PIP2-BD: Searching for New Physics at an Upgraded Fermilab Accelerator Complex

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

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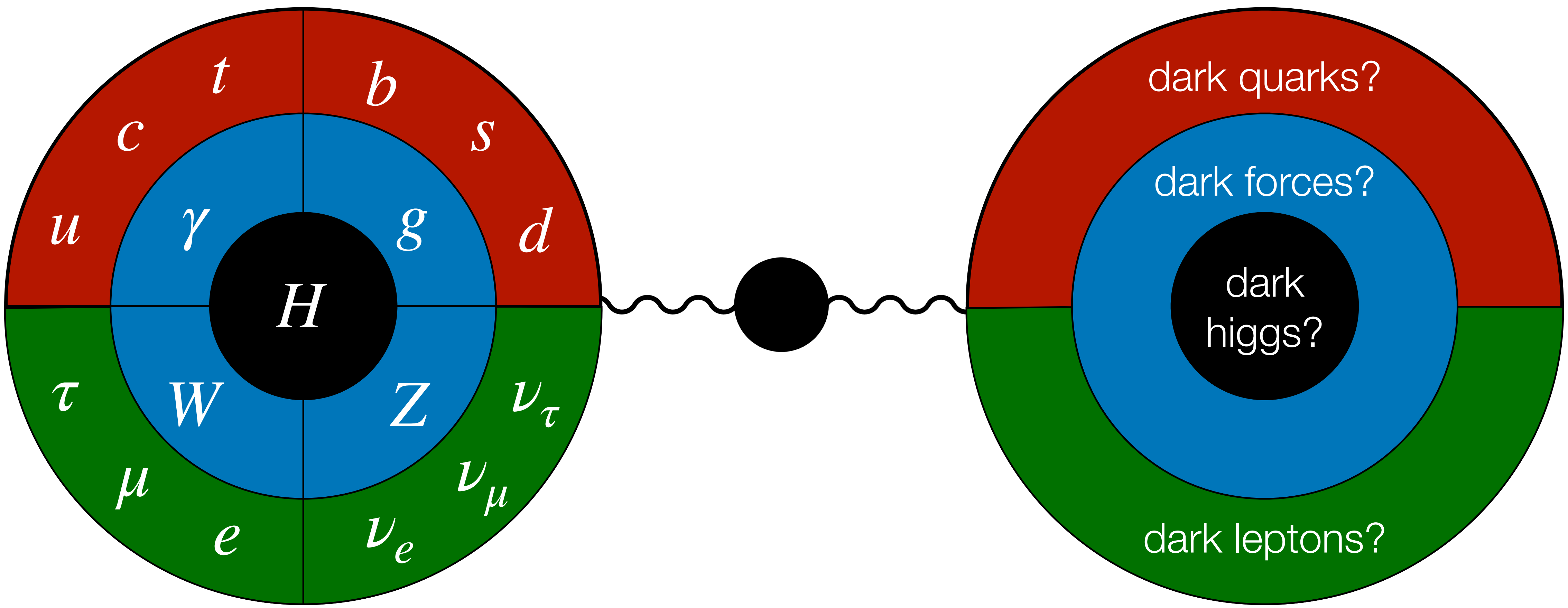
A Dark Sector is motivated by the existence of dark matter

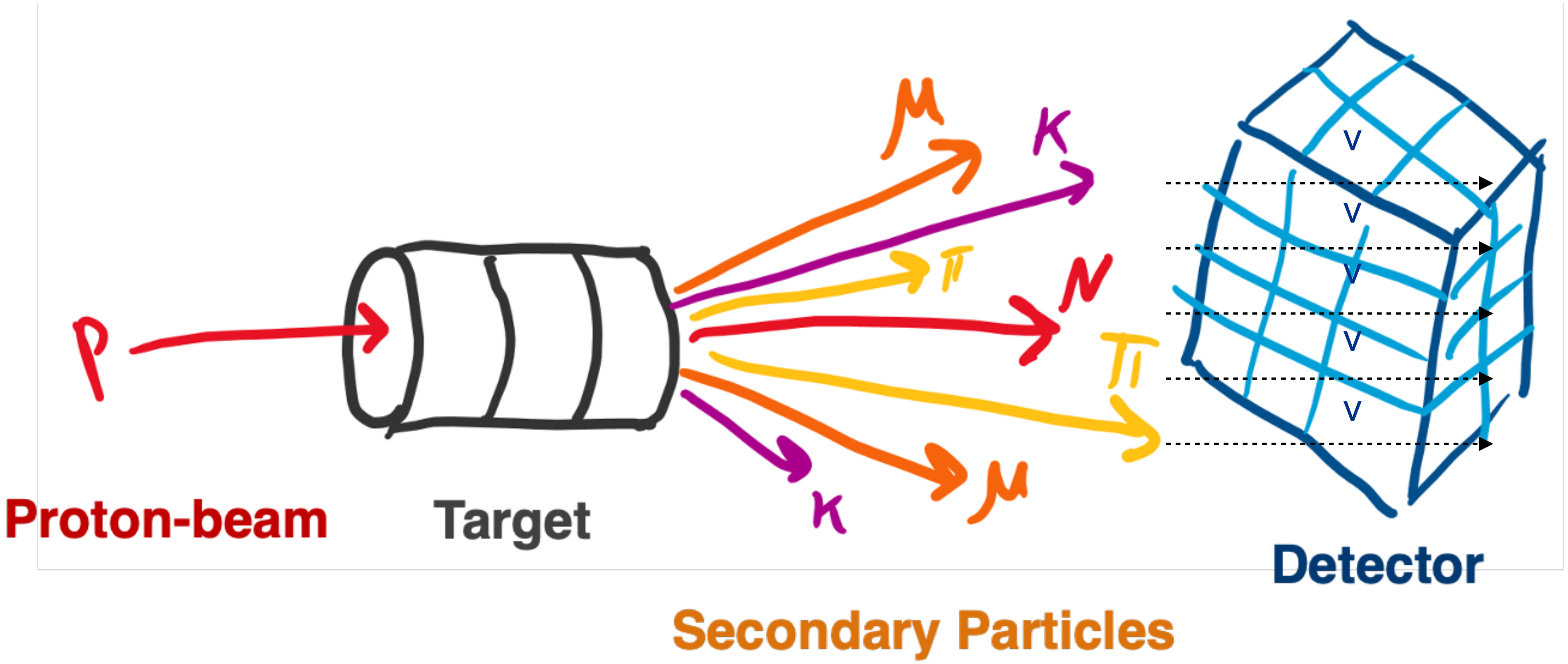
- Potentially has a rich structure



arXiv:2209.04671

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



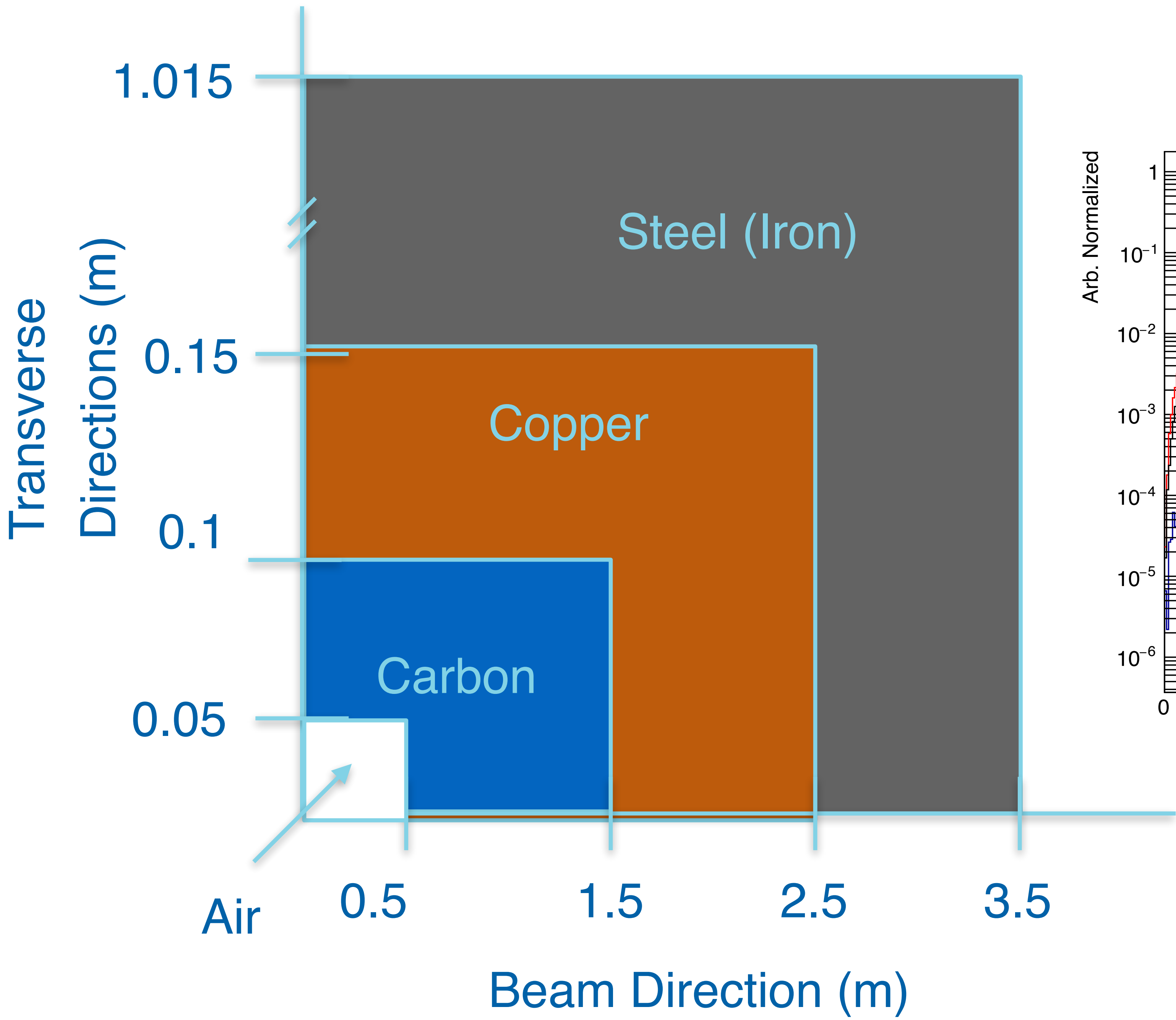
Creating a stopped-pion source with PIP-II: PIP2-BD

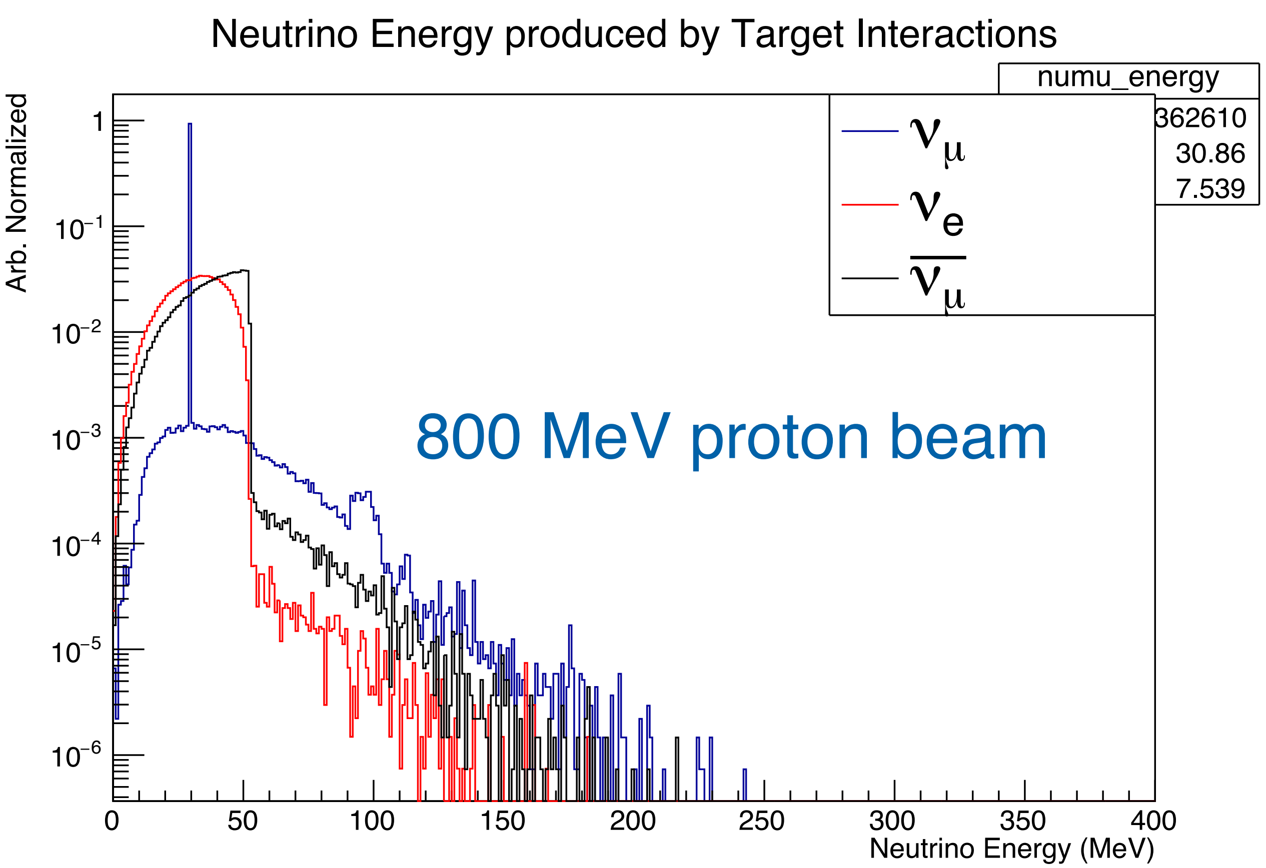
- PIP-II Accumulator Ring (PAR), Compact PIP-II Accumulator Ring (C-PAR), and Rapid Cycling Synchrotron Storage Ring (RCS-SR) are three accelerator scenarios we studied ahead of Snowmass 2022
- PAR and C-PAR are realizable in the timeframe of the start of the PIP-II accelerator and DUNE Phase I
- RCS-SR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

