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Unveiling the Earth's mantle with directional geo-neutrino measurements

Stephen Dye & Michael Leyton
University of Hawaii, Manoa & Pasadena City College

UNIVERSITY of HAWAIʻI® MĀNOA

Purpose and context

Radioactive decays are responsible for 25–65% of the Earth's total heat flow. The geo-neutrinos produced by these decays in the Earth's crust and mantle provide important clues about the origin, formation and thermal evolution of our planet, as well as the composition of its interior.

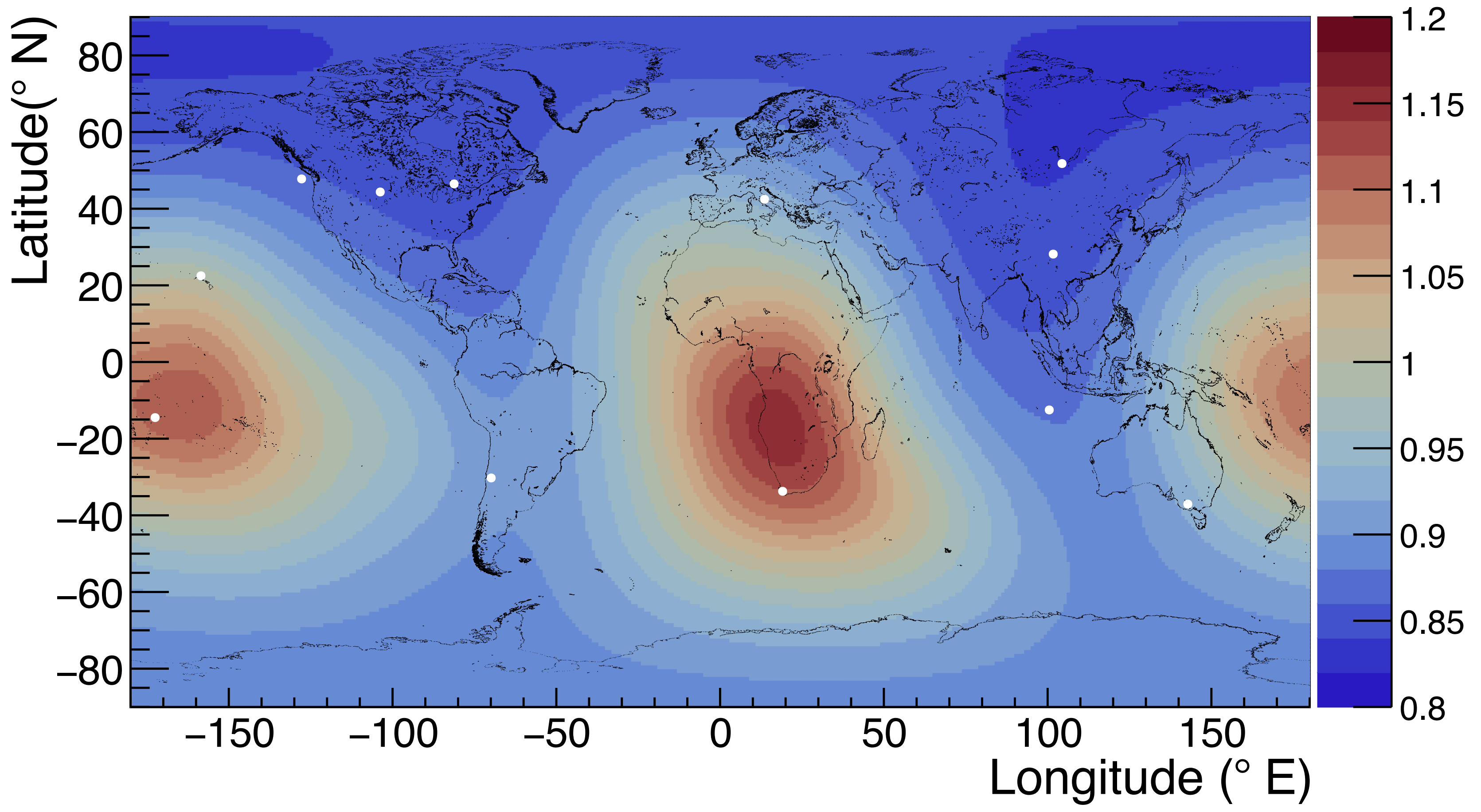
Existing measurements of geo-neutrinos are all non-directional and unable to provide empirical information about the location or spatial distribution of geo-neutrino sources within the Earth. These measurements therefore suffer from large uncertainties when estimating the geo-neutrino contribution from the mantle. A measurement with directional information would help reduce large uncertainties on the primordial vs. radiogenic contributions to the Earth's total heat flow, with important implications on current thermal evolutionary models of our planet.

