GEONEUTRINOS

LIVIA LUDHOVA

IKP-2 FORSCHUNGSZENTRUM JÜLICH AND RWTH AACHEN, GERMANY

HISTORY OF NEUTRINO, 5-7 SEPTEMBER 2018, PARIS, FRANCE

For what concerns
the deep Earth,
we are as
ALIENS ON OUR PLANET
We need more tools!

OUTLINE

- What are geoneutrinos and why to study them.
- The first ideas.
- Expected geoneutrino flux.
- KamLAND and Borexino: from the first geoneutrino detection up to the most recent results.
- Neutrino geoscience: outlook.

Earthquake, L'Aquila, Italy, 2016

Shiveluch vulcano, Kamchatka, Russia, September 2017

Mitglied der Helmholtz-Gemeinschaft

JÜLICH
Forschungszentrum

Karymsky vulcano, Kamchatka, Russia, September 2017

From where is coming
the energy driving these processes?

How can neutrino physics help us to understand?

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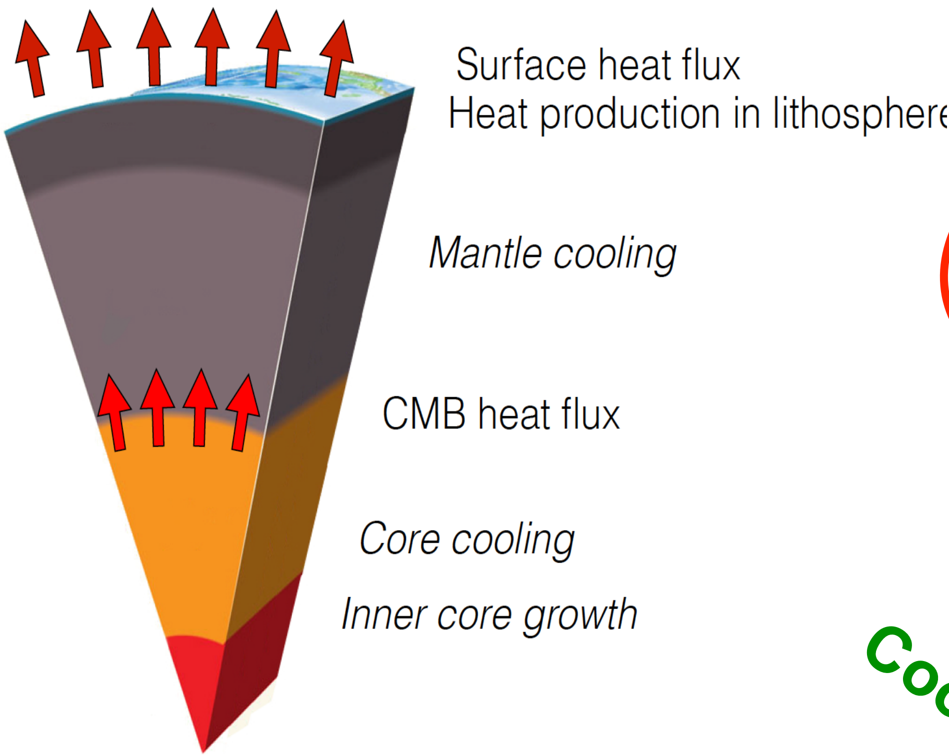
How can neutrino physics help us to understand?

