Quantifying Geochemical Anomalies in the Mantle Using Geoneutrinos

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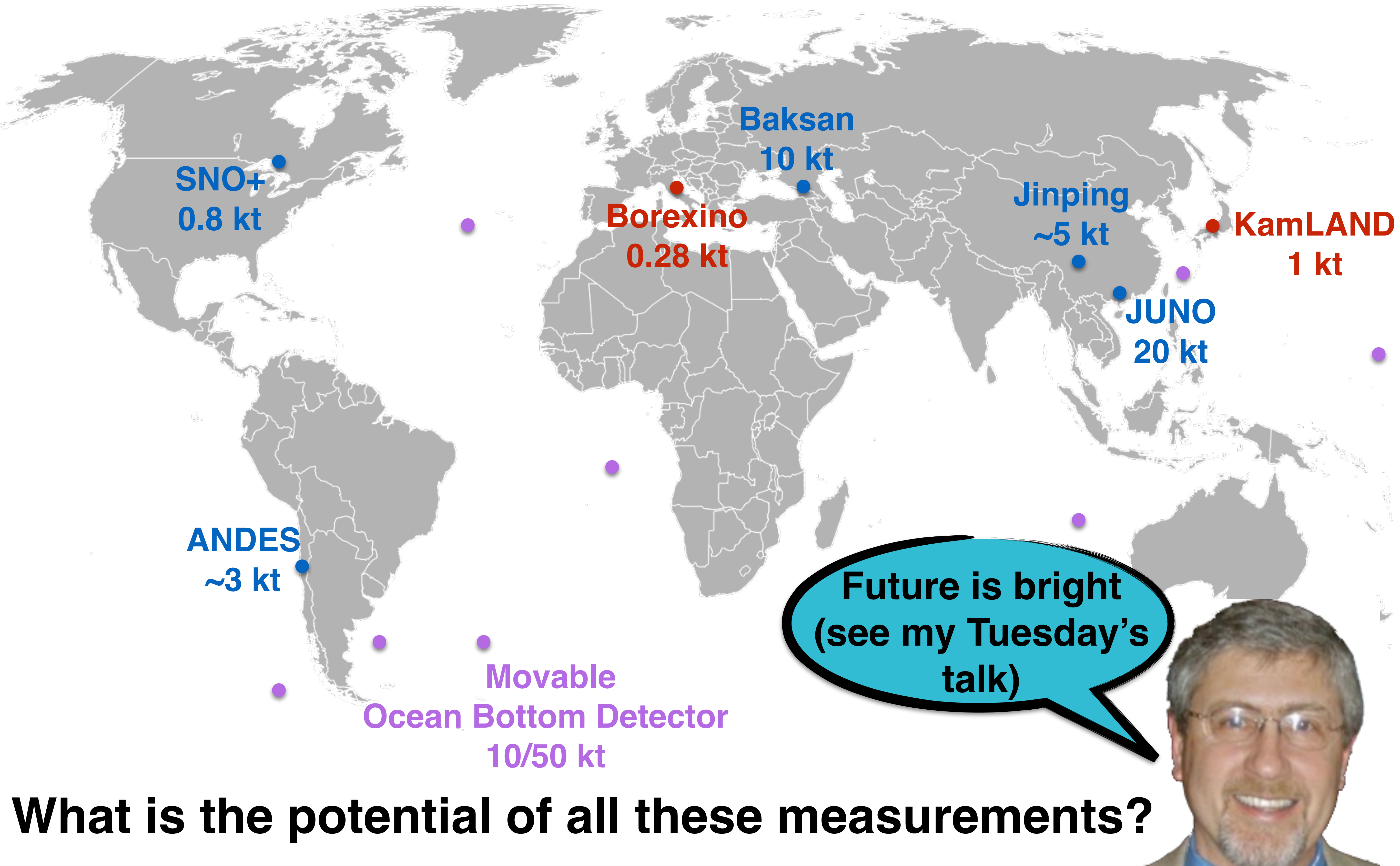
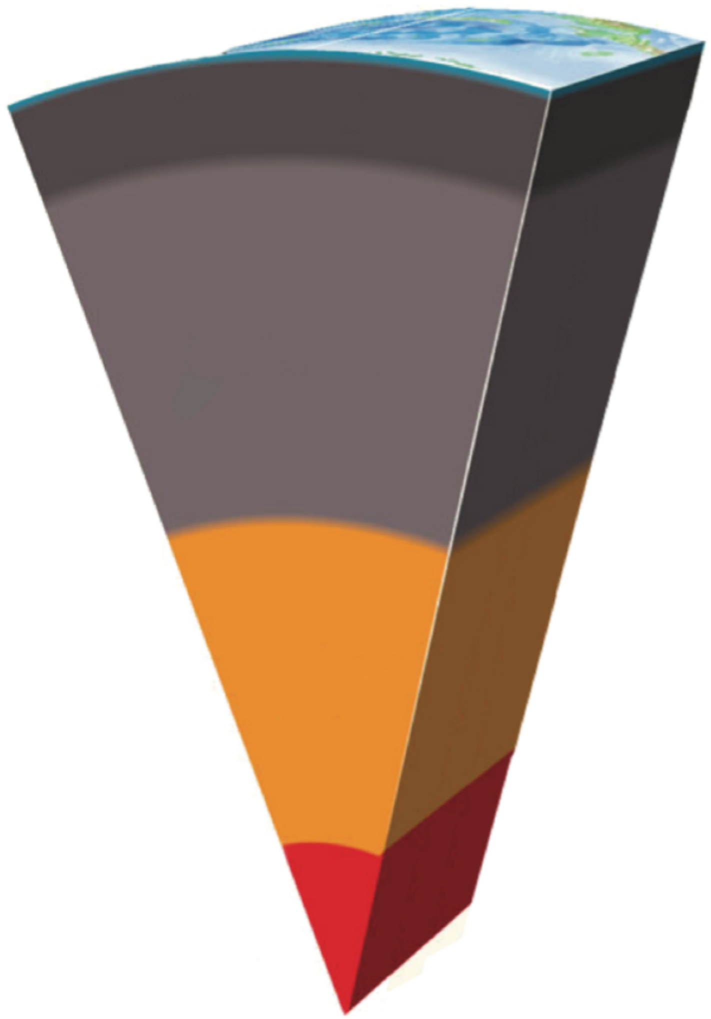
Current and Future Geoneutrino Experiments



What is the potential of all these measurements?

Where Are Geoneutrinos Coming From?



Crust:

- Highly enriched by U and Th
- Continental crust 10-50× more enriched than oceanic crust and few 100× more than underlying mantle
- Continental crust highly heterogenous

Mantle:

- Upper part depleted of U and Th (source of Mid-ocean ridge basalts)
- Bottom part more enriched w.r.t. depleted mantle (source of ocean island basalts)

Core:

- No or very little U and Th (*EPSL 498 (2018) 196-202*)

$$^{238}_{92}\mathrm{U} \rightarrow {}^{206}_{82}\mathrm{Pb} + 8\alpha + 6e^- + 6\bar{\nu}_e + 51.698\ \mathrm{MeV}$$

$$^{235}_{92}\mathrm{U} \rightarrow {}^{207}_{82}\mathrm{Pb} + 7\alpha + 4e^- + 4\bar{\nu}_e + 46.402\ \mathrm{MeV}$$

$$^{232}_{90}\mathrm{Th} \rightarrow {}^{208}_{82}\mathrm{Pb} + 6\alpha + 4e^- + 4\bar{\nu}_e + 42.652\ \mathrm{MeV}$$

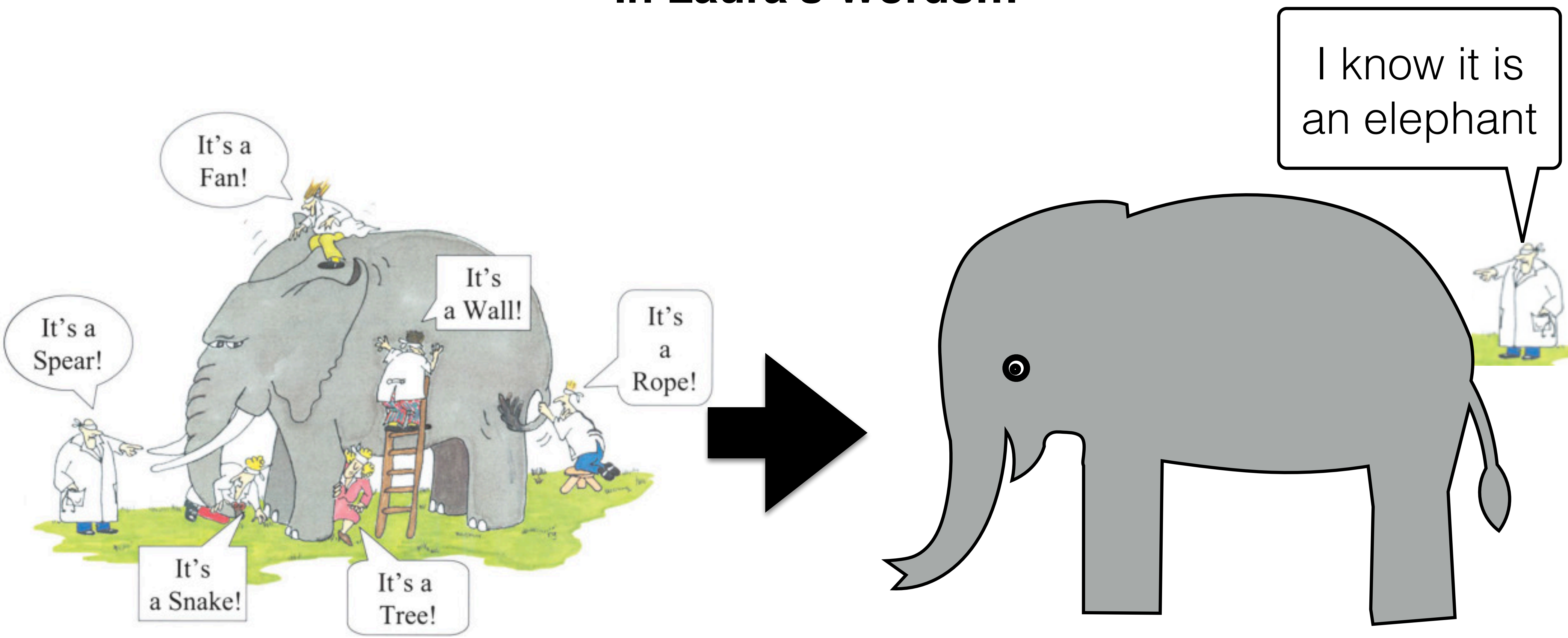
$$^{40}_{19}\mathrm{K} \xrightarrow{89.3\%} {}^{40}_{20}\mathrm{Ca} + e^- + \bar{\nu}_e + 1.311\ \mathrm{MeV}$$

$$^{40}_{19}\mathrm{K} \xrightarrow{10.7\%} {}^{40}_{18}\mathrm{Ar} + \nu_e + 1.505\ \mathrm{MeV}$$

We Know the Crust Assumption

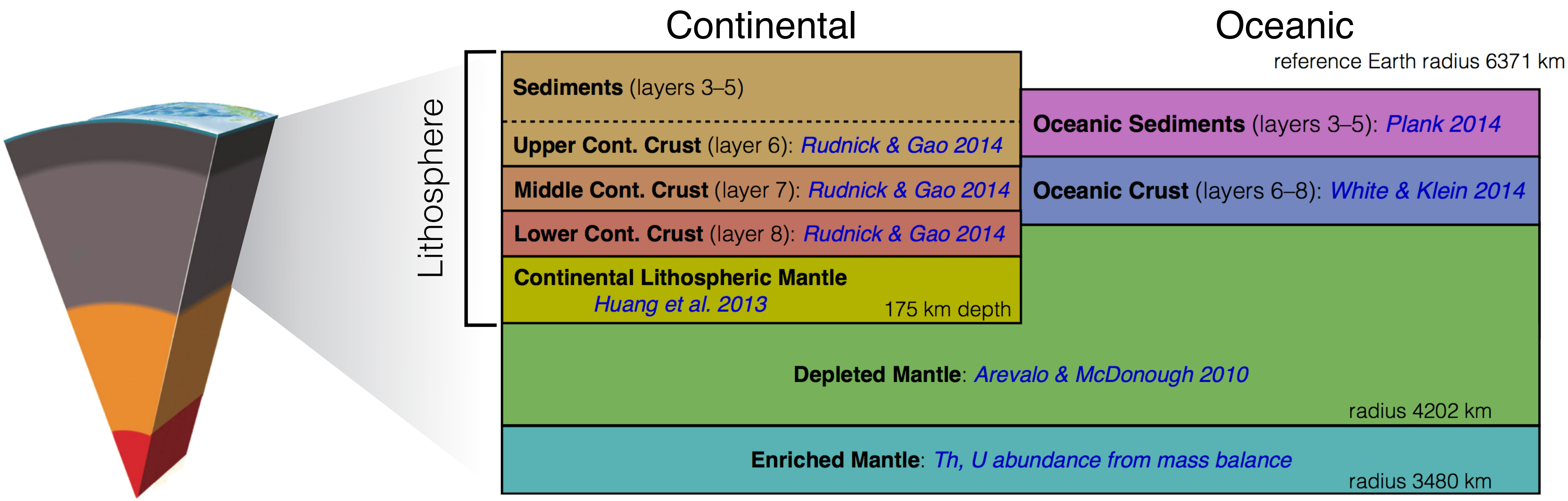
- We assume that we know the crust, up to Šrámek et al. (2016) model precision

In Laura's Words…



Global Geoneutrino Emission Model

Šrámek et al. (2016) model (*SREP 6, 33034 (2016)*)



Highlights:

- Density of the crust from CRUST1.0
- Density of the mantle from PREM
- **Mantle spherically symmetrical!**
- Radiogenic power of the Earth constrained to ~(20±4) TW (*Chem. Geol., 120, 3–4, 1995, 223-253*)