PIP2-BD Target Thoughts

- Have done initial studies using Geant4 on a shielding design around the target to reduce the decay-in-flight component of the neutrino spectra





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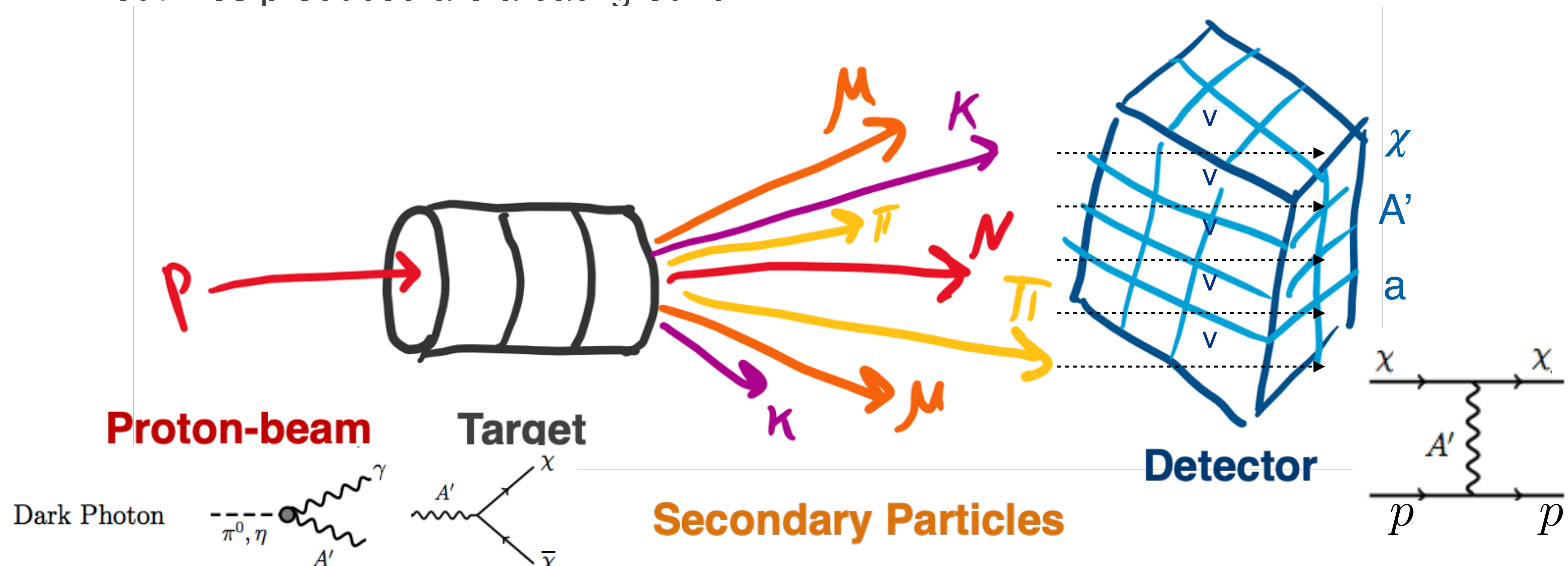
Leveraging Stopped Pion Sources for Dark Sector Searches

- 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!



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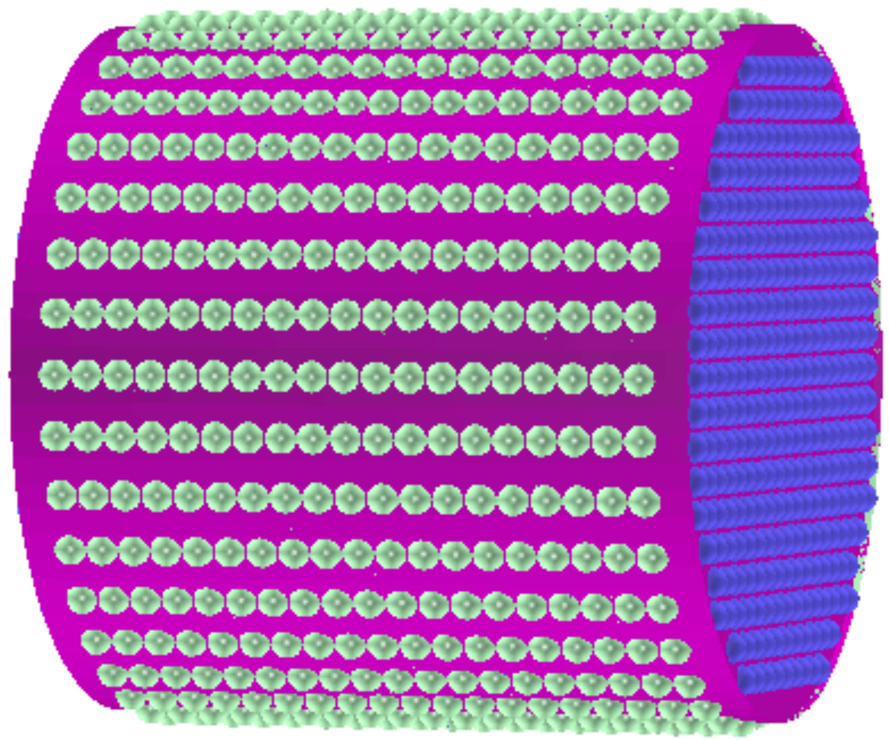
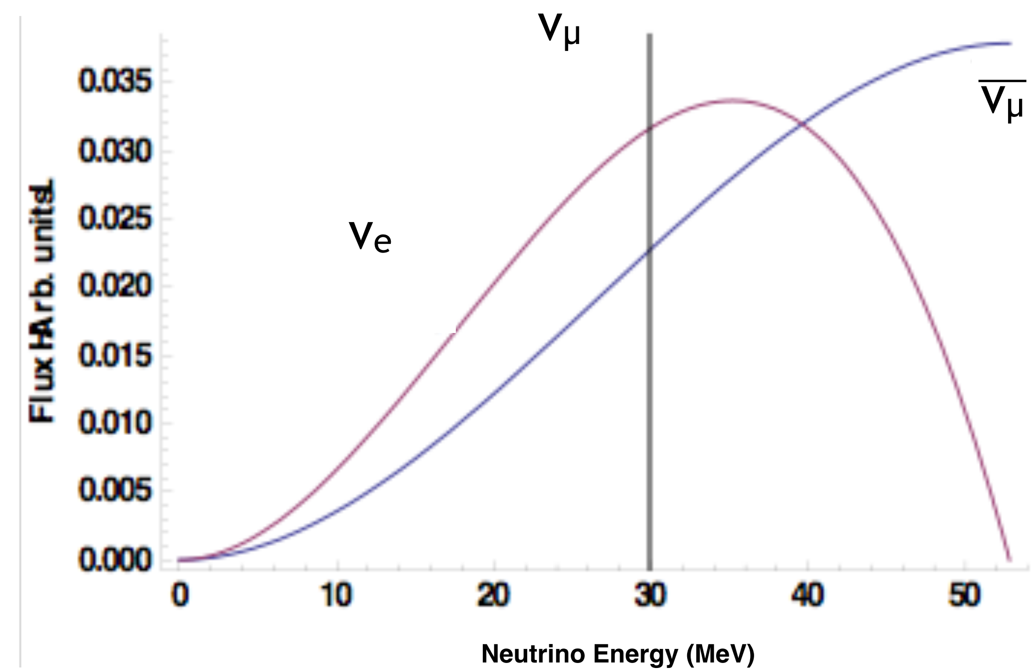
Proposed Detector at PIP-II: PIP2-BD

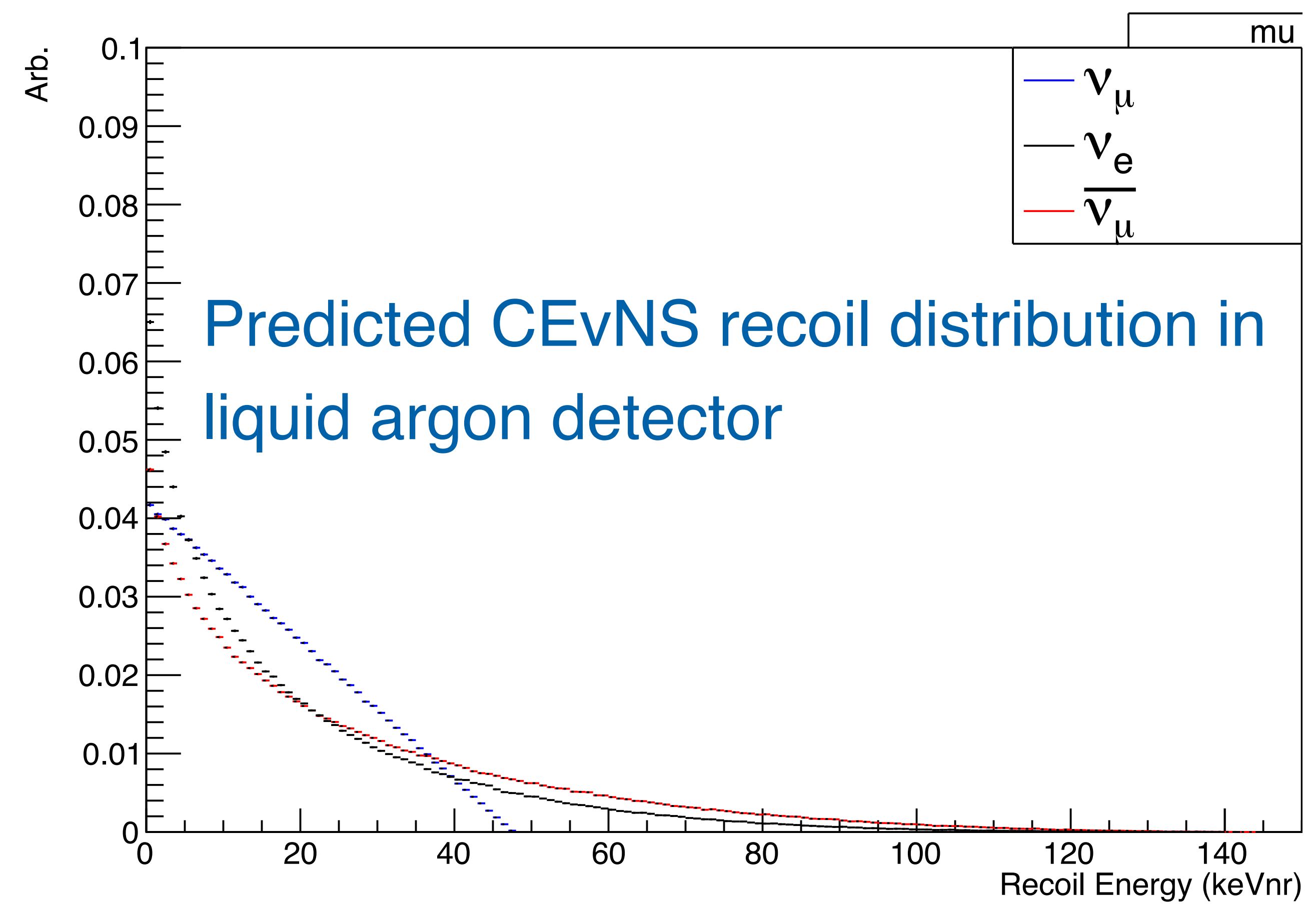
- Single-phase, scintillation only liquid argon (LAr) detector
- Fiducial volume - 4.5 m right cylinder inside box, **~100 tons LAr**
- Surround sides and endcaps of detector volume with TPB-coated 8” PMTs
  - TPB-coated reflector on sides and endcaps for photocoverage gaps
- Preliminary simulations 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