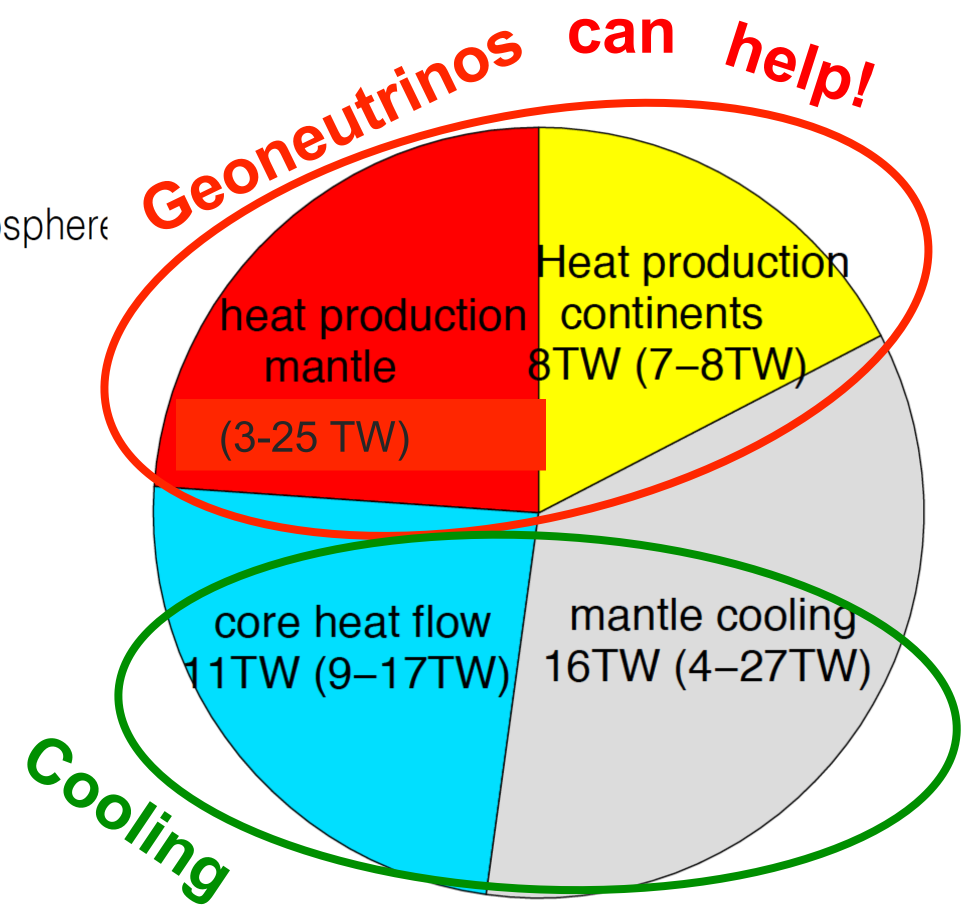
EARTH HEAT BUDGET

Surface heat flux: 47 ± 3 TW

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

IMPORTANT MARGINS FOR ALL DIFFERENT MODELS OF THE EARTH





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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- **released heat and anti-neutrinos flux in a well fixed ratio**
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- in practice (as always) more complicated…..

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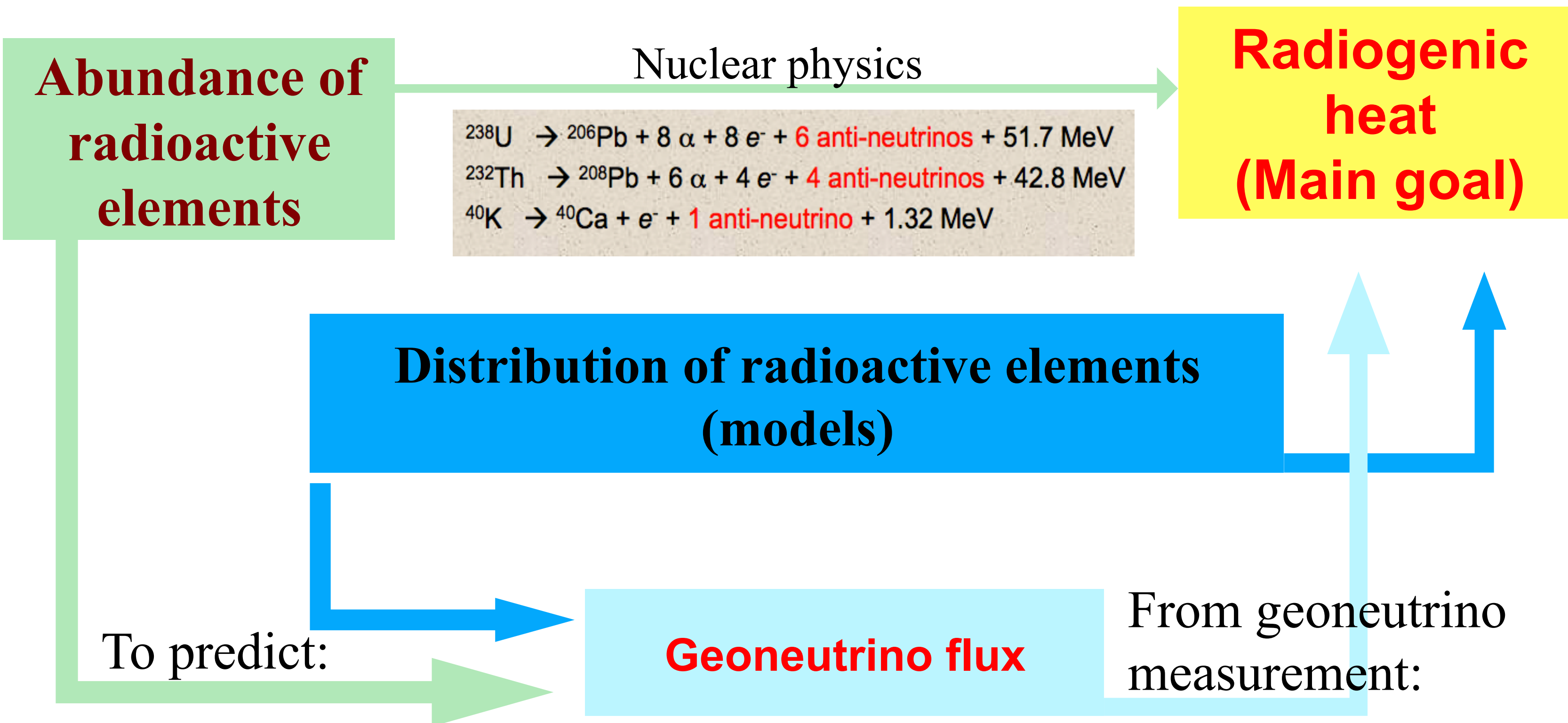
Earth shines in antineutrinos: flux ~10^6 cm^{-2} s^{-1}

