Proton Fixed-Target Searches for New Physics at Fermilab + Booster Accumulator Ring

William Pellico (FNAL), Matt Toups (FNAL), Richard Van de Water (LANL)

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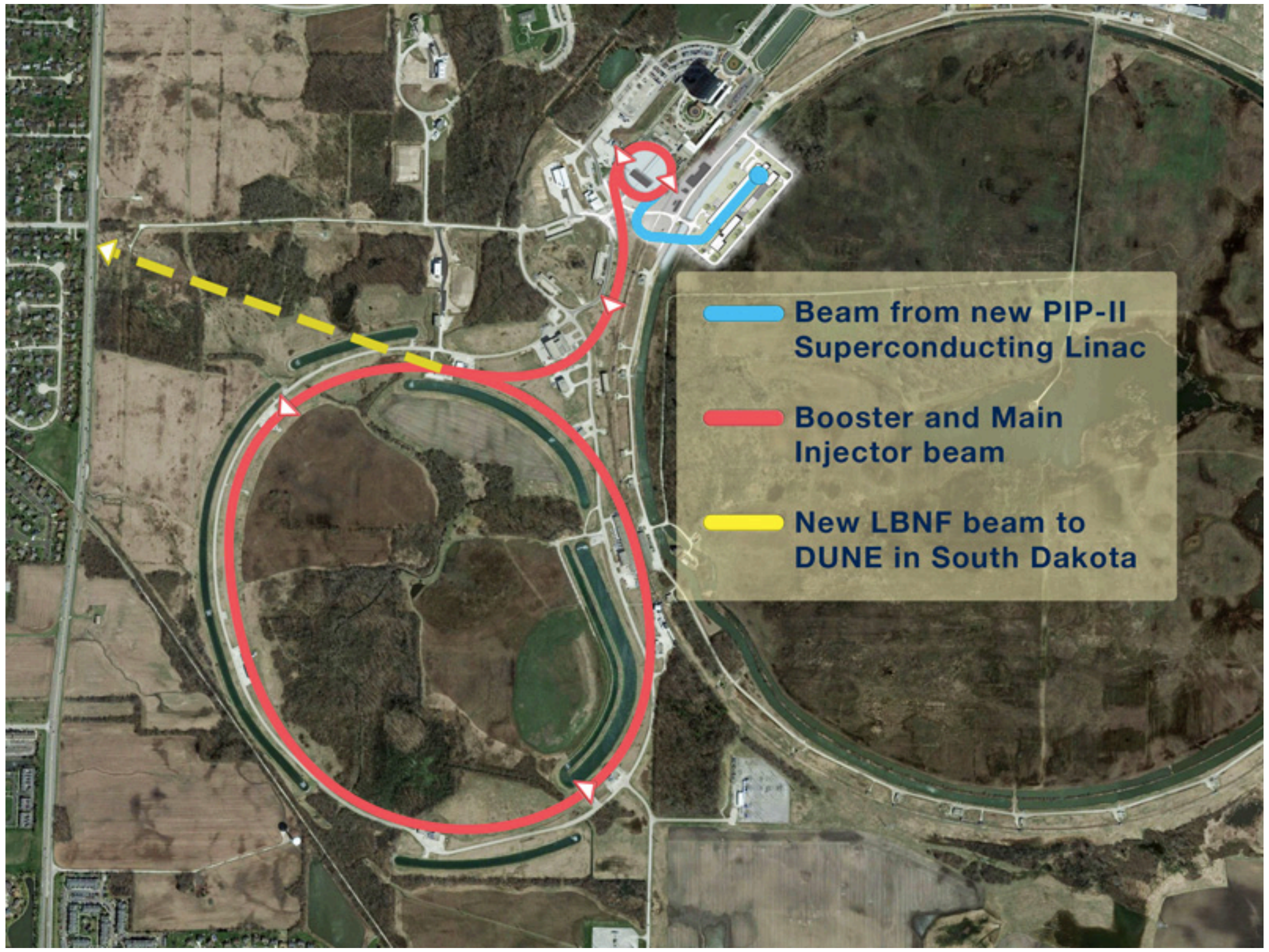
PIP-II will support a world-leading neutrino program @ FNAL

- Expected LINAC commissioning in FY27
  - Ready for baselining this year
- Will be among the highest-power ~GeV proton beams in the world
- Key high-level metrics for LINAC:
  - Capable of 2 mA @ 800 MeV (1.6 MW)
  - DUNE only uses 1.1% of this total beam capacity to achieve its physics goals
  - See Eduard's talk at the RF townhall
- How can we best leverage this advanced beam facility to search for new physics?



Fixed-Target Searches for New Physics with O(10 GeV) Proton Beams at Fermi National Accelerator Laboratory

