



Incorporating external constraints to MicroBooNE/SBN oscillation searches

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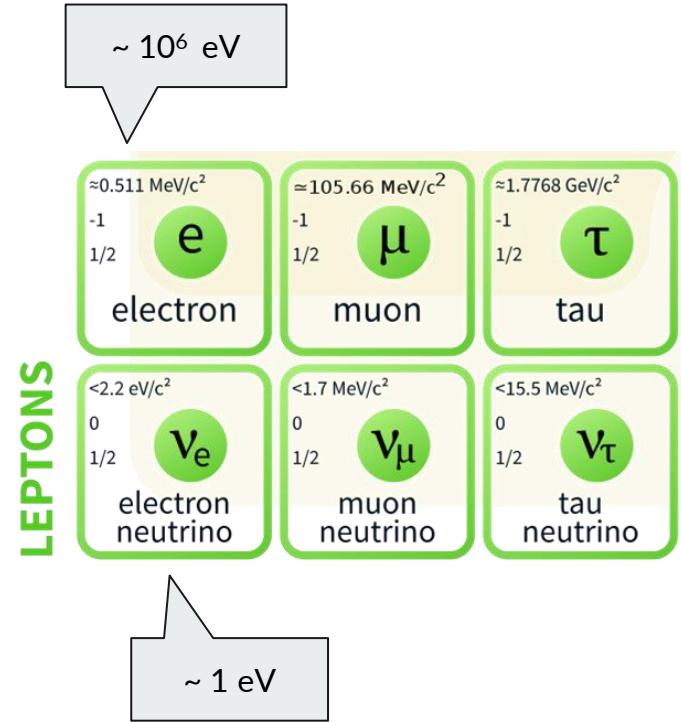
Outline

Incorporating external constraints to the sensitivity analysis
for MicroBooNE's **neutrino oscillation** search

Neutrinos

Standard model predicts 3 neutrino flavours

- ★ Cousins of electron, muon, and tau
- ★ ~~Massless~~ Very small masses
- ★ Neutral (no charge)
- ★ Only interacts through the weak force



Neutrino Flavor Mixing

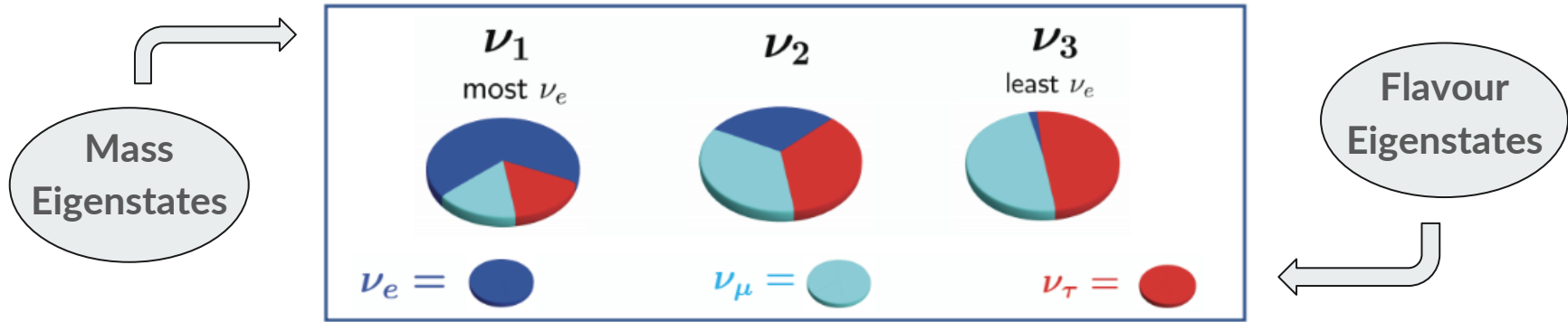
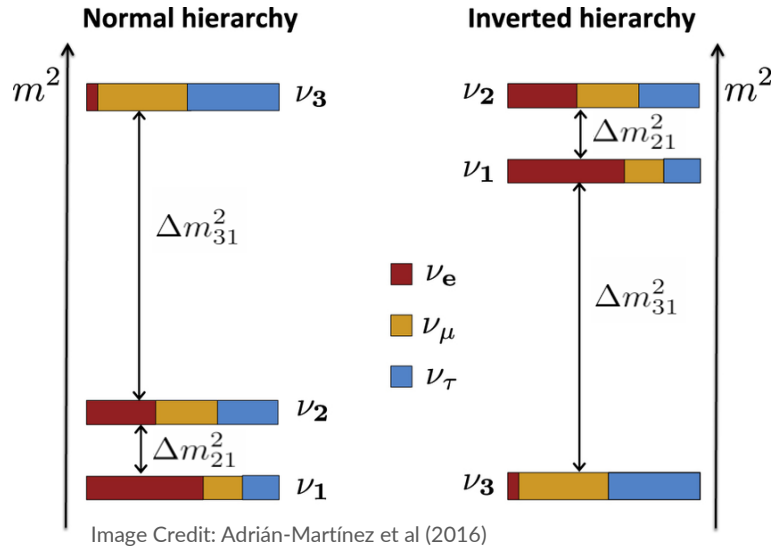


