Proton Fixed-Target Searches for New Physics at Fermilab

Matt Toups, Fermilab

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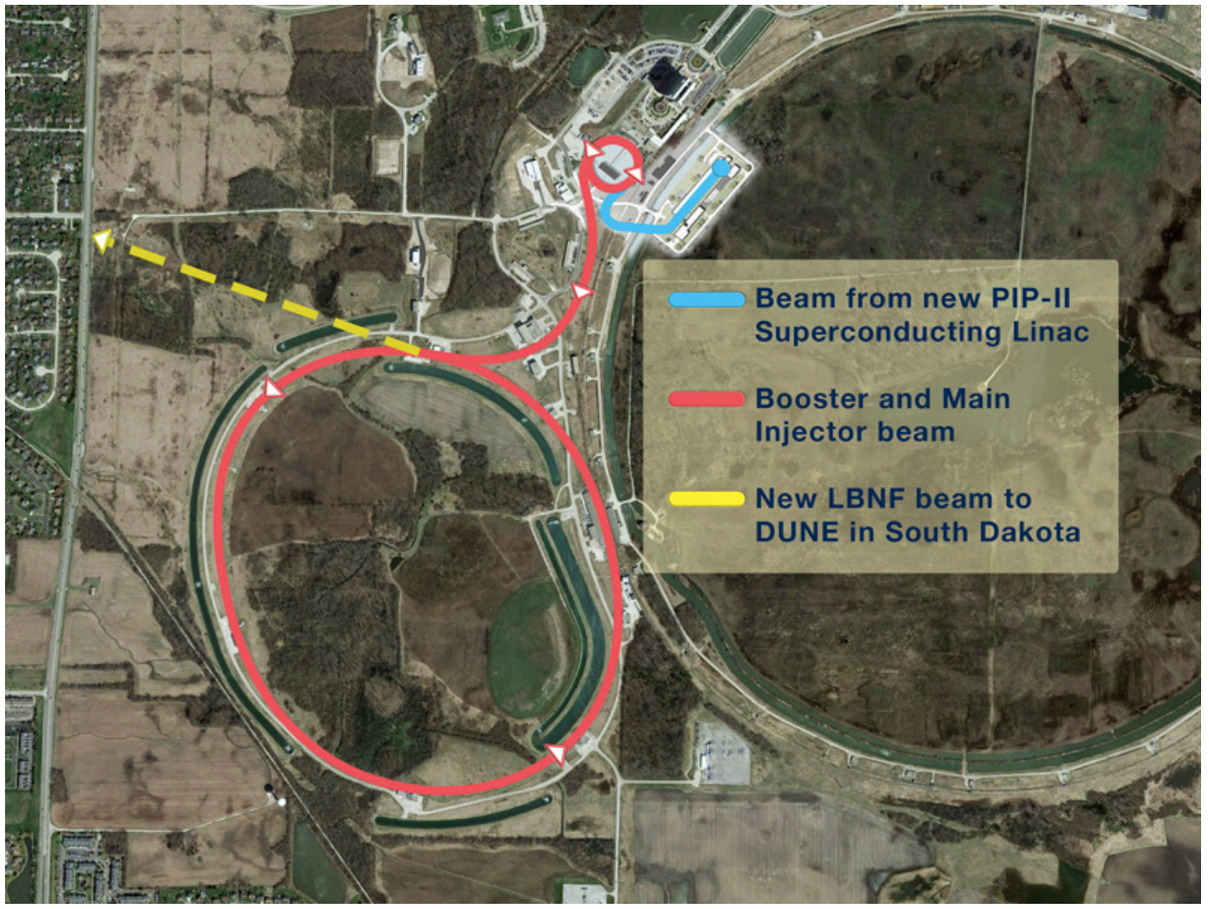
PIP-II will support a world-leading neutrino program @ FNAL

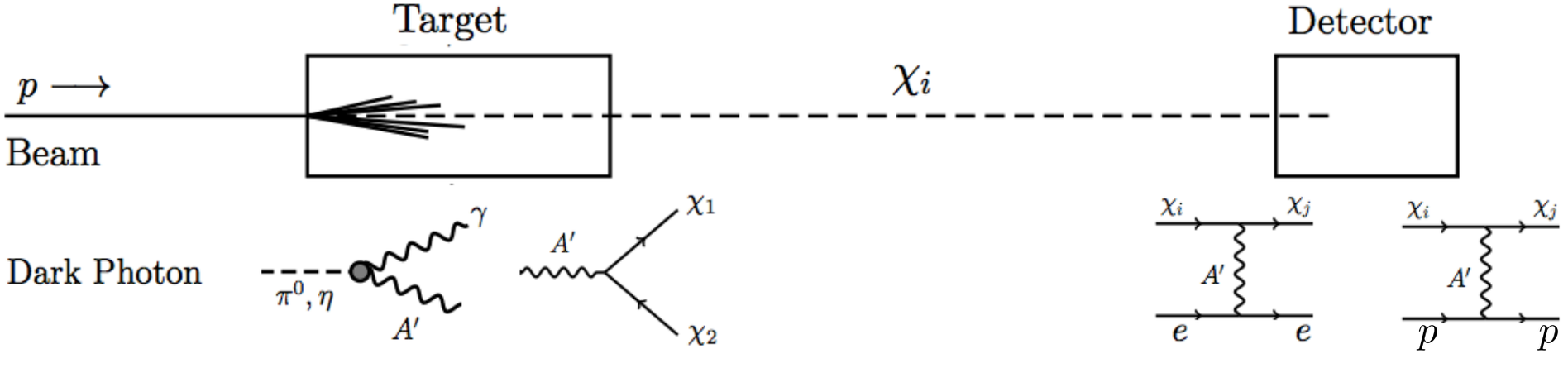
- Expected completion in FY27
  - Ready for baselining (CD2/3a) this year
- Will be among the highest-power ~GeV proton beams in the world
- Key high-level metrics for SC LINAC:
  - Capable of 2 mA @ 800 MeV (1.6 MW)
  - DUNE only uses 1.1% of this beam to achieve its physics goals
- How can we best leverage this advanced beam facility to search for new physics?

