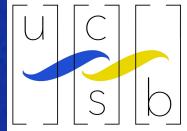


Experimental Status of Neutrino Physics

David Caratelli / UC Santa Barbara
PHENO 2023 - University of Pittsburgh, May 8th 2023

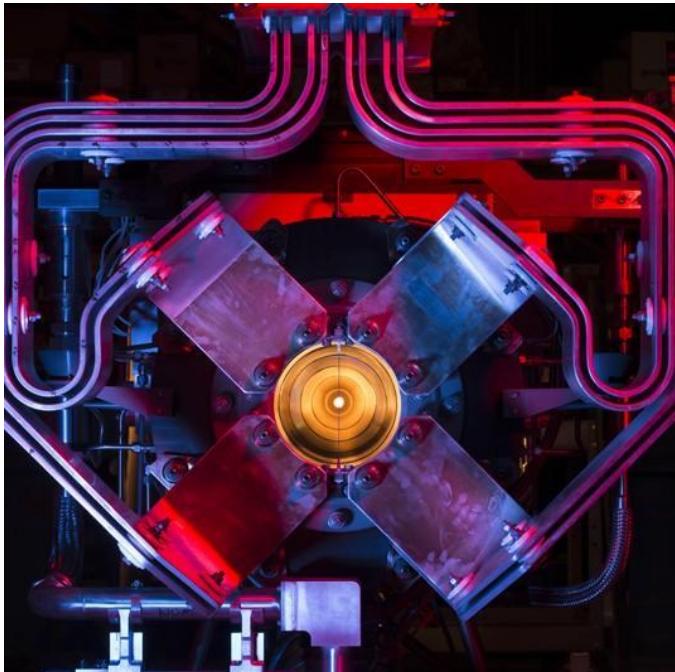
UC SANTA BARBARA



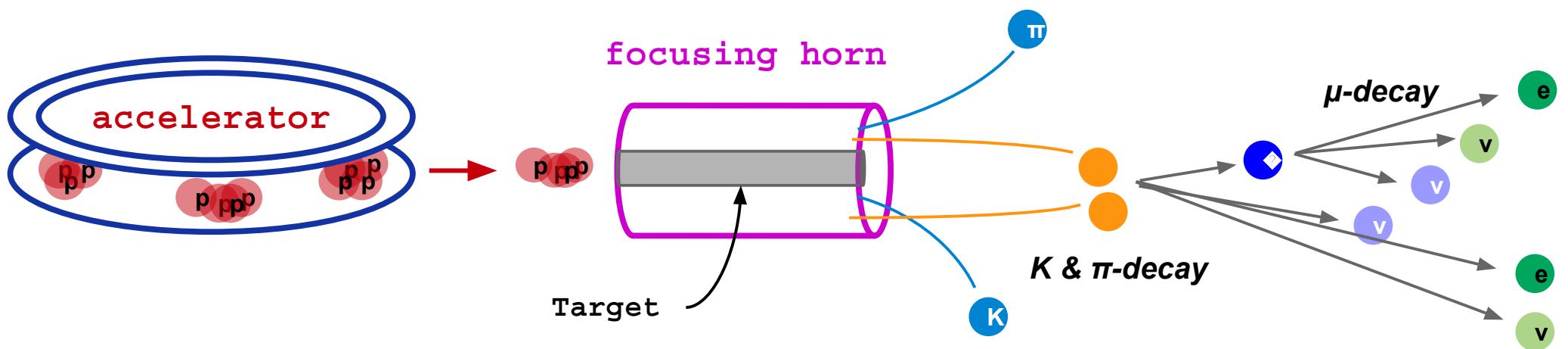
Experimental neutrino physics landscape



Neutrinos from accelerators



Focusing horn for neutrino beam at Fermilab [[credit](#)]

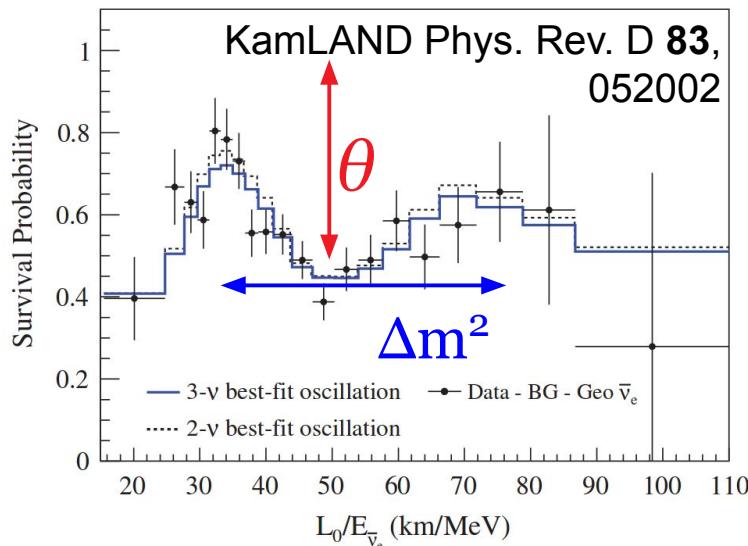


Neutrino Physics

Today's experimental neutrino physics landscape greatly influenced by observation of neutrino oscillations ~two decades ago

Neutrinos have (very small) masses → exciting prospect for new physics

$$\begin{matrix} \text{v}_e \\ \text{v}_\mu \\ \text{v}_\tau \end{matrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{matrix} \text{v}_1 \\ \text{v}_2 \\ \text{v}_3 \end{matrix}$$



Freq. Of oscillation.
Choose L, E appropriate for Δm^2 .

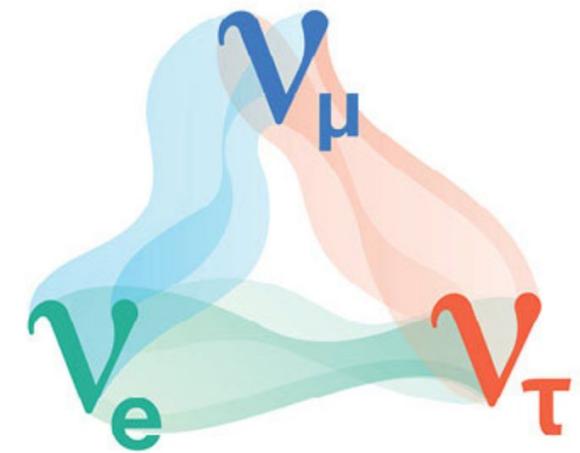
$$P_{\nu_\mu \rightarrow \nu_e} \approx \sin^2(2\theta) \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

sets amplitude of oscillation.
large → “easy” to detect.

Open Questions in Neutrino Physics

Fundamental neutrino physics:

- precision measurement of neutrino mixing
- value of δ_{CP}
- neutrino mass ordering and absolute mass
- Dirac or Majorana nature of neutrinos.



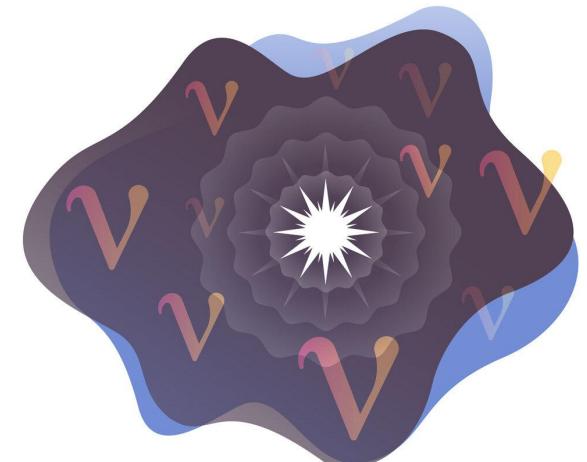
Beyond the Standard Model searches:

- searches for eV-scale “sterile” neutrinos
- Heavy Neutral Leptons
- broader BSM leveraging neutrino facilities

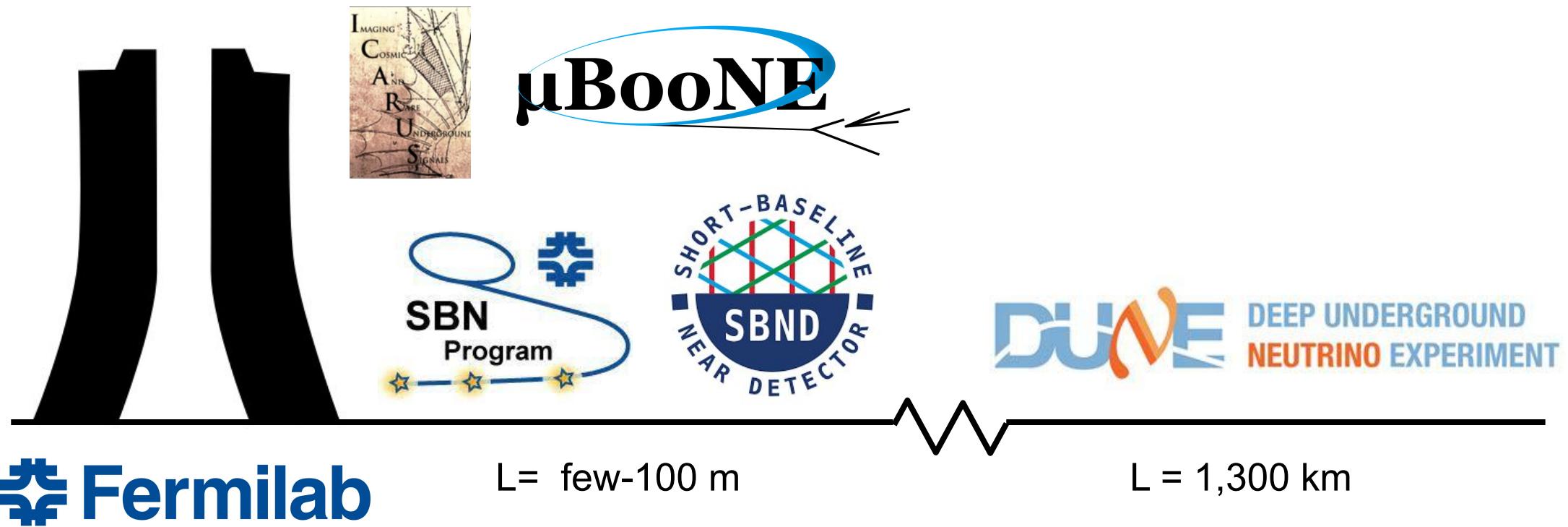


Neutrino astrophysics:

- solar and supernova neutrinos
- extragalactic neutrino sources



US accelerator neutrino physics program

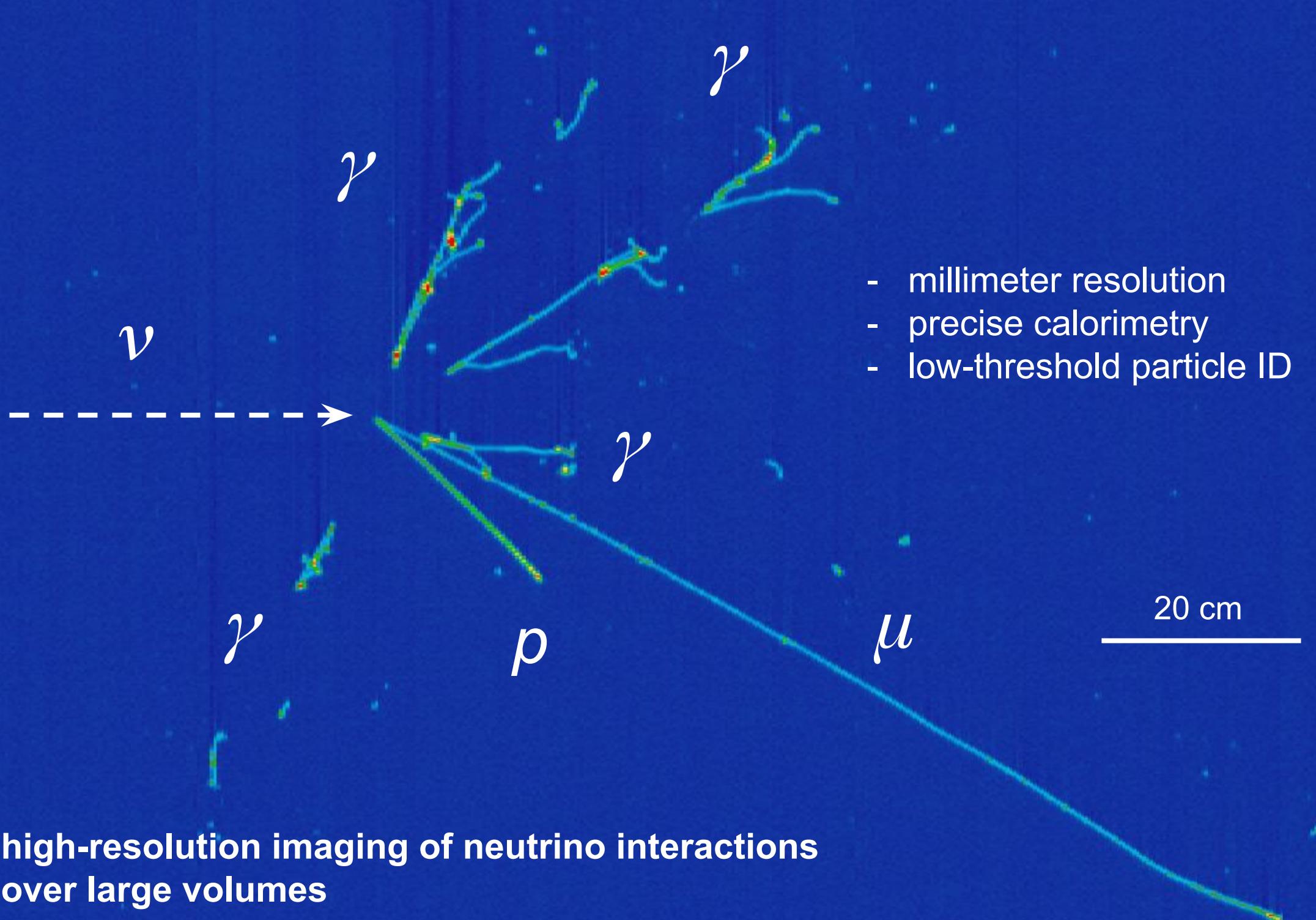


Short- and long-baseline accelerator neutrino physics program in US

Broad scope within experimental neutrino physics:

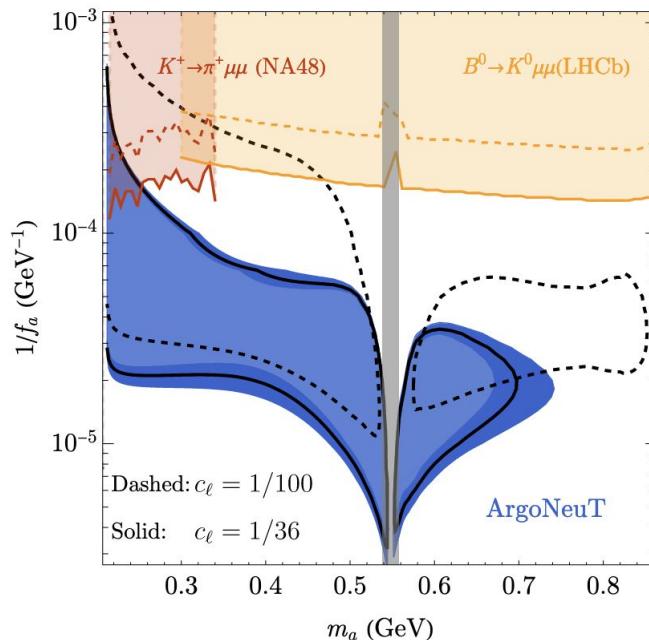
- precision oscillations and δ_{CP}
- searches for new physics
- astrophysics program: supernova and solar neutrinos

Liquid Argon Time Projection Chamber

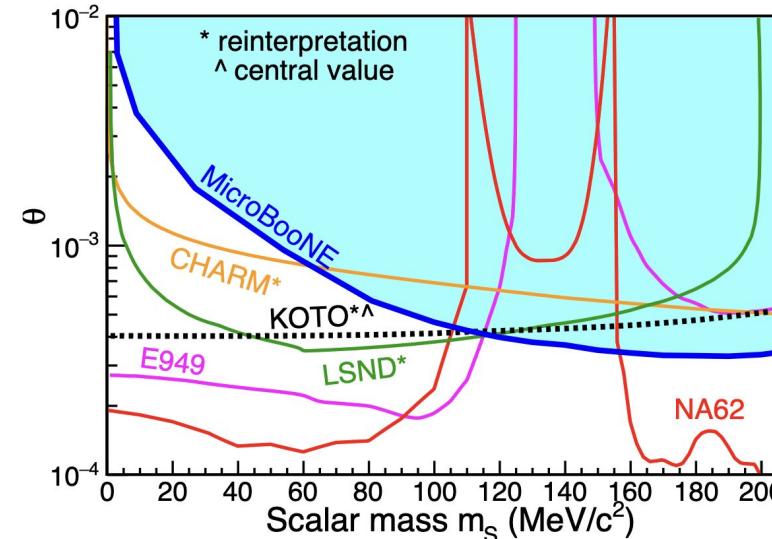


LArTPCs are delivering exciting physics!

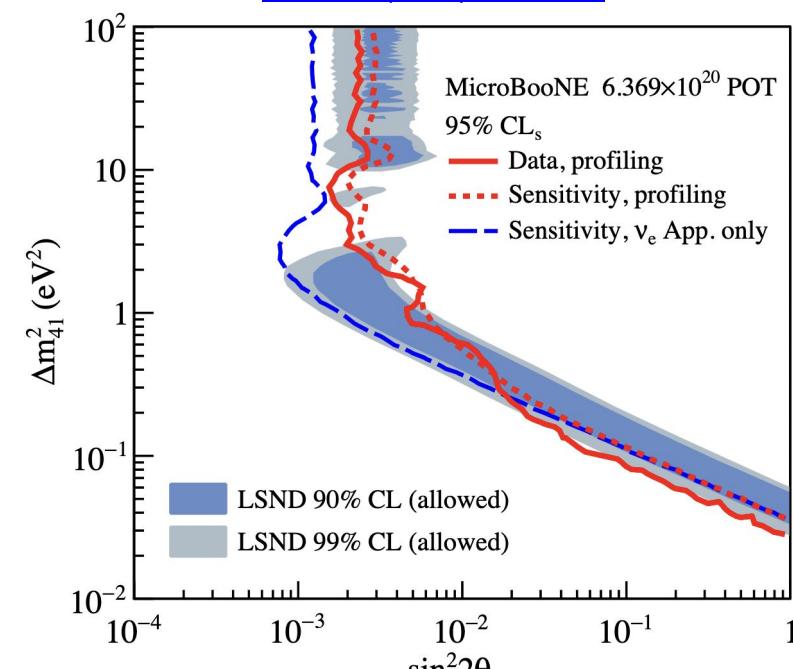
axion searches: [arXiv:2207.08448](https://arxiv.org/abs/2207.08448)



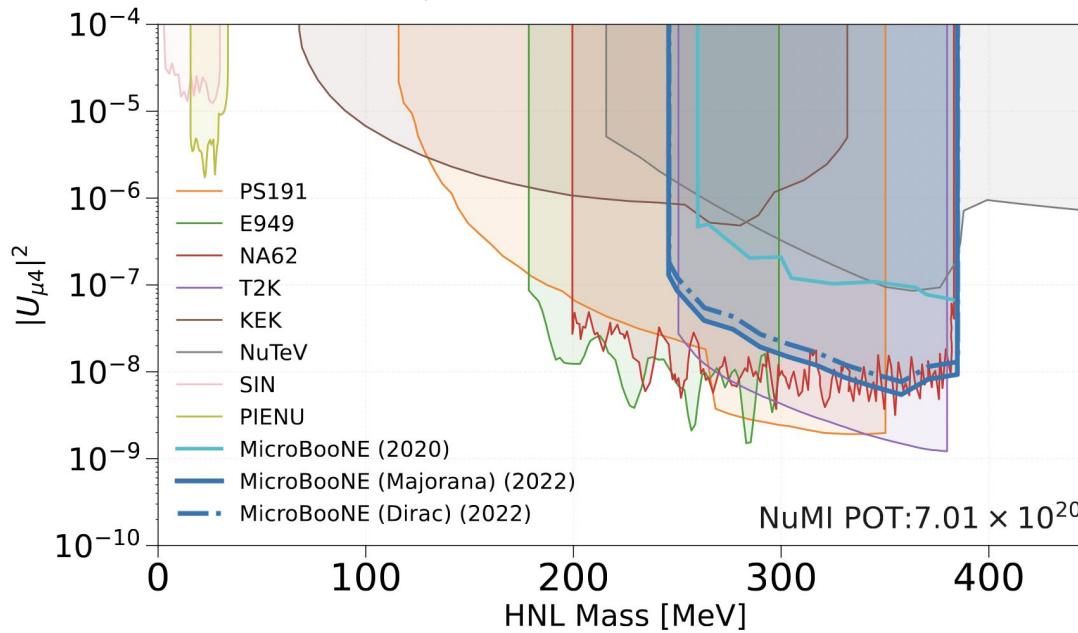
Higgs portal: [PRL 127 \(2021\) 15, 151803](https://doi.org/10.1103/PhysRevLett.127.151803)



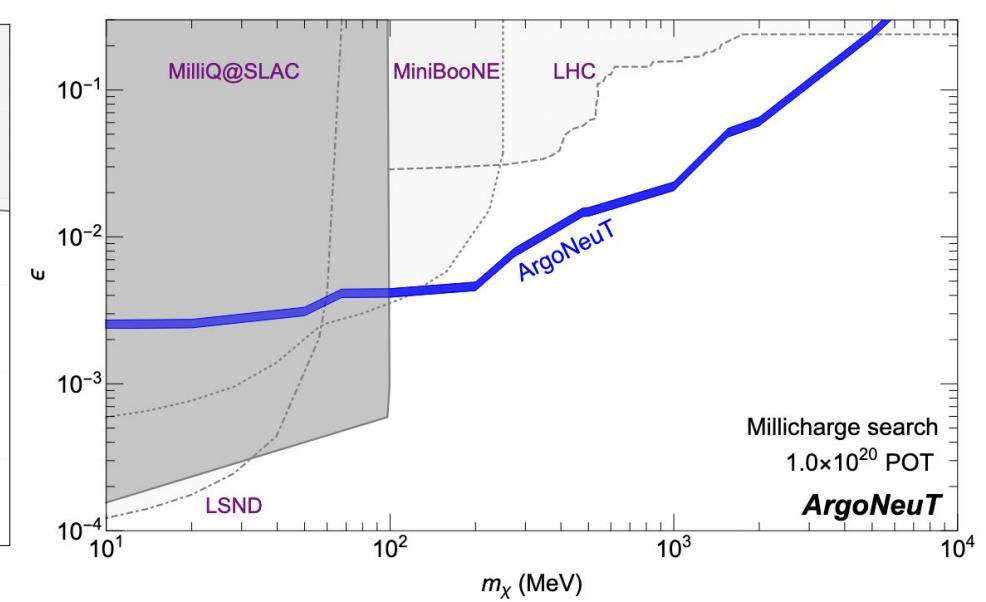
3+1 sterile [PRL 130 \(2023\) 1, 011801](https://doi.org/10.1103/PhysRevLett.130.011801)



