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PIP2-BD: Searches for New Physics with a Stopped-pion Neutrino Source at an Upgraded Fermilab Accelerator Complex

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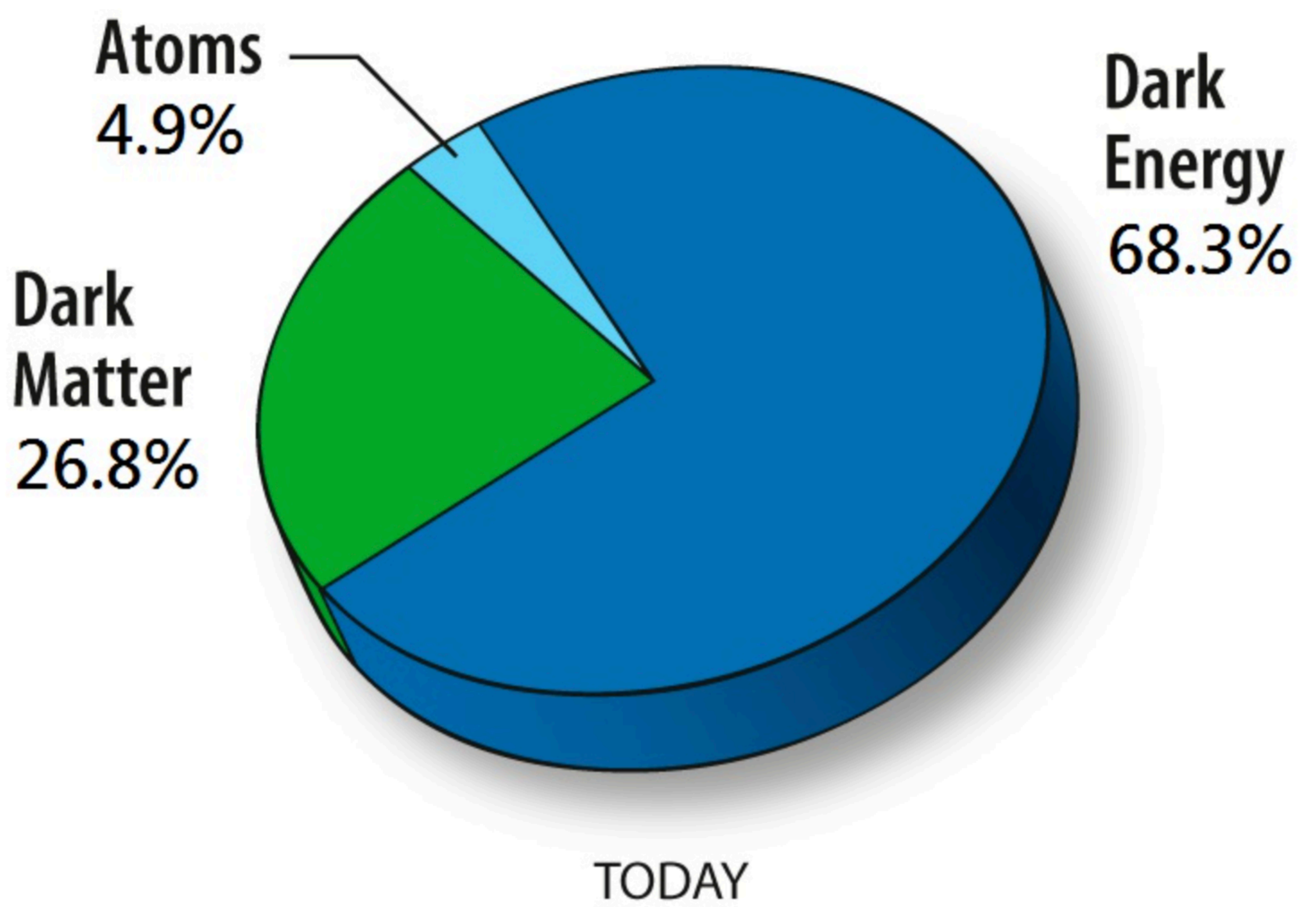
Workshop on a Future Muon Program at Fermilab

California Institute of Technology, Pasadena, CA

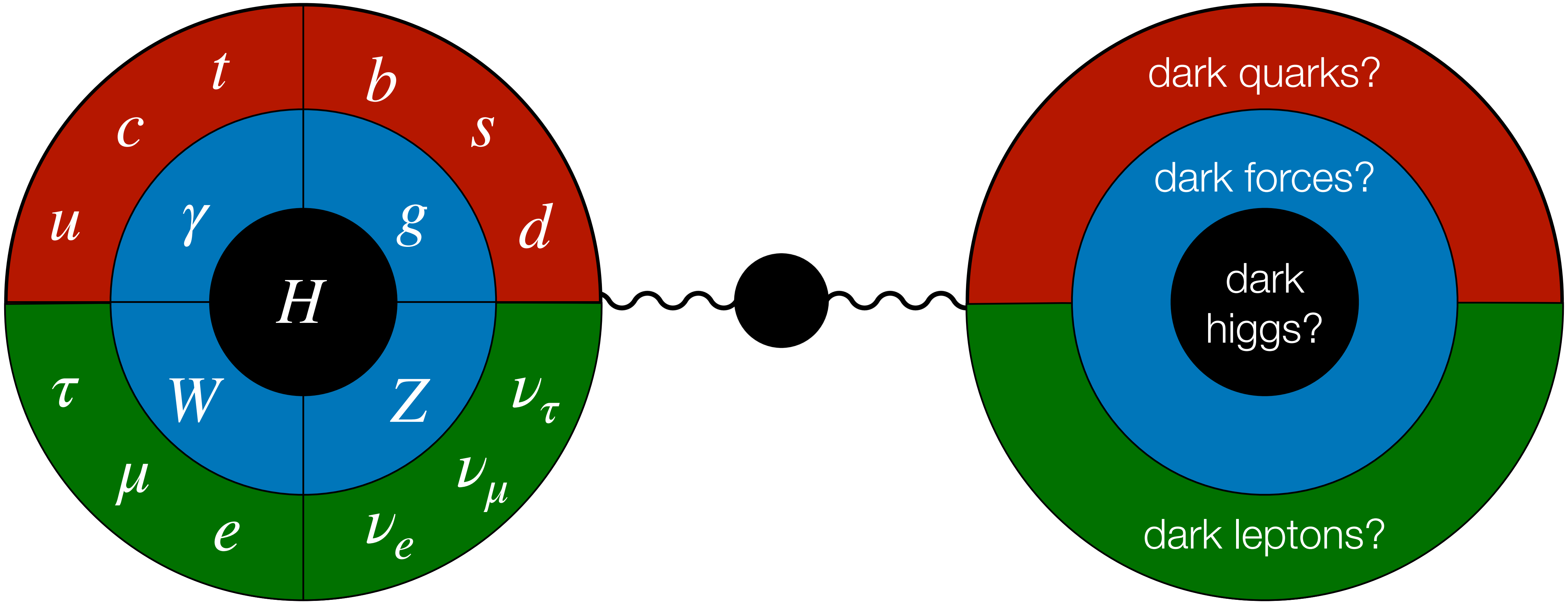
March 29, 2023

The Known Universe



A Dark Sector?

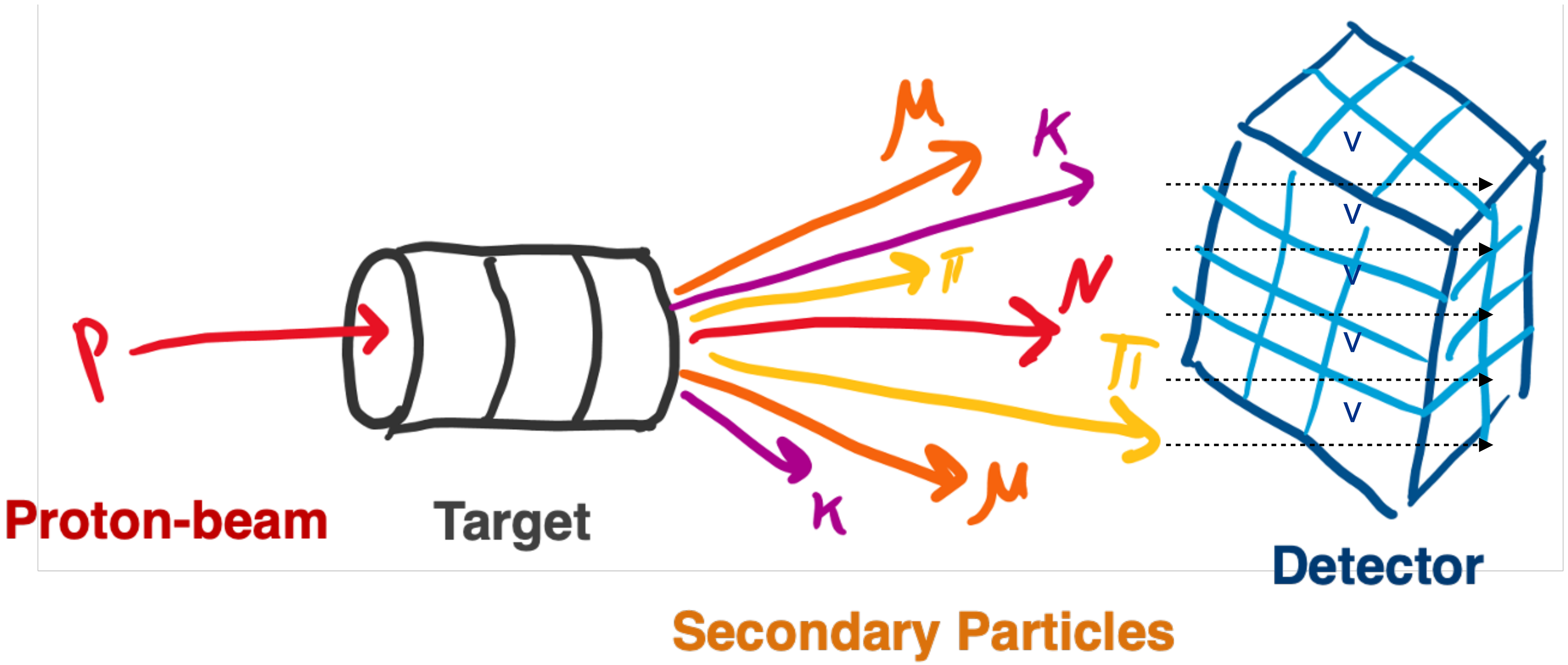
- A dark sector is motivated by the existence of dark matter



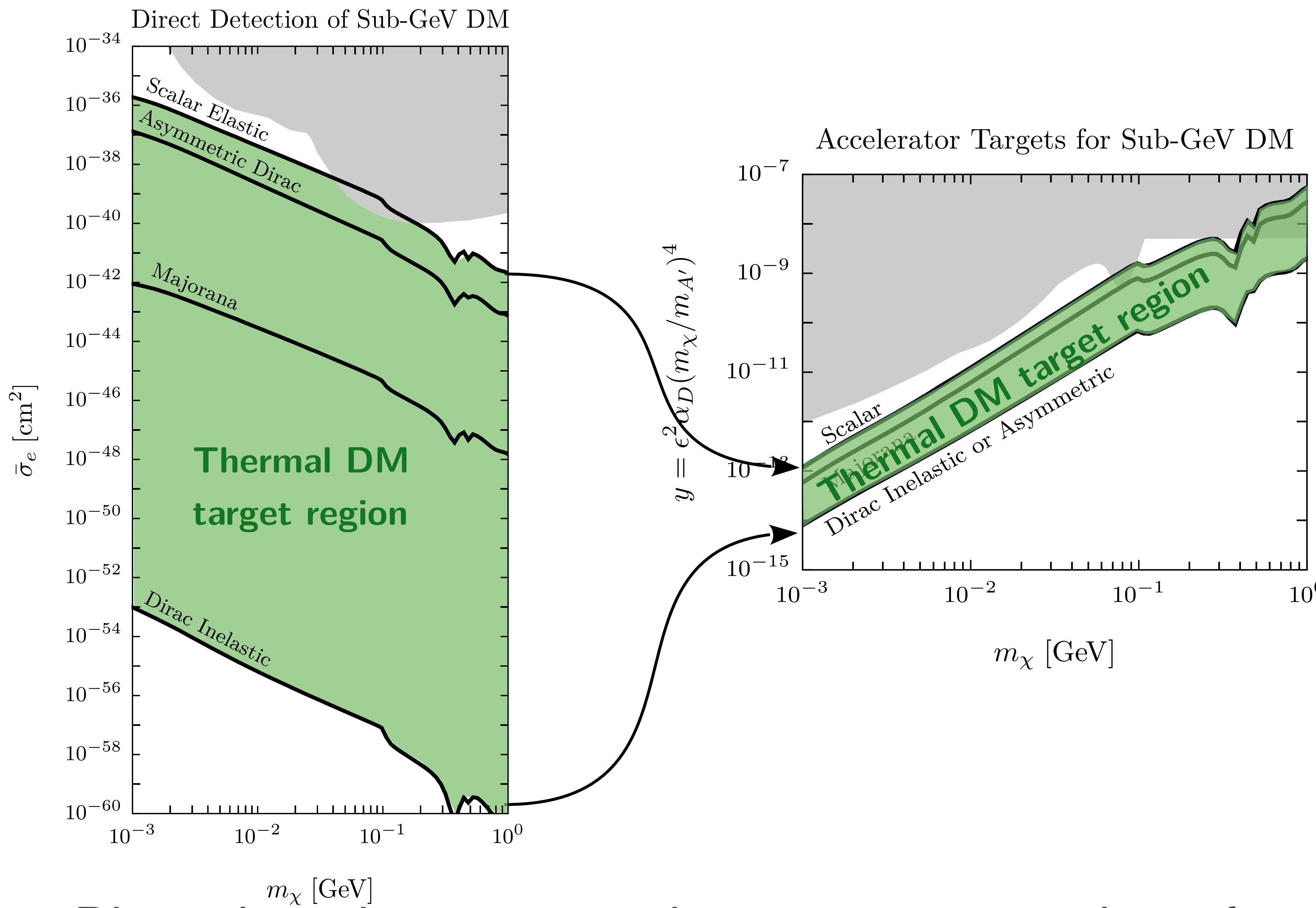
arXiv:2209.04671

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 meson-decay channels as neutrino production from accelerator-based neutrino beams



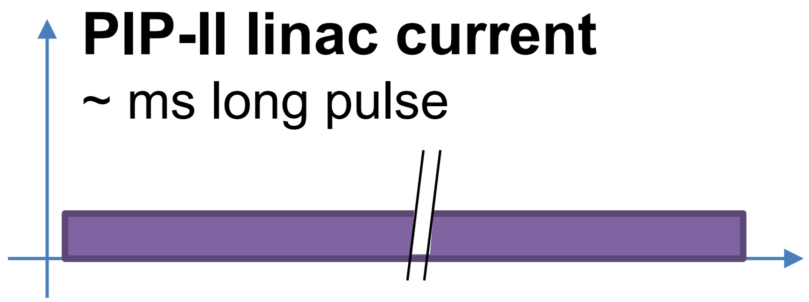
Connections to Direct Detection DM Searches