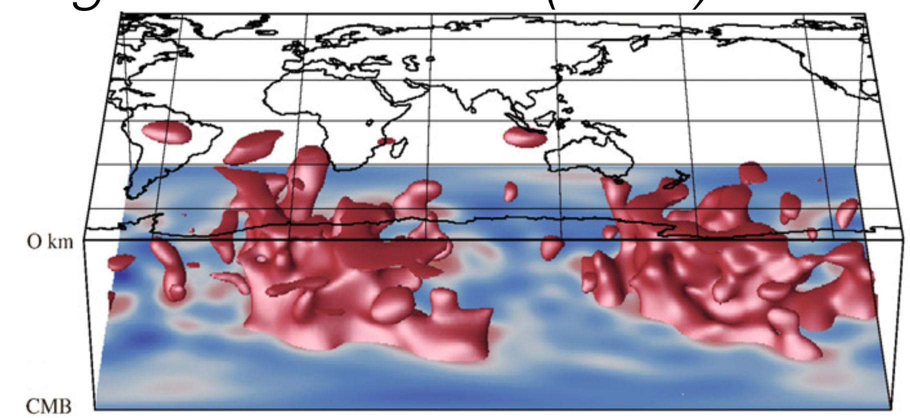
Model U and Th abundances

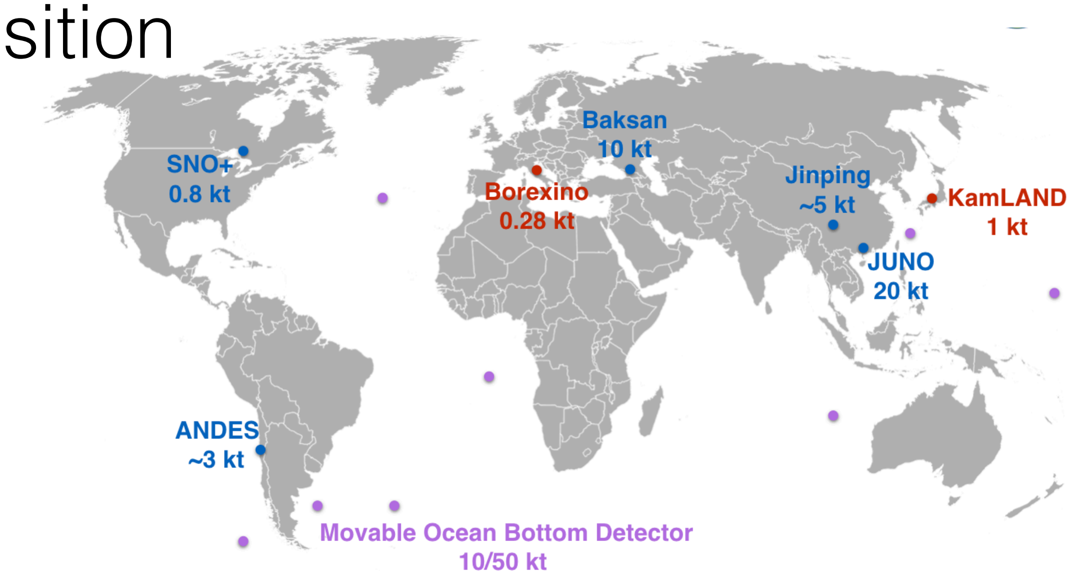
	Th	U
Upper CC + sediments	$(10.5 \pm 10\%) \times 10^{-6}$	$(2.7 \pm 21\%) \times 10^{-6}$
Middle CC	$(6.5 \pm 8\%) \times 10^{-6}$	$(1.3 \pm 31\%) \times 10^{-6}$
Lower CC	$(1.2 \pm 30\%) \times 10^{-6}$	$(0.2 \pm 30\%) \times 10^{-6}$
OC sediments	$(8.10 \pm 7\%) \times 10^{-6}$	$(1.73 \pm 5\%) \times 10^{-6}$
OC crust	$(0.21 \pm 30\%) \times 10^{-6}$	$(0.07 \pm 30\%) \times 10^{-6}$
CLM	$150^{+277}_{-97} \times 10^{-9}$	$33^{+49}_{-20} \times 10^{-9}$
Depleted Mantle	$(21.9 \pm 20\%) \times 10^{-9}$	$(8.0 \pm 20\%) \times 10^{-9}$
Enriched Mantle*	$147^{+74}_{-57} \times 10^{-9}$	$30^{+24}_{-18} \times 10^{-9}$
Bulk Silicate Earth	$(80 \pm 15\%) \times 10^{-9}$	$(20 \pm 20\%) \times 10^{-9}$

Quantifying Mantle Geochemical Anomalies

- In many studies, mantle considered as spherically symmetrical
  - E.g. Šrámek et al. (2016) model
  - Reasonable approximation
- But it might not be exactly symmetrical
  - Observation of Large Low Shear Velocity Provinces (LLSVPs)
  - Several mechanisms propose creation of, among others, chemical inhomogeneities (anomalies)
  - Hard to test with collecting samples, seismic surveys do not completely reveal chemical composition
- **If anomalies enriched by U and Th, can we image them by an array of geoneutrino experiments?**

Fig. from EPSL 278 (2009) 152–162

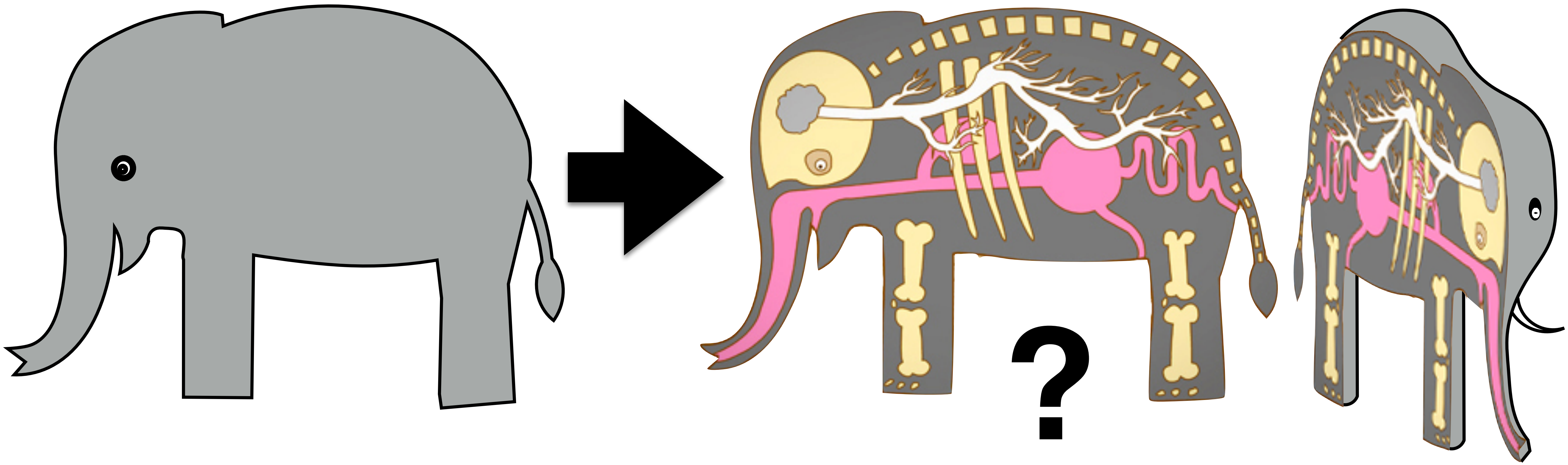


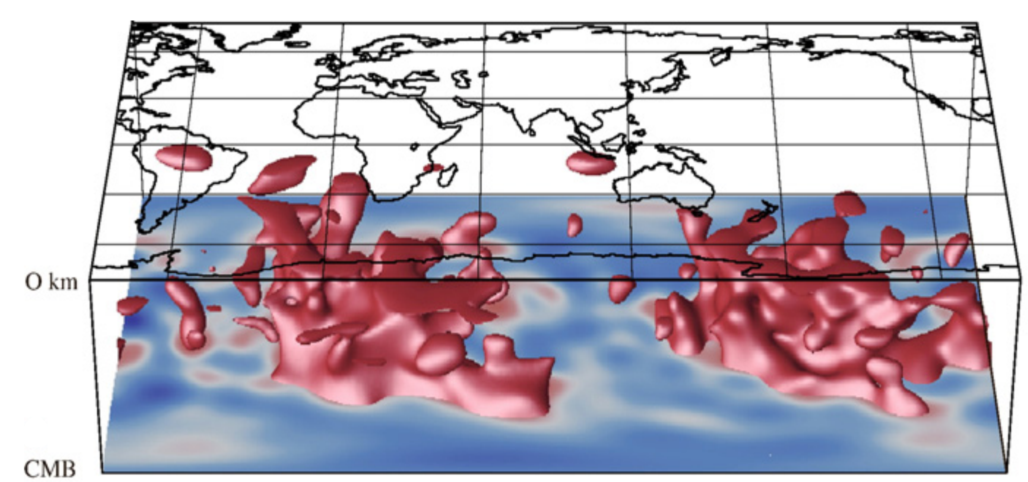


Quantifying Mantle Geochemical Anomalies

- If anomalies enriched by U and Th, can we image them by an array of geoneutrino experiments?

In Laura’s Words…





Investigated Mantle Geochemical Anomalies

- **Early Enriched Regions** - Deep mantle anomalies
  - Large regions at the Core-Mantle Boundary (CMB) enriched in U and Th w.r.t. surrounding mantle - localized bright source of geoneutrinos
- Hypothesized **Second Continents** - Shallow mantle anomalies
  - Up to Australia-size domains of upper crustal material stabilized at the bottom of the Transition Zone at depth ~700 km

Early Enriched Regions (EERs)

1. **Early formed, dense crust, U&Th enriched, and gravitationally stabilized at the CMB" ➔ EER**
   Mass fraction is ~2% of Bulk Silicate Earth (BSE) mass

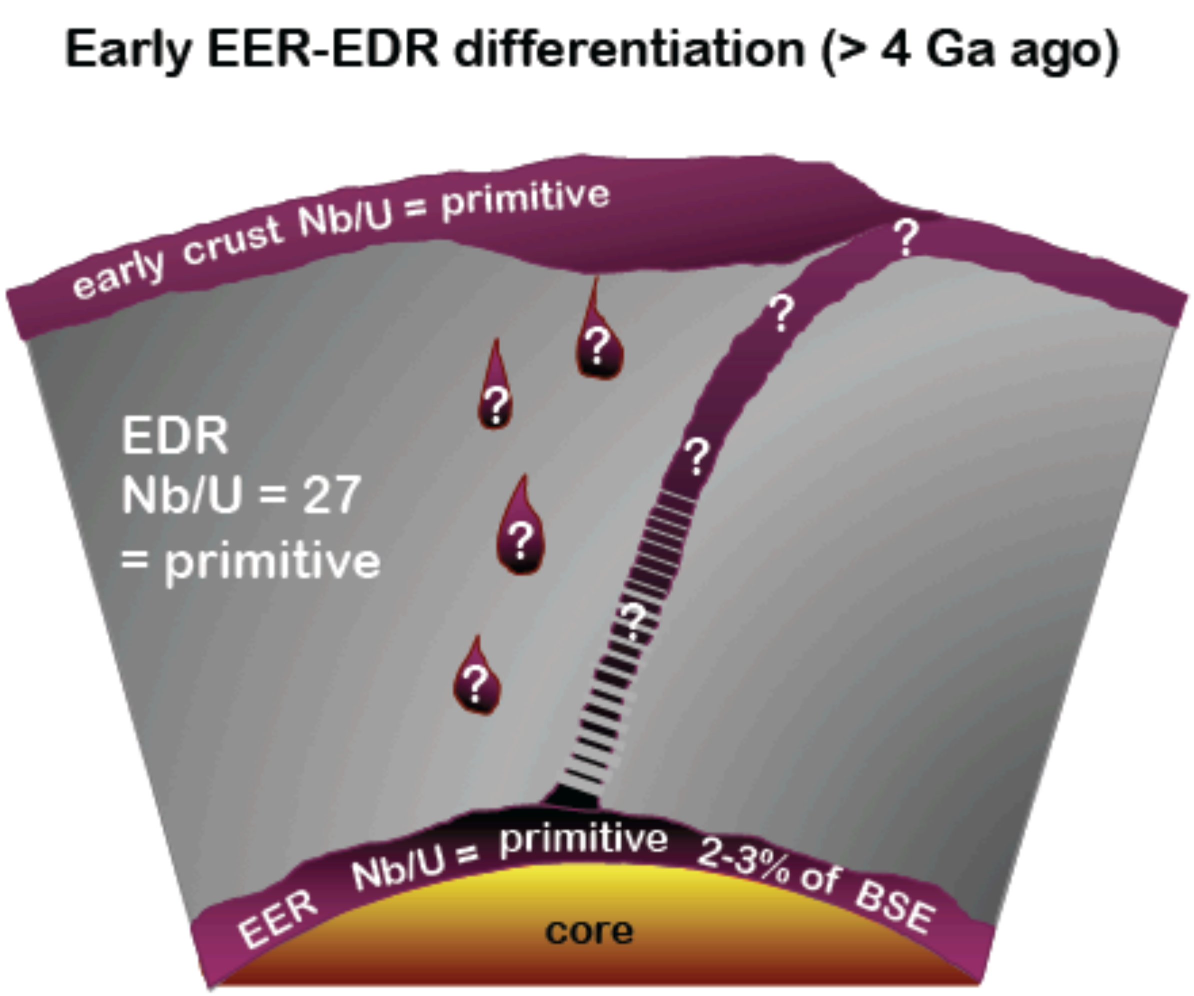


Fig. from "Size and composition of the residual and depleted mantle reservoir", Hofmann at al., paper in review

Early Enriched Regions (EERs)

1. Early (U&Th enriched) crust formation and sinking to the CMB ➔ EER
2. **Current crust formed from Residual Mantle (BSE-EER), EERs remain intact**

