Probing new physics at DUNE operating in a beam-dump mode

Artwork by Sandbox Studio, Chicago with Ana Kova

Path to Dark Sector Discoveries at Neutrino Experiments

June 5-7, 2023

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Northwestern University

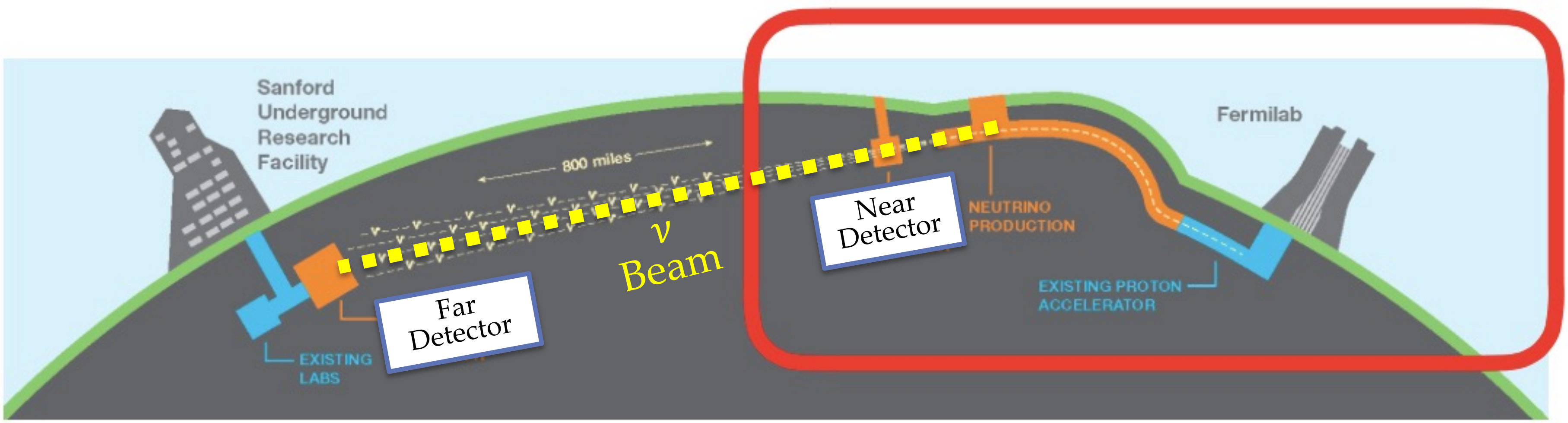
Physics goals of near detectors:

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

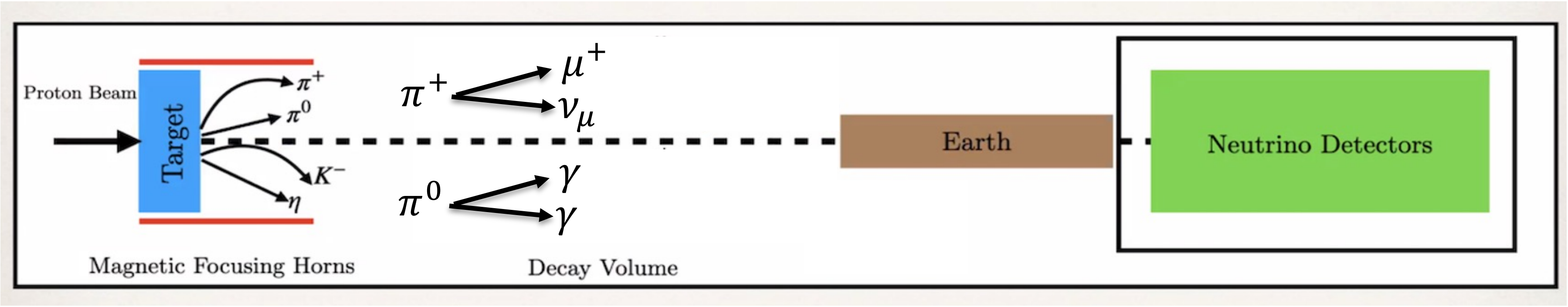


Questions:

- **How can we fully leverage DUNE to search for Dark Sectors?**

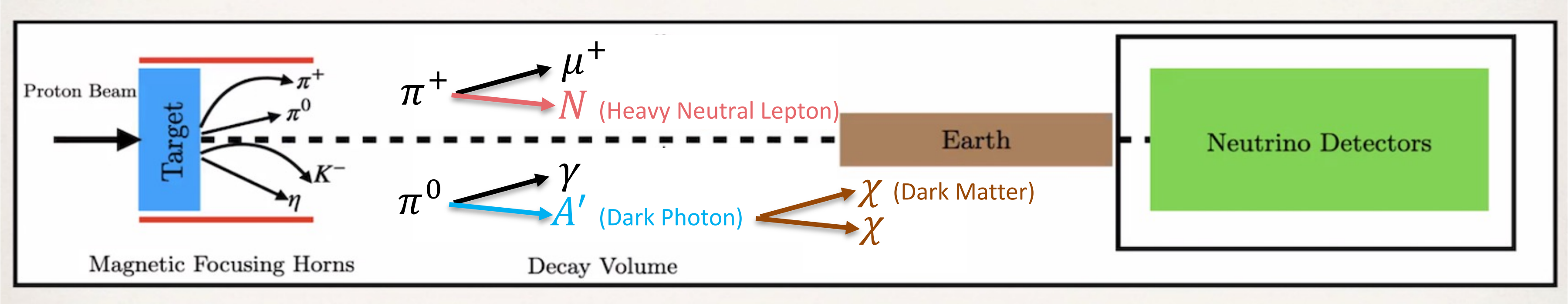
- **Can DUNE probe compelling new physics beyond the reach of high energy colliders?**

Neutrino Experiments as Dark Sector factories!



Credit: Kevin Kelly

The huge fluxes of neutrinos and photons 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)

Outline:

- Light Dark Matter
- Axion-Like Particles
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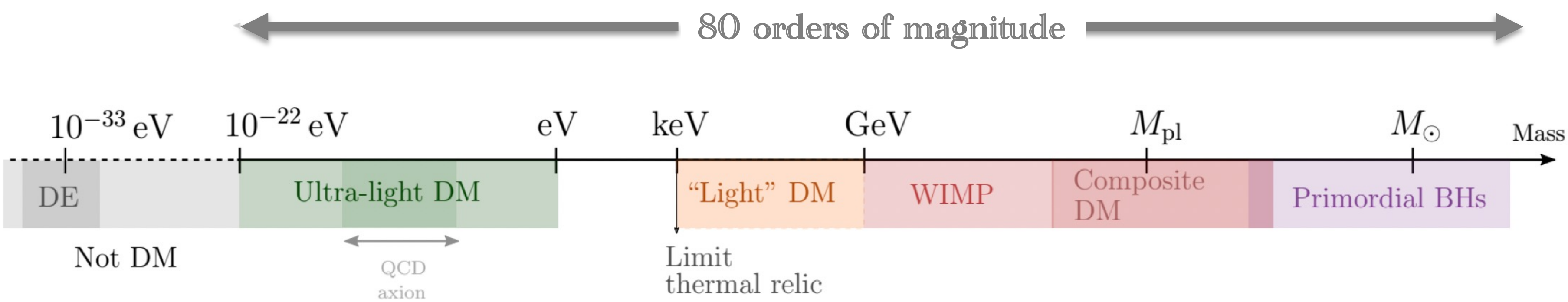
"What is Dark Matter?"

We don't know!

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

"Where is Dark Matter?"

We don't know!



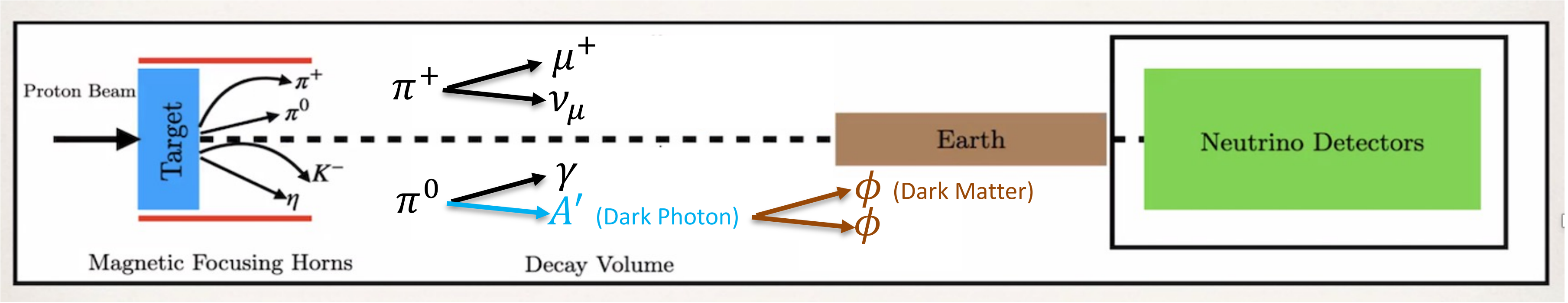
Elisa G. M. Ferreira, arXiv:2005.03254

“How is Dark Matter?”