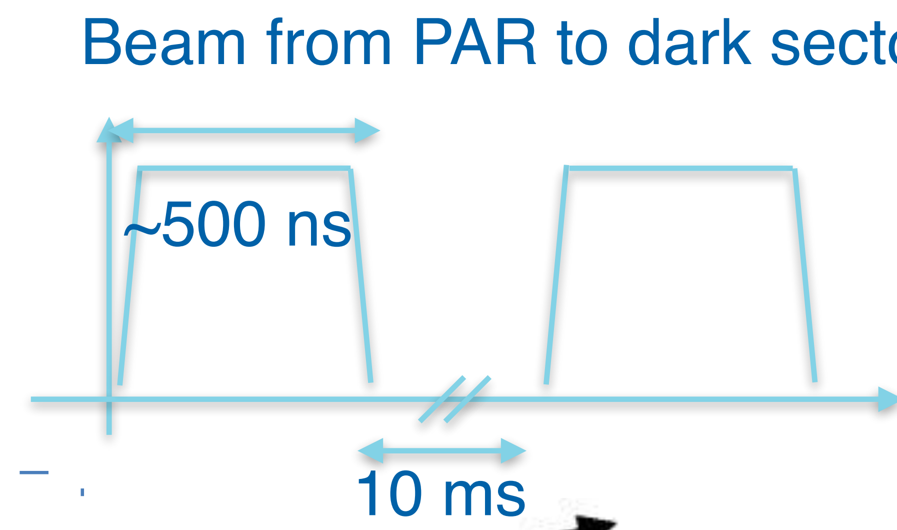


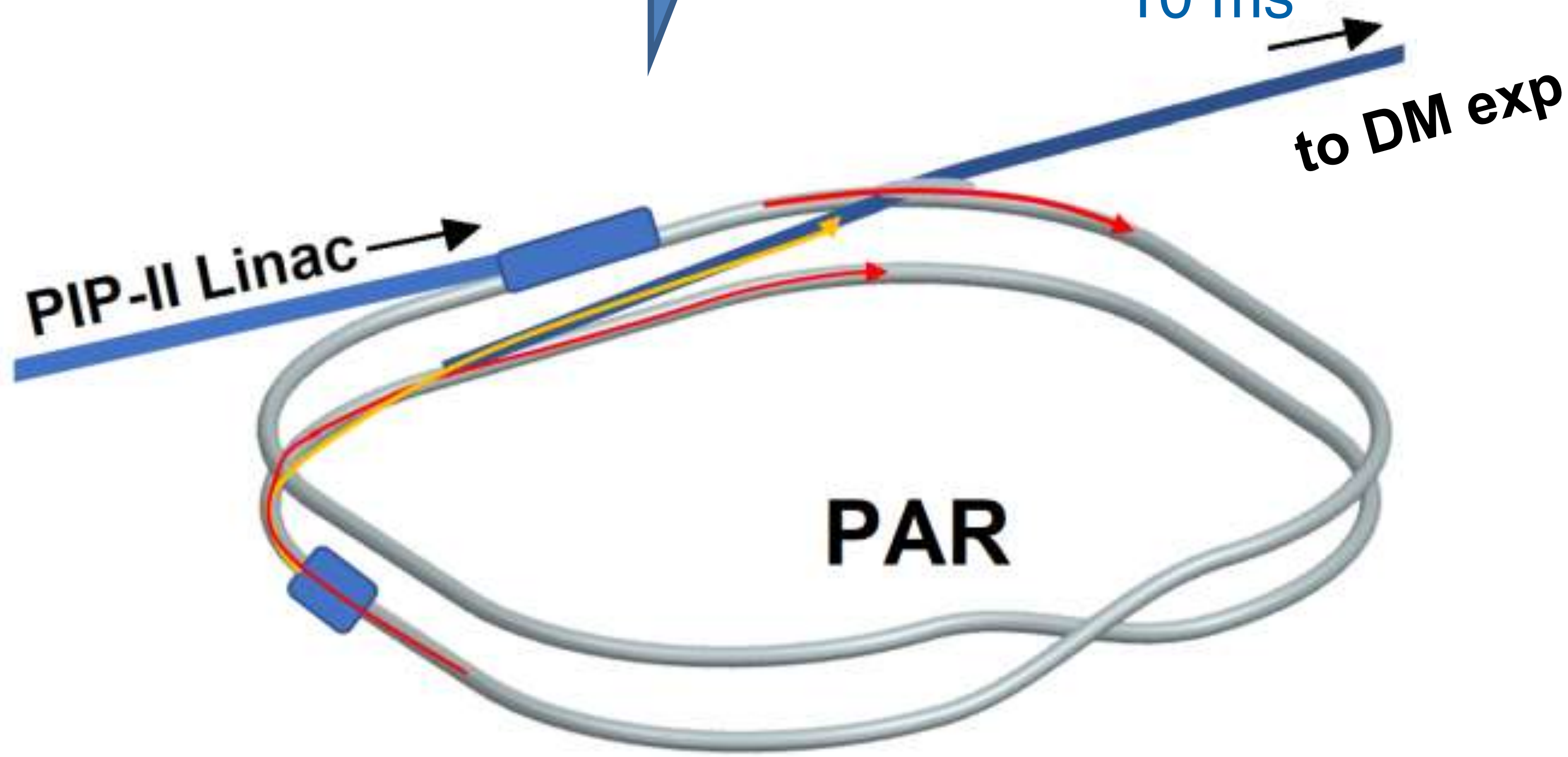
- Direct detection cross-section spans many orders of magnitude due to effects such as DM velocity suppression or spin suppression, which are significant for non-relativistic scattering

arXiv:2209.04671

PIP-II Accumulator Ring (PAR)





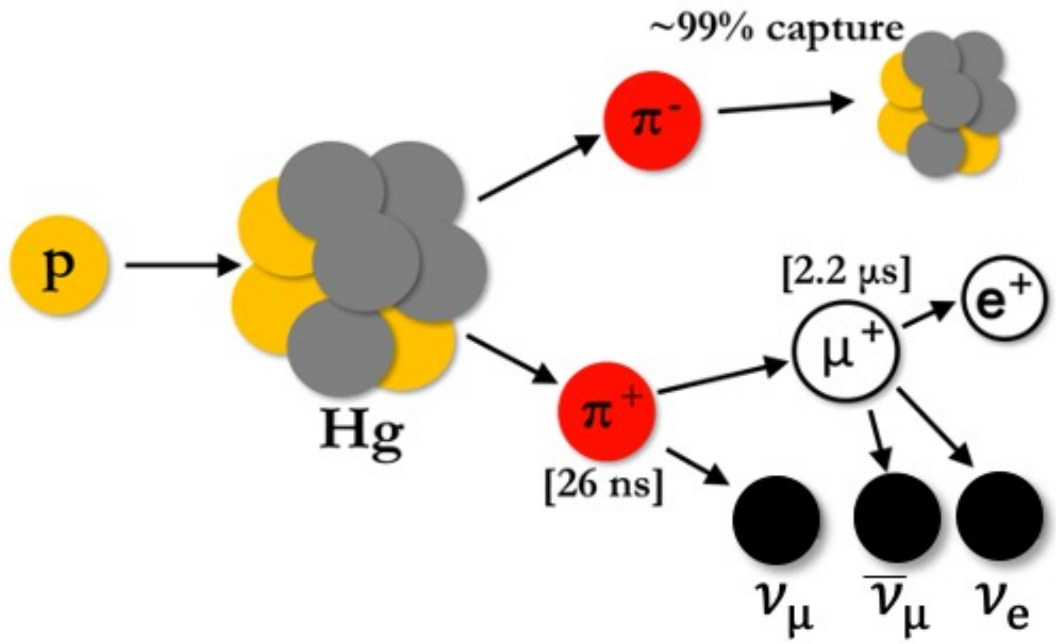


- Only a small percentage of protons (1.1%) from PIP-II needed to support DUNE

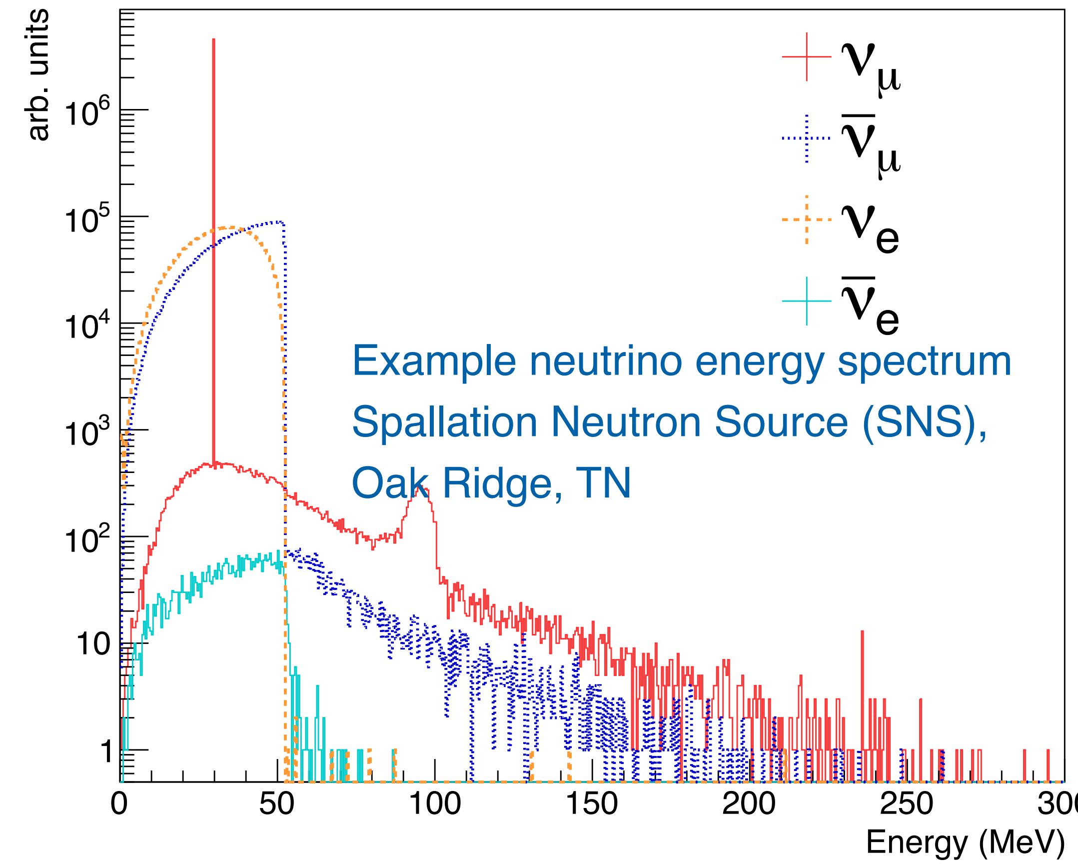
- Can we leverage existing upgrade plans to search for other exciting physics at Fermilab?
  - O(1 GeV) stopped-pion neutrino source program leveraging the available beam
  - Opportunity to build facility to maximize high-energy physics impact
  - PIP2-BD Snowmass 2022 White Paper: https://arxiv.org/pdf/2203.08079.pdf

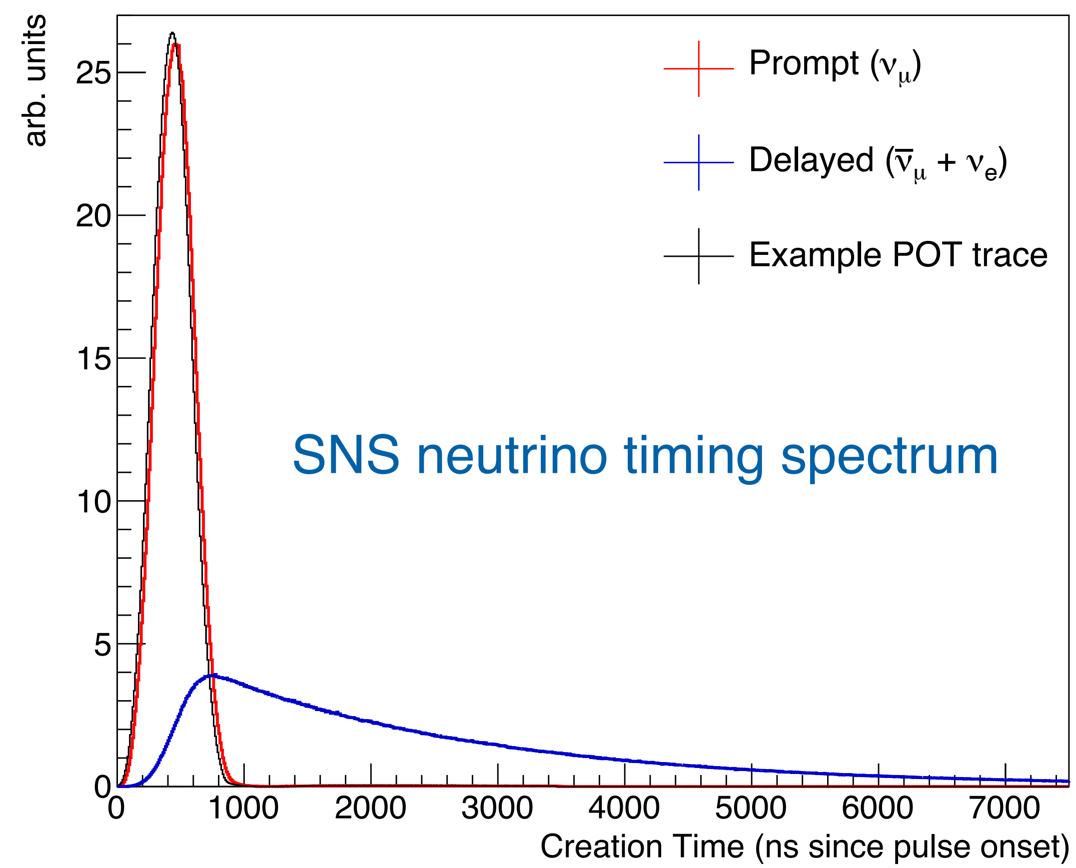
Stopped-pion Neutrino Sources

Stopped-Pion Neutrino Sources



- Neutrinos produced from pion decay-at-rest via proton collisions with target
- Large neutrino flux close to the source
- Steady-state background suppression via pulsed beam
- Physics accessible with these sources include
  - Light dark matter (LDM) / dark sector searches
  - Axion-like particle (ALP) searches
  - And other dark sector models!

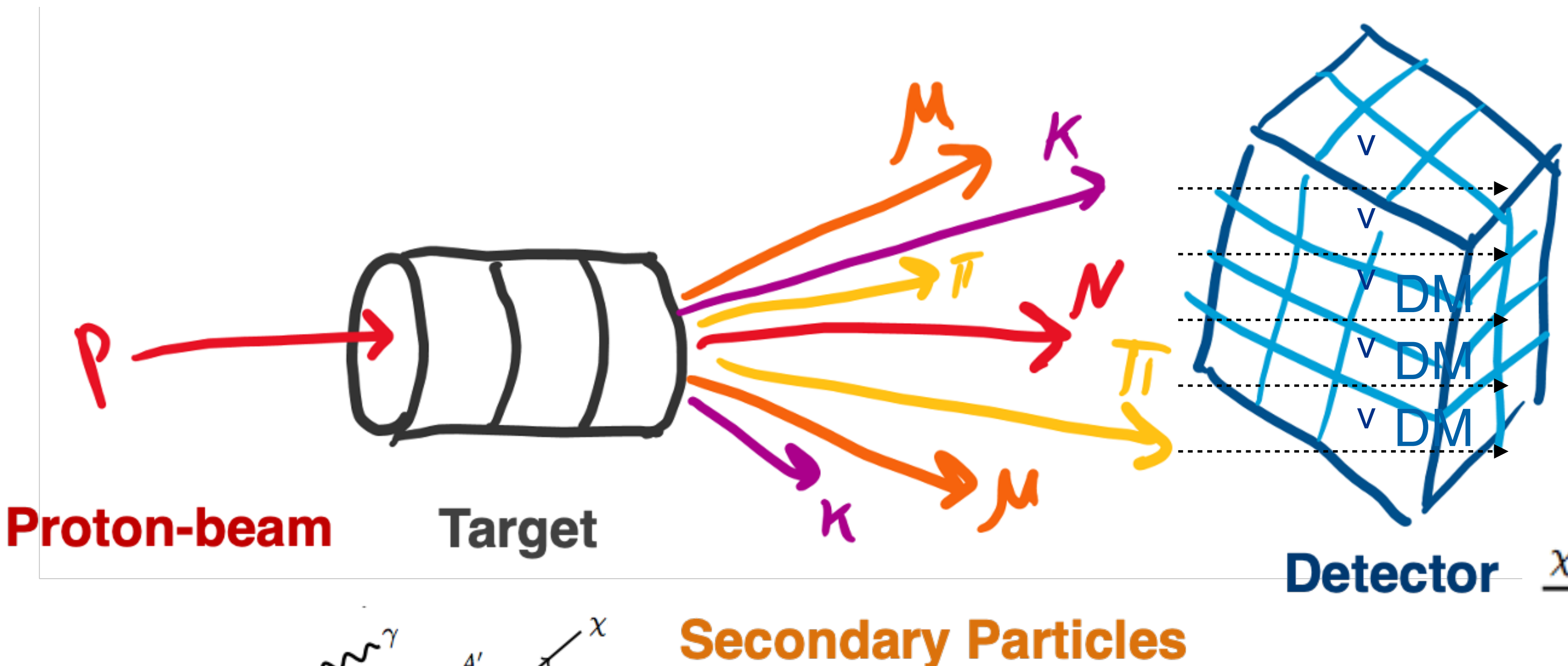




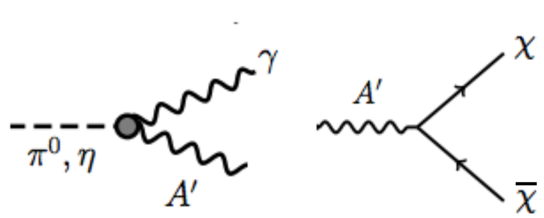
D. Akimov et al. (COHERENT) Phys. Rev. D (2022) 3, 032003

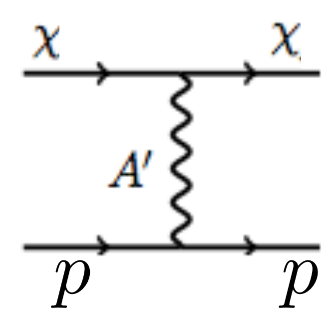
Leveraging Stopped Pion Sources for Dark Sector Searches

- How do we leverage a stopped-pion neutrino source for dark sector searches?
  - Detector capable of low energy, O(10 keV) detector thresholds
  - 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



