Observing the Earth’s Core with Neutrino Oscillations at DUNE

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Neutrino Oscillations with Atmospheric Neutrinos

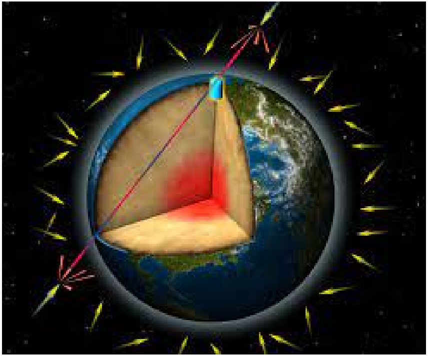
Neutrino Hamiltonian in Matter:

$$H = \frac{1}{2E}\left(U^\dagger \begin{bmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 \\ 0 & 0 & \Delta m^2_{31} \end{bmatrix} U + 2\sqrt{2} G_F N_e E \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}\right)$$

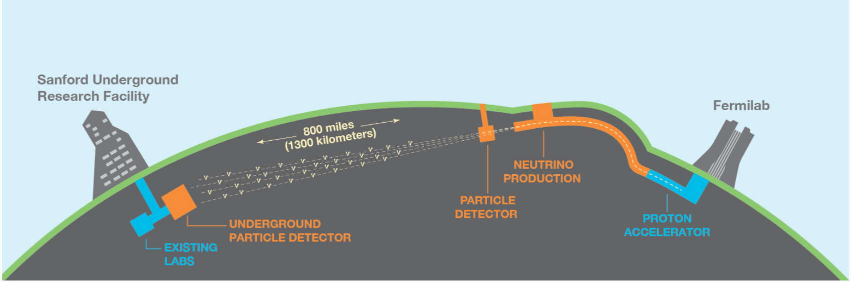
Oscillation probability:

$$P_{\alpha\to\beta}(t) = |\langle \nu_\beta | \nu_\alpha(t) \rangle|^2$$

$$= \left| \sum_{i,j} U_{\beta i} U^*_{\alpha j} \left\langle \nu_i \middle| e^{-iHt} \nu_j \right\rangle \right|^2$$



DUNE: Deep Underground Neutrino Experiment



LArTPC (Liquid Argon Time Projection Chamber) for far detector

$\Rightarrow$ Can determine direction neutrino came from

Energy range: 0.1 GeV-8.0 GeV

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Neutrino oscillations through the Earth's core

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Neutrinos have two properties that make them fairly unique from other known particles: extremely low cross sections and flavor changing oscillations. With a good knowledge of the oscillation parameters soon in hand, it will become possible to detect low-energy atmospheric neutrinos sensitive to the forward elastic scattering off electrons in the Earth's core providing a measurement of the core properties and the matter effect itself. As the dynamics of the Earth's core are complicated and in a difficult to probe environment, additional information from upcoming neutrino experiments will provide feedback into our knowledge of geophysics as well as useful information about exoplanet formation and various new physics scenarios including dark matter. In addition, we can probe the existence of the matter effect in the Earth and constrain the nonstandard neutrino interaction parameter $\epsilon_{ee}^{\oplus}$. We show how DUNE's sensitivity to low-energy atmospheric neutrino oscillations can provide a novel constraint on the density and radius of the Earth's core at the 9% level and the Earth's matter effect at the 5% level. Finally, we illuminate the physics behind low-energy atmospheric neutrino resonances in the Earth.

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Simulating DUNE Set Up

- Detector with DUNE's far detector specs
  - 40 kton
  - 10 years
- Honda flux model averaged over angles for source

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- χ^2 calculated for fits

$$\chi^2 = \sum_i \frac{(\phi_{\text{true}_i} - \phi_{\text{fit}_i})^2}{\phi_{\text{true}_i}} + \sum_j \left(\frac{s_j}{\sigma_j}\right)^2$$

  - Minimized over systematic parameters
  - 1st Fit: Varied ϵ_{ee}
  - 2nd Fit: Varied radius of Earth's core

Neutrino Hamiltonian with NSIs (generic):

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$\epsilon_{\alpha\beta}$ can come from effective Lagrangians like

$$\mathcal{L}_{\mathrm{NSI}} = -2\sqrt{2} G_F \sum_{\alpha,\beta,f} \epsilon^f_{\alpha\beta} (\bar{\nu}_\alpha \gamma^\mu \nu_\beta)(\bar{f}\gamma_\mu f)\,,$$

where $\epsilon_{\alpha\beta} = \sum_f \frac{N_f}{N_e} \epsilon^f_{\alpha\beta}$

Simulating DUNE Non-Standard neutrino Interactions (NSI)

Neutrino Hamiltonian with NSIs (generic):

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$\epsilon_{\alpha\beta}$ can come from effective Lagrangians like

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where $\epsilon_{\alpha\beta} = \sum_f \frac{N_f}{N_e} \epsilon^f_{\alpha\beta}$
So, changing $\epsilon_e e$ effectively changes the magnitude of the matter effect.

