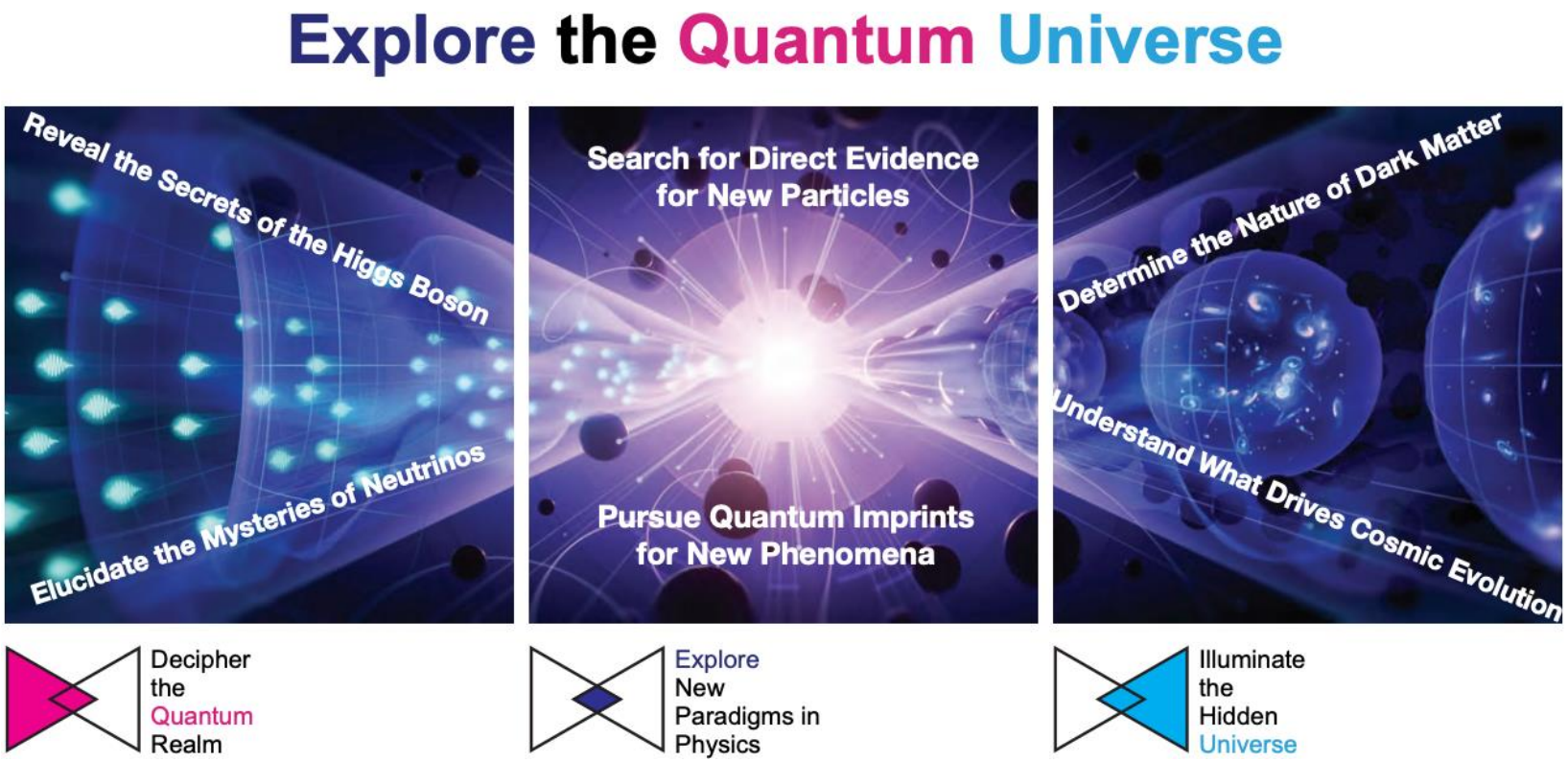
Probing the Dark Sector using a Beam Dump Facility at Fermilab in the PIP-II Era

Matt Toups, Fermilab

TeVPA

Thurs 29 Aug 2024

Report of the 2023 Particle Physics Project Prioritization Panel (P5)



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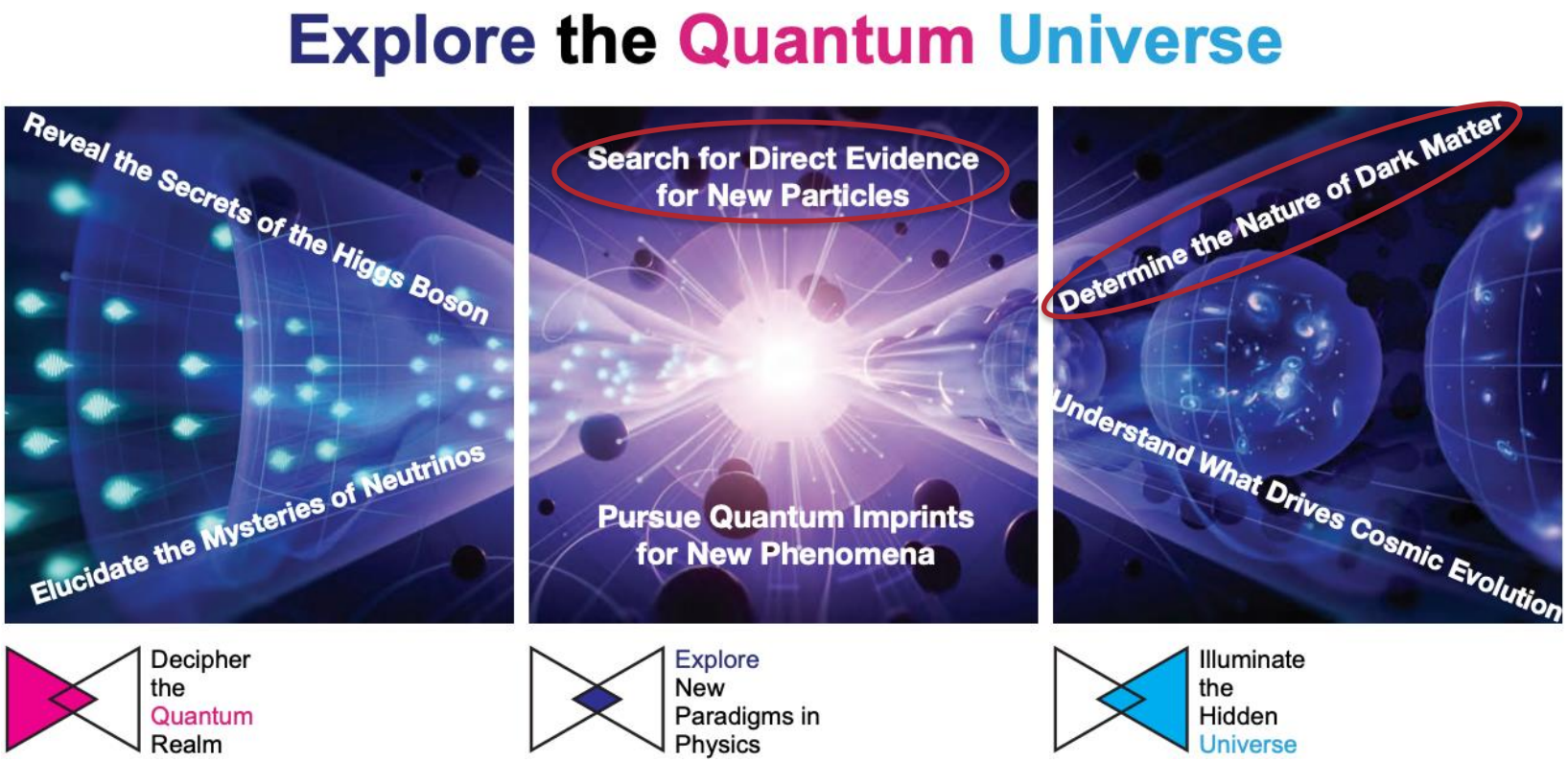
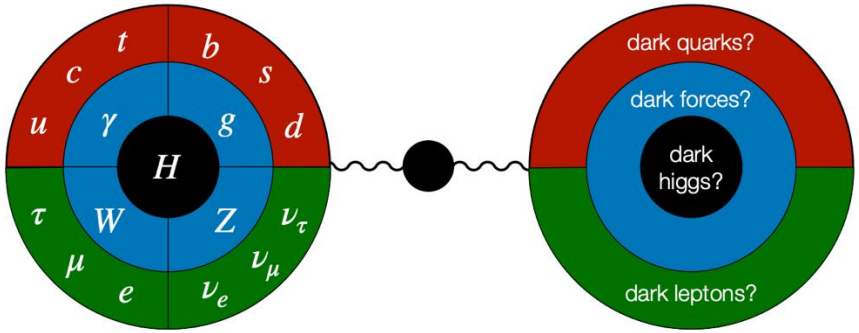


