Abstract

Atmospheric neutrinos provide a powerful probe of physics due to the broad range of both energies and baselines. I will discuss exactly how they play the key role in constraining tau neutrino unitarity via a complex interplay of the matter effect, tau lepton production threshold, misreconstructed tau neutrino energy, and the matter effect. This allows one to identify tau neutrino with no event-by-event discrimination and without assuming unitarity. I will also discuss how low energy atmospheric neutrinos, which will be detected by DUNE, will probe the size of the Earth's core and the matter effect in the Earth.

New Perspectives on Atmospheric Neutrinos

Peter B. Denton

INFN Torino

March 31, 2022

2109.14576
and
2110.01148 with Rebekah Pestes

Speaking from Setauket land

Overview

1. Unitarity constraints on tau neutrinos
2. Tau neutrino appearance in atmospheric neutrinos
3. Impact of different tau neutrino specific effects

4. Low energy atmospheric neutrinos at DUNE
5. Constraining the matter effect
6. Constraining the size of the Earth's core

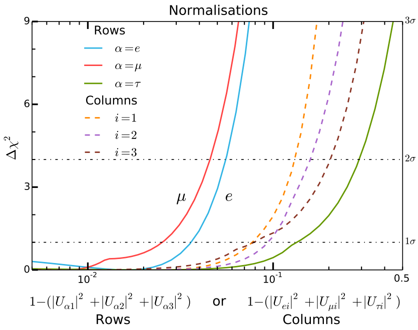
Unitarity Constraints on Tau Neutrinos

Past studies used:

1. $\nu_\mu \to \nu_\tau$ at OPERA
2. SNO NC and CC data

S. Ellis, K. Kelly, S. Li 2008.01088

Z. Hu, J. Ling, J. Tang, T. Wang 2008.09730



S. Parke M. Ross-Lonergan 1508.05095

More Tau Neutrinos!

The global tau neutrino data set:

Experiment	Source	~Events detected
DONuT	Production	7.5
OPERA	Long-baseline	8
SK	Atmospheric	291
IceCube	Atmospheric	1804[1]
IceCube	Astrophysical	2

[1] with $\sim$ 10k en route soon, see J. Koskinen IceCube NuTau2021 talk

Dominant unitarity constraint comes from atmospheric ν_τ appearance

PBD, J. Gehrlein 2109.14575

More Tau Neutrinos!

The global tau neutrino data set:

Experiment	Source	~Events detected
DONuT	Production	7.5
OPERA	Long-baseline	8
SK	Atmospheric	291
IceCube	Atmospheric	1804[1]
IceCube	Astrophysical	2

[1] with ~ 10k en route soon, see J. Koskinen IceCube NuTau2021 talk

Dominant unitarity constraint comes from atmospheric ν_τ appearance

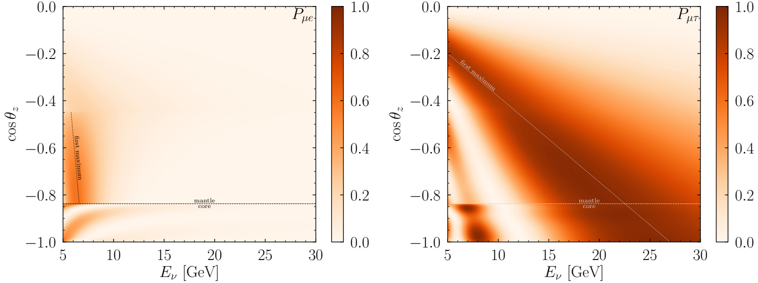
PBD, J. Gehrlein 2109.14575

A word on solar neutrinos:

1. SK 1998: showed that ν_μ-ν_τ mixing is large
2. SNO 2001,2002: ES and NC measured a statistically significant non-ν_e flux
3. $\Rightarrow \nu_e \to \nu_\tau$ at SNO with input from SK

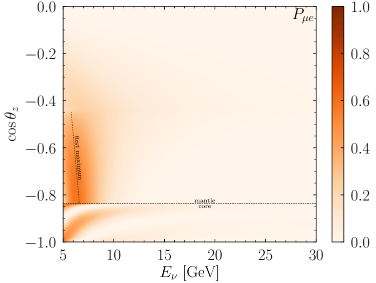
Atmospheric Tau Neutrino Appearance

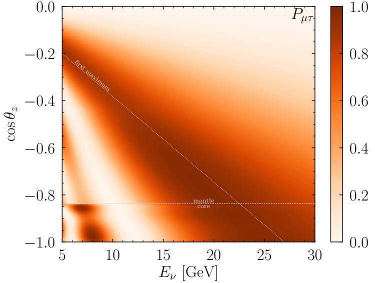
- Atmospheric neutrinos begin as ν_μ and mostly oscillate away to ν_τ

