Investigating the Earth's Core with Neutrinos

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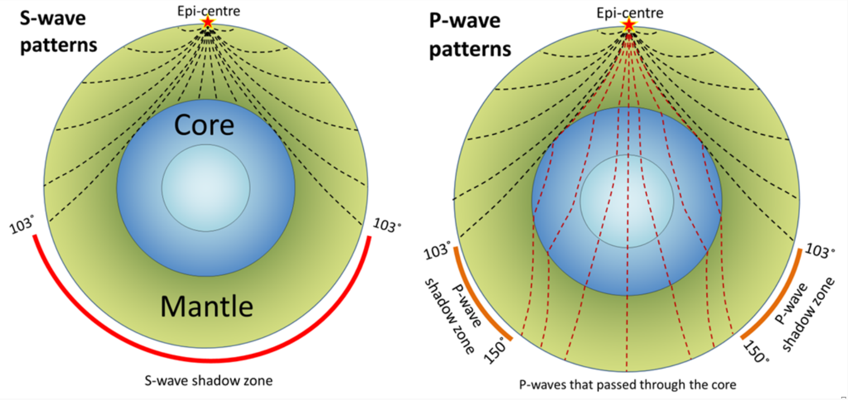
Looking inside the Earth

"View" with Seismography



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

Neutrinos in Matter

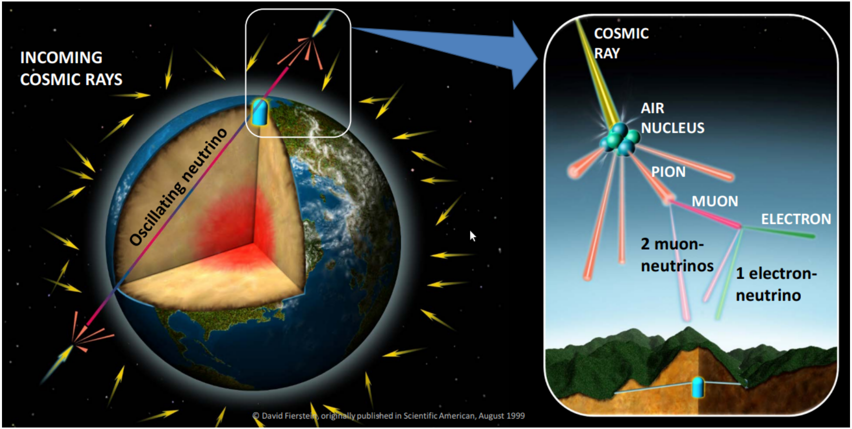
Neutrino Hamiltonian in Matter:

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

Oscillation probability:

$$P_{\alpha\to\beta}(t) = \left|\langle \nu_\beta | \nu_\alpha(t) \rangle\right|^2 = \left| \sum_{i,j} U_{\beta i} U_{\alpha j}^* \left\langle \nu_i \middle| e^{-iHt} \nu_j \right\rangle \right|^2$$

Atmospheric Neutrinos



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Neutrino oscillations through the Earth's core

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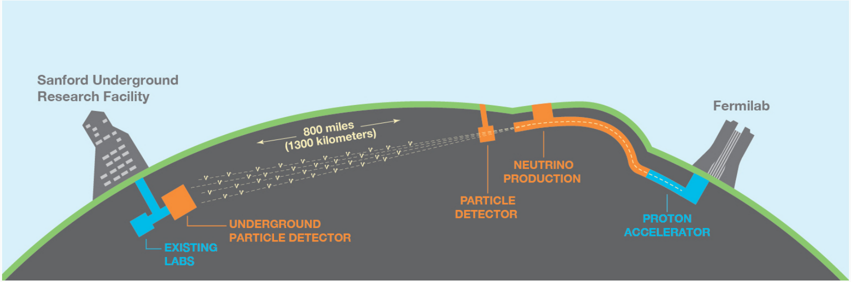
Neutrinos have two properties that make them fairly unique from other known particles: extremely low cross sections and flavor changing oscillations. With a good knowledge of the oscillation parameters soon in hand, it will become possible to detect low-energy atmospheric neutrinos sensitive to the forward 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.

