Neutrino Geoscience 2025 Kingston

Monday 27 October 2025 - Thursday 30 October 2025

Queen’s University and the McDonald Institute

Book of Abstracts

Contents

3

GEONU: An Open-Source Toolkit for Geoneutrino Signal Predictions and Applications to SNO+

Author: Shuai Ouyang[1]

[1] *Shandong University*

GEONU (an open-source MATLAB toolkit) is a computational framework for geoneutrino signal predictions. It was first introduced by Wipperfurth et al. (2019) and made publicly available on GitHub in 2024. The framework supports multiple global crustal datasets, propagates uncertainties in density, thickness, and abundances of heat-producing elements (HPEs), and allows for global signal predictions of geoneutrinos at multiple detector sites.
Motivated by the geoneutrino analysis at SNO+, which requires proper modeling of both regional and global contributions to interpret the observed signal, this work presents an overview of the original and rewritten versions of the GEONU tool. The rewritten GEONU improves modularity, computational performance particularly in terms of speed, and parameter flexibility.
In this talk, I'll present applications of the tool to SNO+, including evaluations of the impact of neutrino oscillation, IBD cross sections, and geoneutrino spectra, as well as ongoing developments to integrate local crustal field modeling in the near future. The original GEONU framework was developed by Tytrice Faison, Laura Sammon, Yu Huang, Scott Wipperfurth, and William McDonough, whose contributions are gratefully acknowledged.

4

Stochastic Crustal Model around KamLAND

Author: Sanshiro Enomoto[1]

Co-authors: Akiko Tanaka [2]; Hiroko Watanabe [3]; Kenta Ueki [4]; Nishikiori Tsukasa [5]; Nozomu Takeuchi [6]; Satoru Haraguchi [6]; Tsutomu Fukuda [5]; Tsuyoshi Iizuka [6]

[1] *University of Washington*

[2] *Tohoku University, Geological Survey of Japan*

[3] *Tohoku University*

[4] *Japan Agency for Marine-Earth Science and Technology*

[5] *Nagoya University*

[6] *University of Tokyo*

To investigate global Earth models with geoneutrino observations, it is crucial to characterize the surrounding crustal composition, since uranium (U) and thorium (Th) in the local crust contribute nearly half of the observed flux. In previous work, we developed a fully stochastic method to describe the 3D distribution of U and Th [1], along with a new geochemical approach to mitigate biases arising from non-ideal rock samples [2]. However, due to unknown structural correlations in geology, we had to adopt the most conservative assumption, which resulted in large uncertainties in the predicted flux.

In this talk, we will review our stochastic framework, discuss the correlation problem in the available geochemical datasets, and present our ongoing efforts to reduce this uncertainty. One promising approach, the use of nuclear emulsion to visualize U/Th distributions in rock samples, will be detailed in a separate presentation.

[1] A. Takeuchi et al., Phys. Earth Planet. Inter. 288 (2019) 37-57
[2] S. Enomoto et al., in "Core-Mantle Co-Evolution", ch. 2. (2013)

5

Revealing mantle heterogeneities with future directional geoneutrino detection

Author: Zhihao Xu[1]

Co-authors: Hiroko Watanabe [1]; William F. McDonough [2]

[1] *Tohoku University*

[2] *Tohoku University, JAMSTEC, University of Maryland*

According to geophysical studies, the Earth's interior is highly heterogeneous, containing large-scale structures. One of the most prominent features is the Large Low Shear Velocity Province (LLSVP), imaged by seismic tomography as regions with anomalously slow S-wave velocities relative to the surrounding mantle. Two major LLSVPs have been identified: one beneath the Pacific Ocean and the other beneath Africa. Several hypotheses have been proposed to explain the origin of such mantle heterogeneities. For example, LLSVPs may result from anomalous chemical compositions enriched in U, Th, and other elements, while an alternative hypothesis suggests that they are formed by the accumulation of downwelling mantle heat.

