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

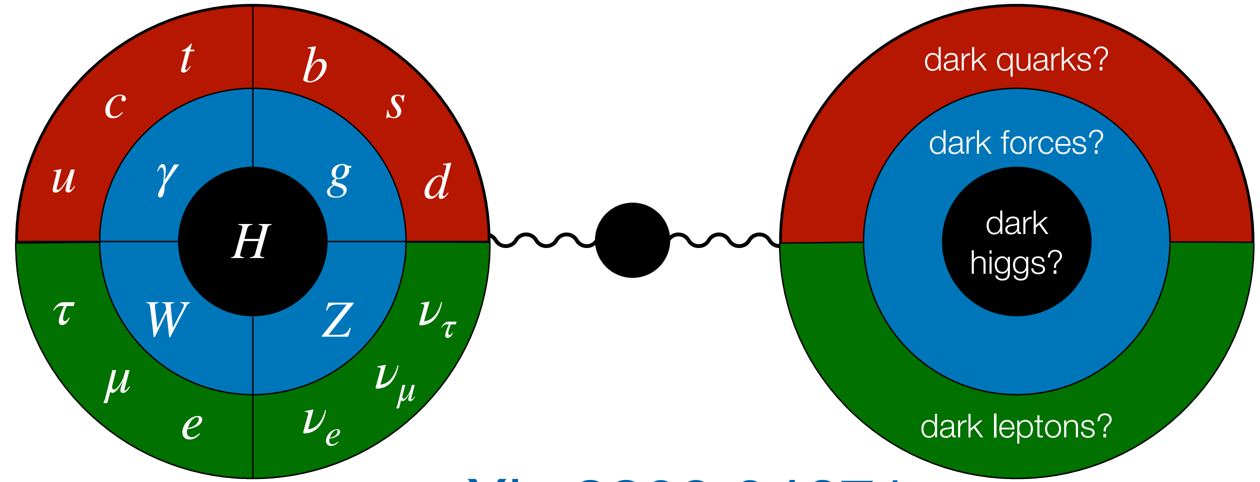
Jacob Zettlemoyer, Fermilab, for the workshop organizers

ACE Science Workshop

June 15, 2023

Why accelerator-based dark sector searches?

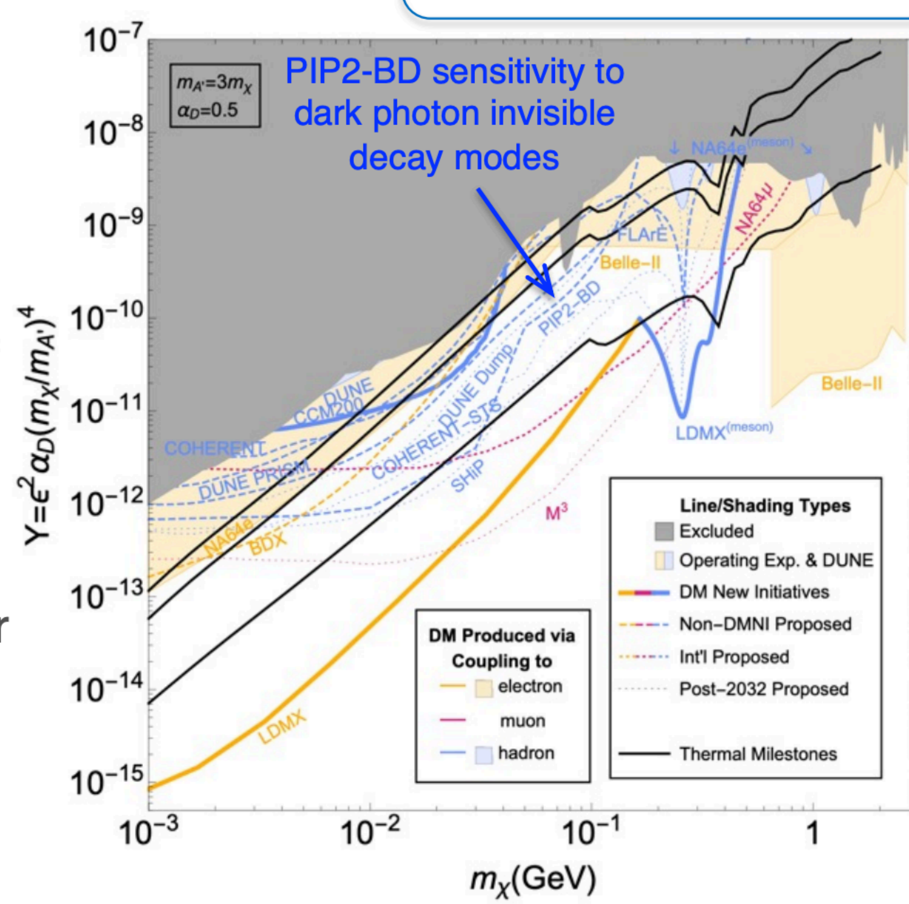
- Accelerator-based dark sector searches were identified as an HEP priority during the most recent Snowmass process
- Proton beam dump-based searches highlighted as part of Fermilab's future program at the Fermilab P5 town hall



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

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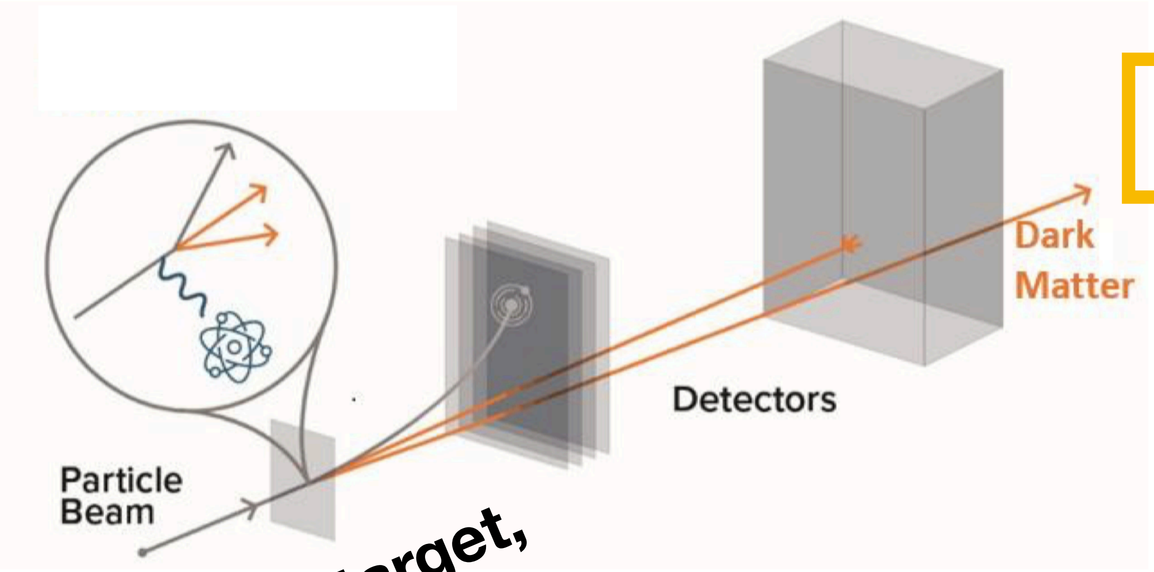
14 03/22/2023 Fleming I Fermilab Program

Searching for Dark Sectors at Beam Dump Experiments

Production of dark matter



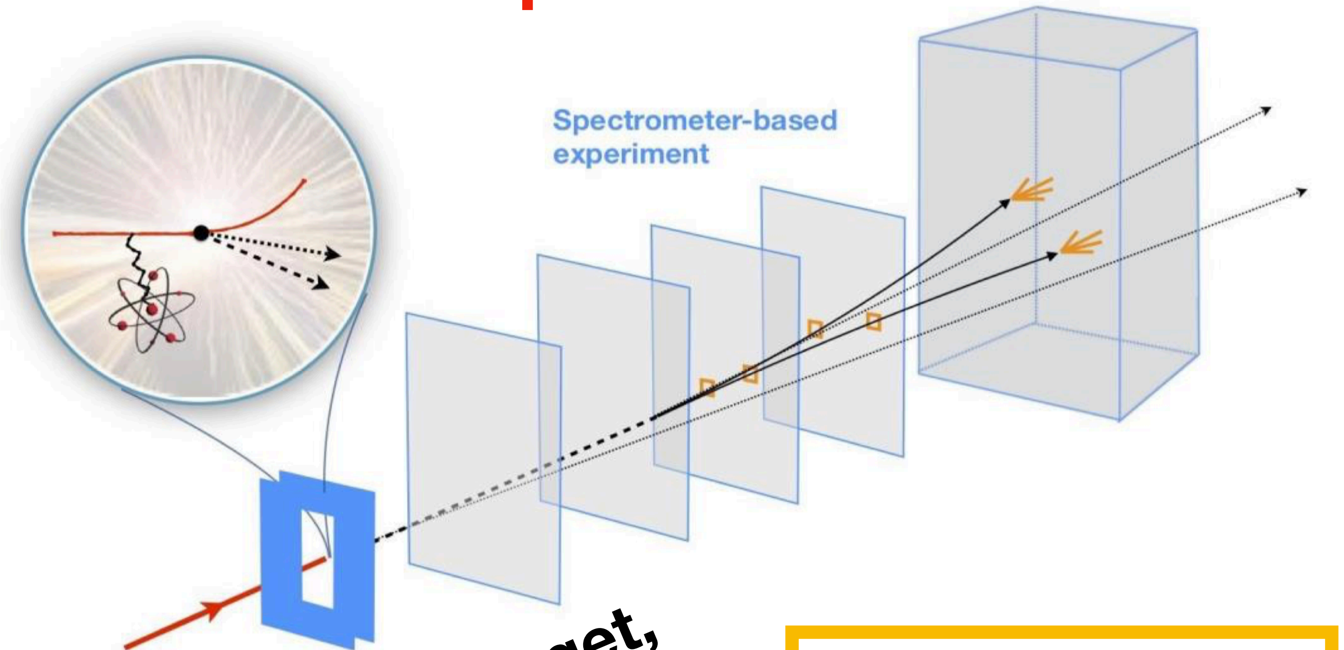
2. Re-scattering

1. 2. fixed target, colliders

1. Missing energy/ momentum/mass

See also G. Krnjaic's talk

Production of unstable dark sector particles



1. 2. fixed target, colliders

3. Visible decay products

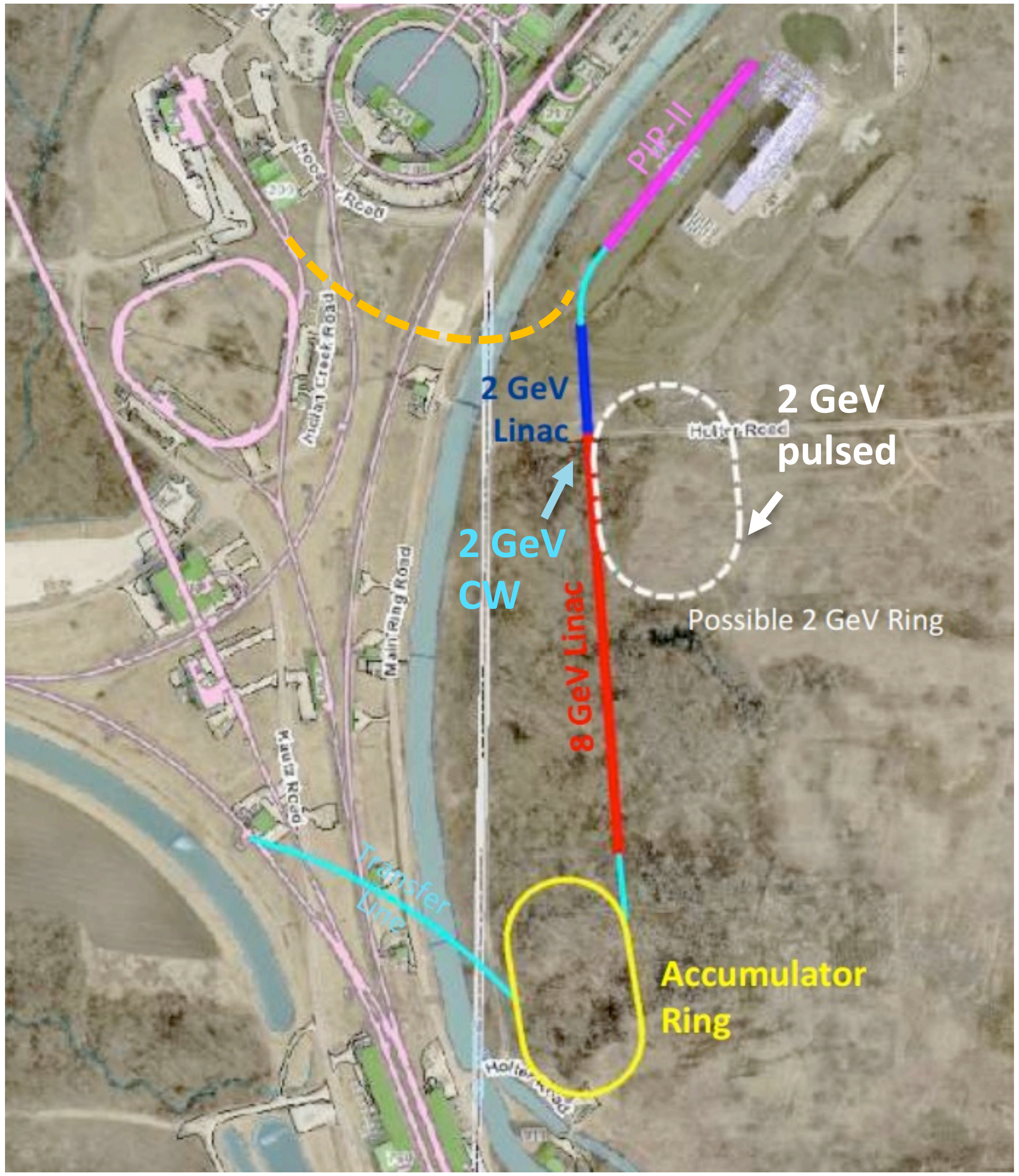
- Breadth of ideas within a program important!
  - In case of discovery, allows for studying dark sector mass and interaction strength
  - Probe generalizations of thermal freeze-out

Adapted from S. Gori, BNL P5 town hall

How we can lead in the PIP-II Era

See also M. Convery, J. Eldred talks yesterday

- Once PIP-II comes online and with the options outlined within and around the ACE program, we have an opportunity to lead in this science at Fermilab
- We can also consider opportunities prior to and independent of the ACE program and those preceding or around the Booster Replacement
- Can think with three different configurations from 0.8-2.0 GeV proton energy
  - PIP-II CW: high power, high duty factor
  - CPAR/PAR: modest power, low duty factor
  - Booster Replacement: high power, low duty factor
- Probe possibilities for dark sector search experiments that can take advantage of all of these scenarios (this talk)



This diagram highlights a lot of the possibilities!

Workshop Overview

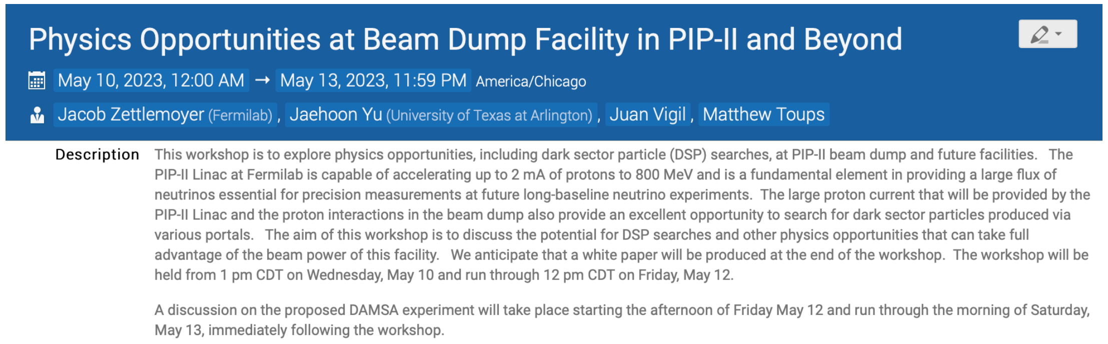
- Organized a workshop on PIP-II beam dump physics with leads of myself, Juan Estrada (FNAL), Matt Toups (FNAL), Jae Yu (UT Arlington), held from May 10-13, 2023 at Fermilab
- Goal to discuss possible experimental programs and theory directions with a focus on dark sectors we could explore at a possible PIP-II based beam dump facility
- Had expertise in theory along with experimental ideas taking advantage of different detector energy-scale thresholds
  - From eV-scale to MeV-scale detection thresholds
- Will summarize discussions on the physics opportunities discussed at this workshop
  - Accelerator options summarized in J. Eldred's talk yesterday
- Output of the workshop is a whitepaper on the accelerator and physics opportunities

Matt Toups
Fermilab

Jae Yu
UT Arlington

Juan Estrada
Fermilab

Jacob Zettlemoyer
Fermilab


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.

A discussion on the proposed DAMSA experiment will take place starting the afternoon of Friday May 12 and run through the morning of Saturday, May 13, immediately following the workshop.

