Neutrino Geoscience 2019 Prague

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Book of Abstracts

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Old Truths and new Views on the Formation and Evolution of the Earth

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Significant progress has been made in our understanding of Earth's formation, composition, and dynamical evolution, however, many first-order problems remain to be solved. In this overview talk I will recap our current view on Earth's history, from the collapse of the solar system's parental molecular cloud core to the emergence of a habitable planet. Along the way I will introduce key concepts of cosmo- and geochemistry and present novel (analytical) approaches that may allow to tackle some of the major open questions.

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Introduction to Geoneutrinos

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This is a brief introduction to start the conference. I will introduce geoneutrinos and the geoscience motivation for studying them. I will highlight upcoming talks in this conference, drawing attention to current experiments and future objectives in this field.

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Dynamics and Energetics of Earth's Core

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A fundamental goal in deep Earth geophysics is to explain the existence of the geomagnetic field for at least the past 3.5 billion years. The field is thought to be generated by turbulent motion of the liquid iron core and so there must have been sufficient power available to keep this dynamo process operating over most of Earth's history. Power is made available to the dynamo as heat is extracted from the core by the overlying rocky mantle. In the standard picture of core evolution, cooling releases heat and leads to freezing of the alloy from Earth's centre thus forming the solid inner core. As the inner core freezes, latent heat is released and the light elements in the mixture partition preferetially into the liquid phase, mixing the core and providing a very efficient power source. Determining the age of the inner core is therefore critical to understanding the thermal, chemical and dynamical history of the core and geomagnetic field. To achieve this requires coupled models of long-term core-mantle evolution that utilise robust determinations of the structural and dynamical properties of Earth materials.

Models of the core's thermal and magnetic history have undergone something of a revolution in recent years following the first calculations of thermal and electrical conductivity of iron alloys at the enormous pressure and temperatures of the deep Earth. These calculations found the core thermal conductivity to be 2-3 times higher than existing estimates based on extrapolation of lower pressure-temperature data, which drastically reduced estimates of the inner core age from 1-1.5 billion years old to perhaps less than 0.5 billion years old. Moreover, these calculations gave rise to the so-called "new core paradox", which claims that there was insufficient energy to drive the ancient geodynamo prior to inner core nucleation. Subsequent work has identified new potential power sources for the ancient dynamo by arguing that solids (e.g. MgO and/or SiO2) could precipitate from the liquid near the top of the core. However, there is still debate surrounding the conductivity calculations and the efficiency of precipitation, while the power provided to the dynamo by radiogenic elements is still poorly understood.

In this talk I will review the energetics and long-term dynamics of the coupled core-mantle system. I will discuss the role of thermal conductivity and precipitation mechanisms and consider the implications of our changing view of core evolution for models of mantle dynamics.

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Geoneutrino flux integration without underestimation of errors

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Following two talks on construction of stochastic crustal model, one by Takeuchi et al. focusing on Bayesian inference of lithology model and one by Ueki / Iizuka et al. focusing on bias-free composition model, we will discuss geoneutrino flux calculation using those models. As commonly done, Monte-Carlo integration was performed here, but we found that proper correlation modeling is necessary on this, which seems not commonly being done, presumably because the problem has not been widely noticed. We show that neglecting correlations, or neglecting crustal inhomogeneity for similar effects, will result in too small errors than deducible from inputs. To complete our calculation, we conservatively assumed maximum correlation, but the resultant flux prediction has too large errors to be usable. We also briefly discuss our on-going effort, as well as its prospects, to model the correlations in order to reduce the final uncertainty to a level comparable to observation errors.

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WINTERC-grav: a new upper mantle thermochemical model constrained coupled geophysical-petrological inversion of seismic waveforms, heat flow, surface elevation and gravity satellite data

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Conventional methods of seismic tomography, topography and gravity data analysis constrain distributions of seismic velocity and density at depth, all depending on temperature and composition of the rocks within the Earth. However, modelling and interpretation of multiple data sets provide a multifaceted image of the true thermochemical structure of the Earth that needs to be appropriately and consistently integrated. A simple combination of gravity, petrological and seismic models alone is insufficient due to the non-uniqueness and different sensitivities of these models, and the internal consistency relationships that must connect all the intermediate parameters describing the Earth involved. In fact, global Earth models based on different observables often lead to rather different, even contradictory images of the Earth.
Here we present a new global thermochemical model of the lithosphere-upper mantle (WINTERC-grav) constrained by state-of-the-art global waveform tomography, satellite gravity (geoid and gravity anomalies and gradiometric measurements from ESA's GOCE mission), surface elevation and heat flow data. WINTERC-grav is based upon an integrated geophysical-petrological approach where all relevant rock physical properties modelled (seismic velocities and density) are computed within a thermodynamically self-consistent framework allowing for a direct parameterization of the temperature and composition variables.