Geoneutrino detection provides a promising approach to probe this problem. Geoneutrinos, generated by the beta decay of radioisotopes inside the Earth, can traverse the planet with little interaction and be detected at the surface. However, previous measurements lack angular resolution, preventing the identification of their source regions. Recent advances, such as gadolinium-doped liquid scintillators that enhance neutron tagging, and segmented detector designs that improve event reconstruction, may enable geoneutrino observations with angular resolution.

In this study, we present a hypothetical exploration of the potential of future geoneutrino detectors equipped with angular resolution. Specifically, we evaluate how precise the angular resolution would need to be in order to identify mantle heterogeneities and to constrain the distribution of heat-producing elements within LLSVPs. Our results suggest that the optimal location for such a detector is near Hawaii, directly above the central Pacific LLSVP, highlighting the strong potential of ongoing projects such as the Ocean Bottom Detector (OBD) to eventually achieve this goal.

6

Development of a High-Speed Detection Method for Alpha Particle Tracks in Nuclear Emulsion Using Machine Learning

Author: Nishikiori TSUKASA[1]

Co-authors: Sanshiro Enomoto [2]; Satoru Haraguchi [3]; Tsutomu Fukuda [1]; Tsuyoshi Iizuka [4]; Nozomu Takeuchi [4]; Akiko Tanaka [5]; Kenta Ueki [6]; Hiroko Watanabe [7]; Shogo Nagahara [1]; Tsuyoshi Kawahara [1]; Tomokazu Matsuo [1]; Naotaka Naganawa [1]; Soichi Takeshita [1]; Akihiro Minamino [8]; Marin Takano [8]; Leona Suzui [1]

[1] *Nagoya University*

[2] *University of Washington*

[3] *Earthquake Research Institute, University of Tokyo*

[4] *University of Tokyo*

[5] *Geological Survey of Japan*

[6] *Japan Agency for Marine-Earth Science and Technology*

[7] *Tohoku University*

[8] *Yokohama National University*

Nuclear emulsion is a radiation detector composed of silver bromide crystals dispersed in gelatin that records charged-particle tracks as sequences of silver grains with submicron spatial resolution.

Although high energy tracks recorded in emulsion can be analyzed with the world fastest readout system (Hyper Track Selector 2: HTS2) , fast and precise detection of α-particle tracks has remained limited. In this study, motivated by geoneutrino measurements, we aim to precisely determine the distributions of uranium and thorium that constitute a dominant background. We expose emulsion to α rays emitted from rocks and apply the YOLO (You Only Look Once) object-detection framework to HTS2 images to accelerate track finding. This approach automatically and accurately identifies α tracks, shortening analysis time relative to manual visual inspection. The method enables visualization of the spatial distribution of α-emitting minerals in granite and thereby supports improved estimation of crustal radioelement distributions relevant to geoneutrinos. Quantitative evaluations of detection efficiency and false-positive rate are in progress. While machine-learning–based methods for nuclear emulsion have been reported, to our knowledge this is the first application that targets stand-alone detection of α-particle tracks. [1],[2]

[1]J. Yoshida et al., Nucl. Instrum. Meth. A, 989 (2021) 164930.
[2]A. Kasagi et al., Nucl. Instrum. Meth. A 1056 (2023) 168663.

7

Effect of Coeval Continents and LLVPs on Mantle Dynamics and Earth's Thermal Evolution

Author: Eric Mittelstaedt[1]

Co-authors: Hadeel Al Harthi [2]; Arnab Roy [1]; Catherine Cooper [2]; Anna Sage Ross-Browning [1]

[1] *University of Idaho*

[2] *Washington State University*

The Earth's mantle is bracketed by continental lithosphere above and Large Low Velocity Provinces (LLVPs) below, both of which can affect the efficiency of convective heat transfer within the mantle. Previous studies argue that continents act like insulators for the mantle, reducing surface heat flow and causing mantle temperatures to rise over time. In contrast, other studies show that LLVPs insulate the mantle from the core, reducing basal heat flow and lowering mantle temperatures over time. However, these studies have not considered the simultaneous effect of both insulators. Thus, the combined impact of competing basal and surface insulators on the global thermal state and mantle dynamics remains unclear. We aim to answer these questions and explore the effects of a dual-insulated system on mantle convection and Earth's thermal evolution.

