Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

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

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NuFACT 2023

Seoul National University, Seoul, Republic of Korea

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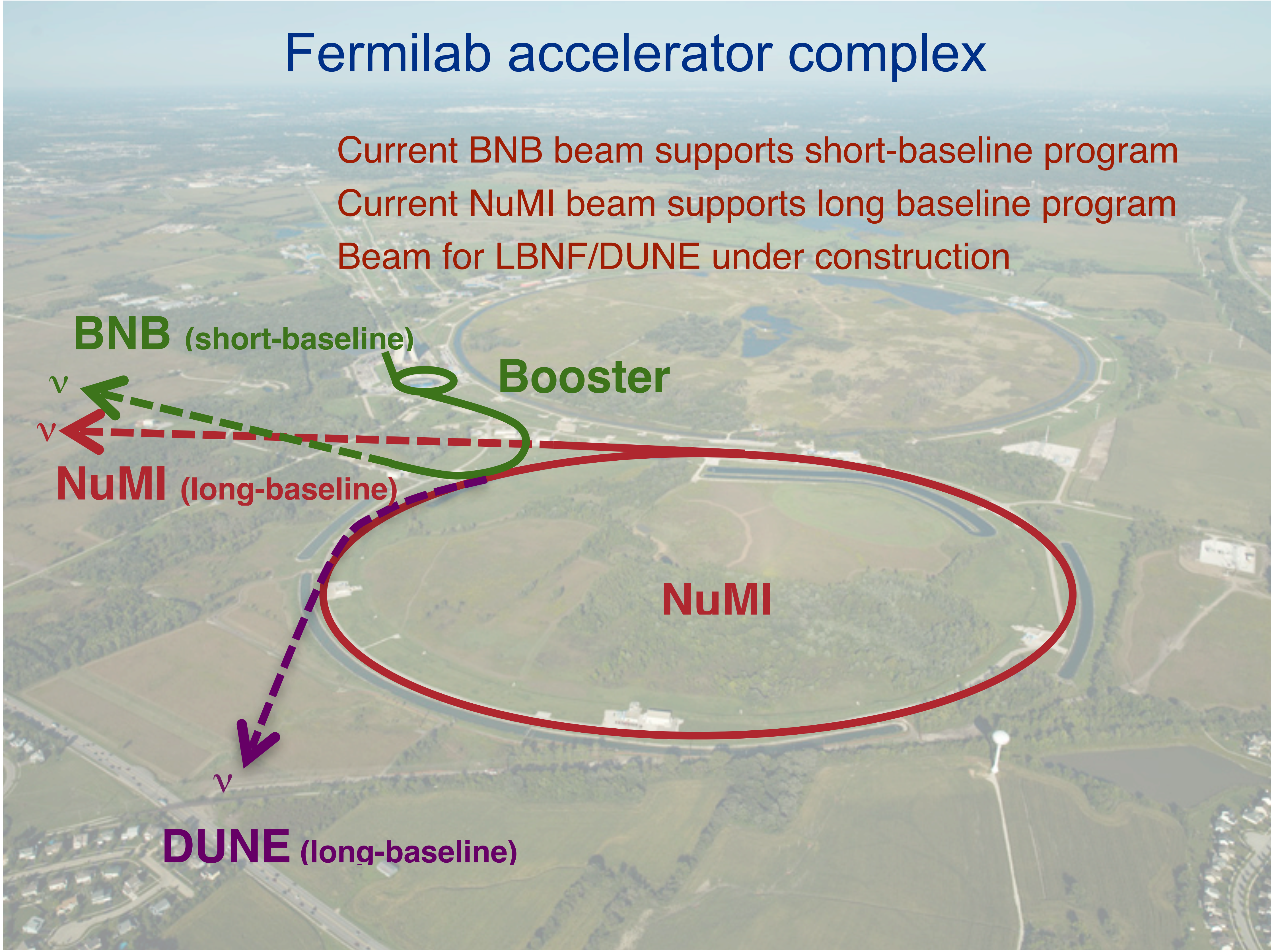
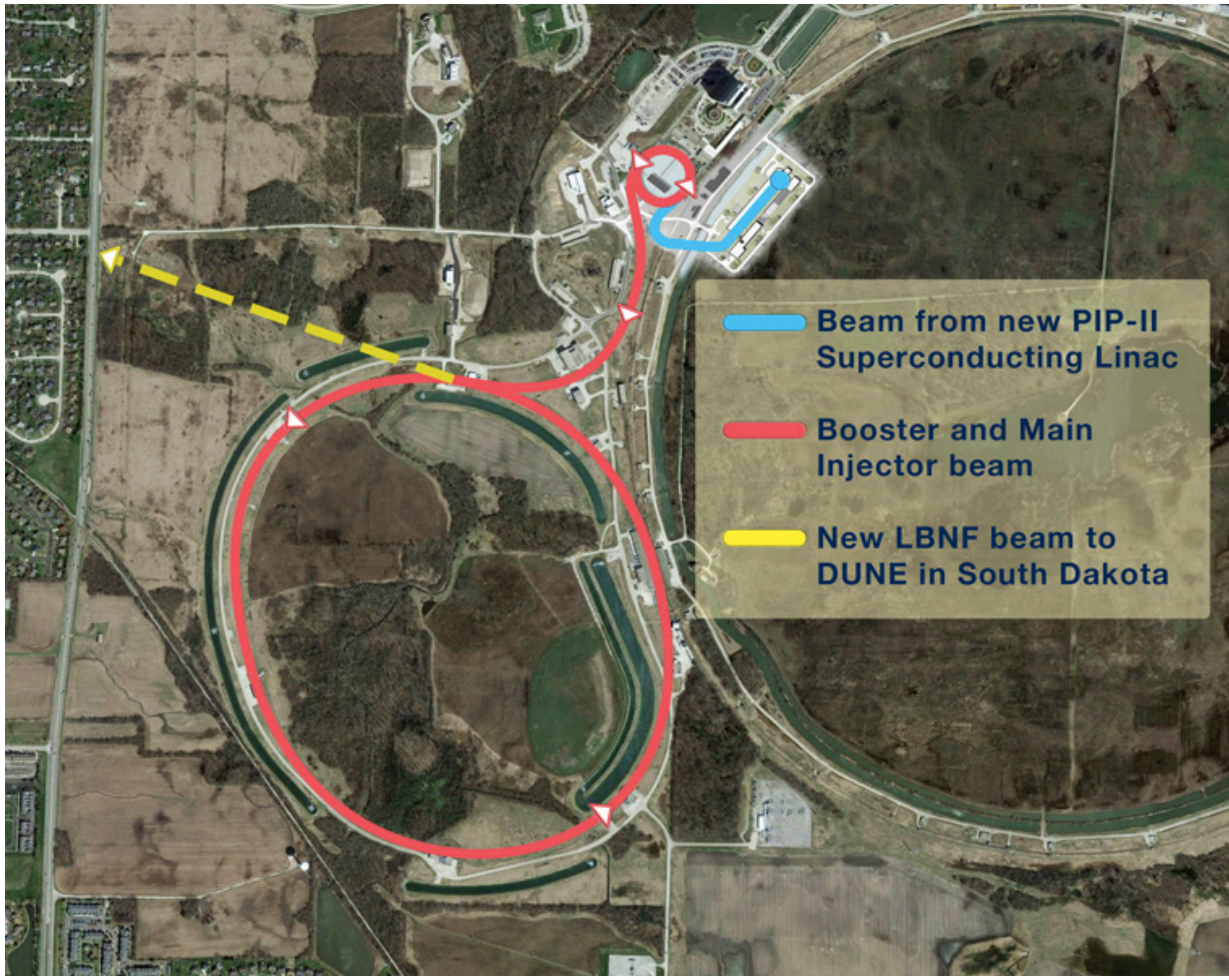
The Current Fermilab Accelerator Complex



The Fermilab Accelerator Complex in the PIP-II Era

- New superconducting RF (SRF) linac for Booster injection at 800 MeV
  - Improved Booster cycle rate upgraded to 20 Hz from 15 Hz
  - Increased proton beam intensity for multi-megawatt beam power from Main Injector
- PIP-II Era scheduled to begin in 2029
  - 800 MeV beam available for other experiments such as a beam dump program
    - Discussed ideas and possible experimental concepts at a workshop held in May 2023 at Fermilab
    - Ideas presented in this workshop that both take advantage of a continuous wave (CW) PIP-II linac and with coupling to a possible accumulator ring



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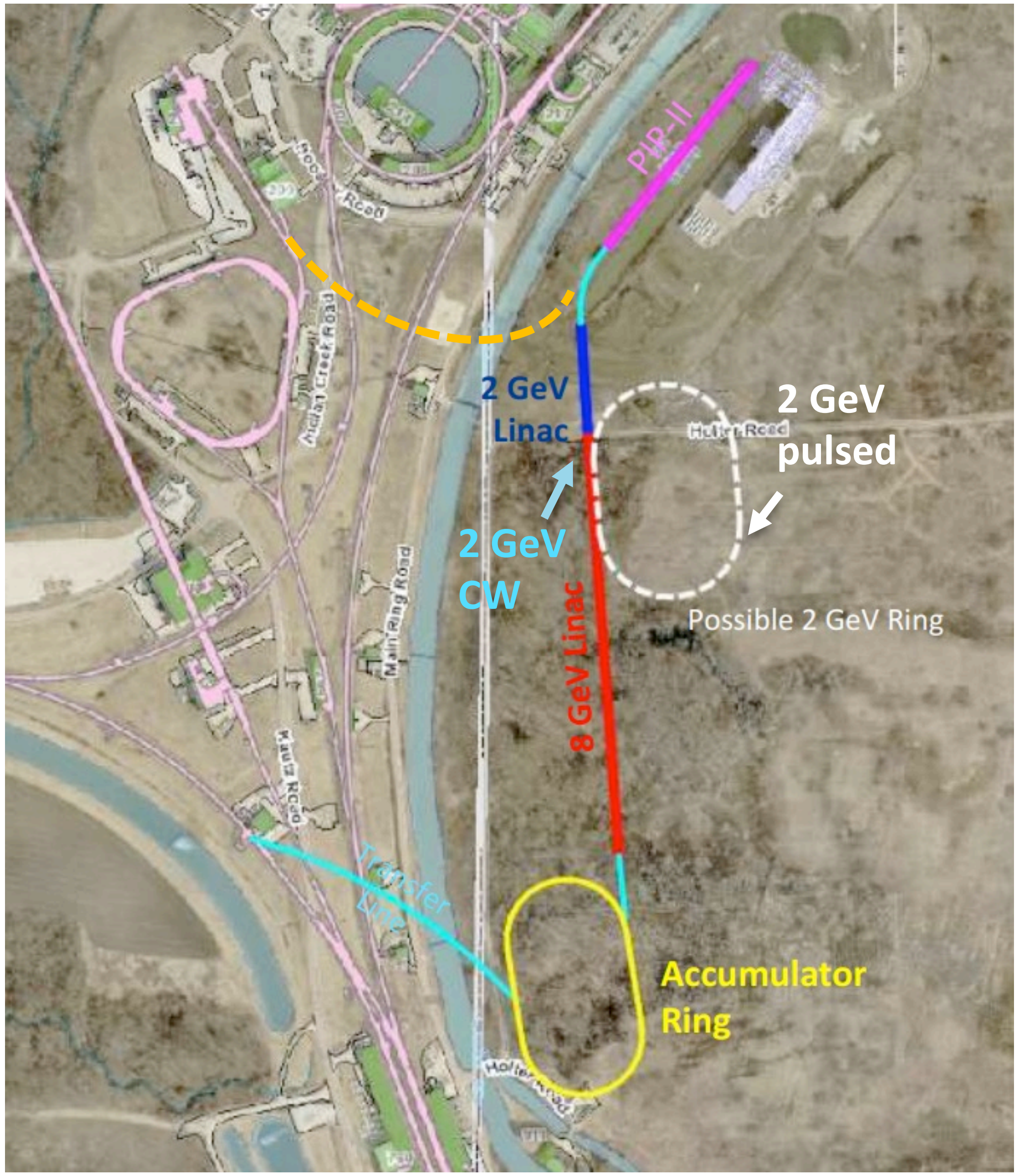
The Fermilab Accelerator Complex Evolution (ACE)

- Upgrades to the Main Injector and Target station in the early 2030s
  - Increase protons on target to DUNE, upgrade target systems for 2.4 MW running, and improve reliability of the complex as a whole
  - There are some possibilities to include an accumulator ring to PIP-II on this timescale as well which could enable powerful beam timing in conjunction with large or low-threshold detectors (more later)
- Establish project to replace the Fermilab Booster (~late 2030's)
  - Provide reliable platform for the future of the FNAL Accelerator Complex
  - Ensure high intensity for DUNE Phase II physics program
  - Enable capability of the complex to serve precision experiments and new physics searches with beams from 1-120 GeV
  - Create capacity to adapt to new discoveries



Highlighting a lot of the possibilities!

Also see J. Eldred's plenary talk from Tuesday!

Opportunities for improvement beyond PIP-II around ACE

- Accumulator Ring
  - Developed 3 scenarios for Snowmass 2022
    - C-PAR is very short pulse accumulator ring that provides flexibility, adaptability, and future upgradeability
    - Could be realized before Booster Replacement, discussion on the timescale
- Booster Replacement scenarios include Linac options as well as Booster-like options

PIP2-BD Scenarios

In the **PIP2-BD Snowmass Paper**, we developed 3 scenarios:

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

PAR, which we just heard about, is a well-developed scenario for a fixed energy ring that can facilitate injection to the PIP-II Booster.
- Compare: LANL PSR is 100kW at 0.8 GeV.

RCS-SR, one of six ACE Booster Replacement scenarios provides for an AR at 2 GeV which can deliver ~MW class beams. The other five are compatible with an optional 0.4-2 MW ring.
- Compare: ORNL SNS is 1.8-2.8 MW at 1.3 GeV.

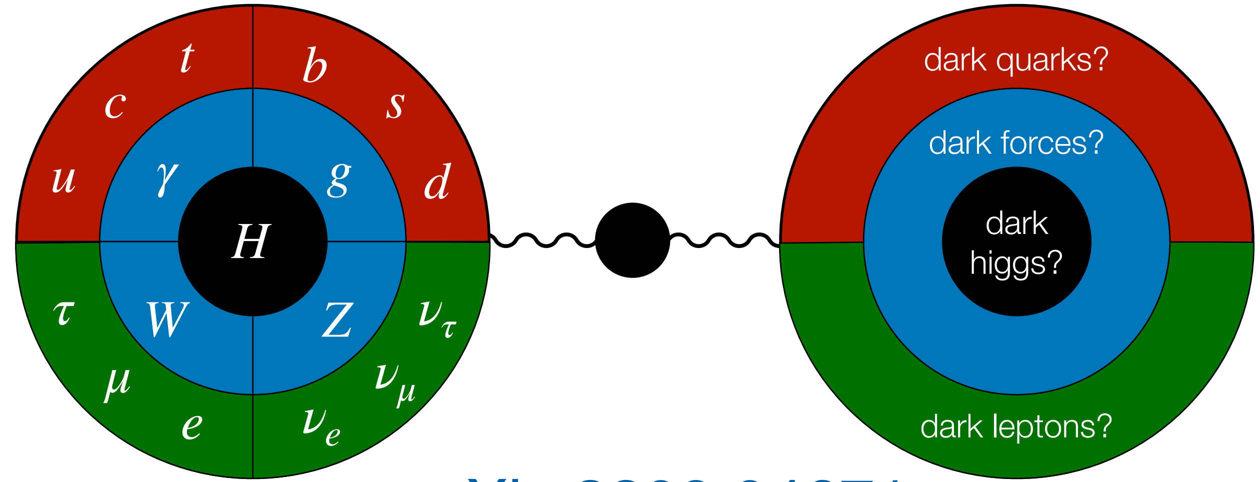
12 Jeffrey Eldred | PIP2BD Beyond PIP-II 6/6/23 Fermilab

Possibilities explored for accumulator ring at PIP-II during Snowmass 2022

A Potential Practical Physics Program at a PIP-II Beam Dump (P5-BD)

Why accelerator-based dark sector searches?

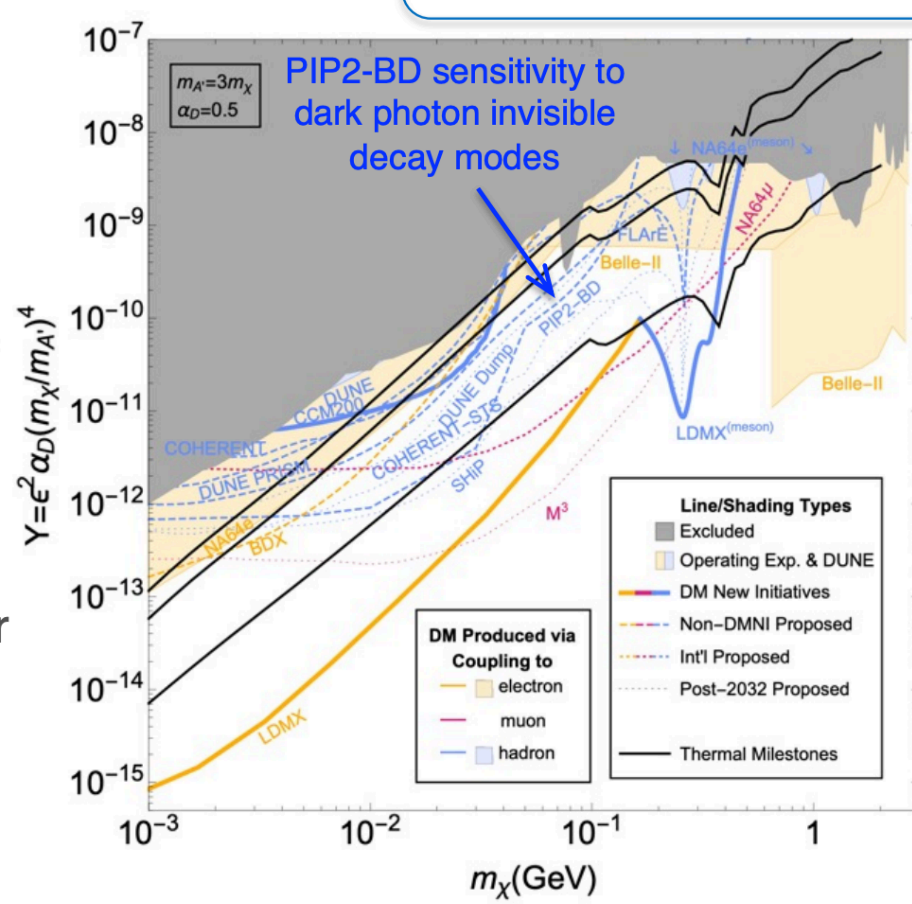
- Accelerator-based dark sector searches were identified as an HEP priority during the most recent Snowmass process
- Proton beam dump-based searches highlighted as part of Fermilab's future program at the Fermilab P5 town hall



arXiv:2209.04671

High Intensity Proton Beam to Explore Dark Matter Portals

- ACE will also enable excellent opportunities for accelerator-based dark sector searches at modest cost and scale
  - At high energy, proton beam dump searches can probe new parameter space making use of existing accelerator infrastructure and experiments
  - **At low energy**, proton beam dump searches can form part of a new neutrino and dark sector facility that leverages the full power of the PIP-II beam (1-8 GeV beam)



B. Fleming, FNAL P5 town hall

14 03/22/2023 Fleming I Fermilab Program

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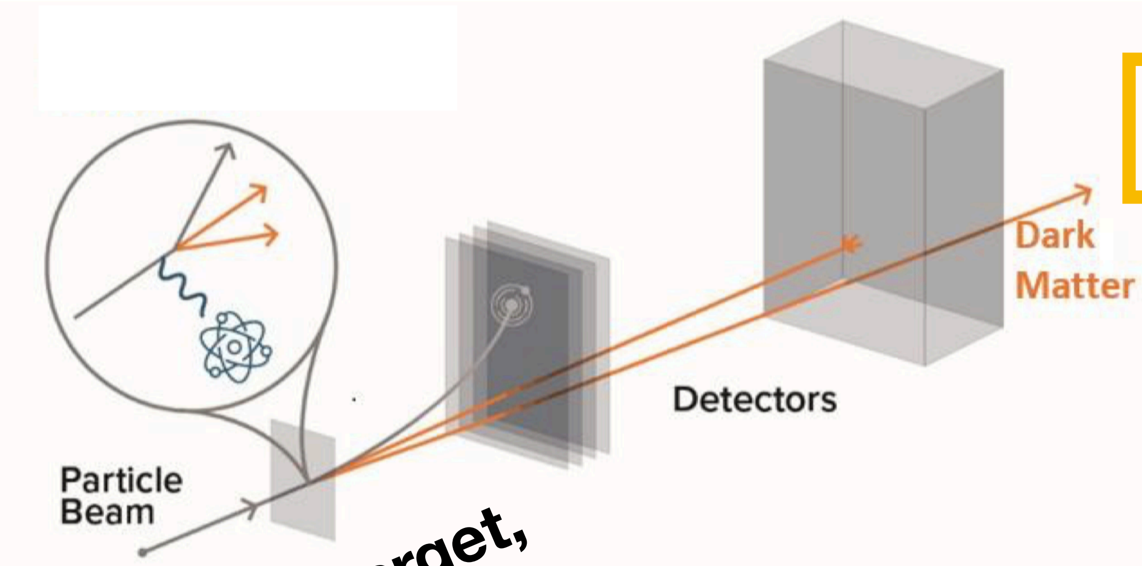
Searching for Dark Sectors at Beam Dump Experiments