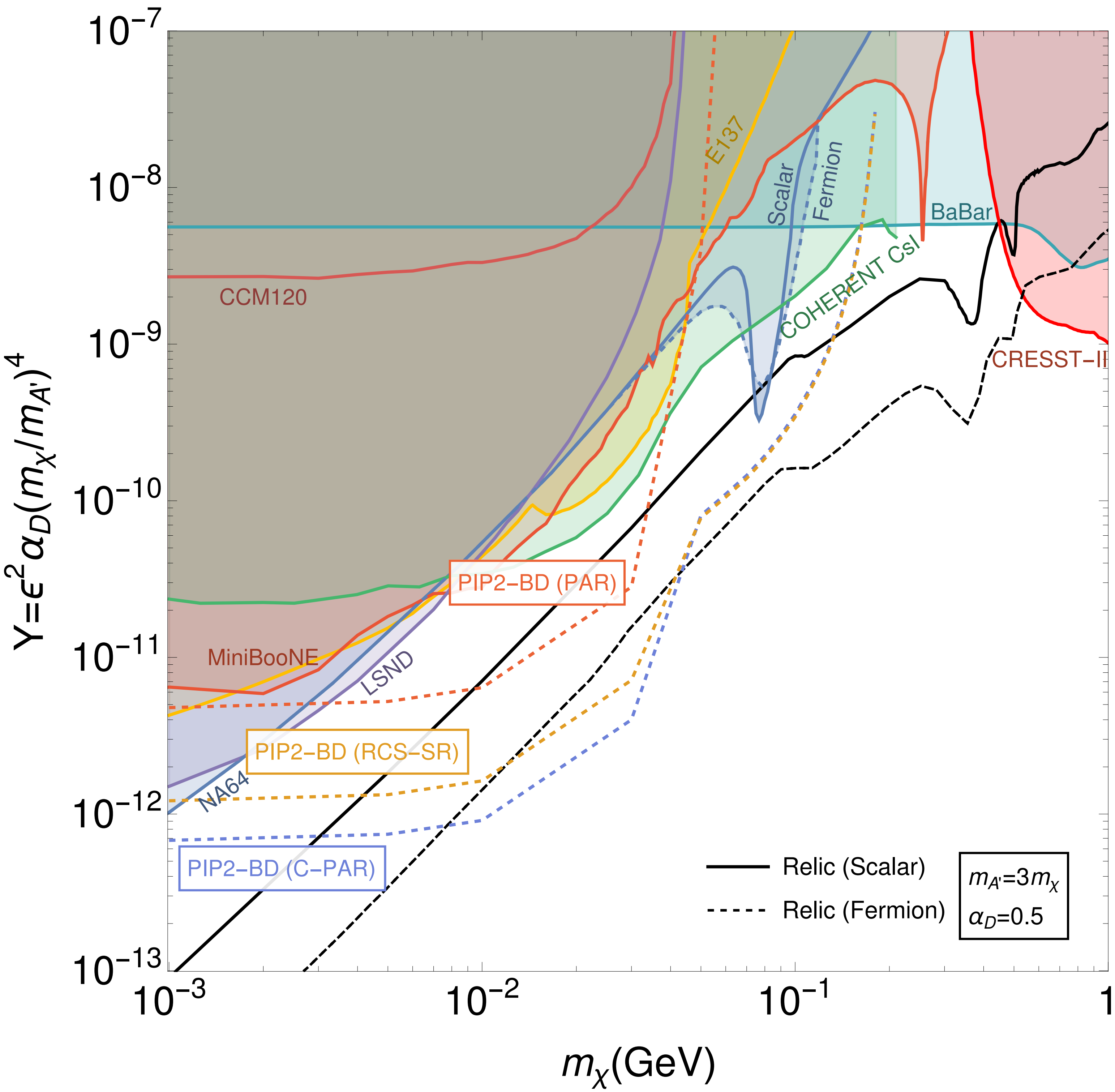




M. Toups et al., arXiv:2203.08079

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



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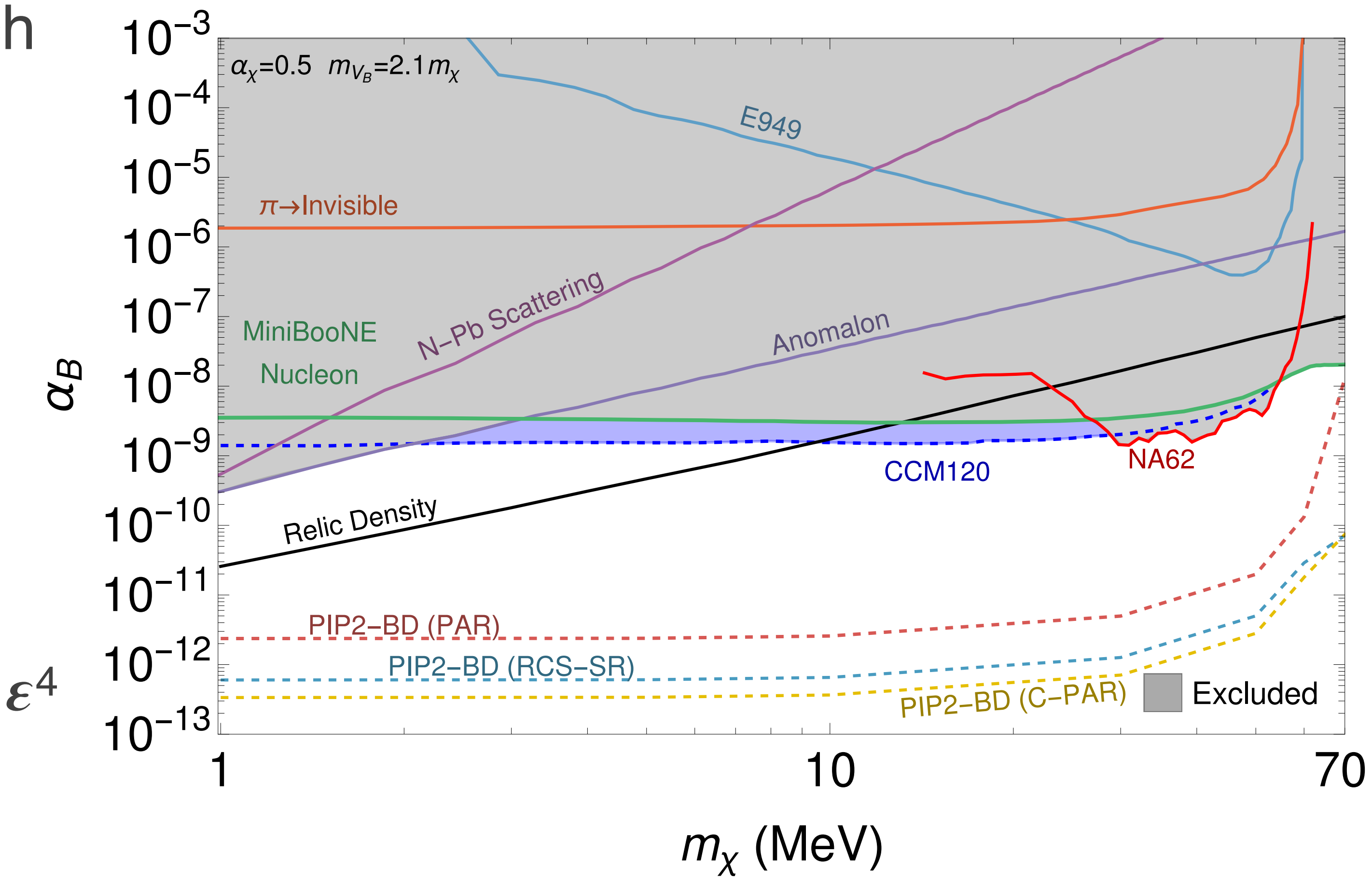
PIP2-BD Leptophobic DM Search

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

$$\mathcal{L}_B \supset -A_B^{\mu}(g_B J_{\mu}^B + g_{\chi} J_{\mu}^{\chi} + \varepsilon_B e J_{\mu}^{\mathrm{EM}})$$

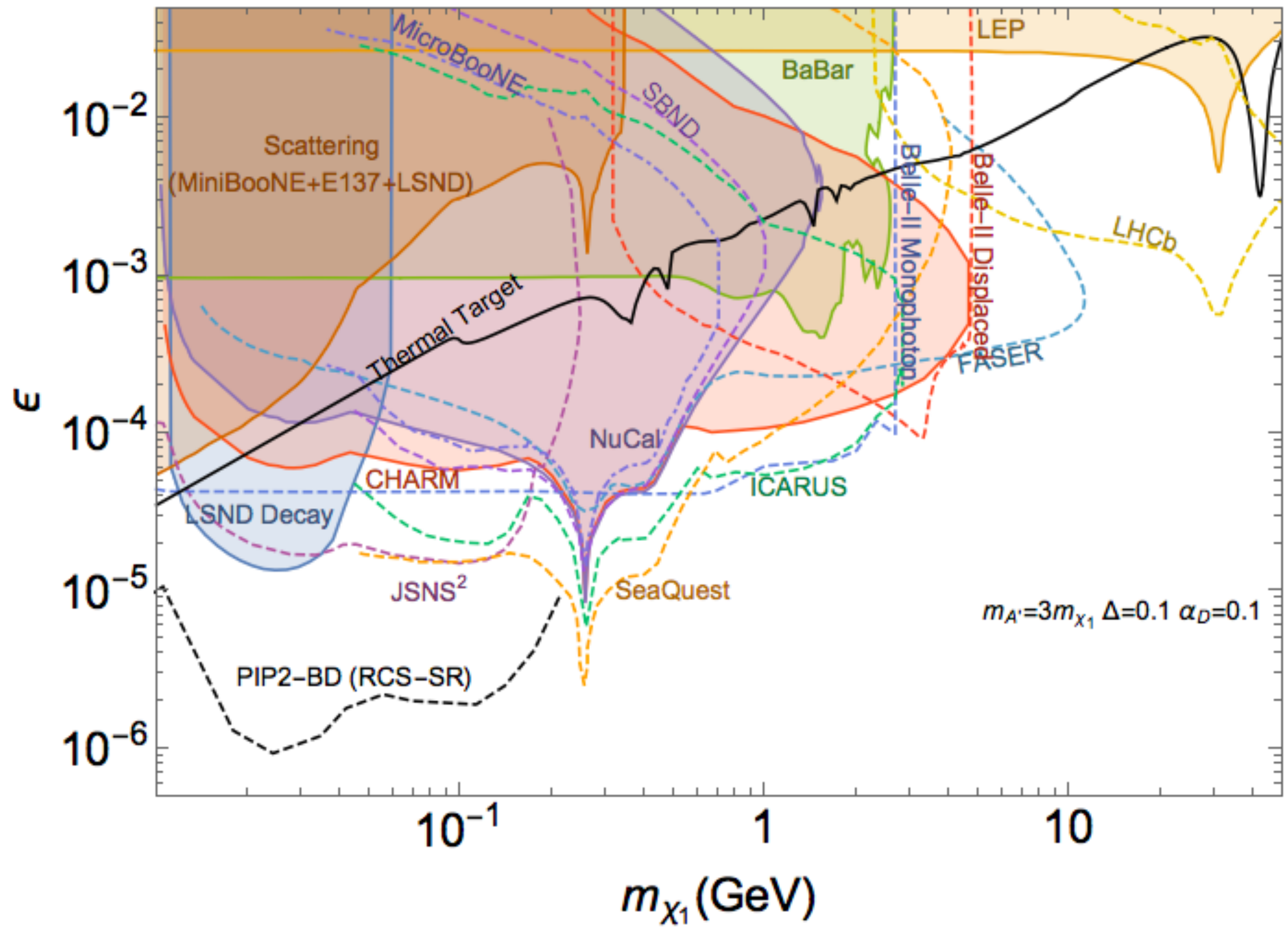
- Model predicts the same DM nuclear recoil energy distributions as the vector-portal model
  - Rate scales with $\alpha_{\chi}\,\alpha^2_{\mathrm{B}}$ as opposed to ε^4
- Same procedure to compute 90% C.L. as for vector-portal model
- 5 year run with the 3 accelerator scenarios



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



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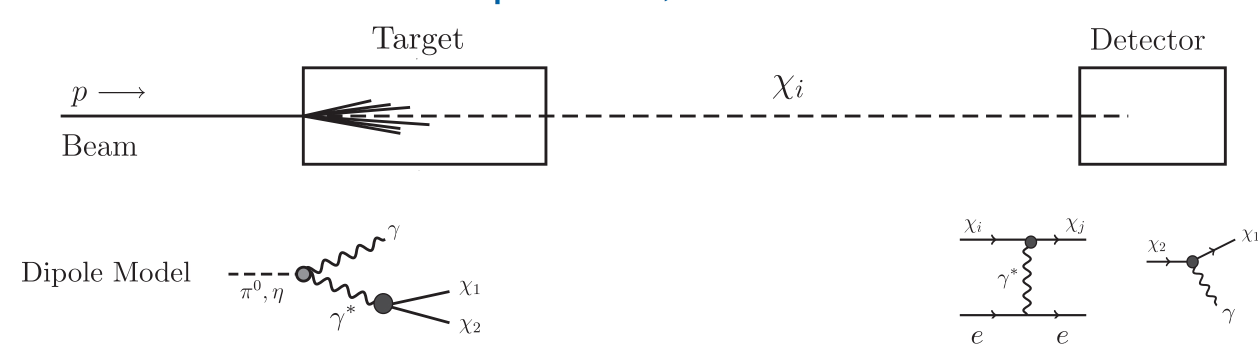

Phys. Rev. D **98**, 075020 (2018)

