Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

Searches for New Physics with a Stopped-Pion Source at the Fermilab Accelerator Complex

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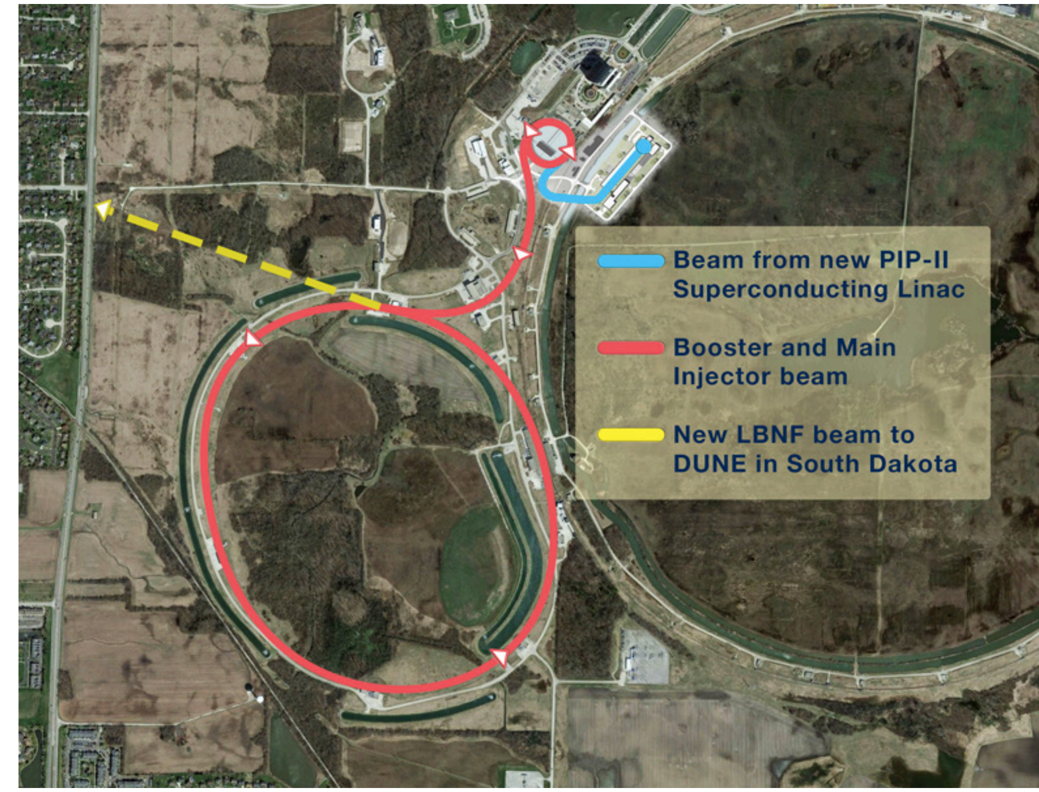
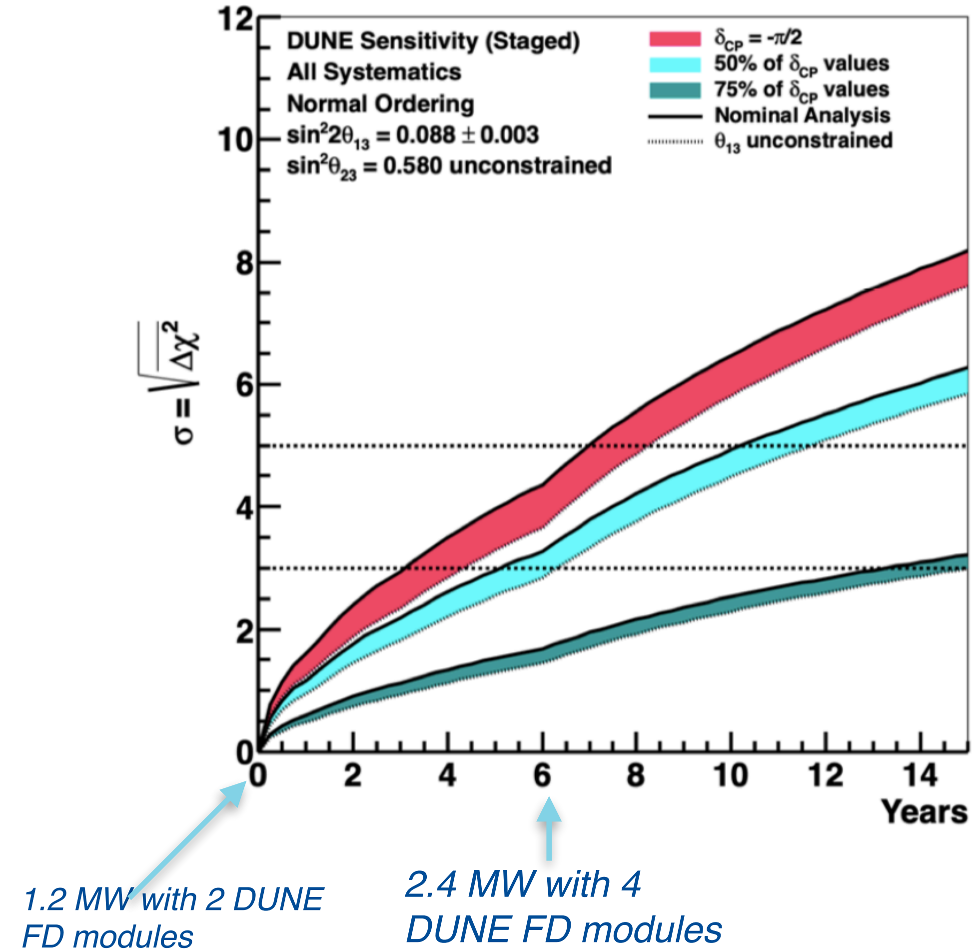
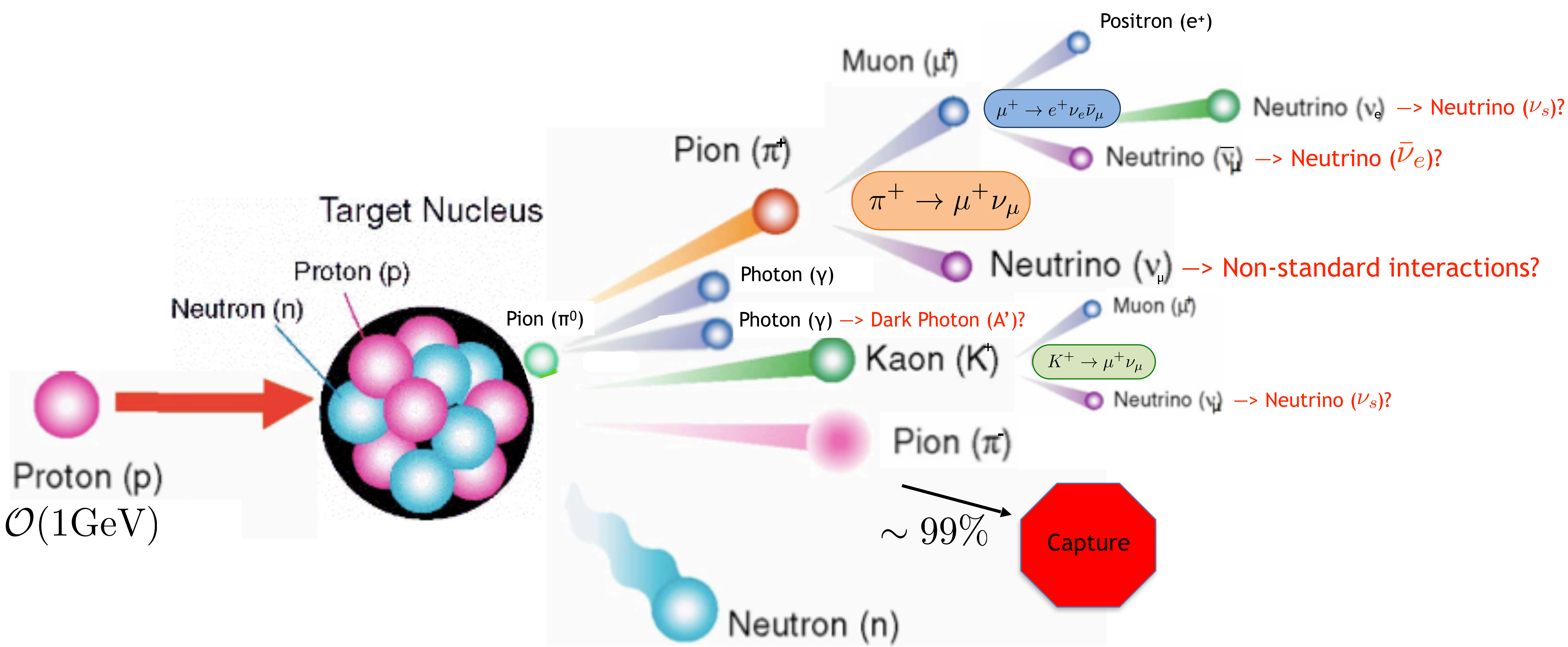
The PIP-II Project

- DUNE major component of US particle physics program in next ~decade
- 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: See J. Eldred's talk or https://arxiv.org/pdf/2106.02133.pdf
  - O(1 GeV) stopped-pion neutrino source program leveraging the available beam
    - Assume 630 kW beam power pulsed at 120 Hz, 800 MeV, 75% uptime
  - Opportunity to build facility to maximize high-energy physics impact





