Searches for new physics with a stopped-pion source at the Fermilab accelerator complex

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Magnificent CEvNS 2020

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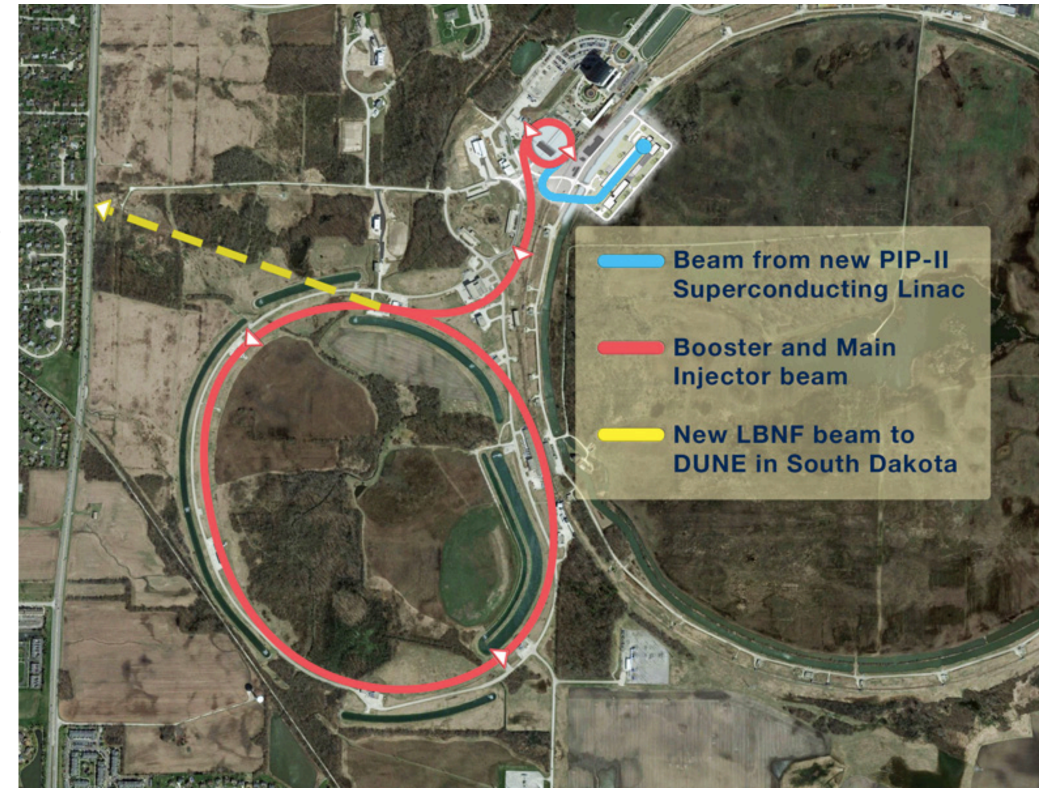
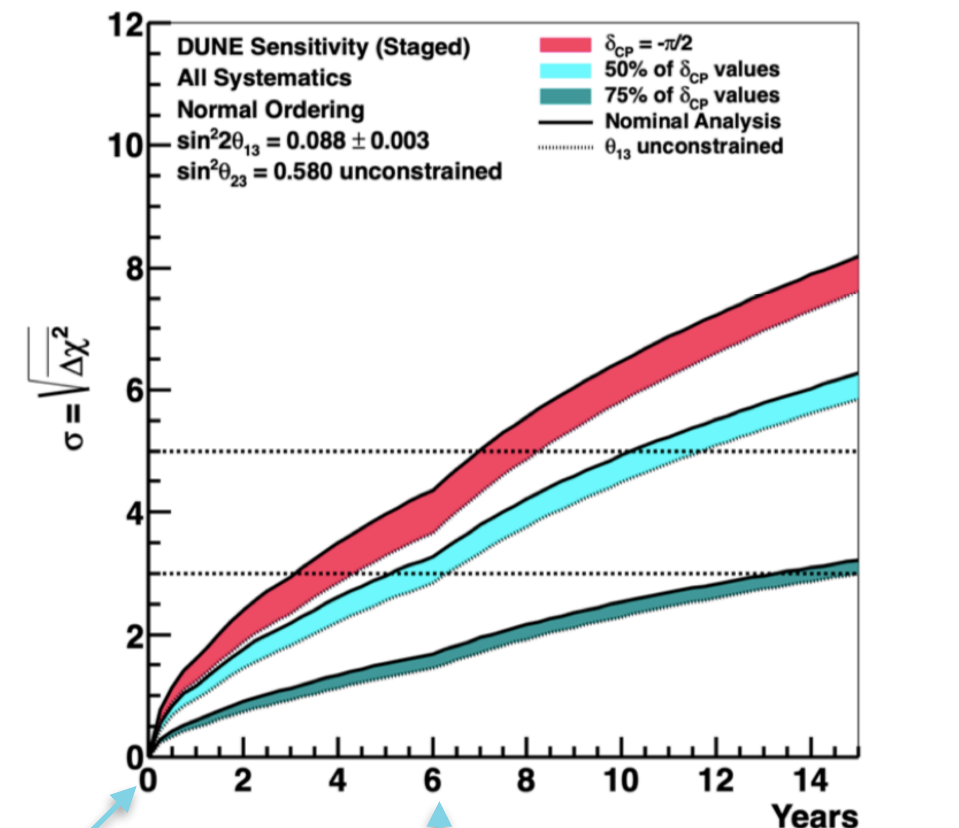
The PIP-II Project

- DUNE major component of US particle physics program in next ~decade
- Upgrade to the current Fermilab accelerator complex driven by DUNE physics goals
- Expected completion FY2027
- 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
  - Opportunity to build facility to maximize high-energy physics impact
    - Dark Sector (DS) searches

