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Searching for New Physics with a Stopped-Pion Facility at an Upgraded Fermilab Accelerator Complex

Jacob Zettlemoyer, Fermilab (jzettle@fnal.gov)

Interplay of Nuclear, Neutrino and BSM Physics at Low-Energies

Institute for Nuclear Theory, University of Washington, Seattle, WA

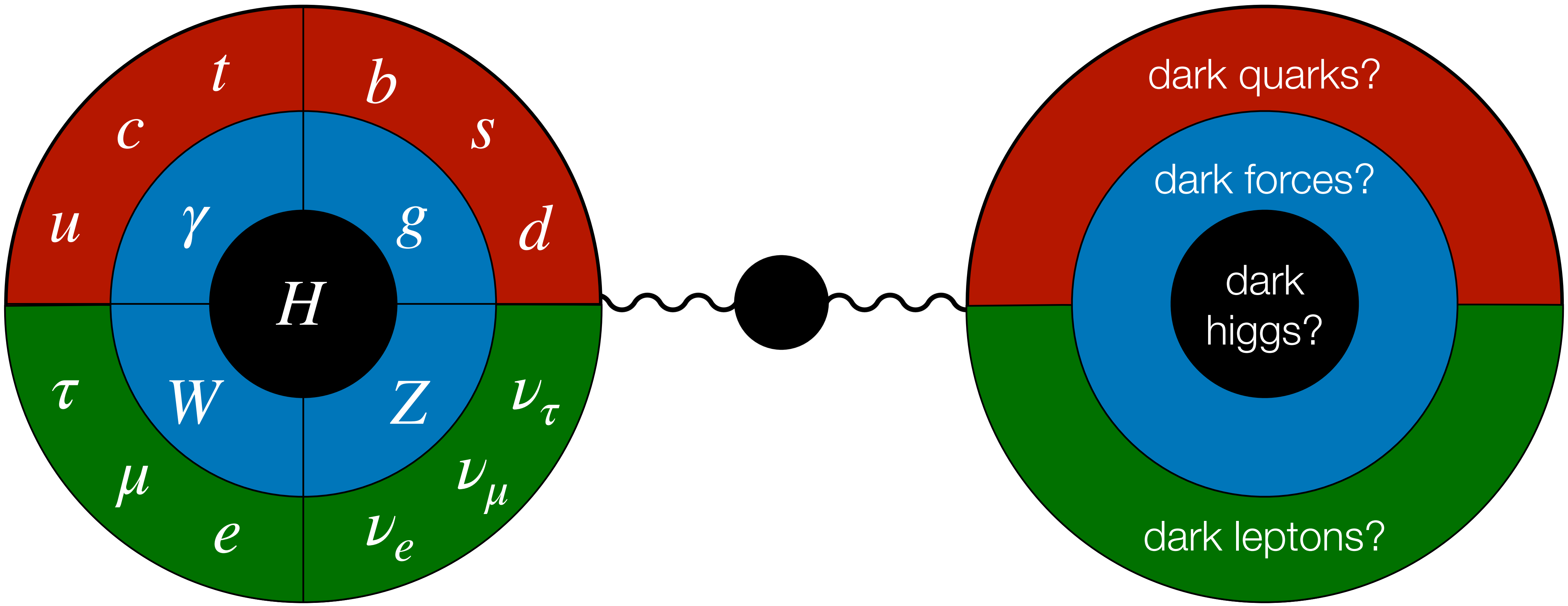
April 21, 2023

Overview

- Interest in Dark Sector Searches
- The Fermilab Accelerator Complex and PIP-II
- Stopped-pion neutrino sources
- Studies with large scale liquid argon detector coupled to PIP-II: PIP2-BD

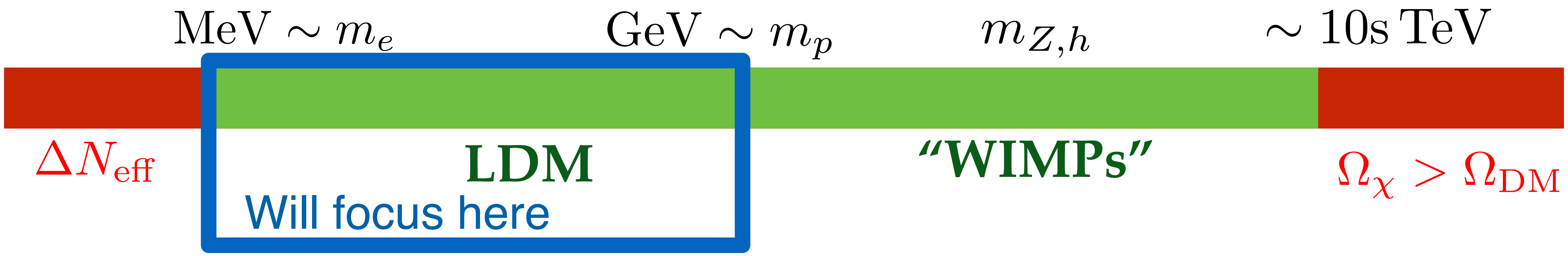
A Dark Sector is motivated by the existence of dark matter

- Potentially has a rich structure



arXiv:2209.04671

Current Landscape of Dark Matter and Dark Sector Searches

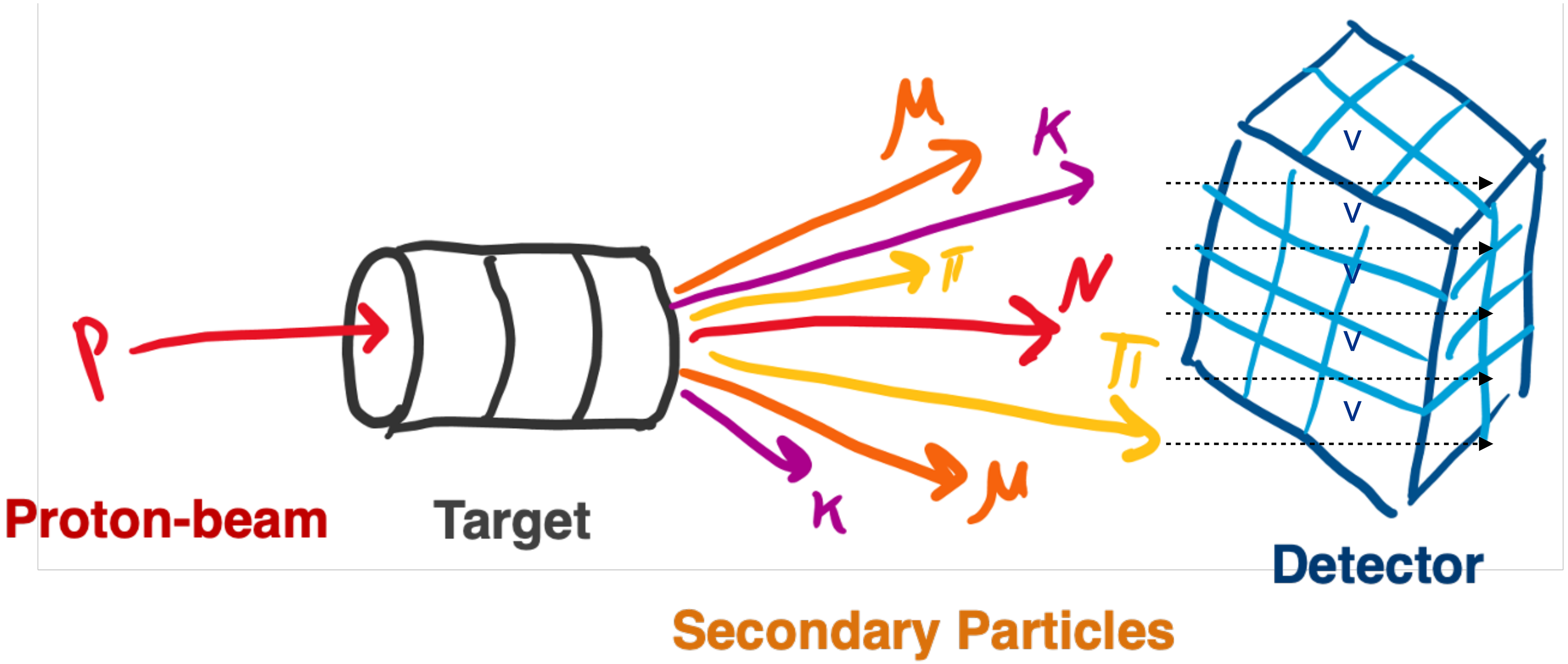


- New physics theorized to be neutral under SM forces
- A finite set of operators serve as a portal to a possible dark sector

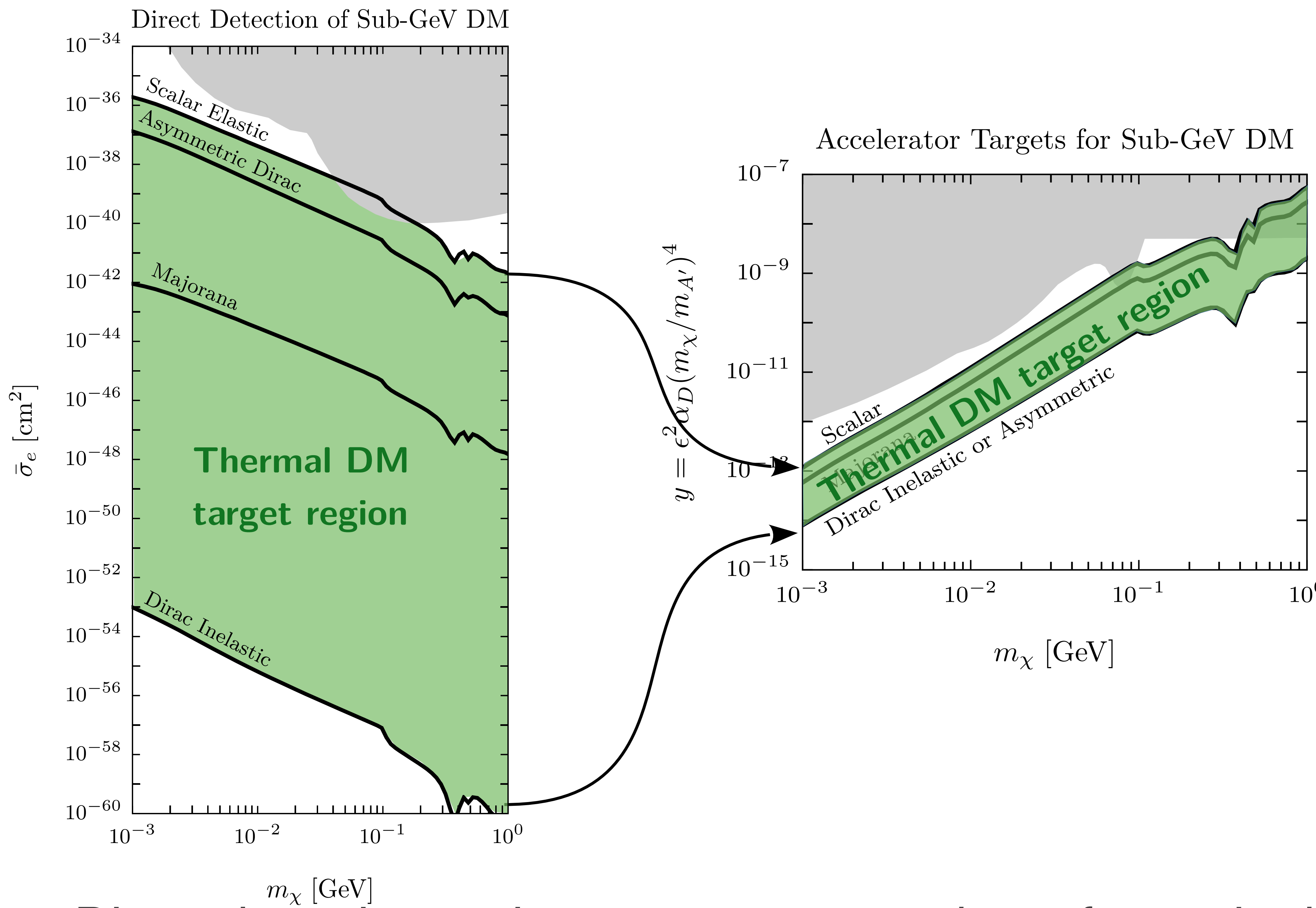
$B_{\mu\nu}$	x	$\epsilon/2\, F'^{\mu\nu}$	Vector portal
$\|h\|^2$	x	$\mu S + \lambda\|\phi\|^2$	Higgs portal
hL	x	$y_N N$	Neutrino portal

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



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

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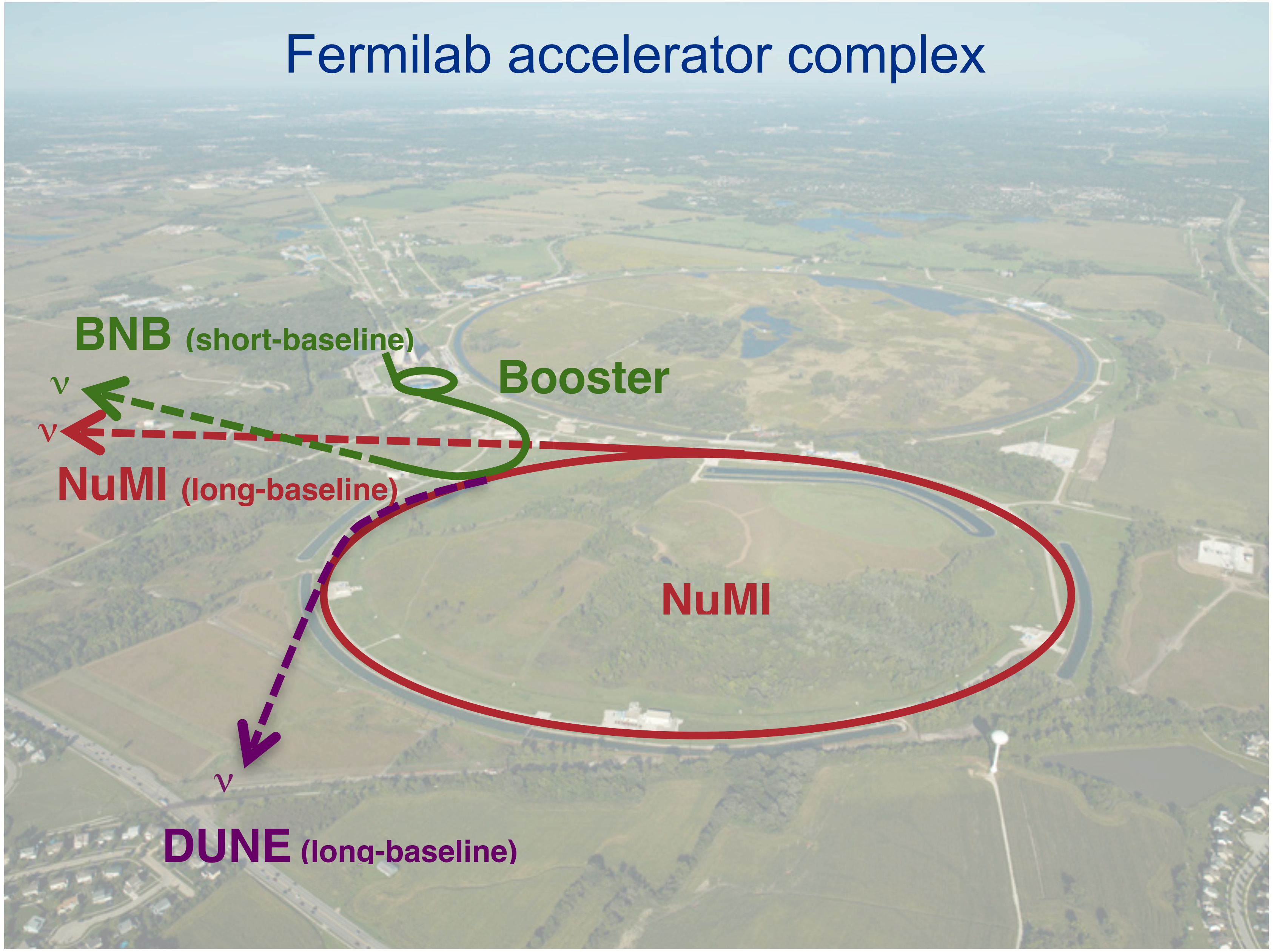
arXiv:2209.04671

The Fermilab Accelerator Complex

Current Fermilab Accelerator Complex



Current BNB beam supports short-baseline program (SBN, MicroBooNE)