Simulating DUNE Set Up

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  - Minimized over systematic parameters
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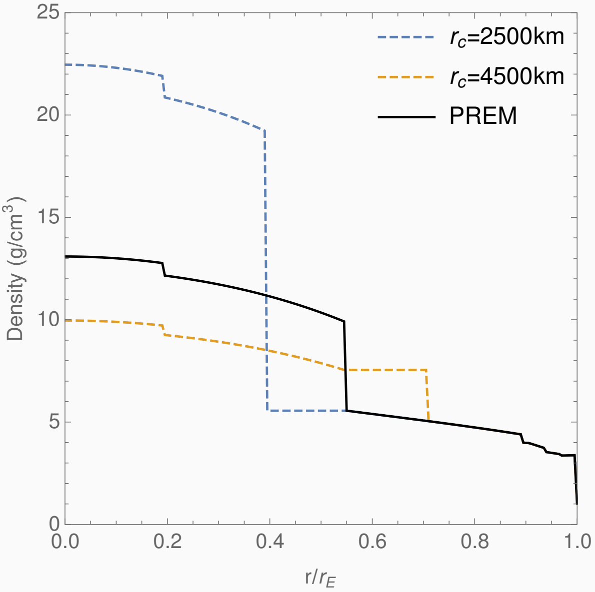
  - 2nd Fit: Varied radius of Earth's core

Simulating DUNE Earth's Density Profile

Model used: Preliminary Reference Earth Model (PREM)

Assumes spherical Earth

When changing core radius, scaled core density to keep Earth's mass constant



Simulating DUNE Systematics

- Flux uncertainties

$$\Phi_\alpha = \Phi_{\alpha,0} f_\alpha(E)(E_\nu/E_0)^\gamma$$

  - $\Phi_{\alpha,0}$ = flux normalization, $1 \pm 40\%$ for $\alpha = \nu_e, \nu_\mu, \bar{\nu}_e, \bar{\nu}_\mu$
  - γ = spectral index, 0 ± 0.2

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  - γ = spectral index, 0 ± 0.2
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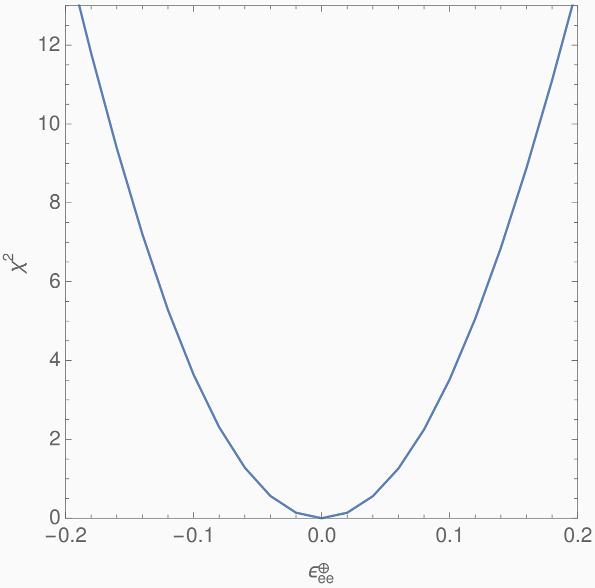
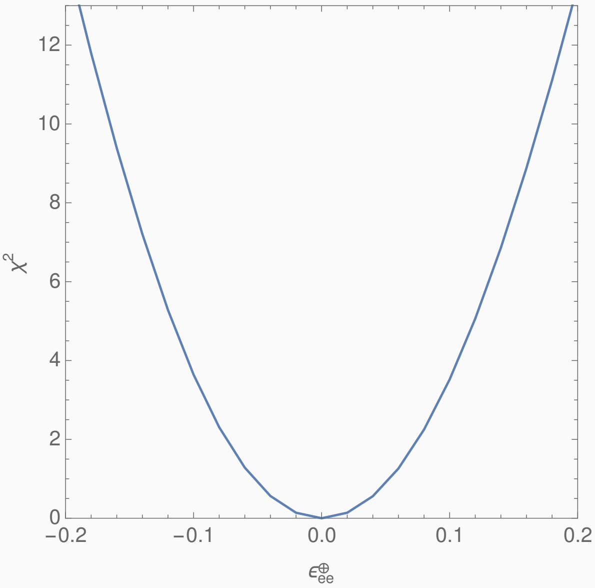
- Assume good flavor discrimination, but no $\nu/\bar{\nu}$ discrimination
- For resolutions:
  - 10 $\cos(\theta_Z)$ bins
  - 43 $\log(E_\nu)$ bins (10% resolution for E_ν)

