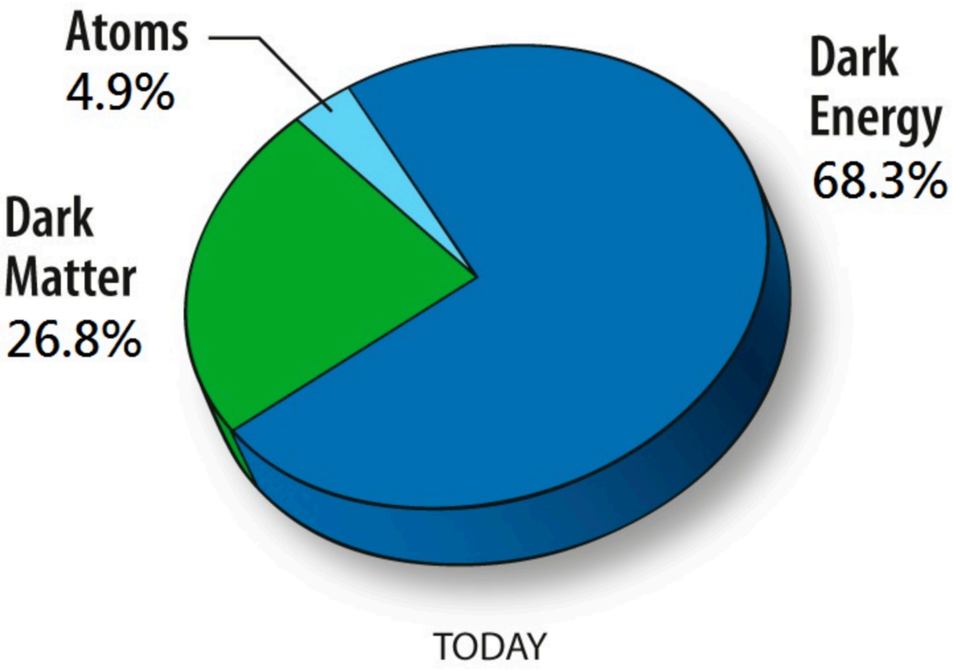
New Proton Beam Dump Experiments at Fermilab

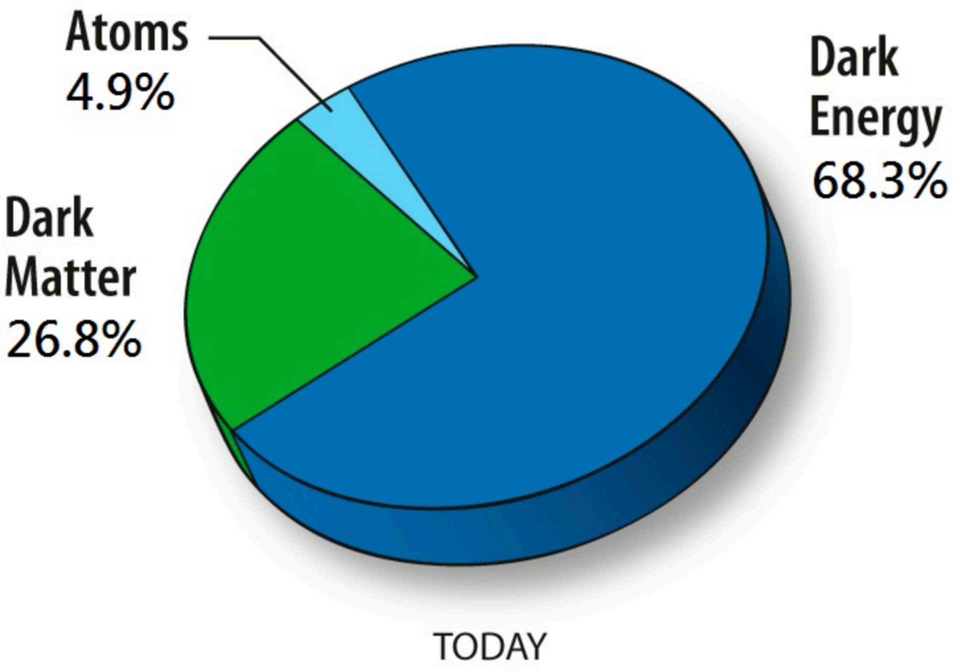
Matt Toups, Fermilab

Accelerators Capabilities Enhancement Workshop
Tues 31 Jan 2023

Mass/Energy Content of the Universe

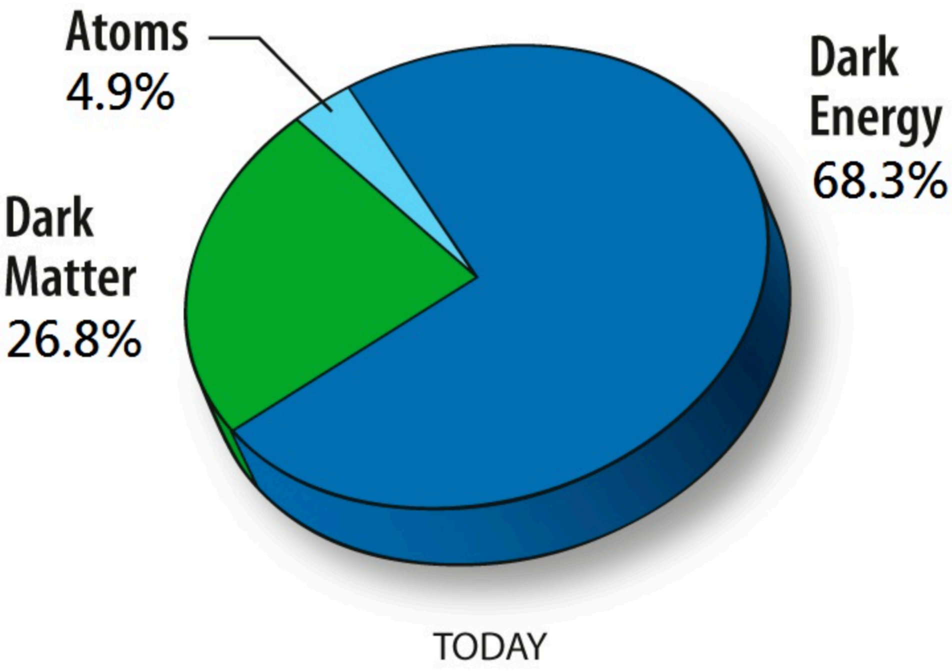


Mass/Energy Content of the Universe



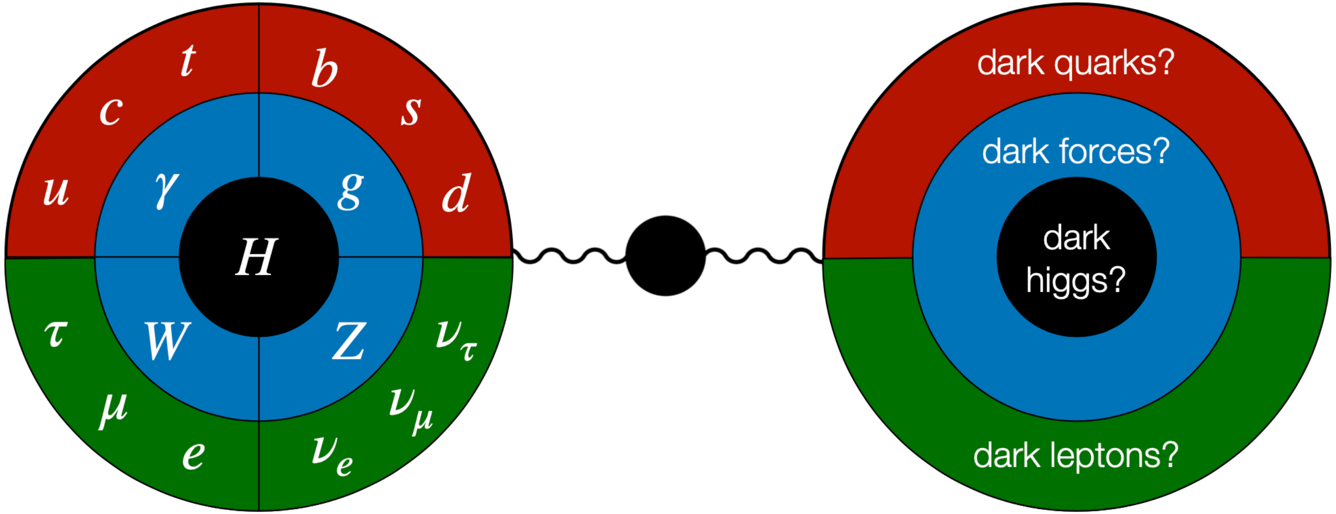
"WIMP miracle": thermal production of a new weakly-coupled particle with a mass in the 100 GeV range gives the correct relic abundance