Dark Photon



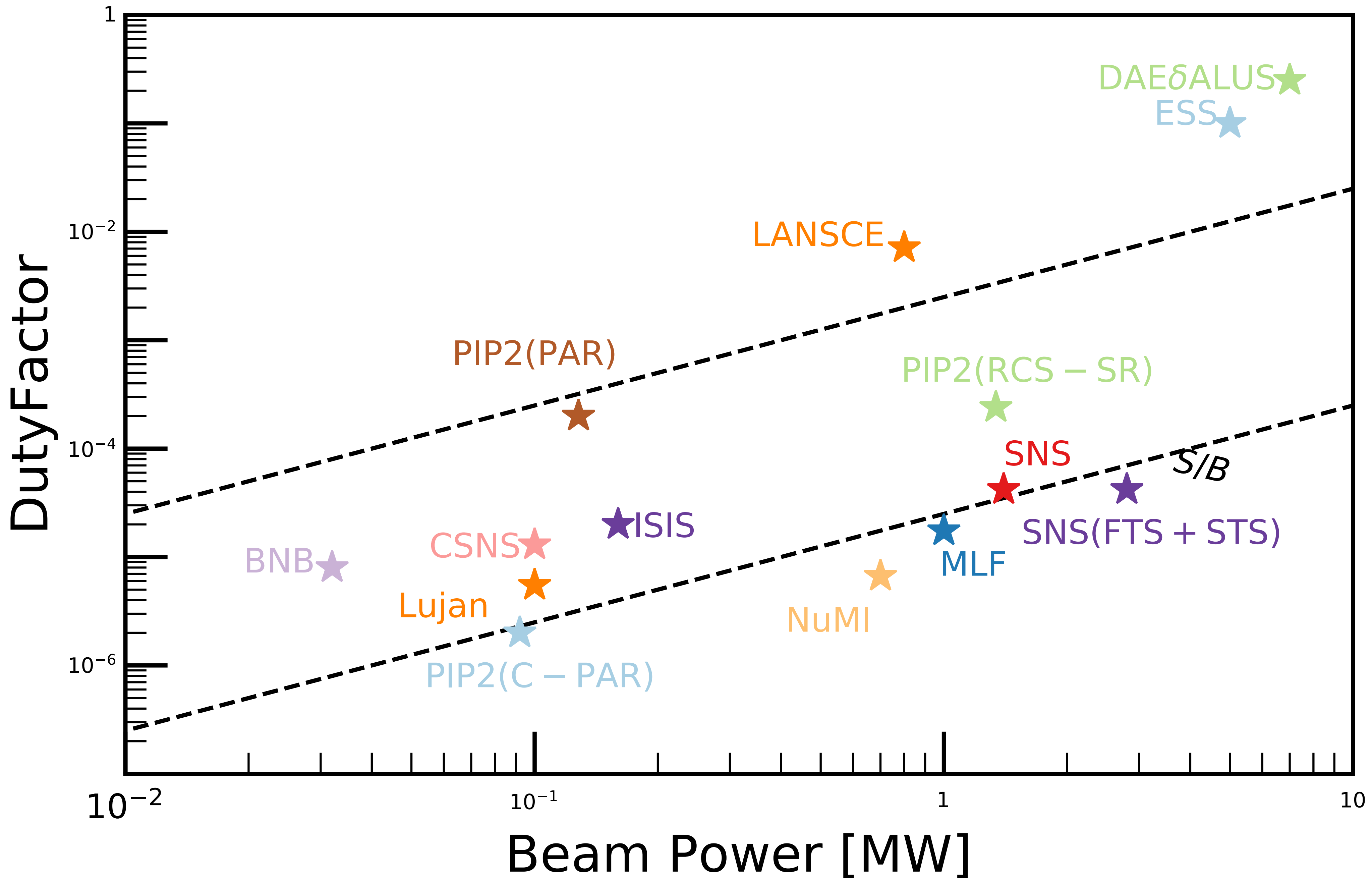


Creating a stopped-pion source with PIP-II: PIP2-BD

- Low mass dark sector searches are enabled at PIP-II with the addition of an accumulator ring on PIP-II, further upgrading the FNAL accelerator complex
  - We have studied three possible accelerator scenarios in advance of Snowmass 2022 that enable dark sector searches
  - PIP-II Accumulator Ring (PAR), Compact PIP-II Accumulator Ring (C-PAR), and Rapid Cycling Synchrotron Storage Ring (RCS-SR)
- PAR and C-PAR are realizable in the timeframe of the start of the PIP-II accelerator and DUNE Phase I -> C-PAR has similar beam timing structure as AMF ring
- RCS-SR is a further upgrade on the timescale of DUNE Phase II -> similar

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

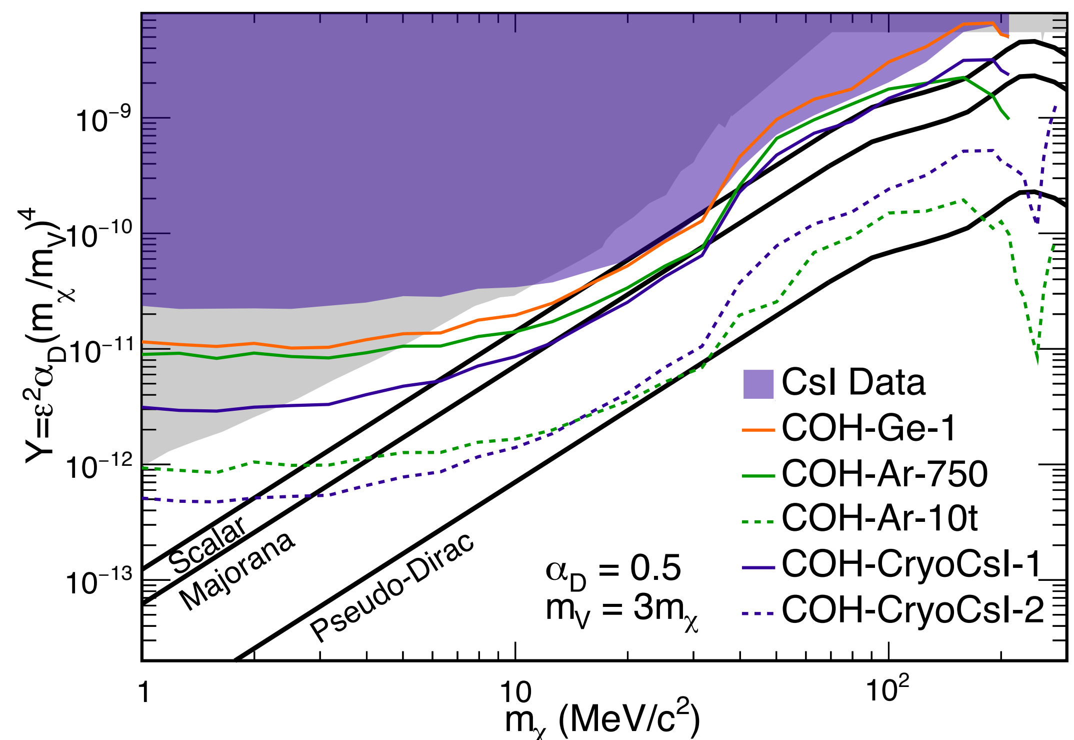
Future Stopped-pion Sources for Dark Sector Experiments



arxiv:2209.07480

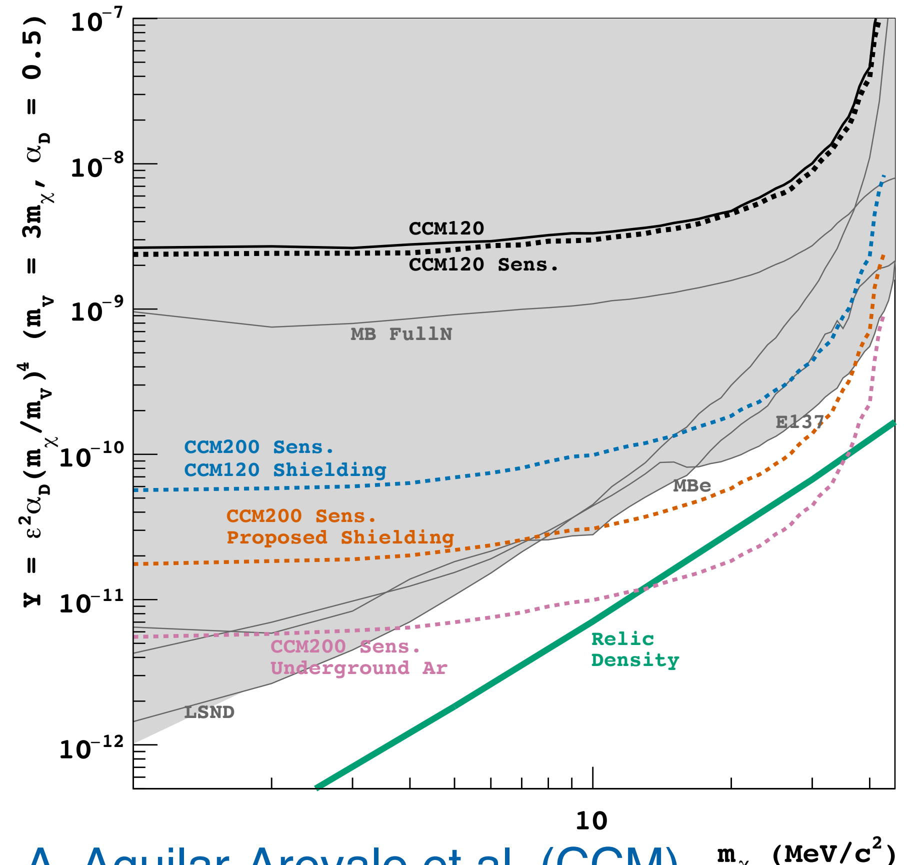
Capabilities of Stopped-pion sources for Dark Sector Searches

- 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 experiment at Oak Ridge National Laboratory recently set limits on vector-portal dark matter using 14.6 kg CsI[Na] detector data
- Coherent Captain-Mills (CCM) set limits with ton-scale single-phase liquid argon detector at Lujan beam at Los Alamos National Laboratory



D. Akimov et al, (COHERENT) arXiv:2110.11453[hep-ex]

D. Akimov et al, (COHERENT) arXiv:2205.12414[hep-ex]

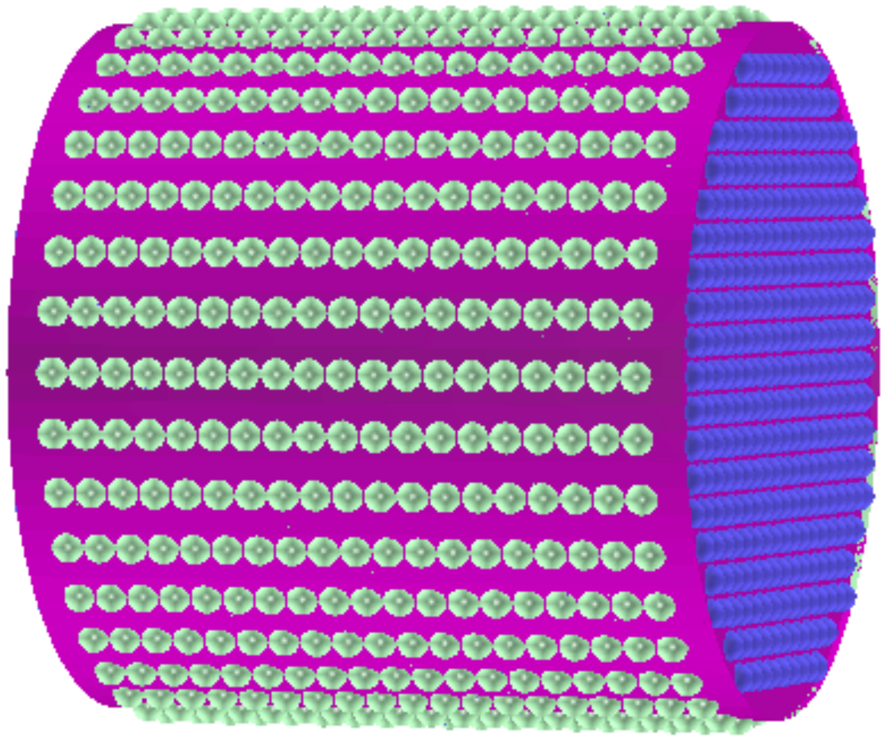


A. Aguilar-Arevalo et al. (CCM), arXiv:2105.14020

The PIP2-BD Experiment

Proposed Detector at PIP2-BD

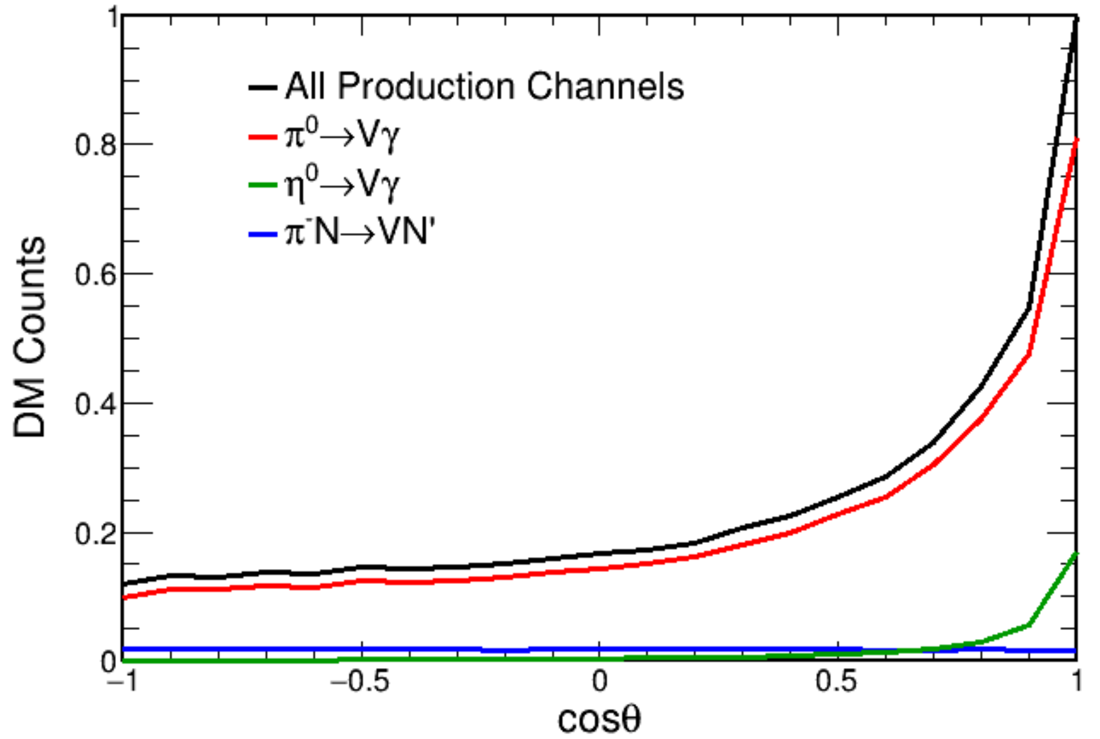
- Single-phase, scintillation only liquid argon (LAr) detector
- Fiducial volume - 4.5 m right cylinder inside box, **~100 tons LAr**
- Surround sides and endcaps of detector volume with TPB-coated 8” PMTs
  - TPB-coated reflector on sides and endcaps for photocoverage gaps
- Preliminary simulations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