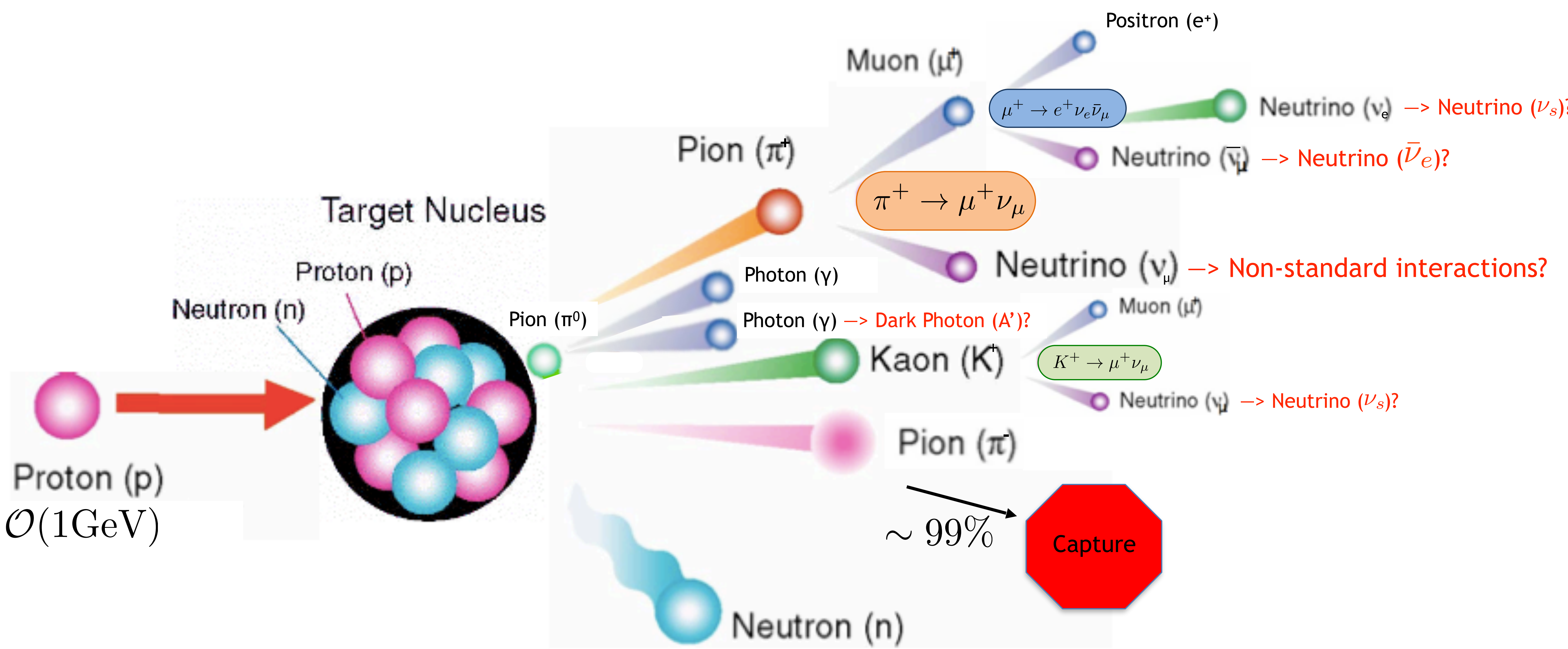




1.2 MW with 2 DUNE FD modules

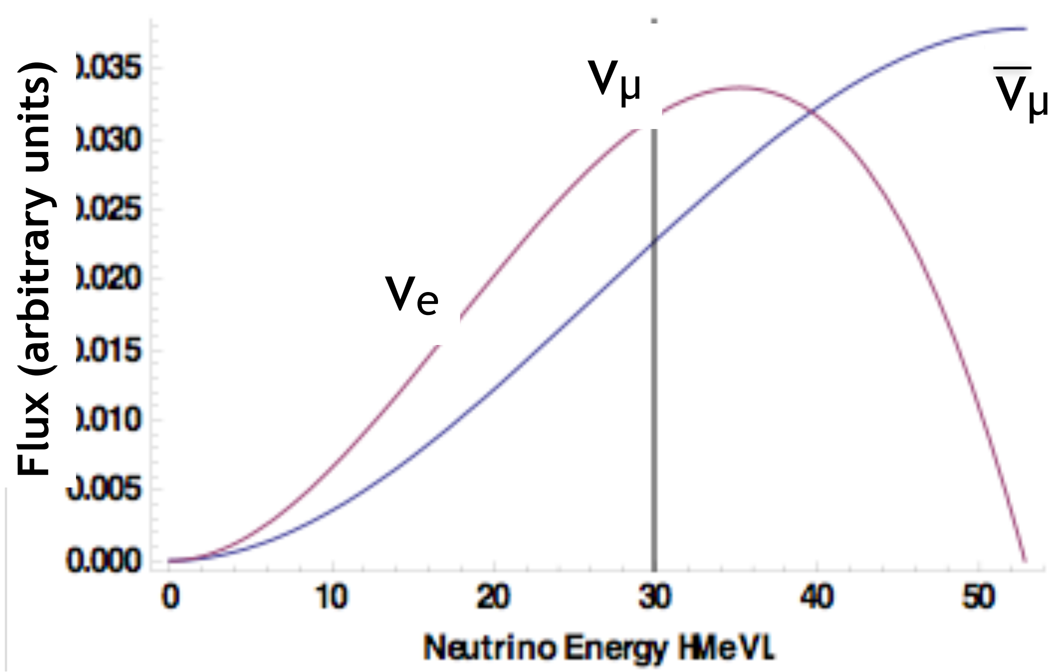
2.4 MW with 4 DUNE FD modules

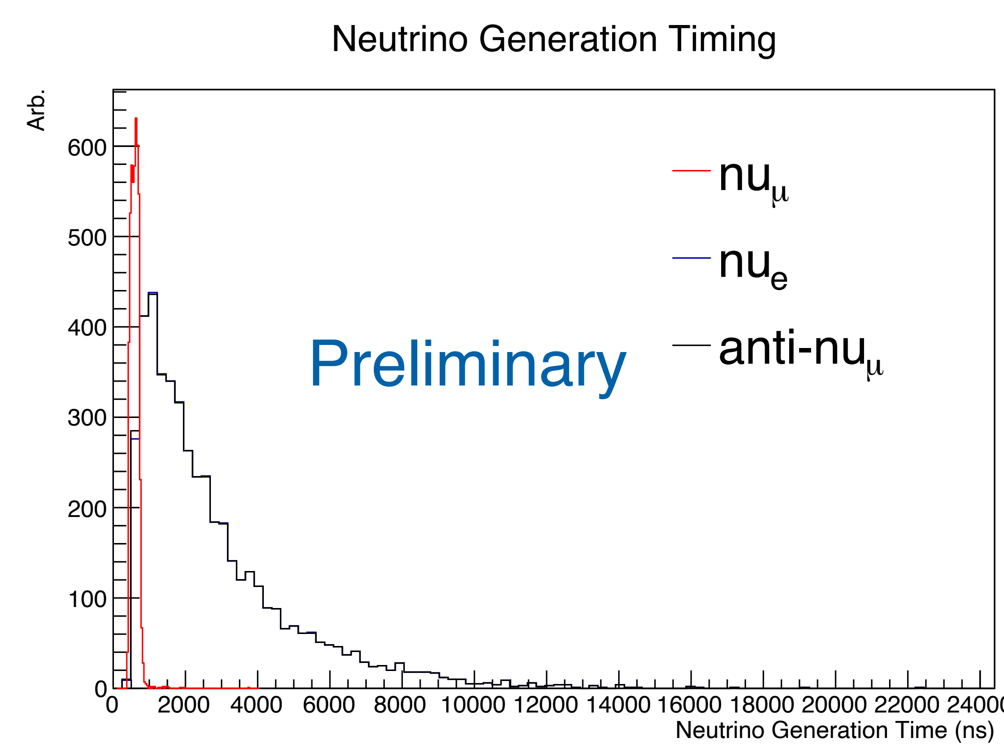
Stopped-pion neutrino source



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