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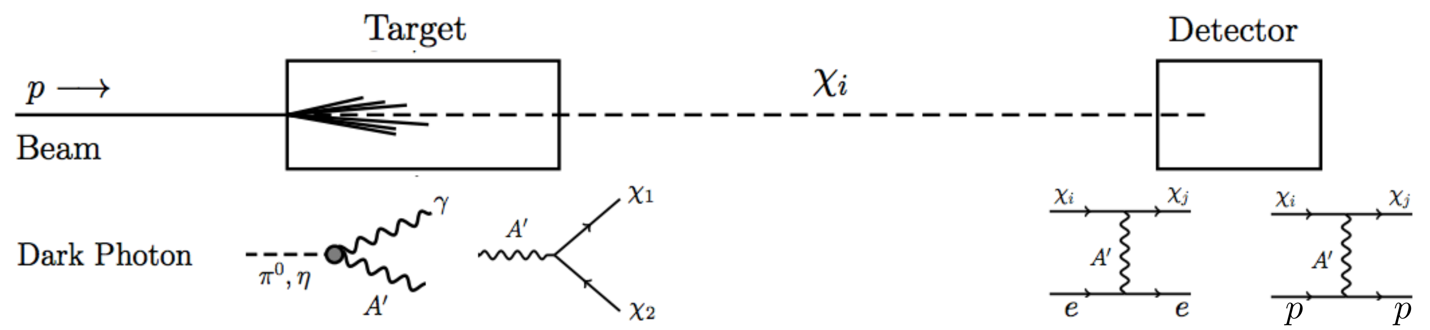
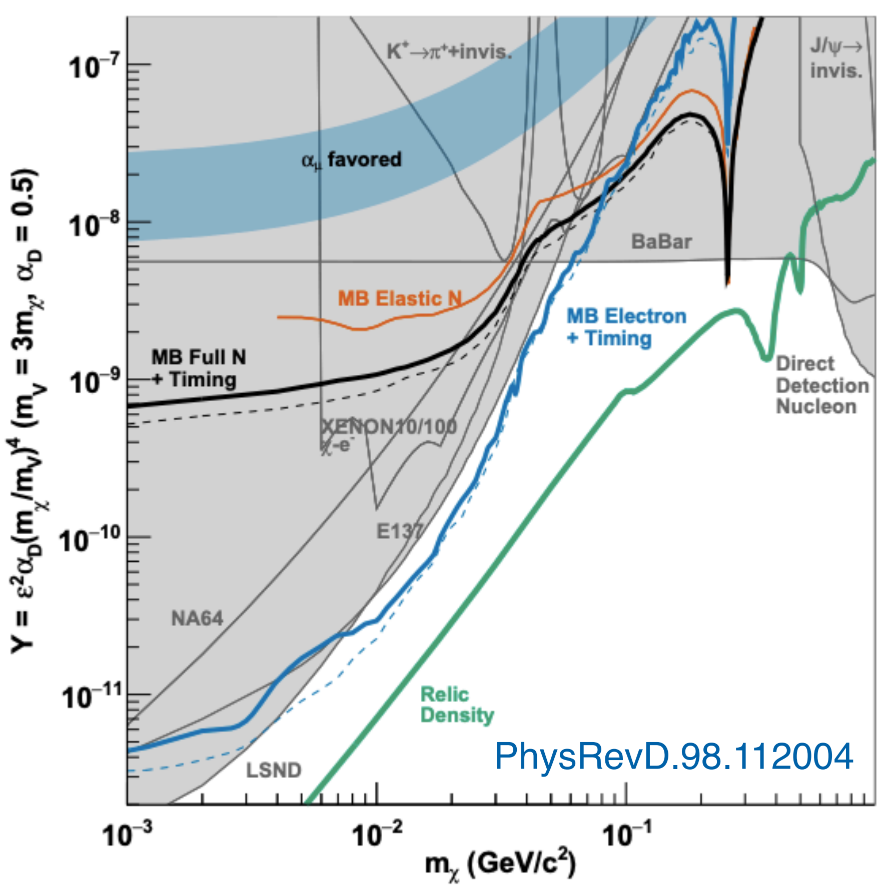
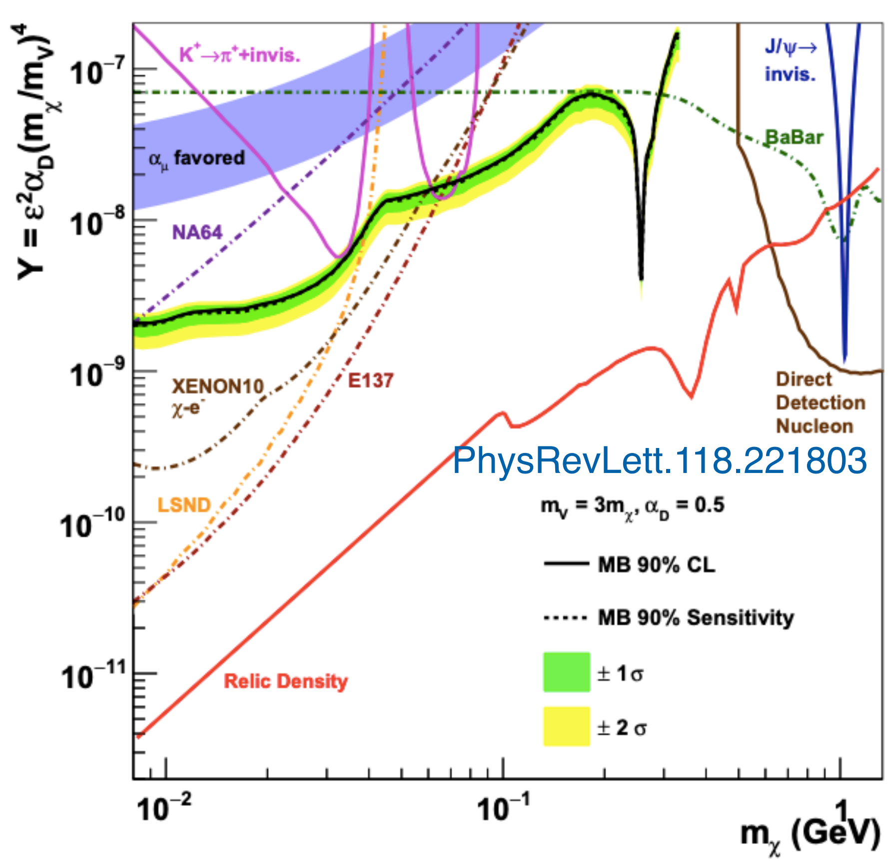
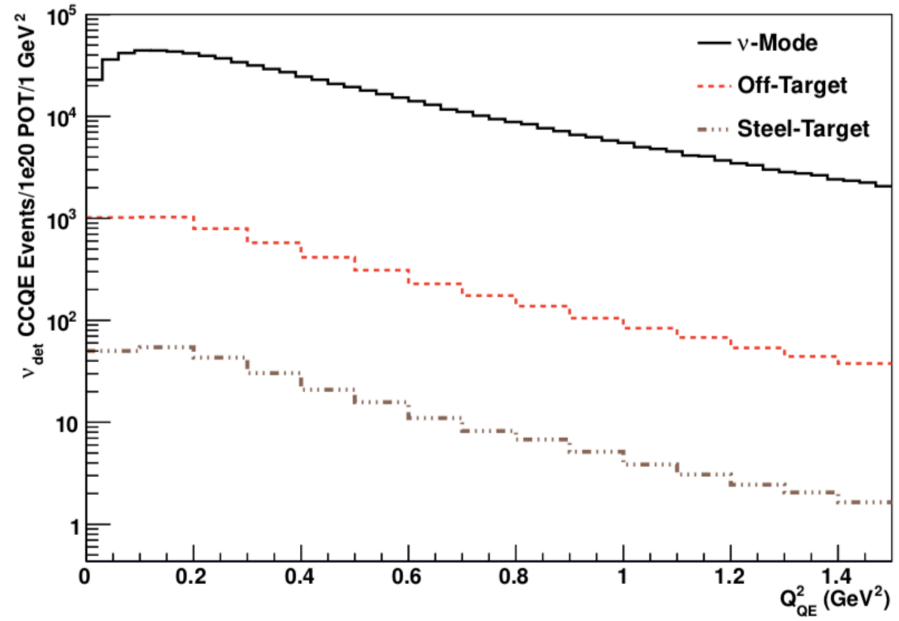
Dark Sector (DS) Searches on the Booster Neutrino Beamline (BNB)