We present results from a suite of convection simulations within a dual-insulated mantle system. Simulations are run in the finite-element code ASPECT, using a two-dimensional, spherical shell geometry and incorporating both the lithosphere and LLVPs. We examine models of increasing rheological and thermal complexity from isoviscous, bottom heated only simulations to models that include radiogenic heating with different concentrations of HPEs in the mantle, continent, and LLVP layers. In addition, we vary the surface coverages of the two insulators, from complete coverage to models without one or both insulators. The resulting effects on mantle temperature and dynamics will be compared between model conditions and to prior research on mantle convection with a single top or bottom insulator. We will discuss the implications of our findings on the thermal evolution of the Earth.

8

Predicted Sensitivity of Neutrino Oscillation Tomography to the Properties of Large Low-Velocity Provinces in the Lower Mantle

Authors: Eric Mittelstaedt[1]; Isabel GOOS[2]; Joao Coelho[3]; Nobuaki Fuji[4]; Stephanie Durand[5]; Veronique VanElewyck[6]; Yael Deniz[1]

[1] *University of Idaho*

[2] *APC, IPGP*

[3] *APC*

[4] *IPGP, IUF*

[5] *LGL-TPE*

[6] *APC, IUF*

Previous studies suggest that the enigmatic seismic anomalies known as Large Low Velocity Provinces (LLVPs), located atop the core-mantle-boundary, may arise from thermal anomalies or a combination of thermal and compositional effects, including the possible incorporation of hydrogen (i.e., water) into high-pressure phases of mantle minerals such as MgSiO3 and CaSiO3. However, the fundamental nature of LLVPs remains poorly understood, particularly their origin (thermal, or thermal and compositional), their composition and density contrast relative to the surrounding mantle, and the potential presence of hydrogen within LLVP material.

Neutrinos are neutral particles that come in three flavors: electron, muon, and tau. Electron and muon neutrinos are produced nearly isotropically in Earth's atmosphere and can traverse the planet due to their weak interaction with matter. As they travel, they undergo flavor transitions (neutrino oscillations) whose probabilities depend on energy, path length, and the electron number density (i.e., matter density × Z/A) of the materials they pass through. This dependence on matter properties enables probing Earth's interior by analyzing the distribution in flavor, energy, and arrival direction of atmospheric neutrino detection at dedicated detectors, in a technique known as Neutrino Oscillation Tomography of the Earth (NOTE). When present in a chemical composition, hydrogen produces a strong signature in the electron number density, significantly affecting oscillation probabilities and enhancing NOTE sensitivity. This makes NOTE a promising tool for detecting hydrogen in deep Earth regions and suggests it may offer direct sensitivity to the density and composition of LLVPs, providing a valuable complement to existing geophysical methods.

In this study, we assess the sensitivity of NOTE to variations in the density, composition, and water content of LLVP regions. Neutrino event distributions are simulated using three-dimensional Earth models and the OscProb framework to compute oscillation probabilities, incorporating parametrizations of detector response for reconstructing both neutrino energy and arrival direction. Two Earth models are considered: (i) a reference model based on the Preliminary Reference Earth Model (PREM), and (ii) a perturbed model containing a localized heterogeneous region with distinct density and compositional contrast, representing an LLVP. Sensitivity to these heterogeneities is quantified using a log-likelihood ratio test, enabling evaluation of the constraints that NOTE can place on the structure and composition of LLVPs.