Image Credit: Fermilab

Neutrinos are in:

- Definite mass states while traveling
- Definite flavour states while interacting through weak force

3 Neutrino Mixing Parameters



$$\rightarrow \Delta m_{21}^2 = m_2^2 - m_1^2$$

$$\rightarrow \Delta m_{31}^2 = m_3^2 - m_1^2$$

$\rightarrow \theta_{12}, \theta_{13}, \theta_{23}$ = Mixing angles between mass states

$\rightarrow \theta_{e\mu}, \theta_{e\tau}, \theta_{\mu\tau}$ = Mixing angles between flavour states

★ We don't know the mass hierarchy, just differences

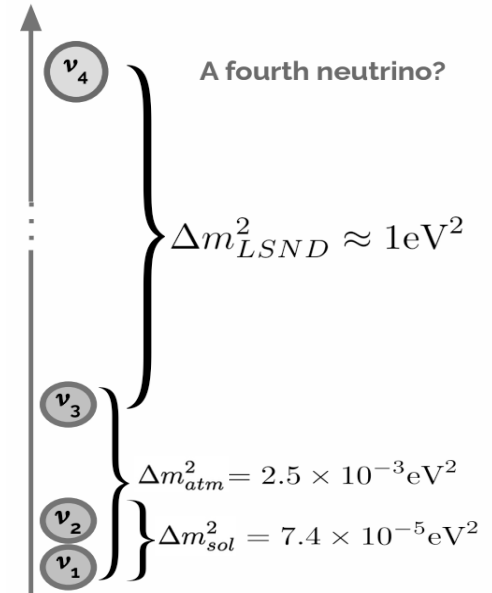
Short-Baseline Oscillations + Sterile Neutrino?

Long-Baseline Oscillations

- Solar neutrino oscillations (1980s)
- Atmospheric neutrino oscillations (1990s-2000s)
- Early reactor and accelerator oscillations

Short-Baseline Anomaly

- Liquid Scintillator Neutrino Detector (LSND) (1990s)
- MiniBooNE + MicroBooNE (2000s-2010s)
- ★ Evidence of neutrino oscillations at SHORT distances, could be explained by additional “sterile” neutrinos





Neutrino Oscillations (3+1)

$$\begin{aligned} \sin^2(2\theta_{ee}) &= 4(1 - |U_{e4}|^2)|U_{e4}|^2 \\ \sin^2(2\theta_{\mu\mu}) &= 4(1 - |U_{\mu4}|^2)|U_{\mu4}|^2 \\ \sin^2(2\theta_{\mu e}) &= 4|U_{e4}|^2|U_{\mu4}|^2 \end{aligned}$$

Simplest sterile neutrino model

→ 3 standard model neutrinos + 1 sterile neutrino which doesn't interact through the weak force

Individual neutrino's flavour can swap between 2 measurements with distance dependent probabilities:

$$P_{\nu_e \rightarrow \nu_e} = 1 - \sin^2(2\theta_{ee})\sin^2(1.27\Delta m_{41}^2 L/E)$$

$$P_{\nu_\mu \rightarrow \nu_\mu} = 1 - \sin^2(2\theta_{\mu\mu})\sin^2(1.27\Delta m_{41}^2 L/E)$$

$$P_{\nu_\mu \rightarrow \nu_e} = \sin^2(2\theta_{\mu e})\sin^2(1.27\Delta m_{41}^2 L/E)$$



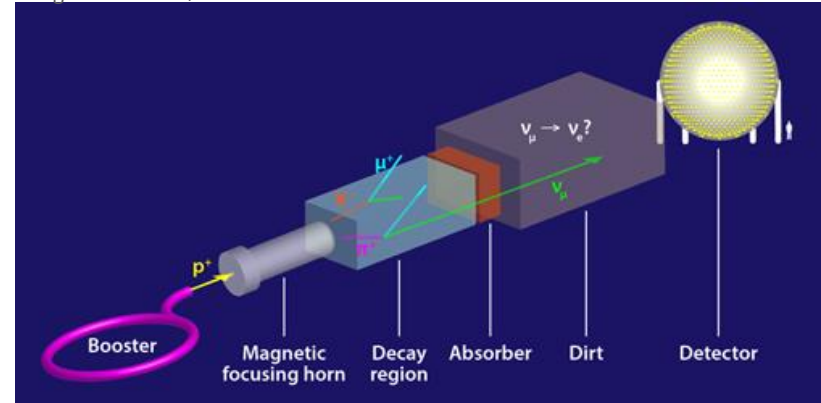
Outline

Incorporating external constraints to the sensitivity analysis
for **MicroBooNE's** neutrino oscillation search

