NEUTRINO TOMOGRAPHY I.
GEONEUTRINOS: A NEW TOOL TO STUDY THE EARTH

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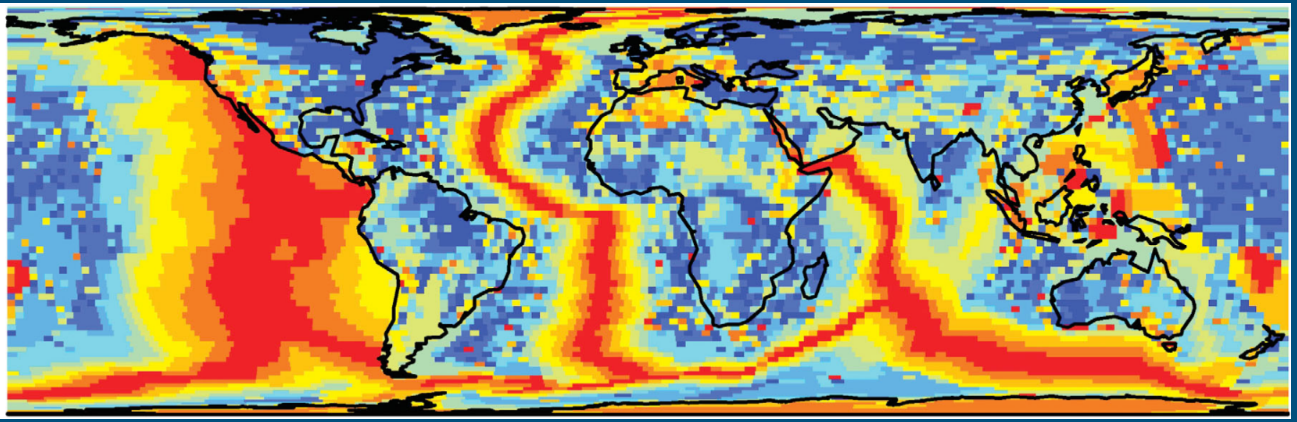

FEBRUARY 11TH, 2019

WORKSHOP ON OBSERVATORY SYNERGIES FOR ASTROPARTICLE PHYSICS AND GEOSCIENCE

INSTITUT DE PHYSIQUE DU GLOBE DE PARIS, PARIS, FRANCE

OUTLINE

For what concerns **the deep Earth,** we are as **ALIENS ON OUR PLANET**

We need more tools!

- What are geoneutrinos and why to study them.
- Expected geoneutrino flux.
- KamLAND and Borexino: geoneutrino measurements.
- Neutrino geoscience: outlook.

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From where is coming the energy driving these processes?

How can neutrino physics help us to understand?

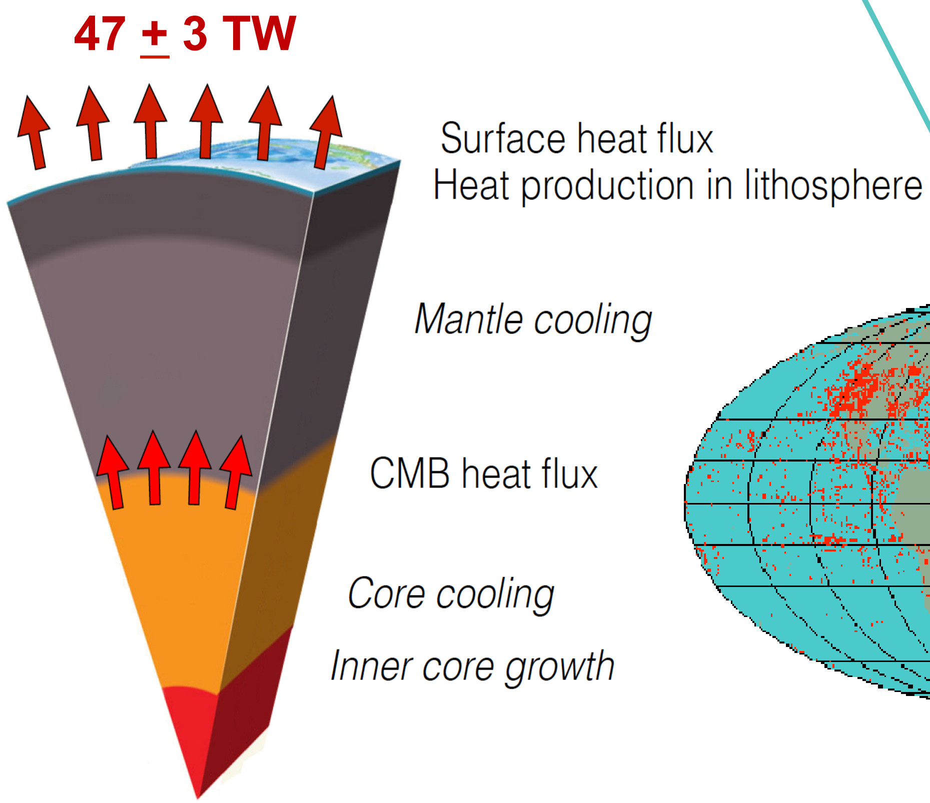
EARTH’S HEAT BUDGET

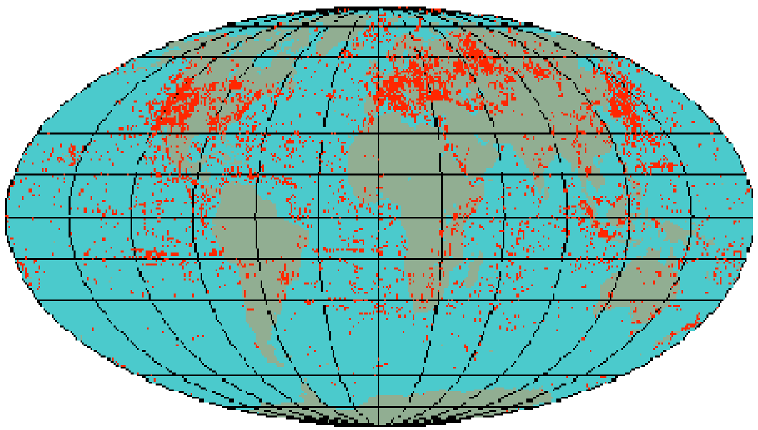
Surface heat flux: 47 $\pm$ 3 TW

(based on the measured temperature gradients along 30,000 bore holes around the globe)

Radiogenic heat: important margin for geological models

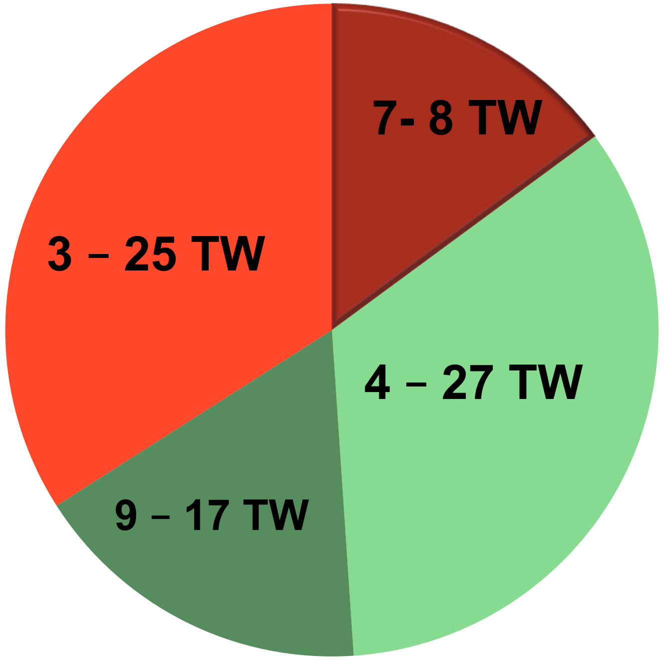
Geoneutrinos can help!





Mantle radiogenic heat Big uncertainty

Crustal radiogenic heat “Well” known



Core cooling

Mantle cooling

Geoneutrinos: electron antineutrinos/neutrinos from the decays of long-lived radioactive isotopes naturally present in the Earth ($^{238/235}$U and ^{232}Th chains and ^{40}K)

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^{238}U (99.2739% of natural U) → $^{206}Pb + 8\,\alpha + 8\,e^{-}$ + 6 anti-neutrinos + **51.7 MeV**
^{232}Th → $^{208}Pb + 6\,\alpha + 4\,e^{-}$ + 4 anti-neutrinos + **42.8 MeV**
^{235}U (0.7205% of natural U) → $^{207}Pb + 7\,\alpha + 4\,e^{-}$ + 4 anti-neutrinos + **46.4 MeV**
^{40}K (0.012% of natural K) → $^{40}Ca + e^{-}$ + 1 anti-neutrino + **1.32 MeV** (BR=89.3 %)
$^{40}K + e^{-}$ → ^{40}Ar + 1 neutrino + **1.505 MeV** (BR=10.7 %)

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- **the only direct probe of the deep Earth**
- **released heat and anti-neutrinos flux in a well fixed ratio**
- measure geoneutrino flux = (in principle) = get radiogenic heat
- in practice (as always) more complicated…..

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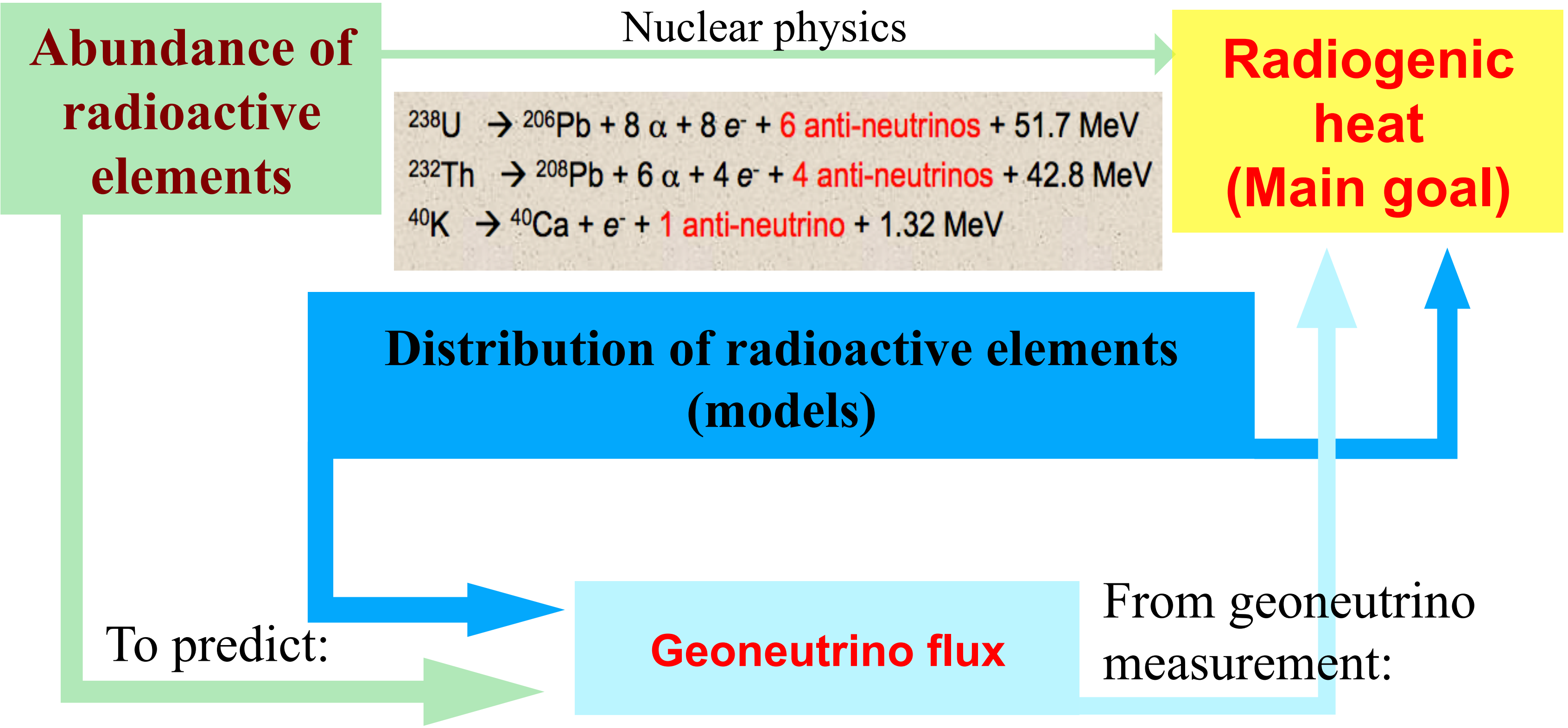
Earth shines in antineutrinos: flux ~10^6 cm^{-2} s^{-1}
leaving freely and instantaneously the Earth interior
(to compare: solar neutrino (NOT antineutrino!) flux ~10^{10} cm^{-2} s^{-1})

GEONEUTRINOS AND WHY TO STUDY THEM



- **Main goal:** determine the contribution of the **radiogenic heat (principally the mantle contribution) to the total surface heat flux**, which is an important margin, test, and input at the same time for many geophysical and geochemical models of the Earth;
- **Further goals: U/Th ratio,** tests and discrimination among geological models, Earth composition models, study of the **mantle homogeneity or stratification**, insights to the processes of Earth'formation, additional sources of heat?, idea of U-based **geo-reactor** in the Earth's core (according to Herndon)

Neutrino geoscience: truly inter-disciplinary field!