Heavy Neutral Leptons: [PRD 106 \(2022\) 9, 092006](https://doi.org/10.1103/PhysRevD.106.092006)



millicharged particle [Phys.Rev.Lett. 124 \(2020\)](https://doi.org/10.1103/PhysRevLett.124.101801)



precision measurements setting world-leading limits

The Short Baseline Neutrino Program

SBND



MicroBooNE



ICARUS



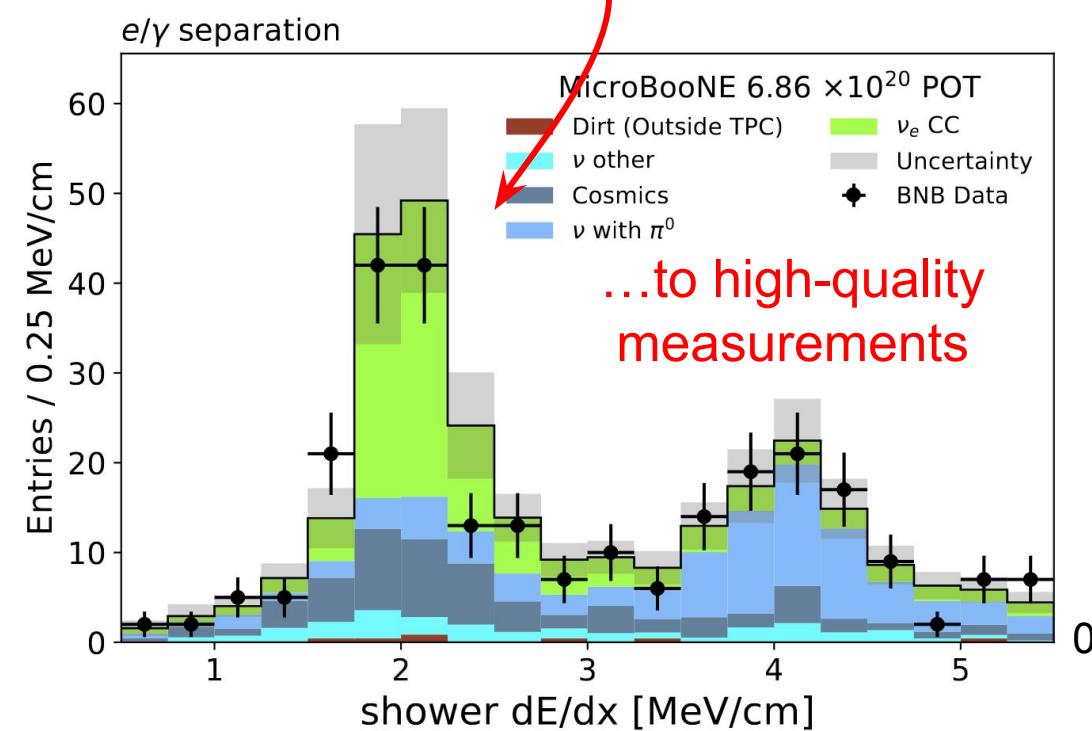
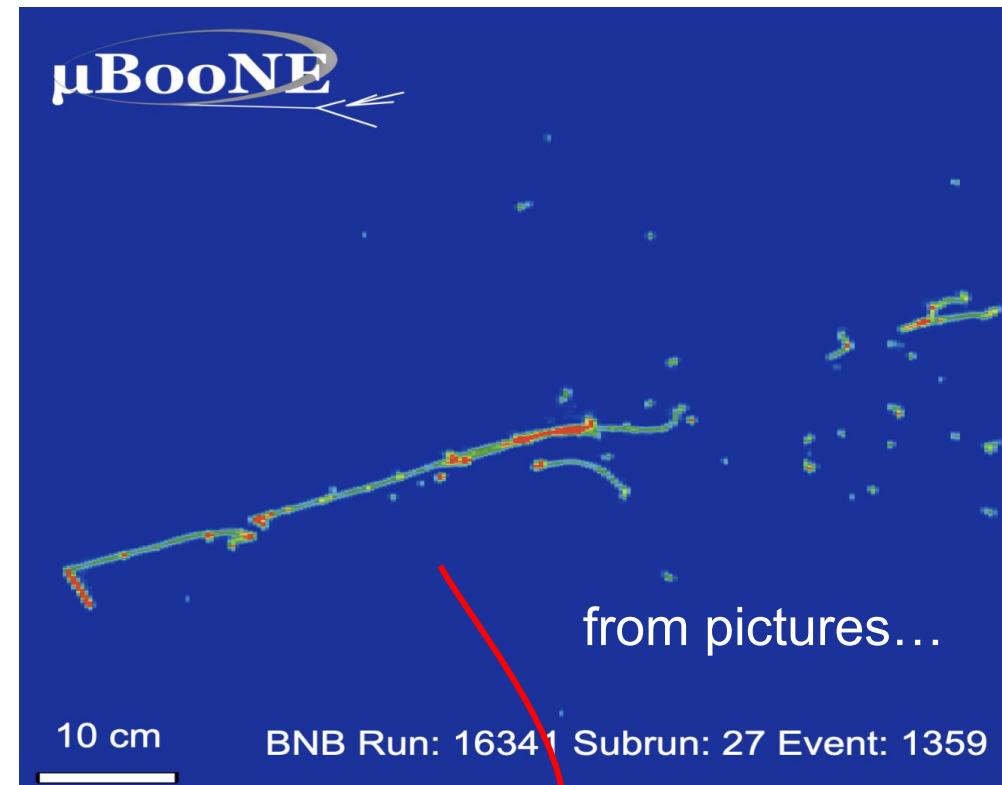
LArTPC detectors sitting on the $O(\text{GeV})$
BNB and off-axis to the NuMI beamlines

few-hundred meter baseline

Step #1: MicroBooNE



Data taking 2015-2021. Recorded $O(10^6)$ neutrino interactions on argon



MicroBooNE Physics: Short Baseline Anomalies

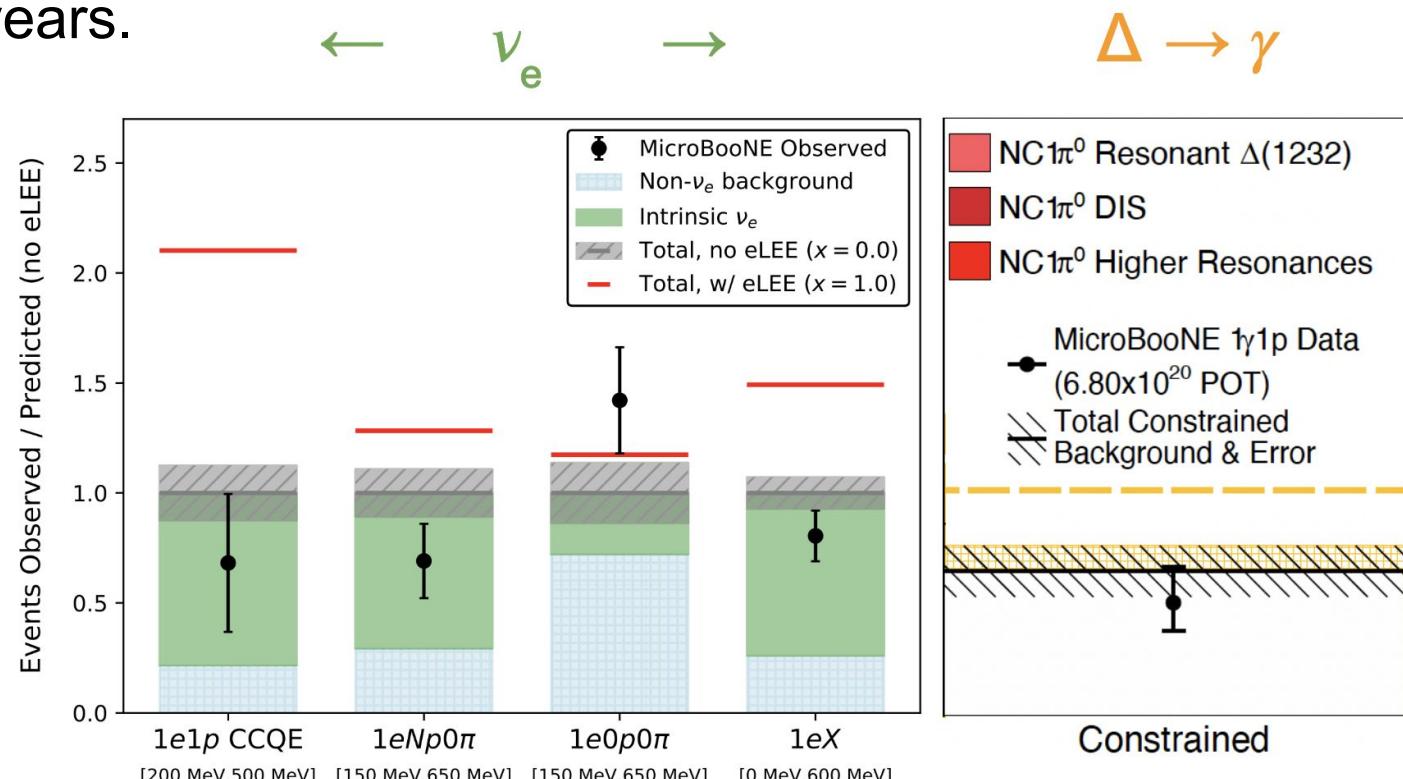
Anomalies in short-baseline neutrino experiments have puzzled the neutrino community for decades

LSND, MiniBooNE, gallium, reactor anomalies

MicroBooNE's first results investigates the MiniBooNE "Low Energy Excess"

- **electron neutrino** and **NC $\Delta \rightarrow \gamma$** channels so far show no excess.

Analysis of full dataset and searches for more exotic BSM signature will complete the picture in the coming years.



MicroBooNE results on
"Low-Energy-Excess":

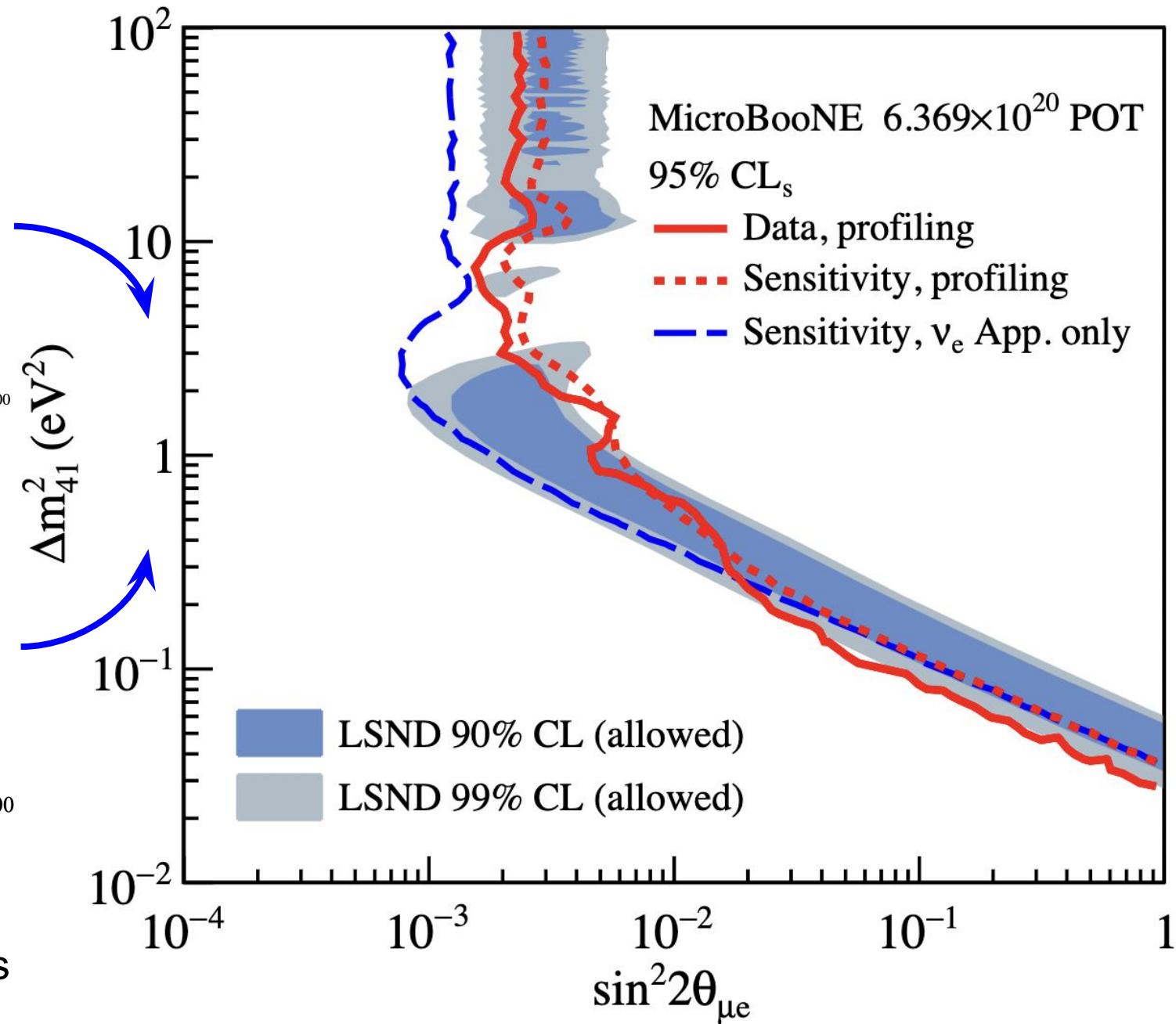
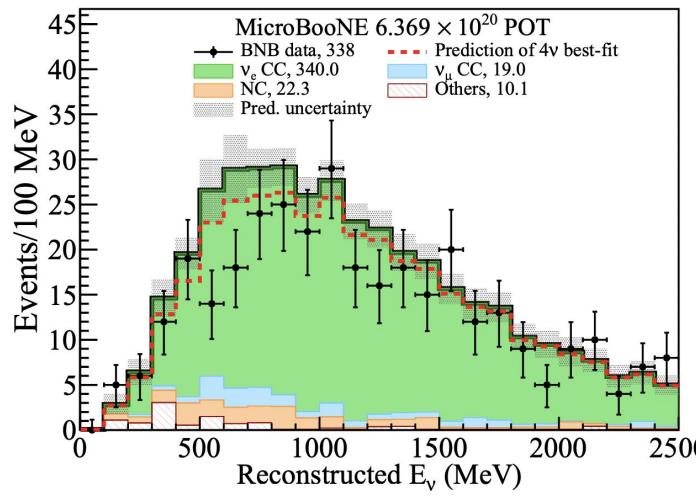
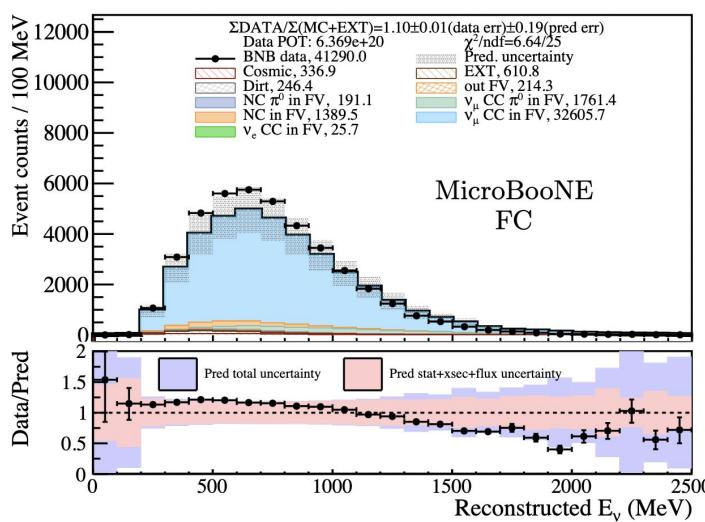
NC $\Delta \rightarrow \gamma$ search

[PRL 128 \(2022\) 11, 111801](#)

electron neutrino search

[PRL 128 \(2022\) 24, 241801](#)

MicroBooNE's first eV-sterile ν search



Next: 3+1 oscillation search with BNB + NuMI beamlines

MicroBooNE "First Constraints on Light Sterile Neutrino Oscillations from Combined Appearance and Disappearance Searches with the MicroBooNE Detector" [Phys.Rev.Lett. 130 \(2023\) 1, 011801](#)

Beyond the Standard Model Physics

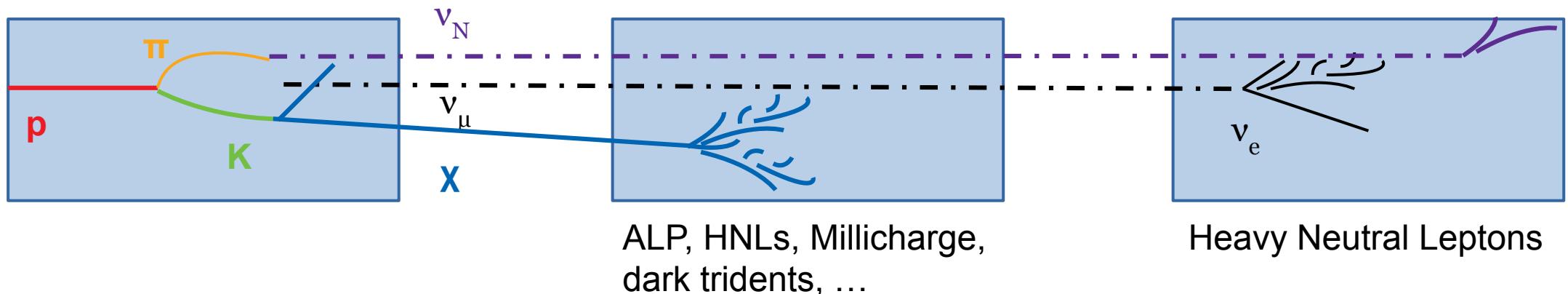


Expansive Beyond the Standard Model physics program @ accelerator neutrino experiments

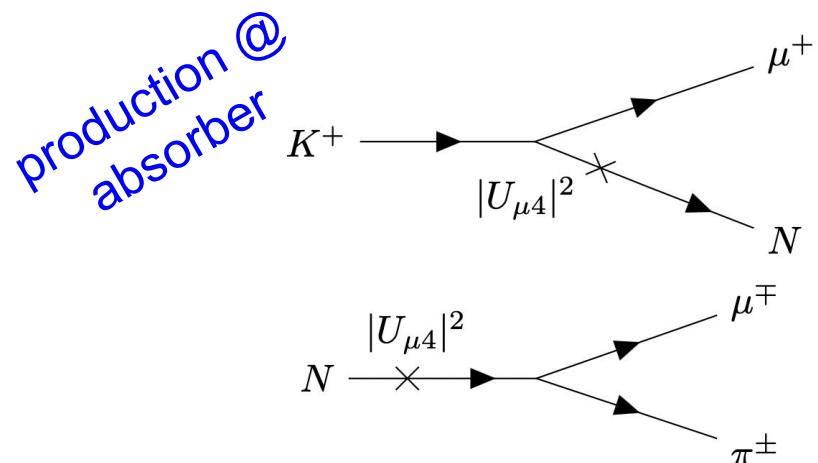
- intense beam → opportunity to produce new particles
- neutrino detectors → designed for rare-process measurement
- LArTPC technology → track particles with few / 10s of MeV threshold

Unique environment for sub-Gev new physics searches
Complementary to broader HEP landscape

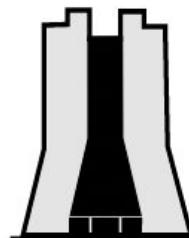
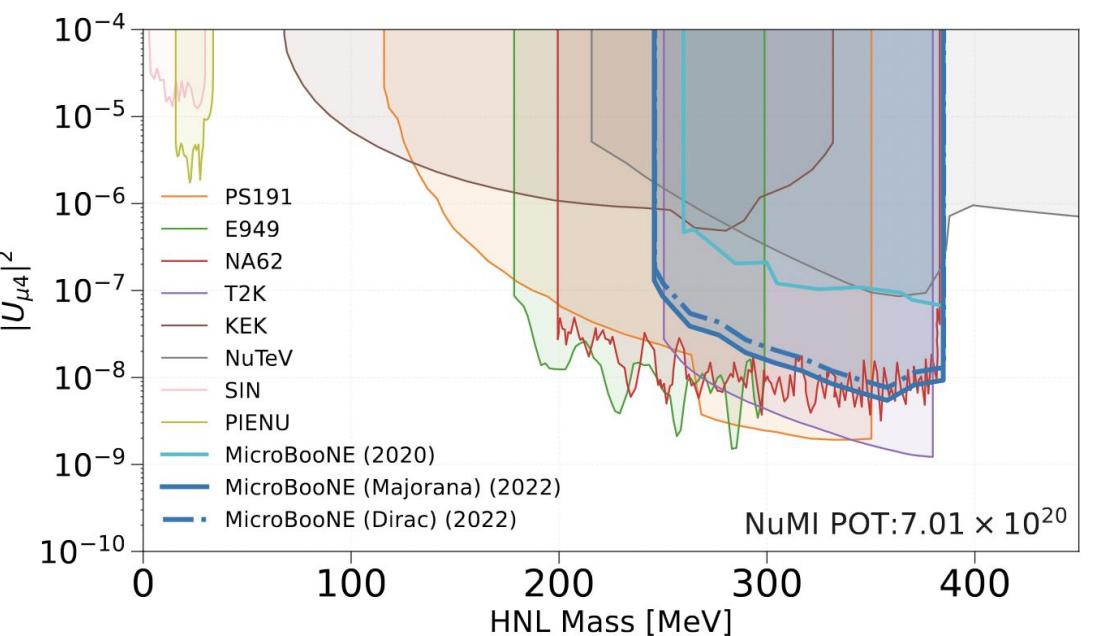
Team effort with theory and phenomenology communities