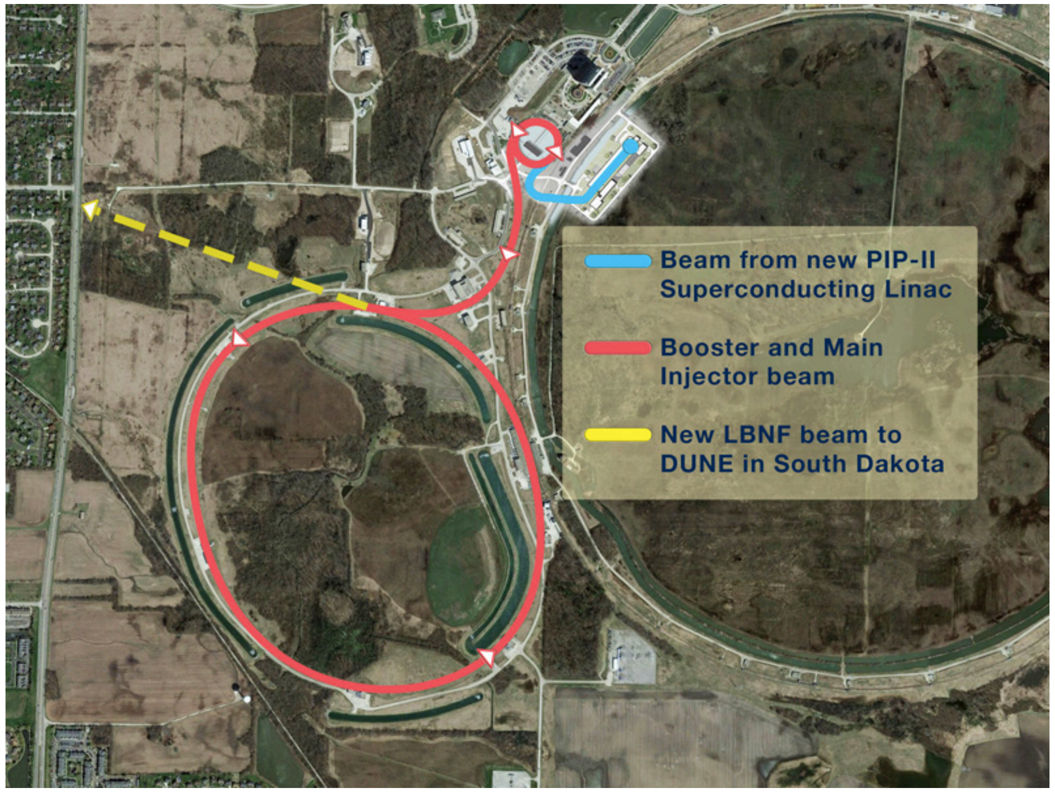
Current NuMI beam supports NOvA, SBN off-axis physics searches

Beam for DUNE under construction

Current Fermilab Accelerator Complex

The PIP-II Project

- DUNE major component of US particle physics program in next ~decade
- Upgrade to the current Fermilab accelerator complex driven by DUNE physics goals
- Among highest power ~GeV proton beams in the world
  - Capable of 1.6 MW at 800 MeV proton energy CW
  - Small percentage of protons (1.1%) needed to support DUNE
- Can we leverage existing upgrade plans to search for other exciting physics at Fermilab?
  - O(1 GeV) stopped-pion neutrino source program leveraging the available beam
  - Opportunity to build facility to maximize high-energy physics impact
  - PIP2-BD Snowmass 2022 White Paper: https://arxiv.org/pdf/2203.08079.pdf



PIP-II Layout at FNAL

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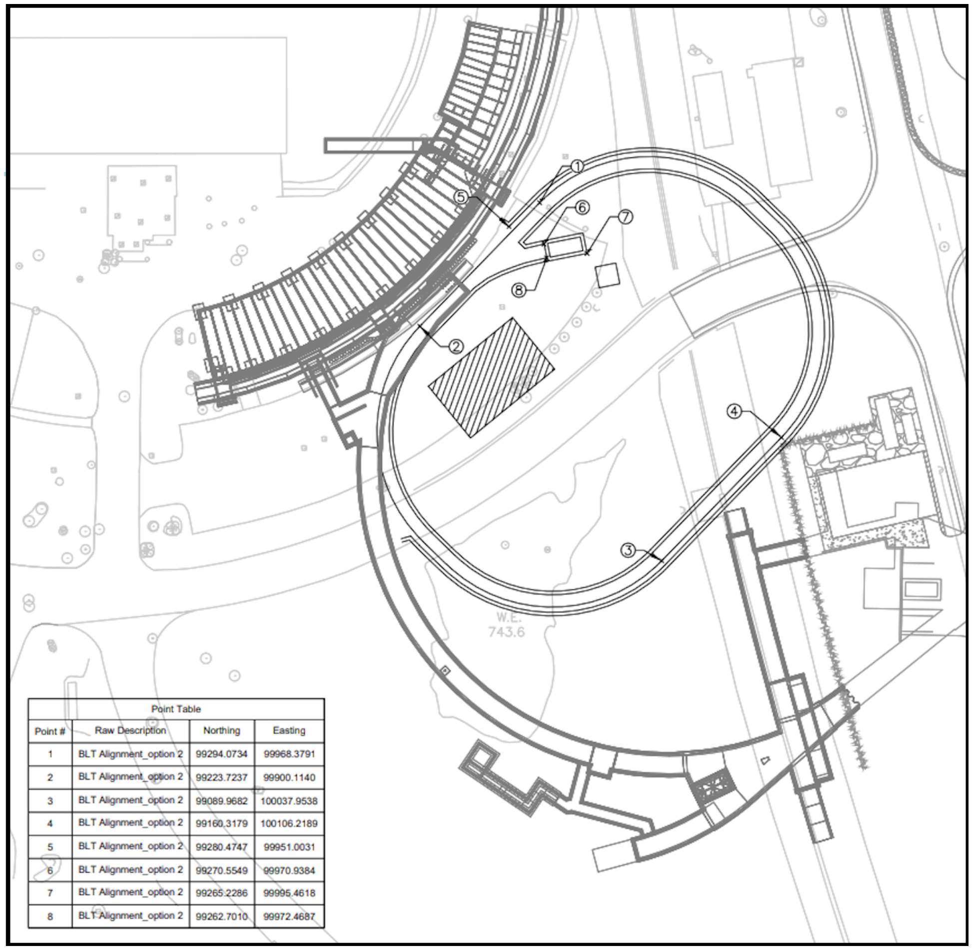
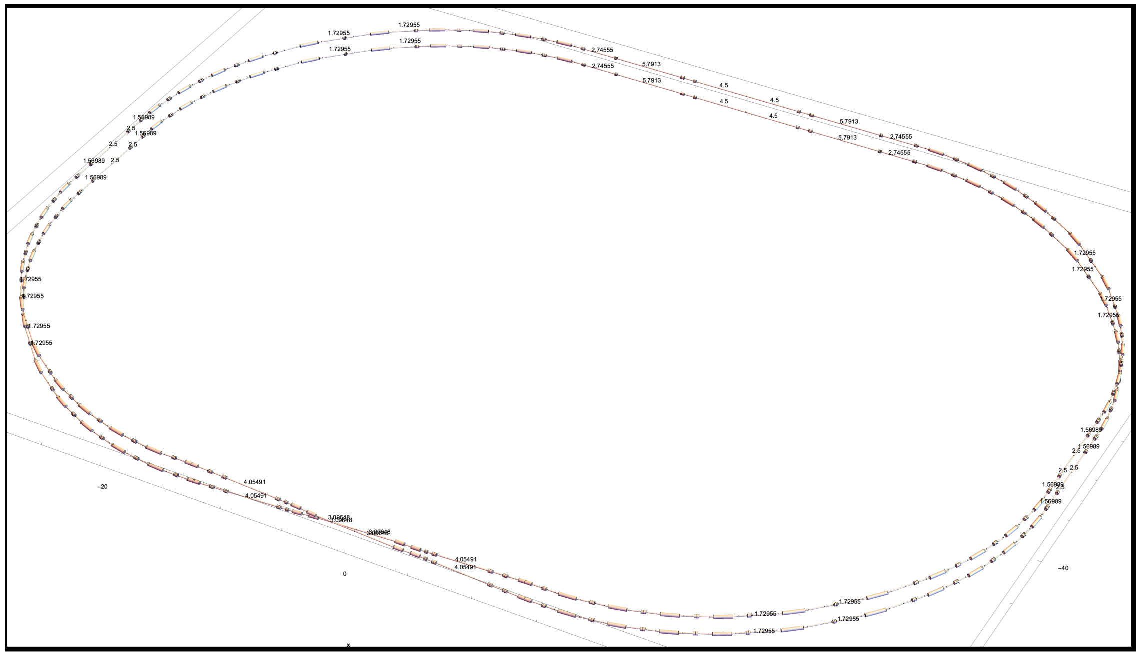
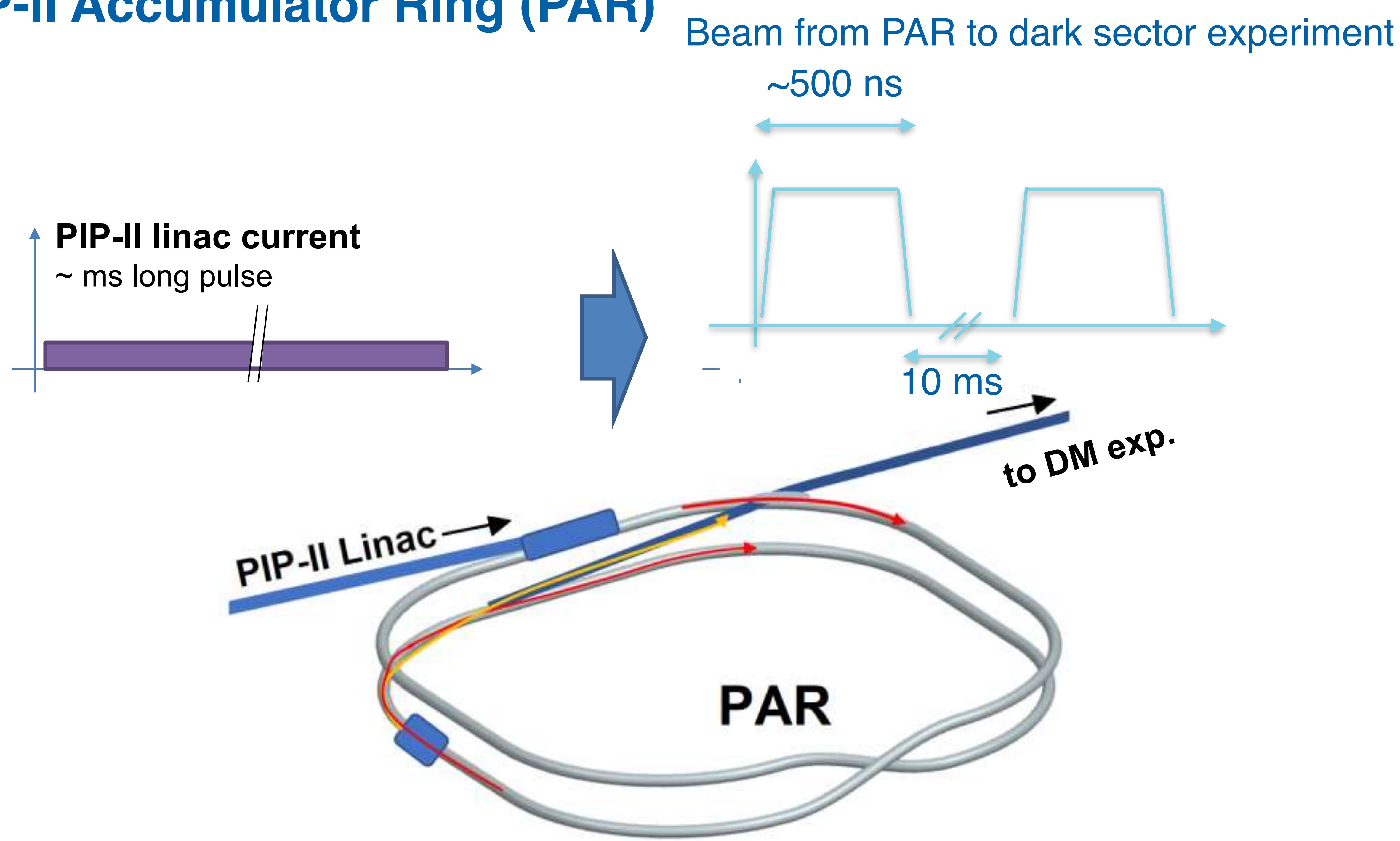
The PIP-II Accumulator Ring (PAR)

- 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





PIP-II Accumulator Ring (PAR)



Ongoing discussions at Fermilab on incorporating PAR into PIP-II civil construction

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

Stopped-pion Neutrino Sources

Creating a stopped-pion source with PIP-II: PIP2-BD

- 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

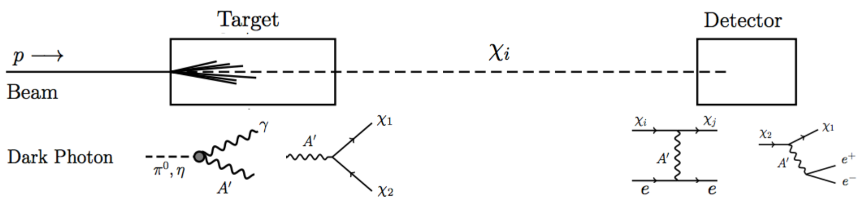
Facility	Beam Energy (GeV)	Repetition Rate (Hz)	Pulse Length (s)	Beam Power (MW)
PAR	0.8	100	$2x10^{-6}$	0.1
C-PAR	1.2	100	$2x10^{-8}$	0.09
RCS-SR	2	120	$2x10^{-6}$	1.3

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

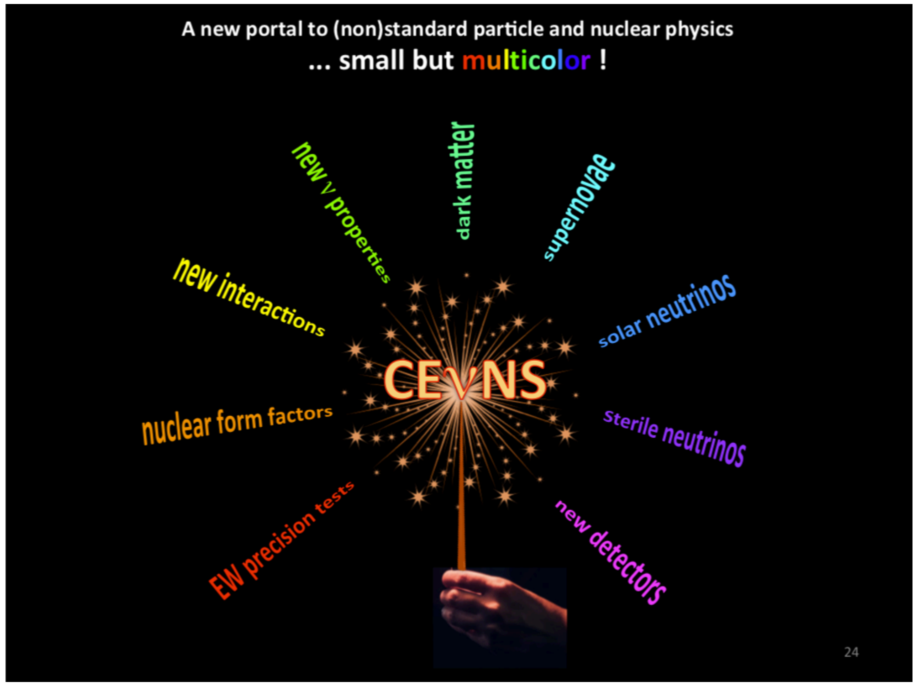
- Light dark matter (LDM) / dark sector searches
  - Decay and/or scattering signatures

Later portion of talk focusing here!

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



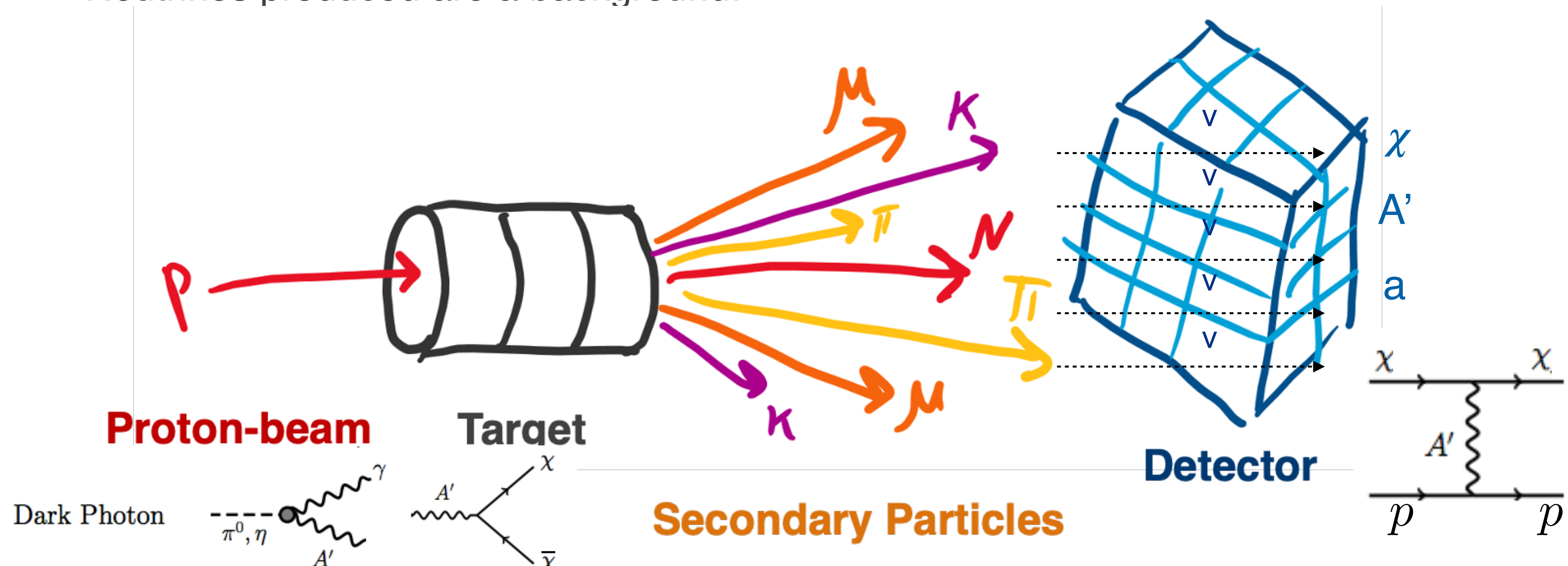
- Coherent elastic neutrino-nucleus scattering (CEvNS)
- Light Sterile Neutrino Searches
  - Both appearance and disappearance possible
- Searches for Non-standard interactions (NSIs), tests of the Standard Model
- Neutrino Cross Section Measurements
- Neutrino-Electron Scattering (LSND-like), MeV-scale



E. Lisi, NuINT 2018

Leveraging Stopped Pion Sources for Dark Sector Searches

- How do we leverage a stopped-pion neutrino source for dark sector searches?
  - Detector capable of low energy, O(10 keV) detector thresholds and reconstructing EM activity up to tens of MeV
  - 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!