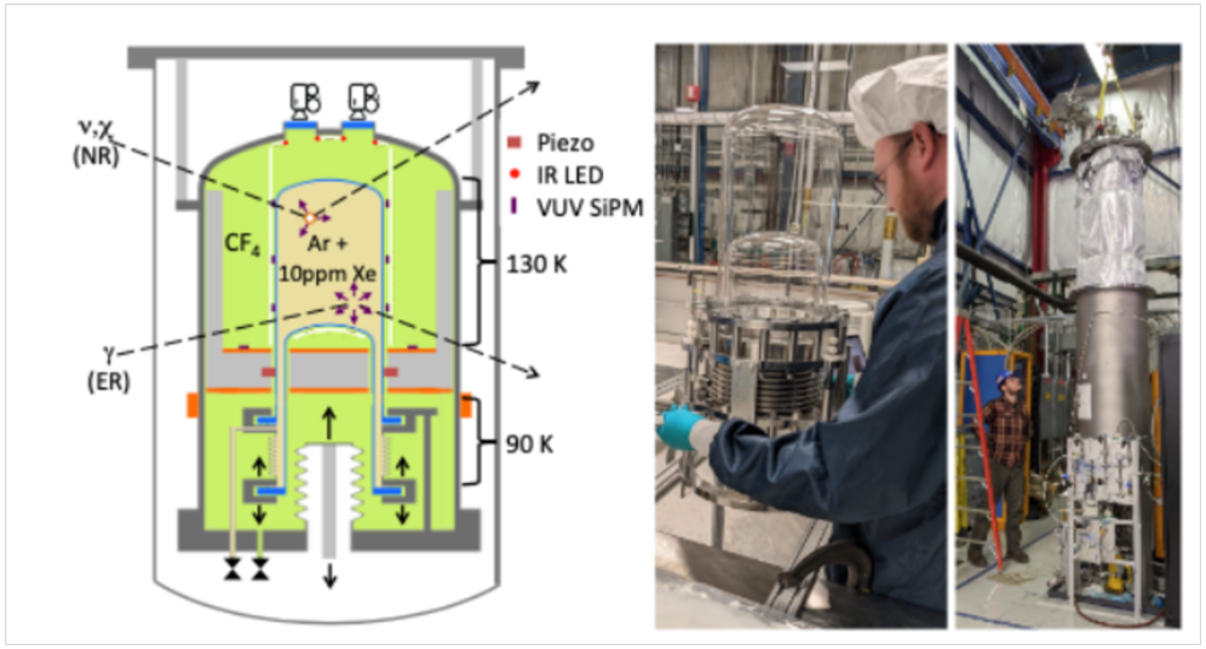
https://indico.fnal.gov/event/59430/

Opportunities at eV-scale detector thresholds

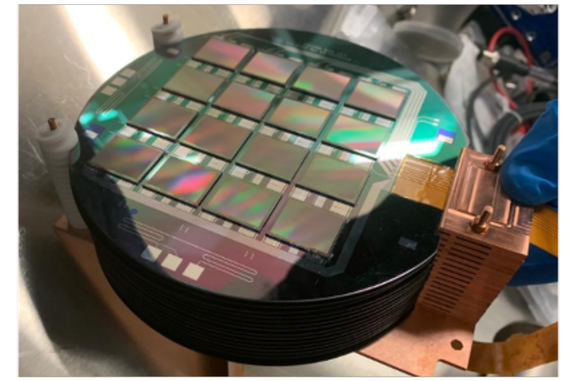
Opportunities for very low threshold detectors

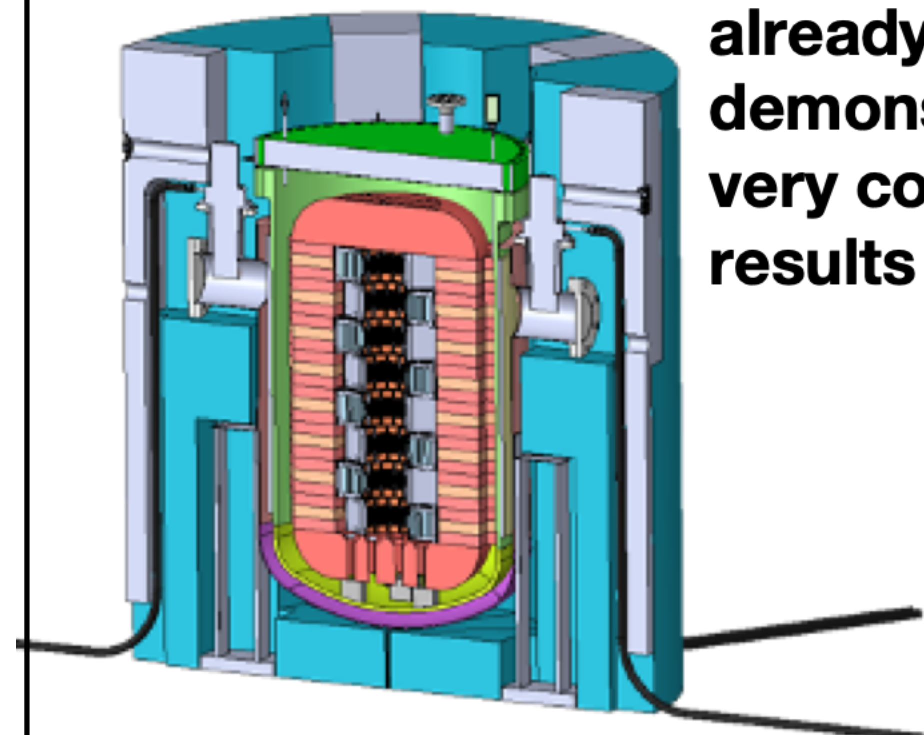
- Significant progress on developing new technologies for detecting low energy nuclear and electron recoils for direct dark matter searches
  - Examples include micro-calorimeters, CCDs, and the Scintillating Bubble Chamber (SBC) effort
- These technologies combined with high intensity proton beams provide 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 low threshold detector technologies



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



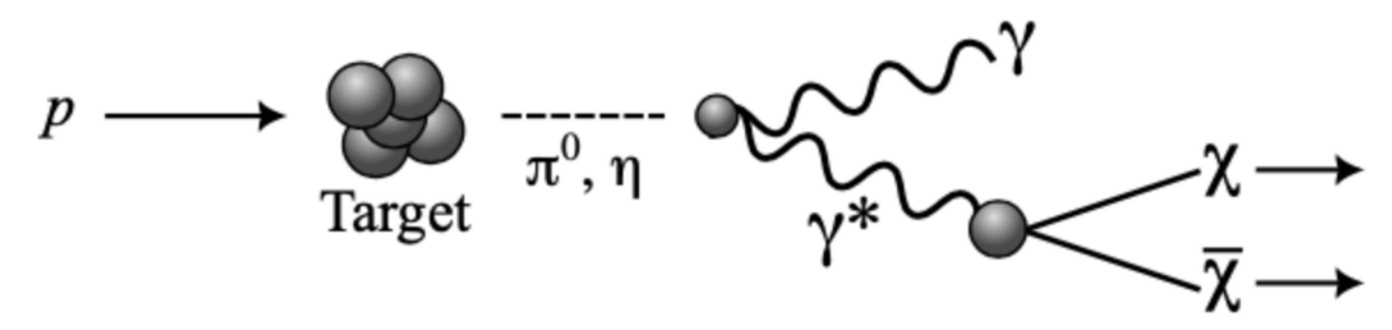


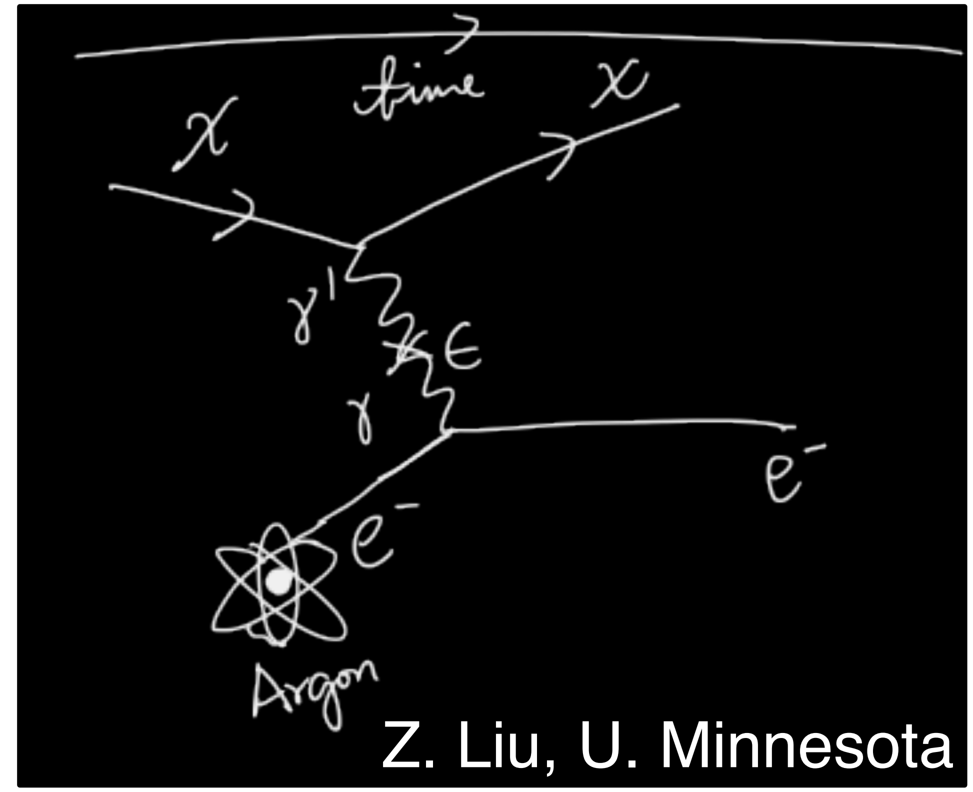
Skipper-CCDs. Single electron counting with silicon. Can get to kg scale, and already demonstrated very competitive results in beam.

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)

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

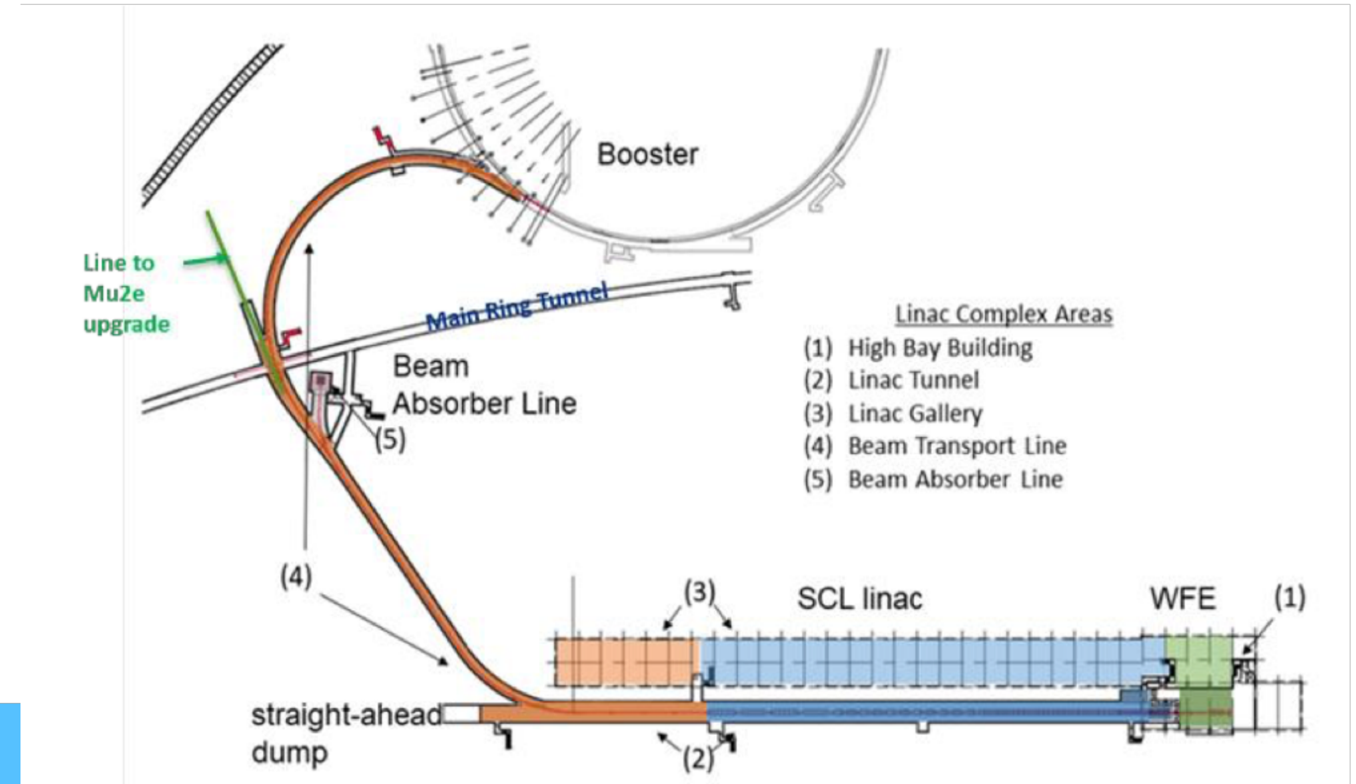


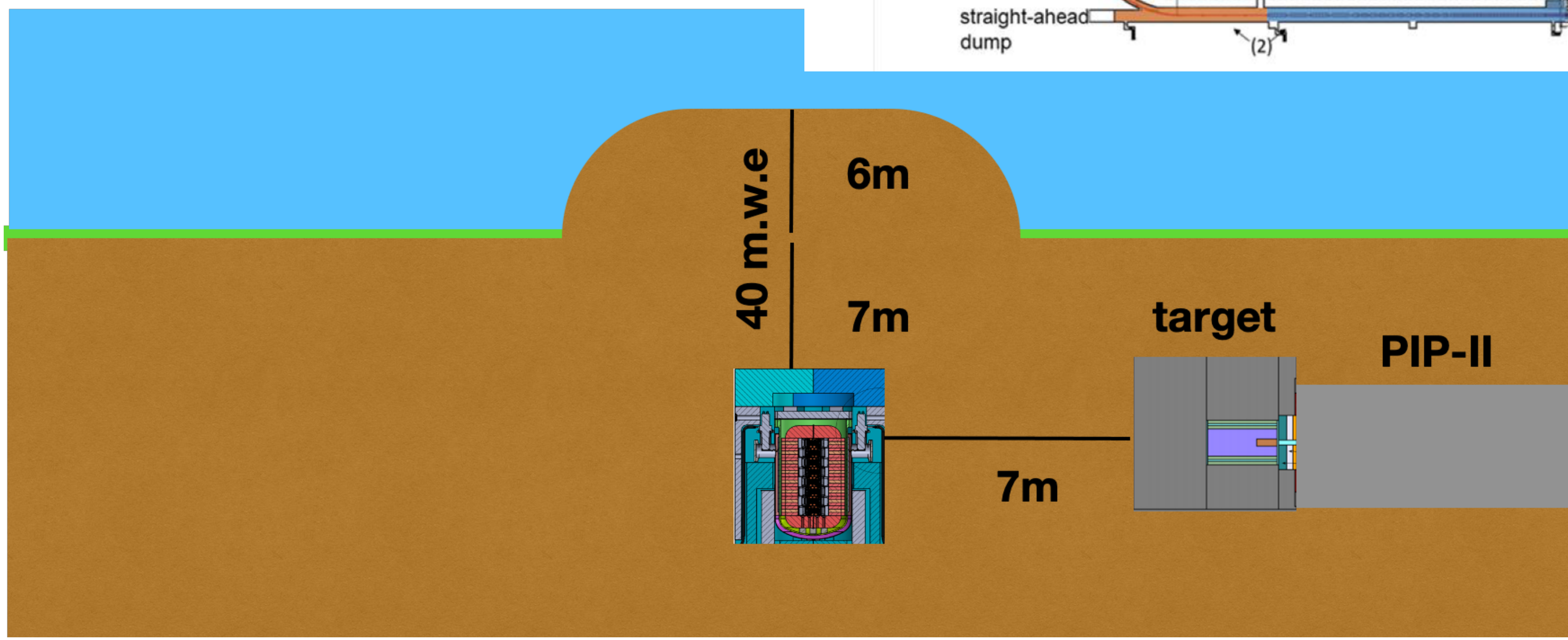


- mCPs produced in high energy collisions at particle accelerators
- Some examples of experiments that can search for mCPs: milliQ, milliQan, LSND, MiniBooNE, and ArgoNeuT

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





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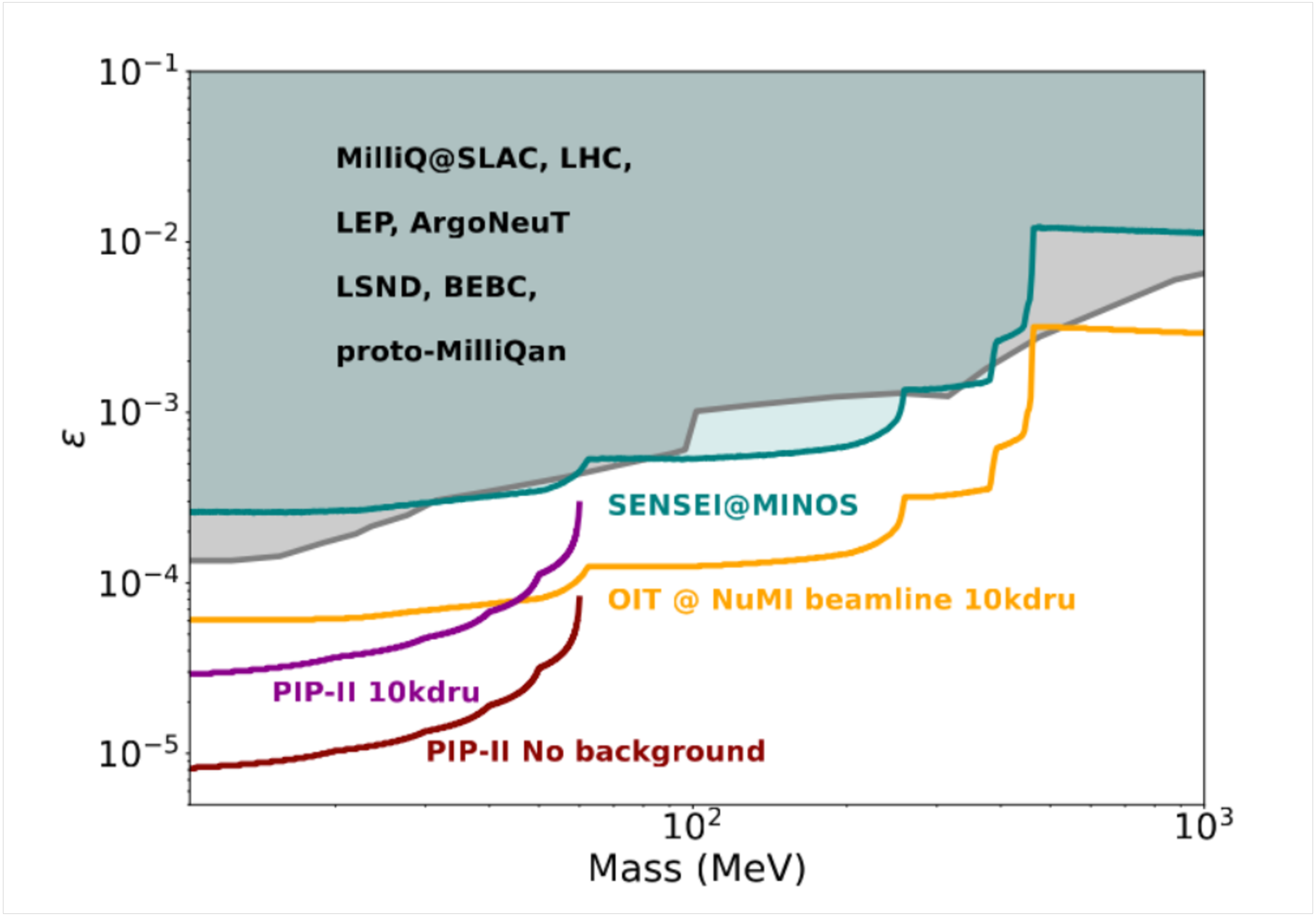
Expected limits for skipper-CCD detectors at PIP-II CW