leaving freely and instantaneously the Earth interior

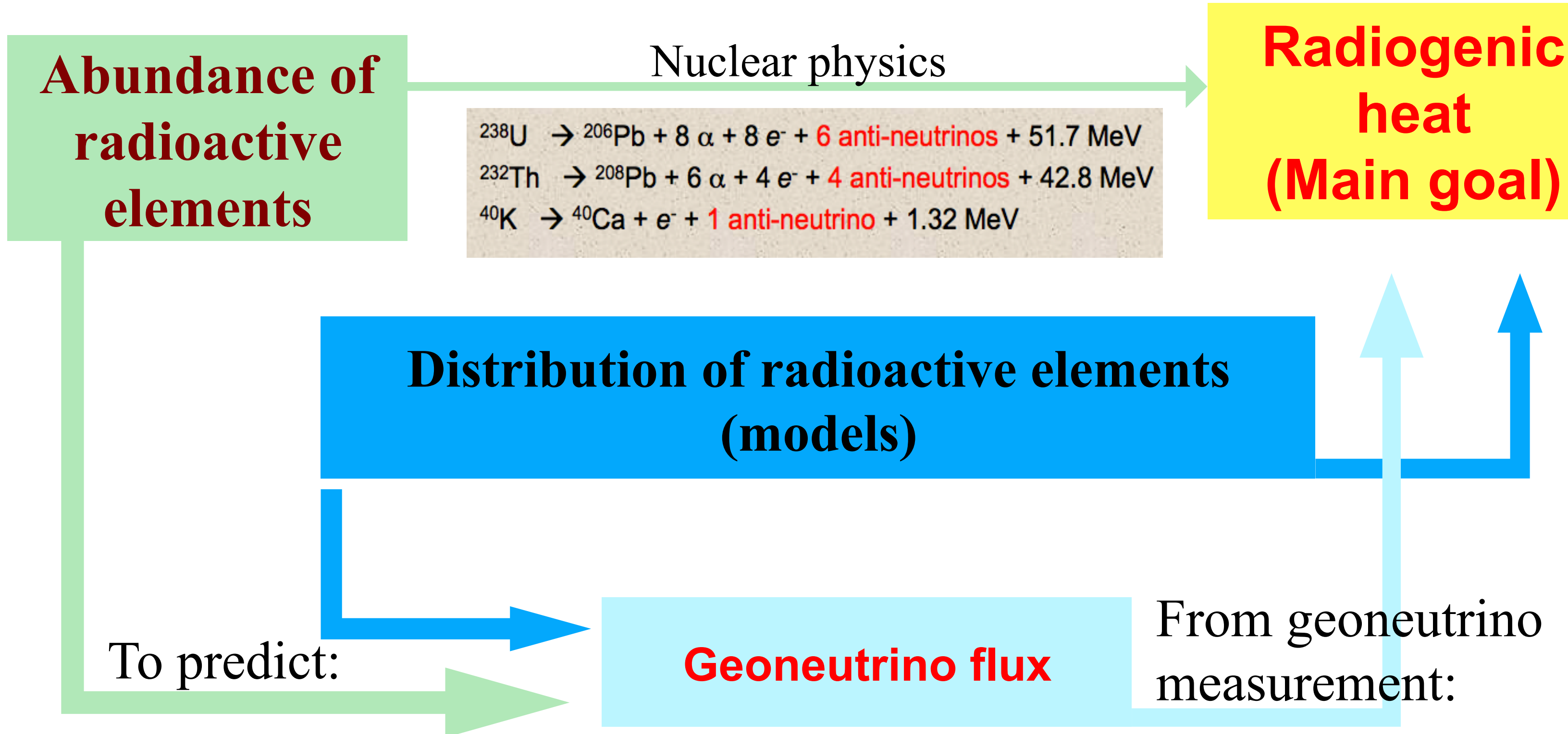
(to compare: solar neutrino (NOT antineutrino!) flux ~10^{10} cm^{-2} s^{-1})

NEUTRINO GEOSCIENCE: TRUELY INTER-DISCIPLINARY FIELD



- **Main goal:** determine the contribution of the **radiogenic heat 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: TRUELY INTER-DISCIPLINARY FIELD



- **Main goal:** determine the contribution of the **radiogenic heat to th… ce heat flux**, which is an important margin, test, and input … physical and geochemical models of the Earth…
- **Further goals: U/Th** … geological models, Earth compo… **ogeneity or stratification**, insights to the proces… additional sources of heat?, idea of U-based **geo-reactor** in the Ea… (according to Herndon)

Most of these had only little hope before geoneutrinos!

THE FIRST IDEAS CONCERNING

1) EXPECTED GEONEUTRINO FLUX
2) POSSIBLE DETECTION TECHNIQUES

THE FIRST IDEAS: G. EDER

8.C.2

Nuclear Physics **78** (1966) 657—662; © *North-Holland Publishing Co., Amsterdam*

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TERRESTRIAL NEUTRINOS

GERNOT EDER

Institut für Theoretische Physik der Universität Giessen, Giessen, Germany

Received 11 October 1965

- Motivation: radiogenic heat as the source of energy for the Earth expansion of 0.8 mm/year
- Expected fluxes: from K, U, and Th, order of **10^8 cm^{-2} s^{-1}**
- Detection for 1.5 MeV neutrinos from ^{40}K: Very small expected rate

$$\nu + {}^{37}\mathrm{Cl} \rightarrow e^- + {}^{37}\mathrm{Ar} - 0.816\ \mathrm{MeV}.$$

- Detection for anti-neutrinos: 4 e+ / day / 500 tons of **water**

$$\bar{\nu} + p \rightarrow e^+ + n - 1.804\ \mathrm{MeV}.$$

→ Used today!

THE FIRST IDEAS: G. MARX

Czech. J. Phys. B 19 (1969)

GEOPHYSICS BY NEUTRINOS*)

G. MARX

Institute of Theoretical Physics, Roland Eötväs University, Budapest

- Motivation: use neutrinos to study also the Earth (along with other objects)
- Expected fluxes: $^{238/235}$U, ^{232}Th, ^{40}K, ^{87}Rb, total flux **10^9 cm^{-2} s^{-1}**
- Induced Beta Decay:

$$\tilde{\nu} + {}^3\mathrm{He} \to {}^3\mathrm{H} + e^+ \ (E_{\min} = 1{\cdot}041\ \mathrm{MeV},\ \log ft = 3{\cdot}03)$$

$$\tilde{\nu} + {}^{35}\mathrm{Cl} \to {}^{35}\mathrm{S} + e^+ \quad (E_{\min} = 1{\cdot}189\ \mathrm{MeV},\ \log ft = 4{\cdot}98)$$

Used today! ←

$$\tilde{\nu} + {}^1\mathrm{H} \to n + e^+ \quad (E_{\min} = 1{\cdot}804\ \mathrm{MeV},\ \log ft = 3{\cdot}13)$$

- Induced Electron Capture for mono-energetic anti-nu:

$$\tilde{\nu} + e^- + X \to Y\,.$$

^{130}Ba → ^{130}Cs	0·44 MeV
^{209}Bi → ^{209}Pb	0·63 MeV
^{112}Sn → ^{112}In	0·65 MeV

Marx G., Menyhárd N.: Mitteilungen der Sternwarte, Budapest No. 48 (1960).

Marx G., Lux I.: Antineutrino Luminosity of the Earth. Talk at the Moscow Conference on Neutrino Physics and Neutrino Astrophysics. ITP-Budapest Report No. 243 (1968).

Marx G., Lux I.: Hunting for Soft Antineutrinos. Acta Phys. Hung. in press. ITP-Budapest Report No. 256 (1969).

THE FIRST IDEAS:

NATURE VOL. 310 19 JULY 1984 REVIEW ARTICLE 191

Antineutrino astronomy and geophysics

Lawrence M. Krauss*, Sheldon L. Glashow† & David N. Schramm‡

* Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138, USA
† Department of Physics, Boston University, Boston, Massachusetts 02215, USA
‡ Department of Physics and Astrophysics, Enrico Fermi Institute, University of Chicago, Chicago, Illinois 60637, USA

- Motivation: composition and dynamics of the Earth
- Expected fluxes: from lithosphere **10^{7} cm^{-2} s^{-1}**
- Radiochemical detection methods discusses in detail
  - Induced Beta Decay
  - Induced Electron Capture for mono-energetic anti-nu

THE FIRST IDEAS: USE OF LIQUID SCINTILLATOR

Raju Raghavan
(1937 – 2011)

Detecting a Nuclear Fission Reactor at the Center of the Earth

R. .S. Raghavan
Bell Laboratories, Lucent Technologies, Murray Hill NJ
and
INFN Laboratori Nazionali del Gran Sasso, Italy

Measuring the global radioactivity in the earth by multidetector anti-neutrino spectroscopy

R.S. Raghavan (Bell Labs), Stefan. Schonert (Munich, Tech. U.), S. Enomoto, J. Shirai, F. Suekane, A. Suzuki (Tohoku U.)

Aug 1997 - 4 pages

Phys.Rev.Lett. 80 (1998) 635-638
DOI: 10.1103/PhysRevLett.80.635

GEOPHYSICAL RESEARCH LETTERS, VOL. 25, NO. 7, PAGES 1083-1086, APRIL 1, 1998

Antineutrino geophysics with liquid scintillator detectors

Casey G. Rothschild, Mark C. Chen and Frank P. Calaprice
Physics Department, Princeton University Princeton, New Jersey

EXPECTED GEONEUTRINO FLUX TODAY

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…..

Amount 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

Crustal models

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

EXPECTED GEONEUTRINO SIGNAL

Input: U and Th
- **abundances**
- **distributions**

- **LOC: Local crust: detailed knowledge** on the continental crust: about 50% of the expected geoneutrino signal comes from the crust within 500-800 km around the detector (Mantovani et al.)
- **ROC: Rest Of the Crust: further crust -> more approximation** Divided in 3D voxels, volumes for upper, middle, lower crust and sediments are estimated and a mean chemical composition is attributed to these volumes (e.g., Huang et al. 2013);
- **Mantle = BSE – (LOC + ROC):** different BSE models are considered and the respective U + Th mass is distributed either homogeneously (maximal signal) or it is concentrated near to the core-mantle boundary (minimal signal);

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PHYSICS LETTERS B
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Neutrinos and energetics of the Earth

G. Fiorentini [a,b], F. Mantovani [c], B. Ricci [a,b]

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[b] Istituto Nazionale di Fisica Nucleare, Sezione di Ferrara, I-44100 Ferrara, Italy
[c] Scuola di Dottorato, Dipartimento di Scienze della Terra, Universitá di Siena, 53100 Siena, Italy

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Editor: G.F. Giudice

concentration for ^{238}U (Mantovani *et al.* 2004)

upper continental crust:	2.5 ppm
middle continental crust:	1.6 ppm
lower continental crust:	0.63 ppm
oceanic crust:	0.1 ppm
upper mantle:	6.5 ppb
core	NOTHING

decreasing

Huge amount of work in predicting the global and local crustal geoneutrino signal

Geochemistry Geophysics Geosystems G3
Article
Volume 14, Number 6
19 June 2013
doi:10.1002/ggge.20129
ISSN: 1525-2027
Published by AGU and the Geochemical Society

A reference Earth model for the heat-producing elements and associated geoneutrino flux

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Viacheslav Chubakov
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SCIENTIFIC REPORTS

www.nature.com/scientificreports

OPEN

AGM2015: Antineutrino Global Map 2015

S.M. Usman[1], G.R. Jocher[2], S.T. Dye[3,4], W.F. McDonough[5] & J.G. Learned[3]

Geoneutrinos at Jinping: Flux prediction and oscillation analysis

Linyan Wan, Ghulam Hussain, Zhe Wang, and Shaomin Chen

Phys. Rev. D **95**, 053001 – Published 3 March 2017

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Available online at www.sciencedirect.com
ScienceDirect
Geochimica et Cosmochimica Acta 75 (2011) 2271–2294
Geochimica et Cosmochimica Acta
www.elsevier.com/locate/gca

U and Th content in the Central Apennines continental crust: A contribution to the determination of the geo-neutrinos flux at LNGS

M. Coltorti[a,*], R. Boraso[a], F. Mantovani[b,e], M. Morsilli[a], G. Fiorentini[b,e], A. Riva[a], G. Rusciadelli[c], R. Tassinari[a], C. Tomei[d], G. Di Carlo[d], V. Chubakov[b,e]

GIGJ: a crustal gravity model of the Guangdong Province for predicting the geoneutrino signal at the JUNO experiment

L. Rossi, M. Reguzzoni, M. Baldoncini, I. Callegari, P. Poli, D. Sampietro, V. Strati, F. Mantovani, G. Andronico, V. Antonelli, M. Bellato, E. Bernieri, A. Brigatti, R. Brugnera, A. Budano, M. Buscemi, S. Bussino, R. Caruso, D. Chiesa, D. Corti, F. Dal Corso, X. F. Ding, S. Dusini, A. Fabbri, G. Fiorentini, R. Ford, A. Formozov, A. Garfagnini, M. Giammarchi, A. Giaz, M. Grassi, A. Insolia, R. Isocrate, I. Lippi, F. Longhitano, D. Lo Presti, P. Lombardi, F. Marini, Y. Mari, C. Martellini, E. Meroni, M. Mezzetto, L. Miramonti, S. Monforte, M. Montuschi, M. Nastasi, F. Ortica, A. Paoloni, S. Parmeggiano, D. Pedretti, N. Pelliccia, R. Pompilio, E. Previtali, G. Ranucci, A. C. Re, B. Ricci, A. Romani, P. Saggese, G. Salamanna, F. H. Sawy, G. Settanta, M. Sisti, C. Sirignano, M. Spinetti, L. Stanco, G. Verde, L. Votano

Strati et al. Progress in Earth and Planetary Science
DOI 10.1186/s40645-015-0037-6

RESEARCH ARTICLE

Expected geoneutrino signal at JUNO

Virginia Strati[1,2*], Marica Baldoncini[1,3], Ivan Callegari[2], Fabio Mantovani[1,3], William F McDonough[4], Barbara Ricci... and Gerti Xhixha[2]

AGU PUBLICATIONS
Geochemistry, Geophysics, Geosystems
RESEARCH ARTICLE
10.1002/2014GC005397

Regional study of the Archean to Proterozoic crust at the Sudbury Neutrino Observatory (SNO+), Ontario: Predicting the geoneutrino flux

Yu Huang[1], Virginia Strati[2,3], Fabio Mantovani[2,3,4], Steven B. Shirey[5], and William F. McDonough[6]

Key Points:
- A 3-D regional crust around SNO+ is built
- Geoneutrino signal from regional

PHYSICAL REVIEW D **69**, 013001 (2004)

Antineutrinos from Earth: A reference model and its uncertainties

Fabio Mantovani,[1,2,3,*] Luigi Carmignani,[1,2,†] Gianni Fiorentini,[4,3,‡] and Marcello Lissia[5,6,§]
[1]Dipartimento di Scienze della Terra, Università di Siena, I-53100 Siena, Italy
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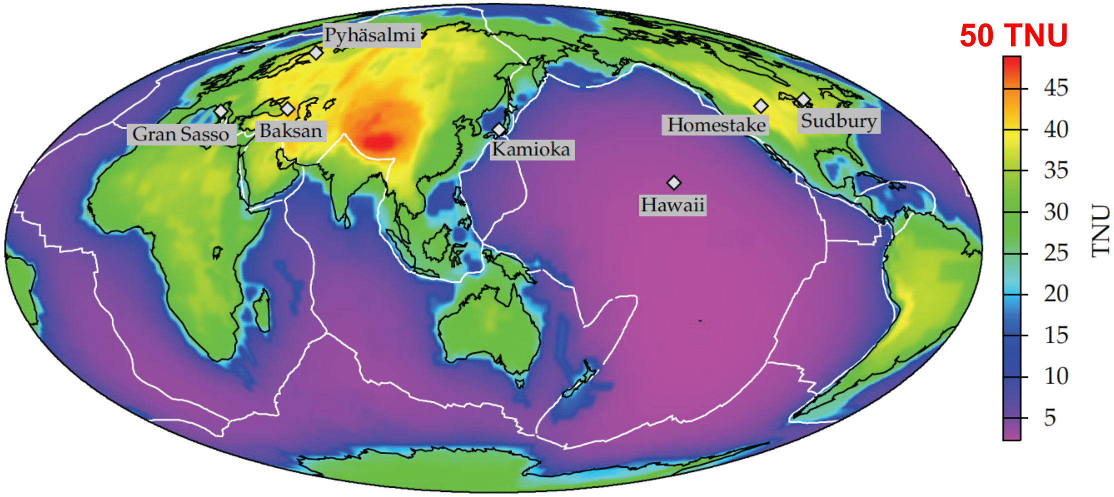
[3]Istituto Nazionale di Fisica Nucleare, Sezione di Ferrara, I-44100 Ferrara, Italy
[4]Dipartimento di Fisica, Università di Ferrara, I-44100 Ferrara, Italy
[5]Istituto Nazionale di Fisica Nucleare, Sezione di Cagliari, I-09042 Monserrato (CA), Italy