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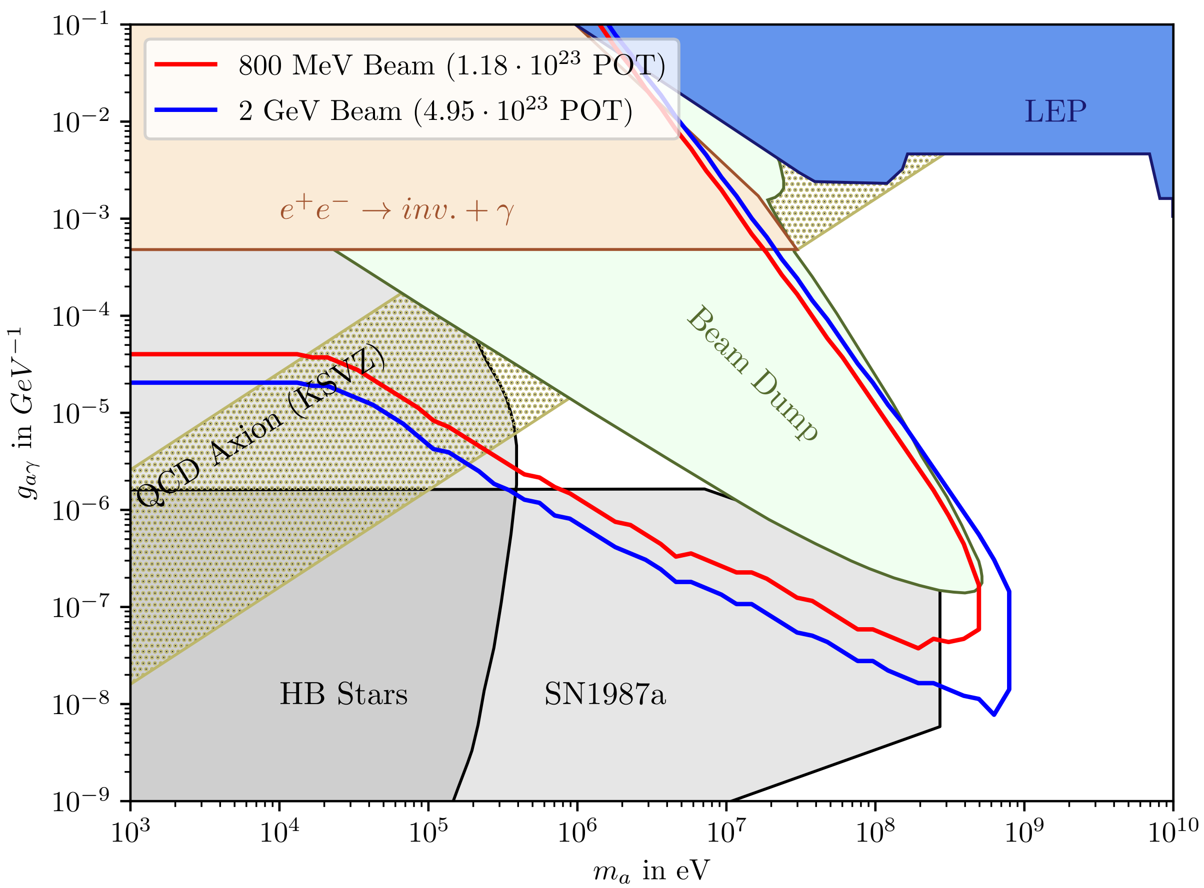
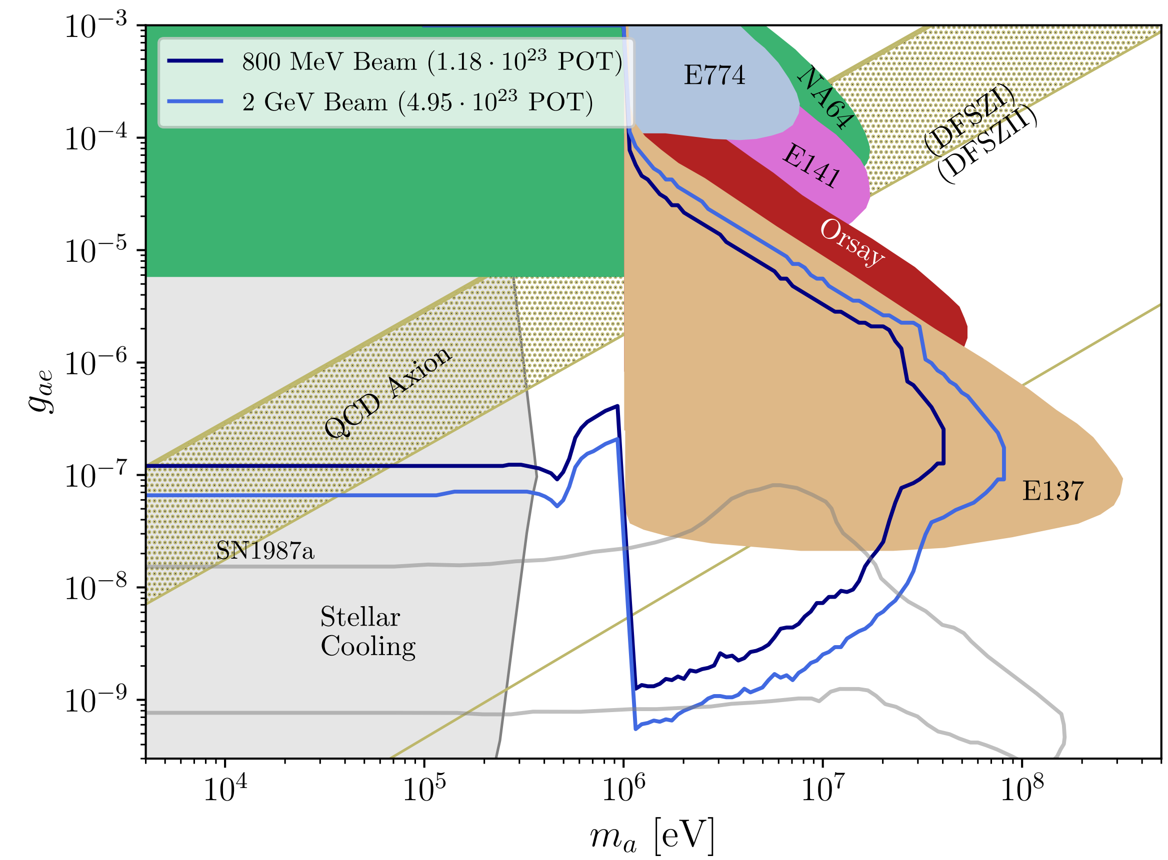
PIP2-BD Axion-like particles (ALP) search

- 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

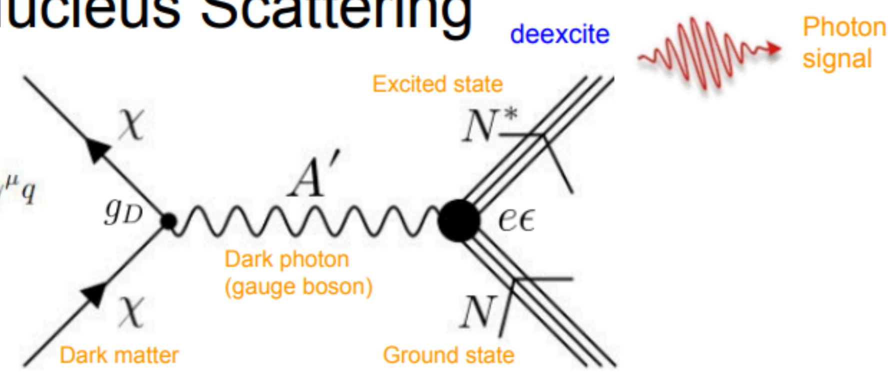
A. Thompson, A. Karthikeyan, B. Dutta, TAMU

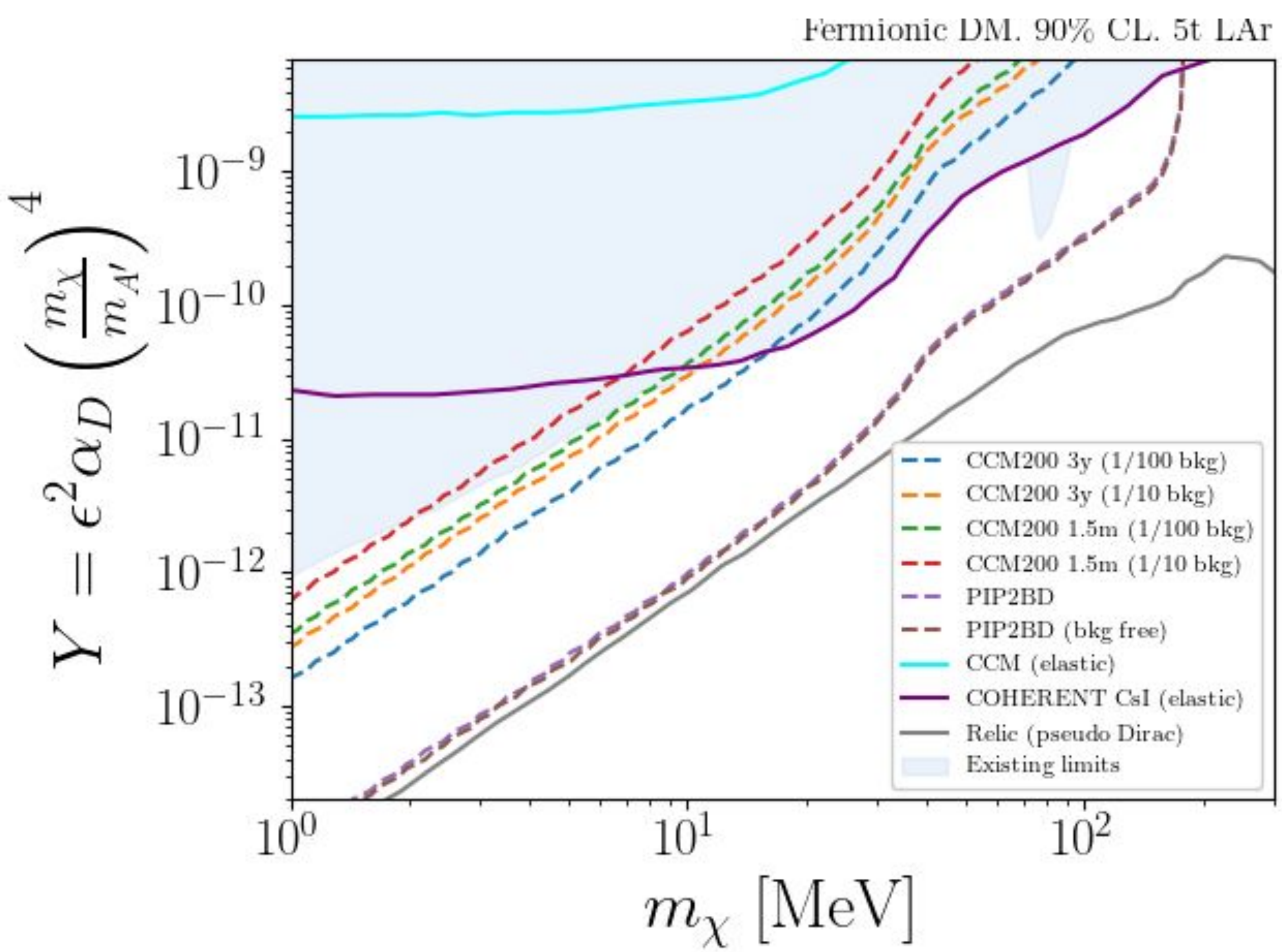
Other Dark Sector Searches with PIP2-BD

Inelastic DM-Nucleus Scattering

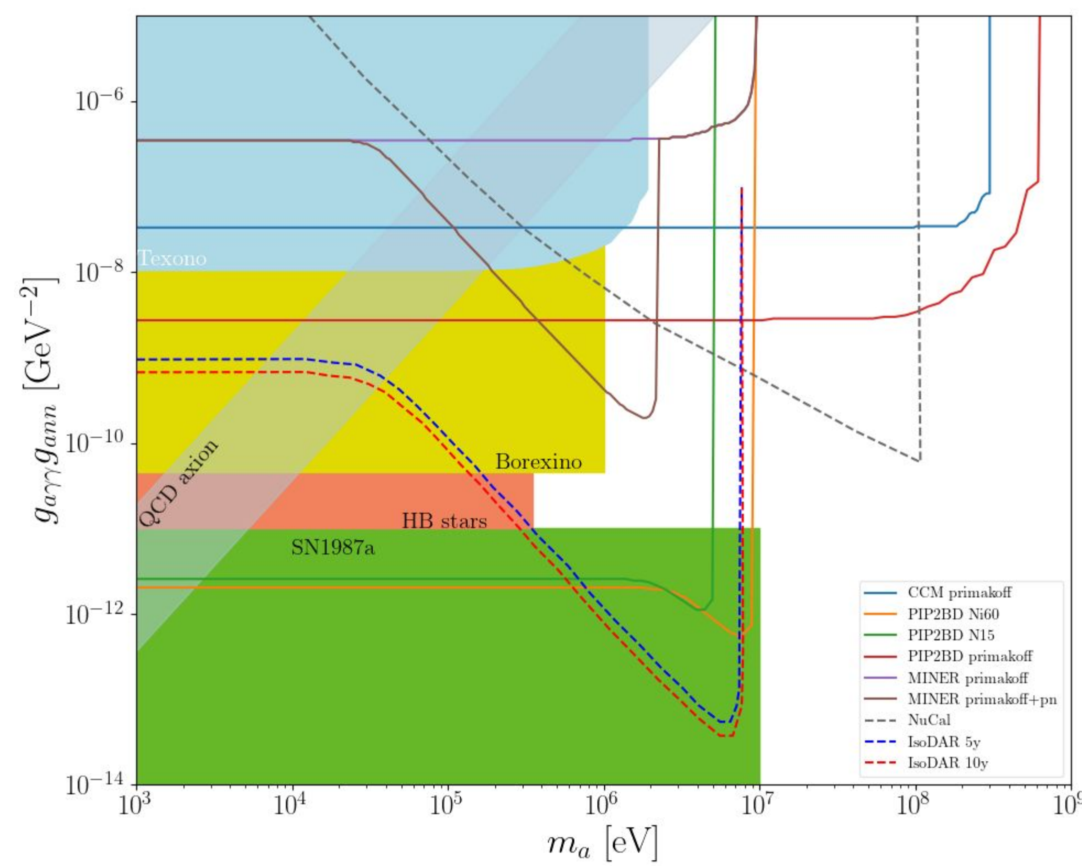
$\mathcal{L} \supset g_D A'_\mu \bar{\chi}\gamma^\mu \chi + e\epsilon Q_q A'_\mu \bar{q}\gamma^\mu q$