Booster Accumulator Ring Concept

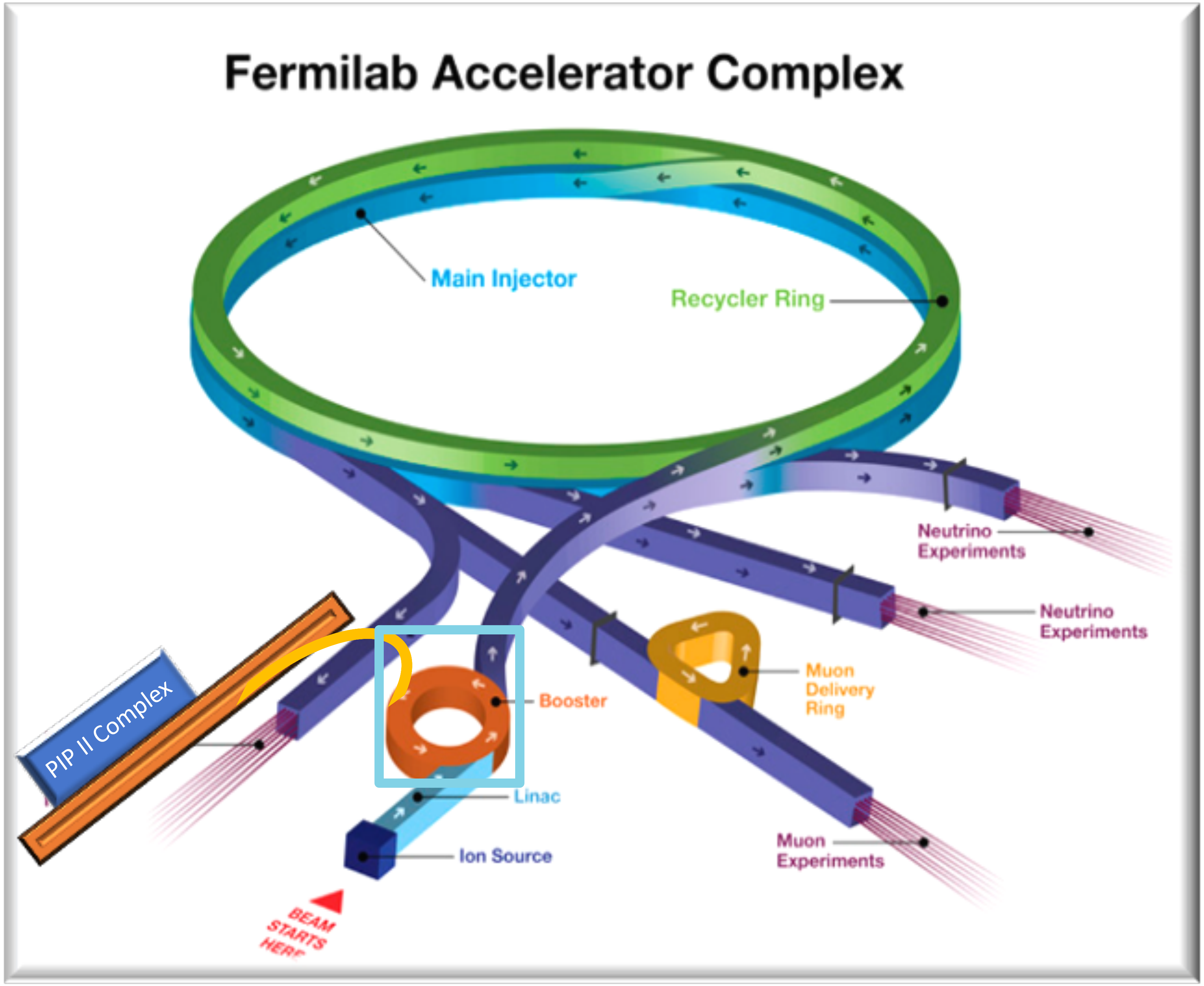
Overview

- 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.

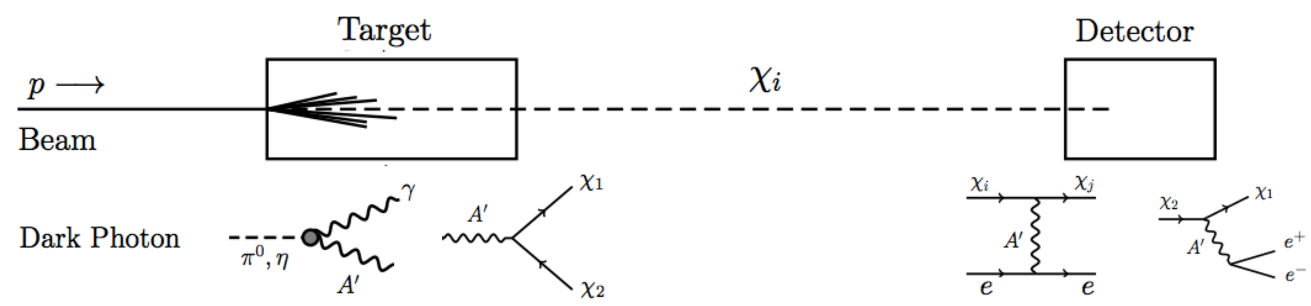


W. Pellico, FNAL

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

