Physics Opportunities at PIP-II with an Accumulator Ring and a keV-scale Detector Threshold

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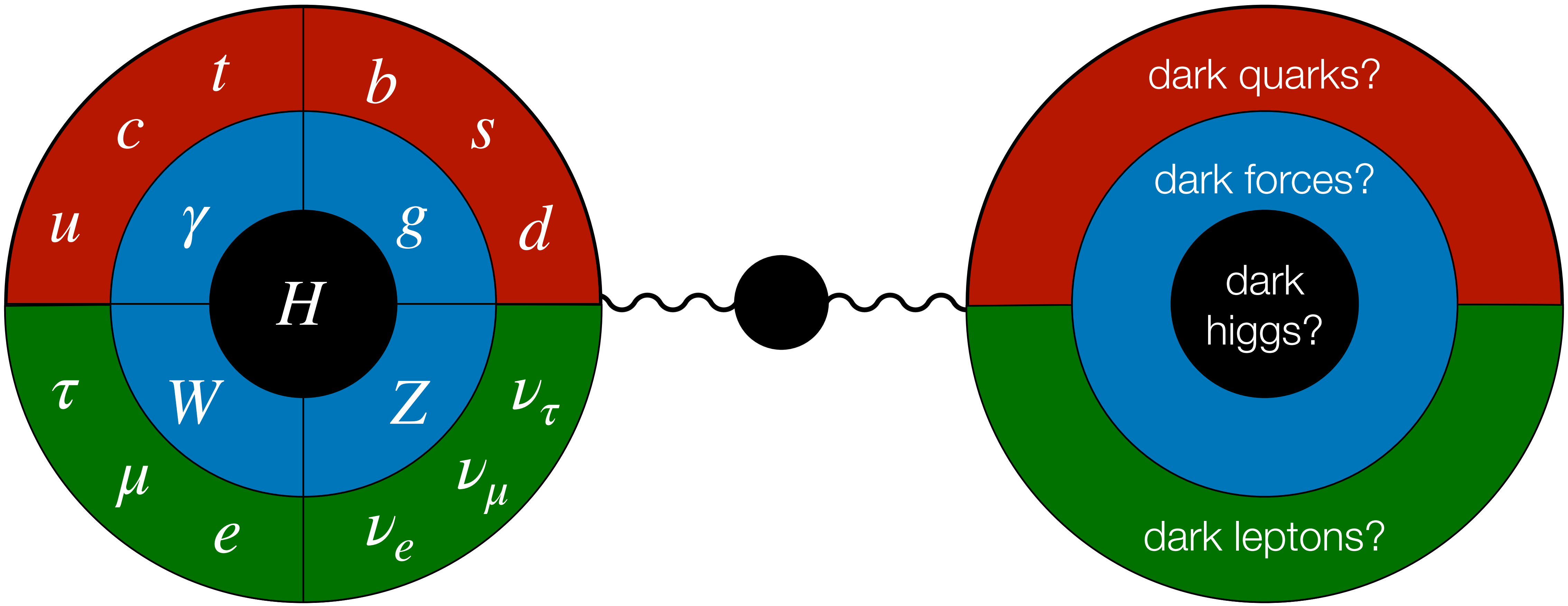
Physics Opportunities at a Beam Dump Facility at PIP-II and Beyond
Fermilab
May 11, 2023

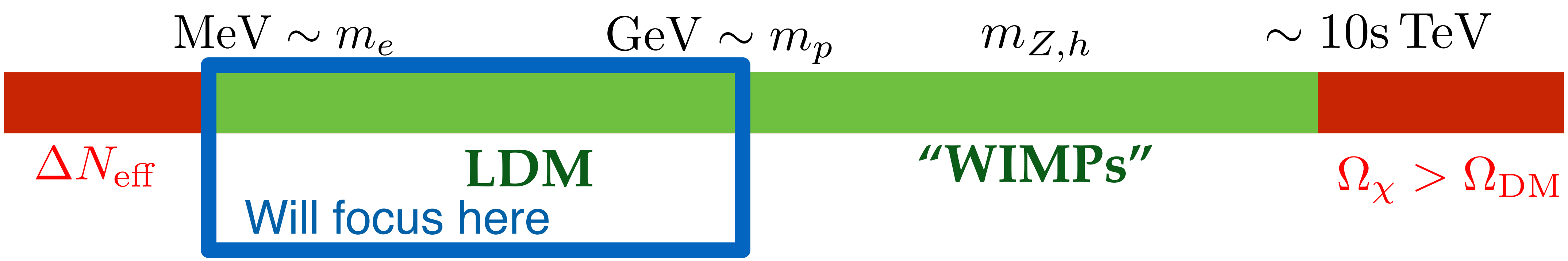
A Dark Sector is motivated by the existence of dark matter

- Potentially has a rich structure



arXiv:2209.04671

Current Landscape of Dark Matter and Dark Sector Searches

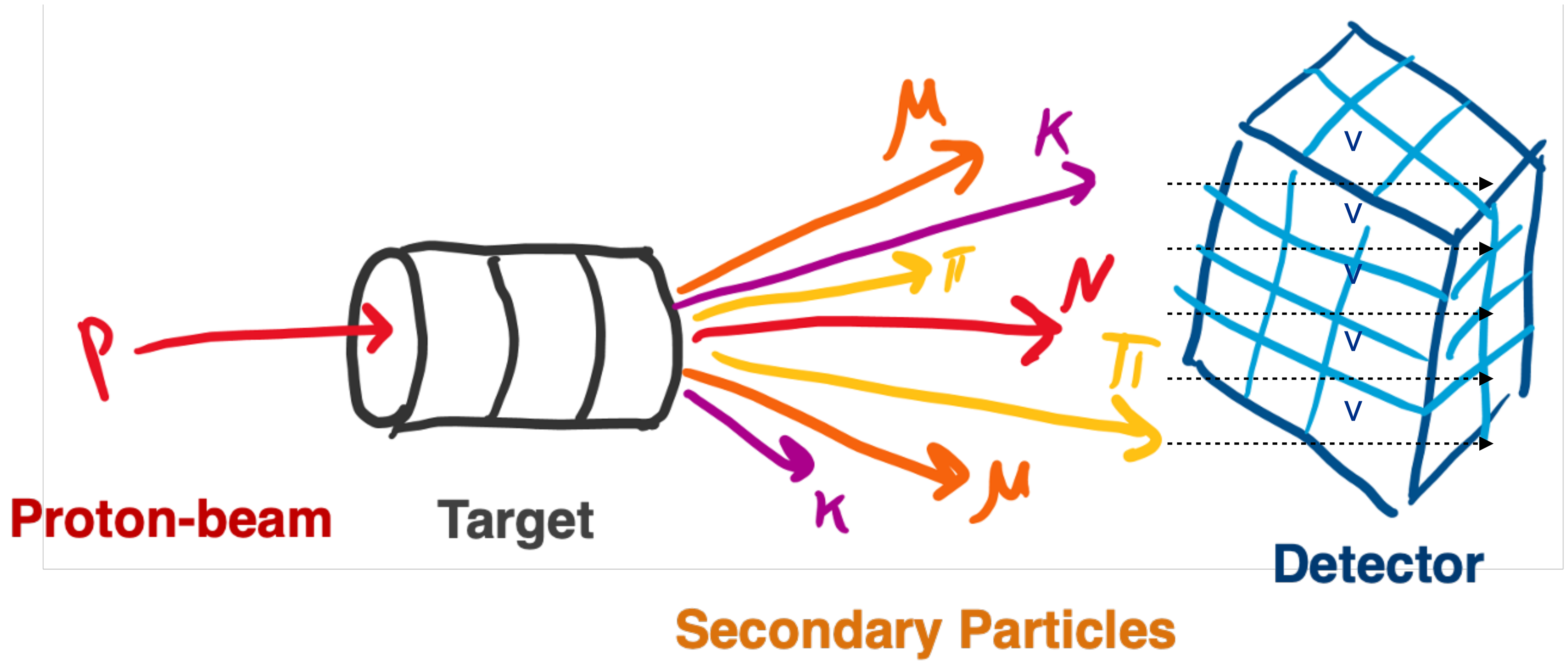


- New physics theorized to be neutral under SM forces
- A finite set of operators serve as a portal to a possible dark sector

$B_{\mu\nu}$	x	$\epsilon/2\, F'^{\mu\nu}$	Vector portal
$\vert h\vert^2$	x	$\mu S + \lambda\vert\phi\vert^2$	Higgs portal
hL	x	$y_N N$	Neutrino portal

Light dark matter at accelerators

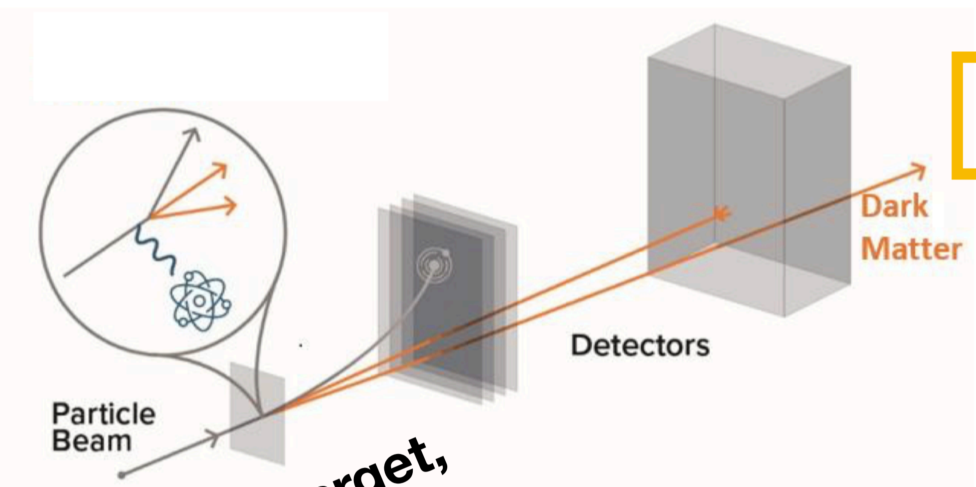
- Dark sector models exist than can both predict sub-GeV dark matter (LDM) and explain the thermal relic abundance of dark matter
- Accelerator-based facilities with intense particle beams represent an excellent opportunity to search for dark sectors
- LDM production possible in some models through similar channels as neutrino production from accelerator-based neutrino beams
  - LDM could also explain existing short-baseline anomalies



How are beam dump experiments complementary?

Search techniques for dark sectors at accelerators

Production of dark matter



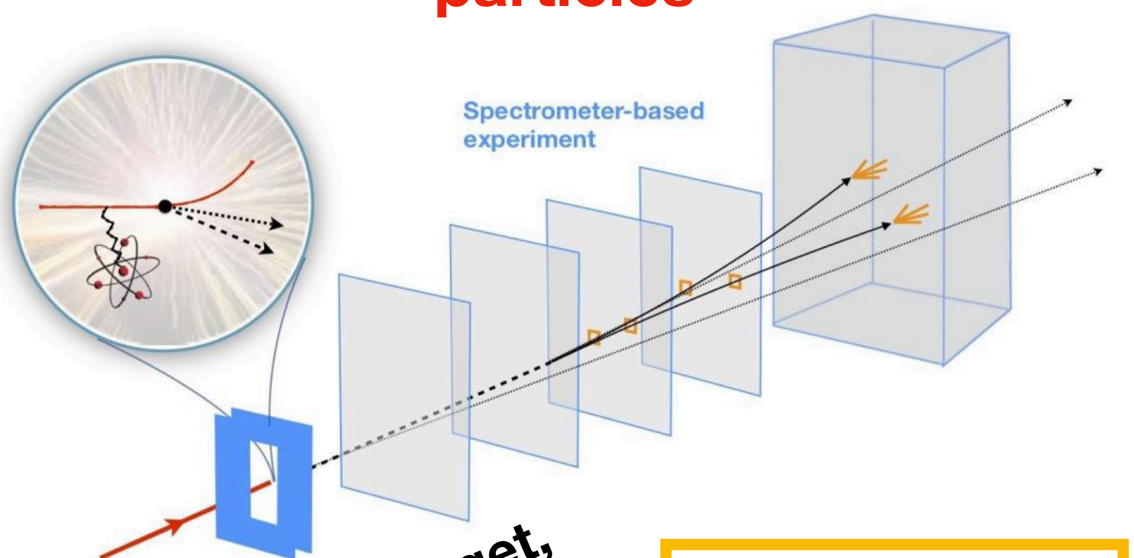
1. fixed target,
2. colliders

1. Missing energy/ momentum/mass

2. Re-scattering

The experimental techniques are only 3

Production of unstable dark sector particles



1. fixed target,
2. colliders

3. Visible decay products

With a breadth of experimental techniques:

Can measure dark sector masses and interaction strengths

Probe generalizations of thermal freeze-out

S.Gori

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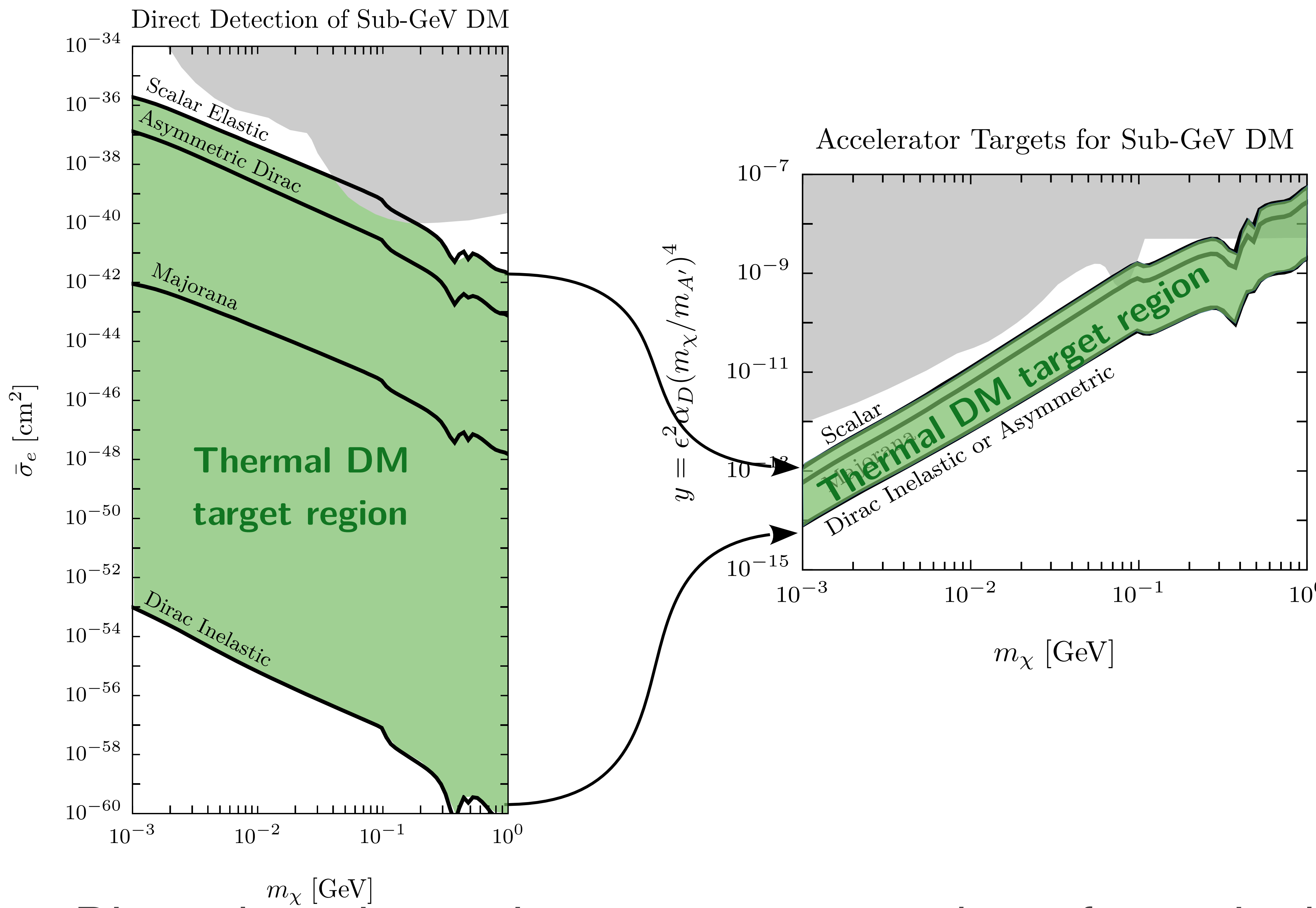
Connections to Direct Detection DM Searches

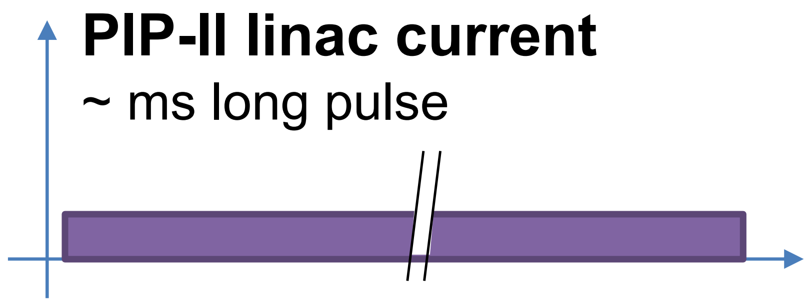


- Direct detection regime spans many orders of magnitude due to effects such as DM velocity suppression or spin suppression significant for non-relativistic scattering

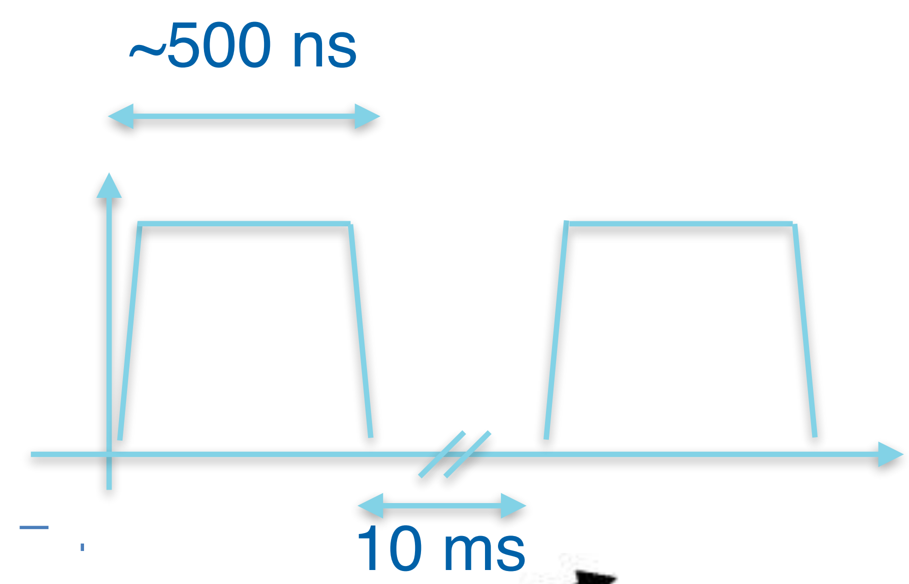
arXiv:2209.04671

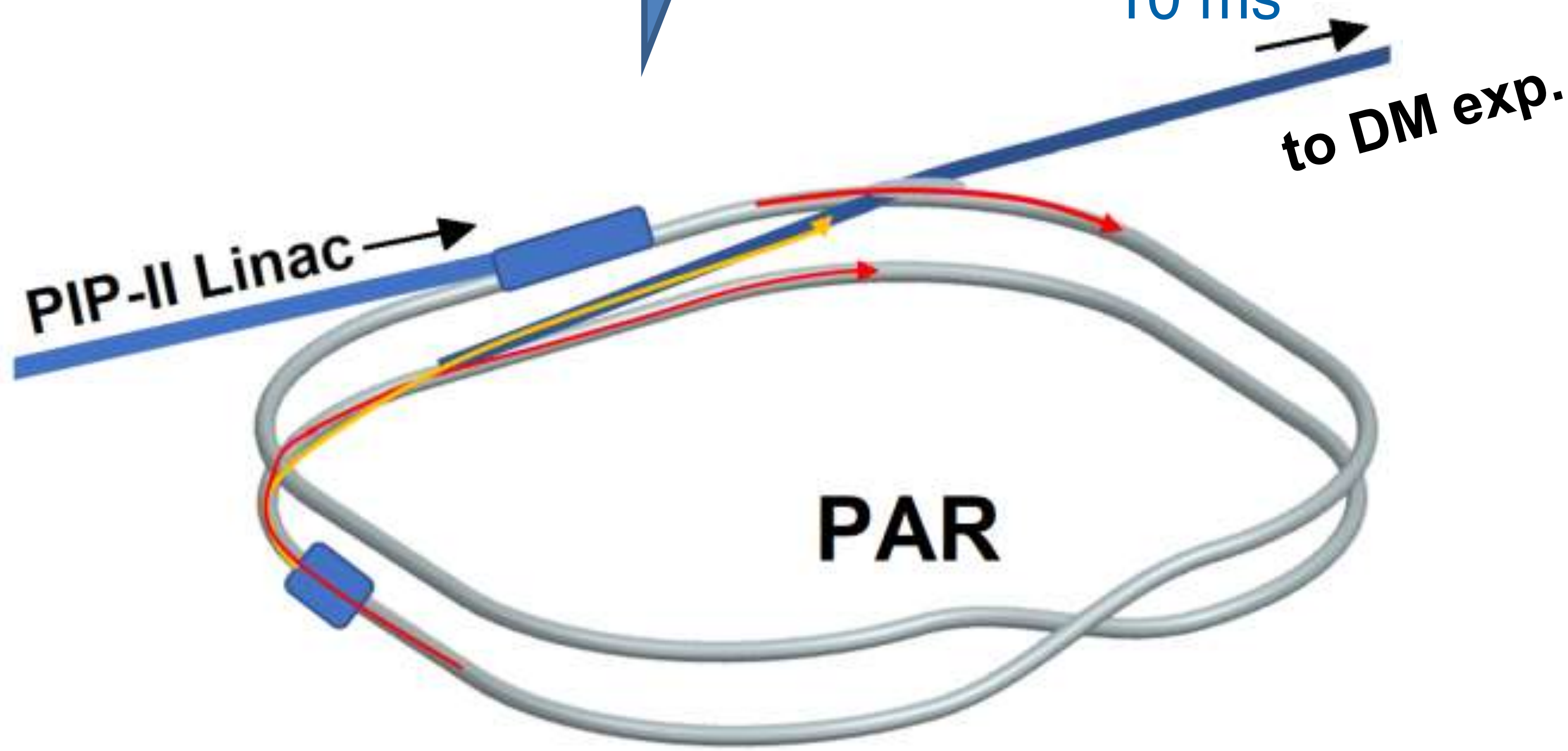
PIP-II Layout at FNAL

PIP-II Accumulator Ring (PAR)



Beam from PAR to dark sector experiment

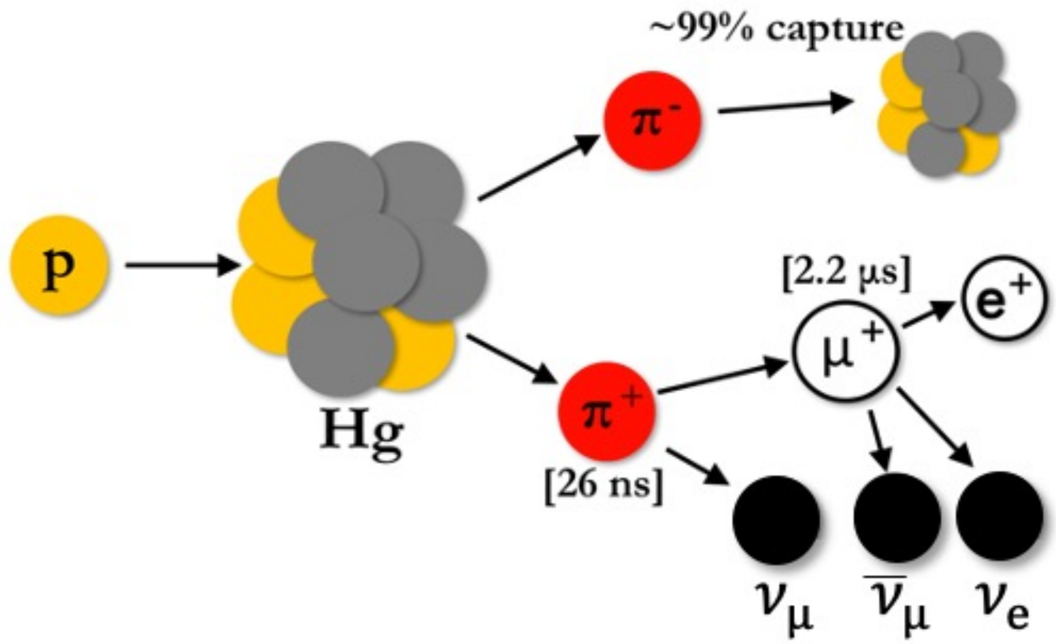


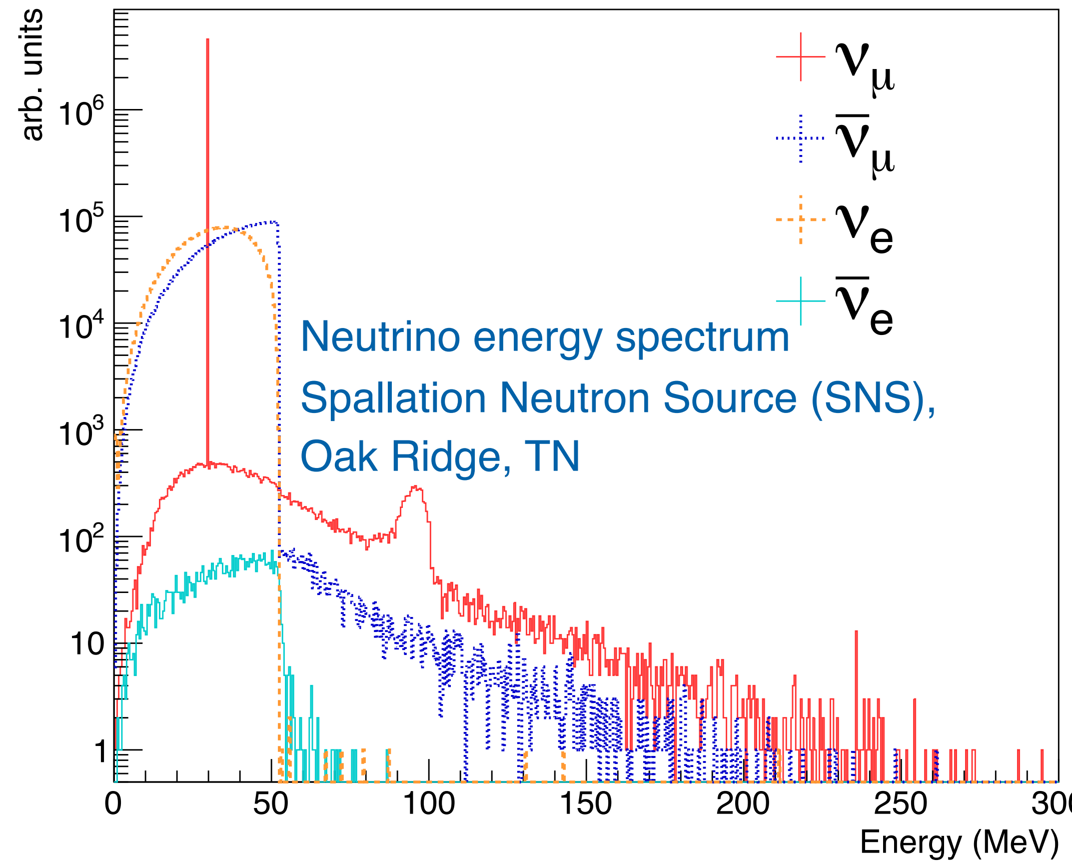


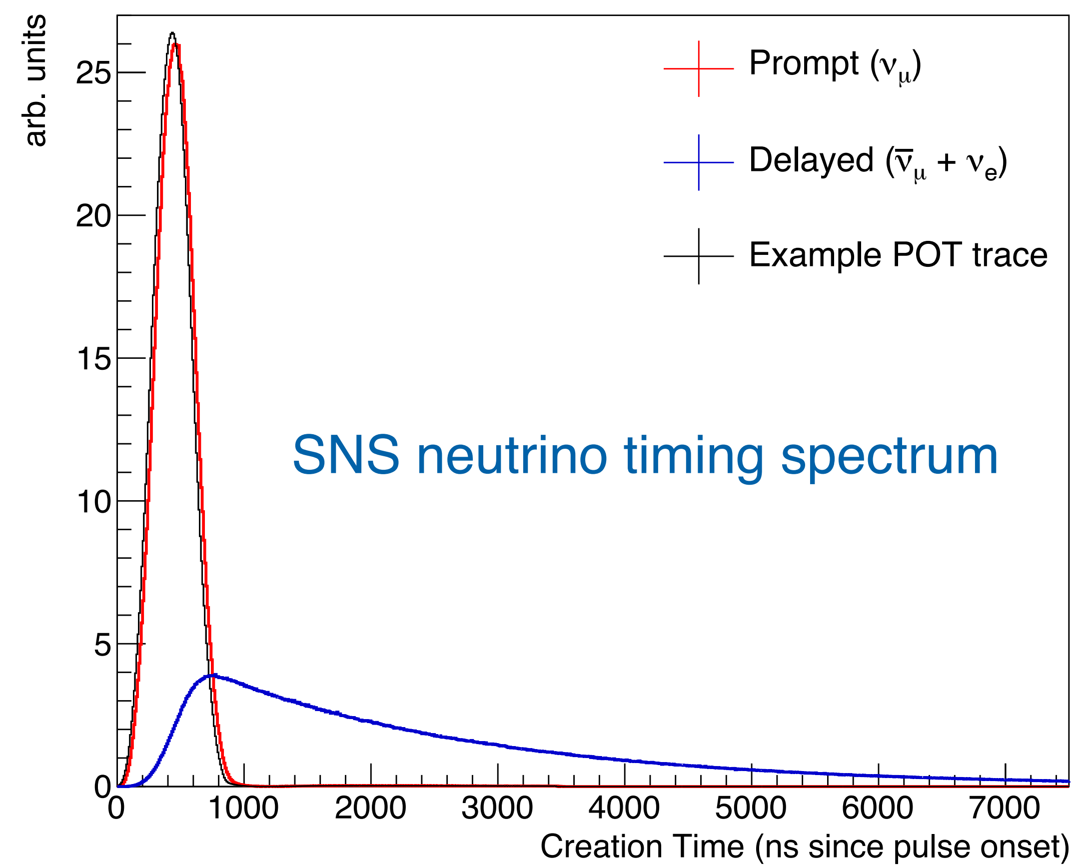
This is one possibility to enable parts of this program!