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

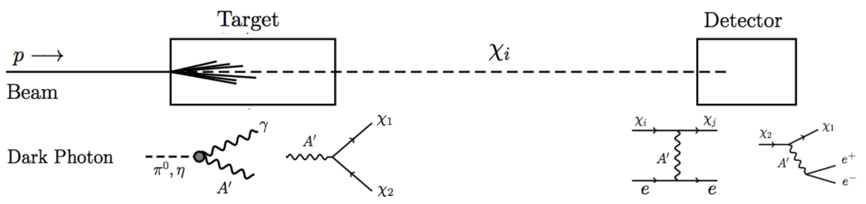


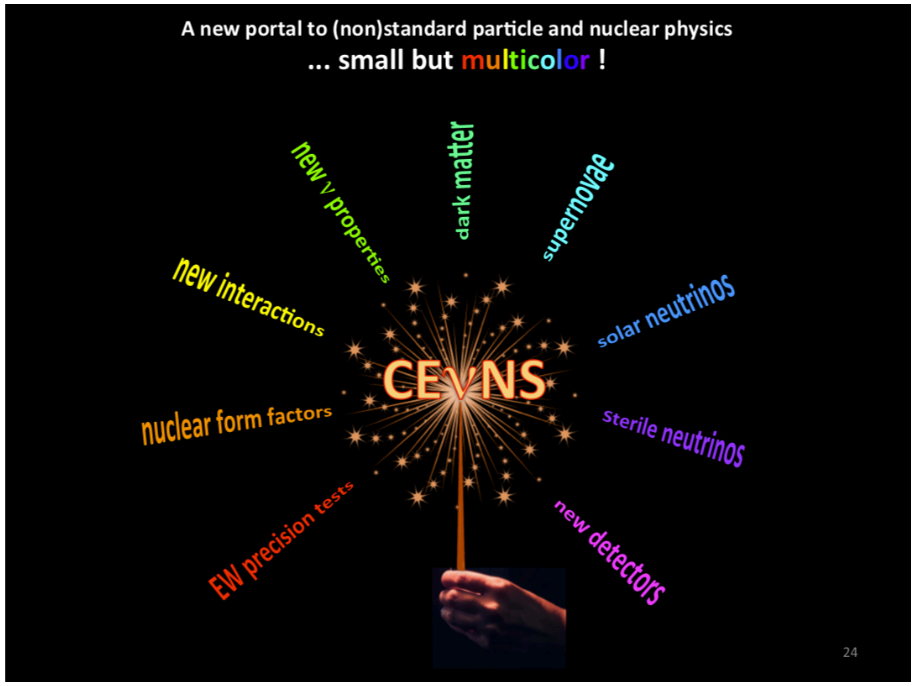
ν_μ with pion decay lifetime (~26 ns), ν_e and anti-ν_μ with muon decay lifetime (2.2 μs)

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.

