

Current and Future Neutrino Experiments in the U. S.

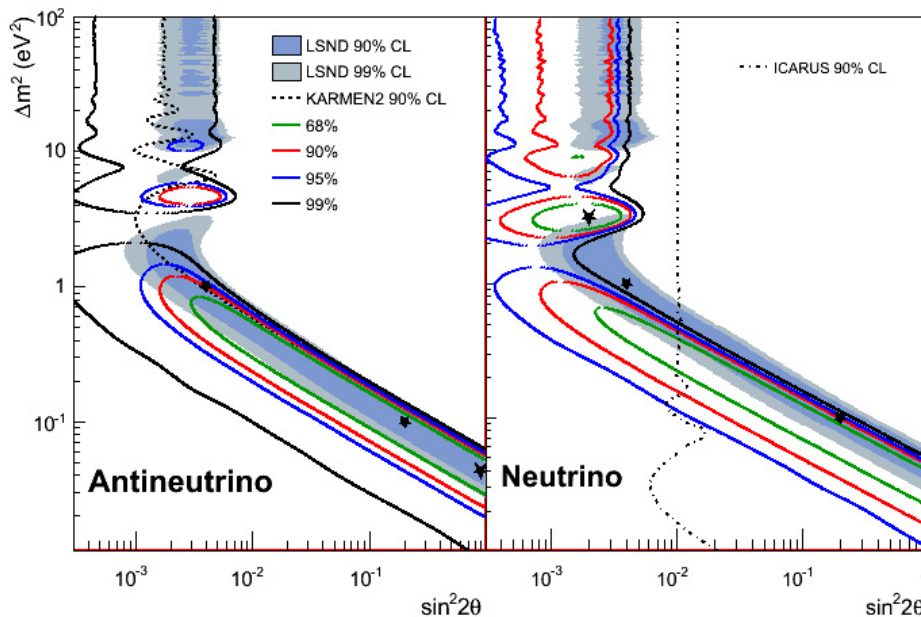
Kam-Biu Luk
UC Berkeley and LBNL

GRC, IAS HKUST, Hong Kong
27 June 2017

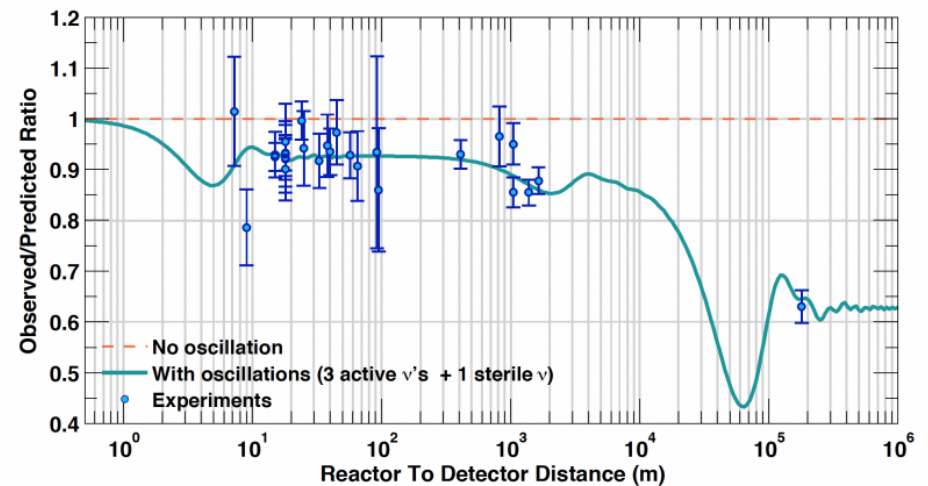
Neutrino Physics To be Addressed

- Determination of mixing/oscillation parameters
 - Measurement: θ_{13} , θ_{23} , $|\Delta m_{32}^2|$
 - Unknowns: mass hierarchy (sign of Δm_{32}^2), CP violation (δ_{CP})
- Search for light sterile neutrinos

Existence hints

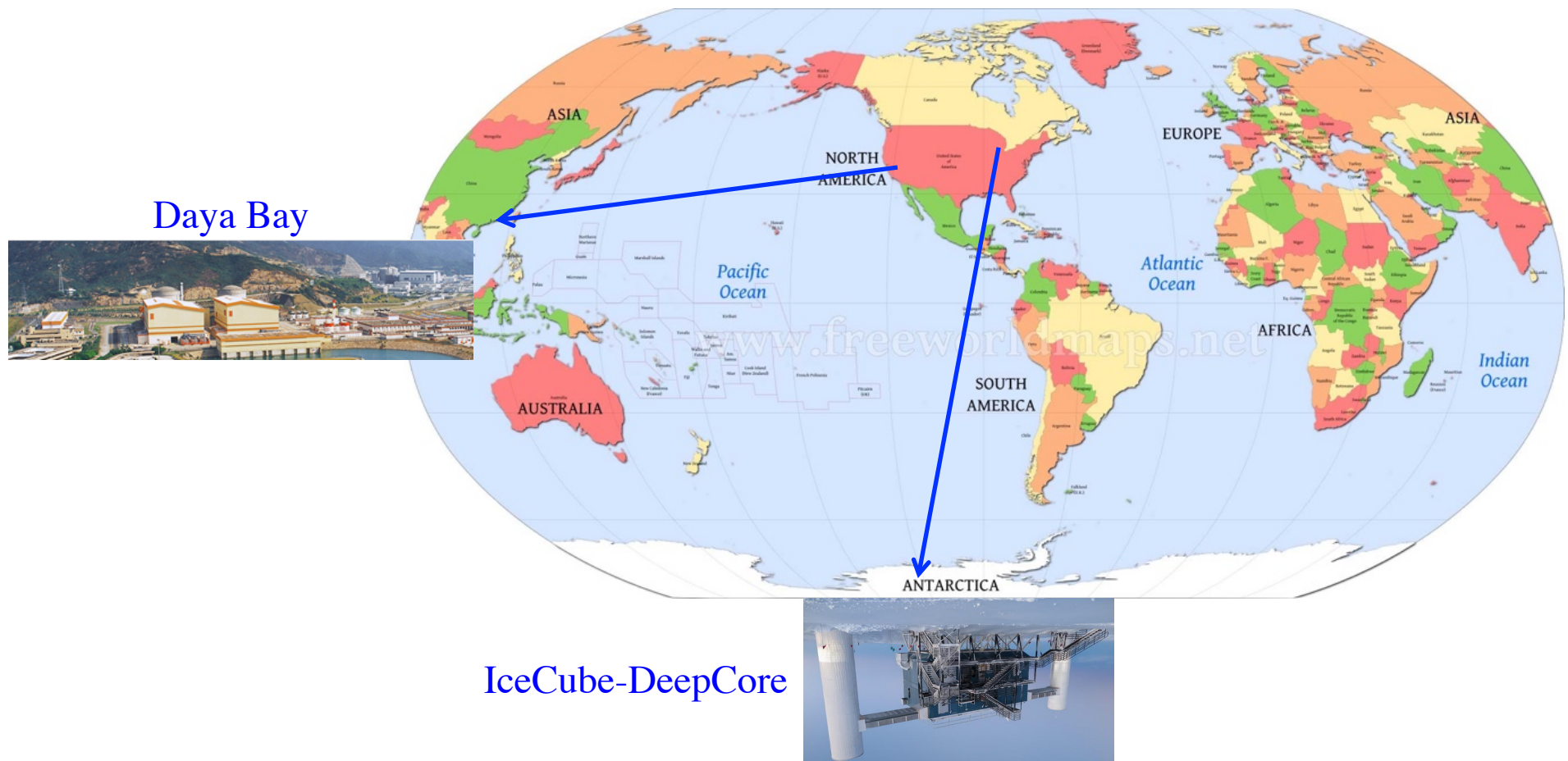


LSND/MiniBooNE Anomaly



Reactor Antineutrino Anomaly

Neutrino Experiments With Major US Involvement



Neutrino Source	Current Experiments	Future
Reactor	Daya Bay	PROSPECT
Accelerator	MINOS+, NOvA, MicroBooNE, MINEvA	DUNE, SBN
Atmospheric/Cosmic	IceCube-DeepCore	Gen2-PINGU (?)

Daya Bay



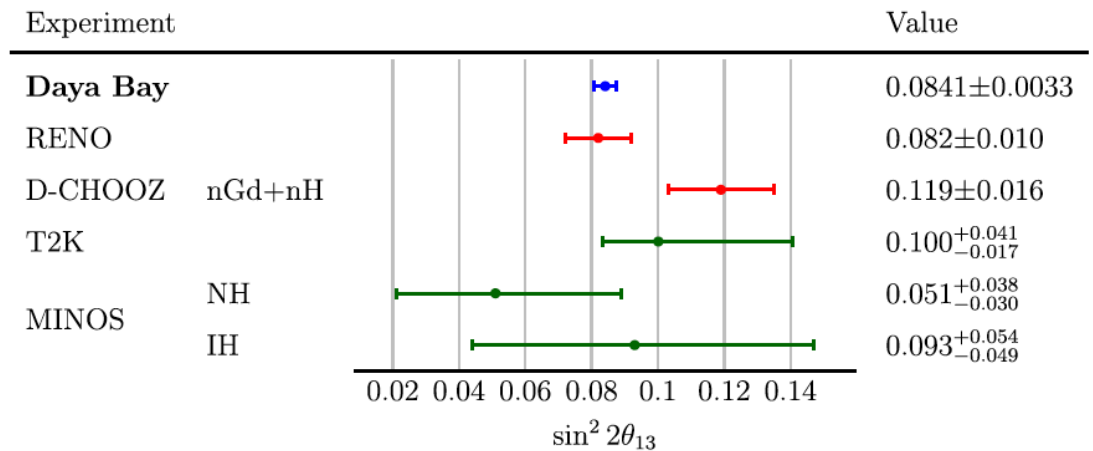
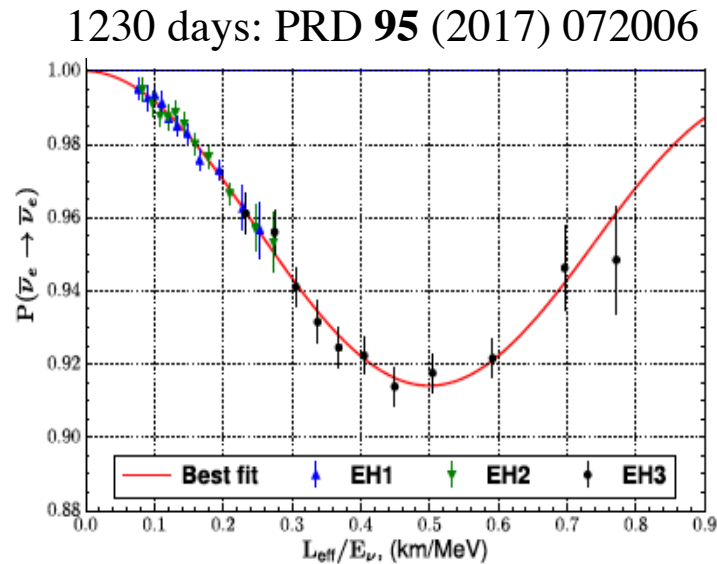
- Ongoing reactor antineutrino experiment focusing on
 - Precise measurement of mixing angle θ_{13} and mass splitting $|\Delta m^2_{32}|$
 - Precise measurement of absolute flux and energy spectrum of reactor antineutrinos
 - Search for a light sterile neutrino
 - Search for new neutrino phenomena
 - Search for supernova neutrinos
- Collect data from 2011 to 2020.



Daya Bay: Most Precise θ_{13}

$$\sin^2 2\theta_{13} = 0.0841 \pm 0.0027 \pm 0.0019$$

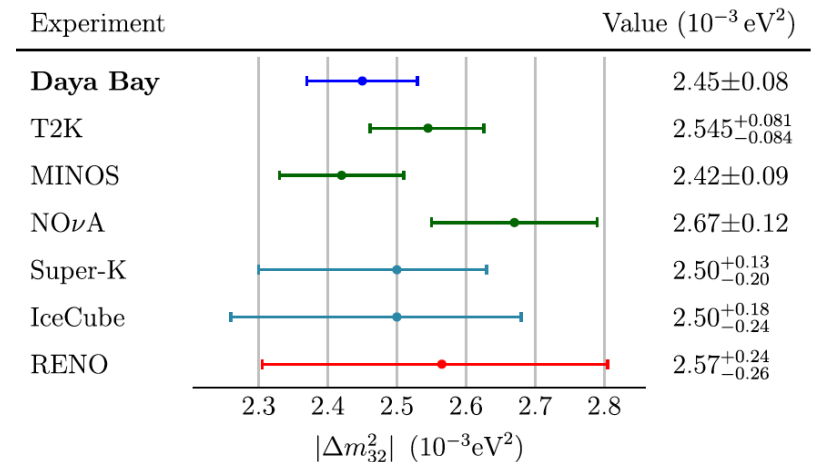
- Ultimate precision ≈ 0.0025 , the best in the foreseeable future.



