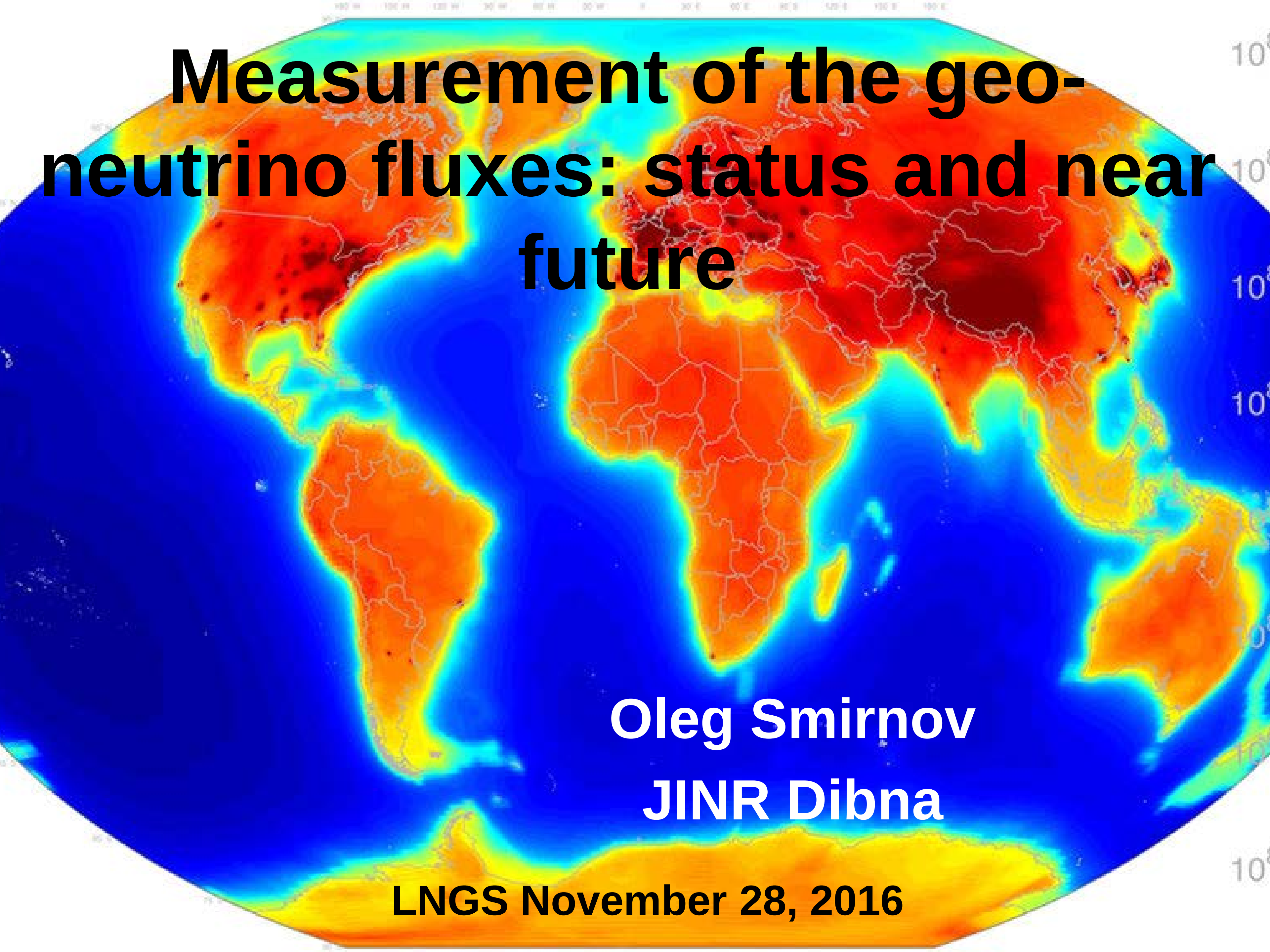
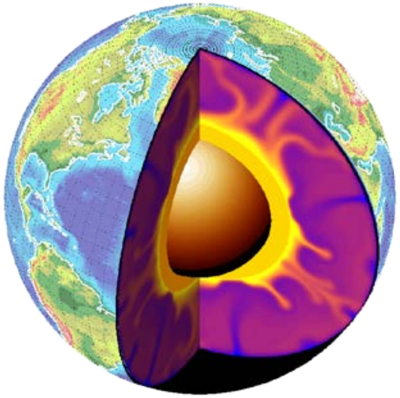


Measurement of the geo-neutrino fluxes: status and near future

Oleg Smirnov
JINR Dibna

LNGS November 28, 2016

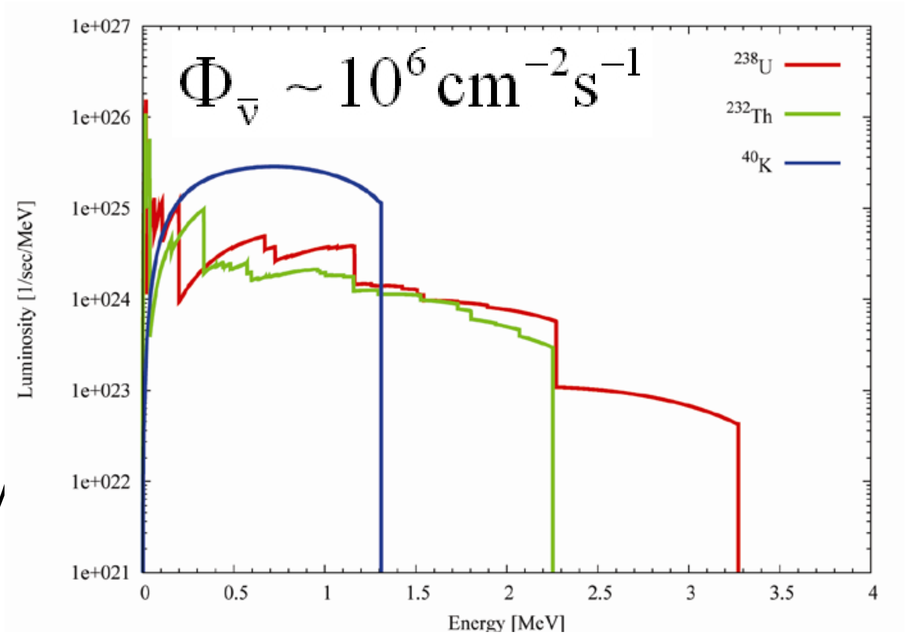
Geo-neutrinos: anti-neutrinos from β-decays of radioactive elements in the Earth



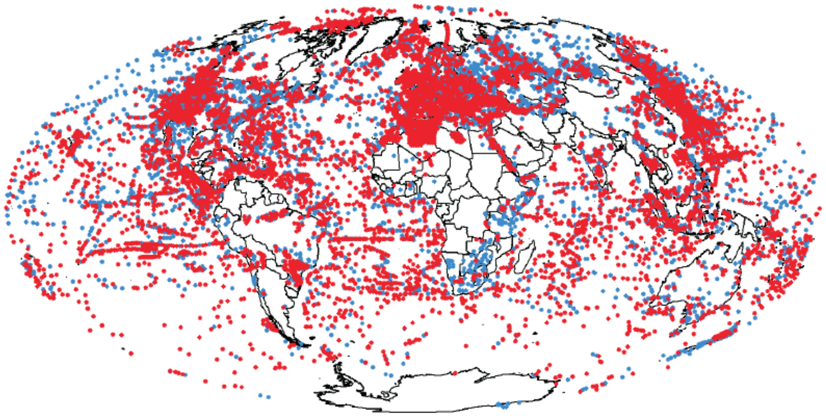
^{238}U, ^{232}Th and ^{40}K (^{87}Rb, ^{235}U) release heat together with antineutrinos

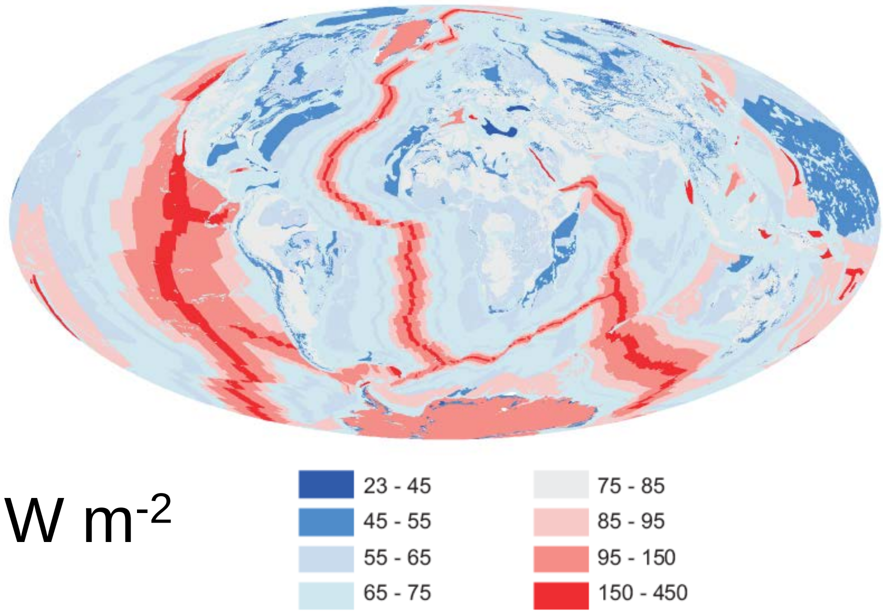
Decay	$T_{1/2}$ [10^9 yr]	$E_{\max}$ [MeV]	Q [MeV]	$\varepsilon_{\bar{\nu}}$ [$\mathrm{kg}^{-1}\mathrm{s}^{-1}$]	ε_H [W/kg]
$^{238}\mathrm{U} \to {}^{206}\mathrm{Pb} + 8\,{}^4\mathrm{He} + 6e + 6\bar{\nu}$	4.47	3.26	51.7	7.46×10^7	0.95×10^{-4}
$^{232}\mathrm{Th} \to {}^{208}\mathrm{Pb} + 6\,{}^4\mathrm{He} + 4e + 4\bar{\nu}$	14.0	2.25	42.7	1.62×10^7	0.27×10^{-4}
$^{40}\mathrm{K} \to {}^{40}\mathrm{Ca} + e + \bar{\nu}$ (89%)	1.28	1.311	1.311	2.32×10^8	0.22×10^{-4}

- Earth emits (mainly) antineutrinos whereas Sun shines in neutrinos.
- A fraction of geo-neutrinos from U and Th are above threshold for inverse β on protons: 1.8 MeV
- Different components can be distinguished due to different energy spectra: e. g. anti-ν with highest energy are from Uranium.



Heat flow through the surface of the Earth





"Earth's surface heat flux", J. H. Davies and D. R. Davies (2010)

47±2 TW

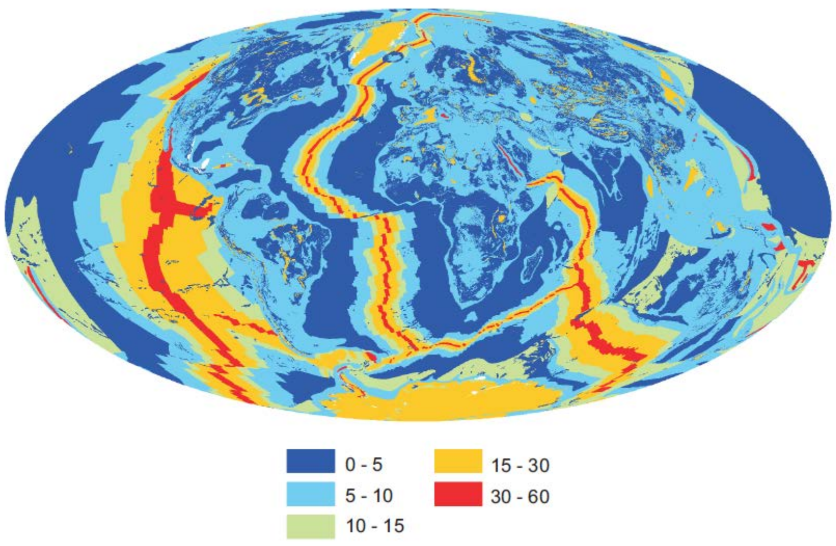
mW m^{-2}

38 347 measurements of the thermal flux

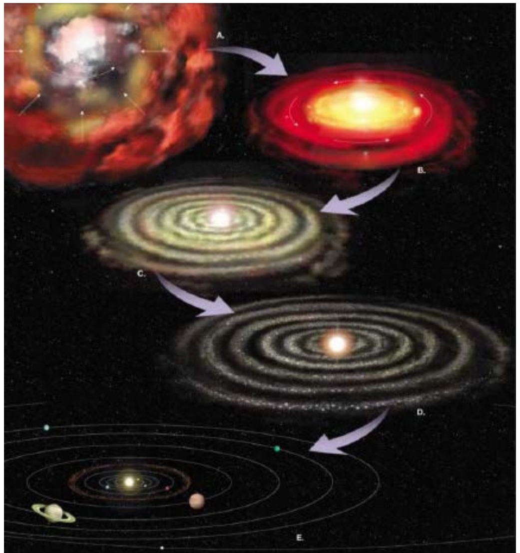
In agreement with previous estimations based on incomplete set of the same data

46±3 TW[Jaupart et al., 2007] and

44±1 TW [Pollack et al., 1993]

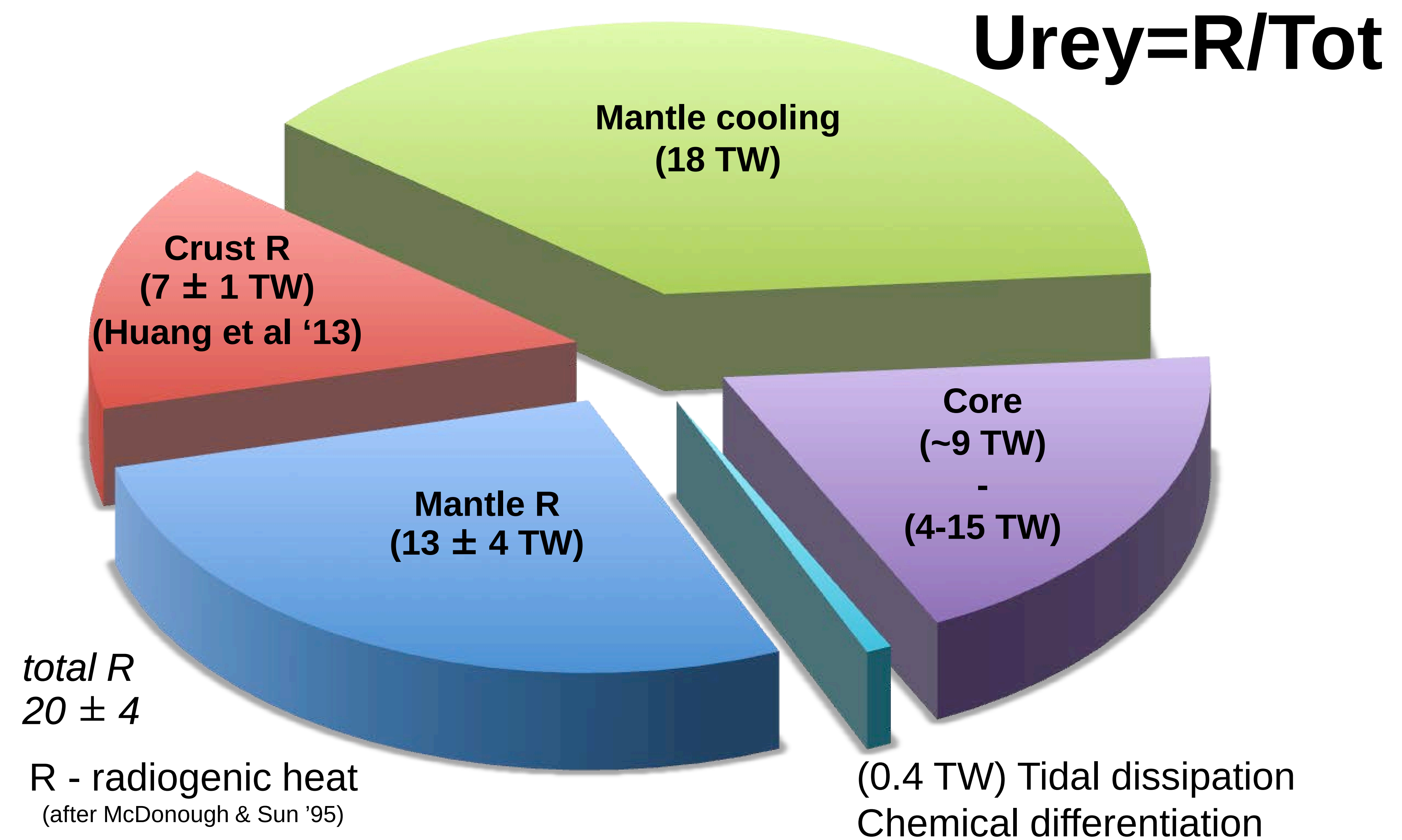


Primordial heat



Primordial heat sources:
Gravitational energy
Short-lived isotopes decays
^{26}Al (7.17×10^5 yr**)**

Earth's surface heat flow 47 ± 2 TW



after Jaupart et al 2008 Treatise of Geophysics

Earth models and radiogenic heat

- **Cosmochemical (based on meteorites composition)** – Earth composition is based on the enstatine chondrites (E-chondrites), the only group of chondrites identical to the Earth composition (Javoy et al., 2010) :

  ~10 TW

- **Geochemical (composition of Earth minerals) –** cosmochemical relative abundancies (based on carbonaceous chondrites CI) with absolute abundancies from petrology (Lyubetskaya & Korenaga,2007; McDonough & Sun, 1995; Palme & O'Neill, 2003):

  ~20 TW

- **Geophysical/geodynamical (parametric convection) –** convection requires viscosity consistent with surface heat flow. Uses using scaling laws to relate heat flow and viscosity, predicting the thermal evolution of the Earth (Crowley et al., 2011; Turco, 1980)**:**

  ~30 TW

Compared to total 47±2 TW
9 - 36 TW are left to the internal non-radiogenic heat, definening the thermal evolution and history of the Earth.

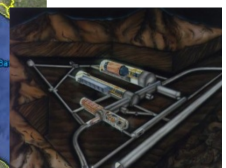
Models of the Earth and thermal flux

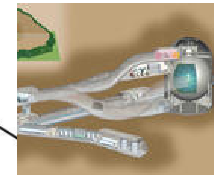
“Geophysical and geochemical constraints on geoneutrino fluxes from Earth's mantle”
Ondrej Sramek et al.

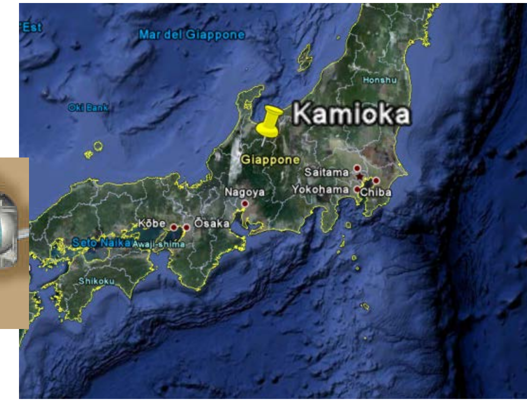
Model	Full thermal flux,TW	Mantle contribution, TW
Cosmochemical	11 ± 2	3 ±2
Geochemical	20 ± 4	12 ±4
Geophysical	33 ± 3	25 ±3

Geophysical models need relatively high contribution of radiogenic heat to explain thermal flux in the mantle (otherwise model leads to the “thermal catastrophe” in archeosoic)

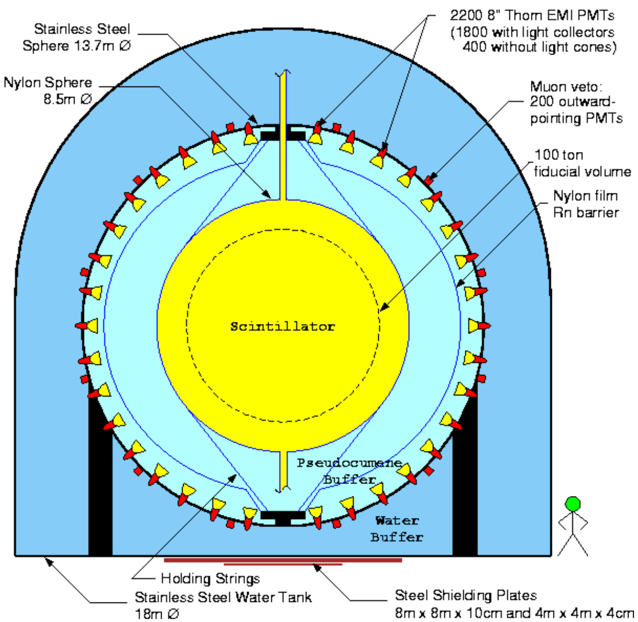
Two detectors measured geo-neutrino

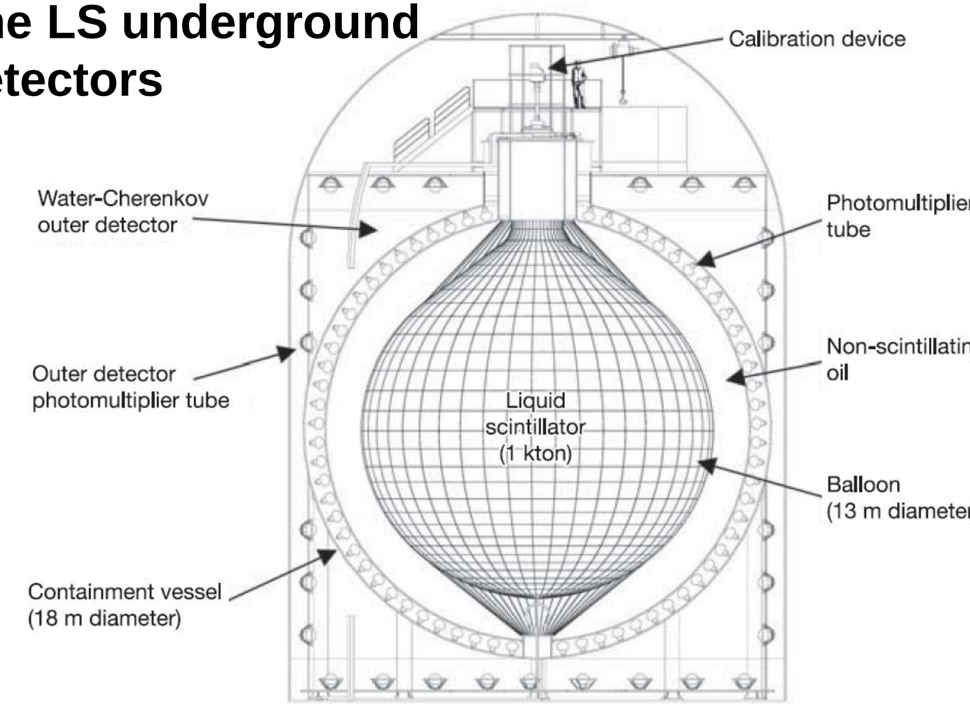






Large volume LS underground detectors





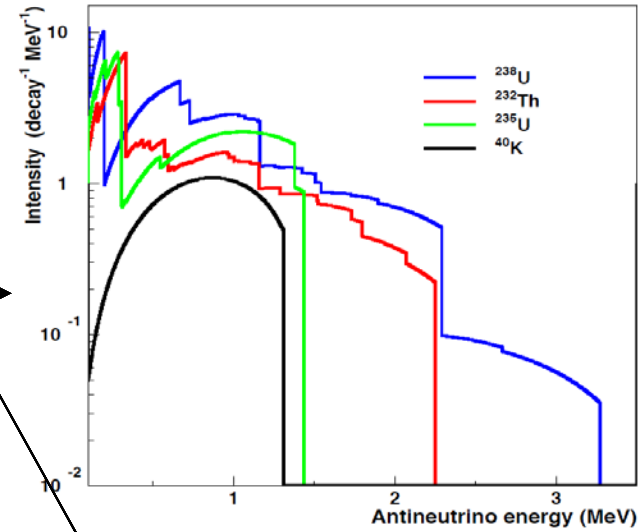
Borexino: 300 t LS (3500 mwe)

KamLAND: 1 kton LS (2200 mwe)

Detection of geo(anti)neutrino

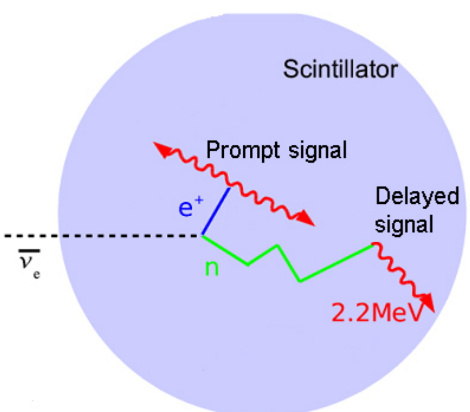
$$\Phi_{\bar{\nu}} \sim 10^{6}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$$

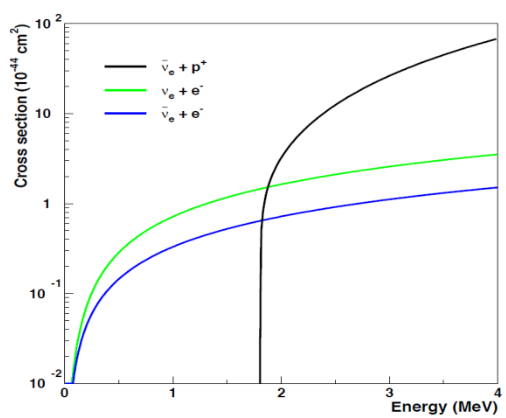
- Earth (in construst to the Sun) emits antineutrino.
- Part of antineutrino in the U and Th decay chains is emitted with E>1.8 MeV (IBD threshold)
- Contributions from U and Th are distinguishable
- Oscillations are averaged: <Pee>=0.54±0.02

