Status and Prospects for Dark Sector Studies at the Deep Underground Neutrino Experiment

Snowmass Community Summer Study
Early Career Parallel Session
July 23 2022
University of Washington, Seattle

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University of Texas Arlington

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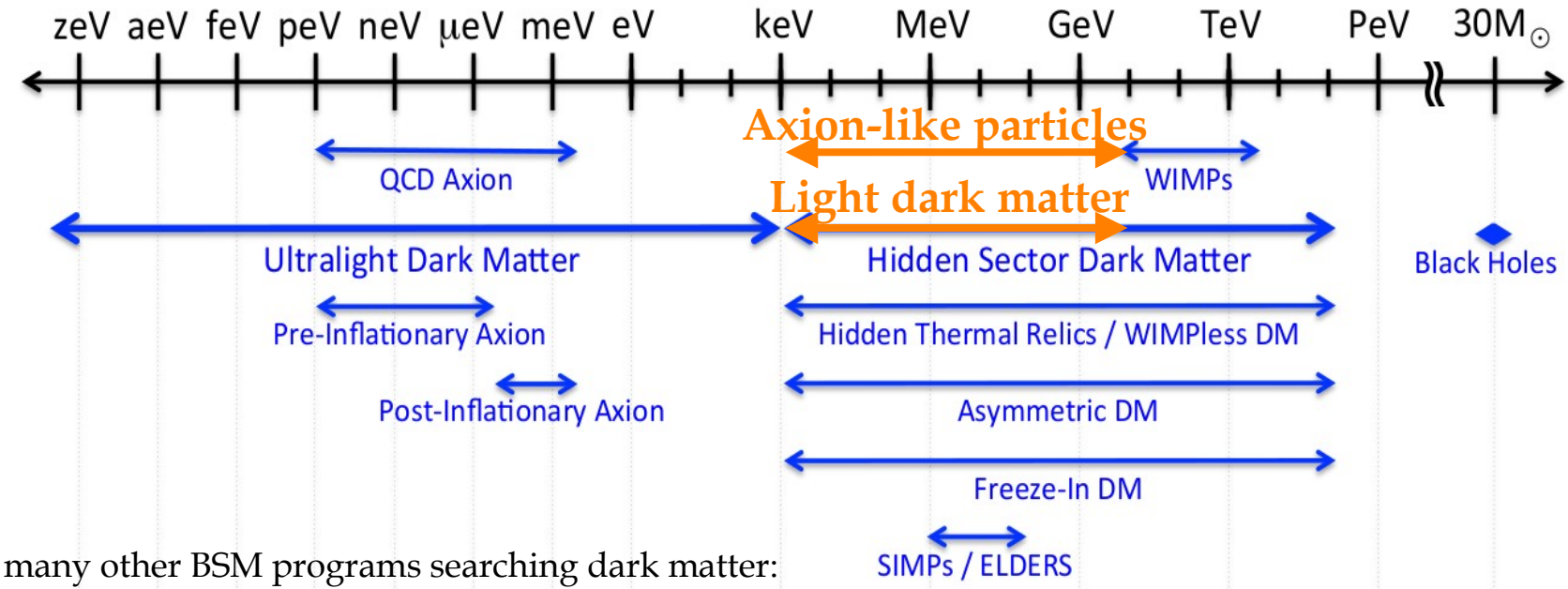
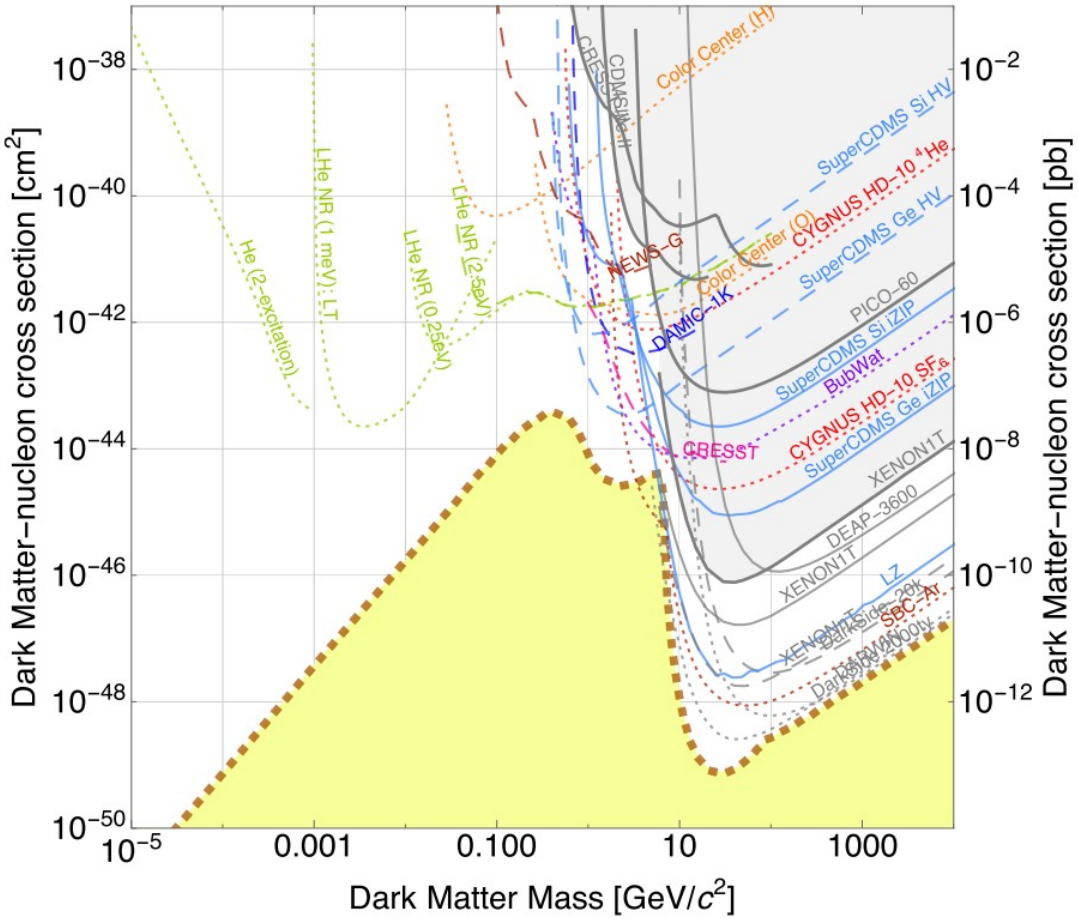


There are many other BSM programs searching dark matter:
Heavy neutral lepton, Sterile neutrino, Boosted dark matter, iBDM

Figure from US Cosmic Vision 2017

Physics Motivation of sub-GeV Dark Sector Search at DUNE



[US Cosmic Vision 2017]

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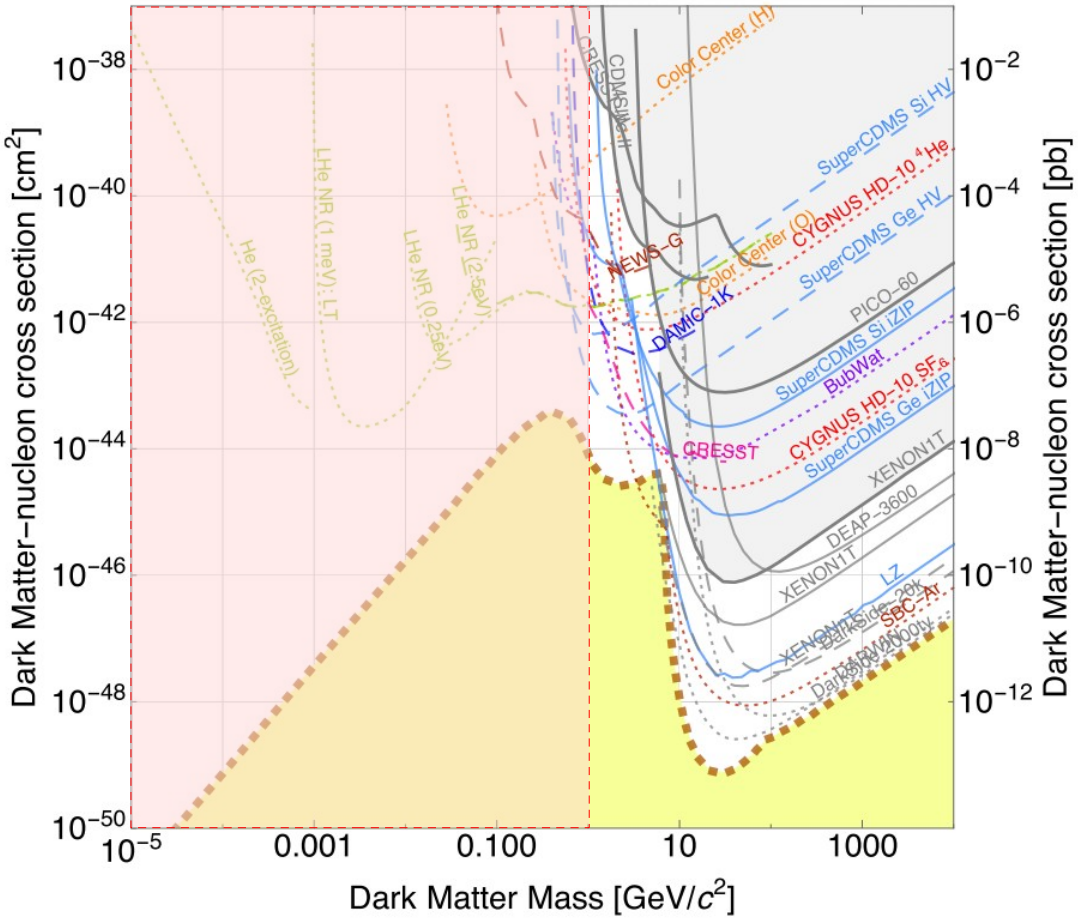

[US Cosmic Vision 2017]

- **Sub-GeV** regime is promising:
  - **Well motivated**, **less explored**.
  - This region is accessible by **Accelerator-based fixed-target** experiments such as DUNE.