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





Axion Searches



W. C. Huang, Texas A&M University

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

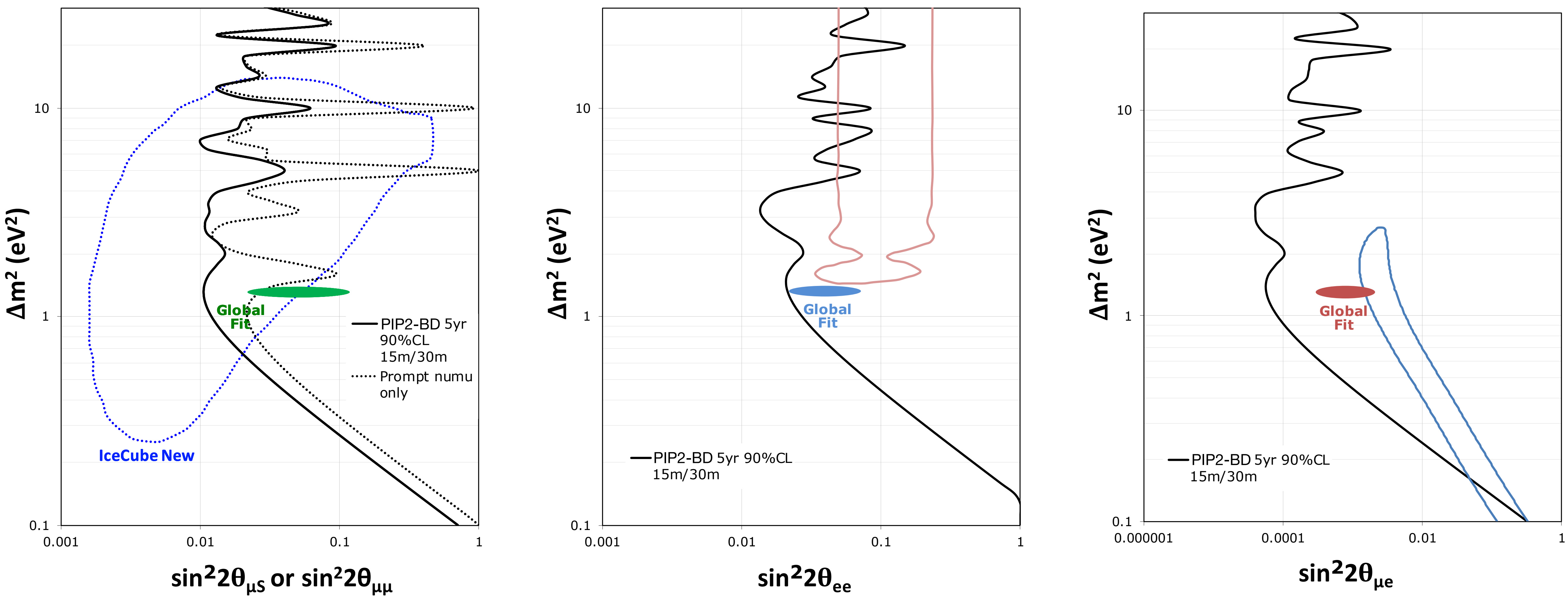


FIG. 13. PIP2-BD 90% confidence limits on active-to-sterile neutrino mixing compared to existing ν_μ disappearance limits from IceCube [45] and a recent global fit [46], assuming a 5 year run (left). Also shown are the 90% confidence limits for ν_μ disappearance (left), ν_e disappearance (middle), and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

M. Toups et al., arXiv:2203.08079

Requires separation of prompt, delayed neutrinos!

Summary

- 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

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
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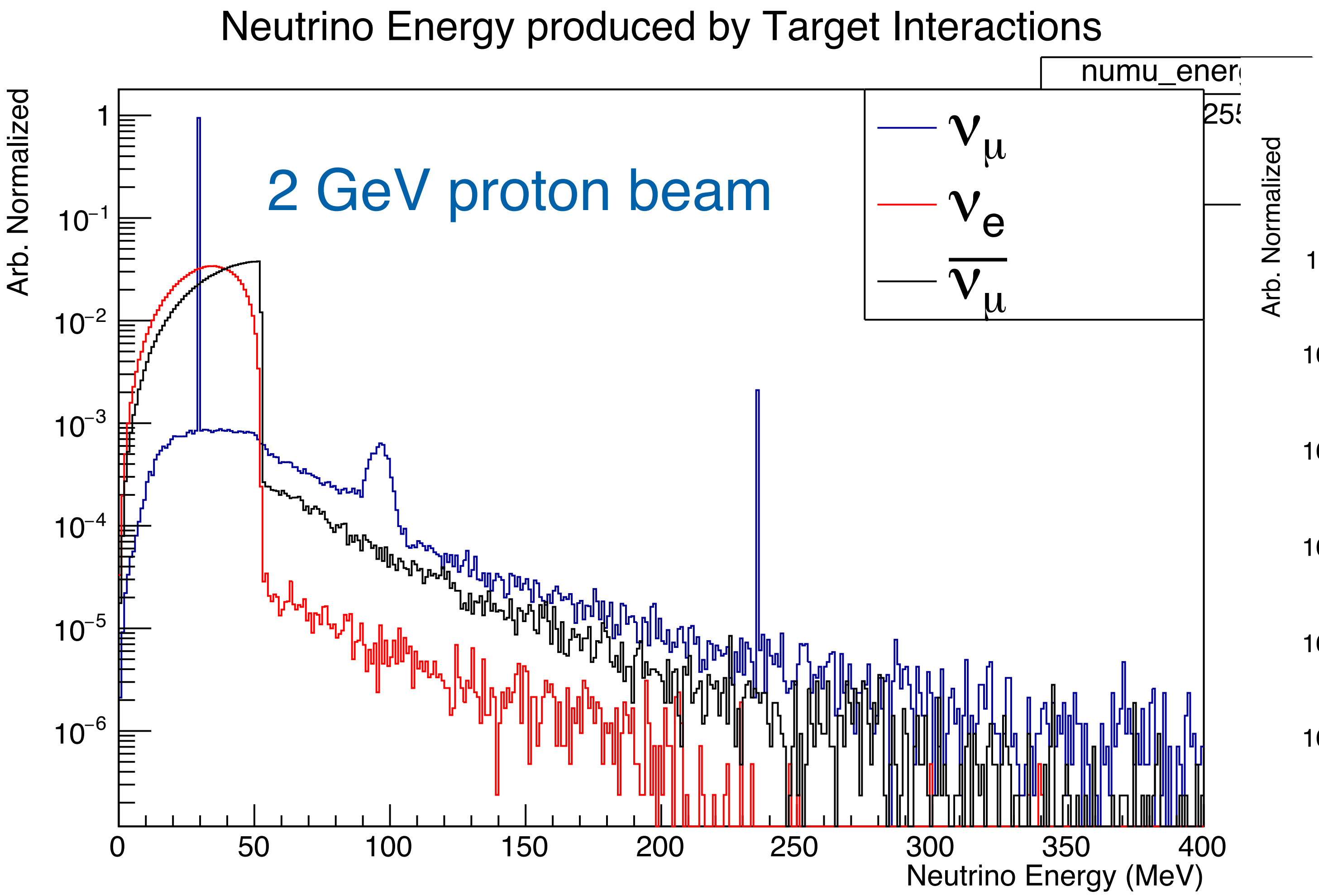
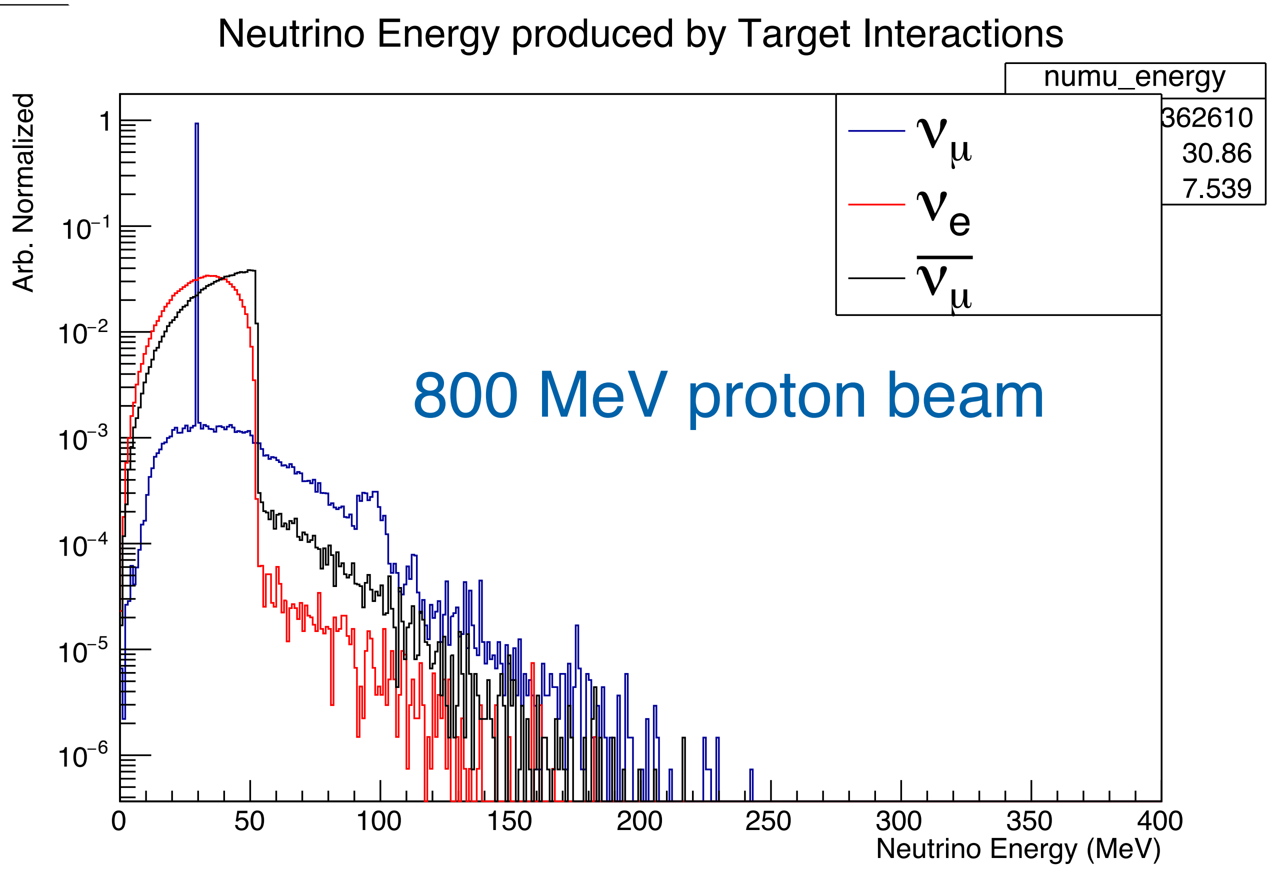
PIP2-BD Predicted Neutrino Flux





