Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

New Proton Beam Dump Experiments at Fermilab: PIP2-BD and SBN-BD

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Snowmass Joint Workshop on New Physics Opportunities with Neutrino Experiments

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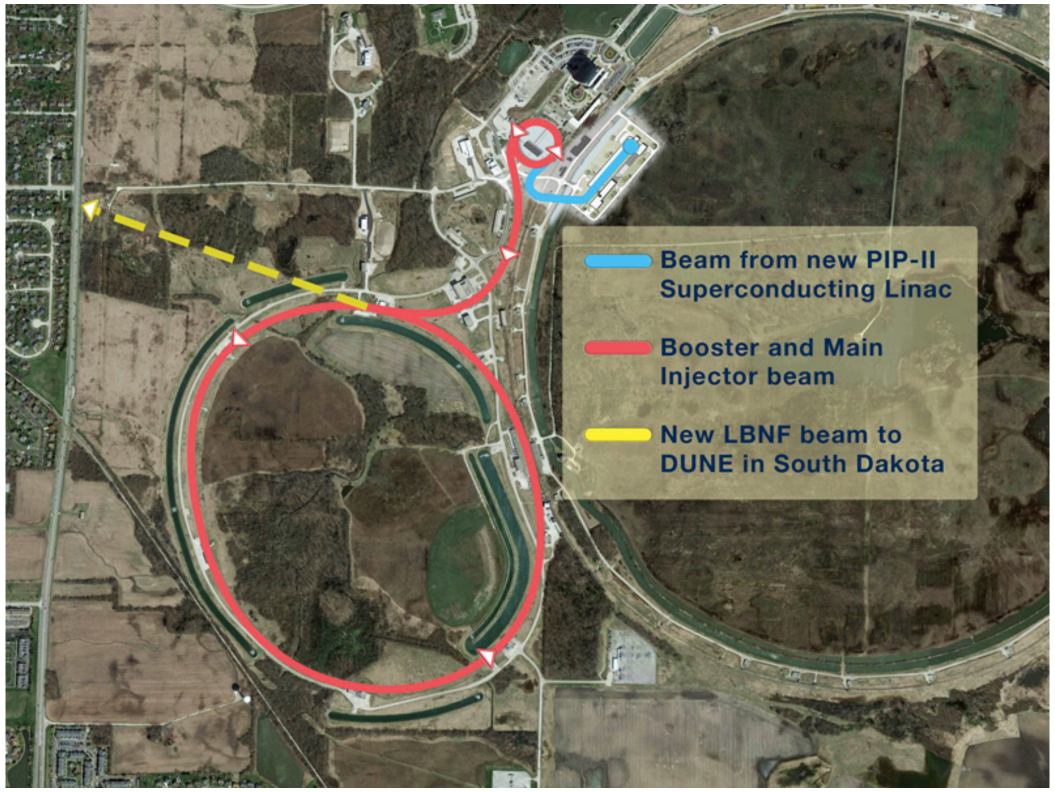
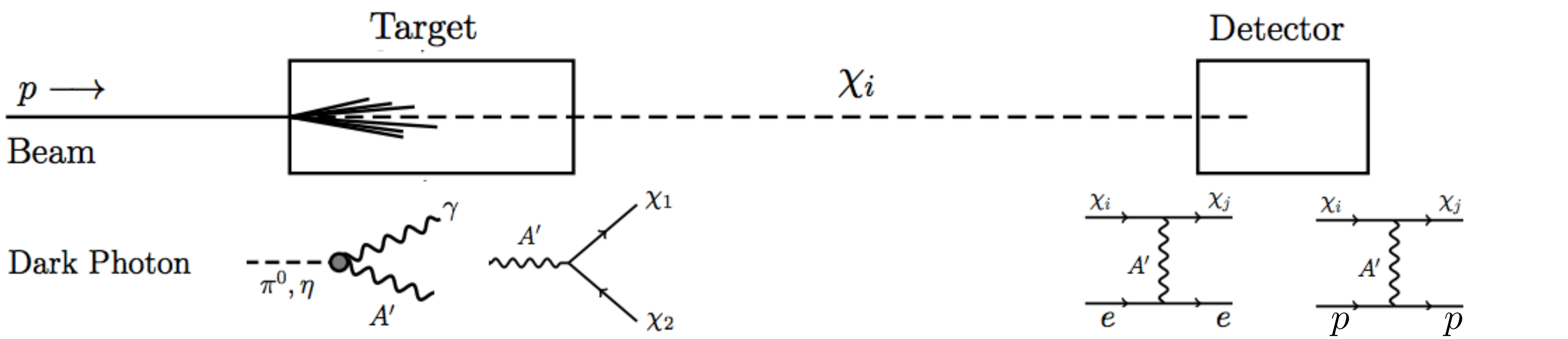
The PIP-II Project

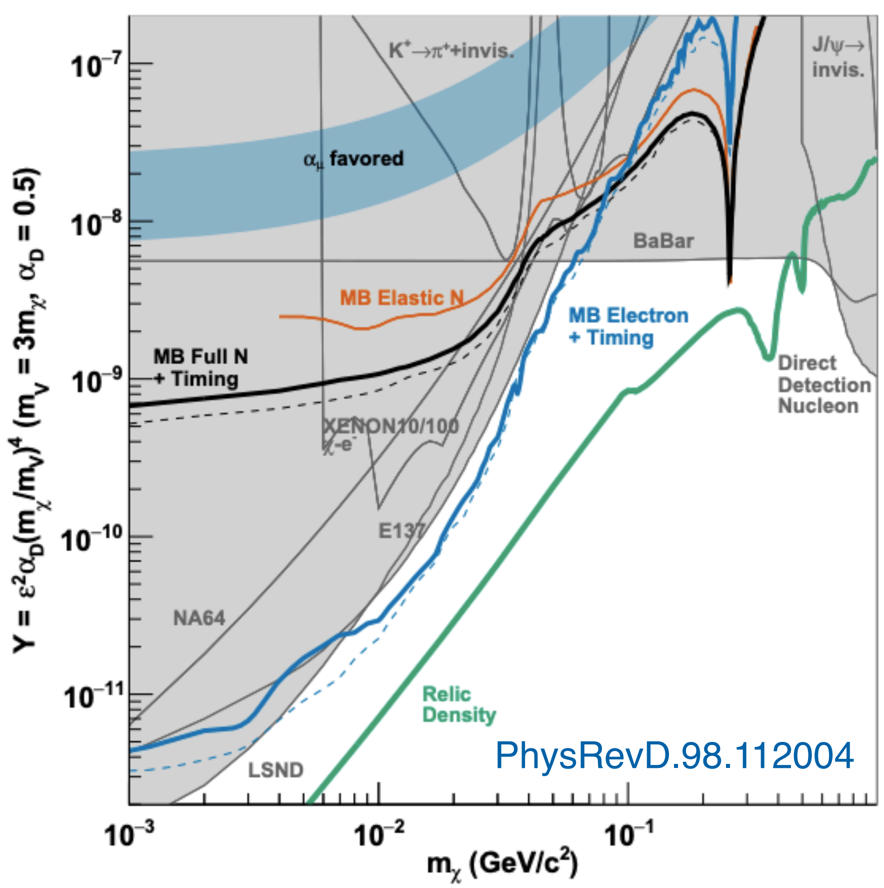
- Upgrade to the current Fermilab accelerator complex driven by DUNE physics goals
- Among highest power ~GeV proton beams in the world
  - Capable of 1.6 MW at 800 MeV proton energy CW
  - Small percentage of protons (1.1%) needed to support DUNE
- Can we leverage existing upgrade plans to search for other exciting physics at Fermilab?
  - Upgrade path for FNAL accelerator complex: https://arxiv.org/pdf/2106.02133.pdf
  - O(1 GeV) stopped-pion neutrino source program leveraging the available beam
    - Possible if PIP-II is coupled to an accumulator ring
  - O(10 GeV) dedicated proton beam dump search at BNB using the existing SBN detectors

