XXXI International Conference on
Neutrino Physics and Astrophysics
Milano (Italy) - June 16-22, 2024

THE UNIVERSITY OF UTAH
Physics & Astronomy

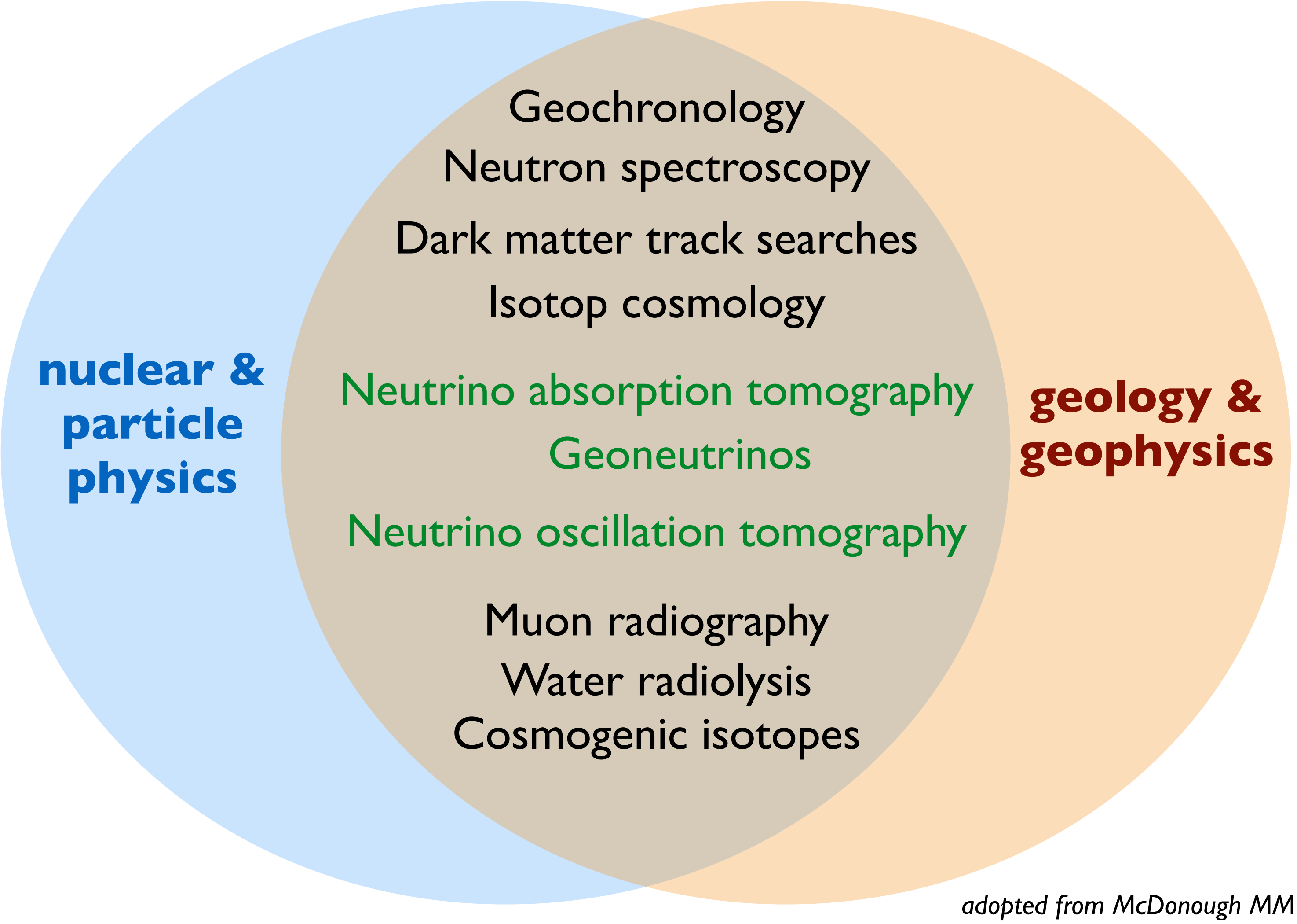
성균관대학교
SUNGKYUNKWAN UNIVERSITY

# Developments in nu applications to the geosciences

Carsten Rott
University of Utah / Sungkyunkwan University

Neutrino 2024

*Venn diagram: Nuclear & Particle Physics + Geology & Geophysics*



**nuclear & particle physics**

Geochronology
Neutron spectroscopy
Dark matter track searches
Isotop cosmology
Neutrino absorption tomography
Geoneutrinos
Neutrino oscillation tomography
Muon radiography
Water radiolysis
Cosmogenic isotopes

**geology & geophysics**

*adopted from McDonough MMTE2023*

*⇒ Enormous amount of shared science and experiences stretching over many centuries*

# Outline

- Motivation
- Understanding the Earth
  - Standard Model of the Earth
  - Open Questions in Deep Earth Science
- Opportunities with Neutrinos
  - Neutrino Absorption Tomography
  - Neutrino Oscillation Tomography
- Other opportunities
- Summary / Outlook

# Motivations

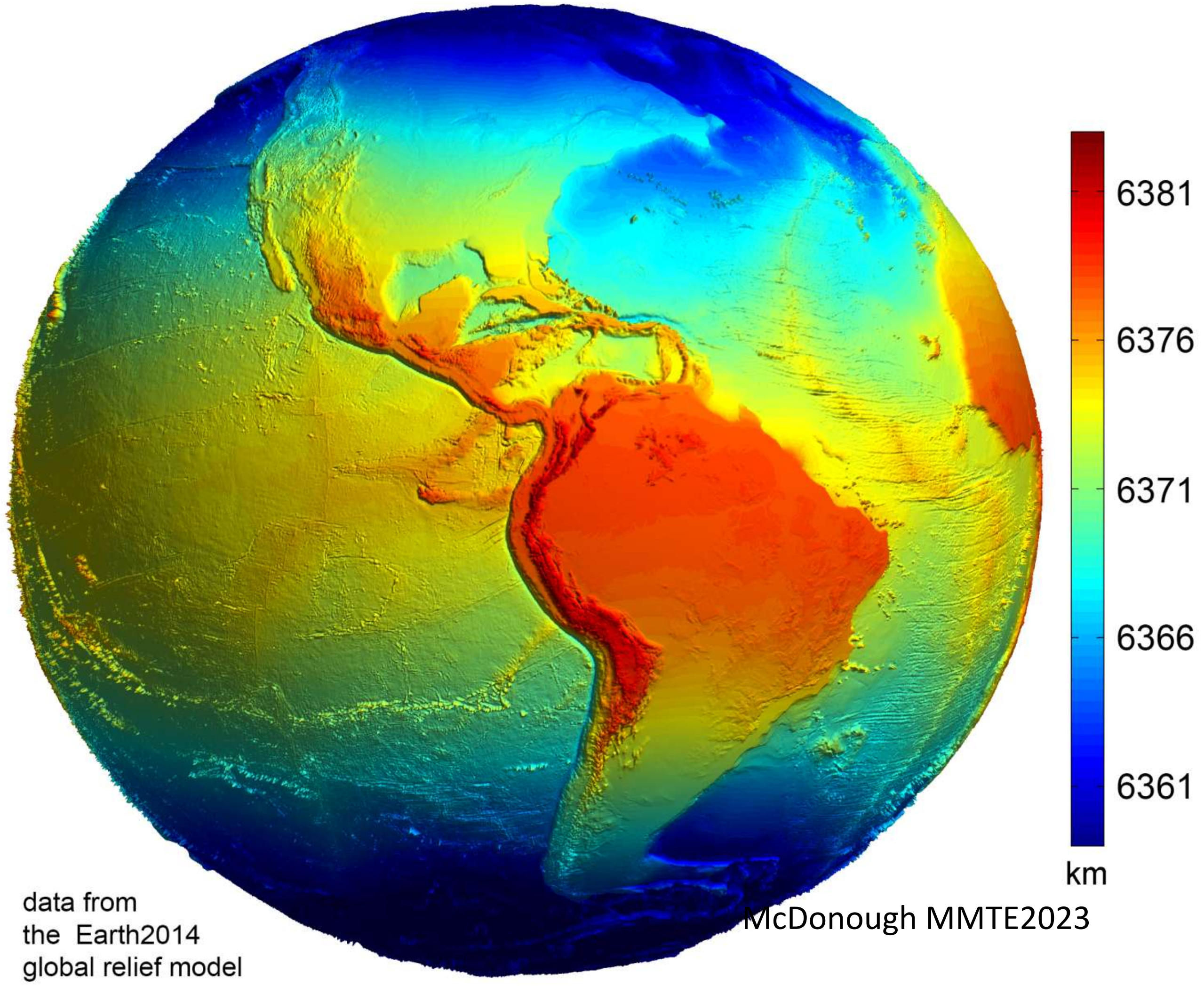
# Motivation

- What lies in the interior of Earth has been a long-standing puzzle
    - Fundamental questions:
        - Formation history, Magnetic field, …
        - Understand the Geodynamo
- The regions deep below the Earth's surface are inaccessible due to large temperatures, pressures, and extreme environments
- Information about the interior of Earth is obtained indirectly using
    - Gravitational measurements
    - Seismic studies
- Neutrinos can penetrate deep inside the Earth and may shed light on internal structure and composition

# The "Standard Model of the Earth"

# What is well known

Shape of the Earth
distances of relief points to the geocentre



data from
the Earth2014
global relief model

image credit:
Geodesy2000
https://commons.wikimedia.org/wiki/File:Earth2014shape_SouthAmerica_small.jpg

## hydrostatic equilibrium constraint

$\rho_M \leq \rho_{OC} \leq \rho_{IC}$

## Earth's mass

gravitational measurement

$M_{\text{Earth-grav.}}=(5.9722\pm0.0006)\times10^{24}\text{kg}$

J. C. Ries, R. J. Eanes, C. K. Shum, and M. M. Watkins, *Progress in the determination of the gravitational coefficient of the earth*, *Geophysical Research Letters* **19** (1992), no. 6 529–531, [https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/92GL00259].

B. Luzum, N. Capitaine, A. Fienga, W. Folkner, T. Fukushima, J. Hilton, C. Hohenkerk, G. Krasinsky, G. Petit, E. Pitjeva, M. Soffel, and P. Wallace, *The IAU 2009 system of astronomical constants: the report of the IAU working group on numerical standards for fundamental astronomy*, *Celestial Mechanics and Dynamical Astronomy* **110** (July, 2011) 293–304.

G. Rosi, F. Sorrentino, L. Cacciapuoti, M. Prevedelli, and G. M. Tino, *Precision Measurement of the Newtonian Gravitational Constant Using Cold Atoms*, *Nature* **510** (2014) 518, [arXiv:1412.7954].

USAO, USNO, HMNAO and UKHO *The Astronomical Almanac* (US Navy, 2020), https://aa.usno.navy.mil/,http://asa.hmnao.com/.

J. G. Williams, *Contribution to the earth's obliquity rate, precession, and nutation*, *Astronomical Journal* **108** (Aug., 1994) 711.

## Earth's moment of inertia

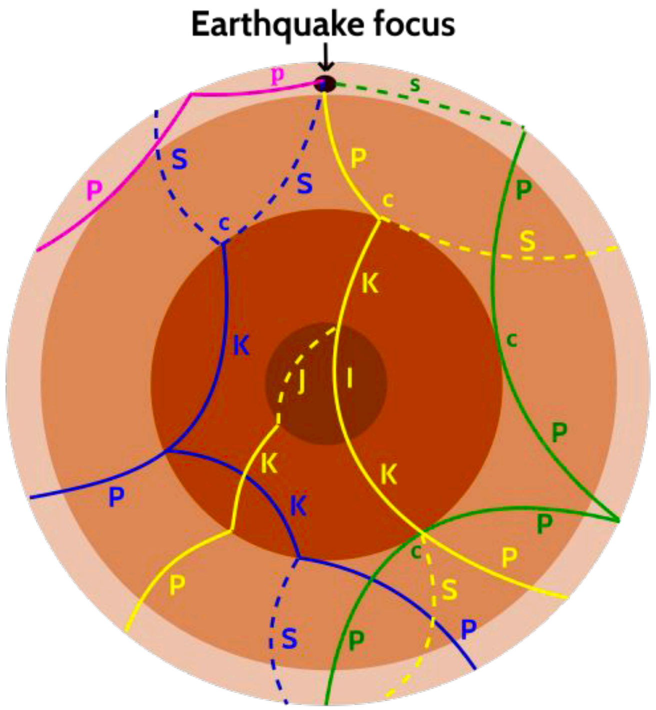
gravitational measurement

$I_{\text{Earth}}=(8.01736\pm0.00097)\times10^{37}\text{kgm}^2$

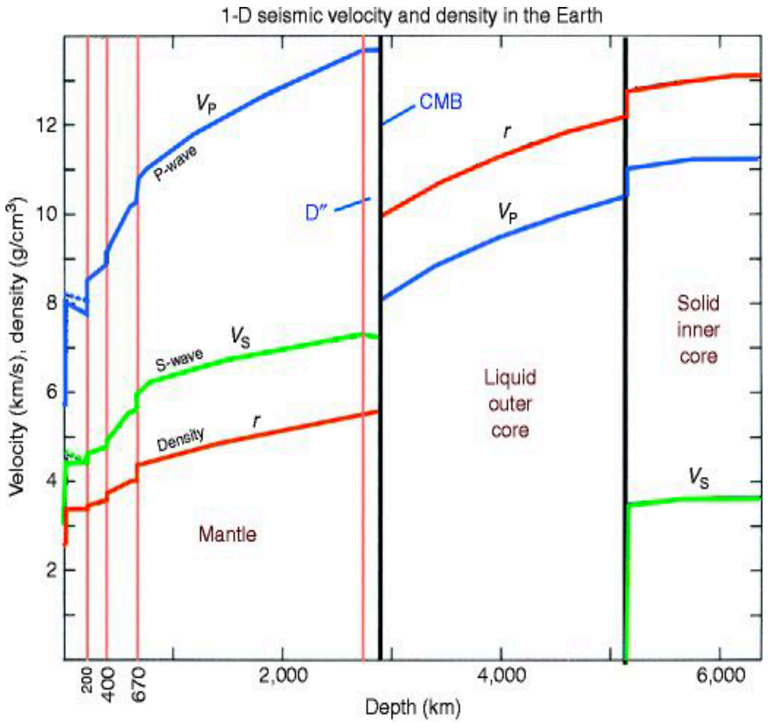
W. Chen, J. C. Li, J. Ray, W. B. Shen, and C. L. Huang, *Consistent estimates of the dynamic figure parameters of the earth*, *Journal of Geodesy* **89** (Oct., 2014) 179–188.

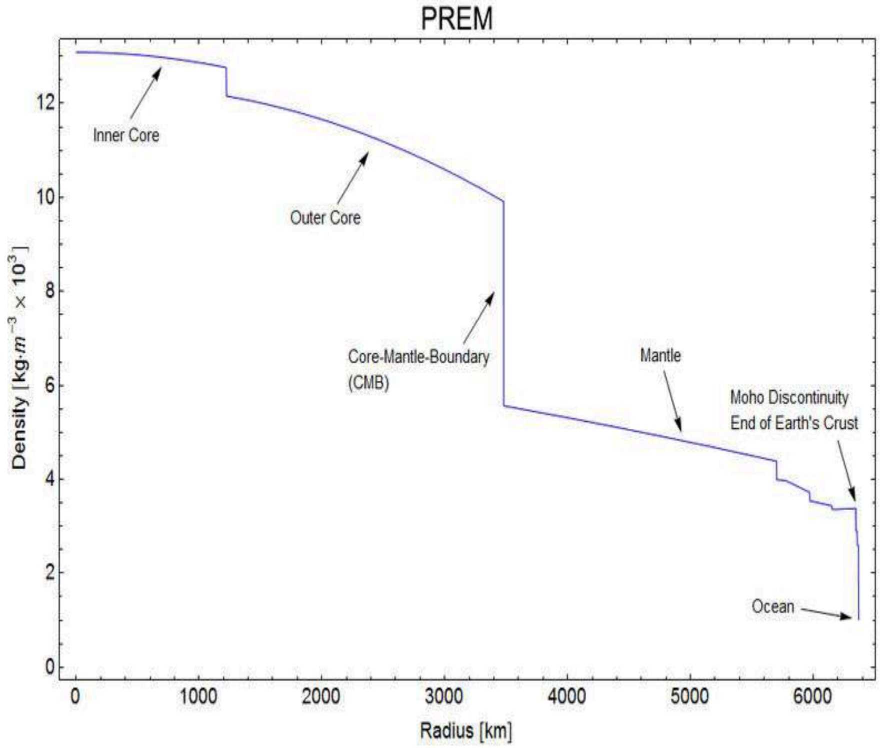
B. Gutenberg, *Ueber Erdbebenwellen. VII A. Beobachtungen an Registrierungen von Fernbeben in Göttingen und Folgerung über die Konstitution des Erdkörpers (mit Tafel)*, *Nachrichten von der Gesellschaft der Wissenschaften zu Göttingen, Mathematisch-Physikalische Klasse* **1914** (1914) 125–176.

# Internal Structure of the Earth



JHEP 04 (2023) 068





A. M. Dziewonski and D. L. Anderson, "Preliminary reference earth model," Phys. Earth Planet. Interiors 25 (1981) 297.

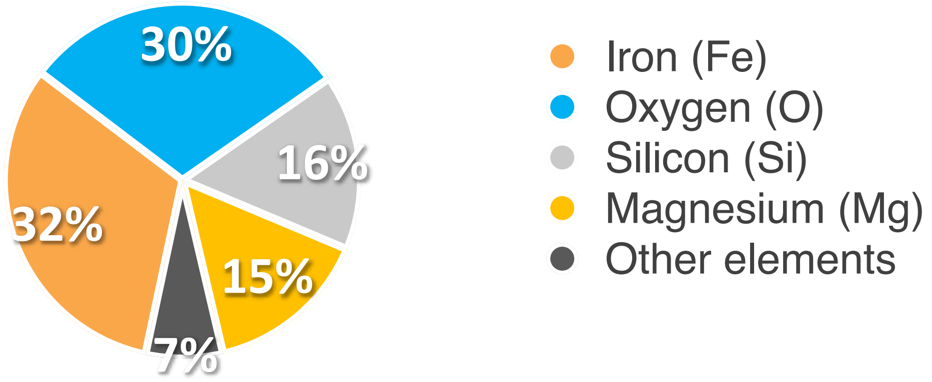
- Earth internal density structure
  - Well known, except for possible layers at top and bottom of the outer core
  - Gravitational and seismic measurements are used to infer the Earth internal density structure.
    - Preliminary Earth Reference Model (PREM), radially-averaged values, 1D model

References:

- Dziewonski, A. & Anderson, D. Preliminary reference Earth model. Physics of the Earth and Planetary Interiors 25, 297–356 (1981).
- Kennett, B., Engdahl, E. & Buland, R. Constraints on seismic velocities in the earth from travel times. Geophysical Journal International 122, 108–124 (1995).
- Dziewonski, A., Hales, A. & Lapwood, E. Parametrically simple earth models consistent with geophysical data. Physics of the Earth and Planetary Interiors 10, 12–48 (1975).

# The “Standard Model of the Earth”

The Bulk Earth’s **mass composition** for **main elements** is well known:



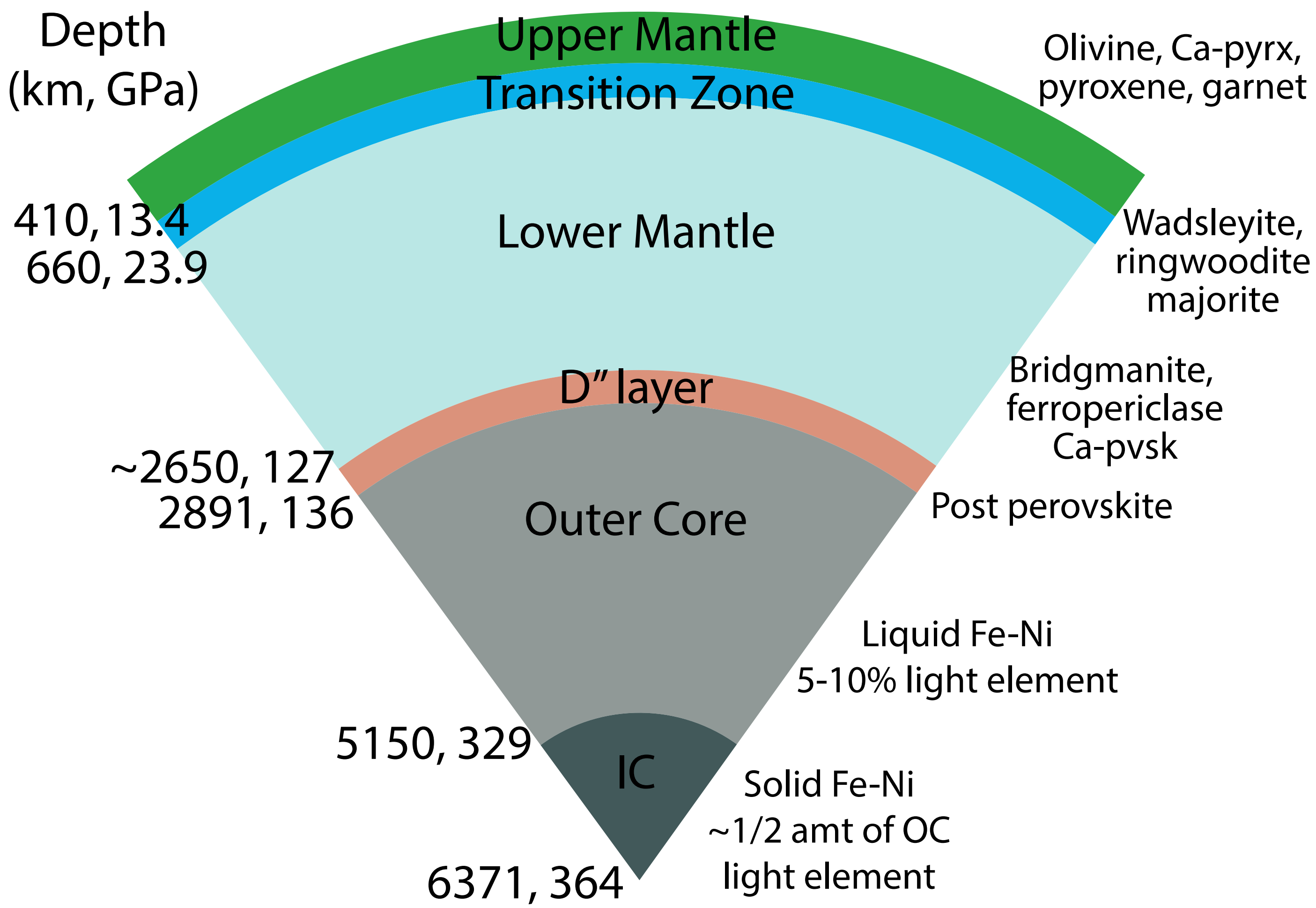
About 0.02% of Earth’s mass is made out of radioactive **Heat Producing Elements (HPEs).**

The most important for activity, abundances and half-life time (comparable to Earth’s age) are:

- **Uranium U** ($M_U$~$10^{-8}$ $M_{Earth}$)
- **Thorium Th** ($M_{Th}$~$10^{-8}$ $M_{Earth}$)
- **Potassium K** ($M_K$~$10^{-4}$ $M_{Earth}$)

Andrea Serafini MMTE2022

## Mineralogy



Depth (km, GPa)

Upper Mantle

Transition Zone

Lower Mantle

D” layer

Outer Core

IC

410, 13.4

660, 23.9

~2650, 127

2891, 136

5150, 329

6371, 364

Olivine, Ca-pyrx, pyroxene, garnet

Wadsleyite, ringwoodite majorite

Bridgmanite, ferropericlase Ca-pvsk

Post perovskite

Liquid Fe-Ni
5-10% light element

Solid Fe-Ni
~1/2 amt of OC
light element

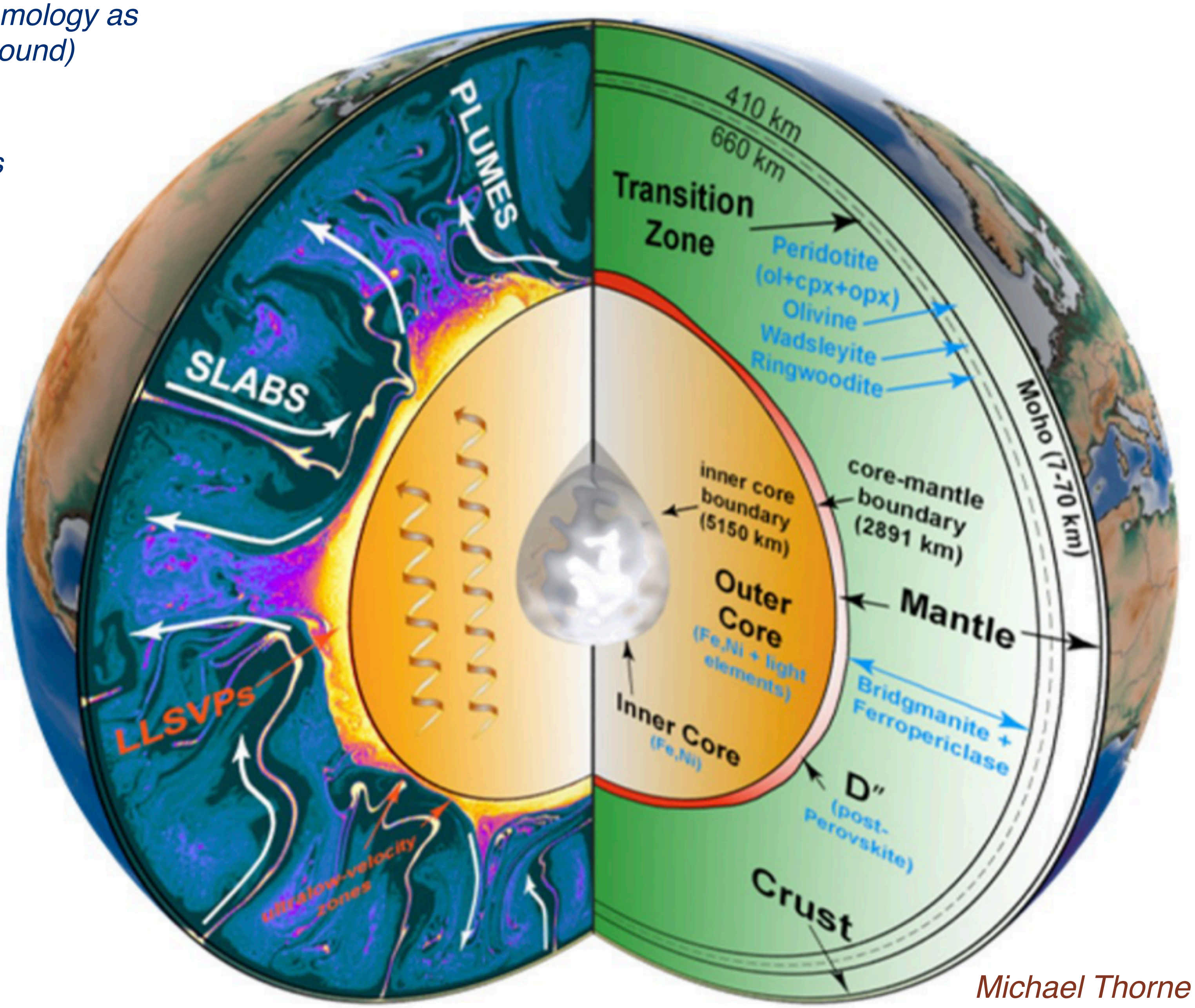
Bill McDonough MMTE2023

- Earth Core
  - Core: Based on cosmochemical models (McDonough & Sun 1995) the core contains Fe with about 5.5wt% Ni. However, the measured density of the core is too light by 7-10% to be a pure Fe-Ni alloy