Mass/Energy Content of the Universe



No Sign of WIMPs so far. **Where is the New Physics?**

Existence of Dark Matter Motivates a Dark Sector



Simple paradigm opens the door to the possibility that BSM Physics exists below the EW scale

Extends "WIMP miracle" to lower mass scales

Dark Sectors

- Focus on energy scales relevant for Fermilab accelerator facilities (up to ~GeV)
- New physics should be neutral ("dark") under SM forces (EM, weak, strong)
- Connects to SM through finite list of "portal" operators, enabling systematic exploration

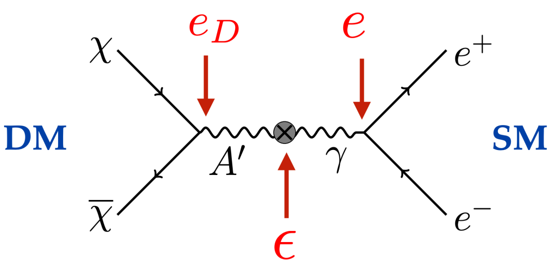
$B_{\mu\nu}$	x	$\epsilon/2\, F'^{\mu\nu}$	Vector portal
$\lvert h\rvert^2$	x	$\mu S + \lambda\lvert\phi\rvert^2$	Higgs portal
hL	x	$y_N N$	Neutrino portal

- Also of interest: axion portal, gauging SM global symmetries, millicharged particles

Dark Sectors - Light Dark Matter

- Minimal models can explain the thermal relic abundance of dark matter and predict sub-GeV dark matter that can be **produced** and **detected** at accelerator-based neutrino facilities

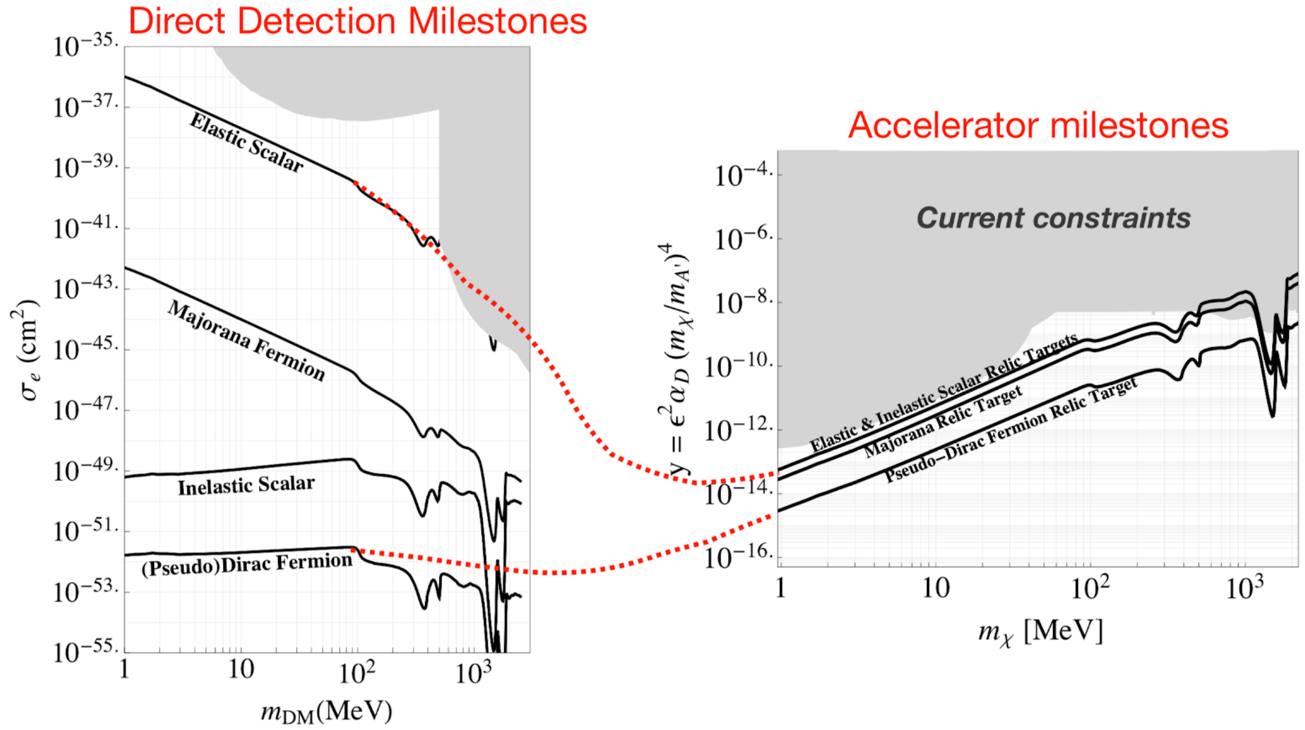
- Representative model: vector portal kinetic mixing with $m_{A'} > m_\chi$



$$\sigma v \propto \epsilon^2 \alpha_D \frac{m_\chi^2}{m_{A'}^4} \equiv \frac{y}{m_\chi^2}$$

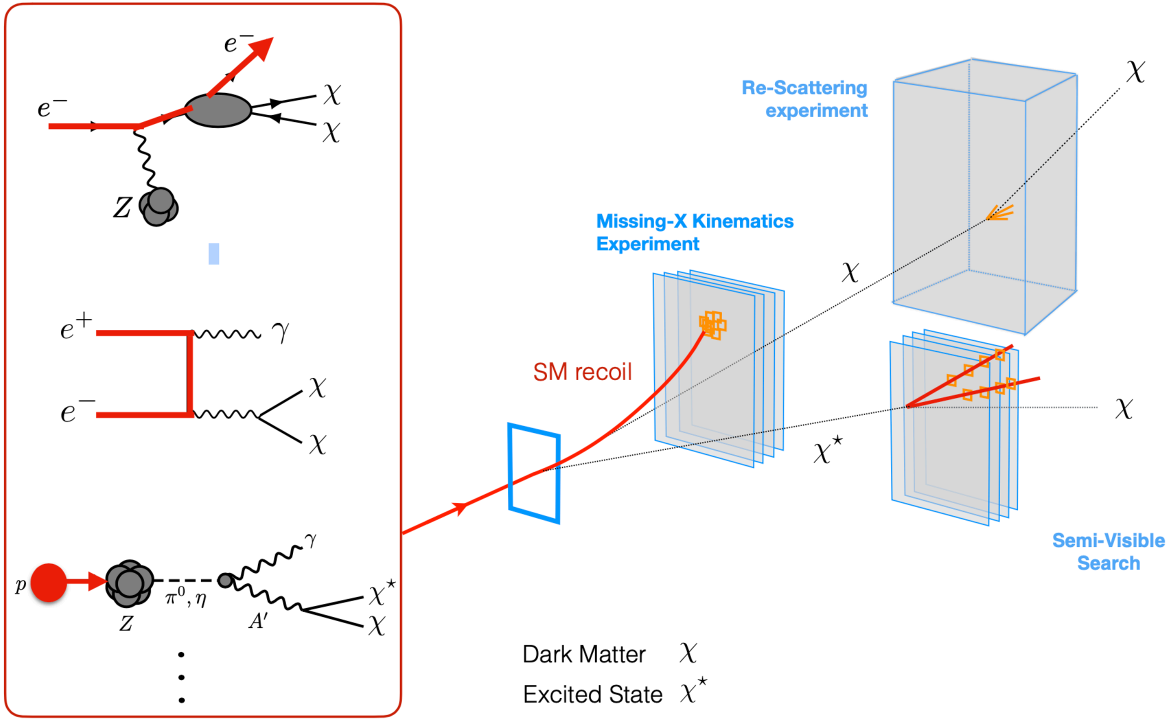
- Minimum SM coupling ϵ required for thermal freeze out

Dark Sectors - Light Dark Matter



Wide class of models that can explain the cosmological dark matter abundance accessible to GeV-scale accelerator-based searches

Dark Sector Searches at Accelerators



Intensity frontier experiments provide a powerful probe of light, weakly coupled dark sectors