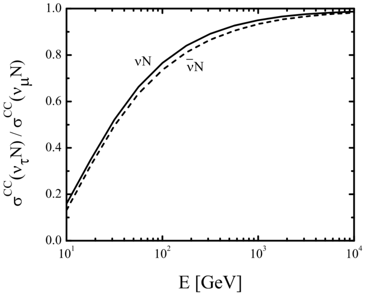


Atmospheric Tau Neutrino Appearance

- Atmospheric neutrinos begin as ν_μ and mostly oscillate away to ν_τ
- High tau lepton production threshold diminishes events



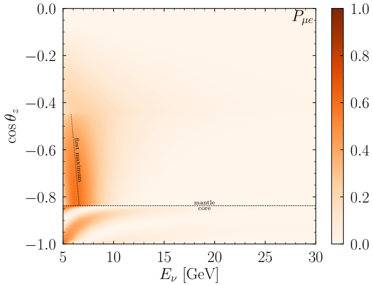


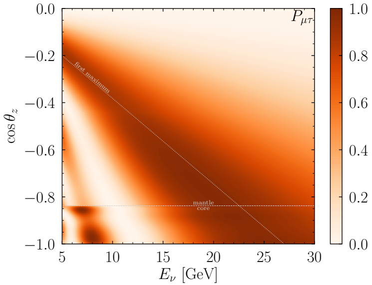


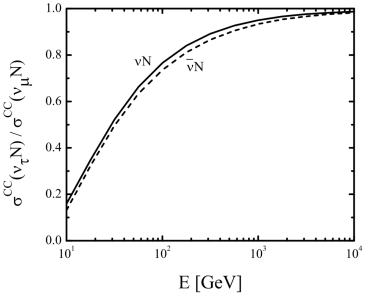
Y. Jeong, M. Reno 1007.1966

Atmospheric Tau Neutrino Appearance

- Atmospheric neutrinos begin as ν_μ and mostly oscillate away to ν_τ
- High tau lepton production threshold diminishes events
- Identifying tau lepton in large coarse detectors is hard





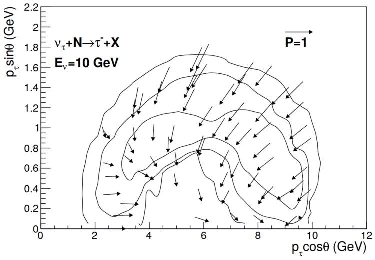


Y. Jeong, M. Reno 1007.1966

Tau Neutrino Appearance at SuperK

SuperK used:

1. Hadronic tau decay information
2. Tau polarization information
3. Neural net
4. *and standard oscillations*



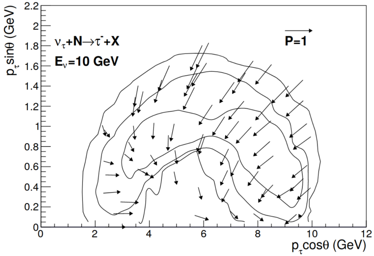
Tau Neutrino Appearance at SuperK

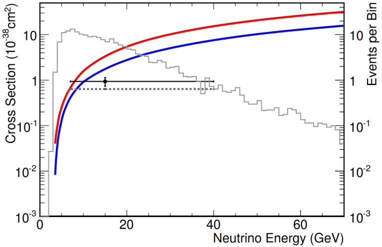
SuperK used:

1. Hadronic tau decay information
2. Tau polarization information
3. Neural net
4. *and standard oscillations*

Detected few hundred tau neutrino events, constrained the ν_τ "normalization"
e.g. weighted cross section: 1.47 ± 0.32 x SM

Super-KamiokaNDE 1711.09436





Tau Neutrino Appearance at IceCube

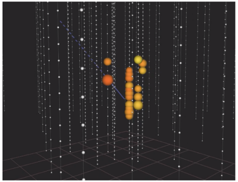
IceCube/DeepCore:

1. Much bigger than SuperK
2. 3D compared to SuperK's 2D
3. Much worse detector than SuperK
4. No ability to differentiate:
   - ν_τ CC that goes to a muon
   - ν_μ CC