# Moving from 1D to 3D

*overlain on this 1-D structure…*
*Dynamics (3-D, imaged in seismology as Variations from the 1-D background)*
- *Subducting slabs*
- *Plumes*
- *Large Low Velocity Provinces (LLVPs)*
- *Ultralow-velocity zones (ULVZs)*

*characterization by composition (the 1-D background)*
- *Crust*
- *Mantle*
  - *Upper Mantle*
  - *Transition Zone*
  - *Lower Mantle*
  - *D”*
- *Outer Core*
- *Inner Core*



*Michael Thorne MMTE2022*

image from https://www.chpc.utah.edu/news/summer2020_newsletter_v2.pdf

*Figure 1. **Cartoon image of the Earth’s interior structure**. On the right-hand side the standard 1-D Earth layering is shown based on composition. But, 3D structure exists in addition to the 1D layering as shown on the left-hand side. Here we show a snapshot of a thermochemical convection simulation (by Mingming Li, Arizona State University). Locations of possible ULVZs near the CMB are indicated*

# Big Questions in Geoscience

# Big Questions in Geoscience

- Composition of the silicate Earth (Mg, Si, Fe, O)
  - Amount of recycled basalt in the mantle
    - In the Transition Zone?
    - In the deep mantle
- Mineralogy of the Lower mantle
  - Mode % ferropericlase (sets the Mg/Si)
  - Mode % Ca-perovskite (sets amount of Th & U in Earth)
- Amount of $H_2O$ in the Mantle and H in the Core
- Geothermal (*viscosity*) gradient Mantle and Core
- Composition of the Core (plus ?? H, C, O, Si, S, ..)
- Radioactive power in the Mantle and Core

see Bill McDonough MMTE2023

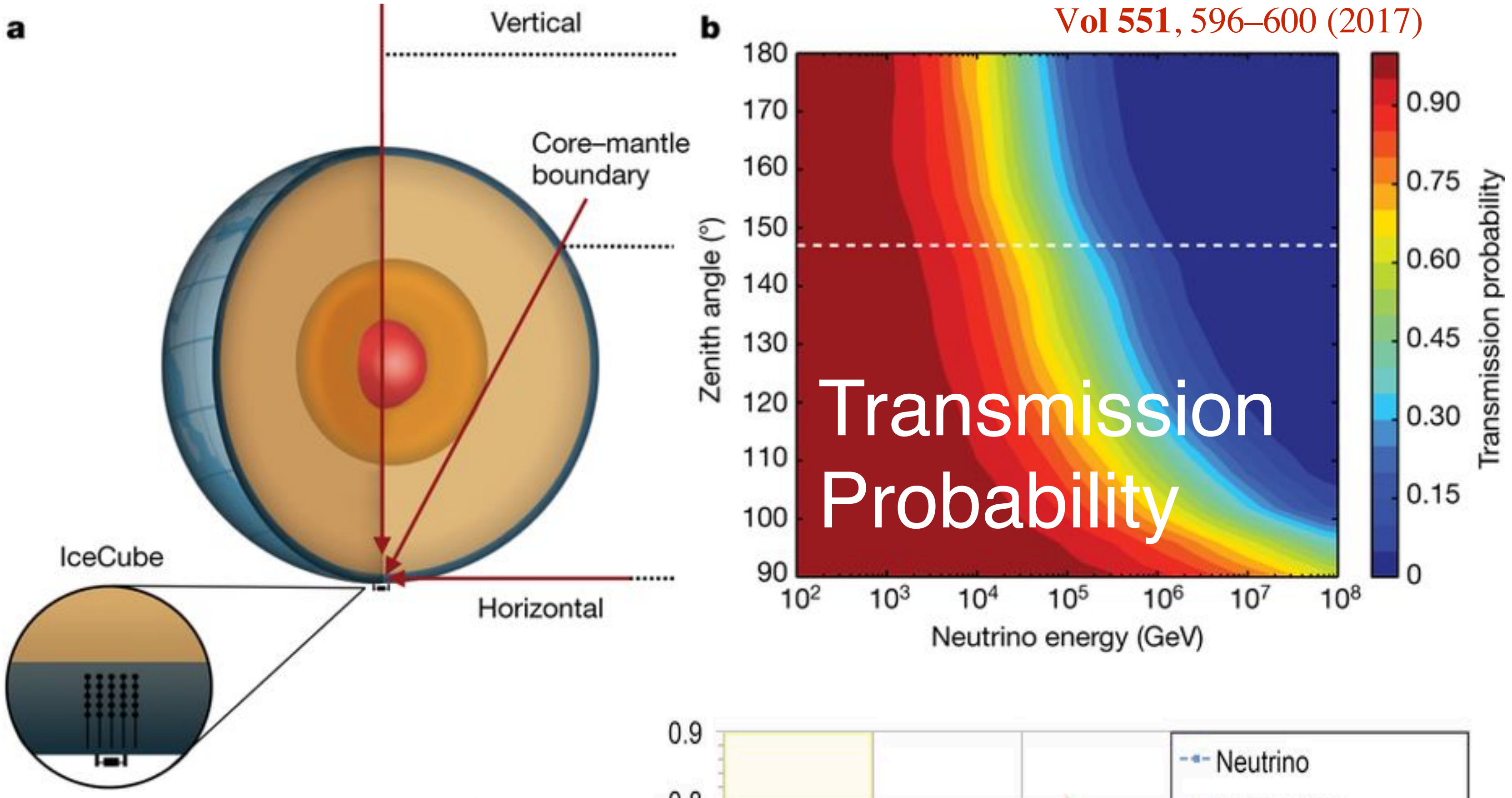
# Neutrino Absorption

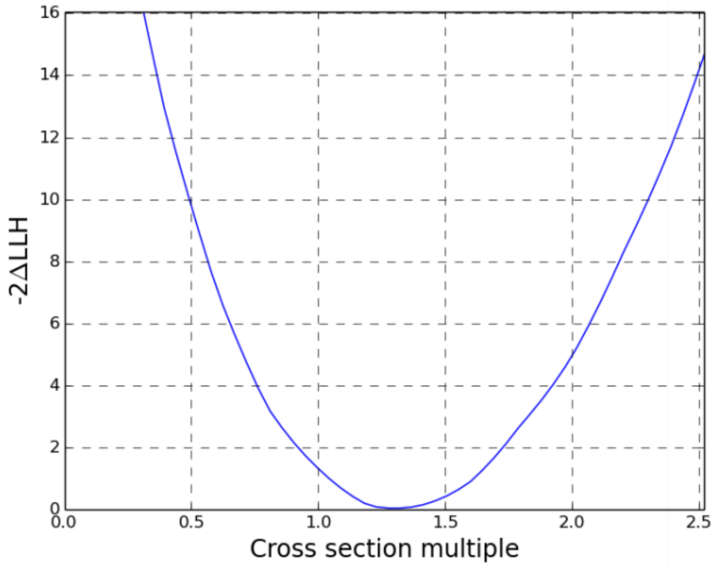
# Neutrino absorption in the Earth / Neutrino Cross section measurement

**Radiography of the Earth's Core and Mantle with Atmospheric Neutrinos**
M.C. Gonzalez-Garcia, Francis Halzen, Michele Maltoni, and Hiroyuki K.M. Tanaka
Phys. Rev. Let. (100) (2008)

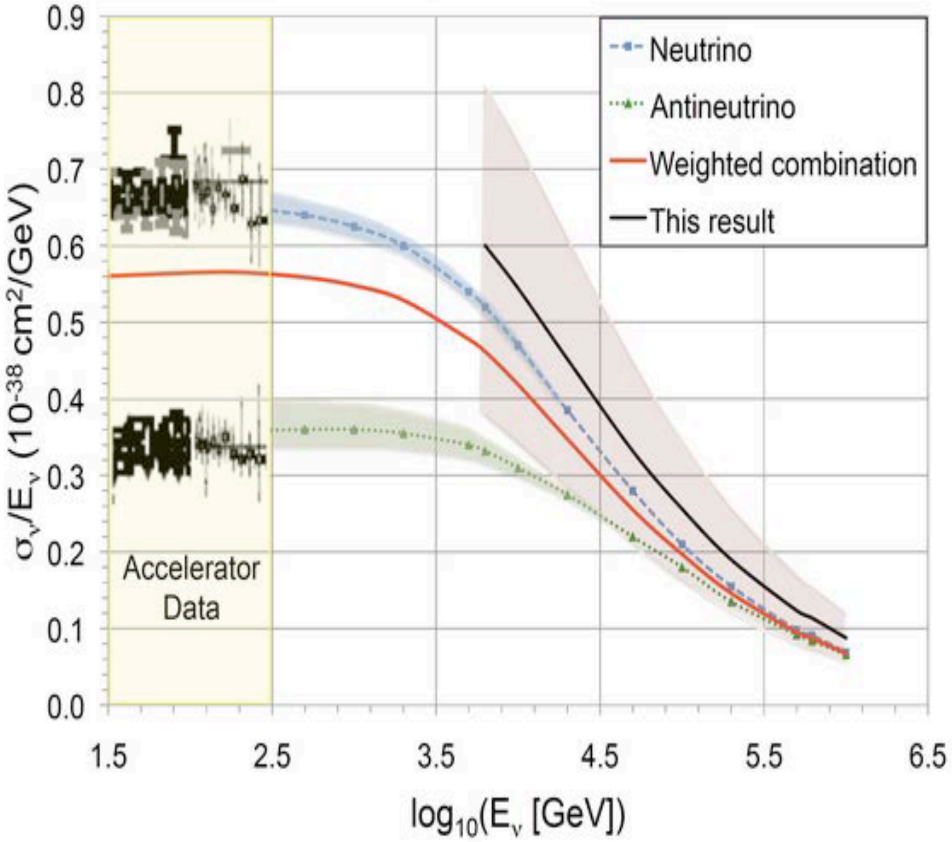
- One year of IceCube data
  - Data acquisition period 2009-2010
- IceCube Detector configuration
  - IC79 (nearly completed detector with 79-strings installed)
- Data sample
  - 10,784 energetic upward-going neutrino-induced muons
- Neutrino energy range
  - $E_\nu$ = 6TeV–1.0 PeV

IceCube Collaboration - *Nature* **Vol 551**, 596–600 (2017)

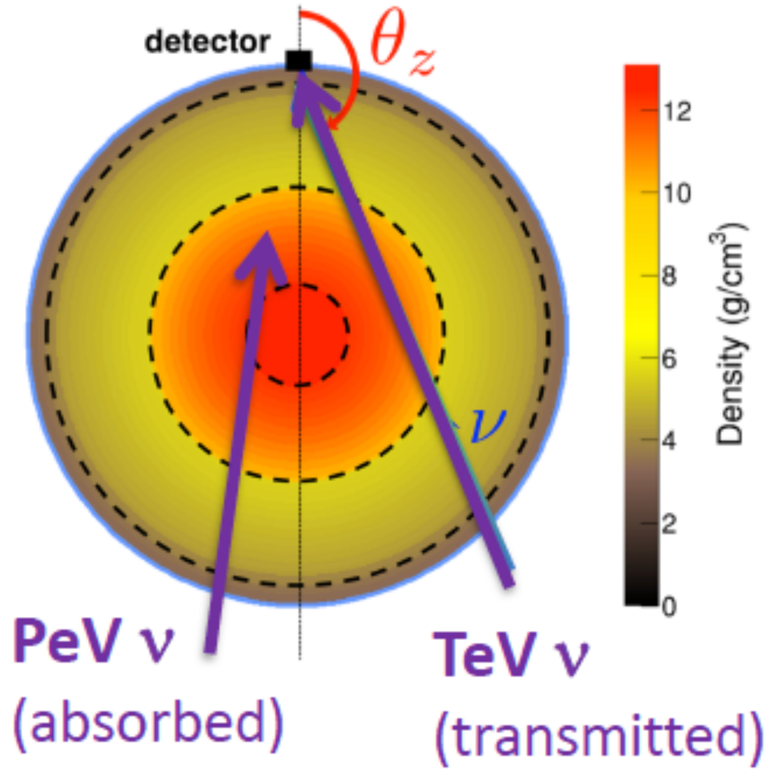




$$\frac{\sigma_{\text{meas.}}}{\sigma_{SM}} = 1.30^{+0.21}_{-0.19}\,(\text{stat.})\,^{+0.39}_{-0.43}\,(\text{syst.})$$



# Neutrino Absorption Tomography

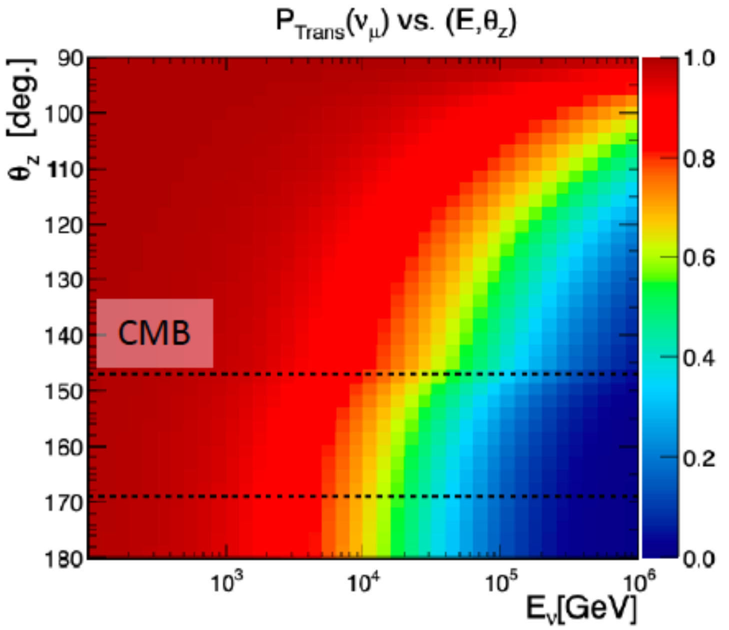


Transmission probability after path length L:

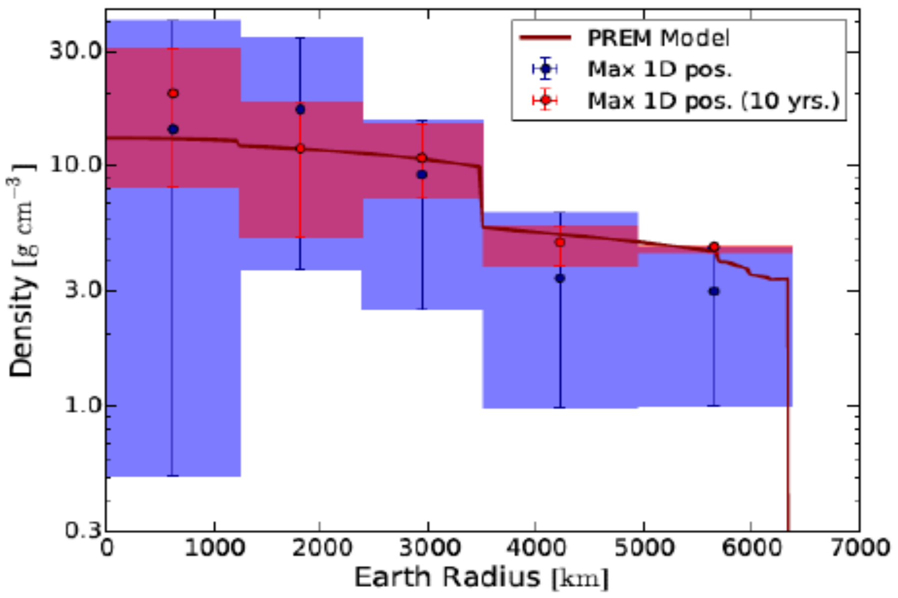
$$P(L) = 1 - \int_0^L \frac{dx}{L} \exp\left(-\frac{x m_N}{\sigma_{\nu N} \rho_m}\right)$$

Neutrino-nucleon cross-section: increases with E

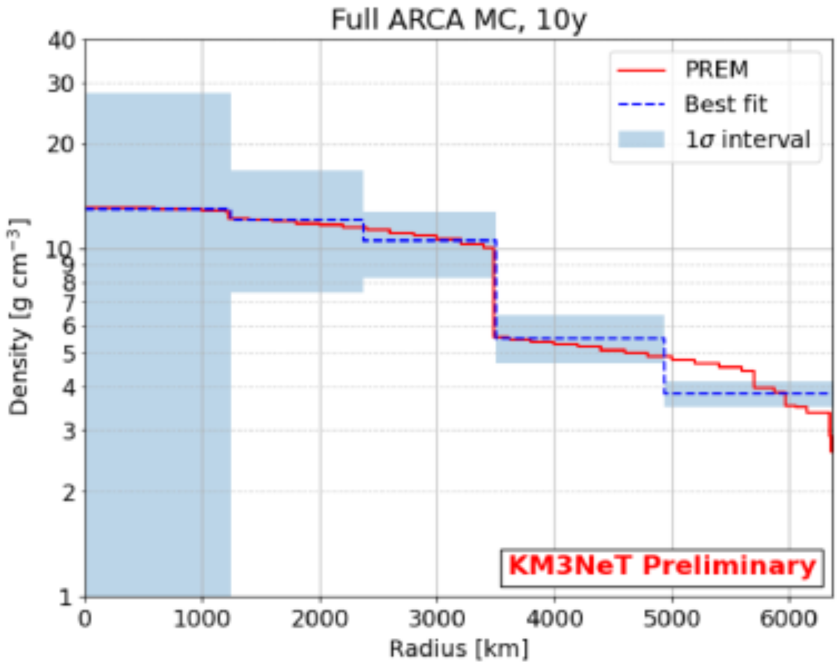
matter density (default: PREM)



*Donini, Palomares-Ruiz, Salvado Nature Phys. 15 (2019) 1, 37-40*



L. Maderer, Ph. D thesis (link)



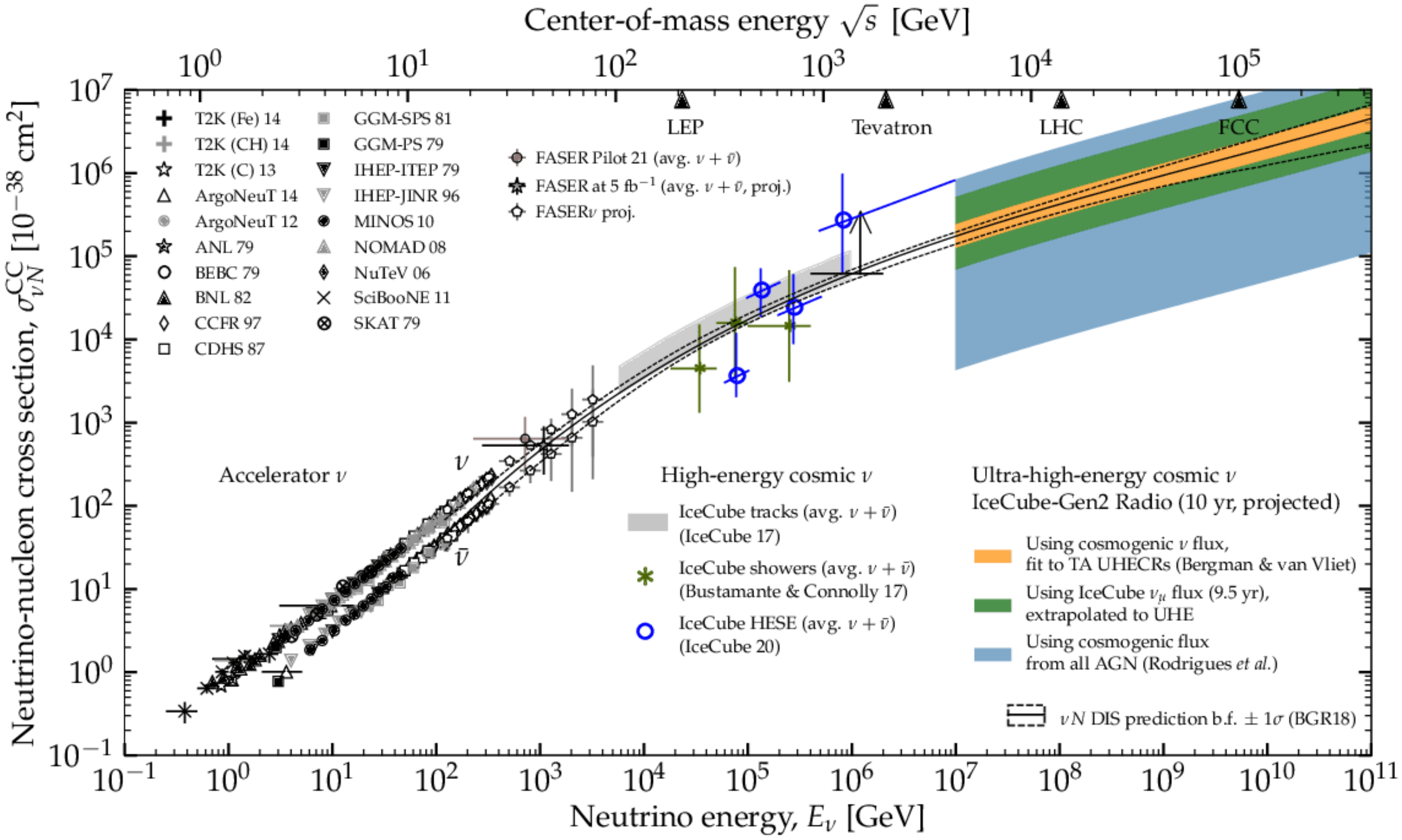
→First measurement of the Earth Mass using the weak force

$$M_\nu = \left(6.0^{+1.6}_{-1.3}\right)\times 10^{24}\ \text{kg}$$

- Compatible projections for IceCube and ARCA
  - Provides a complementary way to measure the matter content and density profile of the Earth
  - Much more statistics needed to reach few % level uncertainty
  - main systematics: neutrino flux, cross sections, detector effects

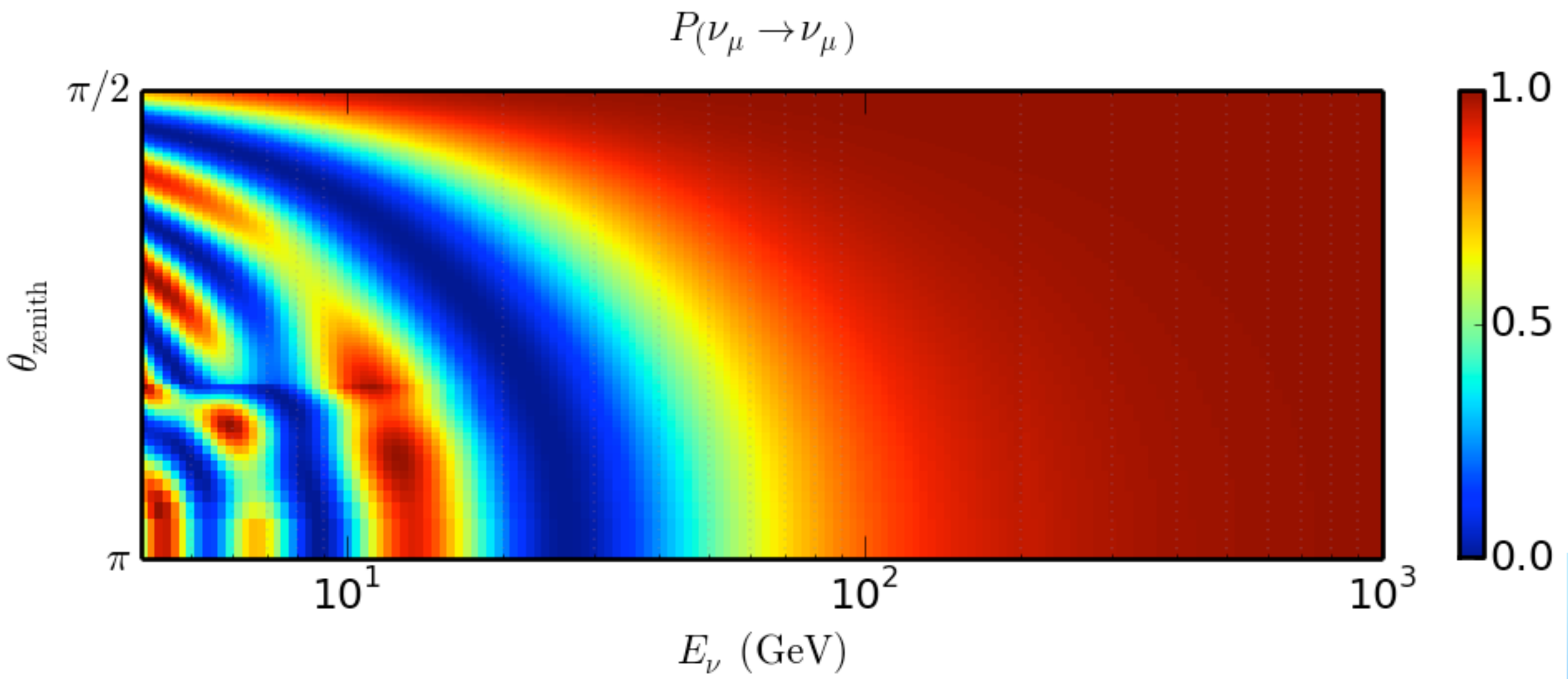
# Neutrino Absorption - Conclusions

- Density structure of the Earth well understood from seismic measurements
- Neutrino absorption measurements have demonstrated that the Earth structure can be measured
    - Reaching a precision that is of interest to Earth Science community will be challenging with current and next generation instruments
- Important to pursue absorption studies:
    - Take the Earth density structure as an input to measure neutrino cross sections beyond the reach of accelerators
    - Search for new phenomena / anomalous events



adopted from Valera, Bustamante, and Glaser JHEP 2022 [arXiv:2204.04237]

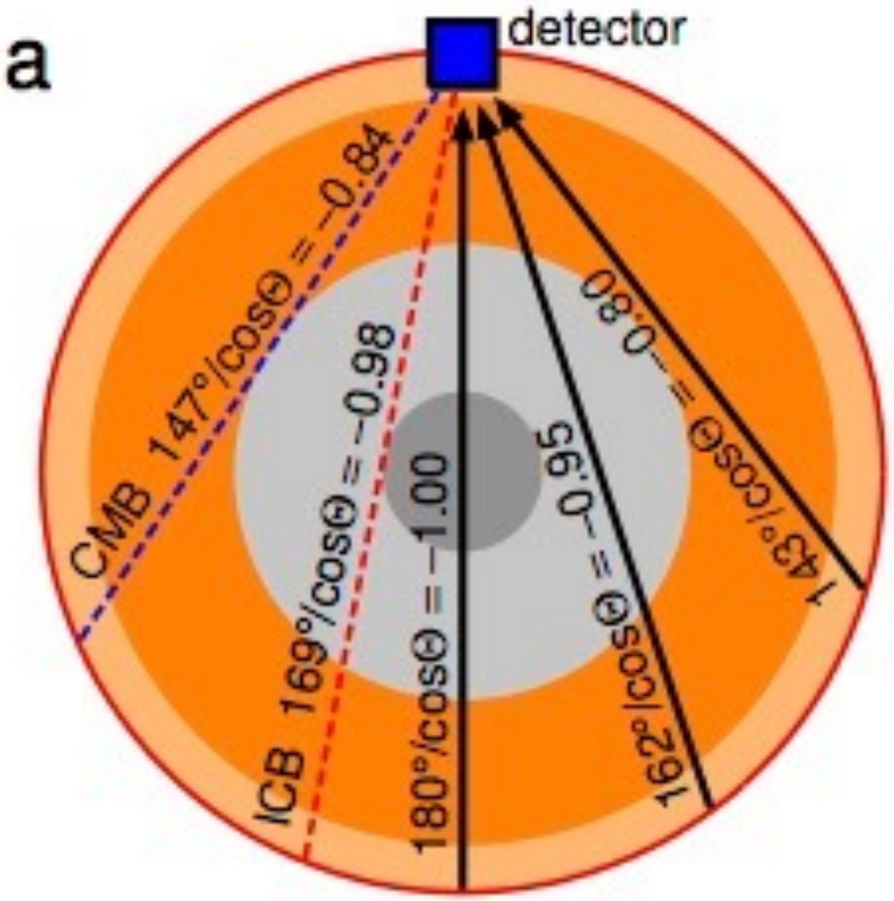
IceCube Gen2 TDR [https://icecube-gen2.wisc.edu/science/publications/tdr/]

