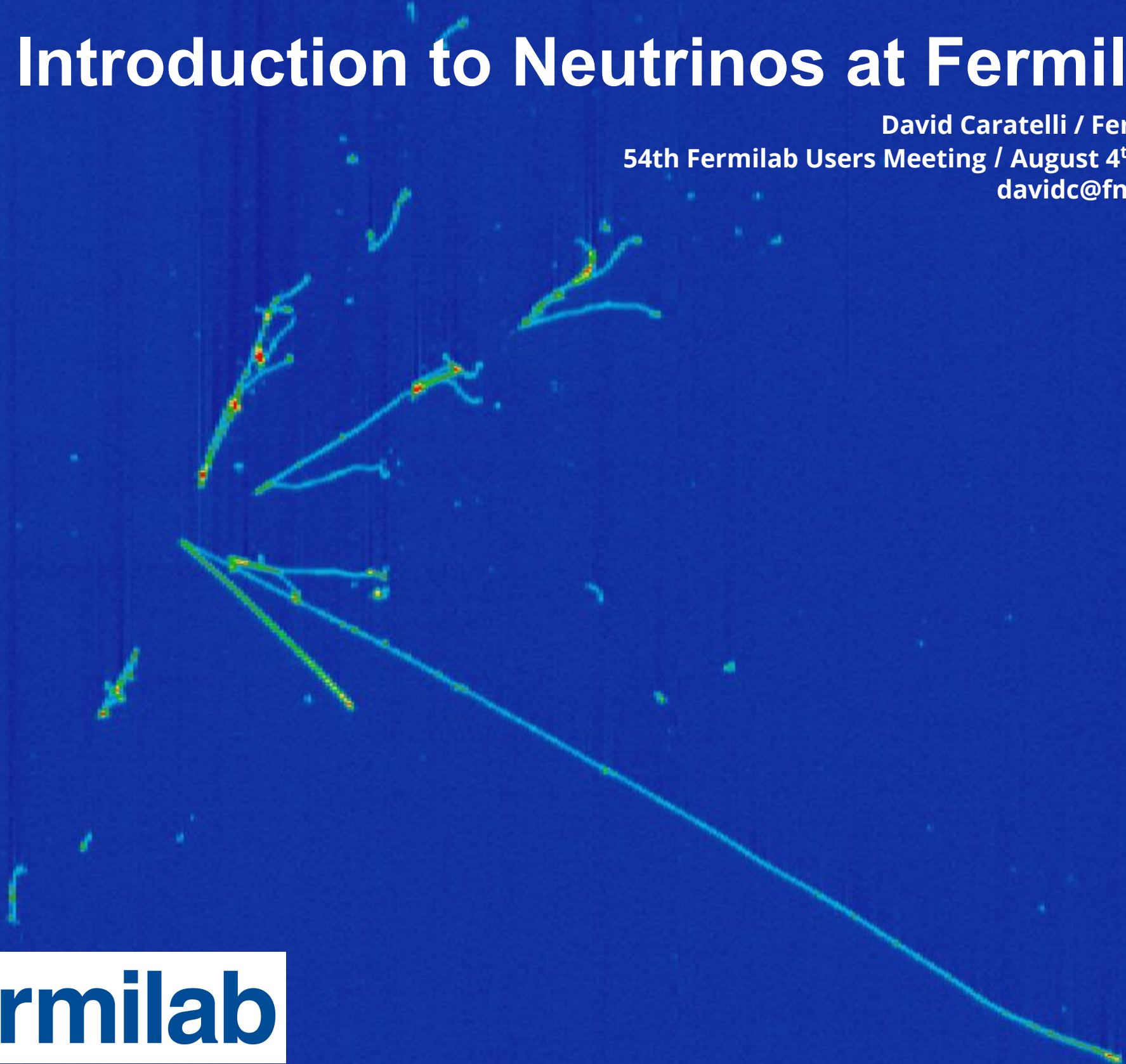


Introduction to Neutrinos at Fermilab

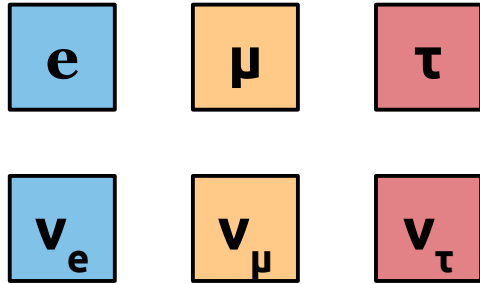
David Caratelli / Fermilab

54th Fermilab Users Meeting / August 4th 2021

davidc@fnal.gov



Introduction to Neutrinos



Neutral leptons. Very small mass.
Left-handed. Interact via weak force.

Neutrinos are elusive...

Trillions pass through our body every second, yet they go by undisturbed.



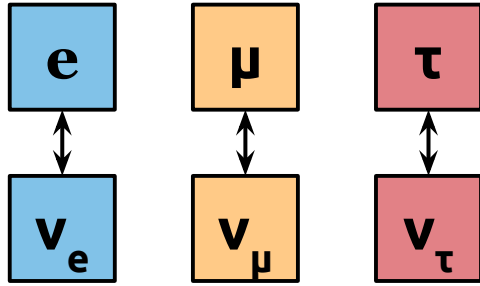
Many open questions...

- How much do neutrinos weigh?
- Why are neutrino masses so small?
- Are neutrinos their own antiparticles?
- More than three neutrino flavors?
- Charge-Parity violation δ_{CP} ?

Neutrinos are everywhere...



