Global models of Earth's composition and geoneutrino flux around Jinping

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How much radiogenic power in this planet?

- How much radiogenic heating in the mantle to power thermal convection?
- Earth's mantle has uniform composition, or is layered, or has complex structure?
- How much is the crust enriched in heat-producing elements relative to the mantle? Local crust around detector?
- What is the composition of material from which Earth was built?
- Rate of cooling of the Earth, at present and over time?

Geoneutrinos – a new tool

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

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

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

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

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

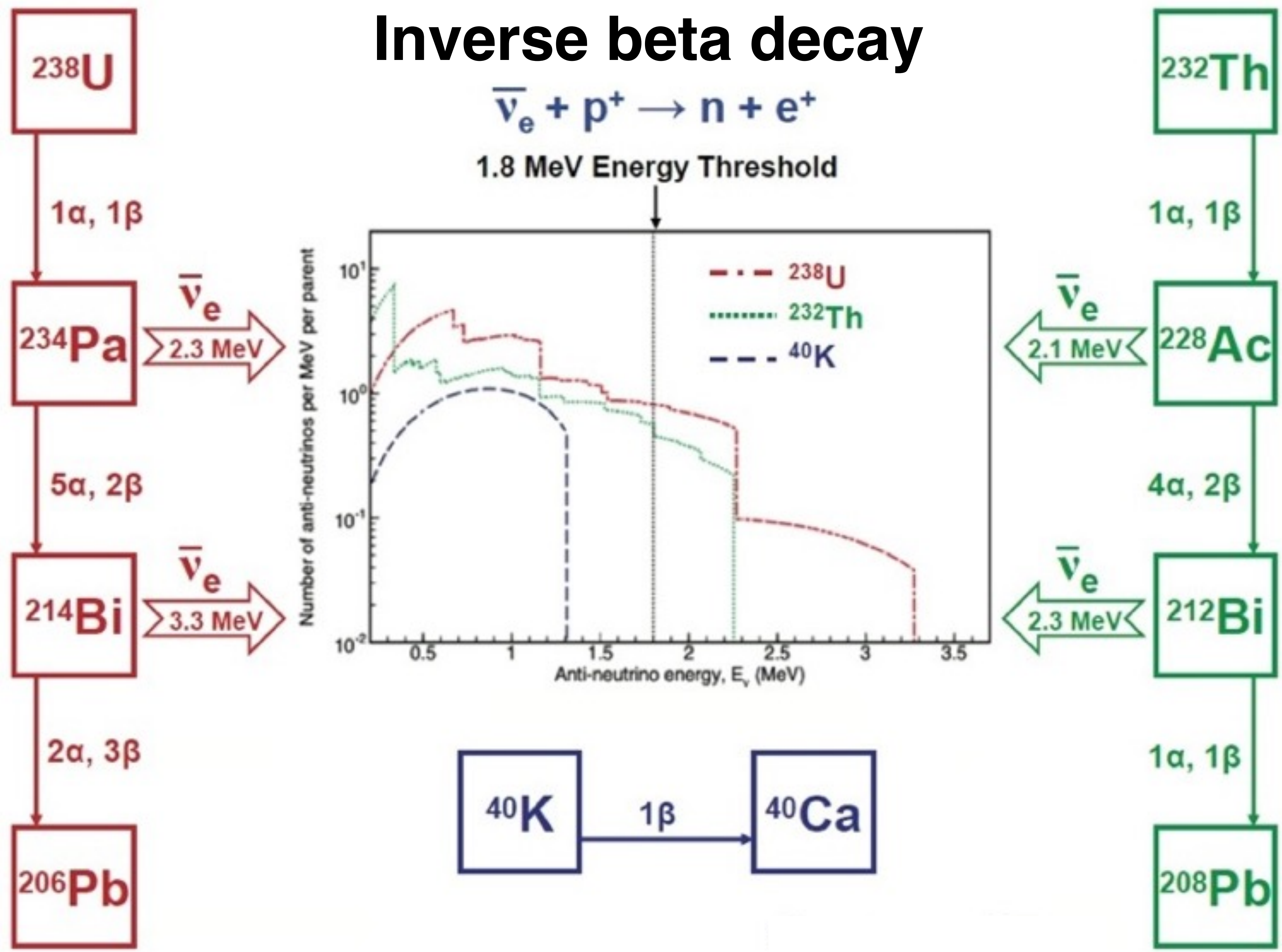
Decay energy
~20% carried away by neutrinos,
~80% heats the Earth's interior,
powering Earth's dynamics

Typical geoneutrino flux at Earth's surface: 10^7 cm^{-2} s^{-1}

some of geo-ν's now detectable ... and have been detected

Measuring radioactivity of the Earth

Geoneutrino detection



slide from Steve Dye

Geoneutrino detection

Antineutrino detection mechanism: **Inverse beta decay**

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

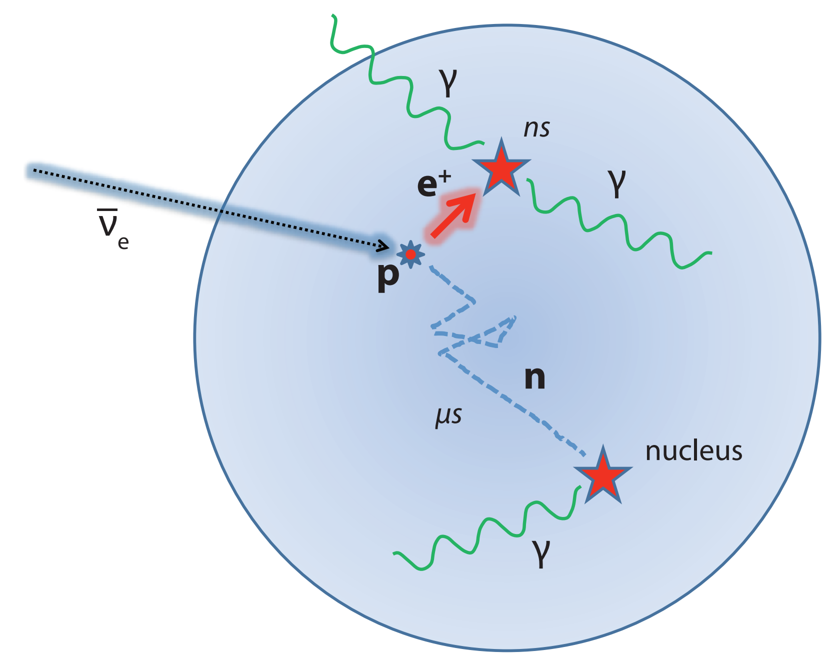
Energy threshold, only works for ^{232}Th and ^{238}U

Small interaction cross section (~10^{-44} cm^2 = 10^{-20} barn)

Liquid scintillator detectors:

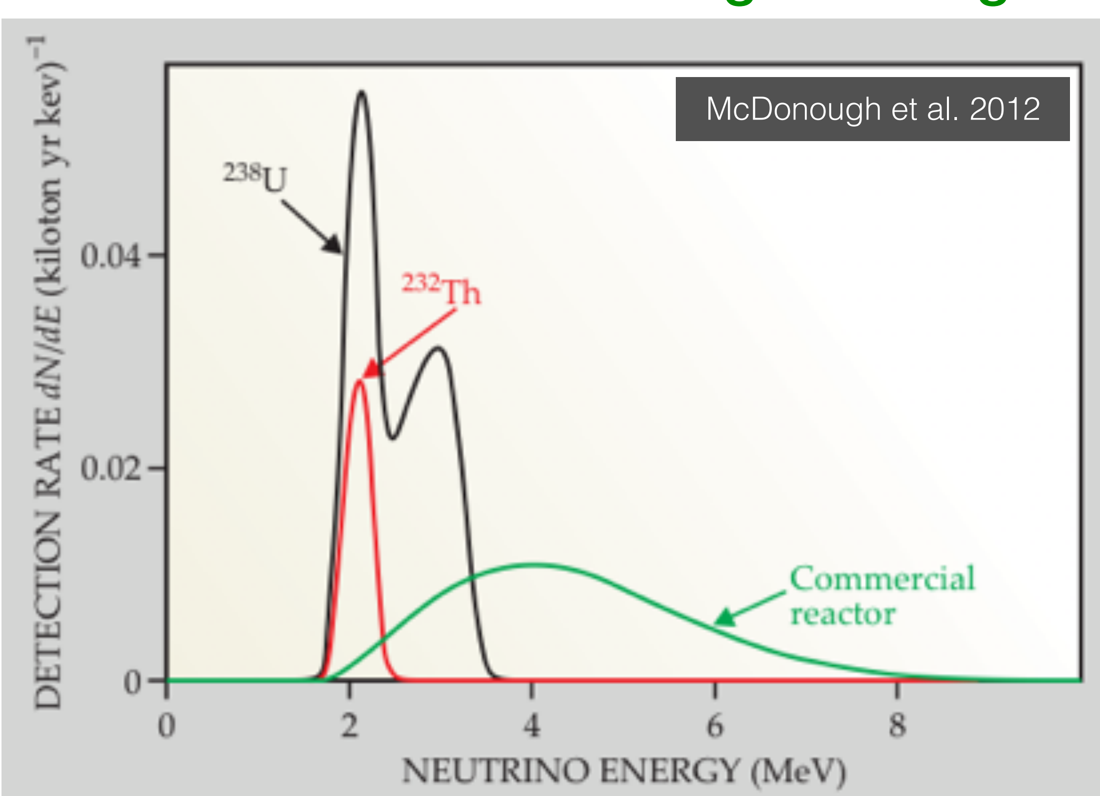
Large ~10^{32} free protons or ~1 kiloton of scintillator

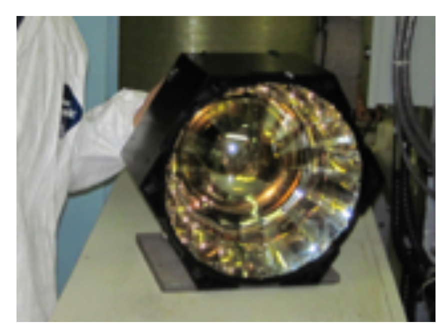
Underground to shield from cosmic ray muon interactions in the atmosphere

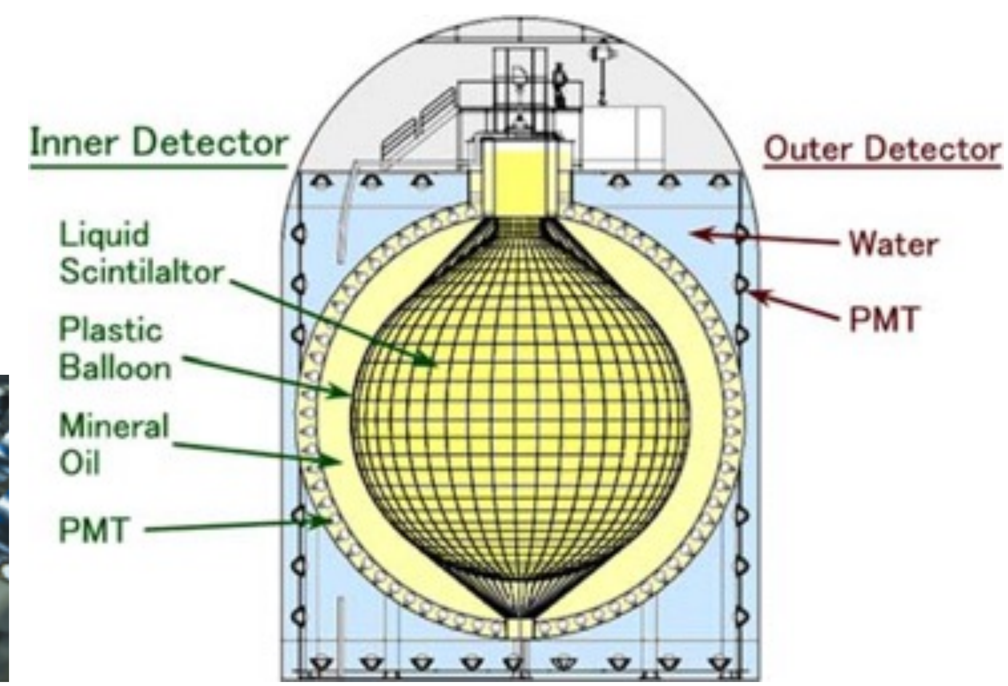


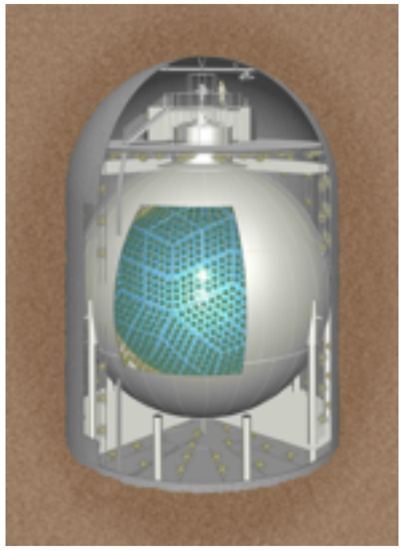
Double-flash coincidence

Reactor antineutrino background signal



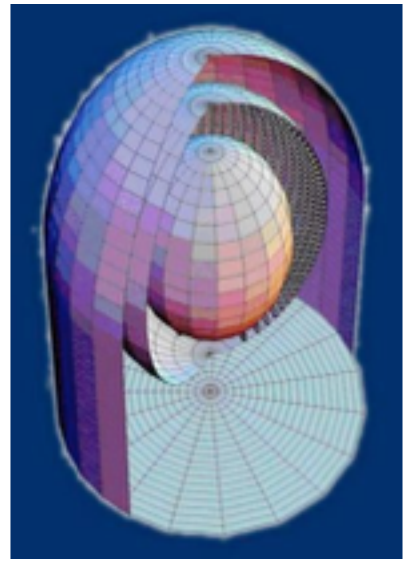






KamLAND
Kamioka, Japan
1 kton

2005
2011
2013



Borexino
Gran Sasso, Italy
0.3 kton

2010
2013
2015

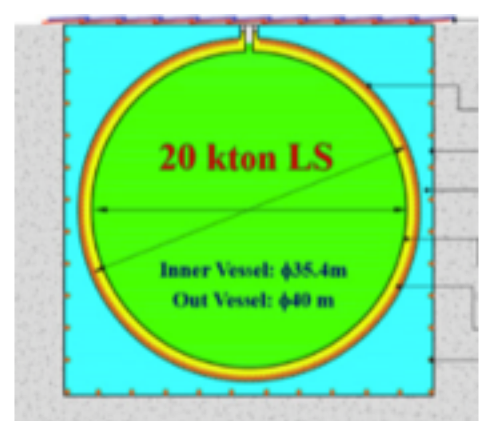
SNO+
Sudbury, Canada
1 kton

online soon...