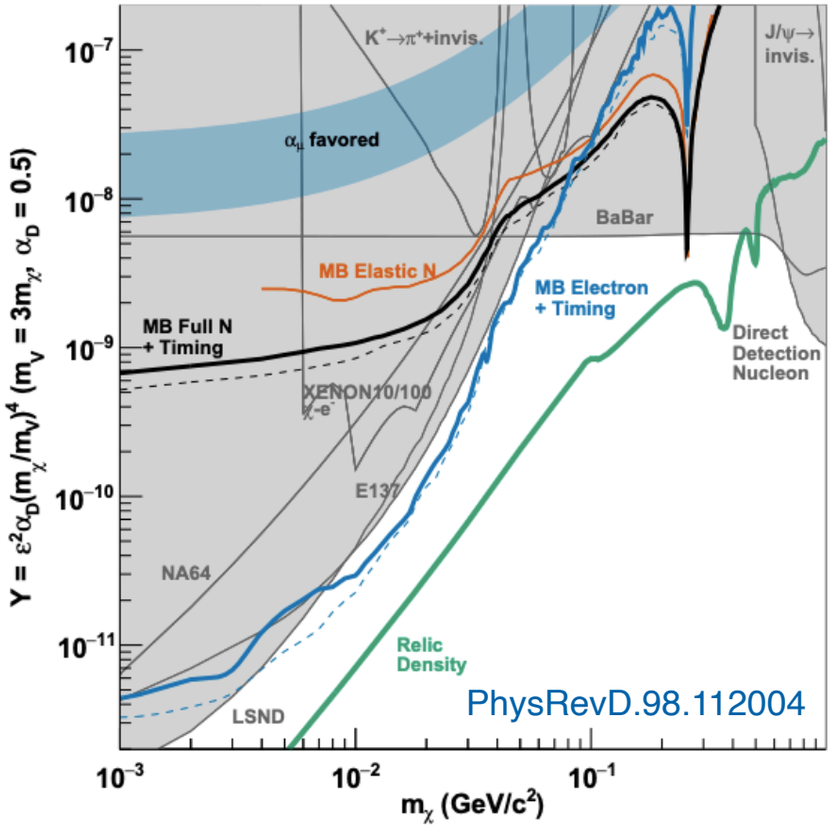


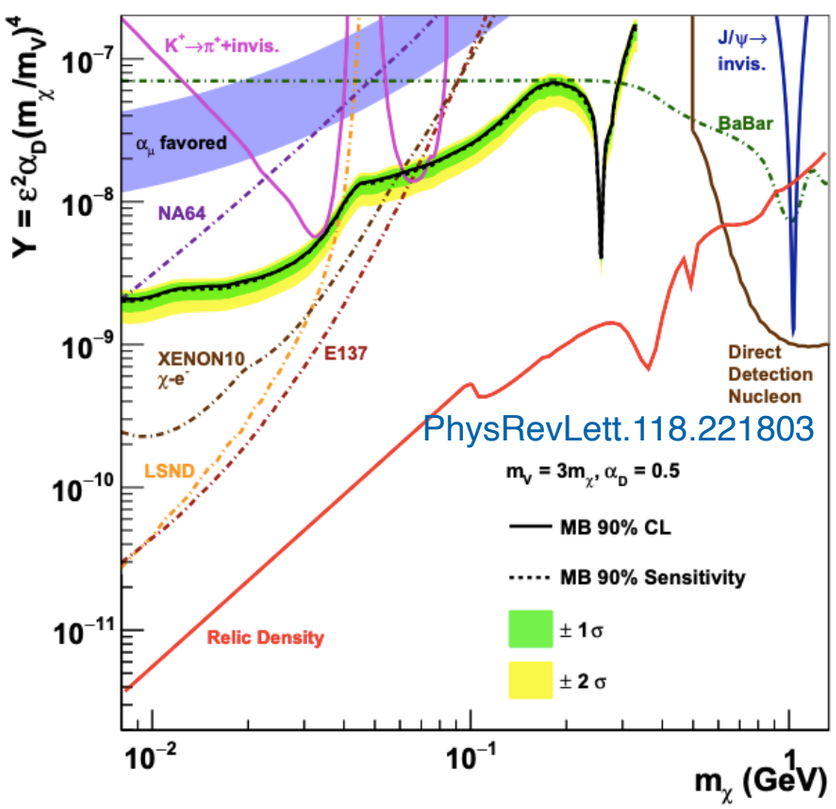
Fixed-Target Searches for New Physics with O(10 GeV) Proton Beams at Fermi National Accelerator Laboratory

