Observing the Earth's Core
with Neutrino Oscillations at DUNE

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Table of Contents

1 **Introduction**

- Neutrino Oscillations in the Earth
- Deep Underground Neutrino Experiment (DUNE)

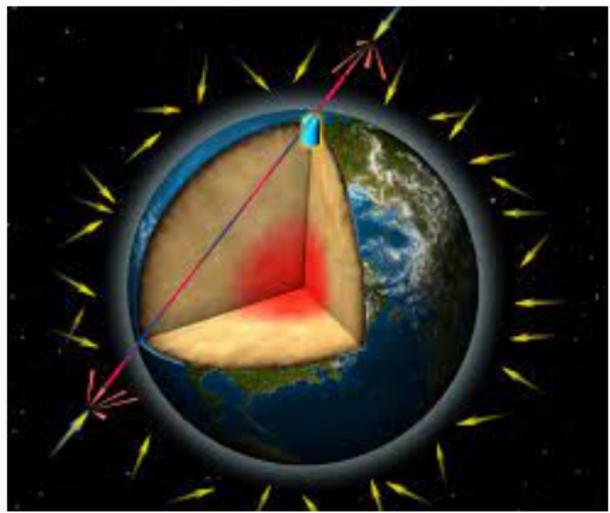**2** Paper with Peter B. Denton (arXiv:2110.01148)

3 Summary

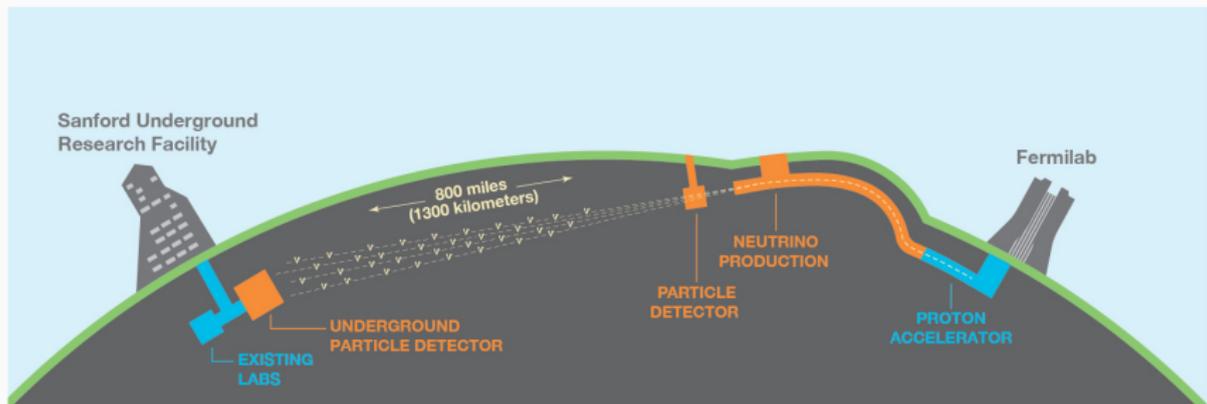# Neutrino Oscillations with Atmospheric Neutrinos

Neutrino Hamiltonian in Matter:

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

Oscillation probability:

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

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

LArTPC (Liquid Argon Time Projection Chamber) for far detector
⟩ Can determine direction neutrino came from
Energy range: 0.1 GeV-8.0 GeV

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.

Detector with DUNE's far detector specs
- 40 kton
- 10 years

Honda flux model averaged over angles for source

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Used nuSQuIDS to calculate oscillated flux