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BULK SILICATE EARTH MODELS (BSE)

Models predicting the composition of the Earth primitive mantle

Various inputs: composition of the chondritic meteorites, correlations with the composition of the solar photosphere, composition of rock samples from upper mantle and crust, energy needed to run mantle convection…..

Abundances of U/Th/K (and thus also radiogenic heat) in
BSE = present-day CRUST (continental + oceanic) **+ MANTLE**

CRUST: 7-8TW (only ~0.2 TW in oceanic crust)

"well" known

MANTLE = BSE – CRUST
3-25 TW (different BSE models)

Big uncertainty

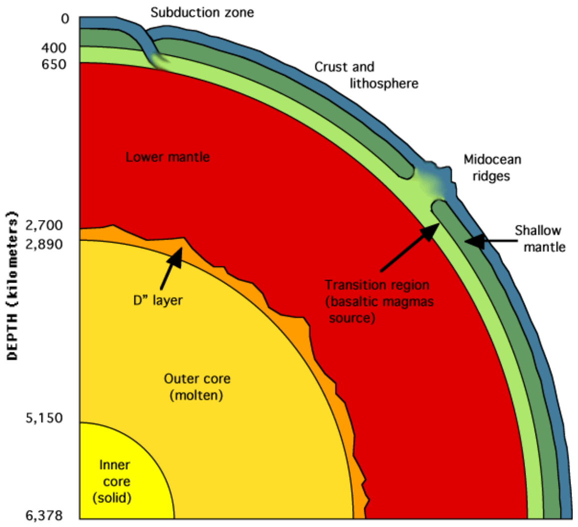
BSE models

Workman and Hart, 2005
Salter and Stracke, 2004
Arevallo and McDonough, 2009
O'Neil and Palme, 2008
Javoy at al., 2010
Javoy, 1999
Lyubetskaya and Korenaga, 2007
Hart and Zindler, 1986
Mc Donough and Sun, 1955
Arevallo at al., 2009
Palme and O'Neill, 2008
Turcotte and Schubert, 2002

increasing abundance U, Th, K

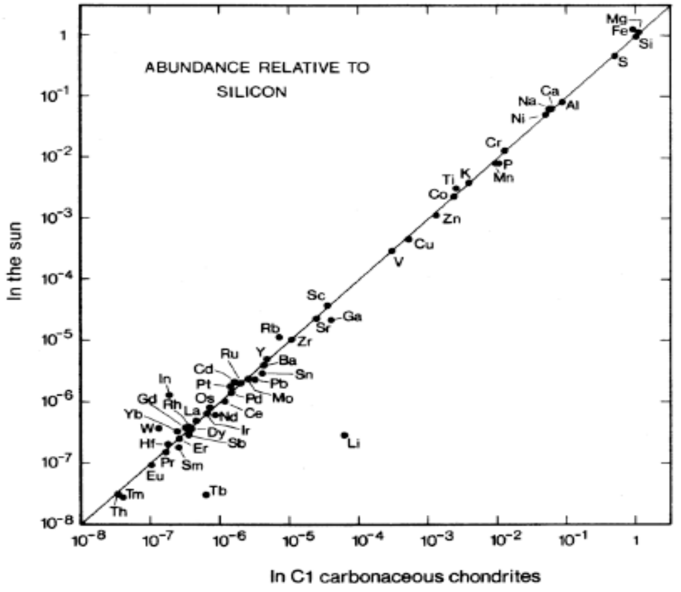
Wadepohl. 1995
Rudnick and Fountain, 1995
Taylor and McLennan, 1995
McLennan 2001
Rudnick and Gao, 2003
Hacker at al., 2011
Huang at al.,2013

Crustal models



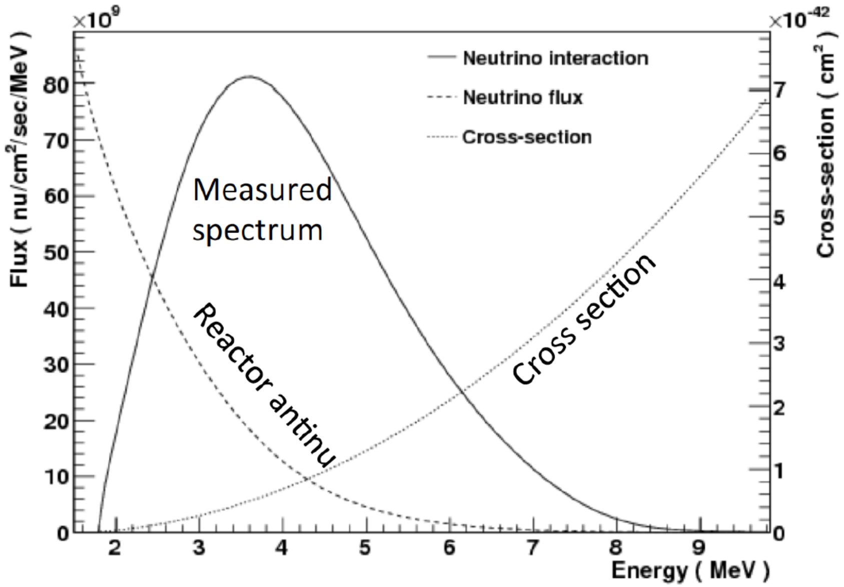
Isotopic compositions of:
1) C1 carbonaceous chondrites
2) solar photosphere
are highly correlated !

Was it the same in the primitive Earth?



ANTINEUTRINO DETECTION WITH LIQUID SCINTILLATORS

•Small interaction cross section;
•Large volume detectors;
•High radio-purity of liquid scintillator and construction materials;
•Underground labs to shield cosmic radiations;

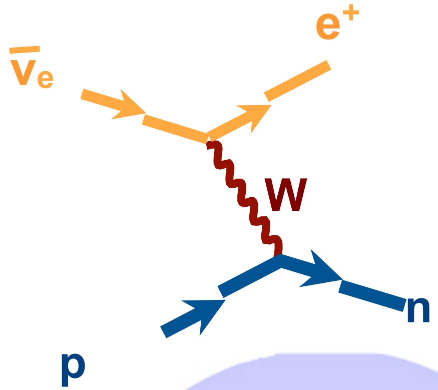


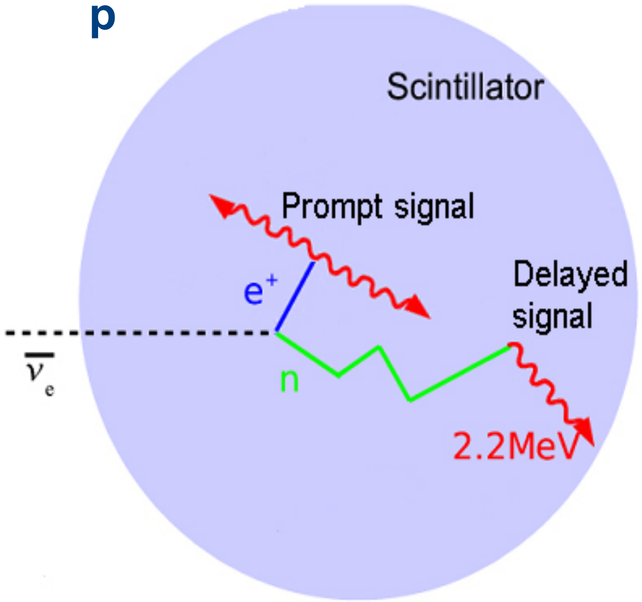
Antineutrino detection: Coincidences (BGR suppression)

- Inverse beta decay (IBD)
- Charge current, e-flavour only

Energy threshold = 1.8 MeV
Electron flavour only
σ@ few MeV: ~10^{-42} cm^2
(~100 x more than scattering)

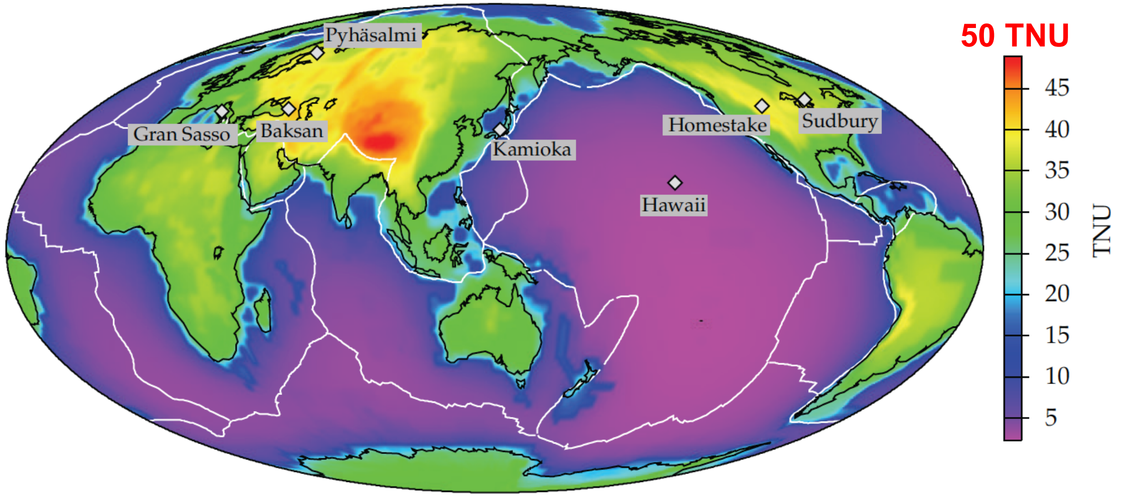
$$E_{prompt} = E_{visible}$$
$$= T_{e+} + 2 \times 511 \text{ keV}$$
$$\sim E_{antinu} - 0.784 \text{ MeV}$$





EXPECTED GEONEUTRINO SIGNAL

Expected "known and big" crustal signal

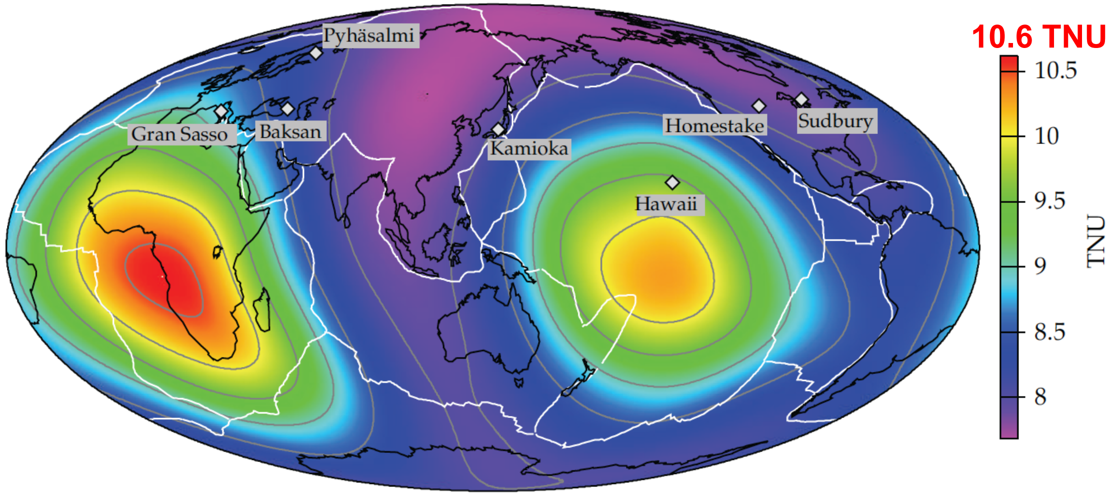


The signal is small, we need big detectors!

