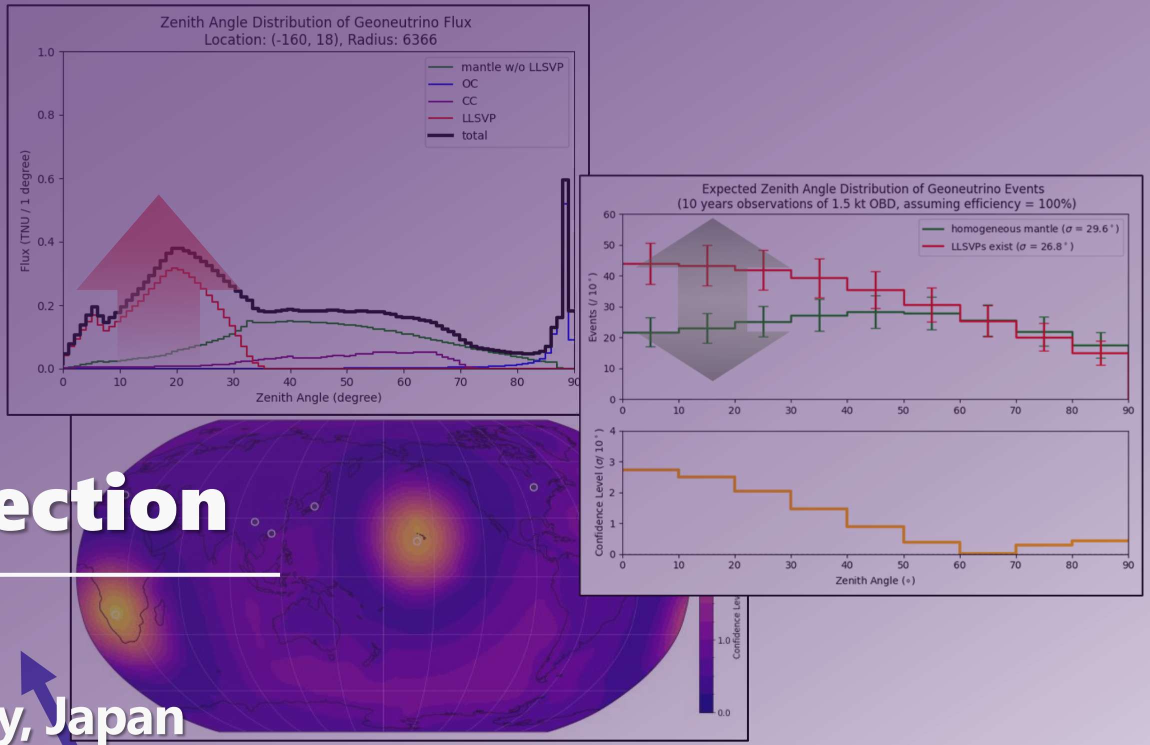
Revealing
Mantle Heterogeneities
with Directional Geoneutrino Detection



<u>Zhihao Xu</u>, for OBD Working Group

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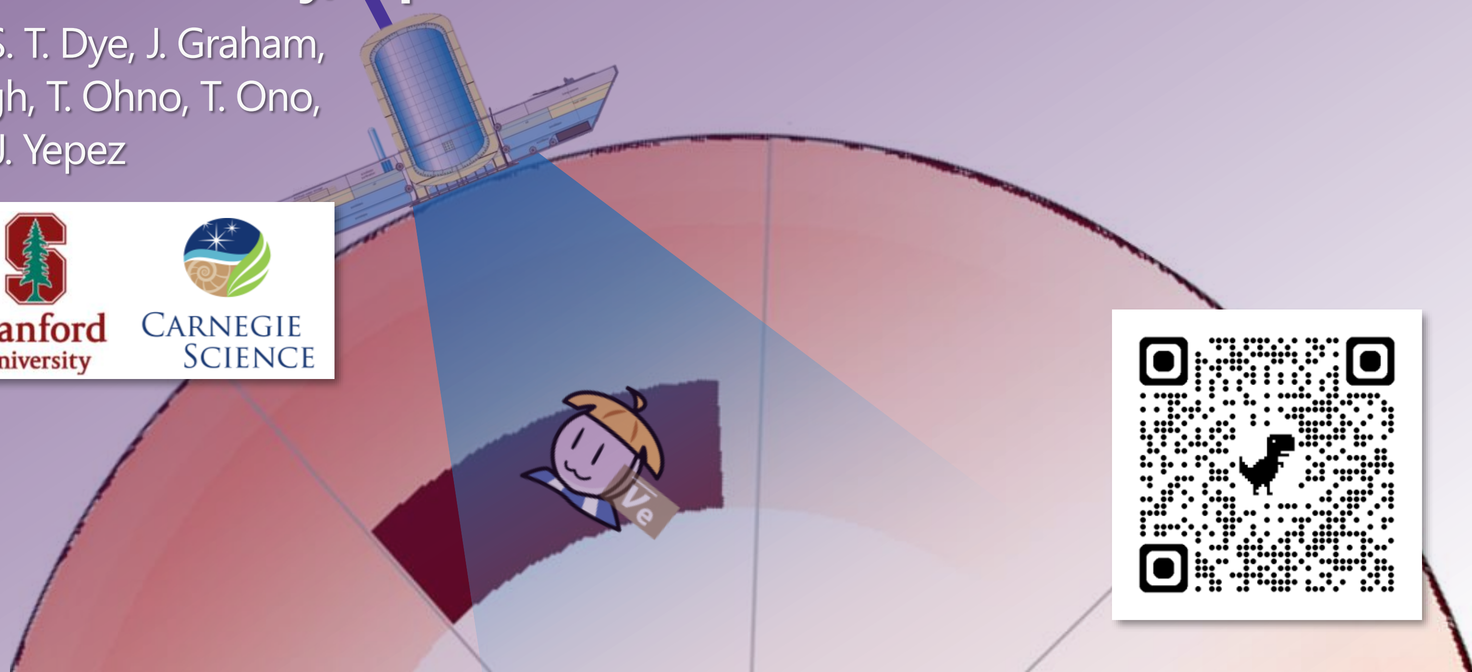
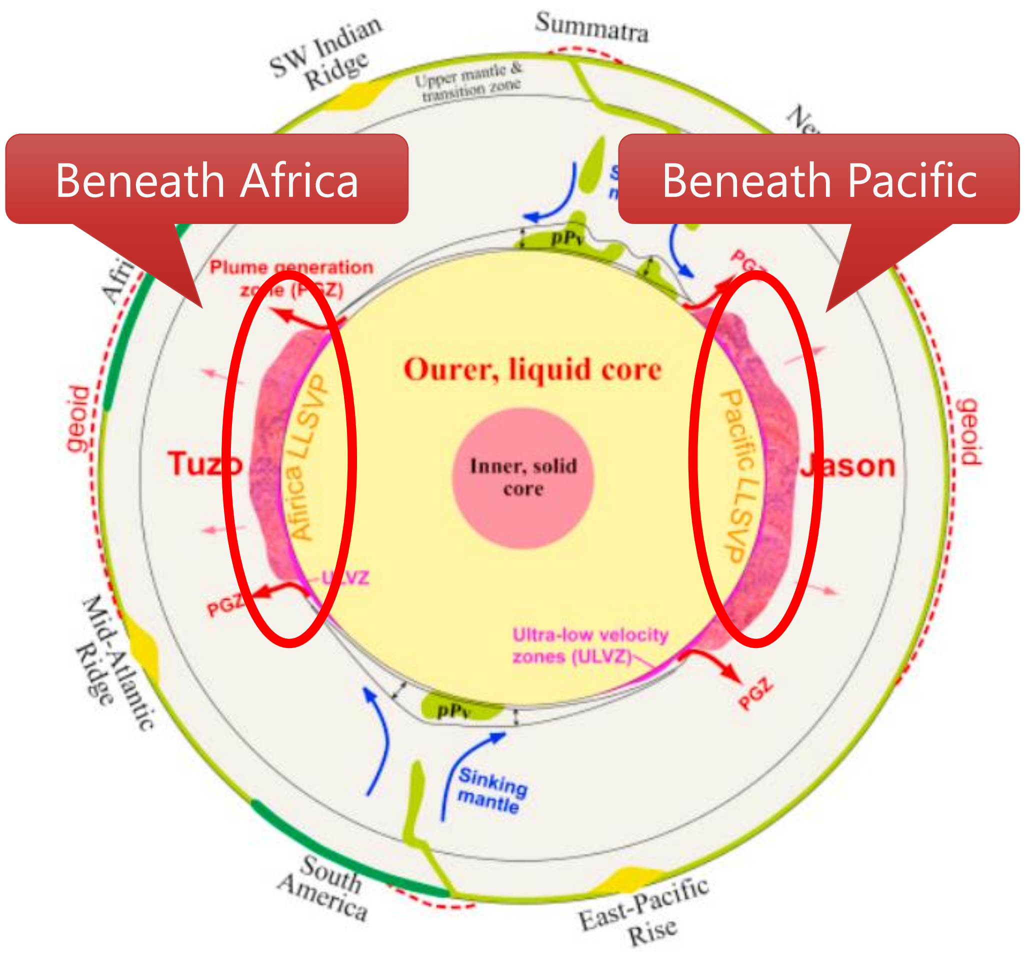
M. Hosoya, K. Inoue, J. G. Learned, V. A. Li, W. F. McDonough, T. Ohno, T. Ono,
T. Sakai, J. Seligman, N. Sibert, D. Vartanyan, H. Watanabe, J. Yepez



Mantle heterogeneity

- **LLSVP:** Large Low Shear Velocity Province



- **What do we know?**
  - Slow earthquake wave velocity
  - 2 LLSVPs
  - Extremely huge (~10% of mantle)

- **What don't we know?**
  - What made this mantle heterogeneity?

Abnormal chemical composition?
(Rich in U, Th, …)

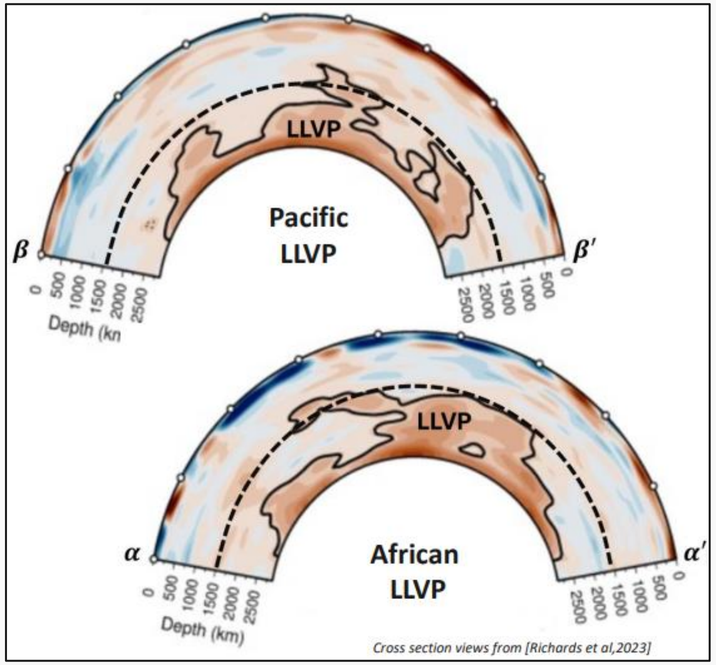
VS

Abnormal thermal structure?
(Accumulated downwelling mantle heat)

Motivation & Background

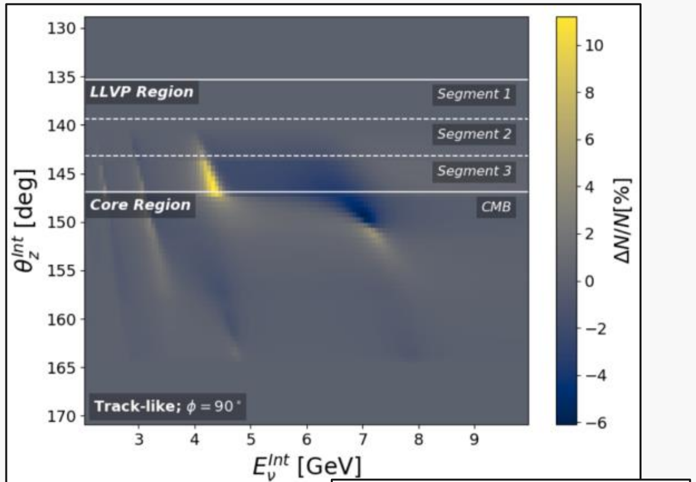
Revealing mantle heterogeneity

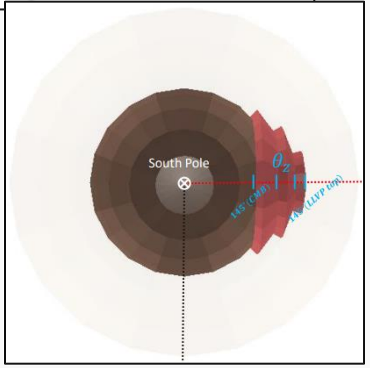
seismic tomography



Cross section views from [Richards et al,2023]