New Physics Searches Beyond 3+N Sterile Neutrinos on the BNB

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







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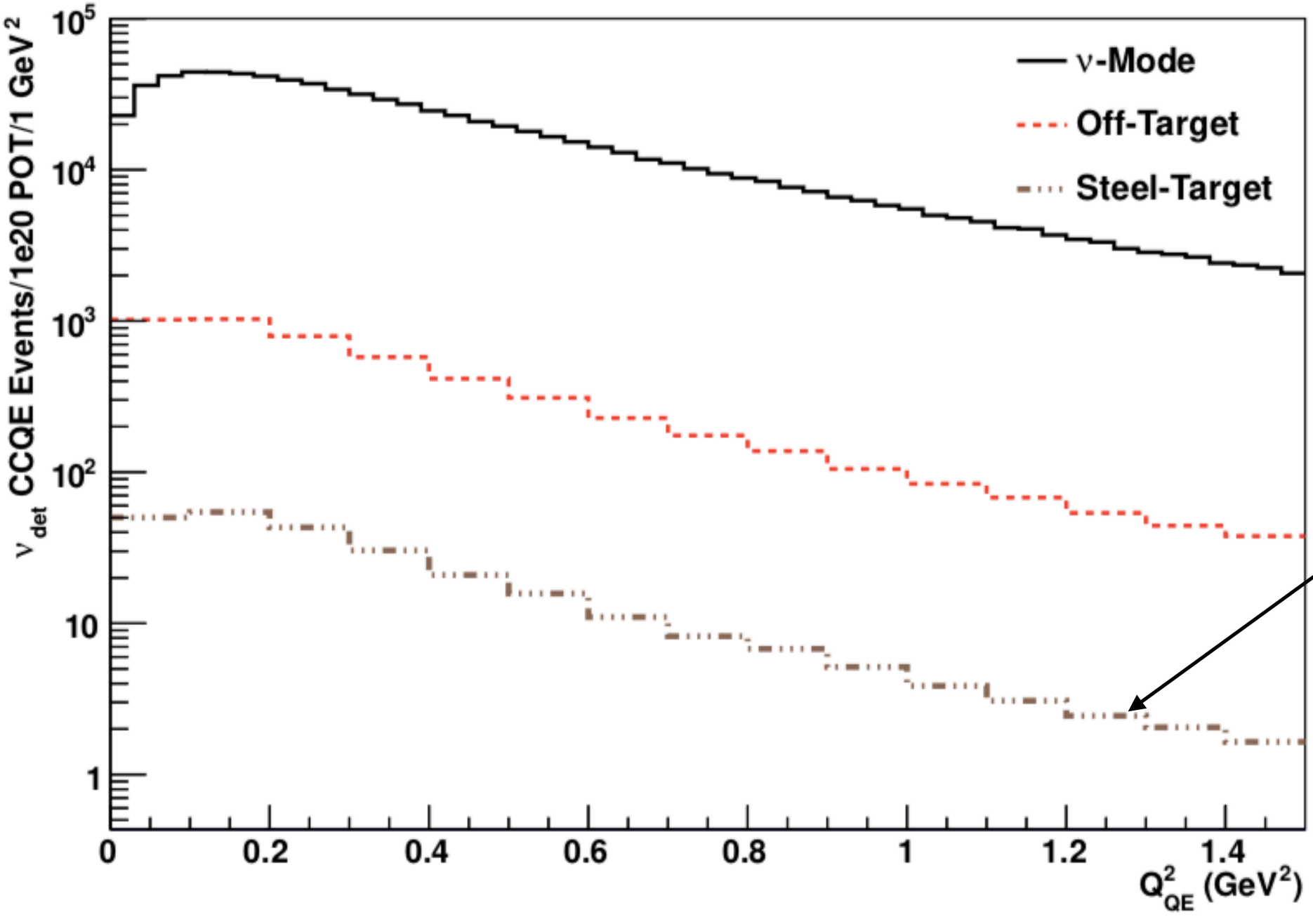
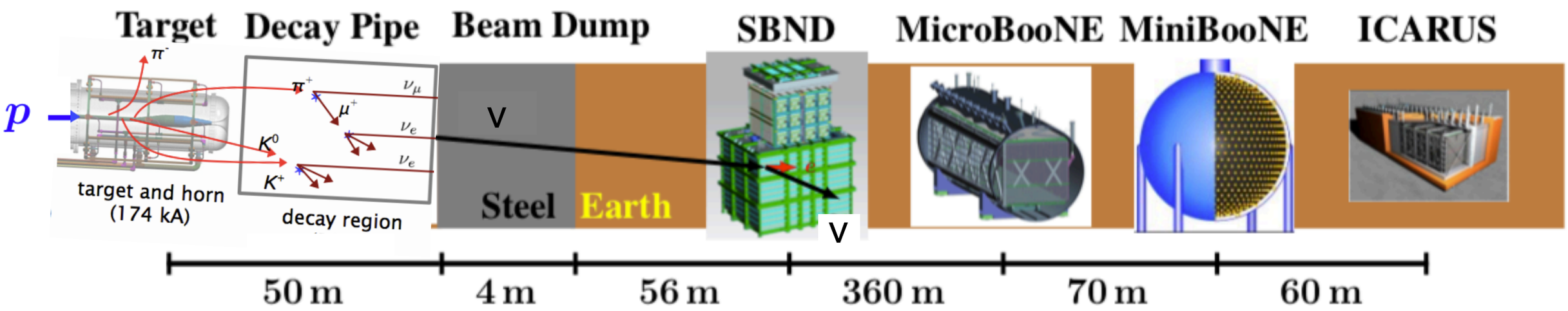
Dedicated Beam Dump Dramatically Decreases ν Background