1 TNU = 1 event / 10^{32} target protons / year
cca 1 event /1 kton /1 year, 100% detection efficiency

Expected mantle signal: m(U+Th+K) = BSE – crust and hypothesis of heterogeneous composition

Motivated by the observed Large Shear Velocity Provinces at the mantle base



To measure mantle signal is more challenging!

O. Šrámek et al. "Geophysical and geochemical constraints on geoneutrino fluxes from Earths mantle", Earth Planet. Sci. Lett., 361 (2013) 356-366)

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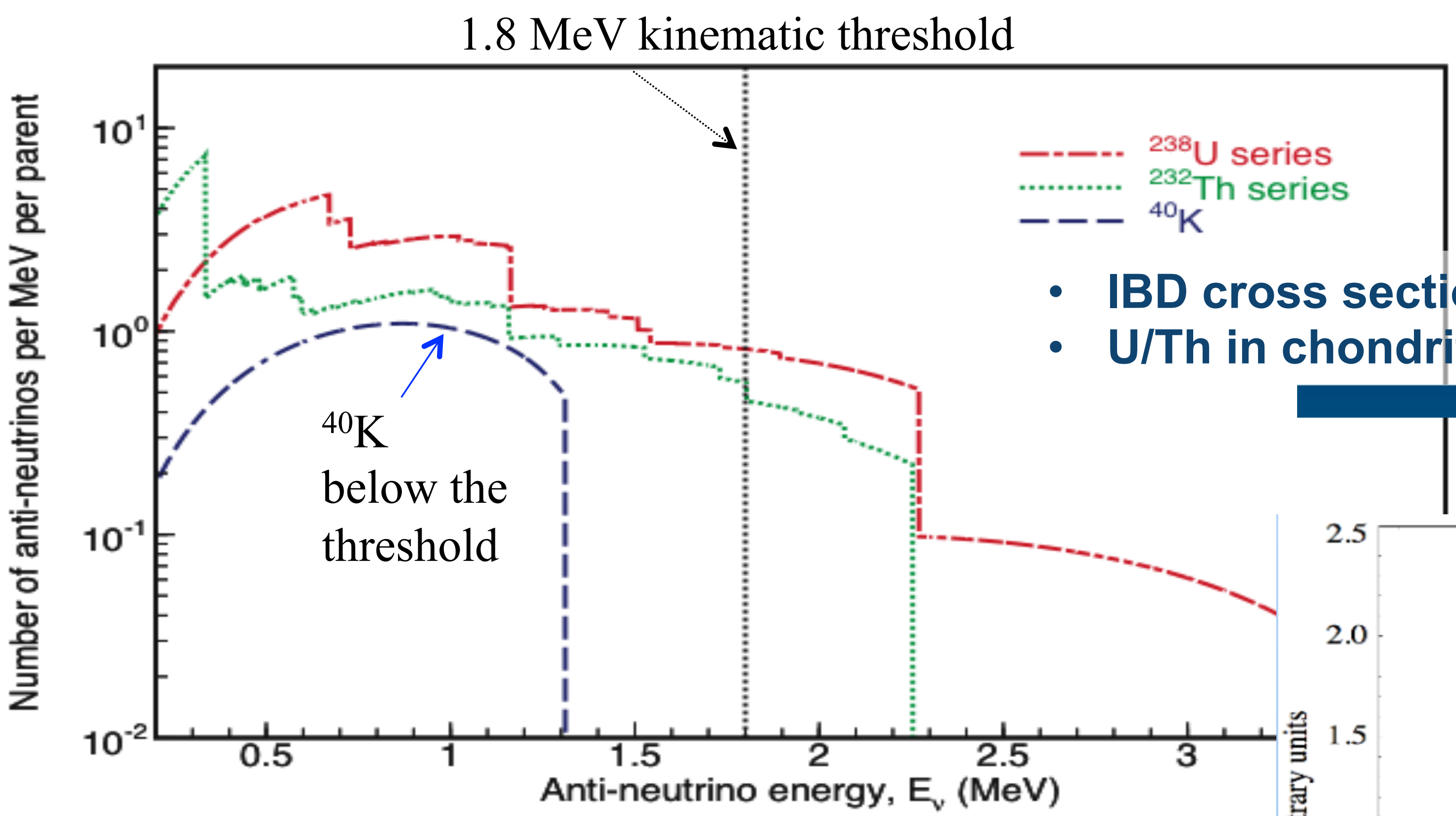
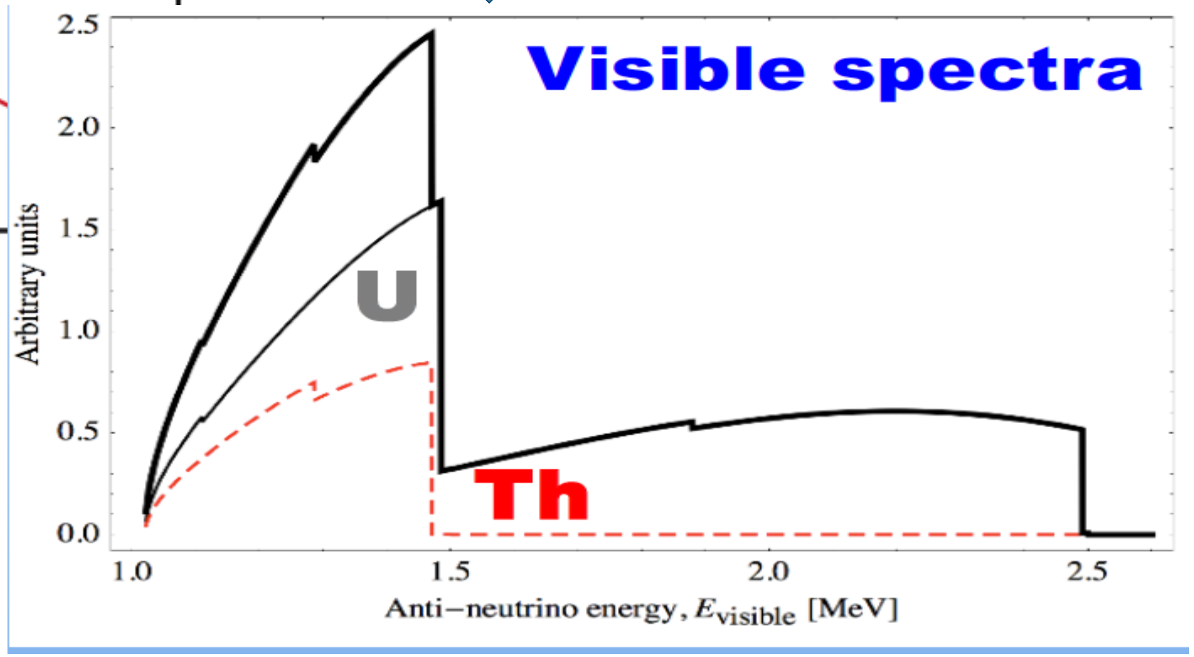
GEONEUTRINO ENERGY SPECTRA



- IBD cross section
- U/Th in chondritic mass ratio



DETECTING GEONEUTRINOS (IBD with LS-detectors)

- only **2 experiments** have measured geoneutrinos;
- both **liquid scintillator detectors**;

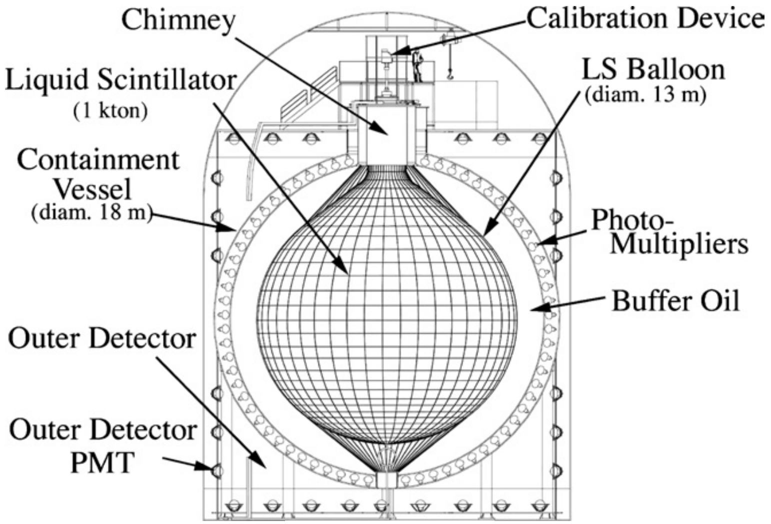
KamLAND in Kamioka, Japan
Border between OCEANIC / CONTINENTAL CRUST

- built to detect reactor anti-ν;
- 1000 tons;
- S(reactors)/S(geo) ~ 6.7 (2010)
- **After the Fukushima** disaster (03/2011) many reactors OFF and **S(reactors)/S(geo) ~ 1!**
- data since 2002;
- 2700 m.w.e. shielding;

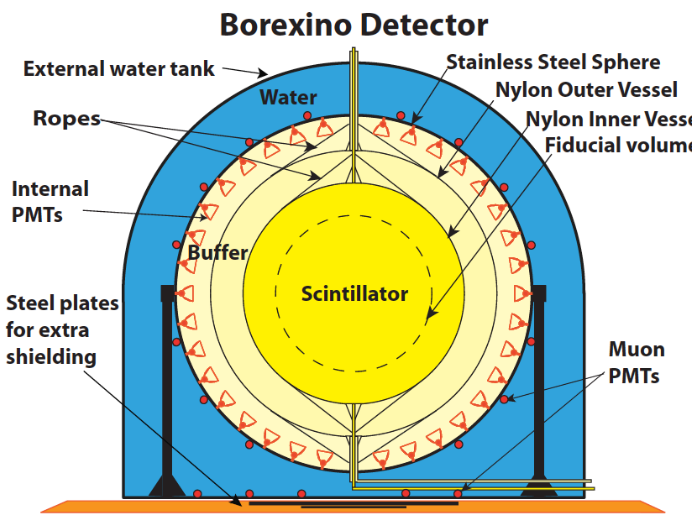
Borexino in Gran Sasso, Italy
CONTINENTAL CRUST

- originally built to measure neutrinos from the Sun (singles due from ν-e scattering) – extreme radio-purity needed and achieved;
- 280 tons;
- S(reactors)/S(geo) ~ 0.3 !!! (2010)
- DAQ started in 2007;
- 3600 m.w.e. shielding;

KamLAND



Borexino



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HISTORY OF GEONU MEASUREMENTS

KamLAND (Japan)