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Borexino: Latest Improvements of the Geoneutrino Results

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Borexino is a 280-ton liquid scintillator detector located at the Laboratori Nazionali del Gran Sasso (LNGS), Italy and is one of the two detectors that has measured geoneutrinos so far. The unprecedented radio-purity of the scintillator, the shielding with higly purified water, and the placement of the detector at a 3800 m w.e. depth have resulted in very low background levels and has made Borexino an excellent apparatus for geoneutrino measurements. This talk will summarize the latest geoneutrino analysis with Borexino, using the data obtained from December 2007 to April 2019. Enhanced analysis techniques, such as an increased fiducial volume, improved veto for cosmogenic backgrounds, extended energy and coincidence time windows, as well as a more efficient α/β particle discrimination have been adopted in this measurement. The updated statistics and these elaborate techniques have led to more than a factor two increase in exposure and an improvement in the precision from 26.2% to 17.8%, when compared to the previous measurement in 2015. The talk will highlight the geological interpretations of the obtained results, namely, the estimation of the mantle signal by exploiting the relatively well-known lithospheric contribution, the calculation of the radiogenic heat, as well as the comparison of these results to the various predictions. Even though the results are compatible with all the Earth models, there is a 2.4σ tension with those models that predict the lowest concentration of heat-producing elements inside the mantle. Additionally, we present the upper limits for a hypothetical georeactor that might be present at different locations inside the Earth.

Poster session / 36

Analysis Strategies for the Updated Geoneutrino Measurement with Borexino:

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Borexino is a 280-ton liquid scintillator detector located at the Laboratori Nazionali del Gran Sasso (LNGS), Italy. It measures antineutrinos via the Inverse Beta Decay reaction and is one of the two detectors that has measured geoneutrinos so far. The updated statistics and the improved analysis techniques have led to a precision of around 18%. The new analysis adopts an enlarged fiducial volume, sophisticated veto for cosmogenic backgrounds, extended energy and coincidence time windows, as well as a more efficient α/β particle discrimination. The evaluation of all relevant backgrounds is also of key importance. This includes reactor antineutrinos, cosmogenic ^{9}Li background, accidentals, (α, n) background due to ^{210}Po contamination, and the different kinds of minor backgrounds that might affect the analysis. The final geoneutrino result was obtained via an unbinned likelihood fit of the charge spectrum of prompt candidates. The main aim of this poster is to summarize the analysis strategies and the various backgrounds, that might be useful for next generation geoneutrino measurements with liquid scintillator detectors.

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JULOC□A Local 3-D High-Resolution Crustal Model in South China for Forecasting Geoneutrino Measurements at JUNO

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Geothermal energy is one of the keys for understanding the mechanisms for driving the plate tectonics and mantle dynamics. The surface heat flux, as measured in boreholes, provide limited insights into the relative contributions of primordial versus radiogenic sources of the interior heat budget. Geoneutrino, electron antineutrino that produced from the radioactive decay of the heat producing elements, is a unique probe that obtain direct information about the amount and distribution of heat producing elements in the crust and mantle. Cosmochemical, geochemical, and geodynamic compositional models of the Bulk Silicate Earth (BSE) individually predicts different mantle neutrino fluxes, and therefore may be distinguished by the direct measurement of geoneutrinos. Due to low counting statistics, the results from geoneutrino measurements at several sites are inadequate to resolve the geoneutrino flux. However, the JUNO detector, currently under construction in South China, is expected to provide an exciting opportunity to obtain a highly reliable statistical measurement, which will produce sufficient data to address several vital questions of geological importance.
However, the detector cannot separate the mantle contribution from the crust contribution. To test different compositional models of the mantle, an accurate estimation of the crust geoneutrino flux based on a three-dimensional (3-D) crustal model in advance is important. This paper presents a 3-D crustal model over a surface area of 10□ × 10□ grid surrounding the JUNO detector and a depth down to the Moho discontinuity, based on the geological, geophysical and geochemical properties. This model provides a distinction of the volumes of the different geological layers together with the corresponding Th and U abundances. We also present our predicted local contribution to the total geoneutrino flux and the corresponding radiogenic heat. Compared to previous studies, our method has helped to effectively reduce the uncertainty of geoneutrino flux prediction by constructing the composition of the surface layer through cell by cell which are independent to each other.