Dark Sector Paradigm

- Below the electroweak scale, new particles should be neutral (“dark”) under SM forces (EM, weak, strong)
- New physics connects to SM through finite list of “portal” operators, enabling systematic exploration
- Also of interest: axion portal, gauging SM global symmetries

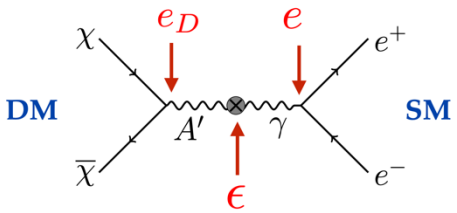


$B_{\mu\nu}$	x	$\epsilon/2\, F'^{\mu\nu}$	Vector portal
$\lvert h\rvert^2$	x	$\mu S + \lambda\lvert\phi\rvert^2$	Higgs portal
hL	x	$y_N N$	Neutrino portal

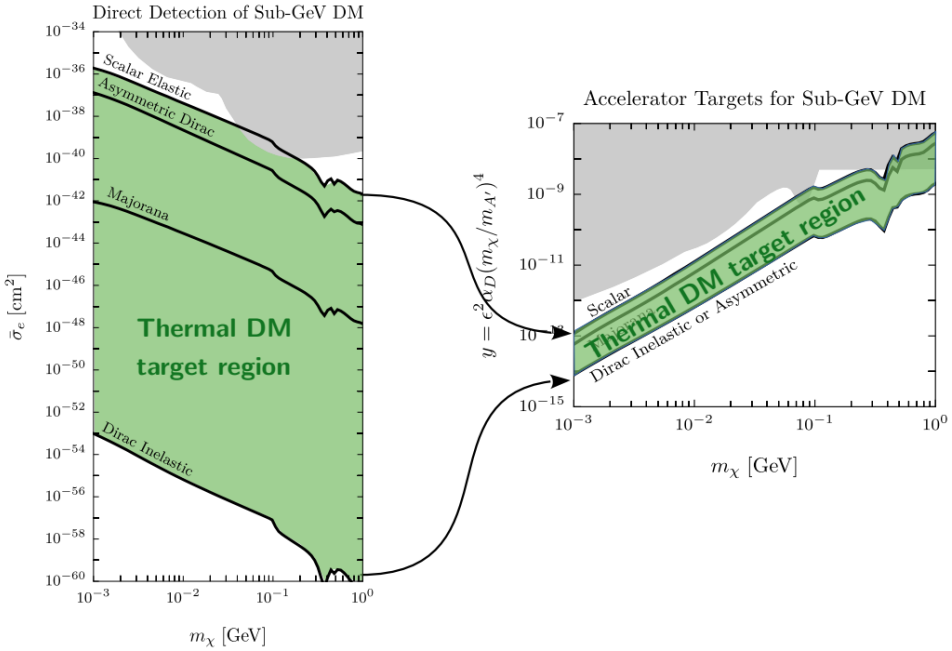
Dark Sector – Light Dark Matter (DM)

- Minimal models provide a thermal relic explanation for sub-GeV DM that give the correct cosmological abundance and predict the DM can be produced and detected at accelerator-based facilities

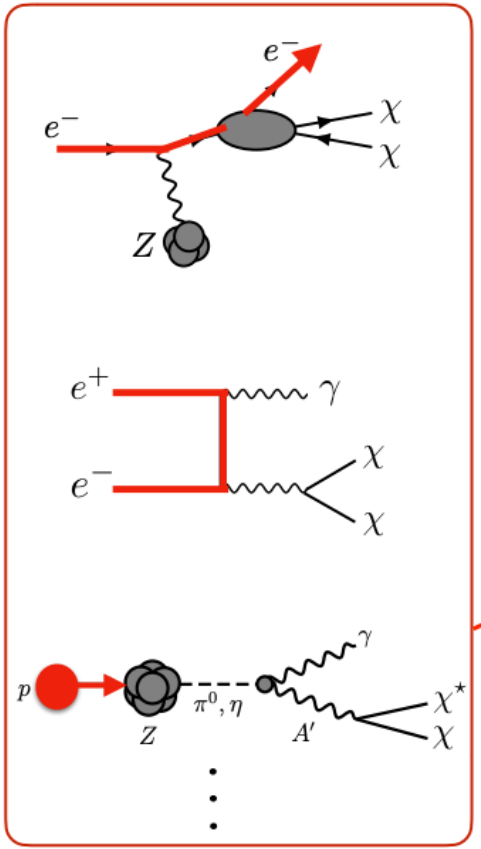
- Representative model: vector portal kinetic mixing with $m_{A'} > m_{\chi}$