Production of dark matter

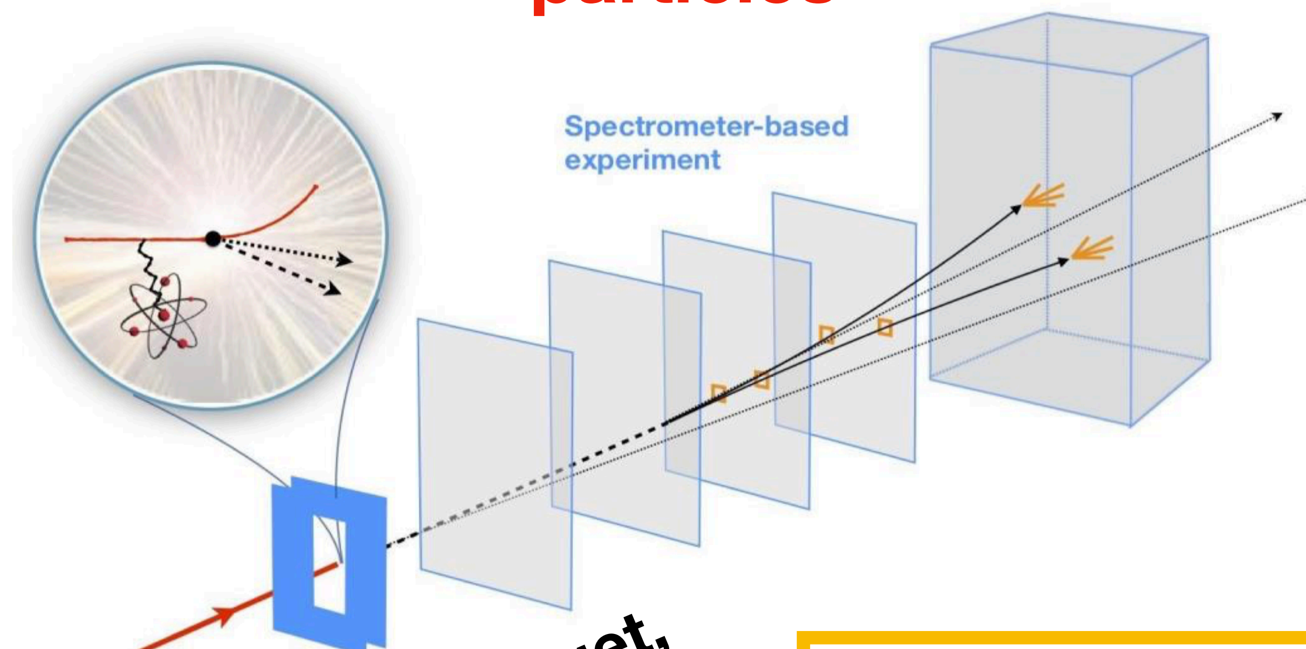


2. Re-scattering

1. 2. **fixed target, colliders**

1. Missing energy/ momentum/mass

Production of unstable dark sector particles



1. 2. **fixed target, colliders**

3. Visible decay products

- Breadth of ideas within a program important!
  - In case of discovery, allows for studying dark sector mass and interaction strength
  - Probe generalizations of thermal freeze-out
  - Can explore ideas for methods 2 and 3 across visible energy detection thresholds!

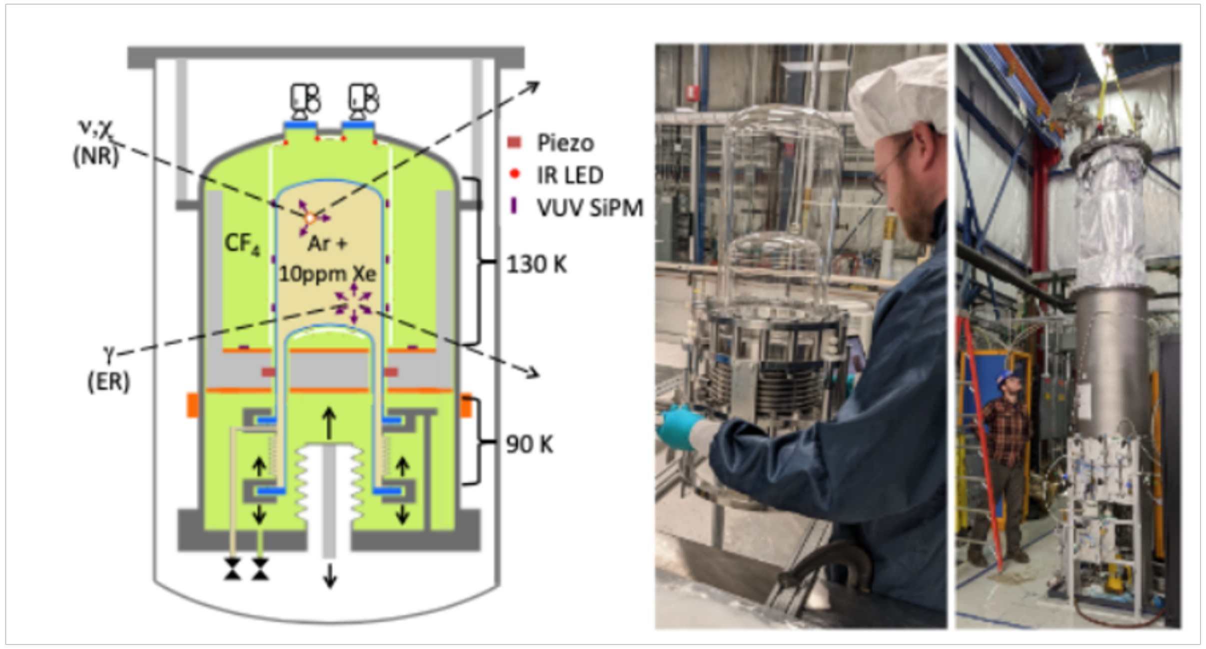
Adapted from S. Gori, BNL P5 town hall

Opportunities at eV-scale detector thresholds

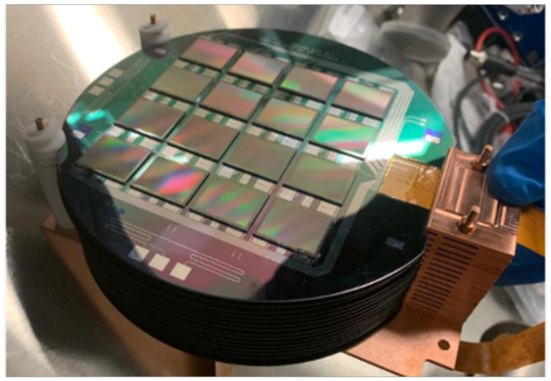
Opportunities for very low threshold detectors

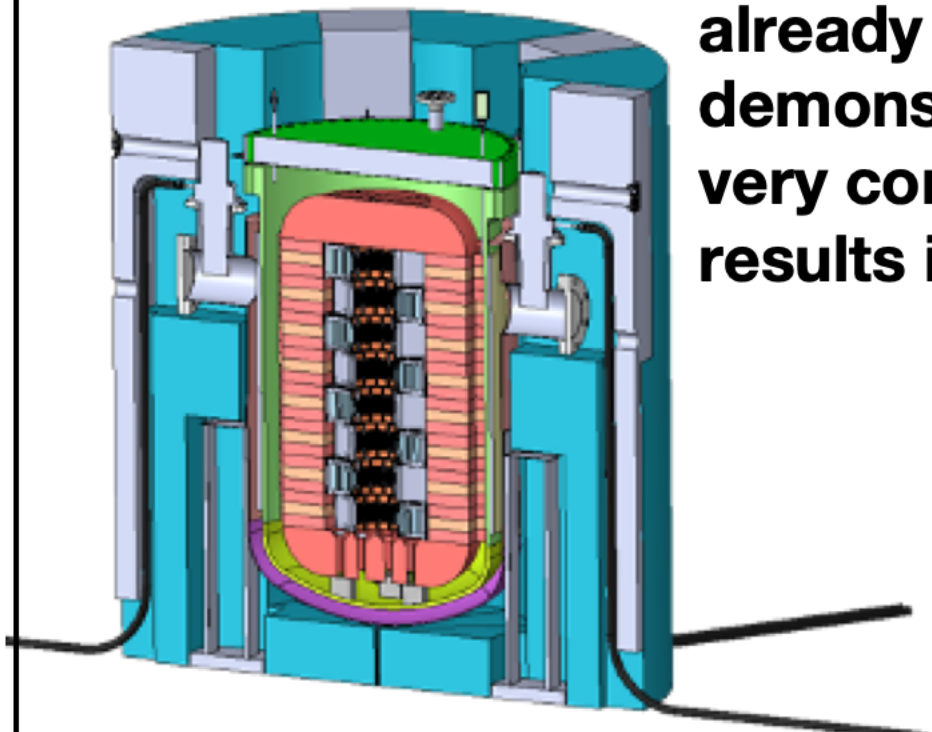
- Significant progress on developing new technologies for detecting low energy nuclear and electron recoils for direct dark matter searches
  - Examples include micro-calorimeters, CCDs, and the Scintillating Bubble Chamber (SBC) effort
- These technologies combined with high intensity proton beams provide new opportunities for dark sector searches
  - Possible searches for millicharged particles, axion-like particles (ALPs), and general kinetic mixing models
- Taking advantage of the accelerator timing structure represents an additional improvement but is not a requirement to get started on a program in this direction

Examples of very low threshold detector technologies



Scintillating Bubble Chamber. Low threshold (<1keV) and discrimination between electron recoils and nuclear recoils.



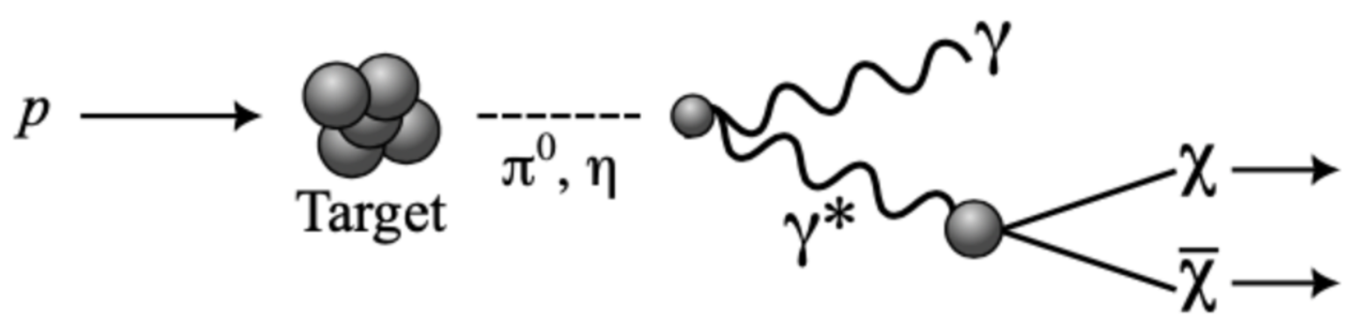


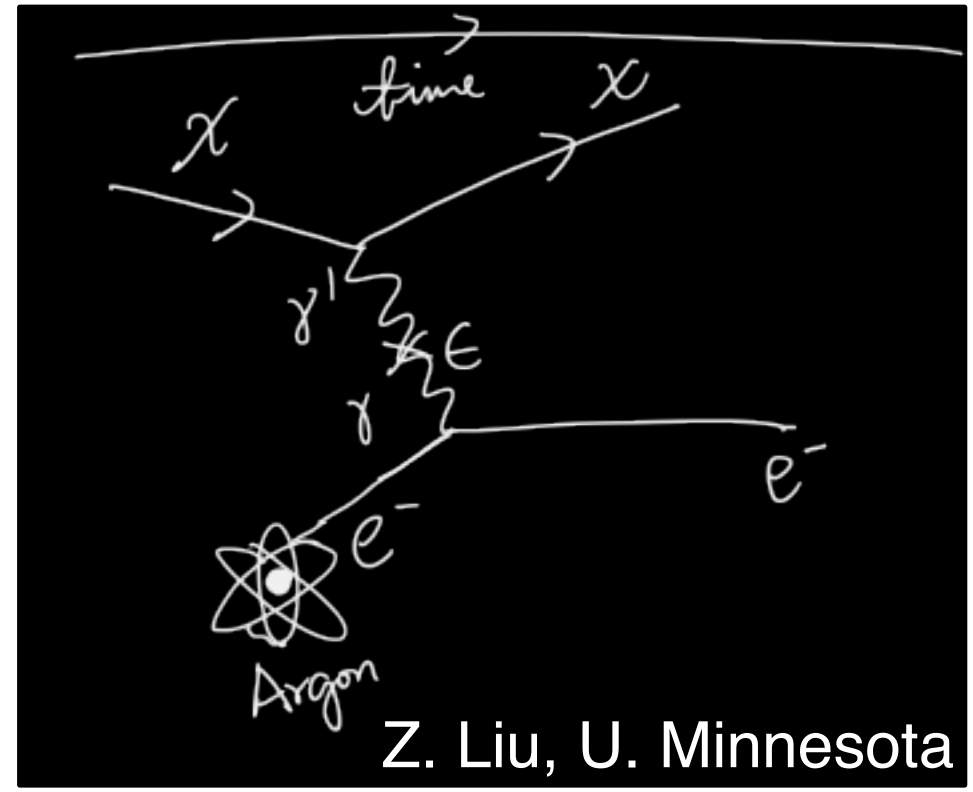
Skipper-CCDs. Single electron counting with silicon. Can get to kg scale, and already demonstrated very competitive results in beam.

Cryogenic micro-calorimenters. (CDMS type detectors) Low threshold (eV) and ER vs NR discrimination.

One idea for a dark sector search at PIP-II with eV-scale detection thresholds: millicharged particles (mCPs)

$$\mathcal{L}_{\rm mCP} = i\bar{\chi}(\not{\partial} - i\varepsilon e \not{B} + M_{mCP})\chi$$

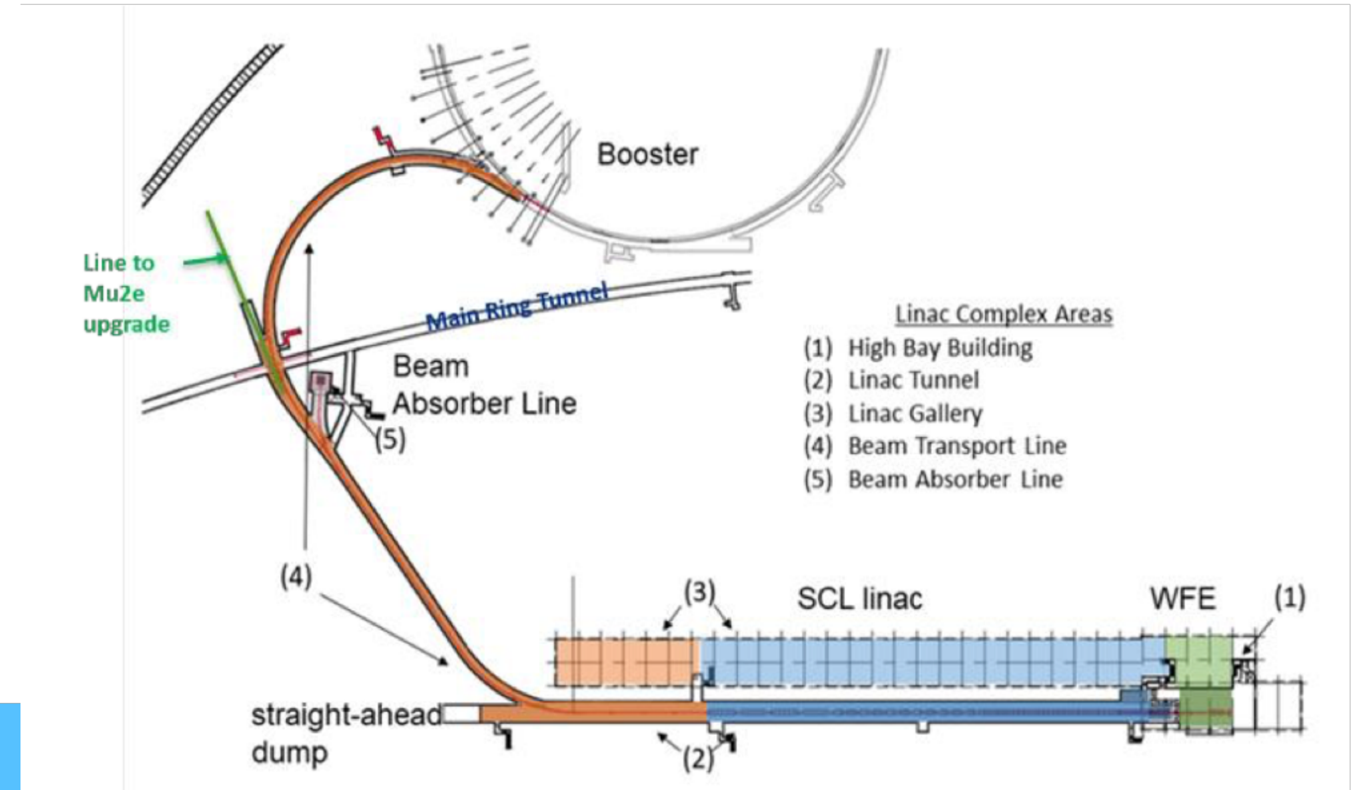


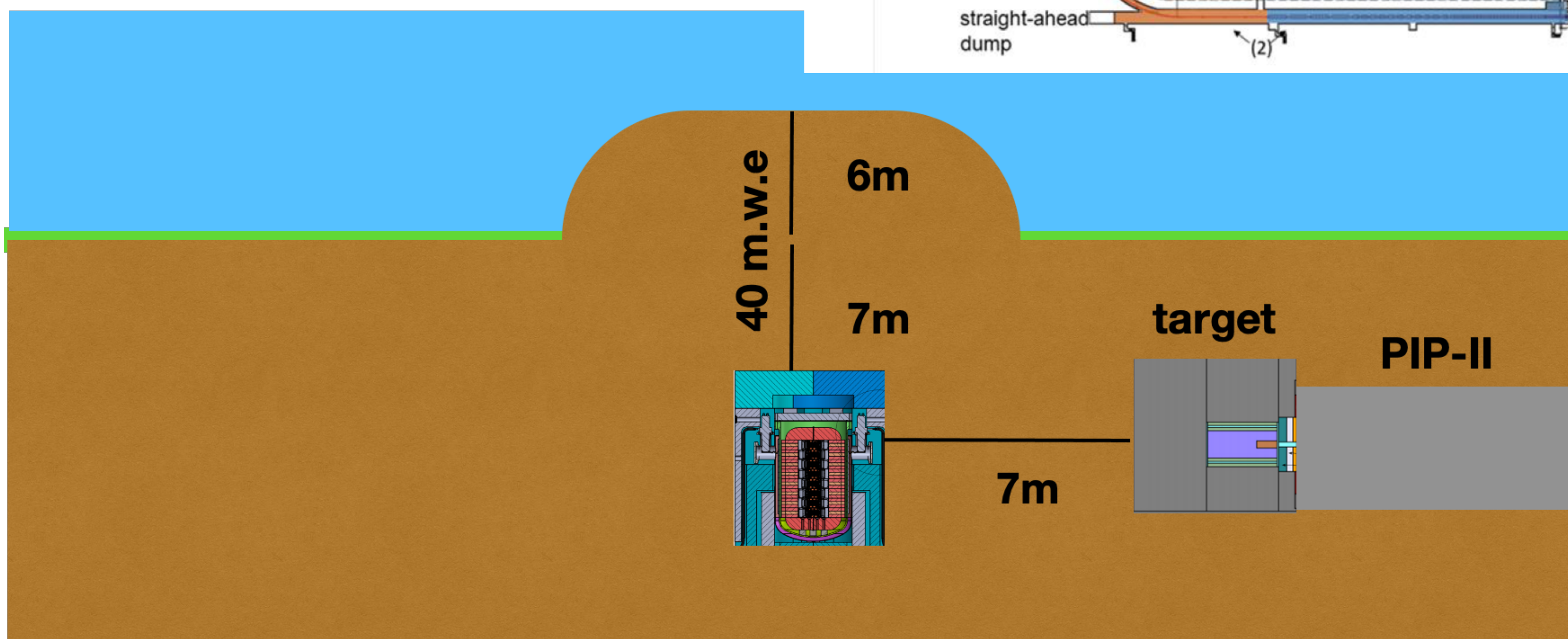


- mCPs produced in high energy collisions at particle accelerators
- Some examples of experiments that can search for mCPs: milliQ, milliQan, and ArgoNeuT

