# Neutrino physics searches with a stopped-pion source at the Fermilab accelerator complex using the BAR

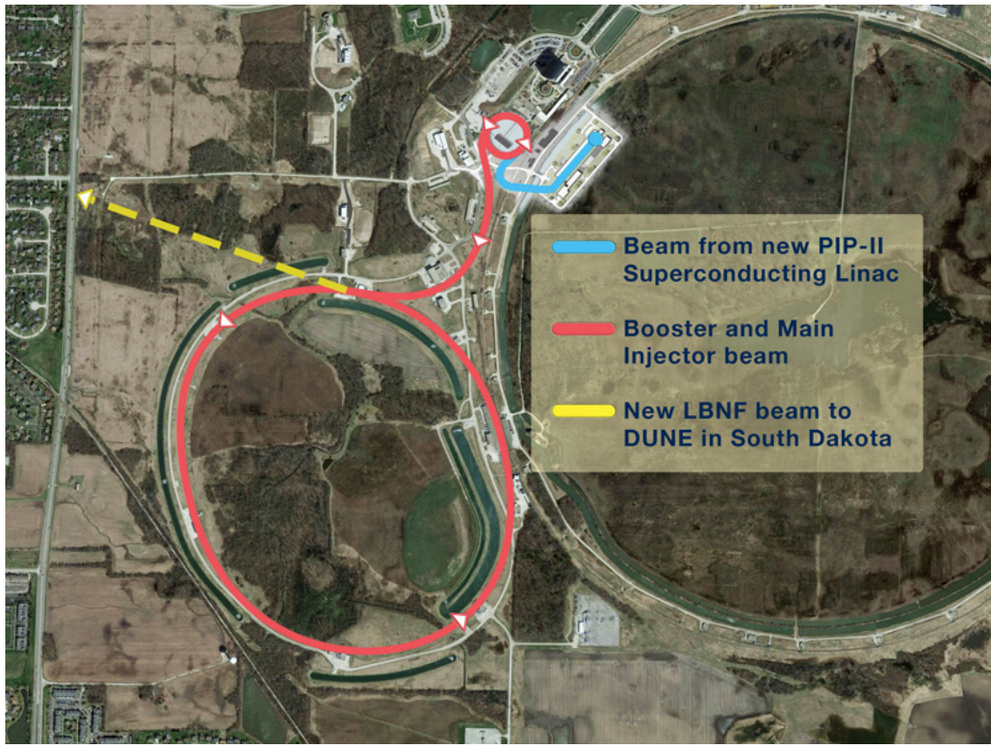
Jacob Zettlemoyer

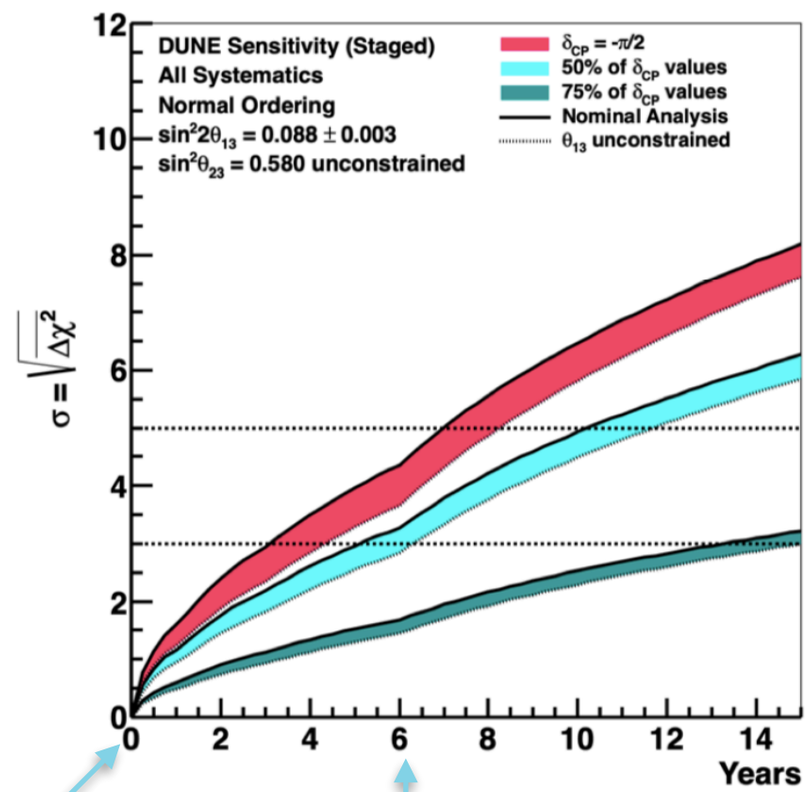
Fermilab Booster Accumulator Ring Workshop

December 15, 2020

# 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?
  - Create stopped-pion neutrino source program leveraging the available beam including a booster accumulating ring (BAR)
  - Opportunity to build facility to maximize high-energy physics impact

