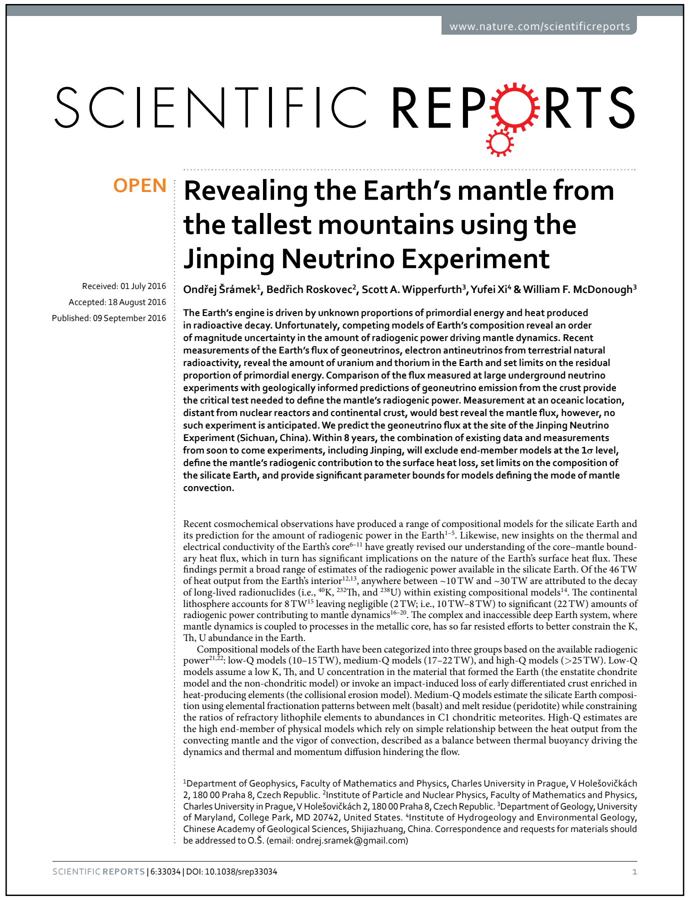

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Revealing the Earth’s mantle from the tallest mountains using the Jinping Neutrino Experiment

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The Earth’s engine is driven by unknown proportions of primordial energy and heat produced in radioactive decay. Unfortunately, competing models of Earth’s composition reveal an order of magnitude uncertainty in the amount of radiogenic power driving mantle dynamics. Recent measurements of the Earth’s flux of geoneutrinos, electron antineutrinos from terrestrial natural radioactivity, reveal the amount of uranium and thorium in the Earth and set limits on the residual proportion of primordial energy. Comparison of the flux measured at large underground neutrino experiments with geologically informed predictions of geoneutrino emission from the crust provide the critical test needed to define the mantle’s radiogenic power. Measurement at an oceanic location, distant from nuclear reactors and continental crust, would best reveal the mantle flux, however, no such experiment is anticipated. We predict the geoneutrino flux at the site of the Jinping Neutrino Experiment (Sichuan, China). Within 8 years, the combination of existing data and measurements from soon to come experiments, including Jinping, will exclude end-member models at the 1σ level, define the mantle’s radiogenic contribution to the surface heat loss, set limits on the composition of the silicate Earth, and provide significant parameter bounds for models defining the mode of mantle convection.

Recent cosmochemical observations have produced a range of compositional models for the silicate Earth and its prediction for the amount of radiogenic power in the Earth[1–5]. Likewise, new insights on the thermal and electrical conductivity of the Earth’s core[6–11] have greatly revised our understanding of the core–mantle boundary heat flux, which in turn has significant implications on the nature of the Earth’s surface heat flux. These findings permit a broad range of estimates of the radiogenic power available in the silicate Earth. Of the 46 TW of heat output from the Earth’s interior[12,13], anywhere between ~10 TW and ~30 TW are attributed to the decay of long-lived radionuclides (i.e., ^{40}K, ^{232}Th, and ^{238}U) within existing compositional models[14]. The continental lithosphere accounts for 8 TW[15] leaving negligible (2 TW; i.e., 10 TW–8 TW) to significant (22 TW) amounts of radiogenic power contributing to mantle dynamics[16–20]. The complex and inaccessible deep Earth system, where mantle dynamics is coupled to processes in the metallic core, has so far resisted efforts to better constrain the K, Th, U abundance in the Earth.

Compositional models of the Earth have been categorized into three groups based on the available radiogenic power[21,22]: low-Q models (10–15 TW), medium-Q models (17–22 TW), and high-Q models (>25 TW). Low-Q models assume a low K, Th, and U concentration in the material that formed the Earth (the enstatite chondrite model and the non-chondritic model) or invoke an impact-induced loss of early differentiated crust enriched in heat-producing elements (the collisional erosion model). Medium-Q models estimate the silicate Earth composition using elemental fractionation patterns between melt (basalt) and melt residue (peridotite) while constraining the ratios of refractory lithophile elements to abundances in C1 chondritic meteorites. High-Q estimates are the high end-member of physical models which rely on simple relationship between the heat output from the convecting mantle and the vigor of convection, described as a balance between thermal buoyancy driving the dynamics and thermal and momentum diffusion hindering the flow.

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Revealing the Earth’s mantle from the tallest mountains using the Jinping Neutrino Experiment

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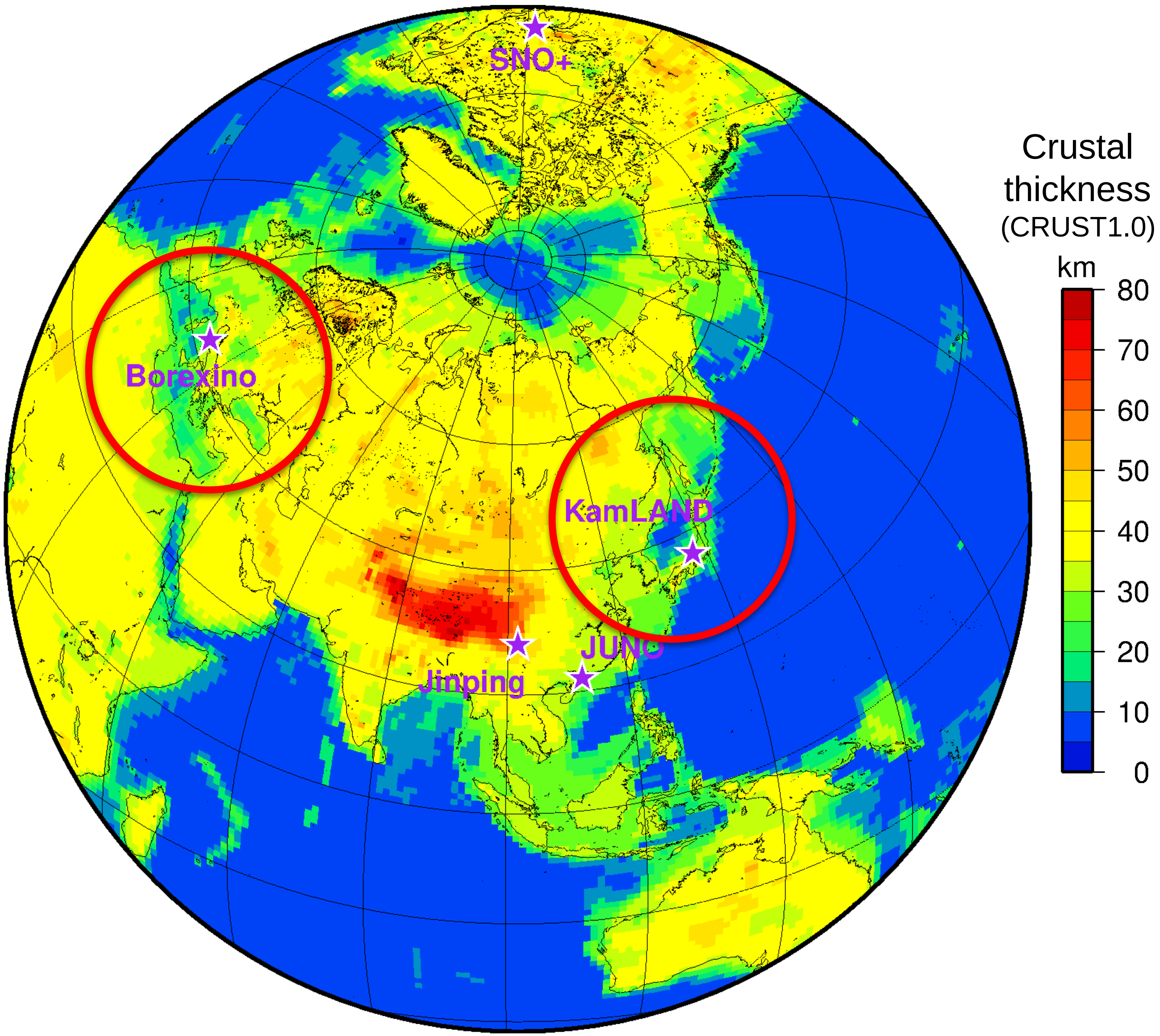
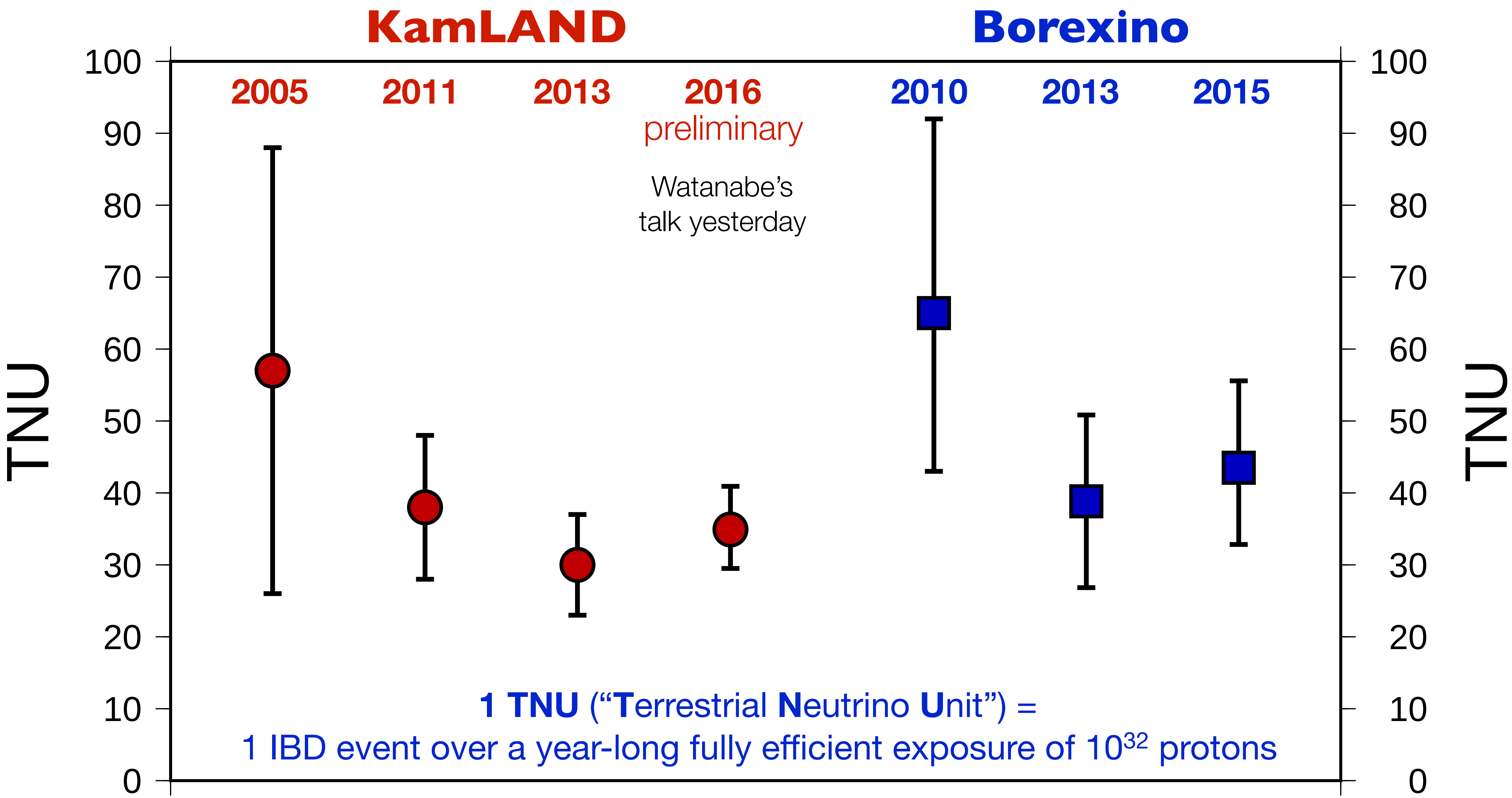
KamLAND
&
Borexino
have measured
geoneutrino flux



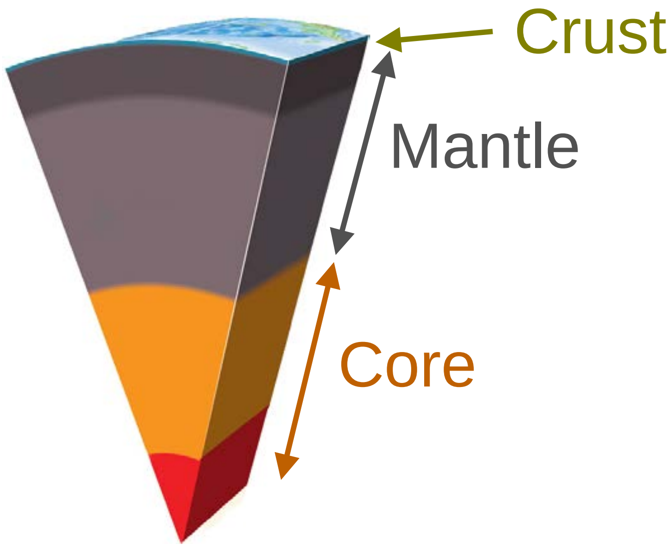
Current geoneutrino measurements



1 TNU (“**T**errestrial **N**eutrino **U**nit”) =
1 IBD event over a year-long fully efficient exposure of 10^{32} protons

Compare to predictions from Earth models
to constrain abundance of Th, U in the Earth

How much radiogenic power in this planet?