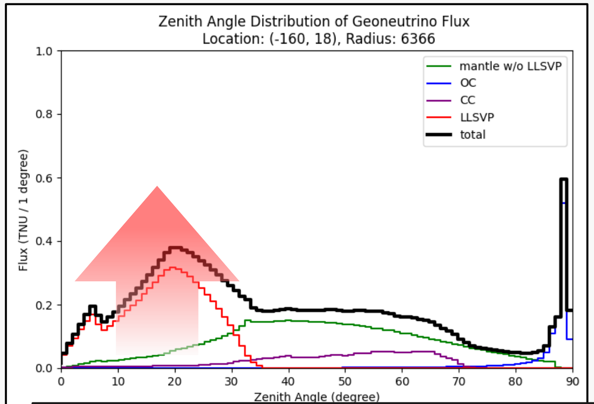
neutrino oscillation

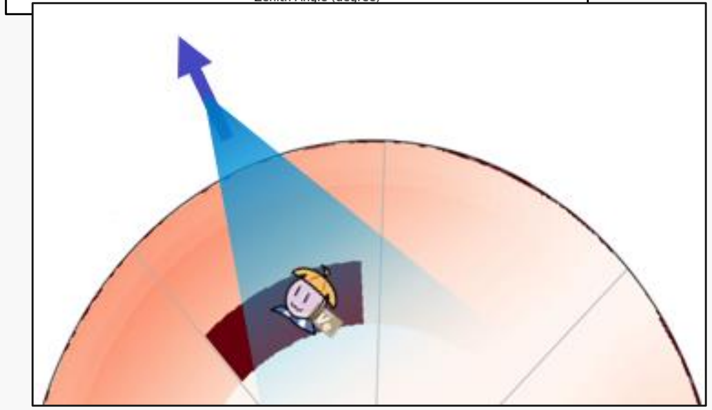




Also see Yael's talk (29th 14:00)

geoneutrino detection





Measuring density profiles

Measuring chemical profiles

Geoneutrino

- **Geoneutrino:** elementary particles generated by radioactive decay within Earth's interior.
- **First detection:** KamLAND (*Nature*, 2005)
- KamLAND's detection was continued to 2024… *Also see Nanami's talk (27th 11:30)*

Heat from U & Th inside the earth

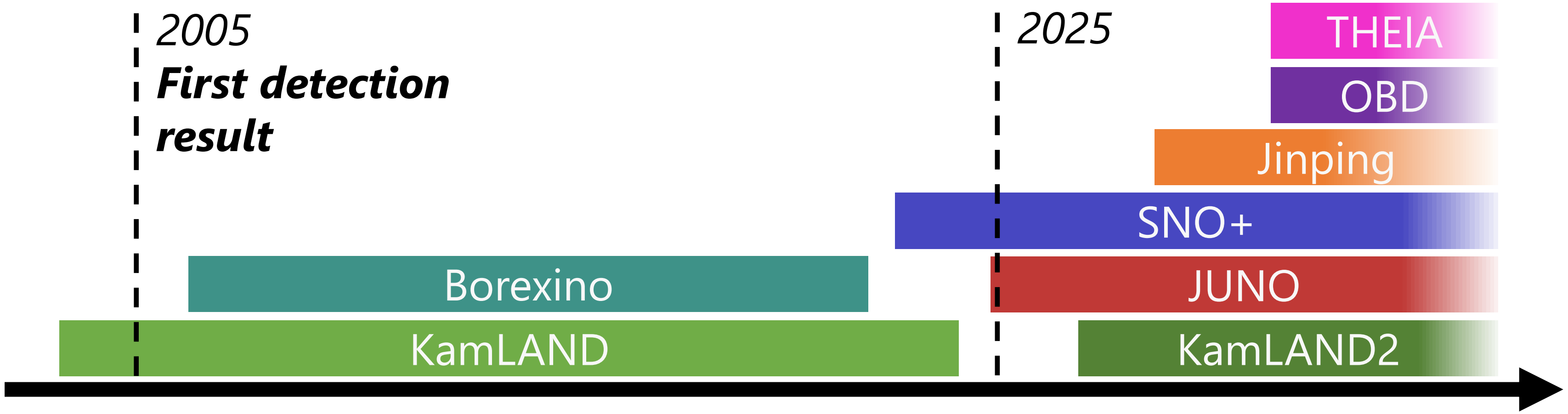
$15.4^{+8.3}_{-7.9}$ TW
(KamLAND, 2022)

Th/U mass ratio in the earth

5.82 ± 4.10
(Li & Xin, 2024)

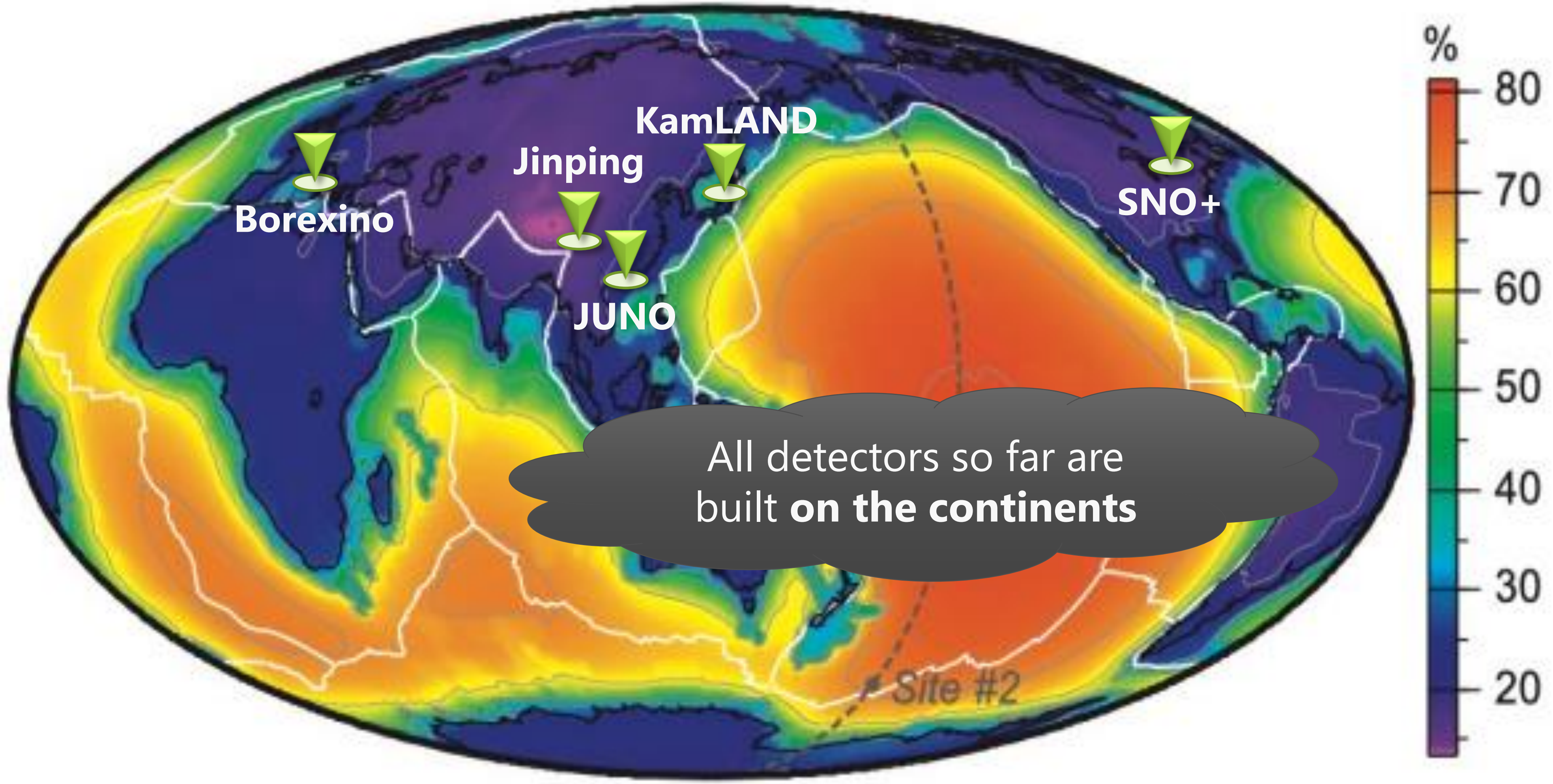
The only way to measure chemical abundances inside the bulk Earth

- More and more detectors are starting geoneutrino detections.


2005
First detection result
2025

Problem so far

Fraction of mantle-derived geoneutrinos (Šrámek et al, 2013)



All detectors so far are built **on the continents**

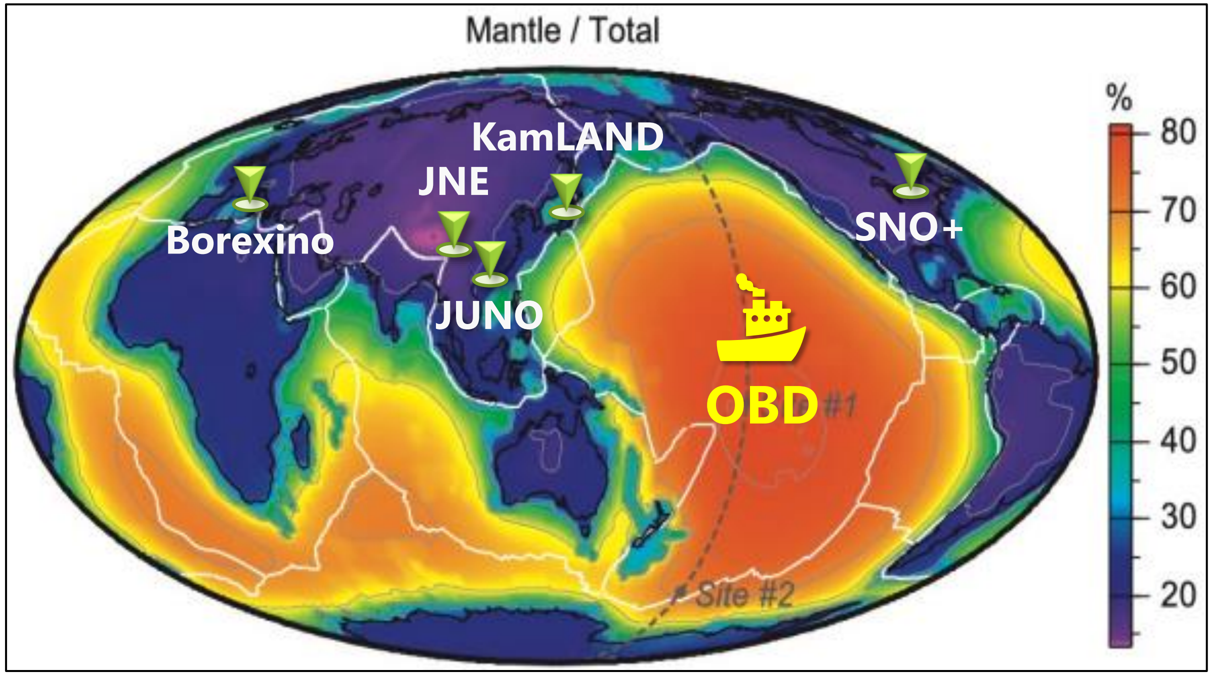
Ocean Bottom Detector (OBD)

- Continental crust is not suitable for geoneutrino detection.

Thick

Contain abundant radioisotopes

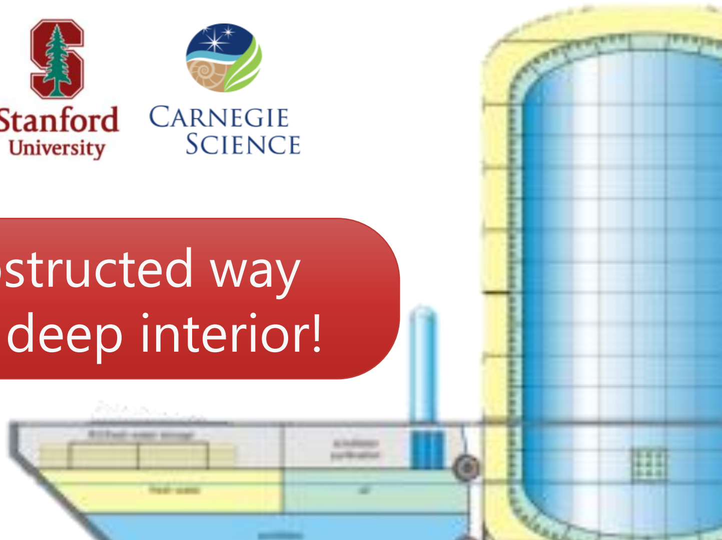
Geoneutrino signals originating from the deep Earth are highly masked.