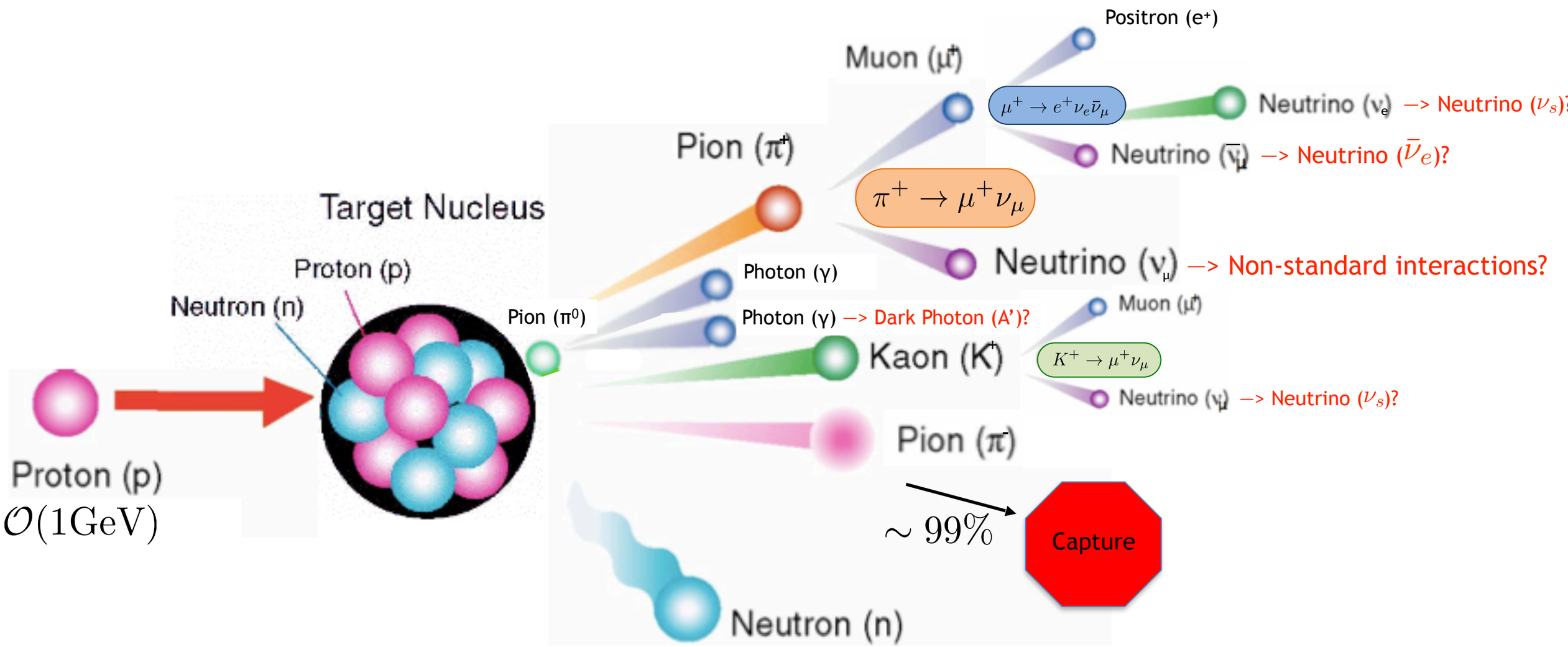



*1.2 MW with 2 DUNE FD modules*

*2.4 MW with 4 DUNE FD modules*

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

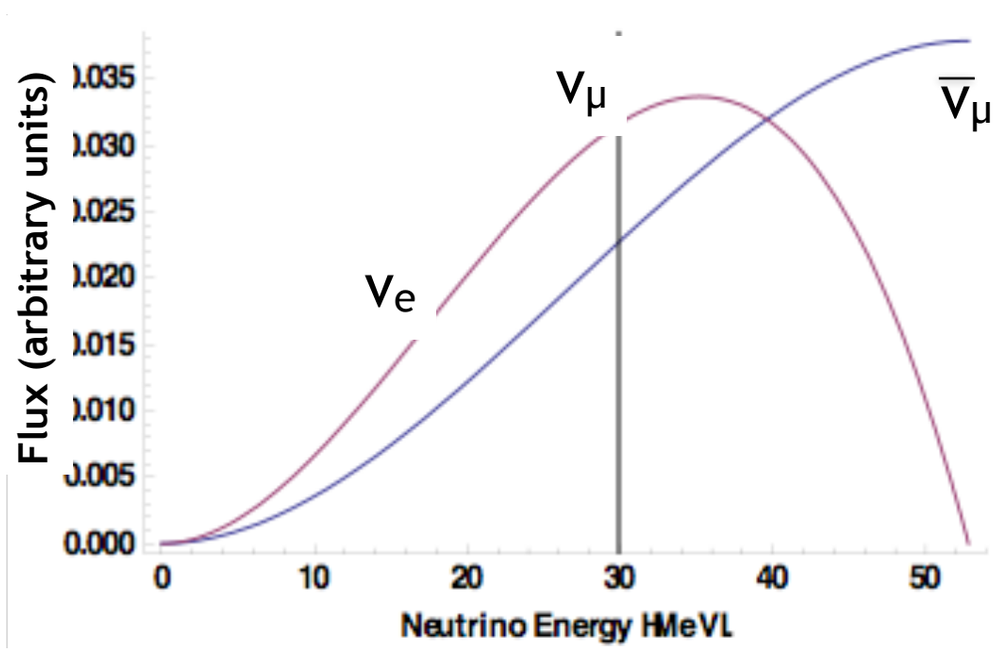


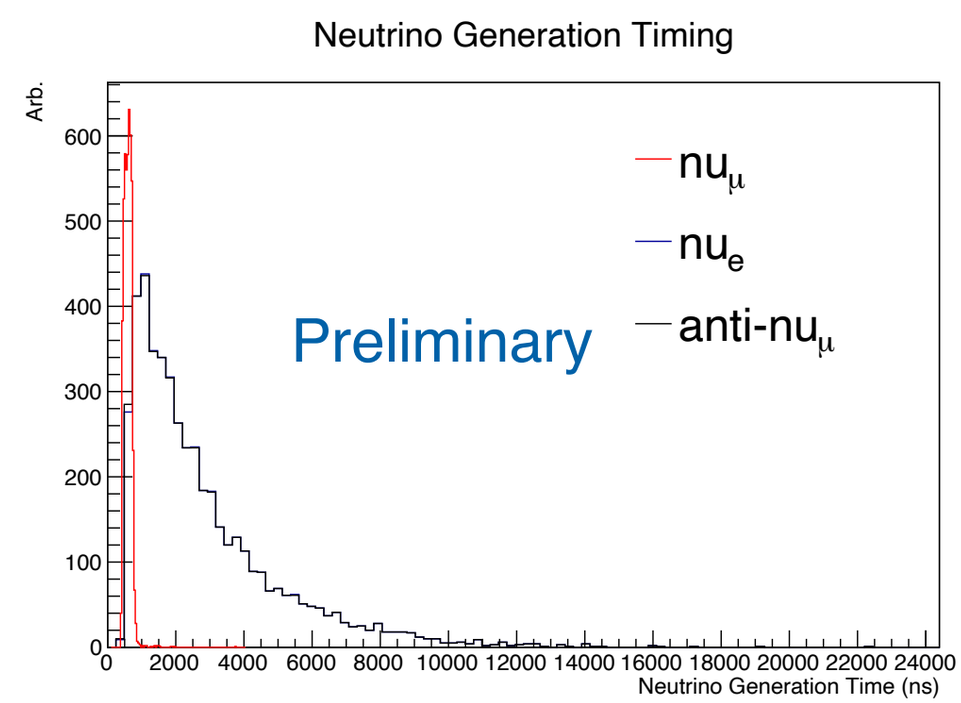

$\nu_\mu$ with pion decay lifetime (~26 ns)

$\nu_e$ and anti-$\nu_\mu$ with muon decay lifetime (2.2 $\mu$s)