MiniBooNE-DM simulation shows large reduction in ν background from beam halo scraping target and proton interactions on air in 50 m decay pipe when instead replacing target station with a beam dump

Short Baseline Neutrino program integration

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



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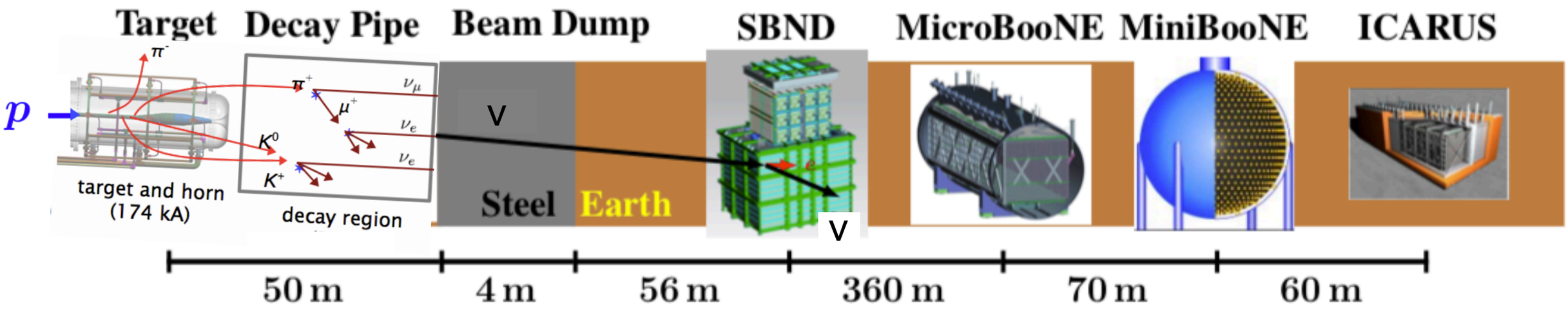

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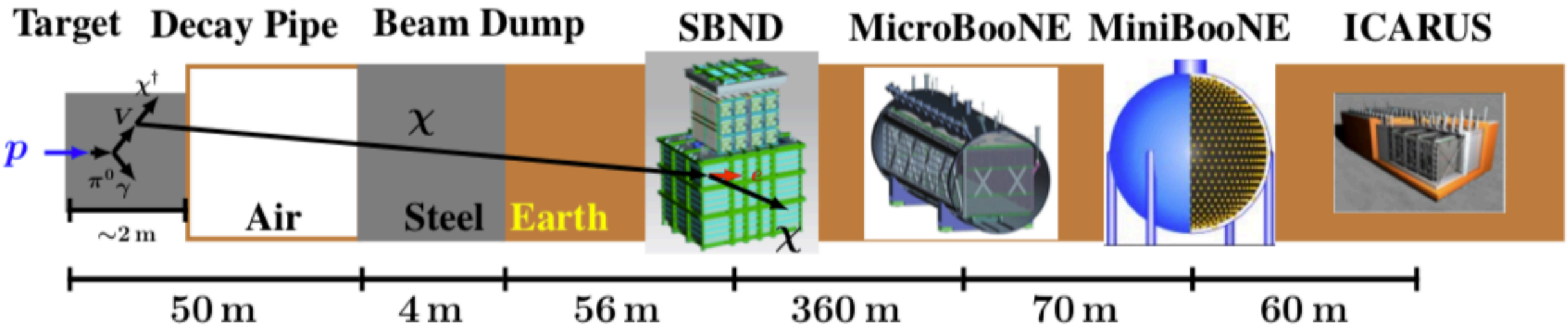
Impinging proton beam on absorber enables LDM search program:



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

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Booster Beam Line in the PIP-II Era

- PIP-II enables higher power to be delivered to the BNB concurrent with LBNF
- The BNB neutrino target and horn have a power limit of 35 kW, but a new dedicated beam dump could be designed to handle increased power
- We consider a light dark matter search in SBND 100 m downstream of a dedicated beam dump receiving 80 kW of beam power
- In a five year run this would result in 6×10^{21} Proton on Target (POT) and achieve an order of magnitude better sensitivity to a benchmark vector portal scalar dark matter model than the current MiniBooNE dark matter sensitivity due to the reduced neutrino background from the dedicated beam dump, the detector's close proximity to the beam dump, and higher protons on target.