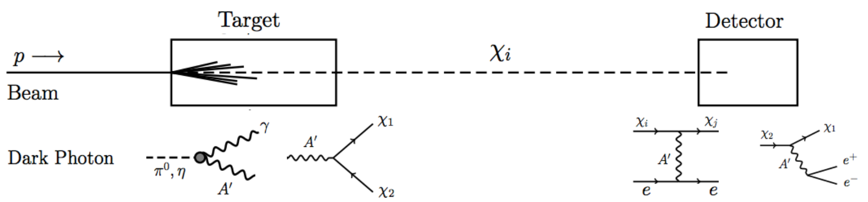


SENSEI@MINOS results: L. Barak et al., arXiv:2305.04964

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



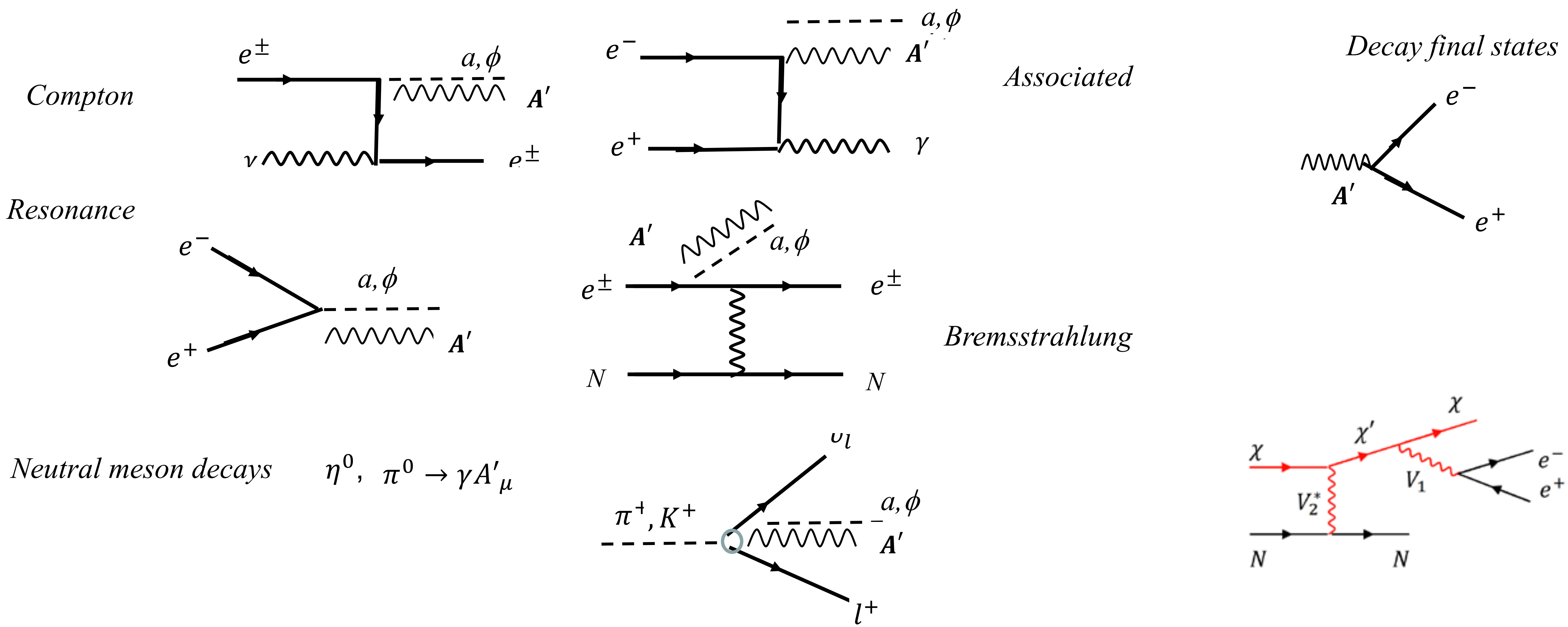
keV

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



keV

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MeV

Axion-like particle scattering and decay
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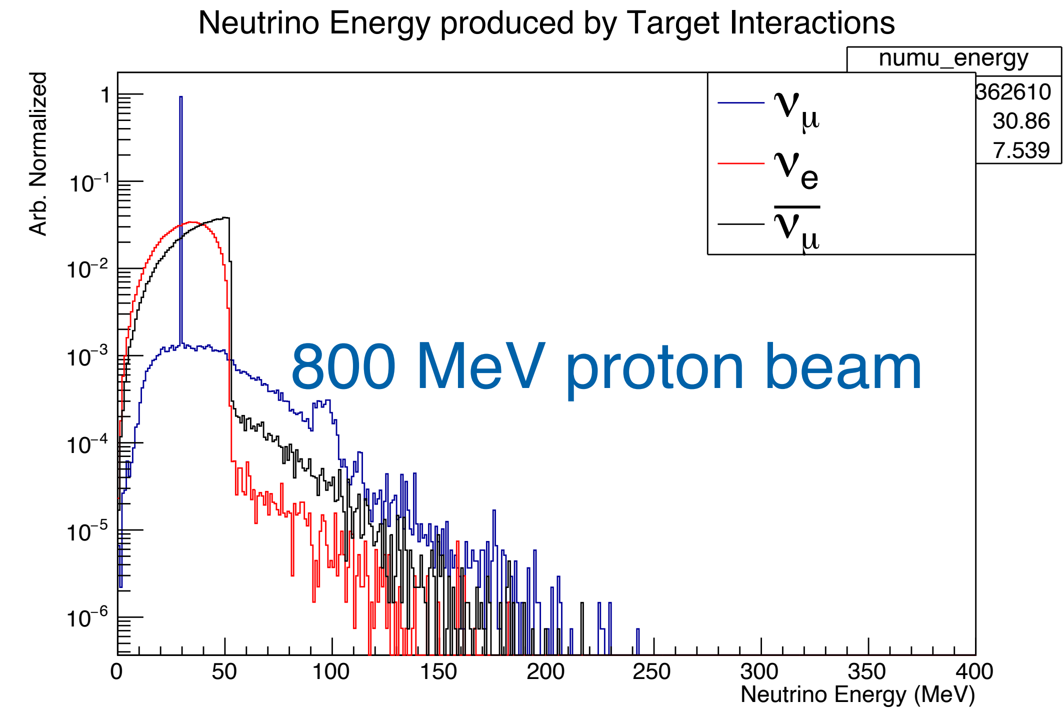
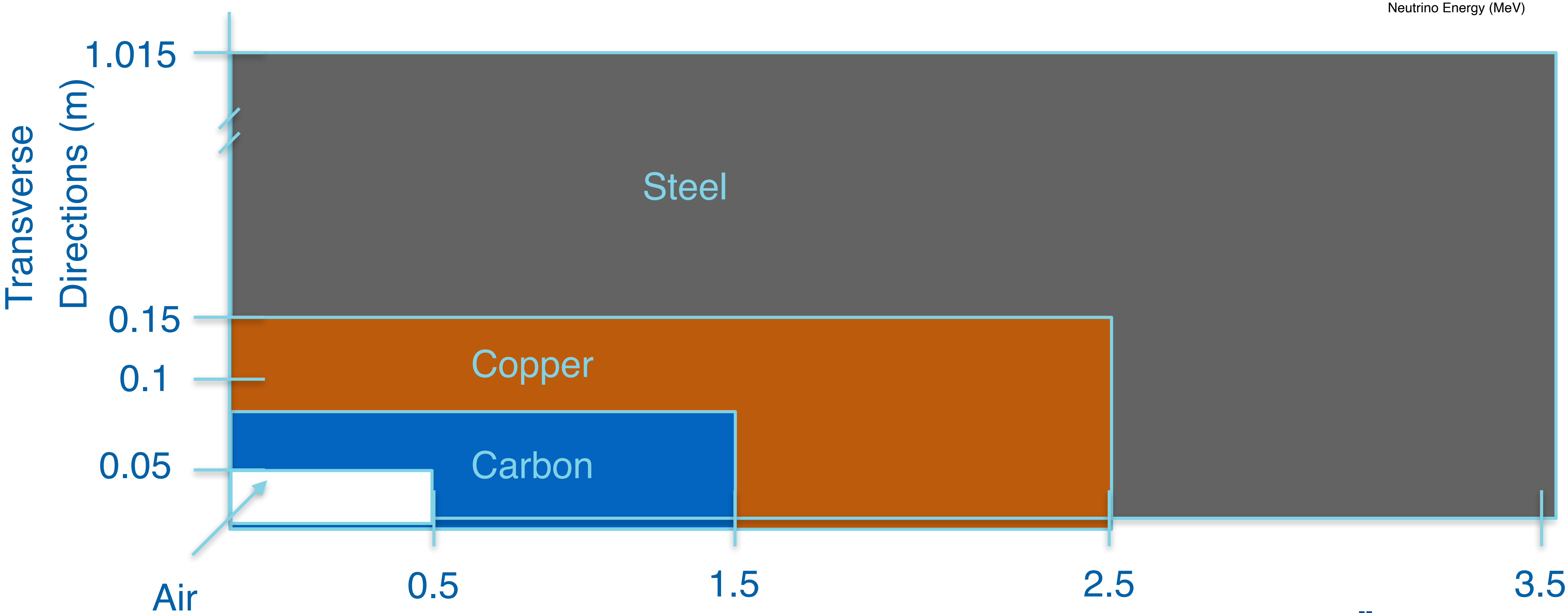
Solar and supernova neutrino detection with LAr scintillator and LArTPCs

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

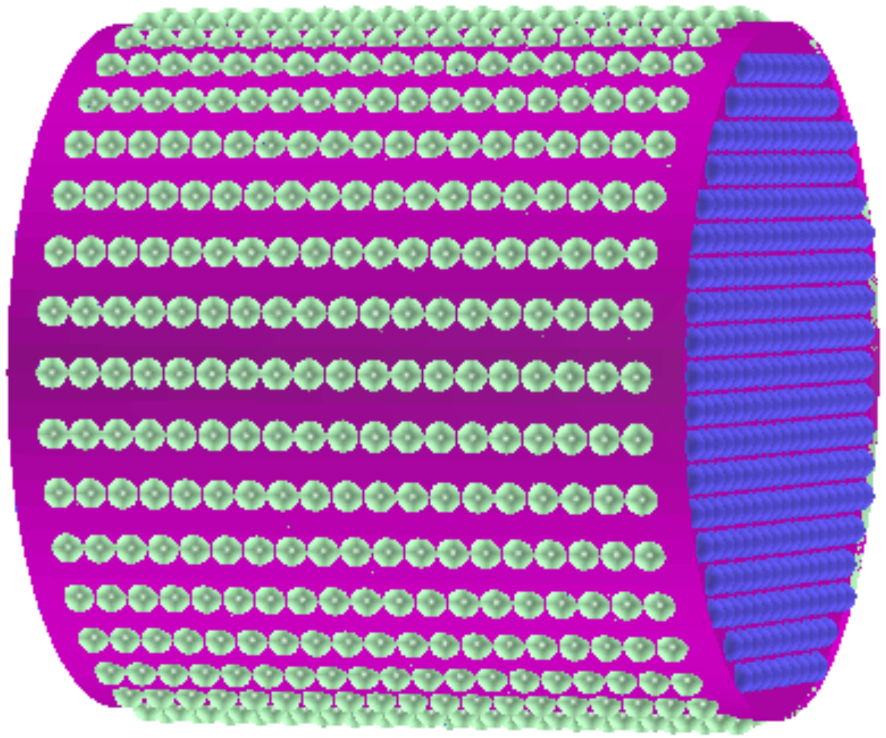
- Have done initial studies using Geant4 on a shielding design around the target to reduce the decay-in-flight component of the outgoing neutrino spectra





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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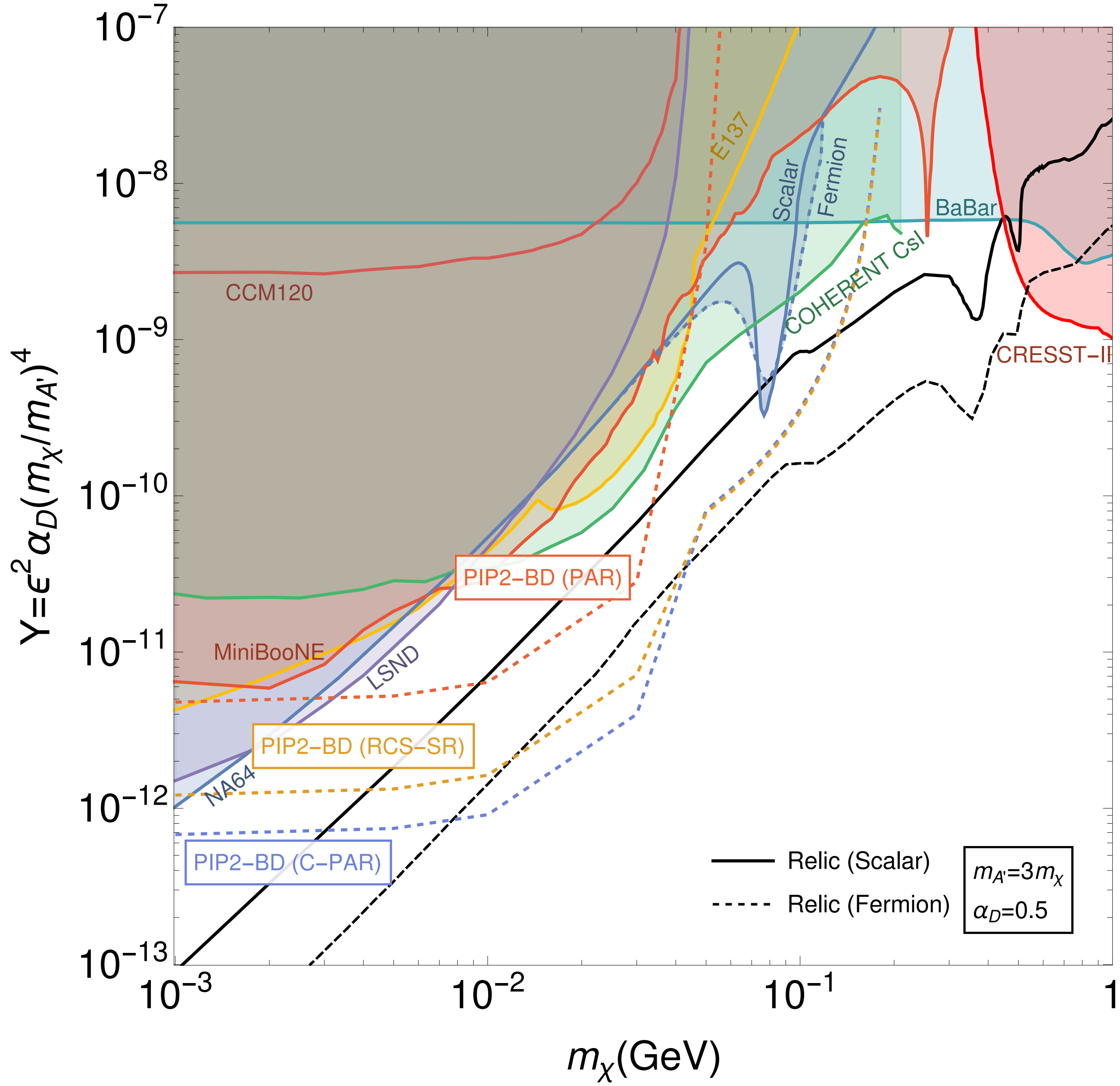
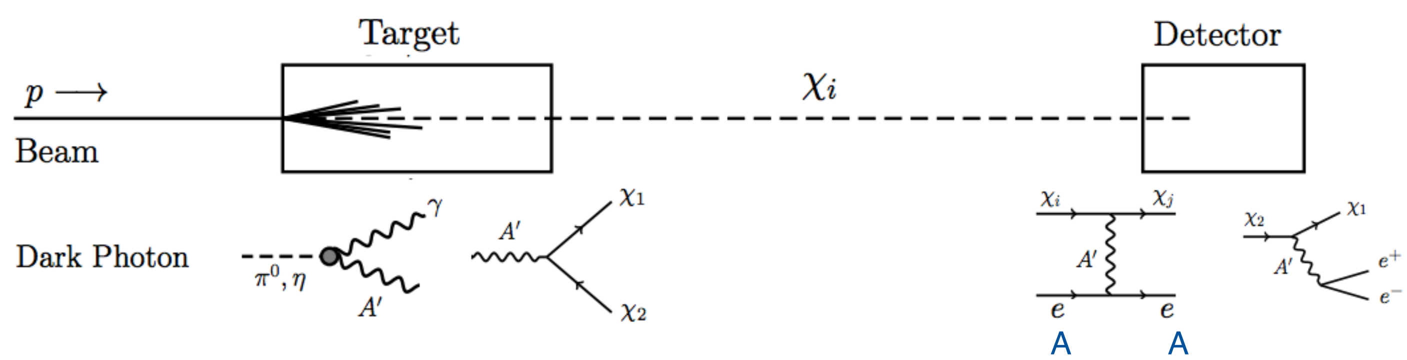
PIP2-BD Vector Portal Dark Matter Search

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

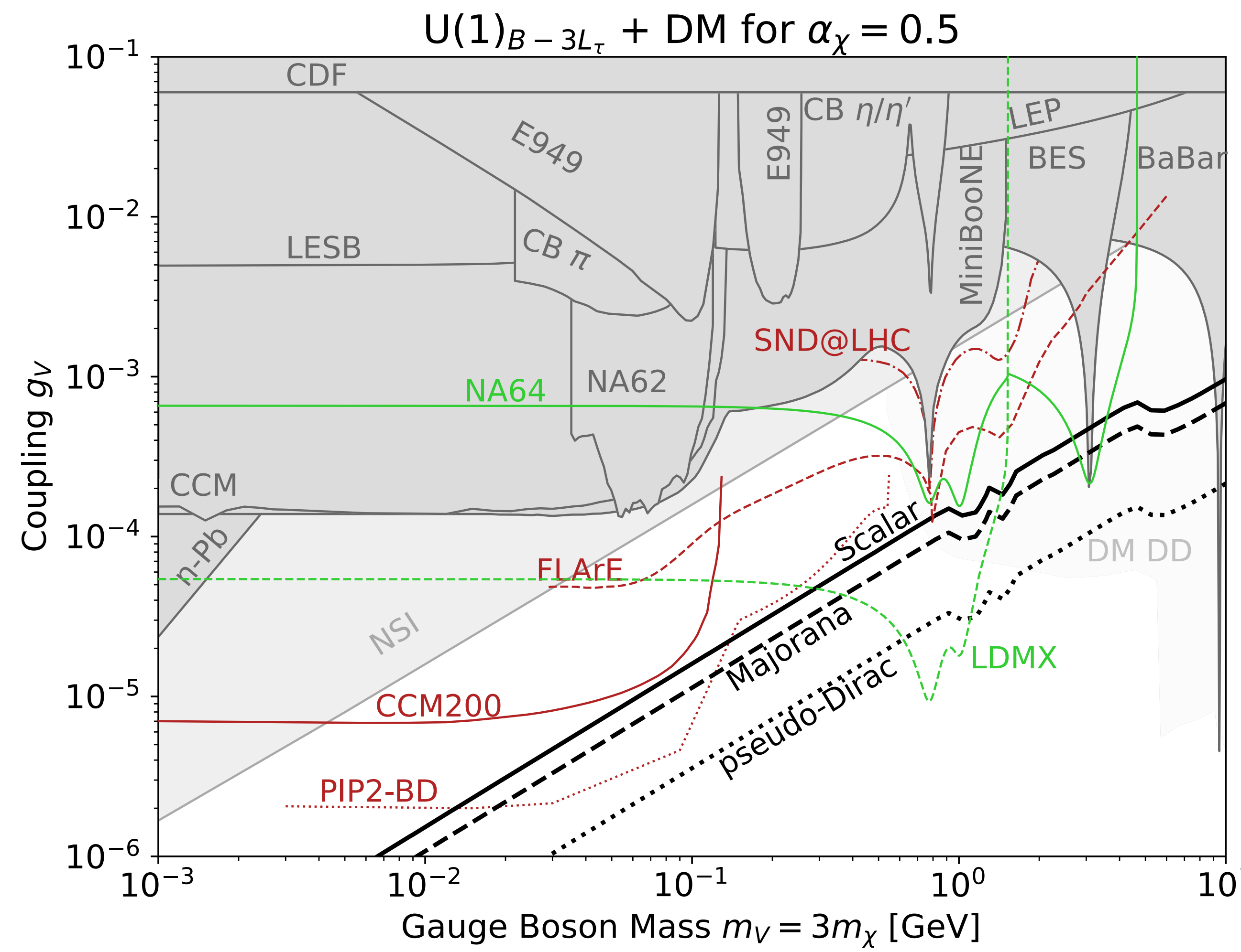




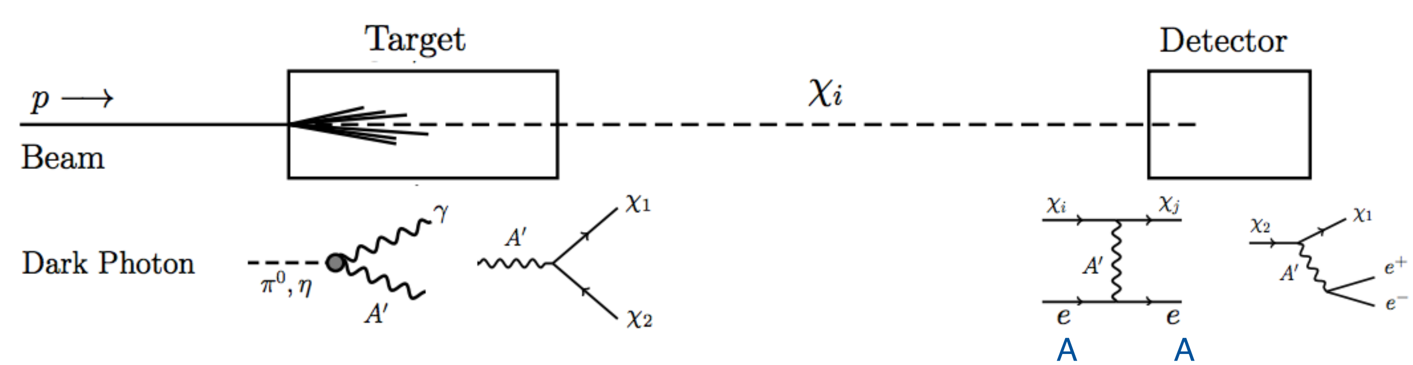
PIP2-BD Vector Portal Dark Matter Search

