Accelerator long-baseline neutrino oscillation experiments

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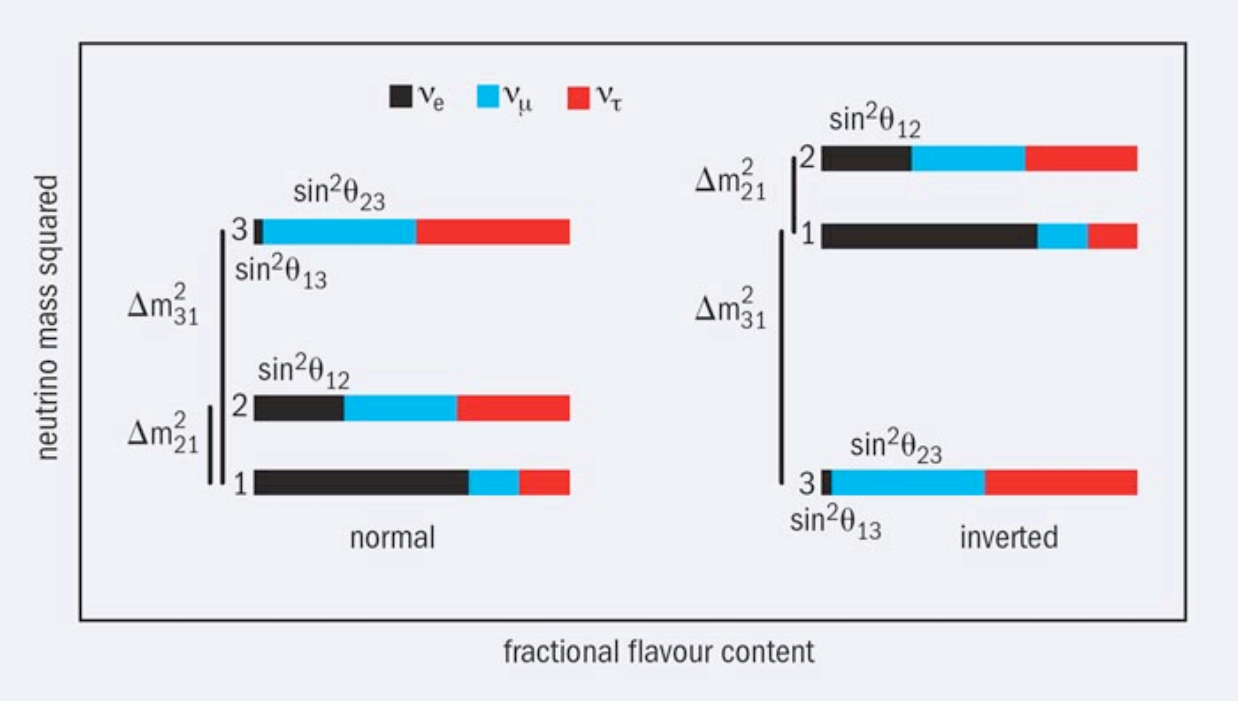
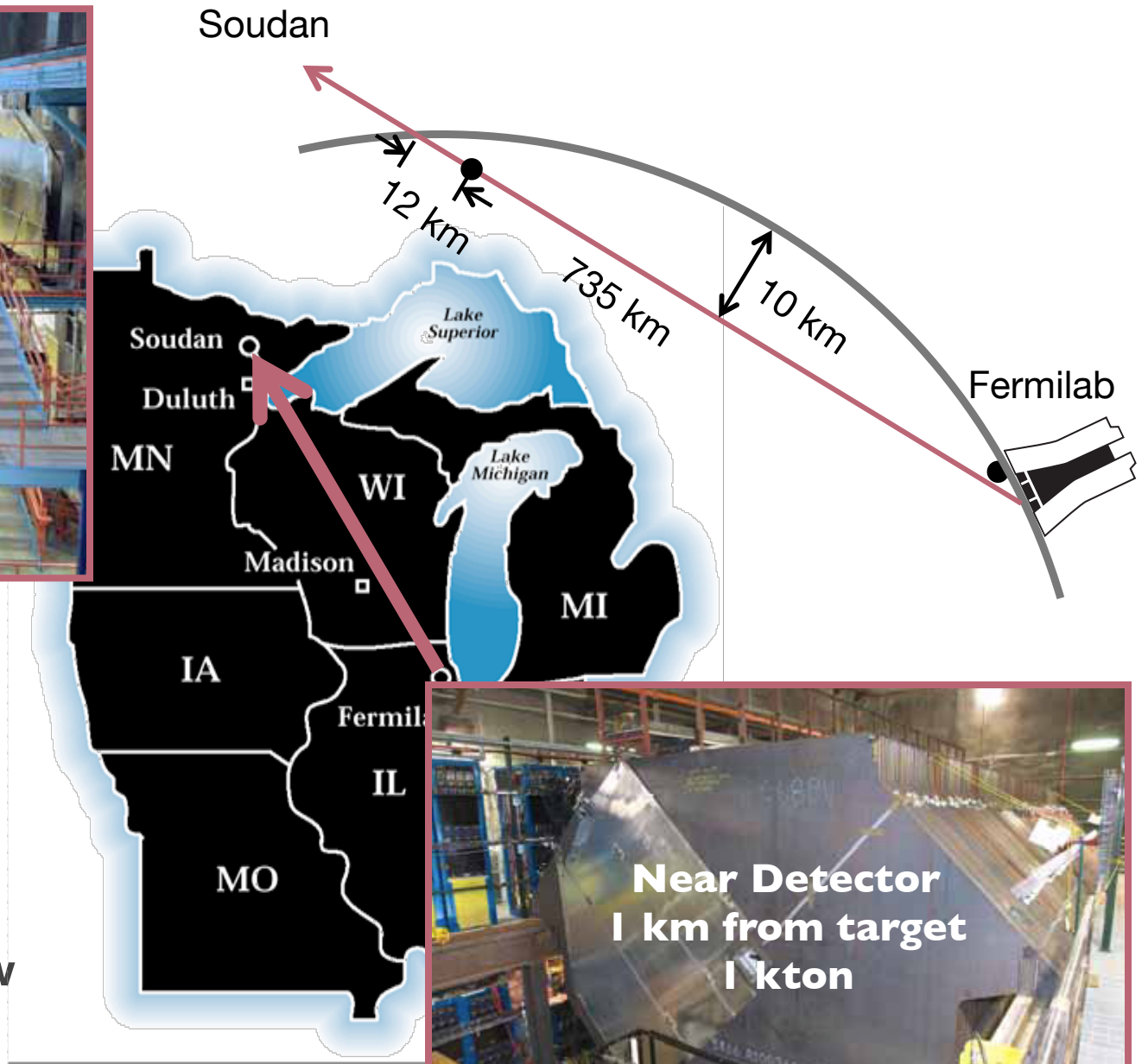
Neutrino mixing and flavor change

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



$$P_{\text{survival}} = f(\theta, \Delta m^2, \delta, L/E)$$

Fundamentals of a long-baseline oscillation experiment



- High intensity neutrino/ antineutrino beam
- Near Detector
- Far Detector
- **Key to success: Powerful beam, large detectors, low background!**

