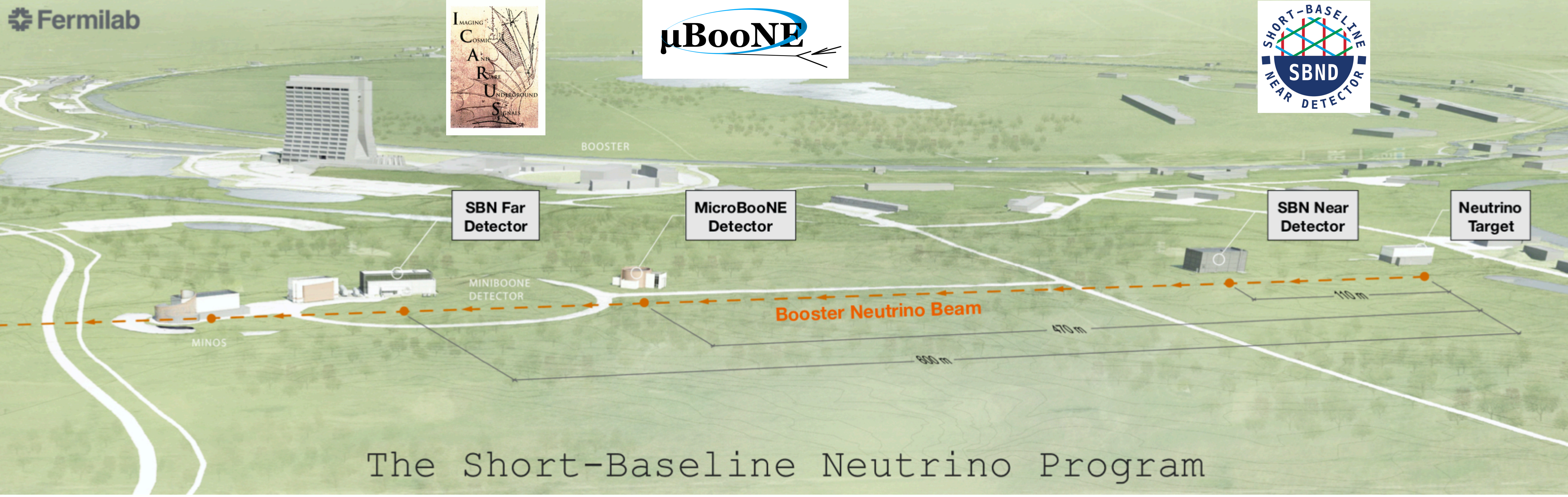


The Short-Baseline Neutrino Program at Fermilab

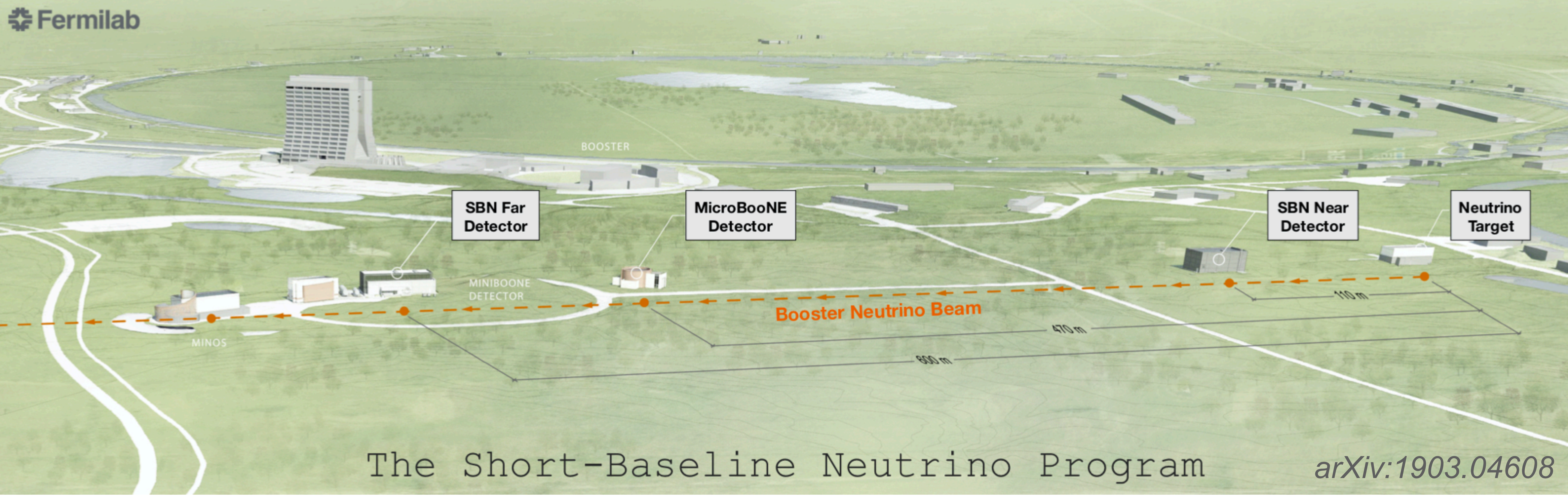
Vishvas Pandey
University of Florida

(For the SBN Collaborations)

SESAPS 2019 November 7-9, 2019

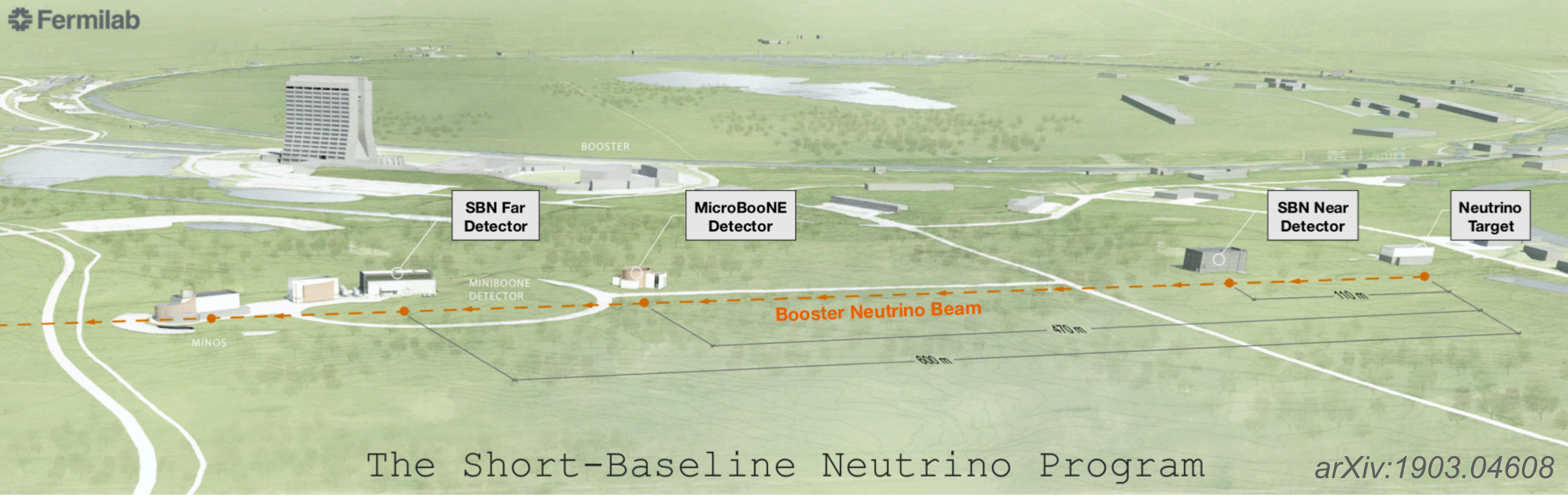
UF UNIVERSITY of FLORIDA

Fermilab



Outline

- Short-Baseline Neutrino Oscillation Anomalies
- The SBN Program at Fermilab
- Physics Capabilities of SBN program



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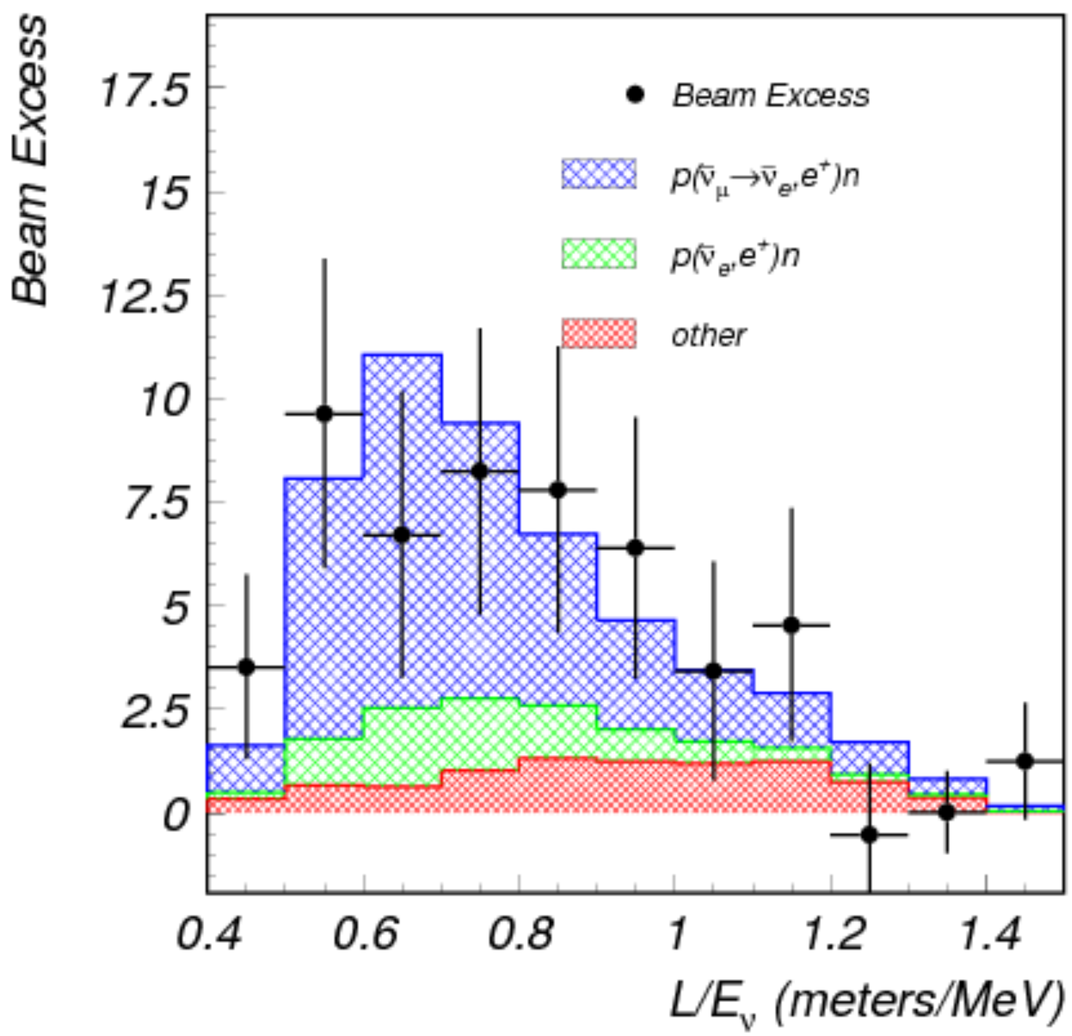
▪ LSND Anomaly