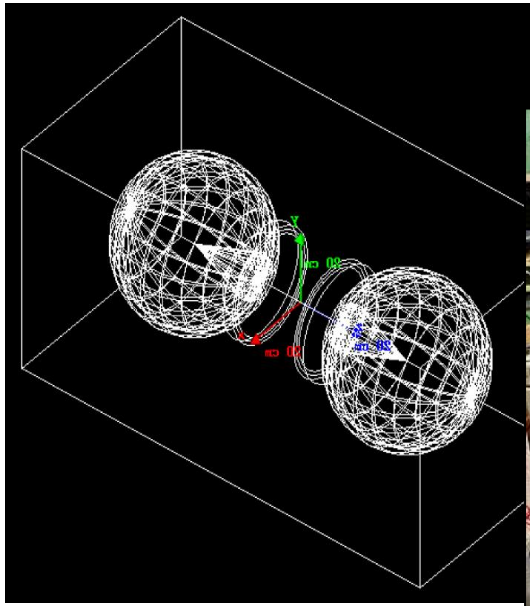
- **Ocean Bottom Detector (OBD)**
  - 1.5 kt LS detector @Hawaii

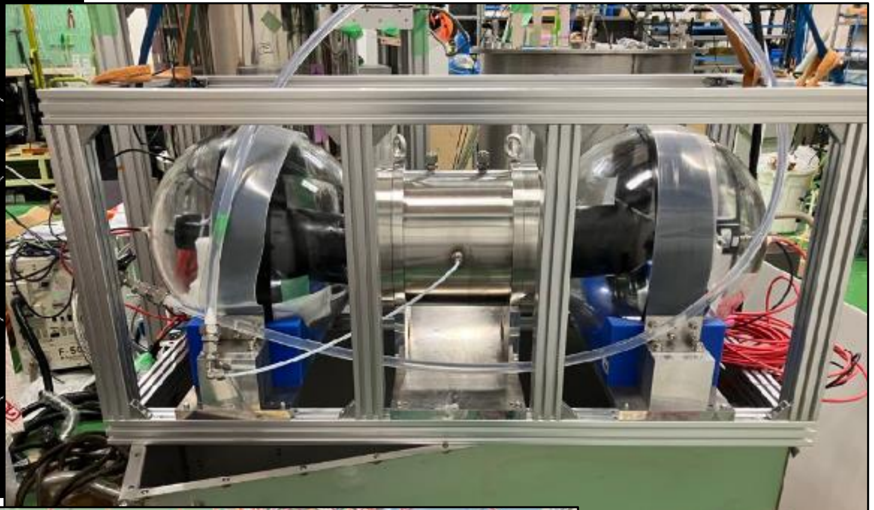
Mantle-derived geoneutrinos account for **70%** of the total signal

A unique and unobstructed way to probe the Earth's deep interior!



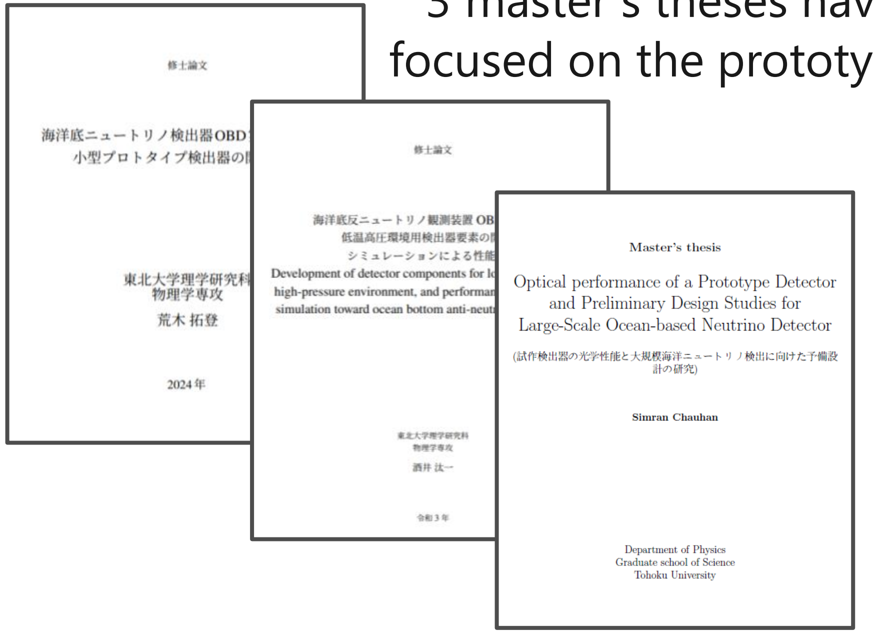
Ocean Bottom Detector (OBD)





JAMSTEC
Hatsushima Observatory

3 master's theses have focused on the prototype.



修士論文

海洋底ニュートリノ検出器OBD
小型プロトタイプ検出器の

東北大学理学研究科
物理学専攻
荒木 拓登

2024年

修士論文

海洋底反ニュートリノ観測装置 OB
低温高圧環境用検出器要素の
シミュレーションによる性能
Development of detector components for lo
high-pressure environment, and performan
simulation toward ocean bottom anti-neutr

東北大学理学研究科
物理学専攻
酒井 汰一

令和3年

Master's thesis

Optical performance of a Prototype Detector
and Preliminary Design Studies for
Large-Scale Ocean-based Neutrino Detector

(試作検出器の光学性能と大規模海洋ニュートリノ検出に向けた予備設計の研究)

Simran Chauhan

Department of Physics
Graduate school of Science
Tohoku University

20-kg prototype is ready
to be deployed underwater!

Detection method & angular resolution

- By using liquid scintillators, which emit light when neutrinos are detected.

Inverse beta decay (IBD): $\bar{\nu} + p \rightarrow n + e^{+}$ $(E_{\text{thre}} = 1.806\ \text{MeV})$

Prompt signal: $e^{+} + e^{-} \rightarrow 2\gamma$

After elastic scatterings

Delayed signal: $n + p \rightarrow {}^{2}\text{H} + \gamma$ $(\Delta T \sim 210\ \mu\text{s})$

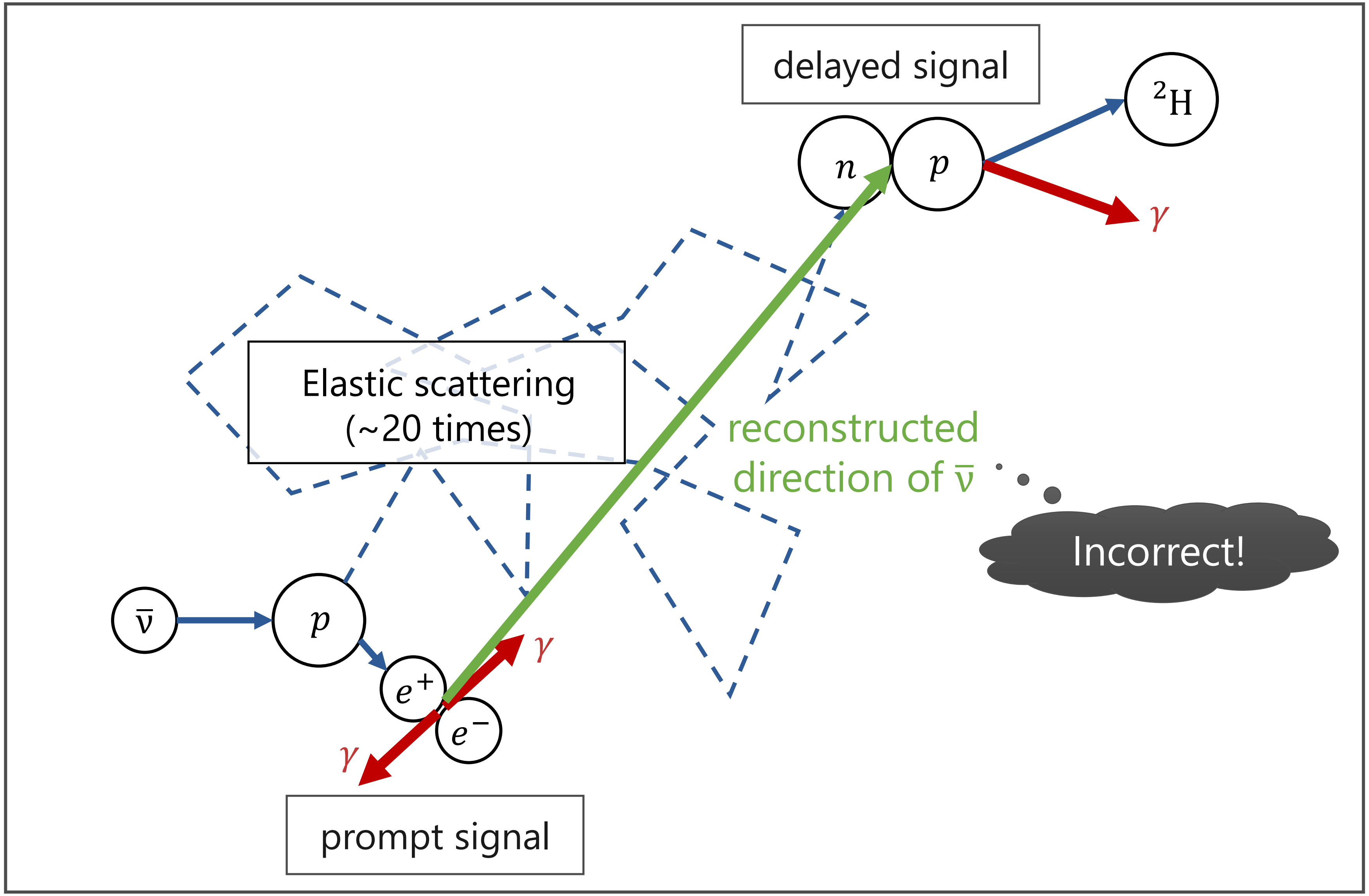
- **Another problem!**

Neutrons undergo significant directional changes

The direction information of $\bar{\nu}$ can not be conserved

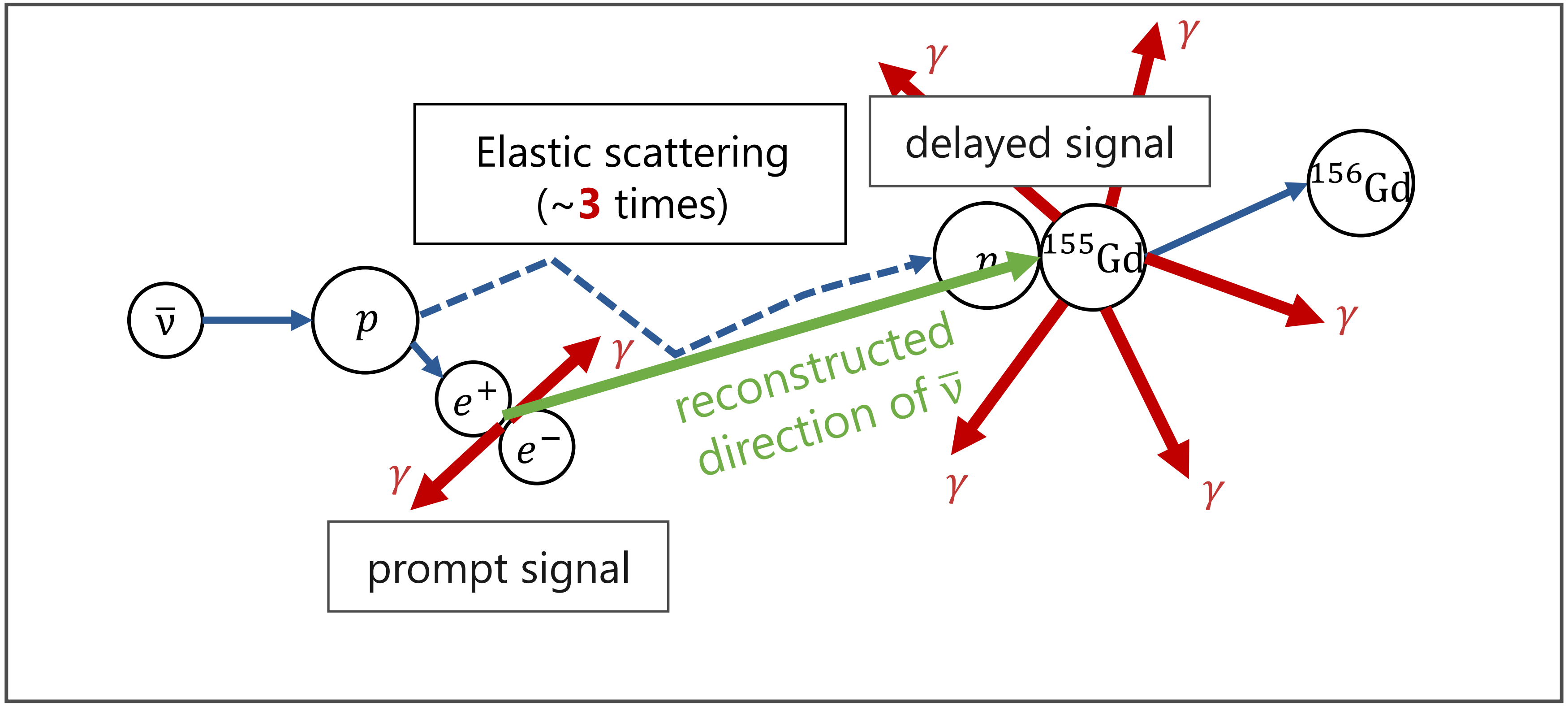
Detection method & angular resolution

- In reality…



Detection method & angular resolution

- If we add Gd to the liquid scintillator…

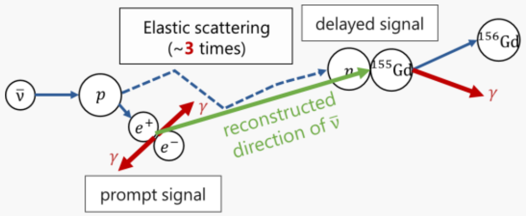


The incoming direction of $\bar{\nu}$ could be determined!

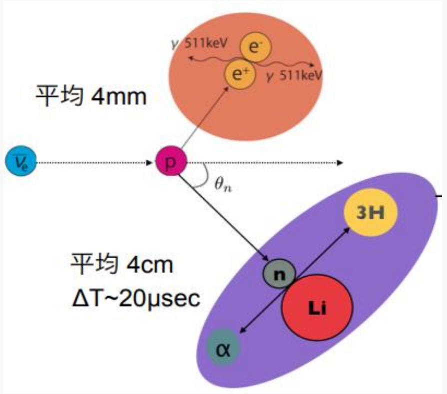
Detection method & angular resolution

- Various methods have been proposed!

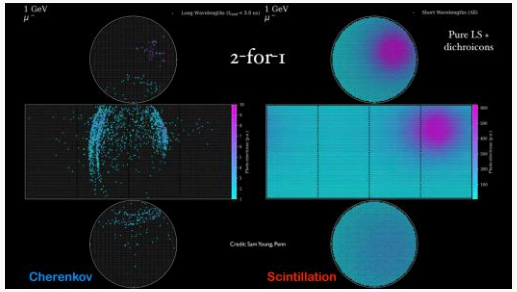
Gd-LS



Li-LS

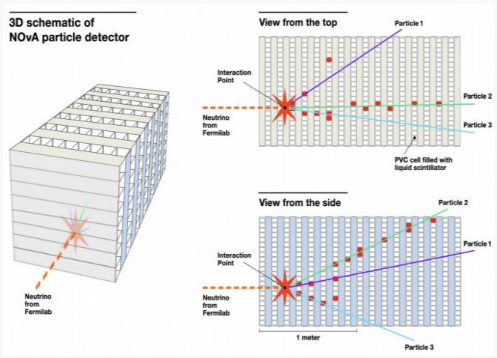


Water-based LS



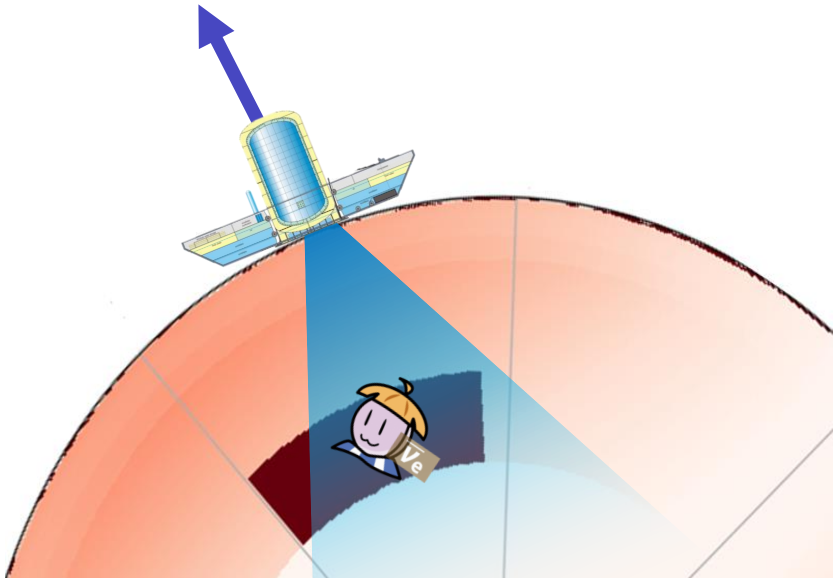
Also see Gabriel’s talk
(27th 16:00)

SANTA



Incident angle of $\bar{\nu}$ can be determined

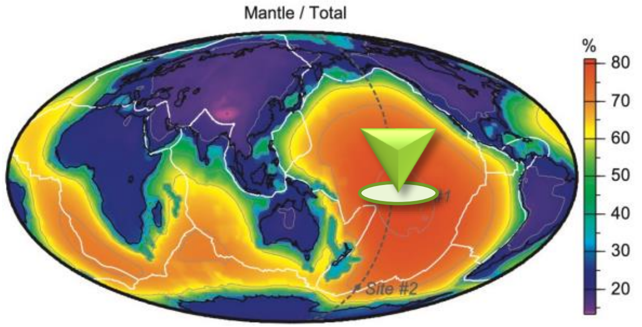
Mantle heterogeneity could be imaged by OBD!



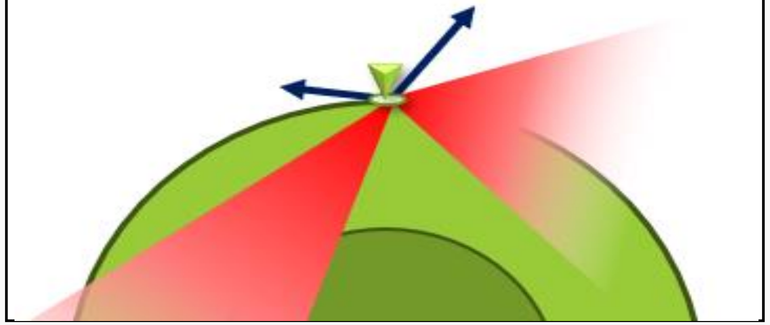
Flowchart of this study

Assumptions

Detect geoneutrinos near Hawaii
(candidate site for OBD)

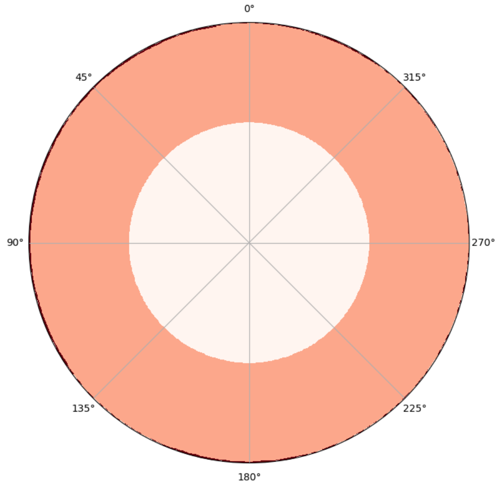


OBD possesses angular resolution
(Gd-LS)

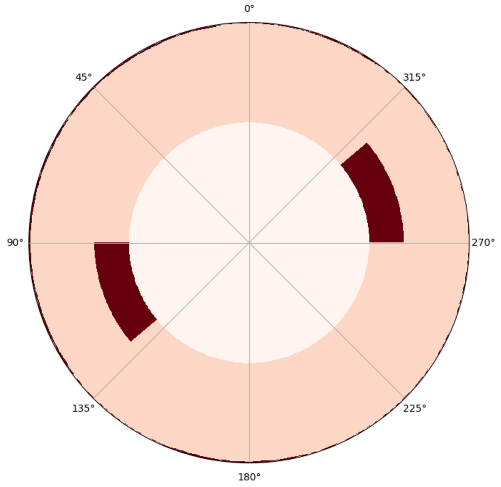


Evaluate the **zenith angle distribution of geoneutrino flux**

homogeneous mantle



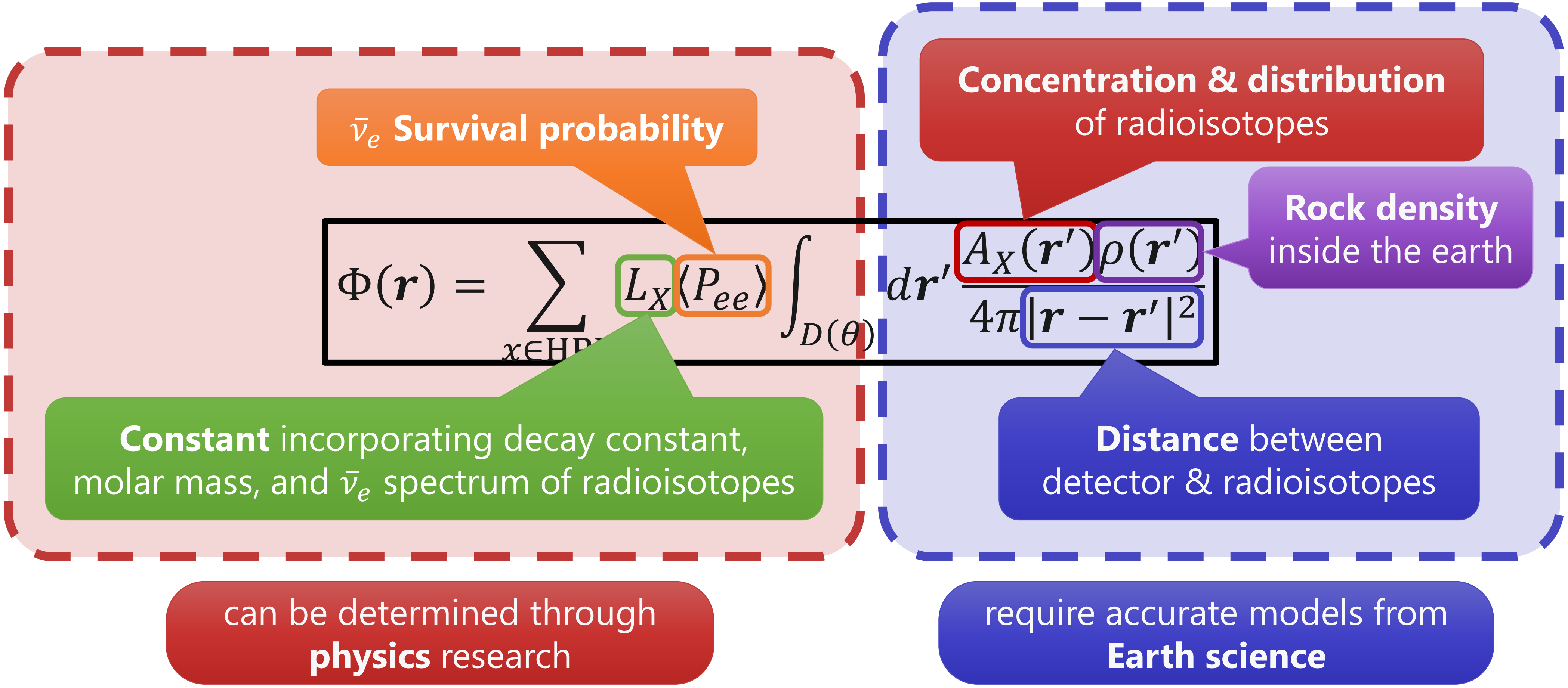
heterogeneous mantle



By comparing the results,
discuss whether OBD with angular resolution can…

- ◆ identify large-scale structures inside the earth.
- ◆ measure the concentration of radioactive materials.

Formula of geoneutrino flux



$\bar{\nu}_e$ **Survival probability**

Concentration & distribution of radioisotopes

Rock density inside the earth

$$\Phi(\boldsymbol{r}) = \sum_{x\in\mathrm{HP}} L_X \langle P_{ee} \rangle \int_{D(\theta)} d\boldsymbol{r}' \frac{A_X(\boldsymbol{r}')\rho(\boldsymbol{r}')}{4\pi|\boldsymbol{r}-\boldsymbol{r}'|^2}$$

Constant incorporating decay constant, molar mass, and $\bar{\nu}_e$ spectrum of radioisotopes

Distance between detector & radioisotopes

can be determined through **physics** research

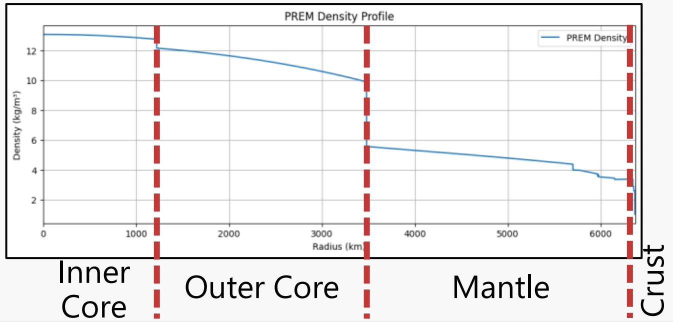
require accurate models from **Earth science**

Construction of Earth models

Density profile

PREM Model

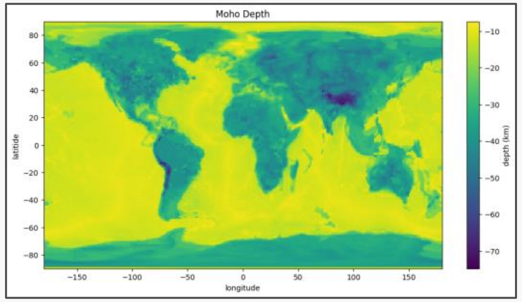
(Dziewonski & Anderson, 1981)



Crust thickness

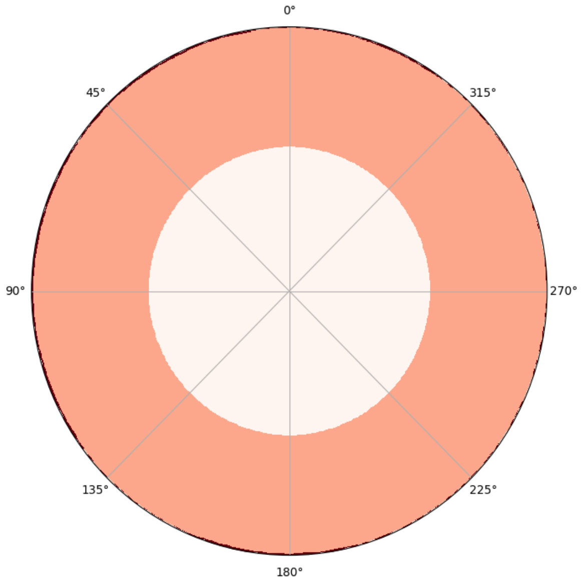
CRUST1.0 Model

(Laske, et al., 2013)



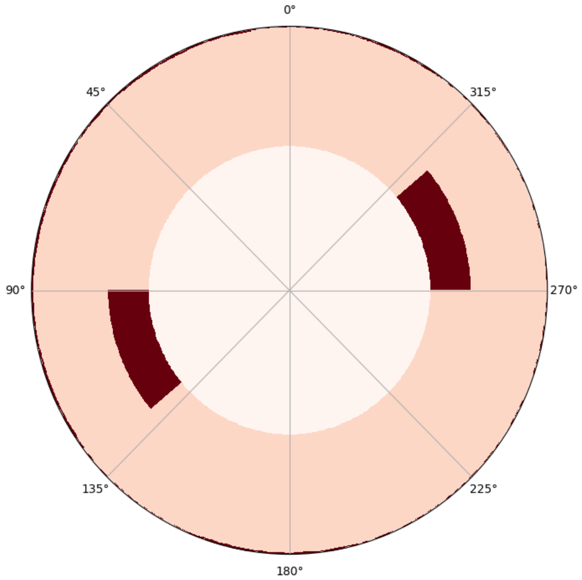
Radioisotope concentration

homogeneous mantle



Huang, et al. (2013)

heterogeneous mantle



compositional contrast = 30×

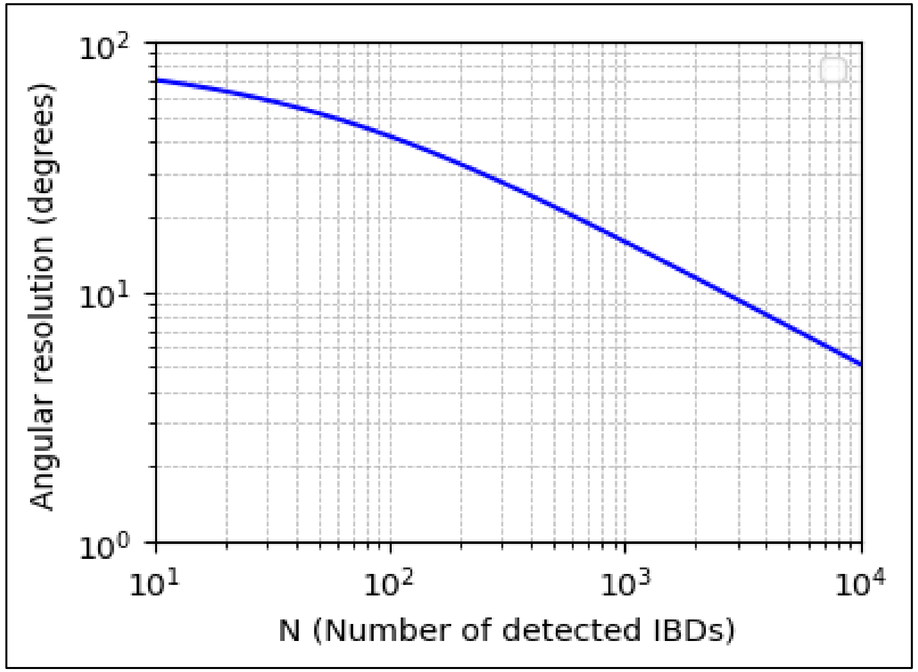
Incorporating angular resolution

- Accurate determination of angular resolution requires detailed modeling and simulations.
- For simplicity, we use the estimation formula and parameters from Duvall et al. (2024).

$$[\Delta\theta]_{1\sigma} = \arctan\frac{P}{d_n\sqrt{N}}$$

(Duvall, et al., 2024)

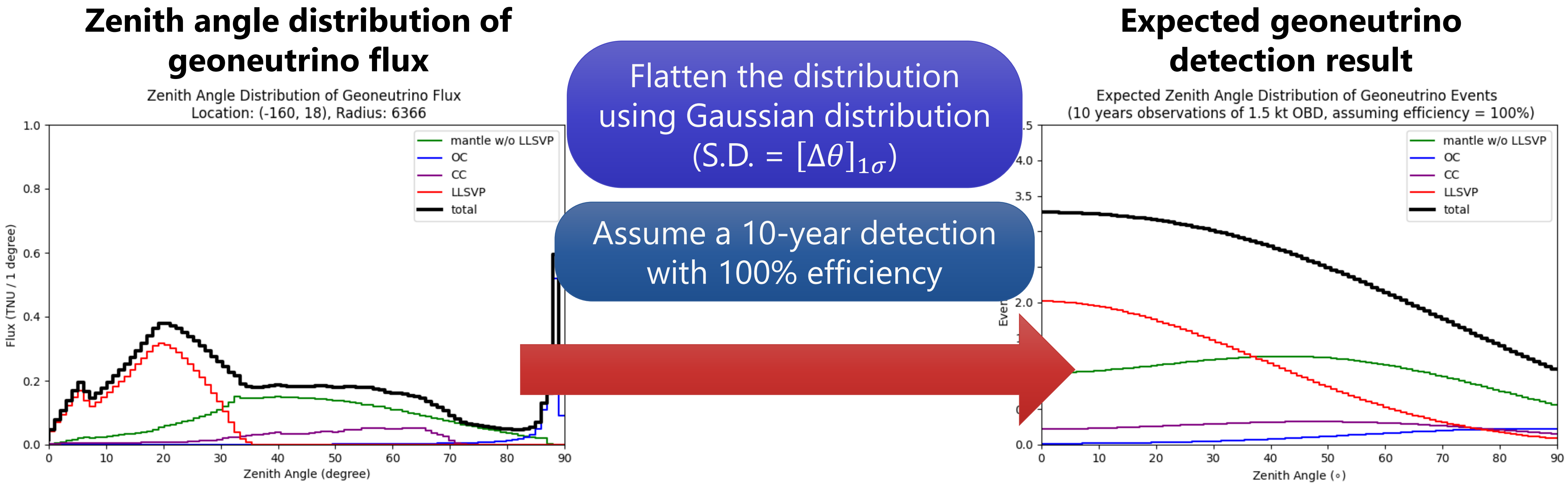
The more neutrino events,
the better angular resolution.



Also see Jackson's talk (30th 11:30)

Incorporating angular resolution

- To derive detection results that are more representative of realistic experimental scenarios…



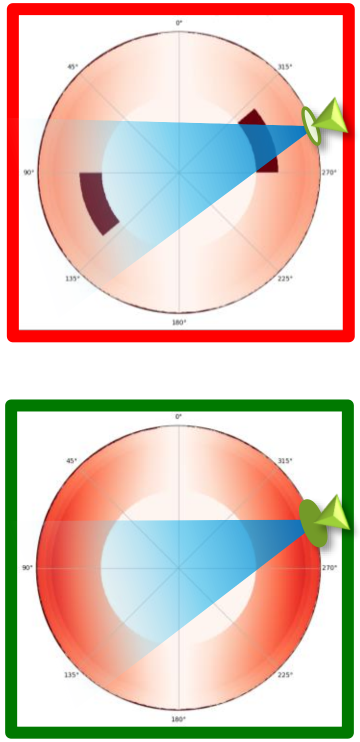
Zenith angle distribution of geoneutrino flux

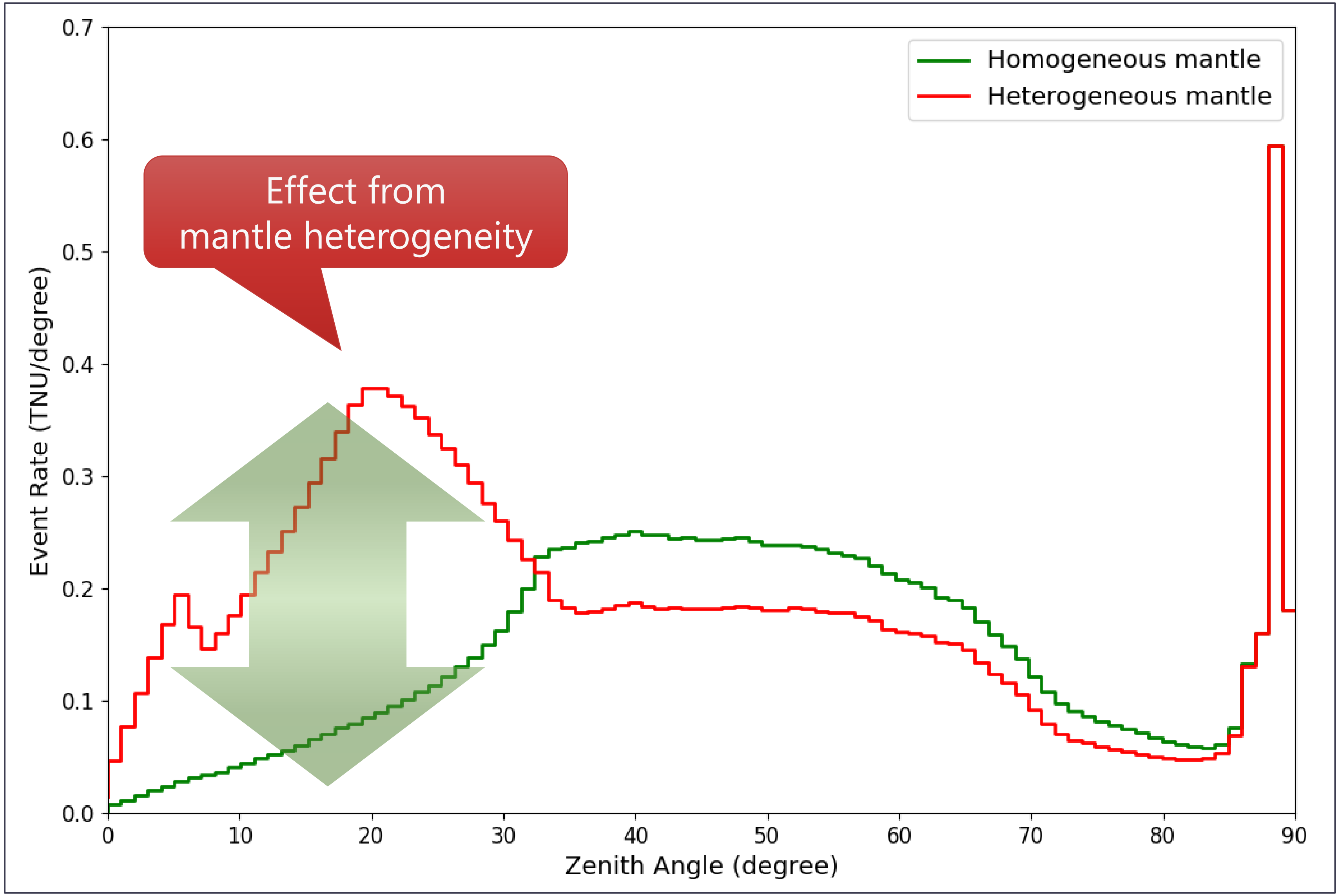
Expected geoneutrino detection result

Flatten the distribution using Gaussian distribution (S.D. = $[\Delta\theta]_{1\sigma}$)