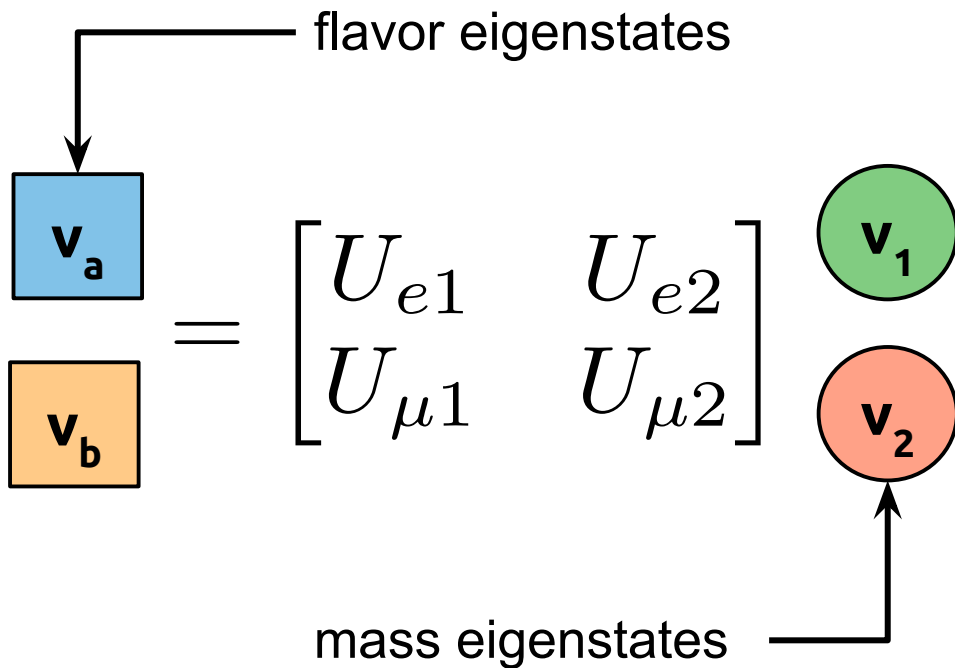
Neutrinos Oscillations



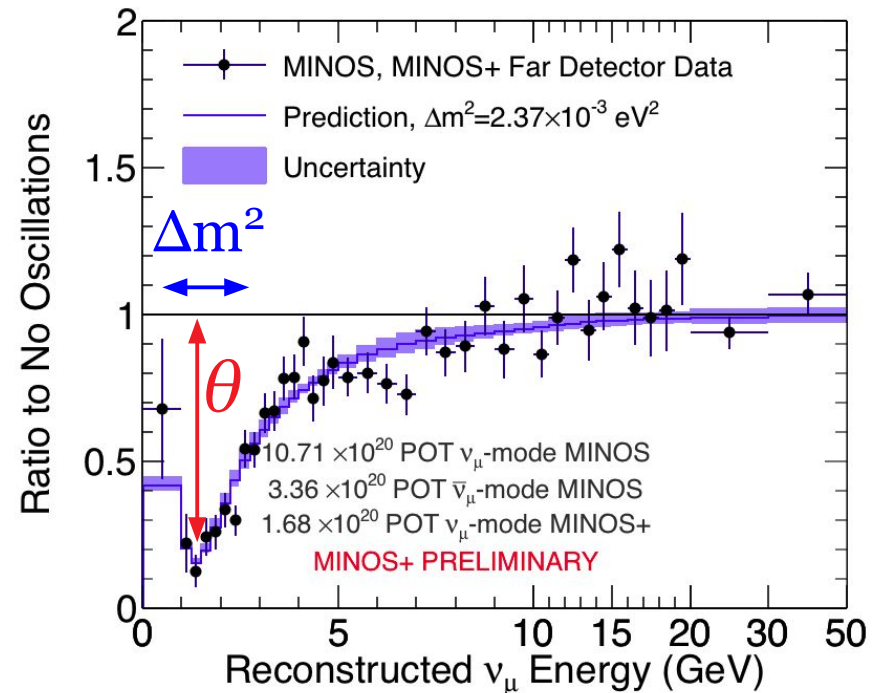
Freq. Of oscillation.
Choose L, E appropriate for Δm^2 .

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

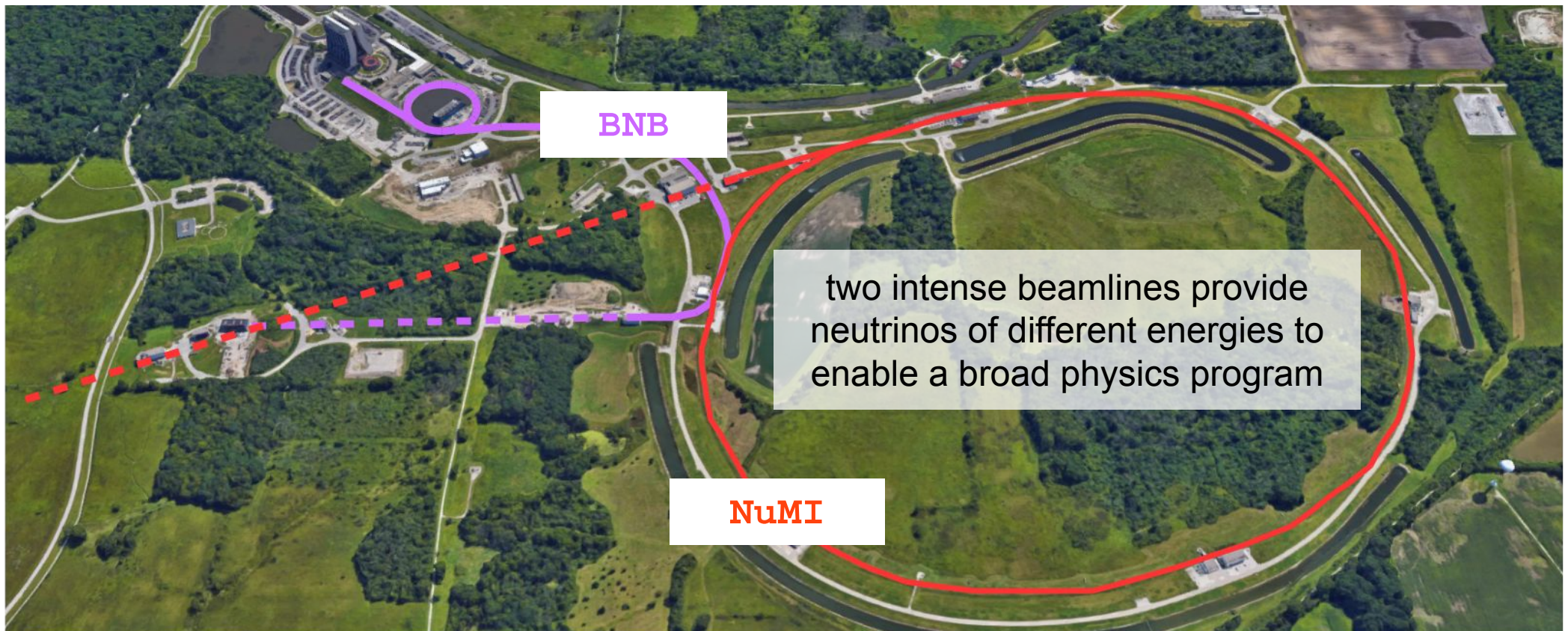
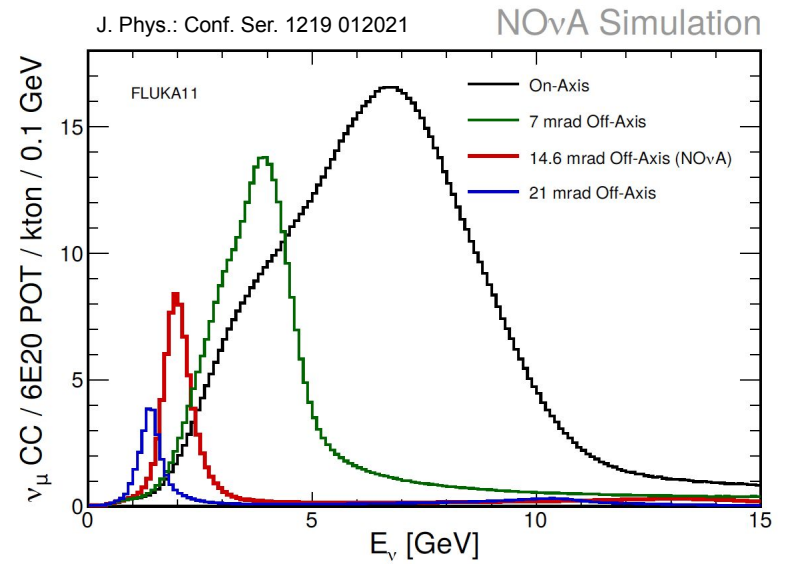
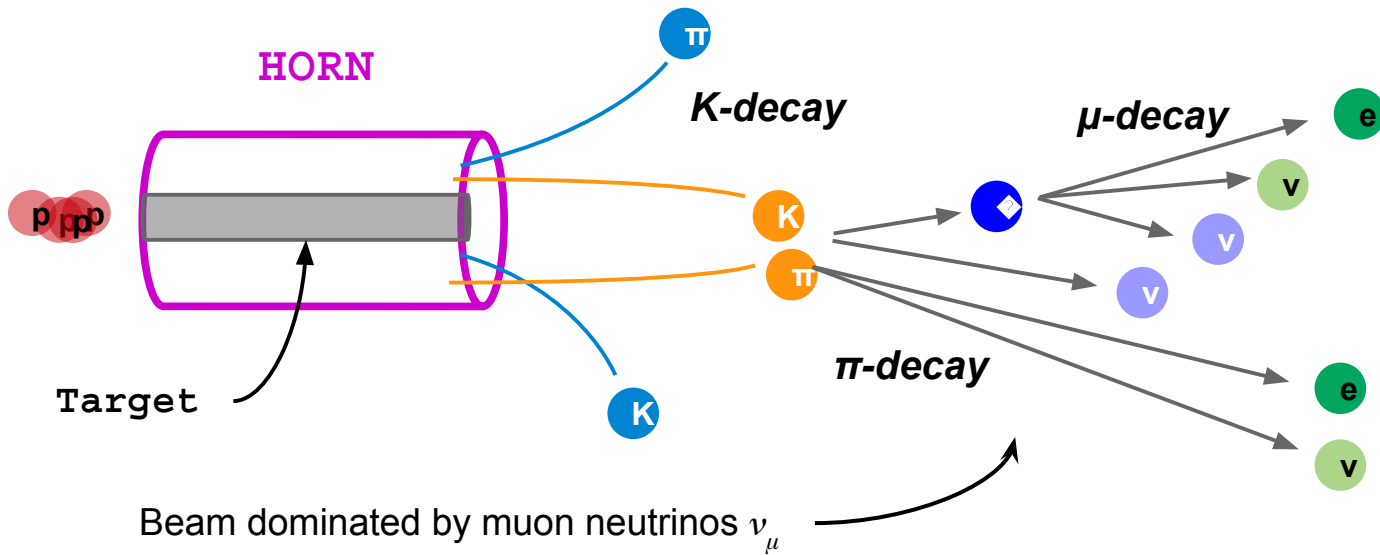
sets amplitude of oscillation.
large \rightarrow "easy" to detect.