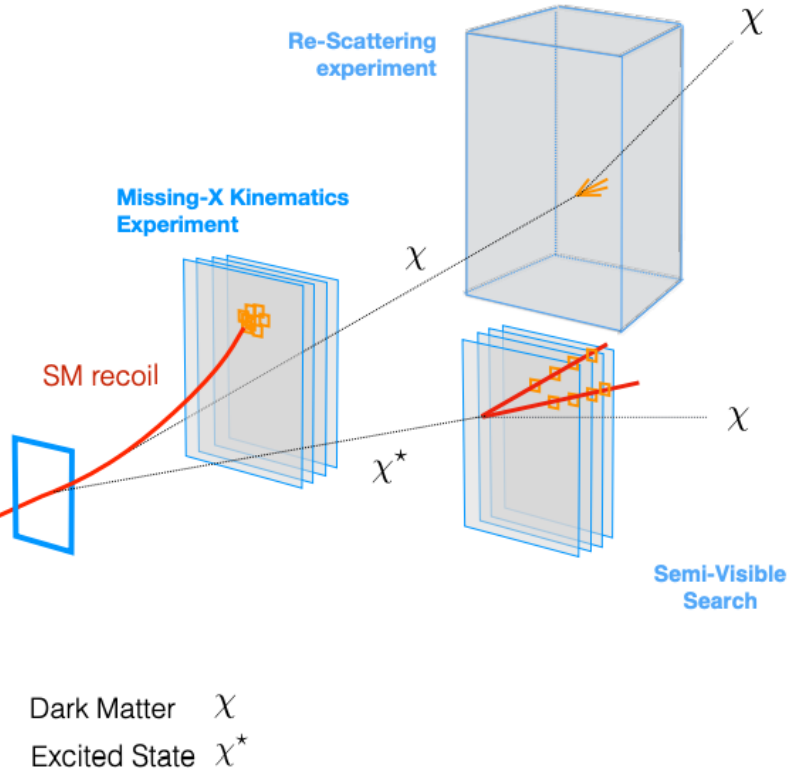


- Thermal freeze out mechanism viable above some minimum SM coupling ϵ



Mimicking Big Bang DM Production at Accelerators





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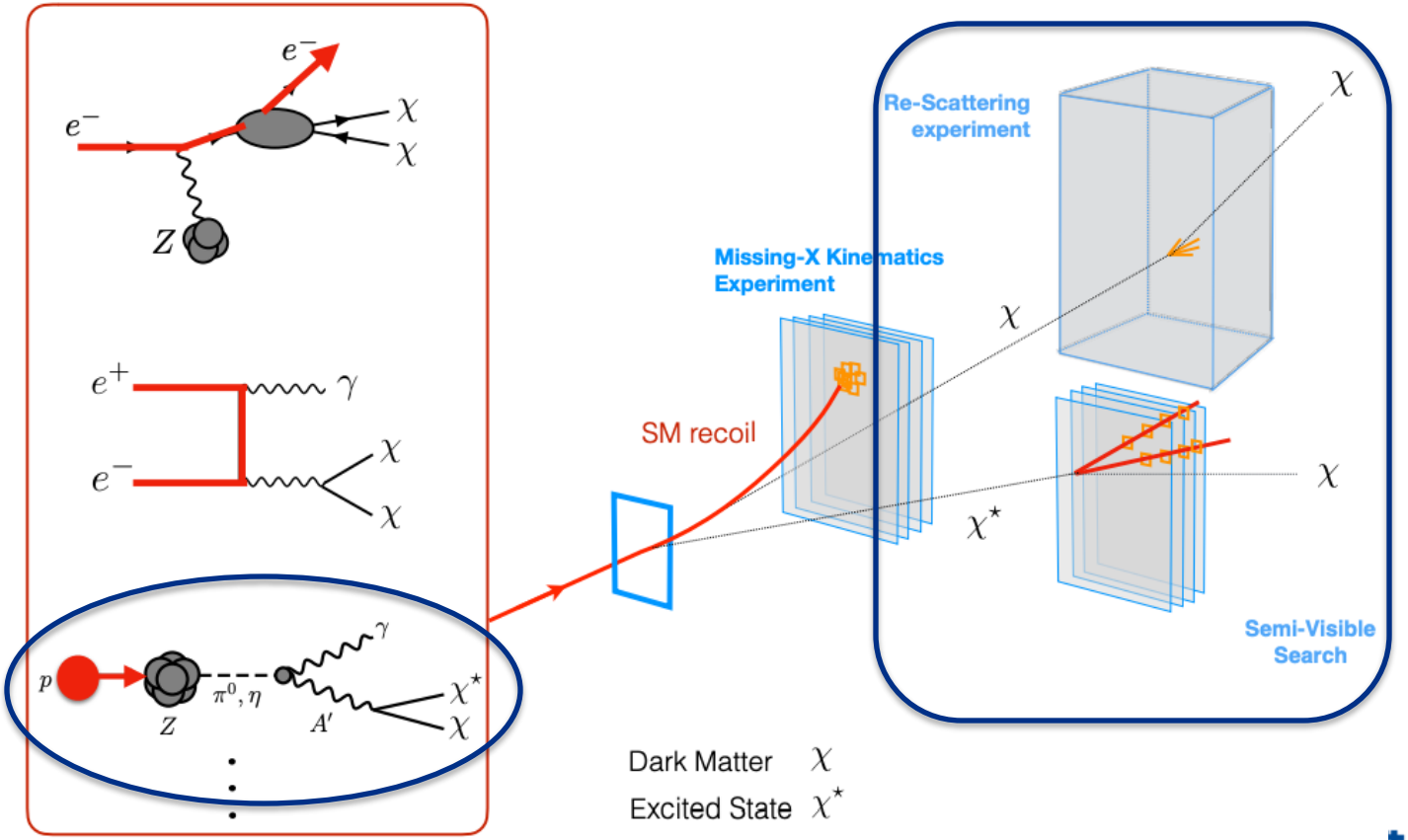
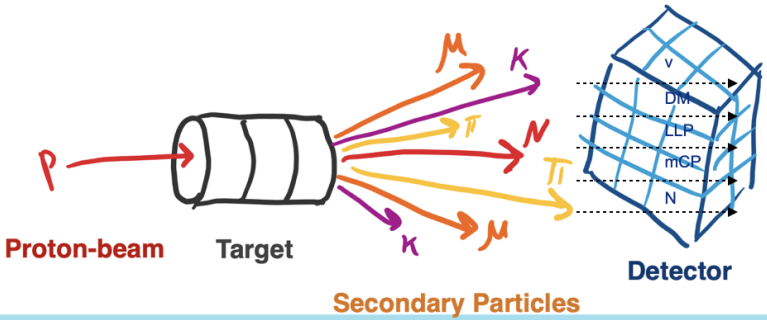
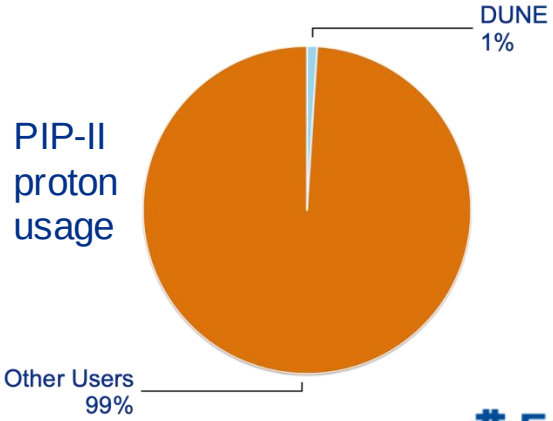


PIP-II Linac Under Construction at Fermilab

- Expected completion by the end of the decade
- Will provide among the highest-power ~GeV proton beams in the world
- Key high-level metrics
  - Capable of 2 mA @ 800 MeV (1.6 MW)[SEP]
  - DUNE only uses 1.1% of this beam to achieve its physics goals[SEP]
  - Proton beam is ~continuous wave
- Excellent opportunity for an accelerator-based dark sector program at Fermilab





Fermilab Facility for Dark Sector Discovery (F2D2)

- PIP-II beam dump facility to host dark sector “agile projects”

New Initiative: A Portfolio of Agile Projects to Search for Direct Evidence of New Particles

Exploring the Quantum Universe

the hidden sectors through the Vector and Heavy Neutral Lepton portals. At Fermilab, PIP-II is expected to make many more protons than needed for DUNE, and we anticipate proposals for experiments using the excess protons. These experiments should compete in the portfolio for agile projects (see Recommendation 3a and Section 6.2).