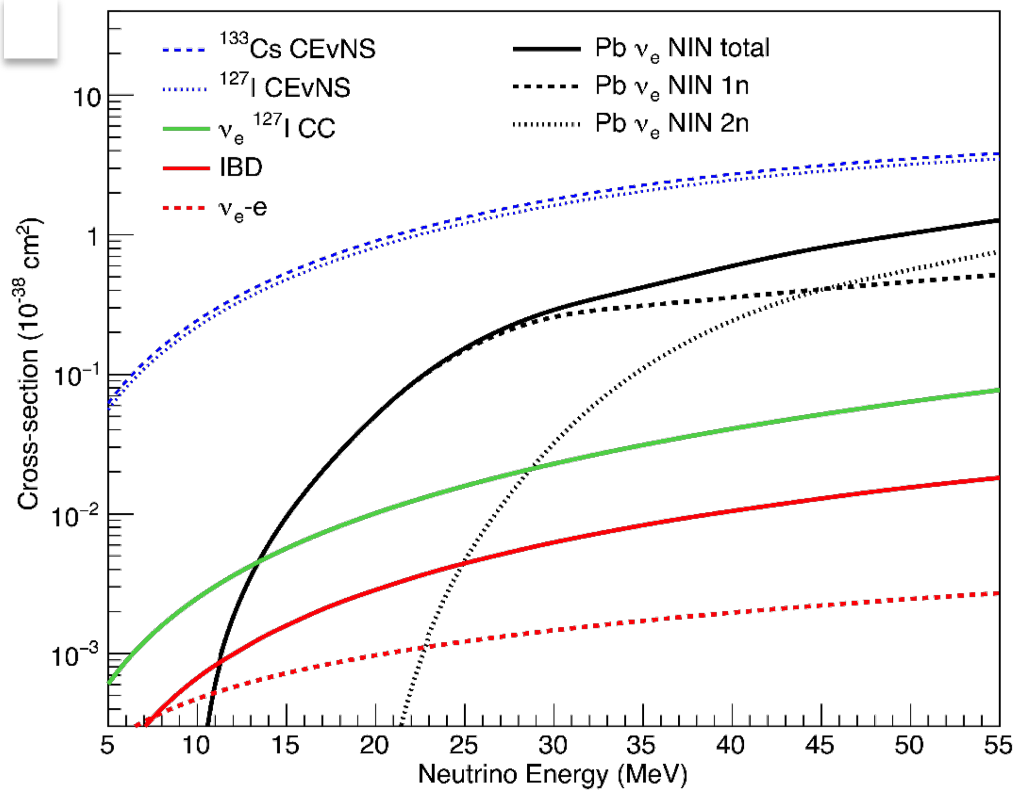


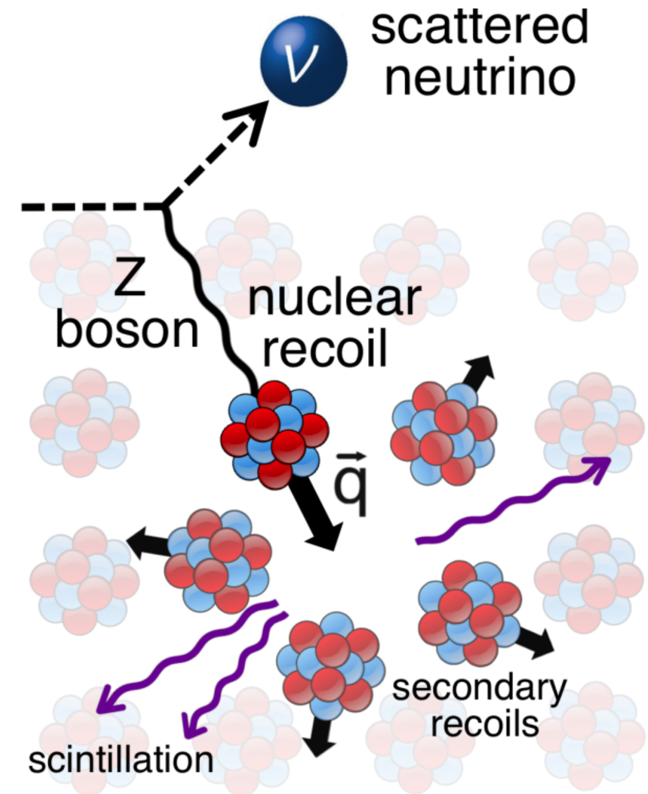


E. Lisi, NuINT 2018

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

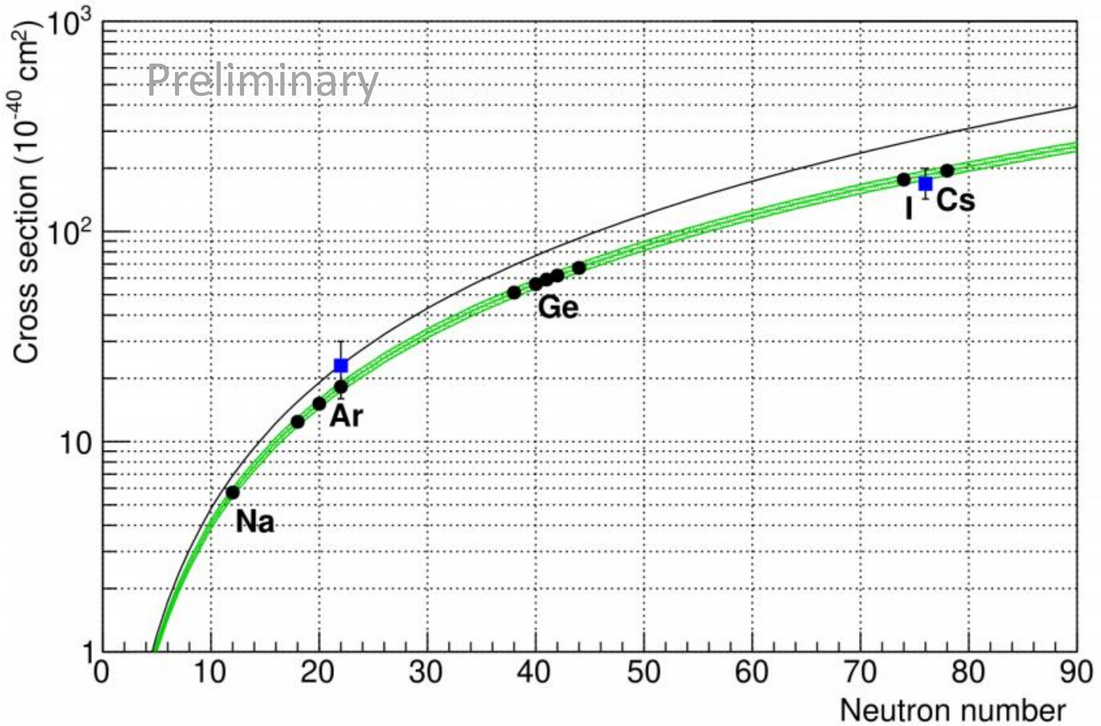




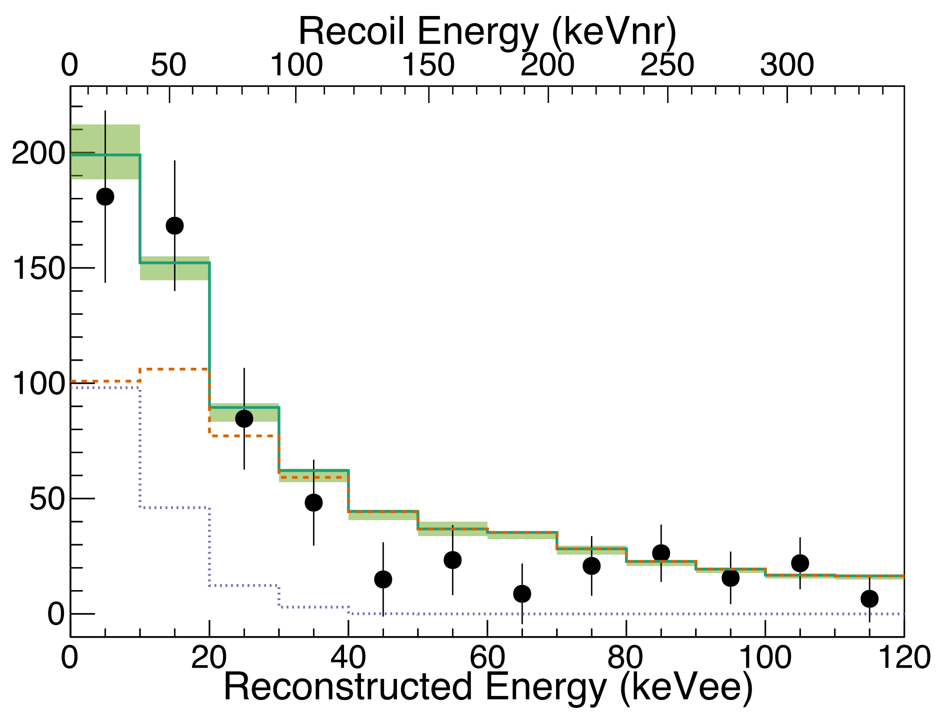
D. Akimov et al. (COHERENT). Science 357, 1123-1126 (2017)

Liquid Argon (LAr) for CEvNS-based new physics detection

- 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



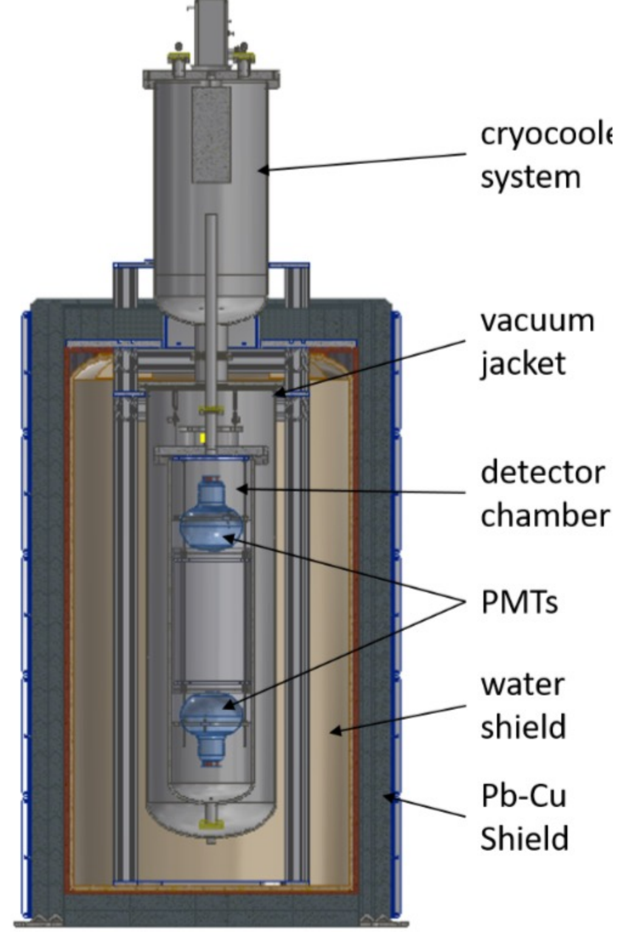
D. Pershey, Magnificent CEvNS 2020

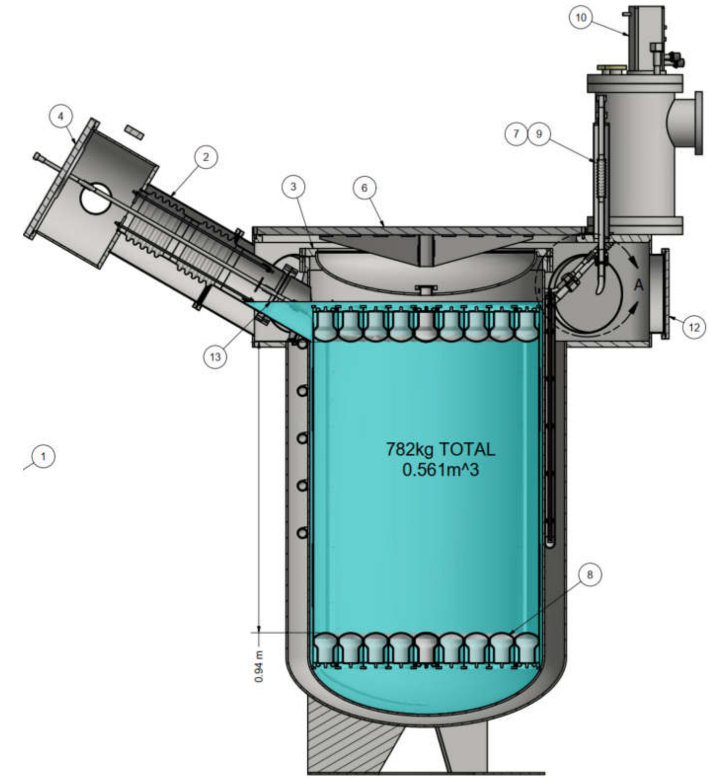


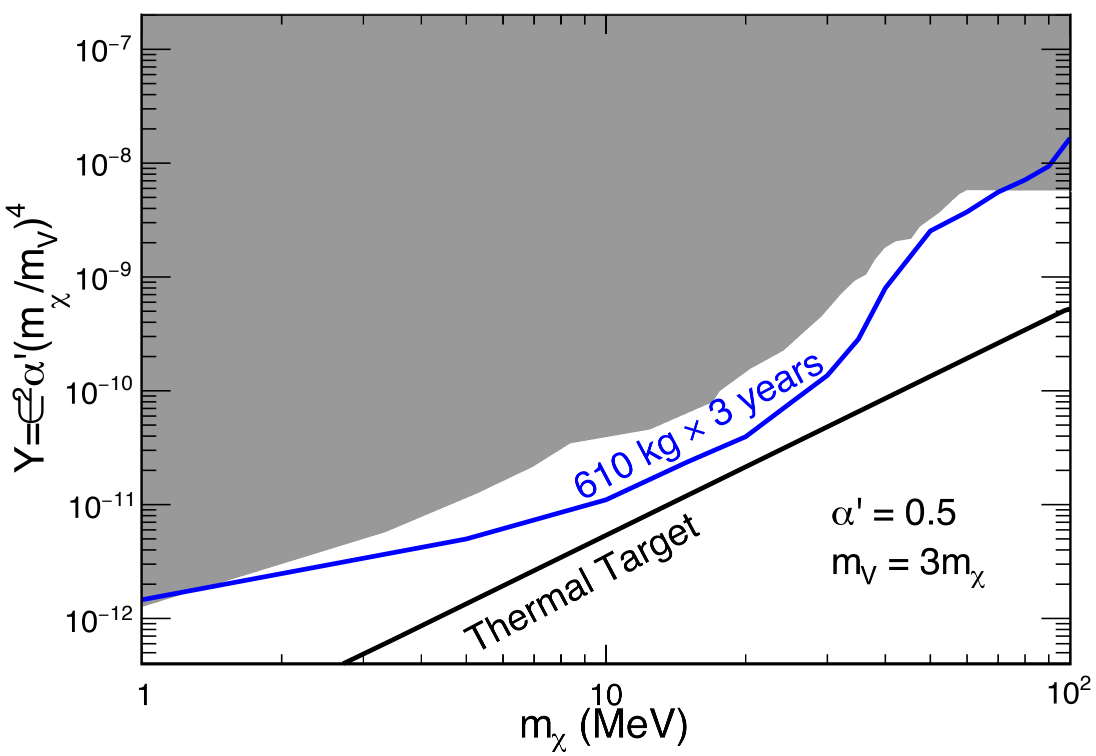
D. Akimov et al. (COHERENT), Phys. Rev. Lett. 126 (2021) 1, 012002