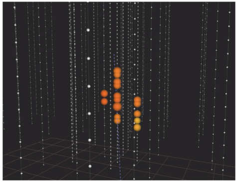
   or

   - ν_τ CC (that go to an electron or hadrons)
   - ν_e CC
   - ν NC

Track with
energy of 26 GeV



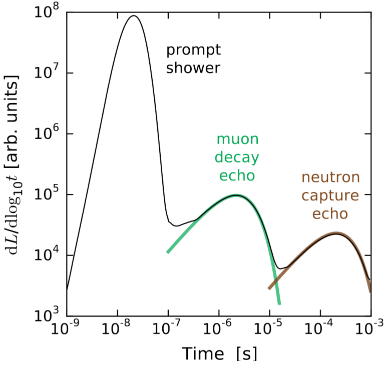
Cascade with
energy of 30 GeV



M. Rodriguez IceCube slides

Possible Means of Identifying Tau Neutrinos Event-By-Event

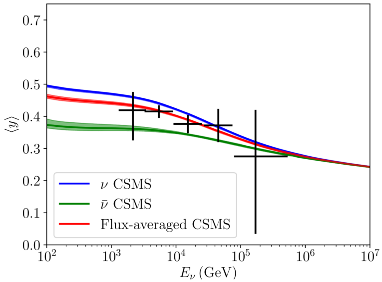
Hadronic showers contain far more muons and neutrons than electromagnetic showers



In practice, not possible

S. Li, M. Bustamante, J. Beacom 1606.06290

Inelasticity correlates with E_ν not $E_{\rm dep}$ and could be used

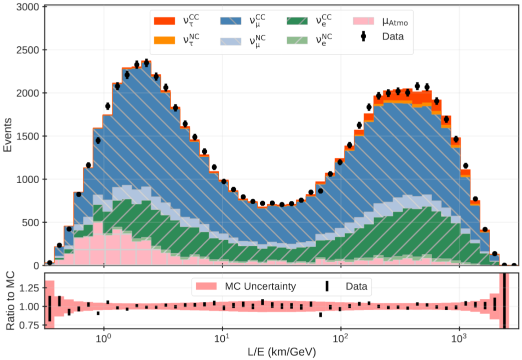


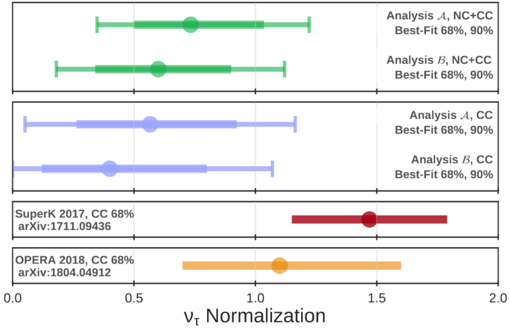
IceCube 1808.07629

Too hard to measure at low energies

IceCube Results

Using oscillation parameters IceCube finds:





IceCube 1901.05366

Past Work

Tau neutrino appearance in a large coarse detector is possible with:

1. Tau neutrino threshold
2. NC

T. Stanev astro-ph/9907018

Seeing extra low energy tau neutrinos could indicate astrophysical sources

H. Athar, F. Lee, G. Lin hep-ph/0407183

Both papers largely overlooked

My Motivation

- Tau neutrino identification is relevant for unitarity

  yet neither SuperK nor IceCube constrained unitarity with their data
- IceCube has the biggest data sets
- IceCube has extremely limited particle identification

  cascades vs. tracks
- It would seem like $\nu_\mu \to \nu_e$ could mimic $\nu_\mu \to \nu_\tau$

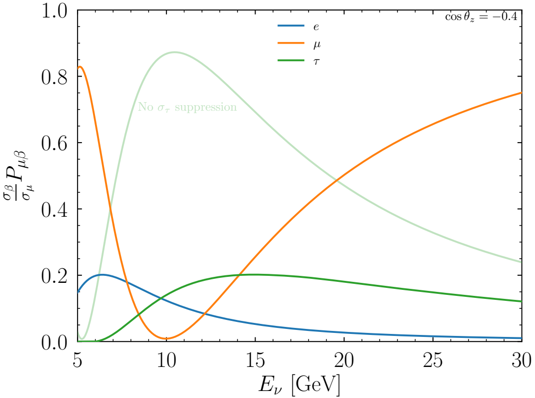
  For different oscillation parameters or with unitarity violation

What, if any, physical effects allows for the identification of tau neutrinos without particle identification and without assuming unitarity?

Mimicry Isn't Always Flattery

How to mimic $\nu_\mu \to \nu_\tau$ with $\nu_\mu \to \nu_e$ in the Earth:

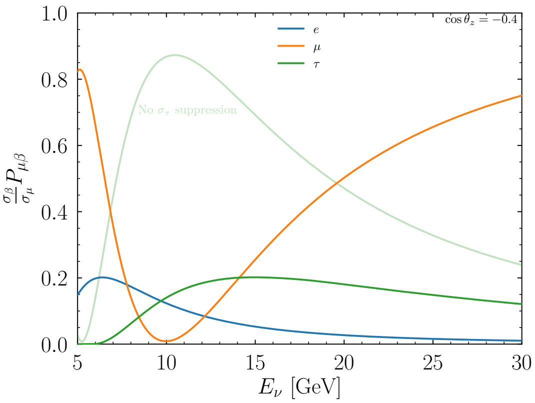
Through the mantle:



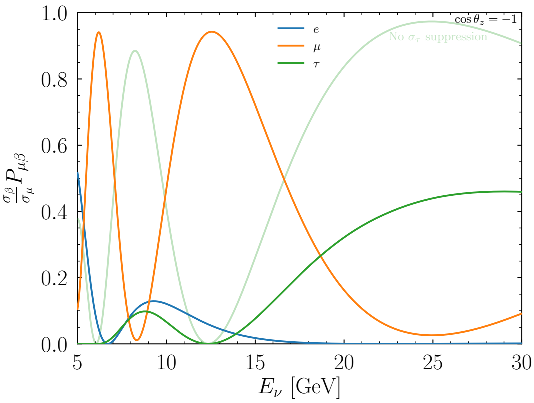
Mimicry Isn't Always Flattery

How to mimic $\nu_\mu \to \nu_\tau$ with $\nu_\mu \to \nu_e$ in the Earth:

Through the mantle:



Through the core:



Unitarity Violation Framework

- Suppose there are m total neutrinos and n kinematically accessible: (m, n)

Accessible: [10 eV, 15 MeV]; inaccessible: $\gtrsim$ 40 MeV

ν_τ is an exception to this that requires care

  - Standard: (3,3)
  - One accessible sterile: (4,4)
  - Two heavy steriles: (5,3)
- Include matter effect
  - Steriles don't experience it - relevant for $m = n$
  - It modifies the probability - relevant for $m > n$
- For $m = n$ oscillation probabilities can be calculated in the usual fashion
- For $m > n$ care is required:
  - Flux, cross sections, and weak interaction need to be rescaled
  - Oscillation probability needs to be rescaled and carefully calculated:

$$P^r_{\alpha\beta} = \left| \left[N^* W e^{-i\Lambda L} W^\dagger N^T \right]_{\alpha\beta} \right|^2$$

N: $m \times m$ submatrix

W, Λ eigenvectors/eigenvalues of Hamiltonian in mass basis with matter effect

Back to IceCube Observables

Define this cascade ratio:

$$\mathcal{R}_c(E_{\rm reco},\cos\theta_z)\equiv\frac{\frac{d^2N_c}{dE_{\rm reco}\,d\cos\theta_z}}{\Phi_i(E_{\rm reco})\sigma_{\rm tot}(E_{\rm reco})}$$

$$= f_{\rm CC}\left[P^r_{\mu e}(E_{\rm reco},\cos\theta_z)+\eta_{\nu_\tau}^{\gamma-1}R_{\tau\mu}(E_{\rm reco}/\eta_{\nu_\tau})(1-f_{\tau\mu})P^r_{\mu\tau}(E_{\rm reco}/\eta_{\nu_\tau},\cos\theta_z)\right]$$

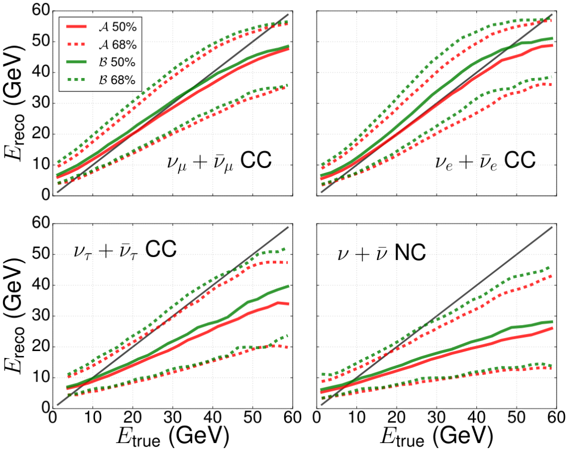
$$+(1-f_{\rm CC})\eta_{\rm NC}^{\gamma-1}\sum_{\beta\in\{e,\mu,\tau\}}P^r_{\mu\beta}(E_{\rm reco}/\eta_{\rm NC},\cos\theta_z)$$

- ν_e CC appearance
- ν_τ CC appearance with $\tau\to\nu_\tau+(e,X)$
- τ production threshold
- Reconstructed energy shift from spectrum and cross section