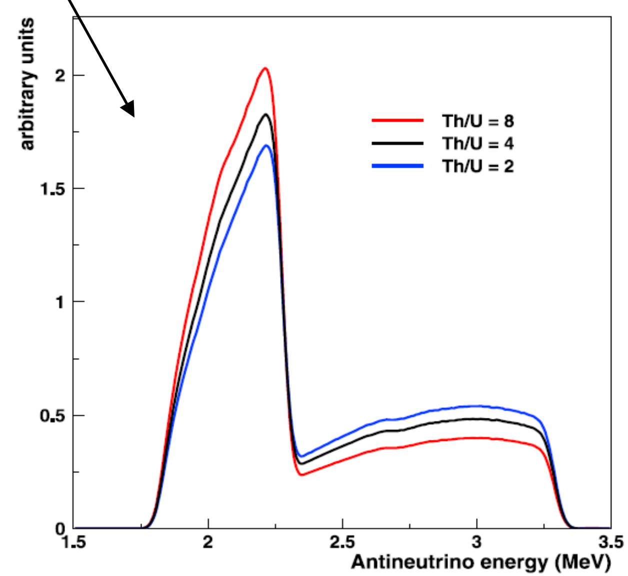


$$\bar{\nu} + p \rightarrow n + e^{+}$$

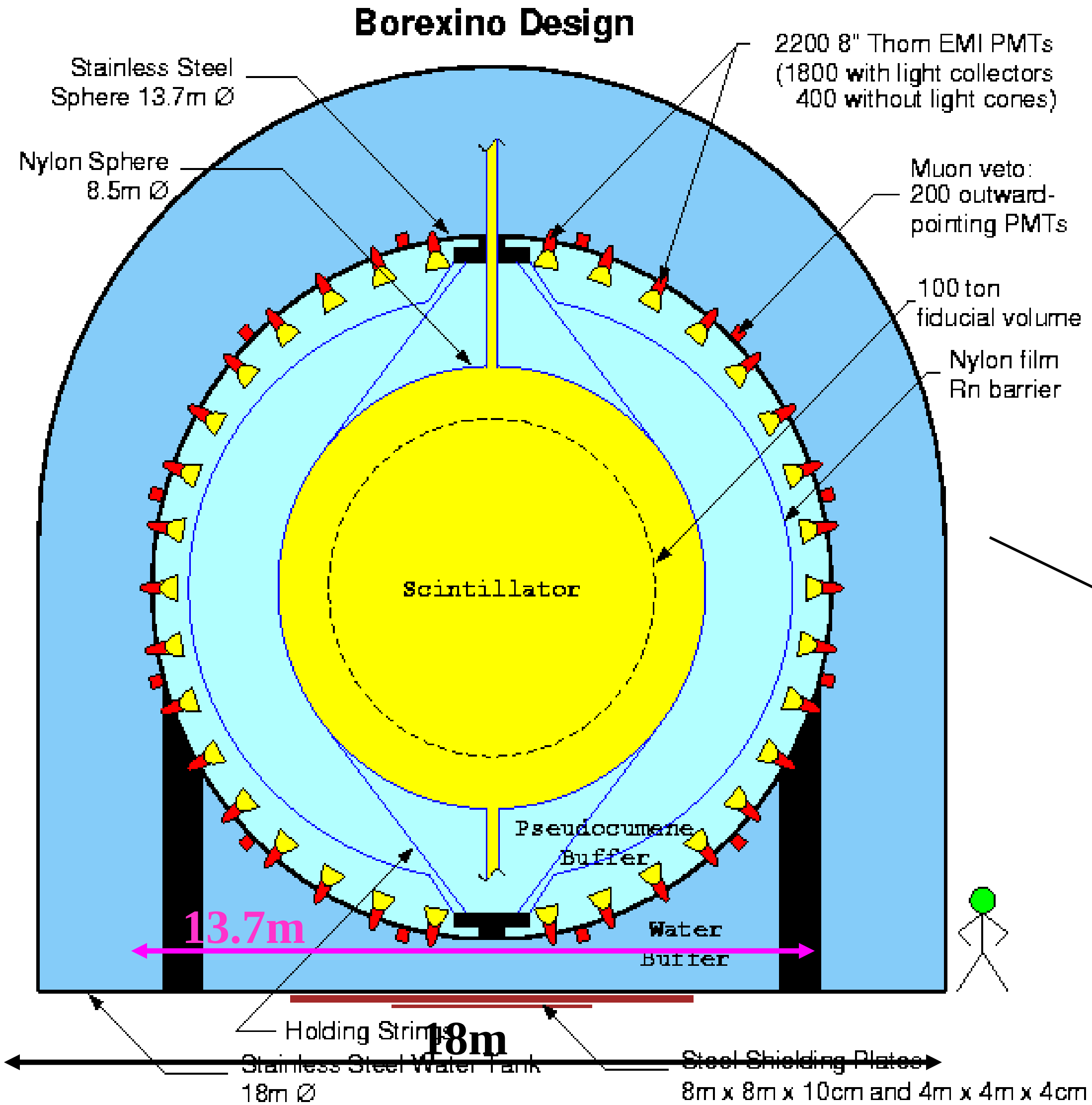
E_{ν}>1.8 MeV



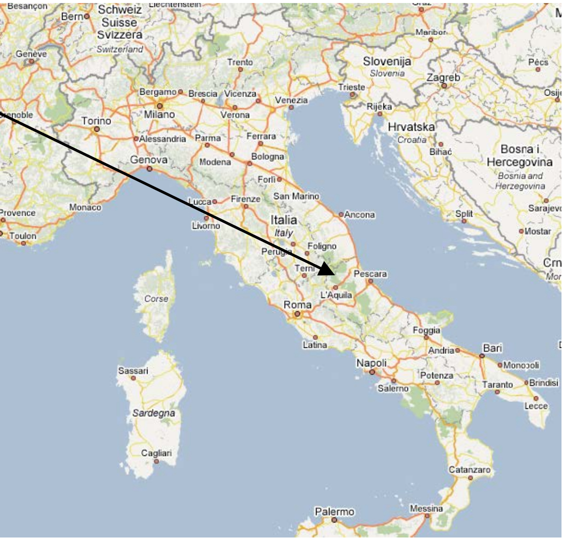




BOREXINO



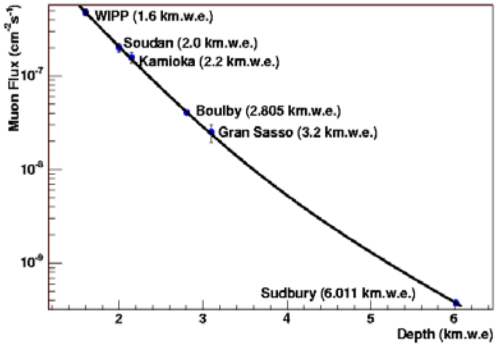
- 278 t of liquid organic scintillator PC + PPO (1.5 g/l)
- (ν,e)-scattering with 200 keV threshold
- Outer muon detector



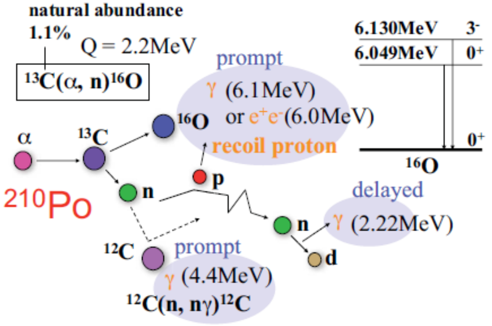
Main backgrounds in geo-neutrino measurements

1) Reactor antineutrinos (81% of the total antineutrino signal in KamLAND geo-nu window [0.9-2.6 MeV] and ~36% for the Borexino case): Geo/Reactor ratio 0.23 in KL vs 1.8 in Borexino;

2) Cosmic muons induced backgrounds, including cosmogenic production of (βn)-decaying isotopes (at LNGS the muons flux is of about factor 7 lower than at the Kamioka site)



3) Internal radioactive contamination: accidental coincidences, (αn) reactions



Data selection for geo-neutrino analysis

- **Total exposition is 907±44 t·yr taking into account detection efficiency**
- **Antineutrino are detected using delayed coincidence tag from the inverse beta- decay on proton (~256 μs)**

$$\overline{\nu_e} + p \rightarrow e^+ + n$$

$$\downarrow \approx 250\ \mu s$$

$$n + p \rightarrow d + \gamma(2.2 MeV)$$

- **~500 p.e./MeV for electrons**
- **438 p.e./2 x 511 keV γ's**

Set of antineutrino cuts

tuned to select maximum of correlated events in space and time with max. suppression of acc.coincidences

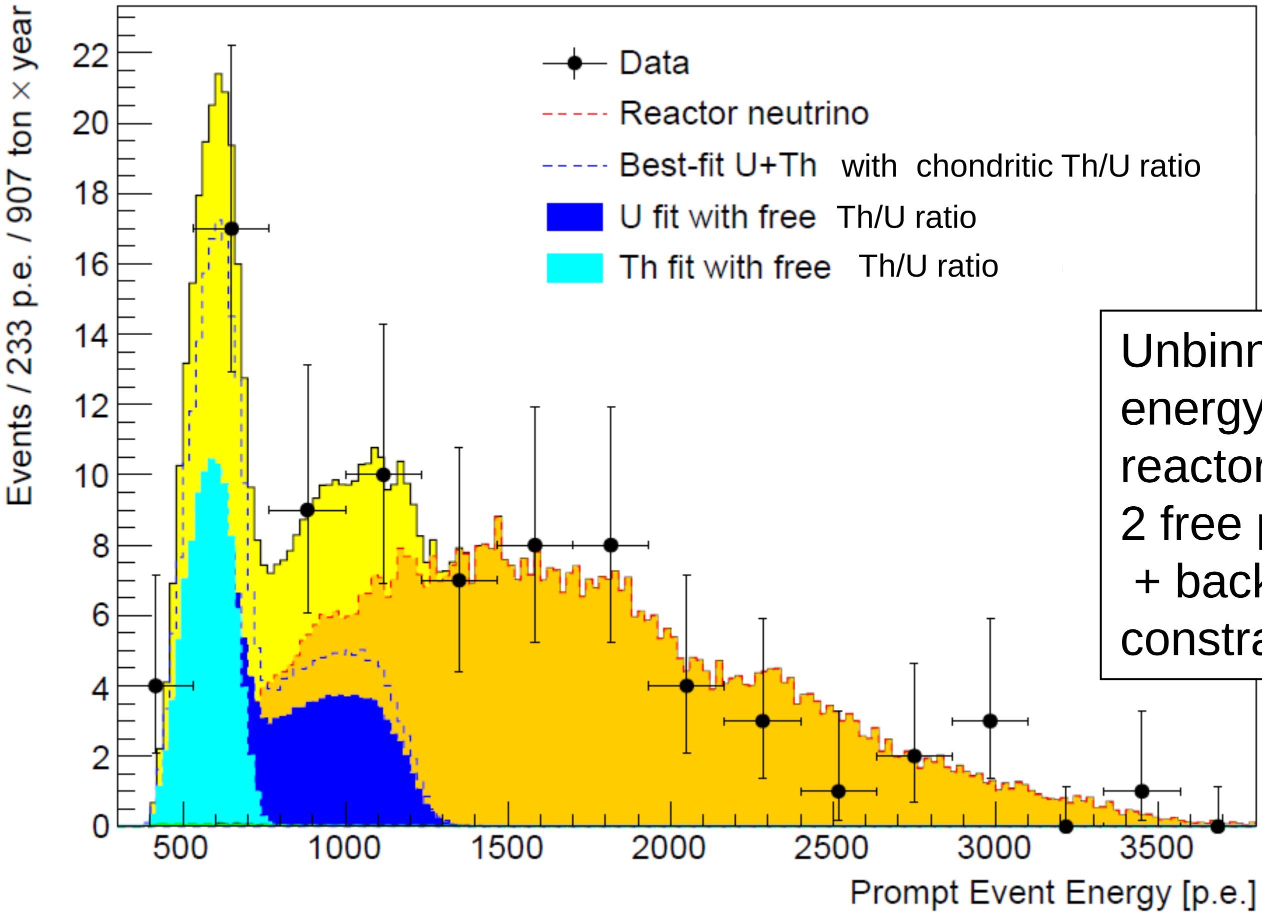
1. **Q_{prompt}>408 p.e. : 3σ(E) above $2m_e$**
2. **860 <$Q_{delayed}$<1300 p.e**
3. **ΔR<1 m;**
4. **20 <Δt<1280 μs**
5. **Pulse shape. $g_{\alpha\beta}$(delayed)<0.015 : selecting e-like events (prompt signal from fast n is α-like)**
6. **T_μ>2 ms : fast neutrons after muon**
7. **T_μ>2 s** for every muon passing through internal detector. Long-lived cosmogenic (βn) isotopes. ~10% of live time loss.
8. **Multiplicity cut: no n-like events in ±2 ms window**
9. **R_{IV}(Θ,φ)-R_{prompt}(Θ,φ)>0.30 m : dynamical, follows IV shape**
10. **FADC cut : independent check of candidates features with 400 MHz digitizing system**

Total efficiency=84.2±1.5% (MC). 77 candidates selected

Summary of backgrounds

Source	events
Cosmogenic ^{9}Li and ^{8}He	$0.194 \pm 0.015(\text{stat})^{+0.124}_{-0.088}$ (syst)
Fast neutrons from μ in Water Tank	< 0.01 (90% CL) (measured)
Fast neutrons from μ in rock	< 0.43 (90% CL) (MC)
Non-identified muons	0.12 ± 0.01
Accidental coincidences	0.221 ± 0.004
Time correlated background	$0.035 \pm 0.028(\text{stat})^{+0.006}_{-0.004}$ (syst)
Spontaneous fission in PMTs	0.032 ± 0.003
(α,n) reactions in the scintillator [^{210}Po]	0.165 ± 0.010 (stat)
(α,n) reactions in the buffer [^{210}Po]	< 0.66 (90% CL)
^{214}Bi-^{214}Po	0.009±0.013
TOTAL	$0.78^{+0.13}_{-0.10}$

Borexino 2015: antineutrino spectrum (77 events)

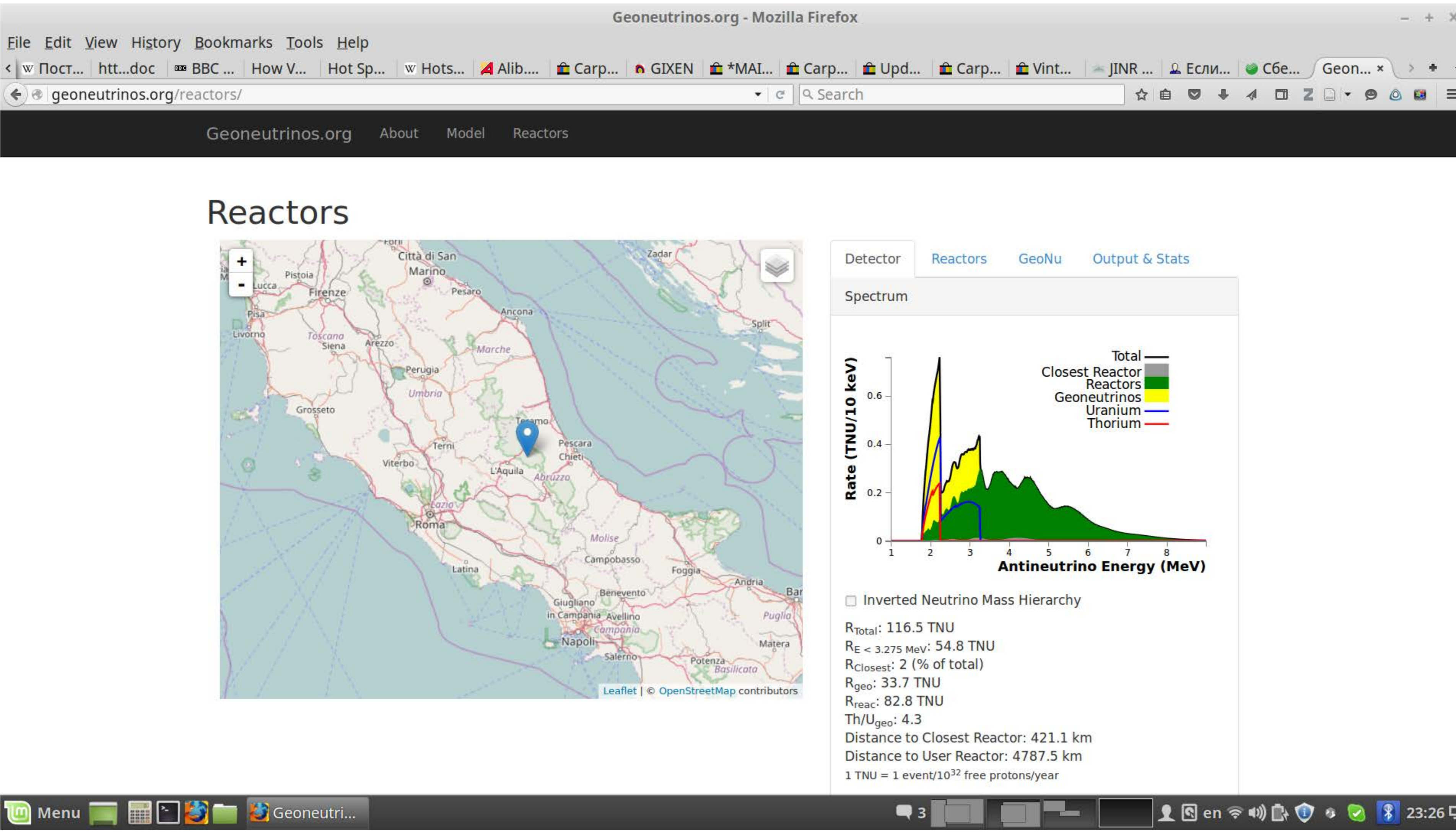


Unbinned likelihood fit using MC energy spectra for geo and the reactor antineutrinos
2 free parameters S_{geo} and S_{react}
+ backgrounds components constrained

$$Q_{vis} = 438\,p.e.(2\gamma) + Q(E_{\bar{\nu}} - 1.8MeV)$$

~500 p.e./MeV (electrons)
gammas are quenched

geoneutrinos.org



Borexino: fit results for fixed M(Th)/M(U)=3.9

$N_{geo}=23.7^{+6.5}_{-5.7}(stat)^{+0.9}_{-0.6}(syst)$ events

$S_{geo}=43.5^{+11.8}_{-10.4}(stat)^{+2.7}_{-2.4}(syst)$ TNU

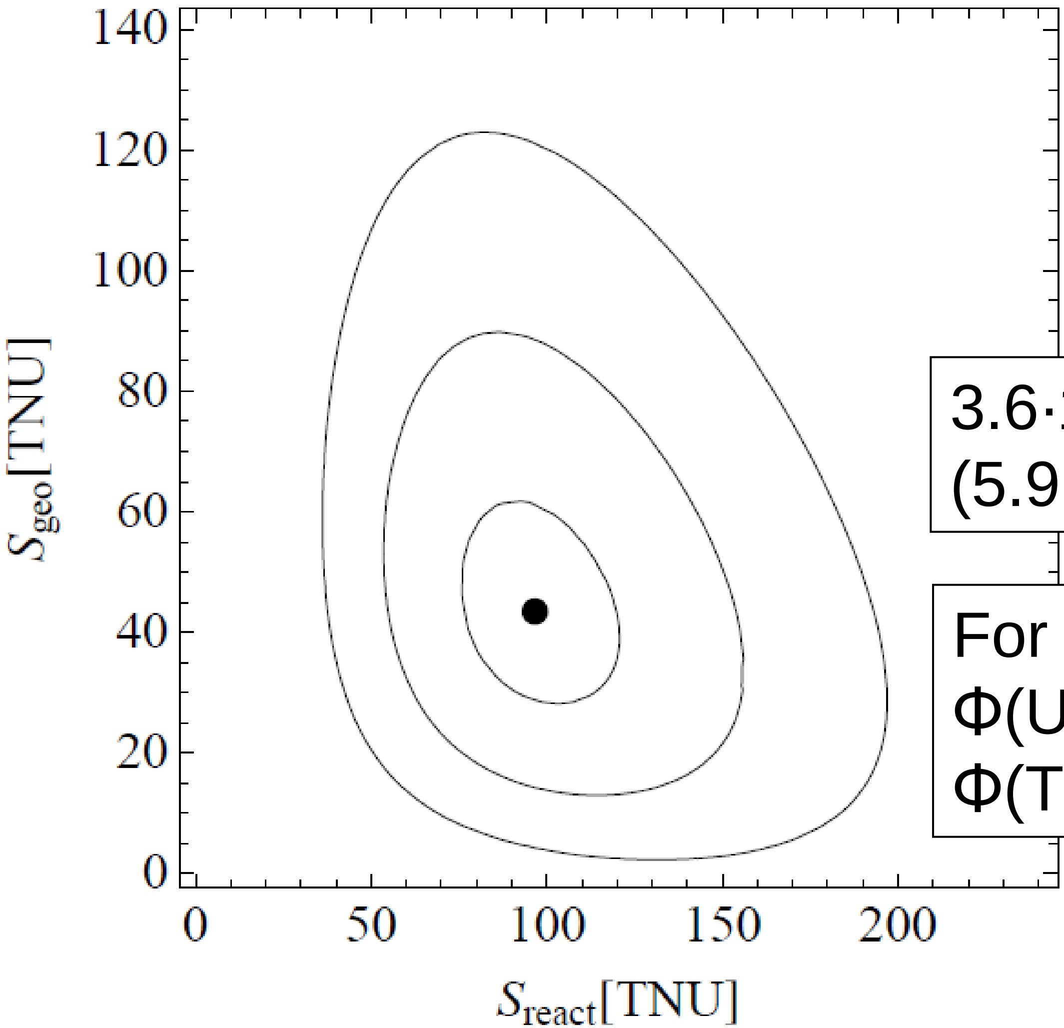
- $N_{react}=52.7^{+8.5}_{-7.7}(stat)^{+0.7}_{-0.9}(syst)$ events

  $S_{react}=96.5^{+15.6}_{-14.2}(stat)^{+4.9}_{-5.0}(syst)$ TNU

Predicted reactor signal 87±4 TNU

- Systematics: 4.8% on FV and 1% on the energy scale
- *1 TNU = 1 event on 10^{32} protons in 1 yr (~1 kt of LS)

S_{geo}:S_{react} for fixed Th/U=3.9

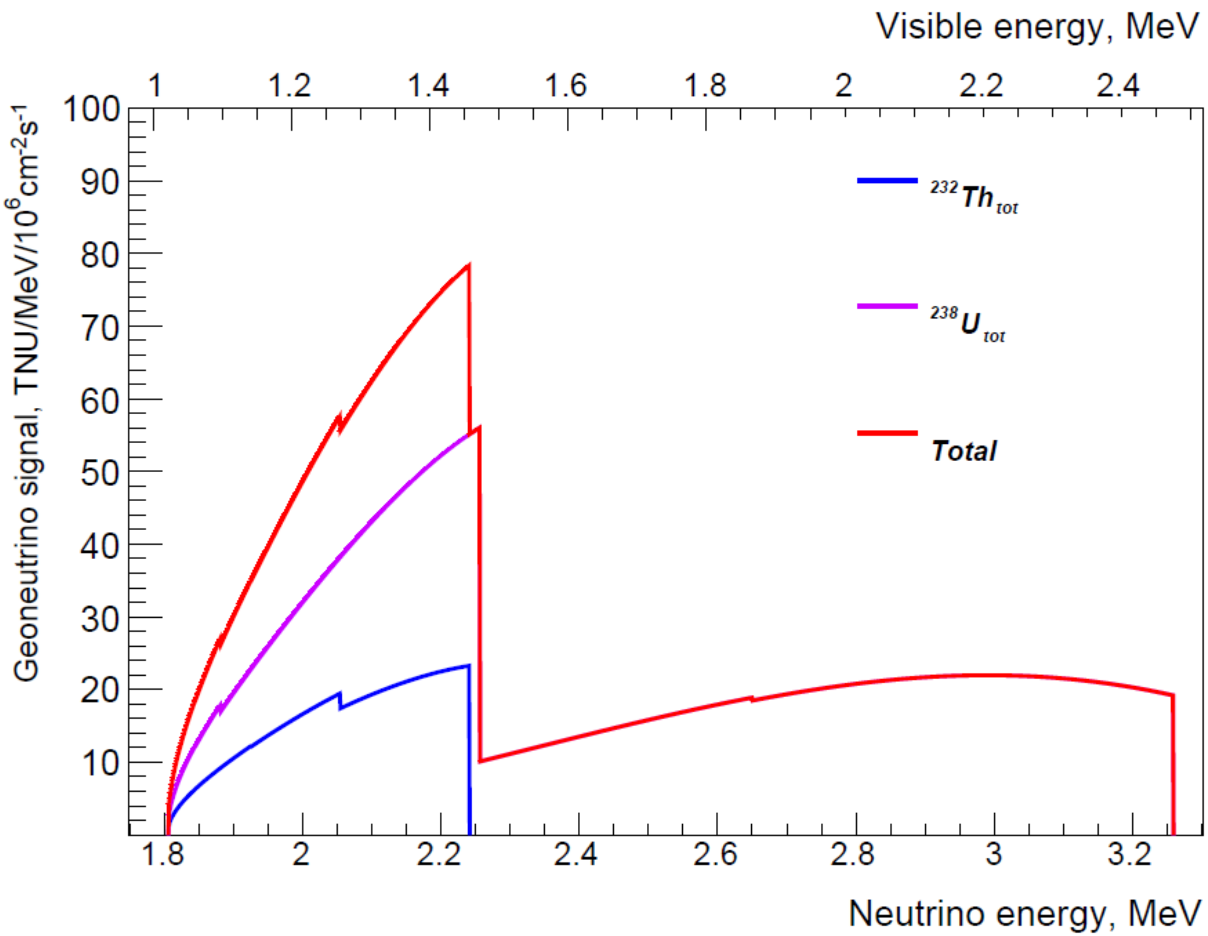


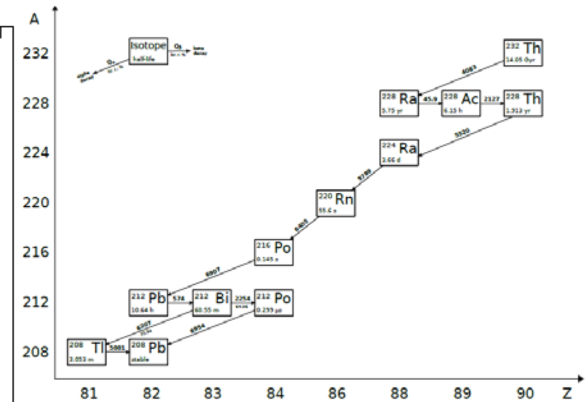
$3.6\cdot10^{-9}$ probability of N_{geo}=0 (5.9 σ)

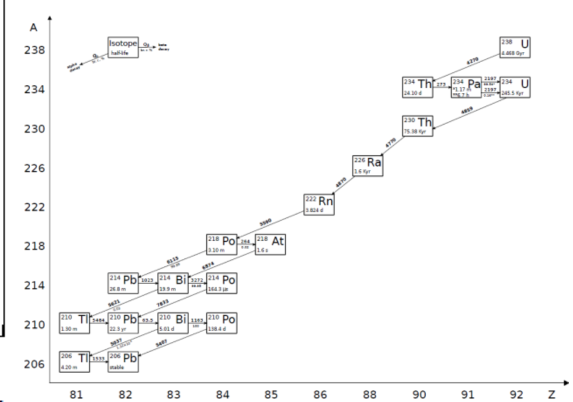
For Th/U=3.9 :
$\Phi(U)=(2.7^{+0.8}_{-0.7})\times10^{6}\ cm^{-2}s^{-1}$
$\Phi(Th)=(2.3^{+0.7}_{-0.6})\times10^{6}\ cm^{-2}s^{-1}$

1,3 and 5 σ contours for S_{geo}:S_{react} signals

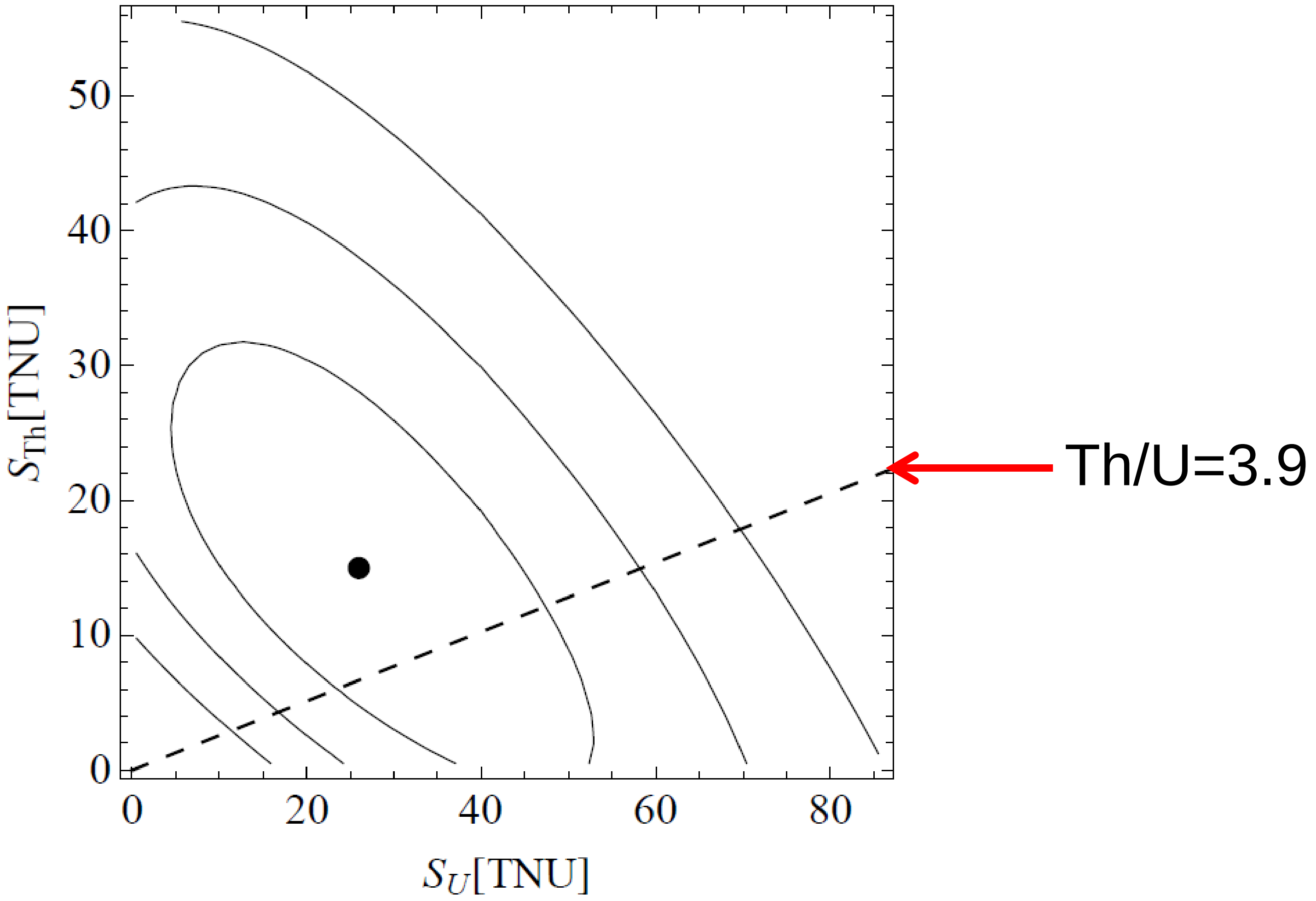
U/Th signal (no energy resolution)





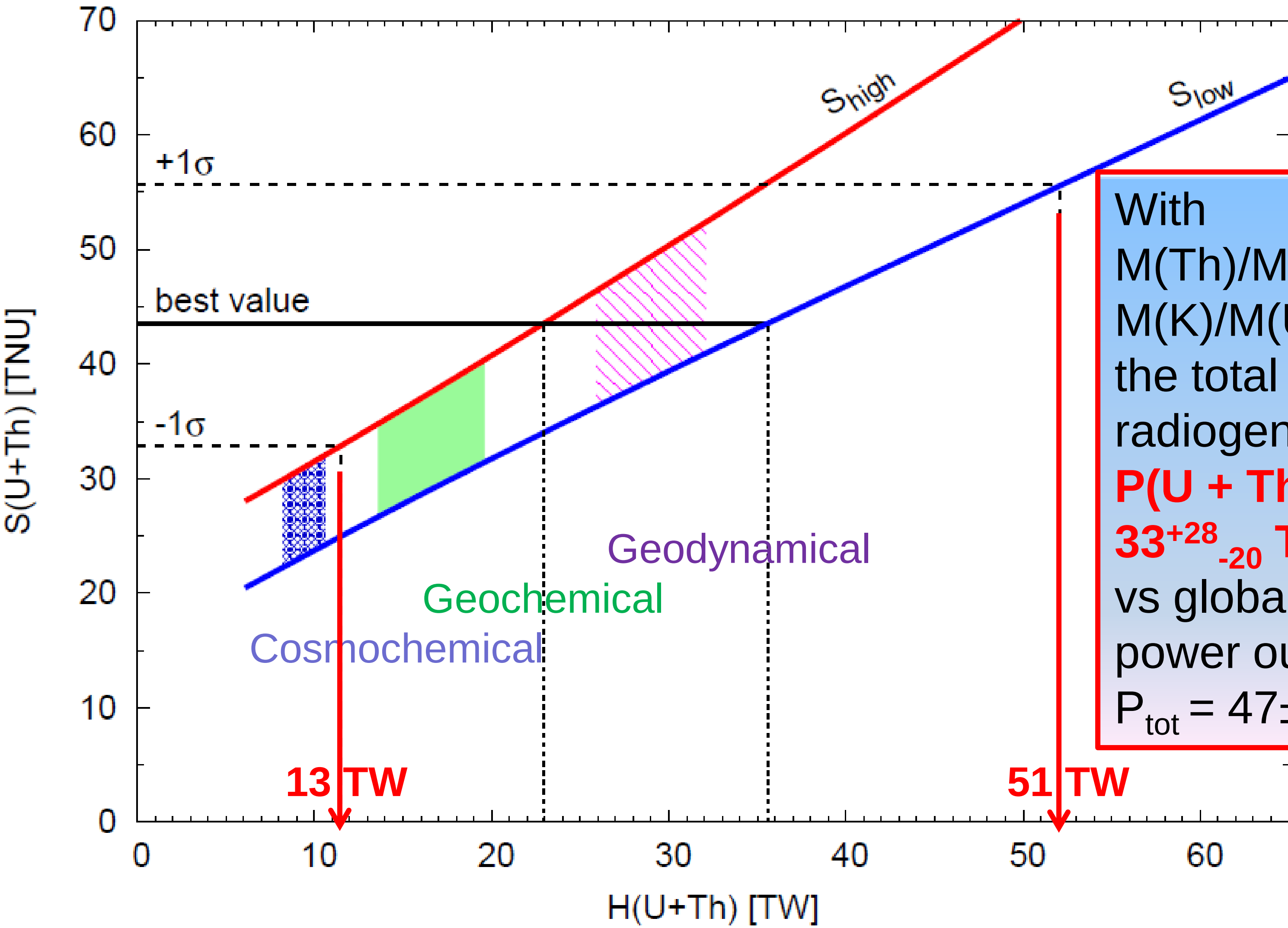


Unconstrained U/Th analysis



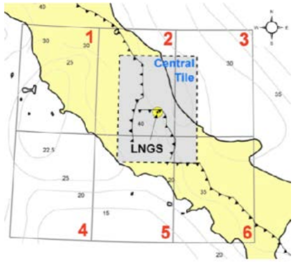
1,2 and 3 σ contours for S_U:S_{Th} signals

Radiogenic heat: Borexino



With M(Th)/M(U)=3.9 & M(K)/M(U) = 10^4 the total terrestrial radiogenic power :
P(U + Th + K) = 33^{+28}_{-20} TW,
vs global terrestrial power output P_{tot} = 47±2 TW

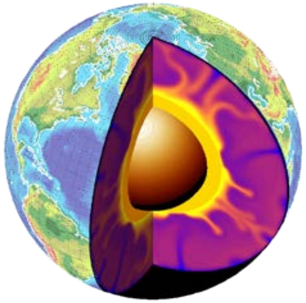
Red line: ROC+LOC+1σ, homogenios mantle
Blue line: ROC+LOC-1σ, radiogenic material on the mantle/core interface



Signal from the mantle

- ***Total contribution from the Earth crust (Coltorni et al.,* Huang et al.) *(LOC + ROC) is S_{geo}(Crust) = (23.4 ± 2.8) TNU -> 12.75 ±1.53 events (+stat.smearing)***

- **subtraction of probability distributions for the total signal (from the fit) and pdf for crust (normal approximation). Non-physical values of difference are excluded and final p.d.f. renormalized to unity.**



p.d.f.(Mantle)=p.d.f. (Geo)-p.d.f.(Crust) :

$$S_{geo}(Mantle) = 20.9^{+15.1}_{-10.3}\ \text{TNU}$$

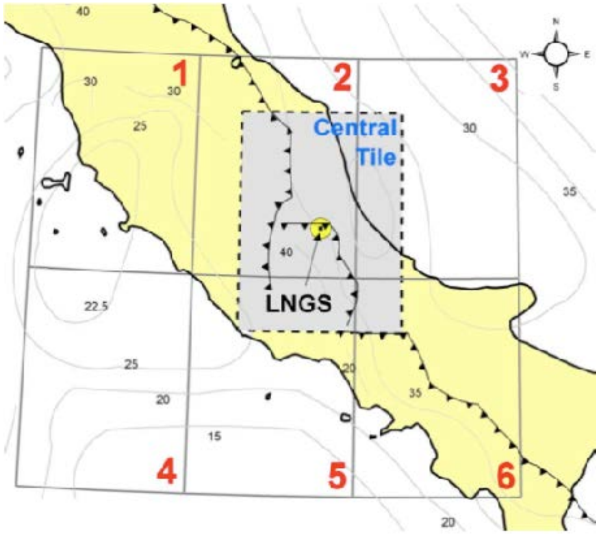
Mantle could have as little as 1-3 TW or as much as 28 TW

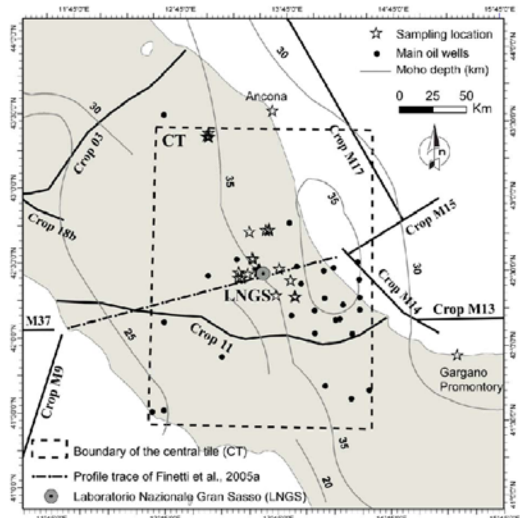
with a probability of 98% we observe at least 1 event from the mantle

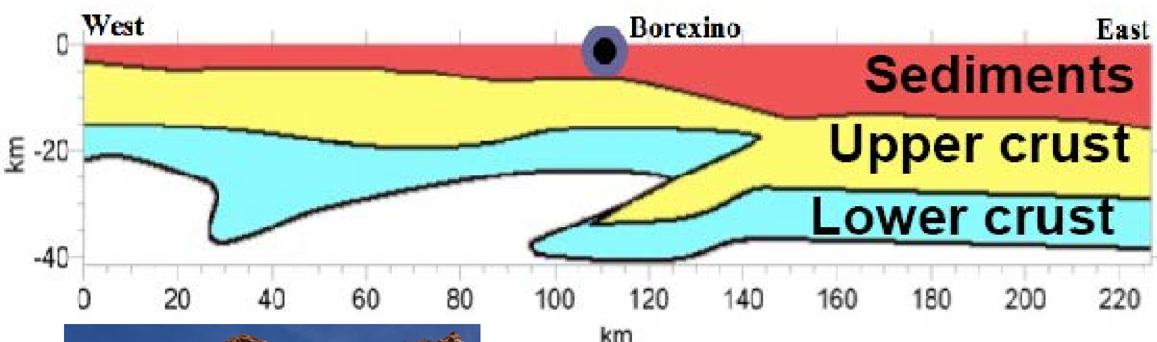
- Note:
  - Mean value is bigger compared to a simple difference $<S_{geo}>-<S(Crust)>=43.5-23.5=20.1$ as a result of excluding non-physical values from p.d.f.
- LOC: M. Coltorti et al., Earth Planet. Sci. Lett. 293 (2010) 259.
- ROC: Y. Huang et al. Geochemistry, Geophysics, Geosystems 14, 2003 (2013).

Study of the local geology LNGS

(Coltorti et al., Geo.Cosm. Acta 75(2011) 2271)







Distances R< 900 km gives ~50% of the signal.

U and Th content in samples

***Using available seismical and stratigraphical data (relative geological age of sediments) 3D model has been constructed (down to Moho depth) for 10^6 cells with 1 km^3* volume**

Contribution from the local crust
S_{geo}(LOC) = (9.7±1.3) TNU.

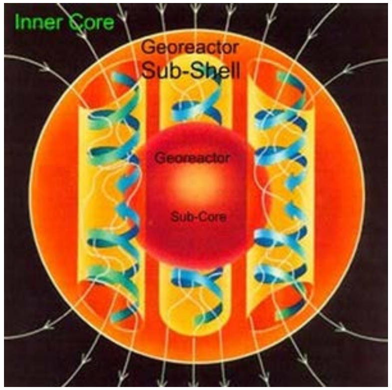
1 TNU = 1 event per 10^{32} target nuclei in 1 yr

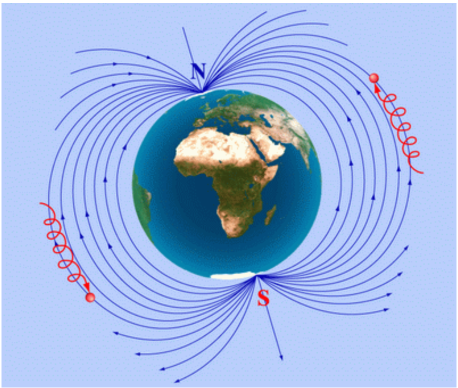
Antineutrino measurements with Borexino

Year	Live time, days	Exposition t·yr	N_{cand}	N_{geo}	S_{geo} TNU	P(0)
2010	537.2	252.6	21	$9.9^{+4.1}_{-3.4}$	$65.2^{+27.0}_{-22.4}$	$3 \cdot 10^{-5}$ (4.2σ)
2013	1363	613 $\pm$ 26	46	14.3±4.4	38.8±12.0	$6 \cdot 10^{-6}$ (4.9σ)
2015	2056	**907±44**	77	$23.7^{+6.5}_{-5.7}$	$43.5^{+12.1}_{-10.7}$	$3.6 \cdot 10^{-9}$ (5.9σ)

2010)G. Bellini, et al. Phys. Lett. B 687 (2010) 299
2013)G. Bellini, et al. Phys. Lett. B 722 (2013) 295
2015)M. Agostini, et al, Phys. Rev. D 92, 031101 (2015)

Georeactor

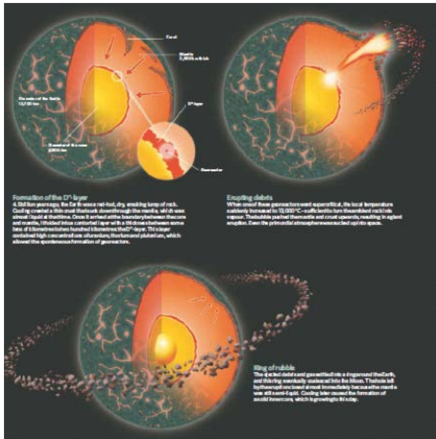


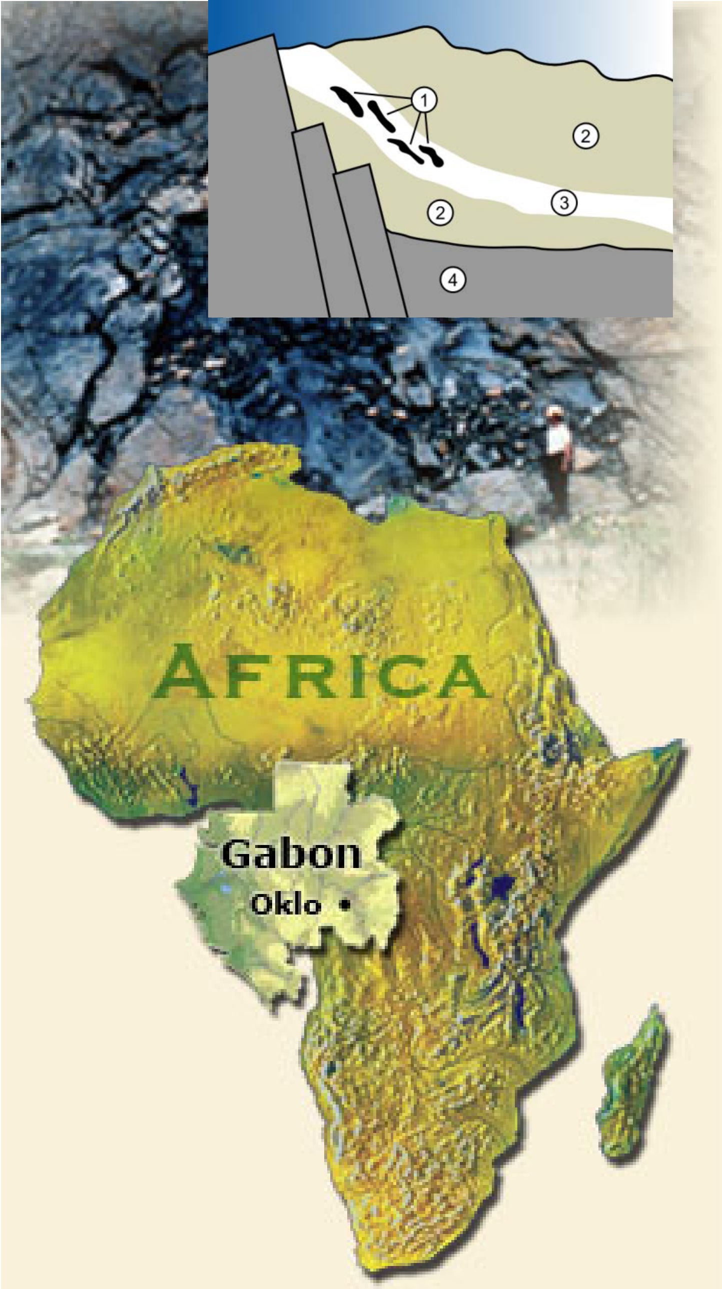


- **In the core (Herndon) on the core/mantle border (Rusov и de Meijer)**
- **5-10 TW will help to explain heating, convection, He3 anomaly, geomegnetism and some other problems.**
- **Both are critisized by geochemists**
- **Easy to test with geoneutrinos, Borexino excludes georeactor with 4.5 TW power at 95% C.L.**

Forming the Moon from a geo-reactor at the core-mantle boundary 4.5 Ga

Forming the Moon from terrestrial silicate-rich material (2013)
R.J. de Meijer, V.F. Anisichkin, W. van Westrenen



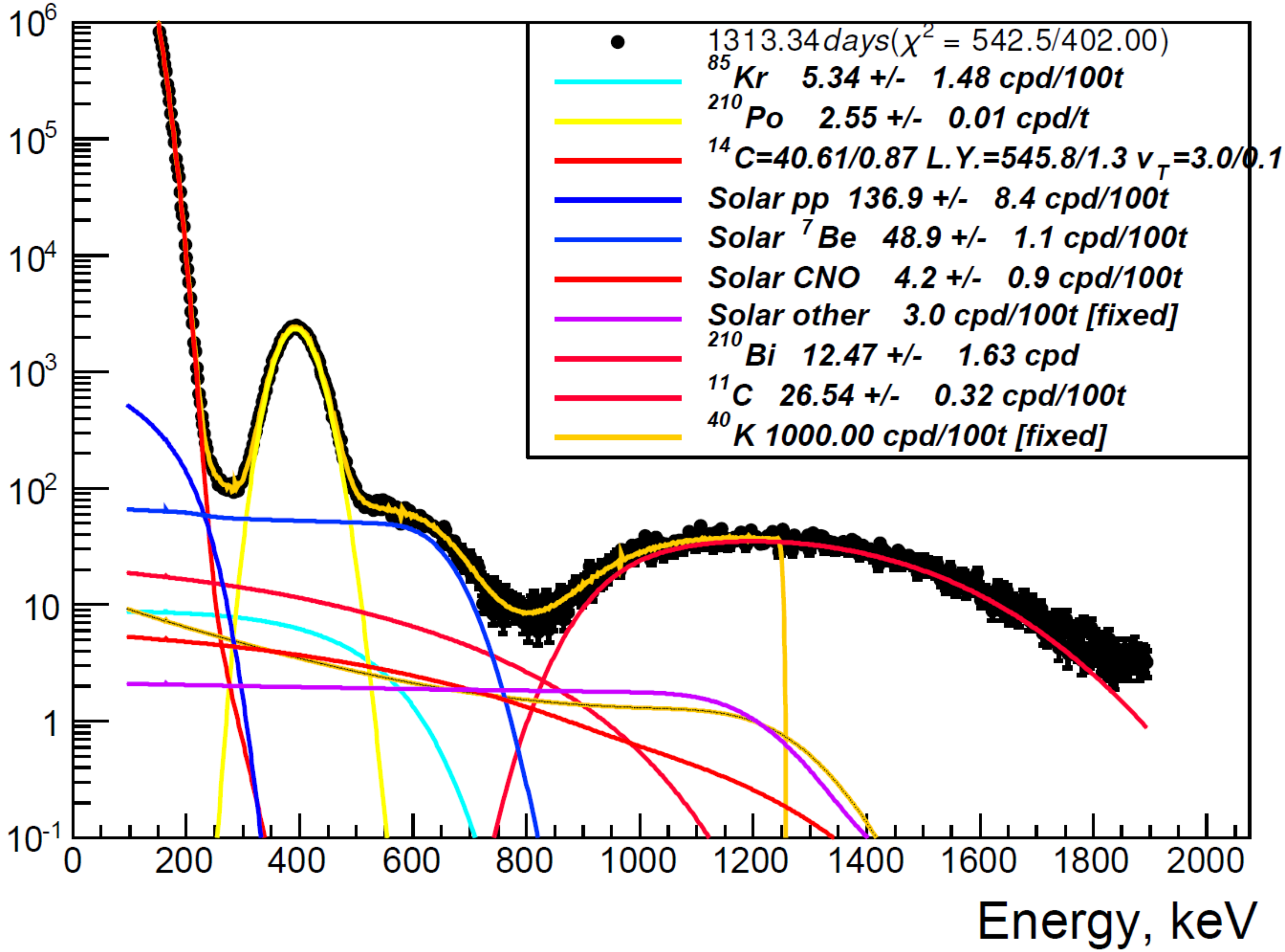


The uranium isotopes found at Oklo strongly resemble those in the spent nuclear fuel generated by today's nuclear power plants.

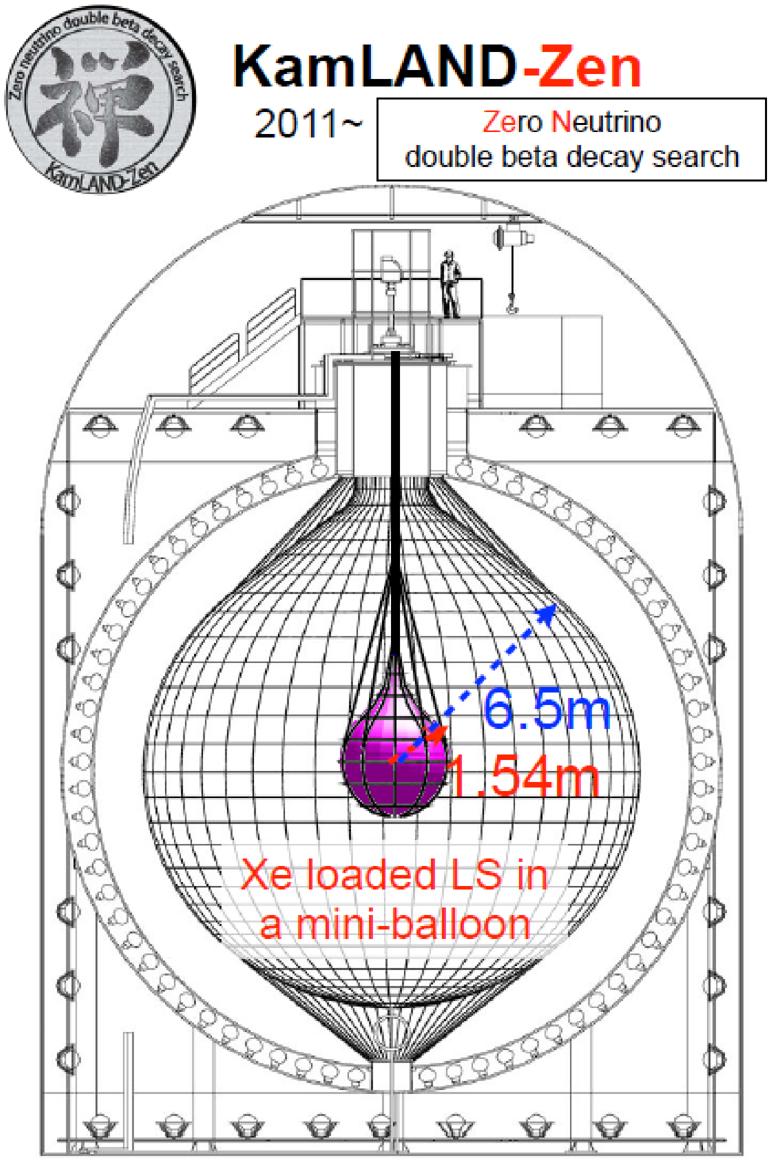
Another measurement with Borexino?

- We have accumulated another ~1.5 yrs of data and will run at least 1 yr more in solar mode before SOX program (+ ~50% statistics)
- Tuning of the muon-veto cut will save 9% of live-time
- We consider the possibility to perform a spectral fit in all volume (+ ~50%)
- Better understanding of “external” background” (close to the IV walls) is needed

Signal from ^{40}K



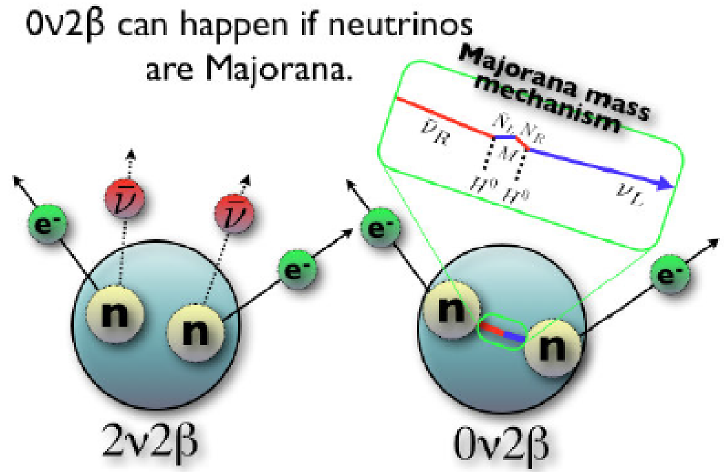
KamLAND



- Detector Features

  ^{136}Xe loaded LS was installed in KamLAND
  (344 kg 90% enriched ^{136}Xe installed so far)

- Physics



neutrino-less double beta decay

World best limit on neutrino effective mass

$$\langle m_{\beta\beta} \rangle < (61 - 165) \text{ meV}$$ PRL 117, 082503 (2016)

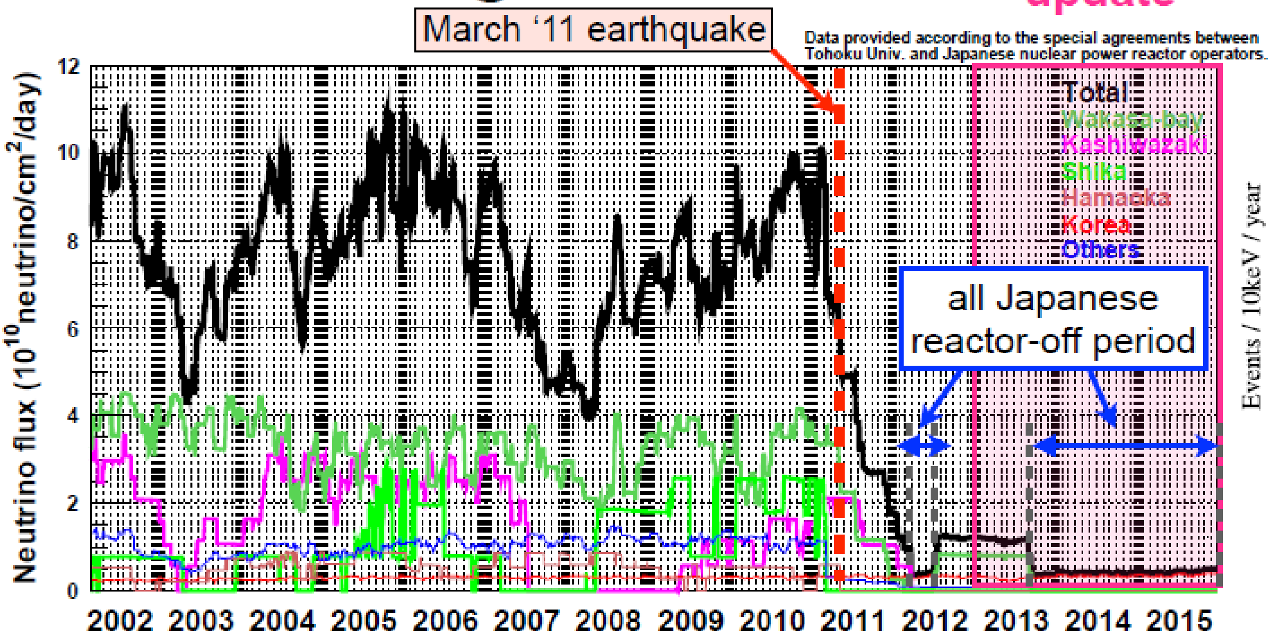
Continue to use LS volume outside of mini-balloon to measure anti-neutrino signals

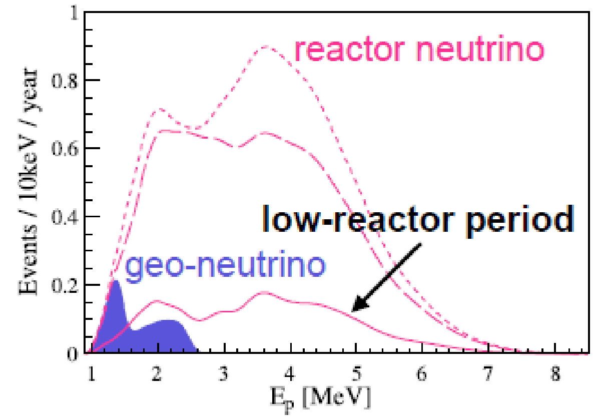
From the talk by Hiroko Watanabe

Current dataset

Reactor Neutrino Flux @Kamioka

update





Reactor neutrino background is decreased significantly.

PRD 88, 033001 (2013)

Preliminary

2013 data-set : 2991 days 4.90×10^{32} proton-year

→

2016 data-set : 3901 days 6.39×10^{32} proton-year

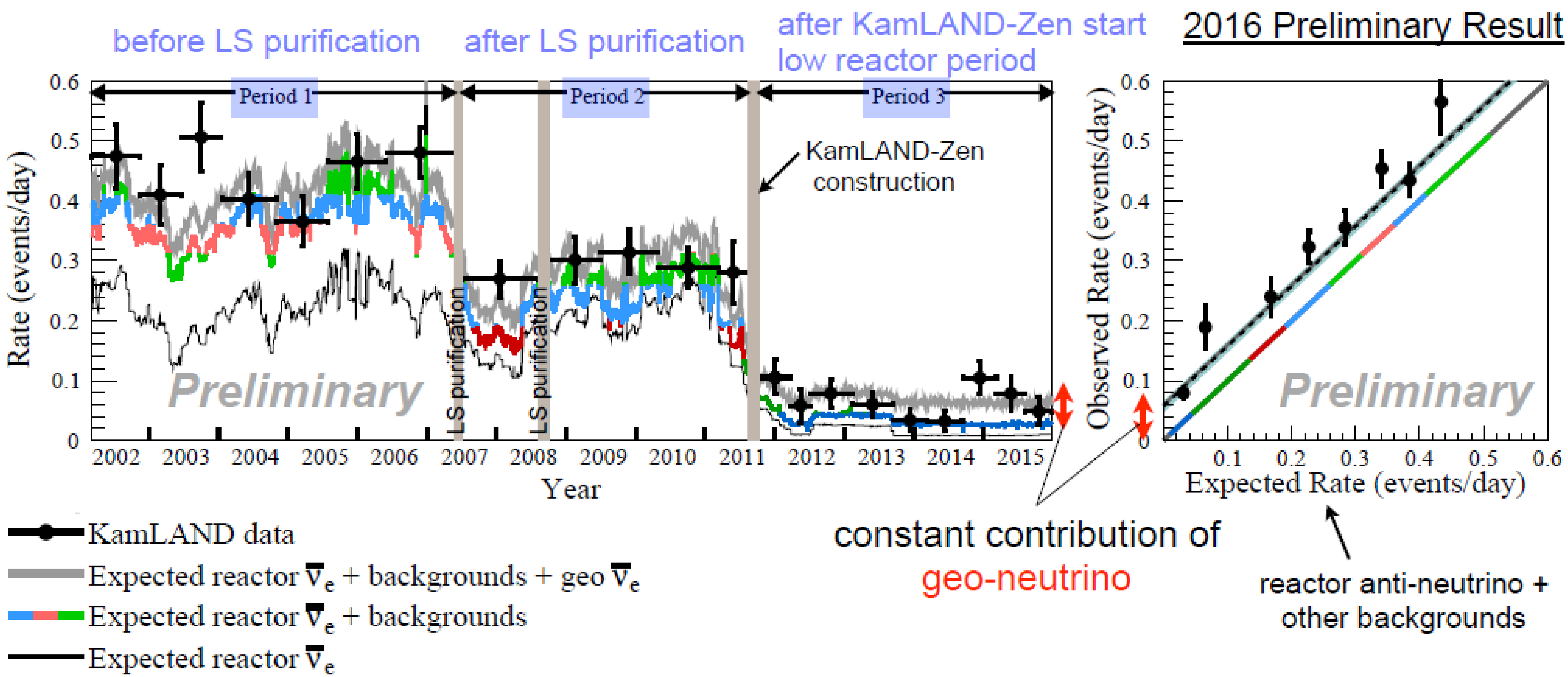
- 1.3 times of 2013 data-set

advantages {
- low-reactor operation period : **~3.5 years** livetime
- **all Japanese reactor-off period : ~2.0 years** livetime

Precise understanding of reactor neutrino spectrum enhances geo-neutrino measurement.

From the talk by Hiroko Watanabe

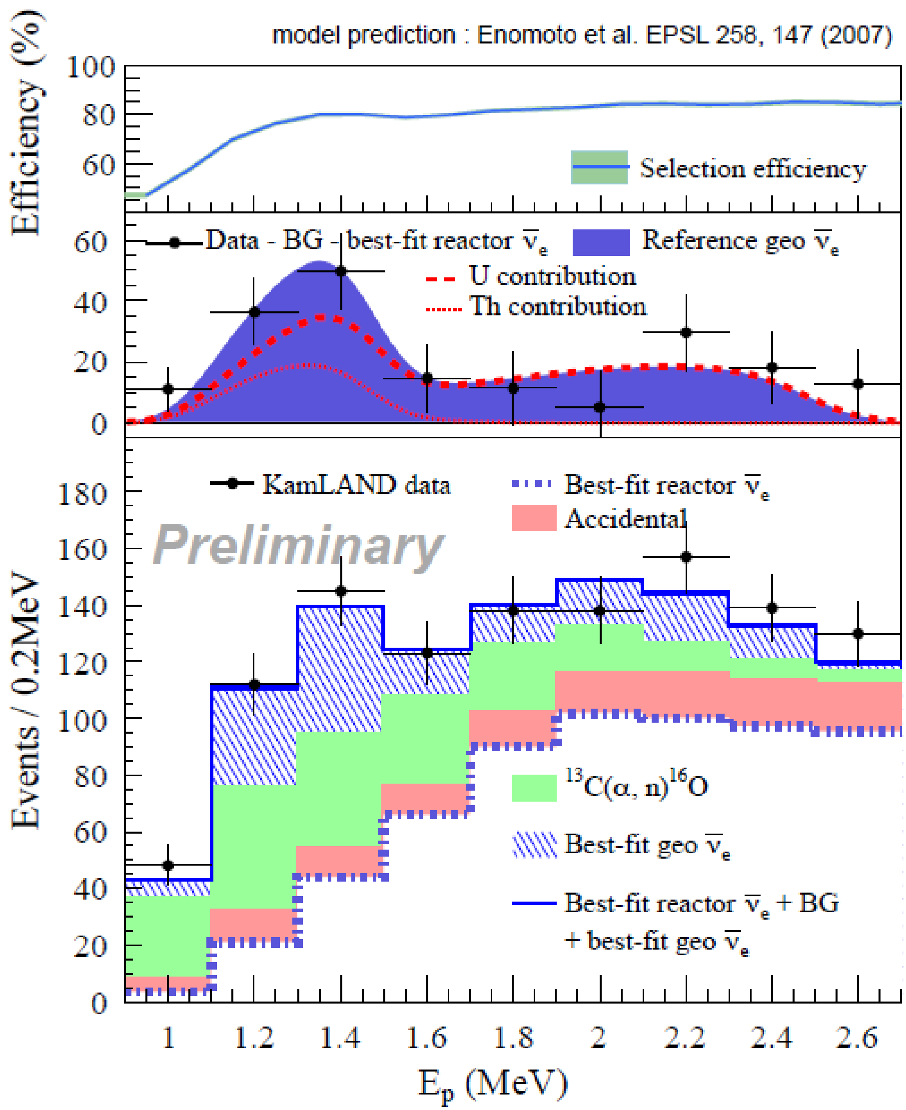
Event Rate Time Variation (0.9-2.6 MeV)



- Backgrounds :
  LS purification → non-neutrino backgrounds reduction
  Earthquake → reactor neutrino reduction
- Constant contribution of geo-neutrino
  Time information is useful to extract the geo-neutrino signal

From the talk by Hiroko Watanabe

Energy Spectrum (0.9-2.6 MeV)



2016 Preliminary Result

Livetime : 3900.9 days

Candidate : 1130 ev

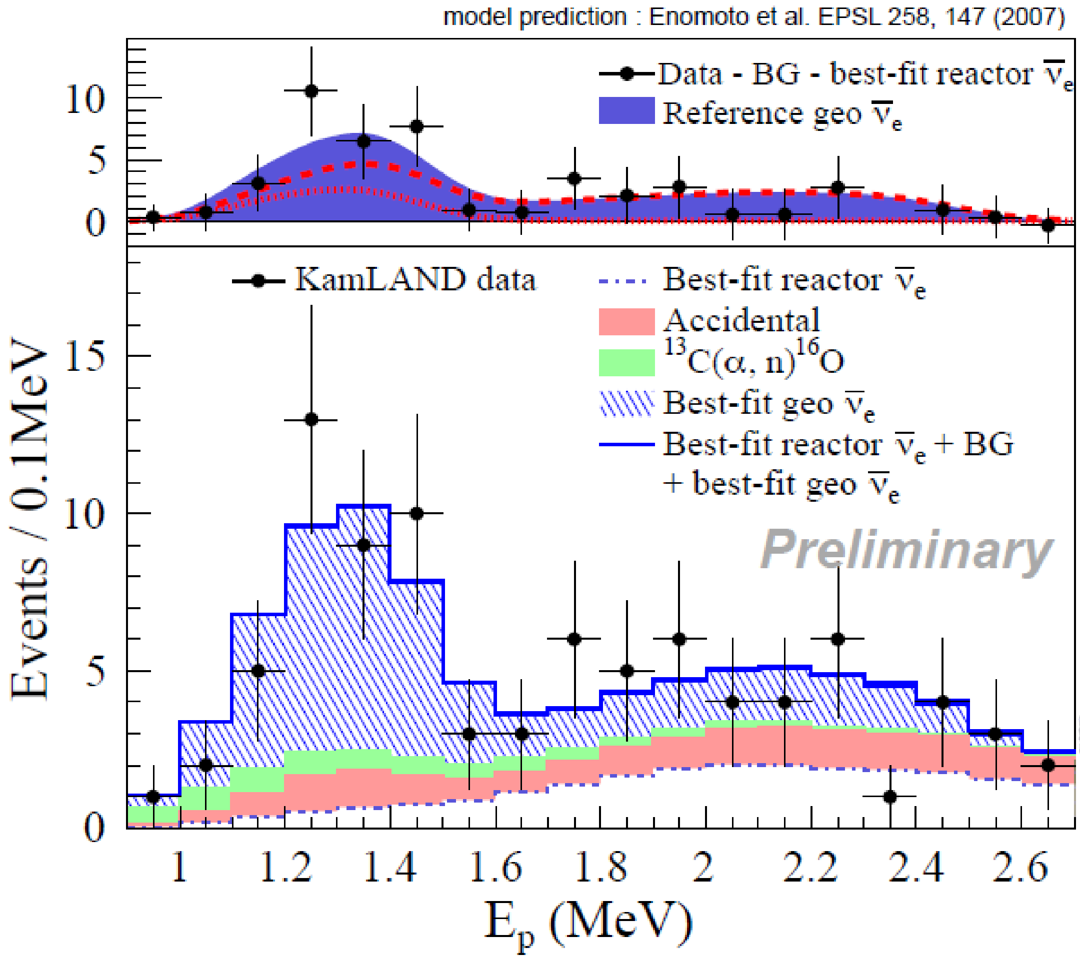
Background Summary

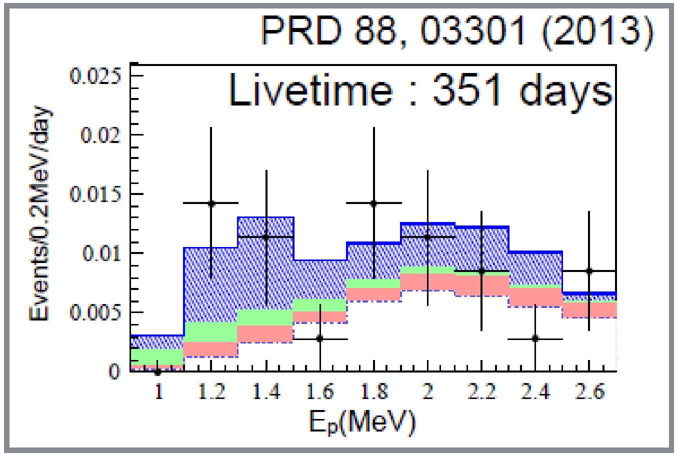
^{9}Li	3.4 ± 0.1
Accidental	114.0 ± 0.1
Fast neutron	< 4.0
$^{13}C(\alpha, n)^{16}O$	205.5 ± 22.6
Reactor $\overline{\nu}_e$	**618.9 ± 33.8**
Total	941.8 ± 40.9

From the talk by Hiroko Watanabe

Energy Spectrum, Period 3 (0.9-2.6 MeV)

Livetime : 1259.8 days 2016 Preliminary Result





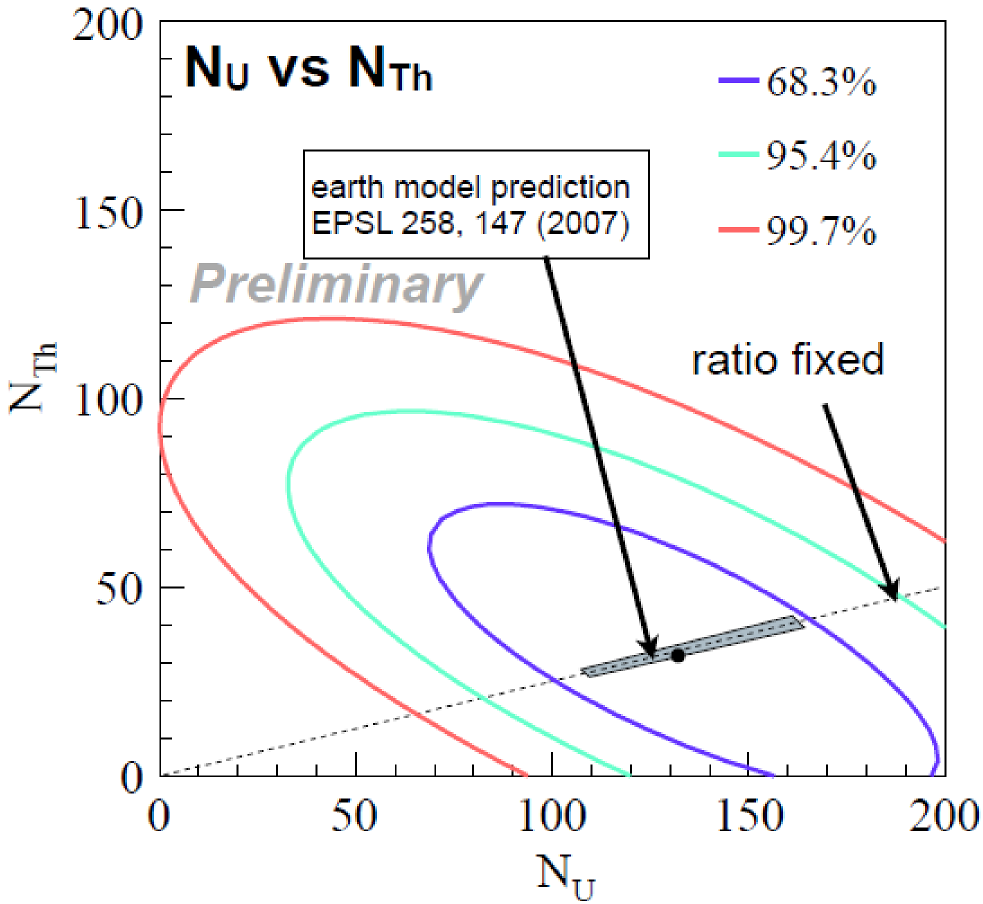
☑ We measured clear distribution of geo-neutrino events.

best-fit : Period 3 analysis

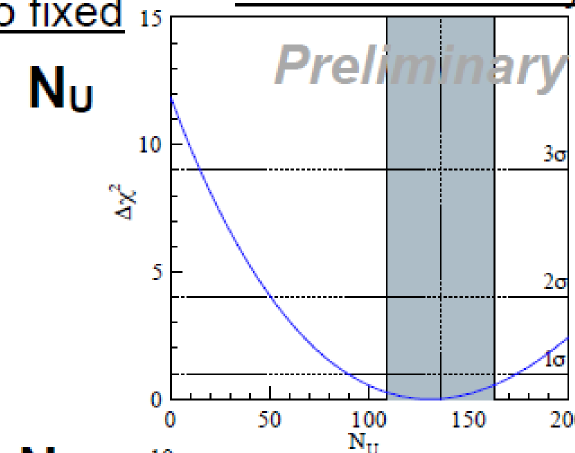
From the talk by Hiroko Watanabe

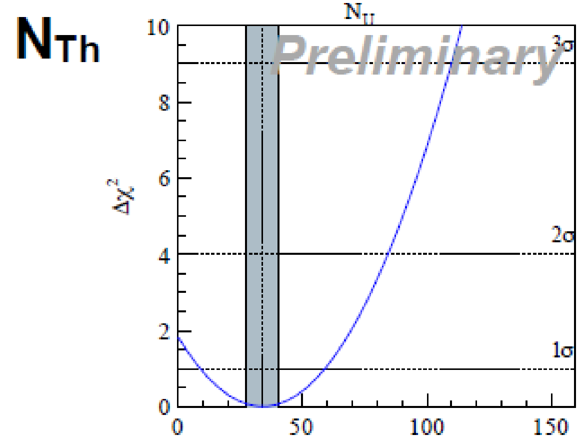
Rate + Shape + Time Analysis

2016 Preliminary Result



ratio fixed





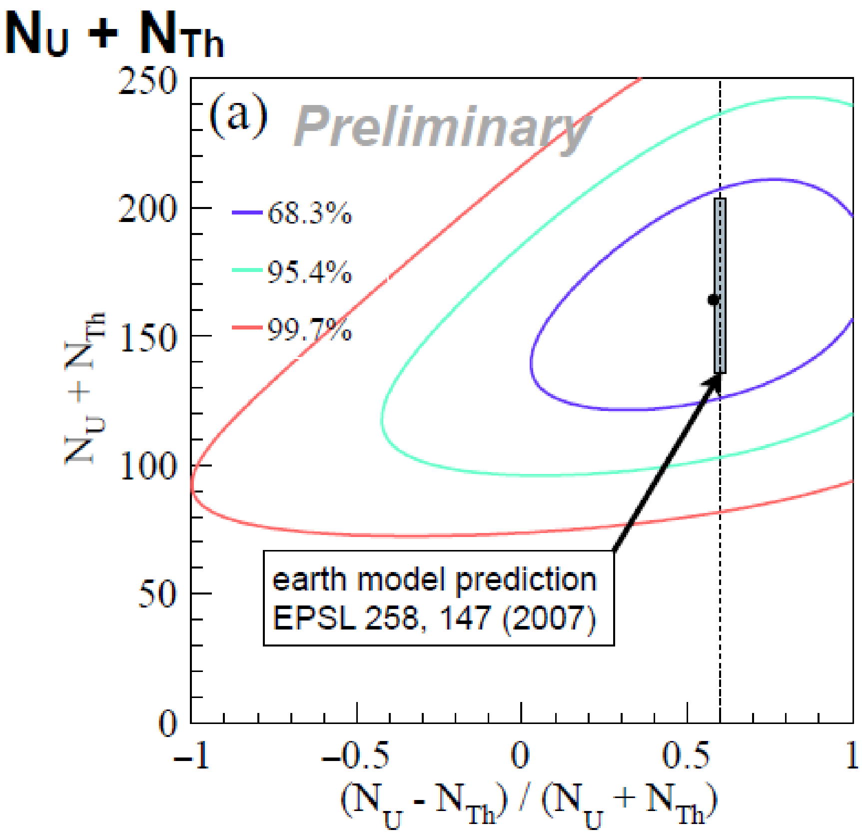
model prediction : Enomoto et al. EPSL 258, 147 (2007)

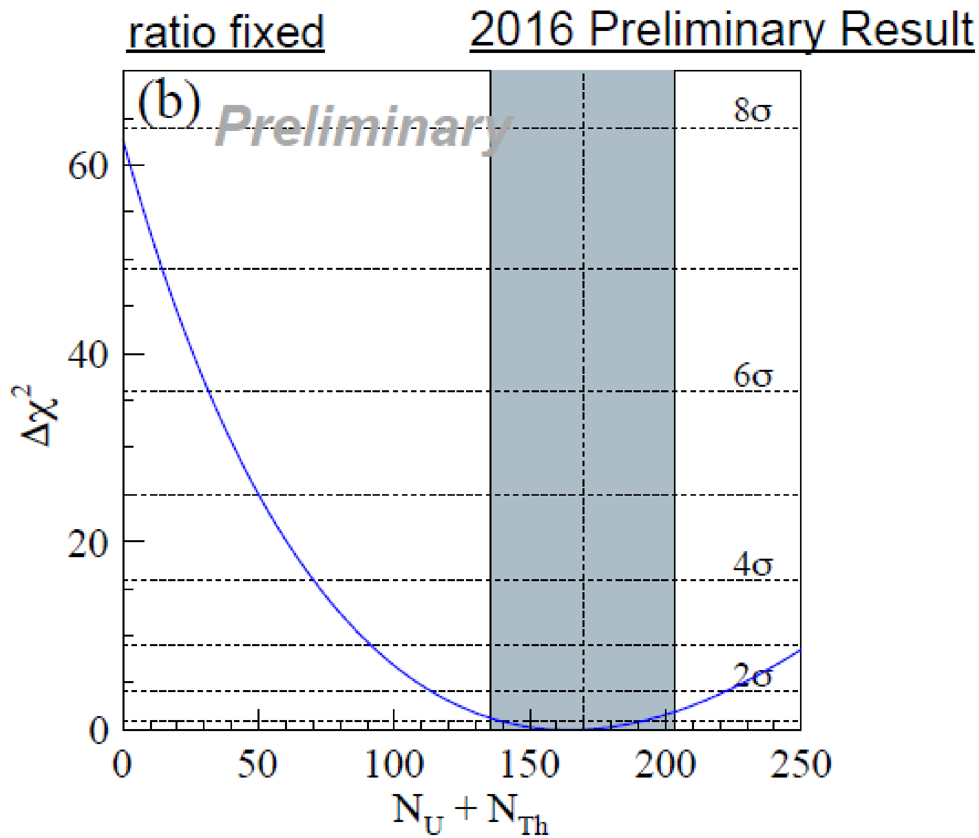
ratio fixed

	[event]	[TNU]	Flux [$\times 10^5$ cm^{-2}s^{-1}]		0 signal rejection
			best-fit	model	
U	128 +46/-39	27.1 +9.8/-8.3	20.8 +7.5/-6.4	22.0	3.44σ
Th	32 +27/-23	6.9 +5.9/-5.0	17.2 +14.5/-12.5	18.6	1.34σ

From the talk by Hiroko Watanabe

Rate + Shape + Time Analysis





best-fit $(N_U, N_{Th}) = (130, 34)$
$N_U + N_{Th} = 164$

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

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**

Th/U Mass Ratio

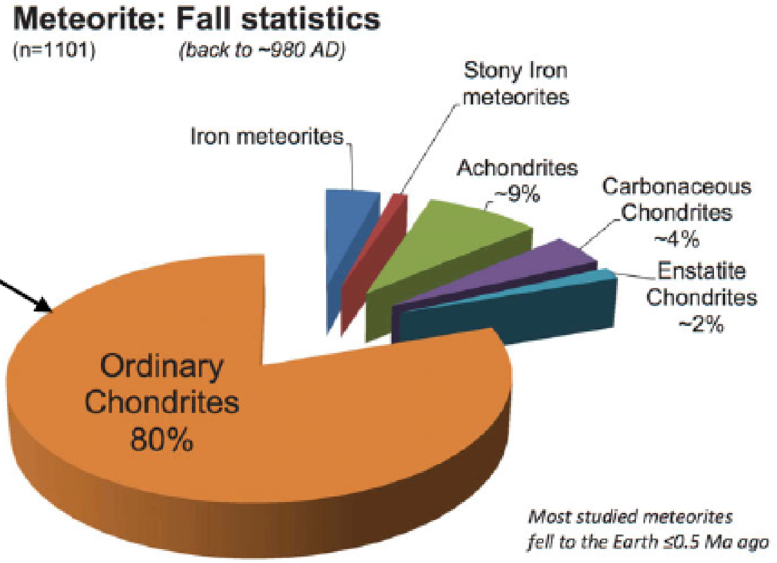
- According to geochemical studies, ^{232}Th is more abundant than ^{238}U. Mass ratio (Th/U) in bulk silicate Earth is expected to be **around 3.9.**

Models : 3.58-4.2

4.2 : Allegre et al. (1986)	3.76 : Hart & Zindler (1986)
3.92 : McDonough & Sun (1995)	3.71 : Lyubetskaya & Korenaga (2007)
3.89 : Taylor (1980)	3.62 : Jagoutz et al (1979)
3.85 : Anderson (2007)	3.58 : Javoy et al. (2010)
3.77 : Palm & O'Neil (2003)	

- Chondrite samples analysis : **1.06-6.42**

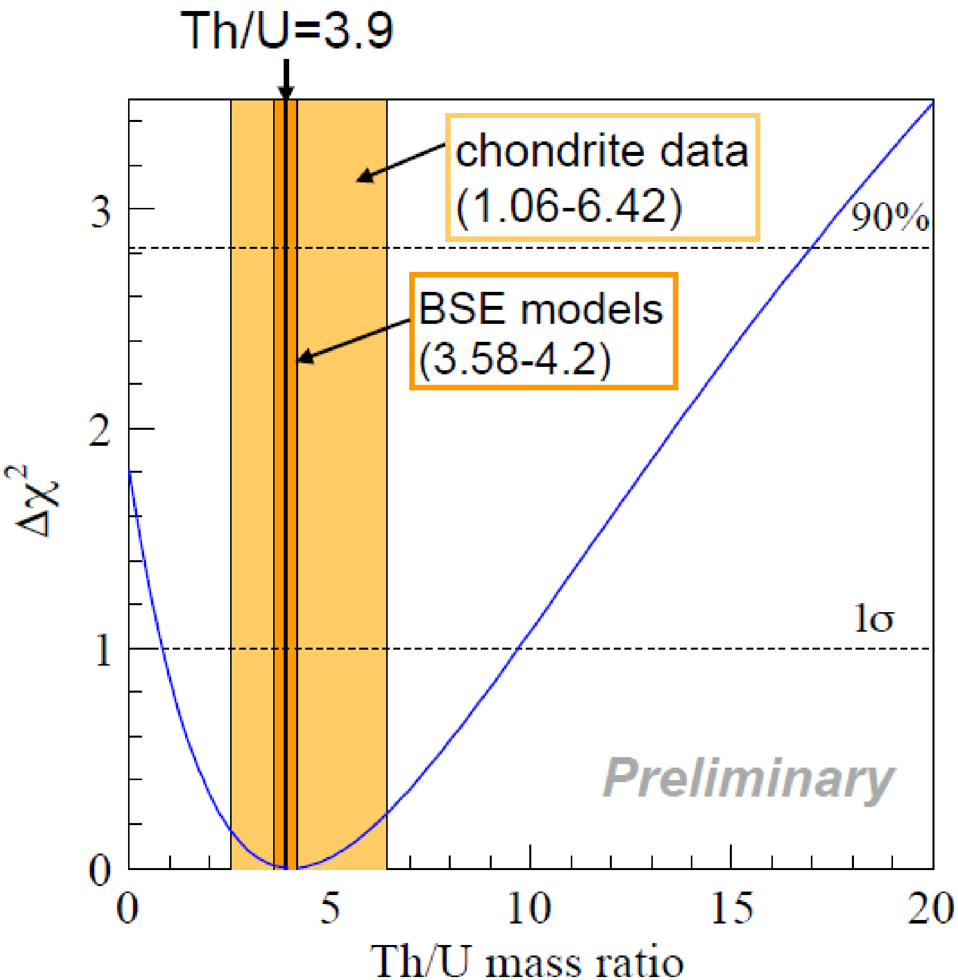
Fall statistics for the meteorites identified and catalogued since 980 A.D.



- Geo-neutrino observed rate can be converted to amount of Th & U assuming homogeneous distribution. **Independent & direct measurement of entire Earth**

slide from McDonough, 2015, in Ehime

Th/U Mass Ratio



2016 Preliminary Result

Best fit

Th/U = 4.1 $^{+5.5}_{-3.3}$

Th/U < 17.0 (90% C.L.)

ref) 2013 paper Th/U < 19 (90% C.L.)

- ☑ **We have a sensitivity of Th/U mass ratio of entire Earth.**
- ☑ **KamLAND best-fit is consistent with chondrite data and BSE models.**

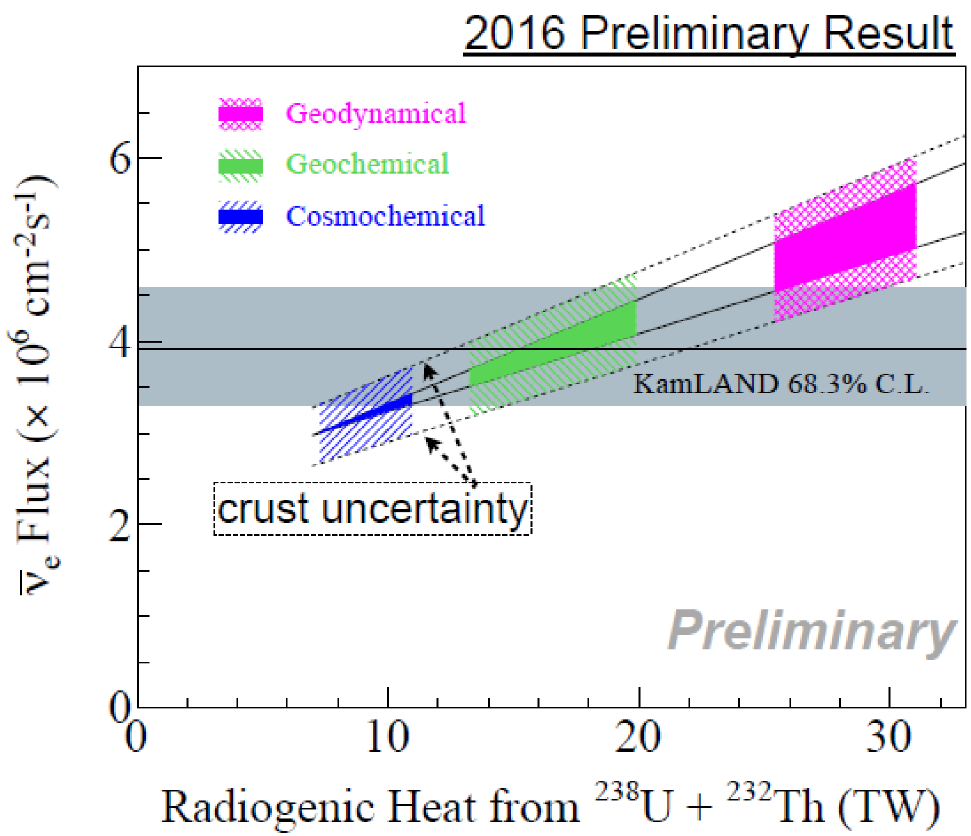
ref) chondrite data

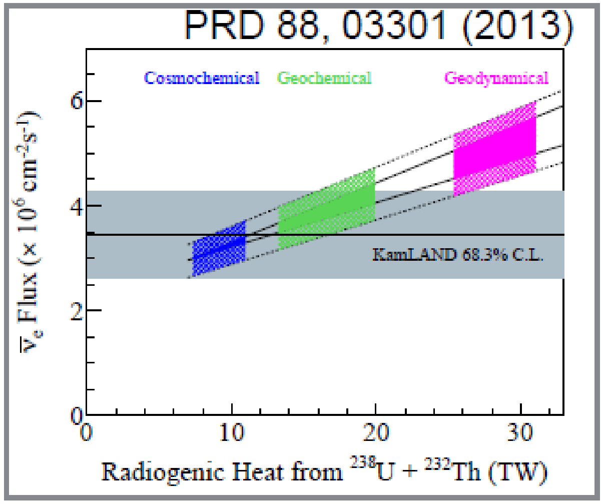
Ordinary Chondrites : J. S. Goreva & D. S. Burnett, Meteoritics & Planetary Science 36, 63-74 (2001)

Carbonaceous Chondrites : A. Rocholl & K. P. Jochum, EPSL 117, 265-278 (1993)

Enstatite Chondrites : M. Javoy & E. Kaminski, EPSL 407, 1-8 (2014)

Data vs Earth Models





[BSE composition models]

Geodynamical

based on balancing mantle viscosity and heat dissipation

Geochemical

based on mantle samples compared with chondrites

Cosmochemical

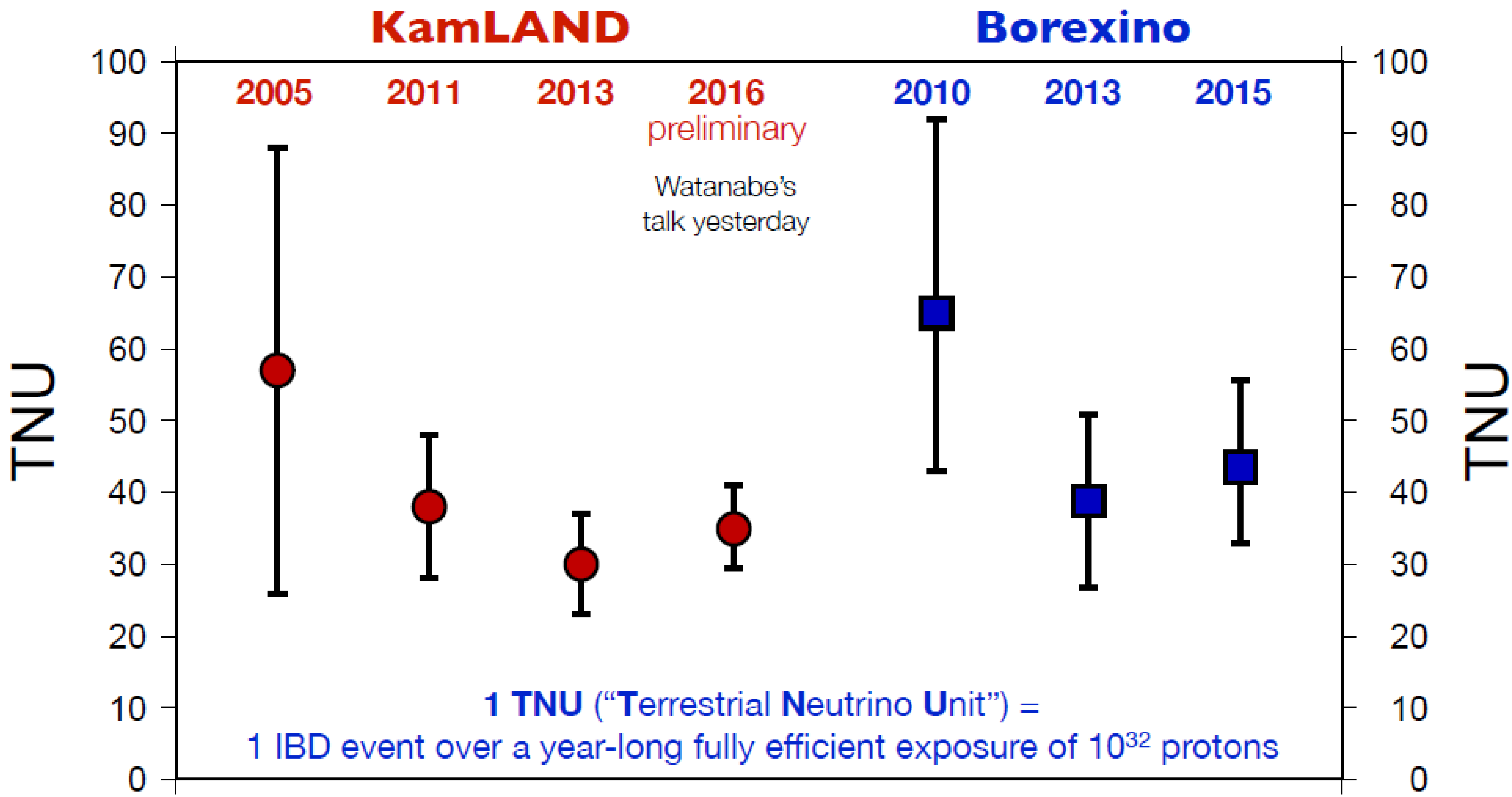
based on isotope constraints and chondritic models

From the talk by Hiroko Watanabe

Geo-neutrino measurements with KamLAND

Year	Live time, days	Exposure p·yr	N_{cand} [0.9-2.6] MeV	N_{geo}	φ_{geo} $\times10^6$ $cm^{-2}s^{-1}$	P(0)
2005	749.1	$(7.09\pm0.35)\times10^{31}$	152	$28.0^{+15.6}_{-14.6}$	$5.1^{+3.9}_{-3.6}$	$4.6\cdot10^{-2}$
2008	1486	2.44×10^{32}		73 ± 27	4.4 ± 1.6	$4.5\cdot10^{-3}$
2011	2135	$(3.49\pm0.07)\times10^{32}$	841	$\mathbf{106^{+29}_{-28}}$	$4.3^{+1.2}_{-1.1}$	$\mathbf{3\cdot10^{-5}}$ **(4.2σ)**
2013	2991	$(4.90\pm0.10)\times10^{32}$		$\mathbf{116^{+28}_{-27}}$	3.4 ± 0.8	$\mathbf{2\cdot10^{-6}}$
2016	3901	6.39×10^{32}	1130	$\mathbf{164^{+28}_{-25}}$	$3.9^{+0.7}_{-0.6}$	**(7.92σ)**

2005) Araki T., et al., Nature 436 (2005) 499.
2008) Araki T., et al., Phys. Rev. Lett. 100 (2008) 221803.
2011) Gando A., et al., Nature Geoscience 4 (2011) P.647--651.
2013) Gando A., et al., Phys. Rev. D 88 (2013) 033001
2016) Watanabe H., talk at “Neutrino Research and Thermal Evolution of the Earth”



KamLAND
Borexino
2005
2011
2013
2016
preliminary
Watanabe's talk yesterday
2010
2013
2015
TNU
100
90
80
70
60
50
40
30
20
10
0
1 TNU ("Terrestrial Neutrino Unit") =
1 IBD event over a year-long fully efficient exposure of 10^32 protons

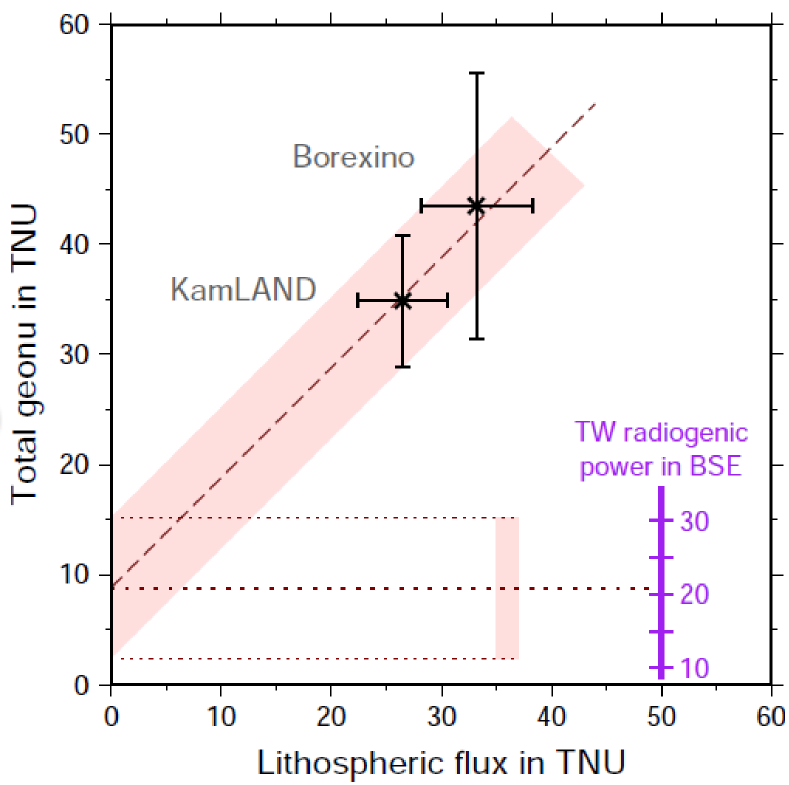
Results from detectors combined

Current status

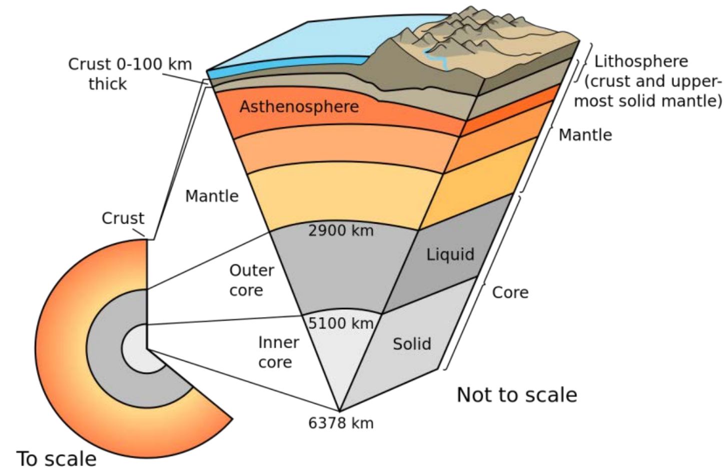
Measured
by physics:

Total geonu

KamLAND 2016
Borexino 2015
measurements



Predicted from geology: **Lithosphere**
Emission model



Result:

Mantle = 8.8 ± 6.4 TNU

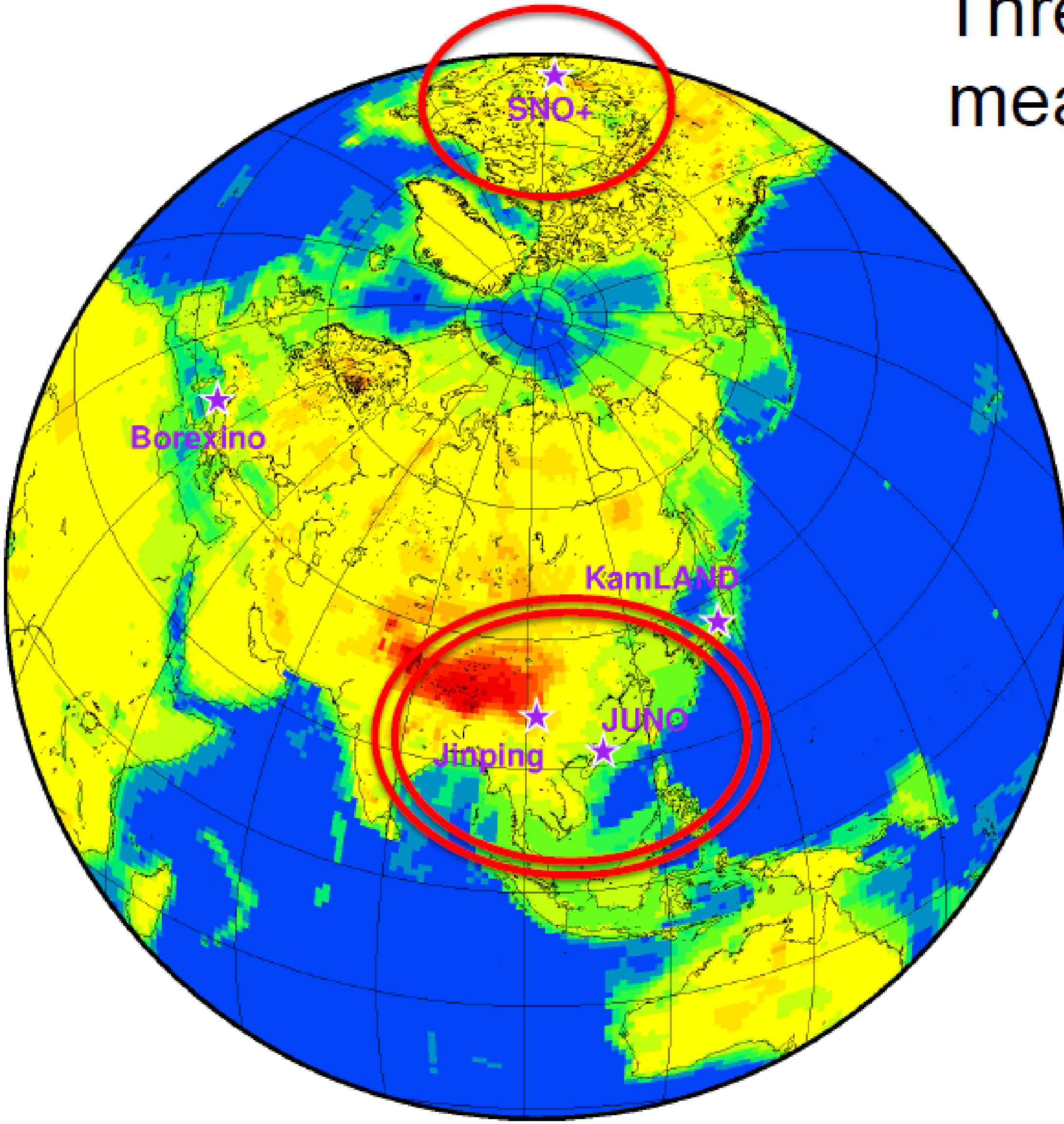
(72% rel. uncertainty)

From the talk by Ondrej Sramek

BRX: $20.9^{+15.1}_{-10.3}$ TNU

KL : $8.2^{+6.6}_{-6.0}$ TNU

Three more experiments measuring geoneutrinos to come



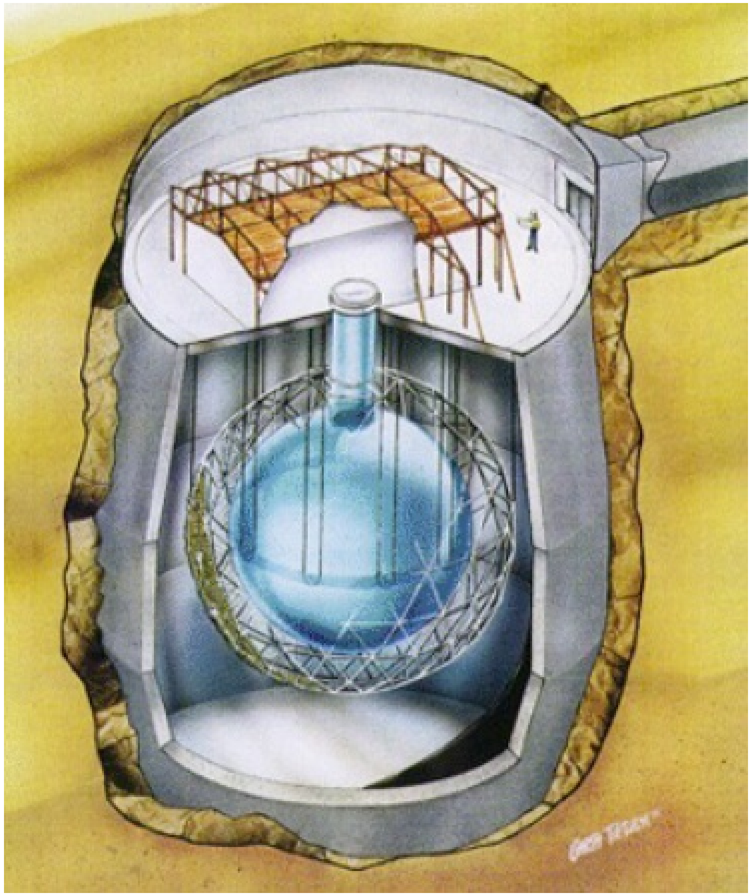
SNO+ (soon)

JUNO (2020)

Jinping (>2020)

From the talk by Ondrej Sramek

Upcoming experiment: SNO+

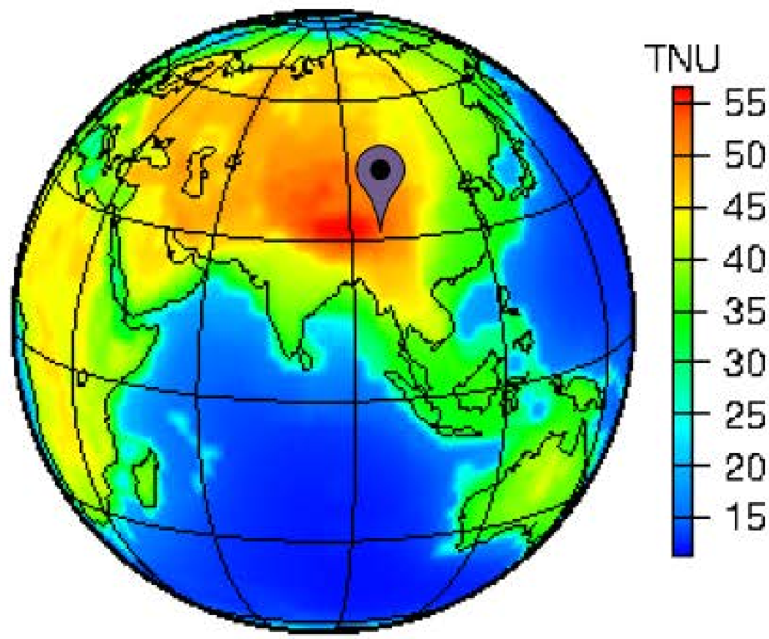


29 geo-neutrino events per live-year (in 780 tones LAB) compared with 26 events from reactors in the same energy range

Local Geology around Sudbury ***maybe the best understood portion of crust in the world***

Jinping

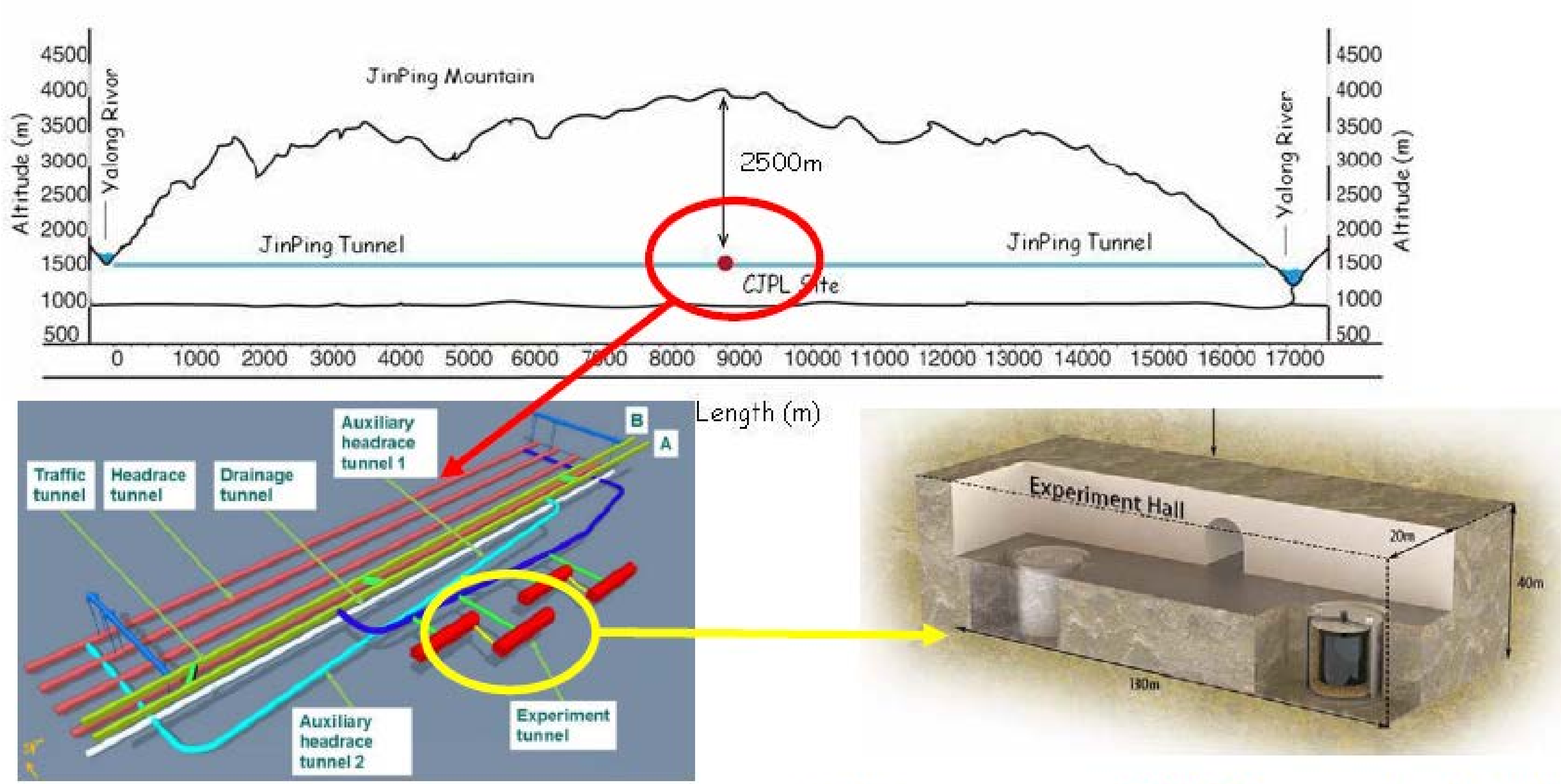
CJPL: Location



- ❑ Near Himalaya mountains.
- ❑ Located in Sichuan, China. 2 hours drive from Xichang airport.

From the talk by Linyan Wan

CJPL: Tunnel View



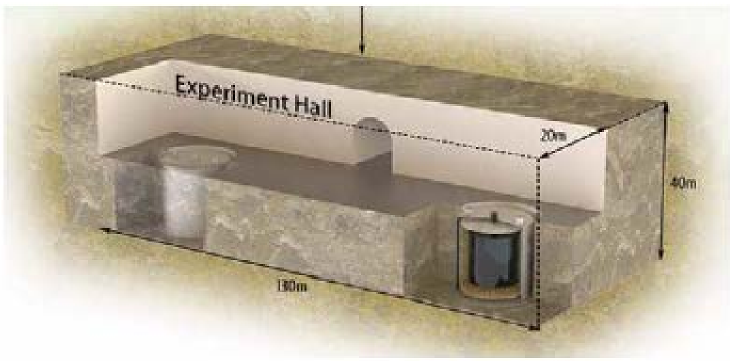
- ❑ Tunnel construction nearly finished.
  [岩土工程学报, Vol.38 Supp.2, 67]

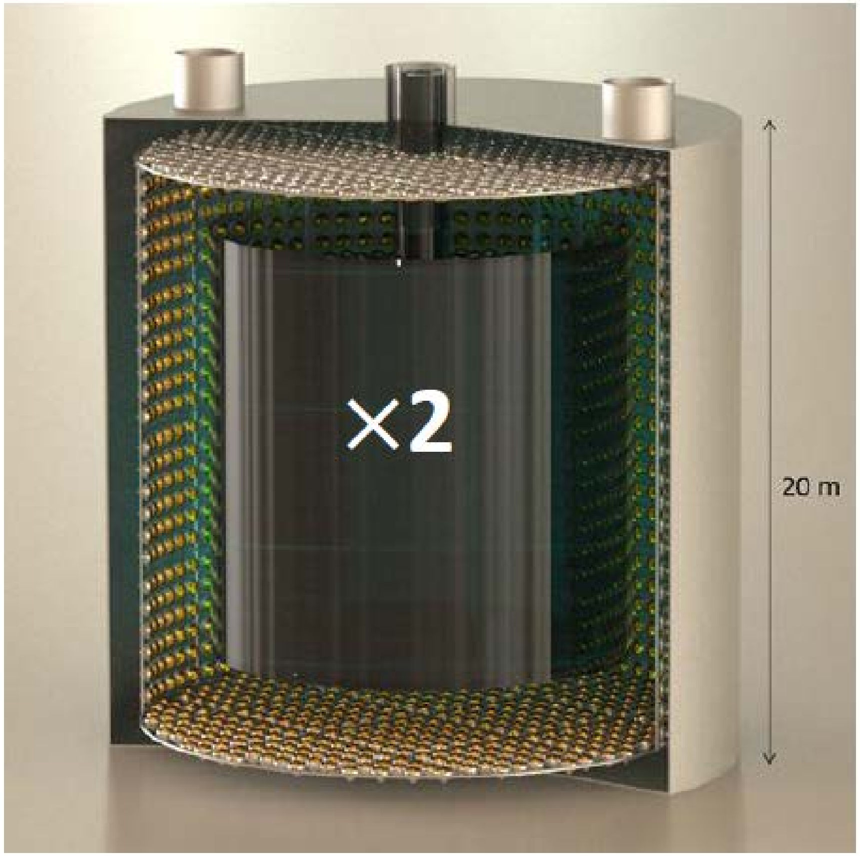
- ❑ On average **2,400 m** rock shielding;
- ❑ 20 m * 100 m experiment hall;

From the talk by Linyan Wan

Detector Concept

- ❑ 1.5 kton×2 Fiducial for IBD
- ❑ PMT coverage >70% with self-designed light concentrator
- ❑ Energy Resolution: 500 p.e.

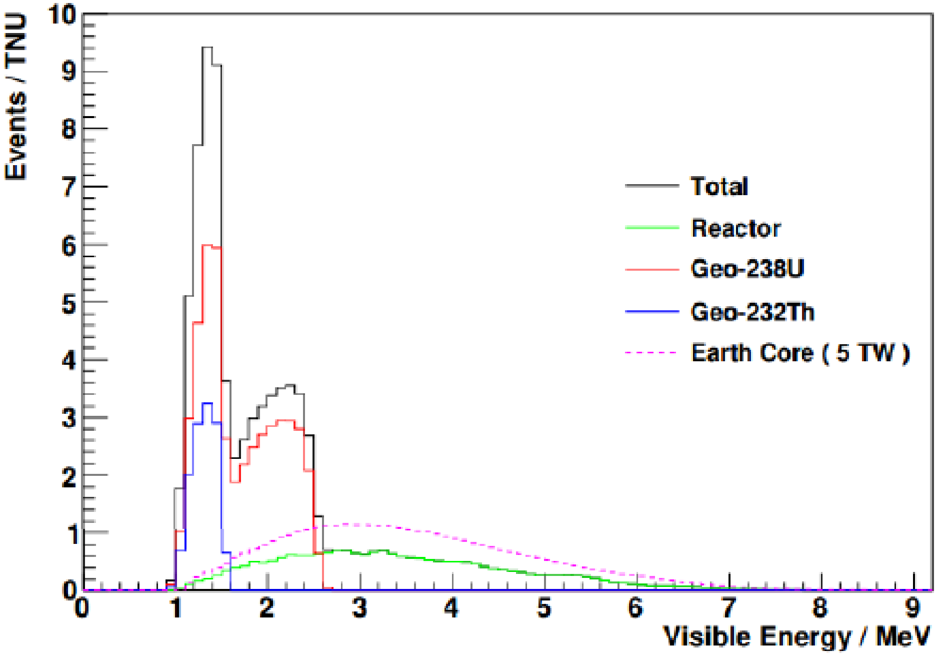




From the talk by Linyan Wan

Prediction: IBD Events at Jinping

- 500 p.e. energy resolution
- The calculation of geo neutrino signal will be covered in Sramek's talk.
- Signal/Background ratio > 8 in SER.

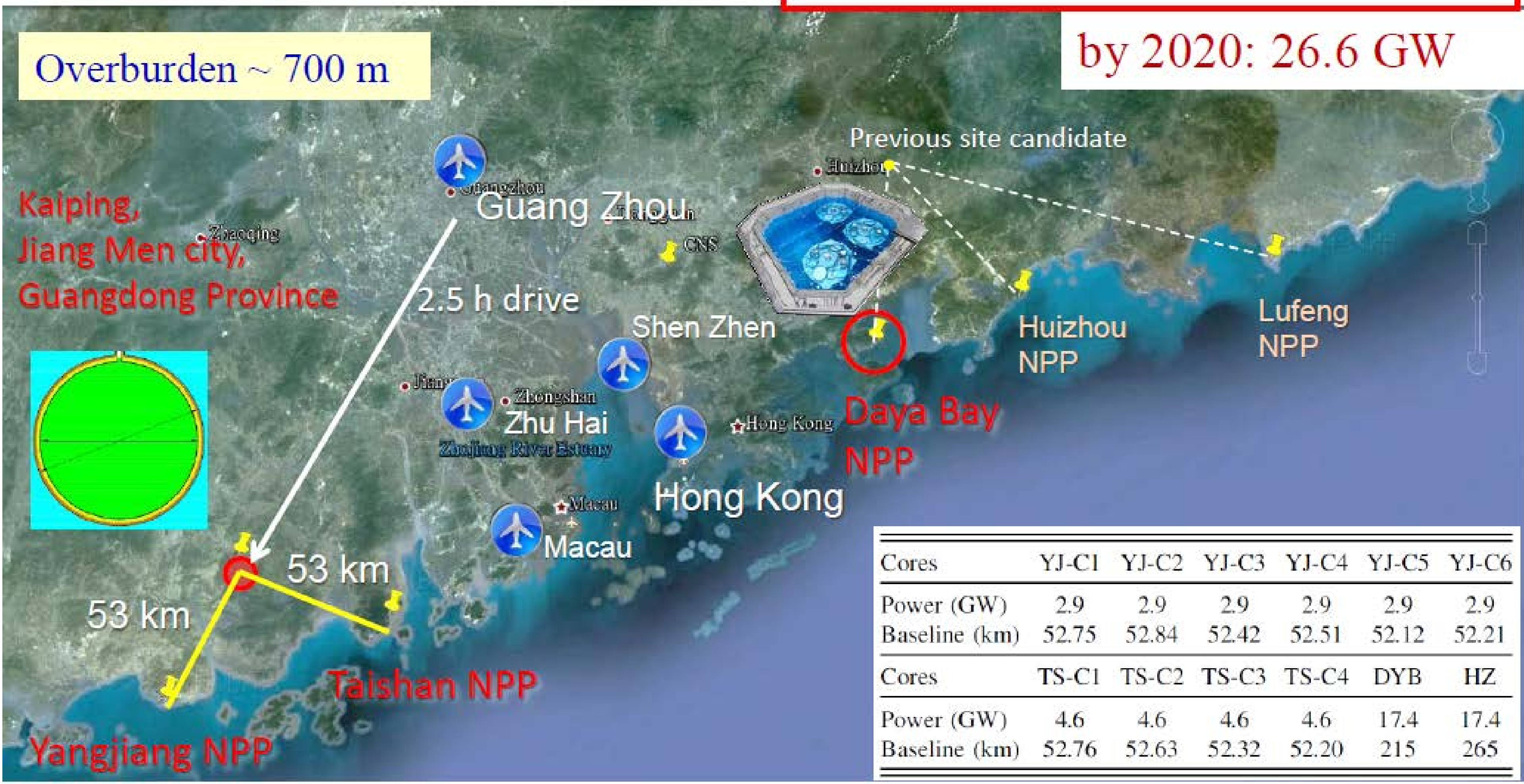


	Geo-neutrino			Reactor	
	^{238}U	^{232}Th	Total	FER	SER
Rate / TNU	47.0	11.5	58.5	29.0	7.1

From the talk by Linyan Wan

Location of JUNO

NPP	Daya Bay	Huizhou	Lufeng	Yangjiang	Taishan
Status	Operational	Planned	Planned	Under construction	Under construction
Power	17.4 GW	17.4 GW	17.4 GW	17.4 GW	18.4 GW



Cores	YJ-C1	YJ-C2	YJ-C3	YJ-C4	YJ-C5	YJ-C6
Power (GW)	2.9	2.9	2.9	2.9	2.9	2.9
Baseline (km)	52.75	52.84	52.42	52.51	52.12	52.21
Cores	TS-C1	TS-C2	TS-C3	TS-C4	DYB	HZ
Power (GW)	4.6	4.6	4.6	4.6	17.4	17.4
Baseline (km)	52.76	52.63	52.32	52.20	215	265

JUNO is mupltipurpose detector

"Neutrino physics with JUNO", J.Phys.G 43 (2016) 030401

- Neutrino mass hierarchy study
- Precision measurement of neutrino oscillation parameters
- Supernova bursts and diffuse supernova neutrinos
- Solar neutrinos
- Atmospheric neutrino
- **Geoneutrino**
- Sterile neutrino
- Nucleon decays
- Neutrinos from DM
- Exotic searches with neutrinos

R.Han, Y.-F. Li, L.Zhan, W.F.McDonough, J.Cao, L.Ludhova
"Potential of geoneutrino measurements at JUNO"
Chinese Phys. C, Vol 40, No3 (2016) 033003

V. Strati, M.Baldoncini,I,Callegar, F.Mantovani, W.F.McDonough, B.Ricci,G.Xhixha "Expected geoneutrino signal at JUNO"
Progress in Earth and Planetary Science 2, 1 (2015).

Expected antineutrino spectrum

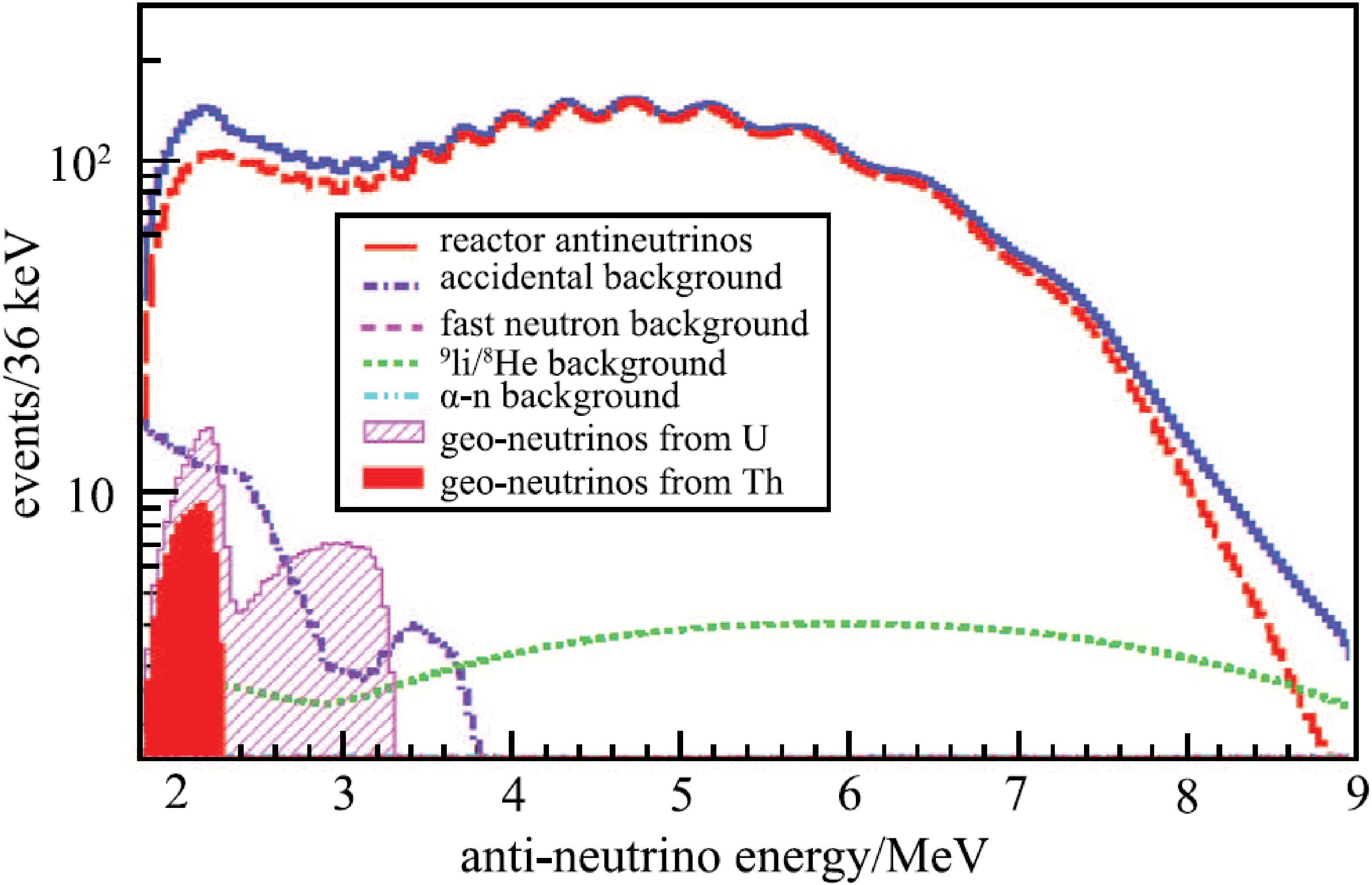


Fig. from R.Han, et al., Chinese Phys. C, Vol 40, No3 (2016) 033003

Expected signals

- **Expected total reactor signal**

1569± 88 TNU*

(~90% contrinution from Taishan and Yangjiang nuclear power stations)

***1 TNU = 1 event on 10^{32} protons an year**

- **Reactor signal in the geoneutrino energy window [1.8-3.27 MeV]:**

351± 21 TNU

- **Expected geoneutrino signal:**

$$\mathbf{Stot=39.7^{+6.5}_{-5.2}\ TNU}$$

$$\mathbf{S_{LOC}=17.4^{+3.3}_{-2.8}\ TNU}$$

(V. Strati, et al.)

Backgrounds for geo-neutrino measurement

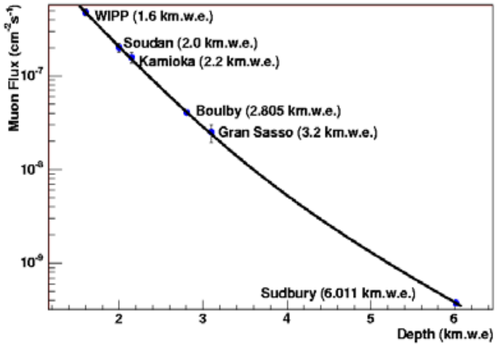
1)Reactor antineutrinos (90% of the total antineutrino signal in geo-nu window):

Geo/Reactor ratio

KL= 0.23 (before reactors shutdown)

Borexino=1.8

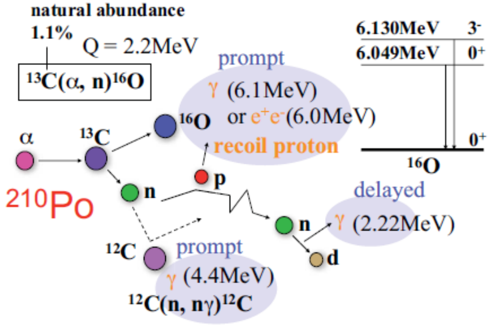
JUNO=0.11



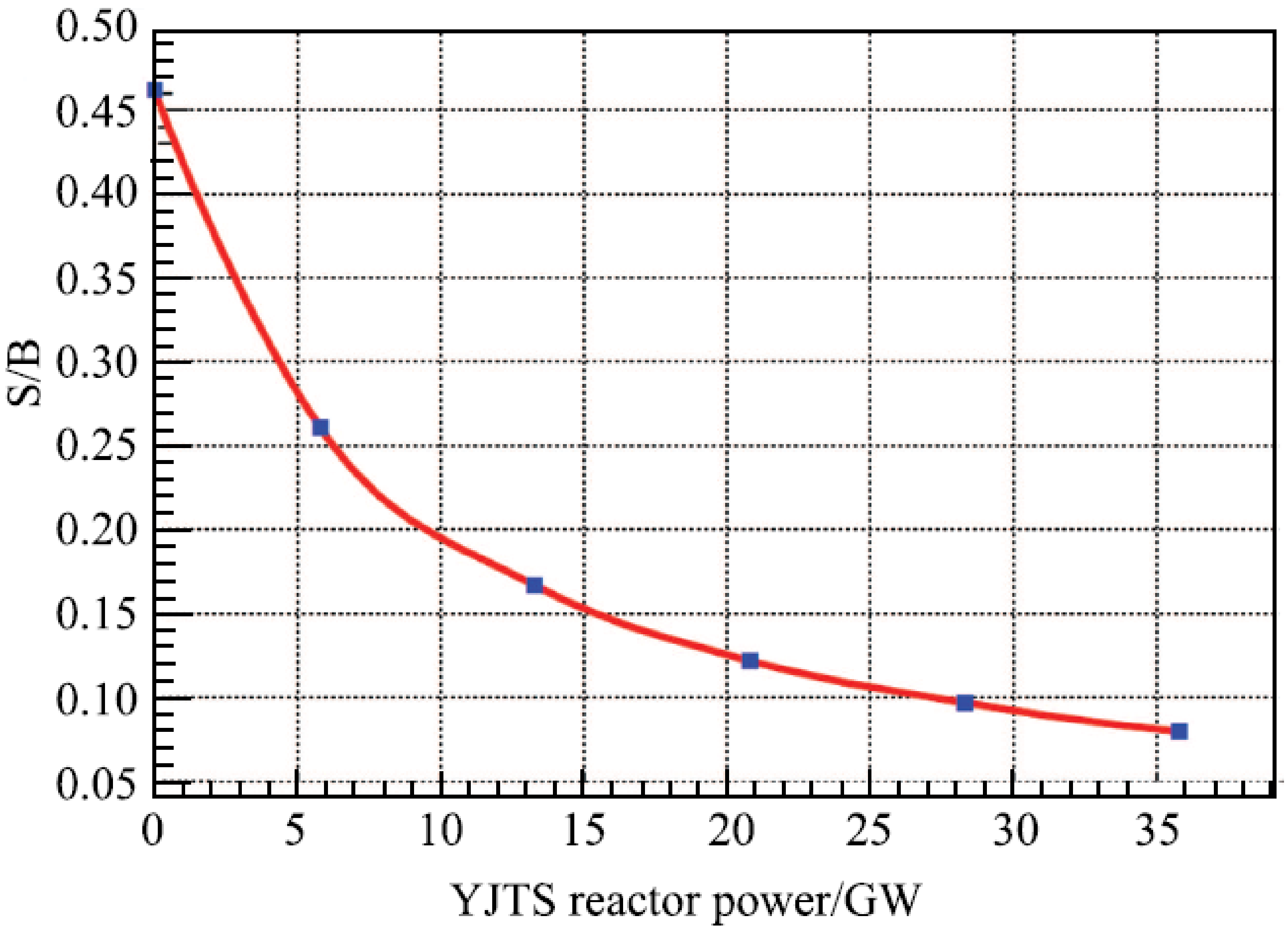
2)Cosmic muons induced backgrounds, including cosmogenic production of (βn)-decaying isotopes (2000 m.w.e.)

3)Internal radioactive contamination: accidental coincidences,

(αn) reactions



GeoNu/Backround depends on the thermal power of 2 reactors



Summary of expected rates

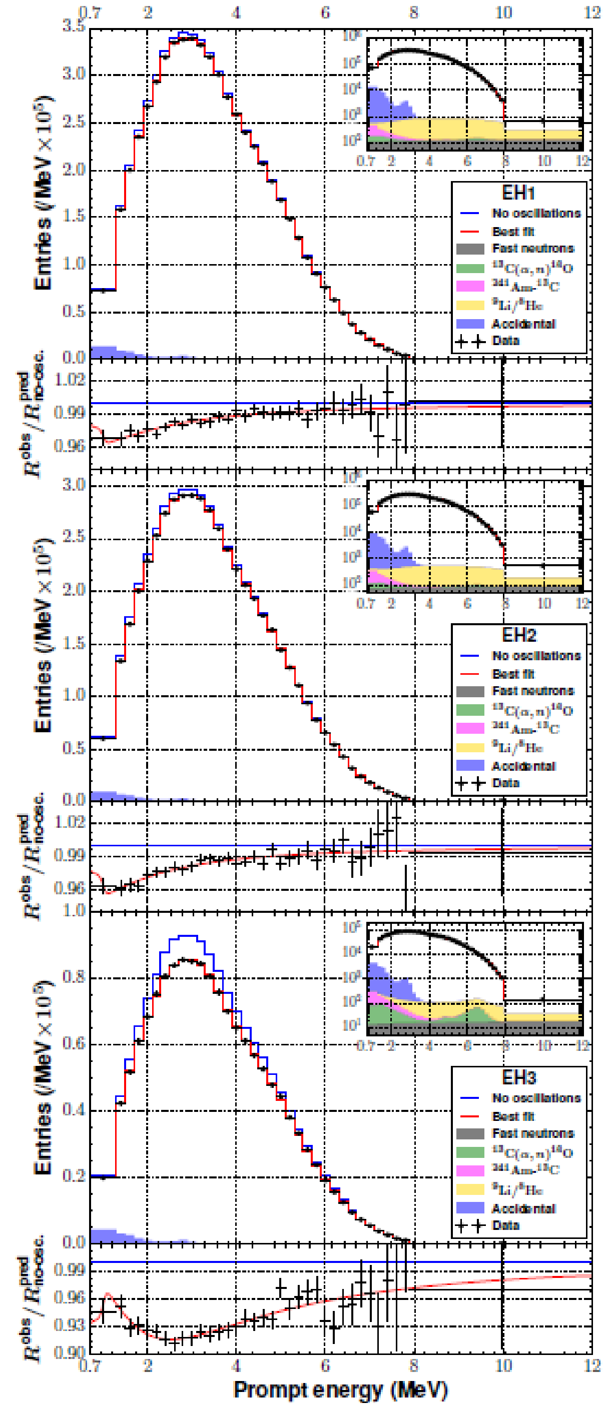
Source	[1.8-9.0] MeV ev/yr	[1.8-3.3] MeV ev/year	Uncertainty
geo	408	406	
reactor	16100	3653	±2.8%(rate)±1%(shape)
$^{8}Li/^{8}He$	657	105	±20%(rate)±10%(shape)
fast n	36.5	7.7	±100%(rate)±20%(shape)
αn	18.2	12.2	±50%(rate)±50%(shape)
accidental	401	348	±1%(rate)

20t->FV(R<17.2m) 18.35t or $12.85\cdot10^{32}$ protons
ε=80% detection efficiency assumed in calculations
acrylic vessel (^{238}U: 10 ppt, ^{232}Th: 10 ppt)
LS: 10^{-15} g/g $^{238}U/^{232}Th$

Reactor spectrum: Daya Bay

F. P. An, et al., “Measurement of electron antineutrino oscillation based on 1230 days of operation of the Daya Bay Experiment”, arXiv:1610.04802v1 [hep-ex] 16 Oct 2016

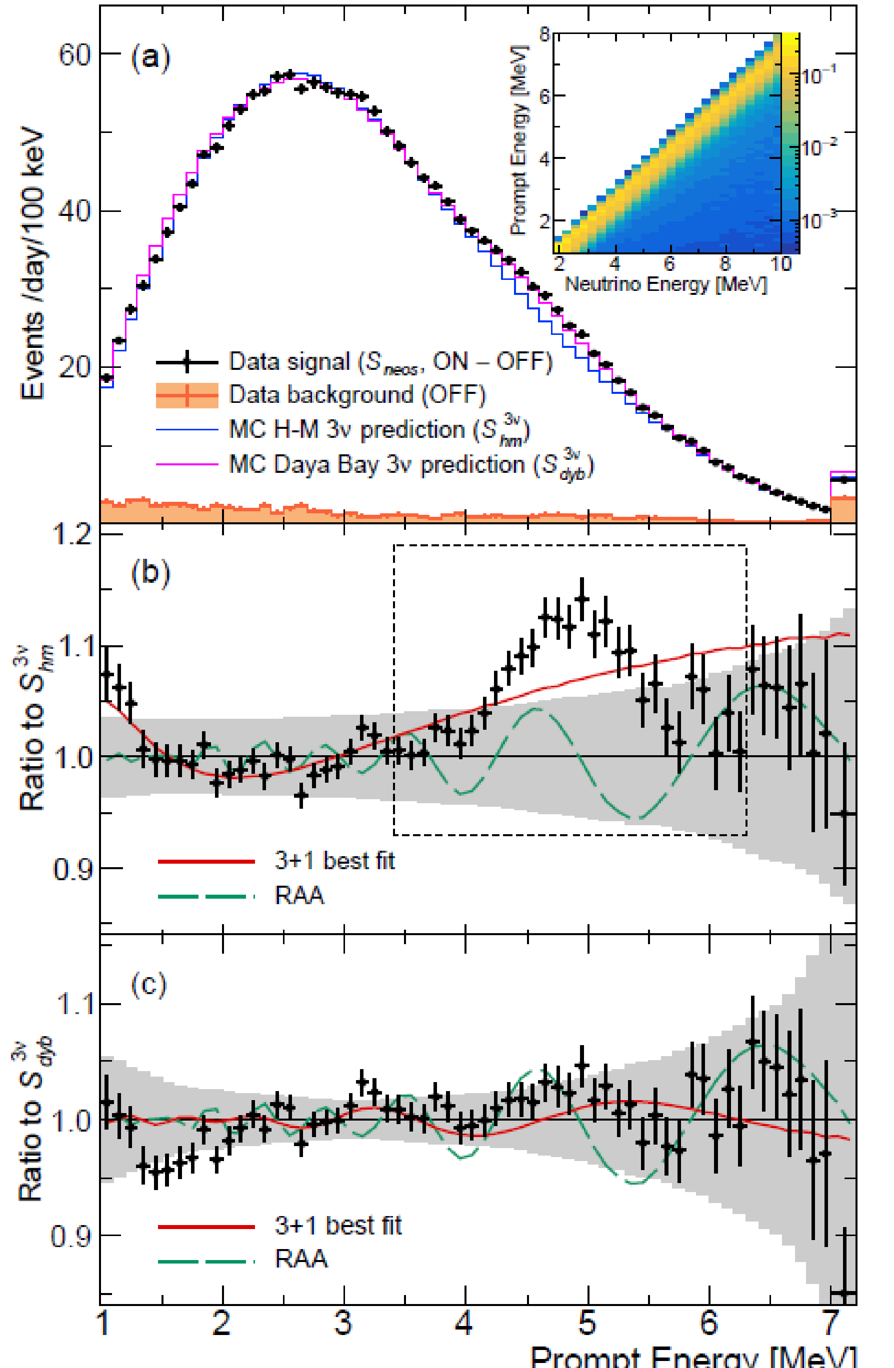
1230 days
>2.5 10^6 antineutrino events
Near detectors 350-600 m



Reactor spectrum

Y.J. Ko, et al., "A sterile neutrino search at NEOS Experiment"
arXiv: 1610.05134v1 [hep-ex] 17 Oct 2016

24 m from reactor
R(E)=5% @ 1 MeV
1965 ev/day
46 days reactor OFF
180 days reactor ON
Refers to F. P. An et al. (Daya Bay), (2016), arXiv:1607.05378 [hep-ex] (621 days of data)
The differences between the fission fractions for the NEOS data and the ones for Daya Bay are taken into account and small corrections are made using the H-M flux model.



Geoneutrino signal extraction precision fixed M(Th)/M(U)=3.9

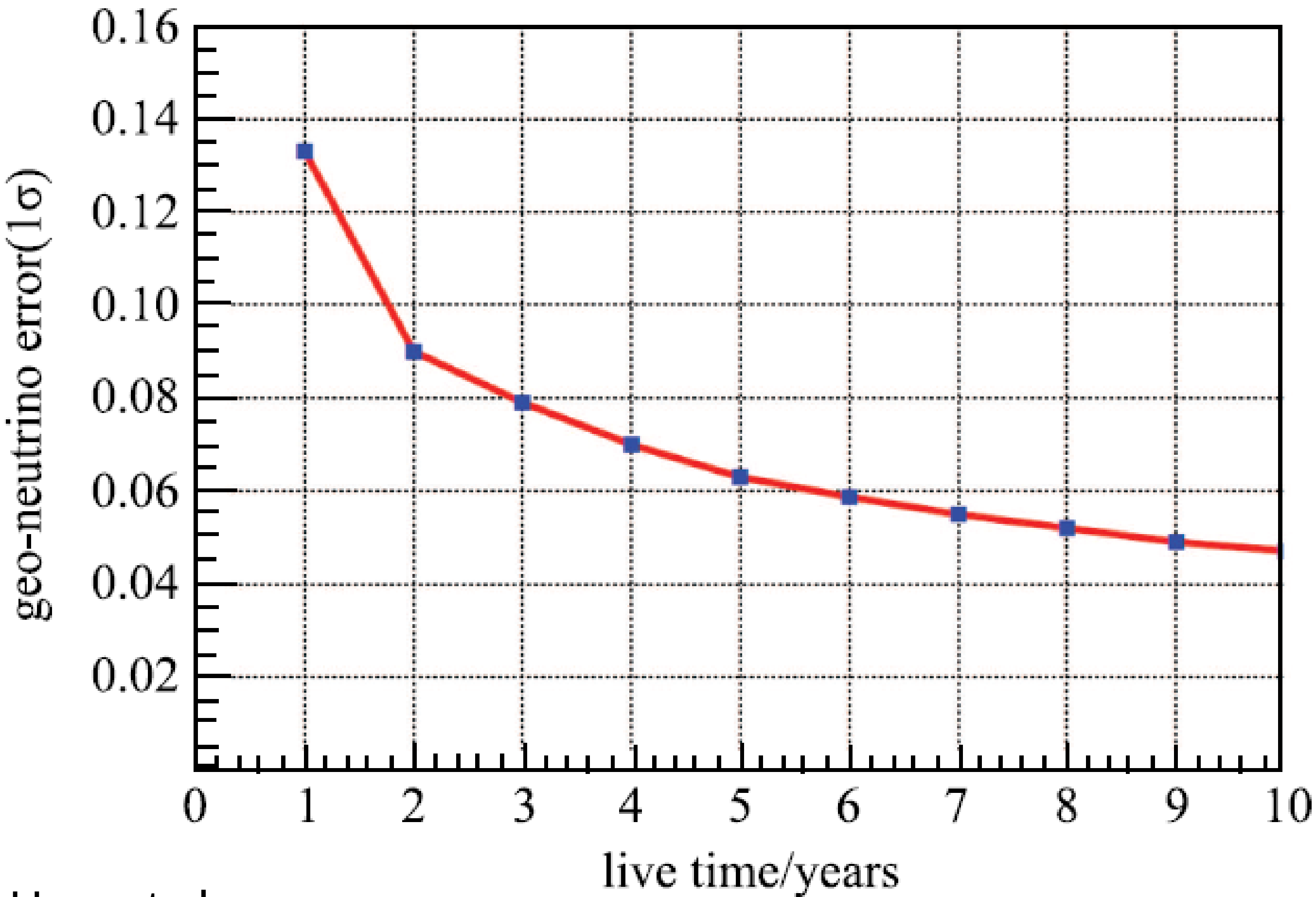
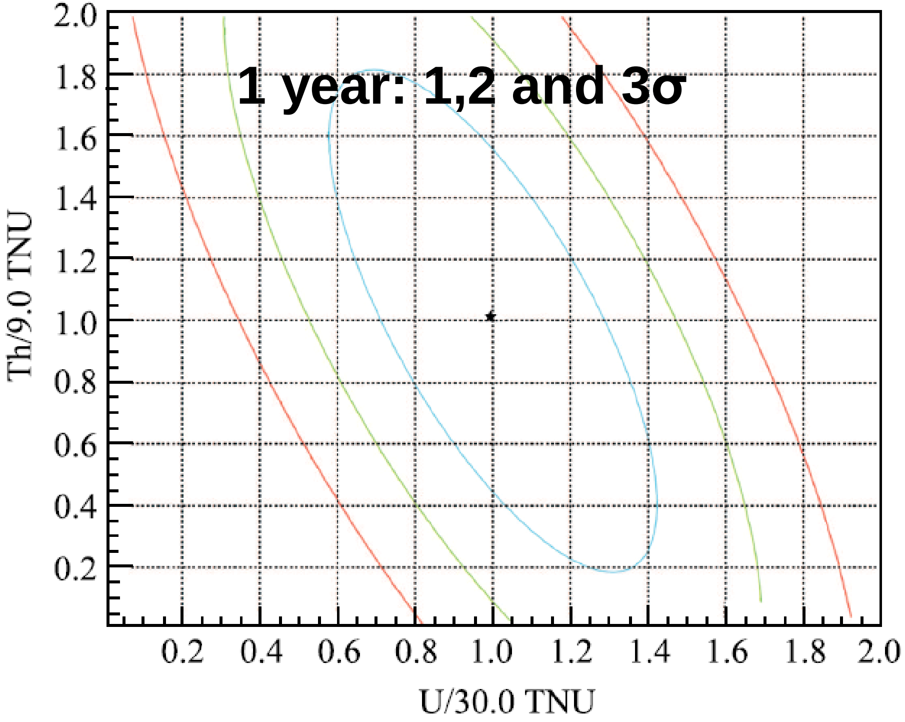


Fig. from R.Han, et al.

In JUNO publication the sensitivity was estimated as 18% for 1 yr with -4% syst.bias

Geoneutrino signal extraction precision
free Th and U components

Figs. from R.Han, et al. : no bias



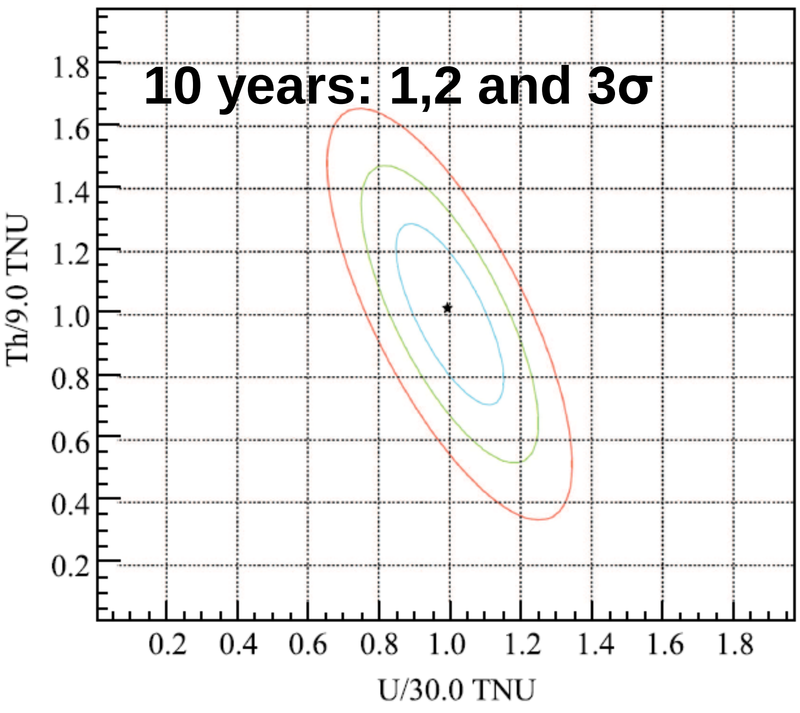
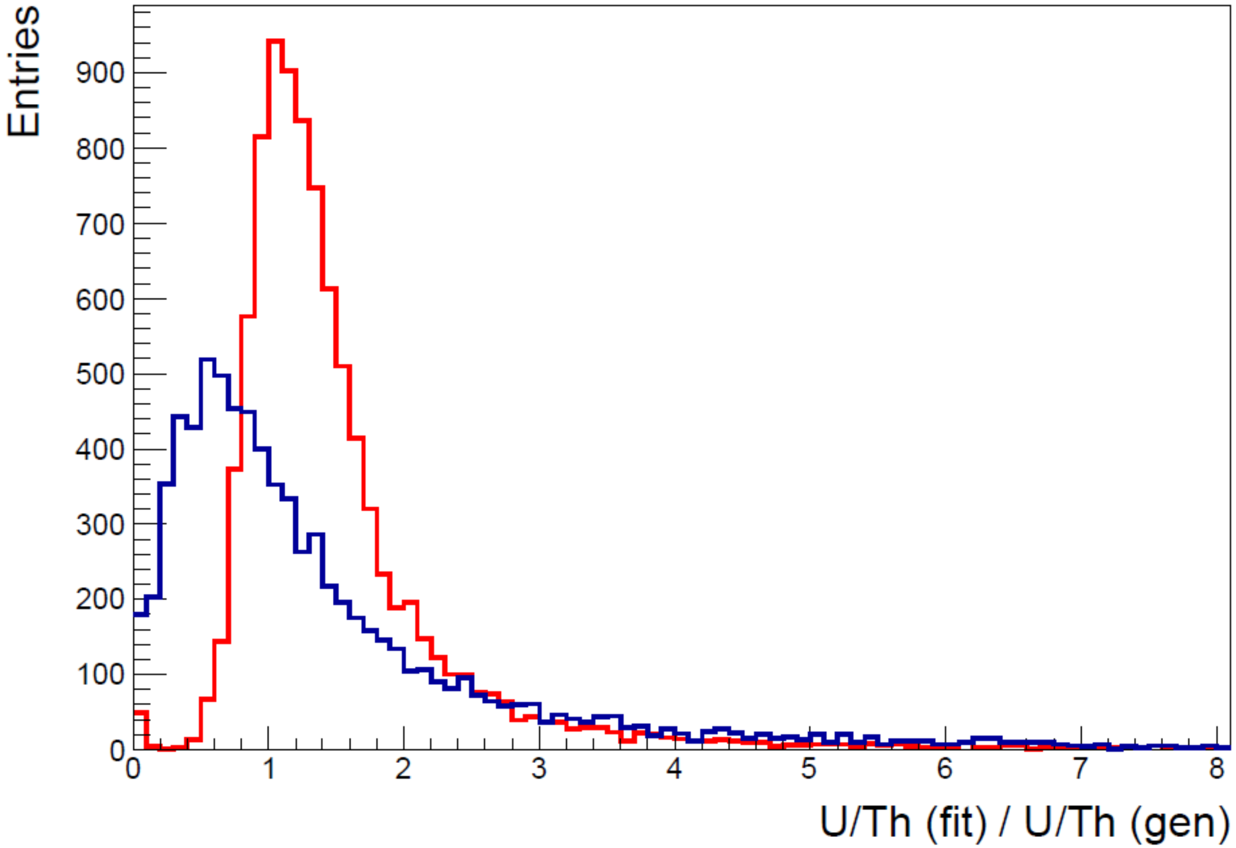


Table from JUNO publication

Number of years	U + Th (fixed chondritic Th/U ratio)	U (free)	Th (free)
1	0.96 ± 0.17	1.02 ± 0.32	0.83 ± 0.60
3	0.96 ± 0.10	1.03 ± 0.20	0.80 ± 0.38
5	0.96 ± 0.08	1.03 ± 0.16	0.80 ± 0.28
10	0.96 ± 0.06	1.03 ± 0.11	0.80 ± 0.19

U/Th ratio reconstruction



Distribution of the ratio reconstructed-to-generated U/Th ratio for 1 (blue line) and 10 (red line) years of lifetime after cuts. The simulations resulting in zero Th contribution are not plot here (fig. from JUNO publication).

Radiogenic heat

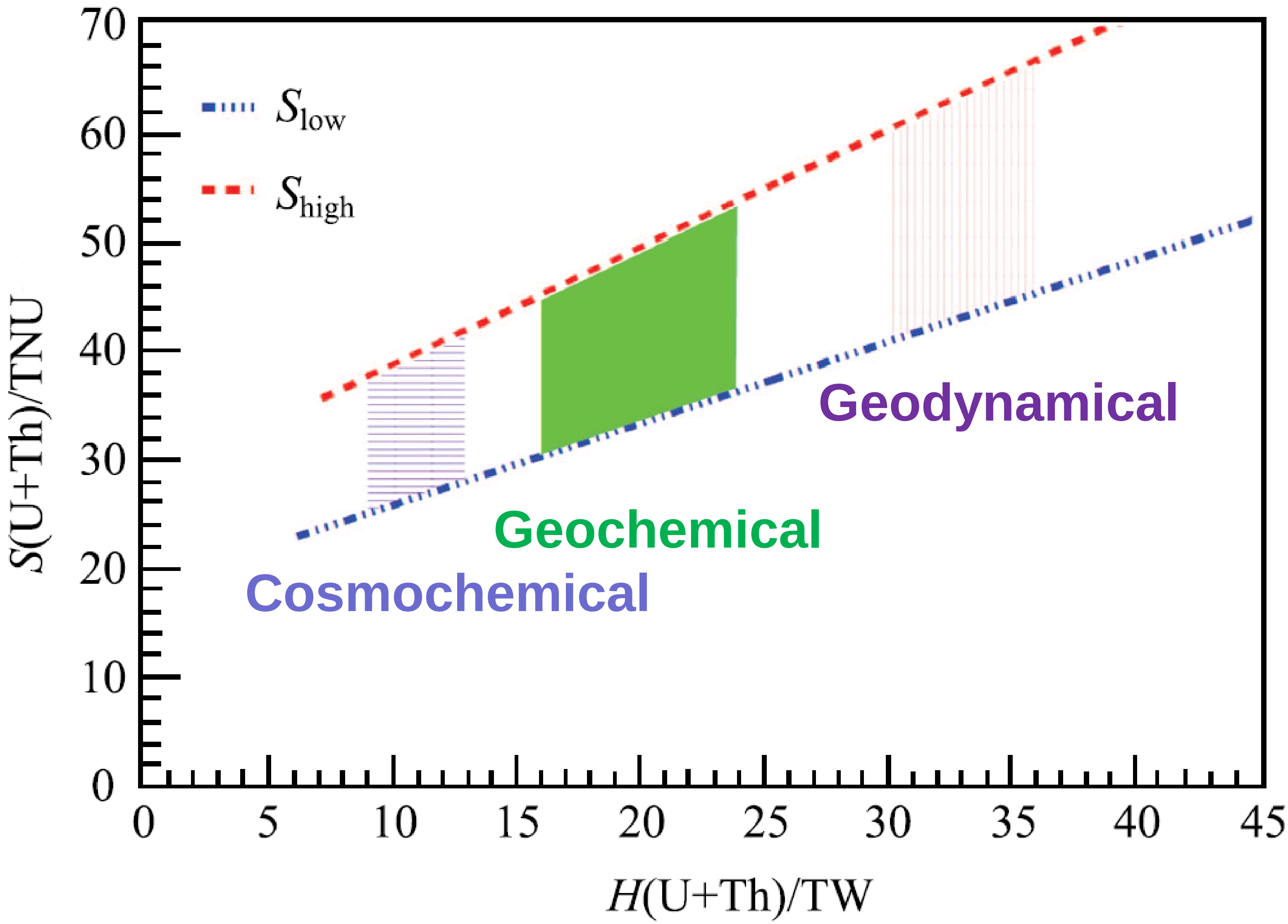


Fig. from R.Han, et al.

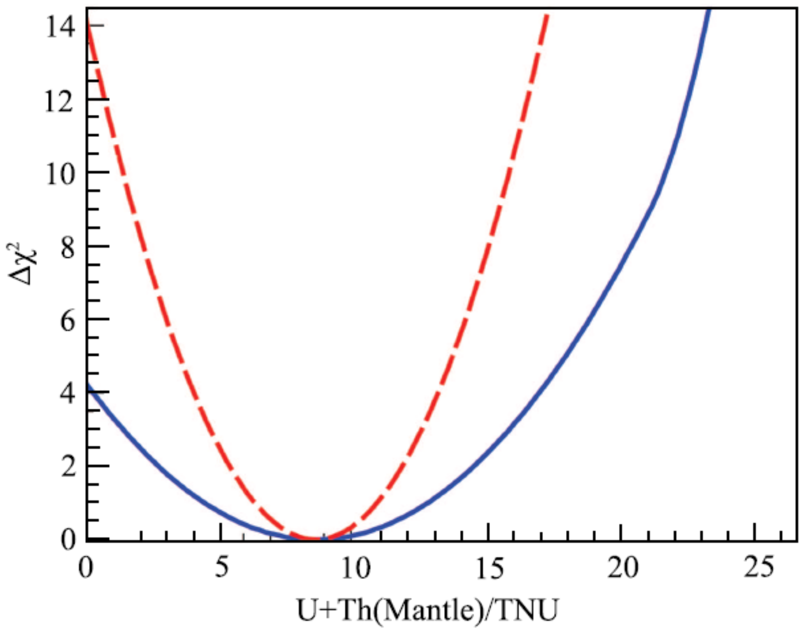
Signal from the mantle

Type equation here.Can be extracted from the measurement if crust contribution is known

R(Mantle)=R(Geo, measured)-R(Crust, predicted)

Current prediction (V. Strati, et al.) for the R(Crust) has 18% uncertainty – blue line in the plot

Red line : 8% crust contribution knowledge (KamLAND level)

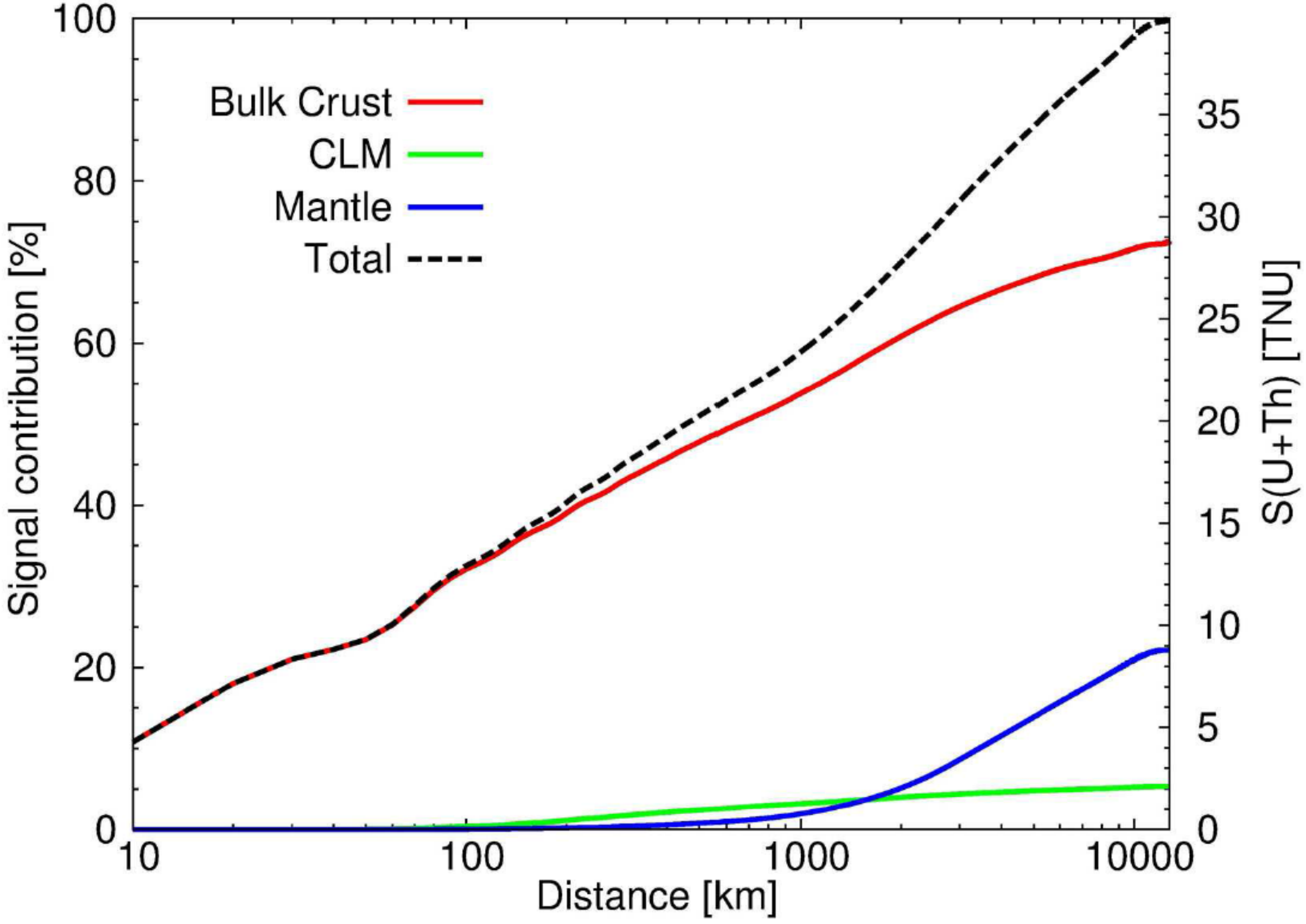


$$\Delta N_M = \sqrt{(\varepsilon_{Geo} N_{Geo})^2 + (\varepsilon_C N_C)^2 + N_C}$$

$$\varepsilon_M = \frac{1}{1 - r_C}\sqrt{(\varepsilon_{Geo})^2 + (\varepsilon_C r_C)^2 + \frac{r_C}{N_{Geo}}}$$

$$r_C \equiv \frac{N_C}{N_{Geo}} \qquad \varepsilon \equiv \frac{\Delta N}{N}$$

Importance of local contribution prediction



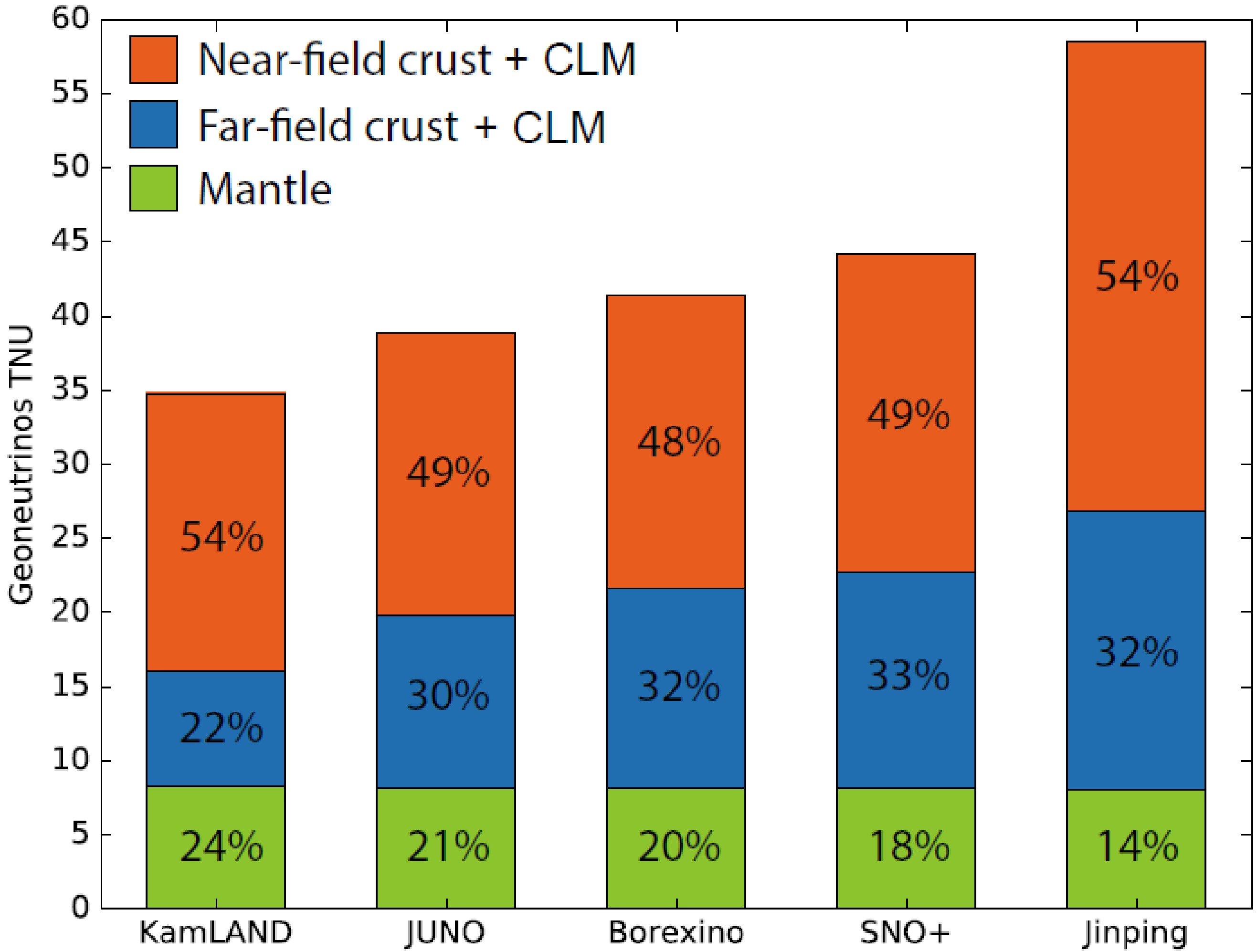
local (<500 km) crust contributes 50% of geoneutrino signal

Directionality?

- The average forward shift of neutrons in the direction of incoming antineutrinos have been observed by reactor experiments (i.e. by CHOOZ).
- The basic idea is to search for the small statistical displacement of the capture vertex of the neutron with respect to the vertex of the prompt positron event.
- The neutron from the inverse beta decay of geoneutrino carries energy up to tens of keV and is emitted in a relatively narrow range (below ~ 55 degrees) of angles around the incoming antineutrino. The average forward displacement of the neutron capture vertex is about 1.7 cm, as observed by CHOOZ for reactor neutrinos, while the spread due to neutron drifting is about 10 cm.
- Given the small displacement (~1.7 cm) and the large intrinsic smearing (~25 cm), the direction of the reconstructed antineutrino is only meaningful statistically and needs large statistics. Because the direction to the reactors in JUNO is known, it looks promising exploiting the fit of displacement distribution with predicted separate distributions from geo and reactor antineutrinos in conjunction with the spectral fit. An attempt to separate the crust and mantle geoneutrino components could be made. Both tasks need extensive MC studies.

Geoneutrino flux prediction

at 5 detectors



From the talk by Ondrej Sramek

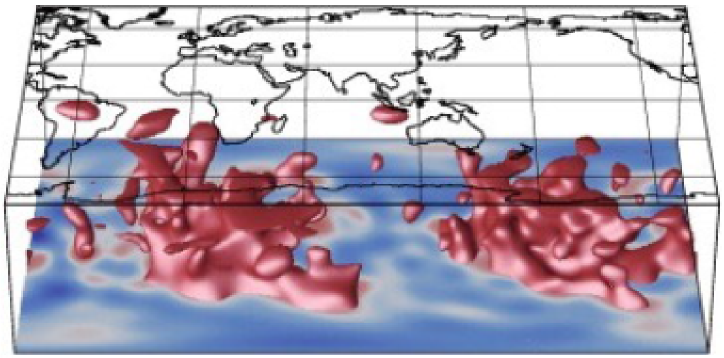
Geoneutrino flux prediction

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

From the talk by Ondrej Sramek

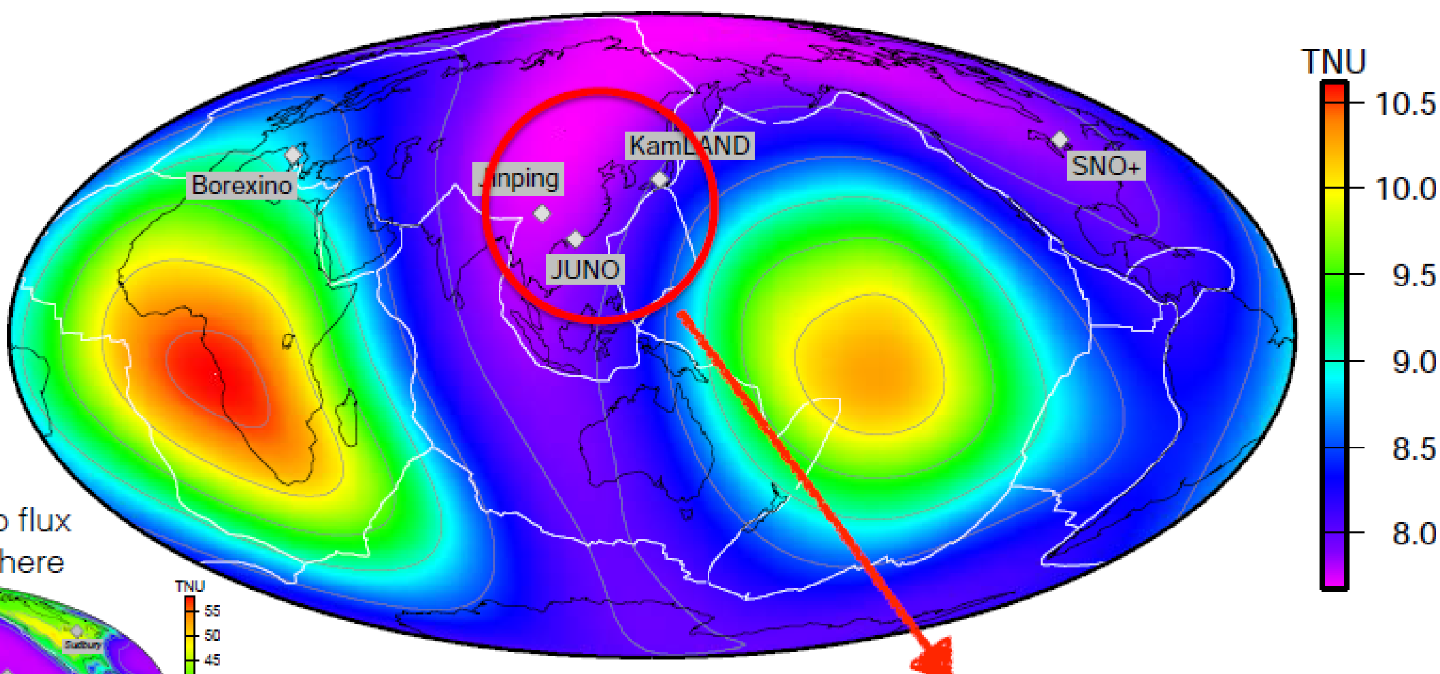


Bull et al 2009, after Ritsema et al 1999

Seismically slow "red" regions in the deep mantle

3-D structure of enriched mantle?

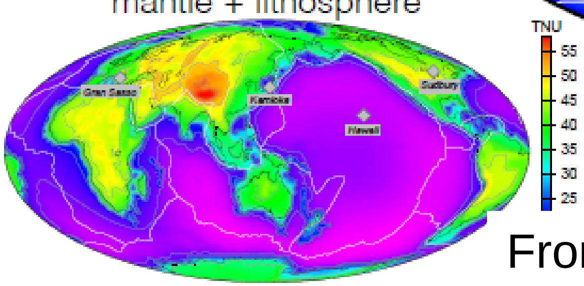
Geoneutrino flux from mantle with enriched "piles"



Šrámek et al. 2013

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

Total geoneutrino flux
mantle + lithosphere



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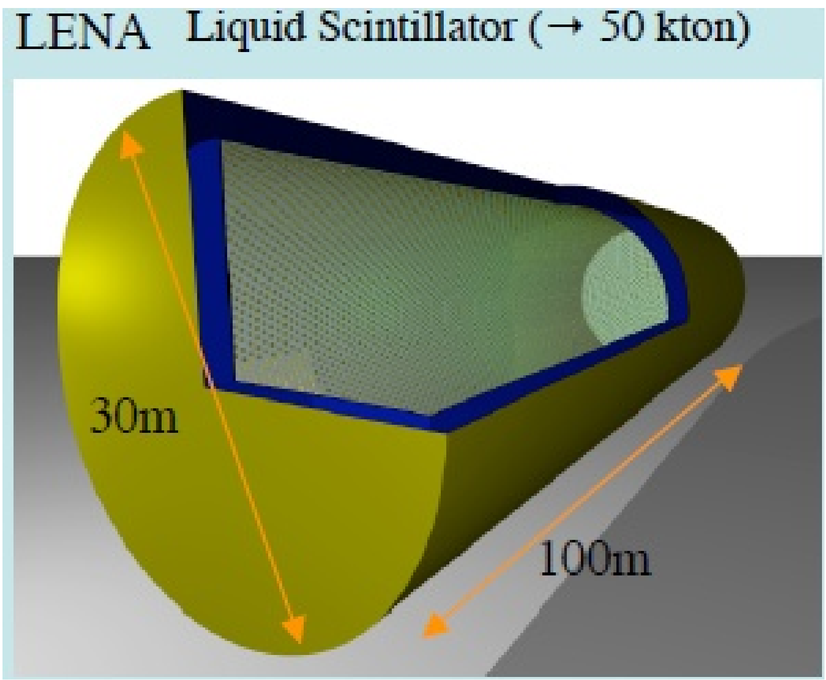
Large Scale Projects

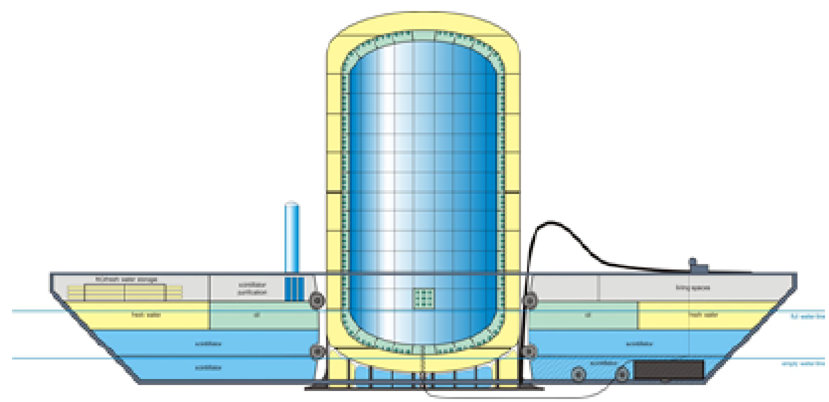
LENA: 50 kton



~1500 geonu events/yr

Hanohano: 10 kton

Extracting mantle contribution is very important from the geophysical point of view. The combination of data from multiple sites and data from an oceanic experiment would provide valuable information.



Hanohano

(~10 kt deep ocean detector)

~100 geonu events/yr

Summary

- Borex: **$23.7^{+6.5}_{-5.7}$** ev (~25%; P(0) excluded @5.9σ)
- KL : **164^{+28}_{-25}** ev (17%; P(0) excluded @7.9σ)

- Mantle signal:

  BRX: $20.9^{+15.1}_{-10.3}$ TNU; P(0)<0.02
  KL : $8.2^{+6.6}_{-6.0}$ TNU

- KamLand: Th/U ratio:

  $M(Th)/M(U)=4.1^{+5.5}_{-3.3}$

Future

- JUNO represents a new opportunity to measure geoneutrinos, recording of 300 to 500 geoneutrino interactions per year. In approximately six months JUNO would match the present world sample of recorded geoneutrino interactions, which is less than 150 events.

Experiment:	events/yr
• KL :	14
• BRX :	4.2
• SNO+ :	20
• Jinping :	100
• JUNO :	400

- Using a well constrained estimate of the reactor signal and reasonable estimates of the non-antineutrino sources, the conclusion is that geoneutrinos are indeed observable at JUNO.
- Maximizing the precision of the mantle geoneutrino measurement at JUNO requires detailed knowledge of the uranium and thorium content in the crust within several hundreds of kilometers to JUNO.
- The statistical power of the geoneutrino signal at JUNO enables a measurement of the thorium to uranium ratio, which provides valuable insight to the Earth's origin and evolution.