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



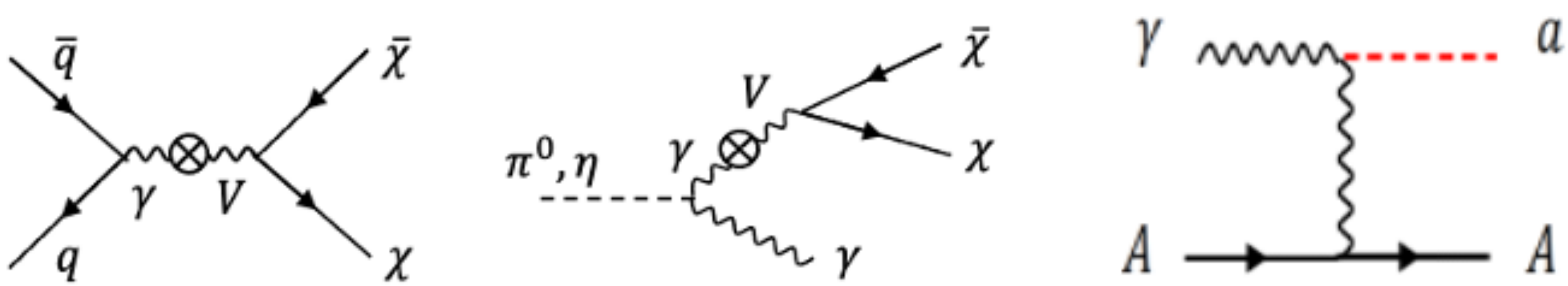
(b) $U(1)_{B-3L_\tau}$, $\alpha_D = 0.5$



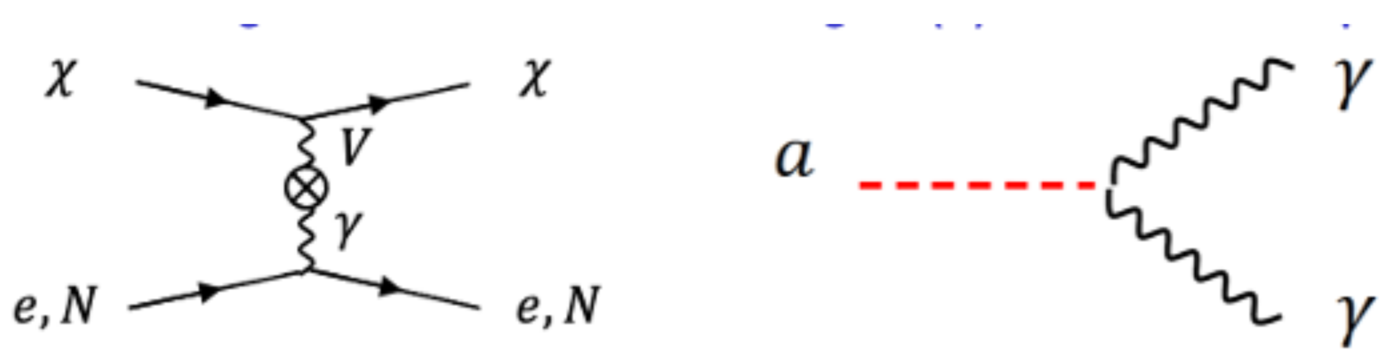
Opportunities at MeV-scale detector thresholds

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



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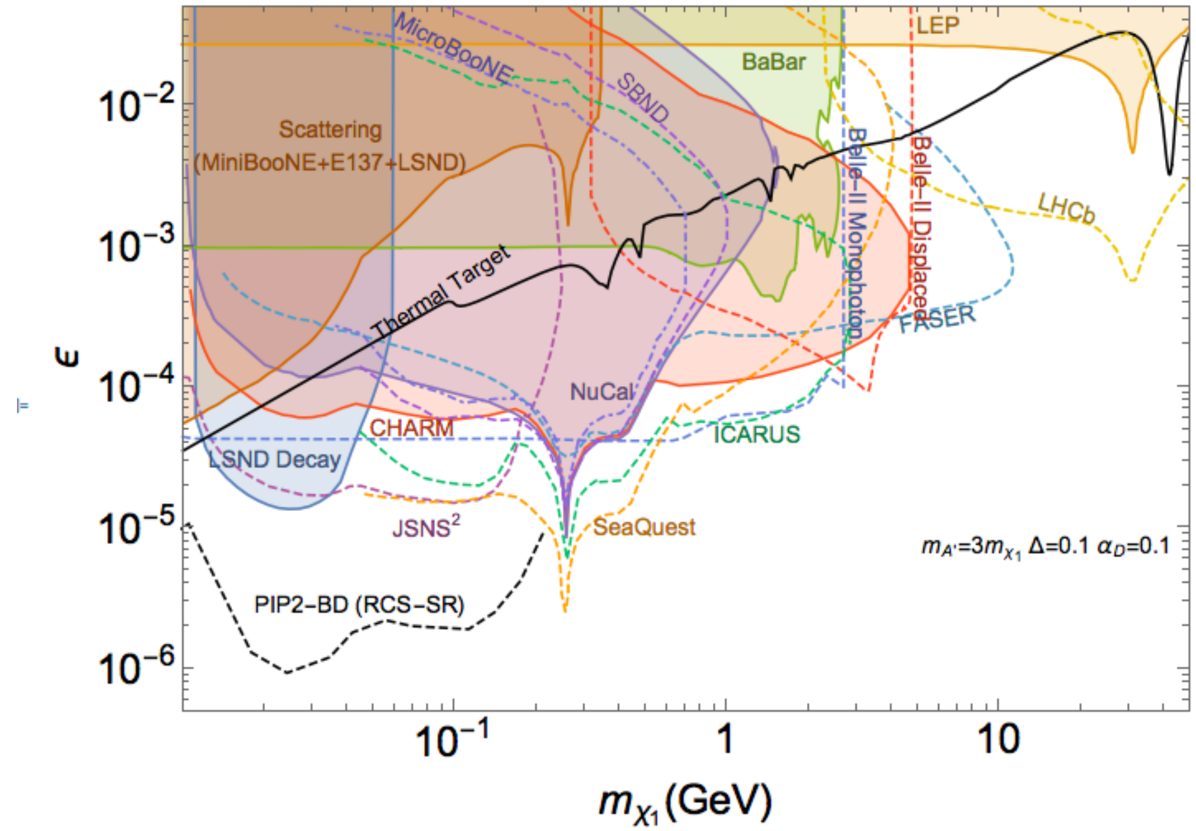
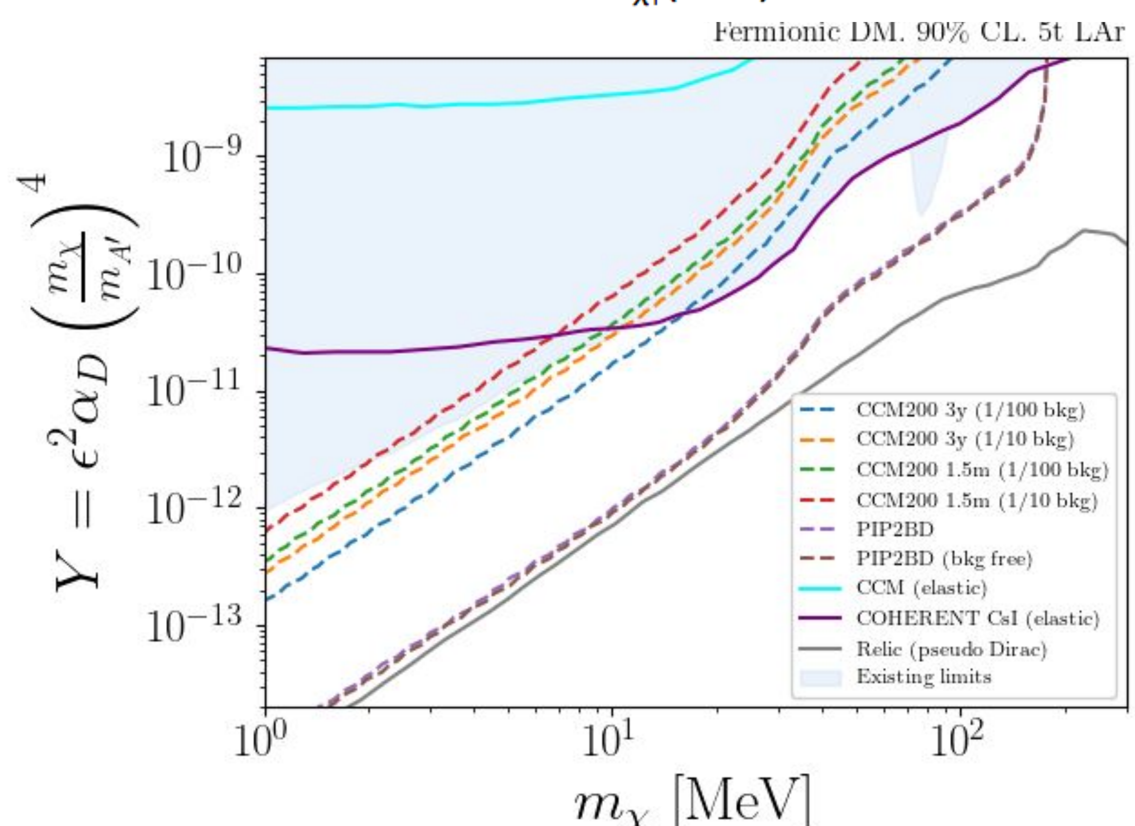
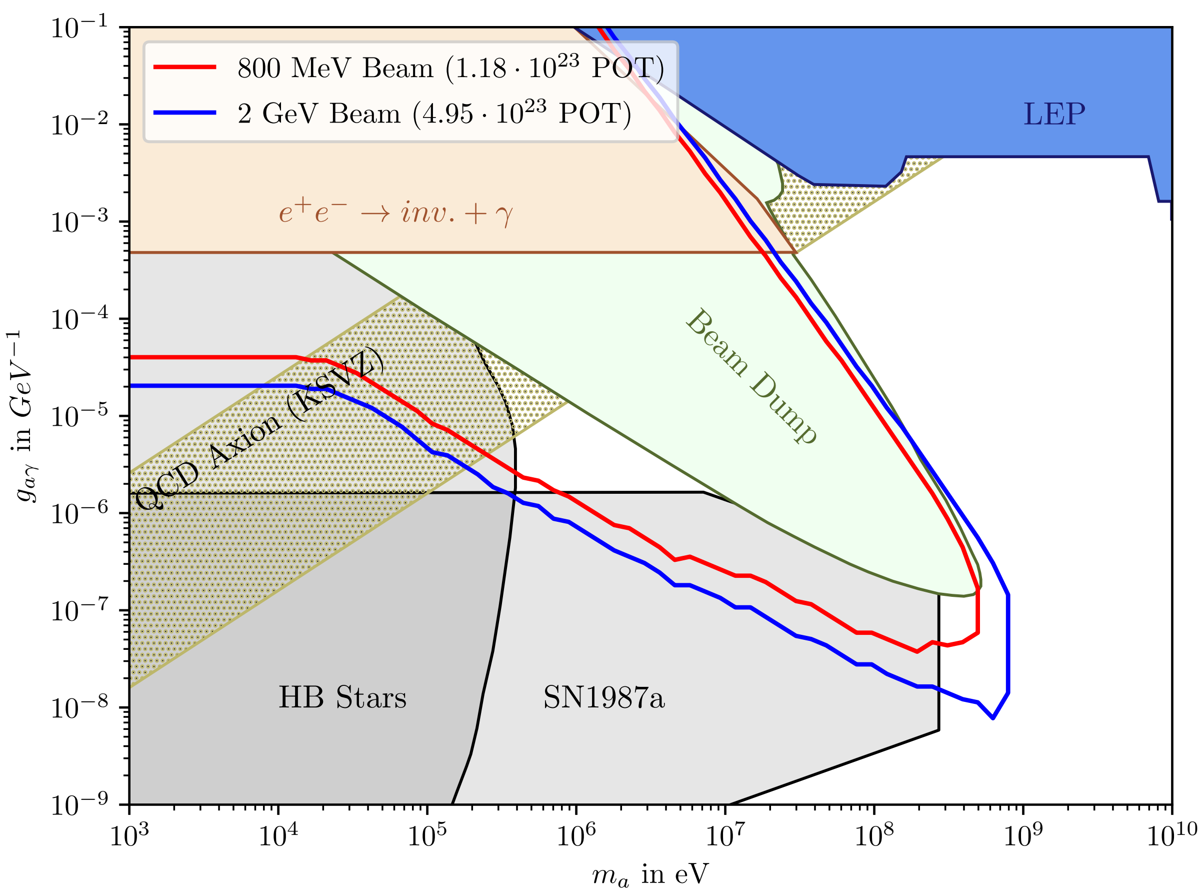
MeV-scale physics at PIP2-BD

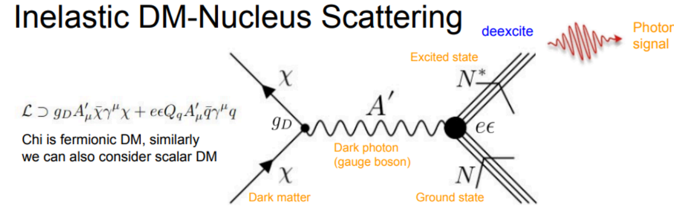
- Detector with MeV-scale dynamic range has further physics reach
- Ideas to search for ALPs, and inelastic DM models
  - Exploring other possibilities with theory colleagues!





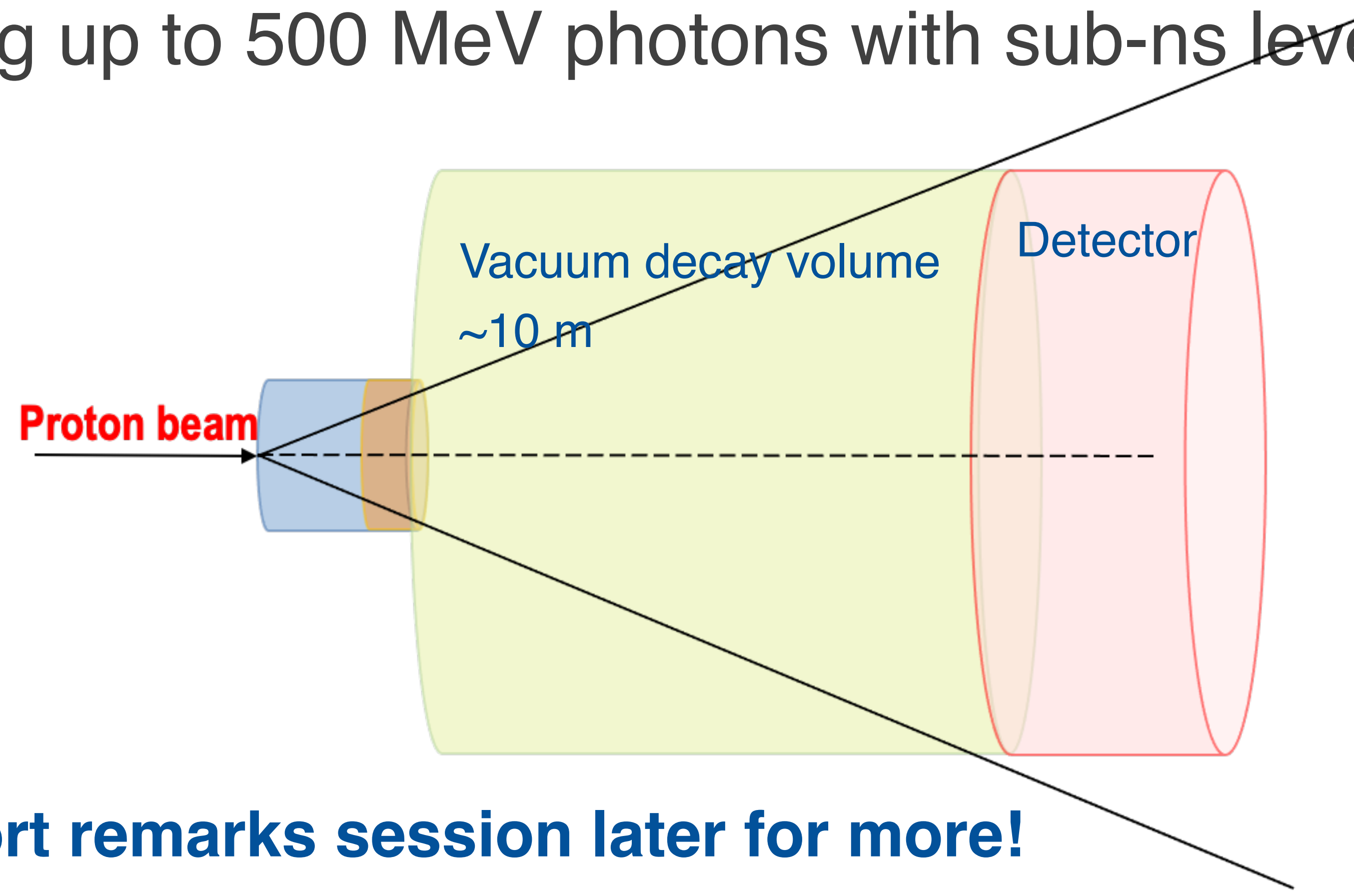


Inelastic DM-Nucleus Scattering



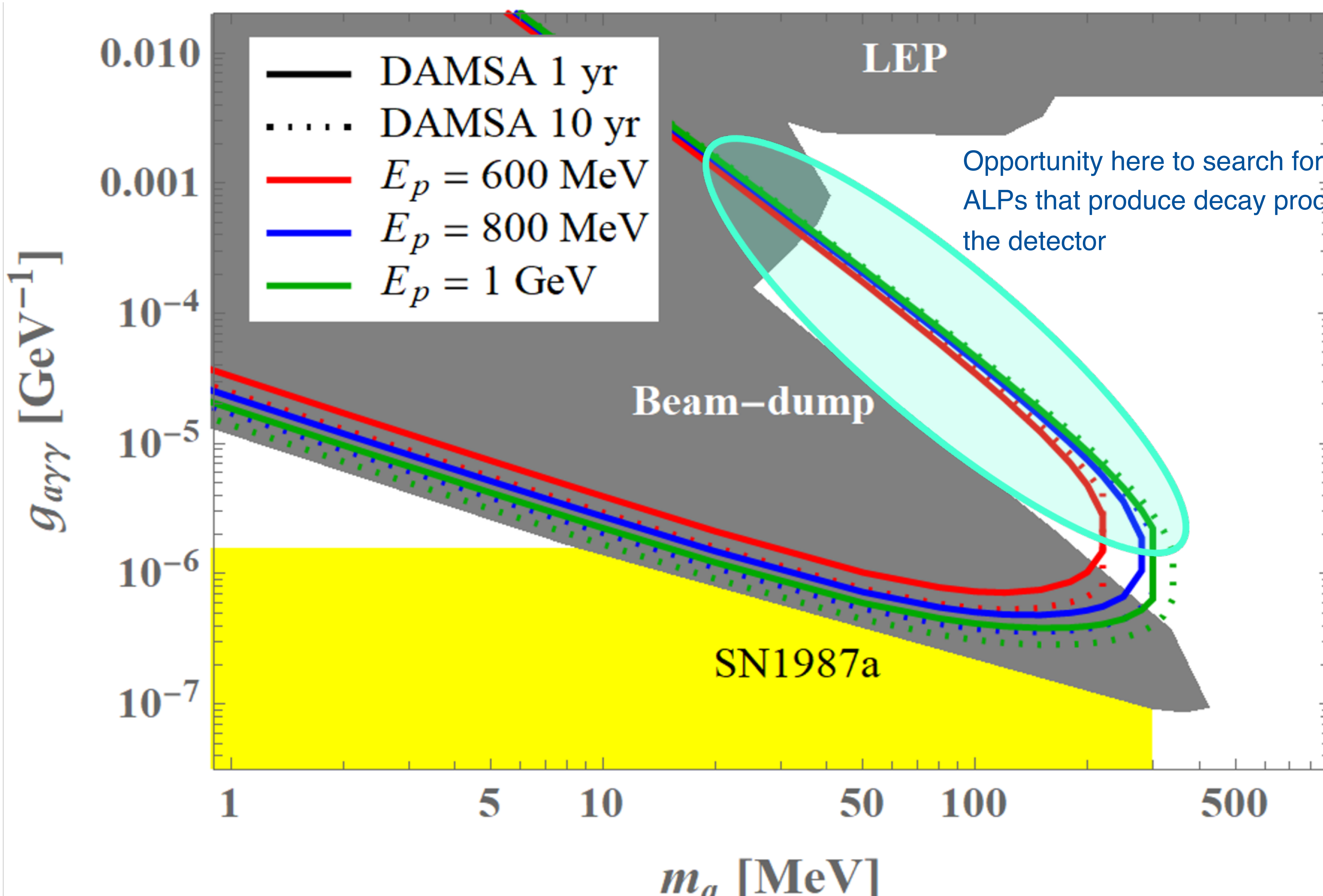
The DAMSA Experiment Concept

- 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



See J. Yu's talk in short remarks session later for more!