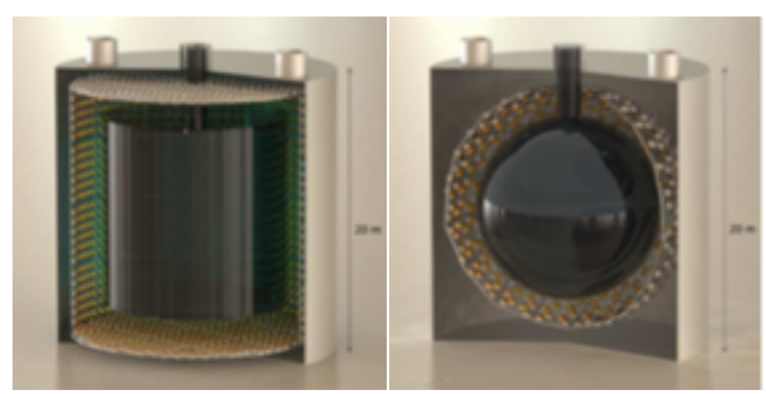
Geoneutrino Detectors

Future:

JUNO (20kt, China)



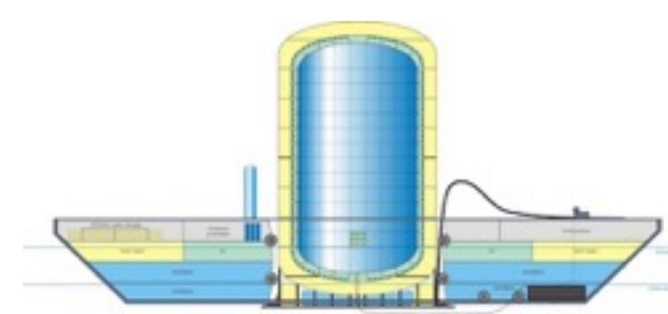
Jinping (4kt, China)



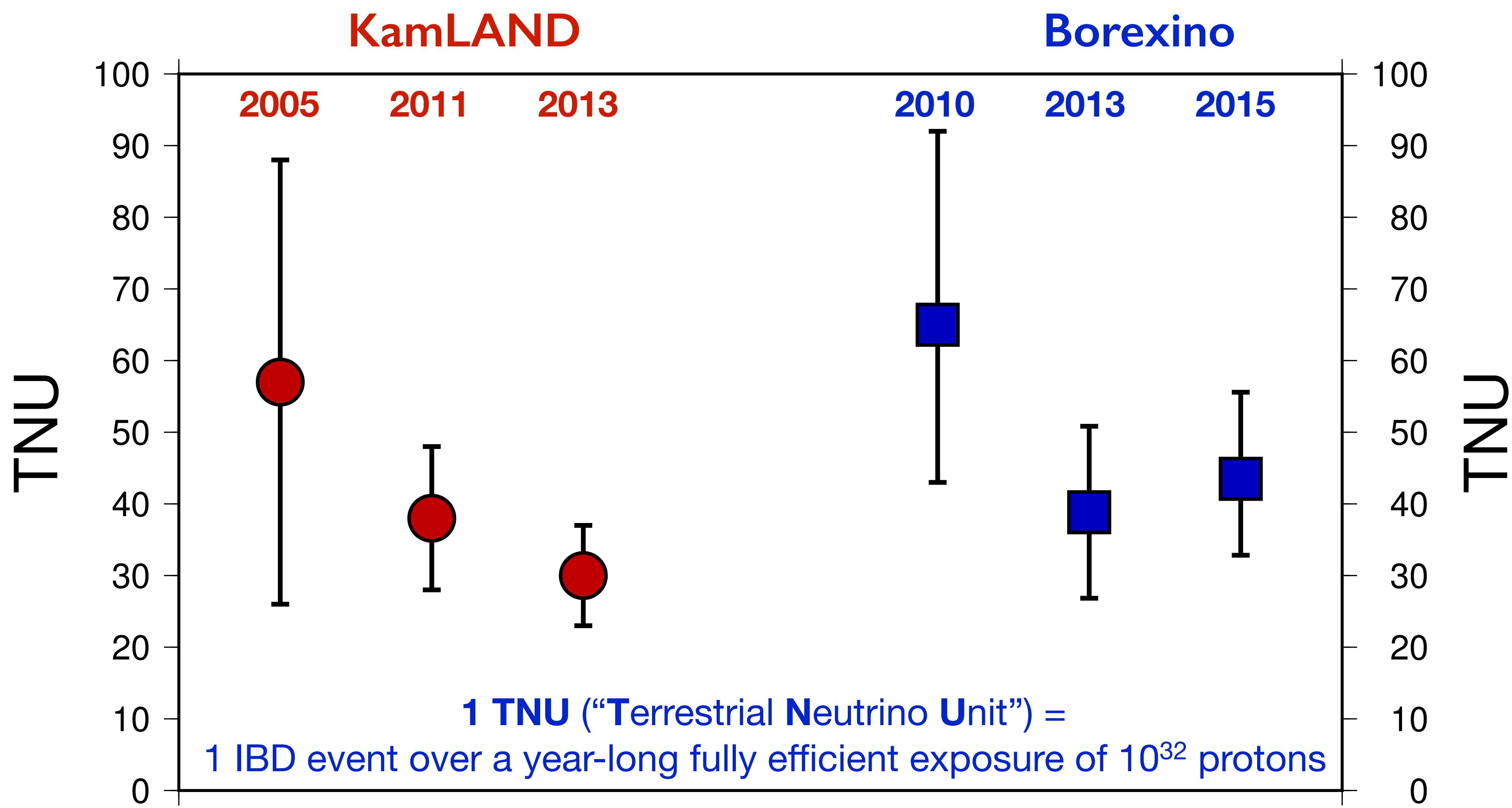
RENO-50? (S.Korea)

LENA? (Europe)

Hanohano? (USA)

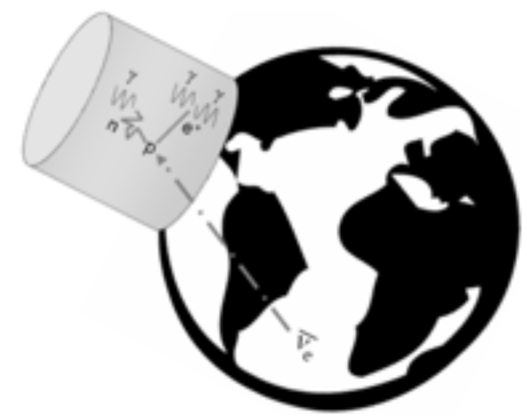


Geoneutrino measurements



What does this tell us? ... relation to Earth?

Geoneutrino inverse problem



- Counting geoneutrinos,
- emitted by Th, U in the Earth.
- Goal is to constrain emitters' abundance, spatial distribution.
- Ok. Only have 2 data points. (Will have 5 in 15 years.)
- Goals:
  Resolve mantle abundance.
  Study crust (Jinping!)

Forward model: predicting geoneutrino flux

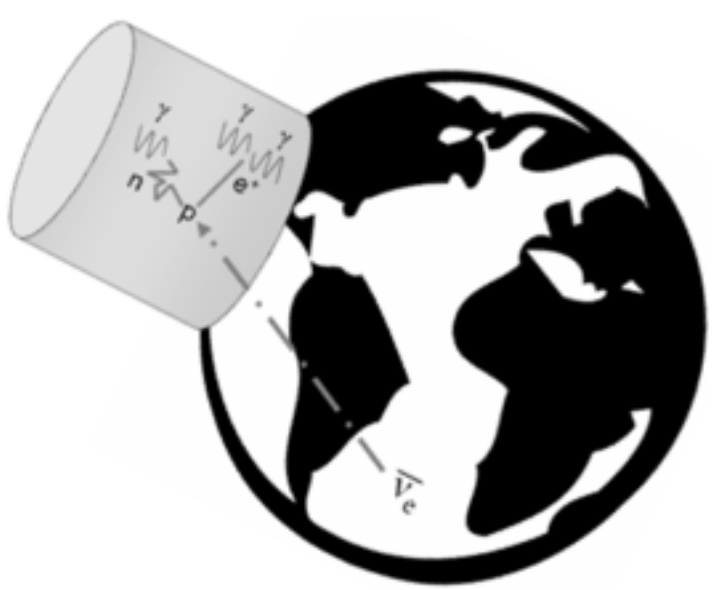
To make sense of geoneutrino measurements.

To motivate new detectors (e.g., where to measure?)

⇒ **Emission models: Calculate predictions for various compositional estimates & architectures of Earth's interior.**

$$\frac{\mathrm{d}\phi(\boldsymbol{r}, E_\nu)}{\mathrm{d}E_\nu} = D\frac{\mathrm{d}n(E_\nu)}{\mathrm{d}E_\nu}\iiint\frac{A(\boldsymbol{r}')\rho(\boldsymbol{r}')P_{ee}(E_\nu, |\boldsymbol{r}-\boldsymbol{r}'|)}{4\pi|\boldsymbol{r}-\boldsymbol{r}'|^2}\mathrm{d}^3\boldsymbol{r}'$$

Flux spectrum $\mathrm{d}\Phi/\mathrm{d}E_\nu$ at position $\boldsymbol{r}$ from a given radionuclide distributed with abundance A in the Earth



Inputs from geoscience:

- chemical abundances A
- density ρ

Inputs from nuclear/particle physics:

- decay rate D, antineutrino intensity spectrum $\mathrm{d}n/\mathrm{d}E_\nu$, antineutrino survival probability P_{ee}

U Th K

Assumption: no K, Th, U in the core

Composition of Silicate Earth (BSE)

TW radiogenic power

- **"Standard"** estimate
  - Ratios of RLE abundances constrained by C1 chondrites
  - Absolute abundances inferred from Earth rock samples
  - *McDonough & Sun (1995), Allègre (1995), Hart & Zindler (1986), Palme & O'Neill (2003),* ***Arevalo et al. (2009)***

  20±4

- **"E-chondrite"** estimate
  - Isotopic similarity between Earth rocks and E-chondrides
  - Build the Earth from E-chondrite material
  - ***Javoy et al. (2010)***
  - also "collisional erosion" models (*O'Neill & Palme 2008*)

  11±2

- **"High"** estimate
  - Based on a classical parameterized convection model
  - Requires a high mantle Urey ratio, i.e., high U, Th, K

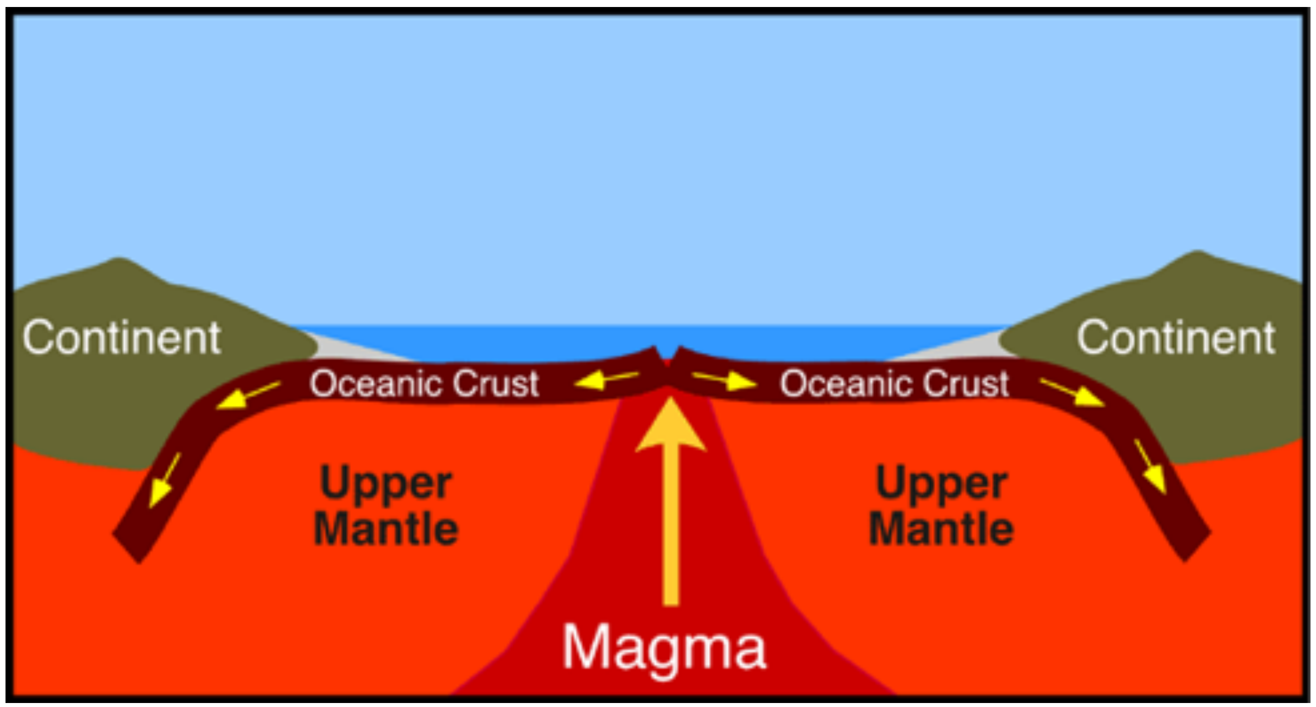
  33±3

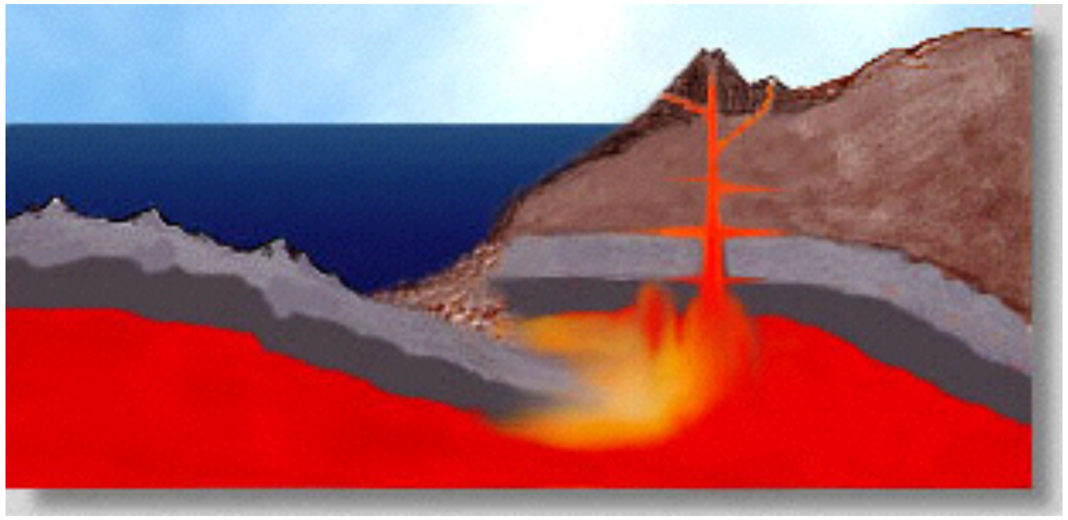
How much radiogenic heating in the Earth?