See W. Pellico and J. Eldred talks yesterday!

Stopped-Pion Neutrino Sources





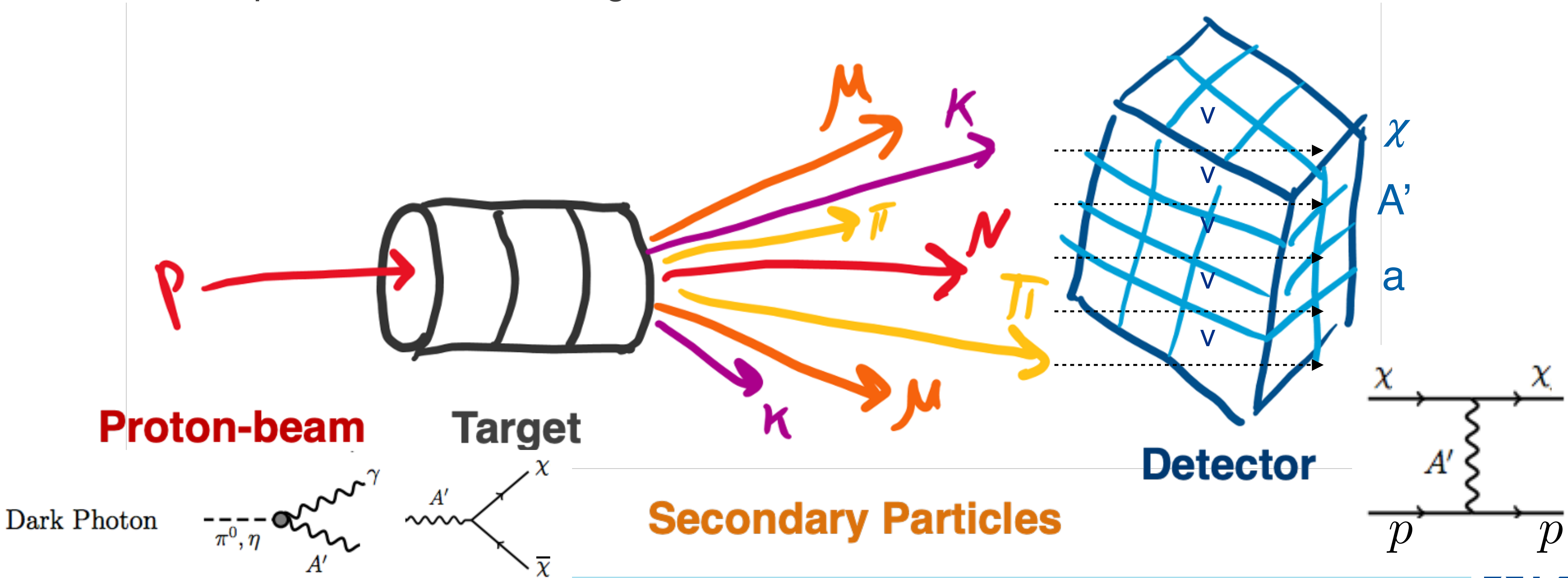


- Neutrinos produced from pion decay-at-rest via proton collisions with target
- Neutrino flux O(10^7)/cm^2/s at ~1 MW and 20 m from source
- Steady-state background suppression via pulsed beam

D. Akimov et al. (COHERENT) Phys. Rev. D (2022) 3, 032003

Leveraging Stopped Pion Sources for Dark Sector Searches

- How do we leverage a stopped-pion neutrino source for dark sector searches?
  - Large-scale detector capable of low energy, O(10 keV) detector thresholds and reconstructing EM activity up to tens of MeV
    - I will cover a large-scale liquid argon detector concept, PIP2-BD, later today
  - Large beam exposures -> rare signals from dark sector models
  - Rejection of steady-state backgrounds via pulsed beam structure
  - Remove beam-related backgrounds
    - Adequate neutron shielding
    - Neutrinos produced are a background!



Creating a stopped-pion source with PIP-II

- PIP-II Accumulator Ring (PAR), Compact PIP-II Accumulator Ring (C-PAR), and Rapid Cycling Synchrotron Storage Ring (RCS-SR) are three accelerator scenarios we studied ahead of Snowmass 2022
- PAR and C-PAR are realizable in the timeframe of the start of the PIP-II accelerator and DUNE Phase I
- RCS-SR is a Booster Replacement scenario under ACE on the timescale of DUNE Phase II

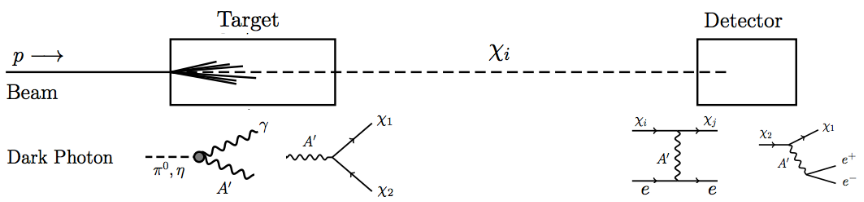
Facility	Beam Energy (GeV)	Repetition Rate (Hz)	Pulse Length (s)	Beam Power (MW)
PAR	0.8	100	2×10^{-6}	0.1
C-PAR	1.2	100	2×10^{-8}	0.09
RCS-SR	2	120	2×10^{-6}	1.3

Physics available with O(1 GeV) stopped-pion source

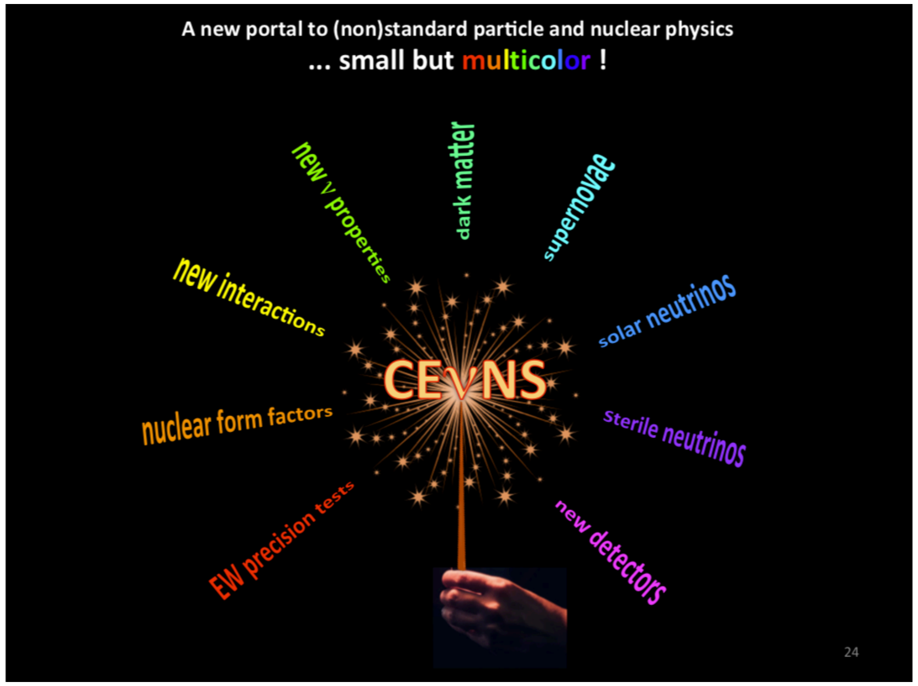
- Light dark matter (LDM) / dark sector searches
  - Decay and/or scattering signatures

Later portion of talk focusing here!

- Axion-like particle (ALP) searches
  - Coupling to photons, e+/e-, and nuclei



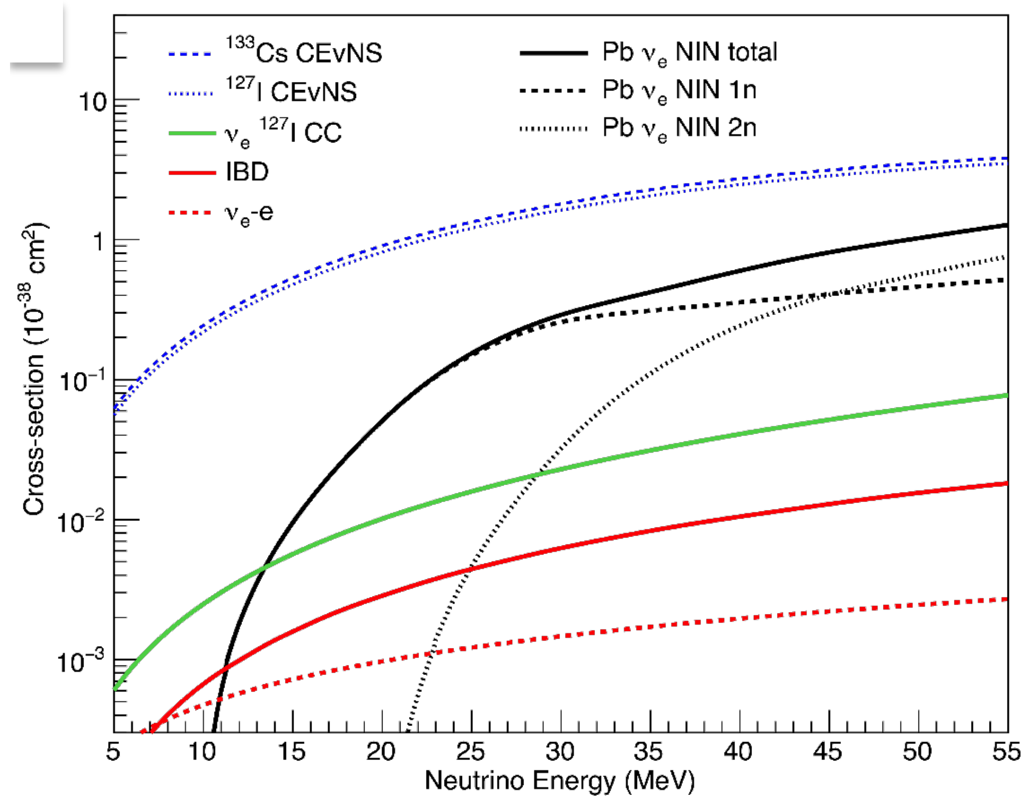
- Coherent elastic neutrino-nucleus scattering (CEvNS)
- Light Sterile Neutrino Searches
  - Both appearance and disappearance possible
- Searches for Non-standard interactions (NSIs), tests of the Standard Model
- Neutrino Cross Section Measurements
- Neutrino-Electron Scattering (LSND-like), MeV-scale

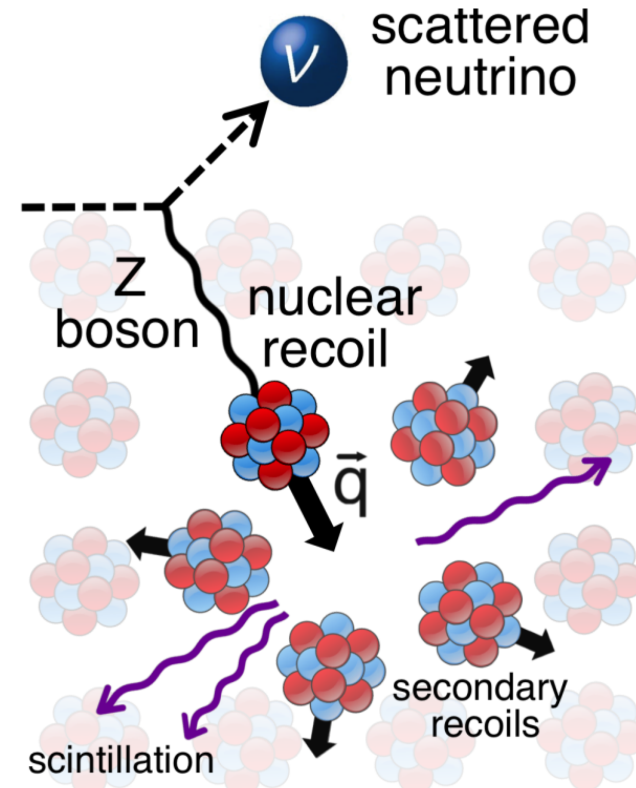


E. Lisi, NuINT 2018

Where does the keV-scale physics come from?