Different for $\tau\to\nu_\tau$ and NC

- NC

Reconstructed vs. True Energy



τ's always decay to invisible energy ν_τ

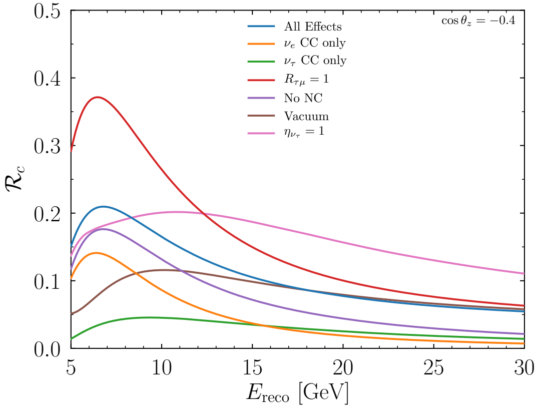
$$\eta_{\nu_\tau} = 0.625$$

NC always loses some energy

$$\eta_{\rm NC} \simeq \frac{1}{3}$$

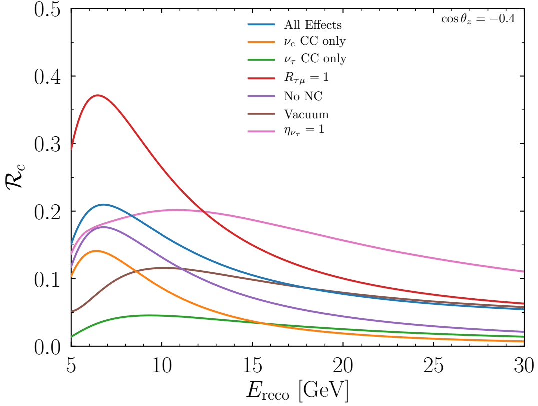
Impact of Effects

Through the mantle:

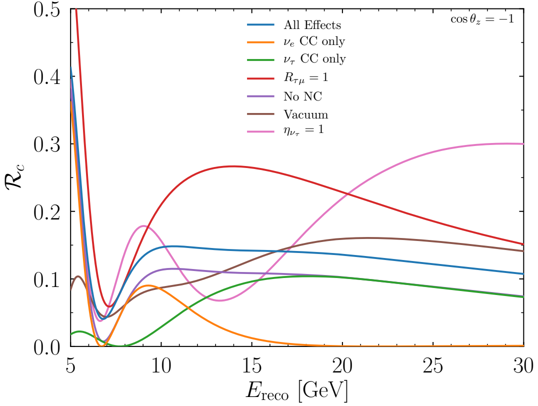


Impact of Effects

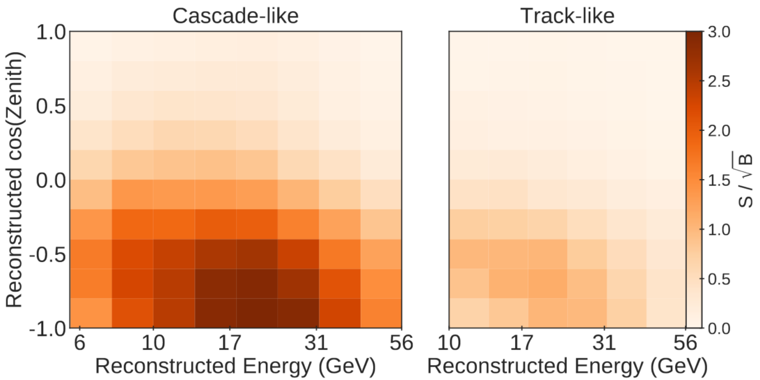
Through the mantle:



Through the core:



IceCube Detector Sensitivities



Contains all information on detector efficiencies, flux, and track/cascade misidentification

Results

Effects considered:

1. NC
2. Matter effect
3. η_{ν_τ}: Tau neutrino reconstruction
4. $R_{\tau\mu}$: Tau lepton production threshold
5. External Δm^2_{31} constraint
6. External ν_e row constraint

Conclusions:

1. **With all known effects tau neutrinos can be identified even without assuming unitarity**
2. With all effects off and no unitarity: ν_τ's cannot be identified.
   Dial up ν_e to match
3. Including NC doesn't matter much
4. Turning on $R_{\tau\mu}$, η_{ν_τ}, or the matter significantly enhances sensitivity
5. Certain combinations approximately cancel:
   Just $R_{\tau\mu}$ and η_{ν_τ} has almost no sensitivity

Atmospheric Appearance Unitarity Key Points

1. Conservatively didn't include down-going or tracks which add more information
2. Assume only oscillations, τ properties, and the matter effect
3. Numerous effects allow for model independent detection of ν_τ with no event-by-event identification
4. Some of the effects actually partially cancel
5. Experiments can confidently report unitarity constraints

Low Energy Atmospheric Neutrinos at DUNE

- DUNE should have sensitivity to low-E atmospheric neutrinos $\nu_\mu \to \nu_e$