Current Dark Sector Searches at Stopped-pion Neutrino Sources

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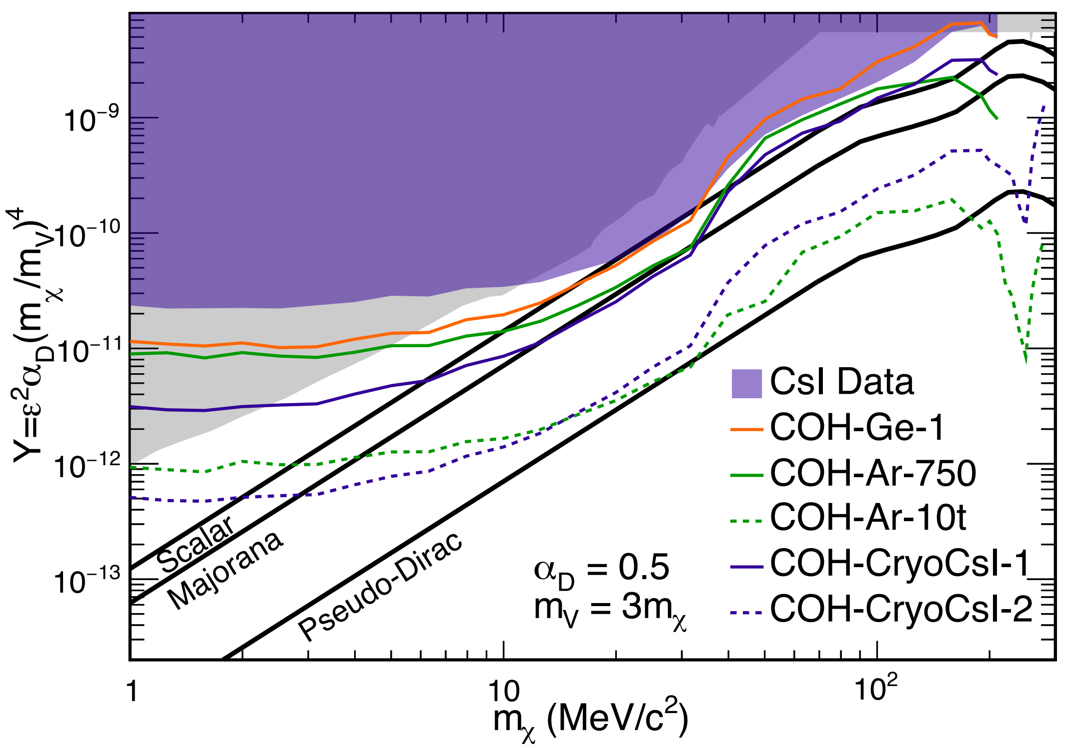
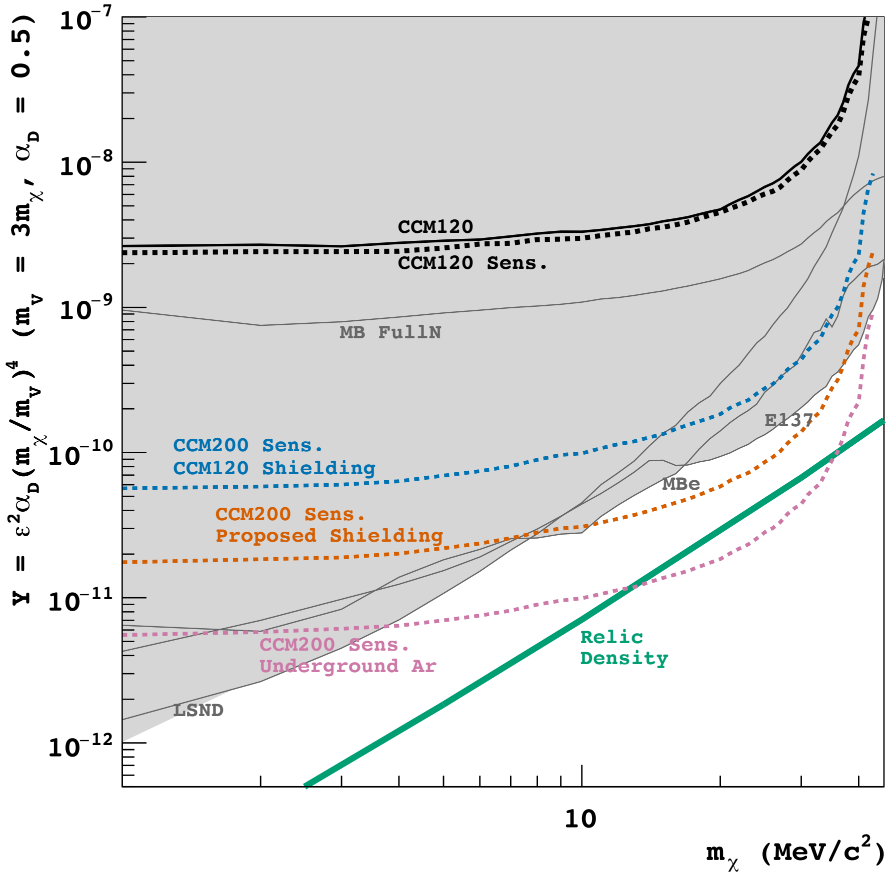
Current Accelerator-based dark sector searches

- 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
- COHERENT recently set limits on vector-portal dark matter using latest CsI[Na] data
  - See K. Scholberg's talk
- Coherent Captain-Mills (CCM) set limits with ton-scale single-phase liquid argon detector at Lujan beam at Los Alamos National Laboratory
  - See R. Van de Water's talk



arXiv:2110.11453v1[hep-ex]

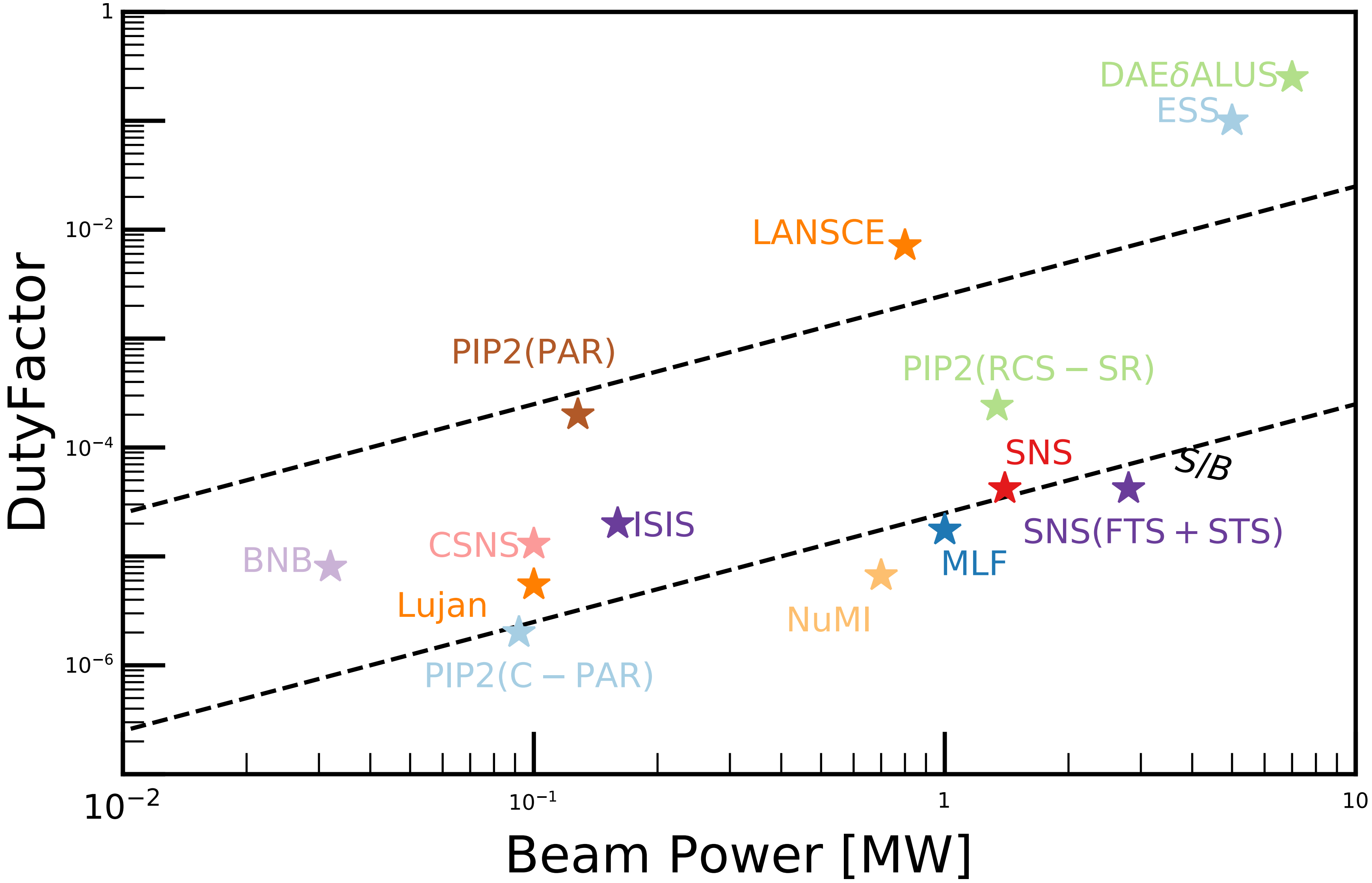
Phys. Rev. Lett 130, 051803 (2023)



Phys. Rev. D 106, 012001 (2022)

Future Stopped-pion Sources for Dark Sector Experiments

- SNS planned proton power upgrade in near future, second target station (STS)
  - See K. Scholberg's talk on future opportunities at the ORNL STS
- European Spallation Source, 2 MW with large duty factor

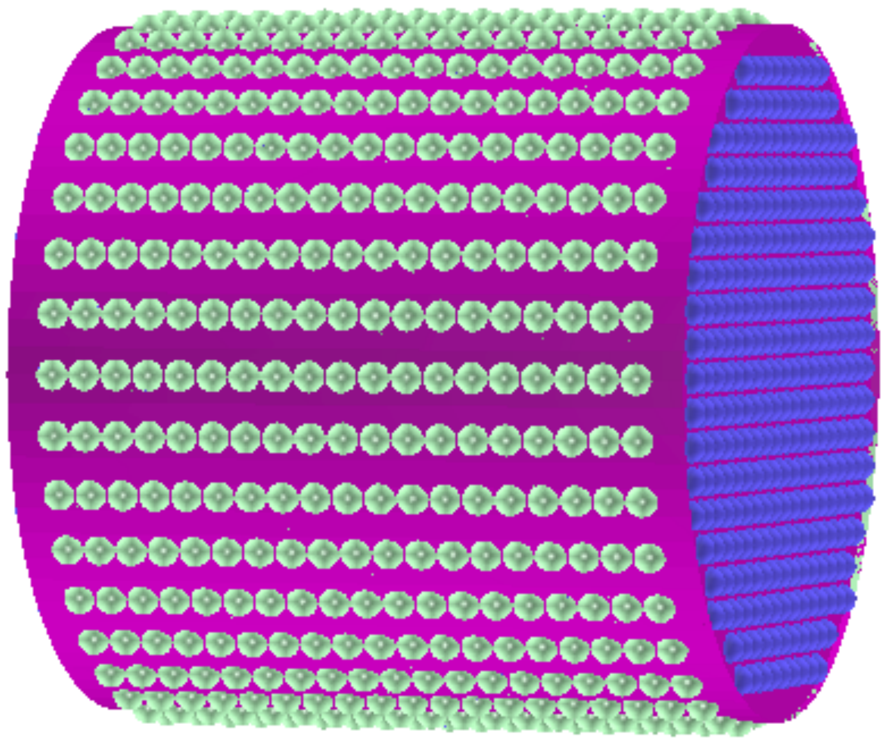


arXiv:2209.07480

The PIP2-BD Detector

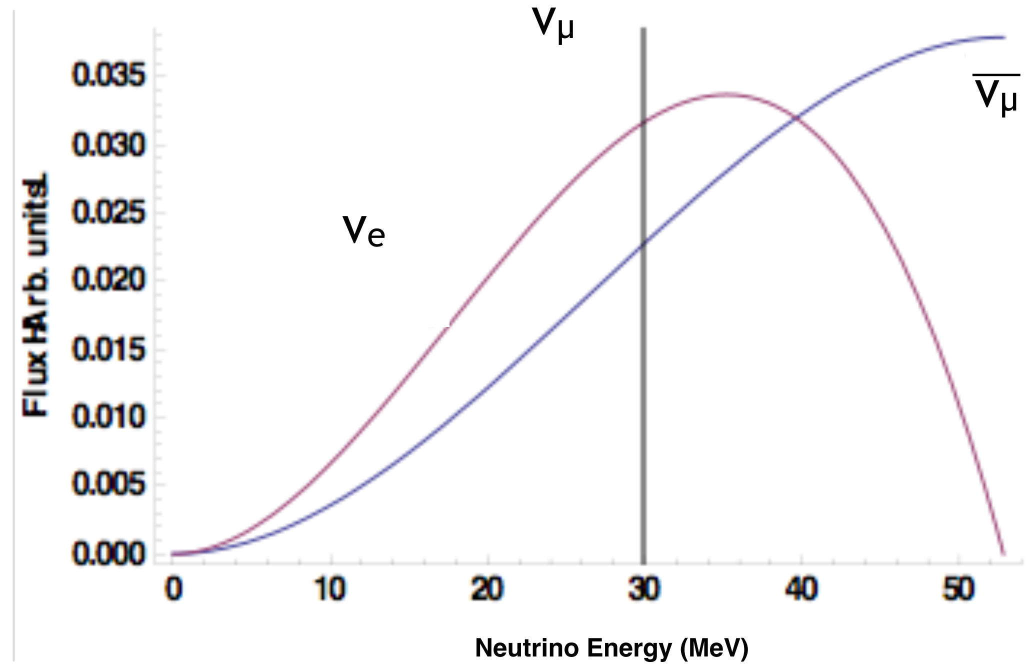
Proposed Detector at PIP-II

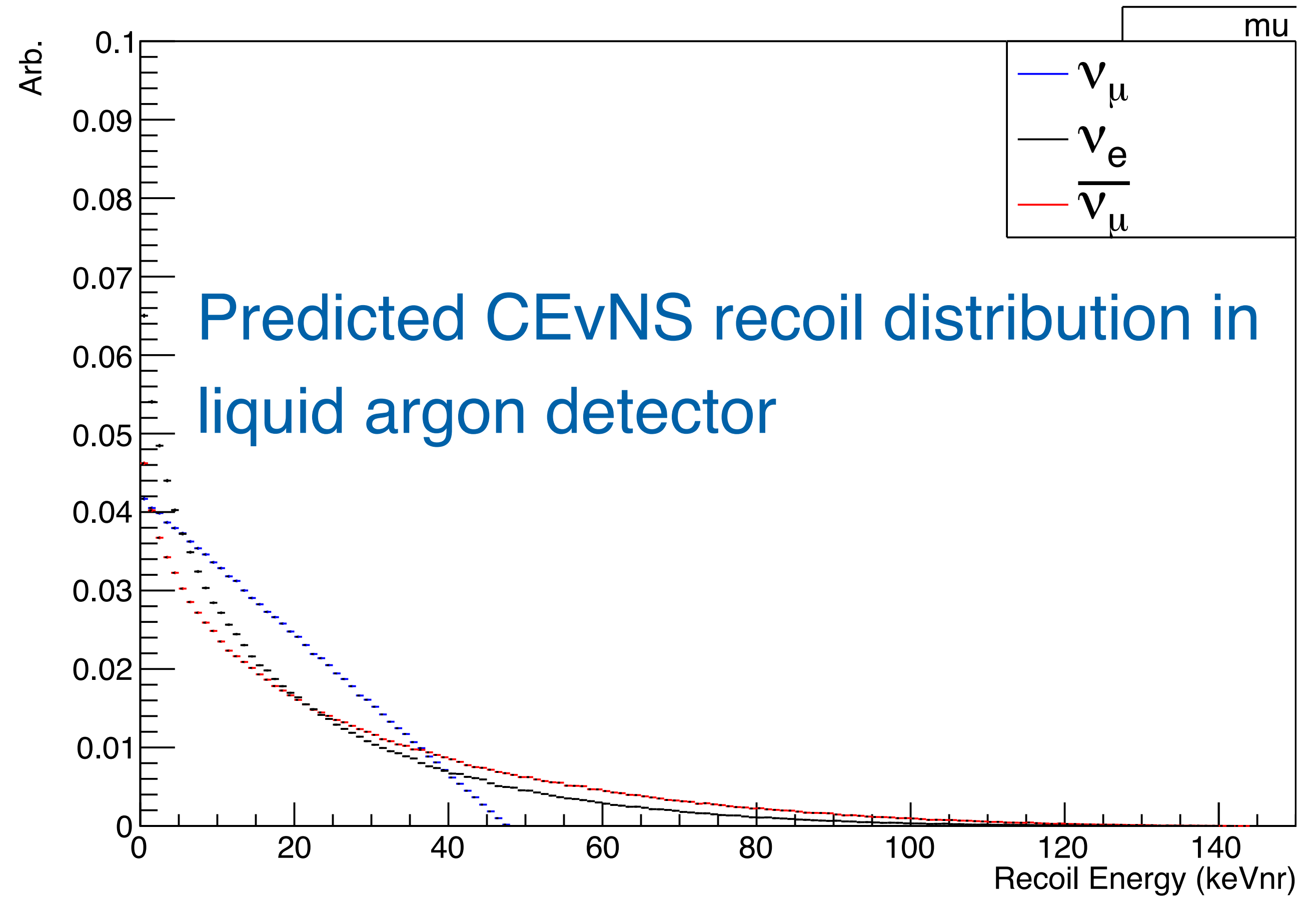
- Single-phase, scintillation only liquid argon (LAr) detector
- Fiducial volume - 4.5 m right cylinder inside box, **~100 tons LAr**
- Surround sides and endcaps of detector volume with TPB-coated 8” PMTs
  - TPB-coated reflector on sides and endcaps for photocoverage gaps
- Preliminary simulations suggest 20 keVnr threshold achievable with this detector
- Existing experiments such as COHERENT and CCM are key for testing many of the experimental techniques to successfully reach the physics goals of a 100-ton scale detector
- Fermilab-funded LDRD to study dark sector searches at proposed stopped-pion facility using PIP-II