# 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



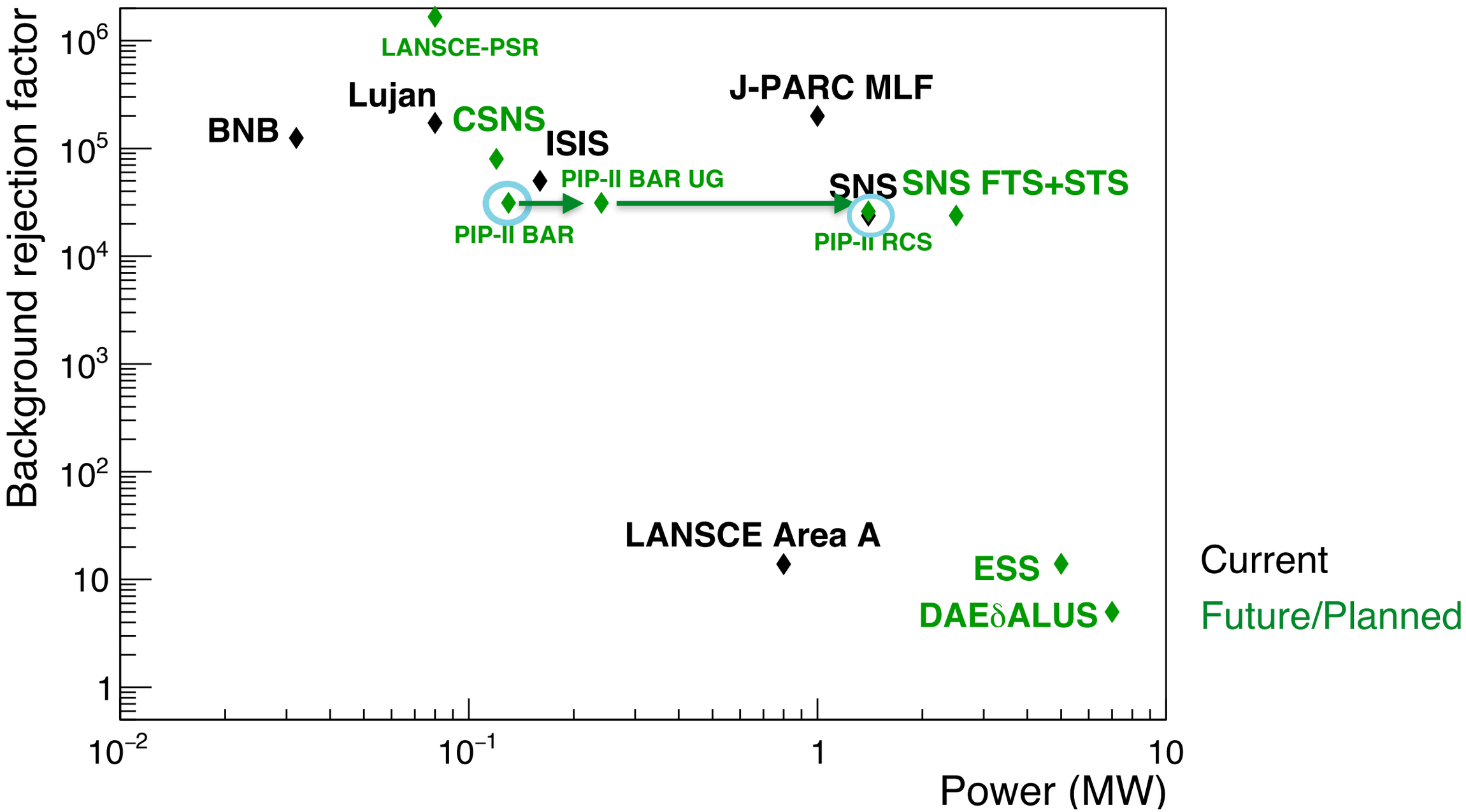



# Evolution of Accelerator Complex

- 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 |

# PIP-II as a Stopped-pion neutrino source




Plot via K. Scholberg

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

- Physics Opportunities At Such a Facility

  - Light dark matter (LDM) / DS Searches (M. Toups' talk)
    - Decay and/or scattering signatures

  - Coherent elastic neutrino-nucleus scattering (CEvNS)
    - Provides new way to search for LDM and sterile neutrinos

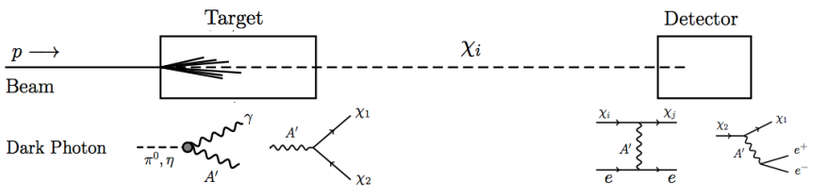
  - Light Sterile Neutrino Searches
    - Both appearance and disappearance possible

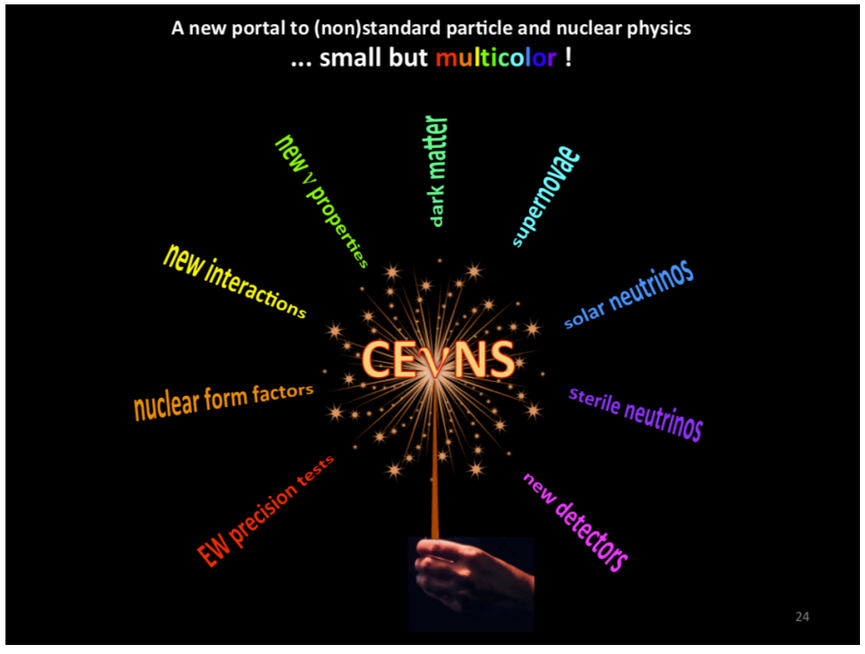
  - Searches for Non-standard interactions (NSIs), tests of the Standard Model

  - Neutrino Cross Section Measurements

  - Neutrino-Electron Scattering (LSND-like), MeV-scale

  - Additional topics:
    - Searches for axion-like particles, 3-ν oscillations, etc.