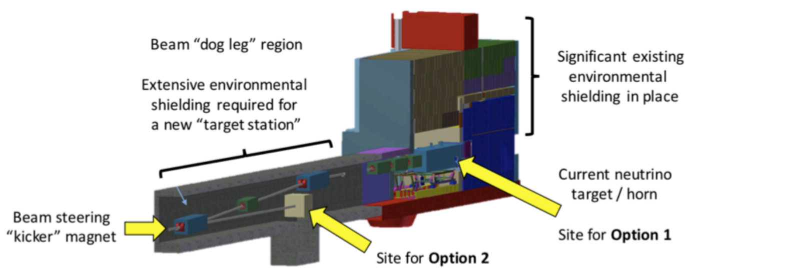
MiniBooNE-DM pioneered accelerator-based searches for benchmark models such as vector portal dark matter (DM) with a light U(1) gauge boson that kinetically mixes with the photon by running off target in beam dump mode





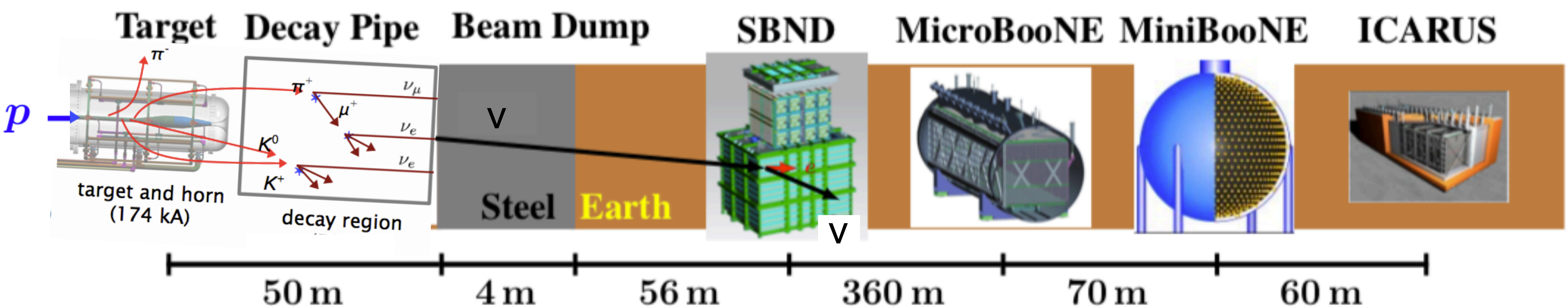






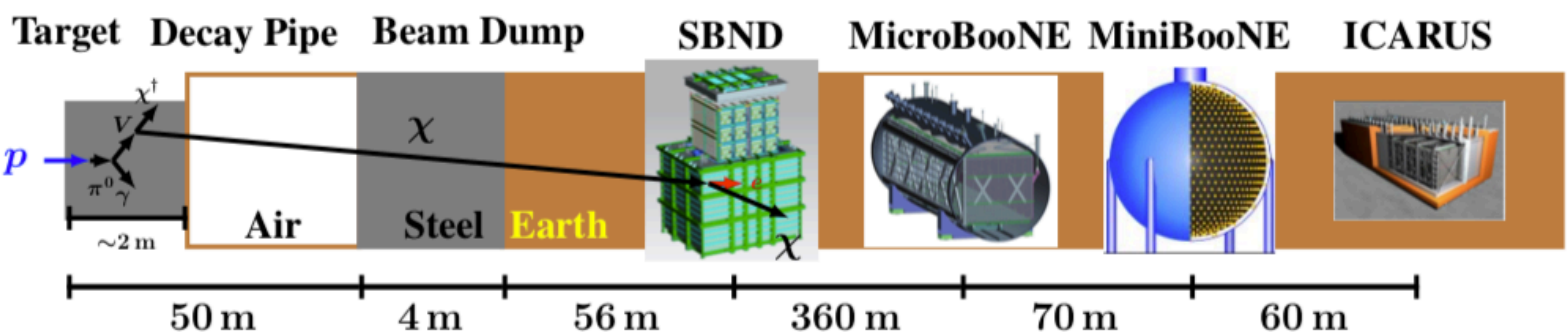
Short Baseline Neutrino program integration