TOM GAULD for NEW SCIENTIST

Light Dark Matter

Credit: Kevin Kelly



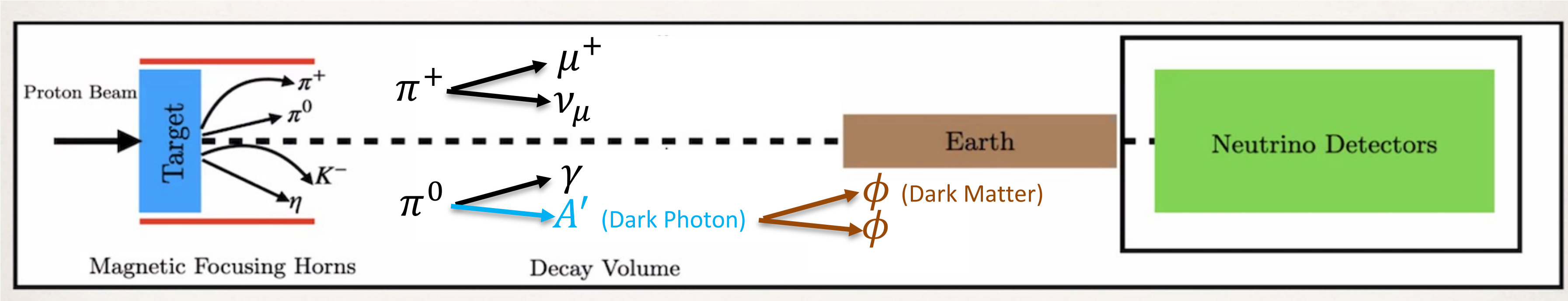
Photons at the target kinetically produce Dark Photons, which decay into dark matter:

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

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

Light Dark Matter

Credit: Kevin Kelly



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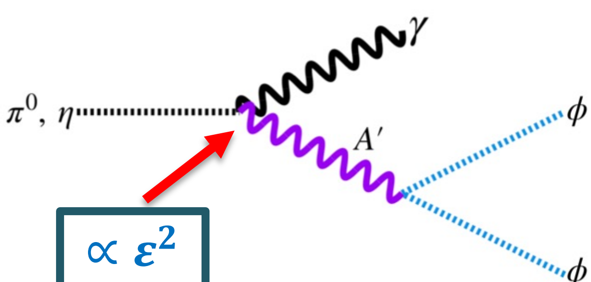
DM production



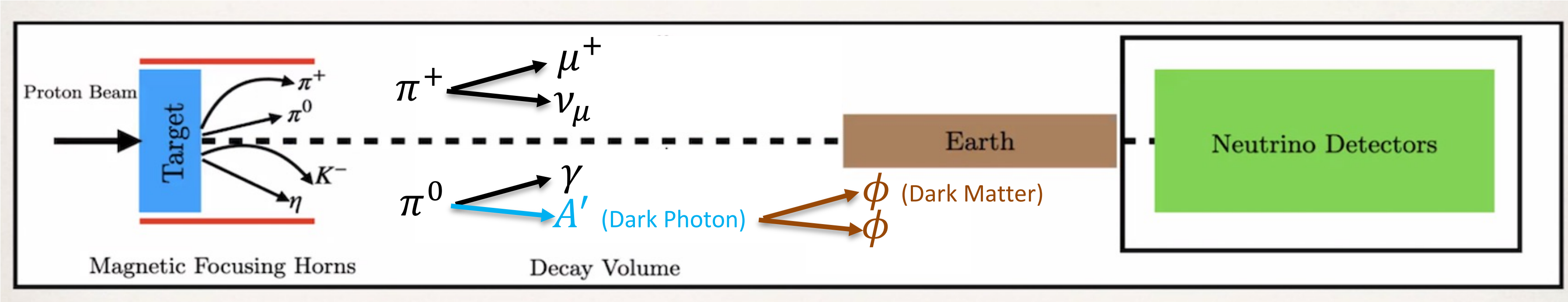
$\propto \varepsilon^2$

De Romeri, Kelly, Machado, PRD (2019)

(also Beam bremsstrahlung and Resonance production)

Light Dark Matter

Credit: Kevin Kelly



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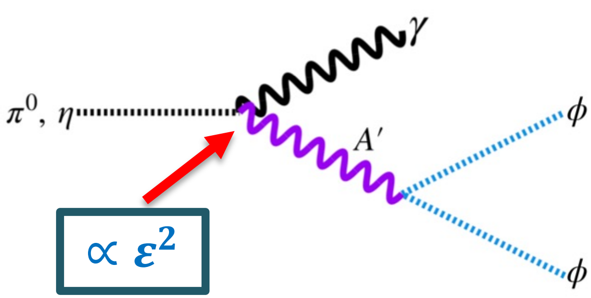

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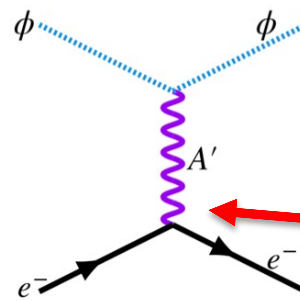
DM detection

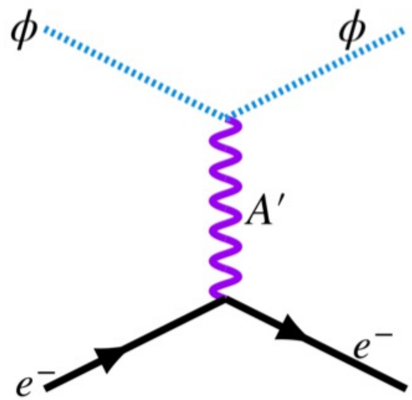


$\propto \varepsilon^2$

DM event rate $\sim \varepsilon^4 \alpha_D$

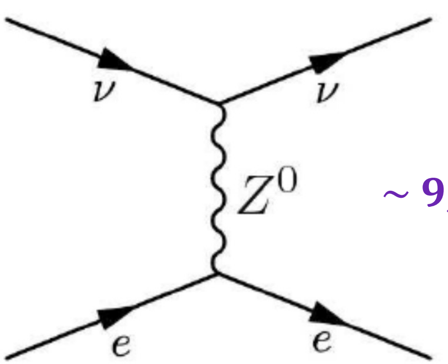
Light Dark Matter

DM signal: elastic scattering on electrons



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

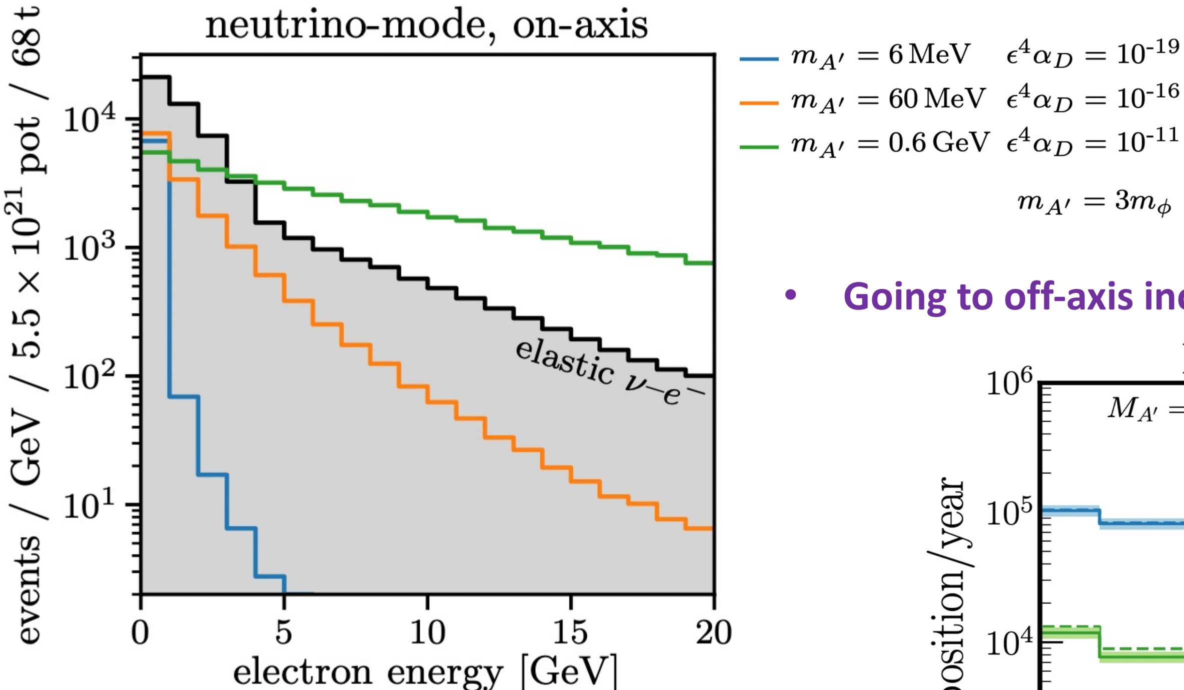
But so do neutrinos!



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

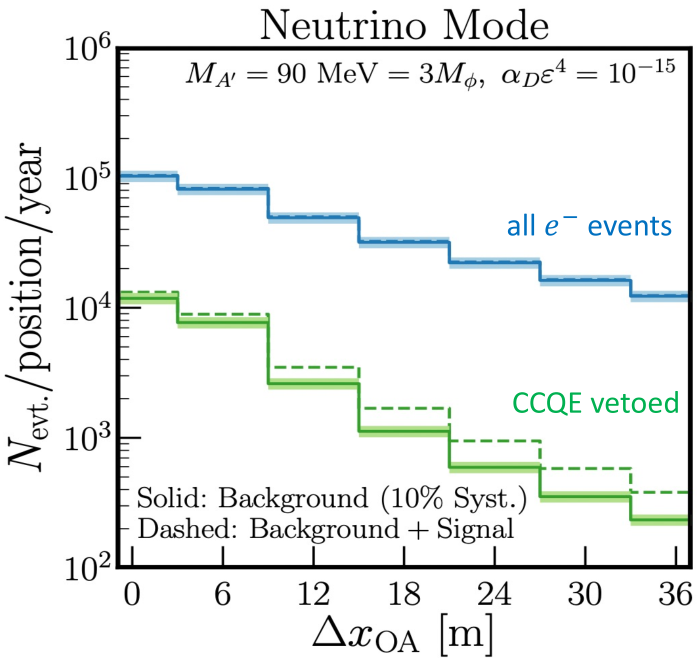
Light Dark Matter

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



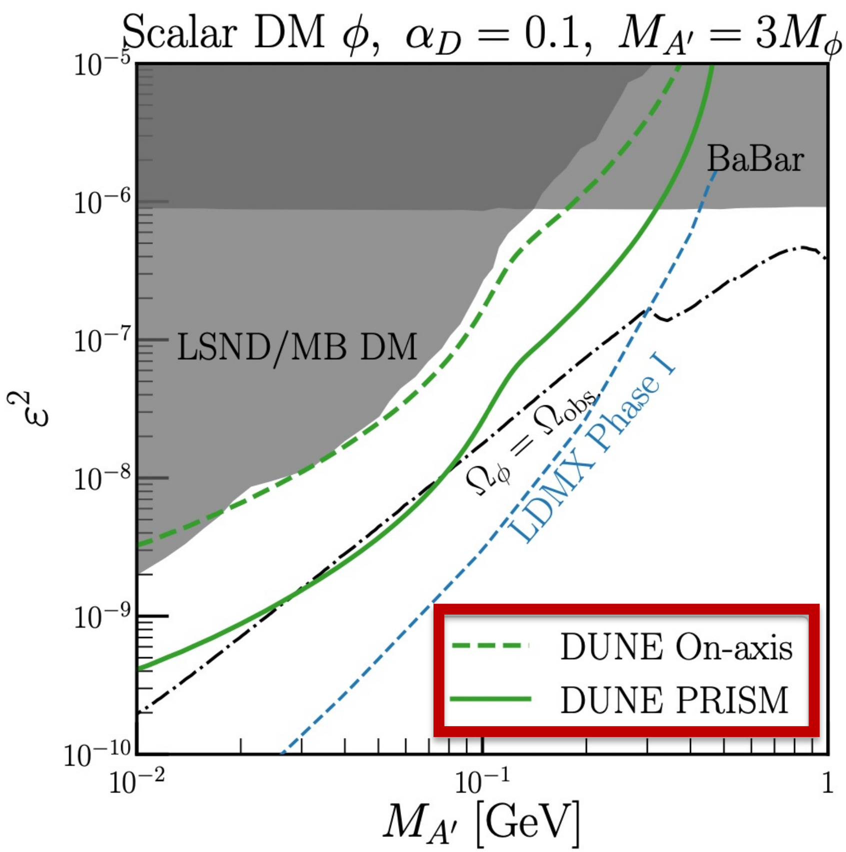
Breitbach, Buonocore, Frugiuele, Kopp, Mittnacht, JHEP (2022)