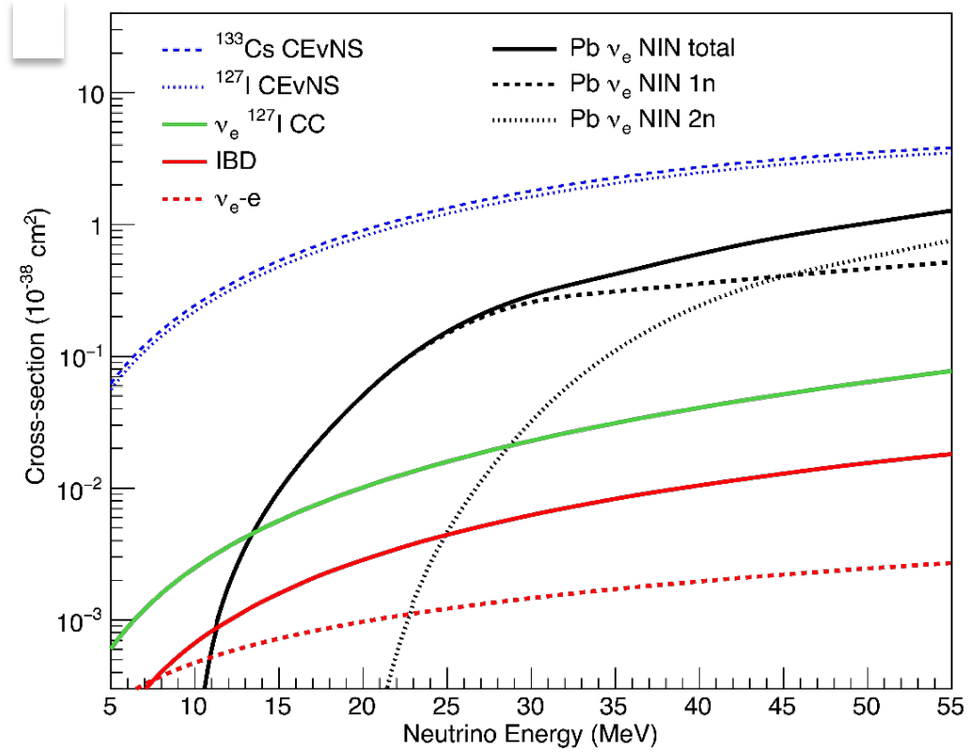


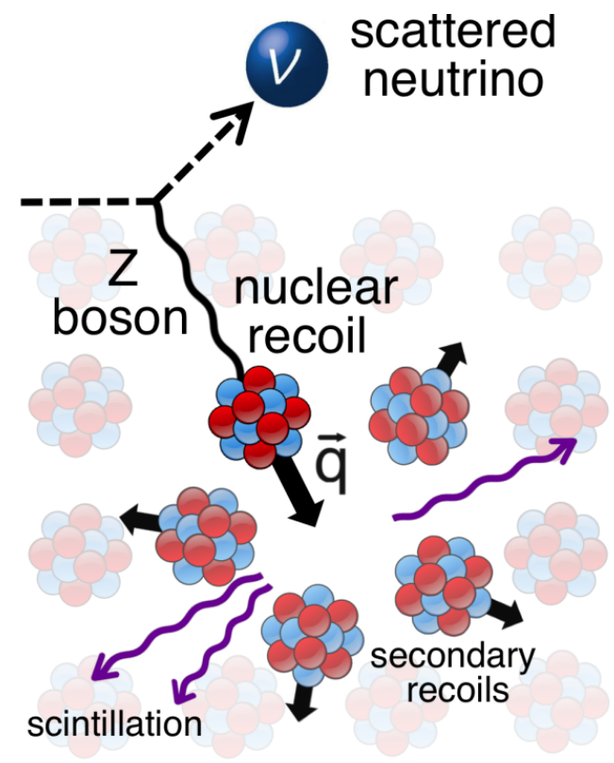




E. Lisi, NuINT 2018

# 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 $N^2$ dependence of cross section

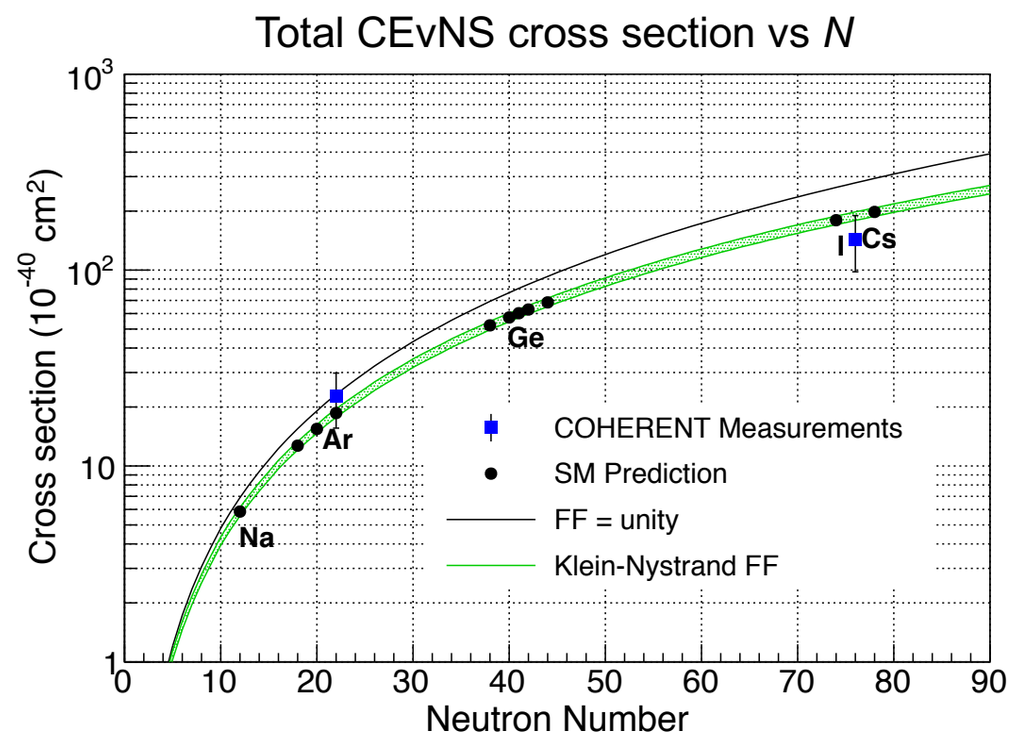


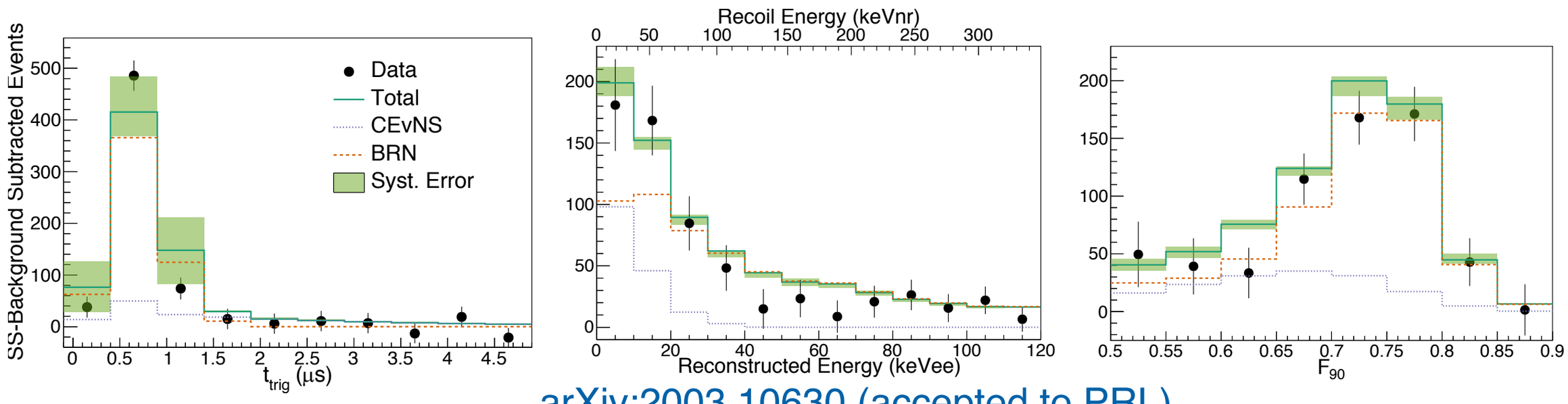




D. Akimov et al. (COHERENT). Science 357, 1123-1126 (2017)

# 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 earlier this year at >3$\sigma$ significance by COHERENT!
- Move toward precision physics and new physics searches with large detectors

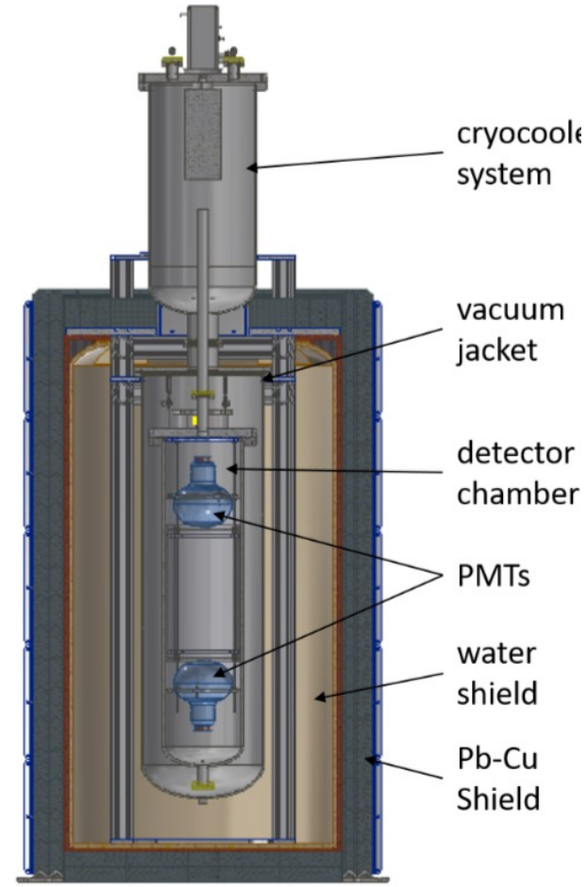


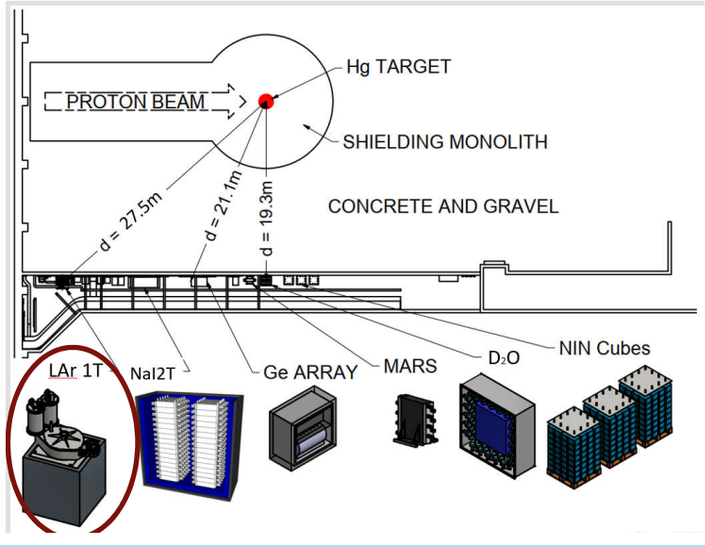




arXiv:2003.10630 (accepted to PRL)