- How much of the 46±3 TW of power coming out of the Earth is due to radioactivity?

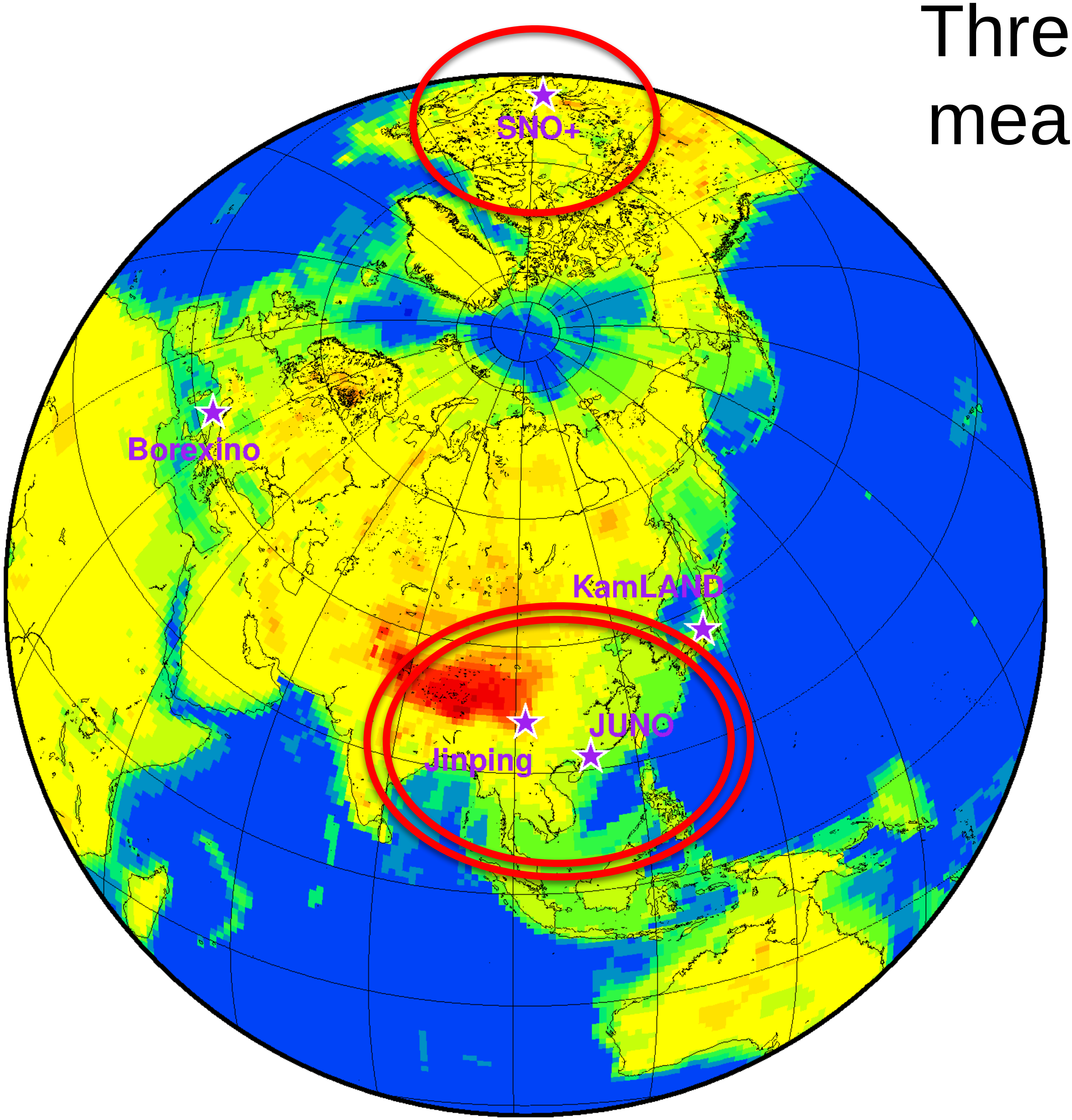
- How much radiogenic heating in the mantle to power thermal convection?

- 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?

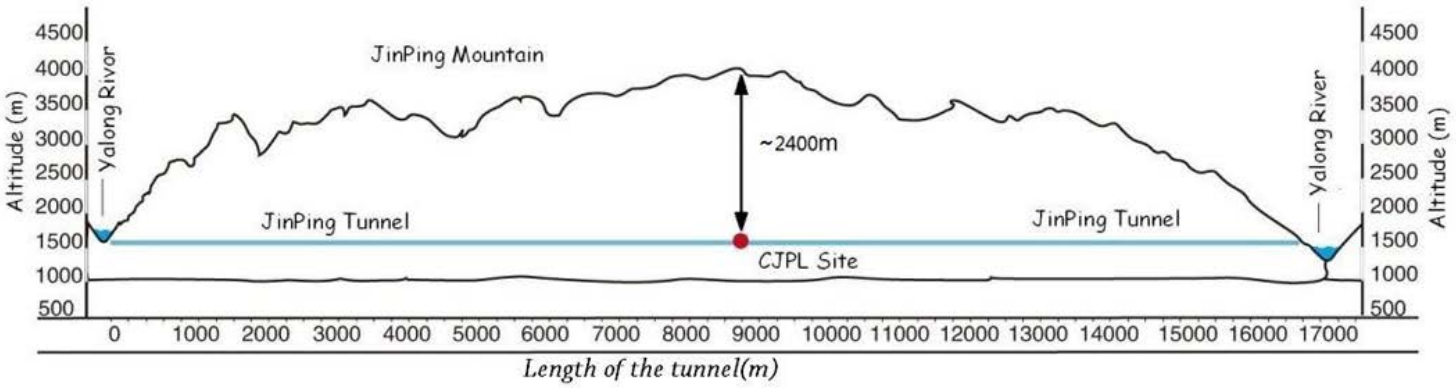


Three more experiments measuring geoneutrinos to come

SNO+	(soon)
JUNO	(2020)
Jinping	(>2020)