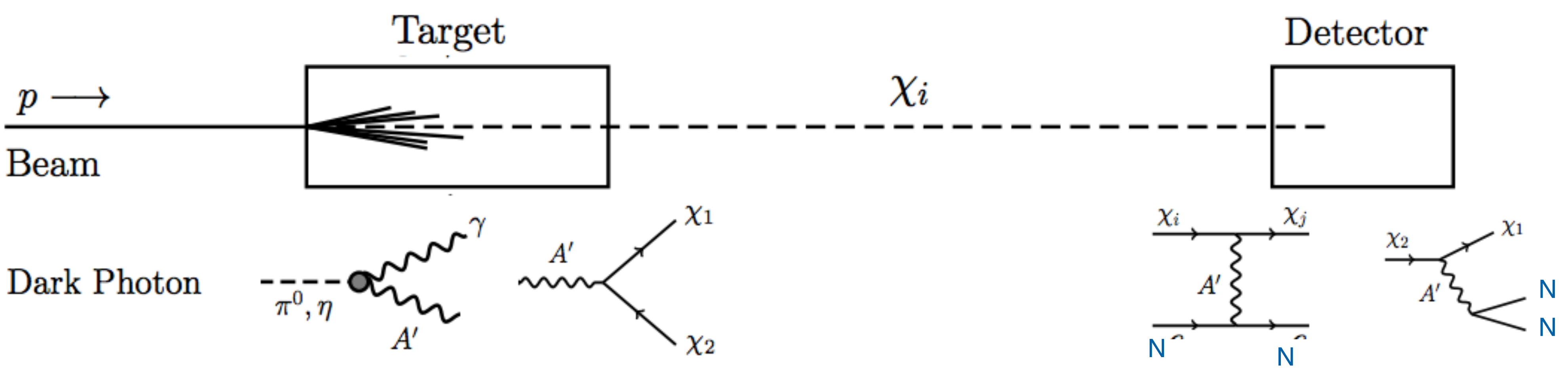
Dark Sector Searches with PIP2-BD

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

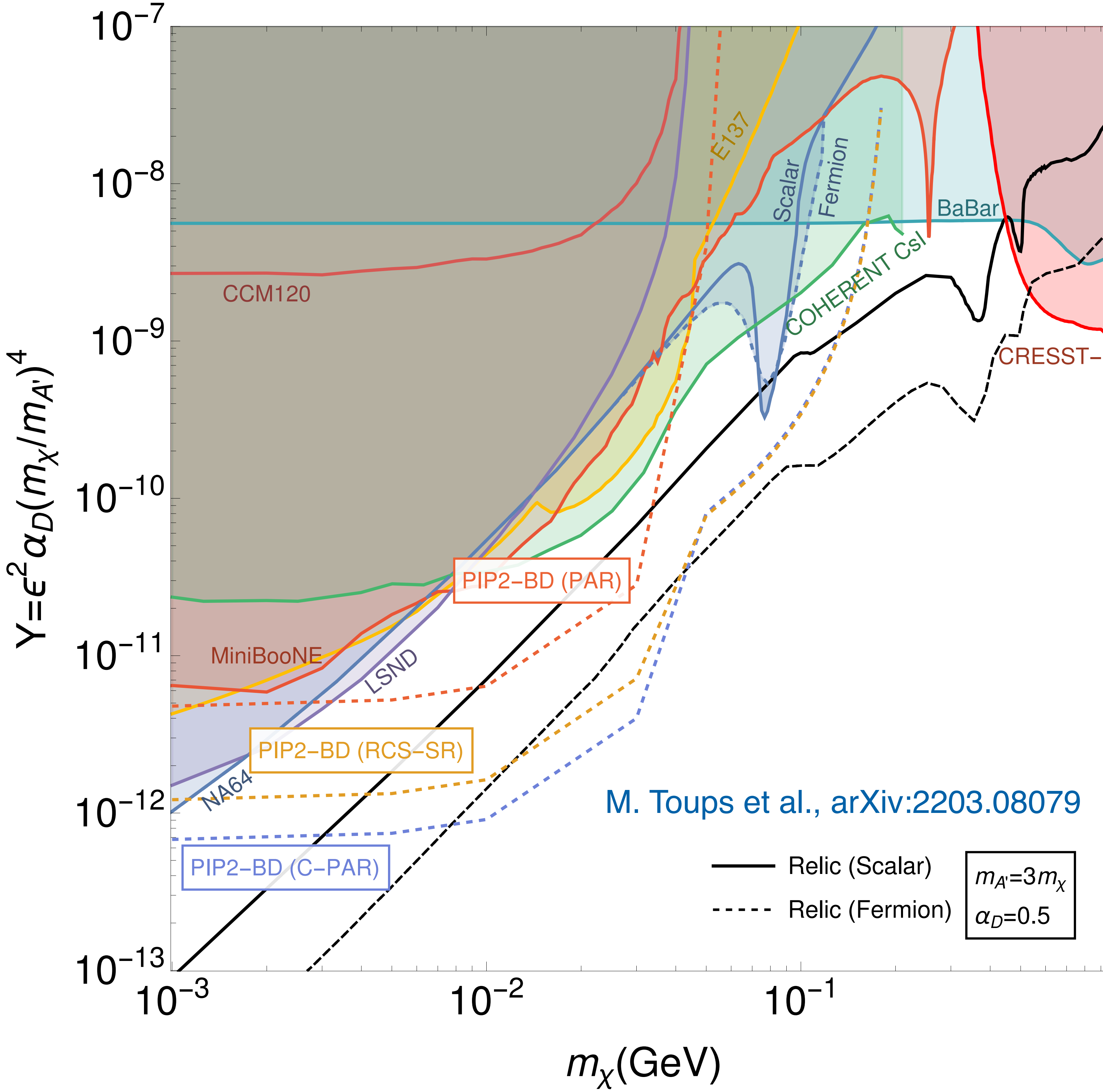


P. deNiverville et al., Phys. Rev. D 92 (2015) 095005

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

PIP2-BD Vector Portal Dark Matter Search

- Detector location 18 m downstream of target, on-axis
- 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



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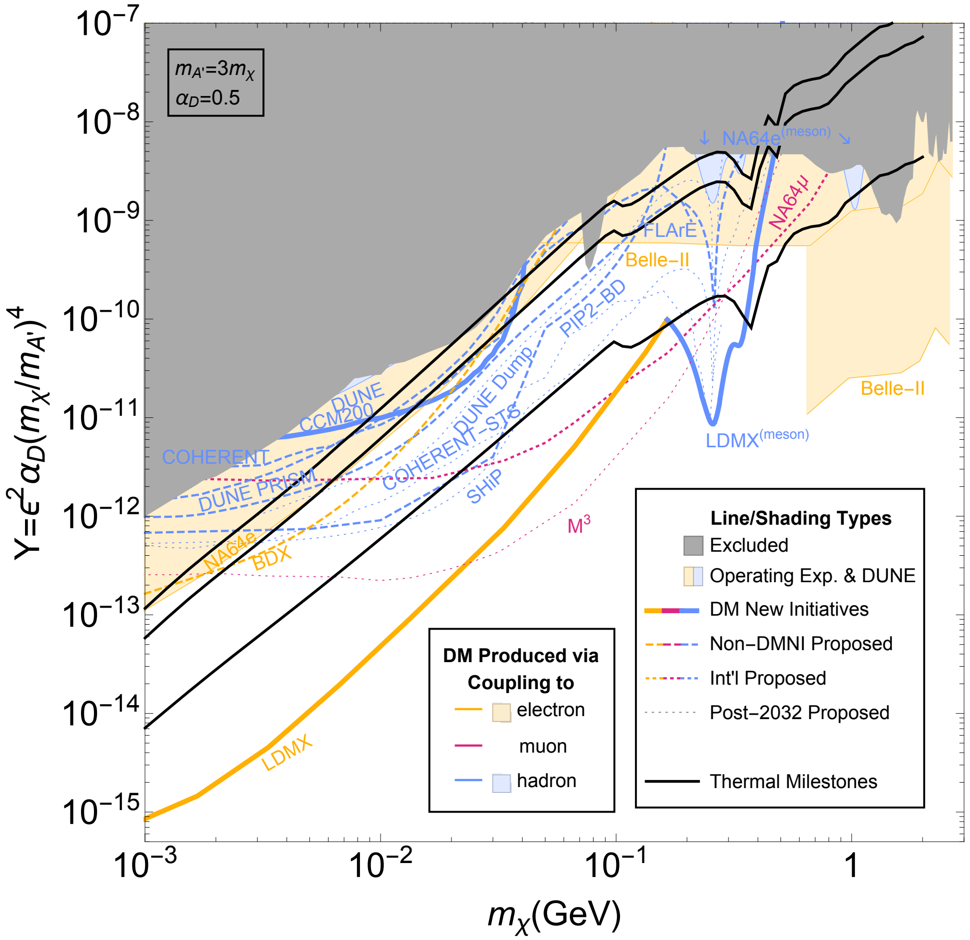
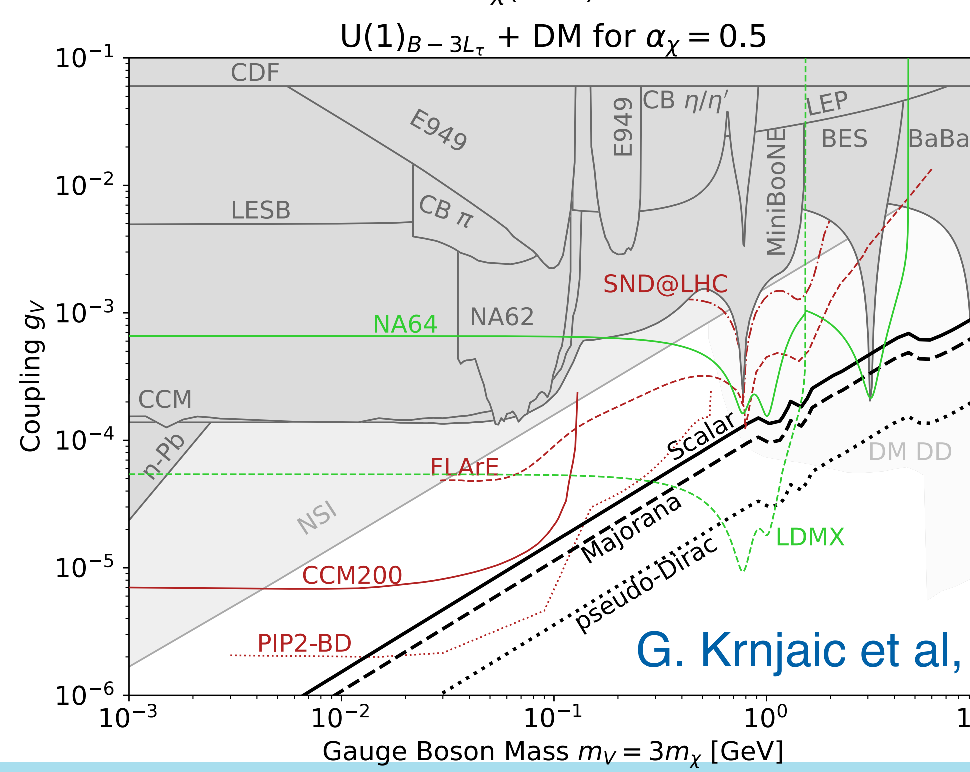
PIP2-BD Vector Portal Dark Matter Search and synergies with AMF

- PIP2-BD coupled to C-PAR already sets strong limits on hadron-coupled light dark matter!

- AMF accumulator ring combines the best elements of the RCS-SR and C-PAR concepts
  - Increase beam power (increase signal rates)
  - Lower beam pulse width (decrease beam-related backgrounds)



arXiv:2209.04671



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

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Summary

- Portals to a dark sector enable searches for new physics
- Stopped-pion sources provide access to a host of physics opportunities such as through CEvNS and searches for the dark sector
  - The addition of an accumulator ring with PIP-II at Fermilab could produce a stopped-pion neutrino source at Fermilab on par with the most powerful in the world
- **With PIP2-BD, we can create a stopped-pion neutrino 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
- The synergies of PIP2-BD with an AMF concept could enable more powerful dark sector searches at PIP2-BD at Fermilab!

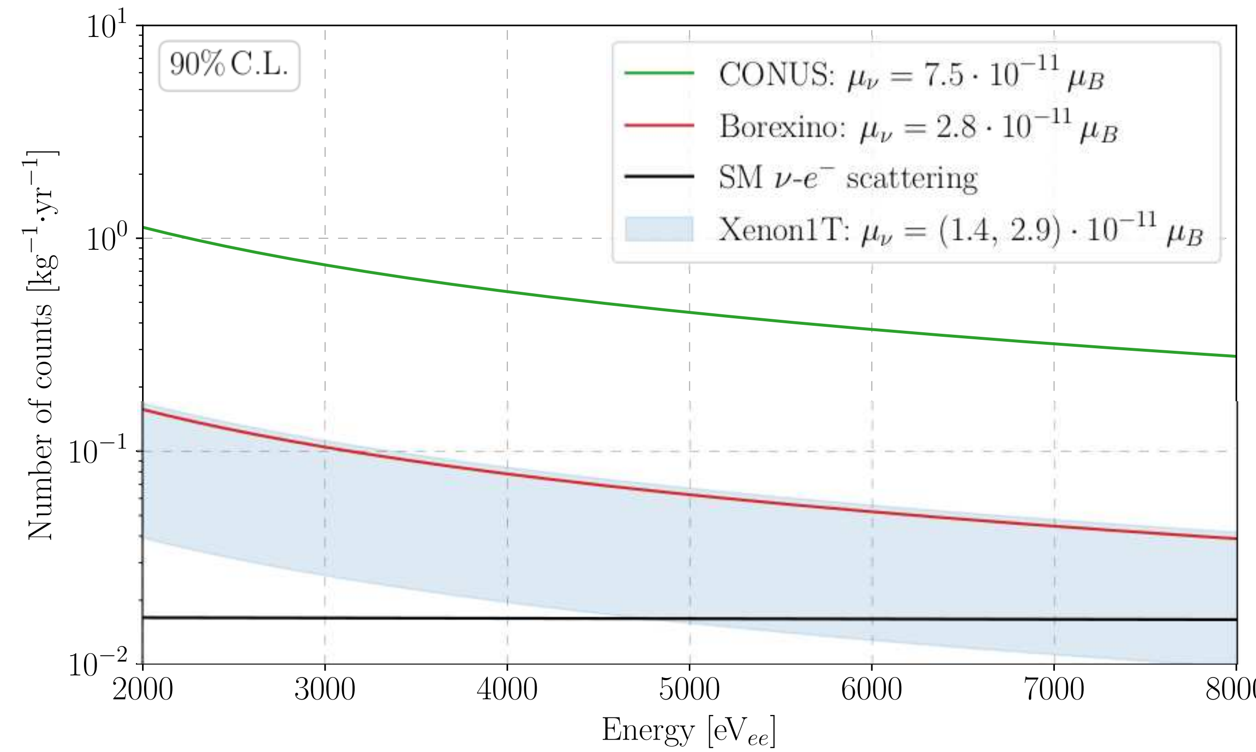
Thank you for your time!

Questions?

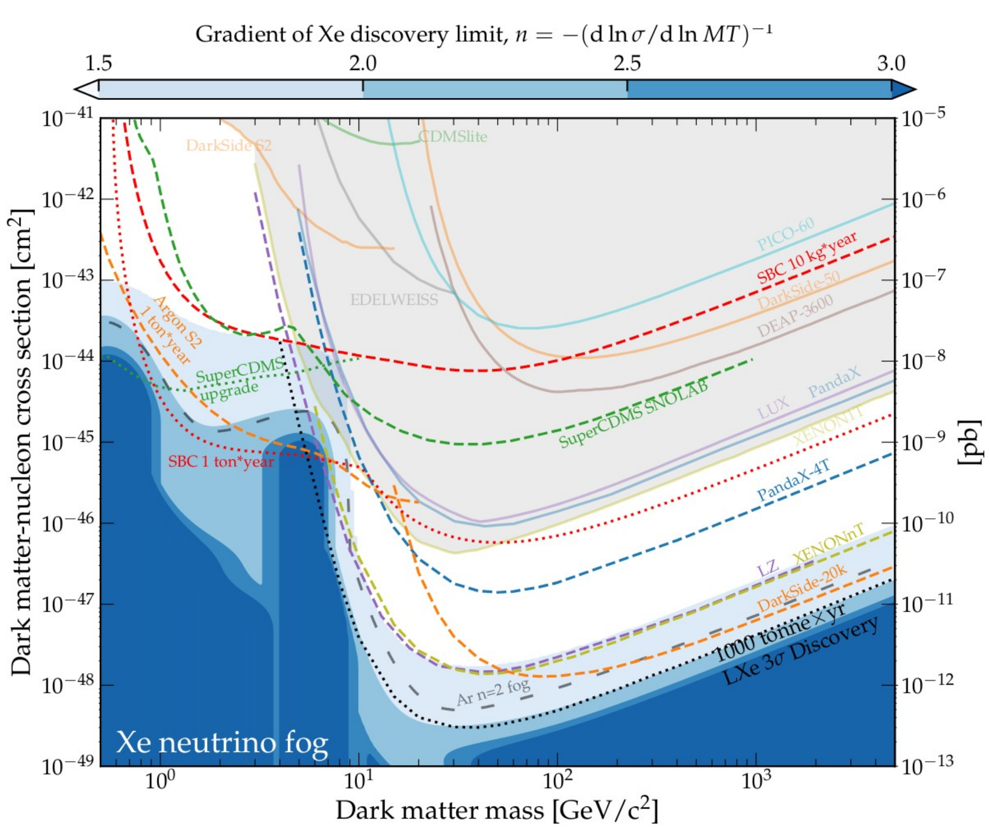
Backup

Physics Motivation for CEvNS

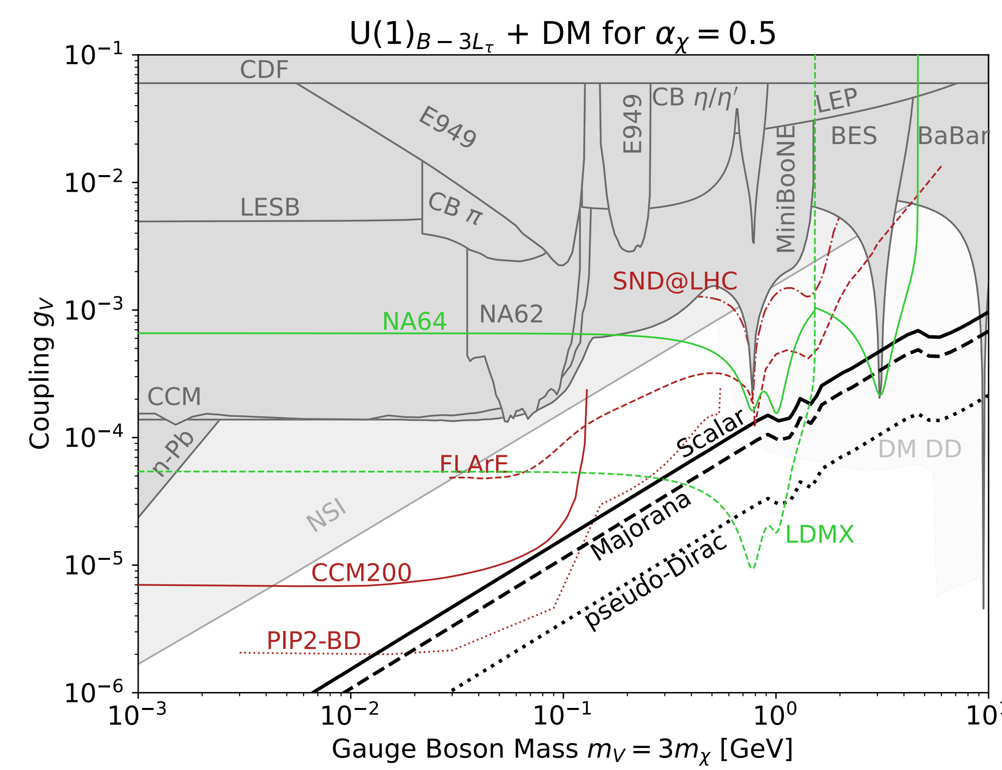
- CEvNS is Standard Model process, opens doors for new physics searches
  - Neutrino magnetic moment, non-standard interactions, etc.
- Dark matter and dark sectors
  - “Neutrino fog” for dark matter direct detection experiments