PHYSICAL REVIEW D **72**, 033017 (2005)

How much uranium is in the Earth? Predictions for geoneutrinos at KamLAND

Gianni Fiorentini,[1,2,*] Marcello Lissia,[3,4,†] Fabio Mantovani,[5,6,2,‡] and Riccardo Vannucci[7,8,§]

Expected "known and big" crustal signal



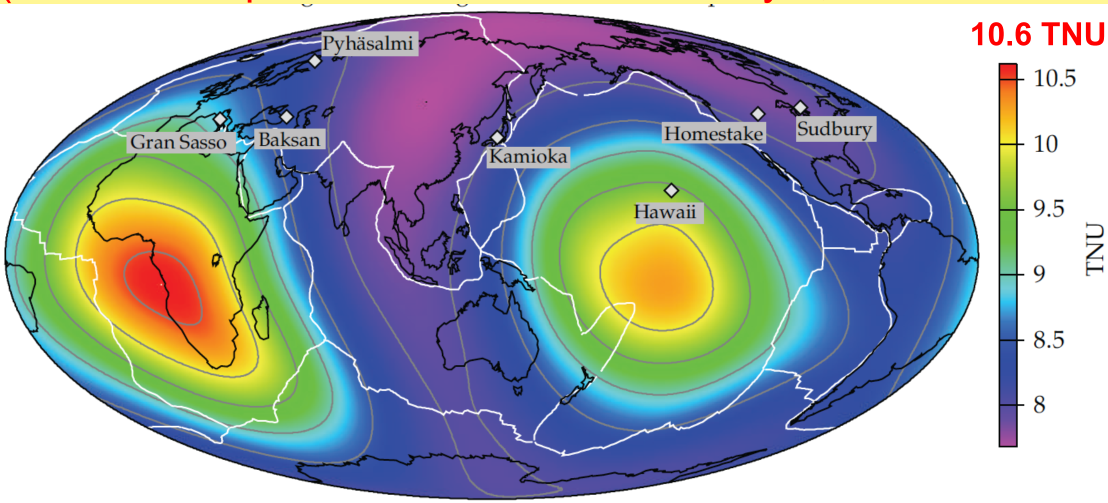
The signal is small, we need big detectors!

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

Expected mantle signal: hypothesis of heterogeneous composition

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

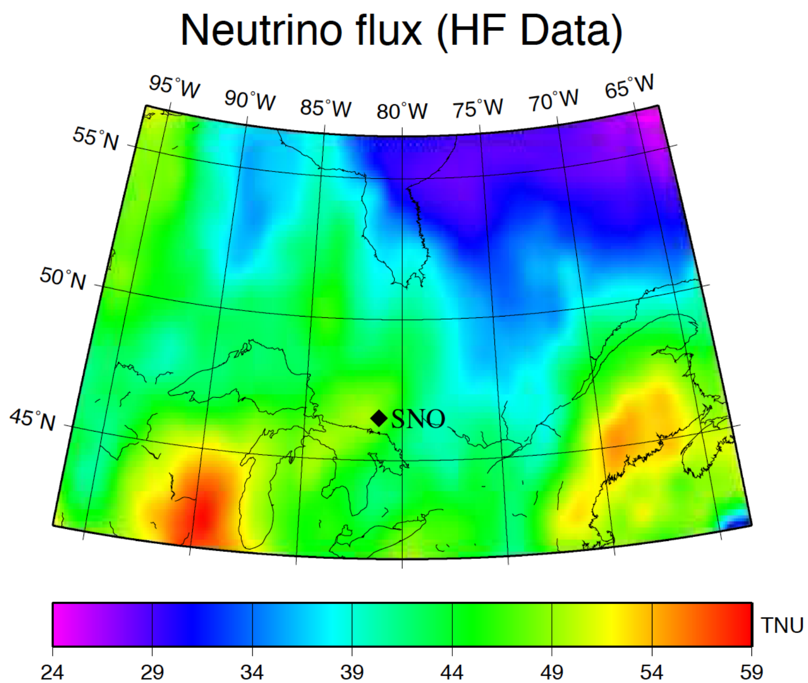
(from: C. Jaupart: remnants of a basal layer, now thinned and deformed by convection?)