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



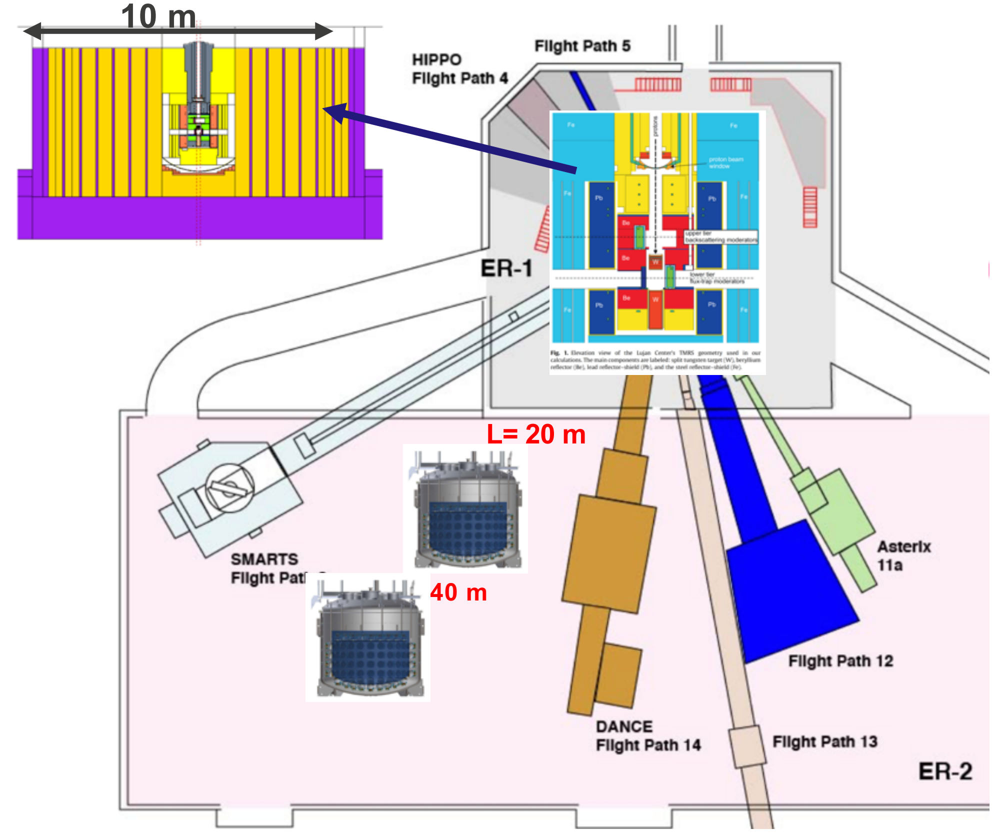


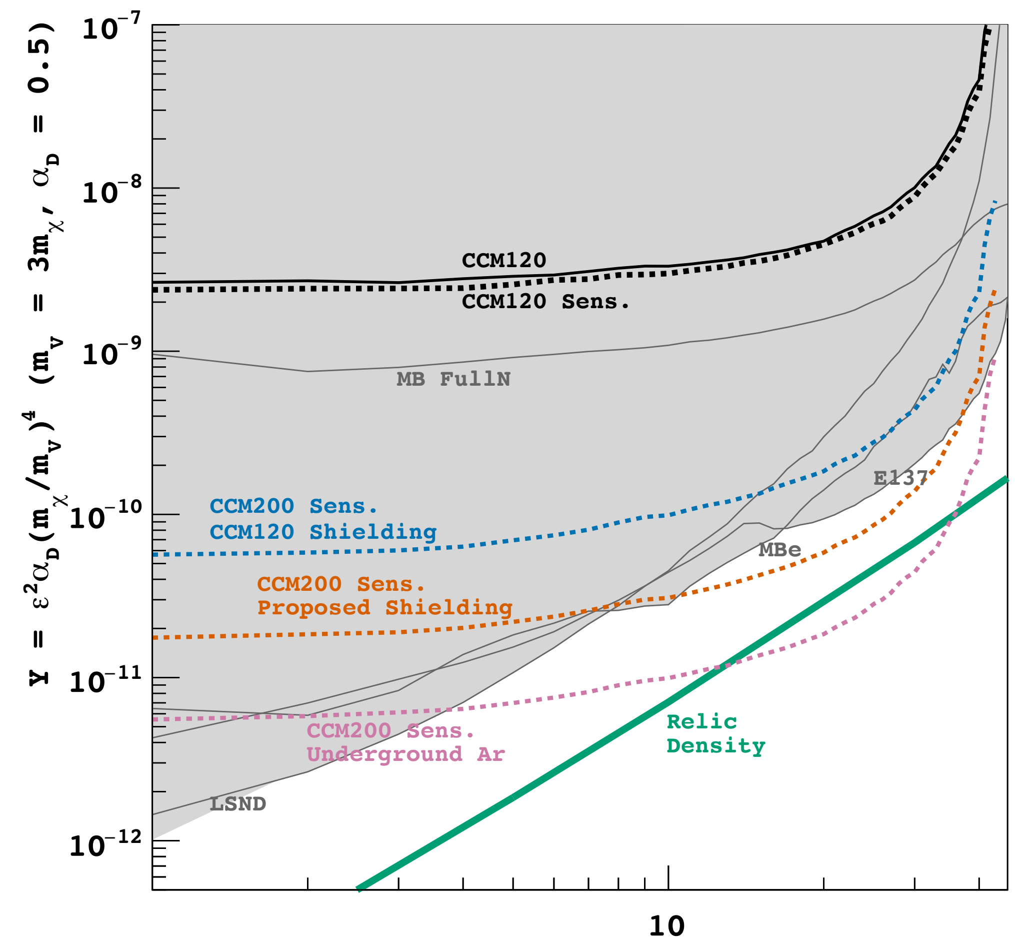


Phys. Rev. D 102, 052007 (2020)

Coherent 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



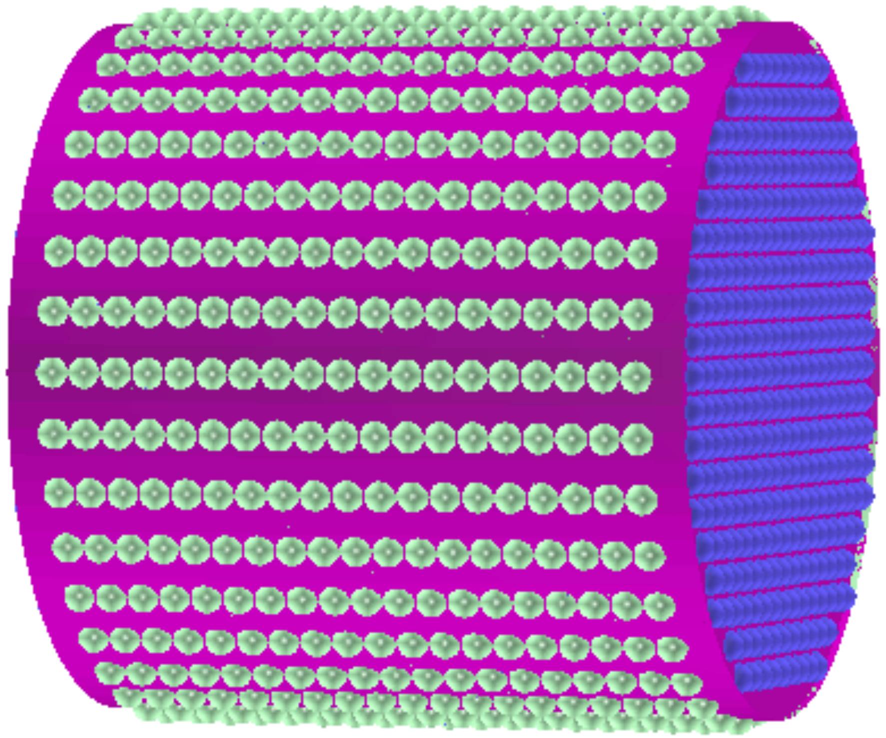


https://arxiv.org/abs/2105.14020 [hep-ex]

Fermilab

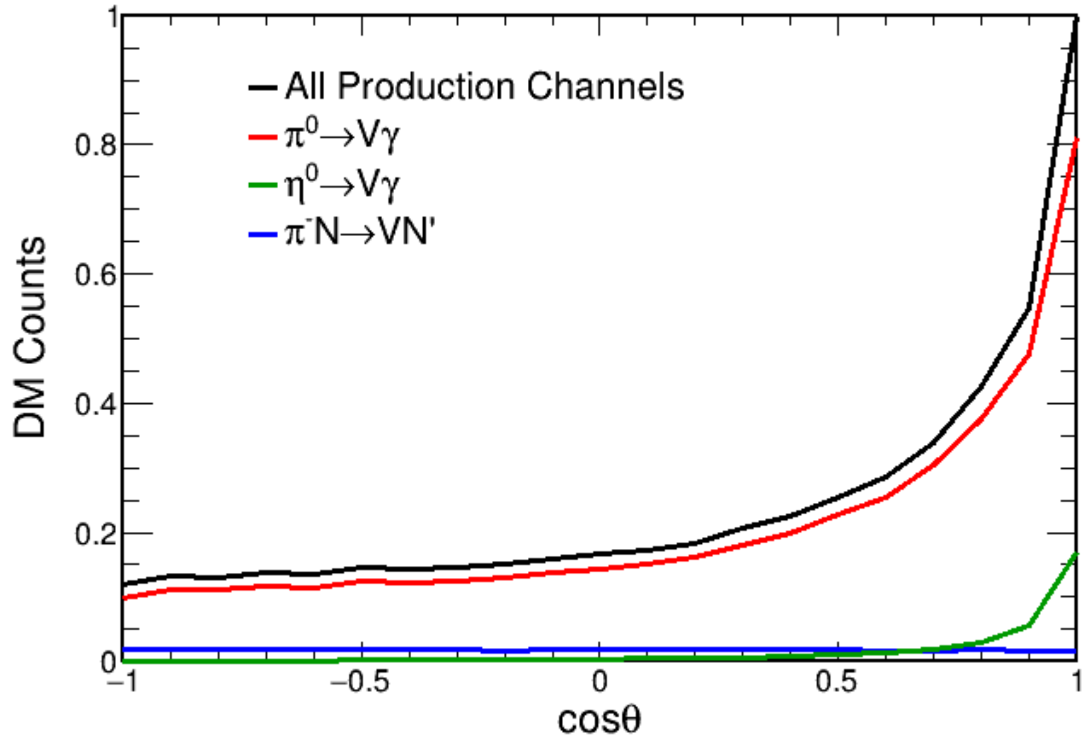
Proposed Detector at PIP-II

- 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

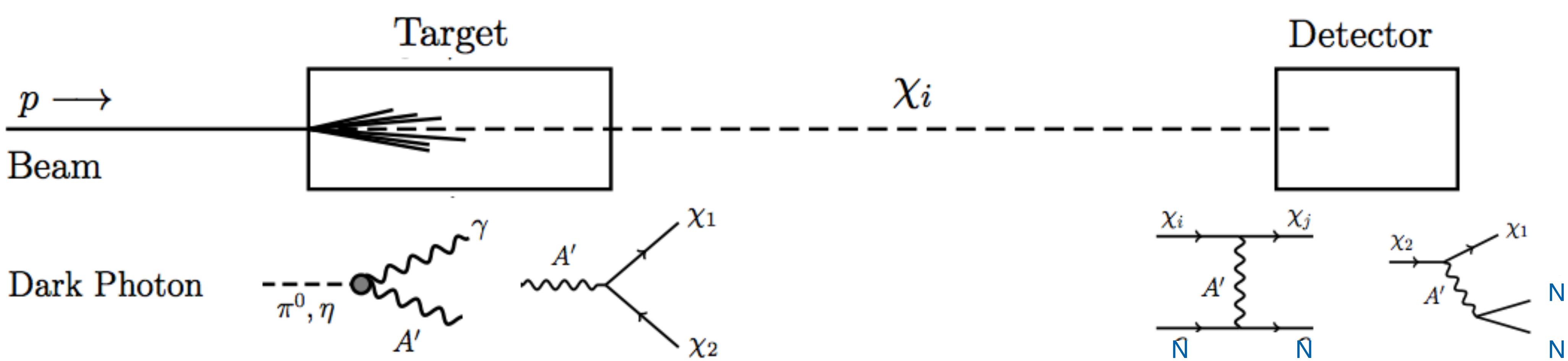


Boosted Vector Portal Light Dark Matter (LDM)