In this poster, we explore the potential for directional geo-neutrino measurements to reveal the contribution from the Earth's mantle. We calculate the exposure and angular resolution needed to probe mantle geo-neutrinos for various continental and oceanic sites around the world.

Geo-neutrino model

- **Crust geo-neutrinos**: We use the CRUST 1.0 [1] seismological model to define the geophysical properties of the crust, using average abundances of thorium and uranium in each of the geological reservoirs from geochemistry.
- **Mantle geo-neutrinos:** We model the mantle in two ways:
    - *Uniform mantle:* a spherical shell with homogenous abundances of uranium and thorium throughout, as given by the Preliminary Reference Earth Model [2]. We use the same elemental abundances as in the crust.
    - *LLVP mantle*: seismic tomography provides evidence of deep mantle structures called large low-velocity provinces (LLVPs) in the Central Pacific and underneath Africa. These structures could have elevated levels of uranium and thorium compared to the surrounding mantle, depleting the remainder of the mantle with respect to the uniform mantle model. We use the S40RTS model with $\delta V_s/V_s < -0.4\%$ [3, 4].

Figure 1: Map of the mantle geo-neutrino flux for the LLVP model with $\delta V_s/V_s < -0.40\%$ relative to the uniform mantle model. The studied sites (see Figure 3) are marked with white dots.



Reactor neutrino model

- **Reactor geo-neutrinos**: We use 2024 average load factors for > 400 operational nuclear power reactors in all IAEA Member States. We assume a PWR/BWR power spectrum for all cores and apply neutrino oscillation parameters from NuFit 6.1 [5], with normal mass ordering, as a function of neutrino energy and reactor distance.