- Physics Opportunities At Such a Facility

  - Light dark matter (LDM) / DS Searches
    - Decay and/or scattering signatures



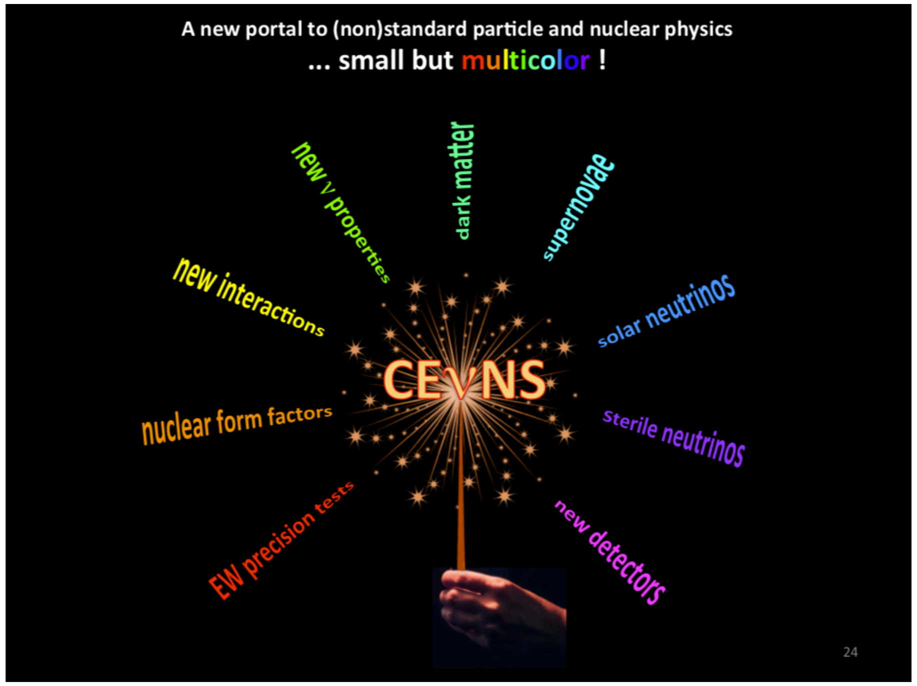
  - Light Sterile Neutrino Searches
    - Both appearance and disappearance possible