DAMSA Sensitivity to ALPs



Opportunity here to search for short-lived ALPs that produce decay products before the detector

Next steps: Writing a Whitepaper

- The output of the workshop is being condensed into a whitepaper and will also be input to further discussions at Fermilab around the ACE plan
- We are in the process of writing a whitepaper that will include the different theoretical and experimental ideas discussed in our workshop

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

author[1]

[1]Univ

June 12, 2023

Abstract

The Fermilab Proton-Improvement-Plan (PIP) II is being implemented in order to support the precision neutrino oscillation measurements at the Deep Underground Neutrino Experiment, the U.S. flagship neutrino experiment. The PIP-II LINAC is presently under construction and is expected to provide 800 MeV protons with 2 mA current. This white paper summarizes the outcome of the first workshop on May 10 through 13, 2023, to exploit this capability for new physics opportunities in the kinematic regime that are unavailable to other facilities, in particular a potential beam dump facility implemented at the end of the LINAC. Various new physics opportunities have been discussed in a wide range of kinematic regime, from eV scale to keV and MeV.

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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
  - Need to better understand and model beam-related experimental backgrounds.
    - This was a focus of the summaries at the end of the workshop
- The input from this workshop is being prepared as a whitepaper and used as input on the science possible at Fermilab under the ACE plan

Thank you!

Questions?

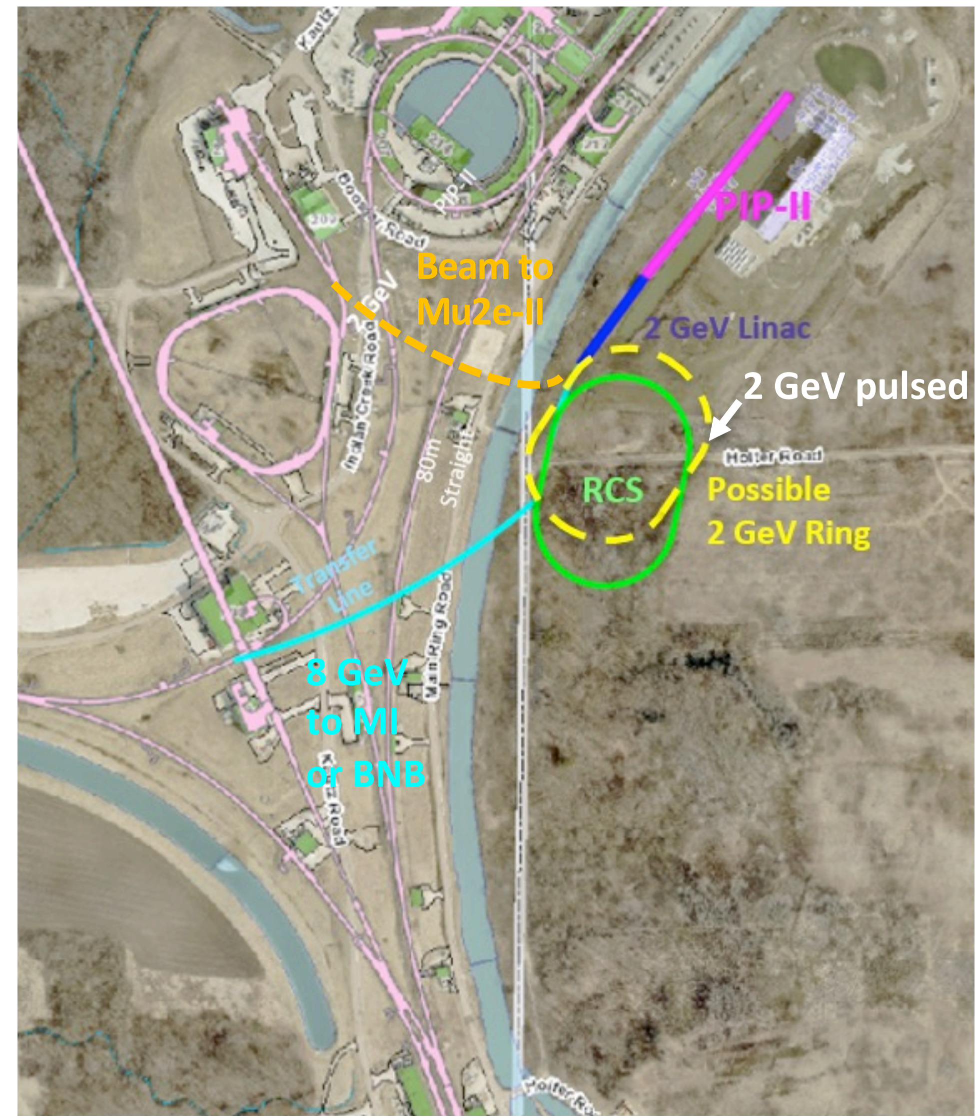
Backup Slides

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

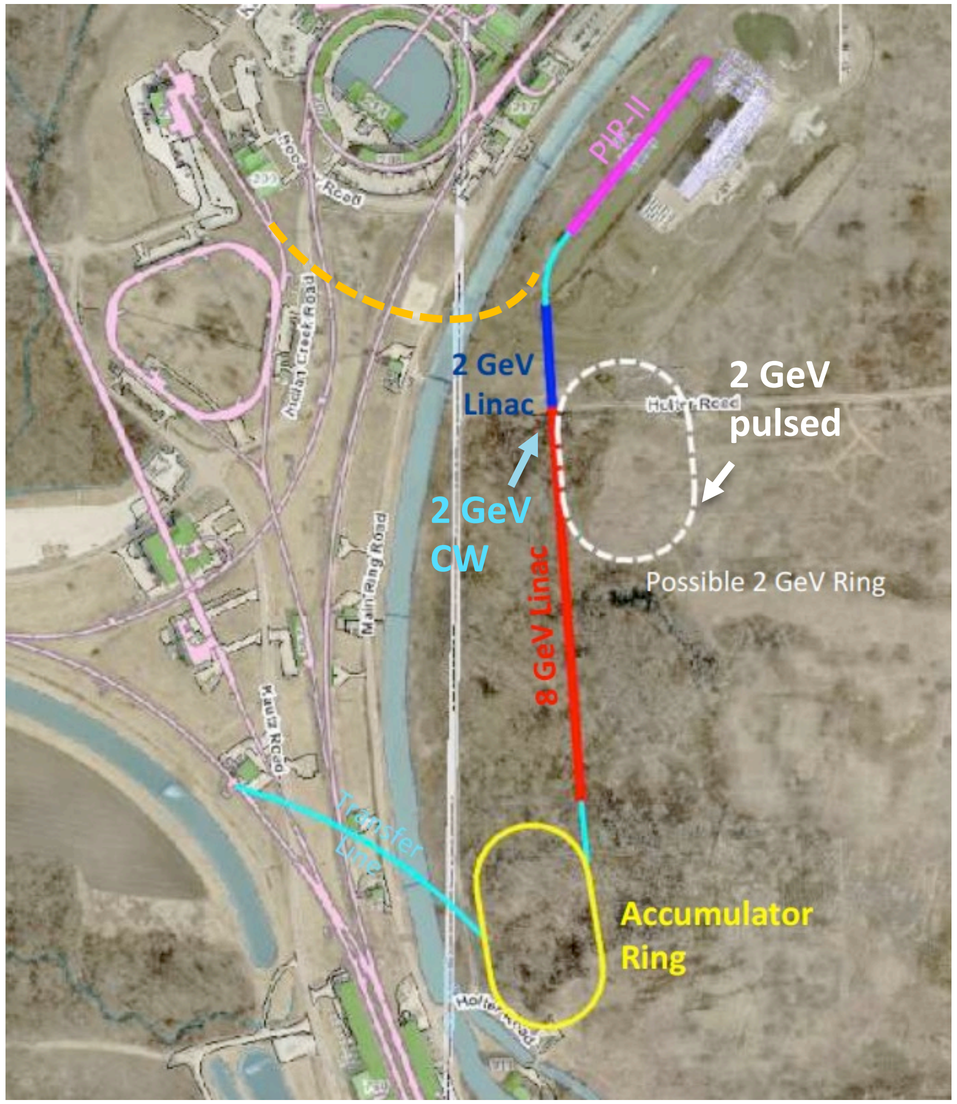
Example Booster Replacement options and possible add-ons

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.

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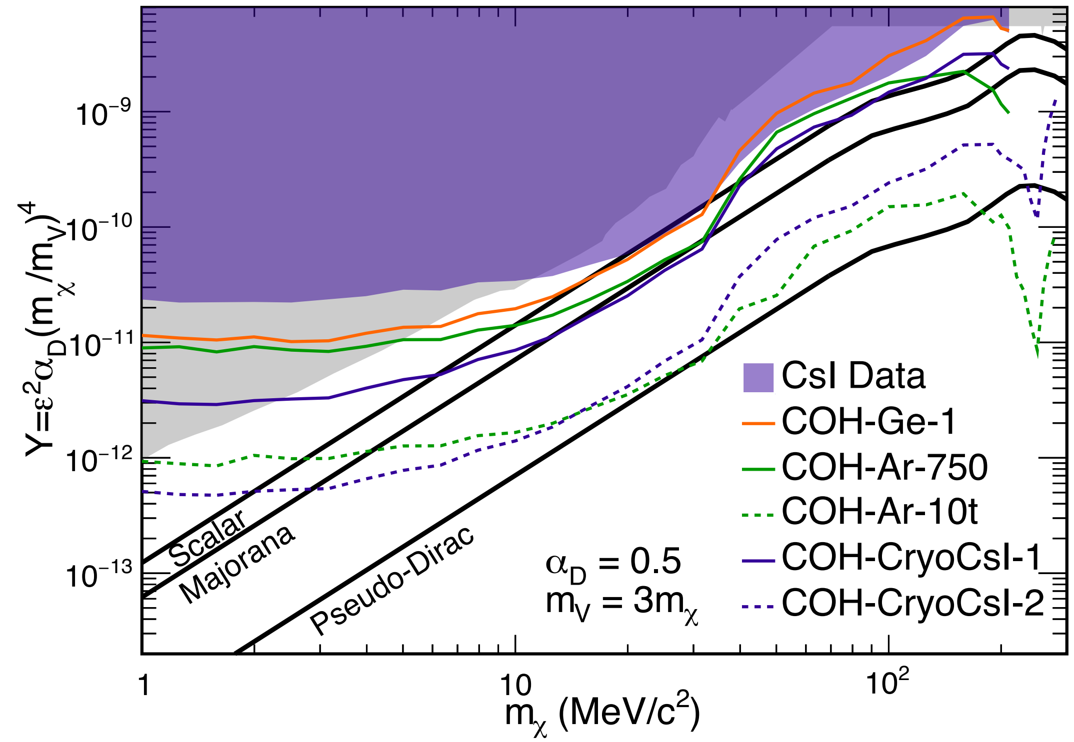
13 Jeffrey Eldred I PIP2BD Beyond PIP-II 6/6/23

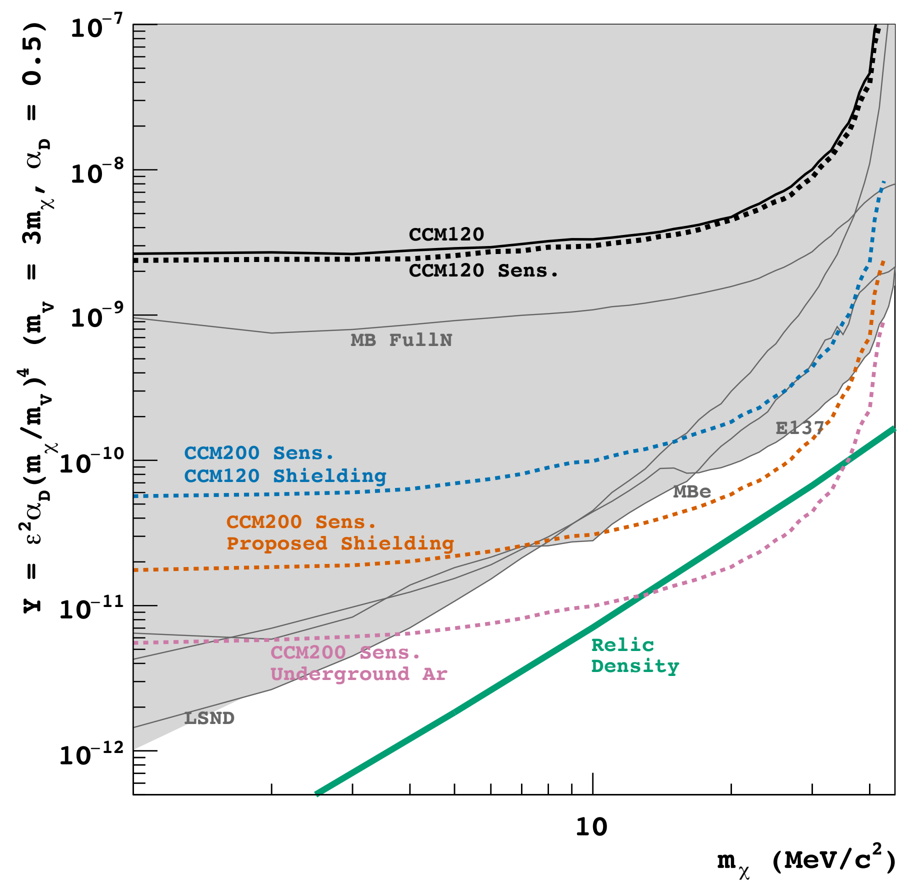
Current Accelerator-based vector-portal dark sector searches

- 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)

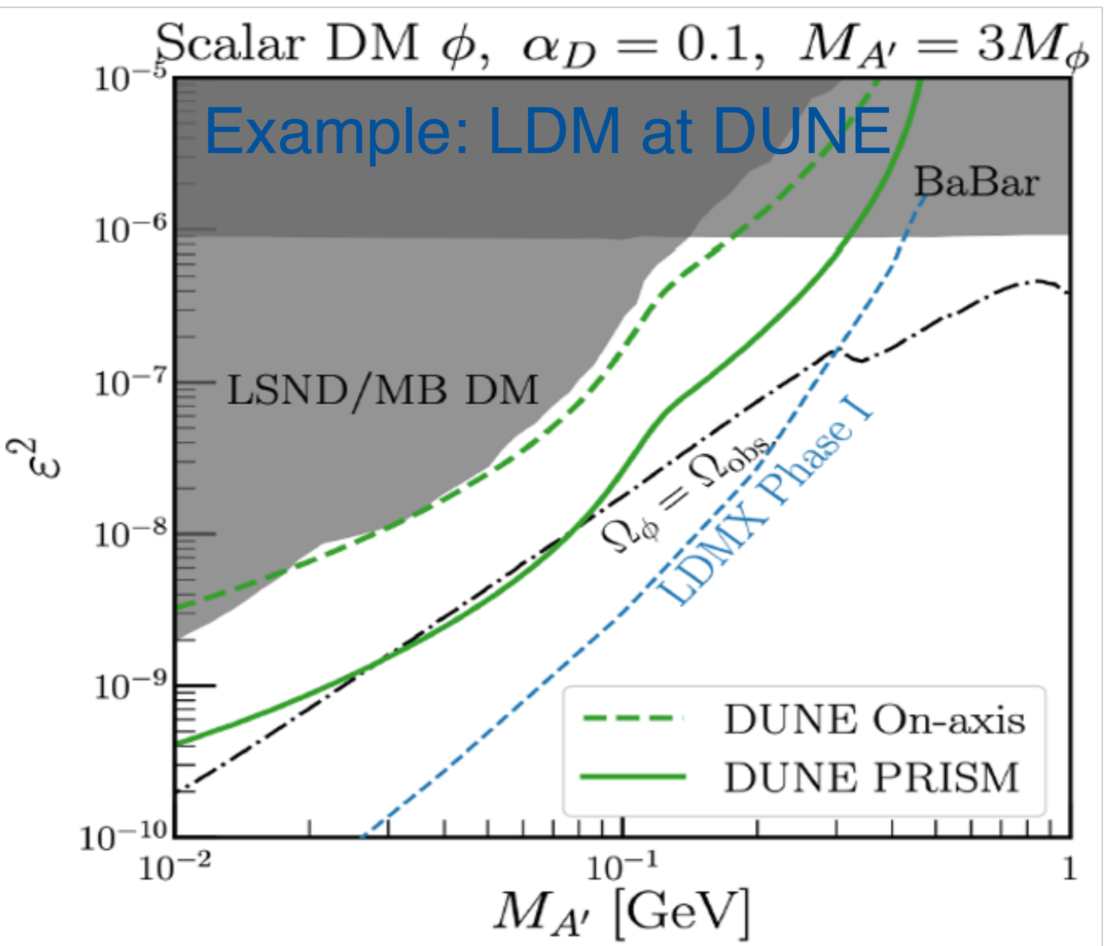


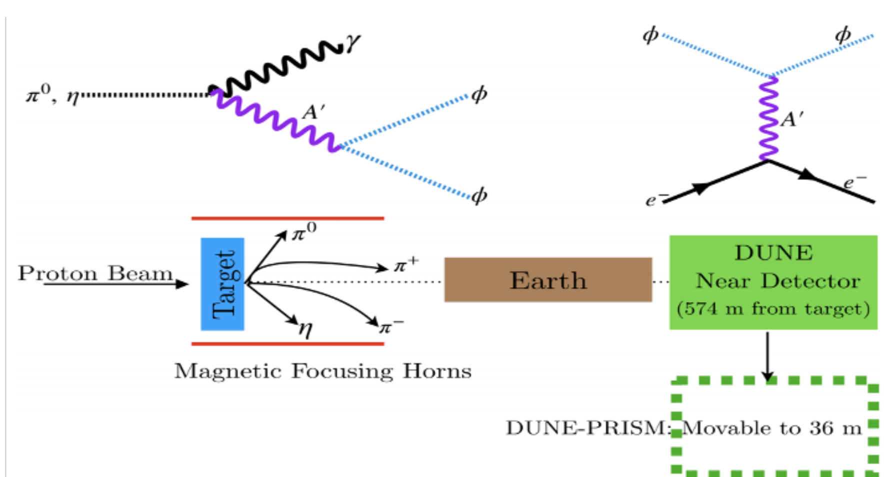
Phys. Rev. D 106, 012001 (2022)