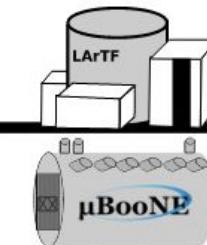
New BSM Results: HNLs from NuMI



detection @ MicroBooNE



NuMI Beamline Side View



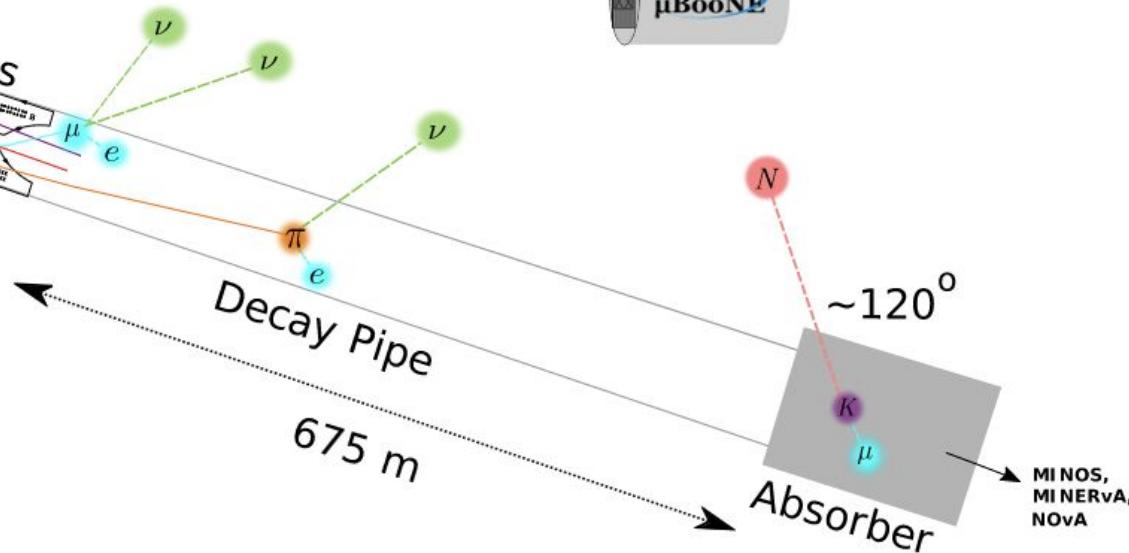
Main Injector

120 GeV Beam

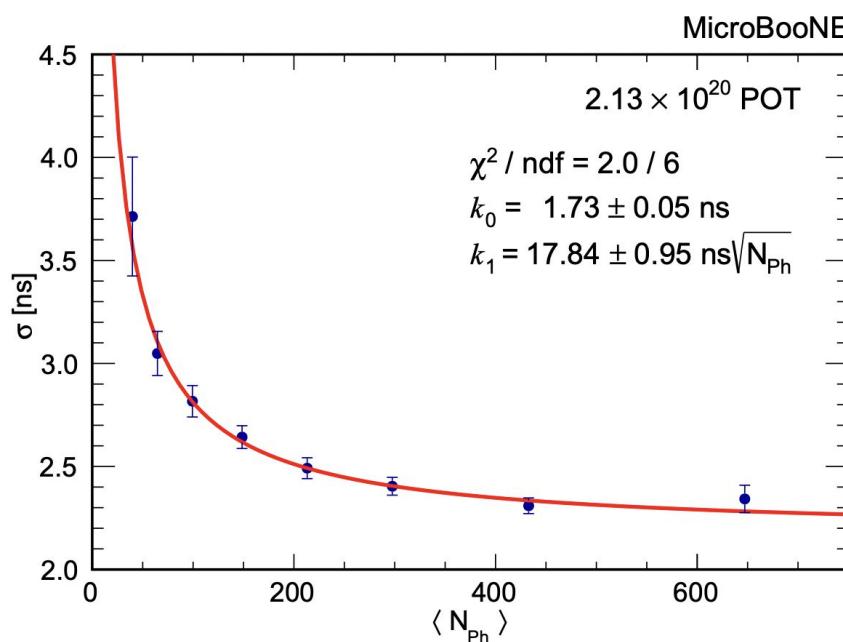
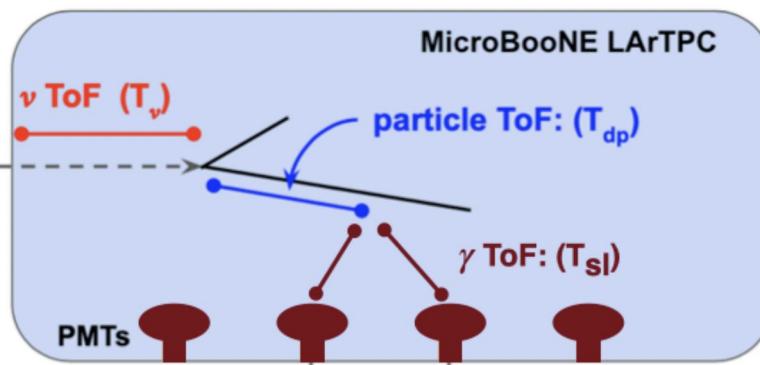
Horns
Target

"Search for long-lived heavy neutral leptons and Higgs portal scalars decaying in the MicroBooNE detector" [PRD 106 \(2022\) 9, 092006](#)

Not to Scale



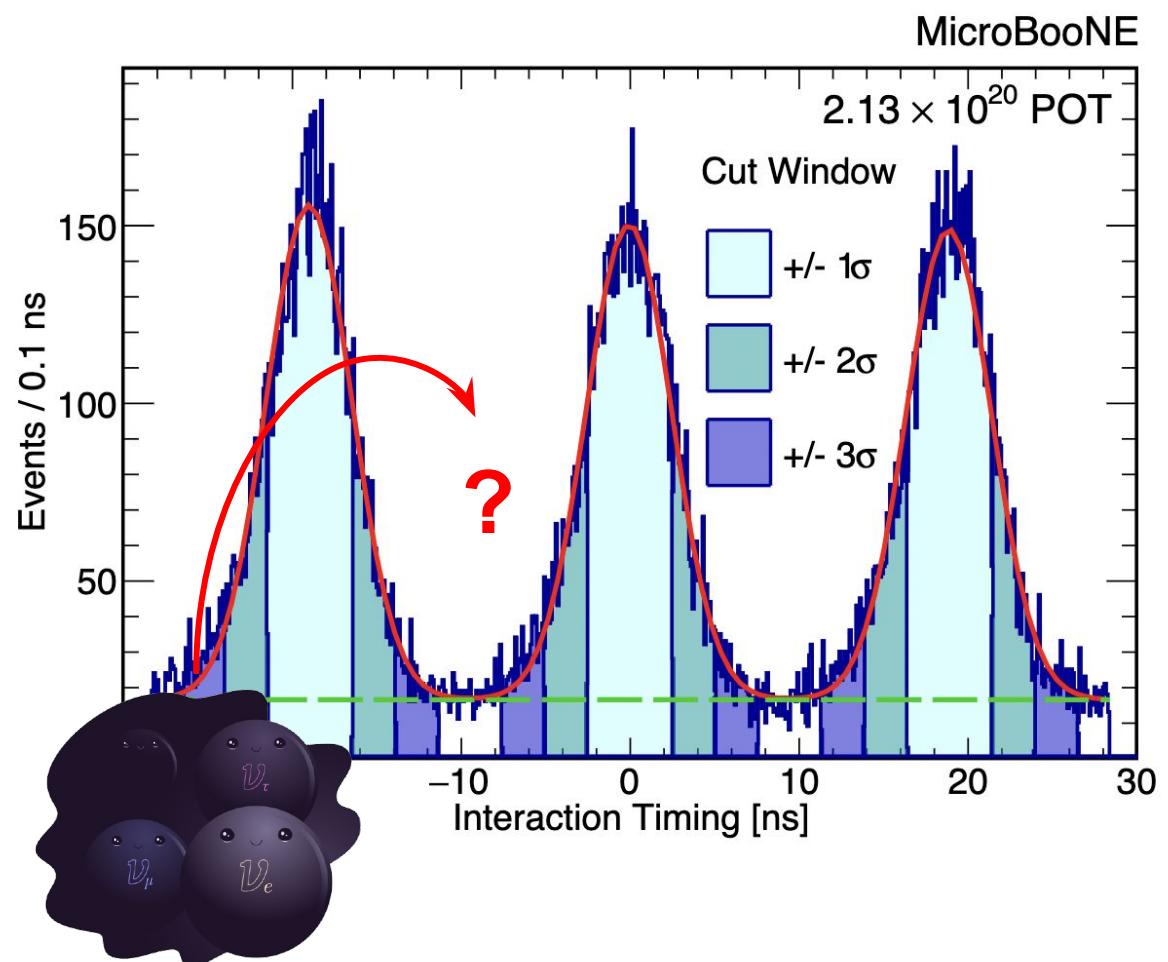
New Opportunities with LArTPCs



x100 improvement in timing resolution!

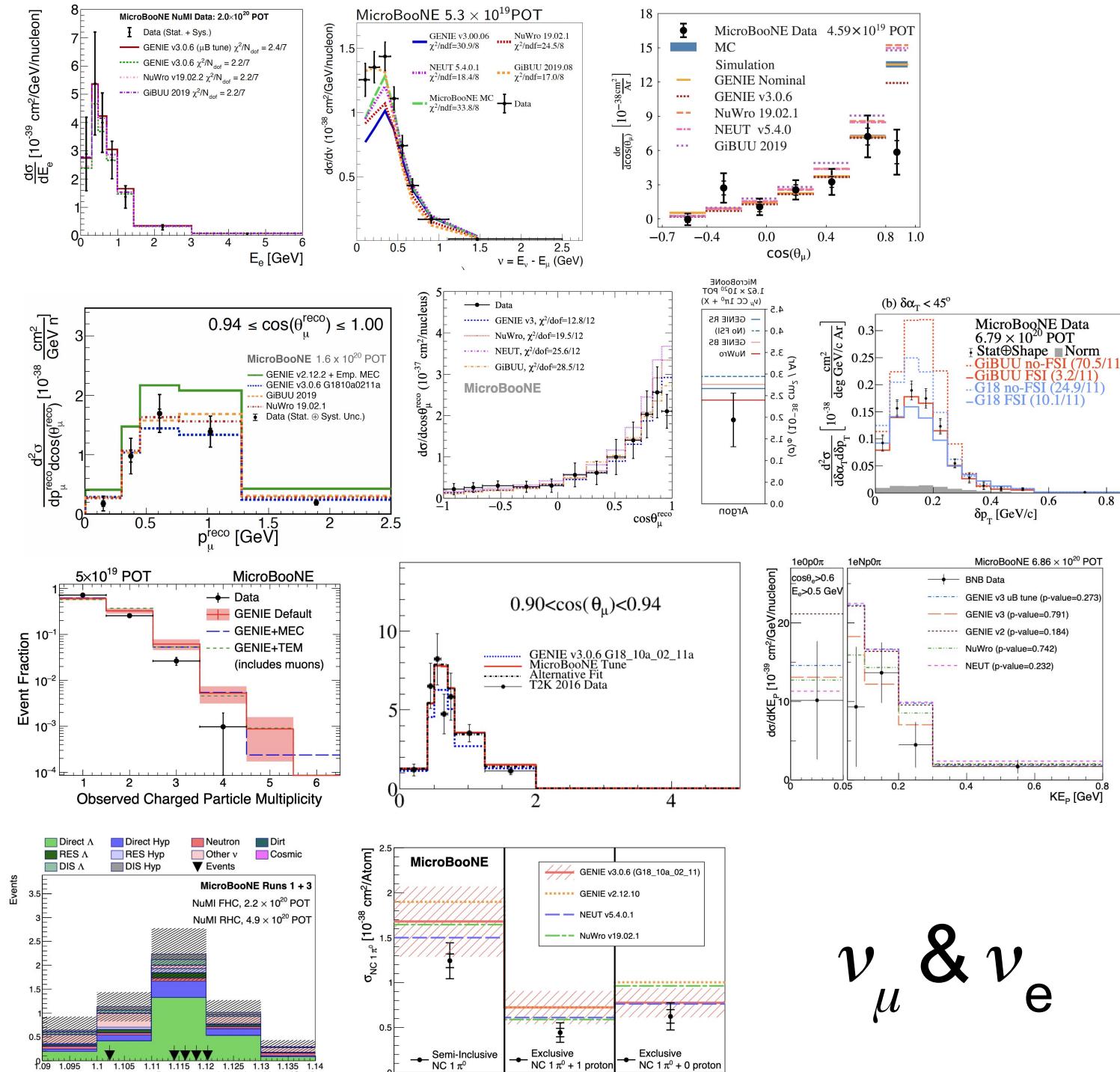
increased sensitivity to low-mass (10s of MeV) long-lived particles traveling from the beam

First demonstration of $O(1\text{ns})$ timing resolution in the MicroBooNE liquid argon time projection chamber [arXiv:2304.02076](https://arxiv.org/abs/2304.02076)



new opportunities for Beyond the Standard Model physics searches of Heavy Neutral Leptons and other long-lived particles.

ν - argon cross section program



ν_μ & ν_e

ν_μ CC Np 0π [1D differential]
[Phys.Rev.D 102 \(2020\) 11, 112013](#)

ν_μ CCQE-like [1D differential]
[Phys.Rev.Lett. 125 \(2020\) 20, 201803](#)

ν_μ CC inclusive [2D differential]
[Phys.Rev.Lett. 123 \(2019\) 13, 131801](#)

ν_μ CC π^0 [integrated]
[Phys.Rev.D 99 \(2019\) 9, 091102](#)

ν_e CC [inclusive]
[Phys.Rev.D 104 \(2021\) 5, 052002](#)

ν_e CC [1D differential]
[Phys.Rev.D 105 \(2022\) 5, L051102](#)

ν_μ CC inclusive [1D differential]
[arXiv:2110.14023](#) [accepted by PRL]

Proton multiplicity
[Eur.Phys.J.C 79 \(2019\) 3, 248](#)

ν_e CC Np [1D differential]
[Phys.Rev.D 106 \(2022\) 5, L051102](#)

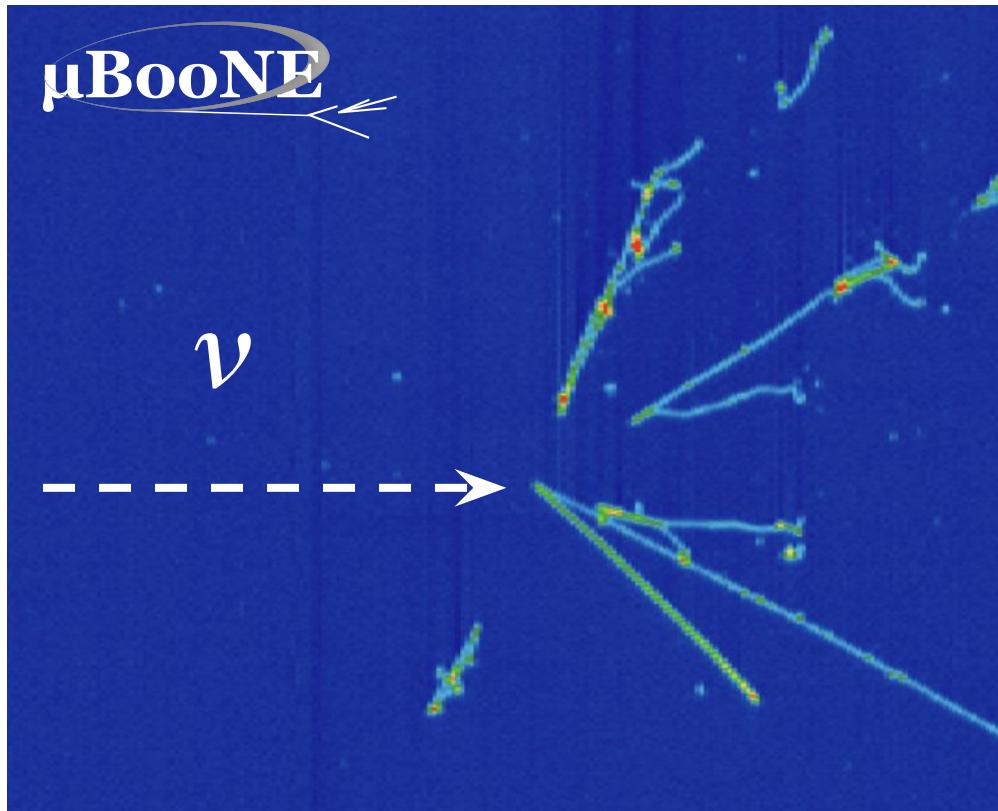
2D ν_μ Np kinematic imbalance
[arXiv:2301.03706](#)

NC π^0 :
[Phys.Rev.D 107 \(2023\)](#)

Lambda barion production
[arXiv:2212.07888](#) [accepted by PRL]

collaboration with theory & generator communities is key!

ν - argon cross sections: oscillations

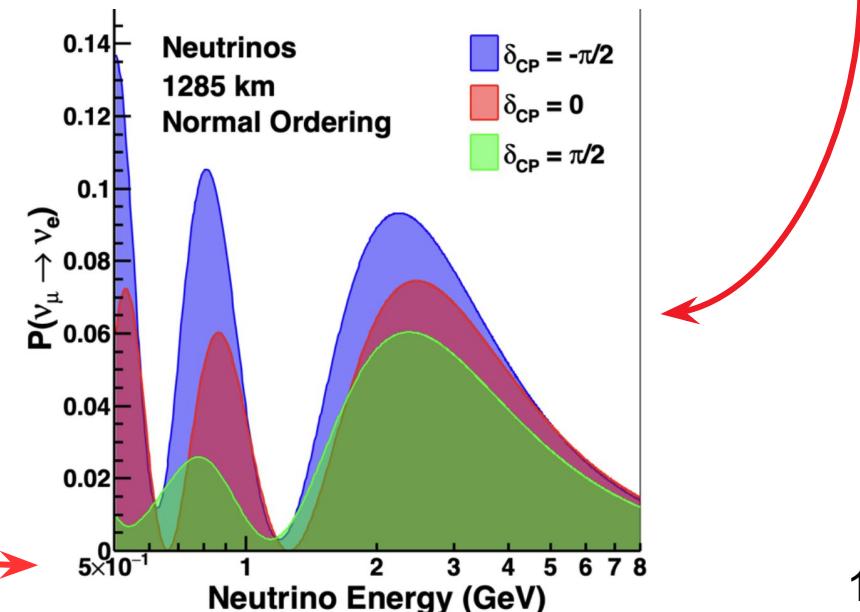


Event rate and visible energy depend on neutrino cross-section

Precision oscillations requires detailed understanding of cross sections

$$N(E) = \int \Phi(E) \sigma(E)$$

DUNE, [Eur.Phys.J.C 80 \(2020\) 10, 978](#)

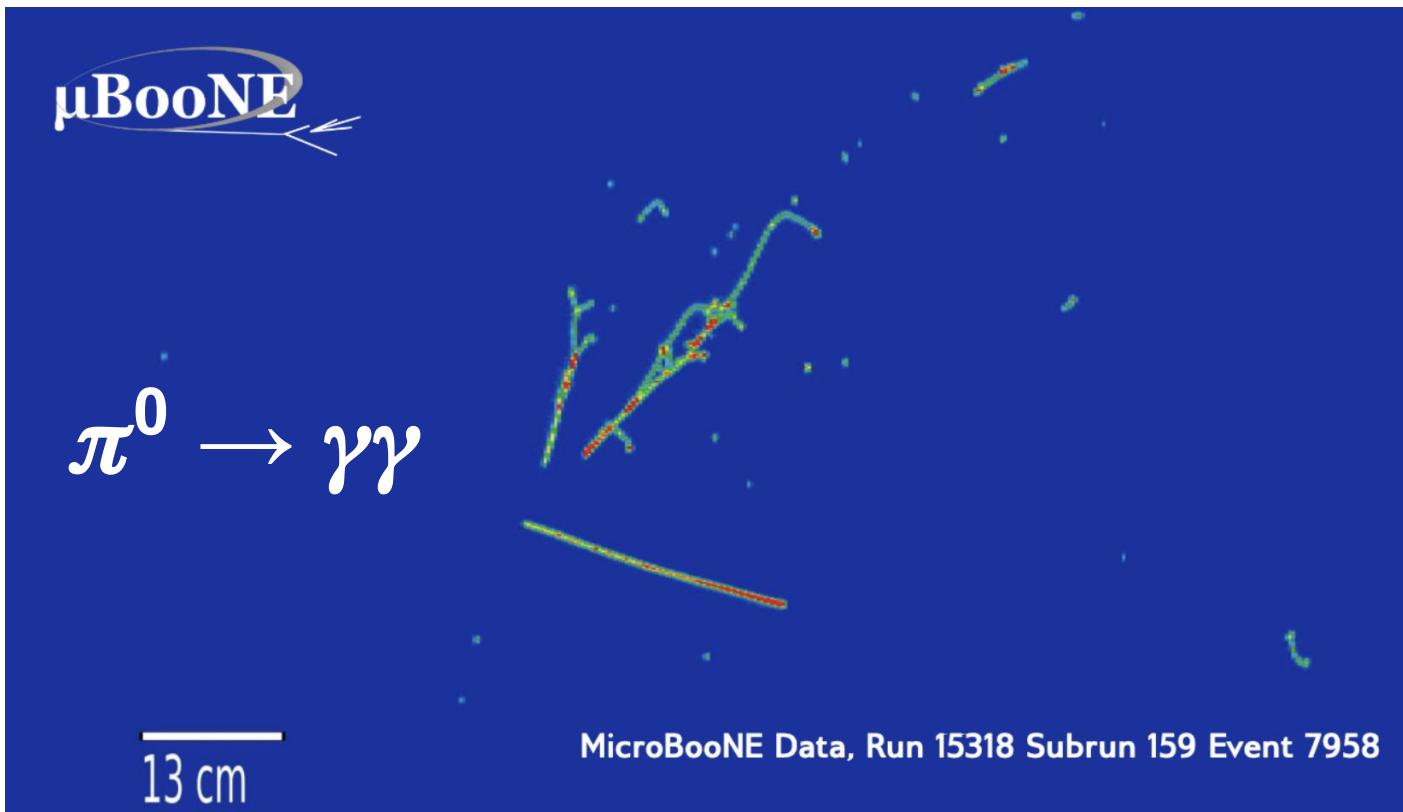


Freq. Of oscillation.
Choose L, E appropriate for Δm^2 .

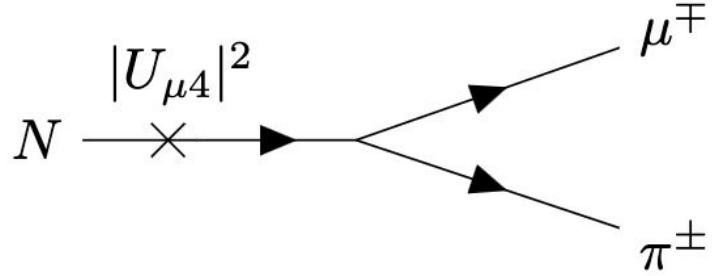
$$P_{\nu_\mu \rightarrow \nu_e} \approx \sin^2(2\theta) \sin^2 \left(\frac{\Delta m^2 L}{4E} \right)$$

sets amplitude of oscillation.
large \rightarrow "easy" to detect.