MicroBooNE

- ★ Created to investigate anomalous neutrino signals at short-baselines

Image Credit: APS/Alan Stonebraker



Short-Baseline Neutrino Program at Fermilab

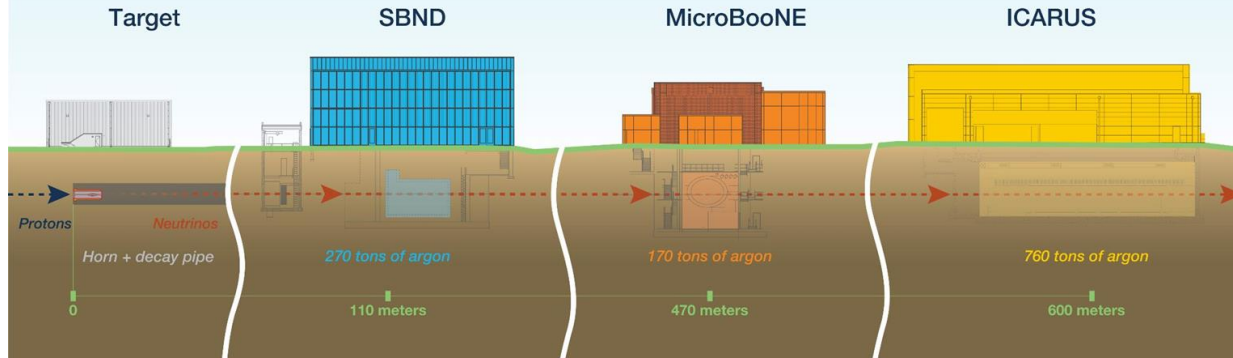


Image Credit: Fermilab

- ★ Liquid-Argon Time Projection Chamber (LaTPC) Detector
- ★ Neutrino beam ~99% muon neutrinos and antineutrinos, <1% electron neutrinos



Outline

Incorporating external constraints to the **sensitivity analysis**
for MicroBooNE's neutrino oscillation search



What is a sensitivity study?

Overall goal for oscillation search:

- Find the values of the the oscillation parameters ($\Delta m_{41}^2, U_{e4}, U_{\mu 4}$) that best fit the observed data

However, some parameter combinations will only cause very small observable oscillation effects

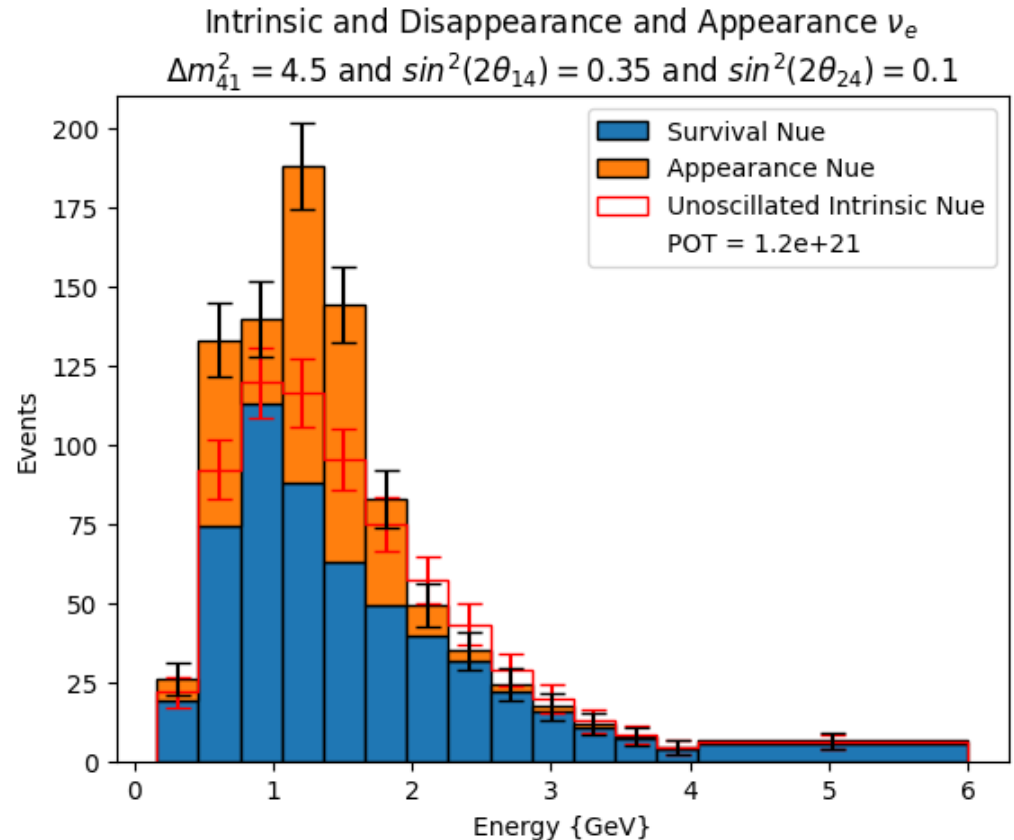
- MicroBooNE cannot detect every single small difference in neutrino flux
- Some uncertainty as to what is an oscillation “signal” and what is background neutrino “noise”