Assumed normal neutrino mass ordering for simulated data

Fixed oscillation parameters

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χ^2 calculated for fits

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

Minimized over systematic parameters

1st Fit: Varied ϵ_{ee}

2nd Fit: Varied radius of Earth's core

Neutrino Hamiltonian with NSIs (generic):

$$H = \frac{1}{2E}\left[U\begin{pmatrix} 0 & 0 & 0 \\ 0 & m_{21}^2 & 0 \\ 0 & 0 & m_{31}^2 \end{pmatrix}U^\dagger + 2\sqrt{2}G_F N_e E \begin{pmatrix} 1+\epsilon_{ee} & \epsilon_e & \epsilon_e \\ \epsilon_e & & \\ \epsilon_e & & \end{pmatrix}\right]$$

can come from effective Lagrangians like

$$L_{\text{NSI}} = 2\sqrt{2}G_F \sum_{f} \epsilon^f (\quad)(f\ f),$$

where $\epsilon = \sum_f \frac{N_f}{N_e}\epsilon^f$

Neutrino Hamiltonian with NSIs (generic):

$$H = \frac{1}{2E} U \begin{pmatrix} 0 & 0 & 0 \\ 0 & m_{21}^2 & 0 \\ 0 & 0 & m_{31}^2 \end{pmatrix} U + \sqrt{2} G_F N_e \begin{pmatrix} 1 + \epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon_{\mu e} & & \\ \epsilon_{\tau e} & & \end{pmatrix}$$

can come from effective Lagrangians like

$$L_{NSI} = \sqrt{2} G_F \sum_{\alpha,\beta,f} \epsilon_{\alpha\beta}^f (\bar{\nu}_\alpha \gamma^\mu \nu_\beta)(\bar{f} \gamma_\mu f),$$

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

So, changing ϵ_{ee} effectively changes the magnitude of the matter effect.

Detector with DUNE's far detector specs

    40 kton

    10 years

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Minimized over systematic parameters

1st Fit: Varied ϵ_{ee}

2nd Fit: Varied radius of Earth's core

    10

Model used:
Preliminary
Reference Earth
Model (PREM)

Assumes spherical
Earth

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

Flux uncertainties

$$= \; _{;0}f \; (E)(E = E_0)$$

$_{;0}$ = ux normalization, 1 $\;$ 40% for $\; = \; e; \; ; \; e;$
= spectral index, 0 $\;$ 0:2

Flux uncertainties

$$= \phi_0 f(E)(E = E_0)$$

$\phi_0 =$ flux normalization, 1 $\pm$ 40% for $\nu = \nu_e; \nu_\mu; \bar{\nu}_e$
$\gamma =$ spectral index, 0 $\pm$ 0:2

Exclude partially contained ν_μ events (reduce ν_μ events by 25%)

Assume good flavor discrimination, but no $\nu / \bar{\nu}$ discrimination

12

Flux uncertainties

$$= \;_{;\,0}f\;(E)(E = E_0)$$

$_{;\,0}$ = ux normalization, 1 40% for = $_e$; ; $_e$;
= spectral index, 0 0:2

Exclude partially contained events (reduce events by 25%)

Assume good avor discrimination, but no / discrimination

For resolutions:

    10 cos($_z$) bins
    43 log(E) bins (10% resolution for E)