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Earth tomography with KM3NeT/ORCA

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The deep-sea neutrino detector KM3NeT/ORCA, currently being built in the Mediterranean Sea near Toulon (France), is optimized for the study of oscillations of atmospheric neutrinos in the few-GeV energy range, with the main goal to determine the neutrino mass hierarchy. This is possible due to matter effects that modify the probability of neutrino oscillations along their path through the Earth. Measuring the energy and angular distributions of neutrinos with ORCA can therefore also provide tomographic information on the Earth's interior and more specifically on the electron density along the trajectory of the detected neutrino, complementary to standard geophysics methods.
In this contribution the latest results of a study of the potential of ORCA for Earth tomography are presented. They are based on a full Monte Carlo simulation of the detector response and including systematic effects. It is shown that after ten years of operation ORCA can measure the electron density in both the lower mantle and the outer core with a precision of a few percent in the case of normal neutrino mass hierarchy.

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Geo-neutrino program at Baksan Neutrino Observatory

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A new neutrino program has been recently lunched at Baksan Neutrino Observatory. It is planned to deploy a 10-kiloton scale detector based on liquid scintillator in the existing shaft at a depth of 4800 m.w.e.. Baksan underground laboratory is profitable in terms of low reactor neutrino flux and well measured backgrounds originating from natural radioactivity. Therefore, the experiment is well suited for geo-neutrino measurements and will enforce the world-wide effort. Besides that this detector has a good potential for registration of solar neutrinos and neutrinos from supernova explosions.

As a preparatory stage, a detector prototype with target mass of 0.5 ton and equipped with 20 10-inch PMTs is currently under construction. Another prototype of 5-ton target mass is planned for the next year. The expected performance of the first prototype and the prospects of the future multi-kiloton detector will be reported.

Poster session / 21

Geoneutrino measurements with Borexino: implications for geoscience

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Borexino is a 280-ton liquid scintillator detector located at Laboratori Nazionali del Gran Sasso (Italy) measuring geoneutrinos from 238U and 232Th decay chains through inverse beta decay of free proton. The improved geoneutrino analysis of some 3263 days of data, taken by Borexino between December 2007 and April 2019, is candidate to provide useful insights into the composition of the Earth's interior as well as into its radiogenic heat budget.
We present the geological implications of the geoneutrinos signal results through a comparison with

the predictions of different Bulk Silicate Earth models. Based on the knowledge of abundances and distributions of U and Th in the lithosphere, the mantle signal is extracted from the spectral fit of the Borexino measurement. Considering different scenarios about natural radioactivity in the deep Earth, the measured mantle geoneutrino signal has been converted to radiogenic heat. The convective Urey ratio is also extracted adopting the total radiogenic heat estimation. Finally, constraints on lower limits of U and Th abundances in the mantle are reported.

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Reference Models for Lithospheric Geoneutrino Signal

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Geophysical models are combined with geochemical datasets to predict the geoneutrino signal at current and future geoneutrino detectors. We propagated uncertainties, both chemical and physical, through Monte Carlo methods. Estimated total signal uncertainties are on the order of $\sim$20%, proportionally with geophysical and geochemical inputs contributing $\sim$30% and $\sim$70%, respectively. Estimated signals, calculated using CRUST2.0, CRUST1.0, and LITHO1.0, are within physical uncertainty of each other, suggesting that the choice of underlying geophysical model will not change results significantly, but will shift the central value by up to $\sim$15%, depending on the crustal model and detector location. Similarly, we see no significant difference between calculated layer abundances and bulk-crustal heat production when using these geophysical models. The bulk crustal heat production is calculated as 7 ± 2 terrawatts, which includes an increase of 1~TW in uncertainty relative to previous studies.

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The Mantle's Radioactive Power - Understanding the Geoneutrino Signal

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Although many assume we know the Earth's abundance and distribution of radioactive heat producing elements (i.e., U, Th, and K), estimates for mantle's heat production varying by an order of magnitude and recent physics findings challenge our dominant paradigm. Geologist predict the Earth's budget of radiogenic power at 20±10 TW (terrawatts, 10^{12} watts), whereas the physics experiments predict $11.2^{+7.9}_{-5.1}$ TW (KamLAND, Japan) and $38.2^{+13.6}_{-12.7}$ TW (Borexino, Italy).

We welcome this opportunity to highlight the fundamentally important resource offered by the physics community and highlight the shortcomings associated with the characterization of the geology of the Earth. We review the findings from the continent-based, physics experiments, the prediction from geology, and assess the degree of misfit between the physics measurements and the predicted models of the continental lithosphere and the underlying mantle. Because our knowledge of the continents is so weak, models for the mantle and the bulk silicate Earth continue to be uncertain by a factor of $\sim$30 and $\sim$4, respectively. Detection of a geoneutrino signal in the ocean, far from the influence of continental, offers the potential to resolve this tension and offer an powerful tools to interrogate the composition of the continental crust.