- 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

PIP-II LDM Search at Fermilab

- Stopped-pion neutrino sources place strong limits on LDM
  - Produced by proton collisions with fixed target
  - π^0 decay into light dark matter
  - Interaction identical to CEvNS
  - DM signal excess over CEvNS
    - Understanding of beam-related backgrounds important!
- Fermilab light DM search probes these models
  - Probe large region below relic density for several models
  - Assumes beam power of 630 kW, 120 Hz
  - 50 keVnr threshold
  - 70% efficiency above 50 keVnr
  - 5 year run with 75% beam time
  - On axis, 18 m downstream from target

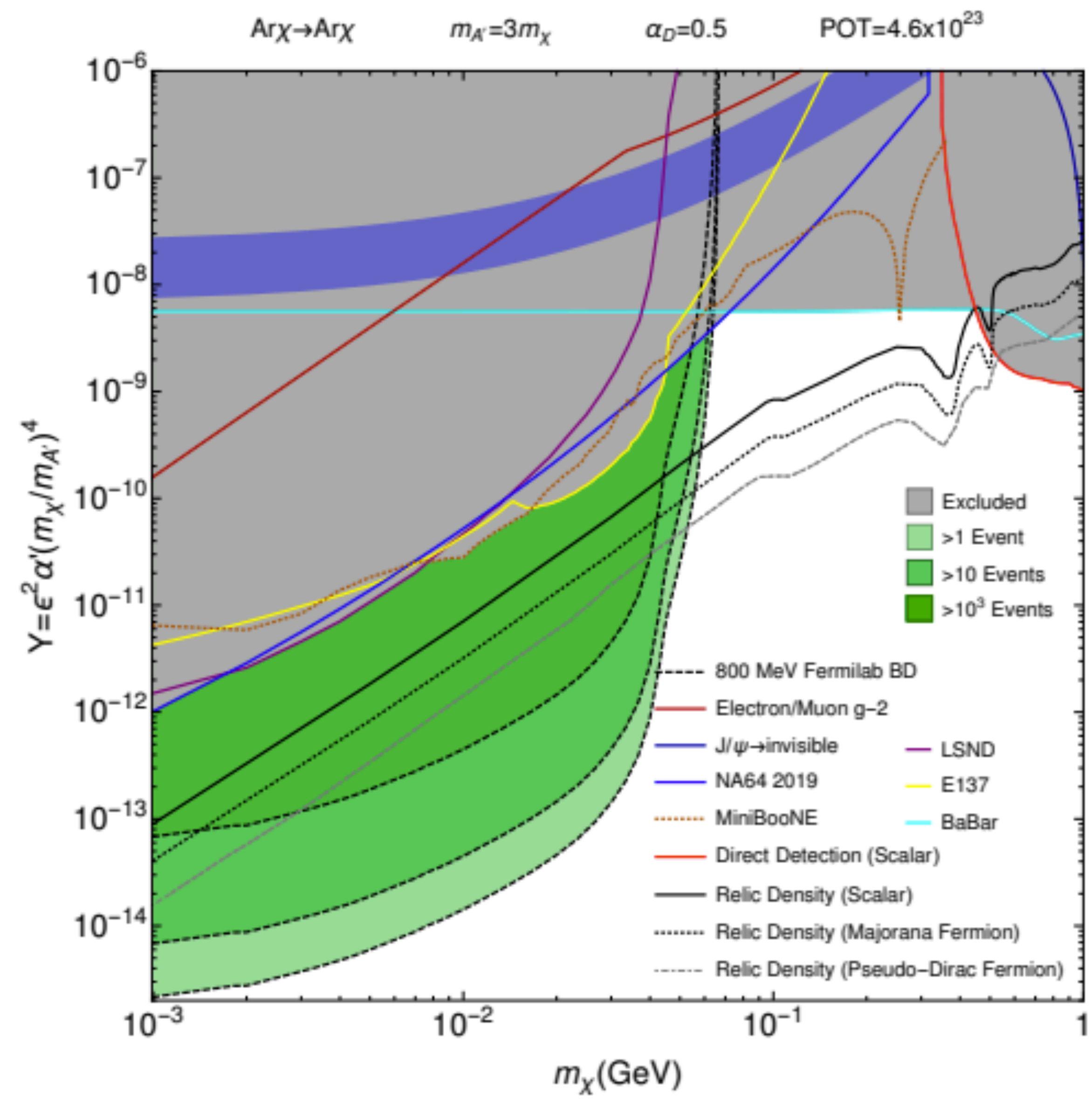


FIG. 1. Fermilab beam dump facility argon recoil event sensitivity curves for 4.6×10^{23} protons on target compared to thermal relic density targets and existing 90% exclusion limits as a function of the dimensionless scaling variable $Y = \epsilon^2\alpha(m_\chi/m_{A'})^4$, assuming $\alpha = 0.5$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

P. deNiverville, LANL

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 $\nu_\mu \to \nu_e$ Appearance given by:

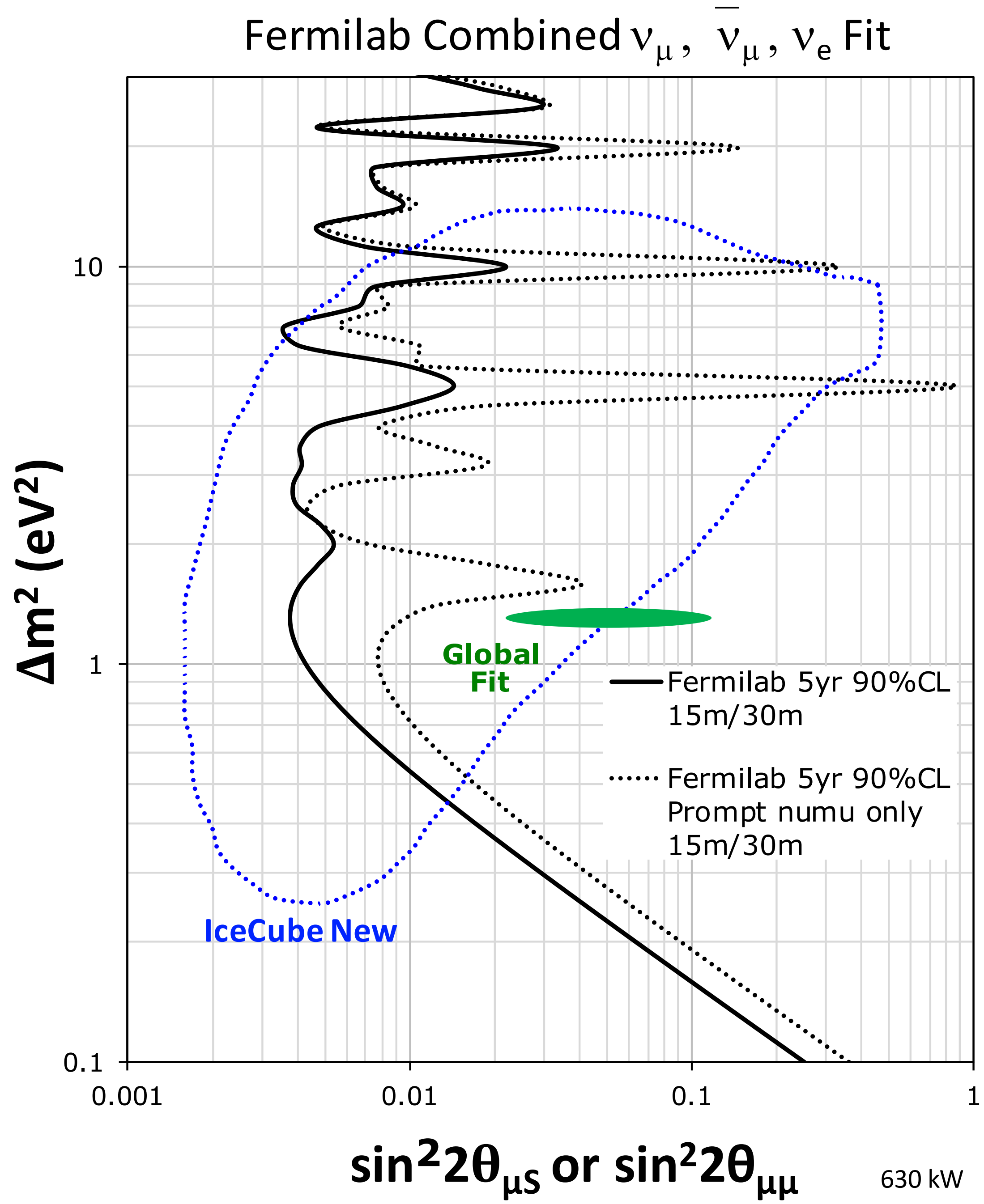
$$\sin^2 2\theta_{\mu e} = 4U_{e4}^2 U_{\mu 4}^2$$

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.

