Geological models for geoneutrino prediction at JUNO:

uncertainties and weak points

Ondřej Šrámek

Department of Geophysics,
Charles University, Prague, Czech Republic

22 July 2017

Presented at Continental margin in South China: Multidisciplinary frontiers in neutrino geoscience
on 21–23 July 2017 at Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China

Geoneutrinos

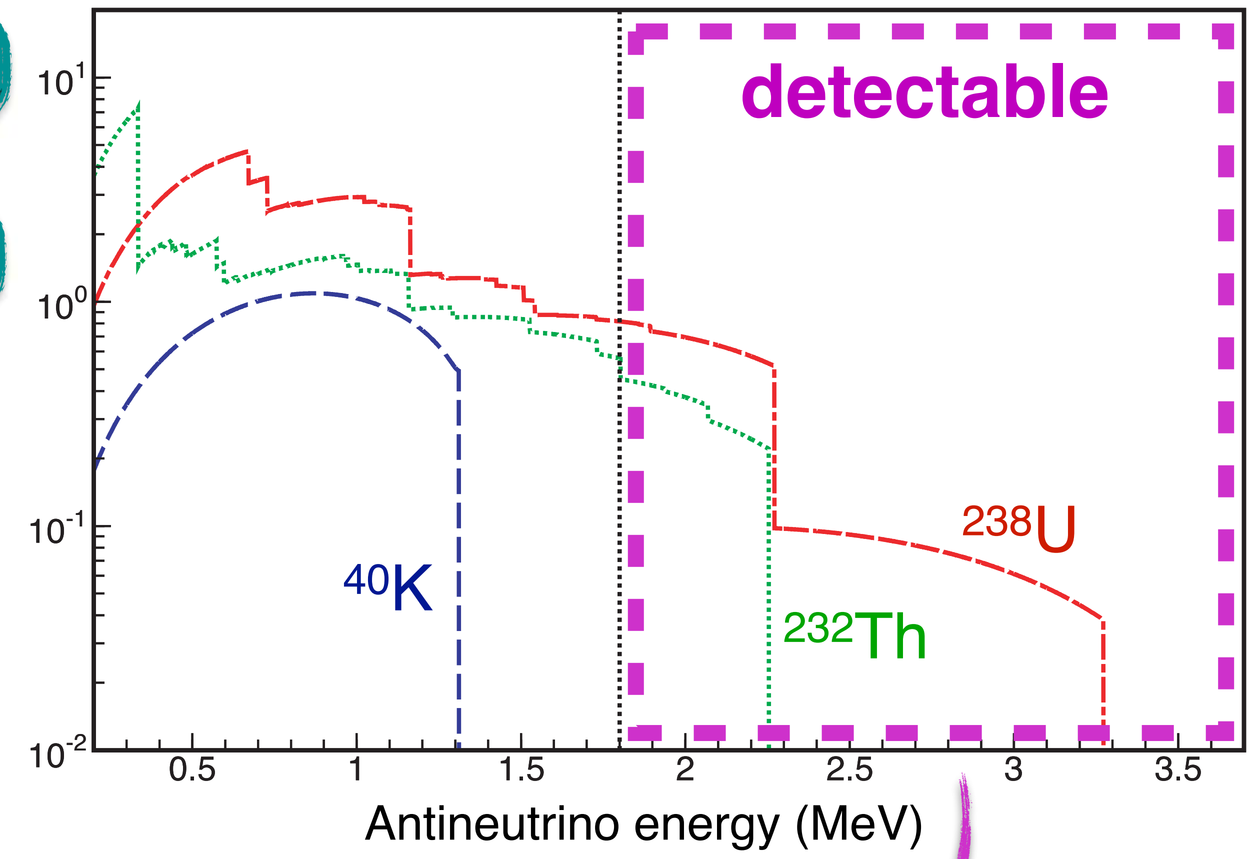
$$^{238}_{92}\mathrm{U} \longrightarrow \; ^{206}_{82}\mathrm{Pb} + 8\alpha + 6e^- + 6\bar{\nu}_e + 51.698\,\mathrm{MeV}$$

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

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

Energy per decay chain
~20% carried by geoneutrinos
~80% heat the Earth

Geoneutrino spectra



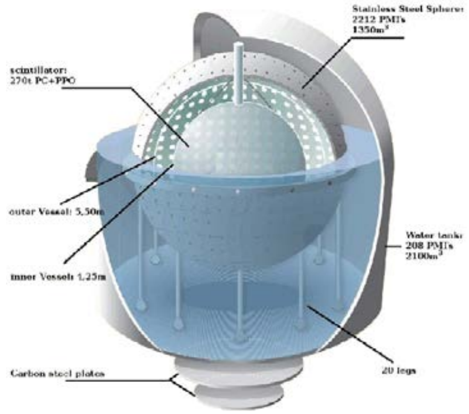
Measuring composition of the Earth using particle physics

How much radiogenic power in the mantle?

Independent test of crustal models?

What is Earth's Th/U ratio?

Geoneutrino detectors

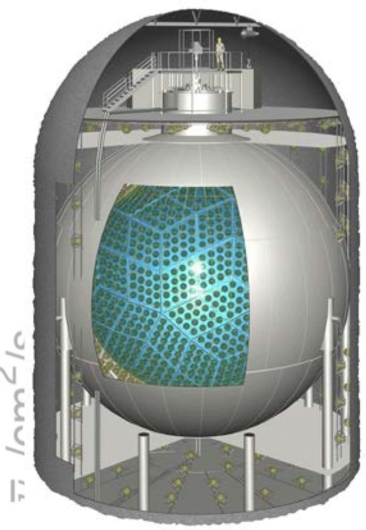


Borexino

0.3 kton
3.7 km.w.e.
running

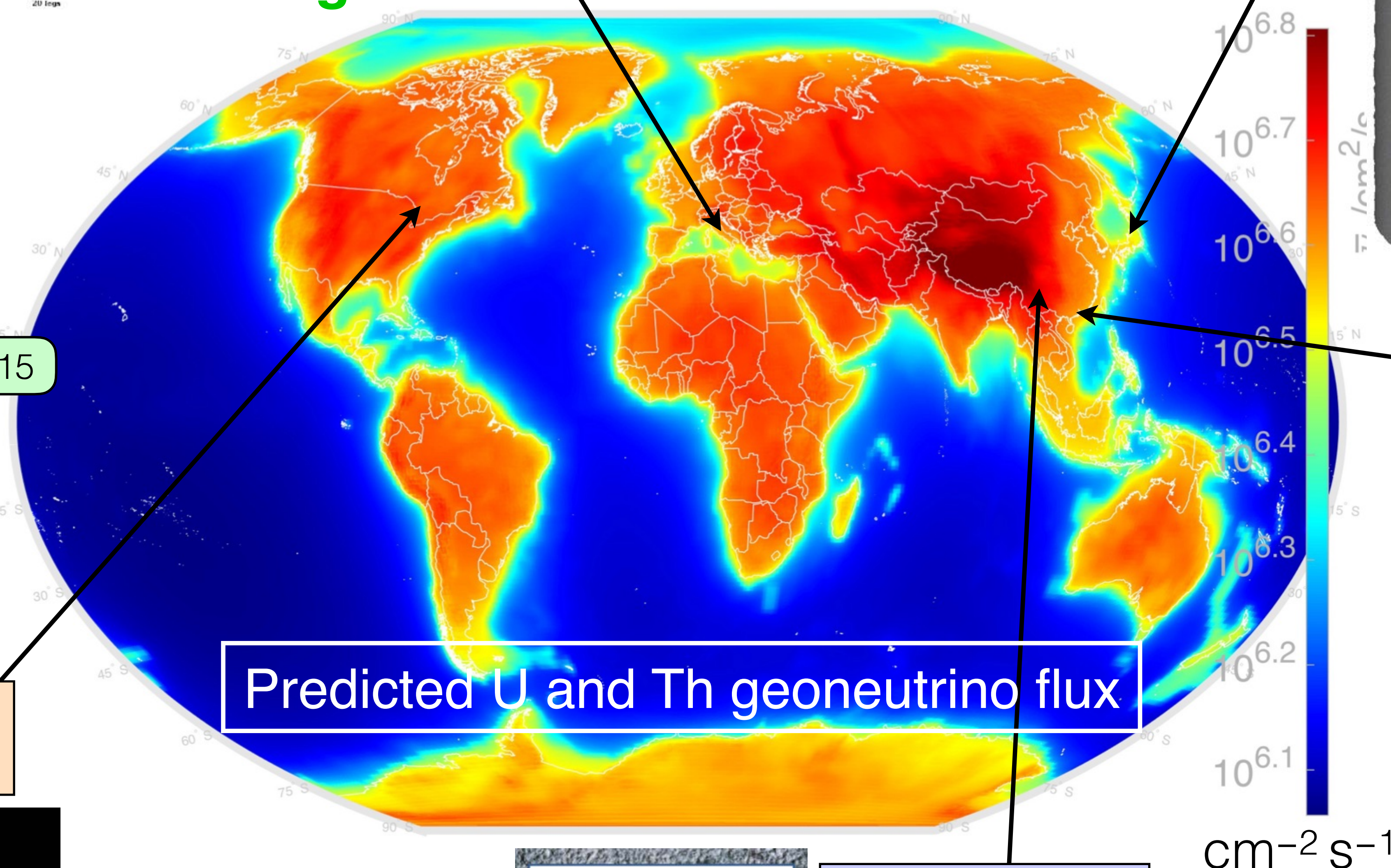
Large (~1 kton)
underground
liquid scintillator
detectors

KamLAND



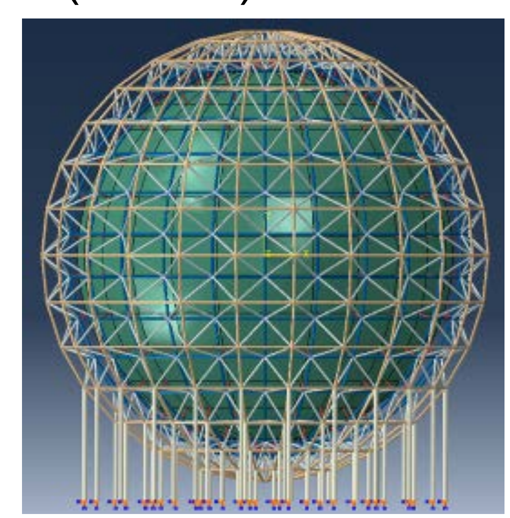
1 kton
2.7 km.w.e.
running

Usman et al. 2015

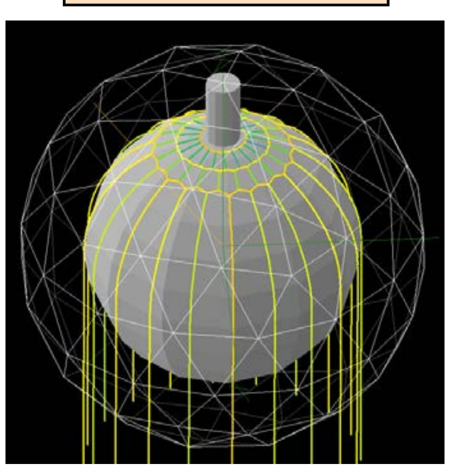


JUNO

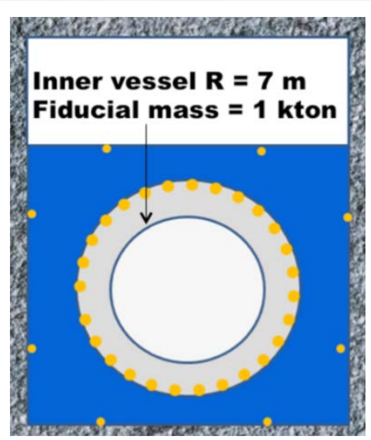
20 kton
1.5 km.w.e.
under constr.
(2020)