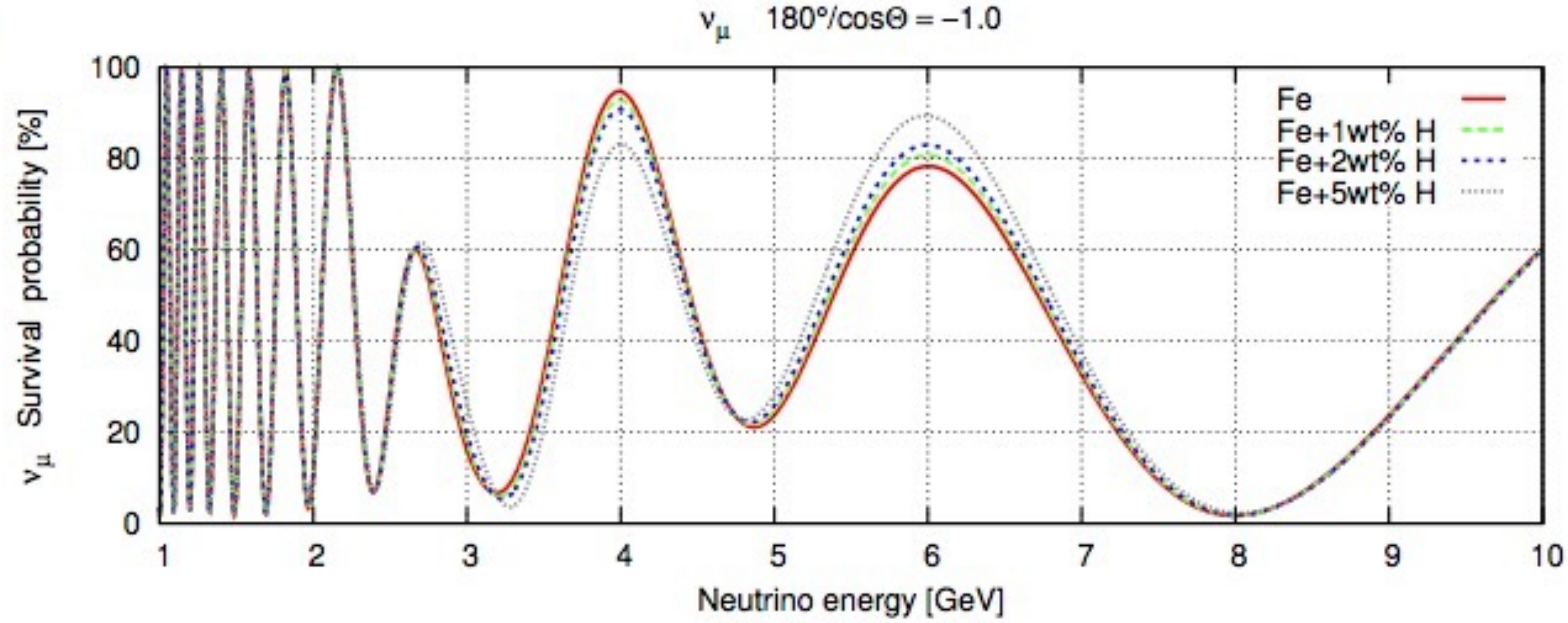


# Neutrino Oscillation Tomography

# Motivation - Methodology

- The Earth **matter density** profile precisely determined from **seismic measurements**
- Matter induced **neutrino oscillation** effects dependent on the **electron density**
- Given a matter density profile the “average” composition (or **Y=Z/A**) along the neutrino path can be determined using neutrino signals (Oscillation tomography)





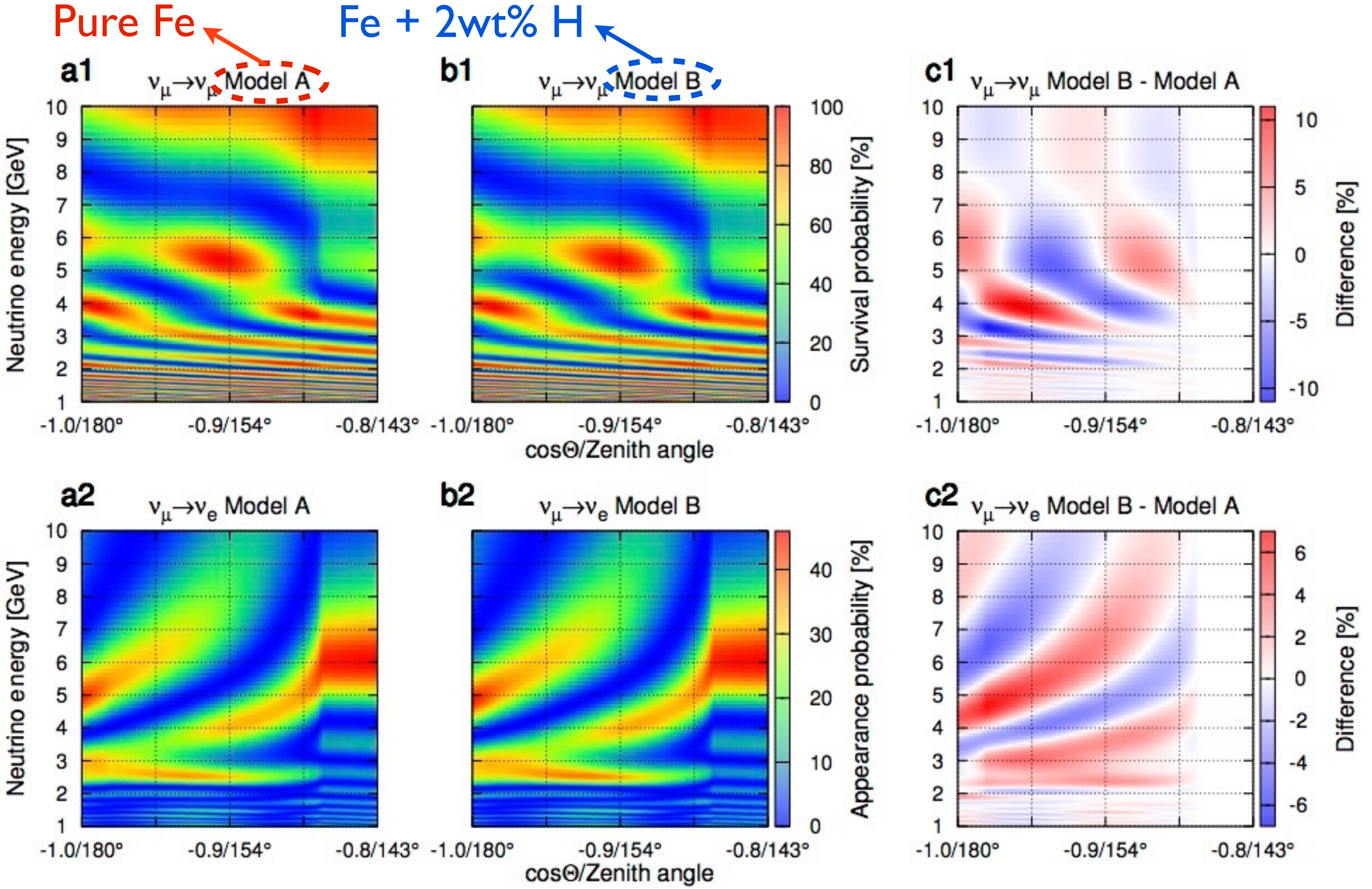
Corresponding zenith angles for boundaries
Inner core $\theta_\nu < 169°$ ($\cos\theta_\nu < -0.98$)
Outer core $\theta_\nu < 147°$ ($\cos\theta_\nu < -0.84$)

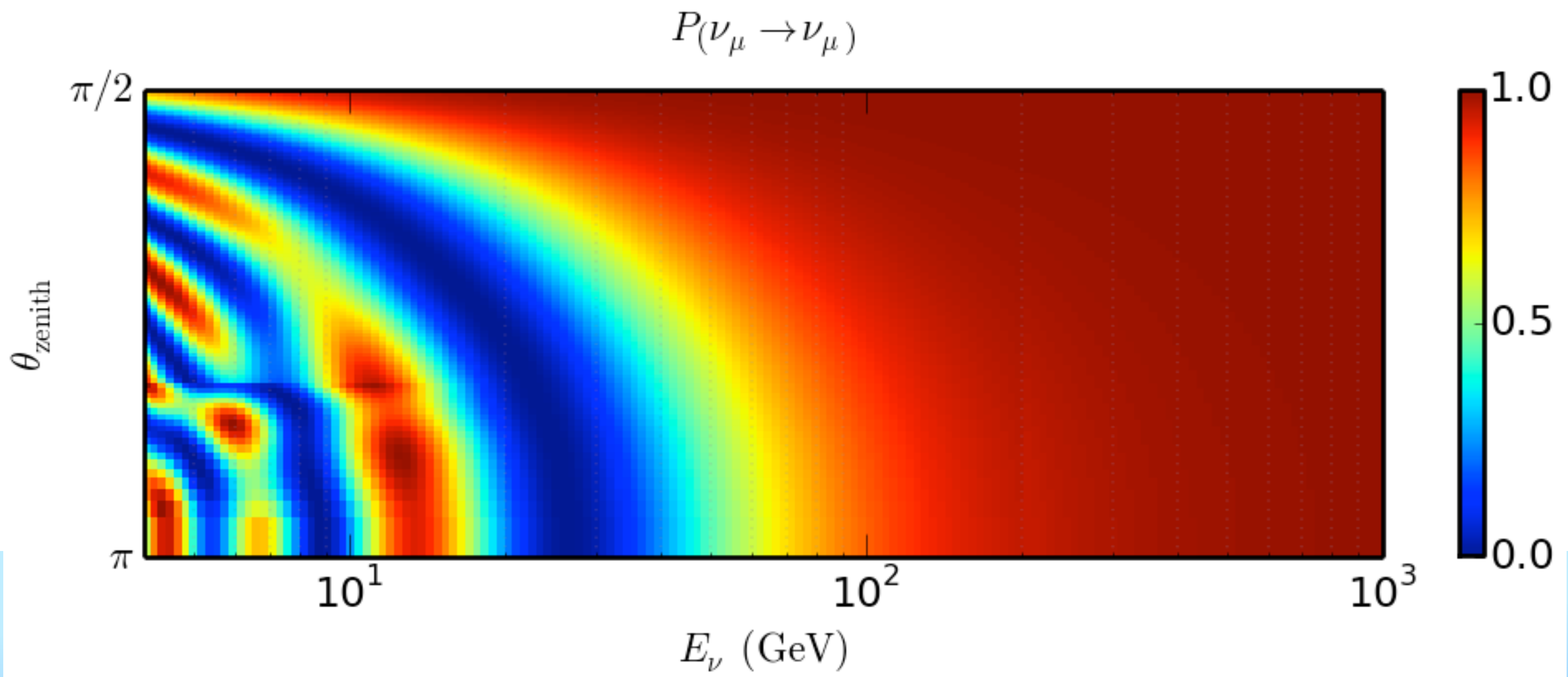
| Element | | Z | A | Z/A |
|---|---|---|---|---|
| Hydrogen | H | 1 | 1.008 | 0.9921 |
| Carbon | C | 6 | 12.011 | 0.4995 |
| Oxygen | O | 8 | 15.999 | 0.5 |
| Magnesium | Mg | 12 | 24.305 | 0.4937 |
| Silicon | Si | 14 | 28.085 | 0.4985 |
| Sulfur | S | 16 | 32.06 | 0.4991 |
| Iron | Fe | 26 | 55.845 | 0.4656 |
| Nickel | Ni | 28 | 58.693 | 0.4771 |

**Z** - Atomic Number **A** - Atomic Mass

Rott & Taketa Scientific Reports (2015)

# Oscillograms





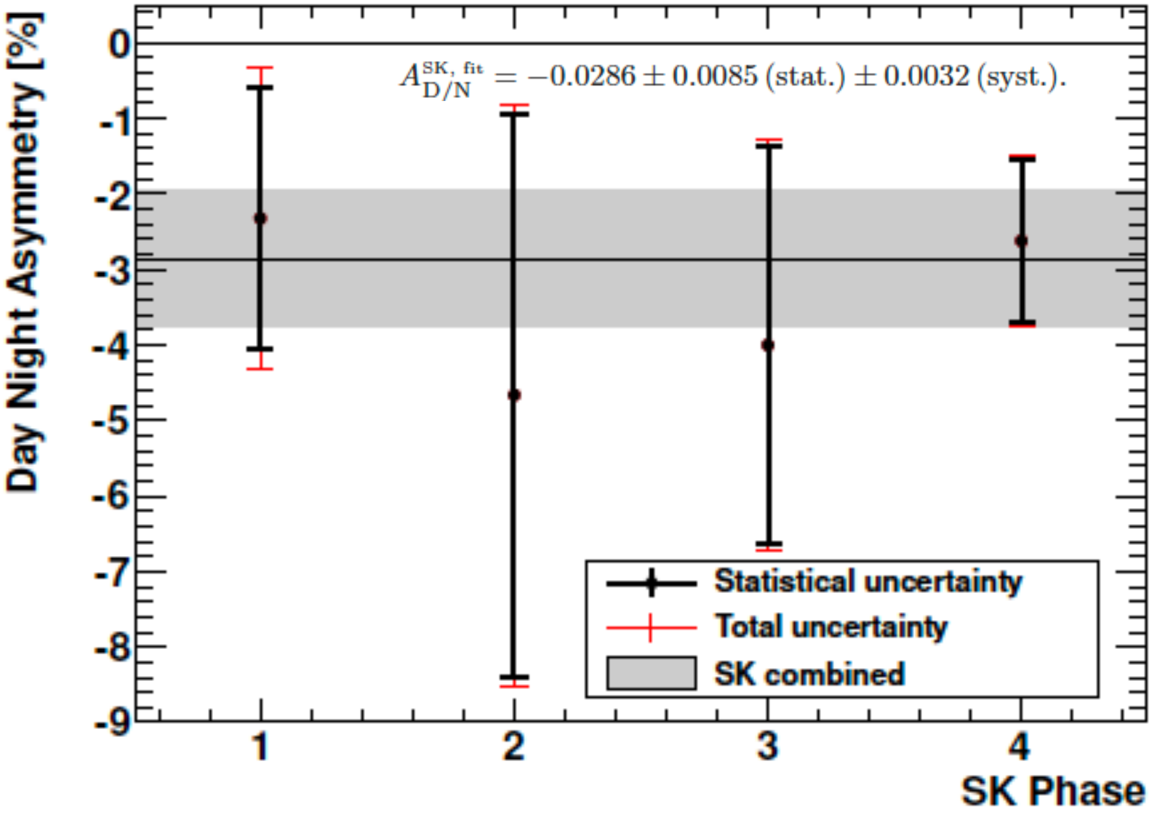
# Neutrino Oscillation Tomography

# Establishing Earth's Matter Effects

- **Objective:** **By rejecting the vacuum hypothesis w.r.t. the PREM hypothesis, one can quantify how well we can see Earth's matter effect in atmospheric neutrino oscillations** irrespective of the uncertainties on oscillation and systematic parameters

- Observing matter effect in the neutrino oscillation data opens an avenue to measure: NMO, octant of $\theta_{23}$, features of PREM profile, and various BSM models – Non-standard interactions, Lorentz invariance violation, Non-unitary neutrino mixing, Long-range interactions, etc

- Super-K (I-IV) excludes vacuum oscillations at **1.6σ** with atmospheric neutrinos **PRD 97, 072001 (2018)**



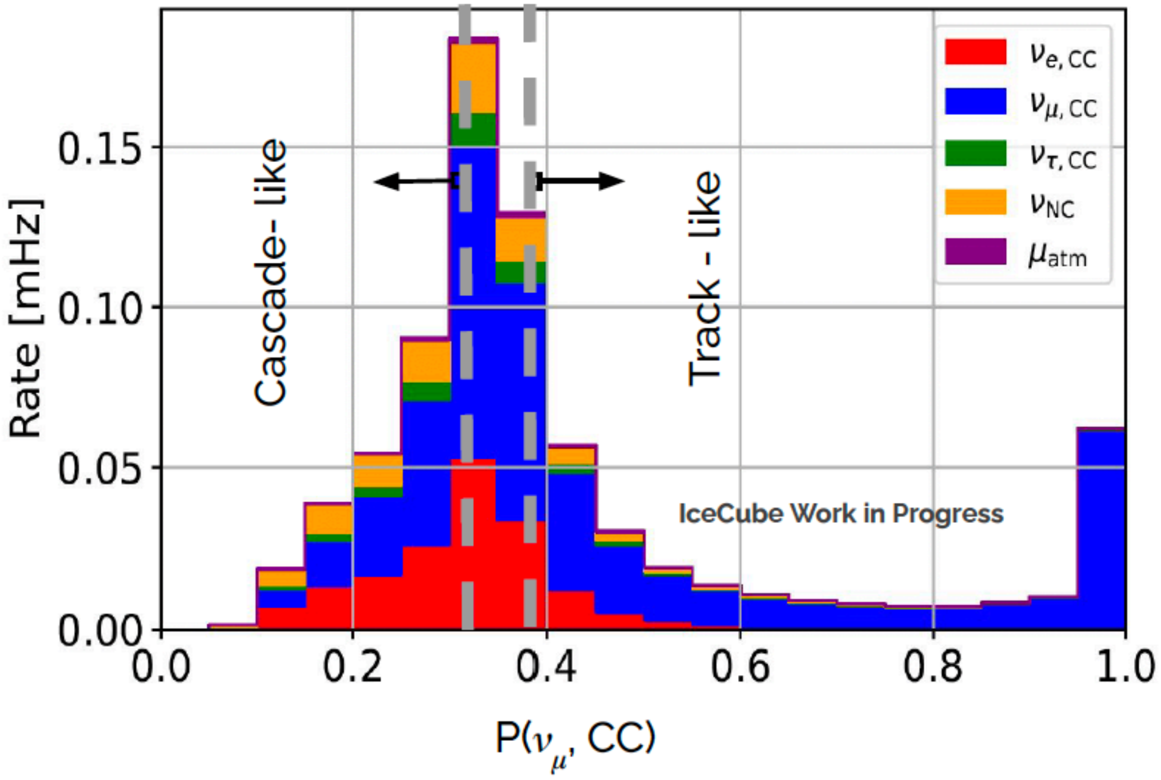
Evidence for evidence for the existence of earth matter effects on solar neutrino oscillation (~**3.2σ**)

Super-K - Phys.Rev.D 109 (2024) 9, 092001

# IceCube Tomography Analysis

Details see presentations:
MMTE2023 talk by Agarwala
Brookhaven forum 2023: Talks by: Upadhyay, Krishnamoorthi and Chattopadhyay

- Objectives
  1. Establishing Earth's Matter Effect (vacuum vs. matter)
  2. Validate Layered Structure Inside Earth (PREM vs. uniform)
  3. Measure the Mass of Earth and the Mass of Core
- Data sample & event selction:
  - 9.3 years of IceCube DeepCore data with FLERCNN selection (see arxiv:2405.02163)



## Binning Scheme & Test Statistic

- **Matter effect signal is significant at lower energies and higher baselines**
- **Reduced the energy threshold down to 3 GeV**

| Observables | Number of Bins | Range | Step |
|---|---|---|---|
| **Energy** | **20** | **[3, 100] GeV** | **log** |
| **cos(zenith)** | **20** | **[-1, 0]** | **linear** |
| **PID** | **3** | **[0, 0.33, 0.39, 1]<br>[Cascade, Mixed, Track]** | **linear** |

- **Following Poissonian LLH**

$$\text{Test Statistics (TS)} = \text{LLH} + \text{Prior pull} = \sum_{\mathrm{i}\in\mathrm{bins}} [-\lambda_\mathrm{i} + \mathrm{x_i}\ln(\lambda_\mathrm{i}) - \ln(\mathrm{x_i}!)] + \frac{1}{2}\sum_{\mathrm{j}\in\mathrm{sys}} \frac{(\mathrm{p_j} - \hat{\mathrm{p}}_\mathrm{j})^2}{\sigma_\mathrm{j}^2}$$

$\mathrm{x_i}$ - Observed value of $i^{th}$ bin
$\lambda_\mathrm{i}$ - Expected value of $i^{th}$ bin
$\mathrm{p_j}$, $\hat{\mathrm{p}}_\mathrm{j}$, and $\sigma_\mathrm{j}^2$ are the nominal, best-fit, and Gaussian prior of $j^{th}$ systematics, respectively

# Validate Layered Structure Inside Earth

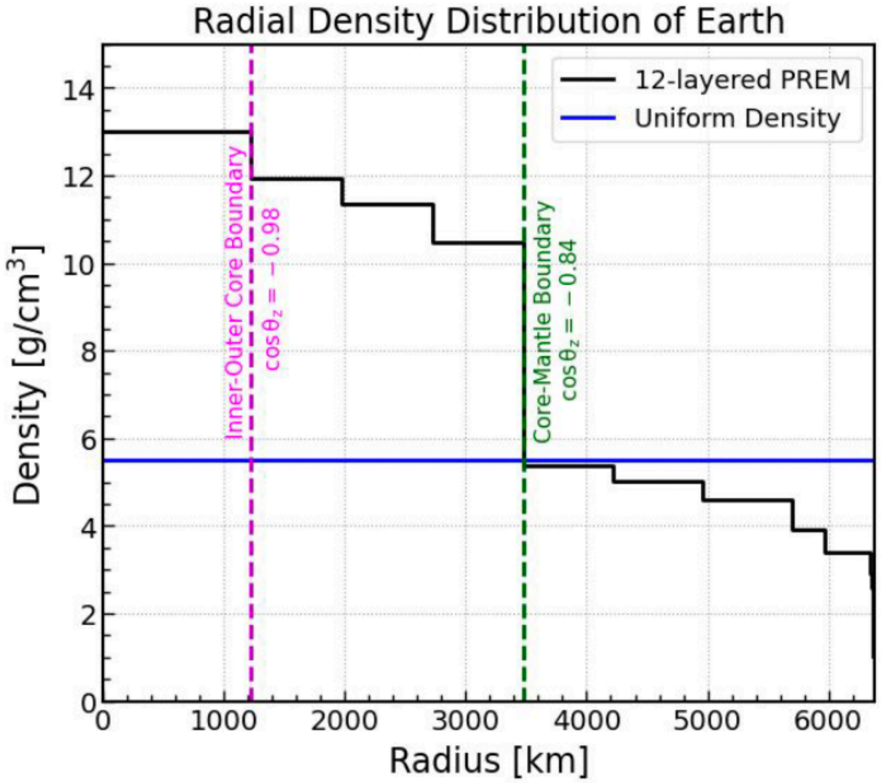
*PREM Profile vs. Uniform Density Profile*

**Can DeepCore rule out the hypothesis of homogeneous matter inside Earth?**

(Motivated by M.C. Gonzalez-Garcia et.al. *Radiography of Earth's Core and Mantle with Atmospheric Neutrinos*, PRL 100 (2008) 061802 )

- In both density profiles, Earth mass and radius are kept constant
- Earth has been considered as neutral ( $N_e = N_p$ ) and isoscalar ( $N_p = N_n$ )
    - ○ Therefore electron number density ratio : $Y_e = N_e/(N_p+N_n) = 0.5$ (only for Uniform density profile)

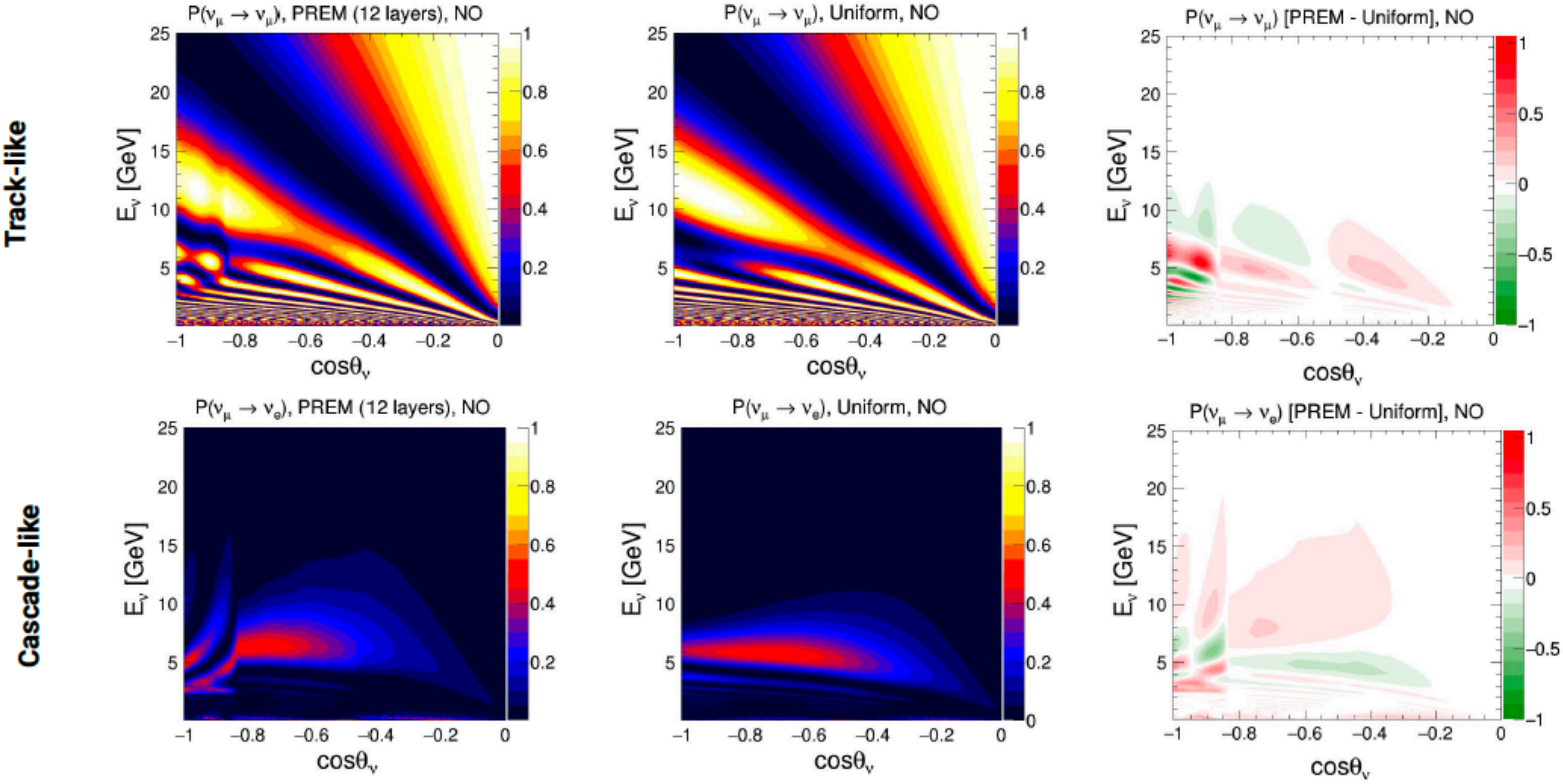
| Earth Density Profile | Layer Boundaries | Layer Density [g/cm3] | Electron Number Density $Y_e$ |
|---|---|---|---|
| **PREM** | **12 Layers** | **12 Densities** | **$Y_{eI}$ (0.4656) / $Y_{eO}$ (0.4656) / $Y_{eM}$ (0.4656)** |
| **Uniform density** | **1 Layer** | **5.53** | **$Y_e$ (0.5)** |
| **Vacuum** | **—** | **-** | **0** |