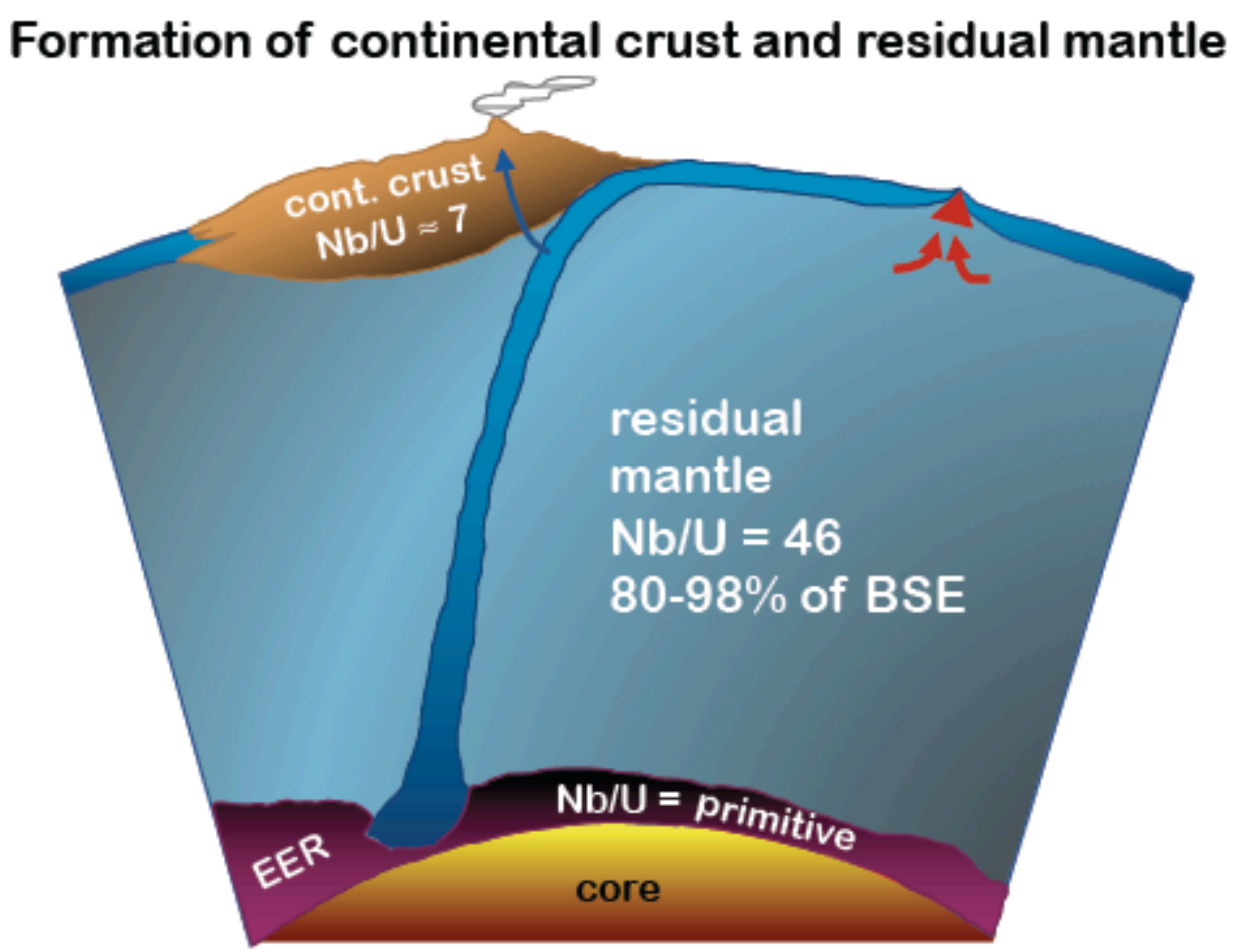
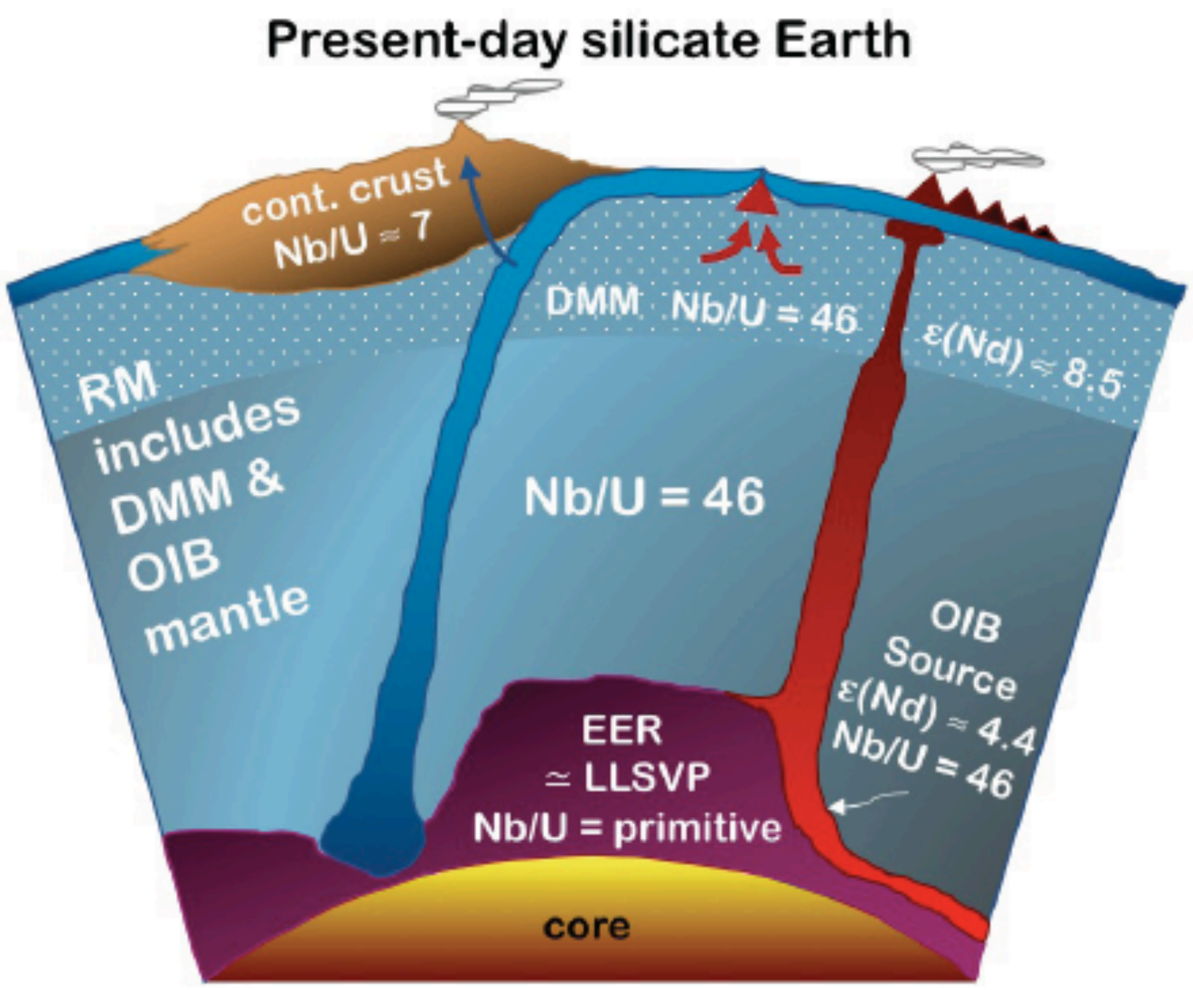


Fig. from "Size and composition of the residual and depleted mantle reservoir", Hofmann at al., paper in review

Early Enriched Regions (EERs)

1. Early (U&Th enriched) crust formation and sinking to the CMB ➔ EER
2. Current crust formed from Residual Mantle (BSE-EER),
   EERs remain intact
3. **Further differentiation of the Residual Mantle, EERs remain intact**



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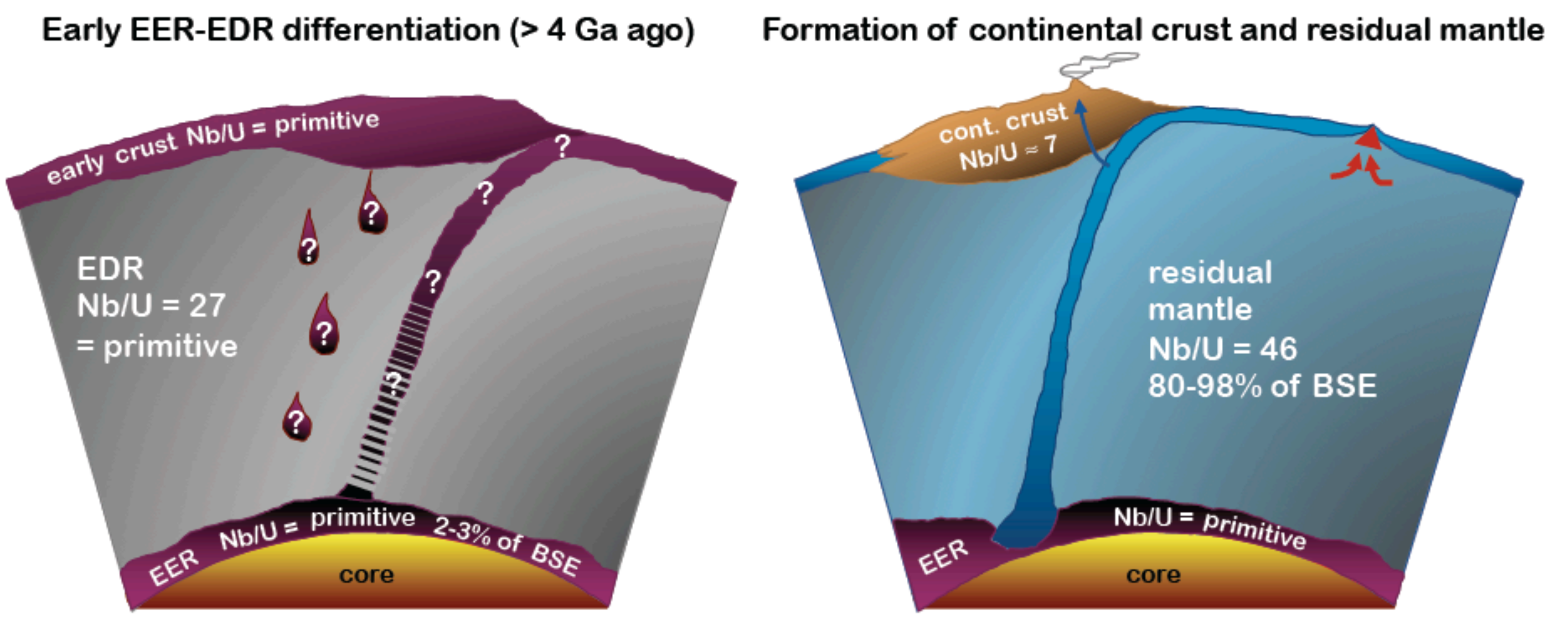
Early Enriched Regions (EERs)



BSE	Bulk Silicate Earth
EDR	Early Depleted Reservoir
EER	Early Enriched (mafic) Reservoir
RM	Residual Mantle - portion of the mantle from which the present-day continental crust has been extracted
DMM	Depleted MORB mantle
primitive	Primitive undifferentiated ratio
MORB	Mid-ocean ridge basalts
OIB	Ocean island basalts

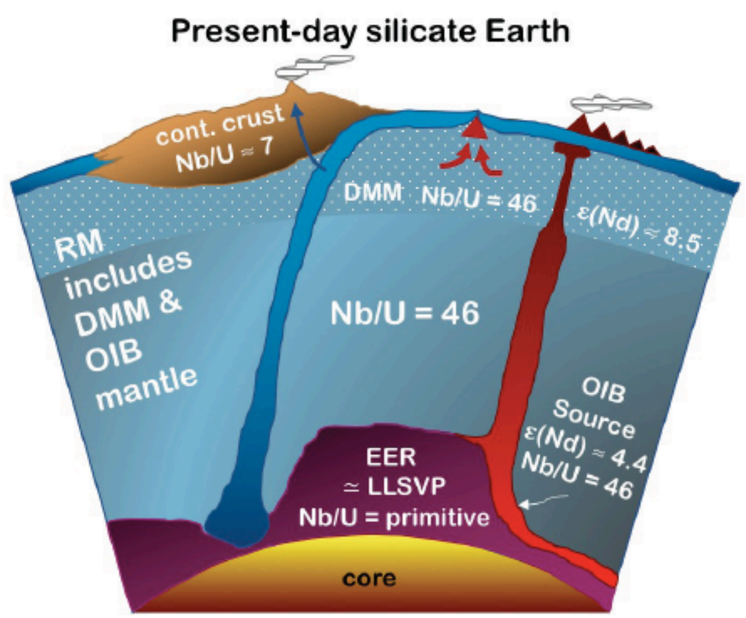


Fig. from Hofmann at al., paper in review

- **Can we identify LLSVPs with EERs?**
- **Can geoneutrinos tell us something?**
- Remember, EERs are enriched by U&Th

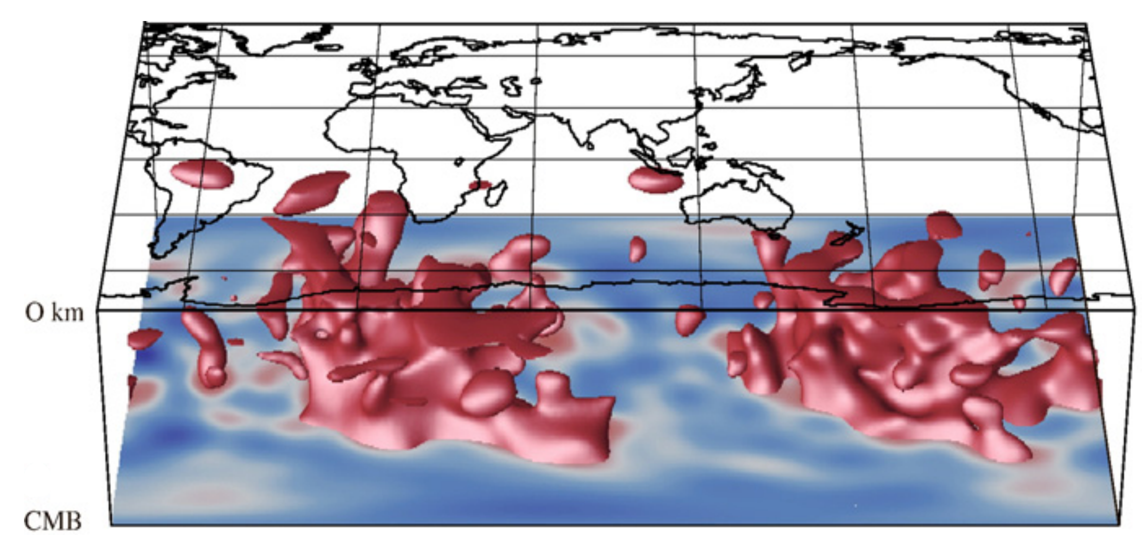
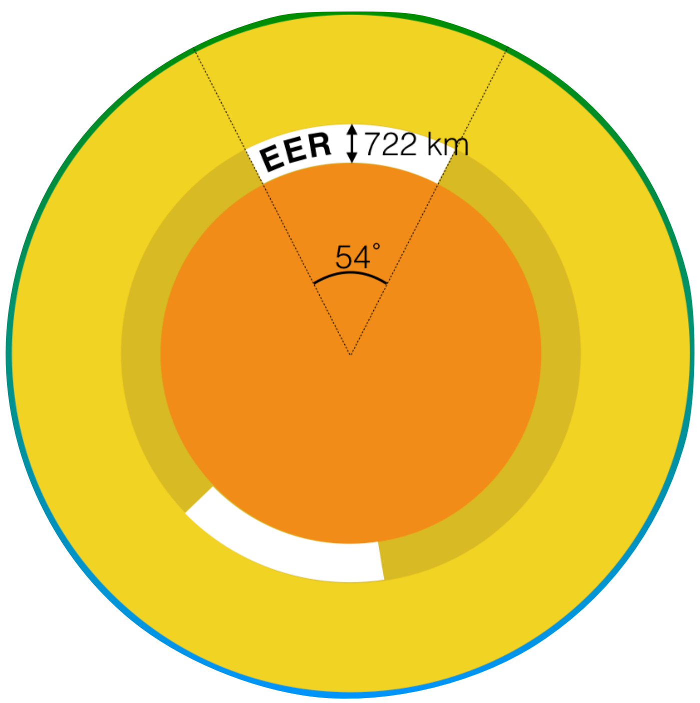


Fig. from Bull et al.(2009) EPSL 278, 152–162

Model of EERs Based on Hofmann et al.