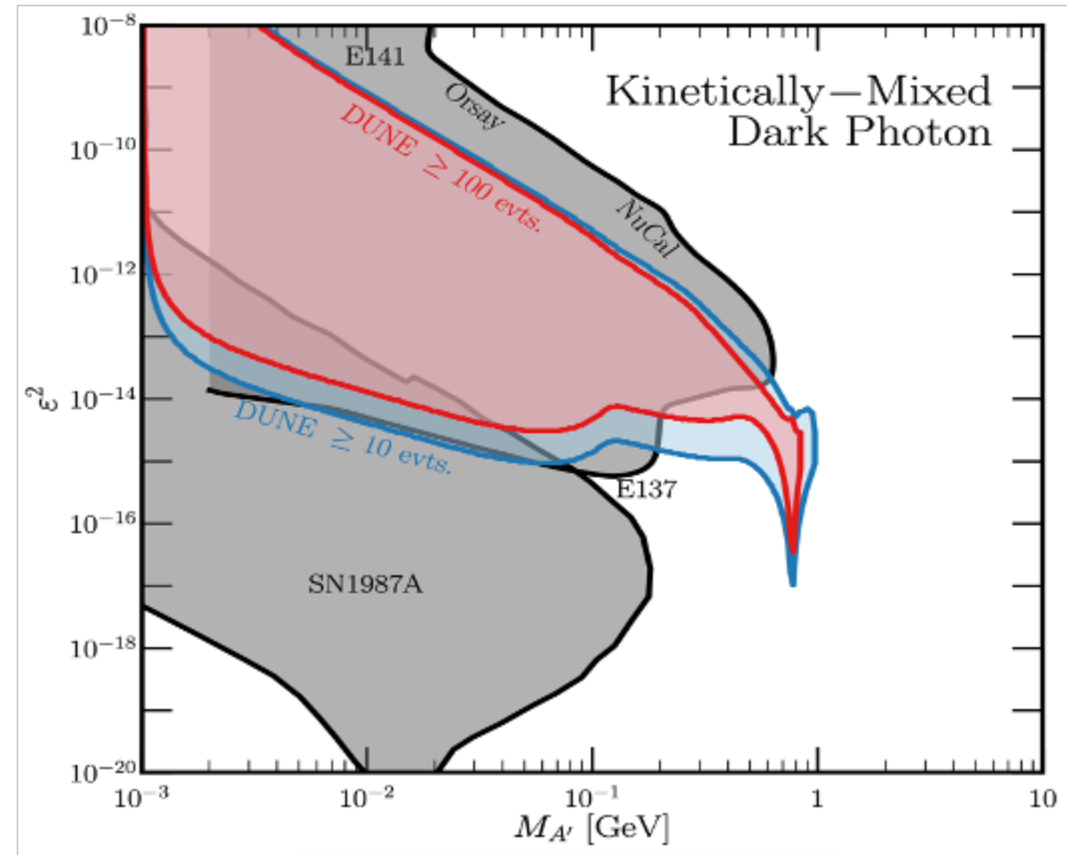
Physics Opportunities with MeV-scale thresholds

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

Example: LDM at DUNE



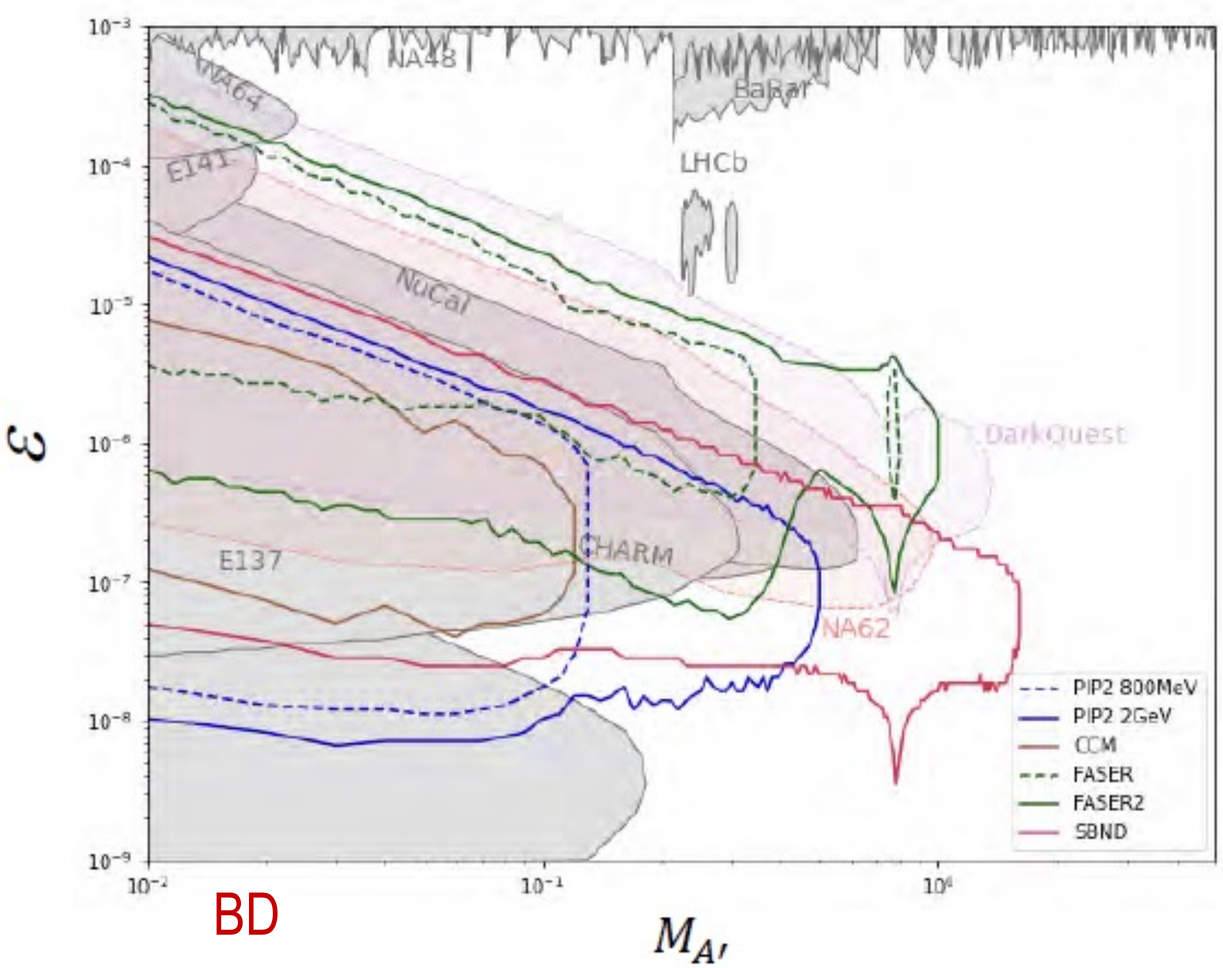




Example: Dark Photon Search at DUNE where dark photon travels to detector and decays into a charged lepton pair

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^-



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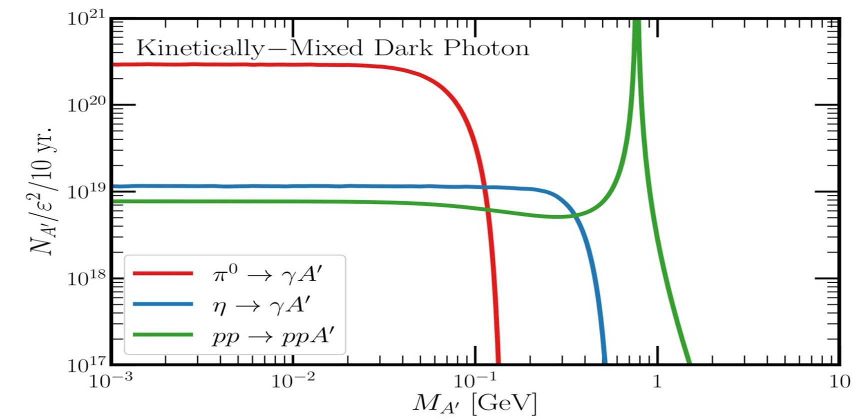

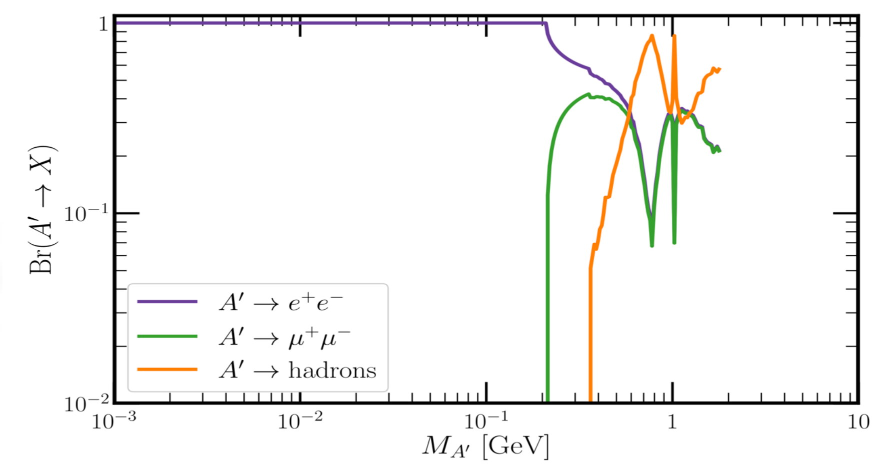

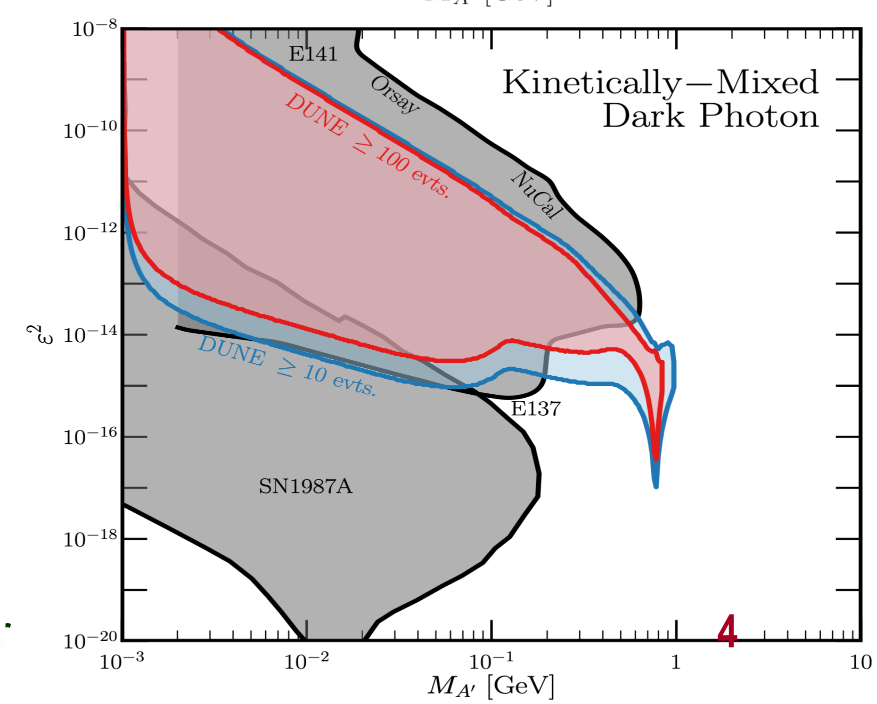

Physics Signatures and Backgrounds

- 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

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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

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Physics Signatures and Backgrounds

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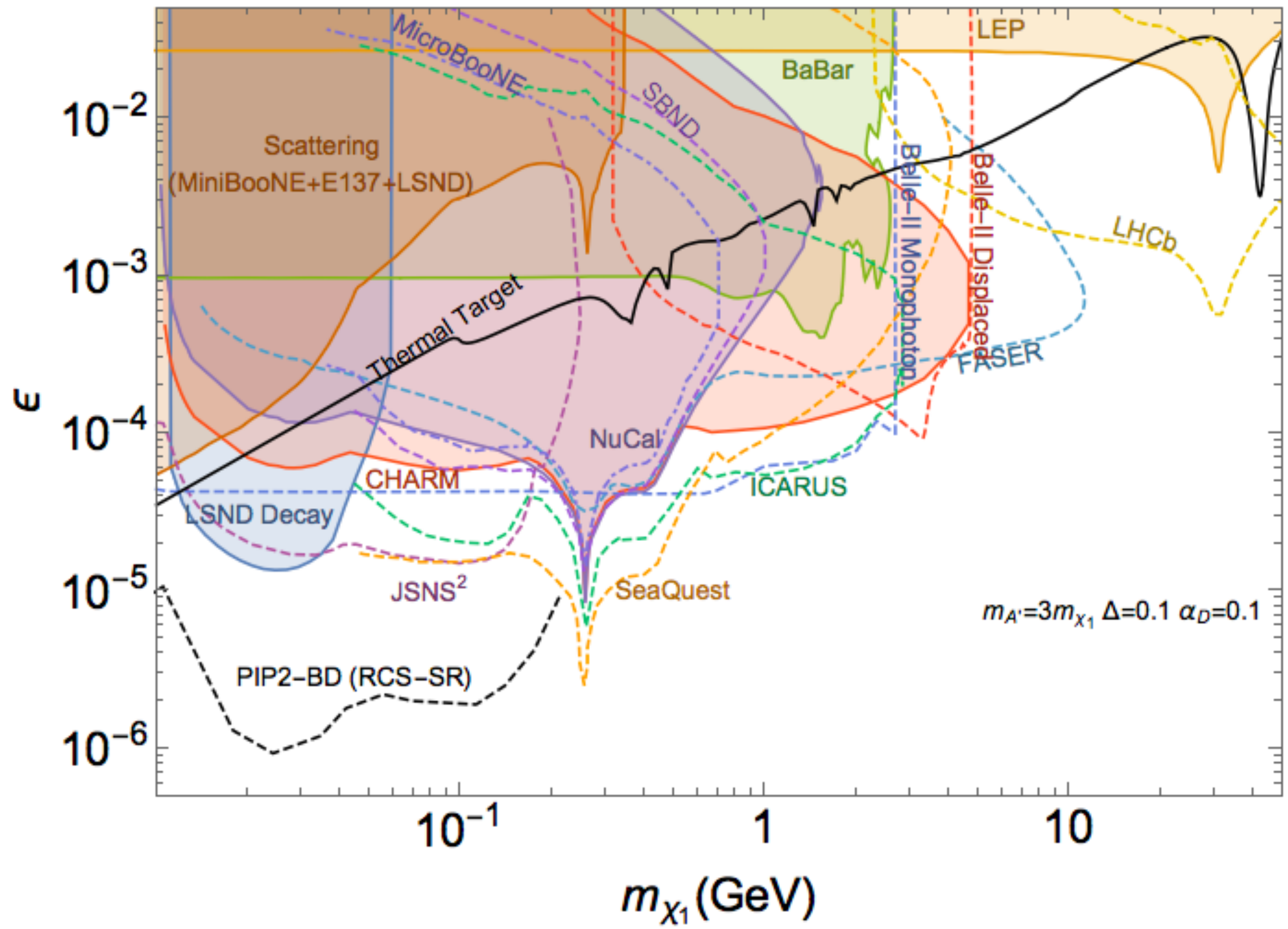
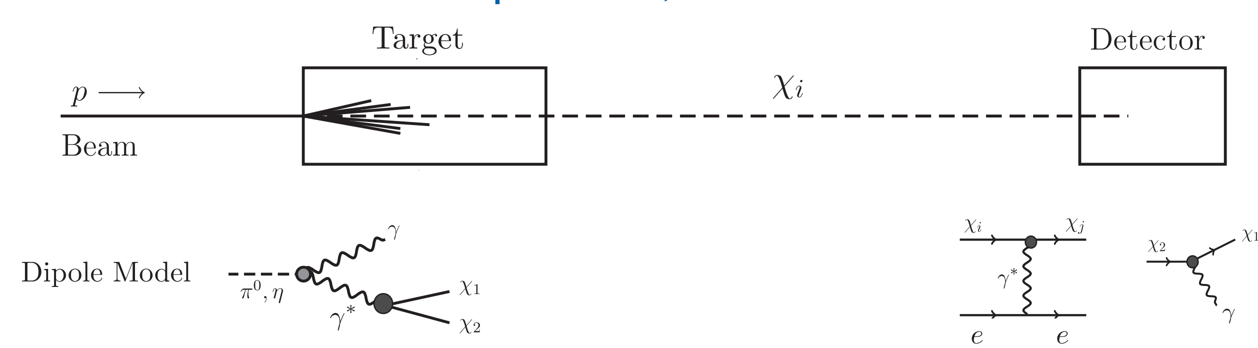
PIP2-BD Inelastic dark matter search