# Validate Layered Structure Inside Earth

details see Krishnamoorthi  BF2023

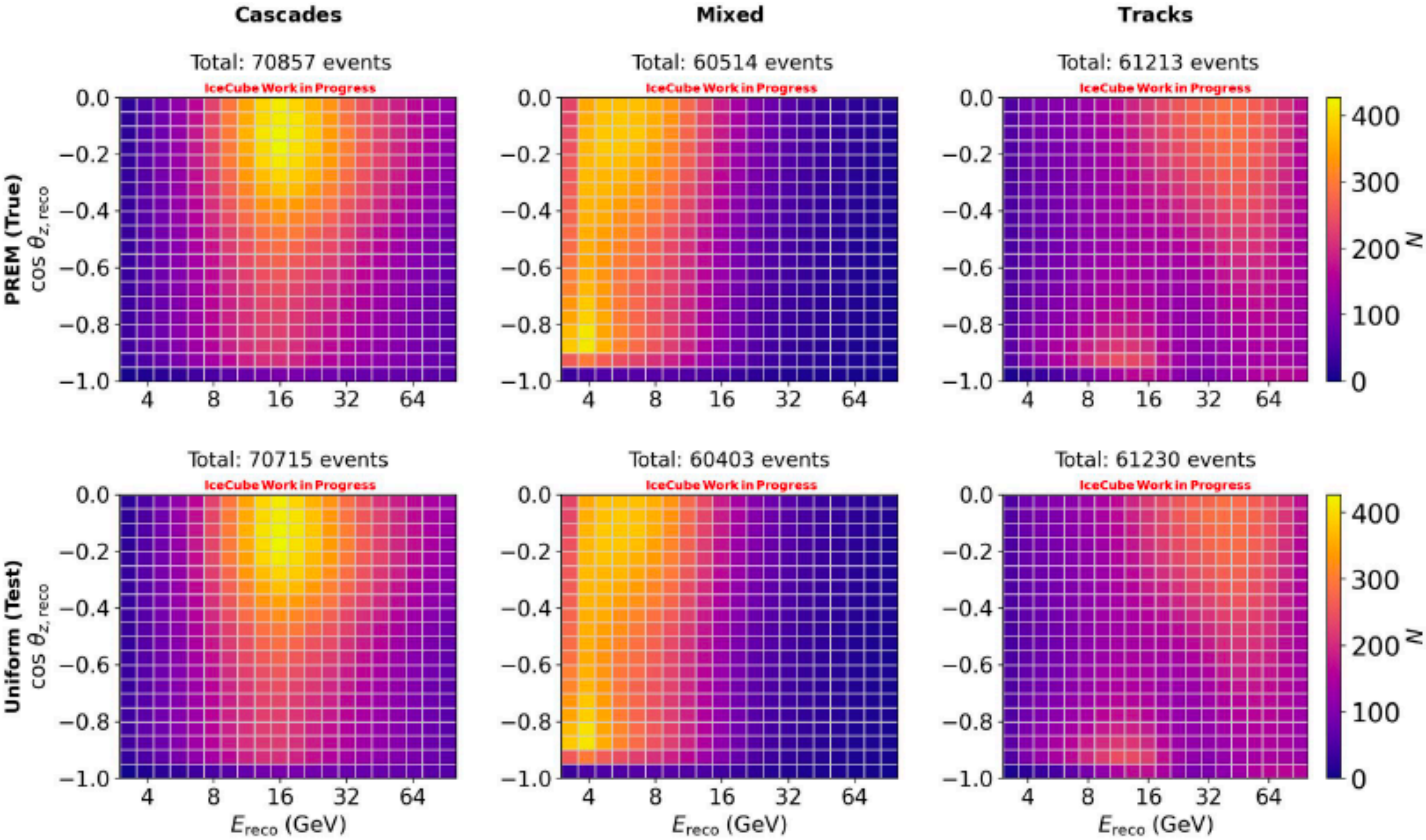
*Probabilities & Their Differences [PREM vs. Uniform], NO*



# Validate Layered Structure Inside Earth

details see Krishnamoorthi BF2023

*Expected Event Distributions [PREM vs. Uniform], NO*

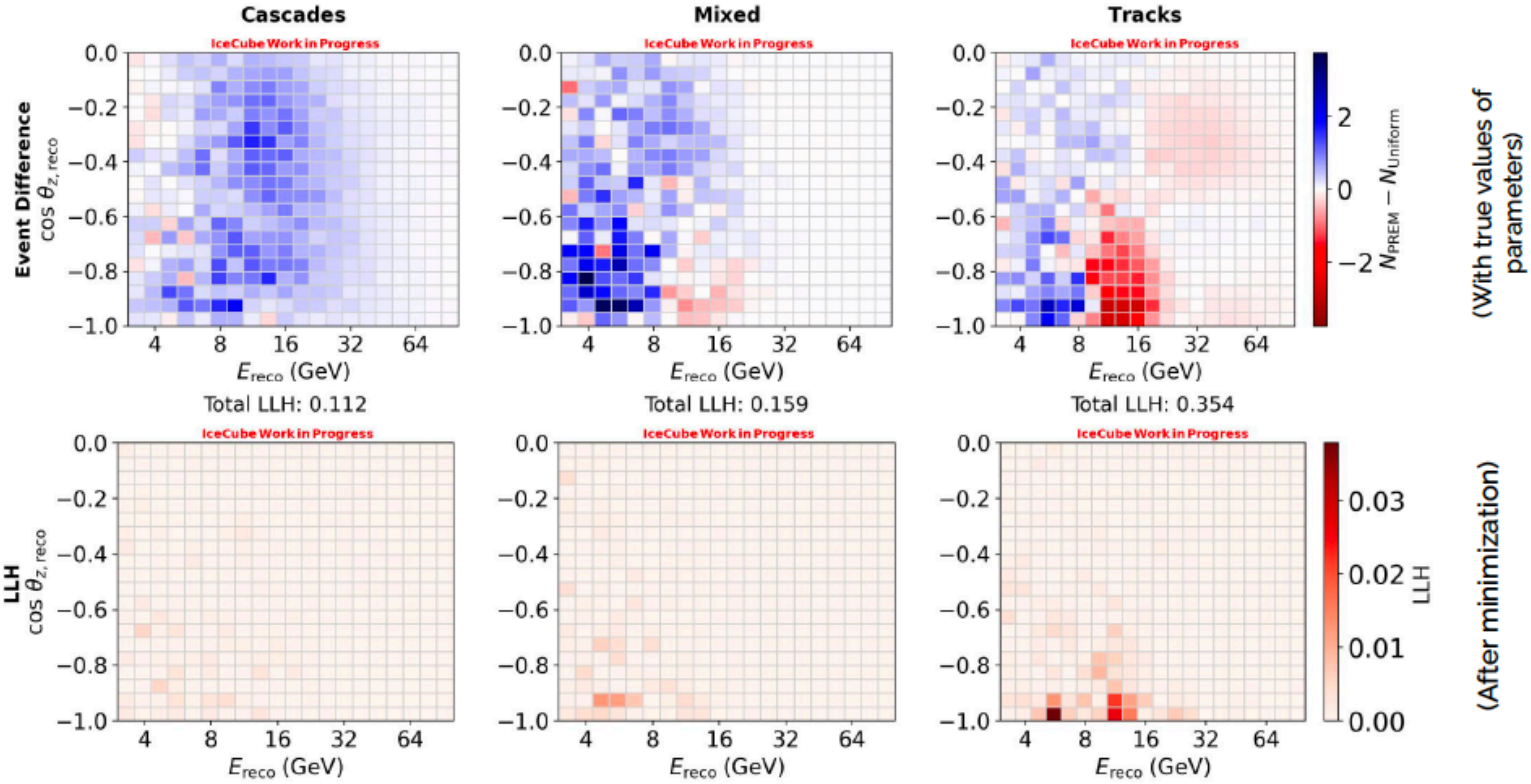


**PREM vs. Uniform:** for true values of all oscillation and systematic parameters

# Validate Layered Structure Inside Earth

details see Krishnamoorthi BF2023

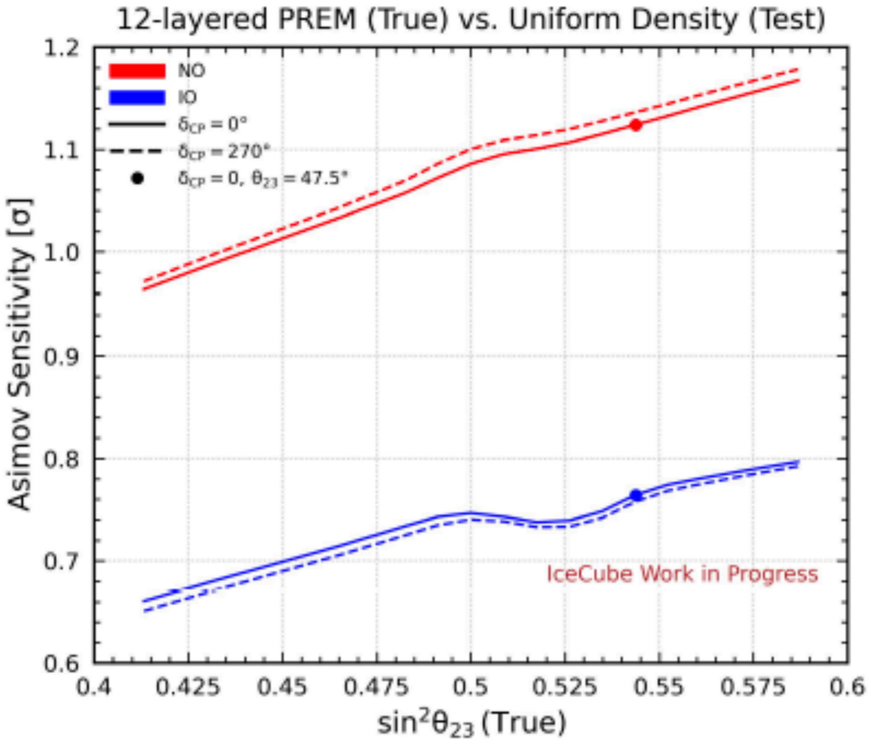
*Distribution of Simulated Event Differences & LLH, NO*



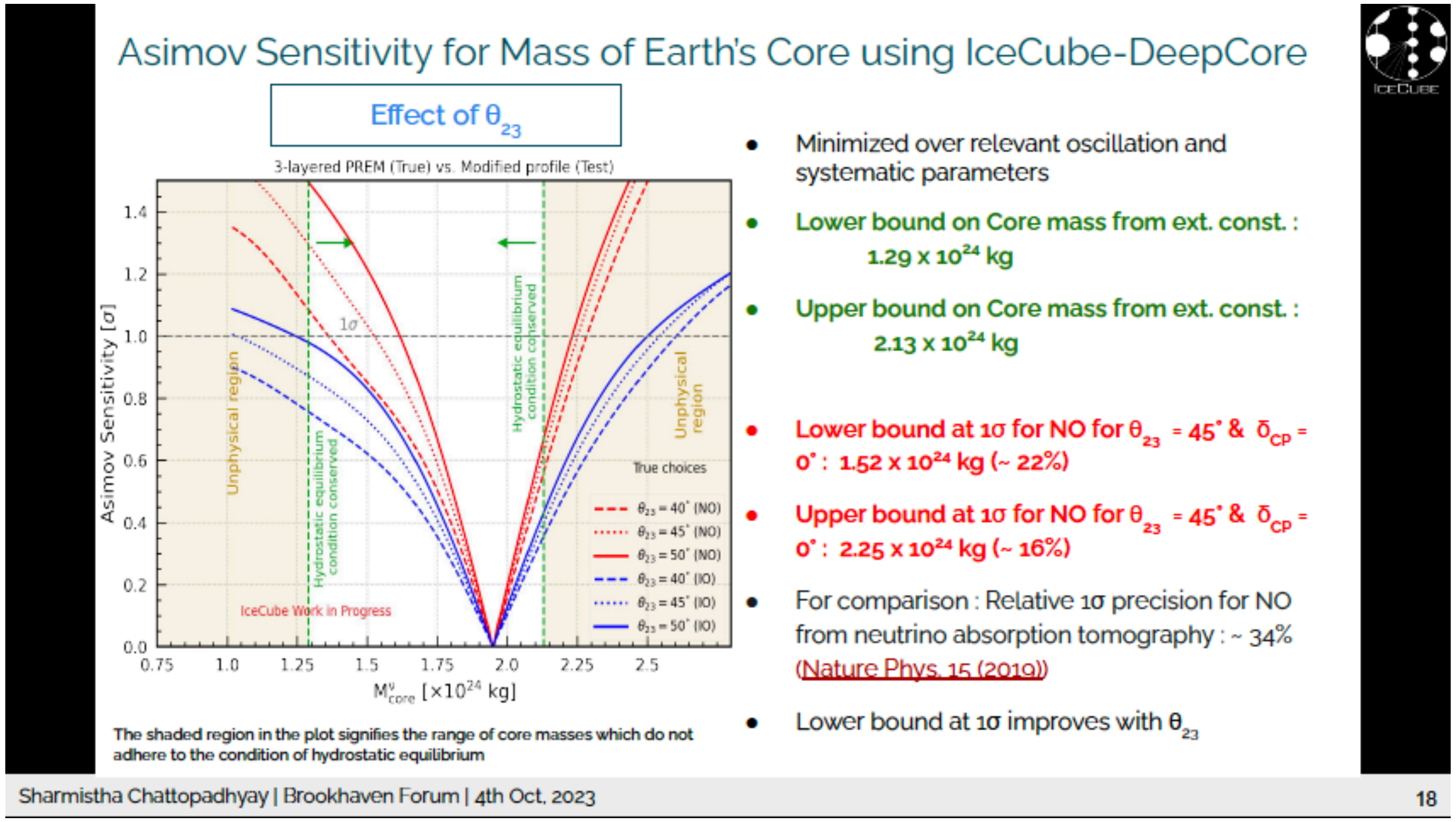
- **Most of the LLH contribution comes from lower energy and higher baselines (core-passing neutrinos)**

# Validate Layered Structure Inside Earth & Earth mass measurement

details see Krishnamoorthi  BF2023



- **True hypo.**: 12-layered PREM
- **Test hypo.**: Uniform density
- Minimized over relevant oscillation and systematic parameters
- Sensitivity depends on neutrino mass ordering
- Sensitivity for NO is higher than IO due to the lower cross section and flux rate of antineutrino
- Sensitivity is increasing with $\theta_{23}$
- **For NO: $\theta_{23}$ = 47.5° & $\delta_{CP}$ = 0°**
    - **Sensitivity = 1.12 σ**
- **For IO: $\theta_{23}$ = 47.5° & $\delta_{CP}$ = 0°**
    - **Sensitivity = 0.76 σ**



Asimov Sensitivity for Mass of Earth's Core using IceCube-DeepCore

Effect of $\theta_{23}$

The shaded region in the plot signifies the range of core masses which do not adhere to the condition of hydrostatic equilibrium

- Minimized over relevant oscillation and systematic parameters
- Lower bound on Core mass from ext. const. : $1.29 \times 10^{24}$ kg
- Upper bound on Core mass from ext. const. : $2.13 \times 10^{24}$ kg
- Lower bound at 1σ for NO for $\theta_{23}$ = 45° & $\delta_{CP}$ = 0° : $1.52 \times 10^{24}$ kg (~ 22%)
- Upper bound at 1σ for NO for $\theta_{23}$ = 45° & $\delta_{CP}$ = 0° : $2.25 \times 10^{24}$ kg (~ 16%)
- For comparison : Relative 1σ precision for NO from neutrino absorption tomography : ~ 34% (Nature Phys. 15 (2019))
- Lower bound at 1σ improves with $\theta_{23}$

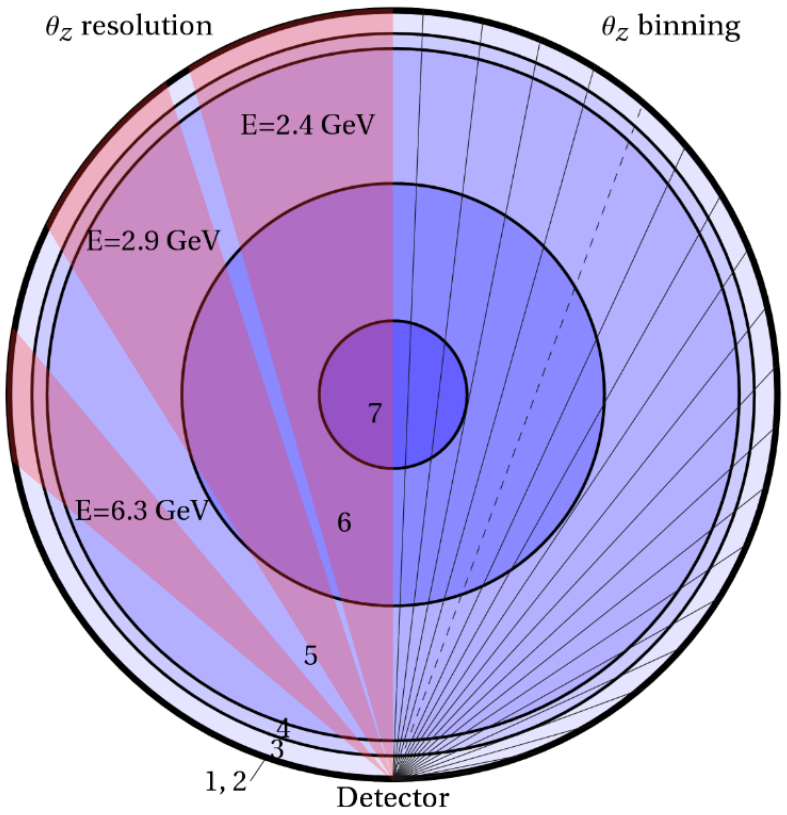
Sharmistha Chattopadhyay | Brookhaven Forum | 4th Oct. 2023    18

- Expect to distinguish layered structure of the Earth with Deep Core over vacuum and uniform density
- Sensitivity on the Earth core mass measurement comparable with those obtained from also absorption tomography
- With the IceCube Upgrade deployment during polar season 2025/2026, significant improvements to this sensitivity can be expected

see posters #310 Kaustav Dutta, #551 Kayla Leonard DeHolton, and IceCube talks

# Prospects for lower mantle measurements

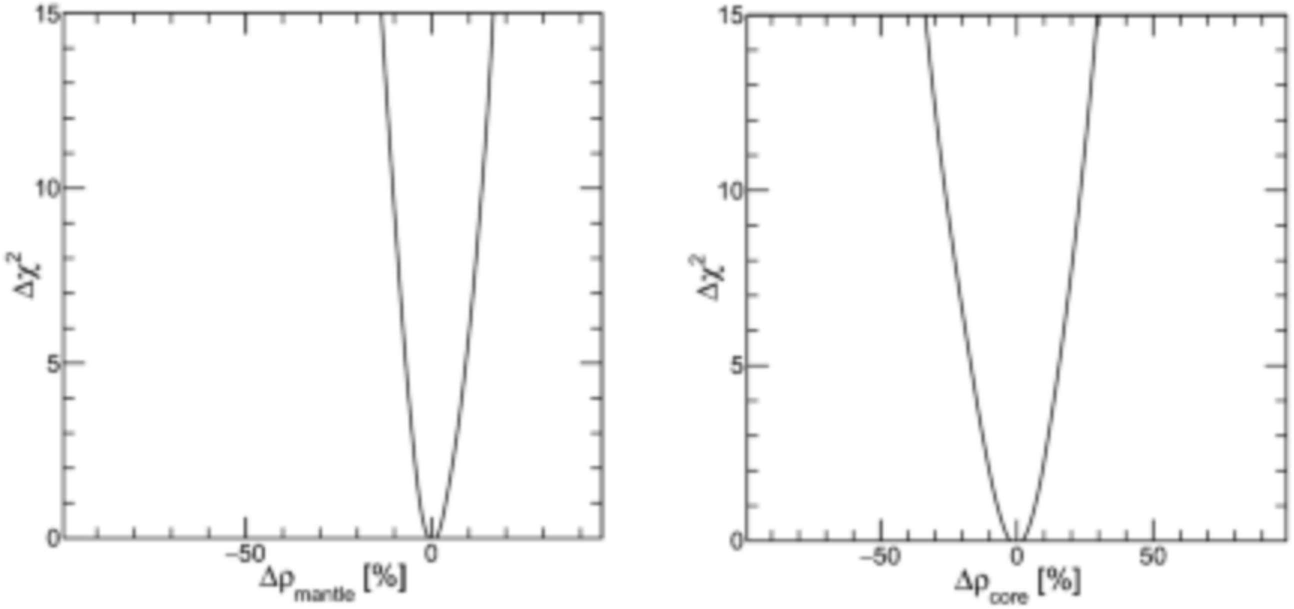
*W.Winter Nucl.Phys. B908 (2016) 250-267*



Excellent sensitivities to the lower mantle density and give a robust lower bound on the outer core density (ideal for ORCA/ PINGU)

Capozzi, F., Petcov, S.T. *Eur. Phys. J. C* **82**, 461 (2022)

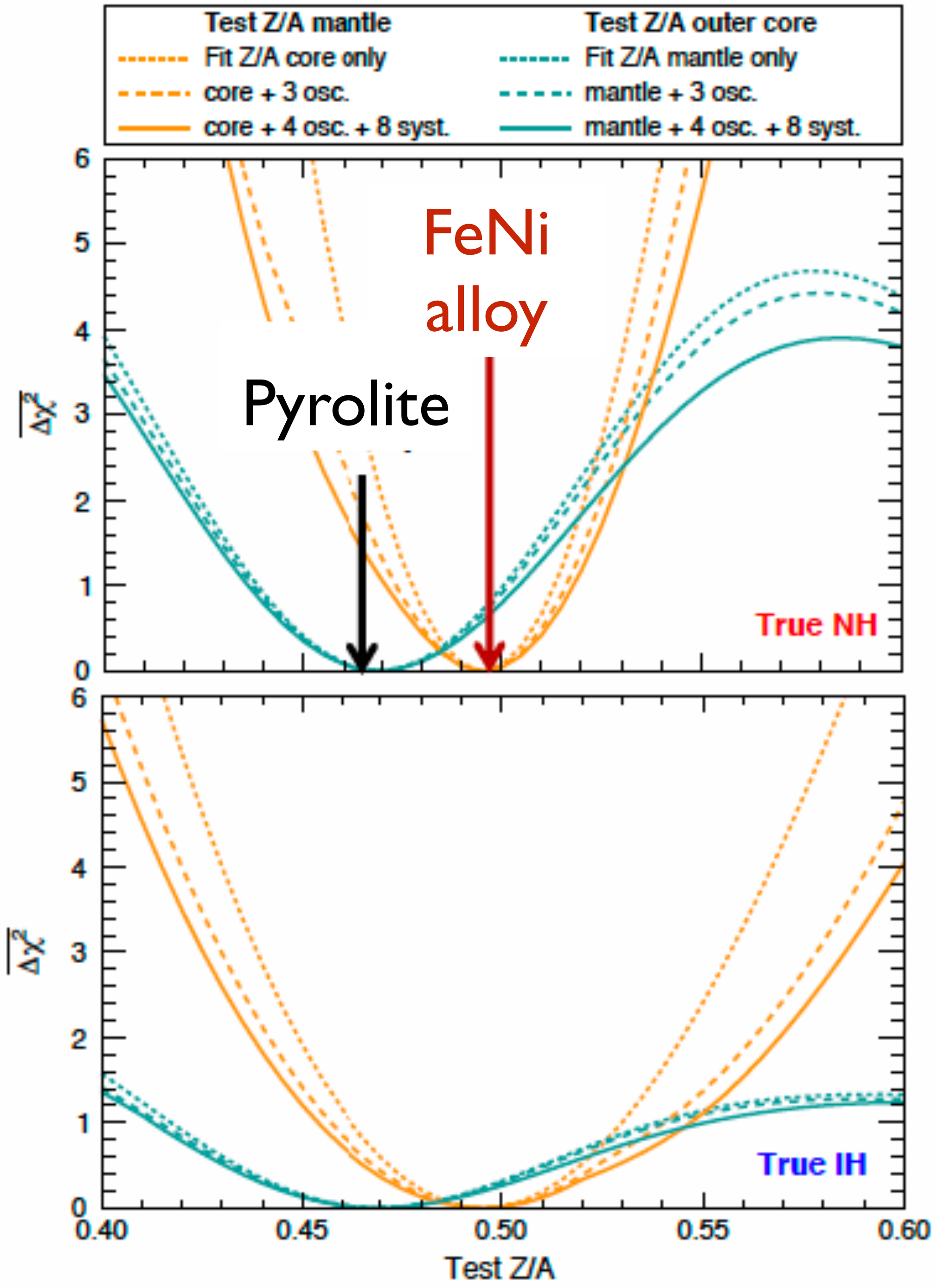
NO spectrum and 10 years of data
“optimistic” systematic uncertainties ORCA LOI -
J. Phys. G **43**, 084001 (2016). arXiv:1601.07459



ORCA can determine, e.g., the OC (mantle) density at 3σC.L. after 10 years of operation with an uncertainty of (– 18%)/+ 15% (of (– 6%)/+ 8%) assuming $\sin^2\theta_{23}$ =0.58 (most optimistic case)

# ORCA

*see also Véronique Van Elewyck MMTE2023*



Preliminary studies (all based on simulations w/full det.)