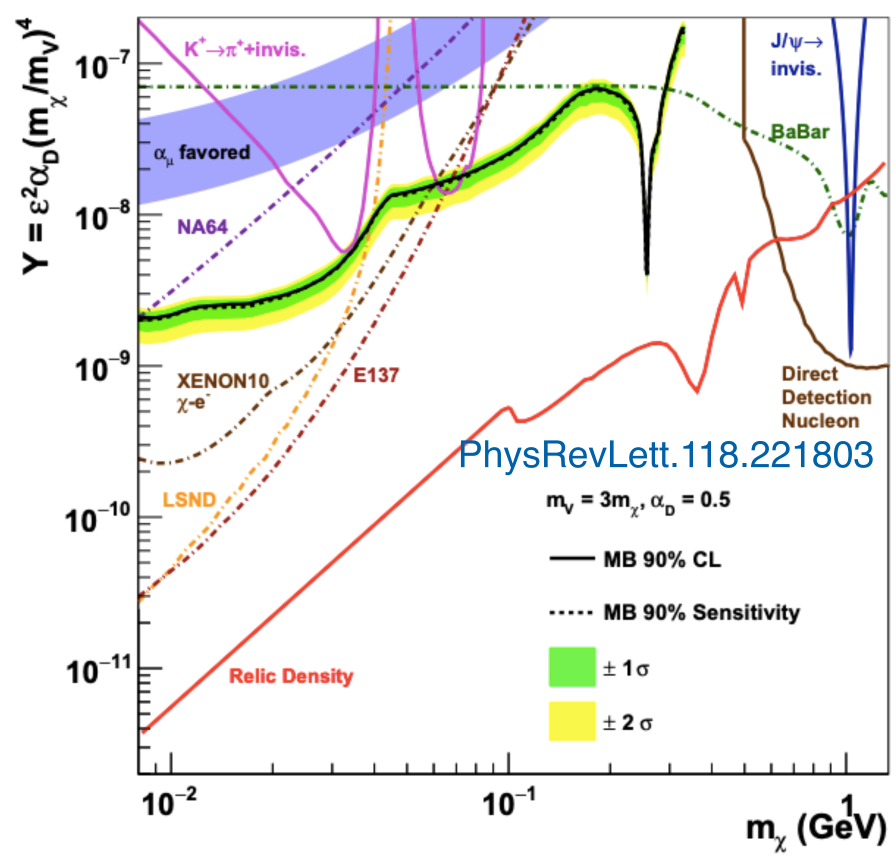


New Physics Searches Beyond 3+N Sterile Neutrinos on the BNB

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

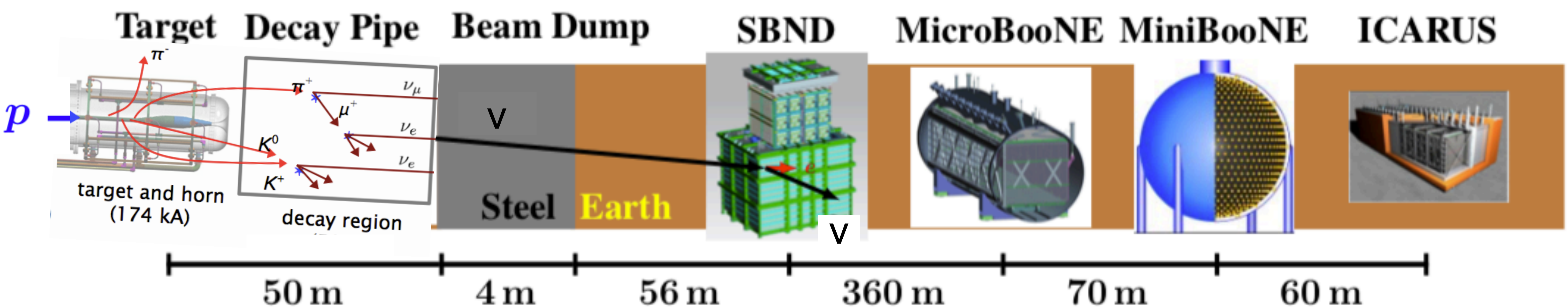






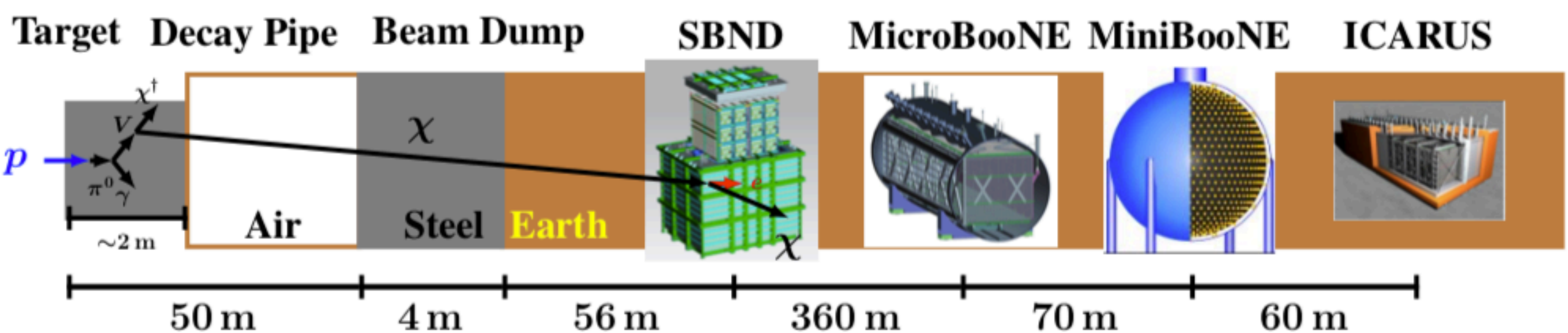
Short Baseline Neutrino program integration

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 LDM search program:



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

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
  - Future upgrades could increase the beam power to 1.2 MW
- 6×10^{21} Proton on Target (POT) in a five-year run
  - Achieve an order of magnitude better sensitivity to a benchmark vector portal scalar dark matter model than the current MiniBooNE dark matter sensitivity
  - Reduced neutrino background from the dedicated beam dump, the detector's close proximity to the beam dump, and higher protons on target.
- LOI submission on this topic: https://www.snowmass21.org/docs/files/summaries/RF/SNOWMASS21-RF6_RF0-NF3_NF0-AF5_AF0-084.pdf

DM Event Sensitivities

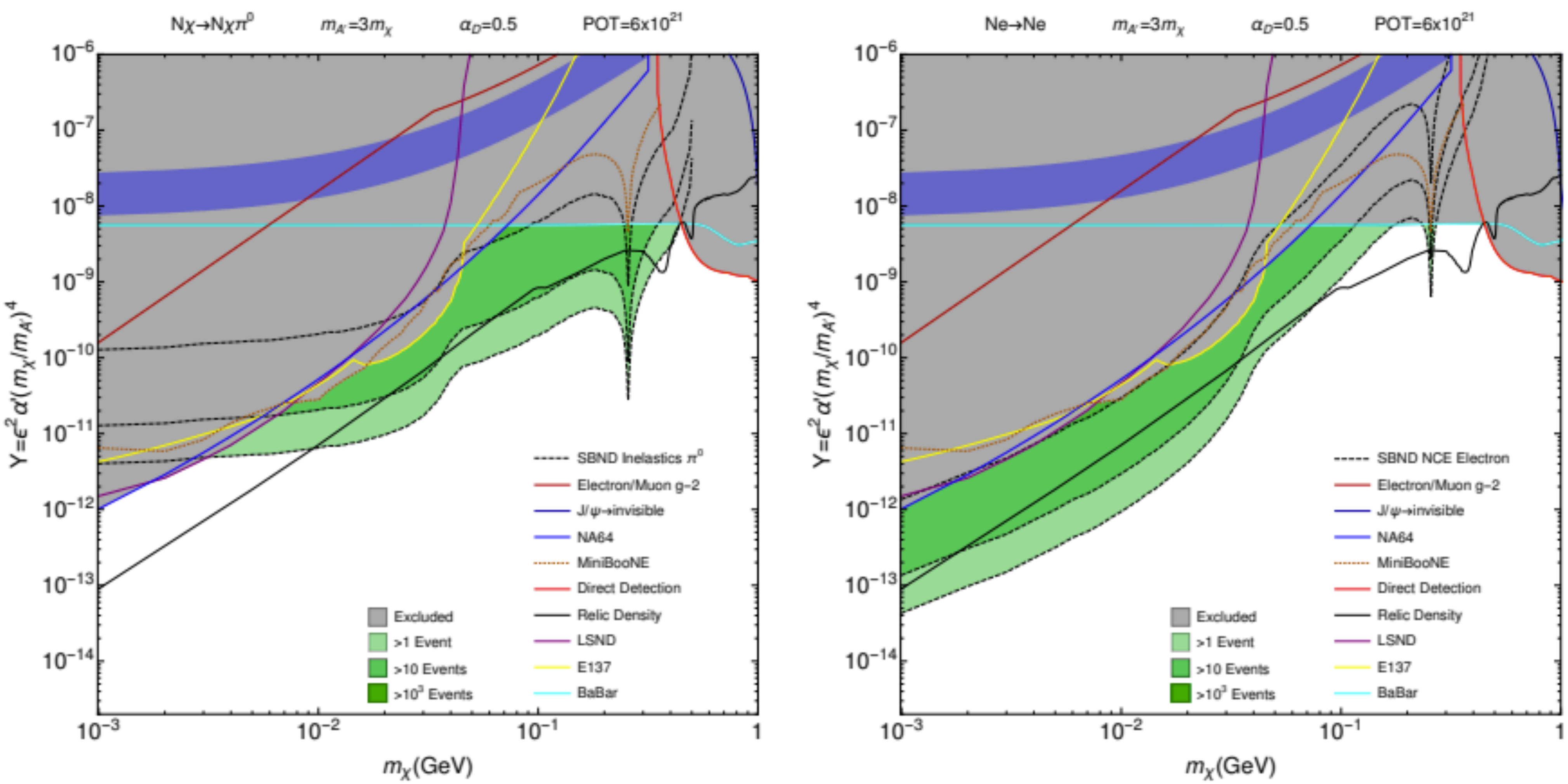
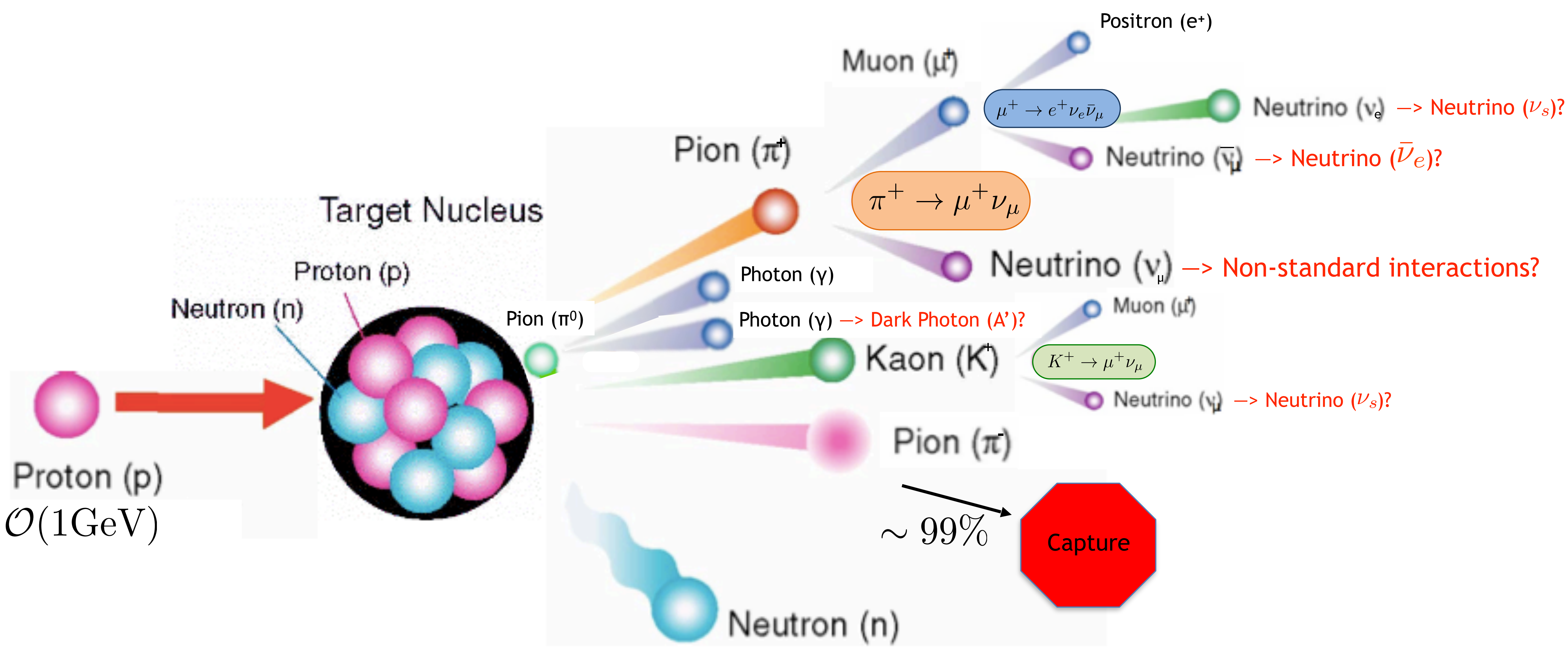


Figure 1: Regions of relic abundance parameter (mixing strength) Y vs. dark matter mass m_χ for 6×10^{21} POT that could be achieved in a five year run with dedicated proton beam dump medium energy running in the PIP-II era. Left is the signal sensitivity for NCπ^0 and right for NC-electron scattering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

Stopped-pion (or decay-at-rest) neutrino source

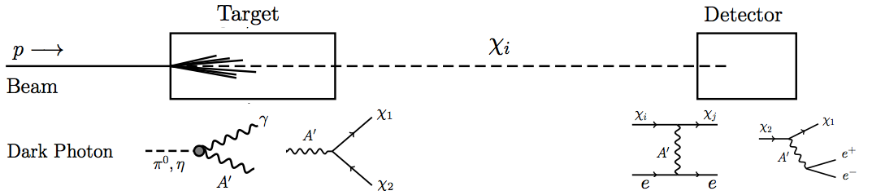


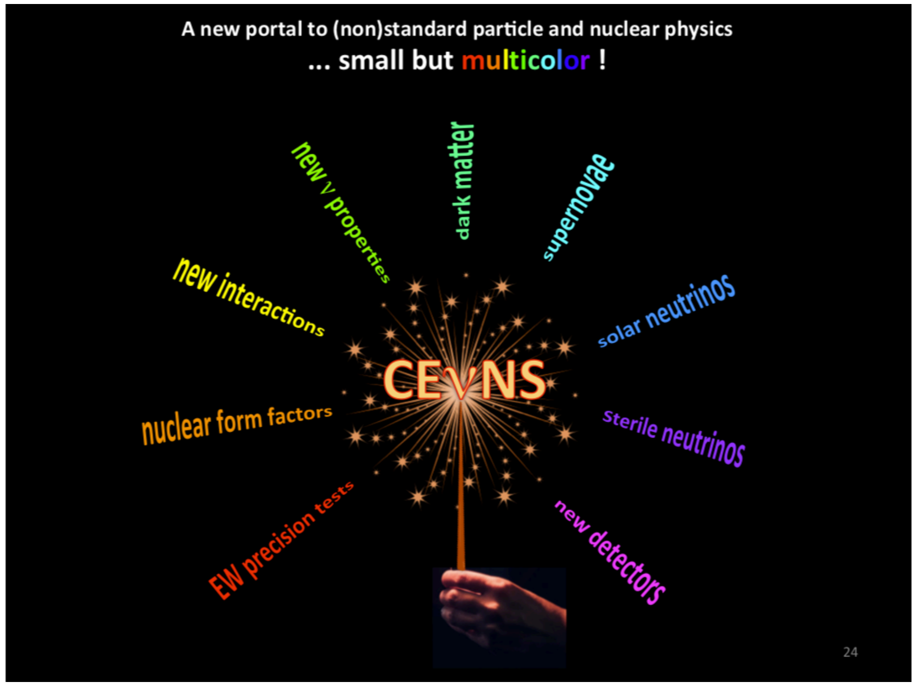
ν_μ with pion decay lifetime (~26 ns), ν_e and anti-ν_μ with muon decay lifetime (2.2 μs)

Such a source possible at Fermilab if PIP-II coupled to an accumulator ring!

Physics available with O(1 GeV) stopped-pion source

- Physics Opportunities At Such a Facility
  - Light dark matter (LDM) / dark sector searches
    - Decay and/or scattering signatures
  - Coherent elastic neutrino-nucleus scattering (CEvNS)
    - Provides new way to search for LDM and sterile neutrinos
  - Light Sterile Neutrino Searches
    - Both appearance and disappearance possible
  - Searches for Non-standard interactions (NSIs), tests of the Standard Model
  - Neutrino Cross Section Measurements
  - Neutrino-Electron Scattering (LSND-like), MeV-scale
  - Additional topics:
    - Searches for axion-like particles, 3-ν oscillations, etc.





E. Lisi, NuINT 2018

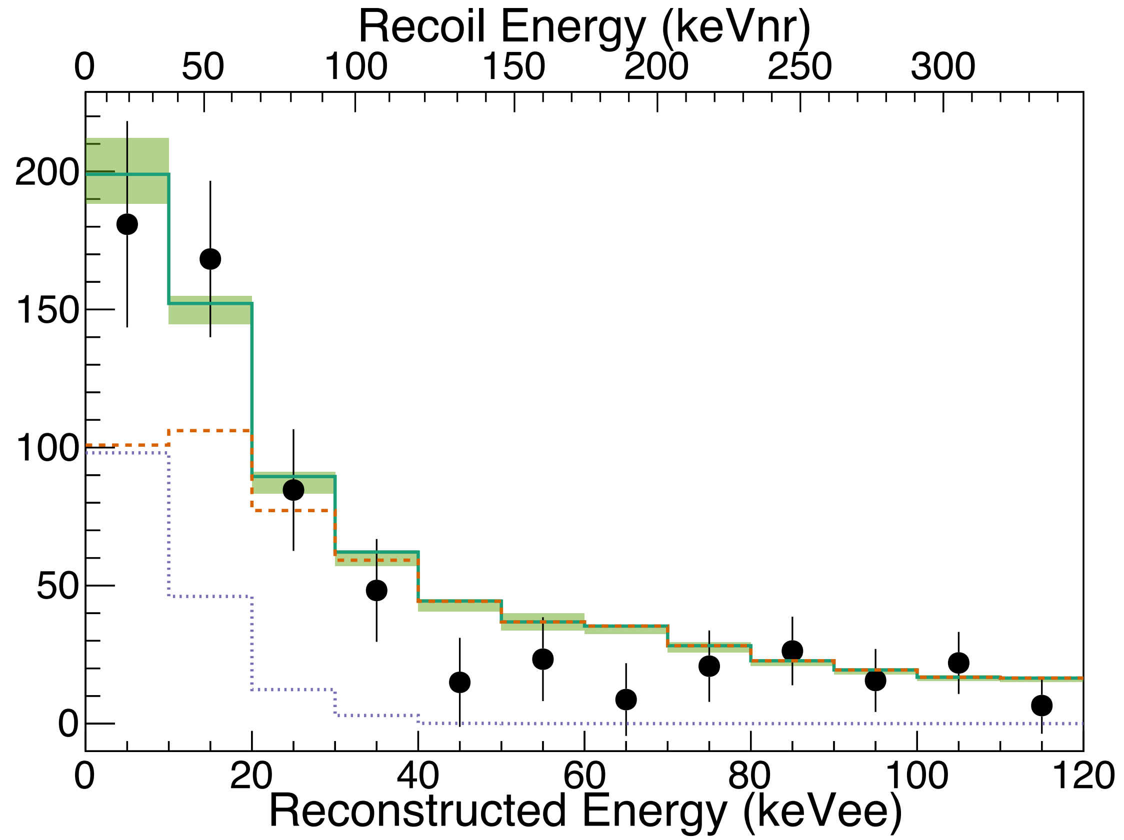
Possible evolution of PIP-II Accelerator Complex

- Possible upgrade paths to an accumulator to either increase the beam power or decrease the pulse width to reduce backgrounds

Technology	Booster Accumulator Ring	ENIGMA-like Accumulator Ring	RCS Accumulator Ring
Intensity	1e13 protons/spill	4.8e12 protons/spill	3.5e13 protons/spill
Repetition Rate	100 Hz	100 Hz	120 Hz
Proton Energy	0.8 GeV	1.2 GeV	2 GeV
Beam Power	130 kW	92 kW	1.3 MW
Pulse Width	2 us	20 ns	2 us
Timescale	With completion of PIP-II	In the 2030s	in the 2030s

Liquid Argon (LAr) for low-energy new physics searches

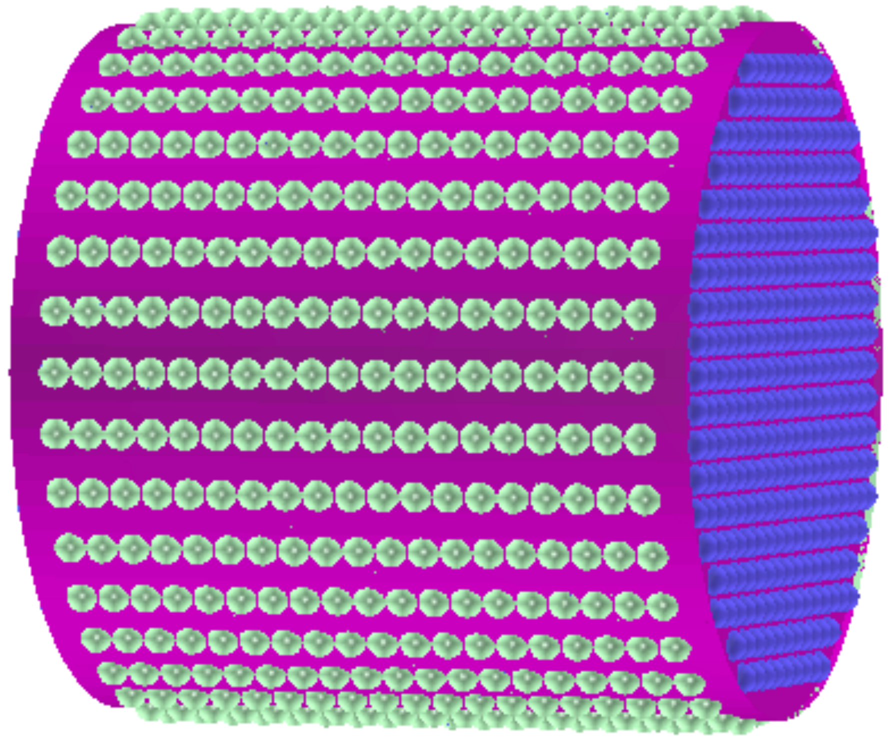
- Large scintillation yield of 40 photons/keV
- Well-measured quenching factor
  - Conversion between nuclear recoil response and scintillation response
- Strong pulse-shape discrimination (PSD) capabilities for electron/nuclear recoil separation
- First CEvNS detection on argon at >3σ significance by COHERENT!
- Move toward precision physics and new physics searches with large detectors



D. Akimov et al. (COHERENT), Phys. Rev. Lett. 126 (2021) 1, 012002

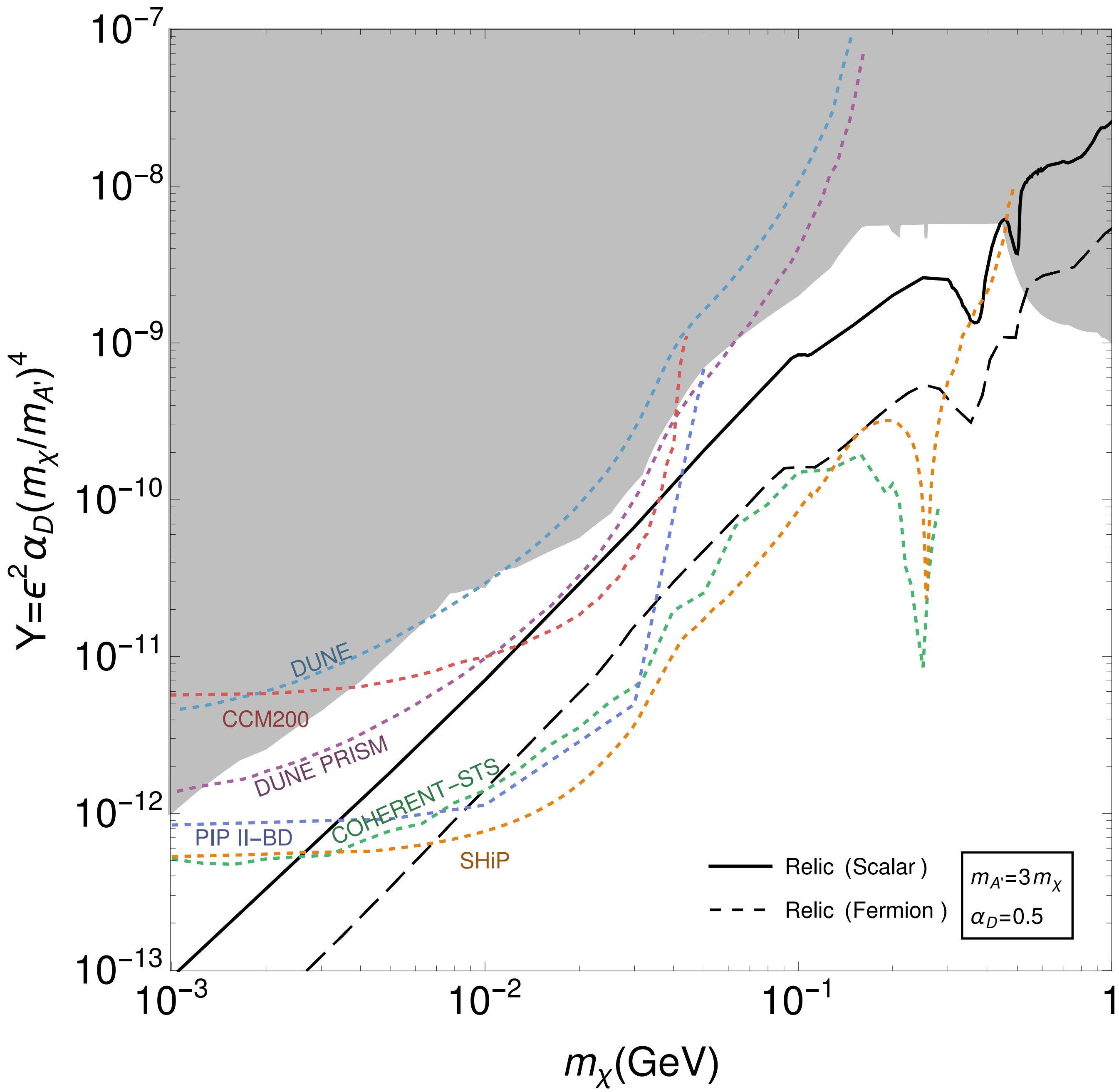
Proposed Detector at PIP-II

- Single-phase, scintillation only liquid argon detector
- Fiducial (active) volume - 4.5 m right cylinder inside box, **~100 ton fiducial volume**
- Surround sides and endcaps of detector volume with TPB-coated 8” PMTs
  - TPB-coated reflector on sides and endcaps for photocoverage gaps
- Preliminary simulations suggest 20 keVnr threshold achievable with this detector
  - Predicted O(100k) CEvNS events/year!
- Existing experiments such as COHERENT and CCM are key for testing many of the experimental techniques to successfully reach the physics goals of a 100-ton scale detector
- Fermilab-funded LDRD to study dark sector searches at proposed stopped-pion facility using PIP-II



PIP-II BD LDM Search at Fermilab

- Vector-portal model
- Stopped-pion neutrino sources place strong limits on LDM
  - Interaction identical to CEvNS
  - DM signal excess over CEvNS
    - Understanding of beam-related backgrounds important!
- PIP-II BD light DM search probes these models
  - Assumes beam power of 90 kW, 100 Hz with a 20 ns beam pulse
  - 5 year run of 5.65e22 POT
  - On axis, 18 m downstream from target



P. deNiverville, LANL

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

B. Dutta et al., Phys. Rev. Lett 124 (2020) 121802

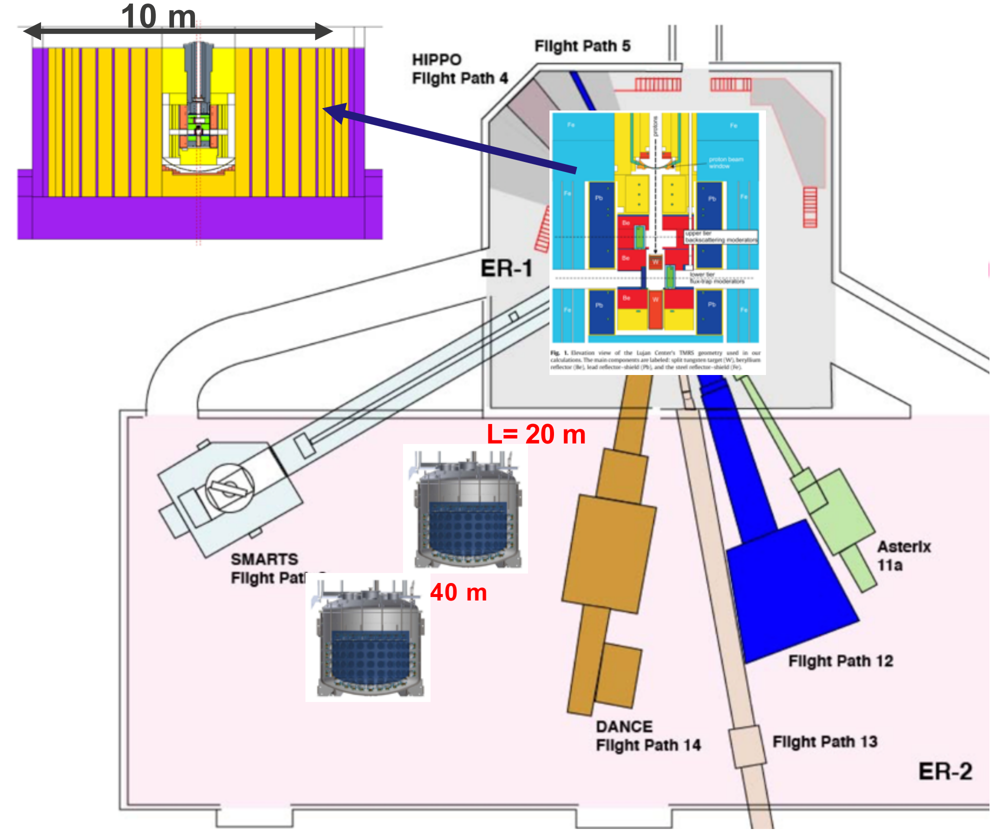
Summary

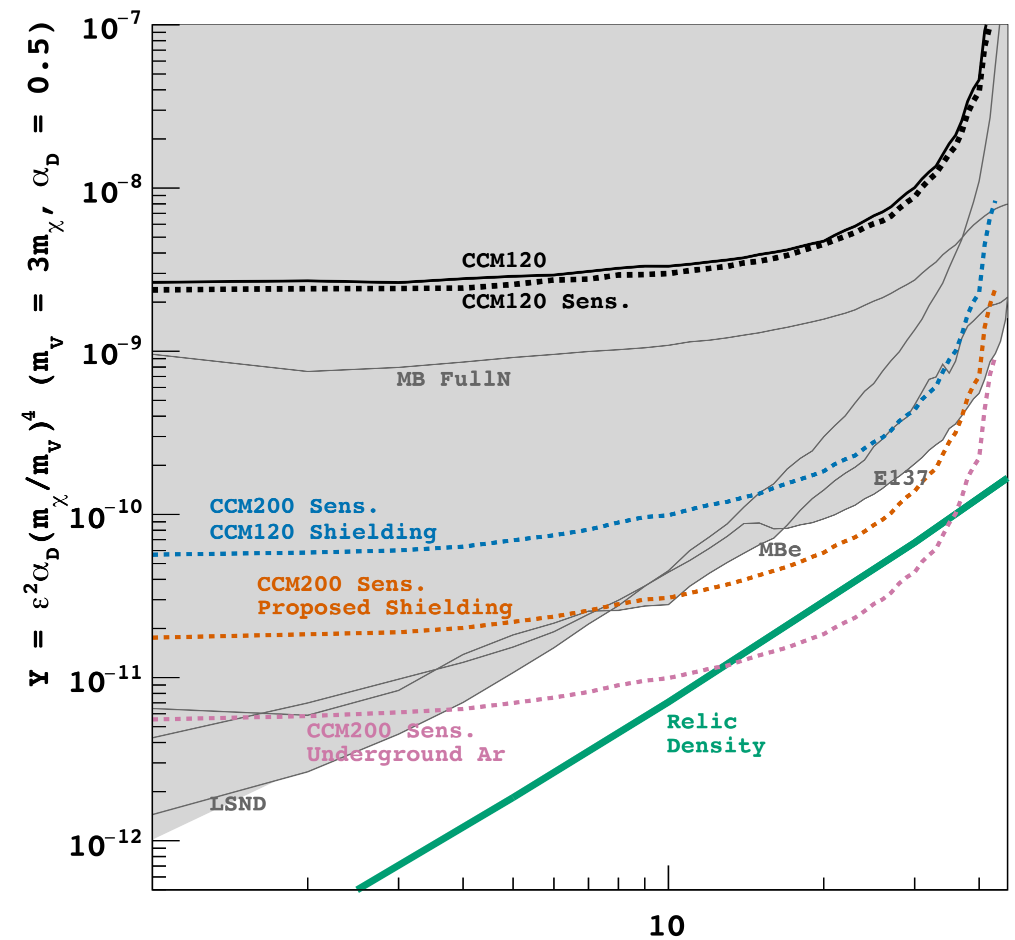
- Completion of PIP-II will support initial 1.2 MW beam to LBNF and can also simultaneously support 1 GeV and 10 GeV beams for other uses
- Further upgrades such as an accumulator ring could produce a stopped-pion neutrino source on par with the most powerful in the world
- Stopped-pion sources provide access to a host of physics opportunities such as through CEvNS
- **Can build stopped-pion neutrino program with facility optimized for HEP searches**
- Preliminary studies using a 100 ton liquid argon detector show the ability for leading probes on light dark sector searches
- We are looking to grow our collaboration! If you’re interested in this effort or have questions, please contact us

Backup

Coherent CAPTAIN-Mills (CCM)

- Operating at Lujan Center at LANL
  - 80 kW, 20 Hz, 270 ns beam width
- 10-ton single-phase scintillation-only LAr detector
- Plans for two identical detectors to perform sterile neutrino search
  - Upgrades to initial detector to improve light collection, additional shielding to reduce beam-related backgrounds
- Also search for sub-GeV dark matter and other BSM models such as axion-like particles (ALPs)
- Successes and lessons learned will help inform large LAr detector at Fermilab

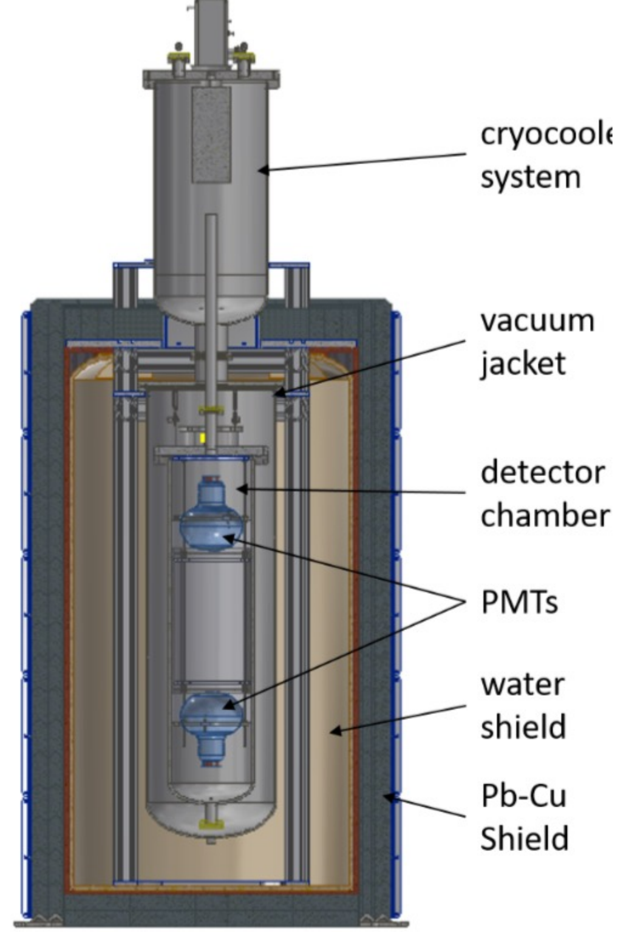


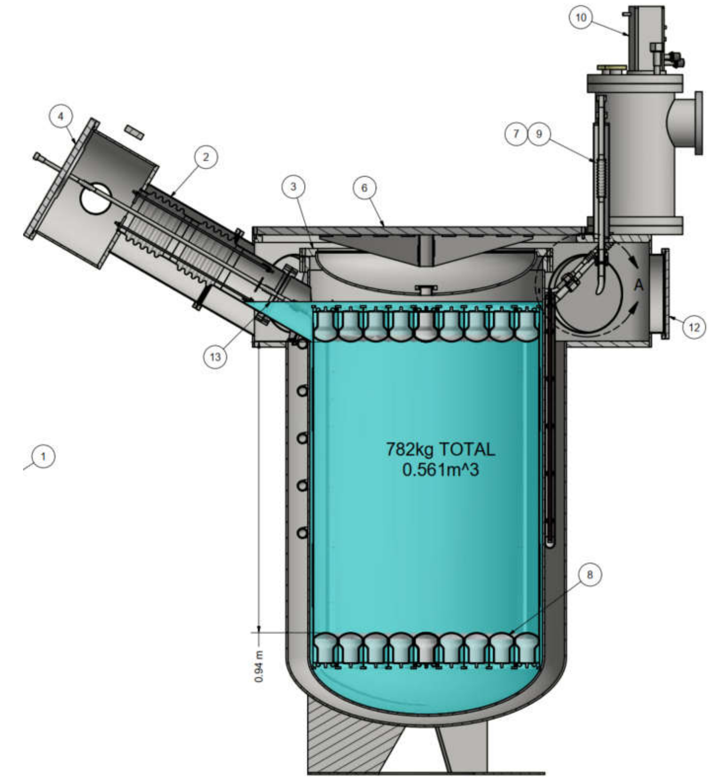


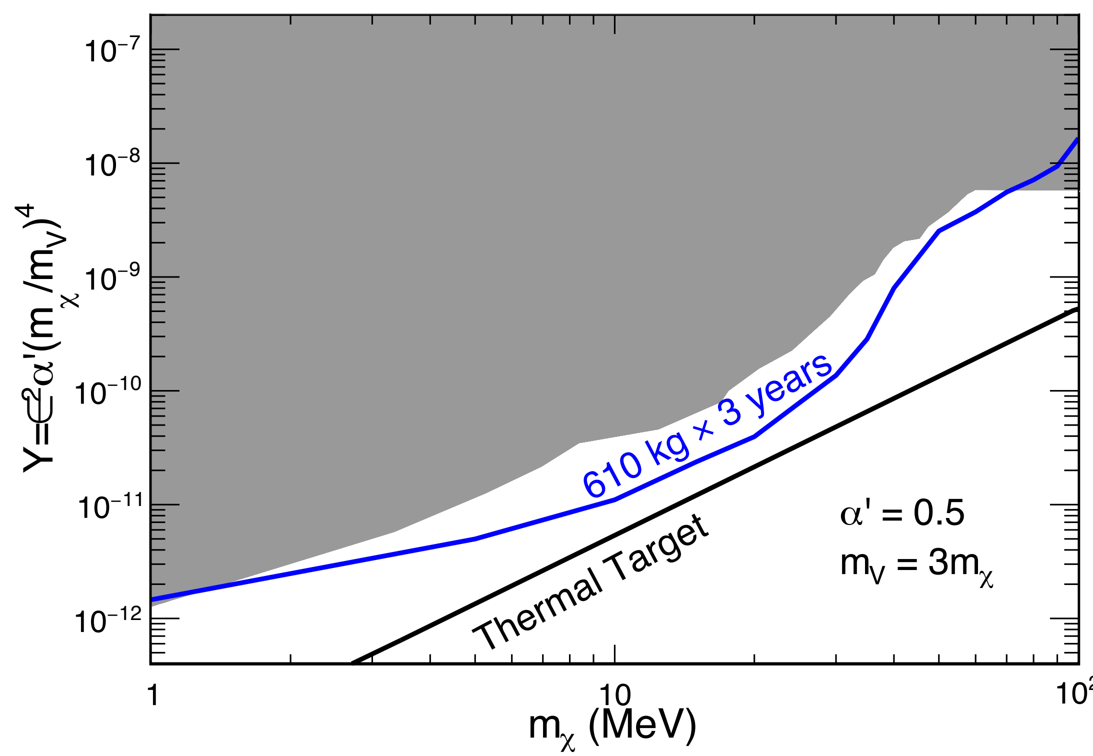
https://arxiv.org/abs/2105.14020 [hep-ex]

COHERENT LAr

- COHERENT operating LAr detector at the SNS at ORNL
  - Beam at 1.4 MW. 60 Hz, 350 ns FWHM
- Currently operating 24 kg COH-Ar-10 detector
- Moving towards ton-scale detector COH-Ar-750
  - O(1000) CEvNS events/year
  - Light dark matter search
  - Design for sensitivity to MeV-scale physics in addition to CEvNS
    - ν_e-Ar CC/NC measurements useful for DUNE low-energy program



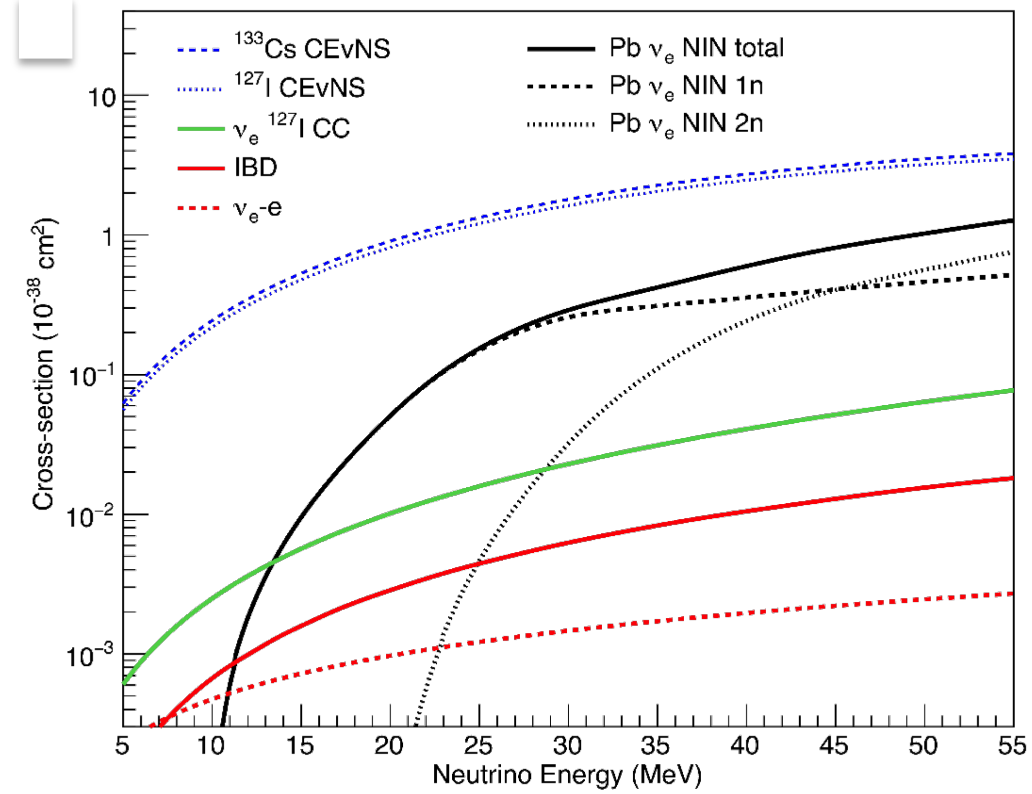


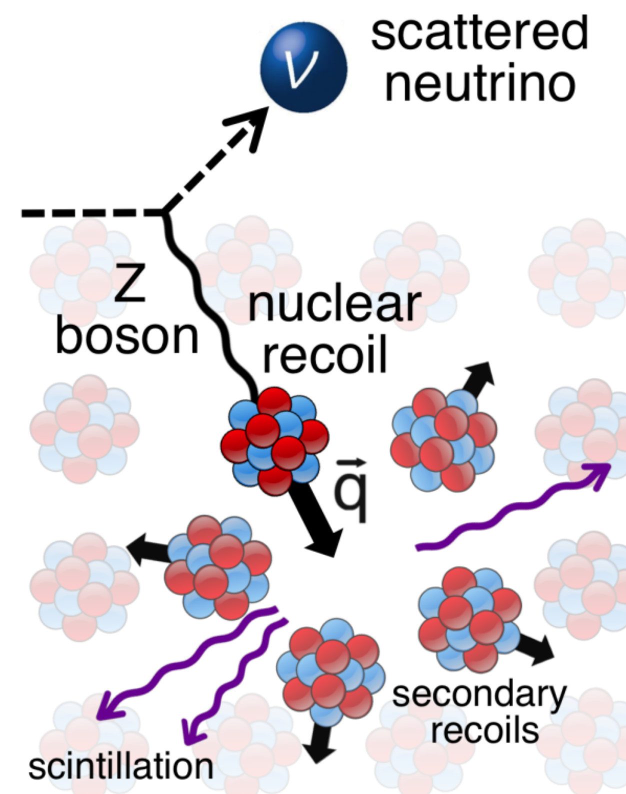


Phys. Rev. D 102, 052007 (2020)

Coherent Elastic Neutrino-Nucleus Scattering (CEvNS)

- First mentioned by Freedman in 1974
- First detected by COHERENT Collaboration with CsI[Na] target in 2017 at SNS at ORNL
- Neutrino interacts coherently with nucleons in target nucleus
- Signature is very-low-energy nuclear recoil
  - O(10 keV) for O(10 MeV) neutrino
- Largest low-energy neutrino cross section on heavy nuclei
- Distinct N² dependence of cross section





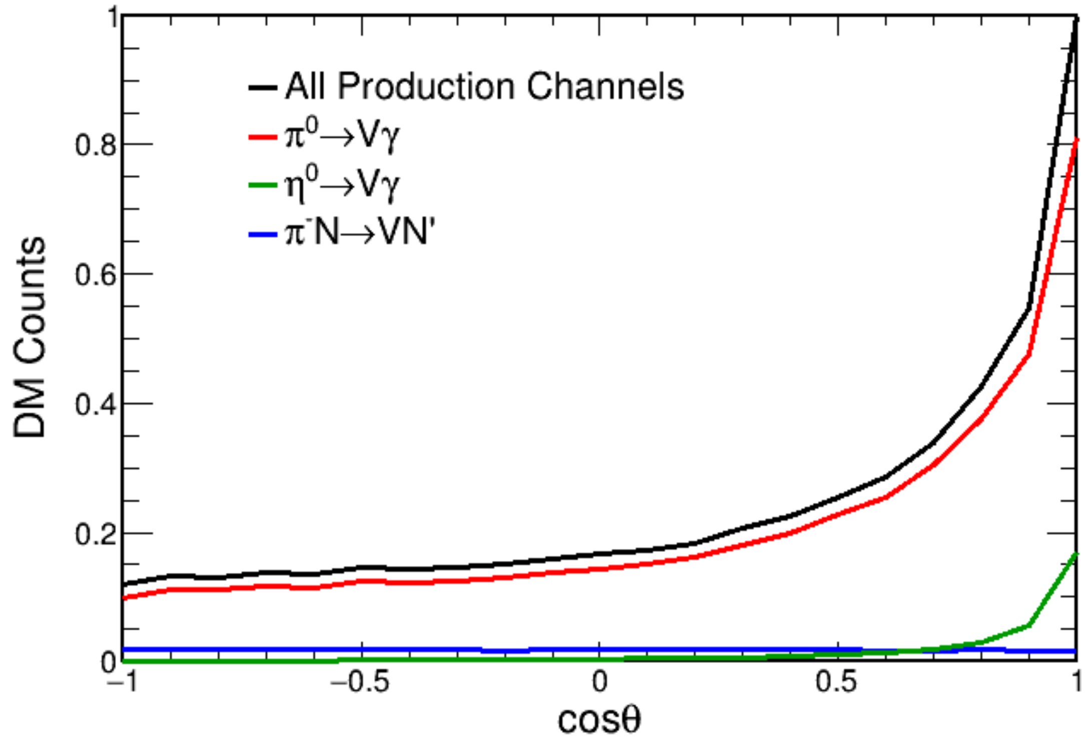
D. Akimov et al. (COHERENT). Science 357, 1123-1126 (2017)

Backgrounds for CEvNS-based physics searches with LAr

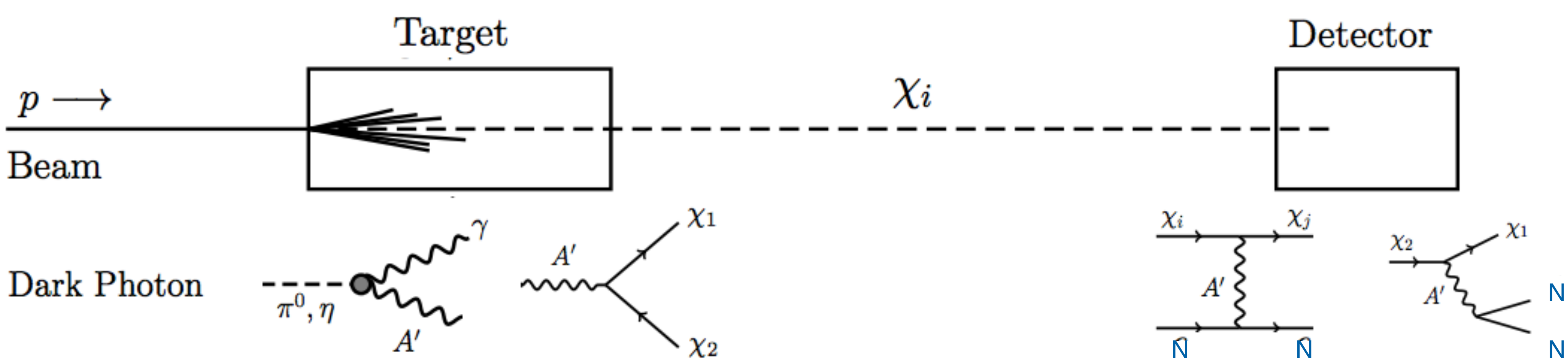
- Main backgrounds to a low-threshold physics search in LAr:
  - Beam-related backgrounds (likely fast neutrons produced by the proton collisions with target)
    - Mitigate with lower Z target material, less neutrons produced than spallation neutron sources with high Z material and shielding
      - Shielding is a challenge, other measurements show this is an achievable goal in building a facility
  - Cosmogenically produced ^{39}Ar
    - Rates of 1 Bq/kg in atmospheric argon, a steady-state background
    - Mitigate with pulsed beam timing or acquiring argon with low ^{39}Ar content (underground argon)
      - Use in direct detection DM experiments show rate lowered to ~1 mBq/kg
- Electron-recoil backgrounds also mitigated by PSD

Boosted 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 boosted dark matter particles tilted towards forward direction
- Signature in detector also low-energy nuclear recoil



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

CEvNS-based Sterile Neutrino searches

- Stopped-pion source at Fermilab provides excellent opportunity for smoking-gun sterile search
  - Three flavors of neutrinos, with the ν_μ separated in time from the ν_e and anti-ν_μ
  - Using CEvNS, there are several disappearance searches available
    - Monoenergetic ν_μ disappearance at 30 MeV
    - Summed disappearance of ν_μ, ν_e and anti-ν_μ to ν_s
    - Constrain ν_μ -> ν_e oscillation parameters

Use coherent measurements of ν_μ plus combined $\left(\bar{\nu}_\mu + \nu_e\right)$ disappearance. to measure mixing elements U_{e4}^2 and $U_{\mu 4}^2$ with at common Δm^2.

Unitarity constraint: $U_{S4}^2 = 1 - U_{e4}^2 - U_{\mu 4}^2$

Oscillations to sterile neutrinos given by:

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

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

Standard Disappearance of active neutrinos:

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

$$\sin^2 2\theta_{ee} = 4U_{e4}^2\left(1 - U_{e4}^2\right)$$

Also, standard $\nu_\mu \rightarrow \nu_e$ Appearance given by:

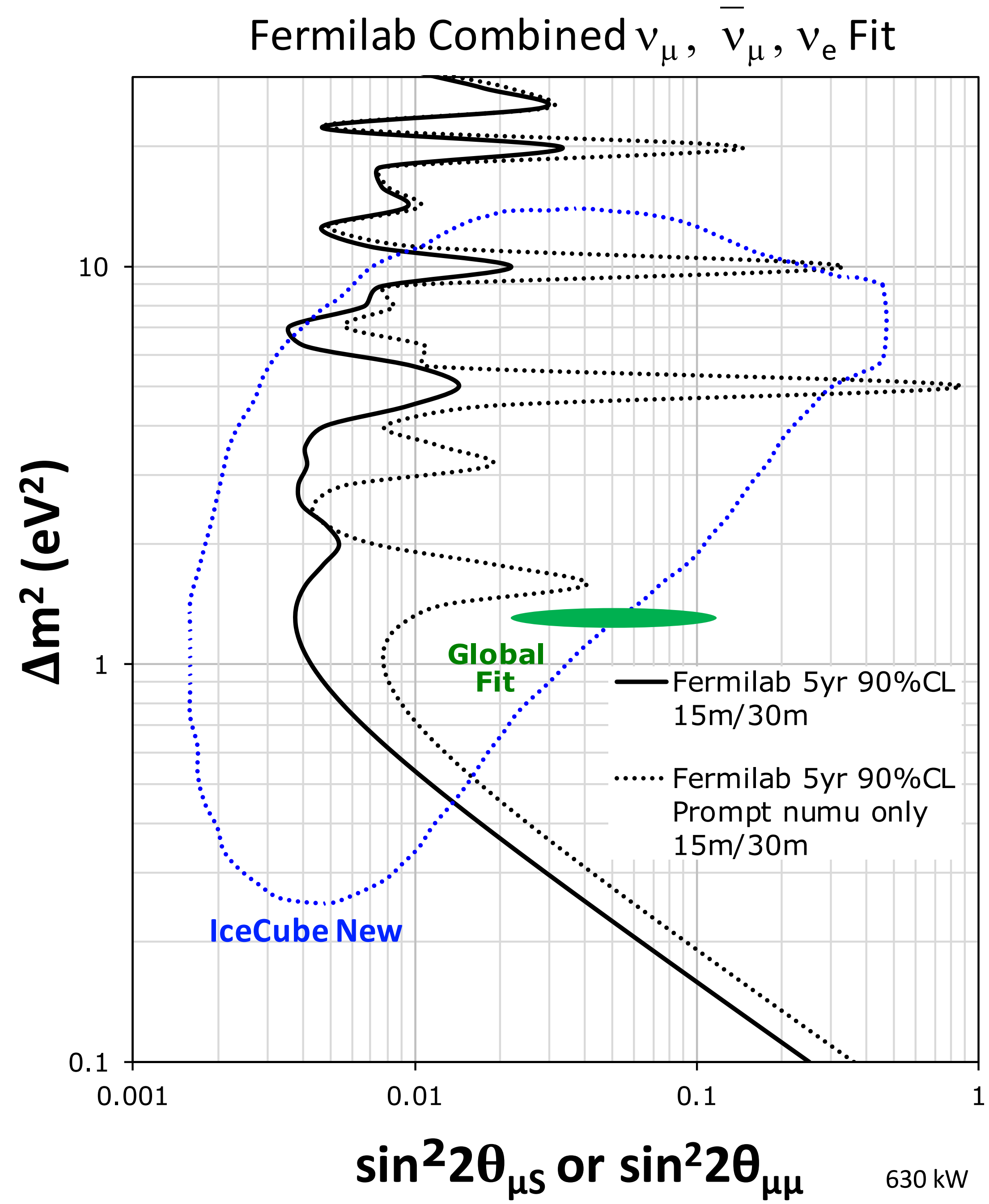
$$\sin^2 2\theta_{\mu e} = 4U_{e4}^2 U_{\mu 4}^2$$