Poster session / 46

Heat flow from the core and the thermal evolution of the Earth

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The role of heat flow coming from the Earth's core has long been overlooked or underestimated in simple models of Earth's thermal evolution. Throughout most of Earth's history, the mantle must have been extracting from the core at least the amount of heat that is required to operate the geodynamo. In view of recent laboratory measurements and theoretical calculations indicating a higher thermal conductivity of iron than previously thought, the above constraint has important implications for the thermal history of the Earth's mantle. In this paper we construct a paramaterized mantle convection model that treats both the top and the core-mantle thermal boundary according to the boundary layer theory, and employs the model of Labrosse (2015) to compute the thermal evolution of the Earth's core. We show that the core is likely to provide all the missing heat that is necessary in order to avoid the so-called "thermal catastrophe" of the mantle. Moreover, we analyze the mutual feedback between the core and the mantle, providing the necessary ingredients for obtaining thermal histories that are consistent with the petrological record and have reasonable initial conditions.

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GIGJ: a crustal gravity model of the Guangdong Province for predicting the geoneutrino signal at the JUNO experiment

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Geoneutrino signal measured by a liquid scintillator detector placed on the continental crust is dominated by the natural radioactivity of the closest geological units, which can be modelled by gravimetric methods. In particular, recent satellite missions have provided the scientific community with

highly accurate and homogeneously distributed gravimetric data, offering an extraordinary opportunity to probe the regional structure of the crustal layers surrounding a geoneutrino detector.
GIGJ (GOCE Inversion for Geoneutrinos at JUNO) is a 3-D numerical model constituted by about 46×10^3 voxels of $50 \times 50 \times 0.1$ km, built by inverting GOCE (Gravity field and steady-state Ocean Circulation Explorer) gravimetric data over the $6° \times 4°$ area centered at the JUNO (Jiangmen Underground Neutrino Observatory) experiment, currently under construction in the Guangdong Province (China). GIGJ results from a finely tuned Bayesian inversion that combines the GOCE gravimetric information with deep seismic sounding profiles, receiver functions, teleseismic P-wave velocity models and Moho depth maps, each of them weighted according to their own accuracy and spatial resolution. Some mathematical regularization is also introduced in order to obtain smooth discontinuity surfaces between crustal layers, as well as smooth lateral and vertical density variations. GIGJ is retrieved by maximizing the posterior probability distribution through Monte Carlo Markov Chains methods and by testing different values of the input regularization parameters. Its estimated uncertainty comprises an estimation error associated to the solution of the inverse gravimetric problem and a systematic error related to the adoption of a fixed sedimentary layer.
GIGJ fits the GOCE gravimetric gravity data with a standard deviation of the residuals of about 1 mGal, compatible with the observation accuracy and thus confirming the good performance of the inversion algorithm. Whereas global crustal models (e.g., CRUST 1.0) report for the upper, middle, and lower crust an equal thickness corresponding to 33% of the total crustal thickness, GIGJ provides a site-specific subdivision of the crustal masses. The consequence of this local rearrangement of the crustal layer thicknesses is a reduction of about 21% and an increase of about 24% of the geoneutrino signal produced by unitary uranium and thorium abundances in the middle and lower crust, respectively. The contribution of the upper crust is basically unchanged. These results are supported by a significant reduction of their estimation uncertainty. Compared to global models, the uncertainty of the estimated geoneutrino signal at JUNO is in fact reduced by 77%, 55%, and 78% for the upper, middle, and lower crust, respectively. The numerical model is available at the website http://www.fe.infn.it/radioactivity/GIGJ.

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Quantifying Geochemical Anomalies in the Mantle Using Geoneutrinos

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Earth crust, enriched in heat producing elements such as U and Th, has been recycling into the mantle. Particular models envisage the material to sink deep to the core mantle boundary and form seismically observed Large Low Shear Velocity Provinces. Other models propose erosion and transport of continental crustal material by subduction, which could lead to the assembling of upper crustal materials that are gravitationally stabilized relatively shallow at the base of the Transition Zone, at some 600 to 700 km depth. If the recycled material remains enriched by U and Th, it would form a geochemical mantle anomaly, which can be imaged using geoneutrinos. We investigate such a possibility in favorable location is the East Asia, where currently operating KamLAND experiment will be in the near future accompanied by JUNO and Jinping detectors. We also investigate the option of using movable Ocean Bottom Detector to explore vast areas of the mantle beneath the oceans. We show that we can successfully detect geochemical mantle anomalies using geoneutrinos, if the amount of the subducted material is large enough and it keeps its high enrichment of U and Th. We discuss the imaging limits based on the size and degree of enrichment of these mantle anomalies. Such a method is complementary to the other geophysical techniques and it specifically reveals the compositional distinctions in the mantle.

