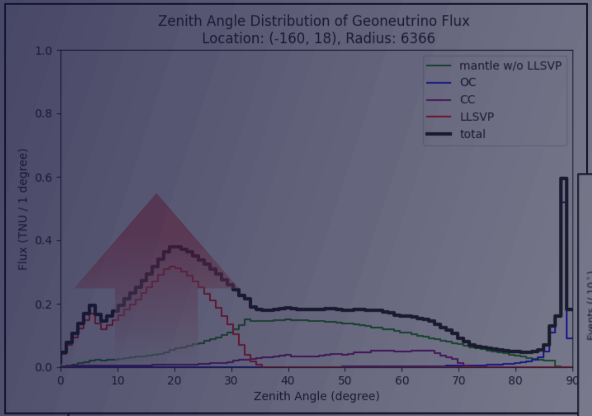
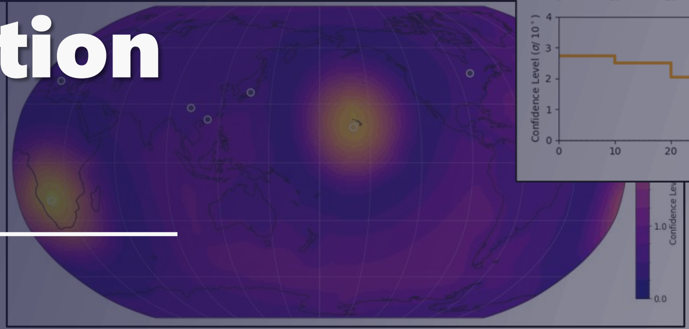
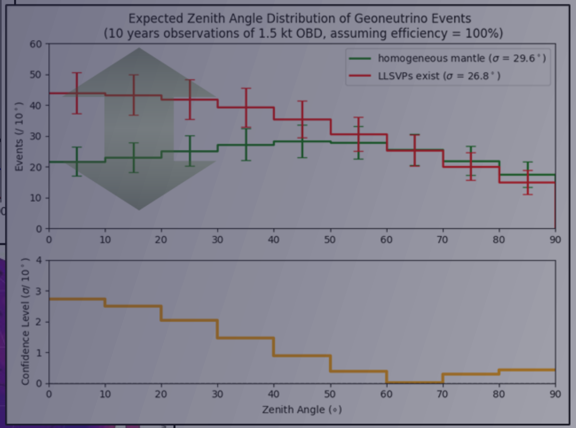
Towards imaging Earth's large-scale structures by directional geoneutrino detection with Ocean Bottom Detector







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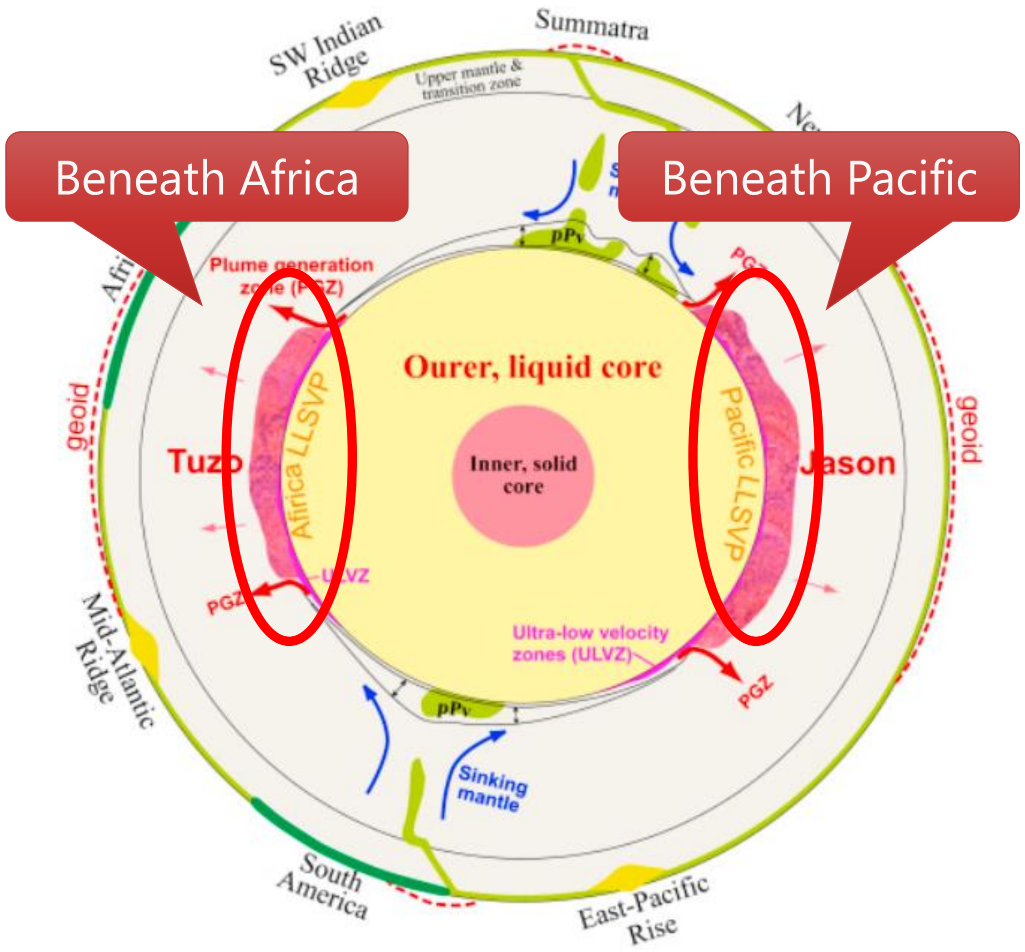
Mantle heterogeneity

- **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)

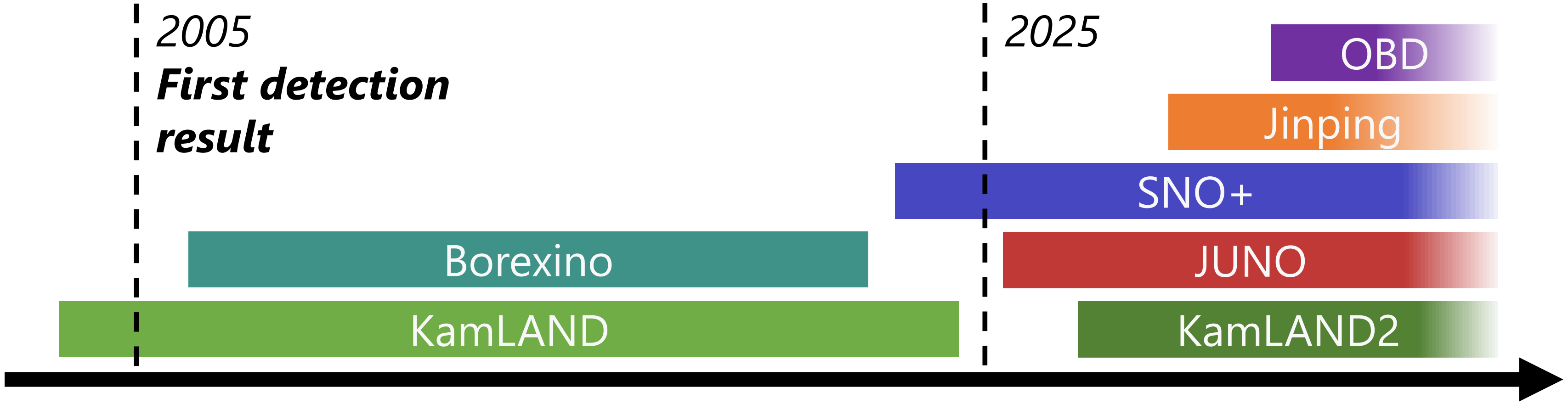
Geoneutrino

- **Geoneutrino:** elementary particles generated by radioactive decay within Earth's interior.
- **First detection:** KamLAND (*Nature*, 2005)
- KamLAND's detection was continued to 2024…

Heat from U & Th inside the earth	Th/U mass ratio in the earth
$15.4^{+8.3}_{-7.9}$ TW (KamLAND, 2022)	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.

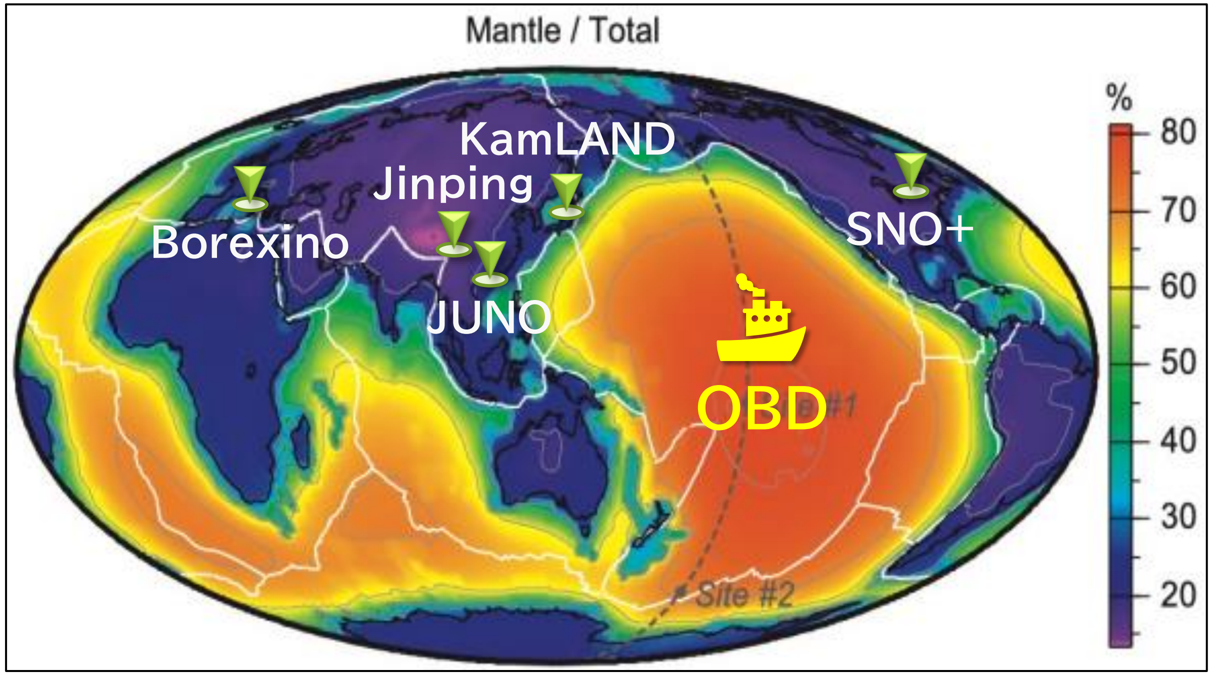


Ocean Bottom Detector (OBD)

- **Why not on the continents?**

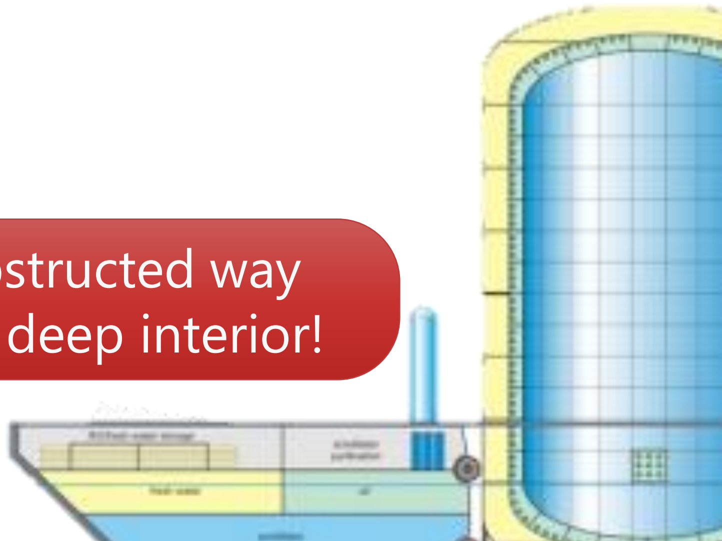
Thick | Contain abundant radioisotopes

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!



Detection method

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

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

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

After elastic scatterings

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

Neutrons undergo significant directional changes, made existing geoneutrino detectors lack angular resolution.

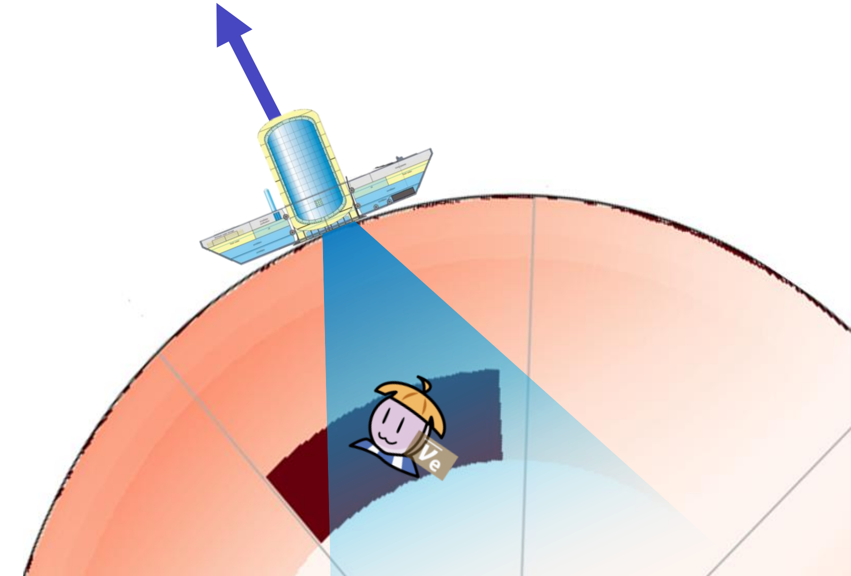
- Solution

Doping Gd, Li, ...

Using water-based LS

→ Incident angle of $\bar{\nu}$ can be reconstructed

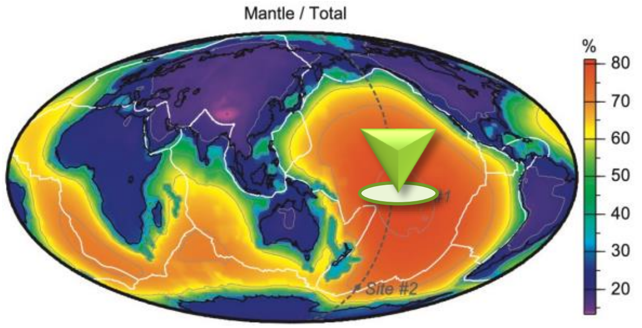
→ **Mantle heterogeneity could be imaged by OBD!**



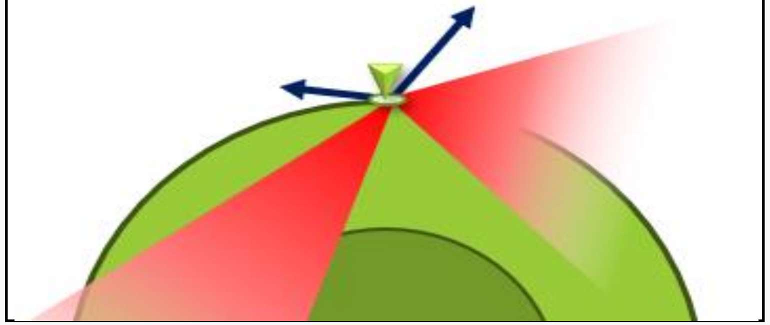
Flowchart of this study

Assumptions

Detect geoneutrinos near Hawaii
(candidate site for OBD)

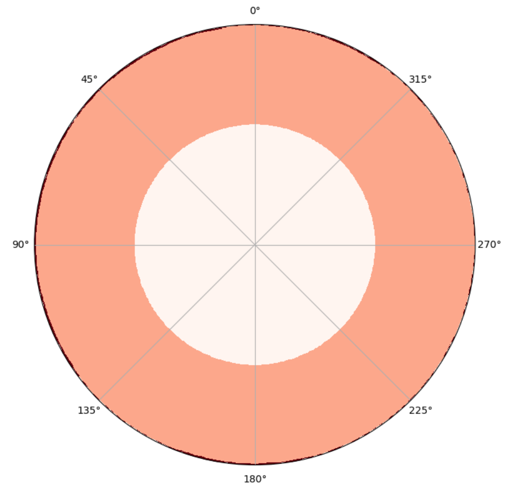


OBD possesses angular resolution

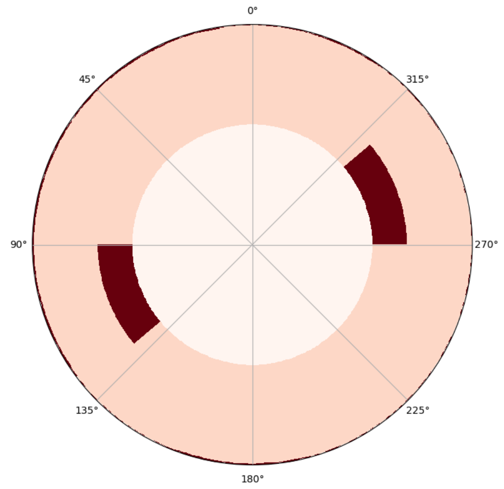


Evaluate the **zenith angle distribution of geoneutrino flux**

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

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

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

Distance between detector & radioisotopes

can be determined through **physics** research

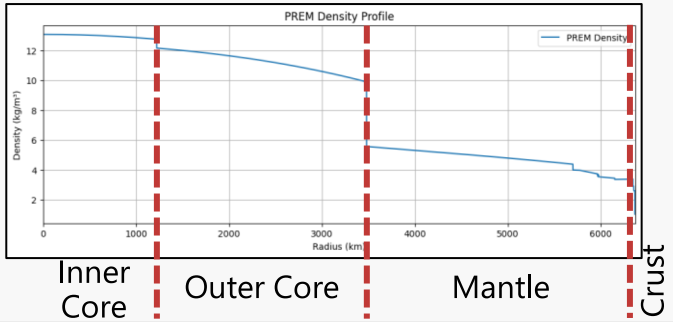
require accurate models from **Earth science**

Construction of Earth models

Density profile

PREM Model

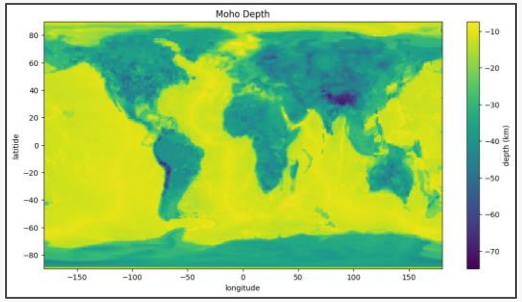
(Dziewonski & Anderson, 1981)



Crust thickness

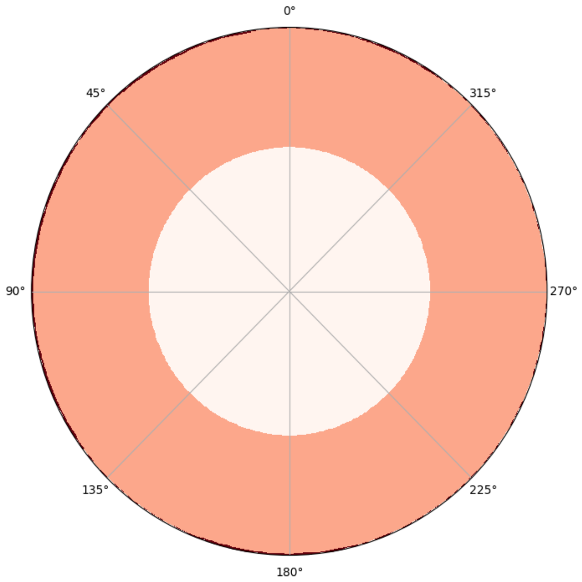
CRUST1.0 Model

(Laske, et al., 2013)



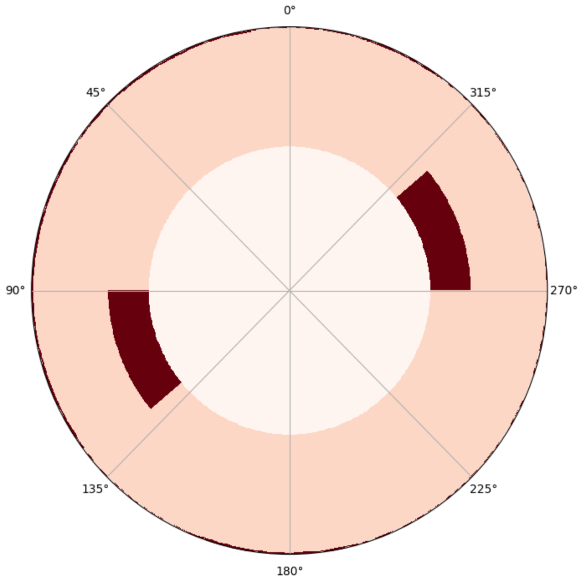
Radioisotope concentration

homogeneous mantle



Huang, et al. (2013)

heterogeneous mantle



compositional contrast = 30×

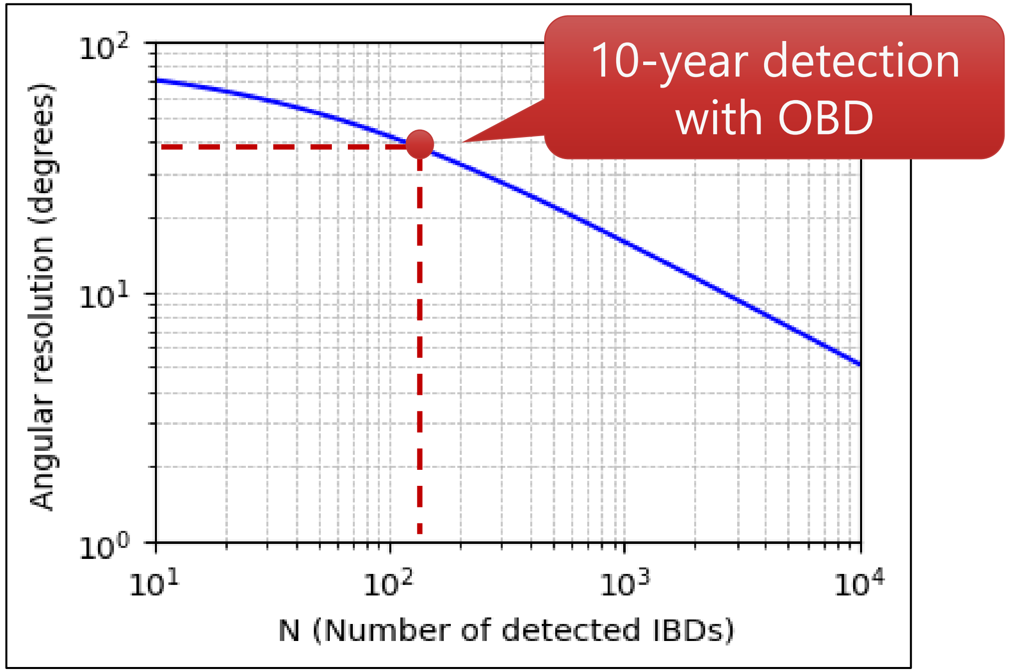
Incorporating angular resolution

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

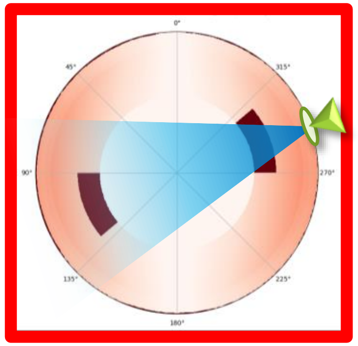
$$[\Delta\theta]_{1\sigma} = \arctan \frac{P}{d_n\sqrt{N}}$$

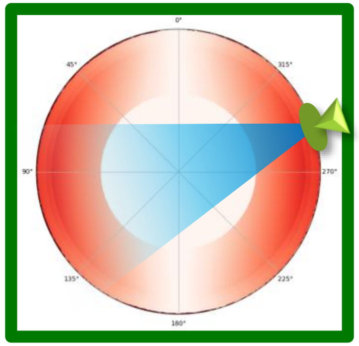
(Duvall, et al., 2024)

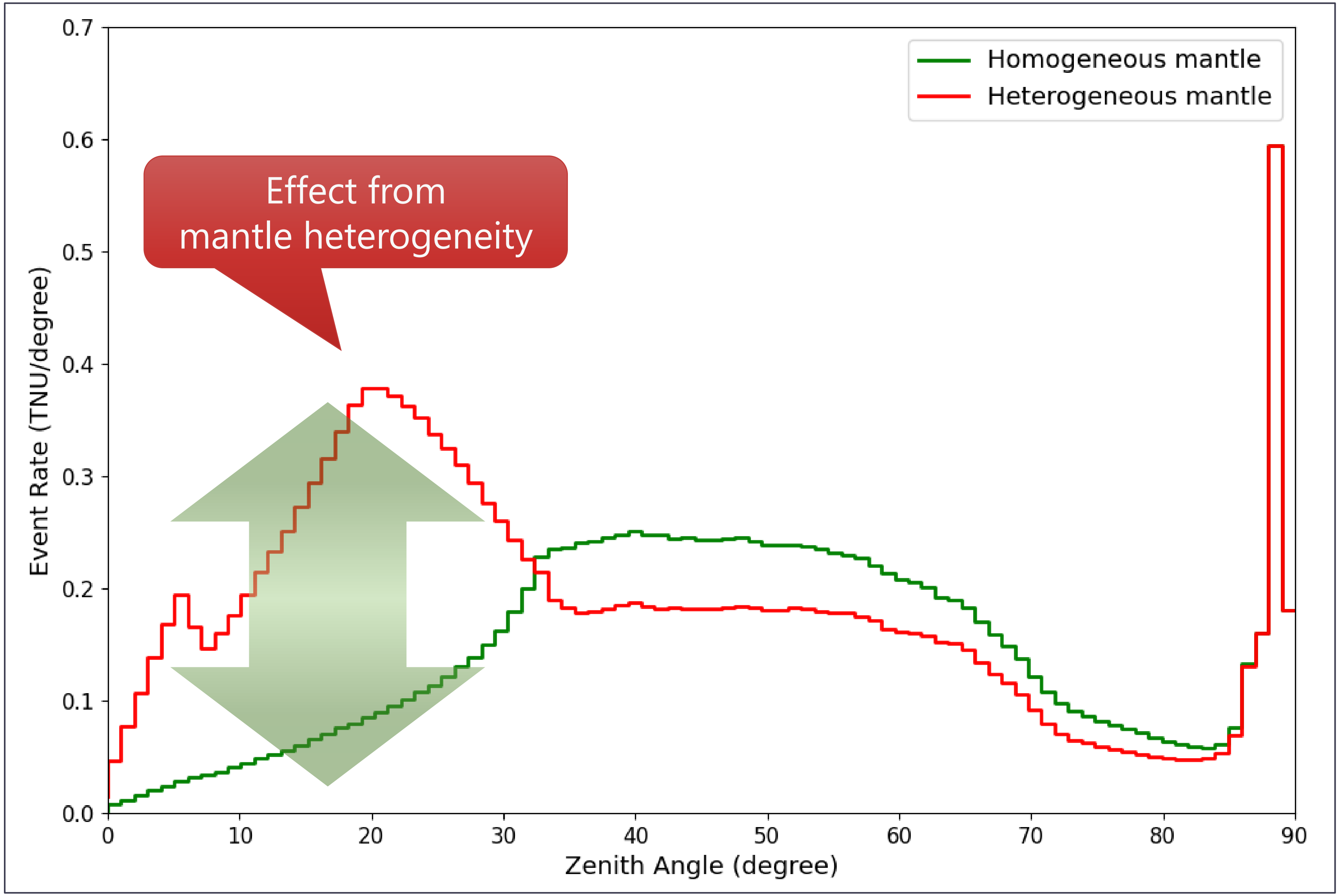
The more neutrino events, the better angular resolution.



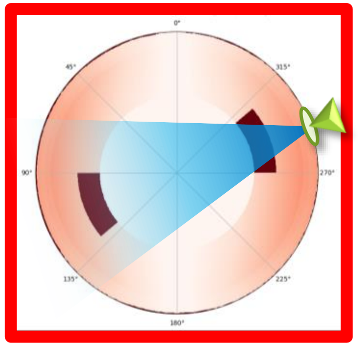
Zenith angle distributions

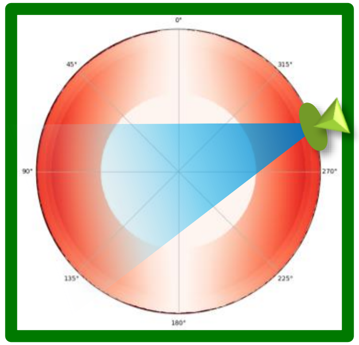


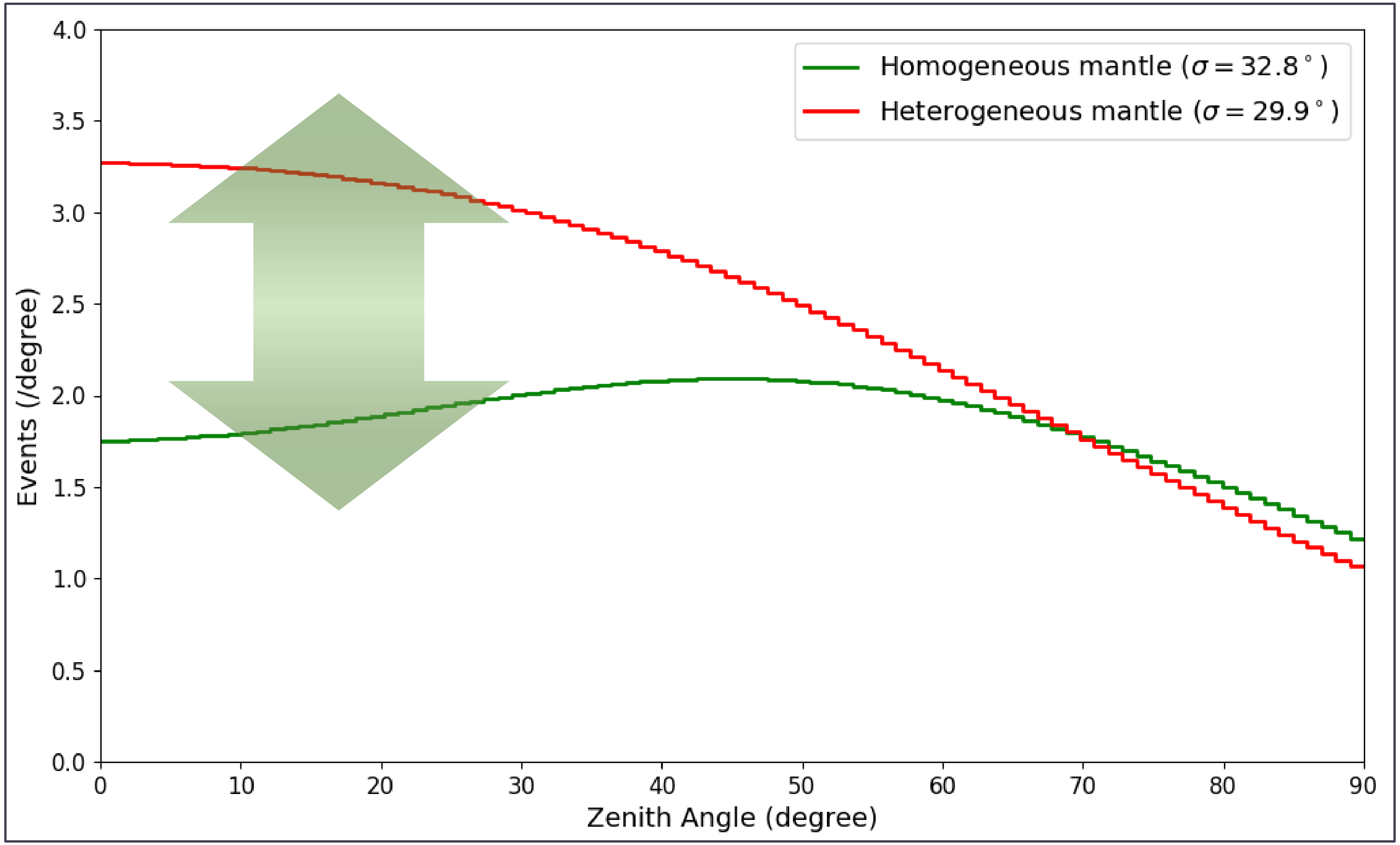




Distributions after applying angular resolution



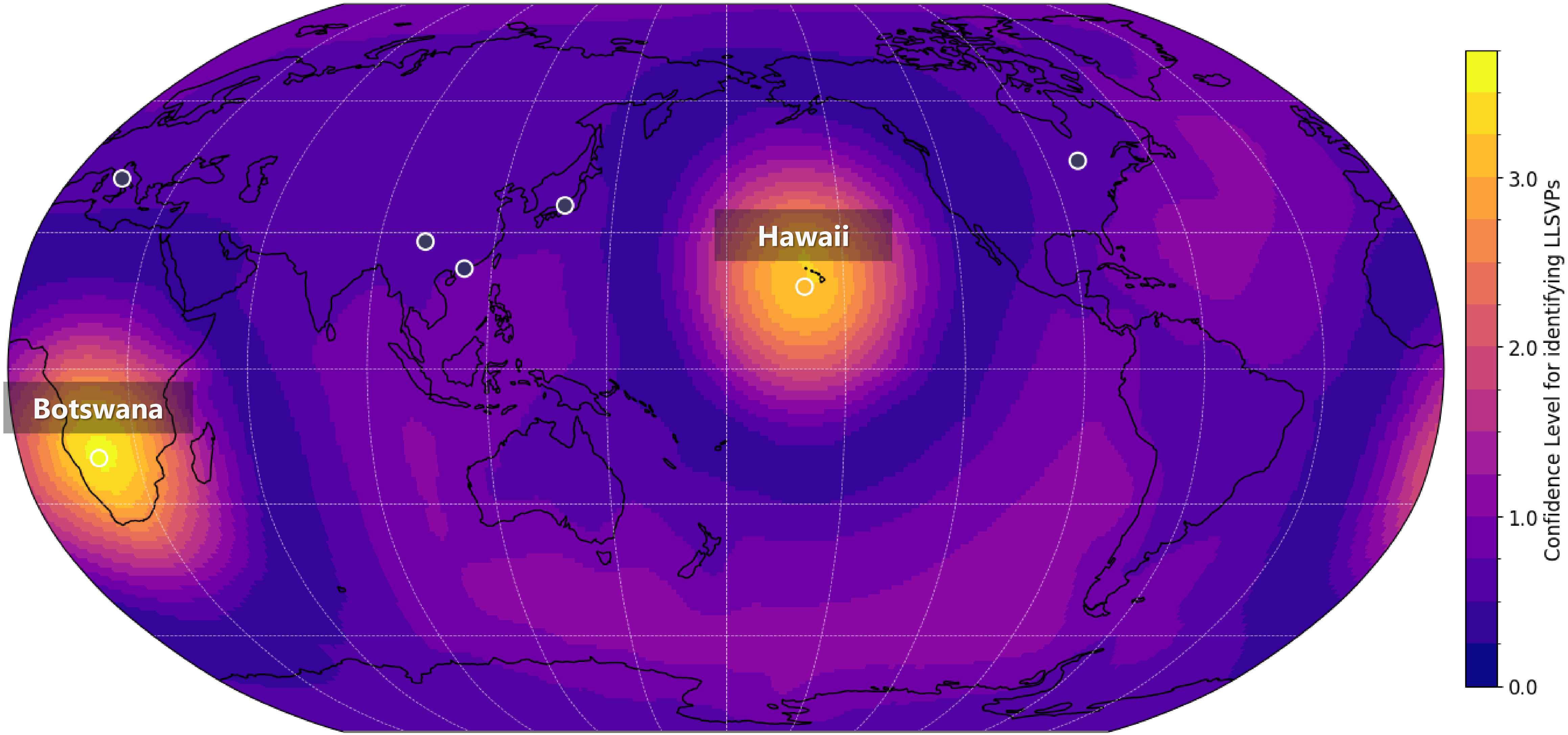




By the difference in the low zenith angle region, it is possible to…

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

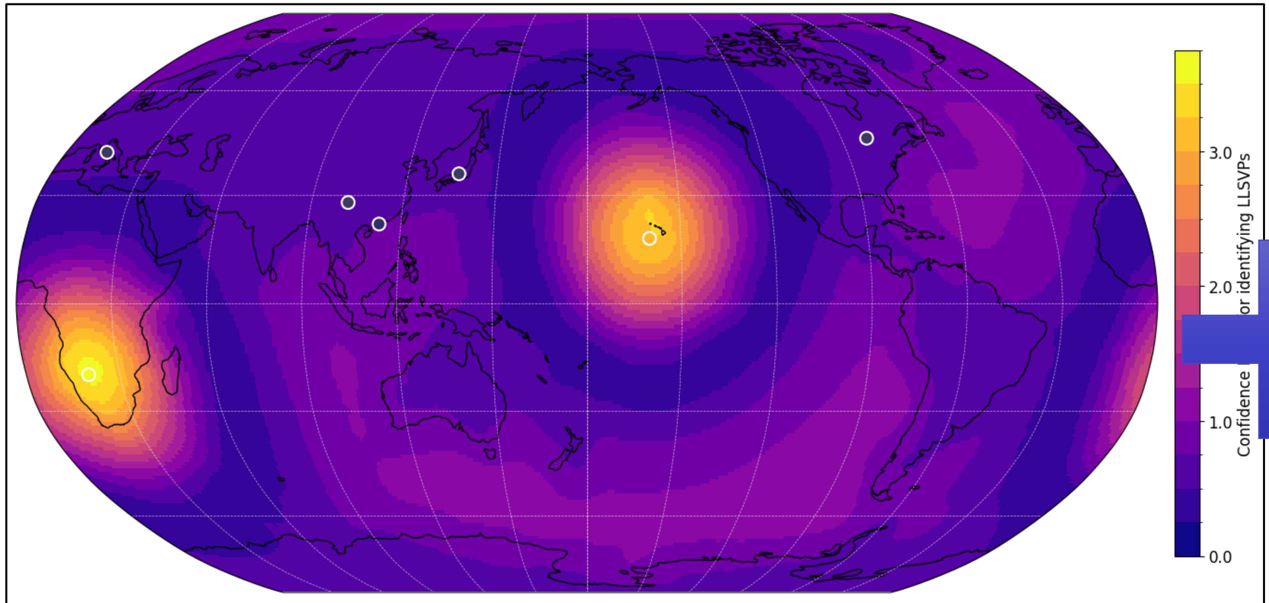
Site selection for revealing mantle heterogeneity



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

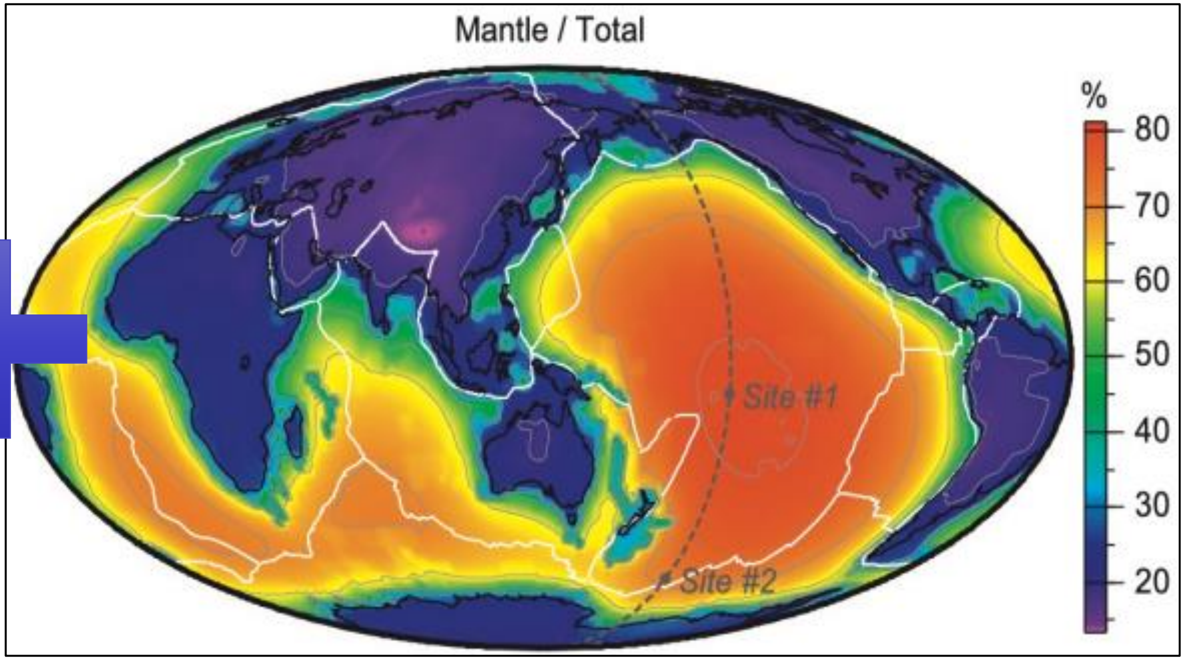
Confidence Level for identifying LLSVPs
(This study)



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

Hawaii & Botswana are suitable for studying LLSVPs

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

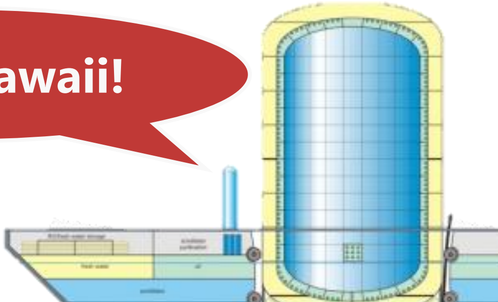


Oceanic crust is suitable for studying deep Earth

- If we take everything into account…

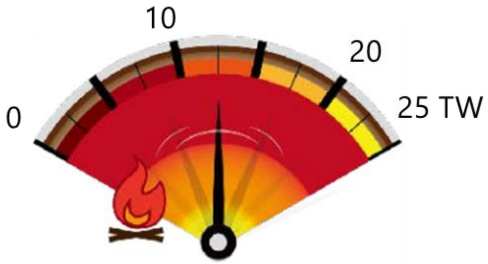
Hawaii is the best place to detect geoneutrinos!

Aloha, Hawaii!



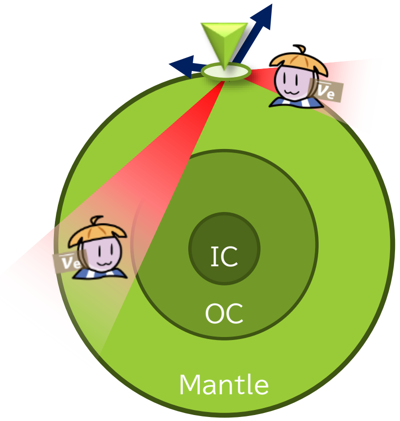
Summary

- 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.

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Models and Parameters

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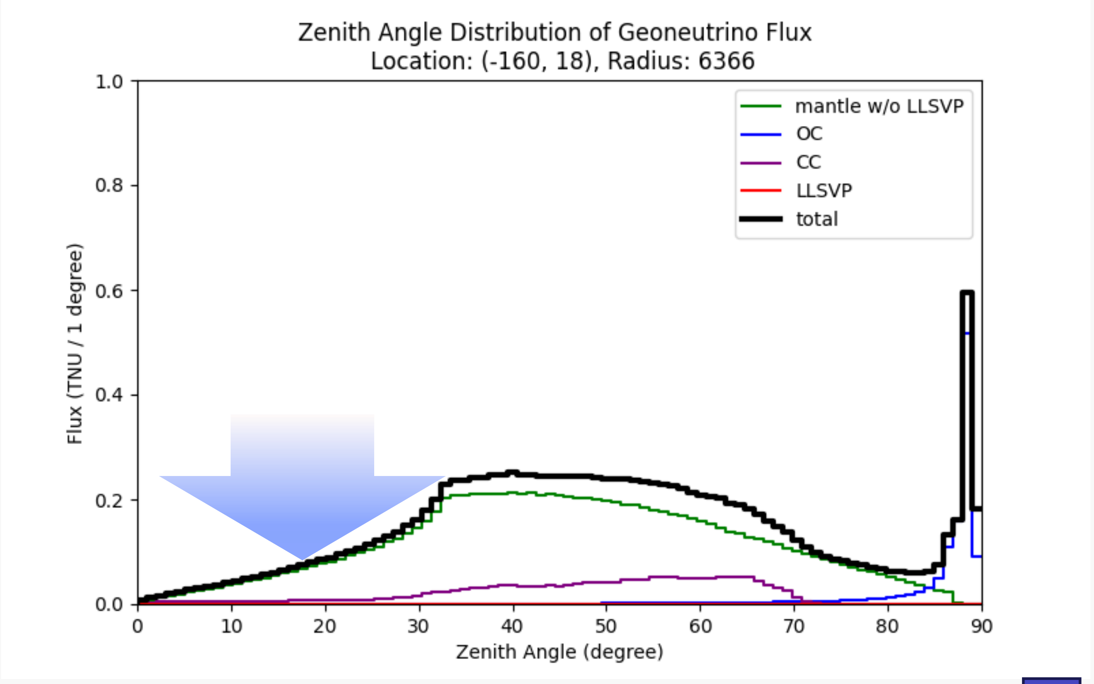
Backup

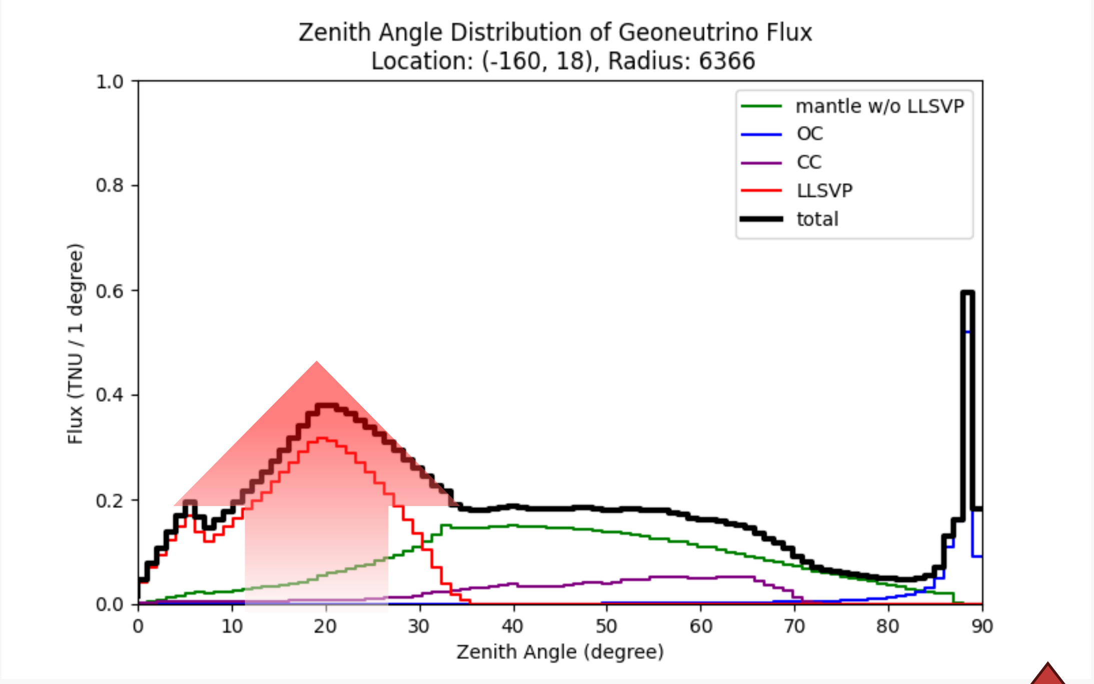
Zenith angle distribution of the geoneutrino flux @Hawaii

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

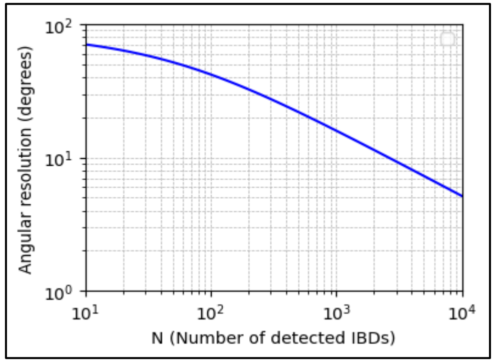
Since it is practically impossible to achieve such precise detection, such a result cannot be obtained…

Geoneutrino detection simulation result @Hawaii

- We can just achieve a limiting angular resolution based on the evaluation formula…

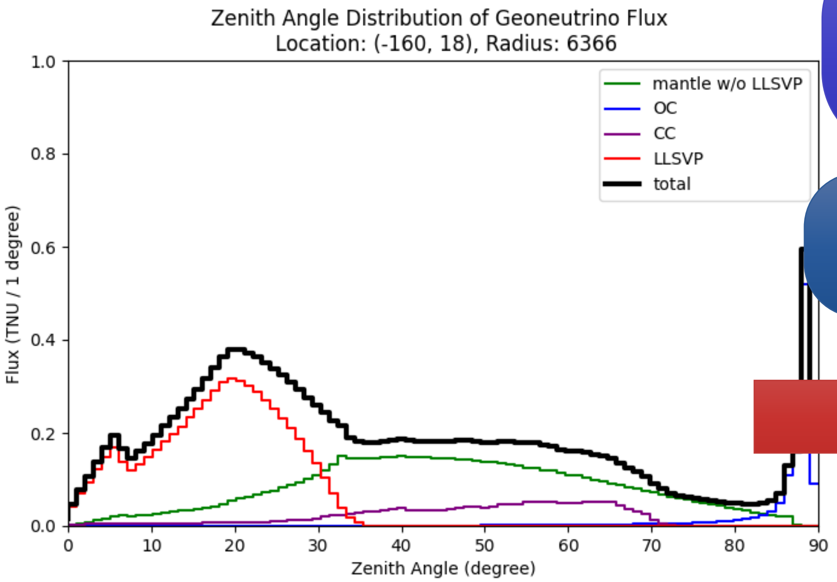
$$[\Delta\theta]_{1\sigma} = \arctan\frac{P}{d_n\sqrt{N}}$$

(Duvall, et al., 2024)



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

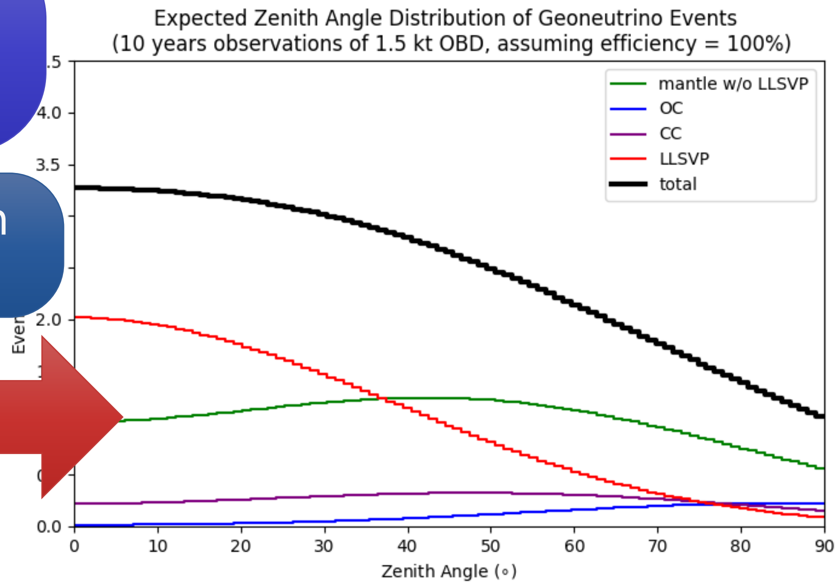
Zenith angle distribution of geoneutrino flux



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

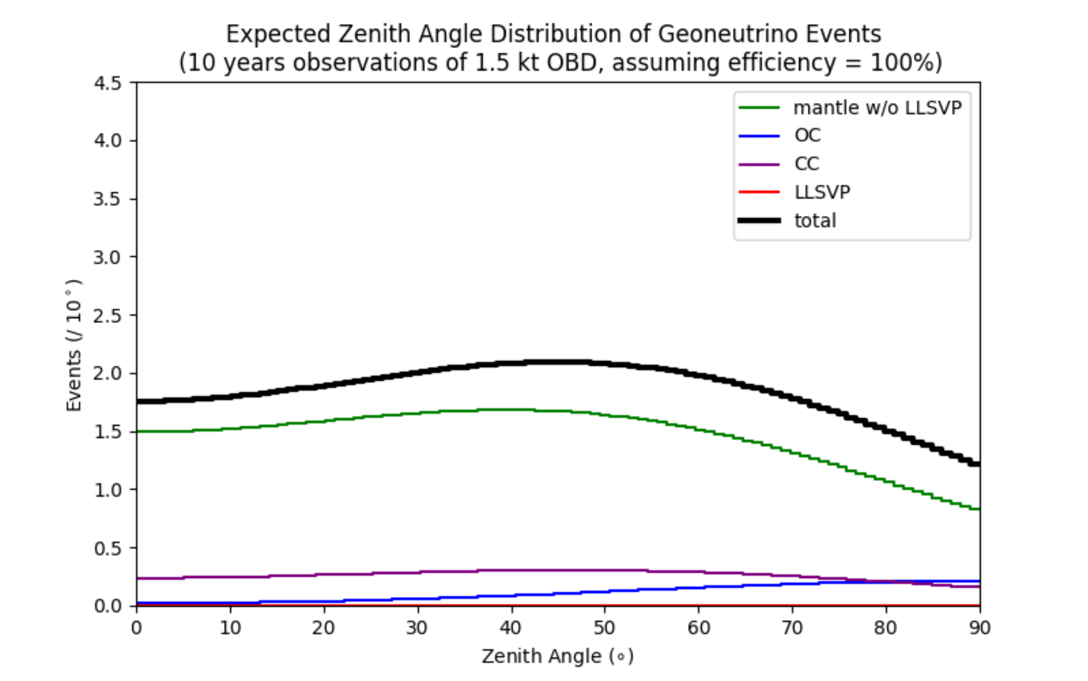
Assume a 10-year detection with 100% efficiency

Expected geoneutrino detection result



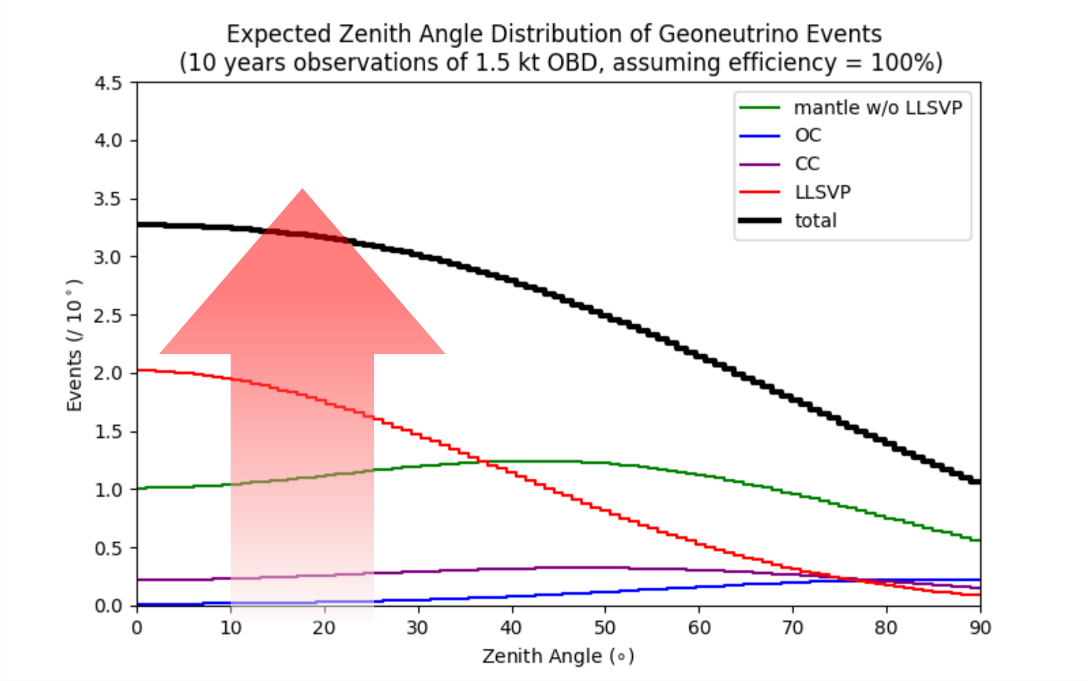
Geoneutrino detection simulation result @Hawaii

the case of a homogeneous mantle

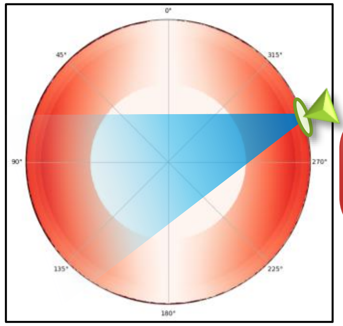


Total events: **195**, Angular resolution: **32.8°**

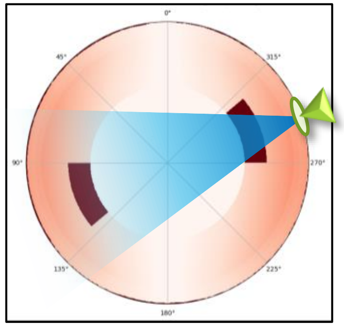
the case of LLSVPs exist



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



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



Detailed formula for calculating geoneutrino flux

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

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}
- is almost independent of E_ν
- shows strong periodicity with respect to $|\boldsymbol{r}-\boldsymbol{r}'|$

→ $P_{ee} \sim \langle P_{ee} \rangle = 0.55$

After various transformations,

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

where

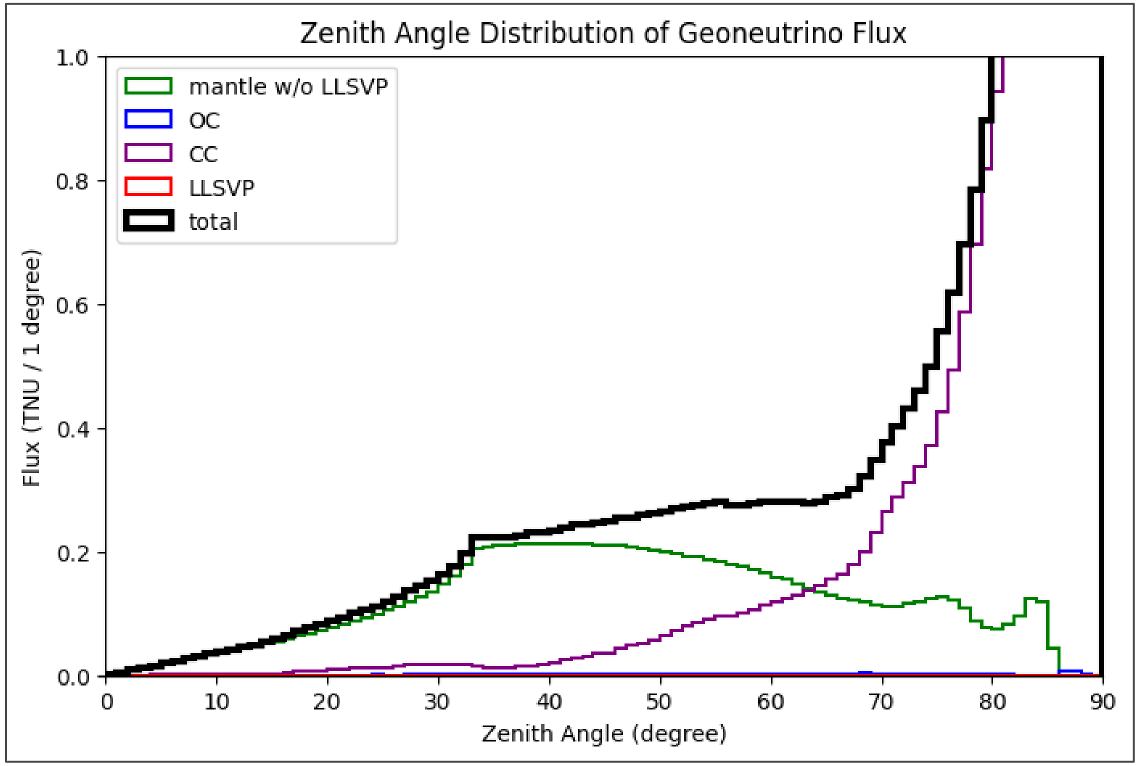
$$L_X \equiv \frac{\varepsilon N_A \lambda_X}{\mu_X} \int_{E_\nu} dE_\nu \frac{dn_X(E_\nu)}{dE_\nu} \sigma_{\mathrm{IBD}}(E_\nu)$$
$$A_X(\boldsymbol{r}') \equiv \rho(\boldsymbol{r}') a_X(\boldsymbol{r}')$$

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

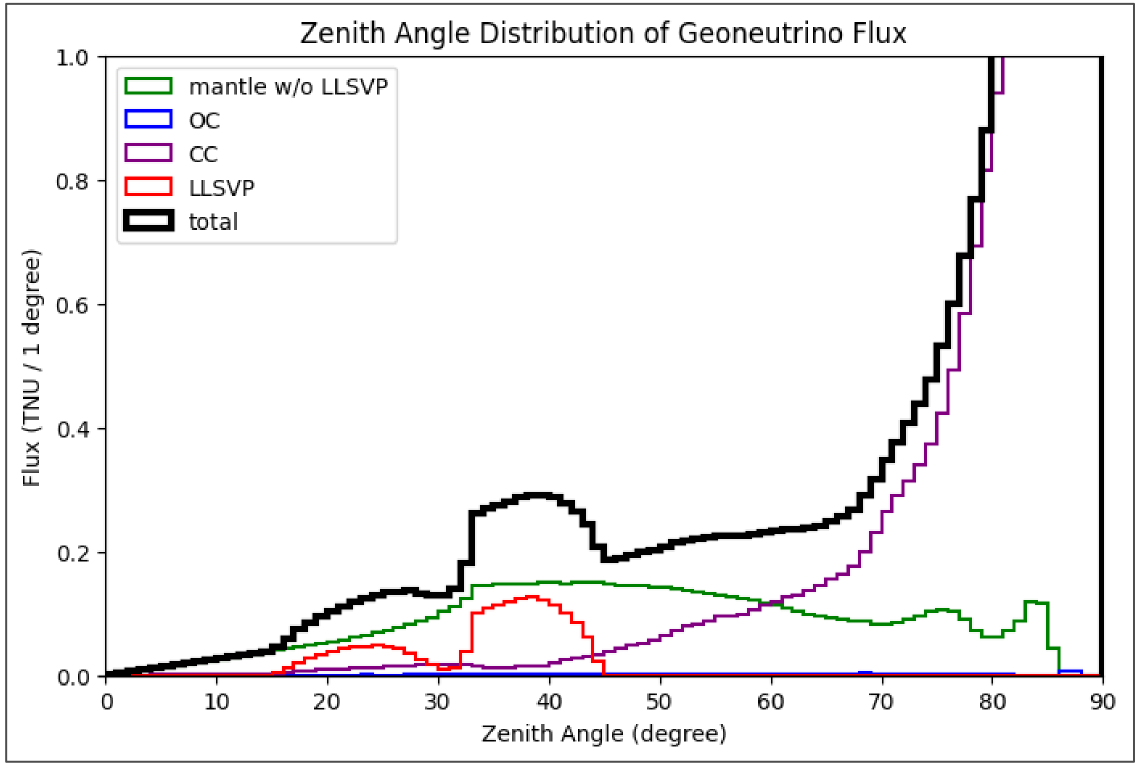
Zenith angle distribution on continental crust

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.