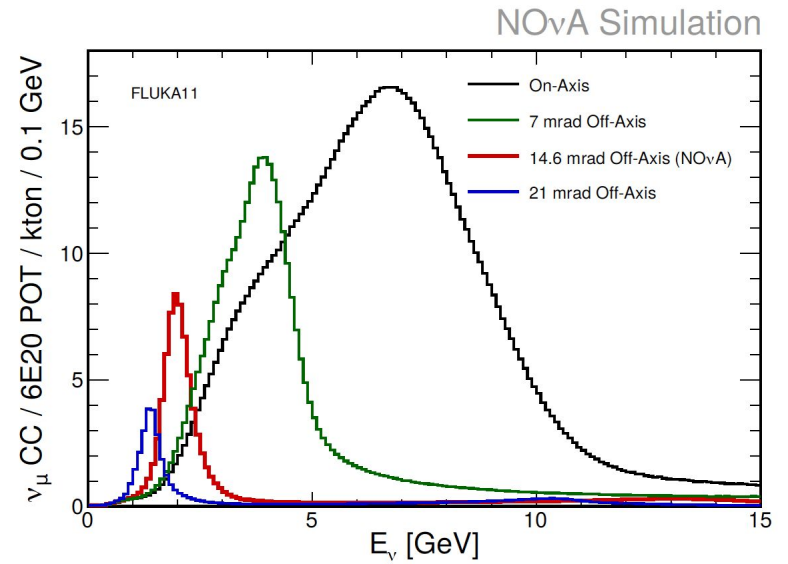
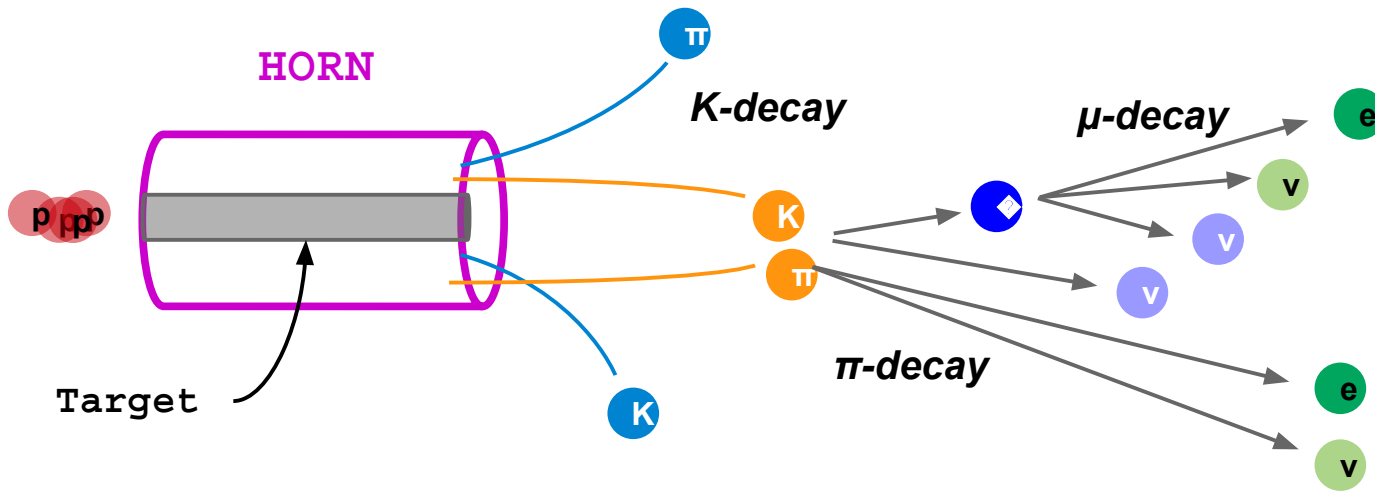
FIRST MINOS+ RESULTS - ν_μ SURVIVAL PROBABILITY CURVE (June 2014)
<https://www-numi.fnal.gov/PublicInfo/forscientists.html>



Neutrinos at Fermilab



Neutrinos at Fermilab



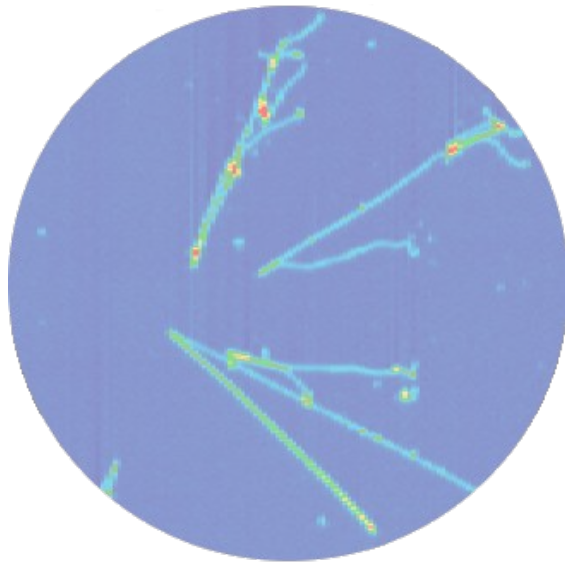
- pulsed beam
- high statistics
- controlled energy range
- fixed baseline