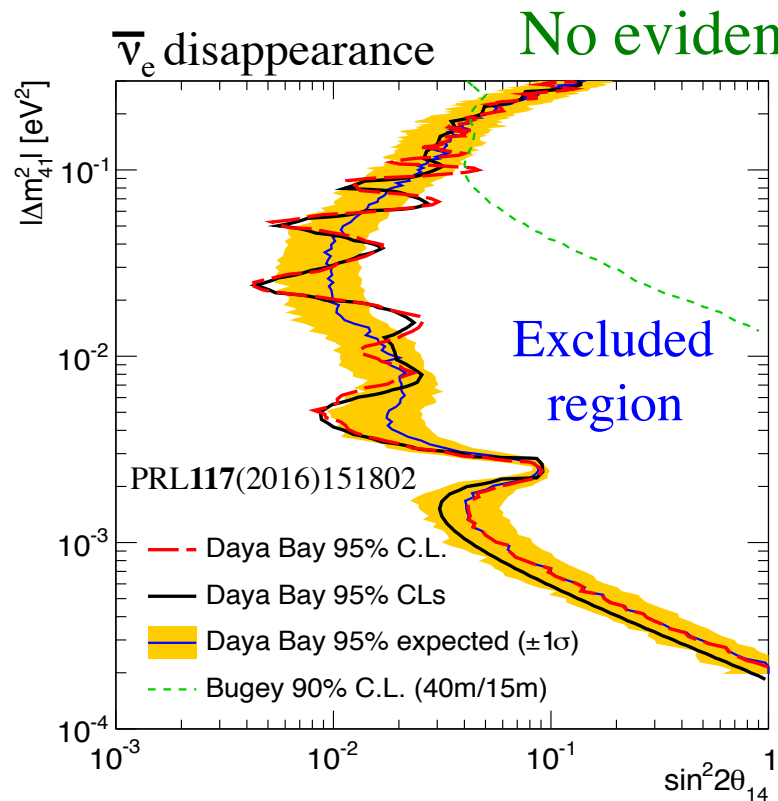
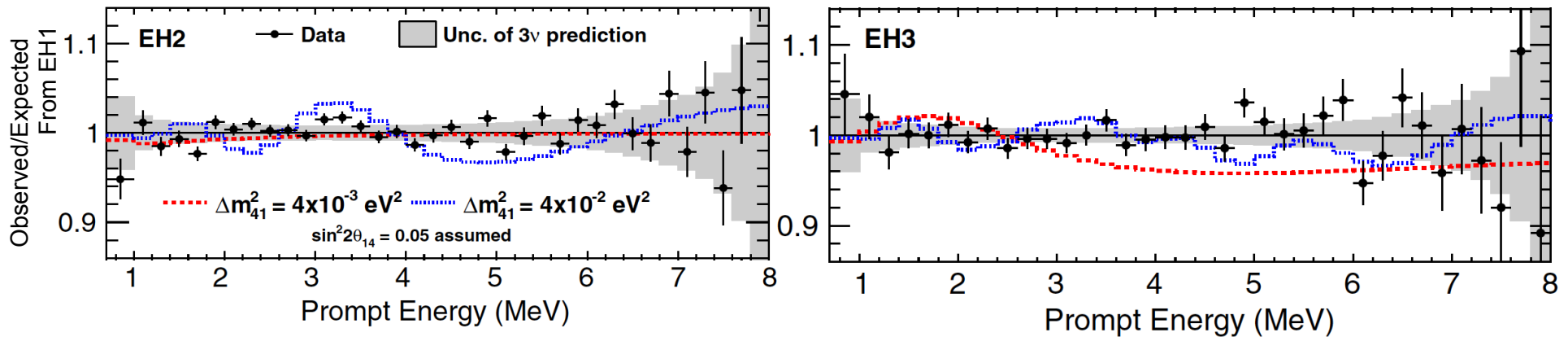
$$\Delta m_{32}^2 = (+2.45 \pm 0.06 \pm 0.06) \times 10^{-3} \text{ eV}^2 \text{ (NH)}$$

$$\Delta m_{32}^2 = (-2.56 \pm 0.06 \pm 0.06) \times 10^{-3} \text{ eV}^2 \text{ (IH)}$$

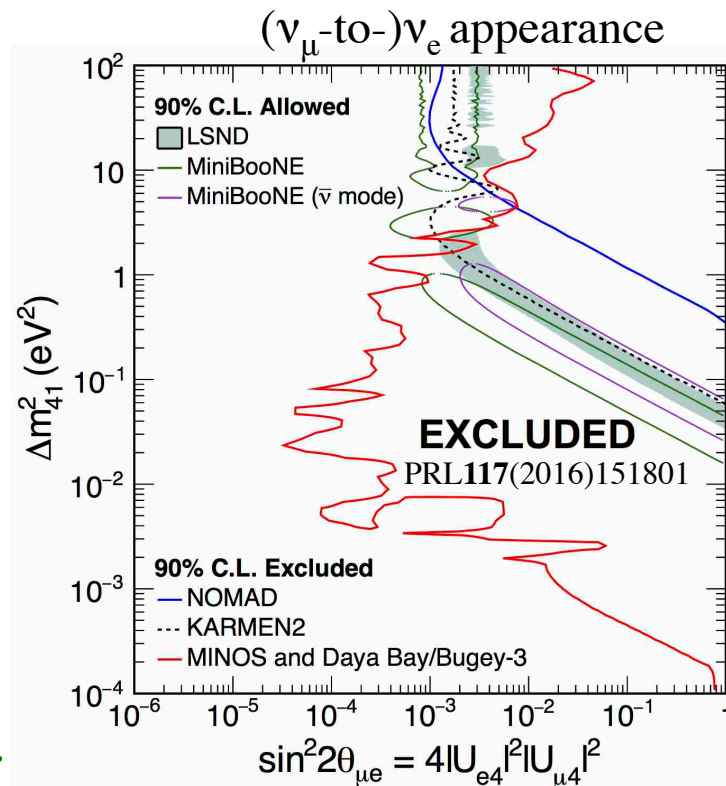
- Final precision $\approx 0.06 \times 10^{-3} \text{ eV}^2$
- Agreement between the ν_e and ν_μ experiments strongly supports 3-flavor mixing.



Daya Bay: Search For Light Sterile Neutrino



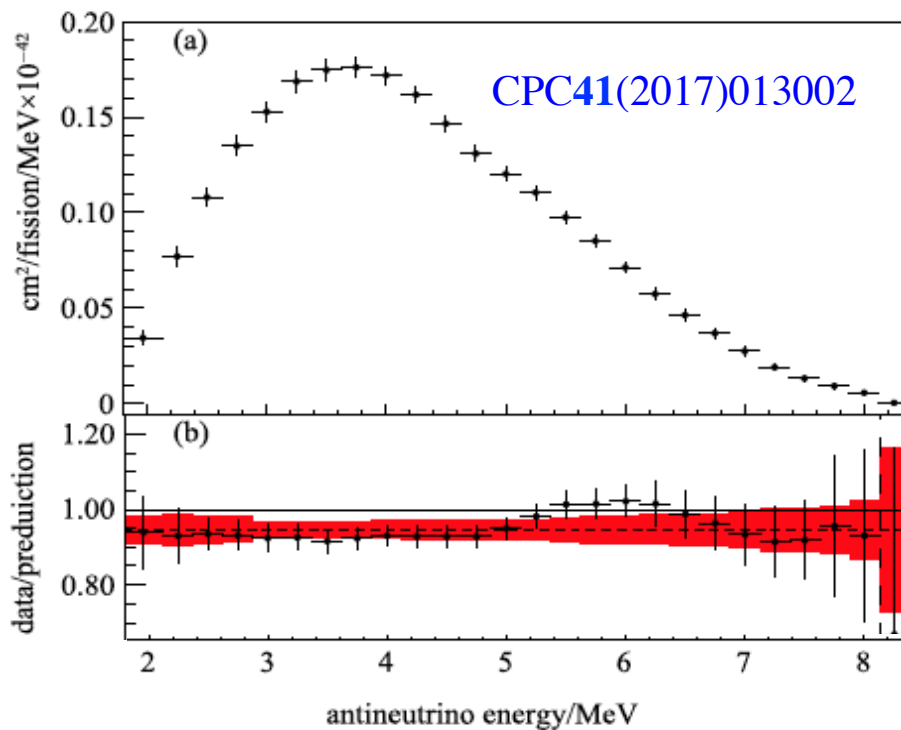
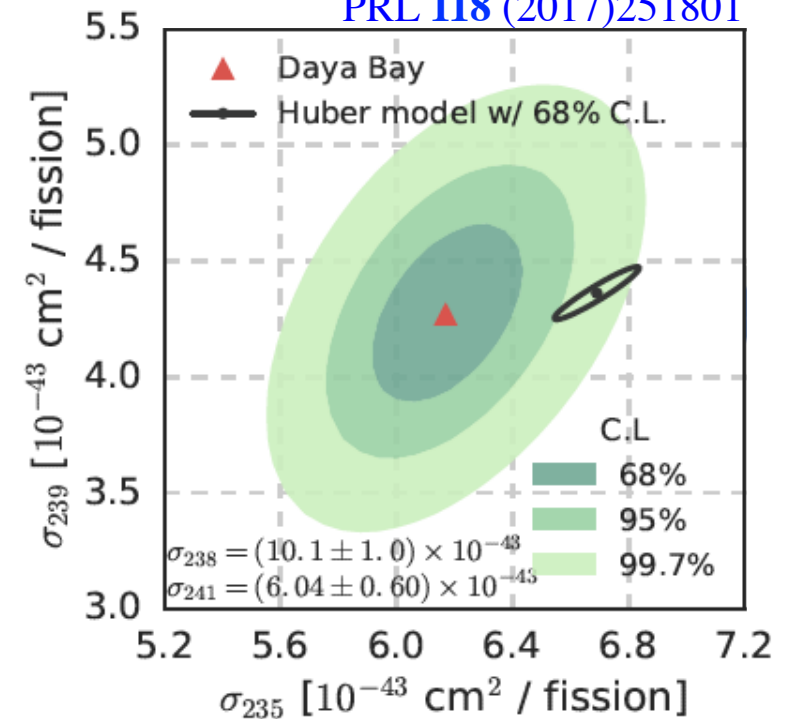
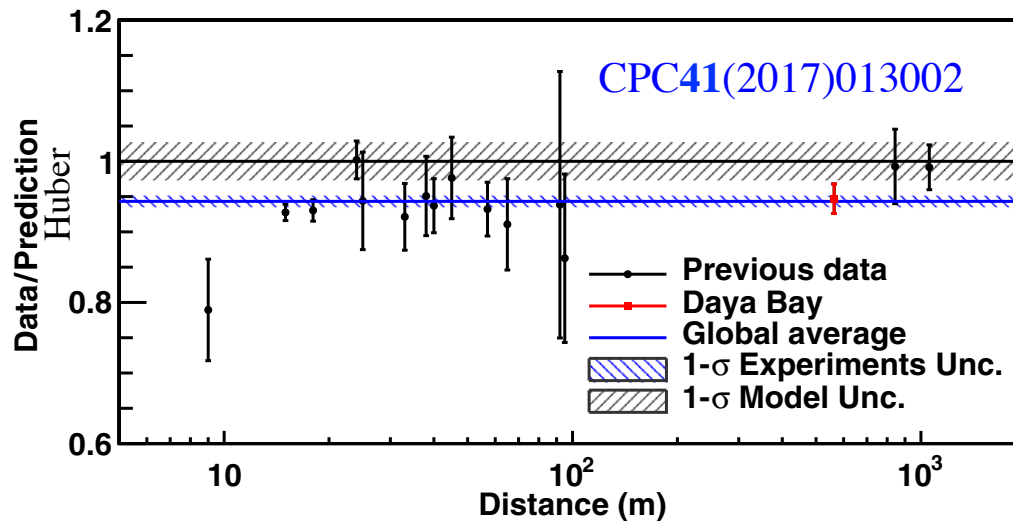
The best limit in this mass range.



Ruled out a good fraction of the LSND and MiniBooNE's allowed regions

Daya Bay: Reactor Antineutrino

PRL 118 (2017)251801

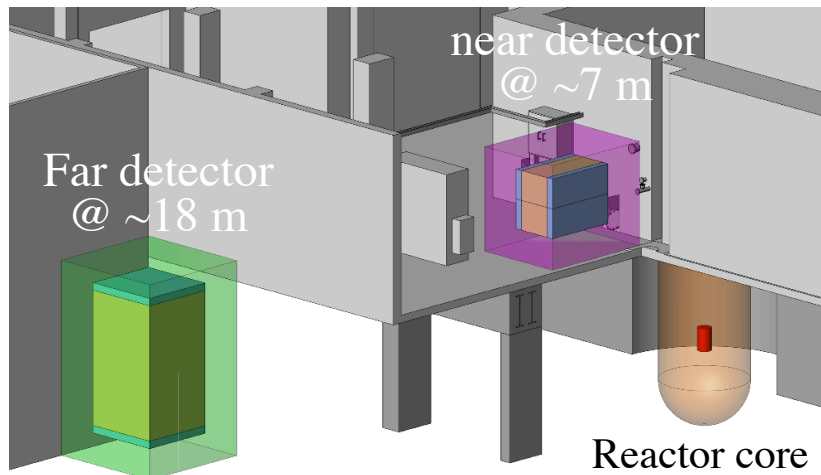


- Precise flux
 - consistent with previous results.
 - disagreed with Huber's model at 3.1σ.
 - yield from ²³⁵U may be the key contributors to the reactor antineutrino anomaly.
- Most precise energy spectrum
 - Observed excess of events with $\bar{\nu}_e$ energy between 5 and 7 MeV.

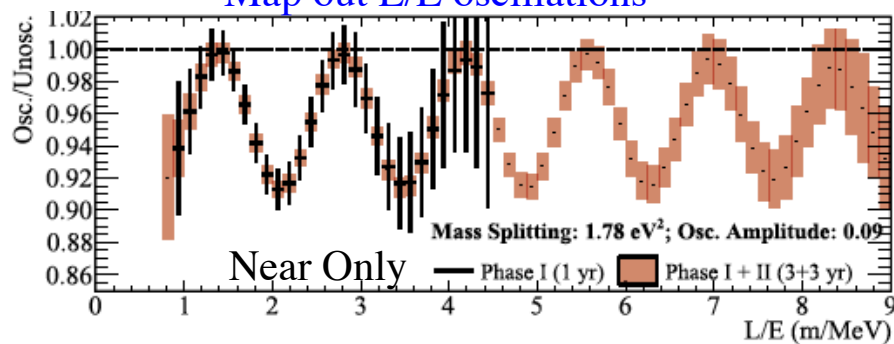
PROSPECT



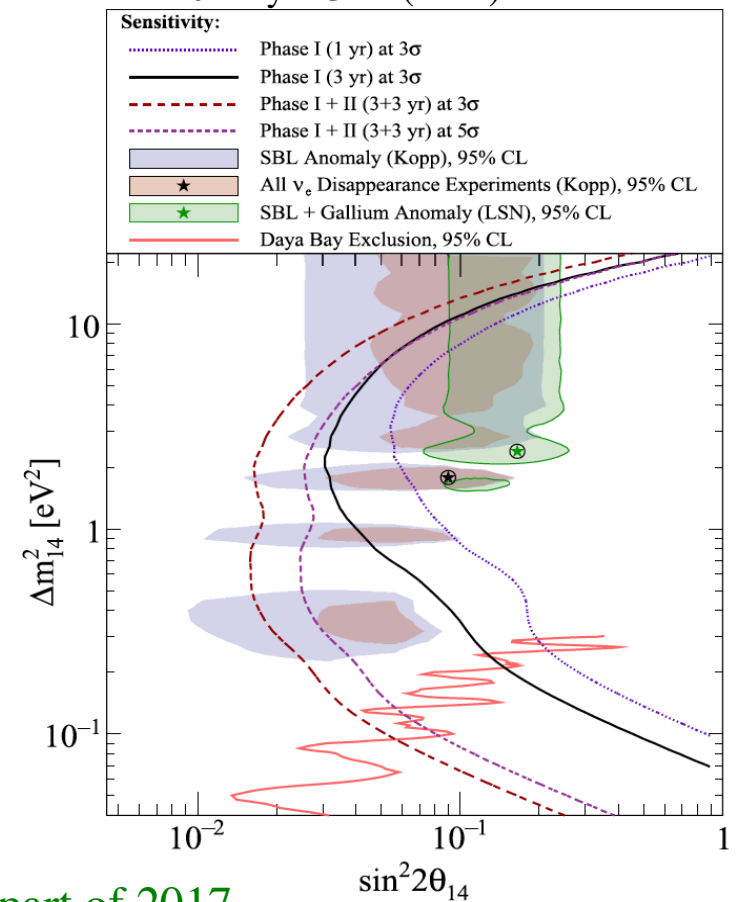
2 ${}^6\text{Li}$ -LS segmented Detectors + 1 ${}^{235}\text{U}$ Reactor



Map out L/E oscillations



J. Phys. G **43** (2016) 113001



- Aim to have first-phase measurement to begin in later part of 2017.