DM Event Sensitivities

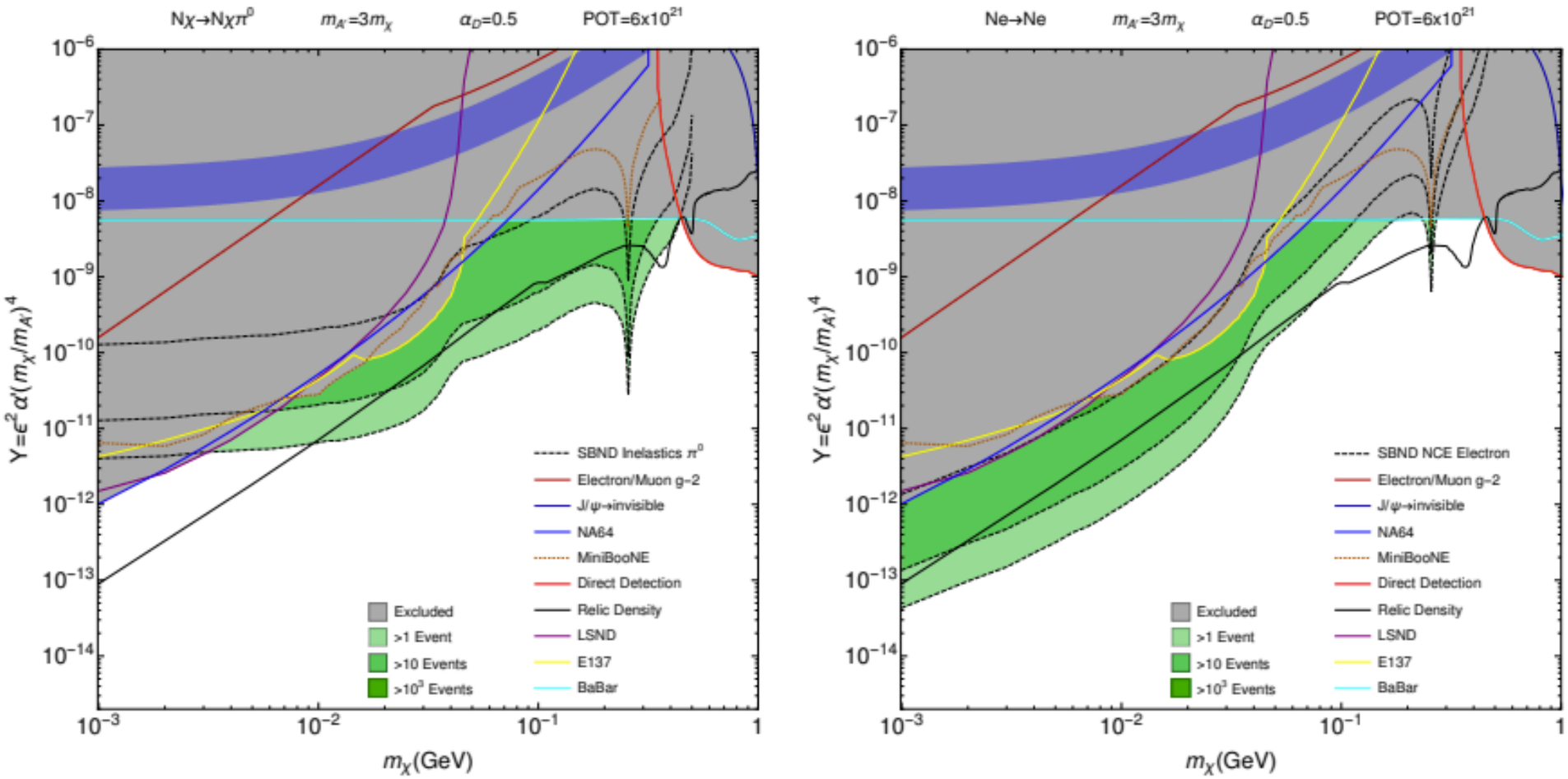
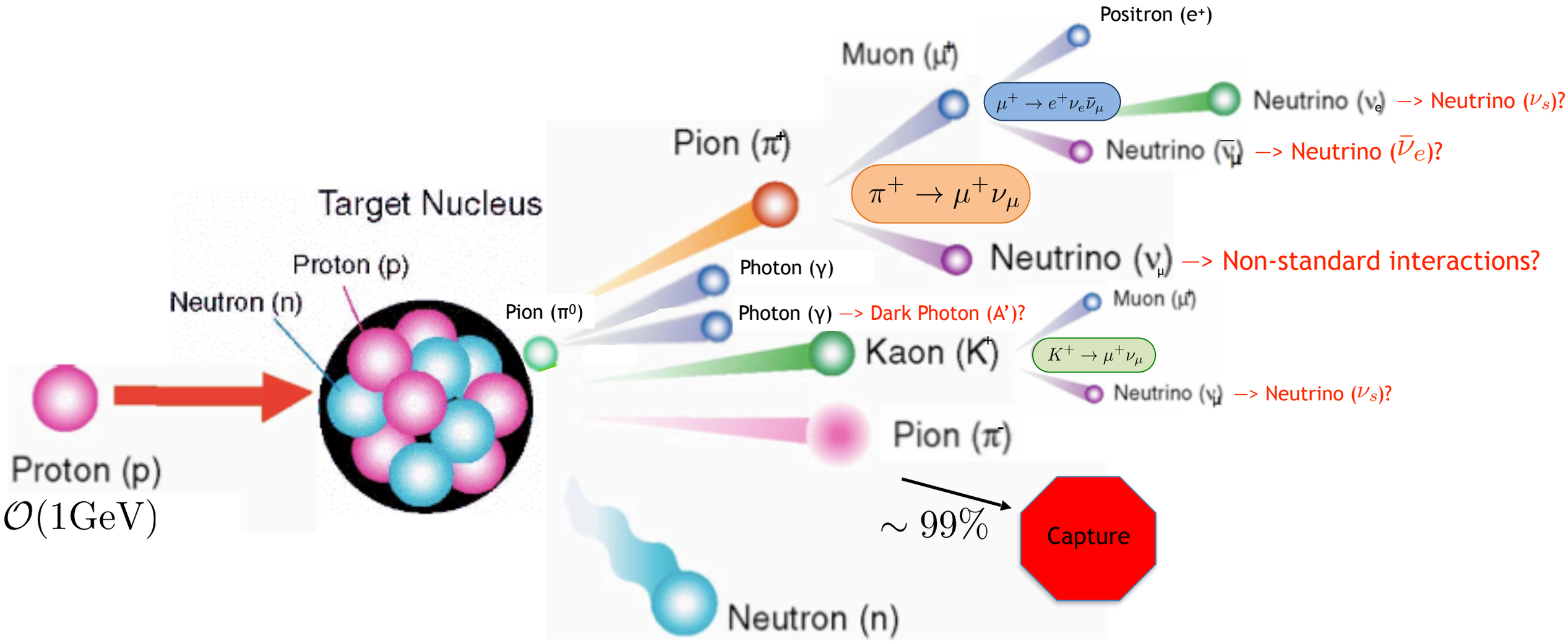