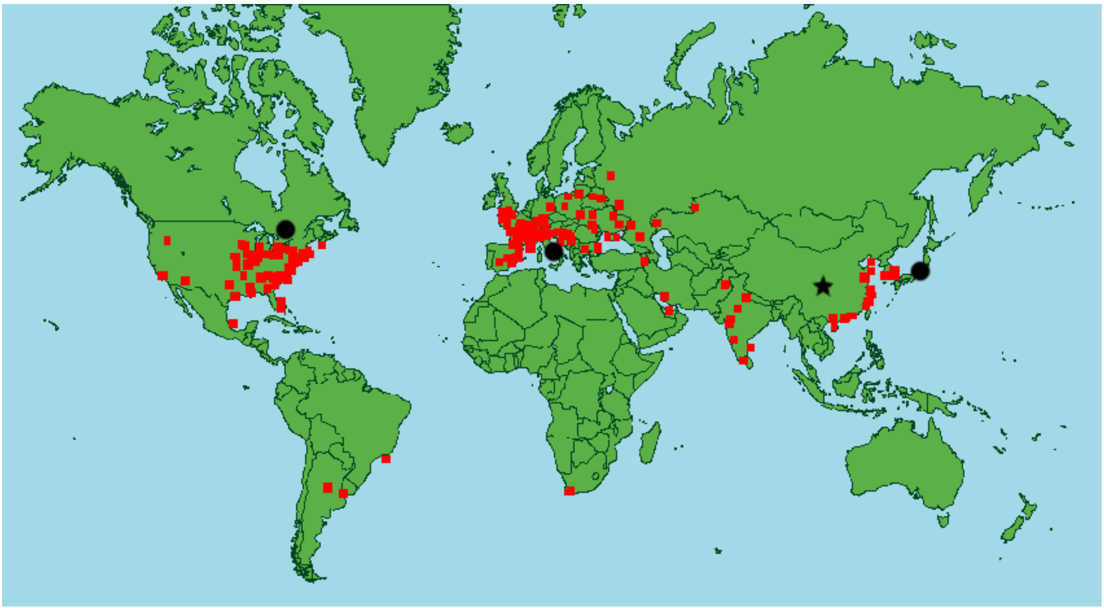
Jinping Neutrino Experiment

Beacom et al. arXiv:1602.01733

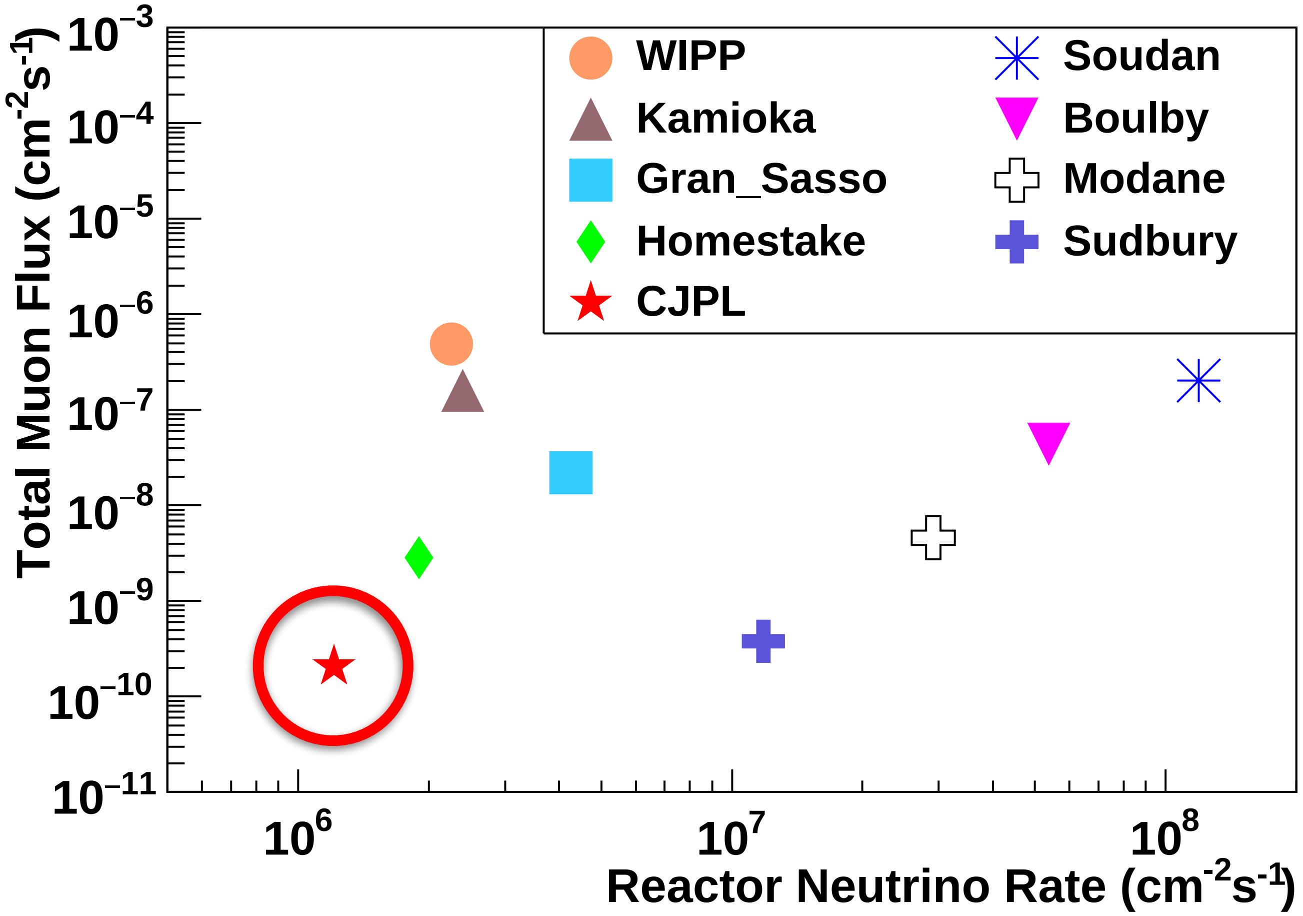


http://jinping.hep.tsinghua.edu.cn

Nuclear reactors



Beacom et al. arXiv:1602.01733



Beacom et al. arXiv:1602.01733

1. Geoneutrino flux prediction at Jinping

2. Prospects for combined analysis of all measurements

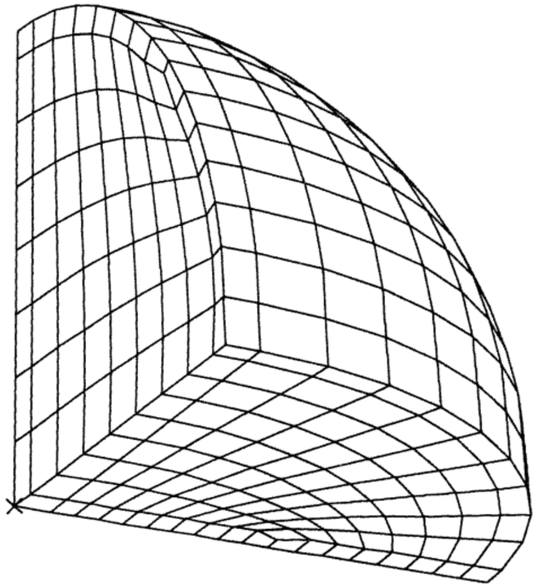
3. Studying lithosphere with geoneutrinos

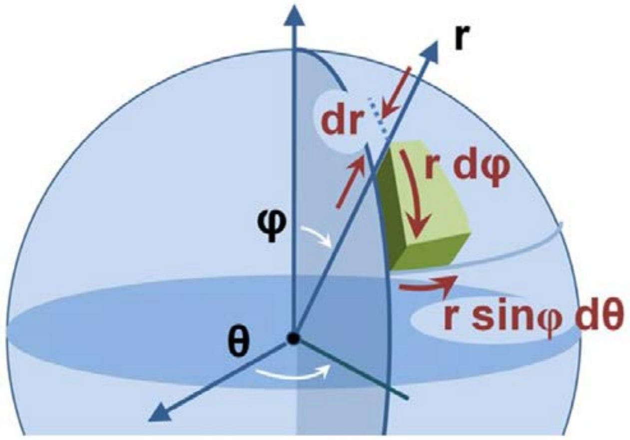
We calculated geoneutrino flux prediction at Jinping

$$\phi(\vec{r}) = \frac{X\lambda N_A}{\mu} n_\nu \langle P_{ee} \rangle \iiint \frac{A(\vec{r}')\rho(\vec{r}')}{4\pi\left|\vec{r} - \vec{r}'\right|^2} d\vec{r}'$$

ϕ … Antineutrino flux
X … Natural isotopic mole fraction
λ … Half-life
N_A … Avogadro's number
μ … Standard atomic mass
n_ν … Number of antineutrinos per decay
$\langle P_{ee} \rangle$ … Average survival probability
A … Elemental abundance
ρ … Mass density
r … position

Predicting geoneutrino flux from emitters (^{232}Th, ^{238}U) distributed spatially with mass fractions *A(r)* in the Earth with mass density *ρ(r)*



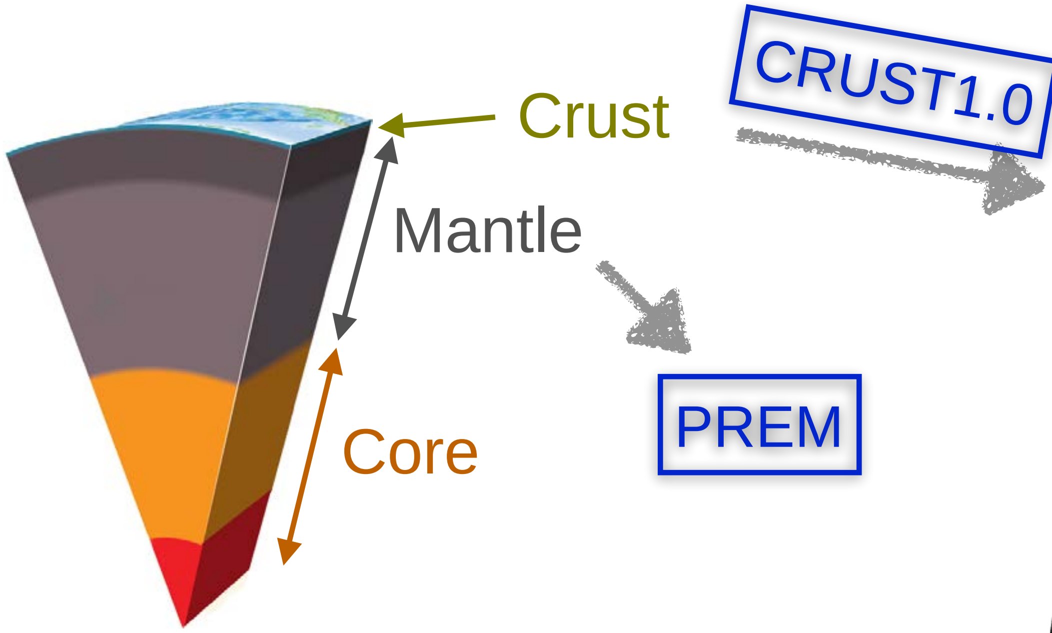


Previous geonu emission models:
(non-exhaustive list)

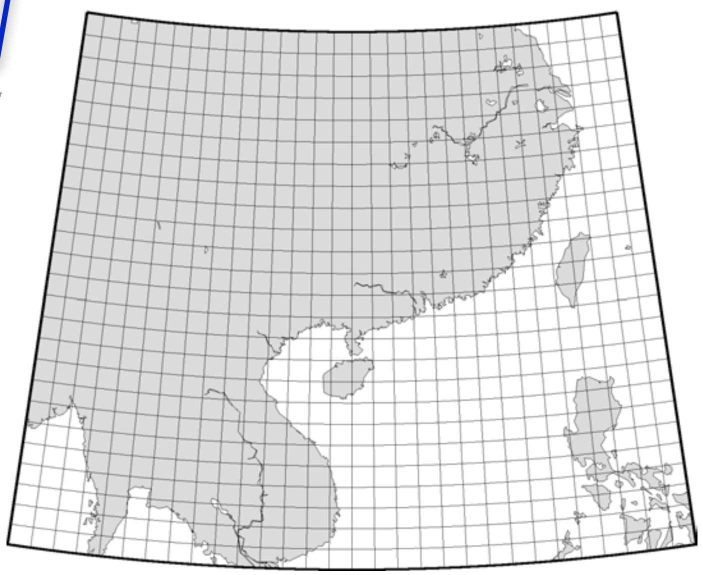
- Krauss et al. 1984
- Kobayashi & Fukao, 1991
- Mantovani et al. 2004
- Enomoto 2005 (PhD)
- Enomoto et al. 2007
- Fiorentini et al. 2007
- Huang et al. 2013
- Usman et al. 2015

Geoneutrino emission model

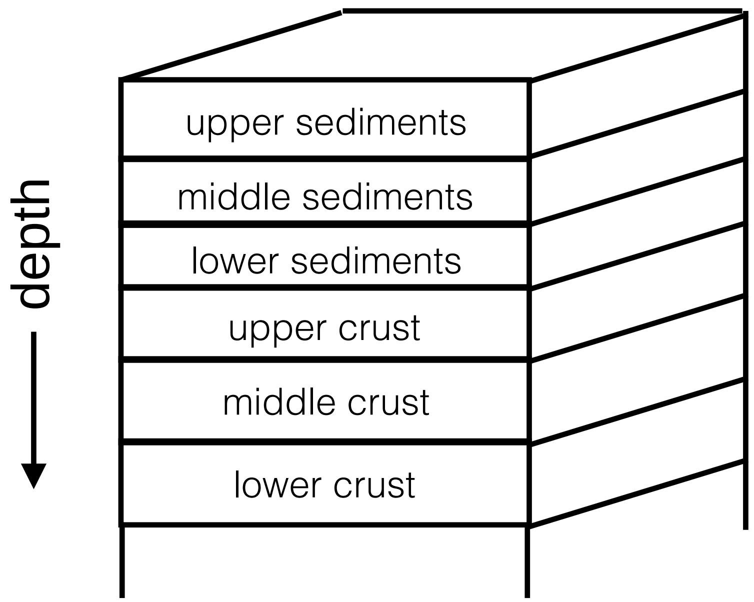
- Model of crustal geometry and material density from **CRUST1.0** model (*Laske et al.*)
- Material density in the mantle from **PREM** model (*Dziewonski & Anderson 1981*)
- Assume negligible Th, U in the core
- Total amount of Th, U in **Silicate Earth** from estimate by *Arevalo et al. 2009*, **20±4 TW** radiogenic power)

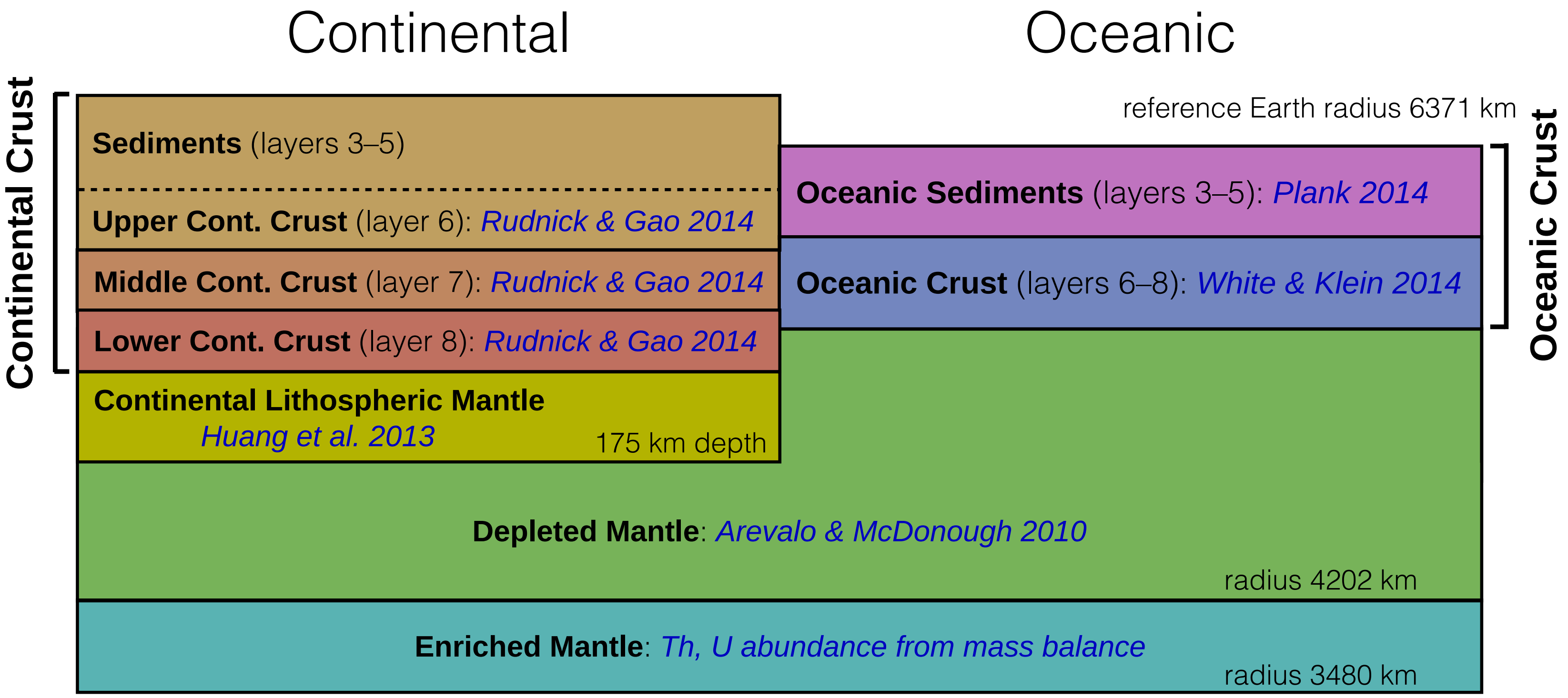


1º lat × 1º lon crustal tiles



Vertical structure of a crustal tile





Sediments (layers 3–5)