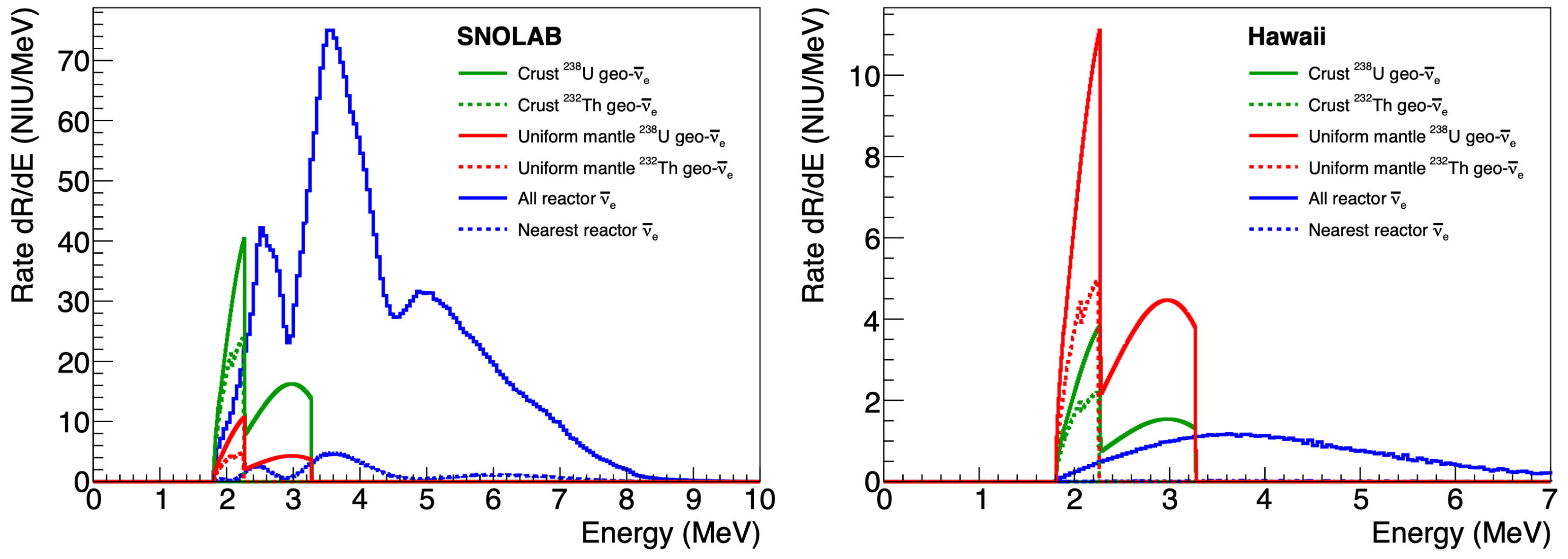


Figure 2: Predicted event rates (NIU/MeV) as a function of neutrino energy (MeV) at a terrestrial site (SNOLAB, *left*) and an oceanic site (Hawaii, *right*). Event rates are calculated using the inverse beta decay cross section from [6]. 1 NIU = 1 Neutrino Interaction Unit = 1 interaction / 10^{32} targets / year.

Analysis

The predicted rate of inverse beta decay interactions is calculated for all studied neutrino types (Figure 2) using the cross section from [6]. An average oscillation survival probability of 0.549 is assumed for all geo-neutrino interactions. We then estimate the sensitivity of a direction-sensitive detector to geo-neutrinos from the mantle as a function of detector exposure and angular resolution, assuming either a uniform mantle or LLVP mantle model.

- At each of the studied sites, we simulate a large (>500M) sample of geo- and reactor-neutrino events, according to the predictions discussed here. Incident azimuthal and polar angles are smeared by a Gaussian distribution whose width is equal to the indicated angular resolution. Energies are also smeared assuming a resolution of $5\%/\sqrt{E_{vis}}$, where E_{vis} is the visible energy in the event, calculated as $E_{vis} = E_\nu - 0.784$ MeV.
- For a given detector exposure and angular resolution, we run a set of 1000 pseudo-experiments, drawing randomly from the simulated distributions and then fluctuated according to the statistical error on the predicted event rates.
- For each pseudo-experiment, we assume that the pseudo-data contains both background and signal and calculate the 90% confidence interval for excluding the null (no mantle) hypothesis. We then calculate the detector exposure required to exclude the null hypothesis for 90% of simulated pseudo-experiments.
- Confidence intervals are calculated using a profile likelihood statistic, taking into account systematic uncertainties on the measured signal and predicted background distributions. We apply a flat ±7% systematic uncertainty on all pseudo-data, a ± 15% uncertainty on the geo-neutrino flux from the crust, and a ± 3% uncertainty on the reactor neutrino flux.
- An energy threshold of $E_{vis} < 2.5$ MeV, corresponding to the endpoint energy of the geo-neutrino spectrum, is used for this study to enhance the signal-to-background ratio and optimize the sensitivity of the analysis. This cut accepts 99-100% of geo-neutrino events and approximately 26-28% of reactor-neutrino events, with some variation across sites.