Figure 1: Regions of relic abundance parameter (mixing strength) Y vs. dark matter mass m_χ for 6×10^{21} POT that could be achieved in a five year run with dedicated proton beam dump medium energy running in the PIP-II era. Left is the signal sensitivity for NCπ^0 and right for NC-electron scattering 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 dark sector models, e.g. hadrophilic DM

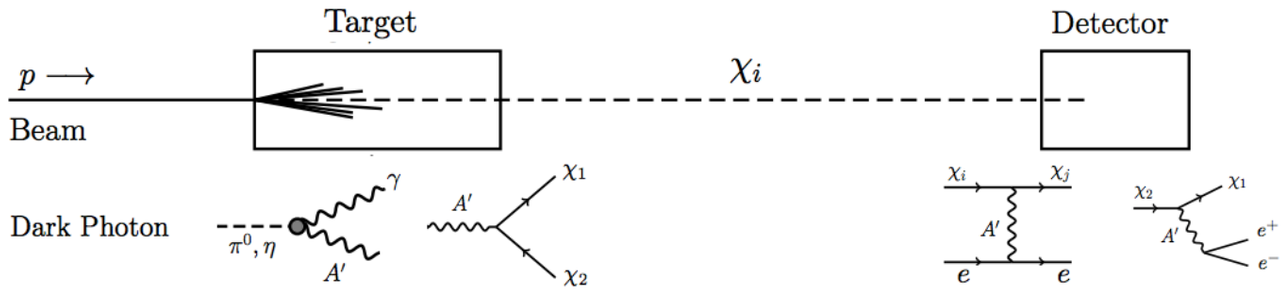
Fixed-Target Searches for New Physics with O(1 GeV) Proton Beams at Fermi National Accelerator Laboratory

PIP-II is <u>simultaneously</u> 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 Dark Matter (LDM) Searches
  - Decay and/or scattering signatures



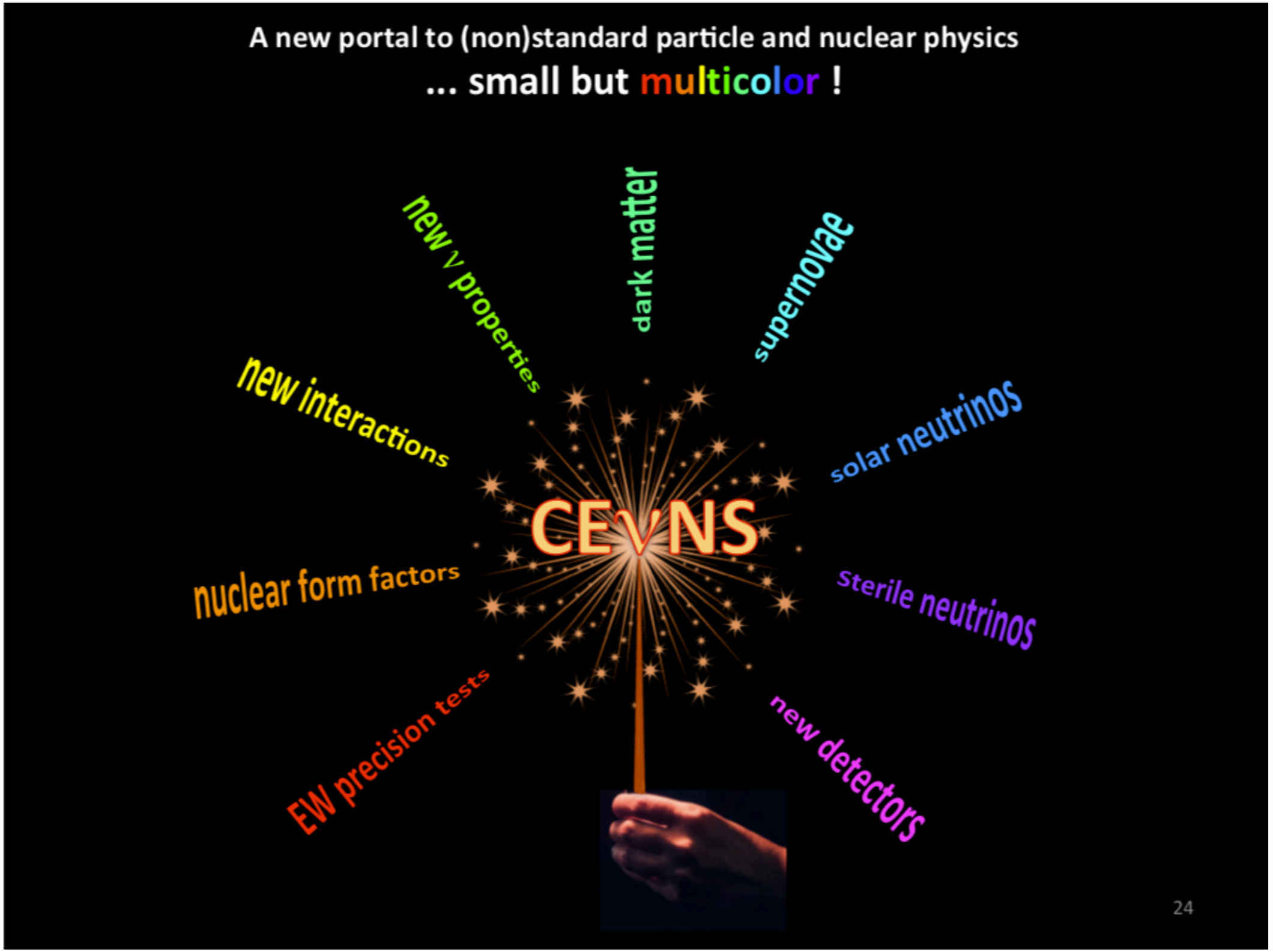
- Light Sterile Neutrino Searches
  - Both appearance and disappearance possible