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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Current/Planned Stopped Pion Sources Worldwide

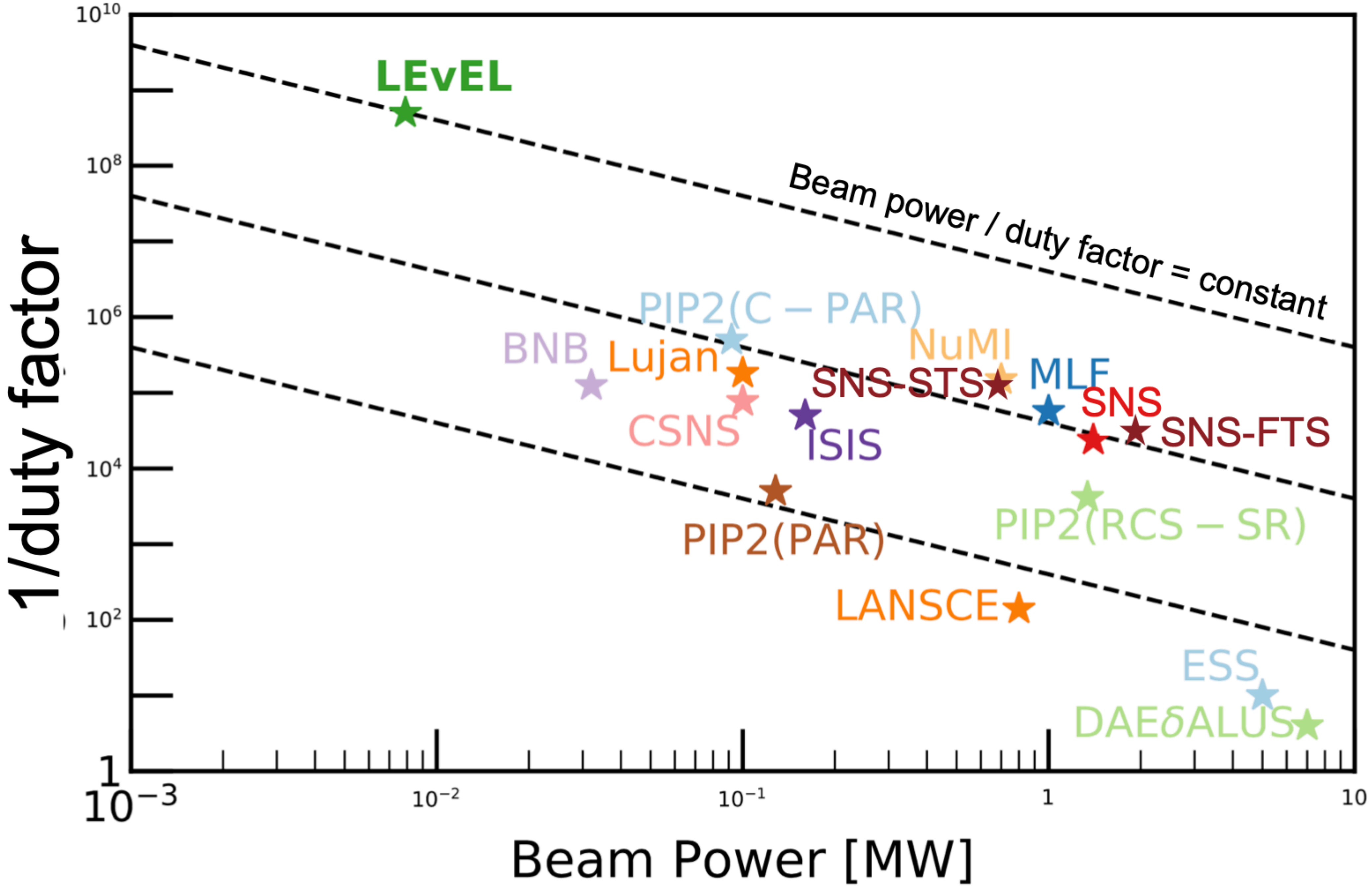

Figure adapted from arxiv:2103.00009

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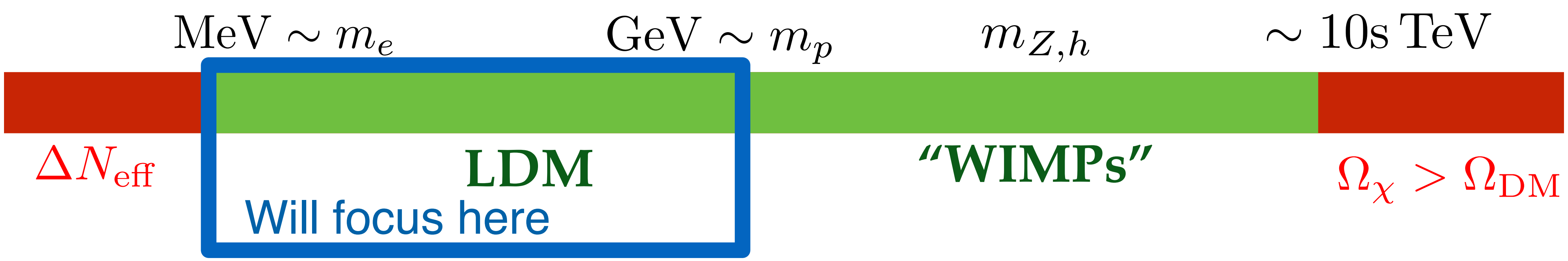
[6] *Indiana University, Bloomington, IN 47405, USA*

Thank you!

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

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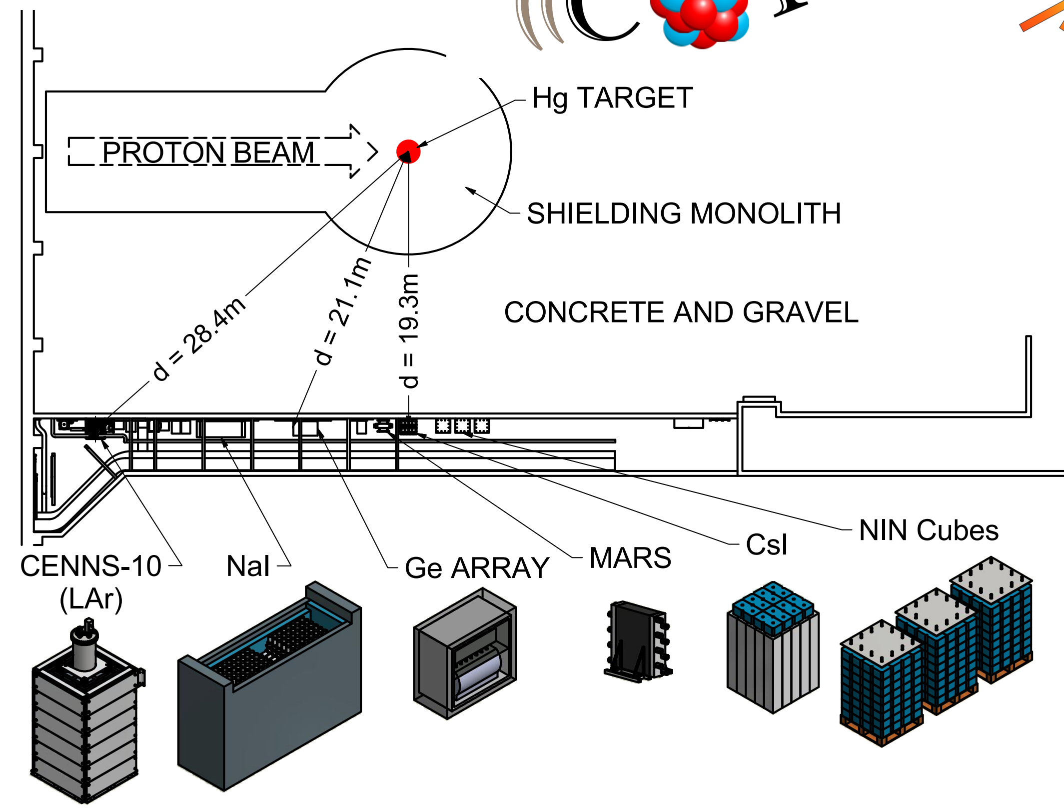
The COHERENT Experiment

- Using pulsed beam at the SNS
- 1.4 MW beam power
- Detectors located in Neutrino Alley at the SNS
- First phase goal to measure CEvNS with multiple detector technologies to test N^2 dependence

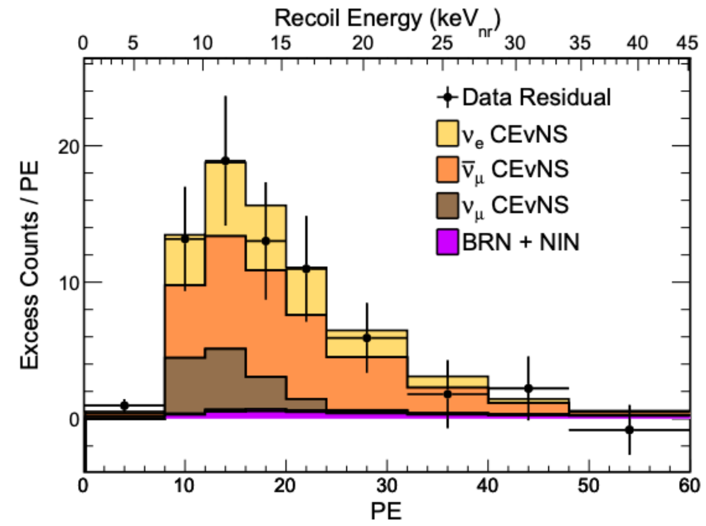


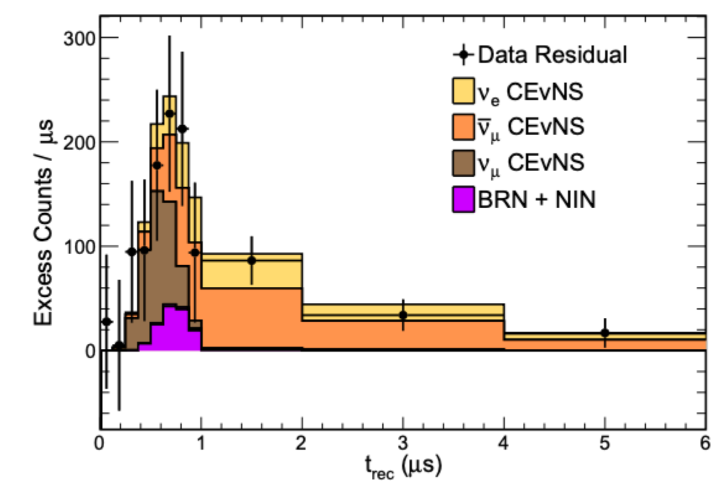
Target Nucleus	Det. Technology	mass (kg)	nuc. recoil threshold (keV)	Deployment
CsI	Scintillating Crystal	14	5	2015-2019
Ar	Single-phase Noble Liquid	24	20	2017-2021
NaI[Tl]	Scintillating Crystal	2500	13	2022
Ge	HPGe PPC	18	<5	2022
Ar	Single-phase Noble Liquid	750	20	2025
Ge	HPGe PPC	50	<5	2025
CsI	Cryogenic CsI	~ 10	1.4	2025

- Additional measurements planned for neutrino flux (D_2O), neutrino induced neutrons (Pb, Fe cubes), neutrino-induced fission (NuThor), and inelastic interactions on Ar

The COHERENT Experiment - First Light

- 2017: Discovery of CEvNS using scintillating CsI[Na] crystal
  - 1.5 years of data, 5 keVnr threshold
  - 6.7σ measurement of CEvNS over null hypothesis
    - Result consistent with Standard Model
  - Updated results in 2022

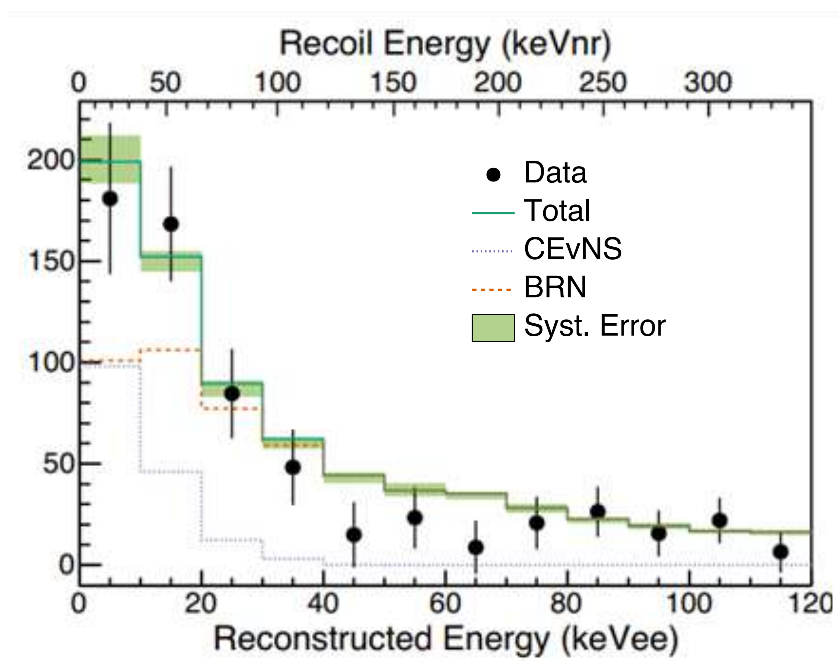


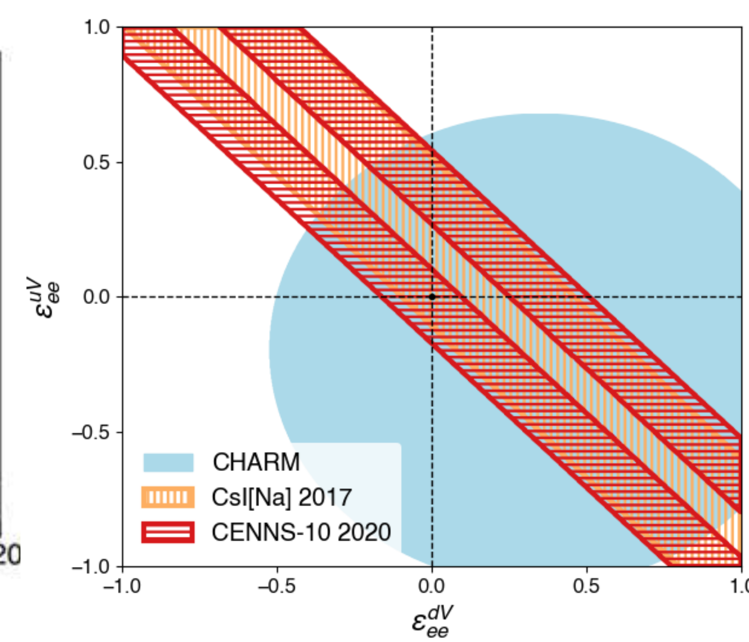


D. Akimov et al. (COHERENT) Science 357 (2017)

D. Akimov et al. (COHERENT) Phys. Rev. Lett 129, 080101(2022)

- 2021: First detection of CEvNS using single-phase LAr detector
  - 1.5 years of data, 20 keVnr threshold
  - 3.5σ observation of CEvNS over null hypothesis
    - Consistent with Standard Model
  - Additional ~2 years of data available, analysis in progress





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

JCZ, Ph.D. thesis, Indiana University, Bloomington (2020)

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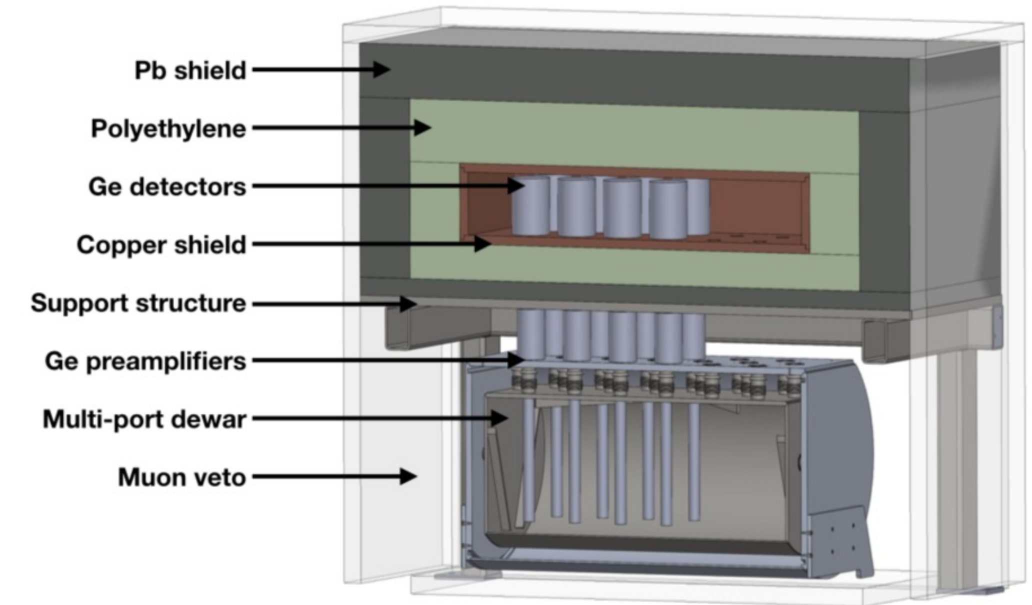
COHERENT Experiment - Near Future

