

Neutrino Oscillation Tomography of Earth

2026 NPN 2026 workshop, 26-28 May

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National
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Foundation

Overview of the Talk :

1. Introduction
2. Multi-messenger Earth Tomography
3. PREM profile of Earth and Seismic measurements
4. Motivation for Oscillation Tomography
5. Matter effect on Neutrino Oscillation → sensitive to chemical composition(Z/A)
6. Multi-detector location in terms of LLSVP?
7. Sensitivity Calculation for Hyper-K like detector(work in progress!!)
8. Conclusion

CMB: Core-Mantle Boundary(not Cosmic-Microwave Background!!)

IC: Inner-Core, **OC:** Outer-Core

LLSVP: Large-Low Shear Velocity Province(now called LLVP)



Introduction :

Mass, Moment of Inertia of Earth

Gravitational Measurements

- Gravitational interactions
- Information on Earth's total mass and moment of inertia

Density of Earth

Neutrino Absorption Tomography

- Weak interactions
- Absorption of high-energy (TeV-PeV) neutrinos

Composition of Earth's Crust

Geoneutrinos

- Brings crucial information about the mantle
- Disclose information on the radiogenic contribution to Earth's heat budget

PREM profile of Earth, composition

Seismic Studies

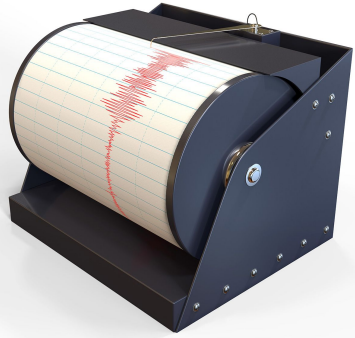
- Use seismic waves from earthquakes
- These are mechanical waves of acoustic energy that travel through or over the Earth
- Reveal the internal structures and identify large-scale variations in matter density and properties

Neutrino Oscillation Tomography

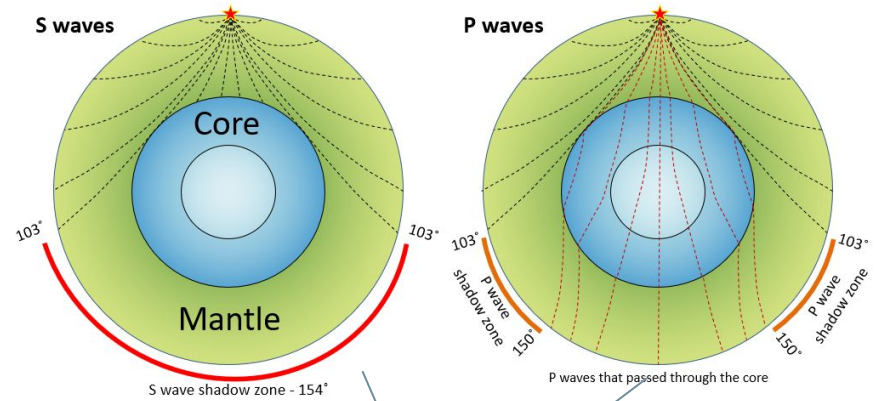
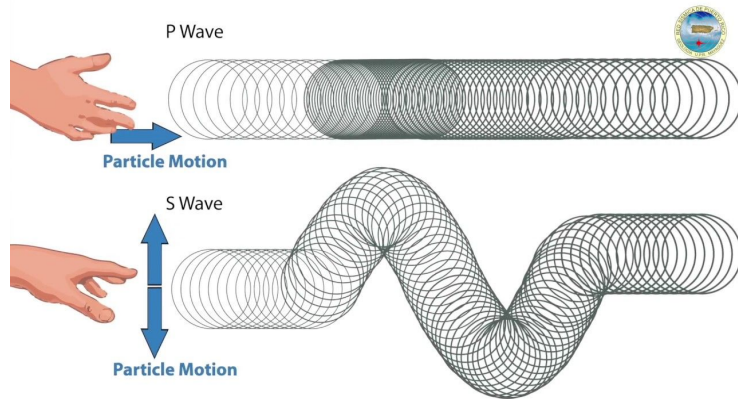
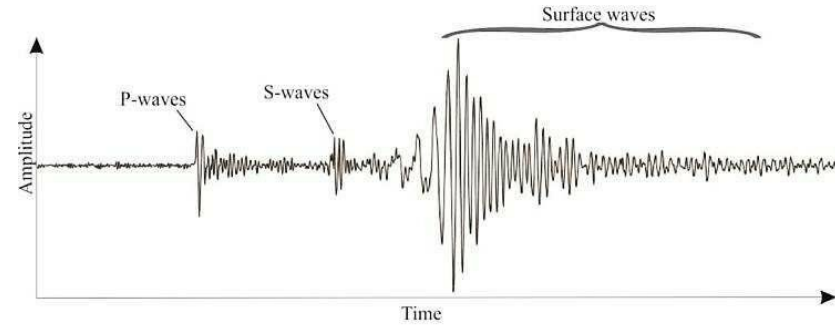
- Weak interactions
- Coherent forward scattering of low-energy (MeV-GeV) electron neutrinos with ambient electrons
- Modify neutrino oscillation patterns



Seismic Measurements :



Geologists study seismic waves from earthquakes using seismograms recorded in seismometer

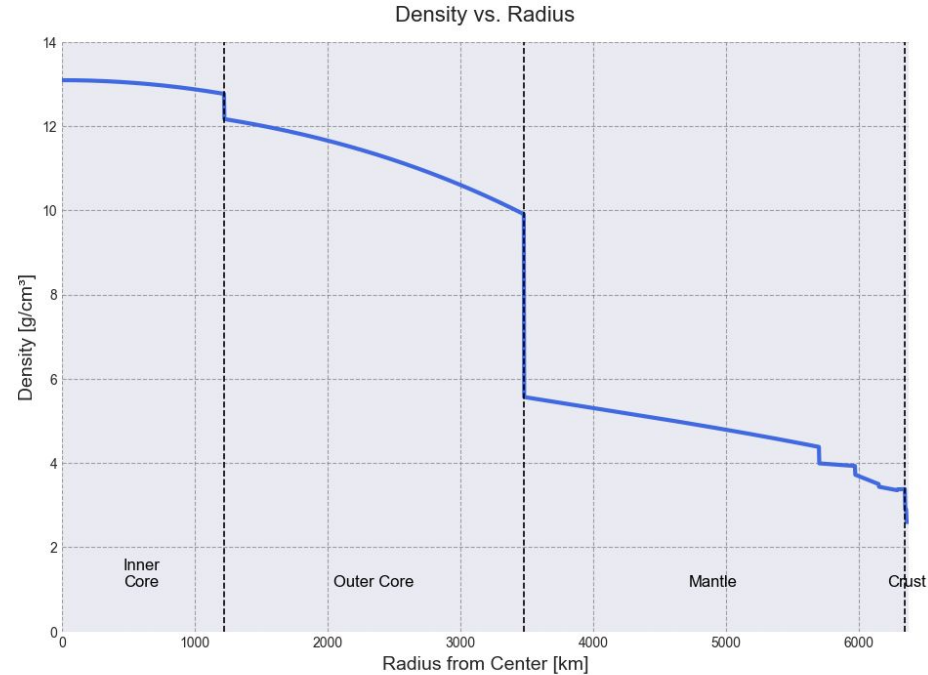
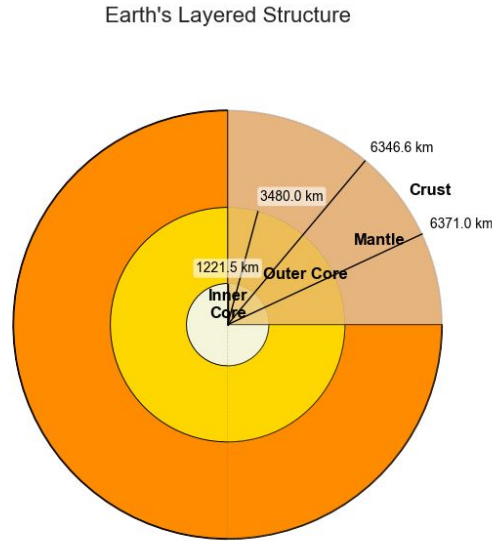


From S, P wave studies we inferred the Earth's Core is liquid



Preliminary Reference Earth Model(Density Profile):

Earth's Density Profile and Structure (PREM)

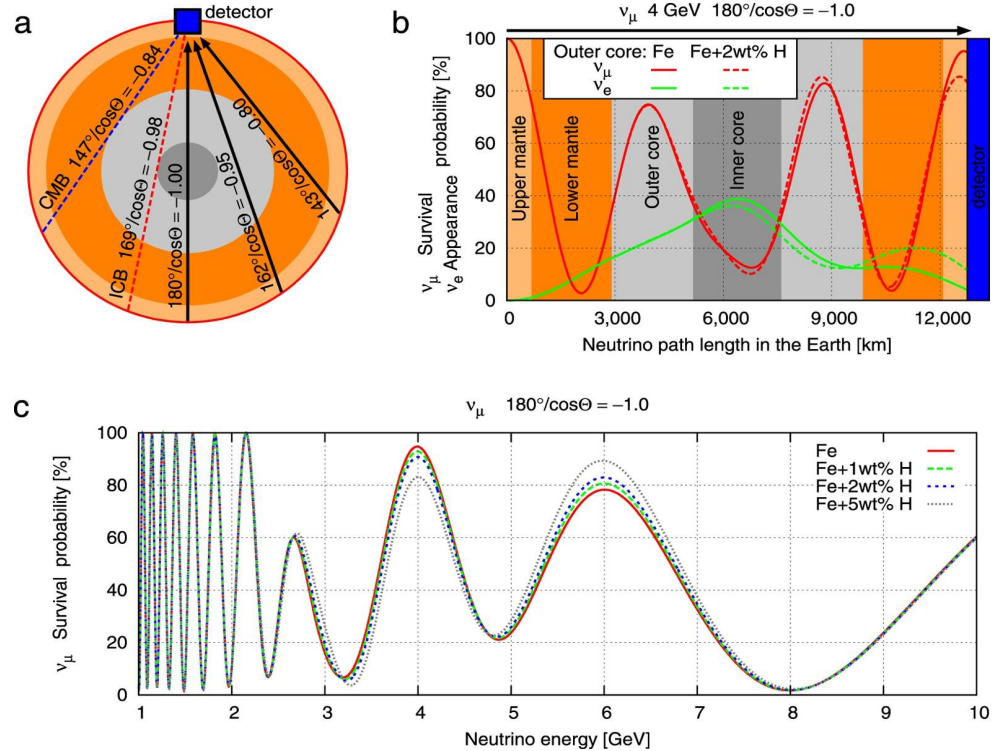


** Preliminary Reference Earth Model(PREM)/ Authors: Adam M. Dziewonski and Don L.Anderson (June 1981)

Motivation : Can we identify the chemical composition of the inner Earth?