EERs:

- $2 \times 1\%$ of BSE mass
- $\rho = 5700\ kg/m^3$
- $A_U = 0.199$ ppm*
- $A_{Th} = 0.783$ ppm*

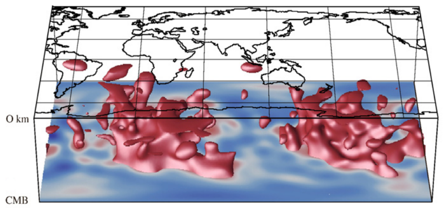


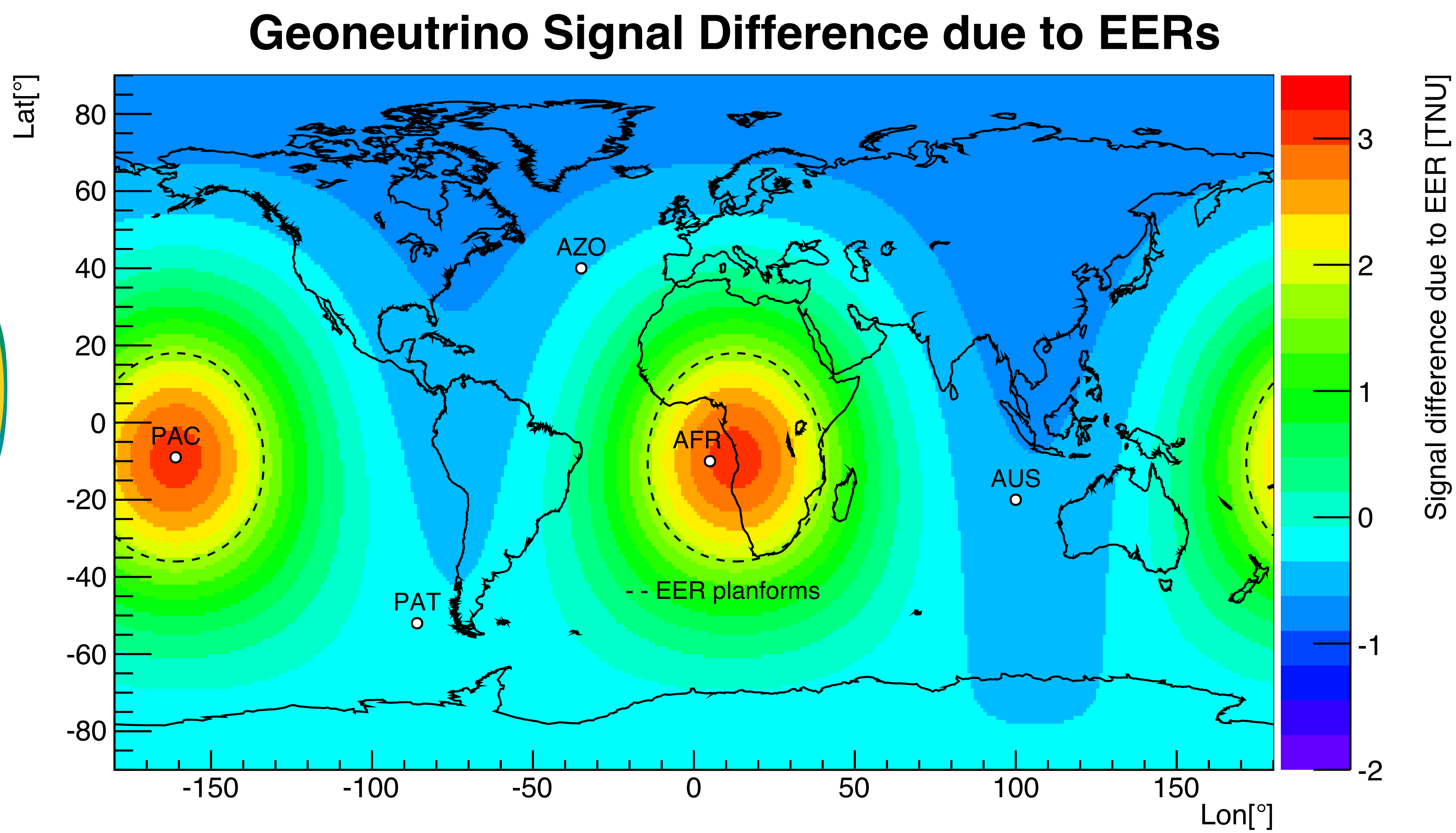
*Our estimation based Hofmann at al. paper

Simplified geometry - core of LLSVPs:

EER1: Central Pacific center: 9°S 161°W

EER2: South Africa center: 9°S 13°E





EER search ideal playground for Ocean Bottom Detector (OBD) (poster by Dr. Watanabe)

Geoneutrino Signal with EERs

- Prediction based on Šrámek et al. (2016) model

Experiment	Location	Predicted signal [TNU]*	Expected signal with ERRs [TNU]*	Measurement uncertainty
Pacific EER (PAC)	9°S 161°W	11.8 ± 2.6	14.9	10%
Africa EER (AFR)	10°S 5°E	16.3 ± 2.5	19.3	10%
Patagonia (PAT)	52°S 86°W	13.6 ± 2.5	13.3	10%
Australia (AUS)	20°S 100°E	13.9 ± 2.5	13.3	10%
Azores (AZO)	40°N 35°W	14.7 ± 2.5	14.3	10%

- Sites selected to either have strong, or weak EER geoneutrino signal
- Assumed 10% Ocean Bottom Detector relative measurement uncertainty: **about 1 year of data taking with 50 kt detector**

Really 50 kt?

Future is bright!

* Geoneutrino signal shown in Terrestrial Neutrino Units (TNU) $\stackrel{\text{def}}{=}$ *Number of geoneutrinos detected by inverse beta decay in 1 yr with 100% efficiency on 10^{32} protons*

EER Discovery Potential

Expected (w/EER) **Predicted w/o EER**

$$\chi^2_{min} = \min_{\alpha} \sum_{i=1,..,5}^{Experimnets} \left(\frac{\overbrace{\bar{E}_i}^{} - \overbrace{\bar{P}_i - \sigma_{pred,i} \times \alpha}^{}}{\sigma_{meas,i}} \right)^2 + \alpha^2$$

Fully correlated prediction uncertainties

Expected (w/EER)

Uncorrelated Measurement Uncertainty

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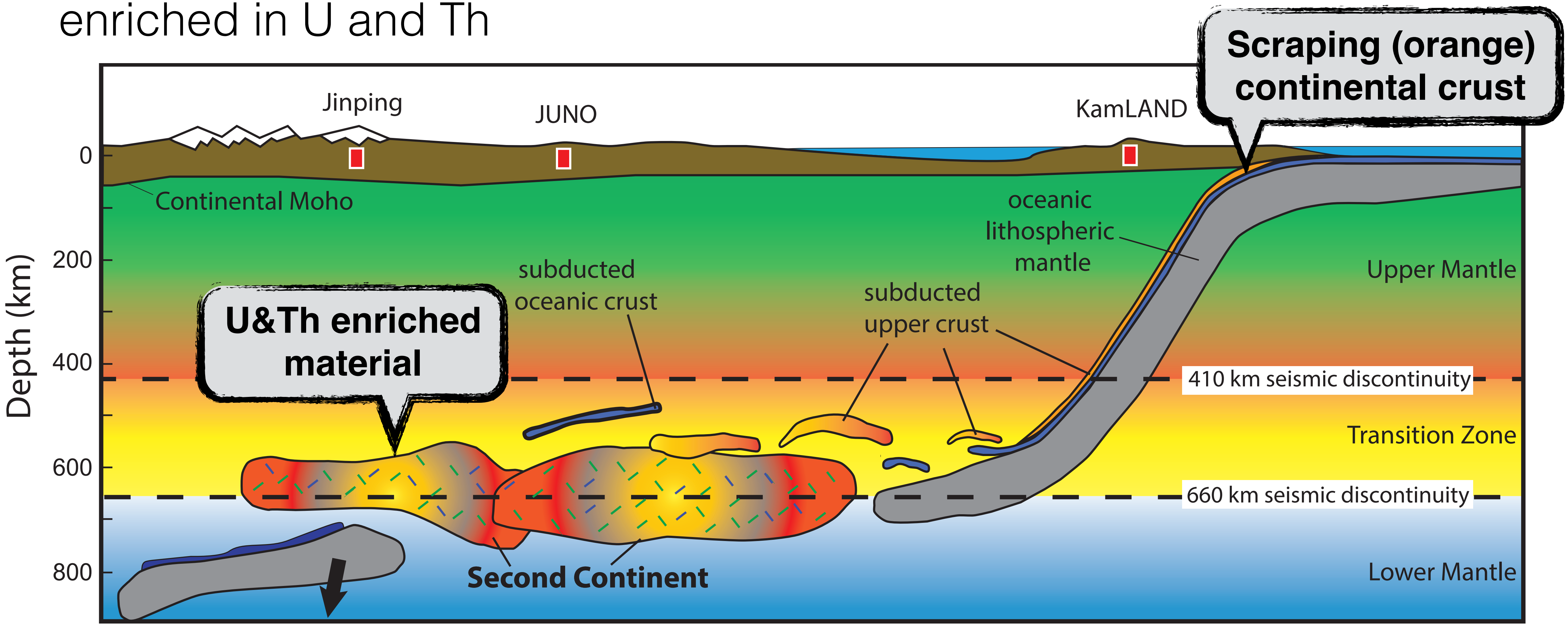
Predicted w/o EER

- **Our model of EER discovery has 2.4σ discovery significance**
- Small variations of our model leads to similar discovery potential
- Larger volume and/or less enriched EERs has lower discovery potential

Introduction to the Second Continent

- Second Continent (SC) - Layer at the bottom of Transition Zone ~660 km enriched in U and Th

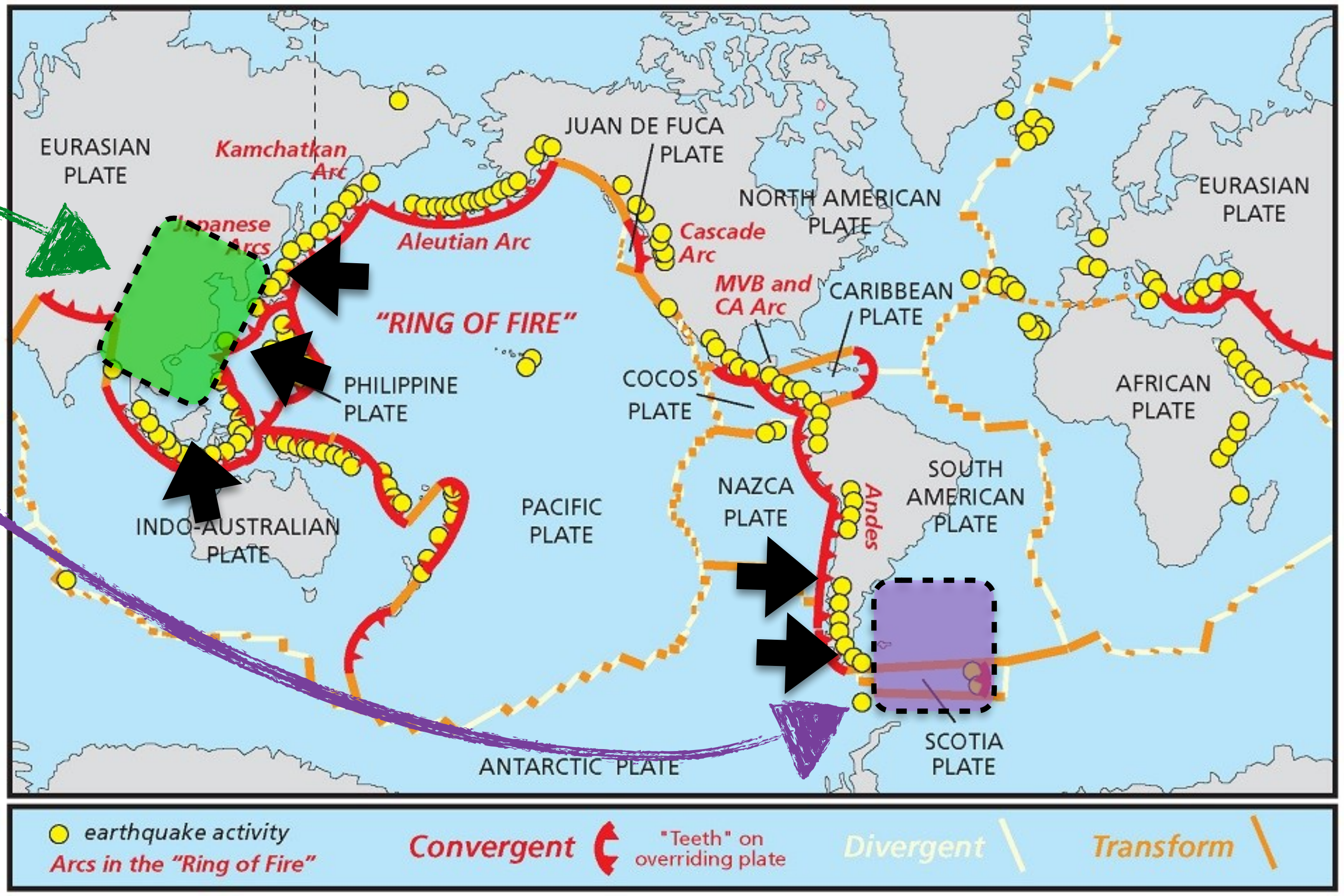


Kawai et al. (2009)
Maruyama et al. (2011)
Kawai et al. (2013)
…

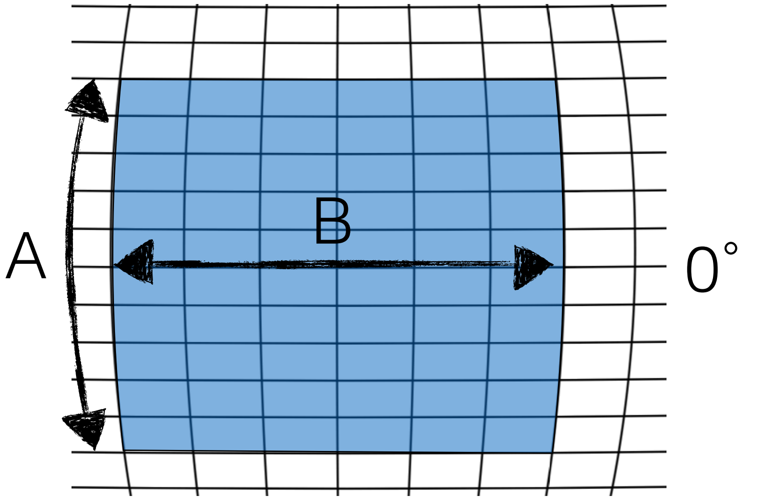
- Second Continent:
  - Density contrast - hard to resolve with seismic data
  - Abundances of Th and U ≤ Upper Continental Crust
  - Powerful heat supplier and **bright source of geoneutrinos!!!**

Localized Second Continent Scenarios

- Two SC scenarios considered at 600-700 km depth:
  - Australia-size (2000×2000 km)*
    SC under China
  - Australia-size (2000×2000 km)*
    SC under the south Atlantic



- Upper Continental Crust (UCC) abundances:
  - $A_U = 2.7\times10^{-6}$ kg×kg^{-1}
  - $A_{Th} = 10.5\times10^{-6}$ kg×kg^{-1}
- Rectangular planform: Variation in shape (not size) does not have a large impact on the result



A=B=2000 km

Based on Ichikawa et al. (2013)

Geoneutrino Signal with Second Continents

- Prediction based on Šrámek et al. (2016) model

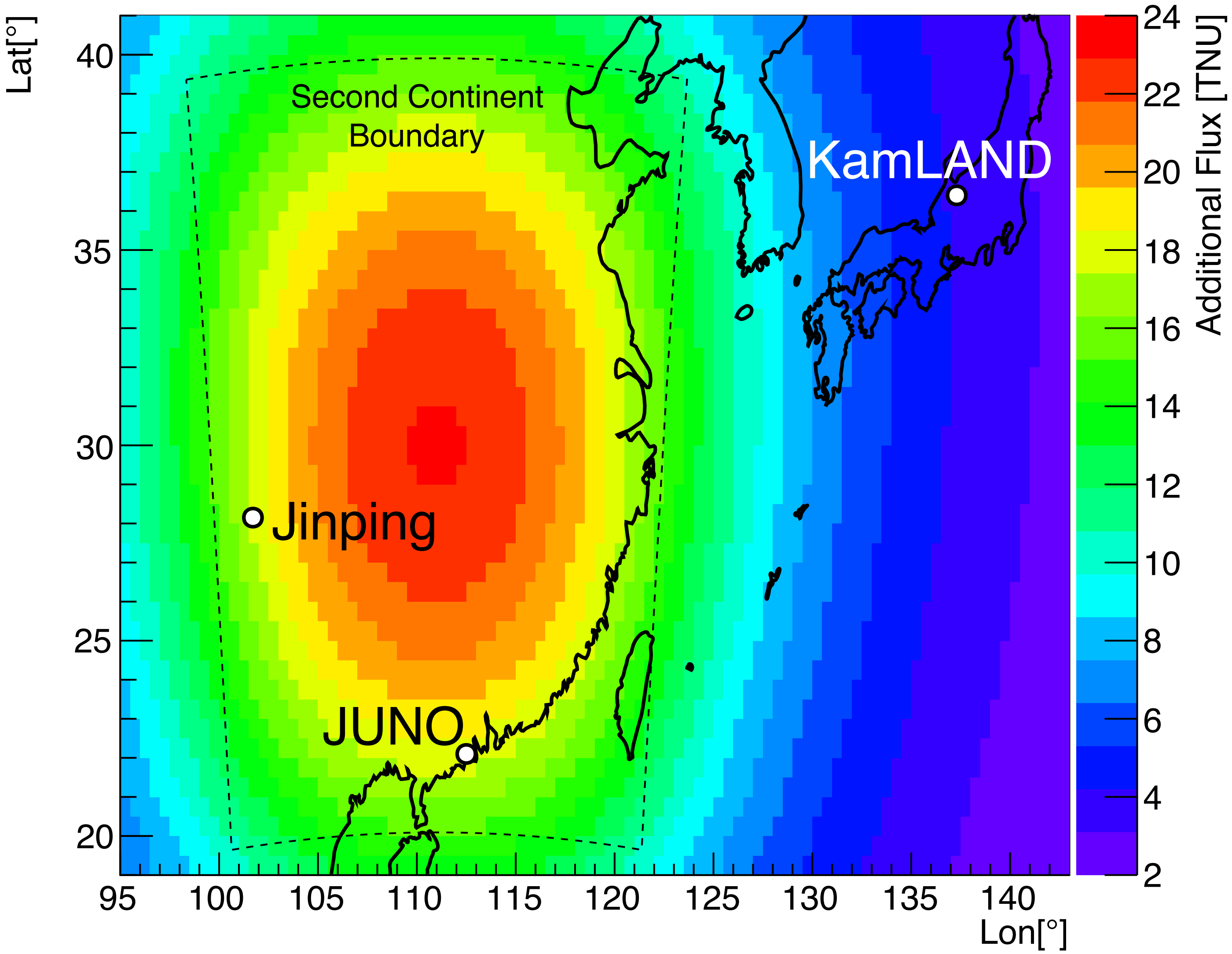
Experiment	Location	Predicted signal [TNU]	Expected signal with SC [TNU]	Measured signal [TNU]	Measurement uncertainty
KamLAND	36.4°N 137.3°E	$34.8^{+4.2}_{-4.0}$	38.8[a]	30.7 ± 7.5	16%
JUNO	22.1°N 112.5°E	$38.9^{+4.8}_{-4.5}$	56.8[a]	-	6%
Borexino	42.5°N 13.6°E	$41.4^{+5.1}_{-4.8}$	-	$47.0^{+8.4+2.4}_{-7.7-1.9}$	18%
ANDES	30.2°S 69.8°W	$41.7^{+4.8}_{-4.7}$	45.8[b]	-	5%
SNO+	46.5°N 81.2°W	$44.2^{+5.3}_{-5.1}$	-	-	9%
Jinping	28.2°N 101.7°E	$58.5^{+7.4}_{-7.2}$	76.1[a]	-	4%
OBD I	44.0°S 47.0°W	$15.5^{+2.4}_{-2.6}$	38.6[b]	-	10%
OBD II	44.0°S 19.0°W	$12.7^{+2.4}_{-2.6}$	17.8[b]	-	10%

[a] Assuming SC under China with a center at 30˚N 111˚E
[b] Assuming SC under south Atlantic with a center at 44˚S 47˚W

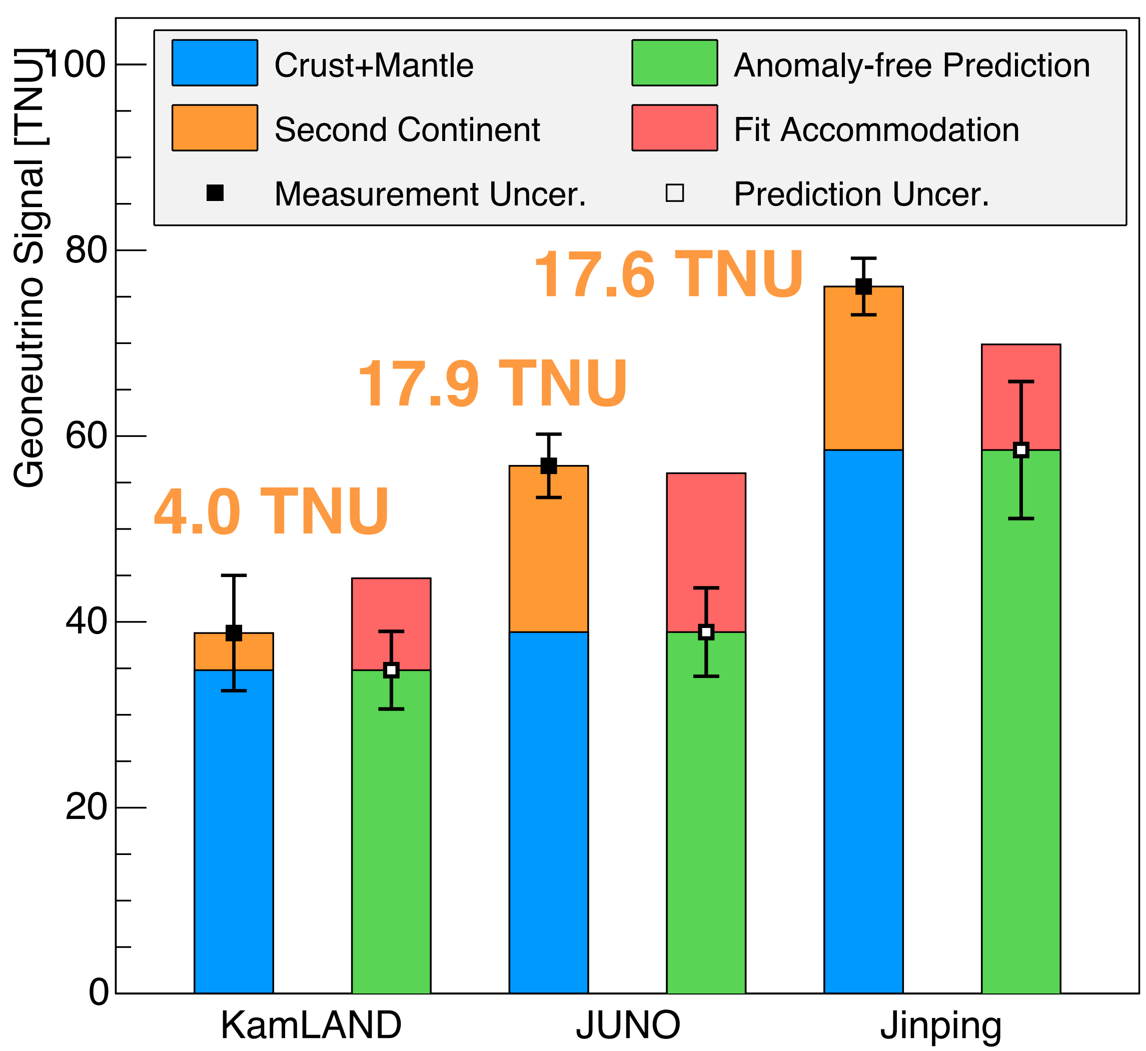
Second Continent Under China Example

- Example of SC location: 30˚N 111˚E
- Resulting from the accumulation beneath China of subducted Pacific plate
- Can be searched by the KamLAND, JUNO and Jinping experiments

Additional geoneutrino signal due to SC



Breakdown of the geoneutrino signal



SC Discovery Potential

$$\chi^2_{min} = \min_{\alpha} \sum_{i=1,2,3}^{Experimnets} \left(\frac{\overbrace{\overline{T}_i + S_i}^{\textbf{Expected (w/SC)}} - (\overbrace{\overline{T}_i + \sigma_{pred,i}}^{\textbf{Predicted w/o SC}} \times \alpha_i)}{\sigma_{meas,i}} \right)^2 + \alpha^T M_{cor} \alpha$$

Uncorrelated Measurement Uncertainty ($\sigma_{meas,i}$)

Partially Correlated Prediction Uncertainty

Expected w/SC ($\overline{T}_i + S_i$)

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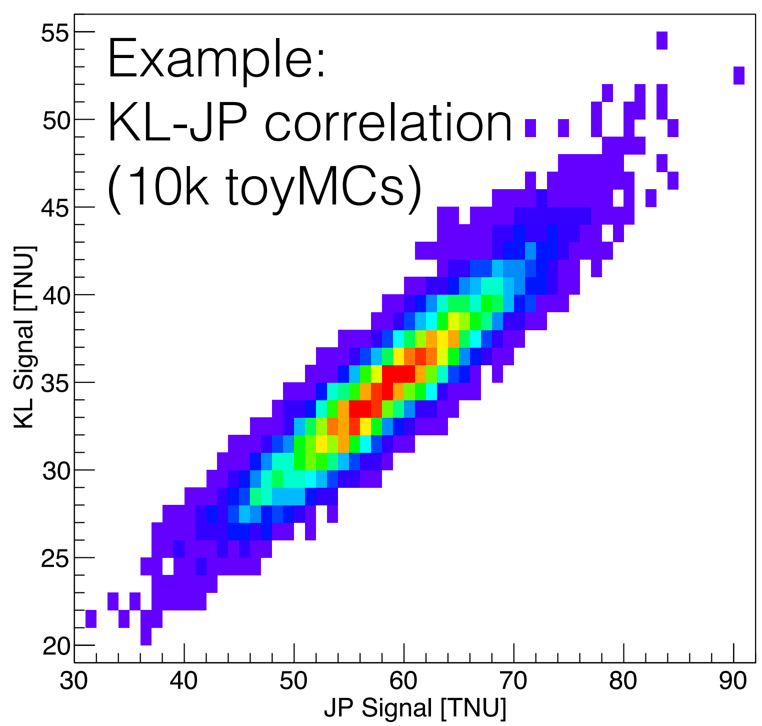
Predicted w/o SC ($\overline{T}_i$)