- **The first investigation in 2005**
  CL < 2σ **Nature 436 (2005) 499**
  7.09 x 10^{31} target-proton year
- **Update in 2008** PRL 100 (2008) 221803
  73 ± 27 geonu's
  2.44 x 10^{32} target-proton year

37%

- **99.997 CL observation in 2011**
  106^{+29}_{-28} geonu's
  (March 2002 – April 2009)
  3.49 x 10^{32} target-proton year
  Nature Geoscience 4 (2011) 647

26%

- **Latest published result in 2013**
  116^{+28}_{-27} geonu's
  (March 2002 – November 2012)
  4.9 x 10^{32} target-proton year
  PRD 88 (2013) 033001

24%

- **Preliminary update in 2016: 7.92σ CL**
  164^{+28}_{-25} geonu's (LOW REACTOR)
  (March 2002 – November 2016)
  6.39 x 10^{32} target-proton year
  (H. Watanabe @ Neut. Res. And Thermal Evol. Earth)

15-17%

Borexino (Italy)

- **99.997 CL observation in 2010**
  $9.9^{+4.1}_{-3.4}$ geonu's
  small exposure but low background level
  (December 2007 – December 2009)
  1.5 x 10^{31} target-proton year
  PLB 687 (2010) 299

34-41%

- **Update in 2013**
  14.3 ± 4.4 geonu's
  (December 2007 – August 2012)
  3.69 x 10^{31} target-proton year
  0-hypothesis @ 6 x 10^{-6}
  PLB 722 (2013) 295–300

31%

- **Latest in June 2015: 5.9σ CL**
  $23.7^{+6.5}_{-5.7}$(stat) $^{+0.9}_{-0.6}$(sys) geonu's
  (December 2007 – March 2015)
  5.5 x 10^{31} target-proton year
  0-hypothesis @ 3.6 x 10^{-9}
  PRD 92 (2015) 031101 (R)

24-27%

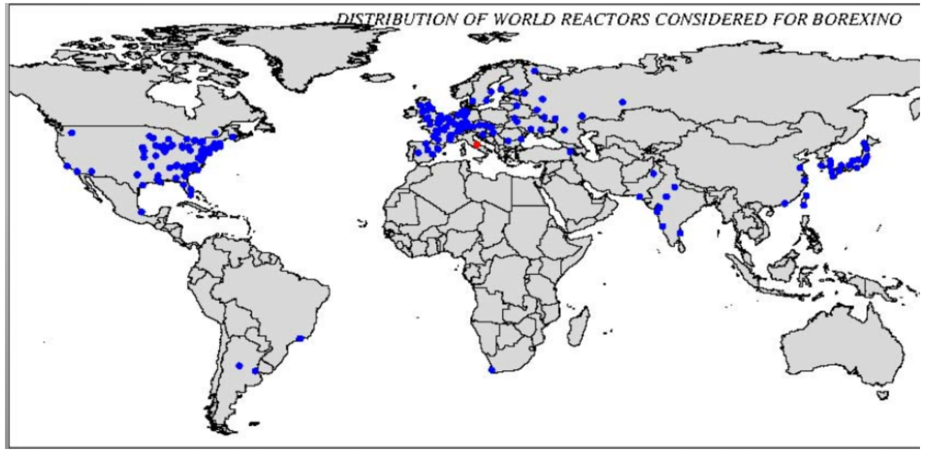
- **NEW UPDATE COMING SOON**

~20%

IMPROVED DATA SELECTION, SEE POSTER S. KUMARAN

BACKGROUNDS

A) Reactor antineutrino background



B) Non-antineutrino background

1) Cosmogenic background

- ^{9}Li and ^{8}He ($T_{1/2}$ = 119/178 ms)
- decay: β(prompt) + neutron (delayed);
- **fast neutrons**

  scattered protons (prompt)

Estimated by studying coincidences detected AFTER muons.

2) Accidental coincidences;

Estimated from OFF-time coincidences.

3) Due to the internal radioactivity:

(α, n) reactions: $^{13}C(\alpha, n)^{16}O$

Prompt: scattered proton, ^{12}C(4.4 MeV) & ^{16}O (6.1 MeV)

Estimated from ^{210}Po(α) and ^{13}C contaminations, cross section.

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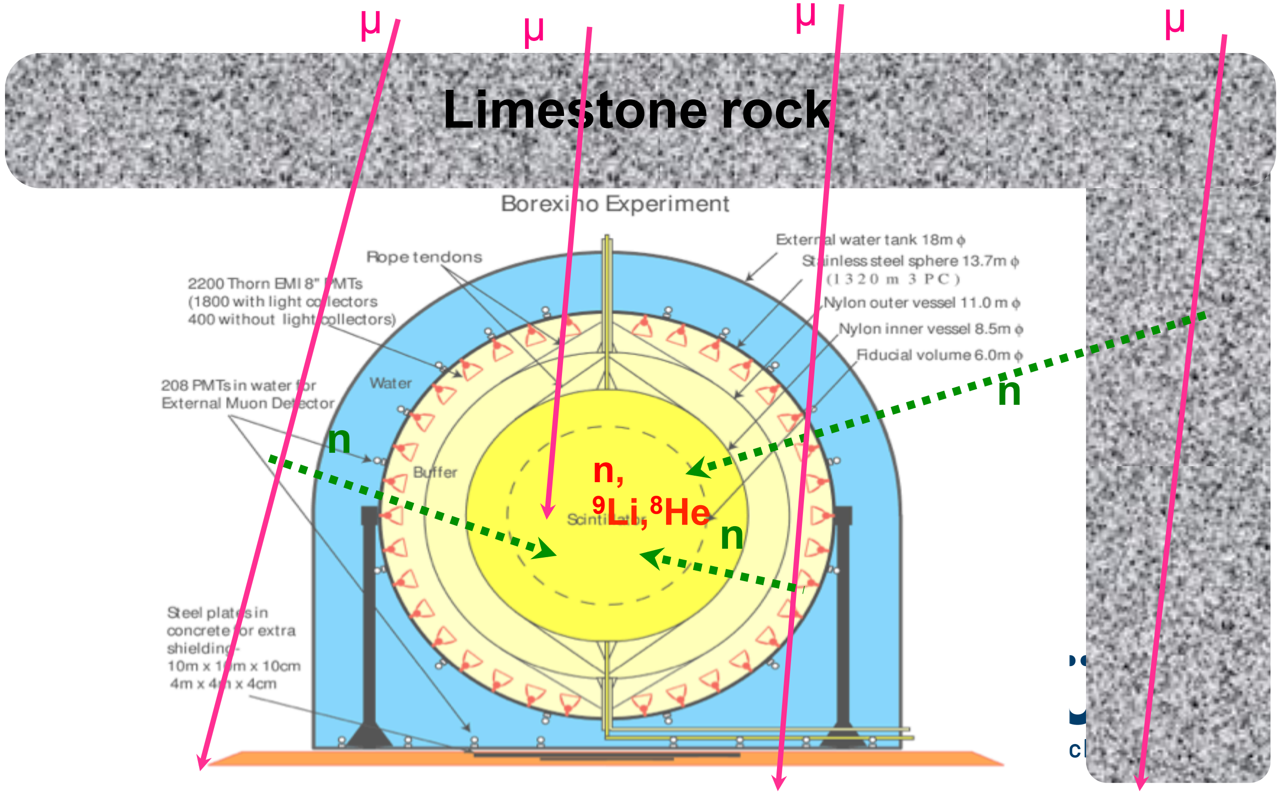
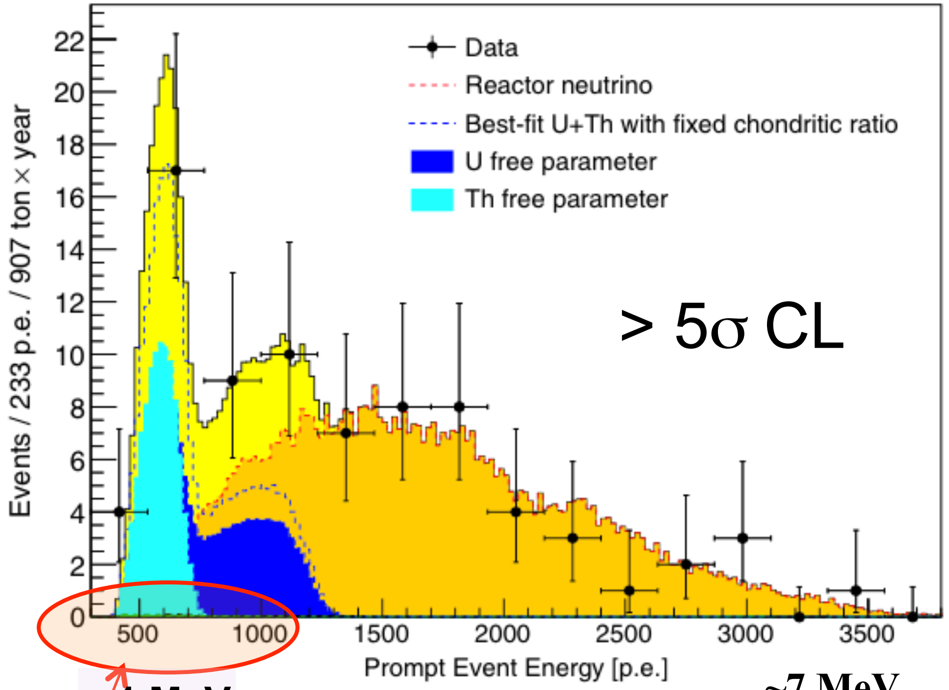


BOREXINO GEONEUTRINO RESULTS AND ANALYSIS

Borexino 2015: **$23.7^{+6.5}$ (stat) $^{+0.9}$ (sys)** geonu's



~1 MeV **~7 MeV**

PRD 92 (2015) 031101 (R)

✓ Non-antineutrino background almost invisible!

✓ 5.5×10^{31} target-proton year

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

TABLE I. Estimated backgrounds for $\bar{\nu}_e$ given in number of events. Upper limits are given for 90% C.L.

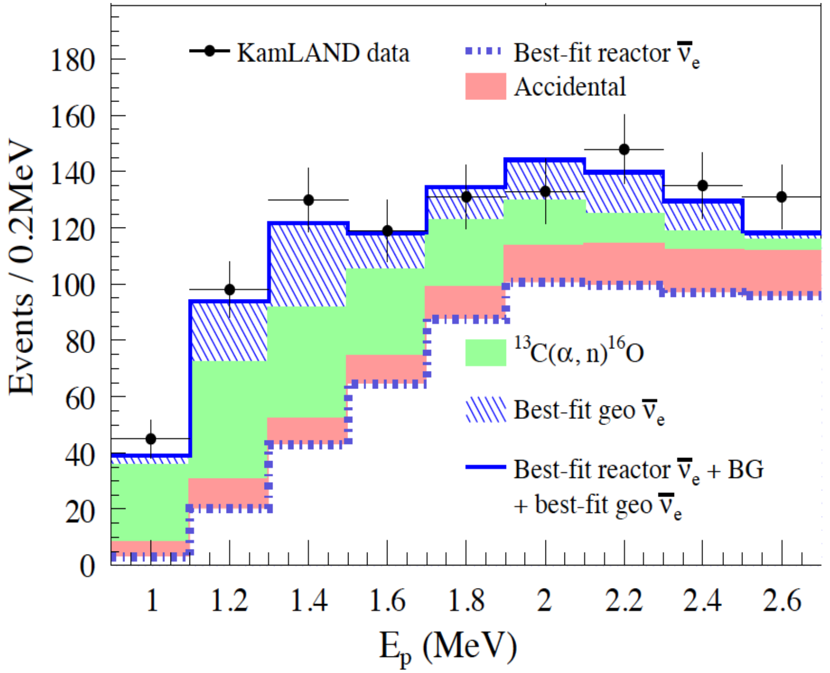
^{9}Li-^{8}He	$0.194^{+0.125}_{-0.089}$
Accidental coincidences	0.221 ± 0.004
Time correlated	$0.035^{+0.029}_{-0.028}$
(α, n) in scintillator	0.165 ± 0.010
(α, n) in buffer	<0.51
Fast n's (μ in WT)	<0.01
Fast n's (μ in rock)	<0.43
Untagged muons	0.12 ± 0.01
Fission in PMTs	0.032 ± 0.003
^{214}Bi-^{214}Po	0.009 ± 0.013
Total	$0.78^{+0.13}_{-0.10}$
	<0.65(combined)

In 2056 days of live time, less than 1 non-antineutrino background event!