Current short-baseline neutrino program uses horn-focused, decay-in-flight neutrino beam:



→ Currently at 35 kW, but we can imagine a similar setup with much higher intensities

Impinging proton beam on absorber enables DS search program:



→ With kicker magnets and second target station, can run concurrently with the above

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Fixed-Target Searches for New Physics with O(1 GeV) Proton Beams at Fermi National Accelerator Laboratory

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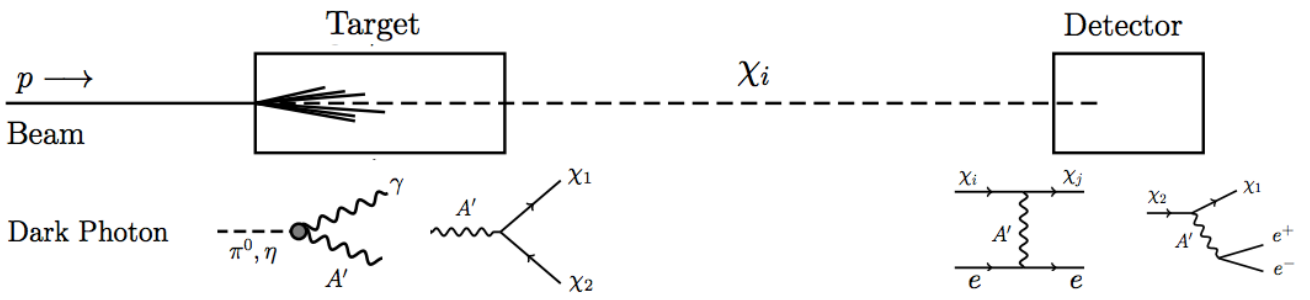
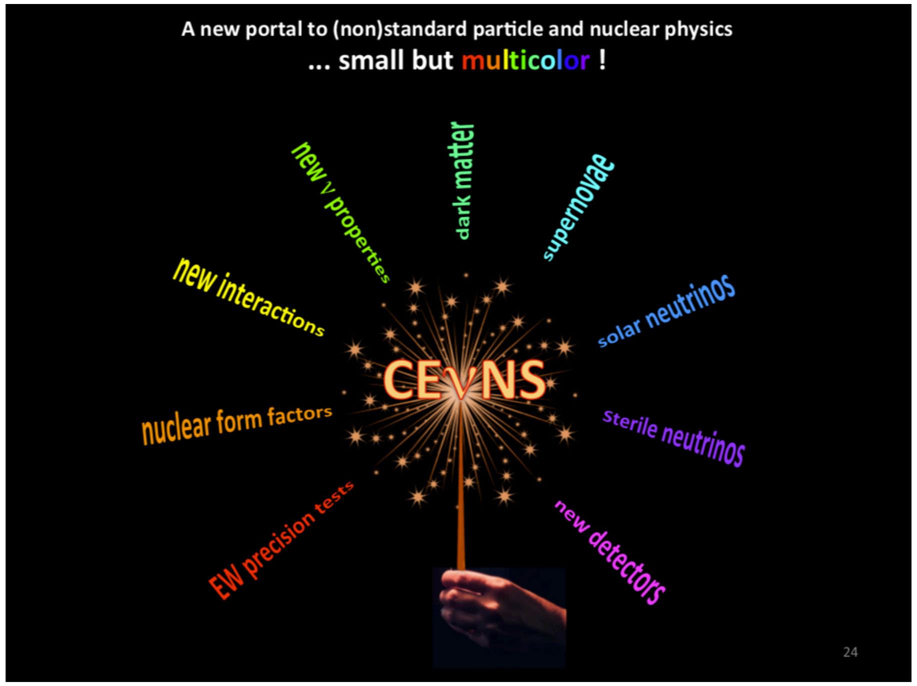
PIP-II is simultaneously capable of driving a MW-class GeV-scale proton fixed target program and a 2.4 MW beam line for DUNE

- Physics Opportunities At Such a Facility



  - Light DM / DS Searches
    - Decay and/or scattering signatures
  - Light Sterile Neutrino Searches
    - Both appearance and disappearance possible
  - Coherent elastic neutrino-nucleus scattering (CEvNS)
    - 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
  - Additional topics:
    - Searches for axion-like particles, 3-ν oscillations, etc.