Summary

- Completion of PIP-II will support initial 1.2 MW beam to LBNF
- Further upgrades 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 and dedicated to HEP searches**
- Preliminary studies using a 100 ton liquid argon detector show the ability for leading probes on CEvNS-based sterile neutrino searches among a wealth of neutrino physics opportunities
- We are looking to grow our collaboration! If you're interested in this effort or have questions, please contact us

More Information

- Snowmass LOI on O(1 GeV) Fixed-Target New Physics Searches at Fermilab
- Snowmass LOI on PIP-II Booster Accumulator Ring
- Snowmass LOI on PIP-II RCS Accumulator Ring Option

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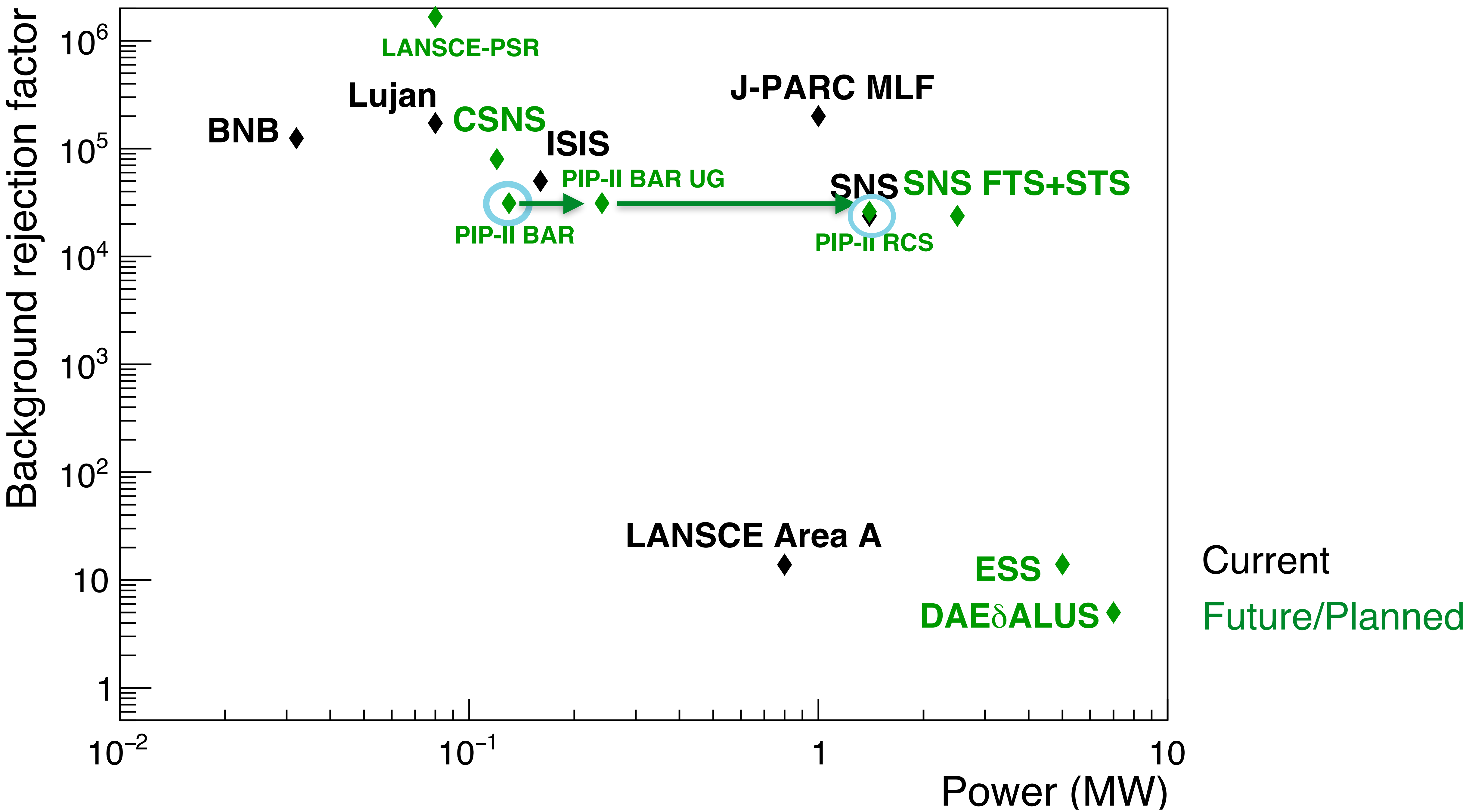
Thank you!

Backup

PIP-II as a Stopped-pion neutrino source



Plot via K. Scholberg

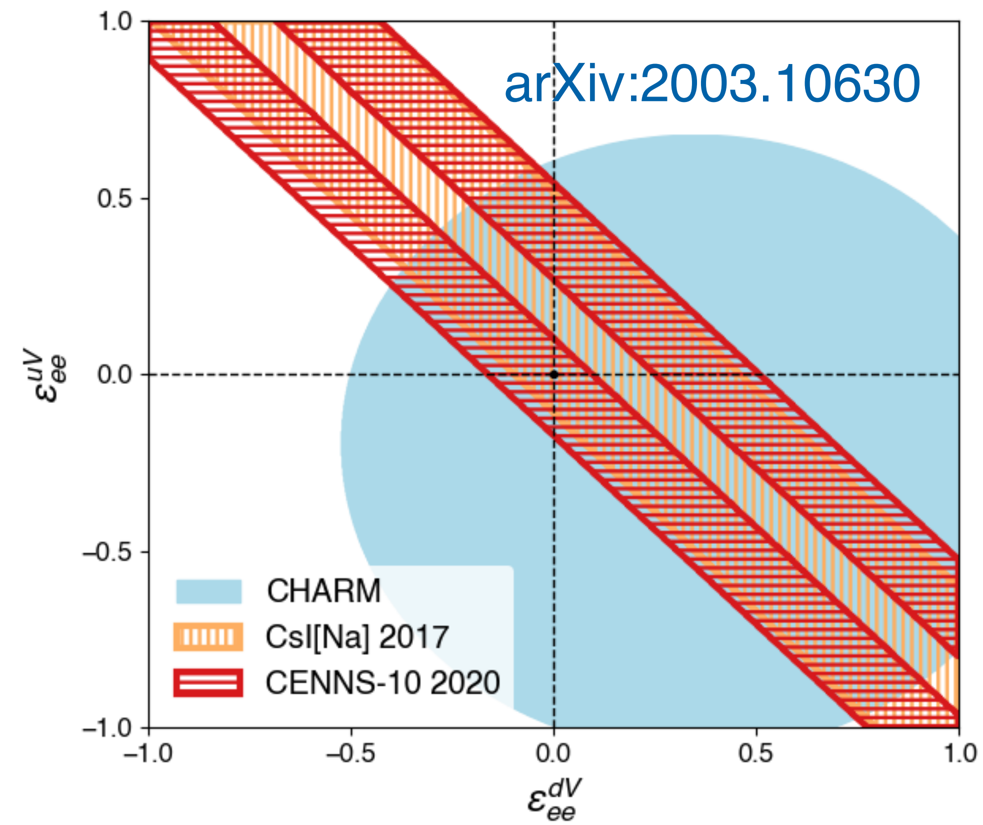
Neutrino non-standard interactions (NSI)

- Addition to SM Lagrangian as modification of weak charge

$$\mathcal{L}_{\rm NSI} = -2\sqrt{2}G_F \sum_{f,P,\alpha,\beta} \epsilon_{\alpha\beta}^{f,P} (\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta)(\bar{f}\gamma_\mu P f)$$

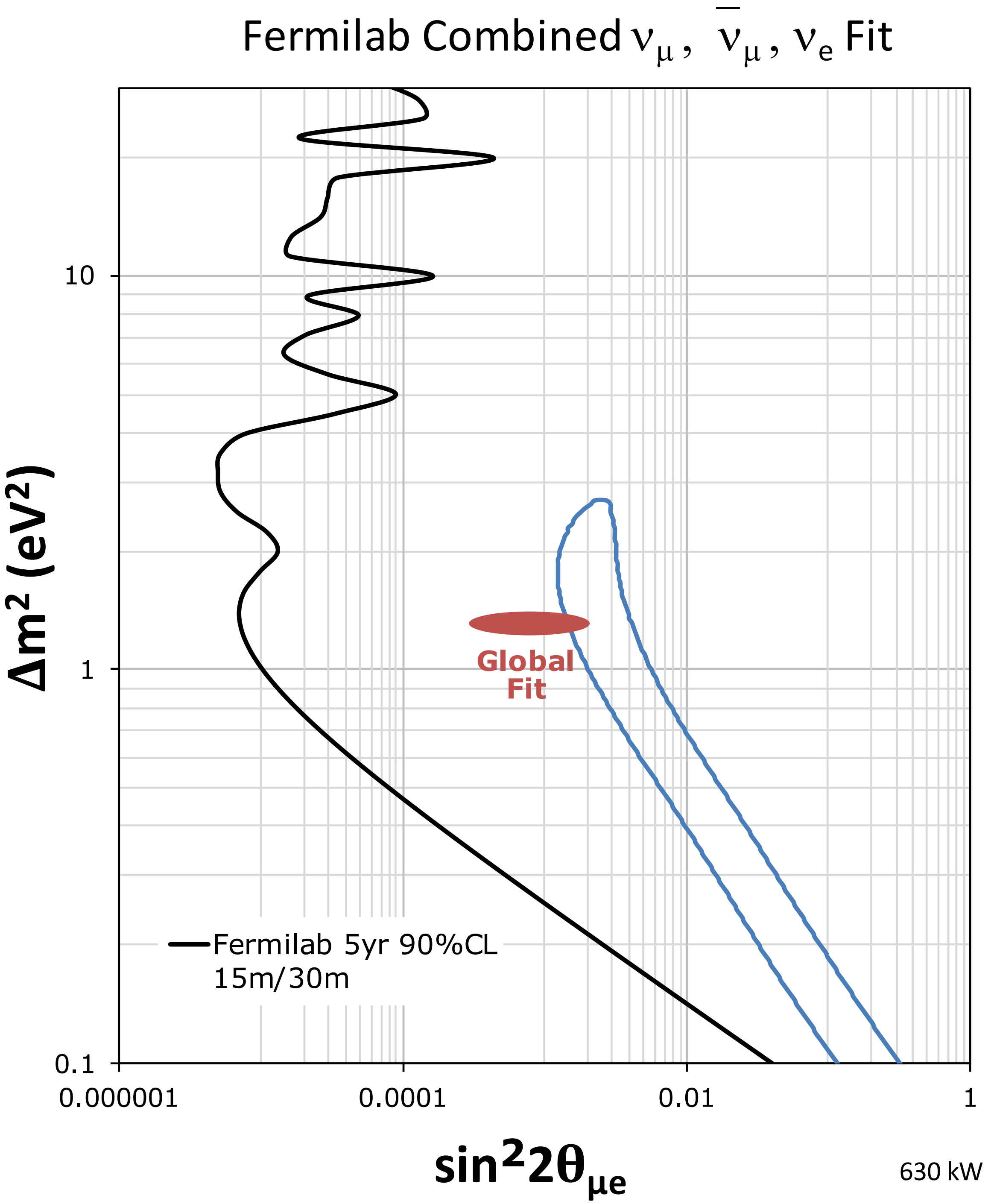
$$Q_W^2 \to Q_{\rm NSI}^2 = 4\left[N\left(-\frac{1}{2} + \epsilon_{ee}^{uV} + 2\epsilon_{ee}^{dV}\right) + Z\left(\frac{1}{2} - 2\sin^2\theta_W + 2\epsilon_{ee}^{uV} + \epsilon_{ee}^{dV}\right)\right]^2$$