- Interactions such as coherent elastic neutrino-nucleus scattering (CEvNS)
  - Standard Model interaction
- Neutrino interacts coherently with nucleons in target nucleus
- Signature is low-energy nuclear recoil
- Largest low-energy neutrino cross section on heavy nuclei
- Distinct N^2 dependence of cross section
- Some vector-portal dark matter models also produce a similar interaction with a dark matter particle scattering coherently off of the nucleus



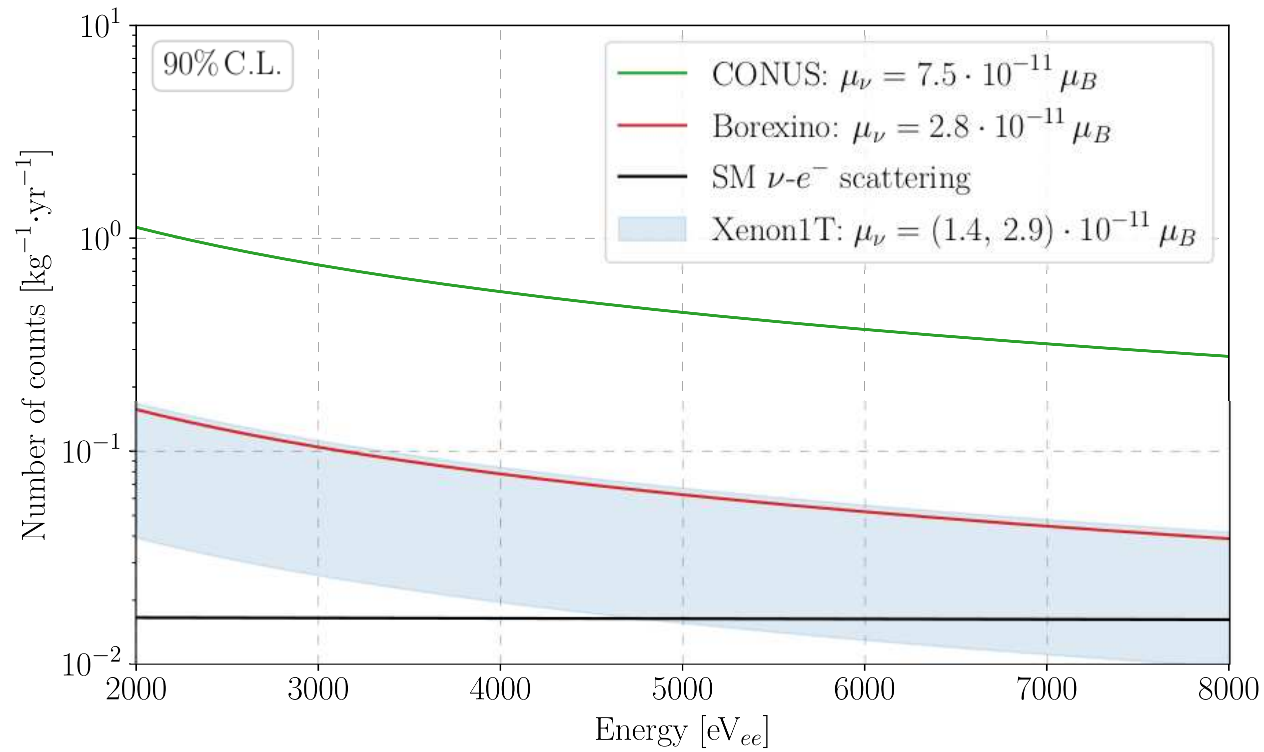


$$\frac{d\sigma}{d\Omega} = \frac{G_f^2}{16\pi^2}(N - (1 - 4\sin^2(\theta_W))Z)^2 E_\nu^2 (1 + \cos\theta) F(Q^2)$$

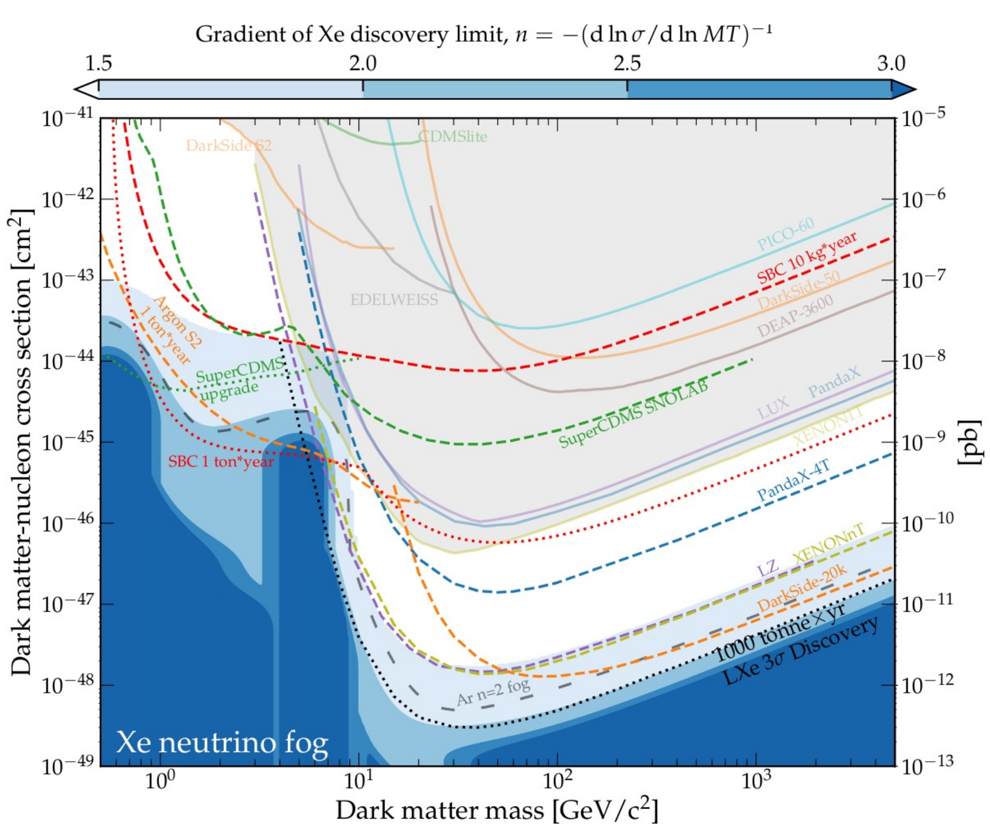
D. Akimov et al. (COHERENT). Science 357, 1123-1126 (2017)

Physics Motivation for CEvNS

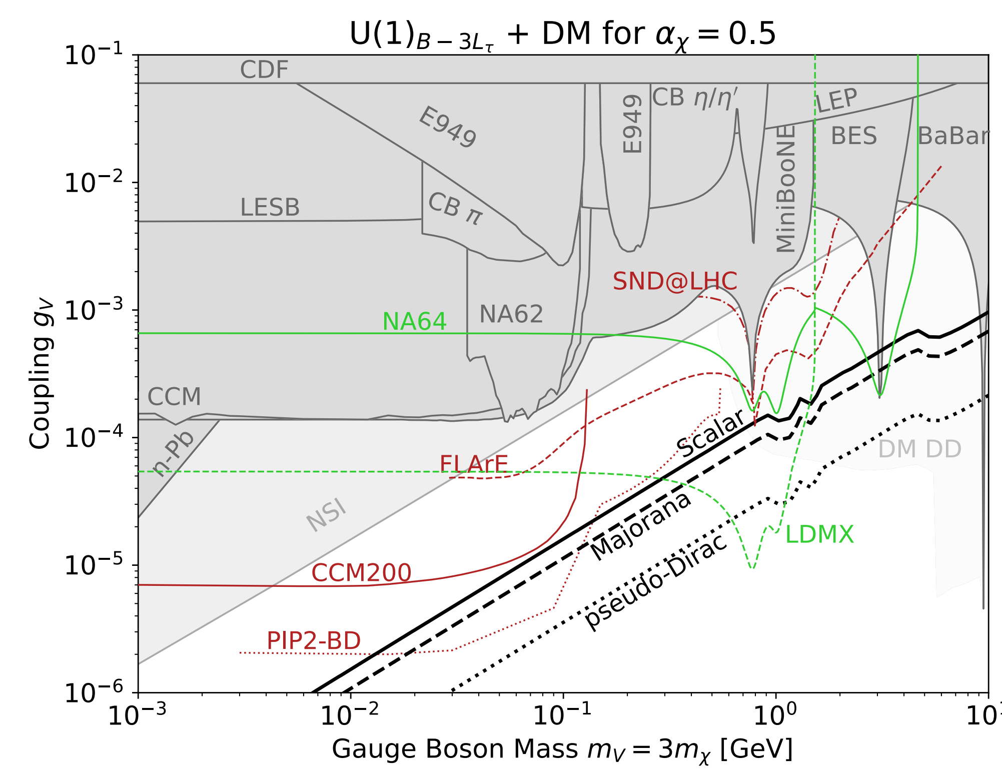
- CEvNS is Standard Model process, opens doors for new physics searches
  - Neutrino magnetic moment, non-standard interactions, etc.
- Dark matter and dark sectors
  - “Neutrino fog” for dark matter direct detection experiments



H. Bonet et al. (CONUS), arXiv:2201.12257[nucl-ex]

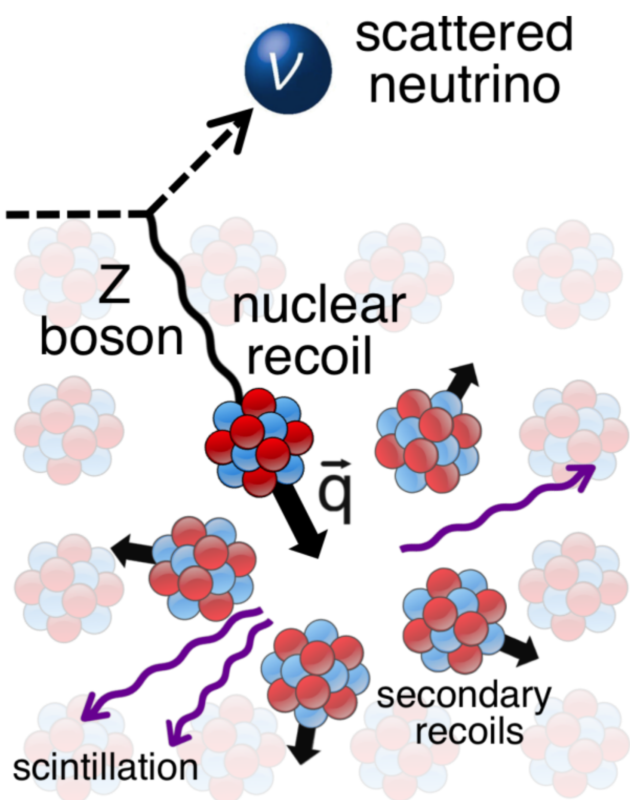


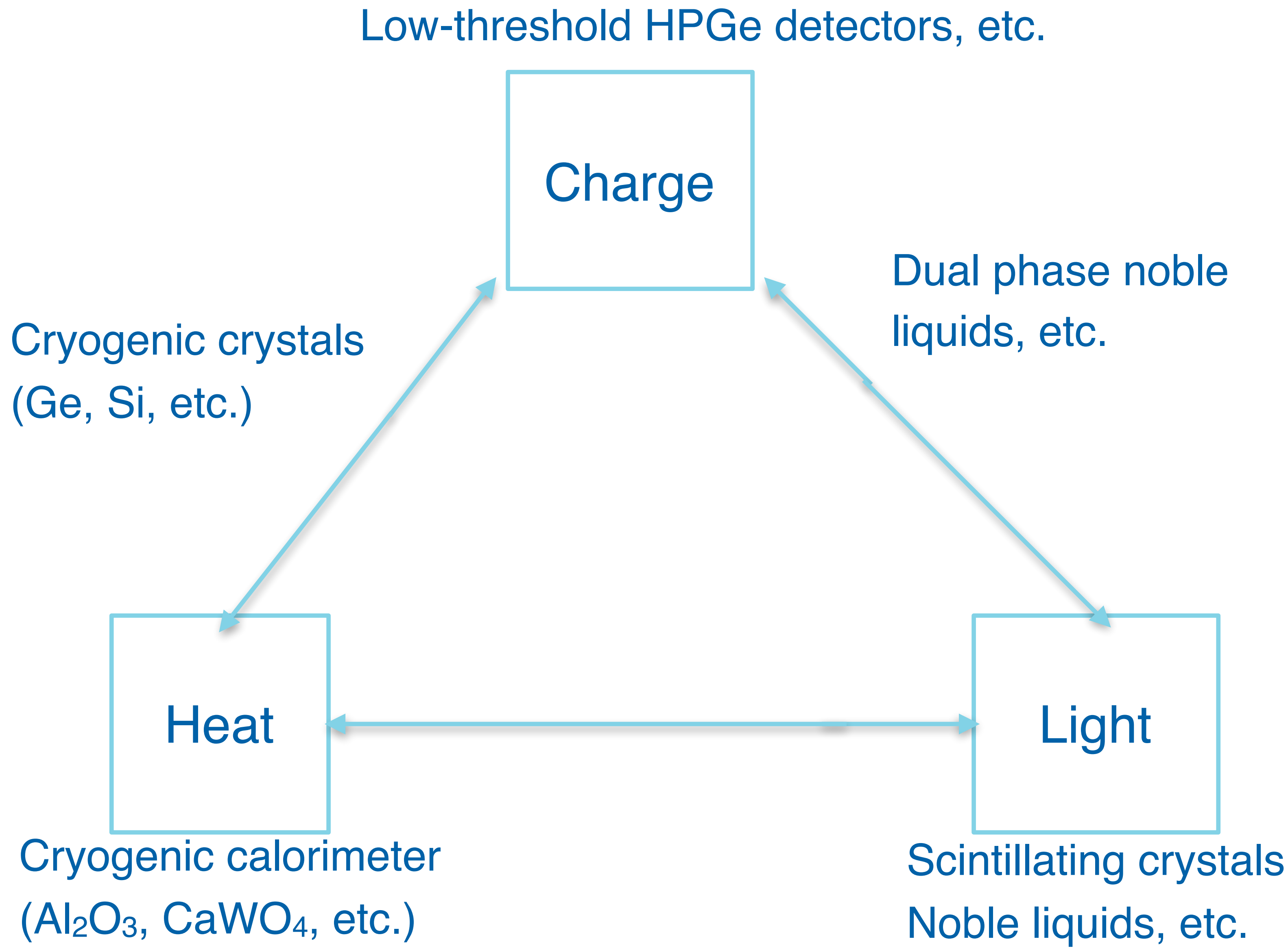
D. S. Akerib et al.,arXiv:2203.08084



G. Krnjaic et al, arXiv:2207.00597[hep-ph]

Detecting these events





- Large cross section allows for small detectors to measure neutrinos/dark matter when placed near an intense source
  - Improvements come in larger mass (i.e. for noble liquid detectors) or lower energy thresholds (i.e. for cryogenic bolometers)
  - Important to achieve background rejection with pulsed source structure, pulse shape discrimination, and neutron background rejection
- Maximum nuclear recoil energy $T_{max} \sim E^2_{nu}/M$

keV-threshold detectors can also detect MeV-scale signatures!