Liquid Argon (LAr) for Dark Sector and other new physics detection

- Large scintillation yield of 40 photons/keV
- Well-measured quenching between nuclear recoil and scintillation response
- Strong pulse-shape discrimination (PSD) capabilities for electron/ nuclear recoil separation
- Move toward precision physics and new physics searches with large detectors





Predicted CEvNS recoil distribution in liquid argon detector

M. Toups et al., arXiv:2203.08079

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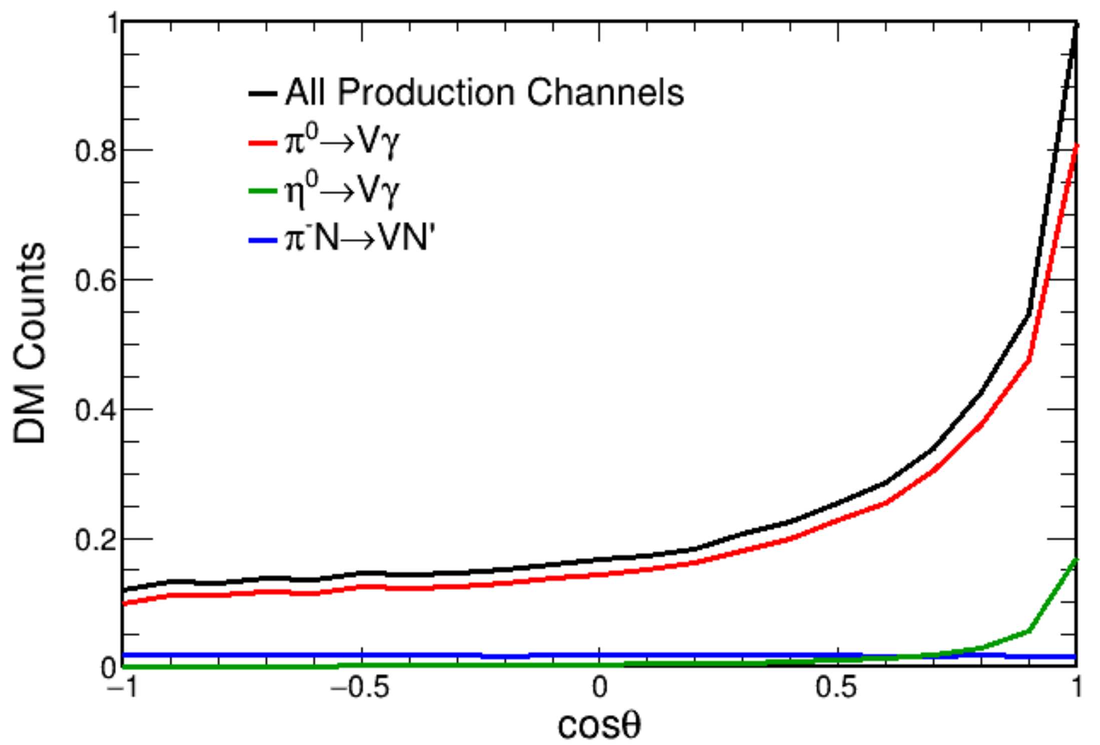
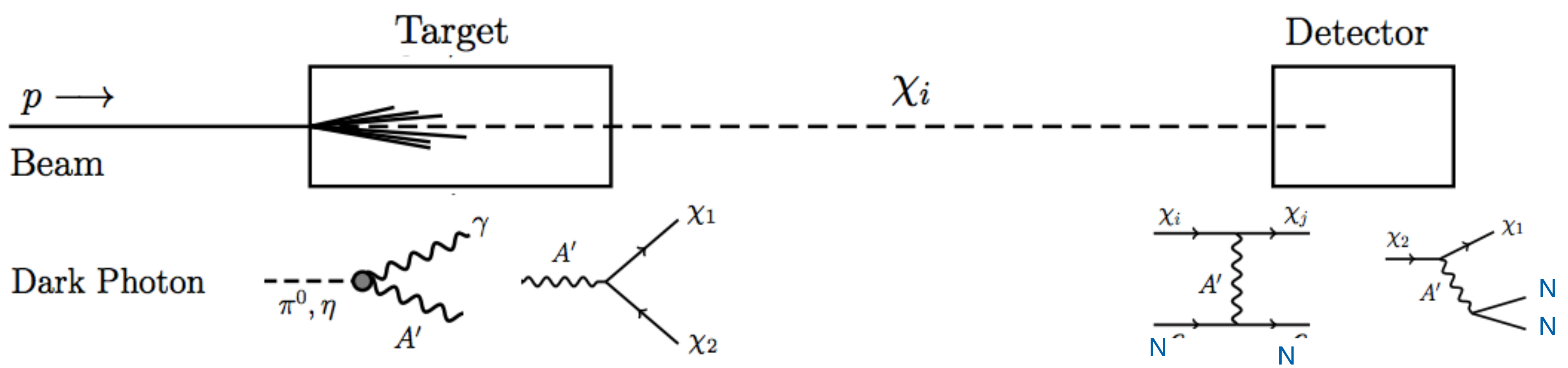
Dark Sector Searches with PIP2-BD

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

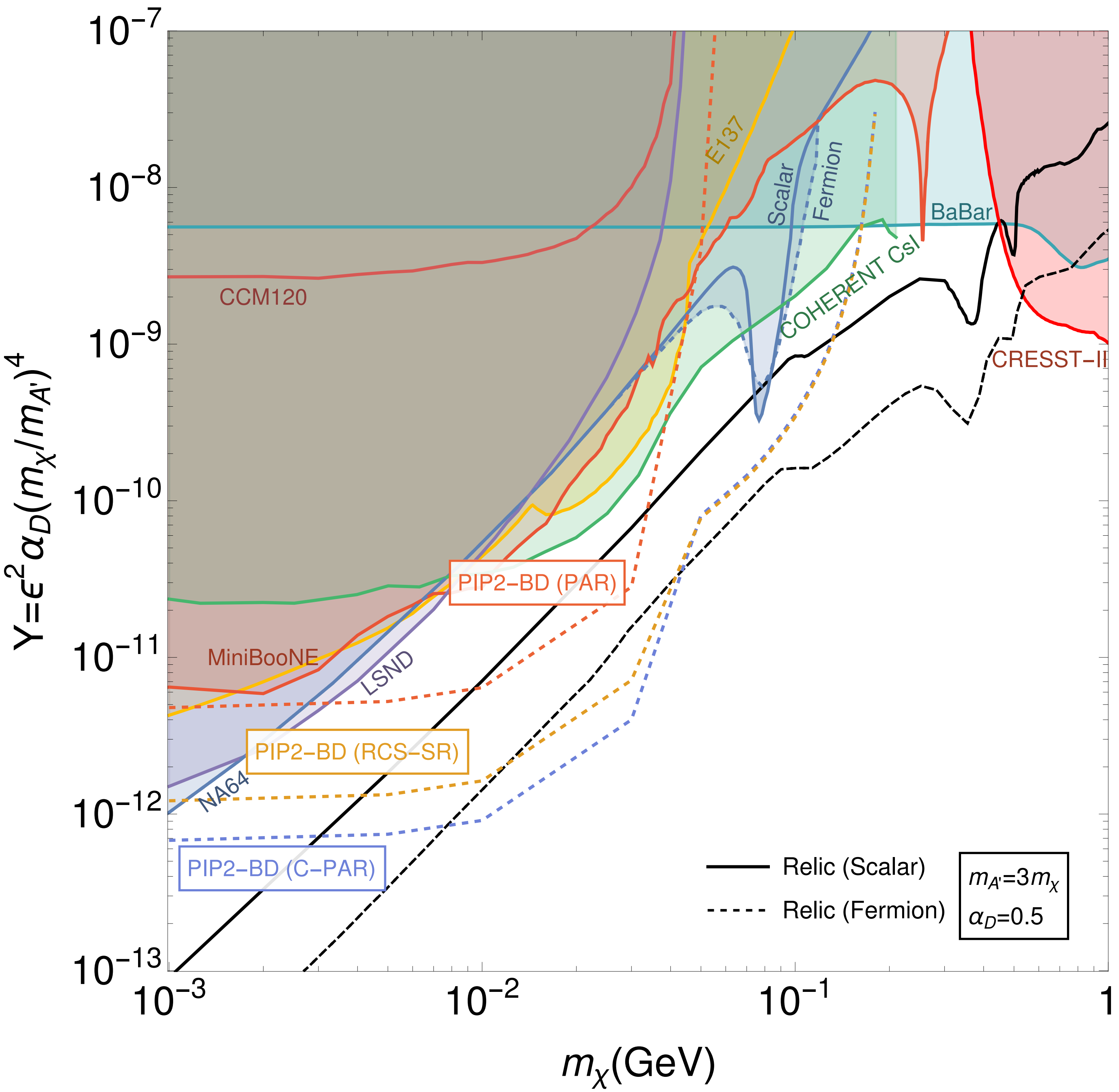


P. deNiverville et al., Phys. Rev. D 92 (2015) 095005

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

PIP2-BD Vector Portal Dark Matter Search

- LDM produced by proton collisions with fixed target
- Detector located on axis, 18 m downstream from target
- Backgrounds simulated using custom Geant4-based simulation
- DM production generated using BdNMC code (Phys. Rev. D 95, 035006 (2017))
- 5 year run for each accelerator scenario
- Sensitivity of detector to MeV-scale physics allows additional sensitivity at low-DM masses via DM-electron scattering



M. Toups et al., arXiv:2203.08079

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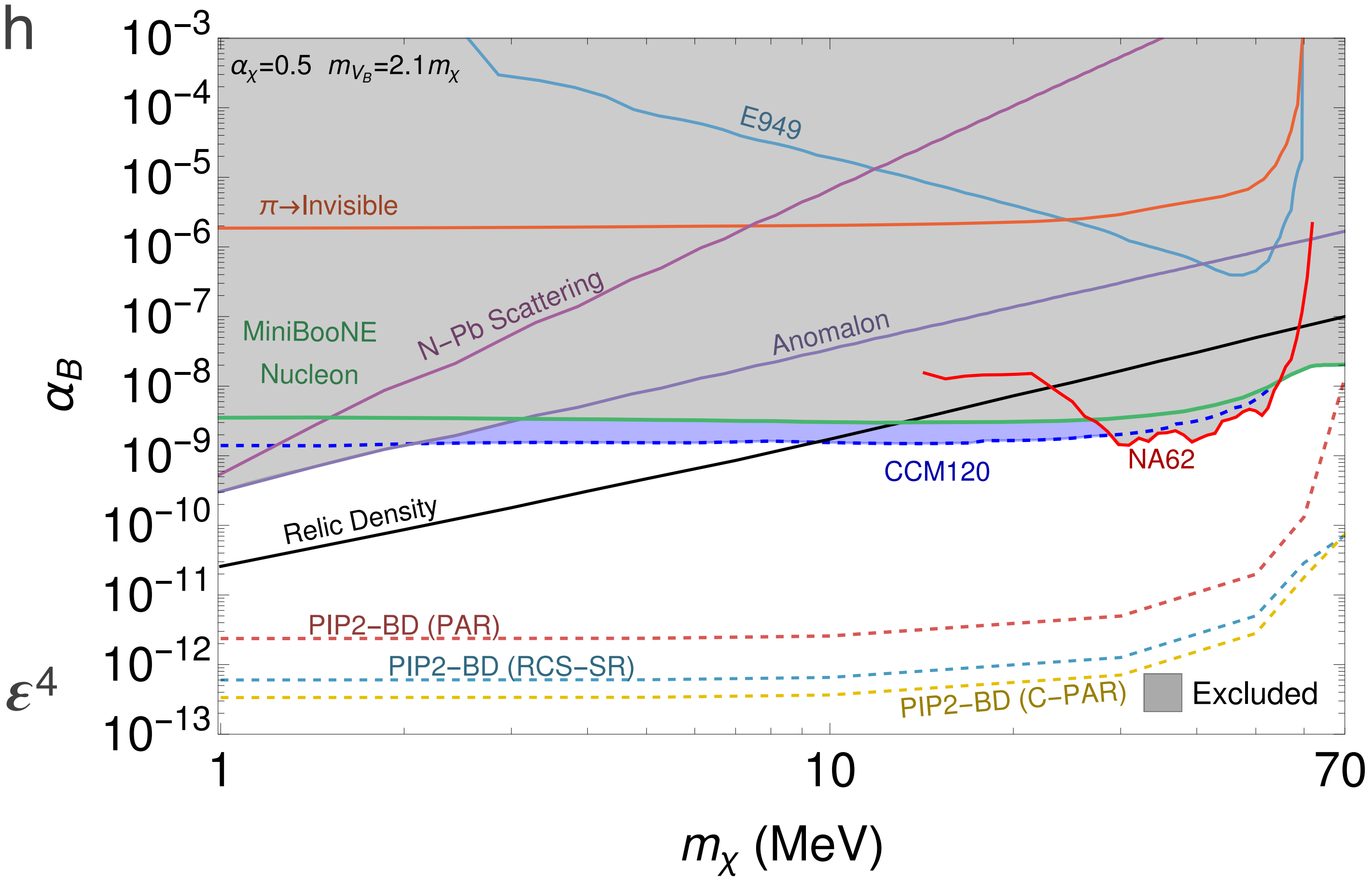
PIP2-BD Leptophobic DM Search

- Dark sector model couples to quarks rather than leptons
  - Example dark matter scenario for which proton beam searches provide robust sensitivity

$$\mathcal{L}_B \supset -A^\mu_B(g_B J^B_\mu + g_\chi J^\chi_\mu + \varepsilon_B e J^{\mathrm{EM}}_\mu)$$