DUNE 2002.03005

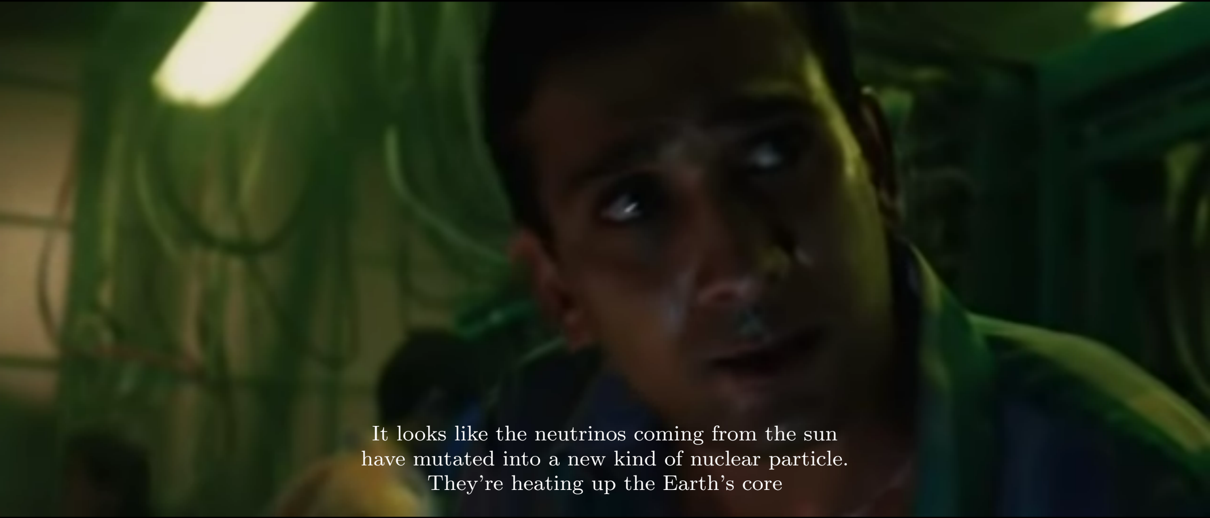
- Lots of oscillation effects at $E \in [100, 1000]$ MeV
- Modest sensitivity to $\delta_{\rm CP}$

K. Kelly, et al 1904.02751

- Modest sensitivity to mass ordering

C. Ternes, et al 1905.03589

Effects come from the Earth's core



2012 the movie

Earth's Core

Given that δ_{CP} from T2HK and DUNE's accelerator program:
Constrain the Earth's core?

Similar simultaneous paper: K. Kelly, et al 2110.00003

- Most knowledge comes from seismographic data
- Inner core: solid, outer core: liquid

from p- and s-waves

- Effects: Coriolis, Lorentz, self-excited dynamo, Alfven waves, magnetic fields
- Outer core is surrounded by uncertain D" layer $\sim$ 200km thick

Past Studies of the Earth with Neutrinos

1. Oscillation sensitivities:
   - Focused on nuclear composition: fixing ρ, varying Z/A varies matter potential
   - Considered PINGU and ORCA, $E \in [1, 10]$ GeV

C. Rott, A. Taketa, D. Bose 1502.04930

W. Winter 1511.05154

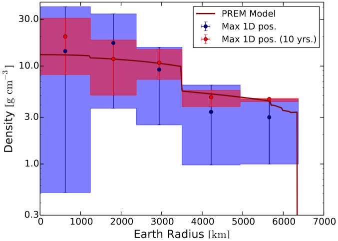
Past Studies of the Earth with Neutrinos

1. Oscillation sensitivities:
   - Focused on nuclear composition: fixing ρ, varying Z/A varies matter potential
   - Considered PINGU and ORCA, $E \in [1, 10]$ GeV

C. Rott, A. Taketa, D. Bose 1502.04930

W. Winter 1511.05154

2. Absorption constraints:
   - High energy neutrinos detected by IceCube are absorbed in the Earth
   - Given the cross section and assuming isotropy



A. Donini, S. Palomares-Ruiz, J. Salvado 1803.05901

Matter Resonant Oscillation Physics

1. Matter effect: modifies oscillation parameters $\Delta m^2_{ij} \to \widehat{\Delta m^2}_{ij}$, $\theta_{ij} \to \widehat{\theta_{ij}}$, $\delta \to \widehat{\delta}$
   - Different for neutrinos and antineutrinos
   - Relevant for DUNE's mass ordering sensitivity

L. Wolfenstein PRD 17, 2369 (1978)

2. Adiabatic effect: start as $\widehat{\nu_i}$ in matter, remain as $\widehat{\nu_i} \to \nu_i$ in vacuum
   - Applies for a broad range of energies
   - The solution to the solar neutrino problem

S. Mikheyev, A. Smirnov, SJNP 42, 913 (1985)

S. Parke PRL 57, 1275 (1986)

Matter Resonant Oscillation Physics

3. Resonant enhancement of a small mixing angle to maximal: $\widehat{\theta_{ij}} \to 45^\circ$
   - Applies at one energy
   - Relevant for sterile neutrino searches at IceCube