- 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

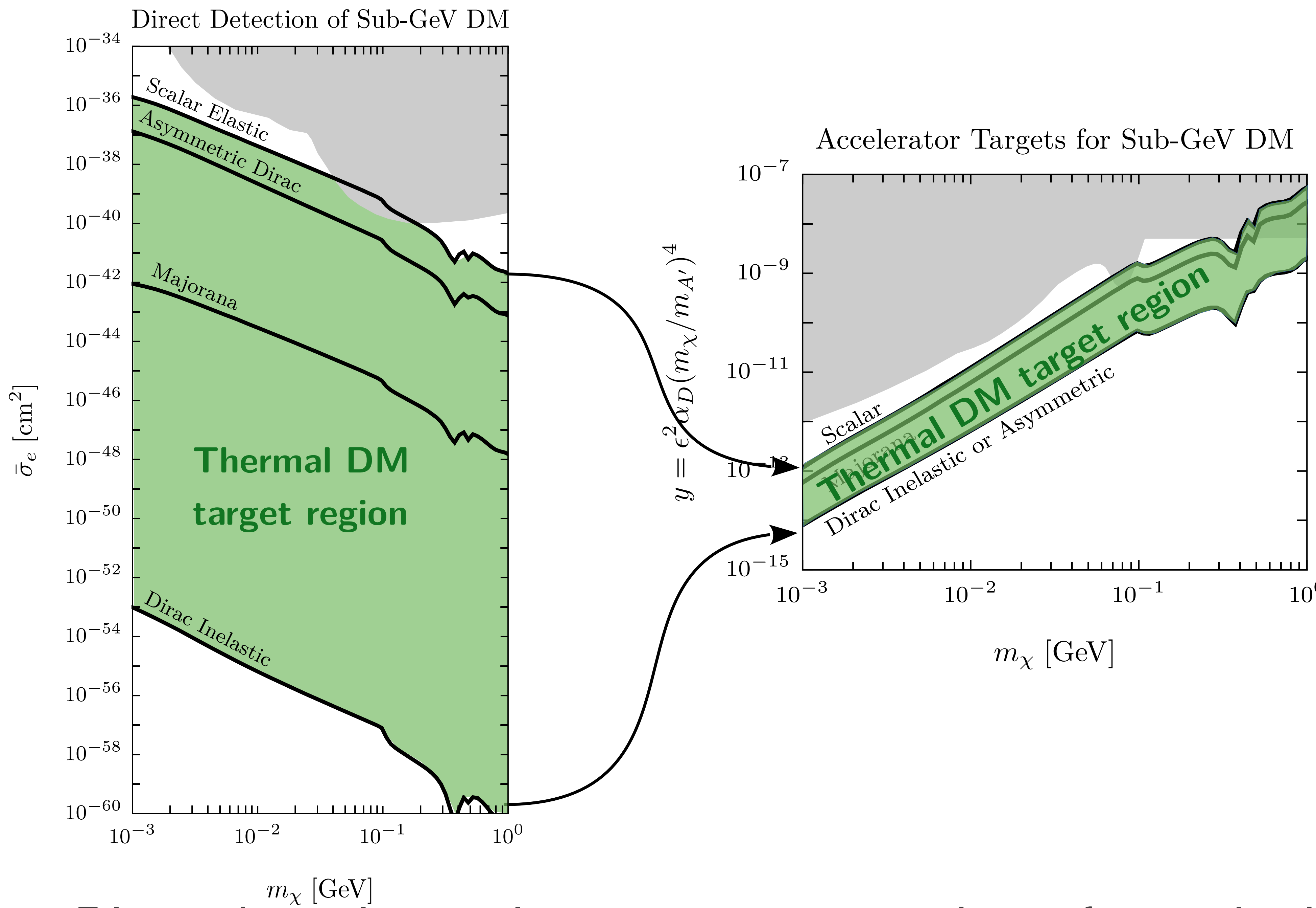


M. Toups et al., arXiv:2203.08079



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

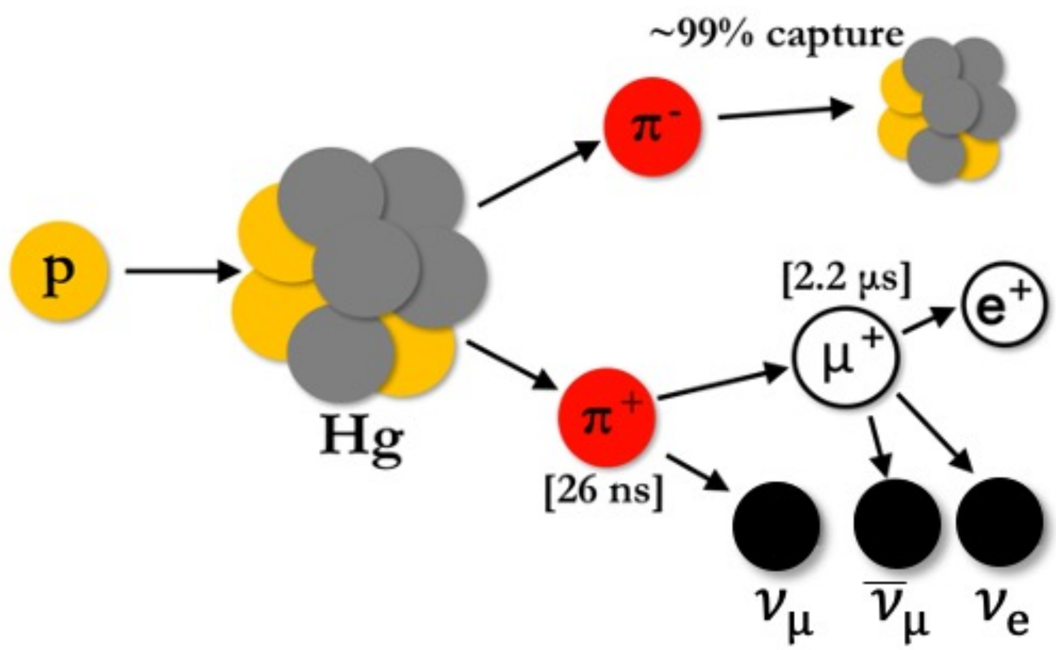
Connections to Direct Detection DM Searches

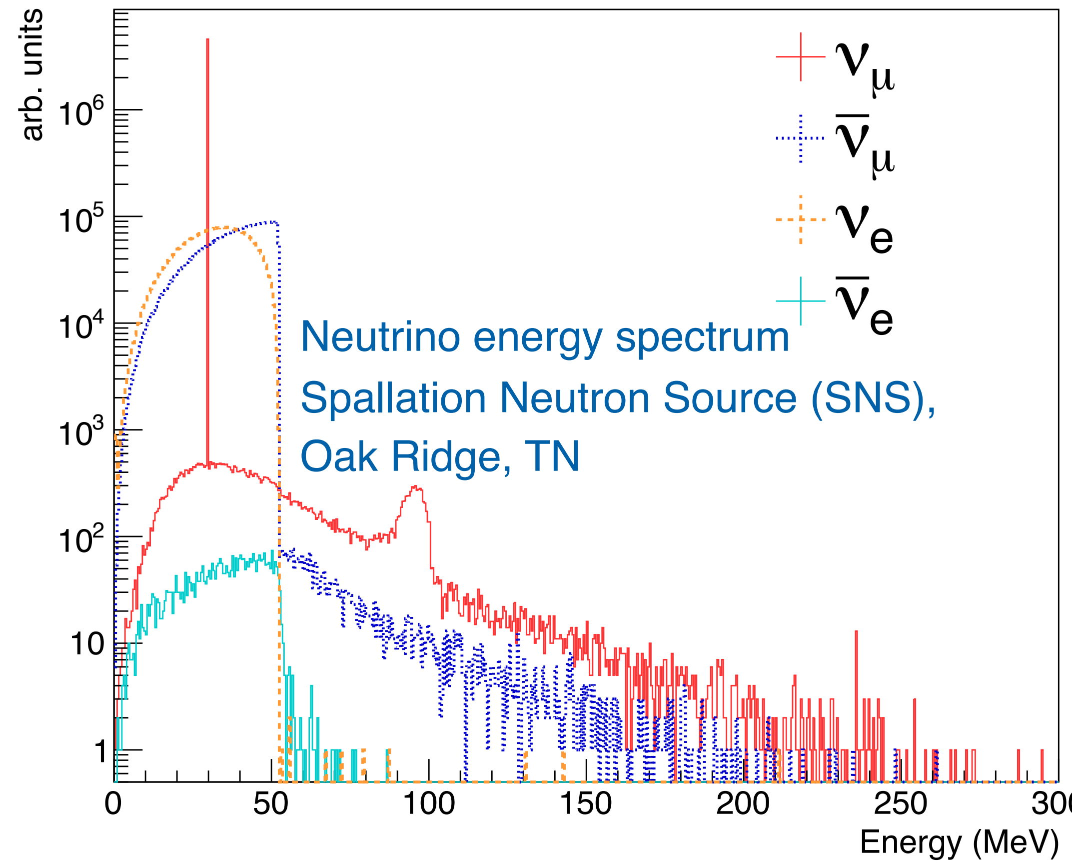


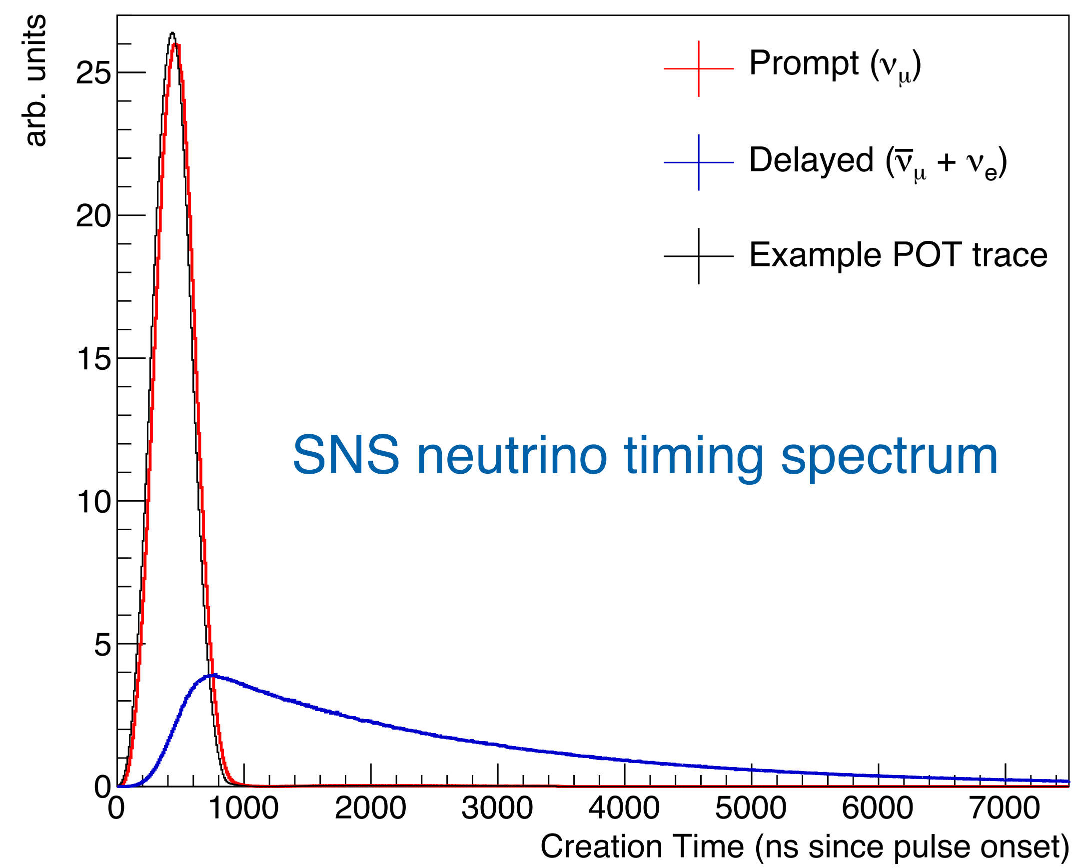
- Direct detection regime spans many orders of magnitude due to effects such as DM velocity suppression or spin suppression significant for non-relativistic scattering

arXiv:2209.04671

Stopped-Pion Neutrino Sources



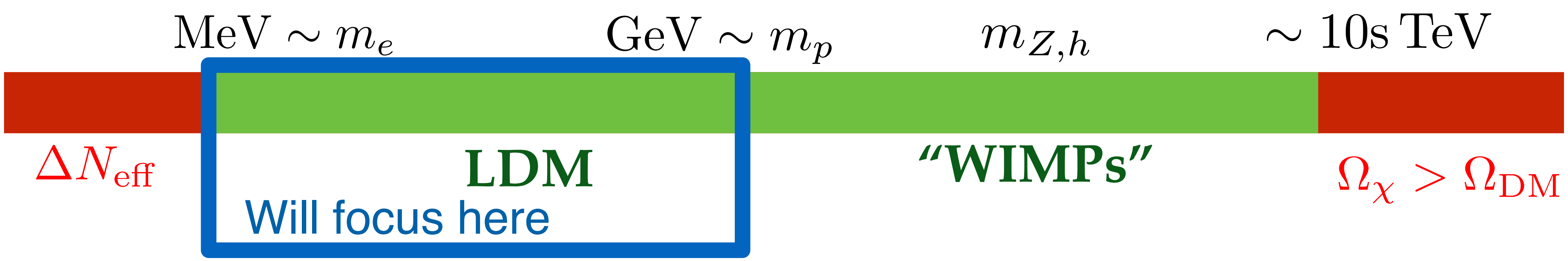




- Neutrinos produced from pion decay-at-rest via proton collisions with target
- Neutrino flux $O(10^7)/cm^2/s$ at ~1 MW and 20 m from source
- Steady-state background suppression via pulsed beam

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

Current Landscape of Dark Matter and Dark Sector Searches

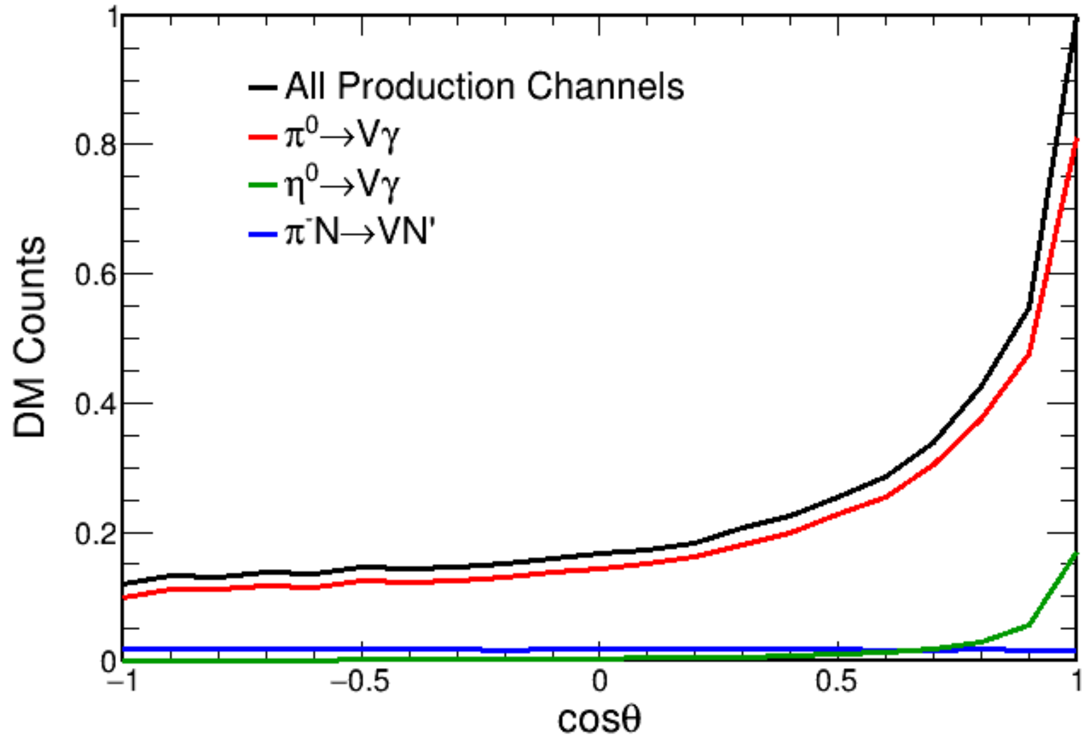


- New physics theorized to be neutral under SM forces
- A finite set of operators serve as a portal to a possible dark sector

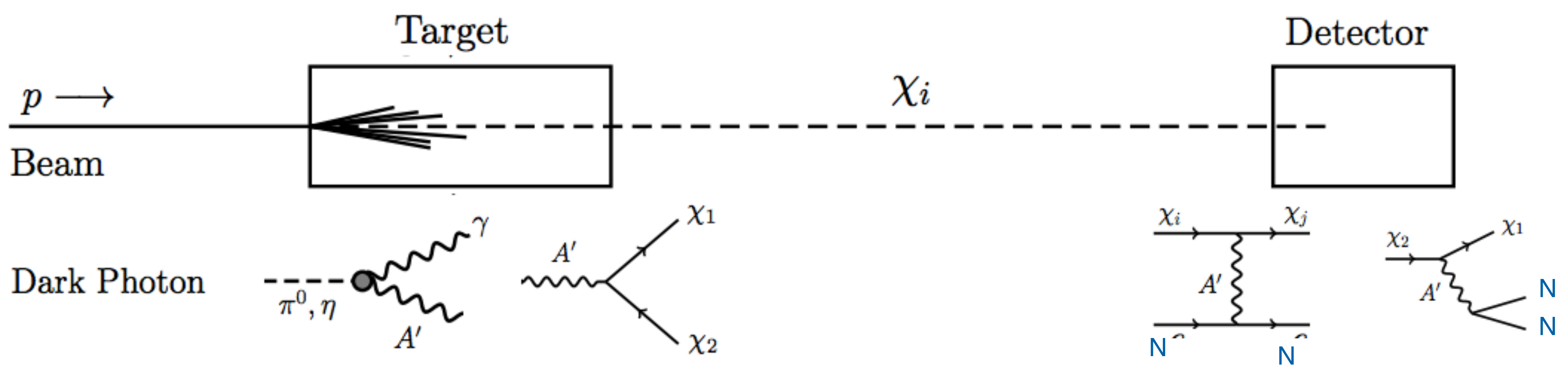
$B_{\mu\nu}$	x	$\epsilon/2\, F'^{\mu\nu}$	Vector portal
$\|h\|^2$	x	$\mu S + \lambda\|\phi\|^2$	Higgs portal
hL	x	$y_N N$	Neutrino portal

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

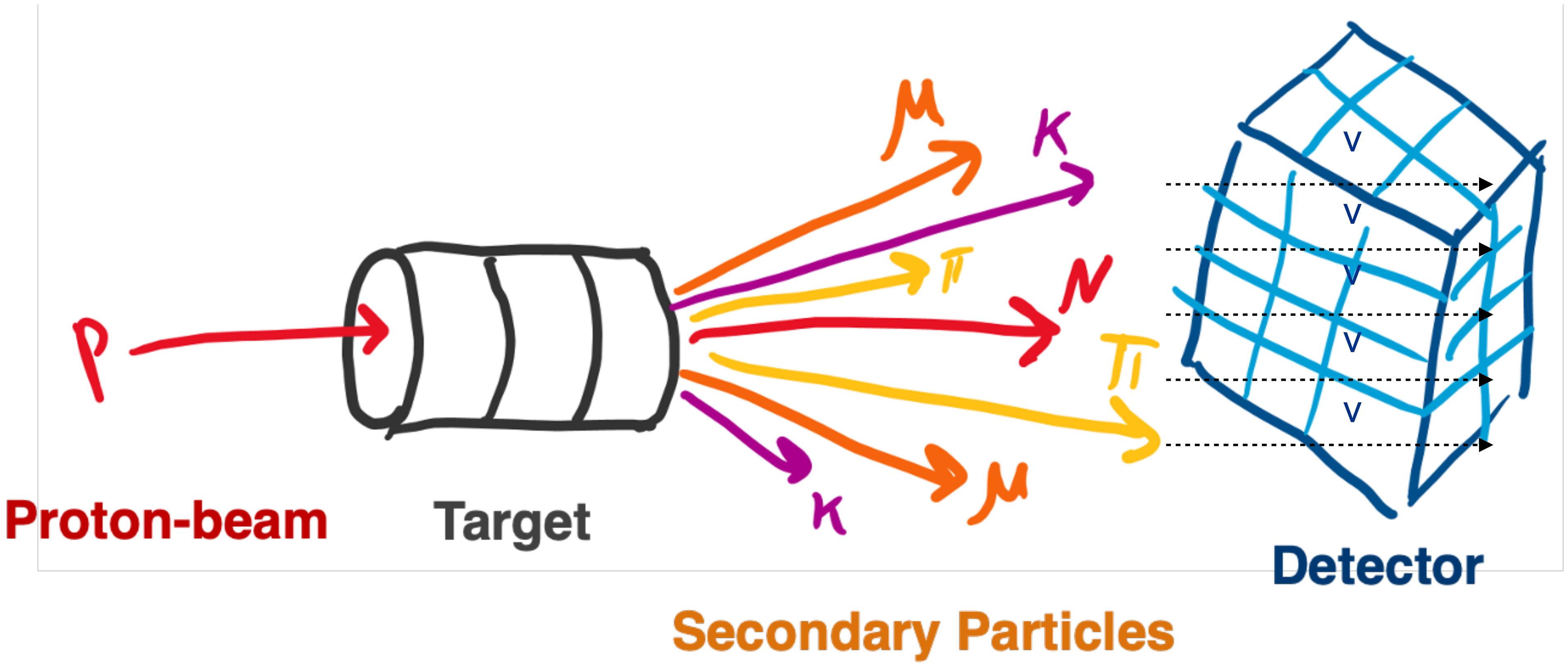


P. deNiverville et al., Phys. Rev. D 92 (2015) 095005

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



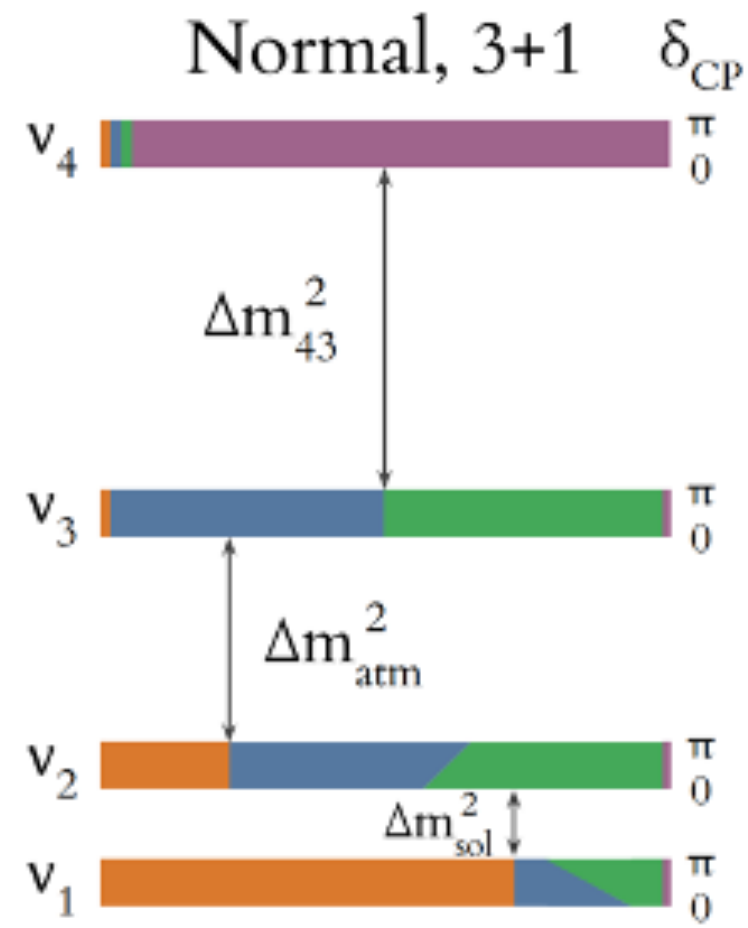
Creating a stopped-pion source with PIP-II