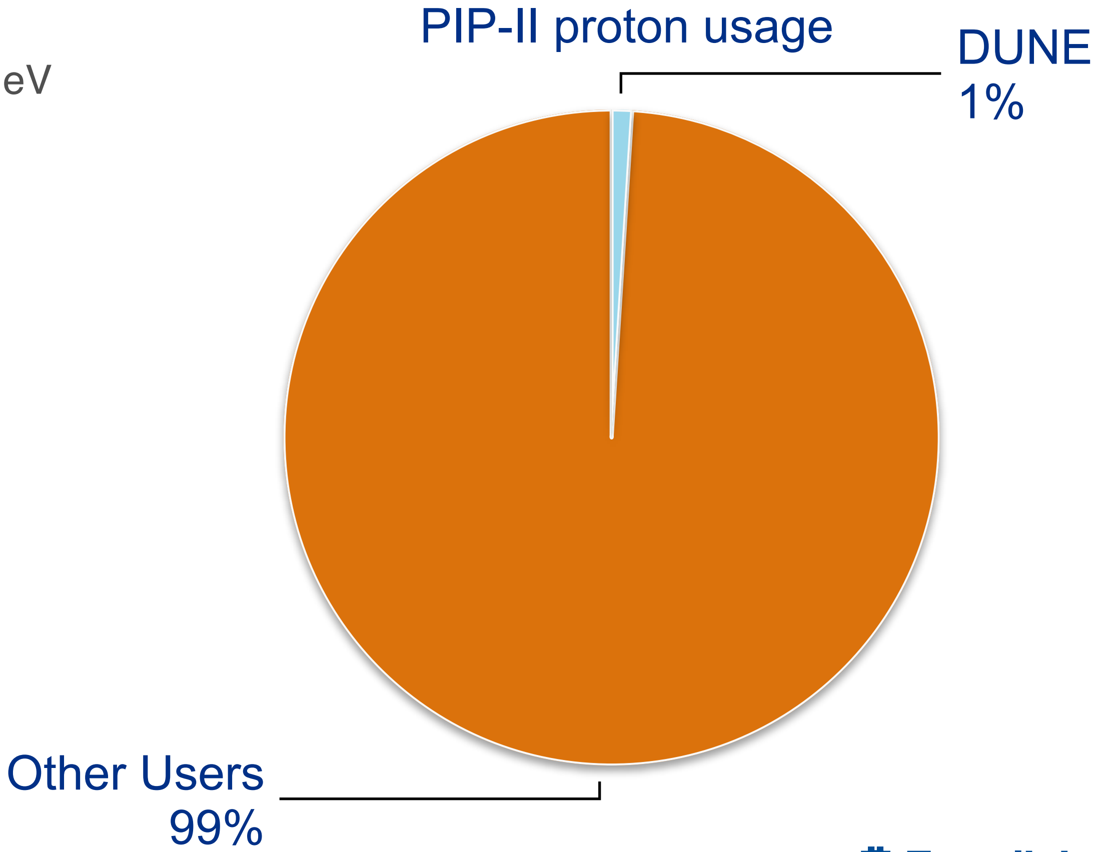
PIP-II Upgrade of Fermilab Accelerator Complex

PIP-II Linac

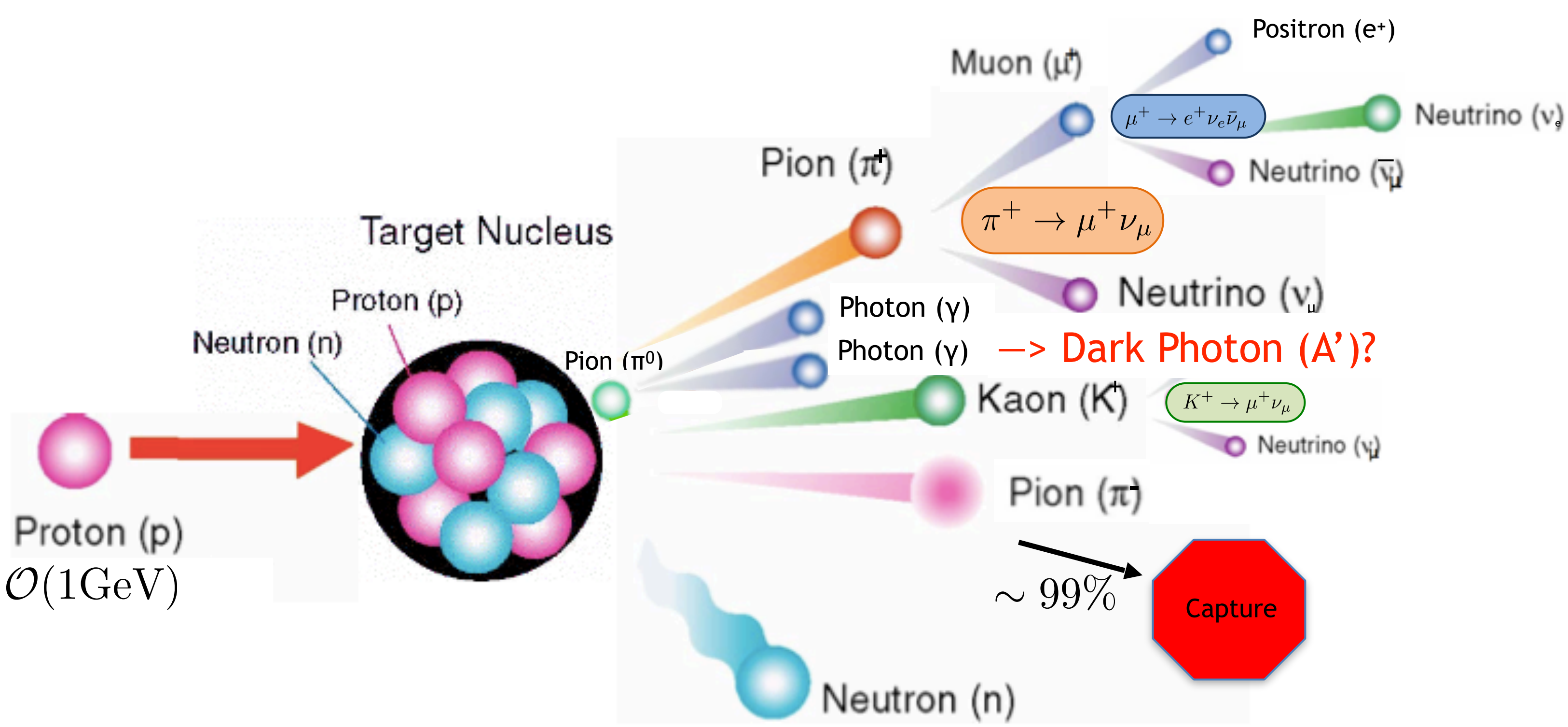
Will provide among the highest-power ~GeV proton beams in the world

Key high-level metrics for SC Linac:

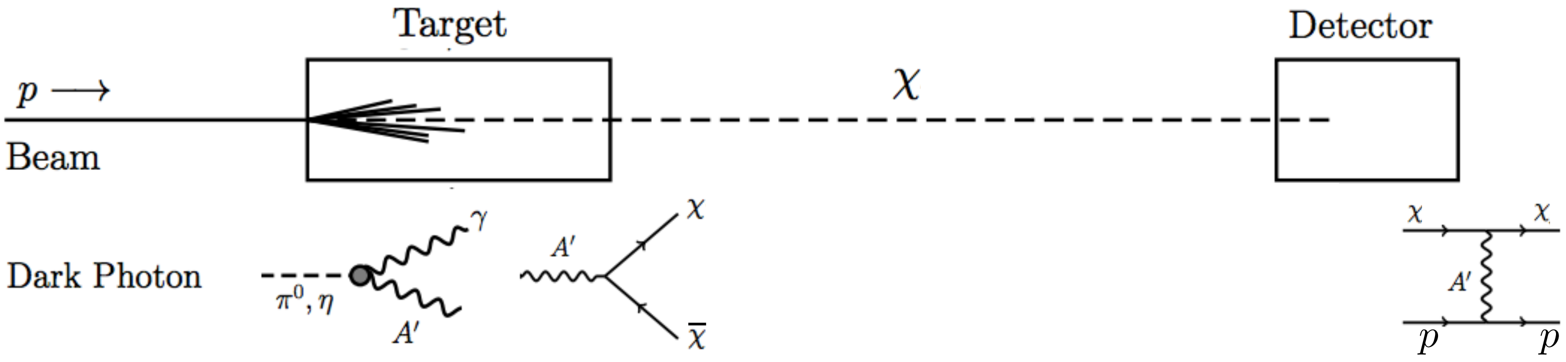
- Capable of 2 mA @ 800 MeV (1.6 MW)
- DUNE only uses 1.1% of this beam to achieve its physics goals
- Proton beam is ~continuous wave



Dark Sector Physics at GeV Proton Beam Dumps



Proton Beam Dumps as Sources of Light Dark Matter: Challenges

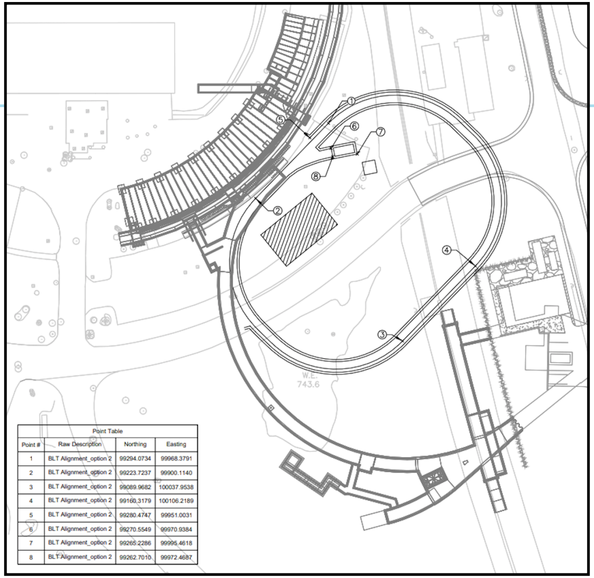


- Low energy nuclear recoil signal —> need low, O(1-10 keVnr) detector thresholds
- Rare signals —> need large beam exposures
- Steady state backgrounds —> need pulsed beams with low, O(10^{-6}-10^{-4}) duty factor
- Beam-related backgrounds —> adequate shielding (neutrons)
  —> beam timing (neutrons, neutrinos)

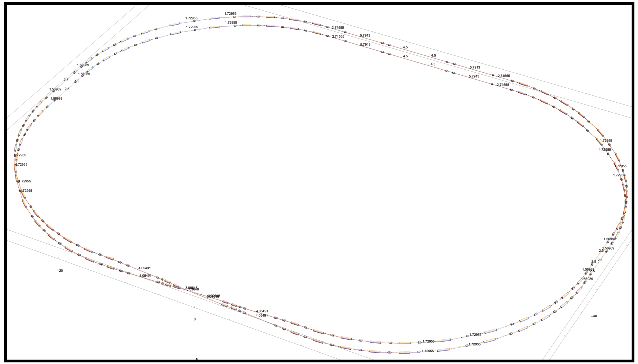
PIP-II Accumulator Ring (PAR)

- Forward-looking design of the PIP-II linac includes provisions that facilitate future upgrades, including:
    - CW multi-user mode of operation
    - Increase in beam energy to 1 GeV and beyond
    - Stub in the beam transfer line to the Booster to provide beam to other users

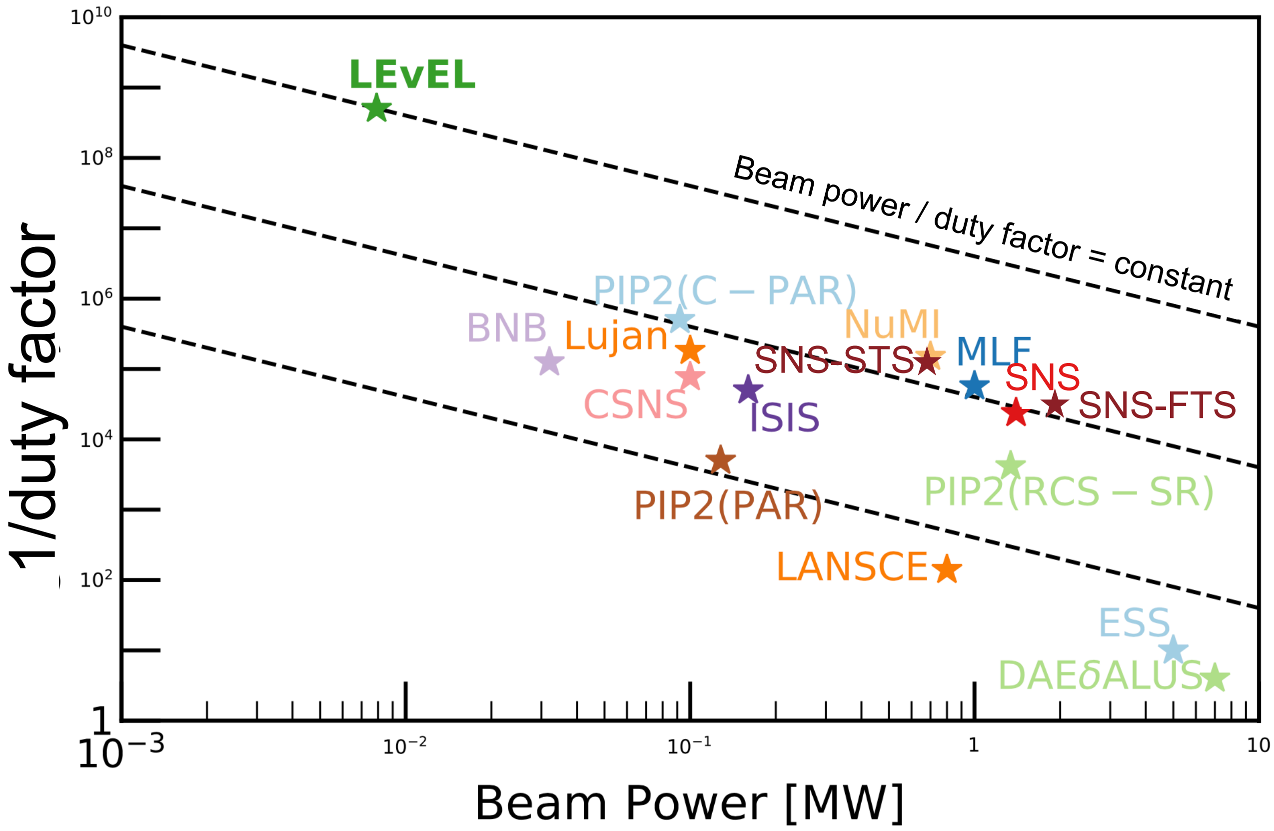
- Co-location of an accumulator ring for modest cost could be realized within the decade
    - Benefits for DUNE
    - Provides a dark sector program on Day 1 of PIP-II operation



Point Table			
Point #	Raw Description	Northing	Easting
1	BLT Alignment_option 2	99294.0734	99968.3791
2	BLT Alignment_option 2	99223.7237	99900.1140
3	BLT Alignment_option 2	99089.9682	100037.9538
4	BLT Alignment_option 2	99160.3179	100106.2189
5	BLT Alignment_option 2	99280.4747	99951.0031
6	BLT Alignment_option 2	99270.5549	99970.9384
7	BLT Alignment_option 2	99265.2286	99995.4618
8	BLT Alignment_option 2	99262.7010	99972.4687



Proton Beam Dump Accelerator Facilities



PIP2-BD: PIP II Beam Dump Experiment

PIP2-BD: GeV Proton Beam Dump at Fermilab's PIP-II Linac

M. Toups,* S.J. Brice, Jeff Eldred, Roni Harnik, Kevin J. Kelly, Tom Kobilarcik, Gordan Krnjaic, Pedro A. N. Machado, V. Pandey, Z. Pavlovic, William Pellico, Jacob Zettlemoyer, and Bob Zwaska
Fermi National Accelerator Laboratory, Batavia, IL 60510, USA

R.G. Van de Water,* Patrick deNiverville, Bill Louis, and R. T. Thornton
Los Alamos National Laboratory, Los Alamos, NM 87545, USA

Brian Batell
University of Pittsburgh, Pittsburgh, PA 15260, USA

Bhaskar Dutta, Aparajitha Karthikeyan, Doojin Kim, Nityasa Mishra, Adrian Thompson
Mitchell Institute for Fundamental Physics and Astronomy,
Department of Physics and Astronomy, Texas A&M University, College Station, TX 77843, USA

B. R. Littlejohn and P. Snopok
Illinois Institute of Technology, Chicago, IL 60616, USA

Michael Shaevitz
Columbia University, New York, NY 10027, USA

Rex Tayloe
Indiana University, Bloomington, IN 47405, USA

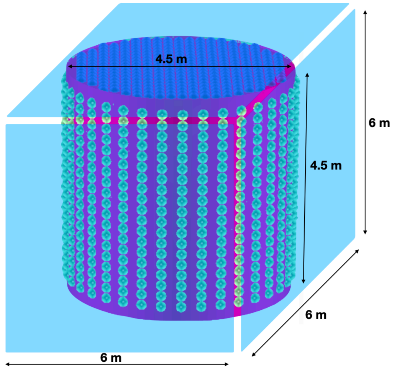
Timothy Hapitas and Douglas Tuckler
Department of Physics, Carleton University, Ottawa, Ontario K1S 5B6, Canada

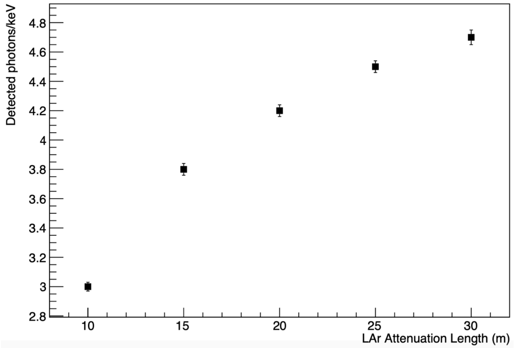
Jaehoon Yu
Department of Physics, University of Texas, Arlington, TX 76019, USA

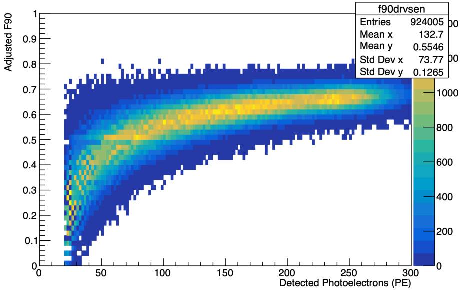
arXiv:2203.08079 [hep-ex]

PIP2-BD

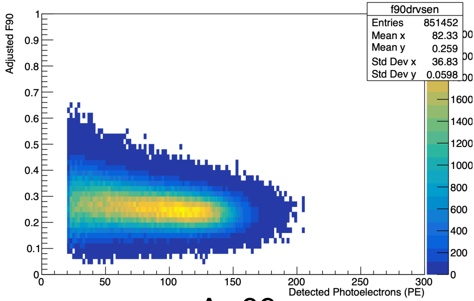
- Single-phase, 100 ton scintillation only liquid argon detector
  - Same technology as CENNS-10, Coherent CAPTAIN-Mills (CCM)
- Cylindrical volume with 1294 TPB-coated PMTs and TPB-coated reflectors on sides and end caps
- Geant4-based simulation of detector response indicate a 20 keVnr threshold is achievable
- Instrumental effects (PMT noise) and Ar-39 also taken into account







CEvNS recoils

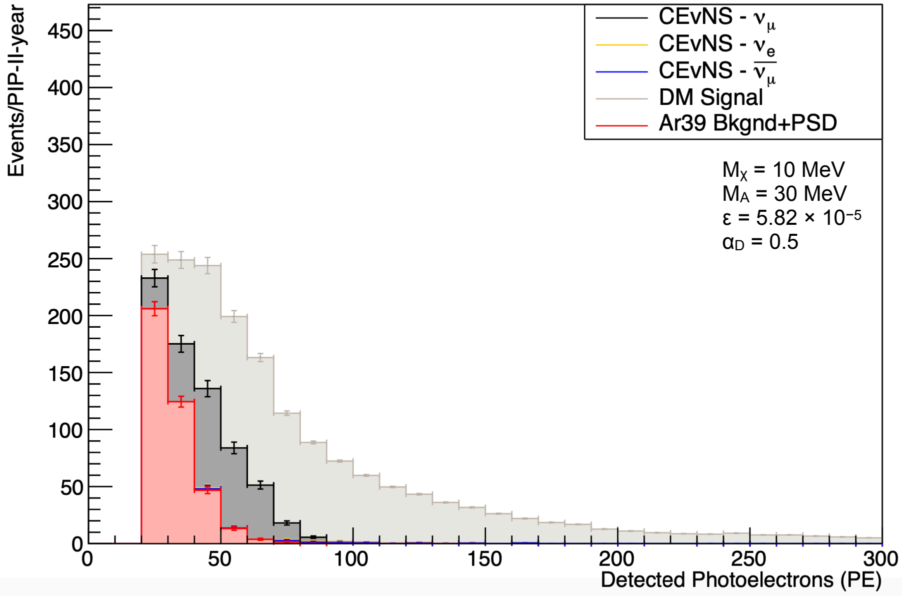


Ar-39

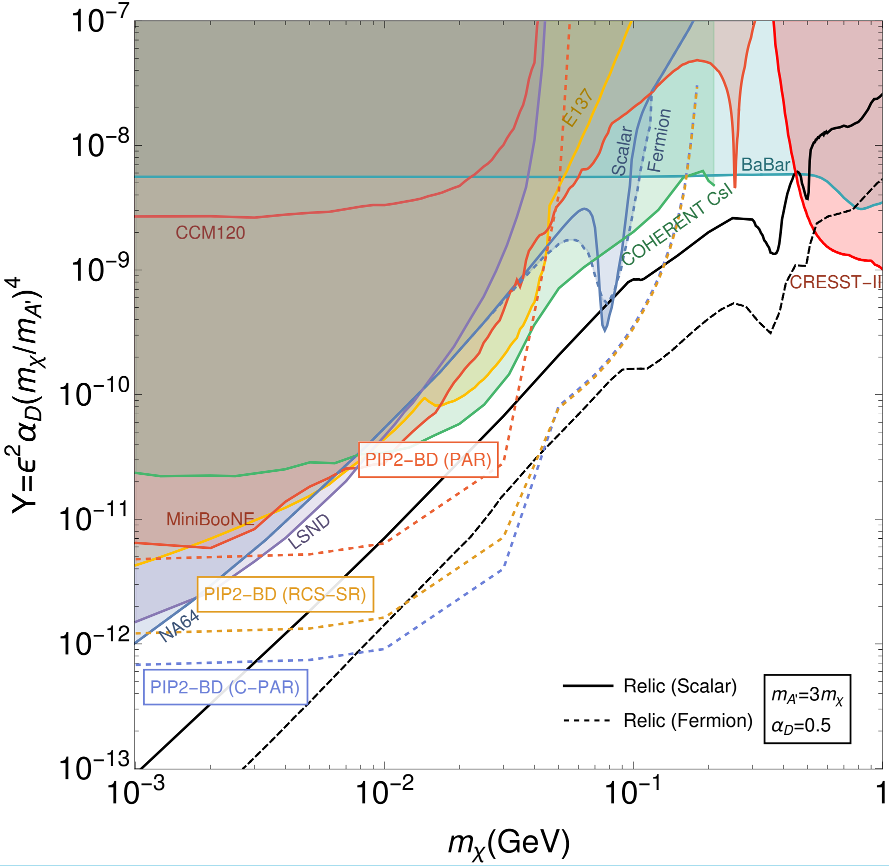
Vector Portal Kinetic Mixing Light Dark Matter Search

- PIP2-BD located 18 m downstream of the dump, on axis
- Geant4-based simulation of proton beam dump used to generate neutrino backgrounds and light meson distributions
- BdNMC used to generate dark matter nuclear recoils in the detector, then fed into the full detector simulation
- Rate-only sensitivity calculated using:

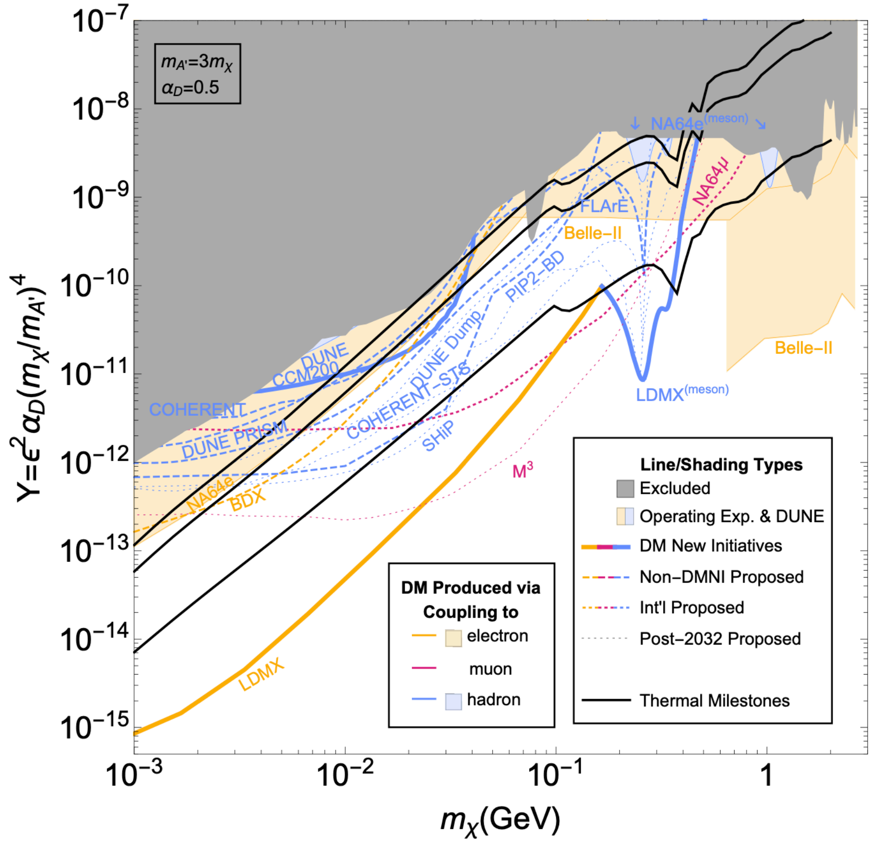
$$\Delta\chi^2 = \frac{N_{\rm sig}^2}{N_{\rm bkg} + \sigma^2 N_{\rm CEvNS}^2}$$



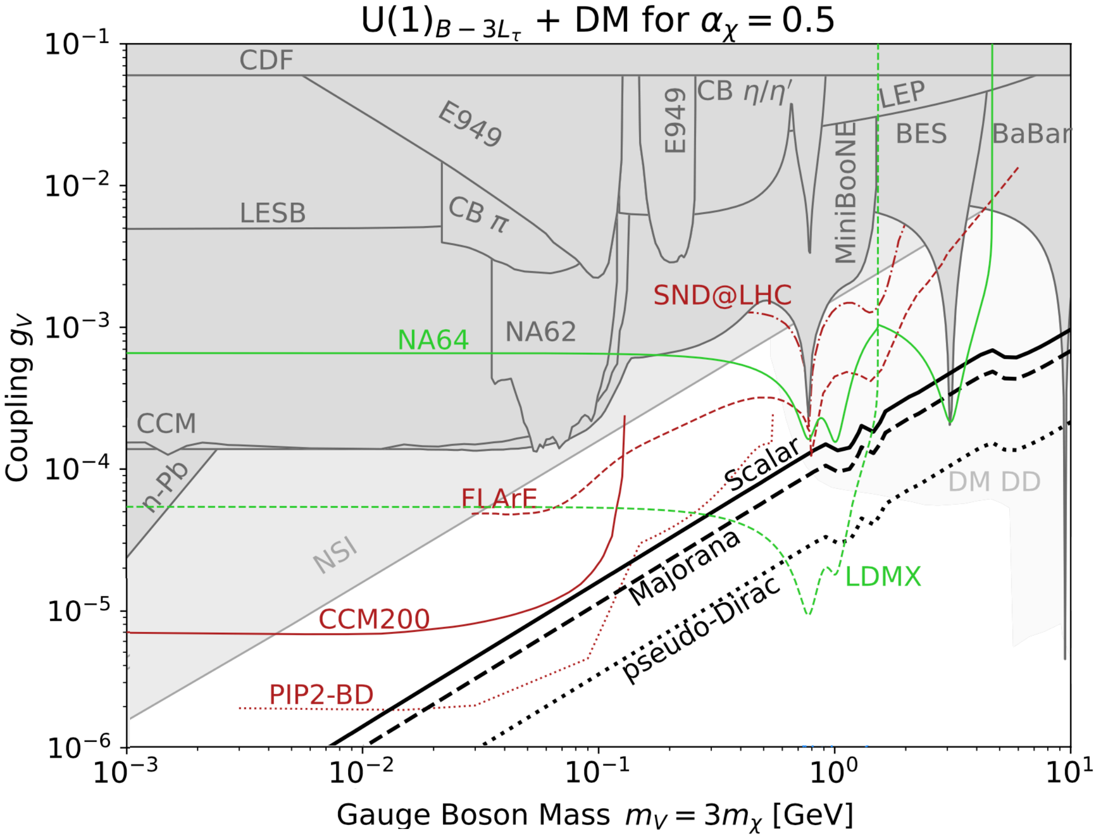
Vector Portal Kinetic Mixing 90% C.L. Sensitivities



Vector Portal Kinetic Mixing 90% C.L. Sensitivities

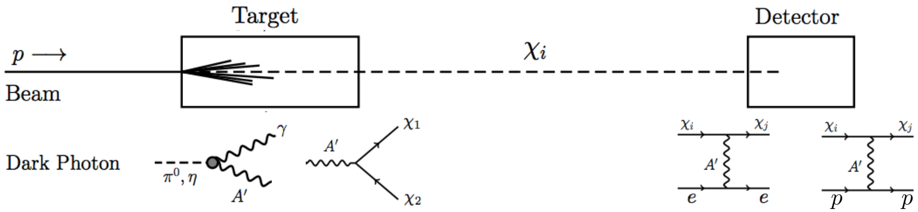


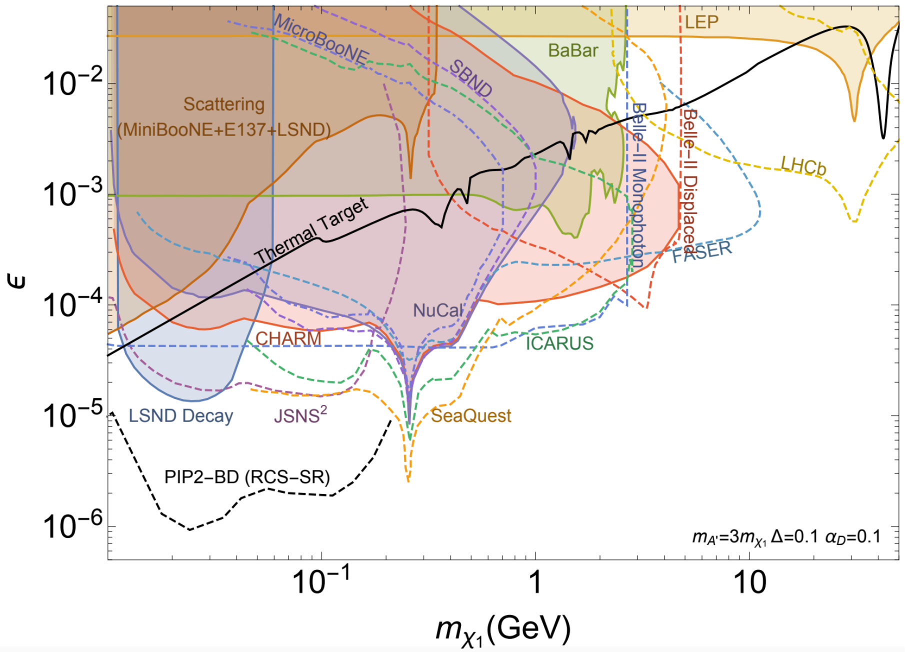
Hadrophilic Dark Matter 90% C.L. Sensitivities



Inelastic Dark Matter 95% C.L. Sensitivities

- Adding an additional dark matter species with a small mass splitting brings in a richer set of phenomenology
- Detection channels now include both scattering and decay signatures



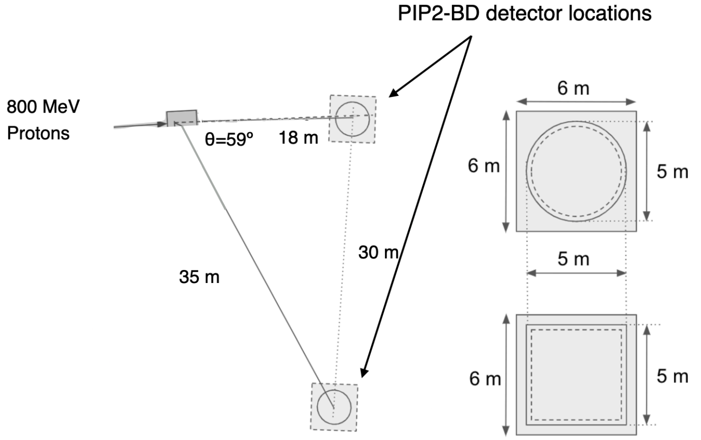


Sterile Neutrinos

- CEvNS-based search provides smoking-gun evidence for sterile neutrinos
  - Three flavors of neutrinos, with the mono-energetic ν_μ separated in time from the ν_e and anti-ν_μ

$$\sin^2 2\theta_{\mu S} = 4U_{\mu 4}^2 U_{S4}^2 = 4U_{\mu 4}^2\left(1 - U_{e4}^2 - U_{\mu 4}^2\right)$$
$$\sin^2 2\theta_{eS} = 4U_{e4}^2 U_{S4}^2 = 4U_{\mu 4}^2\left(1 - U_{e4}^2 - U_{\mu 4}^2\right)$$

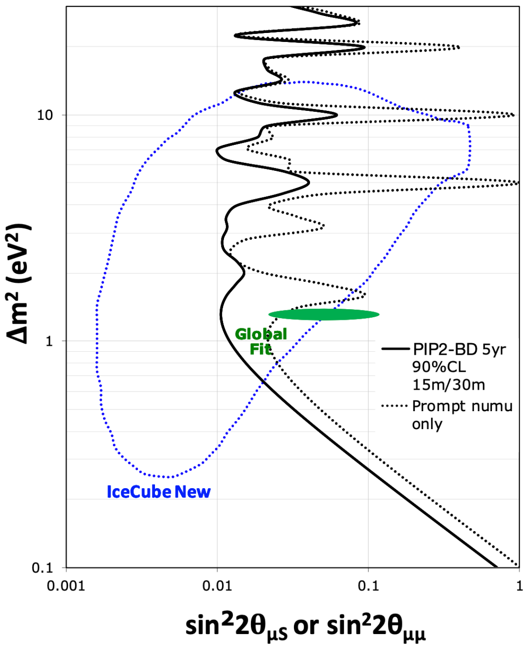
- Leverage advantages of dedicated HEP beam dump facility
  - Flexible detector positioning
    - Near/far setup to cancel flux normalization systematics
  - Low Z target to increase neutrino flux
  - Neutron shielding to reduce beam-correlated backgrounds to negligible levels

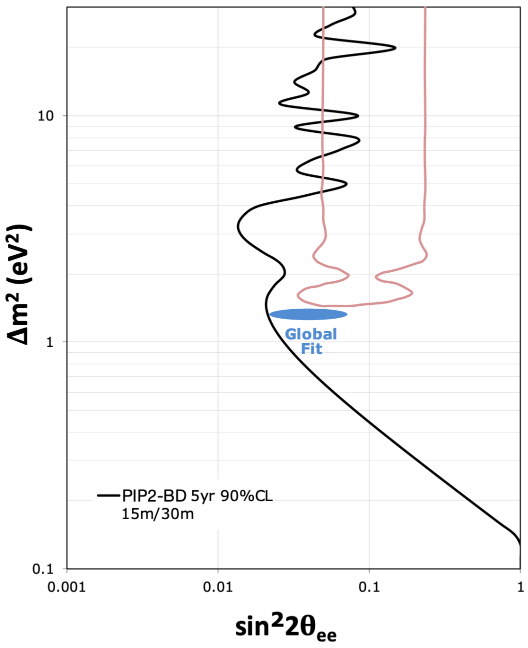


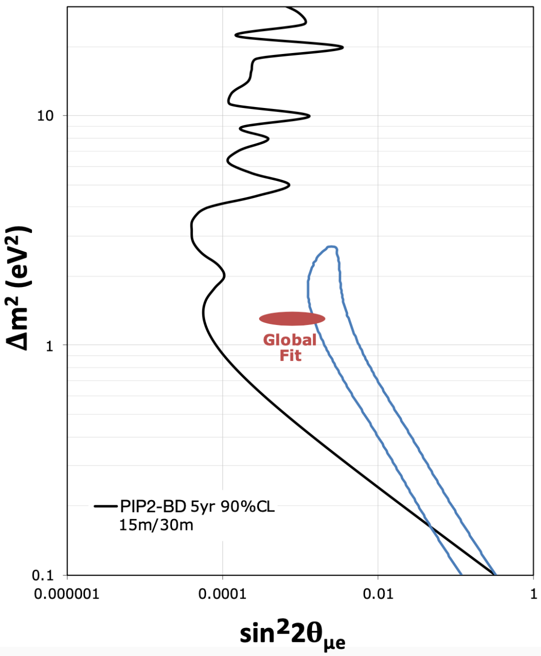
or DUNE PRISM moveable detector concept

- Two identical PIP2-BD detectors at L = 15, 30 m from target

90% C.L. Rate-only Sensitivities (C-PAR)







PIP2-BD also sensitive to alternative dark sector explanations of the MiniBooNE anomaly

DAMSA: Dump-produced Aboriginal Matter Searches at an Accelerator

담사 (冥想) = 깊은생각 – Rumination or Reflection

Search Prospects for Axion-like Particles at Rare Nuclear Isotope Accelerator Facilities

arXiv:2207.02223 [hep-ph]

Wooyoung Jang,[1] Doojin Kim,[2] Kyoungchul Kong,[3] Youngjoon Kwon,[4] Jong-Chul Park,[5] Min Sang Ryu,[6,7] Seodong Shin,[8] Richard G. Van de Water,[9] Un-Ki Yang,[10] and Jaehoon Yu[1]

[1] *Department of Physics, University of Texas, Arlington, TX 76019, USA*
[2] *Mitchell Institute for Fundamental Physics and Astronomy, Department of Physics and Astronomy, Texas A&M University, College Station, TX 77843, USA*
[3] *Department of Physics and Astronomy, University of Kansas, Lawrence, KS 66045, USA*
[4] *Department of Physics & IPAP, Yonsei University, Seoul 03722, Republic of Korea*
[5] *Department of Physics and IQS, Chungnam National University, Daejeon 34134, Republic of Korea*
[6] *Department of Physics, University of Seoul, Seoul 02504, Republic of Korea*
[7] *Department of Physics, Kyungpook National University, Daegu 41566, Republic of Korea*
[8] *Department of Physics, Jeonbuk National University, Jeonju, Jeonbuk 54896, Republic of Korea*
[9] *Los Alamos National Laboratory, Los Alamos, NM 87545, USA*
[10] *Department of Physics, Seoul National University, Seoul 08826, Republic of Korea*

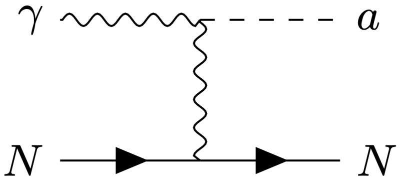
With input from Jaehoon Yu

Axion-like Particles (ALPs)

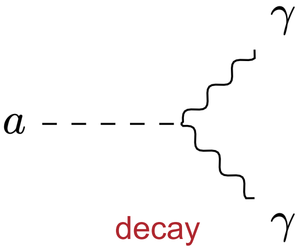
- ALPs can couple to photons and electrons produced in the beam dump
  - Excellent sensitivity due to intense source + large, low-threshold detector nearby

$$\mathcal{L}_{\mathrm{ALP}} \supset -\frac{g_{a\gamma}}{4}\, a\, F_{\mu\nu}\tilde{F}^{\mu\nu} - g_{ae}\, a\, \bar{e}\, i\gamma_5\, e$$

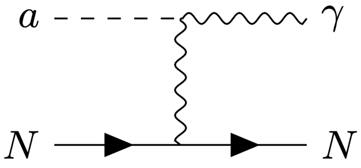
  - Photon coupling example:



production



decay



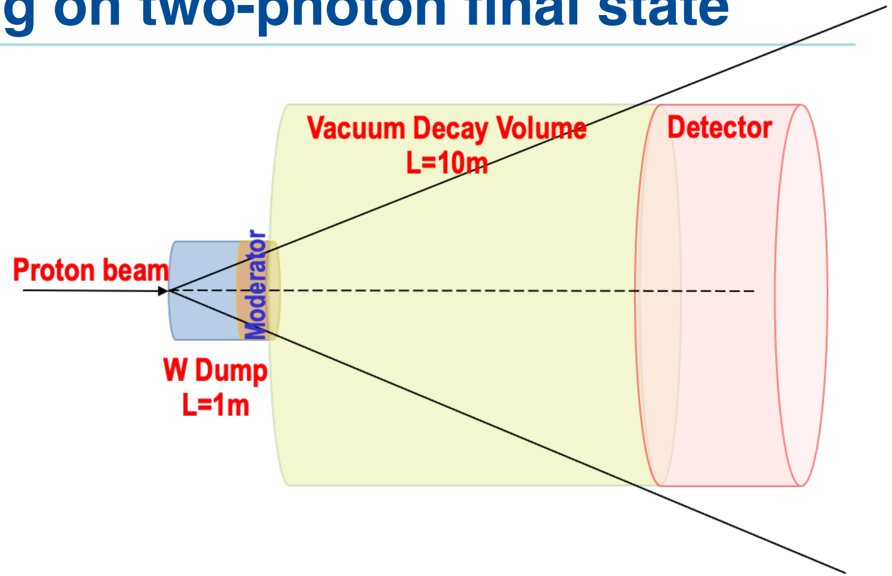
scattering

  - Reducing distance from source to the detector also probes new ALP parameter space