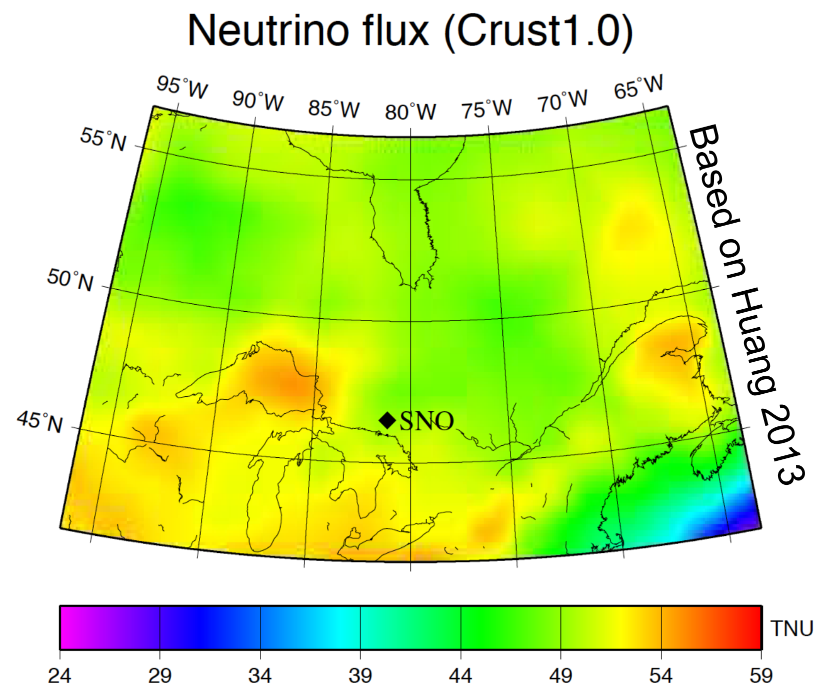


To measure mantle signal is even more challenging!

Ondřej Šrámek, William F. McDonough, Edwin S. Kite, Vedran Lekić, Steve Dye, Shijie Zhong "Geophysical and geochemical constraints on geoneutrino fluxes from Earths mantle", Earth Planet. Sci. Lett., 361 (2013) 356-366)

ALTERNATIVE APPROACH:
EXPECTED CRUSTAL GEONEUTRINO FLUX FROM HEAT FLOW





from J.C. Mareschal, C. Jaupart & L. Iarotski

H.K.C. Perry, J.-C Mareschal & C. Jaupart, Enhanced crustal geo-neutrino production near the Sudbury neutrino observatory, Ontario, Canada, Earth Planet. Sci. Lett., 288, 301–308.

J.-C Mareschal, C. Jaupart, C. Phaneuf & C. Perry, Geo-neutrinos and the energy budget of the Earth, J. Geodynamics 54, 43-54

DETECTING GEONEUTRINOS

- **only 2 experiments have measured geoneutrinos;**
- **liquid scintillator detectors**;
- (Anti-)neutrinos have low interaction rates, therefore:
  - **Large volume detectors needed;**
  - **High radio-purity of construction materials;**
  - **Underground labs to shield cosmic radiations;**

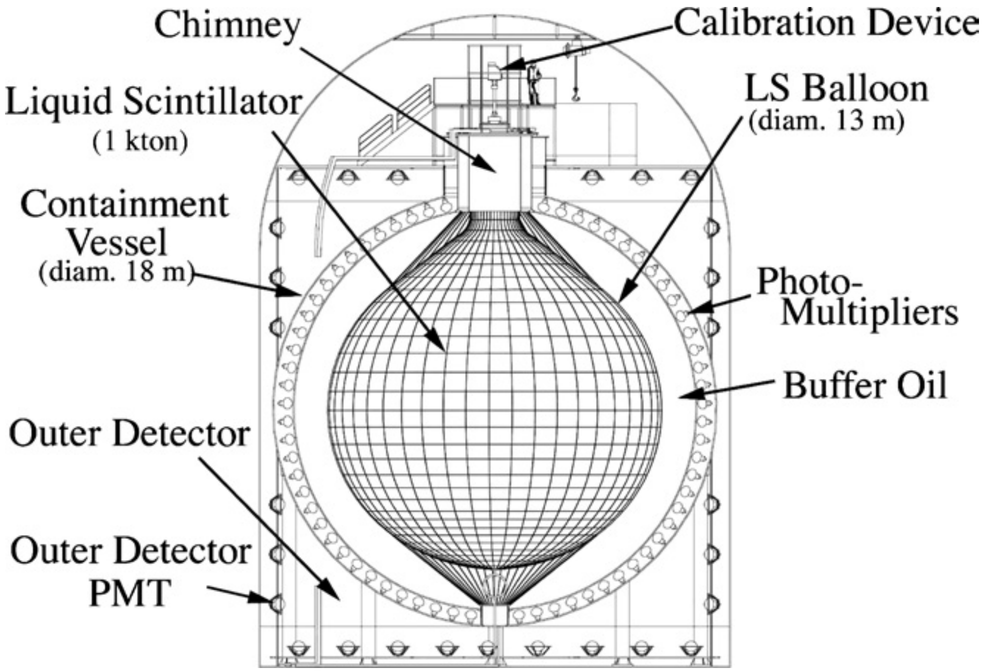
KamLAND in Kamioka, Japan
Border between
OCEANIC / CONTINENTAL CRUST