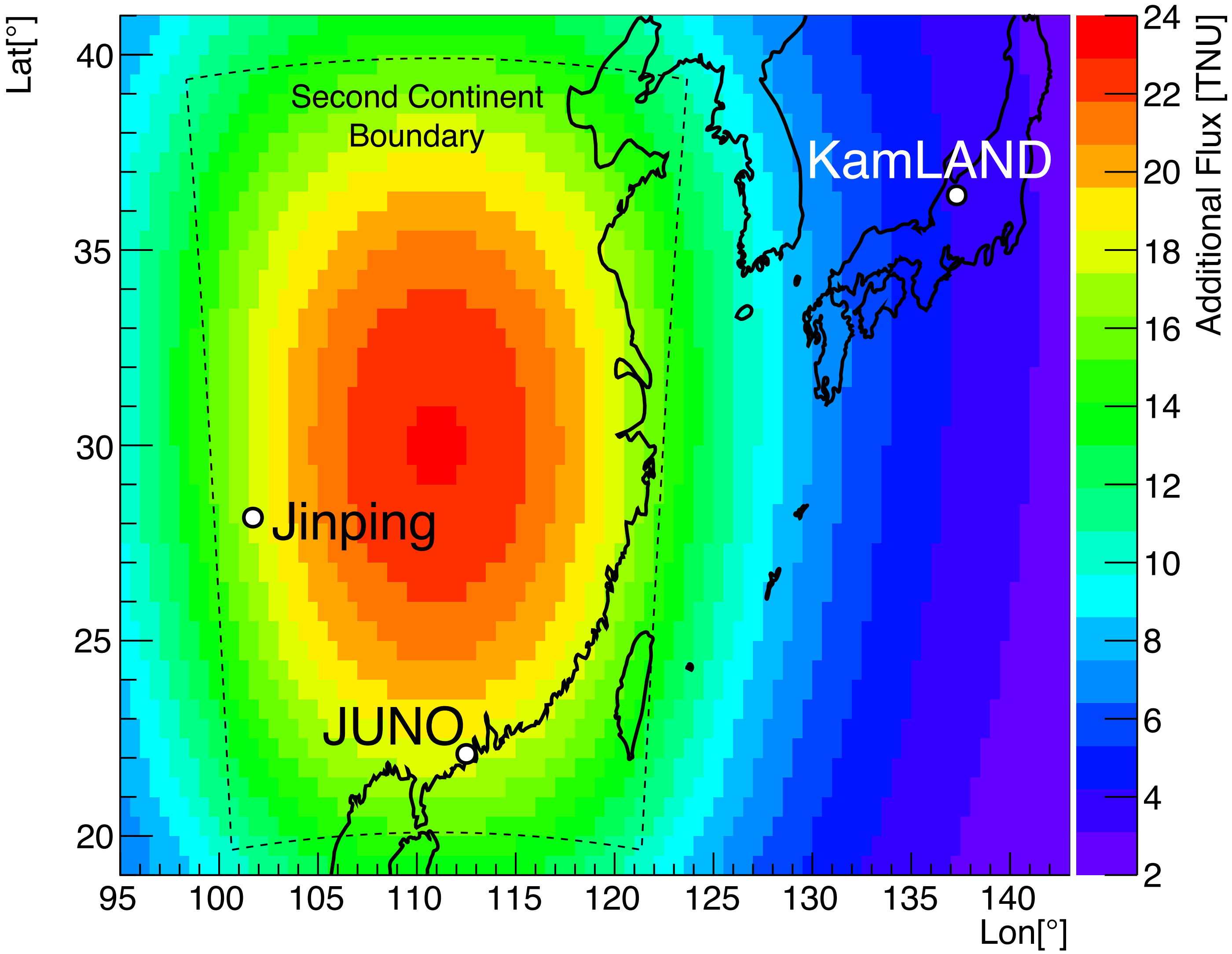
Correlations come from Šrámek et al. (2016) model



Second Continent Under China

- Example of SC location: 30˚N 111˚E
- Resulting from the accumulation beneath China of subducted Pacific plate
- Can be searched by the KamLAND, JUNO and Jinping experiments

Additional geoneutrino signal due to SC



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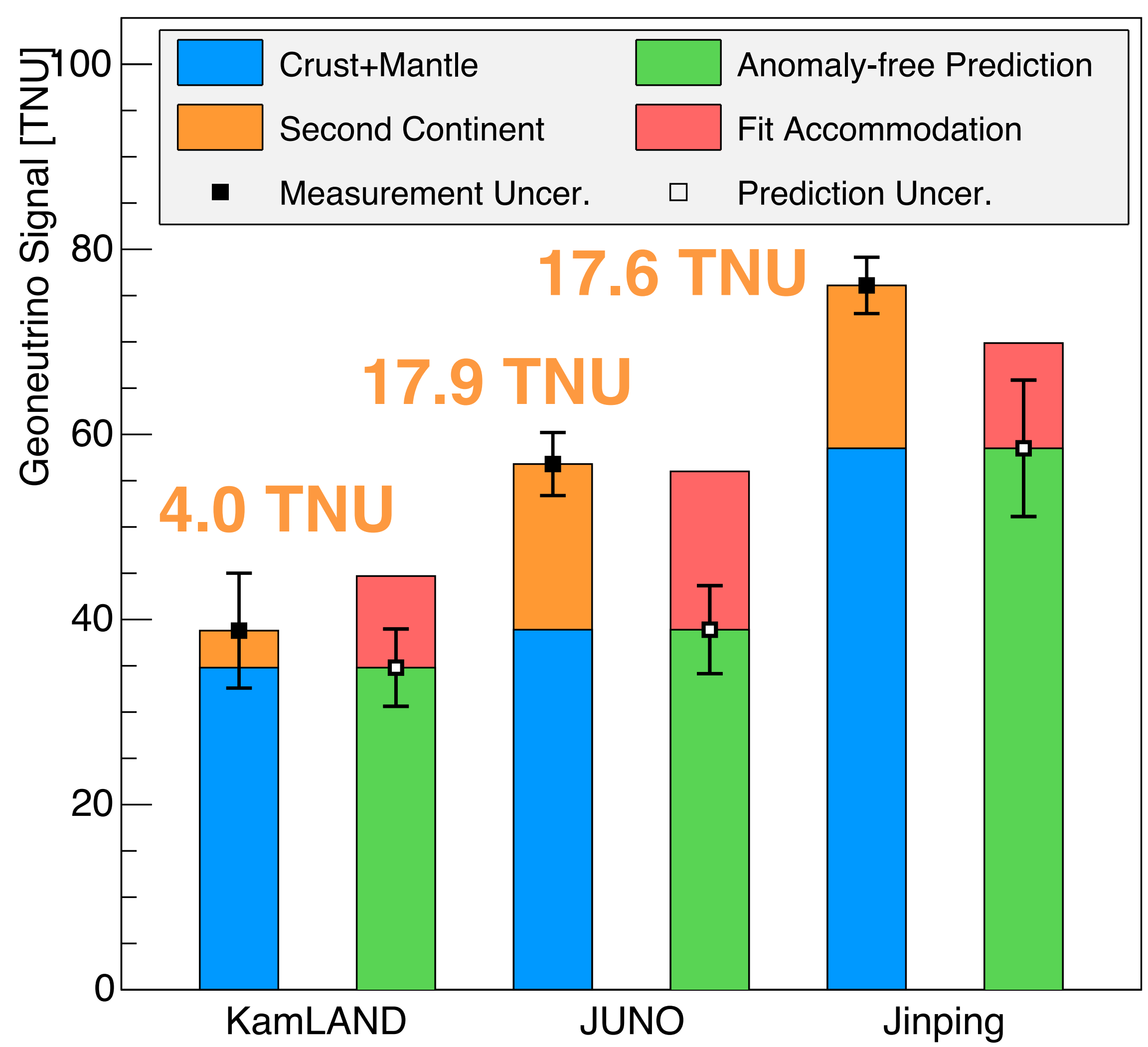
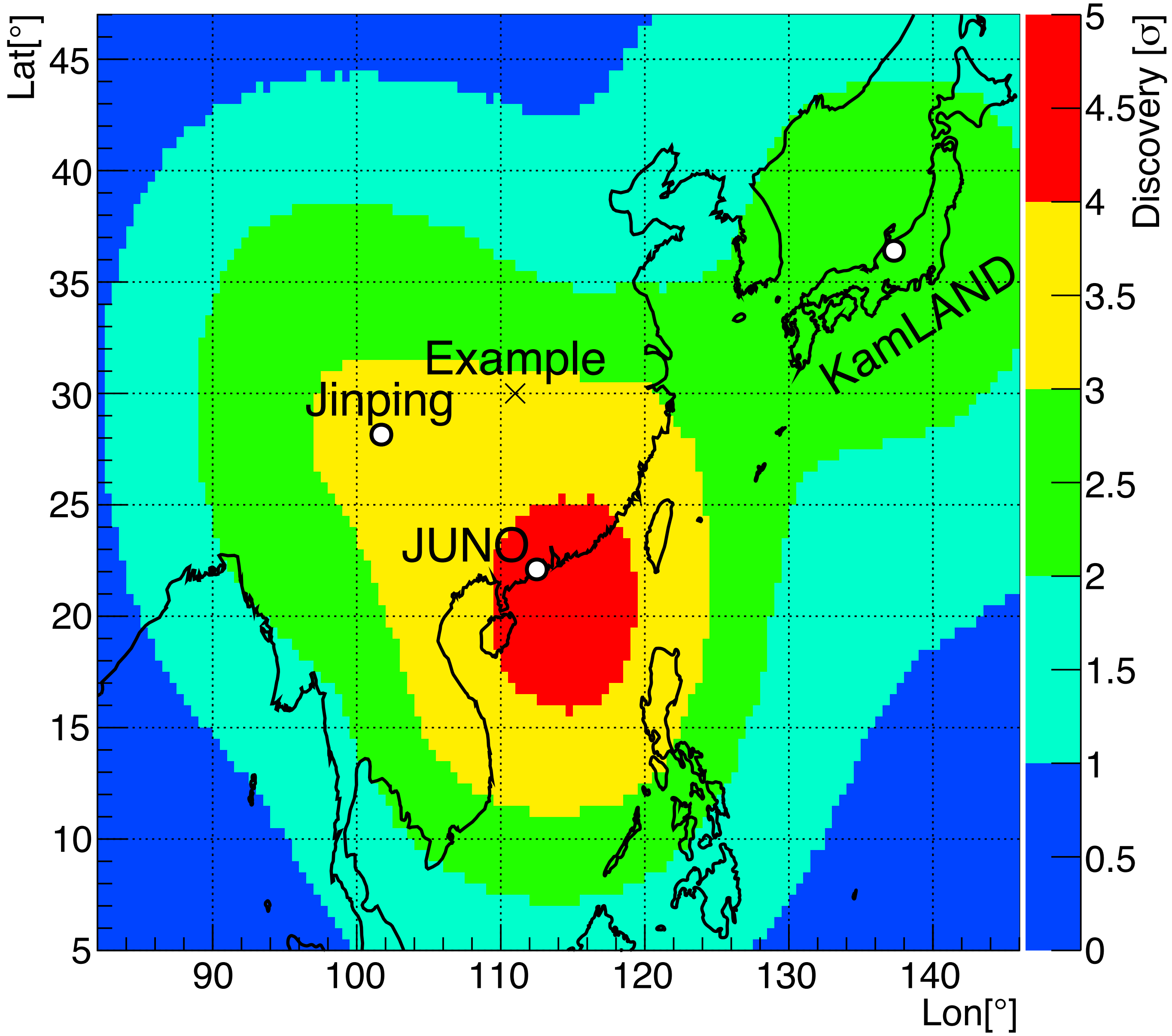
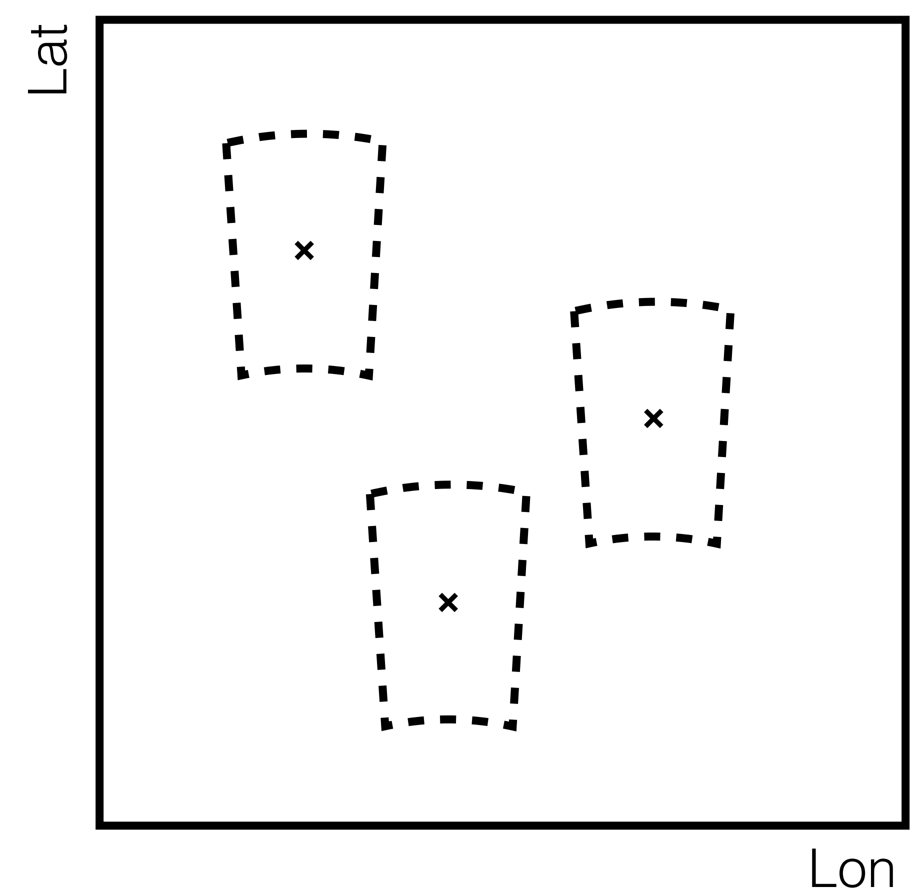