Fermilab Neutrino Experiments

Booster ν beam

MicroBooNE, SBN program

Booster
proton energy: 8 GeV

NuMI ν beam

NOvA, MINERvA, MINOS+

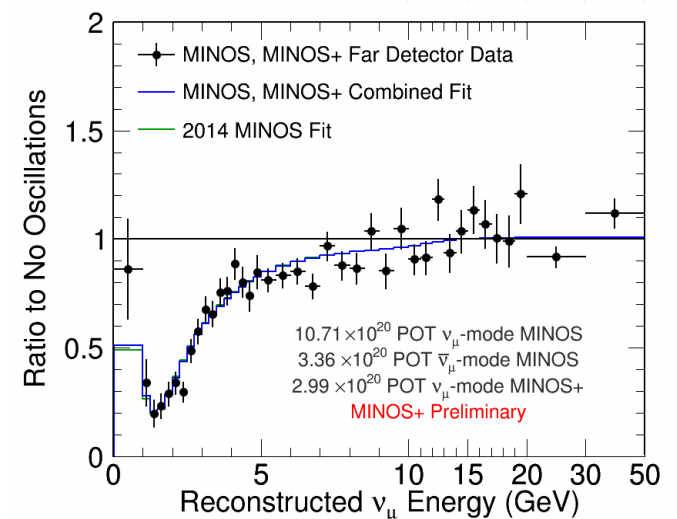
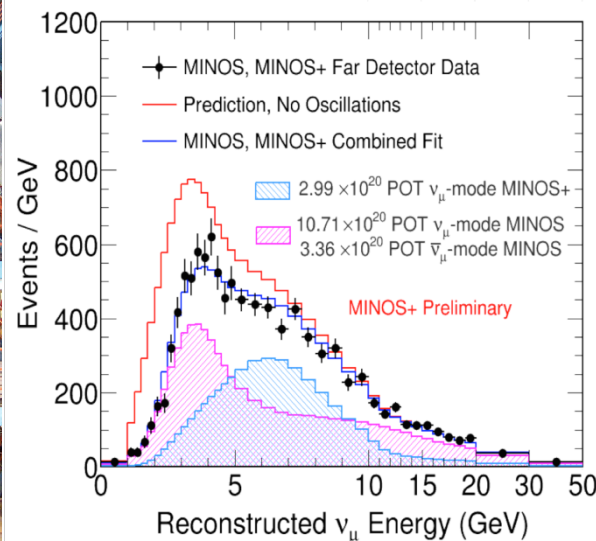
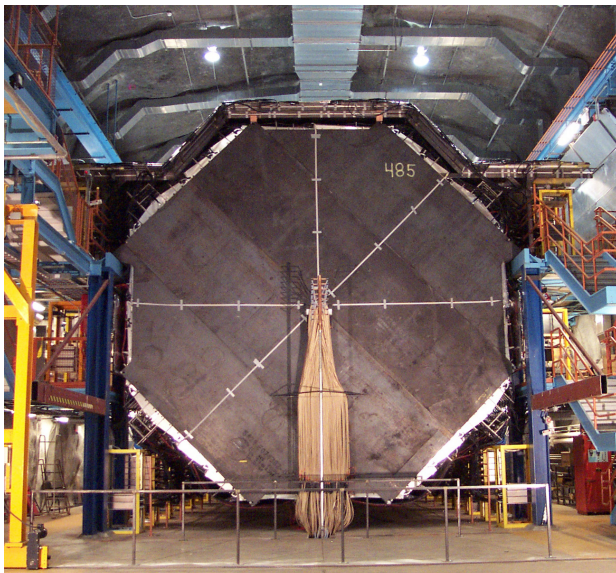
Main Injector
proton energy: 120 GeV

DUNE ν beam

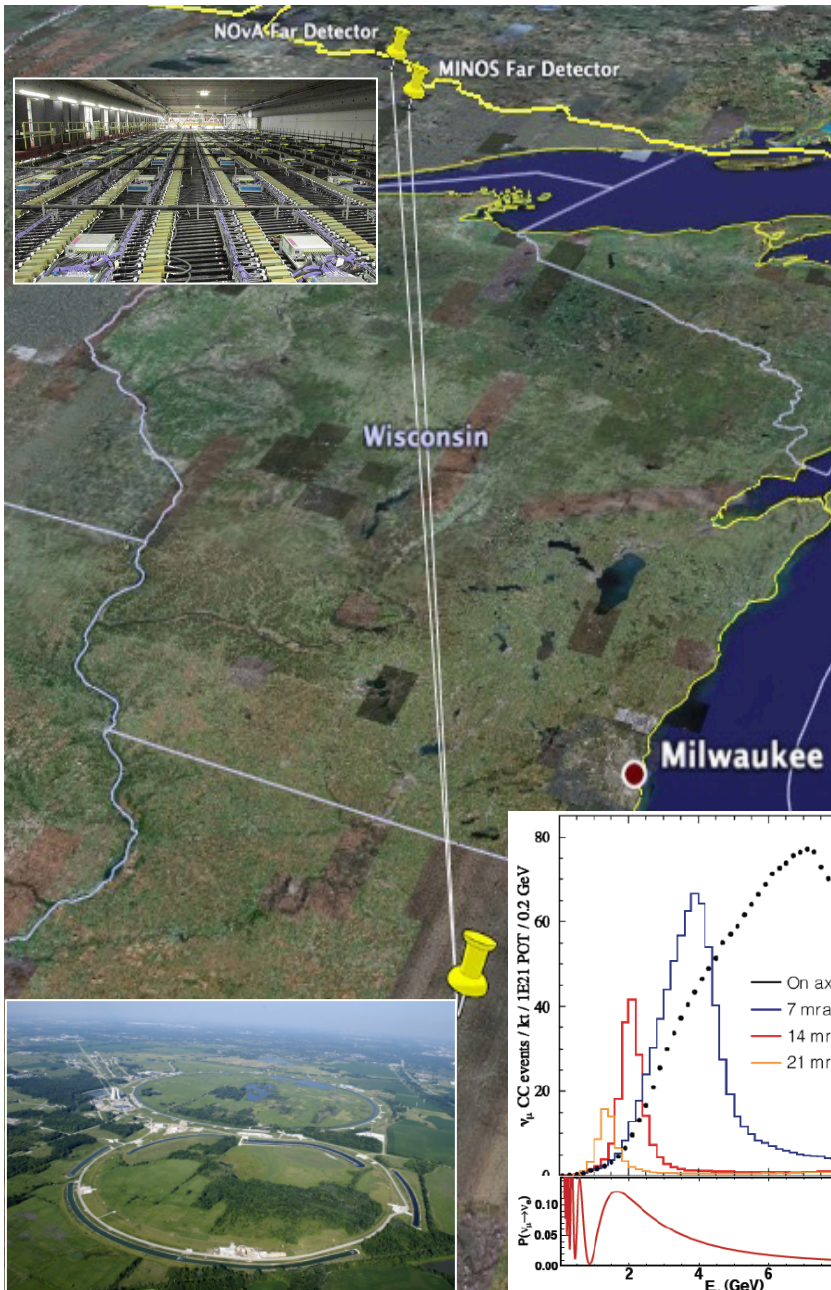
DUNE

MINOS To MINOS+

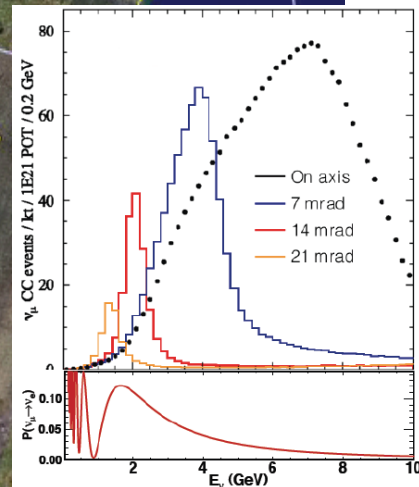
- On-axis ν_μ beam
- Magnetized iron/scintillator-stripe detector
- Collect $>10\text{k}$ charged-current and $>3\text{k}$ neutral-current ν_μ events in the 4-10 GeV range in 2013-2016
- Goals:
 - Search for non-standard neutrino interactions
 - Search for sterile neutrinos
 - Search for extra dimensions



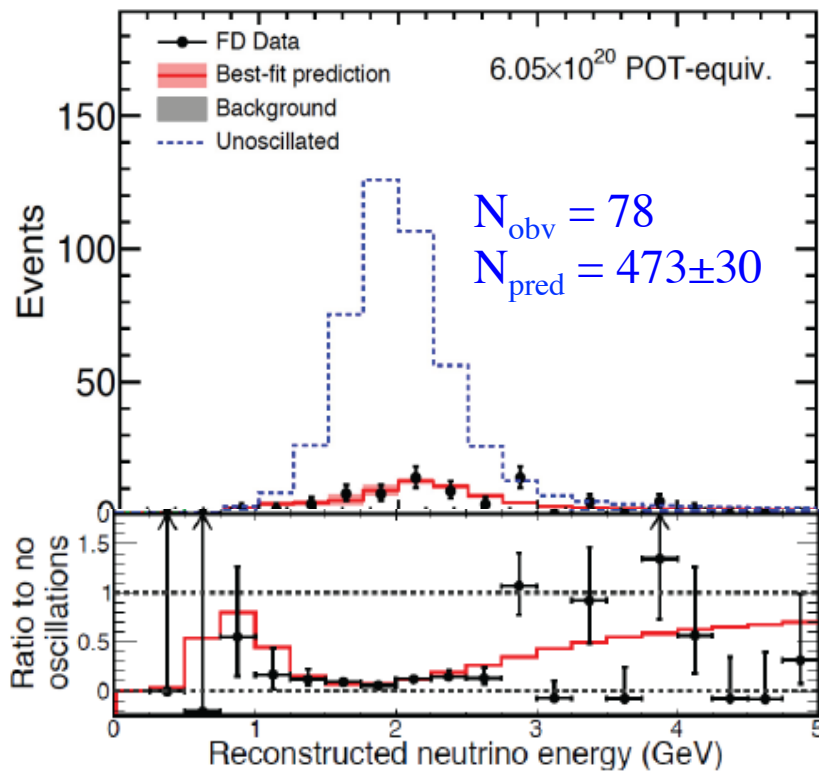
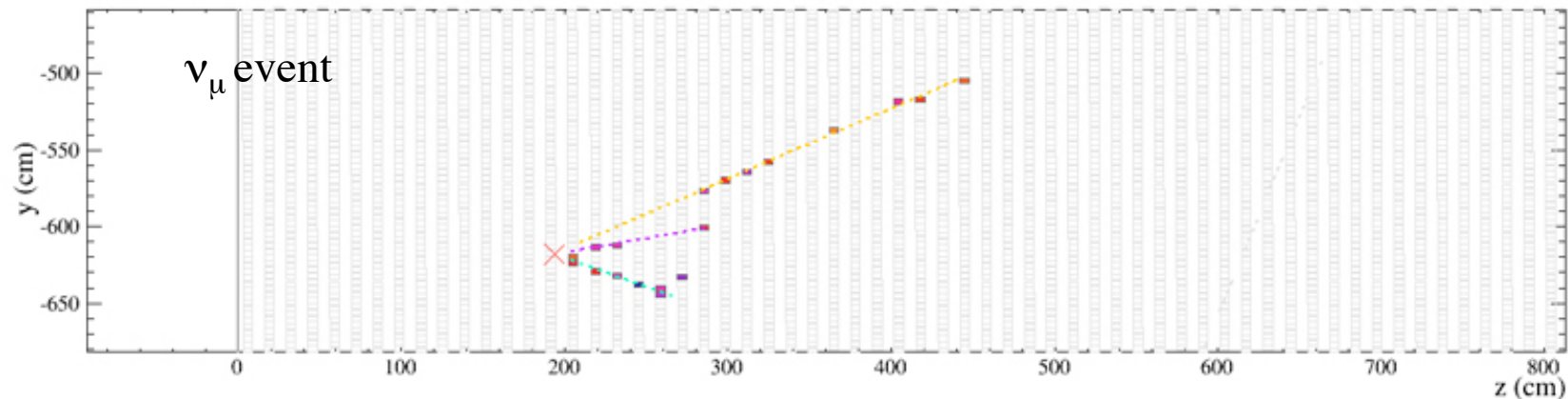
NOvA



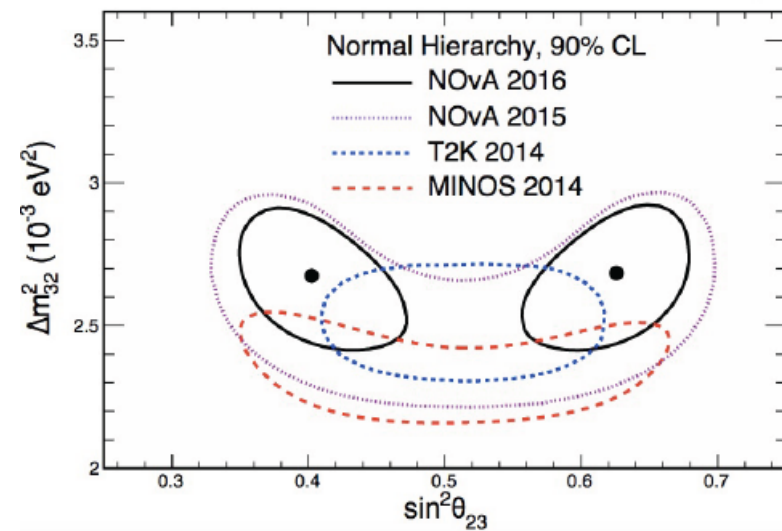
- Upgraded >700 kW NuMI beam
- Off-axis ν_μ beam
 - 14.6 mrad
 - Peak ν_μ energy at 2 GeV at far site
- Far Detector at Ash River, MN
 - 14-kt liquid-scintillator, segmented
- 300-ton functionally identical Near Detector
- Scientific goals:
 - What is the neutrino mass hierarchy?
 - Is θ_{23} maximal?
 - What is the size of θ_{13} ?
 - Is CP violated in the lepton sector?
 - Do sterile neutrinos exist?