- 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

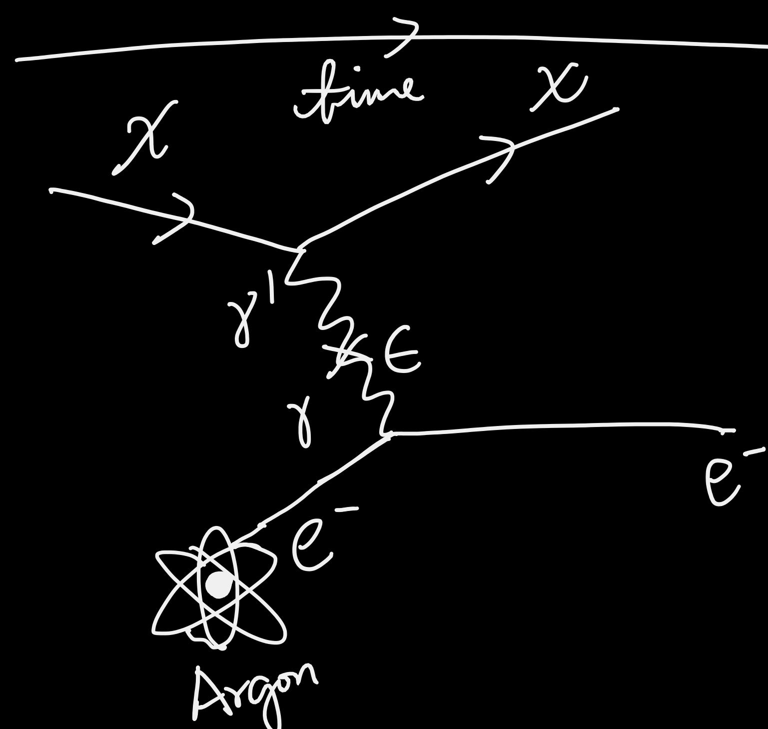
Extension to 3+1 neutrino states

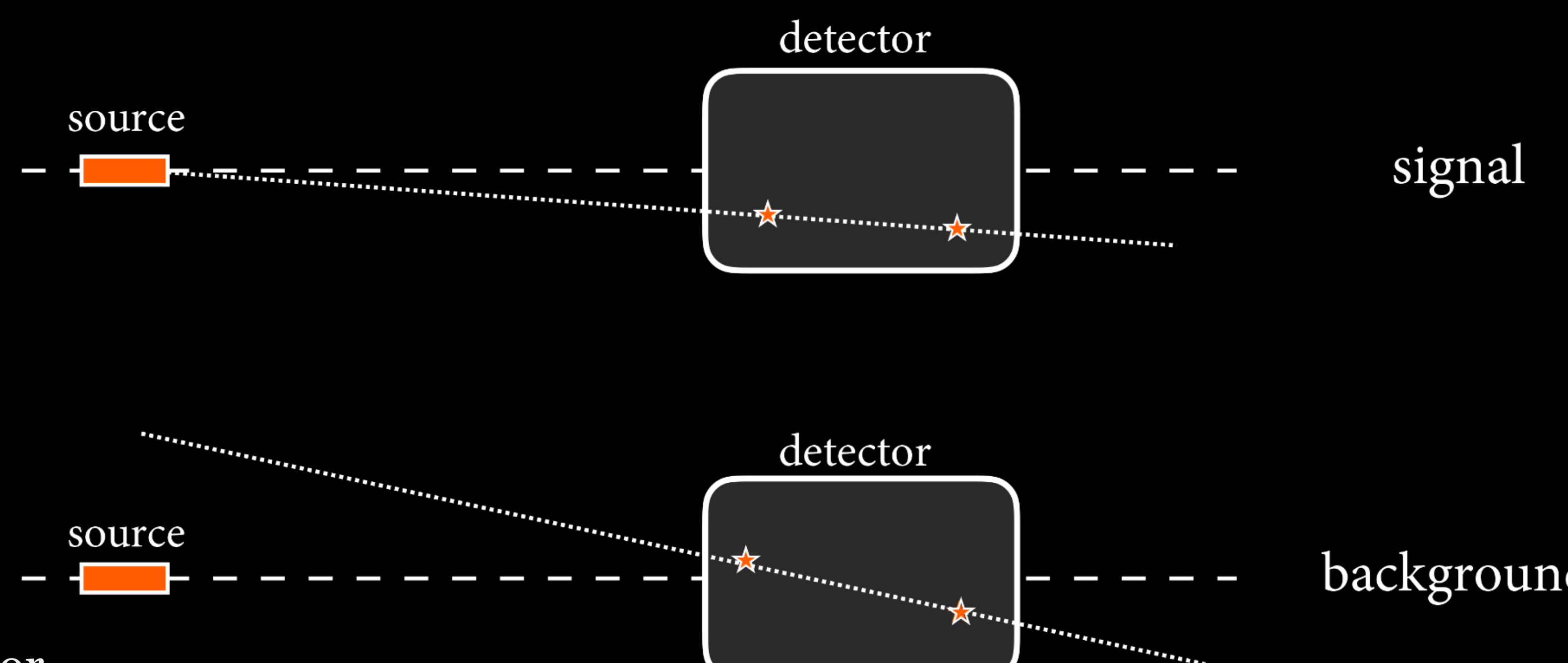
- Can create extensions to the three-flavor model
  - Extend the PMNS matrix to include a fourth, “sterile” neutrino or 3+1 model
- Additional mixing angles and mass splittings based on the fourth neutrino state
- Neutrino fluxes are conserved under the extension
- The fourth neutrino state allows for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



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

Strategy: aligned double rare hits





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

Zhen Liu MCP@PIP-II PIP-II Opportunities 05/10/2023 5

Millicharged particle background rejection strategy

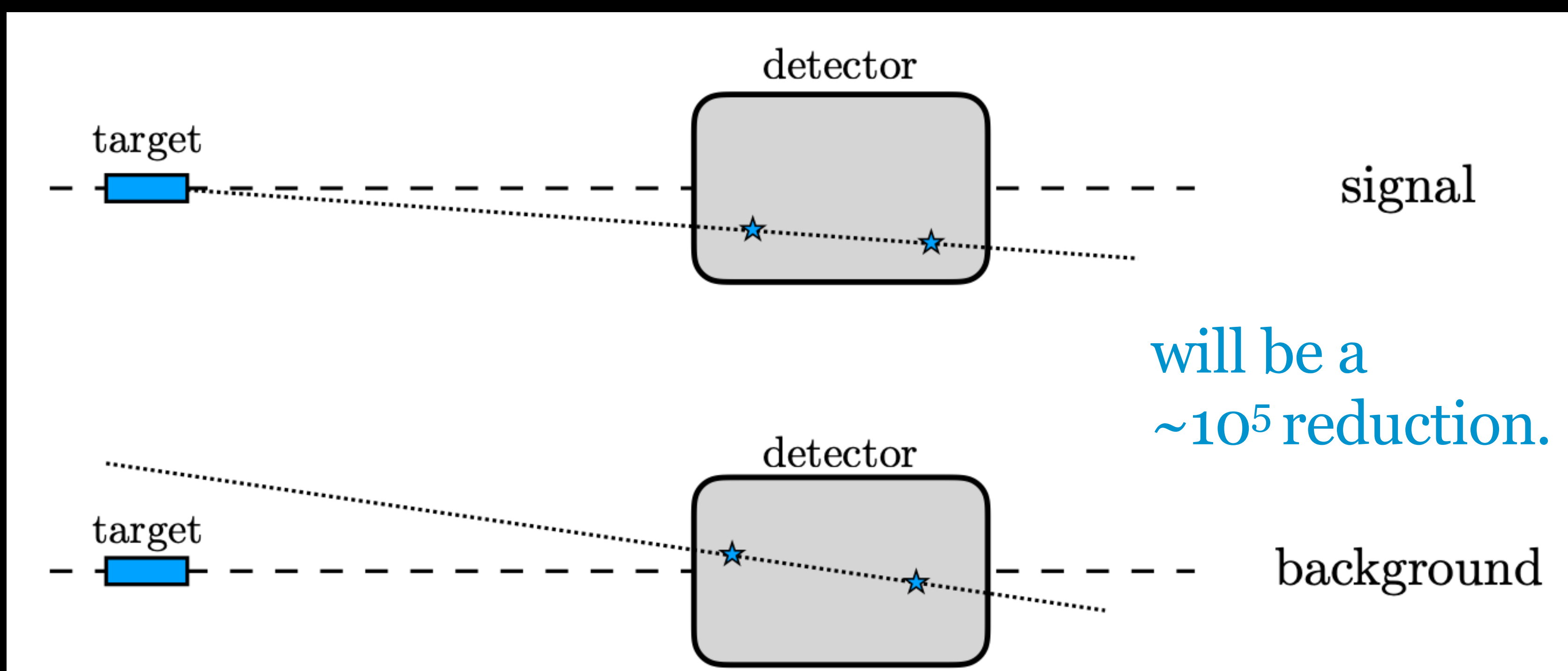
We then recalled a key feature of LAr detectors, and designed a new search:

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

Background Reduction

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

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



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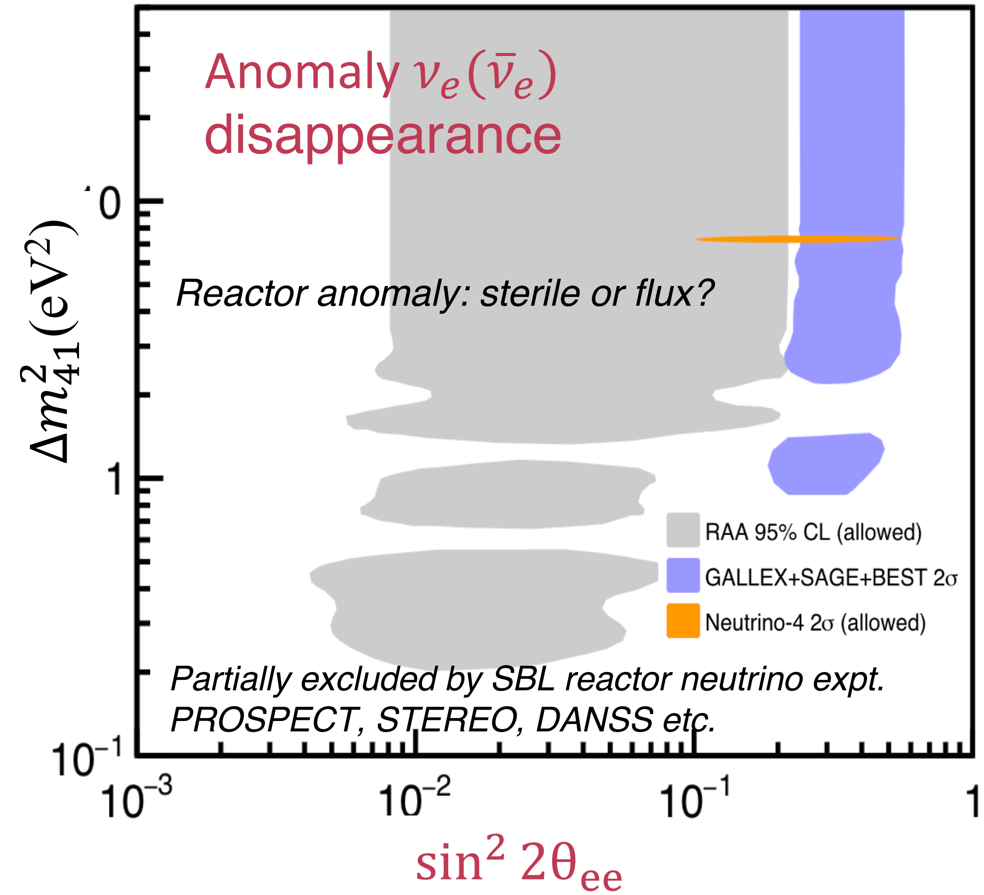
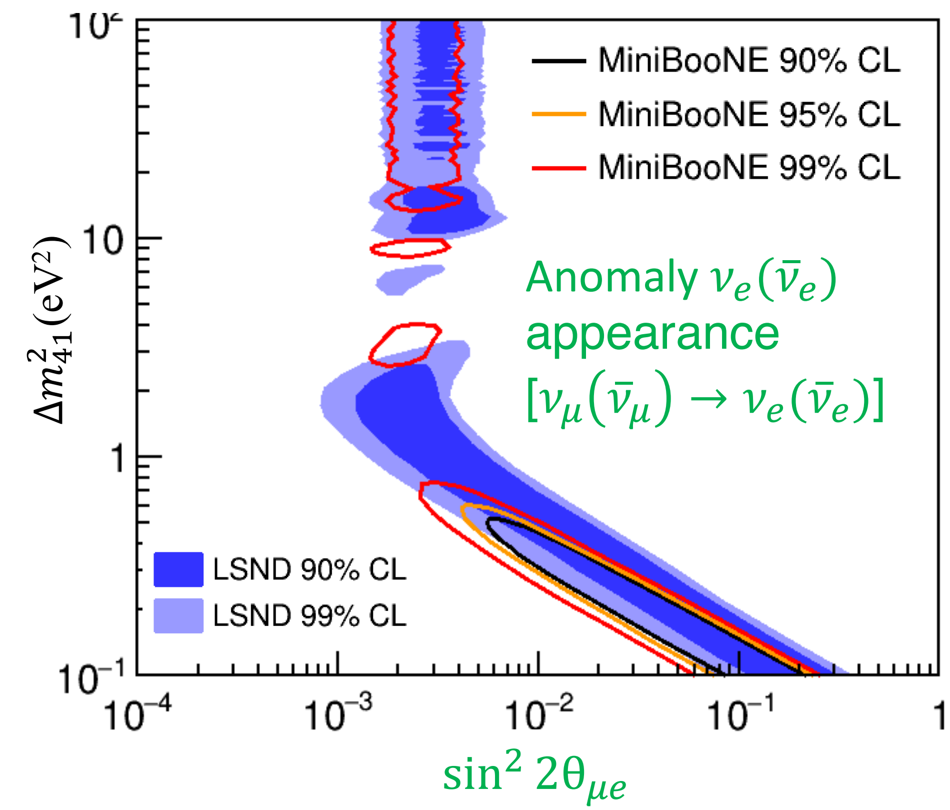
Anomalies in neutrino oscillation measurements

- 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

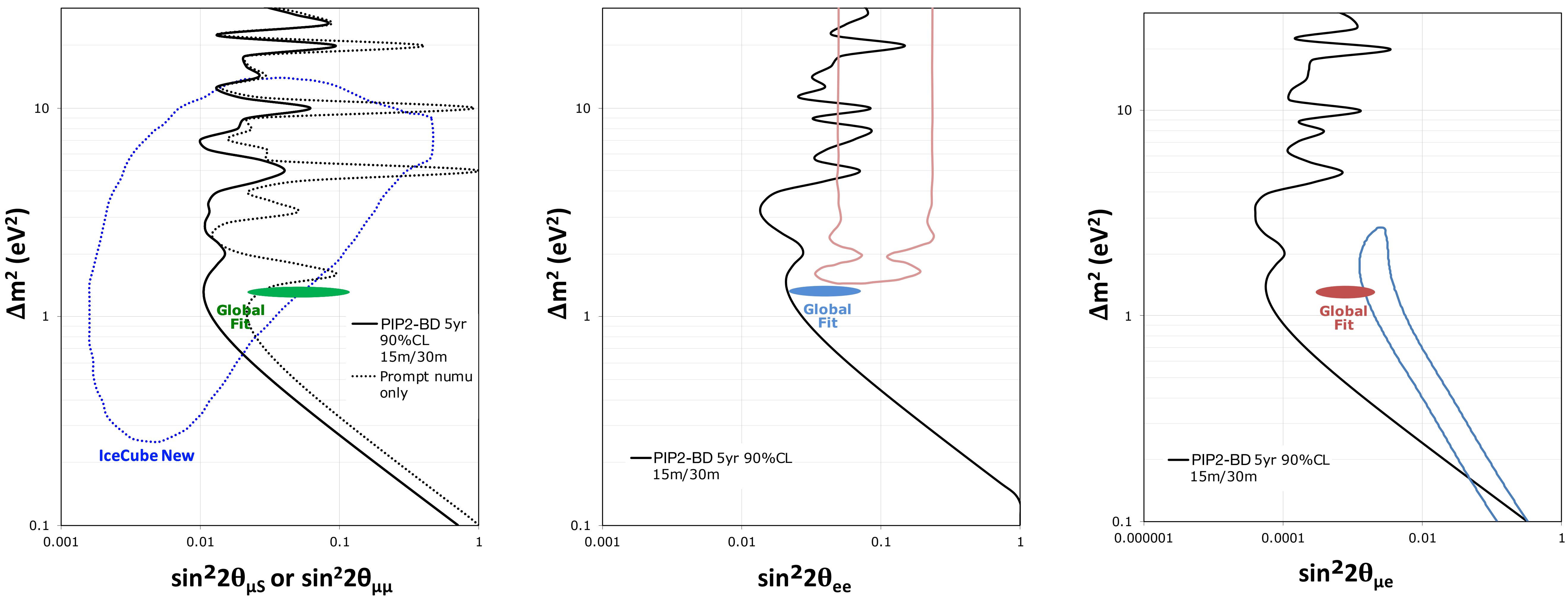


FIG. 13. PIP2-BD 90% confidence limits on active-to-sterile neutrino mixing compared to existing ν_μ disappearance limits from IceCube [45] and a recent global fit [46], assuming a 5 year run (left). Also shown are the 90% confidence limits for ν_μ disappearance (left), ν_e disappearance (middle), and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

Fermilab