SNO+



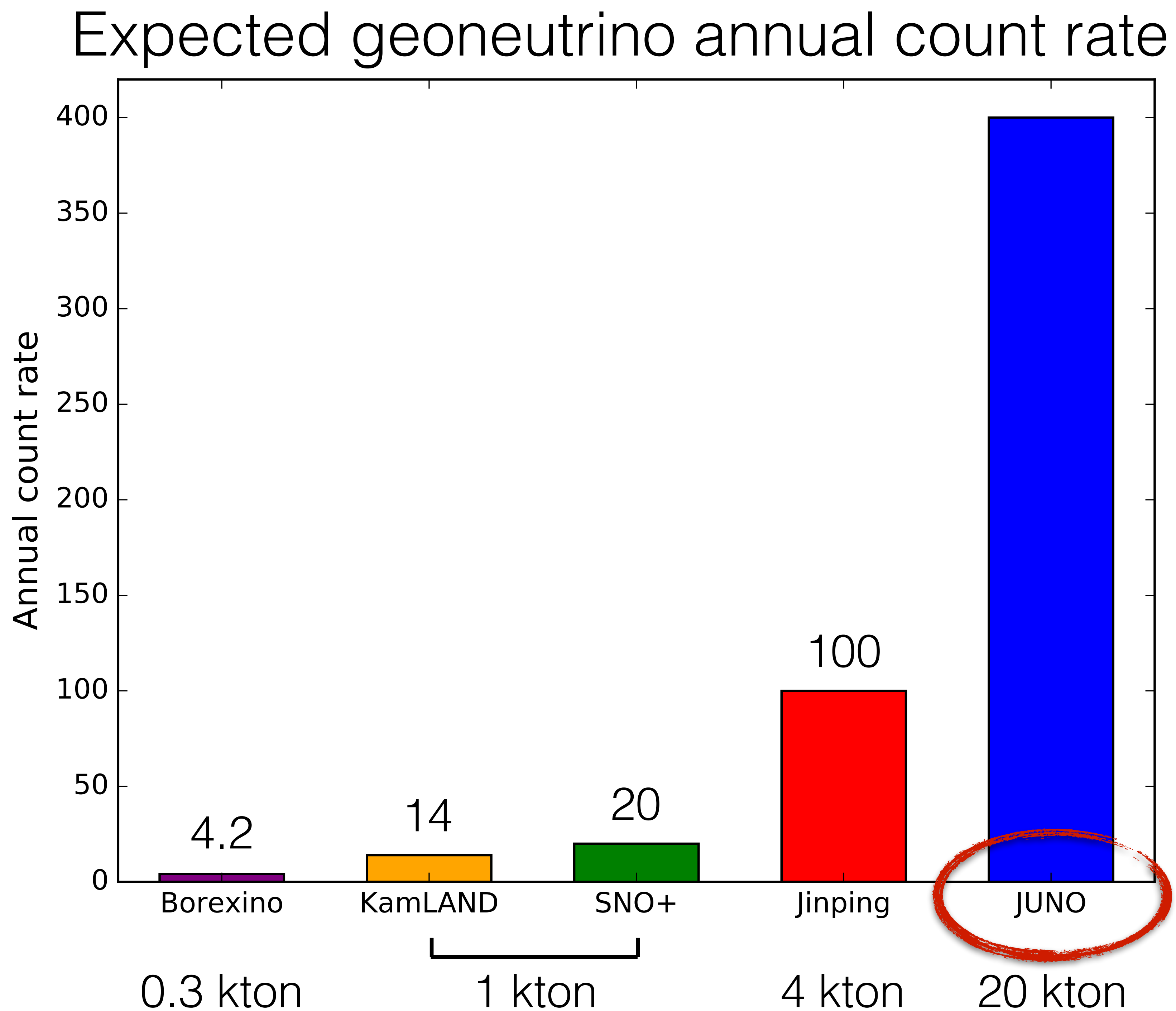
1 kton
5.4 km.w.e.
expected online soon

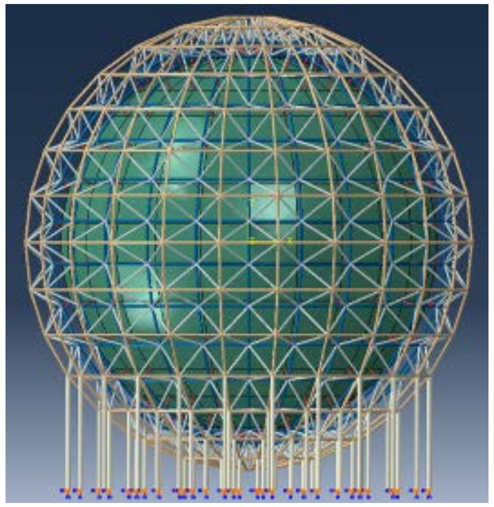


Jinping

4 kton
6.7 km.w.e.
R&D

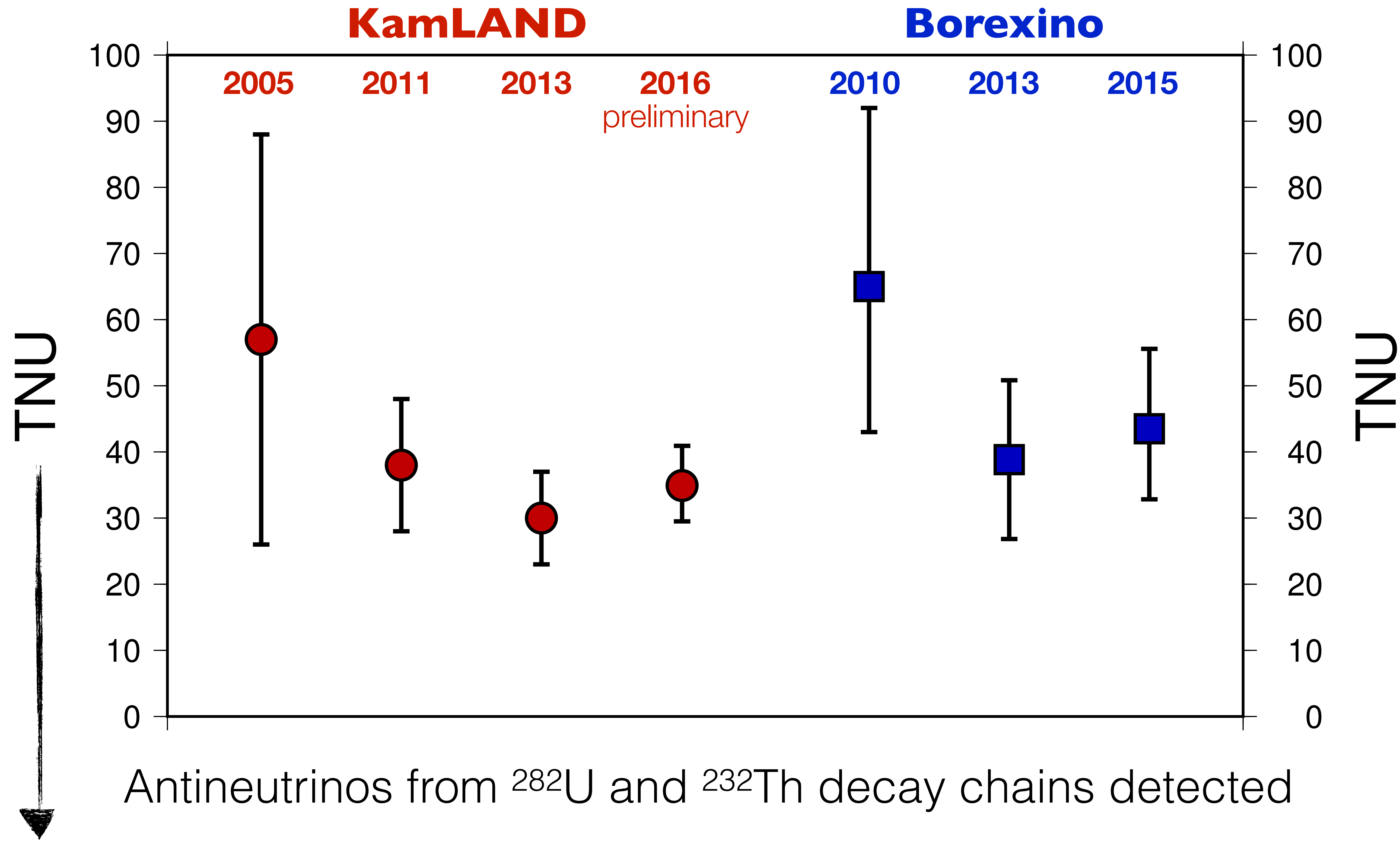
JUNO: 20 kiloton detector





Effect of:
1. Detector size
2. Strength of crustal emission

Current geoneutrino measurements

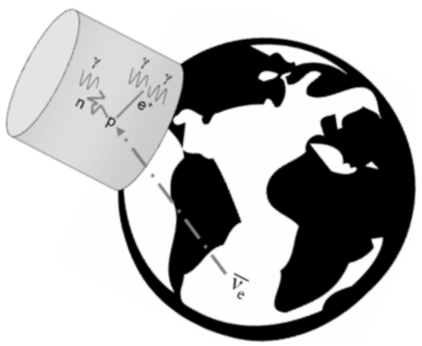


Antineutrinos from ^{282}U and ^{232}Th decay chains detected

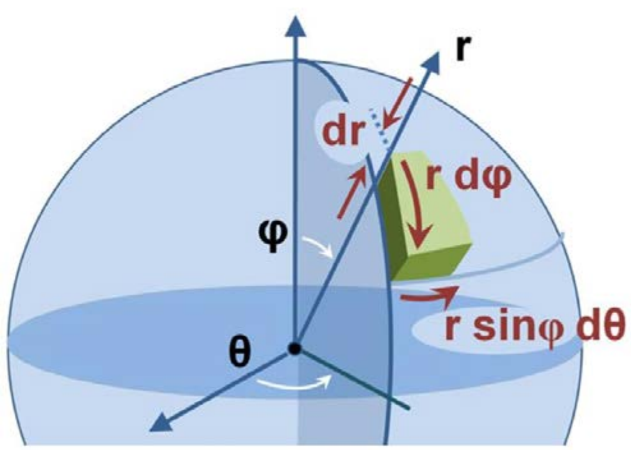
1 TNU ("Terrestrial Neutrino Unit") = 1 event over a year-long exposure of 10^{32} protons

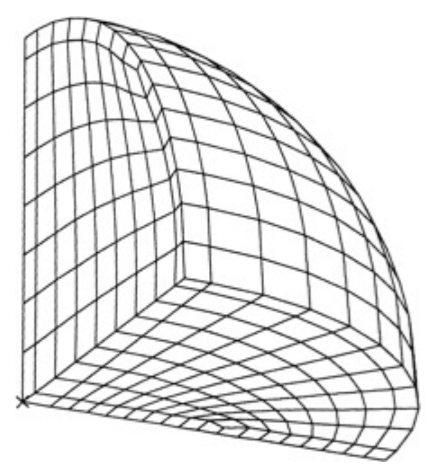
Predicting geoneutrino flux

Antineutrino flux spectrum $d\Phi/dE_\nu$ at position **r** from a given radionuclide distributed with abundance A in the Earth



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





Inputs from geoscience:

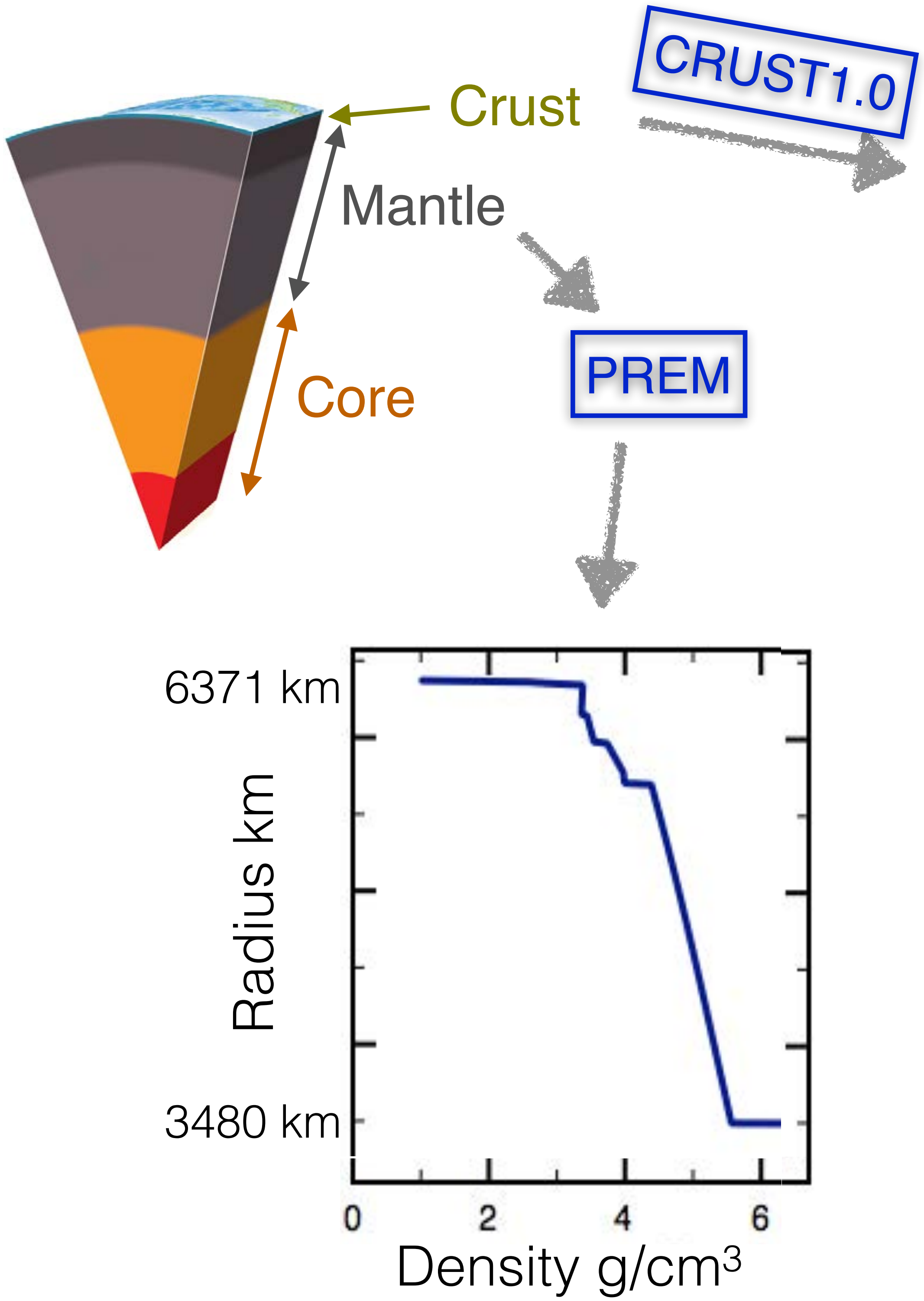
- chemical abundances A:
- density ρ

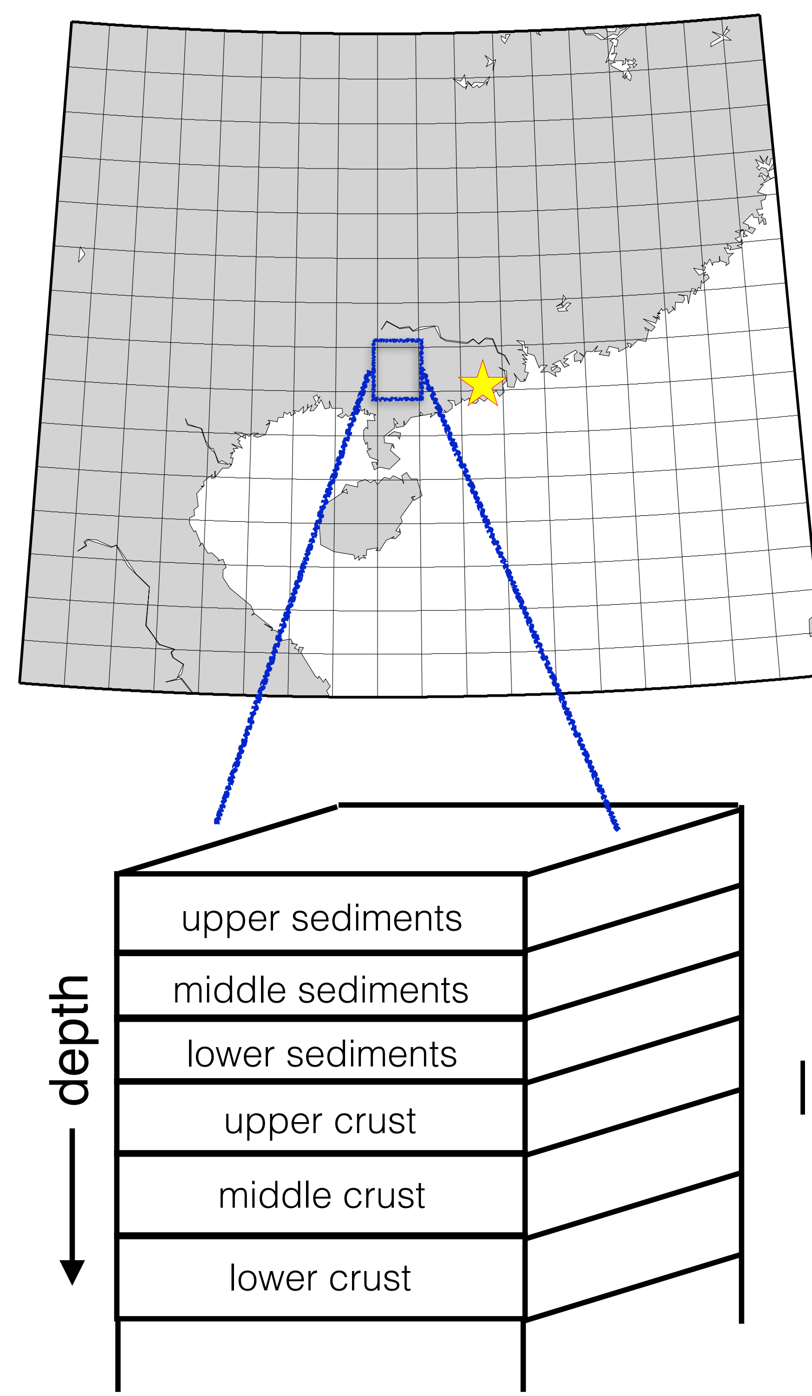
Inputs from nuclear/particle physics:

- decay rate D
- antineutrino intensity spectrum dn/dE_ν,
- antineutrino survival probability P_{ee}

Geoneutrino emission model – structure, density

- 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*)