Known knowns

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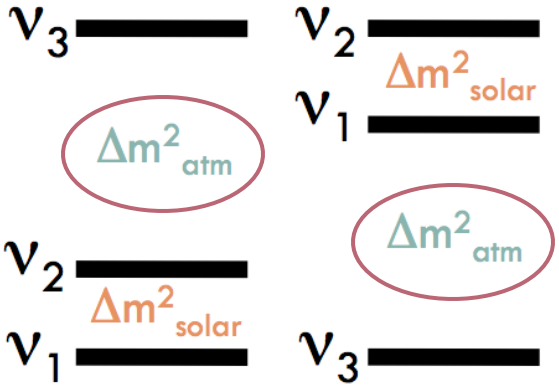
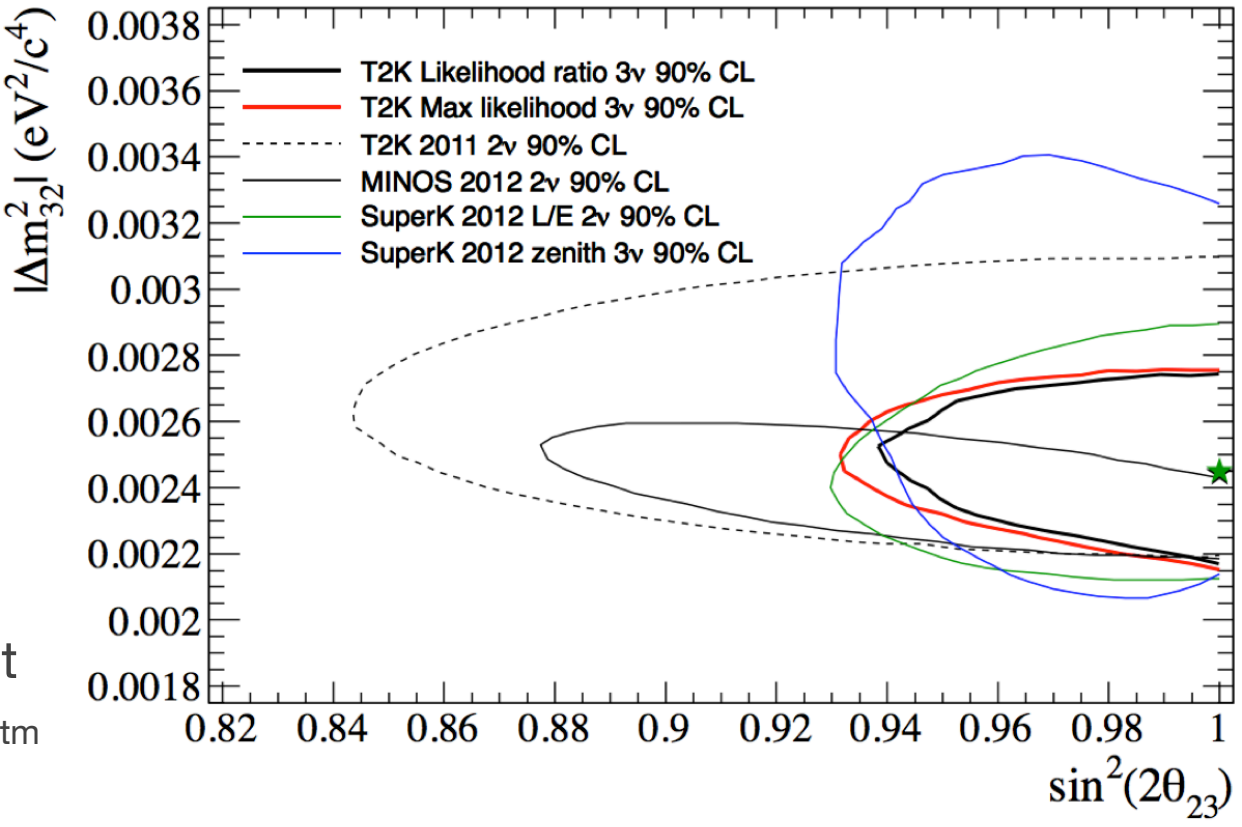


- **MINOS** provides most precise measurement of Δm^2_{atm}
- **T2K** recently reported most precise measurement of θ_{atm}



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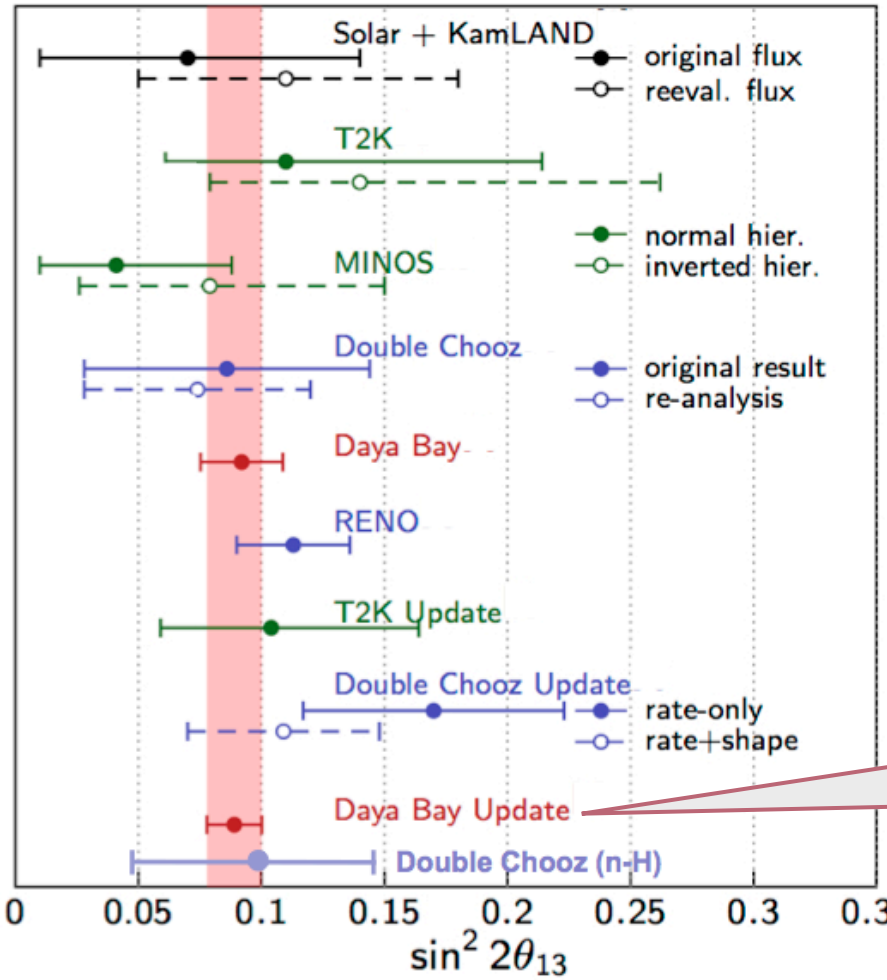

- We now know the last remaining mixing angle, θ_{13}
- Excluded $\theta_{13}=0$
- This makes it possible to access δ

Shoutout to our Daya Bay collegaues!