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

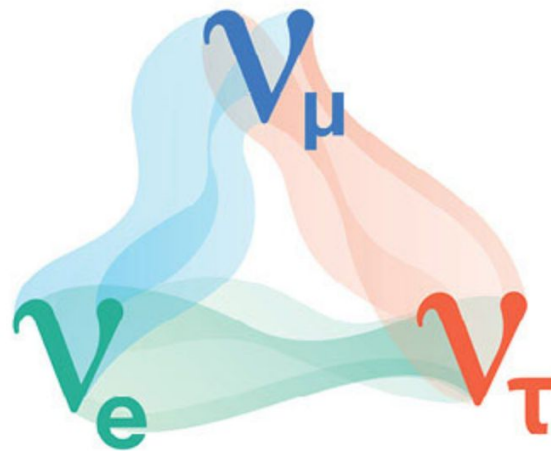
Fermilab's Neutrino Physics Program

Wide range of experiments leveraging Fermilab's accelerator complex for a cutting-edge neutrino physics program.

- How do neutrinos fit in the Standard Model?
- Neutrinos as a probe for Beyond the Standard Model physics.



neutrino scattering

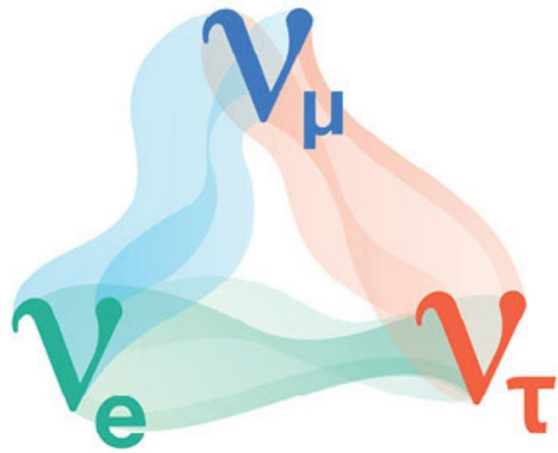


oscillations



new physics searches

Oscillations at Short and Long Baselines



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

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

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

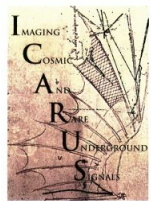
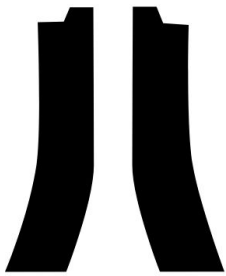
"near" or "far" from beam driven by physics:

long baseline: precision three-flavor oscillations.

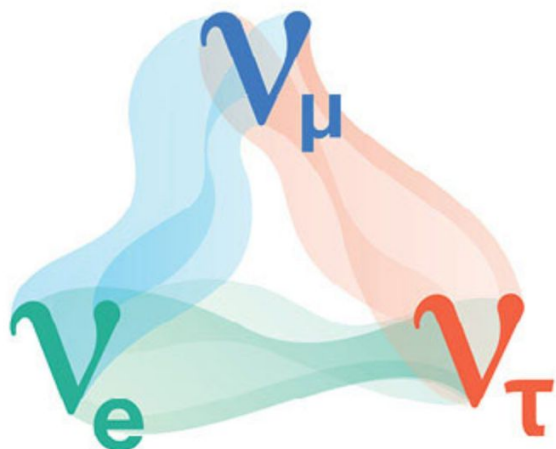
short baseline: eV-scale neutrino searches and cross-section program.

Short Baseline Oscillations
 $L \sim 10^2 - 10^3$ meters $\rightarrow L/E \sim 1$ eV²

Long Baseline Oscillations
 $L \sim 10^2 - 10^3$ km $\rightarrow L/E \sim 10^{-3}$ eV²



Long Baseline Oscillations



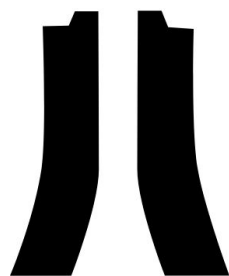
NOvA leading precision oscillation program:

- neutrino mass ordering
- precision oscillation parameters
- Next [talk](#): NOvA oscillations, Erika Catano-mur

DUNE will carry the torch:

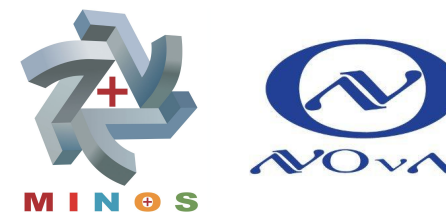
- more statistics (MW beam + larger detector)
- longer baseline.
- Talk by Denver Whittington from Monday [[link](#)]

$$\nu_\mu \rightarrow \nu_e \text{ VS. } \bar{\nu}_\mu \rightarrow \bar{\nu}_e$$

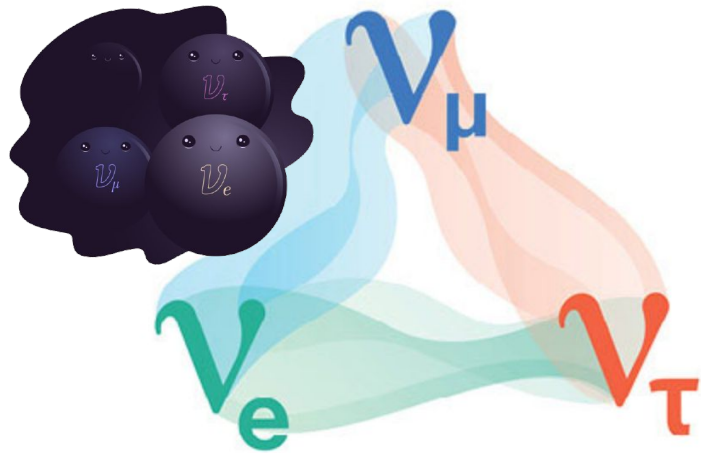


near detector to measure un-oscillated

flux and constrain uncertainties



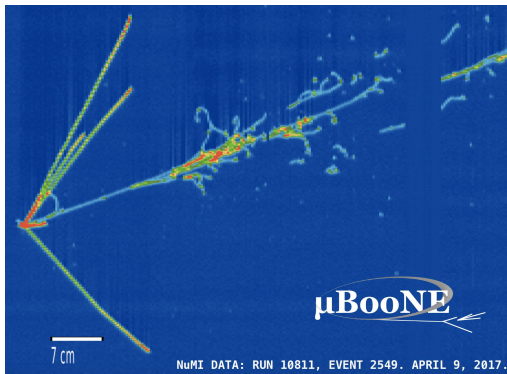
Short Baseline Program



Short baseline program investigates possible existence of eV-scale sterile neutrinos.