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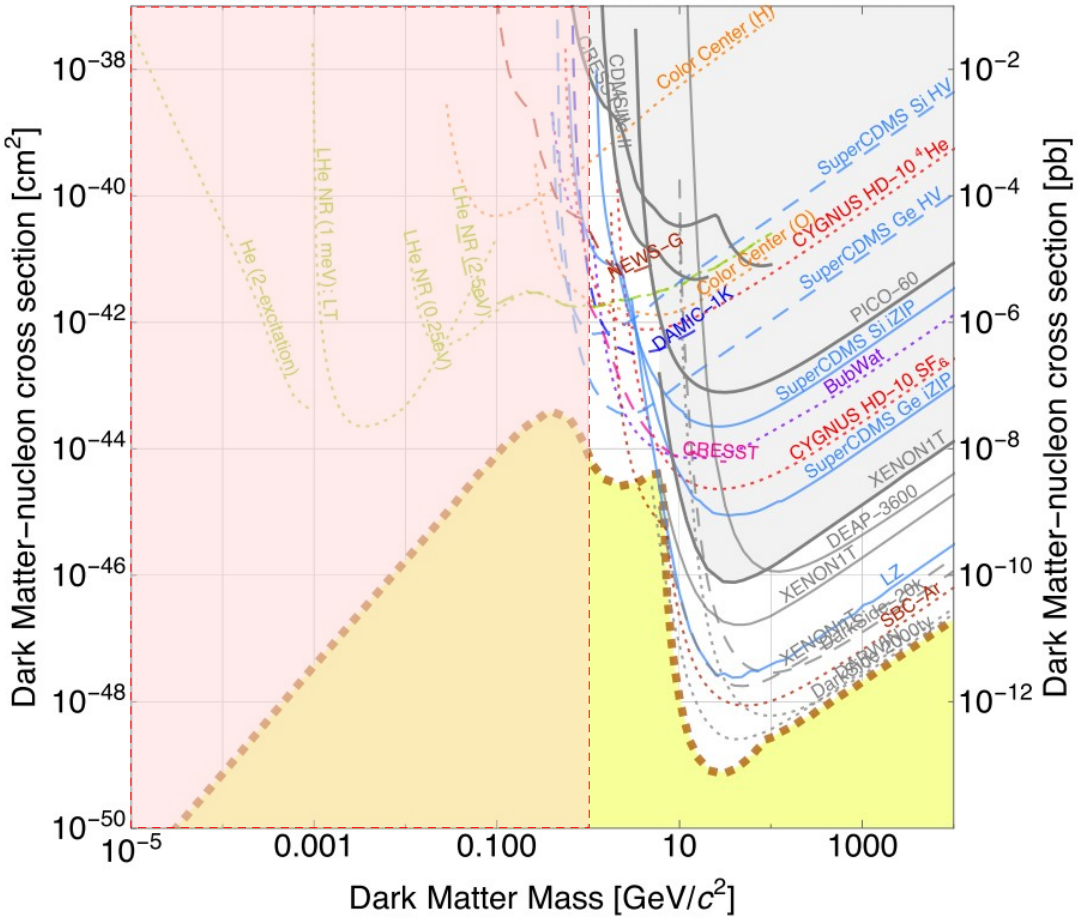
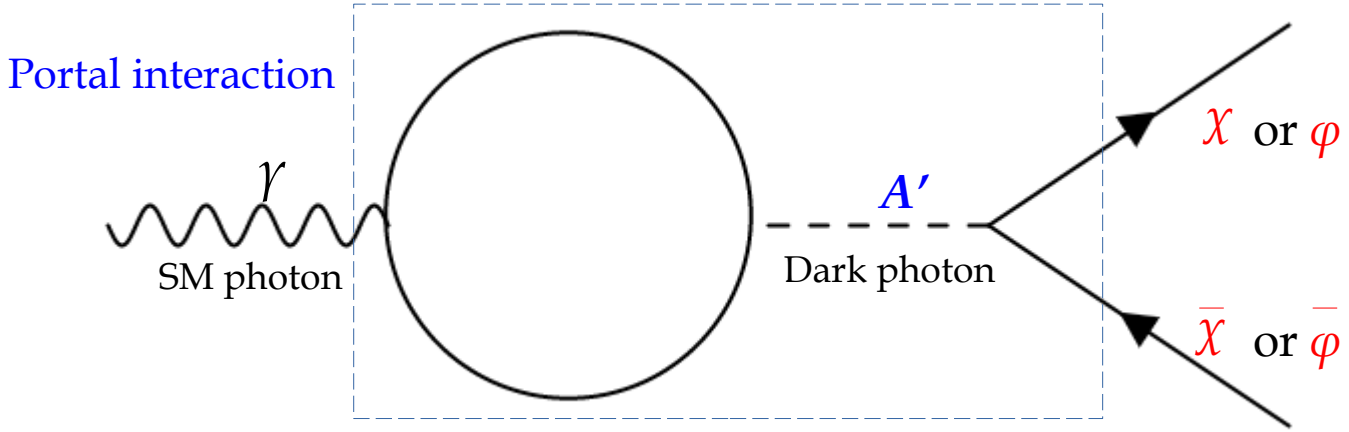


[US Cosmic Vision 2017]

- **Sub-GeV** regime is promising:
  - **Well motivated**, **less explored**.
  - This region is accessible by **Accelerator-based fixed-target** experiments such as DUNE.
- Accelerator-driven neutrino experiment can provide:
  - **High-intensity**, energetic beam
  - **Precision detector system** with high capability of particle identification and background rejection using large mass, large volume detector.
- In that regards, DUNE is an excellent BSM machine.

Light Dark Matter

- In our benchmark light dark matter model, we assume that standard model photon is **kinetically mixed with 'dark photon'.**



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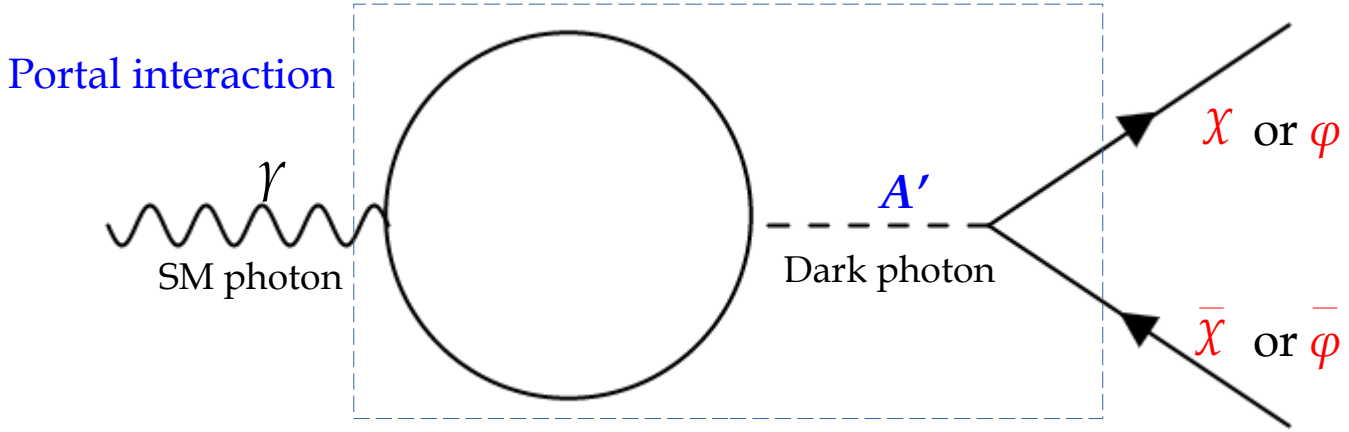
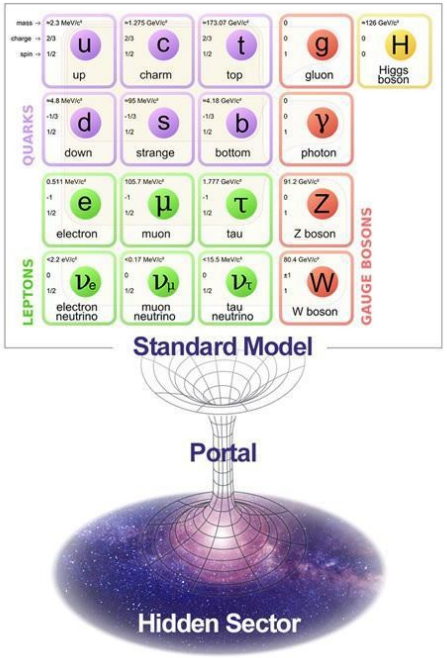
- Dark matter particles can be produced by decay of dark photon through the '**portal interaction**'.





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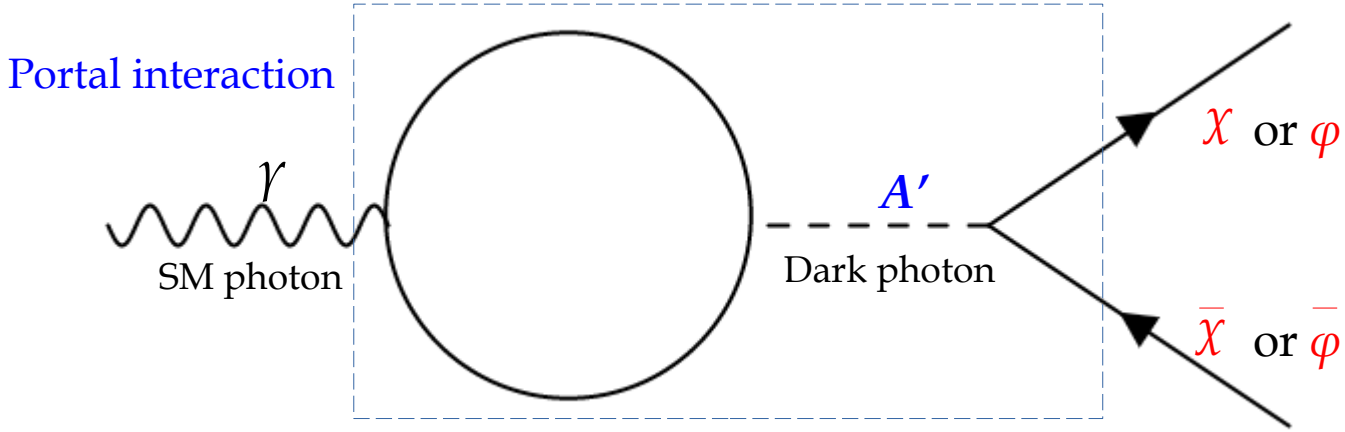
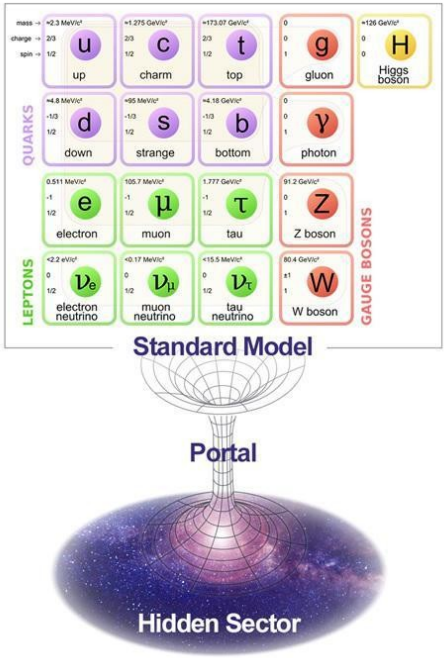




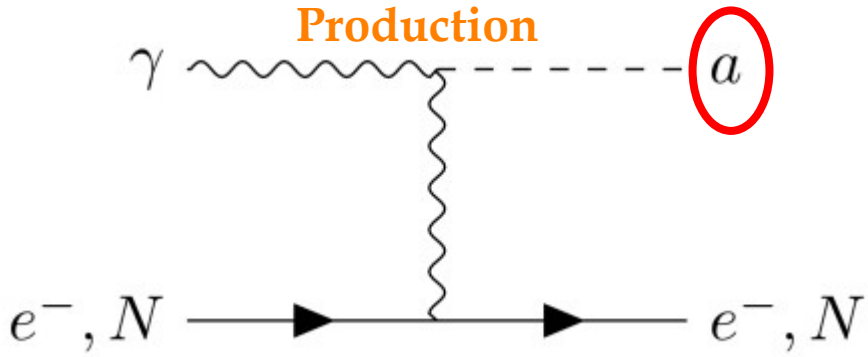
Beam intensity ∝ Photon flux ∝ Dark matter flux

DUNE, equipped with **high-intensity proton beam** provides a great opportunity to test this type of dark matter scenario.