Simulating DUNE Result #1

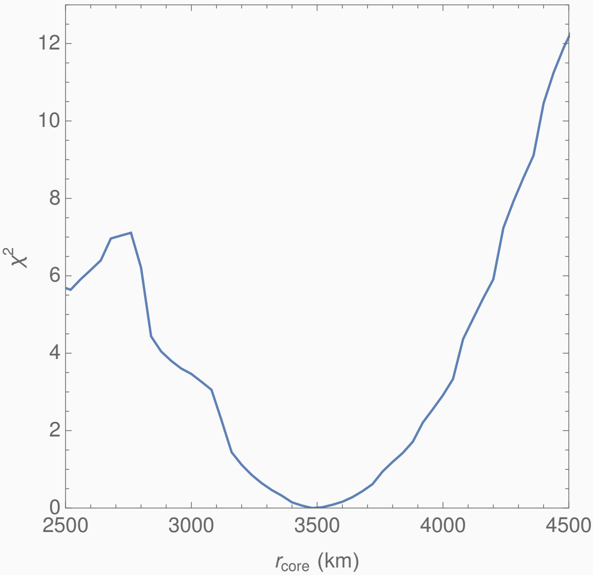


Simulating DUNE Result #1

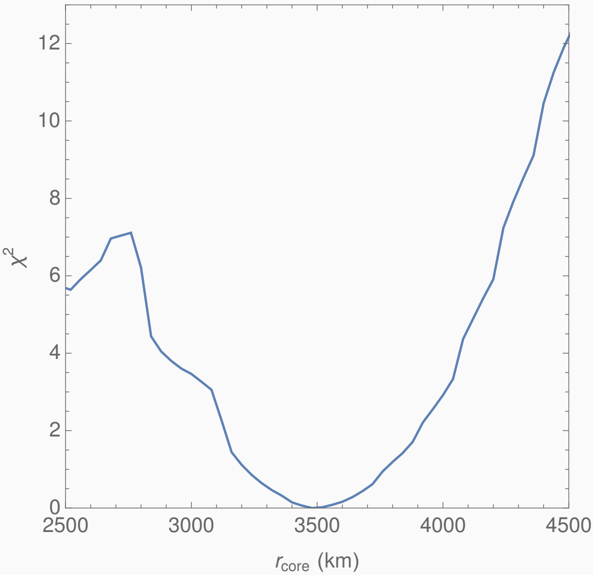


5% measurement of Earth's matter effect

Simulating DUNE Result #2



Simulating DUNE Result #2



9% measurement of radius of Earth's core

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3. **Summary**

Summary

- Using atmospheric neutrinos, DUNE is sensitive to conditions inside the earth
    - Can measure Earth’s matter effect to 5%
    - Can measure the size of the Earth’s core to 9%

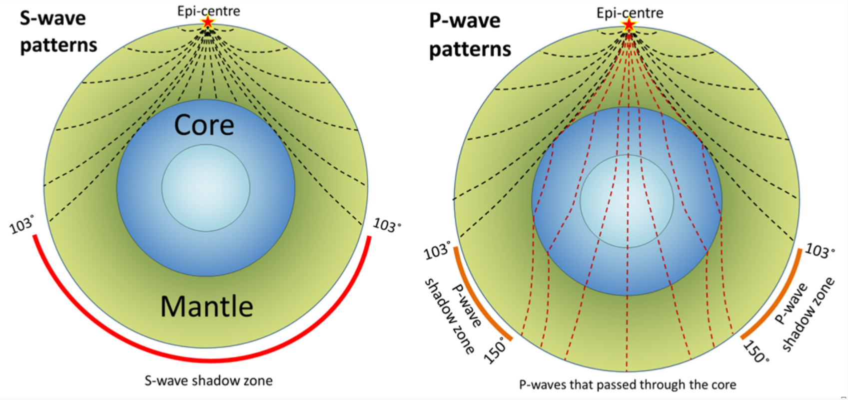
Thank you!

Questions?

This research was funded by the DOE.

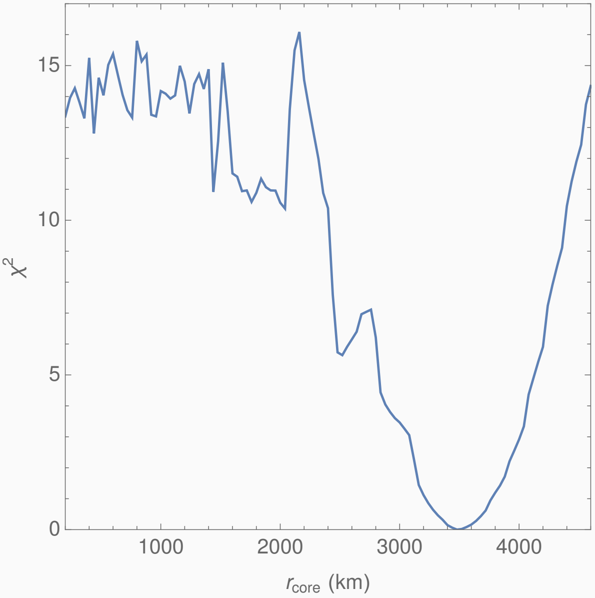
Looking inside the Earth

Earth's interior diagram "View" with Seismography



Measurement depends on composition, pressure, and temperature of the material, as well as exact location and depth of the earthquake

DUNE Simulation Earth's Core Sensitivity - Full Range



Earth's Layers