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Geoneutrino Measurement at JUNO

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The Jiangmen Underground Neutrino Observatory (JUNO) is a multipurpose experiment currently under construction at an equal distance of 53 km from two nuclear power plant complexes in southern China, Yangjian and Taishan, with foreseen start of data taking in 2021. The experiment will primarily study reactor antineutrino oscillations with the goal of determining the neutrino mass hierarchy at the level of ~3σ and of measuring three oscillation parameters (θ_{12}, Δm^2_{31}, Δm^2_{31}) with <1% precision. Antineutrinos will be detected in the 20 kt liquid scintillator central detector, which will be the largest and most precise of its kind in history. In addition to reactor antineutrinos, the experiment will collect an unprecedentedly large sample of geoneutrinos. The measurement of the geoneutrino flux provides important constraints on the abundance of Earth's radiogenic elements and is of much interest to the geoscience community. The JUNO experiment aims to measure this flux with ~5% precision in 10 years. The precision depends heavily on the knowledge of the reactor antineutrino spectrum, the dominant background for geoneutrinos in JUNO. The ~1 t JUNO-TAO reference detector, placed at 30 m from one of Taishan's reactor cores, will be built to measure the shape of the reactor neutrino energy spectrum with very high statistics and an unprecedented resolution. The overview of the JUNO experiment and its current status will be discussed, with a focus on the challenges and opportunities of the geoneutrino measurement.

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Geoneutrino Contributions from the Deep Lithosphere

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Calculations of the expected lithospheric contribution to the geoneutrino signal are essential for understanding the radiogenic power of the mantle. The density structure and distribution of heat producing elements (HPEs) and their uncertainties in the deep crust must be modeled in order to interpret Earth's U and Th abundances. Such calculations prove challenging because the deep crust is sampled only sparsely through high grade metamorphic lithologies. We can make in situ measurements, however, of the seismic velocity of the deep crust. We use empirical and theoretical relationships between composition and measured seismic wave velocity to derive deep crust silica content. Using a joint probability analysis, we then model U as a function of silica. A conserved chondritic Th/U ratio allows us to predict the U and Th content of the deep crust and its contribution to the geoneutrino signal.

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Geo-neutrinos in SNO+

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SNO+ is a multipurpose, low background, liquid scintillator neutrino detector. It is located 2km underground at SNOLAB in Sudbury, Canada. It is currently being filled with 800 tonnes of liquid scintillator, after the successful completion of the water phase of the experiment. Once the detector is filled, studies into several physics topics will begin, including reactor antineutrinos and geo-neutrinos. After the scintillator phase, 4 tonnes of tellurium will be loaded into the liquid scintillator as the primary objective of SNO+ is to search for the neutrinoless double-beta decay of Te-130.

SNO+ can observe geo-neutrinos coming from the uranium and thorium decay chains via inverse beta decay reactions with protons in the liquid scintillator. The measured geo-neutrino flux will be compared with KamLAND and Borexino results in a global analysis to help constrain models of radiogenic heat production in the deep Earth. This talk will present the current status of the SNO+ detector and the geo-neutrino measurement prospects.

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Detecting 40K geoneutrinos with LiquidO

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From 25% to 70% of Earth's internal heat budget is deemed to be generated by the radioactive decays of the so-called heat producing elements (i.e. U, Th and K). Potassium, the only semi-volatile element among them, seems to show from 10% to 30% of its expected chondritic abundance, making thus uncertain any heat balance estimation. Two theories stand on the possible fate of "missing K": i) segregation of potassium into the core or ii) loss to space during planetary accretion. No experimental corroboration allows confirmation of these hypotheses yet. As a consequence, our knowledge on Earth's internal heat budget and its thermal evolution has to rely on compositional models.
Direct geoneutrino detection however permits to constrain, at least in part, Earth's radiogenic heat production and its Urey ratio. Unfortunately, present state-of-the-art detection techniques based on Inverse Beta Decay (IBD) on free protons only permit the detection of geoneutrinos having an energy above 1.8 MeV, leaving 40K-geoneutrinos (whose endpoint is at 1.3 MeV) impossible to detect. Detection via NC interactions such as elastic scattering has been proposed, however, solar and radioactivity backgrounds remain challenges limiting its feasibility.
The novel LiquidO detection technique* allows to enable for the first time the observation of 40K-geoneutrinos. LiquidO opaque detection medium allows for unprecedented particle identification and large loading capabilities for neutrino detection. A clear identification of single positrons event topology is possible upon CC interactions of geoneutrinos. This feature opens the door for the exploitation of loaded isotopes leading to new IBD interactions, making thus possible to lower the minimum detectable antineutrino energy.
A review of possible target candidates able to detect 40K-geoneutrinos will be here presented together with their IBD cross-section and the corresponding expected signal for four different potential experimental sites. A few novel possible isotope targets are presented here for the first time. The detection significance and the statistical uncertainty will then be discussed together with a possible methodology for the 40K-geoneutrino signal extraction.