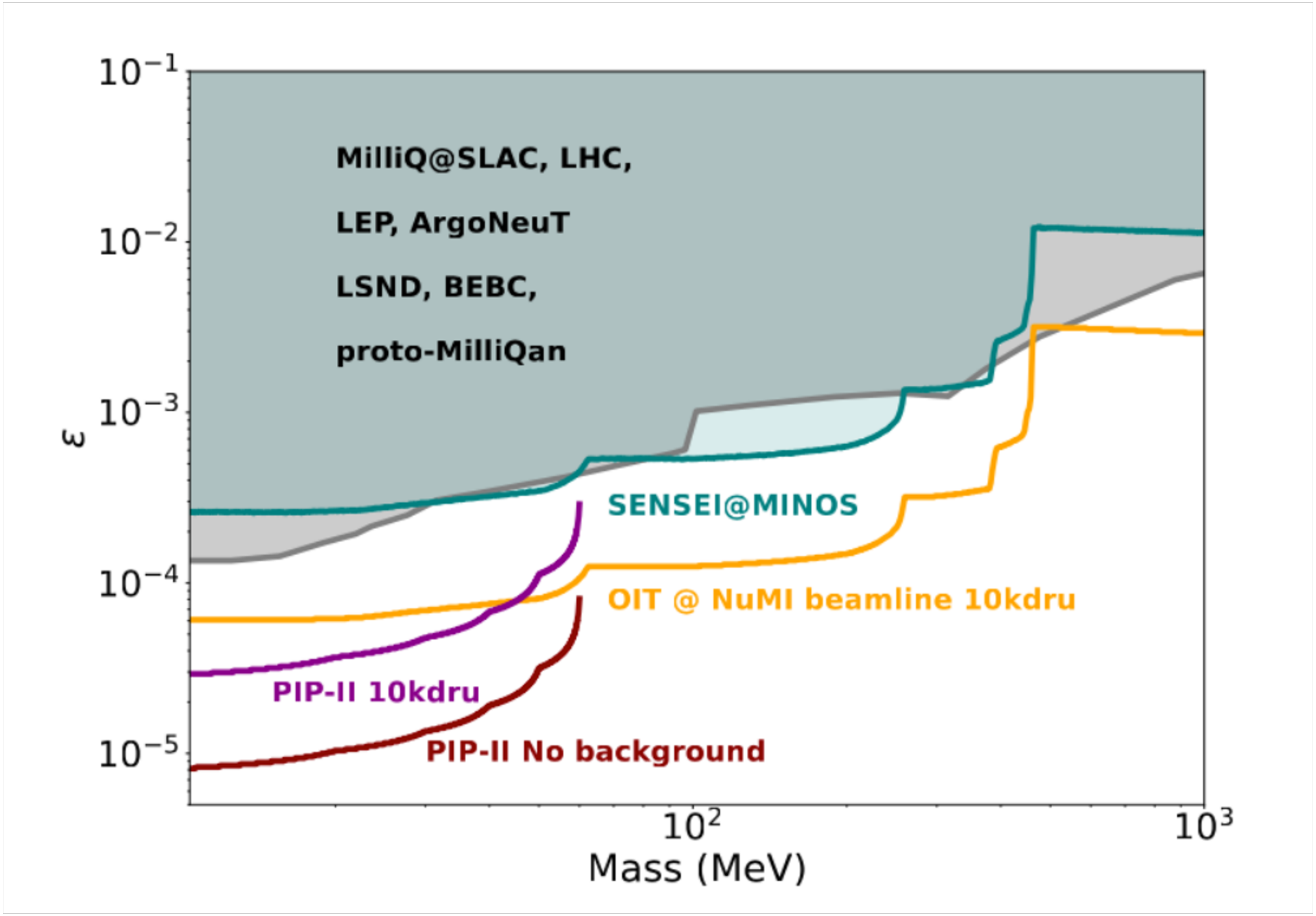
Proposed Experimental siting at PIP-II

- kg-scale skipper-CCD experiment
- ~10 m away from target
- Using full PIP-II CW current
- Place in a shallow underground lab and look for tracks





Expected limits for skipper-CCD detectors at PIP-II CW

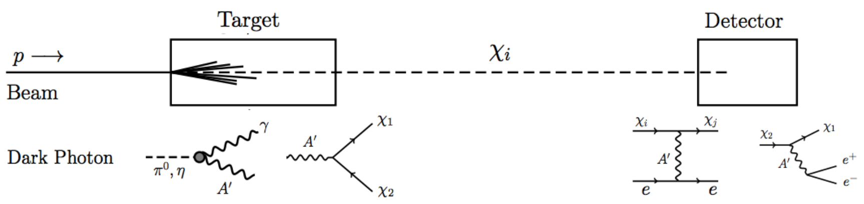


SENSEI@MINOS results: L. Barak et al., arXiv:2305.04964

Opportunities at keV-scale detector thresholds

Physics available with O(1 GeV) proton energy and PIP-II coupled to an accumulator ring

- Searches for dark sectors
- 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



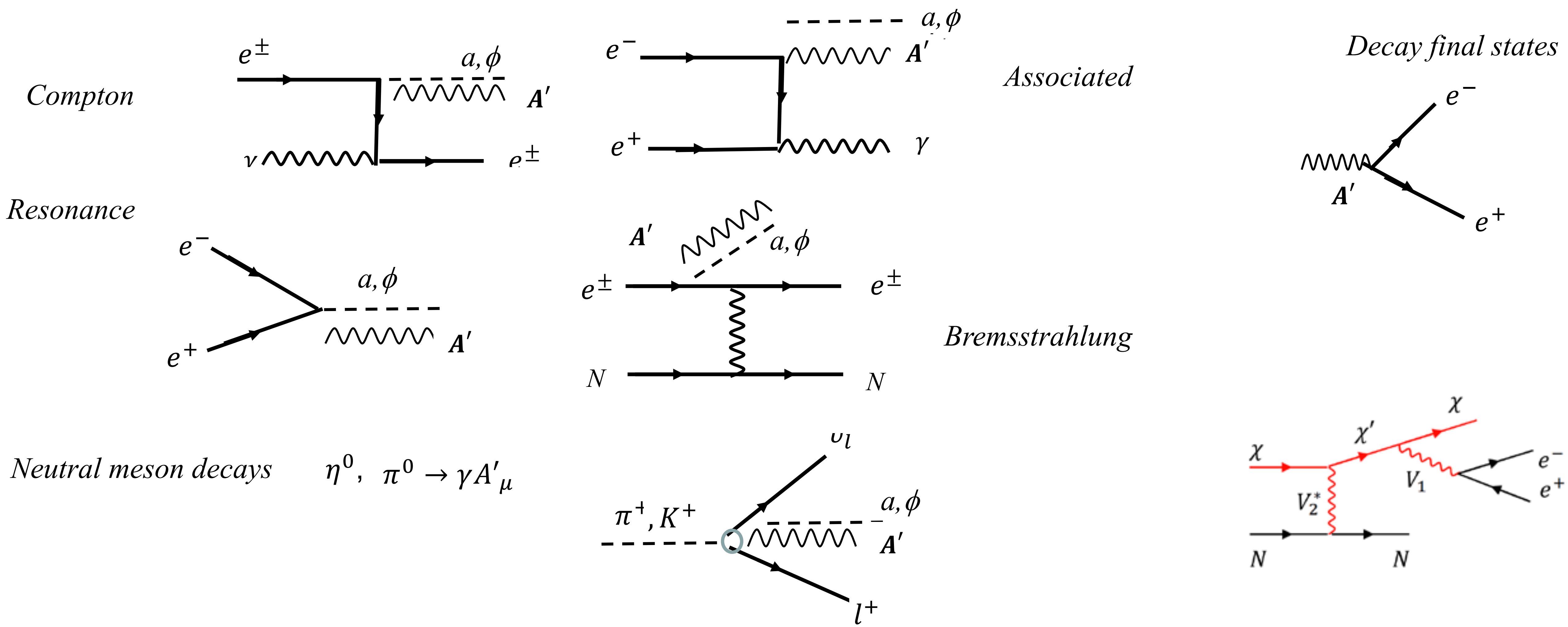
keV

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

MeV

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

(Some) Theory ideas for dark sector searches at beam dumps



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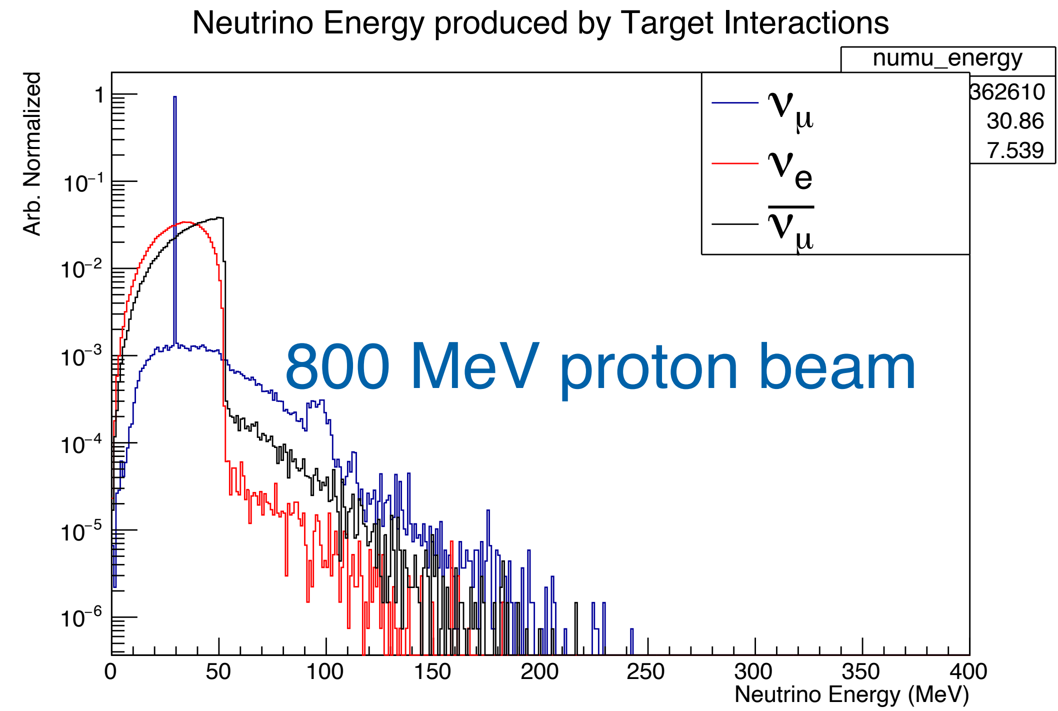
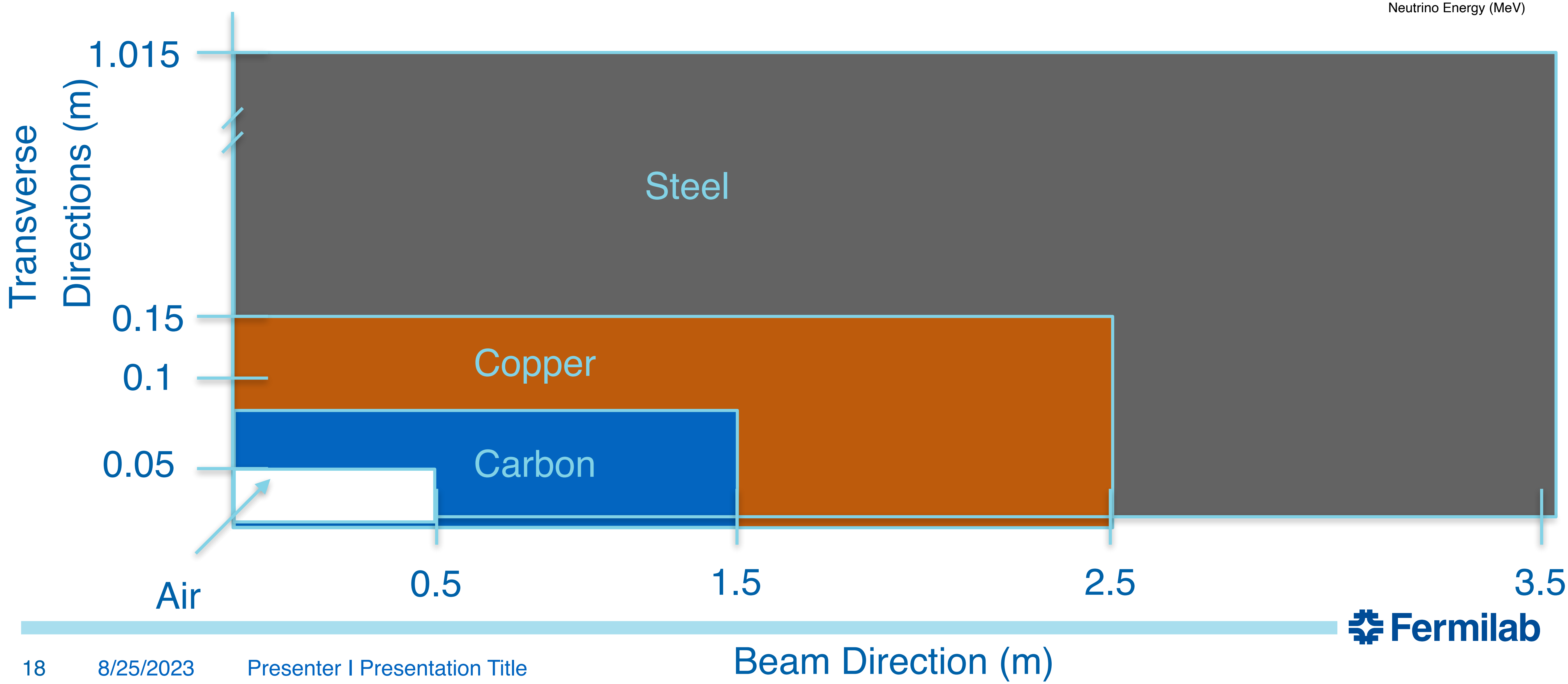
Solar and supernova neutrino detection with LAr scintillator and LArTPCs

One possibility for a target setup at a PIP-II facility

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





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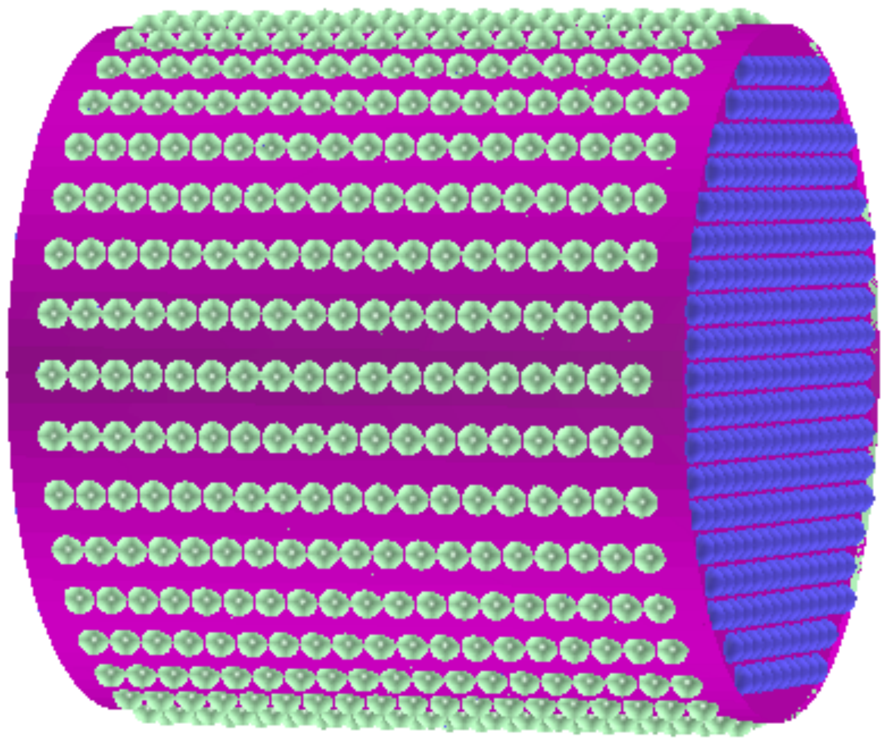
Proposed keV-scale Detector at PIP-II (+acc. ring): PIP2-BD

- 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
- Preliminary simulations suggest O(10) keV threshold achievable with this detector
- Existing experiments such as COHERENT at ORNL and CCM at LANL are key for testing many of the experimental techniques to successfully reach the physics goals of a 100-ton scale detector
  - These experiments are performing dark sector searches!
- Fermilab-funded LDRD to study dark sector searches at proposed stopped-pion facility using PIP-II



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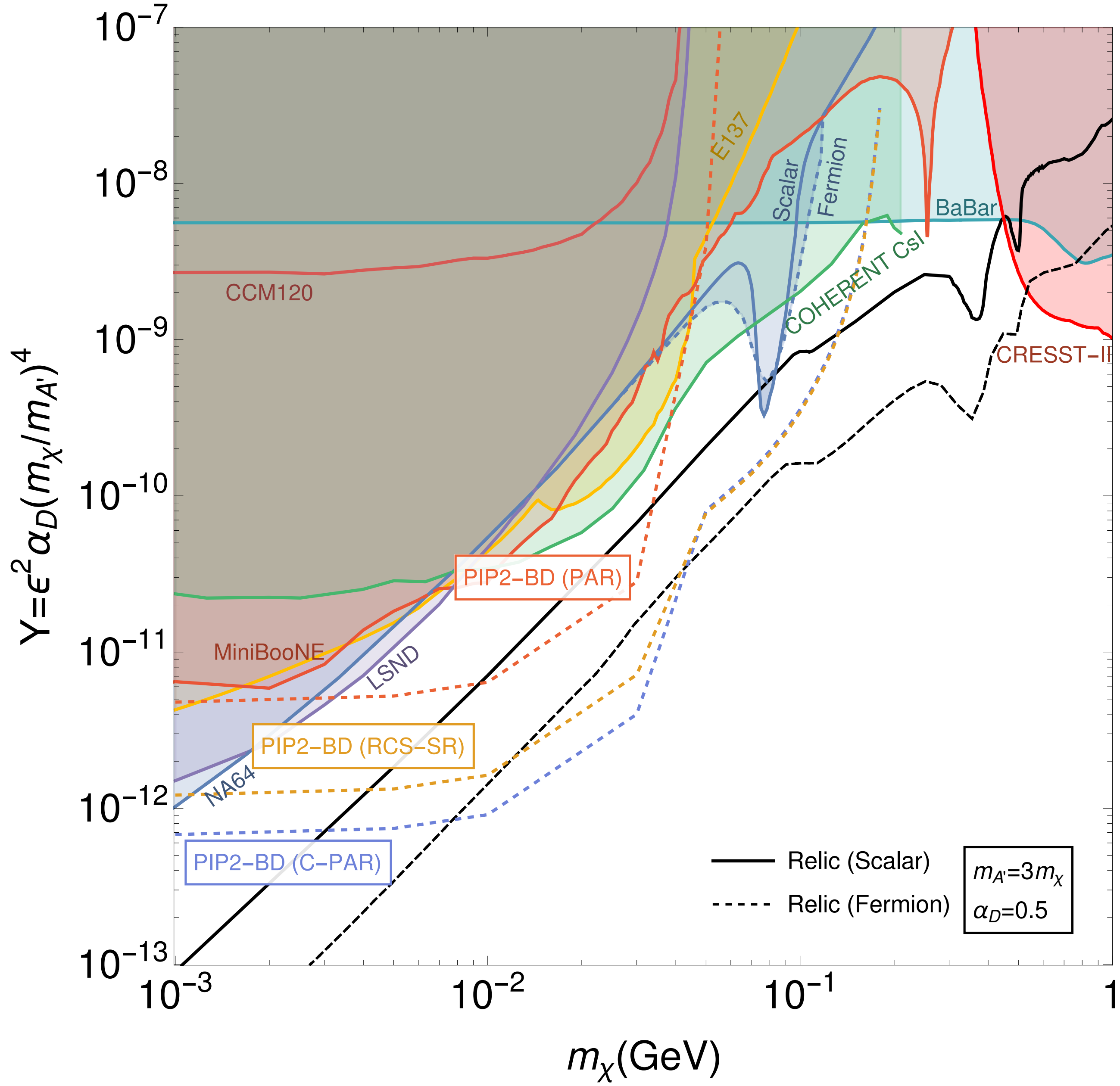
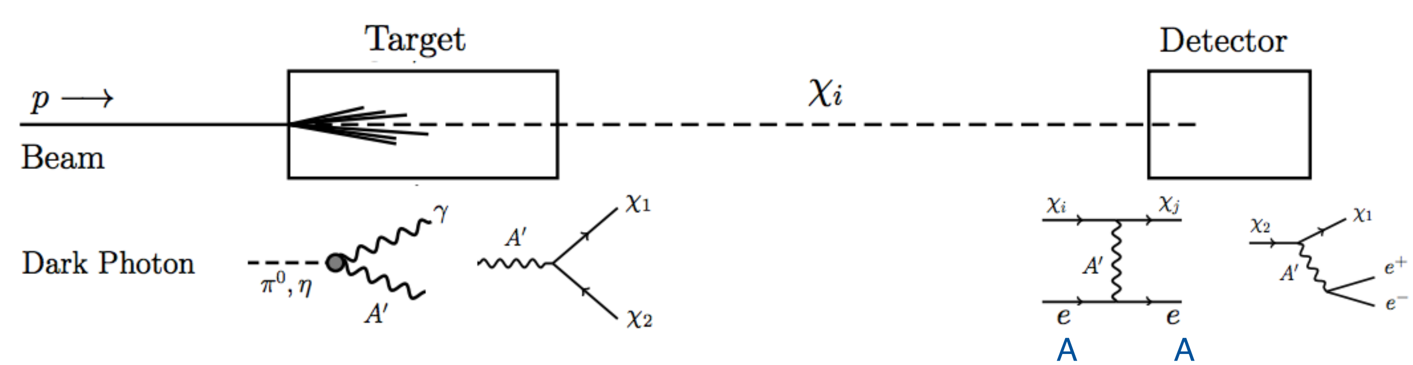
PIP2-BD Vector Portal Dark Matter Search