M. Shaevitz, Columbia Univ.

PIP-II Sterile neutrino search

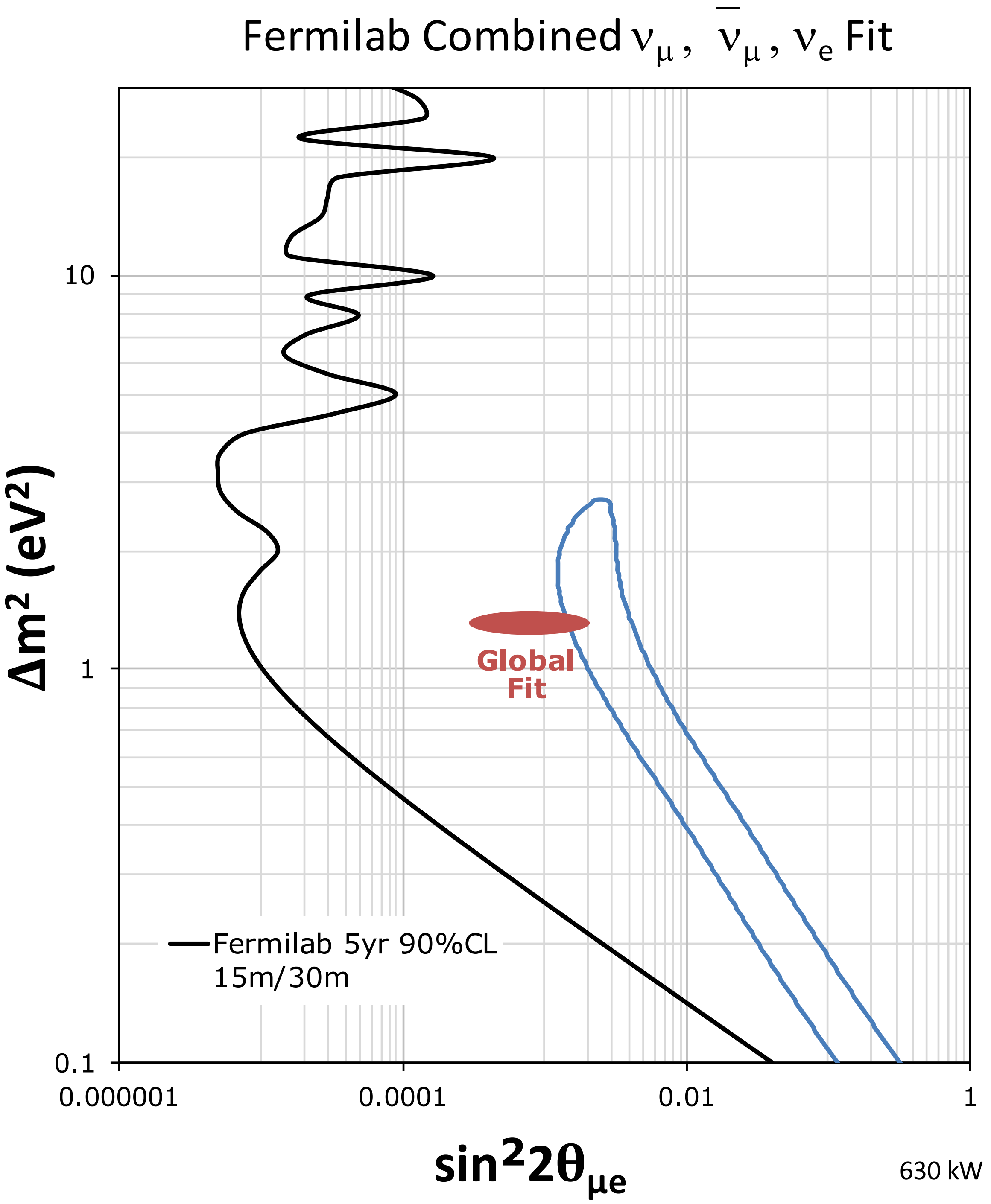
- Two identical, O(100 ton) detectors at L = 15 m and L = 30 m from target
- Optimize facility to reduce beam-correlated backgrounds to negligible levels
- Assume 1:1 signal/background for remaining beam-uncorrelated backgrounds
- Off-axis
- 630 kW beam power at 800 MeV, 75% uptime
- 20 keVnr threshold with 70% efficiency above threshold
- 9% normalization systematic uncertainty correlated between two detectors
  - 36 cm path length smearing

ν_μ disappearance

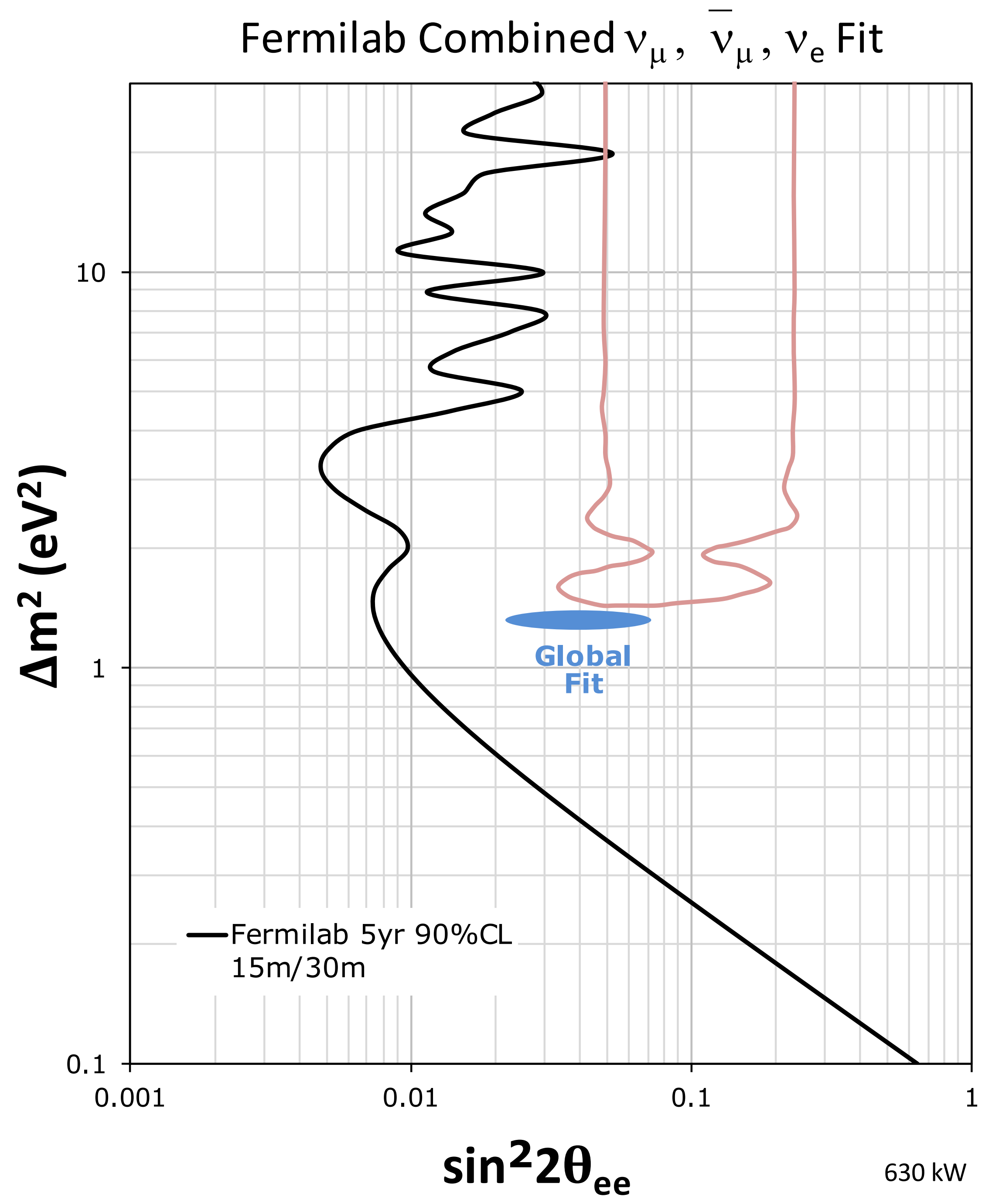


M. Shaevitz, Columbia Univ.

ν_e appearance



ν_e disappearance



Plots by M. Shaevitz, Columbia Univ.

Requires separation of prompt, delayed neutrinos!