keV

- CEvNS
- Dark sector rescattering off nuclei
- Sterile neutrino searches
- Non-standard interactions

MeV

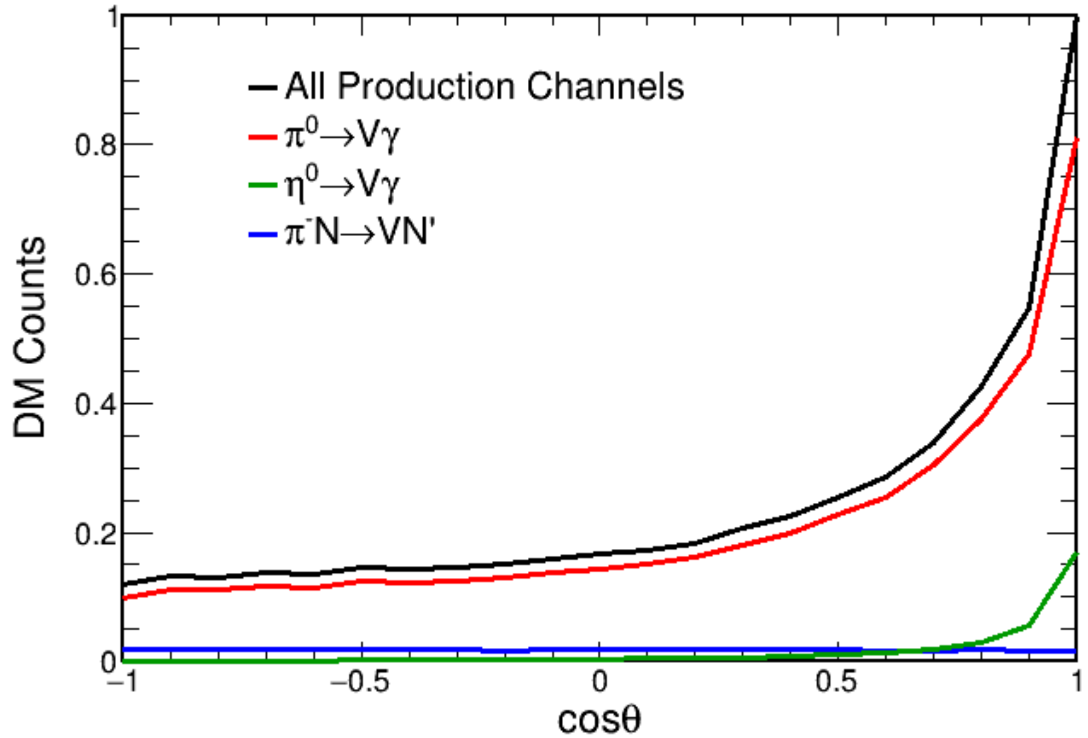
- Axion-like particle scattering and decay
- Dark photon absorption and decay
- Inelastic dark matter scattering
- Solar and supernova neutrino detection

Also see B. Dutta's talk from yesterday afternoon!

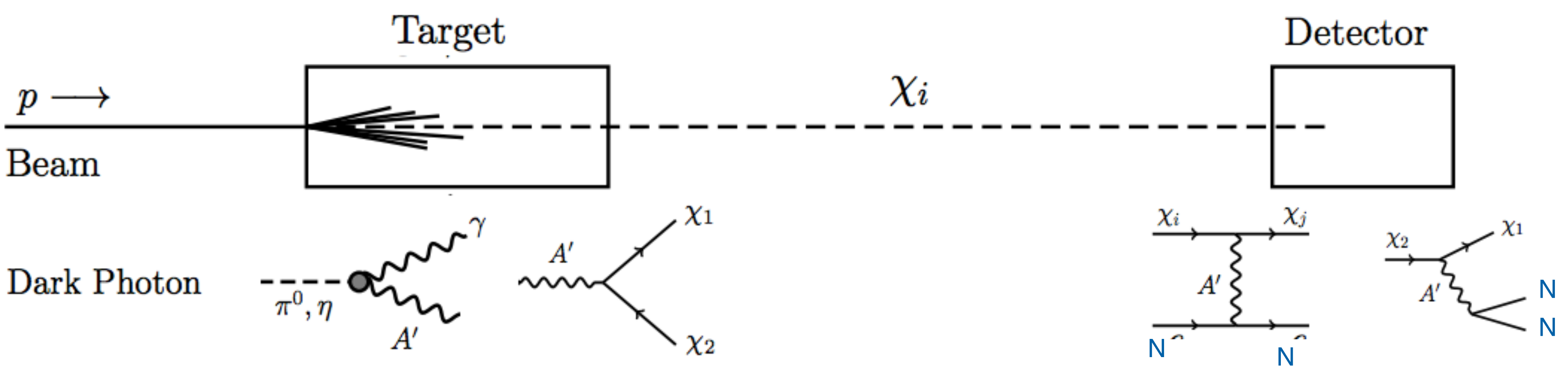
During the parallel sessions can explore possibilities for an experiment or experiments targeting these possibilities or other physics opportunities not listed here!

Vector Portal Light Dark Matter (LDM)

- Proton-target collisions produce dark sector mediators (V) between SM and dark sector (χ)
  - sub-GeV dark matter particle
- Produced dark matter particles boosted towards forward direction
- Signature in detector is low-energy nuclear recoil
  - Understanding beam-related backgrounds important!



Phys. Rev. D 102 (2020) 5, 052007



P. deNiverville et al., Phys. Rev. D 92 (2015) 095005

B. Dutta et al., Phys. Rev. Lett 124 (2020) 121802

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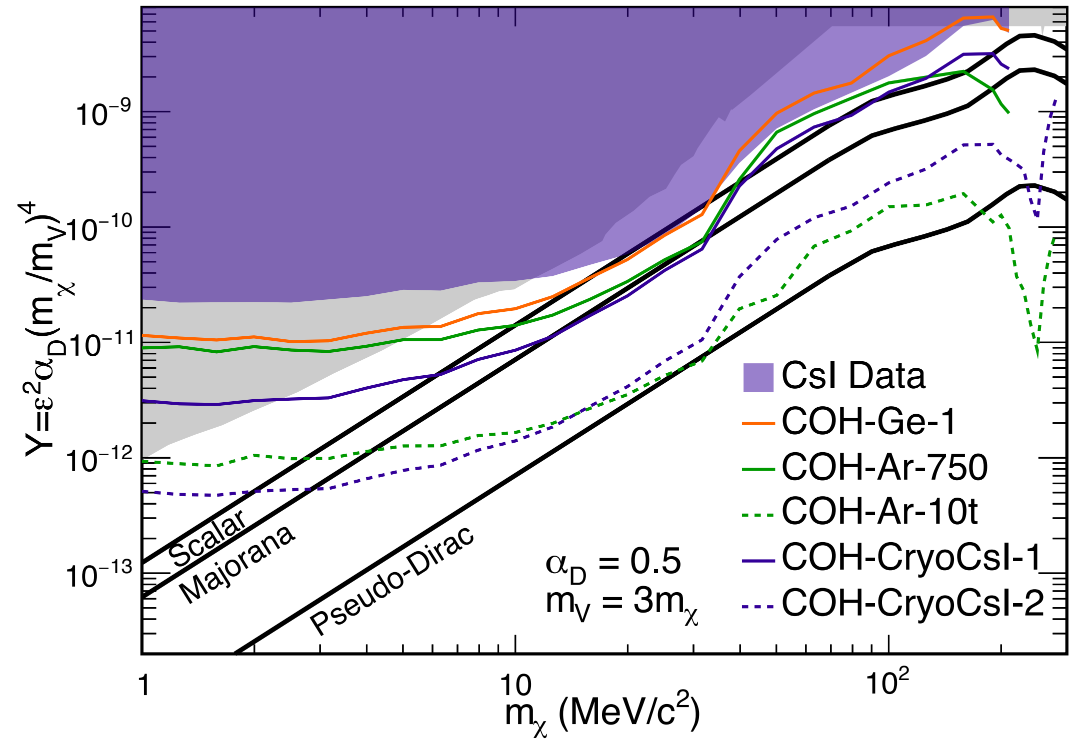
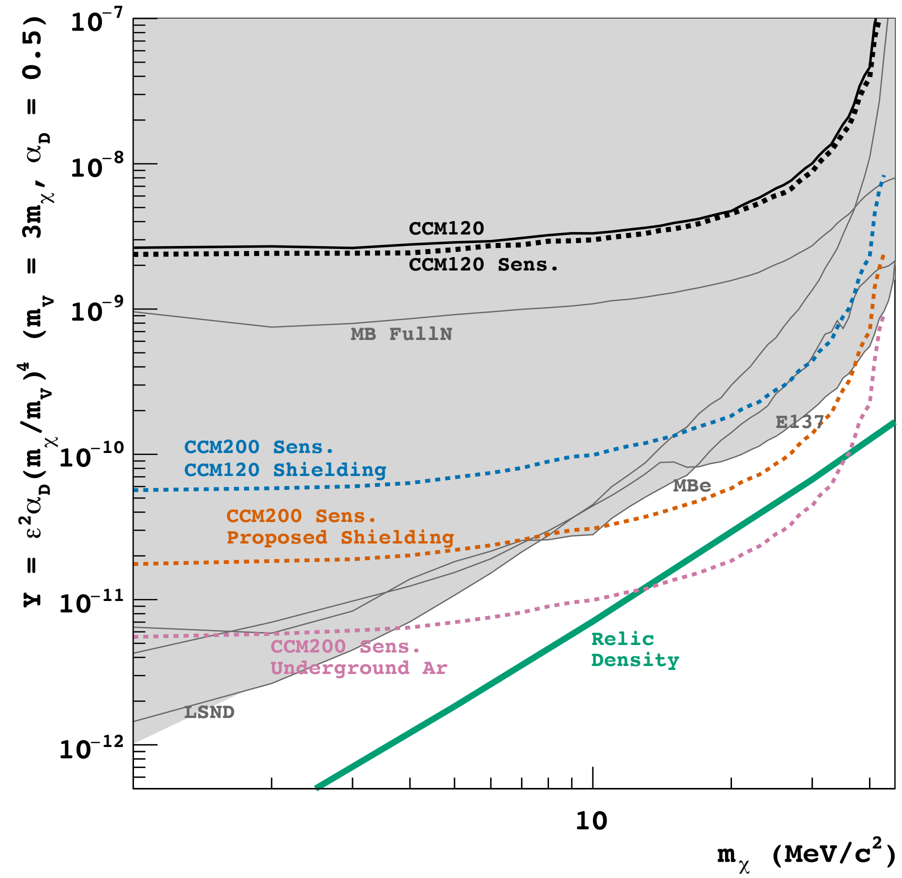
Current Accelerator-based vector-portal dark sector searches

- Low-threshold detectors place strong limits on a variety of accelerator-produced sub-GeV dark matter models
  - Including leptophobic, inelastic DM, and axion-like particle (ALP) models
- The COHERENT collaboration at Oak Ridge National Laboratory recently set limits on vector-portal dark matter using latest CsI[Na] data
- Coherent Captain-Mills (CCM) set limits with ton-scale single-phase liquid argon detector at Lujan beam at Los Alamos National Laboratory
- **We can explore similar models and more with detectors at a PIP-II facility!**



arXiv:2110.11453v1[hep-ex]

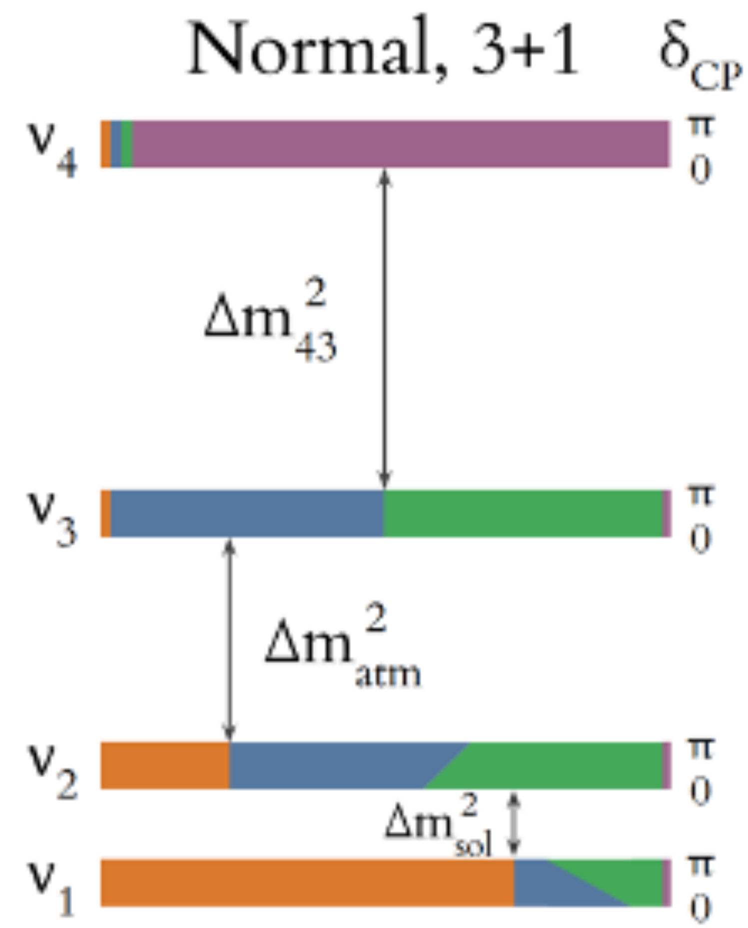
Phys. Rev. Lett 130, 051803 (2023)



Phys. Rev. D 106, 012001 (2022)