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



De Romeri, Kelly, Machado, PRD (2019)

Light Dark Matter



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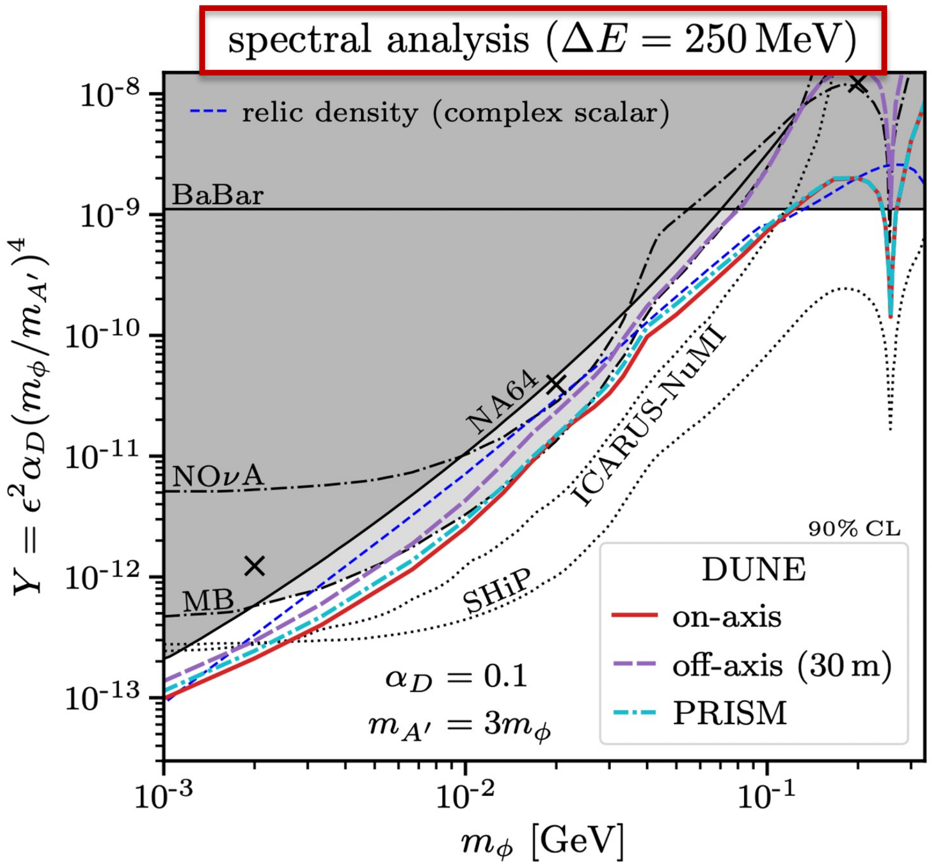
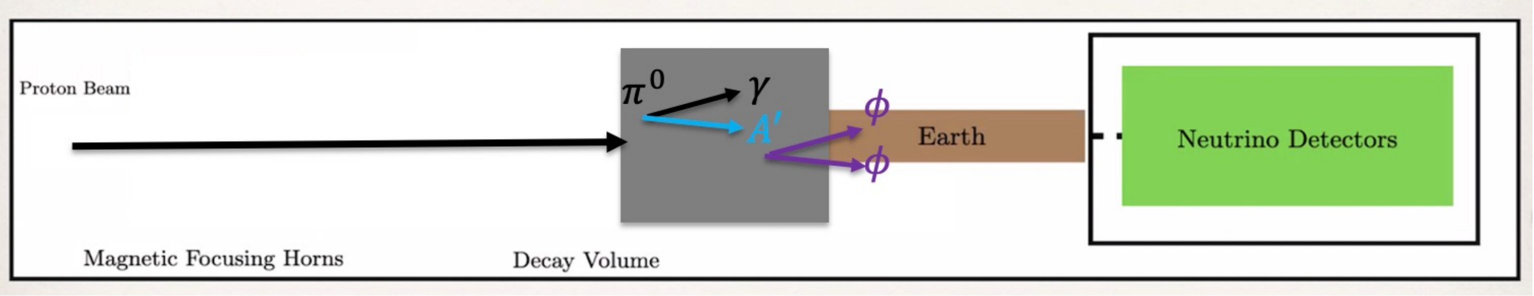


Breitbach, Buonocore, Frugiuele, Kopp, Mittnacht, JHEP (2022)

See talk by Kevin Kelly

Proposing a movable target system at DUNE

Credit: Kevin Kelly



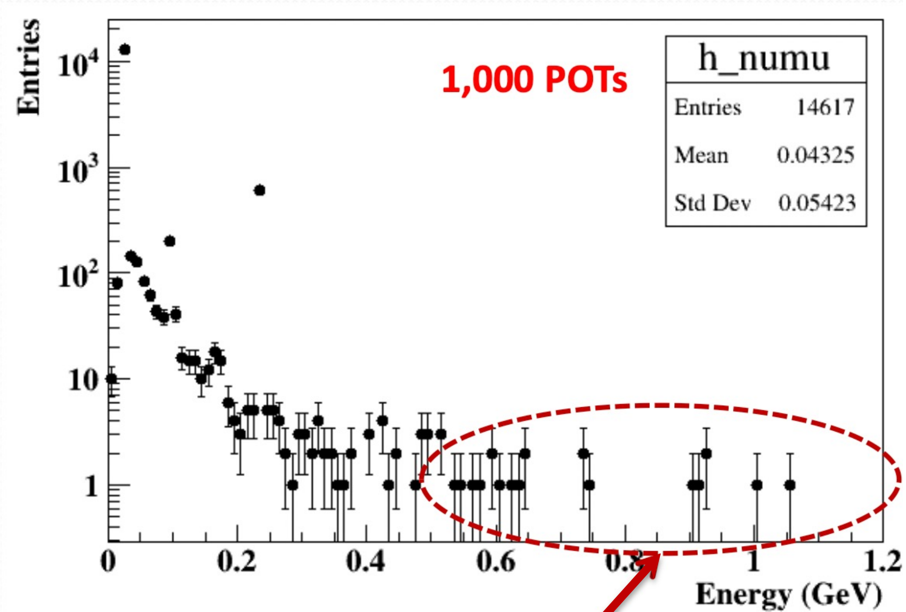
We can dump protons directly to the dump area!

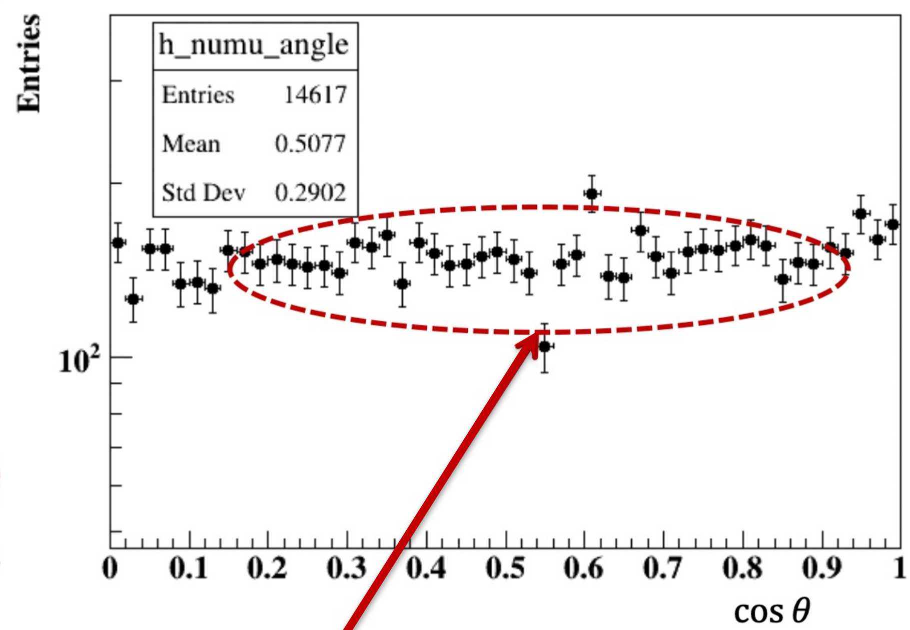
Gains:

- Shorter distance between the source and the detector → more DM signal;
- Charged mesons absorbed in the Al beam dump before decay;
- The ν flux decreases → Much less ν background.