Upper Cont. Crust (layer 6): *Rudnick & Gao 2014*

Middle Cont. Crust (layer 7): *Rudnick & Gao 2014*

Lower Cont. Crust (layer 8): *Rudnick & Gao 2014*

Continental Lithospheric Mantle *Huang et al. 2013* 175 km depth

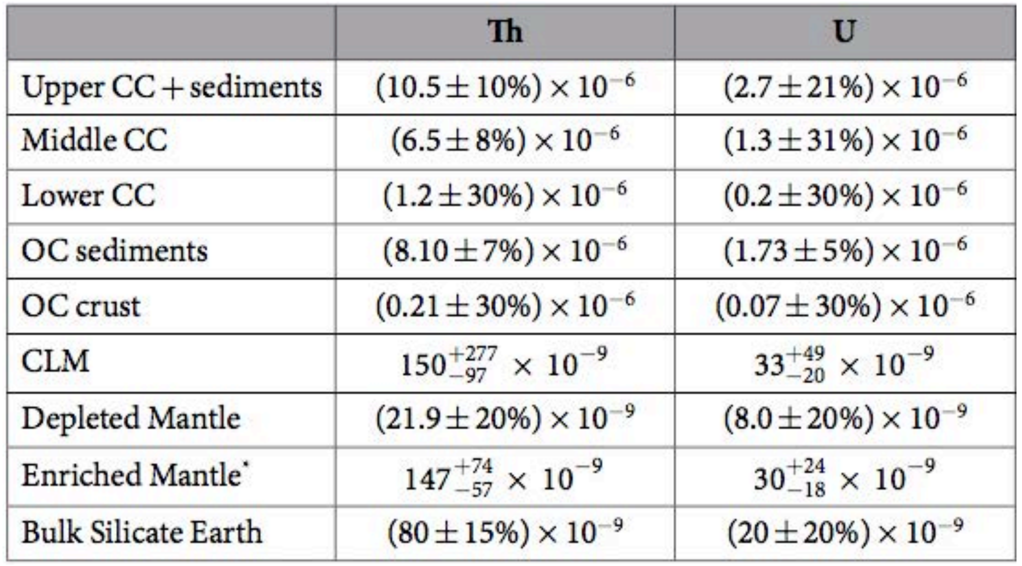
Oceanic Sediments (layers 3–5): *Plank 2014*

Oceanic Crust (layers 6–8): *White & Klein 2014*

Depleted Mantle: *Arevalo & McDonough 2010* radius 4202 km

Enriched Mantle: *Th, U abundance from mass balance* radius 3480 km

Mass fractions of Th and U

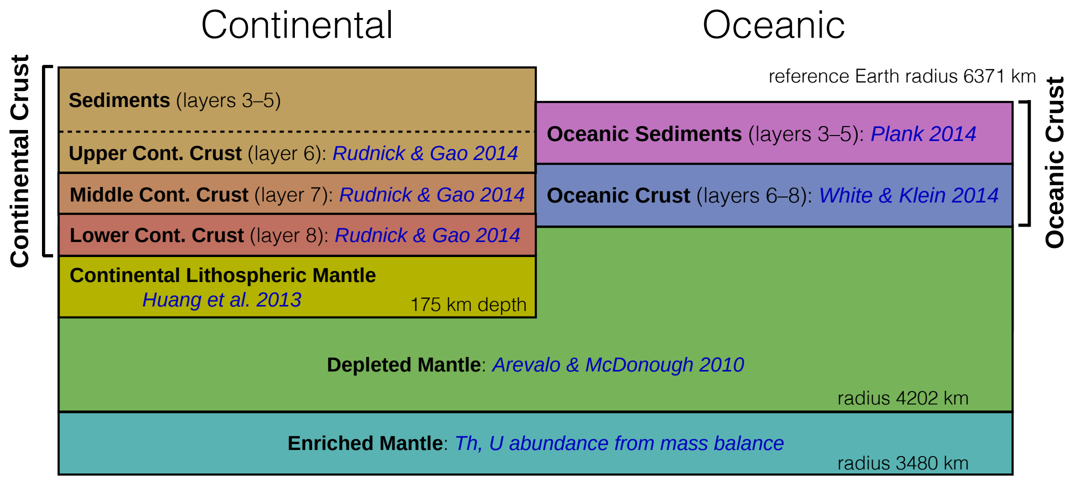


	Th	U
Upper CC + sediments	$(10.5 \pm 10\%) \times 10^{-6}$	$(2.7 \pm 21\%) \times 10^{-6}$
Middle CC	$(6.5 \pm 8\%) \times 10^{-6}$	$(1.3 \pm 31\%) \times 10^{-6}$
Lower CC	$(1.2 \pm 30\%) \times 10^{-6}$	$(0.2 \pm 30\%) \times 10^{-6}$
OC sediments	$(8.10 \pm 7\%) \times 10^{-6}$	$(1.73 \pm 5\%) \times 10^{-6}$
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	$(80 \pm 15\%) \times 10^{-9}$	$(20 \pm 20\%) \times 10^{-9}$

Geoneutrino emission model

Treatment of uncertainties

- 1σ uncertainties on Th, U concentrations adopted from composition estimates
- Uncertainty in crustal structure not included



Continental

Oceanic

Continental Crust

Sediments (layers 3–5)

Upper Cont. Crust (layer 6): *Rudnick & Gao 2014*

Middle Cont. Crust (layer 7): *Rudnick & Gao 2014*

Lower Cont. Crust (layer 8): *Rudnick & Gao 2014*

Continental Lithospheric Mantle *Huang et al. 2013*

175 km depth

reference Earth radius 6371 km

Oceanic Crust

Oceanic Sediments (layers 3–5): *Plank 2014*

Oceanic Crust (layers 6–8): *White & Klein 2014*

Depleted Mantle: *Arevalo & McDonough 2010*

radius 4202 km

Enriched Mantle: *Th, U abundance from mass balance*

radius 3480 km

Monte Carlo approach

- Fluctuate abundances in each chemical reservoir according to the assumed distribution (normal, log-normal)
- Assume U and Th abundances are fully correlated within a layer
- Assume compositional estimates in different reservoirs are independent
- As we throw dice, may run into problem:

More Th and/or U needed to fill **Crust** + **CLM** + **DM**
than what is available in **Silicate Earth**

i.e., negative concentration in EM where EM = BSE – (Crust + CLM + DM)

Filling the Silicate Earth with Th & U

Calculate masses of reservoirs

Generate fluctuated abundances for ***Silicate Earth*** and layers of ***Lithosphere***

Generate fluctuated abundances in ***Depleted Mantle***
Calculate abundances in ***Enriched Mantle***

Is Enriched Mantle enriched? $A_{EM}(U,Th) \geqq A_{DM}(U,Th)$?

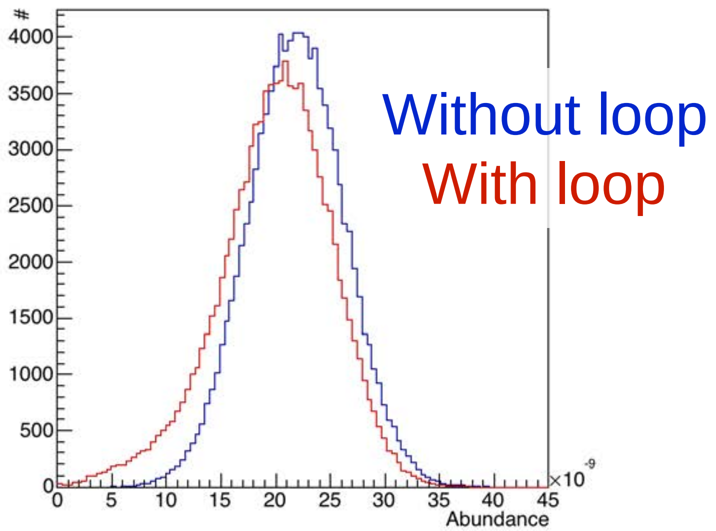
No

Yes

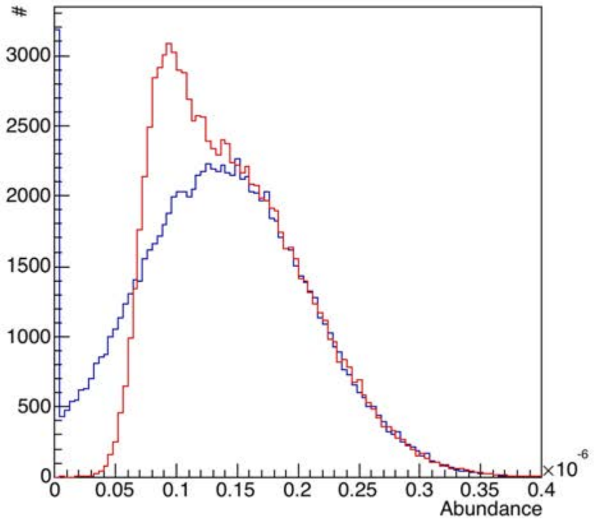
The loop eliminates unphysical values

Calculate geoneutrino flux.