Extension to 3+1 neutrino states

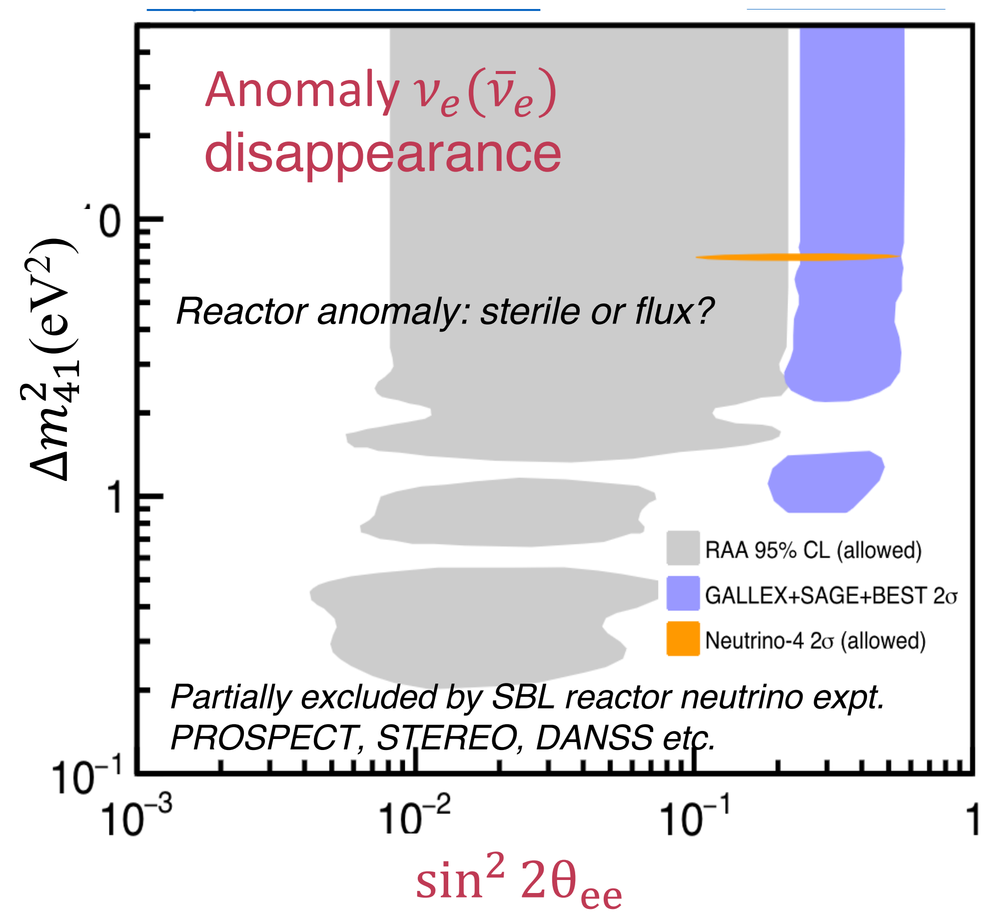
- Can create extensions to the three-flavor model
  - Extend the PMNS matrix to include a fourth, “sterile” neutrino or 3+1 model
- Additional mixing angles and mass splittings based on the fourth neutrino state
- Neutrino fluxes are conserved under the extension
- The fourth neutrino state allows for additional oscillation possibilities and additional appearance/ disappearance measurements

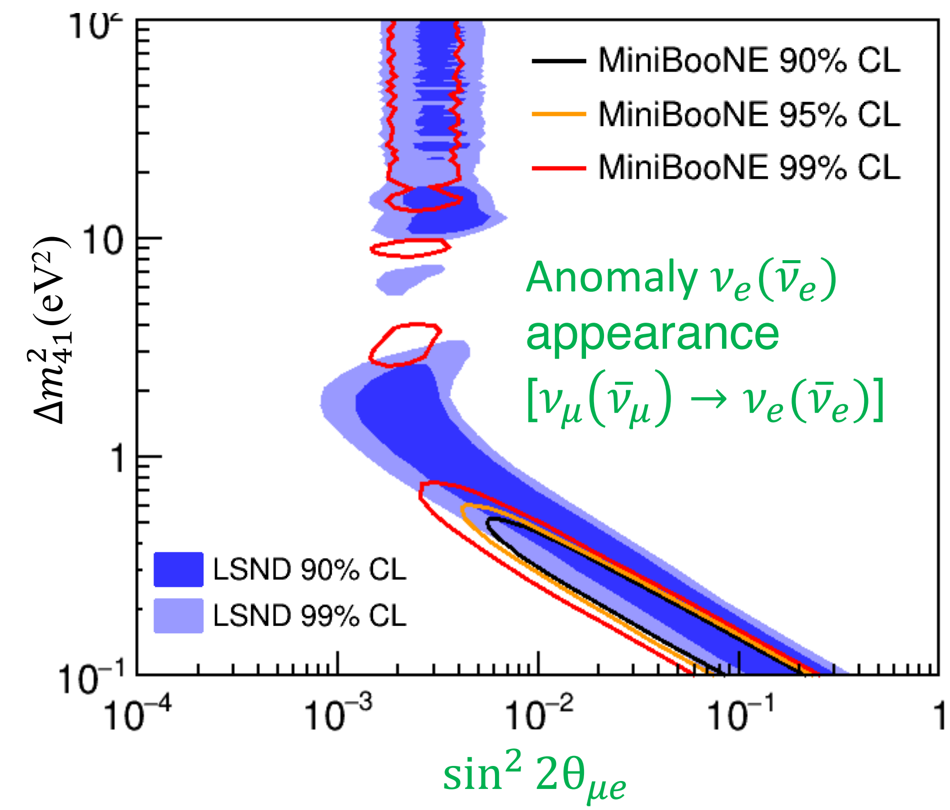


$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\\ \nu_s\end{pmatrix} = \mathbf{U}^{\mathbf{BSM}}_{\mathbf{PMNS}}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\\ \nu_4\end{pmatrix}$$

Anomalies in neutrino oscillation measurements

- Majority of experimental results consistent with 3-flavor neutrino oscillation paradigm
- Anomalies in short-baseline neutrino experiments from LSND and MiniBooNE
- One hypothesis is an eV-scale "sterile neutrino"
- A suite of co-located detectors at a PIP-II accumulator ring facility could use the ν_μ disappearance and the summed disappearance of the three neutrino flavors
- Taking advantage of the keV-scale threshold and CEvNS allows for smoking gun sterile neutrino search through mono-energetic ν_μ





Phys. Rev. D 103, 052002
Phys.Rev. D 64, 112007

Summary

- Portals to a dark sector enable searches for new physics

- Completion of PIP-II will support initial 1.2 MW beam to LBNF
  - Further upgrades in the form of an accumulator ring could produce a stopped-pion neutrino source at Fermilab on par with the most powerful in the world

- Stopped-pion sources provide access to a host of physics opportunities such as searches for the dark sector and opportunities using CEvNS

- Large-scale detectors coupled to these sources will also be able to perform searches for MeV-scale dark sector signatures

Thank you!

Questions, other ideas?

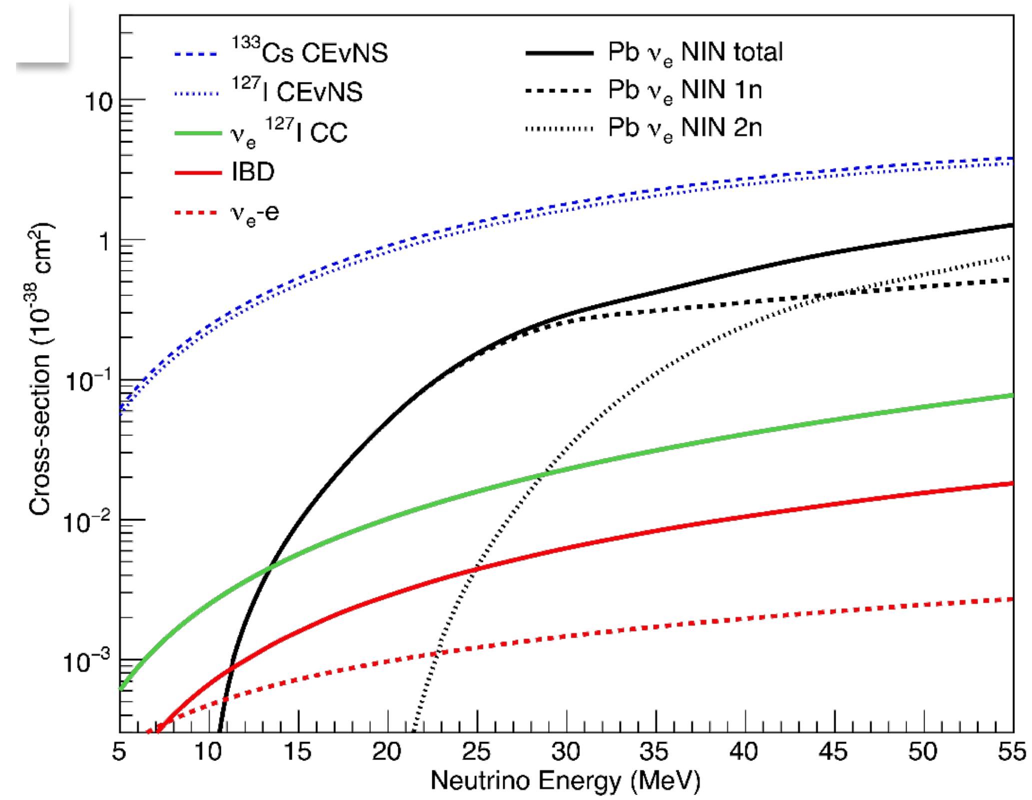
Backup

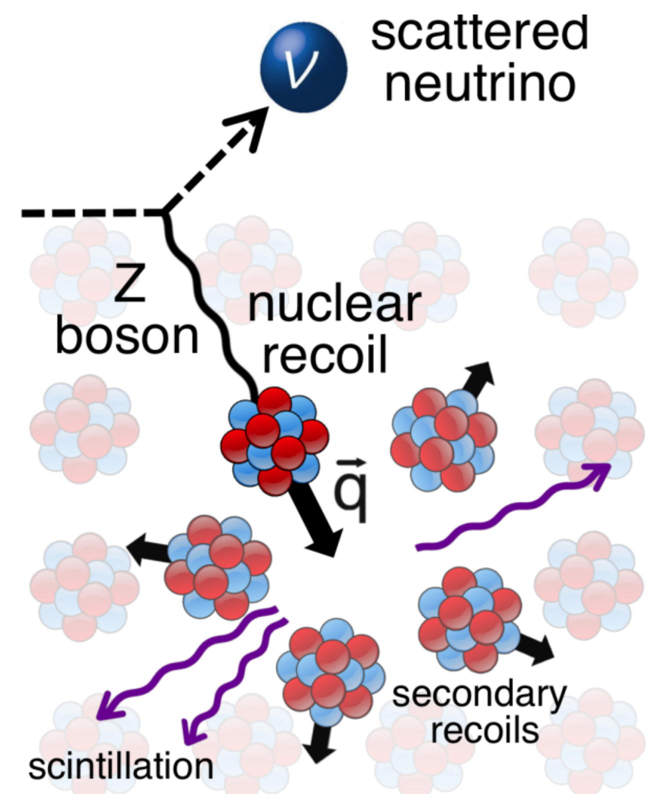
Coherent Elastic Neutrino-Nucleus Scattering (CEvNS)

- Standard Model interaction
- First predicted by Freedman in 1974
- Neutrino interacts coherently with nucleons in target nucleus
  - Neutrino flavor blind, with no energy threshold!
- Signature is low-energy nuclear recoil
- Largest low-energy neutrino cross section on heavy nuclei
- Distinct N^2 dependence of cross section

$$\frac{d\sigma}{d\Omega} = \frac{G_f^2}{16\pi^2}(N - (1 - 4\sin^2(\theta_W))Z)^2 E_\nu^2 (1 + \cos\theta) F(Q^2)$$

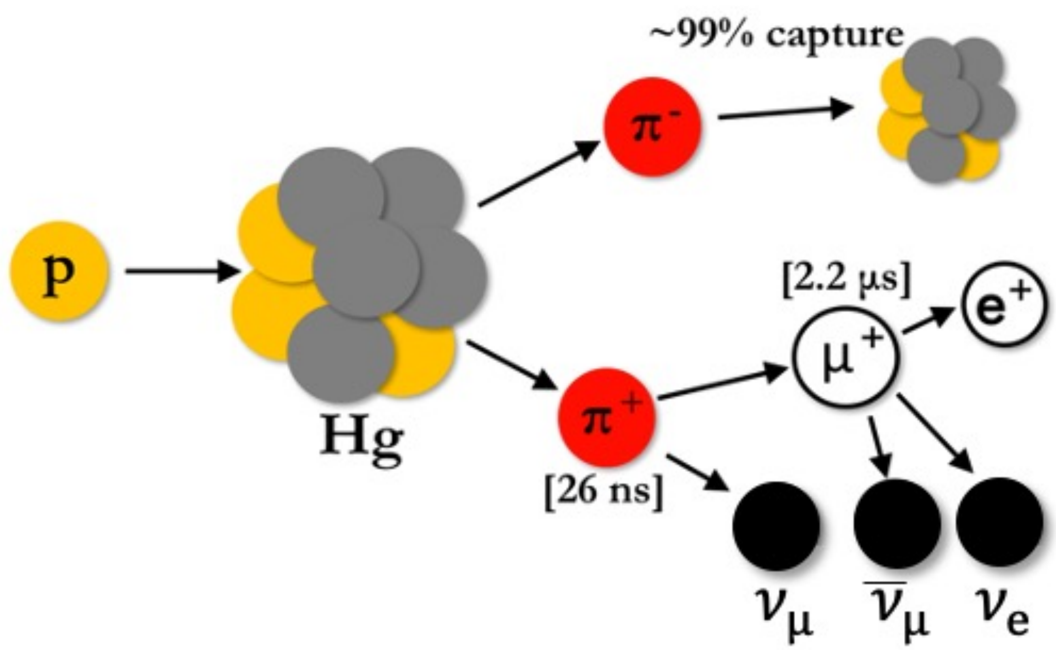
- Searches ongoing using both stopped-pion and reactor neutrino sources