Estimates range from 9 to 36 TW radiogenic power

Forming Earth's crust

"Incompatible" elements U, Th, K concentrate in the crust



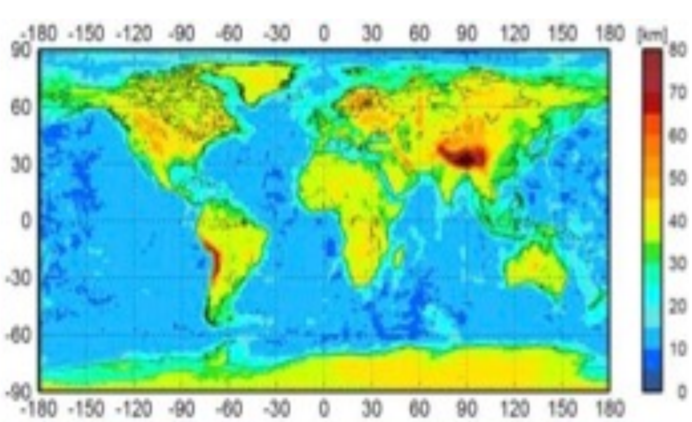


- Some ions do not fit well in the silicate rock crystal structure:
  - "LILE" … large-ion lithophile elements, e.g., **K**
  - "HFSE" … high field strength elements, e.g., **Th, U**
- Upon melting when melt and solid in coexistence, they concentrate in the melt
- Therefore, **crust enriched in K, Th, U**

Radiogenic power in the mantle

	TW radiogenic power BSE	TW radiogenic power Mantle
• **"Standard"** estimate	**20±4**	**13±4**
• **"E-chondrite"** estimate	**11±2**	**4±2**
• **"High"** estimate	**33±3**	**26±3**

BSE = Mantle + Crust



Oceanic: 0.22 ± 0.03 TW

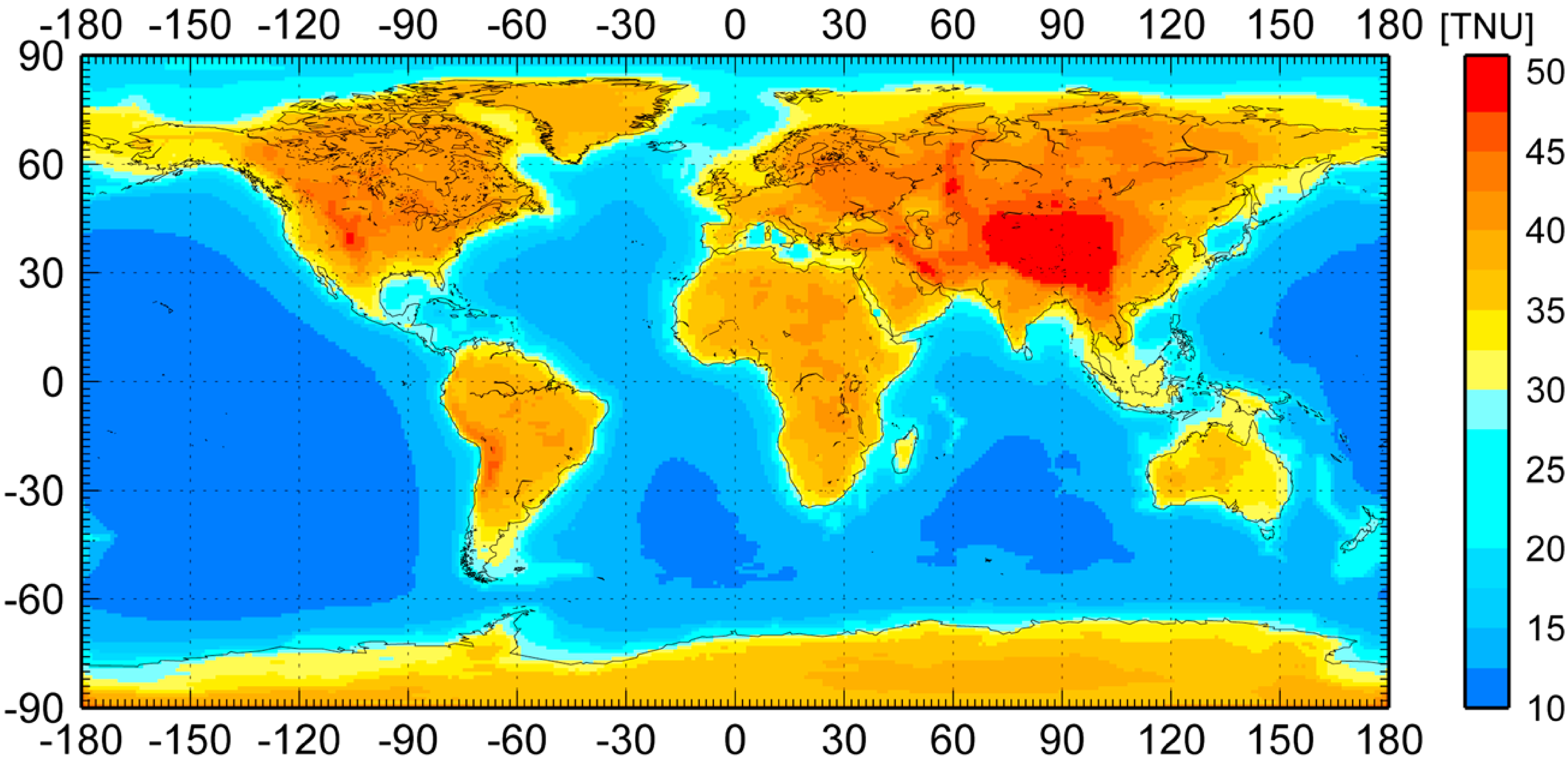
Continental: 6.8 (+1.4/–1.1) TW

Model of ***Huang et al. 2013 G³***

How much radiogenic heating in the mantle to power convection?

Estimates from 2 to 29 TW radiogenic power in the mantle

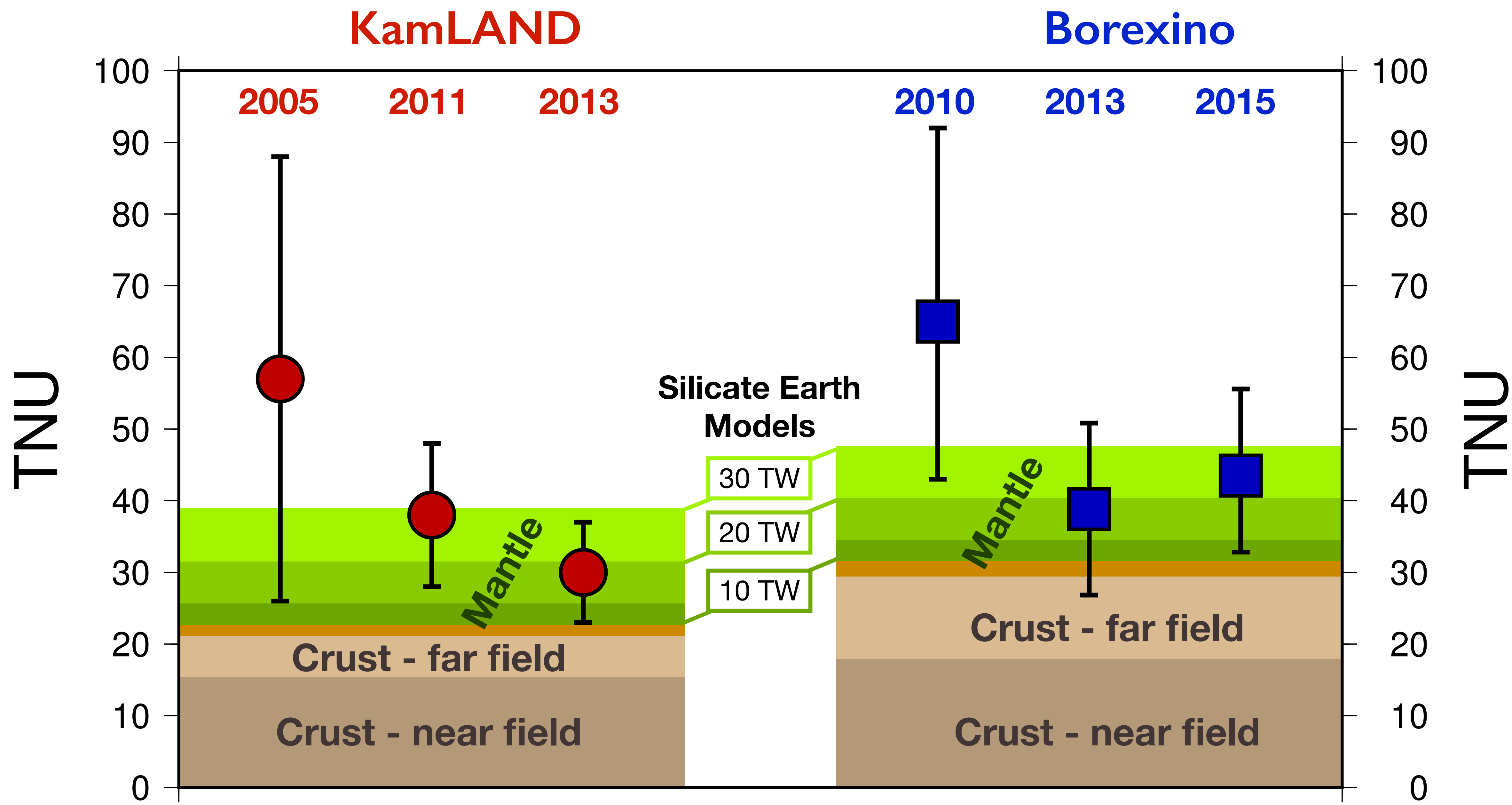
Geoneutrino flux prediction at Earth's surface



Dominated by continental crust

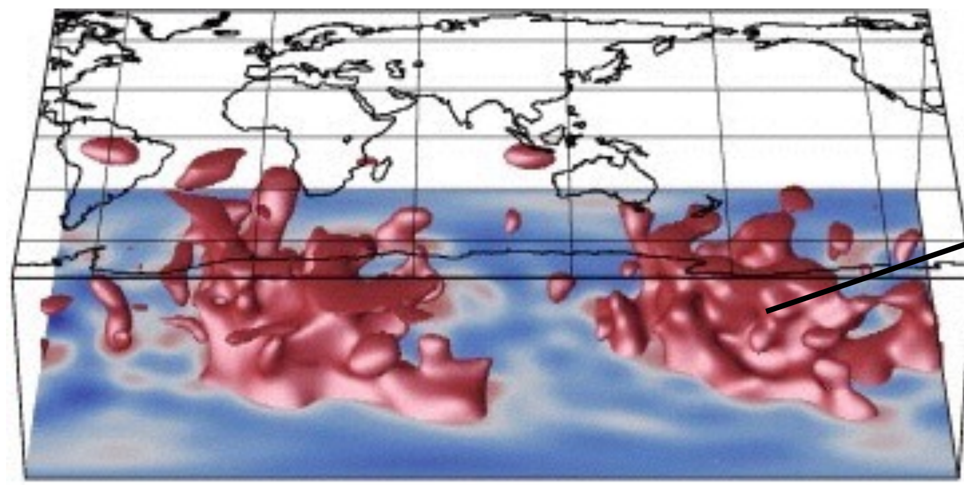
Huang et al. 2013 G3 doi:10.1002/ggge.20129

Geoneutrino measurements vs. predictions



McDonough & Šrámek 2014 EES doi:10.1007/s12665-014-3133-9, updated

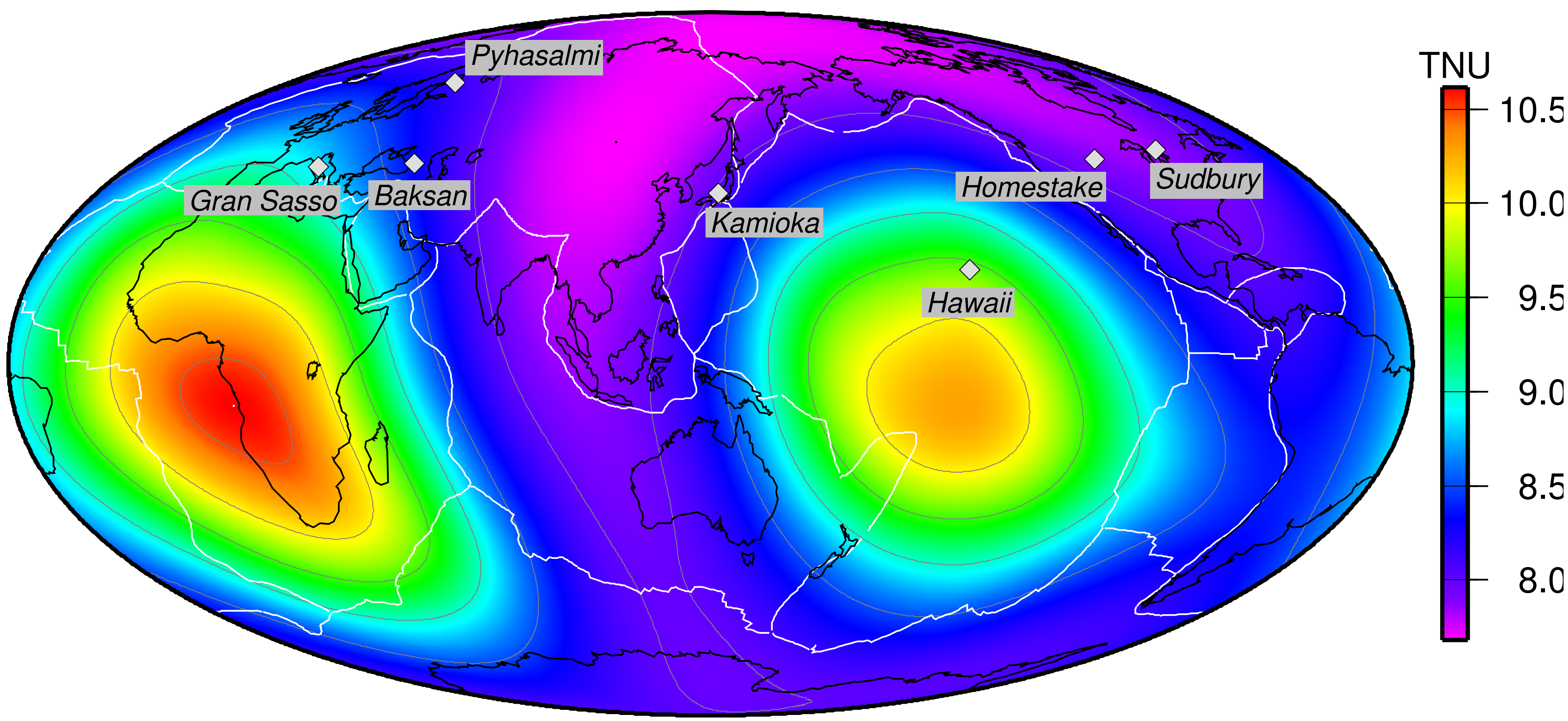
Thermochemical piles in deep mantle?