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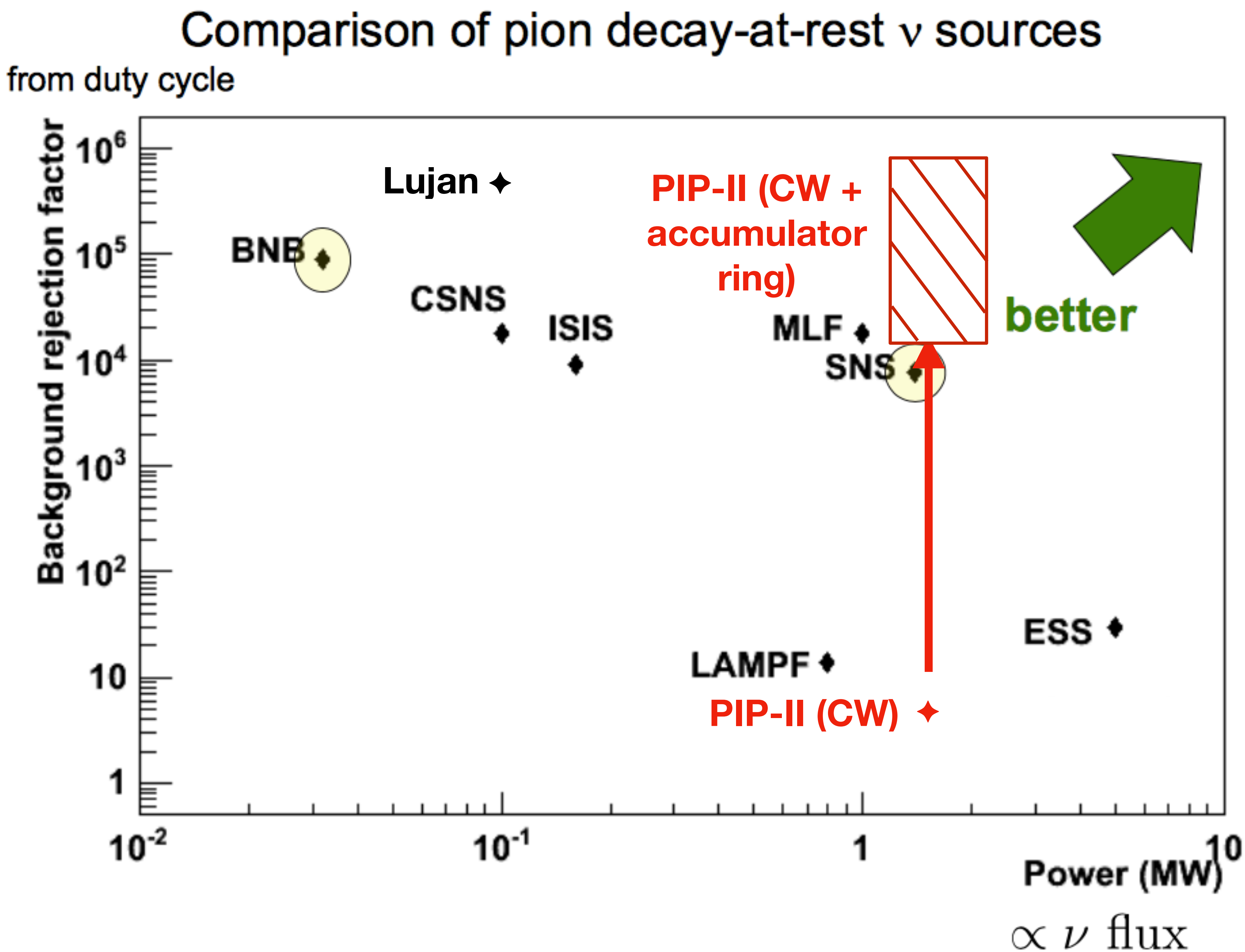
Accumulator Ring Needed For Ultimate Physics Reach (CEvNS)



FNAL Booster Accumulator Ring

William Pellico, Jeff Eldred, Kiyomi Seiya, CY Tan, C. M. Bhat, Matthew Toups[1], Takahiro Watanabe [2], Richard Van De Water [3], and Chamseddine Benabderrahmane[4]

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Booster Accumulator Ring (BAR) Concept