M. Toups et al., arXiv:2203.08079

- 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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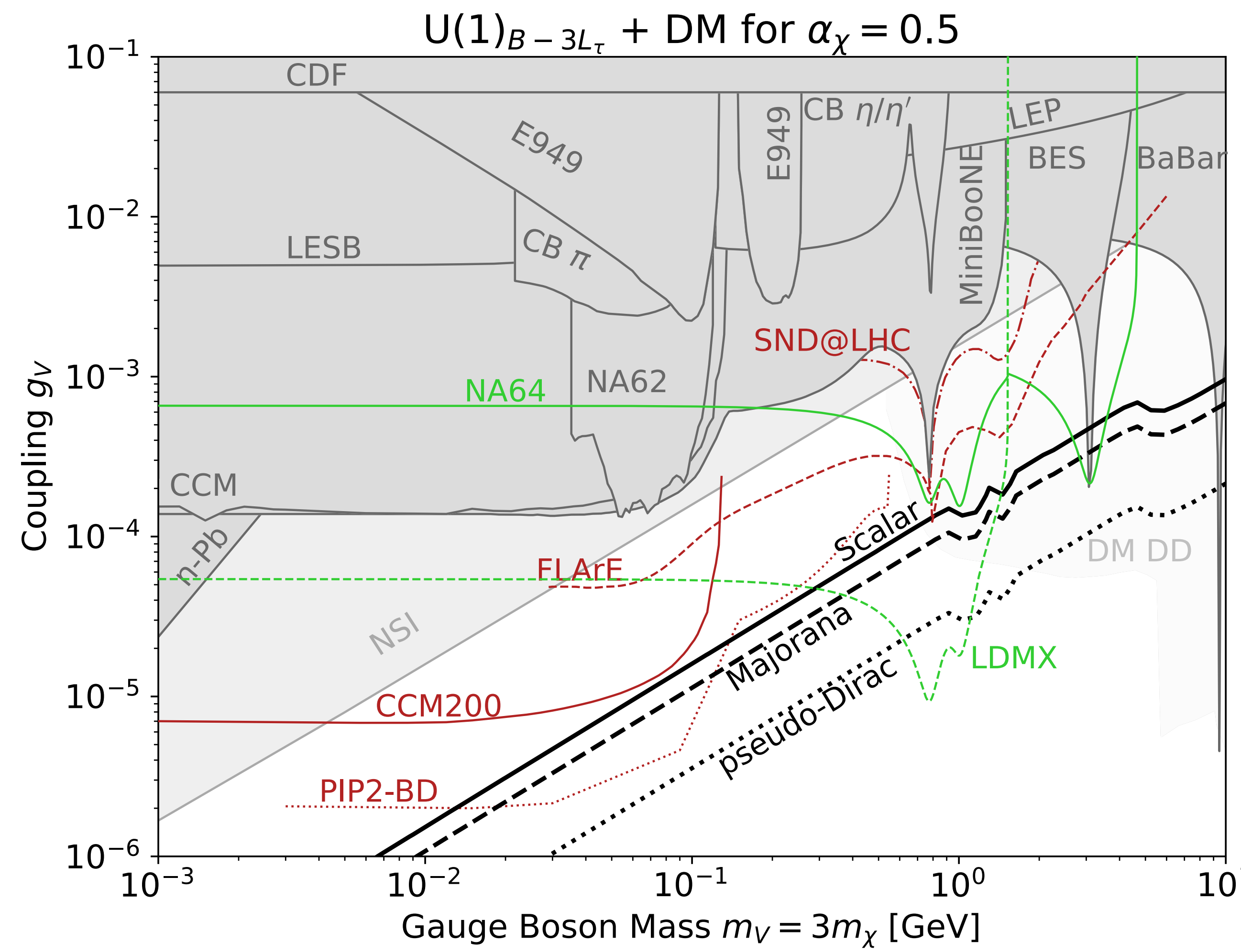
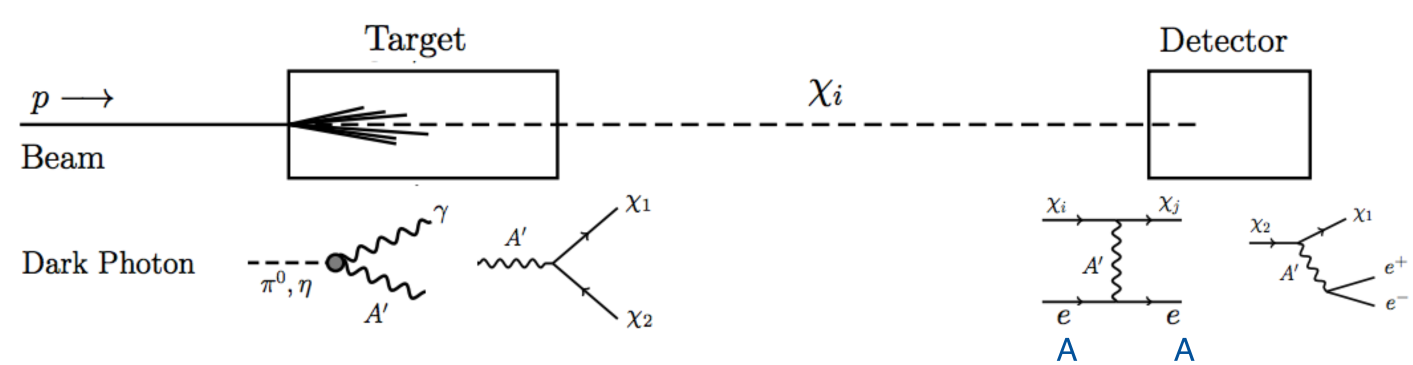
PIP2-BD Vector Portal Dark Matter Search

G. Krnjaic et al., arXiv:2207.00597

- Also consider leptophobic dark matter models where DM couples to quarks instead of leptons
- 5 year run of PIP2-BD



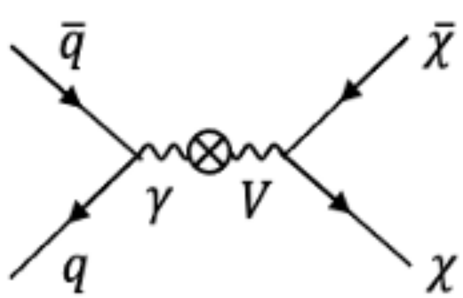
(b) $U(1)_{B-3L_\tau}$, $\alpha_D = 0.5$

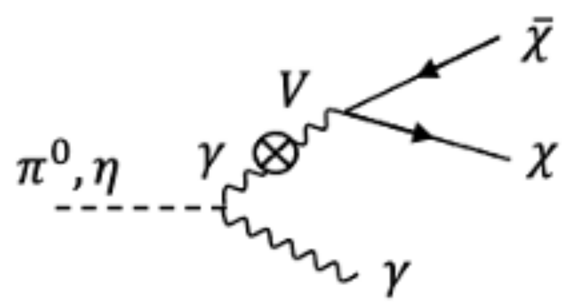


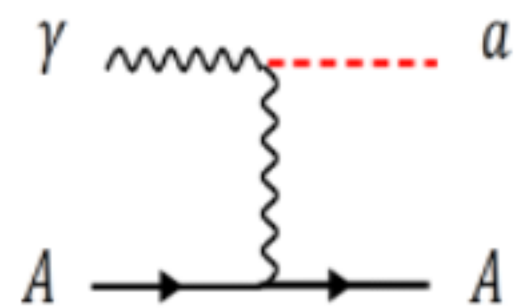
Opportunities at MeV-scale detector thresholds

Opportunities at the MeV-scale

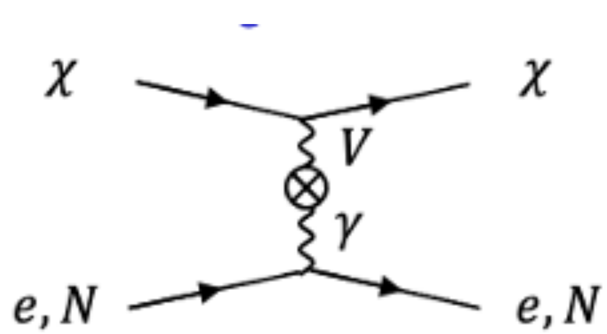
- Dark sector particles can be weakly coupled to visible sector through a mediator or portal
- At this energy scale can focus on photon production from brehmsstrahlung, Drell-Yan, and neutral meson decays
  - Additional coupling of new U(1) gauge to Standard Model photon

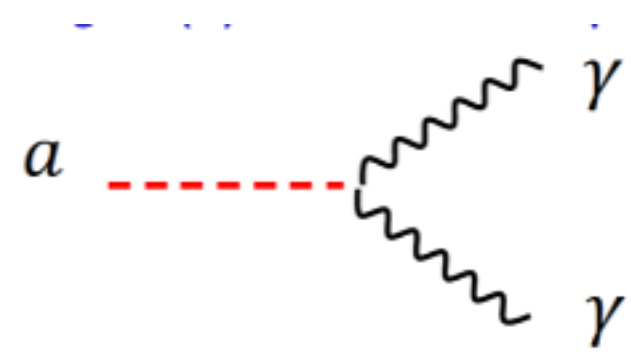






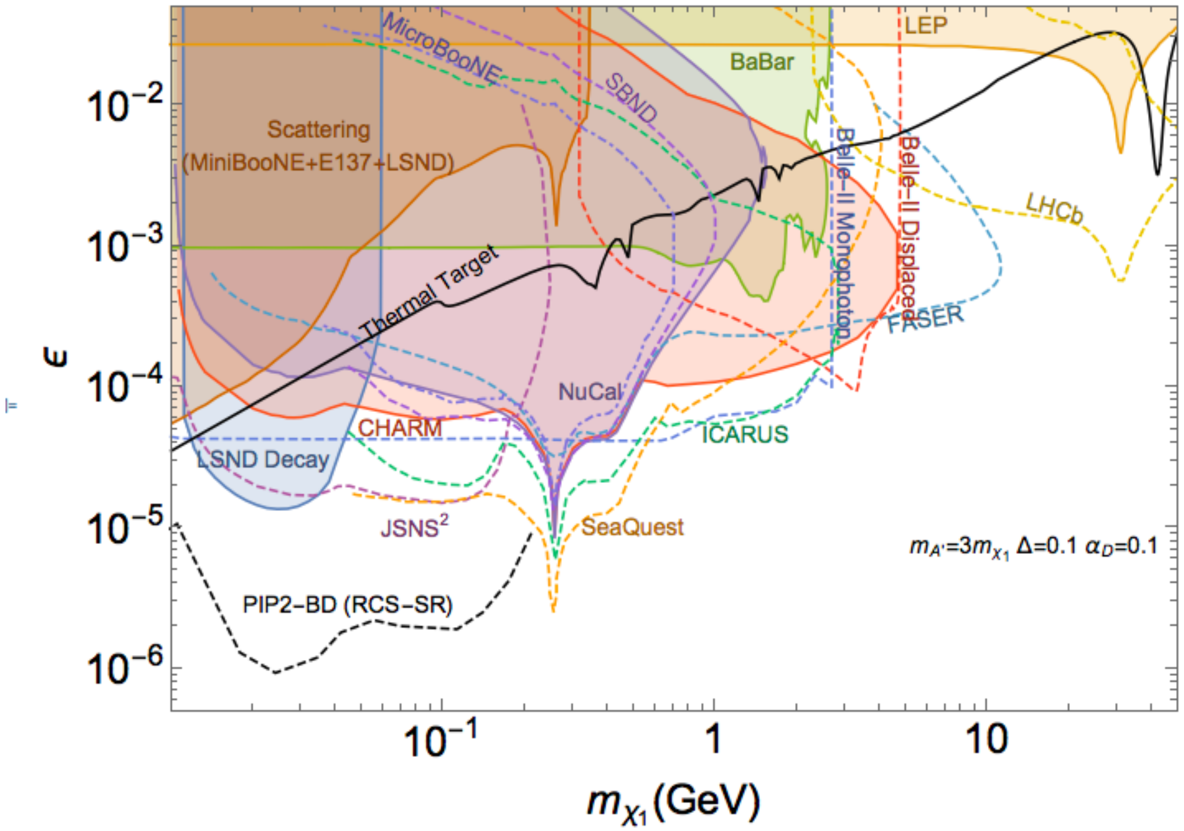
  - Detection through electron scattering, or one and two photon final states

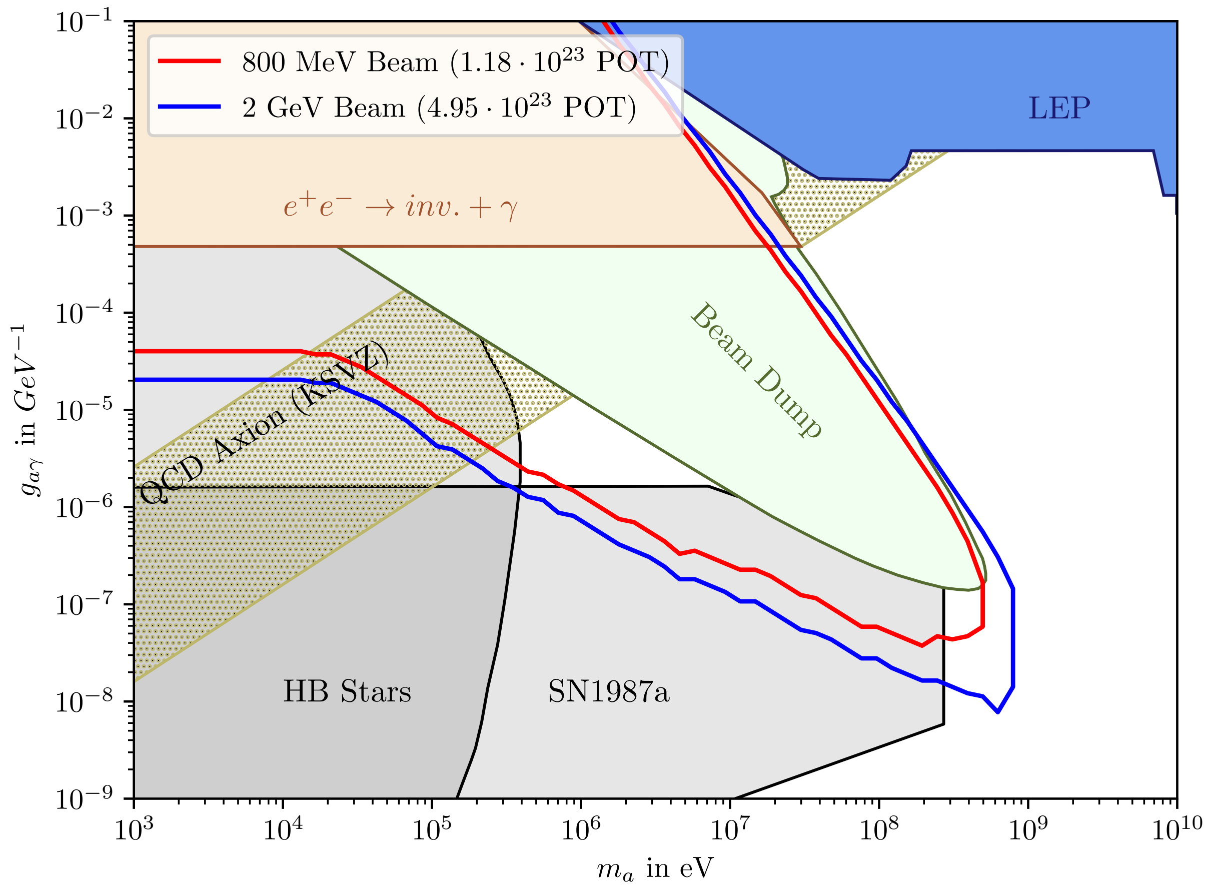


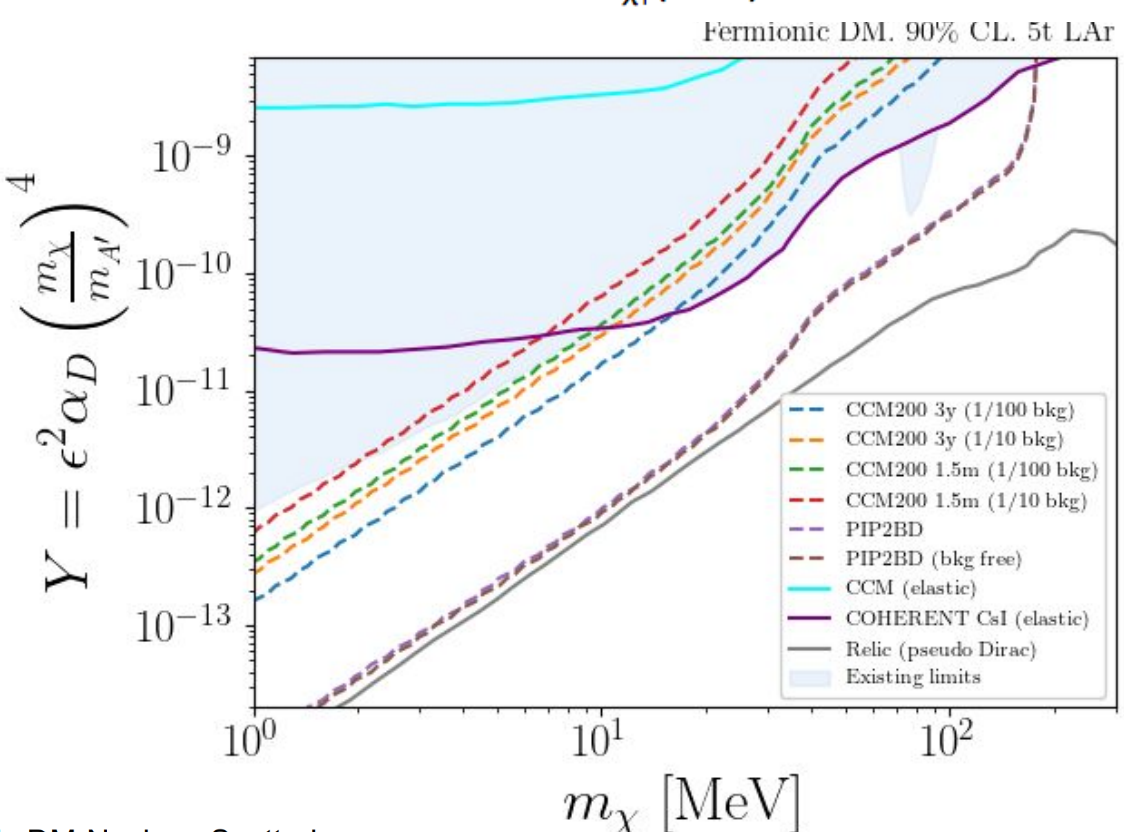


MeV-scale physics at PIP2-BD

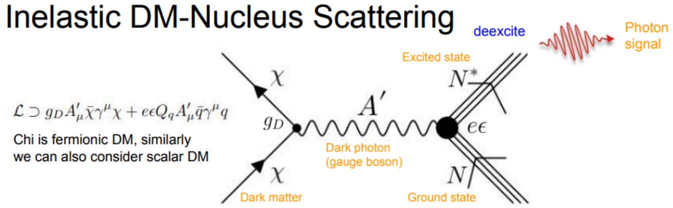
- Detector with MeV-scale dynamic range has further physics reach
- Ideas to search for ALPs, and inelastic DM models
  - Exploring other possibilities with theory colleagues!