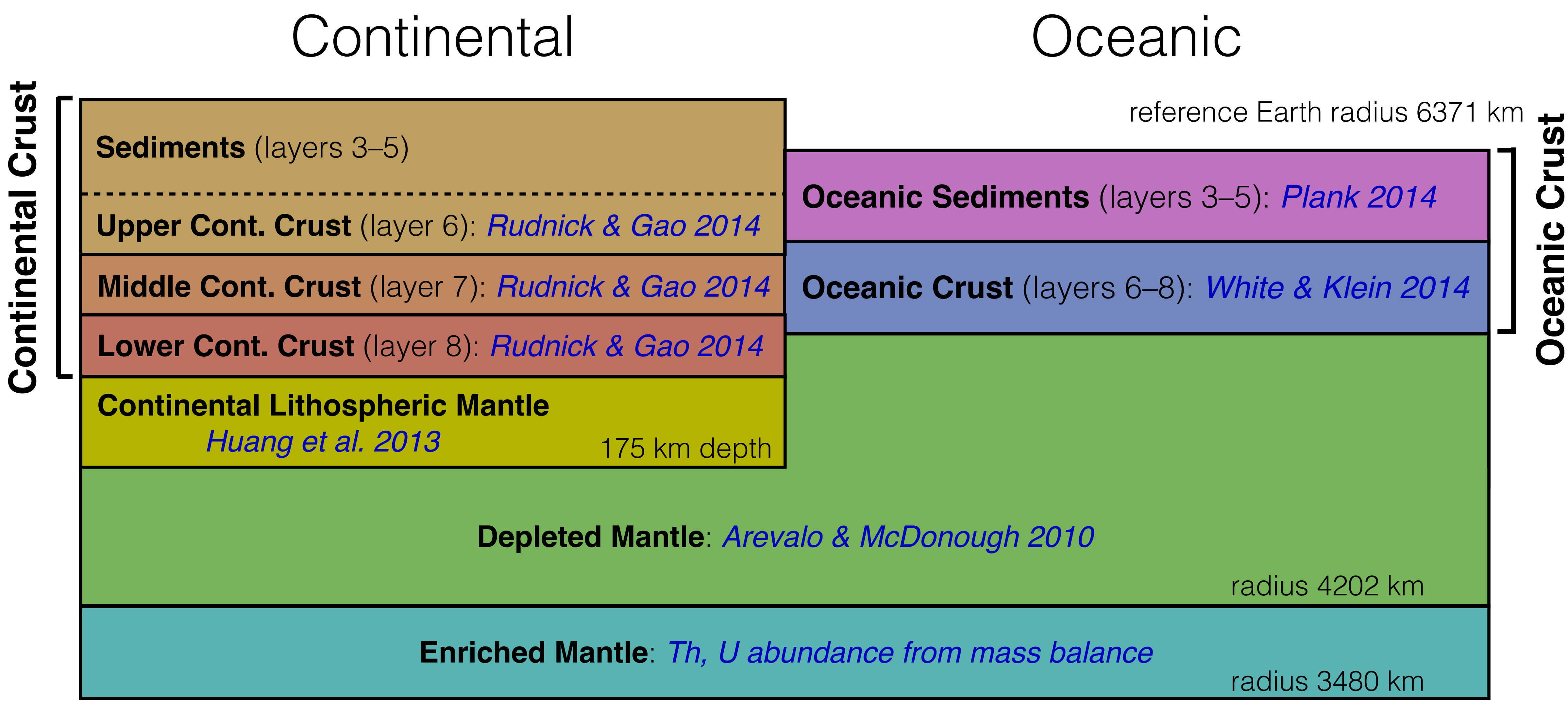


1° lat × 1° lon crustal tiles

Each tile is a layered sandwich

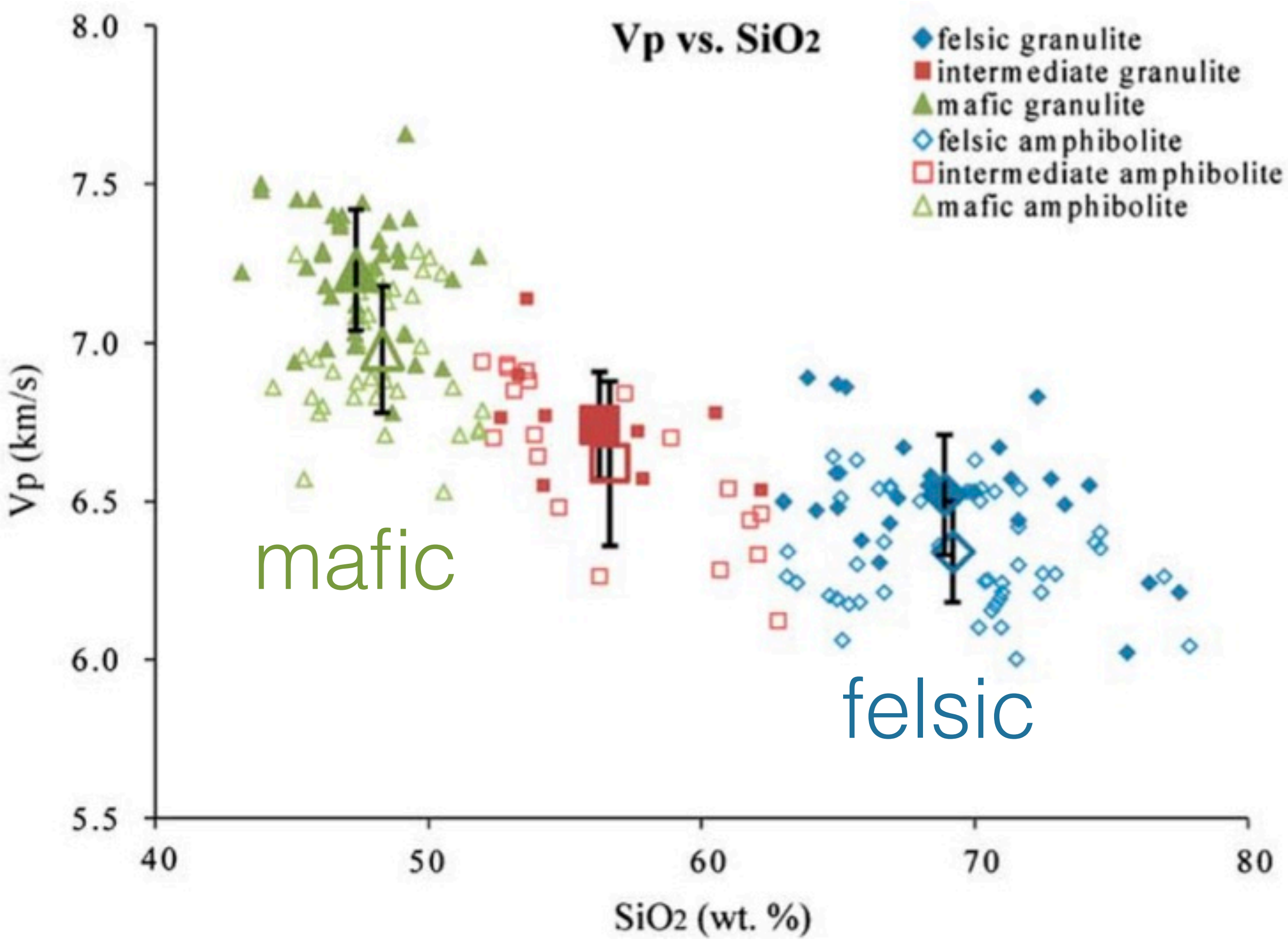
Geoneutrino emission model – Th, U concentrations

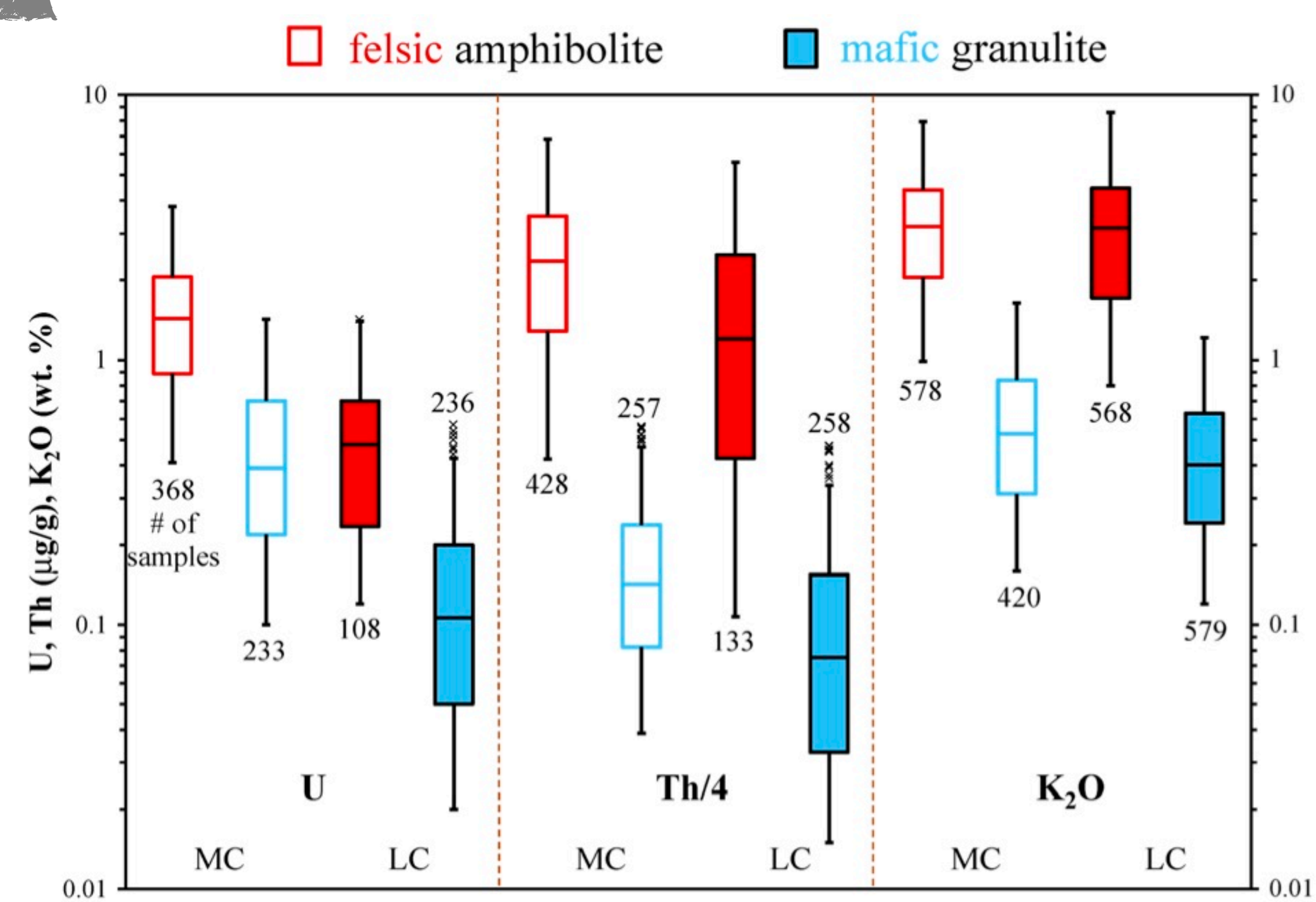
- Assumes negligible Th, U in the core
- Estimate **Silicate Earth** composition … **20 TW Earth? 10 TW? 30 TW?**
- Estimates of **lithospheric** composition – layers of crust, lithospheric mantle below continents … **7–8 TW**
- Remaining T, U in the mantle … *"Silicate Earth = Lithosphere + Mantle"* … **How much radiogenic power in the convecting mantle?**



Deep crust Th, U concentrations

- Use global compositional estimate (what I did)
- Employ V_P to rock type to composition relationships

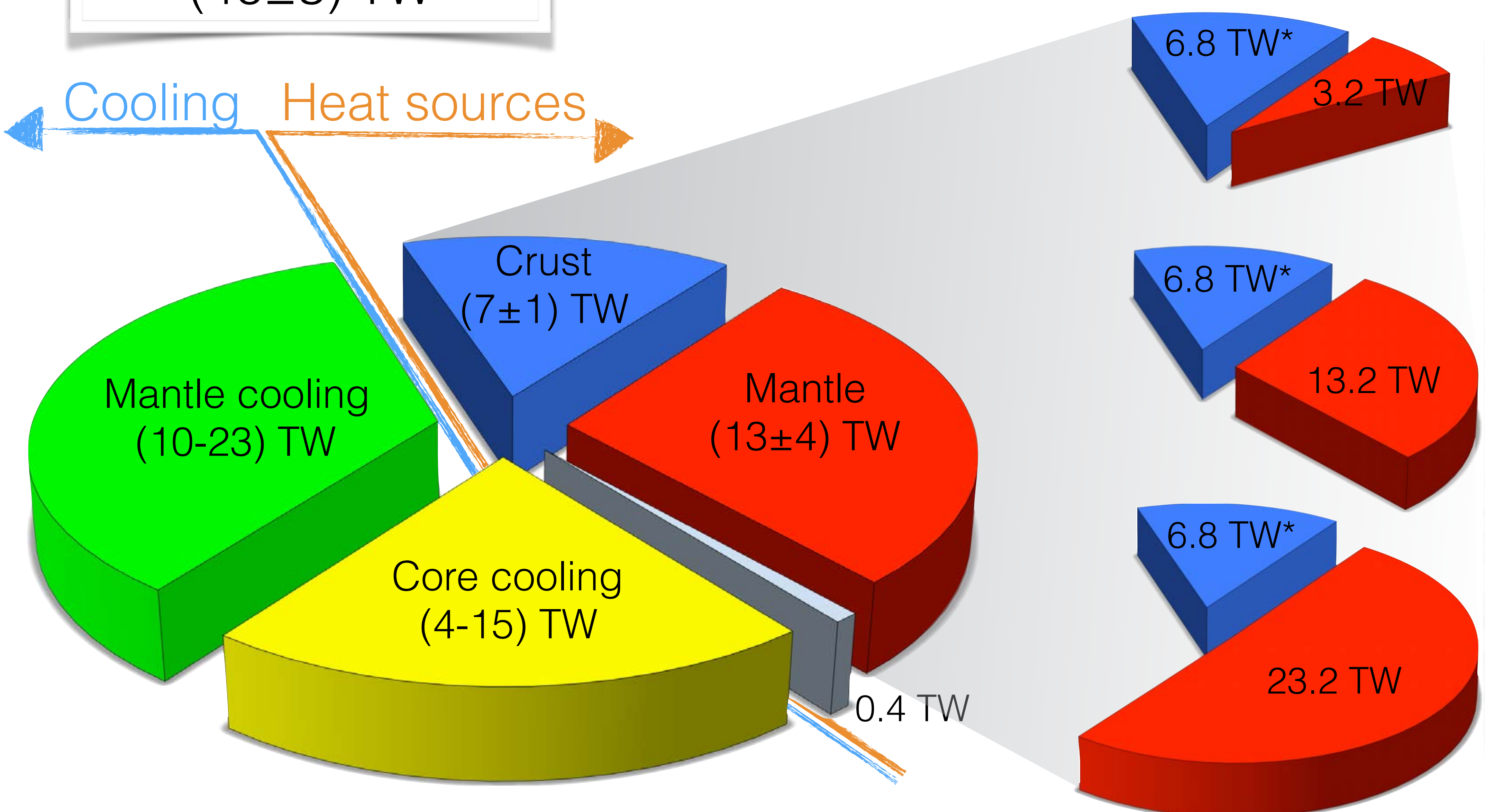




Huang et al. 2013 doi:10.1002/ggge.20129

Earth's energy balance

Surface heat flow
(46±3) TW



BSE: (20±4) TW**

Bulk Silicate Earth (BSE) models:

LowQ
~10 TW

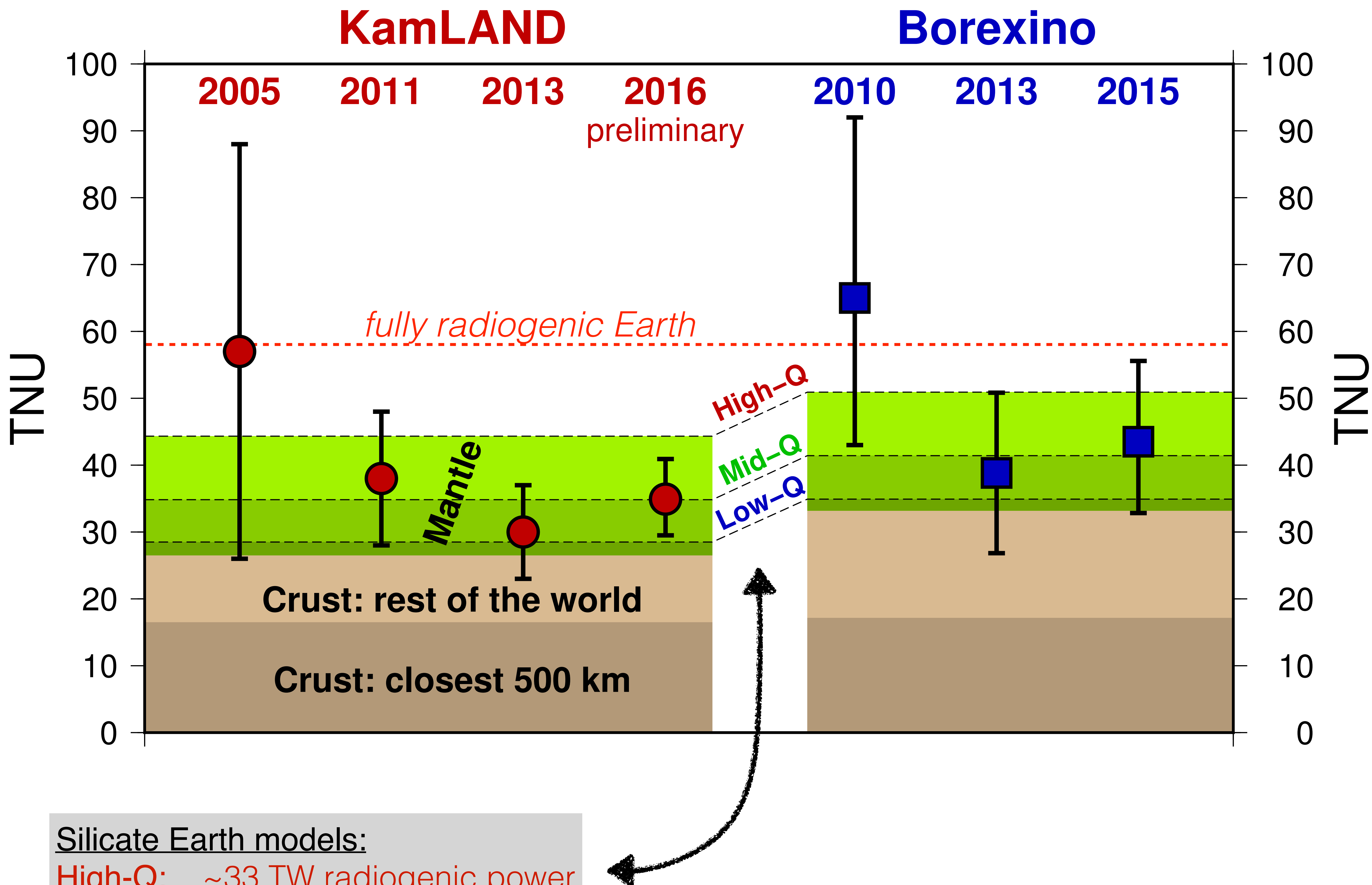
MiddleQ
~20 TW

HighQ
~30 TW

Silicate Earth … models vary by a factor of 3
Mantle … models vary by a factor of 20