9

How can neutrino observations bring new constraints to our understanding of the deep Earth

Authors: Eric Mittelstaedt[1]; Isabel GOOS[2]; Joao Coelho[3]; Nobuaki Fuji[4]; Stephanie Durand[5]; Véronique VAN ELEWYCK[None]; Yael Deniz[1]

[1] *University of Idaho*

[2] *APC*

[3] *CNRS / APC - Paris*

[4] *IPGP, IUF*

[5] *LGL-TPE*

Neutrino oscillation tomography offers an alternative way to probe Earth's deep interior, complementing classical geophysical and geochemical approaches. Neutrinos are subatomic particles that exist in three types, called "flavors": electron, muon, and tau. As they propagate, they can change from one flavor to another, a phenomenon known as neutrino oscillation. Because neutrinos interact only weakly with matter, they can essentially traverse the entire planet, while their oscillation patterns encode information about the electron density along their paths, which depends on both matter density and the proton-to-nucleon ratio (Z/A). Measuring these oscillations can thus provide constraints on Earth's composition and density variations.

In this contribution, we first introduce EarthProbe, the framework we use for forward modeling of neutrino oscillations in the Earth. We then use this tool to perform a sensitivity analysis, studying how neutrino oscillations depend on variations in the electron density of entire Earth layers. To assess the constraints that neutrino oscillation tomography can provide on Earth's structure, we begin with an idealized scenario, modeling its sensitivity to composition and density assuming a perfect detector. We then account for the response (i.e., resolution) of next-generation neutrino telescopes to derive realistic sensitivities. Our results show that while an ideal detector is most sensitive to the outer core, realistic detectors with lower resolution but large detection volumes shift the sensitivity toward shallower depths.

Finally, we present sensitivity kernels from neutrino oscillation tomography for a spherically symmetric Earth model, designed for use in inversions, potentially in combination with seismic data. We examine whether these kernels satisfy the mathematical requirements for inversion methods and discuss both their compliance and the limitations we identified, presenting preliminary results from a first inversion approach.

10

Atmospheric neutrino detection and Earth tomography with the KM3NeT detectors

Author: Véronique VAN ELEWYCK[None]

The KM3NeT Collaboration is incrementally building a network of water-Cherenkov neutrino observatories in the Mediterranean Sea, consisting of two telescopes, named ARCA and ORCA (respectively for Astroparticle and Oscillation Research with Cosmics in the Abyss), sharing the same detection technology. Owing to the different energy ranges covered by its two detectors, KM3NeT will perform both oscillation and absorption neutrino tomography using mainly atmospheric neutrinos. After describing the status of ORCA and ARCA and discussing the latest results obtained so far for atmospheric neutrinos with partial detector configurations, we will present preliminary sensitivity studies addressing the potential of the full KM3NeT detectors for neutrino tomography of the Earth.

11

Status and Prospects of the TRIDENT Neutrino Telescope

Author: Fuyudi Zhang[None]

Building on landmark detections of high-energy astrophysical neutrinos over the last decade, next-generation neutrino telescopes are poised to unlock insights into the most energetic phenomena in the Universe. TRIDENT is a developing neutrino observatory designed to significantly extend the reach and capabilities of current high-energy neutrino experiments. Located 3.5 km deep in the South China Sea, TRIDENT will instrument approximately 10 km^3 of seawater with kilometer-long strings of advanced photosensitive modules. The primary goals of the experiment are to rapidly discover multiple astrophysical neutrino sources, and strongly boost the measurement precision of their neutrino flavor composition. This talk presents the current status and recent progress of TRIDENT, including the imminent deployment of Phase-1, featuring the first 10 detector strings. Prospects of the experiment are also discussed point-source discovery potential, flavor discrimination capabilities, and sensitivity to supernova burst neutrino signals.

12

Novel Method for Rare Event Detection

Author: Jackson Seligman[1]

Co-authors: Brian Crow [1]; Hiroko Watanabe [2]; Jeffrey Yepez [1]; John Learned [3]; Max Dornfest [1]; Nathan Sibert [1]; Viacheslav Li ; William F. McDonough [4]; Zhihao Xu [2]

[1] *University of Hawaii at Manoa*

[2] *Tohoku University*

[3] *University of Hawaii*

[4] *Tohoku University, JAMSTEC, University of Maryland*

Using the Chooz method on segmented detectors has limitations when discussing multiple distributed nonhomogeneous sources, and identification between sources; something that we wish to understand about Earth's core-mantle boundary (CMB). Using our new method of neutrino directionality, we aim to solve these problems by implementing a new mathematical framework in the directional analysis of neutrino sources.