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* Cabrera A. et al. - Neutrino Physics with an Opaque Detector - arXiv:1908.02859 - 2019

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Terrestrial 40K geoneutrinos and Solar CNO neutrinos

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Value of the Earth thermal flux is estimated through temperature gradient method (47 TW). There are exist other ways of heat transfer to the Earth surface from inside, so total heat flux is unknown yet. Non-direct measurements establish Earth thermal flux on the level 200-300 TW. To produce so high flux one needs to add heat produced by 40K to the known isotopes 238U and 232Th. Exact value of potassium in the Earth is unknown. To estimate its content we need to measure 40K antineutrino flux on the surface of the Earth. The problem that solar neutrino fluxes from CNO cycle look very similar to 40K flux. It is needed independent experiment on measuring solar CNO neutrinos to distinguish between 40K and CNO fluxes in a large scintillation detector (e.g. Borexino). We propose to use 115In as a target (R. Raghavan's idea) for solar CNO neutrinos. New type of a detector proposed.

Poster session / 18

Effect of the overburden on the geoneutrino signal at SNO+

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The SNO+ detector is designed to achieve several fundamental physics goals as a low-background experiment, particularly measuring the Earth's geoneutrino flux. The detector is located at SNO-LAB, one of the deepest underground laboratories in the world with an overburden of 2092 m. The goeneutrino signal from originated from the 50 × 50 km upper crust surrounding the detector is estimated adopting a refined 3D model and a full calculation of survival probability. Specifically, the effect of the 2 km overburden on the predicted crustal geoneutrino signal at SNO+ is evaluated. A signal difference corresponding to the ~5% of the total crustal contribution, is found comparting this signal with that obtained by placing SNO+ at sea level.

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Global Crustal Thickness and Velocity Structure From Geostatistical Analysis of Seismic Data

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Active source seismology provides a critical constraint on the global crustal structure. However, the heterogeneous data coverage means that interpolation is necessary to fill the gap between seismic profiles. This has the potential to cause large uncertainties especially if the data are interpolated over a large distance. In previous models, geological intuition was often employed to ensure reasonable results. To investigate crustal model uncertainty, we apply geostatistical analysis to a database of active seismic investigations. Unlike previous models, our workflow in the construction of the crustal model is completely transparent. Apart from the points from the database, we only use an a priori separation in oceanic and continental domains. We calculate global maps of Moho depth and average P wave velocity in the crystalline crust. Additionally, we obtain the interpolation error and error covariance. Overall, our results agree with previous global crustal models such as Crust1.0. Our uncertainty estimates show that the Moho depth uncertainty in the most well studied areas such as North America and Europe is less than 4 km but can reach 10 km or more in frontier regions such as most of Africa. P wave velocity shows the same pattern, but is less accurate overall, due to more small-scale variation. We demonstrate the benefit of having a numerical estimate of uncertainty by propagating the uncertainty to the residual topography. We see two main uses for our crustal model in the geophysical research community: (1) as a starting model for inversions focusing on the crust and upper mantle and (2) as a starting point for including other pointwise information about crustal structure, for example, from passive seismology.

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Mantle convection, plate tectonics and the thermo-chemical evolution of the Earth

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The coupled system of convection of the solid, rocky mantle of the Earth and plate tectonics is the main driver of long-term Earth evolution, being responsible for continental drift, earthquakes, volcanoes, crustal building, mountain building, heat loss from the core that drives the geodynamo, and outgassing/ingassing of volatiles to/from the atmosphere (particularly CO2 and water). The Earth started from a hot, molten state (magma ocean) and has been cooling since then, with radiogenic heating reducing the rate of cooling, although there is considerable uncertainty in the relative proportions of heat loss coming from radiogenic heating and cooling.
The mantle-plate system must be treated as thermo-chemical because there is continuous chemical differentiation caused by partial melting, which results in the production of oceanic and continental crust and has profound implications for the structure of the interior. Another complexity is that plate tectonics may not always have existed; there is much debate about what tectonic mode may have preceded it, and this has a strong effect on early thermo-chemical evolution.
Here, these various aspects are reviewed, uncertainties and important future research directions highlighted.