- CEvNS sensitive to both non-universal and flavor changing neutral currents
  - Place limits on NSI parameter space with CEvNS measurements
- Neutrino-electron scattering also sensitive to NSI

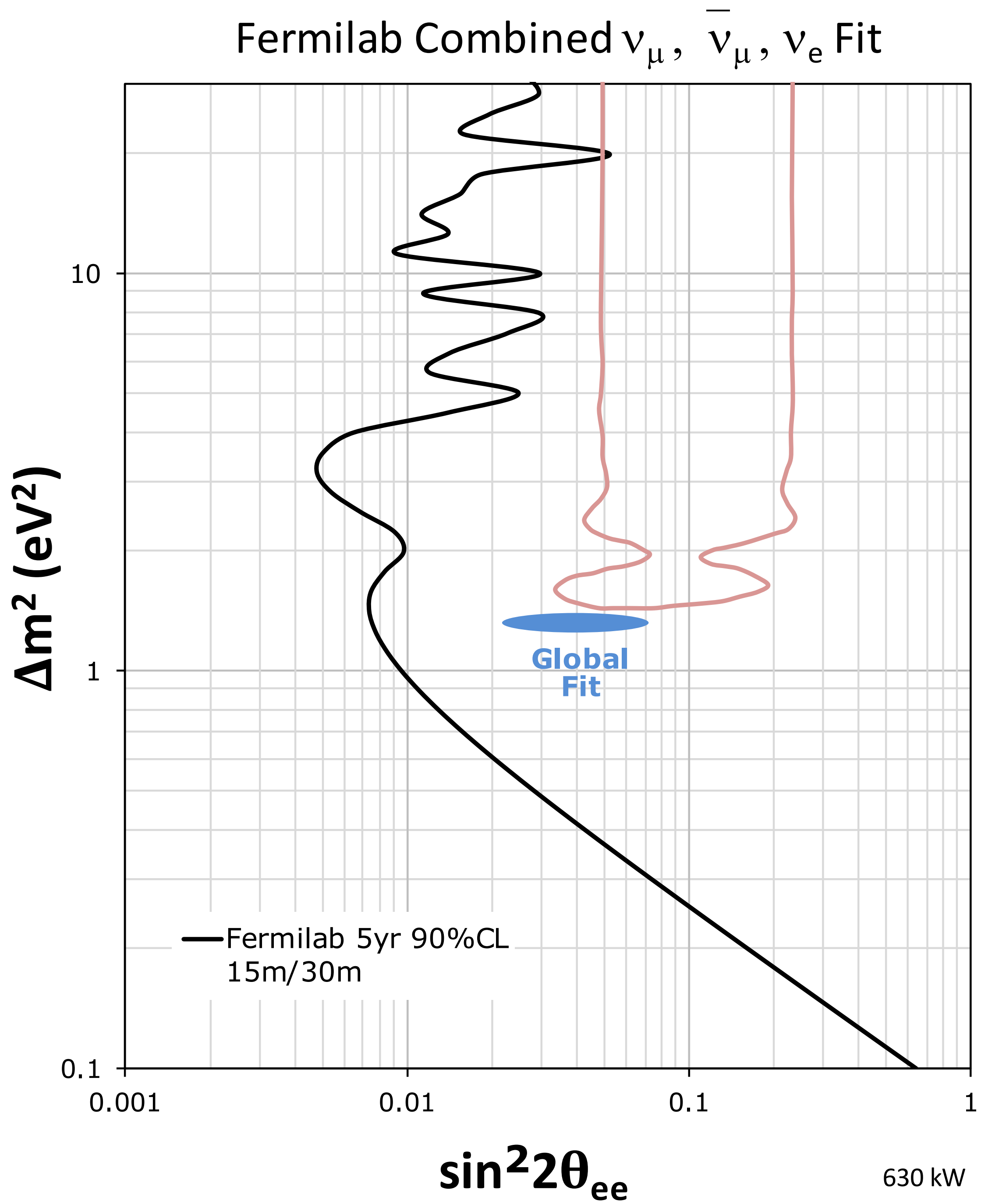


J. Barranco et al., Phys. Rev. D 76 (2007)
J. Billard, J. Johnston, B. Kavanagh arXiv:1805.01798

ν_e appearance



ν_e disappearance



Plots by M. Shaevitz, Columbia Univ.

Requires separation of prompt, delayed neutrinos!

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

Stopped pion source for long baseline oscillations

- Pion-decay-at-rest neutrinos present an additional opportunity for long baseline oscillation searches
  - Well known neutrino spectrum, monoenergetic ~30 MeV ν_μ
  - Neutrino source at Fermilab capable of O(10^{23} POT/year) could allow long baseline oscillation search
  - Large LAr detector used as near detector
  - Consider far detector opportunities, the 1300 km distance to DUNE FD too far (neutrino flux goes as $1/r^2$) for appreciable rate

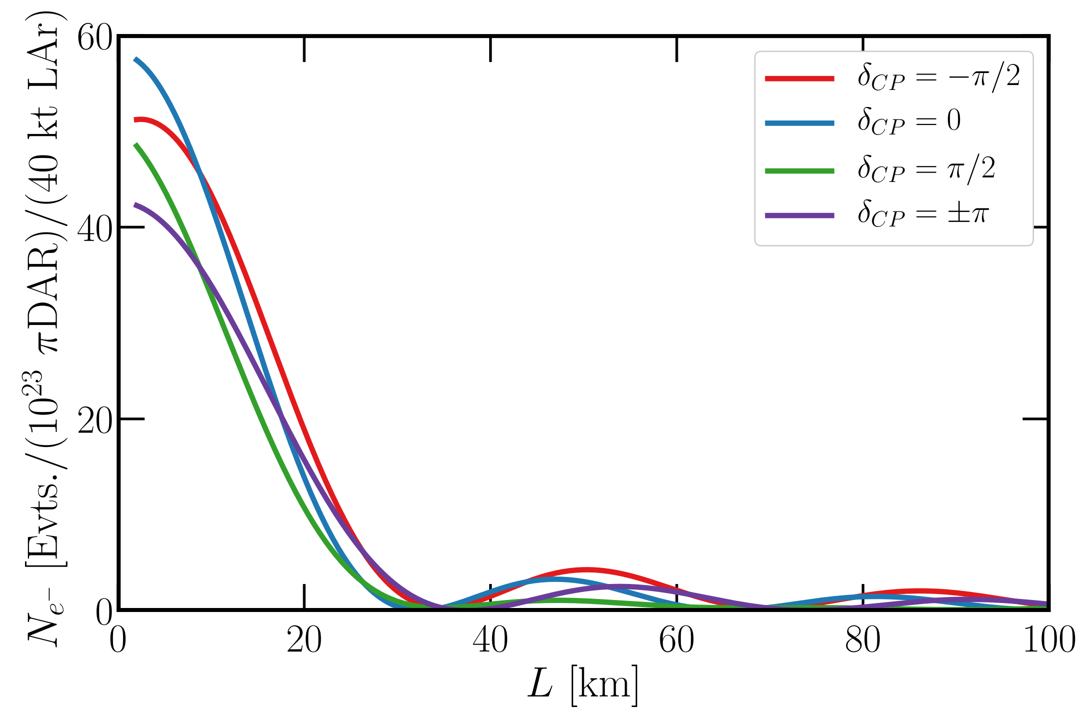
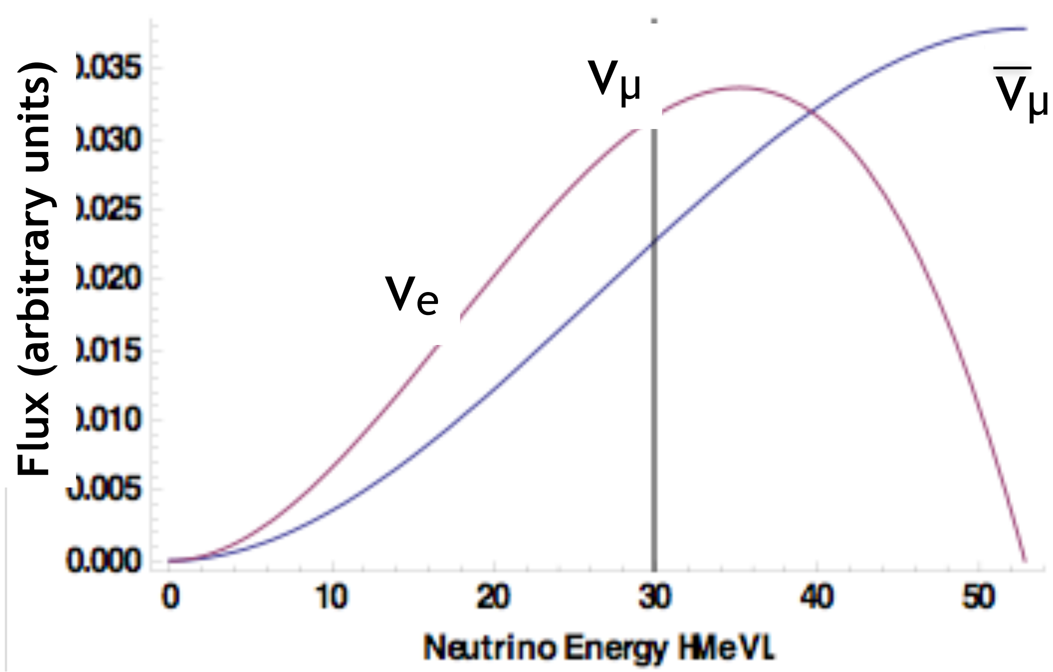