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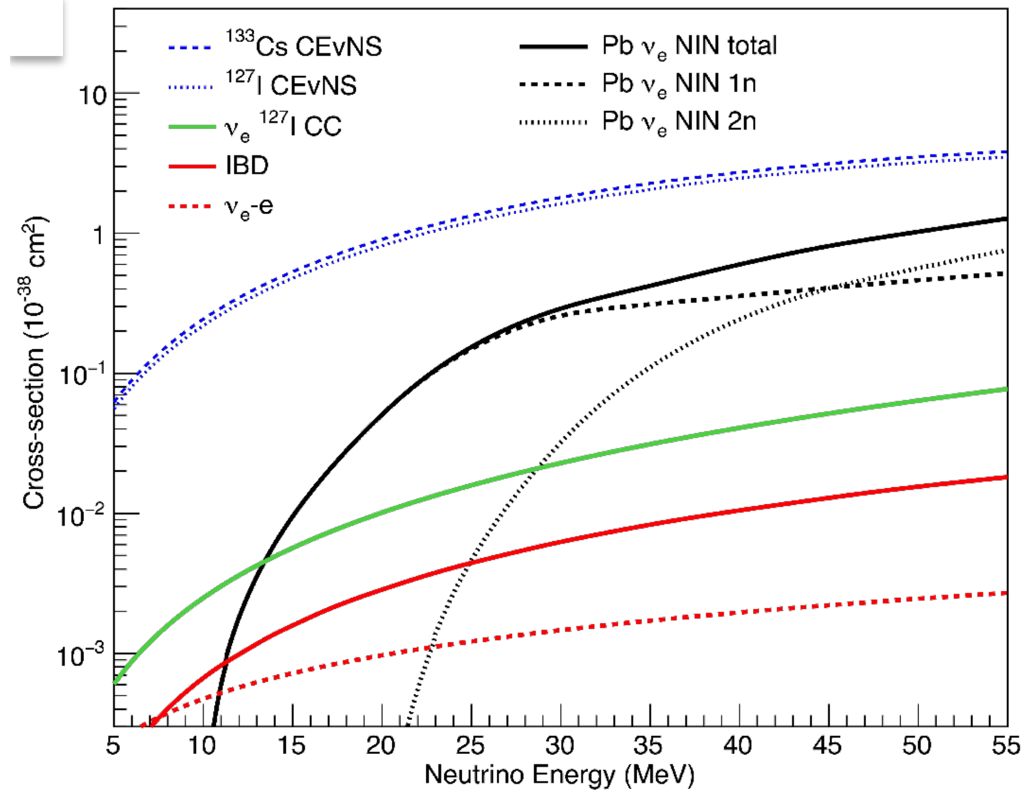
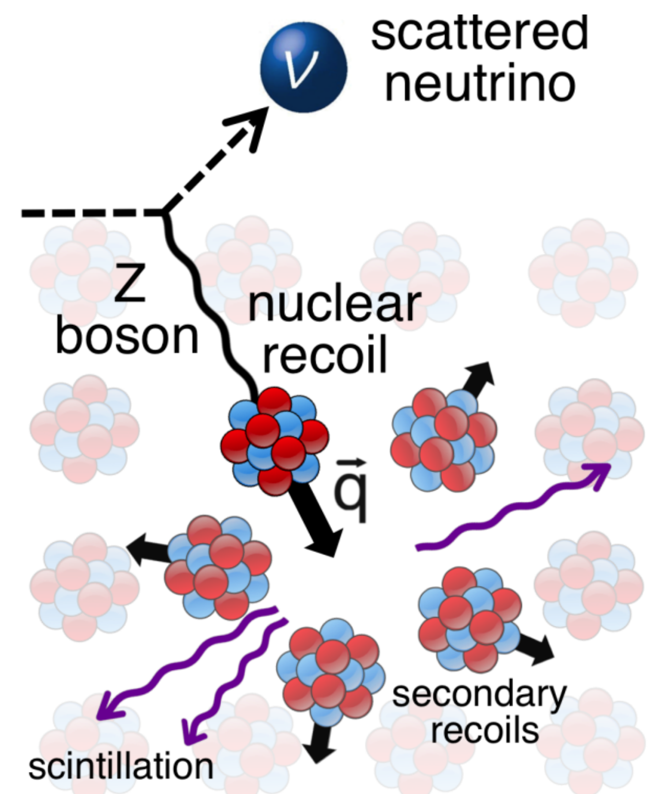
Coherent Elastic Neutrino-Nucleus Scattering (CEvNS)

- 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

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

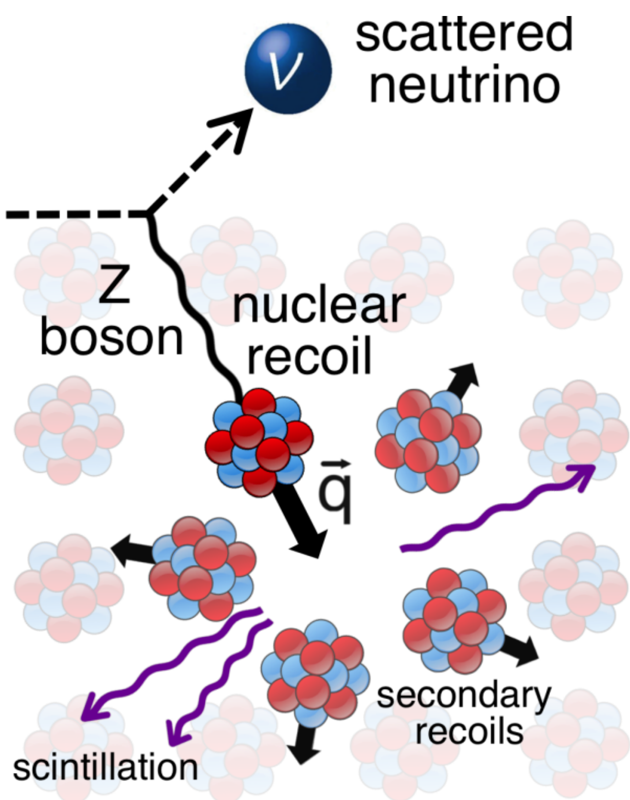
- Searches ongoing using both stopped-pion and reactor neutrino sources

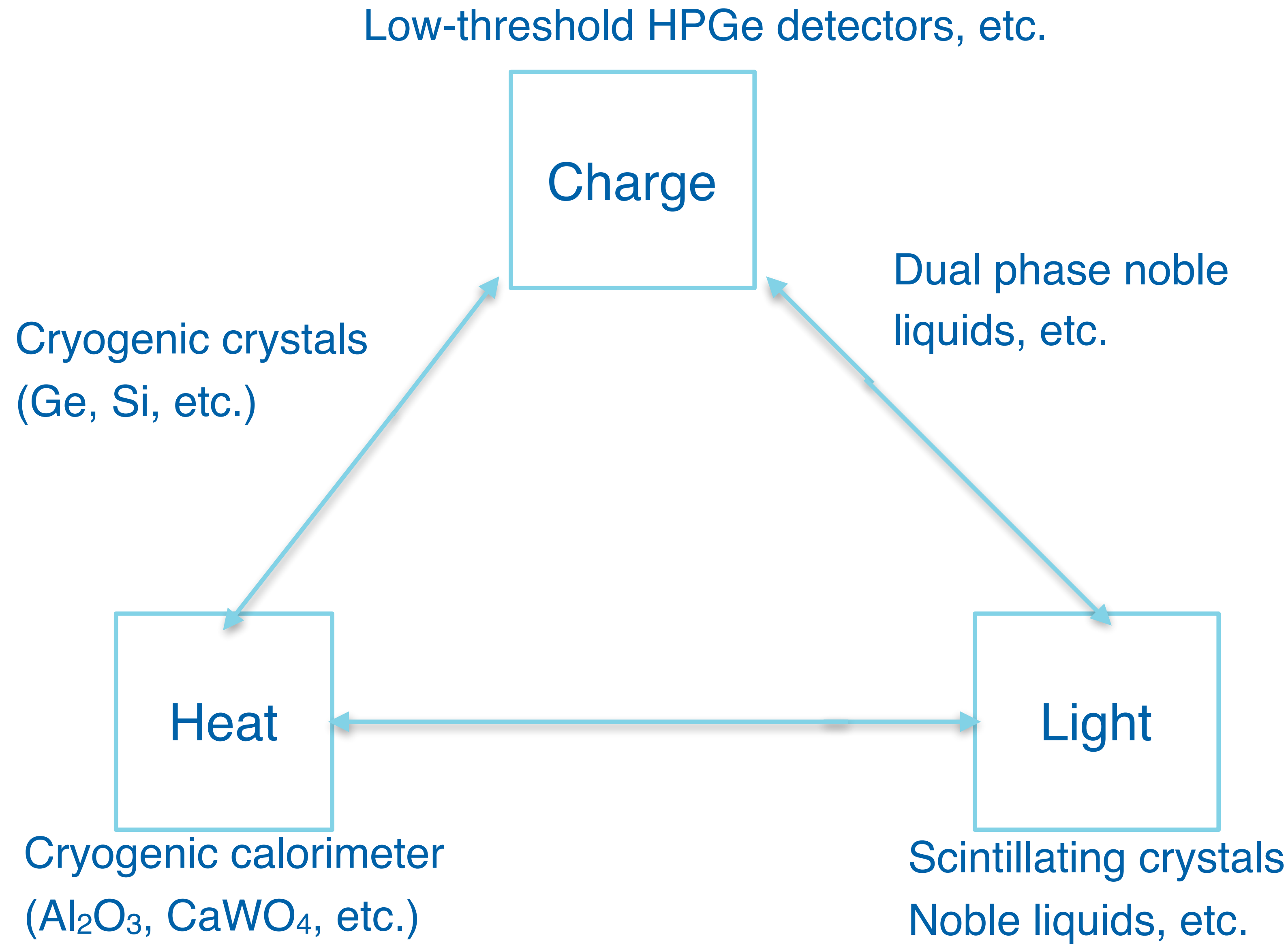




D. Akimov et al. (COHERENT). Science 357, 1123-1126 (2017)

Detecting CEvNS

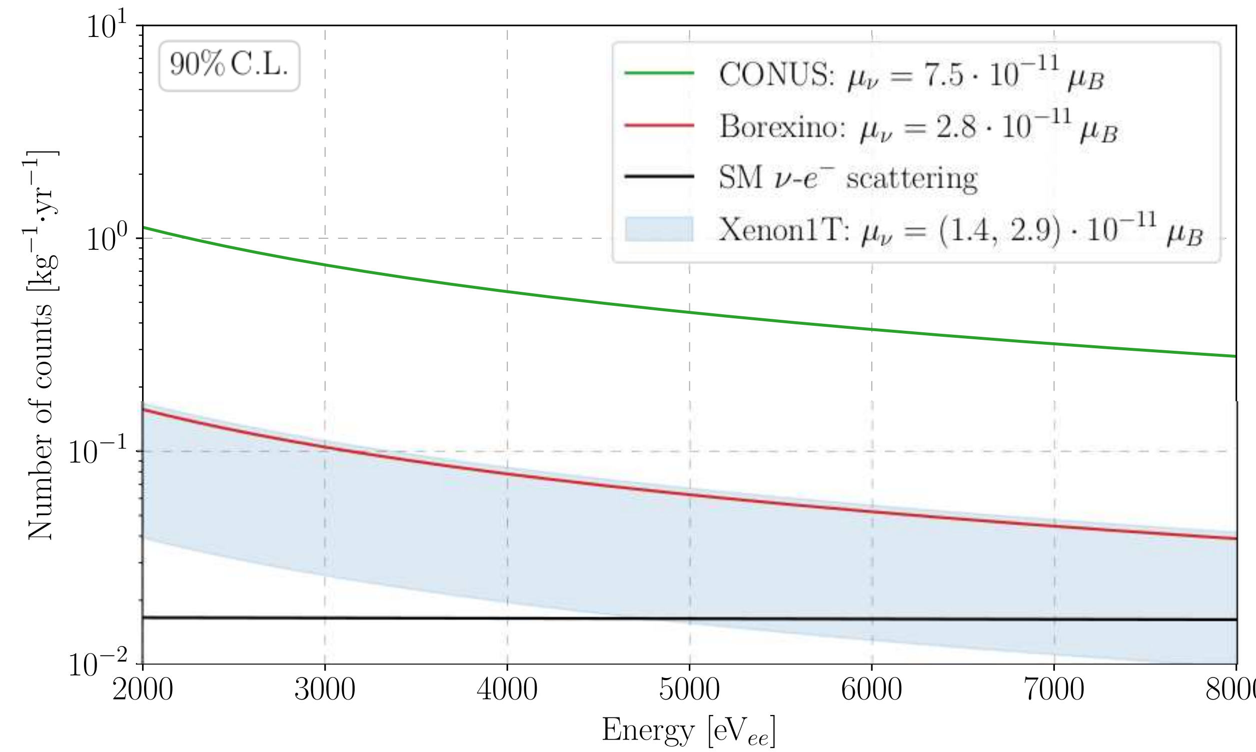




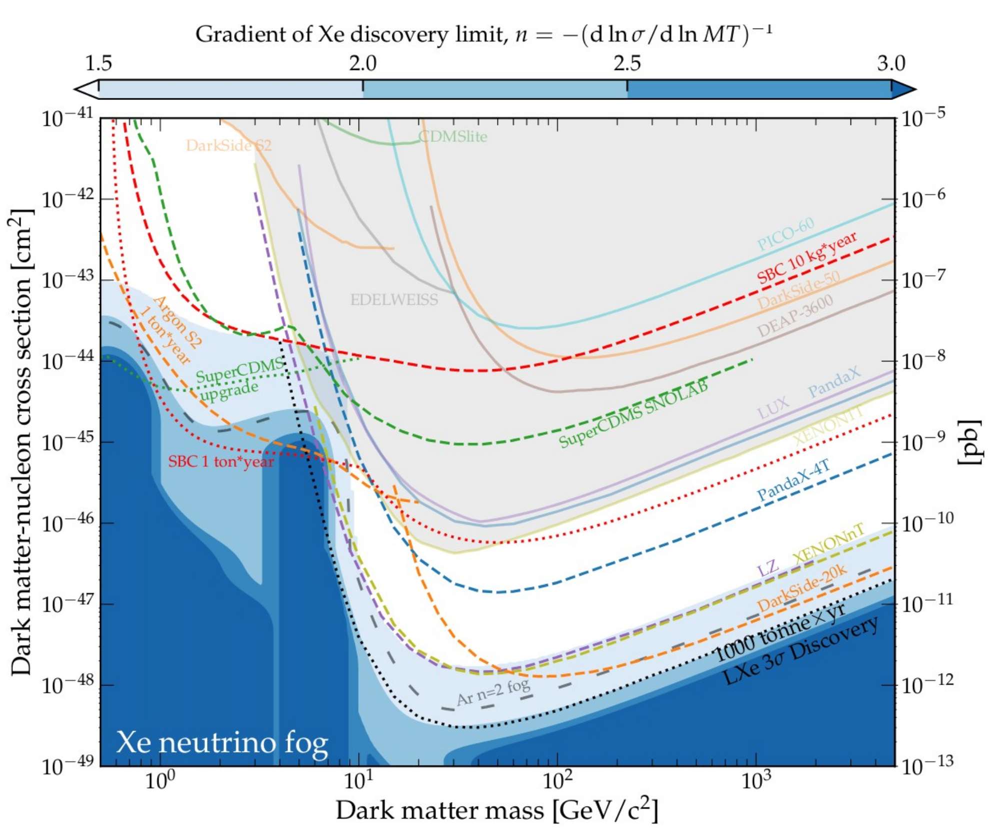
- Large CEvNS cross section allows for small detectors to measure neutrinos
  - Improvements come in larger mass (i.e. for noble liquid detectors) or lower energy thresholds (i.e. for cryogenic bolometers)
- Maximum nuclear recoil energy $T_{max} \sim E^2_{nu}/M$
- Understanding quenching factor = E_{meas}/E_{nr}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