- Unbinned maximum likelihood fit of 77 candidates.
- Non-antineutrino background almost negligible (< 1 event) and constrained in the fit.
- Reactor background left free in the fit: results compatible with expectations.
- 2 kinds of fit:
  - ✓ U/Th left free;
  - ✓ U/Th constrained to chondritic value.
- **Statistical error largely dominates systematic uncertainty** (reactor spectra, uncertainty of backgrounds, and detector response).

KAMLAND GEONEUTRINO RESULTS

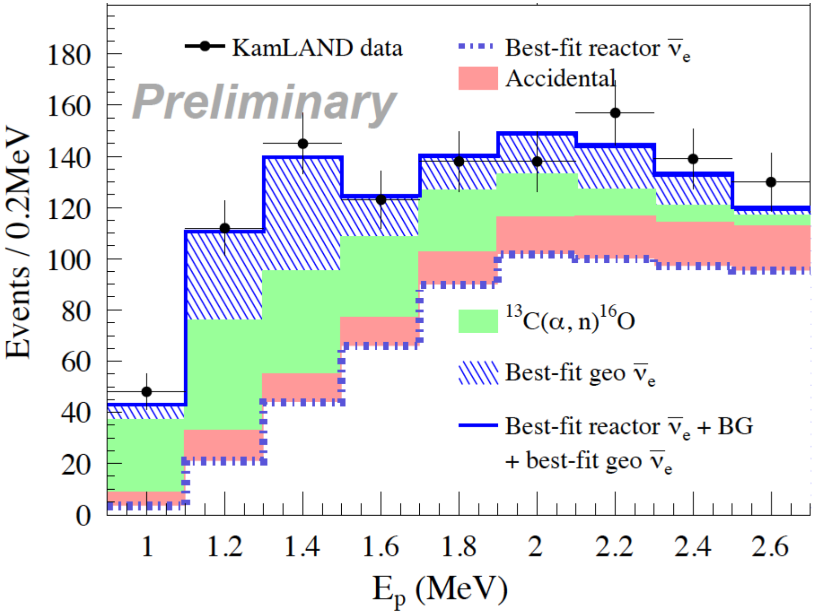
KamLAND 2013: 116^{+28}_{-27} geonu's



- ✓ Live time: 2991 days
- ✓ 4.9×10^{32} target-proton year

PRD 88 (2013) 033001

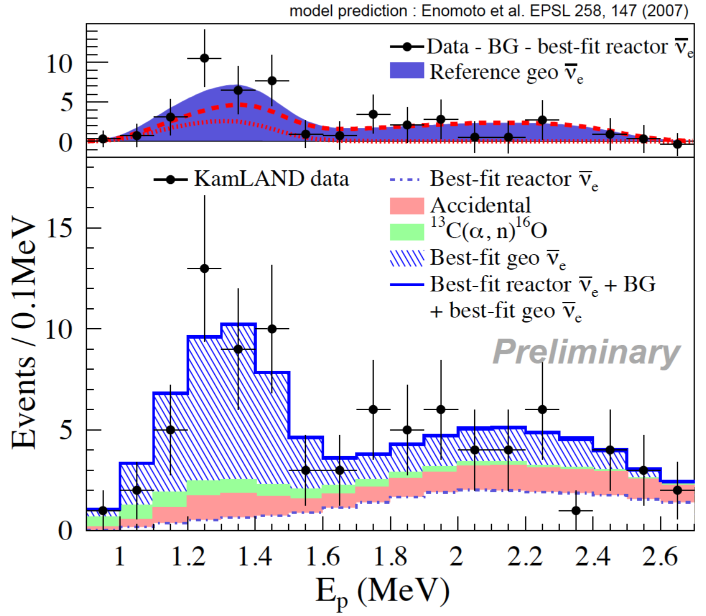
PRELIMINARY 2016: 164^{+28}_{-25} geonu's



- ✓ Live time: 3900.9 days
- ✓ 6.39×10^{32} target-proton year

Awaiting publication soon!

H. Watanabe @ Neut. Res. And Thermal Evol. Earth, 2016



- ✓ Live time: 1259.8 days
- ✓ Phase 3 only with reactors off
- ✓ Clear geoneutrino spectrum

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FIRST GEOLOGICAL INTERPRETATIONS

- Measured **geoneutrino signal is in agreement with expectations**, but we cannot distinguish among various geological models:

  Borexino: $S_{geo} = 43.5\ ^{+11.8}_{-10.4}\ (stat)^{+2.7}_{-2.4}(sys)$ TNU

  KamLAND: $S_{geo} = 34.9\ ^{+6.0}_{-5.4}$ TNU

- **U/Th ratio is compatible with chondritic ratio**, but the errors are too big:

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

- First **indications of the measured non-zero mantle signal**

  Borexino 2015: $S_{mantle} = 20.1^{+15.1}_{-10.3}$ TNU

- Idea of Herndon about the **active geo-reactor in the Earth core excluded**

  Borexino 2010 < 3TW @95% CL

  KamLAND 2011 < 5.2 TW @ 90% CL

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FUTURE RESULTS AND EXPERIMENTS

- **Borexino** (Italy): update with ~20% precision soon;
- **KamLAND** (Japan): update with low reactor-background data soon;
- **SNO+** (Canada): 780 ton & DAQ starting soon & 30-40 geonus/year;
  Low cosmogenics;
- **JUNO** (China): 20 kton & DAQ start in 2021 & 400 geonus/year Should be able to reach the precisions of 17% in the 1st year! *(J. Phys. G: Nucl. Part. Phys. 43 (2016) 030401)*
- **JINPING** (China): 5 kton; deepest lab, far away from reactors, very thick continental crust at Himalayan region; *(PRD 95 (2017) 053001)*
- **HanoHano** (Hawaii): 10 kton underwater detector with ~80% mantle contribution: **"THE" GEONU DETECTOR: MISSING FUNDING!**

  J. G. Learned et al., *XII International Workshop on Neutrino Telescopes*, Venice, 2007.

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Geoneutrino summary

- The new interdisciplinary field is born and collaboration among geologists started **(Neutrino Geoscience conference series** since 2005 (last time in 2015 here in Paris, **next 21-23 October 2019 in Prague**!), **ISAPP Summer School** <u>Using Particle Physics to Understand and Image the Earth</u> in 2016 and 2018);
- Geo-neutrinos has been observed;
- The first results are in agreement with geological expectations;
- New generation experiments needed for geologically highly significant results:
- CHALLENGE 1: **detection of ^{40}K geoneutrinos** (< 1.8 MeV)
- CHALLENGE 2: **directionality** (crust vs mantle contributions)

Mt. Everest group, flight from Kathmandu (Nepal) to Paro (Bhutan), March 2018

Back up slides

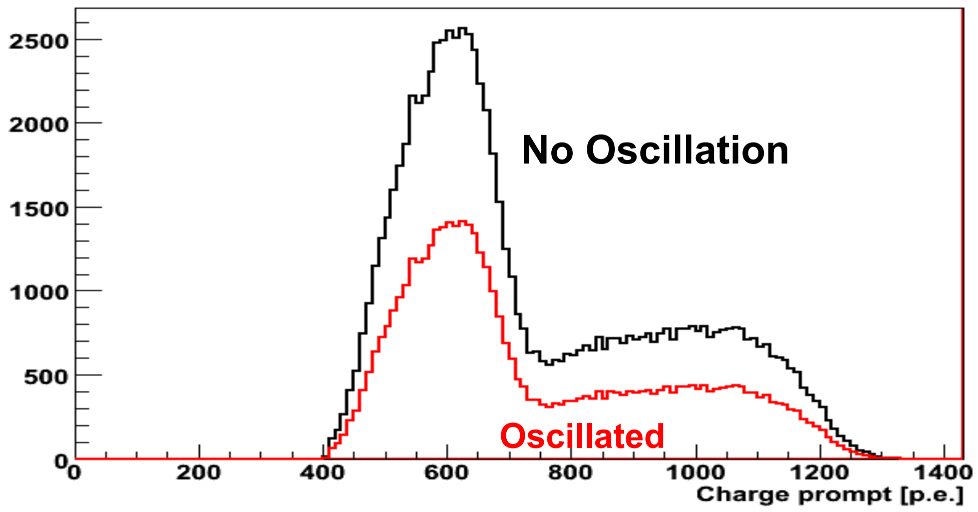
EFFECT OF NEUTRINO OSCILLATIONS

$$P_{ee} = P(\overline{\nu}_e \to \overline{\nu}_e) = \cos^4\theta_{13}\left(1 - \sin^2 2\theta_{12}\sin^2\left(\frac{\delta m^2 L}{4E}\right)\right) + \sin^4\theta_{13}$$

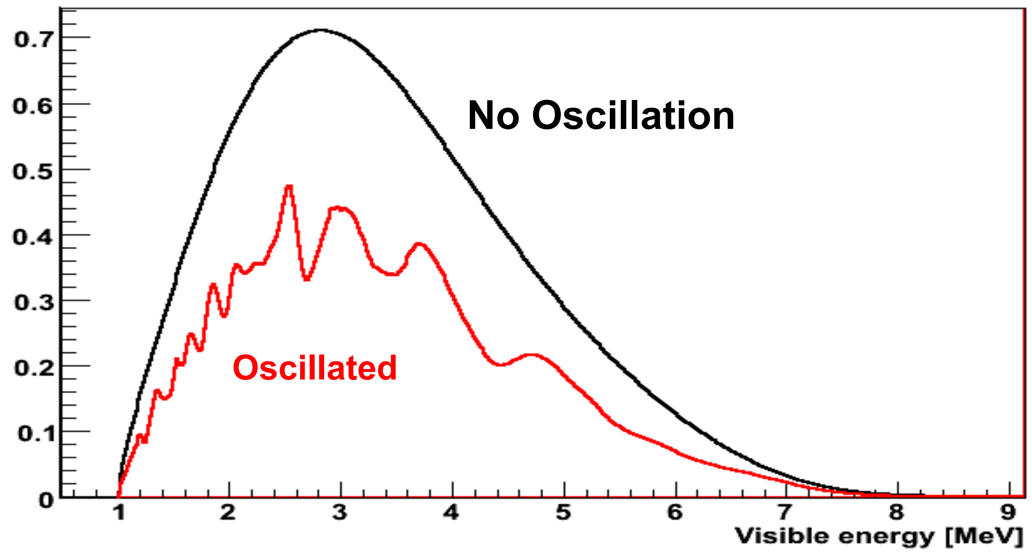
3 MeV antineutrino ..
Oscillation length of ~100 km

for geoneutrinos we can use average survival probability of 0.551 + 0.015 (Fiorentini et al 2012), but for reactor antineutrinos not!