What seismology sees
LLSVPs

Assume these piles represent an enriched reservoir.
δlnVs isocontours ⇒ shape

Mantle geoneutrino U+Th signal prediction (excluding crustal signal)

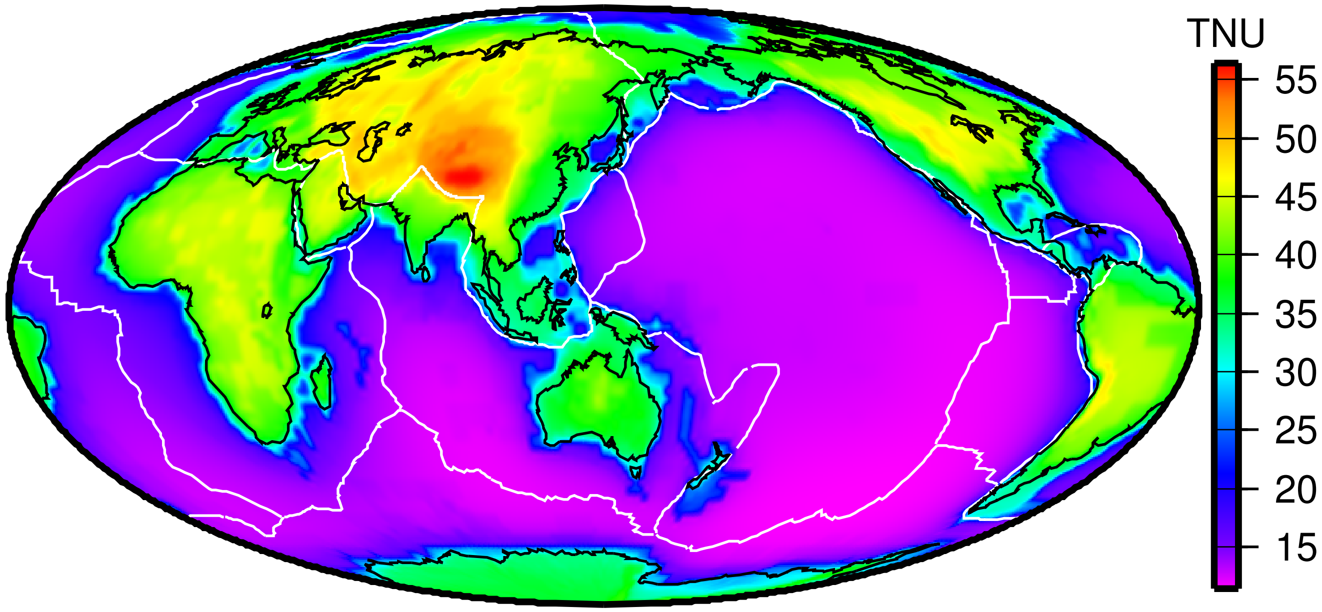


Can we detect such variation in mantle geonu flux?

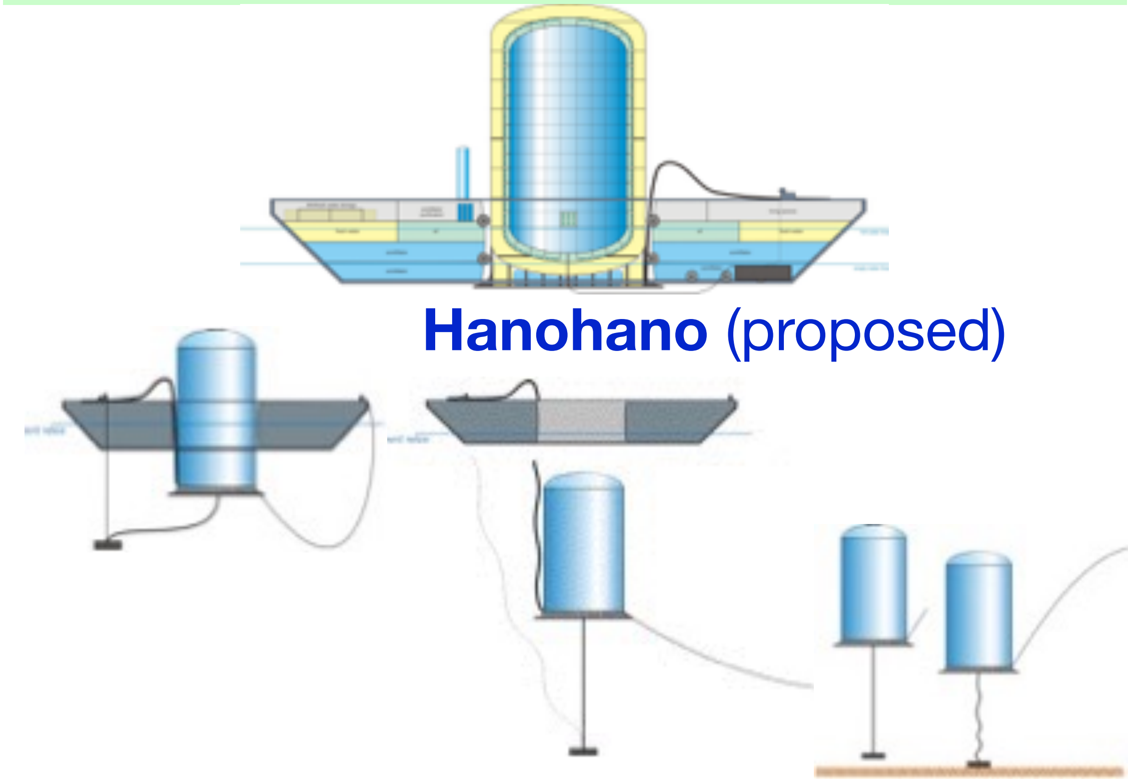
Šrámek et al. 2013 EPSL doi:10.1016/j.epsl.2012.11.001

Measure in the middle of the ocean…

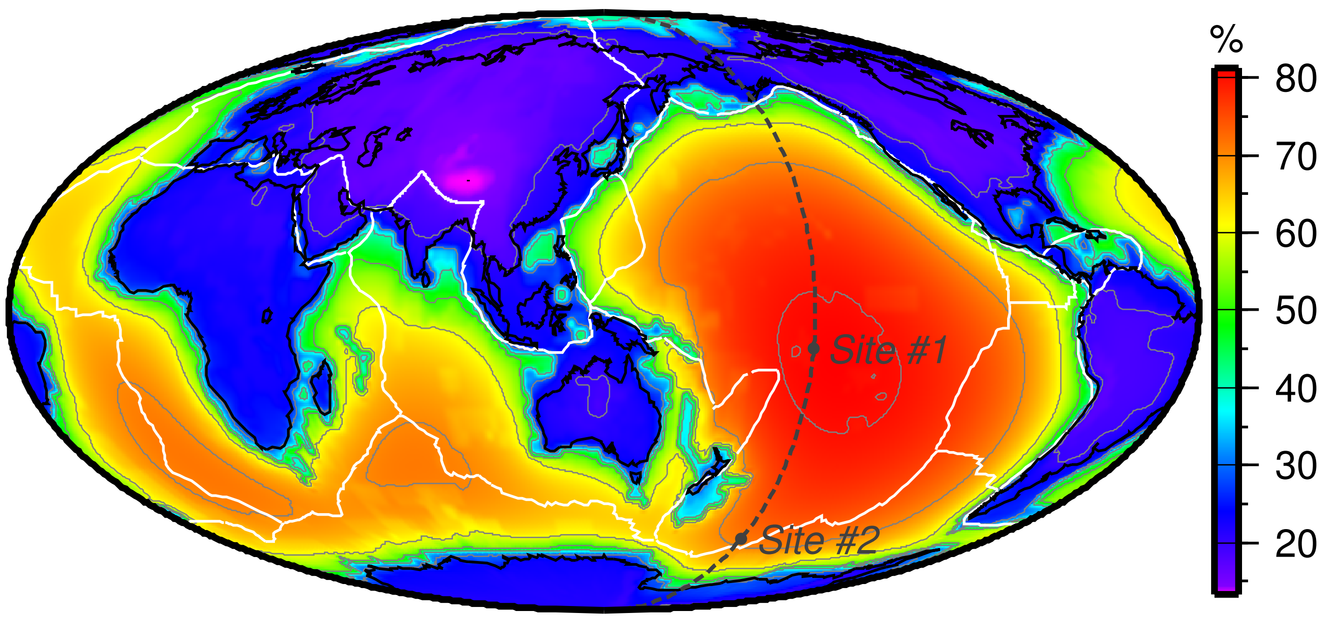
Crust + mantle

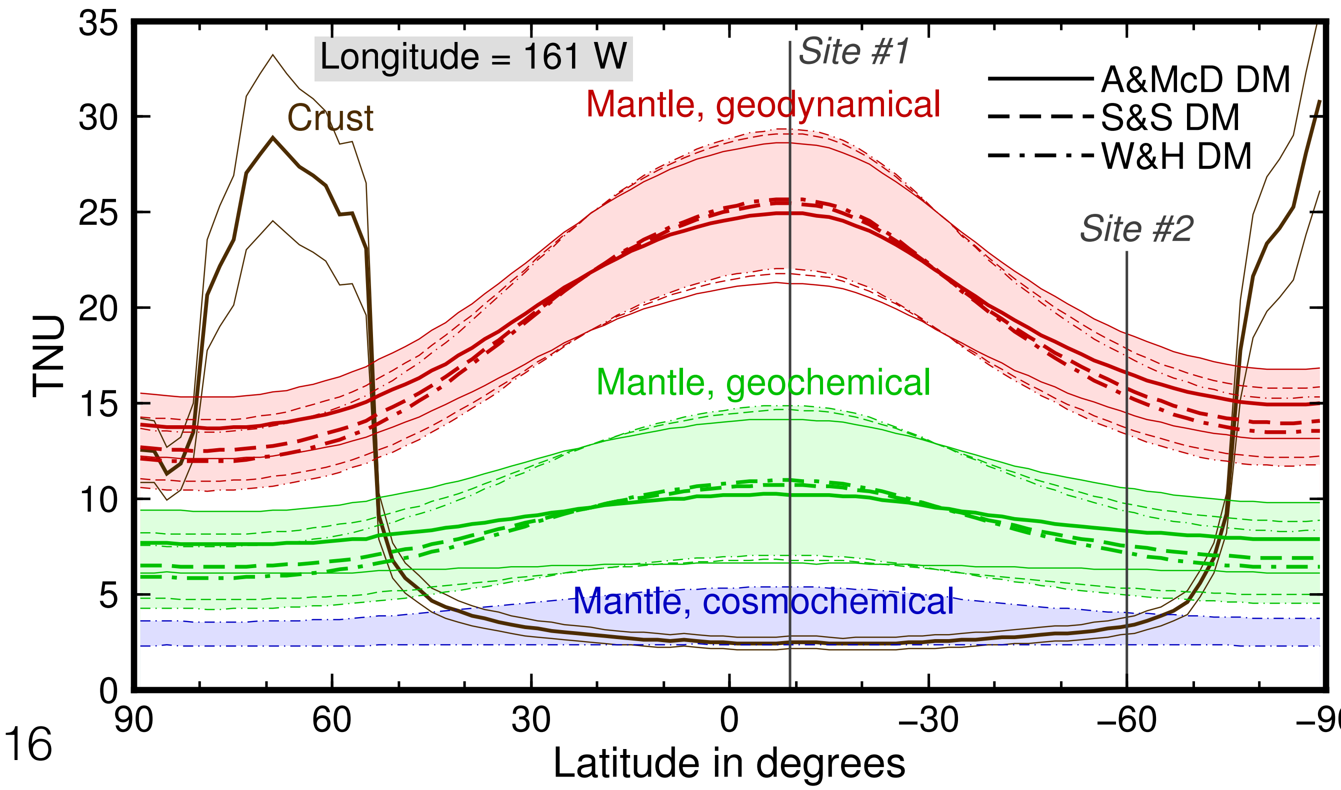


To constrain mantle Th, U, best measure in the ocean.



Mantle contribution to total signal





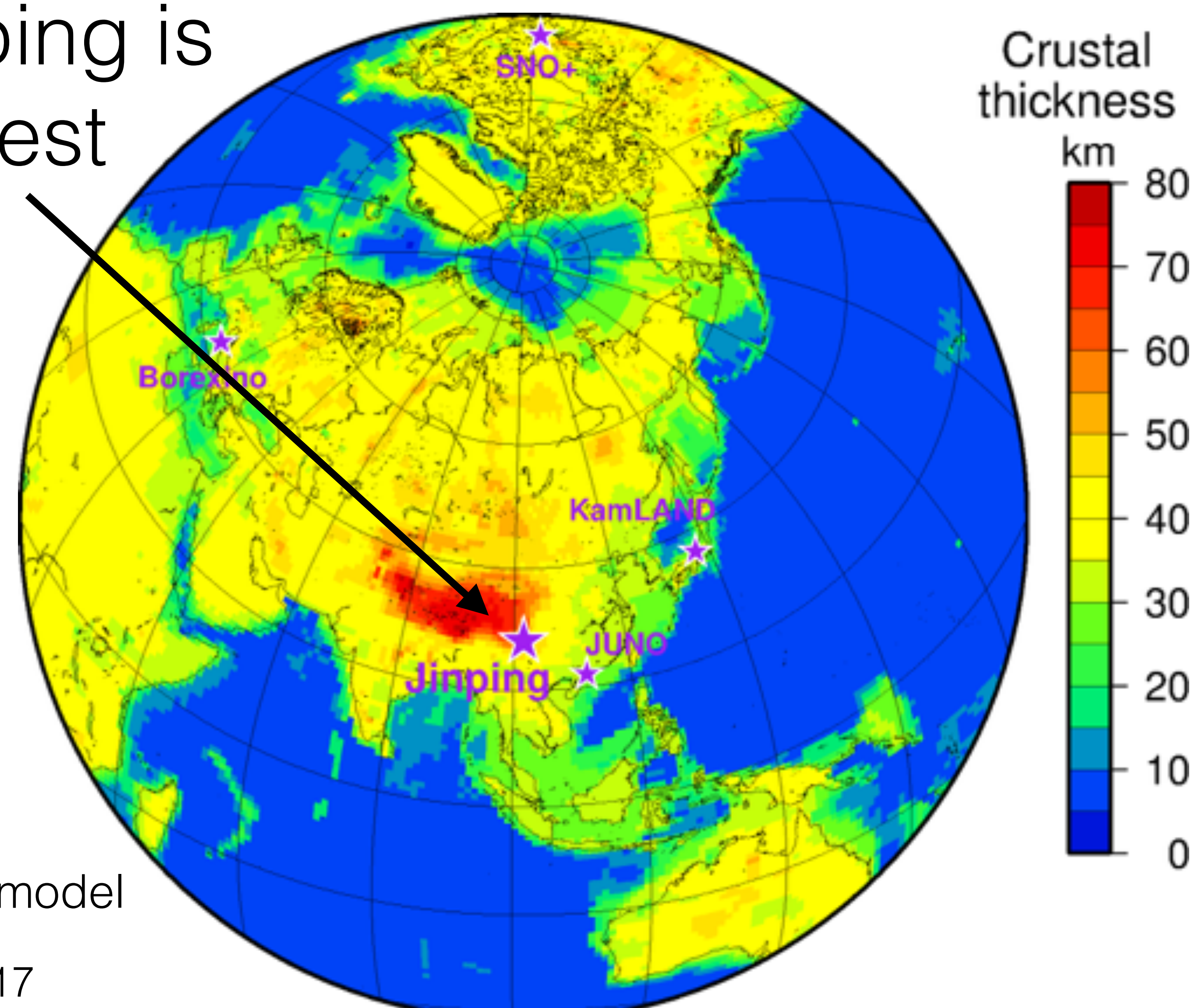
Continental locations: not more than ~25% of geonu signal coming from mantle

Šrámek et al. 2013 EPSL doi:10.1016/j.epsl.2012.11.001

- We do not have an ocean going antineutrino detector

- How can we constrain the mantle?