This talk will specifically focus on this method as an alternative to the Chooz method, justify the math behind it, and discuss its applications to geoneutrino sources located in the crust and upper mantle.

13

A NOBL Pursuit - Neutrino Ocean Bottom Laboratory

Author: Max Dornfest[1]

Co-authors: Brian Crow [2]; Hiroko Watanabe [3]; Jackson Seligman [2]; Jeffrey Yepez [2]; Liz Kneale [4]; Nathan Sibert [2]; Ono Takanobu [3]; Steve Dye ; William F. McDonough ; Zhihao Xu [3]

[1] *University of Hawaii at Manoa - Physics and Astronomy Dept.*

[2] *University of Hawaii at Manoa*

[3] *Tohoku University*

[4] *University of Sheffield*

Understanding the composition and homogeneity of the Earth's core-mantle boundary (CMB) is crucial to understanding the radiogenic heat of the Earth and the science of planetary formation. This talk discusses our work at the University of Hawai'i (UH) in collaboration with Tohoku University on an neutrino ocean bottom detector (OBD) with the goal of observing the CMD.

I will specifically focus on design constraints and ideas, pertaining to our risk assessment whitepaper and on-going work with Station Aloha, UH's ocean bottom experiment site 100km north of Oahu, 5 km below the surface.

14

Radiogenic heat production in the Earth's mantle: Implications for the structure and dynamics of continental cratons

Authors: Claire Currie[1]; Kristina Kublik[1]; Graham Pearson[1]

[1] *University of Alberta*

The tectonic plates form the upper thermal boundary layer of Earth's mantle convection system. In the oldest continental regions (the cratons), the lithospheric plate thickness can exceed 200 km. The thickness and stability of the craton lithosphere is controlled by its thermal structure, which in turn depends on the vigour of the underlying mantle convection and the thermal properties of the lithosphere itself. One key uncertainty arises from the amount of heat generated by the decay of radioactive elements within the craton mantle lithosphere. Estimates based on xenolith measurements and geotherm modeling suggest heat production of 0.01–0.06 μW·m-3. However, these relatively high values may reflect samples biased toward regions of lithosphere that were modified by fluids or melts. A recent study by McIntyre et al. (2021) shows that unmodified mantle lithosphere may have negligible heat production (<0.0001 μW·m-3), whereas refertilized or metasomatized mantle may reach values of 0.006 μW·m-3. Xenoliths are small samples of Earth's lithosphere, proximal to melt transfer channels. Developing improved methods for integrating heat production over larger volumes of lithospheric mantle would yield new constraints on how representative xenolith heat production estimates are.

The magnitude of heat production has important consequences for lithospheric structure and evolution. Steady-state geotherm calculations show that for a given surface heat flow, a lower heat production results in higher temperatures in the craton mantle and thus a thinner lithosphere (by 10-80 km). Such differences influence the long-term stability of cratons and their capacity to host diamonds. Geodynamic models demonstrate that even modest increases in deep lithosphere temperature reduce the strength, making cratons susceptible to destabilization and thinning. Furthermore, localized areas of elevated heat production may create weak regions that promote intraplate deformation. Constraining the spatial distribution of heat-producing elements in craton mantle is therefore crucial for understanding craton longevity and the broader thermal evolution of Earth.

15

Geoneutrino observation with KamLAND

Author: TBA[None]

KamLAND is marked by ability to detect low energy anti-neutrino signals with 1,000 tons of ultra pure liquid scintillator. This feature has the sensitivity to detect geo-neutrinos produced by the decay of 238U and 232Th within the Earth. Owing to the long-term shutdown of Japanese reactors, the flux of reactor anti-neutrinos has been significantly reduced, and the data yield greater sensitivity for geo-neutrinos. Our decade-long measurement, including the reactor-off period, has the level of accuracy possible for adding constraints on composition models of the Earth, and the indicated geo-neutrino measurement provides key information for understanding the Earth. We will present our geoneutrino observation results and future prospects.