- D_2O: Precise Measurement of the Neutrino Flux
  - Reduction of flux uncertainty from 10% to 2% in 5 years of running
  - First stage filled with light water installed and commissioning

D. Akimov et al. (COHERENT) JINST 16 (2021) 08, 08

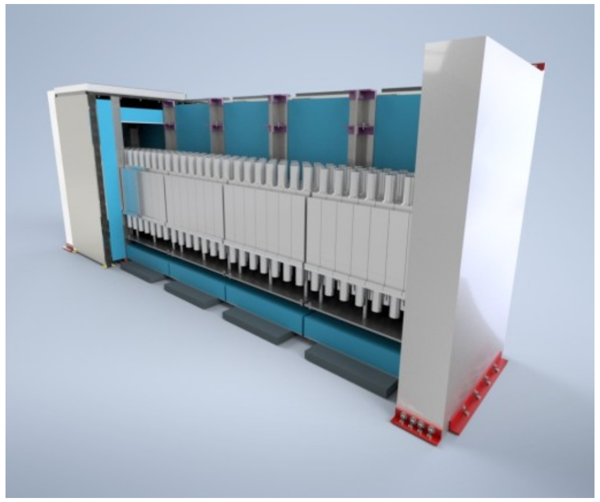
D_2O concept

- NaI[TI] detectors
  - 185 kg of detectors installed in Neutrino Alley since 2016
  - Charged current interaction on I: $^{127}I(\nu_e,e^-)^{127}Xe$
  - Planned upgrade to 3.5 tons of detectors with CEvNS sensitivity
    - Installation ongoing



Ge-Mini detector concept

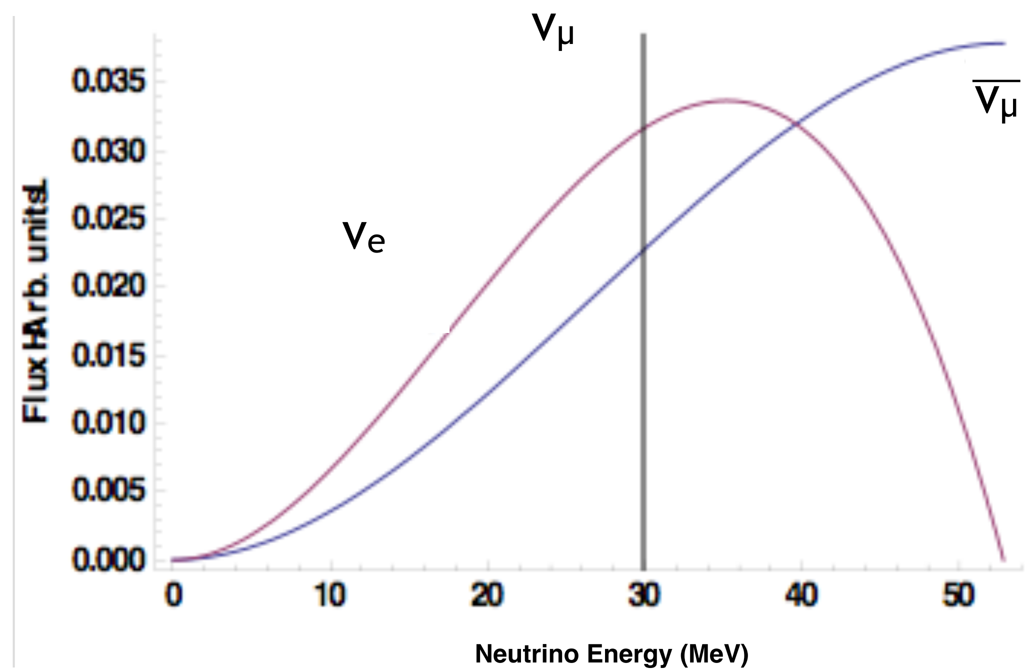
- HPGe detectors
  - 8 kg-scale Ge detectors, 18 kg total mass
  - Low energy threshold expected of <5 keV nuclear recoil energy
  - Installation ongoing

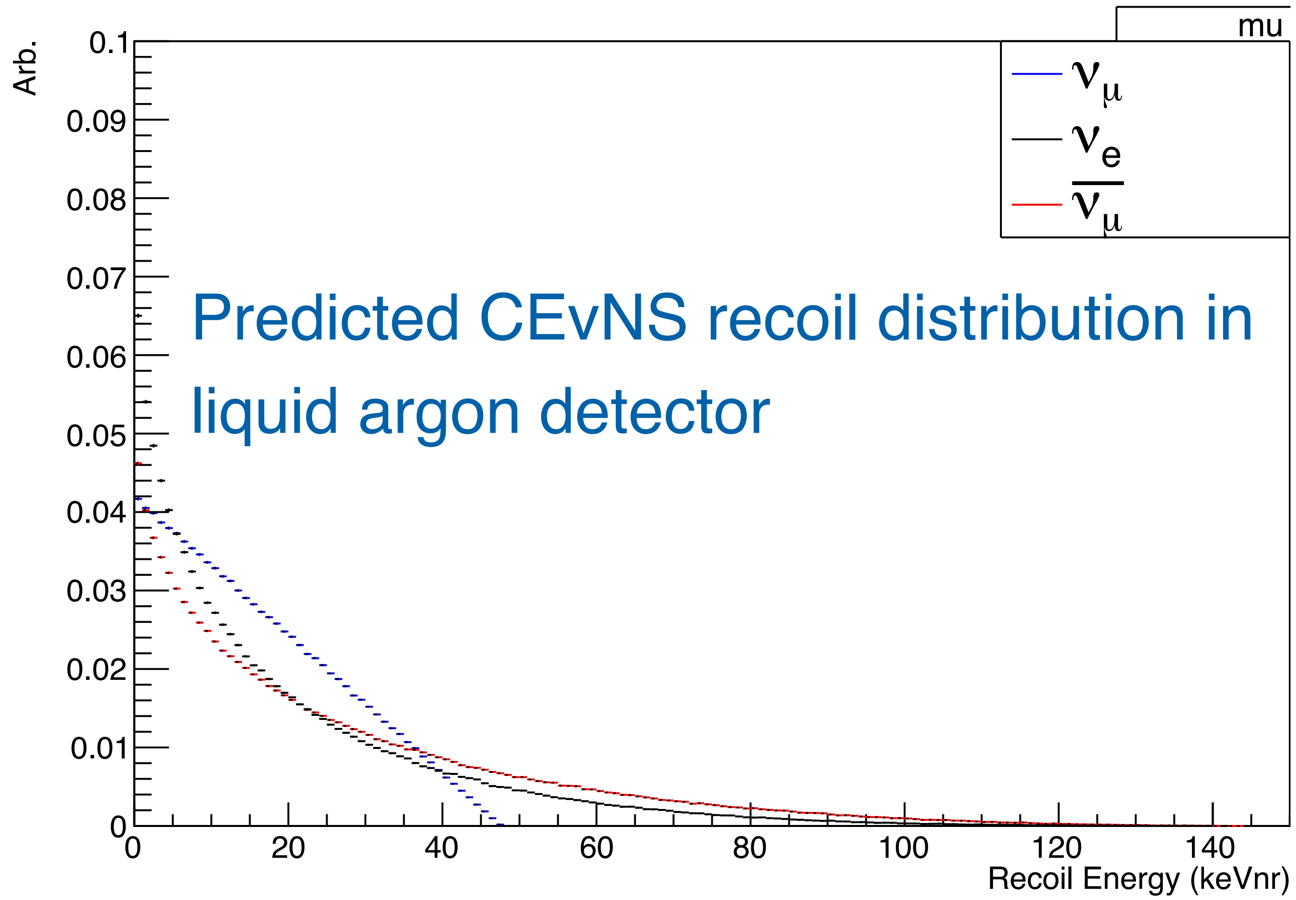


NaIvETE detector concept

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

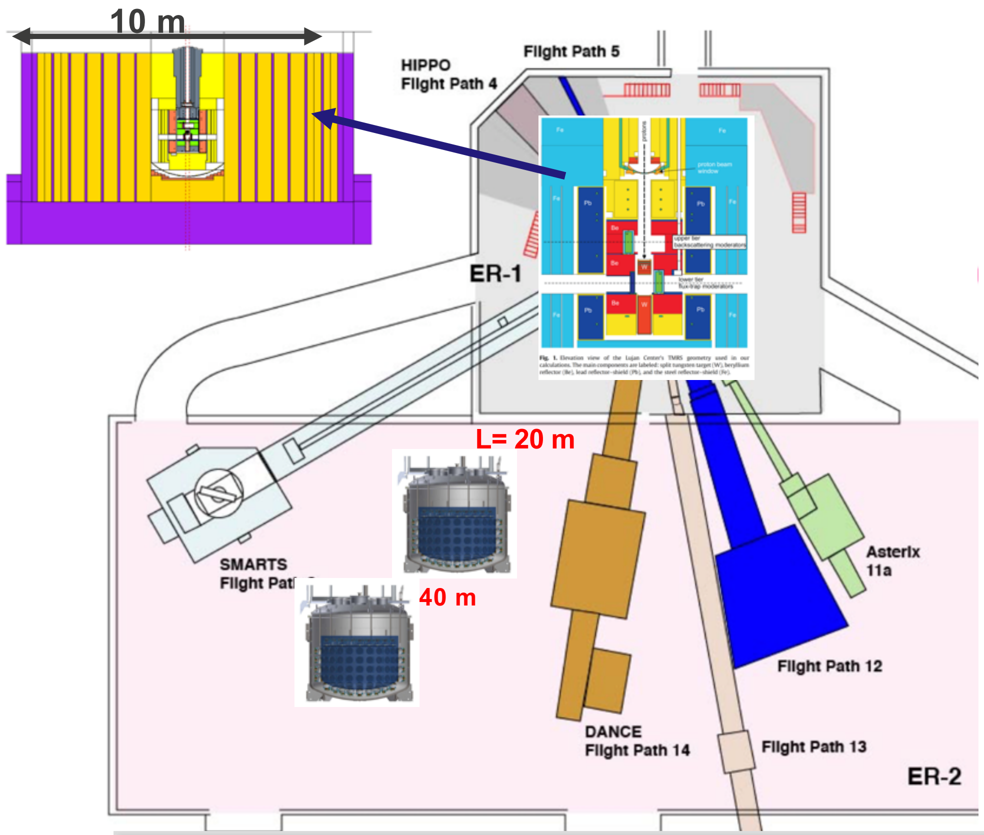


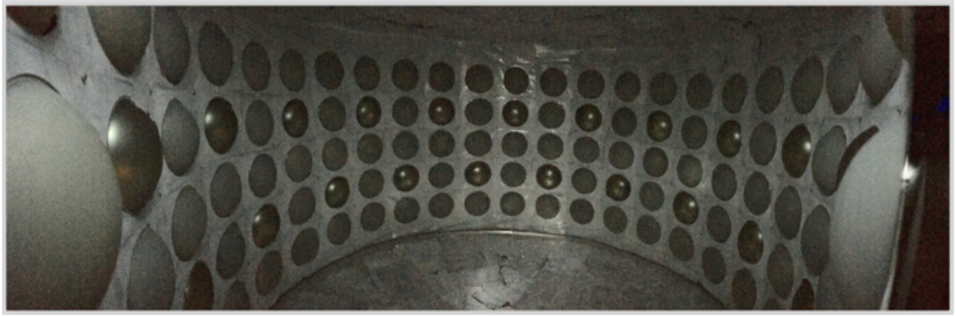


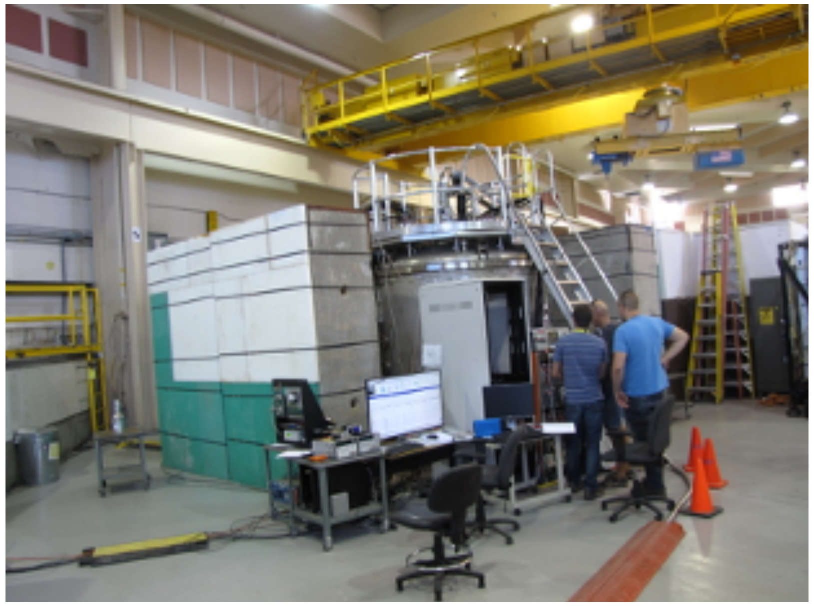
M. Toups et al., arXiv:2203.08079

Coherent CAPTAIN-Mills (CCM)

- Operating at Lujan Center at LANL
  - 80 kW, 20 Hz, 270 ns beam width
- 10-ton single-phase scintillation-only LAr detector
- Initial Engineering Run placed limits on light dark matter using argon detector
- Upgrades to initial detector to improve light collection, additional shielding to reduce beam-related backgrounds
- First large-scale LAr detector searching for CEvNS-based physics
  - Successes and lessons learned will help inform larger LAr detector







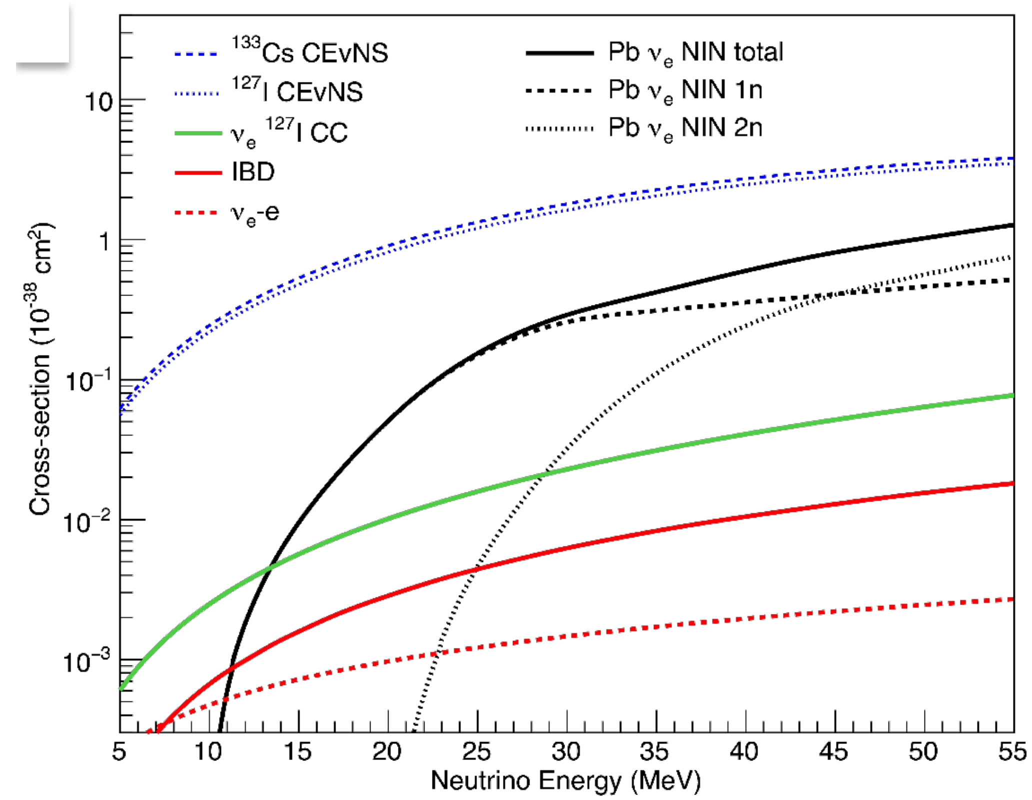
Phys. Rev. D Vol. 106, No. 1 (2022)