Physics Motivation for CEvNS

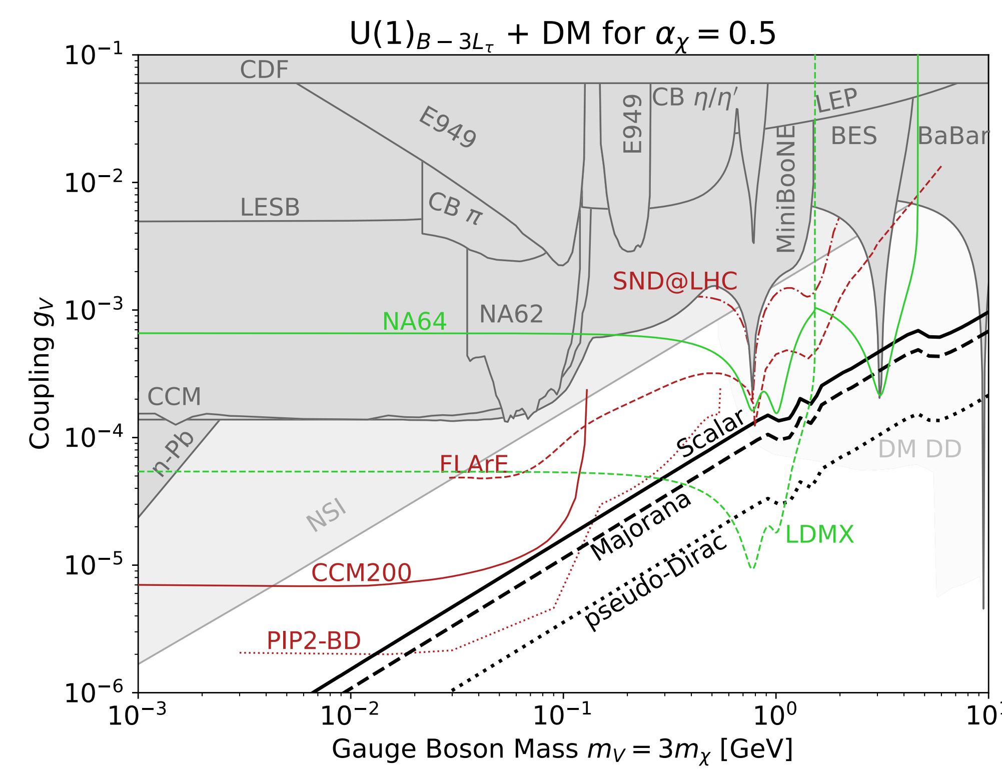
- CEvNS is Standard Model process, opens doors for new physics searches
  - Neutrino magnetic moment, non-standard interactions, etc.
- Dark matter and dark sectors
  - “Neutrino fog” for dark matter direct detection experiments



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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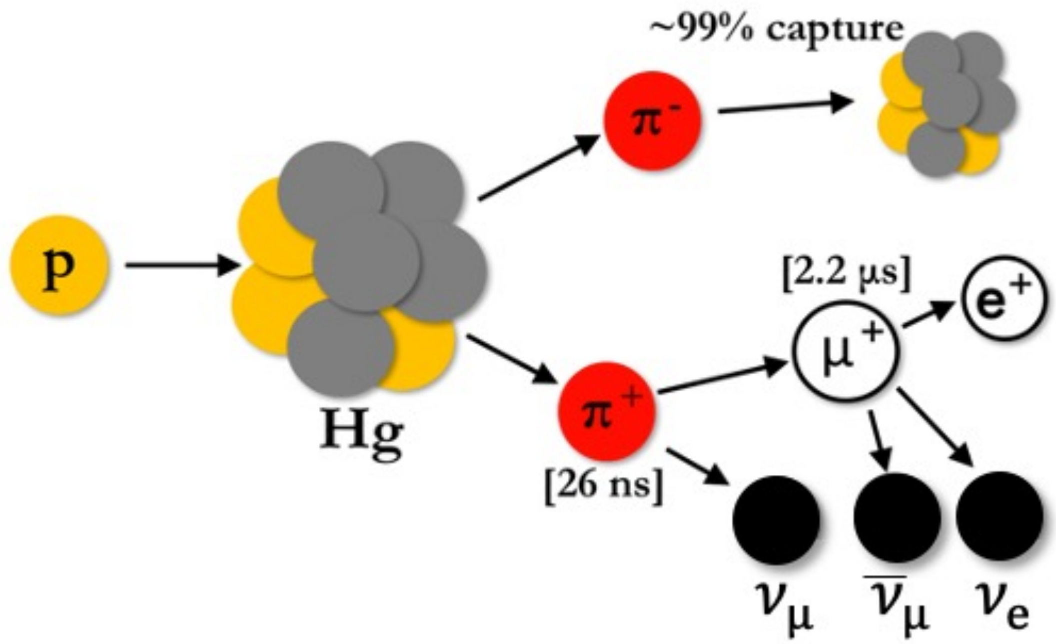
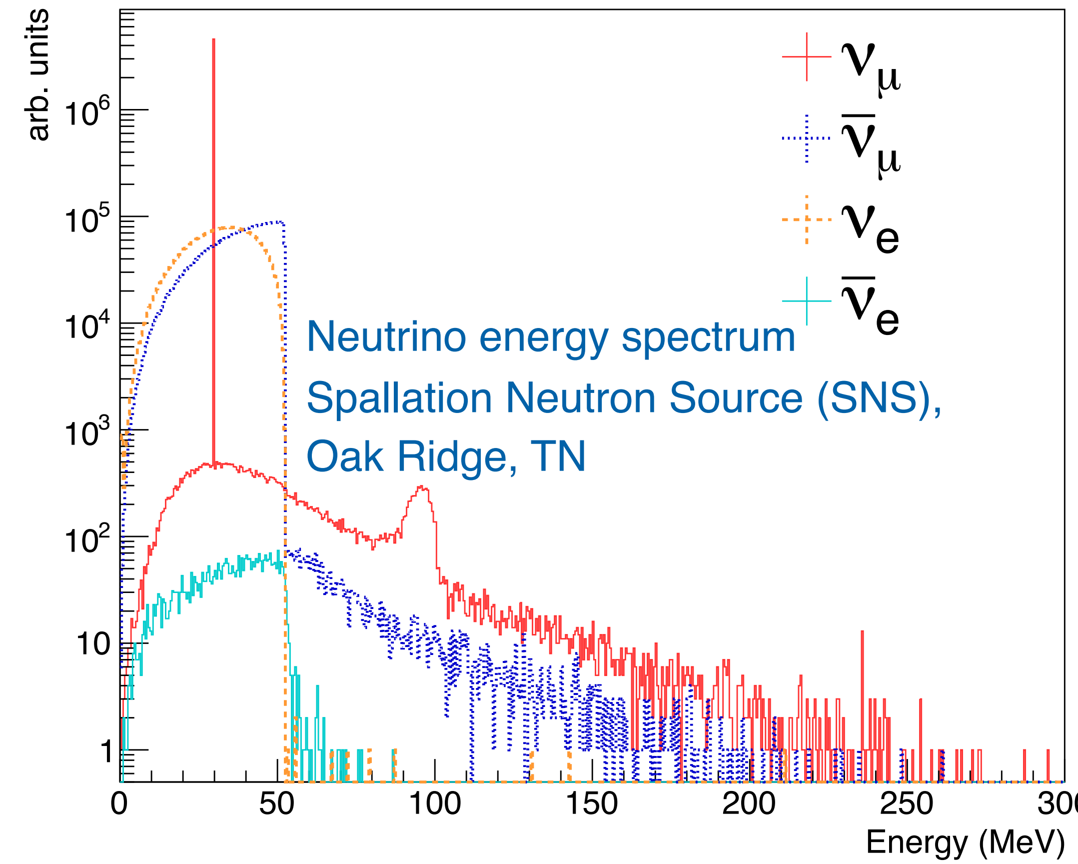
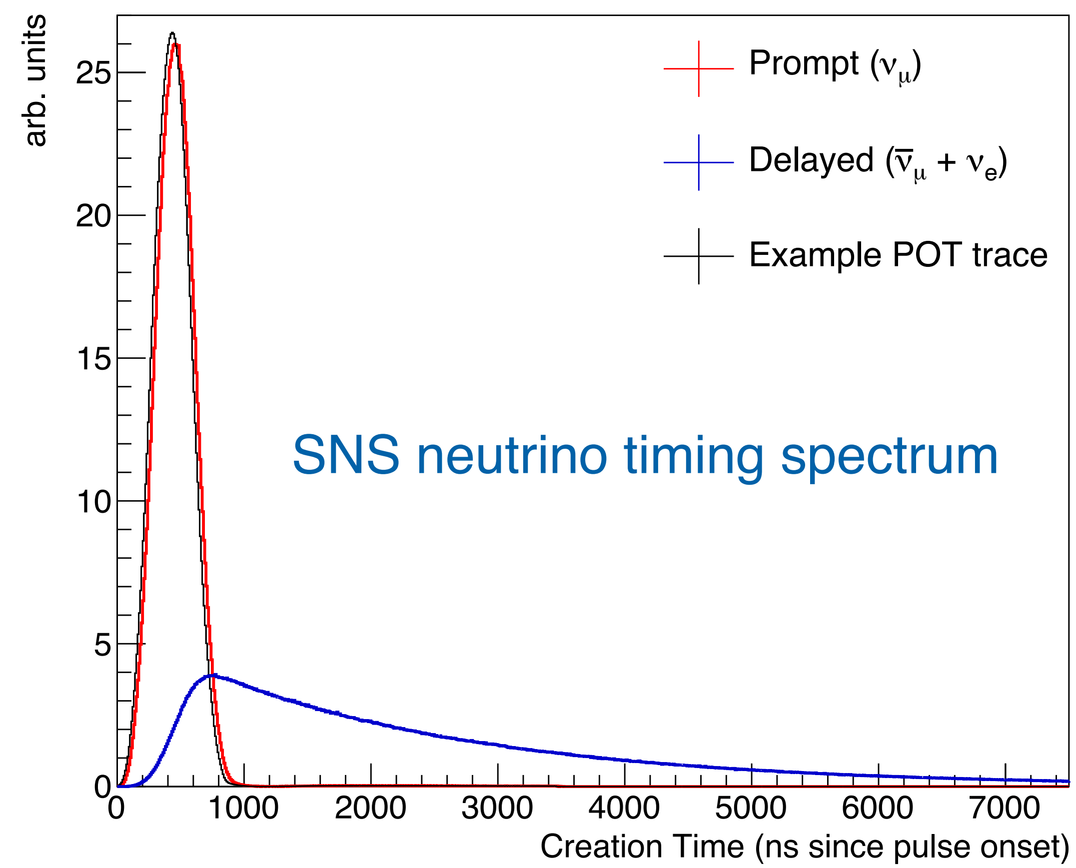
Stopped-Pion Neutrino Sources