Brdar, Dutta, Jang, Kim, Shoemaker, *ZT*, Thompson, Yu
PRD (2023)

A Targetless DUNE:





Low rate of high energy ν's

Isotropic neutrino flux

Brdar, Dutta, Jang, Kim, Shoemaker, *ZT*, Thompson, Yu
PRD (2023)

See the talk by Wooyoun Jang

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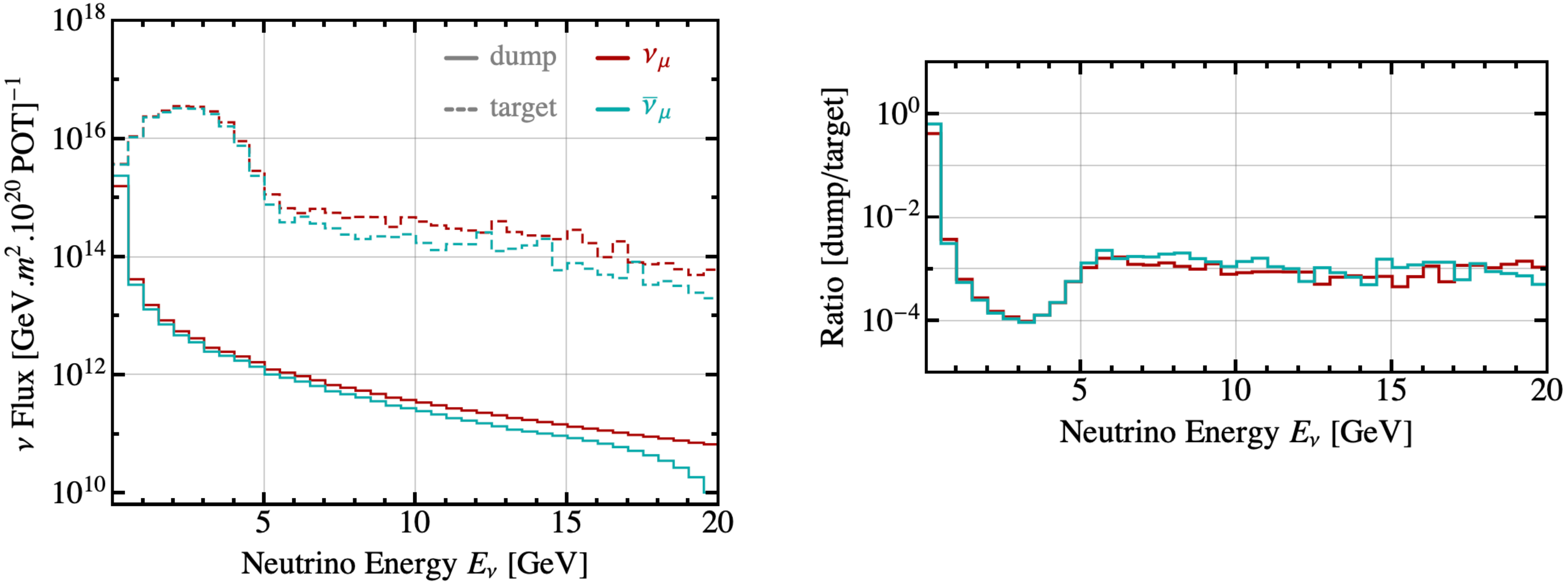
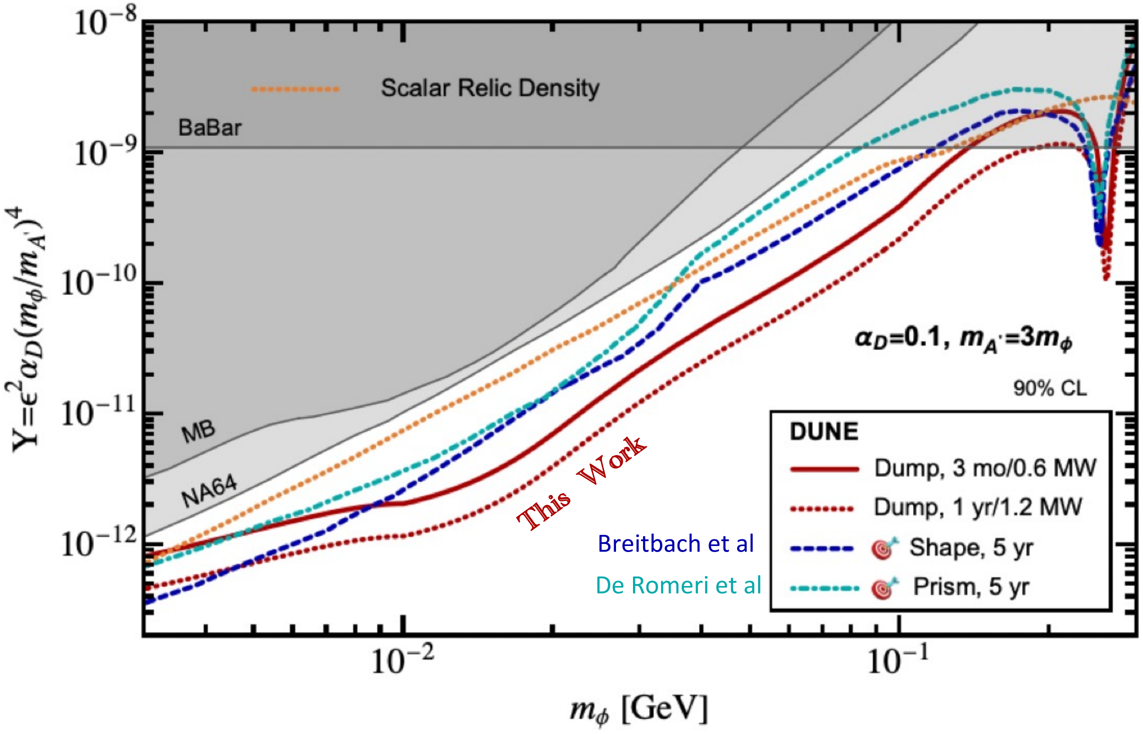


- **The ν flux decreases by 3 orders of magnitude**
- Only 0.5 ν-e background in 3 mo-0.6 MW!

Brdar, Dutta, Jang, Kim, Shoemaker, *ZT*, Thompson, Yu
PRD (2023)

Light Dark Matter at Target-less DUNE



Brdar, Dutta, Jang, Kim, Shoemaker, *ZT*, Thompson, Yu
PRD (2023)

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

Outline:

- Light Dark Matter
- Axion-Like Particles
- Dark Pion/Dark Neutrino
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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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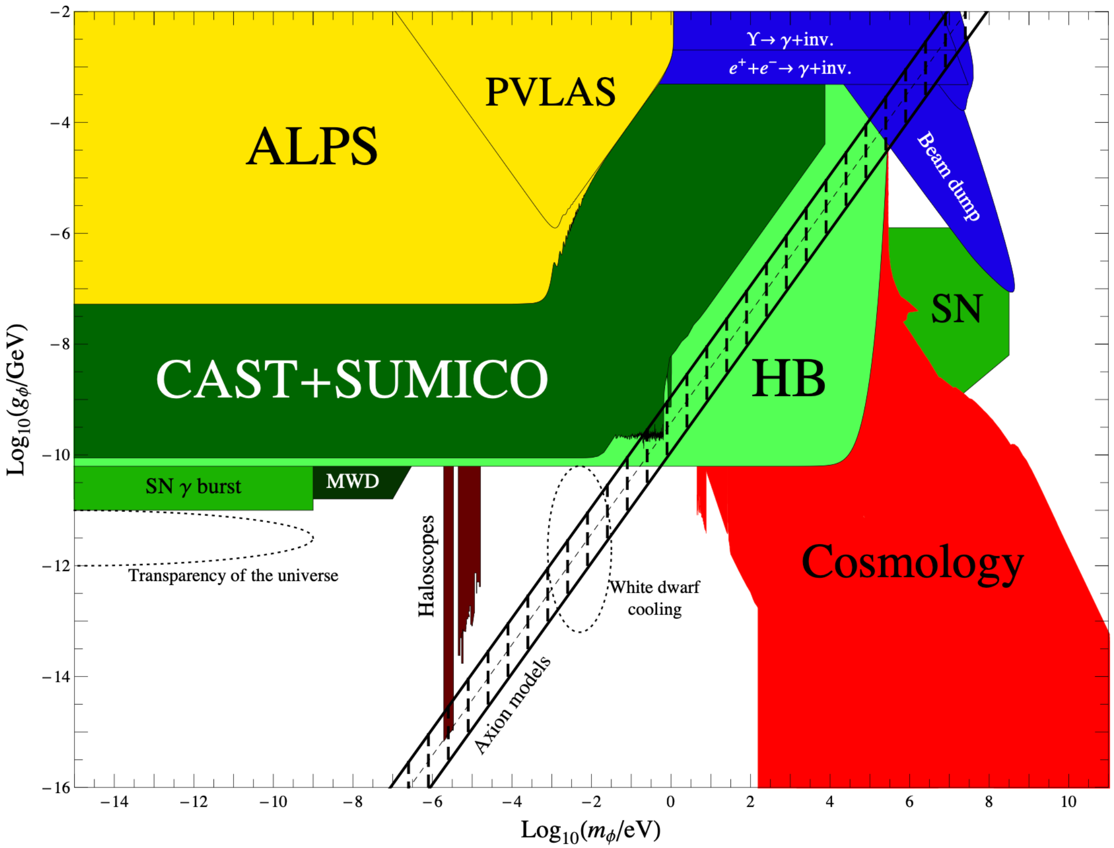