  - 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

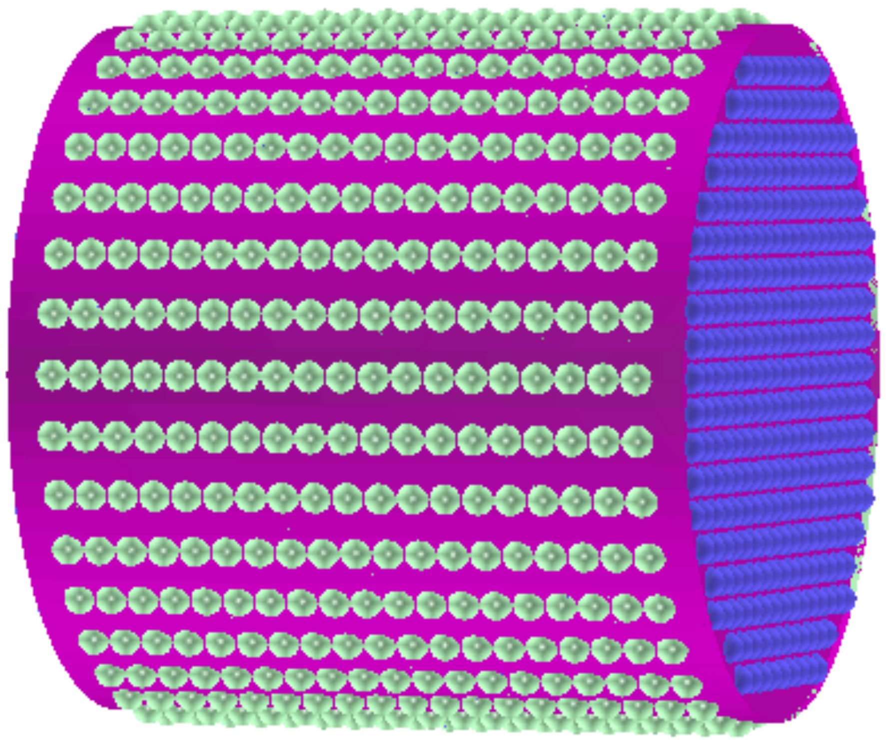
  - Additional topics:
    - Searches for axion-like particles, 3-ν oscillations, etc.



E. Lisi, Neutrino 2018

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(1M) CEvNS events/year with MW-class beam!
- Experiments such as 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 opportunities for a dark-sector search program at an upgraded Fermilab accelerator complex



Fermilab Light Dark Matter Search

- Stopped-pion neutrino sources place strong limits on light dark matter
  - 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

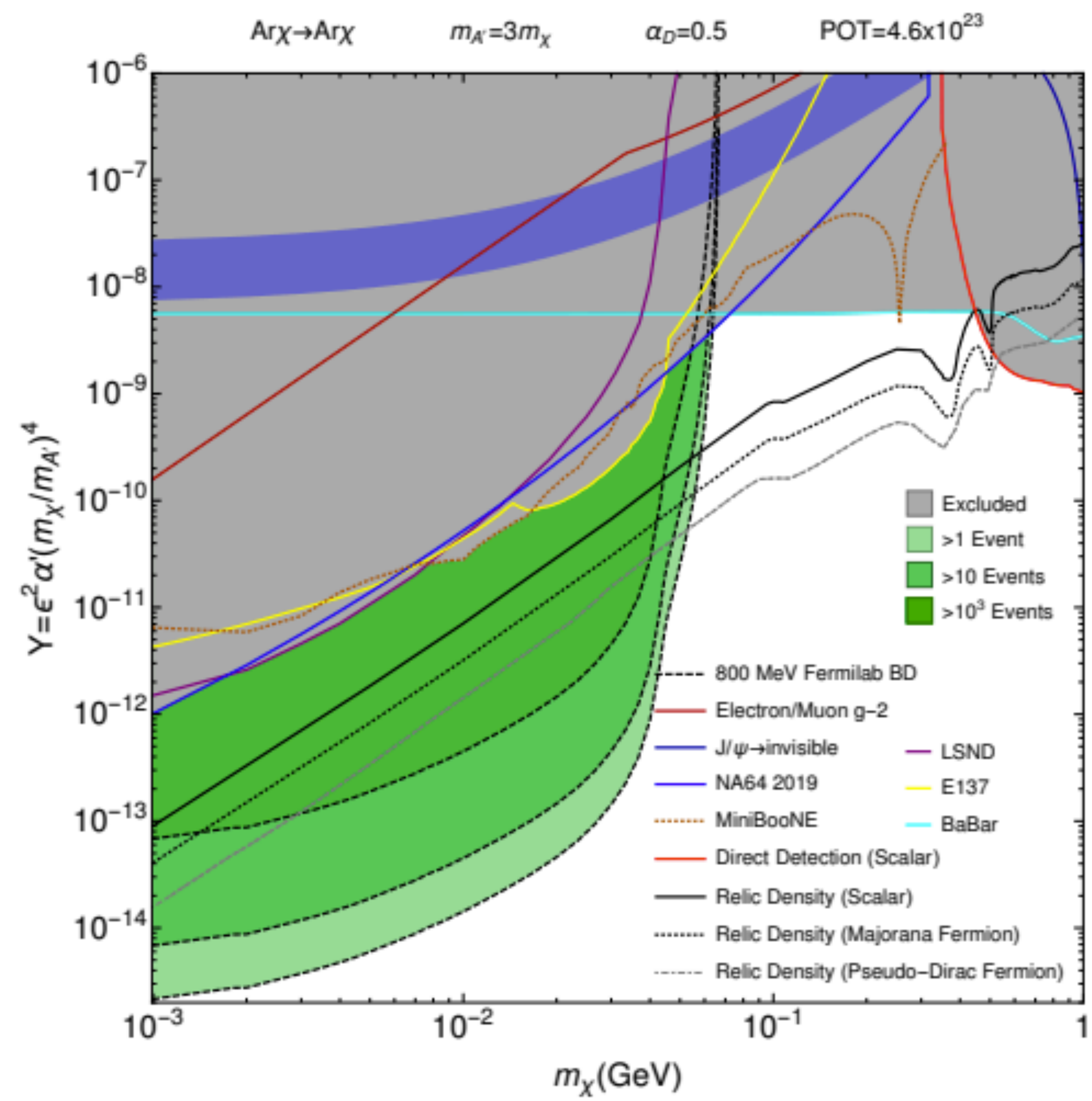


FIG. 1. Fermilab beam dump facility argon recoil event sensitivity curves for 4.6×10^{23} protons on target compared to thermal relic density targets and existing 90% exclusion limits as a function of the dimensionless scaling variable $Y = \epsilon^2\alpha(m_\chi/m_{A'})^4$, assuming $\alpha = 0.5$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