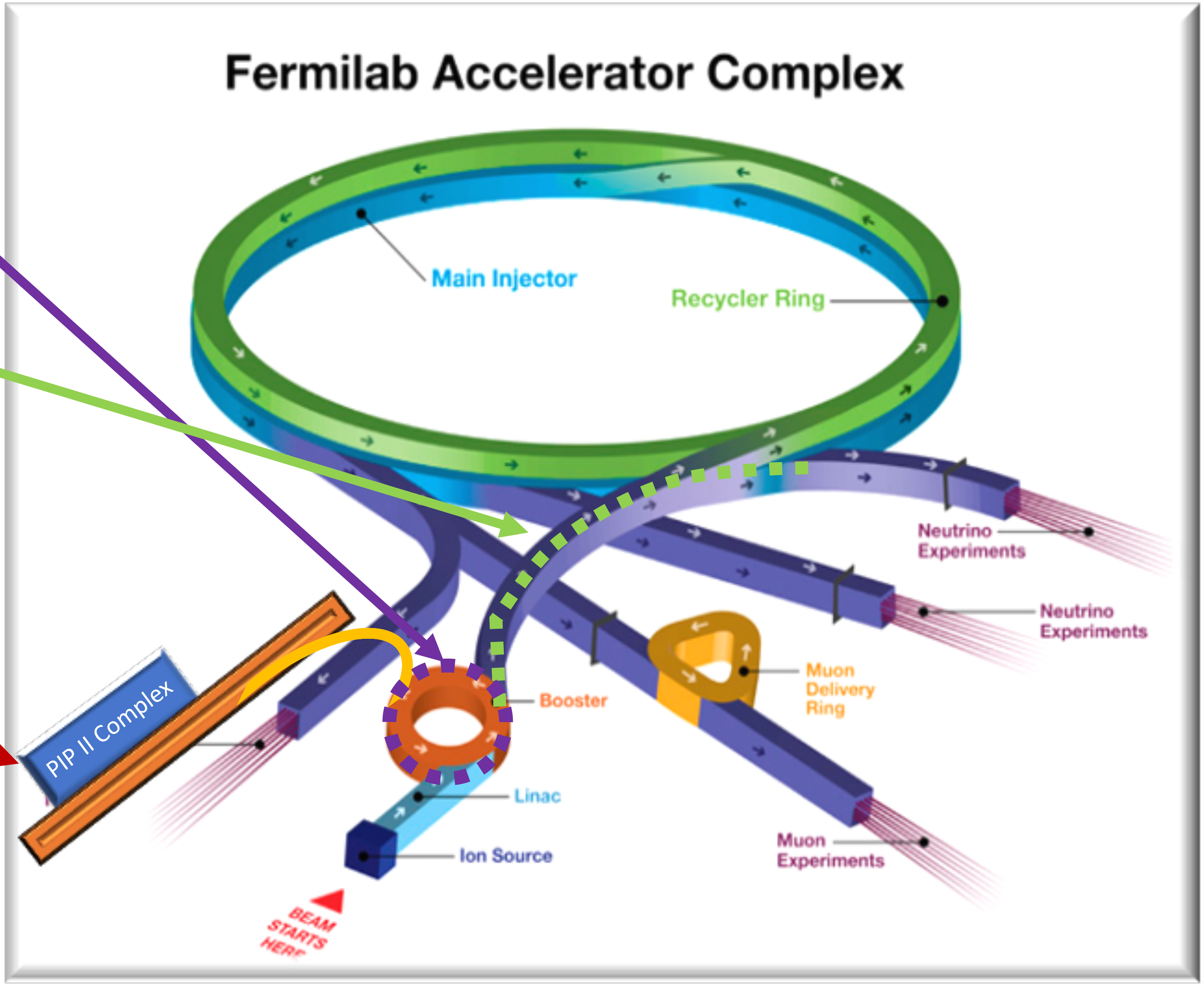
Overview

- A permanent magnet accumulator ring could be built in the Booster enclosure that could greatly benefit PIP II/DUNE program and set FNAL on the path to a large DS program.
- The existing Booster to BNB enclosure will be contain the new 1 GeV line.

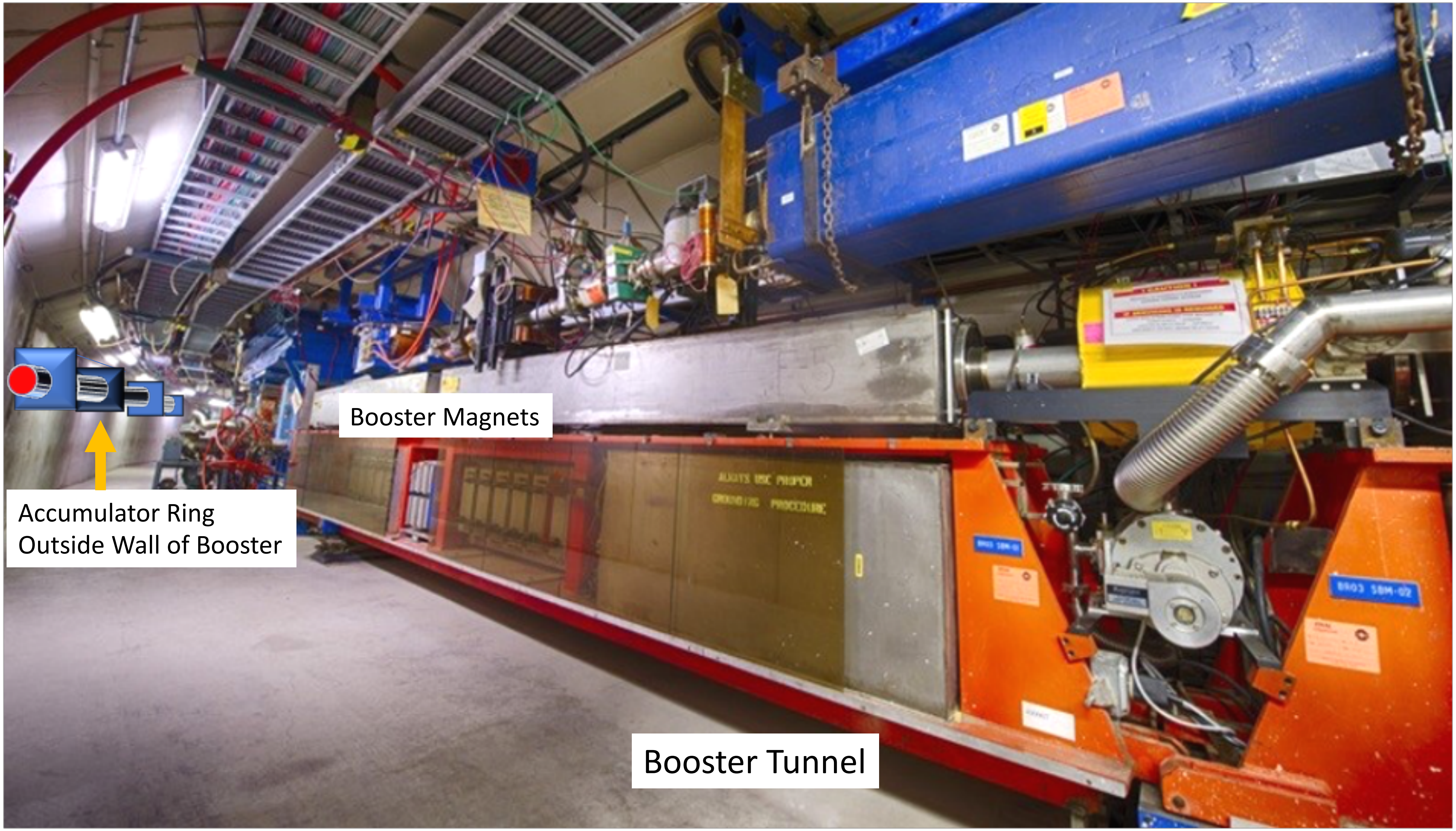
Cost and time for this approach is greatly reduced due to synergy to PIP II and present BNB complex.