M. Chizhov, M. Maris, S. Petcov hep-ph/9810501

S. Mikheyev, A. Smirnov, SJNP 42, 913 (1985)

4. Parametric resonance: exponentially enhances a small mixing angle
   - Works even for small absolute matter potential
   - Requires specifically varying matter potential
   - Only realistically relevant for the Earth's core

E. Akhmedov, SJNP 47, 301 (1988)

P. Krastev, A. Smirnov PLB 226, 341 (1989)

Matter Resonances For Low Energy Atmospherics

For atmospheric neutrinos $E \in [100, 1000]$ MeV:

1. Matter effect: mixing parameters are non-trivially modified
2. Adiabatic effect does not apply:
   neutrinos are produced in vacuum and experience discrete jumps in density
3. Resonant enhancement: occurs for solar parameters when

$$2\sqrt{2}G_F N_e E = \Delta m^2_{21}\frac{\cos 2\theta_{12}}{c^2_{13}}$$

   which is $E \sim 130, 70, 35$ MeV in crust, mantle, and core
   Crust is $\cos\theta_z \in [-0.1, 1]$ but the first maximum is at -0.2
   Enhancement is $33^\circ \to 45^\circ$ only a 20% increase
   Only happens for relatively narrow energy range

Parameter Matter Resonances For Low Energy Atmospherics

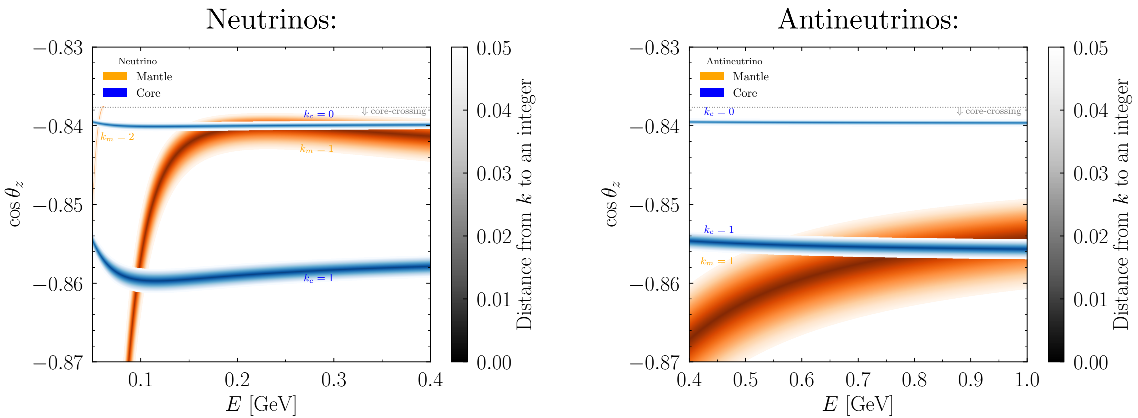
For some k_m, k_c, simultaneously satisfy

$$\left|\frac{\widehat{\Delta m^2_{21}}_m L_m}{4E}\right| = \frac{\pi}{2}(2k_m + 1) \qquad \text{and} \qquad \left|\frac{\widehat{\Delta m^2_{21}}_c L_c}{4E}\right| = \frac{\pi}{2}(2k_c + 1)$$

$\Delta\widehat{m^2}_{21}$ is Δm^2_{21} in matter

PBD, S. Parke 1902.07185

Parametric Resonances

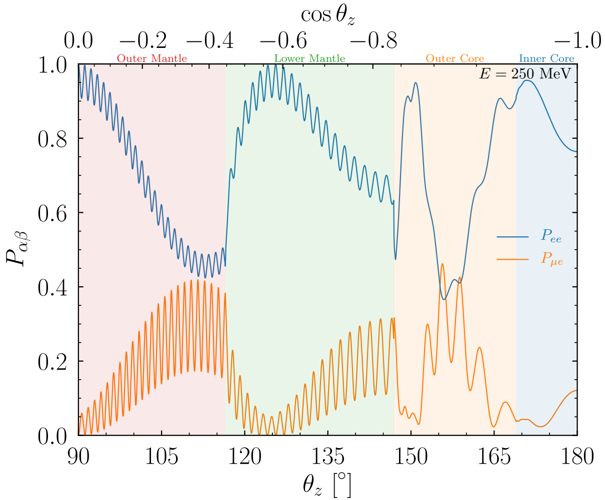


Largest region occurs for neutrinos $E \sim 250$ MeV

Very narrow $\cos\theta_z$ region

Blue curves separated by $\sim 5-10^\circ$: experimental resolution is $\sim 10-20^\circ$