- $\bar{\nu}_\mu \to \bar{\nu}_e$ **oscillations**

- A 3.8σ excess of $\bar{\nu}_e$-like events over the background



Phys. Rev. D ***64****, 112007 (2001)*

- L/E ~ 0.5 to 1.5 m/MeV

LSND Anomaly

- $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ **oscillations**
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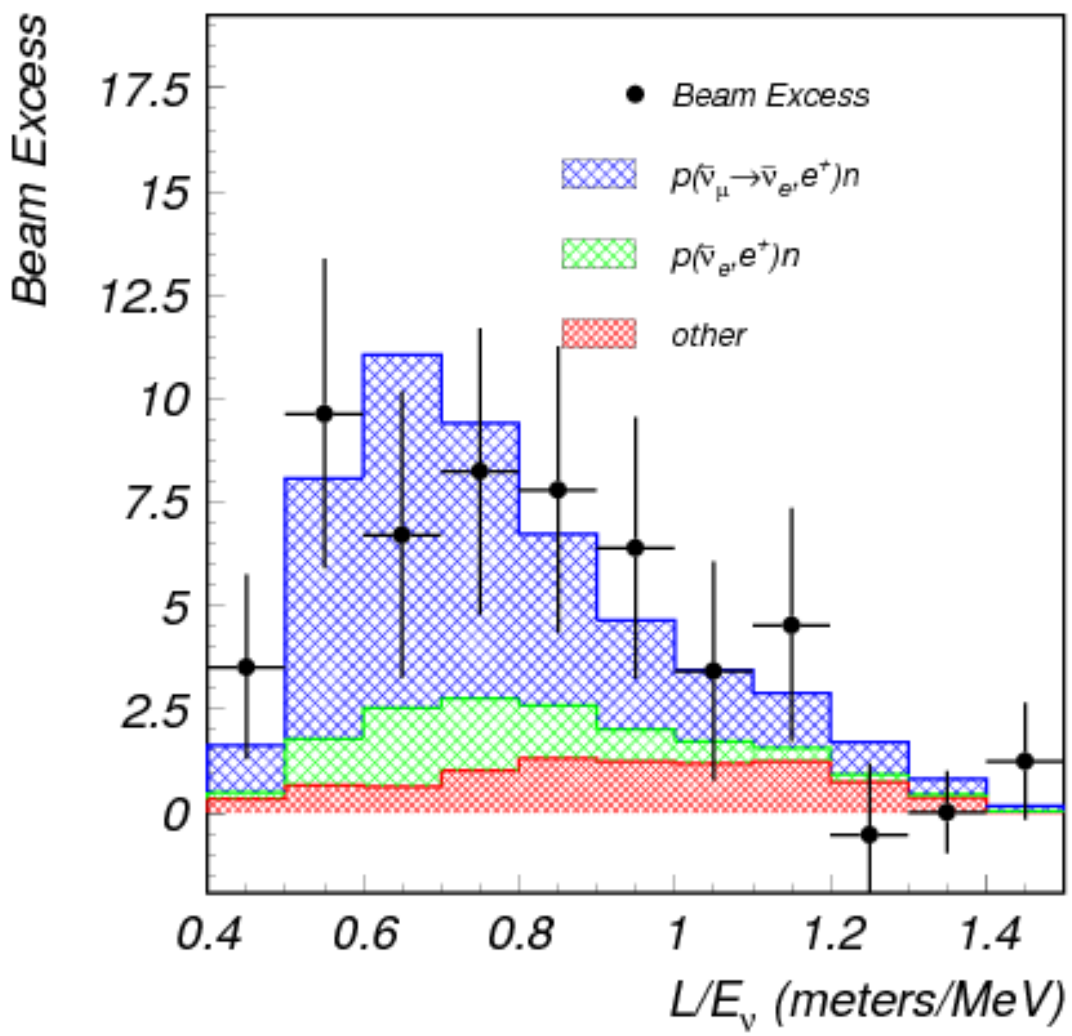
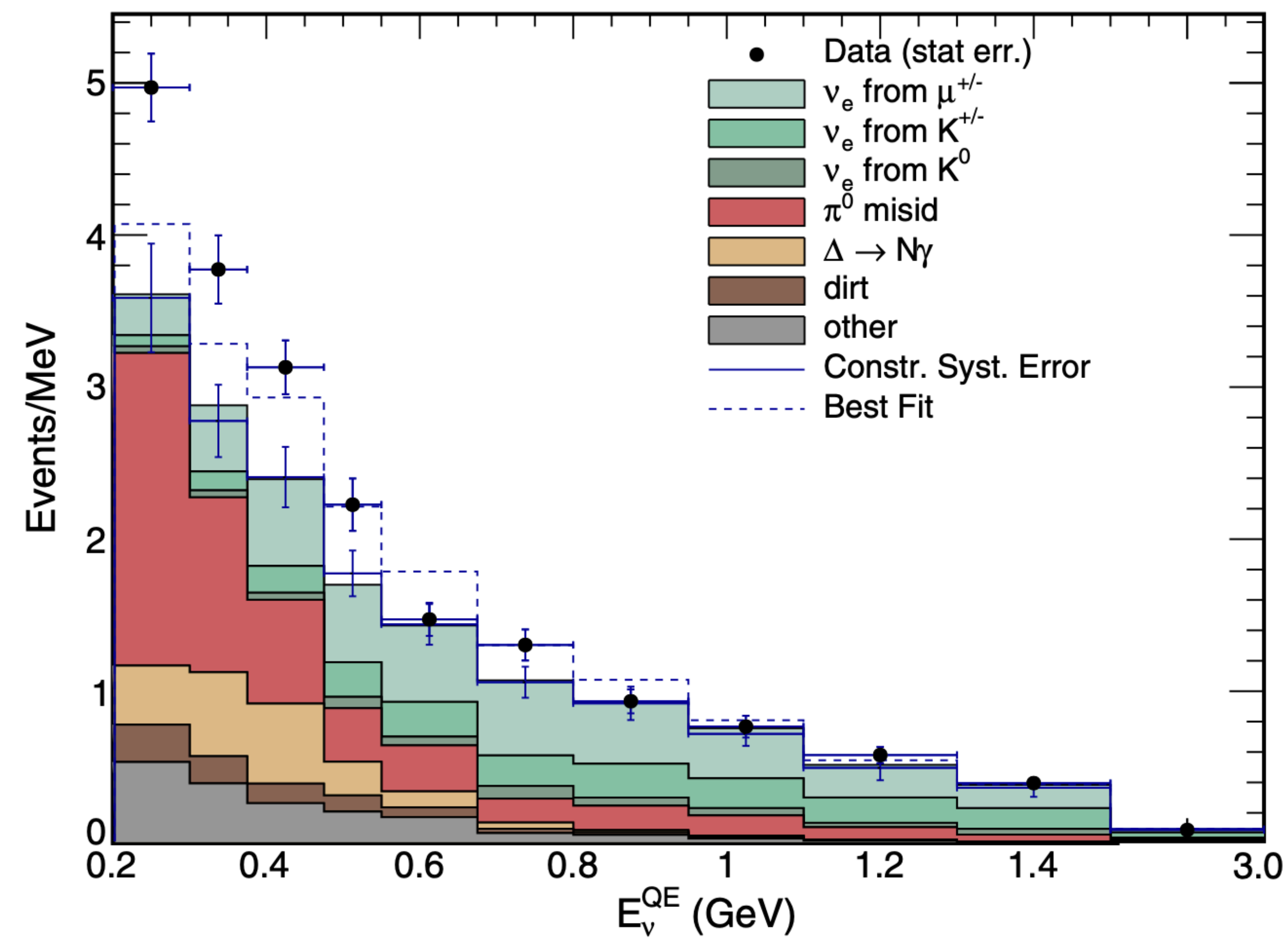


Phys. Rev. D ***64***, *112007 (2001)*

- L/E ~ 0.5 to 1.5 m/MeV

MiniBooNE Anomaly

- $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$, $\nu_\mu \rightarrow \nu_e$ **oscillations**
- An excess of 4.5σ (2.8σ) ν_e ($\bar{\nu}_e$) events over the background
- MiniBooNE low-energy anomaly



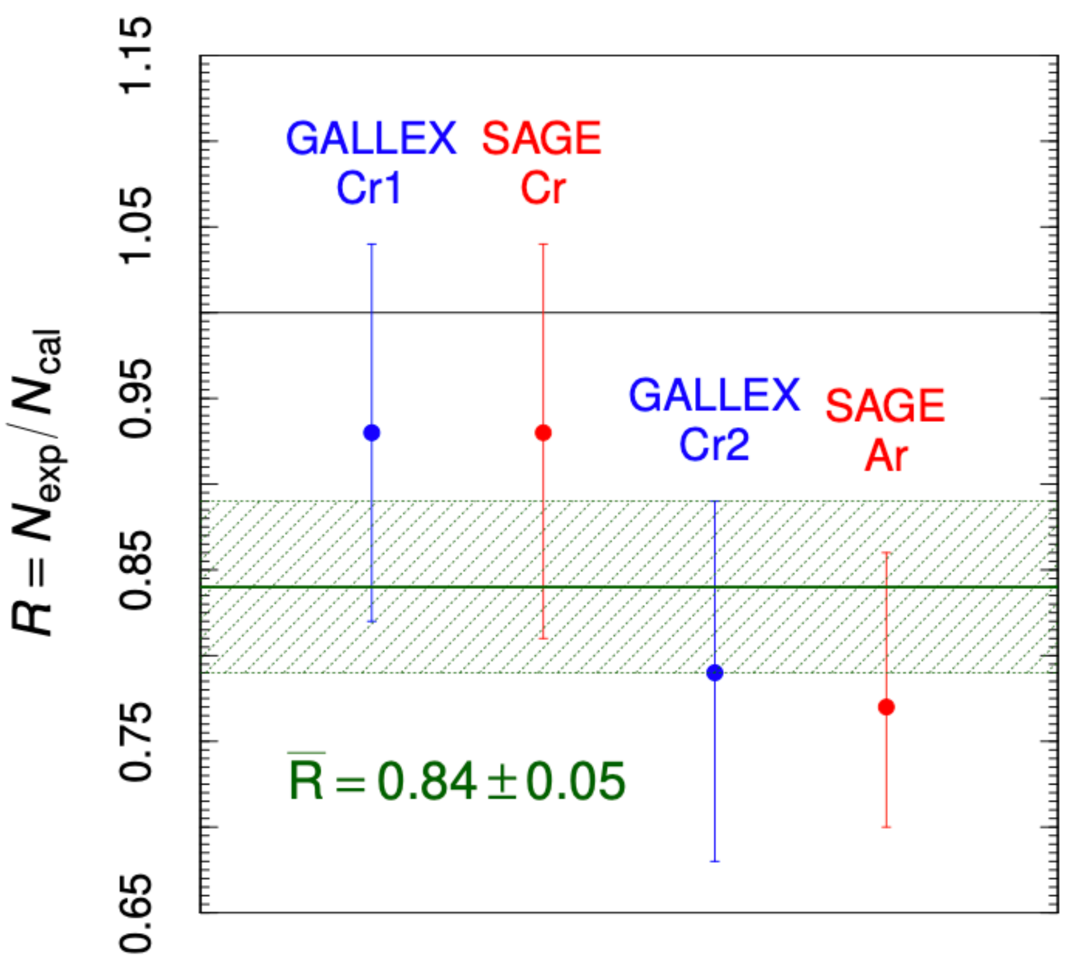
Phys. Rev. Lett. ***121****, 221801 (2018)*

- L/E ~ 0.18 to 2.7 m/MeV
- Electrons and photons are indistinguishable in MiniBooNE - its not clear <u>if the excess is electron-like or photon-like</u>?

Gallium (neutrino) Anomaly

- ν_e **disappearance**

- A 2.9σ deficit was observed in the ν_e events measured in the Gallium solar neutrino detectors (GALLEX and SAGE).



C. Giunti, T. Lasserre, Ann. Rev. Nucl. Part. Sci. ***69****, 163 (2019).*

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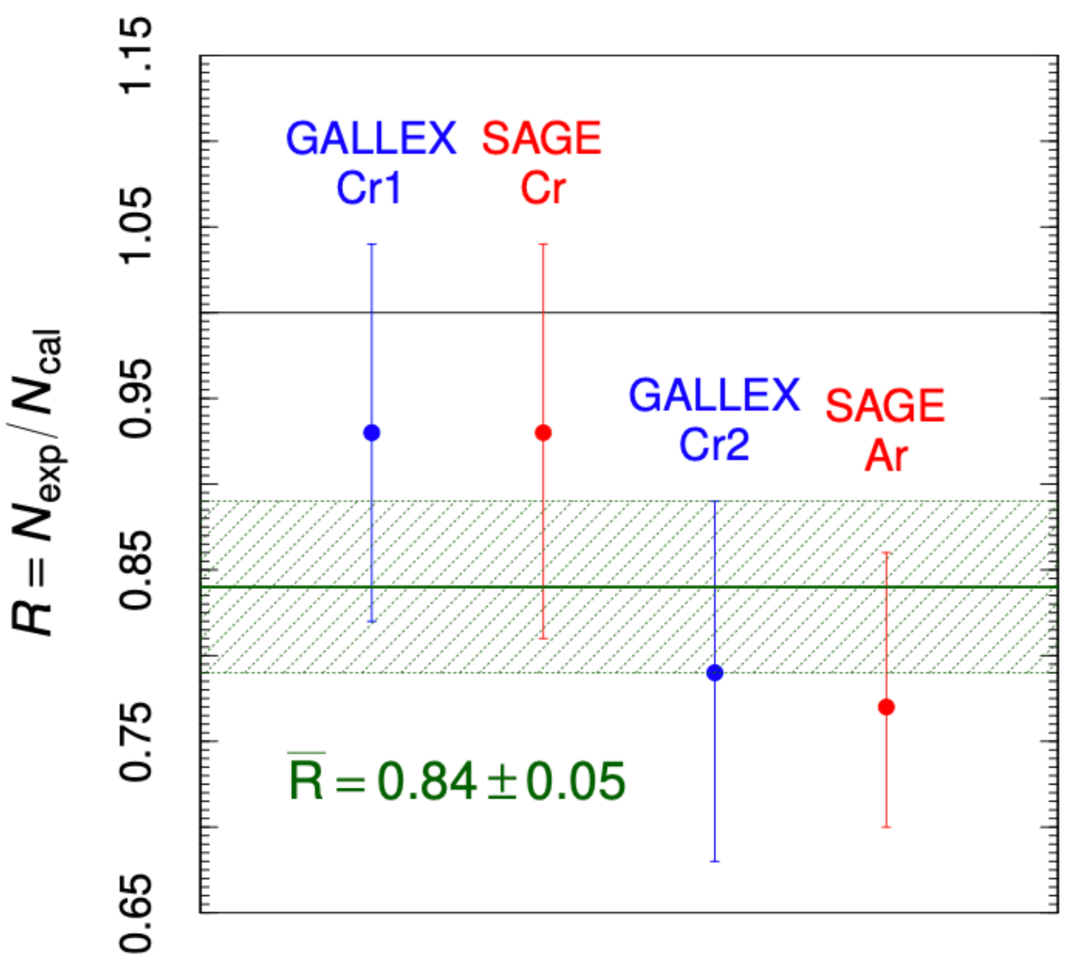
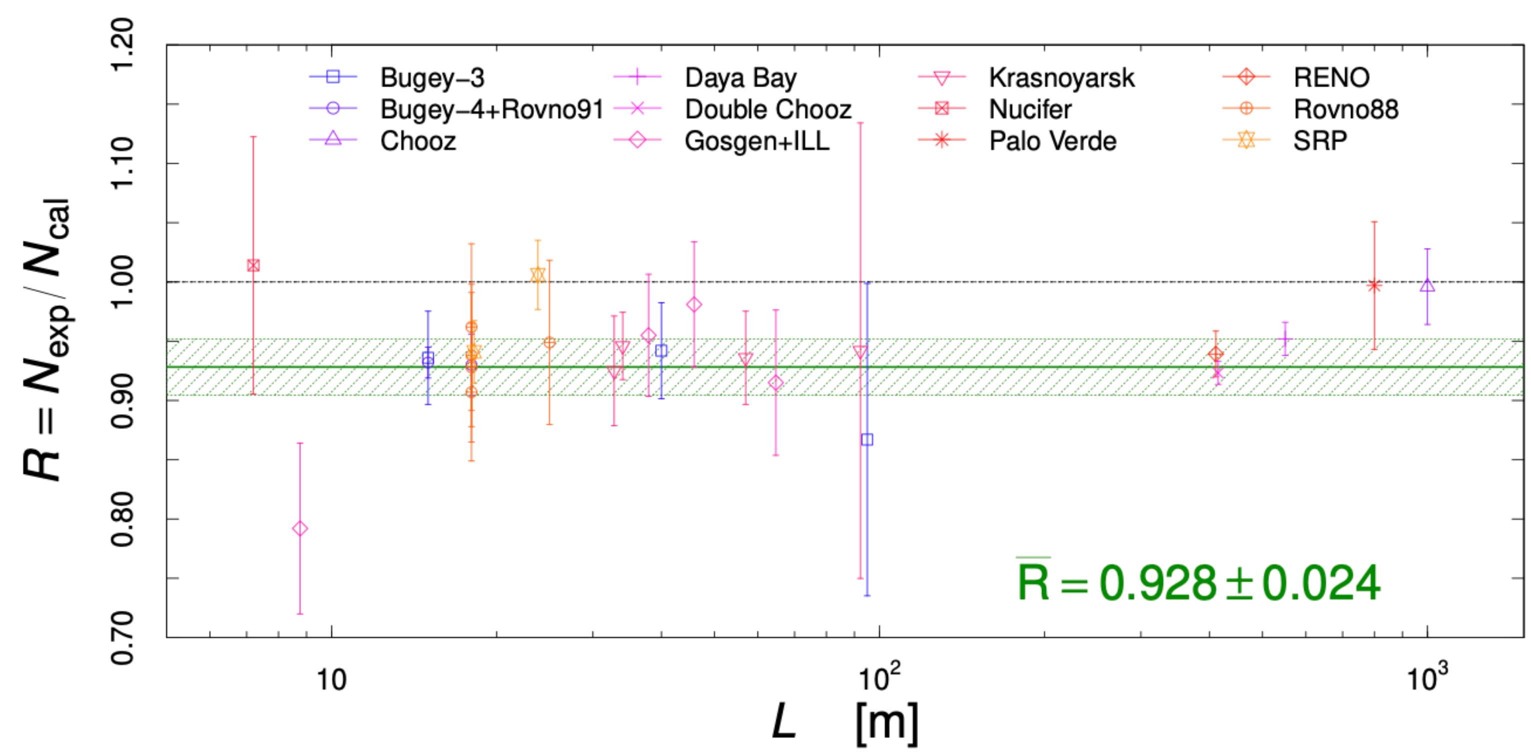


Reactor (antineutrino) Anomaly

- **$\bar{\nu}_e$ disappearance**
- A ~3.0σ deficit of the rate of reactor antineutrino detected in several experiments at distances between about 10 and 100 m.



C. Giunti, T. Lasserre, Ann. Rev. Nucl. Part. Sci. ***69****, 163 (2019).*

eV-scale Sterile Neutrinos?

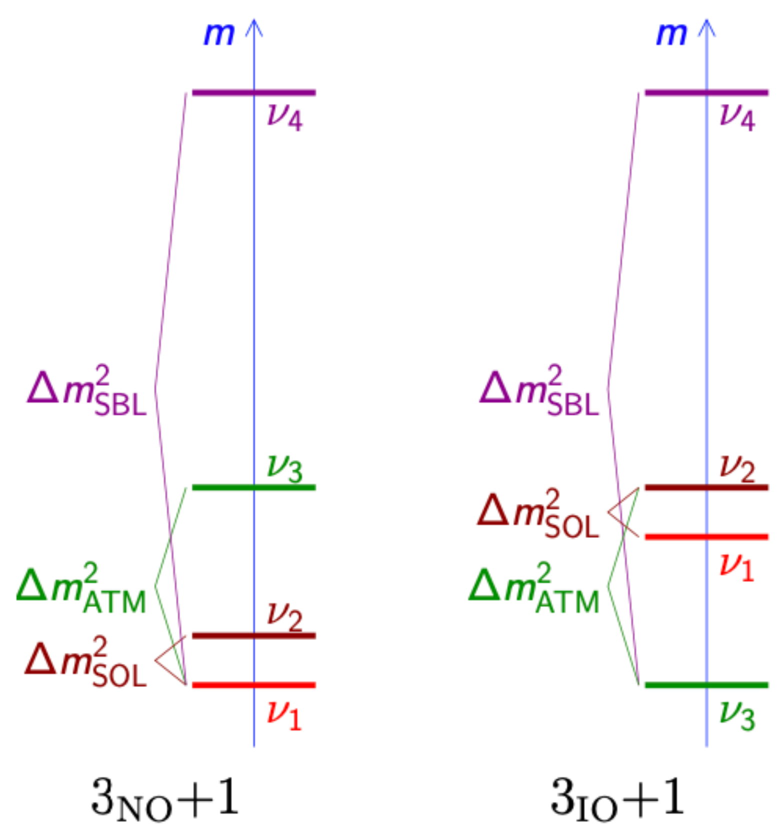
LSND	Accelerator (decay-at-rest)	$\bar{\nu}_\mu \to \bar{\nu}_e$	$3.8\ \sigma$
MiniBooNE	Accelerator (decay-in-flight, BNB)	$\nu_\mu \to \nu_e$ $\bar{\nu}_\mu \to \bar{\nu}_e$	$4.5\ \sigma$ $2.8\ \sigma$
Gallium	Source (electron capture)	ν_e disappearance	$2.9\ \sigma$
Reactor	Beta decay	$\bar{\nu}_e$ disappearance	$\sim 3.0\ \sigma$

- These anomalies consistently hint a new heavier mass state with mass-splitting $\Delta m^2_{SBL} \sim \mathcal{O}\,(1eV^2)$ that can generate neutrino oscillations at short-distances.
- Currently, no theoretical limits on number of sterile neutrinos, their masses or mixing. Must be determined experimentally.
- In an effective, 3+1 neutrino mixing scheme, the effective short-baseline oscillation probabilities can be written as:

$$P^{\rm SBL}_{\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\beta} = \left|\delta_{\alpha\beta} - \sin^2 2\vartheta_{\alpha\beta} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)\right|$$

$$\sin^2 2\vartheta_{\alpha\beta} = 4|U_{\alpha 4}|^2 \left|\delta_{\alpha\beta} - |U_{\beta 4}|^2\right|$$

$$\Delta m^2_{41} = \Delta m^2_{\rm SBL}$$



Appearance-Disappearance Tension

$$P^{\text{SBL}}_{\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\beta} = \left| \delta_{\alpha\beta} - \sin^2 2\vartheta_{\alpha\beta} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)\right|$$

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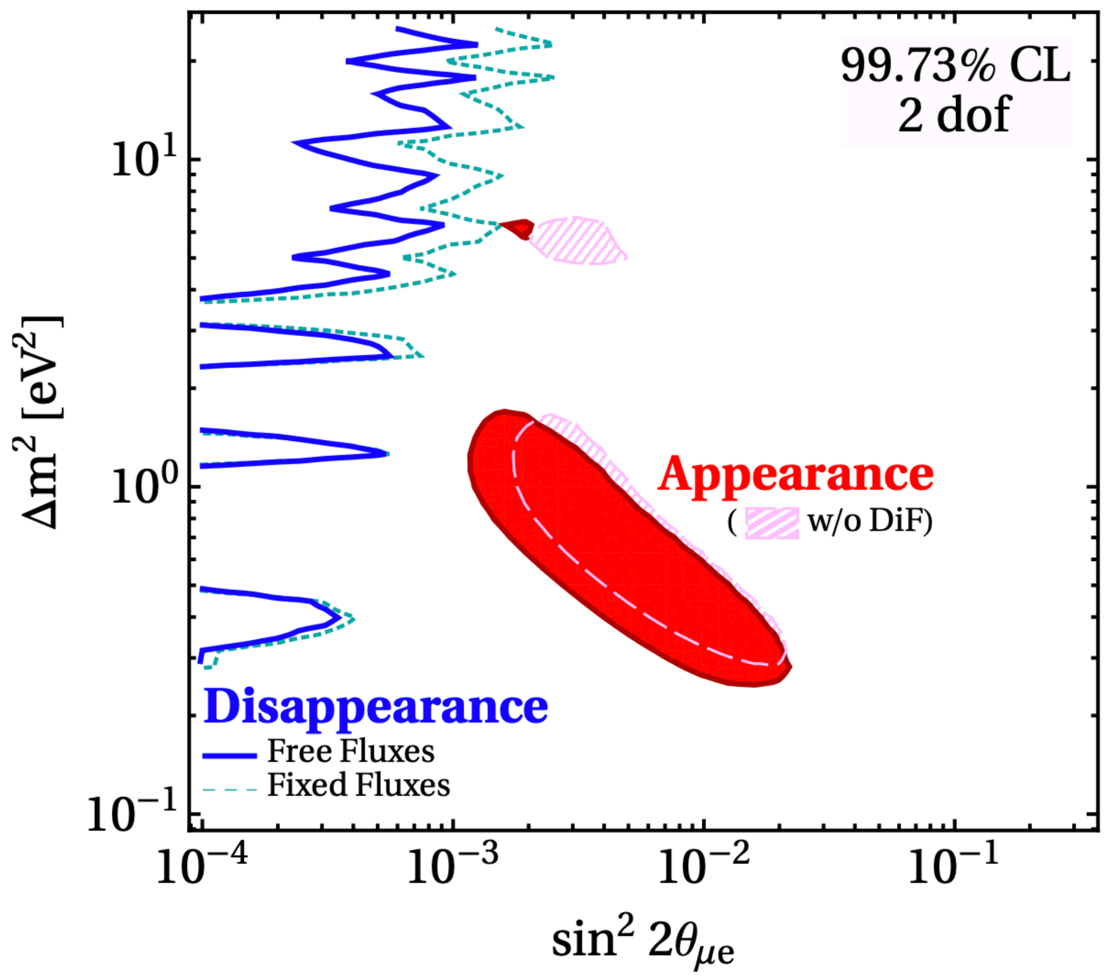
$$\Delta m^2_{41} = \Delta m^2_{\text{SBL}}$$

- The global fit of short-baseline data has a severe appearance-disappearance tension.
- Tension implies many possible scenarios (including the ones that imply no-oscillation), these scenarios needs to be resolved by new generation of precision experiments.



*M. Dentler et al., JHEP**10**, 1808 (2018)*

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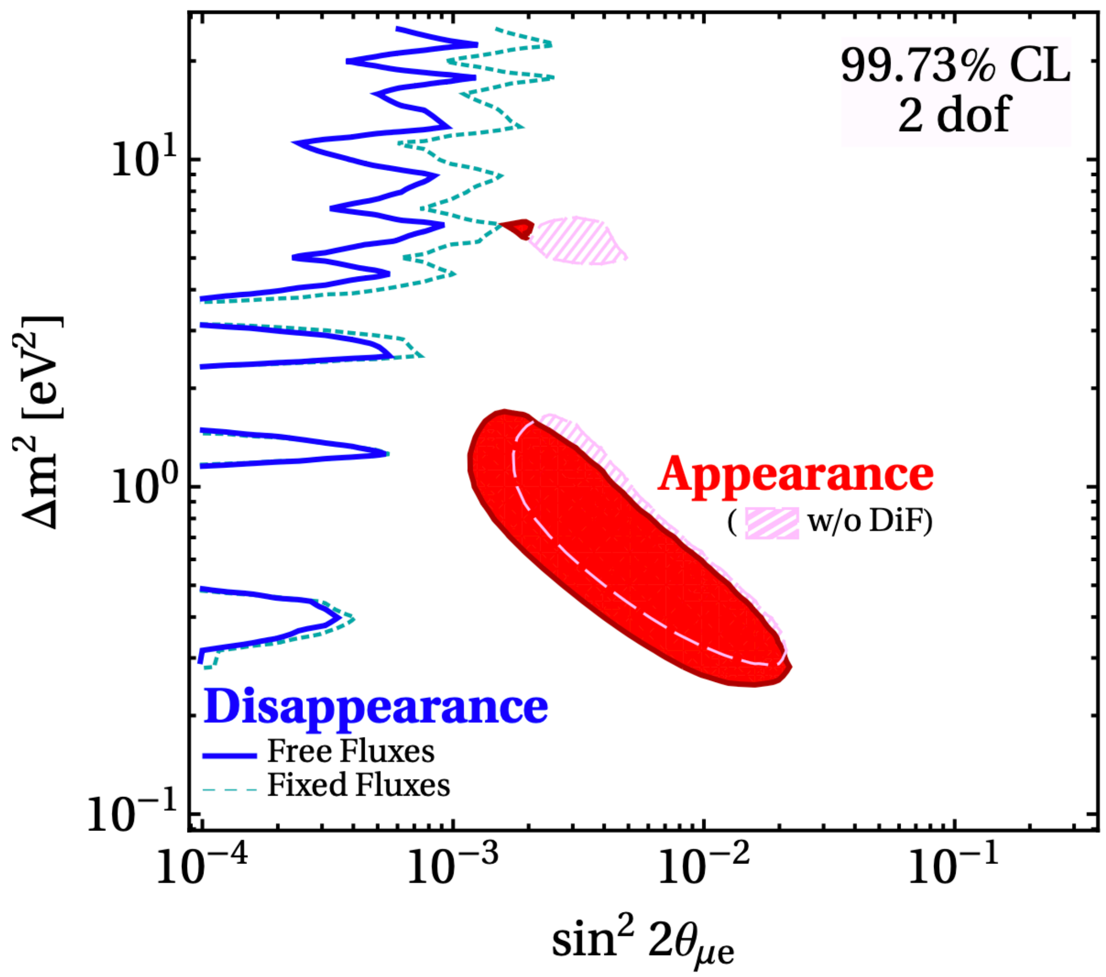
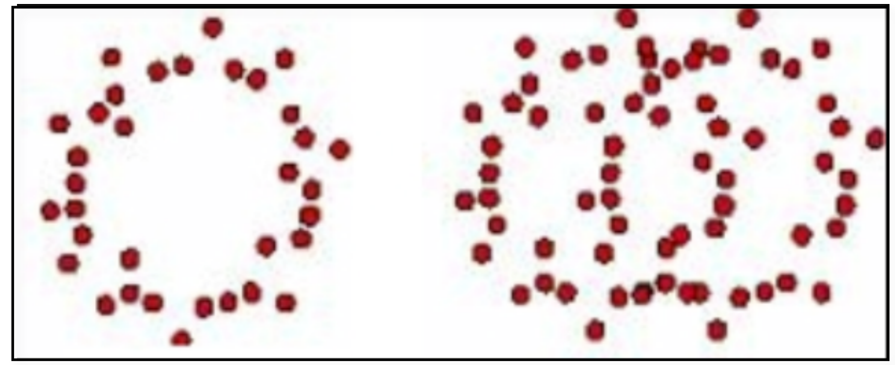


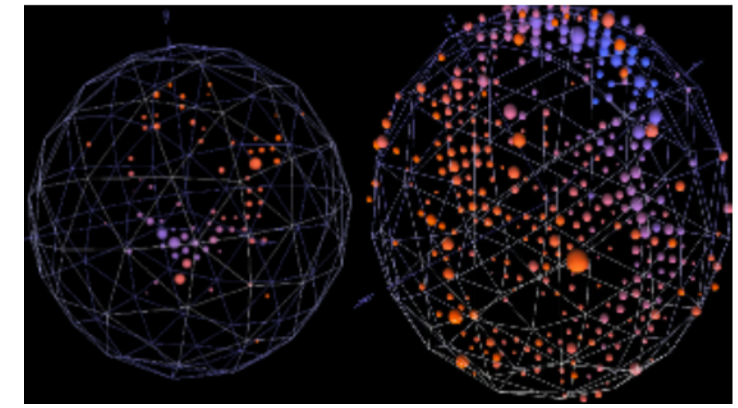
*M. Dentler et al., JHEP**10**, 1808 (2018)*

- The **SBN program at Fermilab** will play a key role in resolving this long-standing puzzle using multiple, functionally identical LArTPC detectors along the same neutrino beam.
- SBN will be very sensitive to both $\nu_\mu(\bar{\nu}_\mu) \to \nu_e(\bar{\nu}_e)$ **appearance** and $\nu_\mu(\bar{\nu}_\mu)$ **disappearance** channels. Plus, the electron and photon discrimination capability of LArTPC will be vital to understand the signal/background nature of the ν_e-like event excess observed in MiniBooNE.

Cherenkov Detector

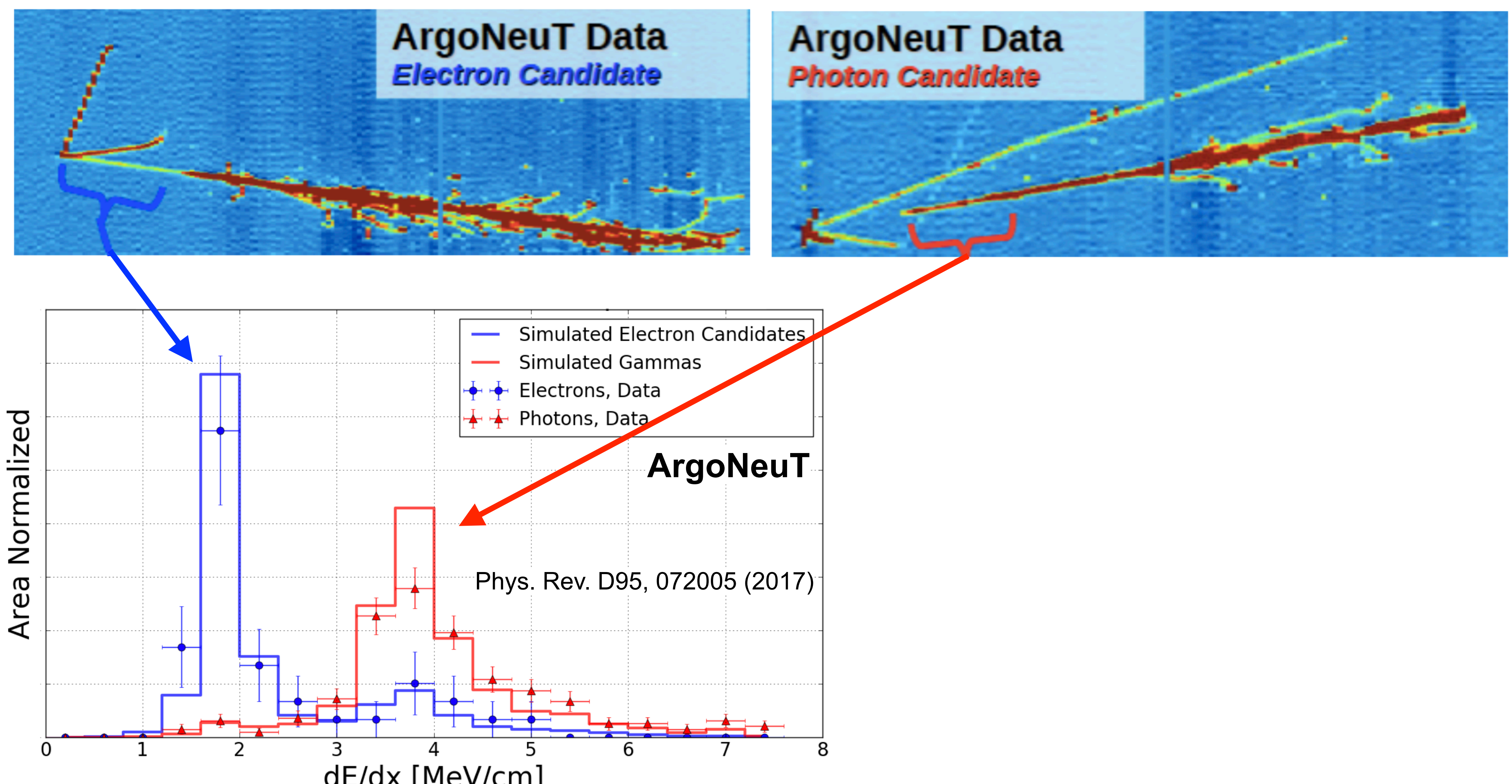


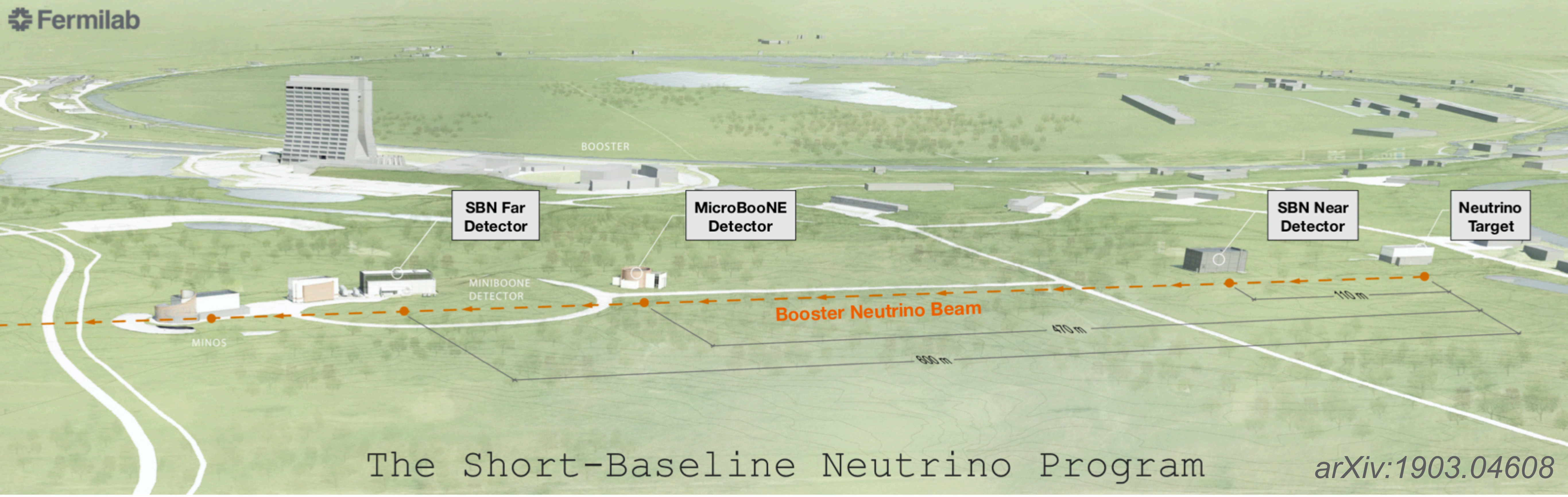
Electron, Photon $\pi^0 \rightarrow \gamma\gamma$



Liquid-Argon Detector

- Analyzing topology
- Analyzing dE/dx





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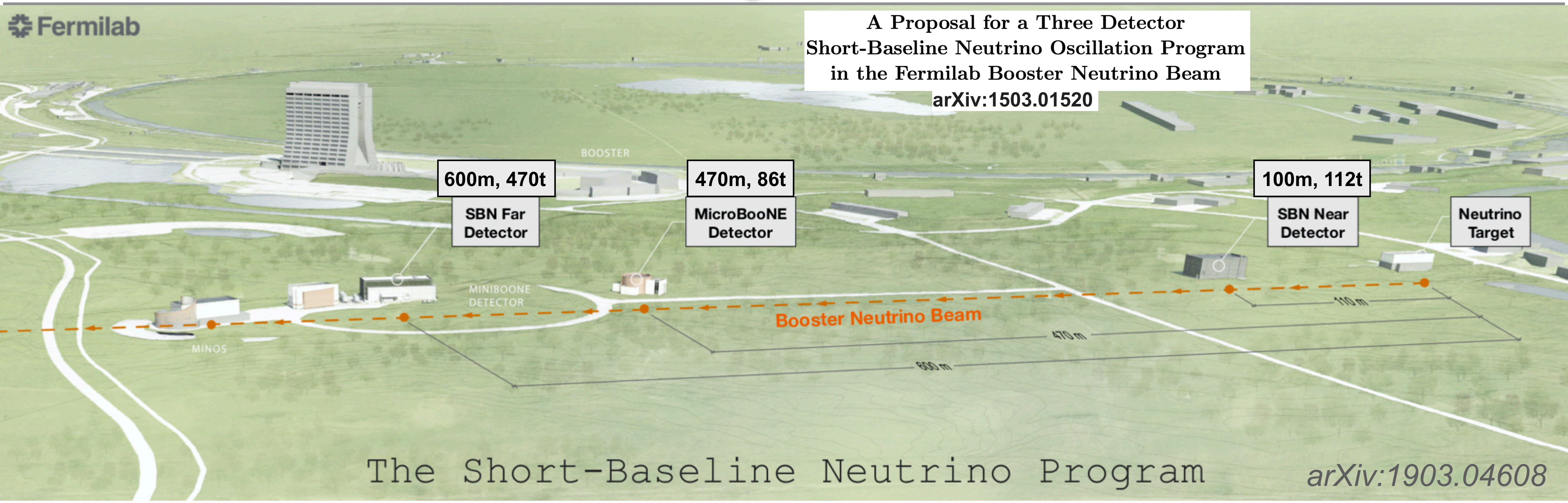
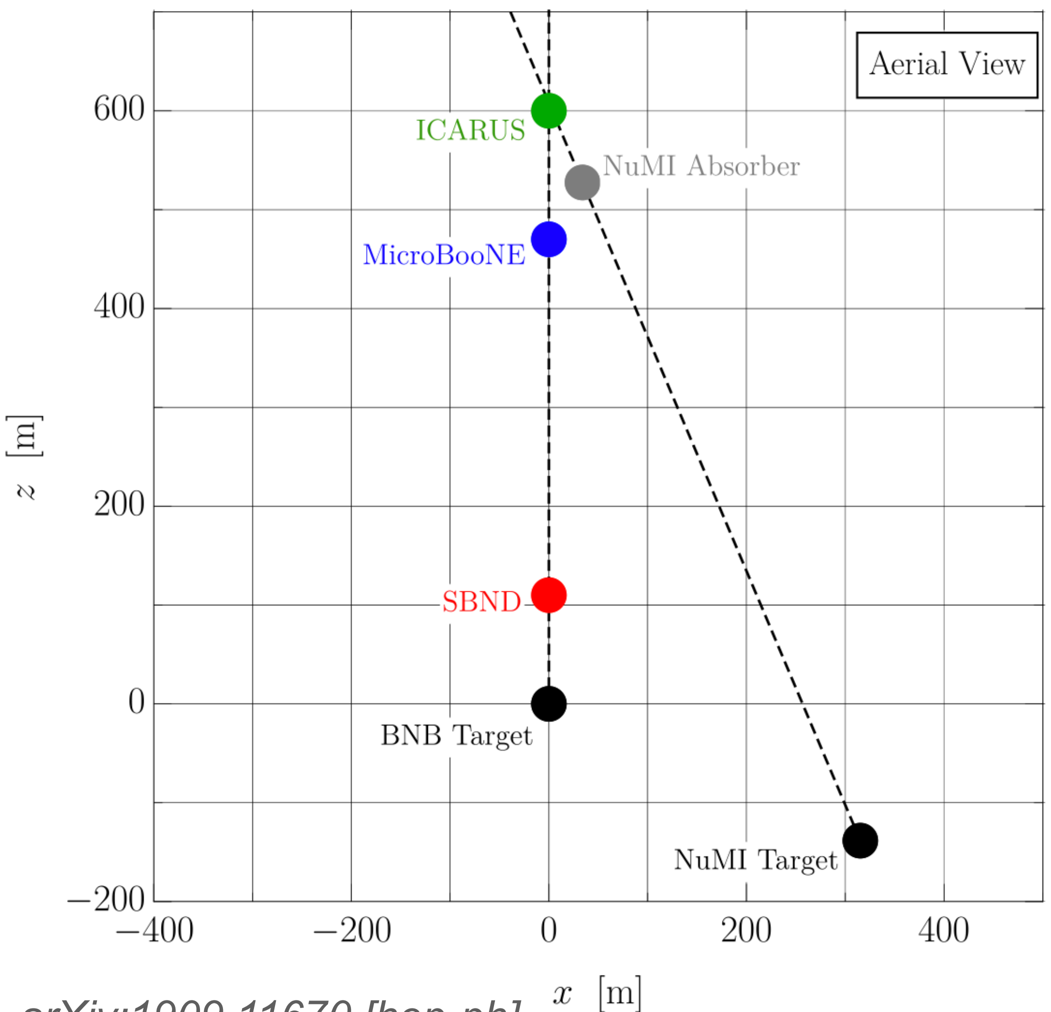
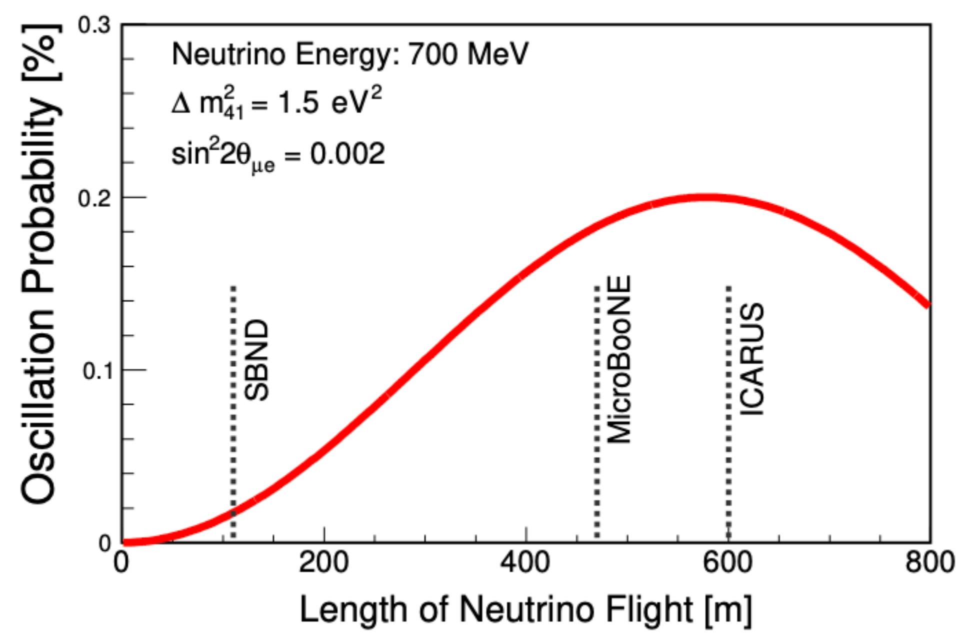
The SBN Program at Fermilab

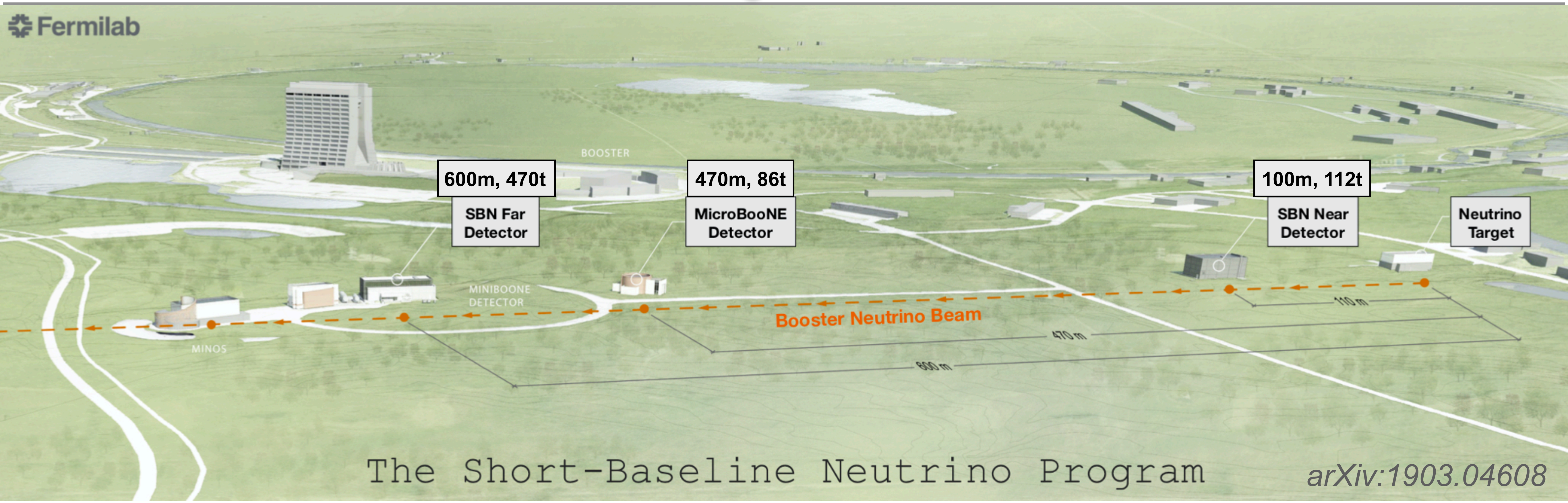




arXiv:1909.11670 [hep-ph]

- Three functionally identical LArTPC detectors (same nuclear target and detector technology) will measure the same neutrino beam at different distances from the source - reducing systematic uncertainties.

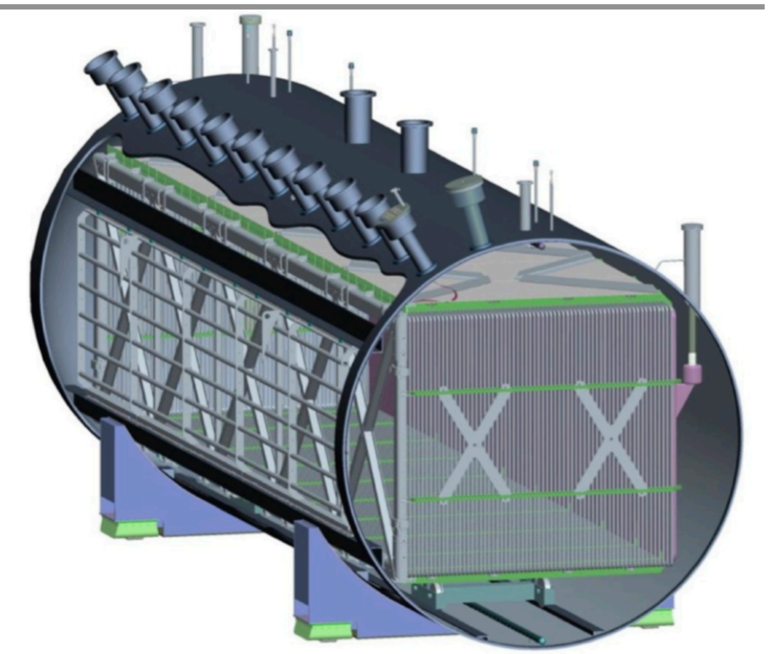




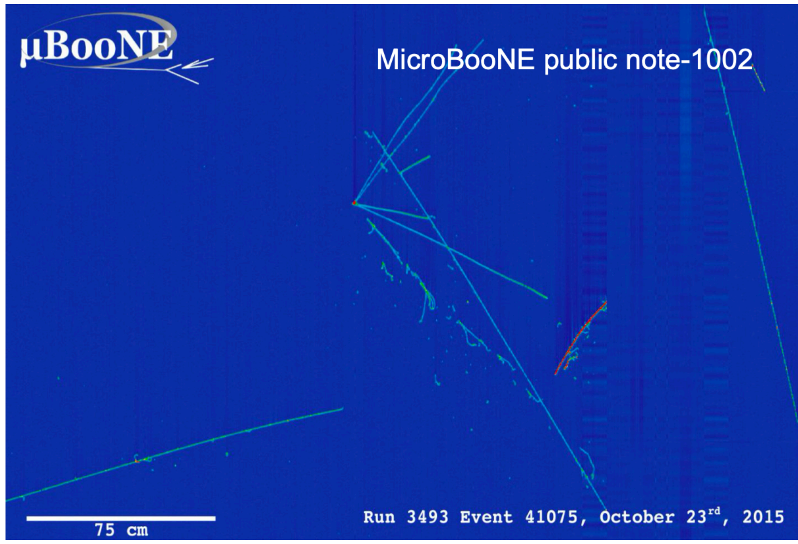
Goals

- Search for eV-scale sterile neutrinos by looking for $\nu_\mu(\bar{\nu}_\mu) \rightarrow \nu_{\mathbf{e}}(\bar{\nu}_{\mathbf{e}})$ appearance and $\nu_\mu(\bar{\nu}_\mu)$ disappearance oscillations at $\Delta m^2_{SBL} \sim \mathcal{O}\ (1eV^2)$
- Detailed study of neutrino-argon interactions at the GeV energy scale
- Advancement of the liquid argon detector technology that will be used in DUNE
- Search for new/rare physics processes in the neutrino sector and beyond

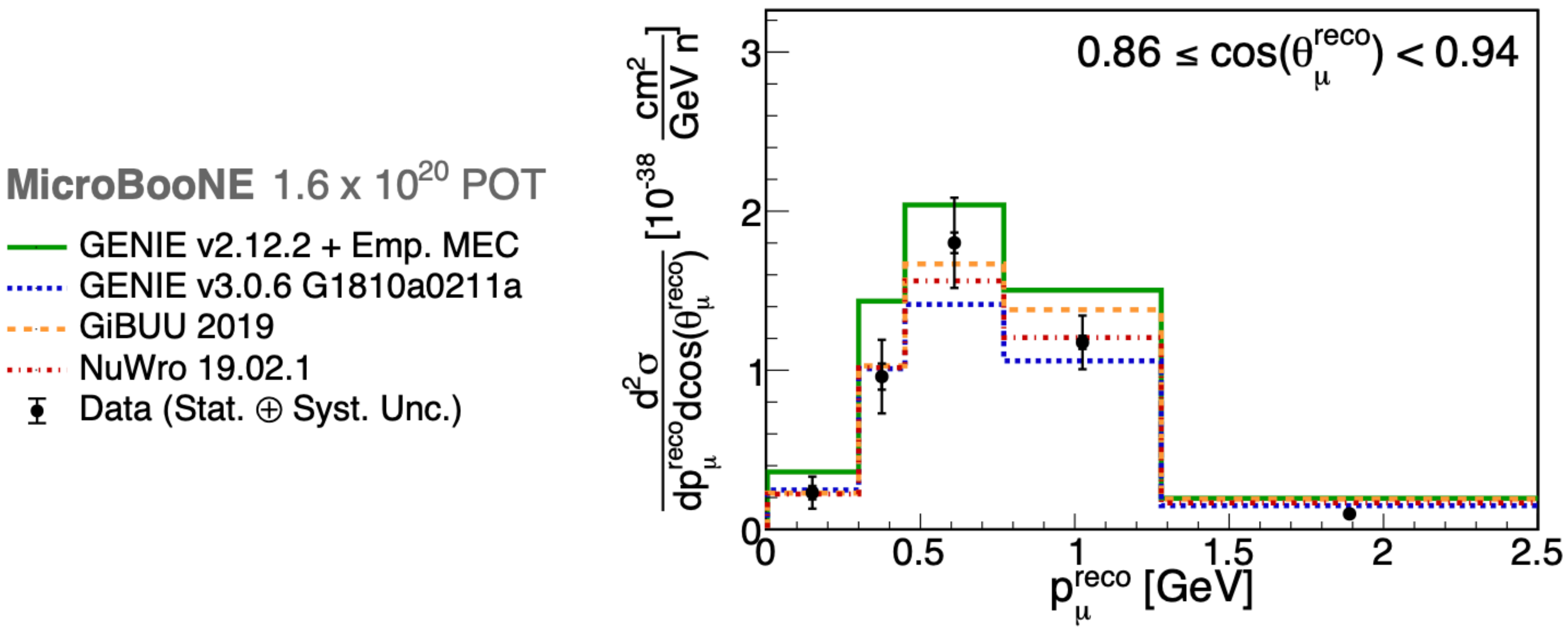
- Installation completed in 2015. Stable operation since October 2015.
- 1 TPCs with 2.3 m drift. TPC active volume: 89 ton of LAr. 32 8” PMTs
- 470 m from the source

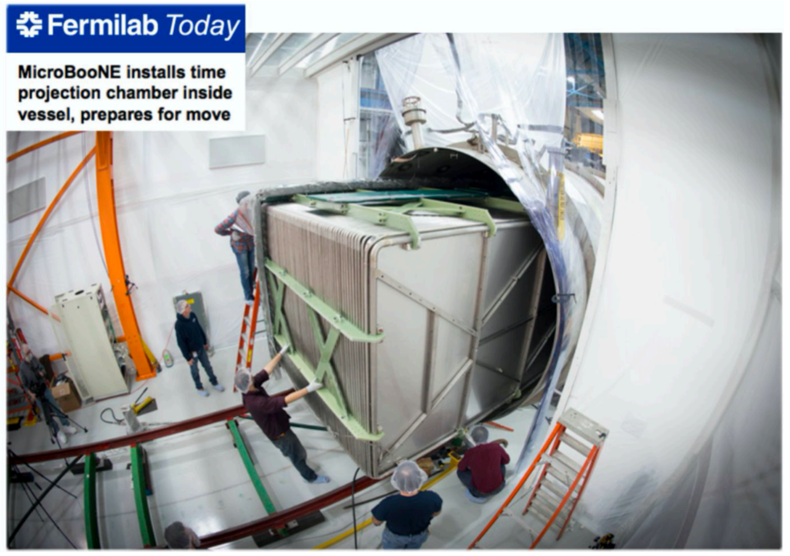


- MicroBooNE is doing the groundwork for LArTPC calibration, simulation, reconstruction and analysis for future detectors.
- Understanding the detector effects (noise, diffusion, recombination, space charge, etc.). A list of publications and public notes are available at: http://www-microboone.fnal.gov/publications/publicnotes

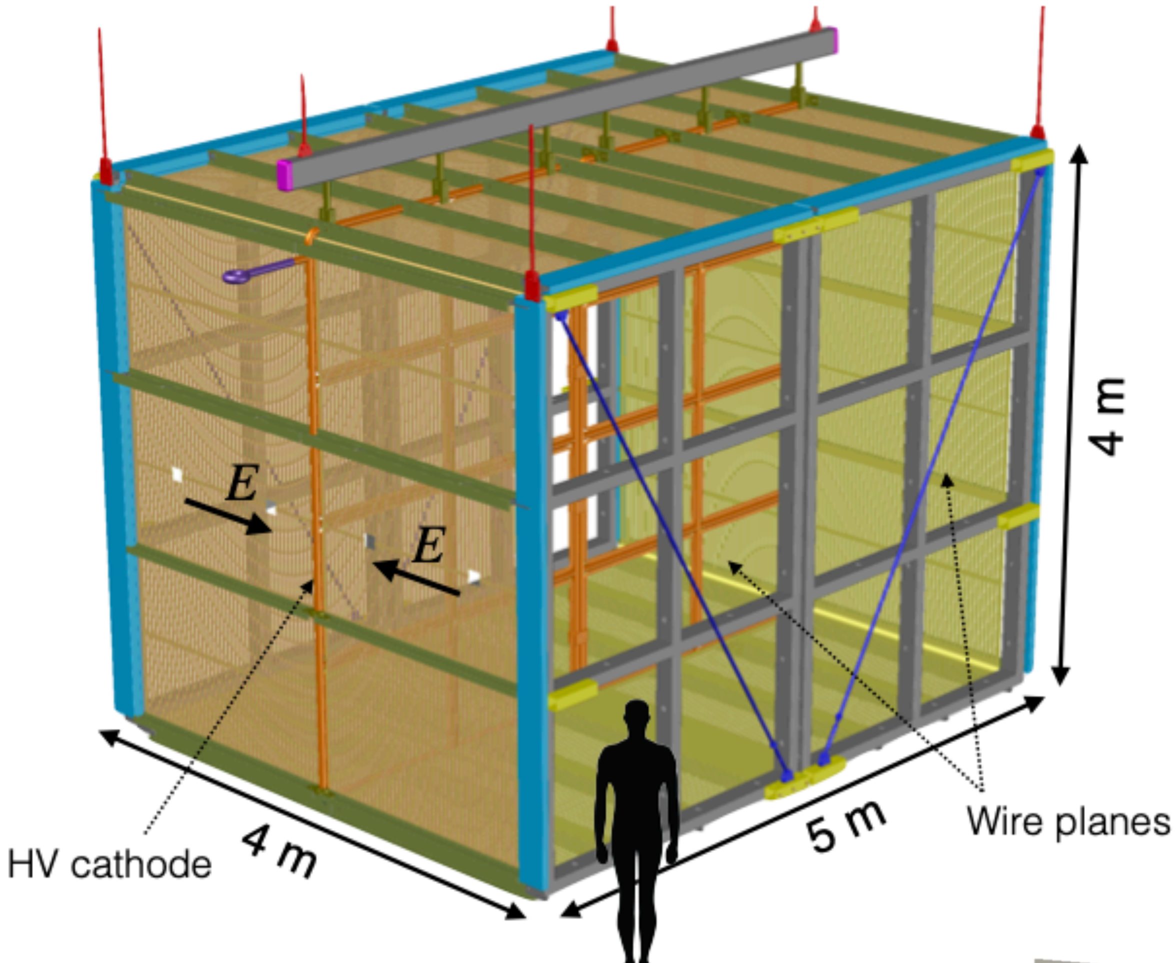


- Investigating MiniBooNE low-energy excess (independent ongoing e-like and γ-like analysis)
- First measurement of ν_μ CC inclusive differential cross section *[Phys. Rev. Lett. 123, 131801 2019]*, *and* CC π^0 total cross section on argon *[Phys. Rev. D 99, 091102 (2019)]*.





SBND

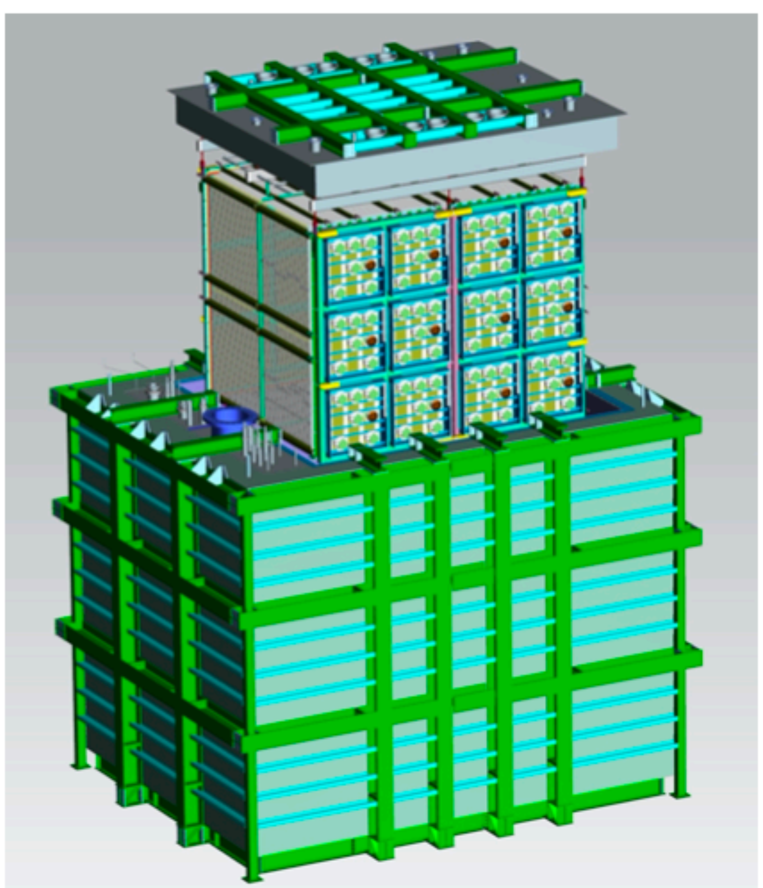


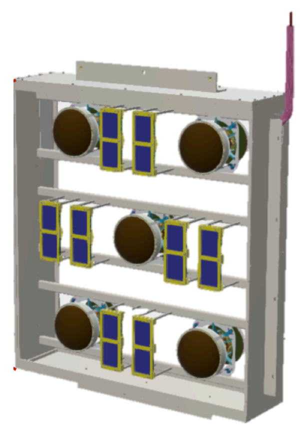
Short Baseline Near Detector

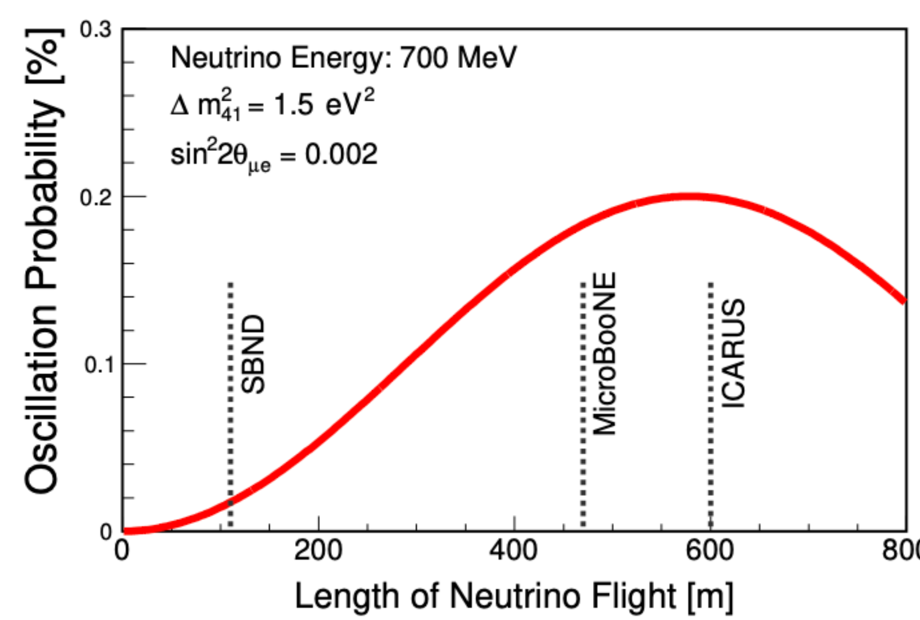
- Near Detector: 110 m from the source
- TPC active volume: 112 ton of LAr [4m x 4m x 5m]
- Two TPCs with 2 m drift
- Composite photodetection system: 120 8” PMTs, and photon trap acrylic bars ARAPUCAs
- Full CRT coverage

Overall, the design philosophy of the SBND detector is similar to the DUNE detector.

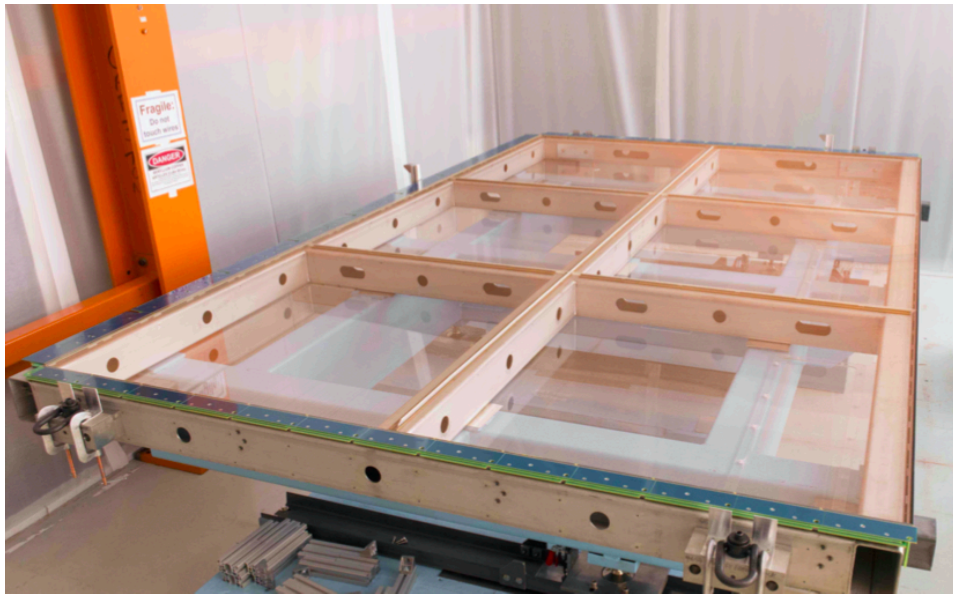
- SBND data will help in constraining BNB flux (un-oscillated beam) and cross-section modeling (enormous dataset), and hence will be crucial in reducing systematic uncertainties.