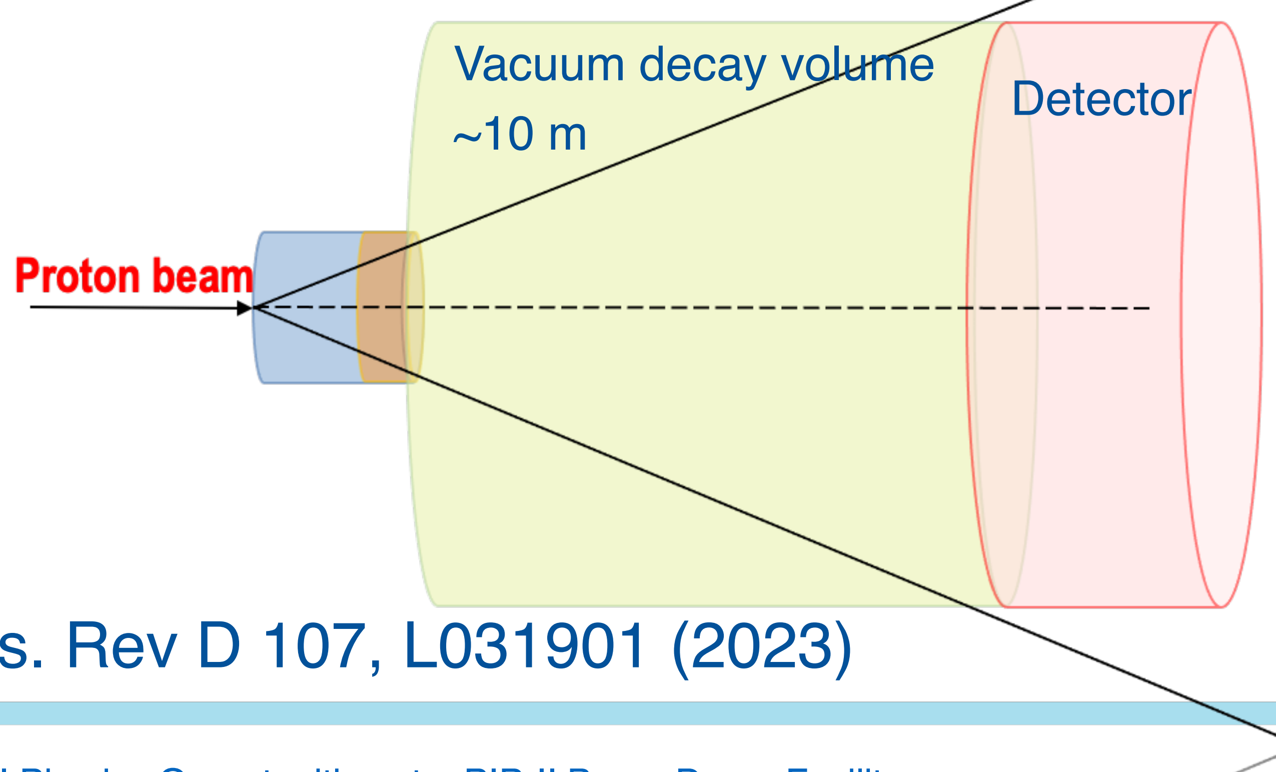


Inelastic DM-Nucleus Scattering



The DAMSA Experiment Concept

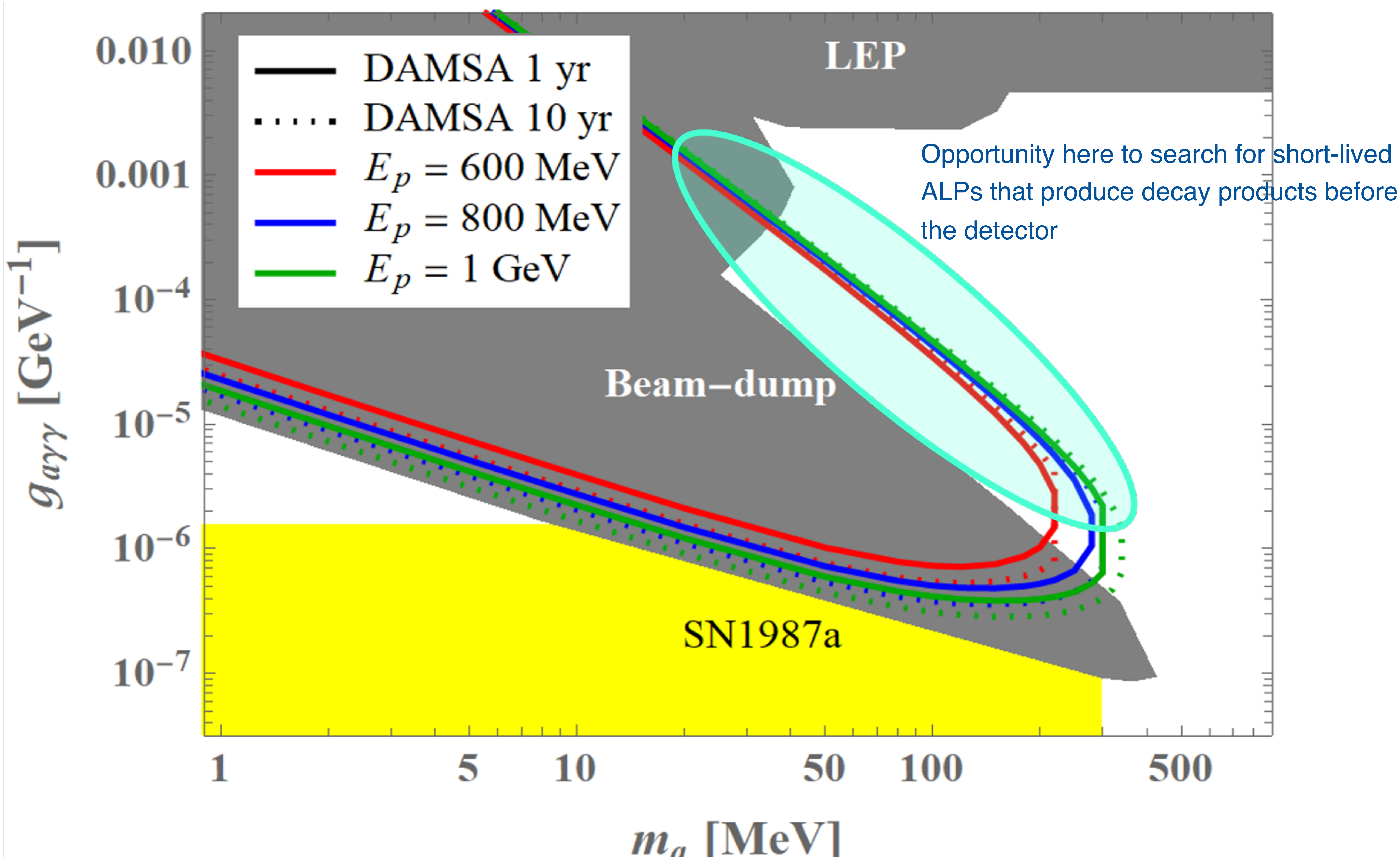
- Dump-produced Aboriginal Matter Searches at an Accelerator
- Search for axion like particles decaying to two photons via Primakoff process
- Place detector very close to the source (i.e. fixed target) with broad angular coverage
- Backgrounds from neutral particles: Neutrino NC and CCQE interactions producing
  - Neutron spallation is main background, key to understand how to minimize beam-related neutron backgrounds
- Goal of measuring up to 500 MeV photons with sub-ns level timing resolution



W. Y. Jang et al., Phys. Rev D 107, L031901 (2023)

DAMSA Sensitivity to ALPs

Adapted from W. Y. Jang et al., Phys. Rev D 107, L031901 (2023)



Summary

- The Fermilab Accelerator Complex is undergoing upgrades to begin the PIP-II era beginning at the end of the decade
- There are opportunities to further enhance the complex which will undergo further upgrades in the form of the ACE plan
  - This could include an accumulator ring with short-pulse structures
- There are significant physics opportunities at a PIP-II beam dump facility for different detector types with varying threshold at a dedicated experimental hall

Thank you!

Questions?

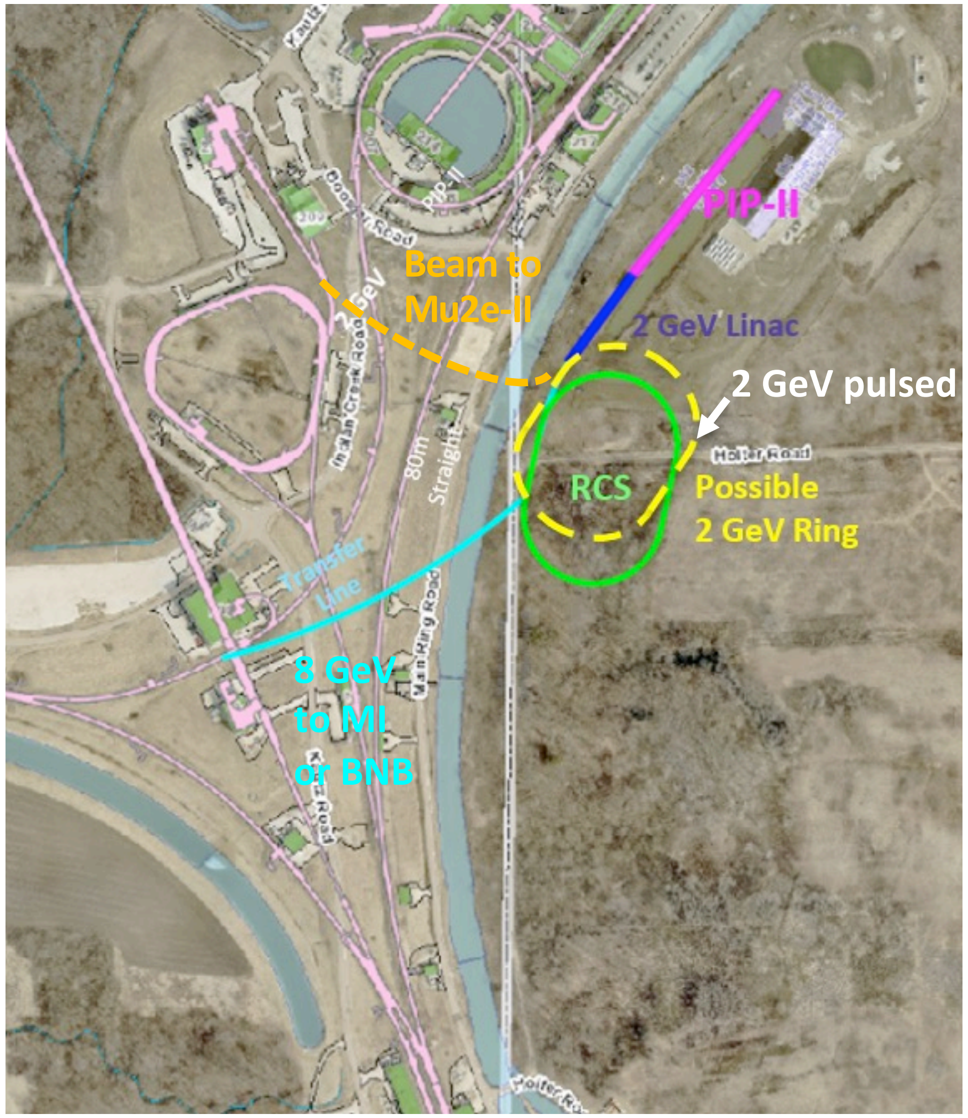
Backup Slides

Example Booster Replacement options and possible add-ons

C1b: 20Hz RCS + 2 GeV Accumulator ring

Main Elements:

- 1-2 GeV Linac
- 1-2 GeV Accumulator Ring
- 20 Hz 8 GeV RCS



Opportunities for Beam Dump Experiments: 1-2, 8, 120 GeV

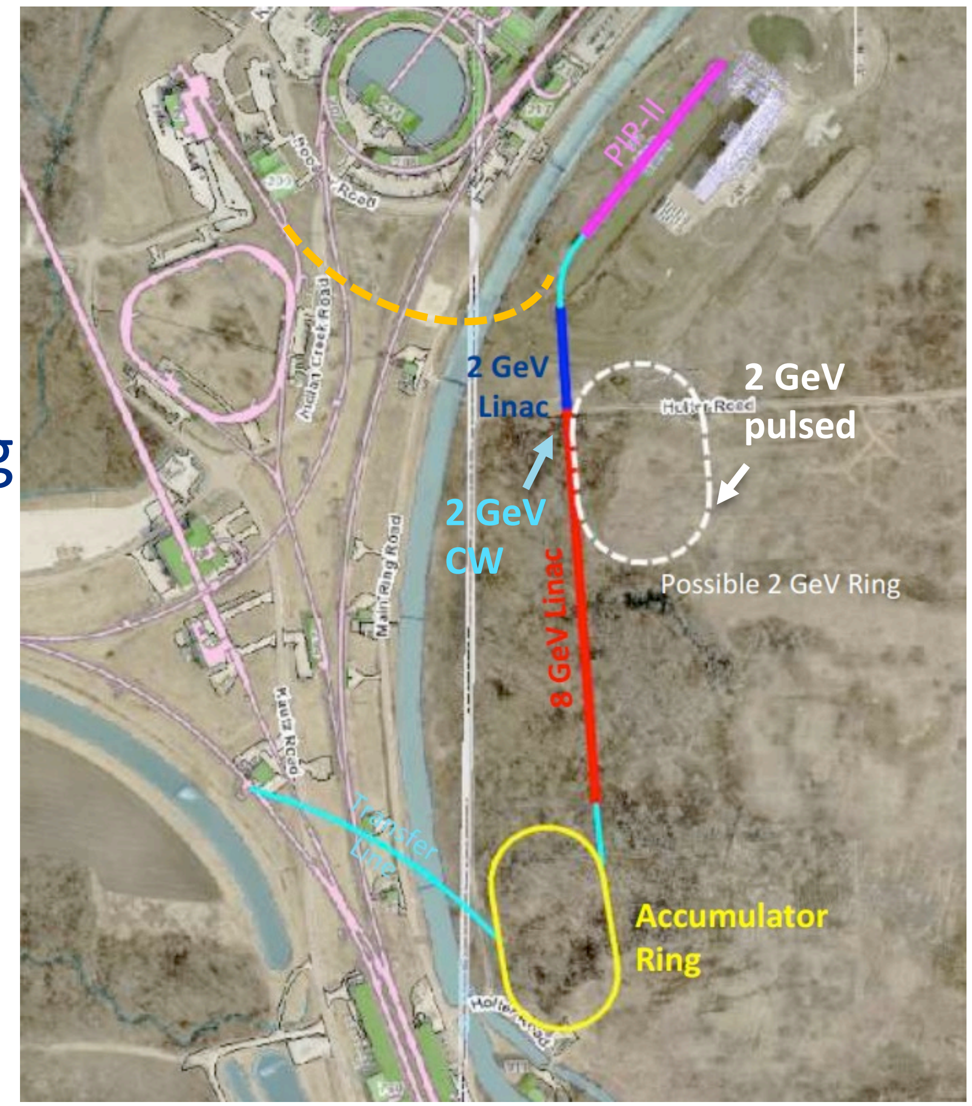
Example Booster Replacement options and possible add-ons

C2a: SRF Linac + 8 GeV Accumulator ring

Main Elements:

- 1-2 GeV Linac
- Optional ~1-2 GeV Accumulator Ring
- 8 GeV Linac
- 8 GeV Accumulator Ring

Opportunities for Beam Dump Experiments: 1-2, 8, 120 GeV



PIP2-BD Scenarios

CPAR, is what you get if you optimize PAR away from PIP-II Booster injection and towards short-pulse experimenters.

Flexible: This is *one set of parameters* but other combinationations of energies, powers, pulse lengths possible.

- One of the goals for this workshop can be to develop relevant benchmarks for accelerator performance.

Adaptable: Given a design of a CPAR ring, we can also operate with multiple modes of beam extraction for different experimenter needs.

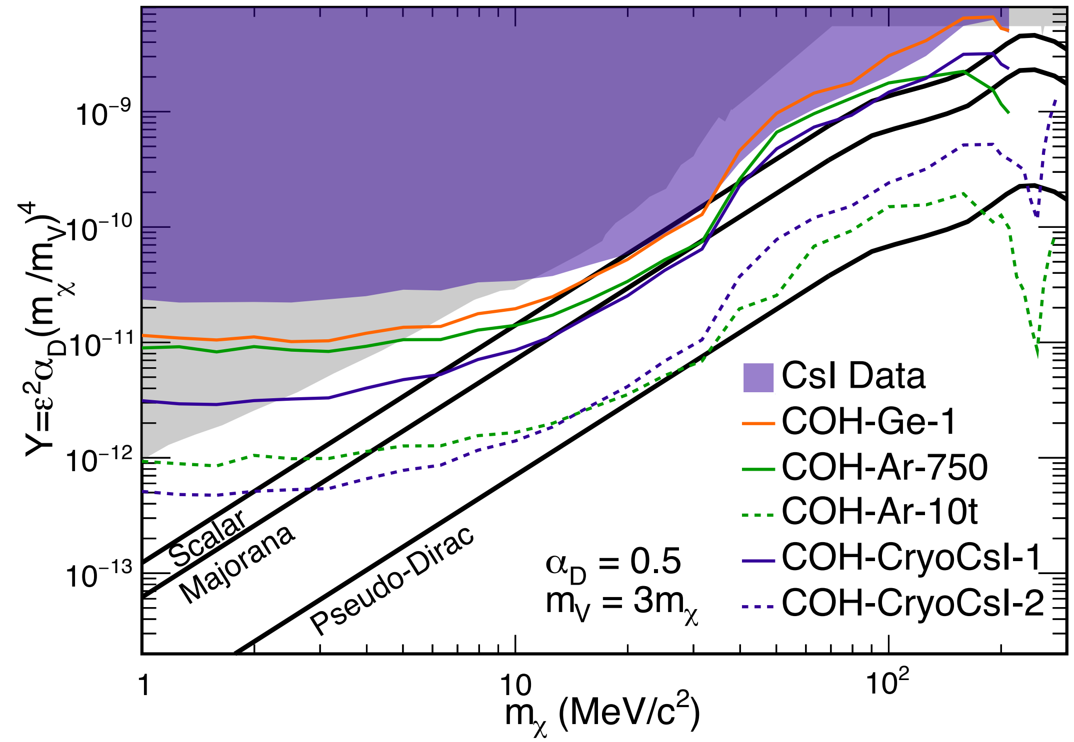
- More detail on next few slides.

Upgradeable: The ring energy is fixed and if the PIP-II linac beam power is abundant, then we are limited only by the performance of the ring.

- Long-term upside potential is large.
- A defacto intense beams R&D program.
  - synergy with future short-pulse programs.

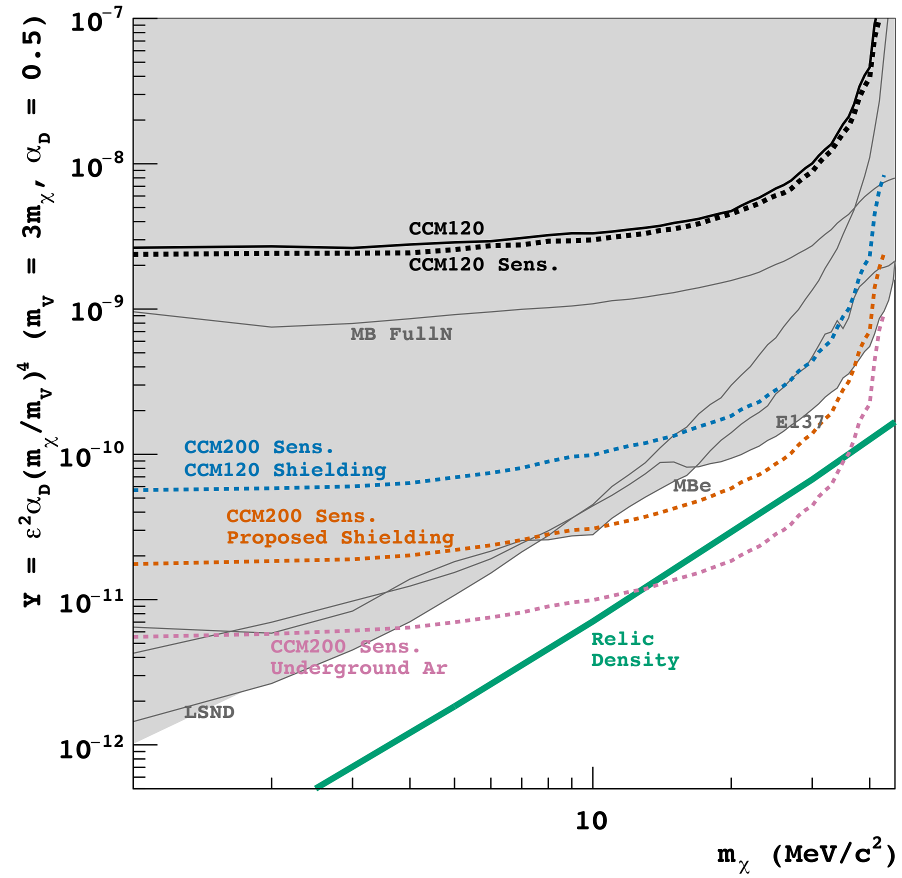
Current Accelerator-based vector-portal dark sector searches

- 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)