Axion-like Particles

- On the other hand, axion-like particle (ALP) is also very promising model in sub-GeV mass scale.
- ALP is general extension of QCD axion and also considered seriously as one of the dark matter candidates.

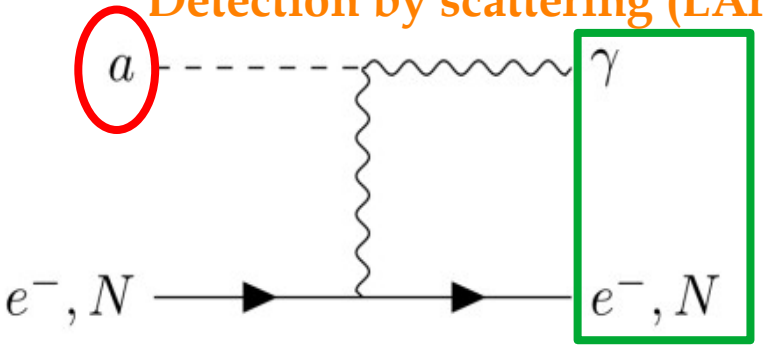
Production



(Primakoff Process)

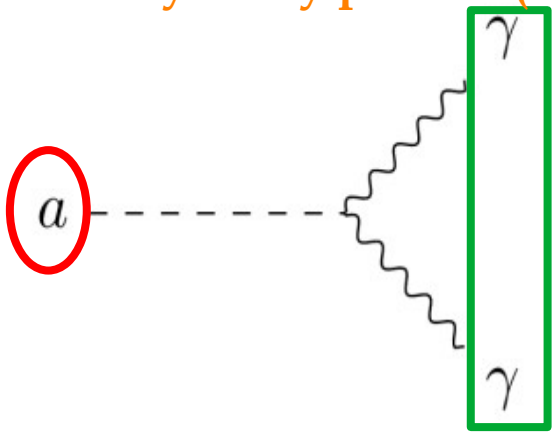
Beam intensity ∝ Photon flux ∝ ALP flux

Detection by scattering (LAr)

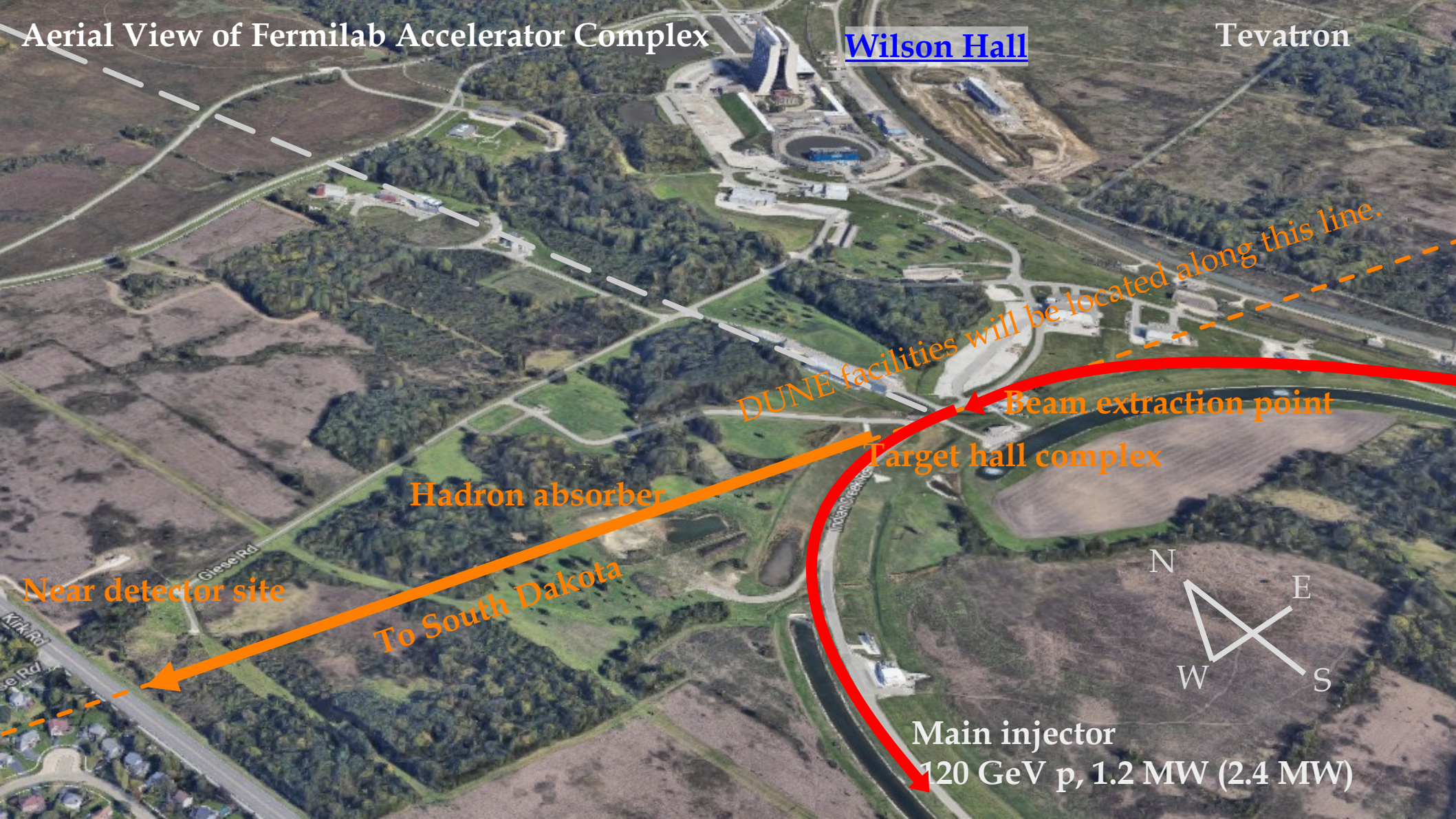


(Inverse Primakoff Process)

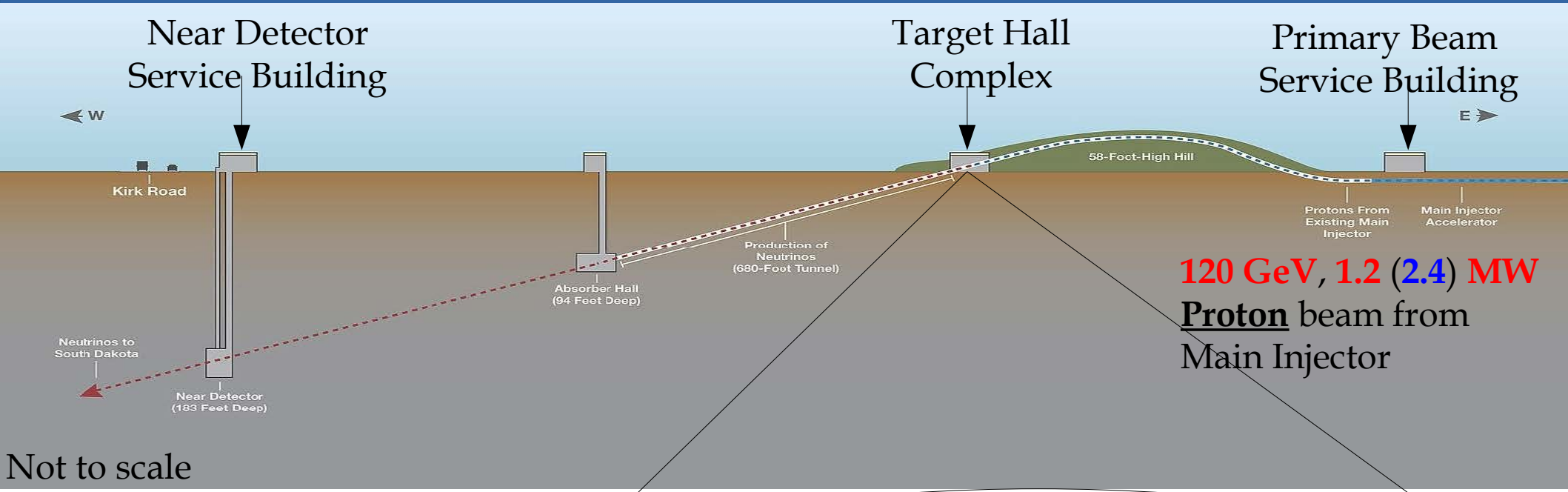
Detection by decay process (GAr)



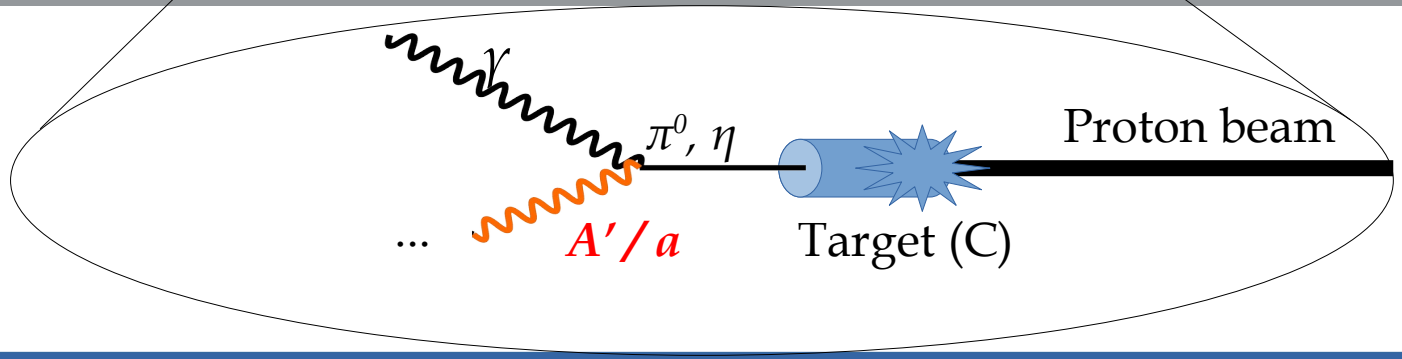
Again, **DUNE** is a great place to test this model.