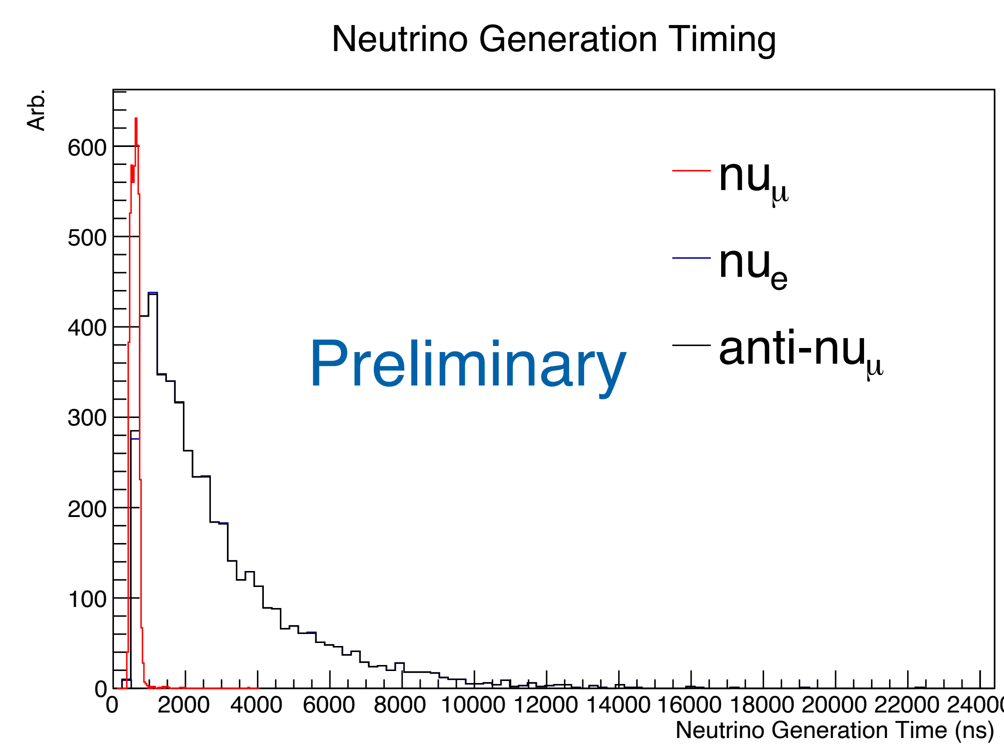
FIG. 5. Number of electron-neutrino events from pion decay-at-rest neutrinos that have undergone the oscillation $\nu_\mu \to \nu_e$ and interacted in a liquid argon detector. We present the number of events as a function of distance between the pion decay-at-rest source and the detector L, assuming a 40 kt liquid argon detector and a total of 10^{23} pion decays.

R. Harnik, K.J. Kelly, P.A.N. Machado, Phys. Rev. D 101, 033008 (2020)

Booster Accumulator Ring (BAR) Concept

- Accumulator ring to compress pulses (300-400 ns pulse width goal)
  - Reduce duty factor to levels of 10^{-5} for steady-state background rejection
- Initial operation at ~100 kW, 100 Hz, 0.8 GeV protons
  - Upgrade path to >200 kW, 1 GeV protons
- Target facility and experimental hall can be optimized for HEP-based physics searches such as CEvNS, dark sector, or light sterile neutrino searches
  - Low-Z target such as carbon, improve pion/proton ratio
    - Preliminary simulations of thick carbon target predict **0.12 nu/flavor/proton at 800 MeV proton energy**
  - Optimize for neutron background suppression, large detectors at flexible locations





Fermilab

Evolution of Accelerator Complex

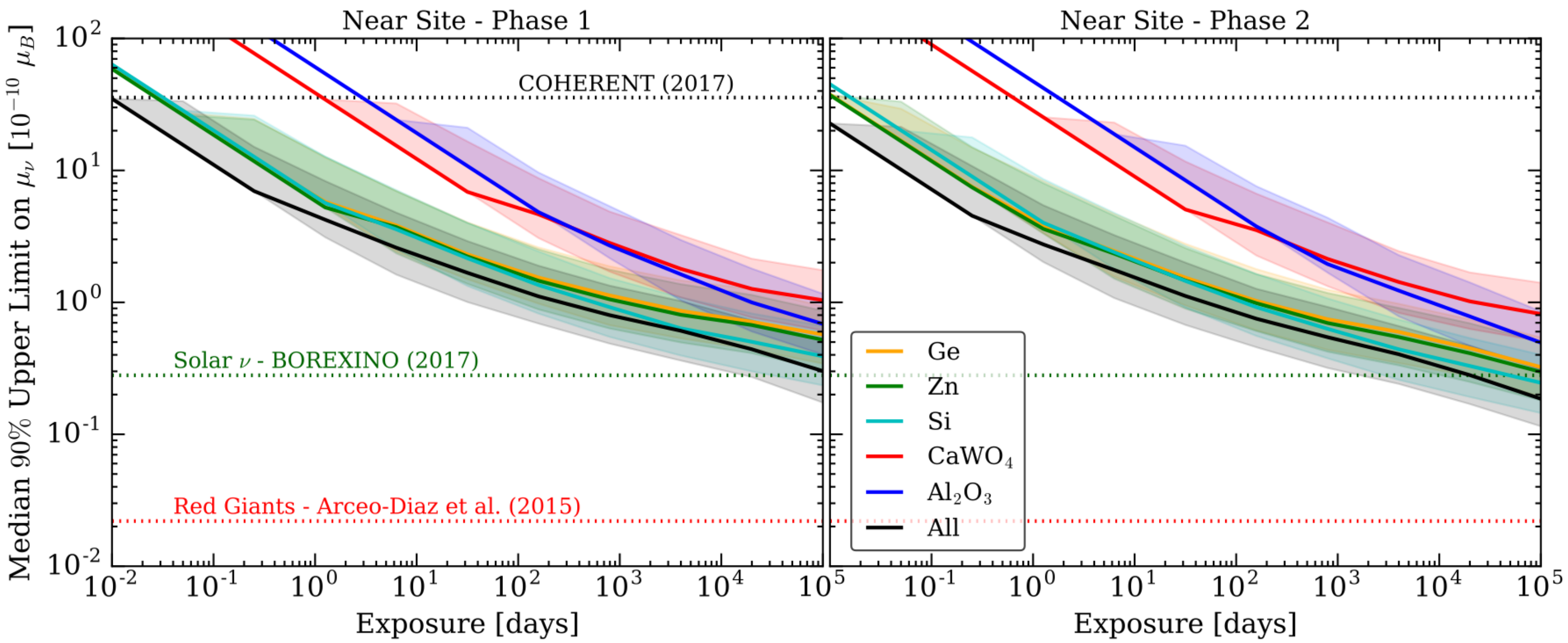
- Modest upgrades to PIP-II and the BAR to allow for 1 GeV proton energy increases the available beam power to 240 kW while increasing the power to LBNF
- Ultimately, if an RCS will be constructed to deliver 2.4 MW to LBNF this increases the available beam power for an O(1 GeV) fixed target program to MW scale

Technology	BAR	BAR Upgrade	RCS Accumulator Ring
Intensity	1e13 protons/spill	1.5e13 protons/spill	3.6e13 protons/spill
Repetition Rate	100 Hz	100 Hz	120 Hz
Proton Energy	0.8 GeV	1 GeV	2 GeV
Beam Power	130 kW	240 kW	1.4 MW
Pulse Width	300-400 ns	300-400 ns	300-400 ns
Timescale	2027	Late 2020's-early 2030's	in the 2030s

Neutrino magnetic moment

- Both neutrino-nucleus and neutrino-electron scattering able to probe neutrino magnetic moment
  - Can we do better than LSND? ($<6.8 \times 10^{-10}\ \mu_B$)
- Current DAR CEvNS limits not competitive with existing solar neutrino limits or reactor-based CEvNS projections
  - Different set of systematics
  - Can large scale detector be competitive?
- Combined analysis of nucleus and electron scattering channels?

$$\left(\frac{d\sigma}{dT_A}\right)_{\mathrm{EM}} = \frac{\pi a_{\mathrm{EM}}^2 \mu_\nu^2 Z^2}{m_e^2}\left(\frac{1 - T_A/E_\nu}{T_A}\right) F^2(Q^2)$$



J. Billard, J. Johnston, B. Kavanagh arXiv:1805.01798