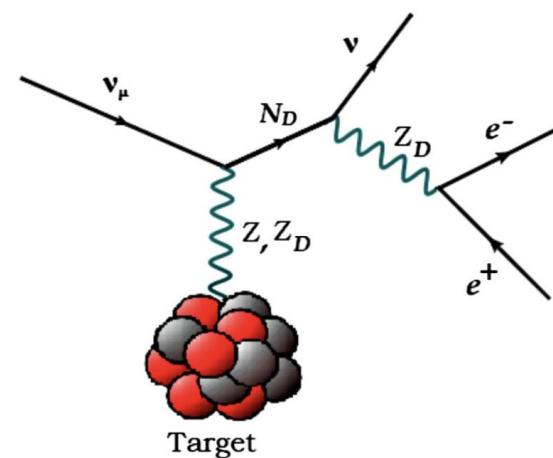
ν - argon cross sections: BSM physics



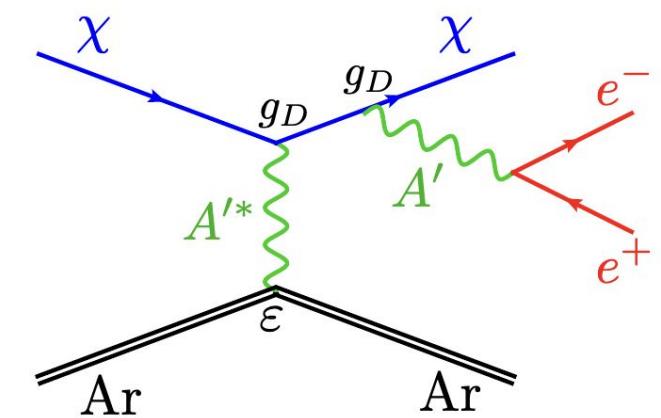
Phys.Rev.D 101 (2020) 5, 052001



PRL 121, 241801 (2018)



JHEP 01 (2019) 001



top right figure: “Search for long-lived heavy neutral leptons and Higgs portal scalars decaying in the MicroBooNE detector” Phys.Rev.D 106 (2022) 9, 092006

The Short Baseline Neutrino Program

SBND



MicroBooNE



ICARUS



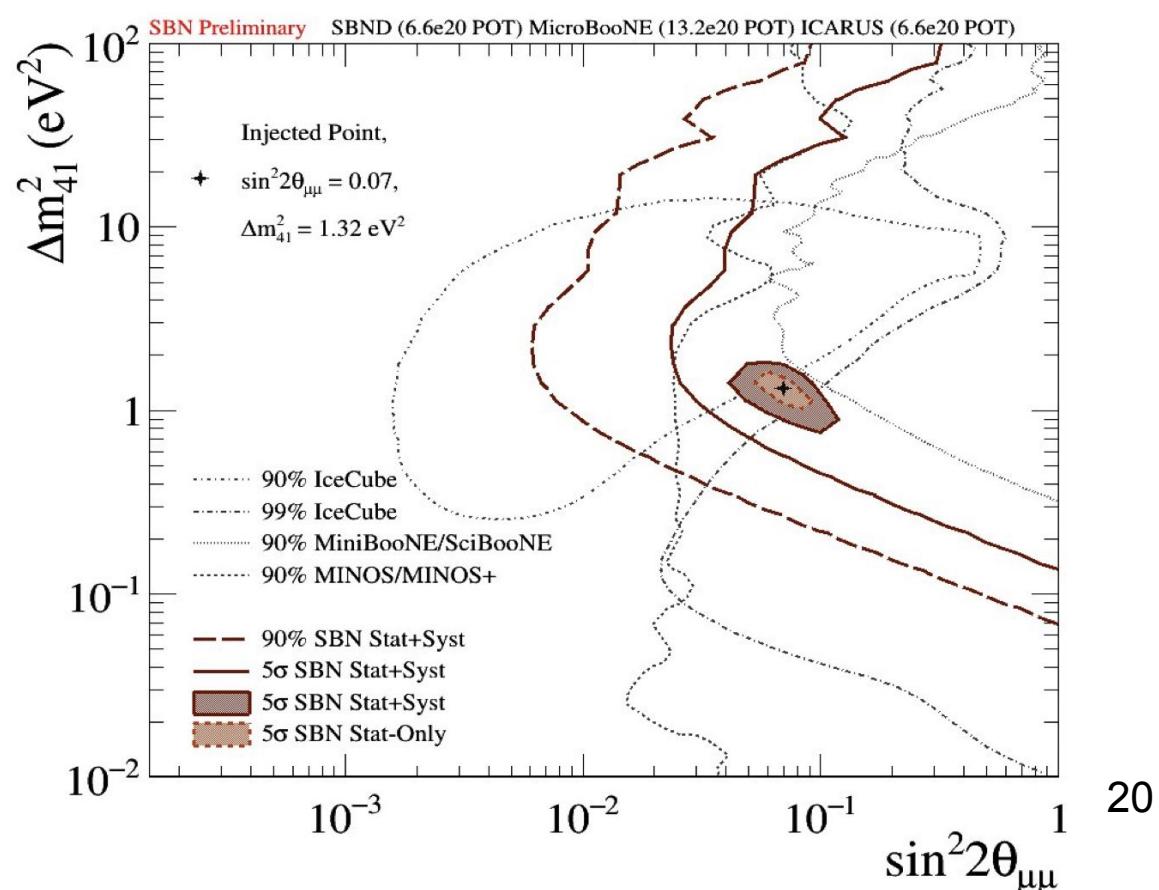
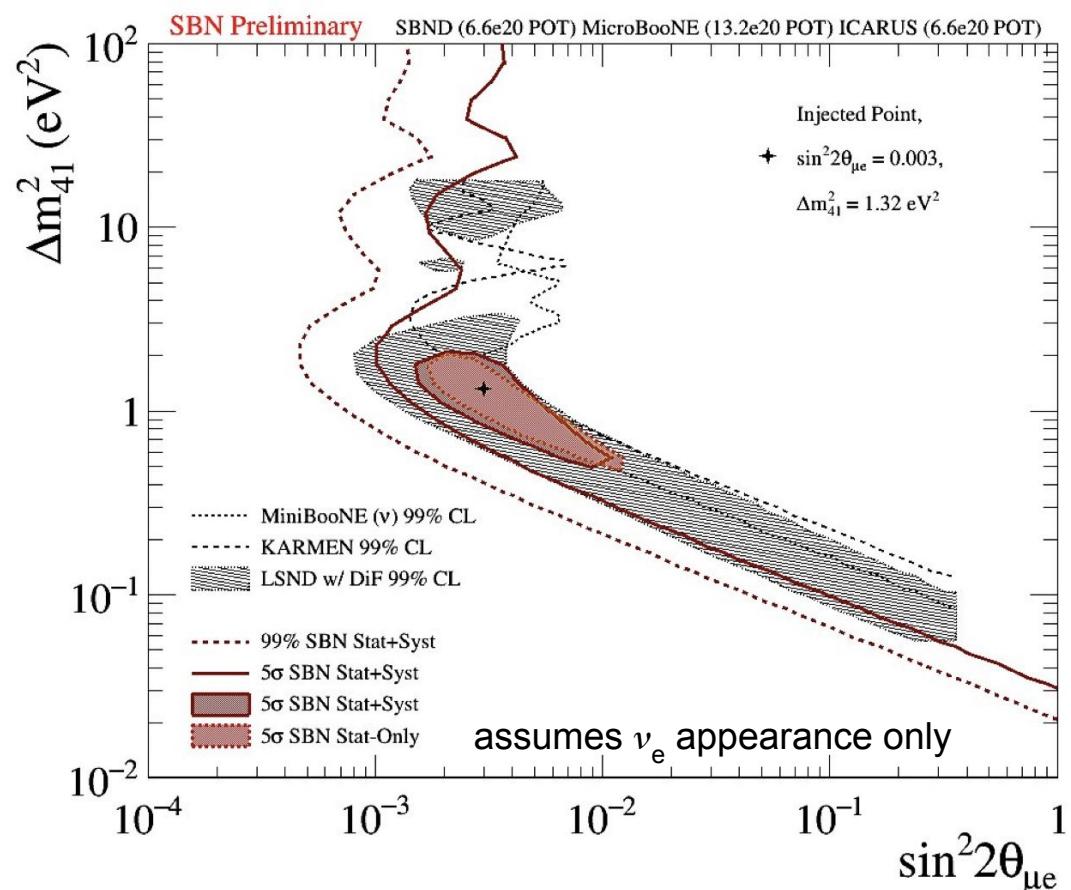
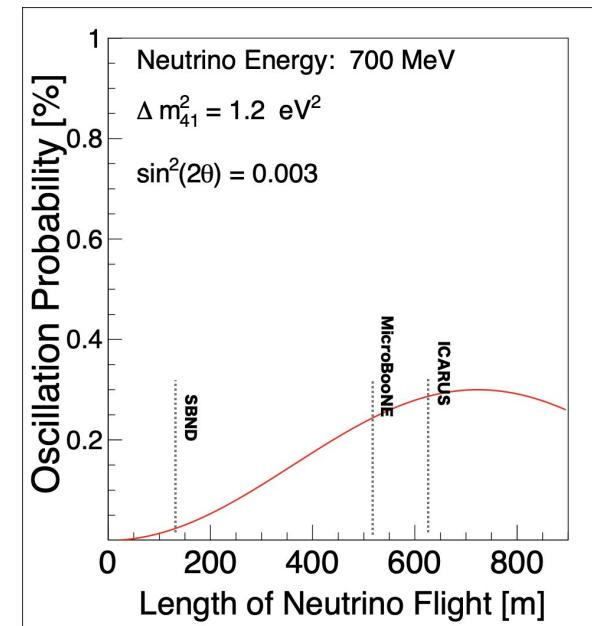
LArTPC detectors sitting on the O(GeV)
BNB and off-axis to the NuMI beamlines

few-hundred meter baseline

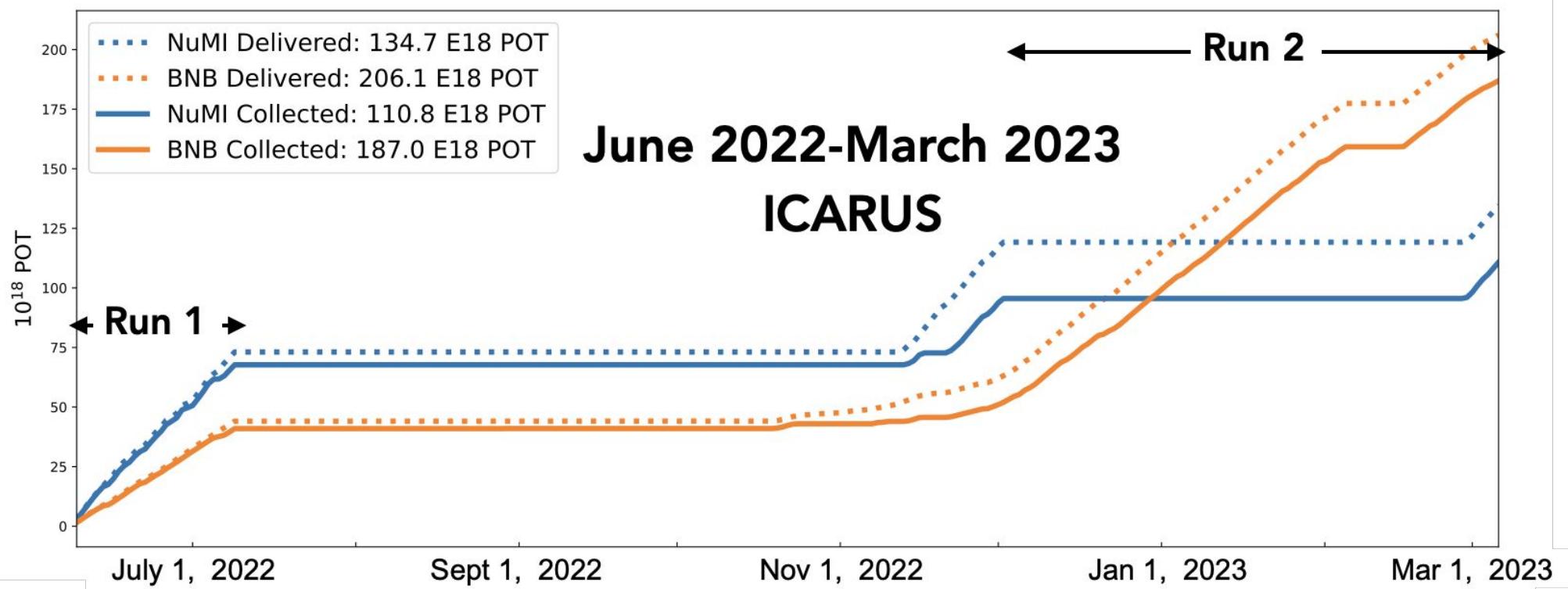
SBN physics program

Multi-detector eV sterile-neutrino search at short baselines.

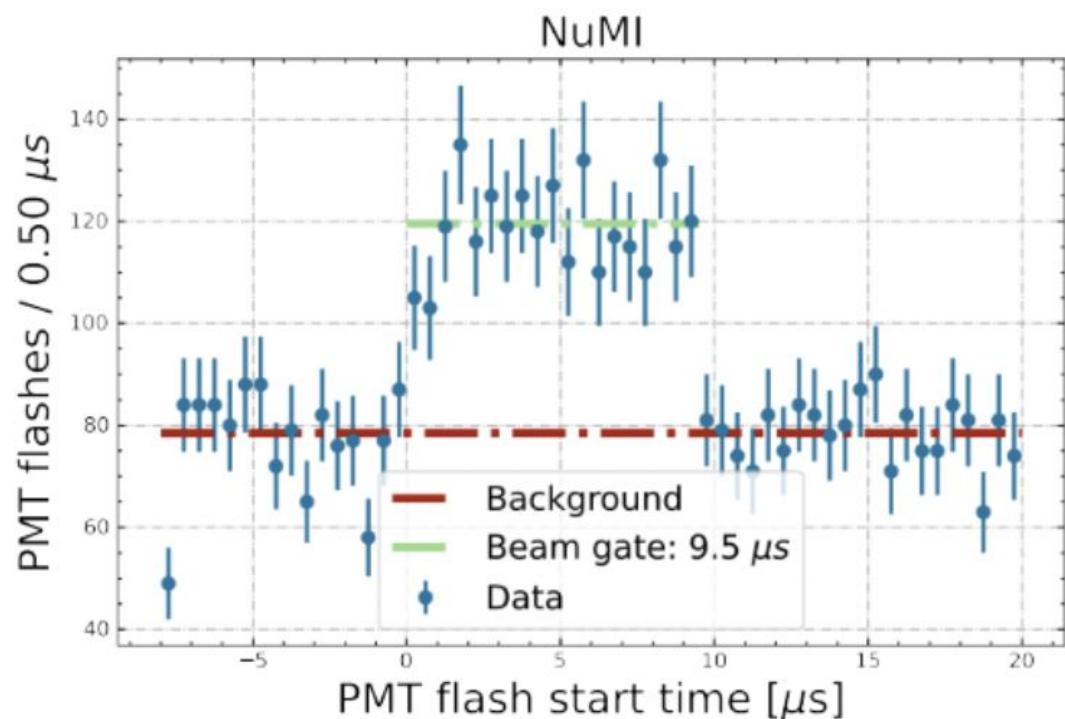
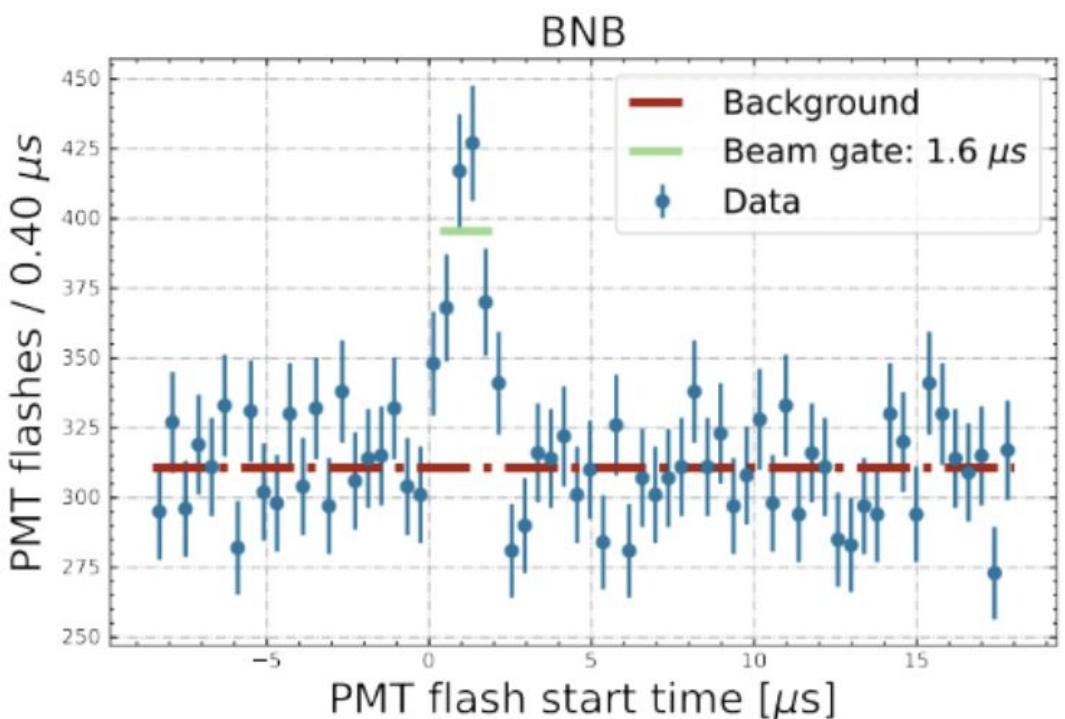
- near detector: in-situ constraint of un-oscillated flux and cross sections
- filling a clear gap in experimental neutrino landscape!



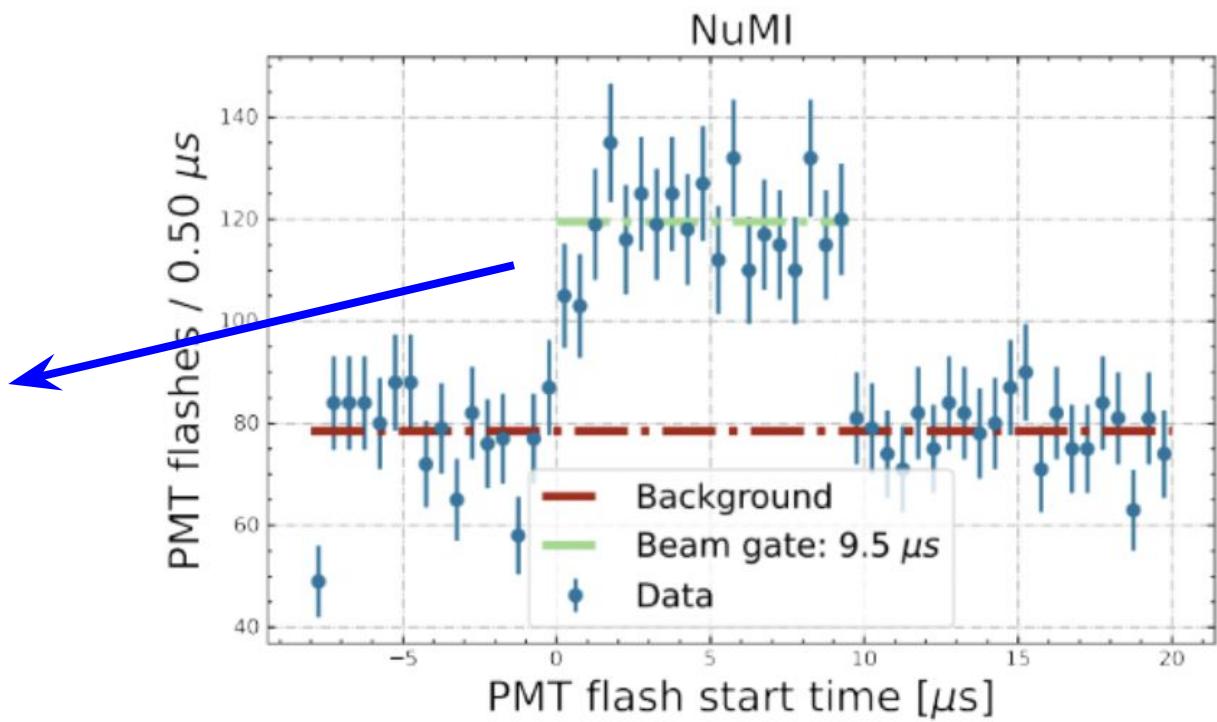
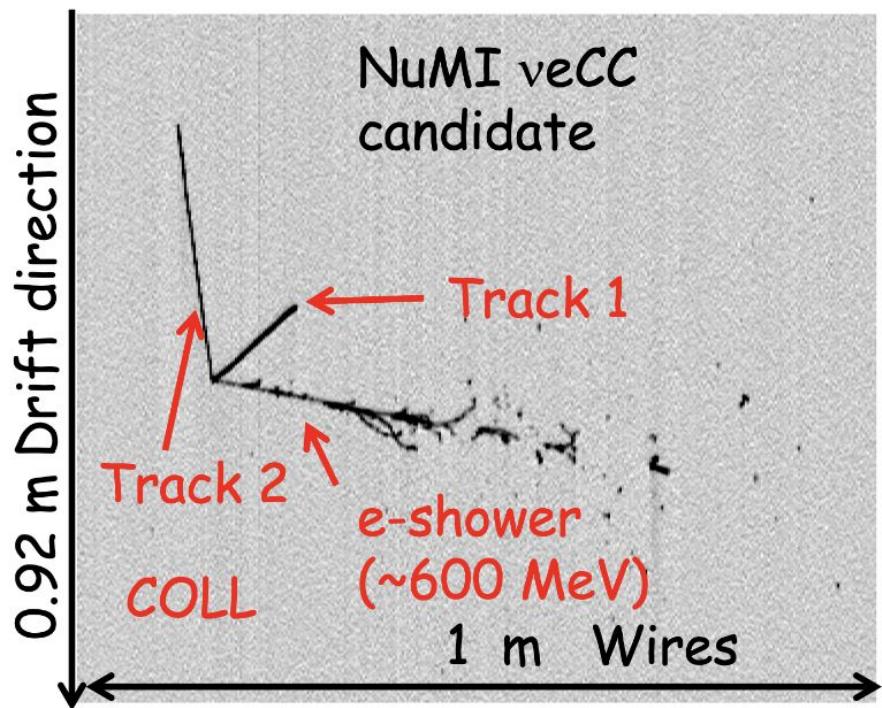
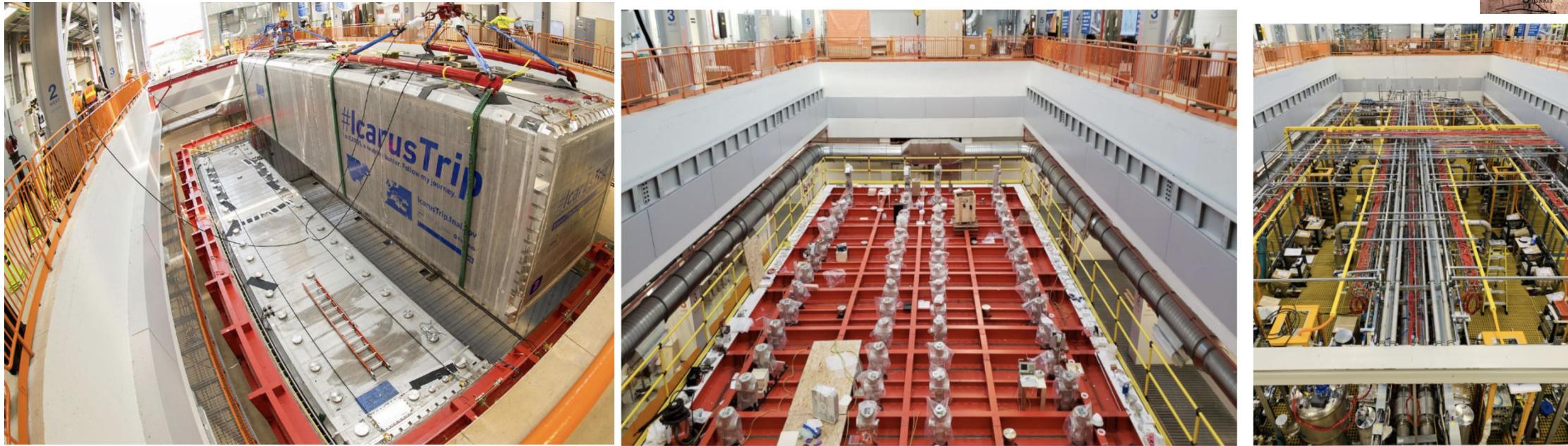
ICARUS: first neutrino data!



ICARUS: first neutrino data!