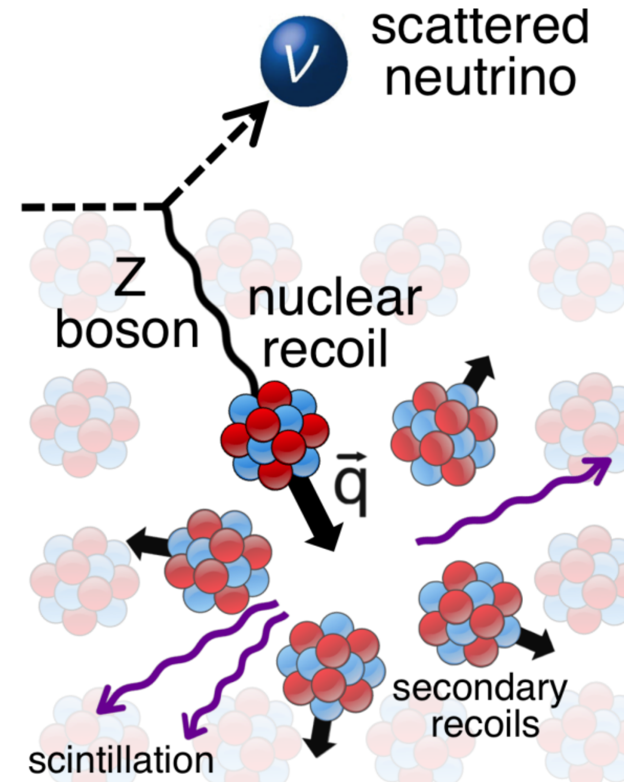
Coherent Elastic Neutrino-Nucleus Scattering (CEvNS)

- 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

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

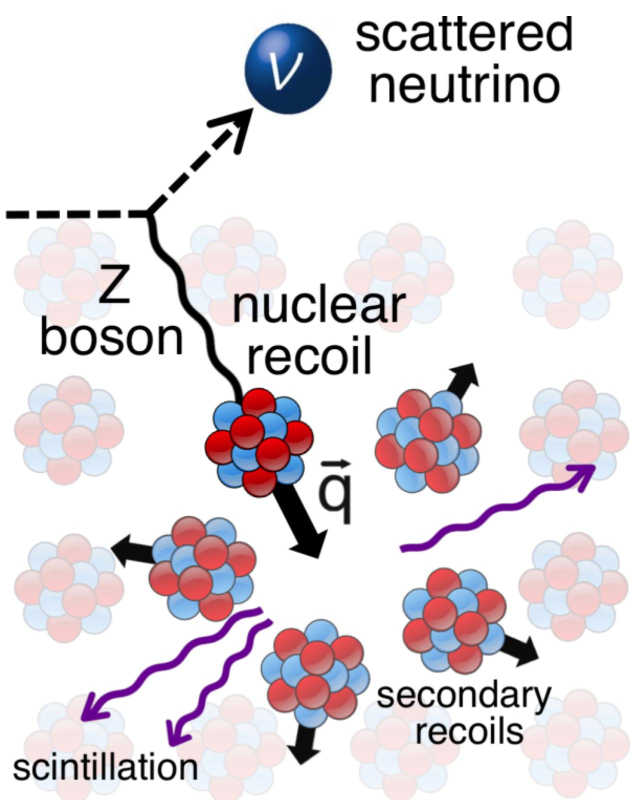
- Searches ongoing using both stopped-pion and reactor neutrino sources

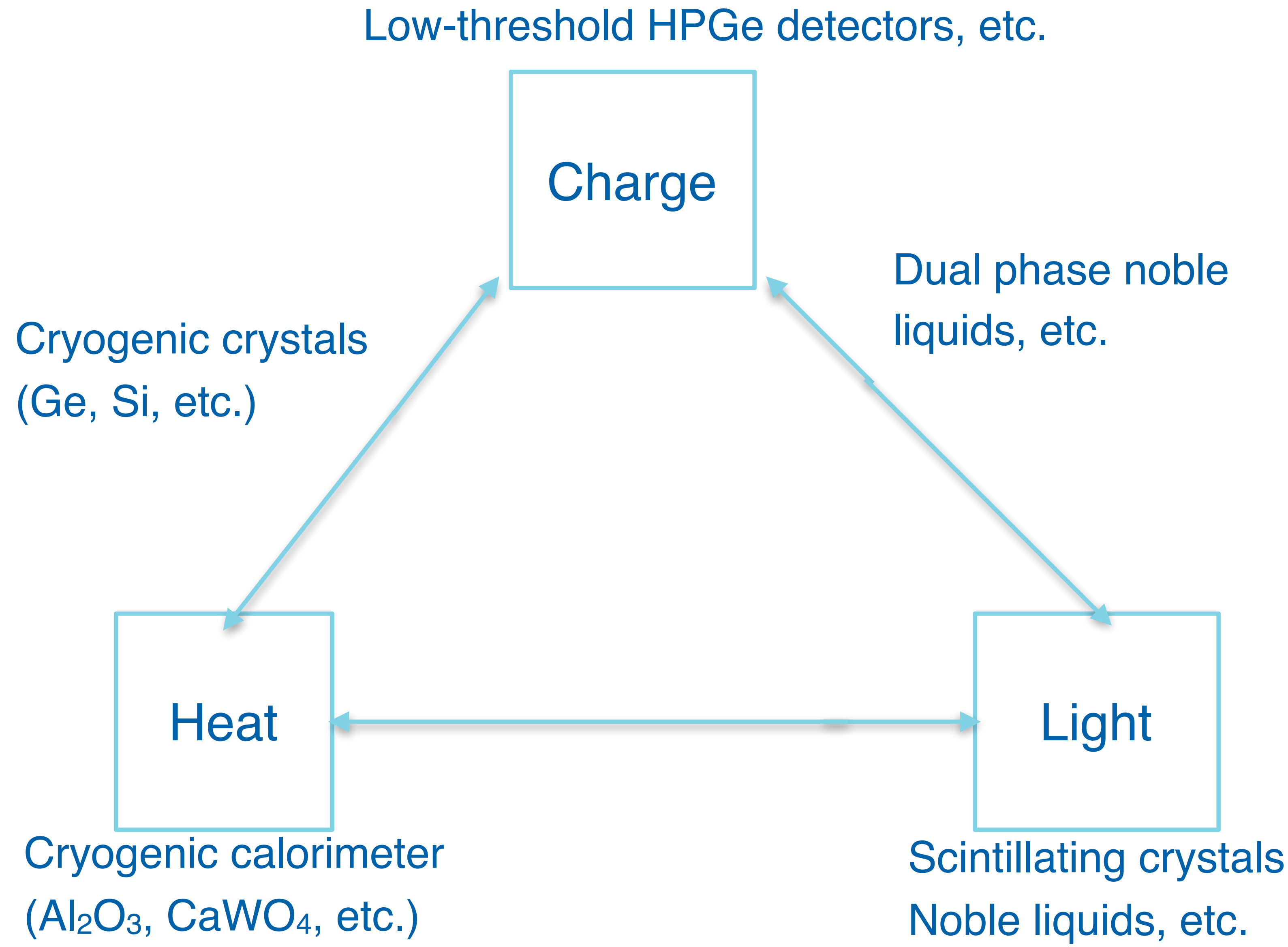




D. Akimov et al. (COHERENT). Science 357, 1123-1126 (2017)

Detecting CEvNS

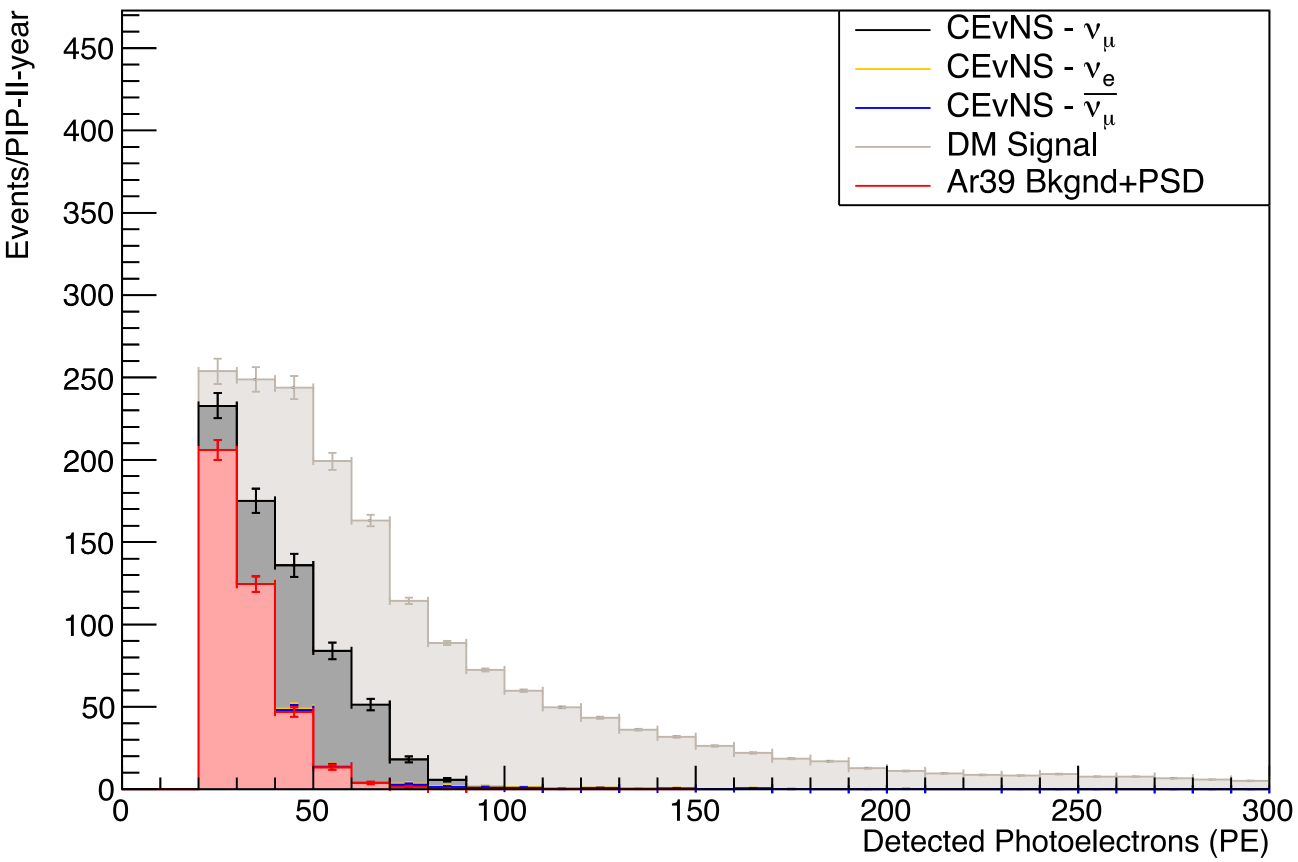




- Large CEvNS cross section allows for small detectors to measure neutrinos
  - Improvements come in larger mass (i.e. for noble liquid detectors) or lower energy thresholds (i.e. for cryogenic bolometers)
- Maximum nuclear recoil energy $T_{max} \sim E^2_{nu}/M$
- Understanding quenching factor = E_{meas}/E_{nr}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

PIP2-BD Vector Portal Dark Matter Search

- Stopped-pion neutrino sources place strong limits on LDM
  - Produced by proton collisions with fixed target
  - 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
  - Sensitivity of detector to MeV-scale physics allows additional sensitivity at low-DM masses via DM-electron scattering



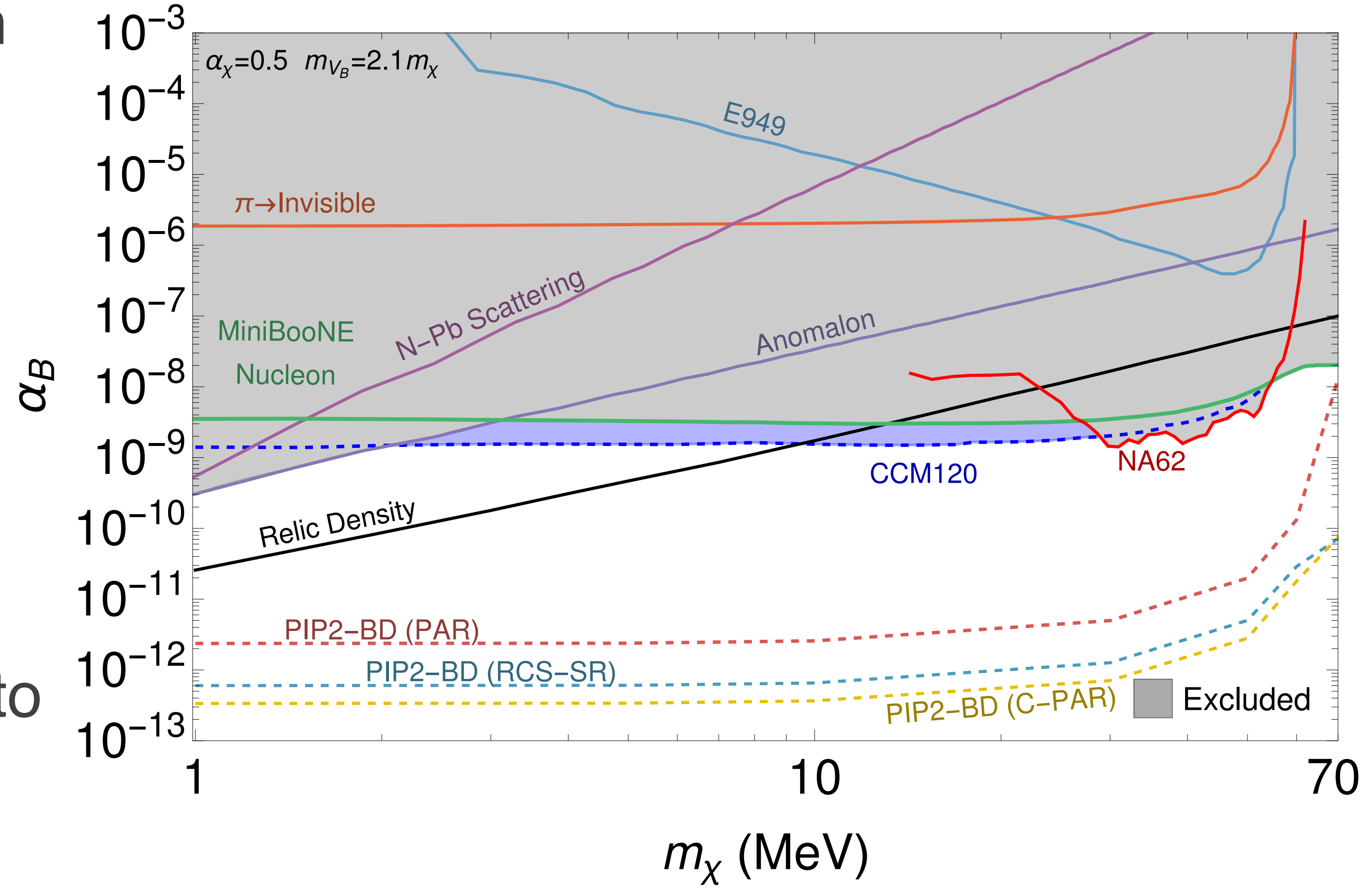
Fermilab

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

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

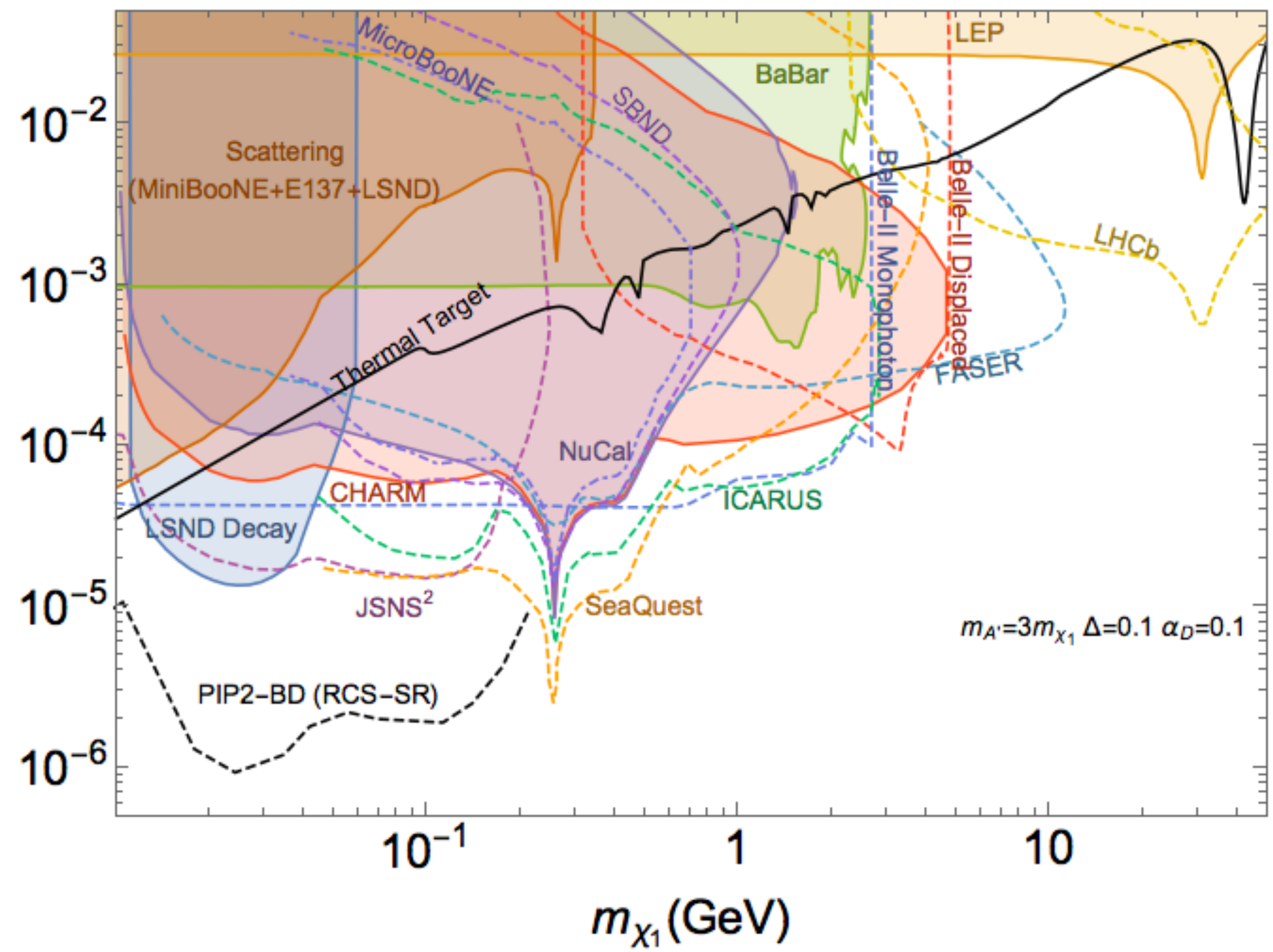
- Model predicts the same DM nuclear recoil energy distributions as the vector-portal model
  - Rate scales with as $\alpha_\chi \, \alpha^2_{\mathrm{B}}$ as opposed to ε^4
- Same procedure to compute 90% C.L. as for vector-portal model
- 5 year run with the 3 accelerator scenarios