- Constraining the core & mantle composition

$$\boxed{N_e} = \frac{N_A}{m_n} \times \frac{Z}{A} \times \rho_{matter}$$

Atmospheric neutrino oscillations

assume PREM

Constrain $\frac{Z}{A} = \sum_i w_i \frac{Z_i}{A_i}$

- 1σ sensitivity on Z/A after 10 years:

5% in mantle

6% in outer core

assuming normal hierarchy

(systematics included, MC response & PID)

*S. Bourret [KM3NeT Coll.], EPJ Web Conf. 207 (2019) 04008*

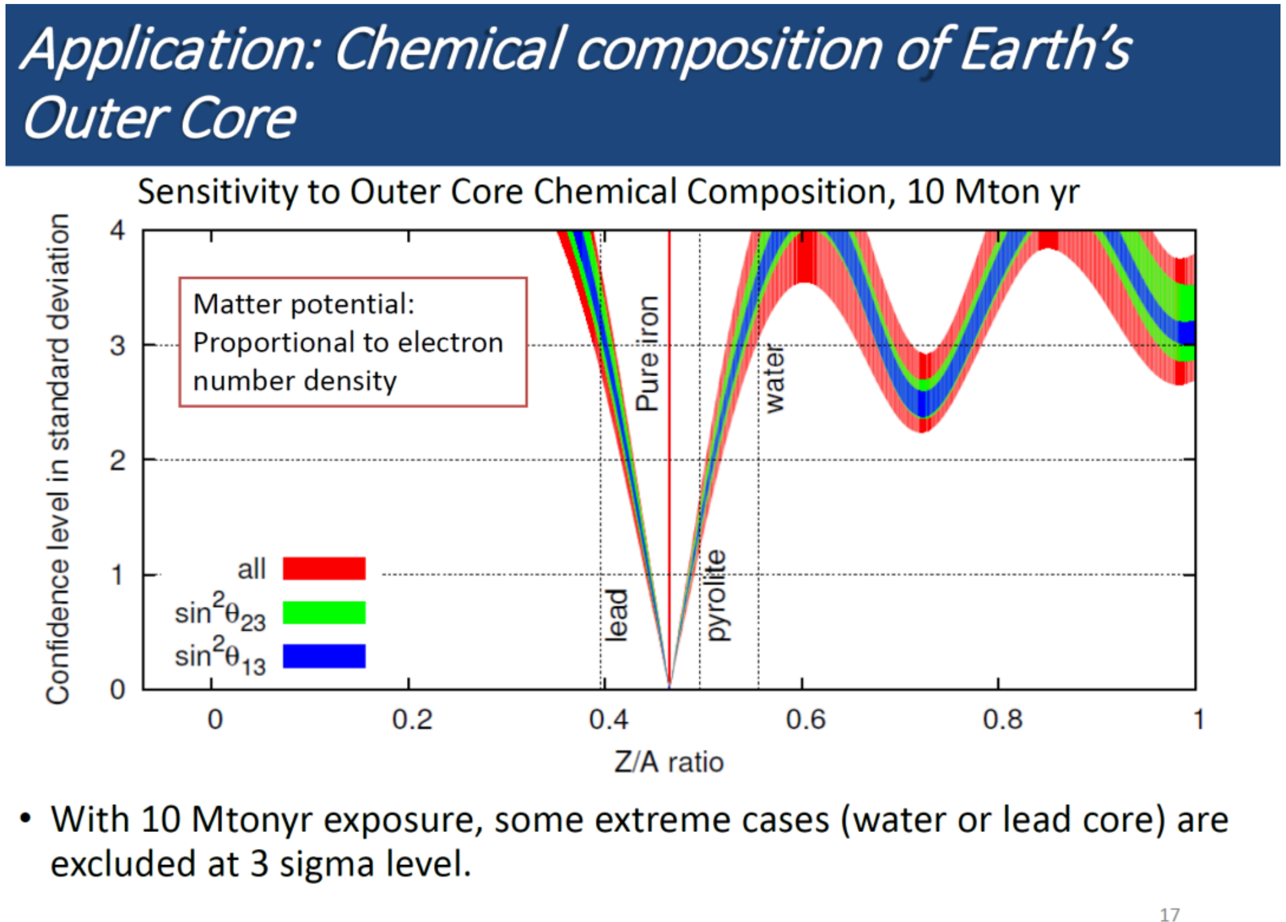
ORCA-low energy (1-100 GeV) 7 Mton-detector oscillation tomography: matter density profile & composition: core, LLSVPs,…

# Future Experiments

## Outer core composition - what are the light elements in the outer core ?

### Hyper-K

*Hyper-Kamiokande Design Report*
*arXiv:1805.04163v2*



*Application: Chemical composition of Earth's Outer Core*

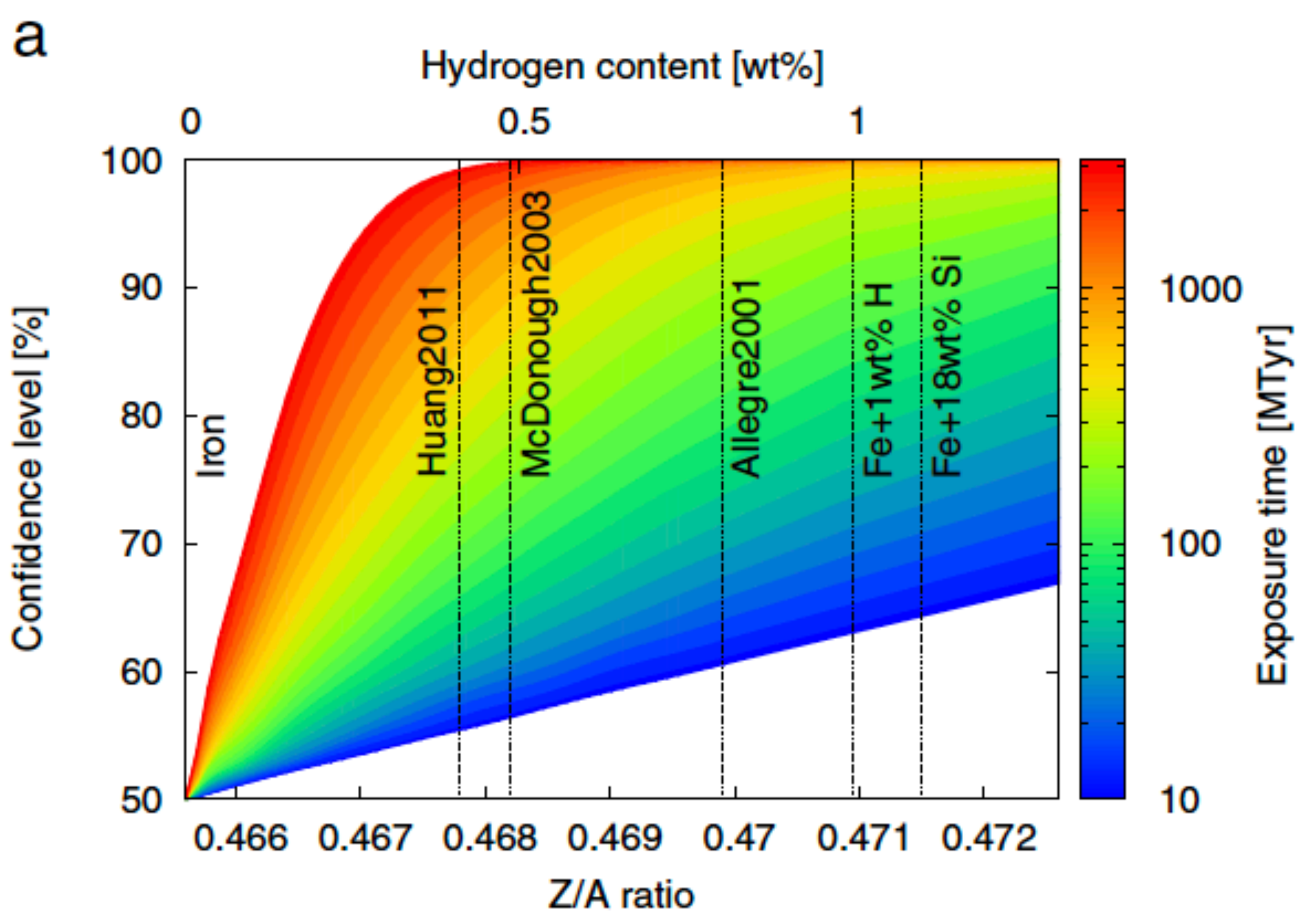
Sensitivity to Outer Core Chemical Composition, 10 Mton yr

- With 10 Mtonyr exposure, some extreme cases (water or lead core) are excluded at 3 sigma level.

17

### Generic Water Cherenkov

C. Rott, A. Taketa, D. Bose, Scientific Reports 2015



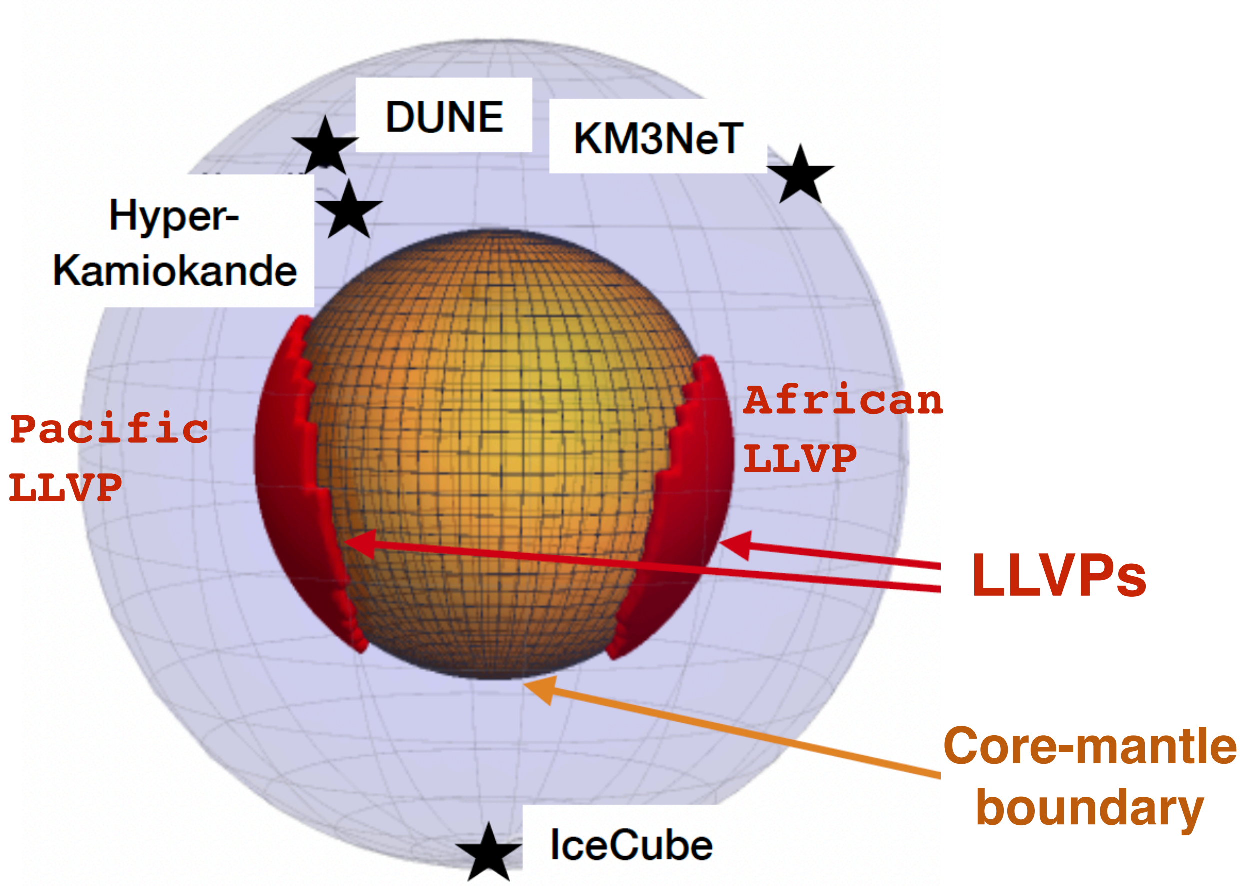
Within the next few years combined measurements will start to put meaningful constraints on the Hydrogen content in the outer Earth core

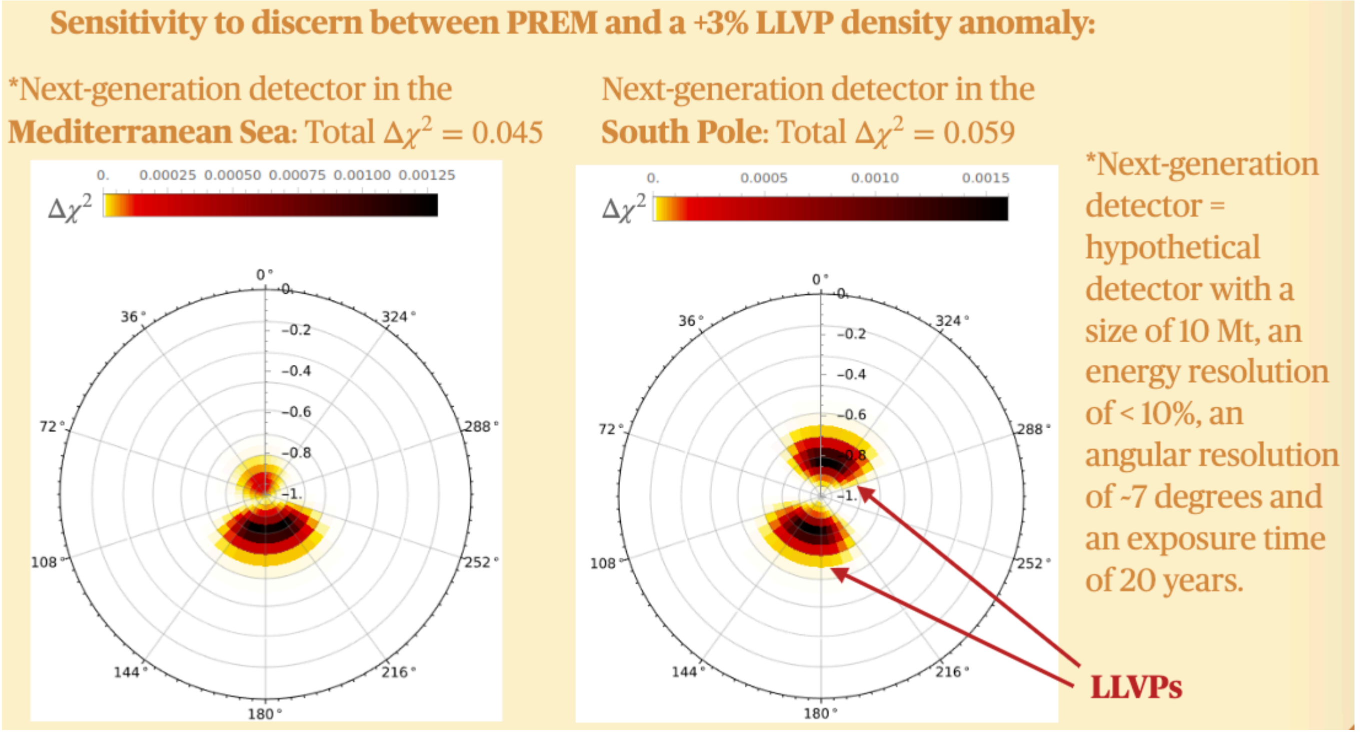
With a combined exposure of ~100MTyrs specific core composition models could be started to be ruled out !

**Core compositions models see:**
Allègre, C., Manhes, G. & Lewin, E. Earth. Planet. Sci. Lett 185, 49–69 (2001).
McDonough, W. F. Treatise on Geochemistry vol. 2, 547–566 (Elsevier, 2003).
Huang, H. et al. Nature 479, 513–6 (2011).

# Prospects for lower mantle measurements

Neutrino tomography of the Earth’s lower mantle: first study with a full 3D model (*see poster* #512 *Joao Coelho*)





**Sensitivity to discern between PREM and a +3% LLVP density anomaly:**

*Next-generation detector in the **Mediterranean Sea**: Total $\Delta\chi^2 = 0.045$

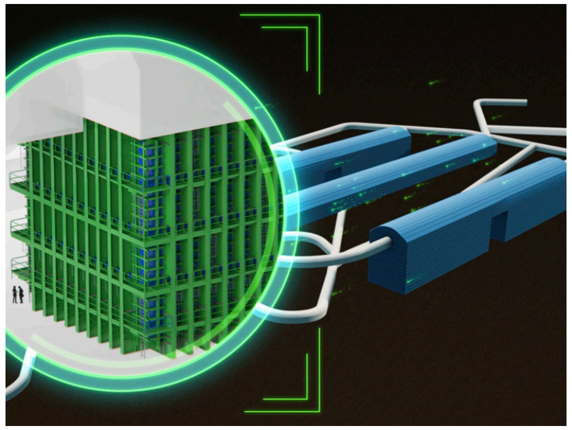
Next-generation detector in the **South Pole**: Total $\Delta\chi^2 = 0.059$

*Next-generation detector = hypothetical detector with a size of 10 Mt, an energy resolution of < 10%, an angular resolution of ~7 degrees and an exposure time of 20 years.

Sensitivity to discern between PREM and a +3% LLVP density anomaly
(for 200Mtyrs, ΔE/E~10%, angular res ~7°)

- Proof of concept for the detection of large inhomogeneities in the deep Earth by neutrino detectors
- Ongoing study exploring the requirements for next-generation neutrino detectors to achieve desired sensitivity

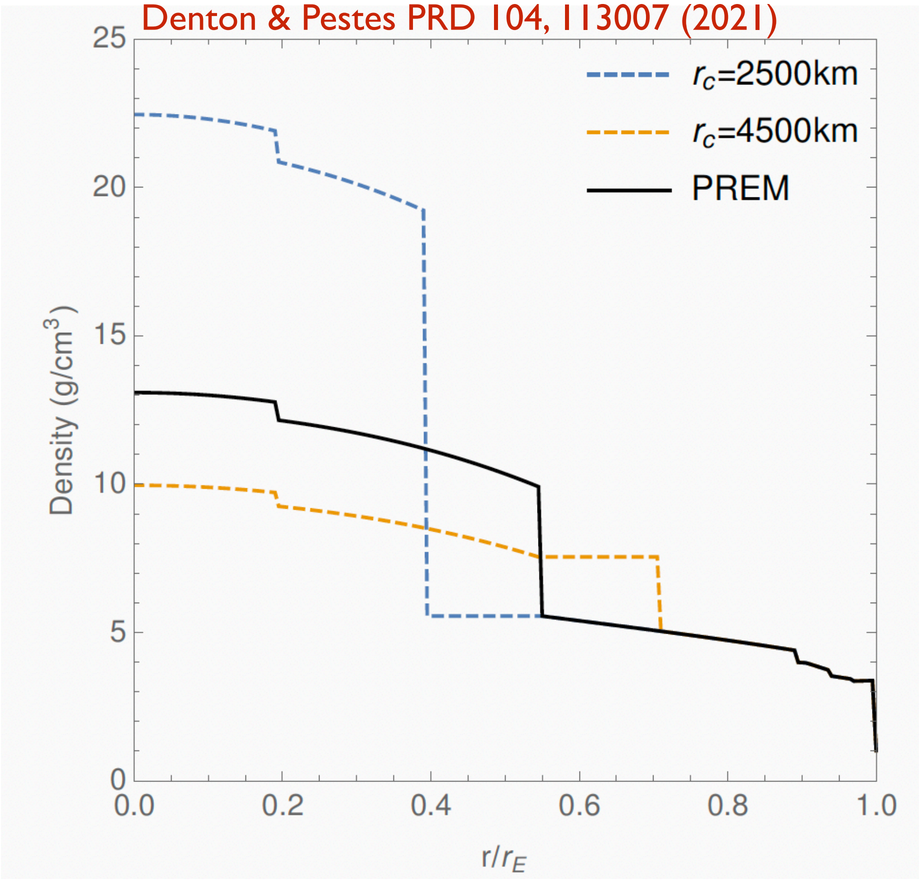
# Future Experiments



## DUNE

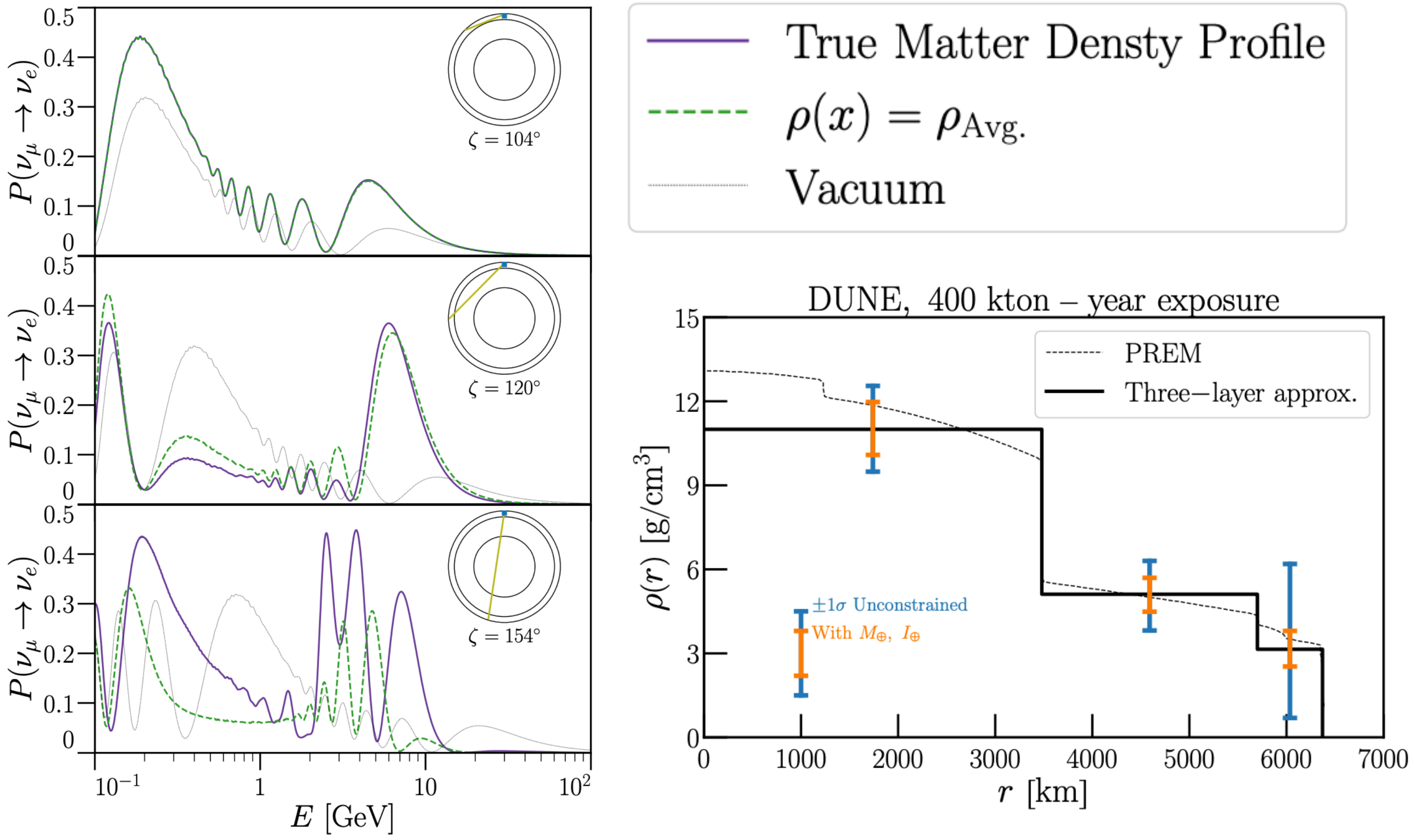
https://lbnf-dune.fnal.gov/

Denton & Pestes PRD 104, 113007 (2021)



- 5% measurement of Earth's matter effect
- Core-mantle boundary sensitivity

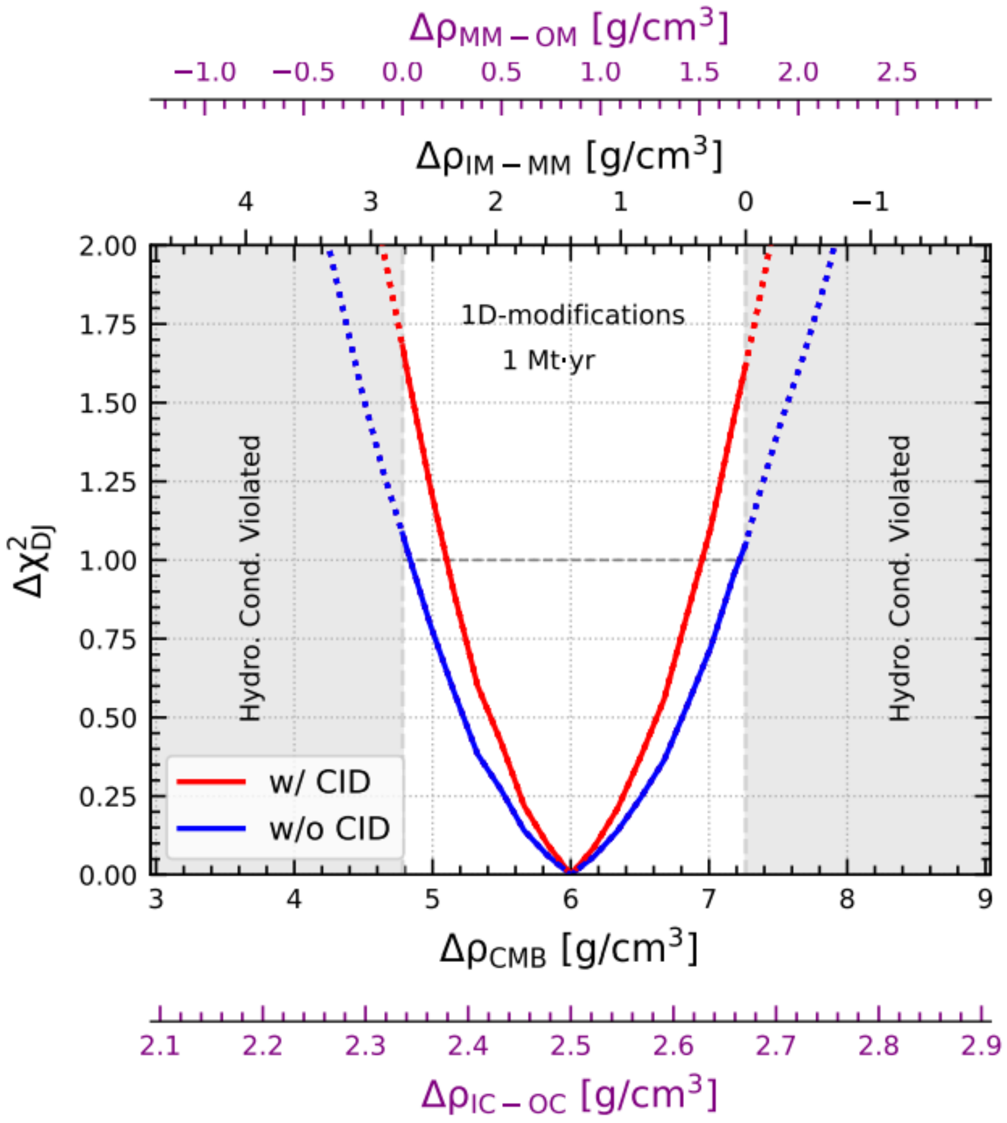
Kelly, Machado, Martinez-Soler, Perez-Gonzalez
JHEP05(2022)187 [arXiv:2110.00003]

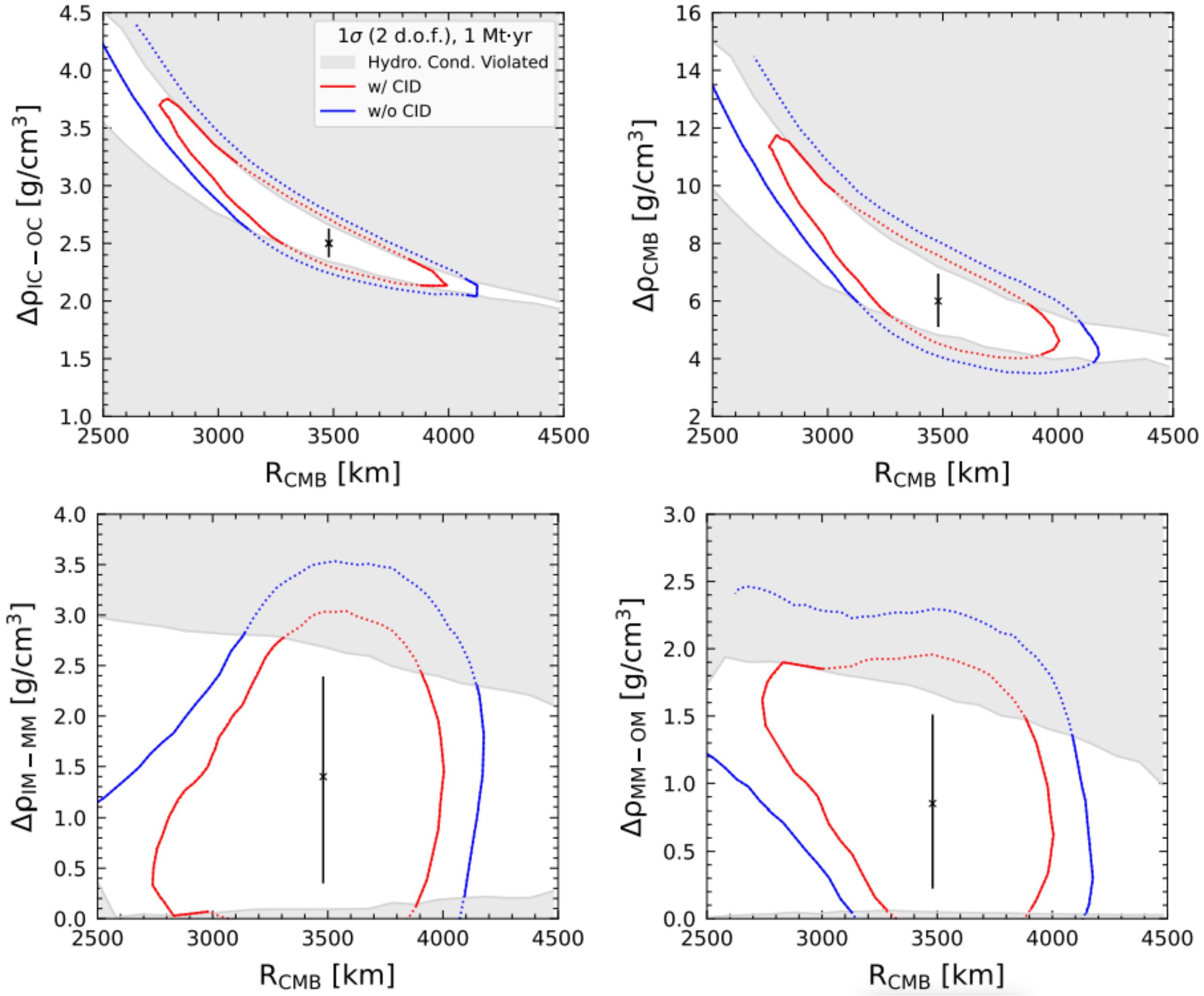


- DUNE can observe solar and atmospheric matter resonances
- Earth at 8.4% precision with an exposure of 400 kton-year