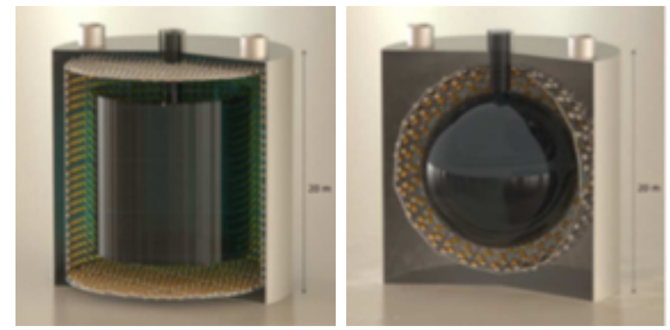
- We have Jinping
  Ok, counterintuitive: Jinping is snuggled up to the thickest crust on Earth (…?)



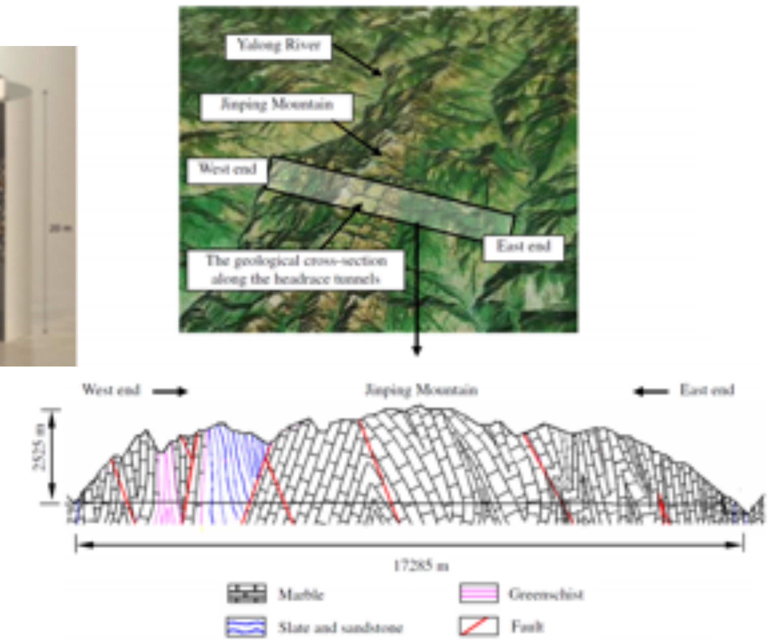
Uses CRUST1.0 model

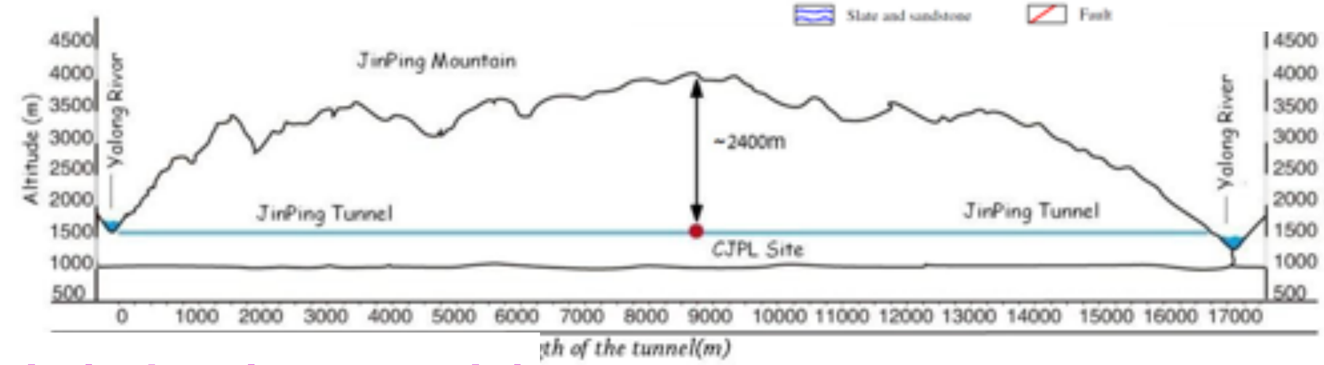
Jinping Neutrino Experiment

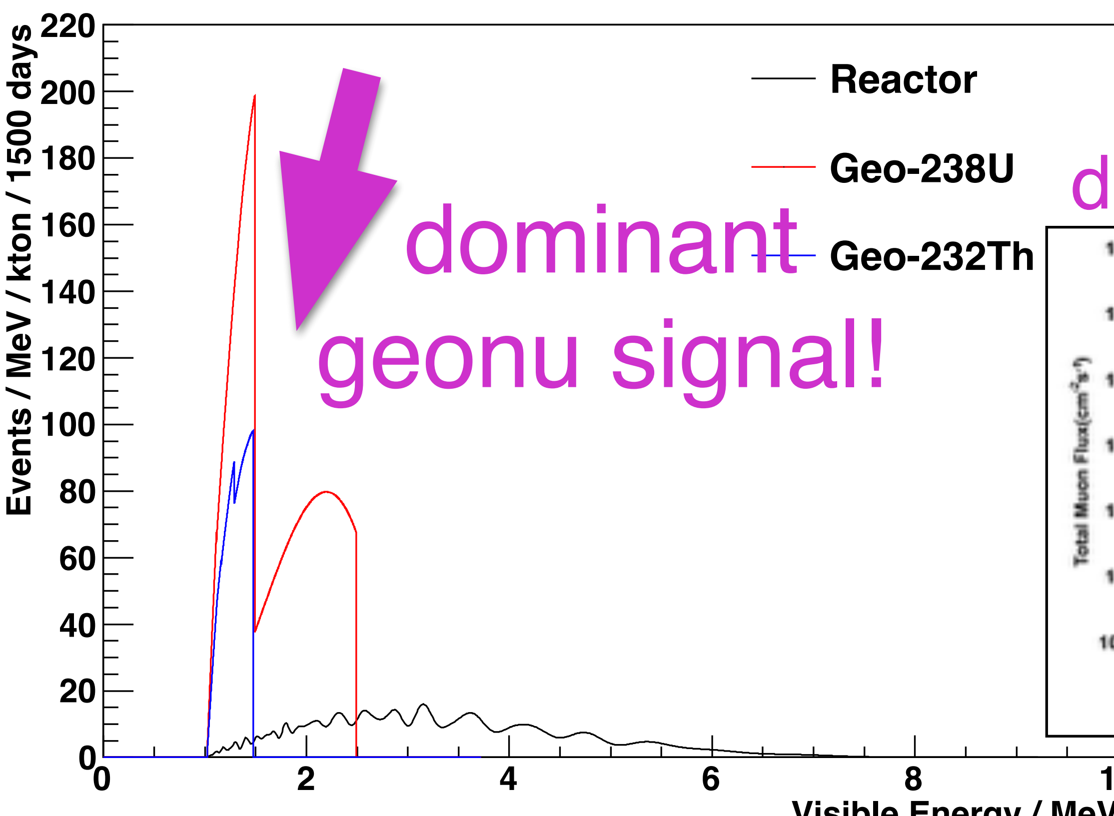
- Website at hep.tsinghua.edu.cn/CJPLNE/
- “Letter of Intent” arXiv:1602.01733



4 kton

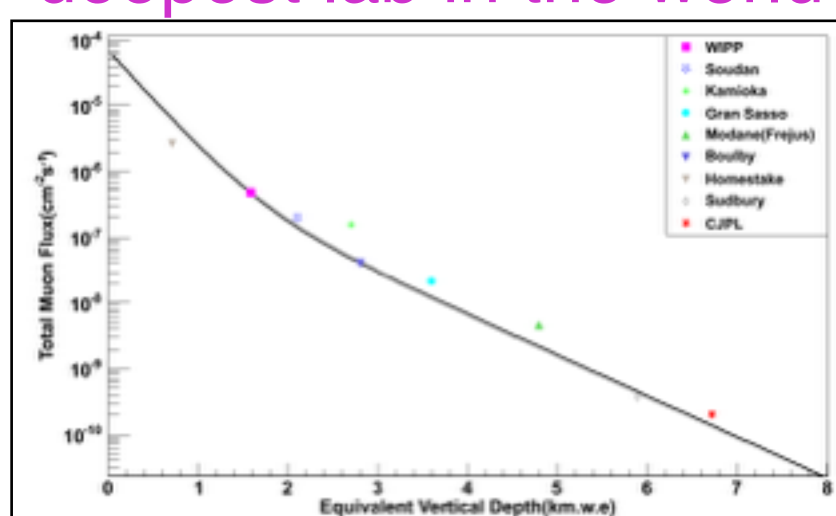




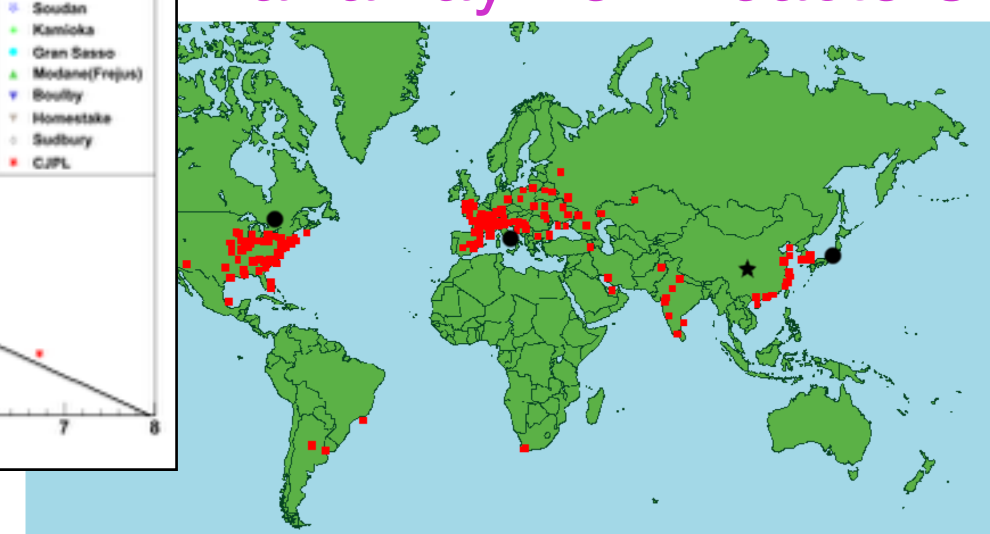


dominant geonu signal!

deepest lab in the world



far away from reactors



Geoneutrino emission model

Global model, layered Earth, chemical reservoirs

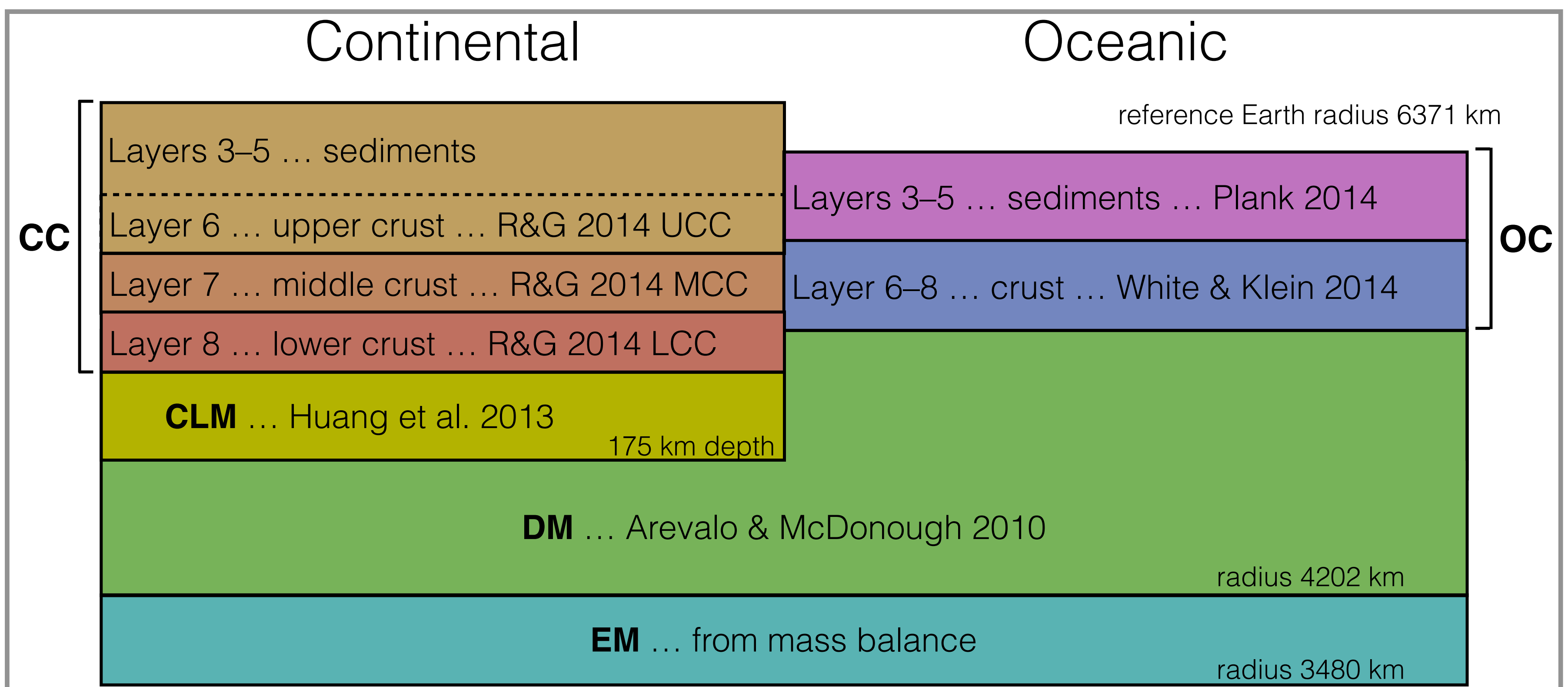
Crustal models:

CRUST1.0 or LITHO1.0 give structure + rock density … 13% difference in CC mass

PREM gives mantle density (Dziewonski & Anderson 1981 PEPI)

Estimates of chemical composition + uncertainty:

Rudnick & Gao 2014, Plank 2014, White & Klein 2014 (all 3 in Treatise on Geochemistry, 2nd ed.), Huang et al. 2013 G^3, Arevalo et al. 2009 EPSL, Arevalo & McDonough 2010 Chem.Geol.