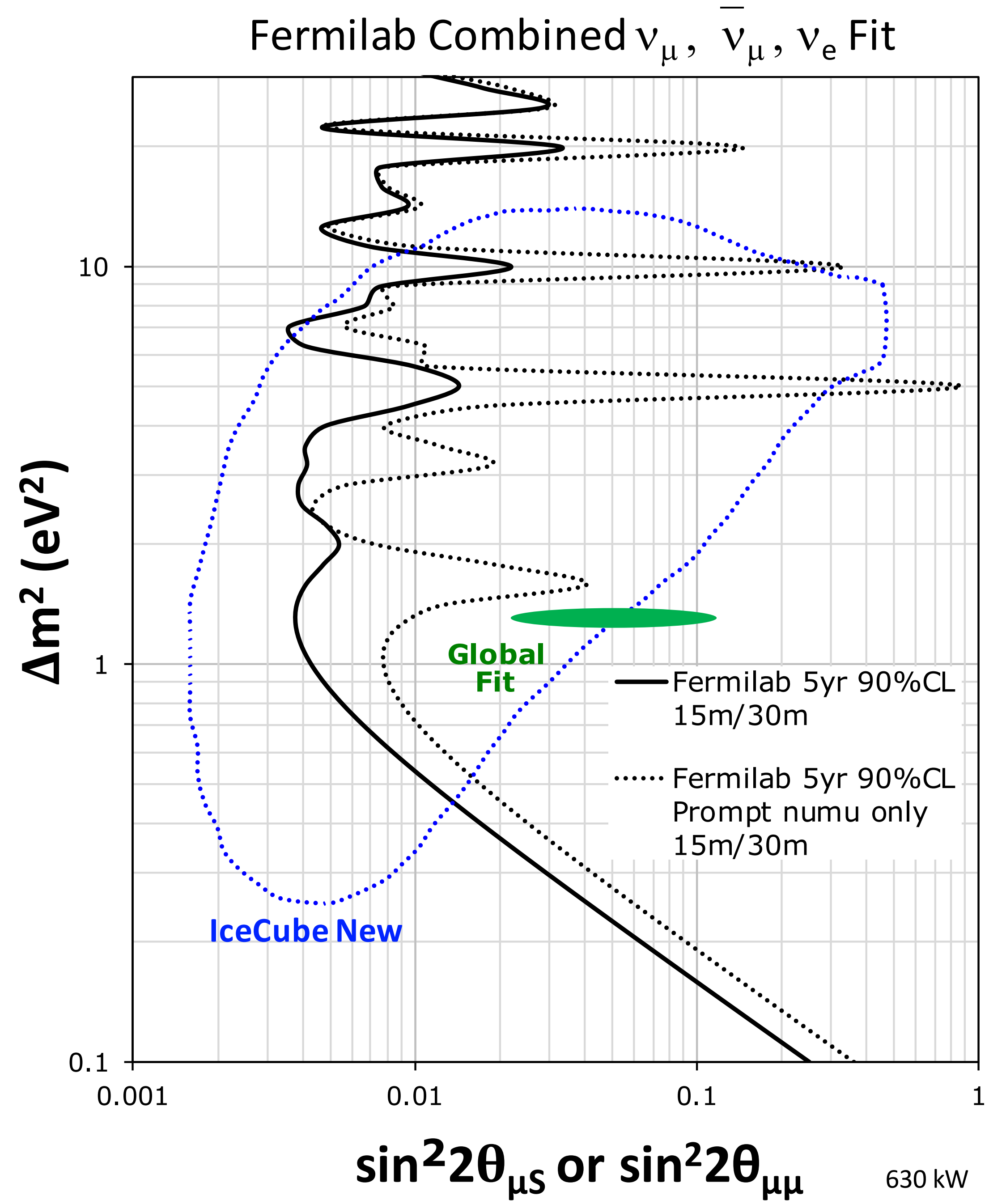
$$\sin^2 2\theta_{\mu e} = 4U_{e4}^2 U_{\mu 4}^2$$