*Huang et al. (2013)
**McDonough & Sun (1995)

Geoneutrinos measurements vs. prediction



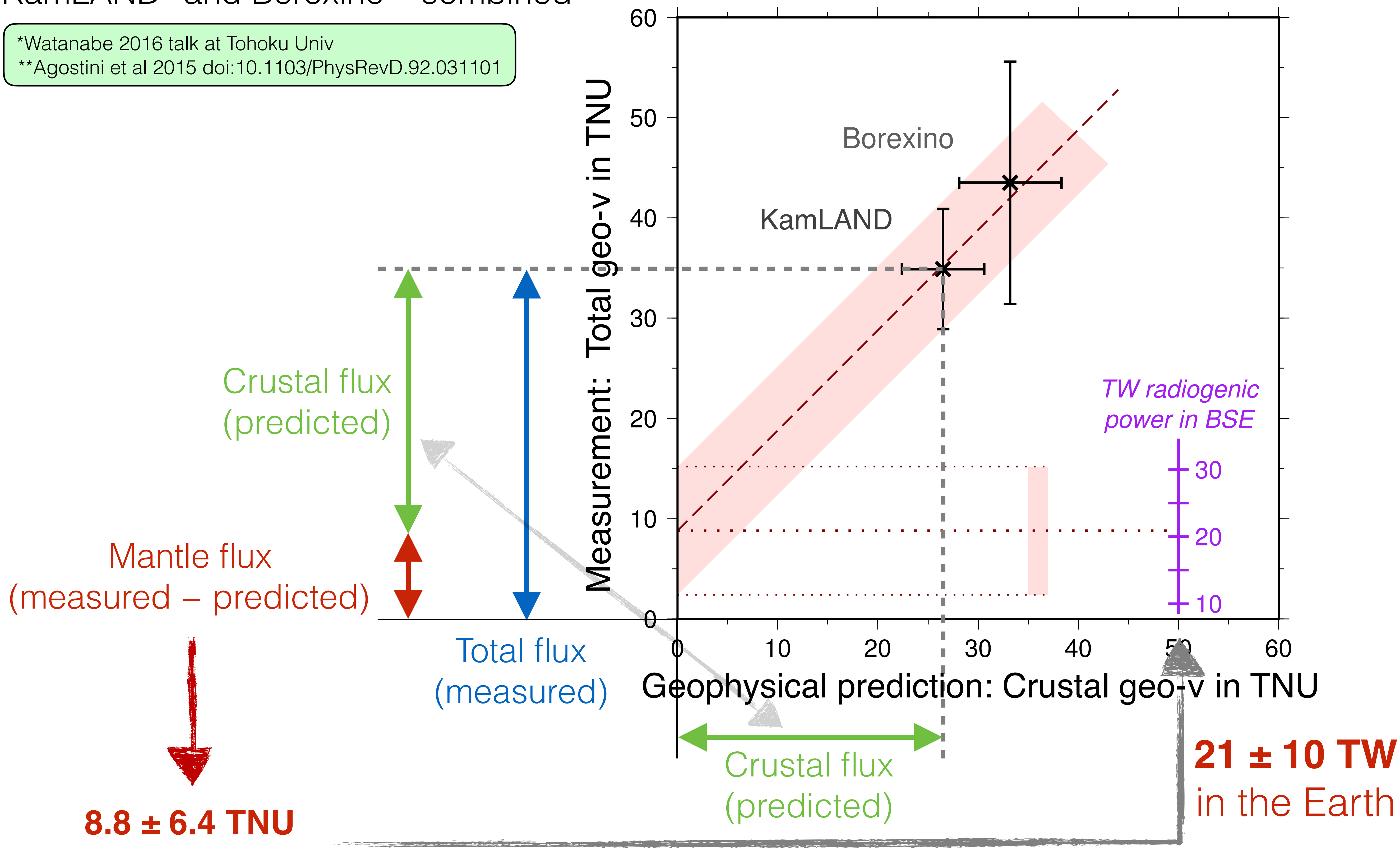
Silicate Earth models:
High-Q: ~33 TW radiogenic power
Middle-Q: ~20 TW
Low-Q: ~11 TW

Geoneutrino prediction from Šrámek et al. 2016 doi:10.1038/srep33034

Measuring the mantle now

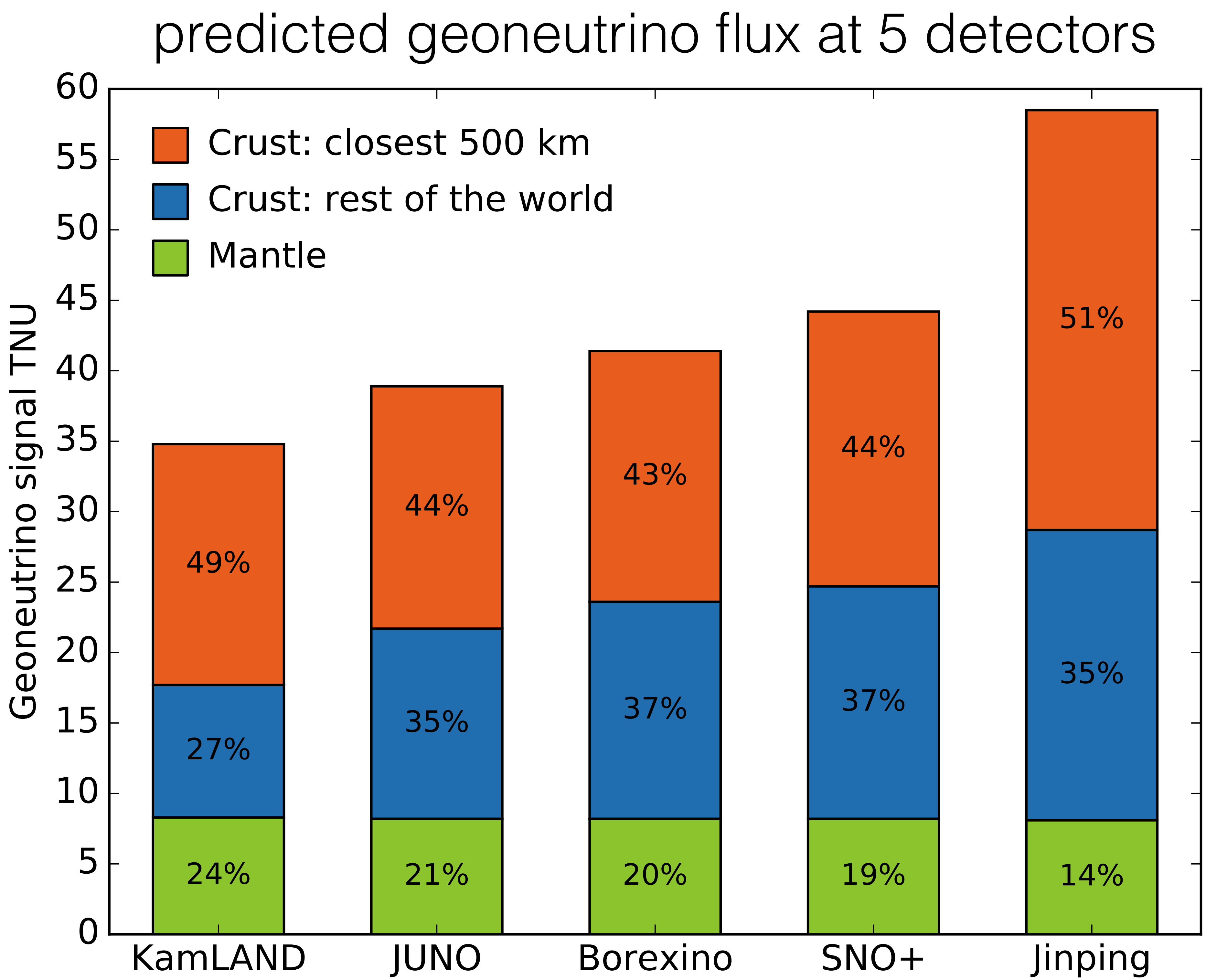
KamLAND* and Borexino** combined

*Watanabe 2016 talk at Tohoku Univ
**Agostini et al 2015 doi:10.1103/PhysRevD.92.031101



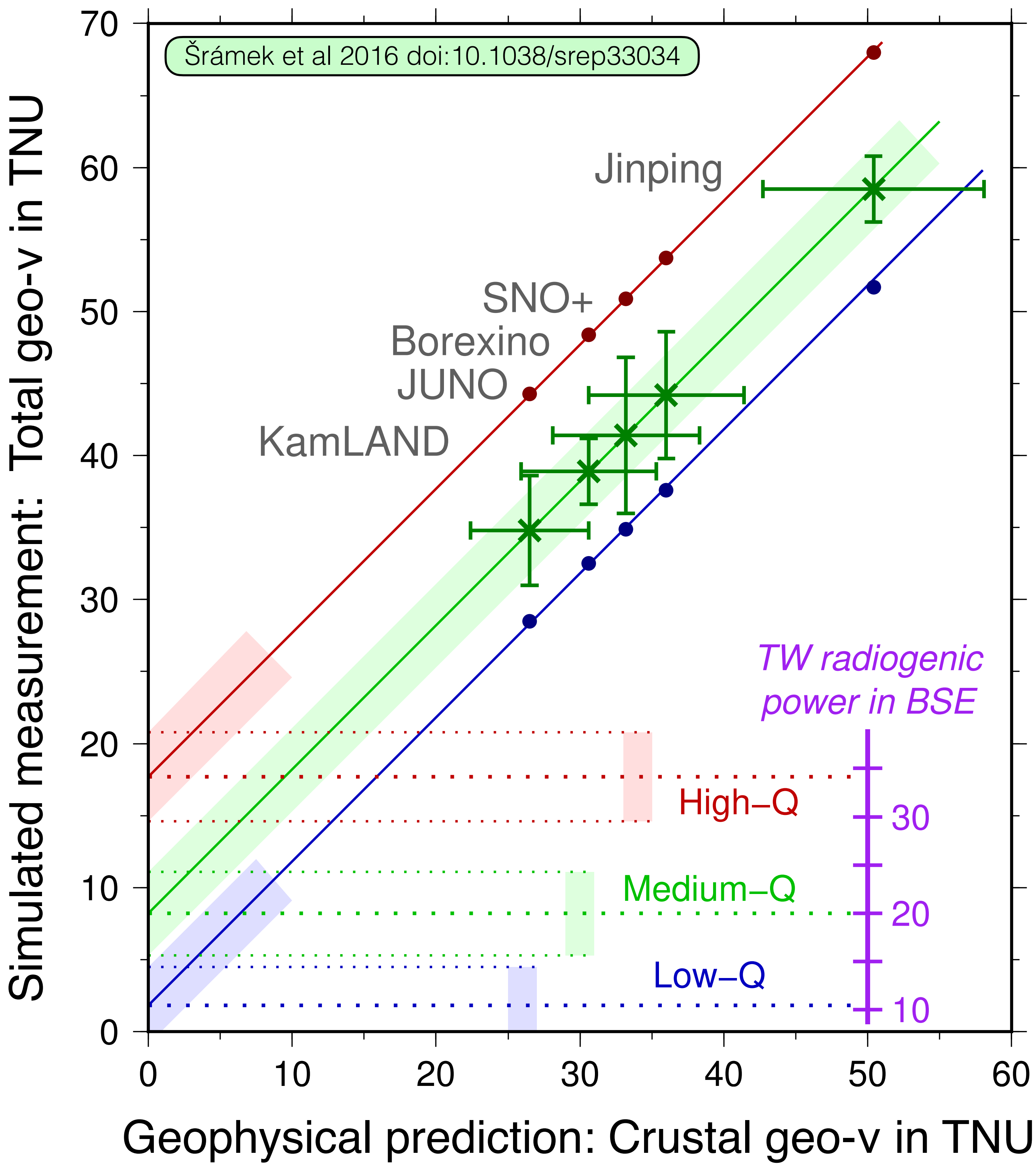
Comparison with LowQ/MiddleQ/High! models

Looking ahead



Šrámek et al 2016 doi:10.1038/srep33034

Measuring the mantle: future prospect



Toward year ≳2026

- Combination of measurements from all detectors expected to tighten limits on mantle heat production

- Challenge for geoscience: Increase precision of crustal prediction to better resolve the mantle.

Abundances of Th, U in emission model

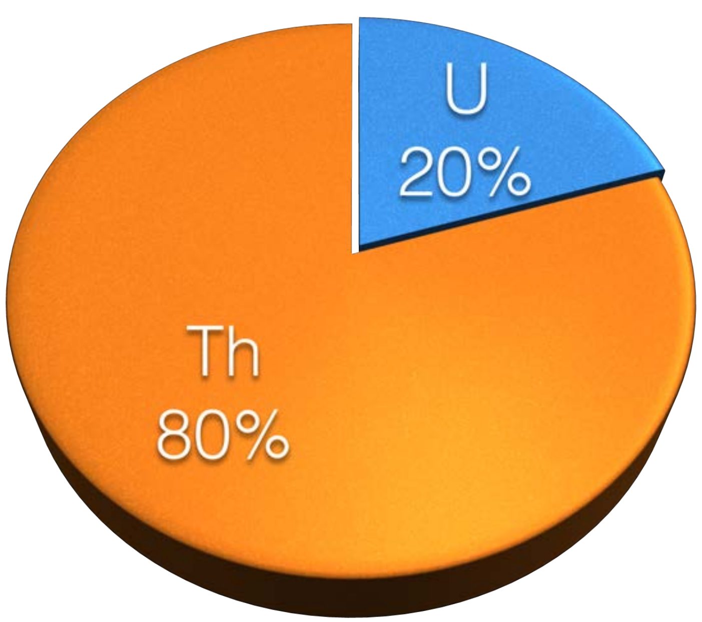
	Th [wt ppm]	U [wt ppm]	Th/U
Bulk Silicate Earth[1]	**0.08**	**0.02**	**4.0**
Upper CC + sediments[2]	10.5	2.7	3.9
Middle CC[2]	6.5	1.3	5.0
Lower CC[2]	1.2	0.2	6.0
Oceanic sediments[3]	8.1	1.7	4.8
Oceanic crust[4]	0.21	0.07	3.0
CLM[5]	0.15	0.033	4.5
Depleted Mantle[6]	0.022	0.008	2.7

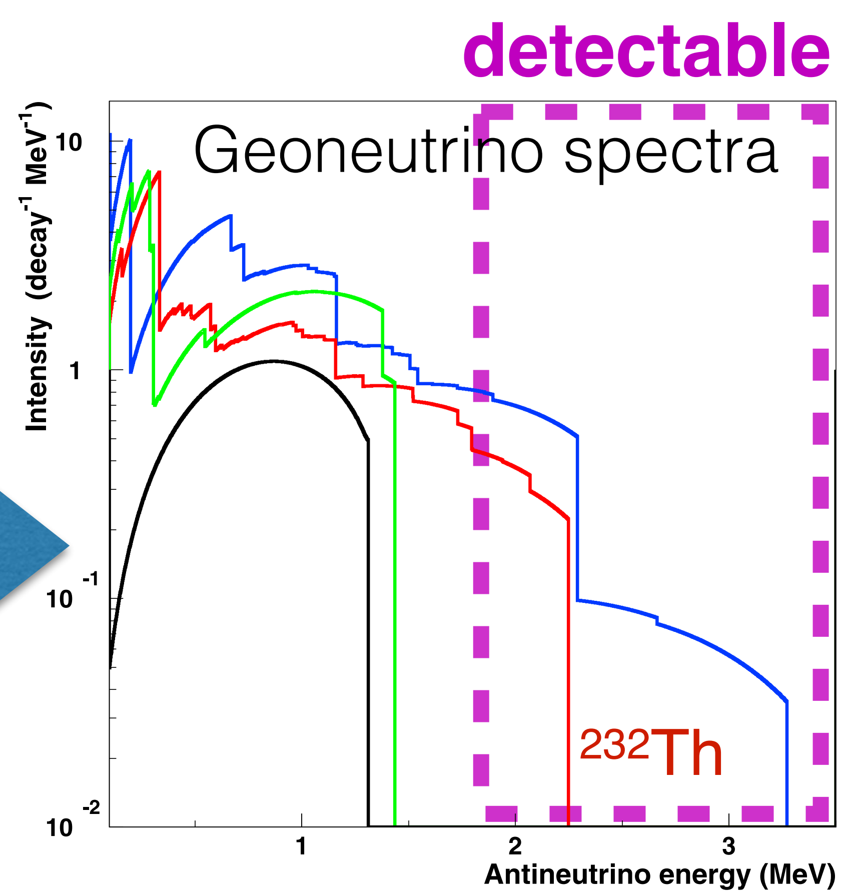
20 TW Earth

+ uncertainties

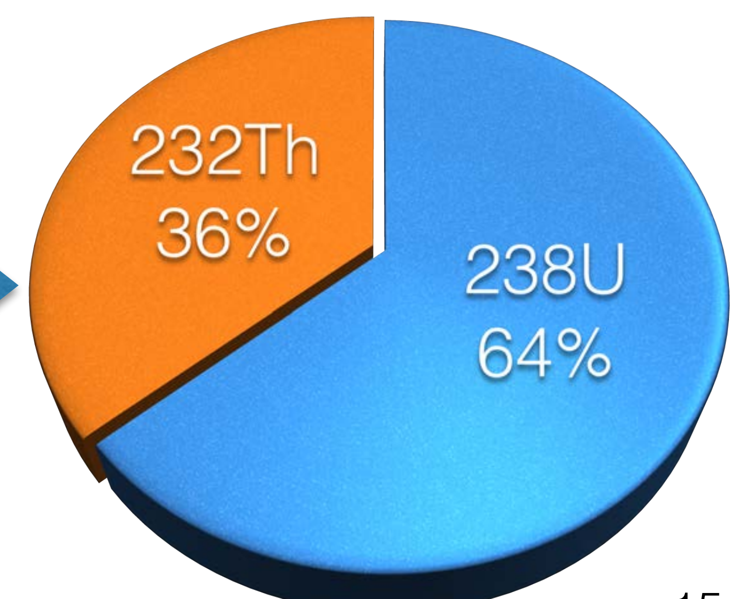
1 Arevalo et al. 2009
2 Rudnick & Gao 2014
3 Plank 2014
4 White & Klein 2014
5 Huang et al. 2013
6 Arevalo & McDonough 2010