Known unknowns

- What are the absolute masses of the neutrinos?
- Are neutrinos their own antiparticle?

- What are the underlying symmetries that generate the ν mixing patterns?
- What is the ordering of neutrino masses?
- Is CP violated in the neutrino sector?
  - What is the CP phase?
- What is the octant of θ_{23}

Unknown unknowns?

- Sterile neutrinos?
- Non-standard interactions?
- Large extra dimensions??

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non oscillation experiments

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neutrino oscillation experiments

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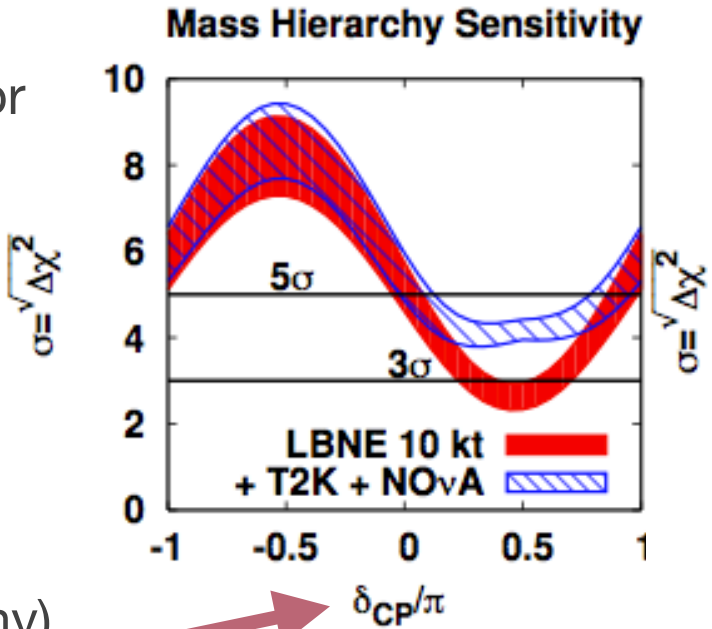
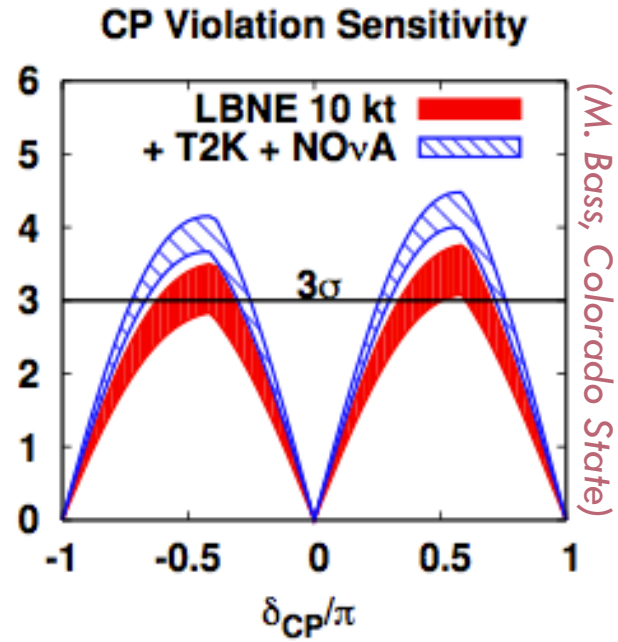
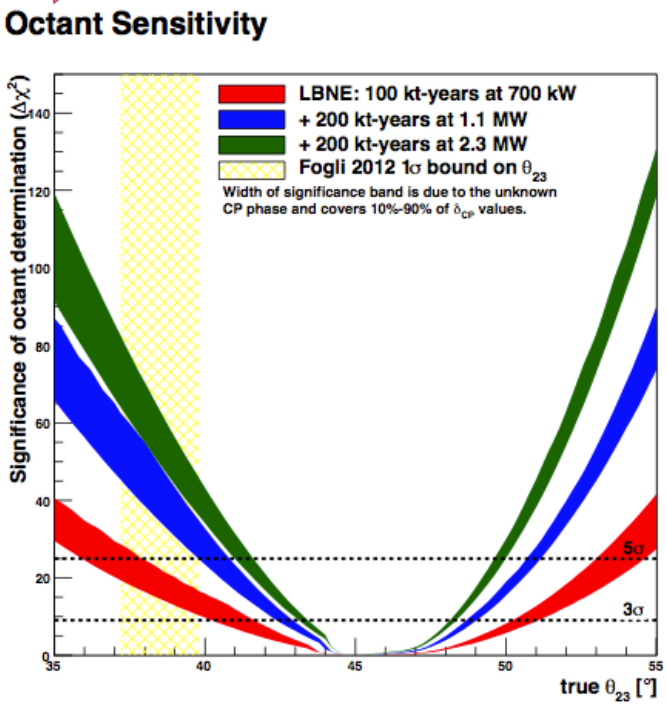
Long-baseline accelerator neutrino physics

- Provides a way to search for unknowns by,
  - ν_e appearance
    - Sensitive to combination of θ_{atm} and θ_{13}
    - Sensitive to matter effects (mass hierarchy) and CP phase
  - ν_μ disappearance
    - θ_{atm}
    - Δm^2_{atm}
  - Both sensitive to octant determination





(M. Bass, Colorado State)

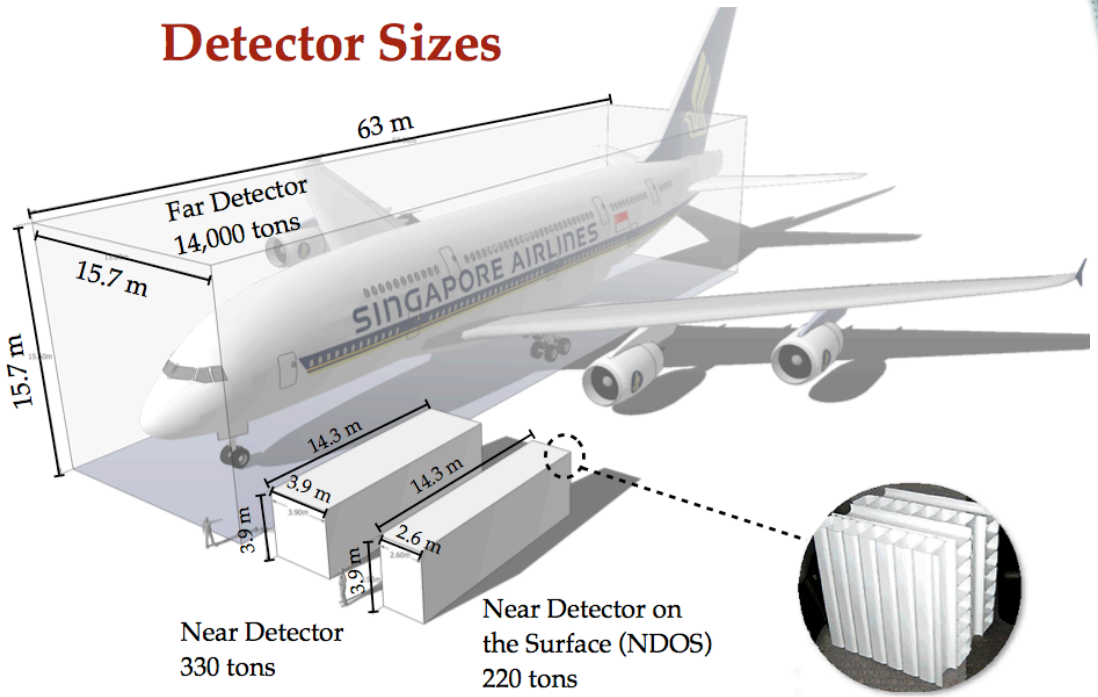


(E. Worcester, BNL)