D. Cadamuro, 1210.3196 [hep-ph]

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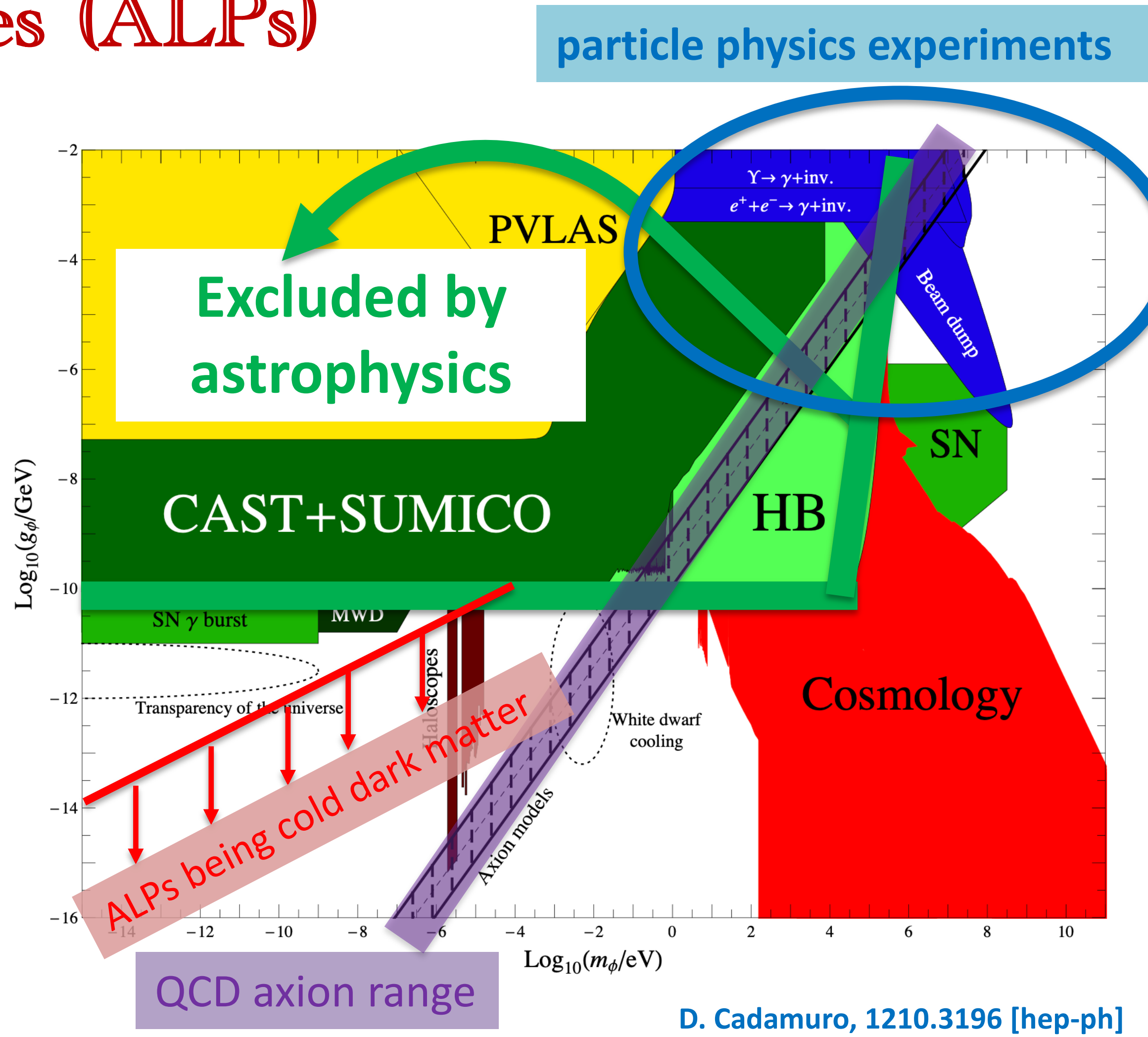

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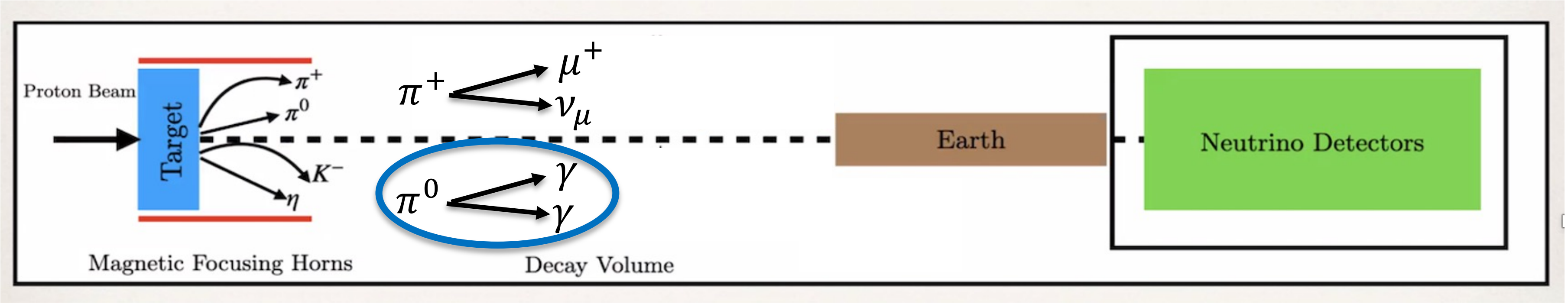
ALPs at Neutrino Experiments

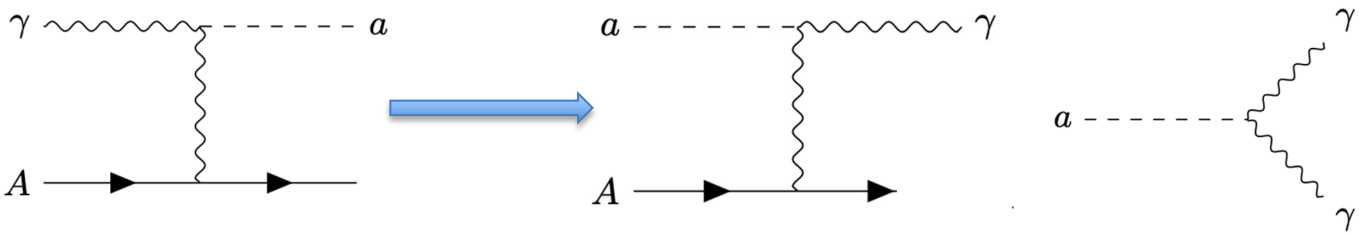


Credit: Kevin Kelly

Using photons to produce ALPs:

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

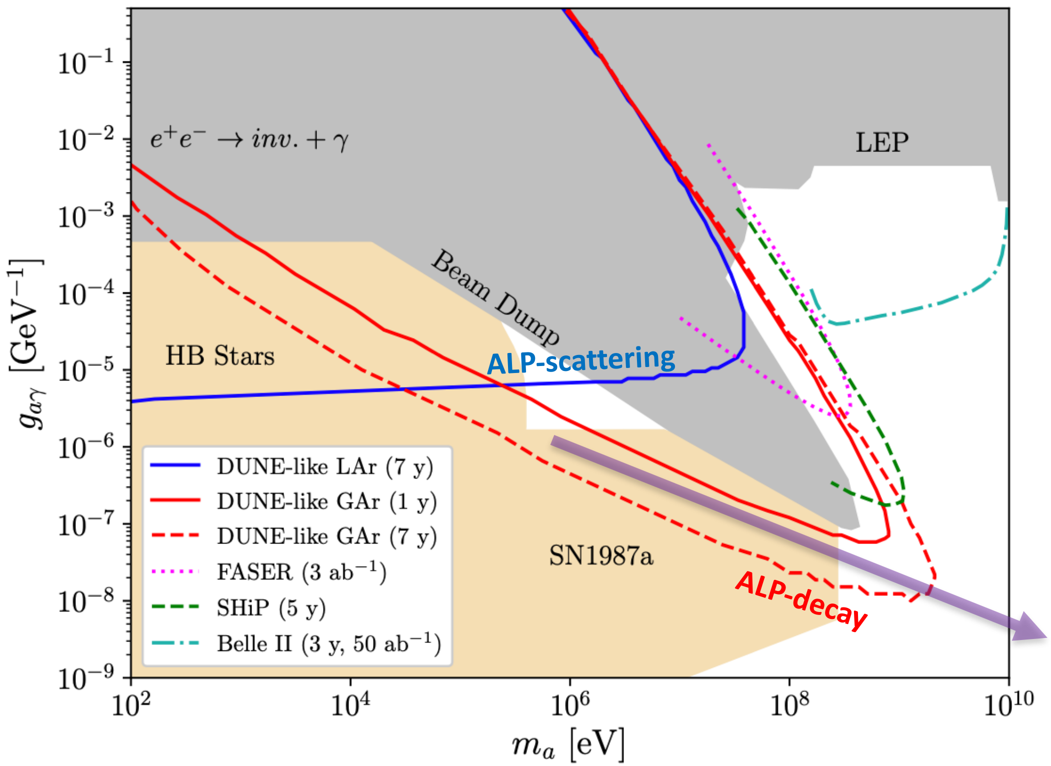
ALP production　　　　ALP detection



Primakoff scattering　　Inverse Primakoff scattering　　ALP decay

Primakoff process: Coherent conversion of $\gamma \to a$ with Z^2 enhancement

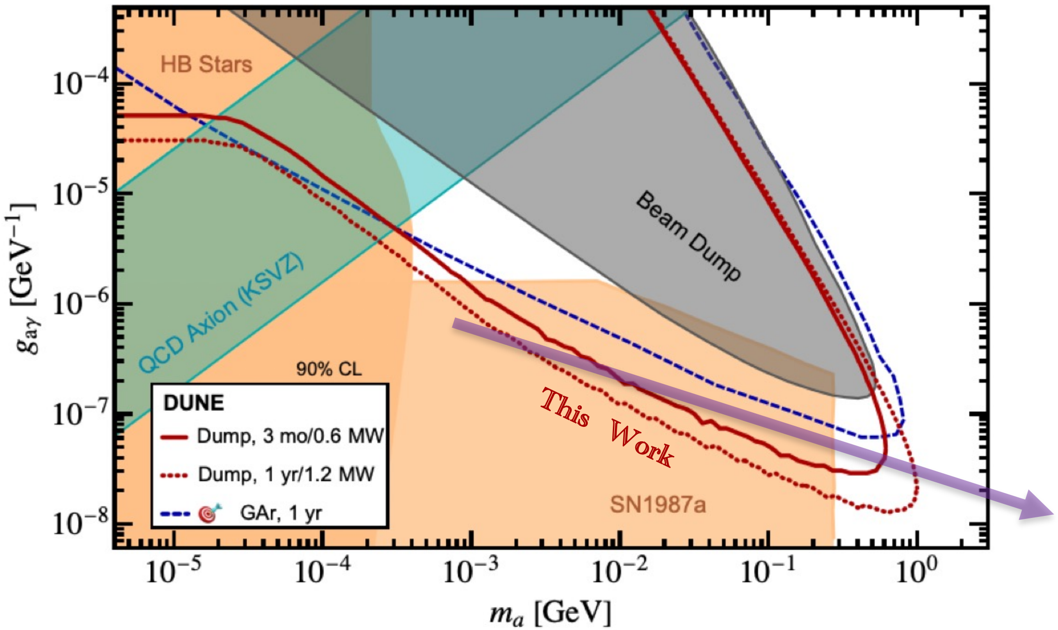
ALP-γ at LAr/GAr DUNE



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

- The only lab-based constraints!
- Gas-detector is the key, due to significantly low background!