More Th than U





More detectable geoneutrinos from U



Geoneutrino prediction at JUNO

22.12°N, 112.52°E, 700 m depth

Geoneutrino signal in **TNU** from 20 TW Earth

	Th	U	Th+U
Upper CC + sed.	4.01±0.40	15.4±3.2	19.4±3.6
Middle CC	1.84±0.15	5.5±1.7	7.4±1.9
Lower CC	0.30±0.09	0.75±0.23	1.05±0.32
OC – sediments	0038±0.003	0.123±0.006	0.160±0.009
OC – crust	0.014±0.004	0.073±0.0022	0.088±0.026
CC + OC	6.2±0.4	21.9±3.7	28.1±4.1
CLM	$0.40^{+0.57}_{-0.25}$	$1.4^{+1.7}_{-0.8}$	$1.8^{+2.3}_{-1.1}$
CC + OC + CLM	$6.7^{+0.8}_{-0.6}$	$23.9^{+4.2}_{-4.0}$	$30.6^{+4.9}_{-4.5}$
DM	$0.68^{+0.15}_{-0.17}$	$3.7^{+0.8}_{-0.9}$	$4.4^{+1.0}_{-1.1}$
EM	$0.87^{+0.44}_{-0.34}$	$2.6^{+2.2}_{-1.6}$	$3.5^{+2.6}_{-2.0}$
DM + EM	$1.6^{+0.4}_{-0.5}$	$6.6^{+2.1}_{-2.2}$	$8.2^{+2.5}_{-2.7}$
TOTAL	$8.4^{+0.8}_{-0.6}$	$30.5^{+4.0}_{-3.9}$	$38.9^{+4.8}_{-4.5}$

Total TNU

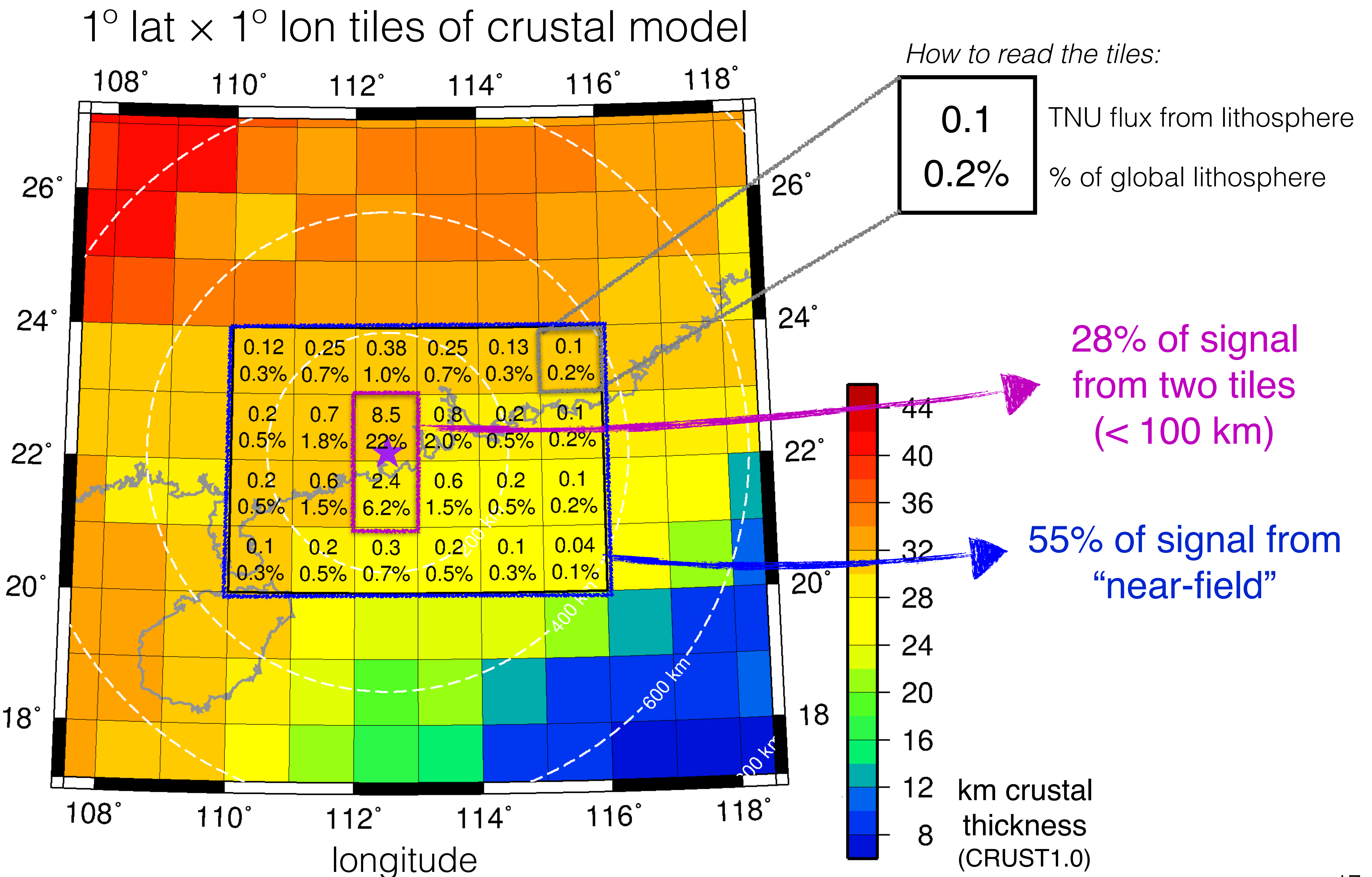
50% from Upper Continental Crust

72% from Crust

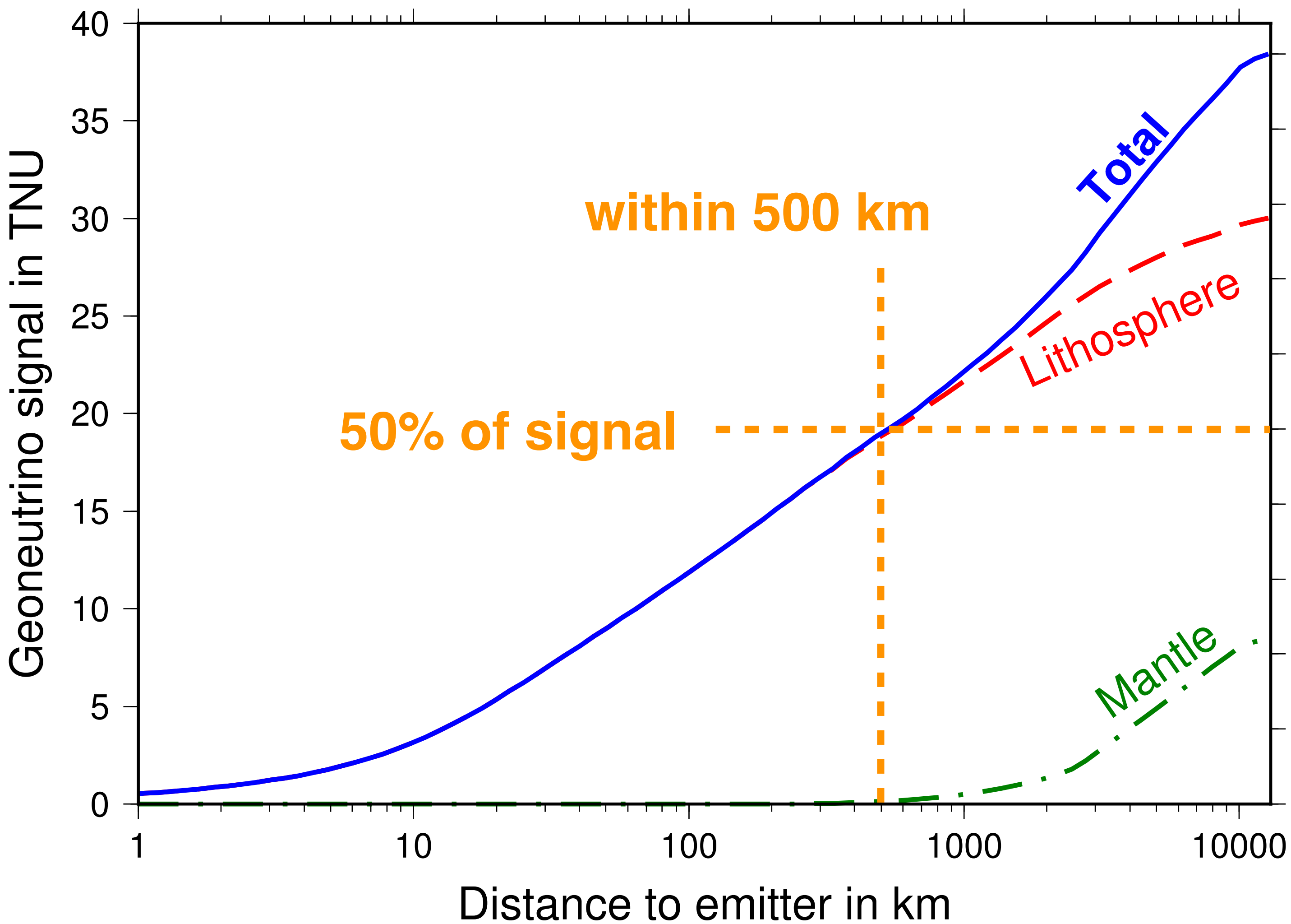
79% from Crust + CLM

21% from Mantle

Prediction at JUNO – lithosphere

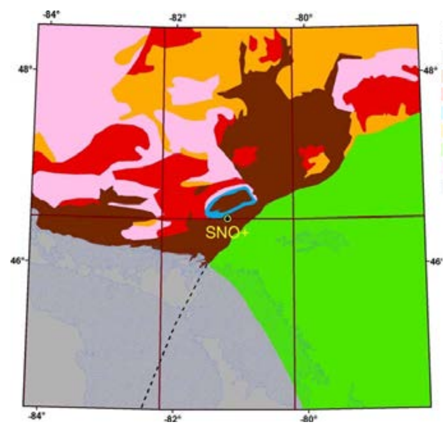


Importance of local model

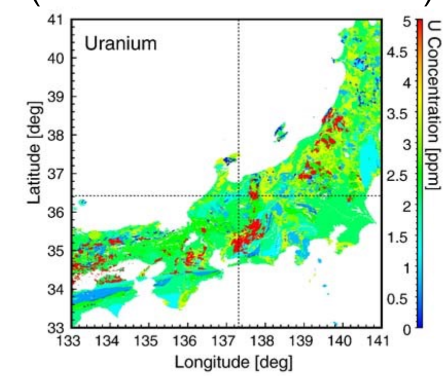


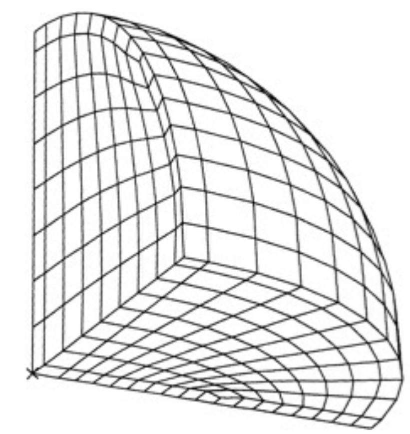
Studies of near-field crust

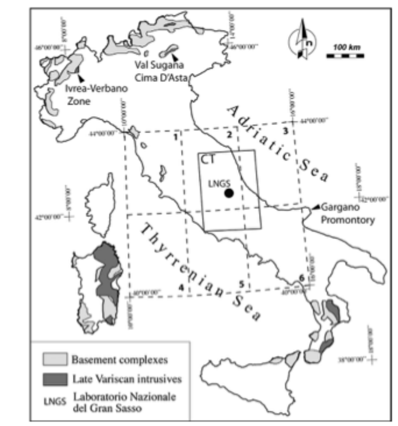
around **SNO+** (*Huang et al. 2014, Strati et al.*)



around **KamLAND** (*Enomoto et al. 2007*)

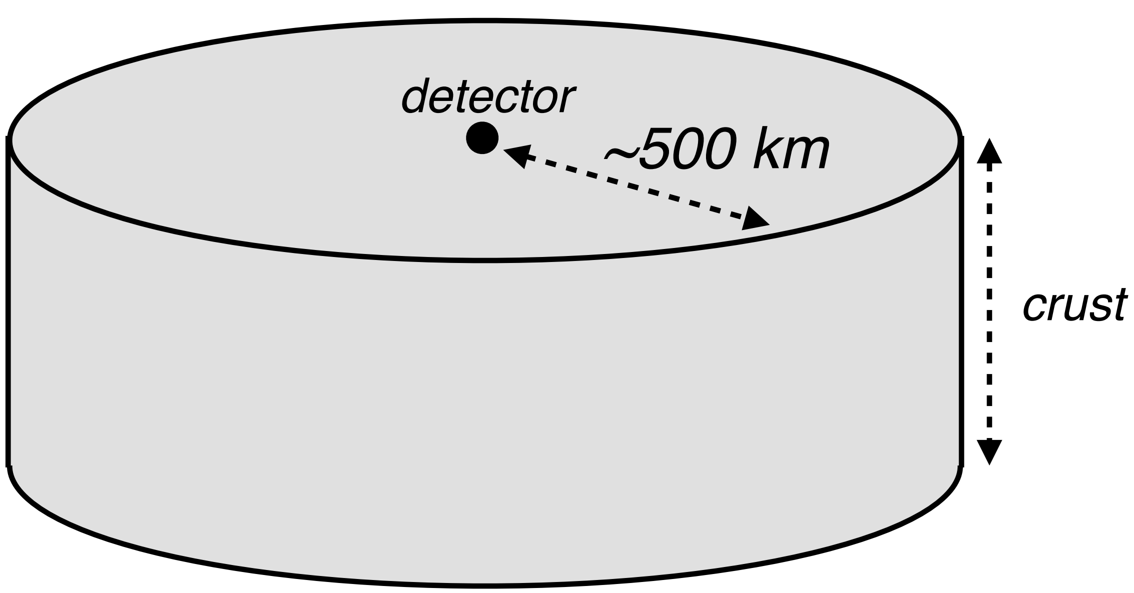






around **Borexino** (*Coltorti et al. 2011*)

Can we build a geological model of crust around JUNO?