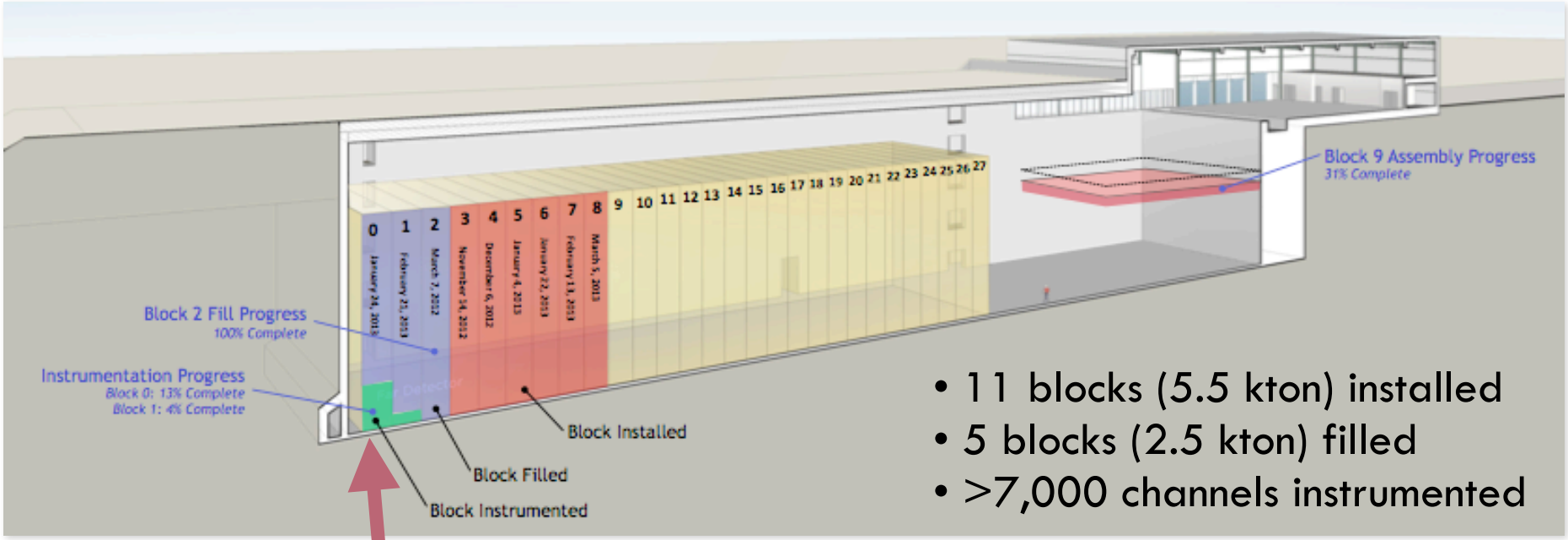
NOvA

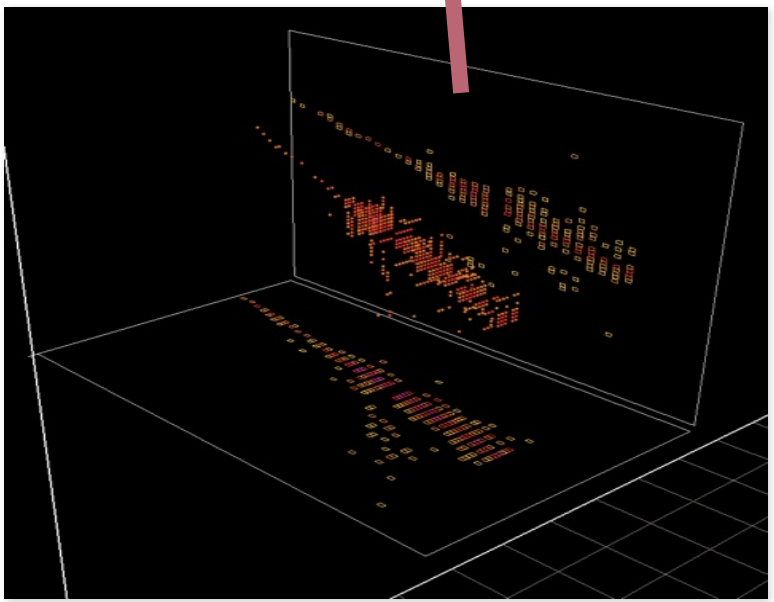
- Next-generation long-baseline experiment that will be fully operational in 2014

- Will study $\nu_\mu \rightarrow \nu_e$ transitions over a distance of 810 km
- An off-axis, narrow band beam
- 14 kton liquid scintillator



NOvA status

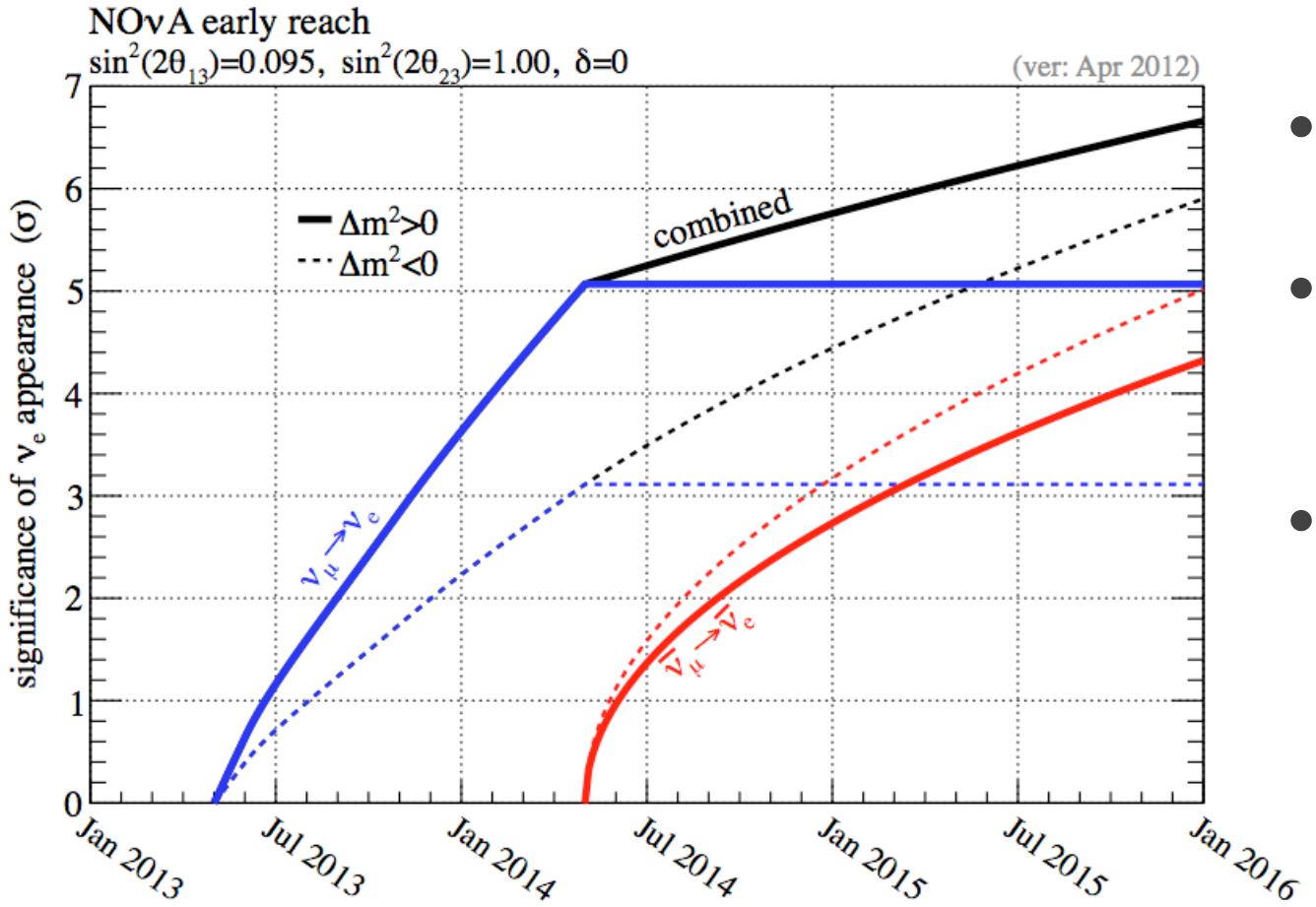




3D image of a cosmic ray muon producing a large shower in the first completed section of the NOvA far detector (March 28, 2013)

• near detector cavern almost complete!

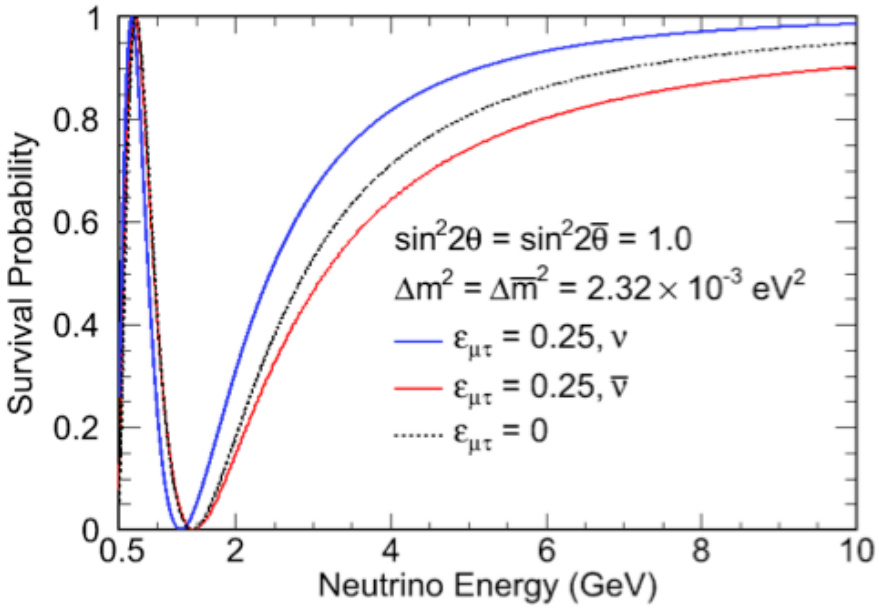
NOvA physics



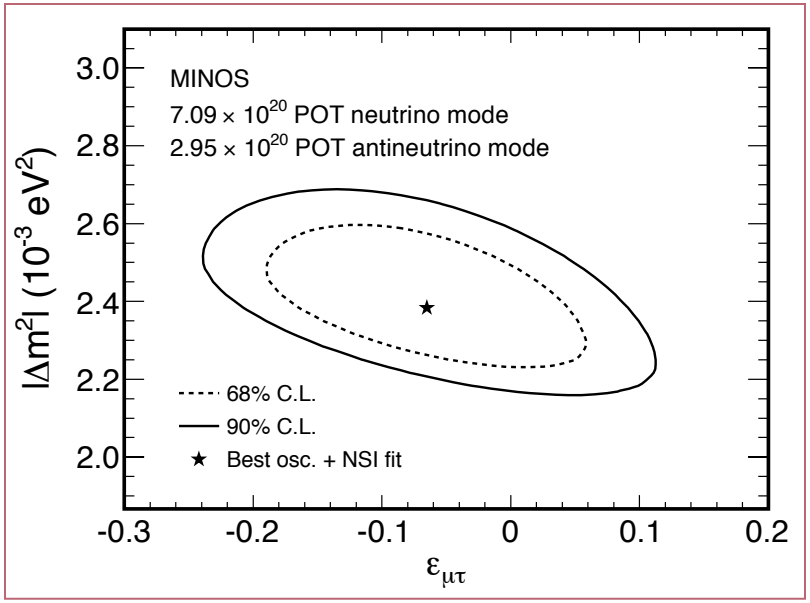
- Start taking neutrino beam in June
- Potential for 5σ ν_e appearance in first year
- Powerful combinations with T2K possible

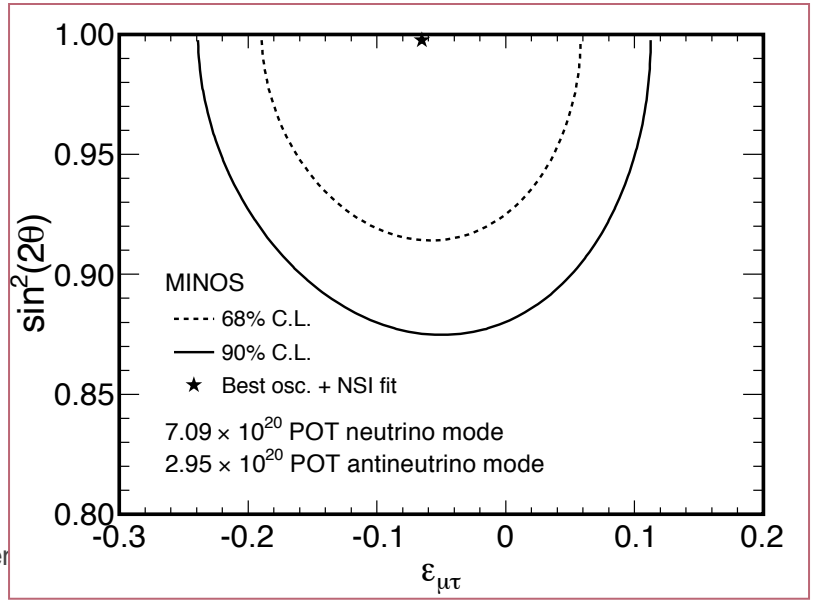
MINOS+

- Will run in the NOvA beam
- Expect ~3,000 events/year
- Looks for new physics in previously unexplored regions, exotics



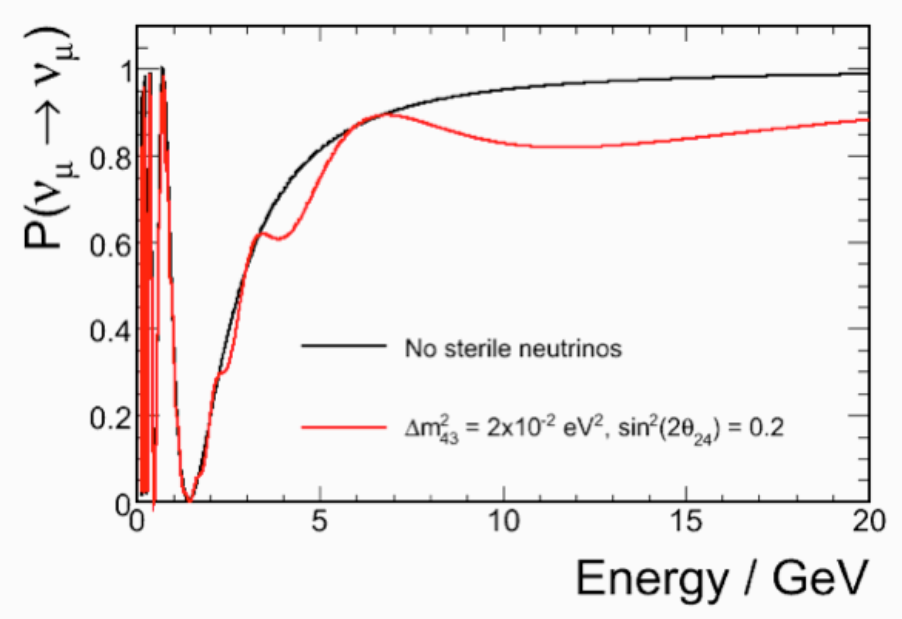
MINOS NSI

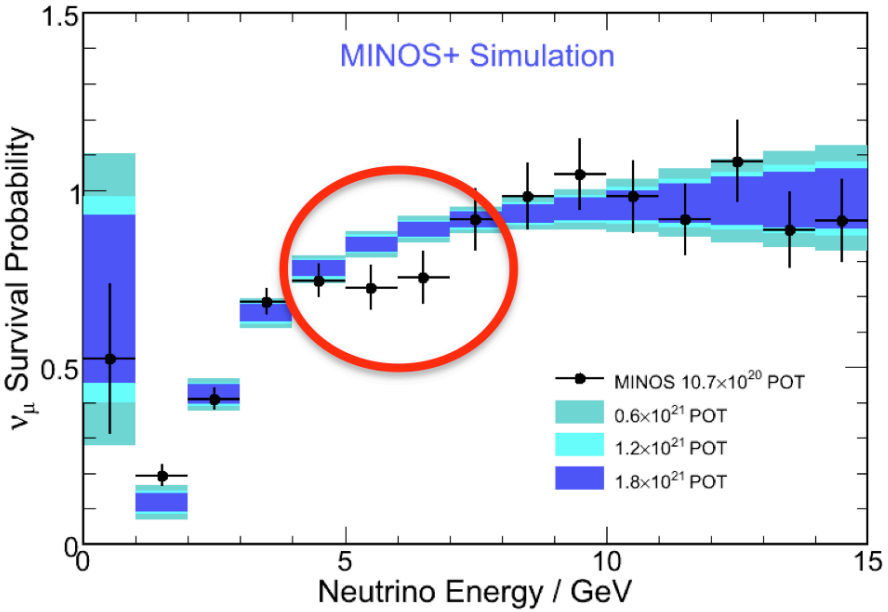


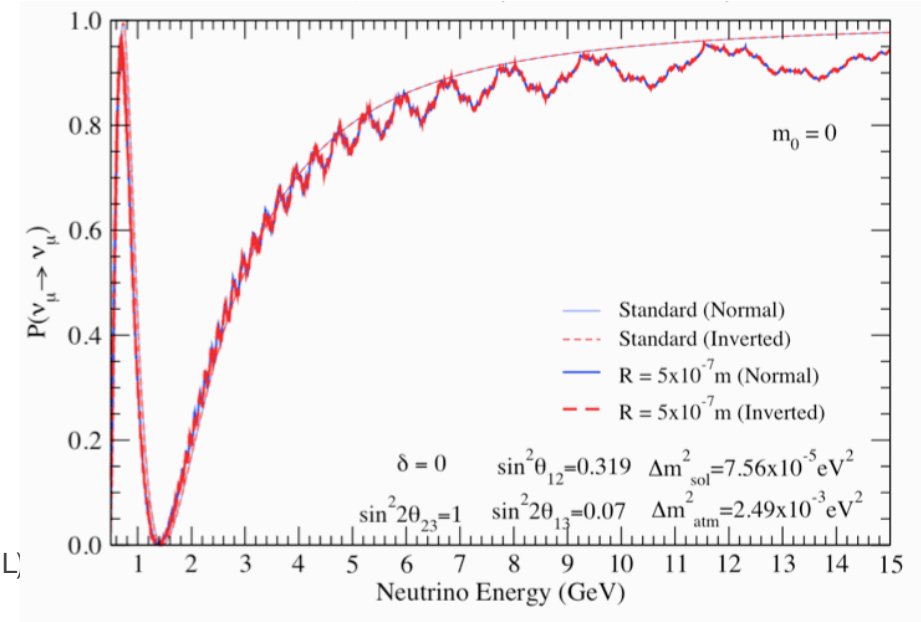


MINOS+

Sterile neutrinos

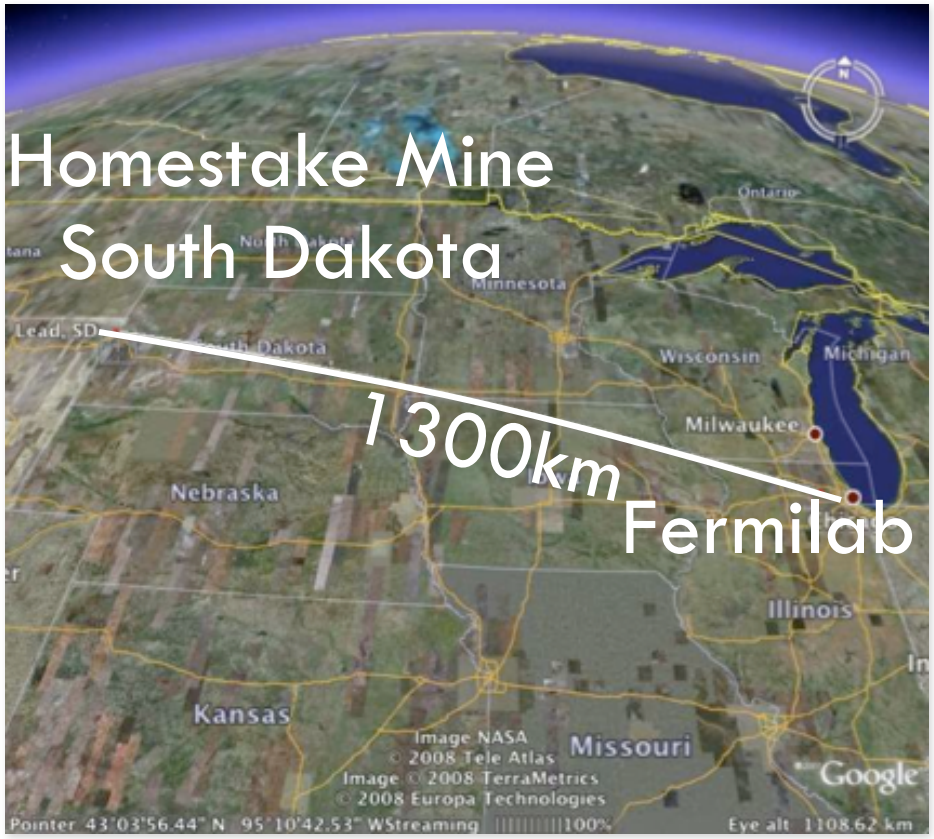






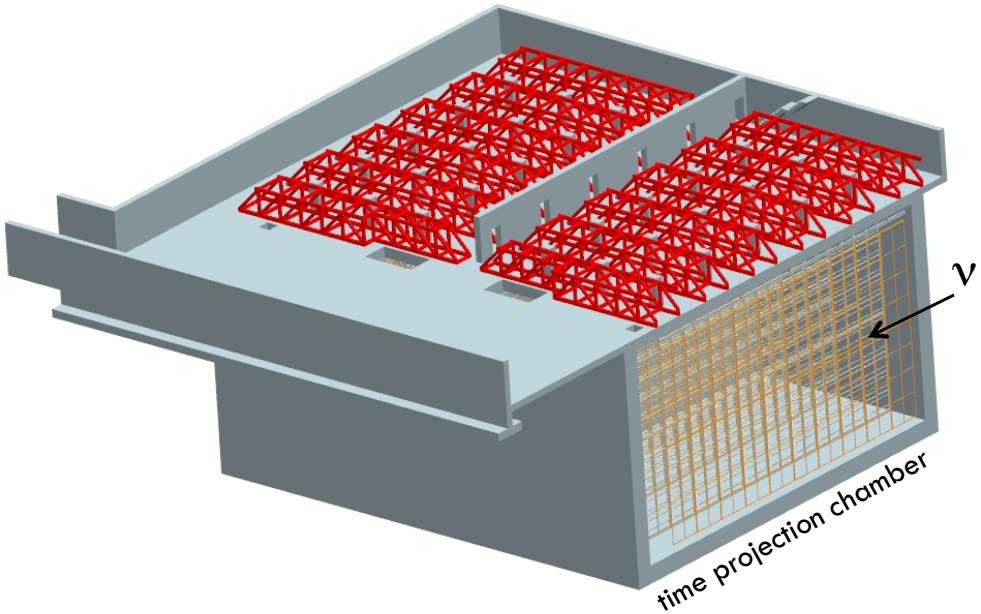
Large extra dimensions

Long-Baseline Neutrino Experiment



- New broad beam, neutrino and antineutrino mode
- Allows for increasing beam power

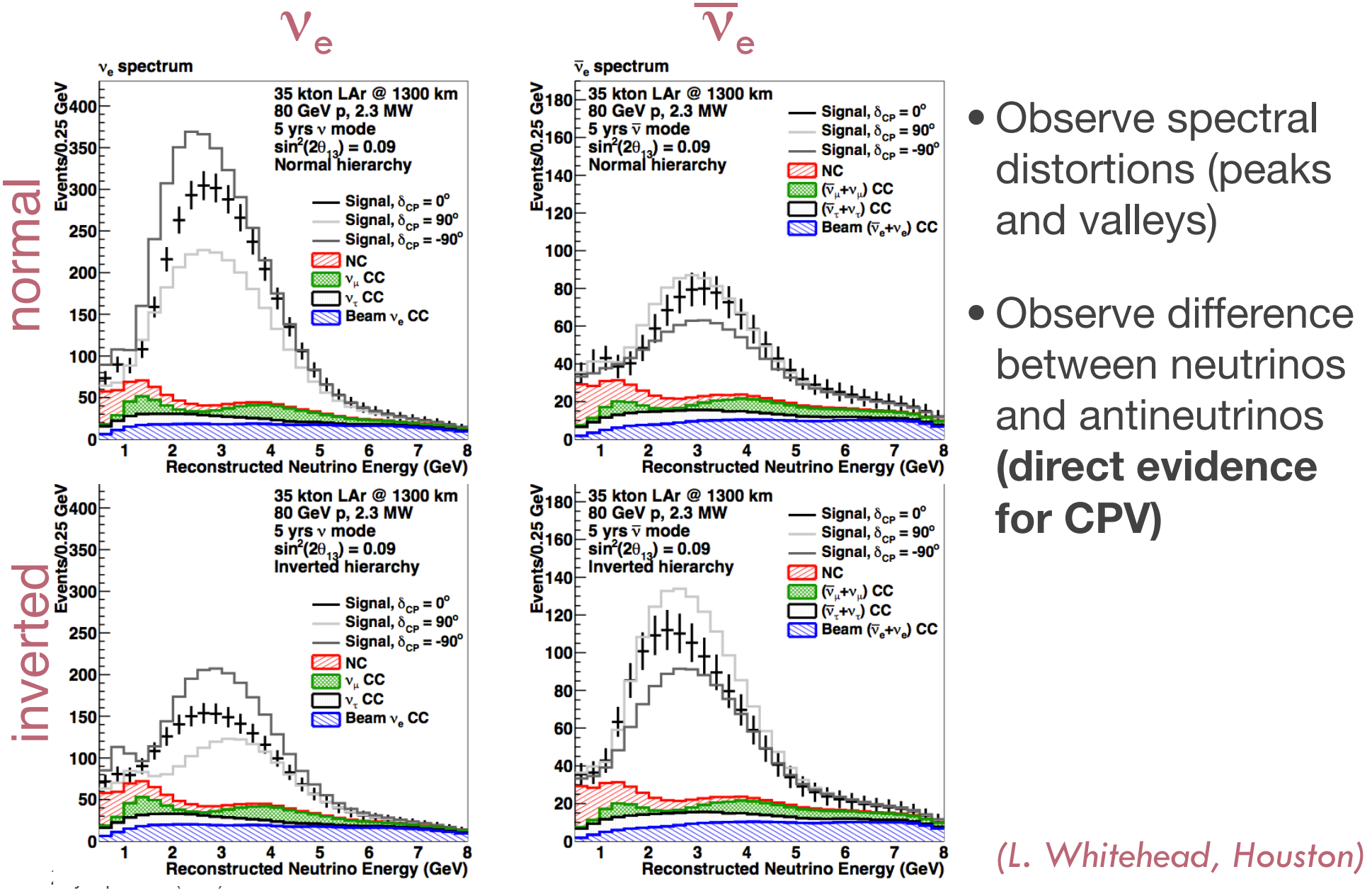
- Baseline optimized for CPV discovery and mass hierarchy determination.
- Liquid Argon (LAr) time projection chamber (TPC)
  - Very low background, high efficiency over broad energy range



LBNE science goals

- **Comprehensive program to measure neutrino oscillations**
- Discover and characterize CP violation in the neutrino sector
- Resolve other missing pieces of the neutrino puzzle
  - Unambiguously resolve the neutrino mass hierarchy
  - Precisely measure neutrino oscillation parameters
    - mixing angles: maximal? octant?
    - mass splittings: hierarchy
  - Search for New Physics (NSI, sterile neutrinos, etc.)
- Pursue fundamental physics enabled by massive *underground* detector
  - Proton decay
  - Supernova burst neutrinos
  - Atmospheric neutrinos

ν_e appearance signal



- Observe spectral distortions (peaks and valleys)
- Observe difference between neutrinos and antineutrinos **(direct evidence for CPV)**

(L. Whitehead, Houston)

LBNE long term plan

- First phase granted DOE CD-1 approval in December 2012
  - >10 kTon underground with a high resolution near detector by attracting additional non-DOE resources
- The LBNE beamline 2.3 MW capable; can take advantage of Project X
  - CP phase resolution improved by 5-10 degrees.

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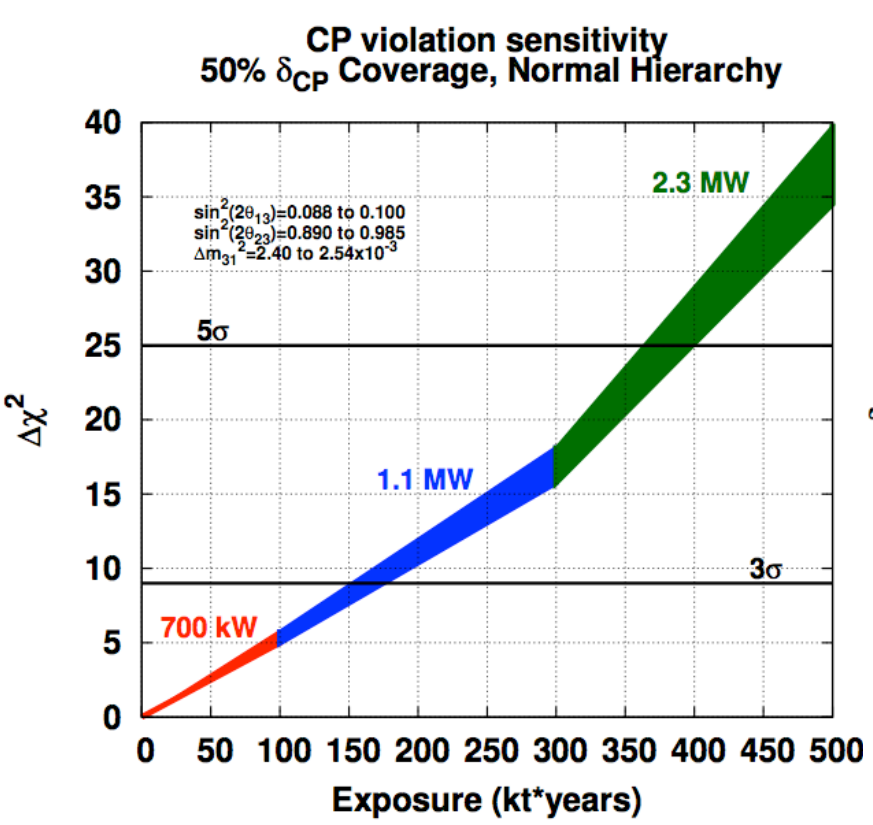

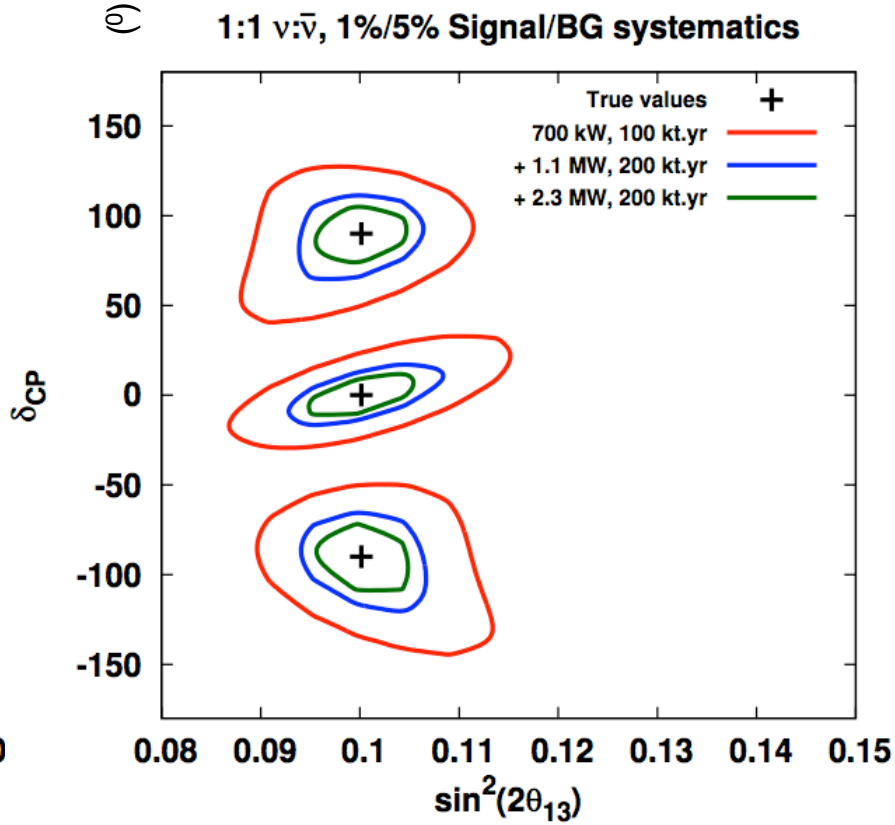

The take-away

- Neutrino physics continues to be an exciting field.
- Accelerator-based long-baseline neutrino oscillation experiments will be working to answer important questions over the next couple of decades.
- Discovery of θ_{13} has made long-baseline path clear: search for CP violation.
- We will determine mass hierarchy and the octant of θ_{23} with these experiments.
- Many other neutrino experiments (short-baseline, reactor, double beta decay etc.) innovating and discovering; together we will paint a better picture of neutrinos.

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Thank you.