Geoneutrinos

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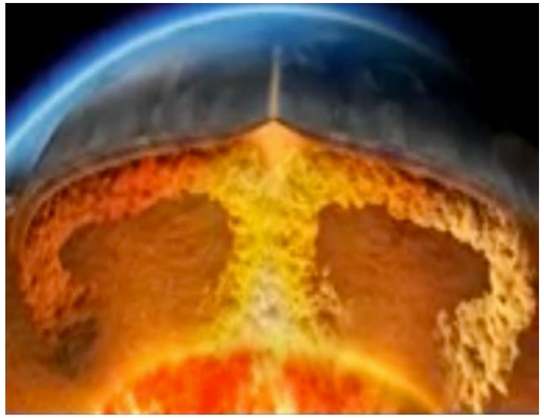
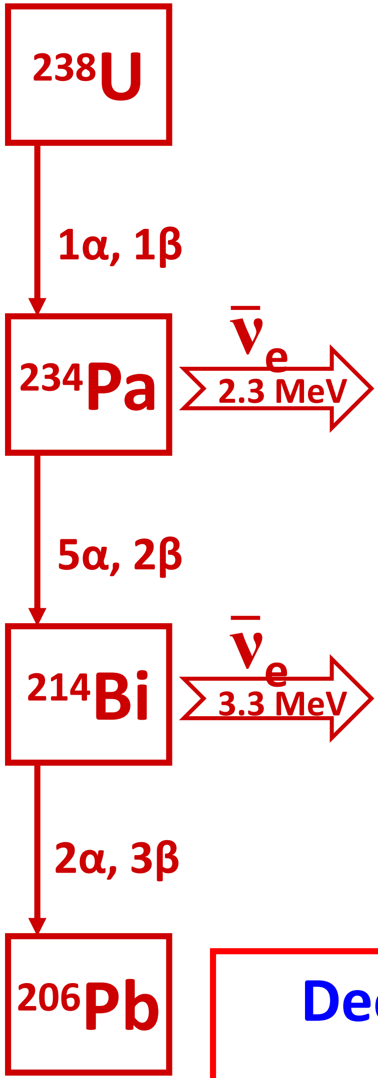
Outline

- What are Geoneutrinos?
- Important Questions in Geosciences(related to geoneutrinos)
- Results from Current Experiments Measurements (KamLAND and Borexino)
- Precise Measures to Future Experiments(JUNO)

What are Geoneutrinos ?

$\sim 10^6/\mathrm{s}/\mathrm{cm}^2$





^{238}U

1α, 1β

^{234}Pa → $\bar{\nu}_e$ 2.3 MeV

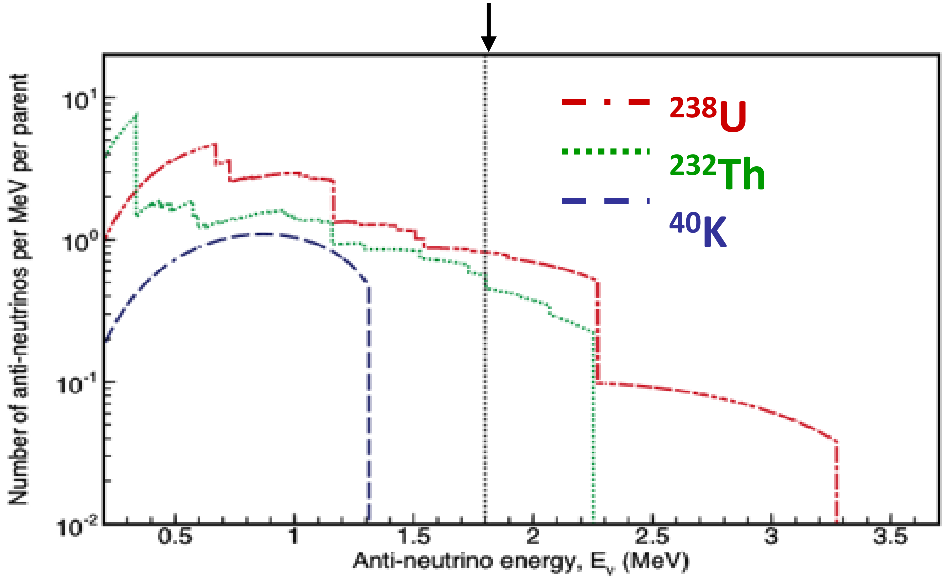
5α, 2β

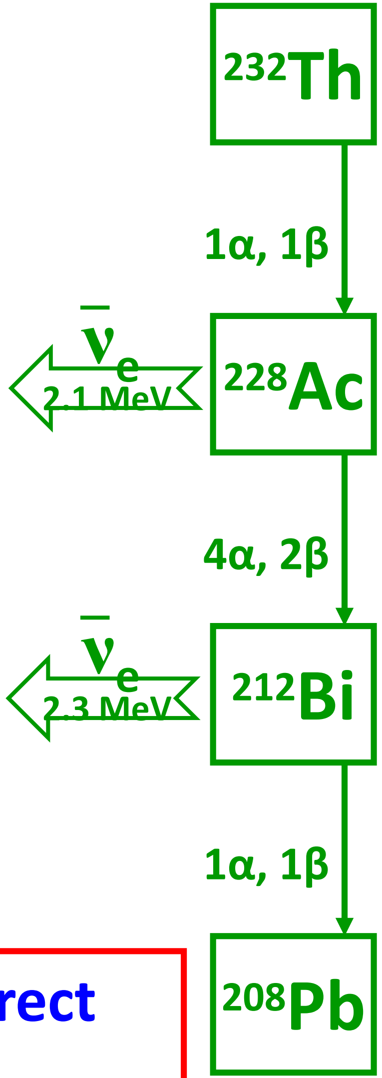
^{214}Bi → $\bar{\nu}_e$ 3.3 MeV

2α, 3β

^{206}Pb

Terrestrial Antineutrinos





^{232}Th

1α, 1β

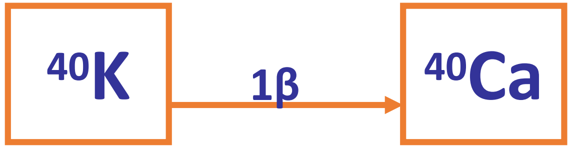
^{228}Ac → $\bar{\nu}_e$ 2.1 MeV

4α, 2β

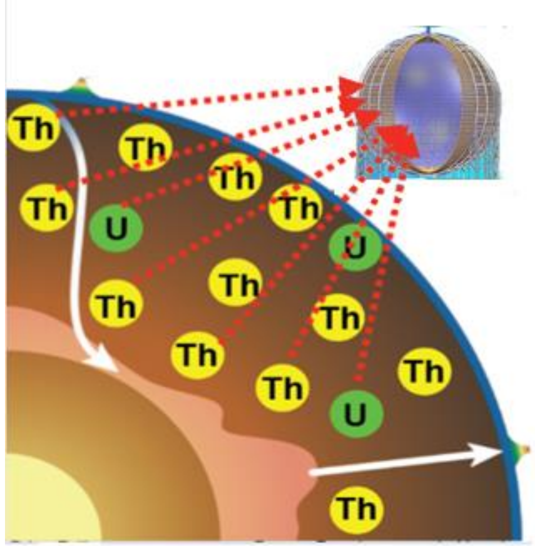
^{212}Bi → $\bar{\nu}_e$ 2.3 MeV

1α, 1β

^{208}Pb



^{40}K → 1β → ^{40}Ca



Decaying HPEs emit antineutrinos in direct proportion to their heating power

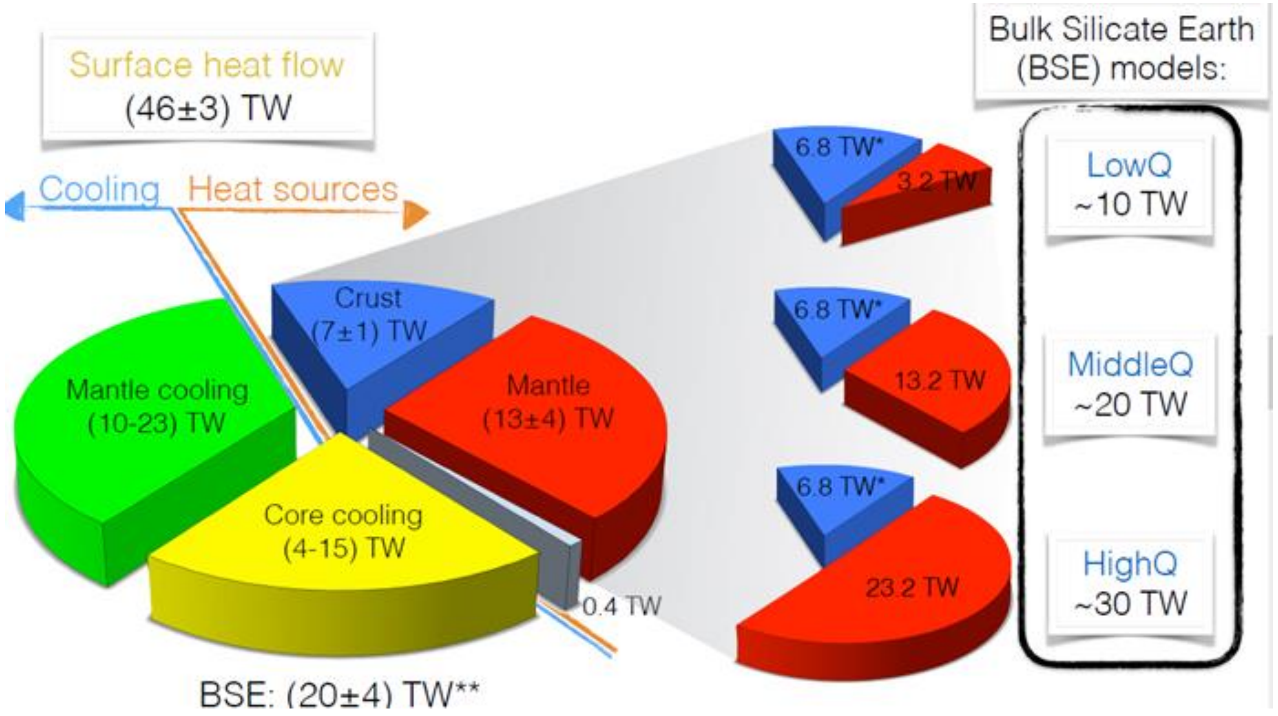
TNU is defined as the event number per 10^{32} target proton per year

Important Questions in Geosciences(related to geoneutrinos)

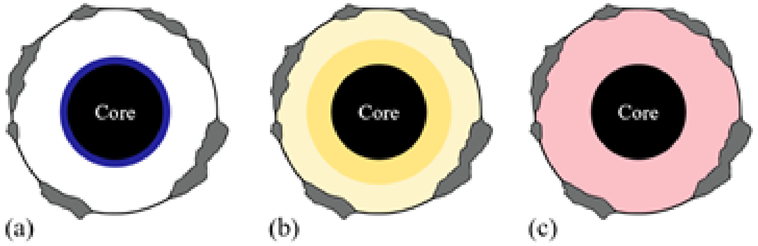
✓what is the radiogenic contribution (U, Th, 40K) to heat flow and energetics in the deep Earth?

✓are the fundamental ideas about Earth's chemical composition and origin correct?

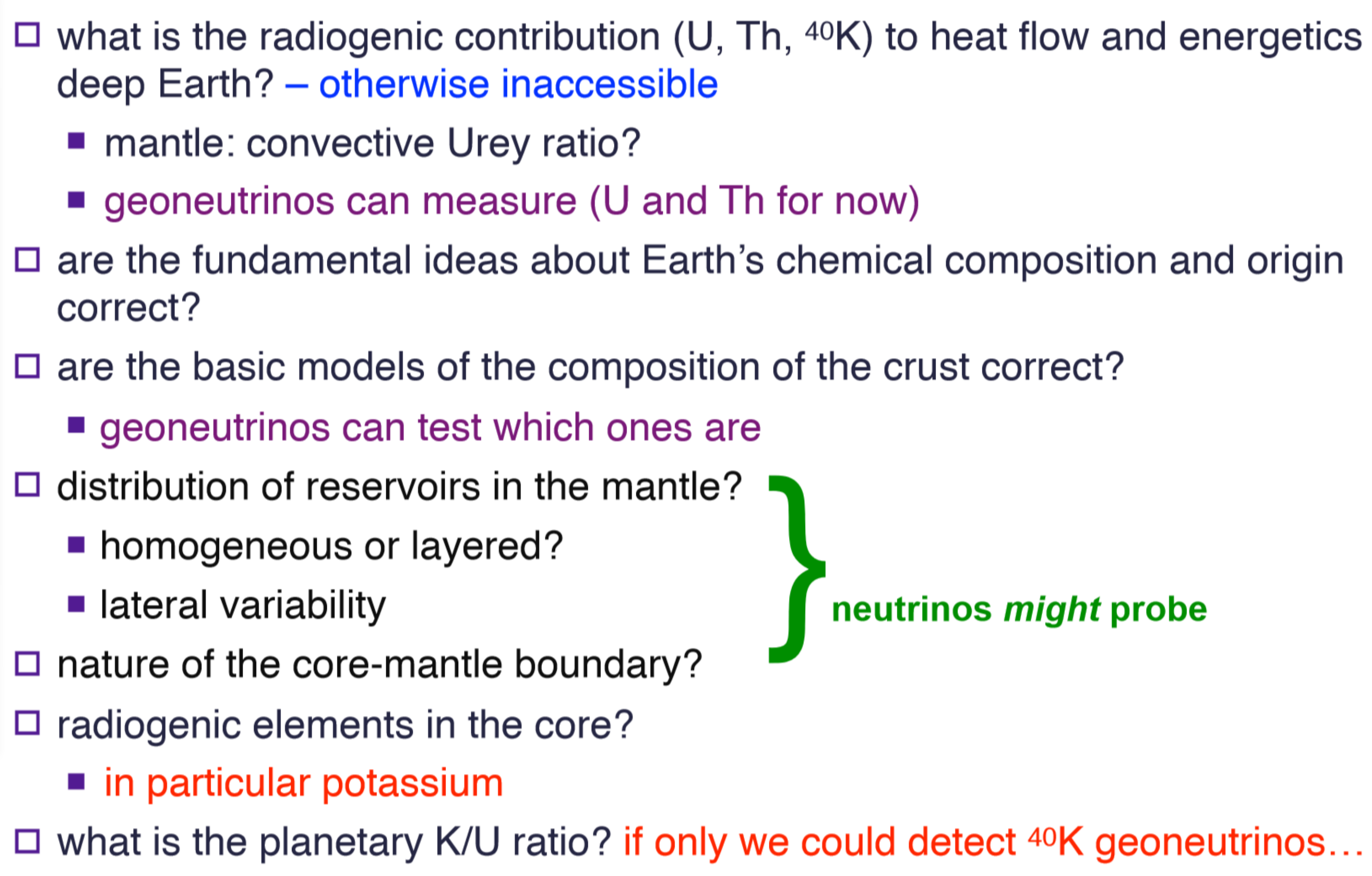
✓ are the basic models of the composition of the crust correct?



- "Cosmochemical" models
  - EH enstatite chondrite (Javoy et al., 2010)
    - 11-14 TW radiogenic heat
- "Geochemical" models
  - CI chondrite (Rocholl & Jochum, 1993; McDonough & Sun 1995)
    - 17-19 TW radiogenic heat
- "Physical" or "Geodynamical" models
  - energetics of mantle convection (Turcotte & Schubert, 2002)
    - 27-35 TW radiogenic heat



Important Questions in Geosciences(related to geoneutrinos)



- ☐ what is the radiogenic contribution (U, Th, ^{40}K) to heat flow and energetics in the deep Earth? – otherwise inaccessible
  - ■ mantle: convective Urey ratio?
  - ■ geoneutrinos can measure (U and Th for now)
- ☐ are the fundamental ideas about Earth’s chemical composition and origin correct?
- ☐ are the basic models of the composition of the crust correct?
  - ■ geoneutrinos can test which ones are
- ☐ distribution of reservoirs in the mantle?
  - ■ homogeneous or layered?
  - ■ lateral variability
- ☐ nature of the core-mantle boundary?

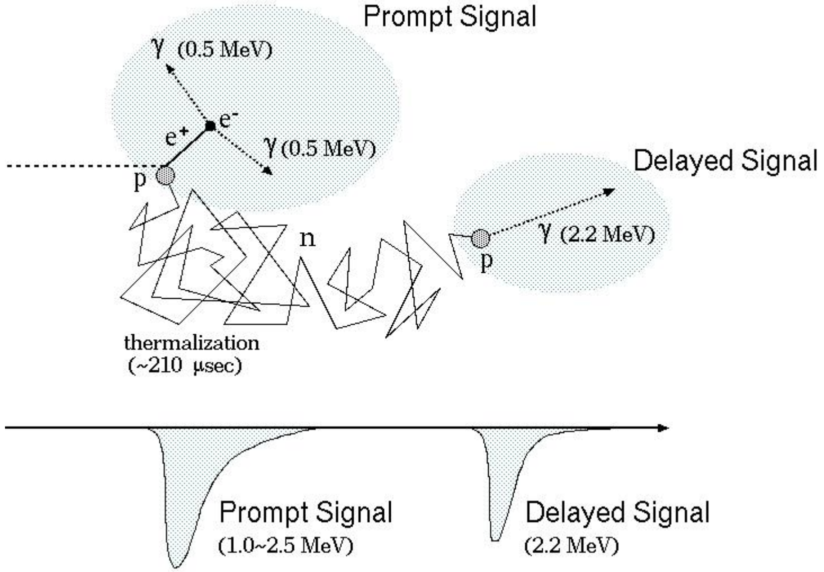
} **neutrinos *might* probe**

- ☐ radiogenic elements in the core?
  - ■ in particular potassium
- ☐ what is the planetary K/U ratio? if only we could detect ^{40}K geoneutrinos…

From Mark CHEN’s slide in Geo-neutrino 2019

Capture the Geoneutrinos

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



e+ and n correlated in time and in position in the liquid scintillator detector

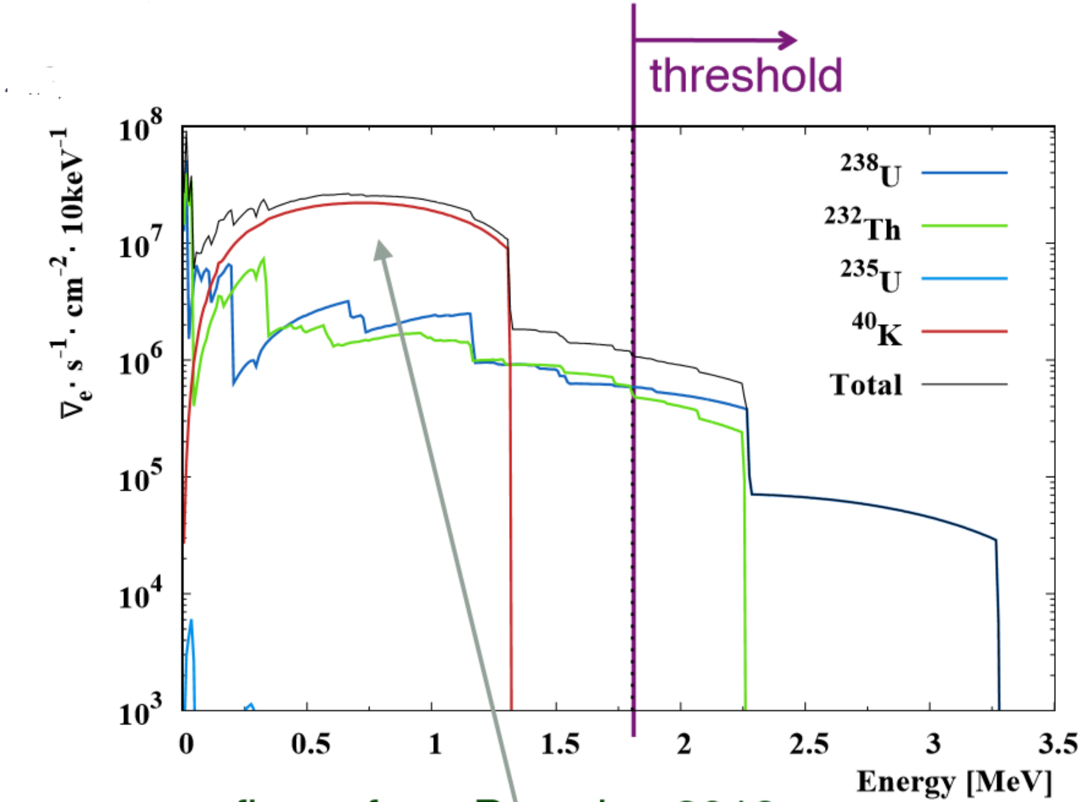
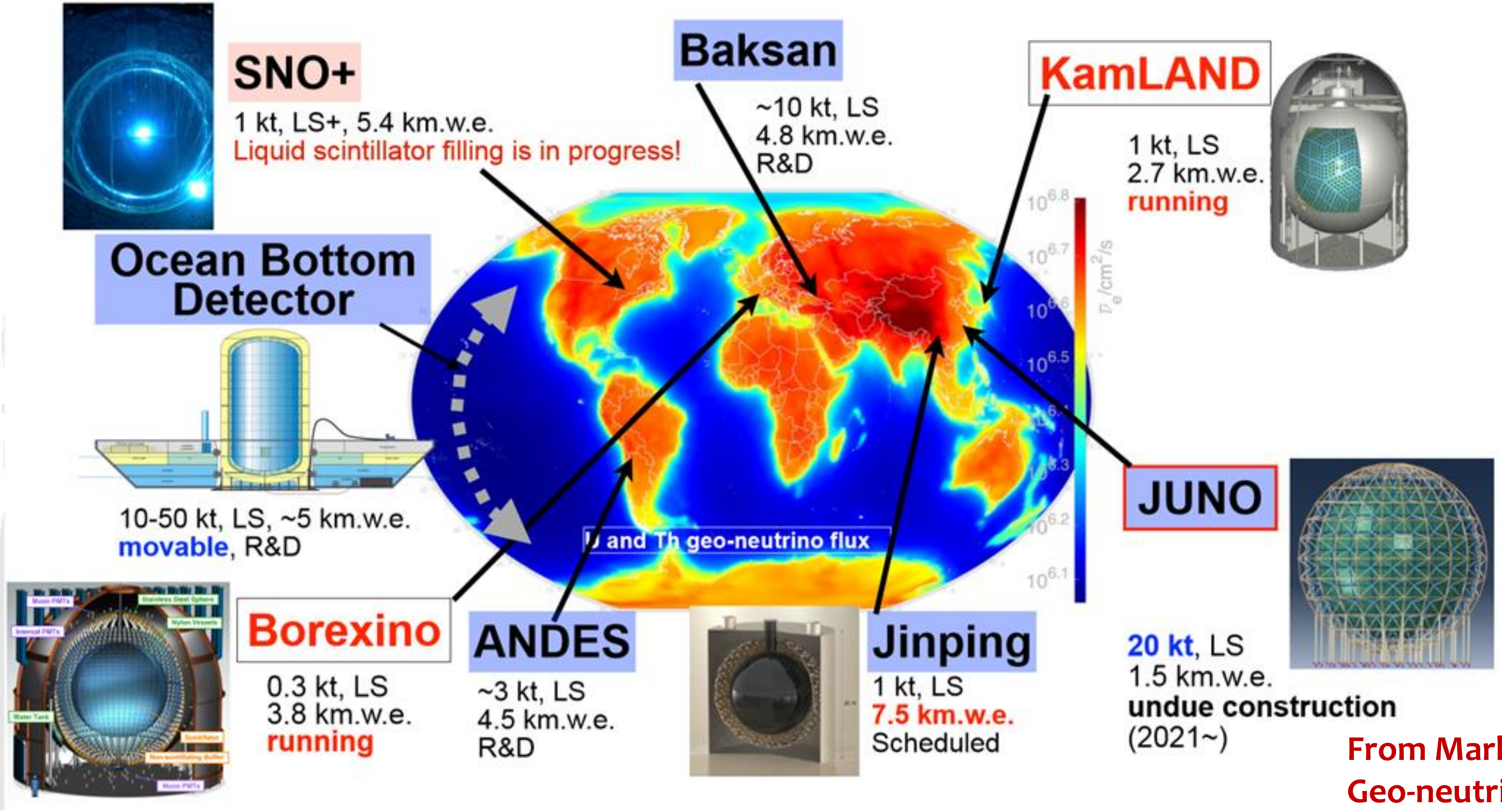


figure from Borexino 2019 paper

can't detect ^{40}K geoneutrinos with this reaction

Geoneutrino Projects around the Globe



SNO+
1 kt, LS+, 5.4 km.w.e.
Liquid scintillator filling is in progress!

Baksan
~10 kt, LS
4.8 km.w.e.
R&D

KamLAND
1 kt, LS
2.7 km.w.e.
running

Ocean Bottom Detector
10-50 kt, LS, ~5 km.w.e.
movable, R&D

JUNO
20 kt, LS
1.5 km.w.e.
undue construction
(2021~)

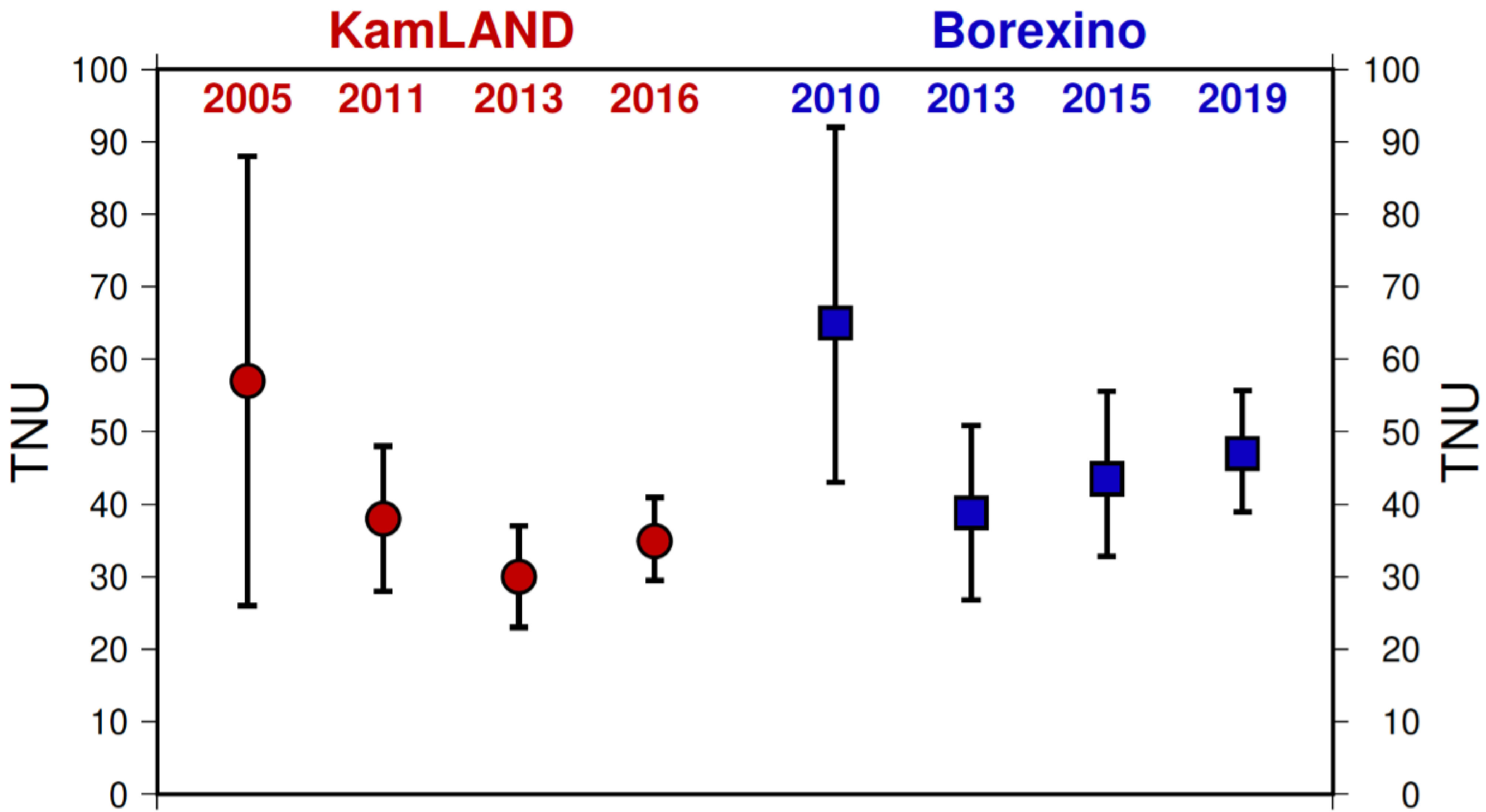
Borexino
0.3 kt, LS
3.8 km.w.e.
running

ANDES
~3 kt, LS
4.5 km.w.e.
R&D

Jinping
1 kt, LS
7.5 km.w.e.
Scheduled

From Mark CHEN's slide in Geo-neutrino 2019

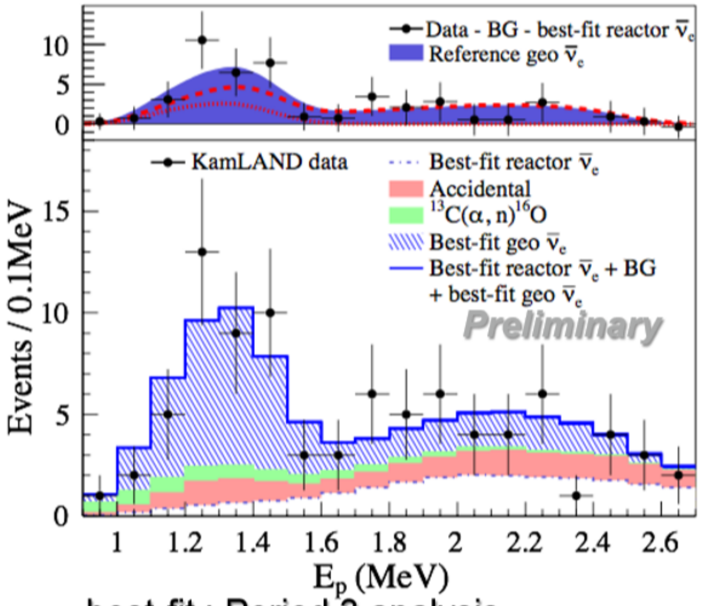
Physics results from the experiments in Japan and Italy



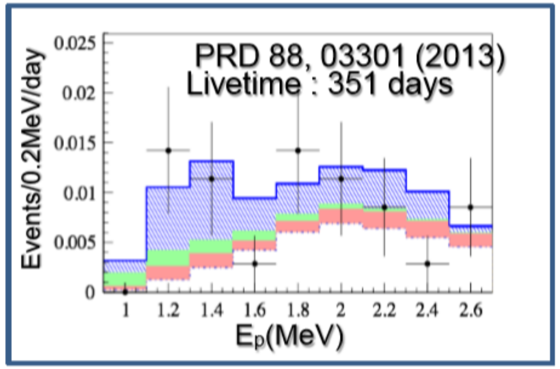
KamLAND 2016 Geoneutrino Published Result

Livetime : 1259.8 days   2016 Preliminary Result

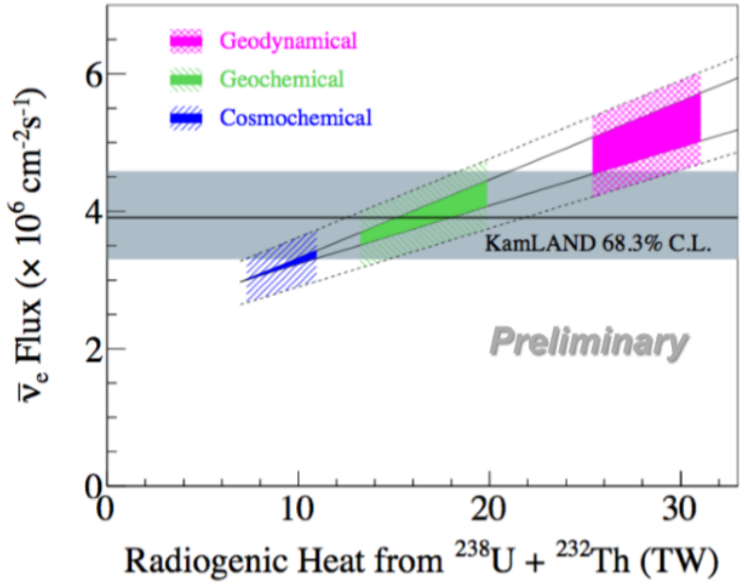
model prediction : Enomoto et al. EPSL 258, 147 (2007)



best-fit : Period 3 analysis



We measured clear distribution of geo-neutrino events!



Rate+Shape+time analysis (ratio fixed)

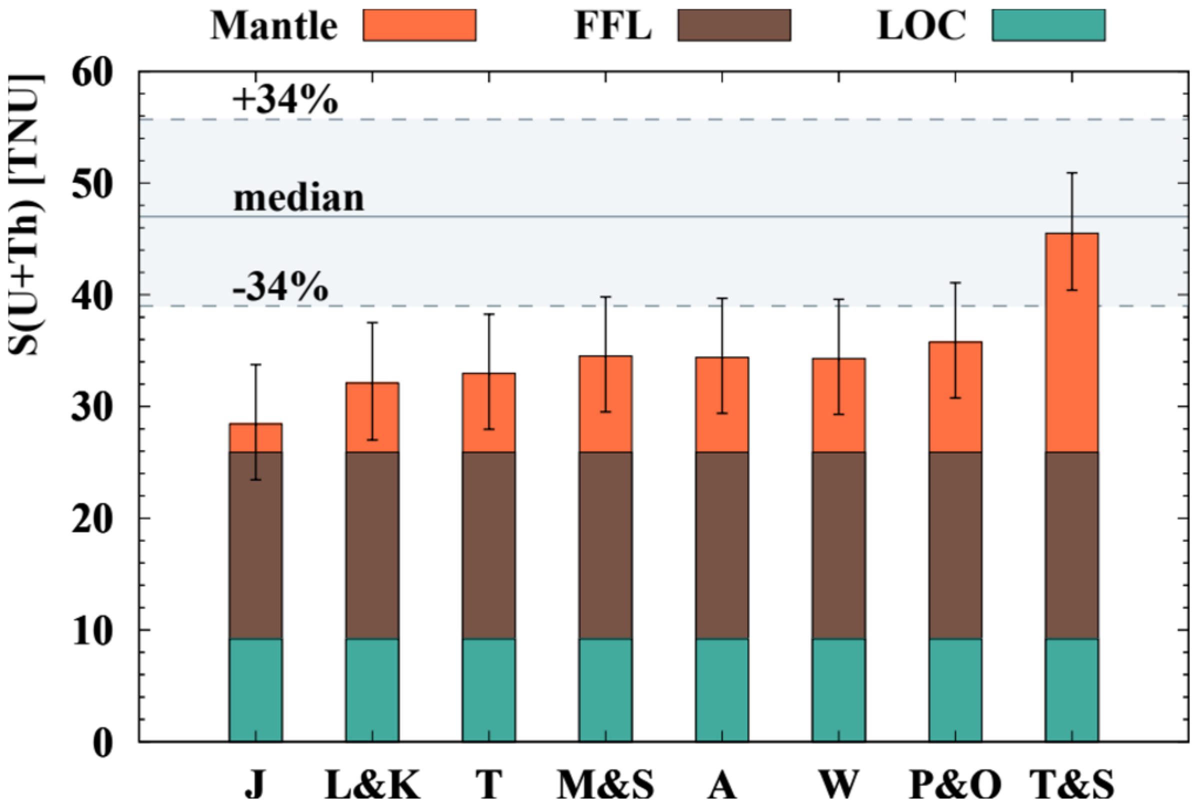
	[event]	[TNU]	Flux [$\times 10^6$ cm^{-2}s^{-1}]		0 signal rejection
			best-fit	model	
U+Th	164 +28/-25 (17%)	34.9 +6.0/-5.4	3.9 +0.7/-0.6	4.1	7.92σ

solid line – model band varies between homogeneous mantle and sunken-layer hypothesis ;

dashed line – incorporates crustal contribution uncertainty

slide from Hiroko Watanabe

Geoneutrino Signal at Borexino 2019

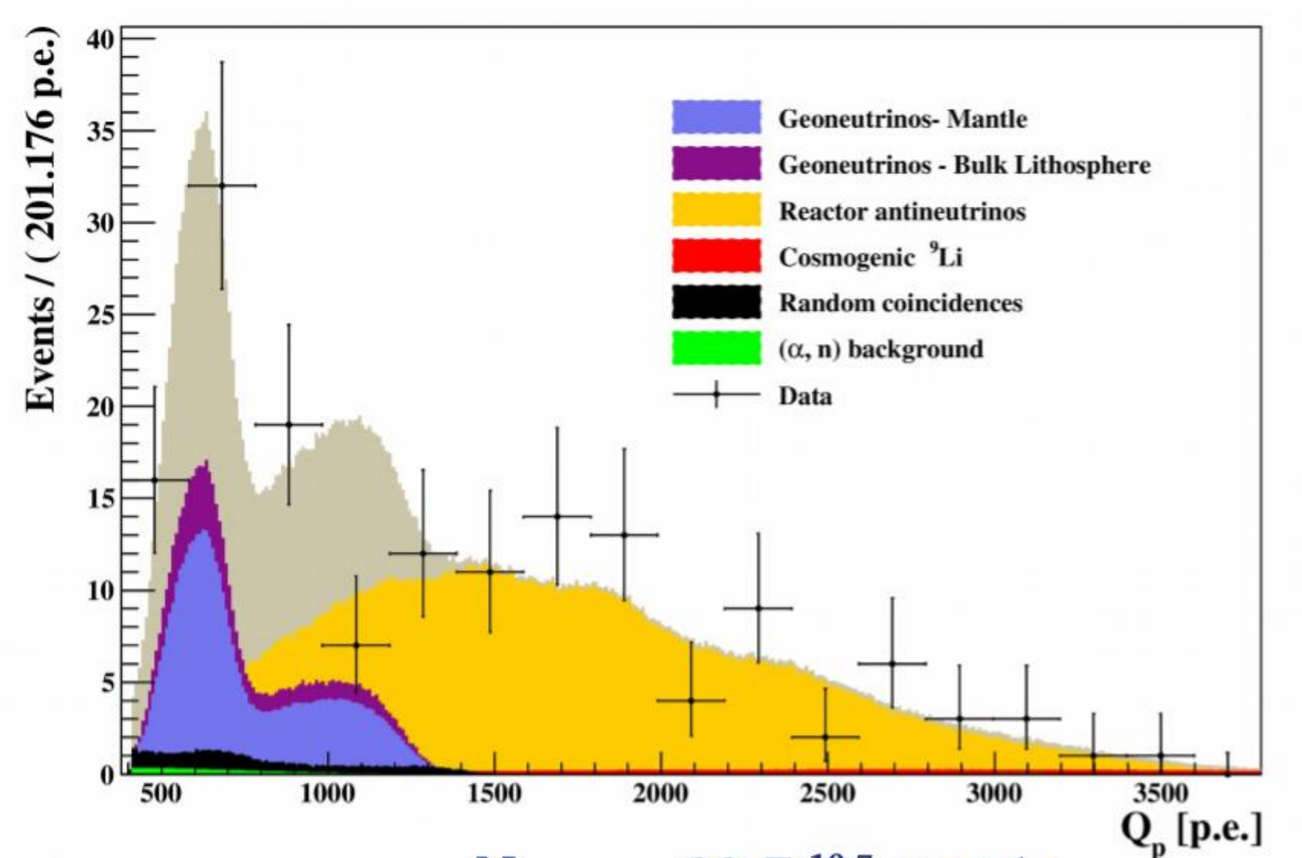


$$S_{\text{geo}}[\text{TNU}] = \frac{N_{\text{geo}}}{\varepsilon_{\text{geo}} \cdot \frac{\mathcal{E}_p}{10^{32}}} = \frac{N_{\text{geo}}}{\frac{\mathcal{E}'_p}{10^{32}}}$$

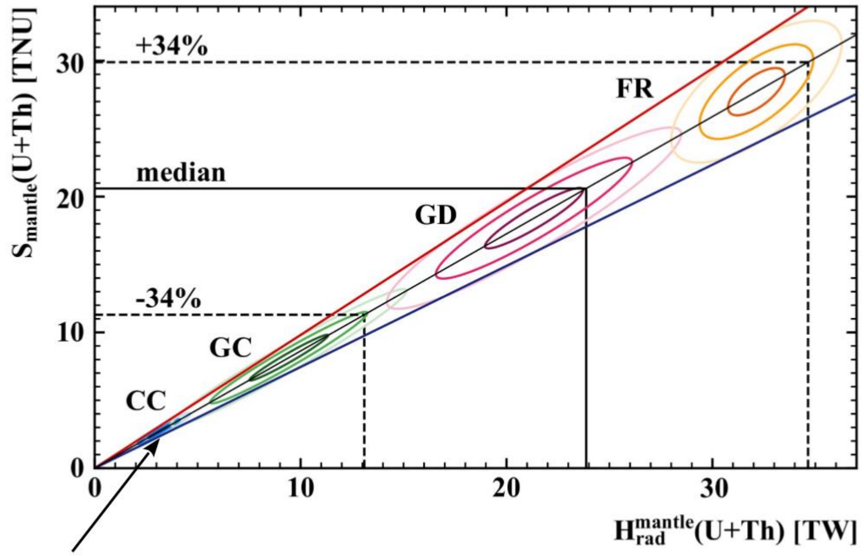
$$\boxed{47.0^{+8.4}_{-7.7}\,(\text{stat})^{+2.4}_{-1.9}\,(\text{sys})\ \text{TNU}}$$

- J: Javoy at al., 2010
- L&K: Lyubetskaya and Korenaga, 2007
- T: Taylor, 1980
- A: Anderson, 2007
- M&S: Mc Donough and Sun, 1995
- W: Wang, 2018
- P&O: Palme and O’Neil, 2003
- T&S: Turcotte and Schubert, 2002

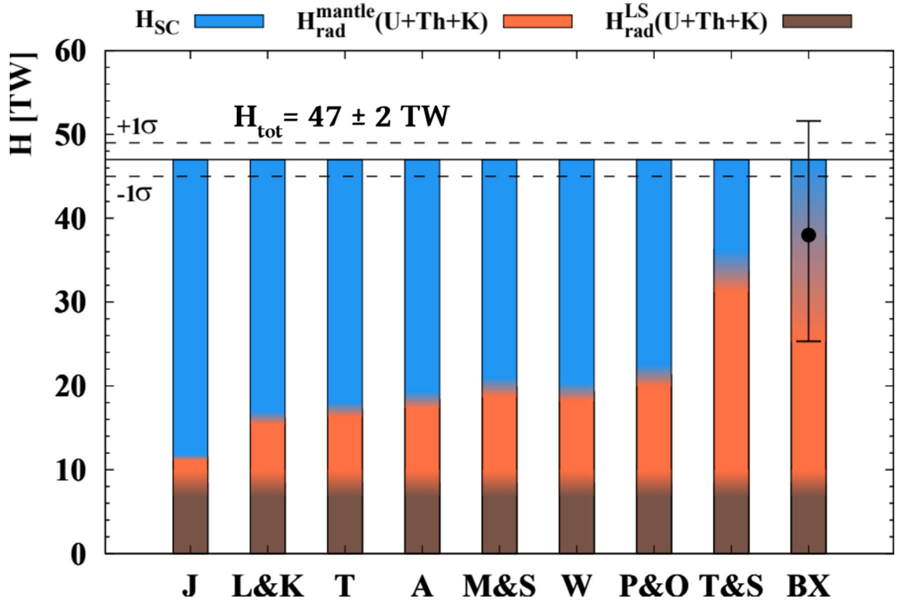
Radiogenic Heat from Mantle Borexino



$N_{mantle} = 23.7^{+10.7}_{-10.1}$ events

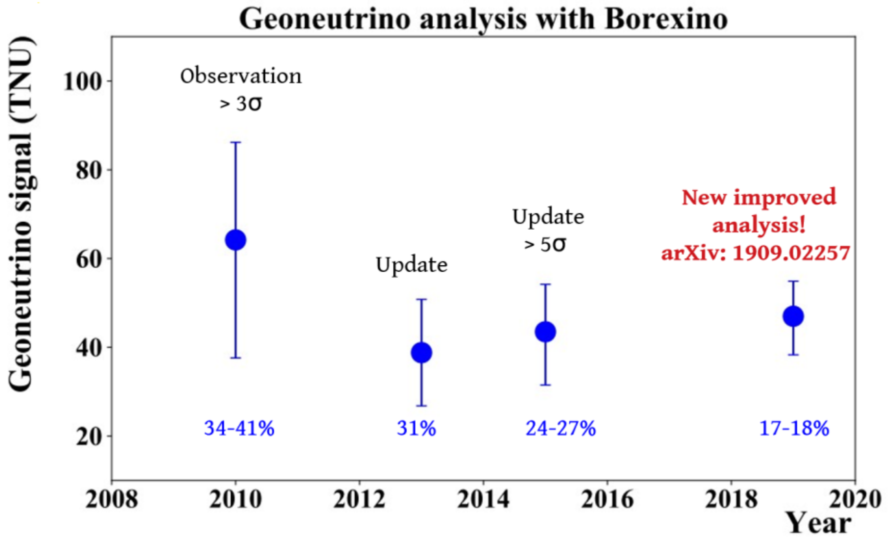


2.4σ tension



Extract the Mantle Information From Data

R(Mantle)=R(total, exp.)-R(Crust, pred.)

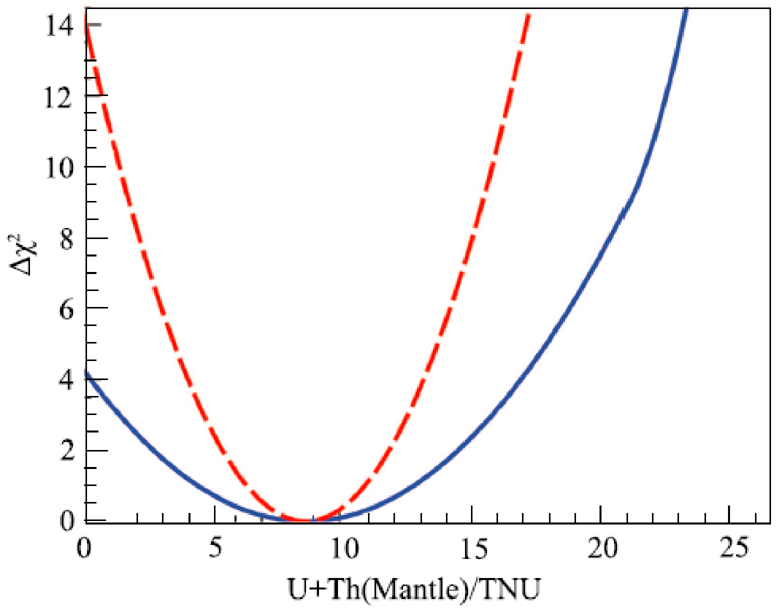


Experiment Uncertainty + Crust Prediction Uncertainty

- ➢ How to reduce Experiment Uncertainty(another topic)
- ➢ How to reduce Crust Prediction Uncertainty

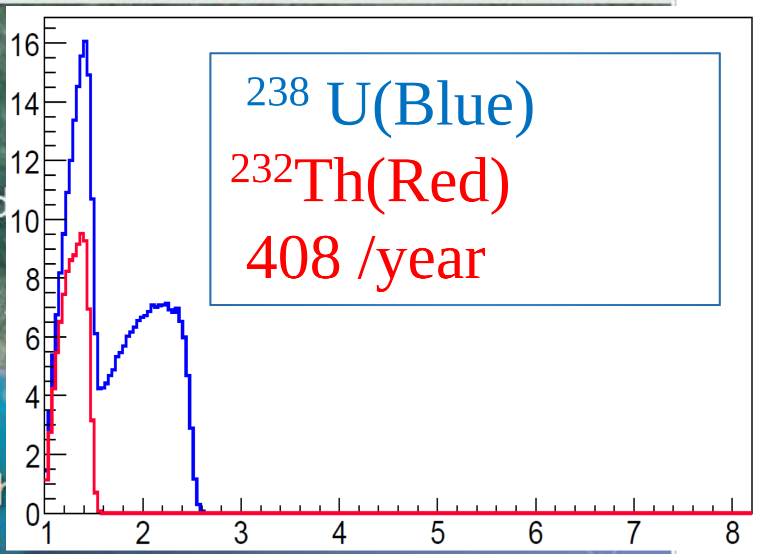
◆ 18% crust prediction uncertainty: confidence level at **2sigma**

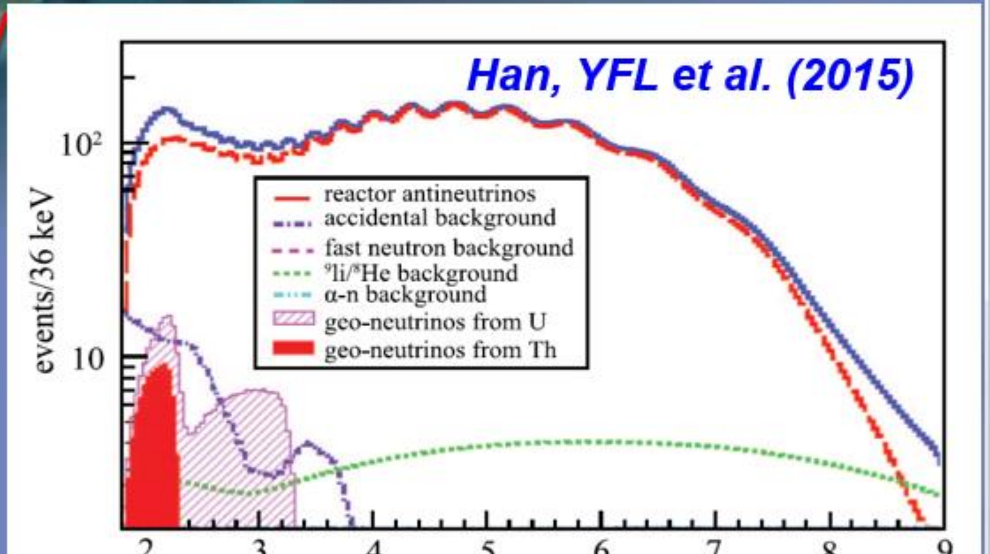
◆ 8% crust prediction uncertainty: confidence level at **4sigma**



The uncertainty from Experiments

- ➢ **In perticular for detectors near the reactor neutrino sources, such as JUNO**

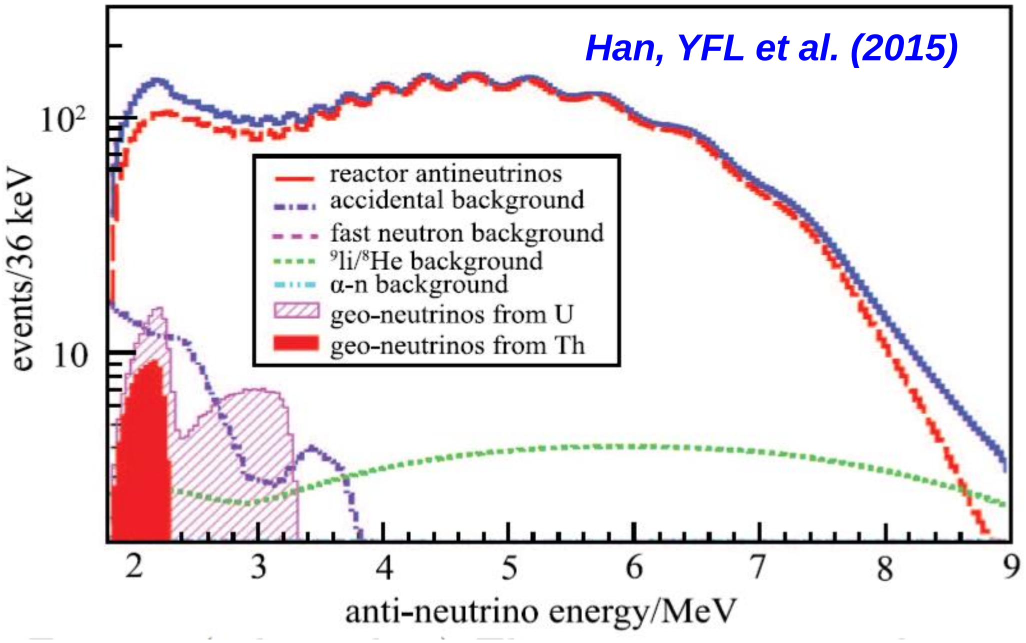


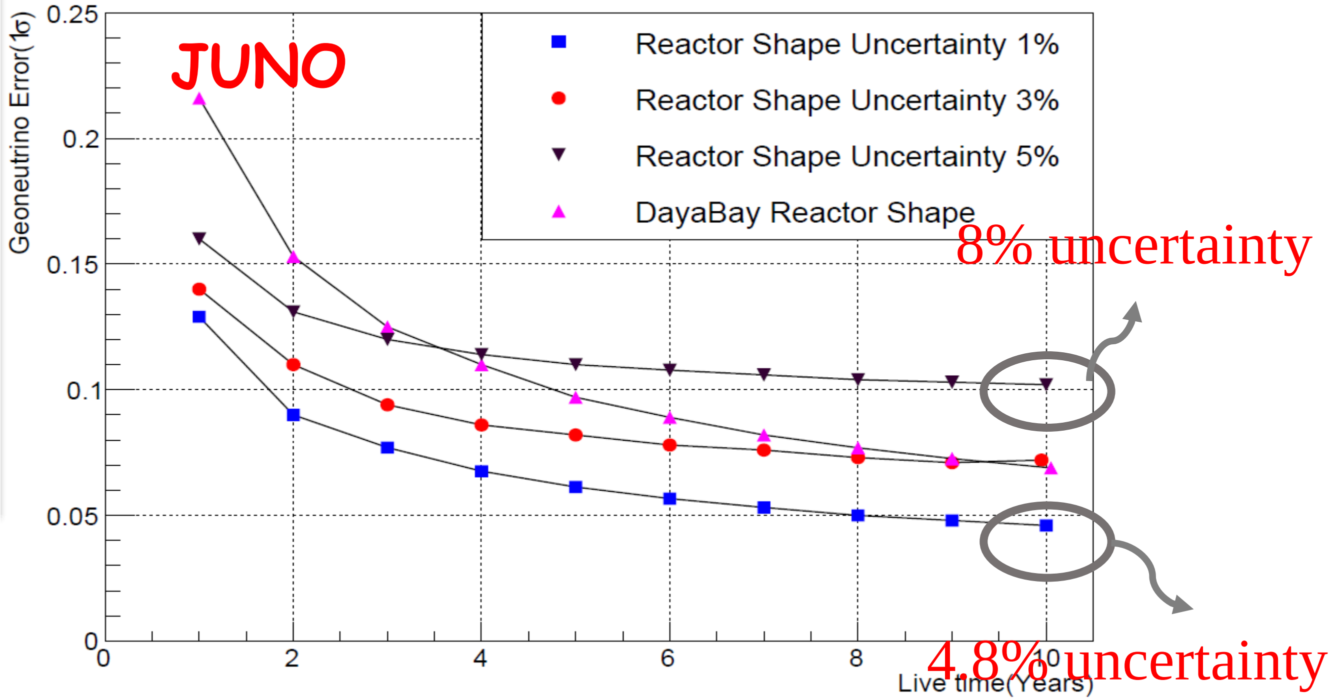


Extract Geo from Reactor with Shape fitting

Method I: using the reference measurements of reactor neutrino spectrum as inputs:

- (A) The existing Daya Bay reactor neutrino spectrum
- (B) Using the JUNO-TAO reference spectrum


Han, YFL et al. (2015)



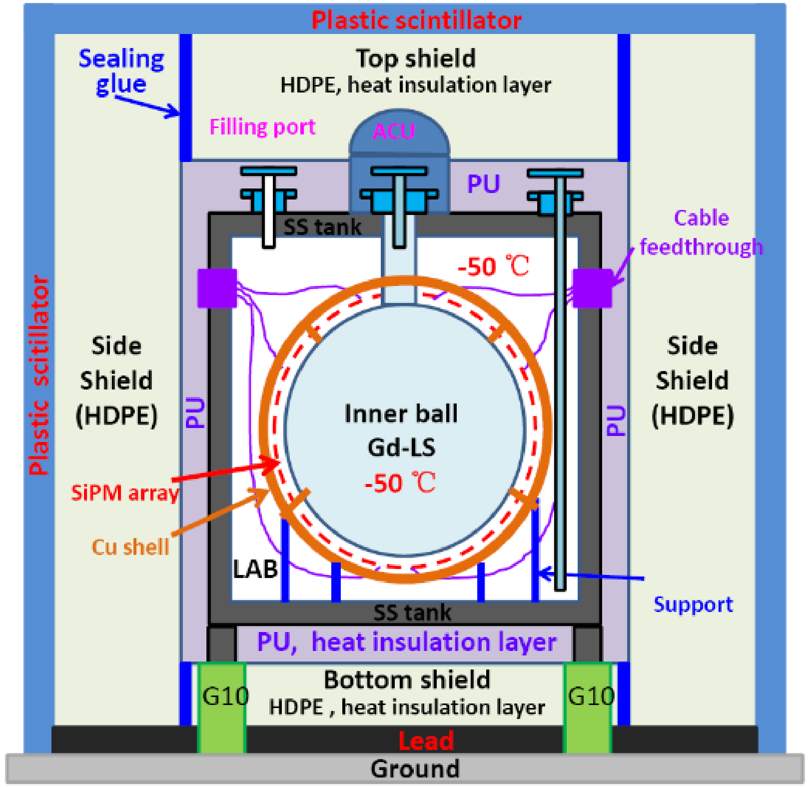
8% uncertainty

4.8% uncertainty

JUNO-TAO

From Jun Cao @IAEA meeting (2019)

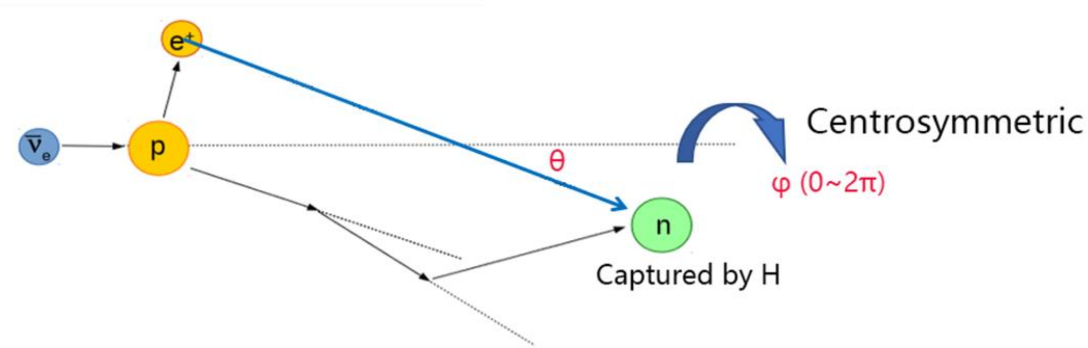
- Taishan Antineutrino Observatory (TAO), a ton-level, high energy resolution LS detector at 30 m from the core, a satellite exp. of JUNO.
- Measure reactor neutrino spectrum w/ sub-percent E resolution.
  - model-independent reference spectrum for JUNO
  - a benchmark for investigation of the nuclear database
- Ton-level Liquid Scintillator (Gd-LS)
- Full coverage of SiPM w/ PDE > 50%
- Operate at -50 ℃ (SiPM dark noise)
- 4500 p.e./MeV
- Taishan Nuclear Power Plant, 30-35 m from a 4.6 GW_th core
- 2000 IBD/day (4000)
- Online in 2021

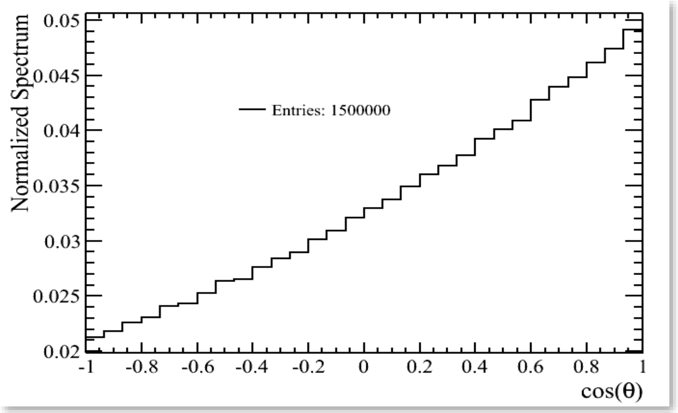


Shape and Direction Joint Fitting to exact the geo-neutrino signal

- Method II: can we use the *statistical* direction information (from IBD) to distinguish reactor & geo neutrinos?

Preliminary results done by Xin Mao





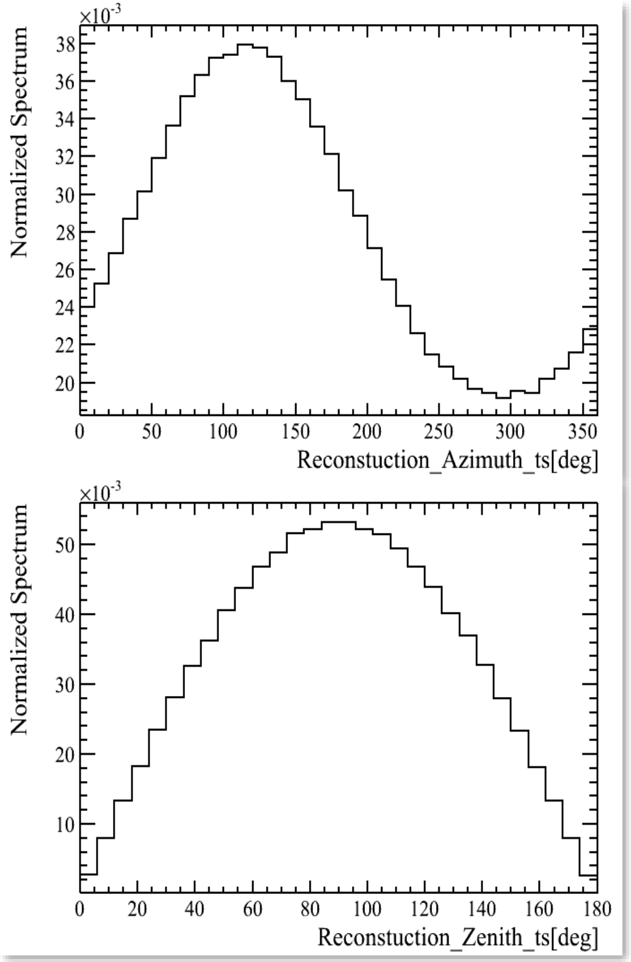
- This method is good for single direction sources, such as the reactor neutrinos from nearby nuclear power plants.

- It would be complicated for geo-neutrinos, which itself already have a rather wide angular distribution.

Joint Fitting to exact the geo-neutrino signal

Preliminary results done by Xin Mao

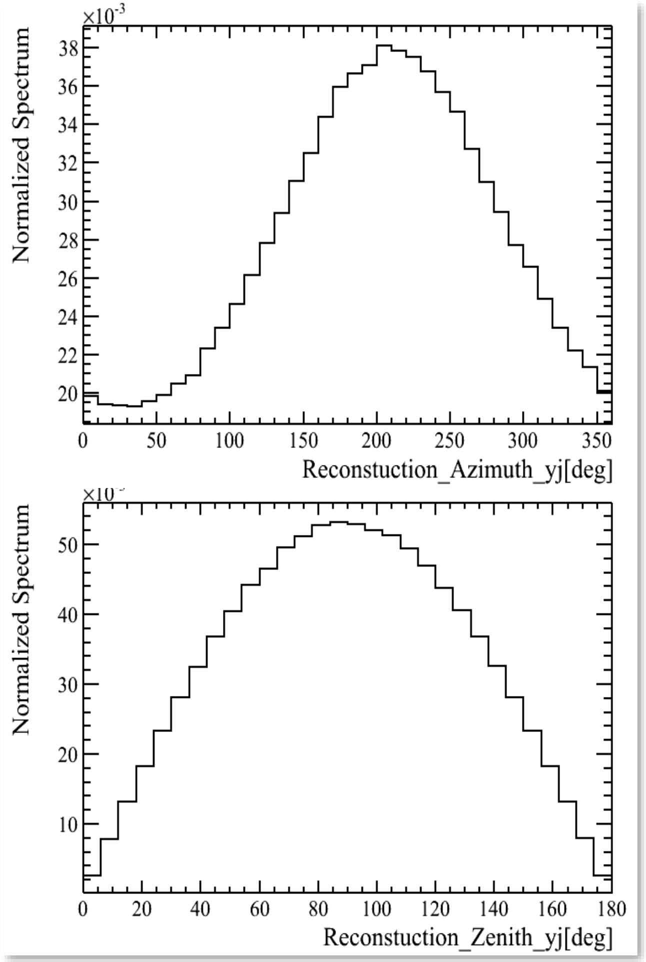
- Method II: reactor neutrino angular distribution



TS

Azimuth	Zenith
115°	90°
210°	90°

YJ

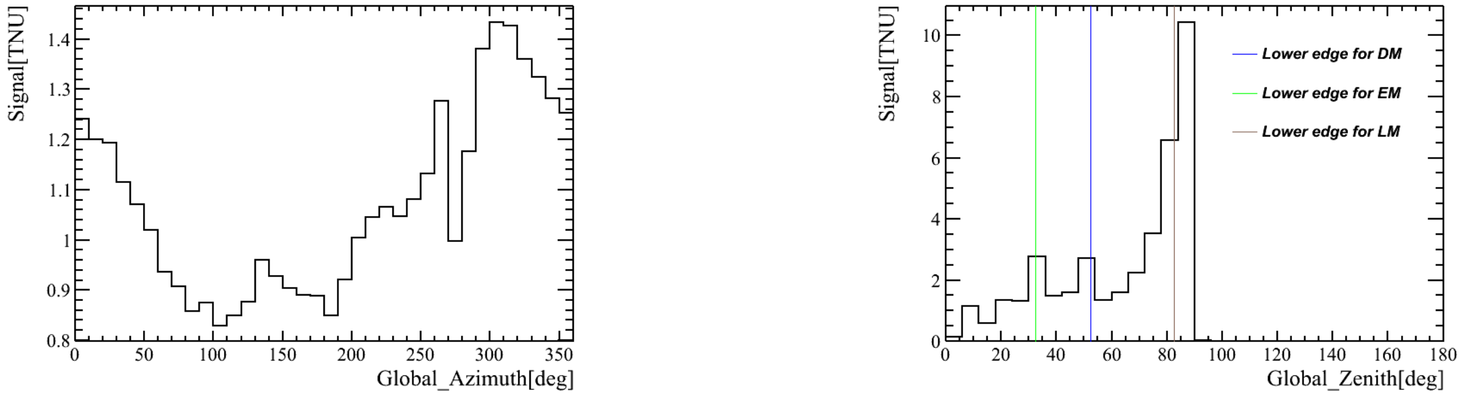


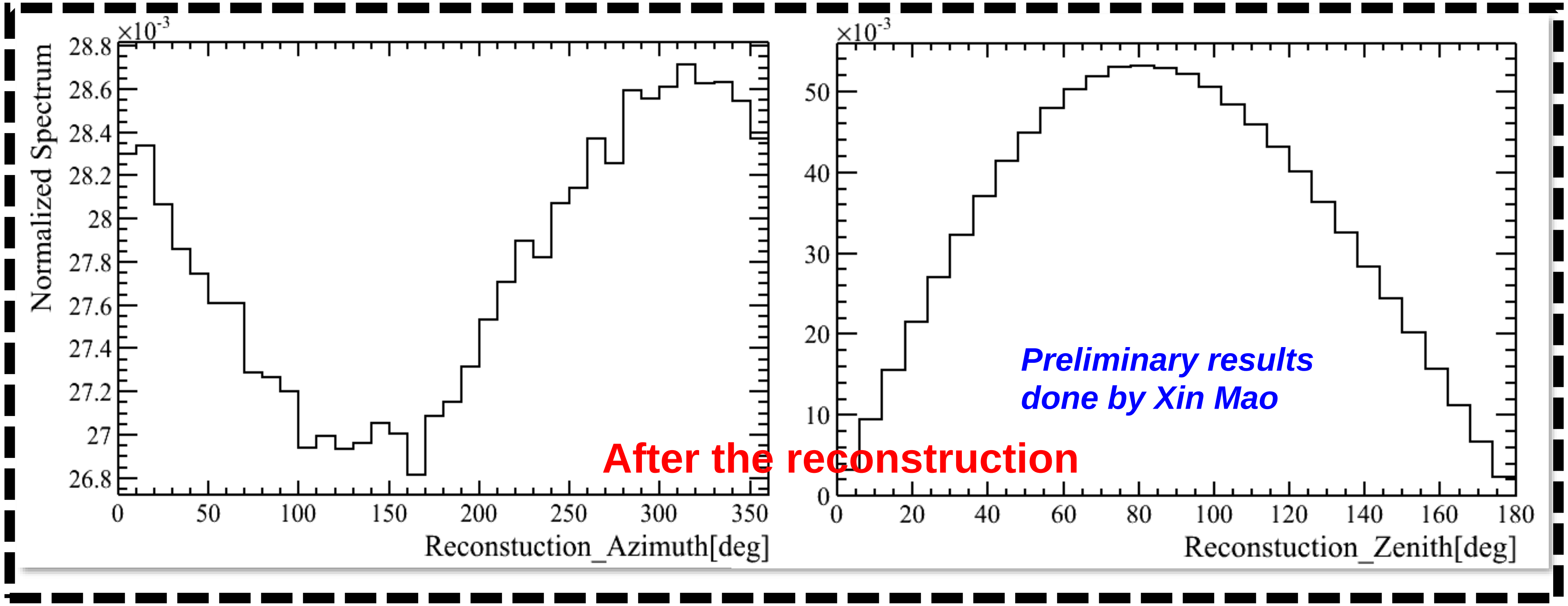
IBD

Reconstruction

Joint Fitting to exact the geo-neutrino signal

Geo-neutrino direction distribution based on CRUST 1.0



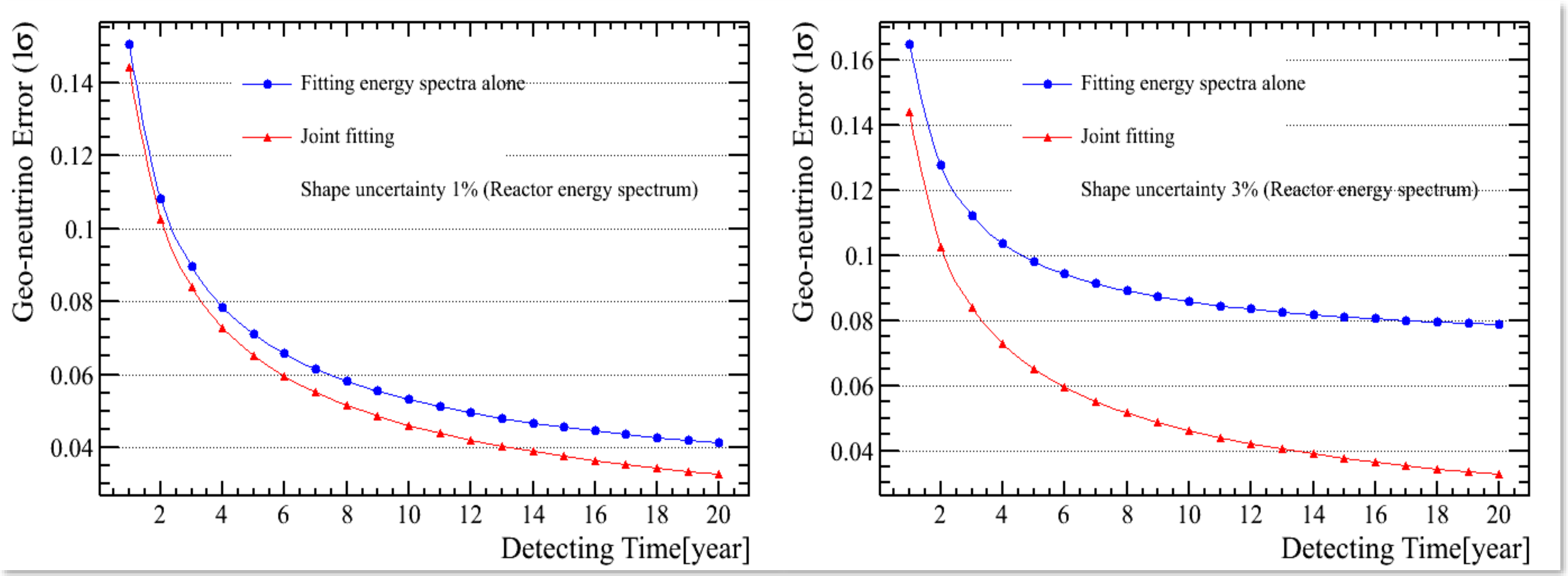


Preliminary results done by Xin Mao

After the reconstruction

Results from Joint Fitting of reactor & geo νs

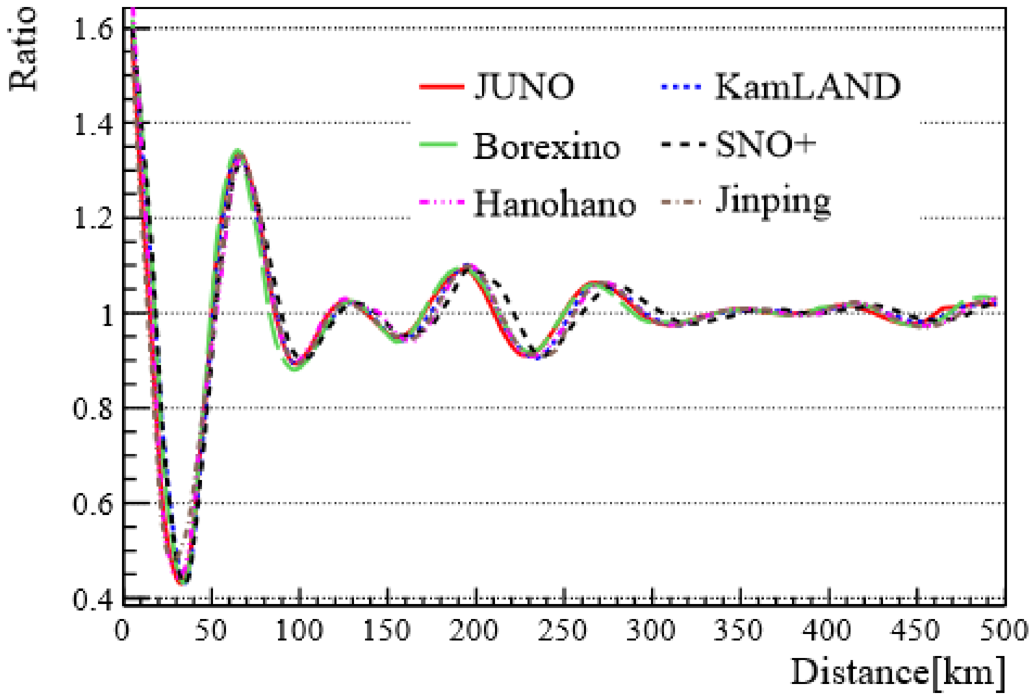
- The advantages would be significant when statistics is high and when the reactor spectrum uncertainty is large.

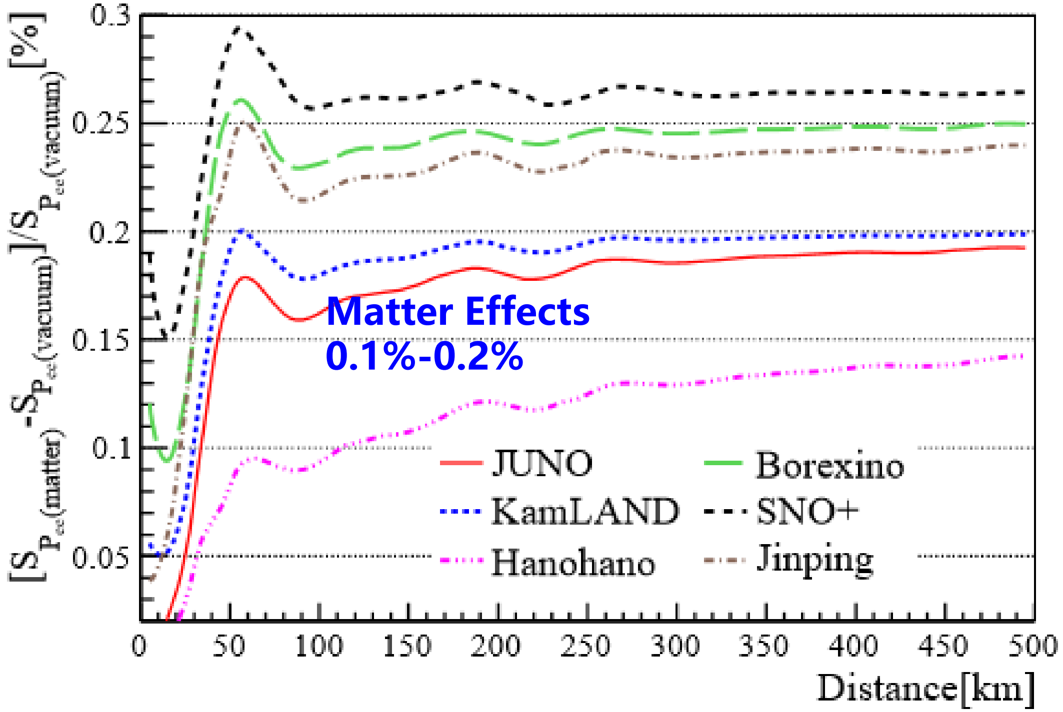


Preliminary results done by Xin Mao

- Position resolution needs to be included.
- Other backgrounds

Uncertainties from Neutrino Oscillation Effects





Matter Effects
0.1%-0.2%

- Based on CRUST1.0, the signal differences are 1.3 TNU (JUNO), 1.28 TNU (KamLAND), 1.25 TNU (Borexino), and 1.21 TNU (SNO+).
- Around 5% of total crust signal
- Within local 300 km, more important for refined local model

Prediction of Geoneutrino from Crust

Activity and number of produced geoneutrinos

Volume of source unit

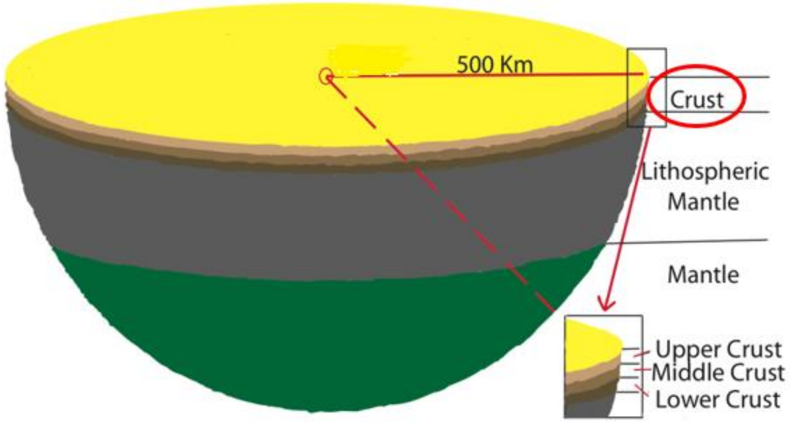
$$\Phi_i = A_i \cdot n_i \cdot P_{\nu_e - \nu_e}(E_\nu, |\vec{L}|) \cdot \int_V \frac{a_i(\vec{L}) \cdot \rho_i(\vec{L})}{4\pi |\vec{L}|^2} dV$$

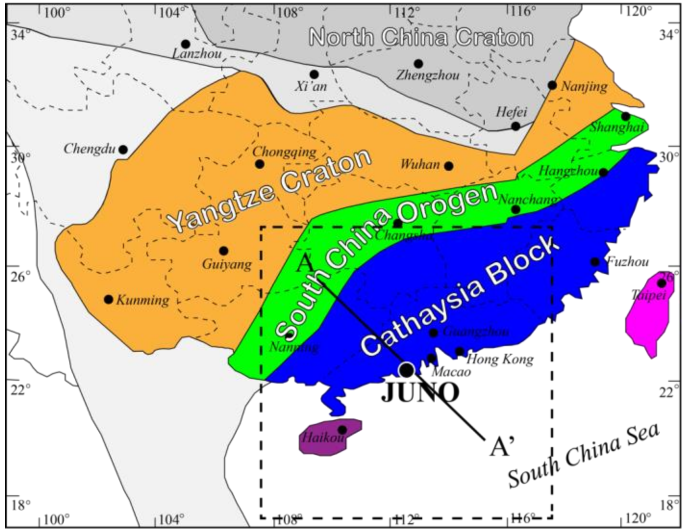
Survival probability function

Abundance and density of the source unit

Distance between source unit and detector

地壳结构 (rho and *L*) and 化学成份 (丰度 *a*)



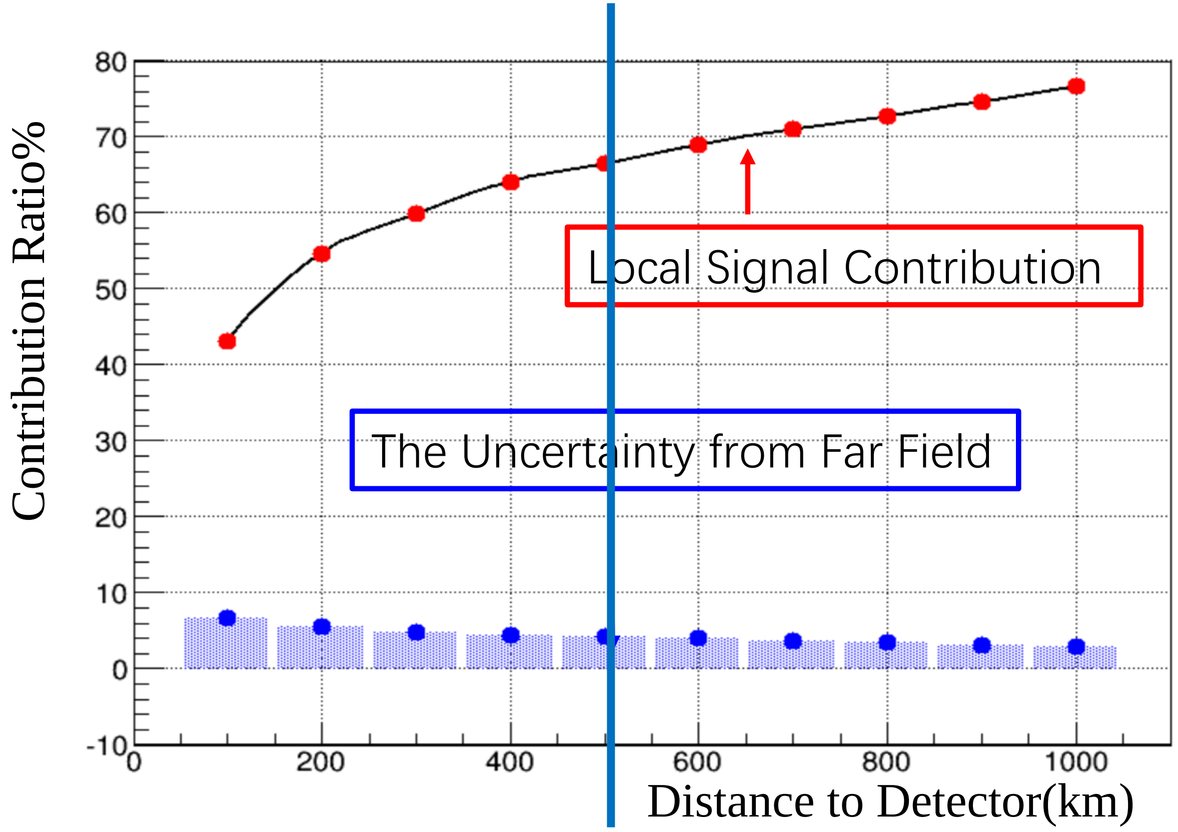


The Uncertainty of Crust prediction

σ （total， crust） =σ (far filed, curst.) + σ(near filed, curst.)

Far from the detector
1- less contribution
2- Hardly to do investigation

Close to detector area
1- large contribution
2- can do some investigation



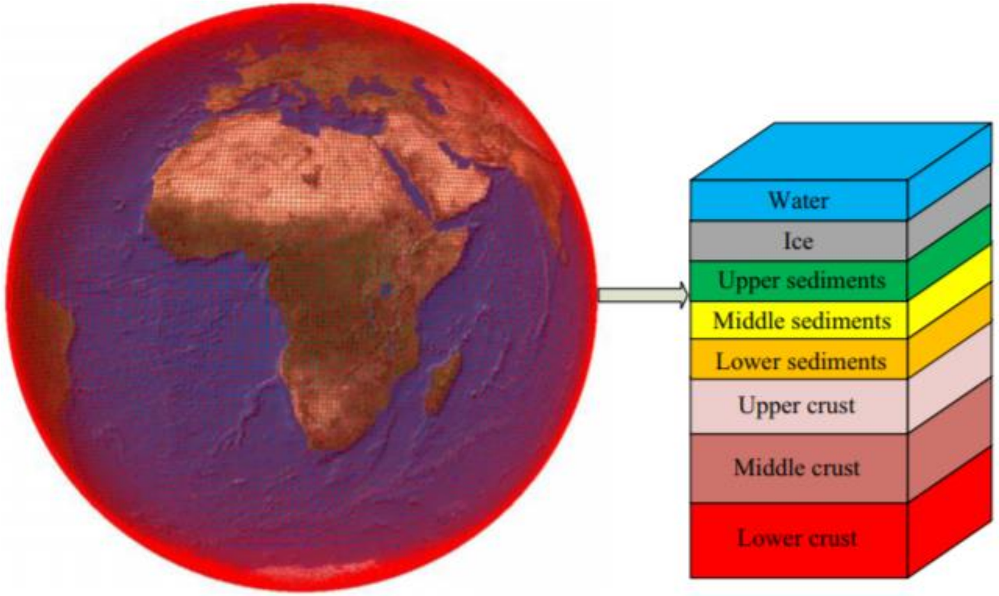
How to define the range of near filed

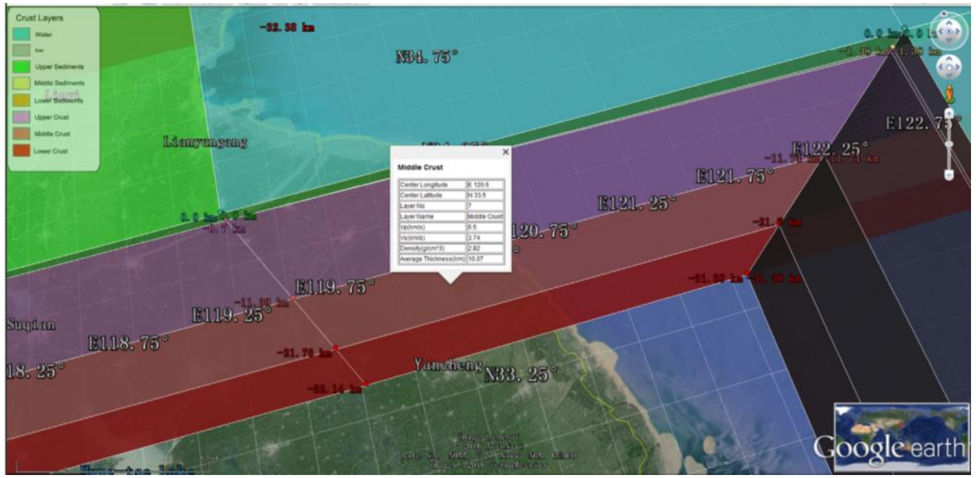
1- the signal contribution

2- the possibility to reach the aim of uncertainty to distinguish different models

The Global Crust Model

Crust2.0, Crust1.0, Litho1.0 Crust Structure

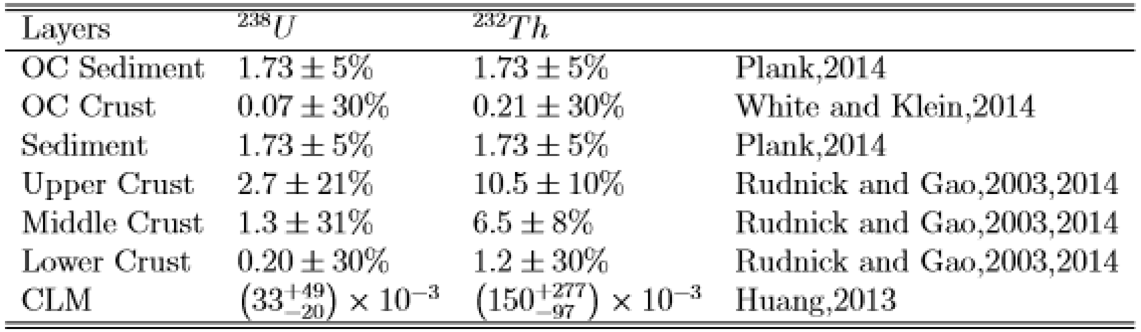




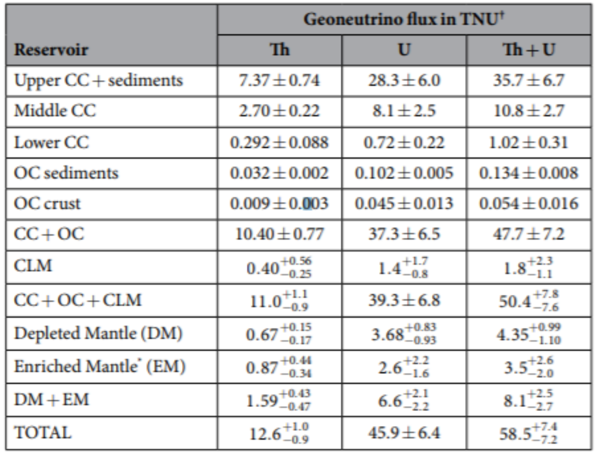
Middle Crust

Center Longitude	E 120.5
Center Latitude	N 33.5
Layer No	7
Layer Name	Middle Crust
Vp(km/s)	6.5
Vs(km/s)	3.74
Density(g/cm^3)	2.82
Average Thickness(km)	10.07

Chemical composition Model (α)



Layers	^{238}U	^{232}Th	
OC Sediment	$1.73 \pm 5\%$	$1.73 \pm 5\%$	Plank,2014
OC Crust	$0.07 \pm 30\%$	$0.21 \pm 30\%$	White and Klein,2014
Sediment	$1.73 \pm 5\%$	$1.73 \pm 5\%$	Plank,2014
Upper Crust	$2.7 \pm 21\%$	$10.5 \pm 10\%$	Rudnick and Gao,2003,2014
Middle Crust	$1.3 \pm 31\%$	$6.5 \pm 8\%$	Rudnick and Gao,2003,2014
Lower Crust	$0.20 \pm 30\%$	$1.2 \pm 30\%$	Rudnick and Gao,2003,2014
CLM	$(33^{+49}_{-20}) \times 10^{-3}$	$(150^{+277}_{-97}) \times 10^{-3}$	Huang,2013



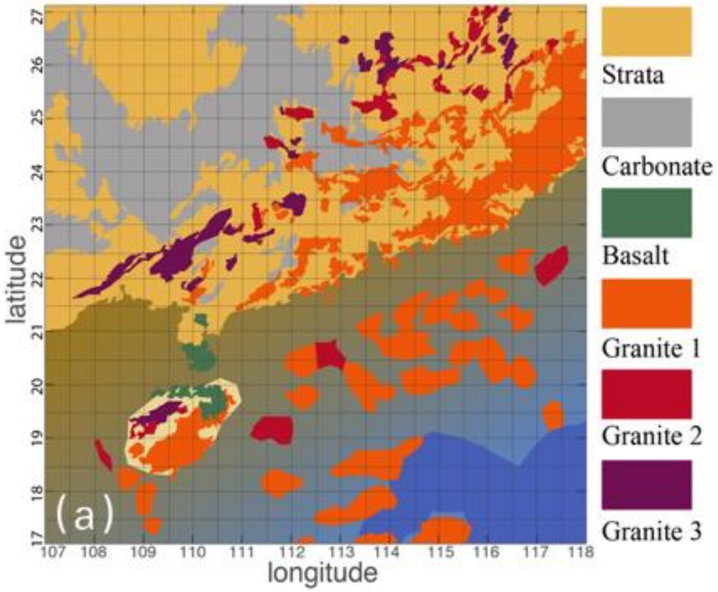
Reservoir	Geoneutrino flux in TNU†		
	Th	U	Th + U
Upper CC + sediments	7.37 ± 0.74	28.3 ± 6.0	35.7 ± 6.7
Middle CC	2.70 ± 0.22	8.1 ± 2.5	10.8 ± 2.7
Lower CC	0.292 ± 0.088	0.72 ± 0.22	1.02 ± 0.31
OC sediments	0.032 ± 0.002	0.102 ± 0.005	0.134 ± 0.008
OC crust	0.009 ± 0.003	0.045 ± 0.013	0.054 ± 0.016
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	$58.5^{+7.4}_{-7.2}$

Table 1. Prediction of geoneutrino flux at Jinping location: 28.15°N, 101.71°E, 2400 m depth, based on CRUST1.0[38] model of the crustal structure. *See text for details on how the EM was determined to satisfy BSE model. †See text for details on units. CC = Continental Crust; OC = Oceanic Crust; CLM = Continental Lithospheric Mantle.

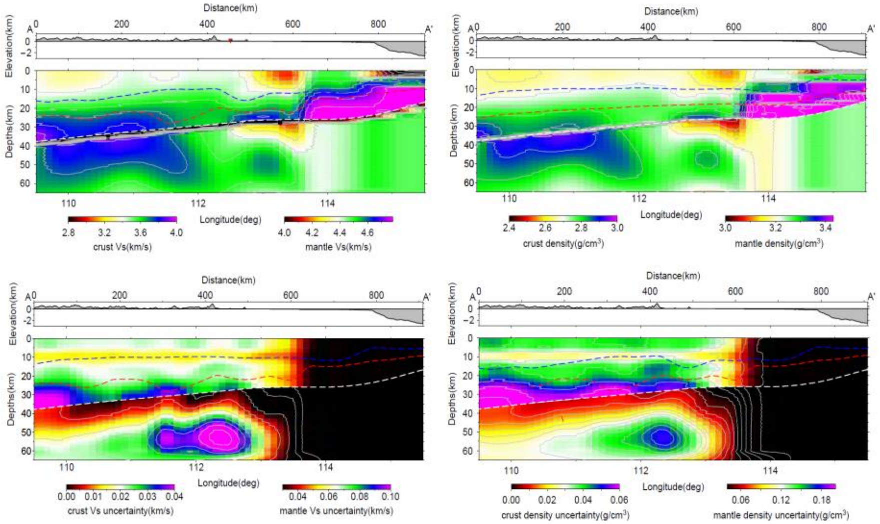
Large Uncertainty
Larger than 25%

The Local Refined Crust Model –JUNO

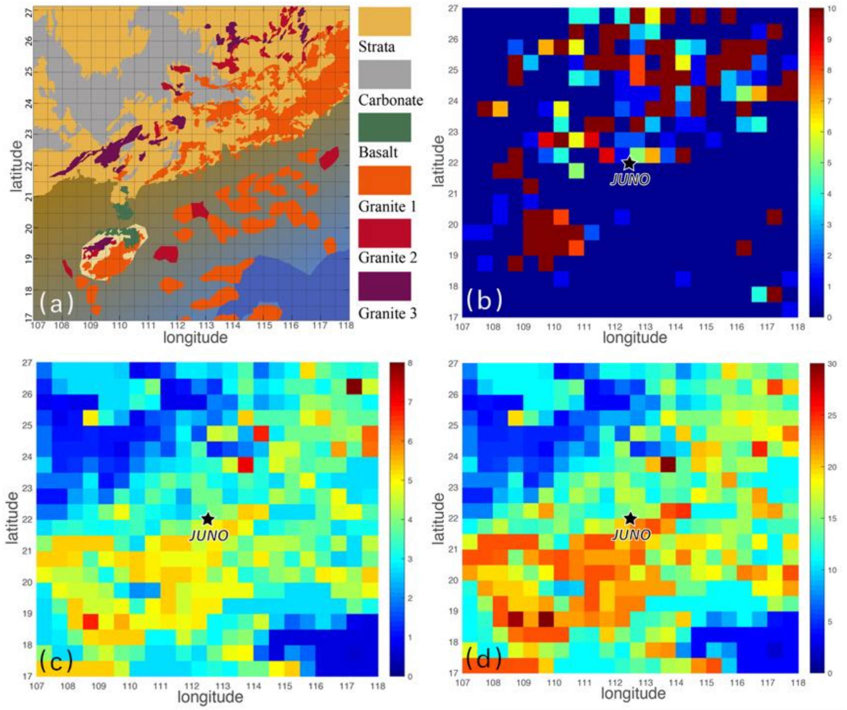
1- Geological map around JUNO



2- Determine crustal thickness, estimates of lower, middle, upper crust thickness and density