DOI: 10.1103/PhysRevD.104.113007

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) includes atmospheric neutrino energies

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

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

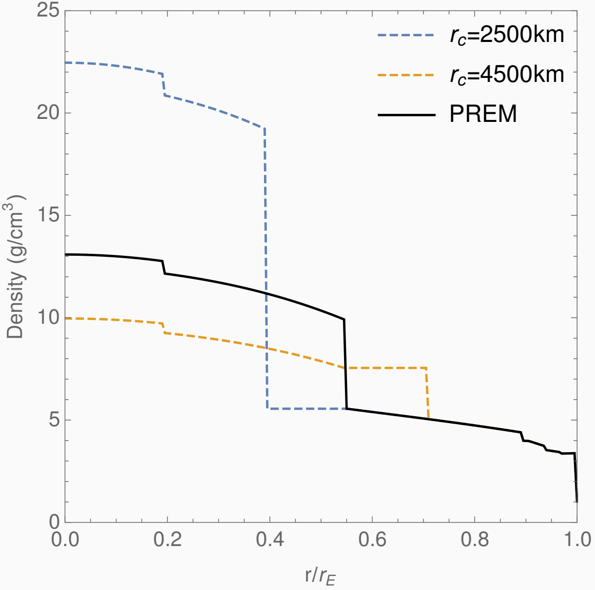
  - Minimized over systematic parameters
  - 1st Fit: Varied ϵ_{ee}
  - 2nd Fit: Varied radius of Earth's core

Simulating DUNE Earth's Density Profile

Accepted model: 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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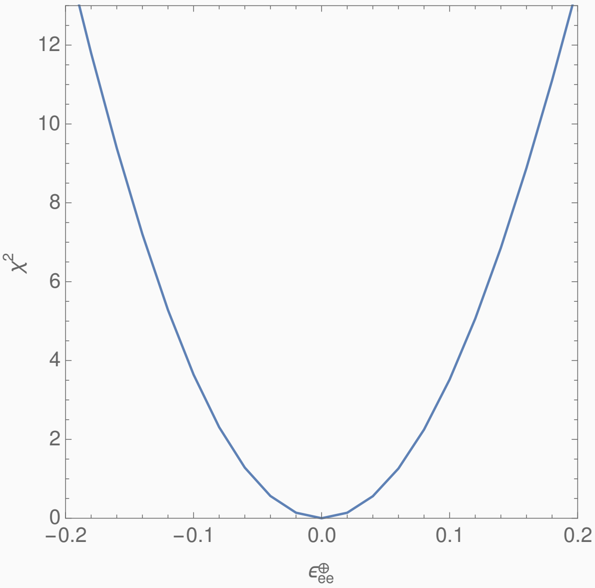
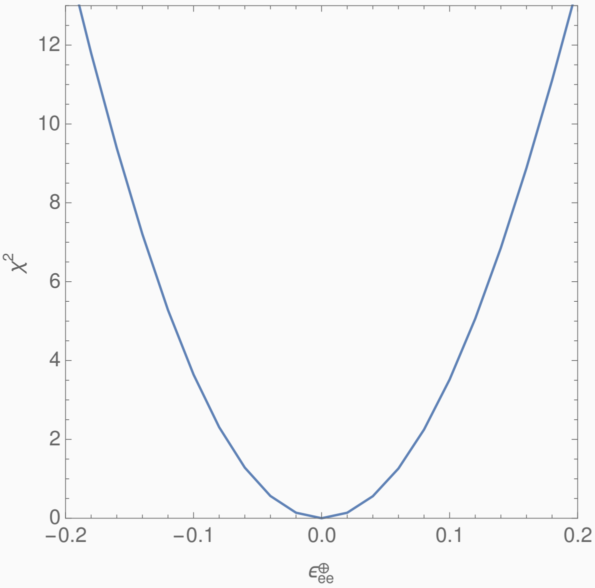
- For resolutions:
  - 10 $\cos(\theta_Z)$ bins
  - 43 $\log(E_\nu)$ bins (10% resolution for E_ν)