Geoneutrinos



Reactor antineutrinos at LNGS



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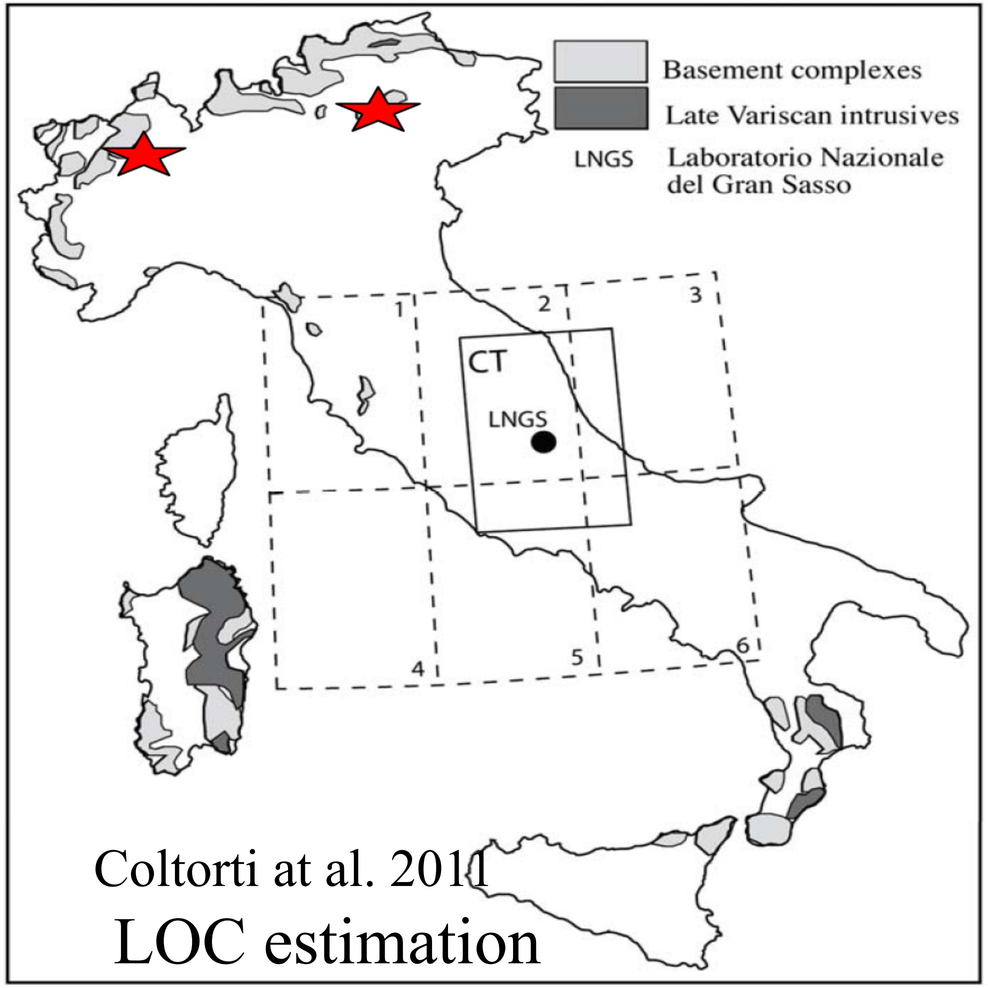
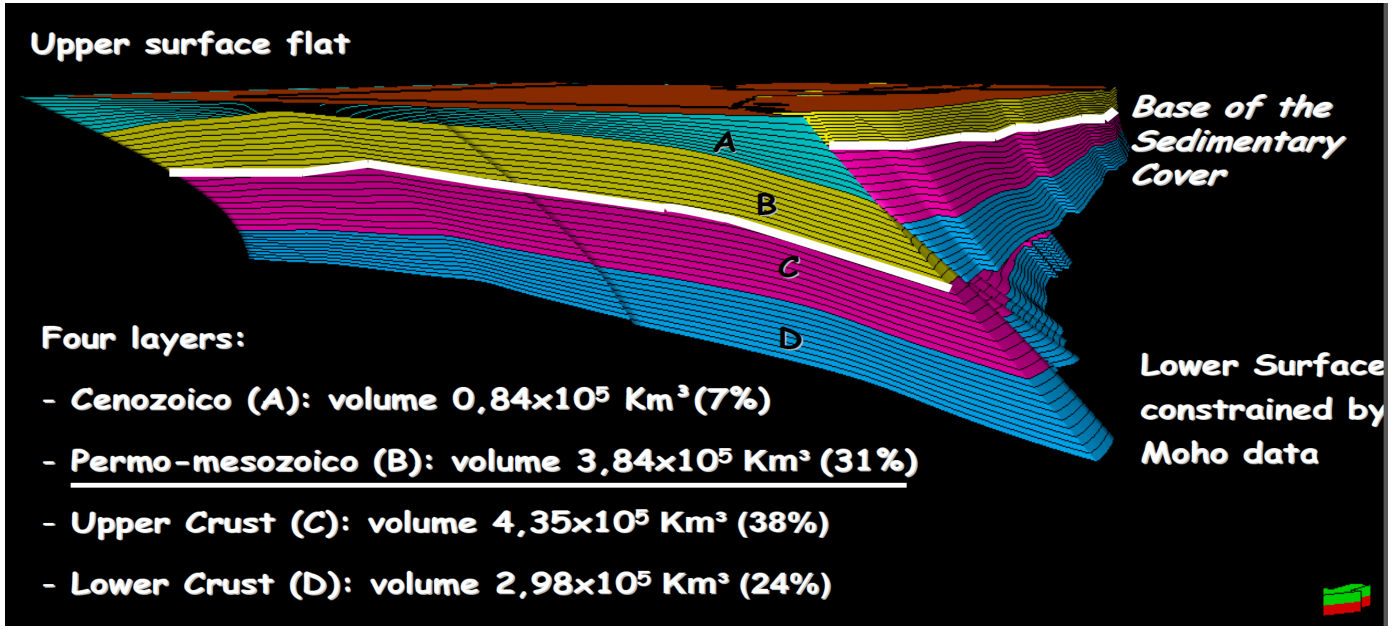
Expected crustal signal at LNGS





Expected crustal signal
local (LOC) + Rest-Of-the Crust (ROC)
23.4 $\pm$ 2.8 TNU

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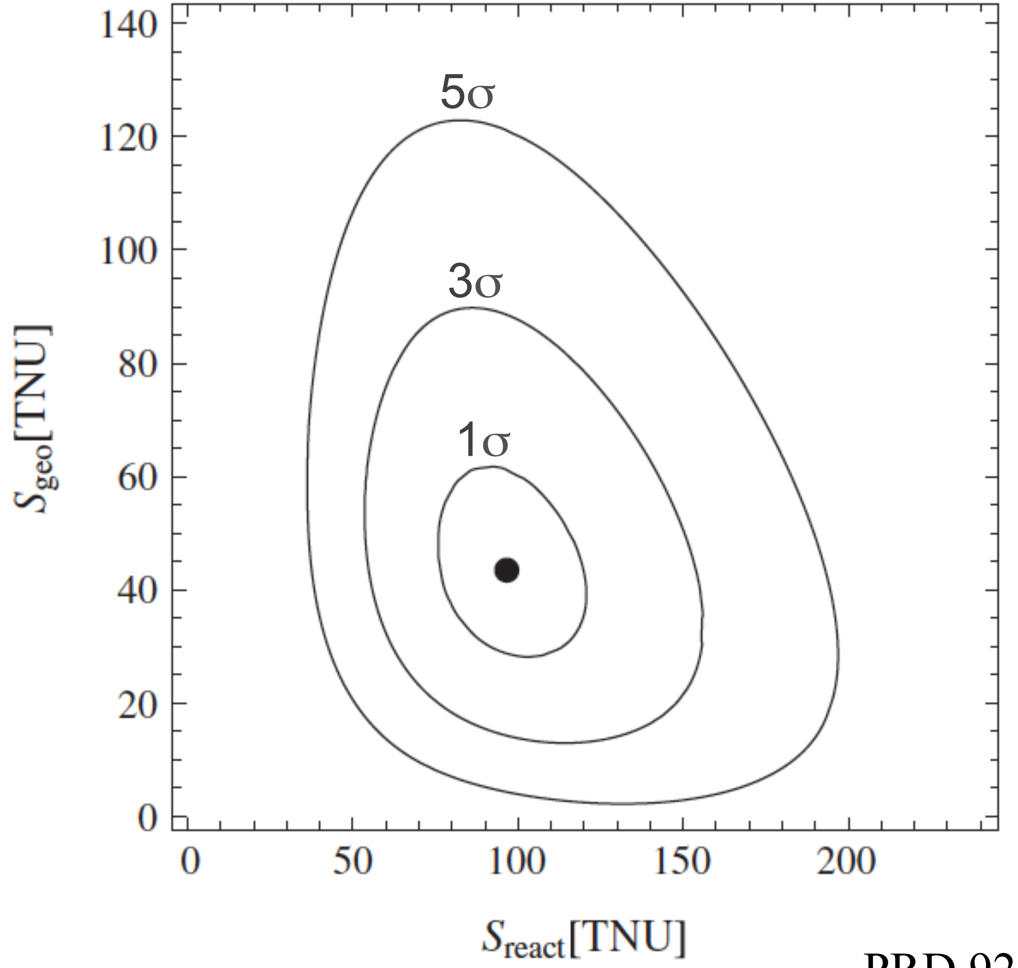
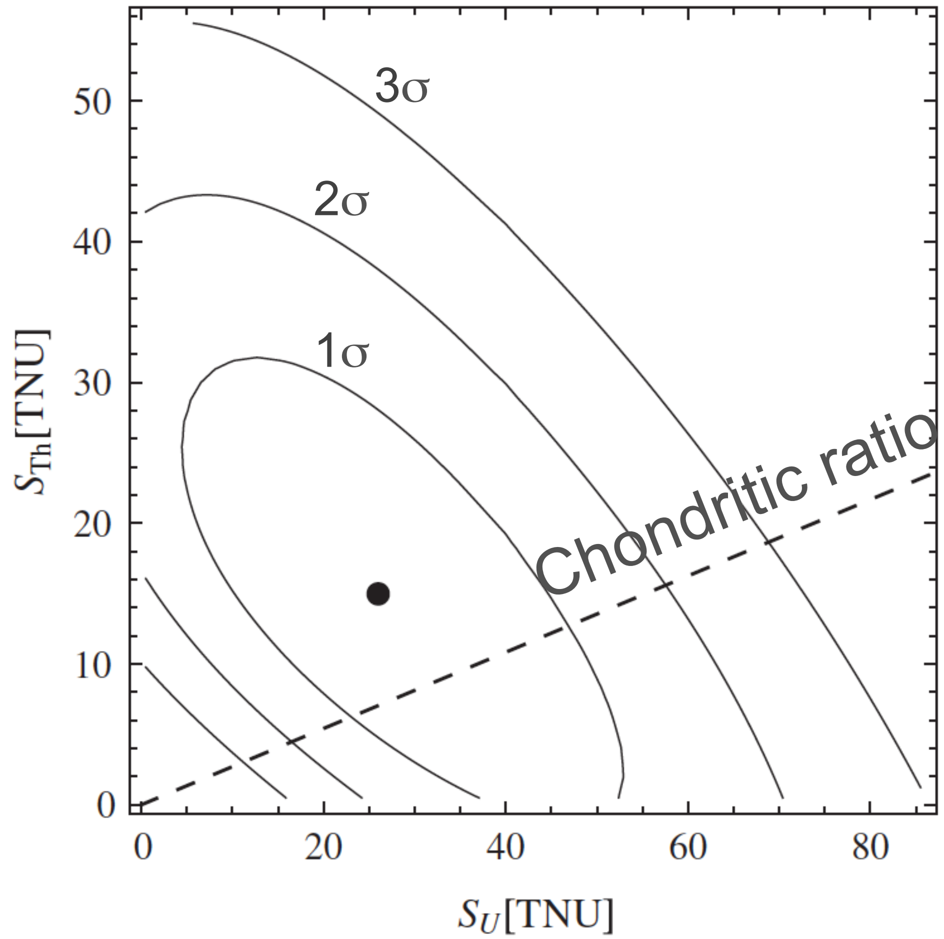
CONTOUR PLOTS (BOREXINO 2015)

Fit with U/Th ratio fixed



Fit with U/Th ratio free



PRD 92 (2015) 031101 (R)