NOvA: ν_μ Disappearance

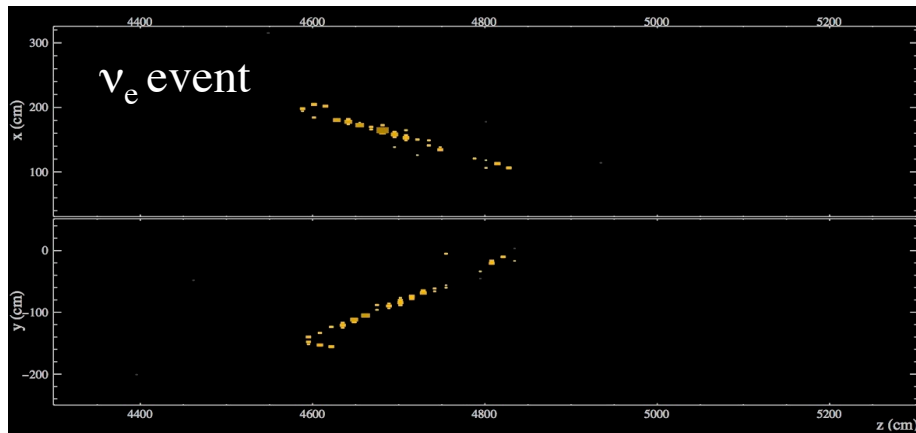


PRL118 (2016)151802

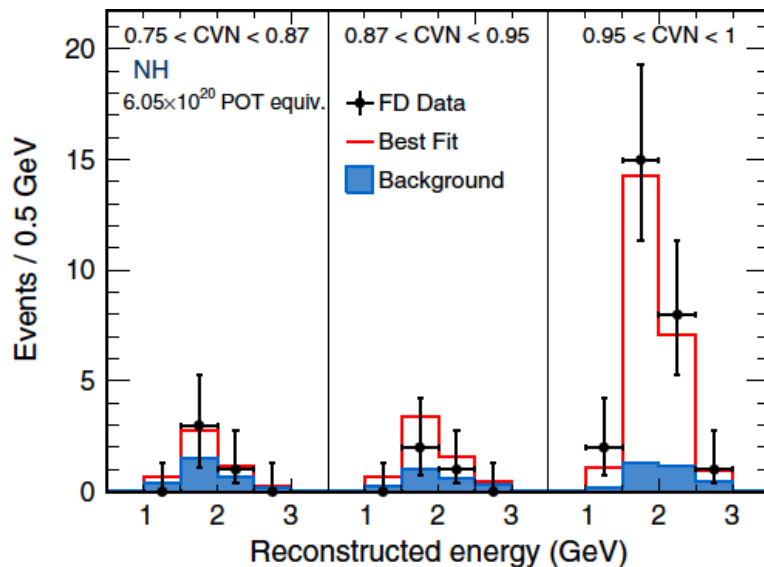


- $\sin^2 \theta_{23} = 0.404^{+0.030}_{-0.022}$ or $0.624^{+0.022}_{-0.030}$ (NH)
Maximal mixing is disfavoured at 2.6 σ
- $\sin^2 \theta_{23} = 0.398^{+0.030}_{-0.022}$ (IH)
- $\Delta m^2_{32} = (+2.67 \pm 0.11) \times 10^{-3} \text{ eV}^2$ (NH)
 $\Delta m^2_{32} = (-2.72 \pm 0.11) \times 10^{-3} \text{ eV}^2$ (IH)

NOvA: ν_e Appearance



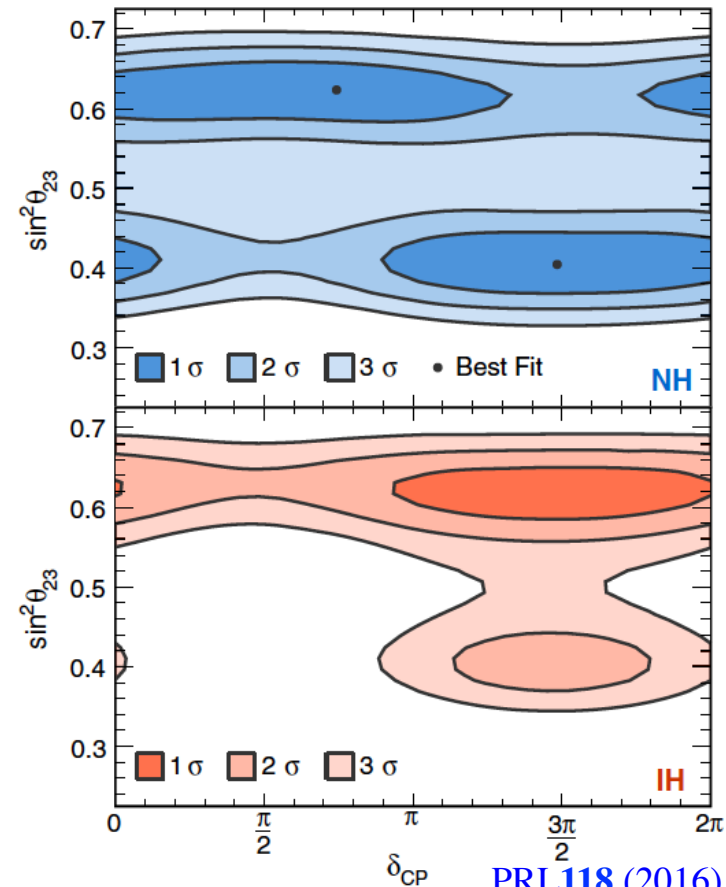
Use machine-learning technique
(Convolutional Visual Network)
to identify ν_e candidates



Obtained 33 ν_e events

Inputs to fit:

- $\sin^2 2\theta_{13} = 0.085 \pm 0.005$ (reactor)
- Δm^2_{32} and $\sin^2 \theta_{23}$ from NOvA

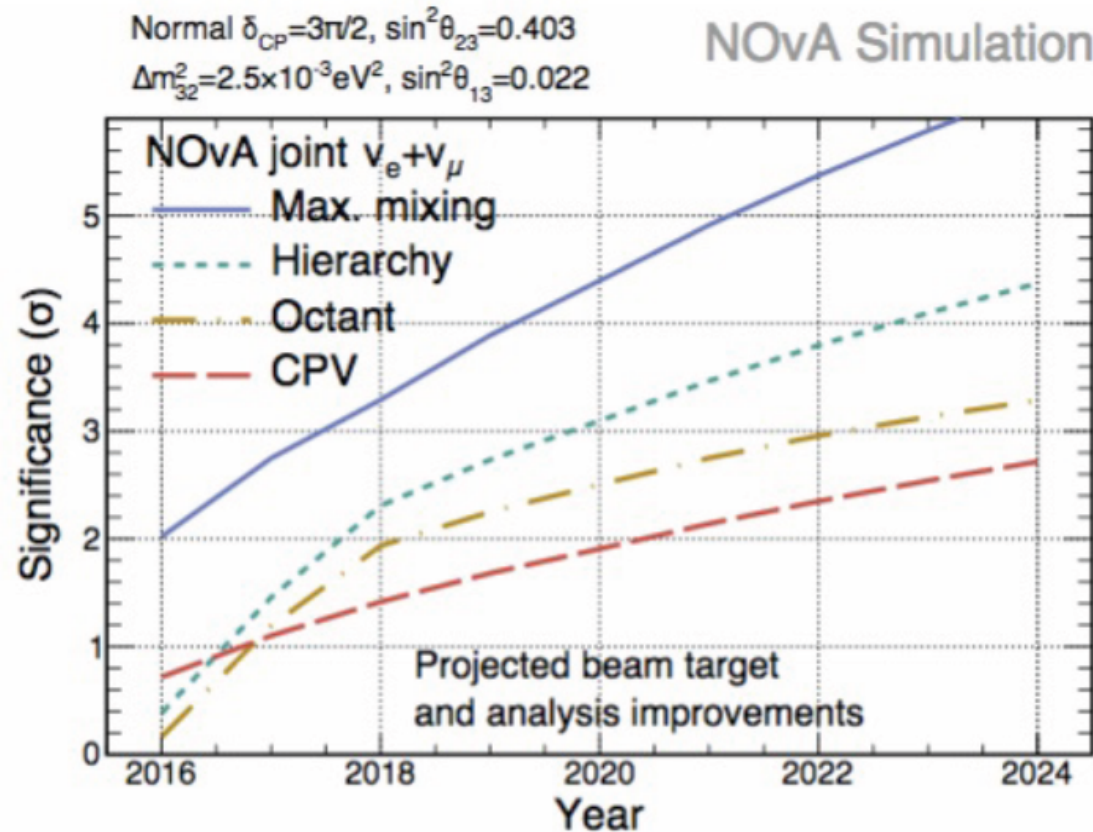


PRL118 (2016) 231801

- NH is slightly preferred
- Best fit: $\sin^2 2\theta_{23} = 0.404$ and $\delta_{CP} = 1.48\pi$
- Use $\bar{\nu}_\mu$ data to resolve degeneracies

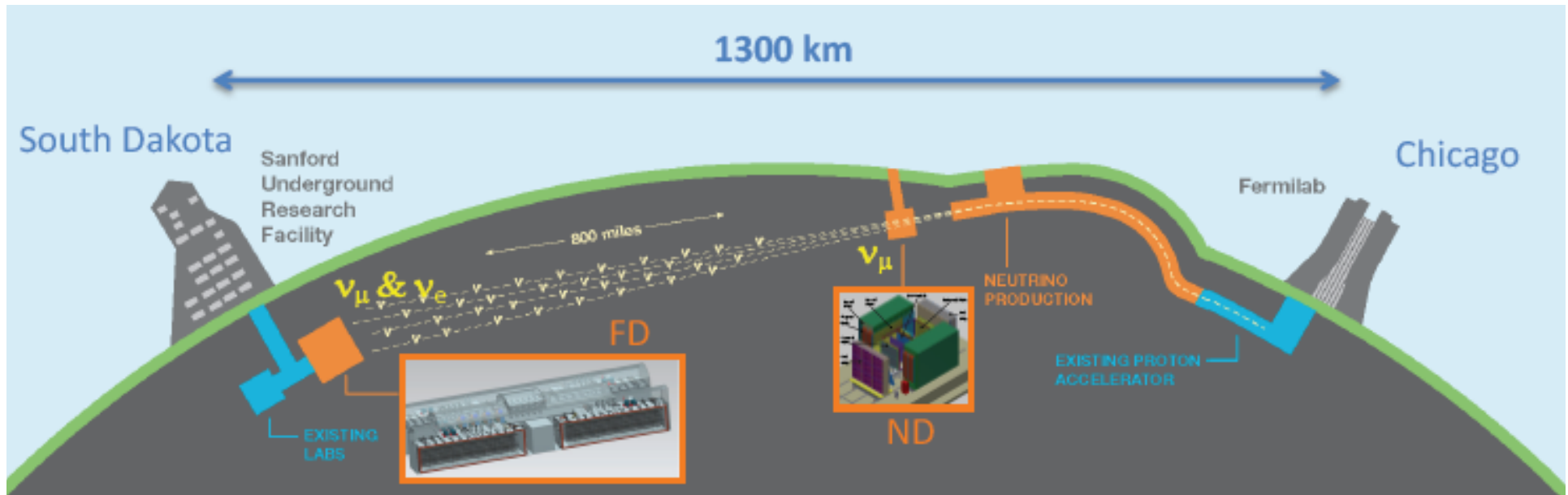
NOvA: Outlook

- Collecting data with an anti-neutrino beam since February 2017
 - Plan to release combined ν_μ and $\bar{\nu}_\mu$ results in the summer of 2018
- Projected significance:



- Beam improvement: extra beam time per year
- Increased beam power: 700 kW (2017), 800 kW (2019), 900 kW (2021)
- Analysis improvement: 25% increase in effective exposure

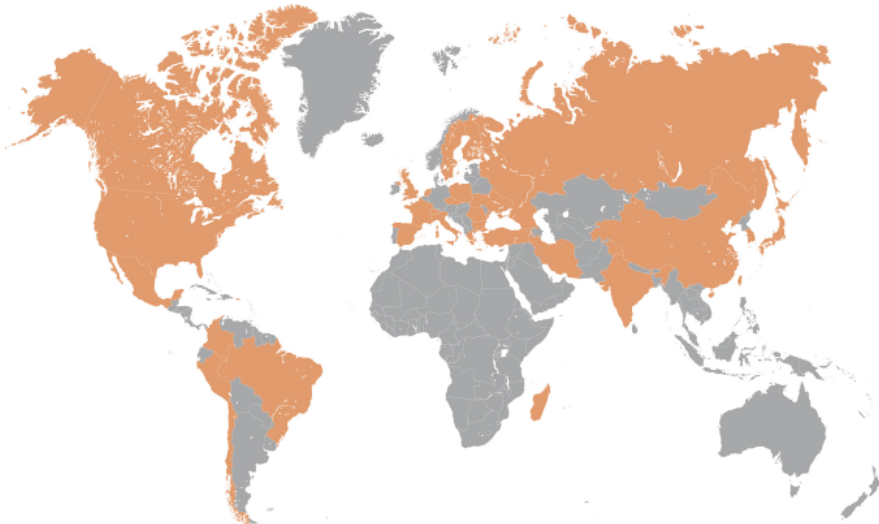
DUNE



- A long-baseline neutrino experiment designed for studying
 - CP violation in neutrino oscillation
 - Study ν_e appearance
 - Neutrino mass-hierarchy problem
 - Precise measurement of mixing angle θ_{23} and mass splitting Δm^2_{32}
 - Nucleon decay
 - Other physics

DUNE Collaboration

- As of May 2017:
970 collaborators from 162 institutions (60% non-US) world wide