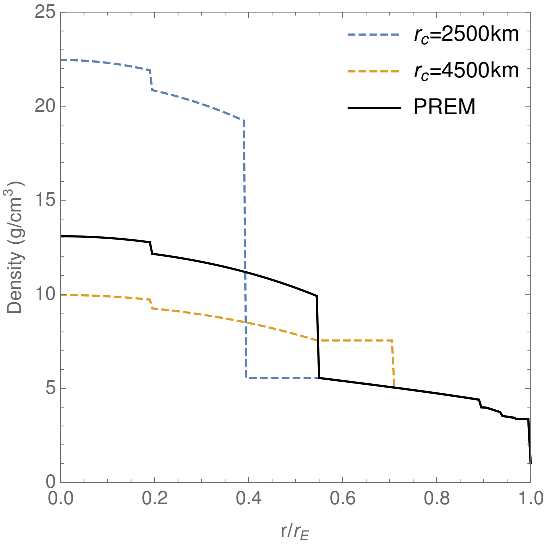
Resonance Validation



Varying the Earth's Core

- Fix the total mass
- Keep shape the same
- Shift the core radius
- Rescale the core density

Could also fix the inertia, we let it float



Existing Constraints on the Matter Effect in the Earth

1. Solar matter effect: combine solar (SNO, Borexino, SK) and KamLand
   Slight tension, difficult solar measurements $\Rightarrow \epsilon_{ee}^{\odot} \in [0,1]$

   SM: $\epsilon = 0$

   I. Esteban, et al 1805.04530

   P. Coloma, PBD, et al 1701.04828
2. In Earth: night time solar neutrinos at SK: 1.9σ detection

   Y. Nakajima SK talk at Neutrino 2020
3. Future: DUNE LBL: $\sim 3\sigma$ sensitivity

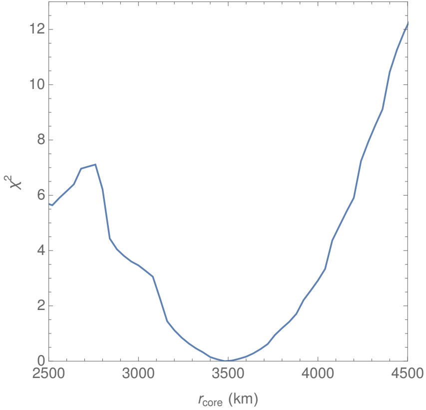
   K. Kelly, S. Parke 1802.06784
4. Future DUNE night time solar

   F. Capozzi, et al 1808.08232

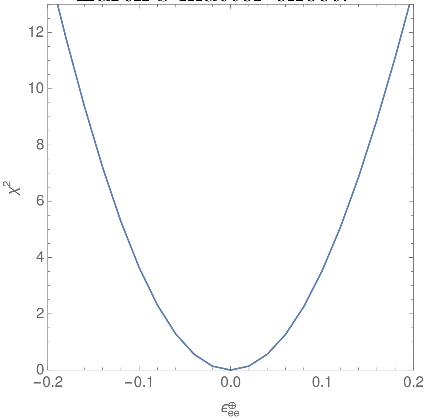
Constraints

10 years of DUNE

Earth's core's radius:



Earth's matter effect:



Final Core Thoughts

- Better understanding of the Earth's core connects with exoplanets
- Different measurements probe different things, relevant for DM accumulation:

  L. Krauss, M. Srednicki, F. Wilczek, PRD 33, 2079 (1986)

  A. Gould ApJ 321, 571 (1987)

  - Seismography: baryonic inertial mass
  - Neutrino absorption: weak charge, heavy mediator
  - Oscillations: non-universal flavor content, any mediator
- DM accumulation in the Earth could affect each case differently

Key Points

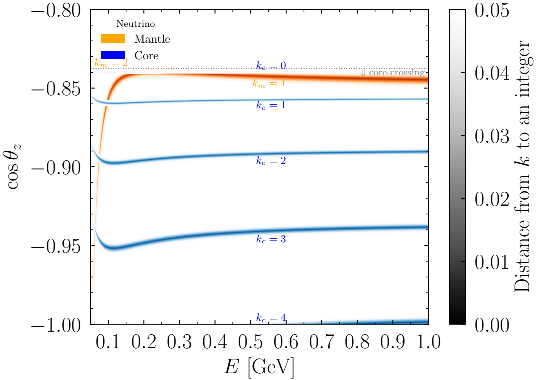
- Lots of tau neutrinos in atmospheric data sets
- Possible to identify them with a minimal number of assumptions
- Will be able to probe the Earth's core with oscillations with DUNE

Thanks!

Backups

Parametric Resonances

Neutrinos:



Antineutrinos: