Geo-neutrinos 地球中微子

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Outline

(1) Introduction

(2) Observation of geo-neutrinos

(3) Prediction of geo-neutrinos

(4) The JUNO geo-neutrino measurement

(5) Connecting to geo-sciences

Does the Earth Shine?

1) The Sun shines with Heat and Neutrinos:

Heat flux: 1.4 kW m^{-2} (from nuclear reaction)

Neutrinos: 3.6×10^{10} cm^2 s^{-1} (at the Earth)

2)The Earth shines with Heat and Antineutrinos:

Heat flux: (60-90) mW m^{-2} (different contributions)

Antineutrinos: 2×10^{6} cm^2 s^{-1} (at the surface)

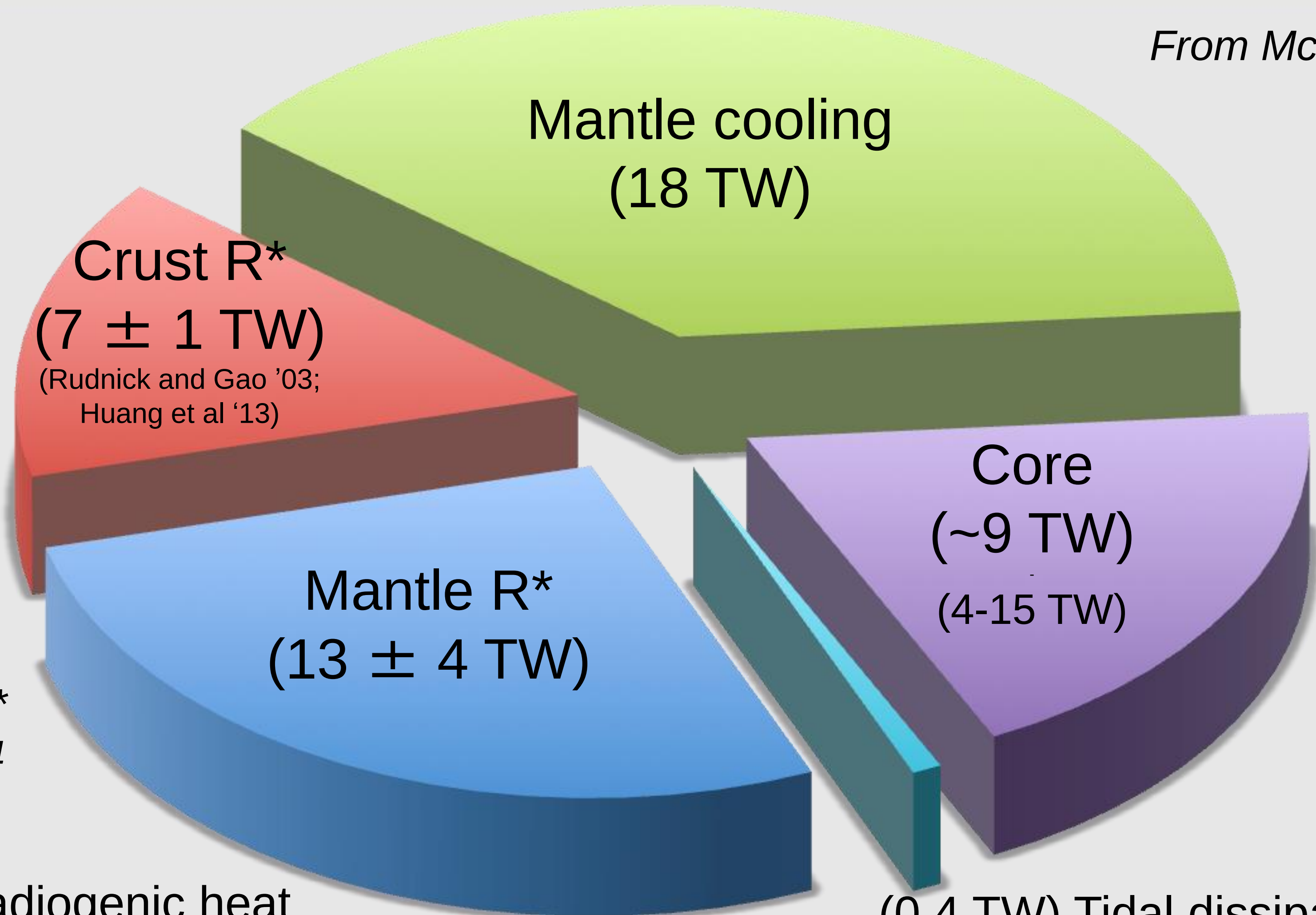
Terrestrial heat flux: ~45 TW

→ radiogenic heat: correlated with the neutrino flux

→ non-radiogenic heat

Surface heat flow: 46 ± 3 (47 ± 1) TW

From McDonough



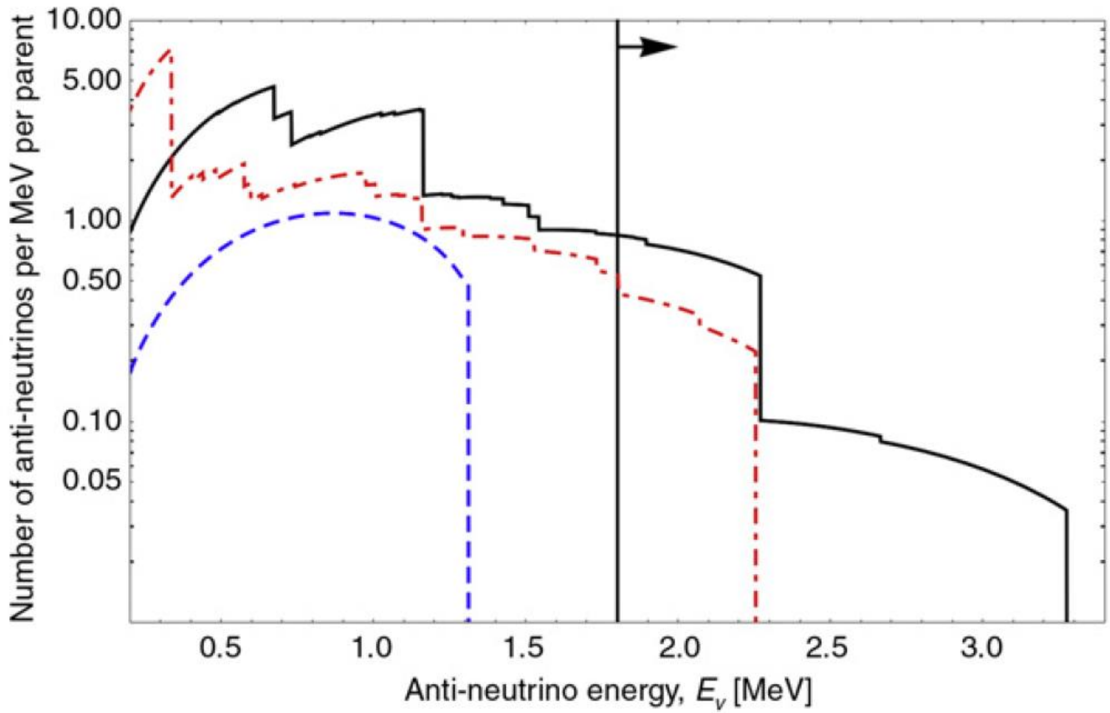
*total R**
20 ± 4

*R radiogenic heat
(after McDonough & Sun '95)

(0.4 TW) Tidal dissipation
Chemical differentiation

Geo-neutrino production from HPEs

Decay	Natural isotopic abundance	$T_{1/2}$ (10^9 yr)	E_{max} (MeV)	Q (MeV)	Q_{eff} (MeV)	$\varepsilon_{\bar{\nu}}$ (kg^{-1} s^{-1})	ε_H (W kg^{-1})	$\varepsilon'_{\bar{\nu}}$ (kg^{-1}s^{-1})	ε'_H (W kg^{-1})
$^{238}U \to ^{206}Pb + 8\,^4He + 6e + 6\bar{\nu}$	0.9927	4.47	3.26	51.7	47.7	7.46×10^7	0.95×10^{-4}	7.41×10^7	0.94×10^{-4}
$^{232}Th \to ^{208}Pb + 6\,^4He + 4e + 4\bar{\nu}$	1.0000	14.0	2.25	42.7	40.4	1.62×10^7	0.27×10^{-4}	1.62×10^7	0.27×10^{-4}
$^{40}K \to ^{40}Ca + e + \bar{\nu}$ (89%)	1.17×10^{-4}	1.28	1.311	1.311	0.590	2.32×10^8	0.22×10^{-4}	2.71×10^4	2.55×10^{-9}
$^{40}K + e \to ^{40}Ar + \nu$ (11%)	1.17×10^{-4}	1.28	0.044	1.505	1.461	=	0.65×10^{-5}	=	0.78×10^{-9}
$^{235}U \to ^{207}Pb + 7\,^4He + 4e + 4\bar{\nu}$	0.0072	0.704	1.23	46.4	44	3.19×10^8	0.56×10^{-3}	2.30×10^6	0.40×10^{-5}
$^{87}Rb \to ^{87}Sr + e + \bar{\nu}$	0.2783	47.5	0.283	0.283	0.122	3.20×10^6	0.61×10^{-7}	8.91×10^5	0.17×10^{-7}



Fiorentini et al.Phys. Rep. 2017

HPEs: Heat producing elements

Dominate isotopes:
U238, Th232, K40

In Liquid Scintillator with free protons, only U238, Th232 are observable.

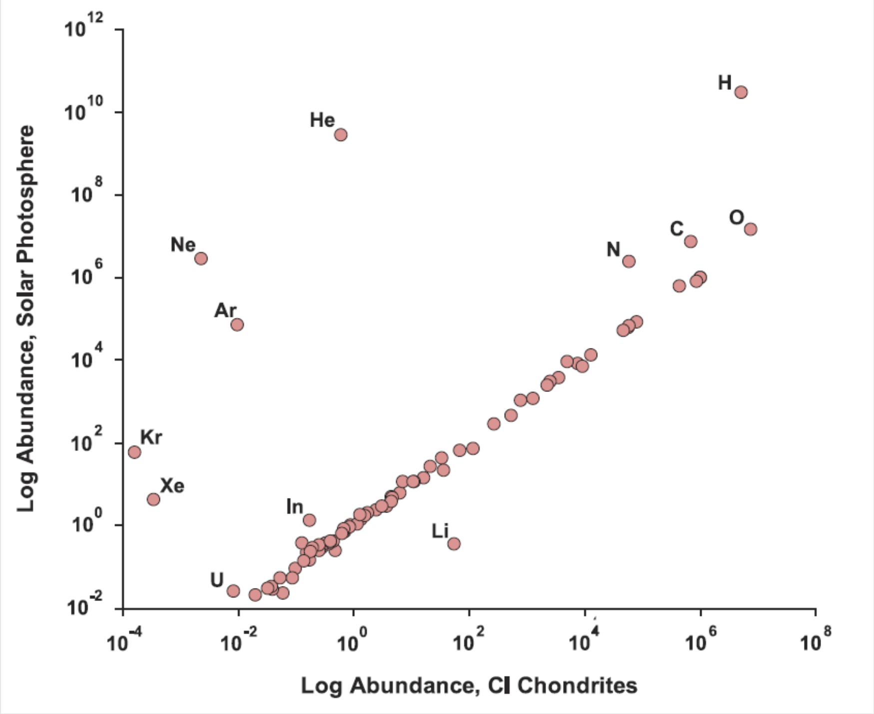
$$\bar{\nu}_e + p \to e^+ + n - 1.806\,\text{MeV}$$

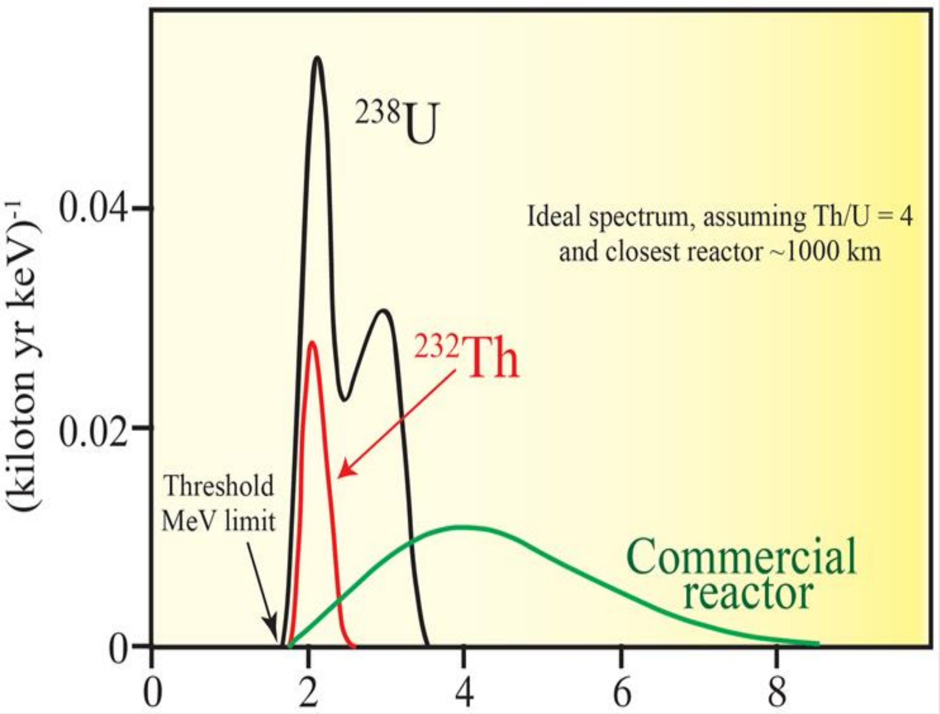
U and Th contributions: chondritic ratio

the ratio of chondritic meteorites (球粒陨石)

$$m(\mathrm{Th})/m(\mathrm{U}) = 3.9$$

$$\frac{S(\mathrm{Th})}{S(\mathrm{U})} = 0.32 \times \frac{\Phi^{(\mathrm{arr})}(^{232}\mathrm{Th})}{\Phi^{(\mathrm{arr})}(^{238}\mathrm{U})} \approx 0.32 \times \frac{L(^{232}\mathrm{Th})}{L(^{238}\mathrm{U})} \approx \frac{1}{16} \times \frac{m(^{232}\mathrm{Th})}{m(^{238}\mathrm{U})}.$$

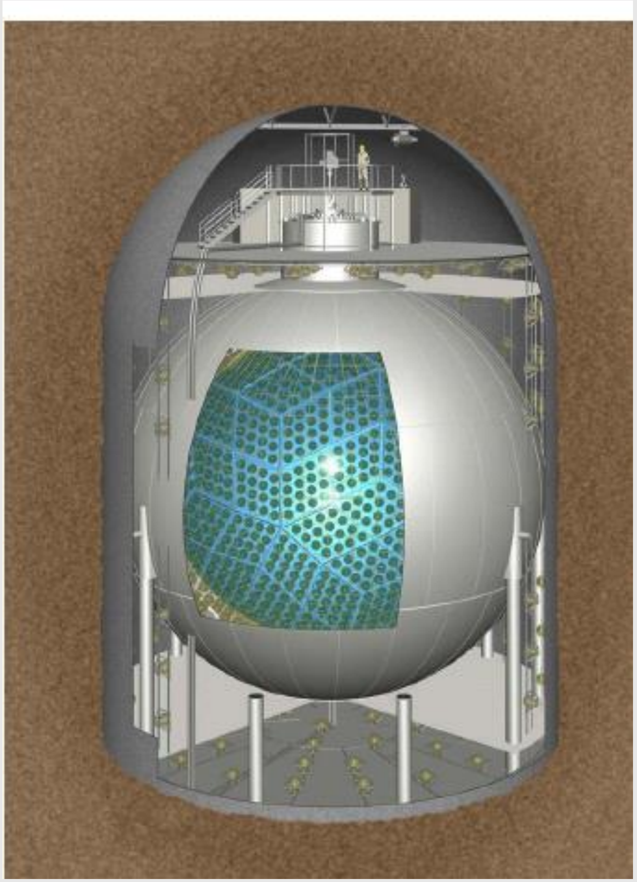




Observation of geo-neutrinos

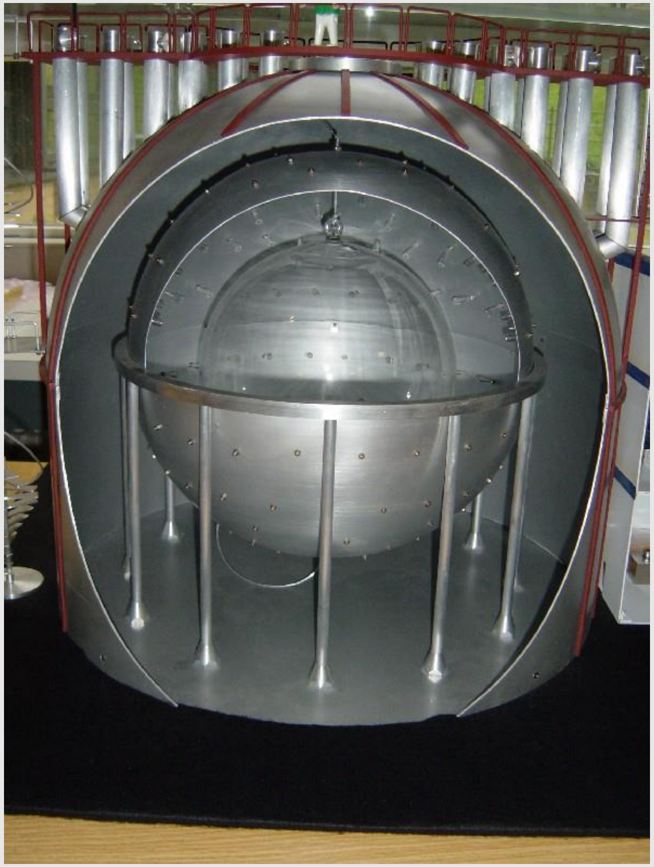
First observed in 2005 by KamLAND, then in 2010 by Borexino

KamLAND, Japan (1kt)



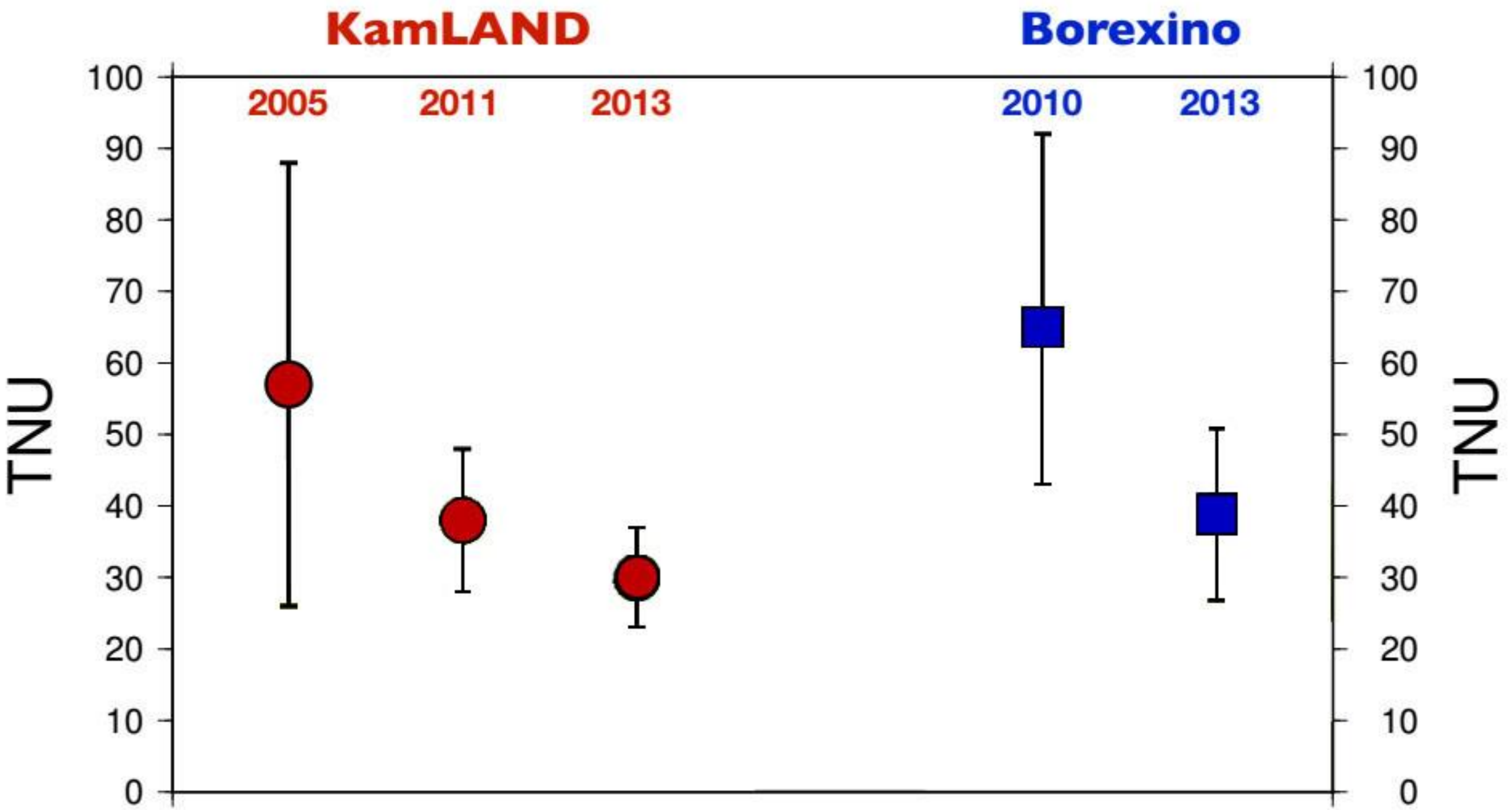
~1 event/30 days

Borexino, Italy (0.6kt)



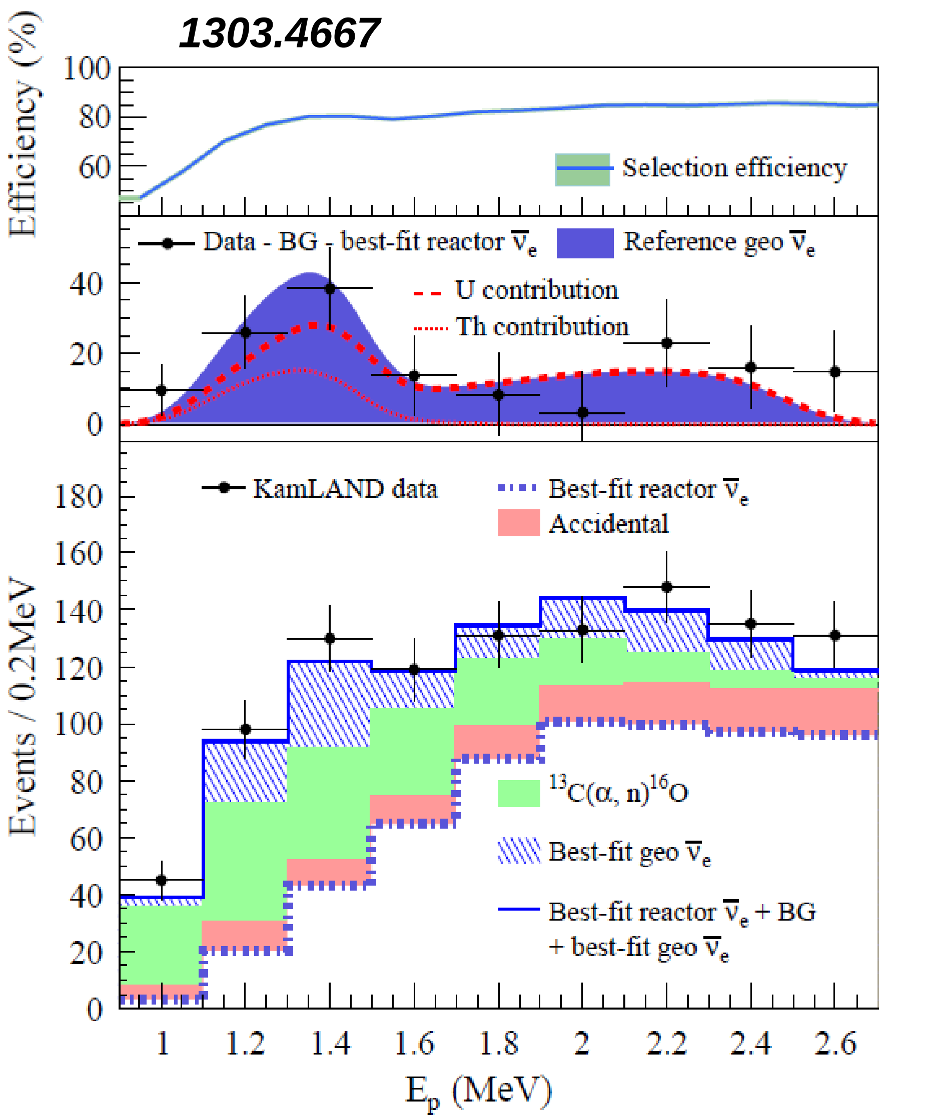
~1 event/70 days

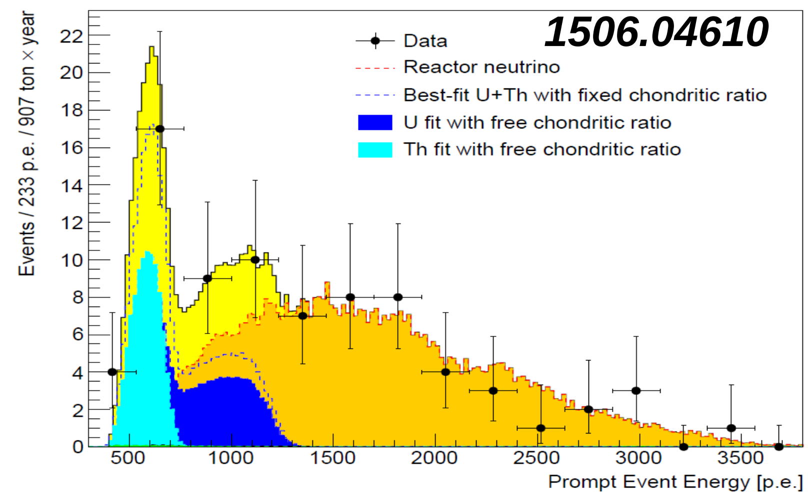
Current experimental status

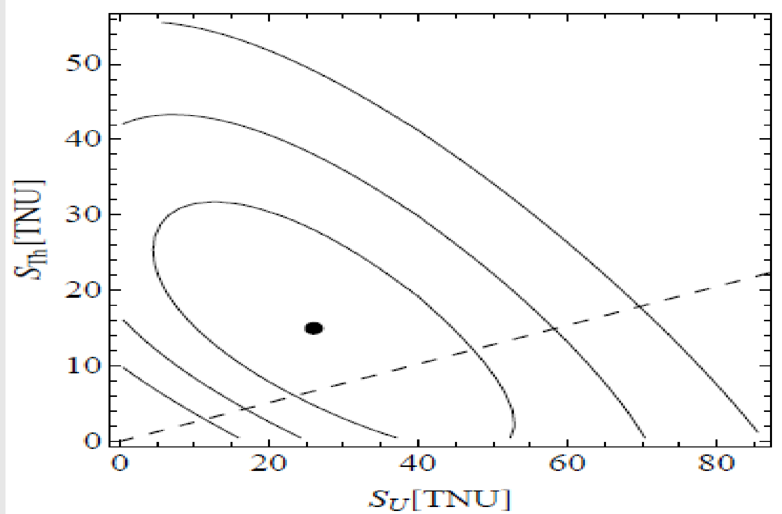


TNU: **one event per 10^{32} free protons (a kiloton) per year**

Spectral information: U v.s. Th







Spectral information helps in the U & Th seperation.

Connecting measurements to predictions

To extract useful geological/geophysical/geochemical information of the Earth, one need to connect measurements to predictions.

Activity and number of produced geo-neutrinos

Volume of source unit

$$\Phi_i = A_i \cdot n_i \cdot P_{\nu_e - \nu_e}(E_\nu, |\vec{L}|) \cdot \int_V \frac{a_i(\vec{L}) \cdot \rho_i(\vec{L})}{4\pi |\vec{L}|^2} \cdot dV$$

Survival probability function

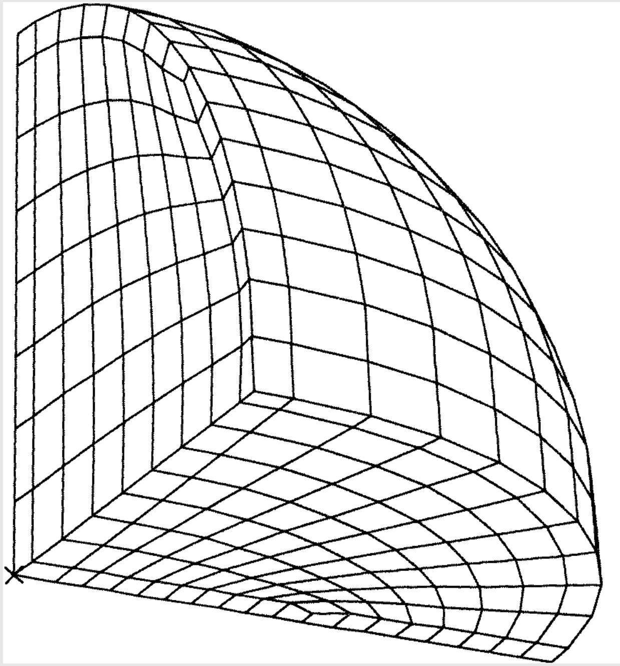
Abundance and density of the source unit

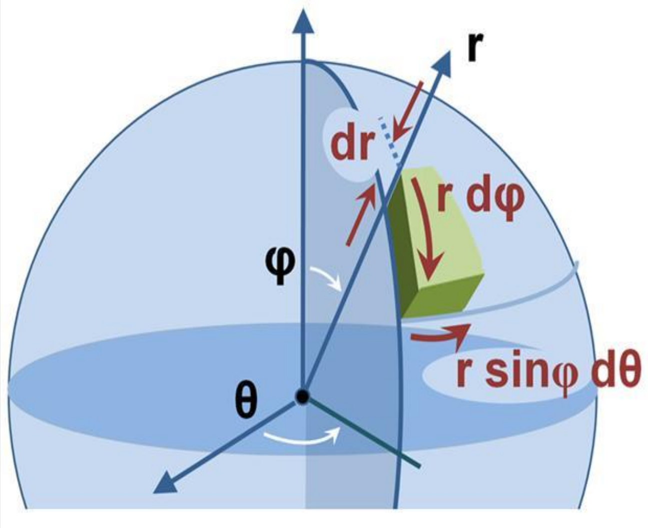
Distance between source unit and detector

Earth structure (ρ and L) and **chemical composition** (a)

Constructing a 3-D reference model of the Earth

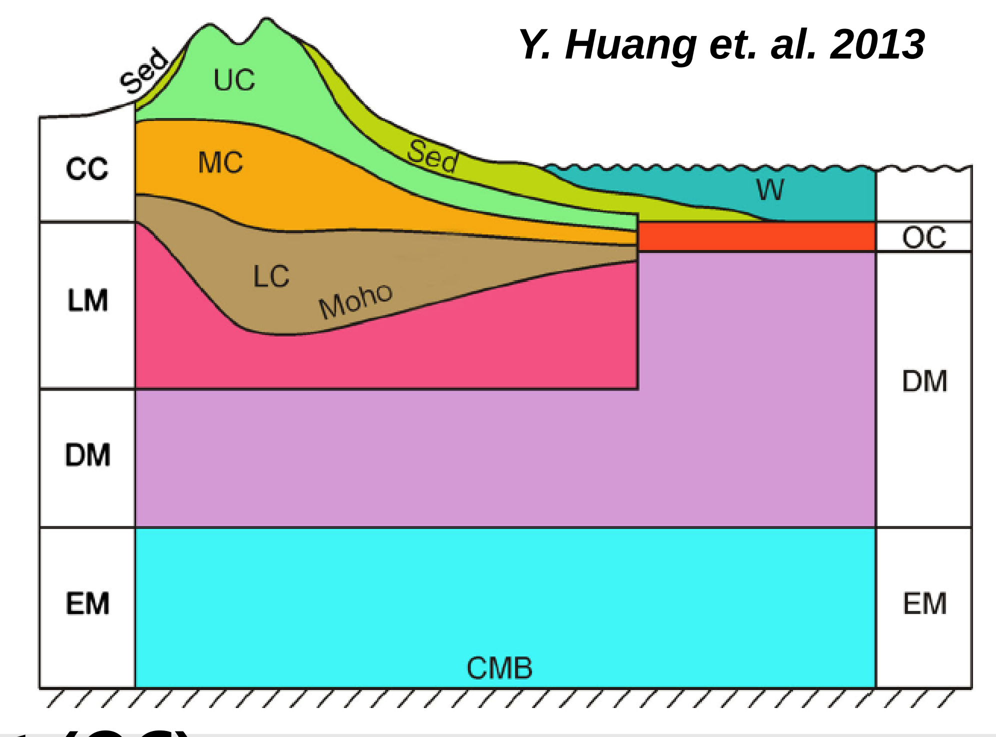
Assigning chemical and physical states to Earth volume units





The BSE paradigm: Bulk Silicate Earth

BSE= Primitive Mantle = Modern Mantle + Crust: the source of HPEs



Crust layers:
continental v.s. oceanic
a) sediment + upper crust (UC) + middle crust (MC) +lower crust (LC)
b) sediment + oceanic crust (OC)

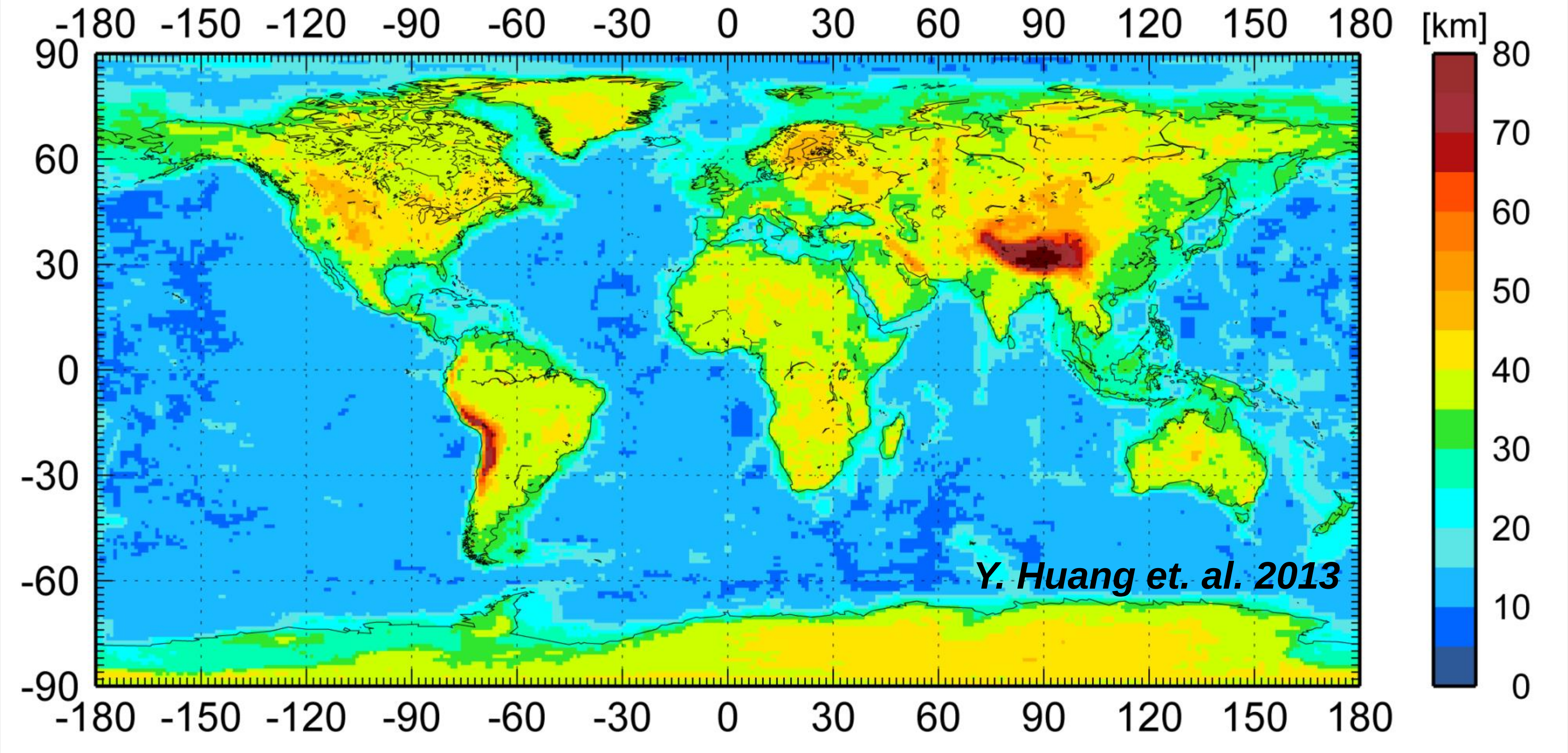
Mantle layers:

Continental Lithospheric Mantle (LM)岩石圈地幔

depleted mantle (DM) and enriched mantle (EM)

Defining Crustal Thickness: 3 models

- **Refraction and Reflection seismic waves:** CRUST 2.0
- **Surface seismic waves:** CUB 2.0
- **Gravitational potential field and gradiometer:** GEMMA



Abundance and Density

		ρ (g/cm^3)	d (km)	M (10^{21} kg)	Abundance			Mass			H (TW)
					U (μg/g)	Th (μg/g)	K (%)	U (10^{15} kg)	Th (10^{15} kg)	K, (10^{19} kg)	
CC	Sed	2.25[a]	1.5 ± 0.3	0.7 ± 0.1	1.73 ± 0.09	8.10 ± 0.59	1.83 ± 0.12	$1.2^{+0.2}_{-0.2}$	$5.8^{+1.1}_{-1.1}$	$1.3^{+0.2}_{-0.2}$	$0.3^{+0.1}_{-0.1}$
	UC	2.76	11.6 ± 1.3	6.7 ± 0.8	2.7 ± 0.6	10.5 ± 1.0	2.32 ± 0.19	$18.2^{+4.8}_{-4.3}$	$70.7^{+10.7}_{-10.2}$	$15.6^{+2.3}_{-2.1}$	$4.2^{+0.7}_{-0.6}$
	MC	2.88	11.4 ± 1.3	6.9 ± 0.9	$0.97^{+0.58}_{-0.36}$	$4.86^{+4.30}_{-2.25}$	$1.52^{+0.81}_{-0.52}$	$6.6^{+4.1}_{-2.5}$	$33.3^{+30.0}_{-15.5}$	$10.4^{+5.7}_{-3.7}$	$1.9^{+0.9}_{-0.6}$
	LC	3.05	10.0 ± 1.2	6.3 ± 0.7	$0.16^{+0.14}_{-0.07}$	$0.96^{+1.18}_{-0.51}$	$0.65^{+0.34}_{-0.22}$	$1.0^{+0.9}_{-0.4}$	$6.0^{+7.7}_{-3.3}$	$4.1^{+2.2}_{-1.4}$	$0.4^{+0.3}_{-0.1}$
	LM	3.37	140 ± 71	97 ± 47	$0.03^{+0.05}_{-0.02}$	$0.15^{+0.28}_{-0.10}$	$0.03^{+0.04}_{-0.02}$	$2.9^{+5.4}_{-2.0}$	$14.5^{+29.4}_{-9.4}$	$3.1^{+4.7}_{-1.8}$	$0.8^{+1.1}_{-0.6}$
OC	Sed	2.03	0.6 ± 0.2	0.3 ± 0.1	1.73 ± 0.09	8.10 ± 0.59	1.83 ± 0.12	$0.6^{+0.2}_{-0.2}$	$2.8^{+0.9}_{-0.9}$	$0.6^{+0.2}_{-0.2}$	$0.2^{+0.1}_{-0.1}$
	C	2.88	7.4 ± 2.6	6.3 ± 2.2	0.07 ± 0.02	0.21 ± 0.06	0.07 ± 0.02	$0.4^{+0.2}_{-0.2}$	$1.3^{+0.7}_{-0.5}$	$0.4^{+0.2}_{-0.2}$	$0.1^{+0.04}_{-0.03}$
DM[b]		4.66	2090	3207	0.008	0.022	0.015	25.7	70.6	48.7	6.0
EM[c]		5.39	710	704	0.034	0.162	0.041	24.0	113.7	28.7	6.3
BSE[d]		4.42	2891	4035	0.020	0.079	0.028	80.7	318.8	113.0	20.1

Crust density from CRUST 2.0, Mantle density from PREM

Abundance of Sed, UC: Direct Sampling

Abundance of MC, LC, LM: Seismic data + Lab measurement

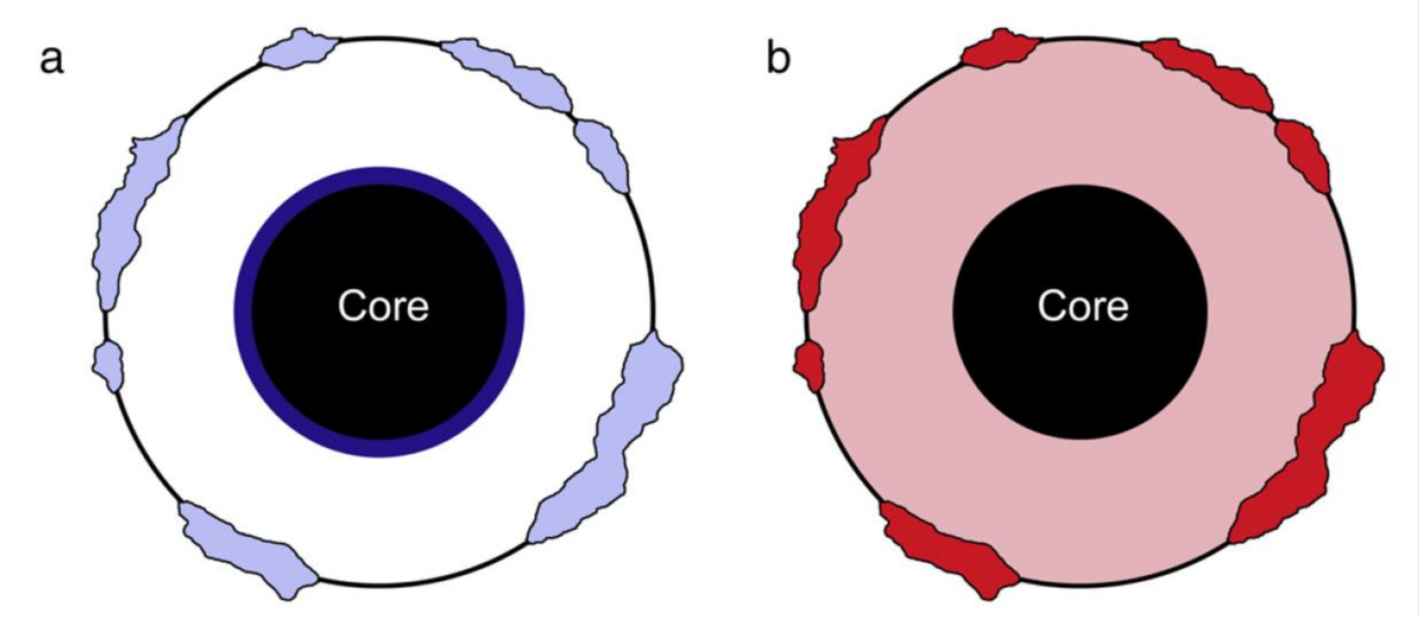
Made of felsic (长英质) fraction and mafic (镁铁质) fraction

$$f + m = 1$$
$$F_v \times f + F_m \times m = Vc$$
$$a = f \times a_f + m \times a_m$$

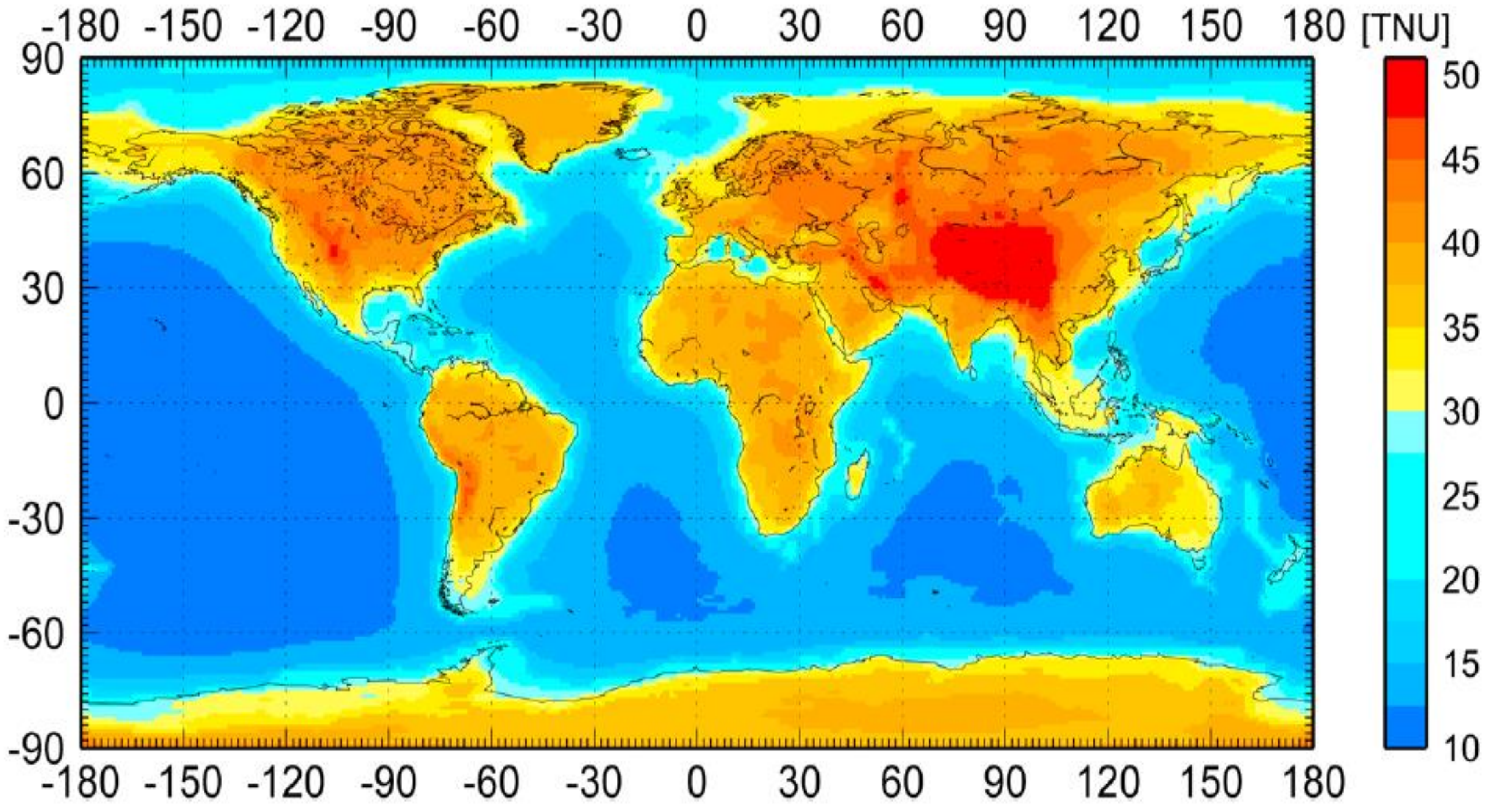
$$F_v = F_v(lab) + 2*(P-0.6) \times 10^{-4} - 4*(T-25) \times 10^{-4}$$
$$F_m = F_m(lab) + 2*(P-0.6) \times 10^{-4} - 4*(T-25) \times 10^{-4}$$

Mantle contribution: very uncertain

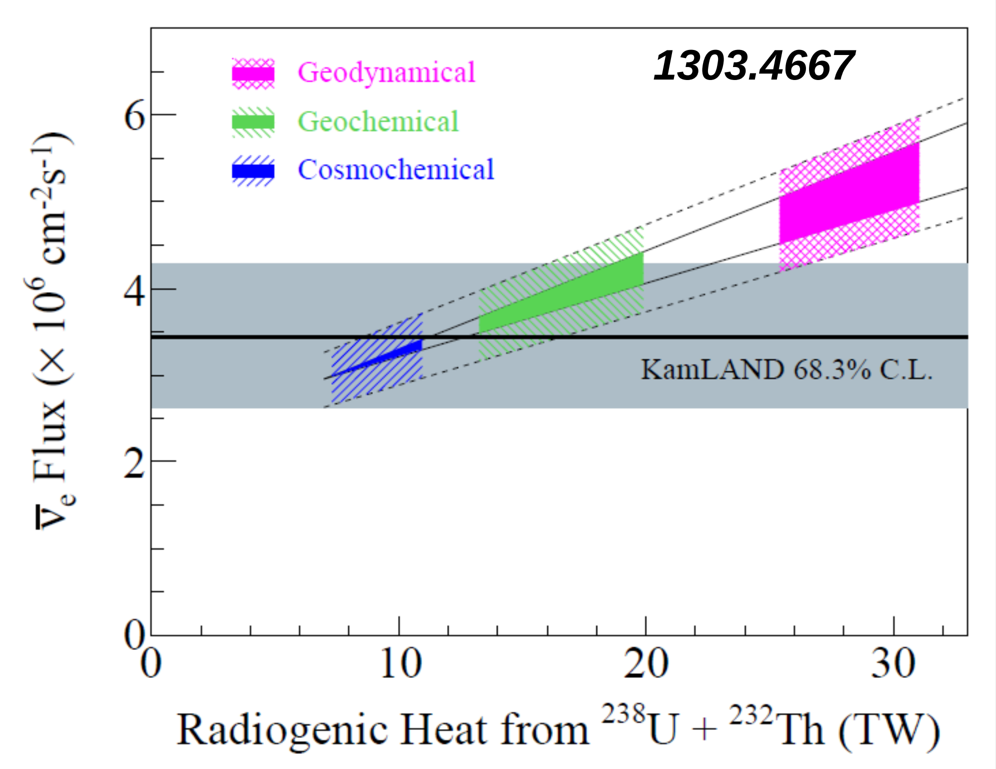
continental Lithospheric Mantle (LM):
the base of the continental crust, (as deep as 200 km)
the same treatment as the crust
depleted mantle (DM) and enriched mantle (EM):
homogeneous structure
very different mantle predictions

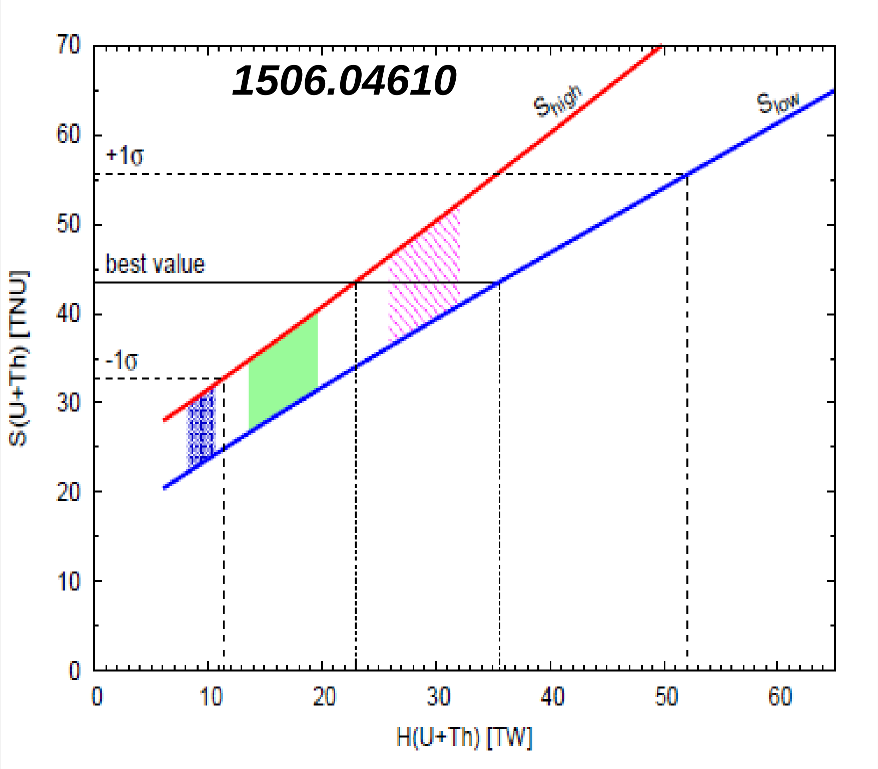


Predicted Global geo-neutrino flux



Model testing

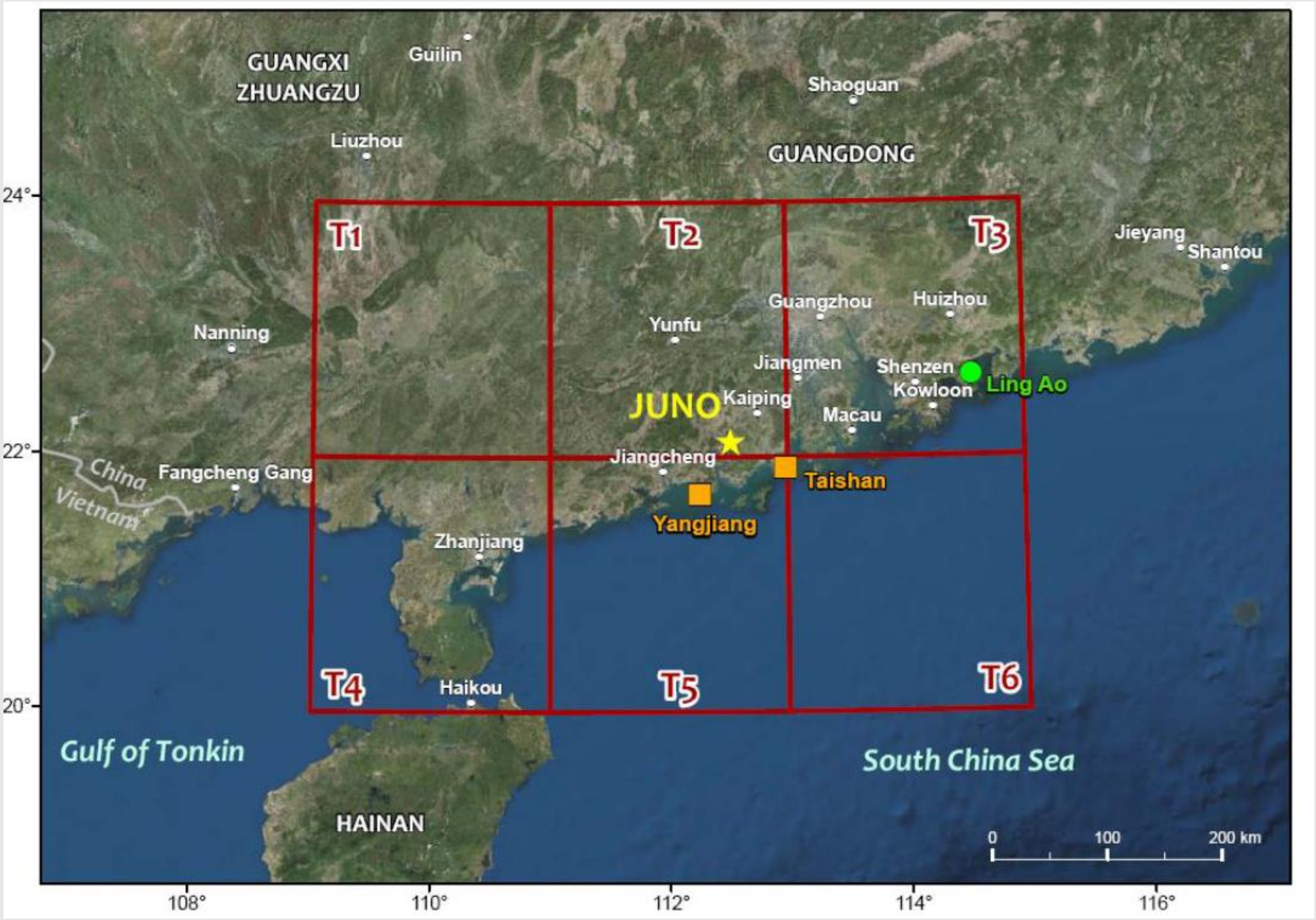




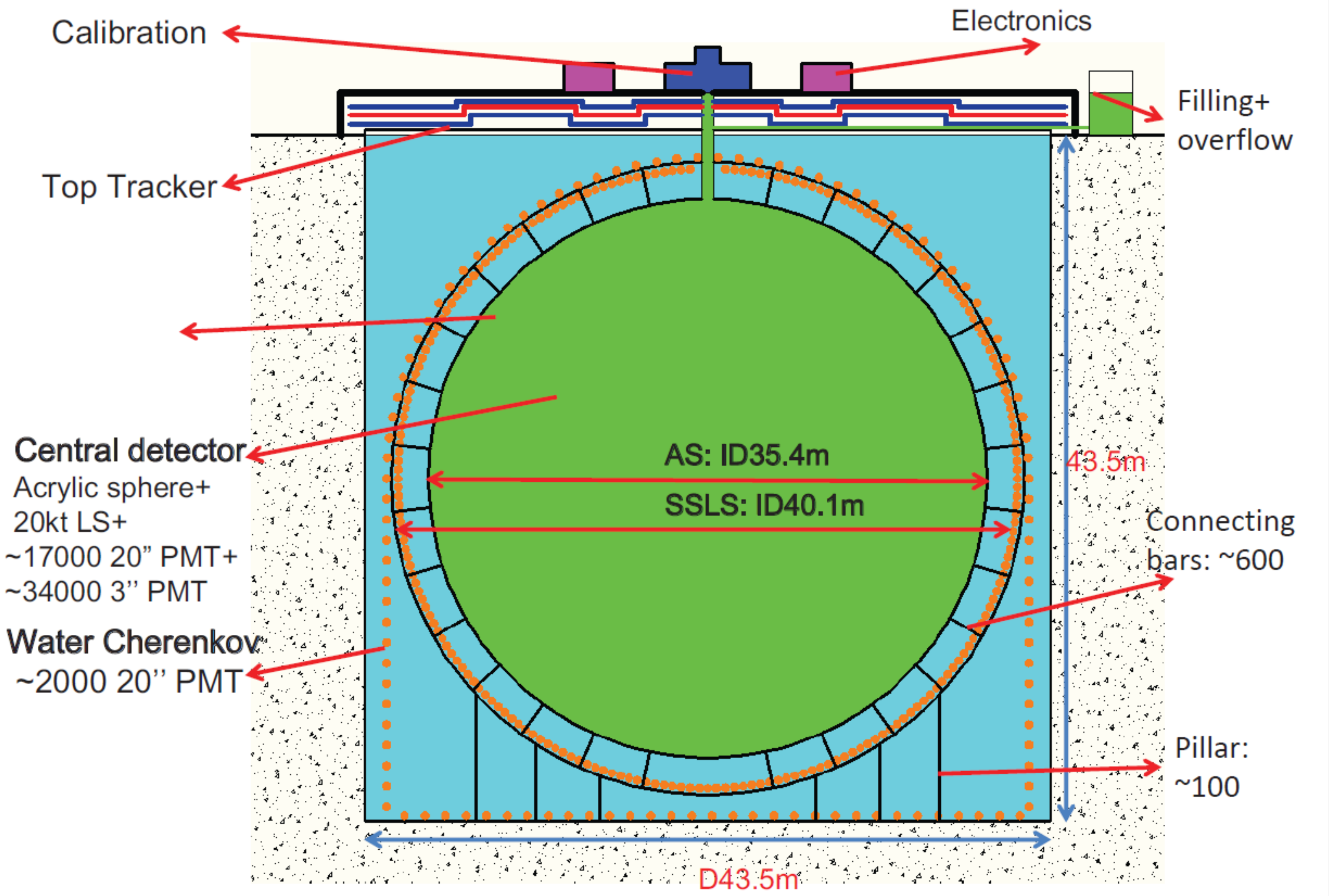
Current measurements (KamLAND and Borexino) versus different predictions

Still cannot distinguish models

Experimental site of JUNO



JUNO detector: 20 kt (versus 1 kt of KamLAND, 0.6kt of BX)



AS: Acrylic sphere; SSLS: stainless steel latticed shell

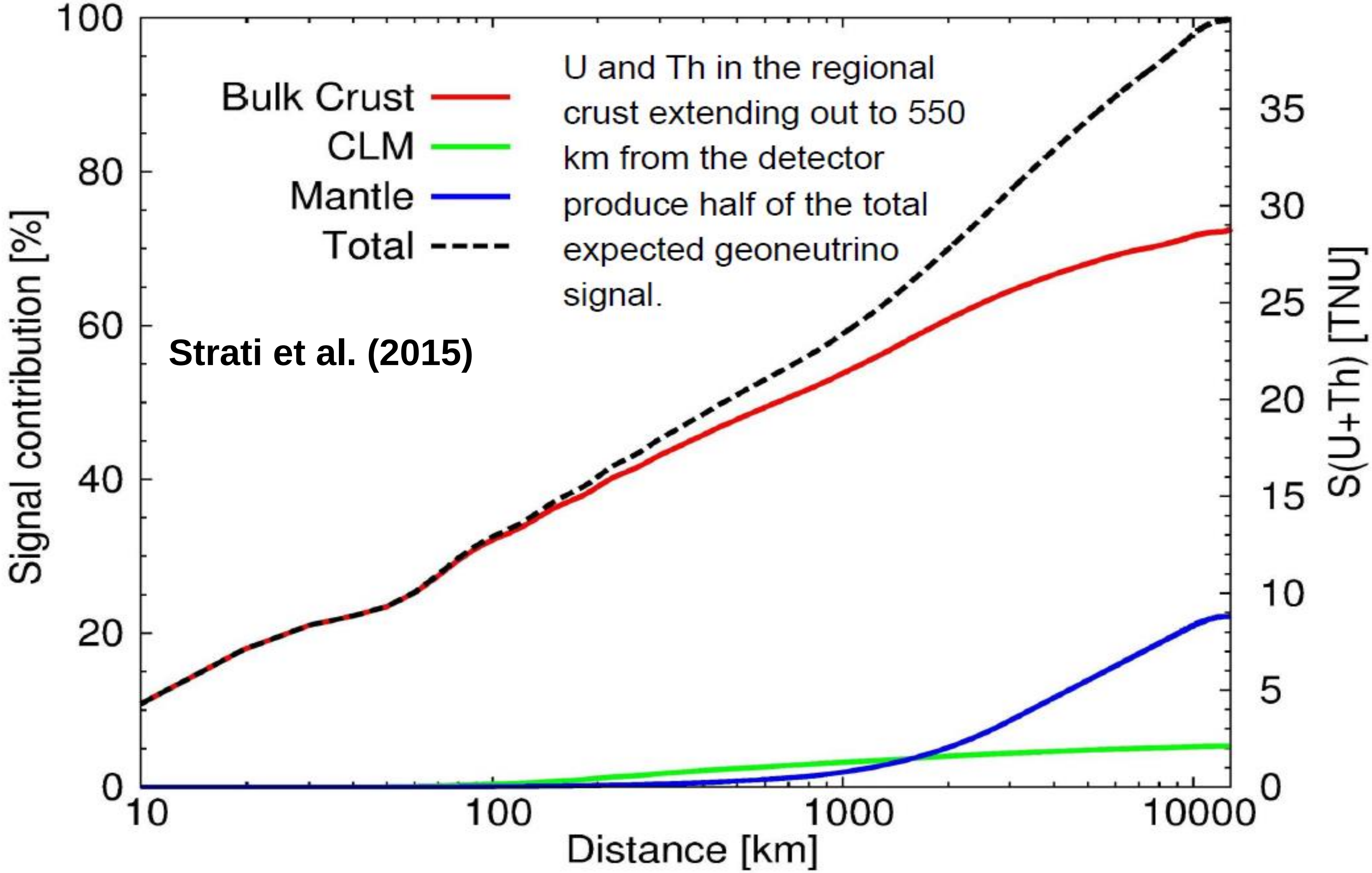
Predicted geo-neutrino flux at JUNO

Table 1. Geoneutrino signals from U and Th expected in JUNO. The inputs for the calculations are taken fromn (Huang et al. 2013) and the signals from different reservoirs indicated in the first column are in TNU.

Strati et al. (2015)

	S (U)	S (Th)	S (U+Th)
Sed CC	$0.5^{+0.1}_{-0.1}$	$0.16^{+0.02}_{-0.02}$	$0.64^{+0.1}_{-0.1}$
UC	$14.6^{+3.5}_{-3.4}$	$3.9^{+0.5}_{-0.5}$	$18.5^{+3.6}_{-3.4}$
MC	$4.7^{+3.0}_{-1.8}$	$1.7^{+1.6}_{-0.8}$	$6.8^{+3.6}_{-2.3}$
LC	$0.9^{+0.7}_{-0.4}$	$0.4^{+0.7}_{-0.2}$	$1.5^{+1.0}_{-0.6}$
Sed OC	$0.08^{+0.02}_{-0.02}$	$0.03^{+0.01}_{-0.01}$	$0.11^{+0.02}_{-0.02}$
OC	$0.05^{+0.02}_{-0.02}$	$0.01^{+0.01}_{-0.01}$	$0.06^{+0.02}_{-0.02}$
Bulk Crust	$21.3^{+4.8}_{-4.2}$	$6.6^{+1.9}_{-1.2}$	$28.2^{+5.2}_{-4.5}$
CLM	$1.3^{+2.4}_{-0.9}$	$0.4^{+1.0}_{-0.3}$	$2.1^{+2.9}_{-1.3}$

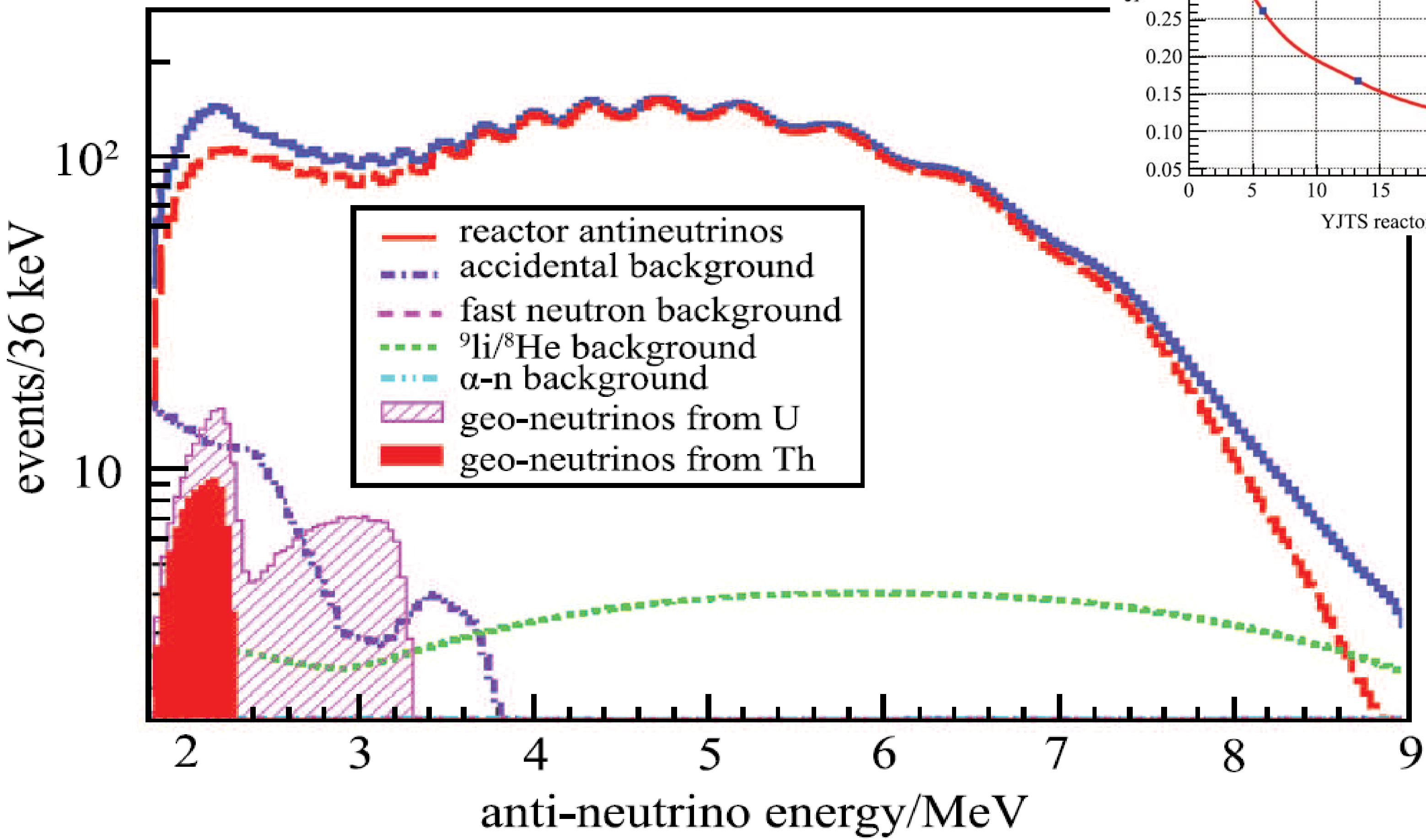
Cumulative geo-neutrino signal

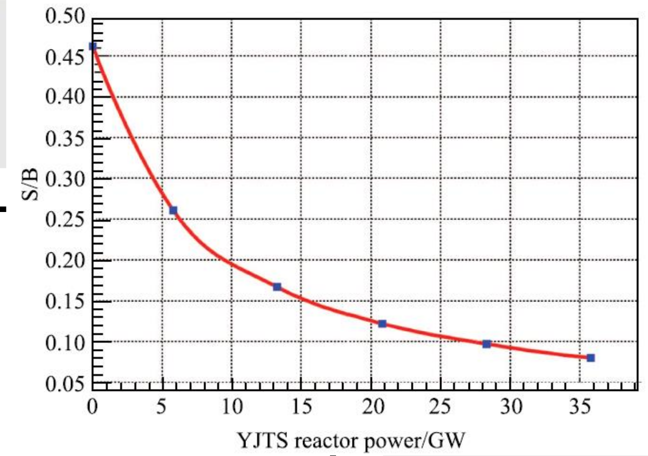


An independent calculation: R. Han, J.C. He & Y.F. Li

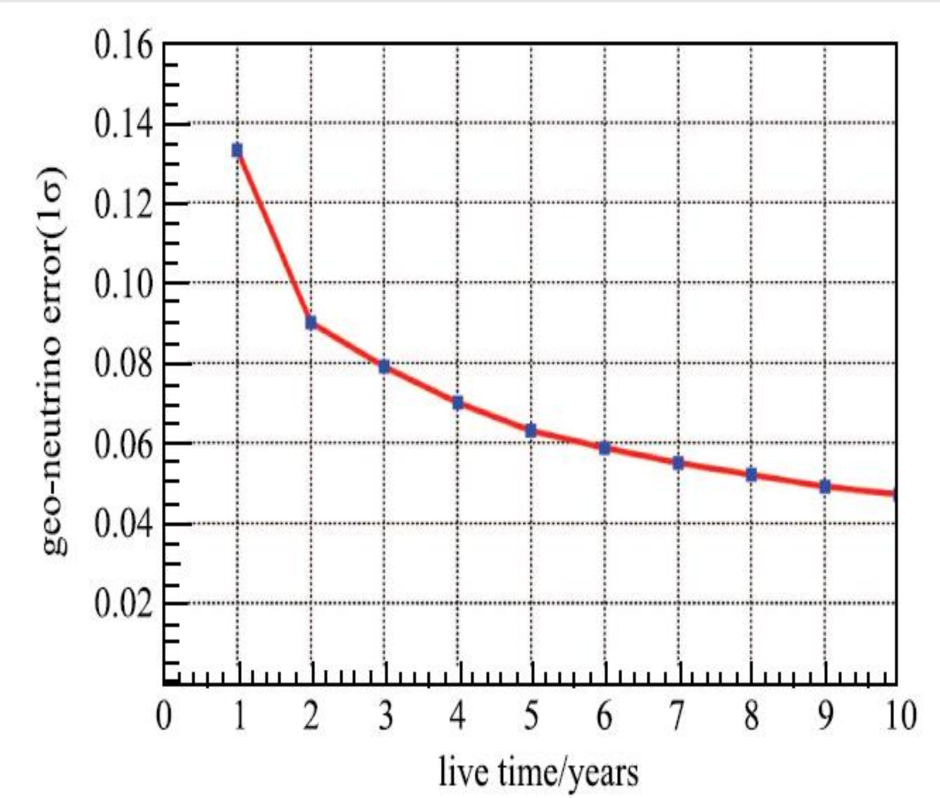
Layer	Our S(U)	Other S(U)	Our S(Th)	Other S(Th)	Our Total signal	Other Total signal
Sed	0. 778	0. 5	0. 253	0. 16	1. 031	0. 64
UC	15. 153	14. 6	4. 089	3. 9	19. 242	18. 5
MC	4. 887	4. 7	1. 699	1. 7	6. 586	6. 8
LC	0. 724	0. 9	0. 302	0. 4	1. 026	1. 5
SUM	21. 543	21. 3	6. 342	6. 6	27. 885	28. 2

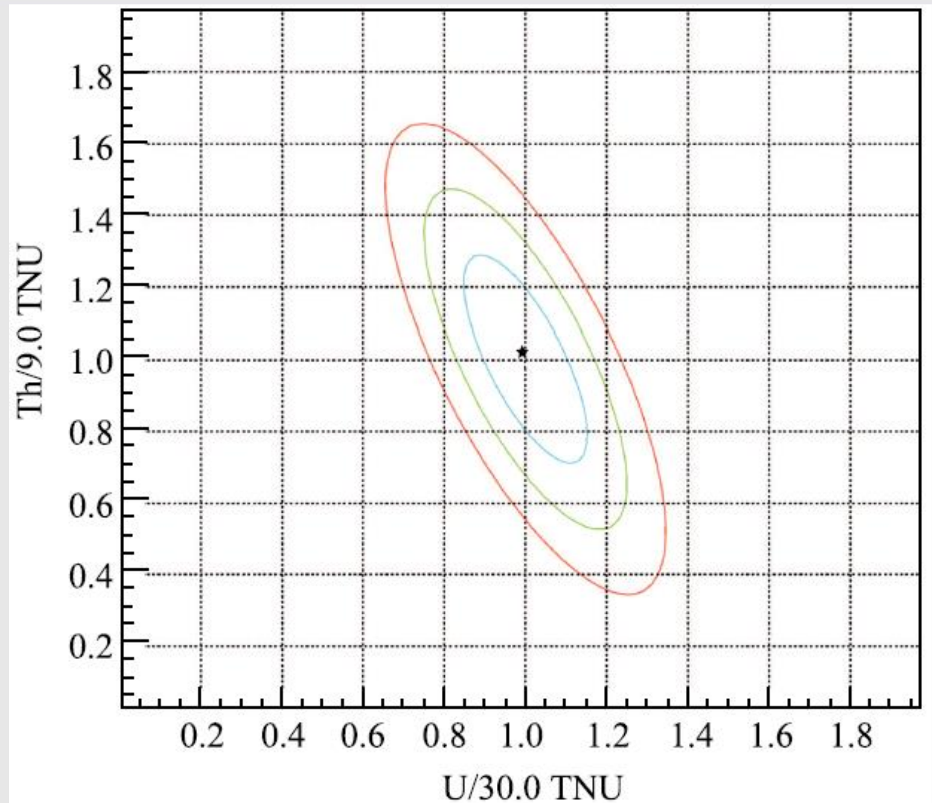
Signal and background: Yellow book & Han et al. (2015)





Physics Potential: Han et al. (2015)



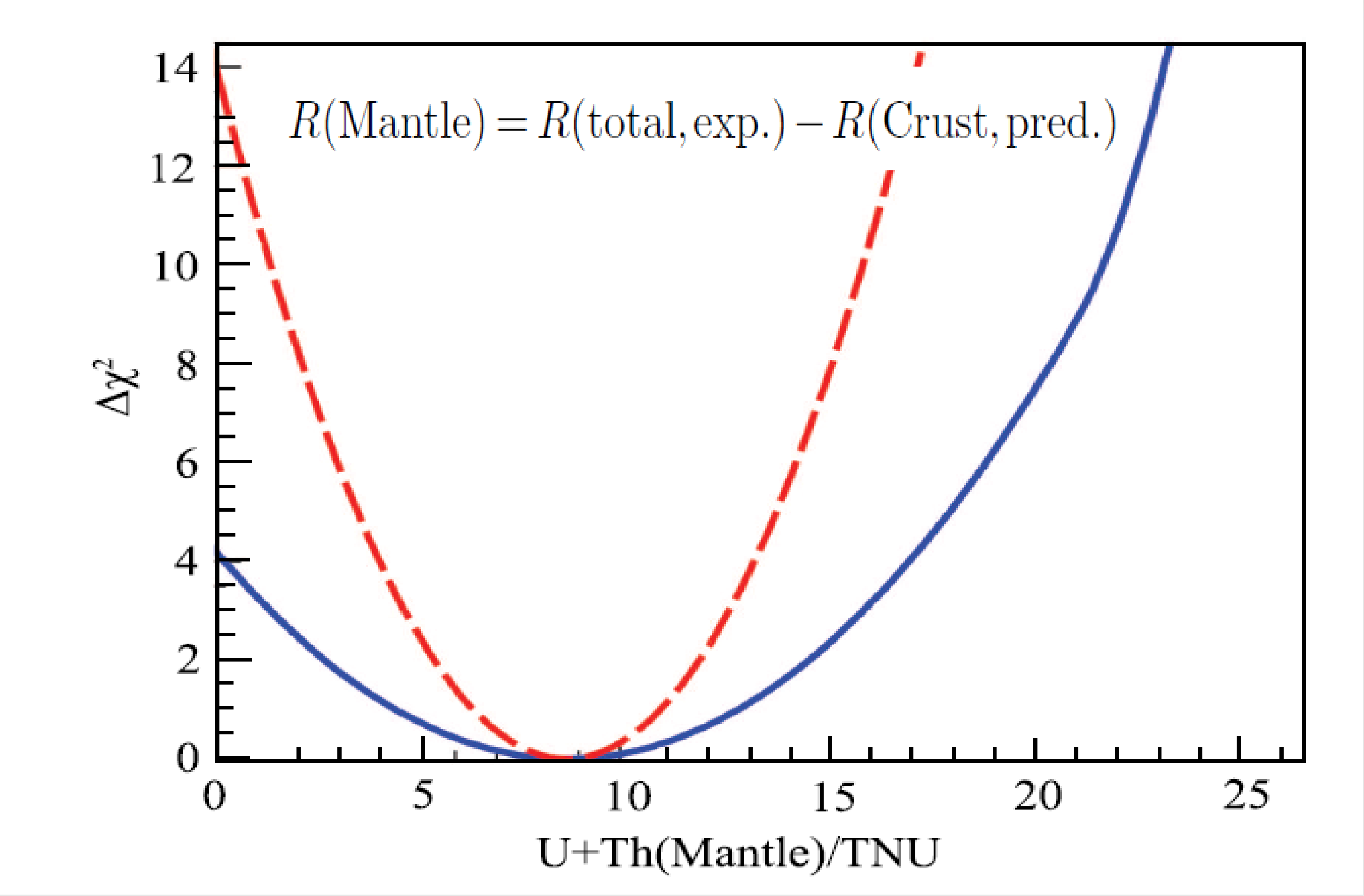


With 10 years:

Total uncertainty reach 5% (2 TNU)

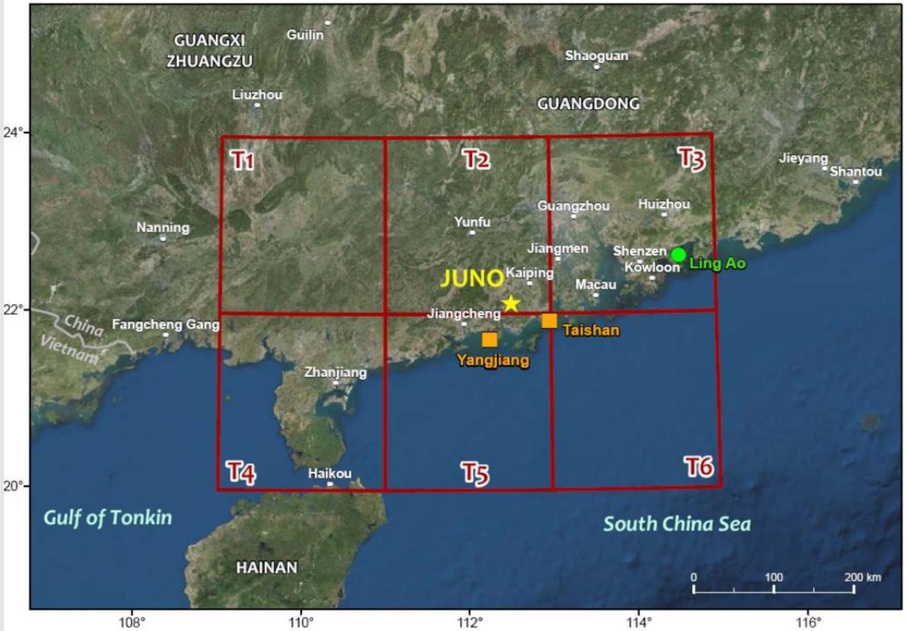
U: 15% and Th: 30% assuming with a free Th/U ratio

Extracting the mantle contribution



Comparison of the global reference model (18% crust) and a benchmark accuracy of the local model (8% crust)

Refinement with local data: mandatory



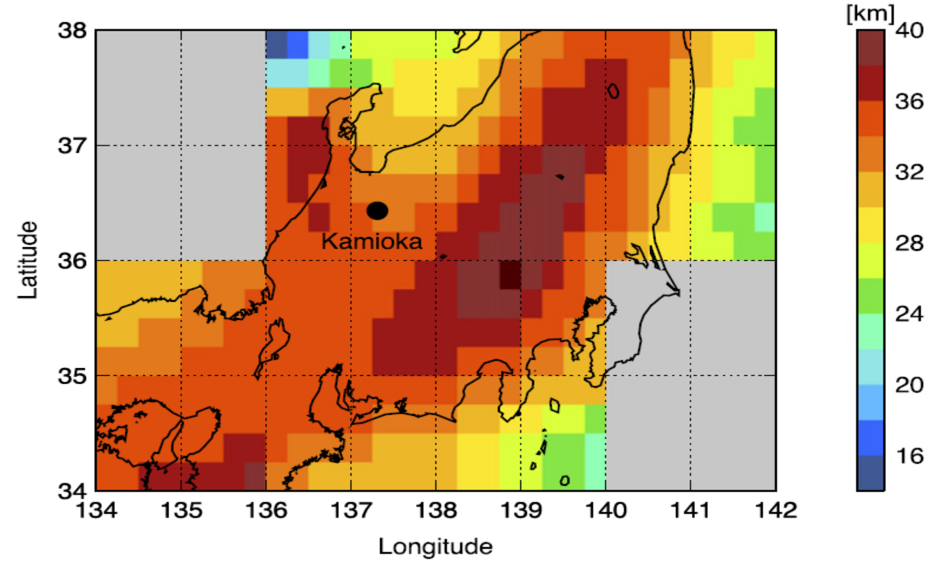


Fig. 8. Moho depth of the local refined model around KamLAND [93].

T2 produces $10.8^{+2.1}_{-1.8}$ TNU, corresponding to 27% of the total geo-neutrino signal.

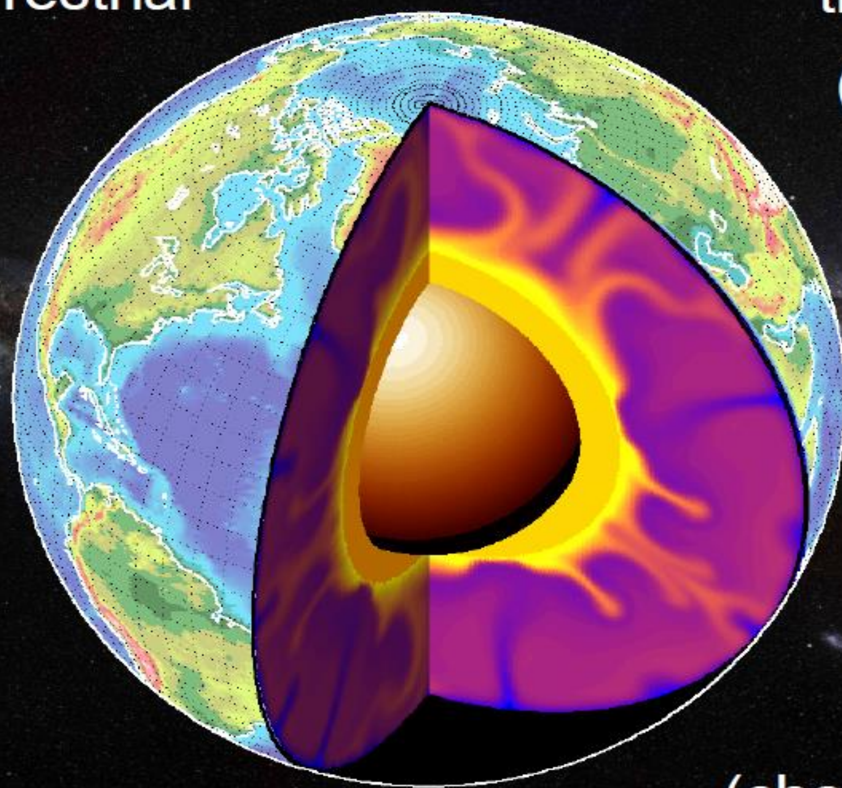
Characterized by a thick UC, which gives $7.6^{+1.5}_{-1.4}$ TNU, a refined geophysical and geochemical model of the UC of this Tile is highly desired.

Need help from our geo scientists!

Open questions about natural radioactivity in the Earth

- ✓ What is the radiogenic contribution to terrestrial heat production?
- ✓ How much U and Th in the crust and in the mantle?
- ✓ What is the distribution of radioactivity in the mantle?
- ✓ What is hidden in the Earth's core? (geo-reactors…)

From Fabio Mantovani



- ✓ What are the building blocks (chondritic meteorites) that formed the Earth?

Future prospective

Geo-neutrino measurement:

Directionality:
a limitation of current LS detectors → Li6/B10 doped

Site:
ocean-based detector to minimize the crustal signal

Geoscience:
Using all available geological/geophysical/geochemical data, heat flux data, and geo-neutrino data

A reference earth model→ a standard earth model

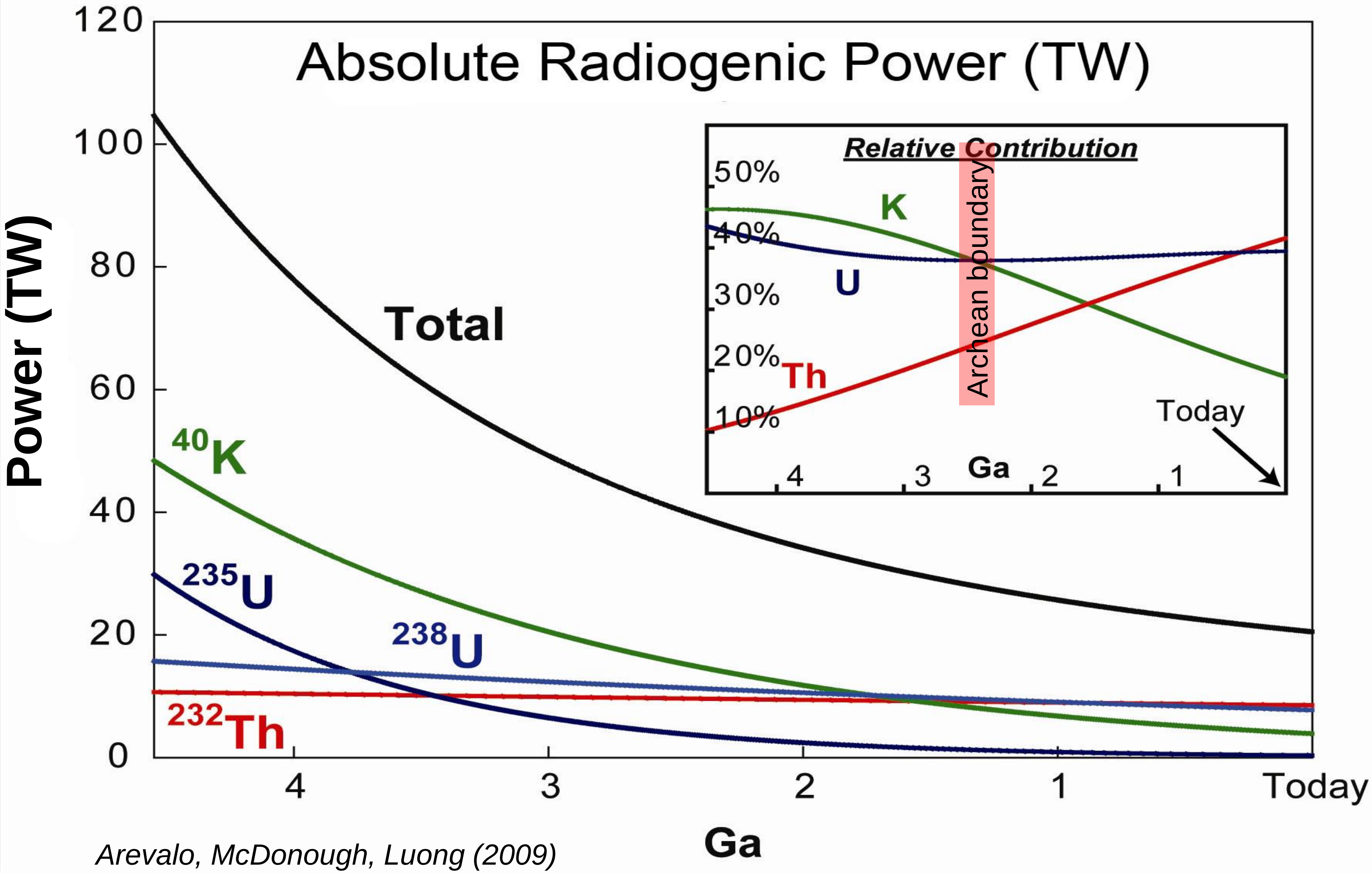
Thank you

Backup

Table 1
Properties of the Earth. Data from [32,33,17,28].

Radii [m]	
Mean radius of the Earth	$6{,}371{,}010 \pm 20$
Equatorial radius	$6{,}378{,}138 \pm 2$
Polar axis	6,356,752
Inner (solid) core radius	$(1.220 \pm 10) \times 10^6$
Outer (liquid) core radius	$(3.483 \pm 5) \times 10^6$
Thickness [m]	
Continental crust	$(34 \pm 4) \times 10^3$
Oceanic crust	$(8.0 \pm 2.7) \times 10^3$
Mass [kg]	
Earth	5.9736×10^{24}
Inner (solid) core	9.675×10^{22}
Outer (liquid) core	1.835×10^{24}
Core	1.932×10^{24}
Mantle	4.043×10^{24}
Oceanic crust	$(0.67 \pm 0.23) \times 10^{22}$
Continental crust	$(2.06 \pm 0.25) \times 10^{22}$
Bulk crust	$(2.73 \pm 0.48) \times 10^{22}$
Ocean	1.4×10^{21}
Atmosphere	5.1×10^{18}
Fractional mass contributions	
-Bulk silicate Earth	
Oceanic crust	0.17%
Continental crust	0.51%
Mantle	99.32%
- Earth	
Silicate Earth	67.7%
Core	32.3%
Inner core to bulk core	5.0%
Volume [m^3]	
Earth	1.083×10^{21}
Inner (solid) core	7.606×10^{18}
Outer (liquid) core	1.694×10^{20}
Bulk core	1.770×10^{20}
Bulk silicate Earth	9.138×10^{20}

Earth's thermal evolution: role of K, Th & U

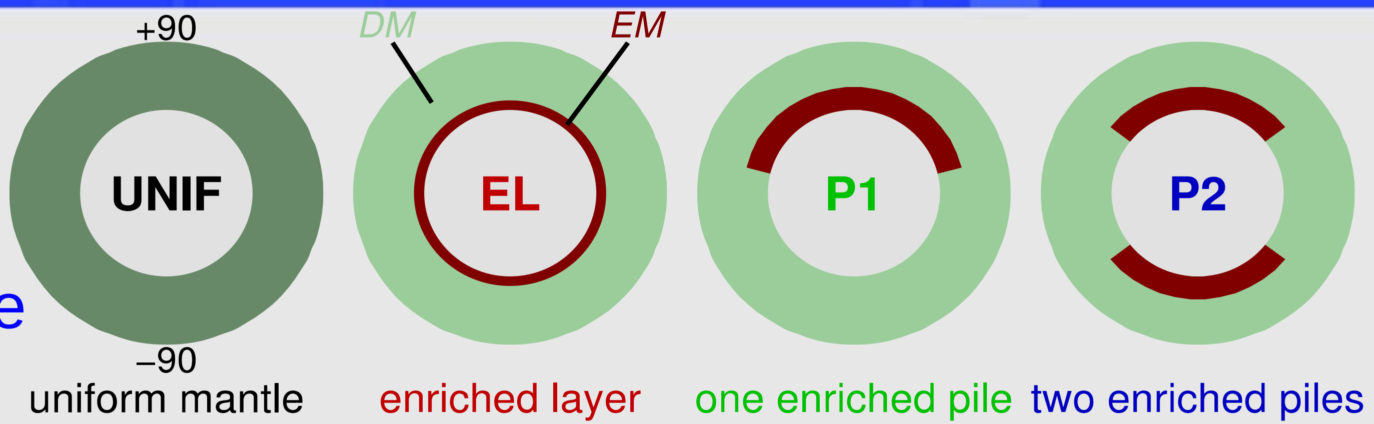


Arevalo, McDonough, Luong (2009)

Models for understand Th & U in the Modern Mantle

Inputs

- Bulk Sil. Earth
- Cont. Crust
- Depleted Mantle



Data vs Models