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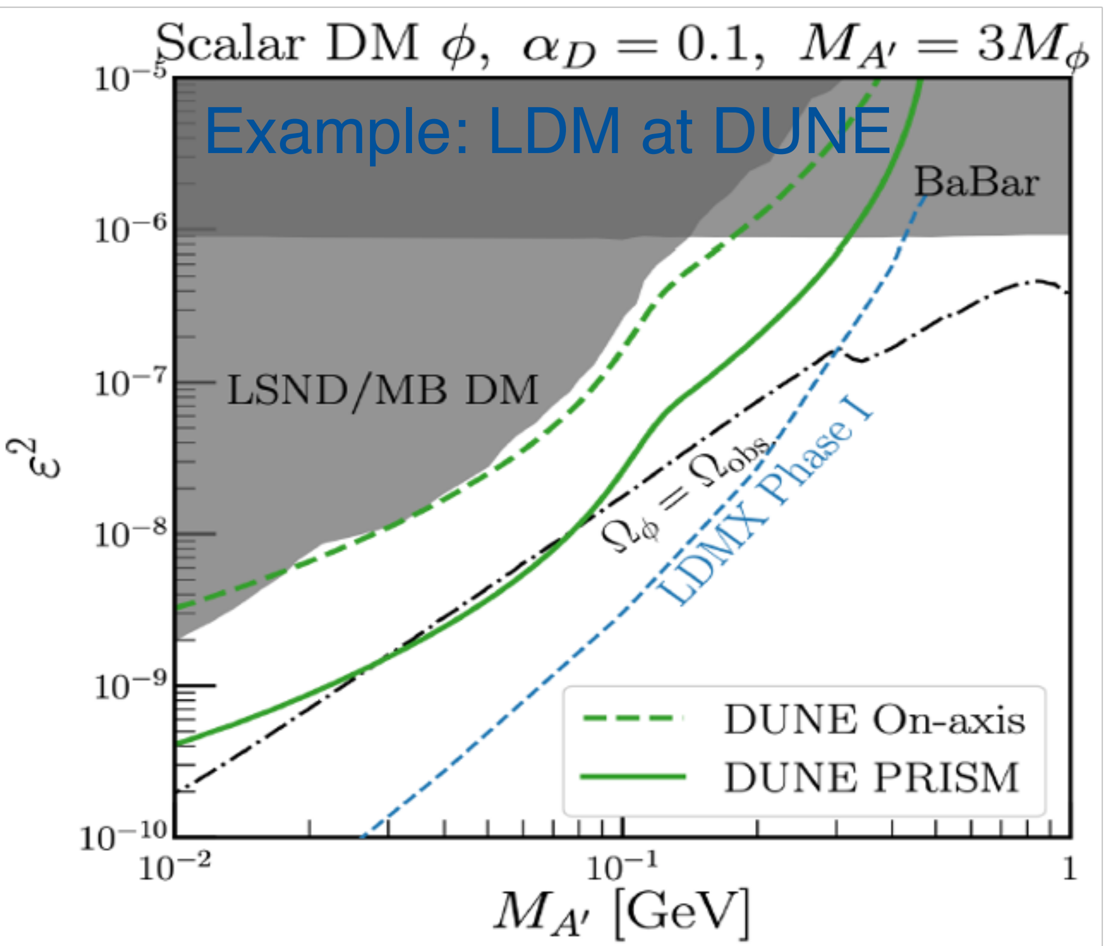
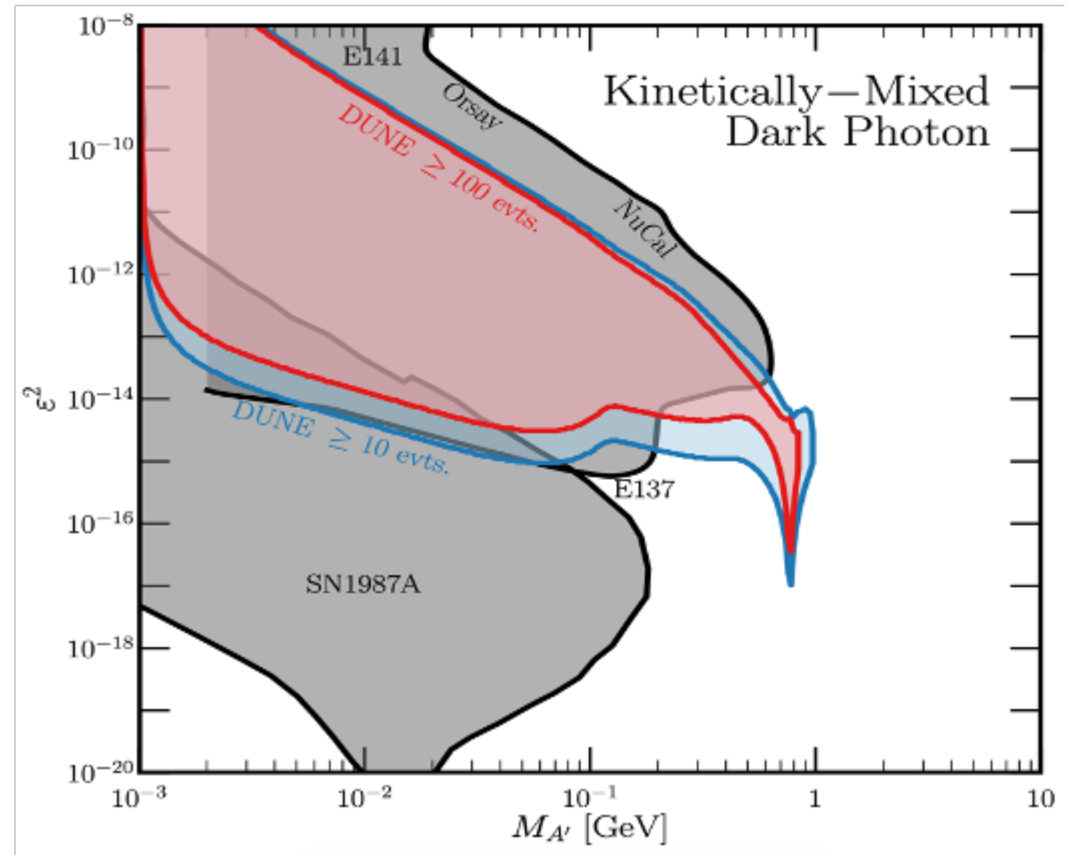
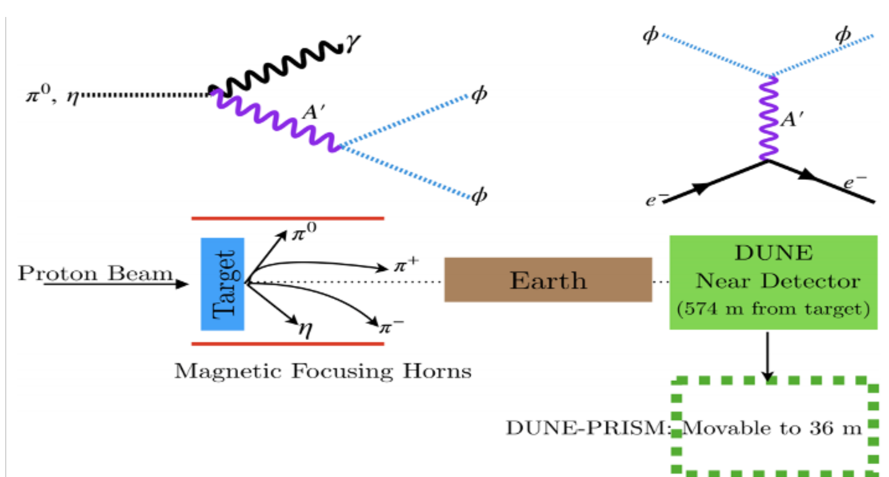
Physics Opportunities with MeV-scale thresholds

- ALPs, Light Dark Matter (kinetic mixing model), and dark photon models

Example: LDM at DUNE







Example: Dark Photon Search at DUNE where dark photon travels to detector and decays into a charged lepton pair

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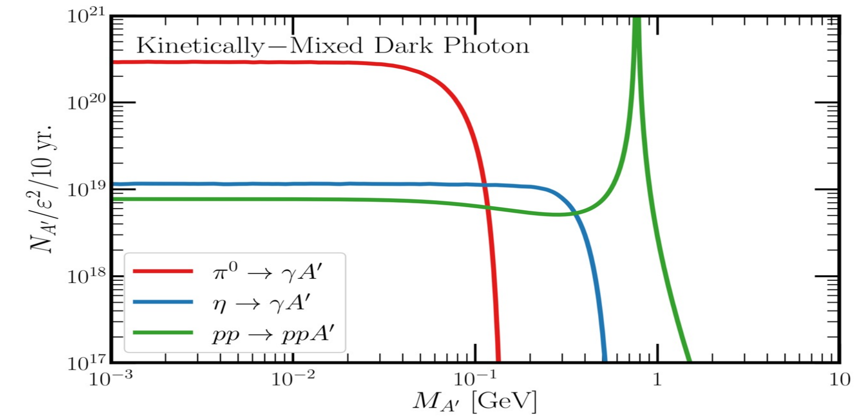
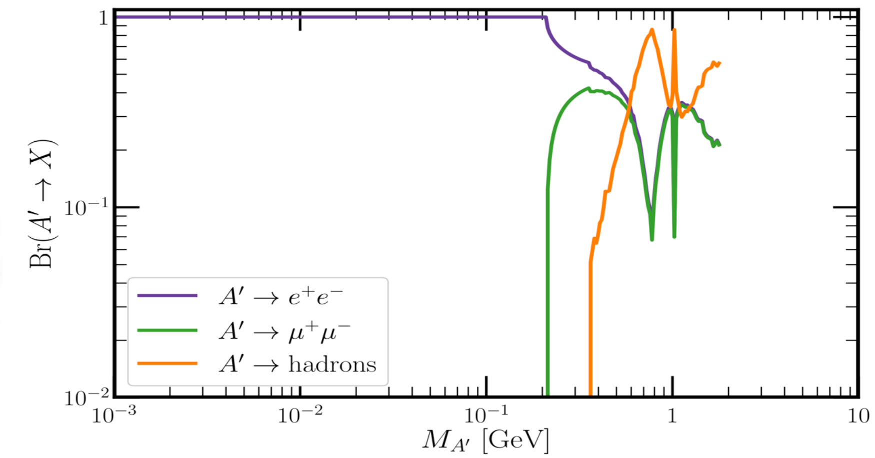
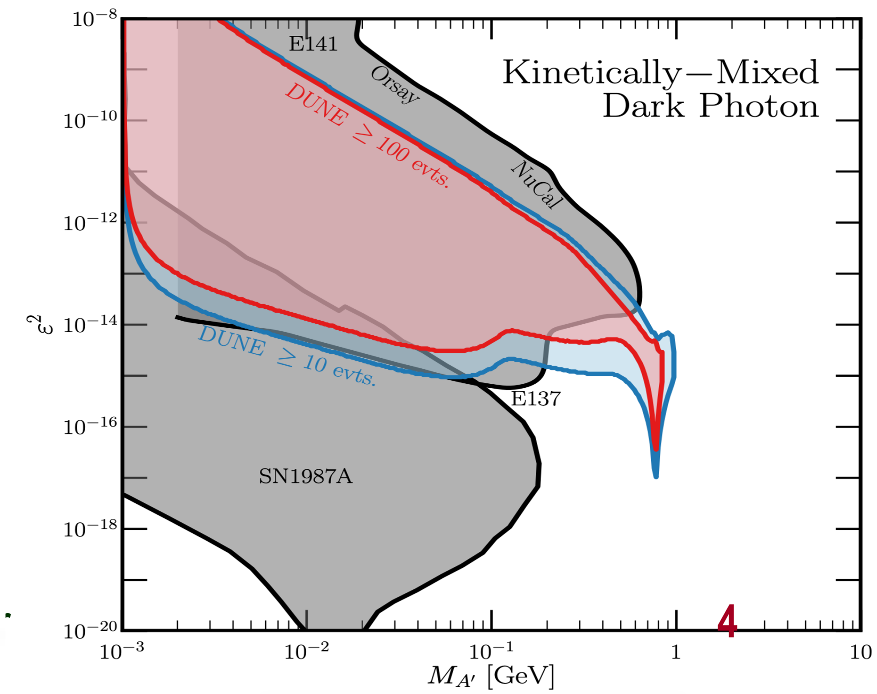
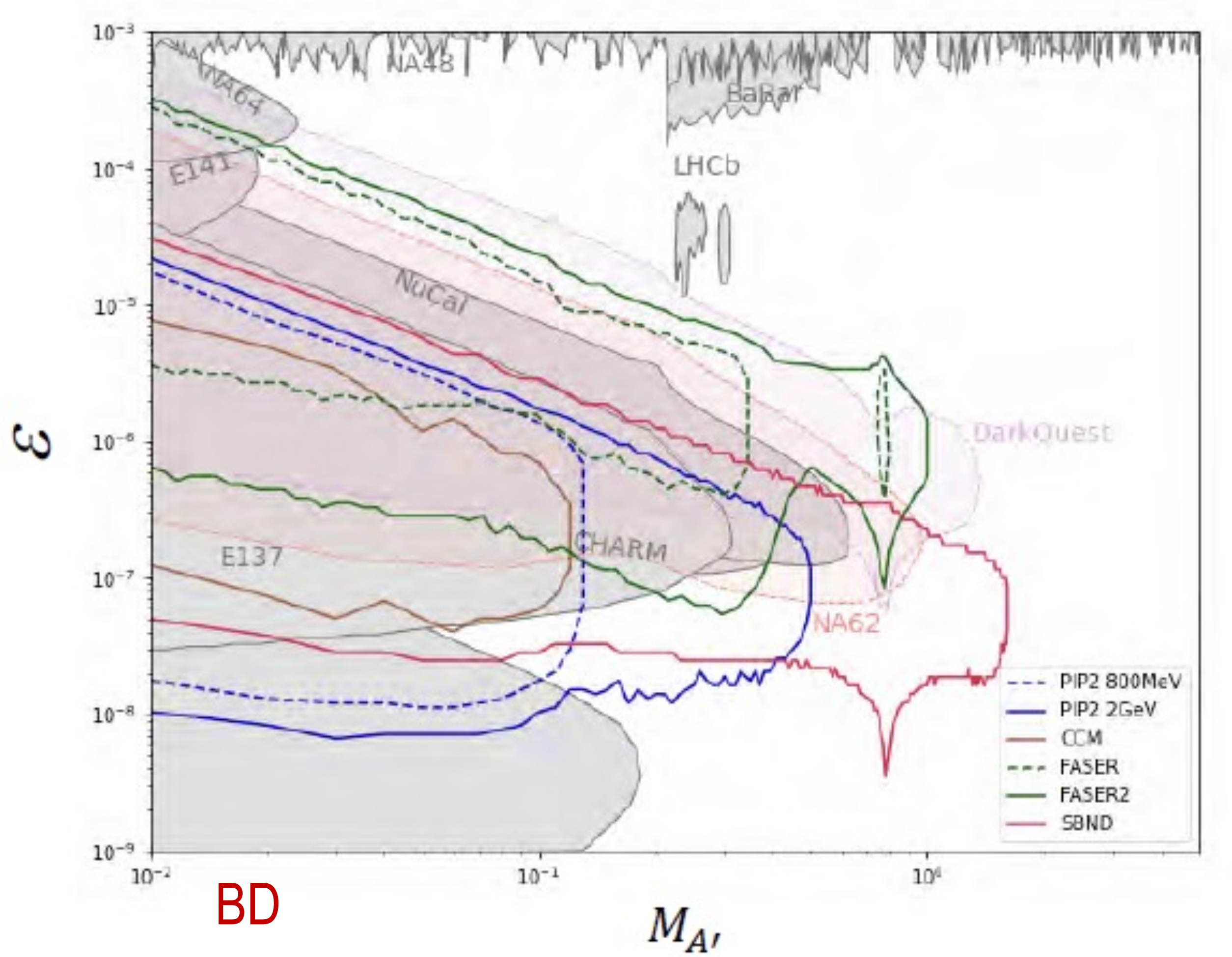
Dark Photon Searches

- New U(1) could kinetically mix with a SM γ from scalar meson decays or direct DY
- If these dark photons can live sufficiently long to reach the DUNE ND ➔ Look for their decays to a charged lepton pair
  - A’ → e^+e^-









Fermilab

Physics Signatures and Backgrounds

- The most optimal signatures involves photons and electrons in the final states
- Two EM particle final states, such as ALP's and dark photons, have a clear advantage over single EM particle final states
  - The impact of the ν-N interaction backgrounds less for more EM particle final states
  - The uncertainties in ν-N interaction modeling effect smaller
- BRNs become primary backgrounds for PIP-II energy level, especially for the shorter distances between the beam source and the detector
- These should factor into the selection of detector technologies and the experimental environments

May 11, 2023 DAMSA 9

DAMSA Detector Requirement Specifics

- Capable of measuring up to 500 MeV photons with a MeV and a good energy and mass resolutions
- Fine granularity for excellent shower position (better than 1cm) and angular resolutions
- Fast timing capability, ideally at the sub-ns level resolution
- High vertex and pointing resolution

May 11, 2023 DAMSA 8

Physics Signatures and Backgrounds

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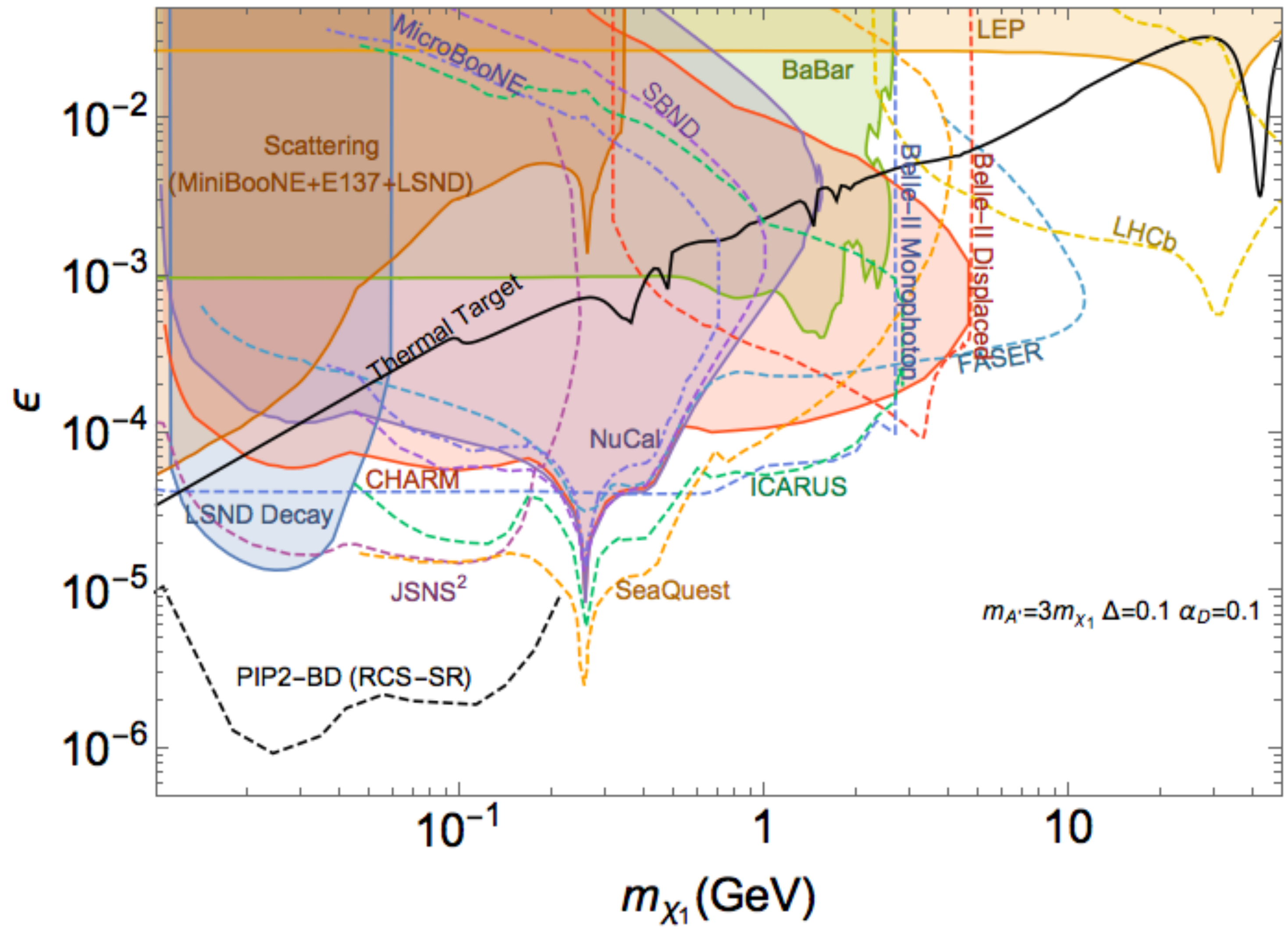
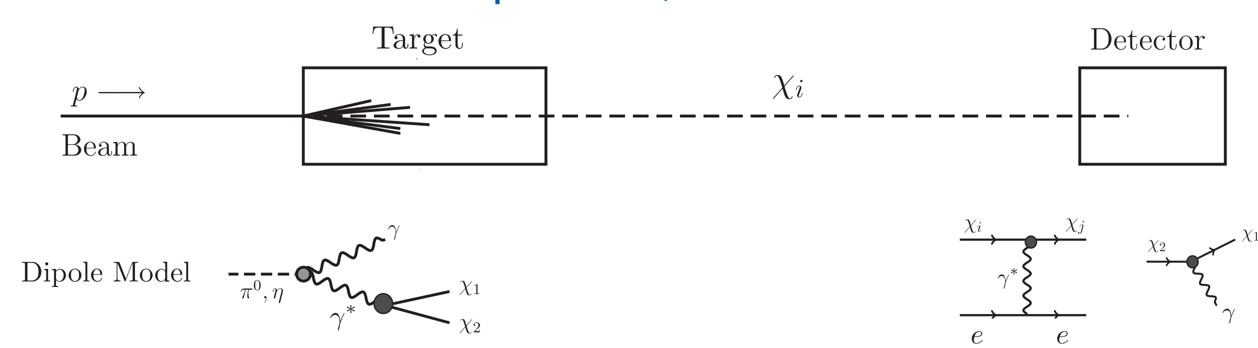
PIP2-BD Inelastic dark matter search