With input from Jaehoon Yu

DAMSA ALP search at PIP II focusing on two-photon final state

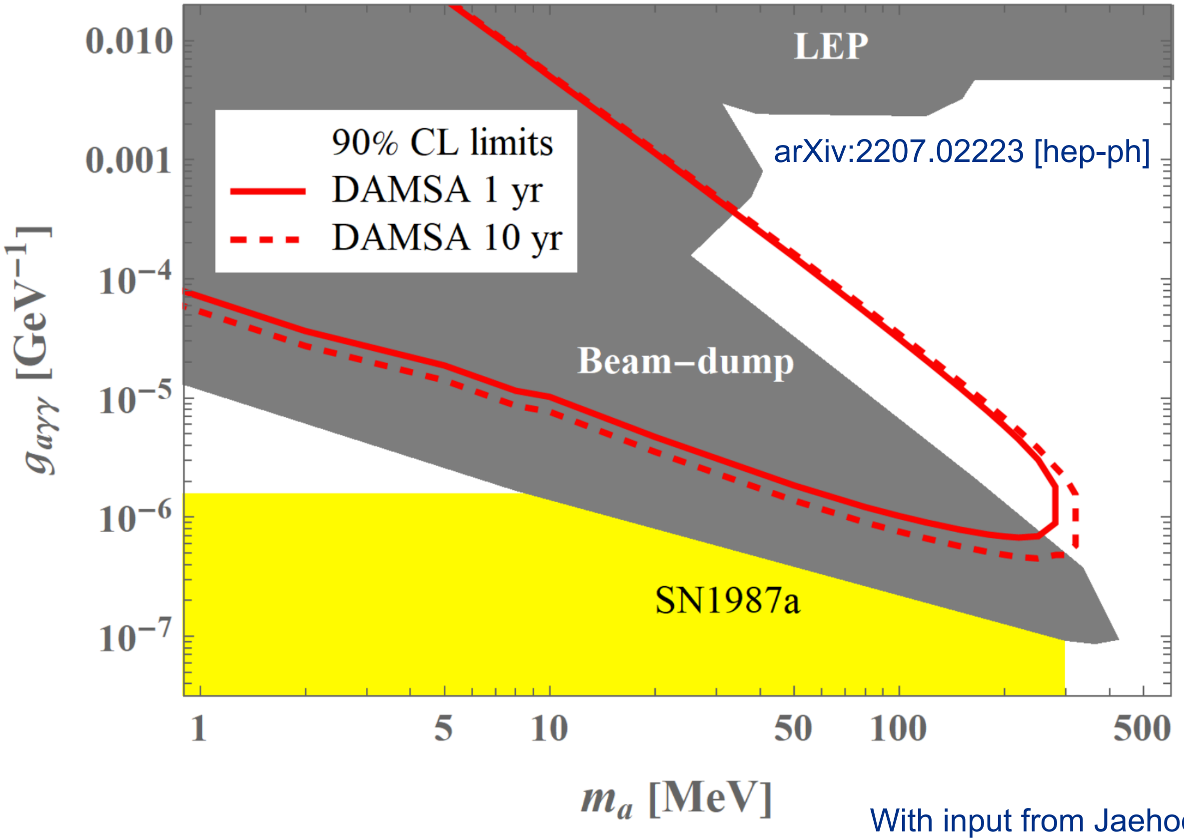
- Produce as many photons as possible in the beam source
- Capture as many ALPs in as wide a mass range as possible
  - Minimize the distance from the source to the detector
  - Increase the detector angular coverage
- Minimize the backgrounds from neutral particles
  - Neutrino NC/CCQE interactions produce $\pi^0 \rightarrow 2\gamma$
    - Can be minimized if the beam energy is just right
  - Neutron spallation —> accidental photon overlaps —> primary background
- This can be accomplished in a beam dump



- Inject and absorb as many low-E (1GeV or less) proton beam particles in the dump as possible
- Allow higher mass ALP’s to decay with as small a number of neutrons which generate spurious photons as possible
- Place the detector as close to the dump as possible on axis to expand the mass reach to higher mass region

With input from Jaehoon Yu

DAMSA ALP 90% C.L. Sensitivities



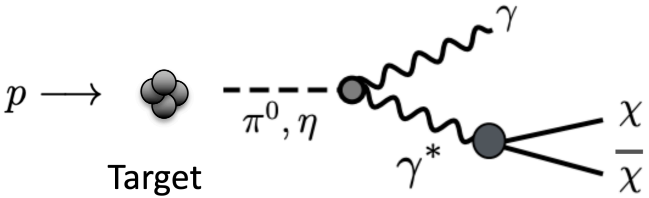
With input from Jaehoon Yu

Millicharged Particles

- Millicharged particles arise naturally in models with a massless dark photon

$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{4}B'_{\mu\nu}B'^{\mu\nu} - \frac{\kappa}{2}B'_{\mu\nu}B^{\mu\nu} + i\bar{\chi}(\partial\!\!\!/ + ie'B\!\!\!/' + iM_{\rm MCP})\chi$$

- Production in proton beams analogous to light dark matter:

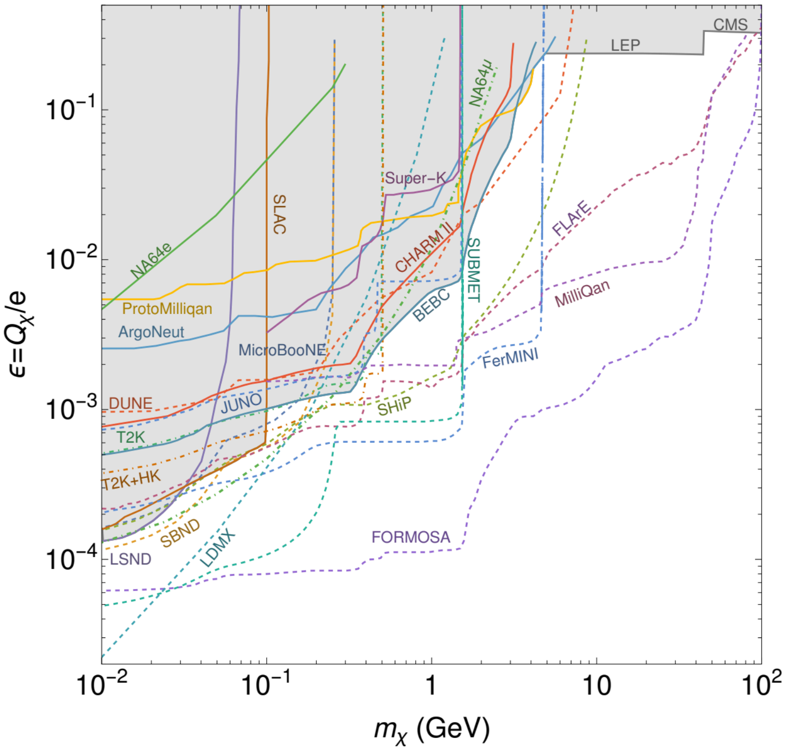


- Detection Signatures
  - Hard (MeV-level) electron scattering
  - Very low-energy (eV-level) electron scattering
    - Leverages the fact that the cross section $\propto 1/E_r^{min}$

Improving Constraints on Millicharged Particles

- Opportunity to extend low mass limits from LSND by deploying eV threshold detector at a PIP2 beam dump
  - Noble Elements Detectors: ~20 eV threshold by focusing exclusively on the ionization channel
    - DarkSide-LowMass, LBECA, NEWS-G
  - Charge Detectors: Solid-state devices can detect single ionized electrons, including charge-coupled devices (CCDs) and semiconductor crystals
    - Oscura, SENSEI, DAMIC-M
  - Phonon Detectors: cryogenic detectors with sub-eV resolution, optimized to trigger below 20 eV
    - superCDMS, CRESST, EDELWEISS, MINER, TESSERACT

- Similar analysis strategy for surface deployment
  - Reject backgrounds via timing, tracks pointing back to dump



With input from Juan Estrada

Conclusion

Exciting prospect for dark sector discoveries over the coming decade

PIP-II Linac 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 (which uses only 1.1% of full beam capacity) and intense low (~GeV) energy protons beam

PAR could enable a GeV-scale proton beam dump program to be realized within the decade

- Key feature of such a beam dump facility at Fermilab is that it can be designed for and dedicated to HEP searches

Excellent opportunity for a proton beam dump based dark sector (and neutrino physics) program at Fermilab that more fully utilizes PIP-II infrastructure

- Interest in planning a near-term workshop to collect ideas from the community

Thank you for your attention!

Backups

Proton Beam Dump Stopped Pion Decay-at-rest Neutrino Flux