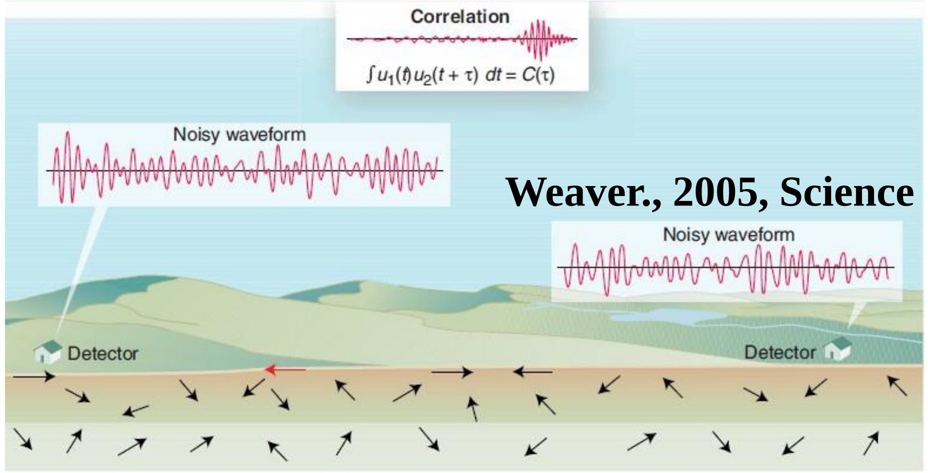
3.Upper crustal compositional data



arXiv:1903.11871

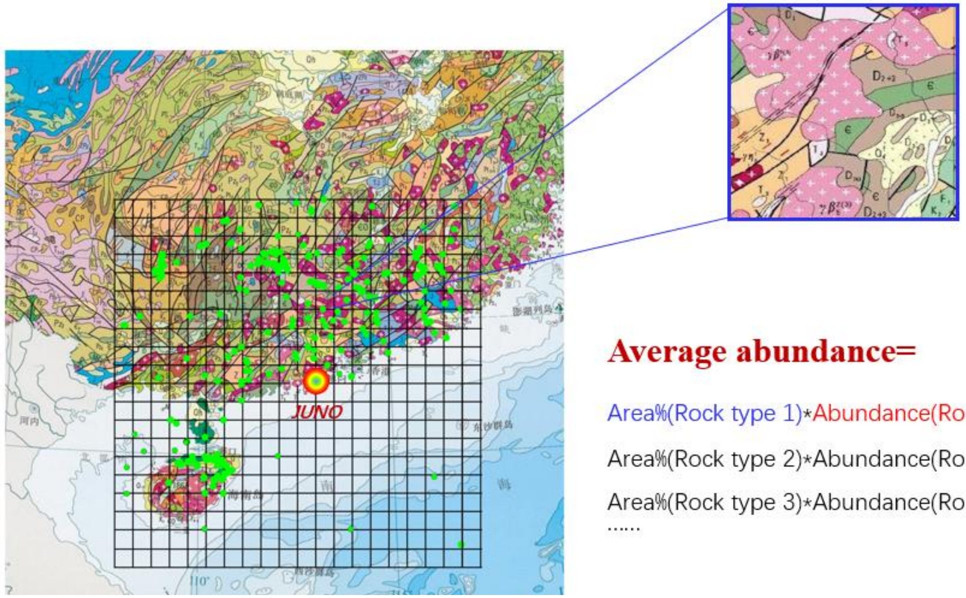
The Advantage of JUNO Local Crust Model

- **High-resolution 3-D crustal model can be obtained beneath seismic array with seismic ambient noise data.**



Weaver., 2005, Science

- **The Cell by Cell Composition**



Average abundance=

Area%(Rock type 1)*Abundance(Rock type 1)+

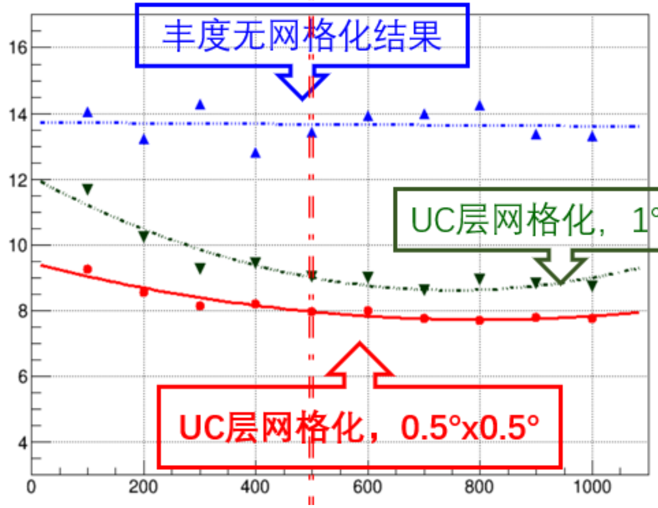
Area%(Rock type 2)*Abundance(Rock type 2)+

Area%(Rock type 3)*Abundance(Rock type 3)+

……

- ✓ **Our model is much better than the global CRUST1.0 model with higher-resolution and reliability.**
- ✓ **With bootstrap method, we evaluate the model uncertainty. It is less than ~ 1% for most areas at depths from 0 ~ 60 km.**

By Zhi wei LI



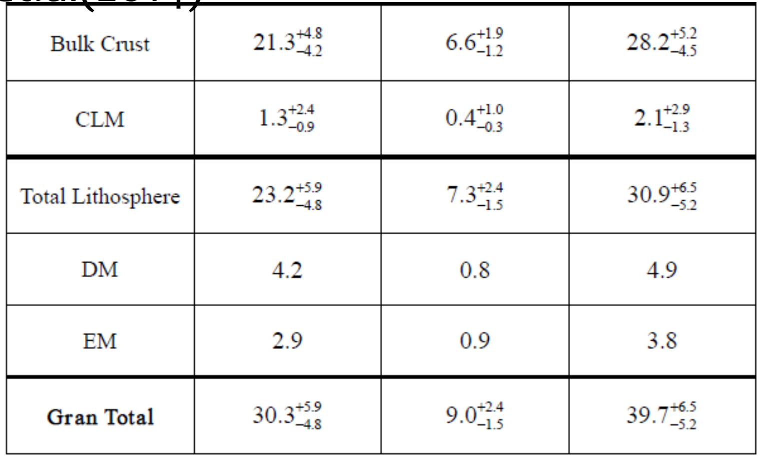
Cell by Cell error with out correlation

- ✓ **Enough data sample**
- ✓ **The error of abundance distribution is larger than other errors**

By Ruohan.GAO/Andong Wang

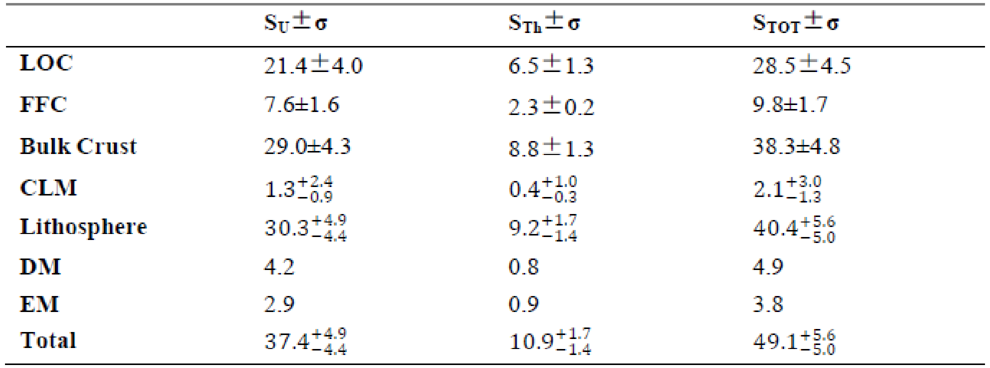
The Crustal Geoneutrino Flux

Strati et.al(2014)



Bulk Crust	$21.3^{+4.8}_{-4.2}$	$6.6^{+1.9}_{-1.2}$	$28.2^{+5.2}_{-4.5}$
CLM	$1.3^{+2.4}_{-0.9}$	$0.4^{+1.0}_{-0.3}$	$2.1^{+2.9}_{-1.3}$
Total Lithosphere	$23.2^{+5.9}_{-4.8}$	$7.3^{+2.4}_{-1.5}$	$30.9^{+6.5}_{-5.2}$
DM	4.2	0.8	4.9
EM	2.9	0.9	3.8
Gran Total	$30.3^{+5.9}_{-4.8}$	$9.0^{+2.4}_{-1.5}$	$39.7^{+6.5}_{-5.2}$

Table 3. Summary of geoneutrino signals and their uncertainties (1 standard deviation) in TNU expected for JUNO, from Uranium (S_U), Thorium (S_{Th}), and their sum (S_{TOT}). The Bulk Crust contribution includes that of Local Crust (LOC) and Far Field Crust (FFC). Lithosphere contribution is the sum of the Bulk crust and Continental Lithospheric Mantle (CLM) contributions. And the total signal is the sum of that of Lithosphere, Depleted mantle (DM), and Enriched Mantle (EM).



	$S_U \pm \sigma$	$S_{Th} \pm \sigma$	$S_{TOT} \pm \sigma$
LOC	21.4±4.0	6.5±1.3	28.5±4.5
FFC	7.6±1.6	2.3±0.2	9.8±1.7
Bulk Crust	29.0±4.3	8.8±1.3	38.3±4.8
CLM	$1.3^{+2.4}_{-0.9}$	$0.4^{+1.0}_{-0.3}$	$2.1^{+3.0}_{-1.3}$
Lithosphere	$30.3^{+4.9}_{-4.4}$	$9.2^{+1.7}_{-1.4}$	$40.4^{+5.6}_{-5.0}$
DM	4.2	0.8	4.9
EM	2.9	0.9	3.8
Total	$37.4^{+4.9}_{-4.4}$	$10.9^{+1.7}_{-1.4}$	$49.1^{+5.6}_{-5.0}$

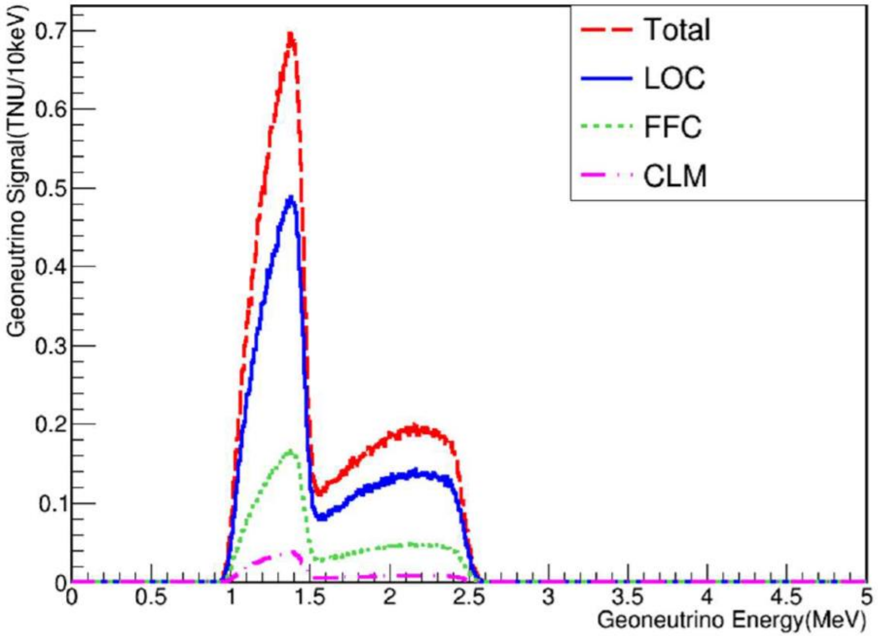
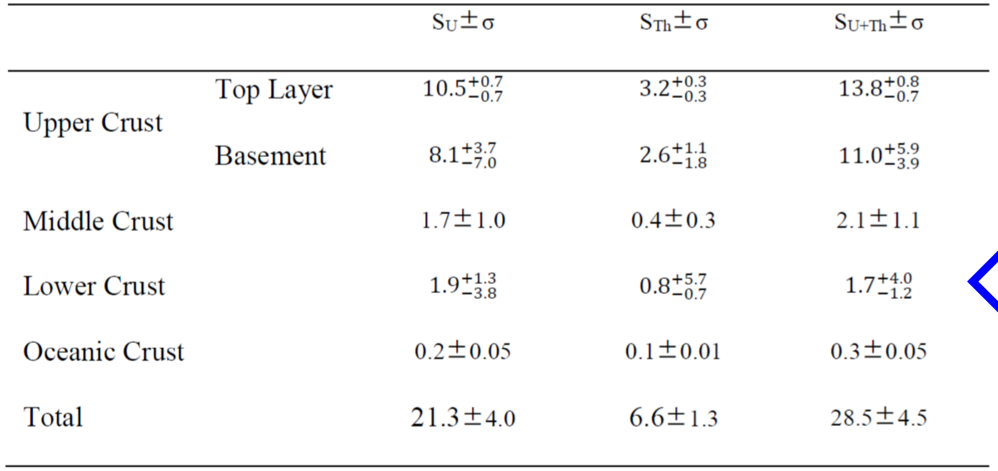


***Table2** the predicated geoneutrino signal(S) from local crust in the 10°x10° area around JUNO and uncertainty(σ) in TNU, the results include the contribution from Continental Crust and Oceanic Curst, the geoneutrino signal spectrum are in Fig. B1 in Appendix B.*



		$S_U \pm \sigma$	$S_{Th} \pm \sigma$	$S_{U+Th} \pm \sigma$
Upper Crust	Top Layer	$10.5^{+0.7}_{-0.7}$	$3.2^{+0.3}_{-0.3}$	$13.8^{+0.8}_{-0.7}$
	Basement	$8.1^{+3.7}_{-7.0}$	$2.6^{+1.1}_{-1.8}$	$11.0^{+5.9}_{-3.9}$
Middle Crust		1.7±1.0	0.4±0.3	2.1±1.1
Lower Crust		$1.9^{+1.3}_{-3.8}$	$0.8^{+5.7}_{-0.7}$	$1.7^{+4.0}_{-1.2}$
Oceanic Crust		0.2±0.05	0.1±0.01	0.3±0.05
Total		21.3±4.0	6.6±1.3	28.5±4.5

6.0%

45%

52.1%

~100%

Summary

- Geo-neutrinos is a new frontier of joint efforts from particle physics, geology, geo-physics & geo-chemistry

- Geoneutrino signal can tell how many U and Th is in the deep Earth

- Currently, the measurement interpretations using local models: BOREXINO and KamLAND

- From the particle physics aspects: production, propagation, detection

- From the Geology aspects: Near field (NF) models of the upper crust control accuracy and precision of signal predictions