- **Can be discovered on 3.2σ ⇔ >99.8% C.L. !!!**

Discovery Potentials of the SC under China

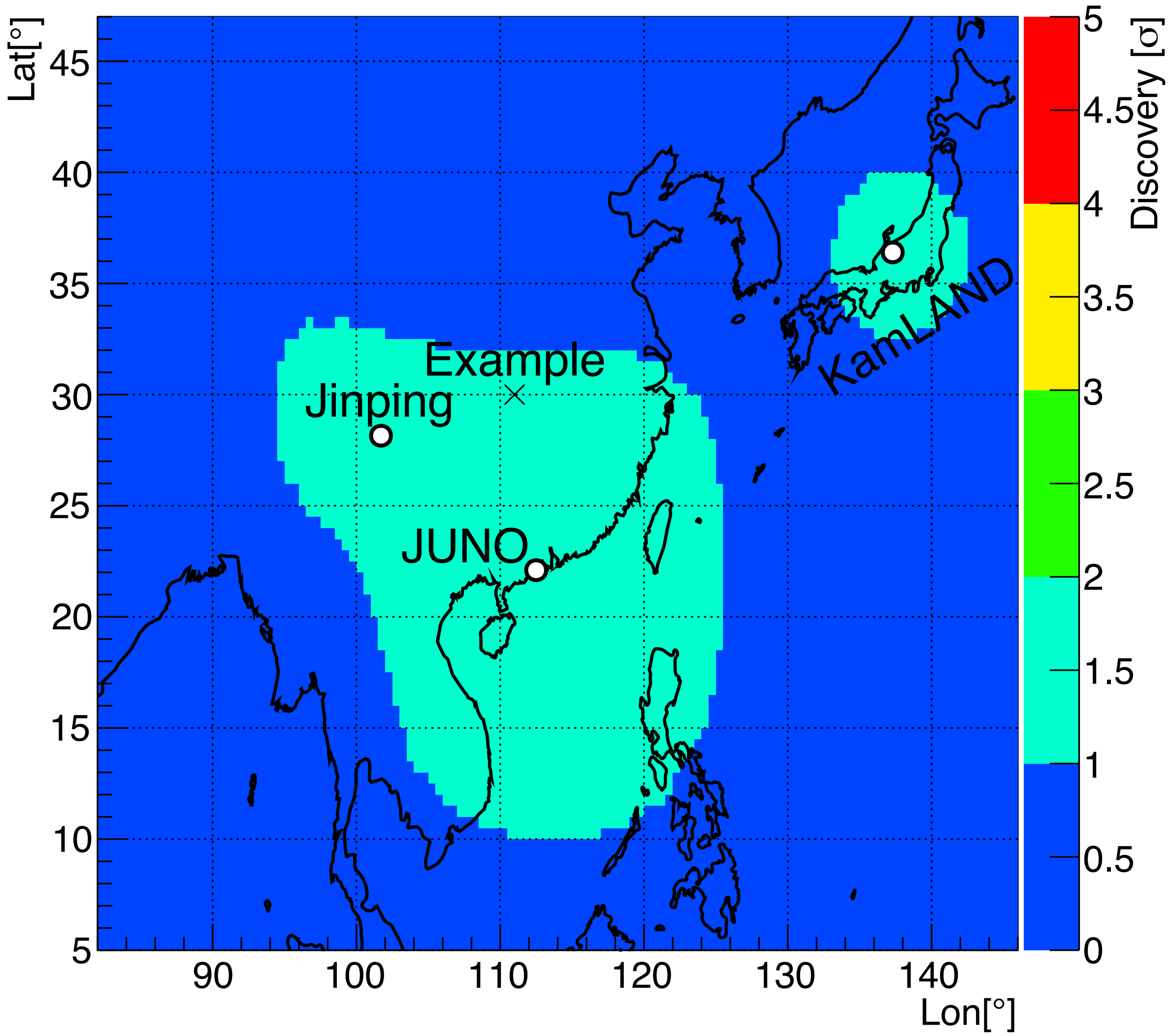
- Each point represents the center of a possible SC of the same size
- The color scale shows its discovery potential in standard deviations (σ)
- >2σ discovery potential of SC under southern China



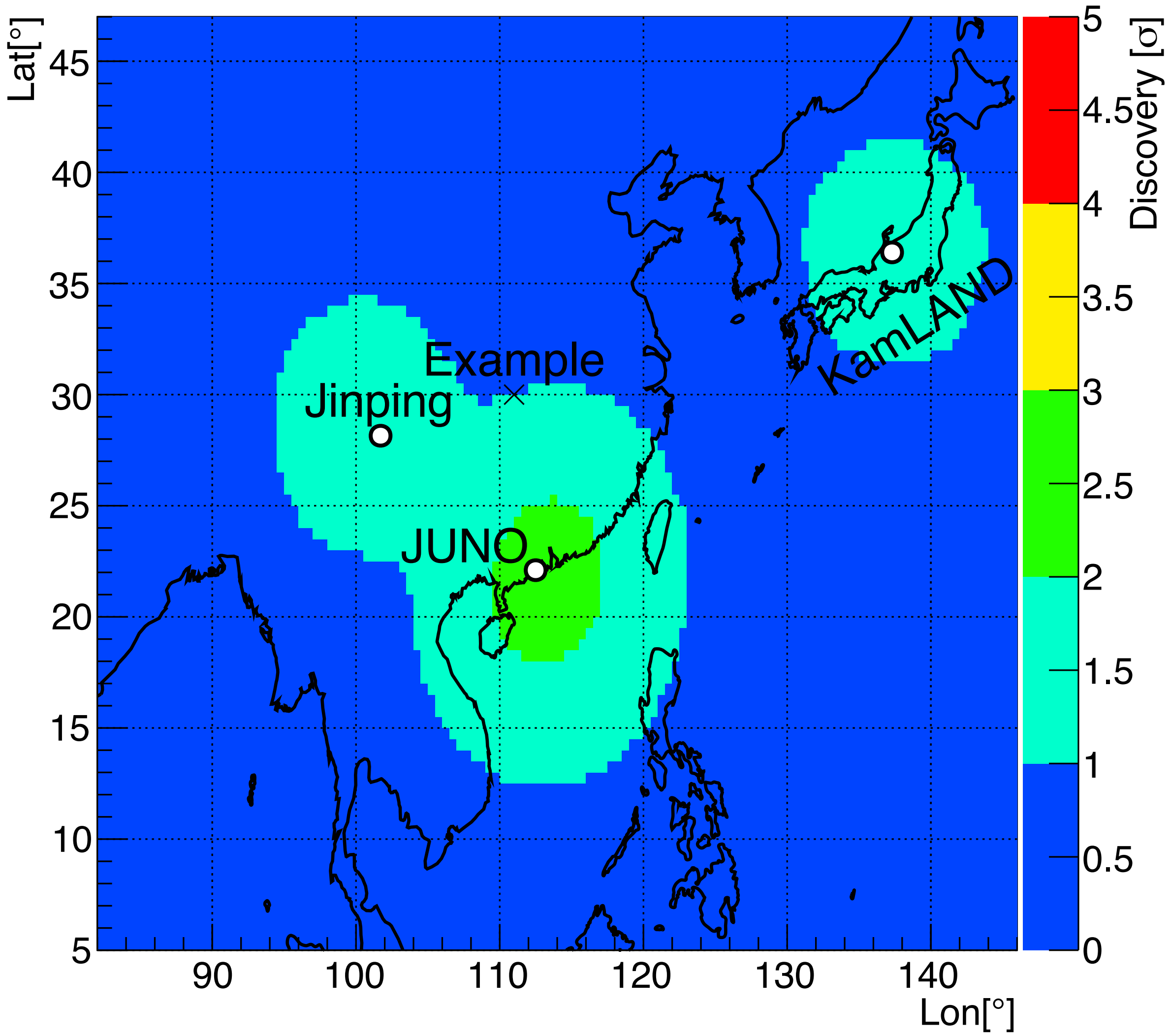


SC Under China Scenario Variations

2000×2000 km Second Continent
with $^{1}/_{3}$ of Upper Crust Abundances



1000×1000 km Second Continent
with Upper Crust Abundances

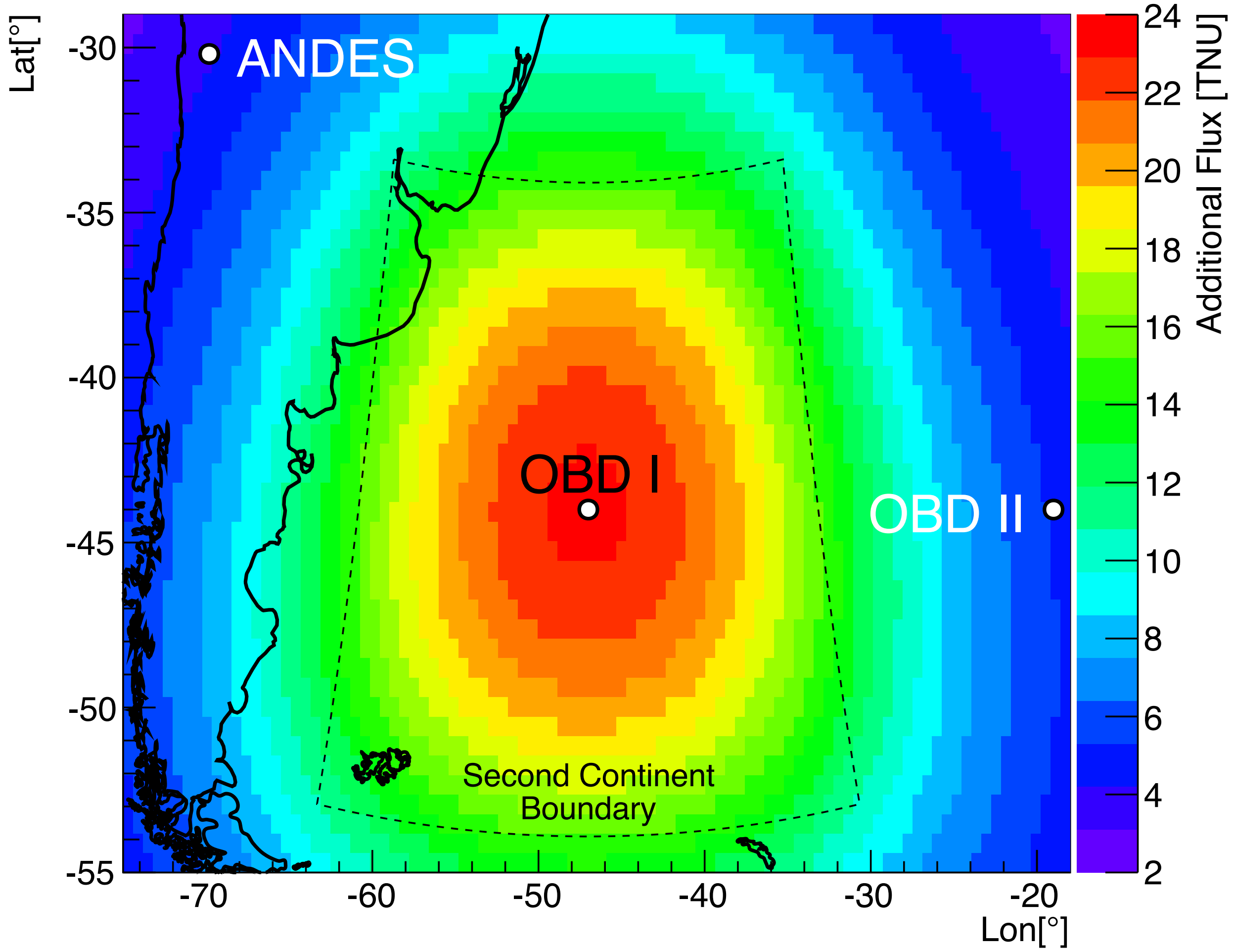


- **We can successfully test large and highly enriched SCs**

Second Continent Under the Atlantic

- Example of SC location 44˚S 47˚W
- Result of Pacific plate subduction under South America
- Can be tested by movable Ocean Bottom Detector I, OBD II and ANDES