# Future Experiments

- Charge identification can significantly enhance sensitivities - opportunities for ICAL
  - Study assumes INO-ICAL with muon angular resolution of ~1° and $\Delta E_\mu/E_\mu \sim 10\%$, $E_{thr} \sim 1\,\mathrm{GeV}$, 1 Mt·yr exposure





**Possibility to constraining Density Jump at CMB**

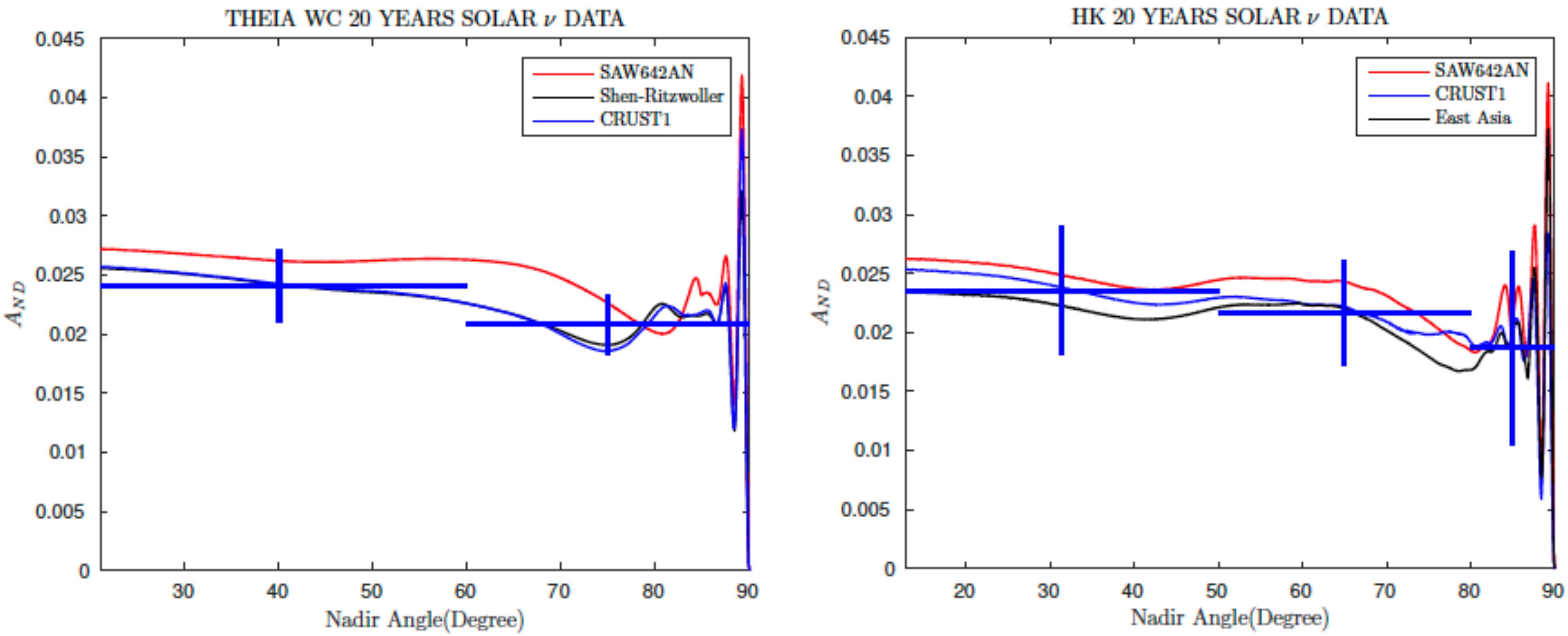
Anuj Kumar Upadhyay, Anil Kumar, Sanjib Kumar Agarwalla, Amol Dighe, arXiv:2405.04986
Anuj Kumar Upadhyay et. al., JHEP 04 (2023) 068, arXiv: 2211.08688
Anil Kumar et. al., JHEP 08 (2021) 139, arXiv: 2104.11740

# Earth Tomography with Solar & SN Neutrinos

# Oscillation tomography with solar neutrinos

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

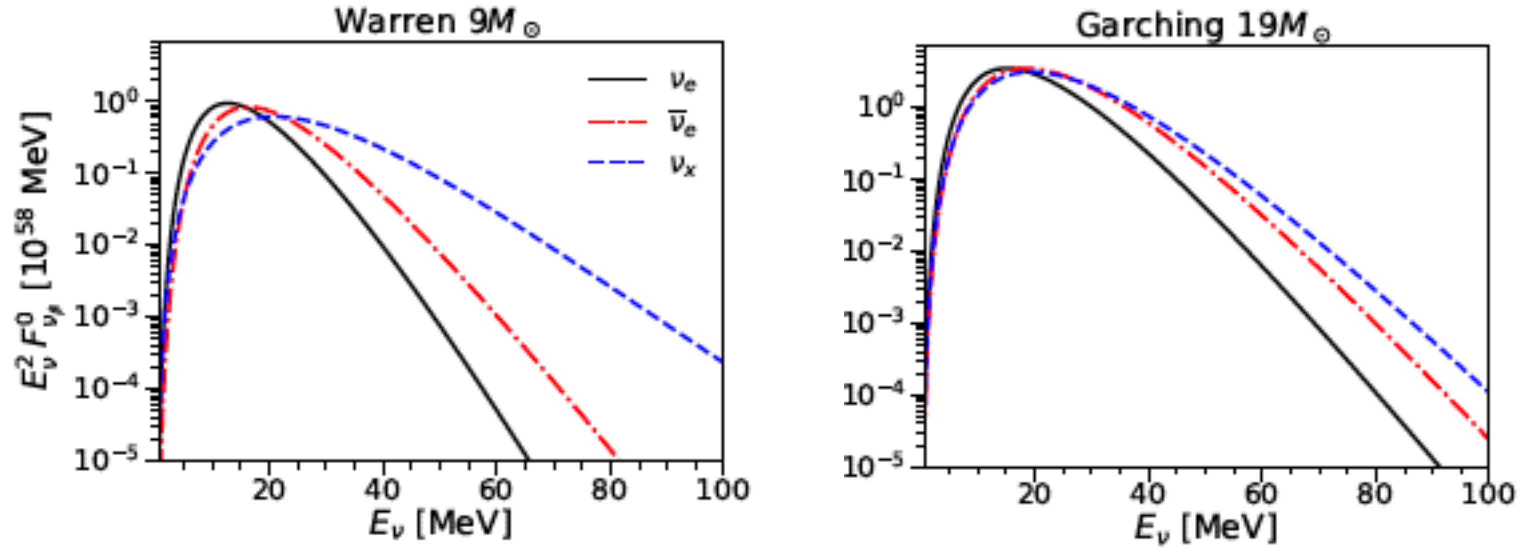
- Study oscillation tomography of the Earth with the boron neutrinos (peak ~ 14MeV)
- Due to the attenuation effect, the Day-Night asymmetry mainly depends on shallow density structures: crust, upper mantle and crust-mantle border
- Next-generation detectors will establish the integrated day-night asymmetry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



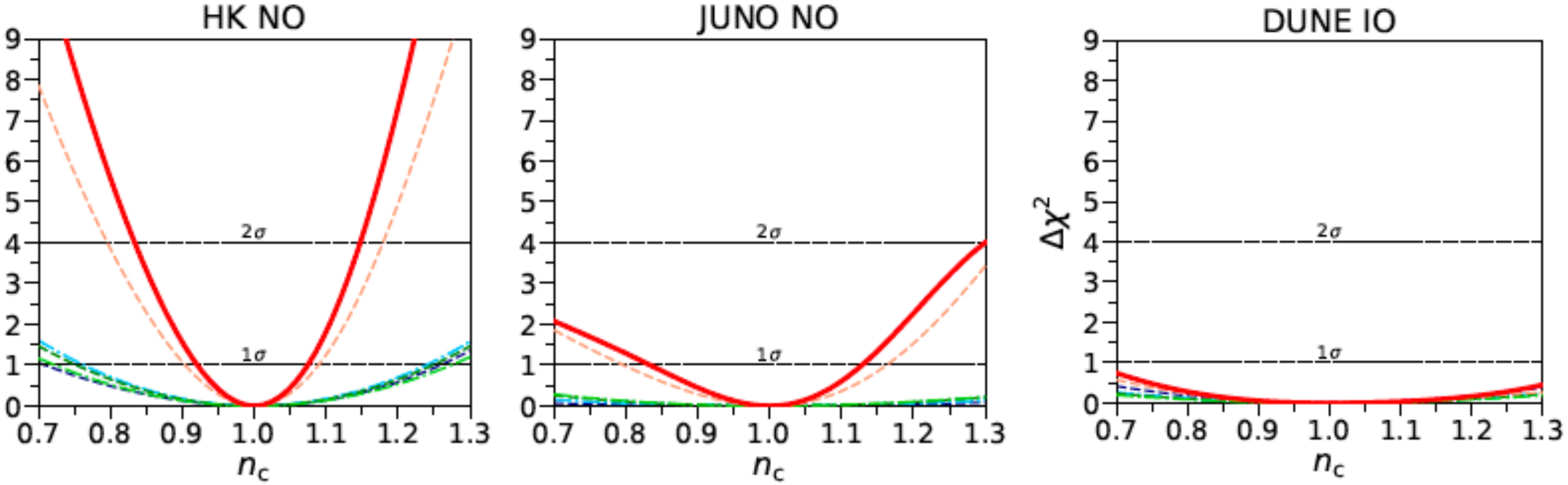
# Earth tomography with supernova neutrinos at future neutrino detectors

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 |
| $\nu_e$-O CC | x | | |
| $\nu_e$-C CC | | x | |
| $\nu_e$-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 $\Delta m^2_{21}$
- Sensitivities not at levels to be of interest to geoscience community

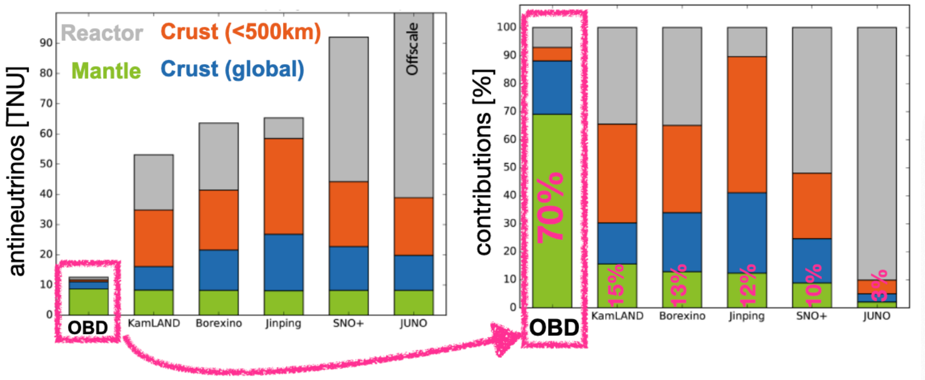
# Prospects for geoneutrinos

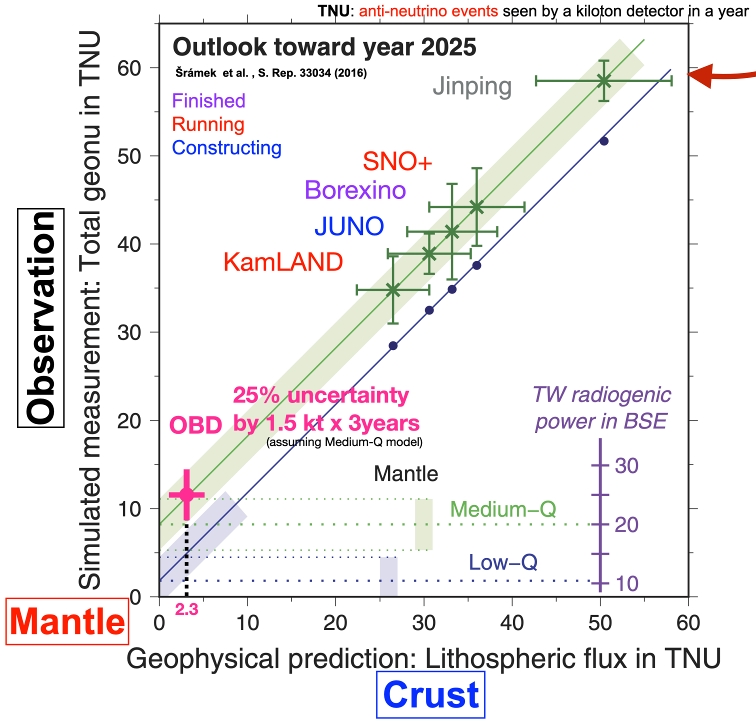
# Ocean Bottom Detector (OBD) Motivations

W.Luo see poster 66
Jinping Neutrino Experiment

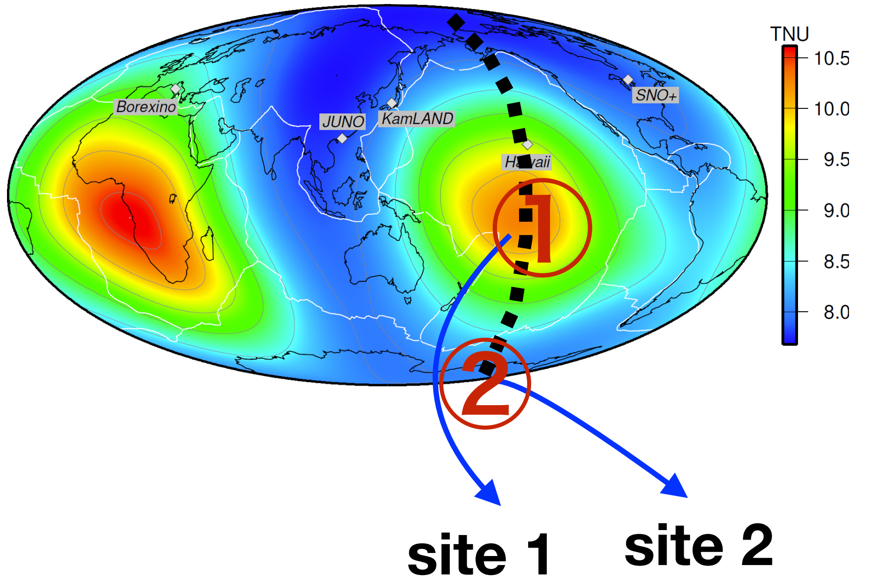
- **Direct Measurement of Mantle**

**need to be far from crust**
**can be far from reactors**





**Mantle Geoneutrino Flux**
*Šrámek et al (2013) EPS, 10.1016/j.epsl.2012.11.001*

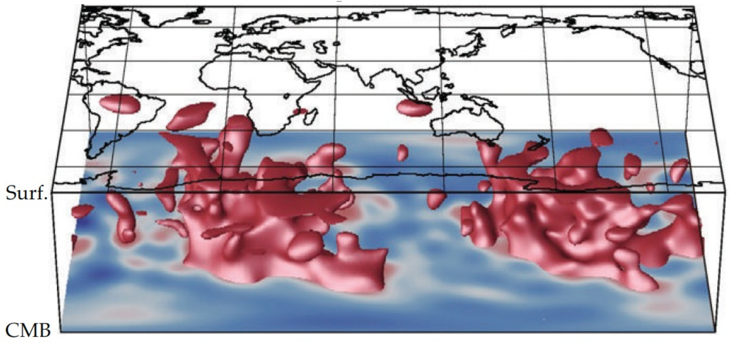


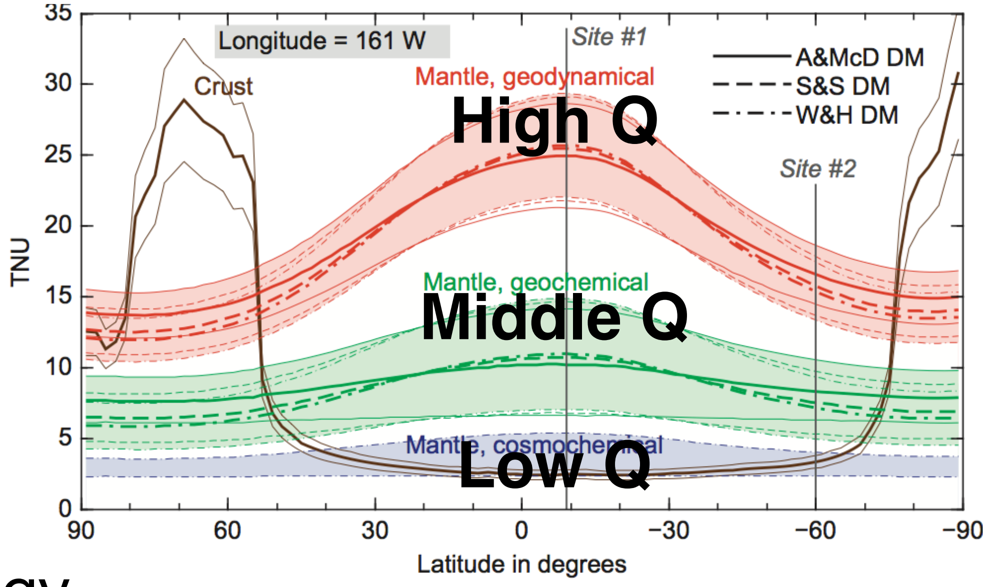
- **Multi-site Measurements**

**Solve the mystery of deep Earth!**

**First detector for mapping**
**the inhomogeneous mantle**

Seismically slow "red" regions in the deep mantle





- **Multidisciplinary Detector**

**Physics**, Geoscience, Mantle drilling, Biology, New technology,…

# OBD: Status and Prospects

Original idea (2005)

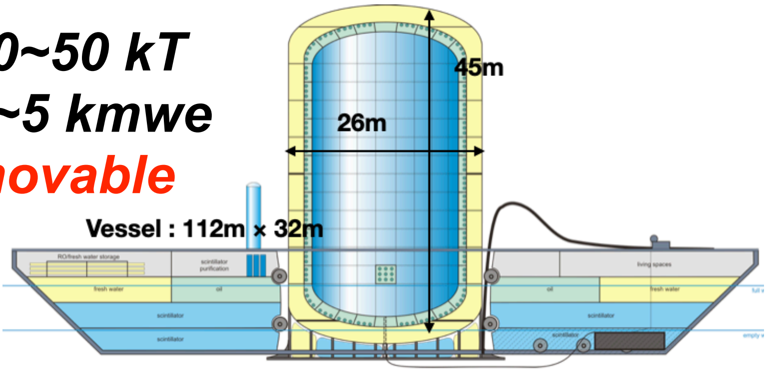
**“Hanohano”**

**U. Hawaii & Makai Ocean Engineering**

***10~50 kT***

***1~5 kmwe***

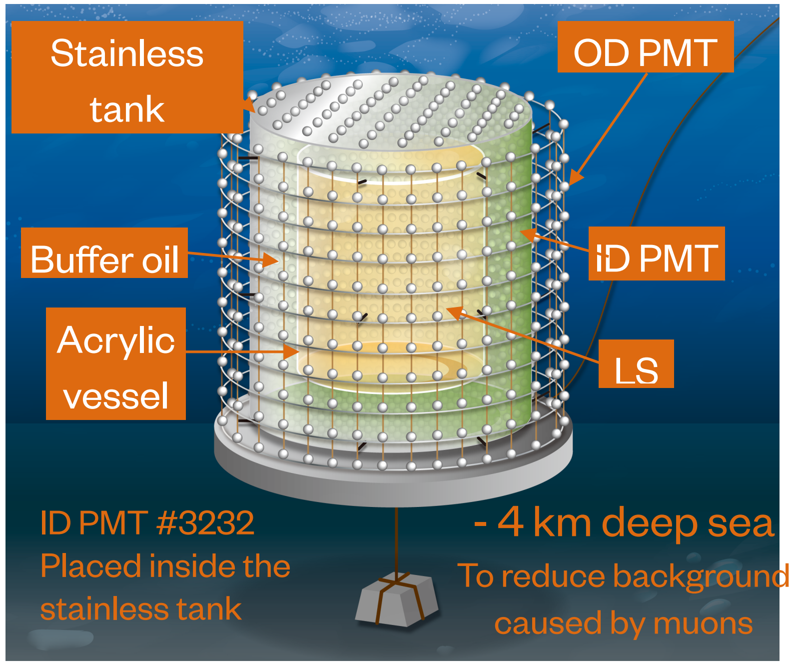
***movable***



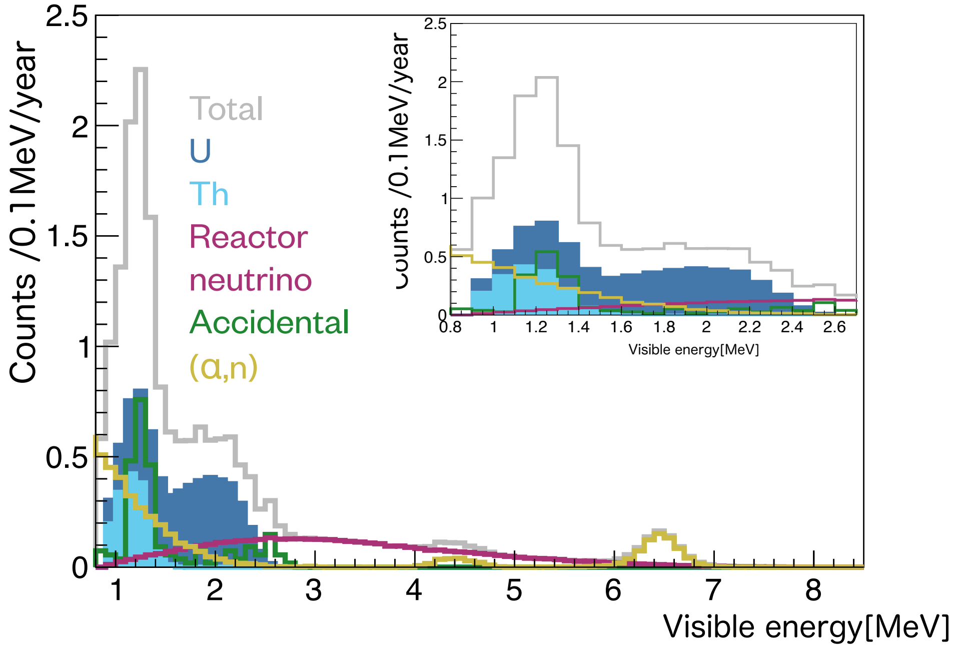
Technical tests and detector design

## Ocean Bottom Detector project (2019~)

1.5 kt LS detector @4km seafloor



*Detector simulation*



**Unique detector which can have water and LS as neutrino targets**

*

**started with JAMSTEC & Tohoku U.!**

July 9, 2019

Joint workshop on OBD with Ocean Engineering, Earth Science and Neutrino Physics

Japan Agency for Marine-Earth Science and Technology

* **Mantle geoneutrino sensitivity**

highQ model: 1year → 3.7σ

middleQ model: 3year→ 3.5σ

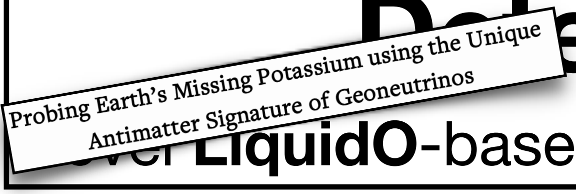
lowQ model: 10year→ 2.5σ

- ✦ Working on development of detector components (workable **@40 MPa, 2-4 °C**)
- ✦ **Prototype detector** is under construction to be installed into **1km depth**
- ✦ Collaboration and community supports are being enhanced. (U. Hawaii, Chiba U., LLNL)

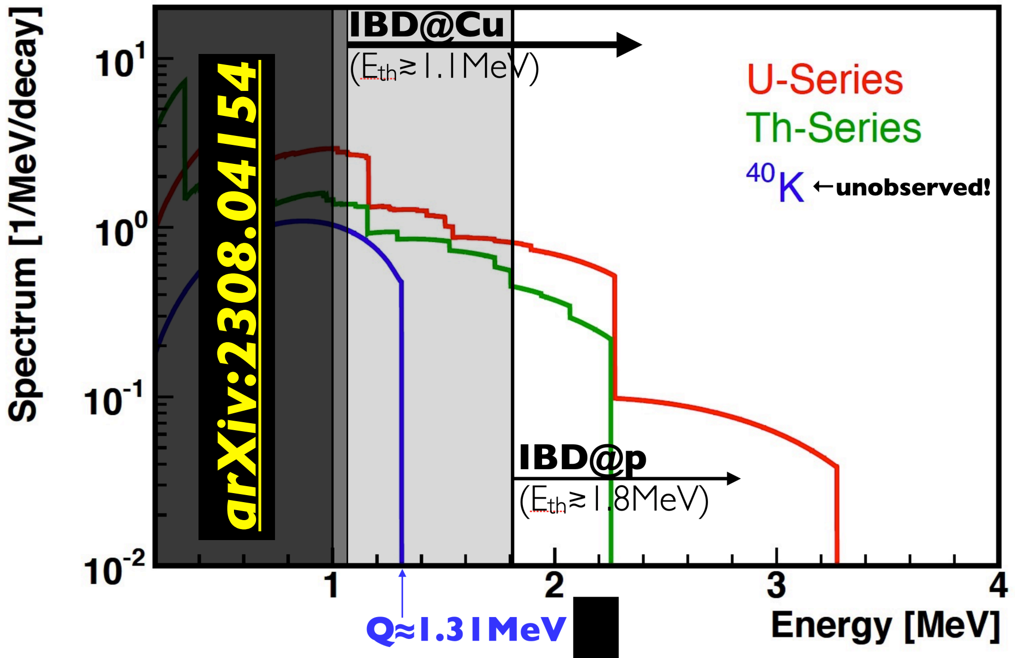
H. Watanabe et al., Underwater Technology 2023

# LiquidO-based methodology

## Detecting $^{40}$K geoneutrinos: possible?

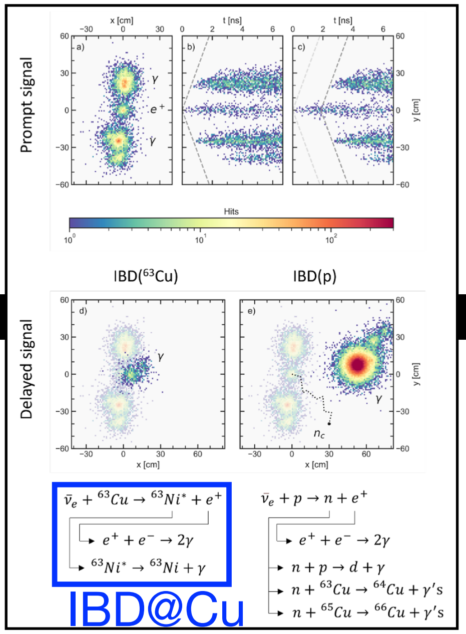

Probing Earth's Missing Potassium using the Unique Antimatter Signature of Geoneutrinos

ver **LiquidO**-based methodology (**e+ ID**)& **new IBD-like interaction** (threshold ≥1.1MeV) on **Cu**



only (small) fraction of geoneutrinos sampled so far

**$^{40}$K geoneutrino→** *Earth model discrimination?*



$\bar{\nu}_e + {}^{63}Cu \rightarrow {}^{63}Ni^* + e^+$

$e^+ + e^- \rightarrow 2\gamma$

${}^{63}Ni^* \rightarrow {}^{63}Ni + \gamma$

$\bar{\nu}_e + p \rightarrow n + e^+$

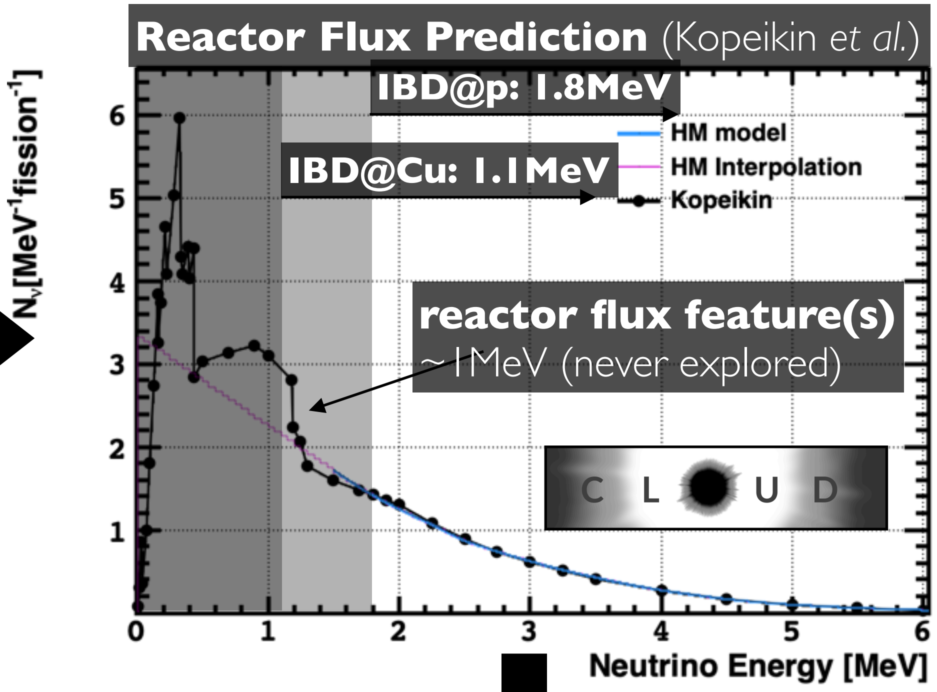
$e^+ + e^- \rightarrow 2\gamma$

$n + p \rightarrow d + \gamma$

$n + {}^{63}Cu \rightarrow {}^{64}Cu + \gamma's$

$n + {}^{65}Cu \rightarrow {}^{66}Cu + \gamma's$

new interaction on Cu



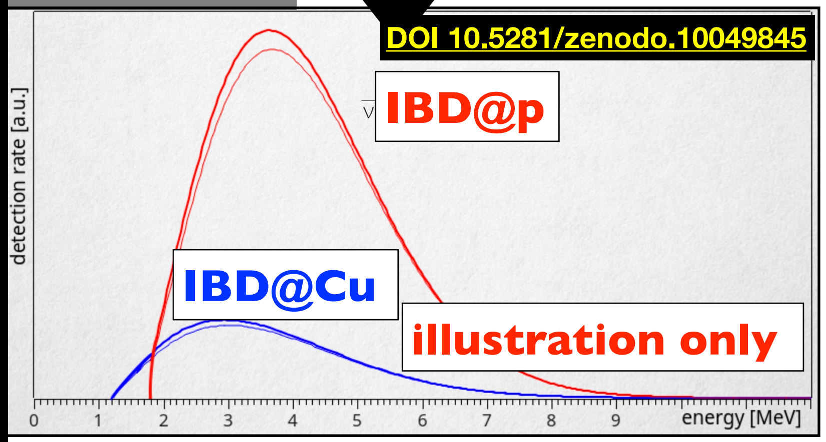
validate @ reactor ("test beam like")

Experimental work ahead:

- **validate cross-section @reactor**
  ⟹ measure relative to IBD@p
- **validate detectability @reactor**
  ⟹ efficiency & feasibility

⟹ CLOUD-III @ Chooz reactor?