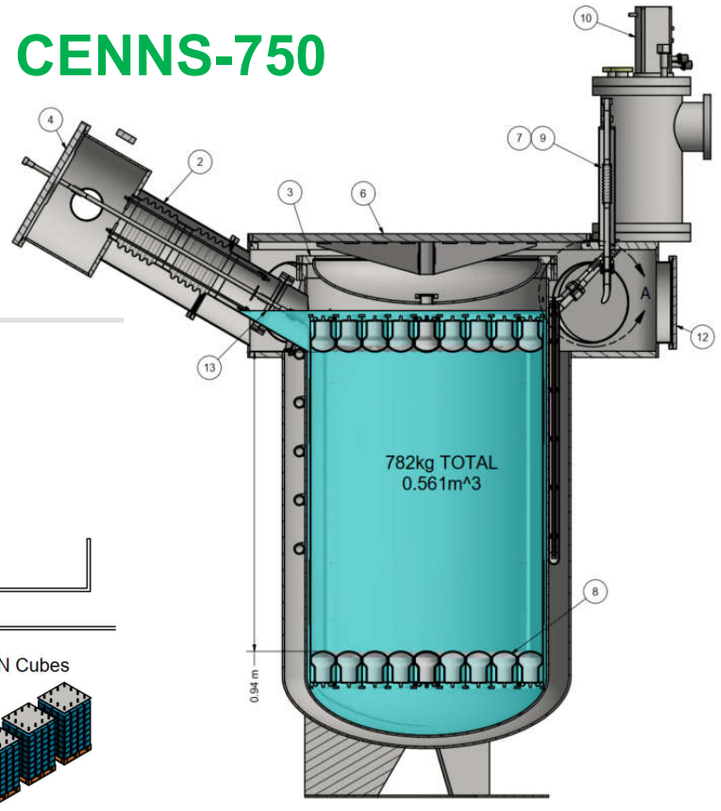
# COHERENT LAr

- COHERENT operating LAr detector at the SNS at ORNL
  - Beam at 1.4 MW. 60 Hz, 350 ns FWHM
- Currently operating 24 kg CENNS-10 detector
  - Operation continues, >2x dataset available
  - O(100) CEvNS events/year
- Results used for a number of phenomenological studies
- 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
    - $\nu_e$-Ar CC/NC measurements useful for DUNE low-energy program



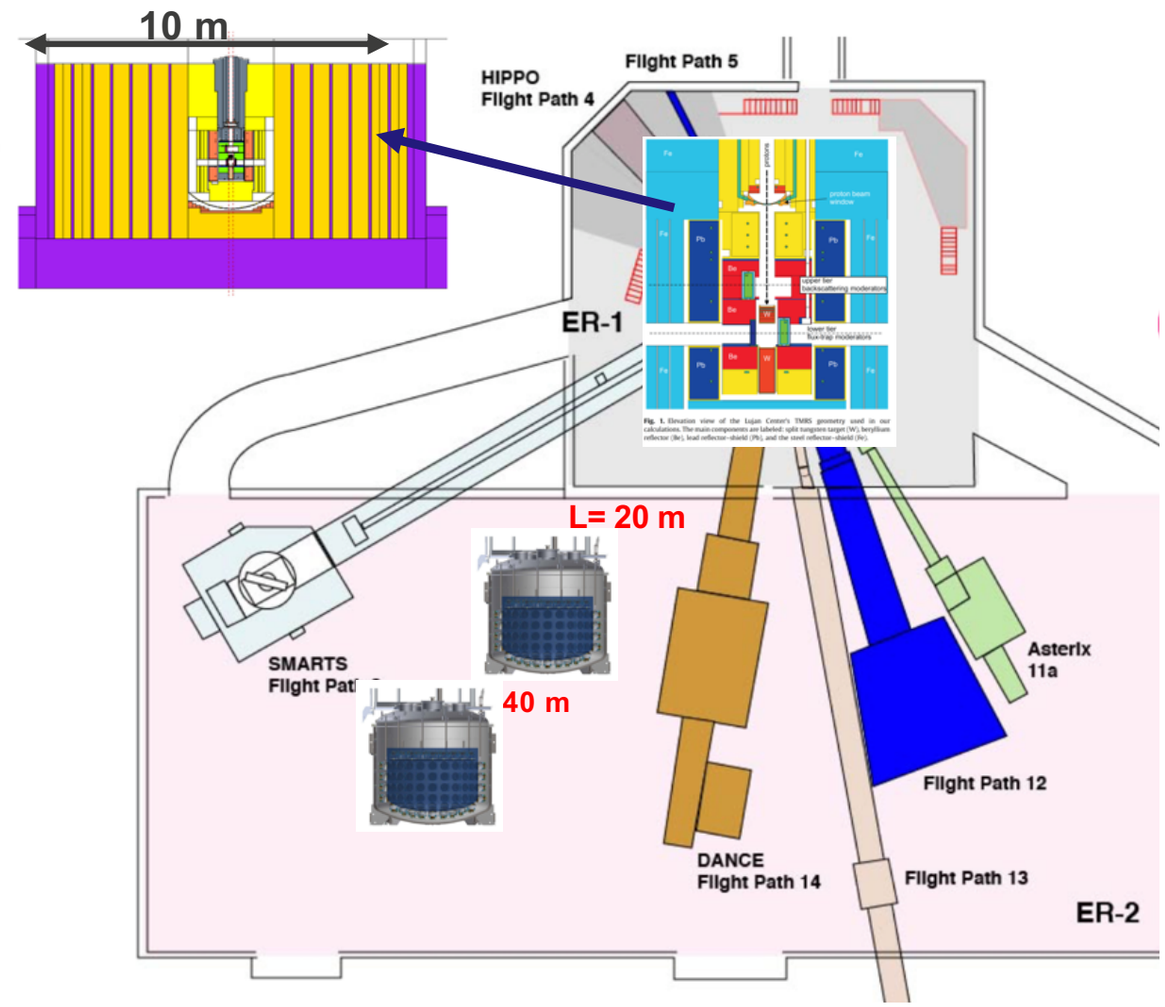



**CENNS-750**



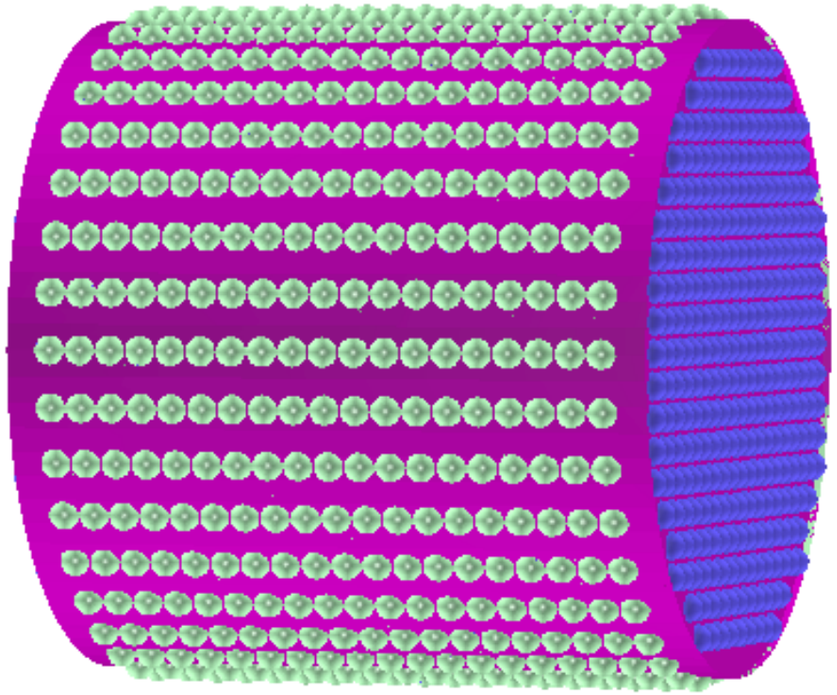
# Coherent CAPTAIN-Mills (CCM)

- 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 search
  - Upgrades to initial detector to improve light collection, additional shielding to reduce beam-related backgrounds
- Successes and lessons learned will help inform large LAr detector at Fermilab



# Proposed Detector

- 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
  - O(100k) CEvNS events/year with BAR!
- 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



# CEvNS-based Sterile Neutrino searches

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

Use coherent measurements of $\nu_\mu$ 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 $\Delta m^2$.