CC = Continental Crust
OC = Oceanic Crust
CLM = Continental Lithospheric Mantle
DM = Depleted Mantle
EM = Enriched Mantle

Different color = different chemical composition

Šrámek, Roskovec, Wipperfurth, Xi Yufei, McDonough, in preparation

Predicted geonu flux at Jinping

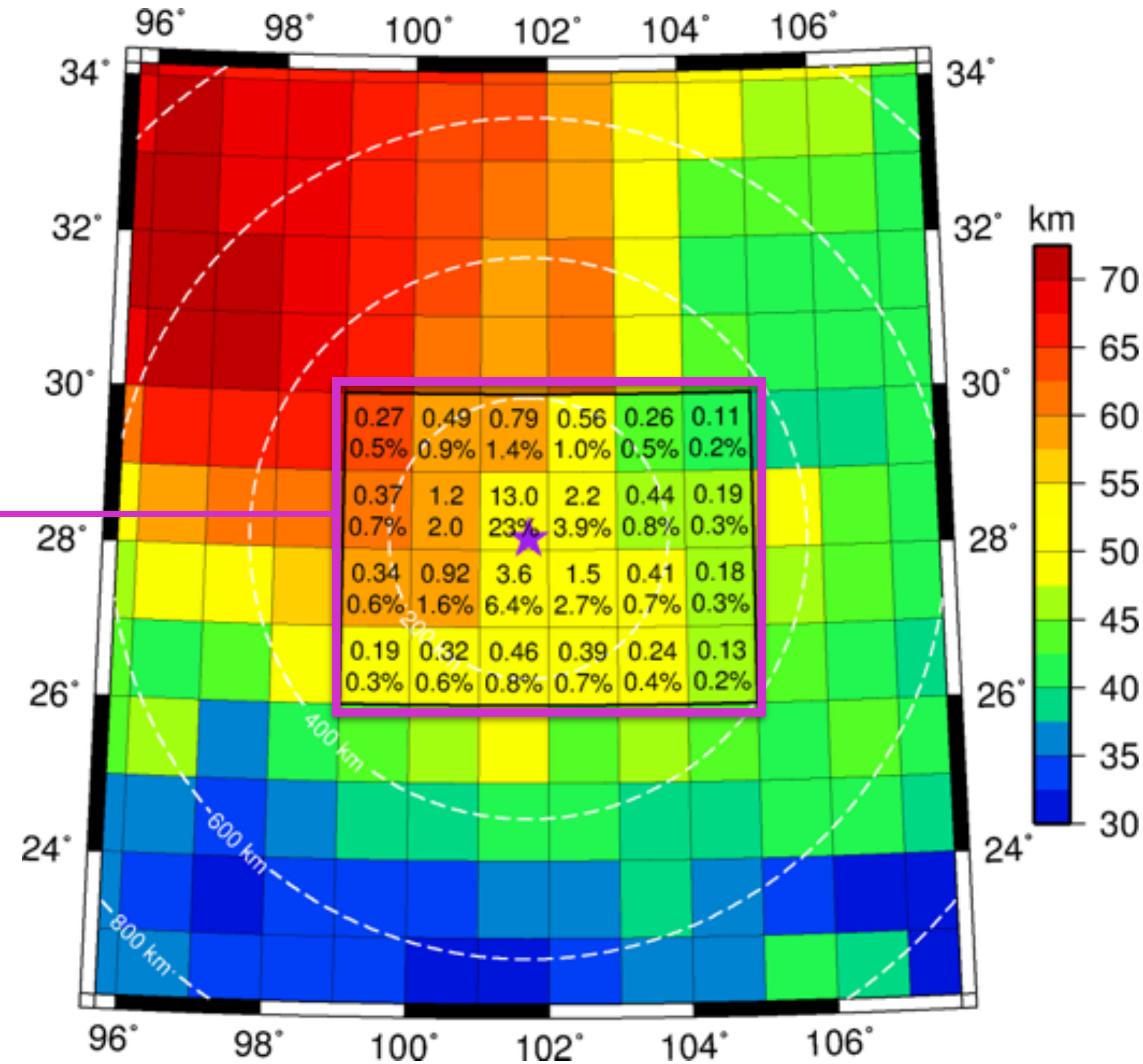
Results using CRUST1.0 model

	TNU
Total	57.0 ± 7.5
Lithosphere	48.8 ± 7.4
Mantle	8.2 ± 1.4
"Near-field crust"	28.7

Uncertainties reflect uncertainty in chemical composition.

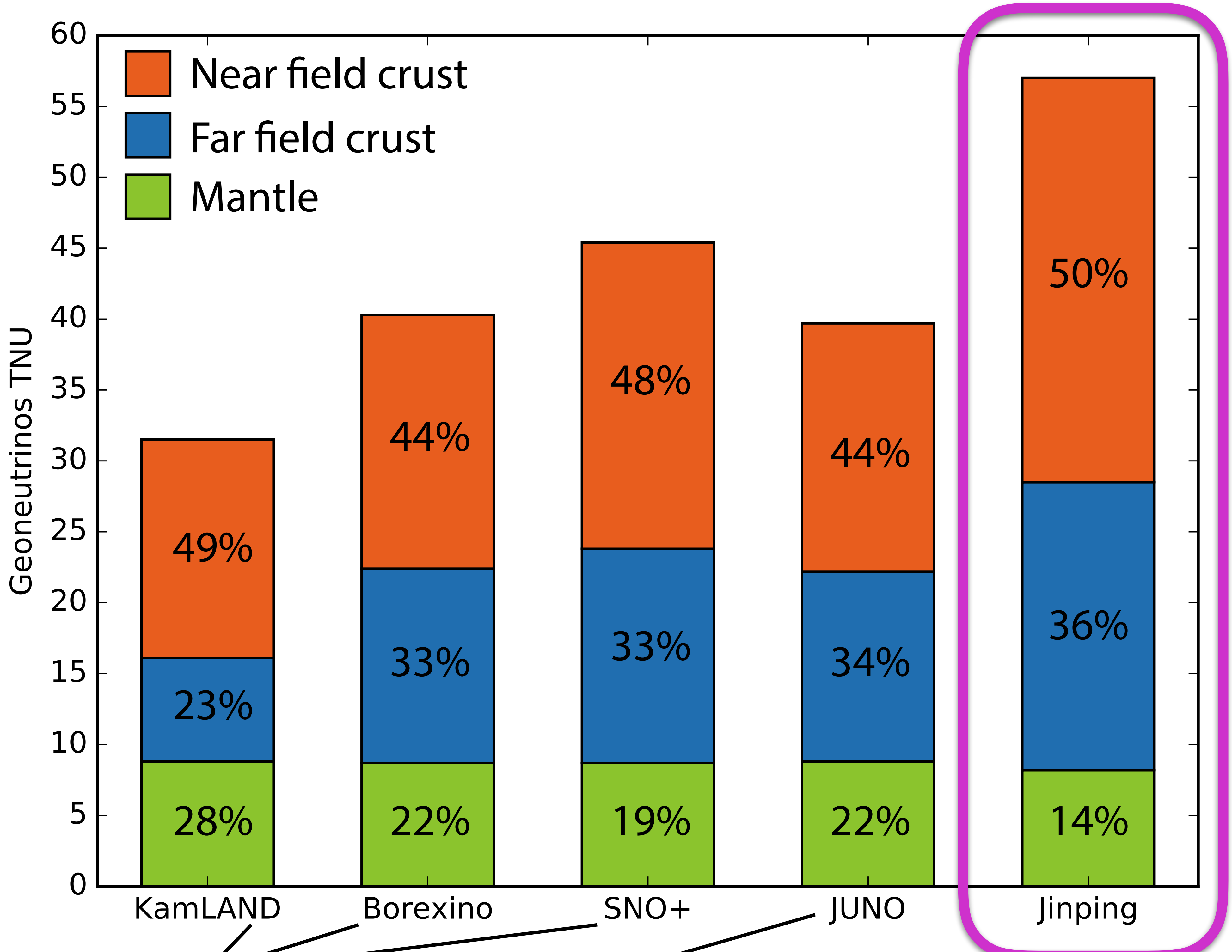
Result using LITHO1.0 model of lithosphere yields flux higher by 5 TNU … estimate of uncertainty in structure/density.

CRUST1.0 crustal thickness in color
TNU and % contribution to total signal



Šrámek, Roskovec, Wipperfurth, Xi Yufei, McDonough, in preparation

Comparison of geoneutrino experiments



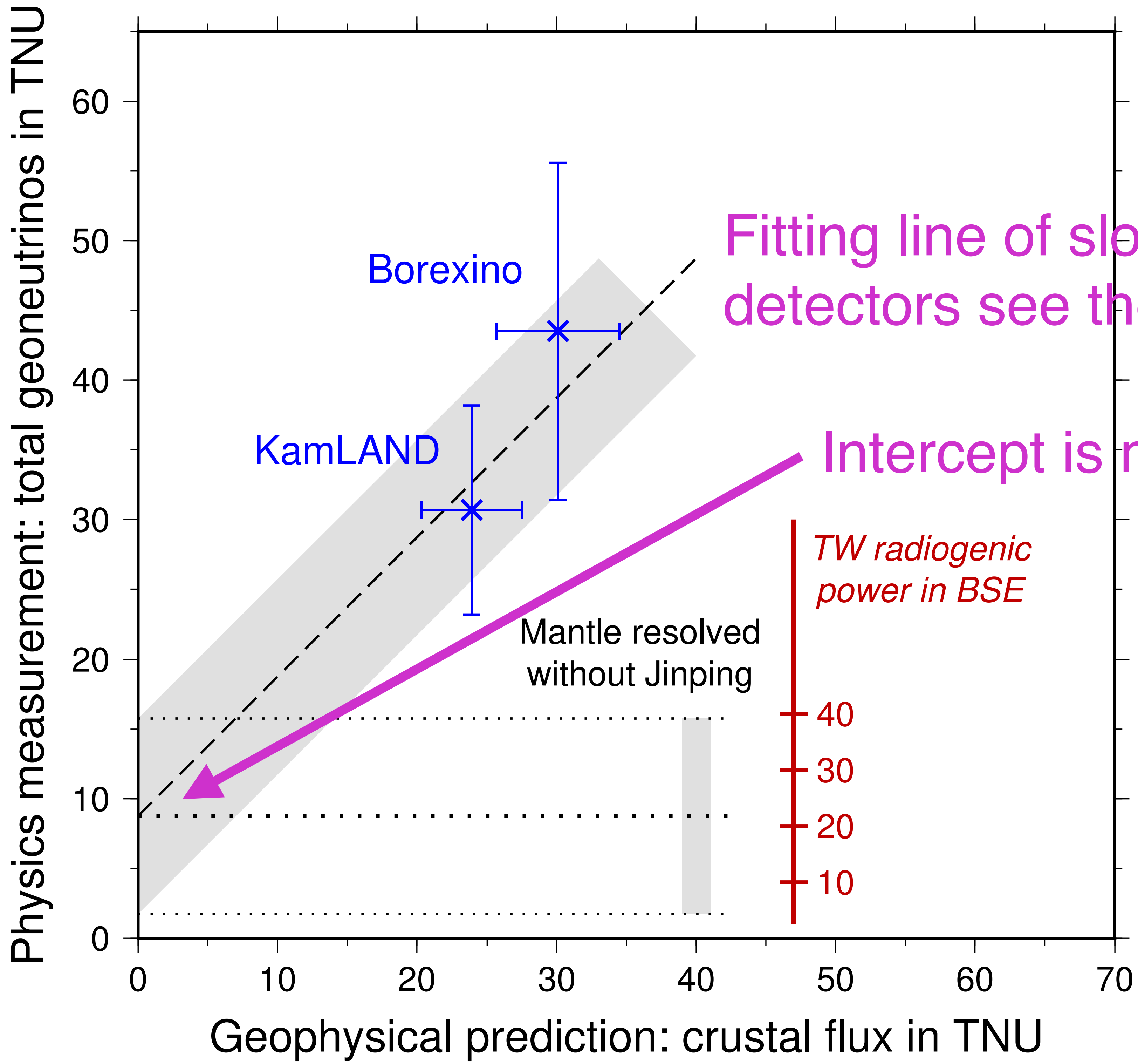
Values from Huang et al. (2013), Strati et al. (2015)

Strongest geonu signal
Highest proportion of crustal signal

Update from McDonough & Šrámek 2014 EES
Šrámek, Roskovec, Wipperfurth, Xi Yufei, McDonough, in preparation