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Crust modeling with quantitative and objective uncertainty estimation

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Geoneutrino observations, first achieved by KamLAND in 2005 and followed by Borexino in 2010, have accumulated statistics and improved sensitivity for more than ten years. The uncertainty of the geoneutrino flux at the surface is now reduced to a level small enough to set useful constraints on U and Th abundances in the bulk silicate earth (BSE). However, in order to make inferences on earth's compositional model, the contributions from the local crust need to be understood within a similar uncertainty. Here we develop a new method to construct a stochastic crustal composition model utilizing Bayesian inference. While the methodology has general applicability, it incorporates all the local uniqueness in its probabilistic framework.

In our method, we consistently use explicit PDFs for all relevant quantities. We utilize Bayesian inference techniques to model the 3-D lithology map by combining seismological data as "observation" with a prior model constructed from local exposure. By using seismological tomography, we avoid the difficulty of dealing with the upper / middle / lower crust classification and boundary definition. For rock composition, we adopt a gamma distribution model, which does not bias the mean value estimation (unlike the log-normal model) and fits consistently well to both highly-skewed and close-to-normal distributions (for which neither log-normal nor normal distributions apply). Convolving the obtained PDFs of lithology distribution map and rock composition, we construct 3-D PDFs of U and Th concentrations.

At the time of the presentation, after showing the flow chart of our modeling method, we will discuss the key features of our lithology map inference. Our lithology model represents a probabilistic distribution map and allows quantitative studies with error estimations, making it fundamentally different from previous models. Note that the probabilistic representation allows us to construct probability density functions and thus errors of various physical quantities (such as abundance of radioactive elements, total mass of the crust, and geoneutrino flux) evaluated from the lithology distribution model, while the deterministic statements only allow estimation of central values. We also discuss the plausibility of our prior and the obtained posterior together with future topics for further improvements.

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Geochemical modeling for no-bias balance calculation

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We report a stochastic modeling of 3-D compositional distribution within the Japan arc crust over three sequential talks by Takecuhi et al., Iizuka et al., and Enomoto et al. In this second talk, we present a new geochemical modeling for rock composition. For calculation of the neutrino flux using the mass of U and Th, conservation of the mean value between input data distribution and a modeled probability density function (PDF) is critical. We show that a gamma distribution model does not bias the mean value estimation and fits consistently well to both highly-skewed and close-to-normal distributions. This is not the case for the log-normal distribution model that has been widely used in geochemistry including geoneutrino modeling studies. In addition, we demonstrate a method to properly treat samples below analytical detection limits. By applying these new methods to newly collected geochemical datasets of rock samples from the Japan arc, rock composition PDFs were constructed for individual rock types. The results demonstrate the importance of proper

geochemical modeling for no-bias neutrino flux calculation and further allow us to link the variable rock compositions to underlying geologic processes.

Poster session / 13

Probing the Earth Core Composition with Neutrino Oscillation Tomography

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Atmospheric neutrinos open the way to alternative probing methods to study the structure and composition of the inner Earth, complementary to geophysical methods. At GeV energies, the flavour oscillations of neutrinos crossing the Earth are distorted due to coherent forward scattering on electrons along their path. The signature of these matter effects in the neutrino angular, energy and flavour distributions may provide sensitivity to the electron density, and thus the composition, in the different layers traversed. The combination of this neutrino-based measurement with a reference mass density profile constrains the effective proton-to-nucleon ratio of the medium (Z/A), providing new insights into the chemical composition of the inner Earth, and in particular its core, whose content in light elements is still controversial.

Such a measurement requires large-sized neutrino detectors with good efficiency in the relevant energy range and precise determination of the neutrino energy, arrival direction, and flavour. Considering a generic but realistic model of detector response, we discuss the influence of various detector performance indicators on the sensitivity to the average Z/A in the core. Starting from specific examples of the next-generation detectors (ORCA, DUNE), we also identify the main improvements required to reach a measurement of the H content of the core at the 1 wt% level.

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Hunting the K40 Geoneutrinos

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Potassium, K, element is volatile, and its precipitation is not the same as refractory U and Th elements in the Earth. A measurement of the K elements in the Earth is of interest to understand the chemical evolution of the Earth. Furthermore, the discussion on the Ar40-K40 system of the air, and the crust and upper mantle is one of the supports for the depleted and enriched two-layer mantle structure. The detection of K40 neutrinos may lead to new knowledge of the Earth. Previously only U and Th geoneutrinos can be detected with the inverse beta process with a 1.8 MeV threshold. K40 geoneutrinos are hard to discover for its low energy and high solar neutrino background. In this work we found that Liquid scintillator Cherenkov neutrino detectors can be used to detect the K40 geoneutrinos. Liquid scintillator Cherenkov detectors feature both energy and direction measurement for charge particles. With the elastic scattering process of neutrinos and electrons, K40 geoneutrinos can be detected without any intrinsic physical threshold. With the directionality, the

dominant intrinsic background originated from solar neutrinos in common liquid scintillator detectors can be suppressed. With the studies of MeV electrons Geant4 simulation, quantum and detection efficiency, and Cherenkov direction reconstruction algorithm, it is found that we can detected K40 energy geoneutrinos with 3 standard deviations with a kilo-ton scale detector. We are on the cutting edge to reveal this geoneutrino component in the near future. The result and relevant features will be reported.