5% measurement
of Earth's matter
effect

9% measurement of radius of Earth's core

Summary

Using atmospheric neutrinos, DUNE is sensitive to conditions inside the earth

Can measure Earth's matter effect to 5%
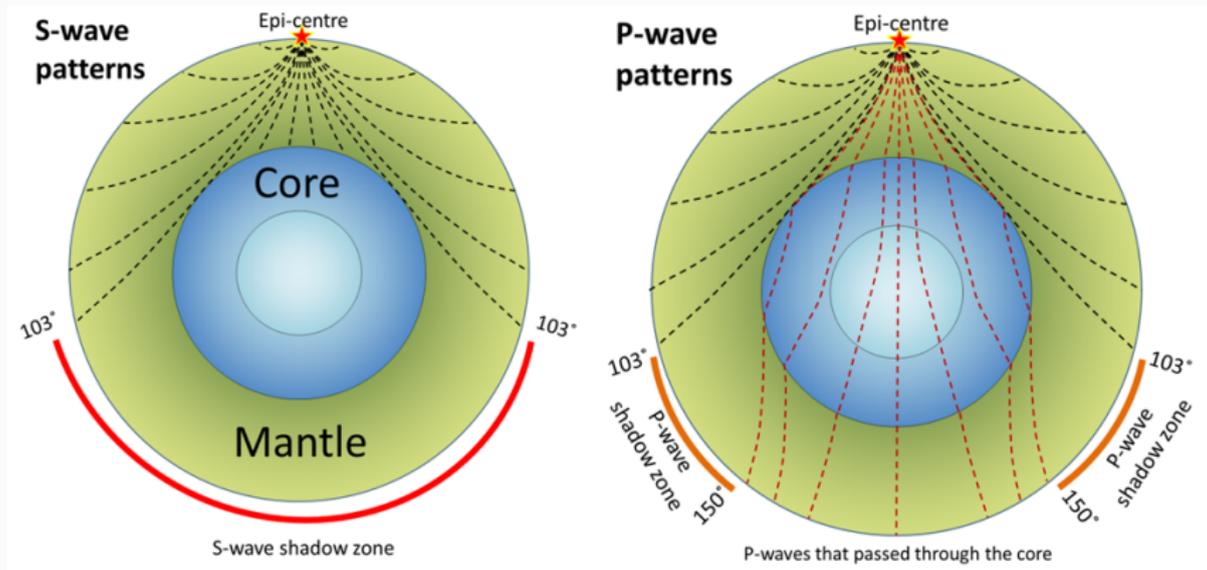Can measure the size of the Earth's core to 9%
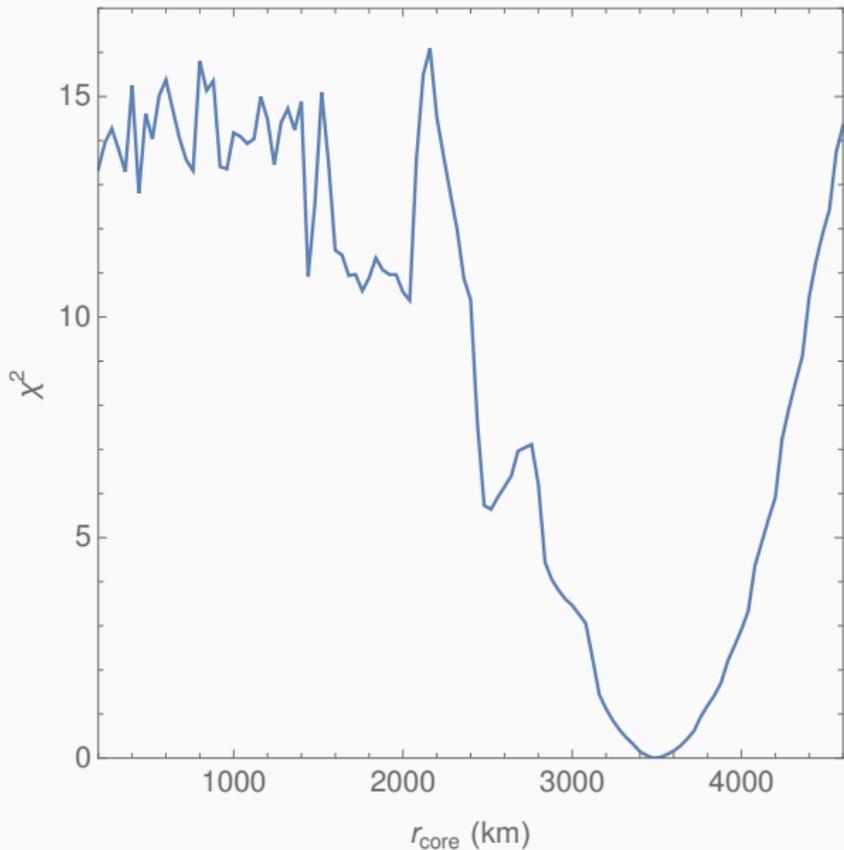
Questions?

This research was funded by the DOE.

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