Introduction to Neutrinos at Fermilab

53rd Annual User's Meeting
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Why Neutrinos?

Neutrino Production

Neutrino Detection

Neutrinos at Fermilab

Theory

Beams

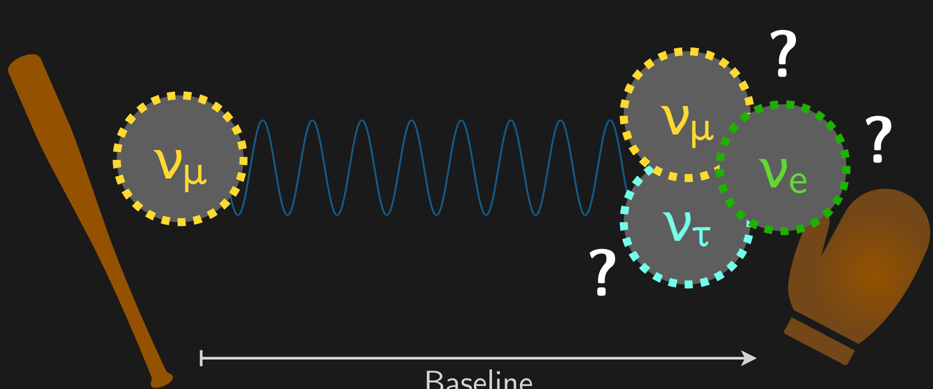
R&D

Neutrino Experiments

Operations and Facilities

Neutrinos?

- **Weak interactions** with other matter (atoms & nuclei)
  - Lots of neutrinos and targets (beams + large detectors)
- Three **flavors**: electron (ν_e), muon (ν_μ), and tau (ν_τ), corresponding to charged leptons
- **Oscillations** changing flavors as neutrinos travel
  - Quantum mechanics at work over very long distances!



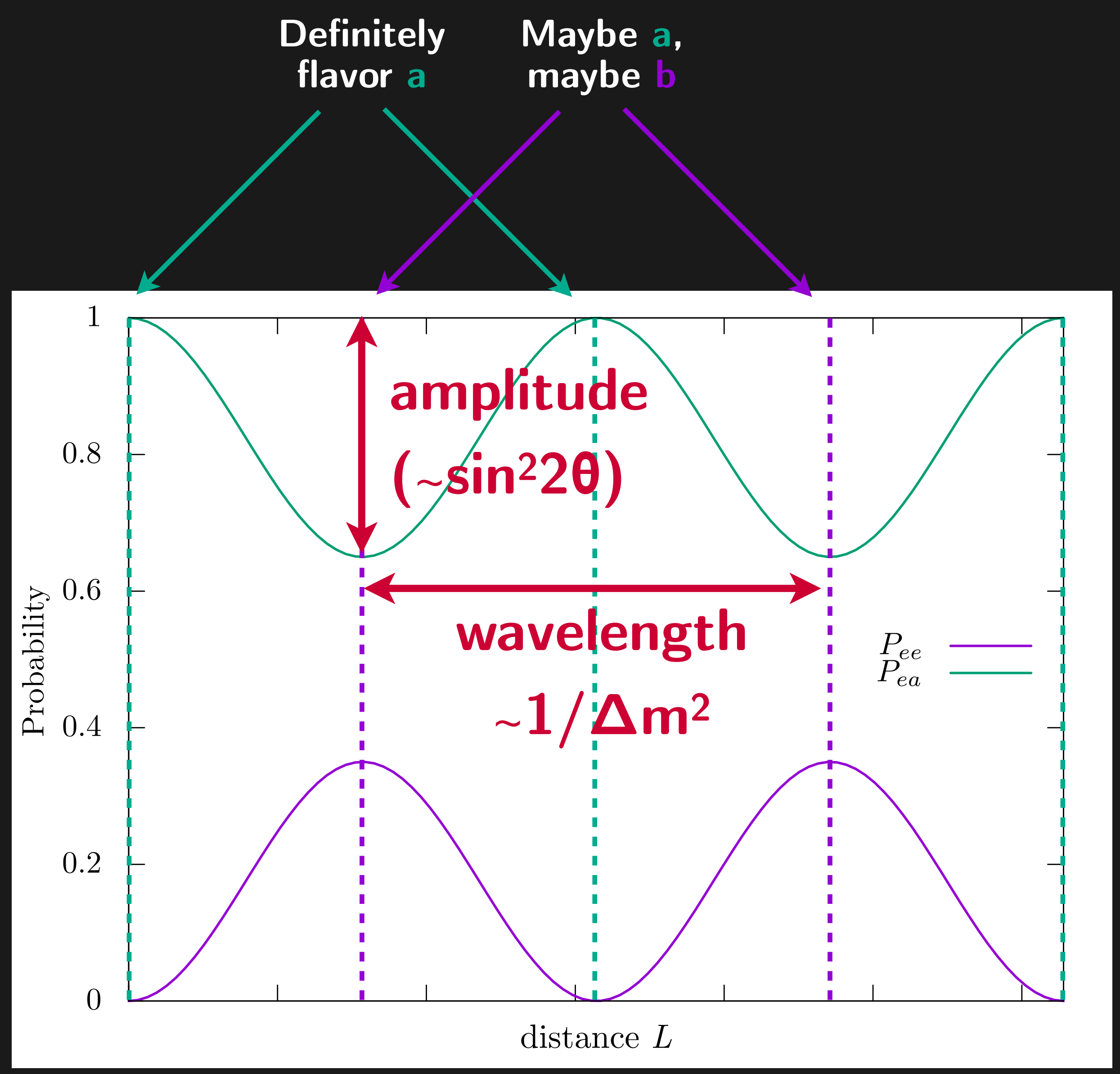
Standard Model Particles

	I	II	III	
QUARKS	u up, $+2/3$, 0.003 GeV/c^2	c charm, $+2/3$, 1.3 GeV/c^2	t top, $+2/3$, 175 GeV/c^2	γ photon, 0, 0
QUARKS	d down, $-1/3$, 0.006 GeV/c^2	s strange, $-1/3$, 0.1 GeV/c^2	b bottom, $-1/3$, 4.3 GeV/c^2	g gluon, 0, 0
				$W^\pm$ W boson, ±1, 80.4 GeV/c^2
LEPTONS	ν_e electron neutrino, 0, $<10^{-8}$ GeV/c^2	ν_μ muon neutrino, 0, $<10^{-4}$ GeV/c^2	ν_τ tau neutrino, 0, <0.02 GeV/c^2	Z^0 Z boson, 0, 91.2 GeV/c^2
LEPTONS	e^- electron, -1, 511 keV/c^2	μ^- muon, -1, 0.106 GeV/c^2	τ^- tau, -1, 1.78 GeV/c^2	H Higgs boson, 0, 125 GeV/c^2

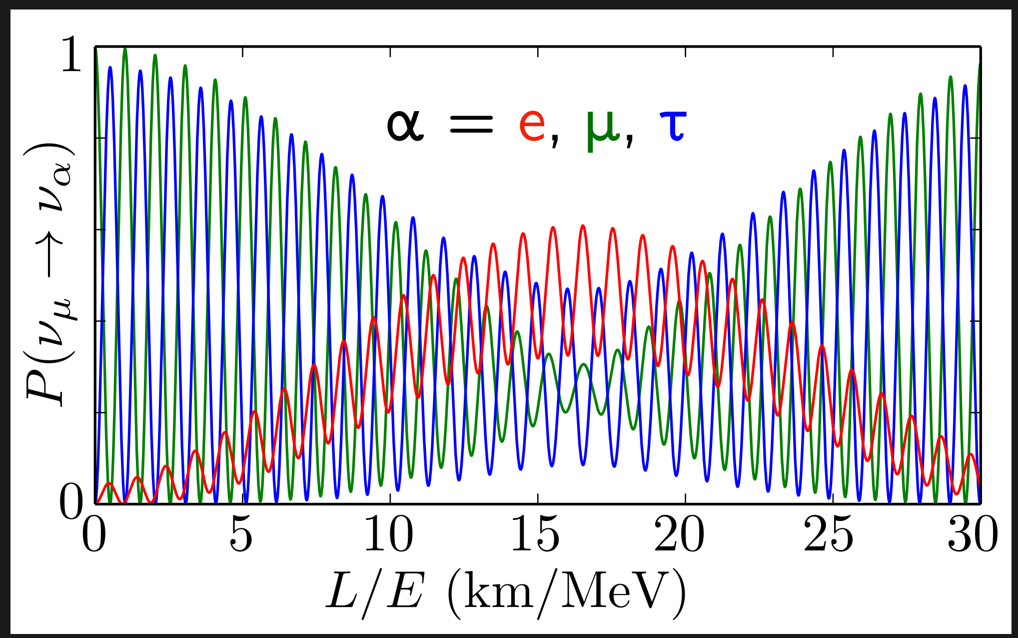
Neutrinos?

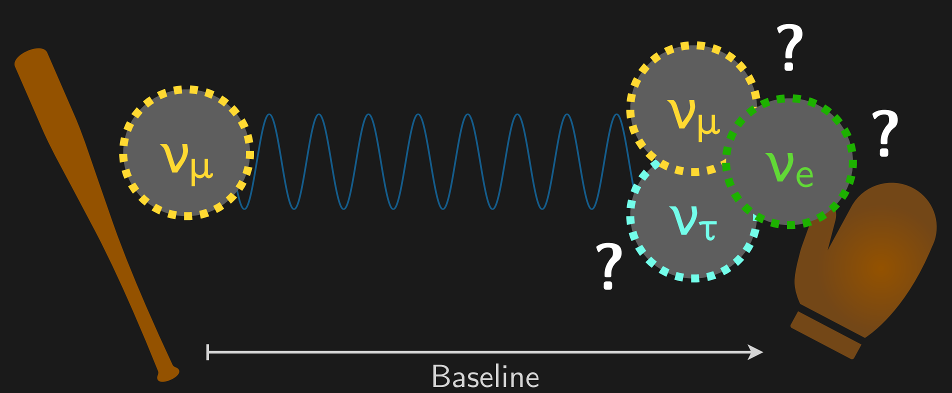
- A neutrino of **energy *E*** starts out as **flavor a**
- Travels for a **distance *L***
- Detected as **flavor a** or **b**

- Oscillations are determined by
  - A few parameters we control: **distance *L***, **energy *E***
  - A few we try to measure: the **amplitude** and **wavelength**, which is related to differences between neutrino masses, Δm



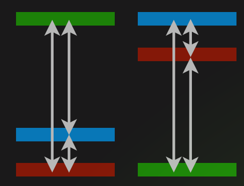
In our three-neutrino universe...





Why Neutrinos?

Oscillations



What is the ordering of the neutrino masses?

$\delta_{\rm CP}$

Oscillations

Are there matter/antimatter differences in oscillations ***(CP violation)***, helping to explain our matter-filled universe?

$$\nu \stackrel{?}{=} \bar{\nu}$$

Is the neutrino its own antiparticle?

Standard Model Physics

Beyond the Standard Model

What is the mass of the neutrino, and why is it so small?

Are there new interactions we could discover via neutrinos?

Oscillations

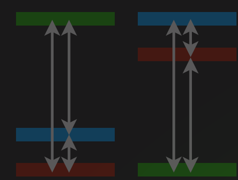
ν_s

Are there additional ***sterile neutrinos*** beyond the known three types?

Oscillations

Why Neutrinos?

Oscillations



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Oscillations

δ_{CP}

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Standard Model Physics

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$\nu \stackrel{?}{=} \bar{\nu}$