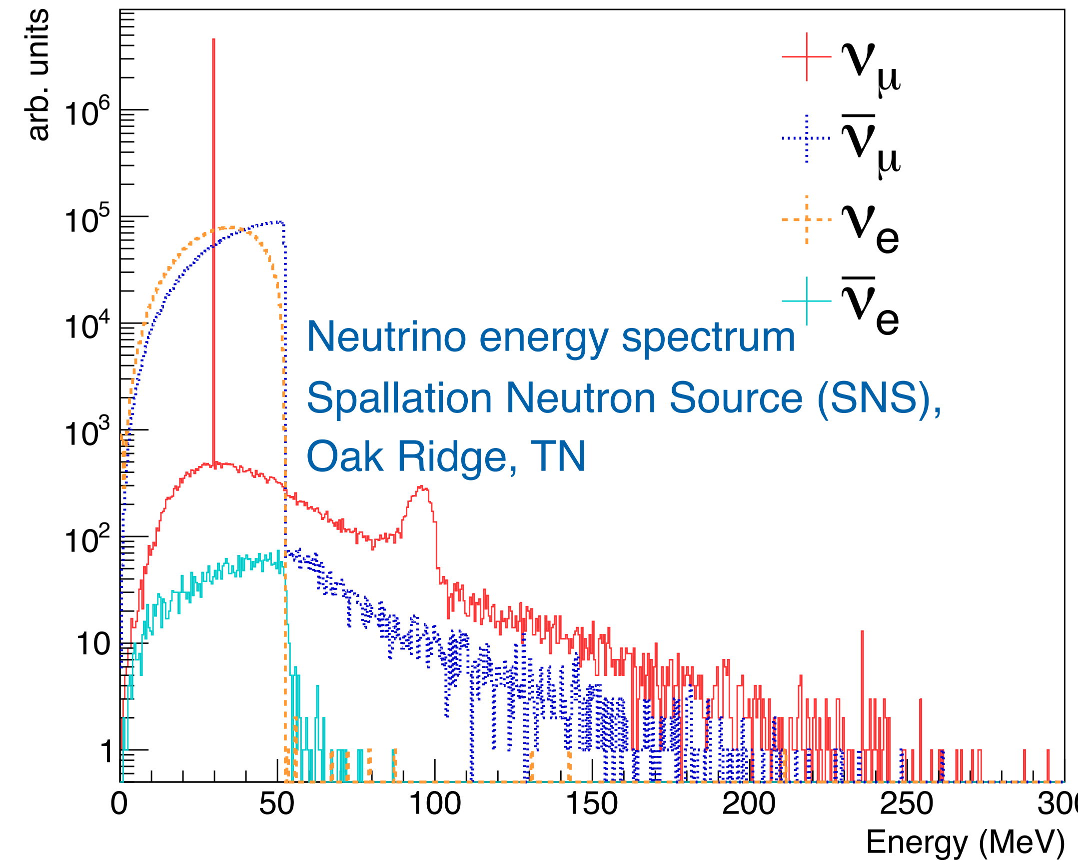


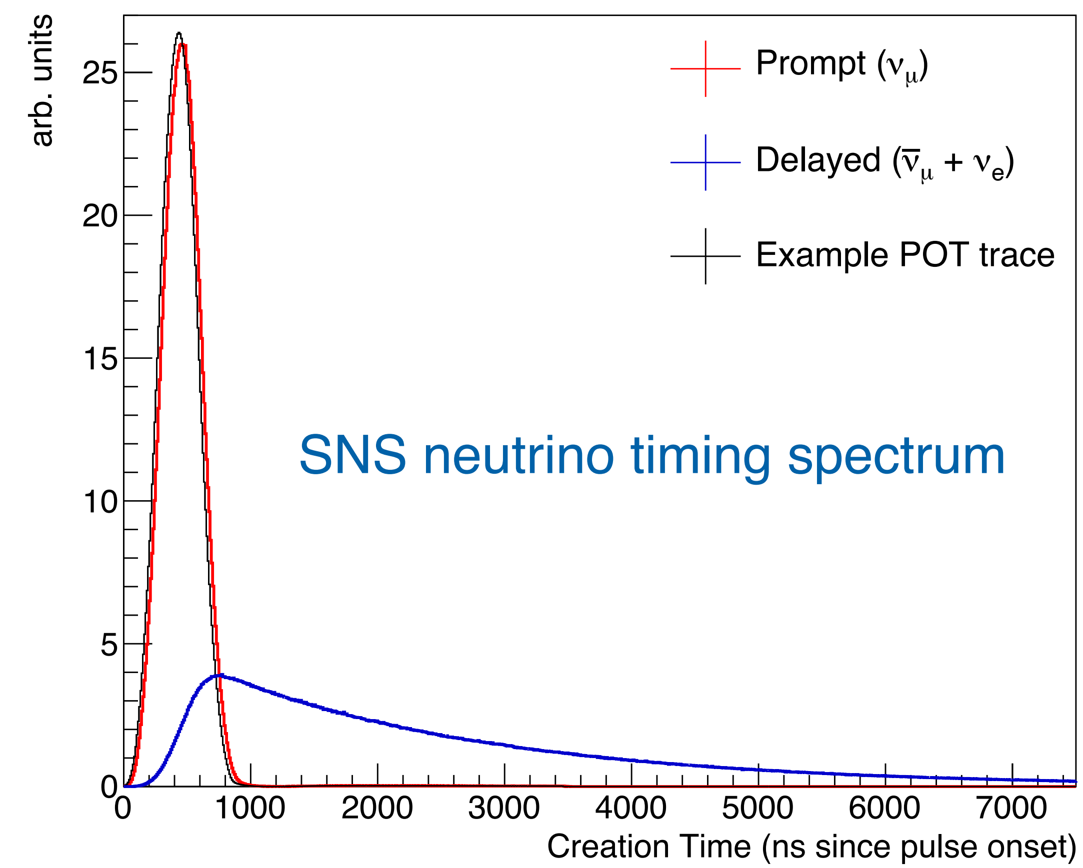
D. Akimov et al. (COHERENT). Science 357, 1123-1126 (2017)

Stopped-Pion Neutrino Sources



- Neutrinos produced from pion decay-at-rest via proton collisions with target
- Neutrino flux O(10^7)/cm^2/s at ~1 MW and 20 m from source
- Steady-state background suppression via pulsed beam

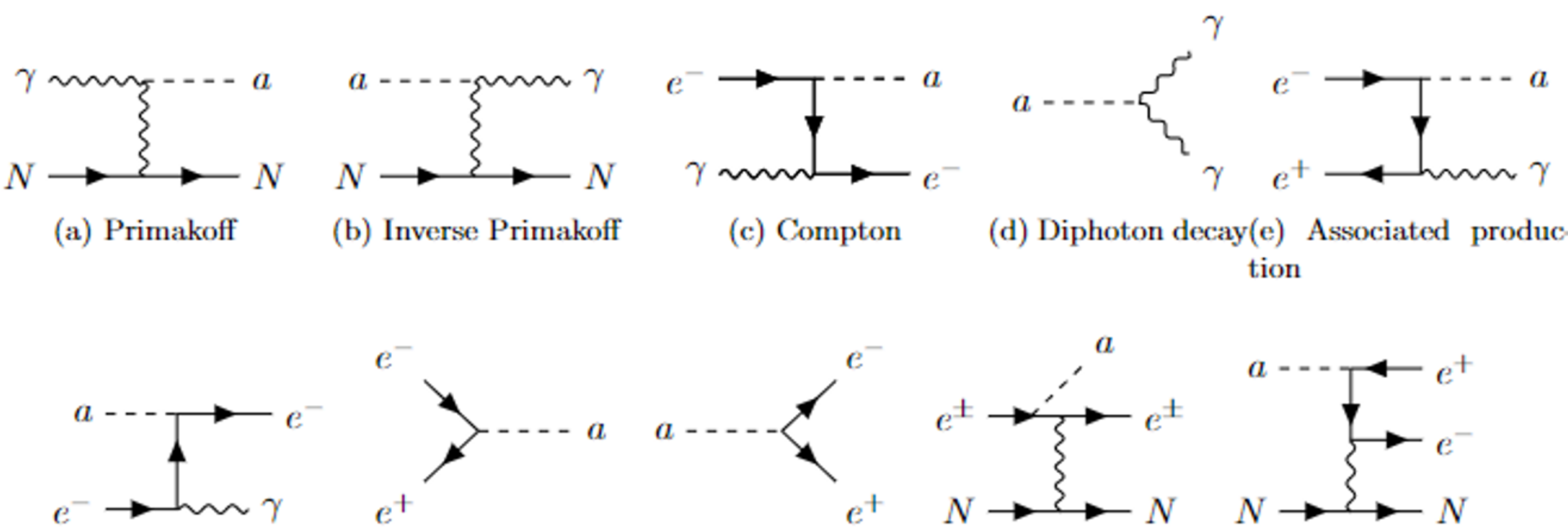




D. Akimov et al. (COHERENT) Phys. Rev. D (2022) 3, 032003

Axion-like particle (ALP) searches with PIP-II

- ALPs that couple to photons can be produced in the beam dump via Primakoff process, detectable via inverse Primakoff process or decay into two photons
- ALPs coupling to electrons detectable via inverse Compton, e+e- conversion, or decay to e+e-



(a) Primakoff (b) Inverse Primakoff (c) Compton (d) Diphoton decay (e) Associated production

(f) Inverse Compton (g) Resonant production (h) e^+e^- decay (i) ALP-bremsstrahlung (j) External pair conversion

arXiv:2112:09979

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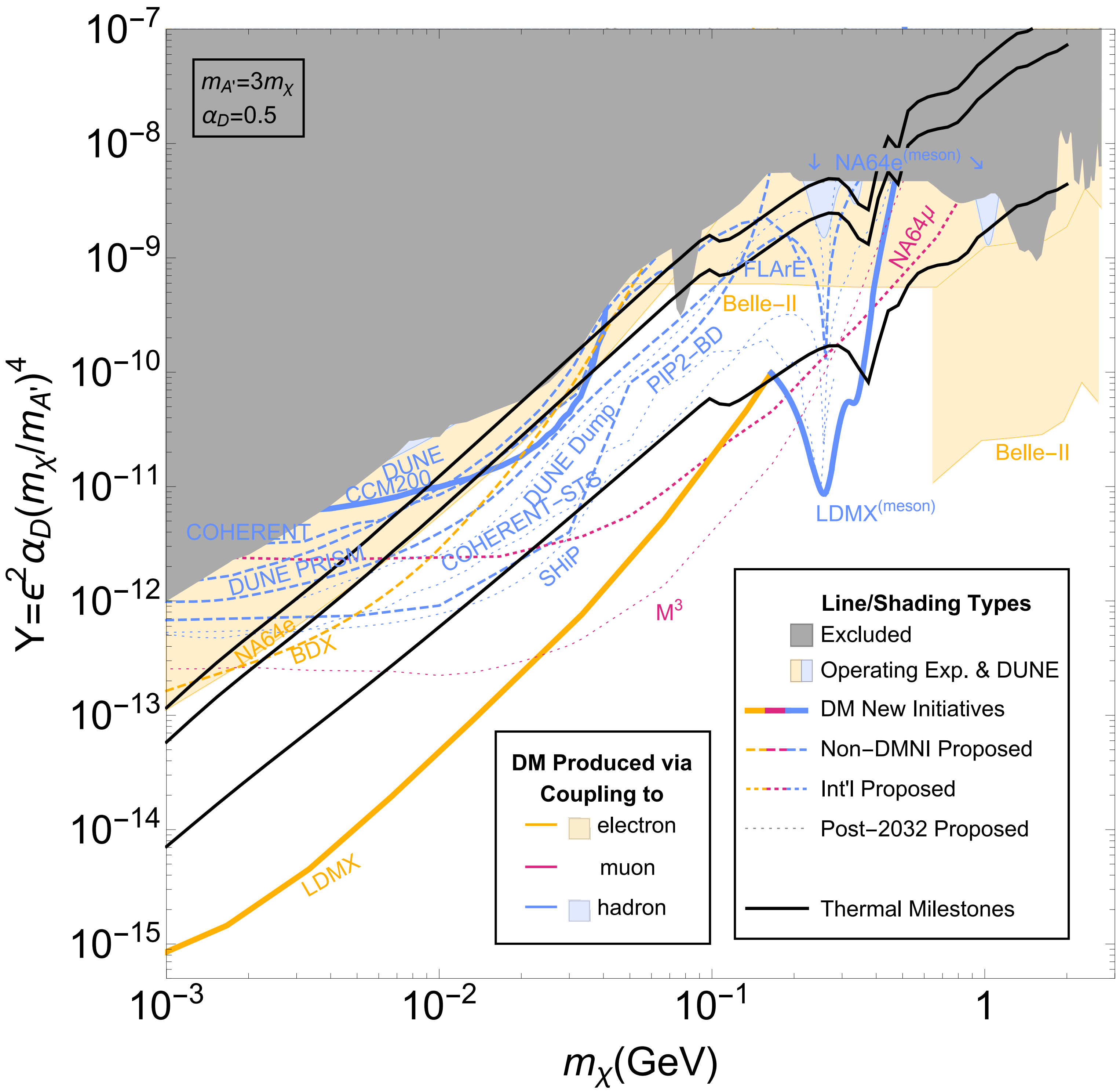
PIP2-BD Vector Portal Dark Matter Search