1st step: MicroBooNE

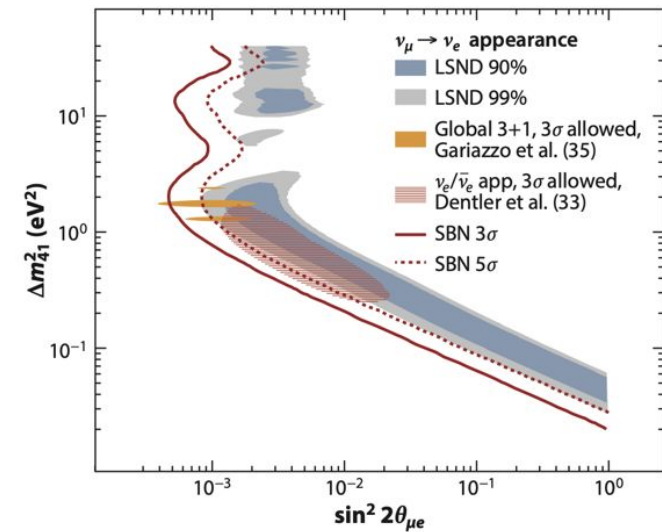
- Data collection 2015-2020
- Address MiniBooNE “excess”



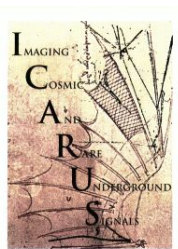
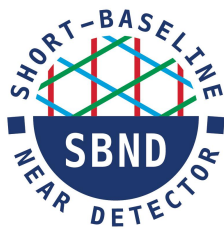
+



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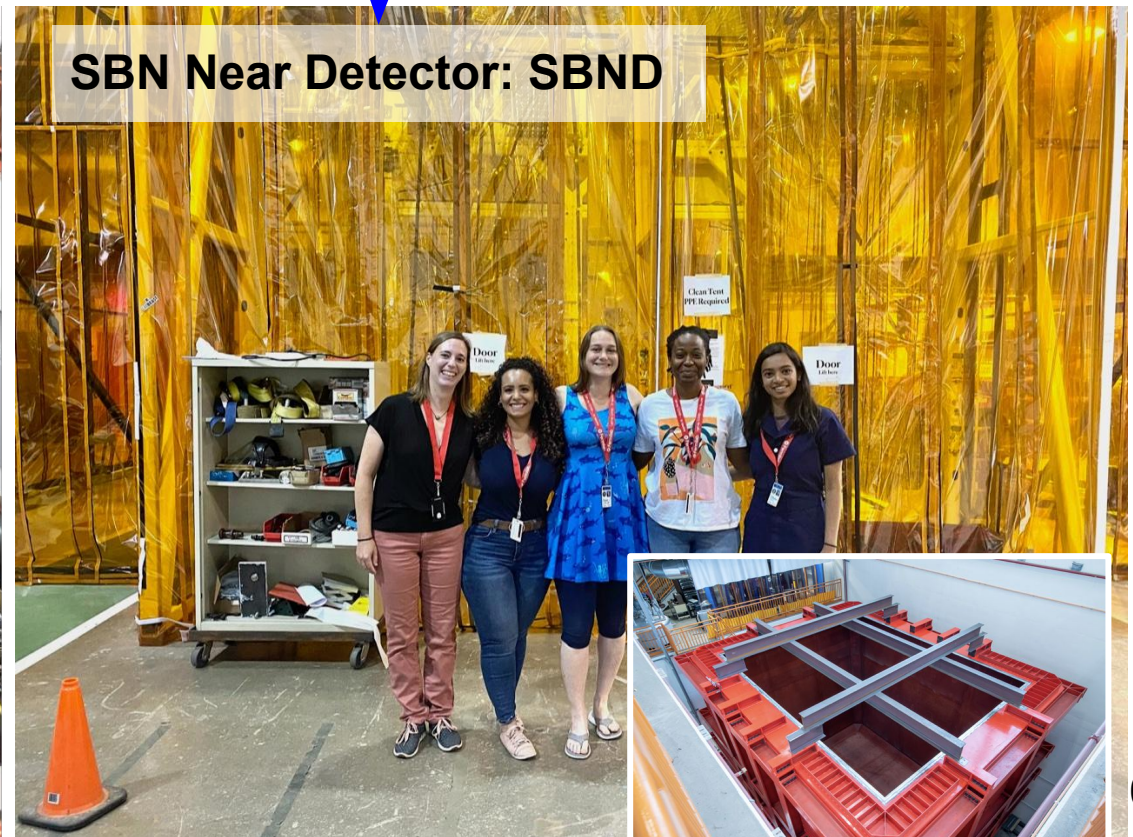
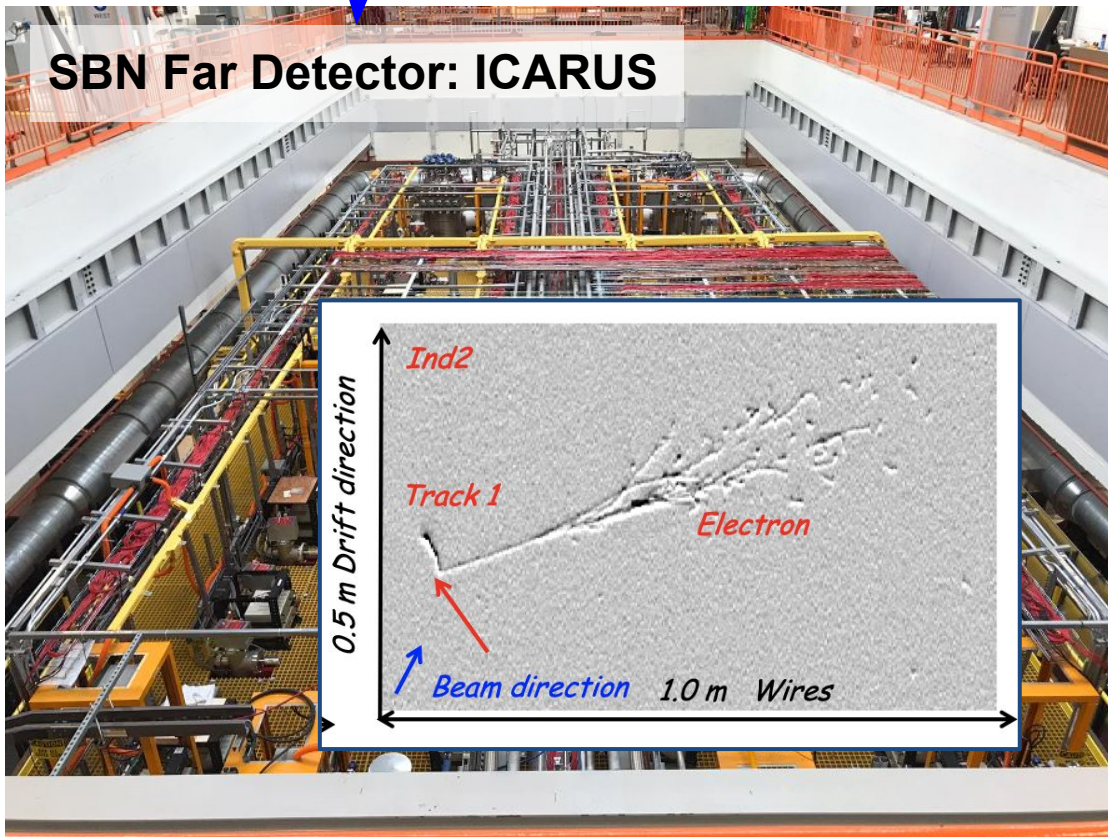
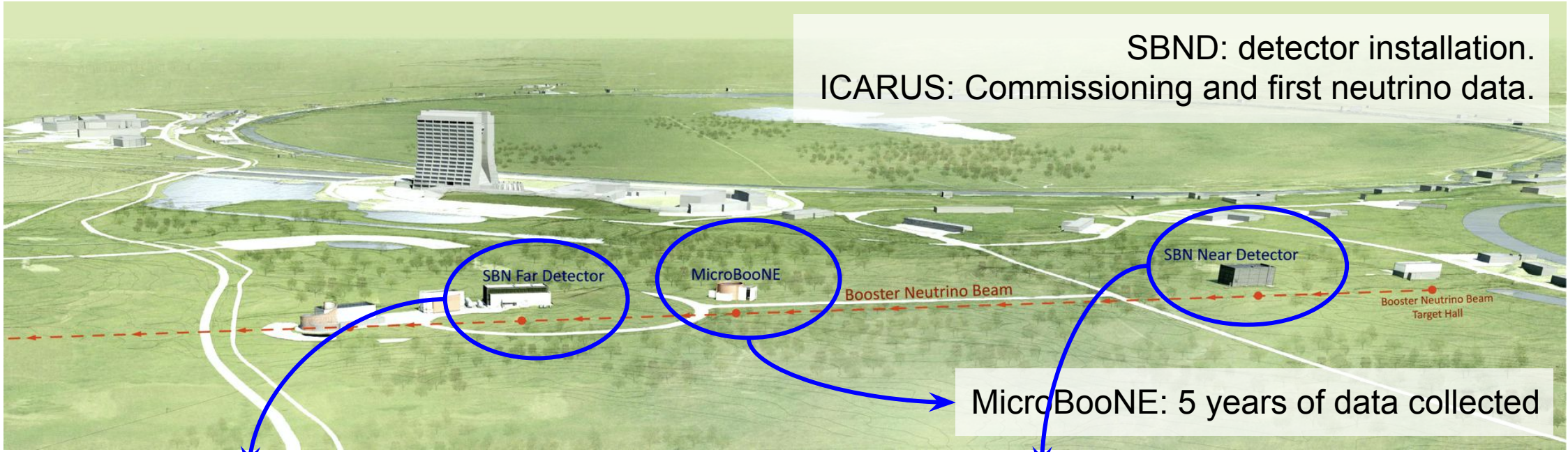