Thus, we need to find the region in parameter space which MicroBooNE is sensitive to

- Where we can statistically differentiate between the background and oscillation neutrinos if the signal actually exists

Plotting Spectra

1. Intrinsic beam electron neutrinos
2. Electron neutrino disappearance
(from electron neutrino oscillation)
3. Electron neutrino appearance (from
muon neutrino oscillation)





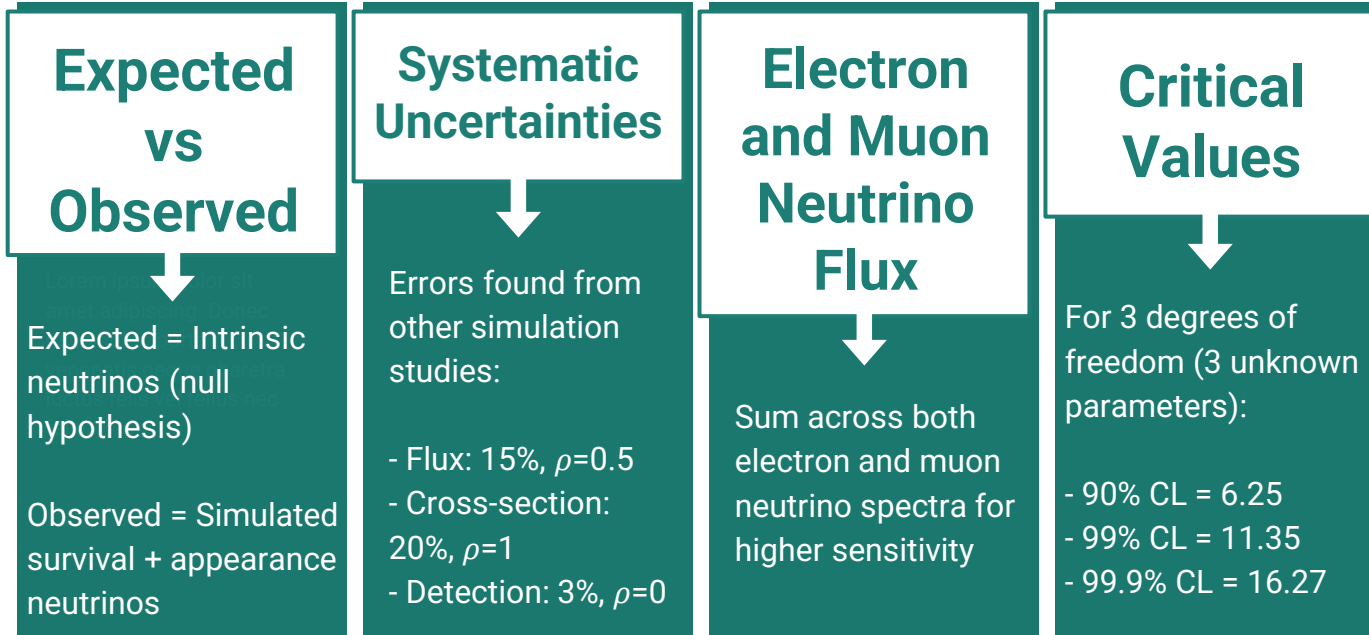
Chi2 Equation

$$\chi^2 = \sum_i^N \sum_j^N (Observed_i - Expected_i) * M_{ij}^{-1} * (Observed_j - Expected_j)$$

Where M is the full covariance matrix encapsulating the following errors added in quadrature:

- σ^2 statistical error = N_i ρ_{ij} is the correlation coefficient between bins i and j
- σ_{flux}^2 systematic flux error = $N_i * N_j * \sigma_{flux,i} * \sigma_{flux,j} * \rho_{ij}$
- σ_{cross}^2 systematic cross-section error = $N_i * N_j * \sigma_{cross,i} * \sigma_{cross,j} * \rho_{ij}$
- σ_{detect}^2 systematic detection error = $N_i * N_j * \sigma_{detect,i} * \sigma_{detect,j} * \rho_{ij}$

χ^2 in context of oscillation



ν_e and ν_μ Spectra χ^2 Sensitivity to Variations in U_{e4}^2 , $U_{\mu4}^2$, and Δm_{41}^2
POT = 1.2e+21

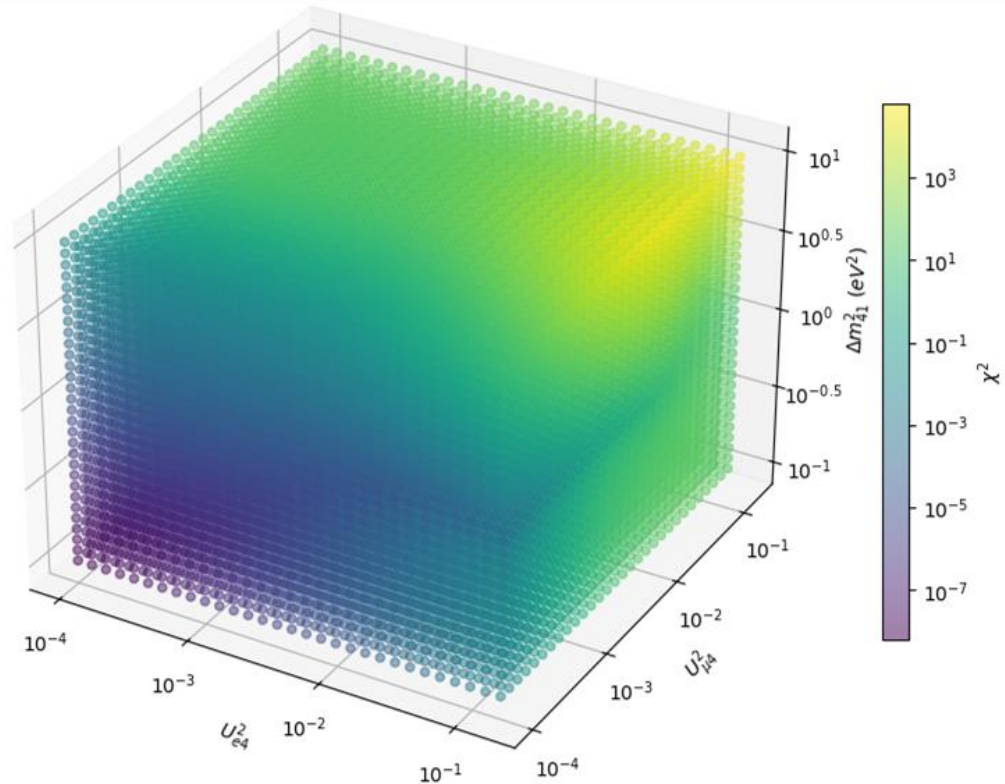
3D Parameter Space

Parameter limits set by previous experimental results:

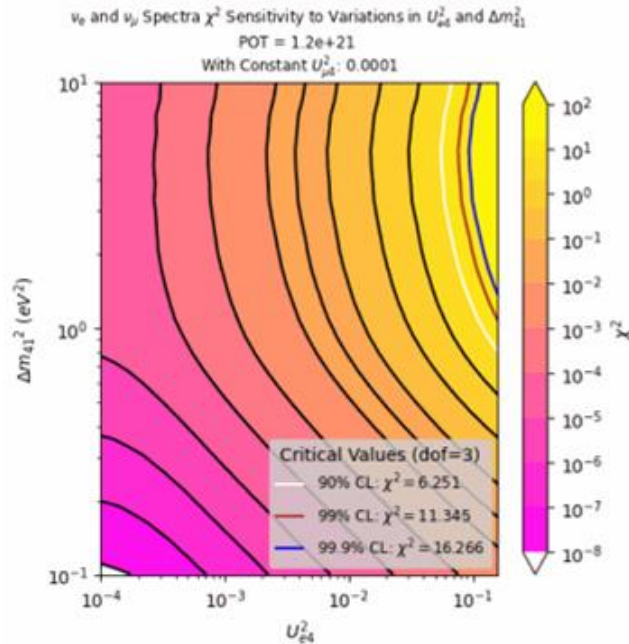
Δm_{41}^2 : [0.1, 10], log-scale

U_{e4} : [0.0001, 0.1], log-scale

$U_{\mu4}$: [0.0001, 0.1], log-scale

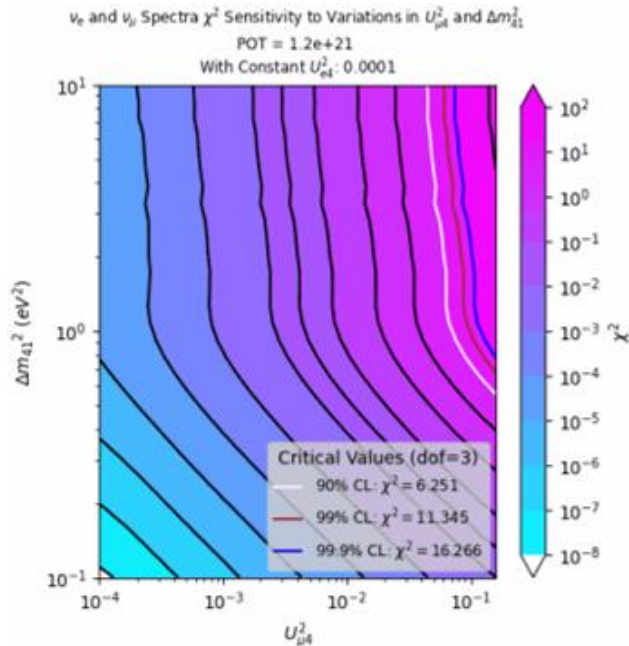


Δm_{41}^2 and U_{e4}^2 Contour



- ★ χ^2 range from $<10^{-8}$ to >100
- ★ MicroBooNE is sensitive to yellow regions above and to the right of the critical value contours
- ★ Sensitivity seems to decrease until $U_{\mu 4}^2 \cong 0.004$, then starts to increase
- ★ This could be due to some cancellation between the electron neutrino appearance and disappearance numbers, thus lowering the χ^2 value

Δm_{41}^2 and $U_{\mu 4}^2$ Contour



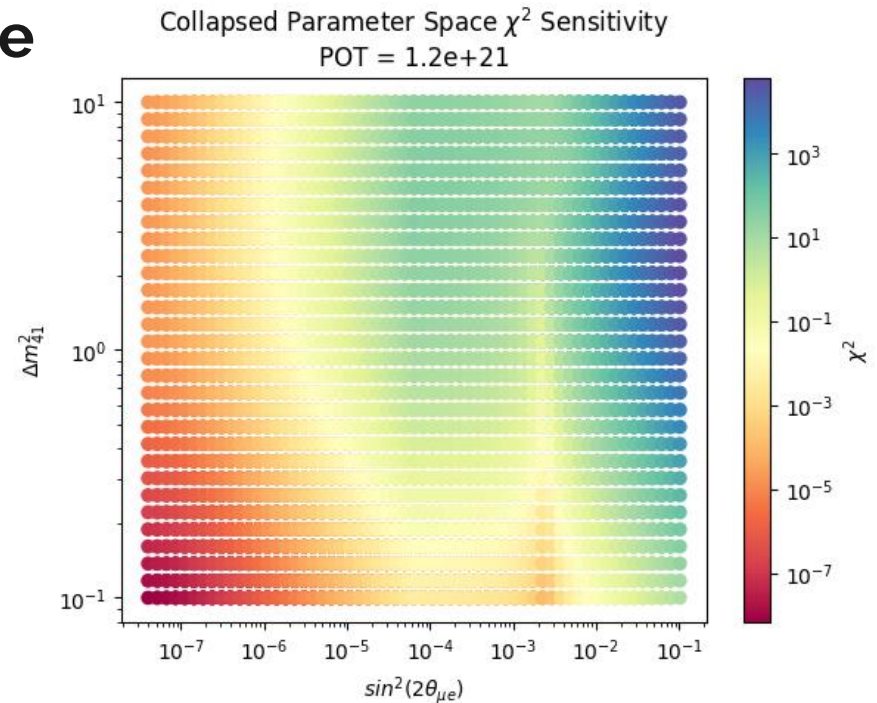
- ★ χ^2 range from $<10^{-8}$ to >100
- ★ At low U_{e4} and $U_{\mu 4}$, MicroBooNE has low sensitivity to the parameter space, particularly when Δm_{41}^2 is also low
- ★ We can now see the “bump” of low χ^2 (low sensitivity) at $U_{\mu 4}^2 \cong 0.006$