Aerial View of Fermilab Accelerator Complex
Wilson Hall
Tevatron
DUNE facilities will be located along this line.
Beam extraction point
Target hall complex
Hadron absorber
Near detector site
To South Dakota
Giese Rd
Kirk Rd
N
E
W
S
Main injector
120 GeV p, 1.2 MW (2.4 MW)

Cross-sectional View of Near Detector Site



We implemented Geant4 simulation for proton beam and target interaction.



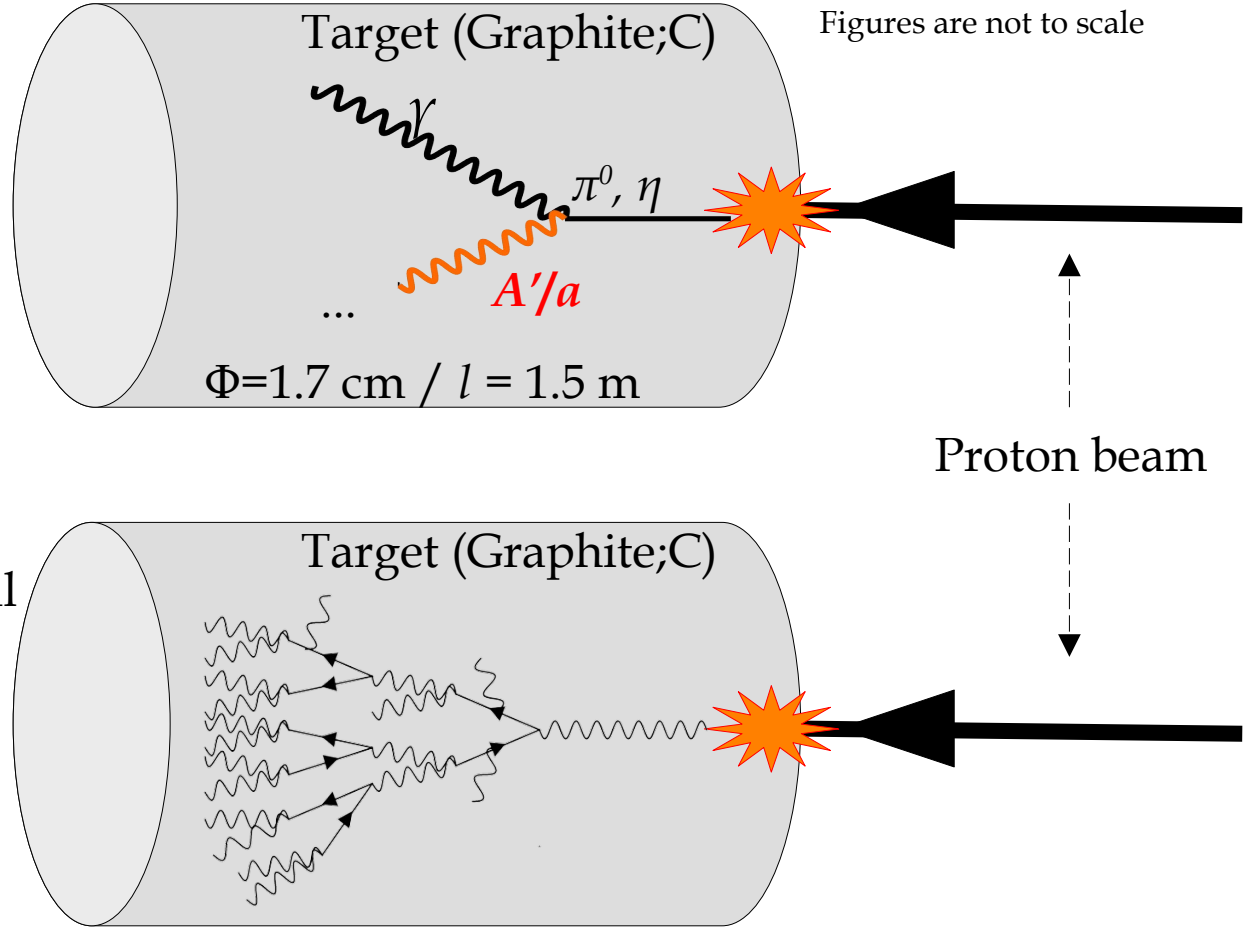
Signal Production – GEANT4 MC Simulation

Geant4 simulation:
We built a target geometry with 1.7 cm diameter, 1.5 m long cylindrical graphite target. The output of this simulation is photon flux produced by beam interaction. There are two major components of them.

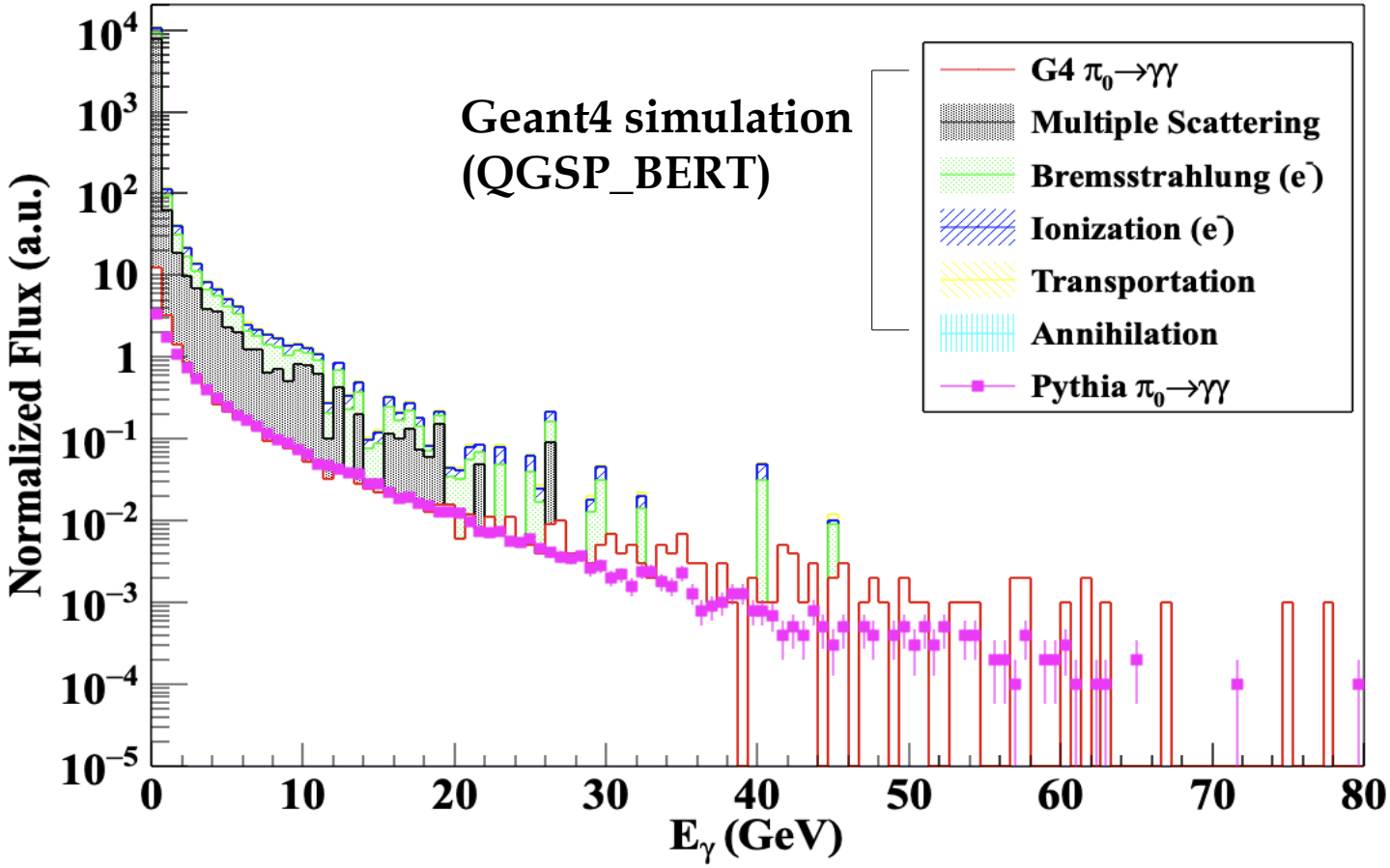
1. Neutral meson decay

2. Photons from EM-shower
Energetic photons produced by neutral meson decay can trigger EM-shower.

This gives additional contribution to the **low-energy** photon flux



Photon Flux Breakdown



This is an example photon flux breakdown by the sources of photon production.

Multiple scattering (black) contributes to low energy spectrum.

Bremsstrahlung (green) has bigger portion of the spectrum in high energy part.