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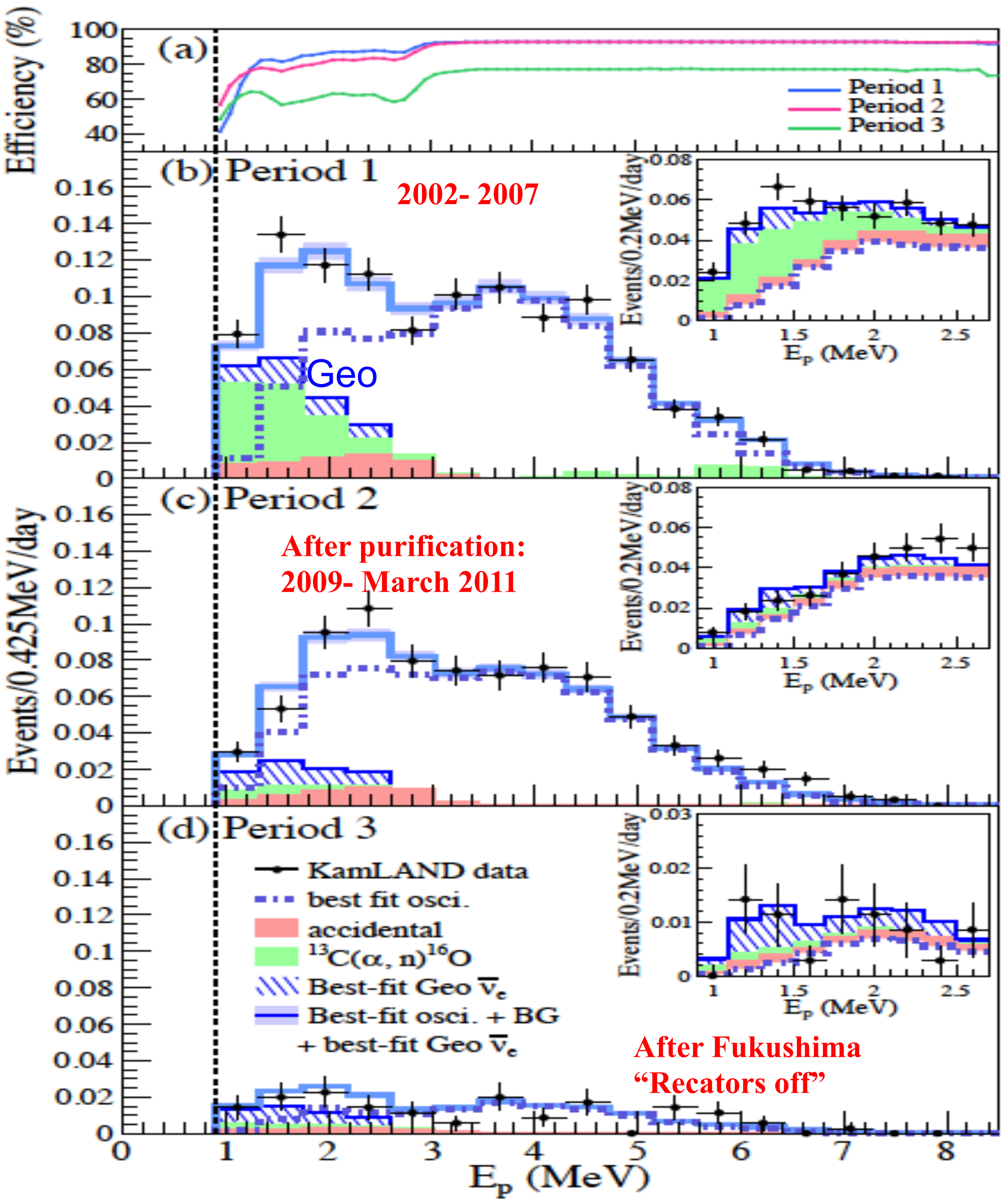
KamLAND-Phases



✓Period 1: 2002 – 2007

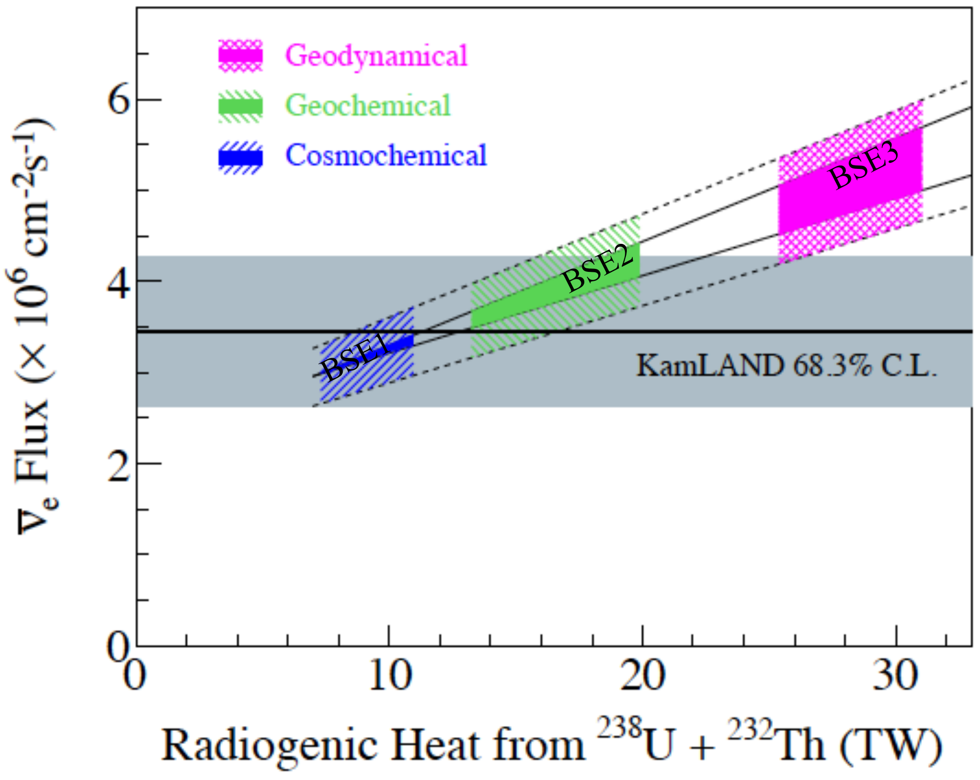
✓Period 2 (After a long purification campaign) 2009 – March 2011 (Fukushima disaster)

✓Period 3 – After Fukushima when many of the nuclear reactors were switched off

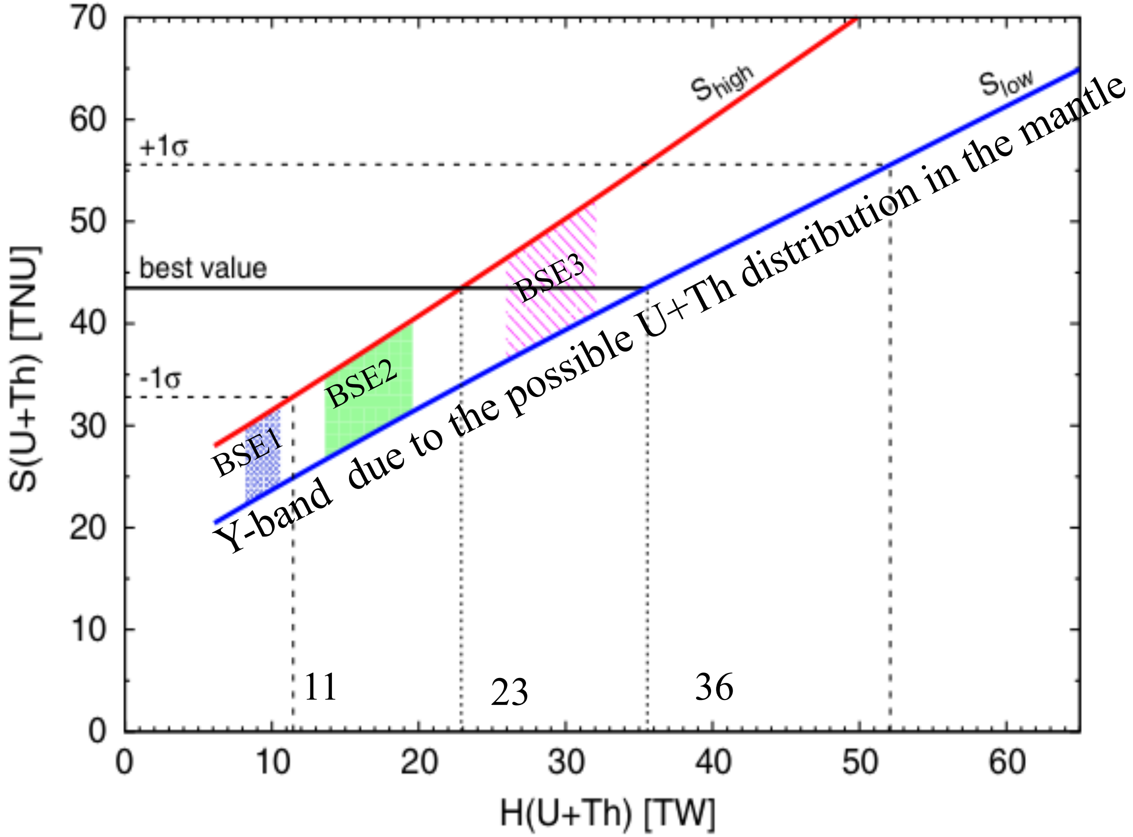
2013 results
PRD 88 (2013) 033001

RADIOGENIC HEAT IMPLICATIONS

KamLAND 2013 PRD 88 (2013) 033001



Borexino 2015 PRD 92 (2015) 031101 (R)



- Radiogenic heat (U+Th): 23-36 TW for the best fit and 11-52 TW for 1σ range
- Considering chondritic mass ratio Th/U=3.9 and K/U = 10^4 : radiogenic heat (U + Th + K) = 33^{+28}_{-20}TW

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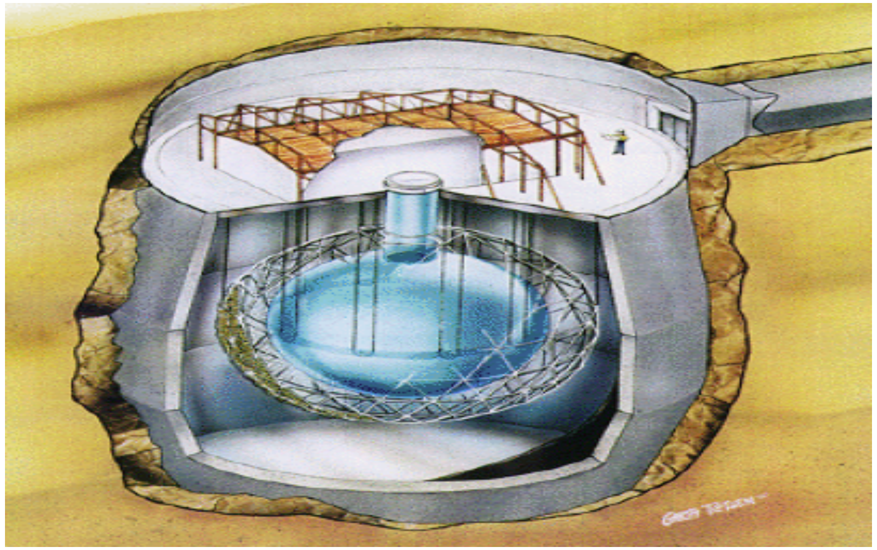
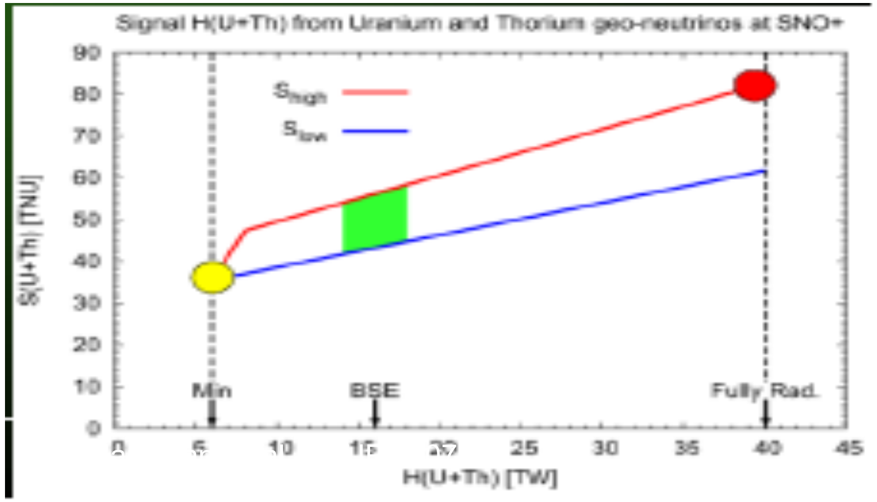
SNO+ AT SUDBURY, CANADA