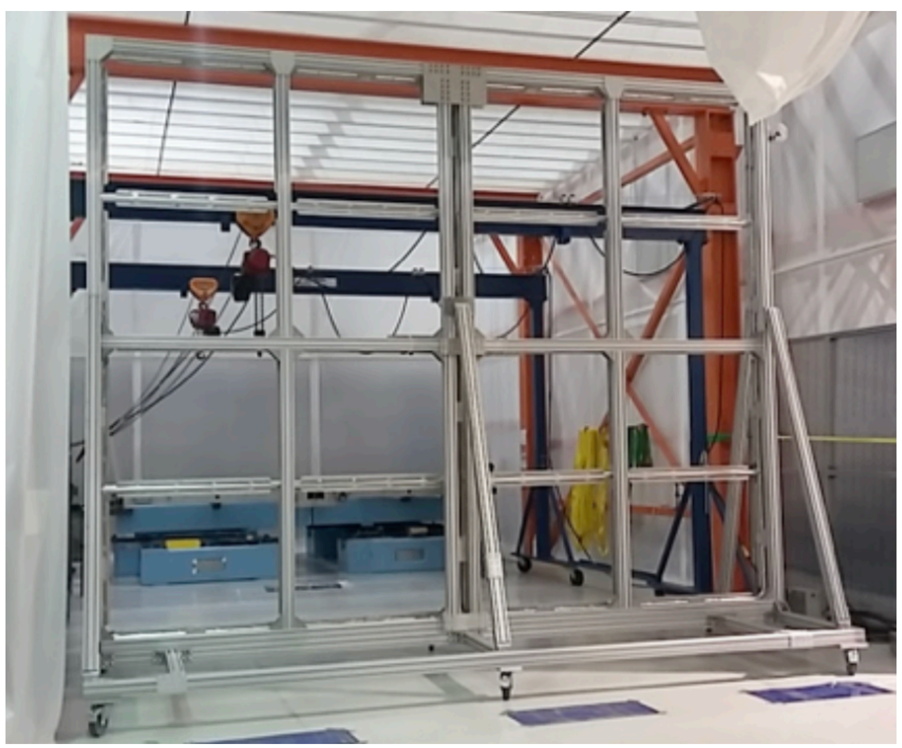
Short Baseline Near Detector



Anode Plane (APA)

SBND commissioning by the end of 2020

The Assembly Transport Frame



Cathode Plane (CPA)

Cryogenic Installation

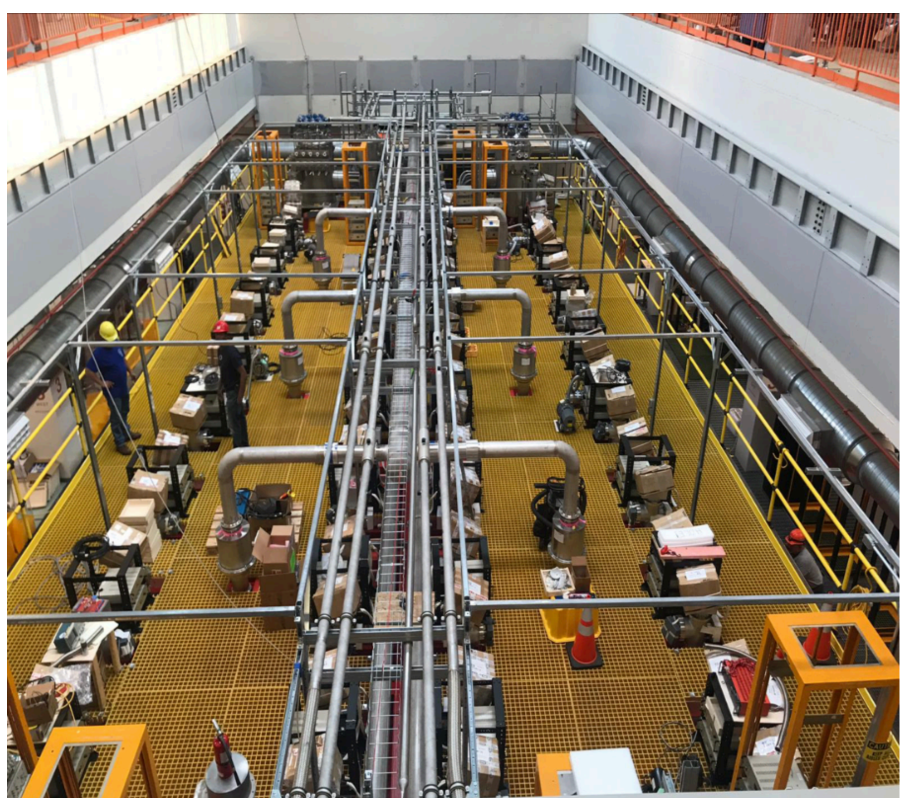
Warm Cryostat

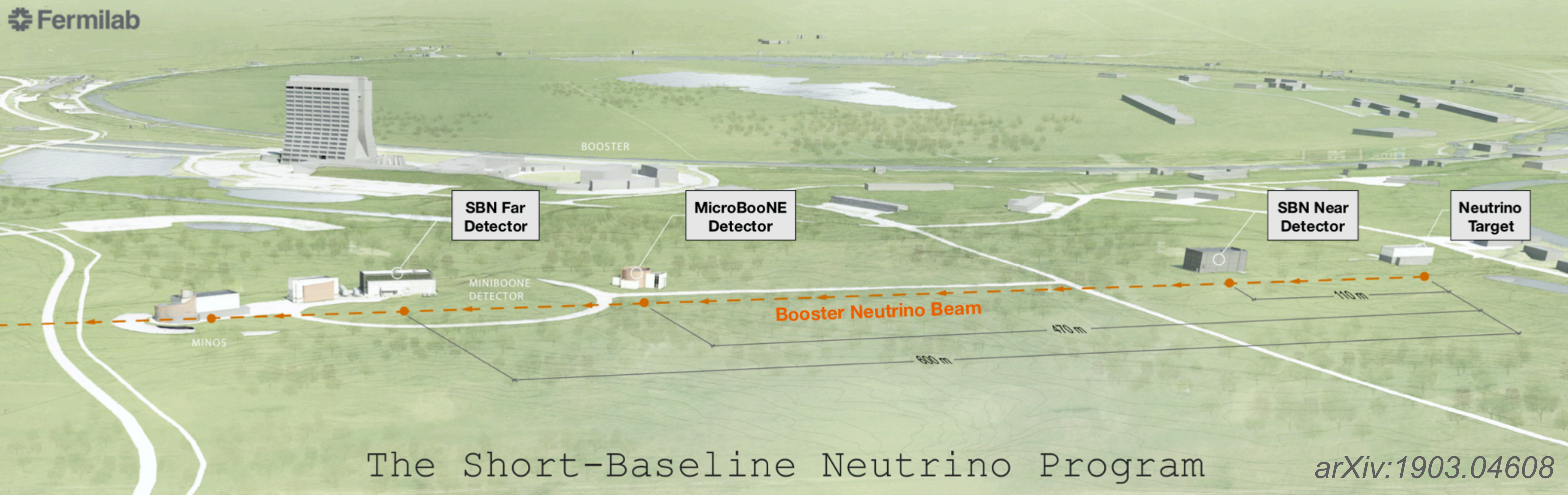
ICARUS

- Far Detector: 600 m from the source
- Four TPCs with 1.5 m drift
- TPC active volume: 476 ton of LAr
- 360 8” PMTs
- Full CRT coverage

- It was operational at LNGS from 2010-2013
- In 2015, sent to CERN for refurbishment
- Shipped to Fermilab in June 2017

ICARUS commissioning early 2020





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Sterile Neutrino Sensitivity

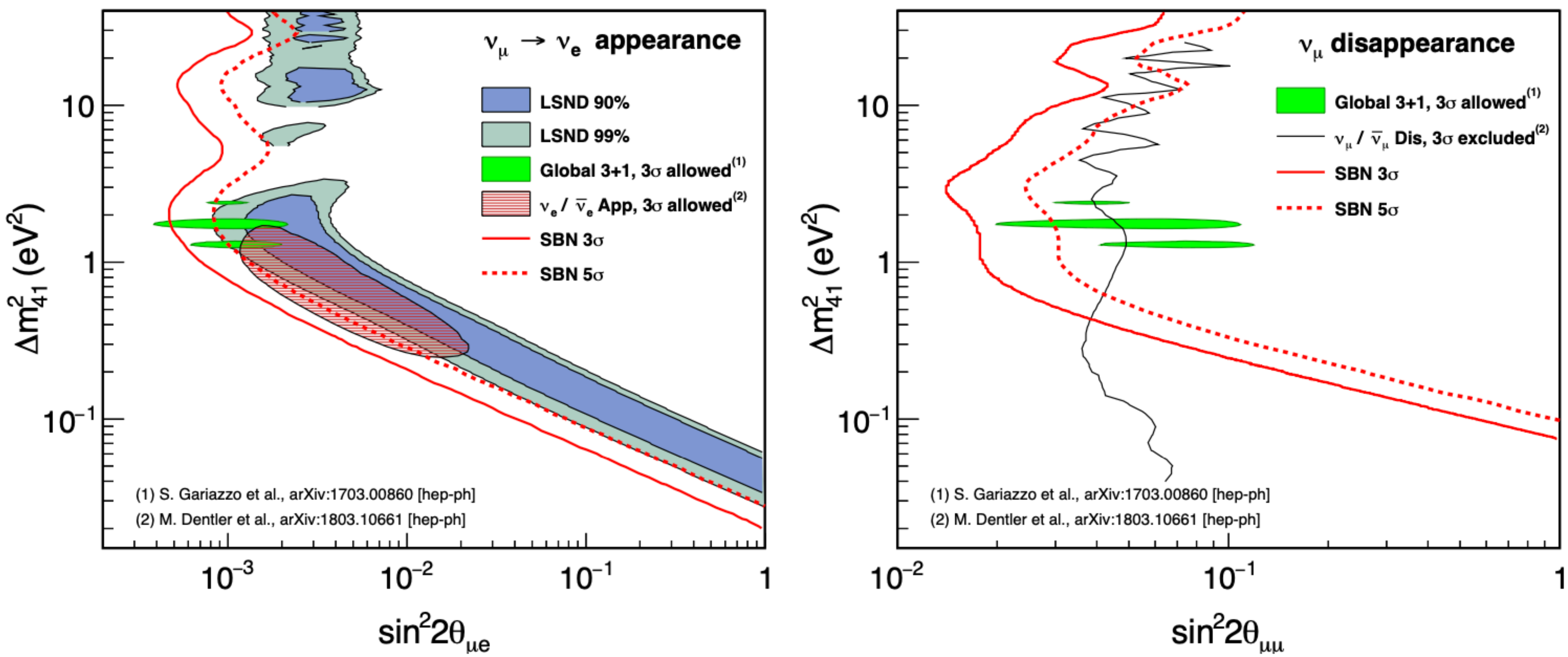
- In order to interpret any electron neutrino excess as being due to the existence of sterile neutrinos, the observation of both muon neutrino disappearance and electron neutrino appearance signal would be essential.

$\nu_\mu \rightarrow \nu_e$ Appearance

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

$\nu_\mu \rightarrow \nu_\mu$ Disappearance

$$\sin^2 2\theta_{\mu\mu} \equiv 4|U_{\mu 4}|^2(1-|U_{\mu 4}|^2)$$

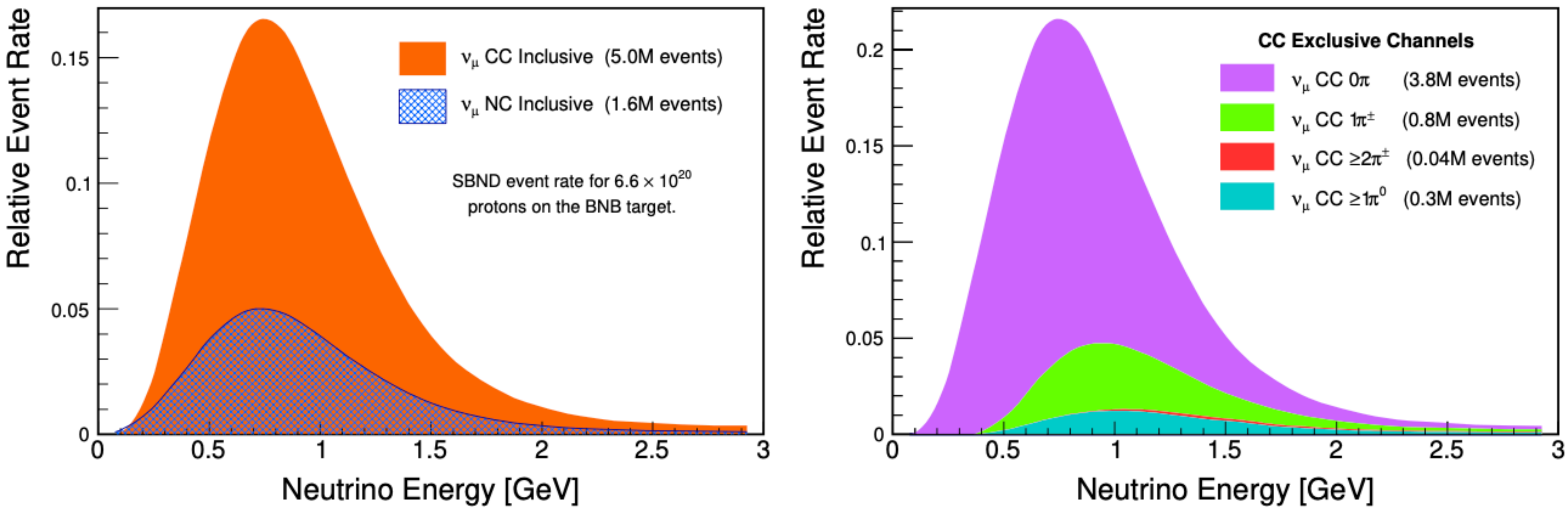


P. A. Machado, O. Palamara, D. W. Schmitz, arXiv:1903.04608

- SBN alone may be able to rule out almost all the global appearance preferred region at 5σ.
- SBN sensitivity on the ν_μ disappearance channel is better than the global constraints for a large range of Δm^2_{41}.