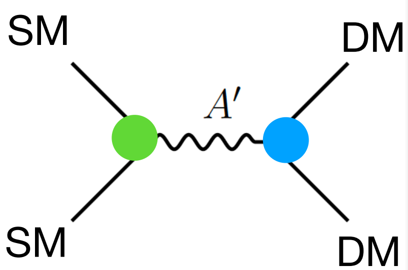


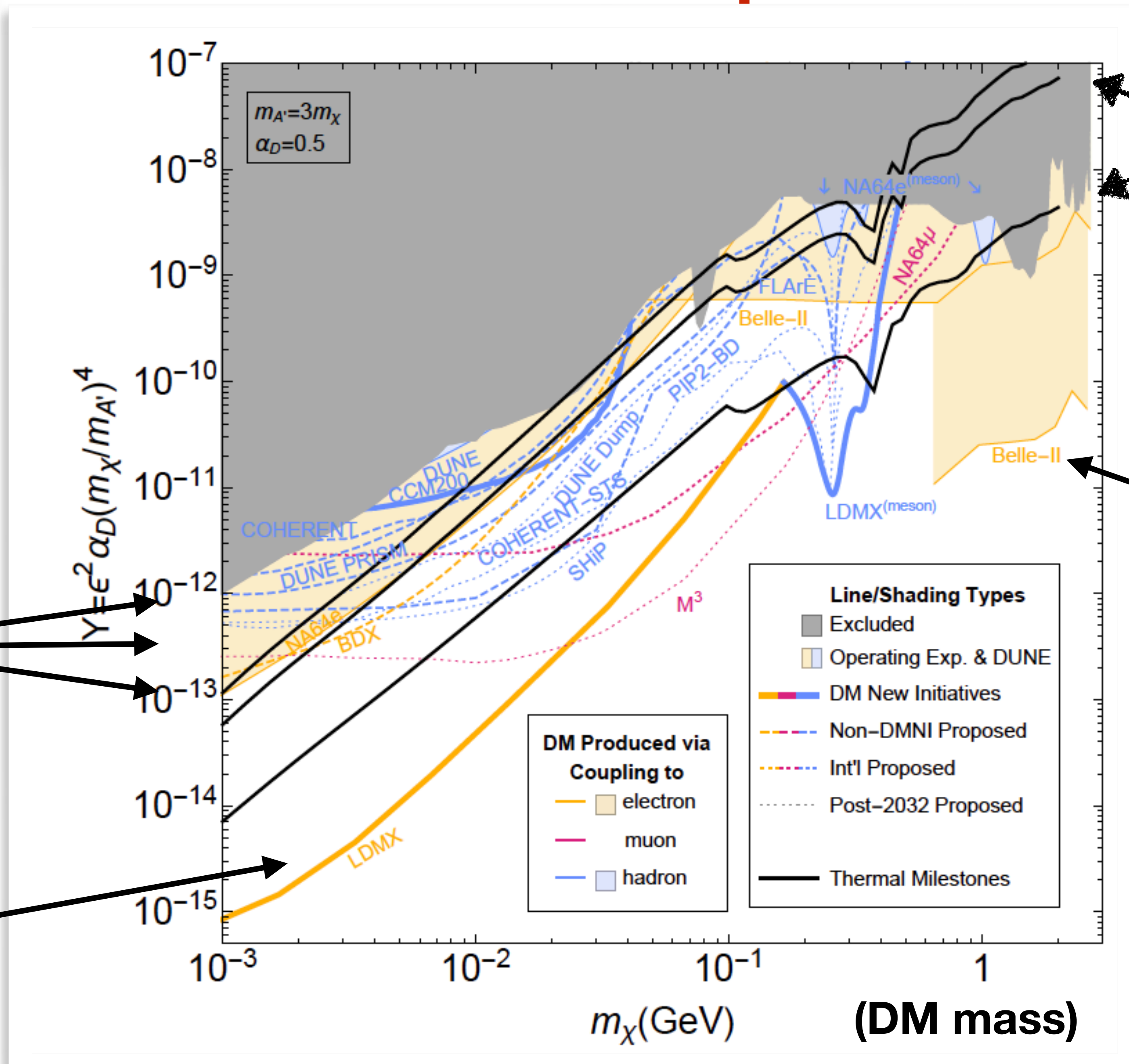
arXiv:2209.04671

DM thermal milestones:
invisible dark photon

$\epsilon B^{\mu\nu} A'_{\mu\nu}$

A'→XX





(DM mass)

benchmarks for thermal DM

(1) Collider, mono-photon search (missing energy)

(2) Re-scattering

(1) Missing momentum

See talk by T. Nelson

S.Gori

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S. Gori, BNL P5 town hall, April 2023

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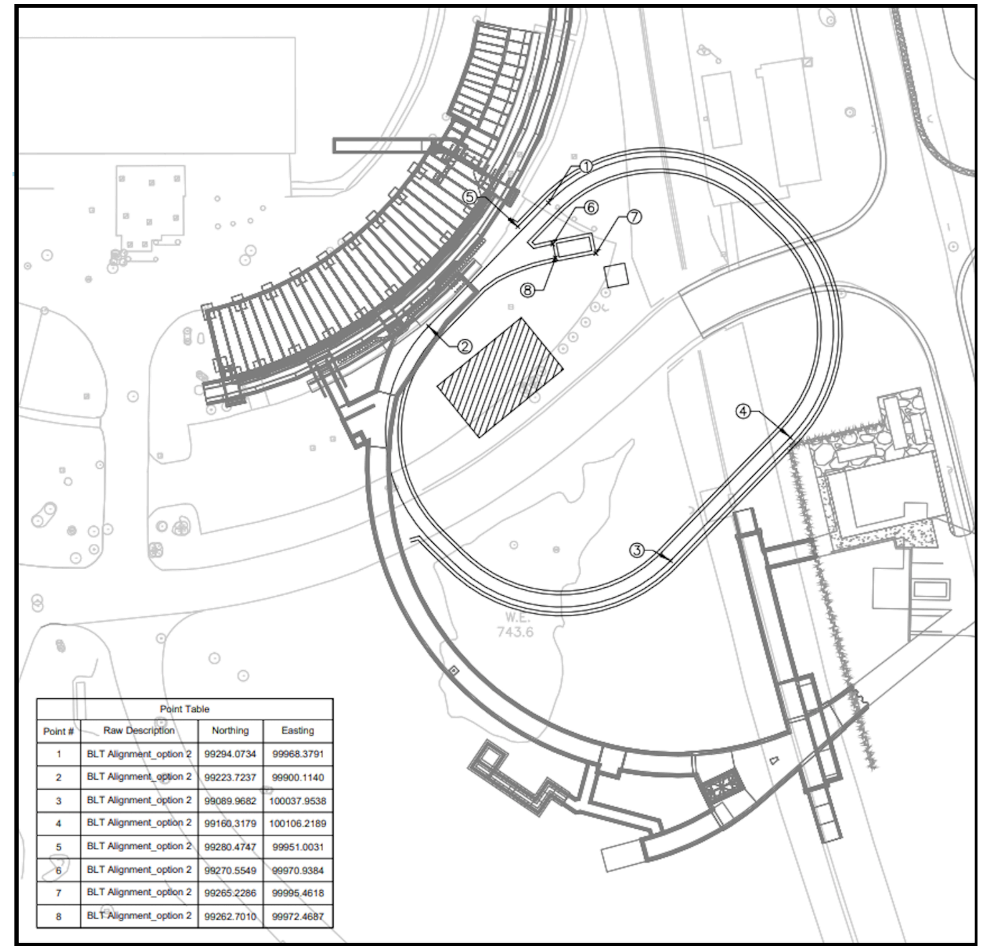
The PIP-II Accumulator Ring (PAR)

- Design of PIP-II linac includes possibilities for future upgrades
  - CW multi-user mode of operation
  - Increase in beam energy to >= 1 GeV
  - Stub in transfer line to the Booster to provide beam to other users
- An extension of the PIP-II beam transfer line tunnel would allow co-location of an accumulator ring for modest cost that could be realized with this decade
  - Allows for dark sector program
  - Enables injection of 1 GeV beam to the Booster as a pathway to higher LBNF beam power



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5	BLT Alignment_option 2	99280.4747	99951.0031
6	BLT Alignment_option 2	99270.5549	99970.9384
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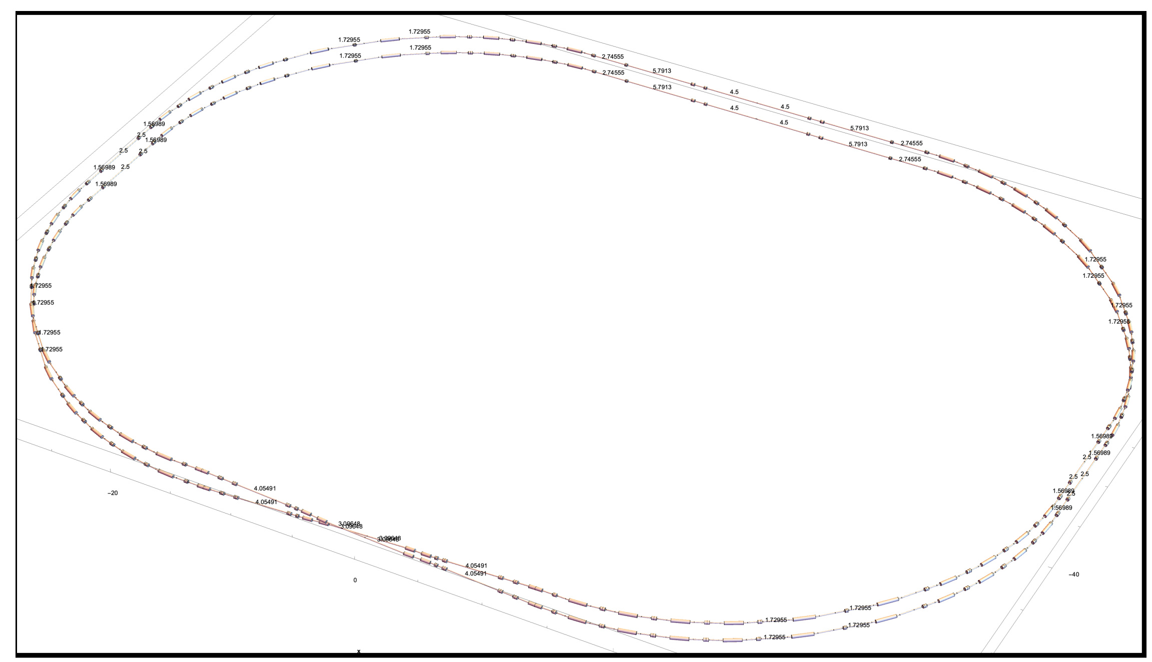

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Beyond PAR: The Fermilab Accelerator Complex Evolution (ACE)

- ACE has two components
  - Upgrades to Main Injector and target station allowing DUNE to achieve results on an accelerated schedule
  - A Booster replacement, which will
    - Provide a robust and reliable platform for the future of the Fermilab accelerator complex
    - Enable the capability of the complex to serve precision experiments and searches for new physics with beams from 1-120 GeV
    - Create the capacity to adapt to new discoveries

Capability

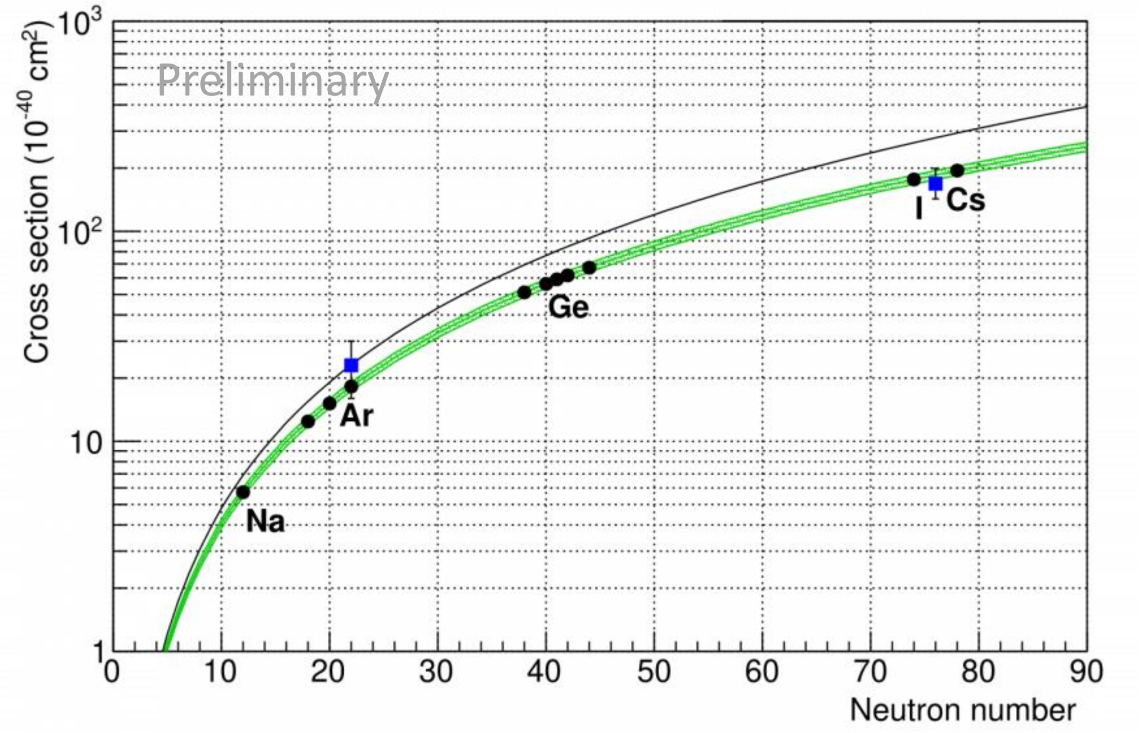
Capacity

Reliability

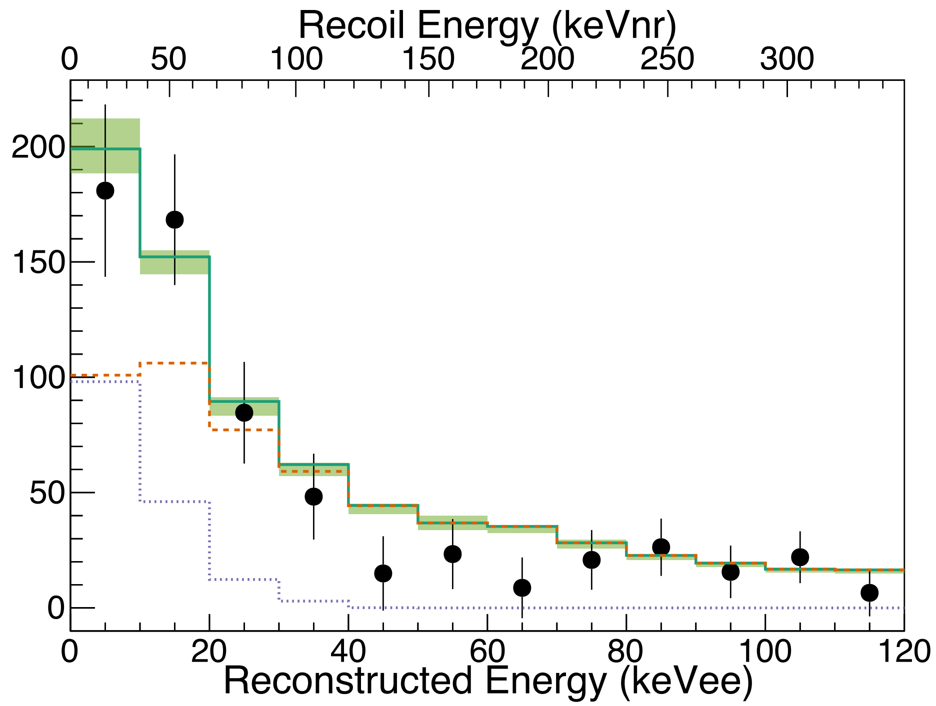
Adapted from B. Fleming, FNAL P5 town hall meeting, March 2023

Liquid Argon (LAr) for CEvNS-based new physics detection

- Large scintillation yield of 40 photons/keV
- Well-measured quenching factor
  - Conversion between nuclear recoil response and scintillation response
- Strong pulse-shape discrimination (PSD) capabilities for electron/nuclear recoil separation
- First CEvNS detection on argon at >3σ significance by COHERENT!
- Move toward precision physics and new physics searches with large detectors



D. Pershey, Magnificent CEvNS 2020



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