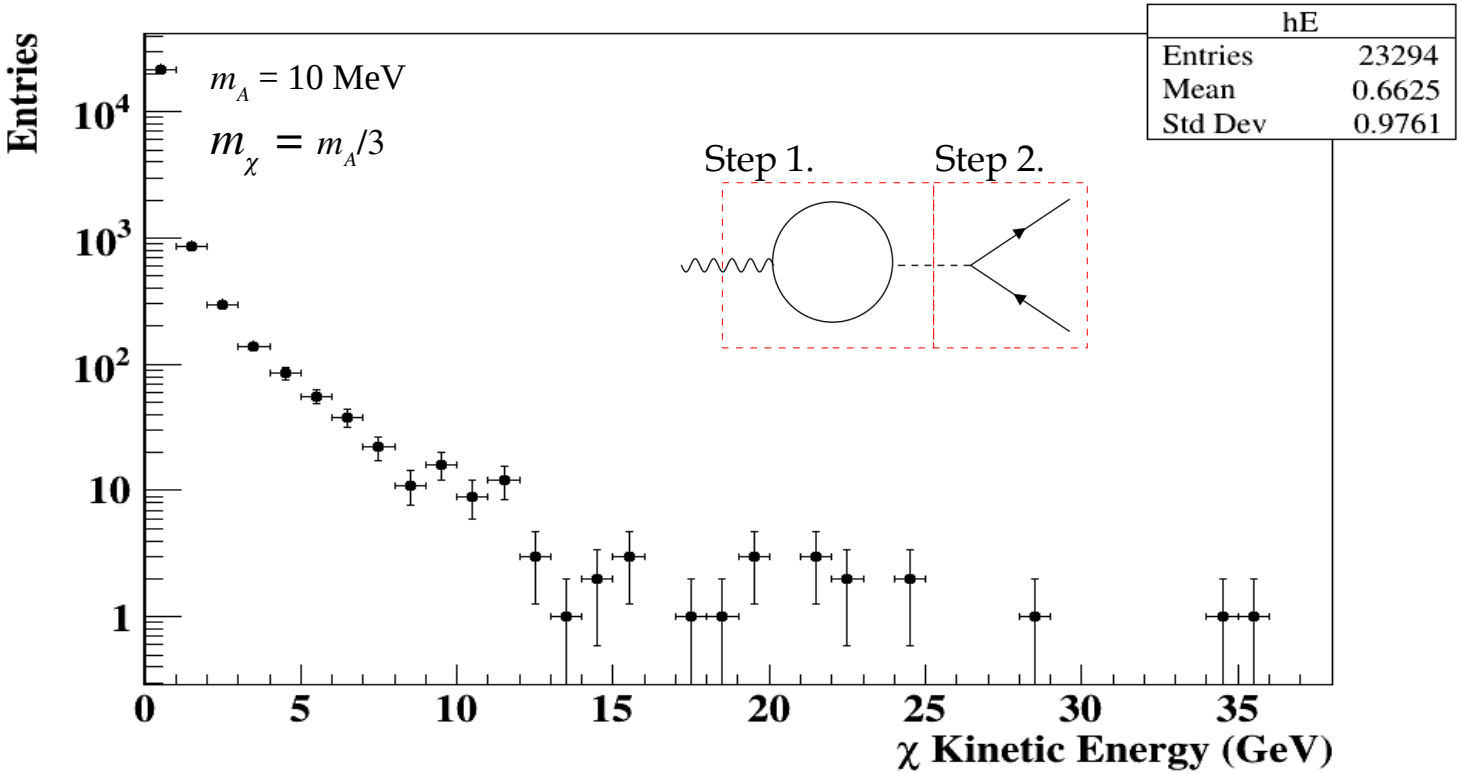
If you compare the magenta data points to the red histogram, you can find good agreement. This good agreement comes from both G4 and Pythia are based on QGSP model. But this graph shows secondary contributions can not be ignored.

Dark Matter Energy Spectrum

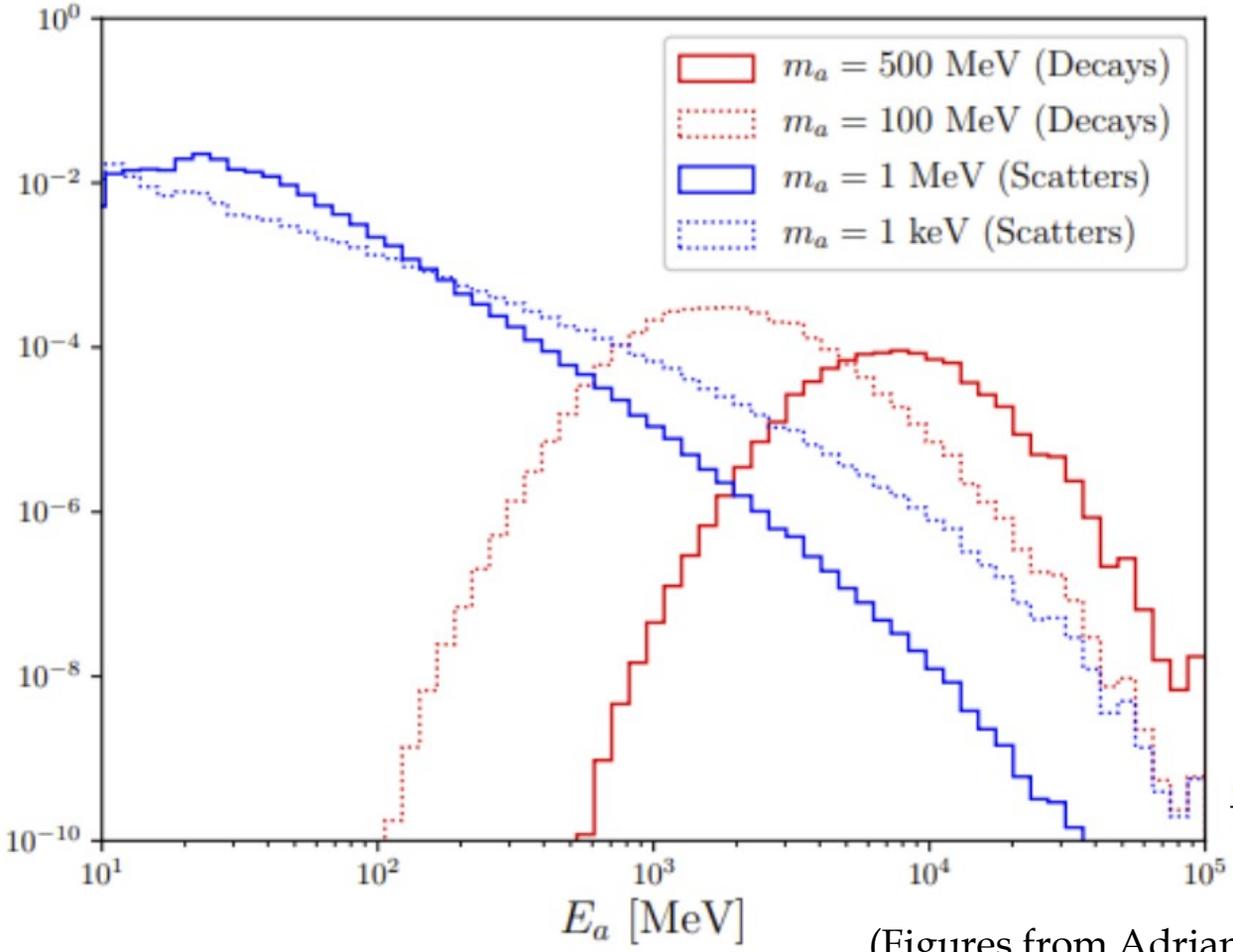
- Once we obtained photon flux from the simulation of proton beam and target, we can convert it to the signal energy spectrum.

- There are two steps for this:

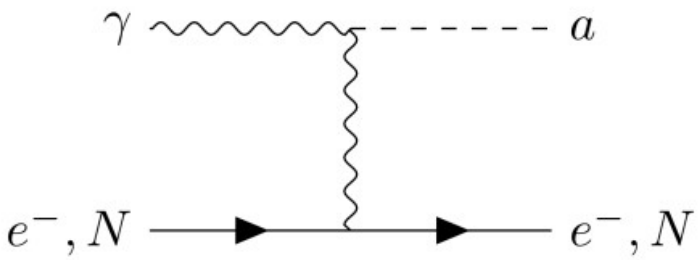
  - Step 1 is to compute conversion of standard model photon into dark photon.
  - Step 2 is kinematics of annihilation of dark photon into dark matter pair.



ALP Flux



- Similarly, energy spectrum of ALP can be taken from the photon flux considering the cross section of Primakoff process.
- The left plot shows spectra with different mass hypotheses and different detection modes.



$$\frac{d\Phi_a}{dE_a} = \frac{1}{\sigma_{PE}} \int_0^{\pi} \int_0^{\pi} \int_0^{2\pi} \frac{\partial^2 \Phi_\gamma}{\partial E_\gamma \partial \theta_\gamma} \frac{d\sigma^{\gamma \to a}}{d\theta_a} \delta(E_a - E_\gamma) \times \Theta(\theta_{ND} - \theta_{a,z}) d\phi'_a d\theta'_a d\theta_\gamma$$

(Figures from Adrian Thompson, DPF 2021)

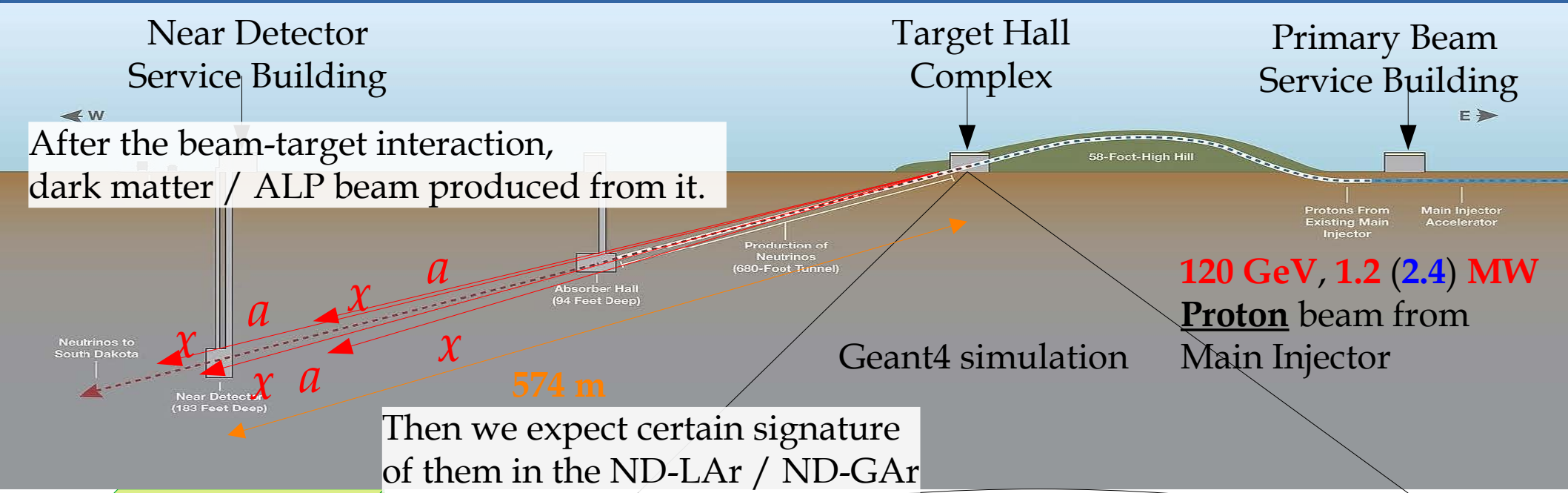
Dark Matter Beam Production

Near Detector Service Building

Target Hall Complex

Primary Beam Service Building

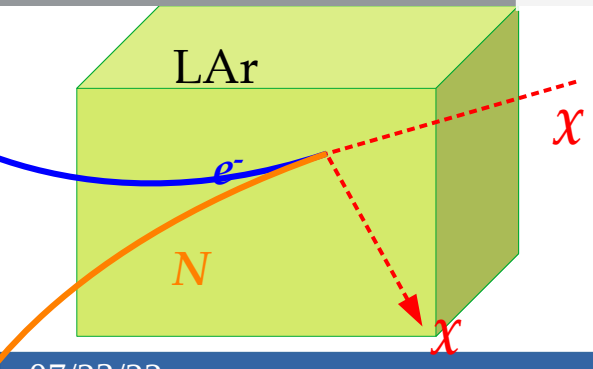
After the beam-target interaction, dark matter / ALP beam produced from it.