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Oscillations

ν_s

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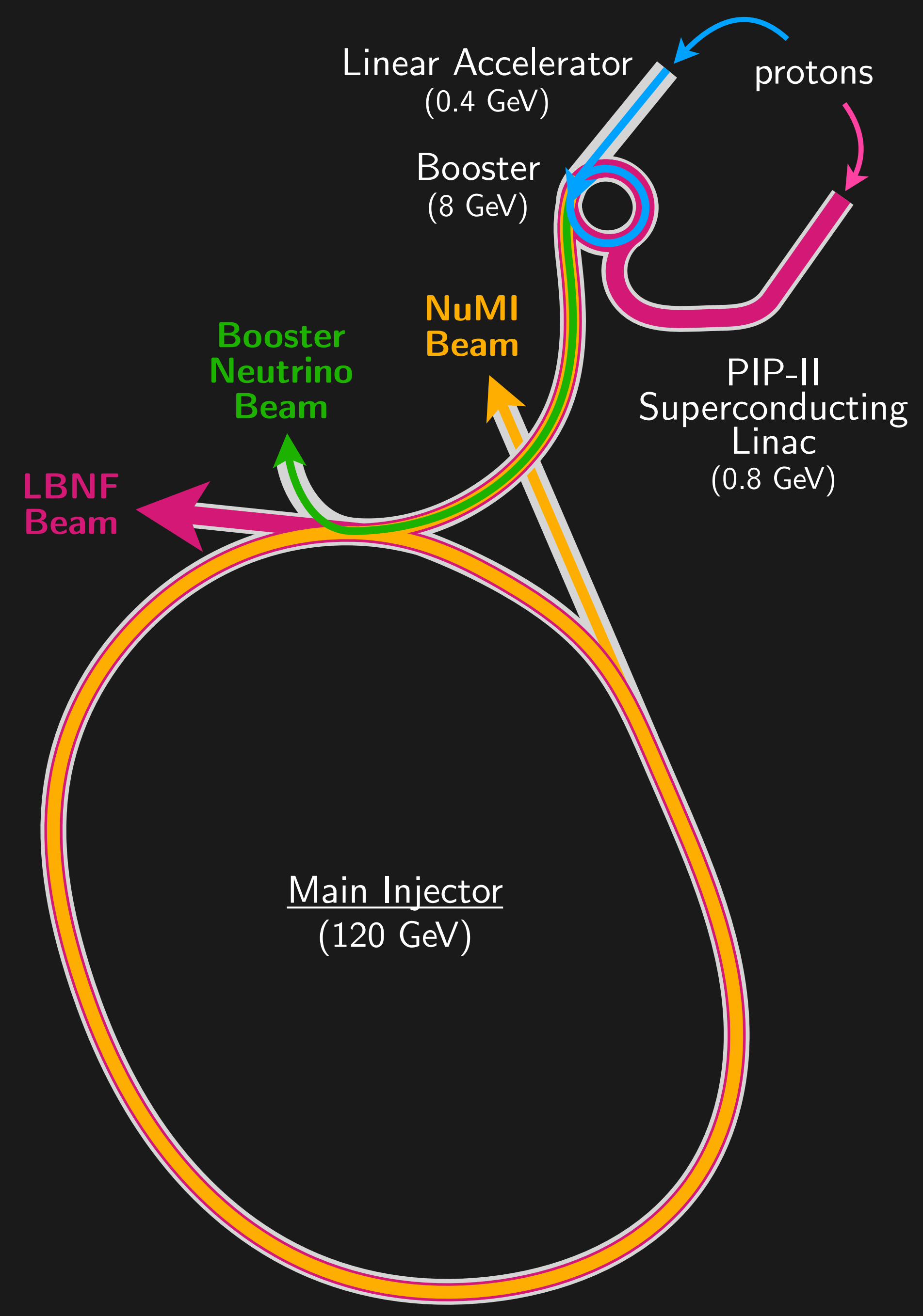
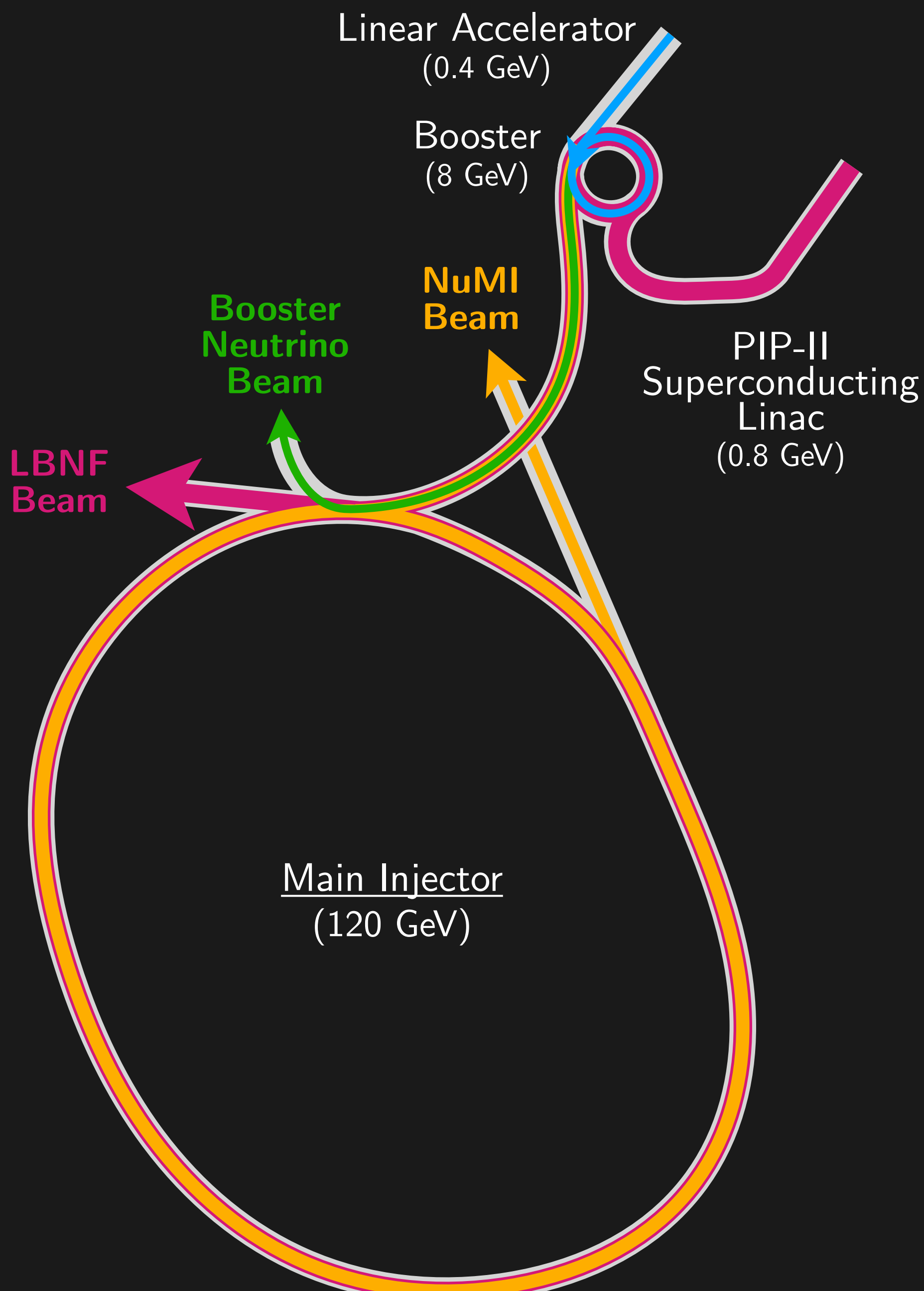
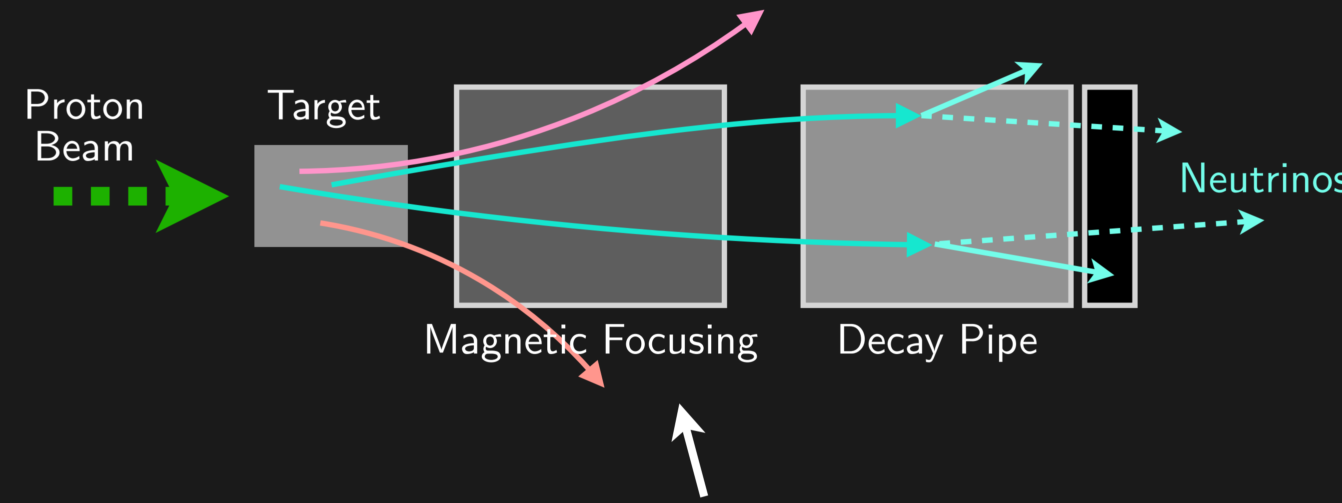
Oscillations

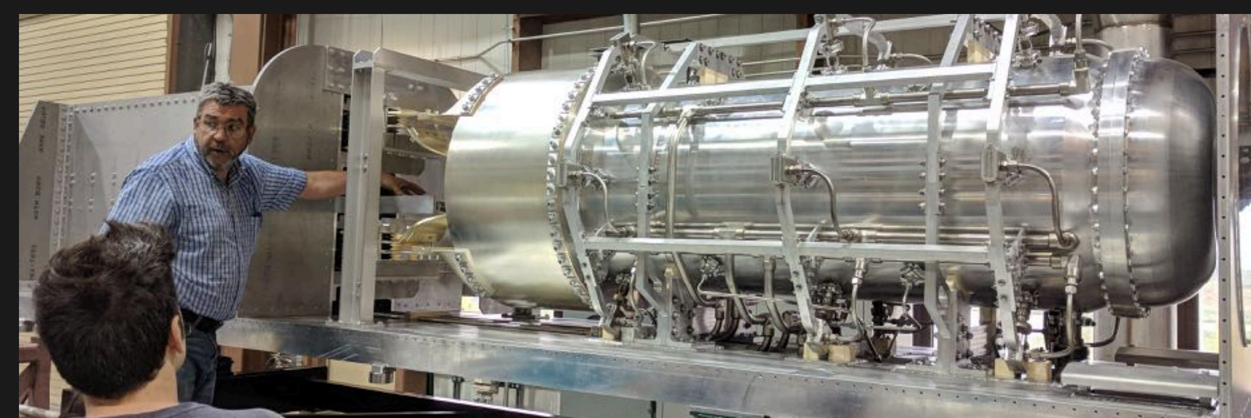
Neutrino Production



Neutrino Production





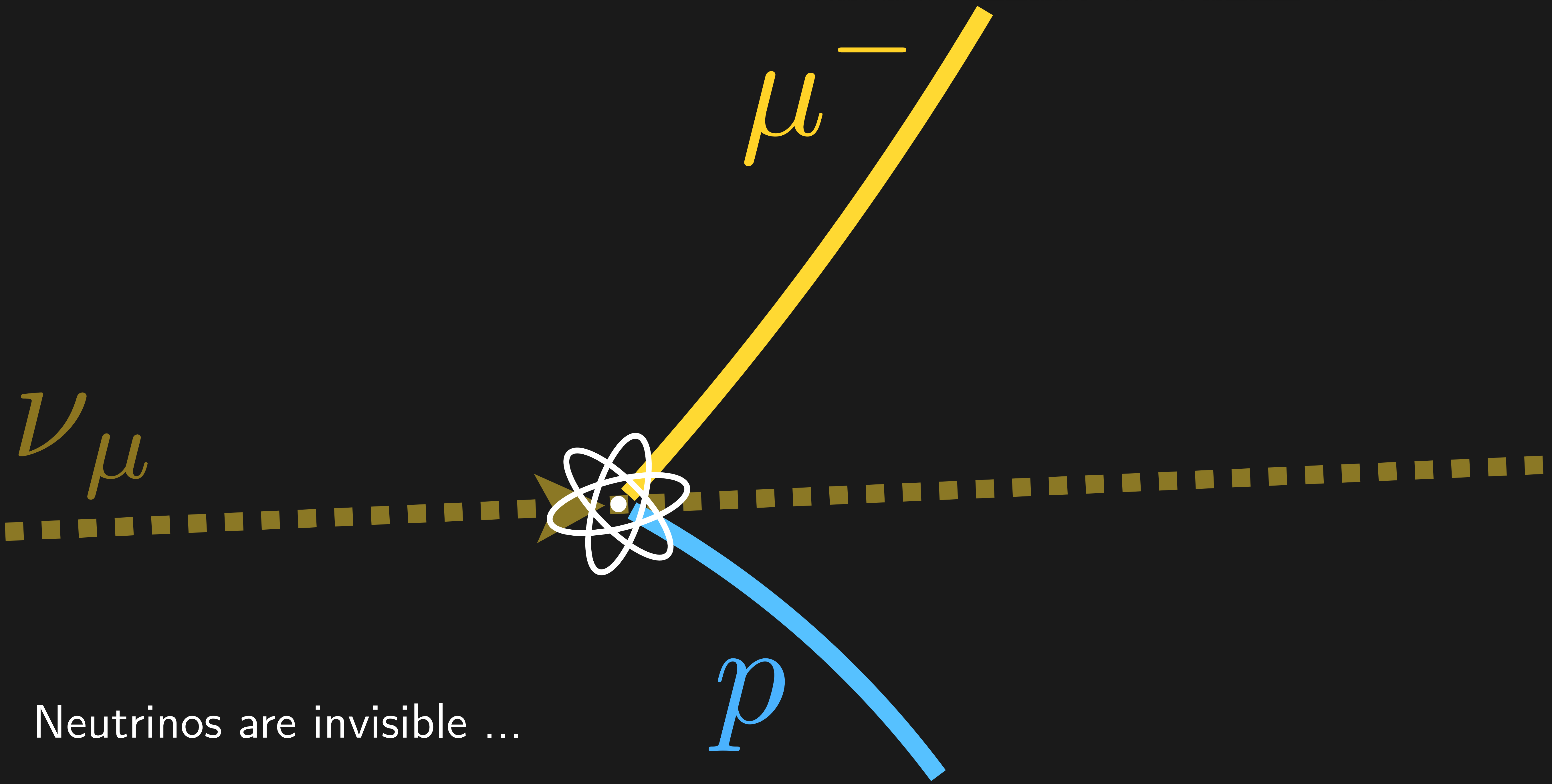


Booster Horn

NuMI horn
(one of two)

More details: See Jeffrey Eldred's "Introduction to Fermilab's accelerators and beams (present and future)" in Session 3

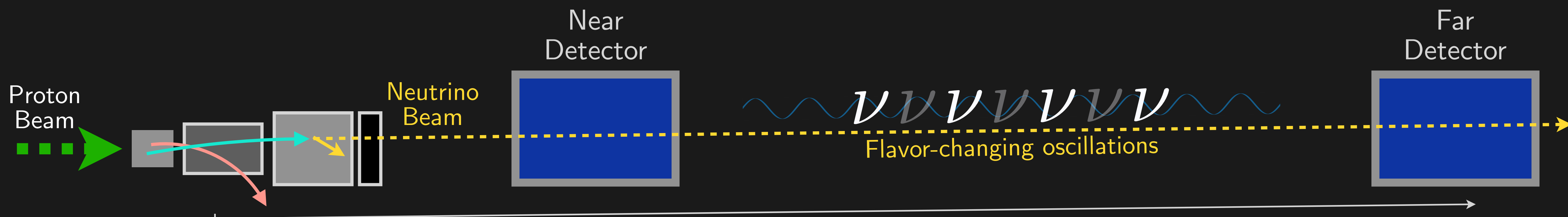
Neutrino Detection



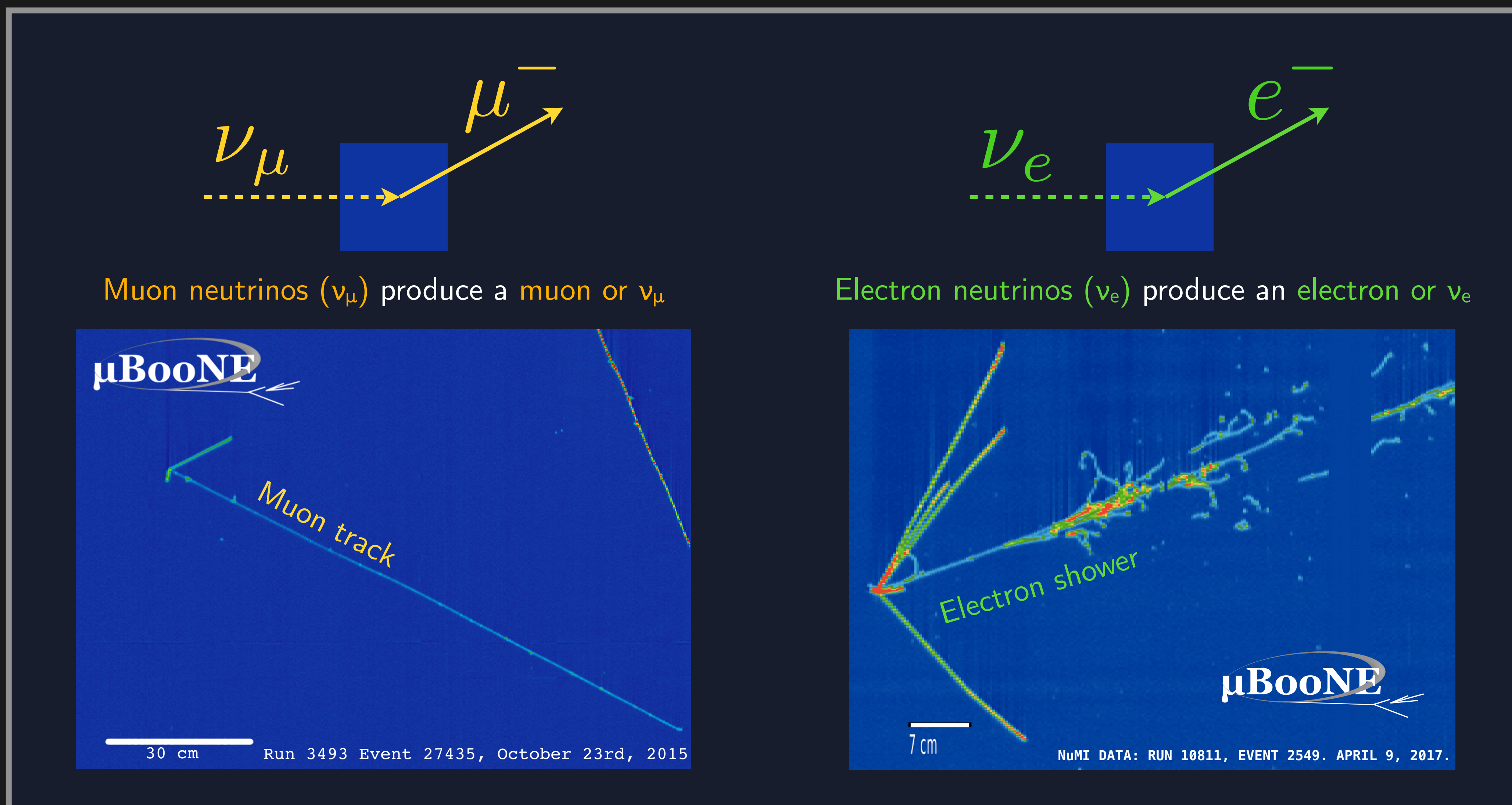
Neutrinos are invisible ...

... and detected via the products of interactions with other matter (nuclei, electrons, etc.)

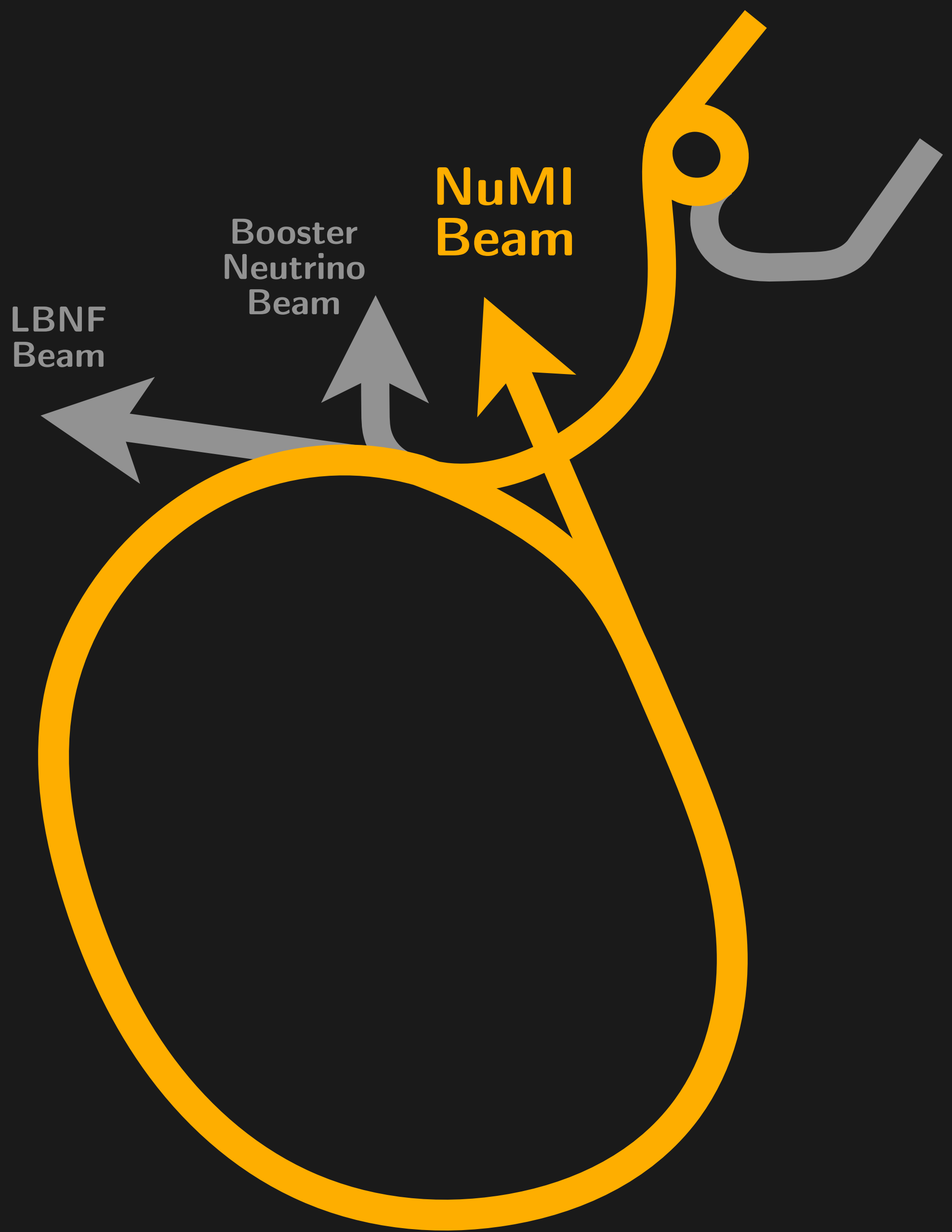
Neutrino Detection



Baseline: ~100 meters is **"short"** and ~1000 kilometers is **"long"** relatively speaking.



Neutrino Program at Fermilab



MINERvA

Precision neutrino interactions

MINOS+

Pioneering long-baseline oscillations

NOvA

Off-axis long-baseline ν_e appearance

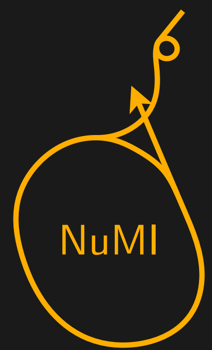
SBN Program

Short-baseline oscillations and new physics

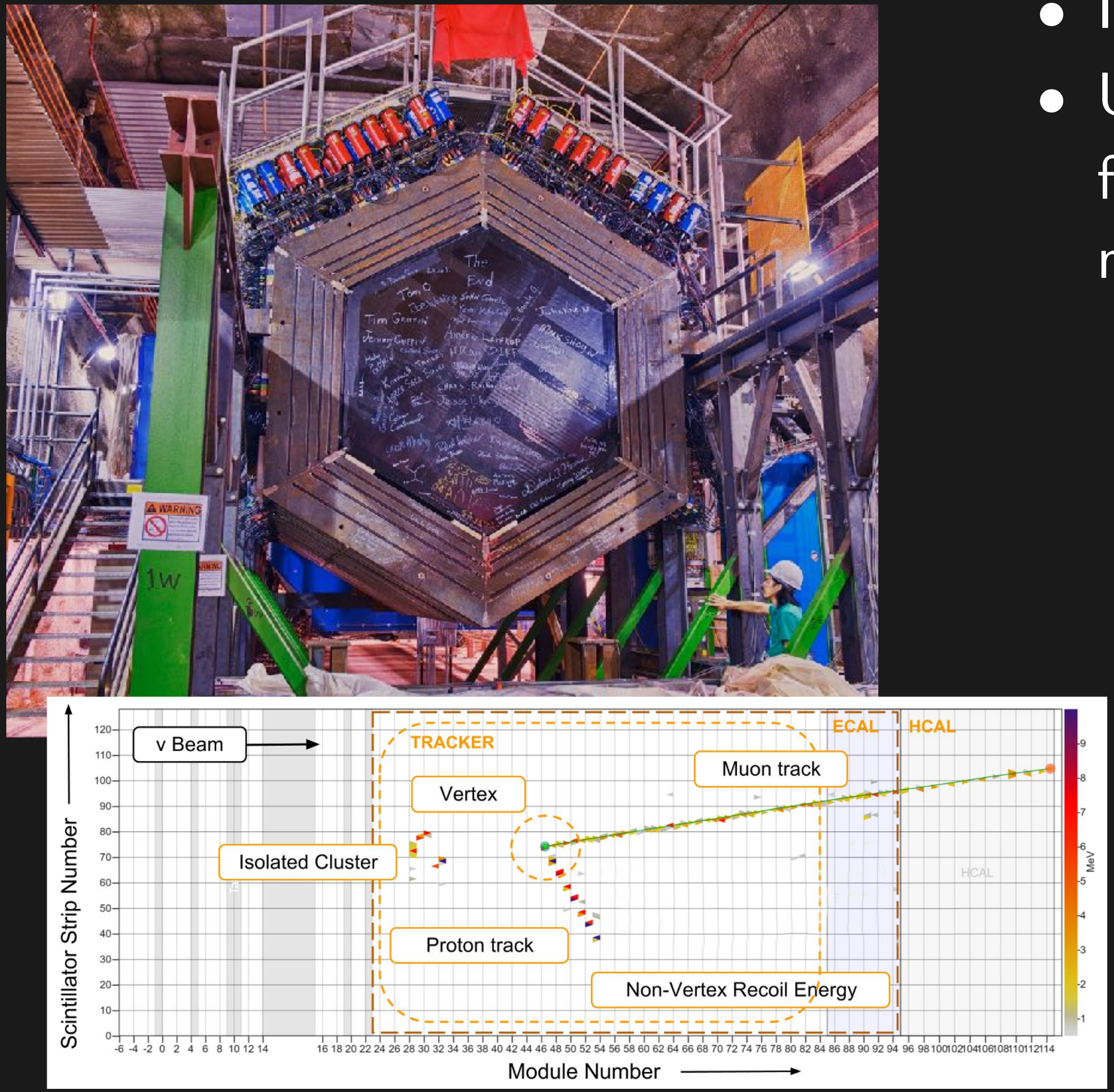
DUNE

Precision long-baseline, CP violation

MINERvA (2010–2019)



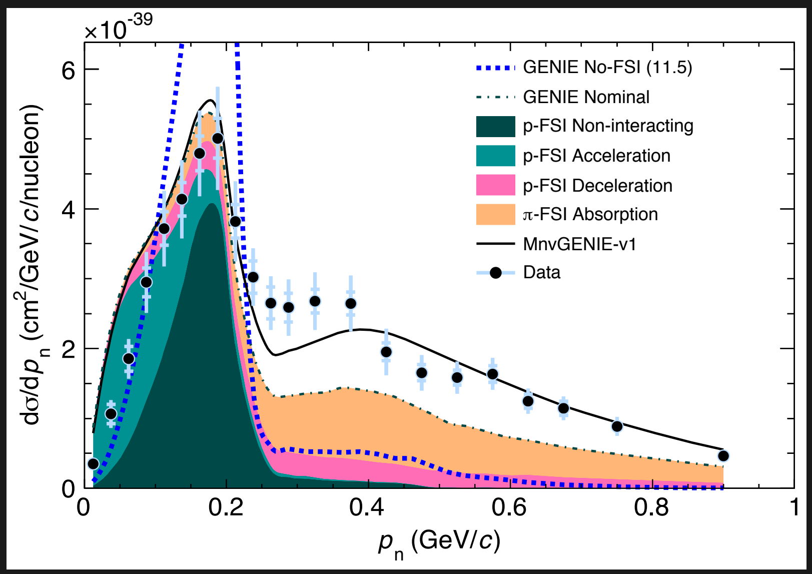
- Several different target materials
- Tracking with scintillator strips
- Underground at Fermilab



A neutrino interaction in MINERvA

- Precision measurements of neutrino **interactions** with a **variety of nuclear targets** (carbon, lead, iron, water, helium)
- Insight into the **structure of nuclei** and forces
- Understanding **neutrino interactions** is crucial for interpreting data in neutrino oscillation and new physics searches

Phys. Rev. Lett. **121**, 022504 (2018)



Example: How are the emitted protons affected by interactions inside the nucleus (final state interactions)? Models are then be tuned to better match the data.

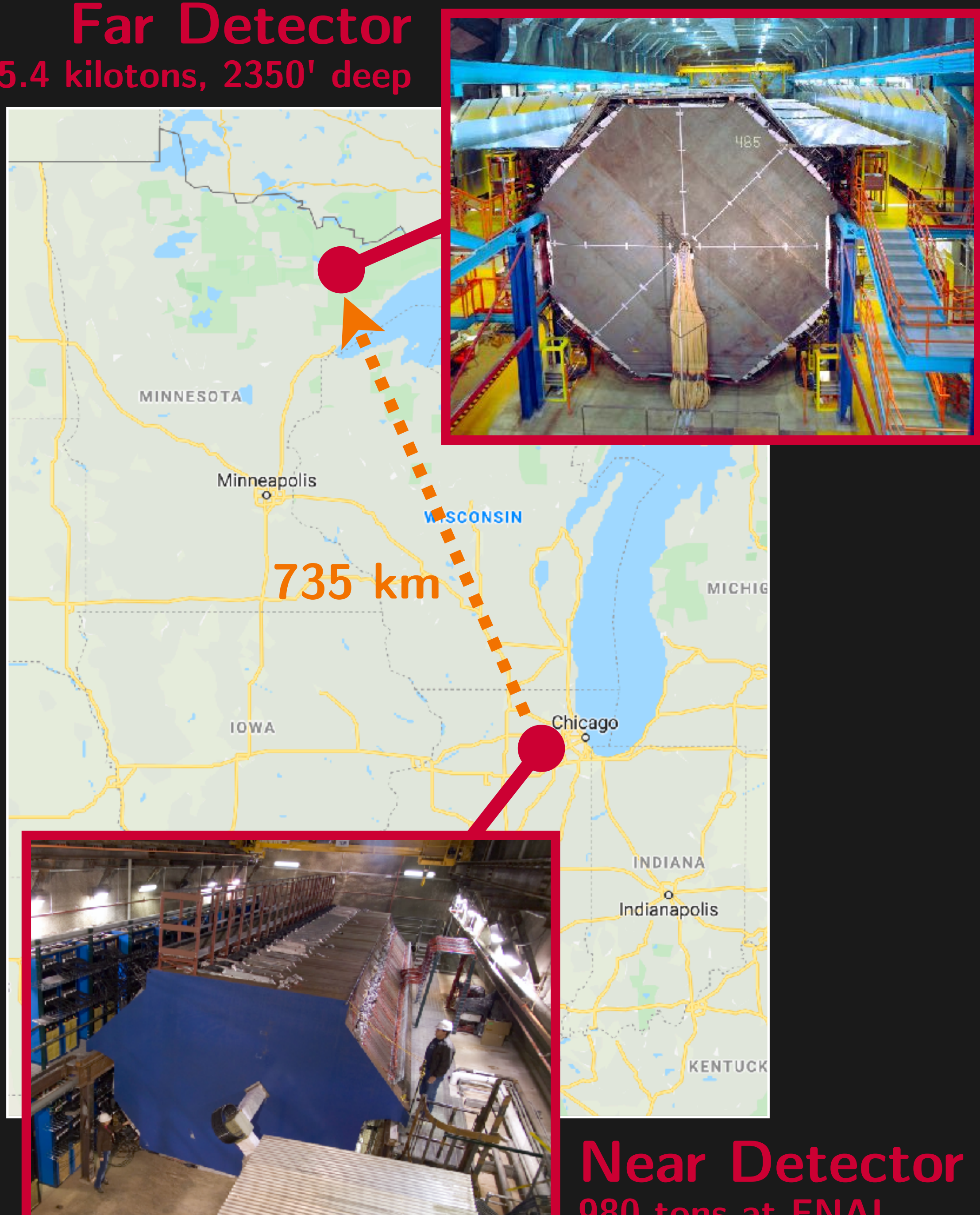
Images: MINERvA

Much more in S. Gardiner's Cross Sections talk, Session 16

MINOS/MINOS+ (2005–2016)

NuMI

Far Detector
5.4 kilotons, 2350' deep

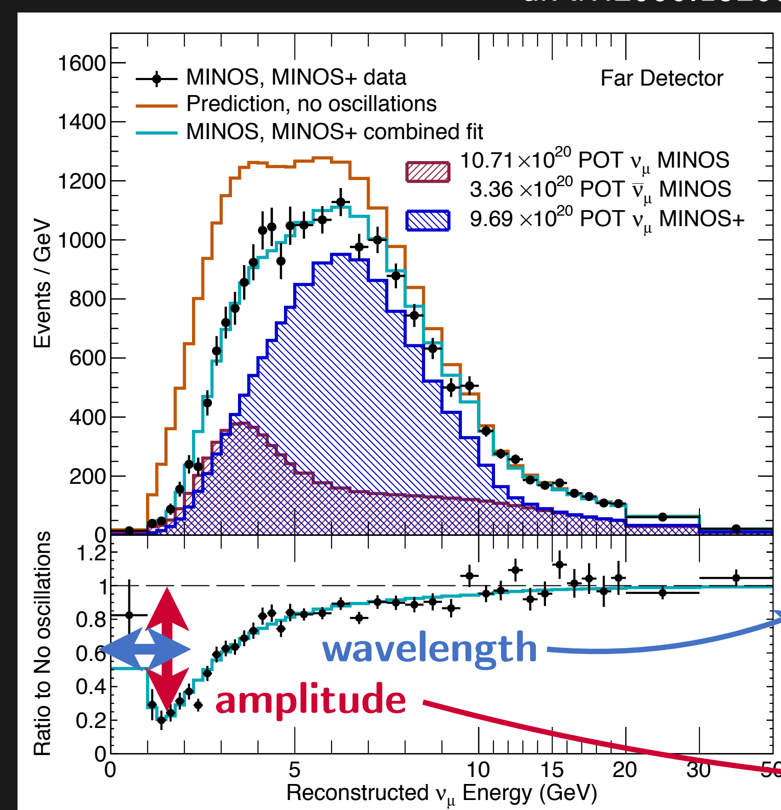


Near Detector
980 tons at FNAL

Magnetized Steel Trackers

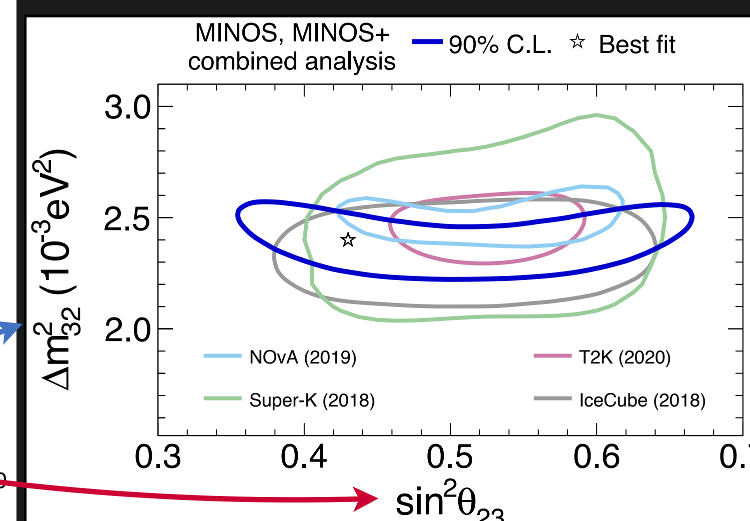
- Long-baseline neutrino **oscillations**
- **Beam** and **atmospheric** neutrinos
- **Final** oscillation results presented July 2020

arXiv:2006.15208



The imprint of oscillations

Measurement of the parameters

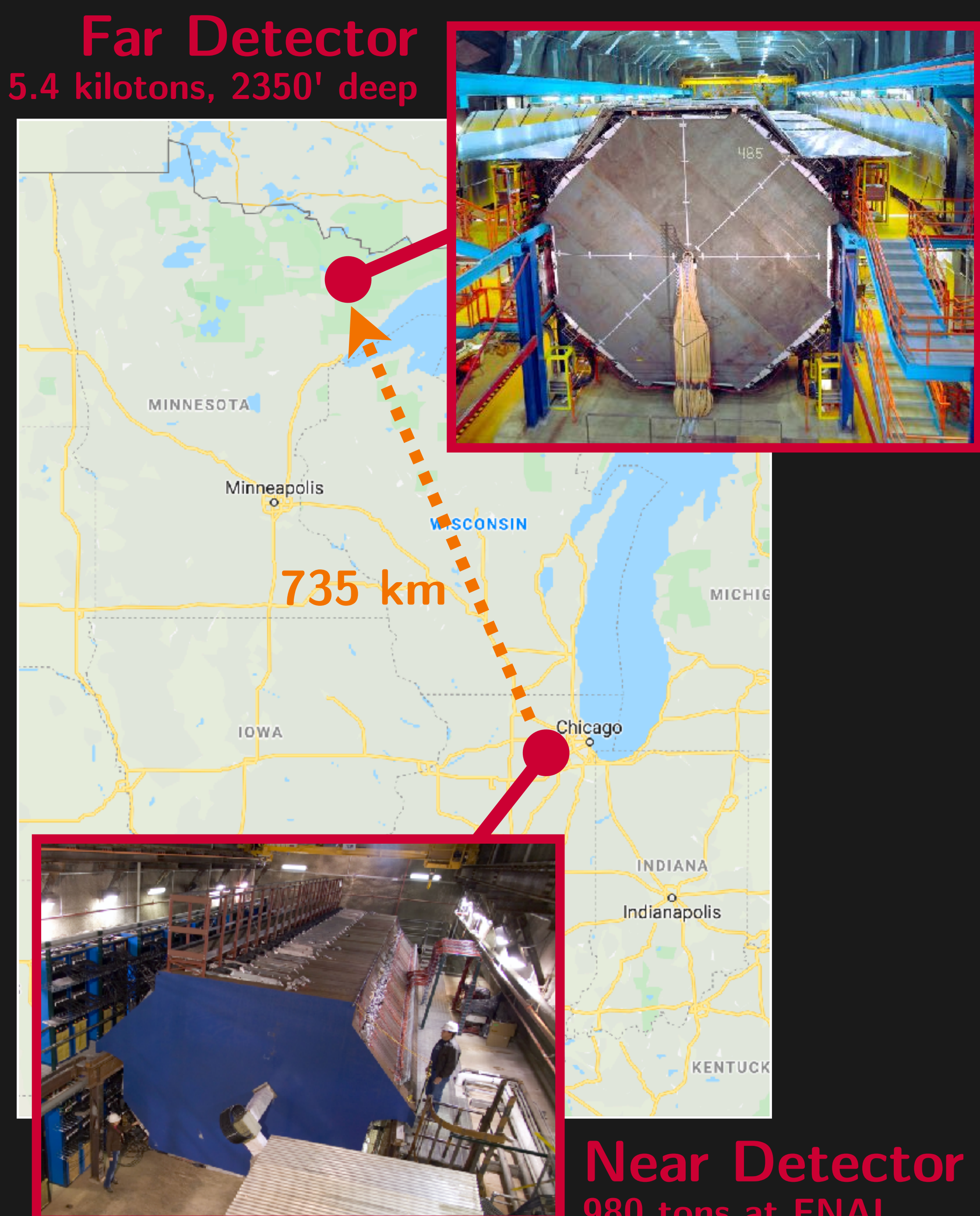


MINOS+ measurements of the parameters controlling three-neutrino oscillations

Images: Fermilab, MINOS/MINOS+

MINOS/MINOS+ (2005–2016)

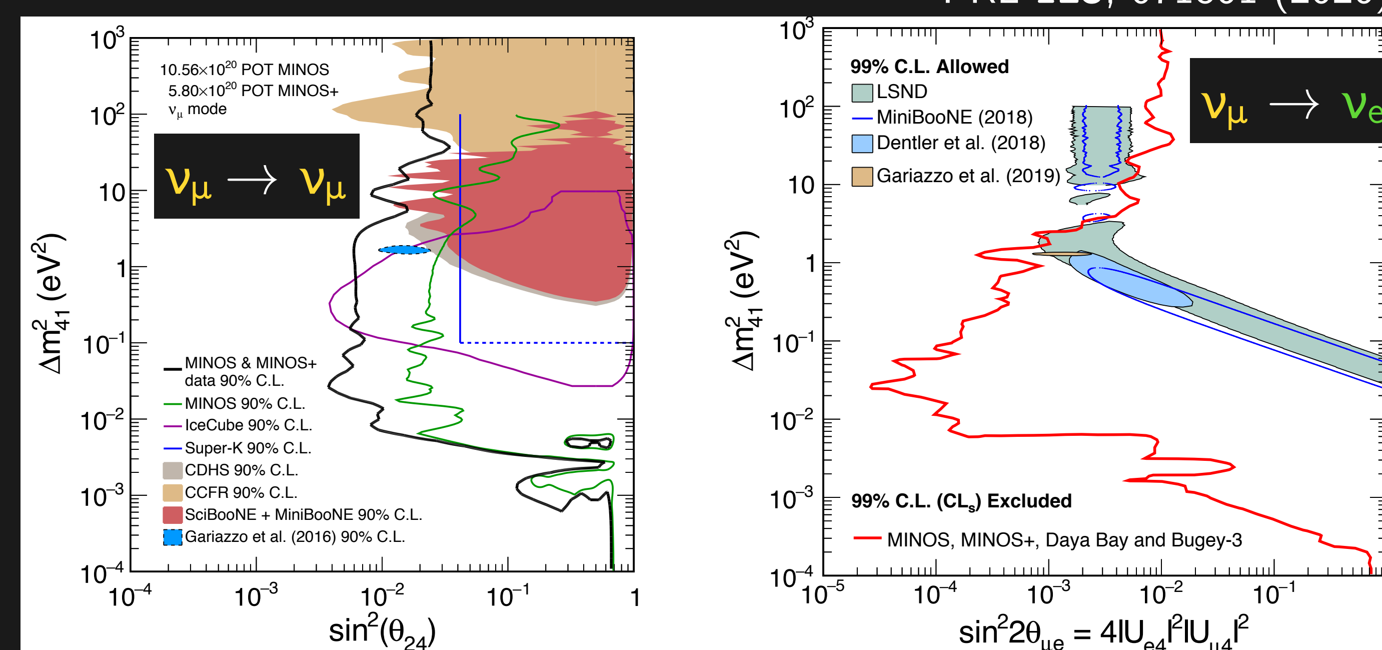
NuMI



Magnetized Steel Trackers

- Long-baseline neutrino **oscillations**
- **Beam** and **atmospheric** neutrinos
- **Final** oscillation results presented July 2020
- Search for **sterile neutrinos**
  - A possible new, additional neutrino type

PRL **125**, 071801 (2020)



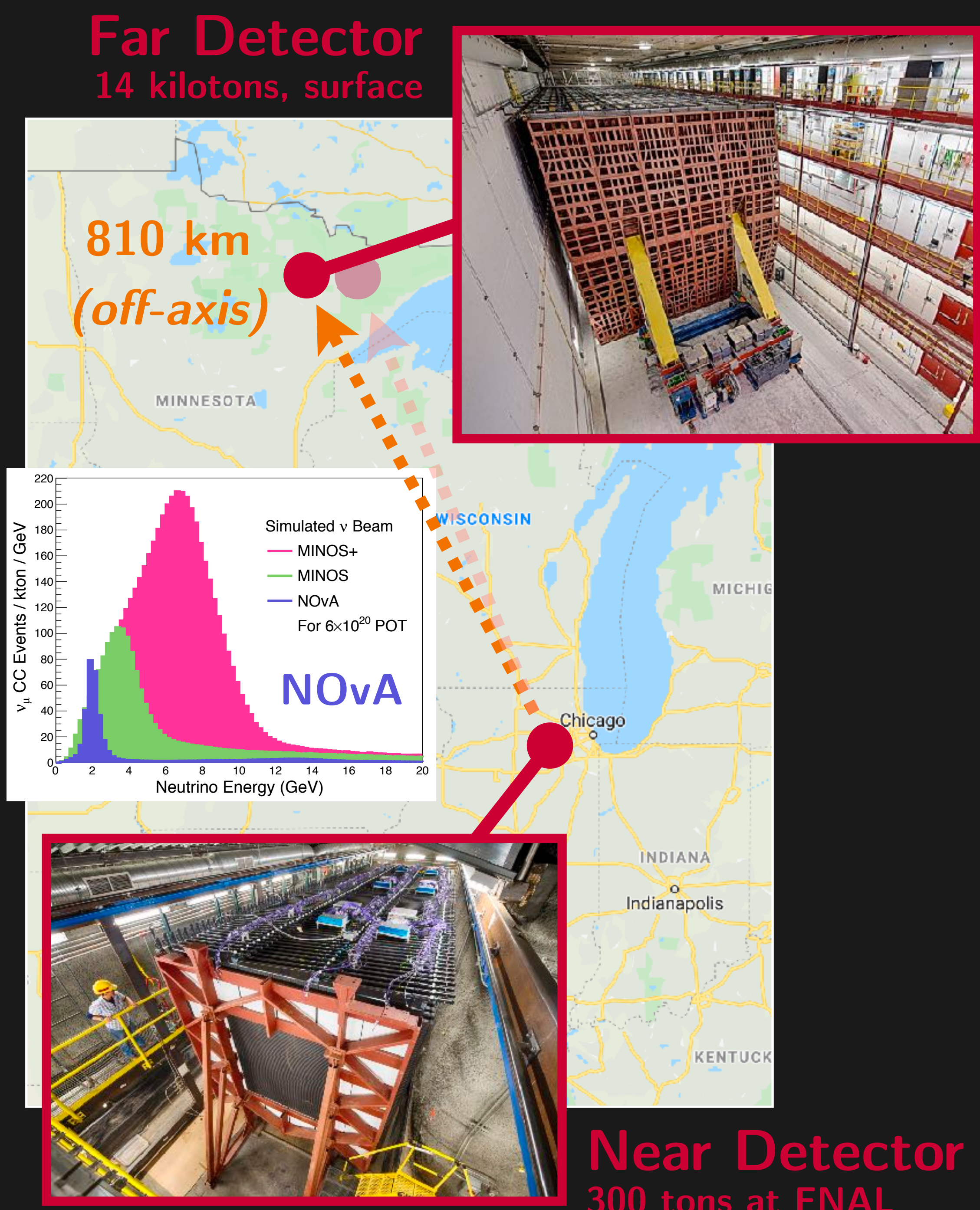
No evidence for sterile neutrinos → strong constraints on these models

Much more in G. Petrillo's Sterile Neutrinos talk, Session 16

Images: Fermilab, MINOS/MINOS+

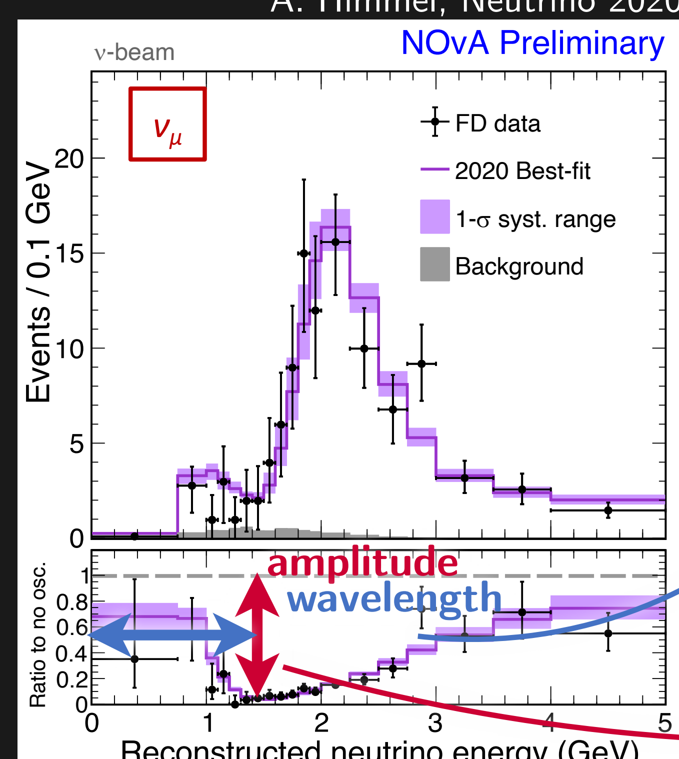
NOvA

- Long-baseline neutrino **oscillations**
- **Beam** and **atmospheric** neutrino analysis
- Neutrino **interactions** with matter
- **Ordering** of neutrino masses, matter-antimatter asymmetry (**CP violation**)
- **Sterile neutrinos** and other new physics



Liquid Scintillator Trackers

A. Himmel, Neutrino 2020



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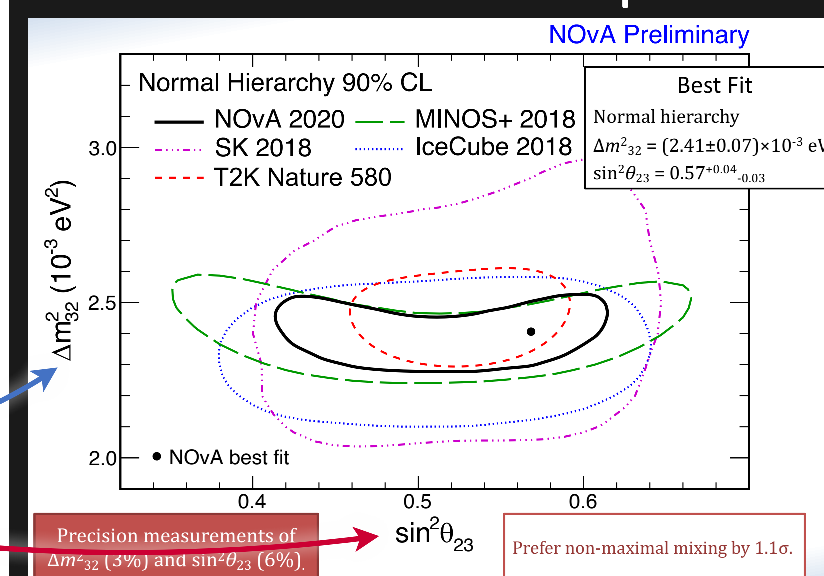
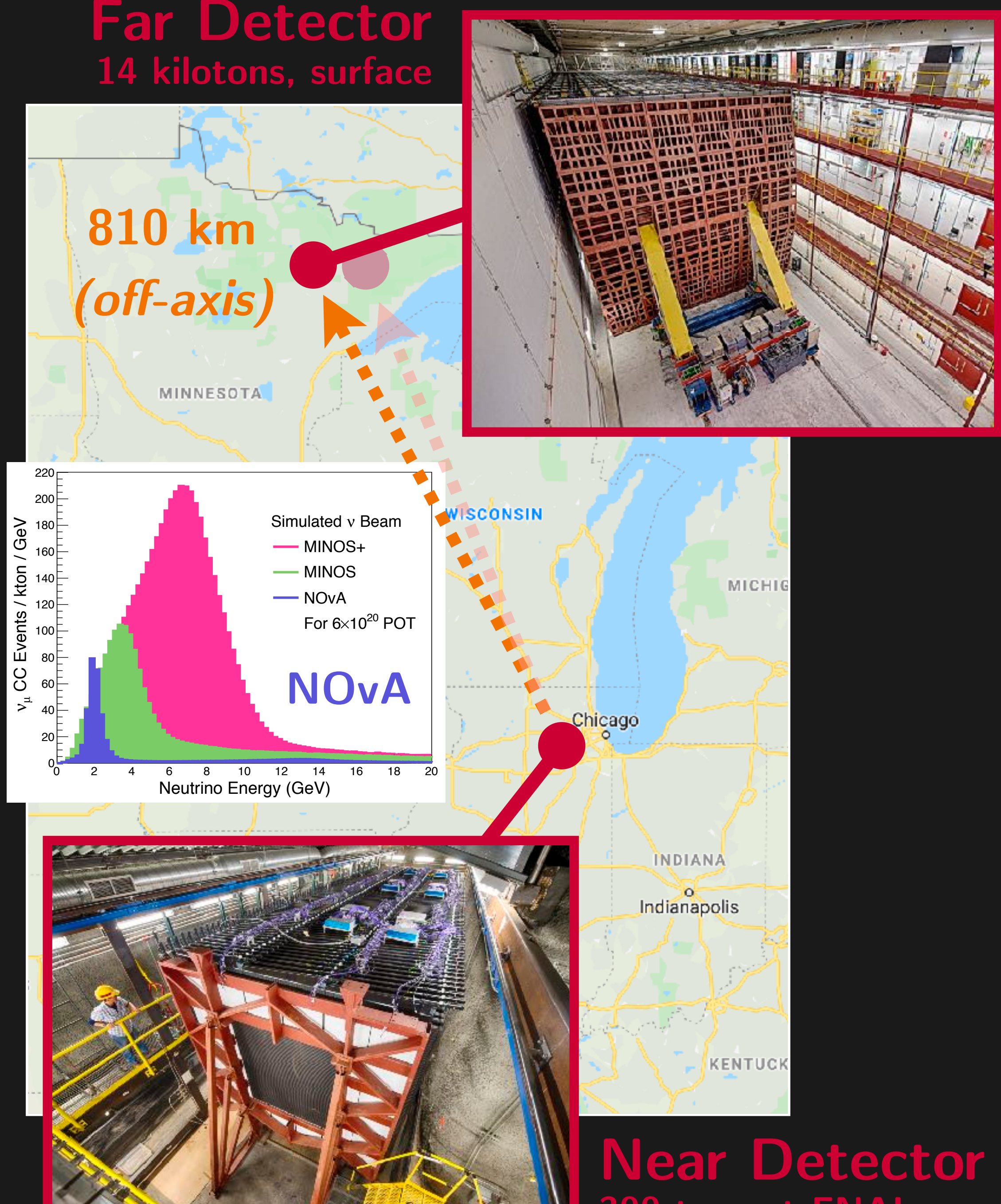


NOvA measurements of the parameters controlling oscillations

NOvA

Far Detector
14 kilotons, surface



Near Detector
300 tons at FNAL

Liquid Scintillator Trackers

- Long-baseline neutrino **oscillations**
- **Beam** and **atmospheric** neutrino analysis
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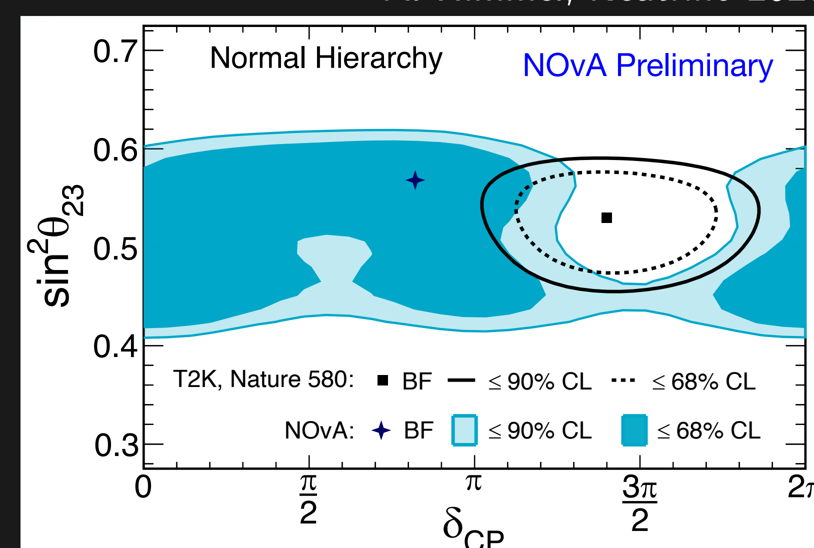
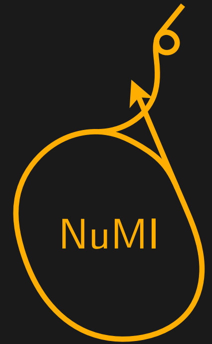
A. Himmel, Neutrino 2020



Insights into a matter/antimatter asymmetry

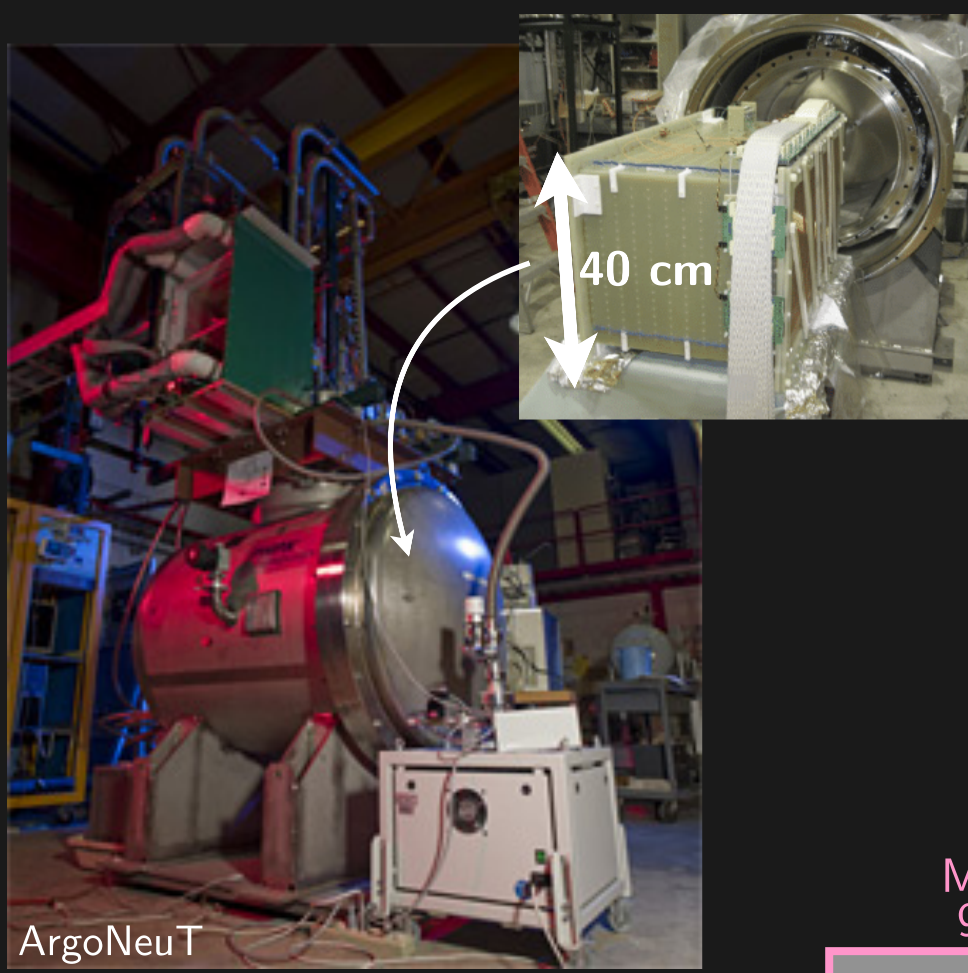
Much more in S. Calvez's NOvA talk, *next* (Session 15)

ArgoNeuT (2009–2010)

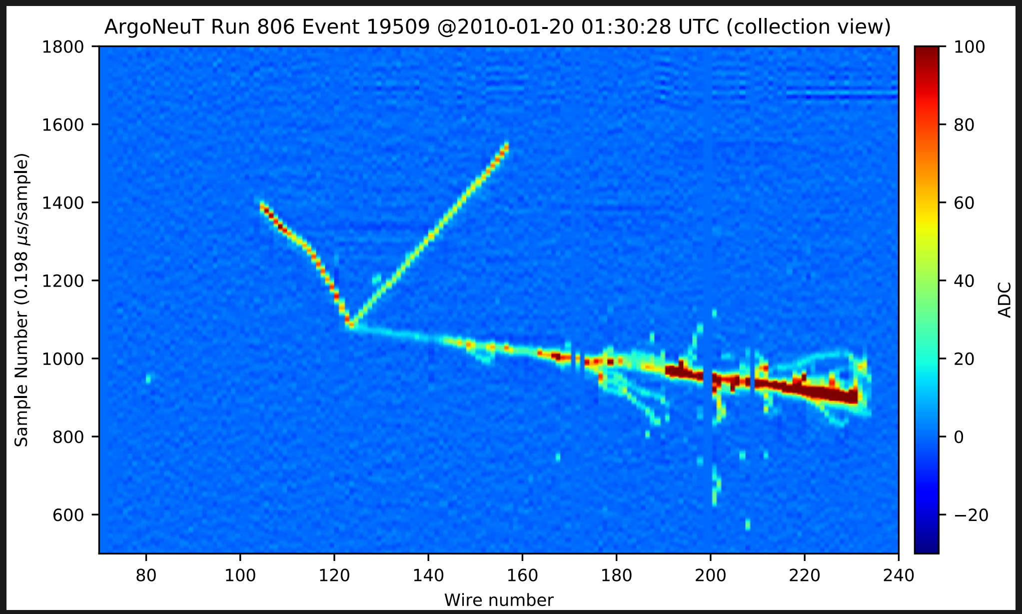


LArTPC: Liquid Argon Time Projection Chamber

3D particle tracking with millimeter-scale resolution

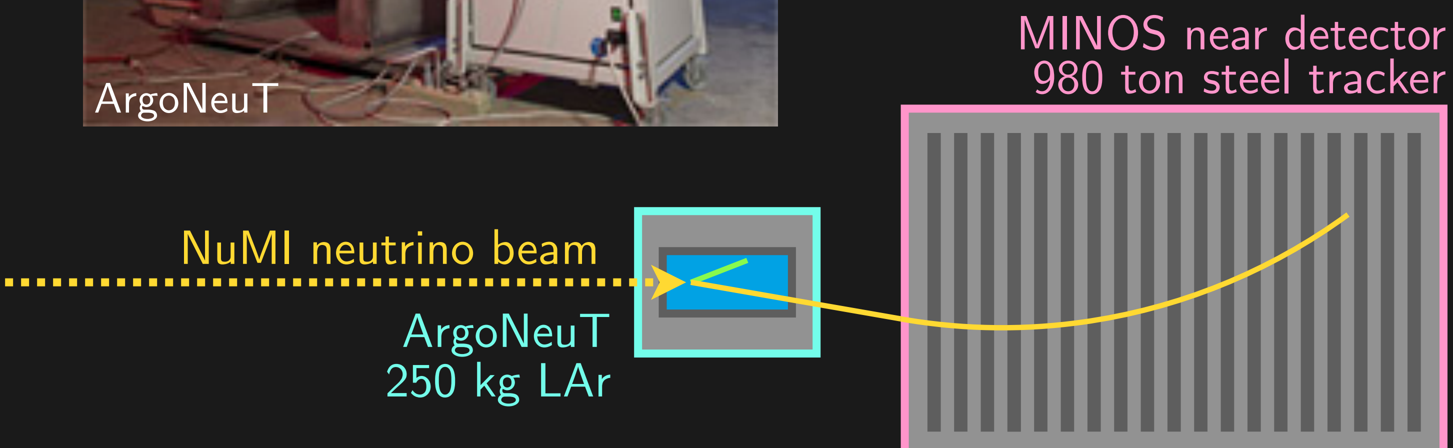


- **Neutrino interactions** with argon
- Physics **Beyond the Standard Model**
- Pioneering measurements of **low-energy interactions** in liquid argon detectors



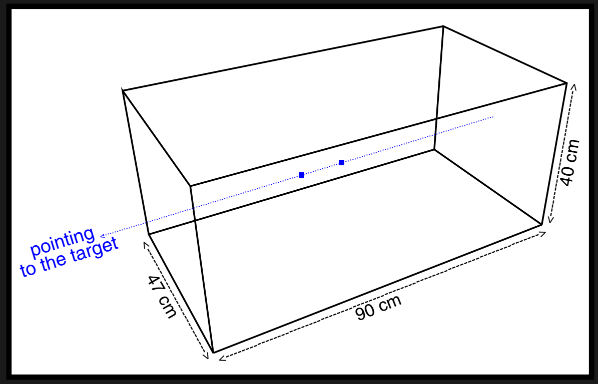
First measurement of the ν_e + argon scattering cross section

Phys. Rev. D 102, 011101 (2020)

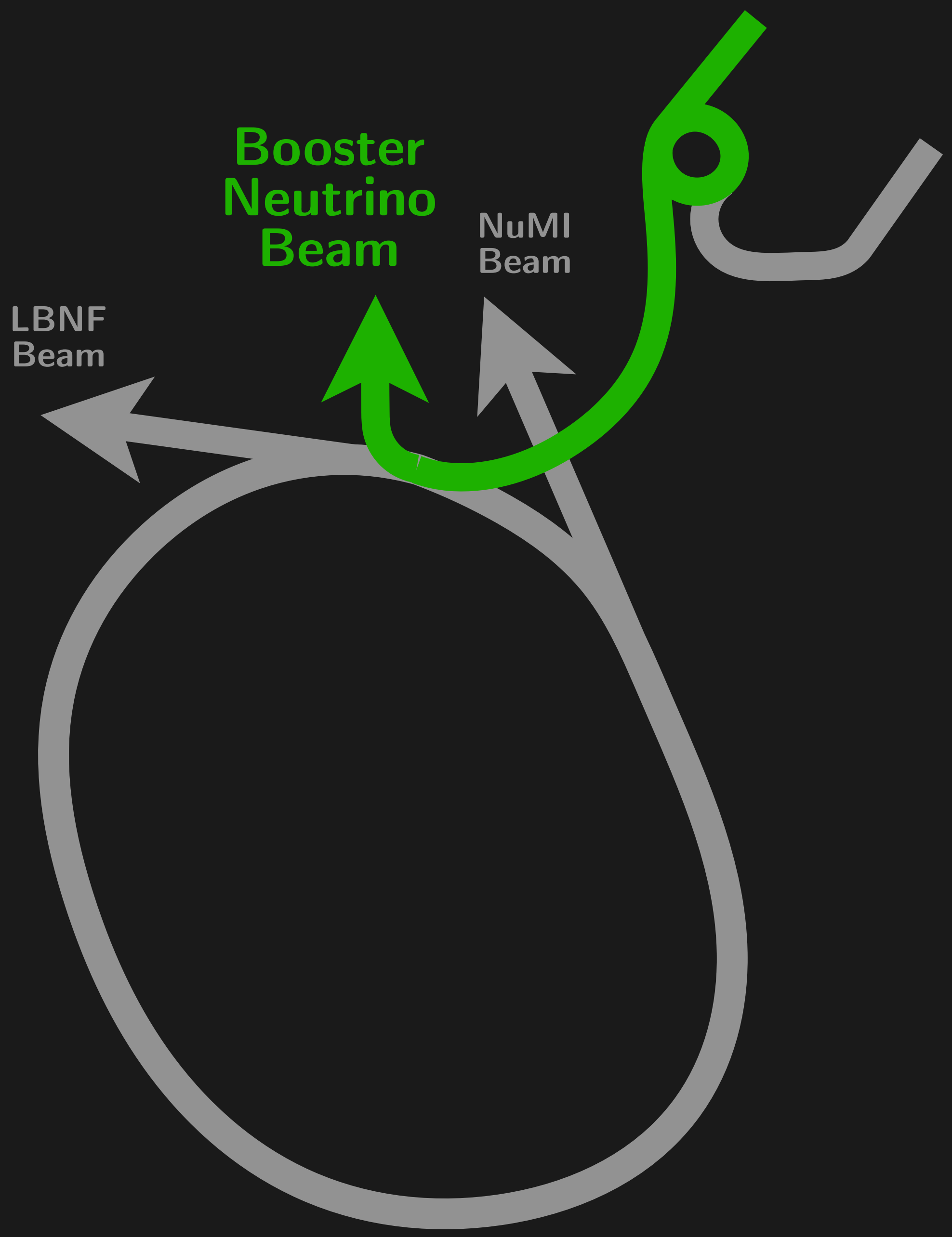


Search for fractionally-charged particles

Phys. Rev. Lett 124, 131801 (2020)



Neutrino Program at Fermilab



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Precision neutrino interactions

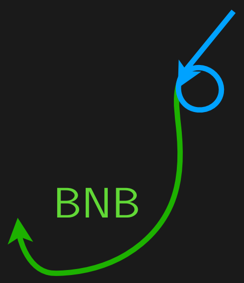
MINOS+
Pioneering long-baseline oscillations

NOvA
Off-axis long-baseline ν_e appearance

SBN Program
Short-baseline oscillations and new physics

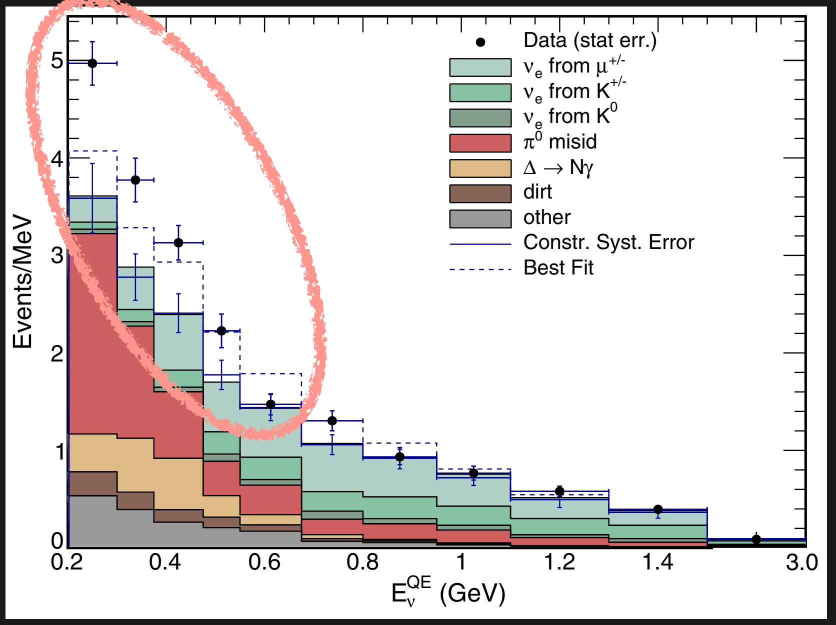
DUNE
Precision long-baseline, CP violation

Short-Baseline Neutrino Program

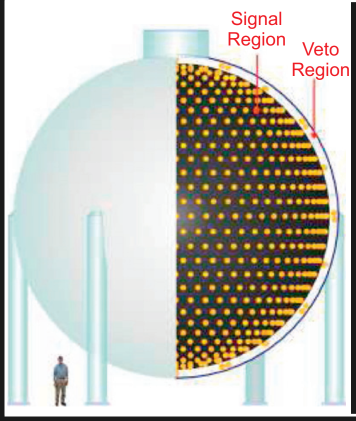


- **Three Liquid Argon TPC detectors**
- Short-baseline oscillations (~600 meters)
  - $\nu_\mu \to \nu_e$ appearance & $\nu_\mu \to \nu_\mu$ disappearance
- **Goal to definitively address outstanding experimental hints of sterile neutrinos**
  - Additional, non-interacting neutrino types
  - Hints from multiple different experiments
- Additional physics **beyond the Standard Model**
- Precise **neutrino-argon** interaction measurements

MiniBooNE's excess of ν_e-like events



MiniBooNE, PRL 121, 221801 (2018)

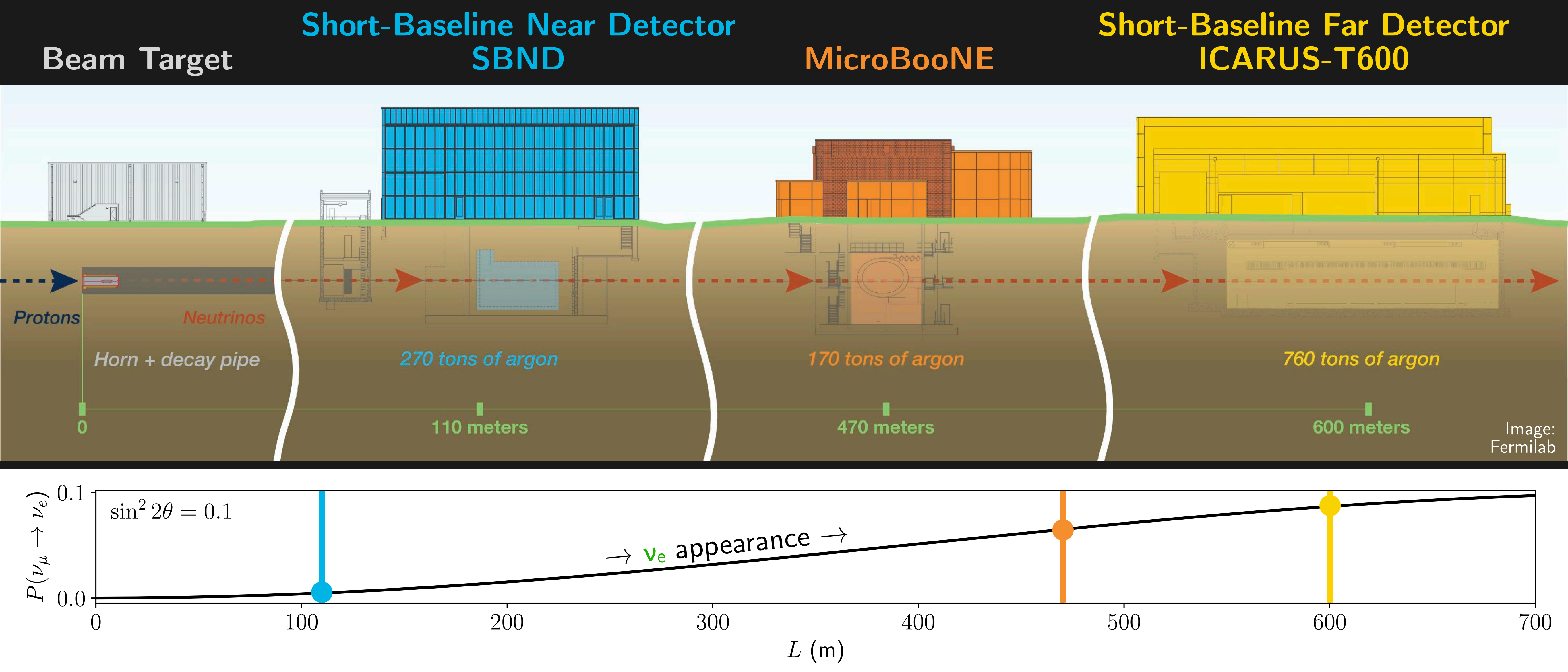


MiniBooNE operated in the Fermilab Booster Neutrino Beam from 2002 – 2019

Updated background analysis presented at Neutrino 2020

Much more in G. Petrillo's Sterile Neutrinos talk, Session 16

Short-Baseline Neutrino Program



Search for short-baseline neutrino oscillations

$\nu_\mu \rightarrow \nu_e$ appearance *and* $\nu_\mu \rightarrow \nu_\mu$ disappearance

Short-Baseline Neutrino Program

Beam Target | **Short-Baseline Near Detector SBND** | MicroBooNE | Short-Baseline Far Detector ICARUS-T600

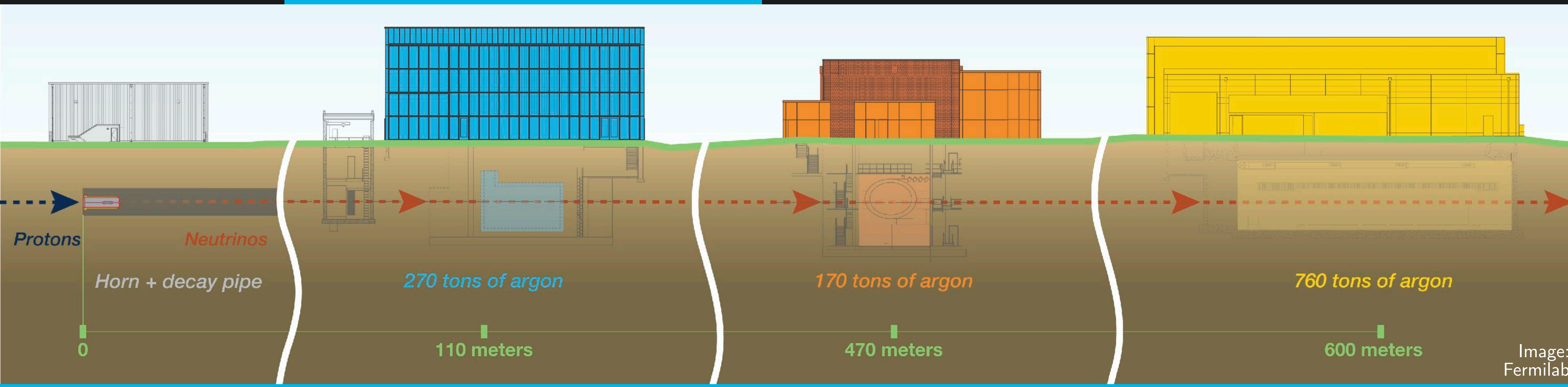
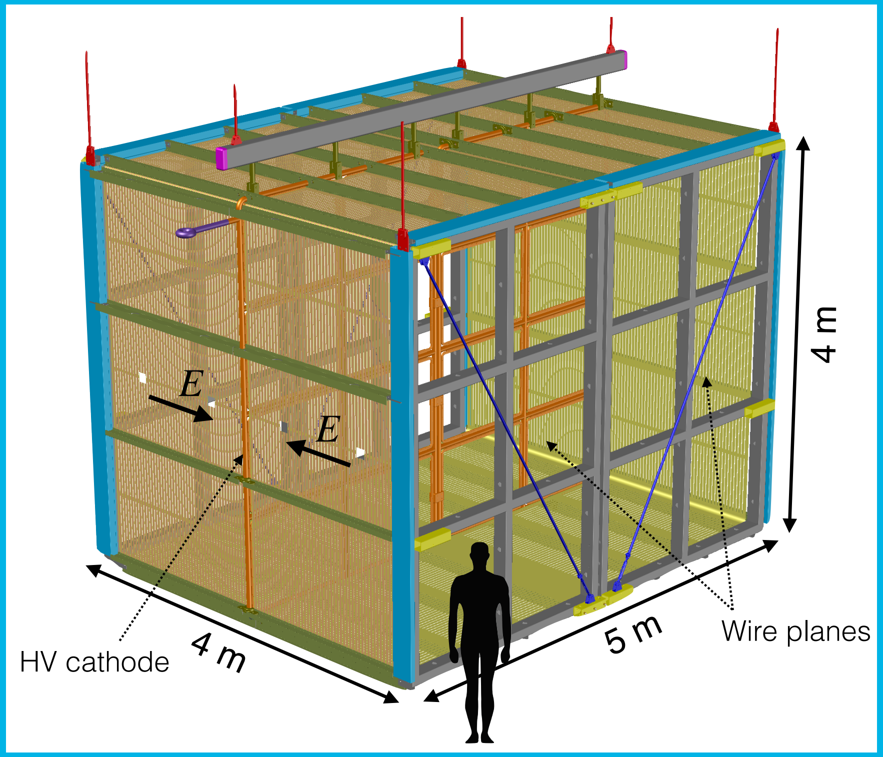


Image: Fermilab

SHORT-BASELINE SBND NEAR DETECTOR

- Construction in 2020
- 112 tons liquid argon
- SBN near detector



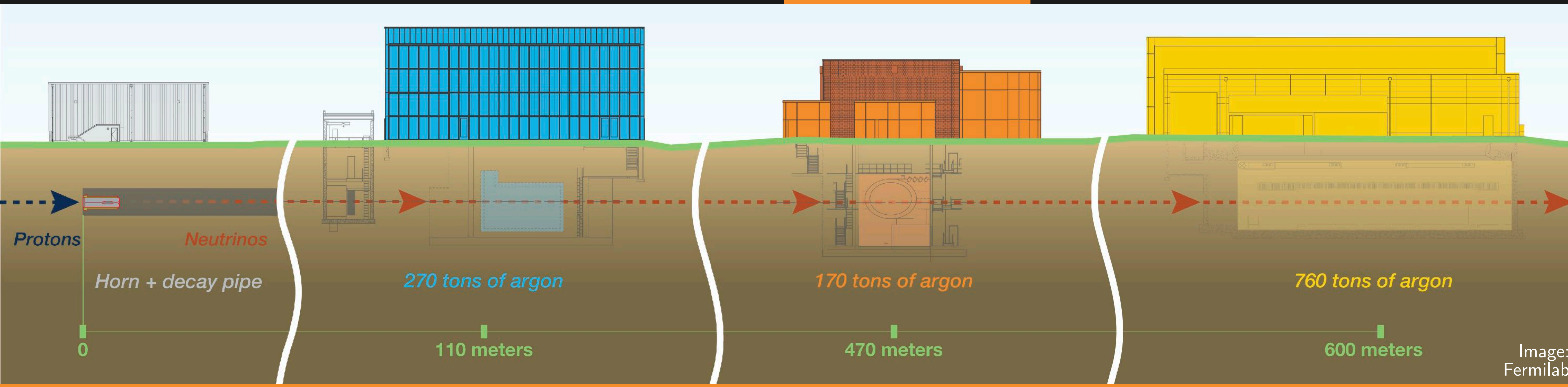
Short-Baseline Neutrino Program

Beam Target

Short-Baseline Near Detector
SBND

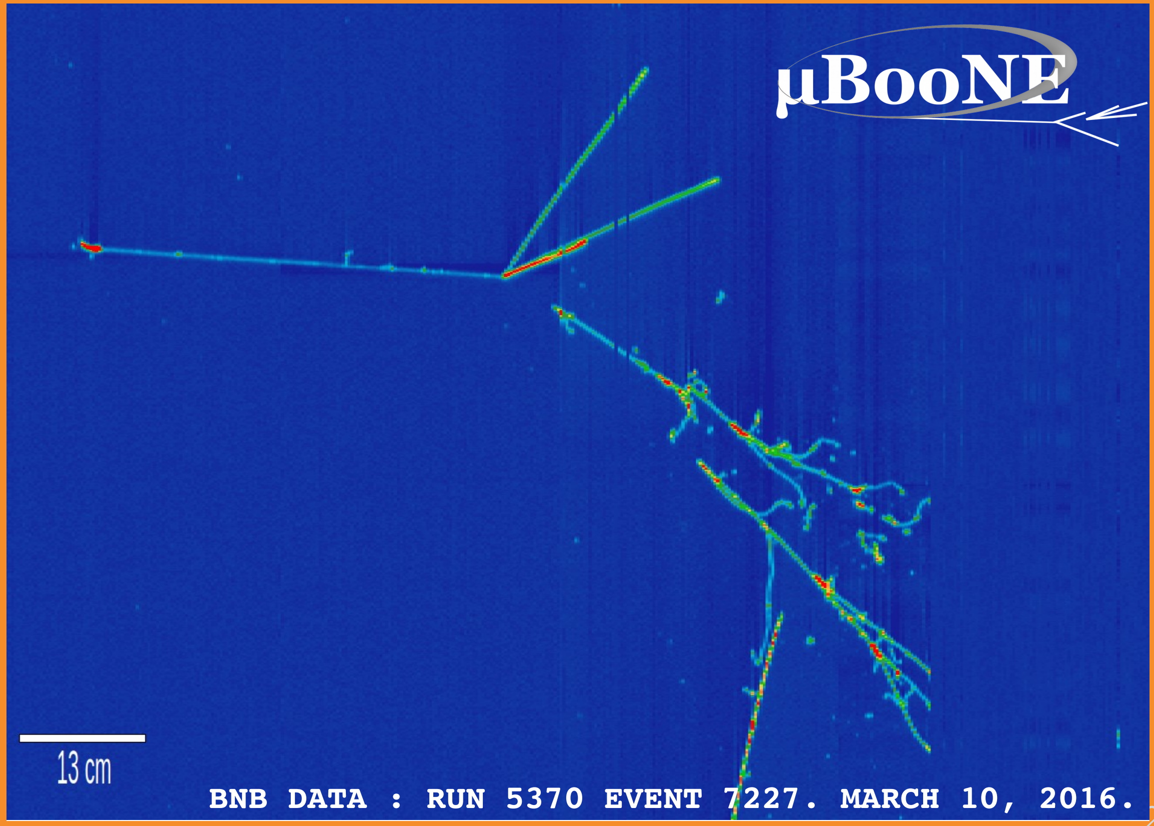
MicroBooNE

Short-Baseline Far Detector
ICARUS-T600



µBooNE

- Running since 2015
- 89 tons liquid argon
- MiniBooNE excess
- Neutrino interactions



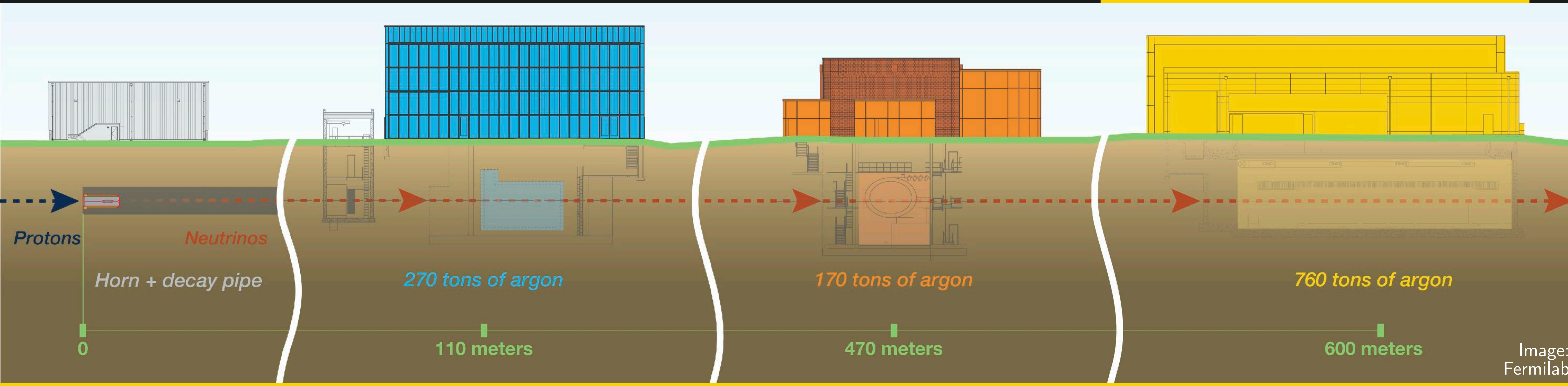
Short-Baseline Neutrino Program

Beam Target

Short-Baseline Near Detector
SBND

MicroBooNE

Short-Baseline Far Detector
ICARUS-T600



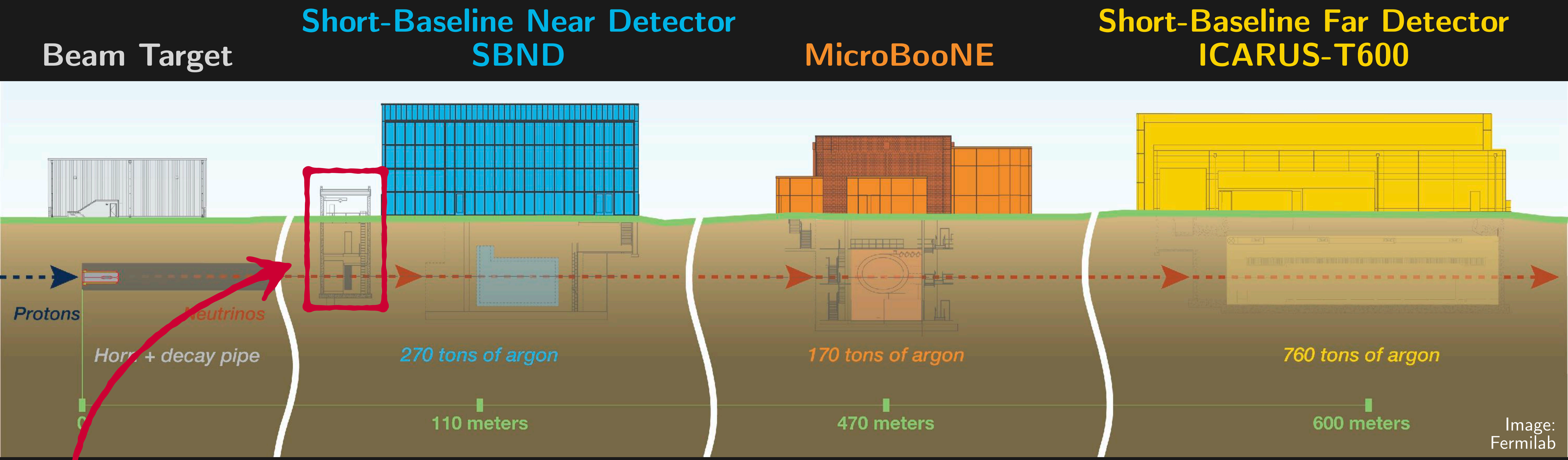
ICARUS@FNAL

- Commissioning 2020
- 600 tons liquid argon
- SBN far detector

Italy (LNGS) → CERN → Fermilab

Installed at Fermilab, April 2020

Short-Baseline Neutrino Program



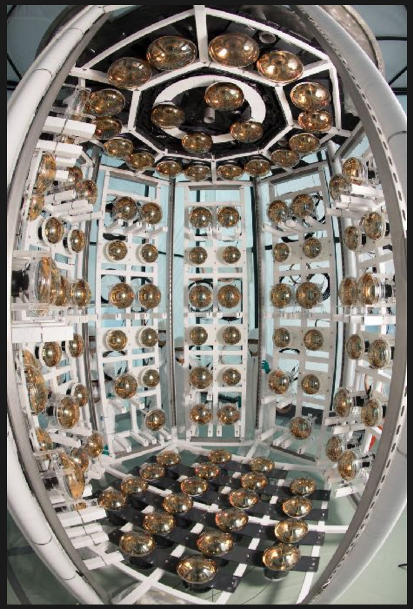
ANNIE: The Accelerator Neutrino Neutron Interaction Experiment

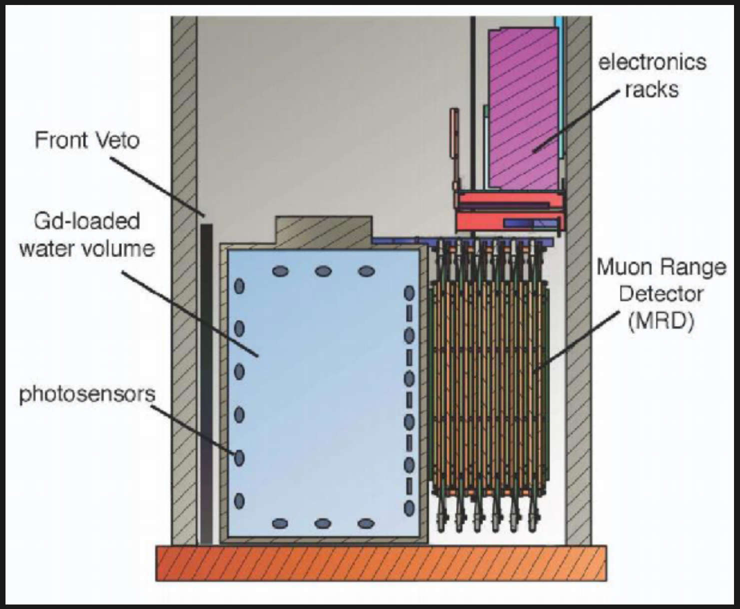
- Cherenkov detector with Gd-loaded water
- **Neutrino interactions** with water
- **Neutron** production in neutrino interactions
- Demonstrate **new technologies**

More details:

S. Gardiner's Cross Sections talk, Session 16

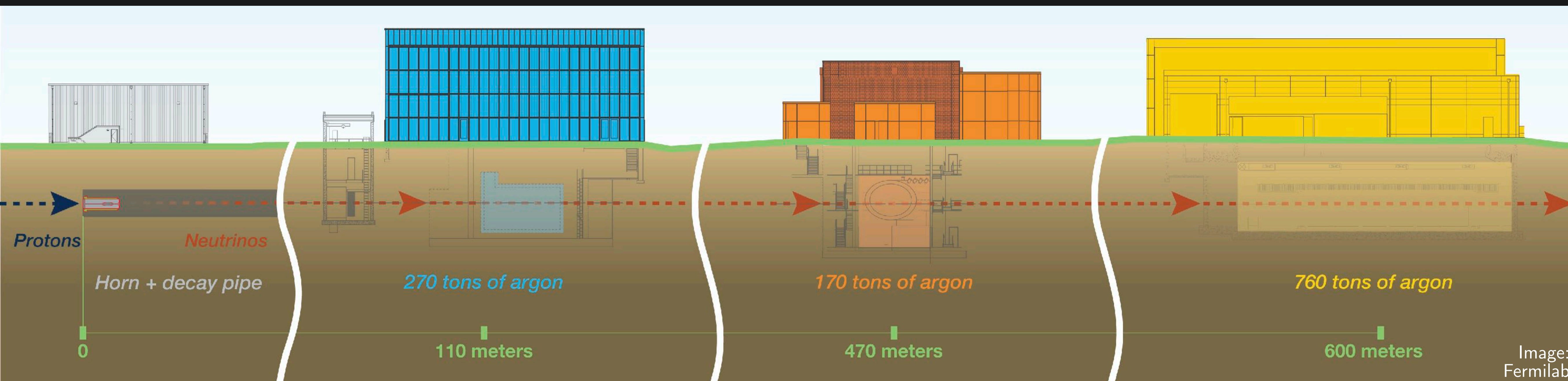
E. Tiras's ANNIE poster





Short-Baseline Neutrino Program

Beam Target | Short-Baseline Near Detector SBND | MicroBooNE | Short-Baseline Far Detector ICARUS-T600



The SBN Program...

- Near/far oscillations with LArTPCs
- Details of neutrino-argon interactions
- Analysis tools development

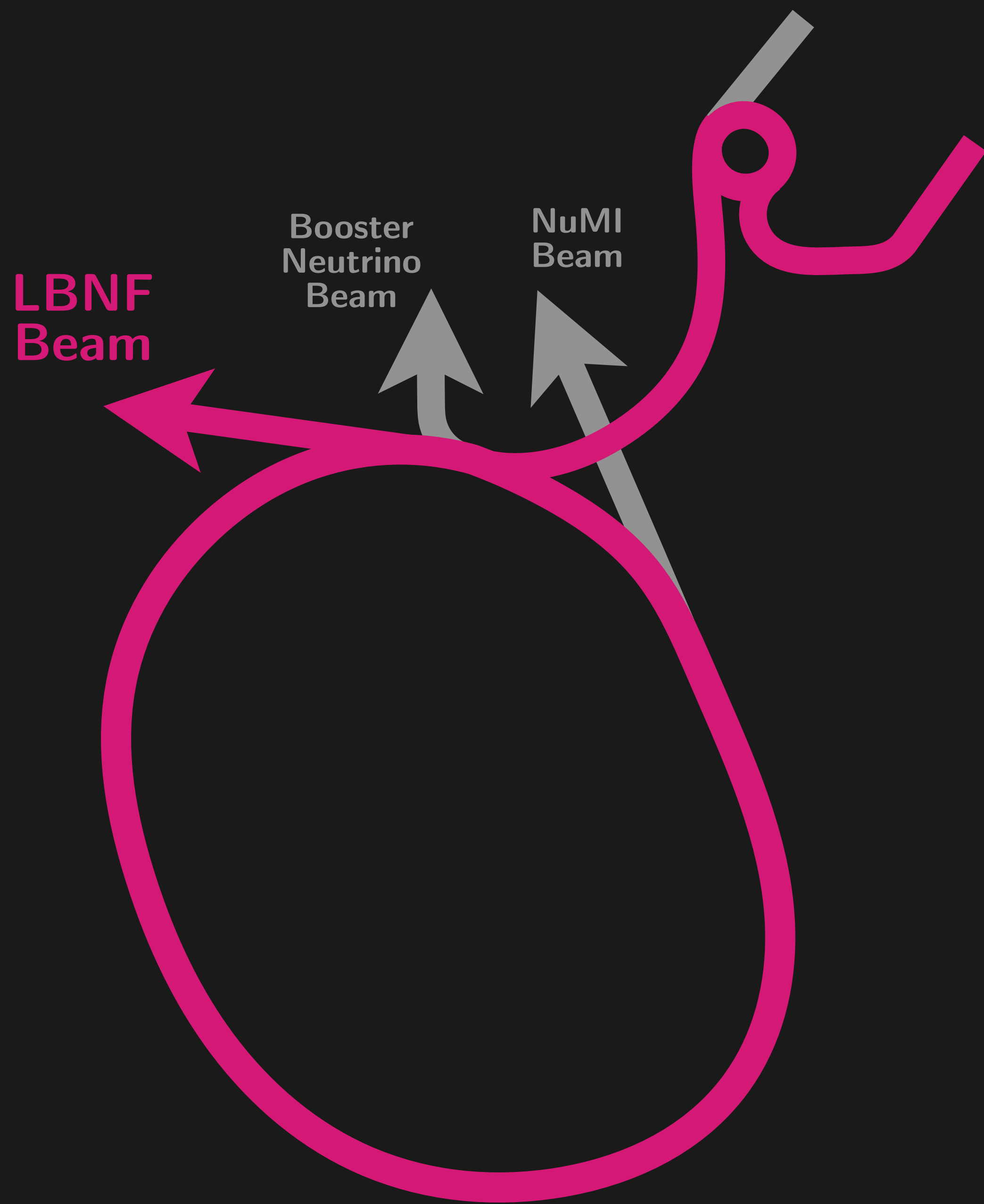
Together with...

- MINERvA: Multi-GeV neutrino interactions
- MINOS+ & NOvA: Long-baseline oscillation measurements in $\nu_\mu \rightarrow \nu_\mu$ and $\nu_\mu \rightarrow \nu_e$

Enable the next frontier in neutrino physics:

DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT

Neutrino Program at Fermilab



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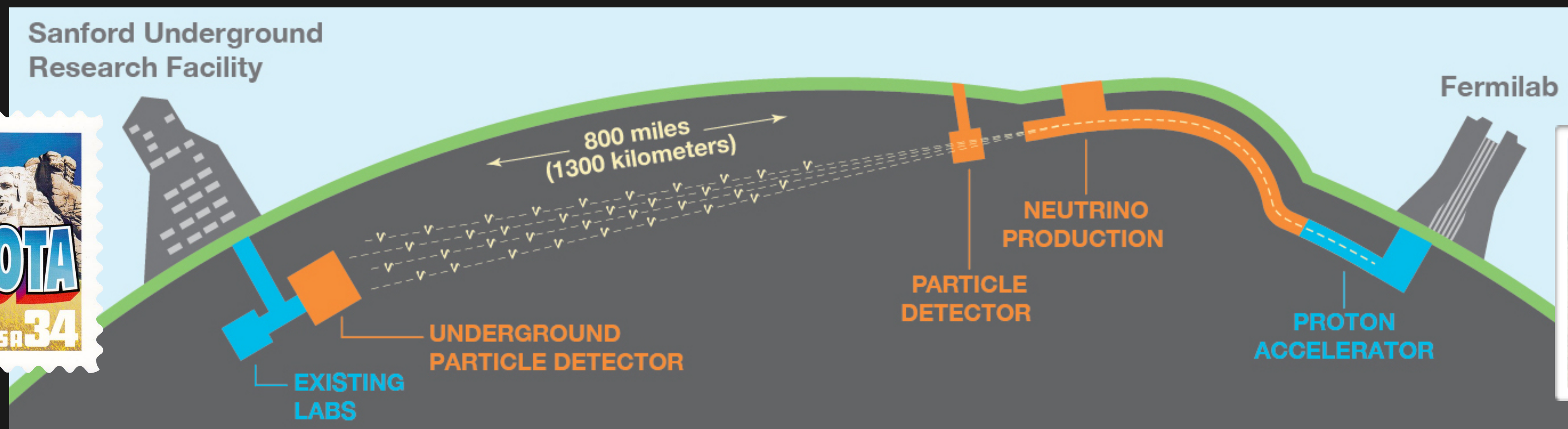
DUNE
Precision long-baseline, CP violation

DEEP UNDERGROUND NEUTRINO EXPERIMENT

LBNF

© USPS



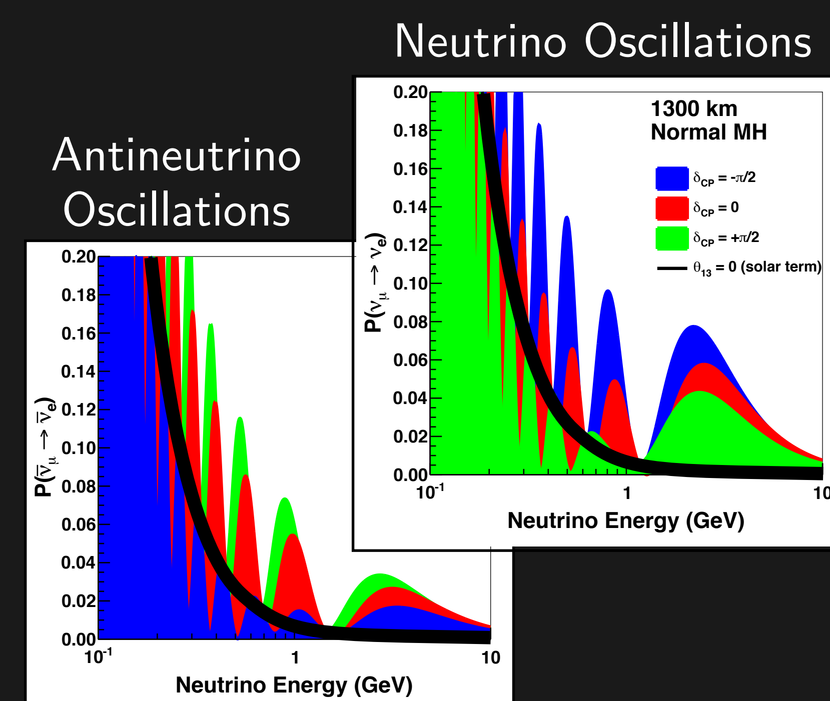
Unification of Forces

Origins of Matter

Supernovae & Black Holes

- **CP violation** and the matter-antimatter puzzle
- Searches for **proton decay**, related to unified theory of fundamental forces
- Detection of **supernova neutrinos**
- **Beyond the Standard Model** physics
  - Dark matter, new interactions, and more

Do neutrinos and antineutrinos oscillate differently?

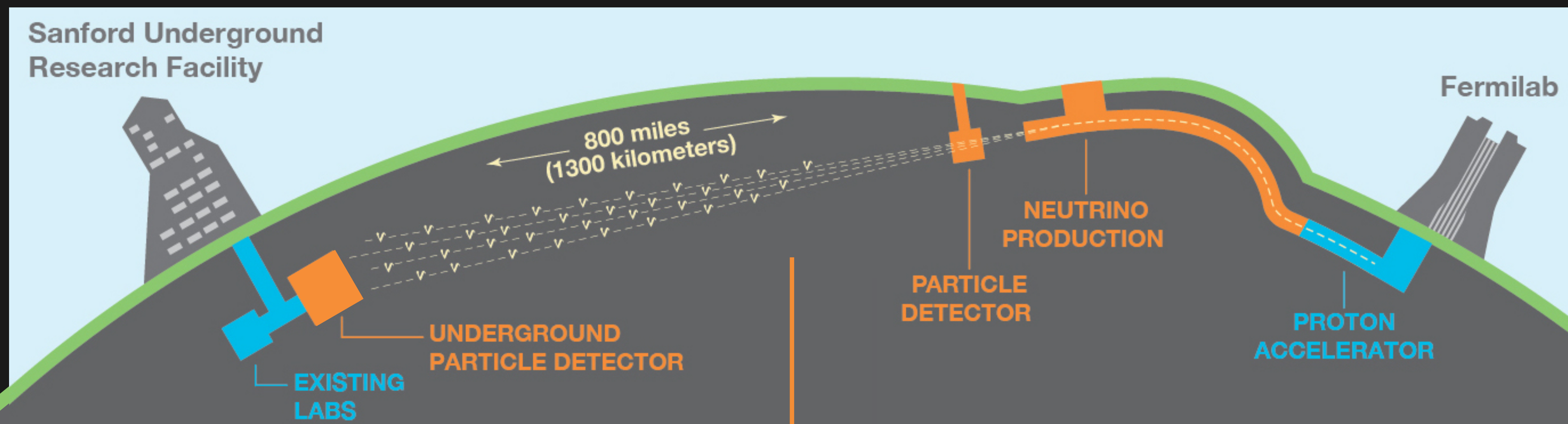


Can this help explain why our universe filled with matter instead of... no stuff at all?

Images: DUNE, Fermilab

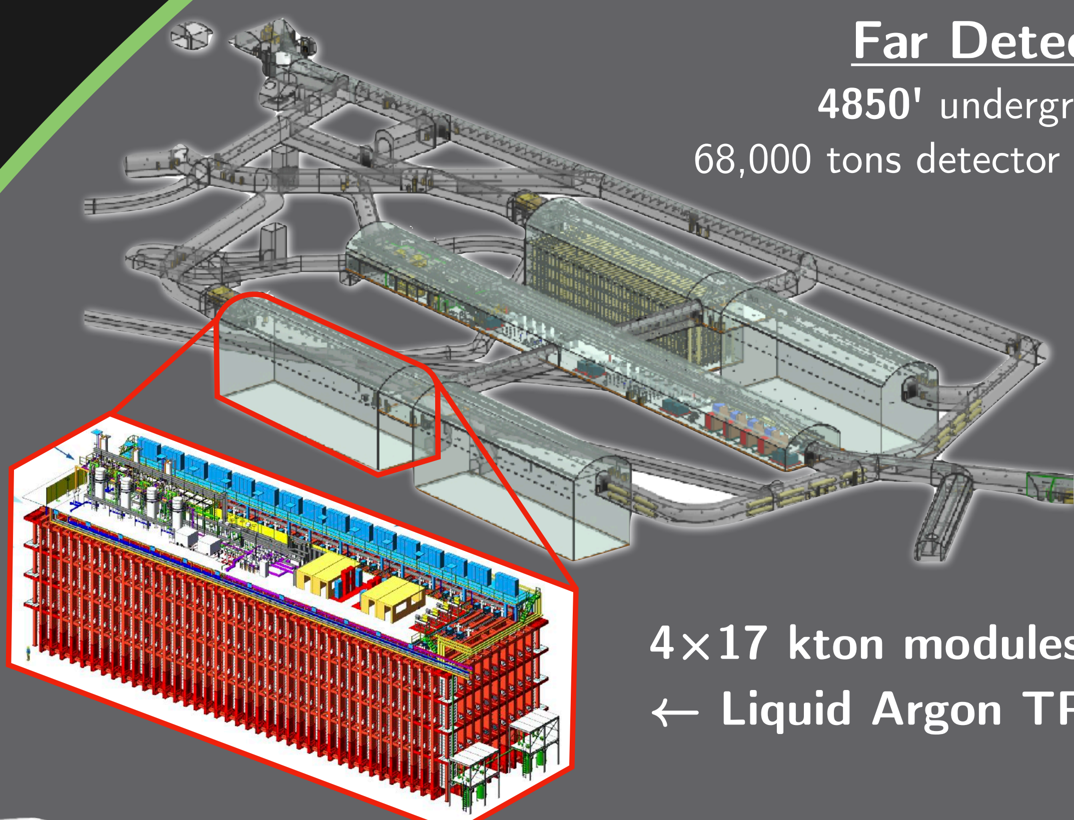
DEEP UNDERGROUND NEUTRINO EXPERIMENT

LBNF

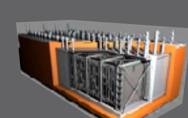


Far Detector

4850' underground
68,000 tons detector mass



4×17 kton modules
← Liquid Argon TPC

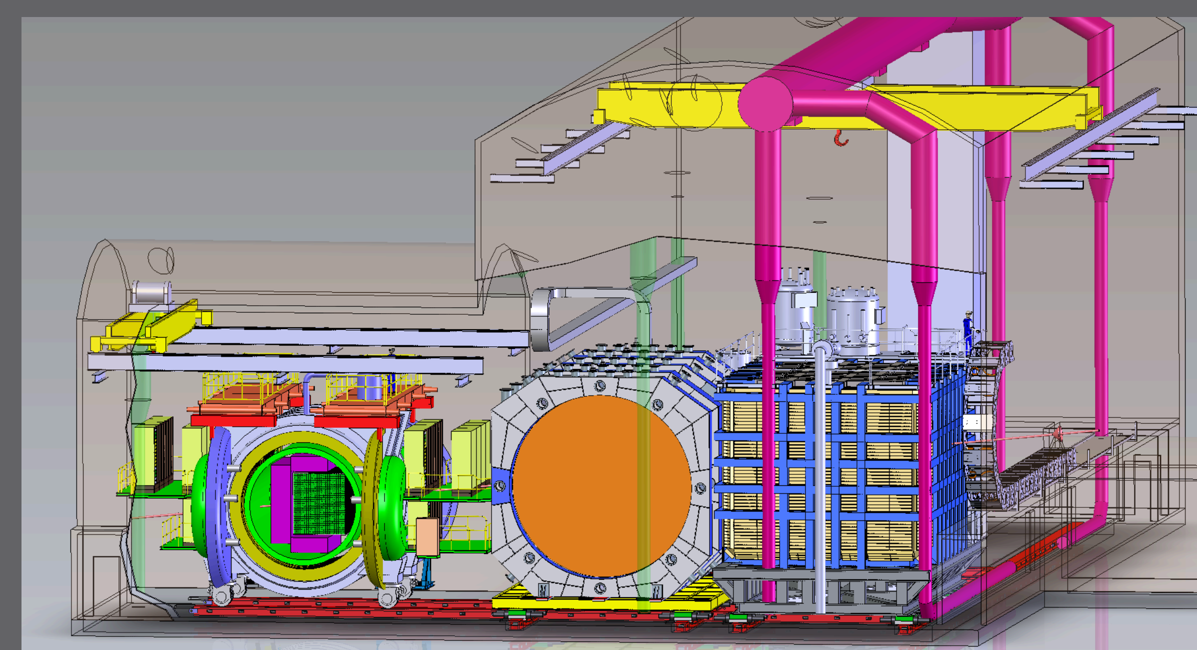


ICARUS
760 tons

(for scale)

Near Detector

On site at Fermilab
Powerful pre-oscillation constraints



Multiple complementary detector technologies

More details in T. Yang's DUNE talk, Session 16

Images: DUNE, Fermilab

Summary

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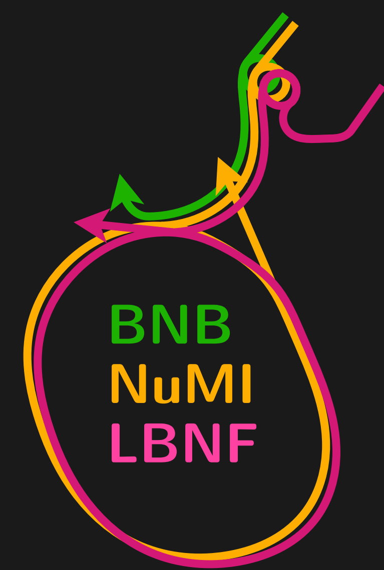
Neutrinos and their oscillations provide a window into the Standard Model and beyond



Fermilab's neutrino beams provide a world-class platform for studying neutrino interactions & oscillations

Fermilab's diverse experimental neutrino program continues to be at the forefront of the our most compelling physics questions

Thank you!

and enjoy the User's Meeting Neutrino Sessions!