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:

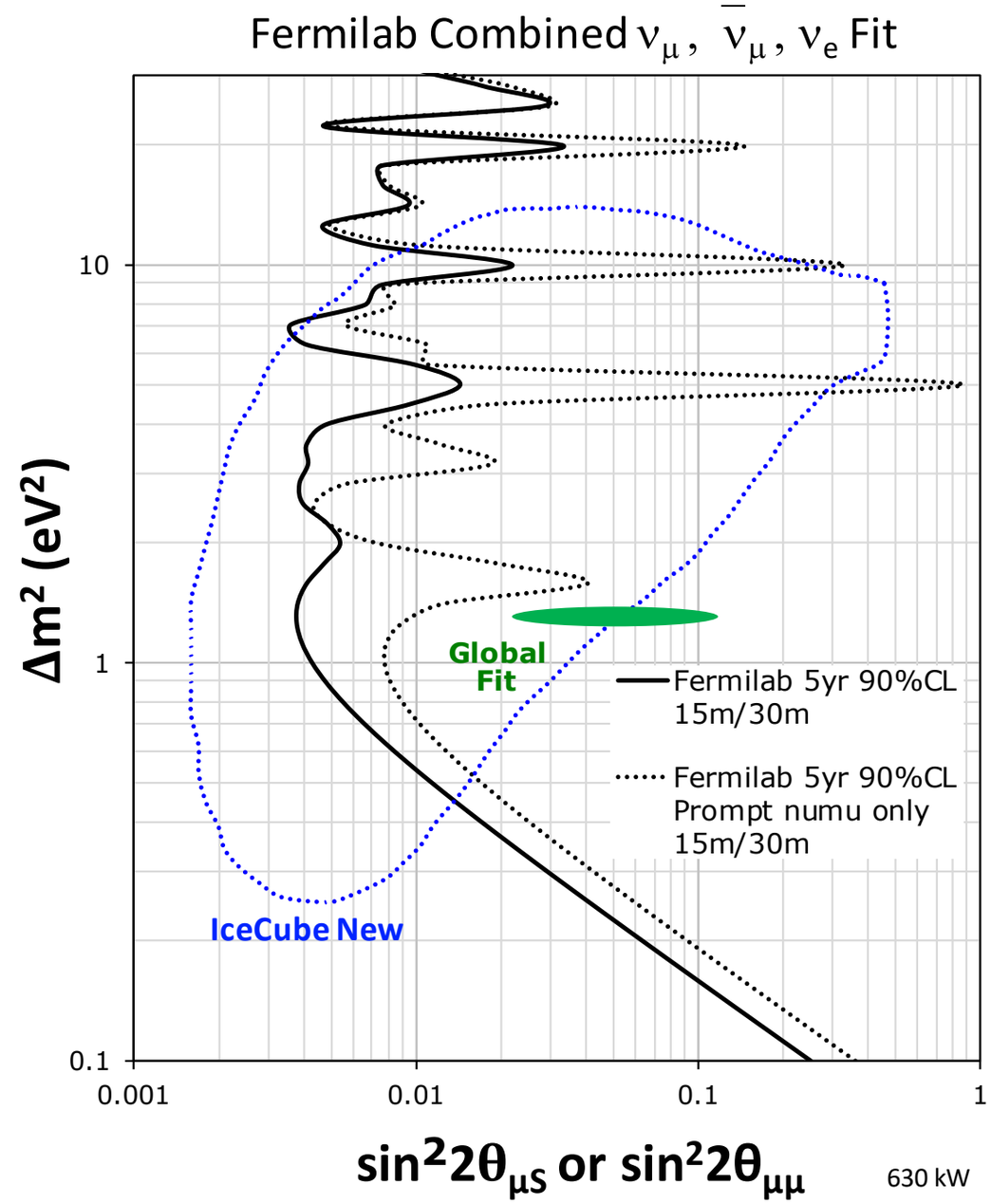
$$\sin^2 2\theta_{\mu e} = 4U_{e4}^2 U_{\mu 4}^2$$

M. Shaevitz, Columbia Univ.

# Fermilab Sterile neutrino search

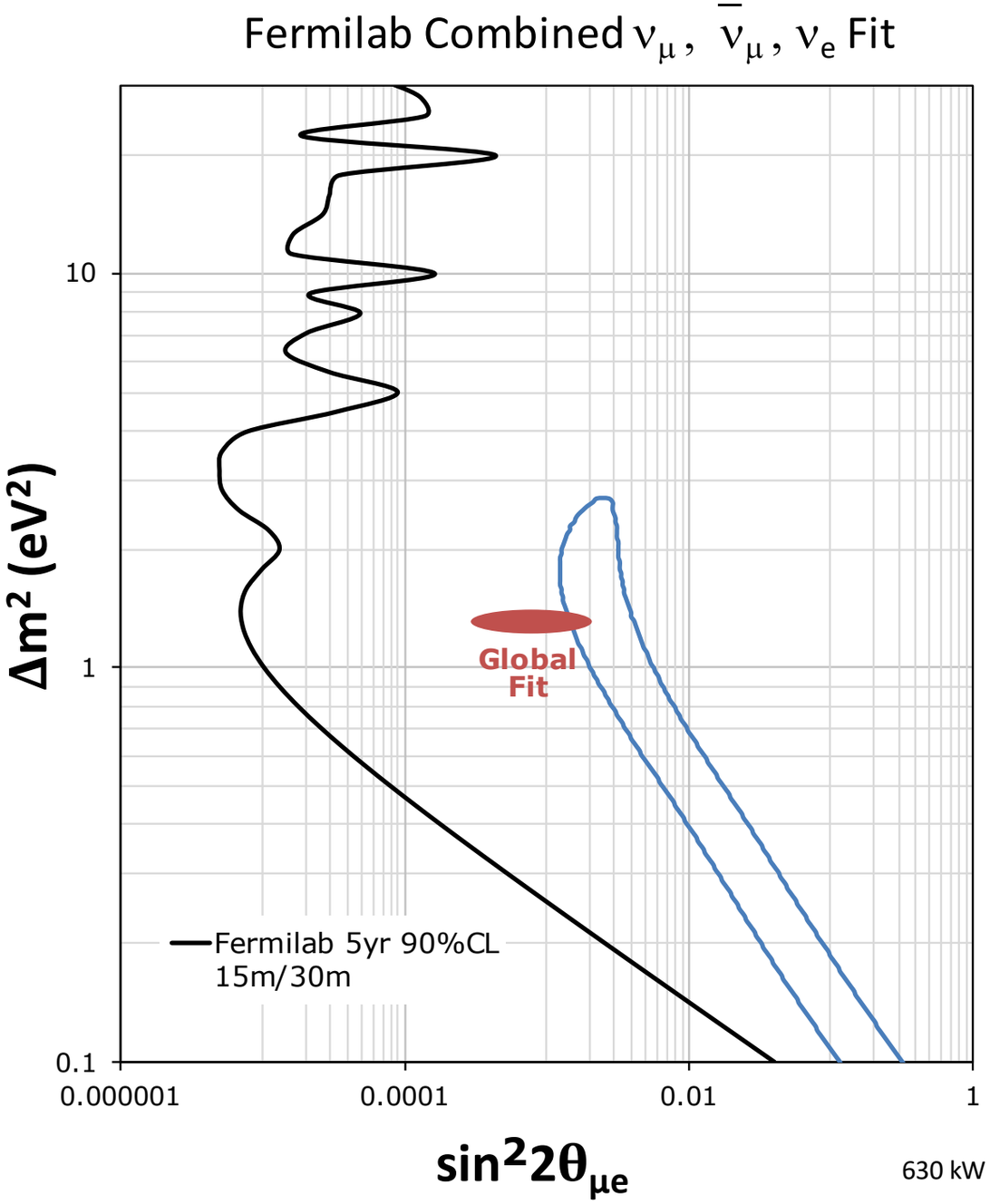
- Two identical, O(100 ton) detectors at L = 15 m and L = 30 m from target
- Optimize facility to reduce beam-correlated backgrounds to negligible levels
- Assume 1:1 signal/background for remaining beam-uncorrelated backgrounds
- Off-axis
- 630 kW beam power at 800 MeV, 75% uptime
- 20 keVnr threshold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