Simulating DUNE Result #1

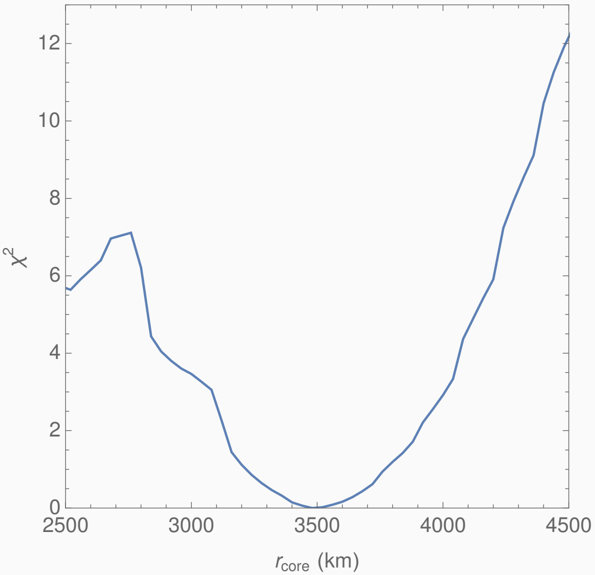


Simulating DUNE Result #1

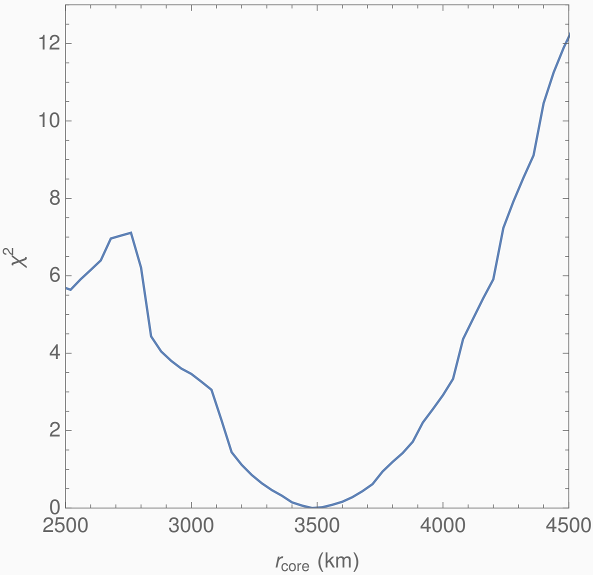


5% measurement of Earth's matter effect

Simulating DUNE Result #2

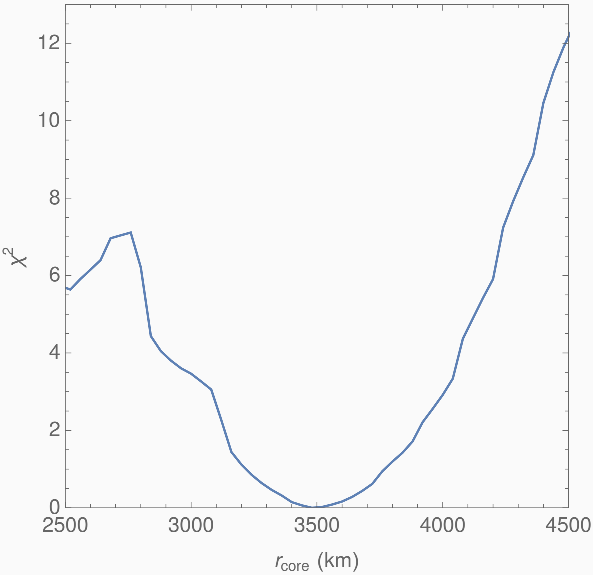


Simulating DUNE Result #2



9% measurement of radius of Earth's core

Simulating DUNE Result #2



9% measurement of radius of Earth's core

Actually, has more to do with weak charge of Earth

Summary

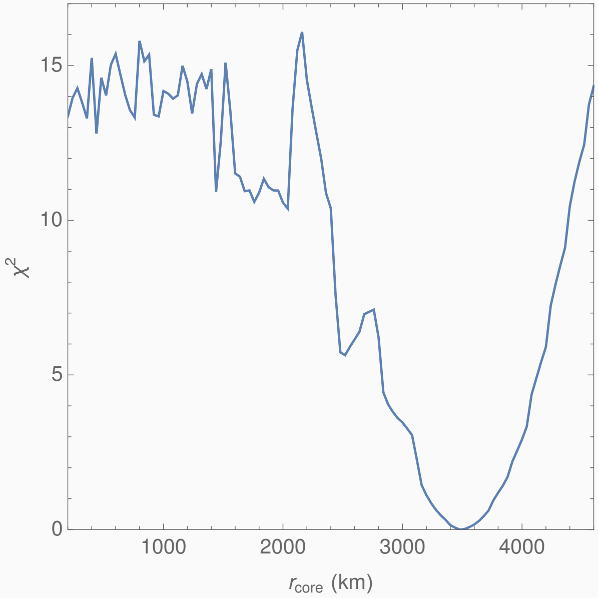
- Seismology measurements of Earth's layers depend on many variables
- Can measure size of Earth's core using atmospheric neutrinos
  - Depends on fewer variables that are not measured using other means
  - Affected by new physics scenarios
- DUNE can measure Earth's matter effect to 5% and the size of the Earth's core to 9%

Thank you!

Questions?

This research was funded by the DOE.

DUNE Simulation Earth's Core Sensitivity - Full Range



Earth's Layers