Collapsed Parameter Space

- ★ Collapse the U_{e4} and $U_{\mu 4}$ parameters into the single parameter:

$$\sin^2(2\theta_{\mu e}) = 4|U_{e4}|^2|U_{\mu 4}|^2$$

- ★ Typical global χ^2 fitting parameter space





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for MicroBooNE's neutrino oscillation search

PROSPECT and IceCube

PROSPECT Detector at Oak Ridge National Lab

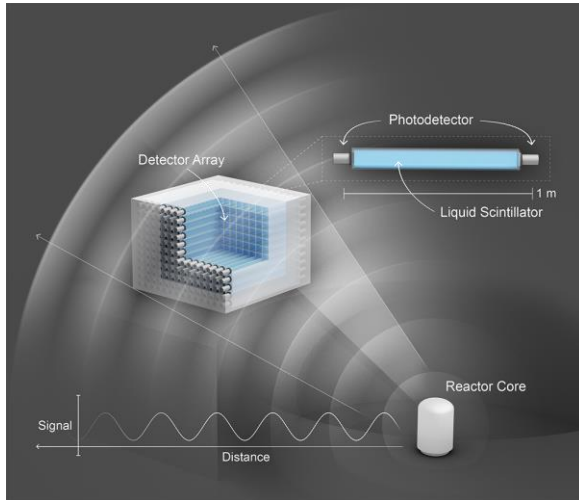
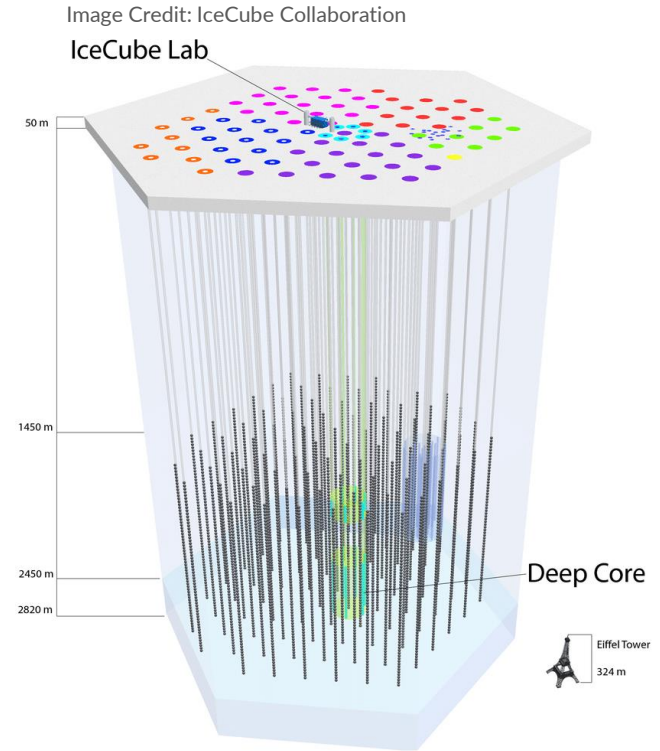


Image Credit: NIST/Sean Kelley

- ★ Independent non-accelerator neutrino detectors
- ★ PROSPECT measures short baseline reactor electron antineutrino disappearance
- ★ IceCube detects all neutrino flavors, but primarily measures atmospheric muon neutrino disappearance



IceCube Detector at the South Pole

Comparison to IceCube

- ★ IceCube best fit values:

$$\Delta m_{41}^2 = 4.5\text{eV} \text{ and } \sin^2(2\theta_{24}) = 0.1$$

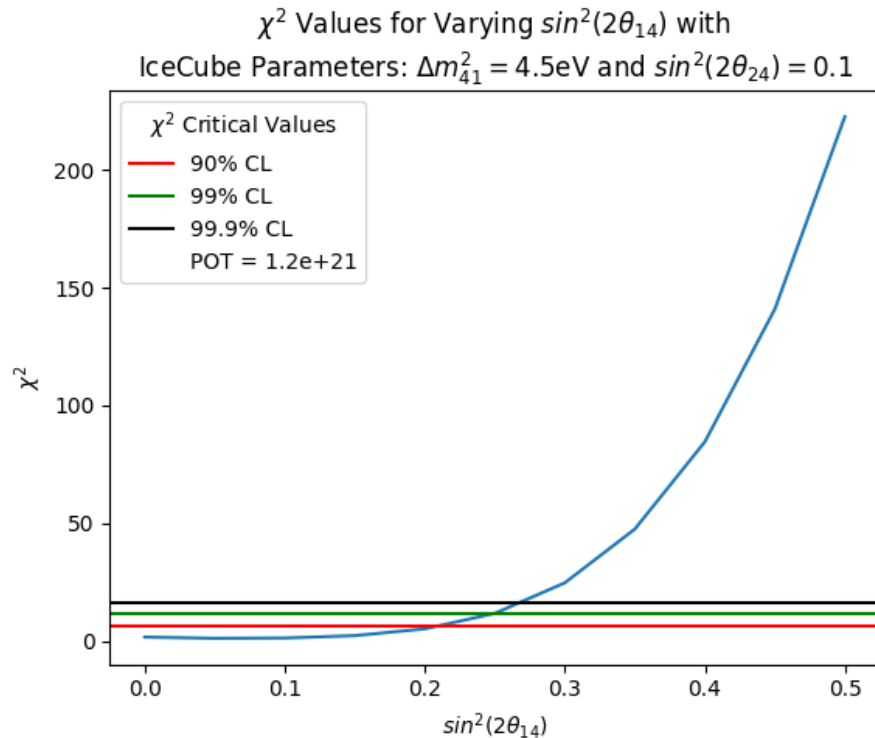
- ★ About $\sim 1/2$ of $\sin^2(2\theta_{14})$ parameter space above critical values, meaning MicroBooNE has sensitivity