**CLOUD-III**

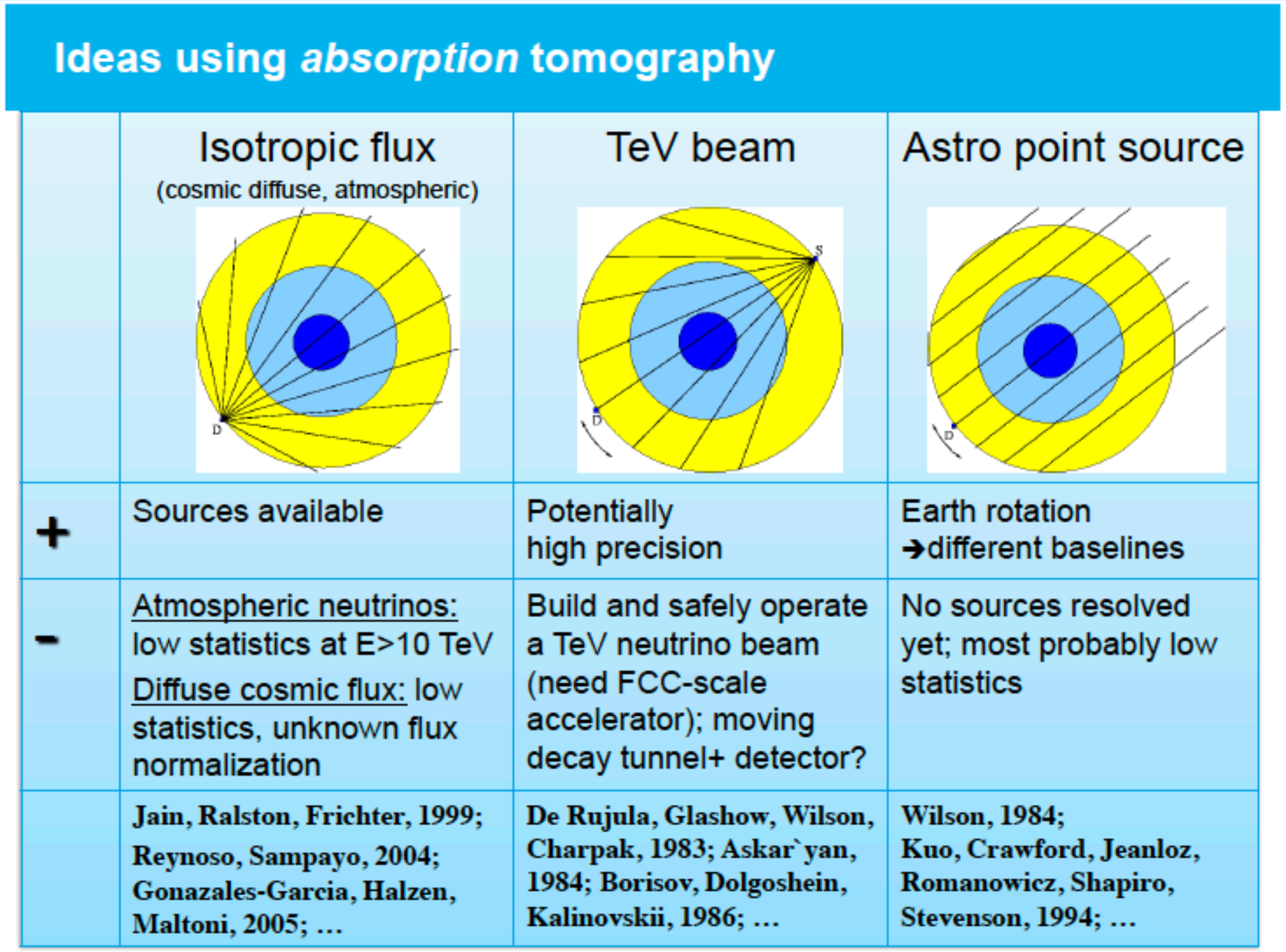


# Conclusions

# Conclusions

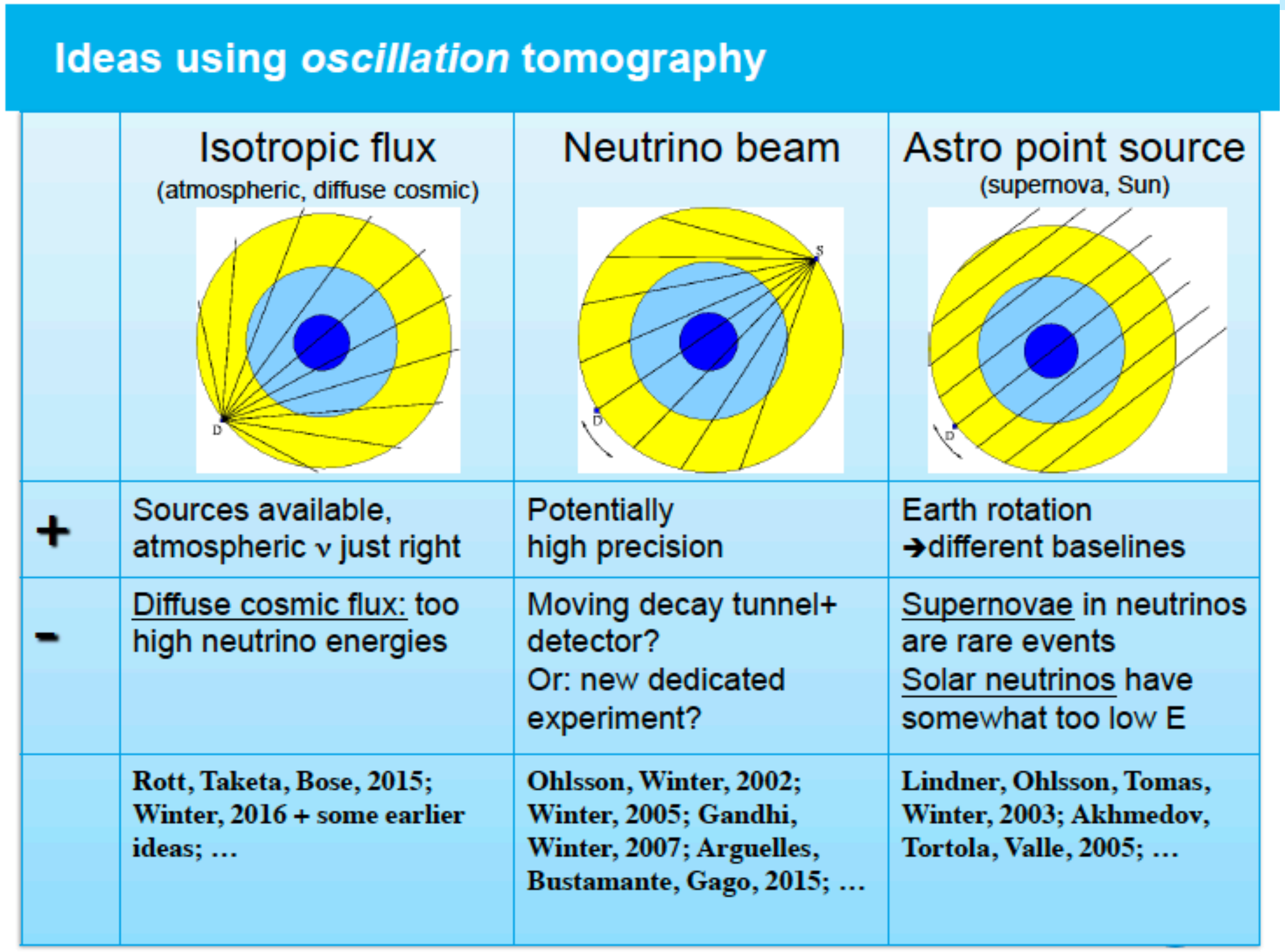
- A detailed understanding of the composition and density structure of the inner Earth is essential to understand the geomagnetic field and Earth's formation and the nature of its building blocks.
- We are at the beginning of a new era in where quantitative measurements with neutrinos using absorption and oscillation measurements can be performed
- Rapid progress in the construction of large neutrino telescopes (km$^3$-scale) with TeV-PeV neutrino sensitives, good angular resolution give new capabilities for neutrino absorption tomography: density profiles, LLVPs, cross sections, BSM physics, …
- Large volume neutrino detectors with good coverage in the 1-20GeV, enable neutrino oscillation tomography: matter density profile, composition - core / LLSVP, etc.
- Essential to connect closely to geoscience community to focus neutrino efforts on the big questions in the field
- Many measurements of neutrino properties rely on input from the geoscience community, working together is essential
- Combining measurement from multiple instruments critical to understand 3D structures and to address some of the most central questions in deep earth science (light elements in the core, …)
- Technological advances offer prospects for further breakthroughs in Earth science to map the inhomogeneous mantle, measure the missing piece to the Earth heat budget, and distinguish earth models

# Historic background and credits



## Ideas using *absorption* tomography

| | Isotropic flux<br>(cosmic diffuse, atmospheric) | TeV beam | Astro point source |
|---|---|---|---|
| **+** | Sources available | Potentially high precision | Earth rotation →different baselines |
| **-** | Atmospheric neutrinos: low statistics at E>10 TeV<br>Diffuse cosmic flux: low statistics, unknown flux normalization | Build and safely operate a TeV neutrino beam (need FCC-scale accelerator); moving decay tunnel+ detector? | No sources resolved yet; most probably low statistics |
| | **Jain, Ralston, Frichter, 1999; Reynoso, Sampayo, 2004; Gonazales-Garcia, Halzen, Maltoni, 2005; …** | **De Rujula, Glashow, Wilson, Charpak, 1983; Askar`yan, 1984; Borisov, Dolgoshein, Kalinovskii, 1986; …** | **Wilson, 1984; Kuo, Crawford, Jeanloz, Romanowicz, Shapiro, Stevenson, 1994; …** |

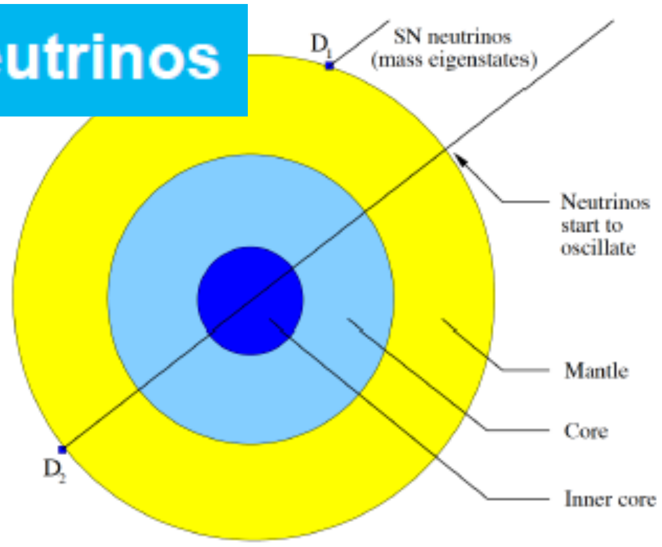


## Ideas using *oscillation* tomography

| | Isotropic flux<br>(atmospheric, diffuse cosmic) | Neutrino beam | Astro point source<br>(supernova, Sun) |
|---|---|---|---|
| **+** | Sources available, atmospheric ν just right | Potentially high precision | Earth rotation →different baselines |
| **-** | Diffuse cosmic flux: too high neutrino energies | Moving decay tunnel+ detector?<br>Or: new dedicated experiment? | Supernovae in neutrinos are rare events<br>Solar neutrinos have somewhat too low E |
| | **Rott, Taketa, Bose, 2015; Winter, 2016 + some earlier ideas; …** | **Ohlsson, Winter, 2002; Winter, 2005; Gandhi, Winter, 2007; Arguelles, Bustamante, Gago, 2015; …** | **Lindner, Ohlsson, Tomas, Winter, 2003; Akhmedov, Tortola, Valle, 2005; …** |

slides from W.Winter - ISAPP summer institute:
Using particle physics to understand and image the earth
GSSI, l'Aquila, Italy July 11-21, 2016

## Supernova neutrinos

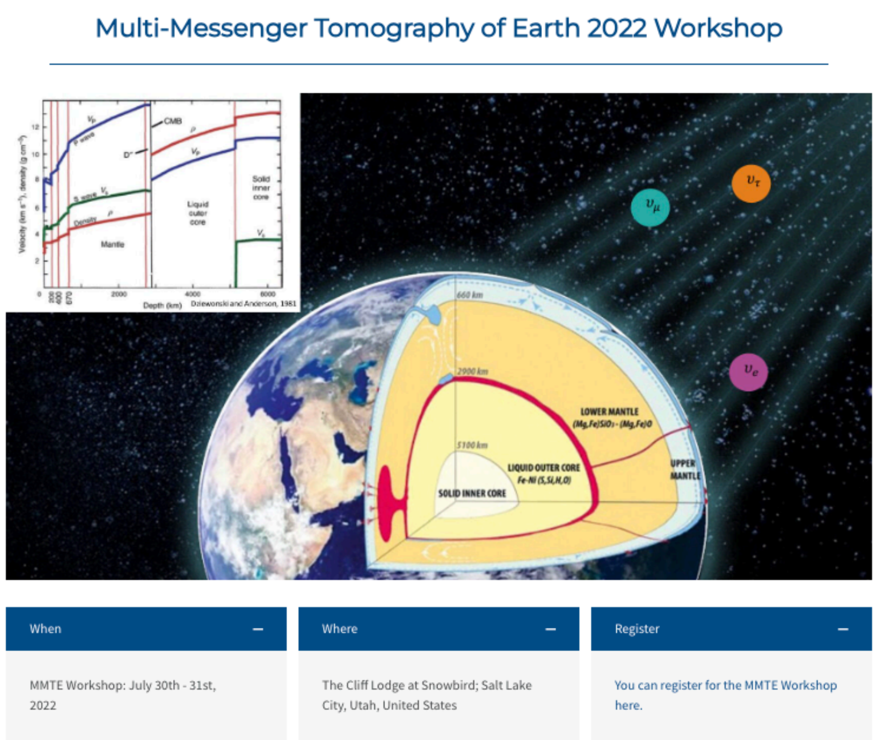


(Lindner, Ohlsson, Tomas, Winter, Astropart. Phys. 19 (2003) 755)

Thank you !

# Past workshops of interest and other resources

https://indico.cern.ch/event/442108/


Multi-Messenger Tomography of Earth 2022 Workshop

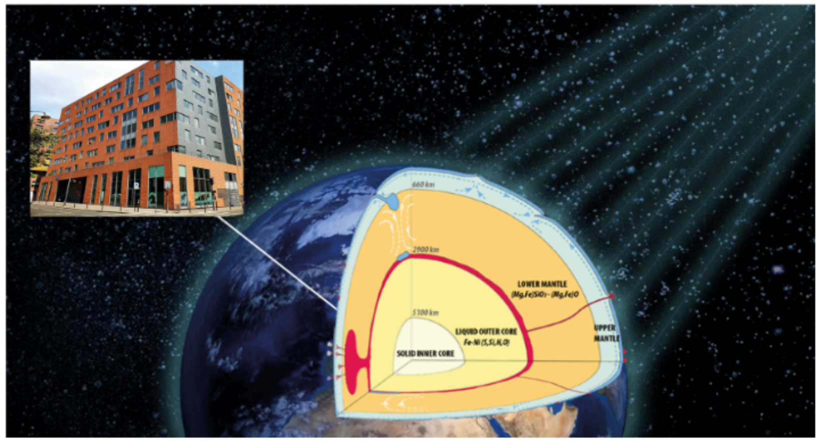
When — MMTE Workshop: July 30th - 31st, 2022

Where — The Cliff Lodge at Snowbird; Salt Lake City, Utah, United States

Register — You can register for the MMTE Workshop here.

https://www.physics.utah.edu/mmte-2022/

**2nd International Workshop on**
**Multi–messenger Tomography of the Earth**
**APC – Université Paris Cité**
**Paris July 4th–7th, 2023**



https://indico.in2p3.fr/event/30001/timetable/

References:

- PREM500 - Dziewonski, A. & Anderson, D. Preliminary reference Earth model. Physics of the Earth and Planetary Interiors 25, 297–356 (1981).
- AK135 - Kennett, B., Engdahl, E. & Buland, R. Constraints on seismic velocities in the earth from travel times. Geophysical Journal International 122, 108–124 (1995).
- PREM-A - Dziewonski, A., Hales, A. & Lapwood, E. Parametrically simple earth models consistent with geophysical data. Physics of the Earth and Planetary Interiors 10, 12–48 (1975).

**Big thanks to for materials and input to this talk:**
Hiroko Watanabe, Bill McDonough, Serguey Petcov, Francis Halzen, Sanjib Kumar Agarwalla, Krishnamoorthy J, Anuj Upadhyay, Anil Kumar, Shiqi Yu, Joao Coelho, Véronique Van Elewyck, Livia Ludhova, Anatael Cabrera, Mark Chen, …

# Backup

# Radiography of the Earth’s Core and Mantle with Atmospheric Neutrinos

**Radiography of the Earth’s Core and Mantle with Atmospheric Neutrinos**
M.C. Gonzalez-Garcia, Francis Halzen, Michele Maltoni, and Hiroyuki K.M. Tanaka
Phys. Rev. Lett. (100) (2008)

**Method**
Use atmospheric muon neutrino absorption in the Earth to detect the core

Observation time

Differential Muon neutrino flux after propagation through the Earth

$$N_{\rm ev}^{\nu_\mu} = T\int_{-1}^{1} d\cos\theta \int_0^\infty dl'_{\rm min}\int_{l'_{\rm min}}^\infty dl \int_{E_\mu^{\rm fin,min}}^\infty dE_\mu^{\rm fin} \int_{E_\mu^{\rm fin}}^\infty dE_\mu^0 \int_{E_\mu^0}^\infty \boxed{dE_\nu \frac{d^2\phi_{\nu_\mu}}{dE_\nu\, d\cos\theta}(E_\nu,\cos\theta)} \underline{\frac{d\sigma_{CC}^\mu}{dE_\mu^0}(E_\nu,E_\mu^0)}\, n_T\, \underline{F(E_\mu^0,E_\mu^{\rm fin},l)}\, A_{\rm eff}^0 \quad (1)$$

Neutrino cross section

Number density of targets

Muon propagation to detector

Muon effective area

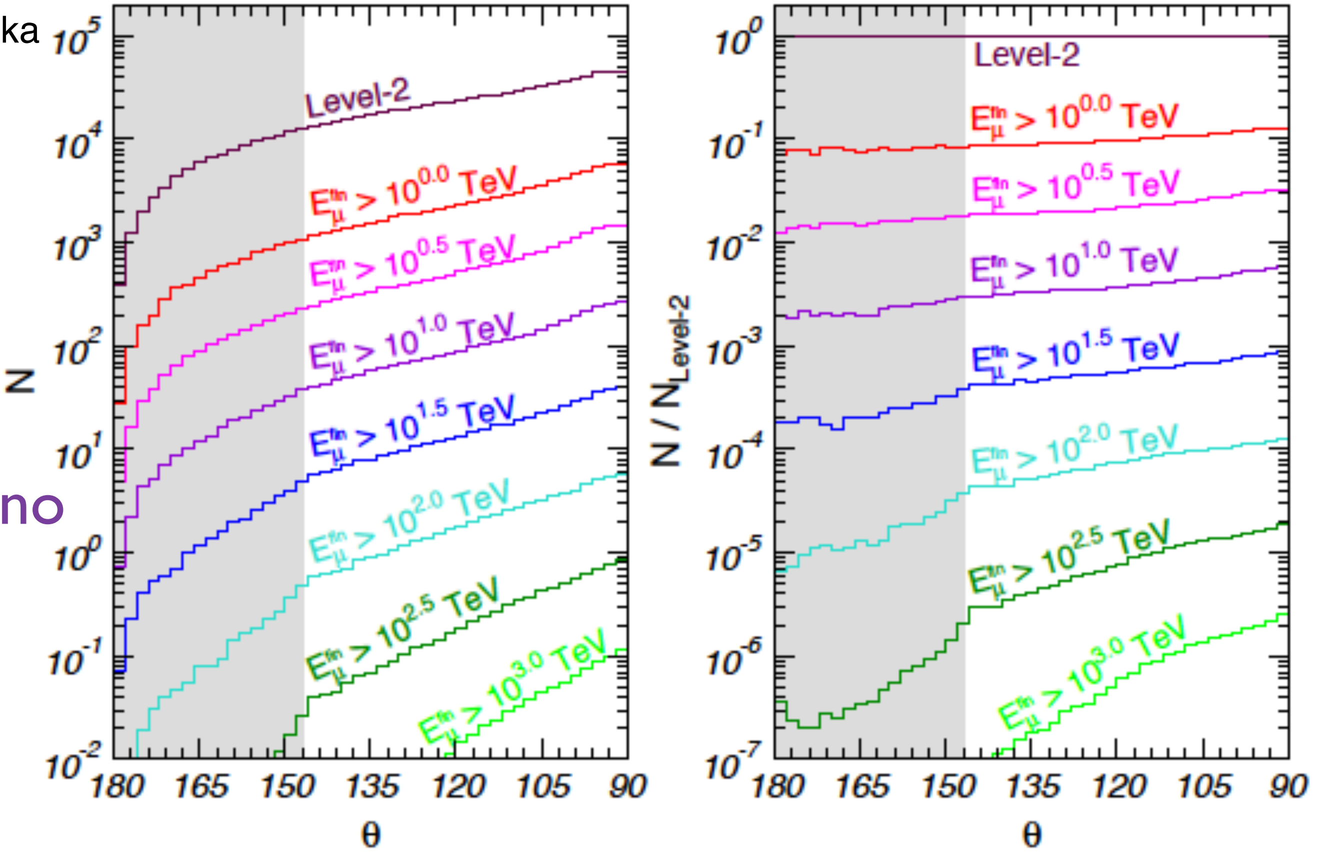
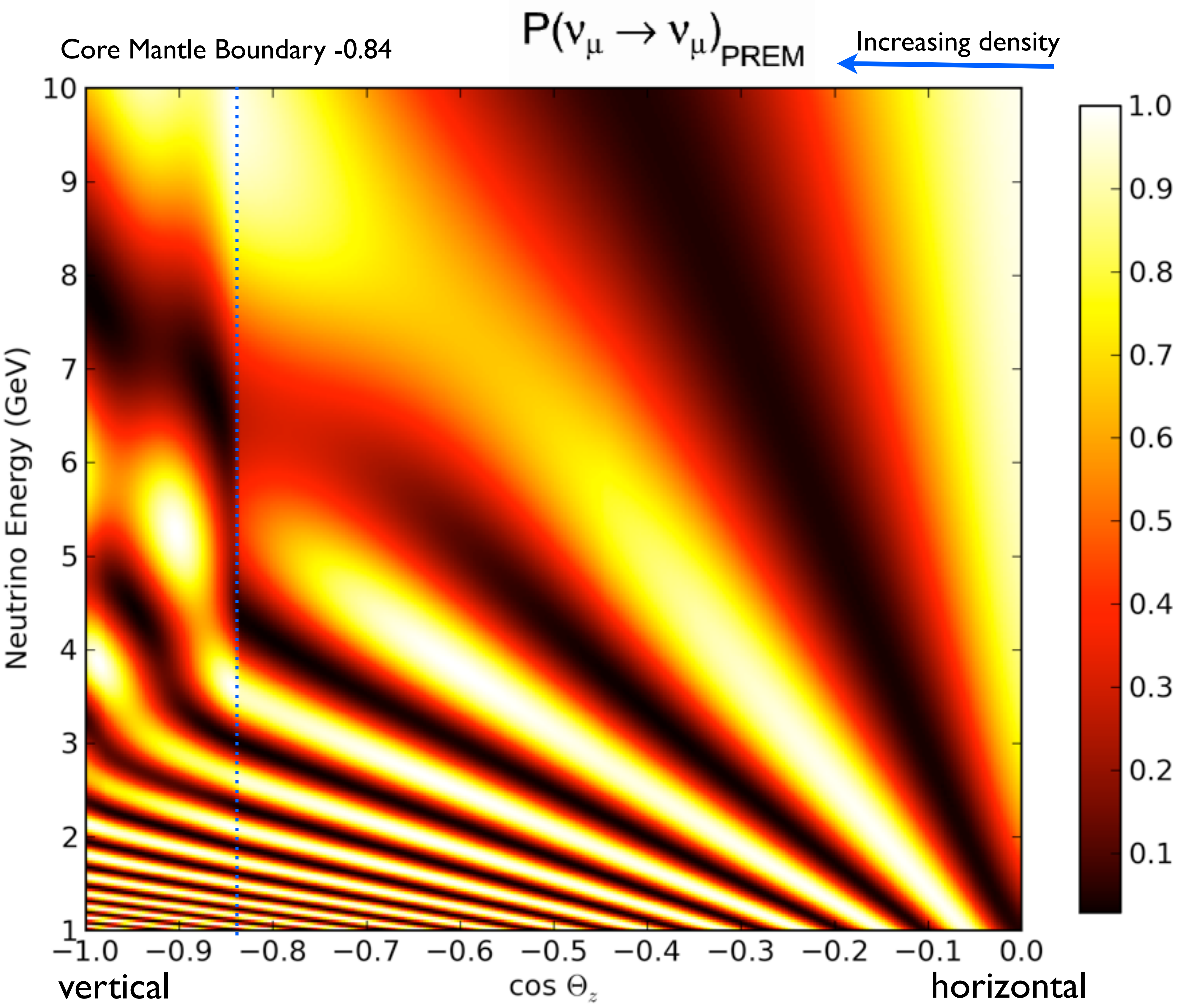