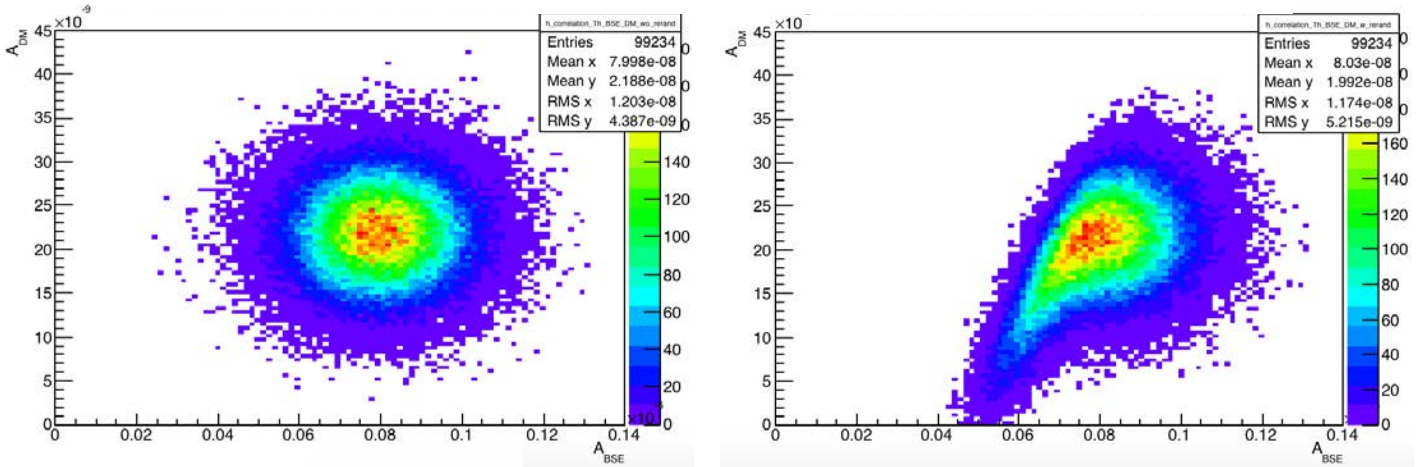
Th abundance in DM



Th abundance in EM



Correlation DM–BSE for Th

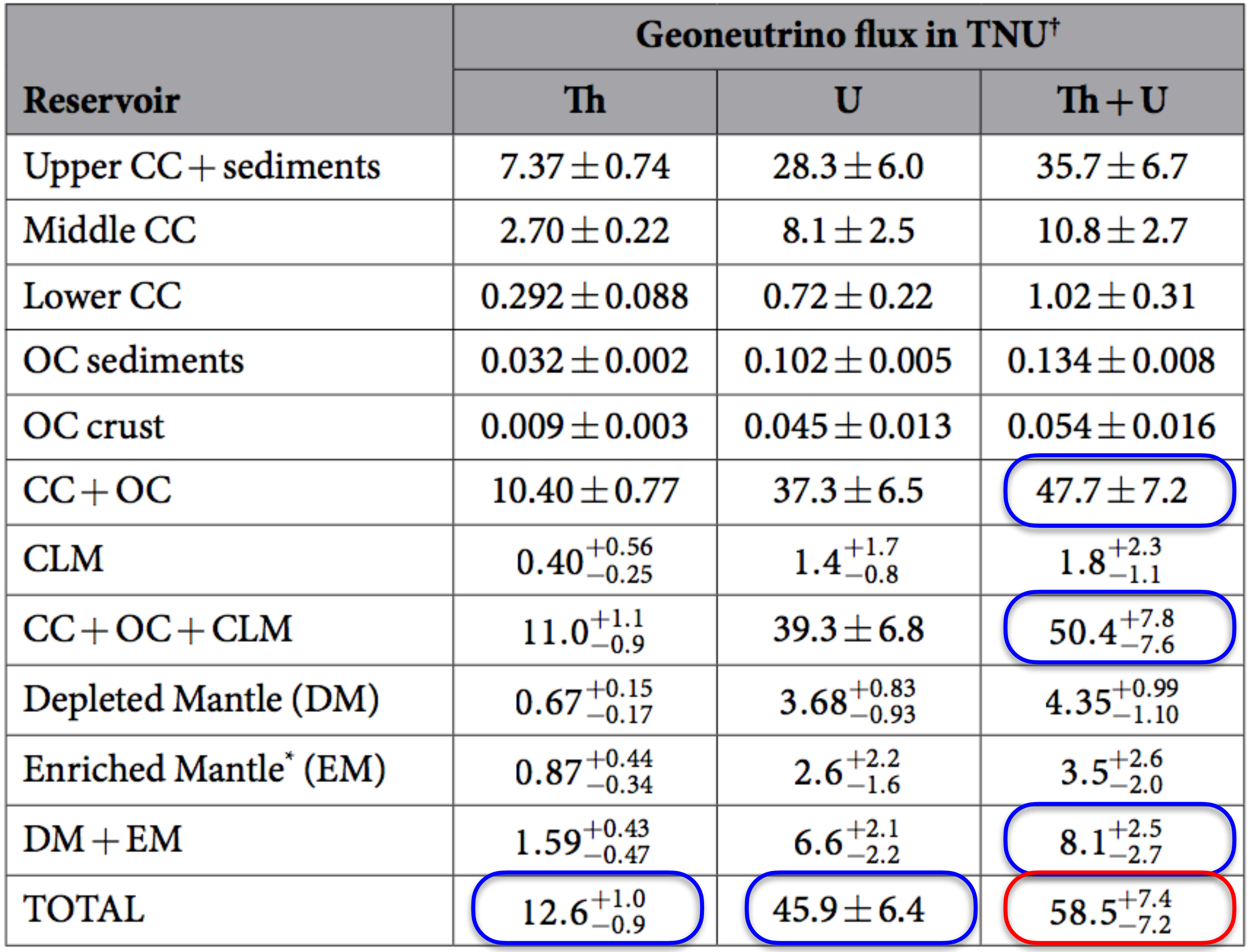


Without loop

With loop

Geoneutrino flux prediction at Jinping

28.15°N, 101.71°E, 2400 m depth



Reservoir	Geoneutrino flux in TNU†		
	Th	U	Th + U
Upper CC + sediments	7.37 ± 0.74	28.3 ± 6.0	35.7 ± 6.7
Middle CC	2.70 ± 0.22	8.1 ± 2.5	10.8 ± 2.7
Lower CC	0.292 ± 0.088	0.72 ± 0.22	1.02 ± 0.31
OC sediments	0.032 ± 0.002	0.102 ± 0.005	0.134 ± 0.008
OC crust	0.009 ± 0.003	0.045 ± 0.013	0.054 ± 0.016
CC + OC	10.40 ± 0.77	37.3 ± 6.5	47.7 ± 7.2
CLM	$0.40^{+0.56}_{-0.25}$	$1.4^{+1.7}_{-0.8}$	$1.8^{+2.3}_{-1.1}$
CC + OC + CLM	$11.0^{+1.1}_{-0.9}$	39.3 ± 6.8	$50.4^{+7.8}_{-7.6}$
Depleted Mantle (DM)	$0.67^{+0.15}_{-0.17}$	$3.68^{+0.83}_{-0.93}$	$4.35^{+0.99}_{-1.10}$
Enriched Mantle* (EM)	$0.87^{+0.44}_{-0.34}$	$2.6^{+2.2}_{-1.6}$	$3.5^{+2.6}_{-2.0}$
DM + EM	$1.59^{+0.43}_{-0.47}$	$6.6^{+2.1}_{-2.2}$	$8.1^{+2.5}_{-2.7}$
TOTAL	$12.6^{+1.0}_{-0.9}$	45.9 ± 6.4	$58.5^{+7.4}_{-7.2}$

82% Crust

86% Crust + CLM

14% Mantle

22% U

78% U

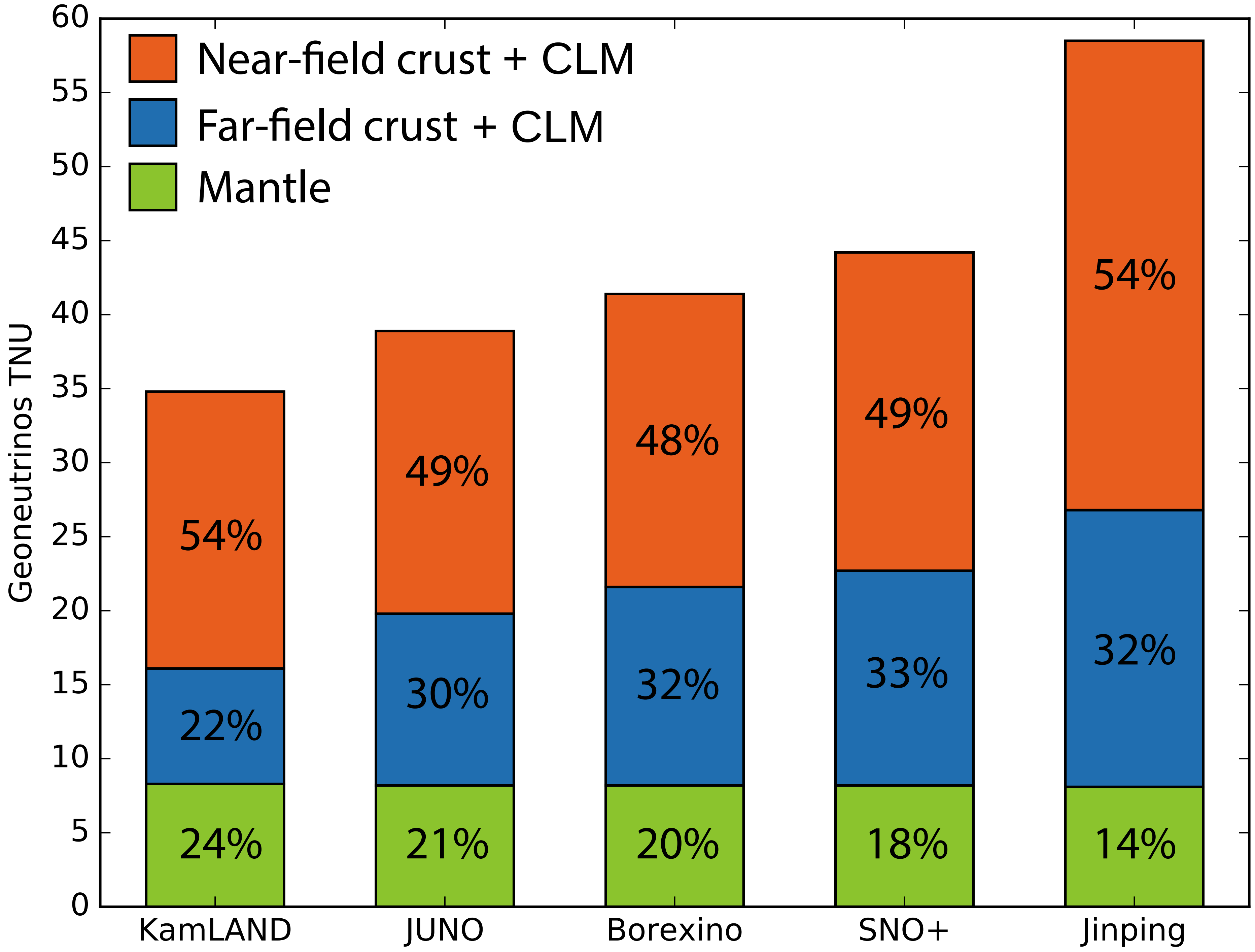
Total TNU

~ Uncertainty of crustal structure – results using different crustal models

CRUST1.0	CRUST2.0	LITHO1.0
47.7 ± 7.2 TNU	42.9 ± 6.4 TNU	51.0 ± 7.6 TNU

Geoneutrino flux prediction

at 5 detectors



Geoneutrino flux prediction

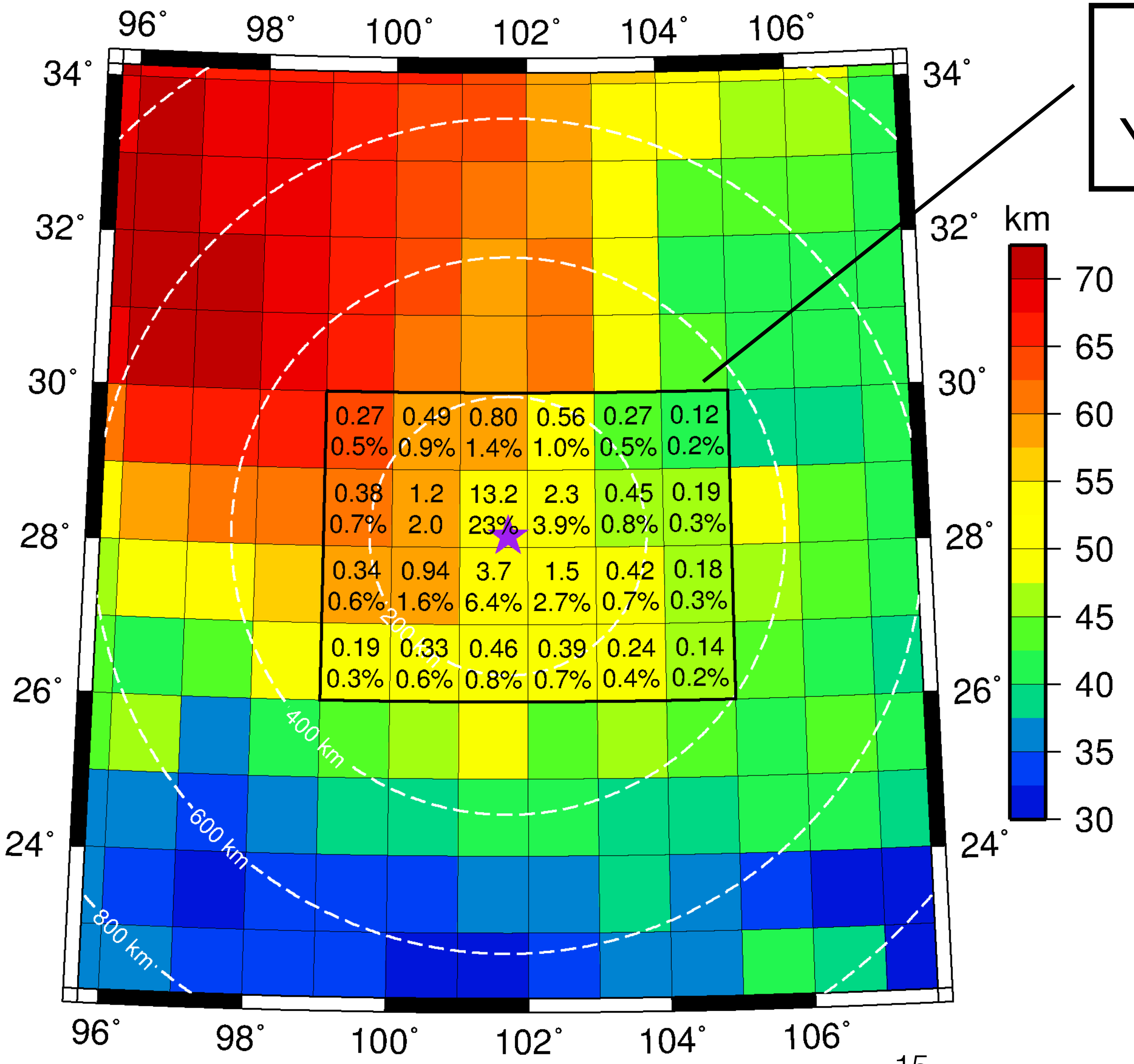
at 5 detectors

	Rad. heat TW	KamLAND TNU	JUNO TNU	Borexino TNU	SNO+ TNU	Jinping TNU
Total flux	20.4	$34.8^{+4.2}_{-4.0}$	$38.9^{+4.8}_{-4.5}$	$41.4^{+5.1}_{-4.8}$	$44.2^{+5.3}_{-5.1}$	$58.5^{+7.4}_{-7.2}$
Mantle (DM + EM)		$8.3^{+2.5}_{-2.7}$	$8.2^{+2.5}_{-2.7}$	$8.2^{+2.5}_{-2.7}$	$8.2^{+2.5}_{-2.7}$	$8.1^{+2.5}_{-2.7}$
Lithosphere (Crust + CLM)	8.2	$26.5^{+4.3}_{-3.9}$	$30.6^{+4.9}_{-4.5}$	$33.2^{+5.3}_{-4.9}$	$36.0^{+5.6}_{-5.2}$	$50.4^{+7.8}_{-7.6}$
Crust	7.4	24.2 ± 3.5	28.1 ± 4.1	30.6 ± 4.5	33.3 ± 4.8	47.7 ± 7.2
Crust *Huang et al. 2013*	6.8	$20.6^{+4.0}_{-3.5}$		$29.0^{+6.0}_{-5.0}$	$34.0^{+6.3}_{-5.7}$	
Crust *Huang et al. 2014*					$30.7^{+6.0}_{-4.2}$	
Crust *Strati et al. 2015*			$28.2^{+5.2}_{-4.5}$			

Comparison to previous studies

Local flux at Jinping

tile-by-tile of CRUST1.0



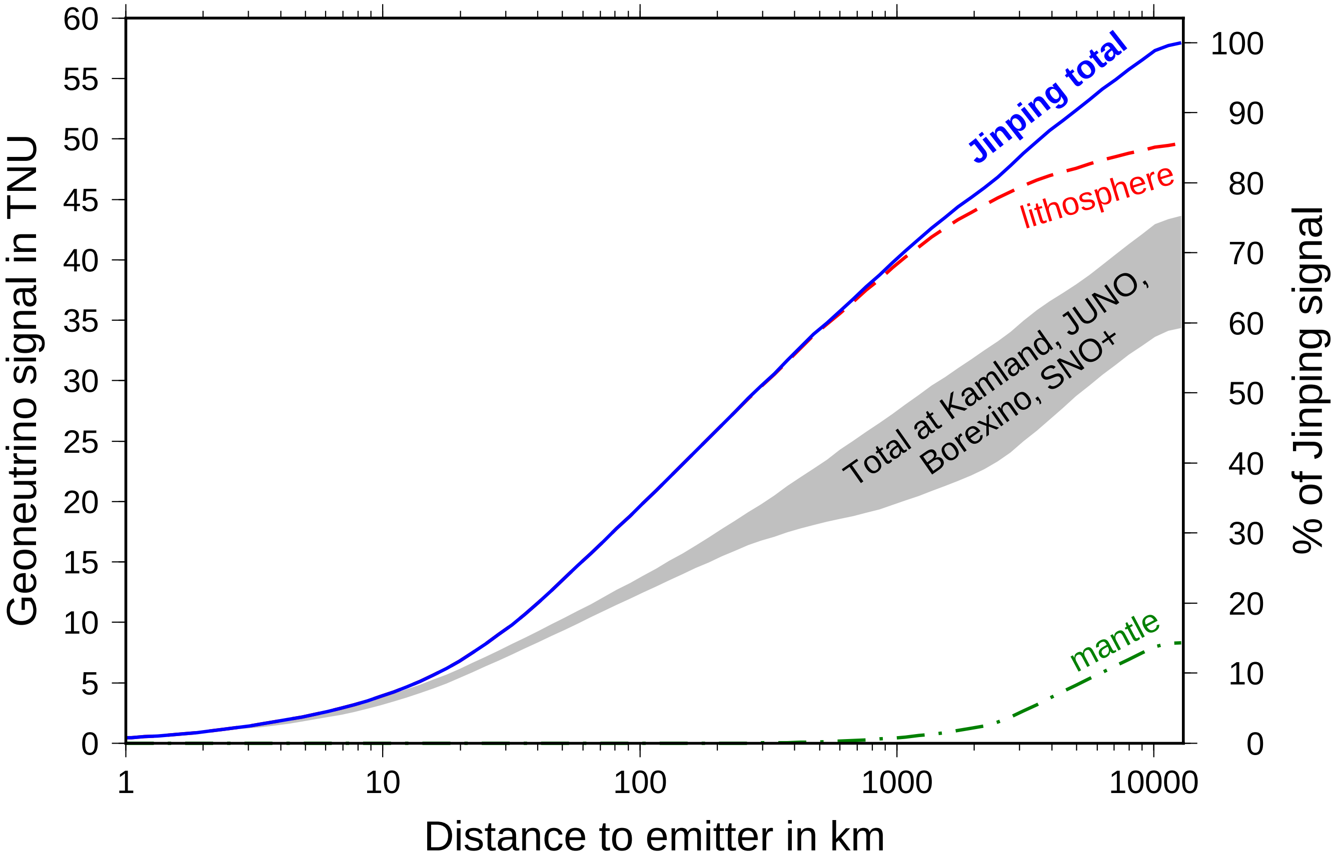
0.27 0.5%	0.49 0.9%	0.80 1.4%	0.56 1.0%	0.27 0.5%	0.12 0.2%
0.38 0.7%	1.2 2.0	13.2 23%	2.3 3.9%	0.45 0.8%	0.19 0.3%
0.34 0.6%	0.94 1.6%	3.7 6.4%	1.5 2.7%	0.42 0.7%	0.18 0.3%
0.19 0.3%	0.33 0.6%	0.46 0.8%	0.39 0.7%	0.24 0.4%	0.14 0.2%

XX	TNU flux from Lithosphere
YY%	% contribution to total Litho.

23% of signal from
“Jinping” tile

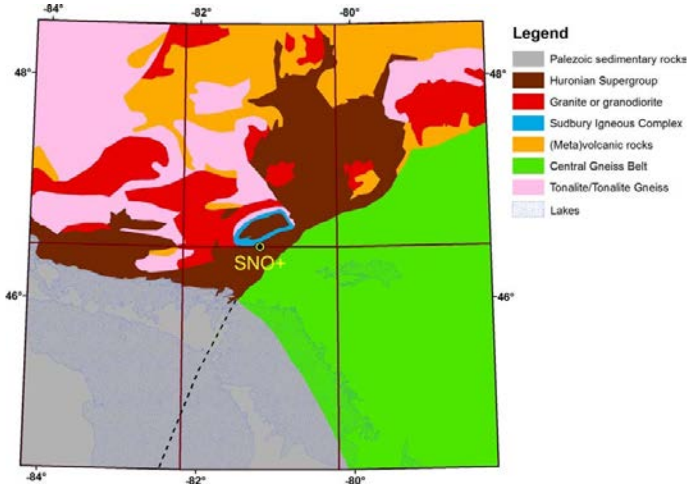
54% of signal from
“near-field lithosphere”
(6º lon × 4º lat region)

Local geonu flux

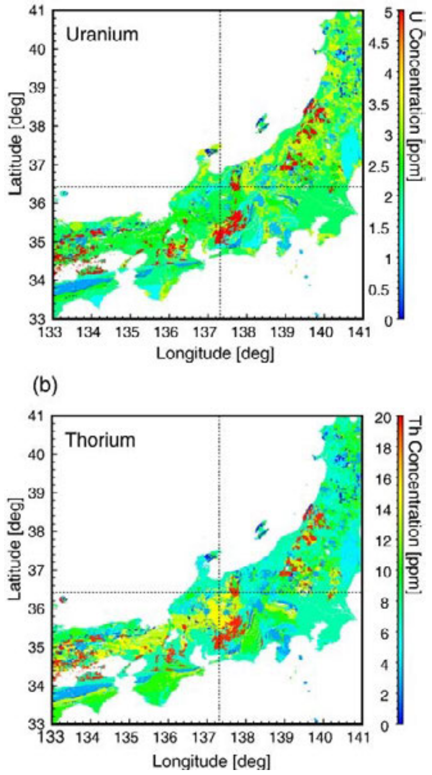


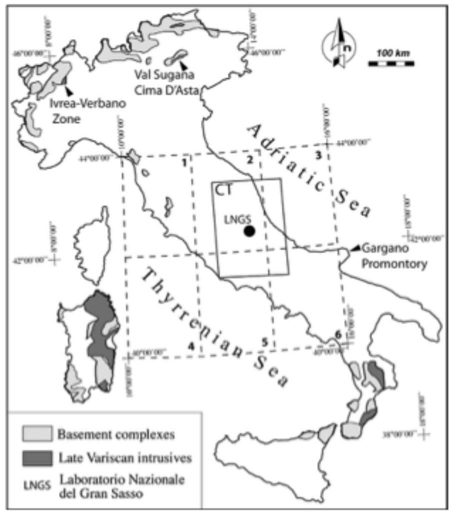
Studies of near-field lithosphere…

around SNO+ (*Huang et al. 2014, Strati et al.*)



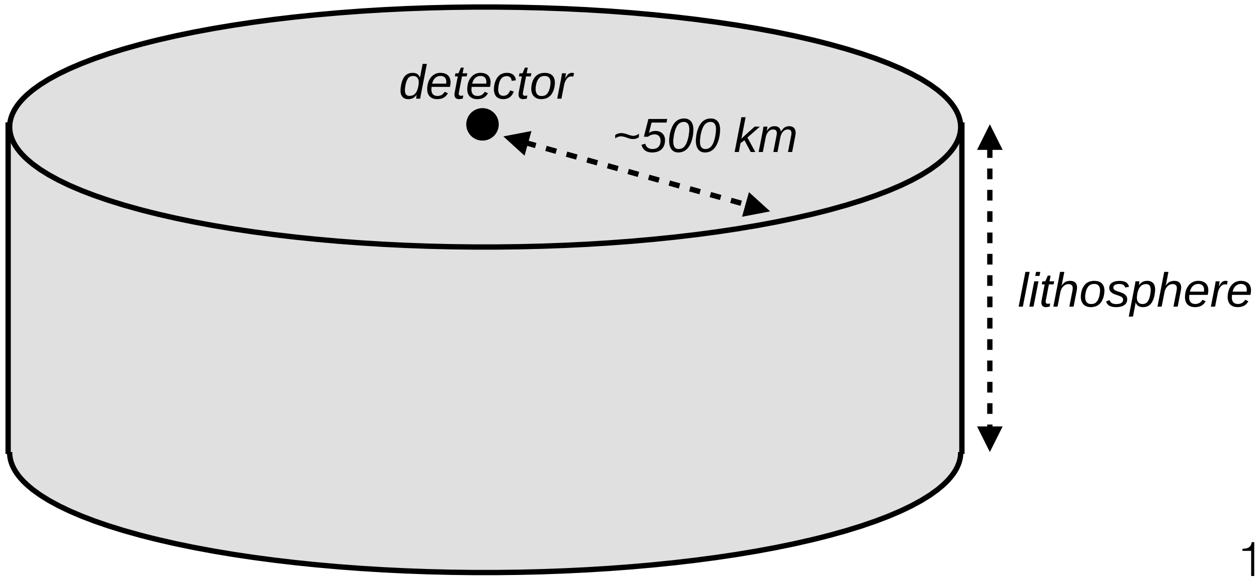
around KamLAND (*Enomoto et al. 2007*)





around Borexino (*Coltorti et al. 2011*)

We need refined models of lithosphere around JUNO and Jinping



Geo* reference model for China

- Refined "voxelated" model of lithosphere
- To each voxel, assign material density, V_p and V_s seismic speeds, heat flux (at surface), chemical composition, …

