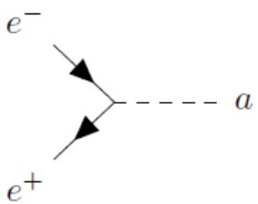
ALP production



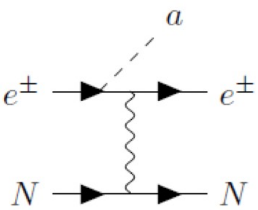
Compton



Associated production

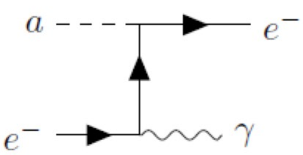


Resonant production

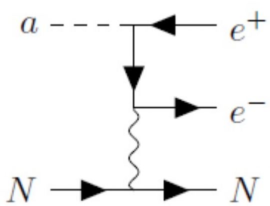


ALP-bremsstrahlung

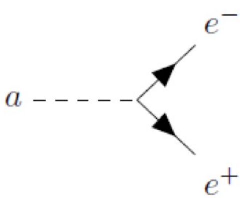
ALP detection



Inverse Compton



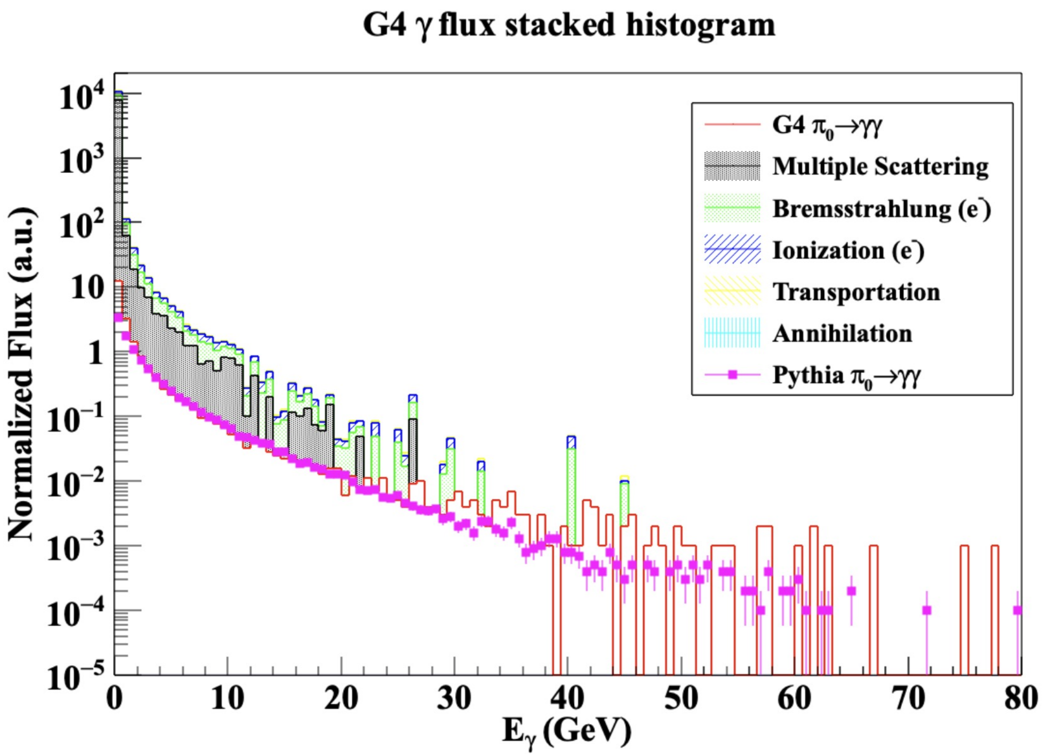
External pair conversion



Di-lepton decay

Axion Like Particles (ALPs) at DUNE:

Photon Flux from GEANT4 Simulation



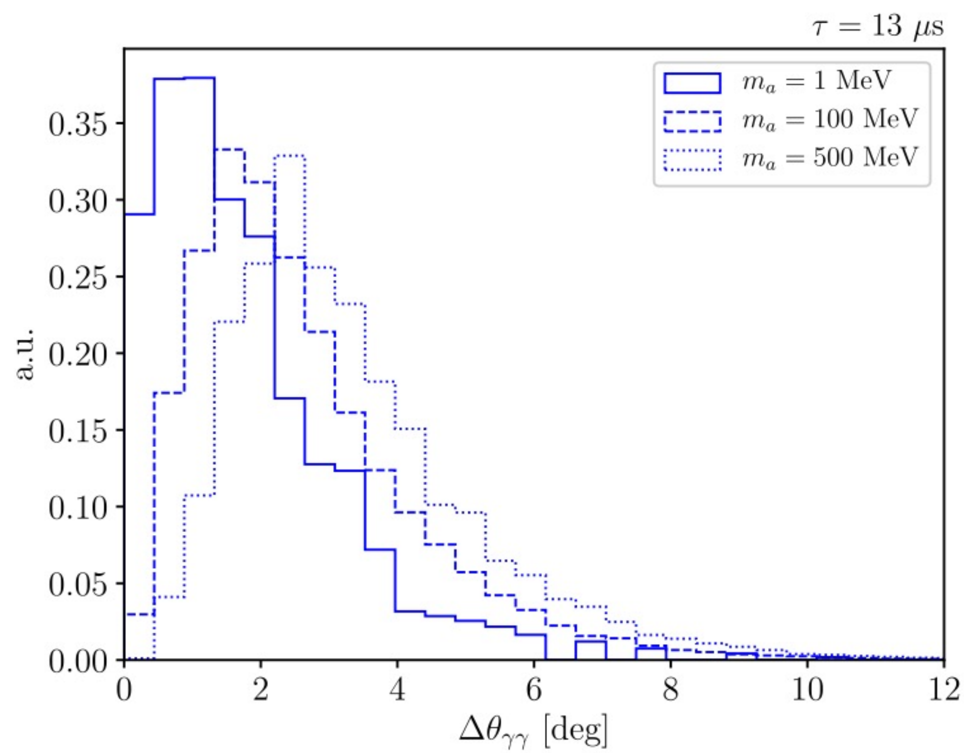
V. Brdar, B. Dutta, W. Jang, D. Kim, I. Shoemaker, **ZT**, A. Thompson, J. Yu
Phys.Rev.Lett. 126 (2021) 20, 201801

Axion Like Particles (ALPs) at DUNE:

- Coherent π^0 production $\nu + A \rightarrow \nu + A + \pi^0$

In GAr:

- We expect ~ 10^6 NC events;
- Vetoing events with hadronic activity remove ~ 80%;
- A cut on the opening angle removes the rest;



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