Annu. Rev. Nucl. Part. Sci. 2019 DOI 10.1146
 Courtesy of Diana Mendez, EPS-HEP 2021

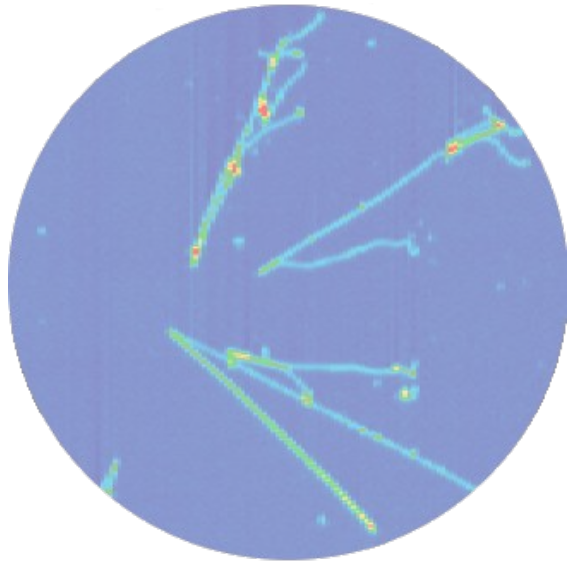


long-baseline experiments play an important role in eV-sterile neutrino searches

SBN Status



Neutrino Scattering



neutrino scattering

Neutrino scattering measurements are a vital component of Fermilab's neutrino program.

Convert visible final-state particles into measured oscillation parameters.

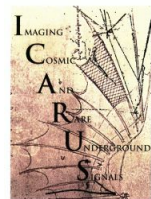
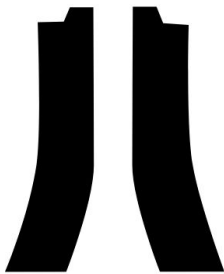
Several talks with results from different experiments:

- [MINERvA](#), Gonzalo-Diaz Bautista
- [MicroBooNE](#), Elena Gramellini
- [NOvA](#), Wenjie Wu

Beyond experiments: key role of neutrino interaction generator, nuclear and theory communities.

→ see [talk](#) by Noemi Rocco, Thursday @ 9:20 AM.

Leverage large neutrino flux for high-statistics interaction measurements.



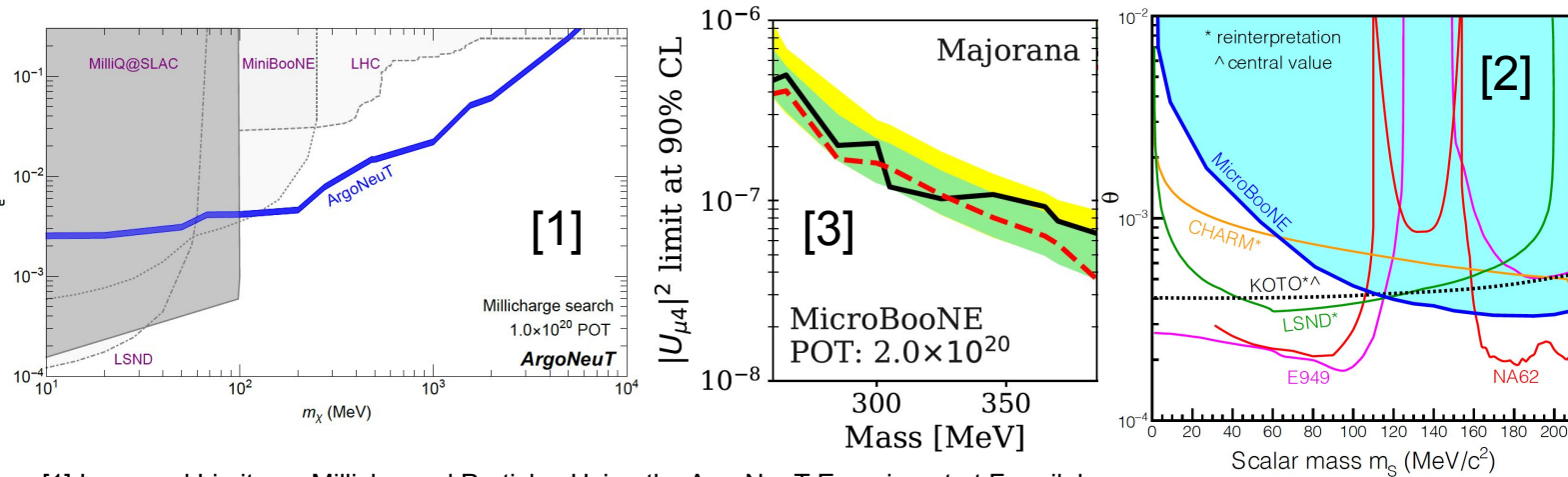
Beyond the Standard Model Searches



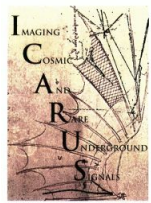
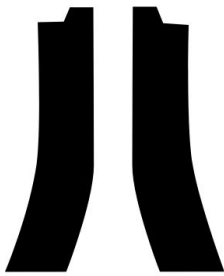
new physics searches

Leverage intense beam for broad range of BSM searches.