$\nu_\mu$ disappearance

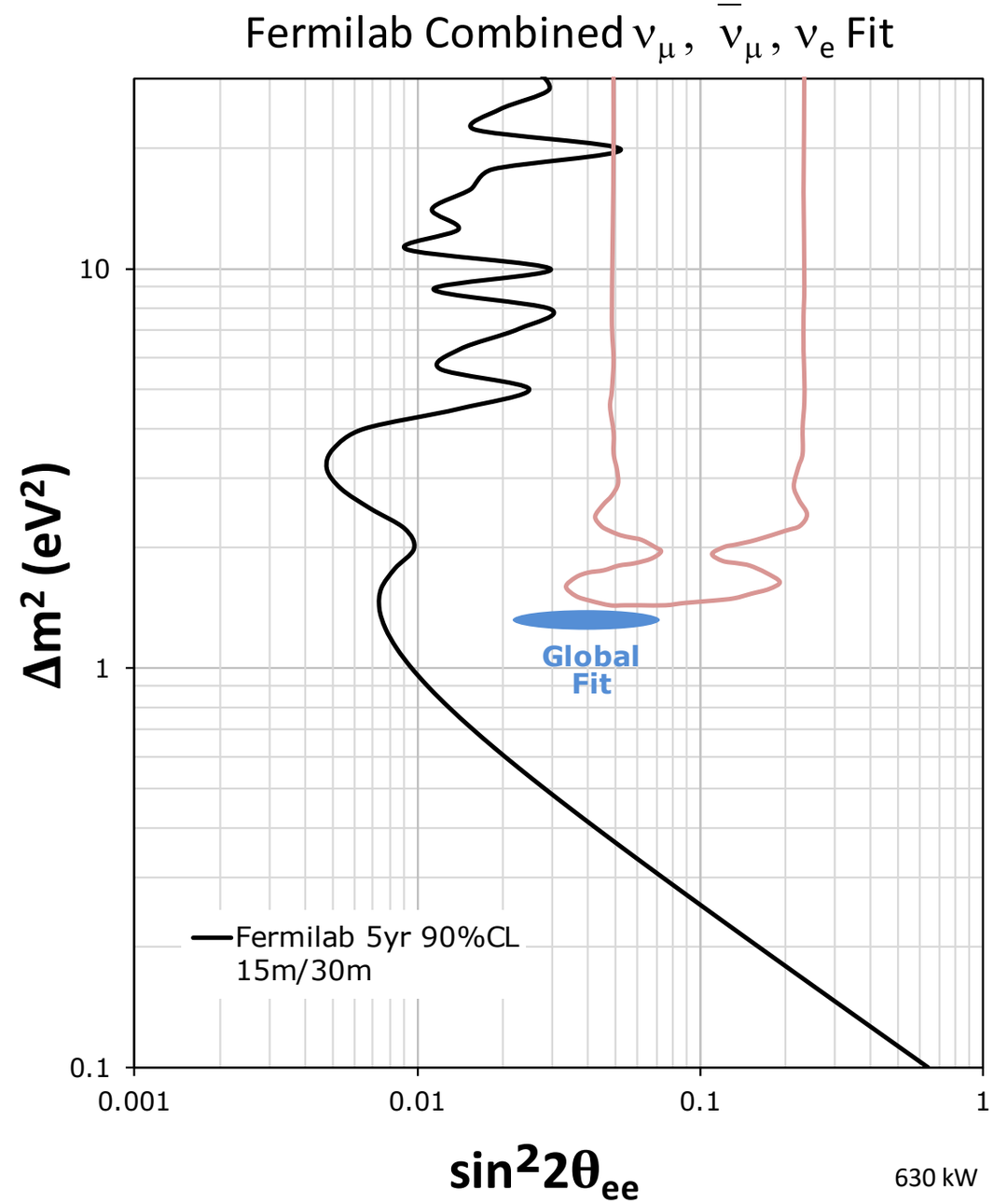



M. Shaevitz, Columbia Univ.

## $\nu_e$ appearance




## $\nu_e$ disappearance




Plots by M. Shaevitz, Columbia Univ.

**Requires separation of prompt, delayed neutrinos!**

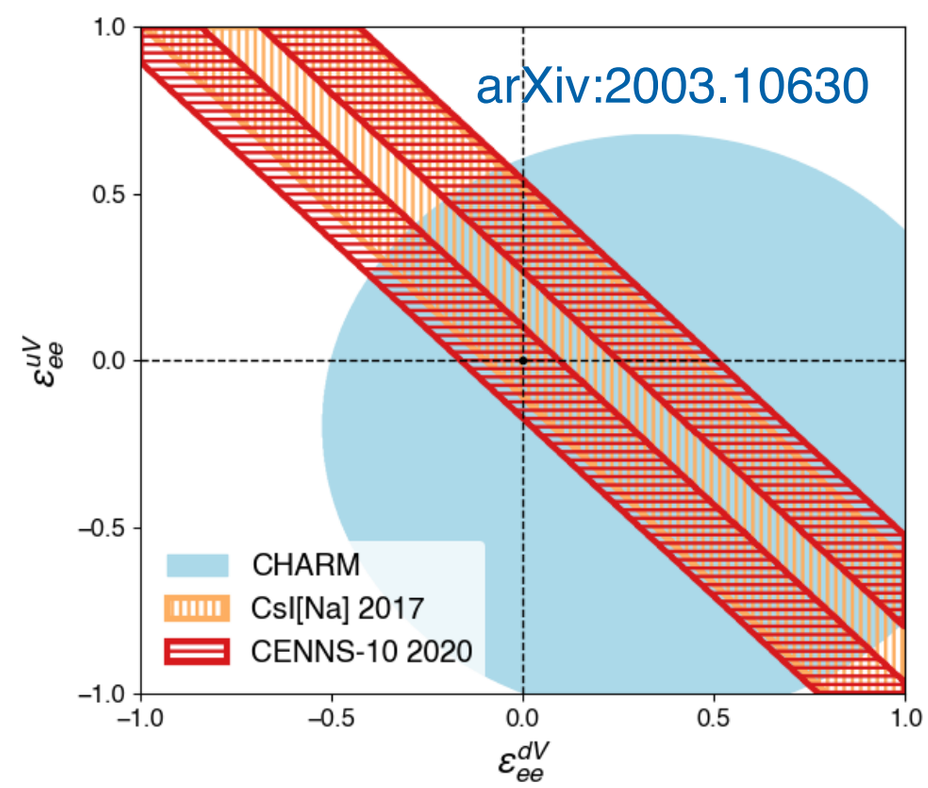
# Neutrino non-standard interactions (NSI)