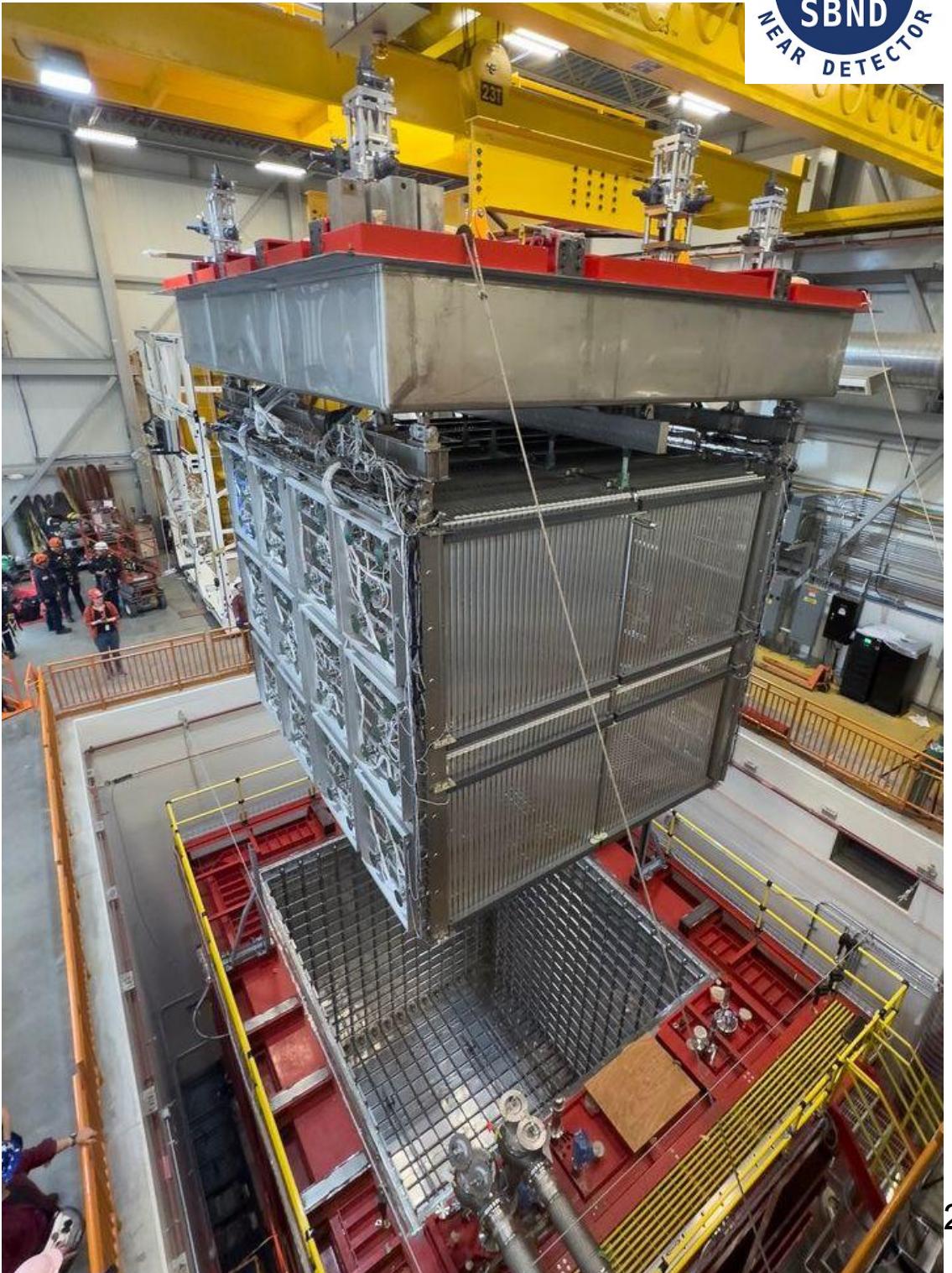
ICARUS: first neutrino data!



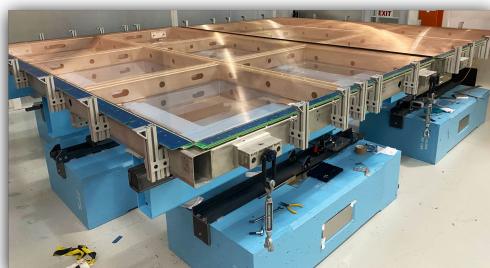
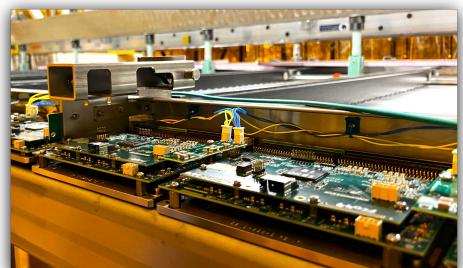
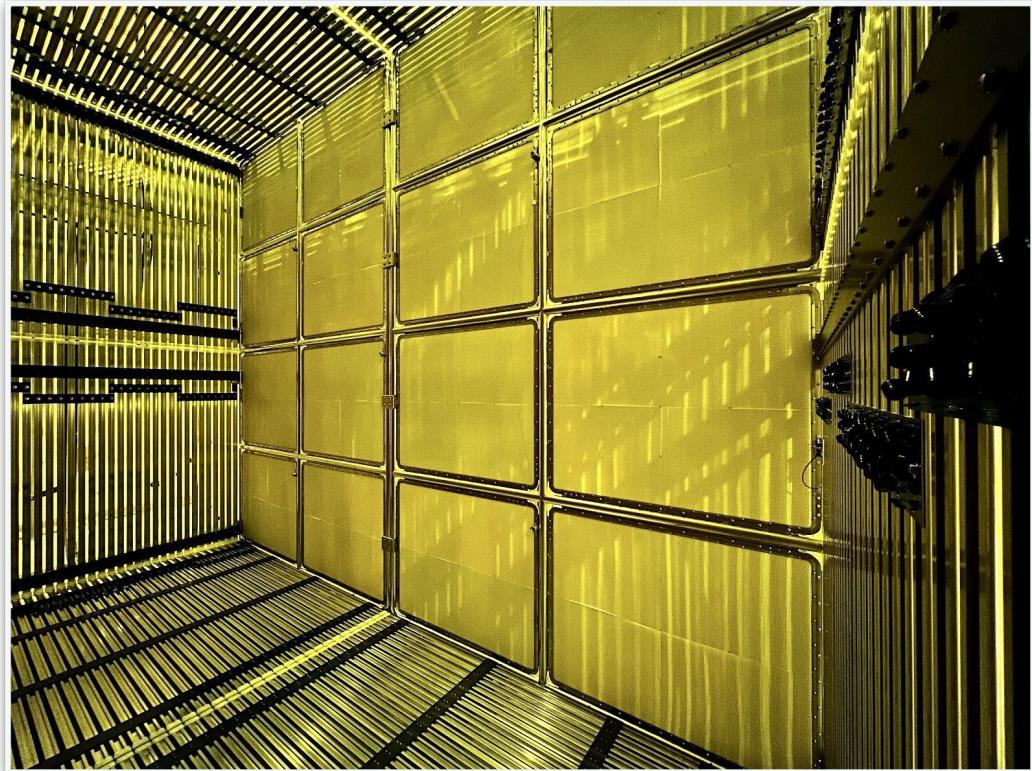
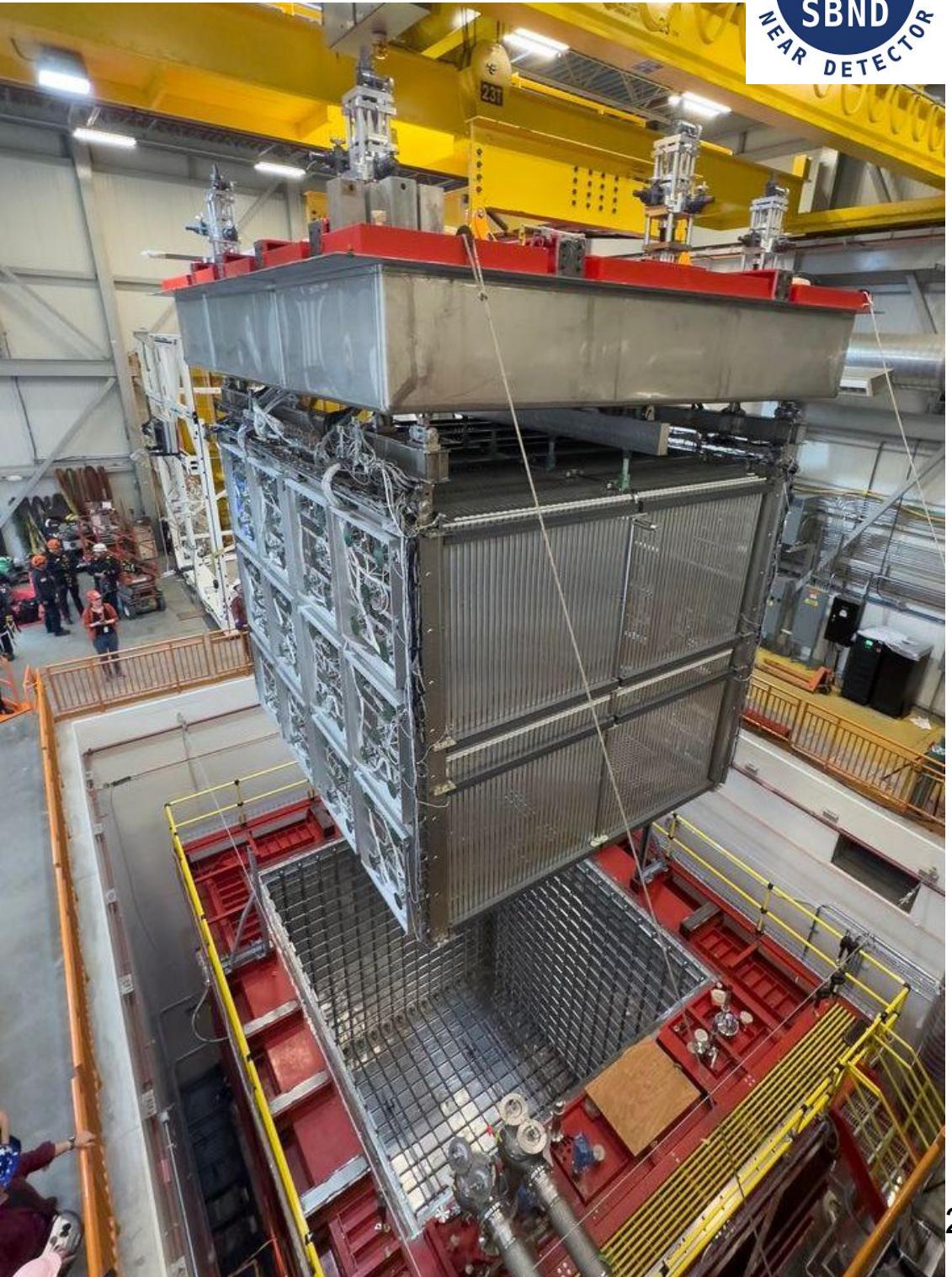
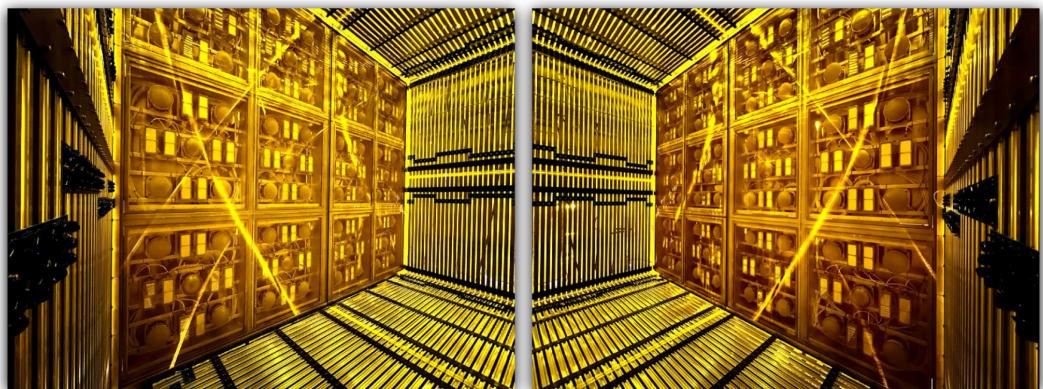
Short Baseline Neutrino Detector [SBND]



SBND lowered in
cryostat on April 25th!



SBND's “state-of-the-art” detector



SBND → lots and lots of neutrinos!

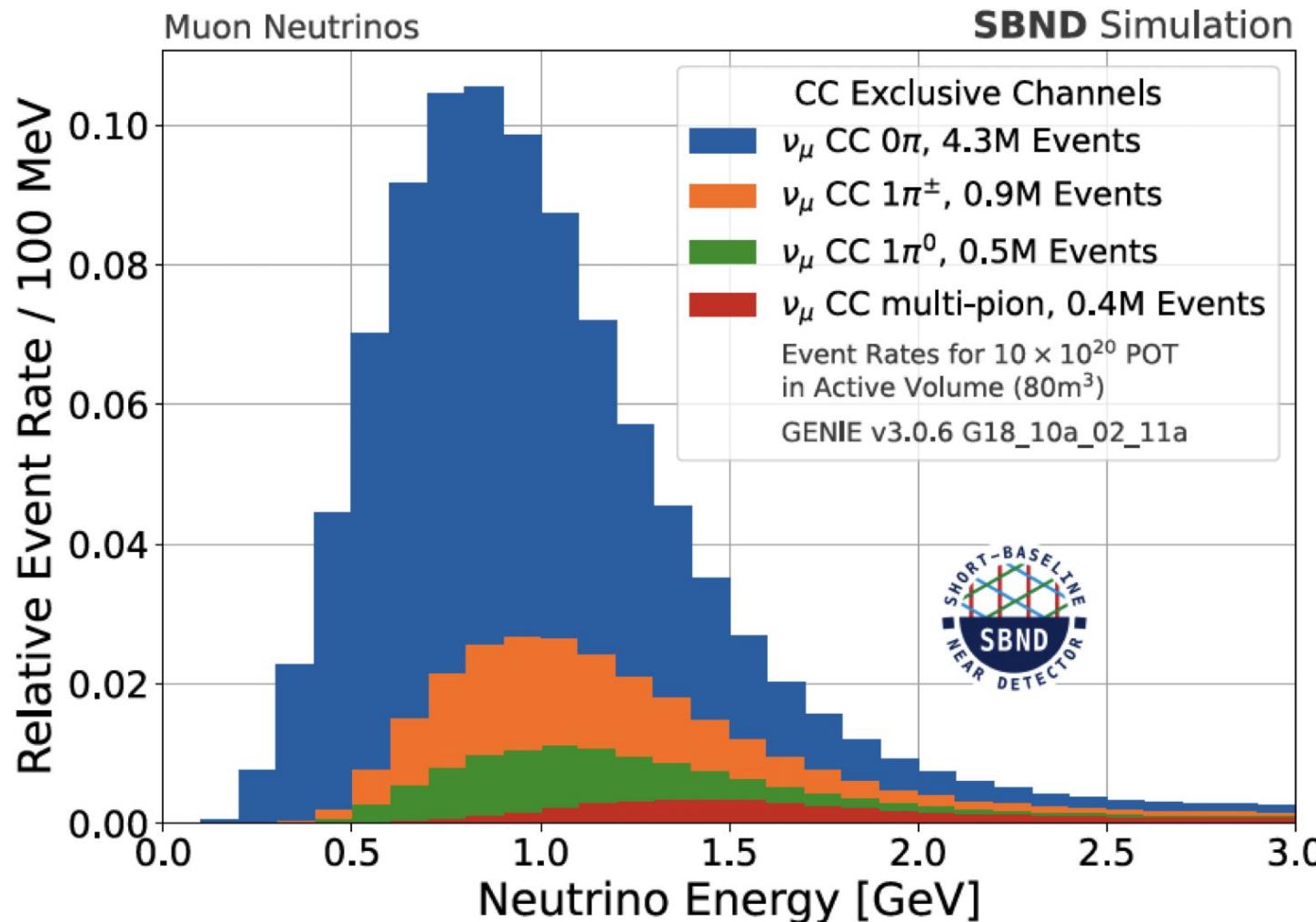


110 meter baseline → large neutrino flux

5,000 neutrino interactions / day!

expect first data in 2024!

15,000 ν_e CC interactions in 1 year



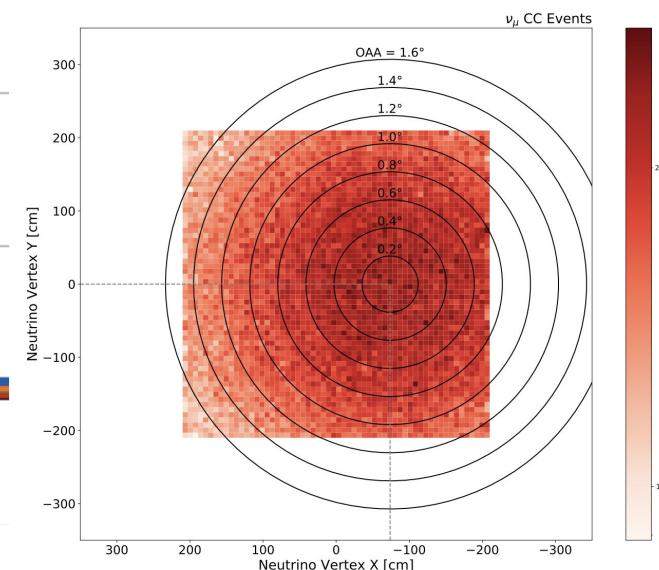
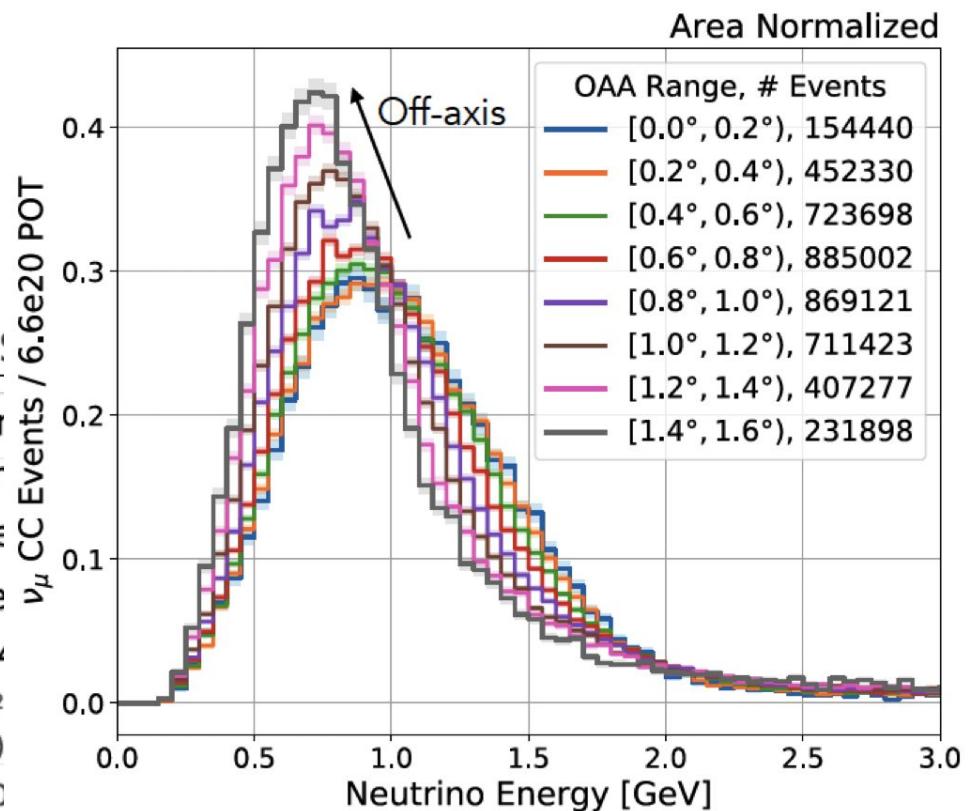
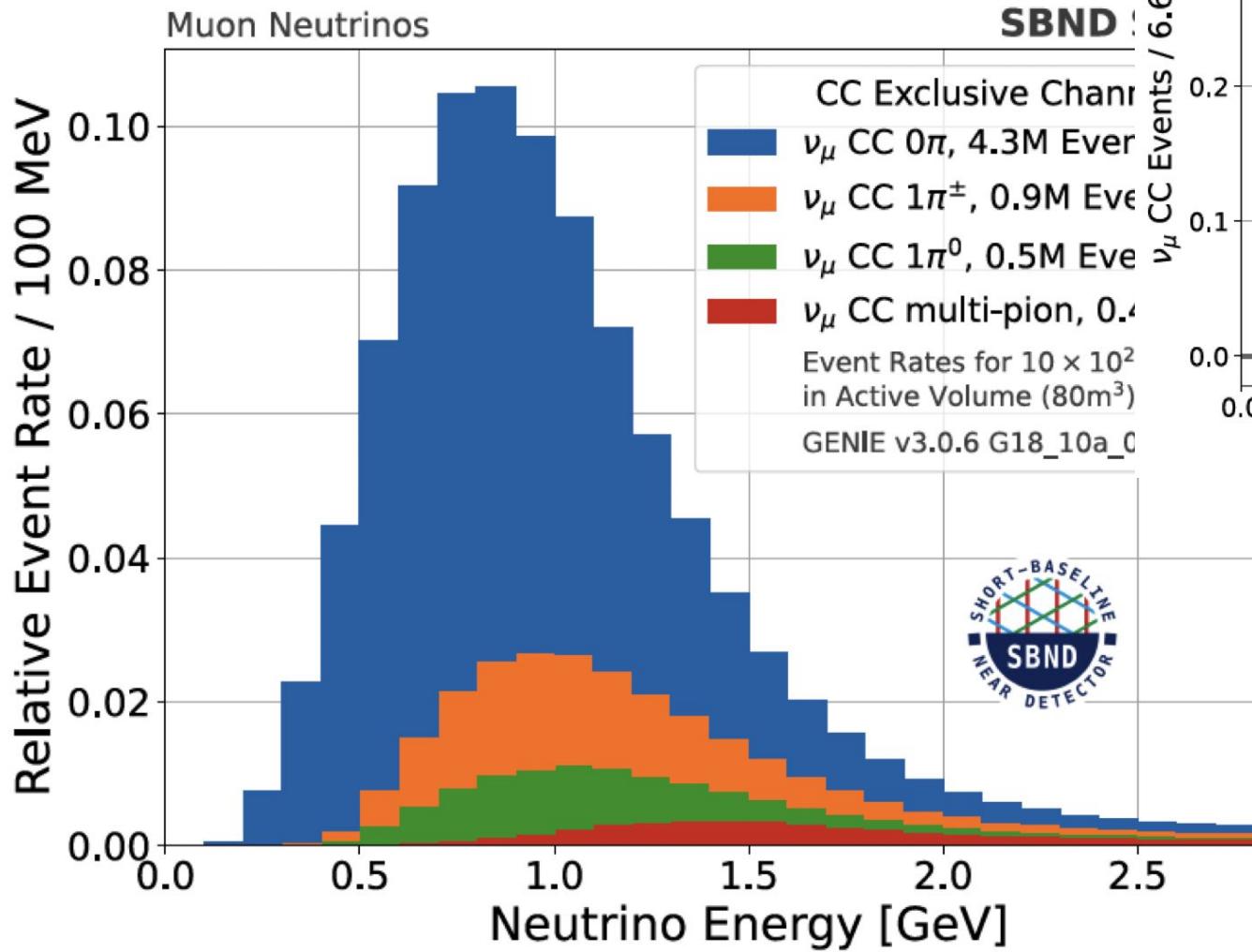
SBND - “prism”



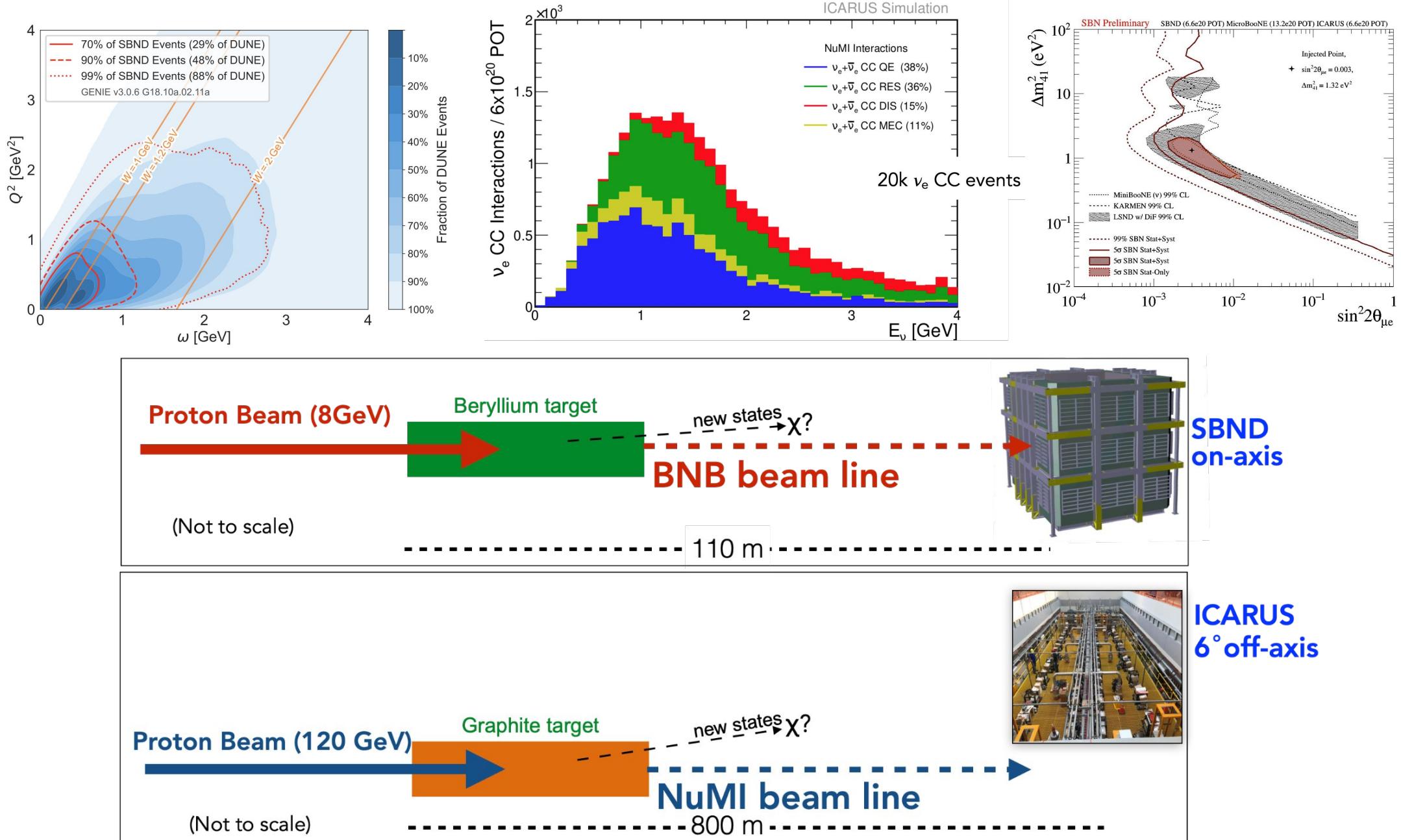
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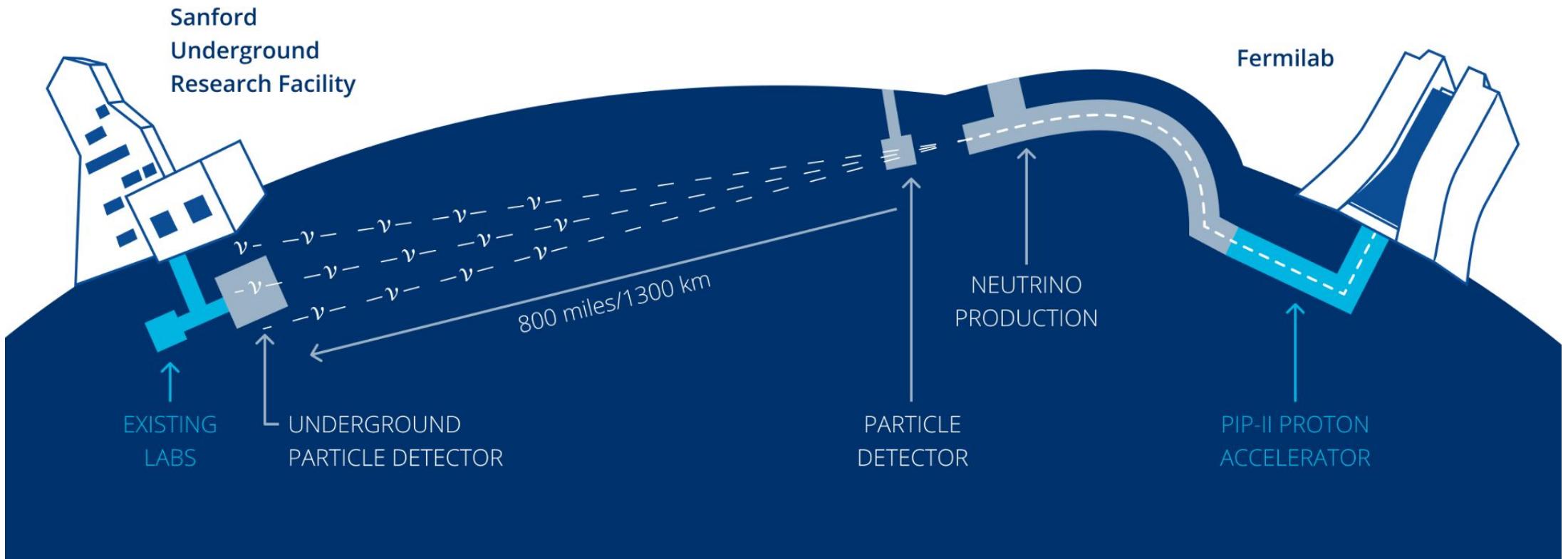
SBN Physics



multiple detectors on two beamlines offer a rich physics program
for Oscillations, BSM, and XSEC measurements

Deep Underground Neutrino Experiment

DUNE



Culmination of long-baseline oscillation program → precision measurements.

Massive experimental endeavor:

1. upgraded neutrino beamline
2. near-detector complex
3. massive far-detector.

DUNE Oscillations Program

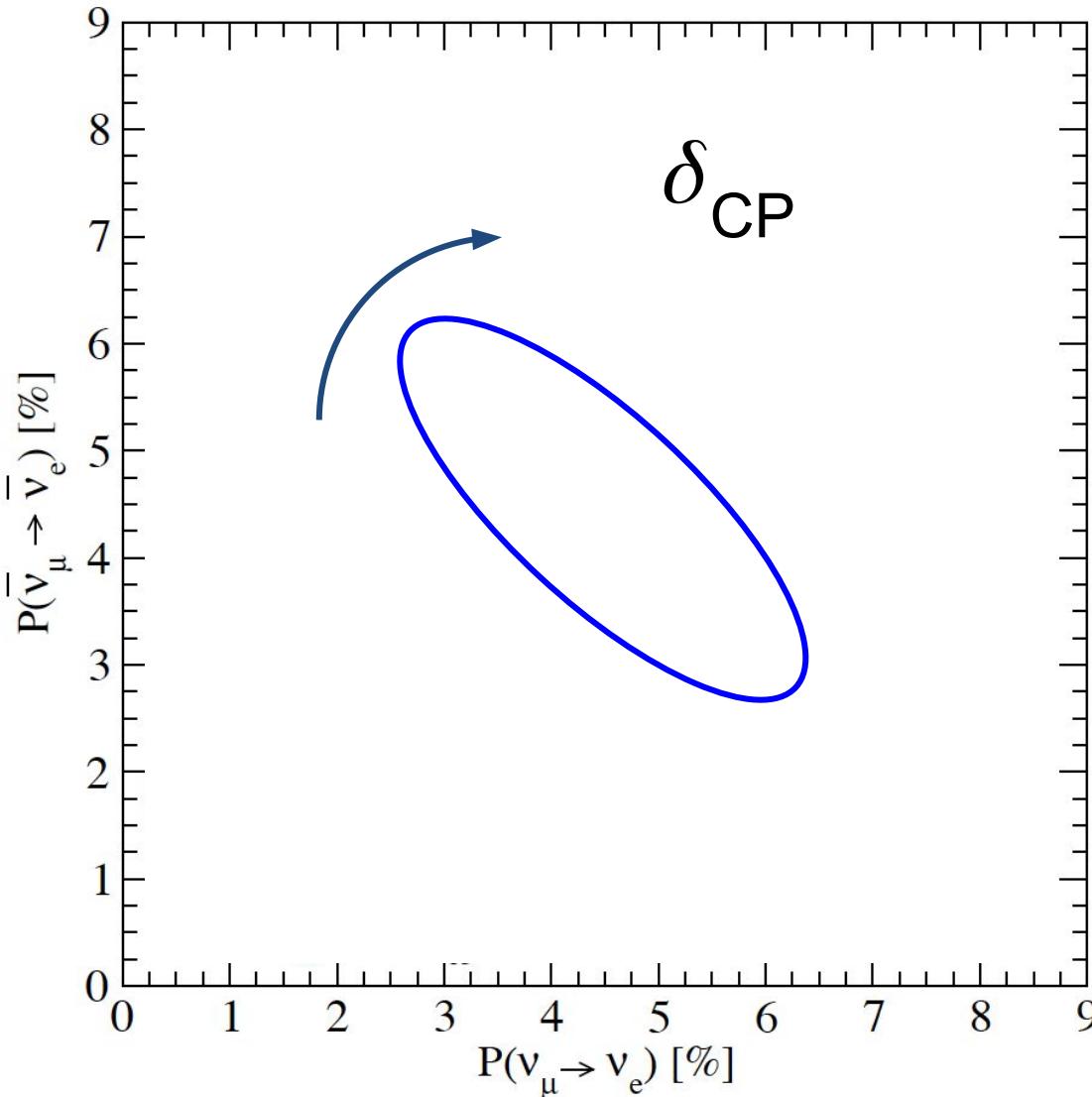
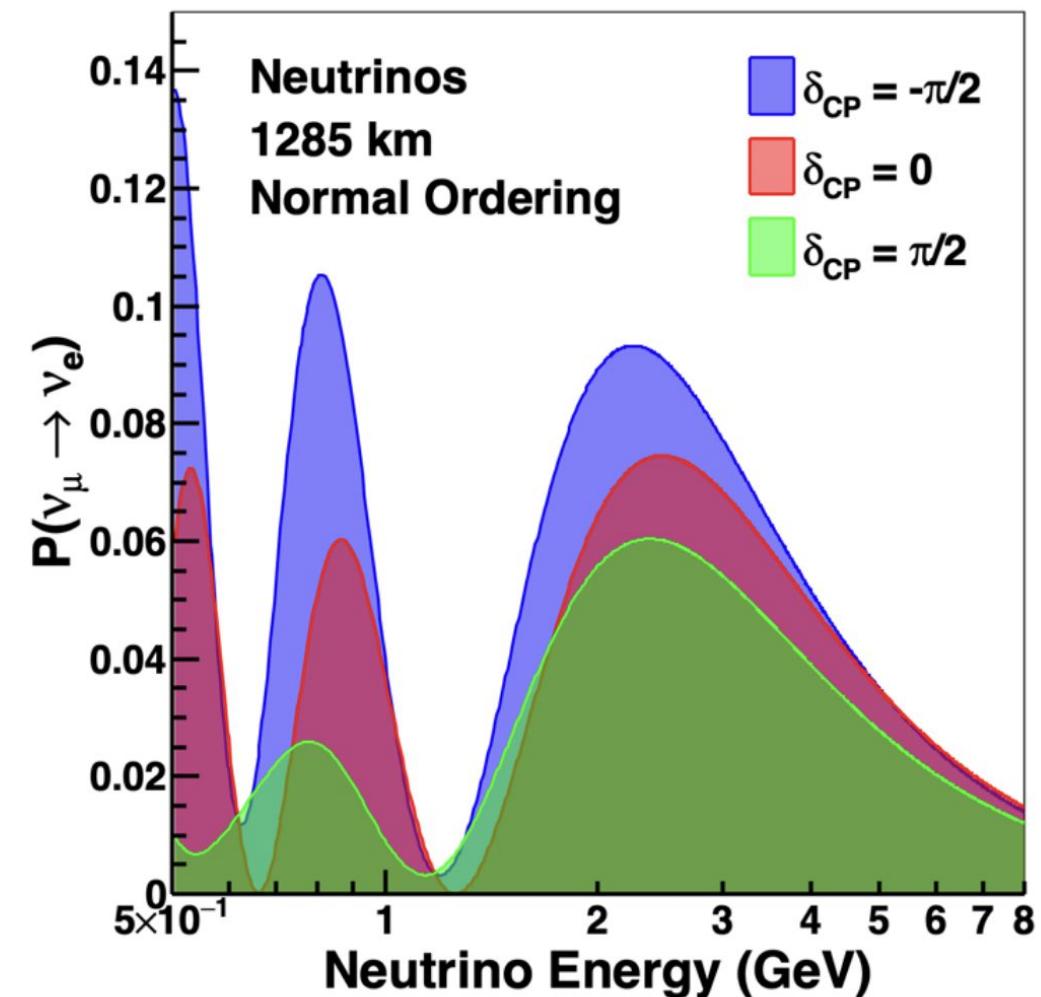


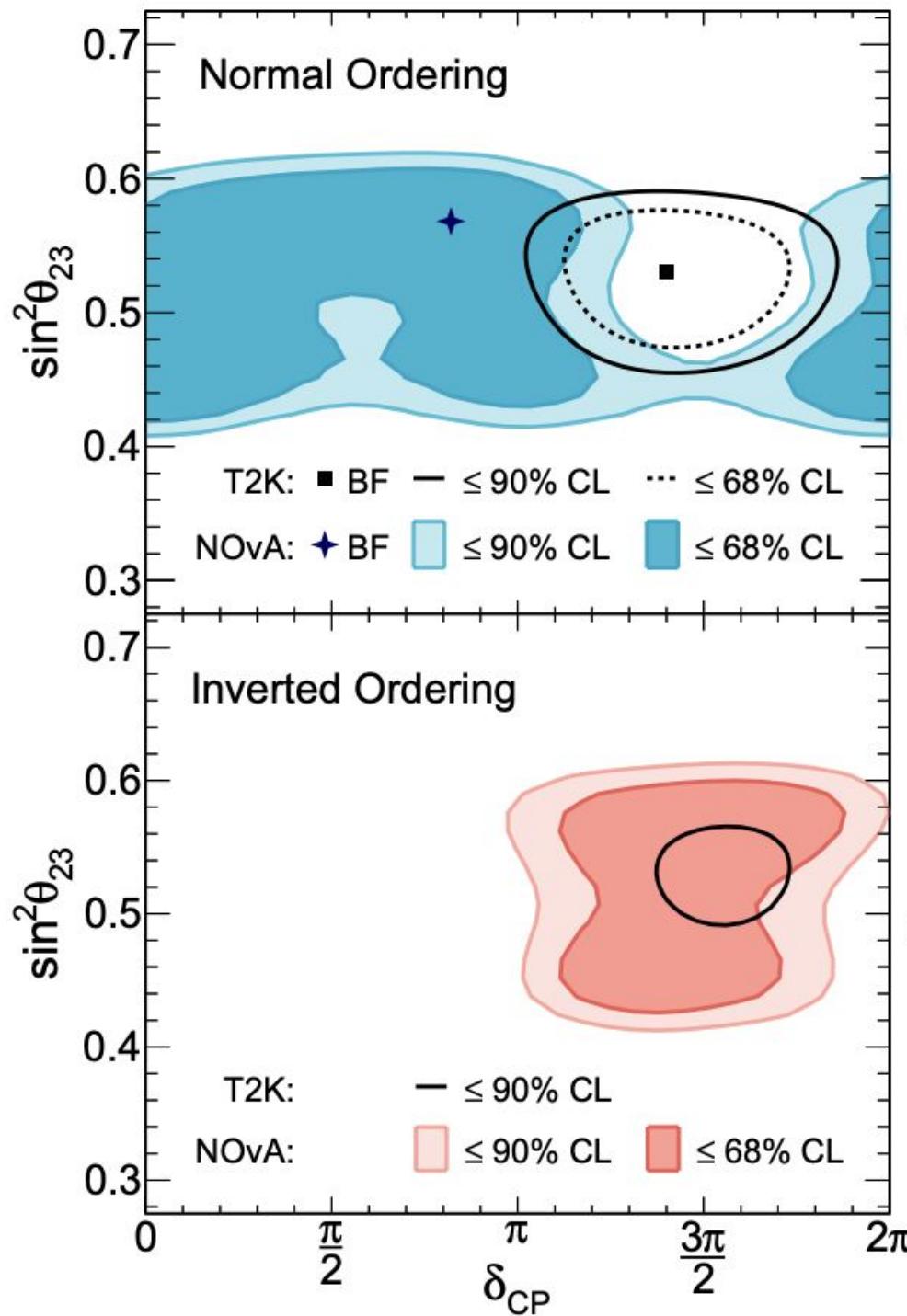
Figure adapted and simplified from:

Hiroshi Nunokawa, Stephen Parke, Jose W. F. Valle, "CP Violation and Neutrino Oscillations", IFIC/07-58, arXiv:0710.0554

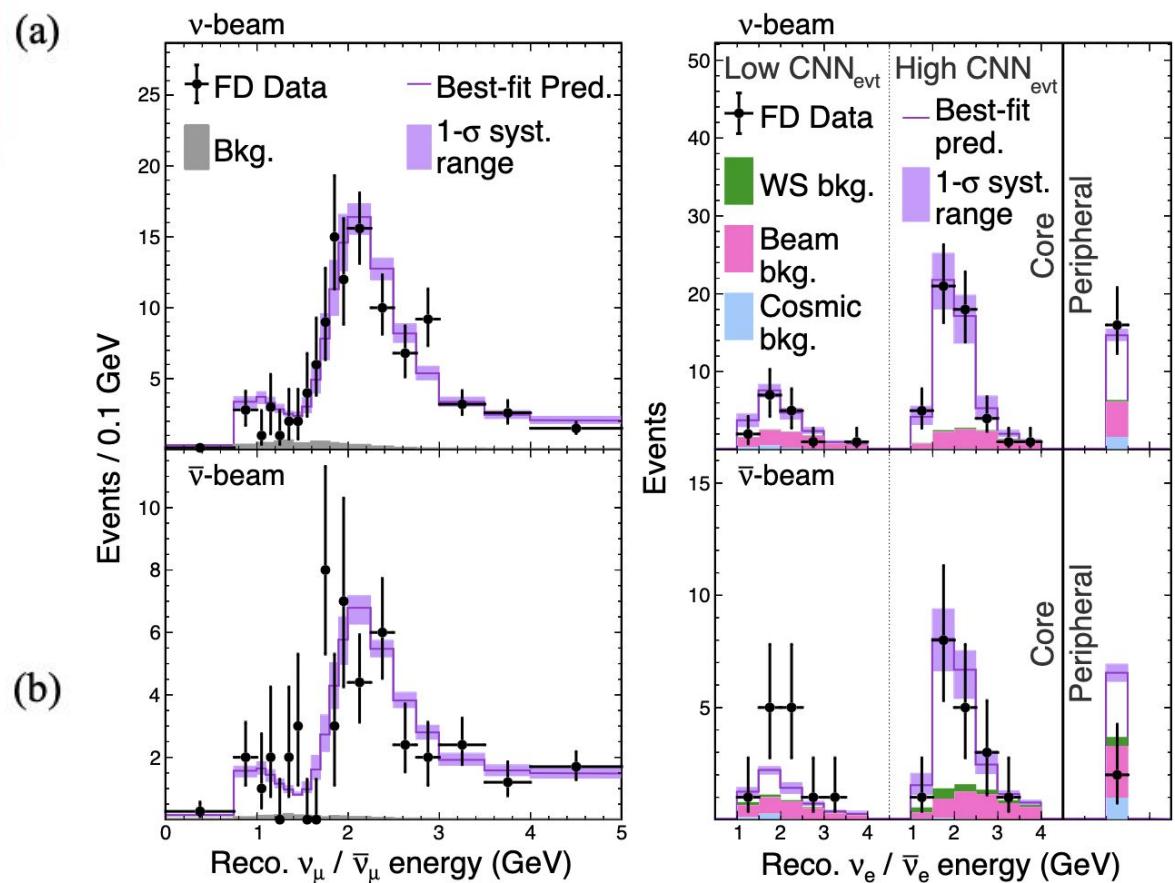


DUNE Collaboration, [Eur.Phys.J.C 80 \(2020\) 10, 978](#)

Current landscape



Long-baseline neutrino experiments
T2K and NOvA currently leading the way



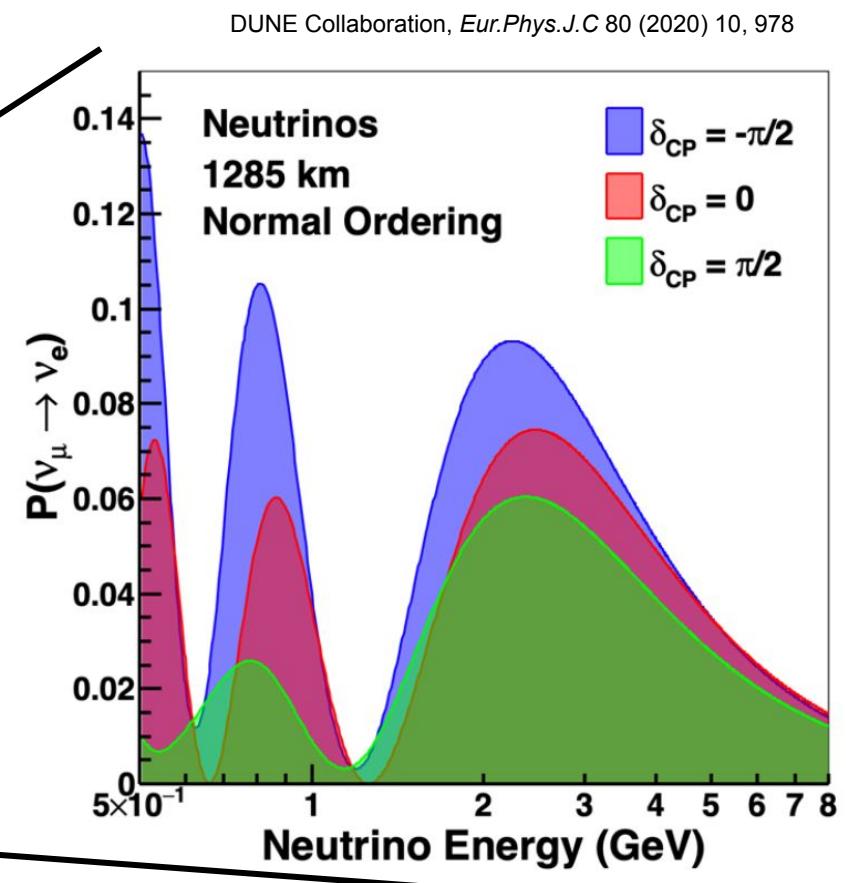
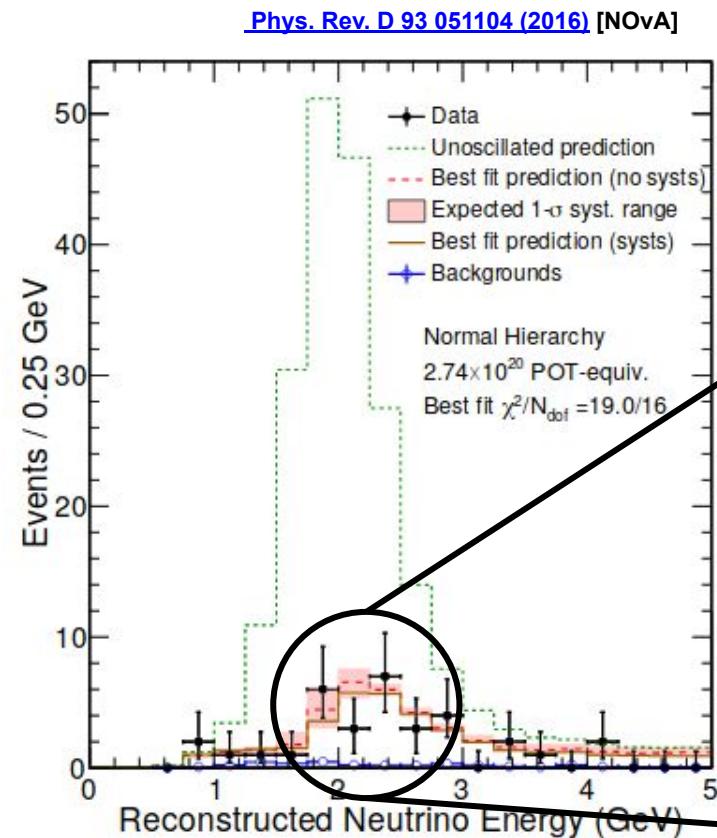
[“Improved measurement of neutrino oscillation parameters by the NOvA experiment”](#) Phys.Rev.D 106 (2022) 3, 032004 [[arXiv:2108.08219](#)]

Precision Oscillations



Addressing this questions requires measuring small effects.