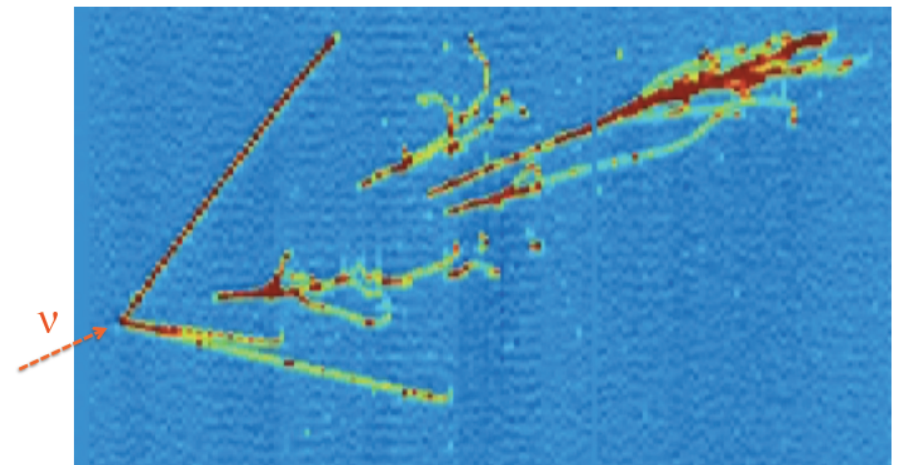
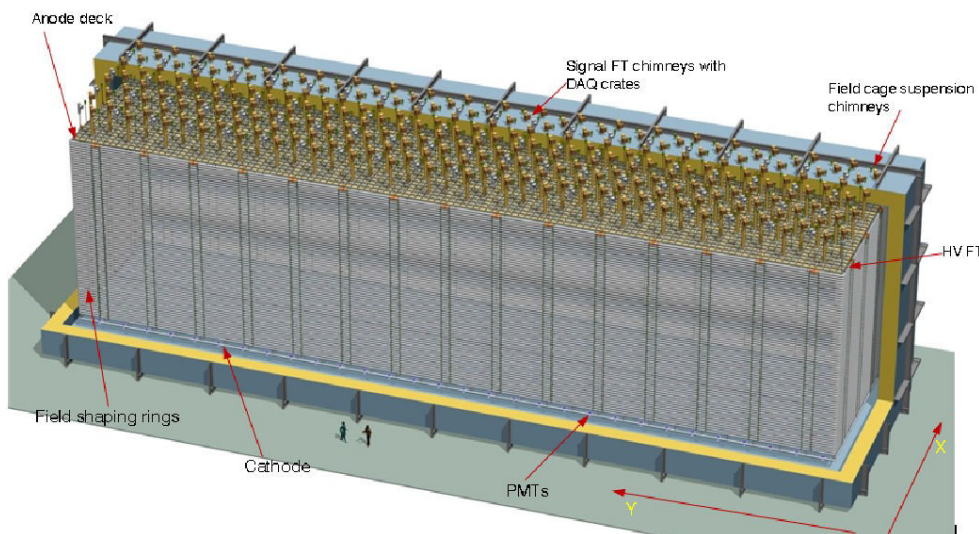


Armenia, Brazil, Bulgaria, Canada, CERN, Chile, China, Colombia, Czech Republic, Spain, Finland, France, Greece, India, Iran, Italy, Japan, Madagascar, Mexico, Netherlands, Peru, Poland, Romania, Russia, South Korea, Sweden, Switzerland, Turkey, UK, Ukraine, USA

- LBNF (Long Baseline Neutrino Facility)
 - US-hosted project with international contributions
 - Beam, near-site and far-site facilities
- DUNE (Deep Underground Neutrino Experiment)
 - Fully international scientific collaboration

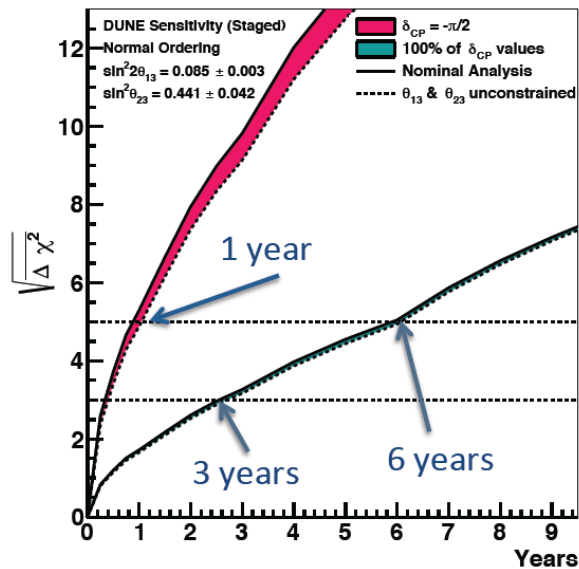
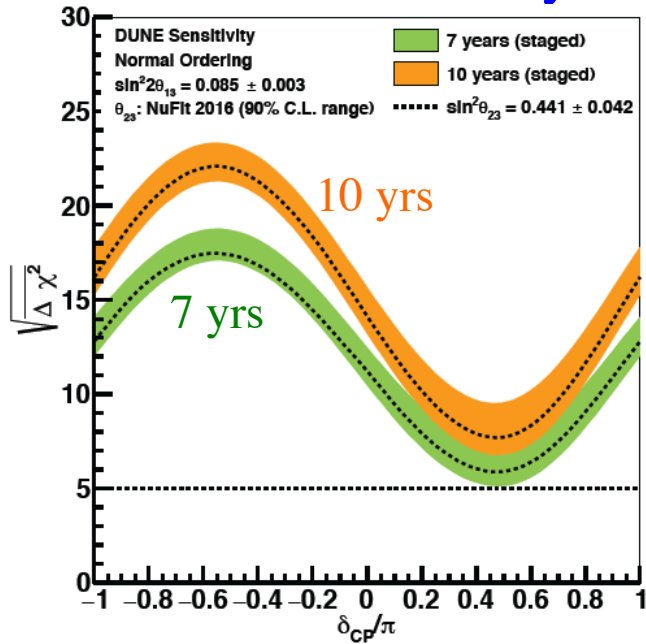
LBNF/DUNE: Overview

- Intense on-axis neutrino/anti-neutrino beams from high-power proton beam
 - 1.2 MW from day one; upgradeable to 2.4 MW
- Near-detector system to characterize the neutrino beam
 - Accumulate $\sim 10^8$ of neutrino interactions
 - Being designed
- Massive far detectors
 - Liquid-argon Time Projection Chamber (TPC)
 - 4 modules, each with 17-kt mass giving fiducial mass of >10 kt
 - Detect $\sim 10^3$ ν_e -appearance events

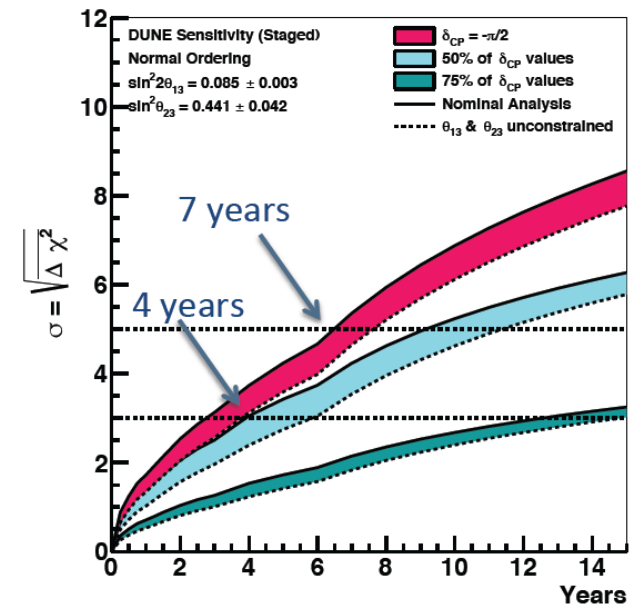
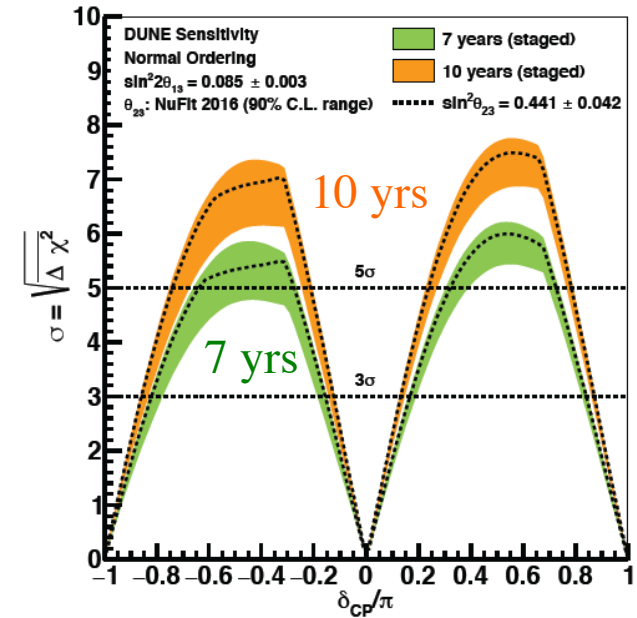


DUNE: Scientific Reach

Mass Hierarchy

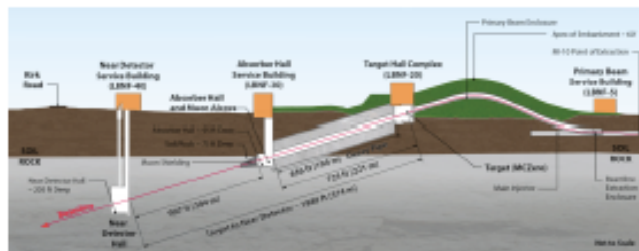
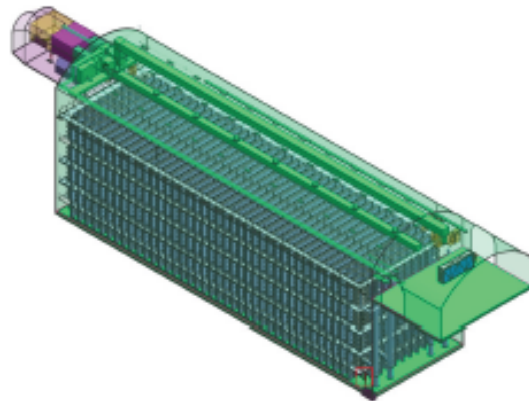
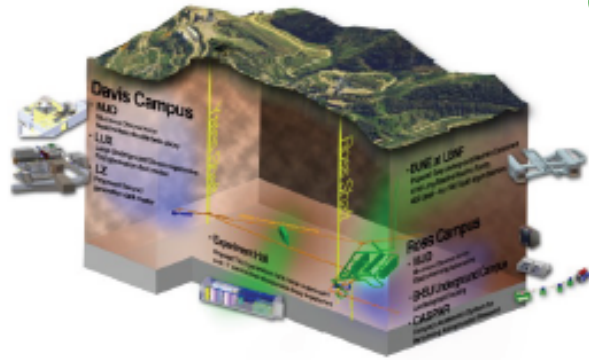


CP Violation



DUNE: Schedule

Groundbreaking: 21 July 2017



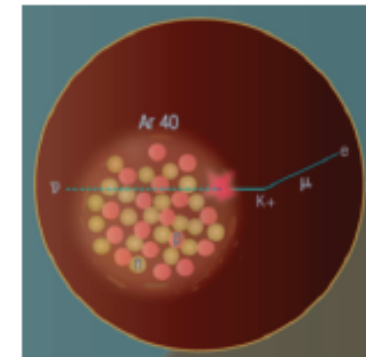
2017: Far Site Construction Begins

2018: protoDUNE at CERN

2021: Far Detector Installation Begins

2024: Physics Data Begins

2026: Neutrino Beam Available

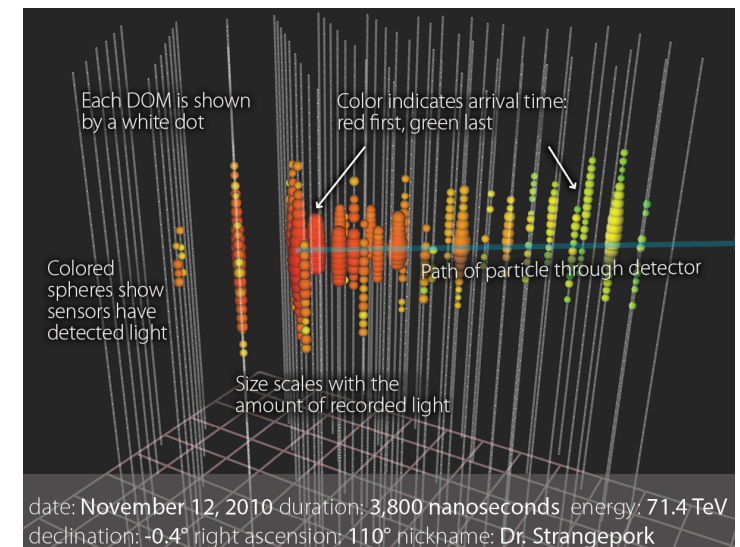
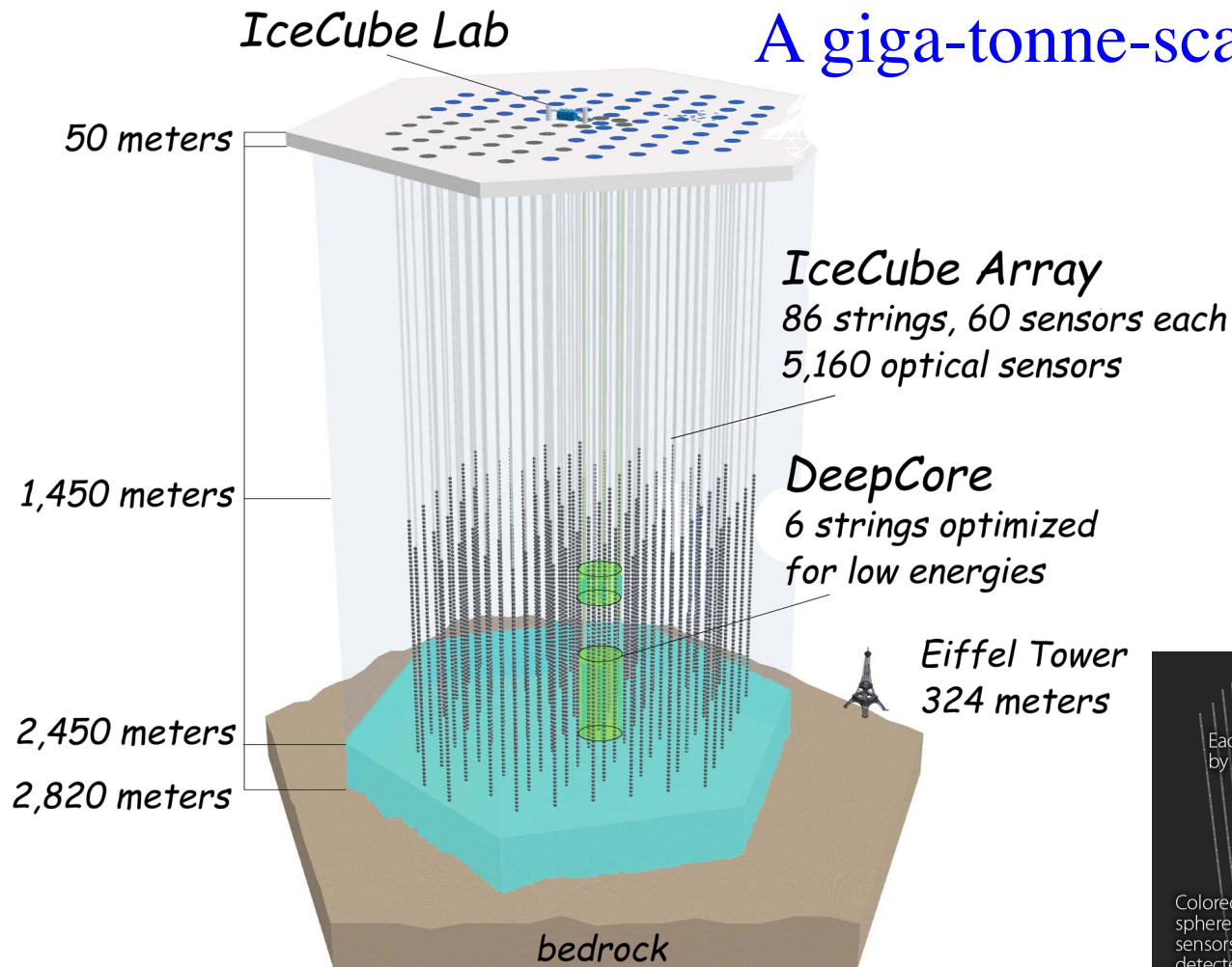


40 kton + 2 MW beam to follow in subsequent years

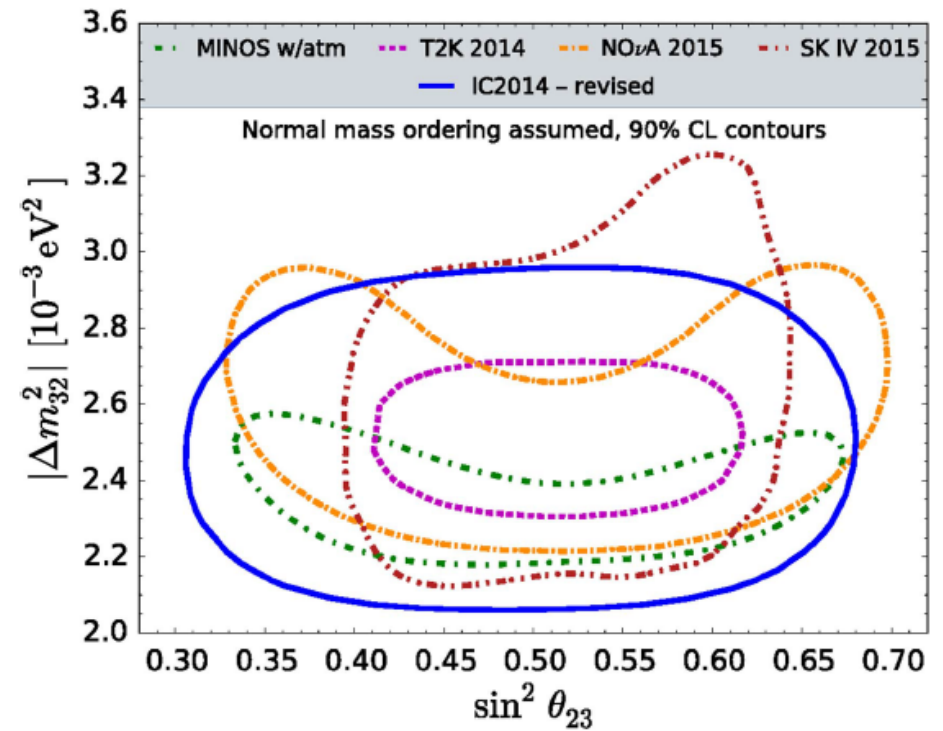
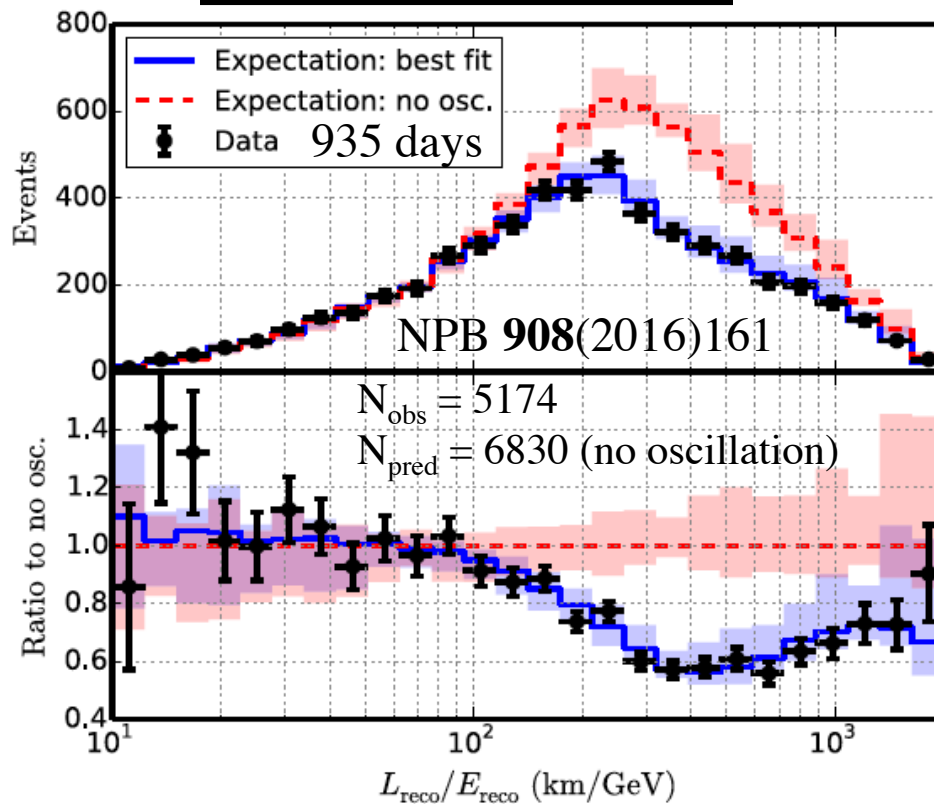
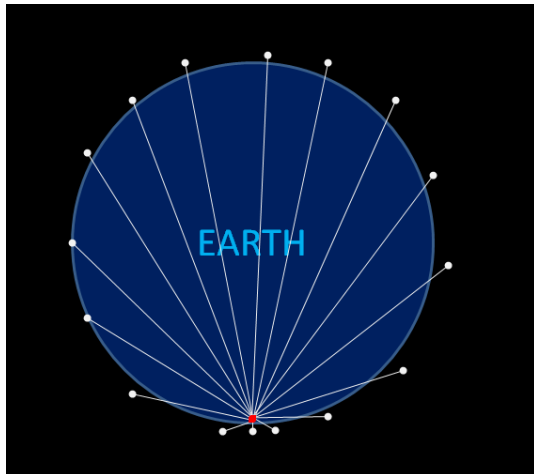
From E. Blucher

IceCube-DeepCore

A giga-tonne-scale neutrino detector



IceCube-DeepCore: Neutrino Oscillation



Best fit:

$$\sin^2 \theta_{23} = 0.53^{+0.09}_{-0.12}$$

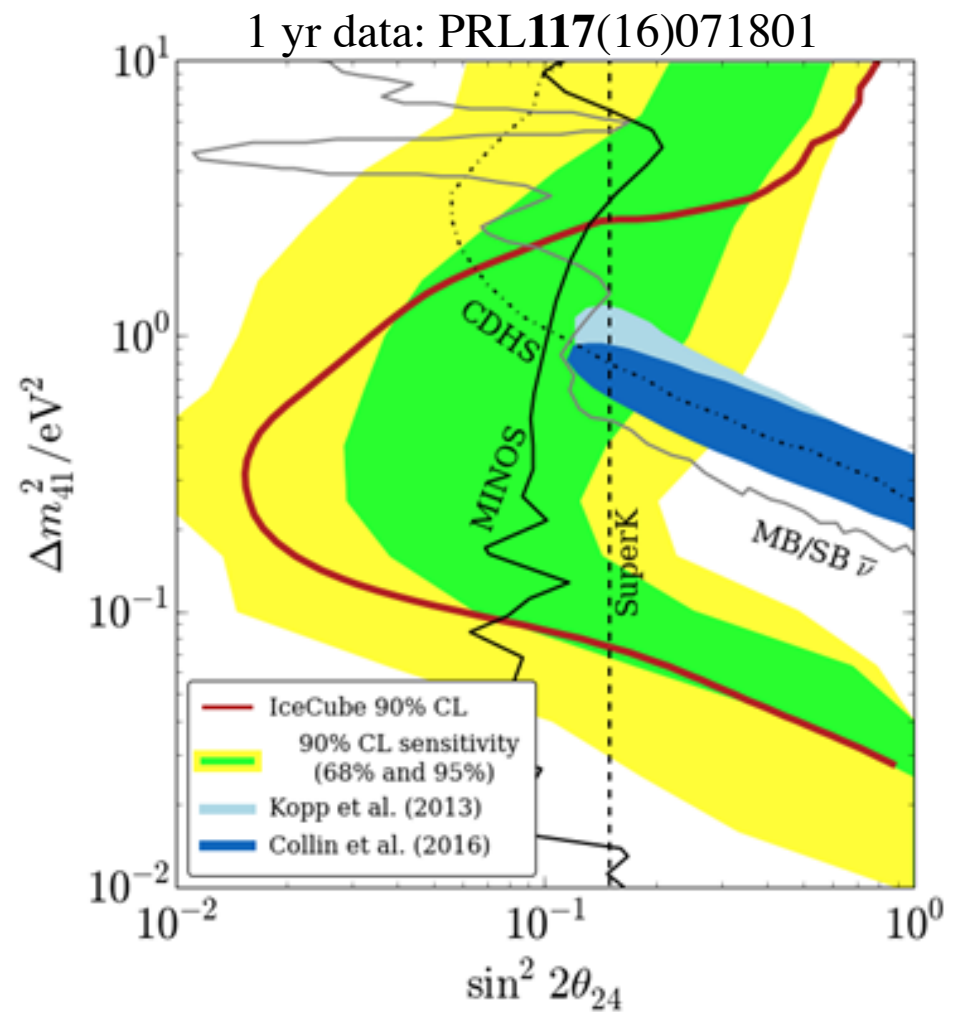
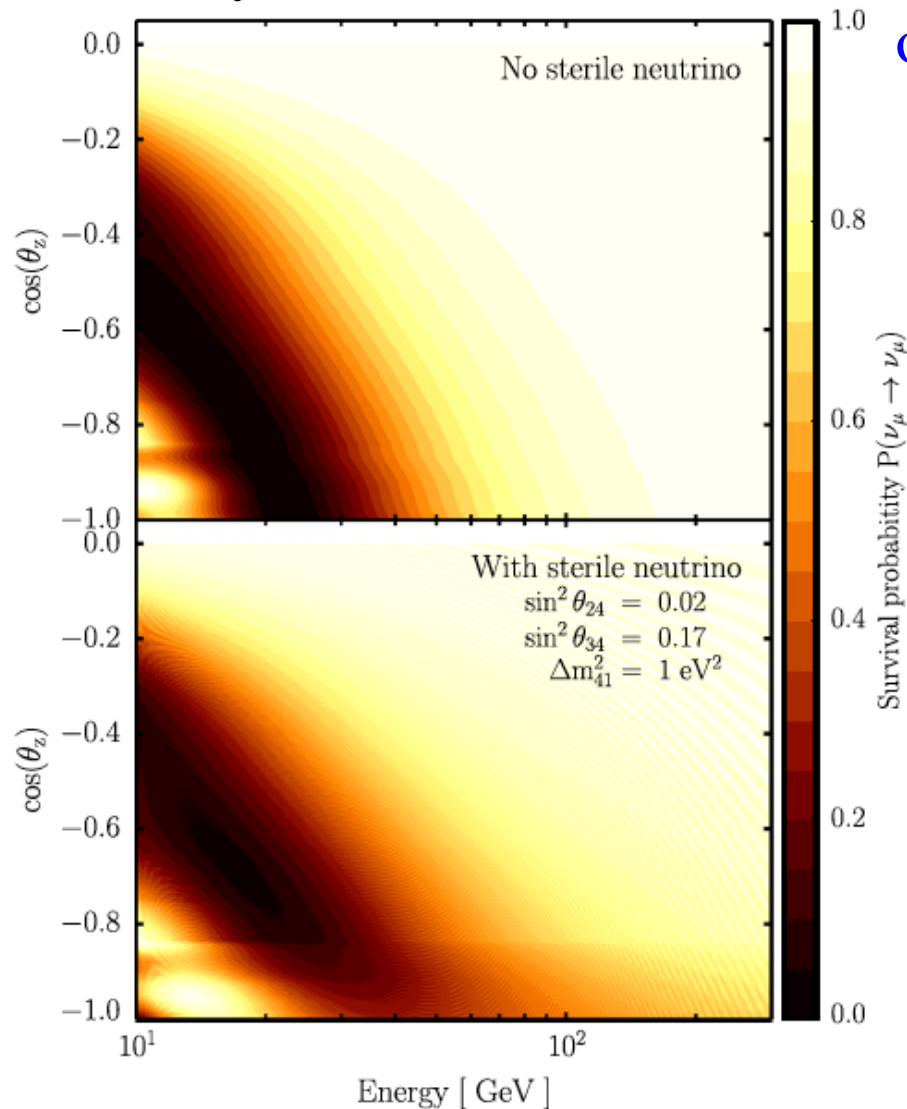
$$\Delta m^2_{32} = (2.72^{+0.19}_{-0.20}) \times 10^{-3} \text{ eV}^2$$

Insensitive to mass hierarchy

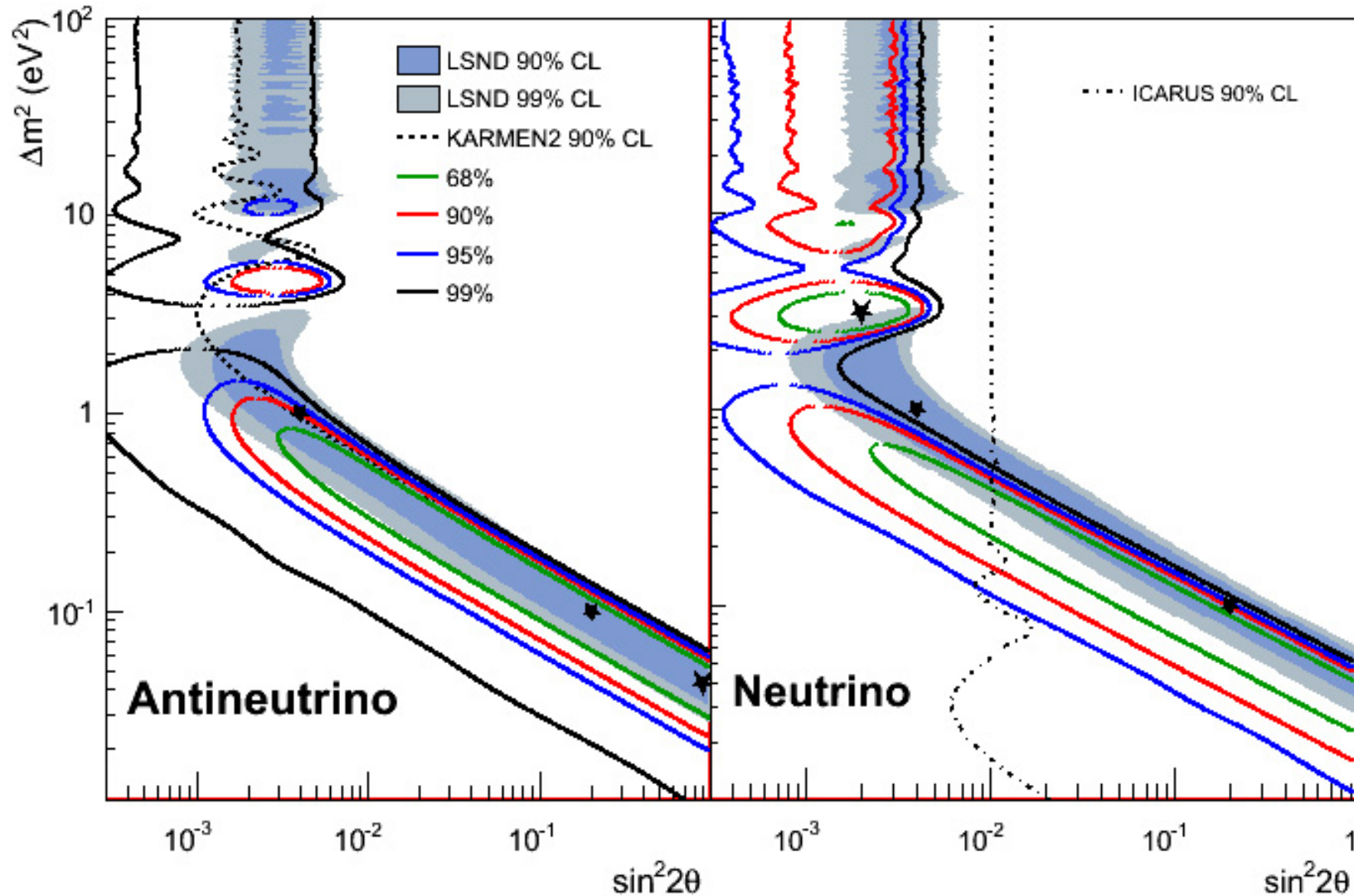
IceCube-DeepCore: Sterile-neutrino Search

Sterile neutrinos induce distortion caused by MSW effect

No reduction of $\nu_\mu + \bar{\nu}_\mu$ disappearance due to matter-enhanced-resonant oscillation found.

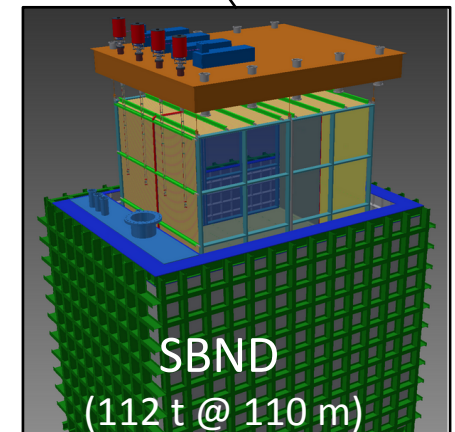
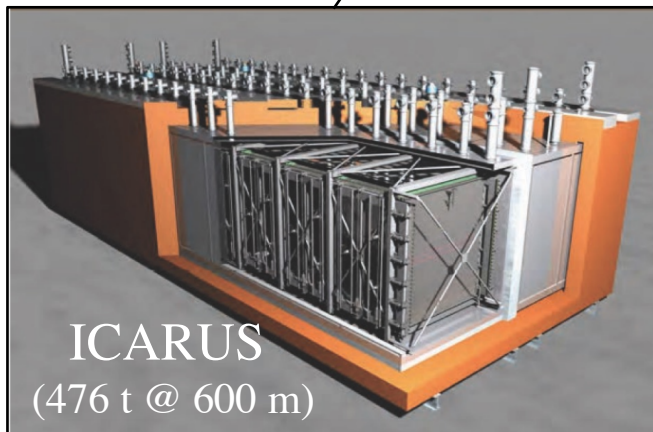
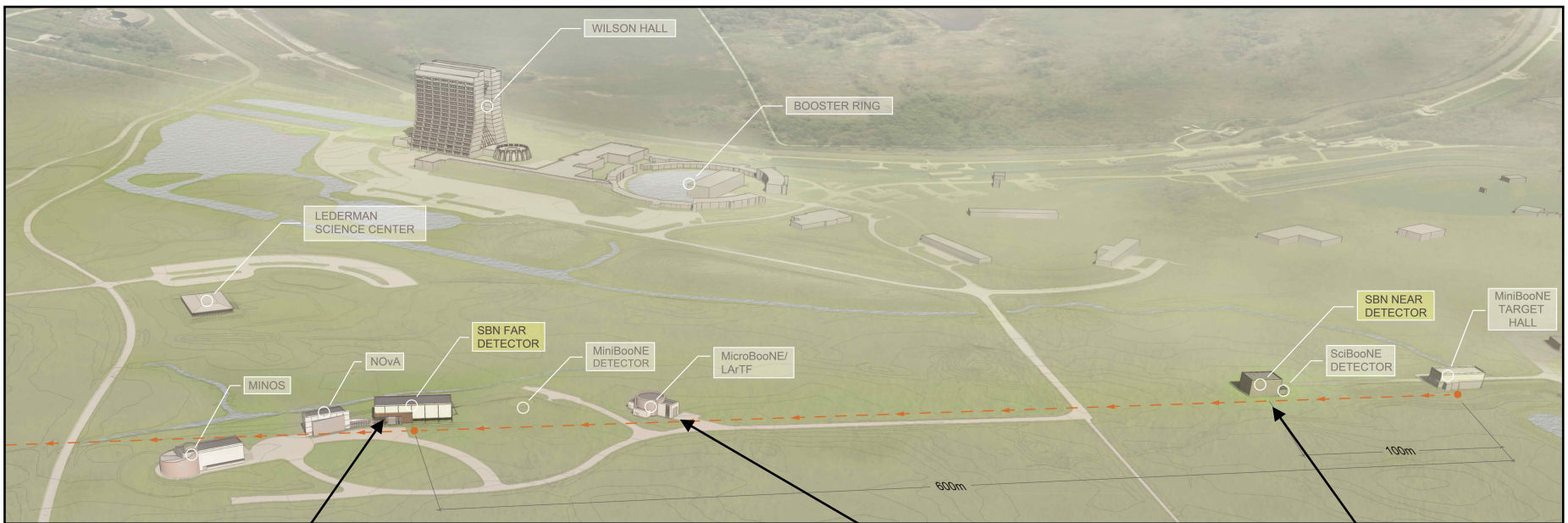


Do Sterile Neutrinos Exist?



None of the current experiments can provide a definitive statement.

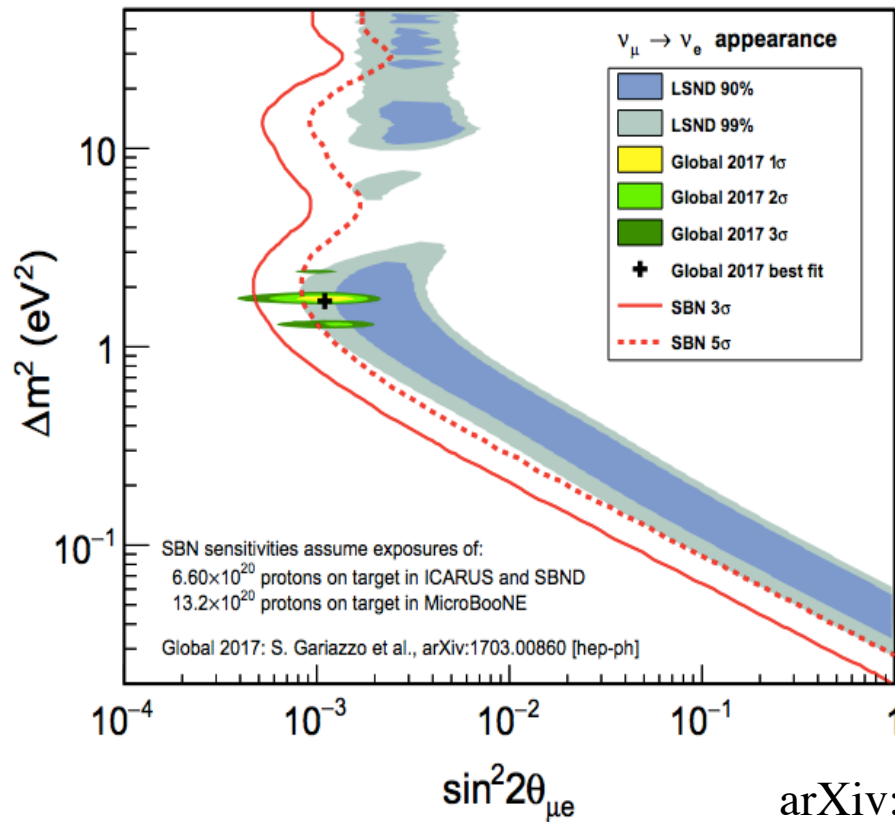
Short-Baseline Neutrino (SBN) Program



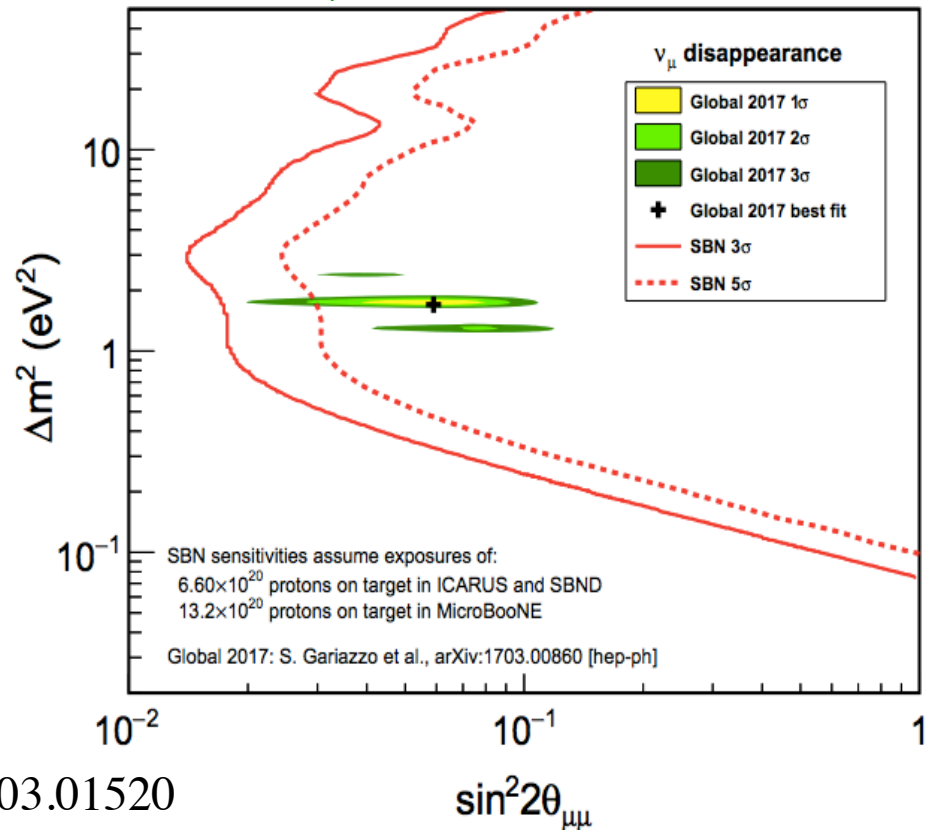
- All three detectors are liquid-argon TPCs
 - ICARUS and MicroBooNE exist
 - Build a DUNE-style detector: SBND