Results from detectors combined

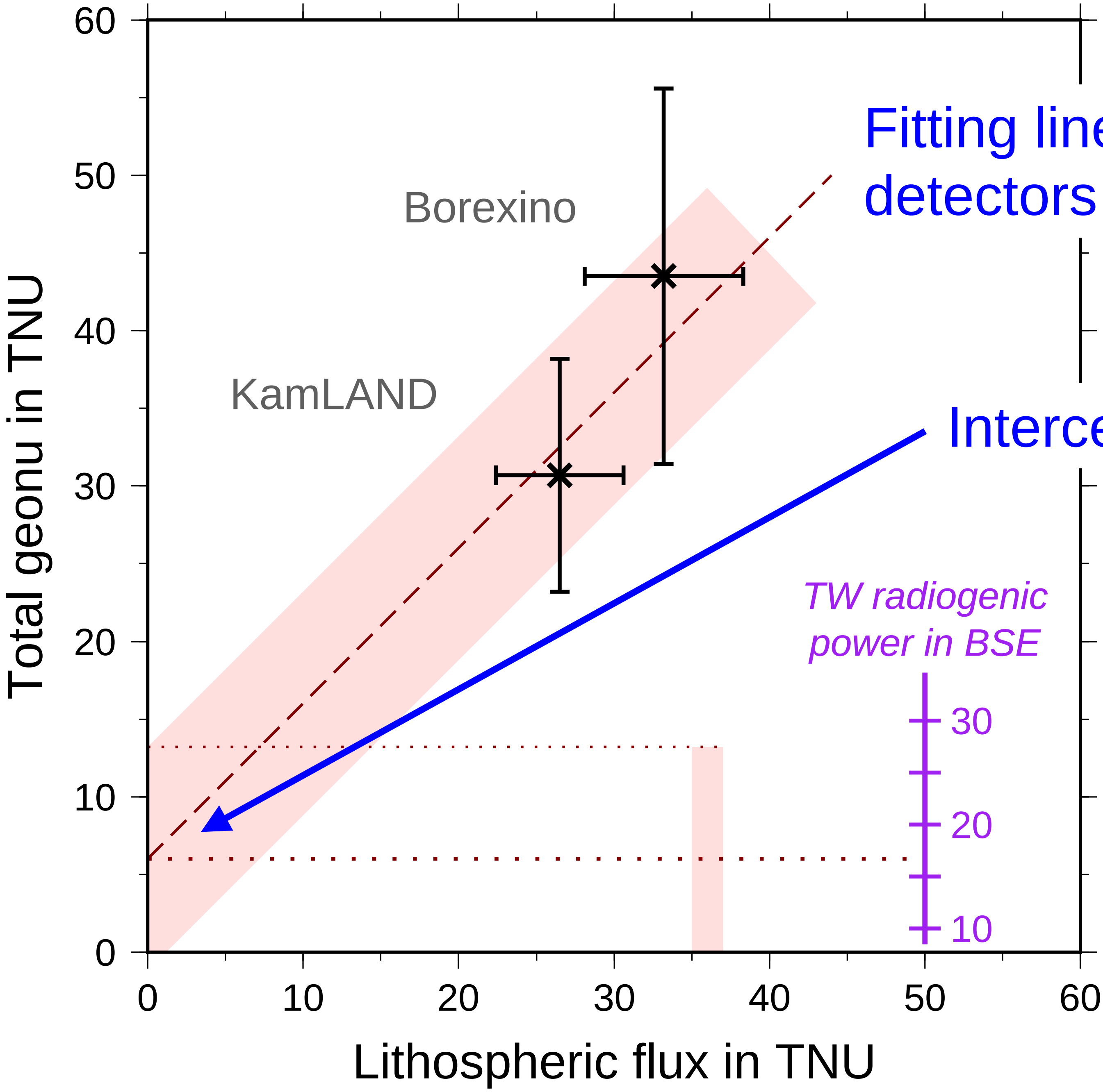
~~Current~~ status

The night before

Measured
by physics:

Total geonu

KamLAND 2013
Borexino 2015
measurements



Fitting line of slope 1:
detectors see the same mantle

Intercept is mantle signal

Predicted from geology: **Lithosphere**
Emission model

Result:

Mantle = 6.0 ± 7.2 TNU

8–27 TW radiogenic
power in the Earth

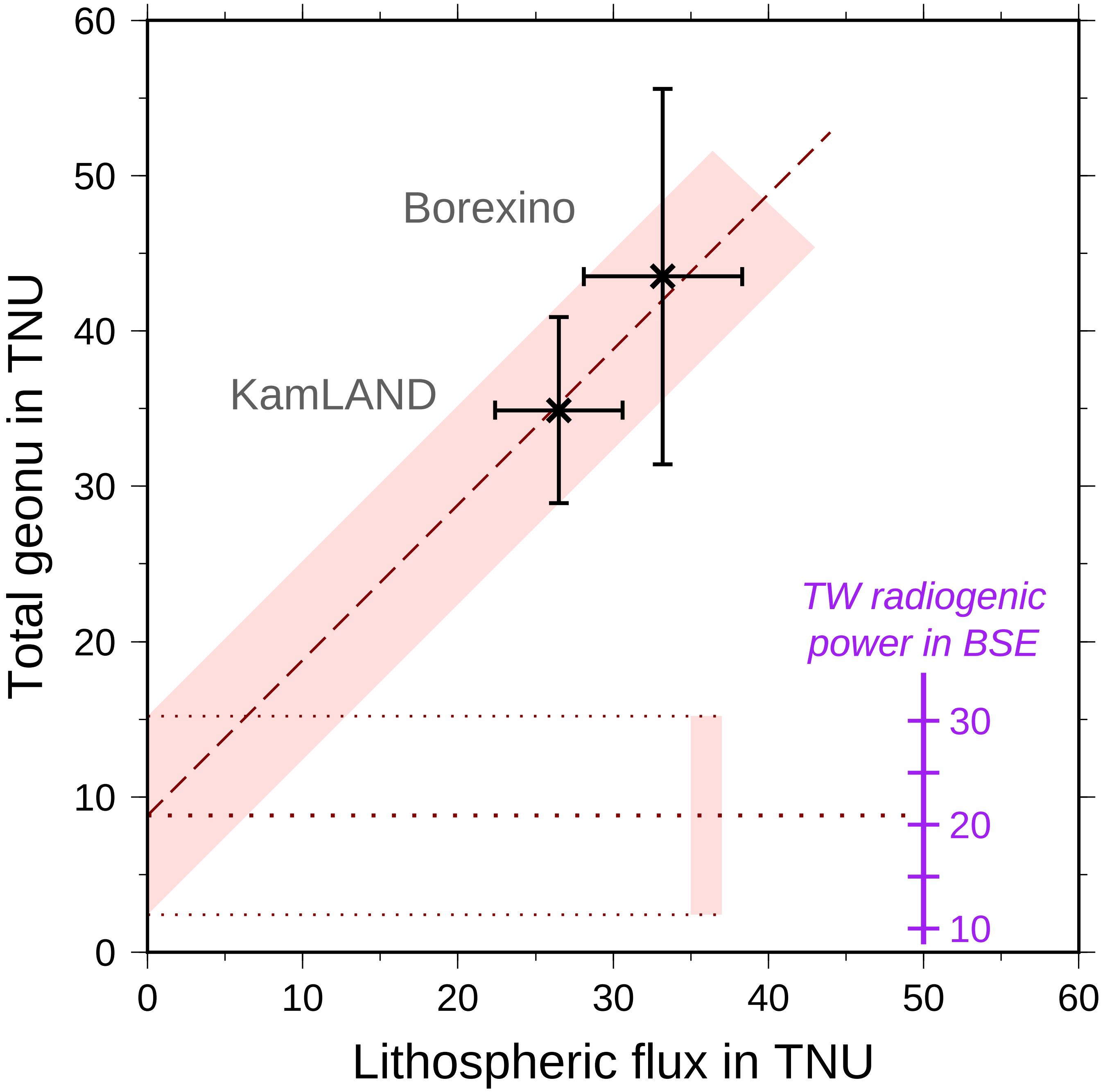
Results from detectors combined

Current status

Measured
by physics:

Total geonu

KamLAND **2016**
Borexino 2015
measurements



Predicted from geology: **Lithosphere**
Emission model

Result:

Mantle = 8.8 ± 6.4 TNU

(72% rel. uncertainty)

Results from detectors combined

Future prospect ~2025

Meaured/expected geov annual count rate

KamLAND	14
Borexino	4.2
SNO+	20
JUNO	400
Jinping	100

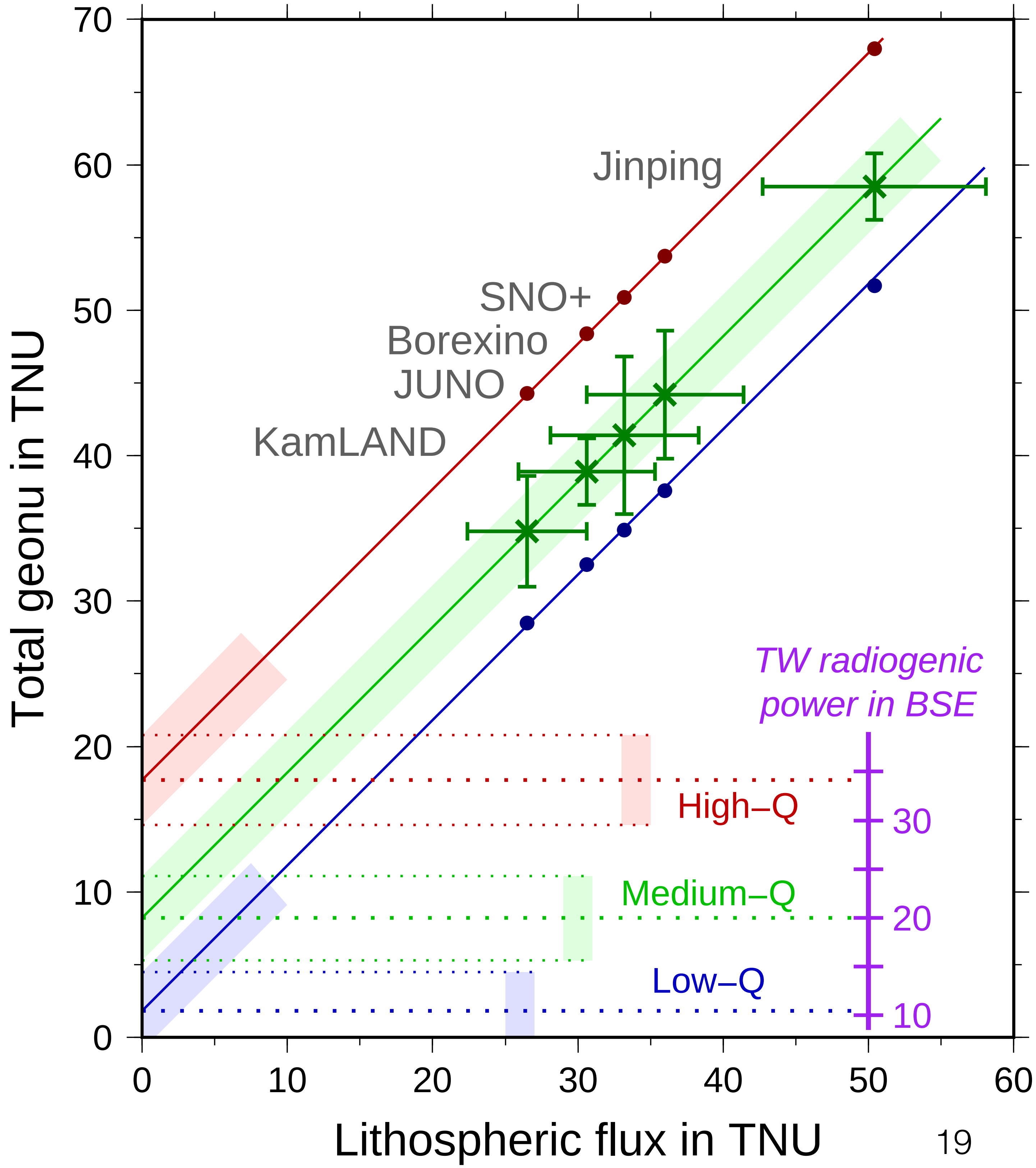
Existing geoneutrino experiments are limited by low statistics, continue to collect data.

What can we expect around 2025 with results from 5 experiments?

- **KamLAND**
  Watanabe talk Jan-2015: expected to reach **11%** uncertainty of geoneutrino measurement in 7 more years of data taking
- **Borexino**
  Extrapolating the statistics, we predict uncertainty of **13%** after 6 additional years
- **SNO+**
  We estimate measurement uncertainty at **9%** after 6 years
- **JUNO**
  Han et al. 2016: **6%** uncertainty after 5 years of live time
- **Jinping**
  Beacom et al. arXiv:1602.01733: uncertainty of **4%** after exposure of 3 kilotons over 5 years

Results from detectors combined

Future prospect ~2025



Horizontal axis

Lithospheric flux from emission model

Vertical axis

Simulated measurement:

- Total flux from emission model
- Uncertainty est. based on previous slide

Mantle result:

High-Q: 17.7 ± 3.1 TNU

Med-Q: 8.2 ± 2.9 TNU

Low-Q: 1.8 ± 2.7 TNU

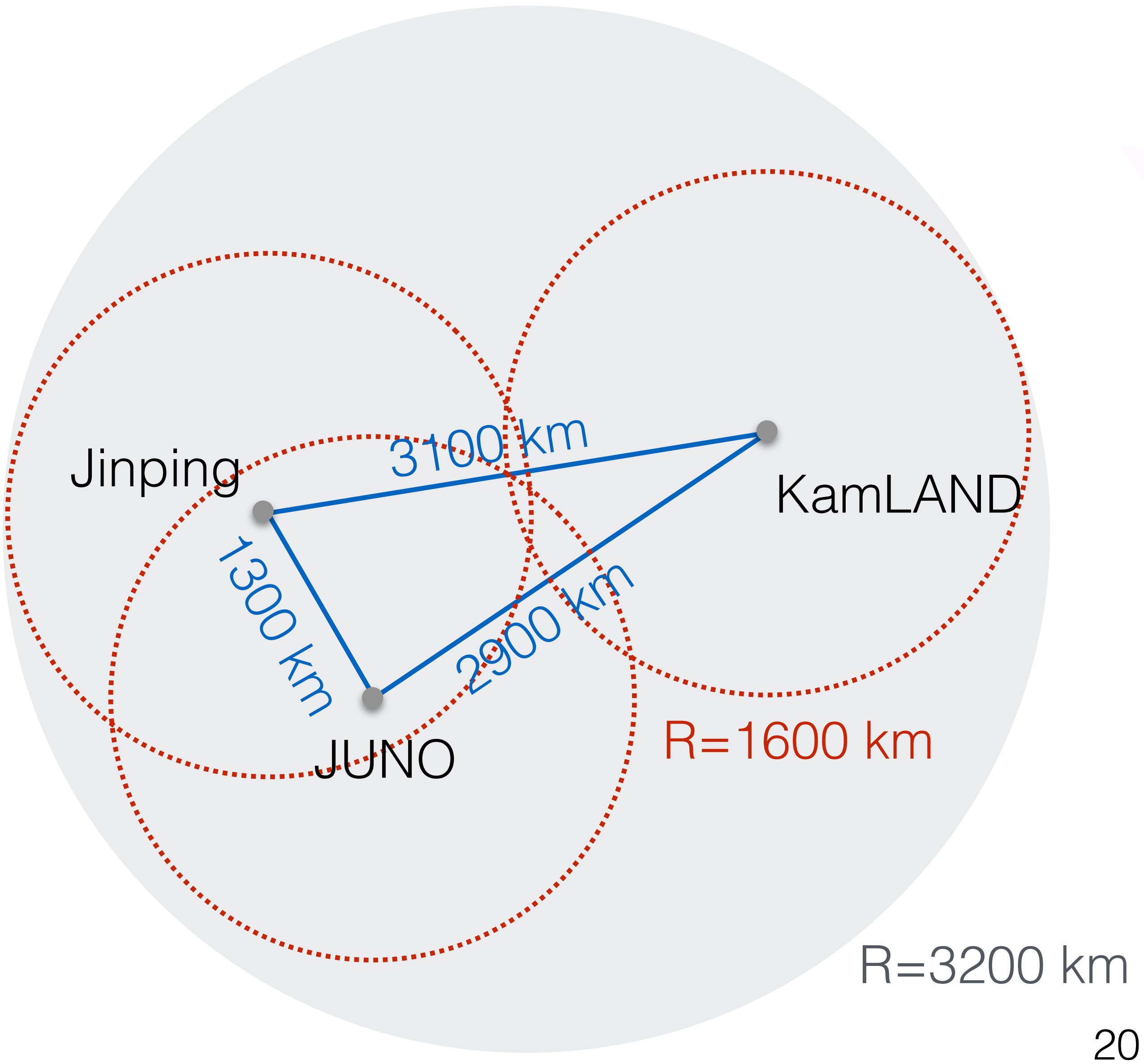
Study lithosphere with geoneutrinos?

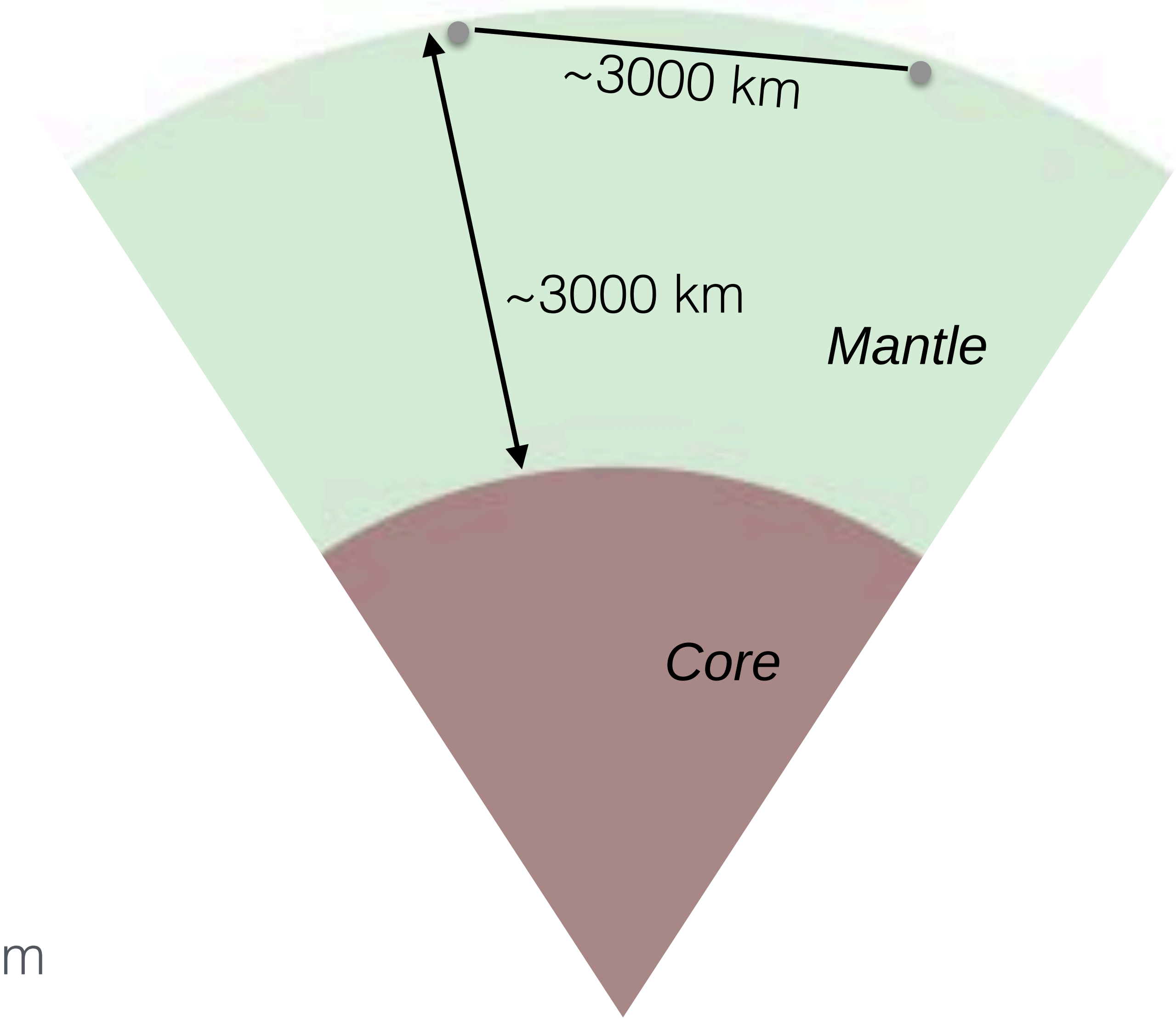
1 detector

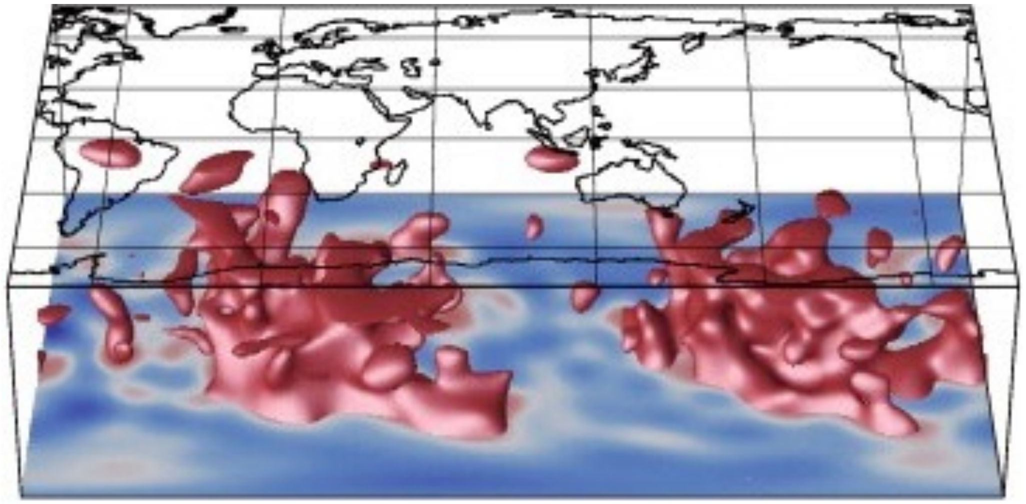
- We measure total geoneutrino flux.
- We “know” the *lithospheric* flux and resolve the *mantle*. (or vice versa)

>1 detectors combined

- Assuming they “see” the same *mantle*, we can test the lithospheric model.





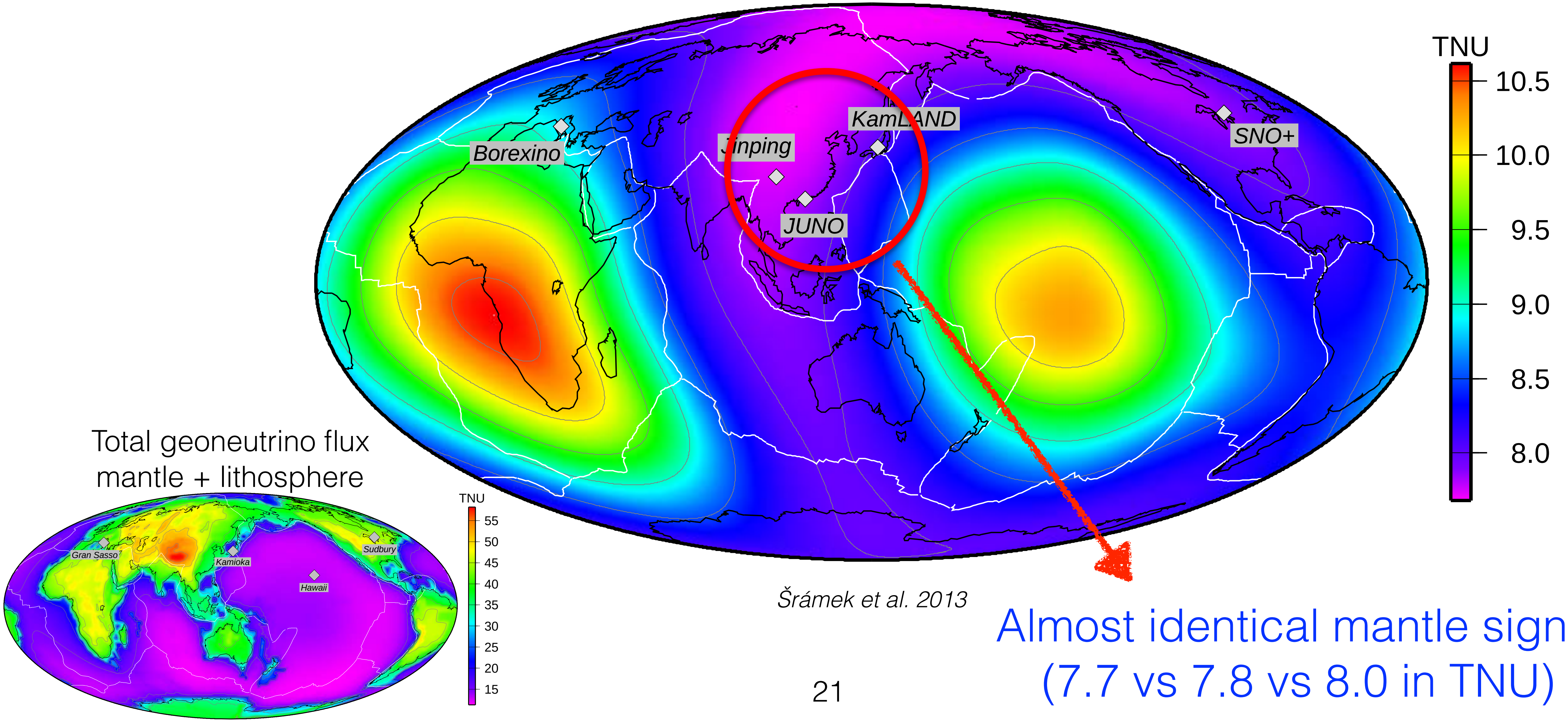


Bull et al 2009, after Ritsema et al 1999

Seismically slow “red” regions in the deep mantle

3-D structure of enriched mantle?

Geoneutrino flux from mantle with enriched “piles”



Šrámek et al. 2013

Total geoneutrino flux
mantle + lithosphere

Almost identical mantle signal
(7.7 vs 7.8 vs 8.0 in TNU)

Testing regional lithosphere

$$\begin{array}{lllllll} G_{1,tot} & = & G_{mantle} & + & G_{3,litho\text{-}far} & + & G_{1,litho\text{-}reg} \\ G_{2,tot} & = & G_{mantle} & + & G_{3,litho\text{-}far} & + & G_{2,litho\text{-}reg} \\ G_{3,tot} & = & G_{mantle} & + & G_{3,litho\text{-}far} & + & G_{3,litho\text{-}reg} \end{array}$$

same for all 3

fixed model

- Measurement
- Mantle: unknown, same for all
- Far lithosphere: fixed
- Regional lith.: Fit to geov data

3 measurements
4 unknowns
1 constraint … minimization of misfit between a priori and tuned regional model