New level of precision for oscillation program.



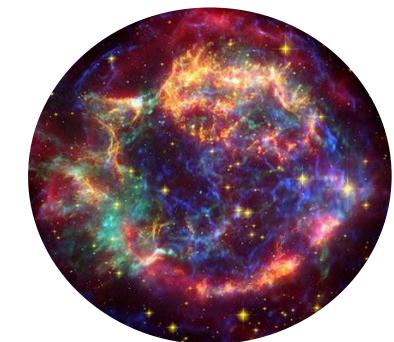
$$P_{\nu_\mu \rightarrow \nu_e} \approx \sin^2(2\theta) \sin^2 \left(\frac{\Delta m^2 L}{4E} \right) \quad \text{vs.}$$

$$\mathcal{A}_{CP} = \frac{P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)}{P(\nu_\mu \rightarrow \nu_e) + P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)}$$

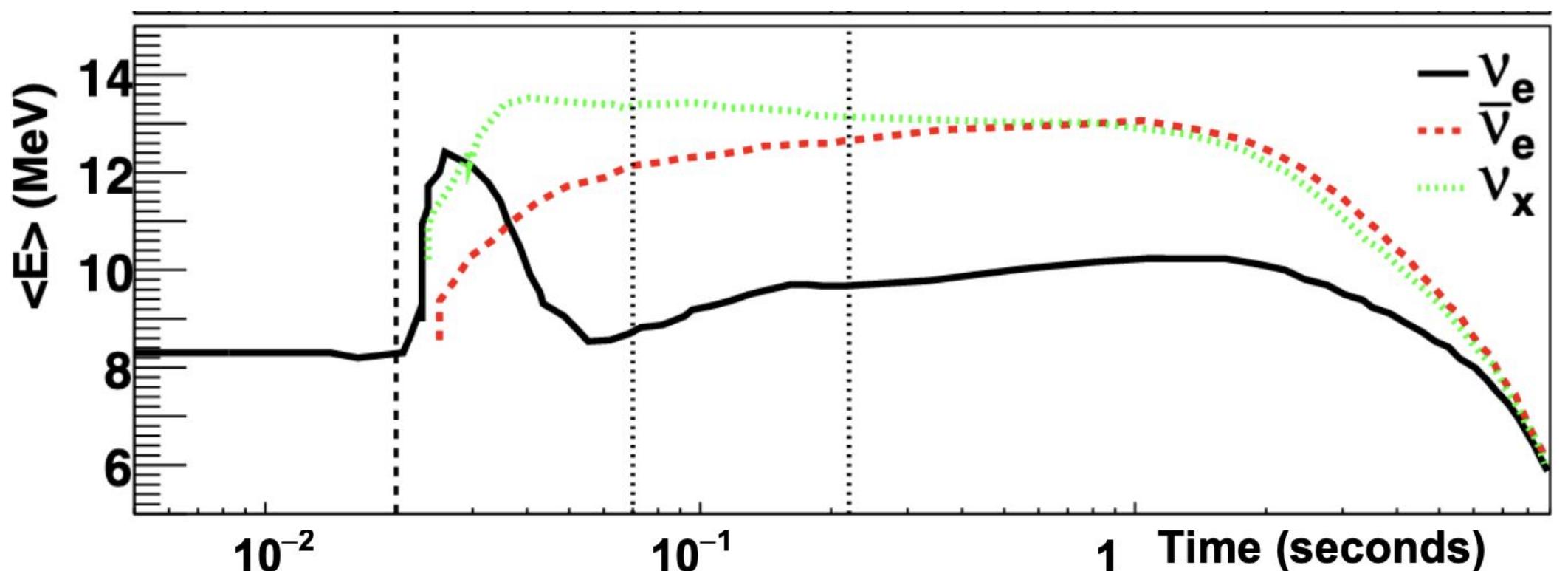
Core Collapse Supernovae

High-statistics measurement of SN Burst neutrinos allows:

- astrophysics of these violent cosmic events.
- fundamental properties of neutrinos (e.g. oscillations).



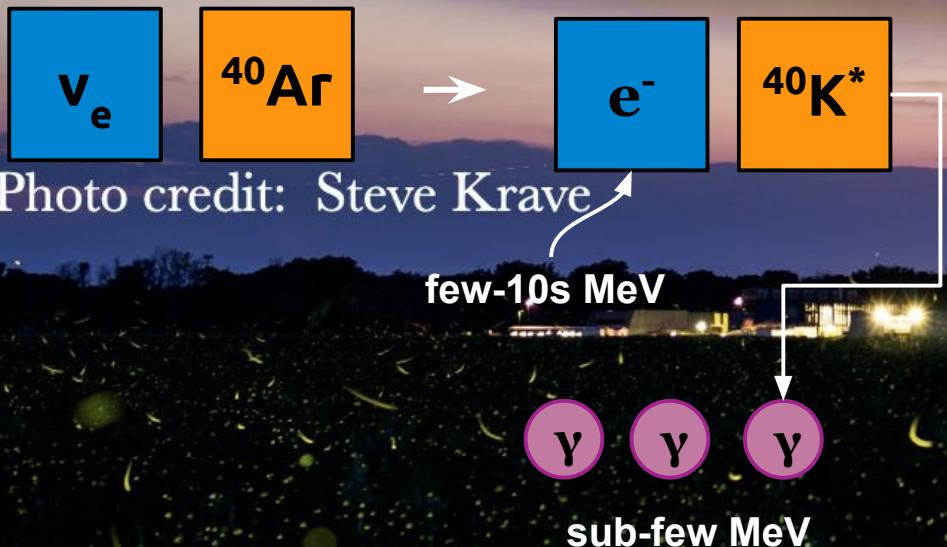
LArTPCs most sensitive to the electron neutrino flux.



DUNE astrophysics



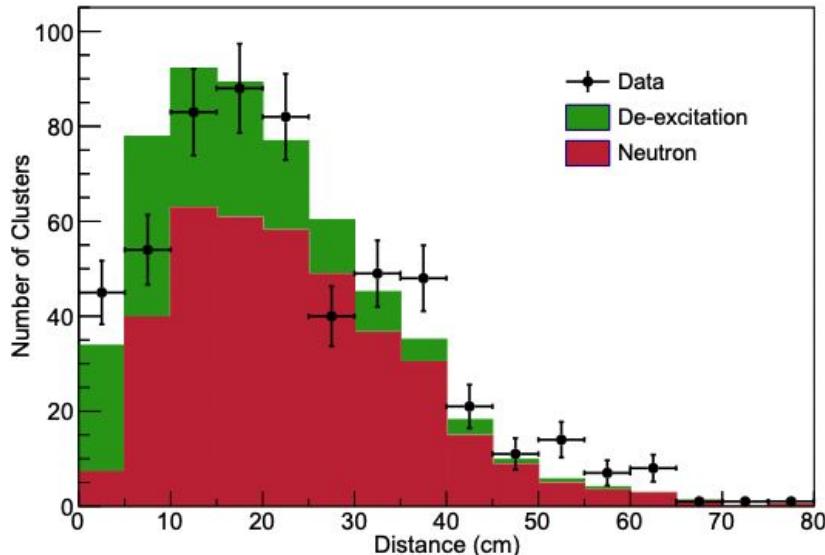
Main channel, strength of LAr



DUNE has unique sensitivity to electron neutrino flux from SN burst.

O(3k) ν_e events for SN burst @ 10 kiloparsec.

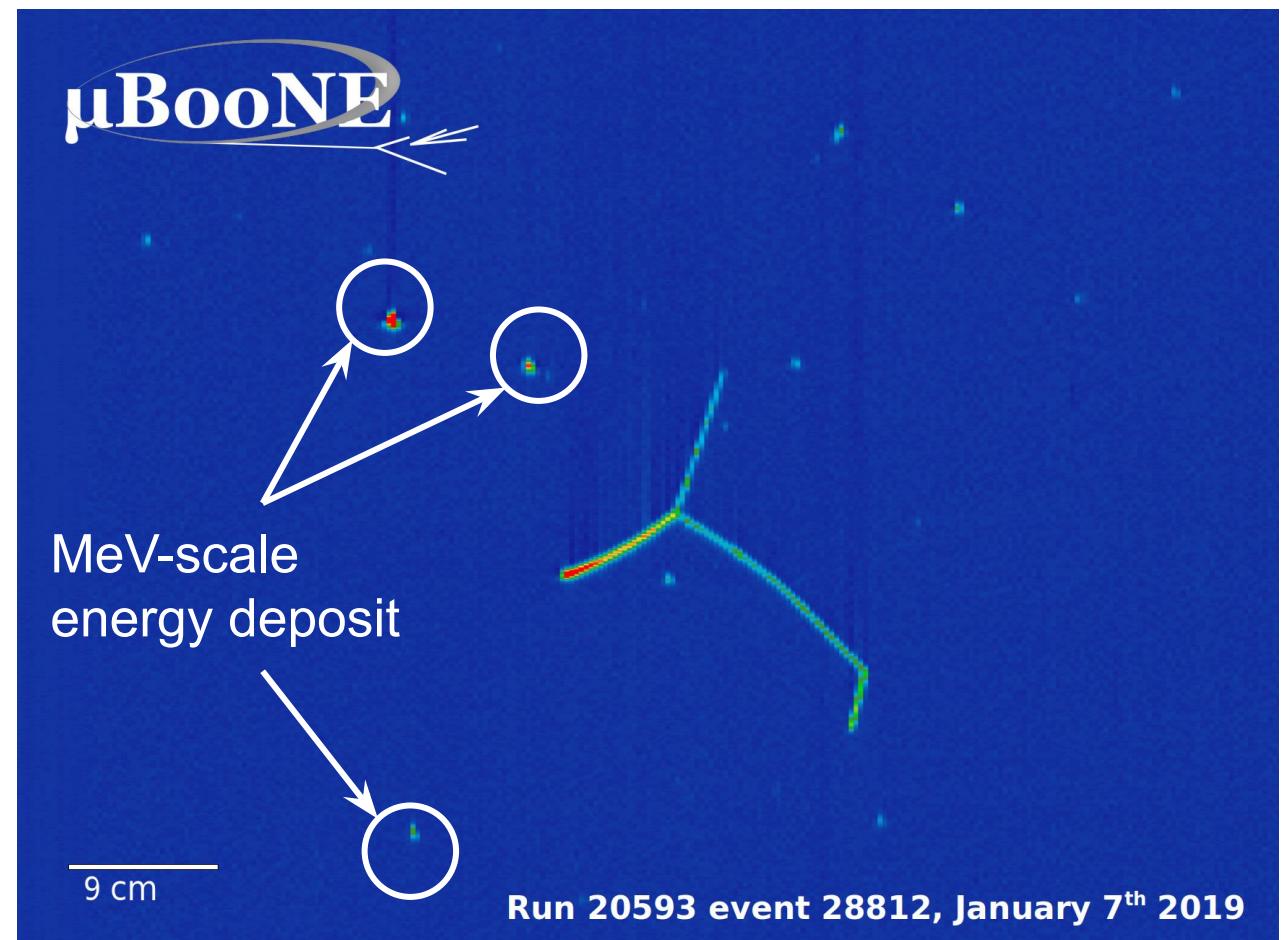
Achieving DUNE's astrophysics goals



ArgoNeut: [Phys. Rev. D 99, 012002 \(2019\)](#)

Needs:

- reconstruction
- calibrations
- cross-section modeling

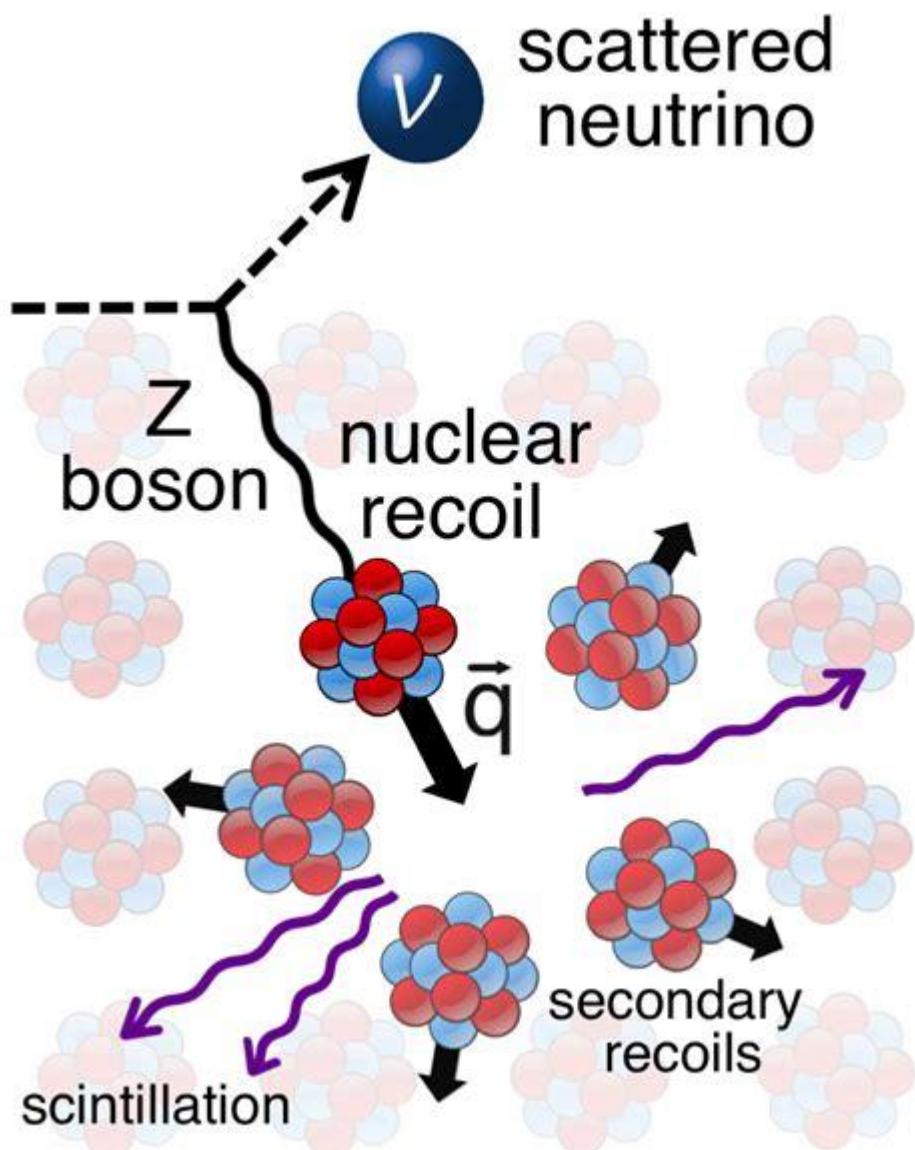


DUNE, "Supernova Neutrino Burst Detection with the Deep Underground Neutrino Experiment",
[Eur.Phys.J.C 81 \(2021\) 5, 423](#)

"Understanding the Energy Resolution of Liquid Argon Neutrino Detectors", Friedland, Li, Phys. Rev. D 99 (2019) 3, 036009

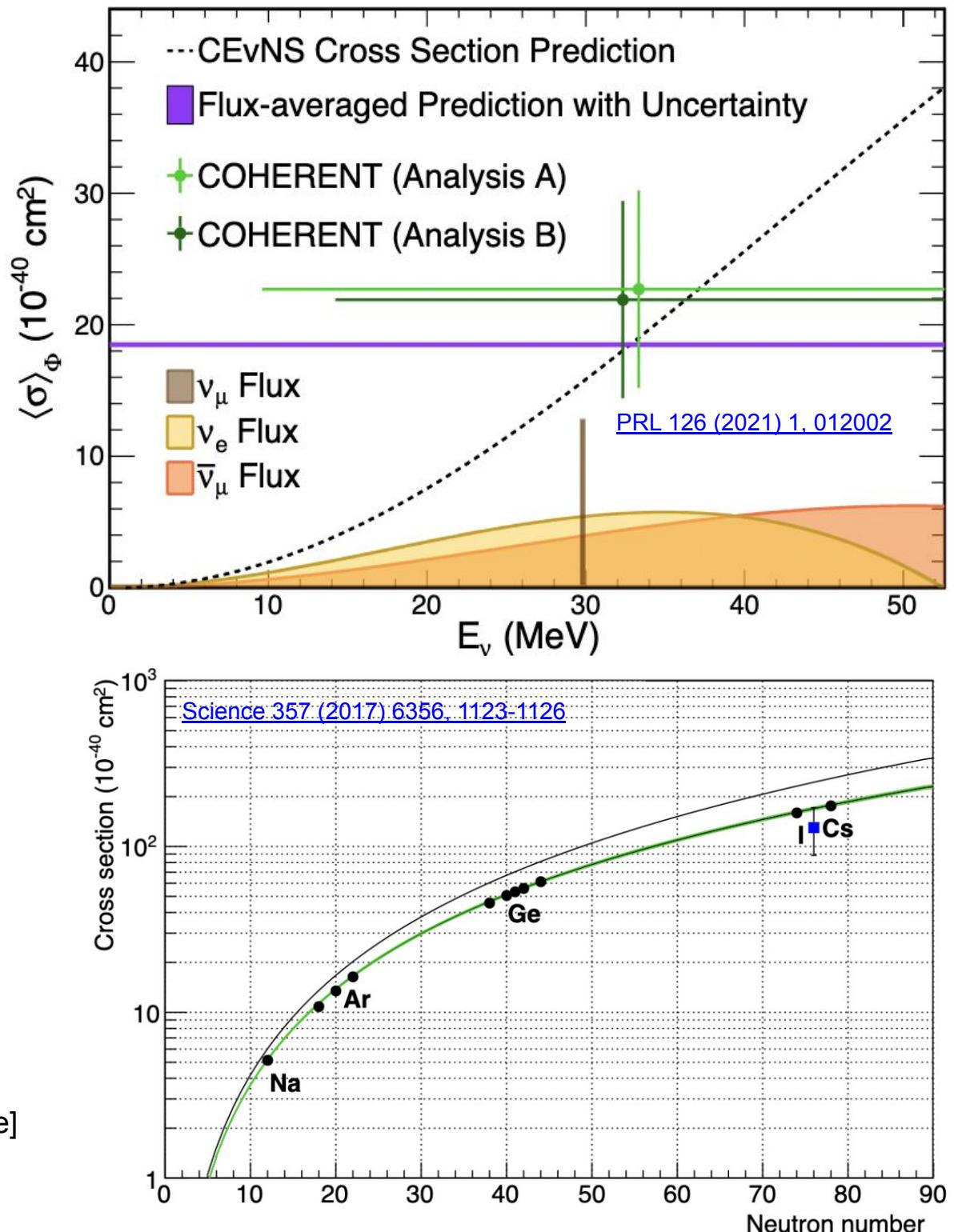
"Low-Energy Physics in Neutrino LArTPCs", Snowmass White-paper, [2203.00740](#)

CE ν NS and COHERENT



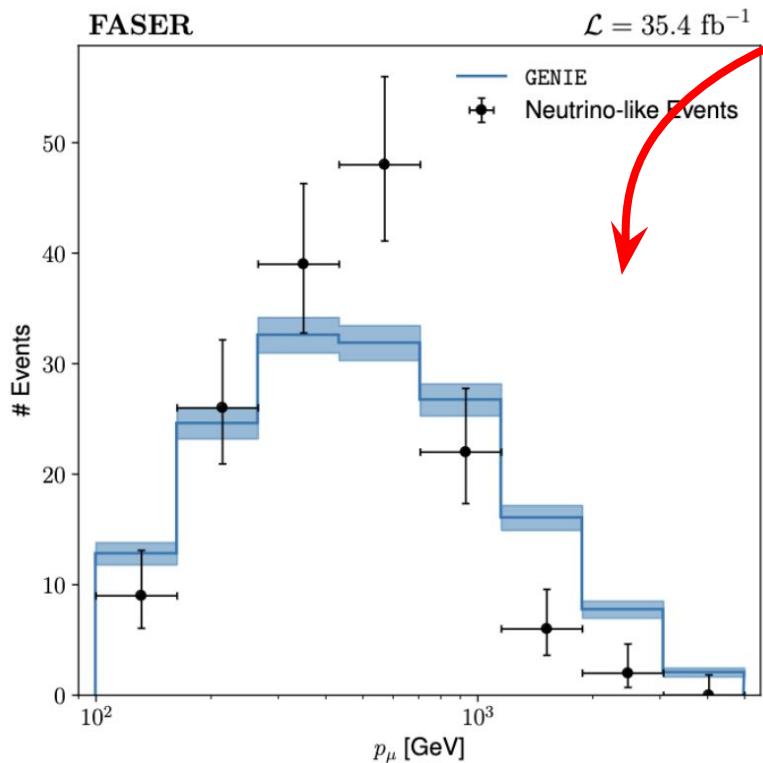
Coherent scattering of neutrinos on atomic nuclei

- observed @ stopped pion facilities [SPS @ Oak Ridge]
- Active experimental effort @ reactors