- Addition to SM Lagrangian as modification of weak charge

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

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

- 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

# Summary

- Completion of PIP-II will support initial 1.2 MW beam to LBNF
- The addition of an accumulator ring allows for a rich HEP-driven stopped-pion neutrino program at Fermilab on the timescale of PIP-II
- Further upgrades via the booster replacement could produce a DAR 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

M. Toups,[1,*] R.G. Van de Water,[2,*] Brian Batell,[3] S.J. Brice,[1] Patrick deNiverville,[2] Jeff Eldred,[1] Roni Harnik,[1] Kevin J. Kelly,[1] Tom Kobilarcik,[1] Gordan Krnjaic,[1] B. R. Littlejohn,[4] Bill Louis,[2] Pedro A. N. Machado,[1] Z. Pavlovic,[1] Bill Pellico,[1] Michael Shaevitz,[5] P. Snopok,[4] Rex Tayloe,[6] R. T. Thornton,[2] Jacob Zettlemoyer,[1] and Bob Zwaska[1]

[1] *Fermi National Accelerator Laboratory, Batavia, IL 60510, USA*
[2] *Los Alamos National Laboratory, Los Alamos, NM 87545, USA*
[3] *University of Pittsburgh, Pittsburgh, PA 15260, USA*
[4] *Illinois Institute of Technology, Chicago, IL 60616, USA*
[5] *Columbia University, New York, NY 10027, USA*
[6] *Indiana University, Bloomington, IN 47405, USA*

# Thank you!

# Backup

# 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 $\nu_\mu$
  - 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

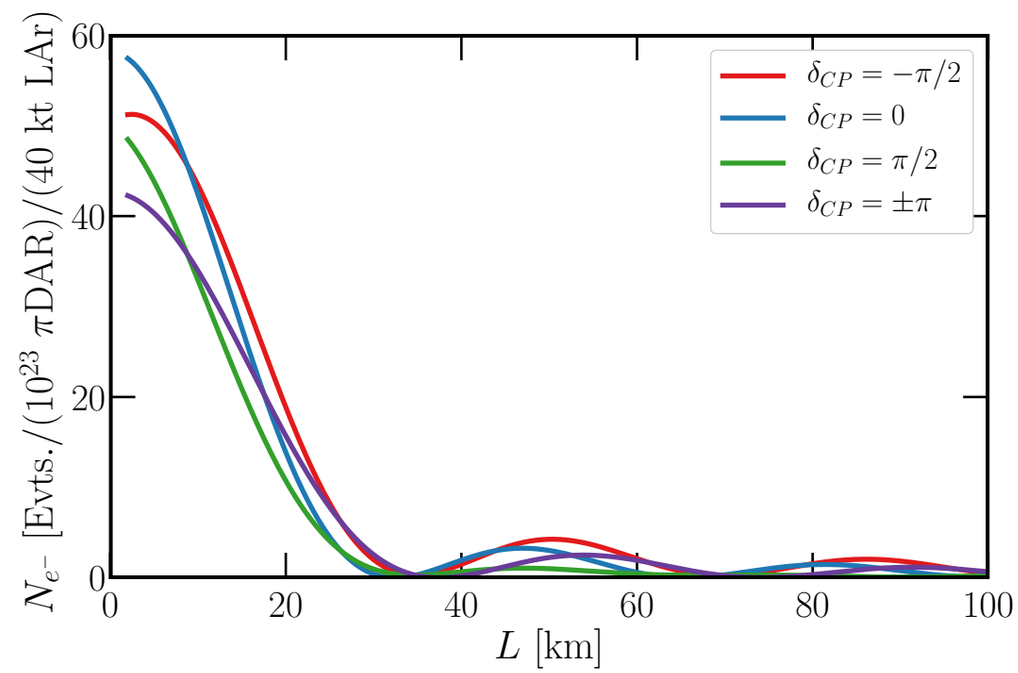


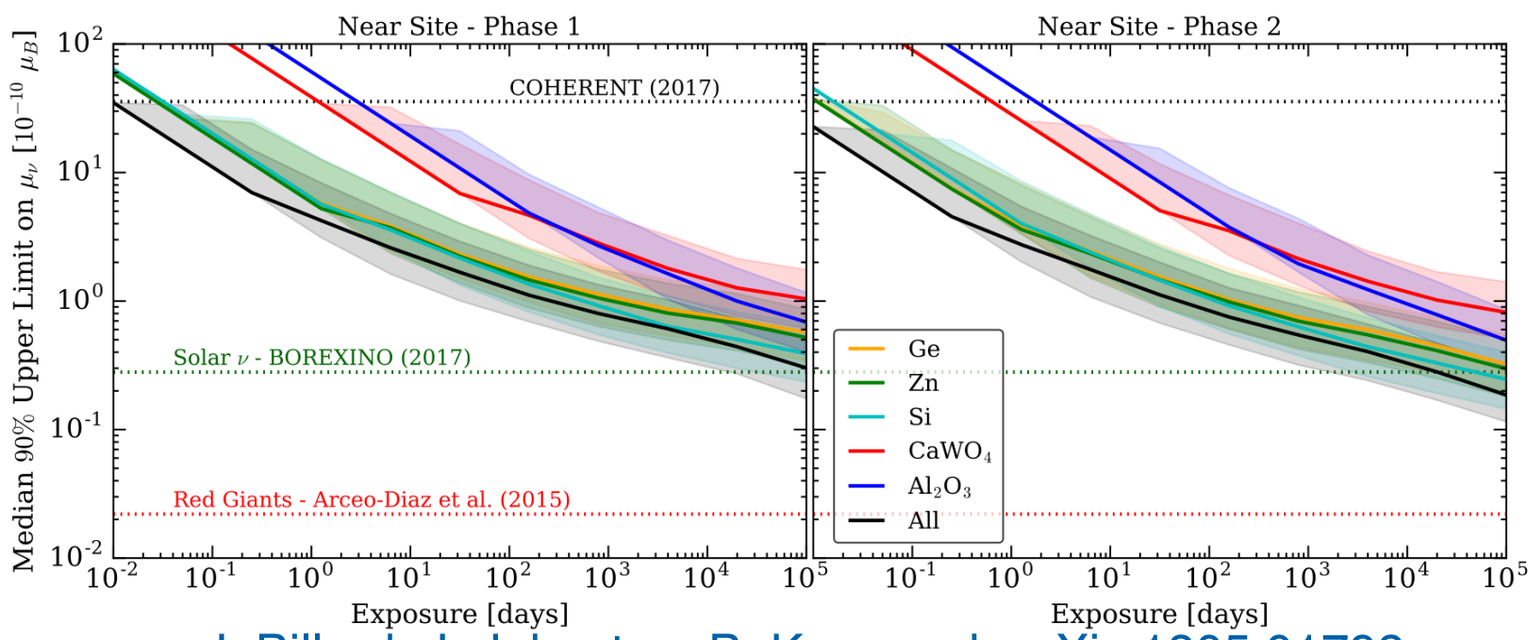

FIG. 5. Number of electron-neutrino events from pion decay-at-rest neutrinos that have undergone the oscillation $\nu_\mu \to \nu_e$ and interacted in a liquid argon detector. We present the number of events as a function of distance between the pion decay-at-rest source and the detector $L$, assuming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

# Neutrino magnetic moment

- Both neutrino-nucleus and neutrino-electron scattering able to probe neutrino magnetic moment
  - Can we do better than LSND? (<6.8 x $10^{-10}$ $\mu_B$)
- 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