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Antineutrino Directional Measurement

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The liquid scintillator detectors have the sensitivity for measuring total amount of geo-neutrinos from the Earth's crust and mantle. However, we do not have the technology to track the direction of incoming geo-neutrinos at present due to the high miss-identification in a neutrino's track reconstruction. The direction- sensitive detector can map out the U and Th distribution inside the Earth and this technic is also applicable to resolving crust versus mantle contributions.The status of technological development and overview of new ideas for directional measurement will be presented.

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Geoneutrino measurement with KamLAND

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KamLAND, Kamioka Liquid-scintillator Anti-neutrino Detector (Japan), utilizes 1 kton liquid scintillator and reported the first experimental study of geo-neutrino in 2005. In 2011, KamLAND geoneutrino measurement results were used to estimate the Earth's radiogenic heat production and constrain composition models of the bulk silicate Earth (BSE). Following the Fukushima reactor accident in March 2011, the entire Japanese nuclear reactor industry, which generates the most serious background for geo-neutrino measurement, has been subjected to a protected shutdown. This unexpected situation allows us to improve the sensitivity for geo-neutrinos. KamLAND geoneutrino results will be presented including new data set.

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Ocean Bottom Detector : toward direct measurement of mantle geoneutrinos

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Geoneutrinos bring unique and direct information on the Earth's composition, which relate to the fundamental mysteries of its heat balance and thermal evolution. To date, we have set limits on the global flux of geo-neutrino that has in turned constrained the range of acceptable models for the Earth's composition, but distinguishing the mantle flux by current detectors, which are all locate on the crust is a challenge, as the crust signal is about 70 % of the total flux plus uncertainties. Given that the oceanic crust is thin and simple, geo-neutrino detector in the ocean makes it sensitive to geo-neutrinos originating from Earth's mantle. Ocean bottom geoneutrino detector represents a breakthrough, which goes beyond the impossibilities of the modern land-based detector, providing transformative insights into the deep Earth.
In 2019, Tohoku University and JAMSTEC started to collaborate to promote the idea of Ocean Bottom Detector. Recent situation of our study will be presented.

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Progress of Jinping Neutrino Experiment Program

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China Jinping underground laboratory is an ideal place for geoneutrino observation. No nuclear reactors are within 1000km, making the geoneutrino signal-to-noise ratio to be more than 5:1. The site is on the corner of the world's thickest crust, tibet plateau, giving more statistics to pin down Th/U ratio by neutrinos.

With 4500 kton-day exposure, more than 500 geoneutrinos will be observed. The geoneutrino flux will be measured to 4% precision and Th/U ratio to be 27%. The data will also be able to confirm or reject the geo-reactor hypothesis of 3-10TW at that exposure.

At this stage, we are focusing on building a ~100-ton scale detector for testing key detection technologies for the ultimate design and aim for the first observation of geoneutrinos from the tibet plateau.

Poster session / 41

Crustal density structure of South China and South China Sea

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The deep structure and its density of South China block and the north margin of the South China Sea is important to understand the regional tectonic evolution and interaction of continent and oceanic plate. The density structures also provide the basic parameters for geoneutrino flux estimation in Jiangmen, China. Based on the gravity data, we inverse the 3D density structure and give the basic geology structures in the study region. The geology structures and the rock physical properties

from previous geophysical works are used for constrains in this study. In the final result, we give the density structure from Crust to the upper Lithosphere.

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Neutrino Research in the Czech Republic

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The talk will provide overall insight to the research in the neutrino physics field carried on by the institutions in the Czech republic. It will cover various experiments starting with the neutrino oscillation on accelerators and nuclear reactors, respectively.The NOvA, DUNE, Daya Bay and JUNE experiments will be described. Furthermore it will be discussed the Katrin experiment for the direct neutrino mass measurement, and finally neutrino-less double decay experiments.

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Reactor Antineutrino Flux and Spectrum

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Reactor antineutrinos are a major source of background in geoneutrino detection. The precise knowledge of their rate and the shape of the energy spectrum is crucial for unbiased geoneutrino flux measurement. In this talk, I will review the current theoretical and experimental knowledge of reactor antineutrino flux and spectrum, with a focus on the most recent results from the Daya Bay experiment.

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Welcome + official kick-off

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poster mini-presentations

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discussion

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discussion and closing remarks