Resolving mantle from KamLAND + Borexino

Measured by physics: total geonu



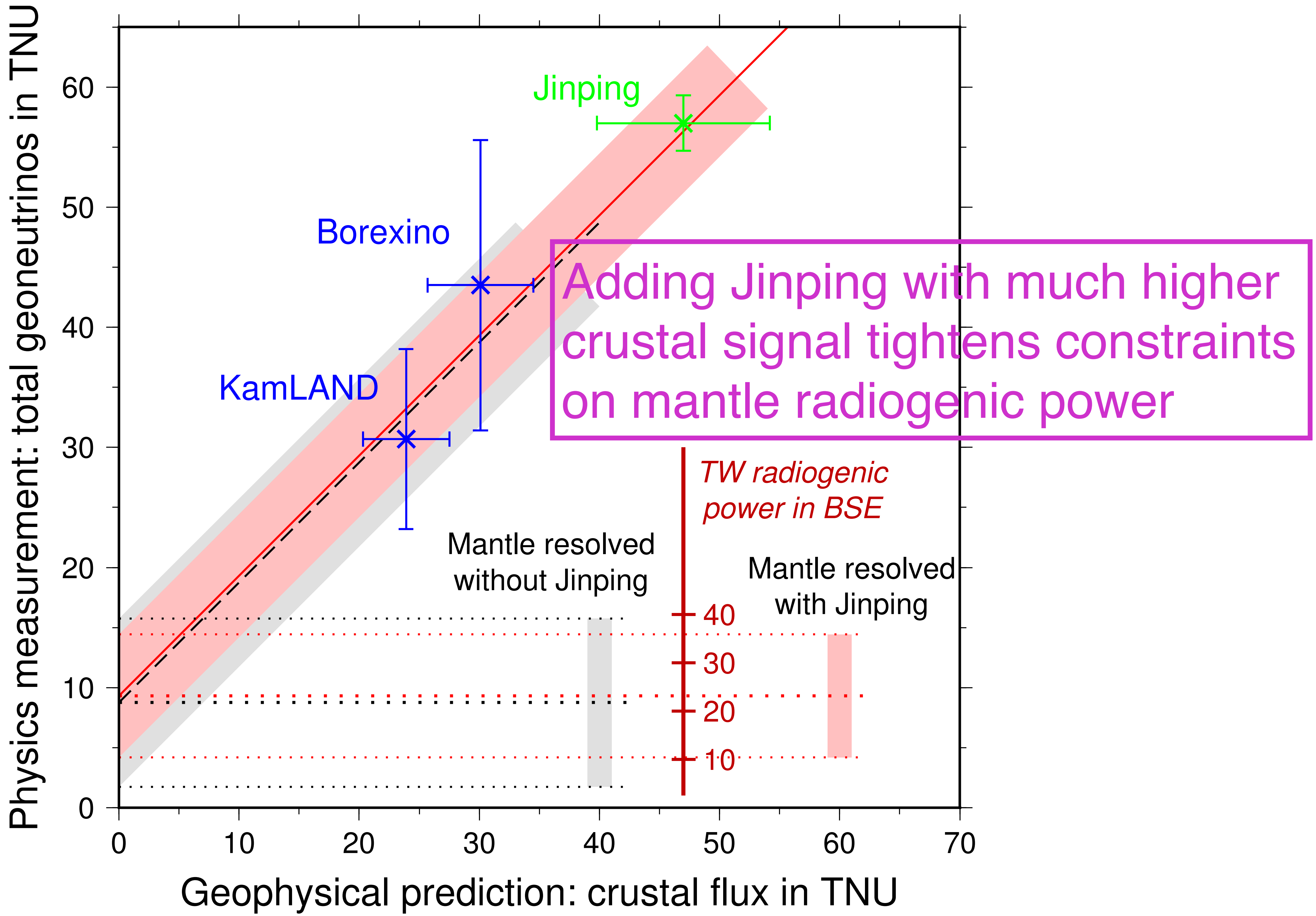
Fitting line of slope 1: detectors see the same mantle

Intercept is mantle signal

Predicted from geology: crust

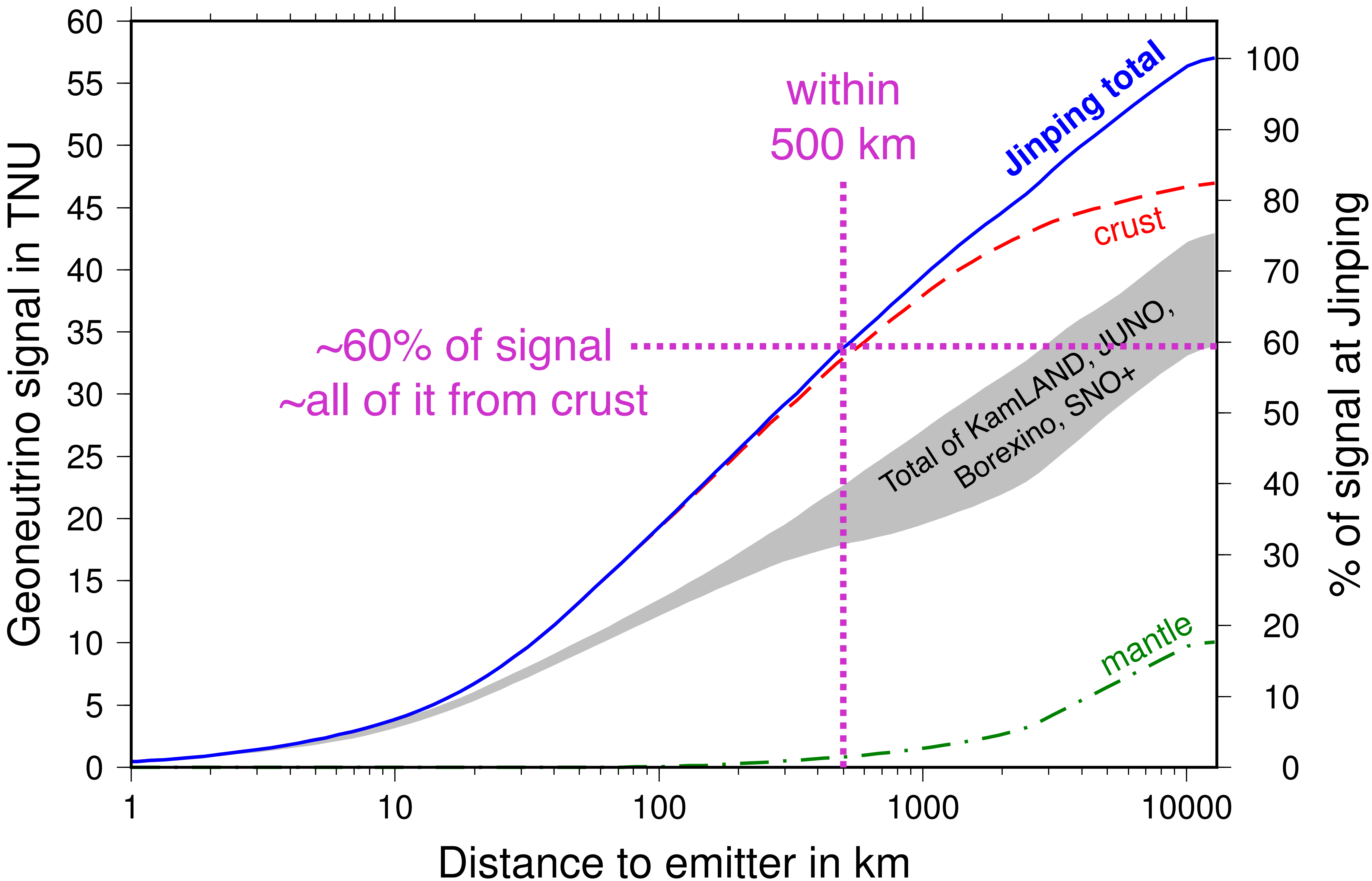
Šrámek, Roskovec, Wipperfurth, Xi Yufei, McDonough, in preparation

Resolving mantle: adding Jinping



Šrámek, Roskovec, Wipperfurth, Xi Yufei, McDonough, in preparation

Geonu flux vs. distance from emitter



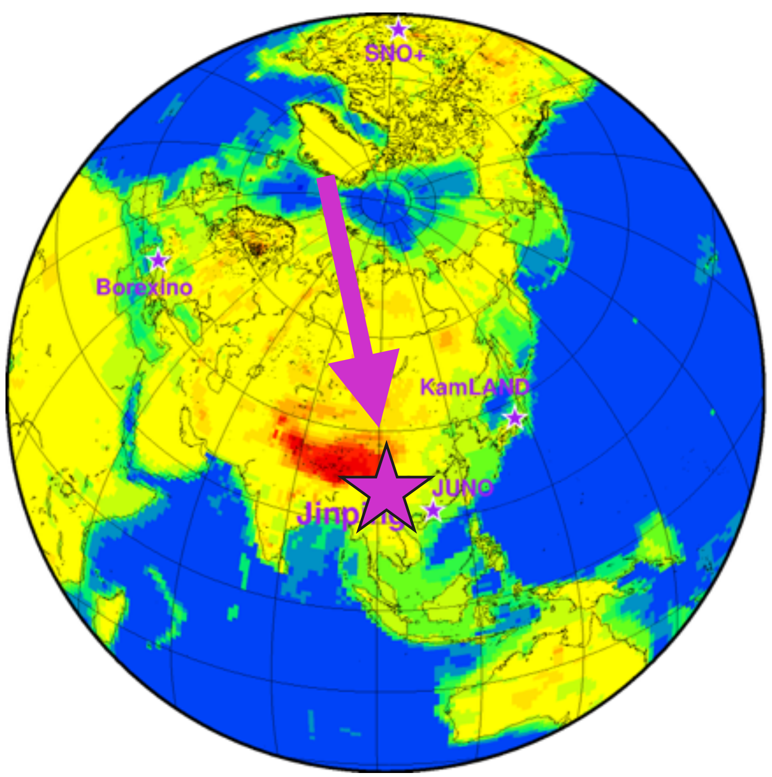
Šrámek, Roskovec, Wipperfurth, Xi Yufei, McDonough, in preparation

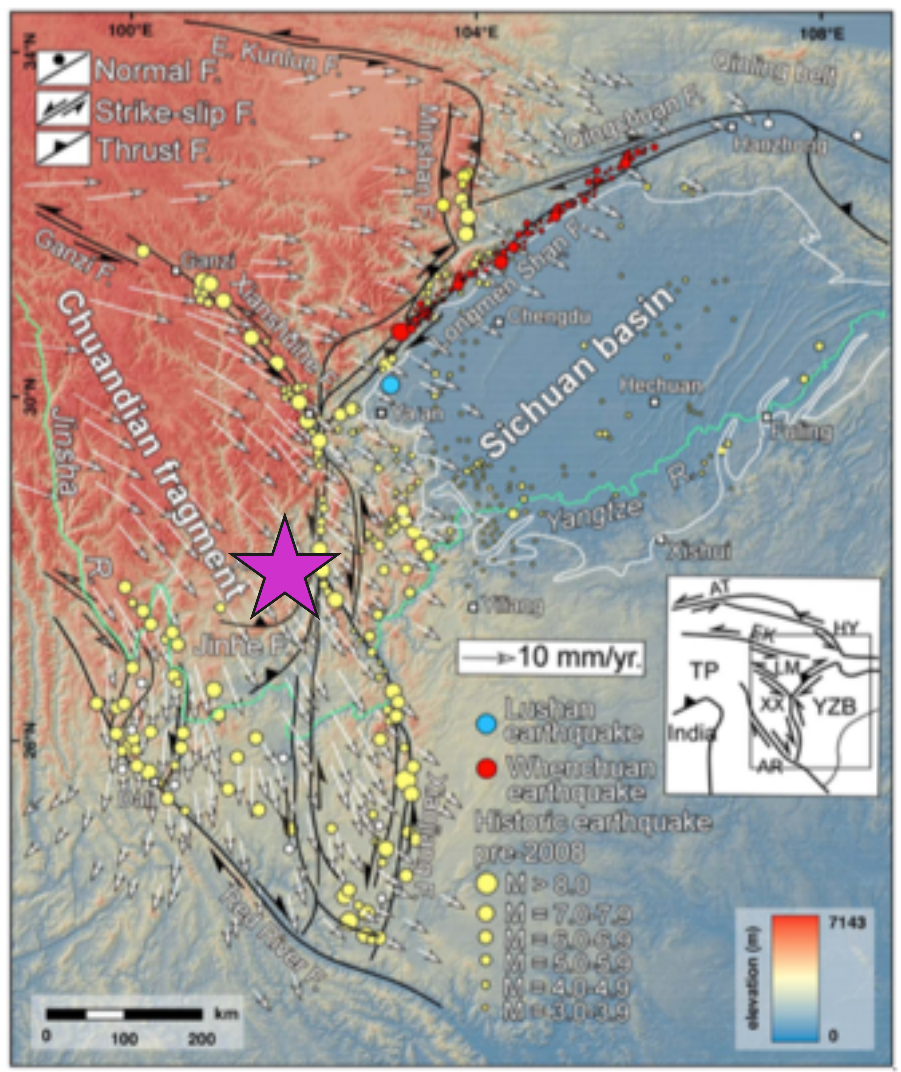
Way forward

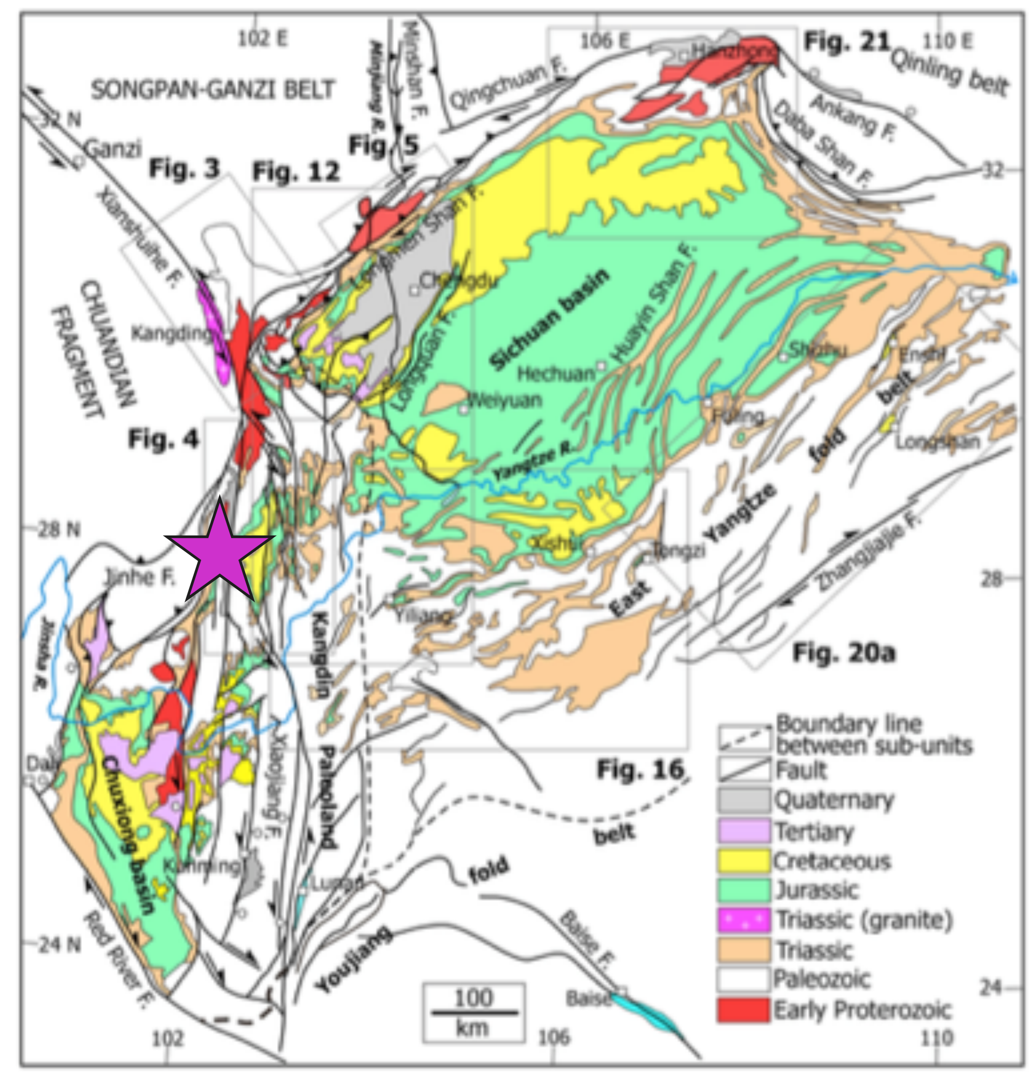
- Global models of crust used in our emission model.
- Need **refined crustal model** specific to Jinping area.
- Given the geological prominence of this area, this can be done and requires involvement of Chinese geoscientist.
- Think about how geoneutrino measurement can be used to study crust around Jinping.