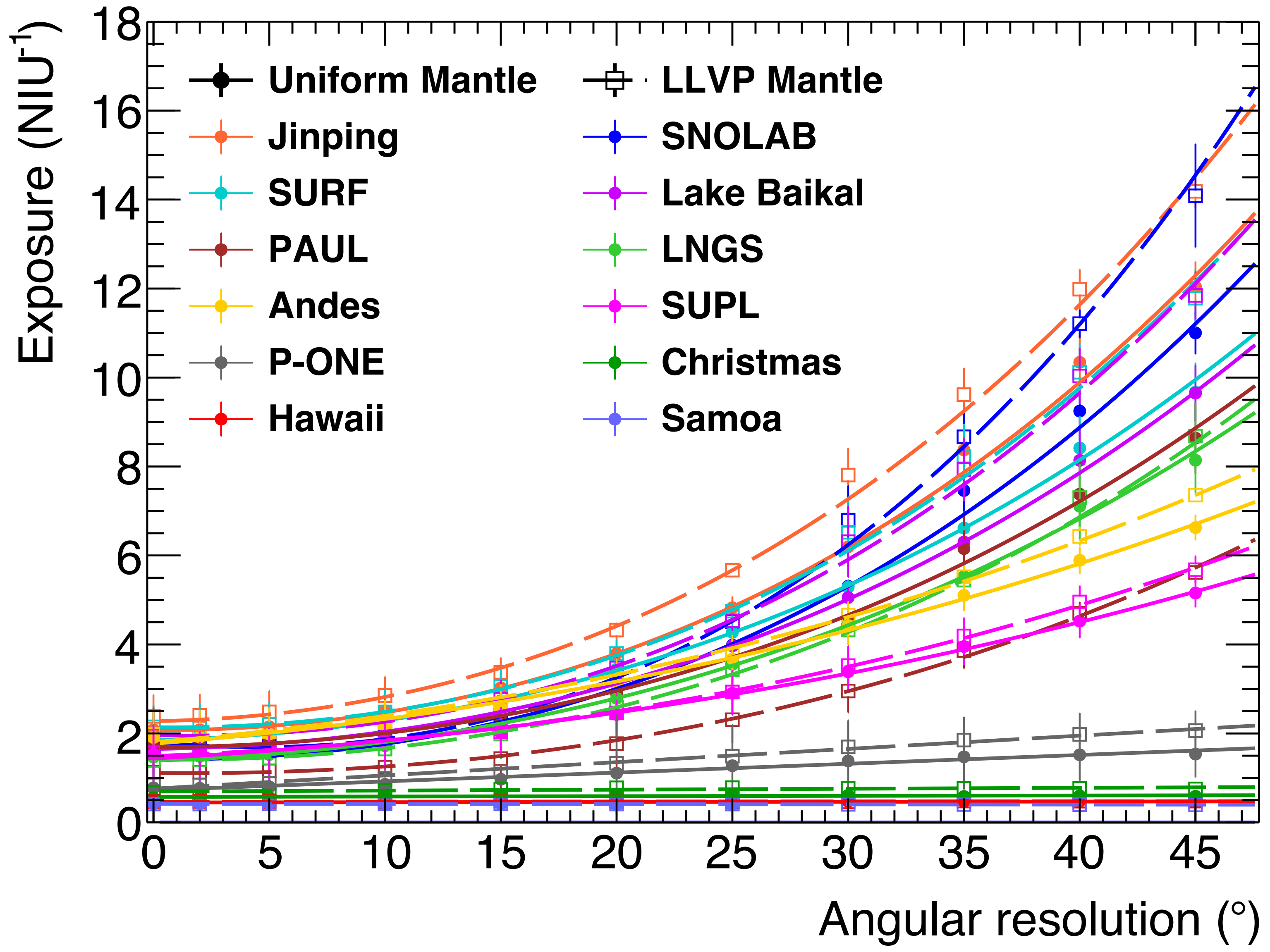


Figure 3: Detector exposure (NIU^{-1}) required to exclude the null hypothesis for 90% of signal + background pseudo-experiments at 90% CL at the 8 terrestrial sites and 4 oceanic sites studied here. Two mantle models are compared at each site: uniform mantle and LLVP model with $\delta V_s/V_s < -0.40\%$ relative to the uniform model. 1 NIU^{-1} = 10^{32} target years.

Discussion

Our results indicate that directional reconstruction of inverse-beta-decay neutrino interactions, with modest angular resolution, can identify geo-neutrinos from the Earth's mantle by discriminating against crust geo-neutrino and reactor neutrino backgrounds commonly thought of as irreducible. A detector located at SURF or SNOLAB could make a measurement of mantle geo-neutrinos with an exposure of 5–7 NIU^{-1}, assuming an angular resolution of 30˚.

Oceanic sites (P-ONE, Christmas, Hawaii, Samoa) require significantly smaller exposures (< 2 NIU^{-1}) to positively identify the mantle geo-neutrino signal, in comparison to the continental sites studied here. Furthermore, the required exposure calculated at each of the four oceanic sites is largely independent of angular resolution, owing to the absence of nearby continental crust and nuclear reactors, as well as their proximity to the mantle through the thin oceanic crust.

These results show that directional reconstruction can significantly improve mantle signal-to-background discrimination at continental sites. Comparing geo-neutrino measurements at multiple sites, e.g. PAUL & SNOLAB or Samoa & Christmas, would enable geo-neutrino tomography for resolving large-scale heterogeneities in the mantle.

References

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Contact

Dr. Michael Leyton
Pasadena City College
Email: mleyton@pasadena.edu