- Coherent elastic neutrino-nucleus scattering (CEvNS)
  - See next slide
  - Provides new way to search for LDM and light sterile neutrinos: NF02 mini-workshop talk
    - CEvNS is neutrino flavor-agnostic —> definitive search for steriles via neutrino disappearance

- 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.



Eligio Lisi, NuINT 2018

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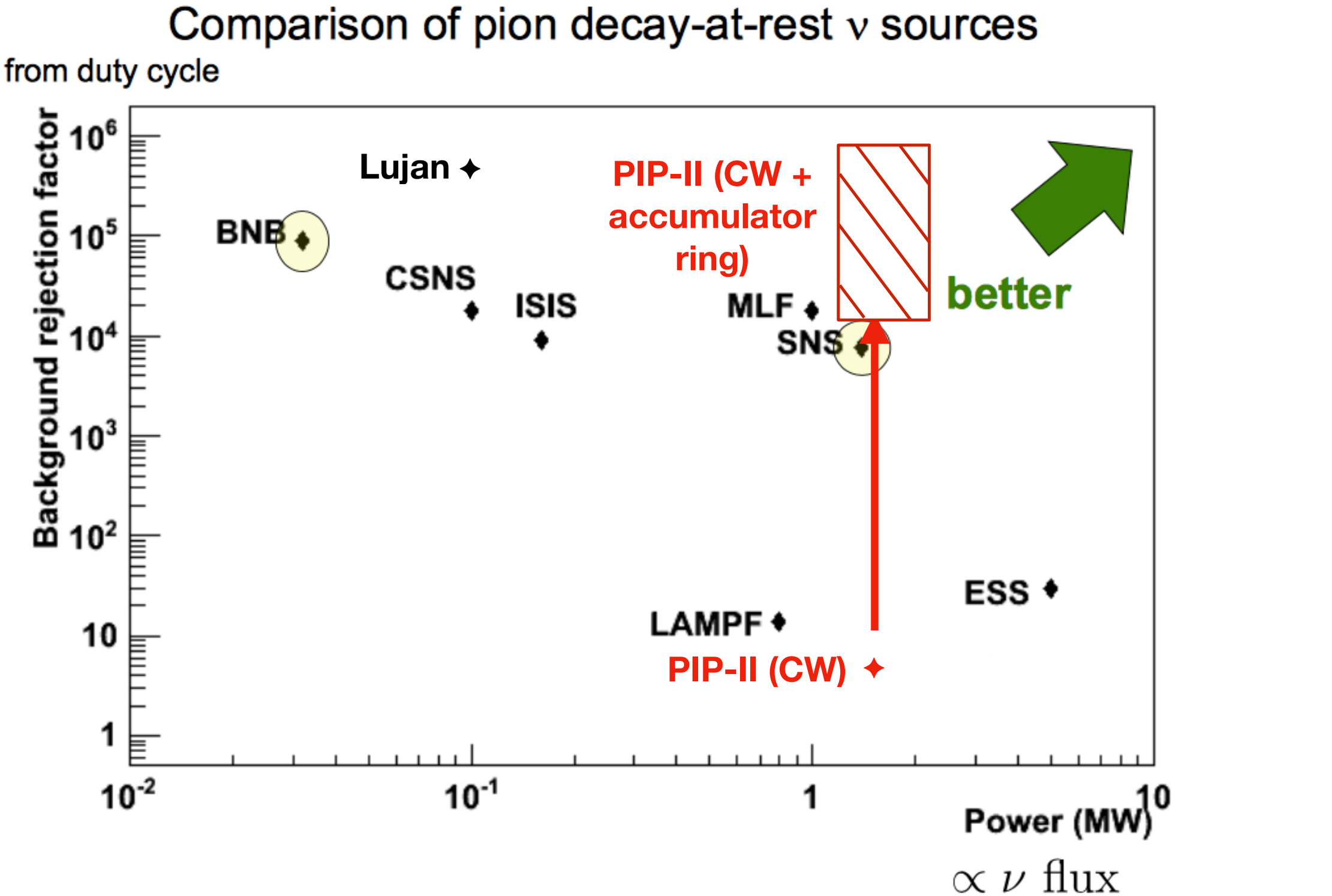
Accumulator Ring Needed For Ultimate Physics Reach