ALP-γ 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)

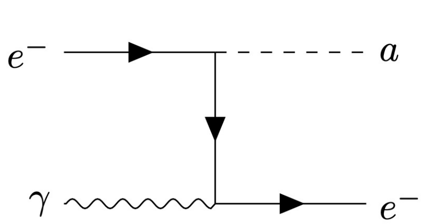
Brdar, Dutta, Jang, Kim, Shoemaker, *ZT*, Thompson, Yu PRD (2023)

ALPs at Neutrino Experiments

Using electrons to produce ALPs:

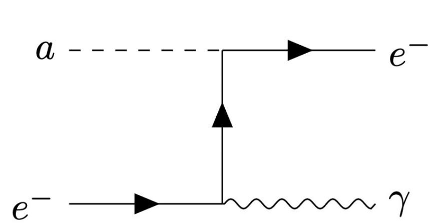
$$\mathcal{L}_{aee} \supset g_{aee} a \bar{\psi} \gamma^5 \psi$$

ALP production

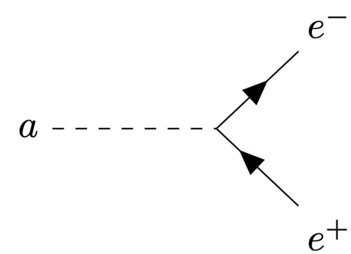


Compton scattering

ALP detection

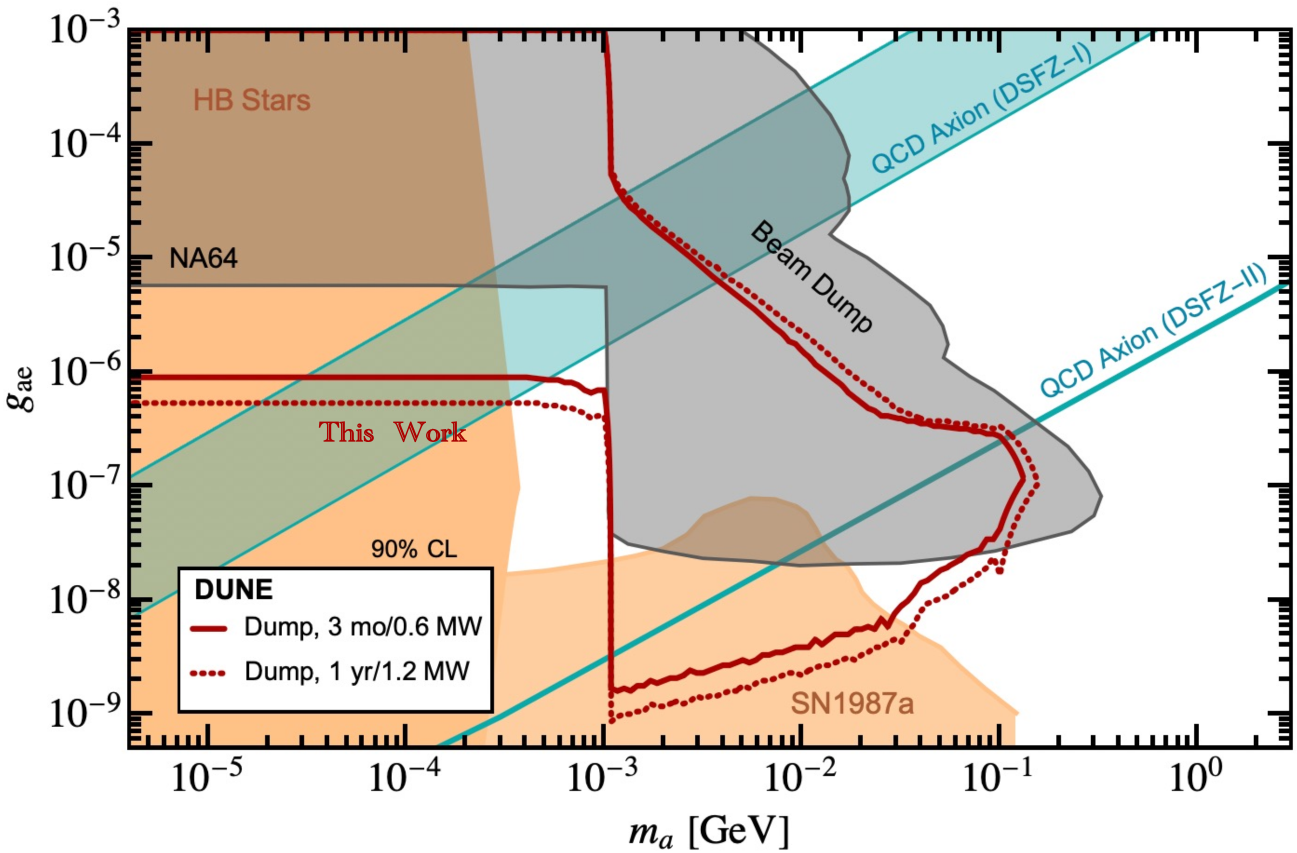


Compton scattering



ALP decay

ALP-e at Target-less DUNE



Brdar, Dutta, Jang, Kim, Shoemaker, *ZT*, Thompson, Yu
PRD (2023)

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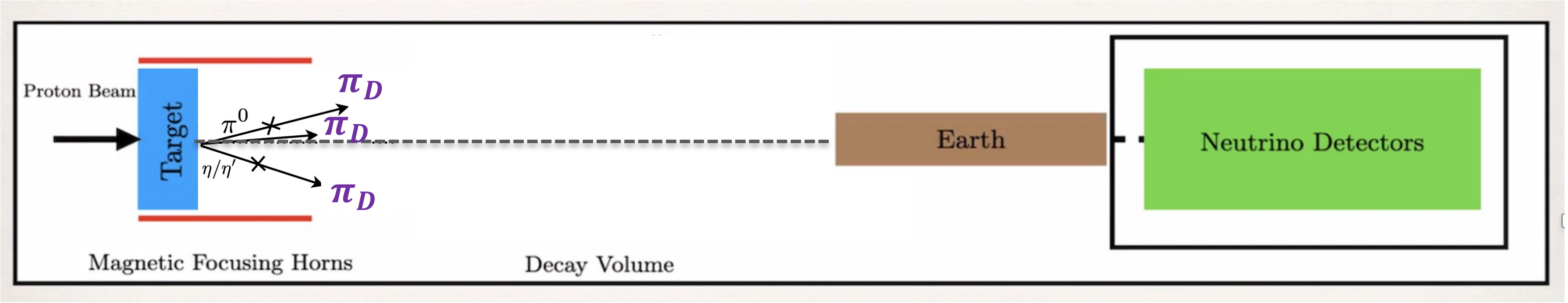
Dark Pion/Dark Neutrino

Credit: Kevin Kelly



Dark Pion could be produces through mixing with neutral mesons:

$$\pi^0 = \pi^0_{phys} + \theta_{\pi_D}\pi_D$$

Kelly, Kumar, Liu, PRD (2021)

Depends on the Dark Sector properties (e.g. mass, etc)

$$\pi_D \to N_D N_D$$

Berryman, de Gouvêa, Kelly, Zhang, PRD (2017)

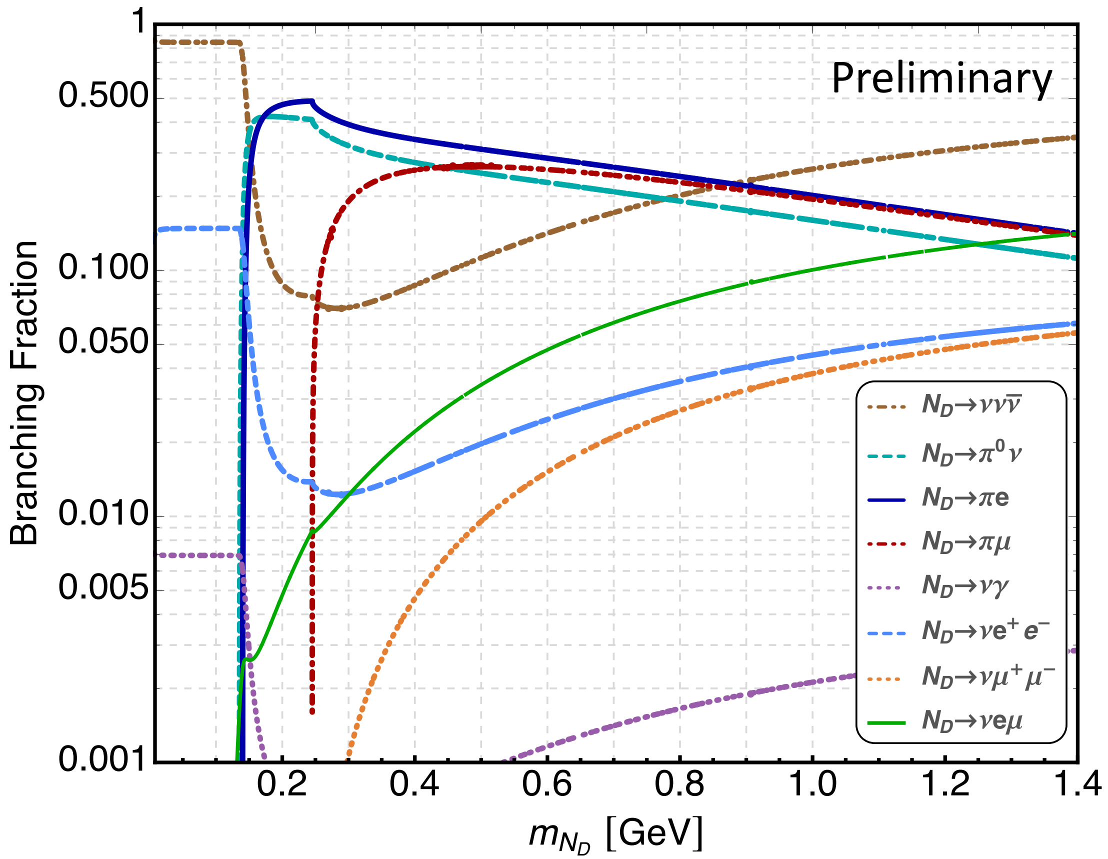
Dark neutrino is an HNL, it can decay inside the detector!