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

A. A. Aguilar-Arevalo[1], J. L. Barrow[2], C. Bhat[3], J. Bogenschuetz[4], C. Bonifazi[5,6], A. Bross[3], B. Cervantes[1], J. D'Olivo[1], A. De Roeck[7], B. Dutta[8], M. Eads[9], J. Eldred[3], J. Estrada[3], A. Fava[3], C. Fernandes Vilela[10], G. Fernandez Moroni[3], B. Flaugher[3], S. Gardiner[3], G. Gurung[4], P. Gutierrez[11], W. Y. Jang[4], K. J. Kelly[8], D. Kim[8], T. Kobilarcik[3], Z. Liu[2], K. F. Lyu[2], P. Machado[3], R. Mahapatra[8], M. Marjanovic[11], A. Mastbaum[12], V. Pandey[3], W. Pellico[3], S. Perez[13], J. Reichenbacher[14], D. Rodrigues[13,15], A. Sousa[16], B. Simons[3,9], D. Snowden-Ifft[17], C.- Y. Tan[3], M. Toups[3], N. Tran[3], Y.-T. Tsai[18], R. G. Van de Water[19], R. Vilar[20], S. Westerdale[21], J. Yu[4], J. Zettlemoyer[3], and R. Zwaska[3]

arXiv:2311.09915

- Focuses on 0.8-2 GeV proton beam dumps adjacent to PIP-II Linac
- Concept builds off a series of workshops laying out future physics opportunities in the PIP-II era, which also included proposals for experiments
  - OSCURA: Skipper CCD, low threshold
  - DAMSA: Very short baseline beam dump experiment
  - PIP2-BD: 100t LAr Scintillator
  - And other opportunities

ACE Science Workshop Report

Stefania Gori (ed.)[1], Nhan Tran (ed.)[2], Karri DiPetrillo[3], Bertrand Echenard[4], Jeffrey Eldred[2], Roni Harnik[2], Pedro Machado[2], Matthew Toups[2], Robert Bernstein[2], Innes Bigaran[2,6], Cari Cesarotti[7], Bhaskar Dutta[8], Christian Herwig[2], Yonatan Kahn[9], Sergo Jindariani[2], Ryan Plestid[4], Vladimir Shiltsev[10], Matthew Solt[5], Alexandre Sousa[11], Diktys Stratakis[2], Zahra Tabrizi[6], Anil Thapa[5], Jacob Zettlemoyer[2], and Jure Zupan[11]

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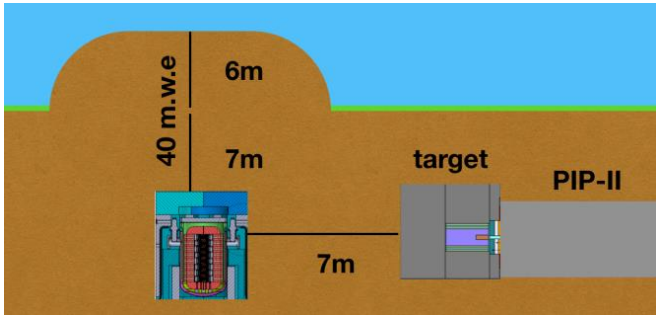
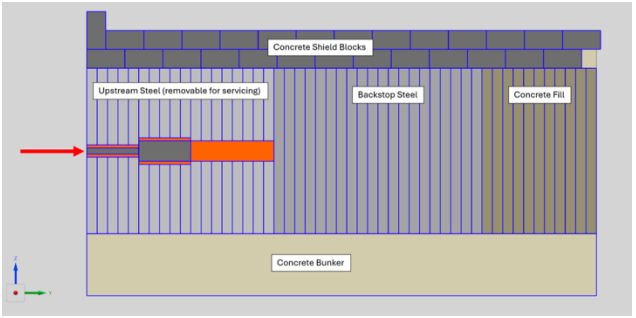
[11]University of Cincinnati, Cincinnati, OH 45221, USA

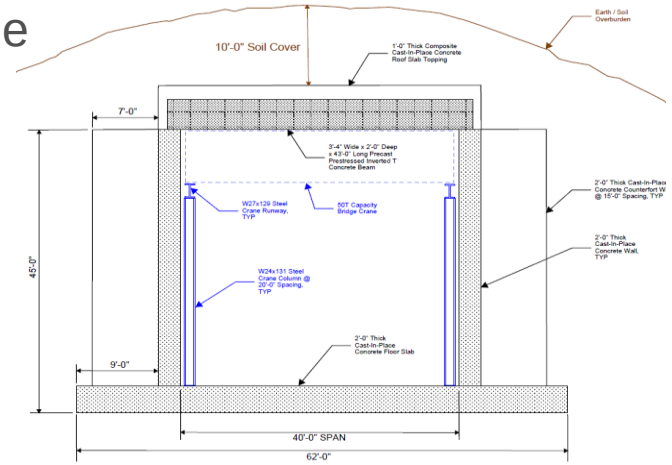
arXiv:2403.02422

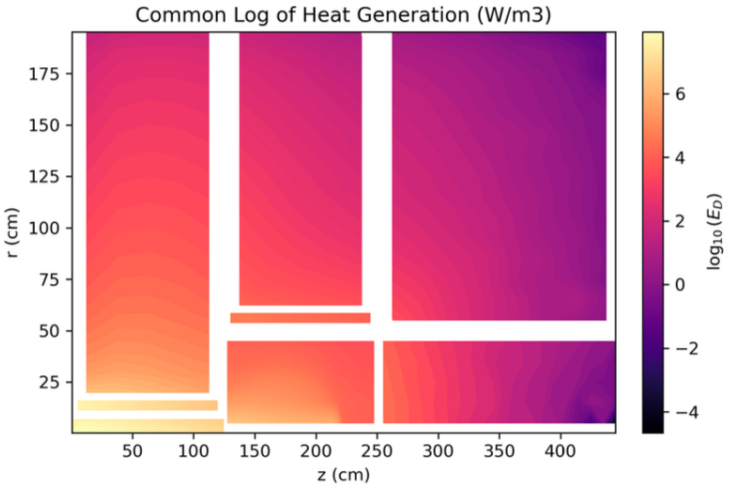
F2D2 Task Force at Fermilab

- Launched this year to study F2D2 feasibility
- Charged with developing a vision and implementation plan for F2D2 to the conceptual level
- Work ongoing following submission of preliminary report