A new 800 MeV line is being designed for the PIP II to Booster Injection. A new accumulator would instead receive the PIP-II linac beam and transfer it to the Booster for DUNE operations.

With the rest of the Linac pulses being used for delivery to the BAR for DS operations.



Location Inside Booster Enclosure



Thank you

DM Event Sensitivities

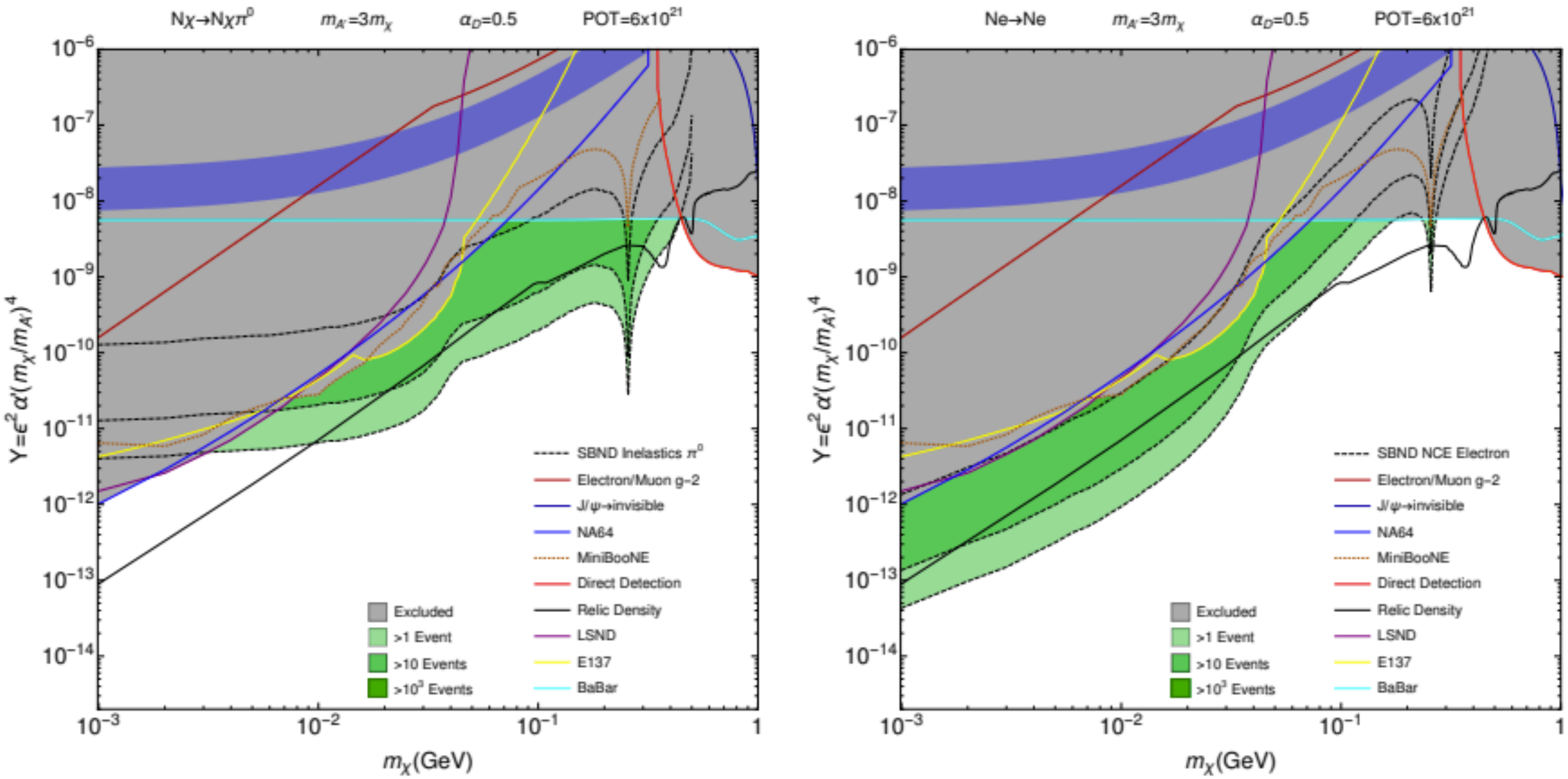


Figure 1: Regions of relic abundance parameter (mixing strength) Y vs. dark matter mass m_χ for 6×10^{21} POT that could be achieved in a five year run with dedicated proton beam dump medium energy running in the PIP-II era. Left is the signal sensitivity for NCπ^0 and right for NC-electron scattering with the SBND detector at 100 m from the dedicated beam dump. Both panels show regions where we expect 1–10 (light green), 10–1000 (green), and more than 1000 (dark green) scattering events. The solid black line is the scalar relic density line that can be probed.

- Setup also has sensitivity to other DS models, e.g. hadrophilic DM

DM Event Sensitivities

- Sensitivities assume a 630 kW 1 GeV proton beam impinging on a low-Z target
- We consider a 100-ton LAr scintillation detector placed 18 m downstream from the target with a 50 keV recoil energy threshold and an efficiency of 70%
- Assuming a 5-year run with a 75% uptime, we compute event sensitivities for 4.6 x 10^{23} protons-on-target
- Not only probes benchmark scalar DM model, but also Majorana fermion, pseudo-Dirac fermion DM, etc.