HNL event rate $\sim \theta_{\pi_D}{}^2 |U_\alpha|^2$

Enhanced wrt the usual HNL if $\theta_{\pi_D}{}^2 \gg |U_\alpha|^2$

Dark Neutrino Decays

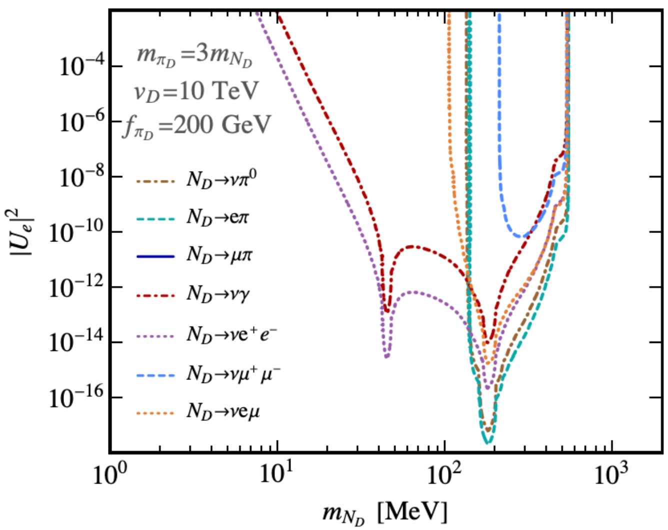
Abdullahi, de Gouvêa, Dutta, Shoemaker, ZT, In Preparation (2023)



Dark Neutrino Decays

Abdullahi, de Gouvêa, Dutta, Shoemaker, ZT, In Preparation (2023)

Preliminary



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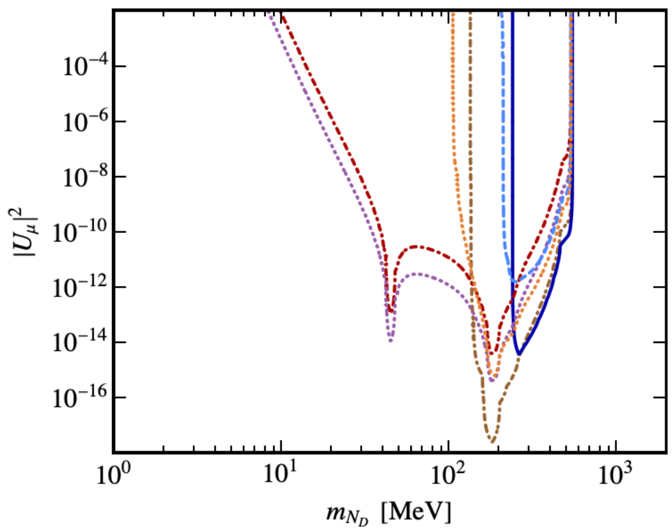

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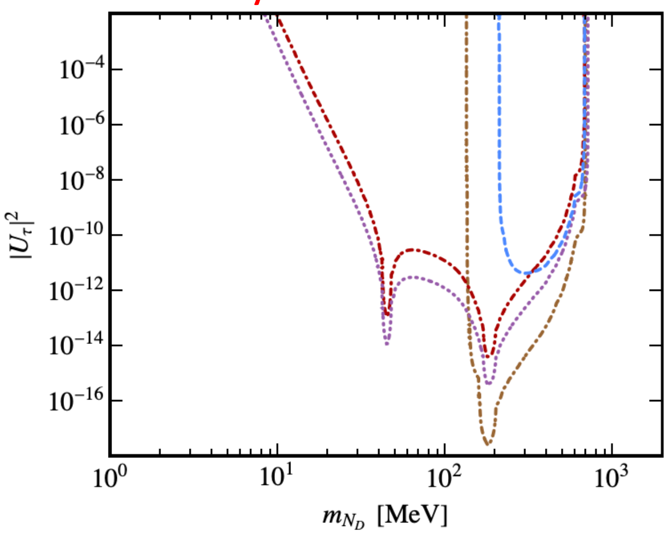
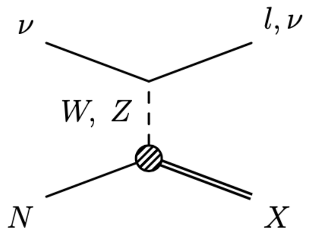


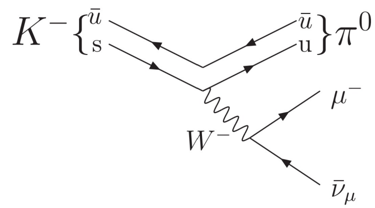
A new way to look for HNL, with much better sensitivity!

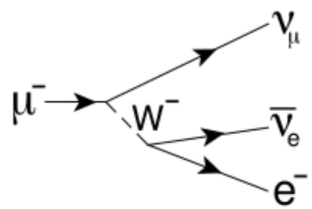
DIS: FASERν

Kaon/Muon decay: ISODAR, KDAR

Solar neutrinos: Borexino







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

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

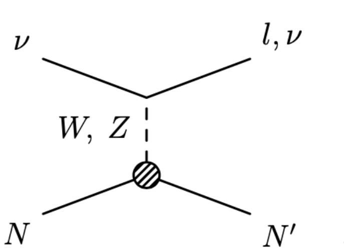
(hep)

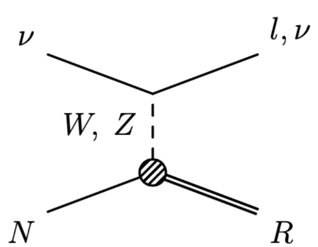
$p + e^- + p \to {}^{2}\mathrm{H} + \nu_e$ ***pep***