M. Toups et al., arXiv:2203.08079

PIP2-BD Inelastic dark matter search

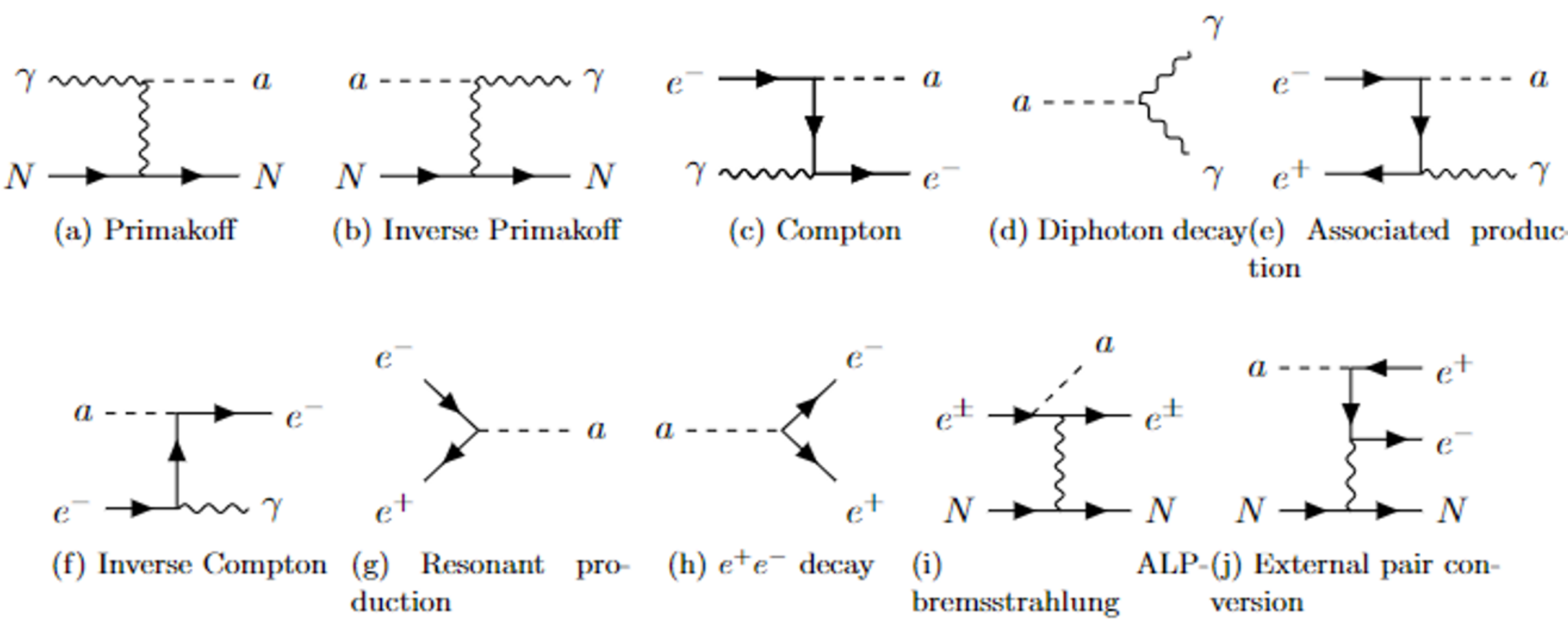
- Extend minimal vector portal scenario to include two DM particles χ_1 and χ_2
- Require $\Delta = (m_{\chi_2} - m_{\chi_1})/m_{\chi_1} > 0$
- Possibility of χ_2 decay into e^+e^-
- If decay not kinematically allowed, DM observation also possible through its up- or down-scattering off of electrons in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



M. Toups et al., arXiv:2203.08079

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

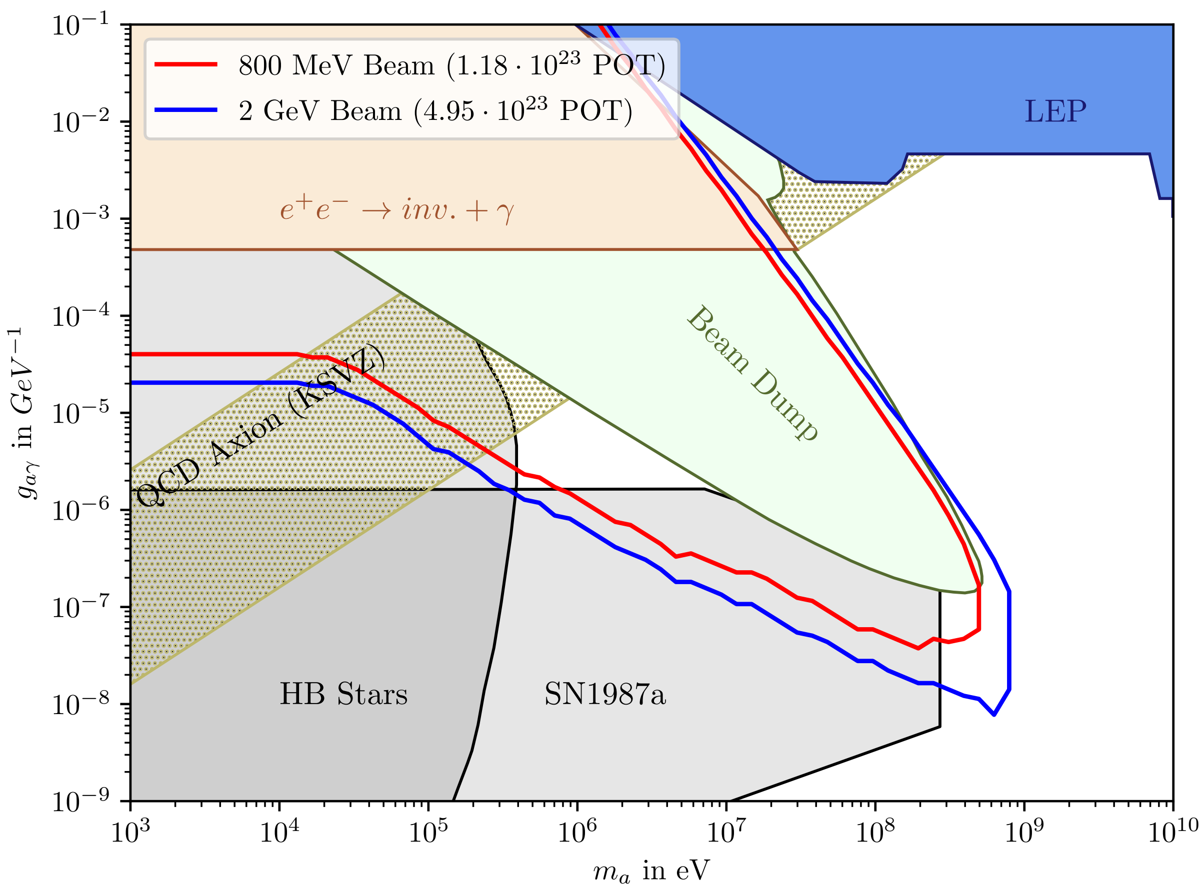
- ALPs that couple to photons can be produced in the beam dump via Primakoff process, detectable via inverse Primakoff process or decay into two photons
- ALPs coupling to electrons detectable via inverse Compton, e+e- conversion, or decay to e+e-



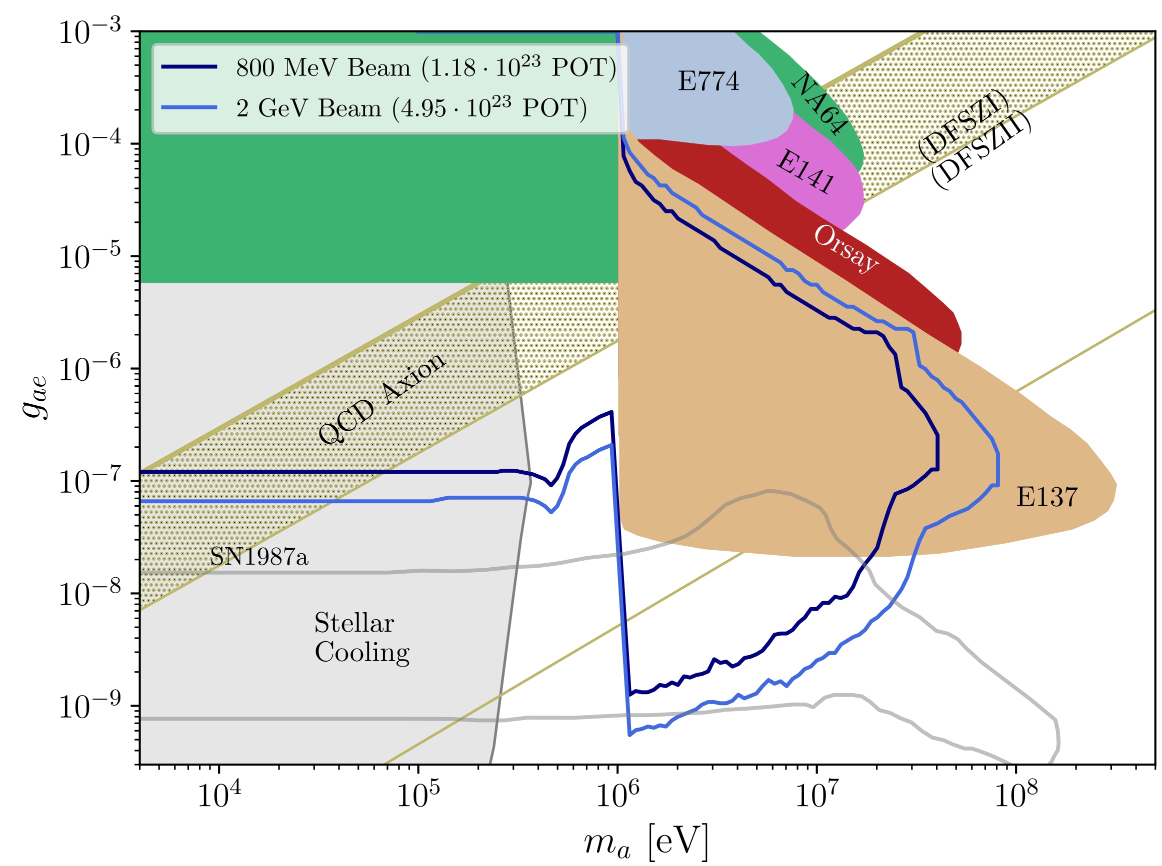
arXiv:2112:09979

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% sensitivity assumed based off of search using the Coherent Captain-Mills (CCM) experiment (arXiv:2112.09979)



ALPs coupling to photons

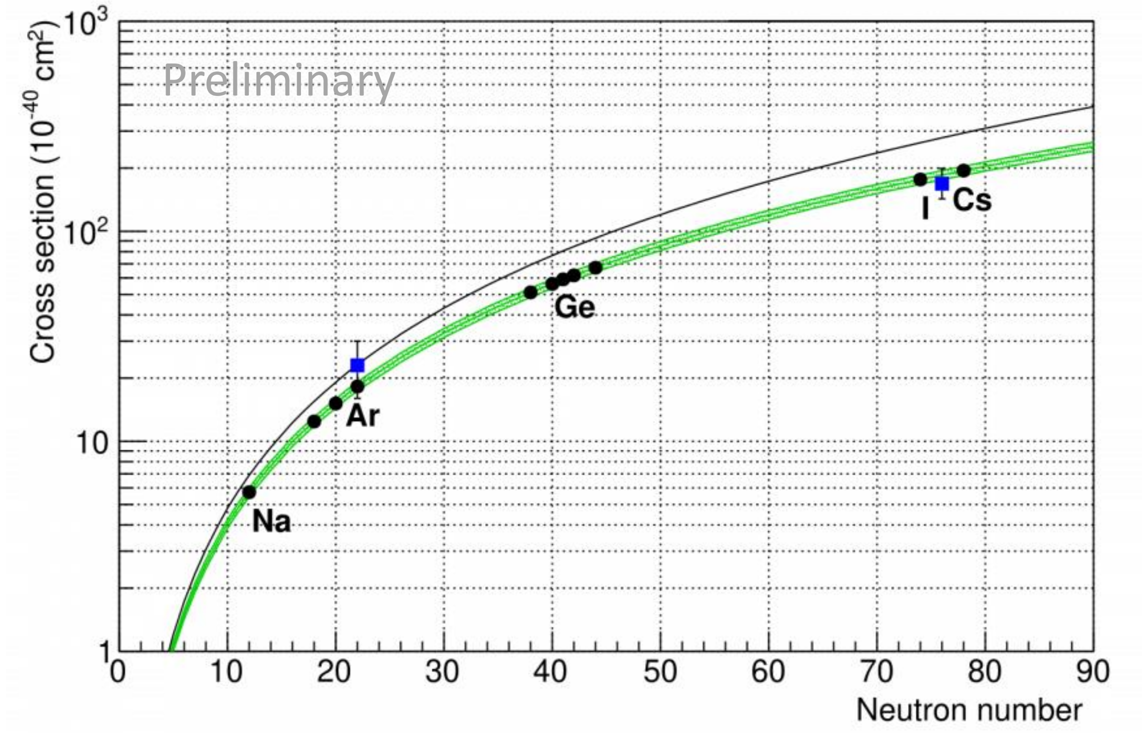


ALPs coupling to electrons

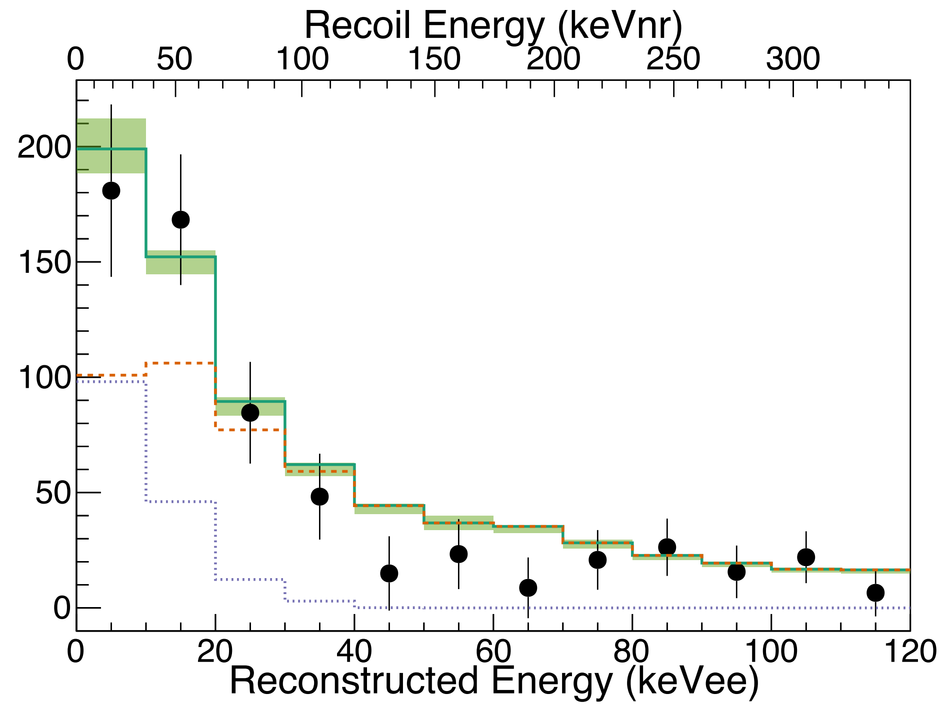
A. Thompson, A. Karthikeyan, B. Dutta, TAMU

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