- 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

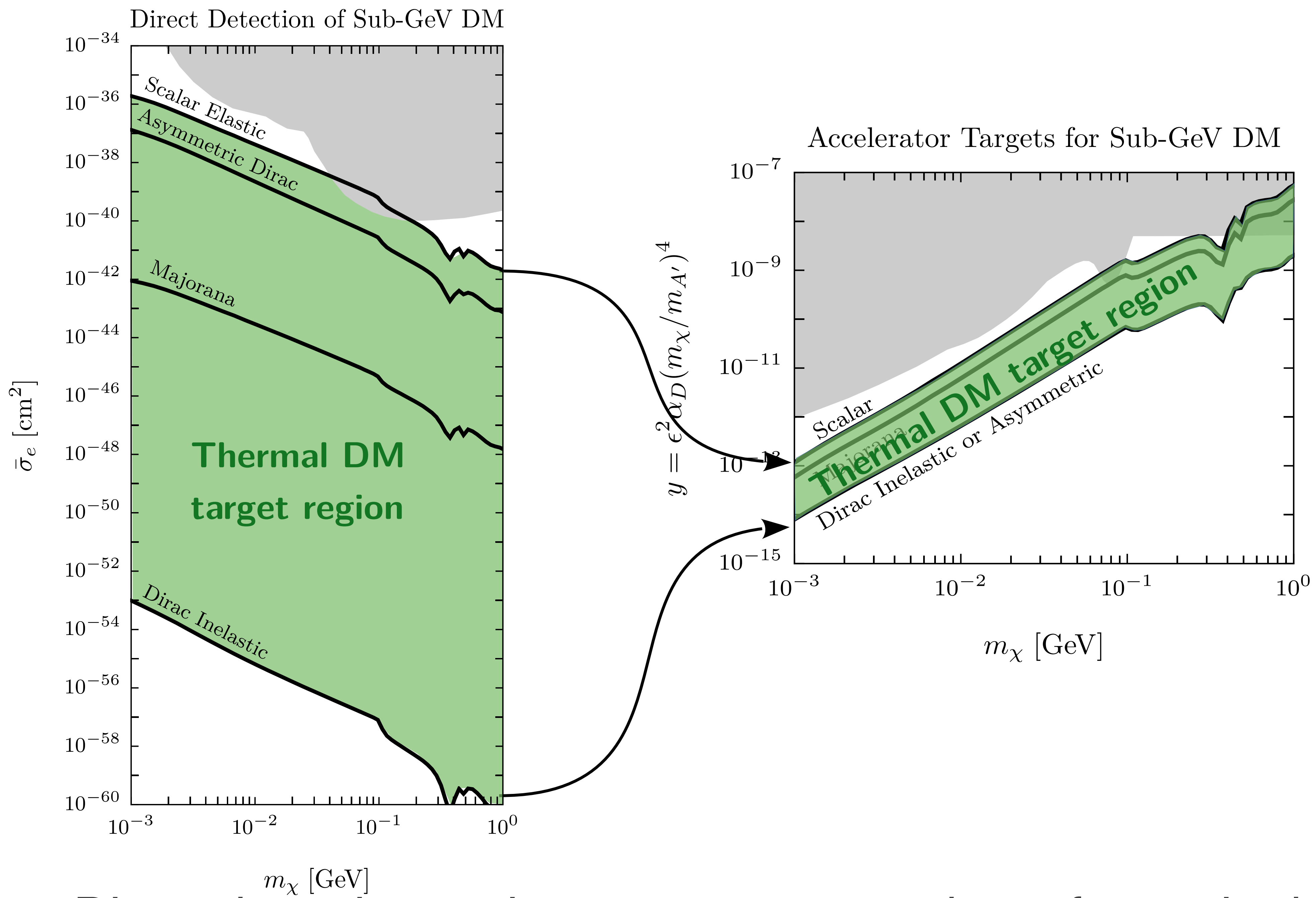


M. Toups et al., arXiv:2203.08079



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

Connections to Direct Detection DM Searches

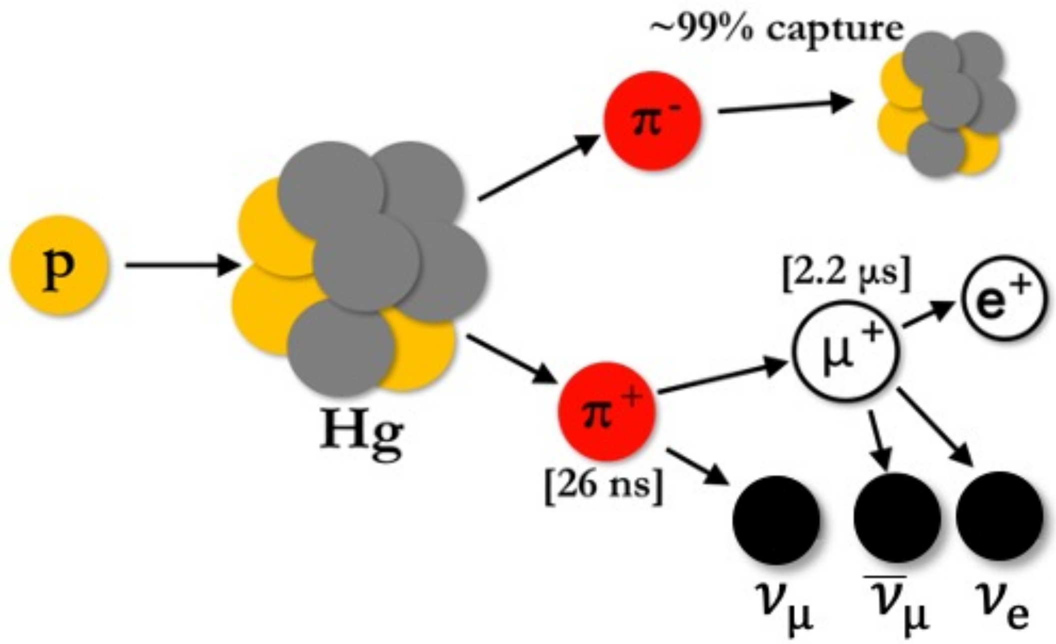


- Direct detection regime spans many orders of magnitude due to effects such as DM velocity suppression or spin suppression significant for non-relativistic scattering

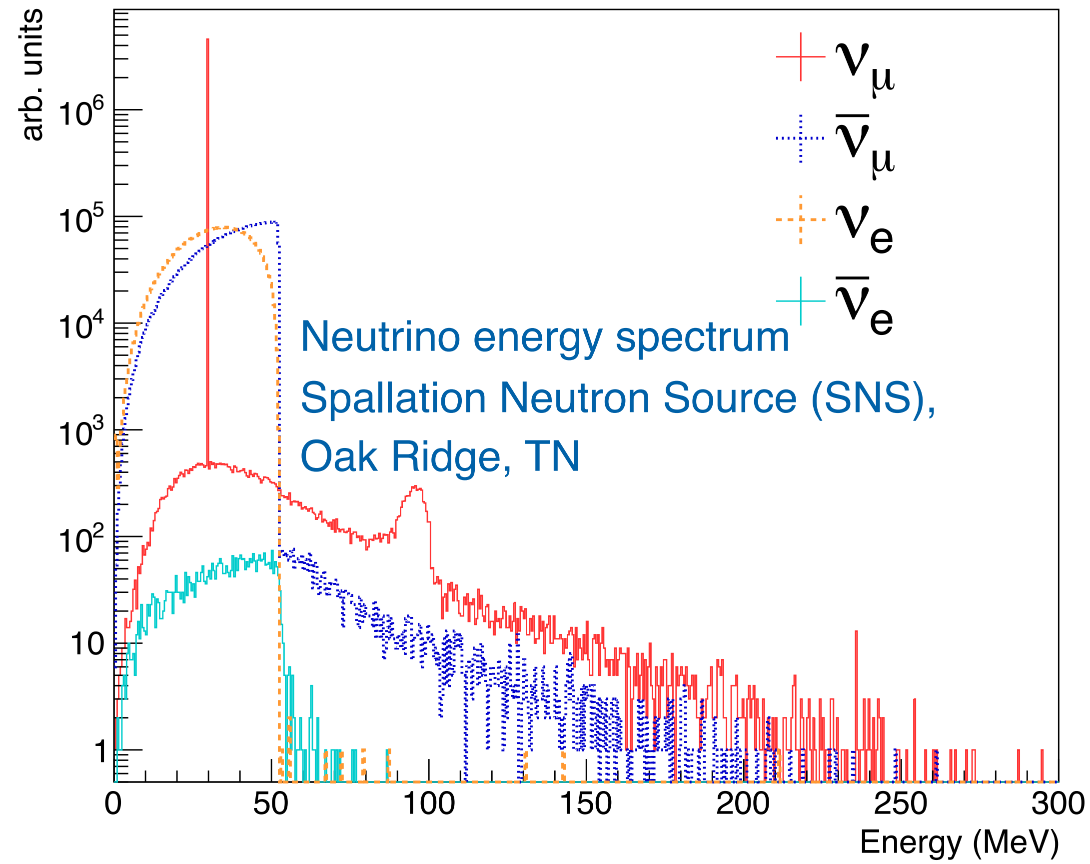
Fermilab

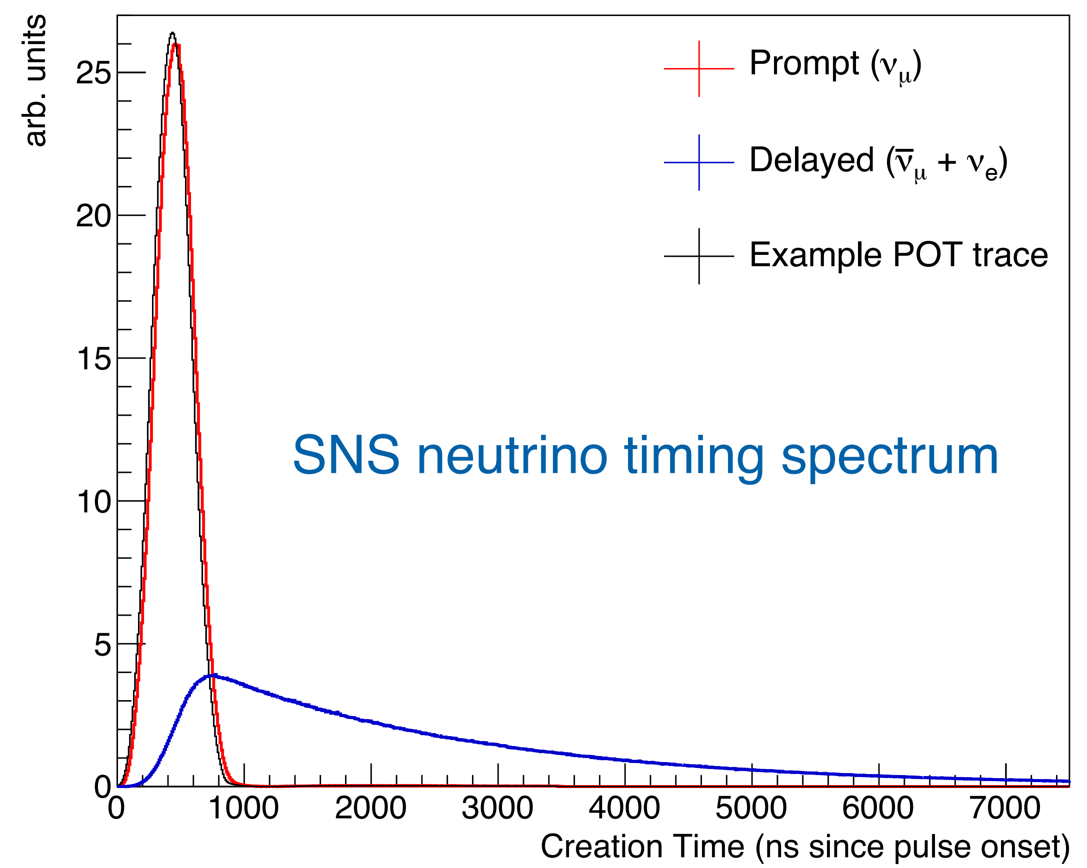
arXiv:2209.04671

Stopped-Pion Neutrino Sources



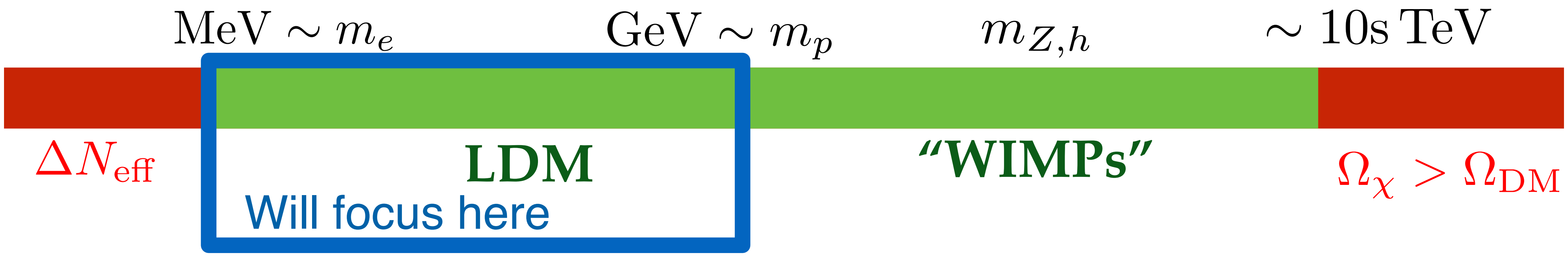
- Neutrinos produced from pion decay-at-rest via proton collisions with target
- Neutrino flux O(10^7)/cm^2/s at ~1 MW and 20 m from source
- Steady-state background suppression via pulsed beam





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

Current Landscape of Dark Matter and Dark Sector Searches

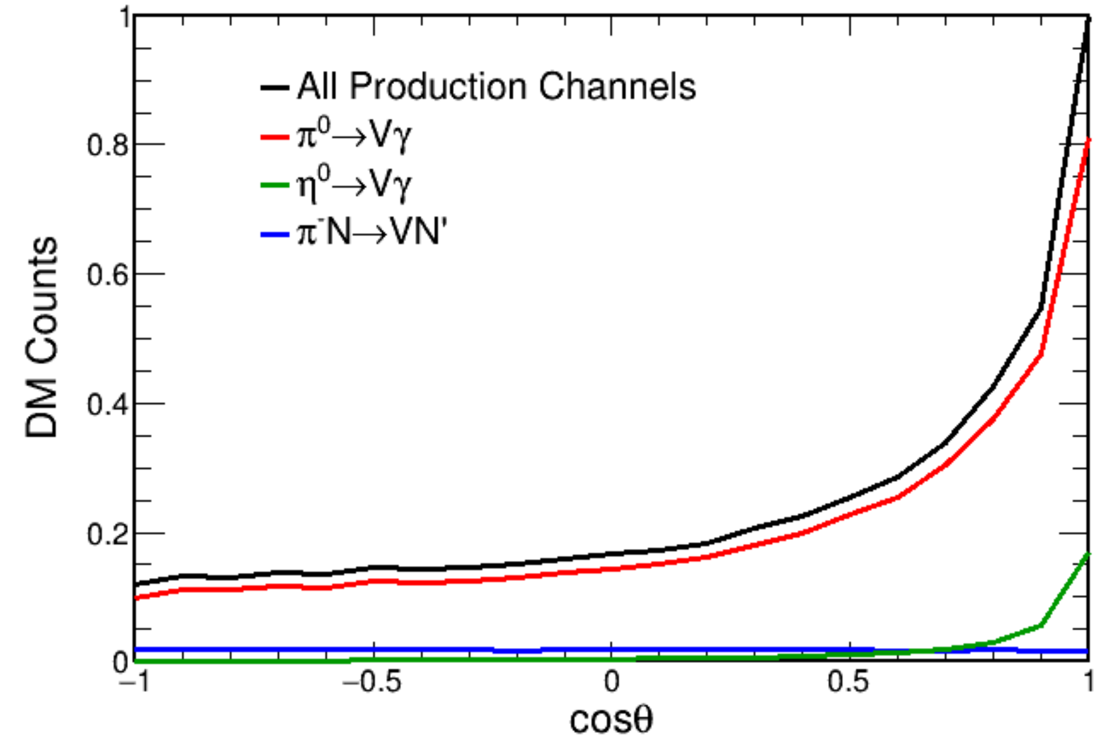


- New physics theorized to be neutral under SM forces
- A finite set of operators serve as a portal to a possible dark sector

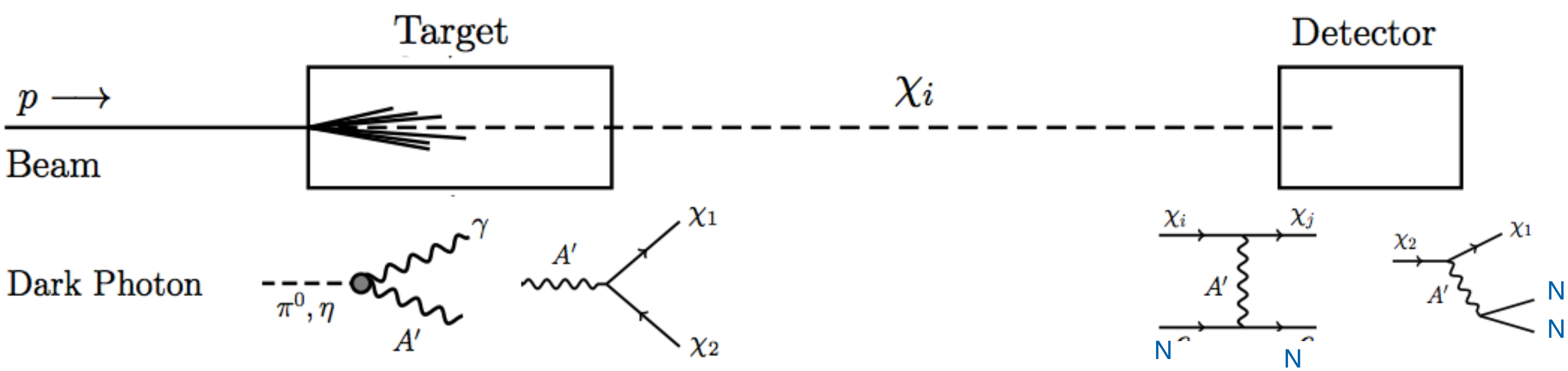
$B_{\mu\nu}$	x	$\epsilon/2\, F'^{\mu\nu}$	Vector portal
$\lvert h\rvert^2$	x	$\mu S + \lambda \lvert\phi\rvert^2$	Higgs portal
hL	x	$y_N N$	Neutrino portal

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

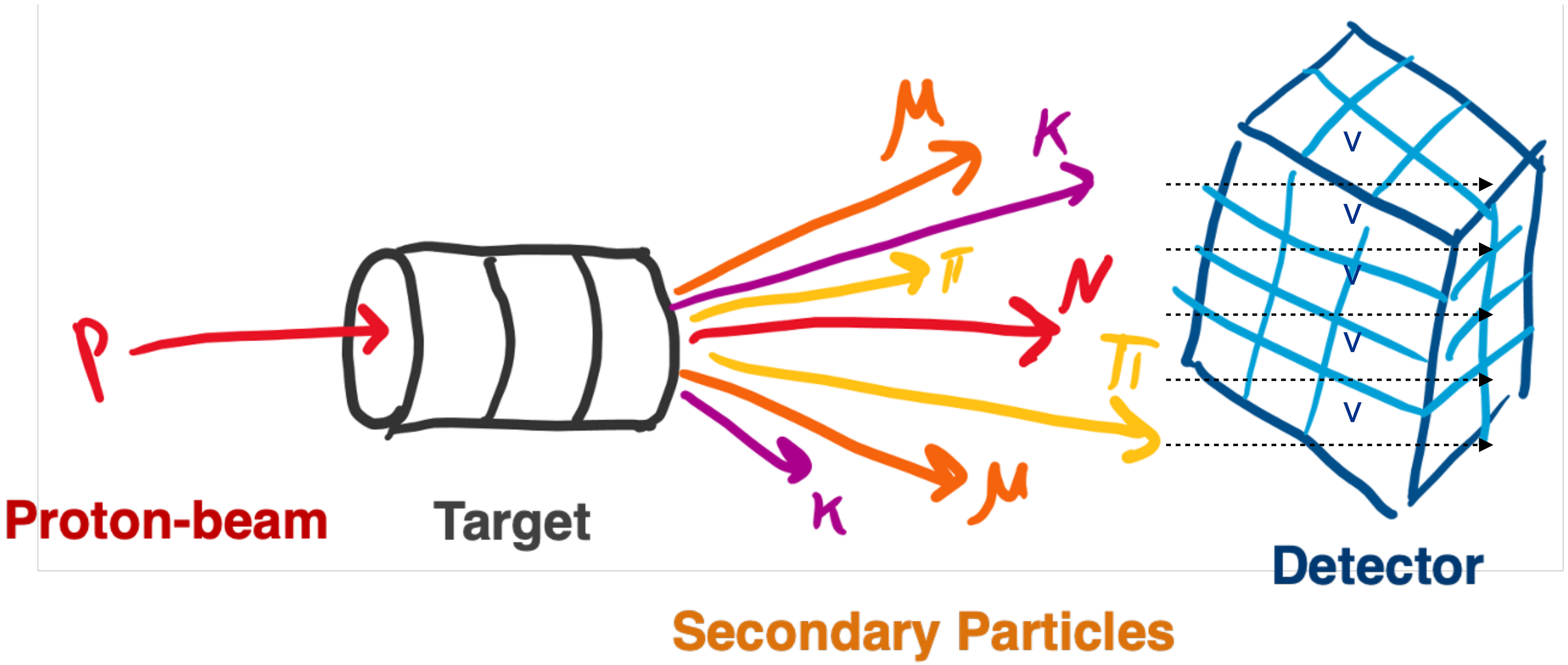


P. deNiverville et al., Phys. Rev. D 92 (2015) 095005

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

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



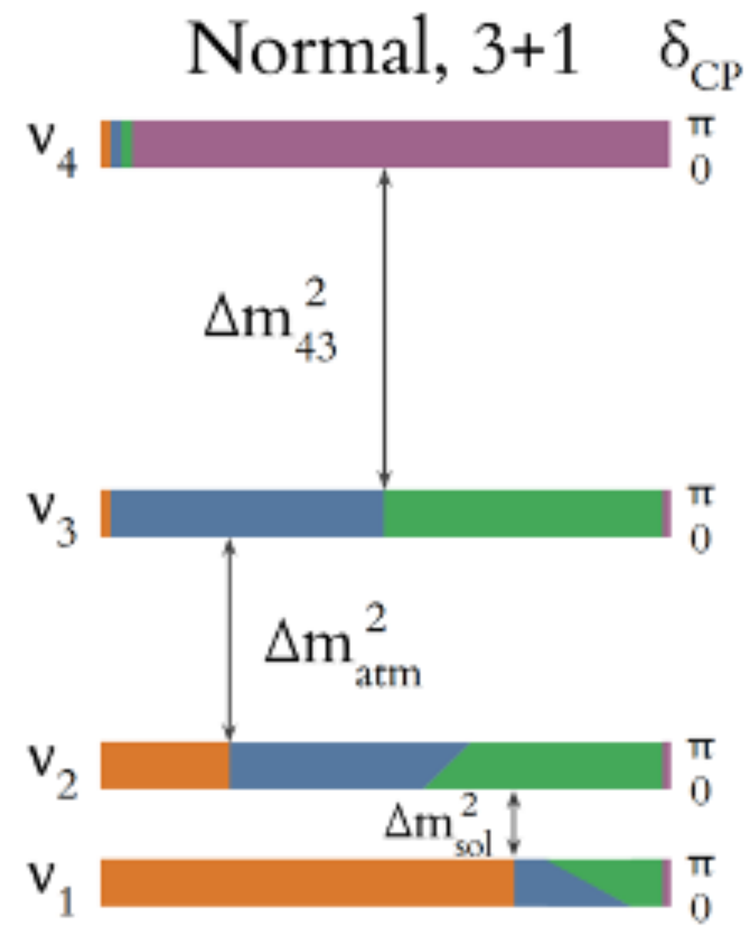
Creating a stopped-pion source with PIP-II