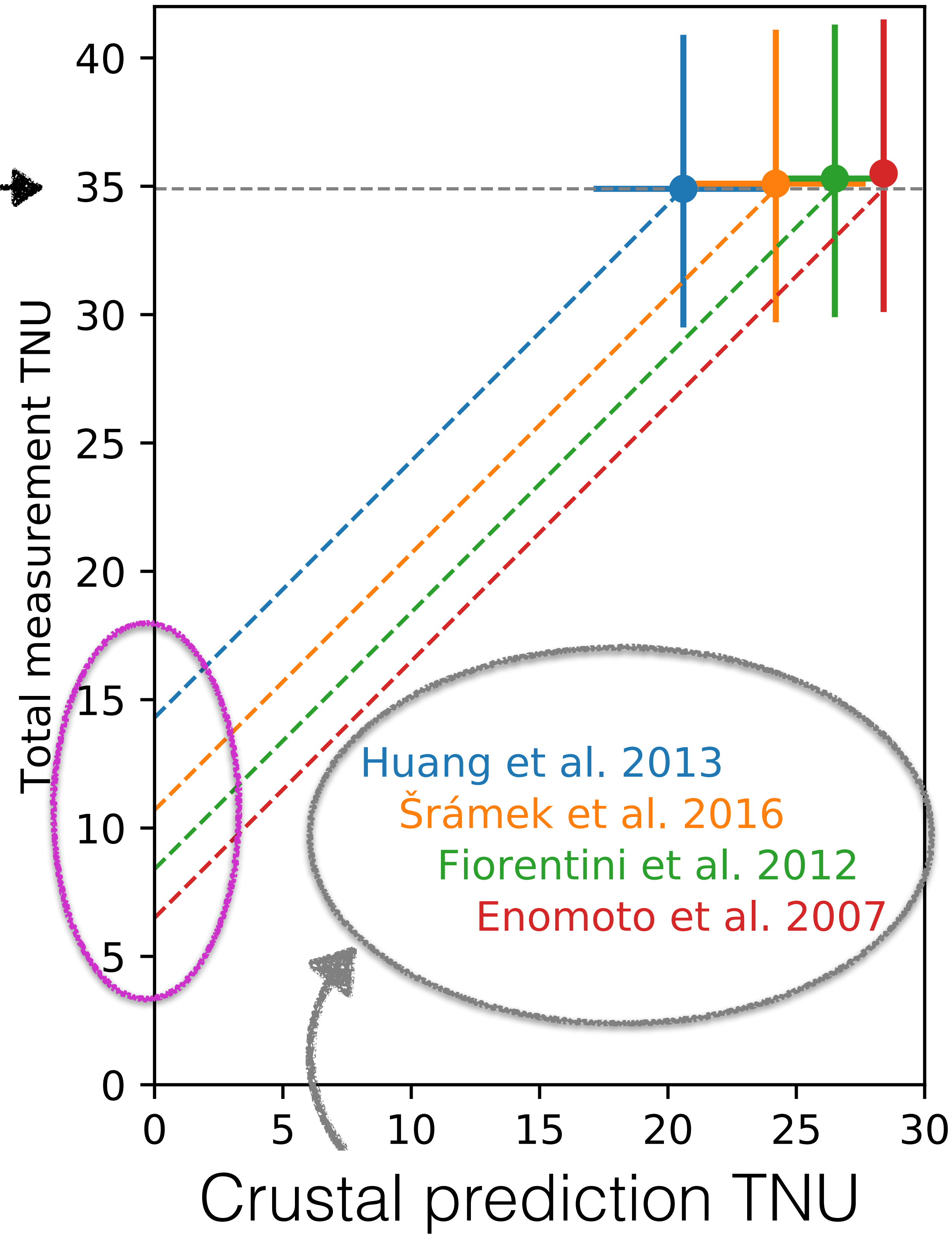
Geo model for JUNO/Jinping/China

- Refined discretized model of lithosphere
- Material density, V_p and V_s seismic speeds, surface heat flux, chemical composition, …

Crustal model matters!

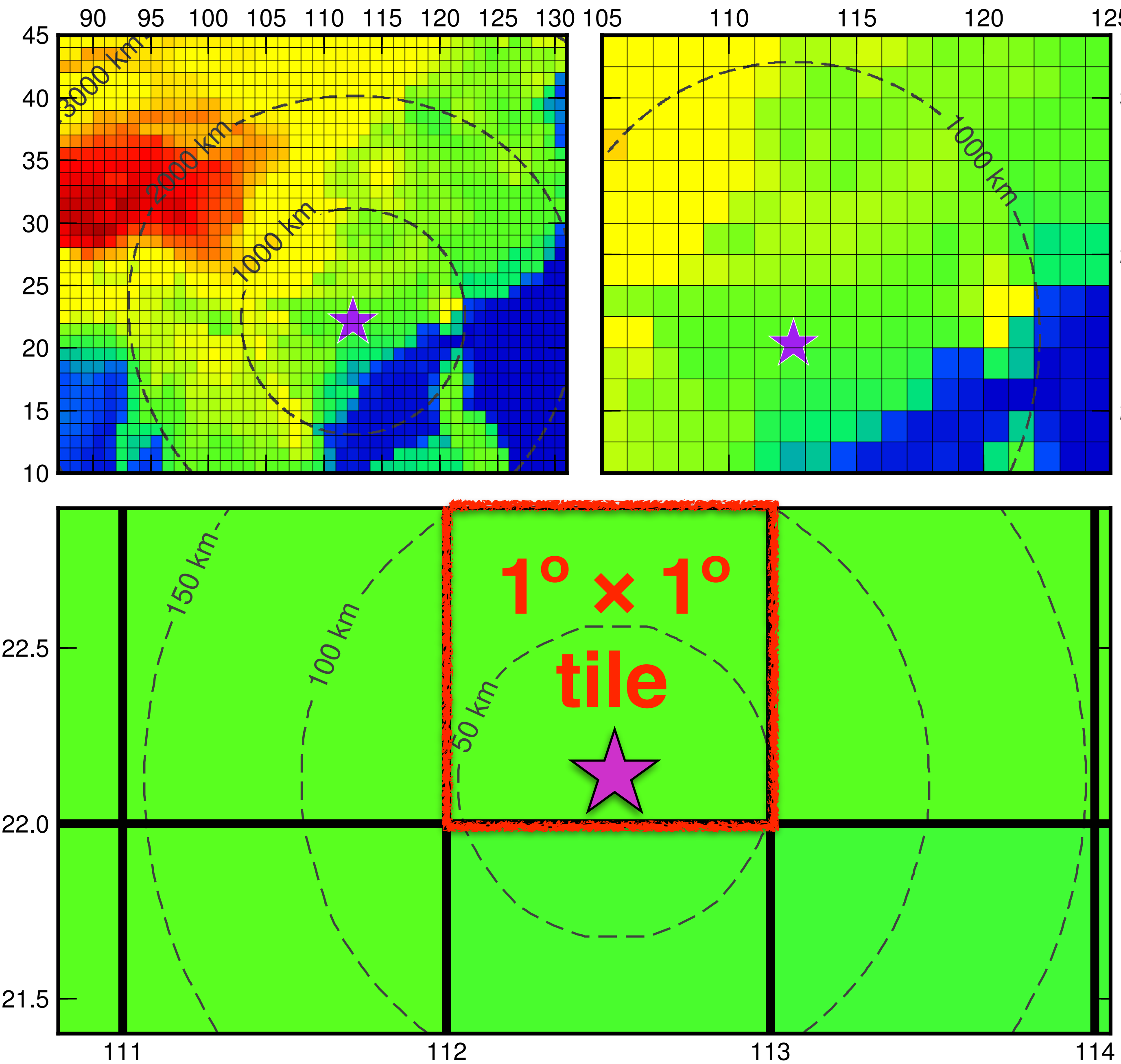
KamLAND measurement

Signal from the mantle…?

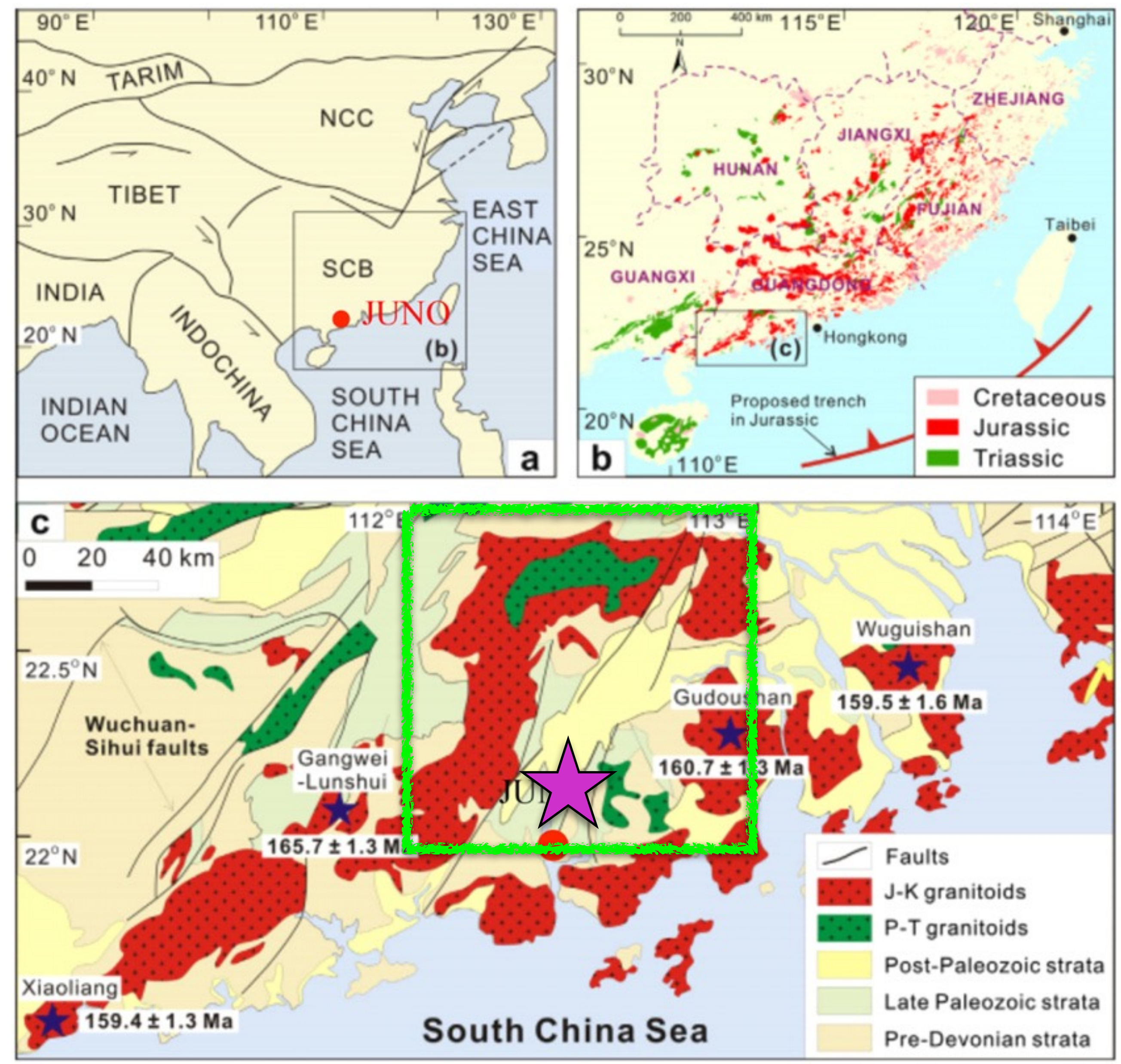


Toward local prediction at JUNO

Current model for geoneutrino emission



Tectonic units, distribution of granites



Huang H-Q et al 2013 doi:10.1016/j.jseaes.2012.09.009

Currently not using any such local information

Challenges of emission models

- Precision of neutrino physics measurement is expected to increase. Inference of mantle signal will be limited by precision of crustal prediction.

- Global emission model are too coarse to well describe nearby crustal contribution (~50% of signal). Can we do better?

- Crustal model = physical + chemical description
  … integrate various measurements and methods

- Which global crustal model?
  … CRUST2.0, CRUST1.0, LITHO1.0 yield difference crustal mass, using same compositional model yield 7.1 TW (C1) or 7.9 TW (L1) in the crust

- Quantification of uncertainty of geo* models.
  … How well do we understand the crust?

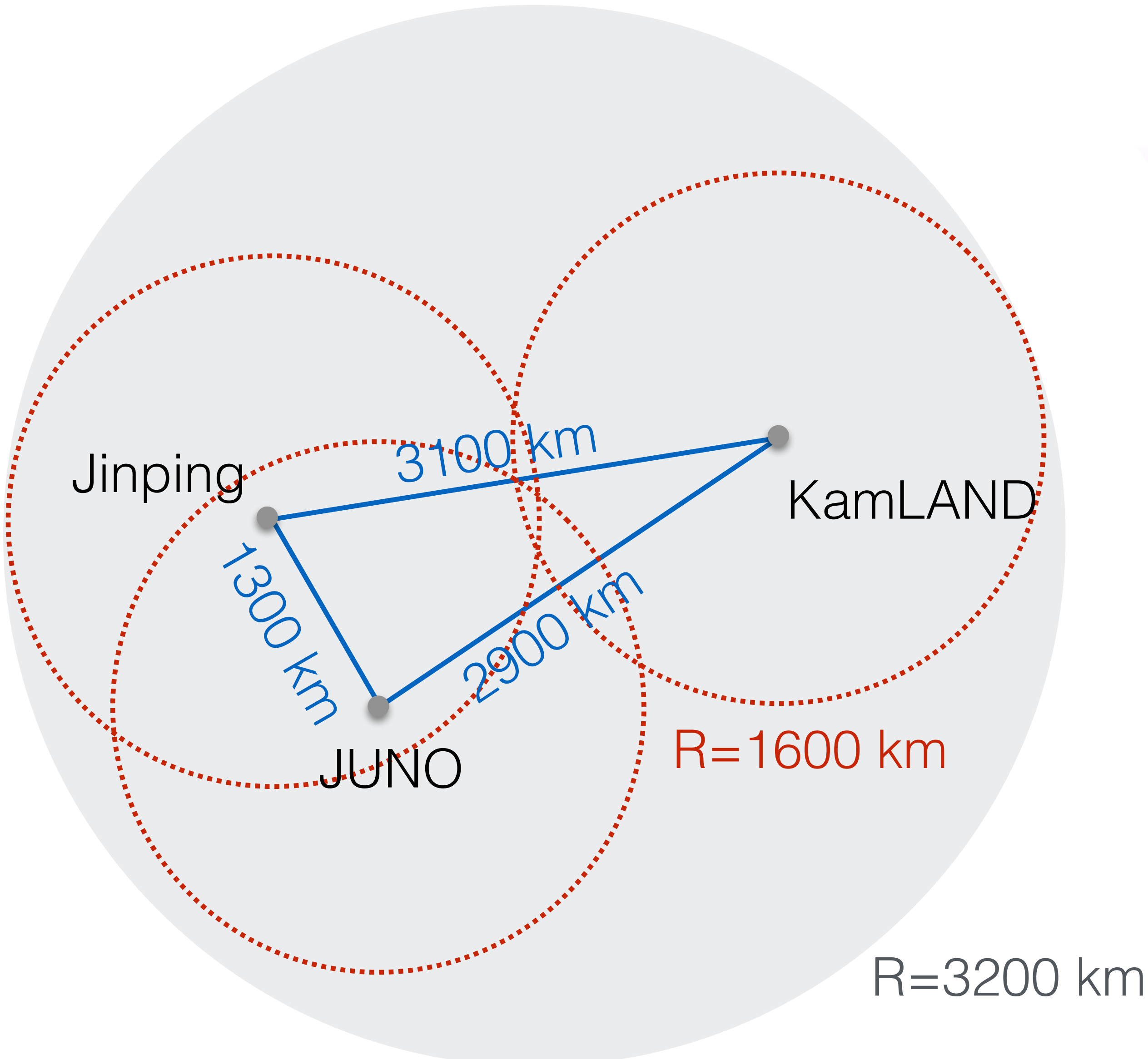
Study lithosphere with geoneutrinos?