Rock (SiO_2): $Z/A \approx 0.4691$ (typical Earth crust)
 Iron (Fe): $Z/A \approx 0.4633$ (Earth core)
 Water: $Z/A \approx 0.5000$ (pure water)

LLVP composition (likely):
 - Oxygen-rich silicates
 - Iron oxide rich
 - $Z/A \approx 0.465-0.475$



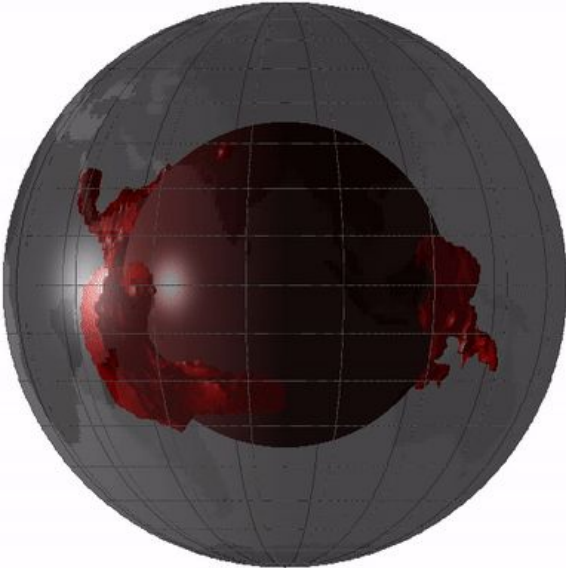
Neutrinos passing through different layers of Earth

Figure: Spectrometry of the Earth using Neutrino Oscillations

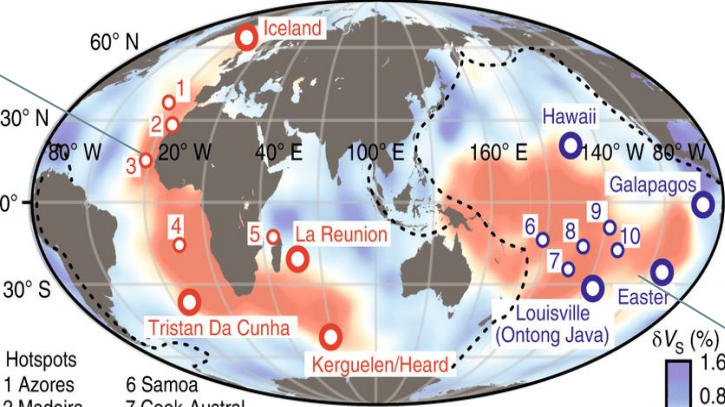
** Rott, C., Taketa, A. & Bose, D. Spectrometry of the Earth using Neutrino Oscillations. *Sci Rep* 5, 15225 (2015). <https://doi.org/10.1038/srep15225>

Motivation : Can we infer 3D Earth structures using Neutrinos?!

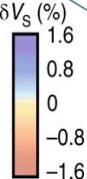
Global maps of the LLSVPs Seismic shear-wave velocity anomalies (δV_s)



African LLSVP



- Hotspots
- 1 Azores
- 2 Madeira
- 3 Cape Verde
- 4 St Helena
- 5 Comores
- 6 Samoa
- 7 Cook-Austral
- 8 Society Island
- 9 Marquesas
- 10 Pitcairn



Pacific LLSVP

** Doucet, L.-S. et al. (2020). *Nature Geoscience*, 13, 511–515. doi.org

**A Large Low-Shear-Velocity Province (LLSVP) is a massive, continent-sized region in the Earth's lowermost mantle, beneath Africa and the Pacific, characterized by anomalously slow seismic shear waves.



Matter effect on Neutrino Oscillation:

$$V_{CC}^{\nu_e} = \pm\sqrt{2}G_F N_e \quad (4)$$

$$V_{NC}^{\nu_{all}} = -\sqrt{2}G_F N_n/2 \quad (5)$$

These affects the total hamiltonian of the system!

Now, N_e can be re-written as:

$$N_e(r) = \frac{Z}{A}(r) \times \rho(r) \times \frac{N_A}{m_n} \quad (6)$$

Measured in neutrino oscillation patterns

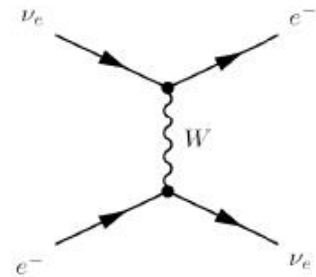
Probes composition in core/mantle

Probes matter density

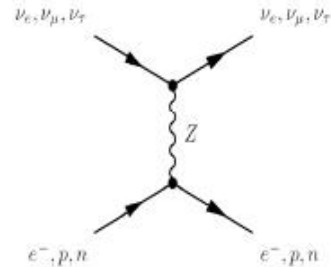
where, N_A is the Avogadro number, ρ is the mass density, and $\frac{Z}{A}$ is the proton-to-nucleon ration defined as:

$$\frac{Z}{A} = \sum_i w_i \frac{Z_i}{A_i} \quad (7)$$

where, Z_i, A_i and w_i are respectively the local atomic number, standard atomic weight and weight fraction of element i of the material. So, different $\frac{Z}{A}$ will generate different oscillation pattern!



(a) Charged current interaction via W boson



(b) Neutral current interaction via Z boson

The Hyper-K experiment is expected to provide competitive sensitivity at the energy scales relevant for tomography study



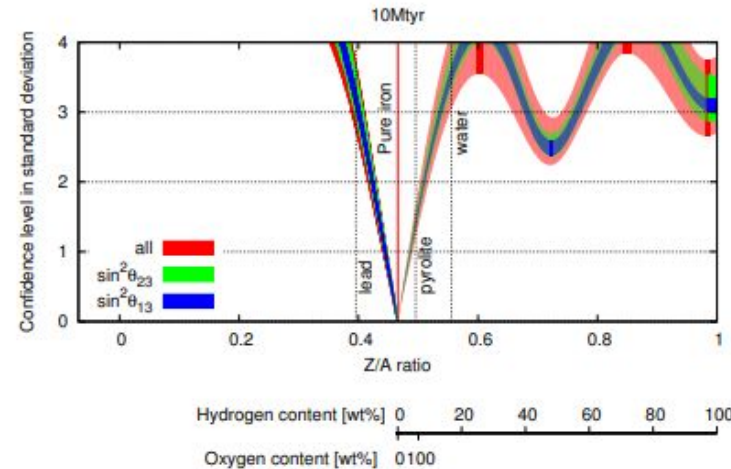
Hyper-Kamiokande

Design Report

(Dated: November 30, 2018)

<https://inspirehep.net/literature/1672899>

The Hyper-K Collaboration has identified tomography as one of their scientific targets. Sensitivity study has been focused on light elements in the outer core.



→ Resonance energy for enhanced neutrino oscillations in matter :

$$E_{\text{res}} \equiv \frac{\Delta m_{31}^2 \cos 2\theta_{13}}{2\sqrt{2}G_F N_e} \simeq 7 \text{ GeV} \left(\frac{4.5 \text{ g/cm}^3}{\rho} \right) \left(\frac{\Delta m_{31}^2}{2.4 \times 10^{-3} \text{ eV}^2} \right) \cos 2\theta_{13}$$

$\cong 3 \text{ GeV (core)}$
 $\cong 7 \text{ GeV (mantle)}$

for neutrinos if $\Delta m_{13}^2 > 0$ / antineutrinos if $\Delta m_{13}^2 < 0$
 → depends on the **neutrino mass hierarchy** – not yet measured...

**Probing the earth's interior with neutrinos, Veronique et al. 2021

We are using Atmospheric Neutrinos(2-10 GeV) for our Tomography study

This is NOT a Hyper-K collaboration talk!!



Public Oscillation frameworks :

1. NuCraft data to generate the oscillograms:

<https://nucraft.hepforge.org/>

2. PISA - Public oscillation package, originally developed by the IceCube collaboration

<https://github.com/icecube/pisa>

3. EarthProbe from APC tomography group,

<https://gitlab.in2p3.fr/apc-tomography/earthprobe>

4. OscProb(base neutrino propagator for EarthProbe),

<https://github.com/joaoabcoelho/OscProb>

Uses symmetric/1D Earth Model

Uses 3D Earth Model

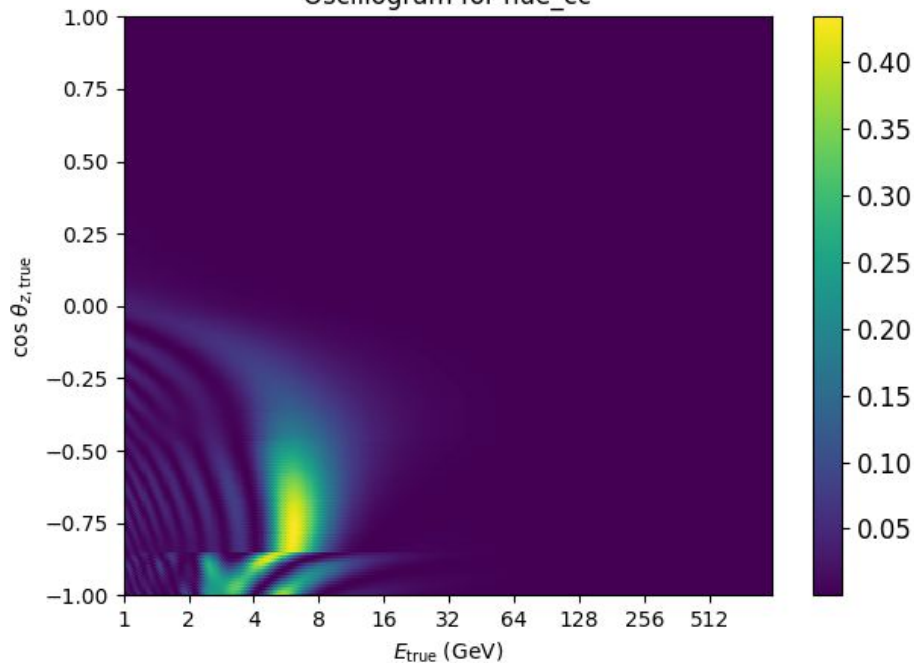


PISA



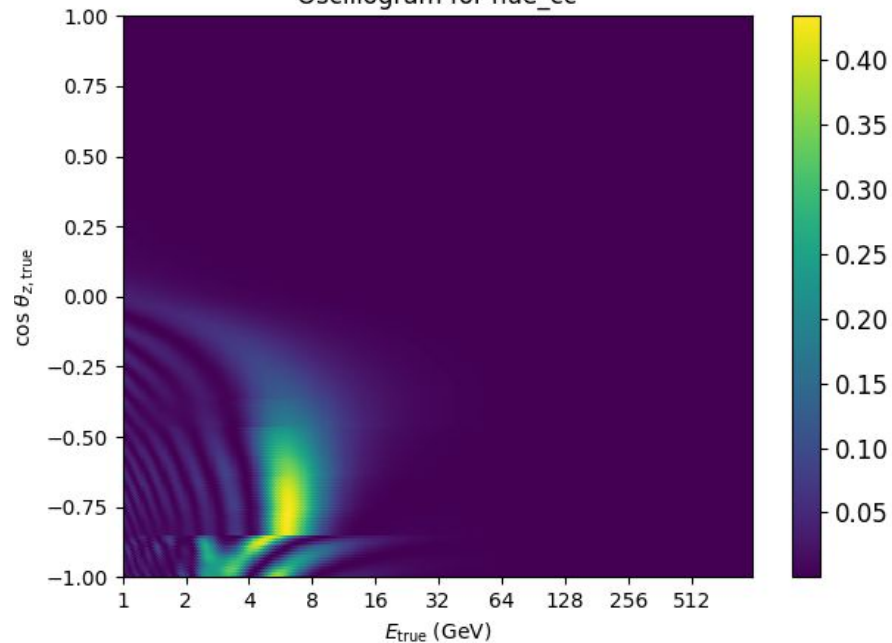
Example Oscillograms from PISA:

Oscillogram for $\nu_{e,cc}$



59 layer PREM profile

Oscillogram for $\nu_{e,cc}$

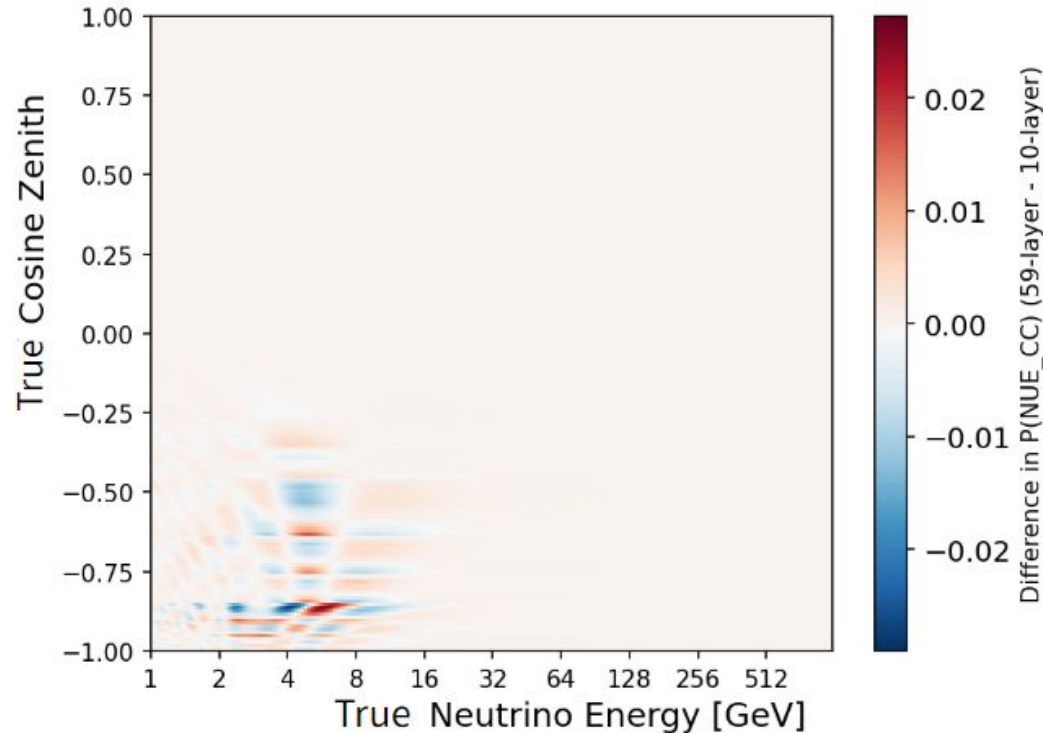


10 layer PREM profile



Example Oscillograms from PISA:

Difference in Oscillation Probability for NUE_CC

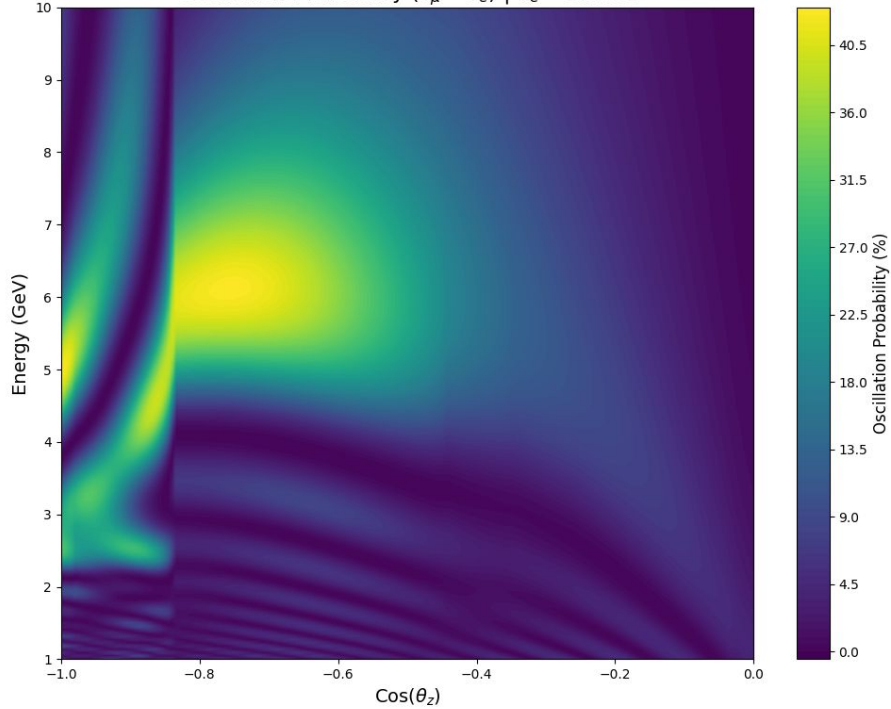


Here, I took the difference between two **different PREM layers**. However, if I would have fixed the PREM layers but **varied Z/A** value, that would be interesting to see.



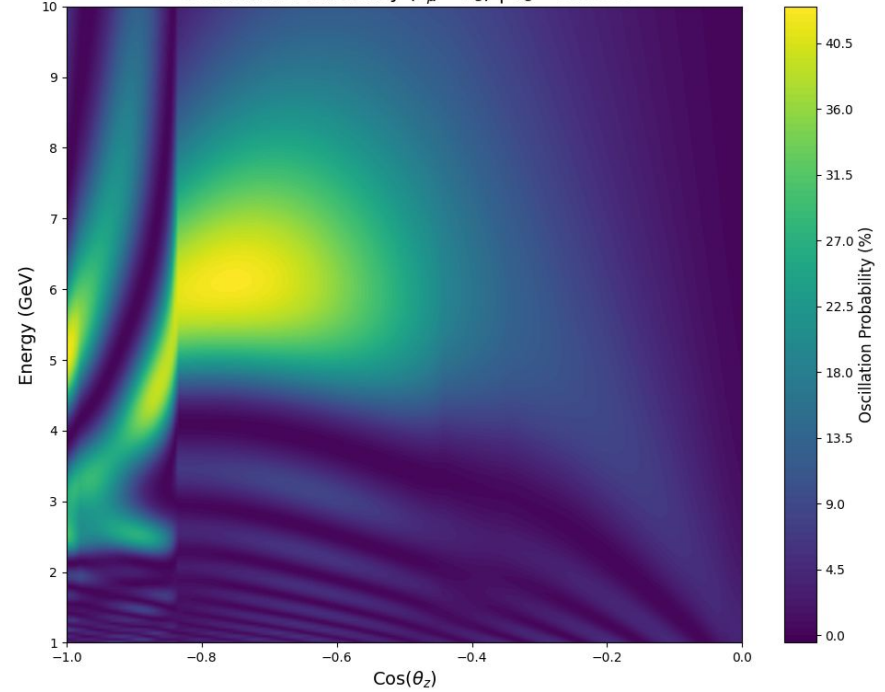
Example Oscillograms from Nucraft:

Oscillation Probability ($\nu_\mu \rightarrow \nu_e$) | $Y_e = 0.4680$



Z/A : 0.4680

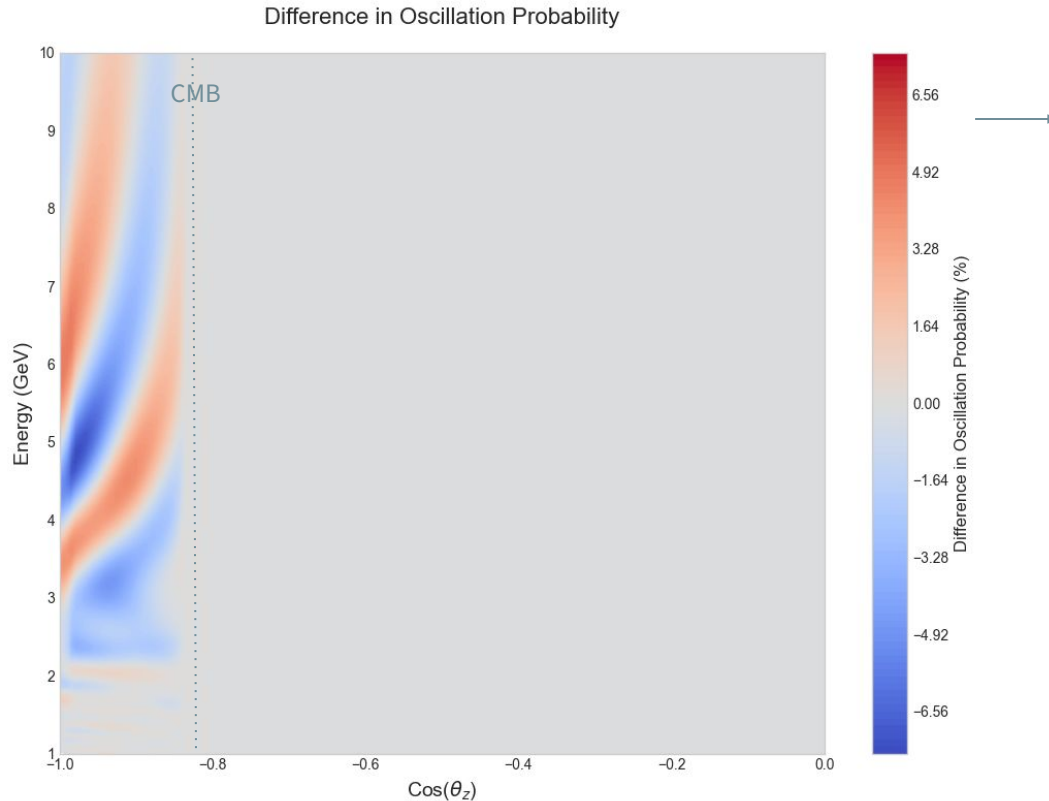
Oscillation Probability ($\nu_\mu \rightarrow \nu_e$) | $Y_e = 0.4550$



Z/A : 0.4550



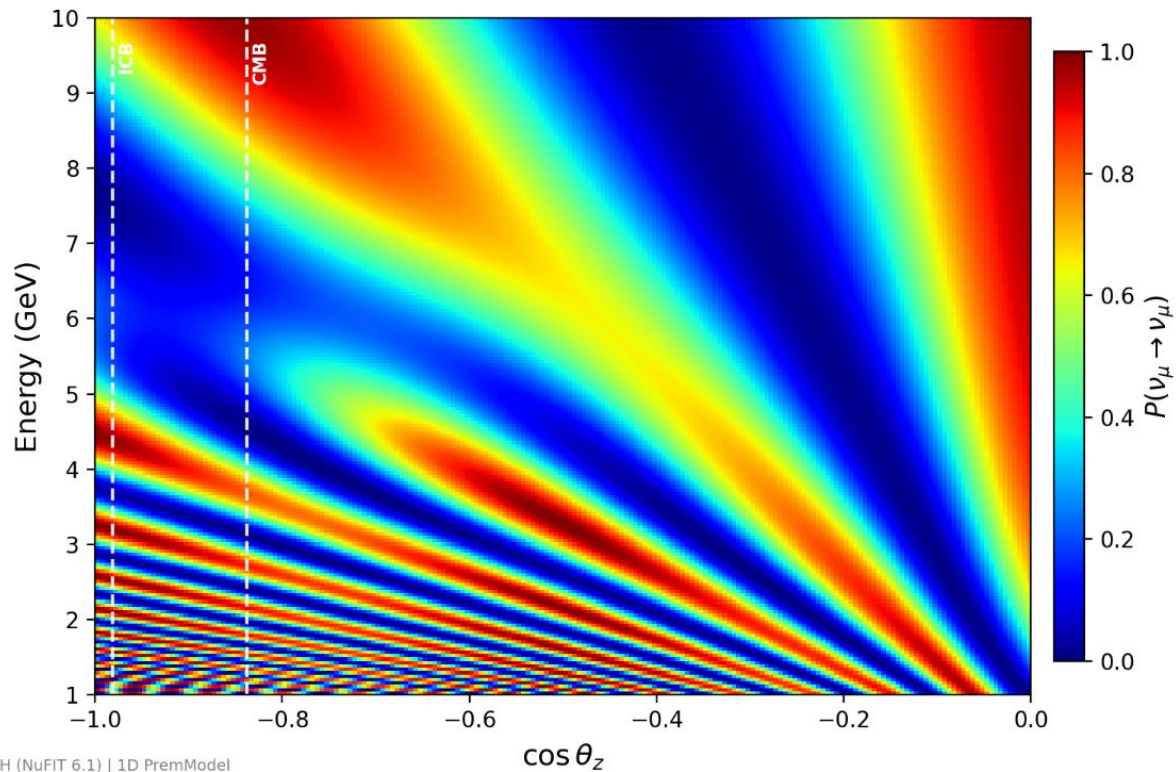
Example Oscillograms from Nucraft:



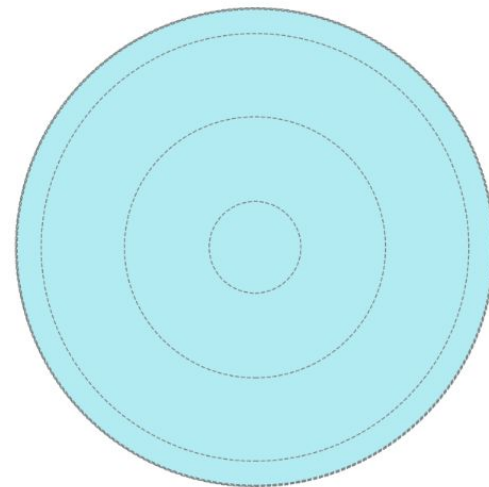
→ This is the probability difference between two oscillograms for two different Z/A (outer core), 0.4680 & 0.4550 (randomly chosen).
With numu \rightarrow nue channel



Earth Layers Affecting the Oscillogram — Uniform Earth

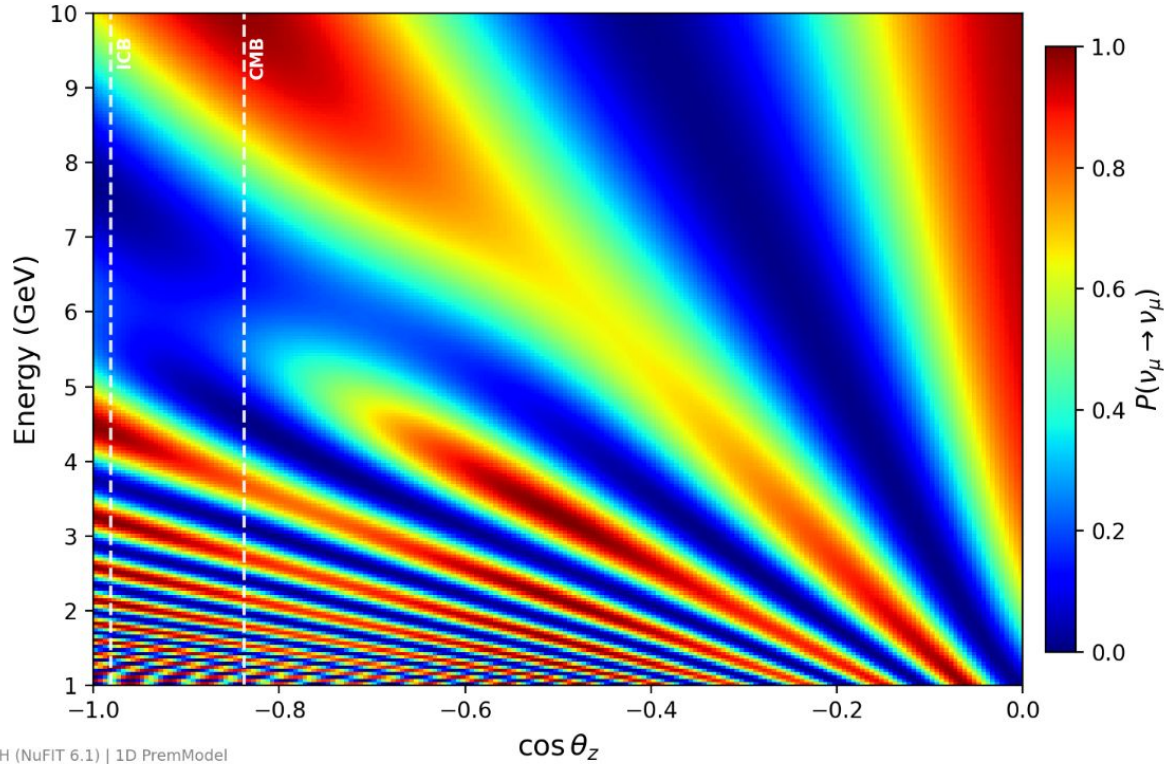


Uniform $\rho \approx 5.51 \text{ g/cm}^3$

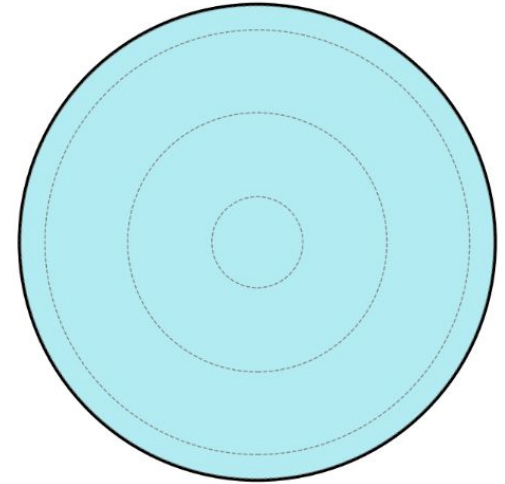


NH (NuFIT 6.1) | 1D PremModel

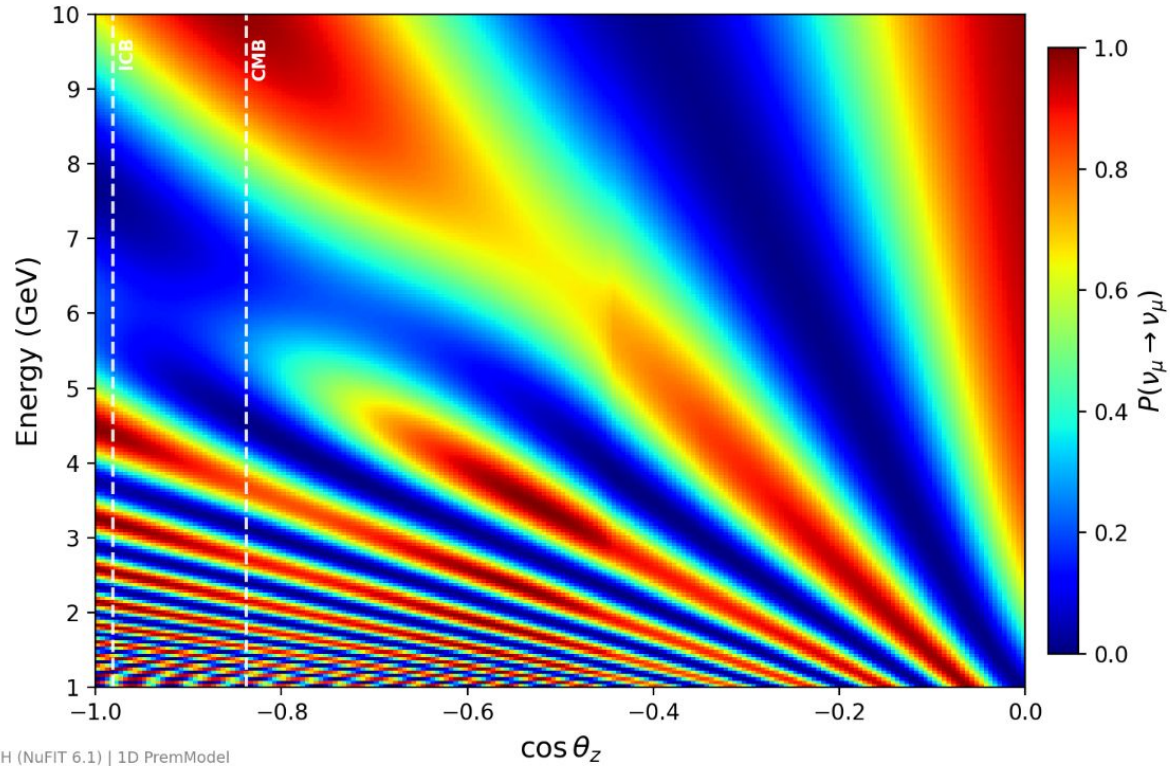
Earth Layers Affecting the Oscillogram — + Crust & Ocean



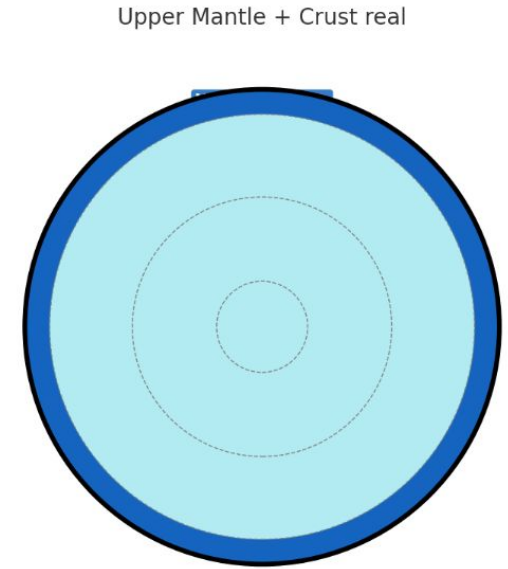
Crust + Ocean at real PREM densities



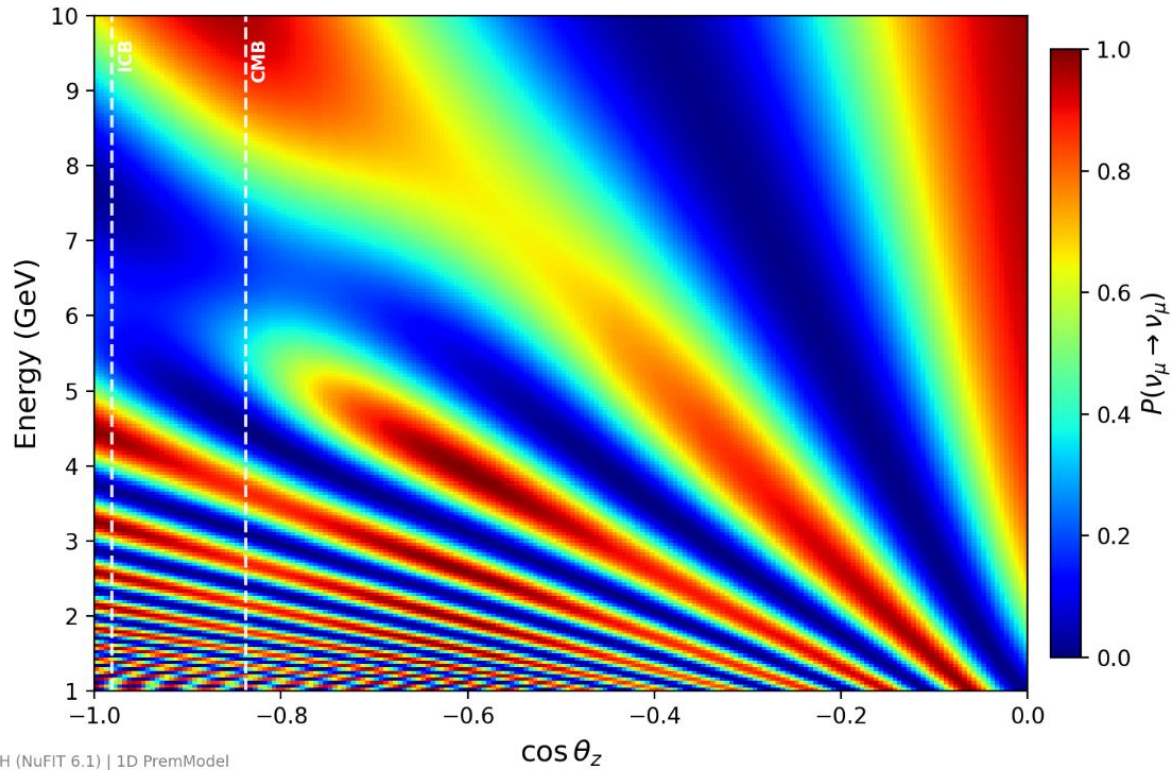
Earth Layers Affecting the Oscillogram — + Upper Mantle



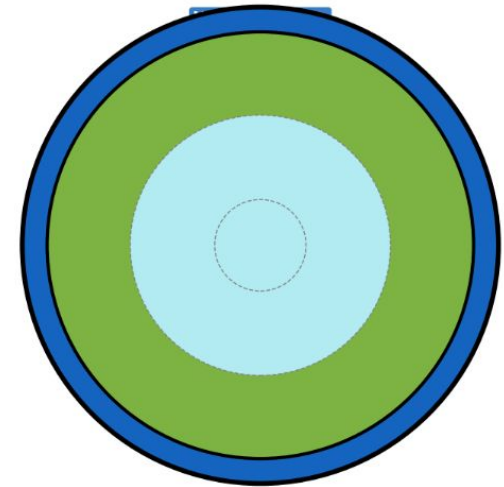
NH (NuFIT 6.1) | 1D PremModel



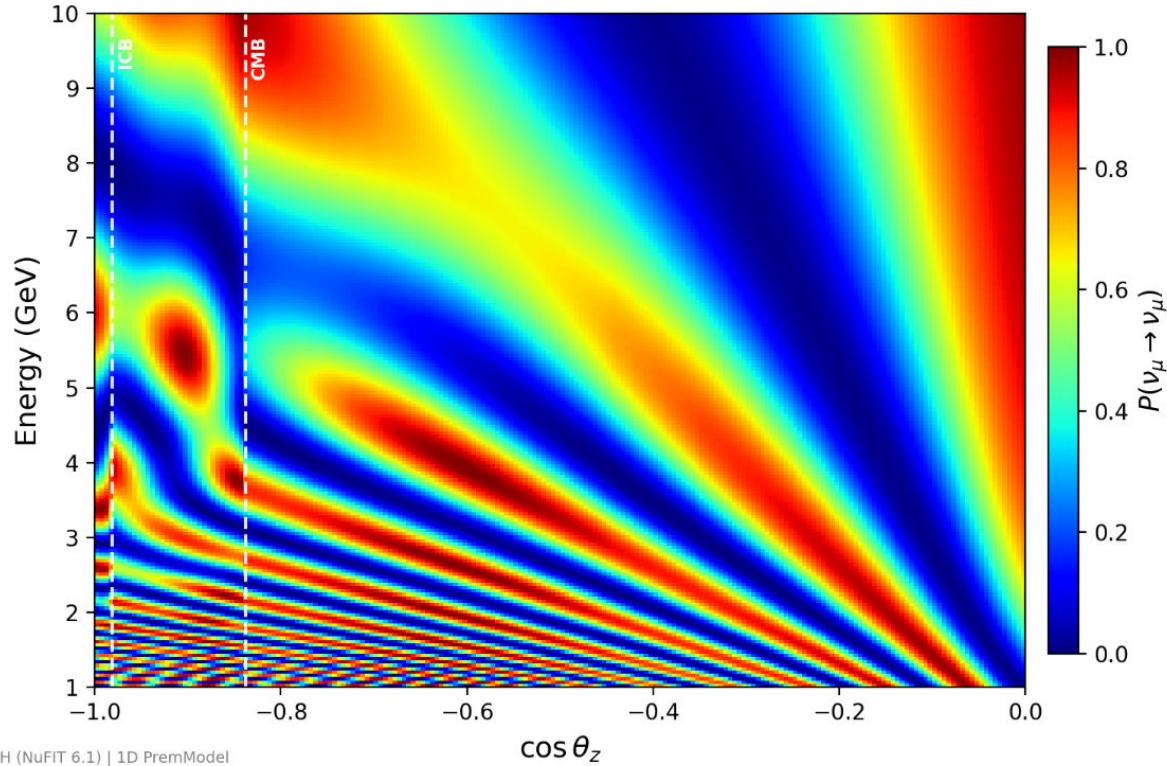
Earth Layers Affecting the Oscillogram — + Lower Mantle (Full Mantle)



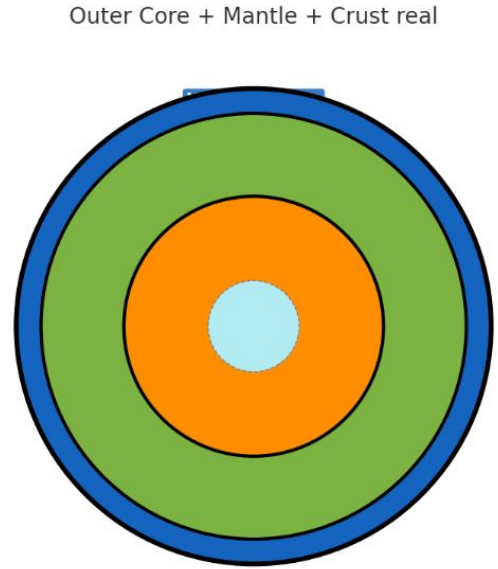
Full Mantle + Crust real



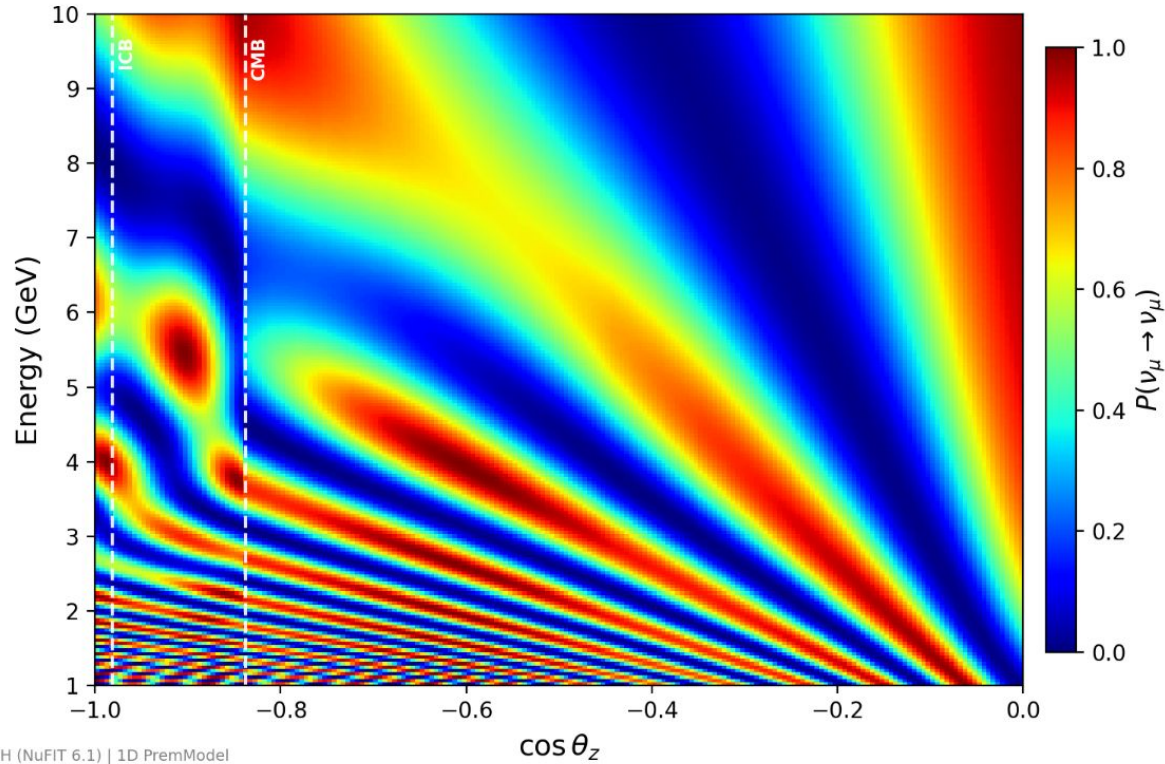
Earth Layers Affecting the Oscillogram — + Outer Core



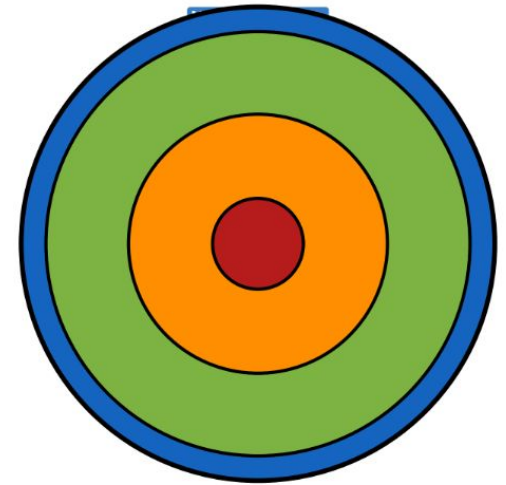
NH (NuFIT 6.1) | 1D PremModel



Earth Layers Affecting the Oscillogram — Full PREM



All layers at real PREM densities (prem_44layers.f)



NH (NuFIT 6.1) | 1D PremModel



Moving to 3D Earth in OscProb :

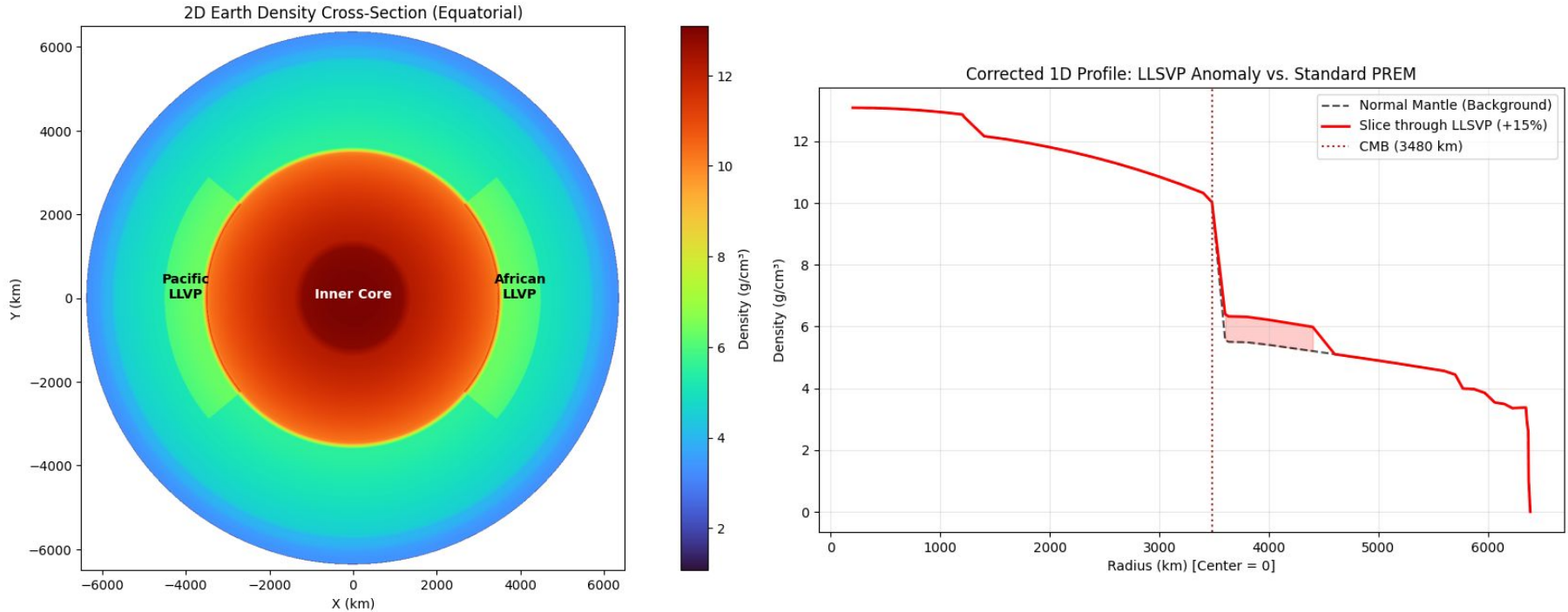
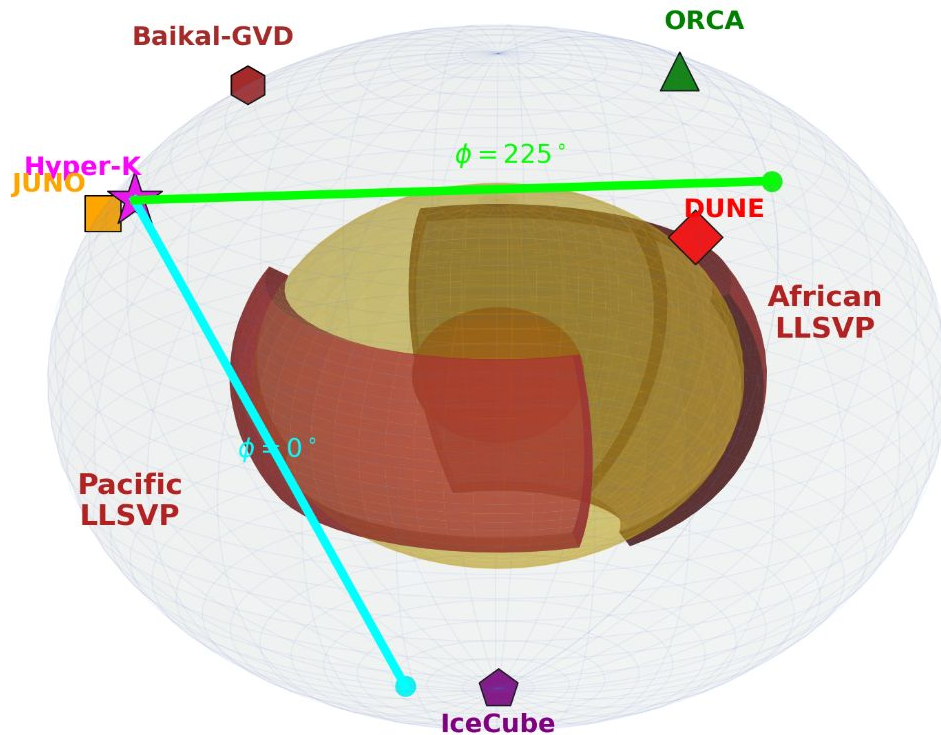


Figure: Modified PREM model with 15% density anomaly near the CMB(core mantle boundary)

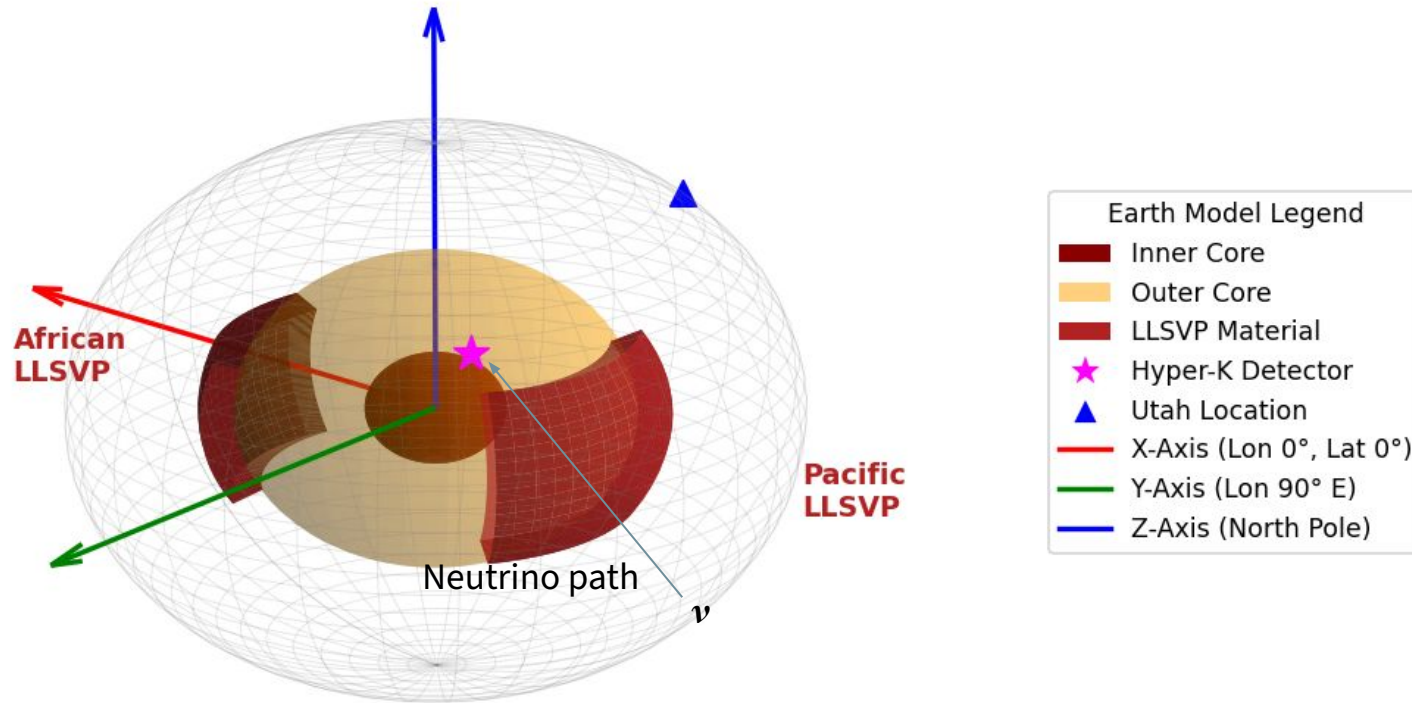
Moving to 3D Earth in OscProb(multi-detector positions) :



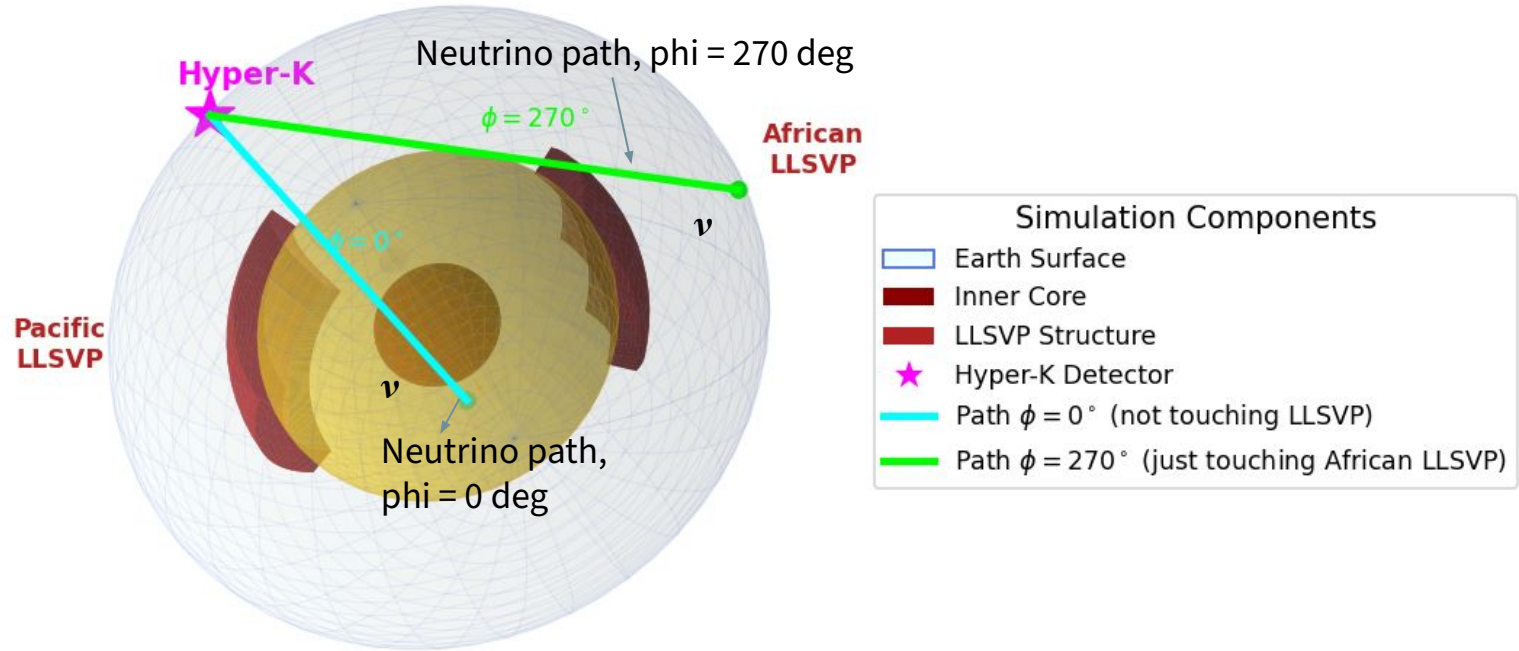
- Components & Detectors
- Earth Surface
 - Core-Mantle Boundary
 - Inner Core
 - LLSVP Structure
 - Path $\phi = 0^\circ$ (no LLSVP)
 - Path $\phi = 225^\circ$ (African LLSVP)
 - Hyper-K (36.4°N, 137.3°E)
 - DUNE (44.4°N, 256.2°E)
 - ORCA (42.8°N, 6.0°E)
 - IceCube (-90.0°N, 320.4°E)
 - JUNO (22.1°N, 112.5°E)
 - Baikal-GVD (51.8°N, 104.4°E)



Moving to 3D Earth in OscProb :

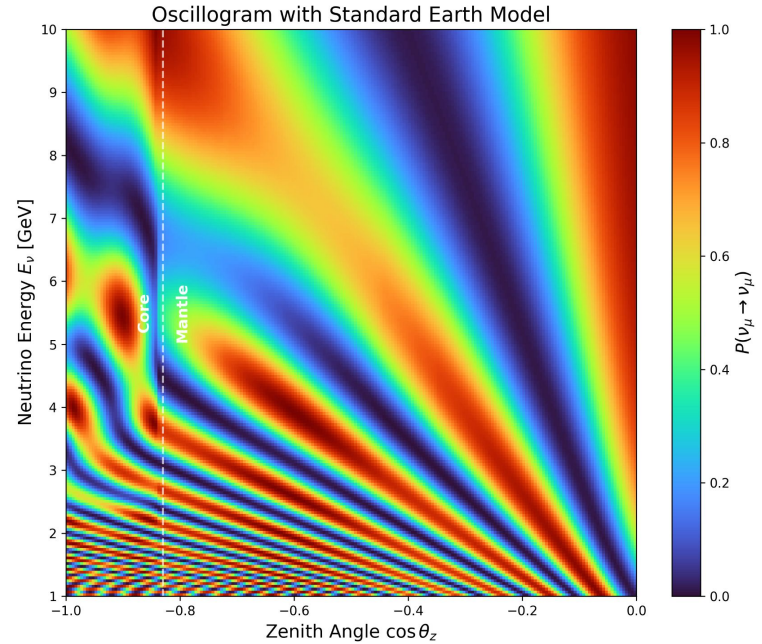
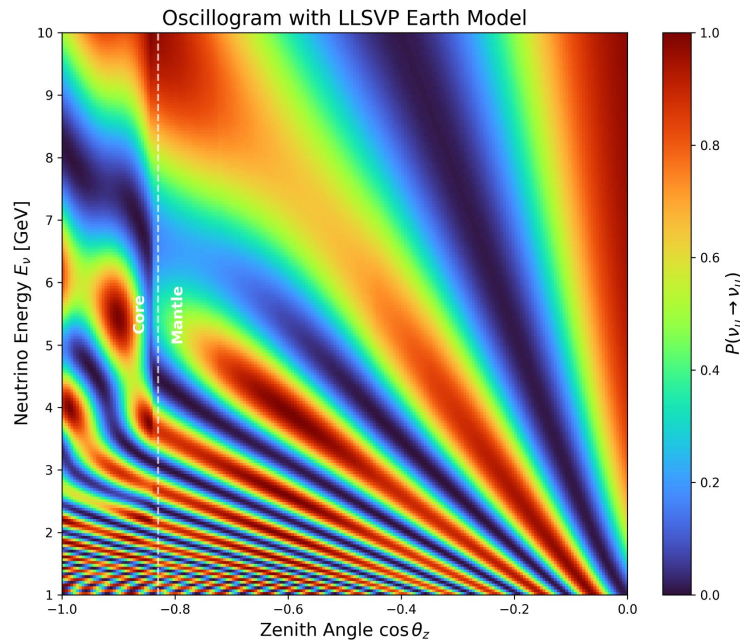


Neutrinos travelling through specific region of Earth :



Oscillograms generated using OscProb(for 3D Earth) :

Recent oscillation parameters from NuFIT 6.1(<http://www.nu-fit.org/?q=node/309>) with Normal Mass Hierarchy



$\phi(\text{azimuth}) = 225 \text{ deg}$

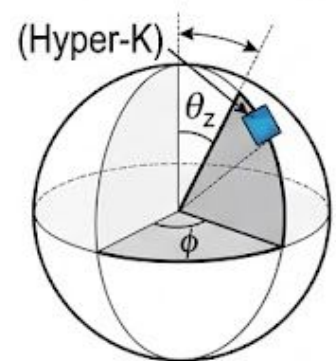
With LLSVP

w/o LLVP



Difference seen in the oscillograms :

Fixed Azimuth Angle

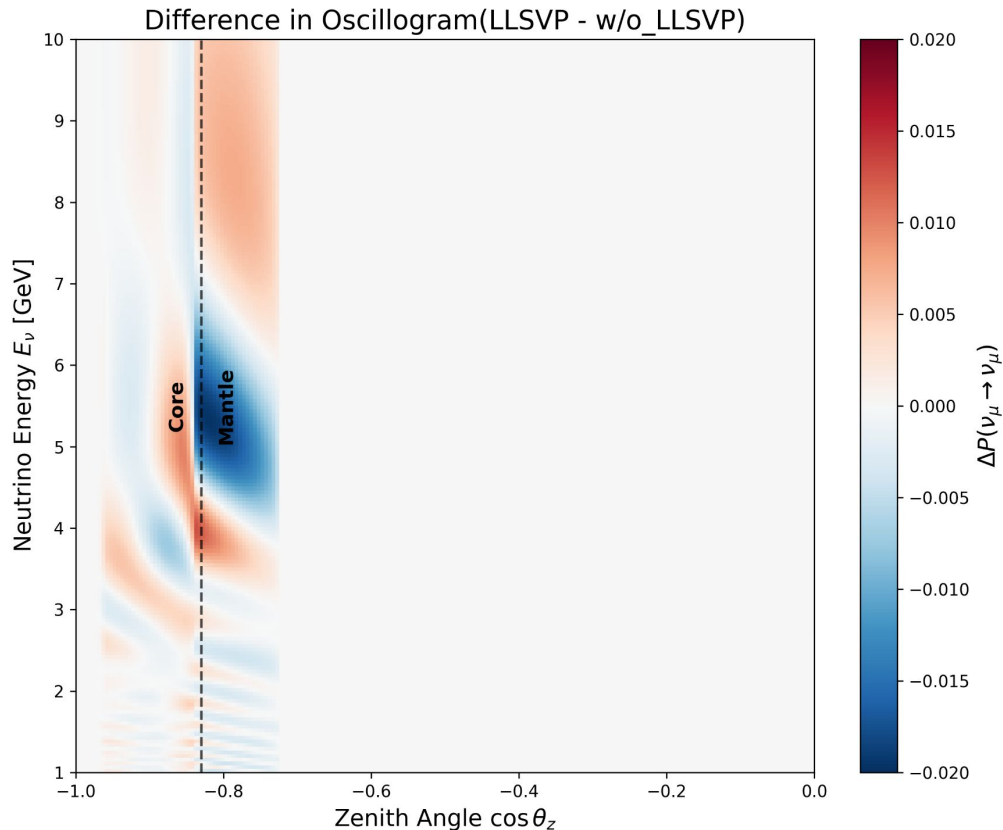


A slice shows a focused longitude sector (ϕ) vs. an average cone.



Fixed Azimuth Angle
 $\phi = 225^\circ$ Slice

- Have to add area search for the sensitivity of the specific region!

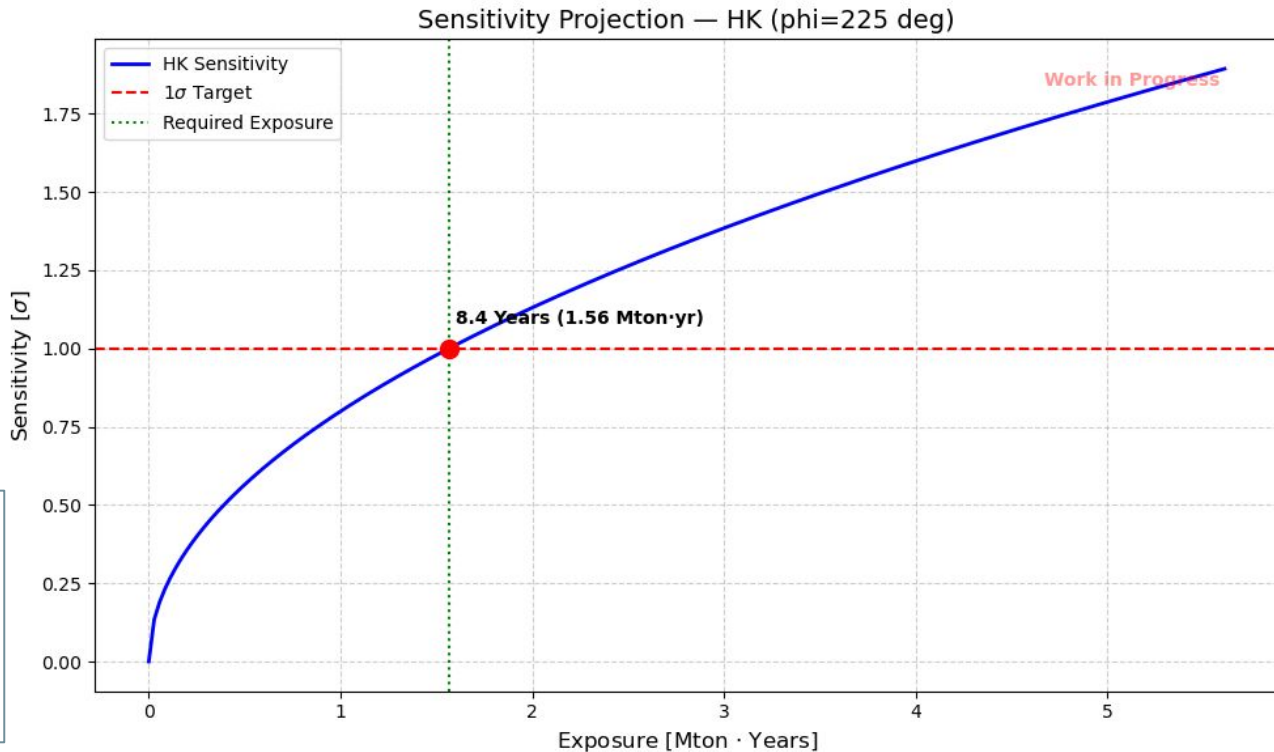


We assume a Hyper-K like detector with the following performance:

- Spectral weighting: $\sim E^{-2.7}$
- Energy Resolution: $\sigma_E/E = 5\%$
- Angular Resolution: $\sigma_\theta = 5^\circ/\sqrt{E}_{\text{GeV}}$
- Significance (σ) = $\sqrt{|\chi^2|}$
- Plots the cumulative significance (σ) as a function of Exposure (Mton·Years).

- For a fiducial mass of 0.187 Mton the atmospheric ν_μ event considered is 22,145 per year, **Note:** Current normalization reflects total global rate; upgoing ν_μ specific scaling is ongoing.

Sensitivity for this data set :



→ Modified PREM model with 5% density anomaly near the CMB (**Core-Mantle Boundary**)

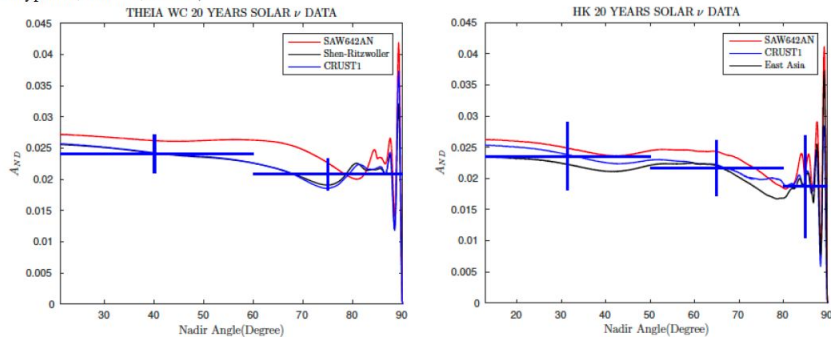


Other Interesting Tomographic studies for Hyper-K (from Carsten's Talk at Neutrino Geoscience 2025):

Oscillation tomography with solar neutrinos

P. Bakhti and A. Y. Smirnov, arXiv:2001.08030, Phys. Rev. D 101 (2020) no.12, 123031.

- Study oscillation tomography of the Earth with the boron neutrinos (peak ~ 14MeV)
- Due to the attenuation effect, the Day-Night asymmetry mainly depends on shallow density structures: crust, upper mantle and crust-mantle border
- Next-generation detectors will establish the integrated day-night asymmetry with high confidence level and can give some indications of the nadir dependence of the effect - different earth models can be distinguished (20yrs for Hyper-K, THEIA, DUNE)



CRUST1 - global 3D model, 1×1 degree grid, density and depth of borders of eight layers of the crust: water, ice, upper sediments, middle sediments, lower sediments, upper crust, middle crust, and lower crust. Mohorovicic discontinuity: $h_{\text{Moho}} = 40\text{ km}$ @ Kamioka. G. Laske, G. Masters, Z. Ma, and M. Pasyanos, *Geophys. Res. Abstr.* 15, 2658 (2013)

SAW642AN - global radially anisotropic mantle shear velocity model based on a global 3D tomography of the Earth. Density profile of mantle starting from the depth of $h_{\text{Moho}} = 24$ km, down to 2900 km. No crust structure is available. C. Mignin and B. Romanowicz, *Geophys. J. Int.* 143, 709 (2000).

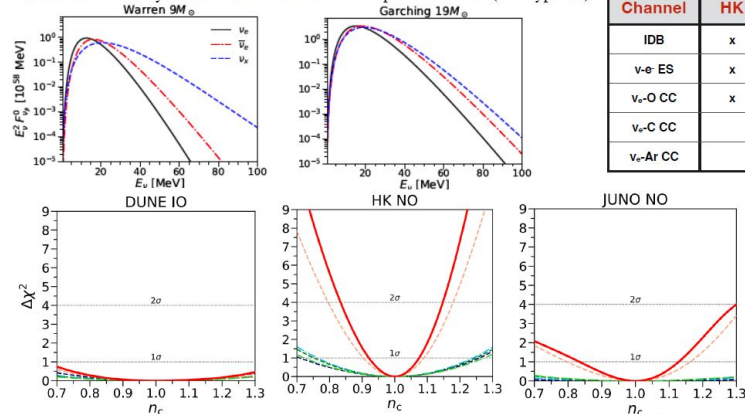
East Asia - East Asia model down to 800km with Mohorovicic discontinuity: $h_{\text{Moho}} = 33\text{ km}$ @ Kamioka. K. Tao, S. P. Grand, and F.N. Niu, *Geochem. Geophys. Geosyst.* 19, 2732 (2018)

Shen-Ritzwoller - North America - Bayesian Monte Carlo inversion of geophysical data. Density change from the sea level surface down to the depth of 150 km with $h_{\text{Moho}} = 52$ km beneath the Homestake - V.V. Shen and M. H. Ritzwoller, *J. Geophys. Res. Solid Earth* 121, 4306 (2016).

Earth tomography with supernova neutrinos at future neutrino detectors

R. Hajjar, O. Mena, S. Palomares-Ruiz *Phys. Rev. D* 108 (2023) 8, 083011 • e-Print: 2303.09369 [hep-ph]

- Assuming adiabatic propagation inside the star
- Oscillations governed by solar mass-squared for SN neutrino spectra (~40-100MeV)
- Assuming a Supernova at a distance of 10 kpc and the SN burst to occur on the opposite side of the detector
- Earth's core density can be determined with <10% precision at 1σ (for Hyper-K)



Channel	HK	JUNO	DUNE
IDB	x	x	
ν -e ES	x	x	x
ν -O CC	x		
ν -C CC		x	
ν -Ar CC			x

- Most optimistic cases: DUNE (IO) via electron neutrino interactions and for HK, JUNE, (NO) for IBD
- Sensitivities strongly depend on the true value Δm_{21}^2
- Sensitivities not at levels to be of interest to geoscience community

Reference: https://indico.global/event/14476/contributions/137722/attachments/63850/123334/Rott_HK_NG25K.pdf

Summary :

1. Neutrino Oscillation Tomography is a complementary tool to scan terrestrial bodies like Earth other than seismic studies!
2. We need more data for studying the chemical composition or 3D structure like LLSVP.
3. Put constraints on the LLSVP region (specific azimuth & zenith) & consider exact density variations for these regions.
4. Include exact oscillation parameters, energy and angular resolution to find Hyper-K like water cherenkov detector's sensitivity to these LLSVP

Thank You