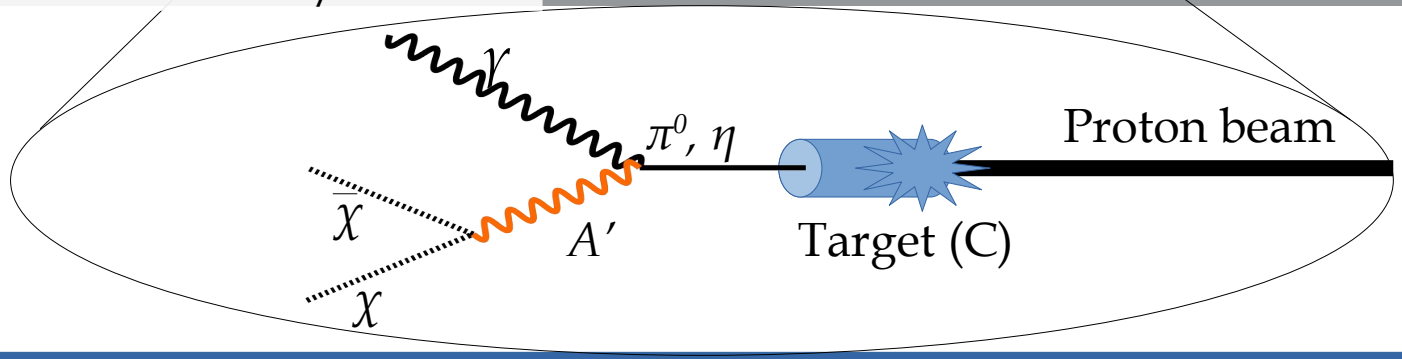


120 GeV, 1.2 (2.4) MW **Proton** beam from Main Injector

Geant4 simulation

Then we expect certain signature of them in the ND-LAr / ND-GAr



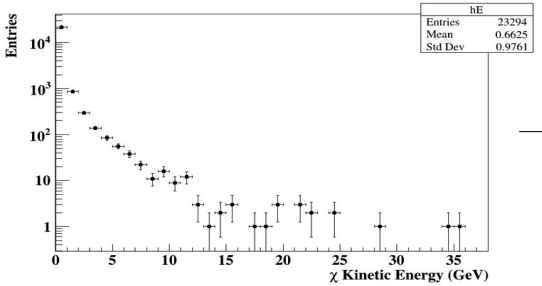


Signal – Detector Interaction: GENIE 3 with BDM

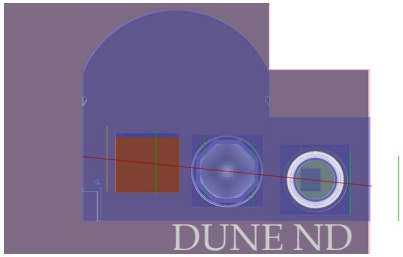
Signal candidates are scattered-off particles inside the detector:

1. LDM-e^-,N scattering ($\varphi+e^-, N \rightarrow \varphi+e^-, N$)

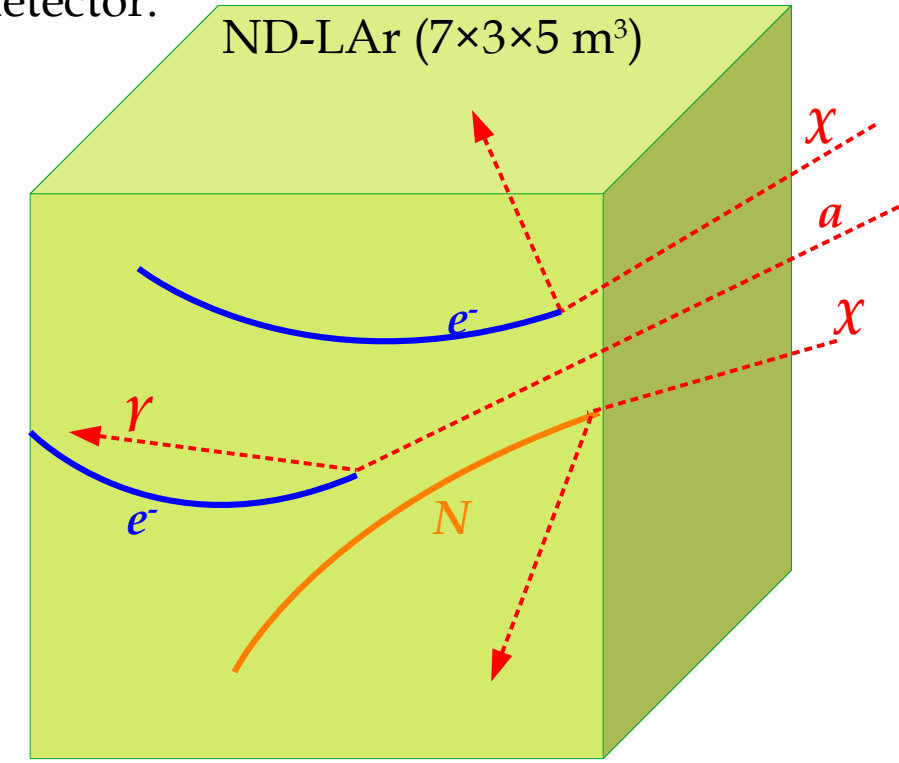
2. ALP scattering ($a+e^-, N \rightarrow \gamma+e^-, N$)



DM flux PDF



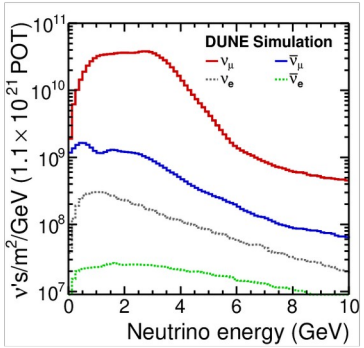
ND geometry



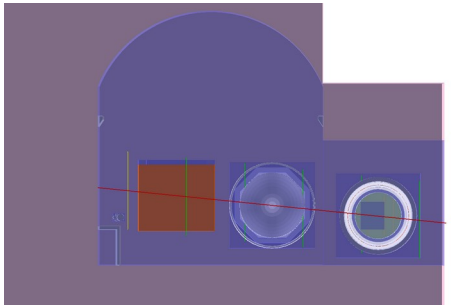
For the event generation, we use GENIE 3(w/ DM package) and the detailed geometrical description of ND.

Background – Detector Interaction: GENIE 3

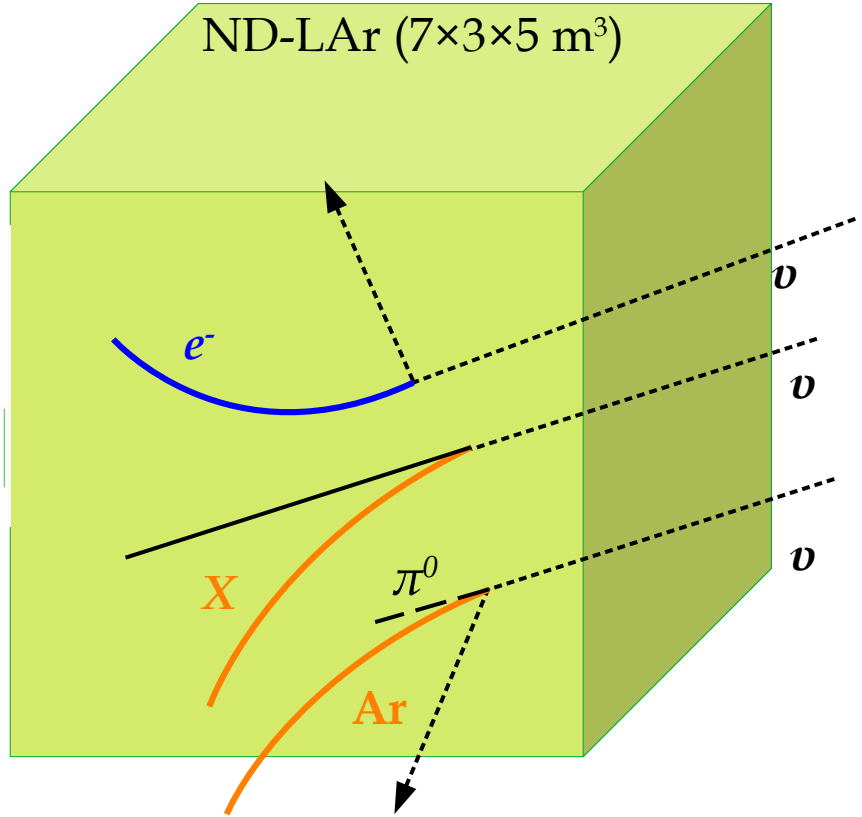
1. υ-e^- scattering ($\upsilon + e^- \rightarrow \upsilon + e^-$)
2. υ_e+Ar→**e-** + X
3. υ+Ar→ υ+**Ar**+π^0



Neutrino flux

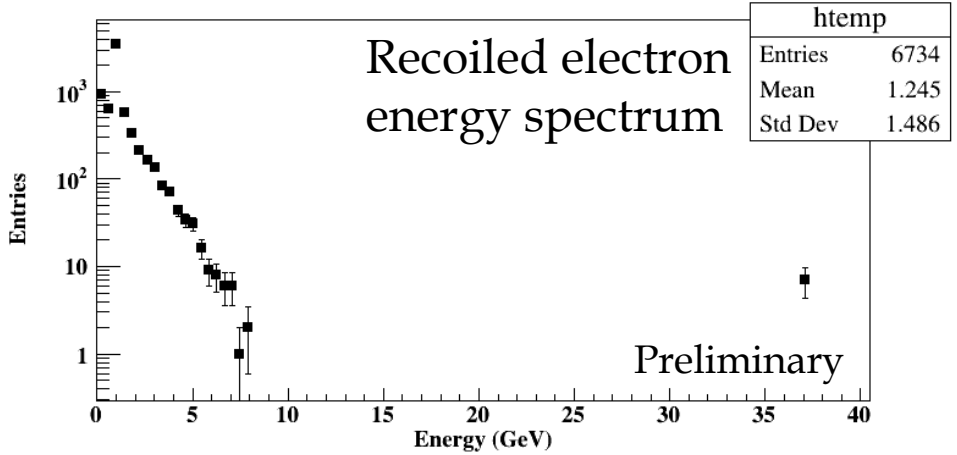


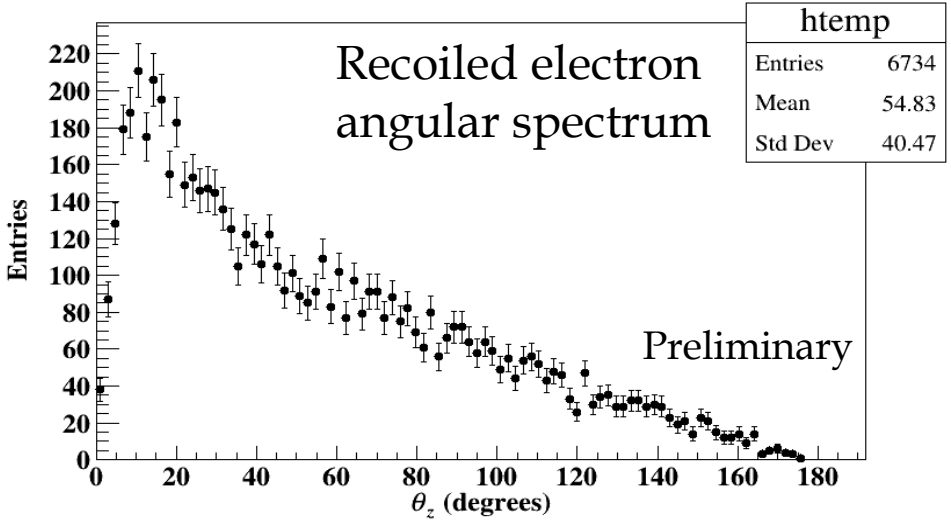
ND geometry

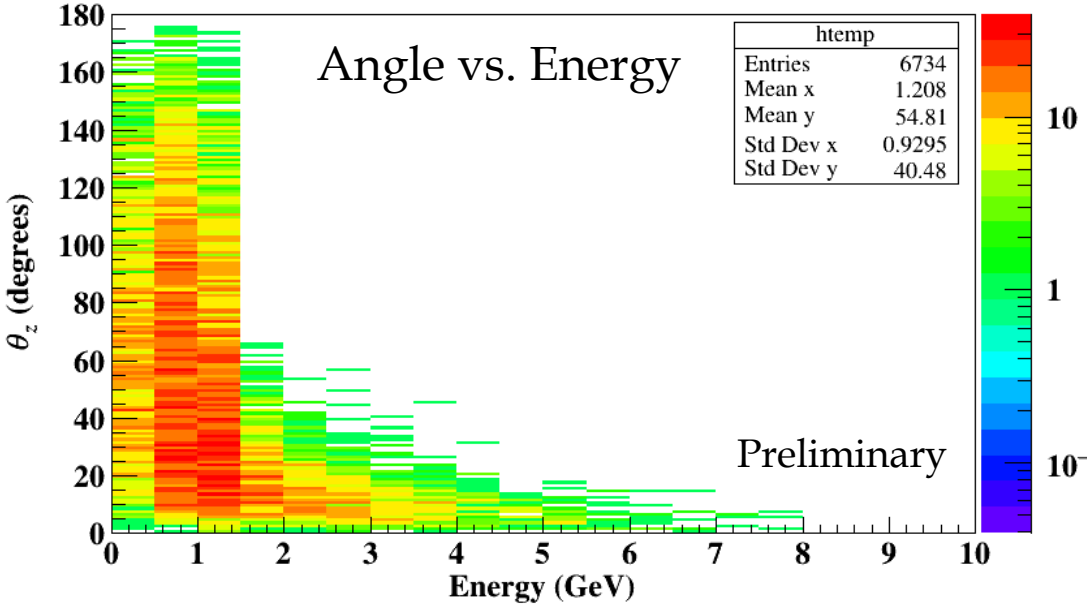


To obtain such background features, we use DUNE neutrino flux simulation.

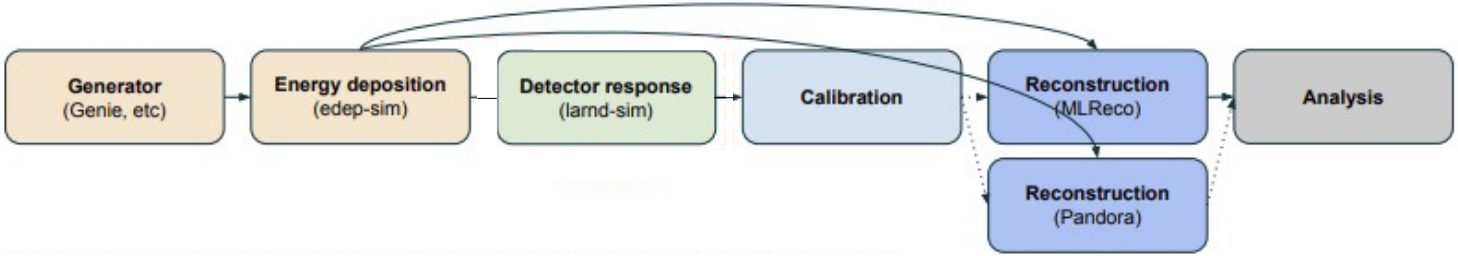
Example GENIE MC Result







Detector Simulation Framework

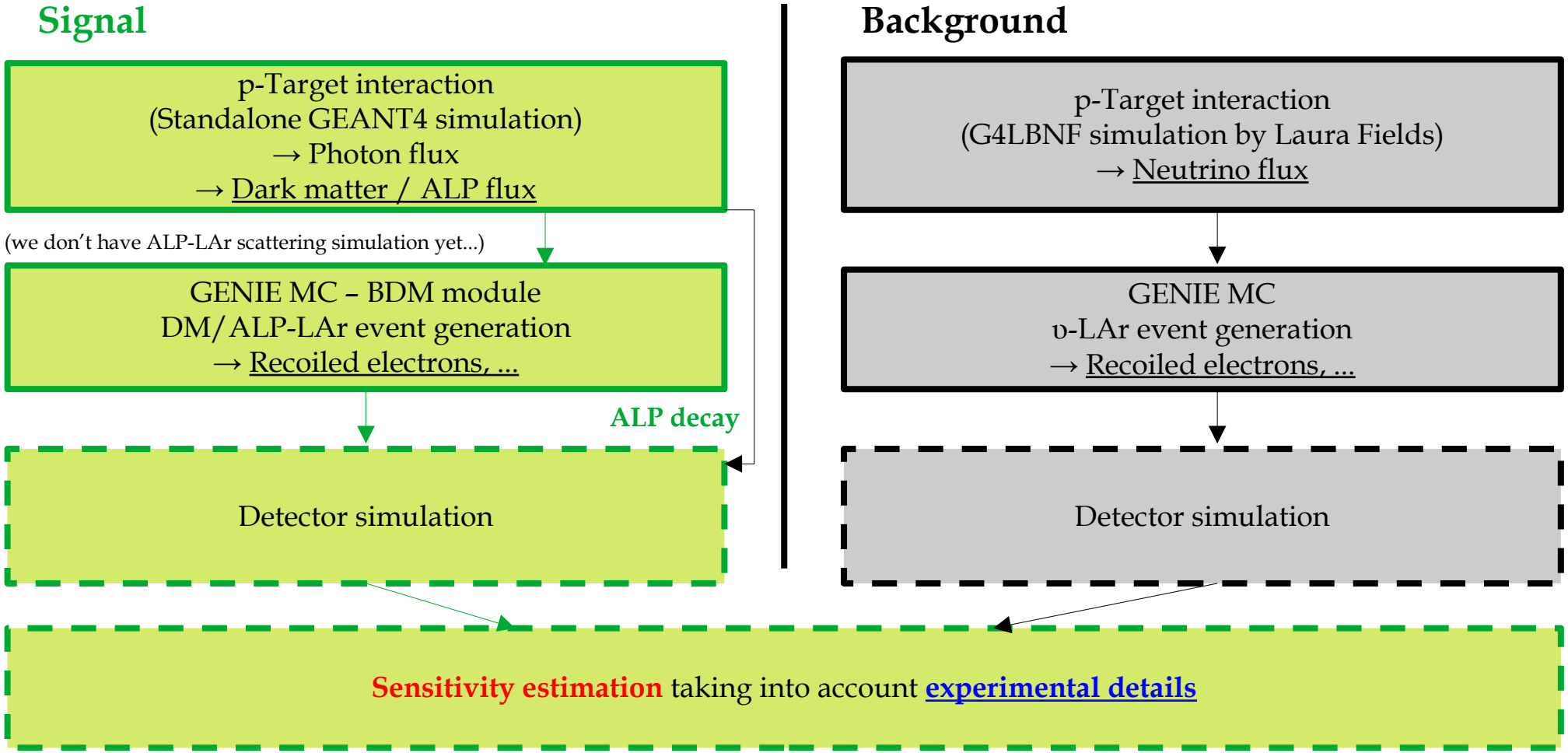


- After the event generator study, the next job is energy deposition simulation.
  - This can be done by software called '**Edep-sim**'.
- Detector response process can be done by feeding the result from **Edep-sim** to **larnd-sim**.
- Calibration simulation.
- Reconstruction.

  1) **MLReco**: utilizes machine learning techniques.
  2) **Pandora**: a compiled framework of multiple reconstruction algorithms.

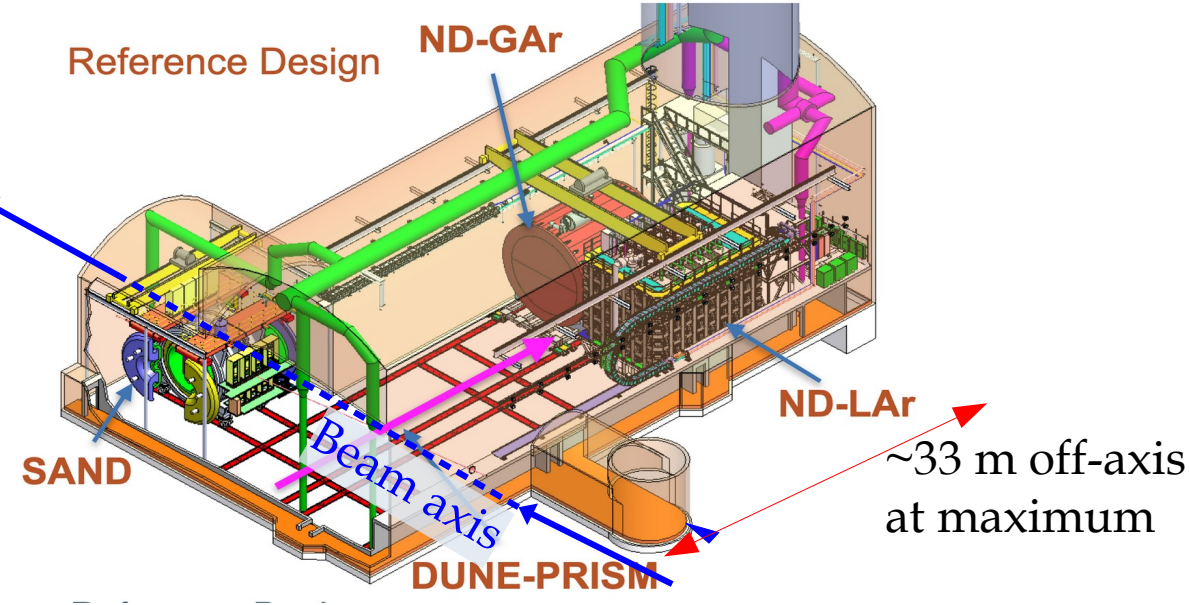
Figure from Peter Madigan, May. 2022, DUNE Collaboration Meeting

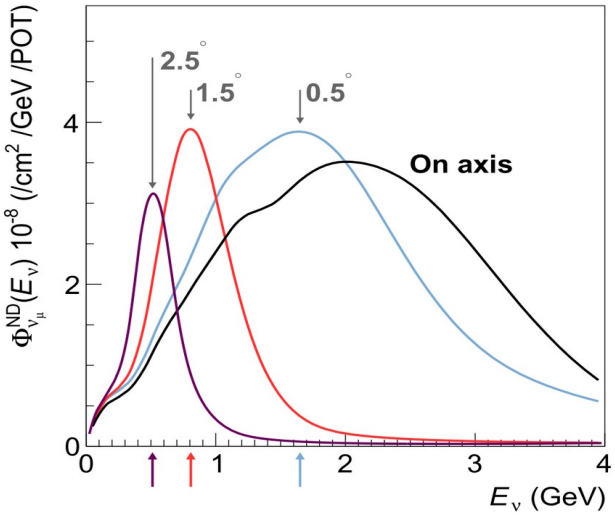
Work-flow Summary

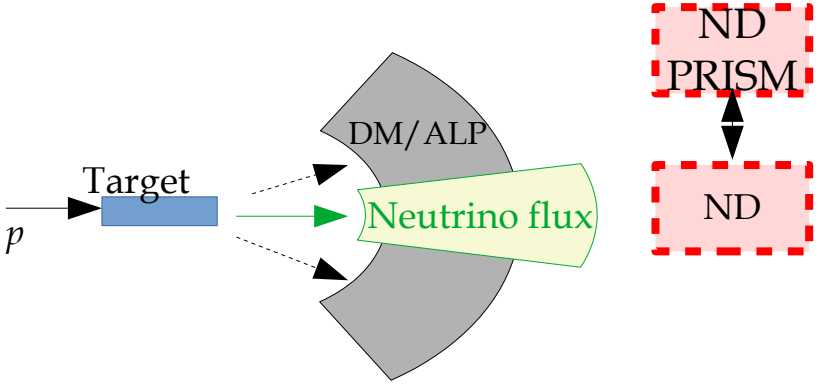


DUNE PRISM

(Precision Reaction-Independent Spectrum Measurement)



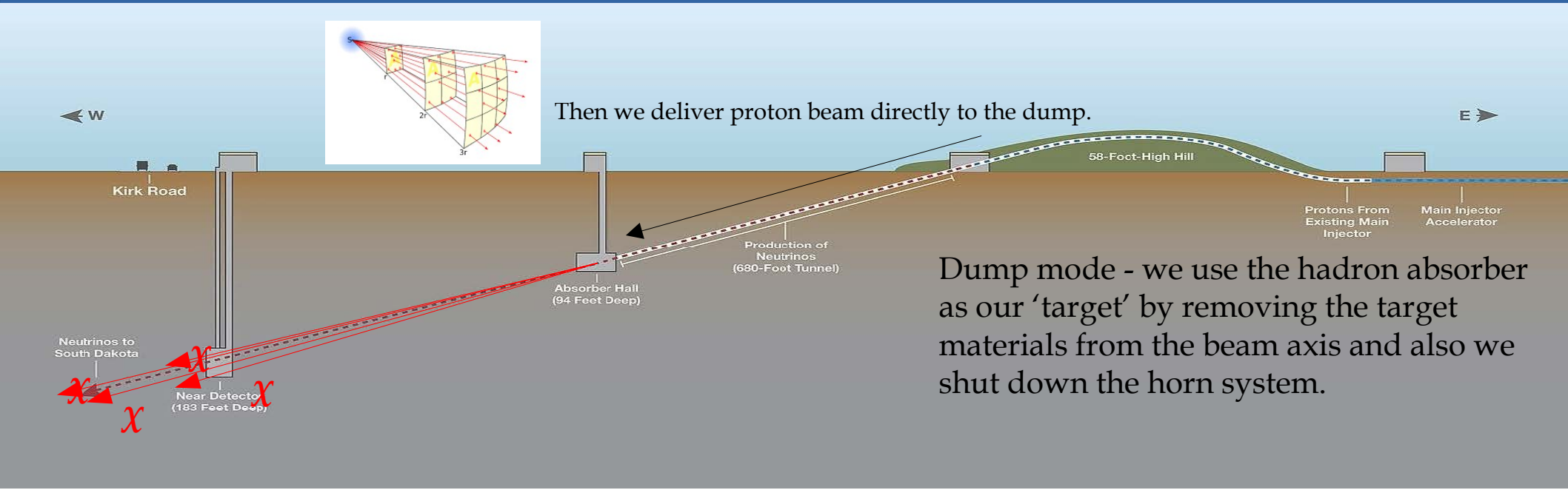




- DUNE Precision Reaction-Independent Spectrum Measurement (PRISM) is introduced to control systematic uncertainties of neutrino oscillation parameters.
- What we're expecting from this: since the effect of focusing horn and lighter mass of neutrinos compare to the dark matter mass, the neutrino beam focused more to forward direction while the heavier dark sector particle tends to have wide angular spectrum. Therefore we expect this feature enhances the signal-to-background ratio effectively.

[Flux - http://home.fnal.gov/~ljf26/DUNEFluxes/]

Dark Sector Search using DUNE Dump Mode(or Targetless Mode)



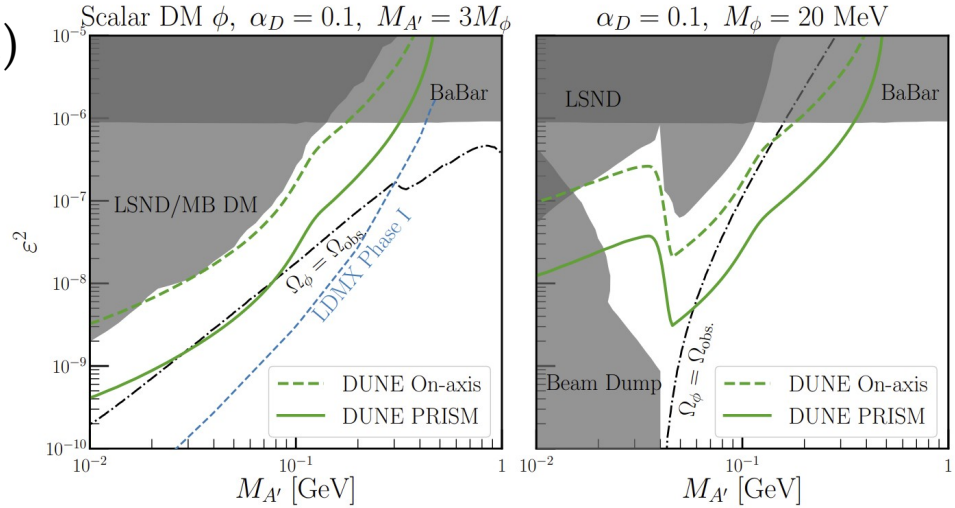
Dump mode - we use the hadron absorber as our 'target' by removing the target materials from the beam axis and also we shut down the horn system.

- 'DUNE Beam Dump Mode' is an operation mode of DUNE proposed earlier this year.
- In this configuration, **signal** flux **enhancement** is expected.
  - because we have shorter distance from the interaction point to detector (574 m → ~300 m)
- **Reduction** of **background** flux is also expected.
  - The dump **absorbs** most of charged mesons, so it prevents neutrino production.

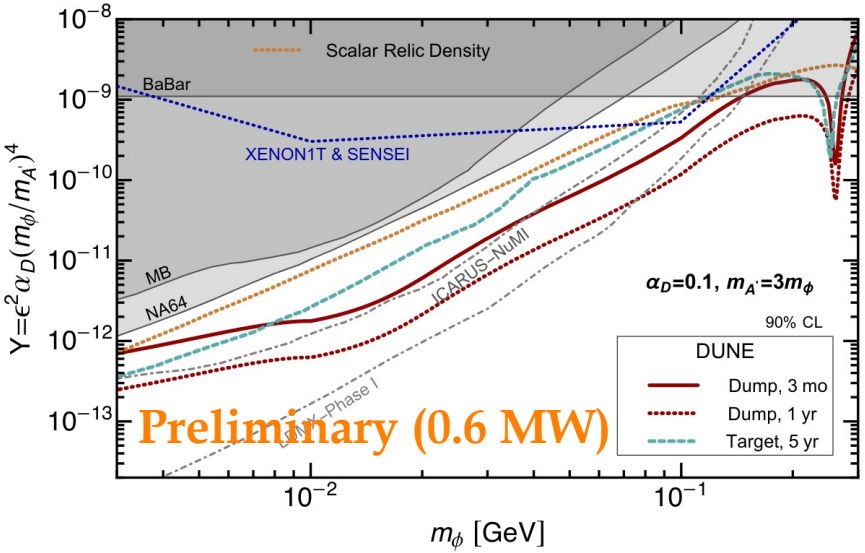
Check arXiv:2206.06380 for more details.

Sensitivity Limits

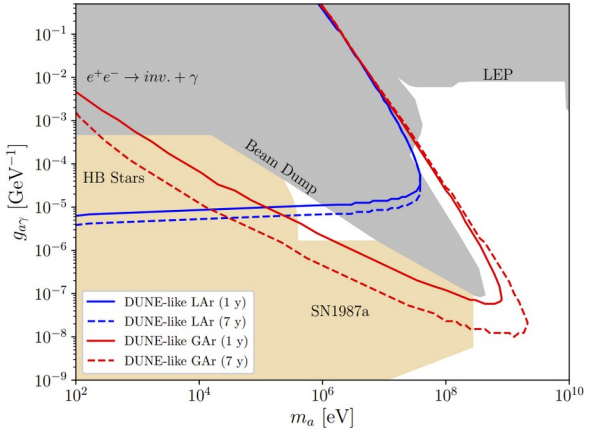
1)



2)



3)



1) Valentina De Romeri, Kevin J. Kelly, and Pedro A. N. Machado, Phys. Rev. D **100**, 095010

2) arXiv: 2206.06380

3) Vedran Brdar et. al, Phys. Rev. Lett **126**, 201801

Summary

- DUNE is a very promising experiment to probe sub-GeV dark sector thanks to its high-intensity proton beam and precision near detector with interesting operation strategies such as PRISM and Dump Mode.
- Simulation work-flow based on Geant4 and GENIE3 is presented.
- For both LDM and ALP, current sensitivity estimation shows promising results. We will add more experimental details to this study.