- 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

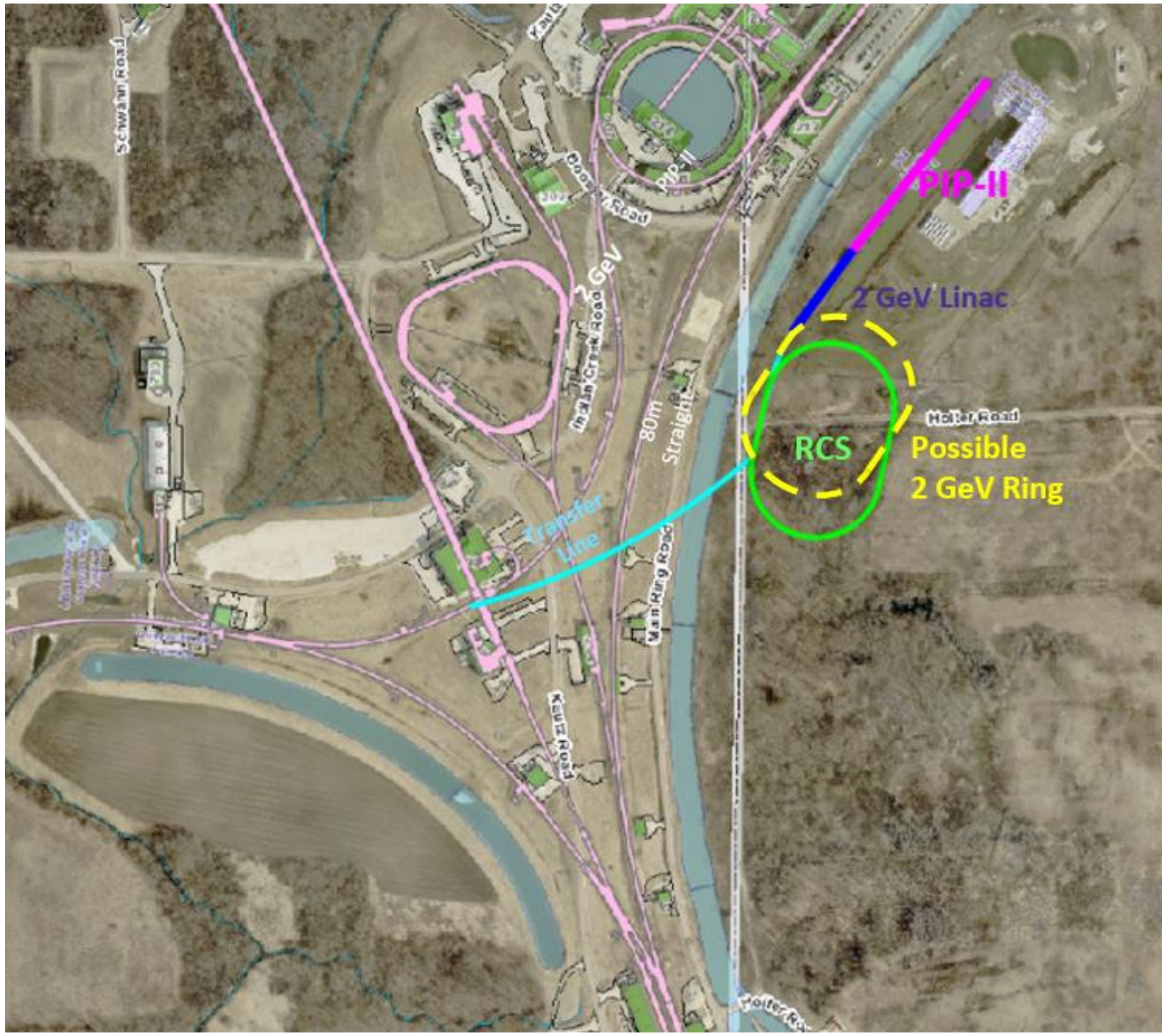
1. Upgrades to Main Injector accelerator systems and infrastructure to enable beam power above 1.2MW through faster cycle time and efficient operations of the complex with the aim of achieving DUNE goals as fast as possible, performed as series of AIP and GPP between 2024 and 2032.
2. Accelerated profile 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.

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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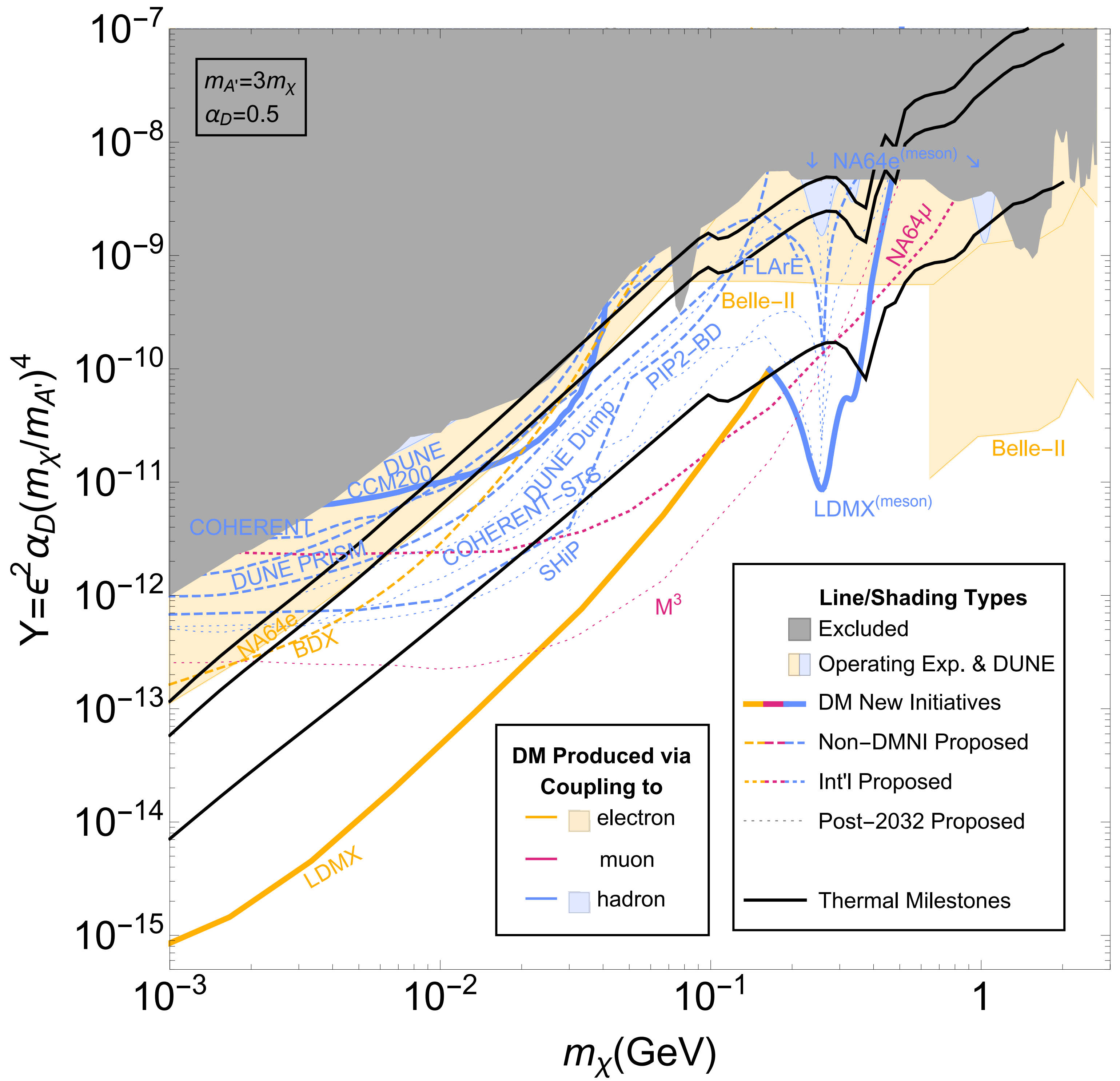
PIP2-BD Vector Portal Dark Matter Search



arXiv:2209.04671

More Information

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

M. Toups,[1,*] R.G. Van de Water,[2,*] Brian Batell,[3] S.J. Brice,[1] Patrick deNiverville,[2] Jeff Eldred,[1] Roni Harnik,[1] Kevin J. Kelly,[1] Tom Kobilarcik,[1] Gordan Krnjaic,[1] B. R. Littlejohn,[4] Bill Louis,[2] Pedro A. N. Machado,[1] Z. Pavlovic,[1] Bill Pellico,[1] Michael Shaevitz,[5] P. Snopok,[4] Rex Tayloe,[6] R. T. Thornton,[2] Jacob Zettlemoyer,[1] and Bob Zwaska[1]

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[6] *Indiana University, Bloomington, IN 47405, USA*

Thank you!

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- Large scintillation yield of 40 photons/keV
- Well-measured quenching factor
  - Conversion between nuclear recoil response and scintillation response
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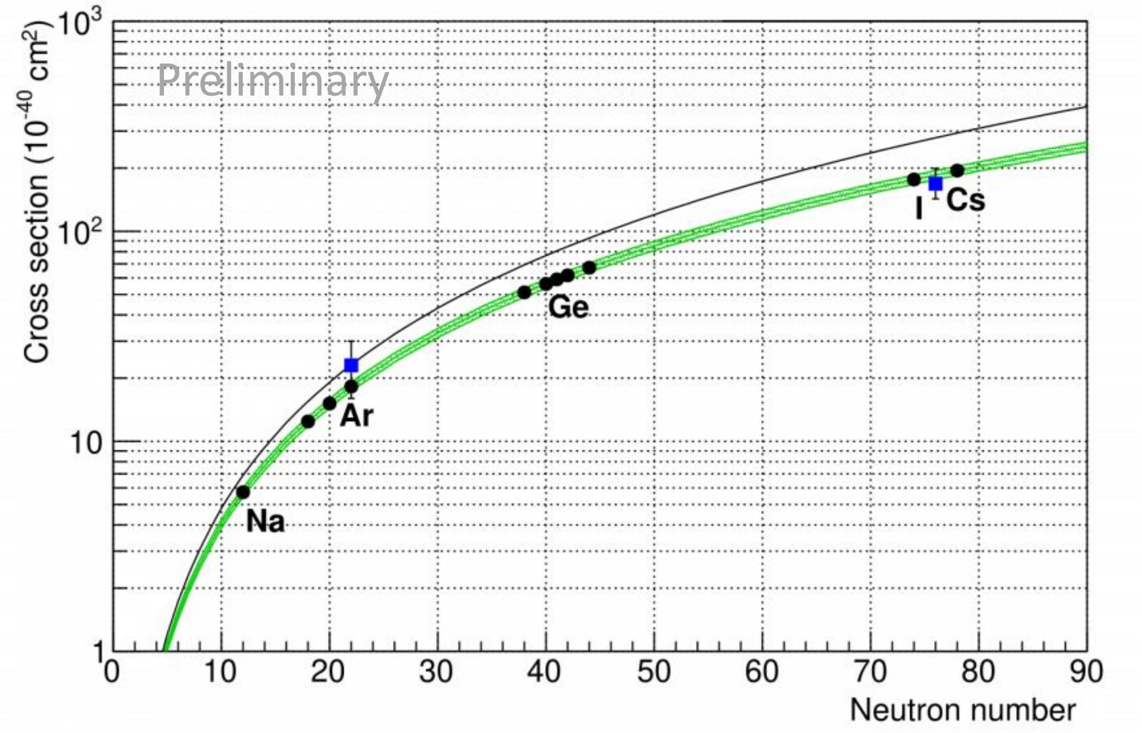
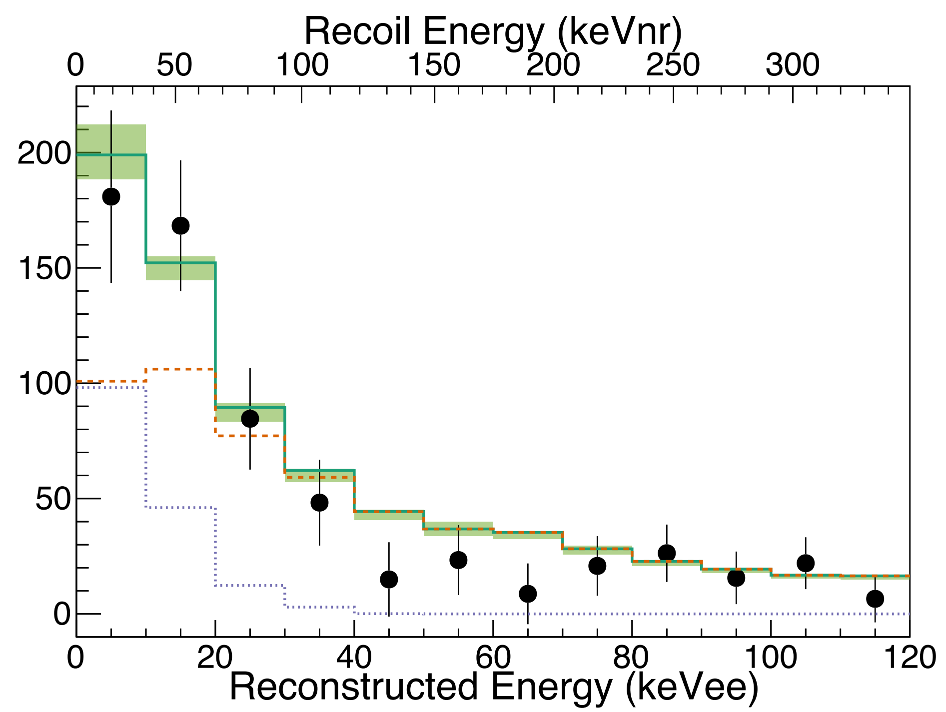


D. Pershey, Magnificent CEvNS 2020



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

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- 5 year run for each accelerator scenario