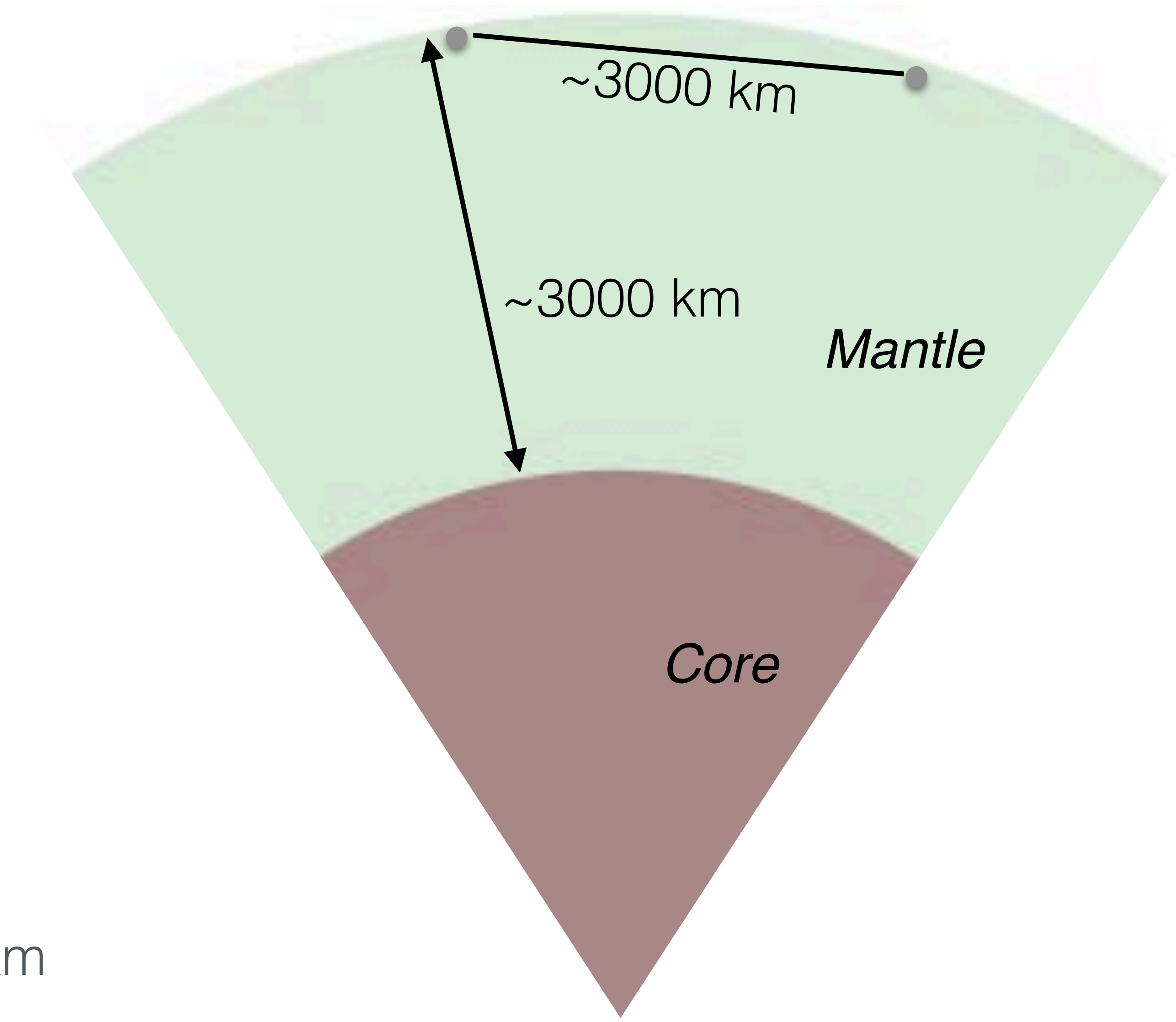
1 detector

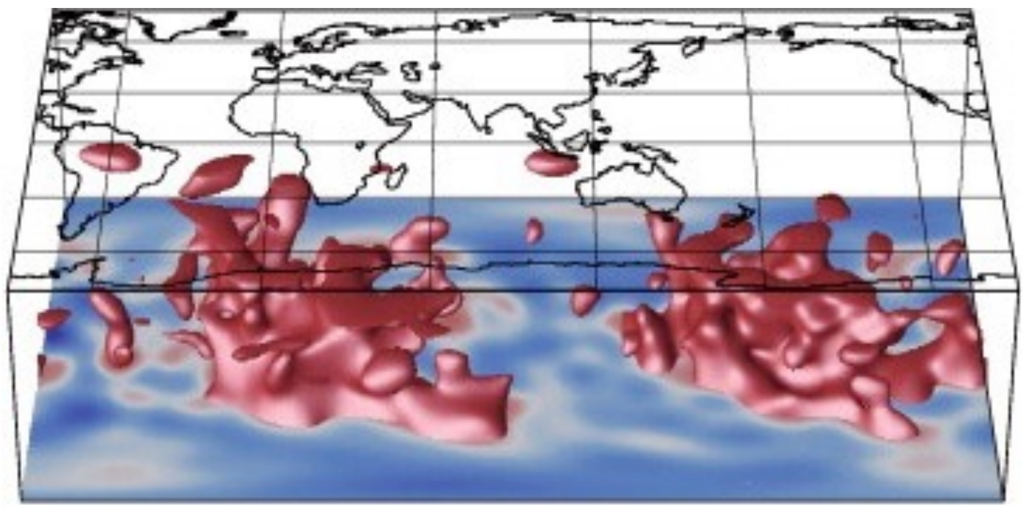
- We measure total geoneutrino flux.
- We predict the ***lithospheric*** flux and resolve the ***mantle***. (or vice versa)

>1 detectors combined

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





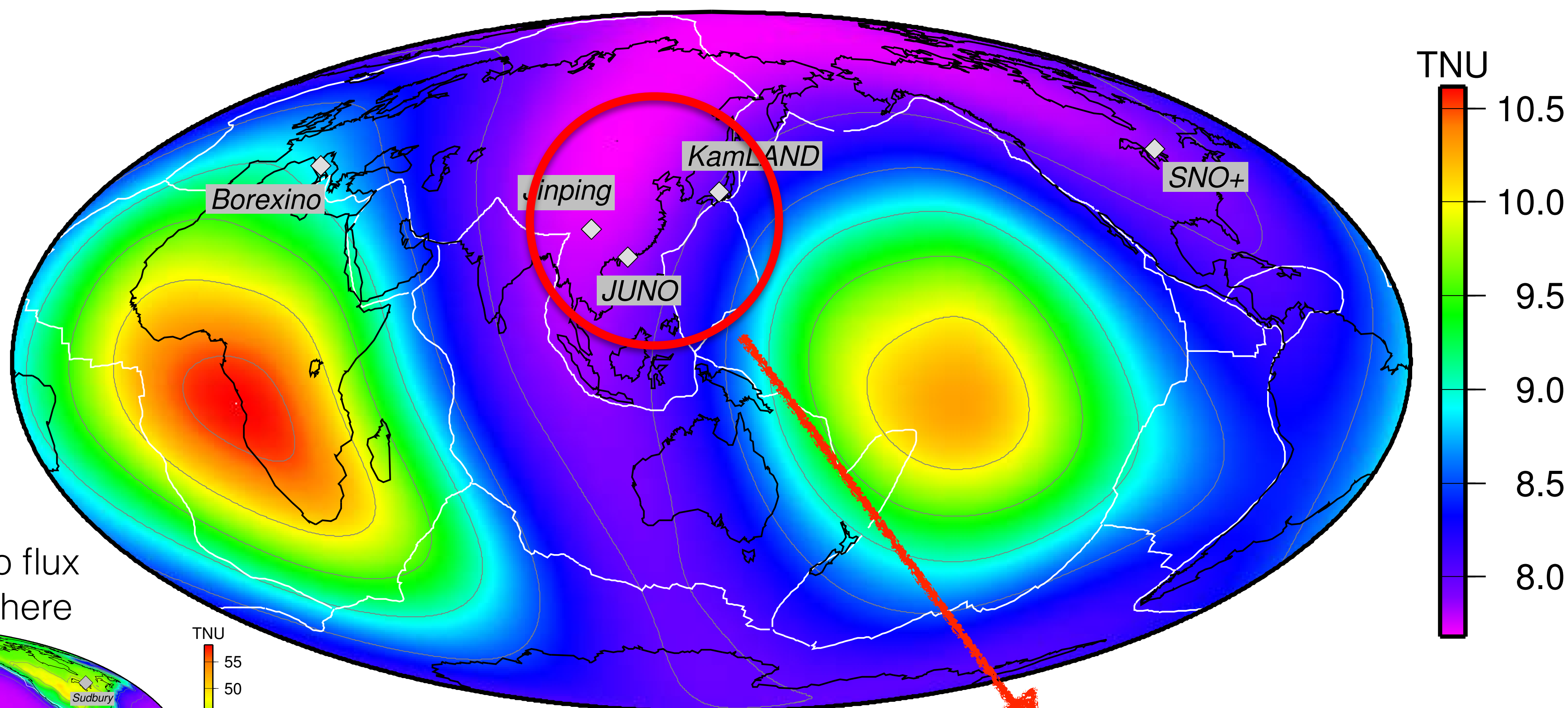


Bull et al 2009, after Ritsema et al 1999

Seismically slow "red" regions in the deep mantle

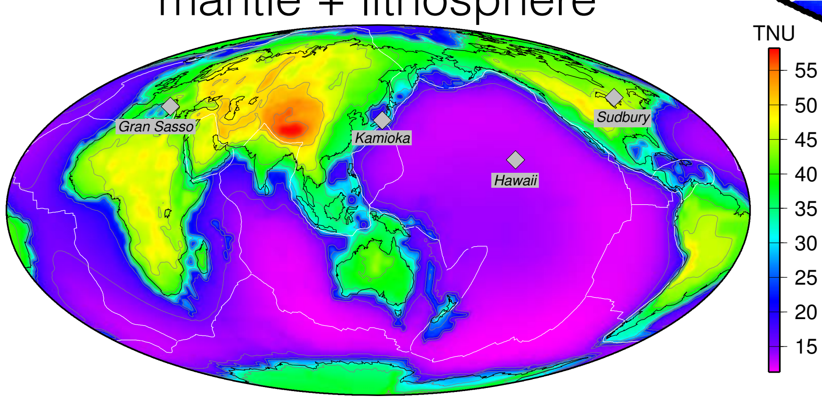
3-D structure of enriched mantle?

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)

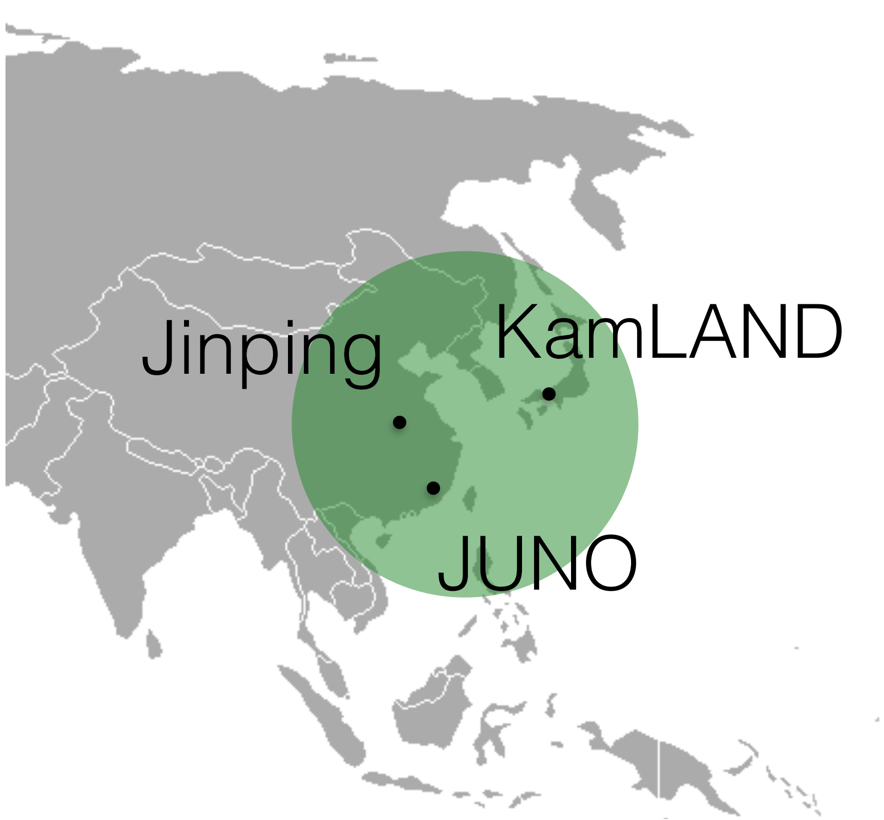
$$G_{1,tot} = G_{mantle} + G_{3,litho\text{-}far} + G_{1,litho\text{-}reg}$$
$$G_{2,tot} = G_{mantle} + G_{3,litho\text{-}far} + G_{2,litho\text{-}reg}$$
$$G_{3,tot} = G_{mantle} + G_{3,litho\text{-}far} + G_{3,litho\text{-}reg}$$

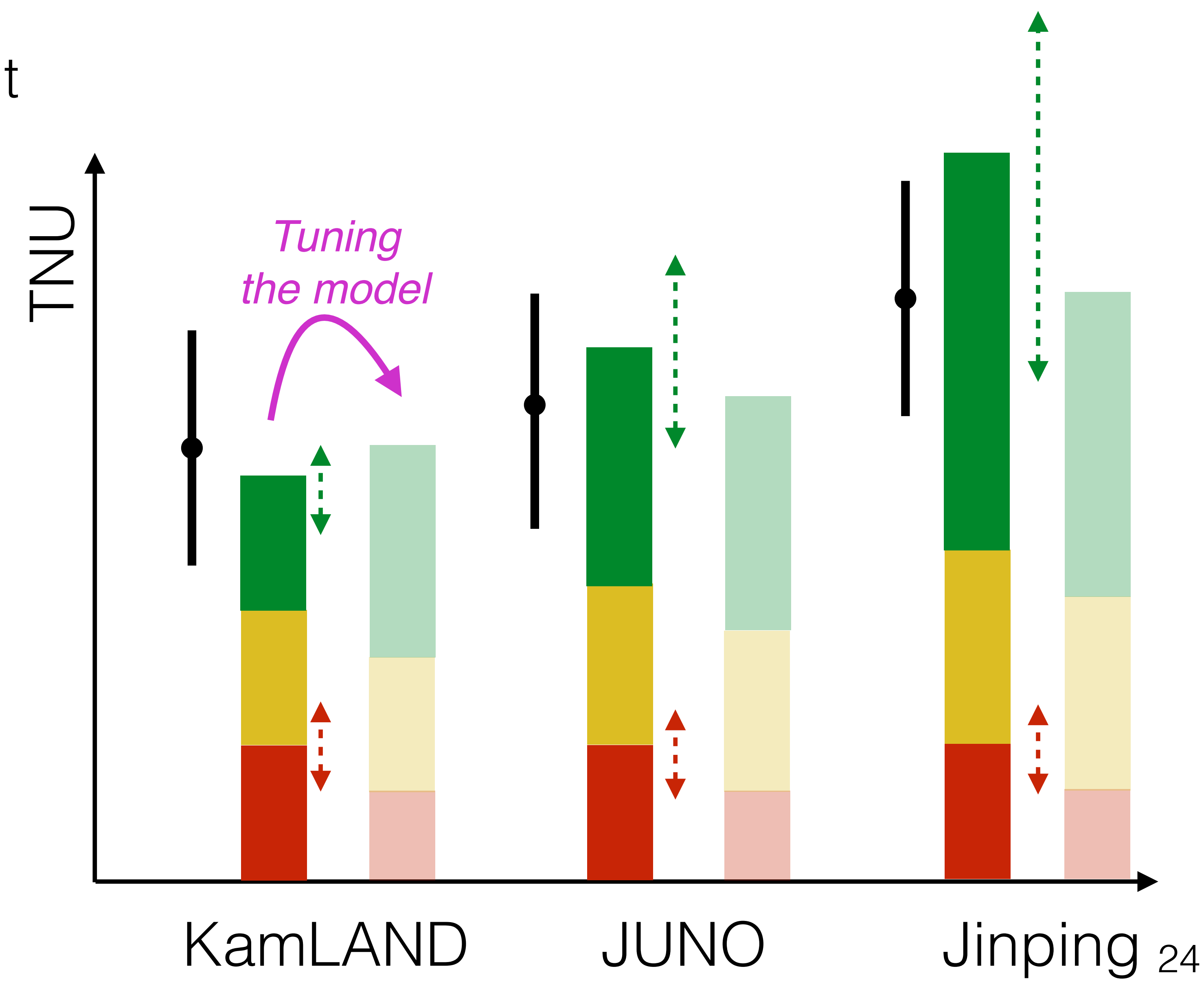
same for all 3 | fixed model

Testing regional lithosphere

- Measurement
- Mantle: unknown, same for all
- Far lithosphere: fixed model
- Regional lith.: *Fit to geo-ν data*