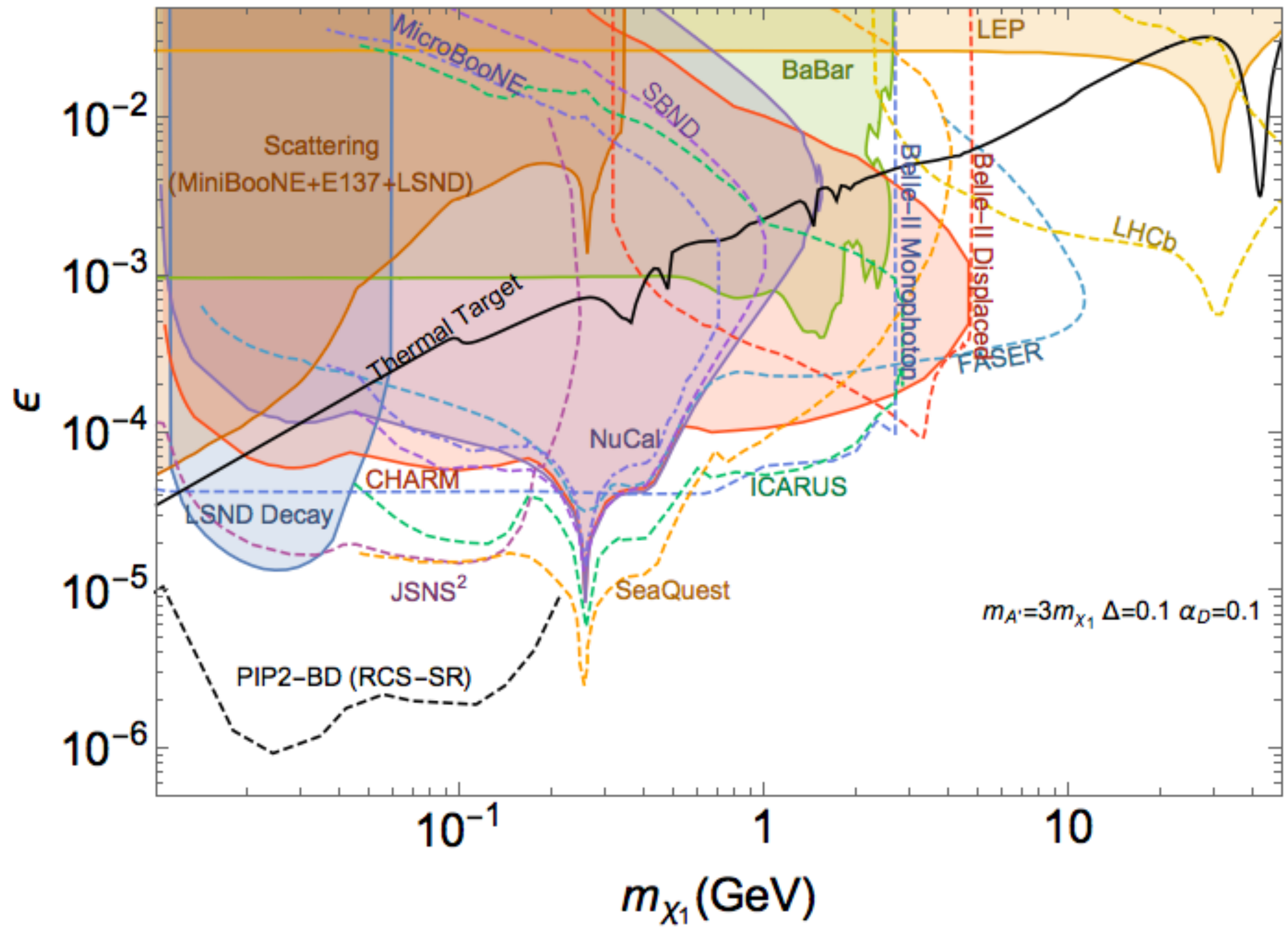
- Model predicts the same DM nuclear recoil energy distributions as the vector-portal model
  - Rate scales with $\alpha_\chi\, \alpha^2_B$ as opposed to ε^4
- Same procedure to compute 90% C.L. as for vector-portal model
- 5 year run with the 3 accelerator scenarios



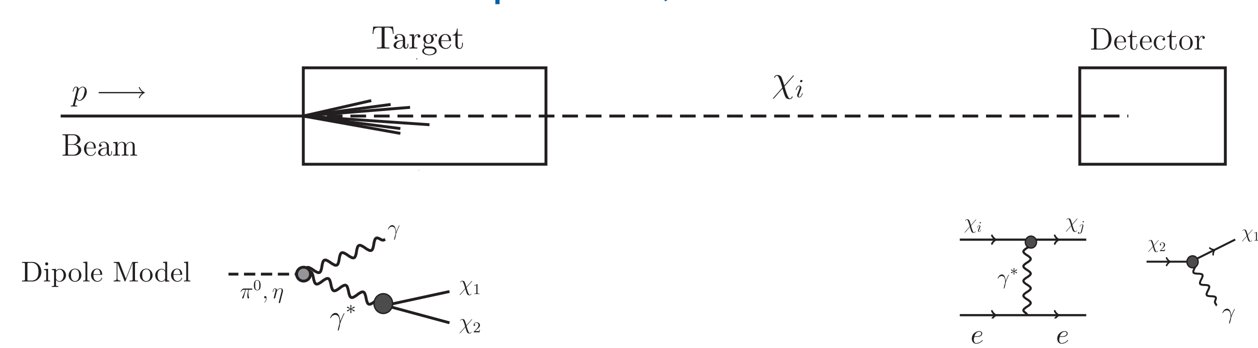
M. Toups et al., arXiv:2203.08079

PIP2-BD Inelastic dark matter search

- Extend minimal vector portal scenario to include two DM particles χ_1 and χ_2
- Require $\Delta = (m_{\chi_2} - m_{\chi_1})/m_{\chi_1} > 0$
- Possibility of χ_2 decay into e+e-
- If decay not kinematically allowed, DM observation also possible through its up- or down-scattering off of electrons in the detector
- Plot 3 event sensitivity through BdNMC for 5 years of data taking
  - Expected backgrounds not yet quantified



M. Toups et al., arXiv:2203.08079



Phys. Rev. D **98**, 075020 (2018)

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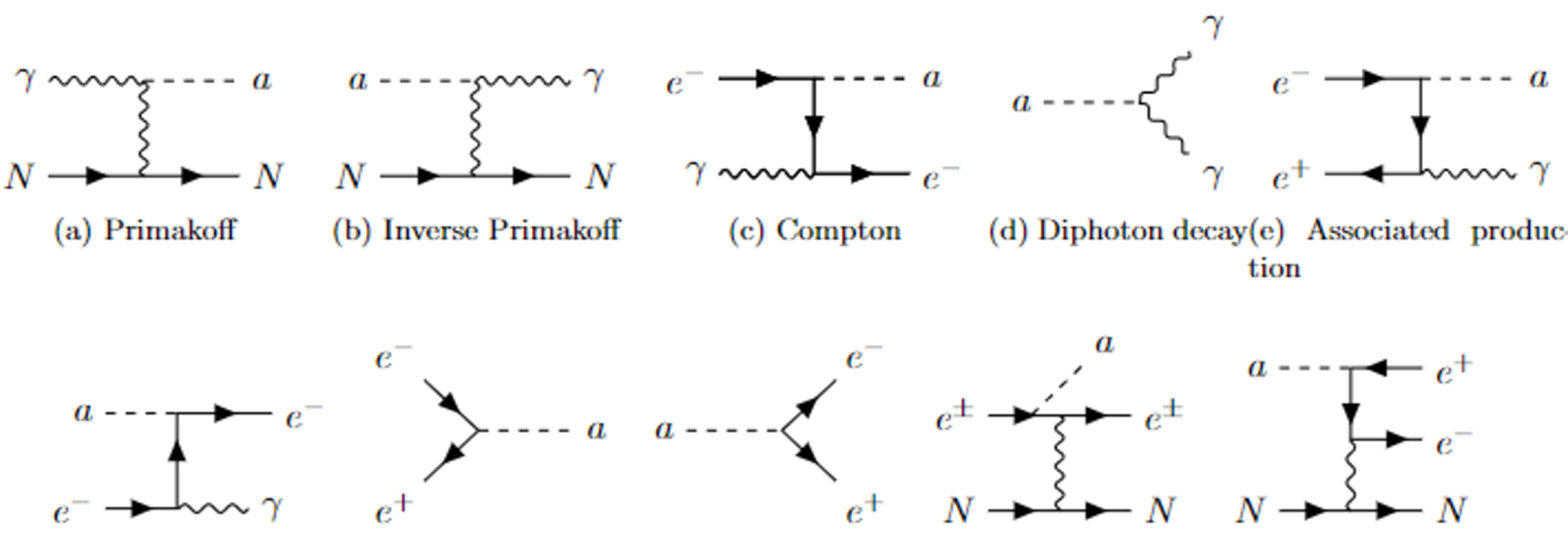
Axion-like particle (ALP) searches with PIP2-BD

- 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-



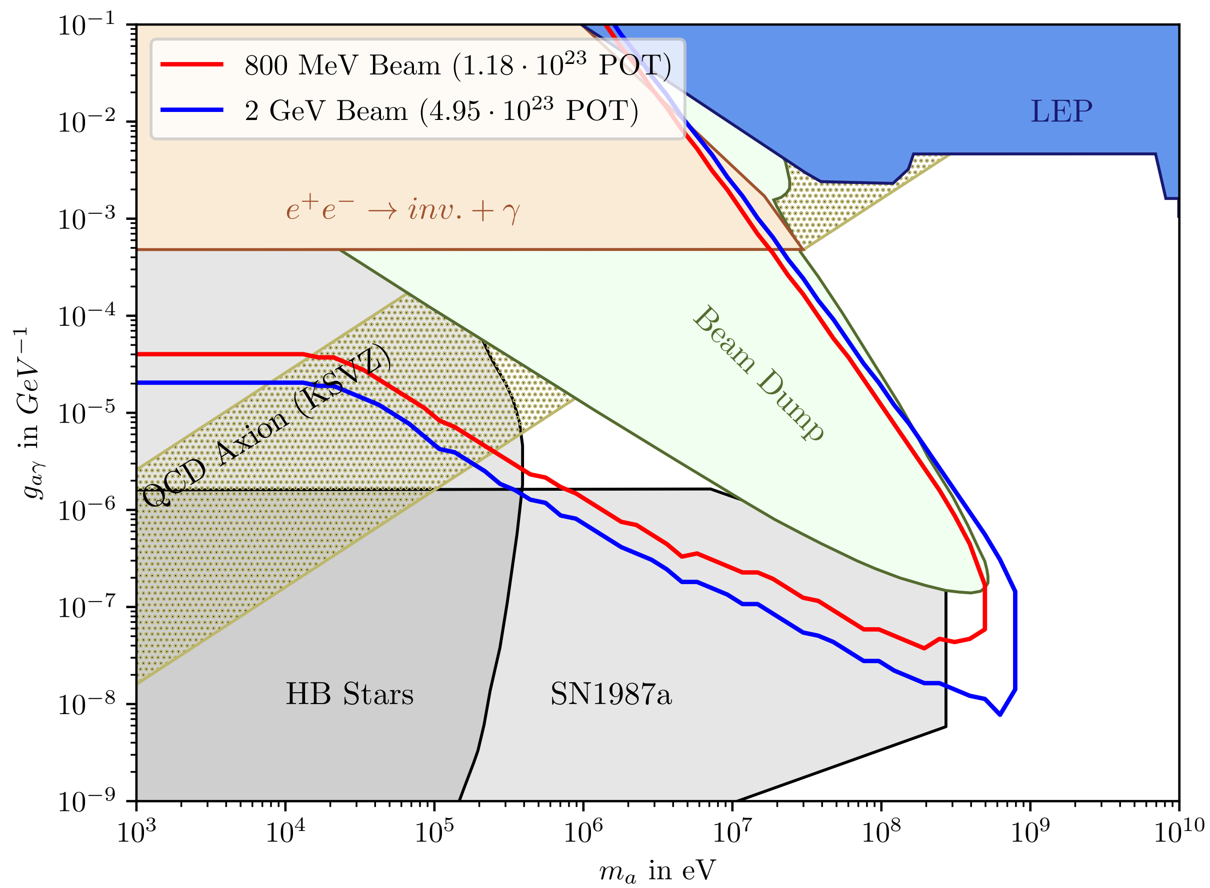
(a) Primakoff (b) Inverse Primakoff (c) Compton (d) Diphoton decay (e) Associated production

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

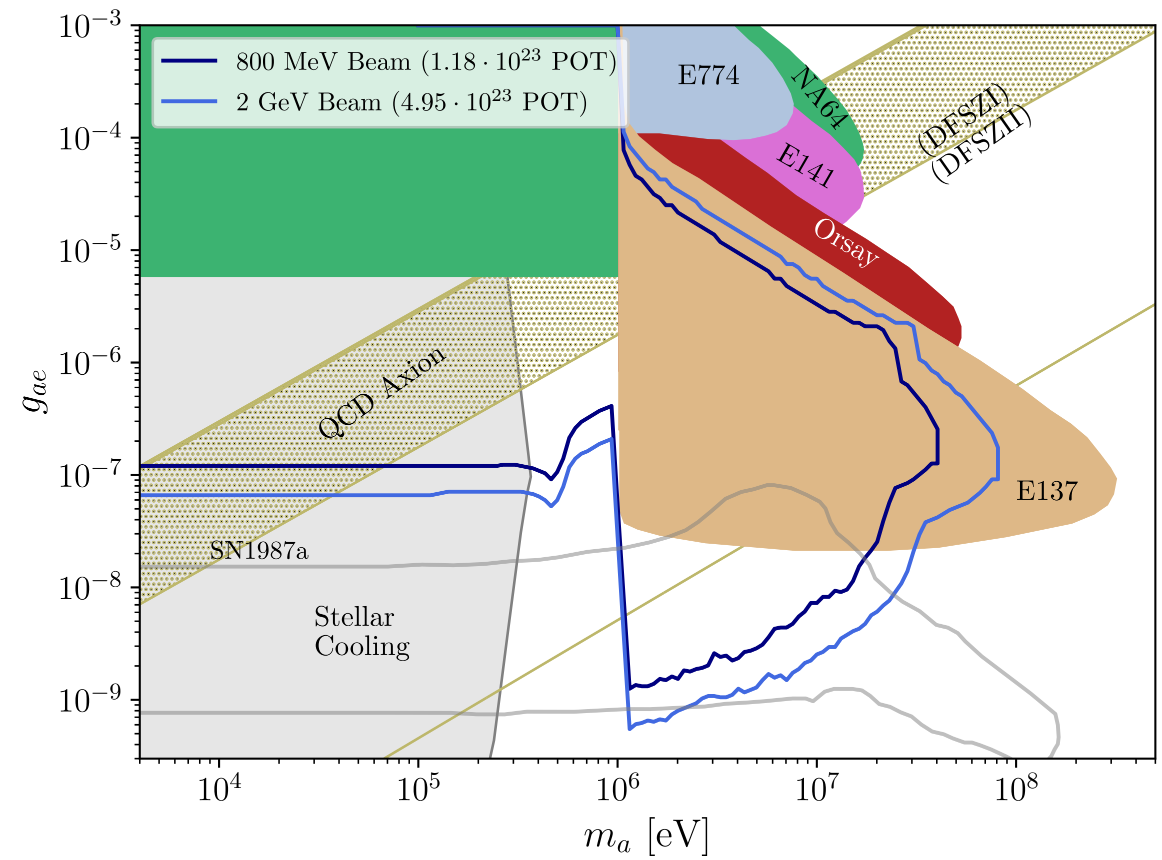
arXiv:2112:09979

PIP2-BD Axion-like particles (ALP) search

- For PIP2-BD, obtain photon flux and e+/e- flux produced in the target above 100 keV
- Compute background-free event sensitivities
- 75% efficiency assumed based off of search using the Coherent Captain-Mills (CCM) experiment (arXiv:2112.09979)



ALPs coupling to photons



ALPs coupling to electrons

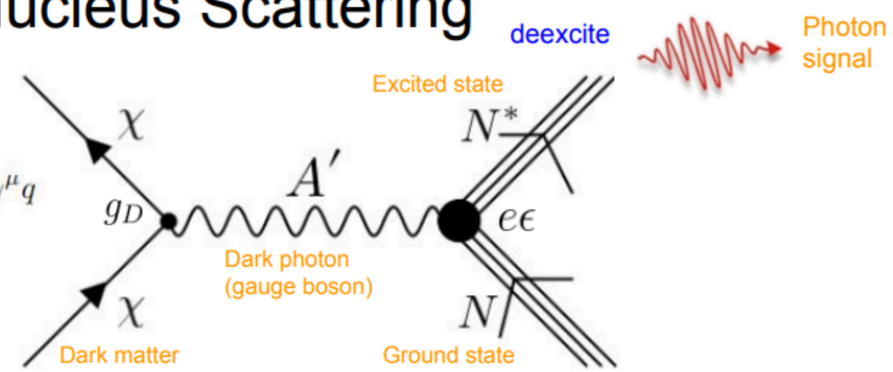
A. Thompson, A. Karthikeyan, B. Dutta, TAMU

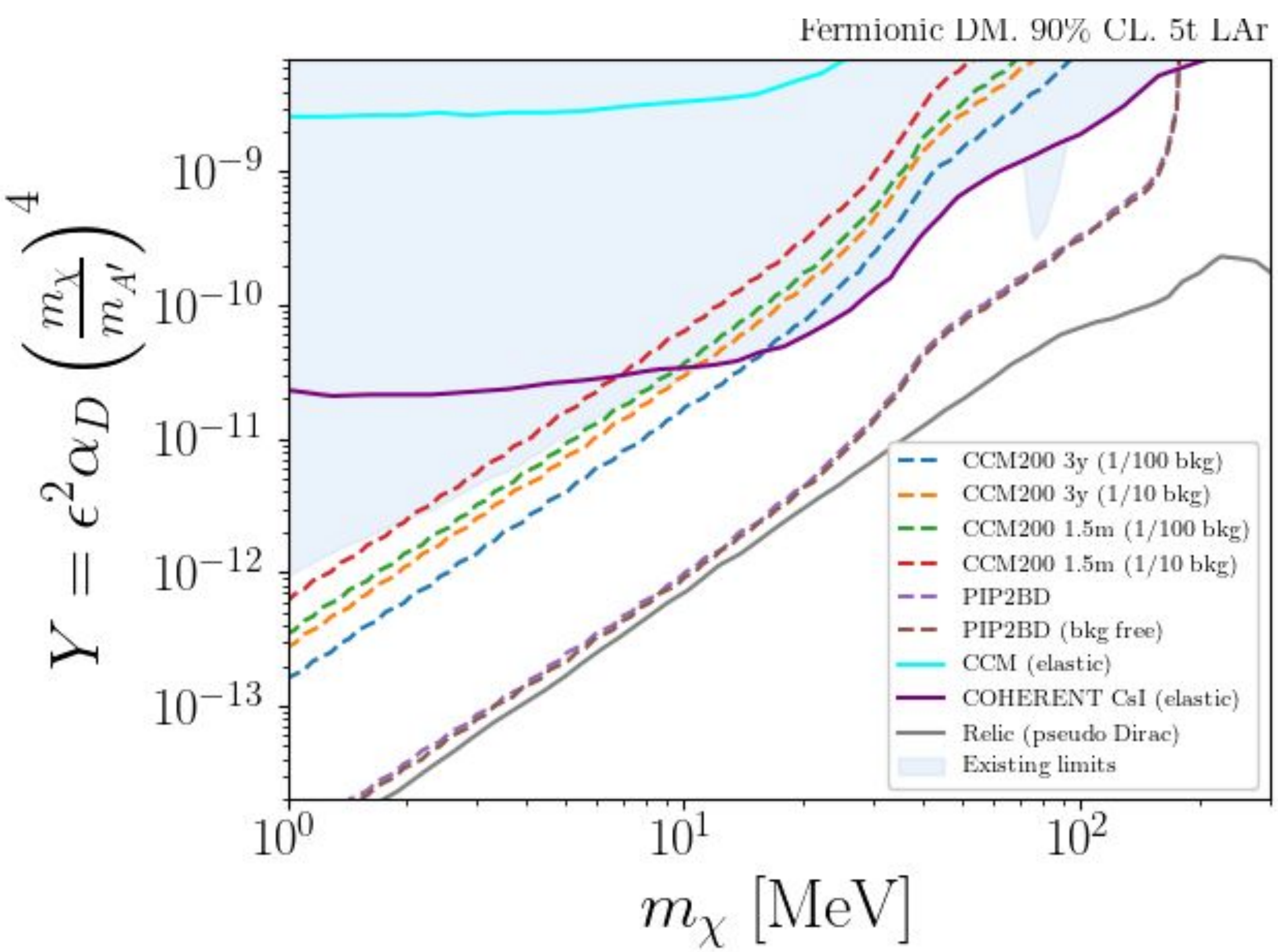
Other Searches with PIP2-BD

Inelastic DM-Nucleus Scattering

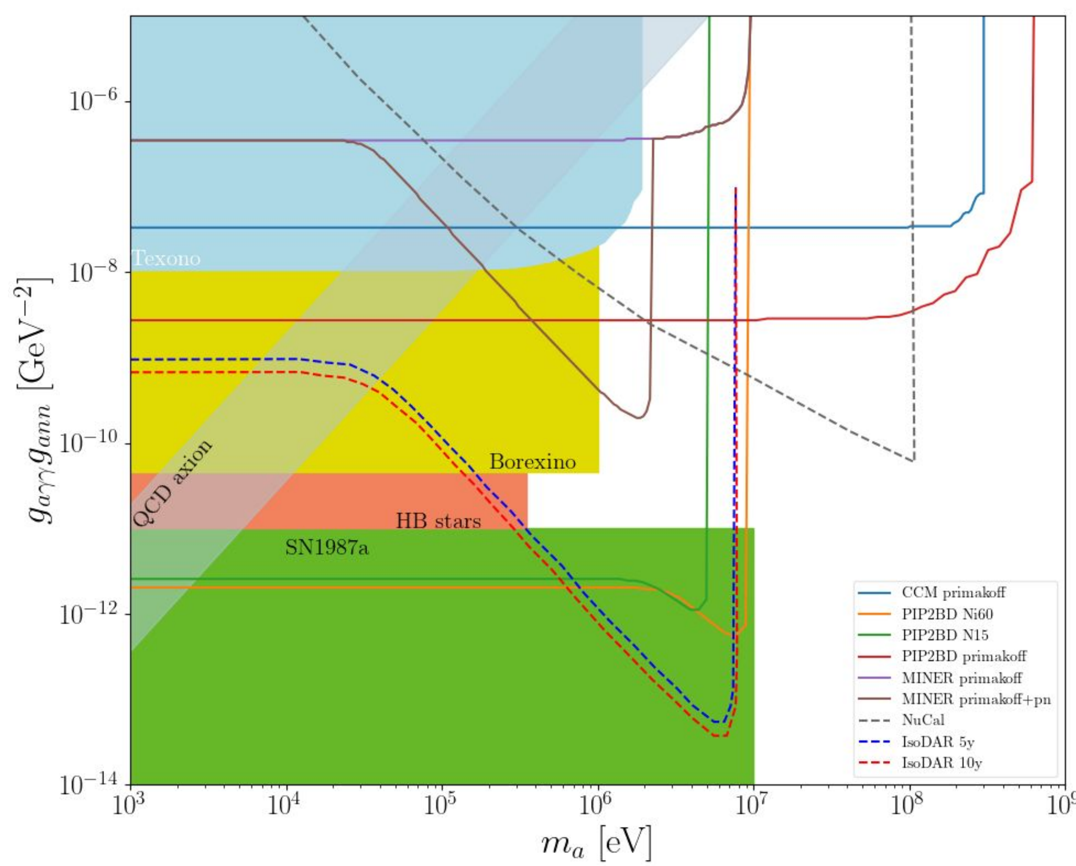
$\mathcal{L} \supset g_D A'_\mu \bar{\chi}\gamma^\mu \chi + e\epsilon Q_q A'_\mu \bar{q}\gamma^\mu q$

Chi is fermionic DM, similarly we can also consider scalar DM





Axion Searches



W. C. Huang, this workshop

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
- **With PIP2-BD, we can create a stopped-pion physics program with a facility optimized and dedicated to HEP searches**
  - **PIP2-BD could also be seen as one of a suite of co-located detectors**
- Preliminary studies using a 100 ton liquid argon detector show the ability for leading probes on accelerator-produced dark sector model searches

Join us for a workshop on these topics!

- We are holding a workshop to discuss physics opportunities with the PIP-II accelerator and beyond at Fermilab from May 10-12!
  - Discussion is **not** restricted only to what I presented here. All ideas, experiment and theory, are welcome!
  - **Register here by April 28: https://indico.fnal.gov/event/59430/**

Physics Opportunities at Beam Dump Facility in PIP-II and Beyond

May 10, 2023, 12:00 AM → May 13, 2023, 11:59 PM America/Chicago

Jacob Zettlemoyer (Fermilab), Jaehoon Yu (University of Texas at Arlington), Juan Vigil, Matthew Toups

Description This workshop is to explore physics opportunities, including dark sector particle (DSP) searches, at PIP-II beam dump and future facilities. The PIP-II Linac at Fermilab is capable of accelerating up to 2 mA of protons to 800 MeV and is a fundamental element in providing a large flux of neutrinos essential for precision measurements at future long-baseline neutrino experiments. The large proton current that will be provided by the PIP-II Linac and the proton interactions in the beam dump also provide an excellent opportunity to search for dark sector particles produced via various portals. The aim of this workshop is to discuss the potential for DSP searches and other physics opportunities that can take full advantage of the beam power of this facility. We anticipate that a white paper will be produced at the end of the workshop. The workshop will be held from 1 pm CDT on Wednesday, May 10 and run through 12 pm CDT on Friday, May 12.

Thank you!

Questions?

Backup

Sterile neutrino searches with PIP2-BD

- Two identical, O(100 ton) detectors at L = 15 m and L = 30 m from target
- Optimize facility to reduce beam-correlated backgrounds to negligible levels
- Assume 1:1 signal/background for remaining beam-uncorrelated backgrounds
- Off-axis
- 630 kW beam power at 800 MeV, 75% uptime
- 20 keVnr threshold with 70% efficiency above threshold
- 9% normalization systematic uncertainty correlated between two detectors
  - 36 cm path length smearing

Sterile neutrino searches with PIP2-BD

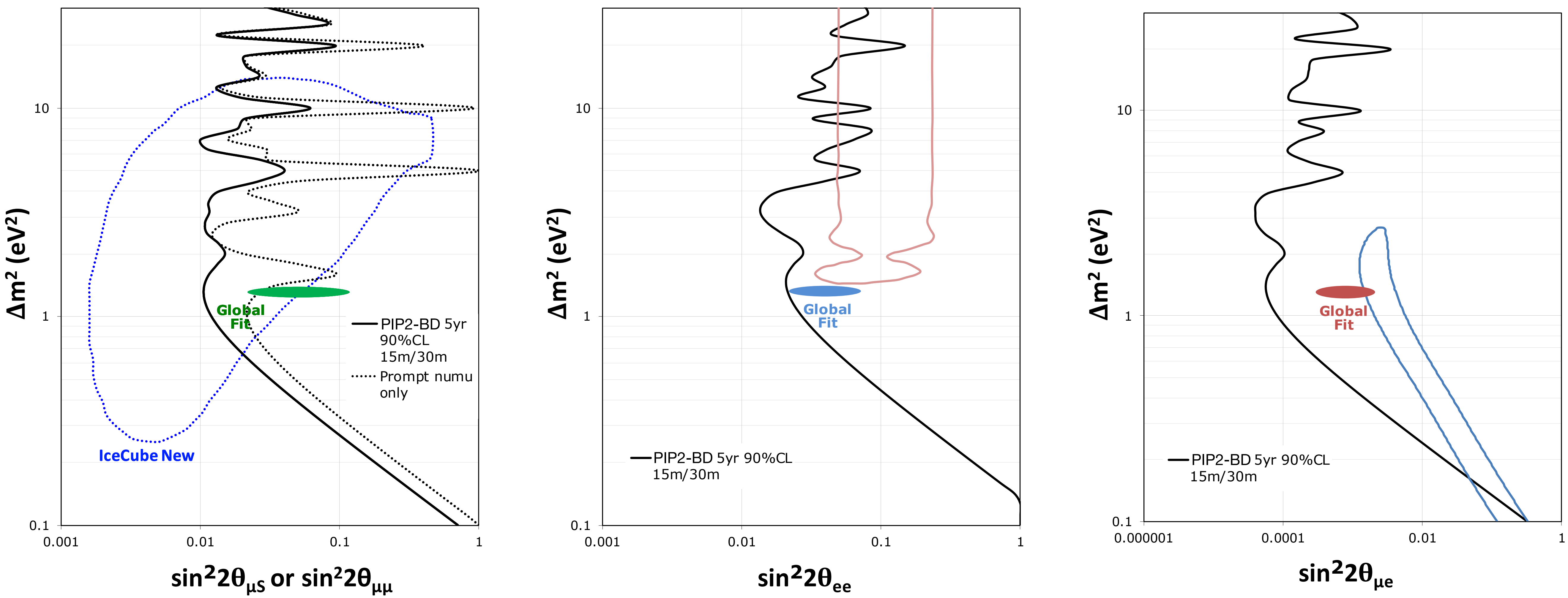


FIG. 13. PIP2-BD 90% confidence limits on active-to-sterile neutrino mixing compared to existing ν_μ disappearance limits from IceCube [45] and a recent global fit [46], assuming a 5 year run (left). Also shown are the 90% confidence limits for ν_μ disappearance (left), ν_e disappearance (middle), and ν_e appearance (right), assuming the $\bar{\nu}_\mu$ and ν_e can be detected with similar assumptions as for the ν_μ.

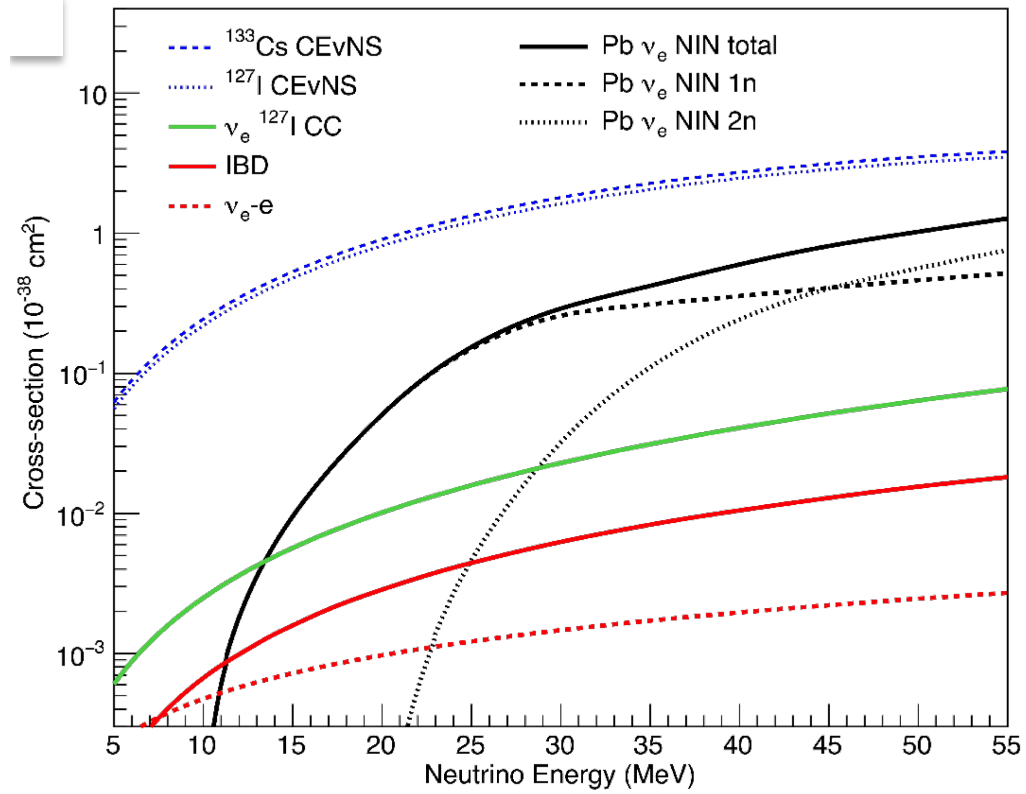
Requires separation of prompt, delayed neutrinos!

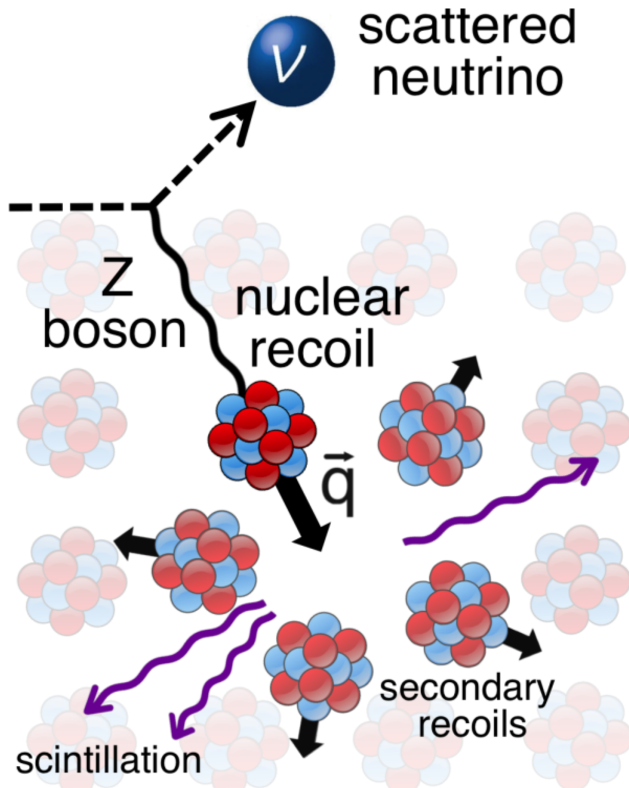
Coherent Elastic Neutrino-Nucleus Scattering (CEvNS)

- 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 N² dependence of cross section

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

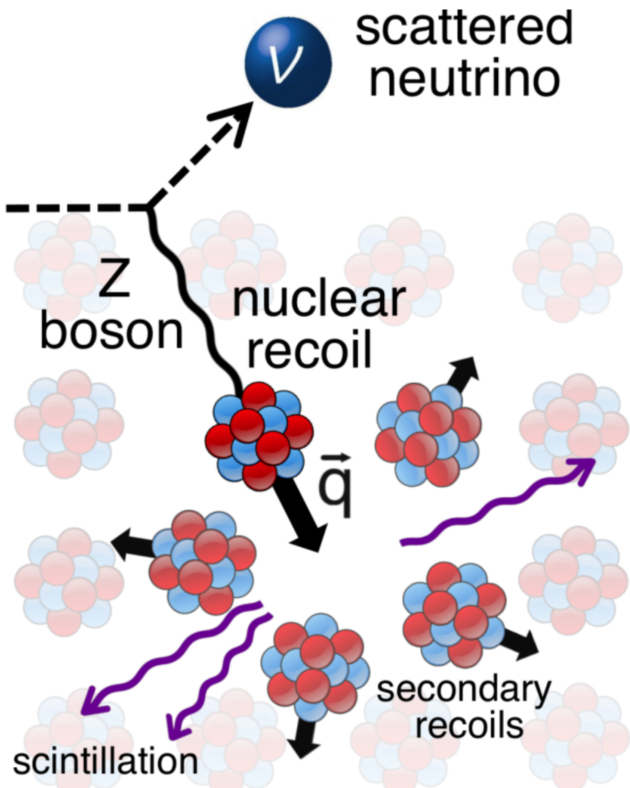
- Searches ongoing using both stopped-pion and reactor neutrino sources

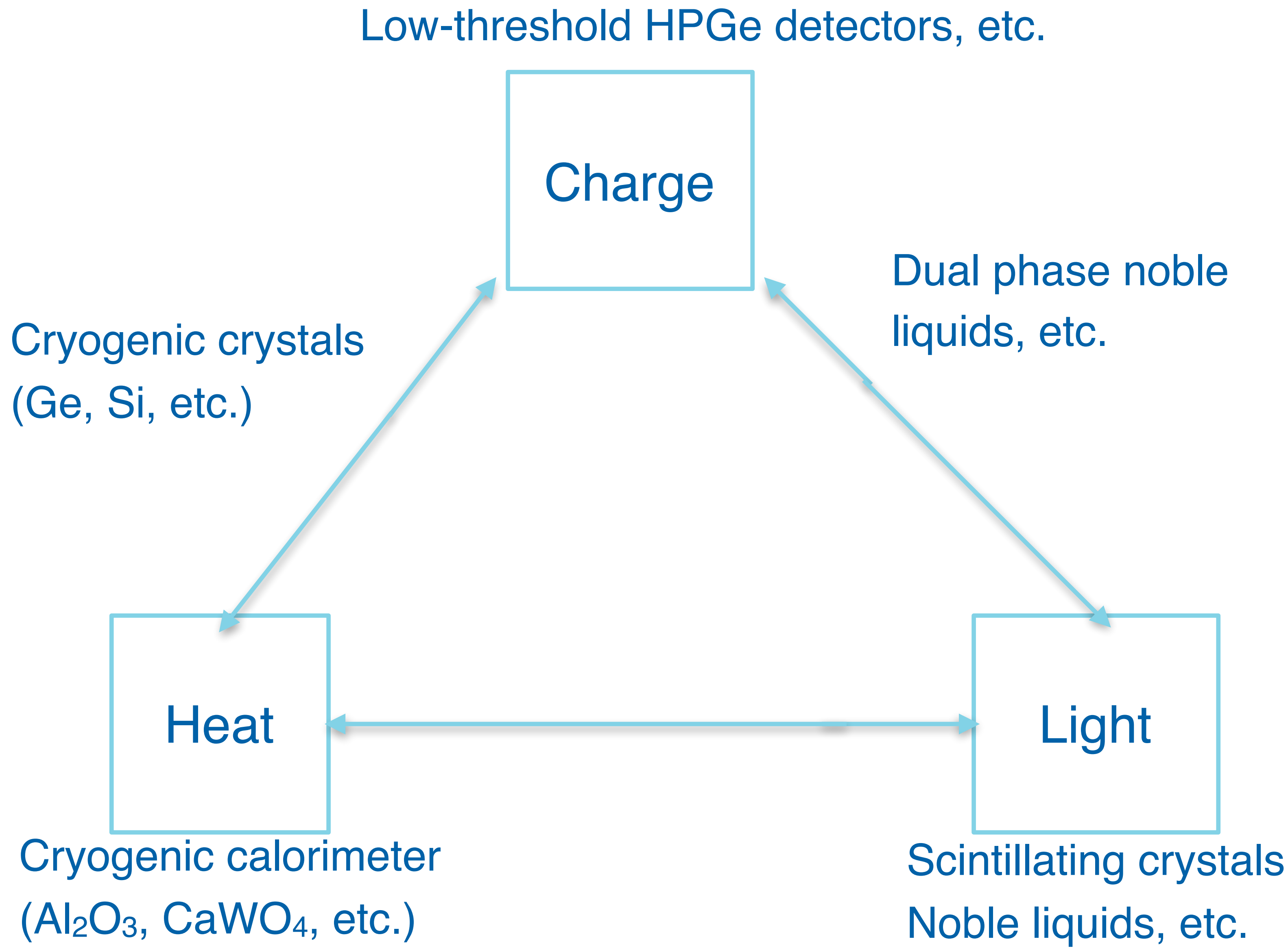




D. Akimov et al. (COHERENT). Science 357, 1123-1126 (2017)

Detecting CEvNS

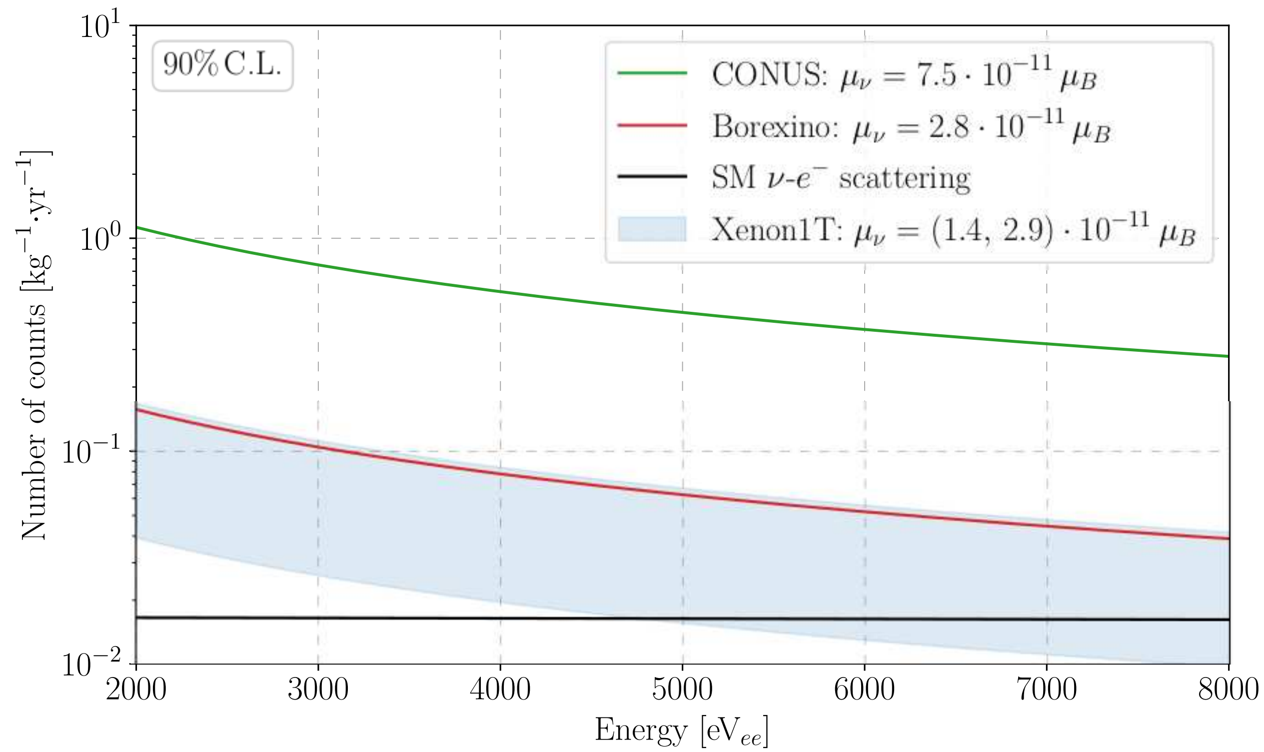




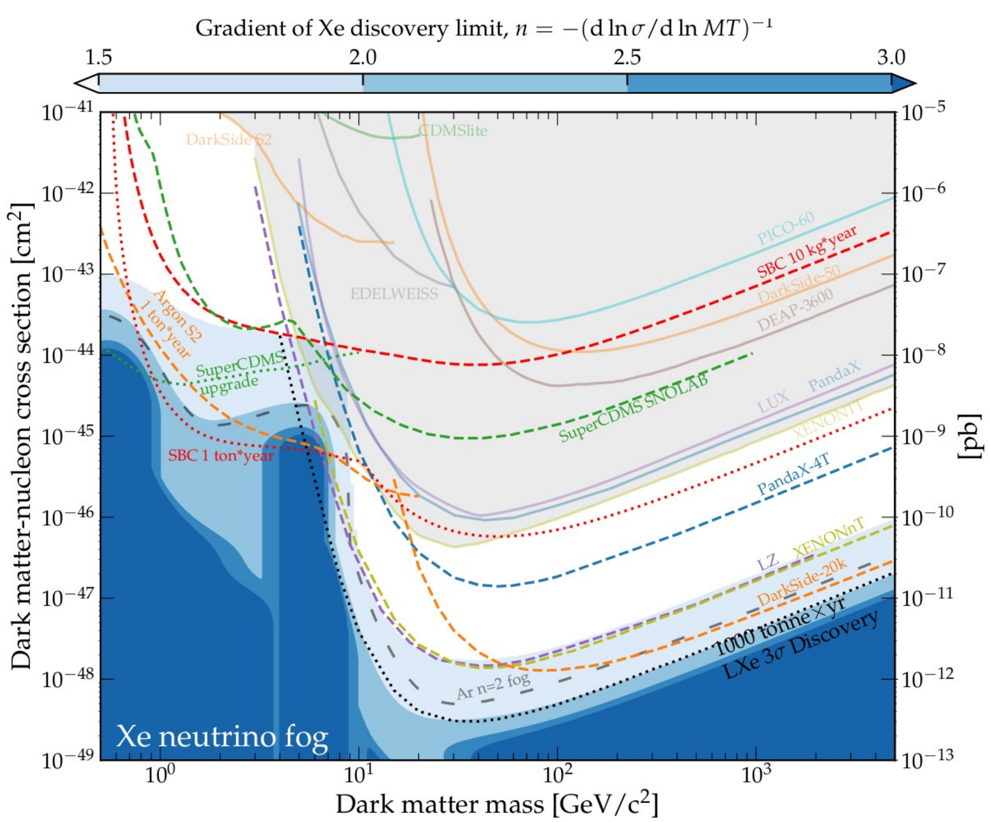
- Large CEvNS cross section allows for small detectors to measure neutrinos
  - Improvements come in larger mass (i.e. for noble liquid detectors) or lower energy thresholds (i.e. for cryogenic bolometers)
- Maximum nuclear recoil energy $T_{max} \sim E^2_{nu}/M$
- Understanding quenching factor = E_{meas}/E_{nr} is important

Physics Motivation for CEvNS

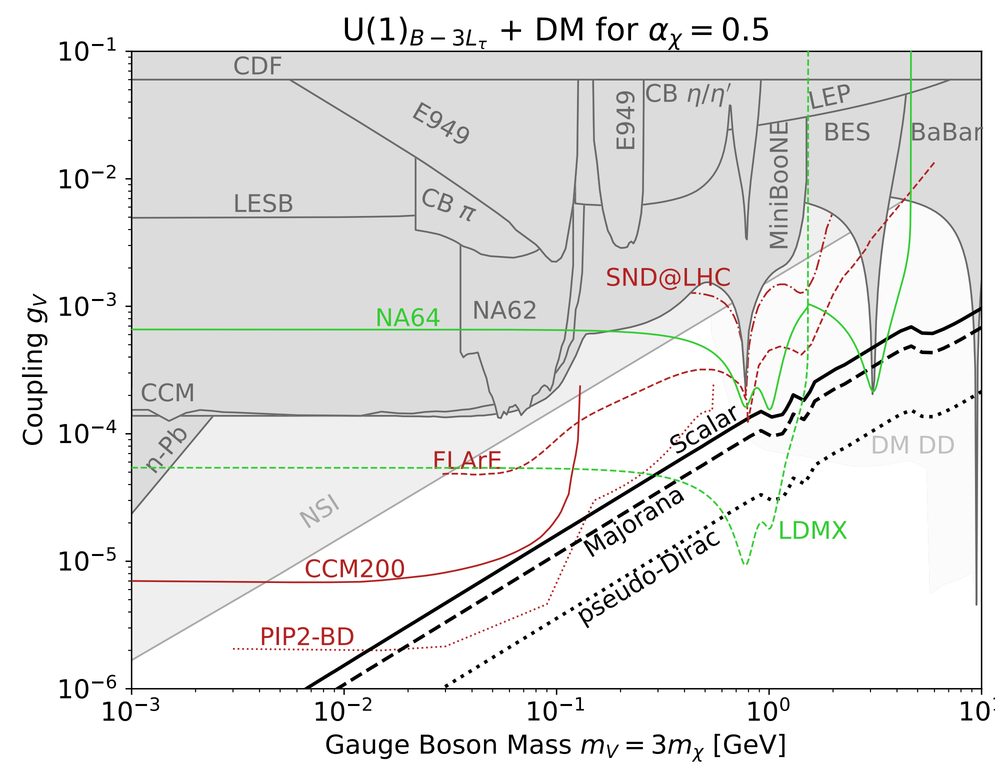
- CEvNS is Standard Model process, opens doors for new physics searches
  - Neutrino magnetic moment, non-standard interactions, etc.
- Dark matter and dark sectors
  - "Neutrino fog" for dark matter direct detection experiments



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]

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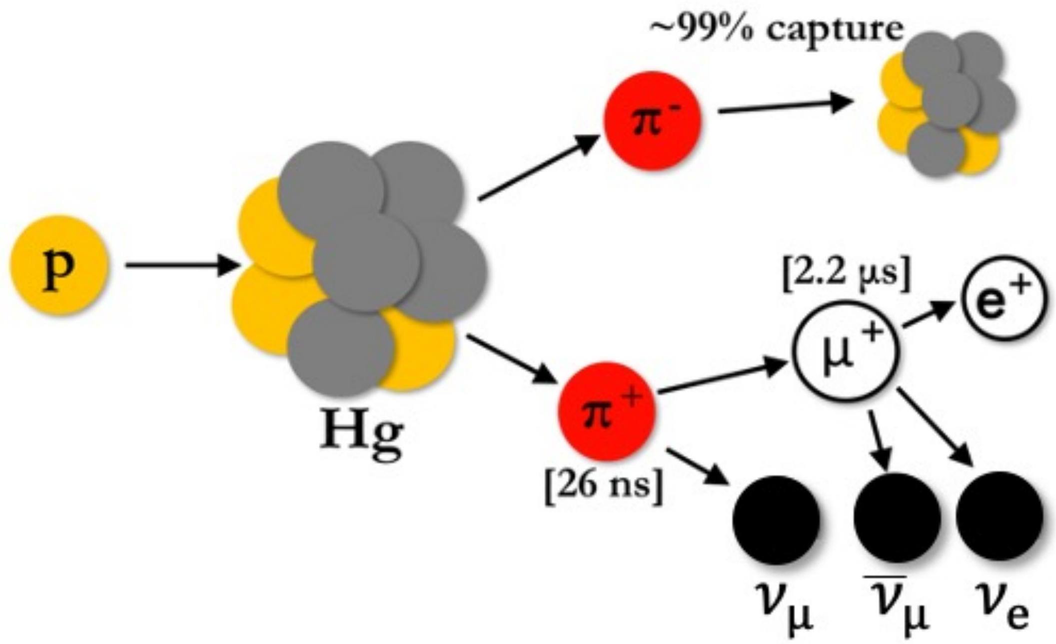
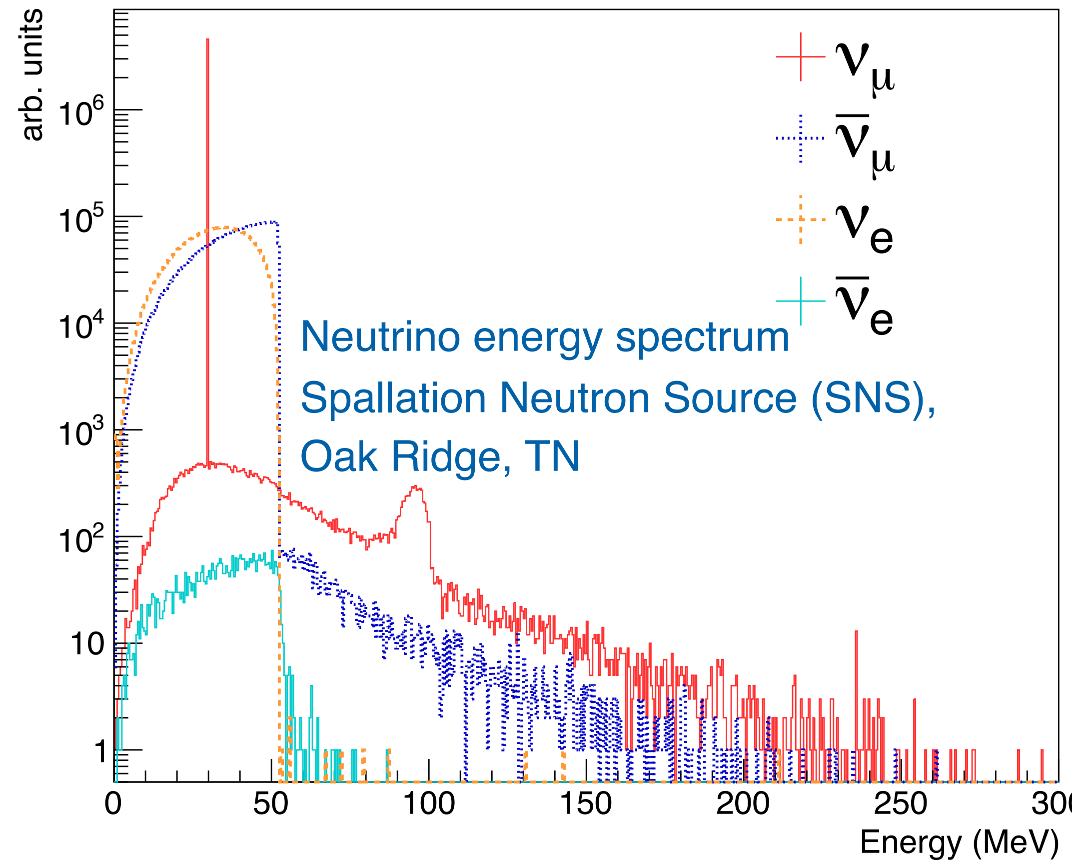
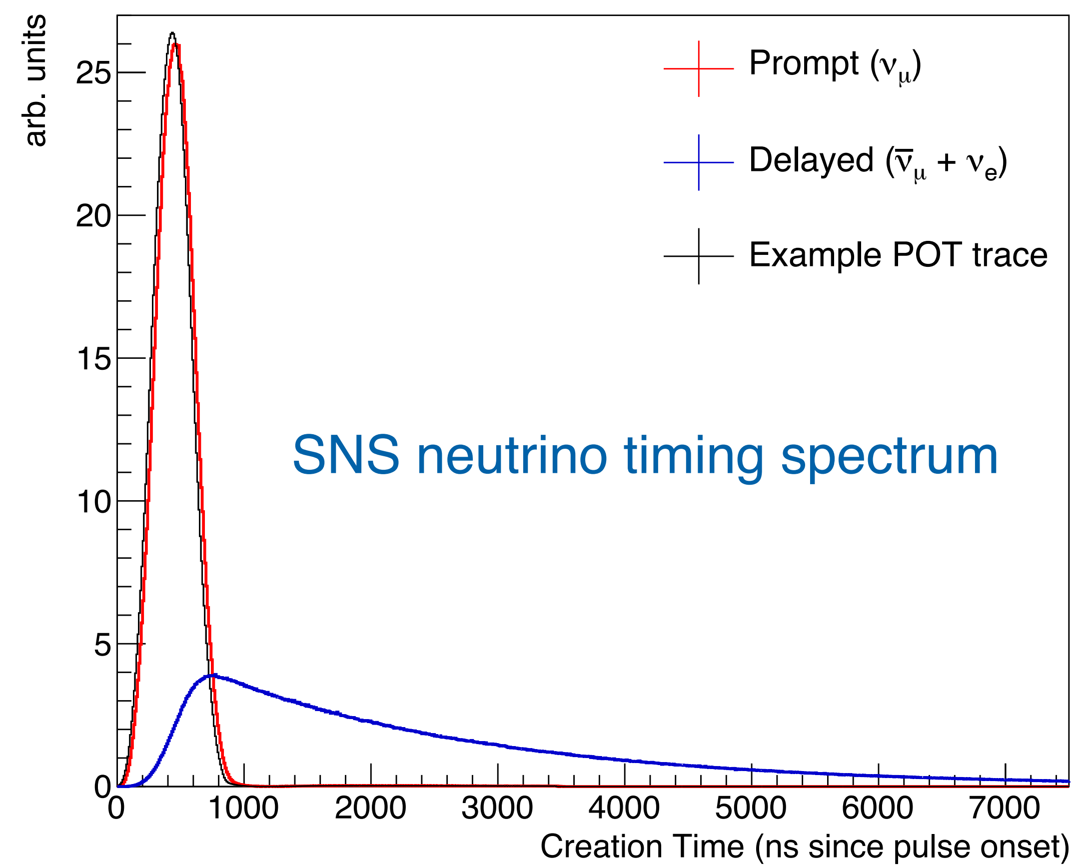
Stopped-Pion Neutrino Sources



- 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

Request to P5

The Accelerator Complex Enhancement (ACE) plan capitalizes on the PIP-II investment and delivers both higher POT to LBNF than PIP-II alone could provide and a Booster Replacement that will provide even higher rates of POT accumulation in addition to a modern and flexible Fermilab Accelerator Complex. We ask P5 to support the ACE plan that includes the following key components

1. Upgrades to Main Injector accelerator systems and infrastructure to enable beam power above 1.2MW through faster cycle time and efficient operations of the complex with the aim of achieving DUNE goals as fast as possible, performed as series of AIP and GPP between 2024 and 2032.
2. Accelerated profile of high-power target system R&D to enable above 1.2MW operations in DUNE Phase I.
3. Establishment of a Project for Booster replacement with superior capacity, capability, and reliability to be tied to the accelerator complex at a time determined by the DUNE physics.

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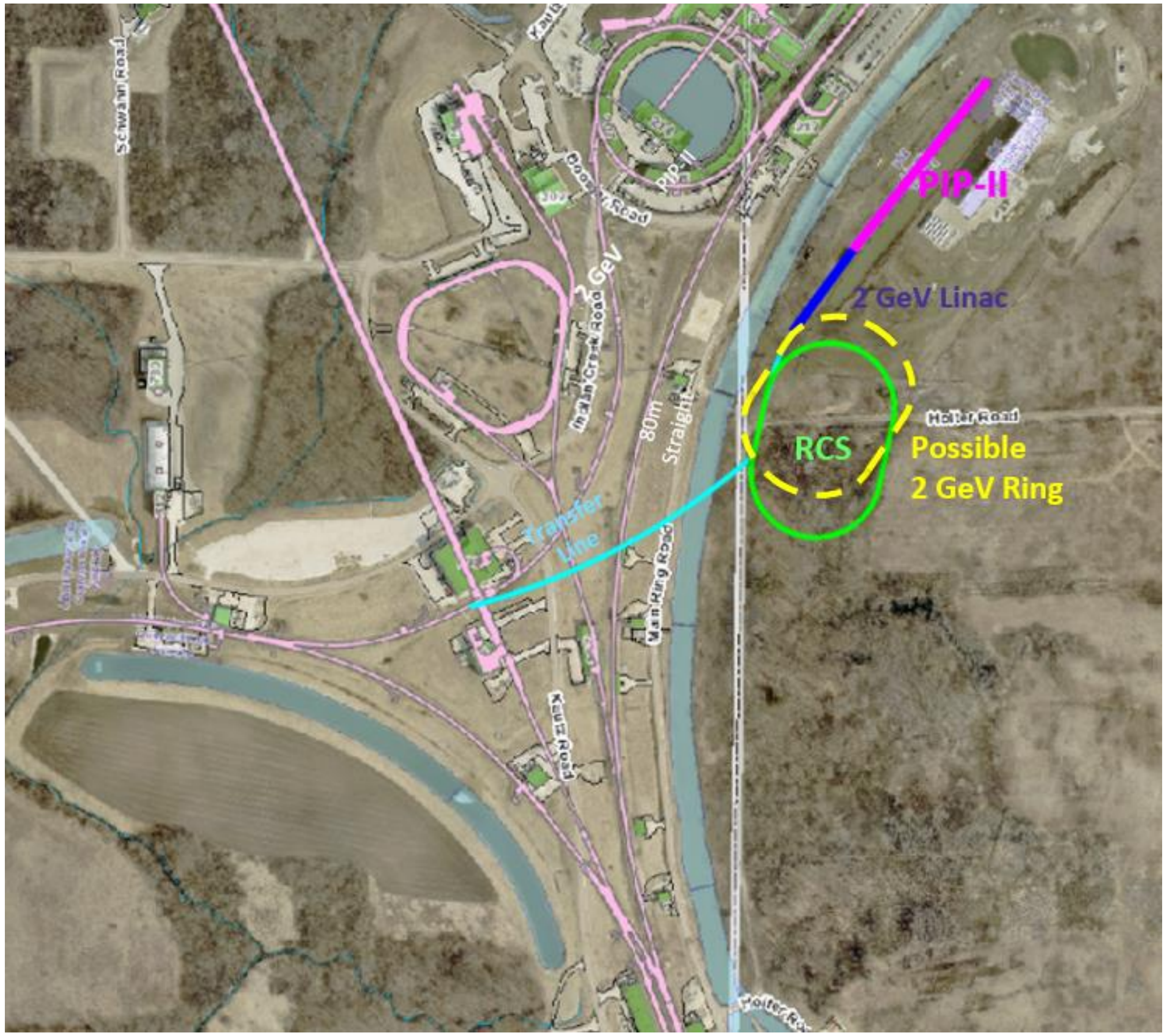
27 3/21/23 Valishev I Fermilab Accelerator Complex Evolution

A. Valishev, FNAL P5 town hall

Example 1

Configuration C1b:

- 20Hz RCS + 2 GeV AR
- Main elements
  - 1-2GeV Linac
  - 20Hz 8GeV RCS
  - 2 GeV Accumulator Ring
  - MI Upgrades
  - Transfer Lines



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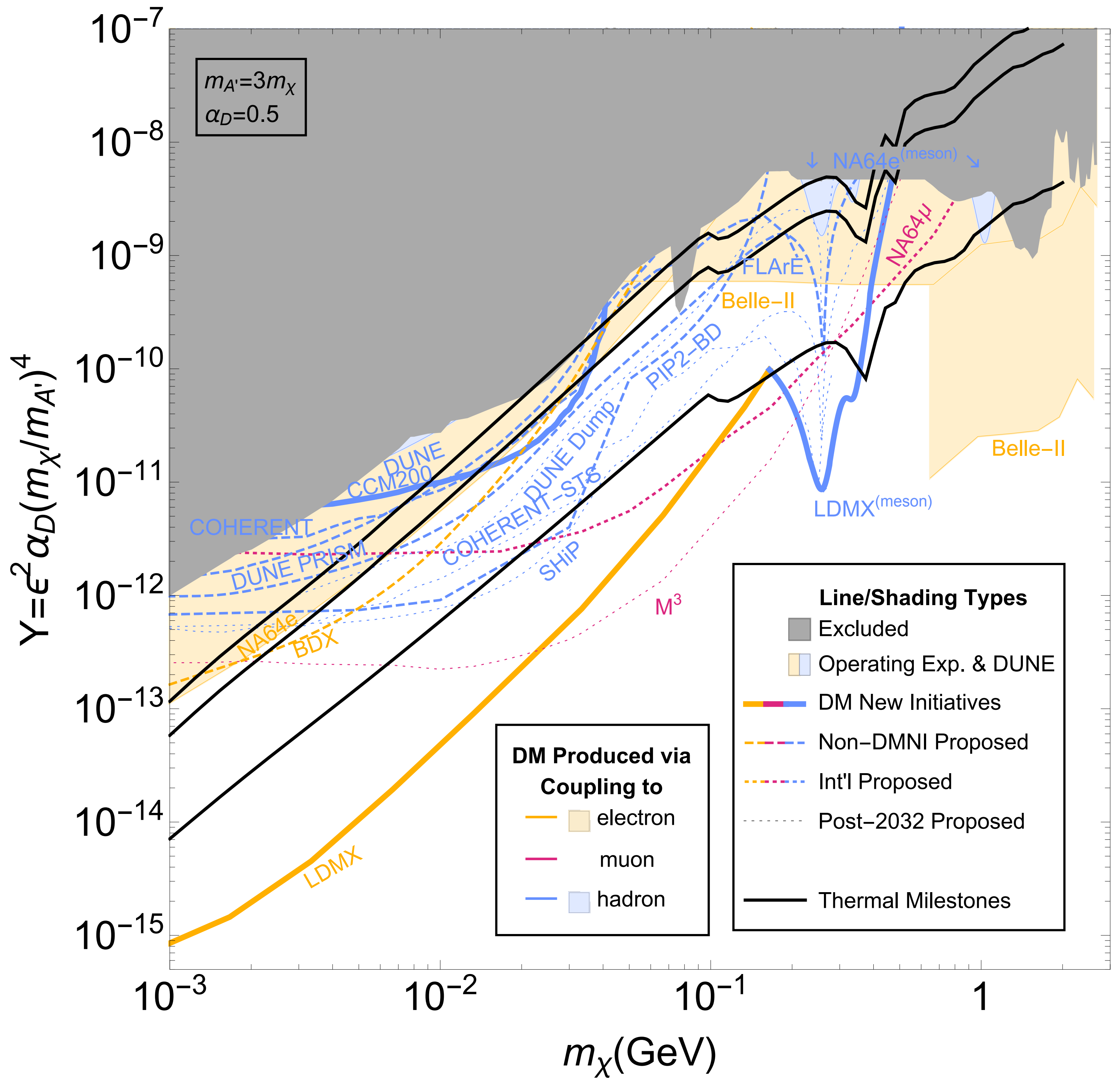
A. Valishev, FNAL P5 town hall

PIP2-BD Vector Portal Dark Matter Search



arXiv:2209.04671

More Information

- PIP2-BD White Paper
- SBN-BD White Paper
- White Paper on RCS option at Fermilab

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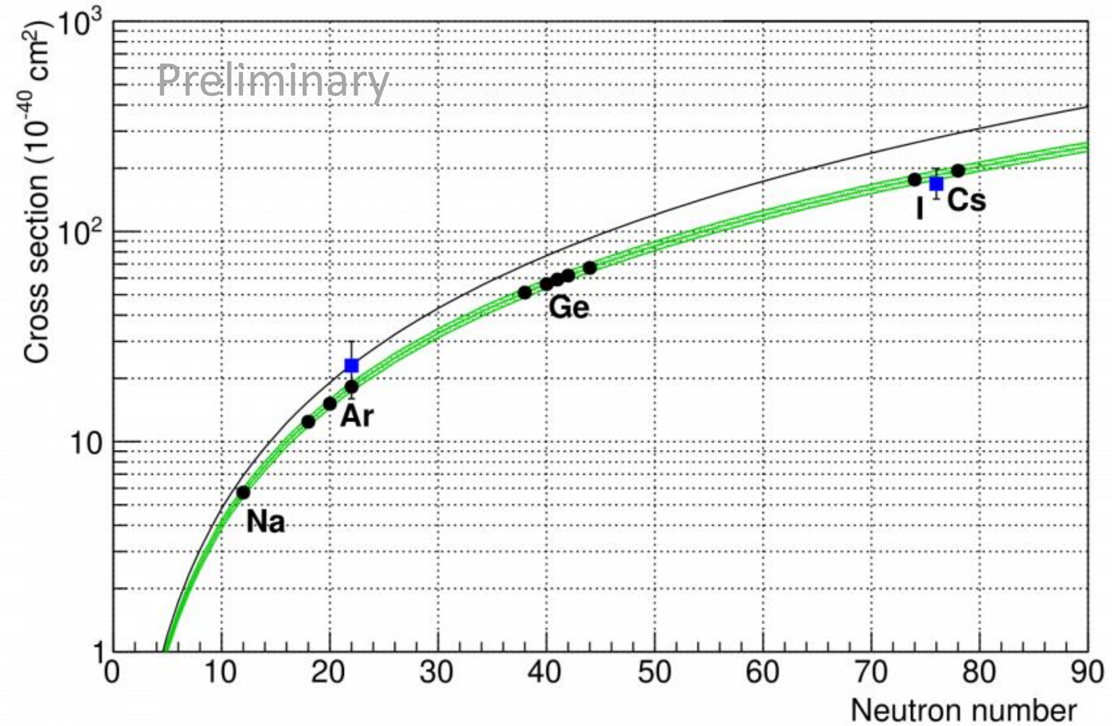
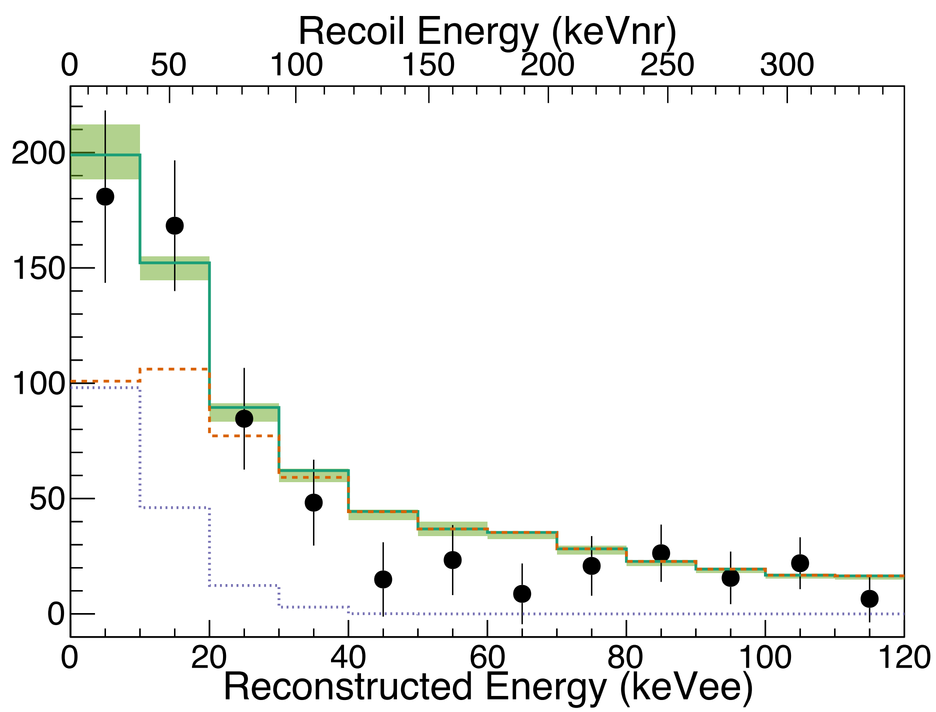
Thank you!

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



D. Akimov et al. (COHERENT), Phys. Rev. Lett. 126 (2021) 1, 012002

PIP2-BD Vector Portal Dark Matter Search

- Detector located on axis, 18 m downstream from target
- 20 keVnr threshold
- Backgrounds simulated using custom Geant4-based simulation
- DM production generated using BdNMC code (Phys. Rev. D 95, 035006 (2017))
  - 90% C.L. curves computed using simulated backgrounds and scaling the DM event rate with ϵ^4
- 5 year run for each accelerator scenario