Neutrino-Nucleus Scattering

- The SBN physics program includes detailed study of high-statistics neutrino-argon cross sections which will play vital role in the precision goal of oscillation experiments (including DUNE).

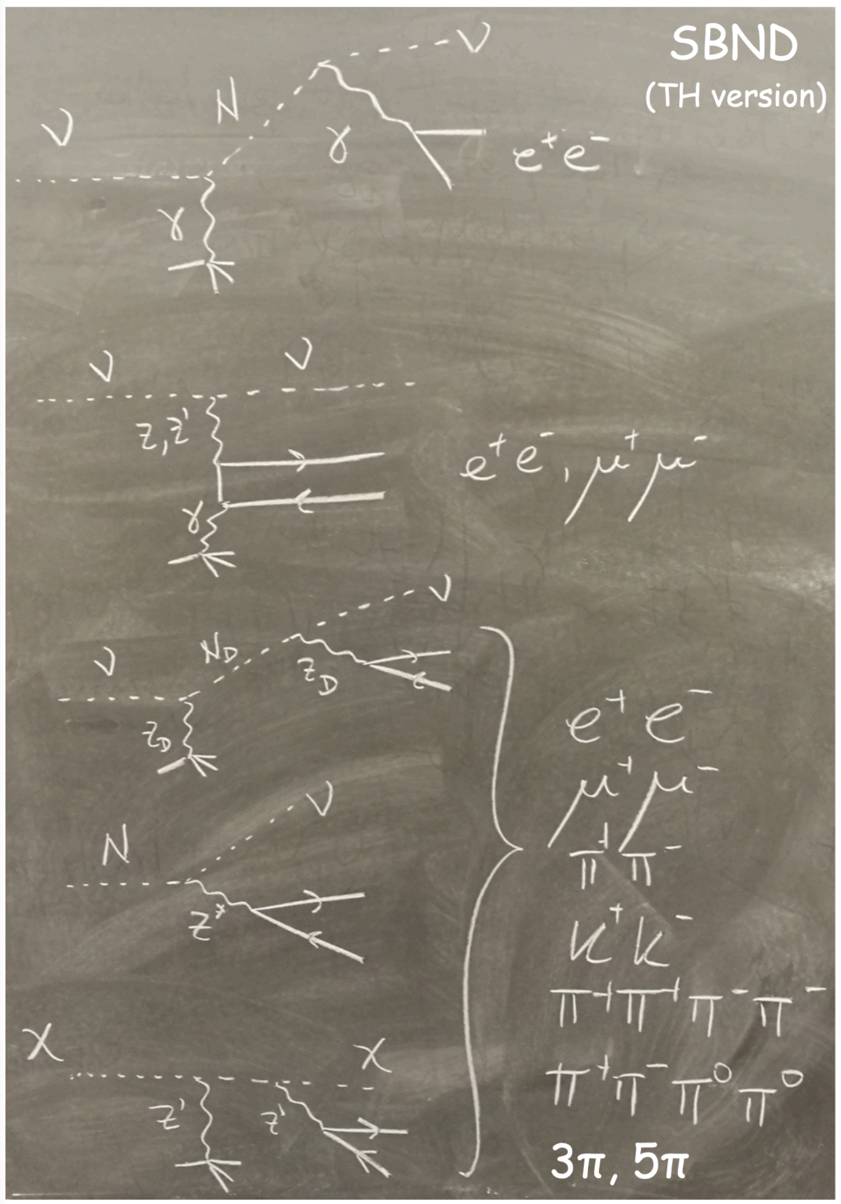


P. A. Machado, O. Palamara, D. W. Schmitz, arXiv:1903.04608

- In particular, the SBND experiment (being closest to the beam) will collect enormous neutrino event samples and will make the world's highest statistics cross section measurements for many neutrino-argon scattering processes. The high statistics data will allow the study of nuclear effects in neutrino interactions in argon nuclei with high precision.

New Physics Opportunities

- A high intensity (BNB) neutrino beam leading to large statistics in Liquid argon TPC detectors (with low threshold, unprecedented event reconstruction, excellent particle identification, and fine-sampling calorimetry) has great potential to probe a vast range of BSM physics at SBN.



Challenges

Some of these signatures are *"clearer"*, like the $\mu^+\mu^-$ trident.

Others are more challenging, specially due to backgrounds.

In several detectors, photons and electrons are indistinguishable

In others, an electron or a photon is indistinguishable from e^+e^-

Interesting features

Signatures depend on mass spectrum

Invariant masses

Angular distributions

dE/dx

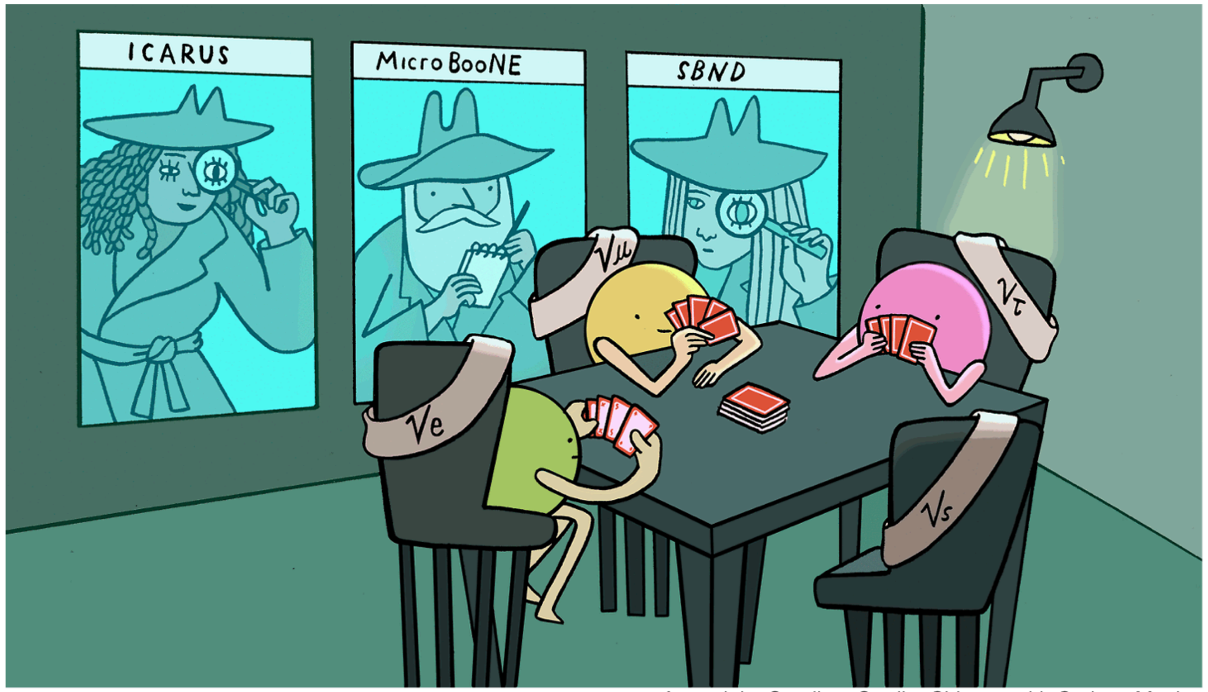
Courtesy of P. Machado

Slide courtesy: Ornella Palamara and Pedro Machado

- Sterile Neutrinos
- Neutrino tridents
- Millicharged particles
- Light dark matter
- Heavy neutral leptons
- ……

- *A range of new physics opportunities at SBN are discussed in:* *[P. A. Machado, O. Palamara, D. W. Schmitz, arXiv:1903.04608]*

- The Short-Baseline Neutrino program at Fermilab consists of three functionally identical LArTPC detectors in the Booster Neutrino Beam and is simultaneously sensitive to both ν_e appearance and ν_μ disappearance oscillation channels - that will play a key role in solving the long-standing puzzle of light sterile neutrinos.

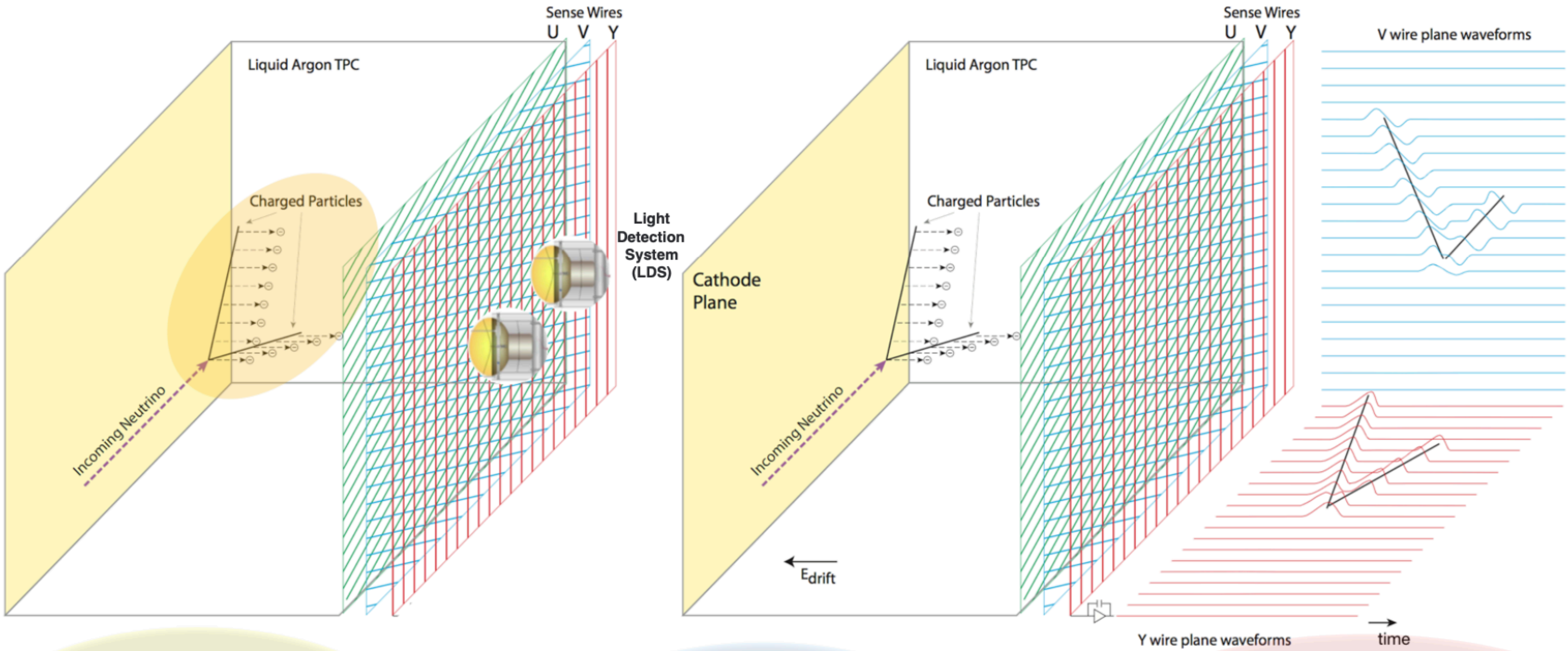


Artwork by Sandbox Studio, Chicago with Corinne Mucha

- SBN has a broad range of physics goals that include - detailed, high-statistics studies of neutrino-nucleus scattering on argon (important for DUNE), and in the exploration of a range of exciting physics beyond the Standard Model theories.
- SBN is also a ground for the liquid argon detector technology development that will be used in DUNE.
- MicroBooNE has been collecting data since October 2015. ICARUS is close to being online, and the SBND construction is well underway.
- Stay tuned for three detector run and its combined results!

Back-up Slides

LArTPC: Operating Principle



Charged particles in LAr produce free ionization electrons and scintillation light

Ionization charge drifts in a uniform electric field towards the readout wire-planes

Digitized signals from the wires are collected [time of the wire pulses gives the drift coordinate of the track and amplitude gives the deposited charge]

m.i.p. at 500 V/cm: ~ 60,000 e/cm
~ 50,000 photons/cm

Electron drift time ~ ms

VUV photons propagate and are shifted into VIS photons

Scintillation light **fast** signals from LDSs give event timing