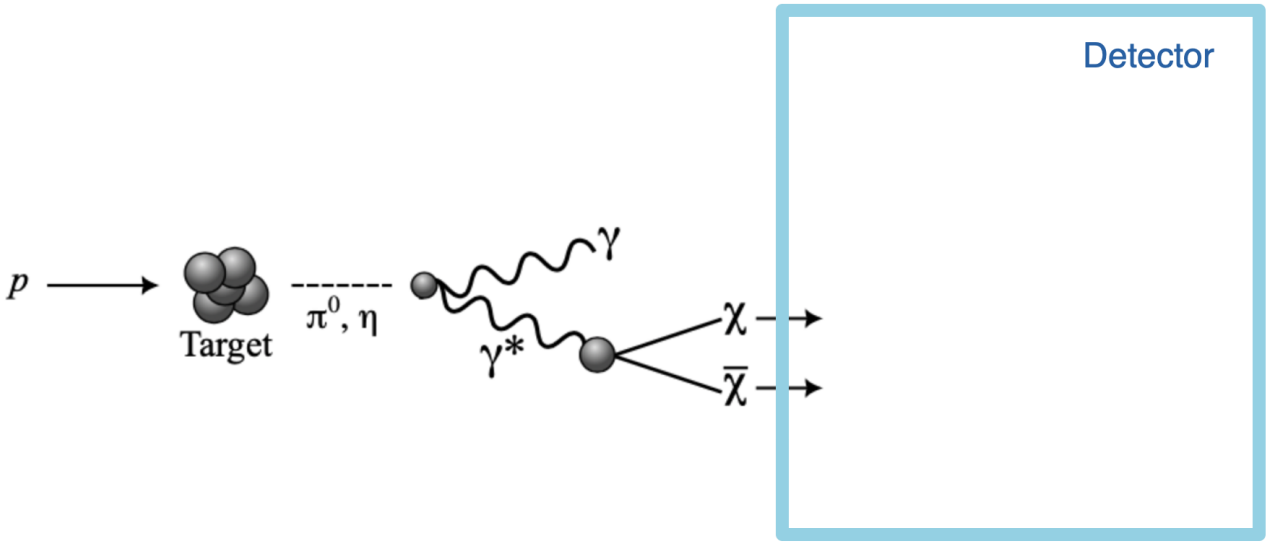






F2D2 Experimental Program

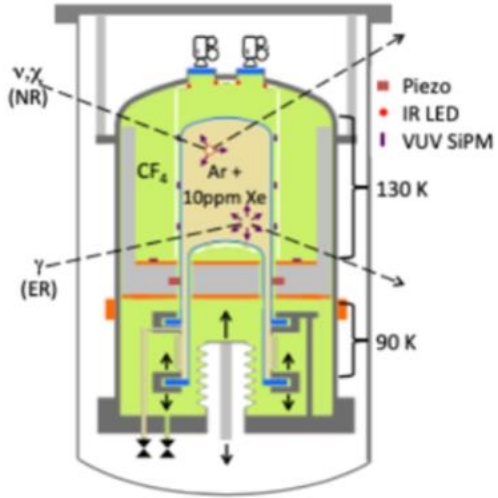
Millicharged Particles (mCPs)



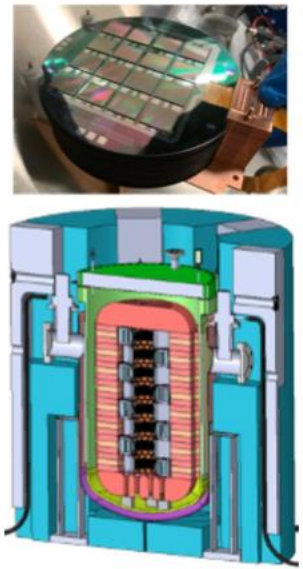
- Millicharged particles arise from extensions of the Standard Model that include a massless dark photon
- Millicharged particles are produced in high energy collisions at particle accelerators

Using DM Direct Detection Detectors for mCP Searches

- Significant progress on developing new detector technologies for direct detection dark matter searches
- Opportunity to leverage these technologies for dark sector searches at high-intensity beams such as millicharged particles



Scintillating Bubble Chamber (SBC)

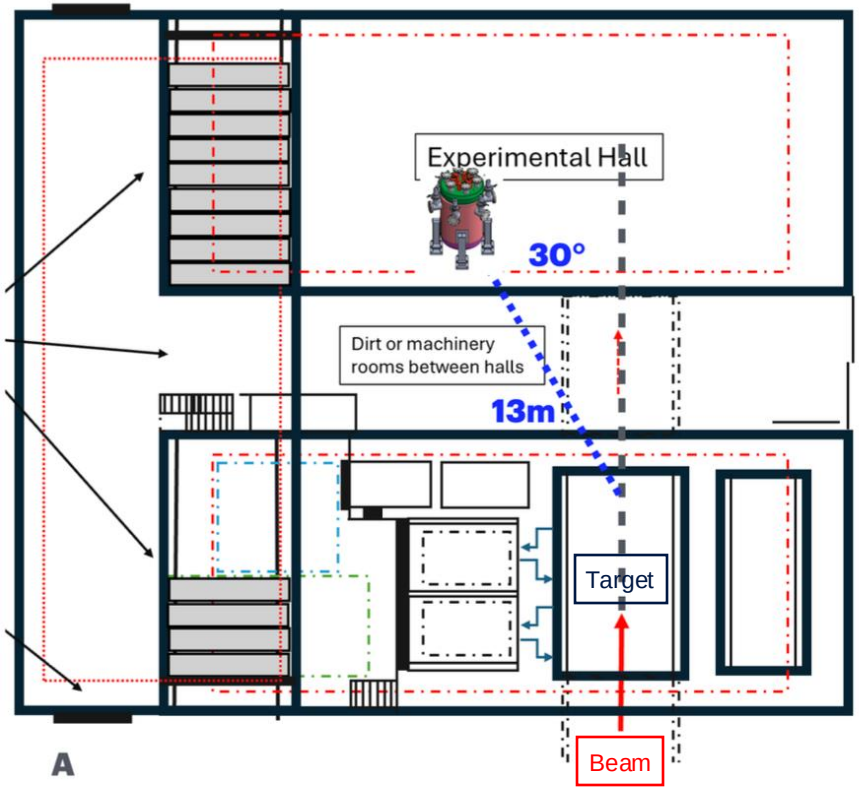


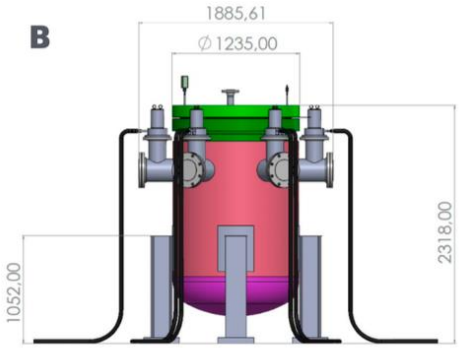
Silicon skipper-CCD detectors

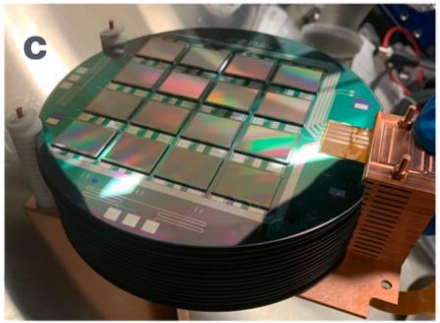
Cryogenic micro-calorimeters

Fermilab

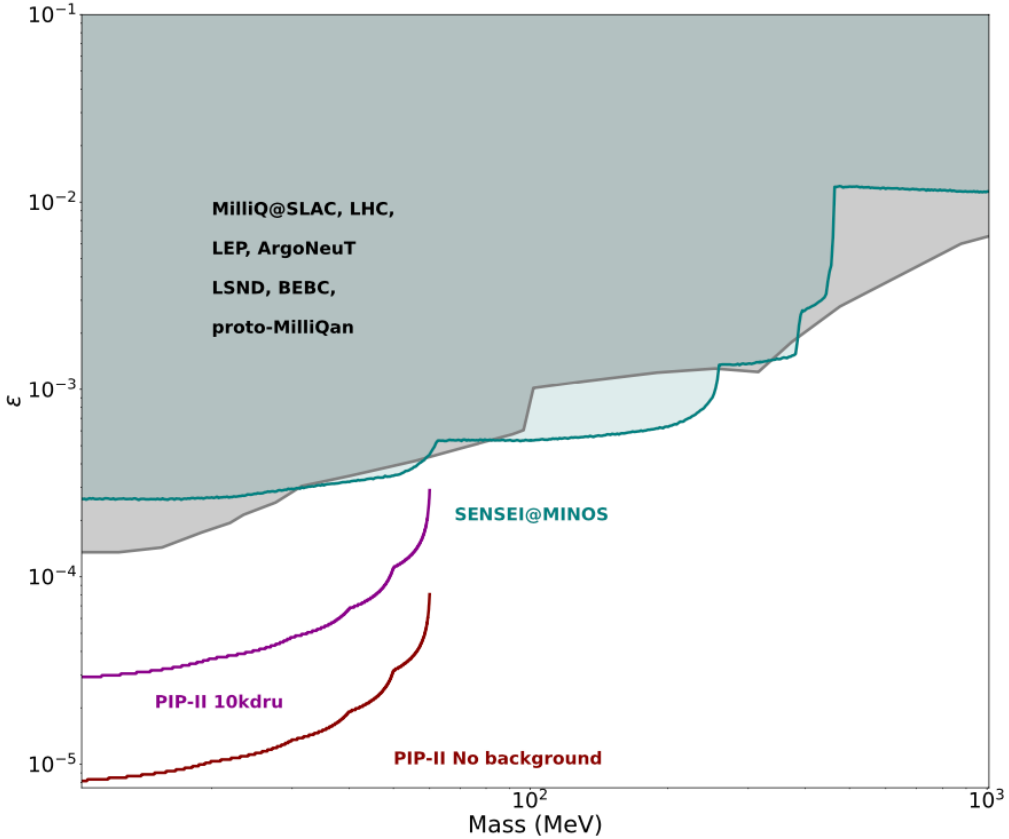
Kg-scale Skipper-CCD Off-axis Experiment at F2D2



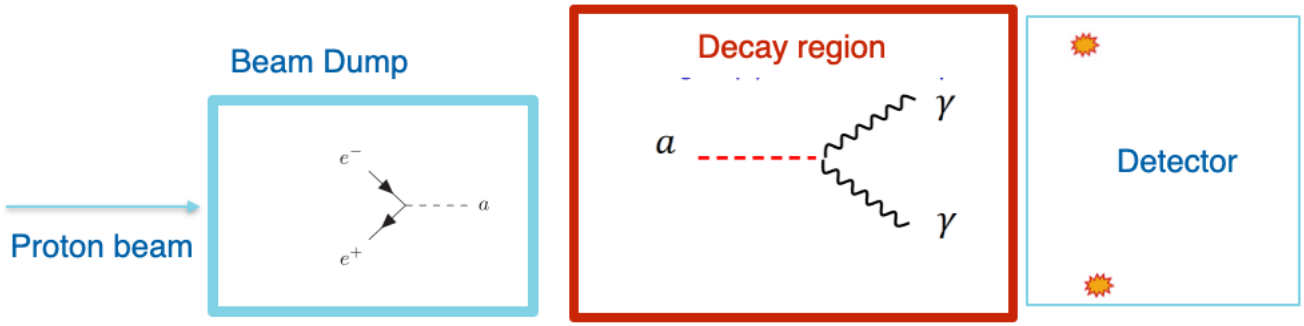




mCP Sensitivity with 1kg-year total exposure



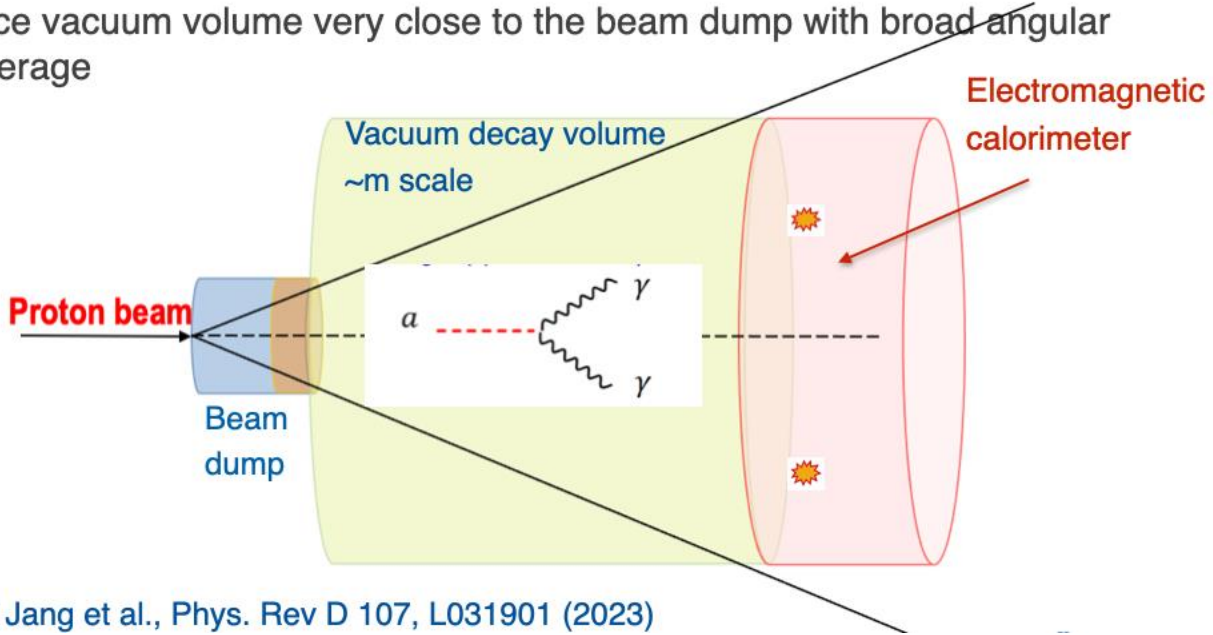
Axion-like Particles



- Some axions are predicted dark sector particles in models that extend the Standard Model
- Axion like particles (ALPs) also produced through copious EM interactions that arise from beam dump collisions
- ALPs are a viable dark matter candidate related to unanswered questions around the strong nuclear force

DAMSA

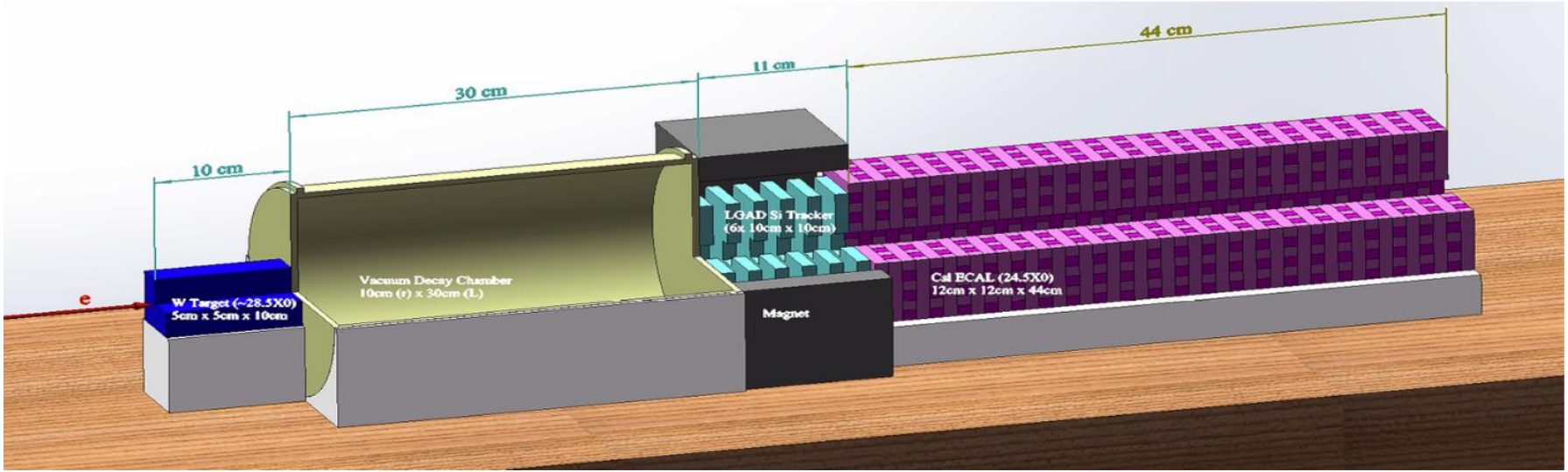
- Dump-produced Aboriginal Matter Searches at an Accelerator (DAMSA)
- Search for axion like particles decaying to two photons, along with possibilities for dark photon decay to e+/e- searches
- Place vacuum volume very close to the beam dump with broad angular coverage



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

Fermilab

DAMSA Experiment Design



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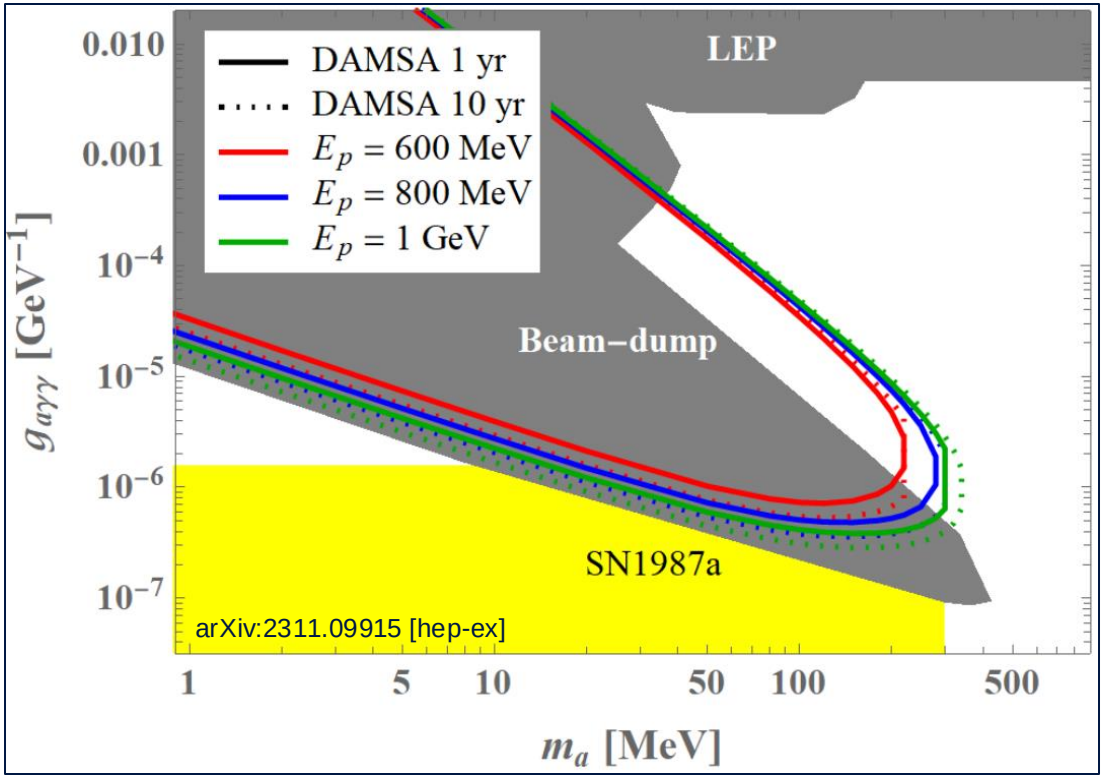
DAMSA ALP Sensitivity



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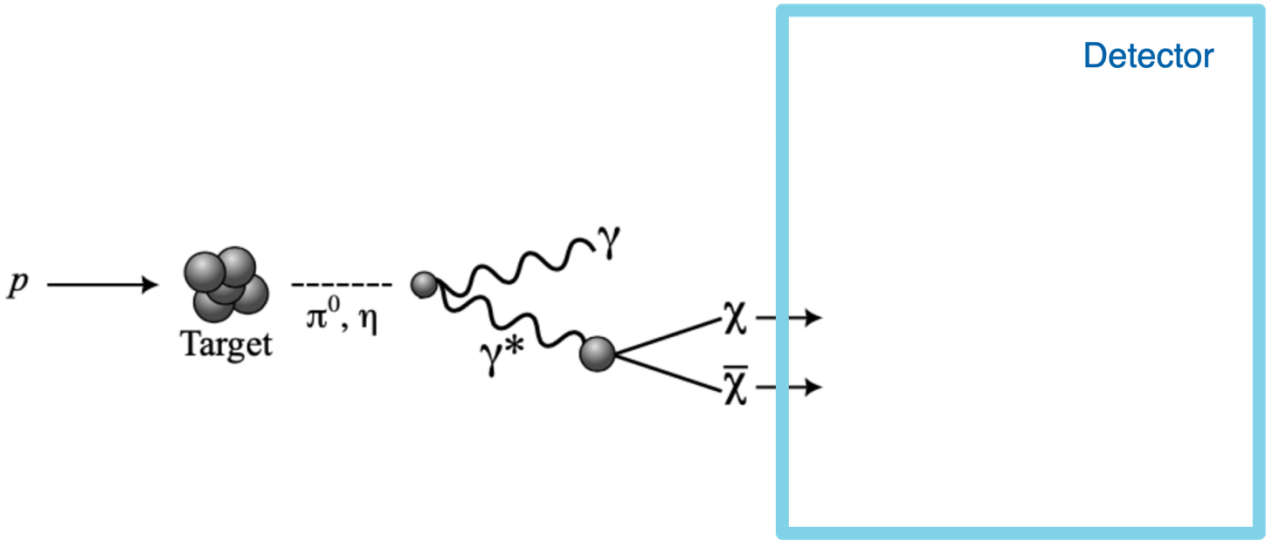
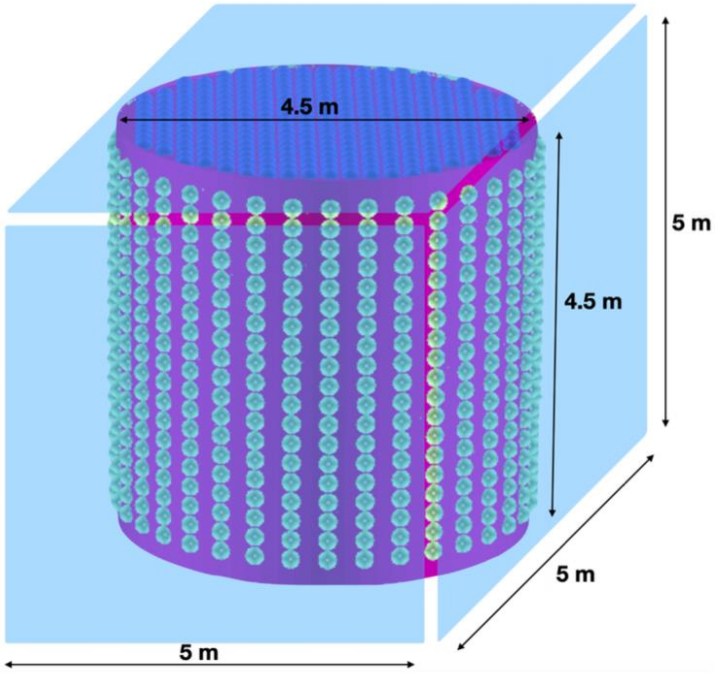
Dark Matter (DM)



- Inelastic DM
  - DM up-scatters to heavier DM state, which then decays in detector
- DM-nucleus inelastic scattering
  - DM excites nucleus, which then decays in detector

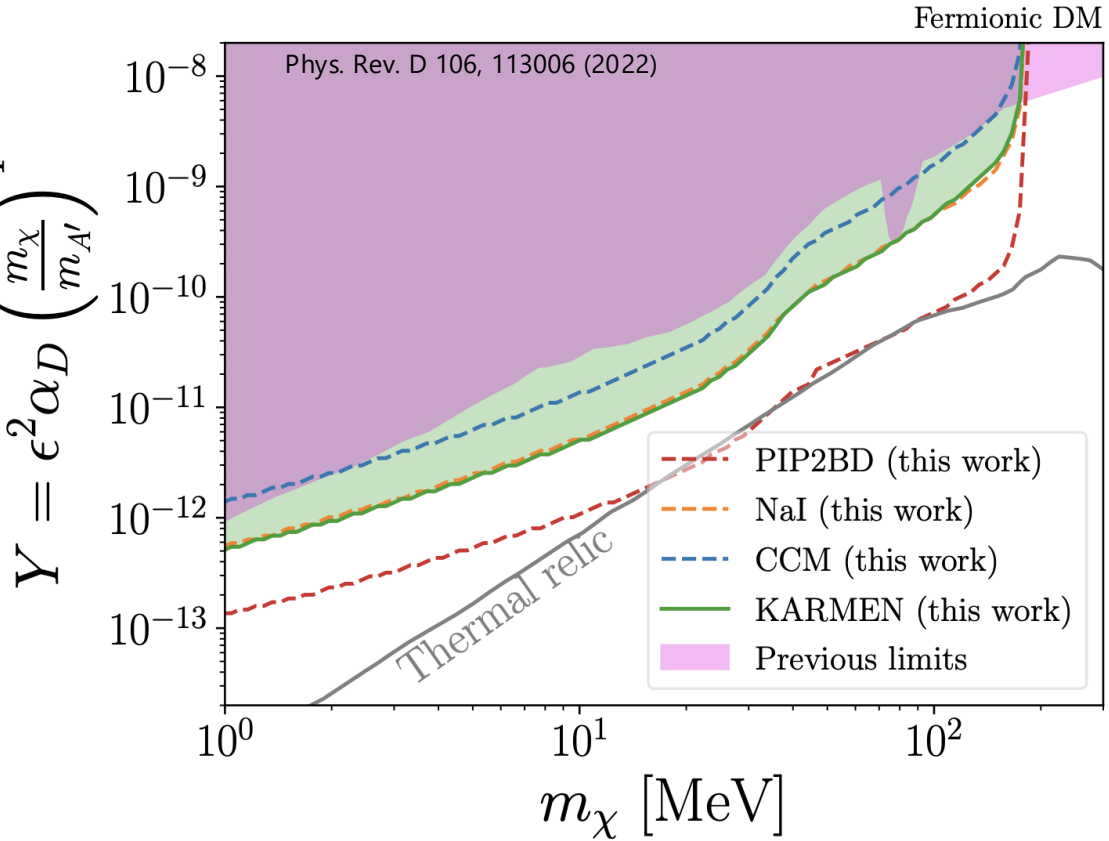
PIP2-BD Liquid Argon Scintillation Detector

- 100 tonne liquid argon (LAr) scintillation detector instrumented with 1200 photomultiplier tubes (PMTs)
- Design similar to Coherent CAPTAIN-Mills
- Multi-purpose detector can search for keV-scale or MeV-scale dark sector signatures



arXiv:2203.08079 [hep-ex]

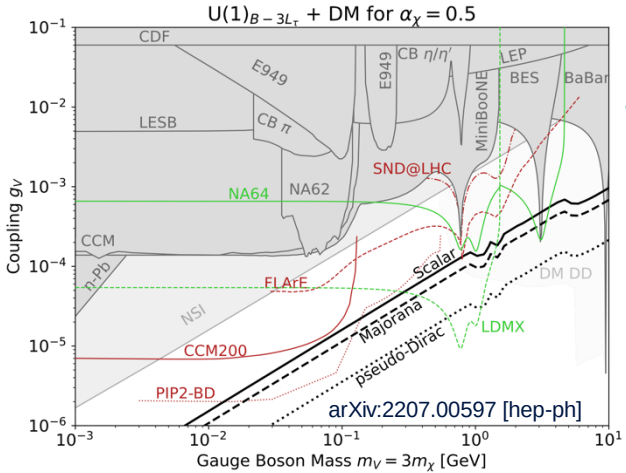
PIP2-BD Sensitivity to Thermal Relic DM (2 GeV proton beam)

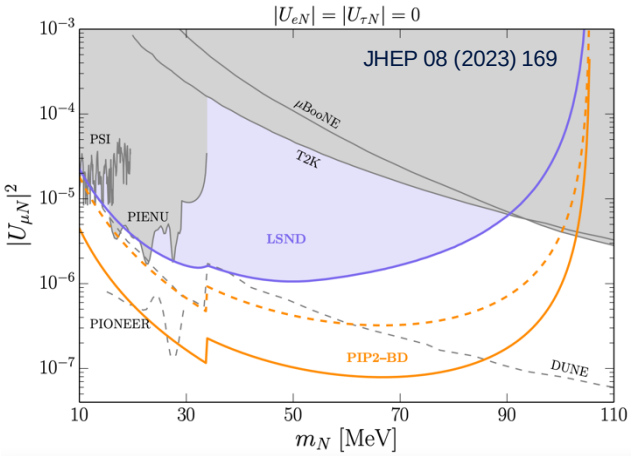


Fermilab

Physics Opportunities at F2D2

- Light dark matter (LDM) / dark sector searches
  - Decay and/or scattering signatures
- Light sterile neutrino searches
  - Both appearance and disappearance
- Coherent elastic neutrino-nucleus scattering
  - Provides new way to search for LDM and sterile neutrinos
- Searches for Non-standard interactions (NSIs), tests of the Standard Model
- Neutrino Cross Section Measurements





Summary

- The PIP-II Linac is coming online at Fermilab at the end of the decade and is capable of driving among the highest-power ~GeV proton beams in the world
  - Can simultaneously support multi-MW high energy beams for LBNF/DUNE and intense low (~GeV) energy protons beam
- Excellent opportunity for a proton beam dump based dark sector (and neutrino) physics program
- Fermilab task force launched to study the feasibility of a Fermilab Facility for Dark Sector Discovery (F2D2) to host future agile projects aligned with P5 vision
  - Key feature of such a facility at Fermilab is that it can be designed for and dedicated to high energy physics
- Exciting prospect for discovering accelerator-produced light dark matter over the coming decade!

Preliminary Report of the Fermilab Facility for Dark Sector Discovery (F2D2) Task Force

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Thank you for your attention!