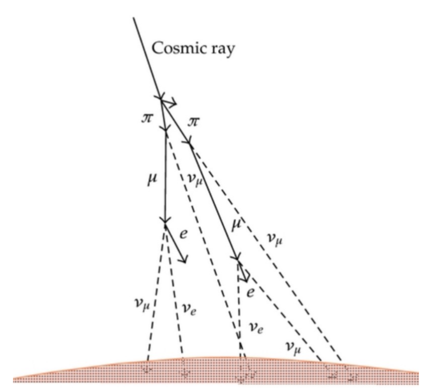
QE, Resonances: MINOS, NOvA, DUNE

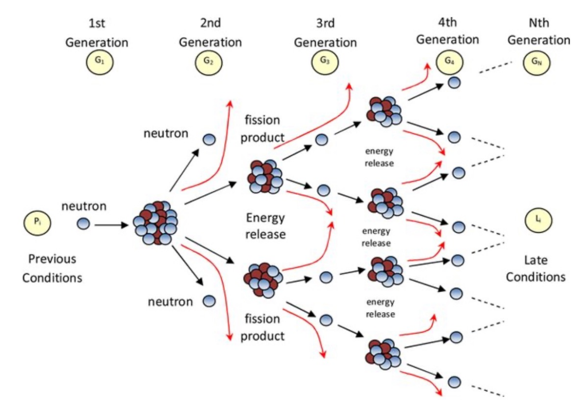
Atmospheric Neutrinos: IceCube

Beta decay and IBD: Reactor Experiments

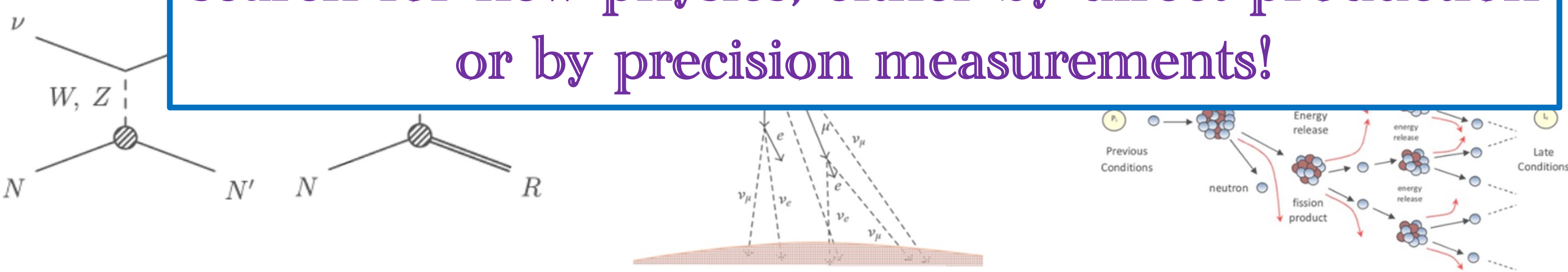






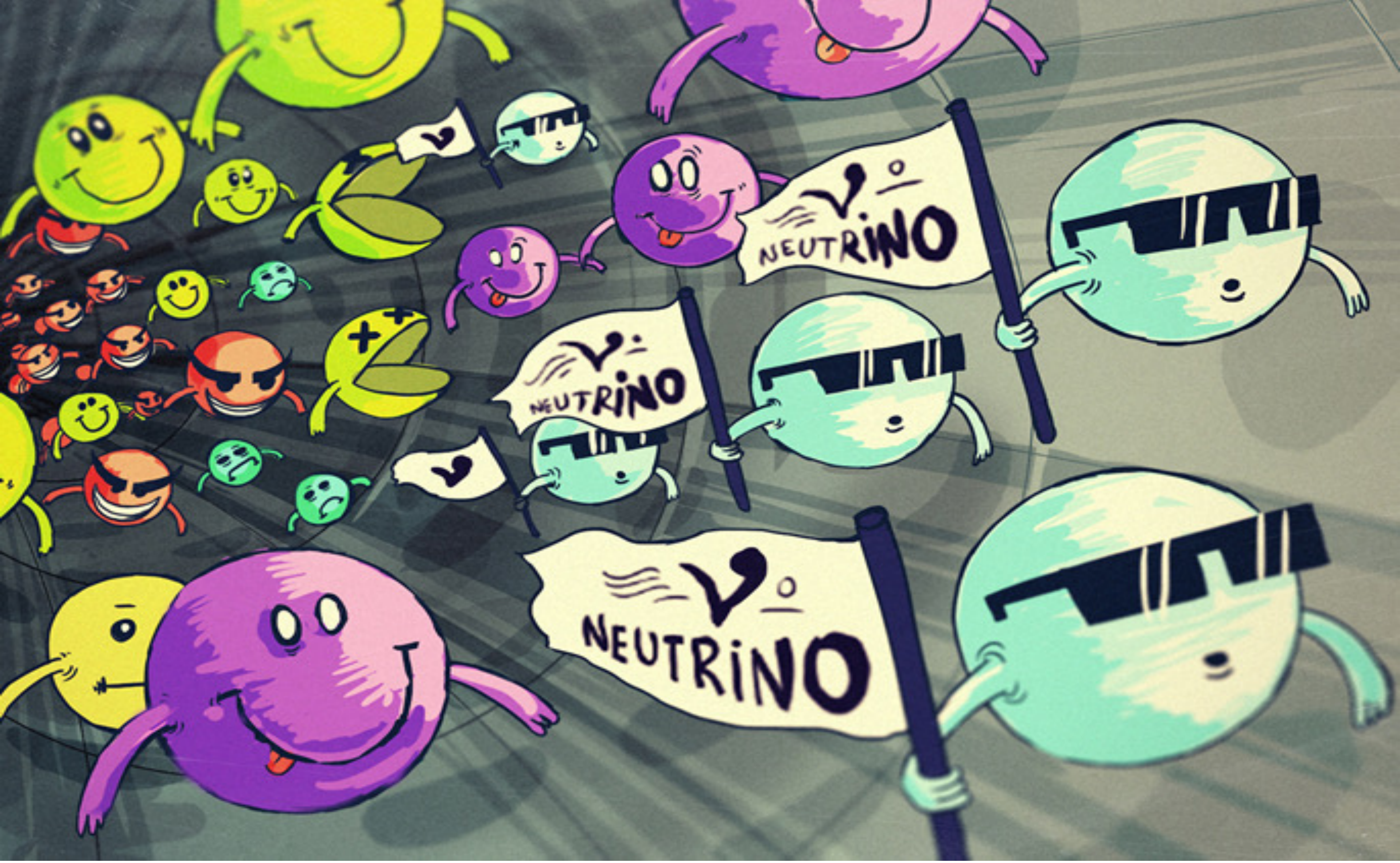


Neutrino experiments give us a powerful tool to search for new physics, either by direct production or by precision measurements!



Conclusion:

- We can use the near detectors to directly search for dark sector (e.g.: ALPs, light DM, Dark pion/Dark neutrino, 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;
- To search for Dark Sectors we need to be inclusive, they could demonstrate themselves in many different ways!
- E.g. much better sensitivity to HNL coming from neutral mesons;

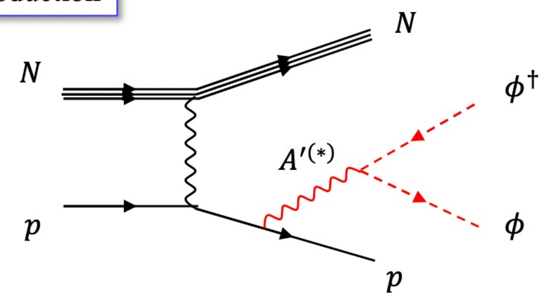


Thanks for your attention

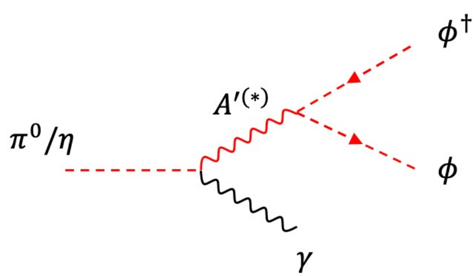
Back up Slides

Production and Detection of Dark Matter

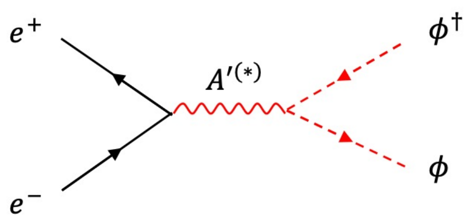
DM production



Beam bremsstrahlung

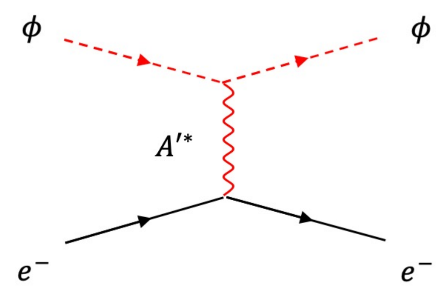


Neutral meson decays



Resonance production

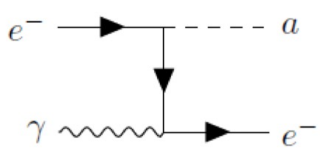
DM detection



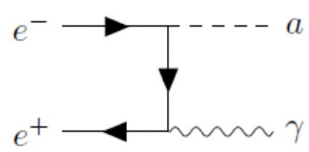
Elastic scattering with an electron

Production and Detection of ALPs

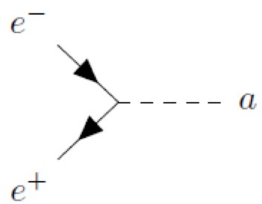
ALP production



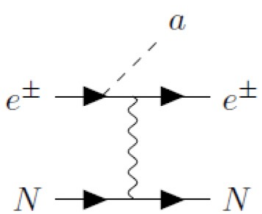
Compton



Associated production

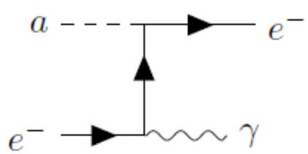


Resonant production

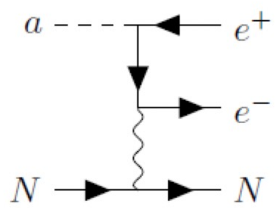


ALP-bremsstrahlung

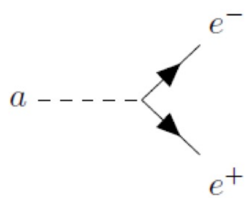
ALP detection



Inverse Compton



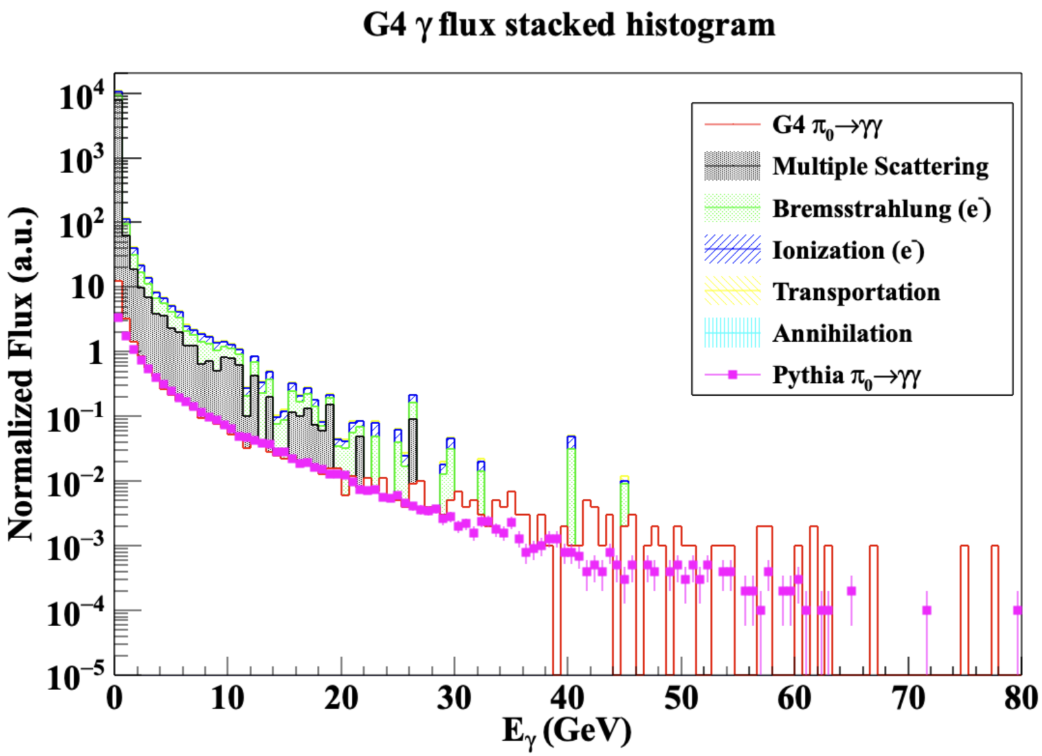
External pair conversion



Di-lepton decay

Axion Like Particles (ALPs) at DUNE:

Photon Flux from GEANT4 Simulation



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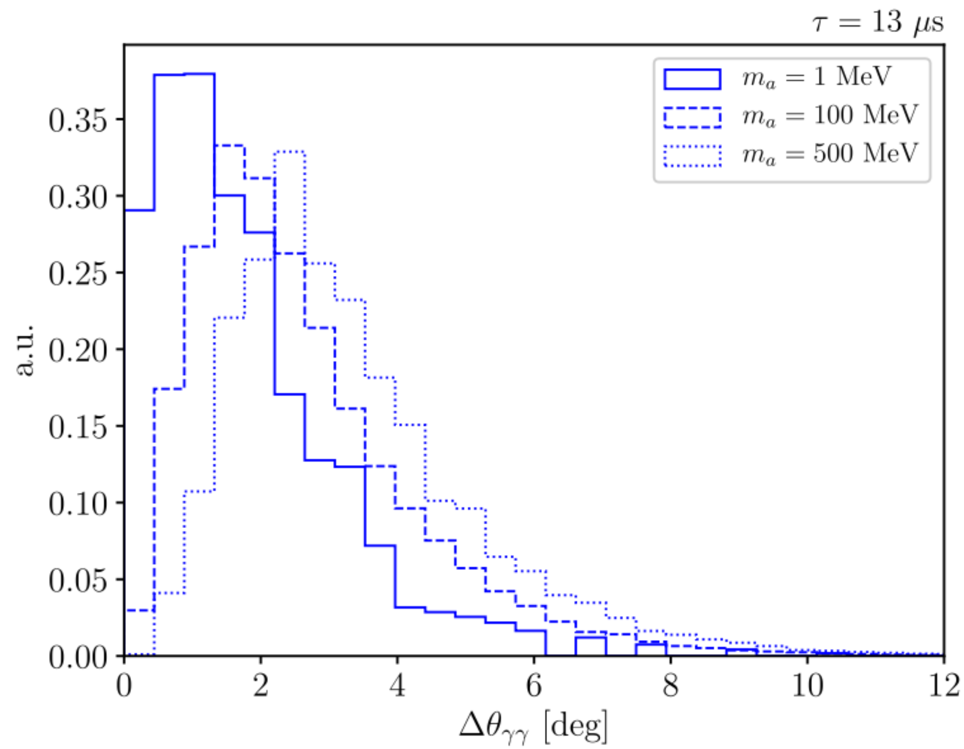
Axion Like Particles (ALPs) at DUNE:

- 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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