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Implementing GeV Proton Beam Dump at Fermilab

- New Booster-sized, permanent magnet accumulator ring (in a new or existing beam enclosure) could compress beam into pulses suitable for a proton beam dump facility (~320 ns goal with a O(10^{-5}) duty factor)

- Initial operation at 100 kW with 800 MeV protons could be realized within the decade, with an upgrade path to MW-class proton beams in the GeV range
  - See e.g. "FNAL Booster Storage Ring" LOI

- Beam dump facility can be optimized and designed from the ground-up for HEP (neutron suppression, large detectors, flexible locations), including sensitive dark sector and CEvNS-based active-to-sterile searches

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.

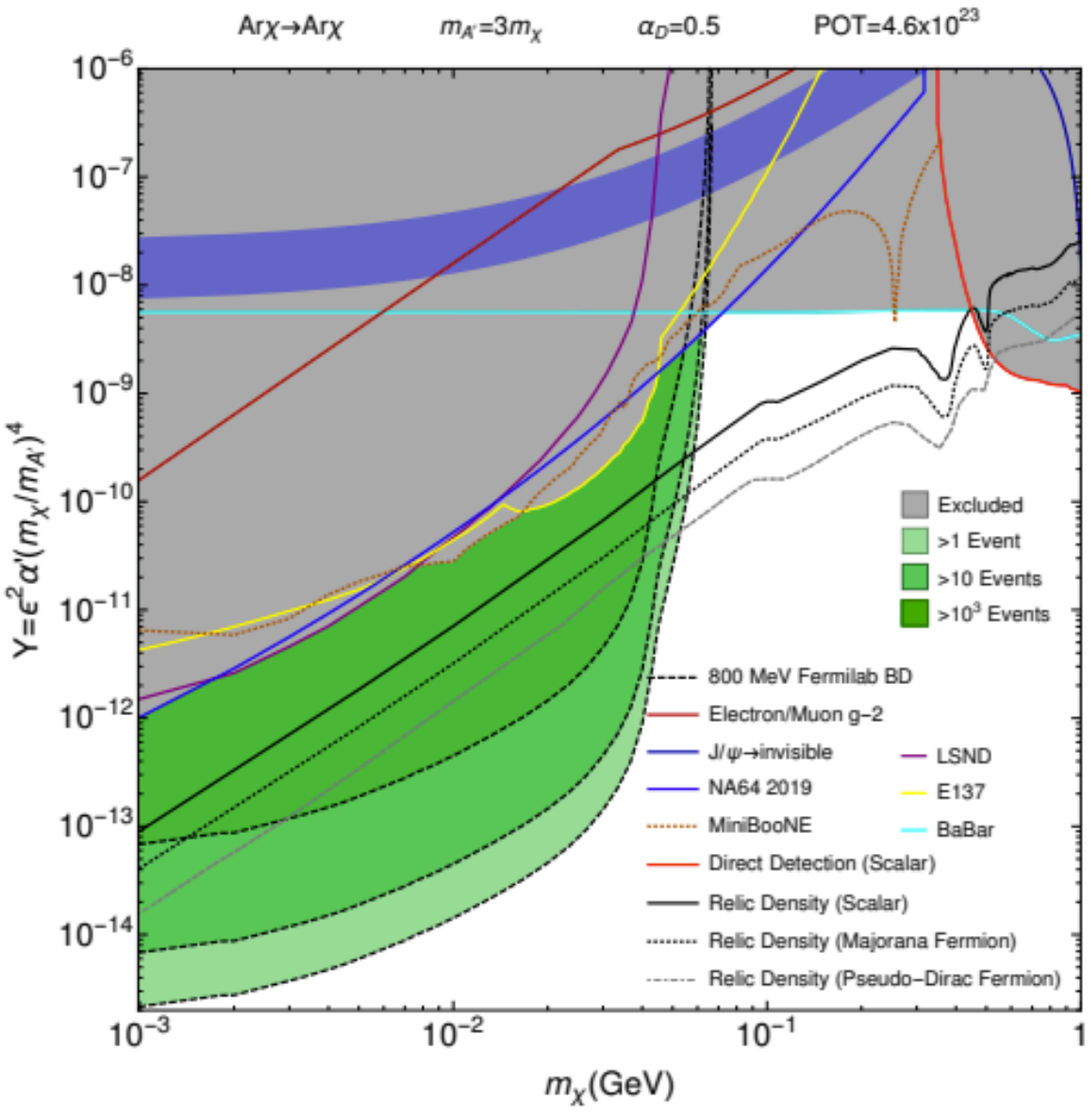

FIG. 1. Fermilab beam dump facility argon recoil event sensitivity curves for 4.6×10^{23} protons on target compared to thermal relic density targets and existing 90% exclusion limits as a function of the dimensionless scaling variable $Y = \epsilon^2\alpha(m_\chi/m_{A'})^4$, assuming $\alpha = 0.5$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

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 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

Thank you