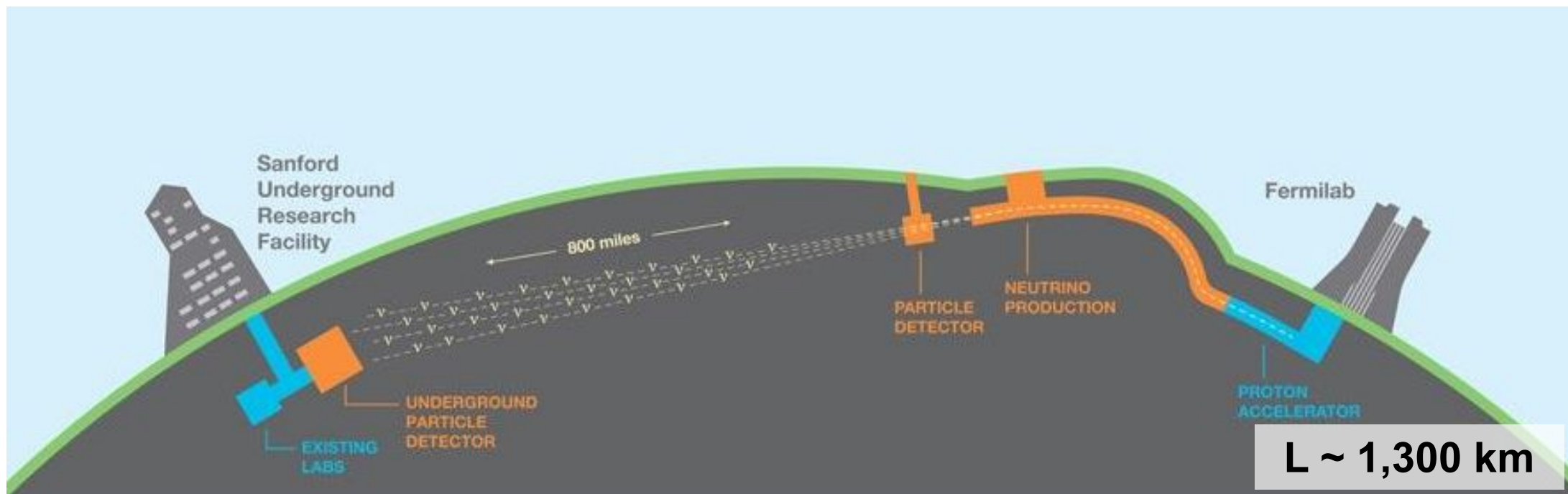
Strong interplay with theory community and group @ FNAL.



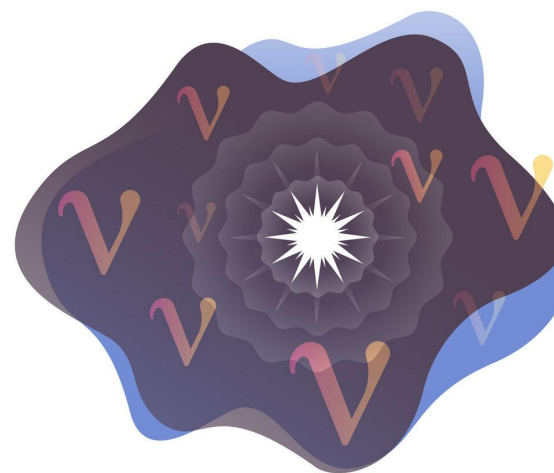
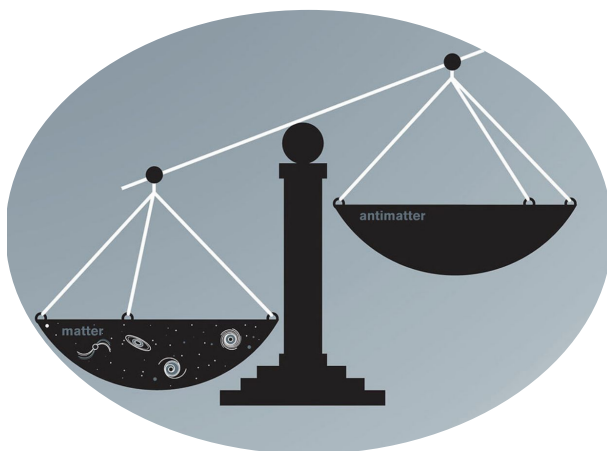
- [1] Improved Limits on Millicharged Particles Using the ArgoNeuT Experiment at Fermilab
- [3] Search for a Higgs portal scalar decaying to electron-positron pairs in the MicroBooNE detector
- [2] Search for Heavy Neutral Leptons Decaying into Muon-Pion Pairs in the MicroBooNE Detector



Deep Underground Neutrino Experiment



<https://www.dunescience.org/>



Impressive physics reach:

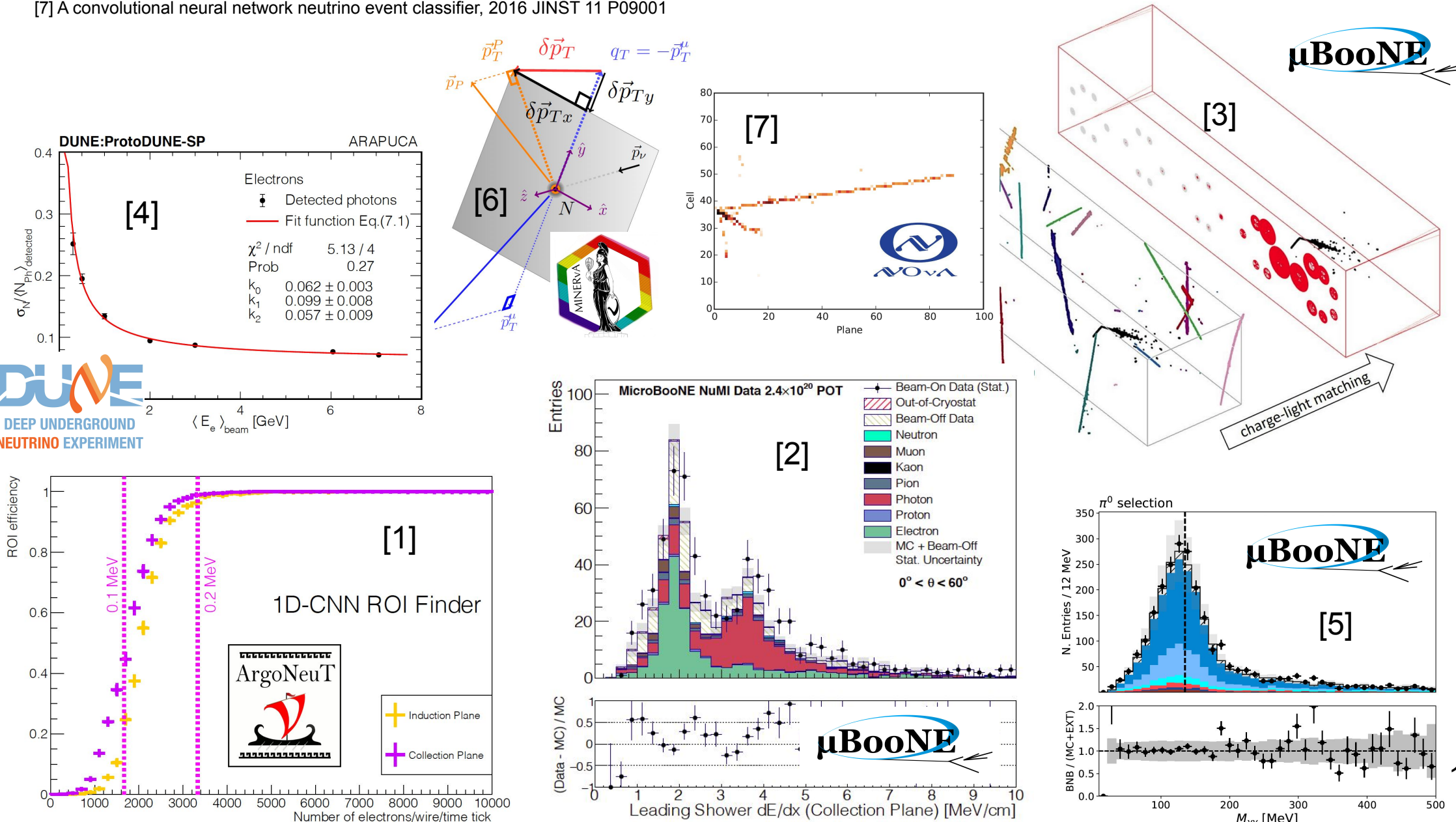
- precision ν -OSC
- ν from supernovae
- nucleon decay
- BSM at near detector
- atmospheric ν
- ...