M. Shaevitz, Columbia Univ.

Fermilab Sterile neutrino search

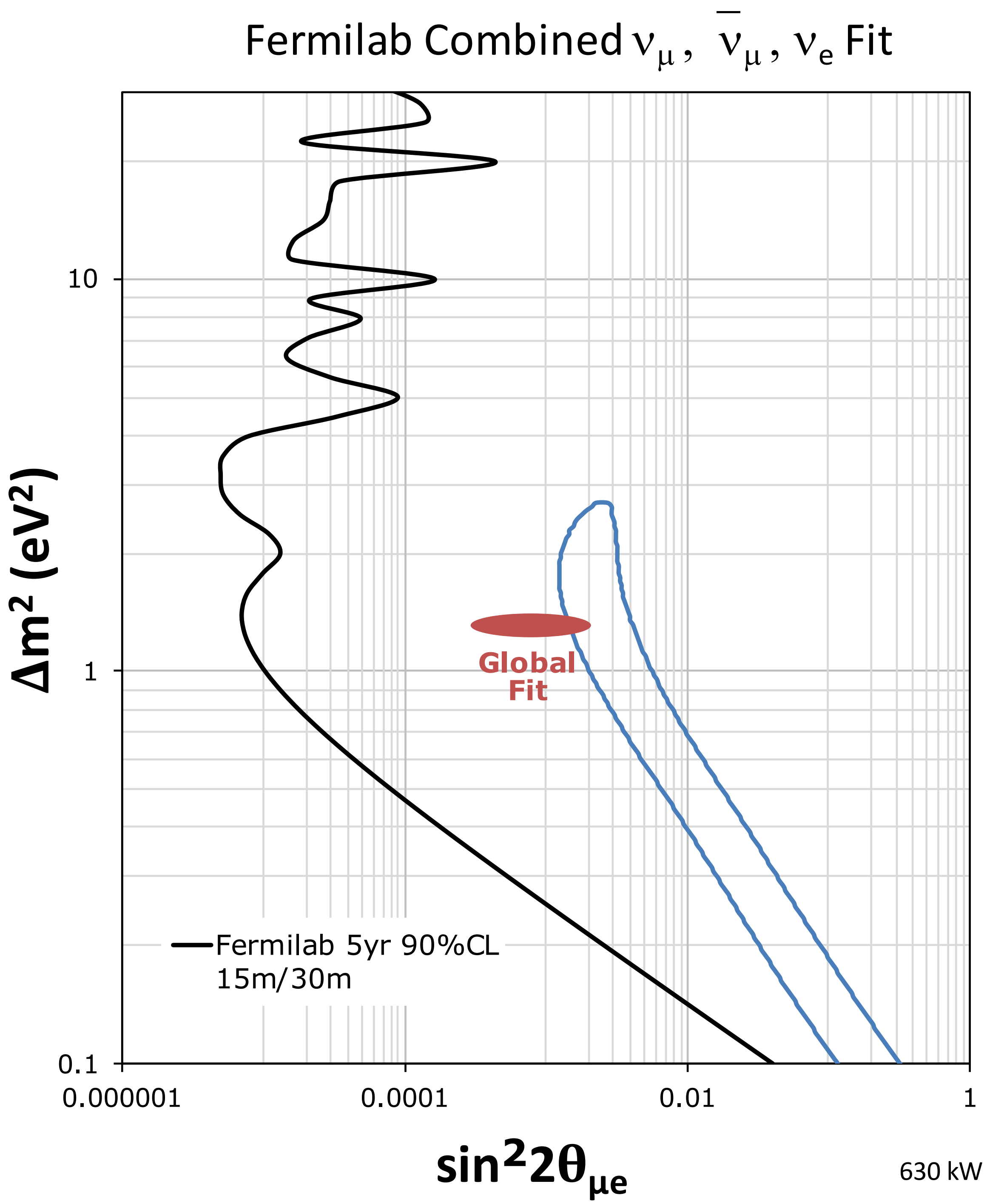
- Two identical, O(100 ton) detectors at L = 15 m and L = 30 m from target
- Optimize facility to reduce beam-correlated backgrounds to negligible levels
- Assume 1:1 signal/background for remaining beam-uncorrelated backgrounds
- Off-axis
- 630 kW beam power at 800 MeV, 75% uptime
- 20 keVnr threshold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