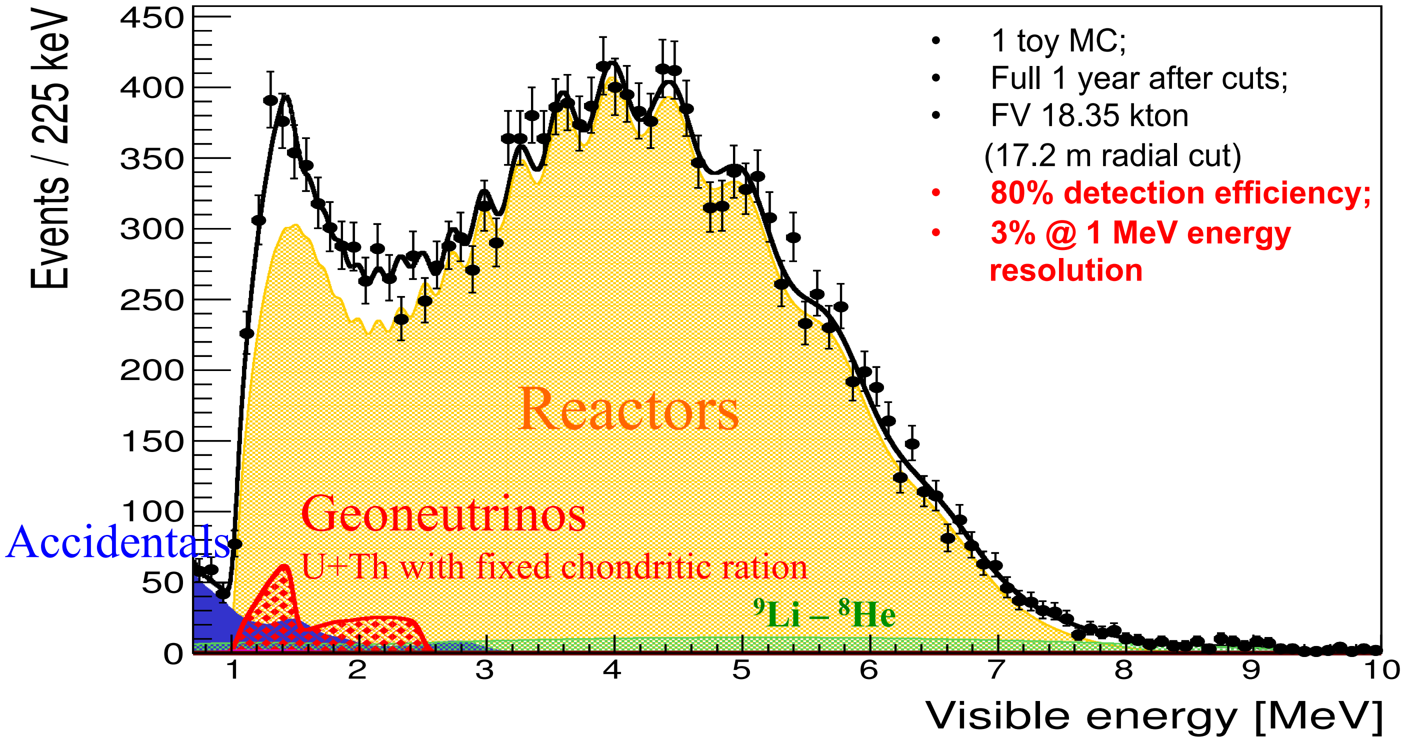
COMING SOON!

After SNO: D_2O replaced by 780 tons of liquid scintillator
M. C. Chen, *Earth Moon Planets* **99**, 221 (2006)

Placed on an old continental crust:
80% of the signal from the crust
(Fiorentini et al., 2005)

BSE: 28-38 events/per year

JUNO potential to measure geoneutrinos



Big advantage:

- ✓ Big volume and thus high statistics (400 geonu / year)!

Main limitations:

- ✓ Huge reactor neutrino background;
- ✓ Relatively shallow depth – cosmogenic background;

Critical:

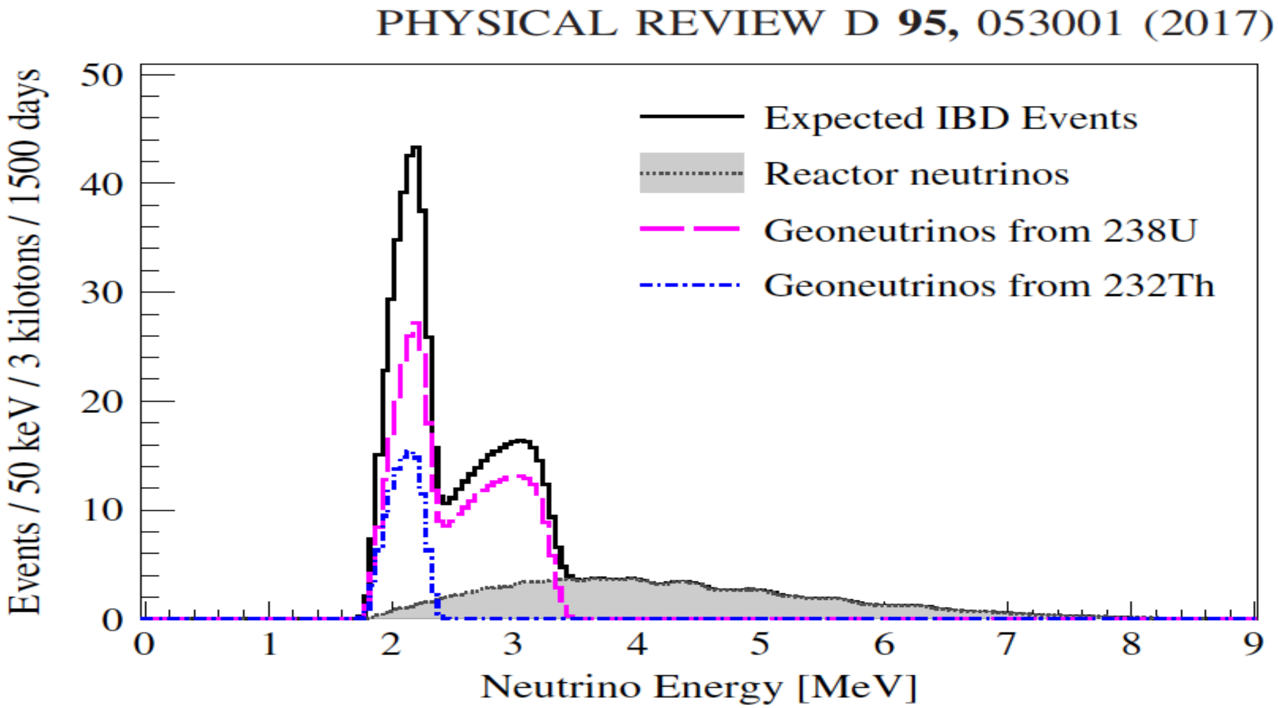
- ✓ Keep other backgrounds (^{210}Po contamination!) at low level and under control;

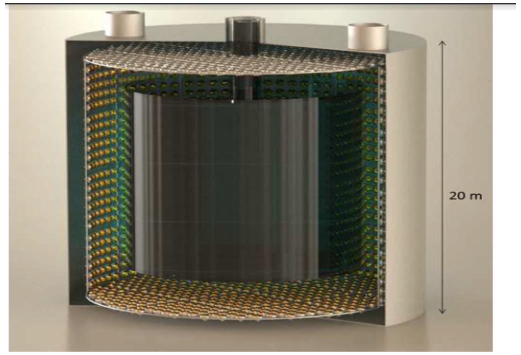
JUNO can provide another geoneutrino measurement with a comparable or even a better precision than existing results at another location in a completely different geological environment;

JINPING: THE DEEPEST LAB IN THE WORLD

Lab under excavation

5 kton liquid scintillator detector





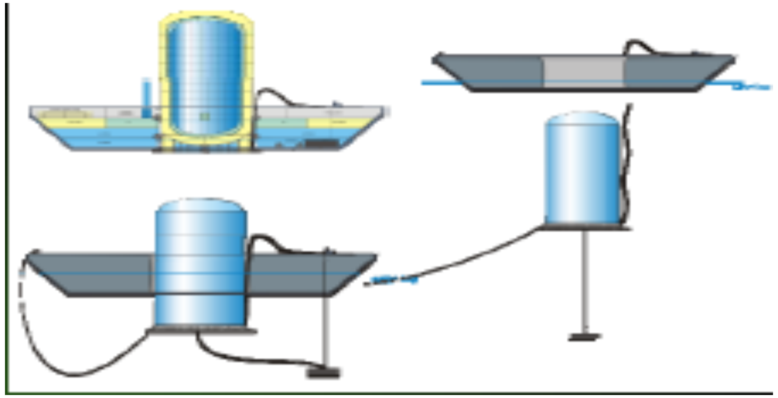
Expected IBD spectrum:
Far away from reactors!!!

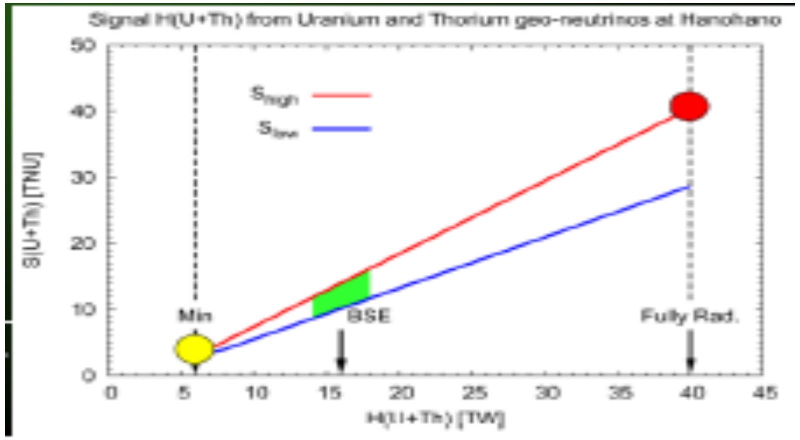
Very deep:
small Li-He (beta, neutron) background

Big signal from the continental crust

HANOHANO AT HAWAII

HAWAII ANTINEUTRINO OBSERVATORY (HANOHANO = "MAGNIFICENT” IN HAWAIIAN





Project for a 10 kton liquid scintillator detector, movable and placed on a deep ocean floor

J. G. Learned et al., *XII International Workshop on Neutrino Telescopes*, Venice, 2007.

Since Hawai placed on the U-Th depleted oceanic crust

70% of the signal from the mantle!

Would lead to very interesting results!
(Fiorentini et al.)

BSE: 60-100 events/per year

Would be the ultimate geoneutrino experiment!