Sensitivities of the SBN Program

ν_e appearance

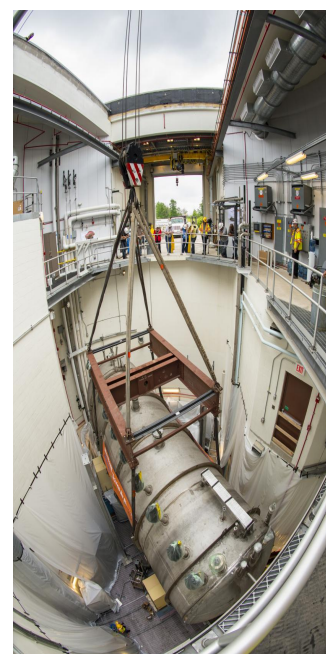


ν_μ disappearance



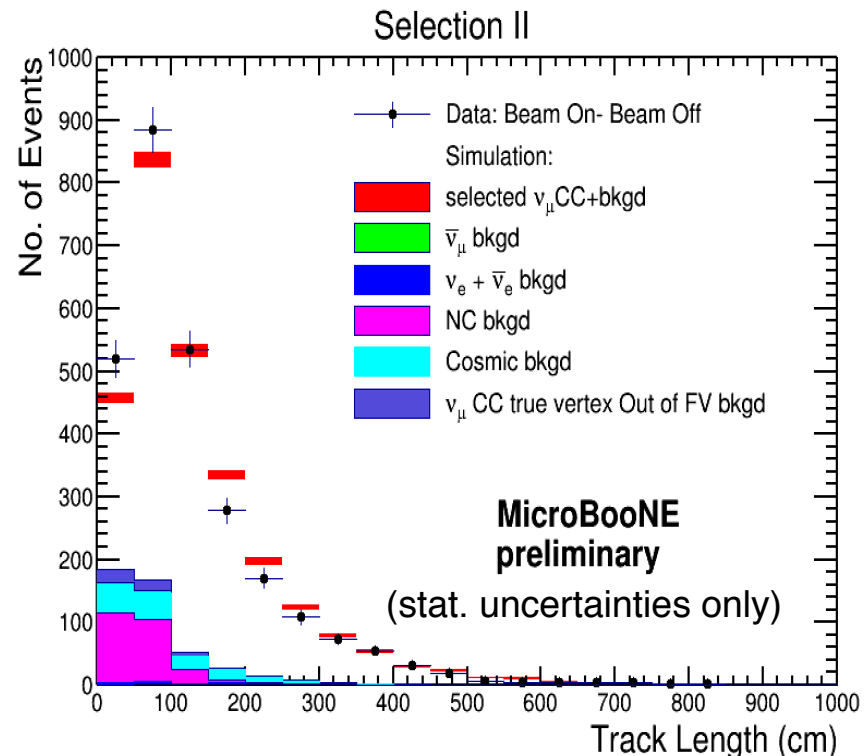
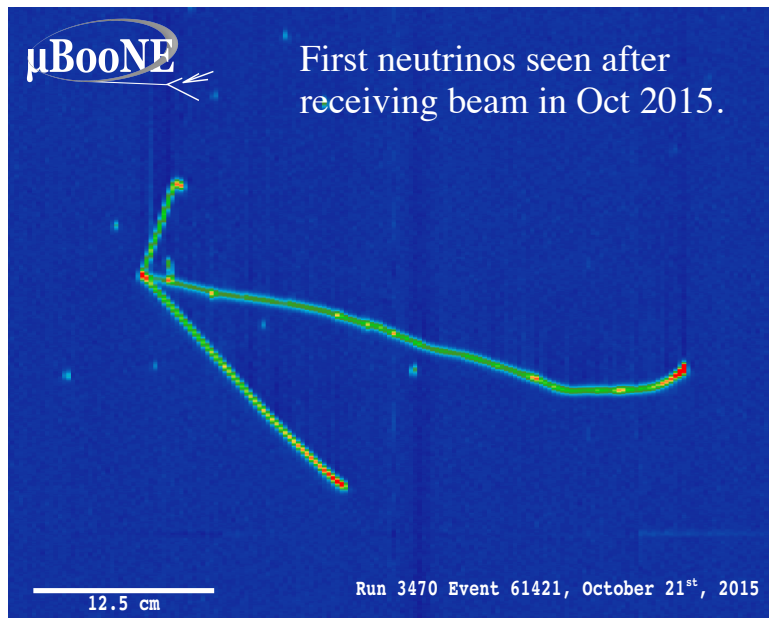
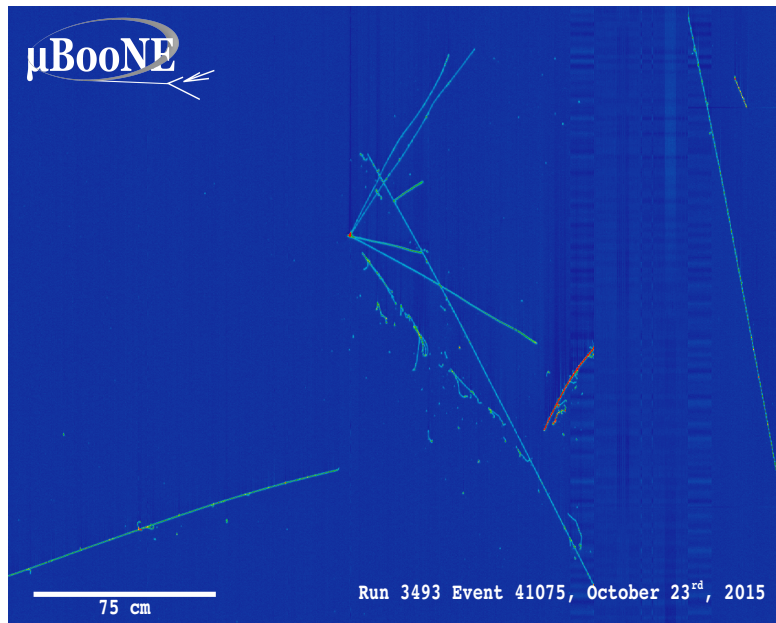
- Appearance and disappearance measurements with the same detectors
- SBN has the potential to cover the entire range of interest

MicroBooNE: Installation Completed in 2015



The First Neutrinos in MicroBooNE

- Began data taking on 15 October 2015
 - have already received $>2.5 \times 10^{20}$ POT
 - stable operation with uptime $>97\%$
- First physics analyses underway!
- First set of kinematic distributions presented at NEUTRINO 2016

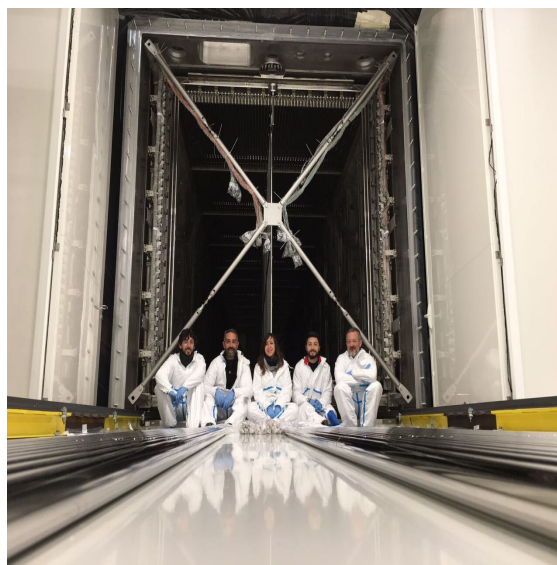


ICARUS: Refurbishment

TPC refurbishment @ CERN



Cold vessel preparation @ CERN



Warm vessel assembled in May 2017



Both TPCs are ready for shipment from CERN to FNAL.

Shipping date: June 12

SBND: Construction



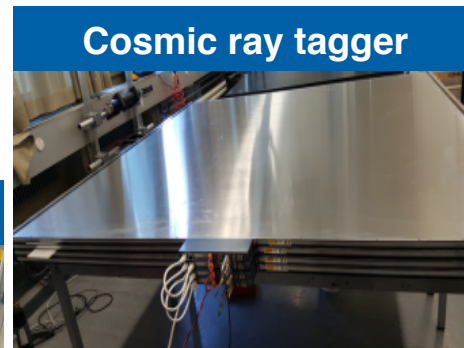
SBND Building



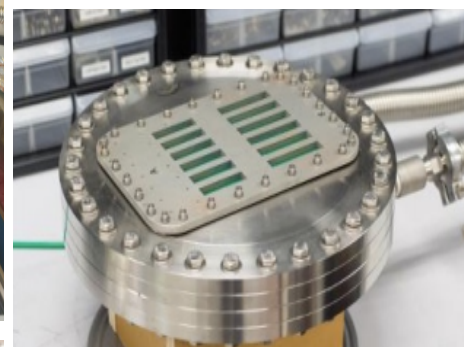
Cathode



HV system



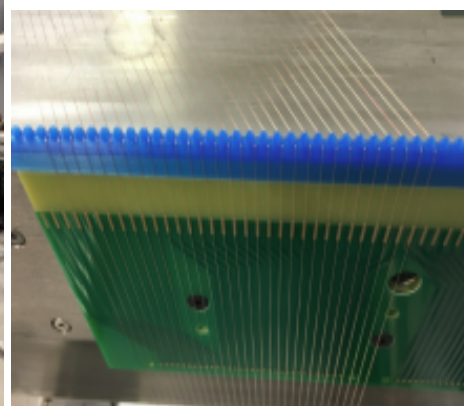
Cosmic ray tagger



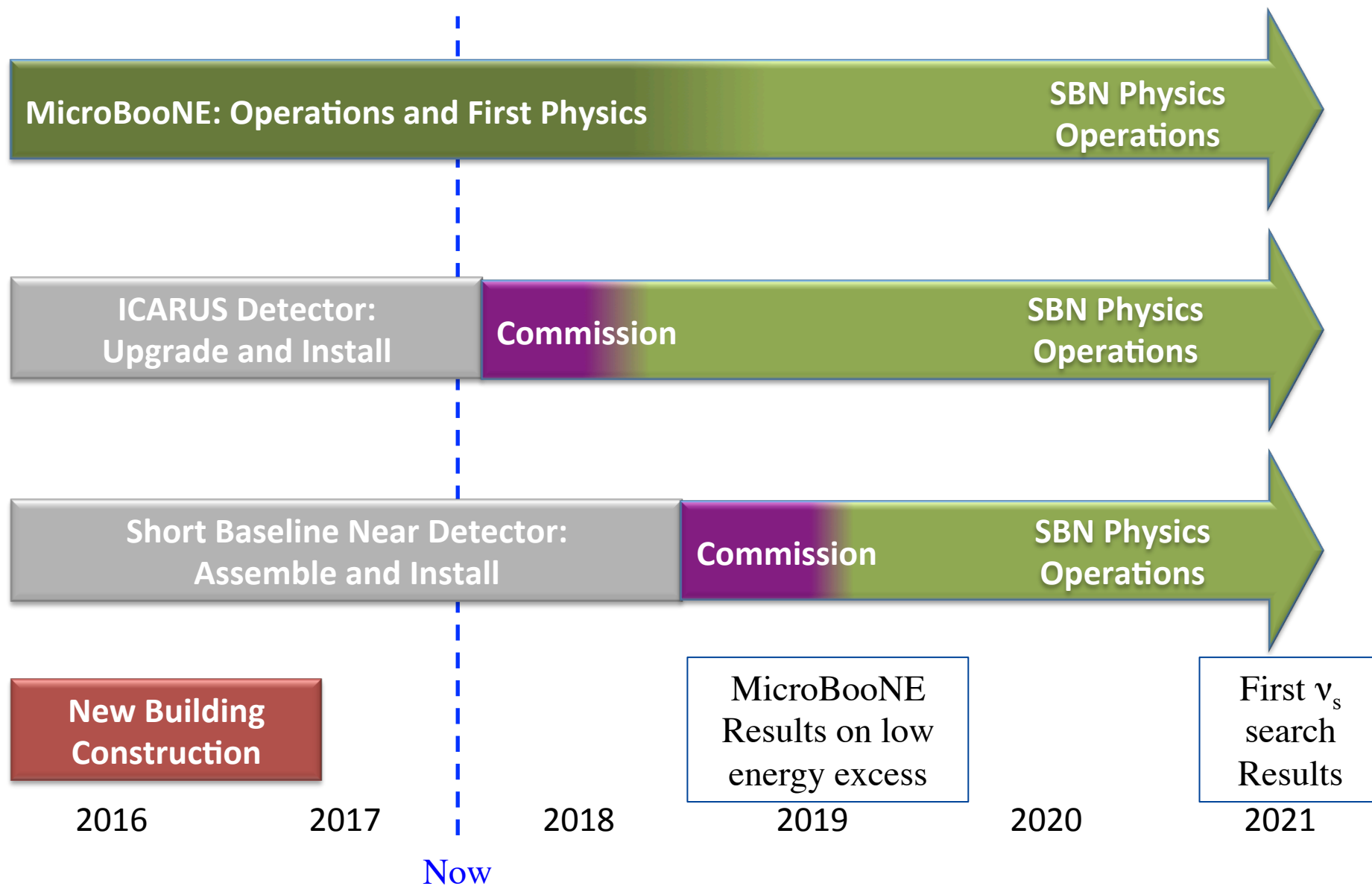
Cold electronics



Anode & wires



SBN: Timeline

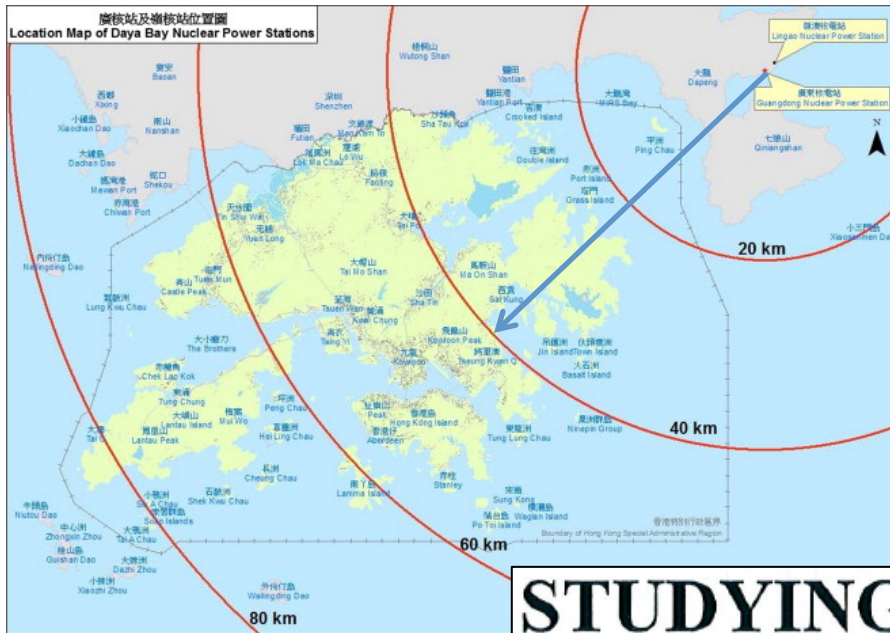


Summary

- The US program on neutrino physics is going strong
 - Several running experiments, lots of data to analyze
 - Improve precision of known parameters
 - Explore unknowns
 - A lot of effort devoted to maturing liquid-argon TPC as the technology for the future
 - Will lead to experience, lessons learned, software and analysis techniques developed,
- DUNE/ProtoDUNEs is ramping up
- This is an exciting and productive time for neutrino physics!

Thank You !

Daya Bay & Hong Kong



STUDYING NEUTRINO OSCILLATION BY USING DAYA BAY NUCLEAR POWER PLANT AS THE NEUTRINO SOURCE

November 28-29, 2003

Room 311, Chong Yuet Ming Physics Building,
Department of Physics,
The University of Hong Kong.