- ★ Parameter conversions $\rightarrow$

$$\sin^2(2\theta_{ee}) \approx \sin^2(2\theta_{14})$$

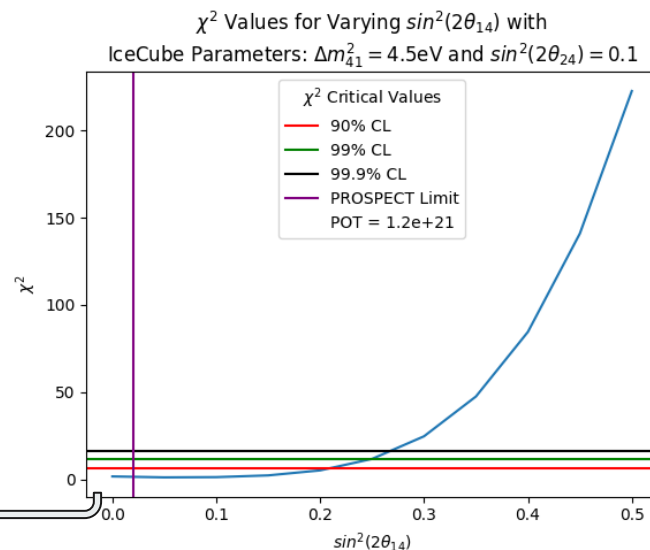
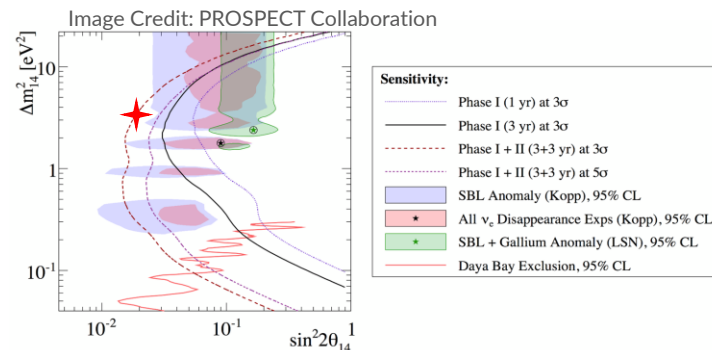
$$\sin^2(2\theta_{\mu\mu}) \approx \sin^2(2\theta_{24})$$

$$\sin^2(2\theta_{\mu e}) \approx \frac{1}{4}\sin^2(2\theta_{14})\sin^2(2\theta_{24})$$



Adding in PROSPECT Limits

- ★ PROSPECT found no evidence for oscillations within its own sensitivity parameter space
- ★ For $\Delta m_{41}^2 = 4.5 \text{ eV}^2$ (given by IceCube), PROSPECT rules out any $\sin^2(2\theta_{14}) > 0.02$ at a 99.73% CL
- ★ MicroBooNE is NOT sensitive to the parameter region allowed by PROSPECT and IceCube's best fit





Conclusions

Calculating χ^2 Values

- Incorporating electron neutrino appearance AND disappearance is important for accurate χ^2 measurements
- Fitting oscillation models across both electron and muon neutrino flux increases χ^2 values (increasing our sensitivity)

Incorporating External Constraints

- MicroBooNE is sensitive to $\sim 1/2$ of IceCube's parameter space at larger $\sin^2(2\theta_{14})$
- Adding in the PROSPECT limit on $\sin^2(2\theta_{14})$, MicroBooNE is NOT sensitive to the combined allowed parameter space region
- Thus, MicroBooNE cannot definitively check the validity of both PROSPECT and IceCube's results

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