ν_μ disappearance

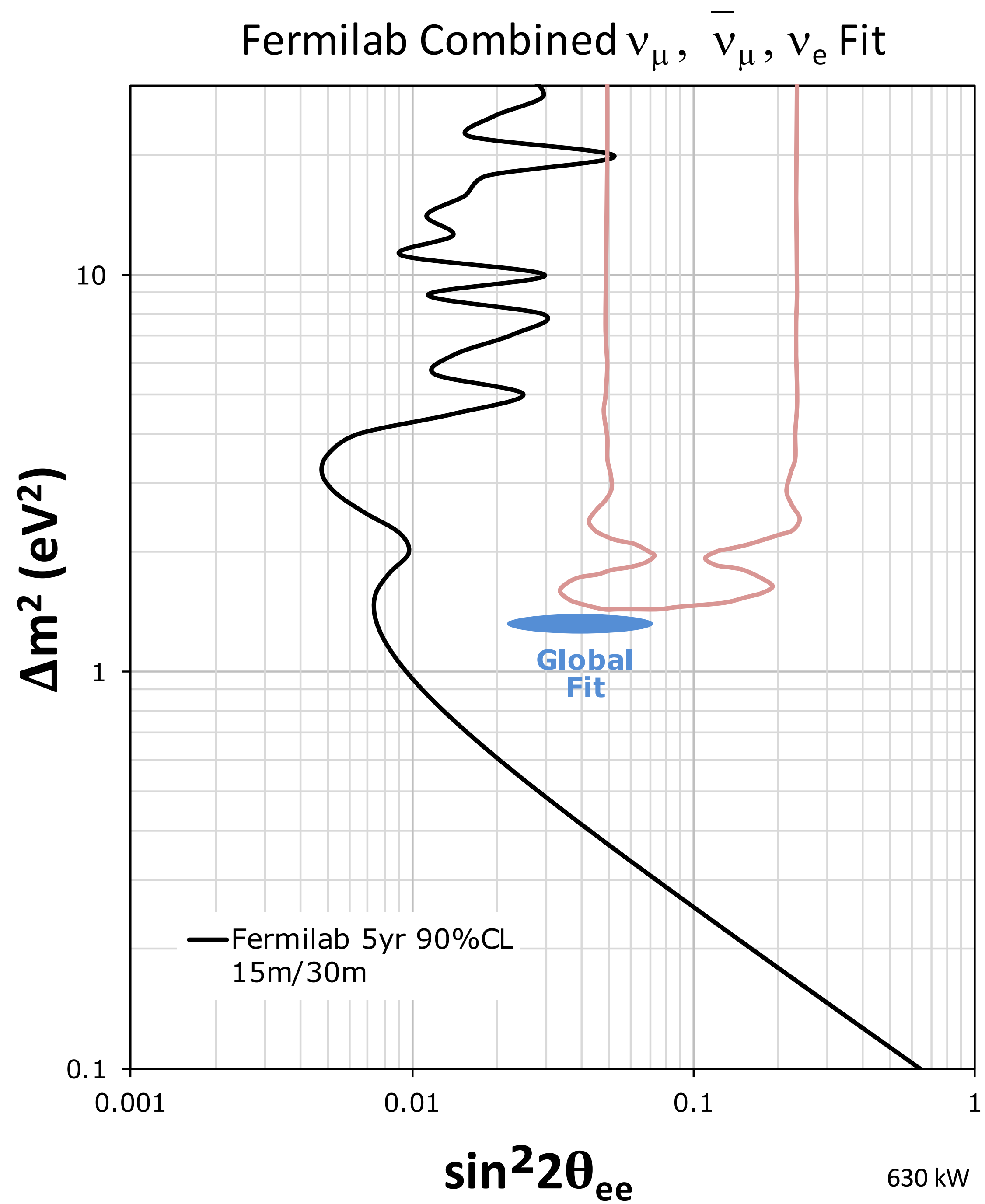


M. Shaevitz, Columbia Univ.

ν_e appearance



ν_e disappearance



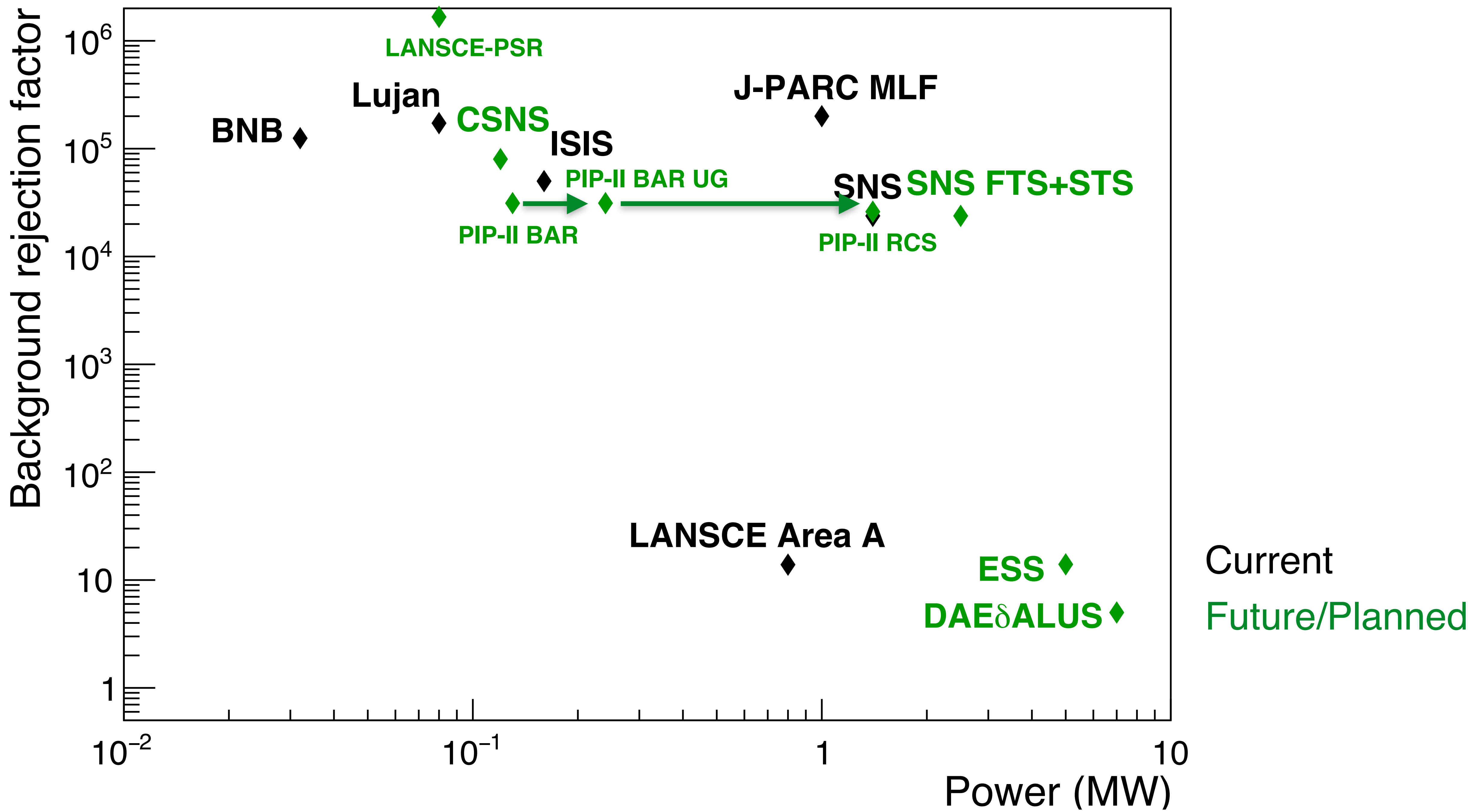
Plots by M. Shaevitz, Columbia Univ.

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, a booster replacement such as a rapid cycling synchrotron (RCS) will be constructed delivering 2.4 MW to LBNF and increasing 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

Summary

- Completion of PIP-II in FY2027 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
- Stopped-pion sources provide access to a host of physics opportunities such as light dark matter and 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 light dark matter models and CEvNS-based sterile neutrino searches
- Possible future upgrades to the accelerator complex include an RCS and improved beam power
- We are looking to grow our collaboration! If you're interested in this effort or have questions, please contact us, Jacob Zettlemoyer (jzettle@fnal.gov), Matt Toups (toups@fnal.gov) and Richard Van de Water (vdwater@lanl.gov)

More Information

- Fermilab Booster Accumulator Ring Workshop: Tuesday December 15, 2020!
  - Register at https://indico.fnal.gov/event/46607/
- 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!