Assume a 10-year detection with 100% efficiency

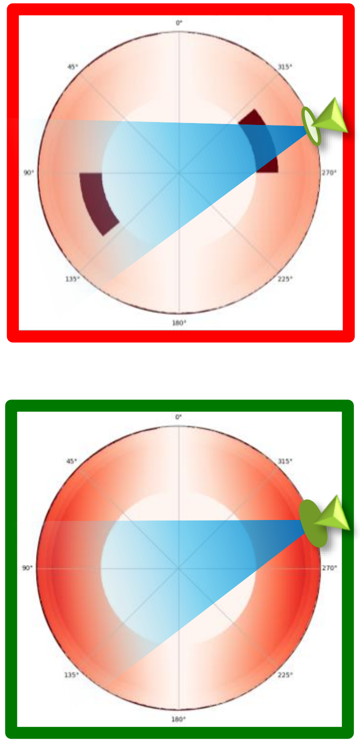
Zenith angle distributions

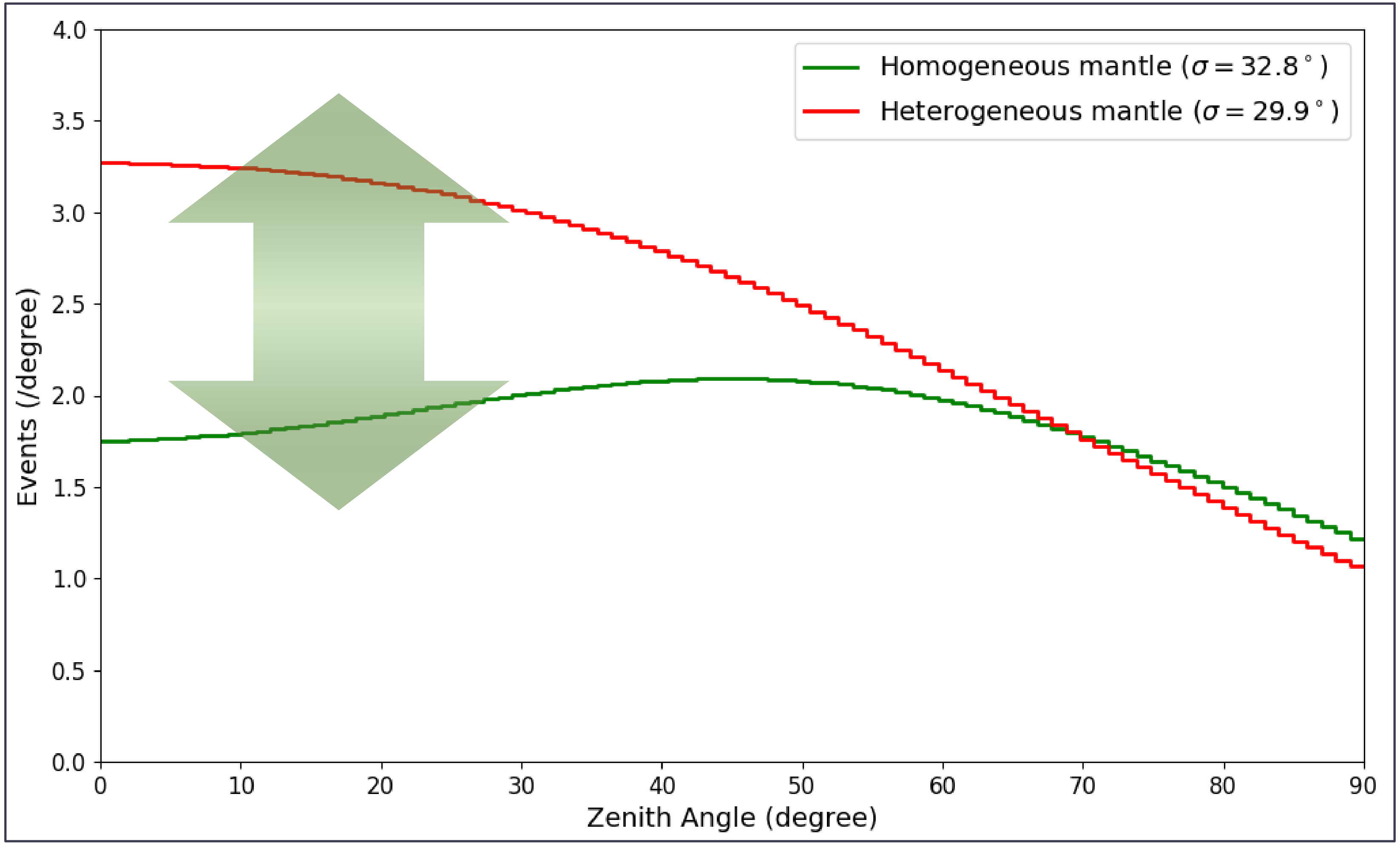




Effect from mantle heterogeneity

Distributions after applying angular resolution



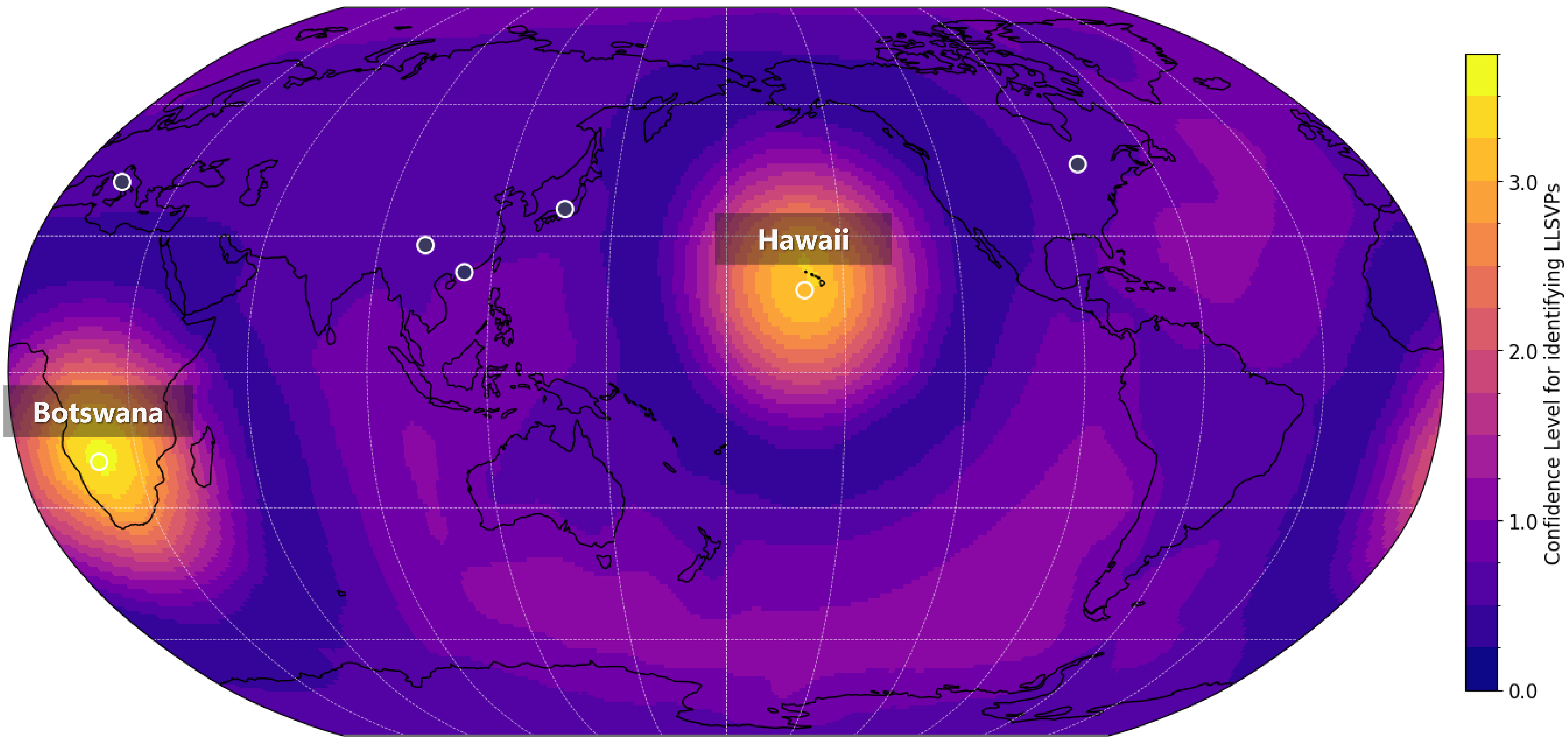


By the difference in the low zenith angle region, it is possible to…

- identify large-scale structures within the earth's interior
- measure its U & Th abundances

Result

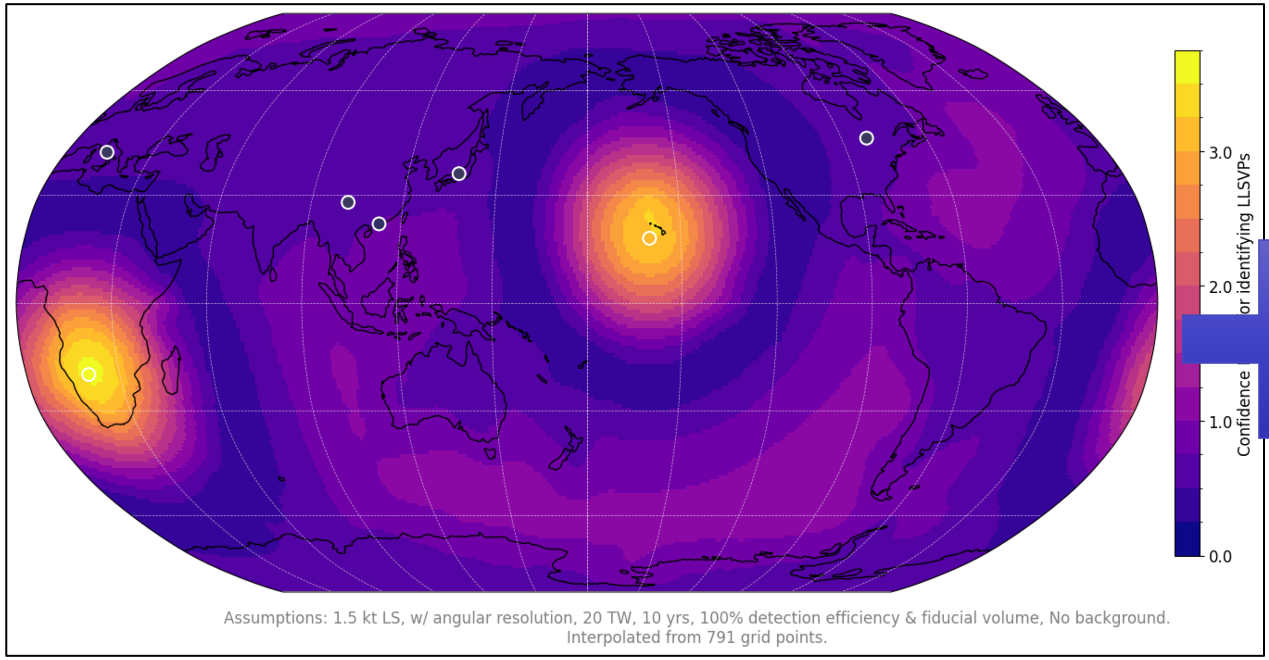
Site selection for revealing mantle heterogeneity



Assumptions: 1.5 kt LS, w/ angular resolution, 20 TW, 10 yrs, 100% detection efficiency & fiducial volume, No background.
Interpolated from 791 grid points.

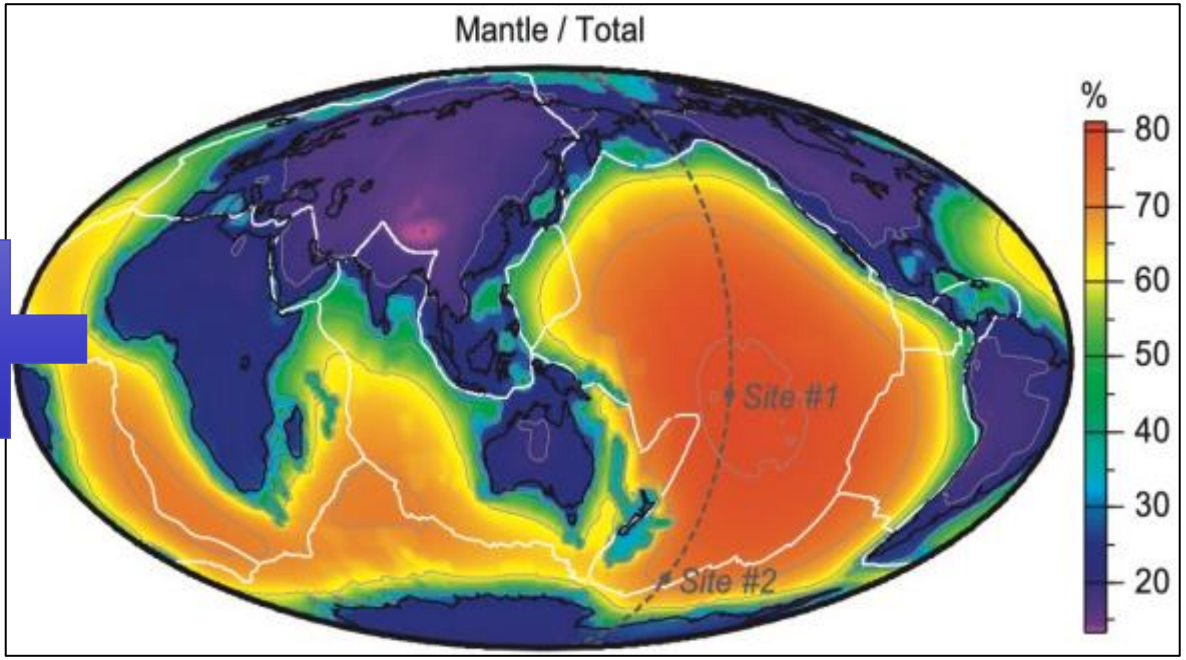
Optimal site: Hawaii

Confidence Level for identifying LLSVPs
(This study)



Assumptions: 1.5 kt LS, w/ angular resolution, 20 TW, 10 yrs, 100% detection efficiency & fiducial volume, No background.
Interpolated from 791 grid points.

Fraction of mantle-derived geoneutrinos
(Šrámek et al, 2013)



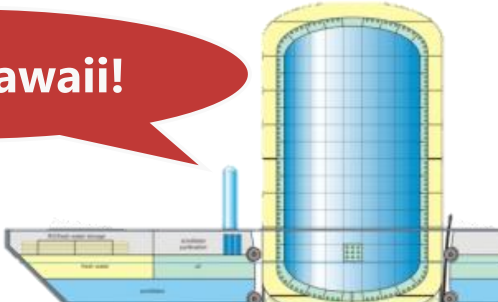
Hawaii & Botswana are suitable for studying LLSVPs

Oceanic crust is suitable for studying deep Earth

- If we take everything into account…

Hawaii is the best place to detect geoneutrinos!

Aloha, Hawaii!



Future prospect

Optimize detector parameters for OBD

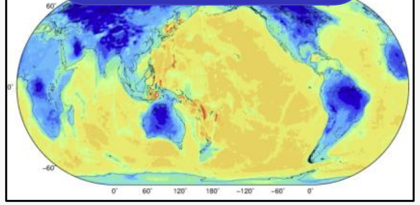
- Gd/Li doping concentration
- Detector size
- Detector location
- Number of PMT

Estimate background signal rate

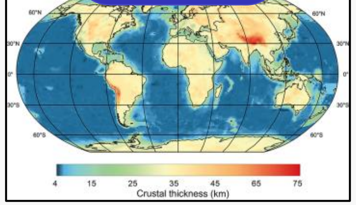
- Reactor antineutrinos
- Accidental coincidences
- 13C(α,n)16O reactions
- Fast neutrons

Incorporate more crustal models

LITHO1.0



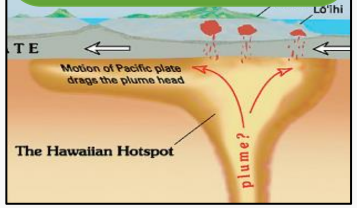
ECM1



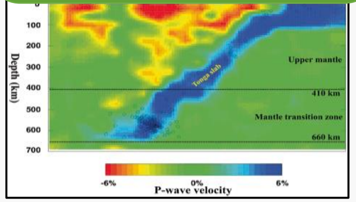
Also see Walter's talk (28th 09:30)

Consider additional geological structures

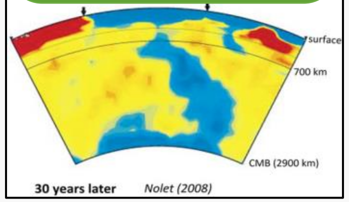
volcanic plume



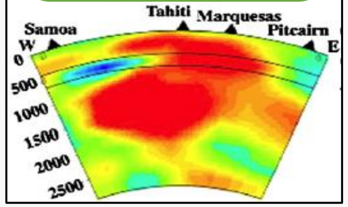
subduction zone



stagnate plate

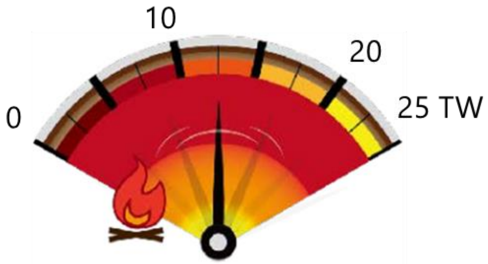


super plume



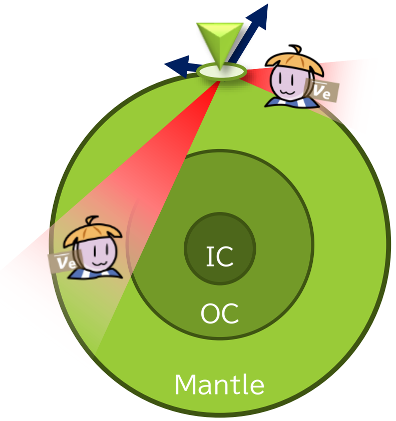
Summary

- By geoneutrino detection, it is possible to…
  - measure the heat generation inside the earth.
  - measure the amount of radioisotope within the earth’s interior.



Contribute to our understanding of Earth's internal heat budget.

- Using Ocean Bottom Detector (OBD) with angular resolution, it is possible to…
  - identify large-scale structures within the earth's interior.
  - measure radioisotope concentrations in large-scale structures.



Help us to understand Earth’s present-day structure.

Provide important constraints on the internal structure of the Earth.

References

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Models and Parameters

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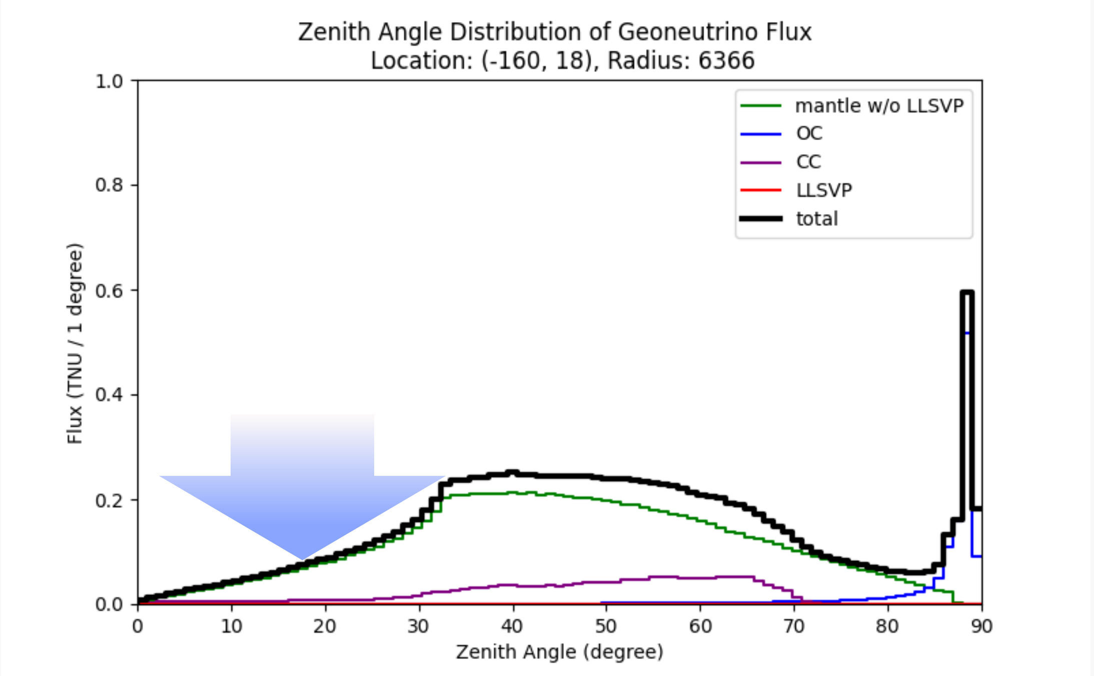
Backup

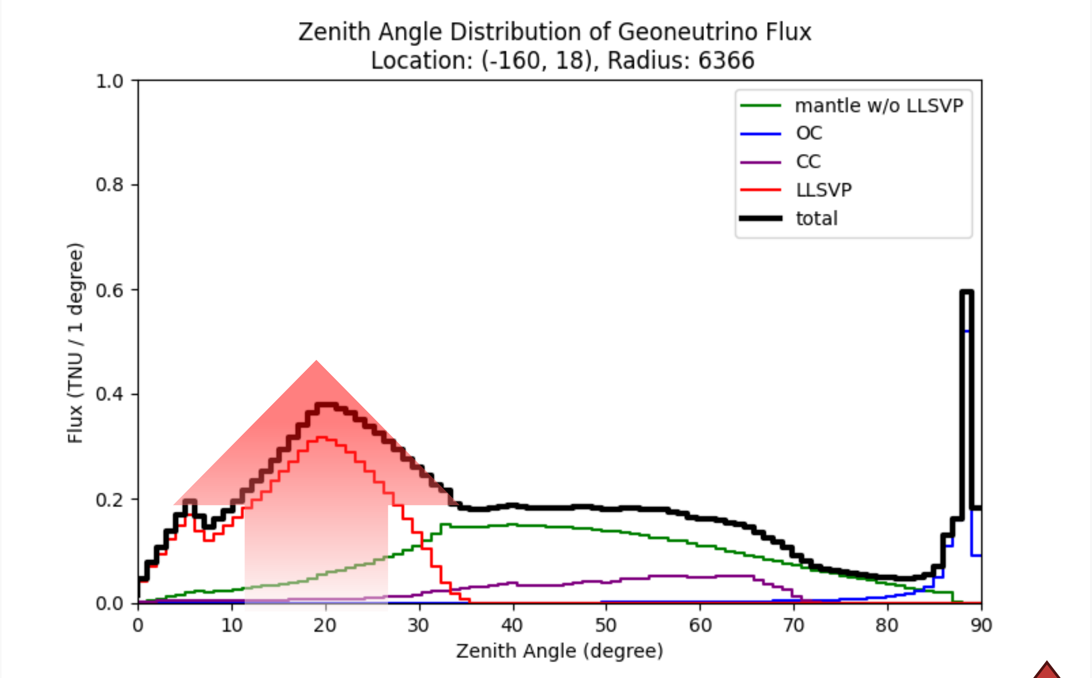
Zenith angle distribution of the geoneutrino flux @Hawaii

the case of a homogeneous mantle



total flux: **13.0 TNU** ≈ **19.5 events/year**

the case of LLSVPs exist



total flux: **16.3 TNU** ≈ **24.5 events/year**

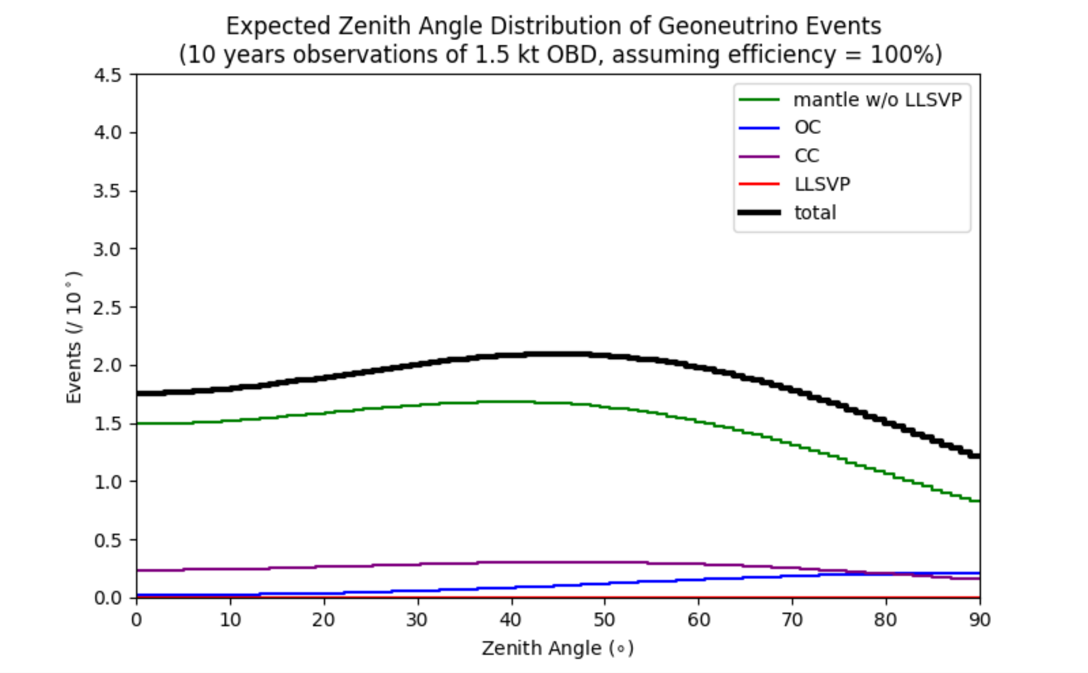
1 TNU = 1 event/10^{32} protons/year ≈ 1.5 event/year for OBD

Since it is practically impossible to achieve such precise detection,
such a result cannot be obtained...

Backup

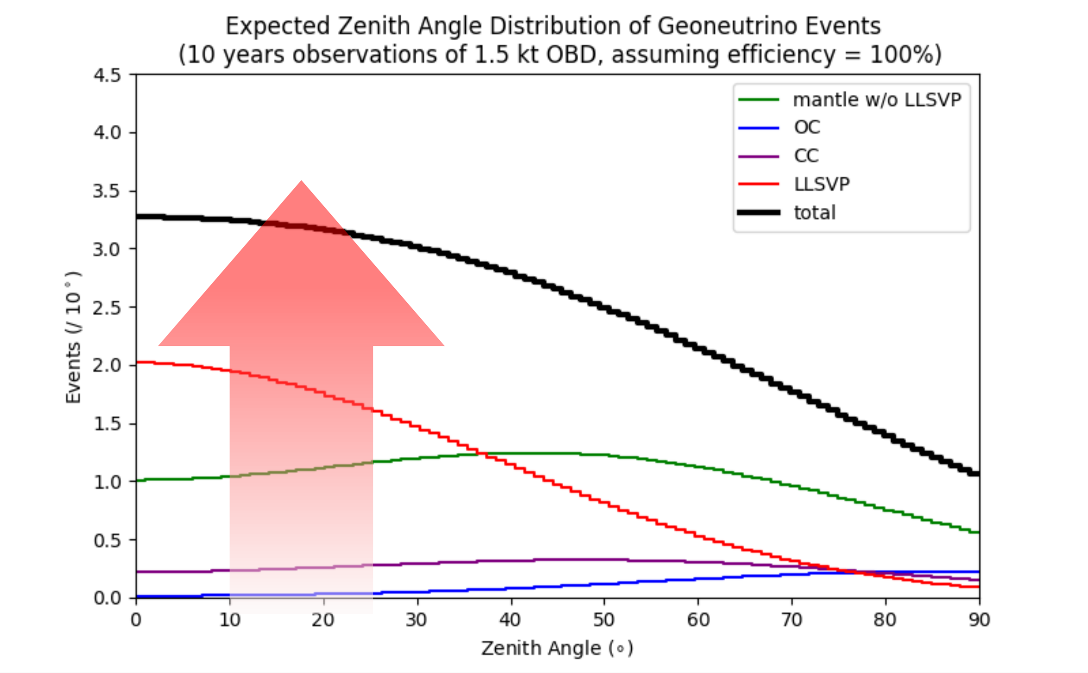
Geoneutrino detection simulation result @Hawaii

the case of a homogeneous mantle

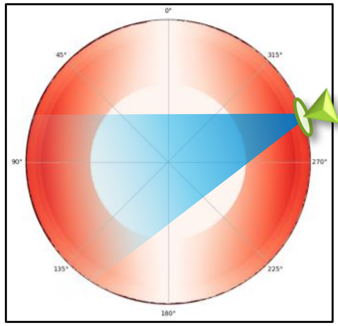


Total events: **195**, Angular resolution: **32.8°**

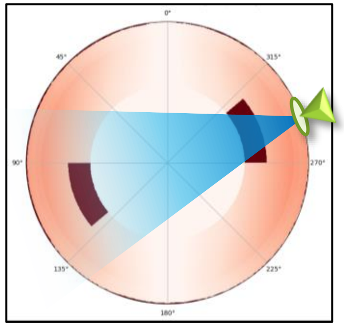
the case of LLSVPs exist



Total events: **245**, Angular resolution: **29.9°**



A huge difference still exist in the low zenith angle region!



Detailed formula for calculating geoneutrino flux

$$\boxed{\Phi(\boldsymbol{r}) = \sum_{X\in\mathrm{HPE}} \frac{\varepsilon N_A \lambda_X}{\mu_X} \int_{D(\theta)} d\boldsymbol{r}' \int_{E_\nu} dE_\nu P_{\mathrm{ee}}(E_\nu, |\boldsymbol{r}-\boldsymbol{r}'|) \frac{\rho(\boldsymbol{r}')a_X(\boldsymbol{r}')}{4\pi|\boldsymbol{r}-\boldsymbol{r}'|^2} \frac{dn_X(E_\nu)}{dE_\nu} \sigma_{\mathrm{IBD}}(E_\nu)}$$

complicated

However, in the energy range of geoneutrinos ($O(\mathrm{MeV})$) and over Earth-sized distances ($O(10^4\ \mathrm{km})$),
For the survival probability of $\bar{\nu}_e$…

$$P_{ee}\left\{\begin{array}{l}\boxed{\text{is almost independent of } E_\nu}\\ \boxed{\text{shows strong periodicity with respect to } |\boldsymbol{r}-\boldsymbol{r}'|}\end{array}\right. \Rightarrow \boxed{P_{ee}\sim\langle P_{ee}\rangle = 0.55}$$

After various transformations,

$$\boxed{\Phi(\boldsymbol{r}) = \sum_{X\in\mathrm{HPE}} L_X \langle P_{\mathrm{ee}}\rangle \int_{D(\theta)} d\boldsymbol{r}' \frac{A_X(\boldsymbol{r}')}{4\pi|\boldsymbol{r}-\boldsymbol{r}'|^2}}$$

where

$$\boxed{\begin{array}{l} L_X \equiv \dfrac{\varepsilon N_A \lambda_X}{\mu_X} \displaystyle\int_{E_\nu} dE_\nu \frac{dn_X(E_\nu)}{dE_\nu} \sigma_{\mathrm{IBD}}(E_\nu) \\ A_X(\boldsymbol{r}') \equiv \rho(\boldsymbol{r}')a_X(\boldsymbol{r}') \end{array}}$$

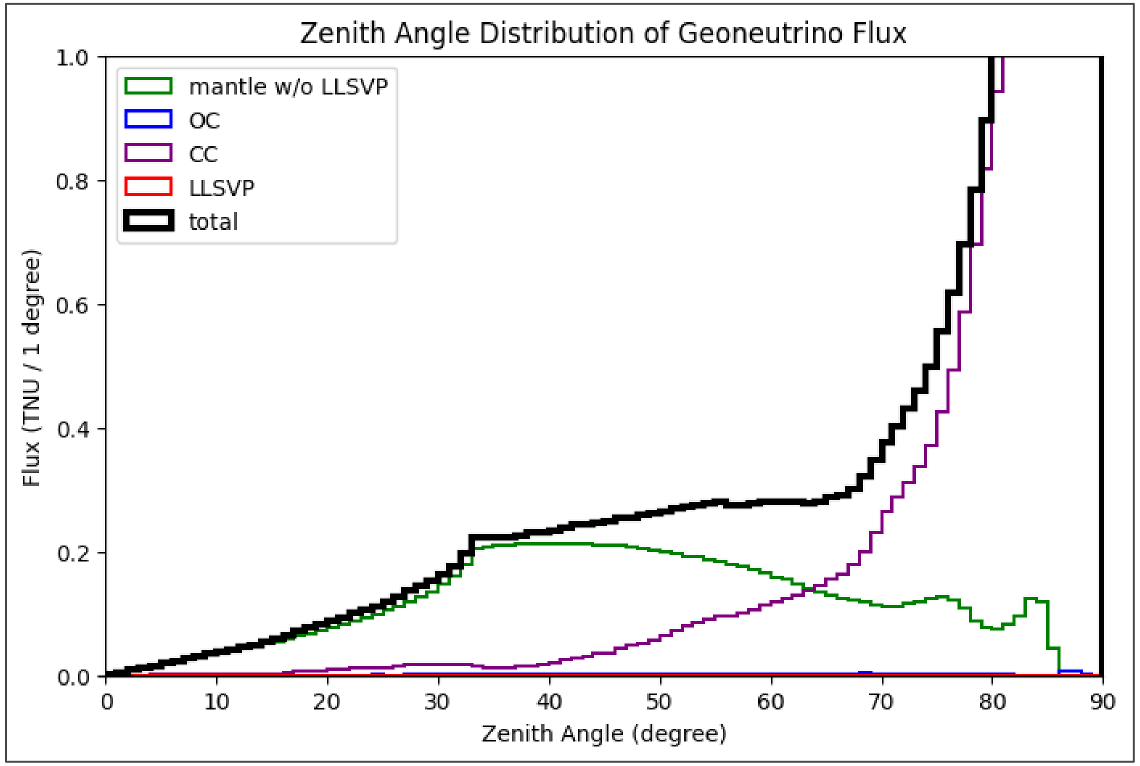
L_X: a quantity representing the signal strength from geoneutrinos produced by 1 g of nuclide *X*.
A_X: abundance of nuclide *X*

Backup

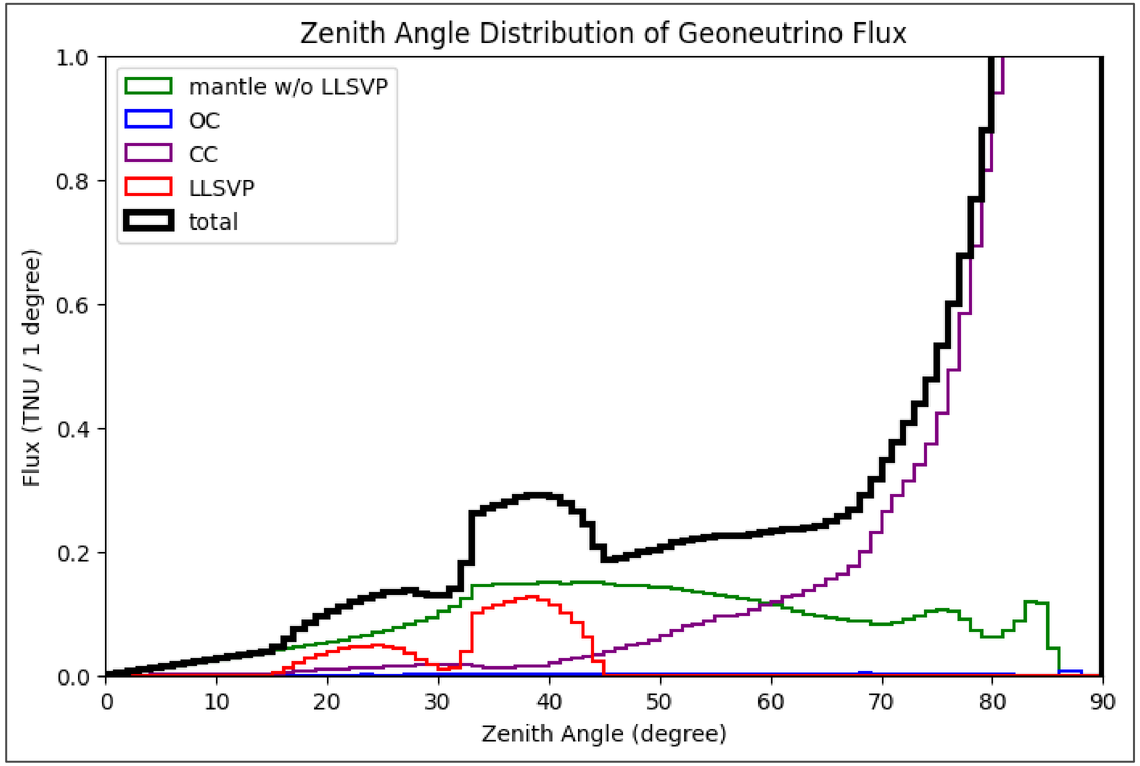
Zenith angle distribution on continental crust

Example: Borexino (Italy)

the case of a homogeneous mantle



the case of LLSVPs exist



The peaks caused by LLSVPs are small,
making it unsuitable for identifying the LLSVP.