Additional geoneutrino signal due to the SC



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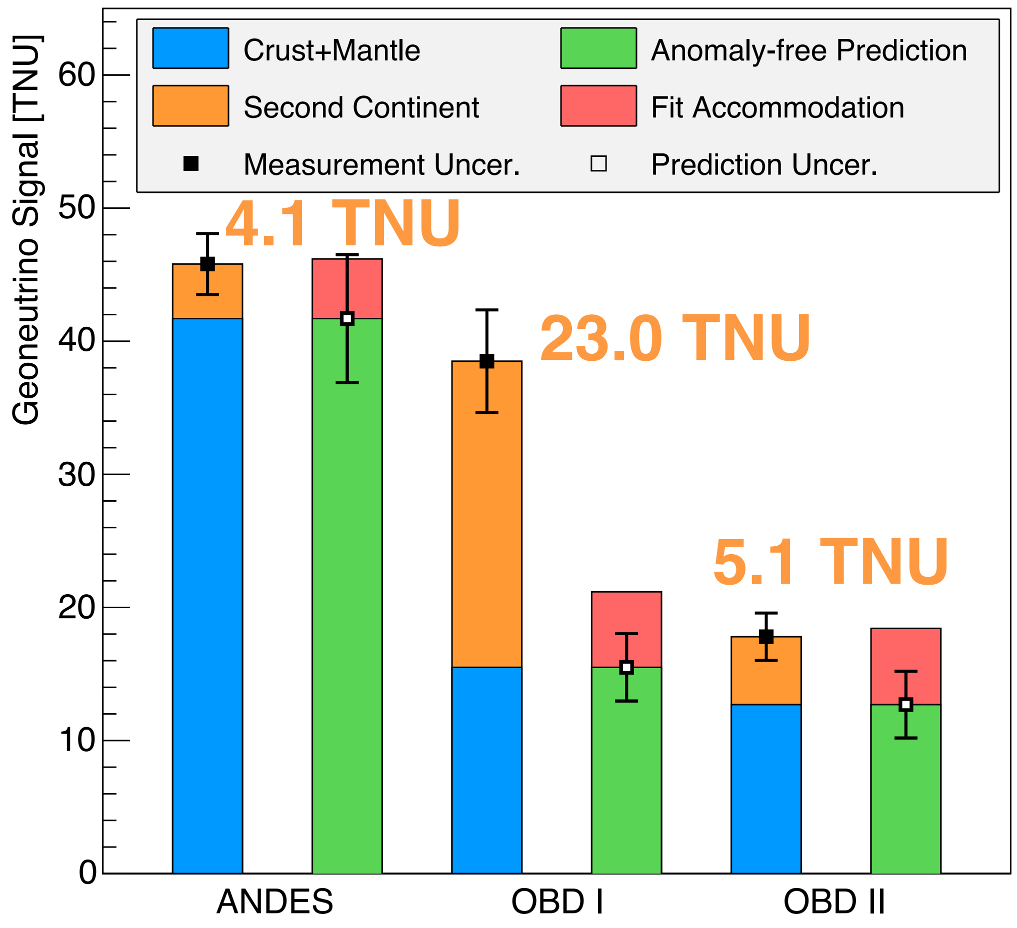
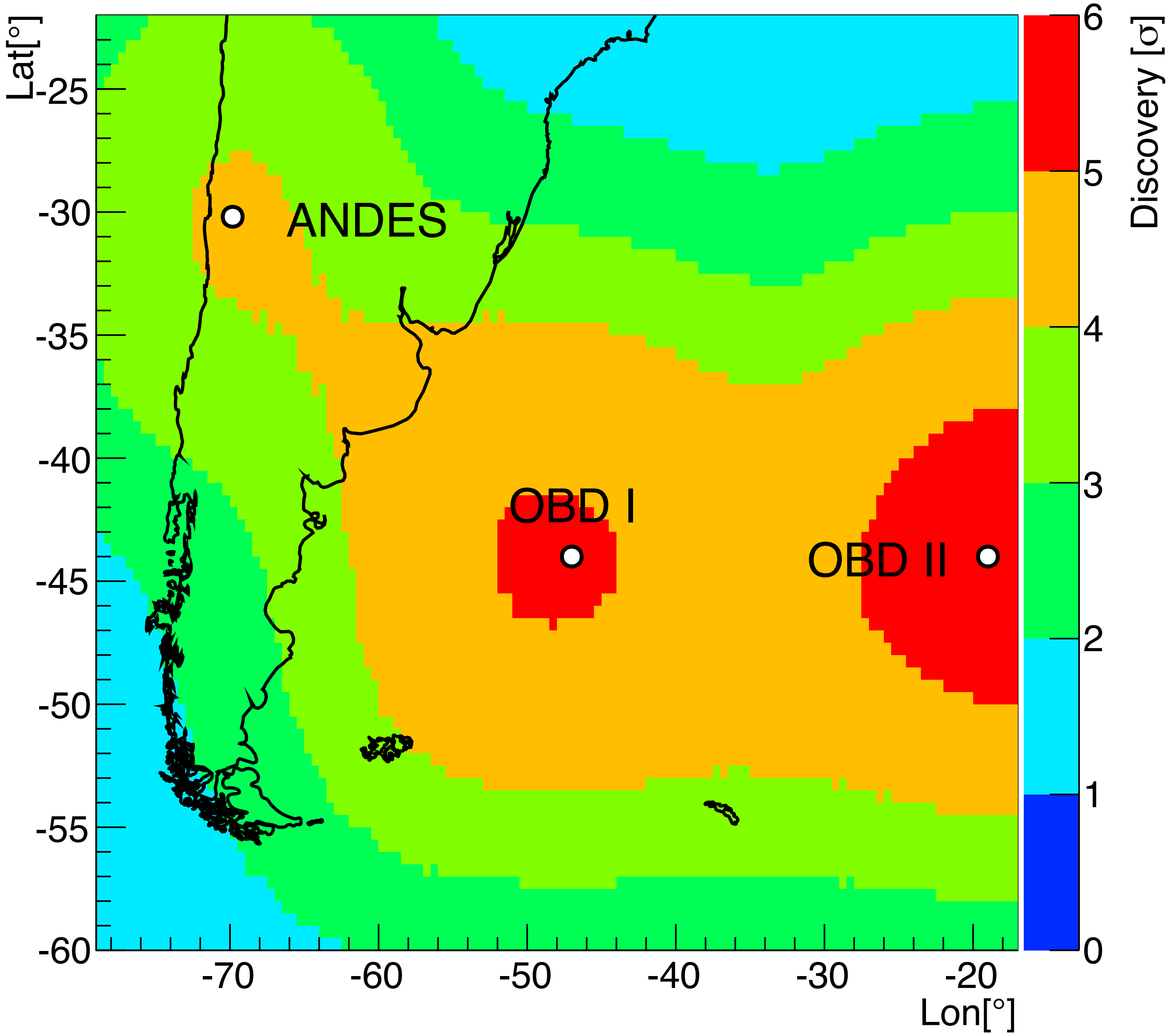
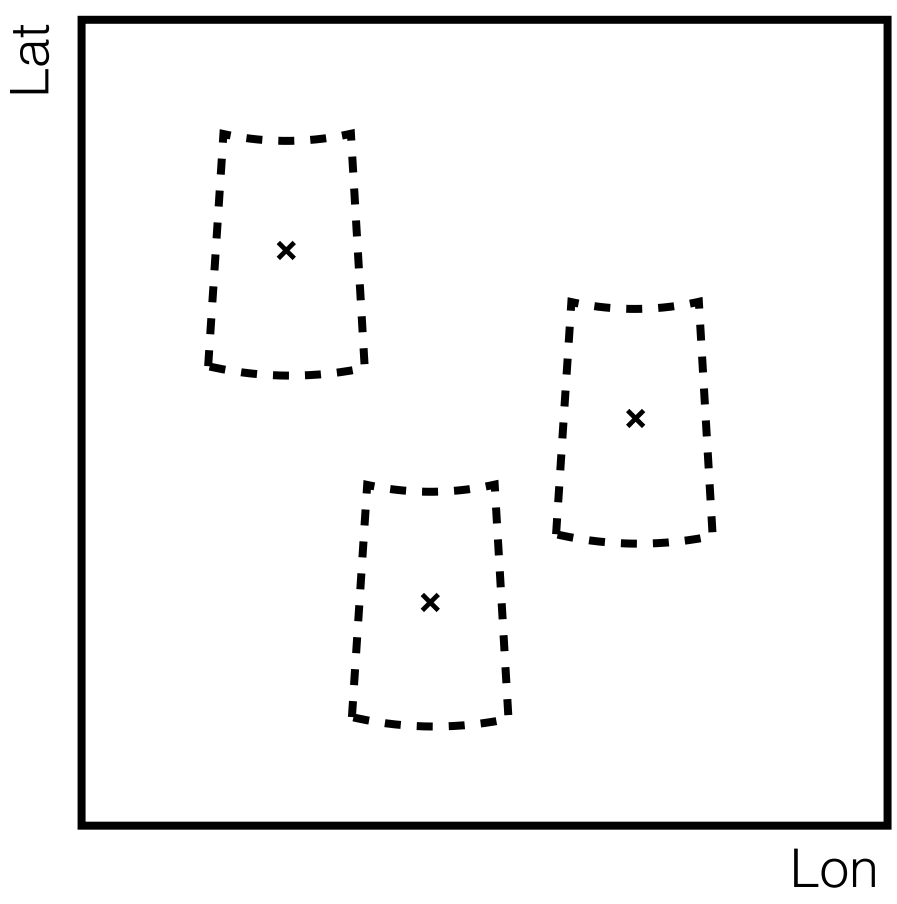


- **Can be discovered on 5.1σ ⇔ >99.99% C.L. !!!**
- **Movable OBD can test other possible SC sites in the ocean**

Discovery Potential vs. Atlantic SC Position

- Each point represents the center of a possible SC of the same size
- The color scale shows its discovery potential in standard deviations (σ)
- >2σ discovery potential at a distance of ~2000 km from OBD locations



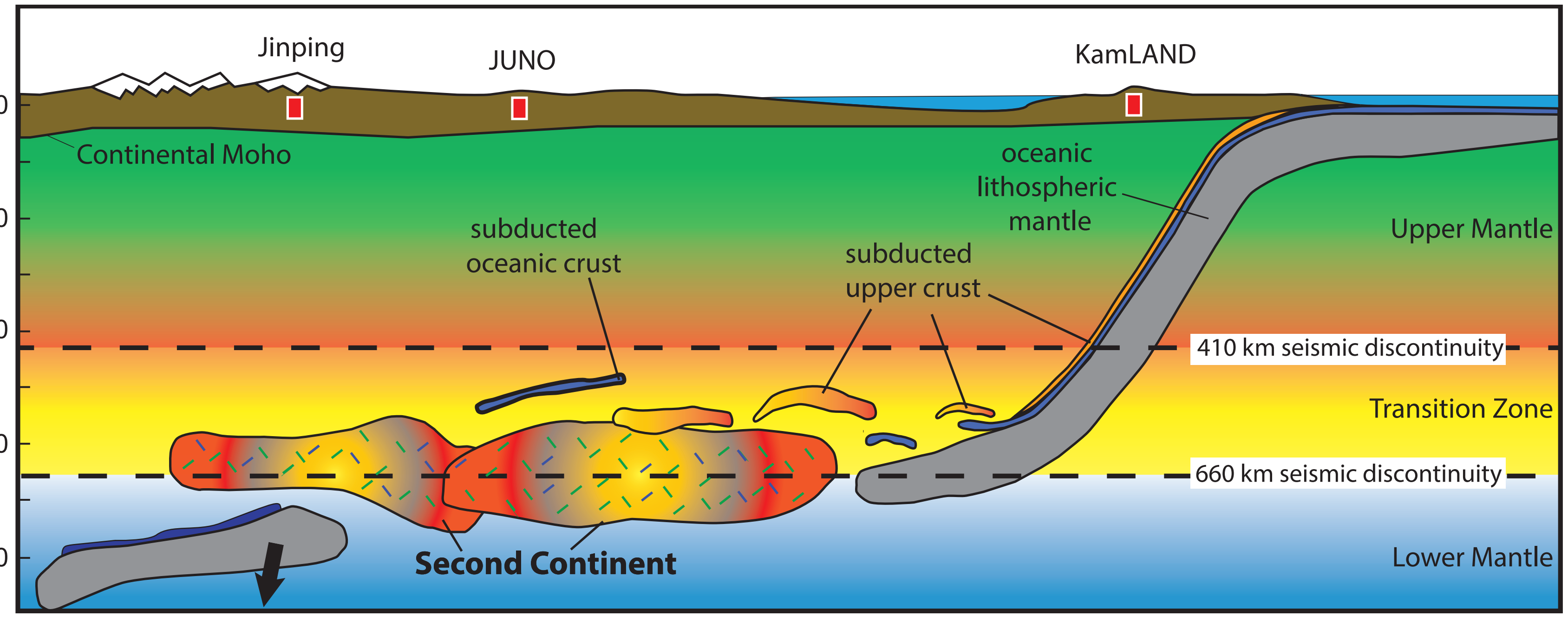


Conclusions

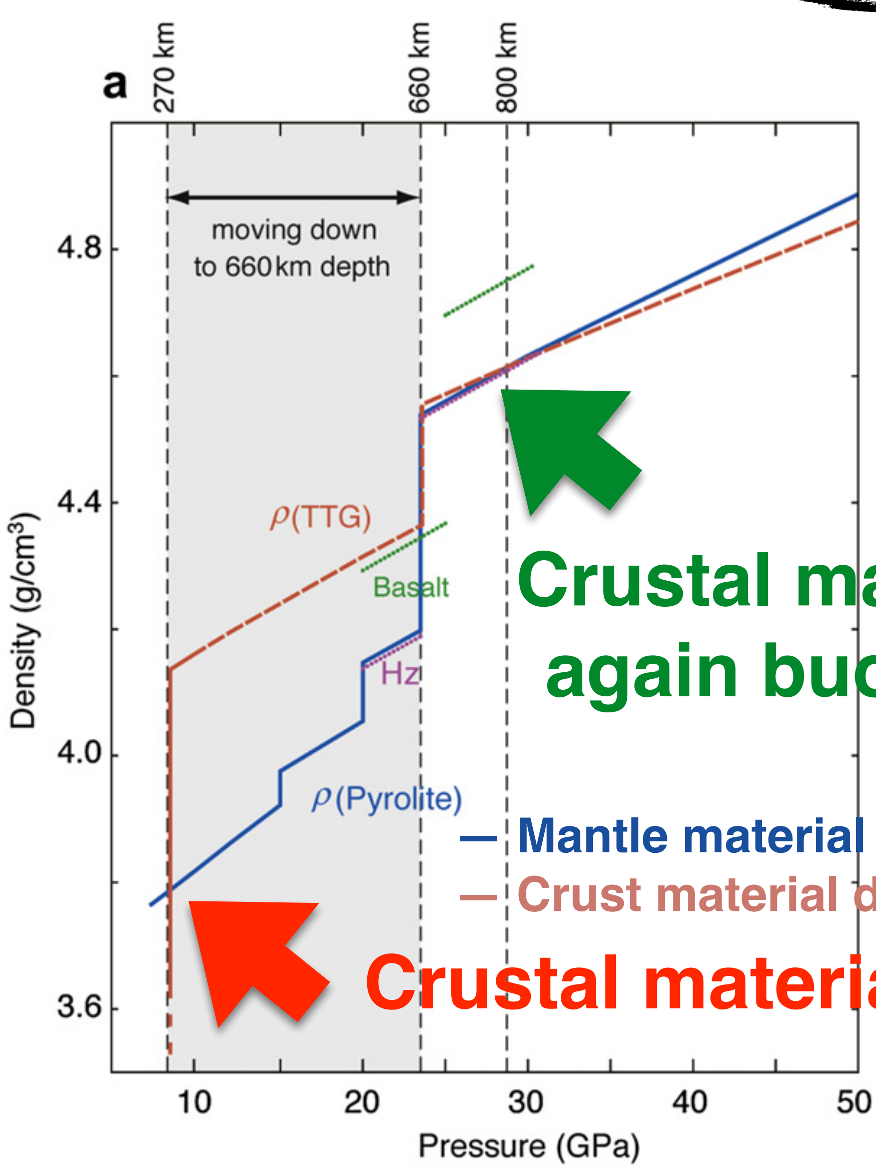
- **We can successfully test the existence of proposed geochemical mantle anomaly scenarios with large net of current and future geoneutrino experiments**
- Key features are: their relatively large geoneutrino signal, comparison of experiments and the correlation of geoneutrino signal predictions
- Discovery potential varies with abundances, size, … - Measurements which are in an agreement with standard predictions help to constrain proposed scenarios
- All this works if only one assumption is met - **we know the crust!**

Extras

Physics behind Second Continent



Bottom of the Transition Zone



Crustal material again buoyant

— Mantle material density

— Crust material density

Crustal material no longer buoyant

Kawai et al. (2013)

- SC material will float above ~800 km
- We assume SC layer at 600-700 km
- Newly created SC would be localized close to the toe of the subduction zone

Key Features in the Search for SCs

- **In principle large geoneutrino signal from SC**
- **Multiple experiments (at the same region)**
  - Experiment further from the SC benchmark the prediction
- **Partial correlation of the predictions can reduce the impact of their uncertainties**
  - Benchmark can be used for experiments exposed to SC geoneutrinos