- 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

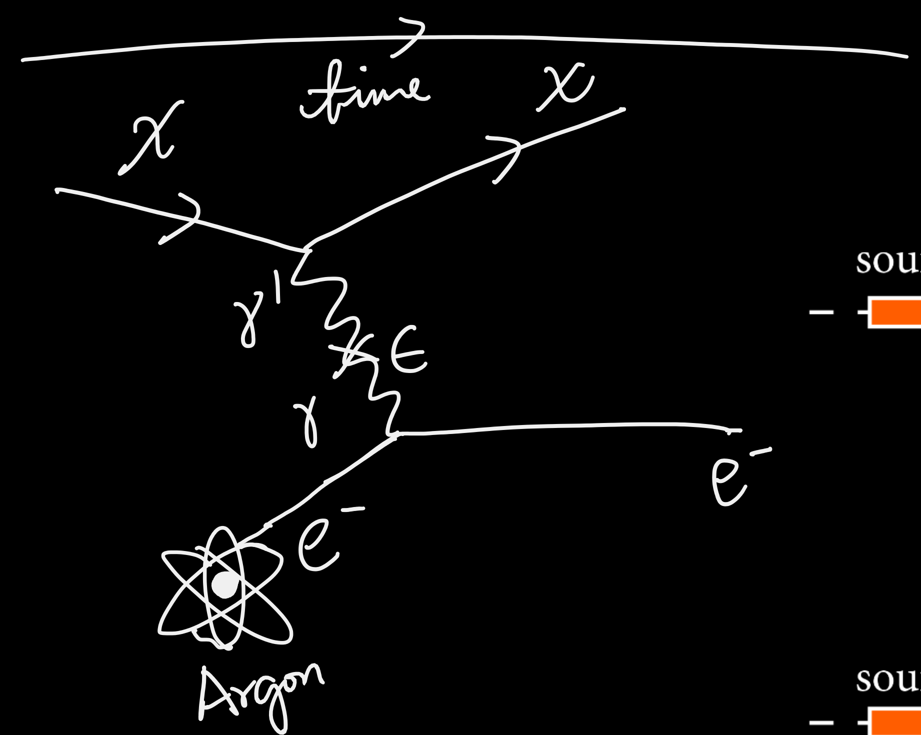
Extension to 3+1 neutrino states

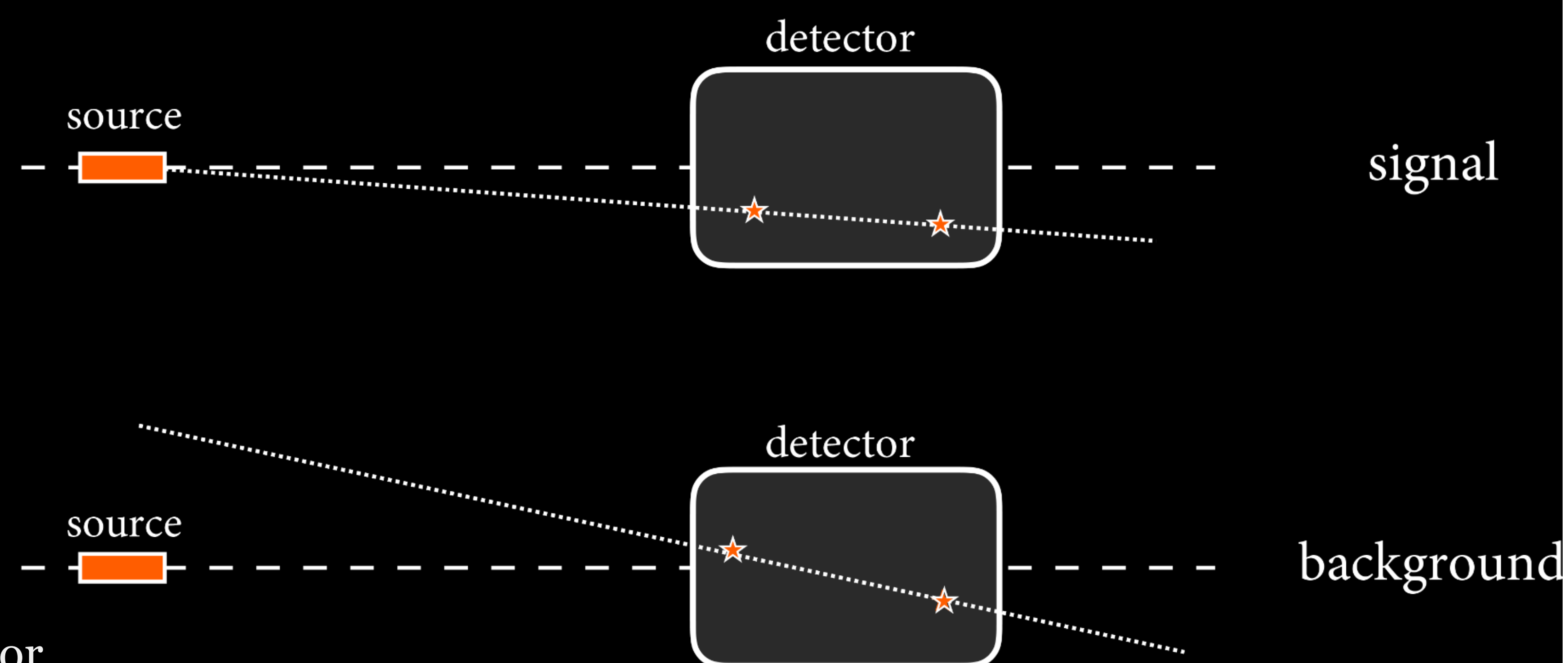
- Can create extensions to the three-flavor model
  - Extend the PMNS matrix to include a fourth, “sterile” neutrino or 3+1 model
- Additional mixing angles and mass splittings based on the fourth neutrino state
- Neutrino fluxes are conserved under the extension
- The fourth neutrino state allows for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



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

Strategy: aligned double rare hits





Liquid Argon High Granularity detector,
proto-type for future neutrino experiments.
Single hits background 100,000

Millicharged particle background rejection strategy

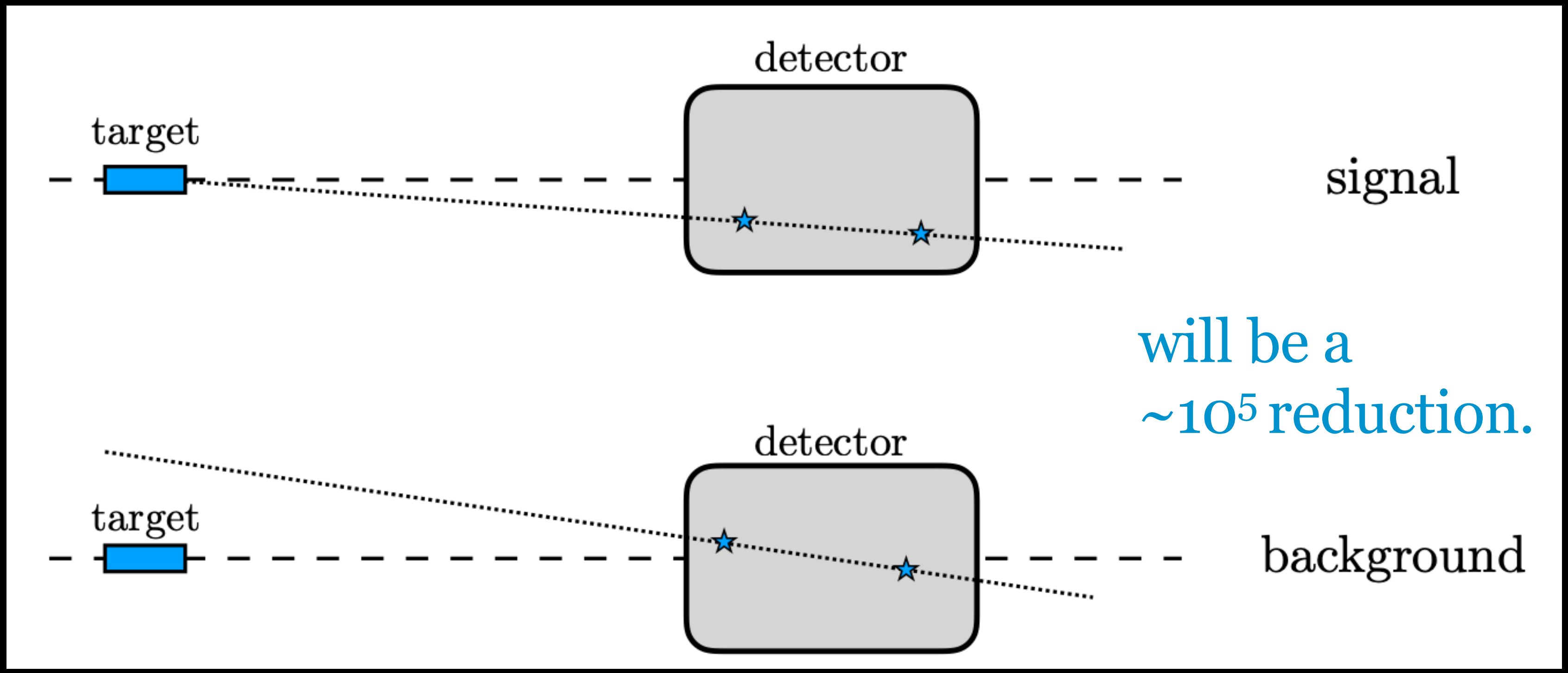
We then recalled a key feature of LAr detectors, and designed a new search:

$$\delta y \times \delta x \times \delta z = 5.6 \ \text{mm} \times 0.3 \ \text{mm} \times 3.2 \ \text{mm}.$$

Background Reduction

- Double hit probability ~ $(P_{hit})^2$.
- If we have spatial resolution → 2-hit BG can be reduced by requiring alignment with target.

$$N_{2\,\text{hit}}^{\text{aligned}} = N_{2\,\text{hit}} \times \left(\frac{\delta x}{\Delta x} \frac{\delta y}{\Delta y} \right)$$

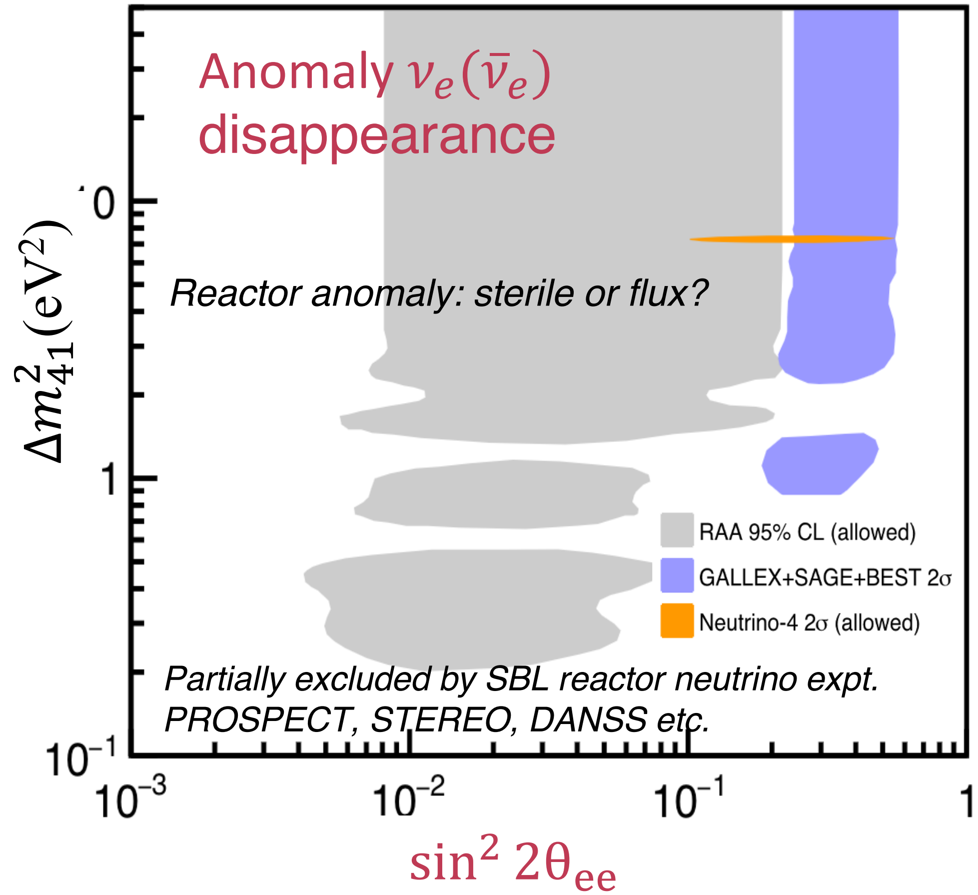


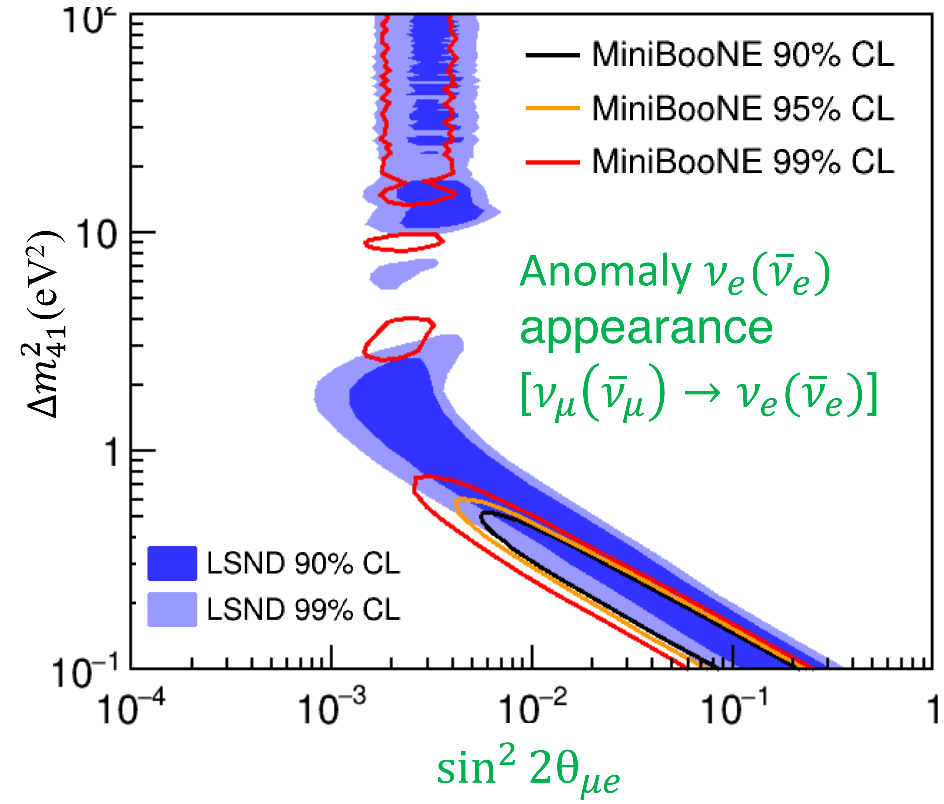
will be a ~10^5 reduction.

Zhen Liu MCP@PIP-II PIP-II Opportunities 05/10/2023 13

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

Sterile neutrino searches with PIP2-BD

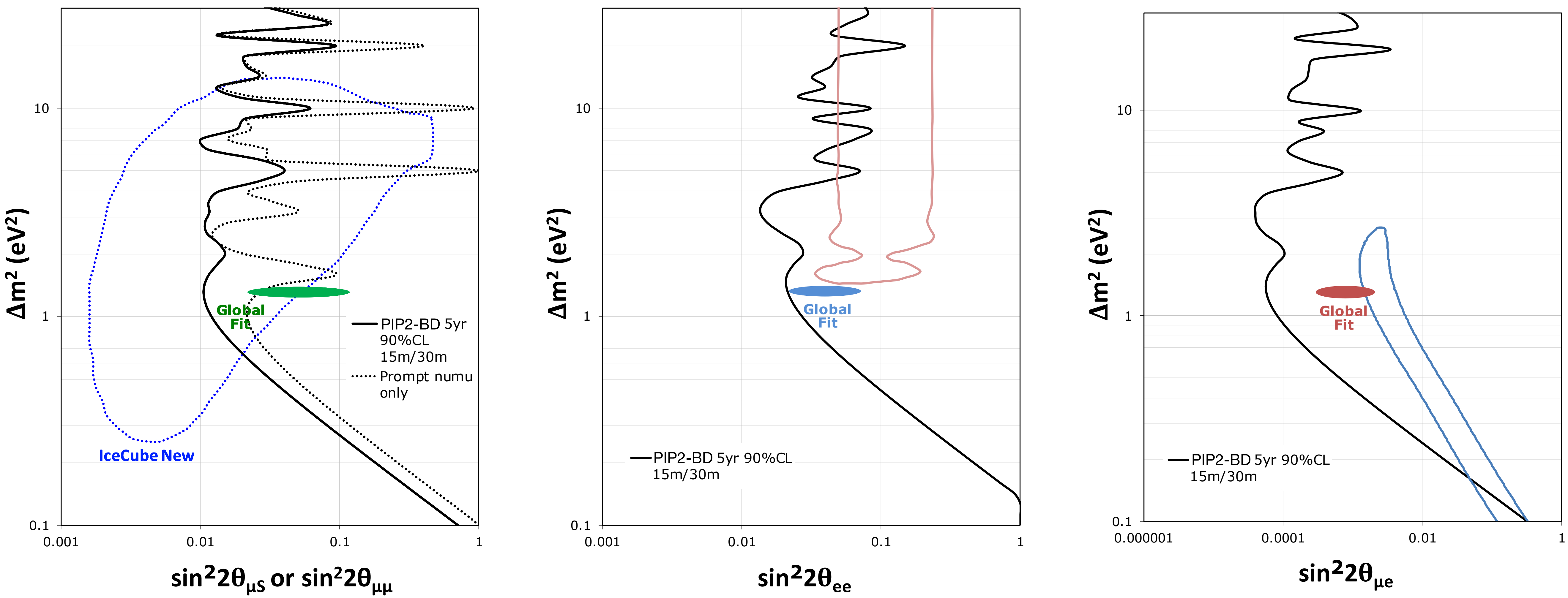


FIG. 13. PIP2-BD 90% confidence limits on active-to-sterile neutrino mixing compared to existing ν_μ disappearance limits from IceCube [45] and a recent global fit [46], assuming a 5 year run (left). Also shown are the 90% confidence limits for ν_μ disappearance (left), ν_e disappearance (middle), and 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!