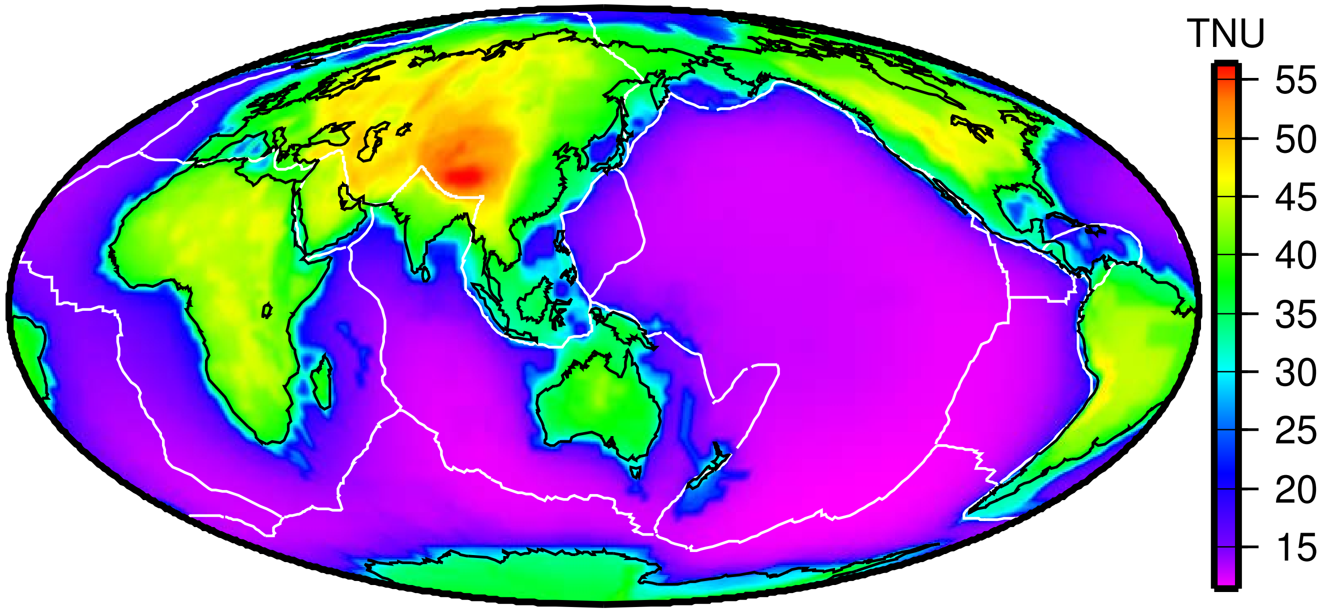
3 measurements
4 unknowns
1 constraint … minimization of misfit between a priori and tuned regional model



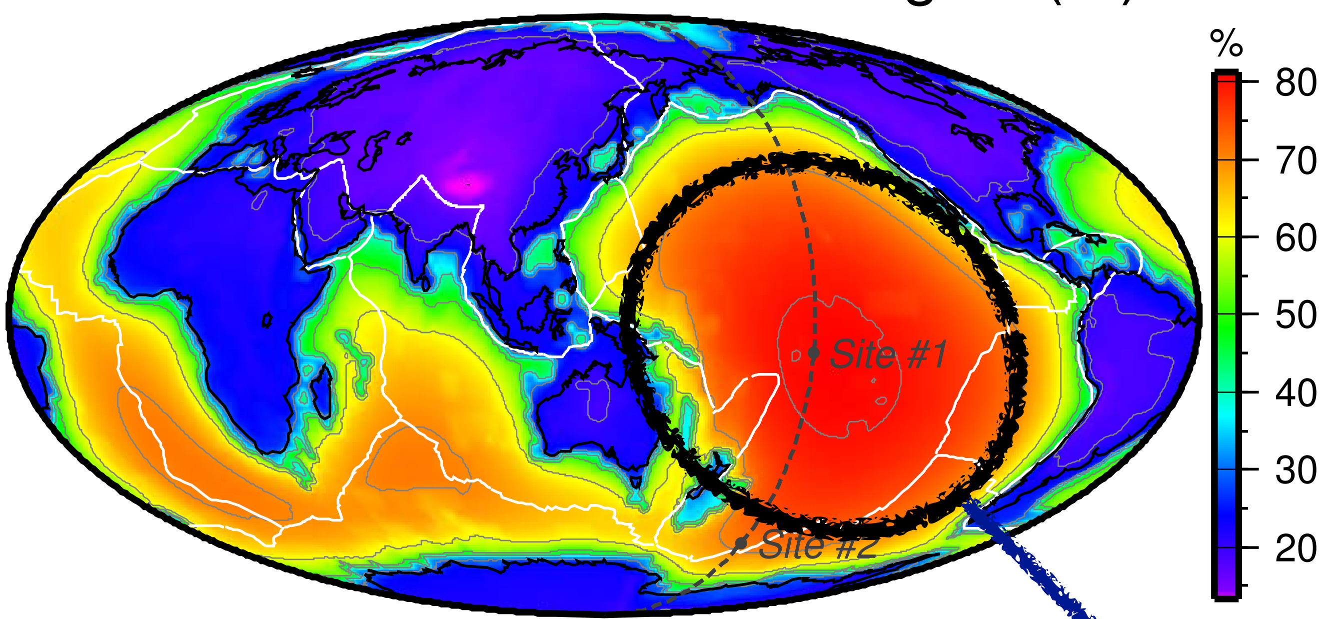


Crust + Mantle geoneutrino emission

Crust + mantle (TNU)

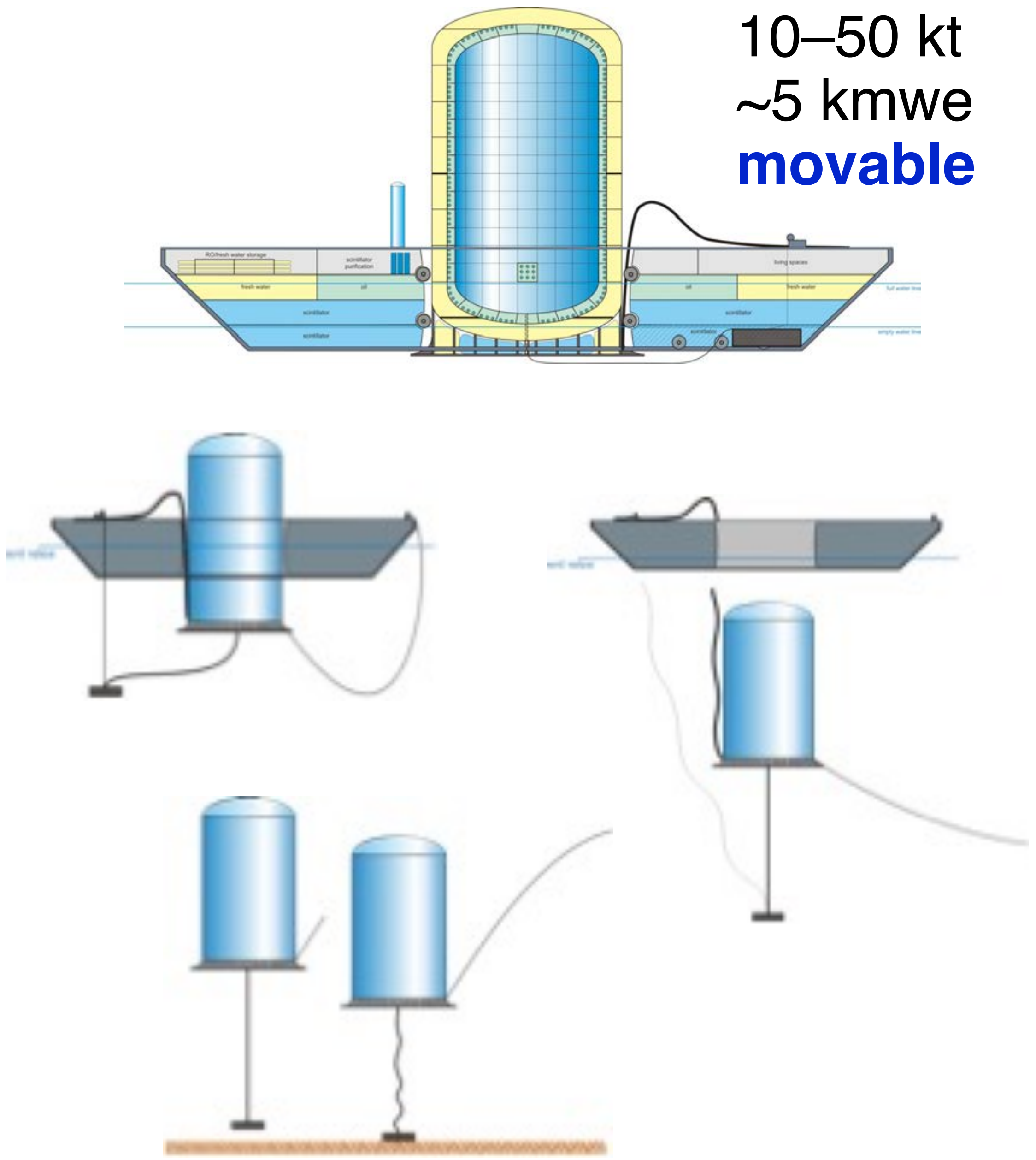


Mantle contribution to total signal (%)



Ocean-Bottom Detector

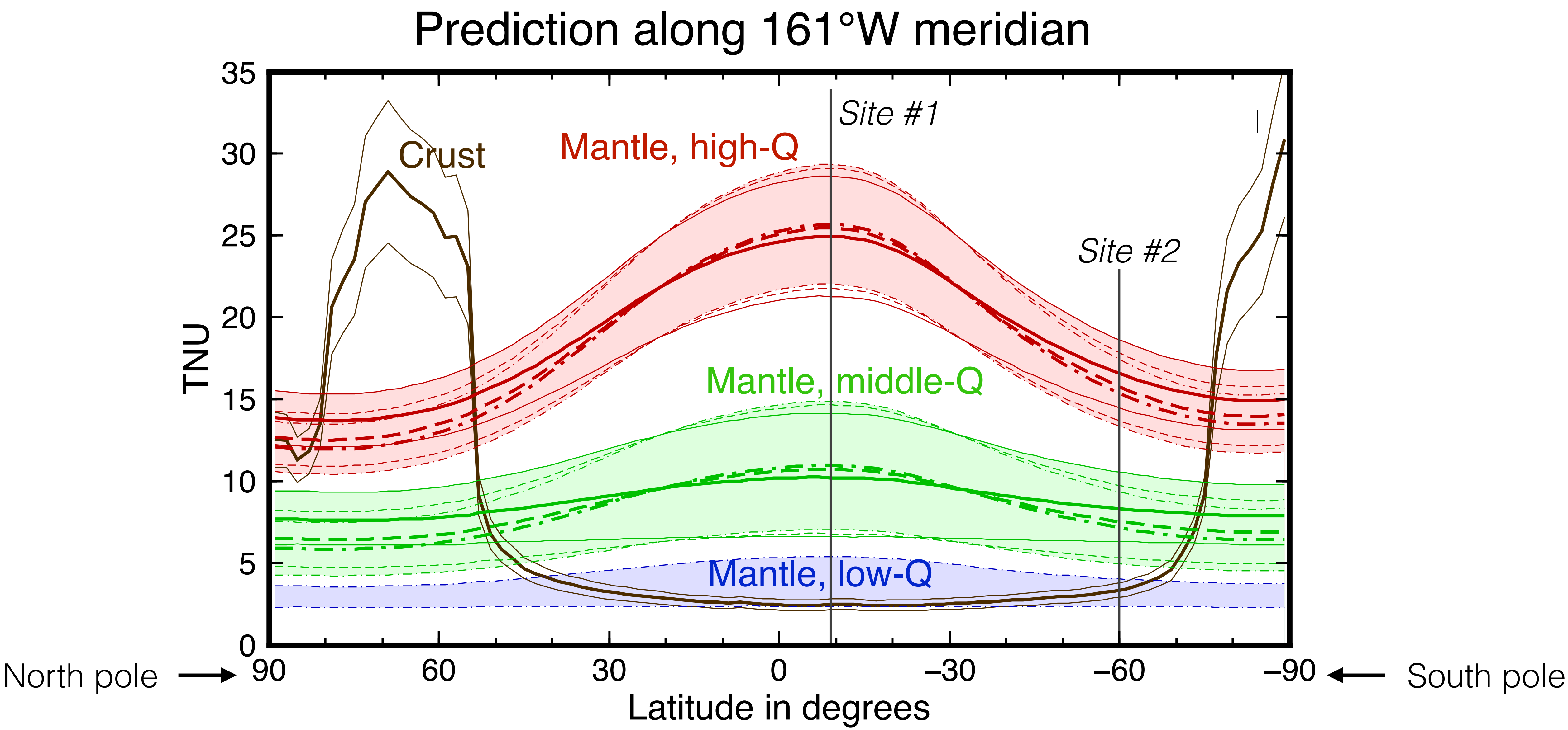
R&D
10–50 kt
~5 kmwe
movable

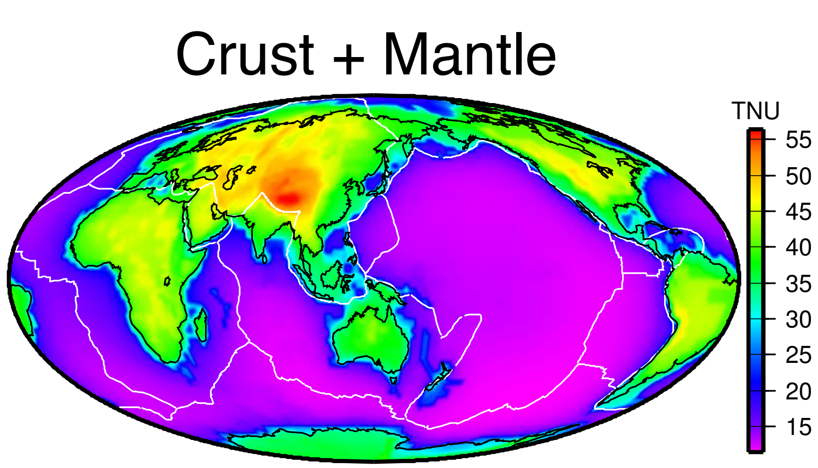


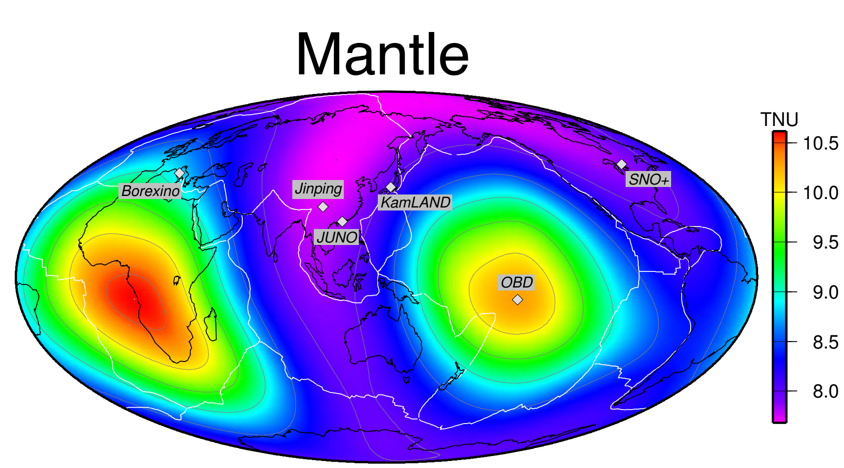
Here is where we would love to measure mantle

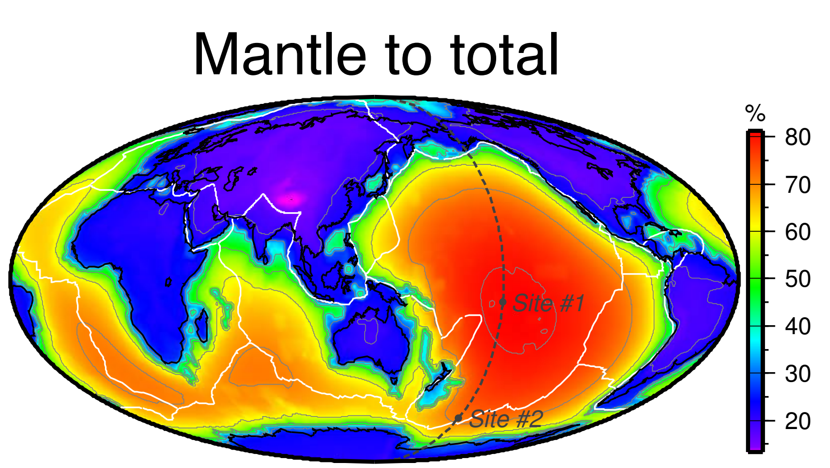
Šrámek et al 2013 doi:10.1016/j.epsl.2012.11.001

"Seeing" enriched piles using Ocean Bottom Detector









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

Conclusions

- Particle physics can measure aspects of Earth's composition.
- Combination of future measurements, including JUNO and Jinping, expected to resolve the amount of radiogenic power in the mantle.
- Geoneutrino measurements can test models of lithosphere.
- Synergy (= interaction and cooperation) between neutrino physics and geoscientific disciplines required.