Measuring δ_{CP} : help understand why we live in a matter-dominated universe.

← Intense ν beam critical to this goal: PIP-II

Building a Strong Foundation for DUNE

- [1] A deep-learning based raw waveform region-of-interest finder for the liquid argon time projection chamber, arXiv:2103.06391
- [2] Measurement of the Flux-Averaged Inclusive Charged-Current Electron Neutrino and Antineutrino Cross Section on Argon using the NuMI Beam and the MicroBooNE Detector
- [3] Cosmic Ray Background Rejection with Wire-Cell LArTPC Event Reconstruction in the MicroBooNE Detector, Phys. Rev. Applied 15.064071
- [4] First results on ProtoDUNE-SP liquid argon time projection chamber performance from a beam test at the CERN Neutrino Platform, JINST 15 (2020) P12004
- [5] Search for Electron Neutrinos in Multiple Topologies with the MicroBooNE Experiment, MICROBOONE-NOTE-1085-PUB
- [6] Nuclear binding energy and transverse momentum imbalance in neutrino-nucleus reactions, Phys. Rev. D 101, 092001 (2020)
- [7] A convolutional neural network neutrino event classifier, 2016 JINST 11 P09001



Advancing the Neutrino Program

MINOS decommissioning @ NUMI underground
Photo: Ryan Postel, Fermilab [1]



ArgonCube's protoDUNE-ND 2x2 prototype
photo: Igor Kreslo [2]



Noble Liquid Detector R&D Facility [PAB]
Photos: Alan Hahn, Reidar Hahn



PAB

PIP-II Cryogenic Plant Building – 29 July 2021

See [talk](#) by Luisella Lari [Monday, Aug. 2nd]



502 PAB
Noble Liquid Detector
R&D Facility
1219 C Road East



[1] <https://news.fnal.gov/2021/07/minos-underground-hall-at-fermilab-is-ready-to-host-new-experiments/>

[2] <https://news.fnal.gov/2021/06/dune-prototype-detector-argoncube-crosses-the-globe/>

Neutrinos Beyond the Lab

New Series!

Even Bananas

with host
Kirsty Duffy

Even Bananas video-series by Kirsty Duffy [\[link\]](#)



Host of all-virtual Neutrino 2020:
[\[http://nu2020.fnal.gov\]](http://nu2020.fnal.gov)

 all things
neutrino

What's a neutrino? Mysteries ▾ Types ▾



FNALNeutrinos
@FNALNeutrinos

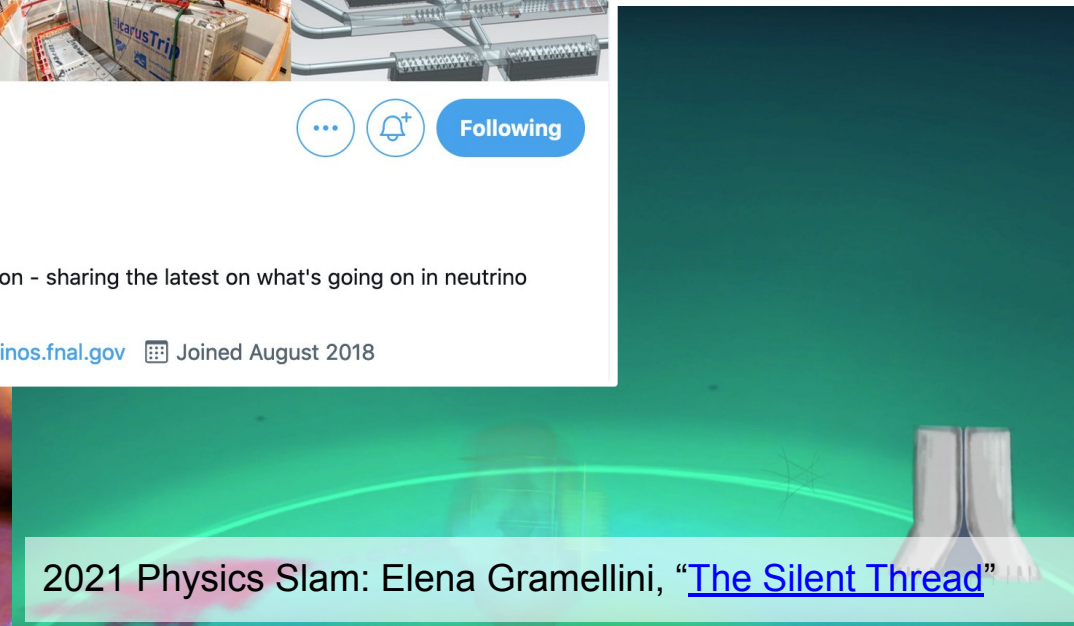
Fermilab Neutrino Division - sharing the latest on what's going on in neutrino physics at Fermilab

📍 Batavia, IL 🌐 neutrinos.fnal.gov 📅 Joined August 2018

Following



Getting started with Neutrinos: <https://neutrinos.fnal.gov/>



2021 Physics Slam: Elena Gramellini, "[The Silent Thread](#)"

Summary

Fermilab hosts a broad experimental neutrino physics program.

Lab's multiple powerful ν beams enable achieving cutting-edge physics.

- Leading results in precision oscillation measurements.
- Wide-range of neutrino cross-section results.
- Growing collection of New Physics tests through novel searches.

Many exciting results and the status of different programs will be presented in several contributions throughout the week.