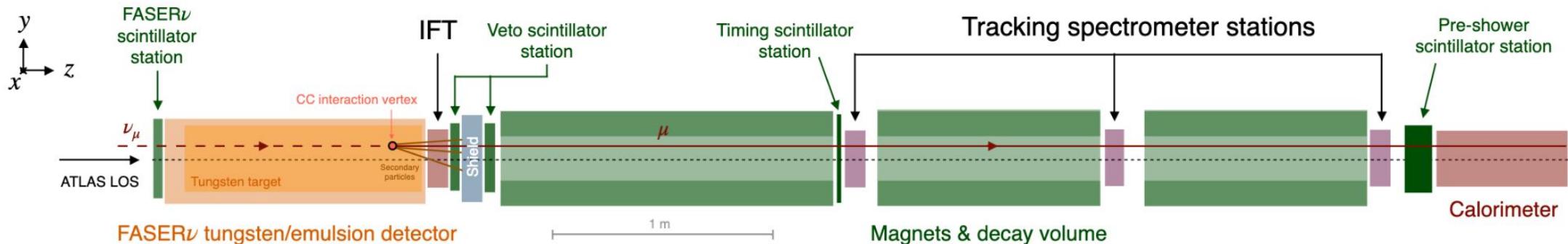
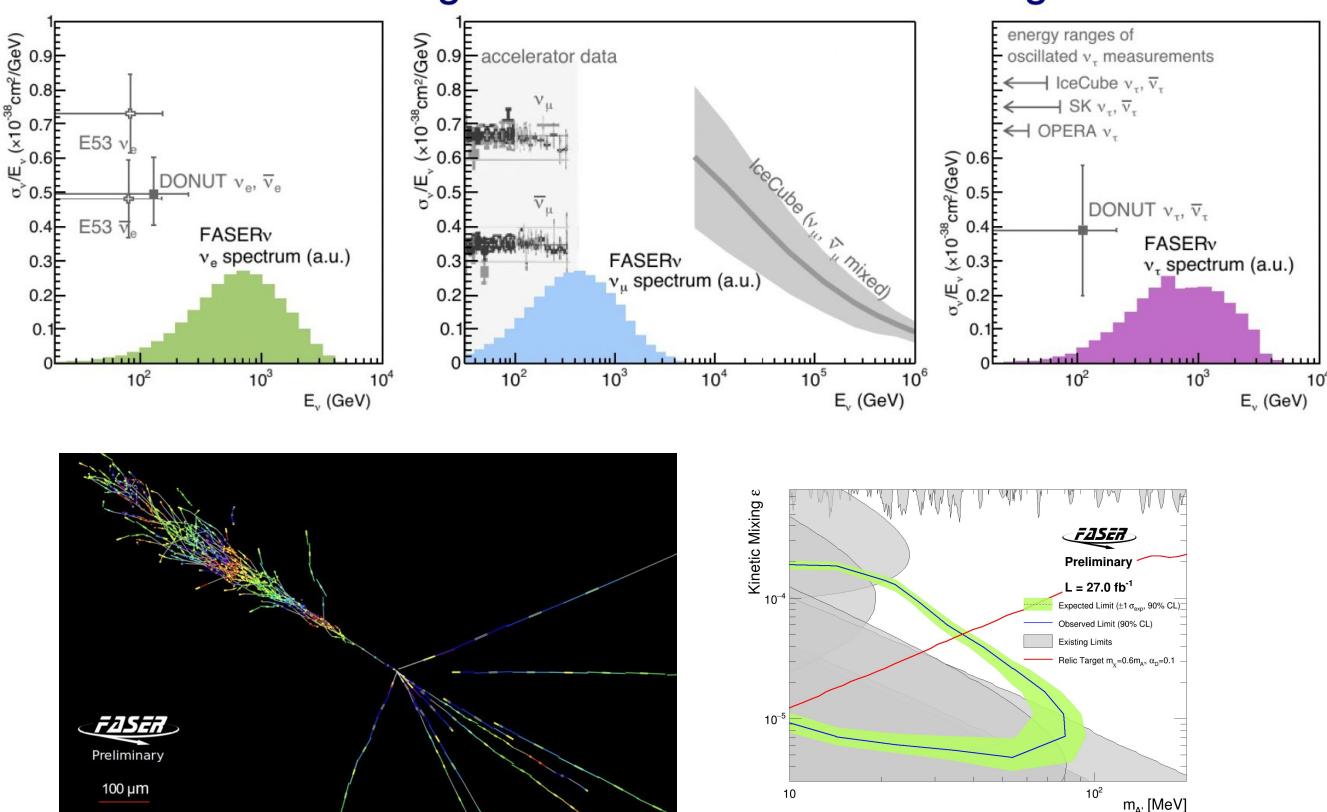


A new neutrino source: p-p collisions @ LHC

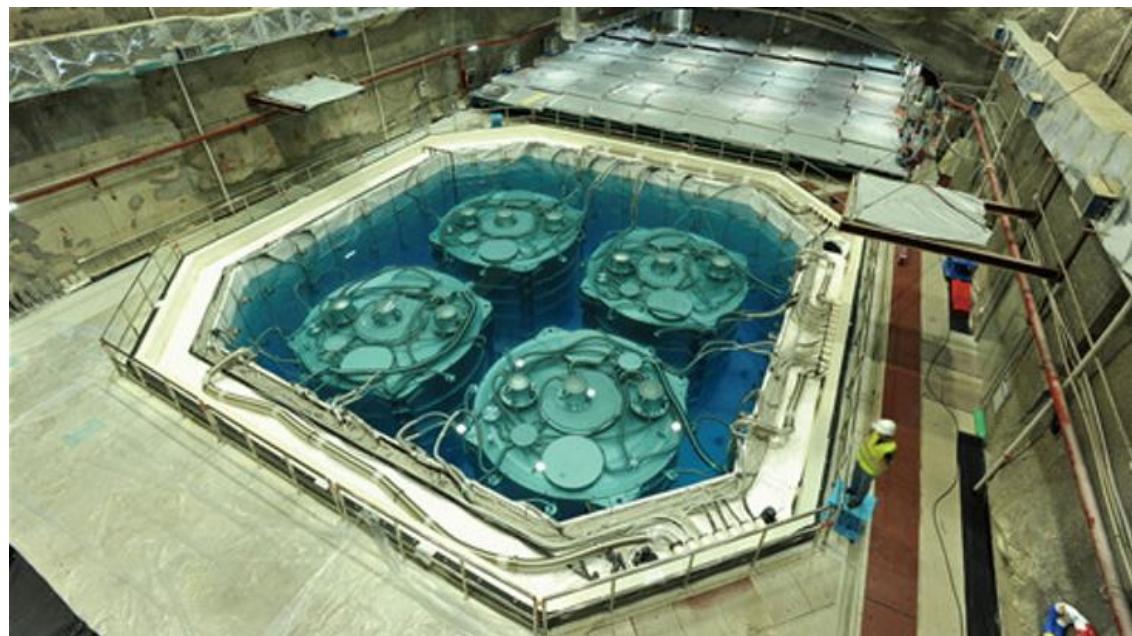
FASER Collaboration “*First Direct Observation of Collider Neutrinos with FASER at the LHC*”
[arXiv:2303.14185](https://arxiv.org/abs/2303.14185)



several plots and figures from Moriond '23 [talk](#)
by Brian Petersen on behalf of FASER

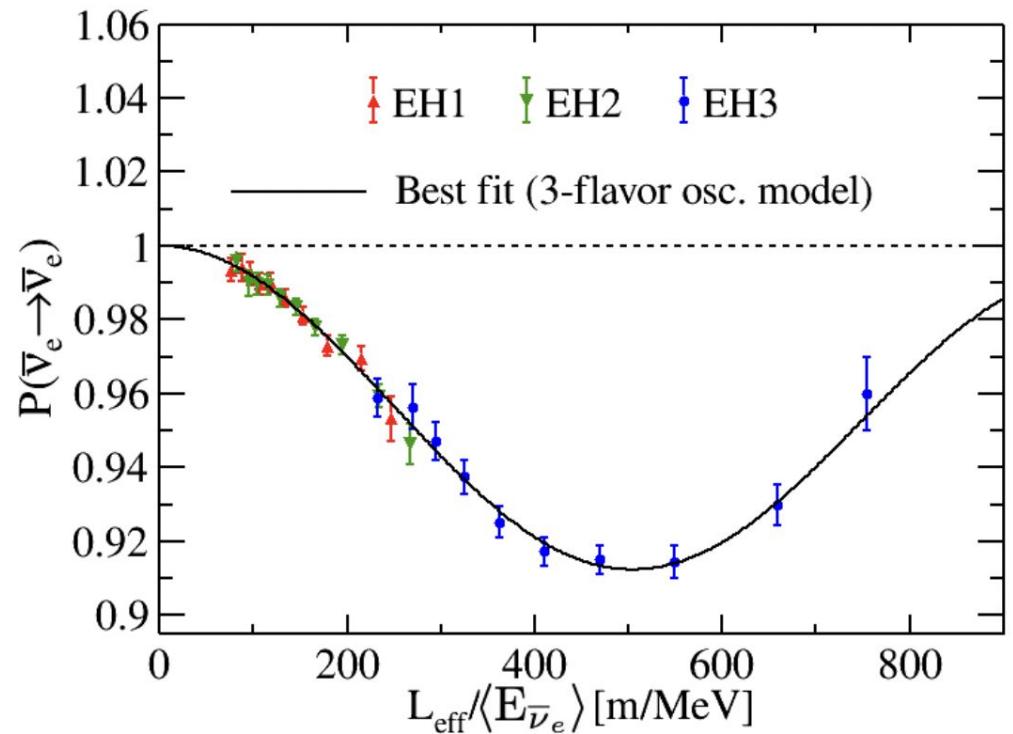


Reactor neutrinos



Daya Bay detector modules

Daya Bay - [Phys.Rev.Lett. 130 \(2023\)](#)



$$\sin^2 2\theta_{13} = 0.0851 \pm 0.0024$$

(for normal ordering)

Lots of progress from this community in addressing the “Reactor” anomaly

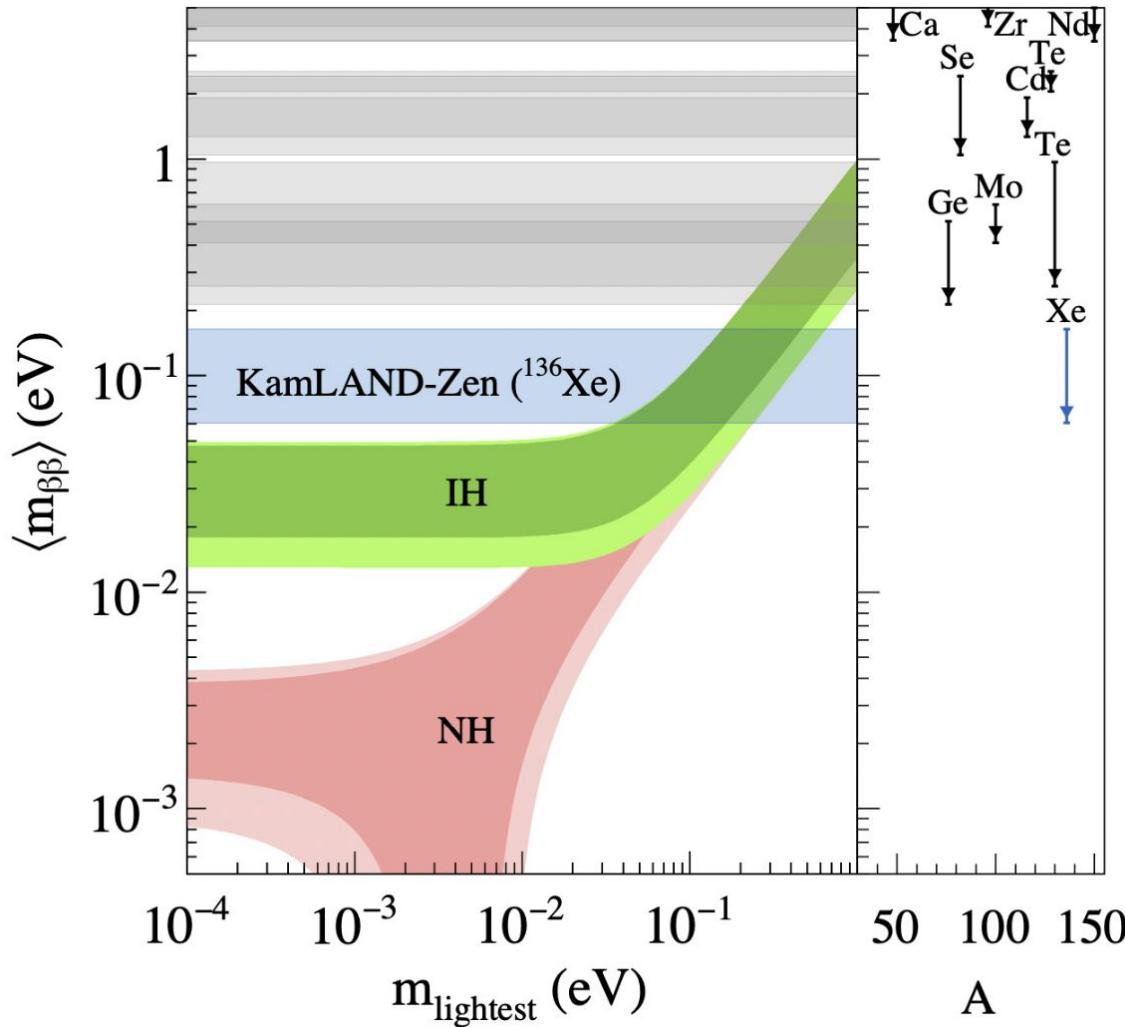
- neutrino flux predictions



Small-scale experiments @ R&D reactors

- O(meter) baselines
- CE ν NS

Neutrinoless Double-Beta Decay: $0\nu\beta\beta$

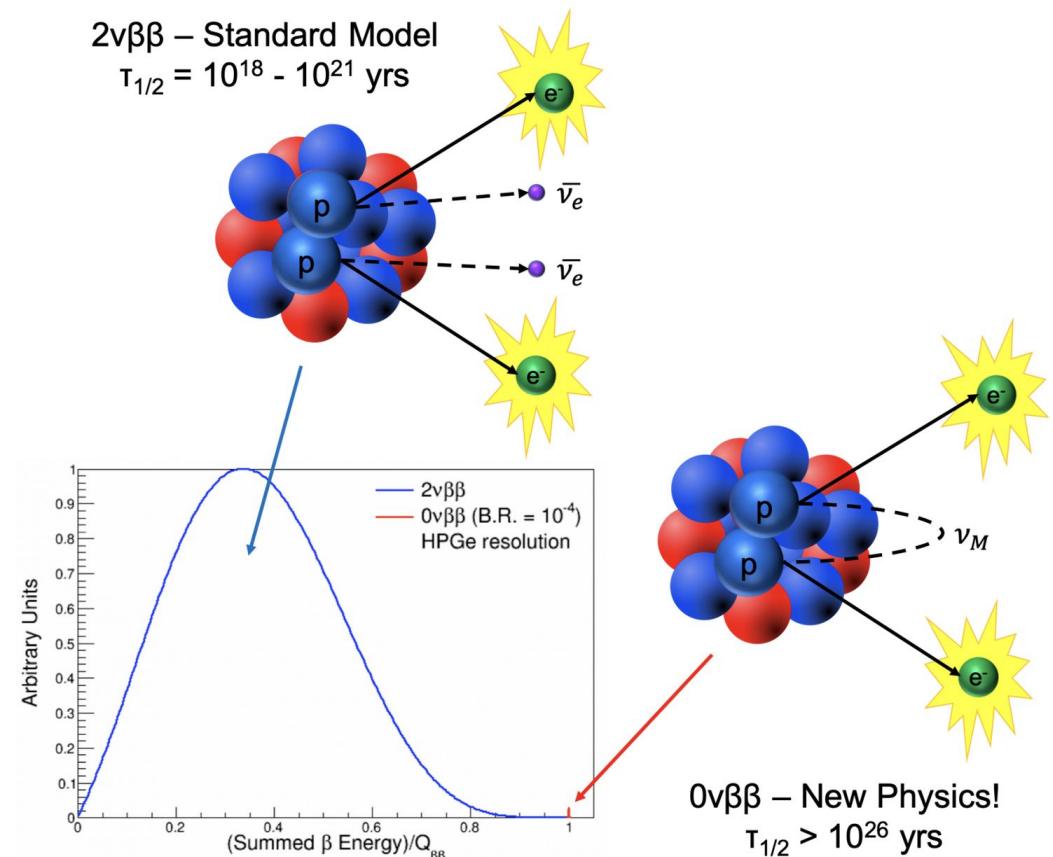


"The Physics of Neutrinoless Double Beta Decay: A Primer" B.J.P. Jones
[arXiv:2108.09364]

broad experimental landscape with multiple detector technologies and target elements

Observation of $0\nu\beta\beta$ would imply:

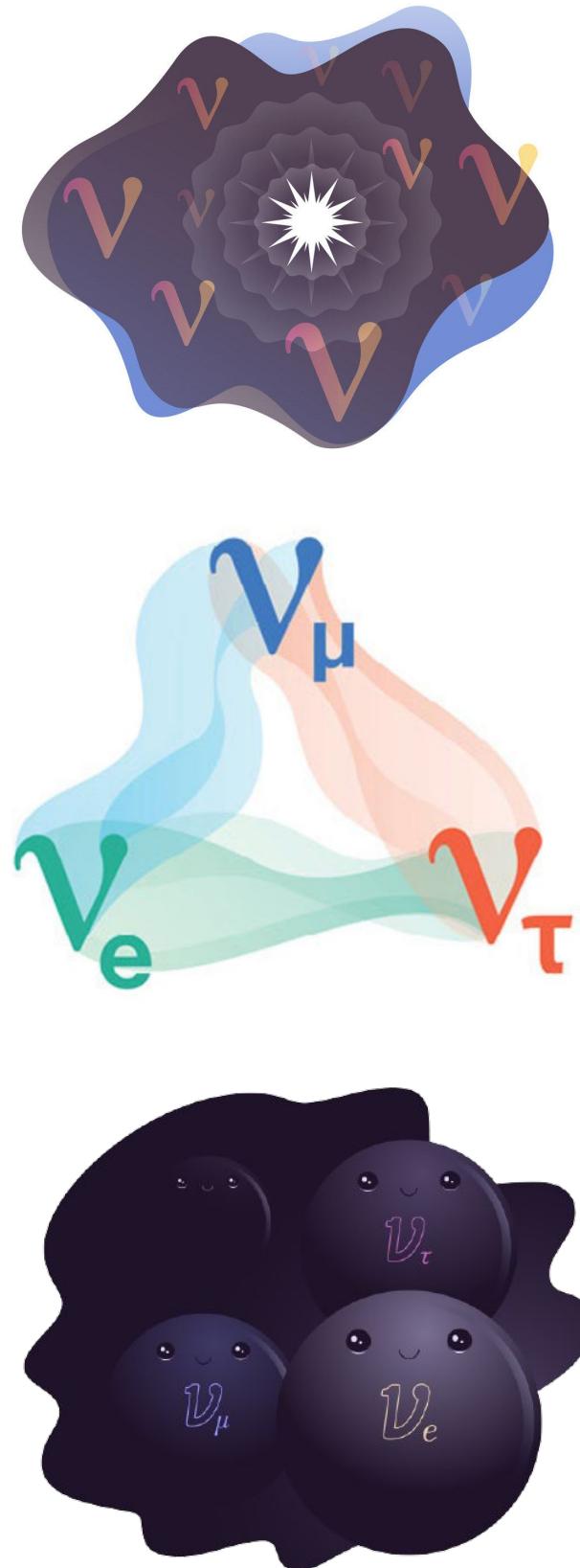
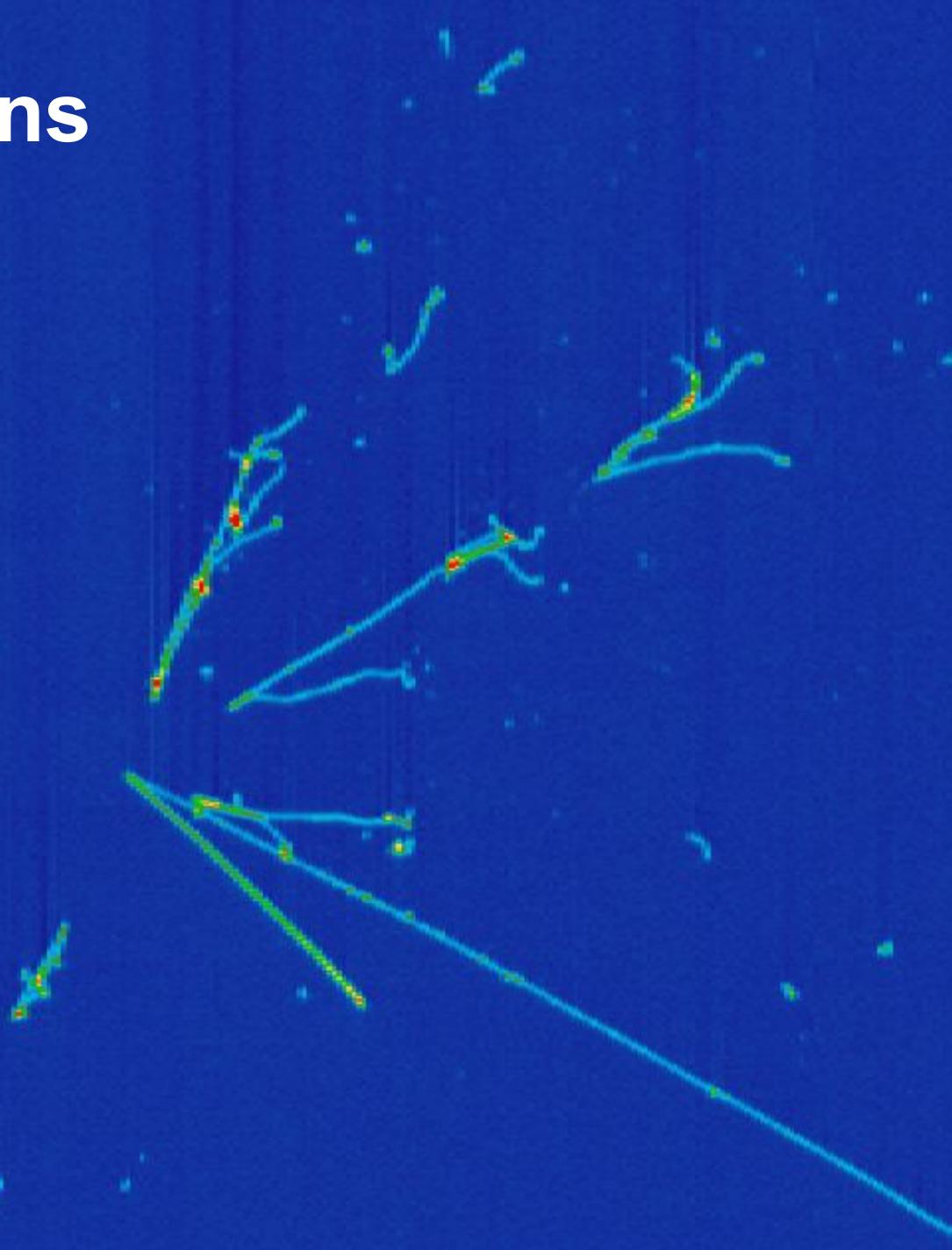
- lepton number violation
- Majorana nature of neutrino



$0\nu\beta\beta$ – New Physics!
 $T_{1/2} > 10^{26}$ yrs

Conclusions

The LArTPC technology is enabling a rich neutrino physics program tackling exiting questions in neutrino physics and astrophysics and BSM searches



Conclusions

14:00

First Measurement of Inclusive Muon Neutrino Charged Current Triple-Differential Cross Section on Argon
London Cooper-Troendle

Recent Results from MicroBooNE's Low Energy Excess Search

Wanwei Wu 

Lawrence Hall 203

14:30 - 14:45

Neutrino forces in neutrino backgrounds

Mitrajyoti Ghosh

Lawrence Hall 203

14:45 - 15:00

15:00

What can the upcoming large neutrino detectors tell us about flavor transitions of galactic supernova neutrinos?
Prof. Guey-Lin Lin



Towards precise predictions of the diffuse supernova neutrino background

Nick Ekanger

Lawrence Hall 203

15:15 - 15:30

Here Comes the Sun: Solar Parameters in Long-Baseline Accelerator Neutrino Oscillations

Dr Peter Denton

Lawrence Hall 203

15:30 - 15:45

High-energy neutrino cross sections

Keping Xie

Lawrence Hall 203

15:45 - 16:00

16:00

Coffee Break

University of Pittsburgh

16:00 - 16:30

The physics program lacking existing questions in neutrino
physics and astrophysics and BSM searches

3+1 oscillations: BNB + NuMI