Geology of Jinping neighborhood

- Boundary between Tibetan Plateau and Sichuan Basin
- Major tectonic faults, seismic activity, tectonic activity







Wang et al. 2014 Tectonics doi:10.1002/2013TC003337

Geology of Jinping neighborhood

- Tectonic activity seen in GPS measurements, complex velocity field with amplitudes >10 mm/yr
- Strong lateral variation in crustal thickness, in seismic speeds in the crust and lithospheric mantle, pattern of anisotropy
- Debate about tectonic deformation mechanisms:
  - Lateral eastward expansion of the southeastern Tibetan Plateau: Movement of rigid crustal blocks along large strike-slip faults? Spatially continuous deformation? Eastward flow of a channel of viscous crustal rocks? (Liu et al. 2014 Nature Geosci.)
  - Block rotation: Southward movement of the Chuandian fragment, counterclockwise rotation of Sichuan basin, clockwise rotation of Chuxiong basin? (Wang et al. 2014 Tectonics)
- **What are the implications of different tectonic models on geoneutrino emission from the local lithosphere around Jinping?**

Call to geoscientists

- Jinping provides opportunity to constrain mantle geoneutrino emission, therefore radiogenic power.

- Input is required from geology/geophysics to construct emission model from the local complex tectonic region.

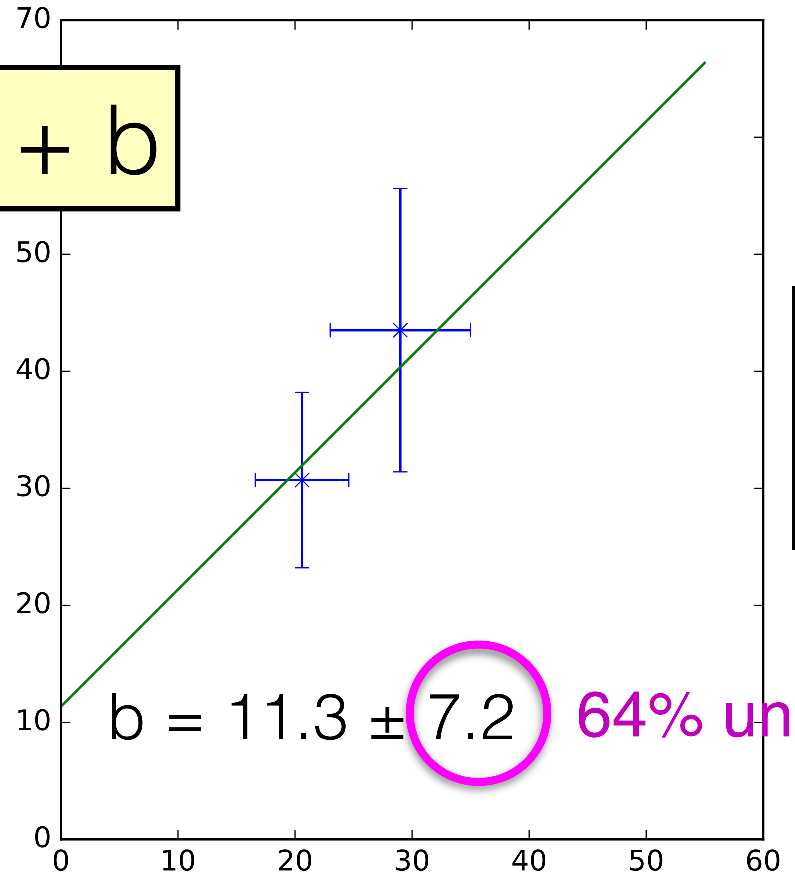
- Use geoneutrinos to study lithosphere around Jinping.

- By working together, we can advance understanding of the deep and the shallow Earth.

Thank you.

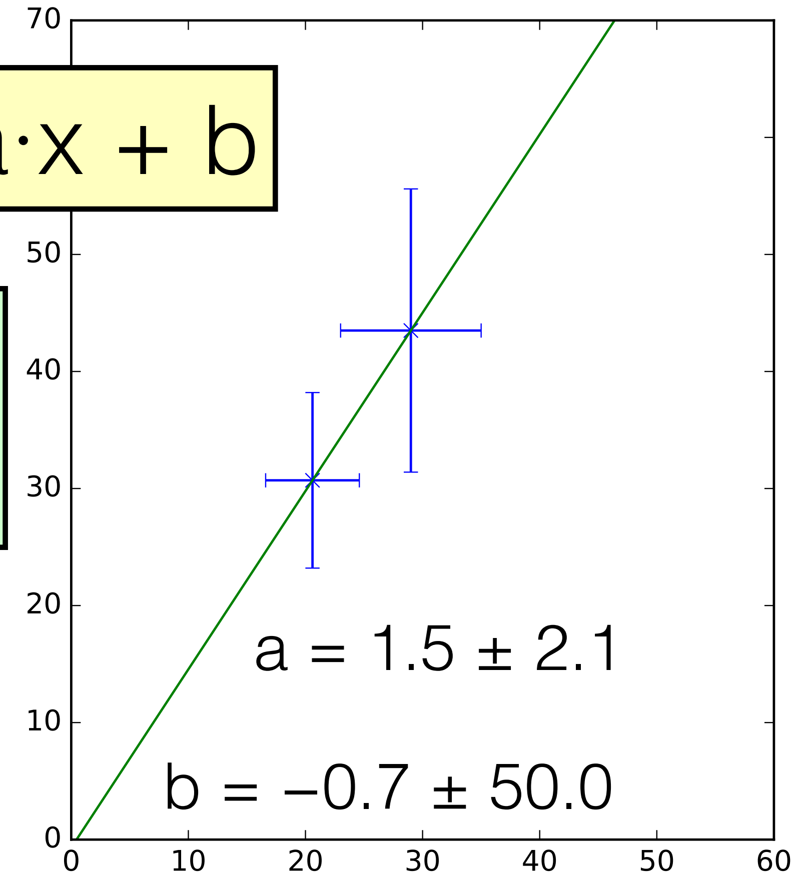
Constrained slope w/out Jinping

$y = x + b$



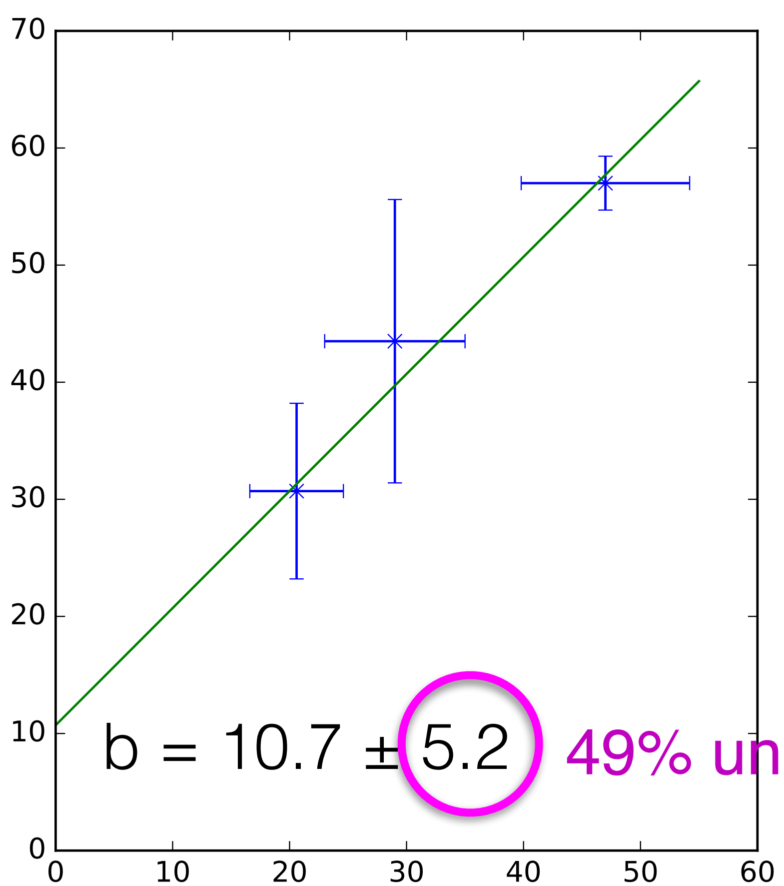
Unconstrained slope w/out Jinping

$y = a \cdot x + b$

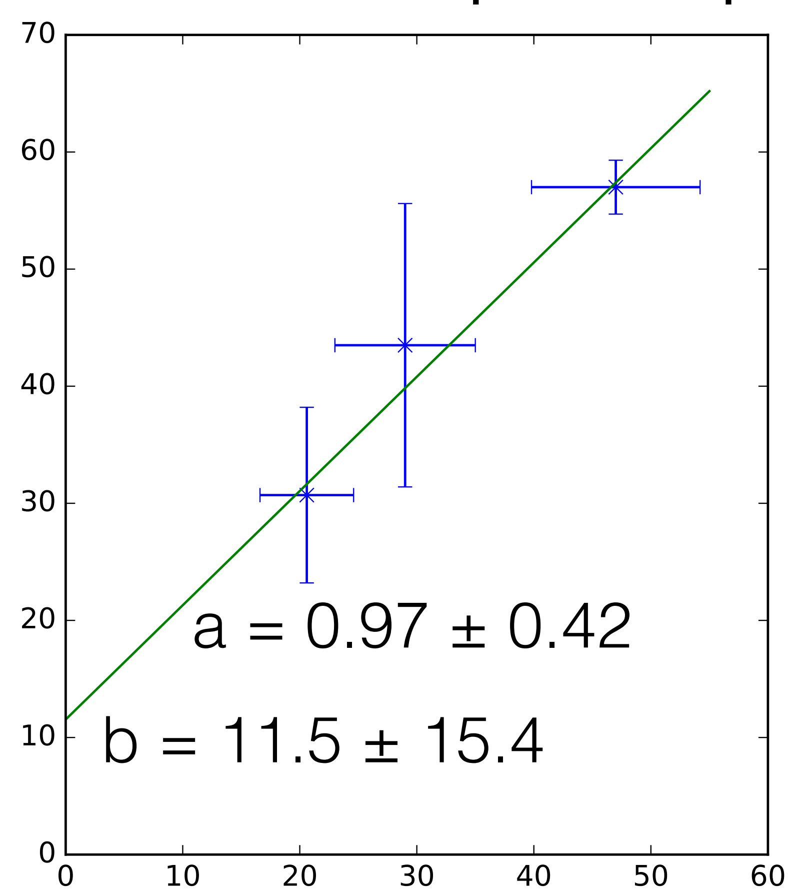


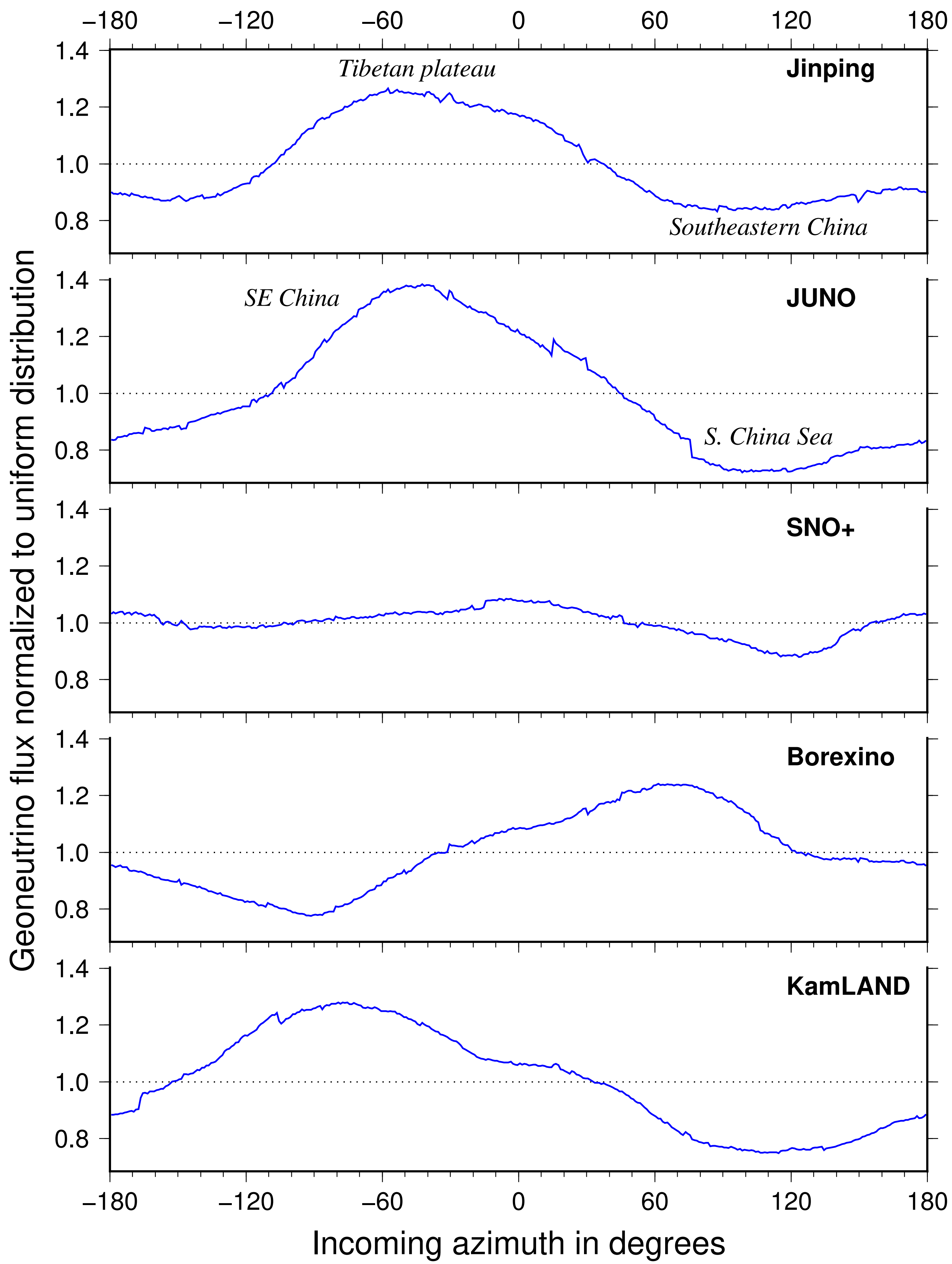
using Huang et al. crustal predictions for KL & BX

Constrained slope w/ Jinping



Unconstrained slope w/ Jinping




Jinping
Tibetan plateau
Southeastern China
JUNO
SE China
S. China Sea
SNO+
Borexino
KamLAND
Geoneutrino flux normalized to uniform distribution
Incoming azimuth in degrees
–180
–120
–60
0
60
120
180
1.4
1.2
1.0
0.8