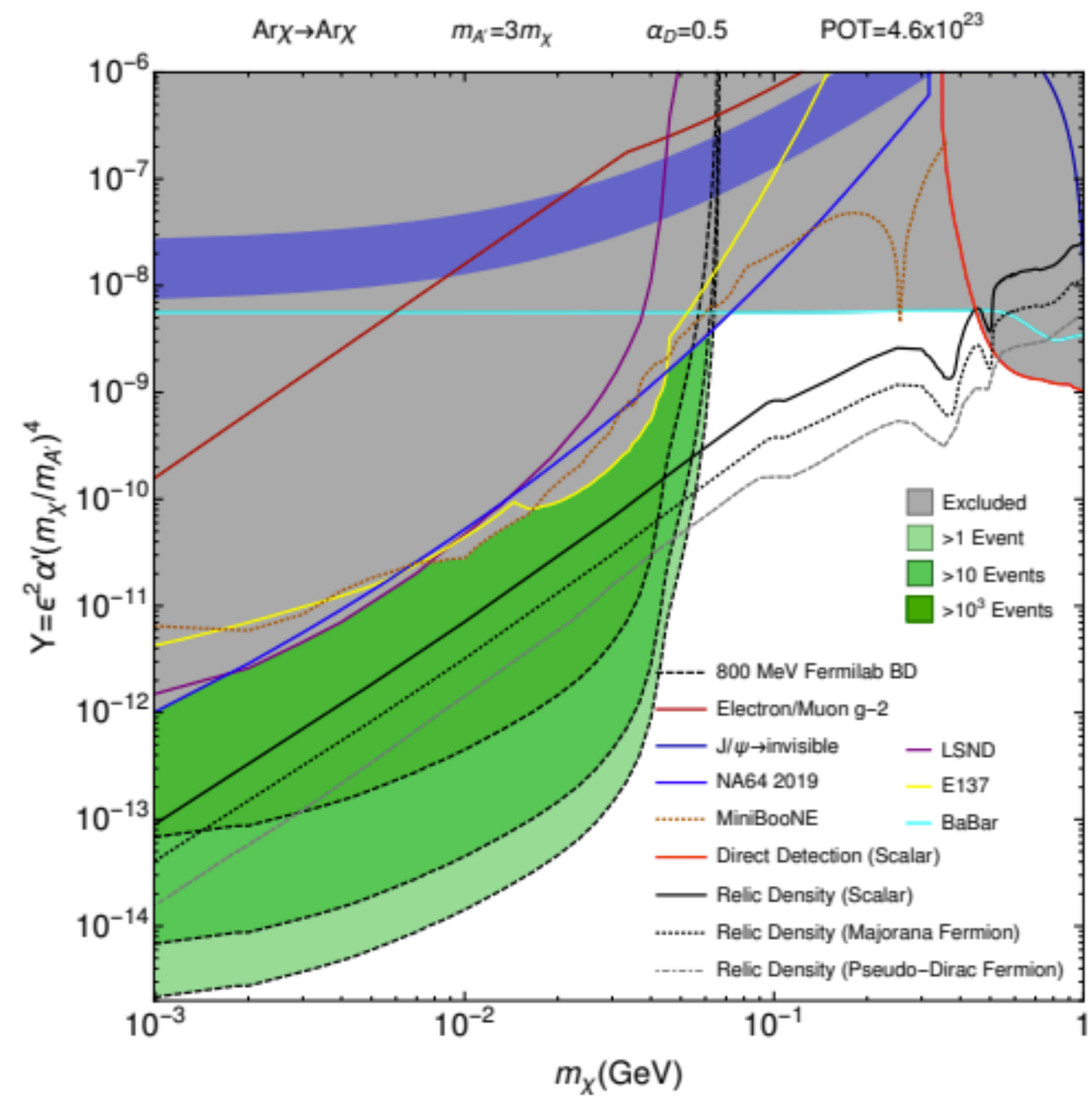


FIG. 1. Fermilab beam dump facility argon recoil event sensitivity curves for 4.6×10^{23} protons on target compared to thermal relic density targets and existing 90% exclusion limits as a function of the dimensionless scaling variable $Y = \epsilon^2\alpha(m_\chi/m_{A'})^4$, assuming $\alpha = 0.5$ and $m_A = 3m_\chi$.

BAR Parameters

Hardware

- Aperture: ~3”
- Cycle rate (being explored)
  - Hardware limitations
    - At least 100 Hz
  - Radiation limitations
    - Shielding assessment
- RF Structure(s)
  - System for Booster/DUNE
    - Pulsed
    - 44 MHz
  - System for Dark Sector RF (CW)
    - Bucket loading
    - Barrier bucket
    - Harmonic flattening
    - Compression

Beam

- Base Power: 130 kW
  - 1.0×10^{13} / batch
    - Space charge limitations
    - Painting
    - RF power
  - 100 Hz
- Goal Power: 200 kW
  - 1.5×10^{13} / batch
    - Upper limit TBD
- Pulses
  - Load time: ~1.5 ms
  - Pulse width TBD
    - Goal of 300-400 ns

BAR/PIP-II Upgrade

- 1 GeV Injection
  - Design to be upgraded
- Power upgraded
  - Base: 160 kW
  - Goal: 240 kW

Summary

- PIP-II LINAC at Fermilab 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) and medium (~10 GeV) energy protons beams
- New beam dump target station on the BNB coupled with SBND detector could improve on existing MiniBooNE vector portal DM limits by more than an order of magnitude and also provide sensitivity to other DM, BSM models
- New Booster-sized, permanent magnet accumulator ring could be realized within the decade for very low cost and enable a GeV-scale proton beam dump program with a rich physics program, including sensitive searches for light DM
  - Key feature of such a beam dump facility at Fermilab is that it can be designed for and dedicated to HEP searches (neutron suppression, large detectors, flexible locations)
- Excellent opportunity for a proton beam dump based dark sector program at Fermilab that more fully utilizes PIP-II LINAC and infrastructure as well as the existing BNB complex
- Plan to develop concepts in these LOIs ahead of Snowmass Summer Study