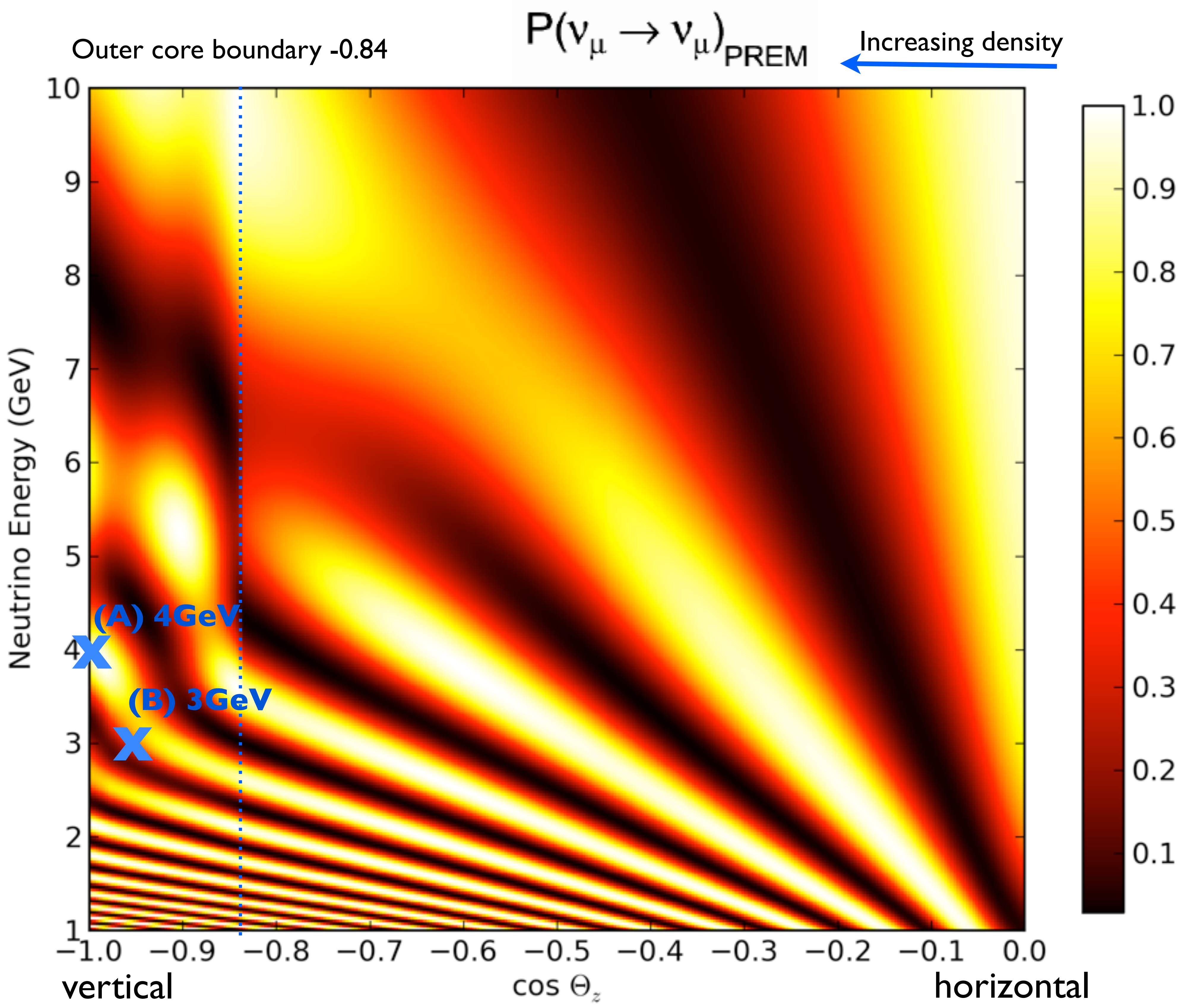
FIG. 1: (a) Expected zenith angle distribution of ATM $\nu_\mu$ induced events in IceCube for different energy thresholds $E_\mu^{\rm fin,min}$ for the PREM. $\theta$ is the neutrino angle (which at these energies is collinear with the detected muon) as measured from the vertical direction (upgoing-$\nu$ corresponding to $\theta = 180$). (b) Ratio of the zenith angle distribution of ATM $\nu_\mu$ induced events in IceCube for different energy thresholds $E_\mu^{\rm fin,min}$ over the corresponding one for L2 cuts only. The shadow areas cover the angular size of the Earth core.

**Predicted:**
IceCube can directly observe the core-mantle transition at the 5σ level in 10 years.

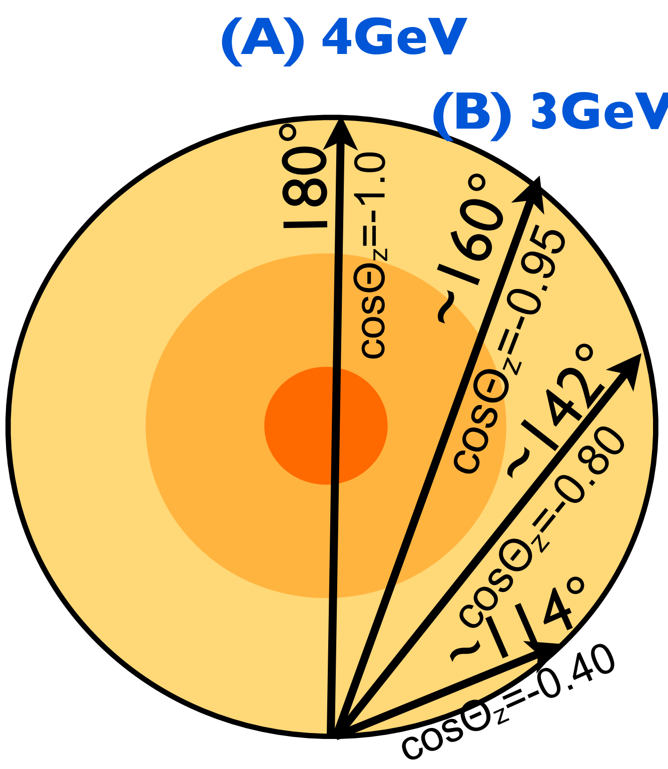
# Oscillograms



# How to read an oscillograms



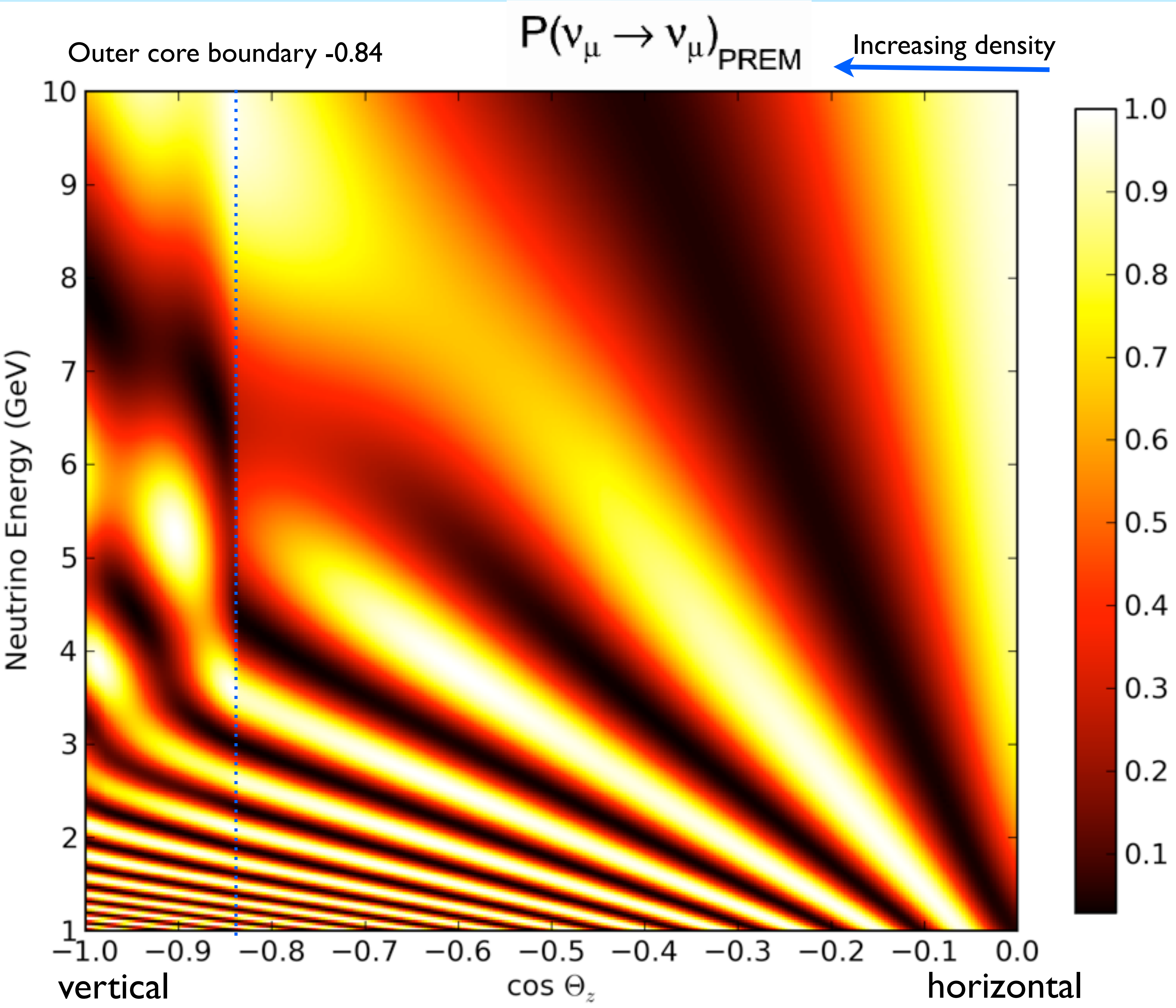
## An example ...



A muon neutrino created at **(A)** with energy 4GeV has a ~**90%** chance to be detected as such after traversing the Earth

A muon neutrino created at **(B)** with energy 3GeV has a ~**40%** chance to be detected as such after traversing the Earth

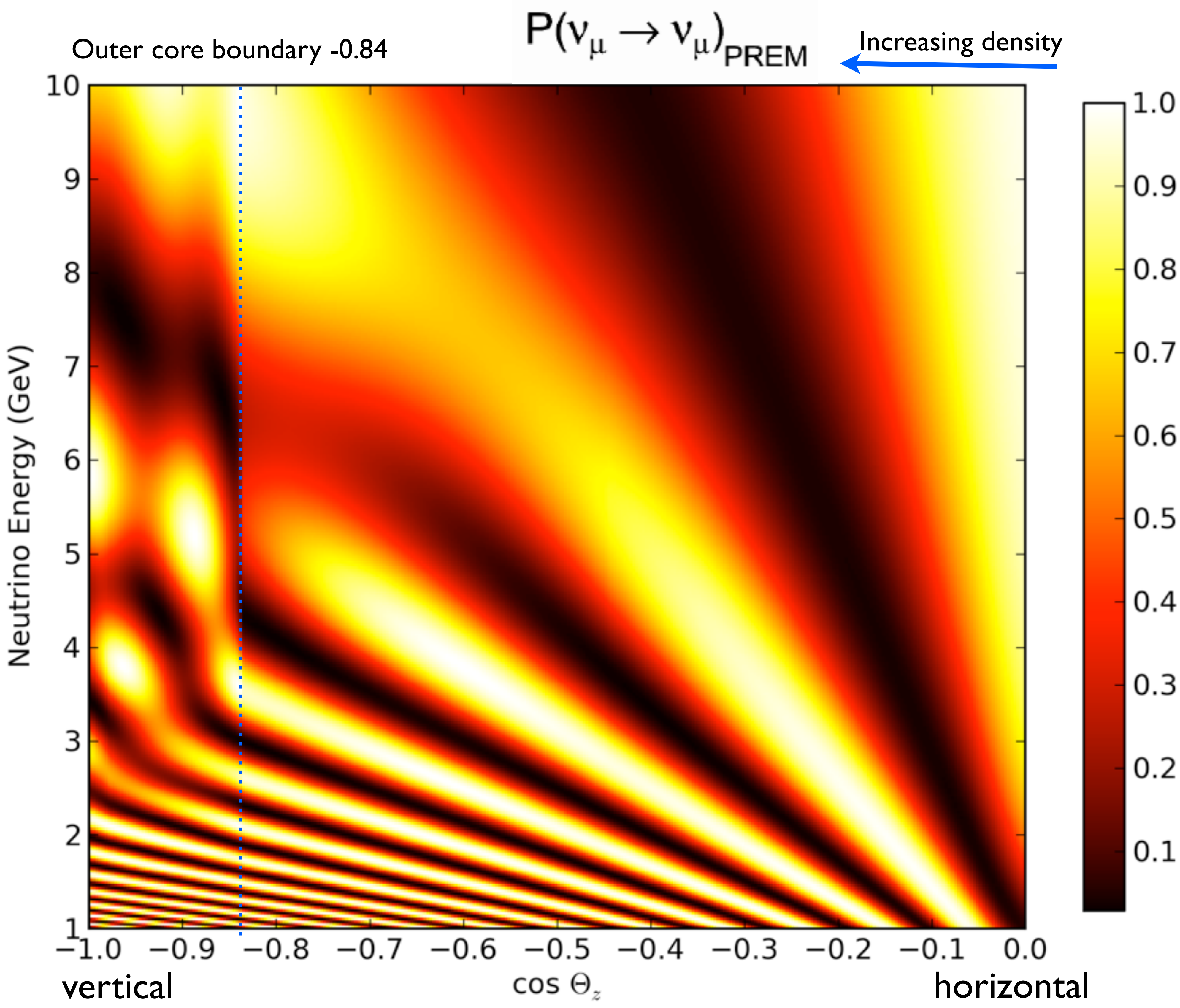
# Oscillogram (“normal” electron density)



vertical

horizontal

# Oscillogram (enhance electron density)

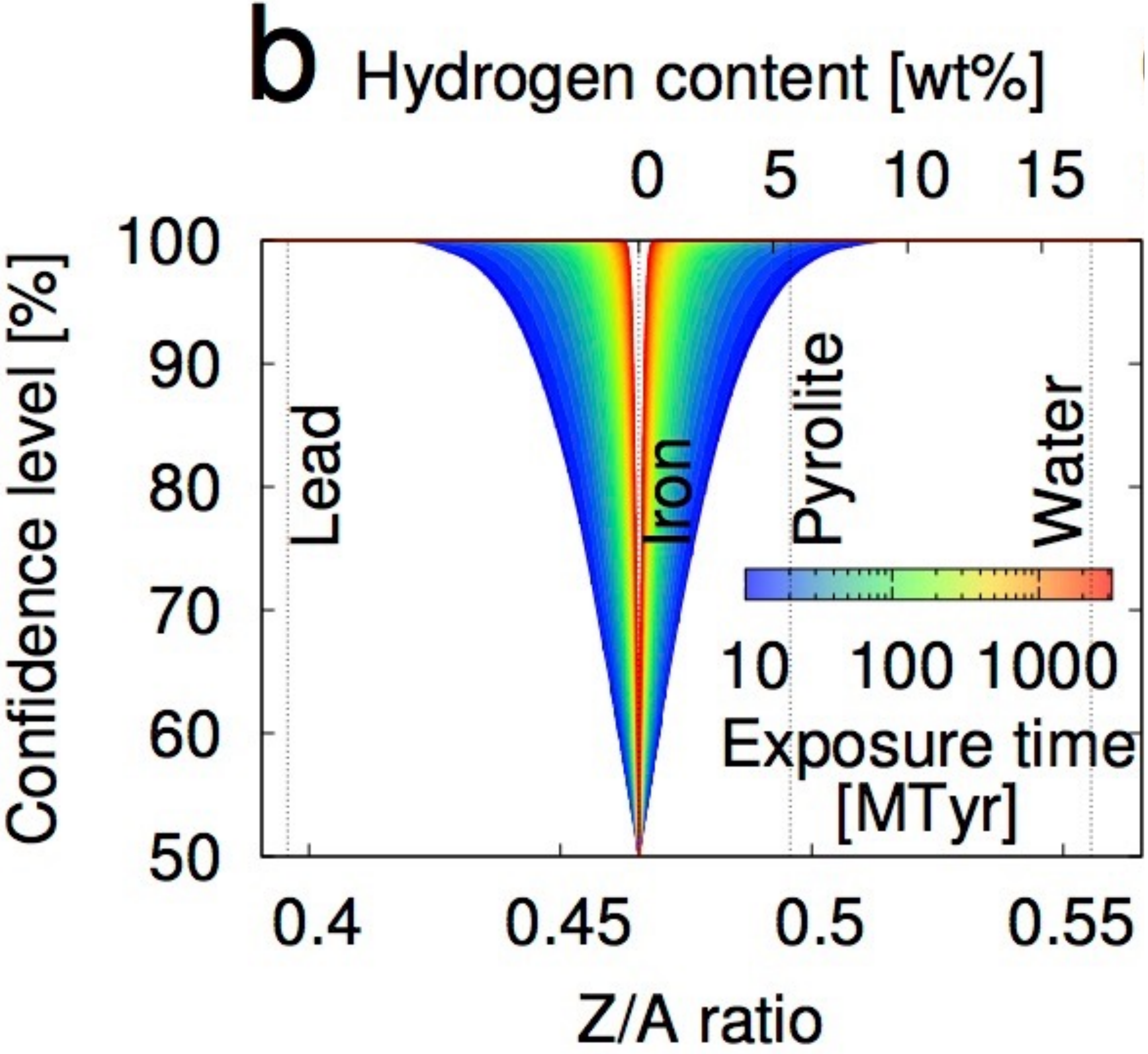


**Change Earth core electron density by 10% to visualize change in survival probability**

Most significant changes are seen in an energy range of **2-10GeV** and for neutrinos passing through the core region(**cosθ < -0.84**)

Rott & Taketa 2015

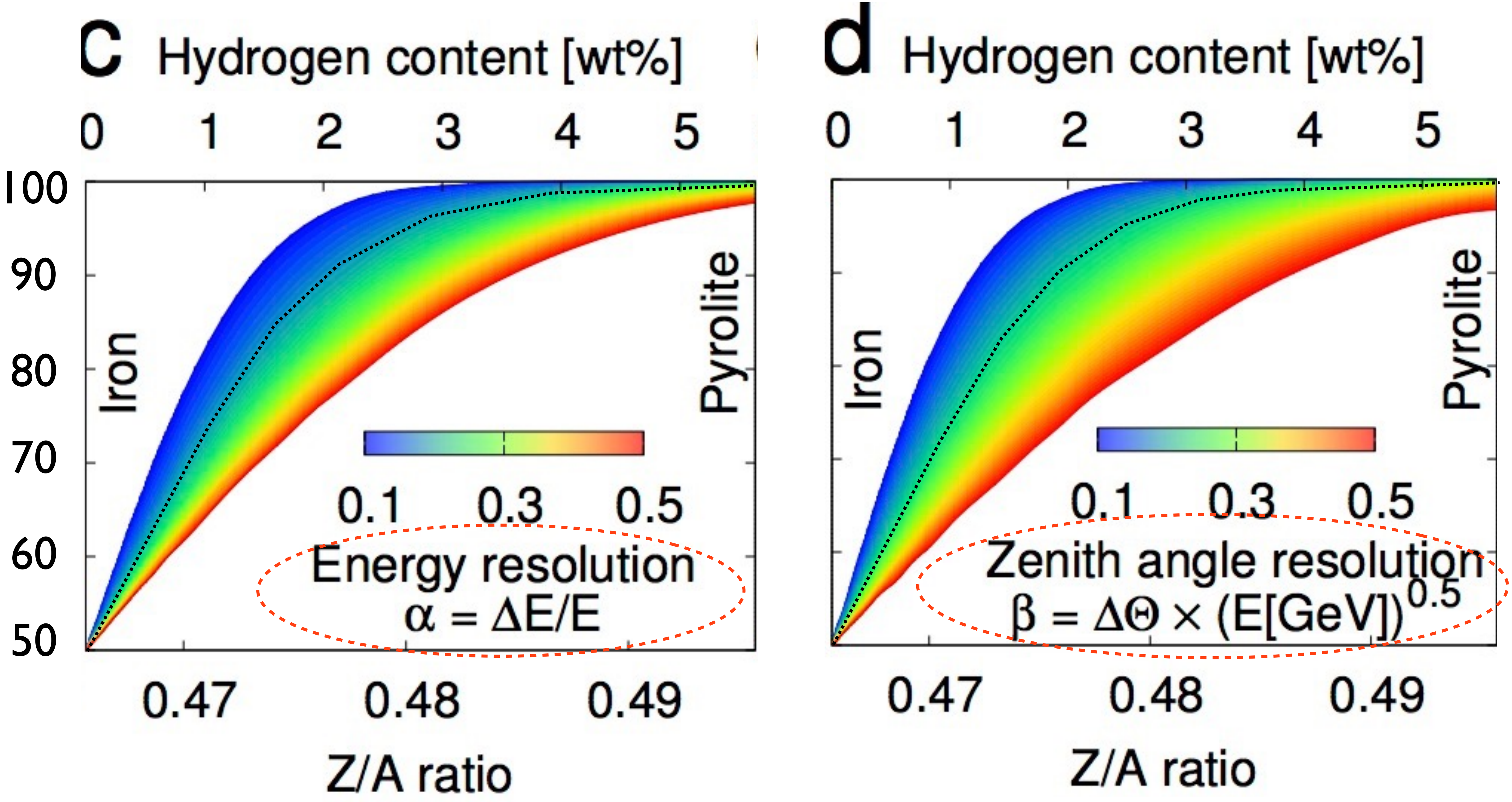
# Sensitivity



- 10MTyrs of a PINGU-like data:
- Probe ~2-4wt% hydrogen
- Reject extreme core composition models

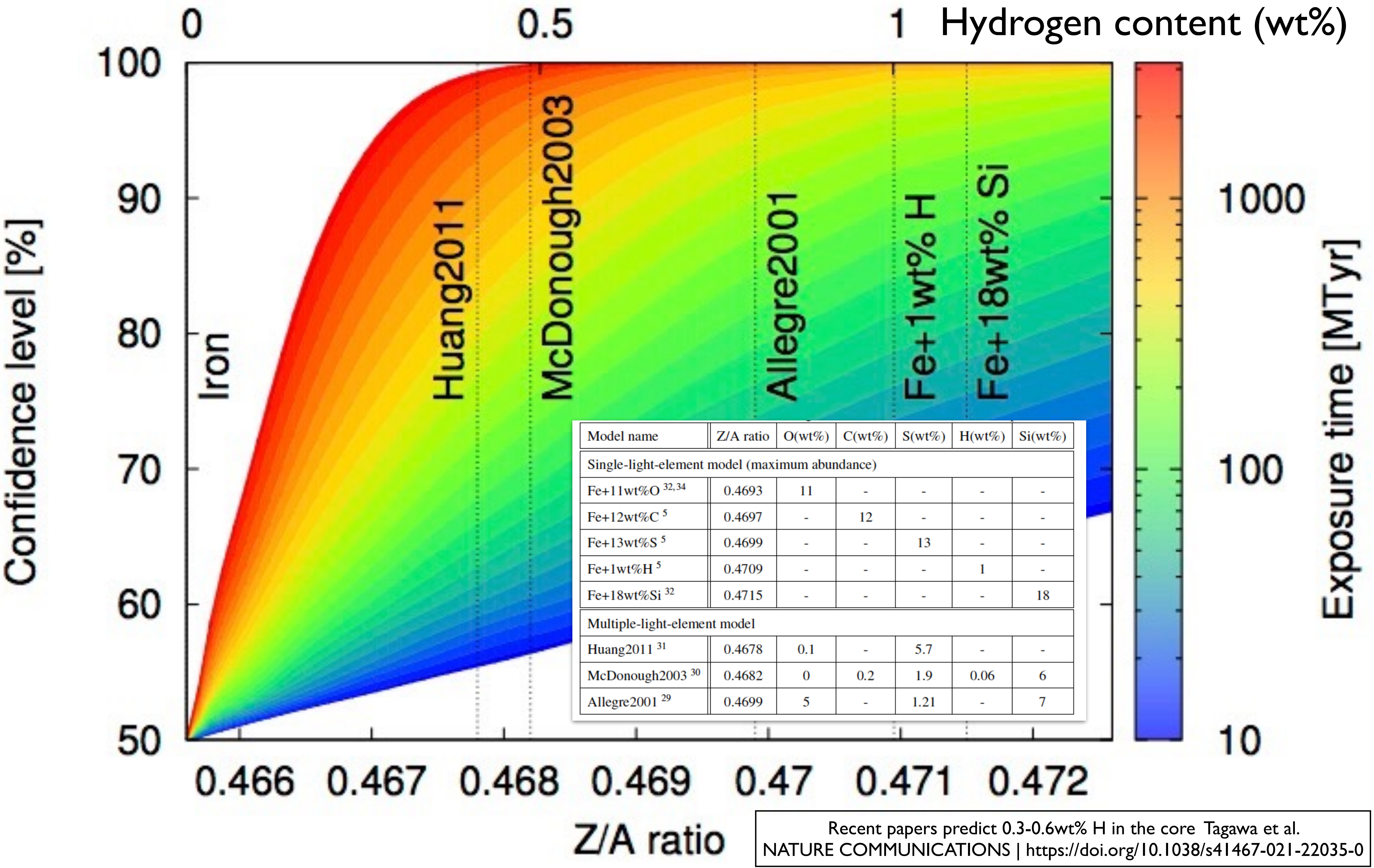
# How can we increase sensitivity ?

- Dependence on the angular resolution and energy resolution
    - Assuming 30MTyrs



Rott & Taketa 2015

# Distinguishing Outer core models



| Model name | Z/A ratio | O(wt%) | C(wt%) | S(wt%) | H(wt%) | Si(wt%) |
|---|---|---|---|---|---|---|
| Single-light-element model (maximum abundance) | | | | | | |
| Fe+11wt%O [32,34] | 0.4693 | 11 | - | - | - | - |
| Fe+12wt%C [5] | 0.4697 | - | 12 | - | - | - |
| Fe+13wt%S [5] | 0.4699 | - | - | 13 | - | - |
| Fe+1wt%H [5] | 0.4709 | - | - | - | 1 | - |
| Fe+18wt%Si [32] | 0.4715 | - | - | - | - | 18 |
| Multiple-light-element model | | | | | | |
| Huang2011 [31] | 0.4678 | 0.1 | - | 5.7 | - | - |
| McDonough2003 [30] | 0.4682 | 0 | 0.2 | 1.9 | 0.06 | 6 |
| Allegre2001 [29] | 0.4699 | 5 | - | 1.21 | - | 7 |

Recent papers predict 0.3-0.6wt% H in the core Tagawa et al.
NATURE COMMUNICATIONS | https://doi.org/10.1038/s41467-021-22035-0