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

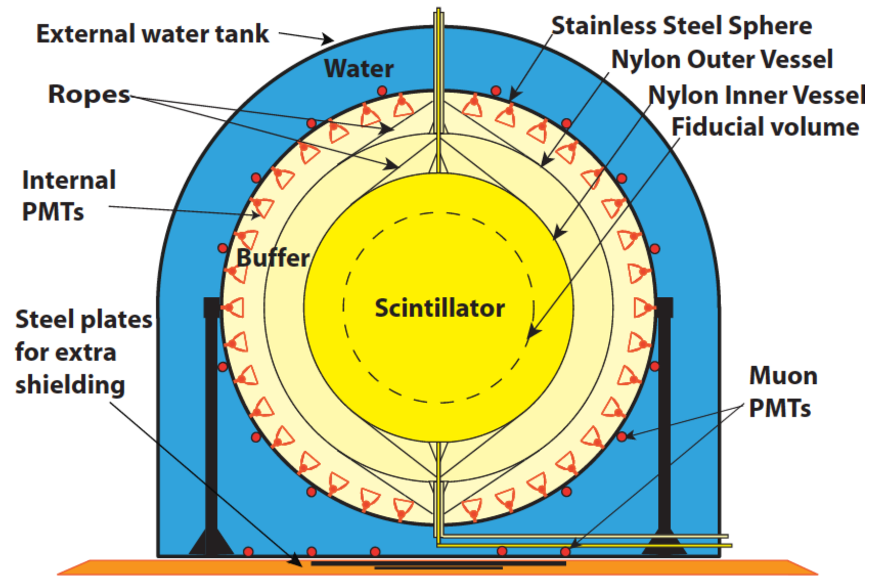
Borexino in Gran Sasso, Italy
CONTINENTAL CRUST

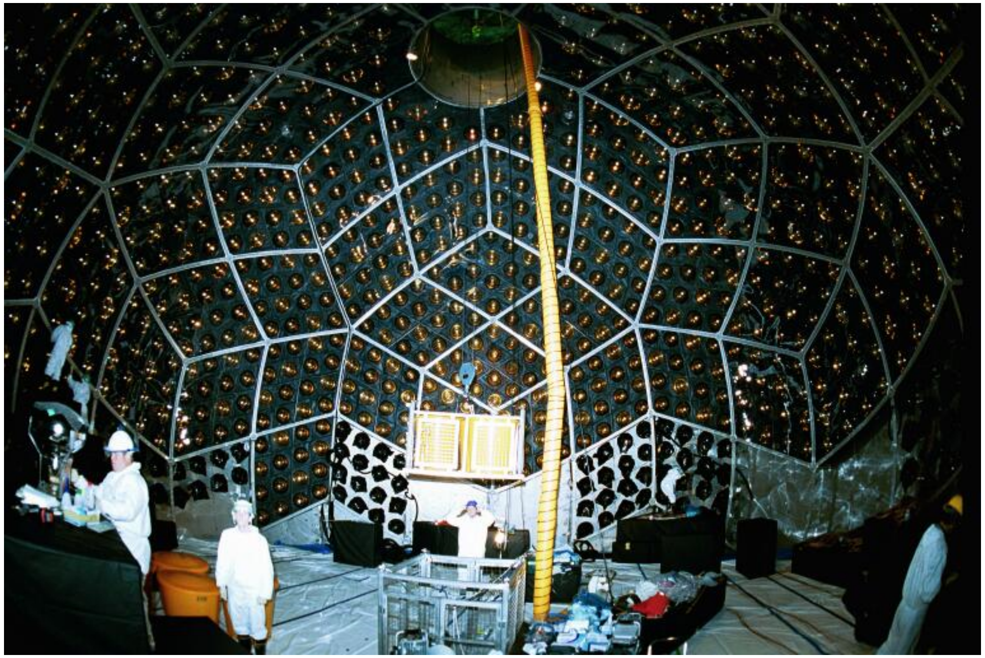
- originally built to measure neutrinos from the Sun – extreme radio-purity needed and achieved;
- 280 tons;
- S(reactors)/S(geo) ~ 0.3 !!! (2010)
- DAQ started in 2007;
- 3600 m.w.e. shielding;

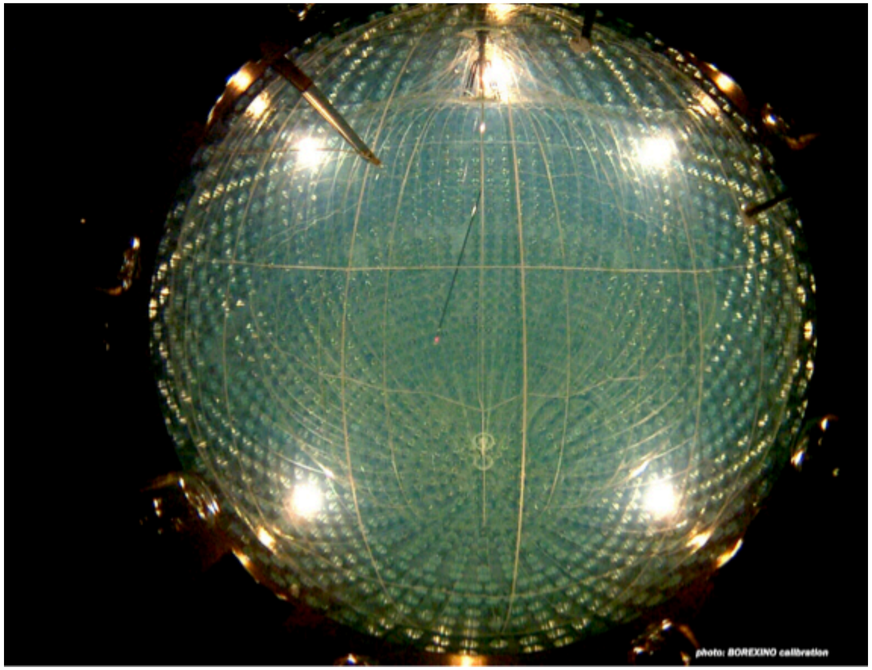
KamLAND



Borexino



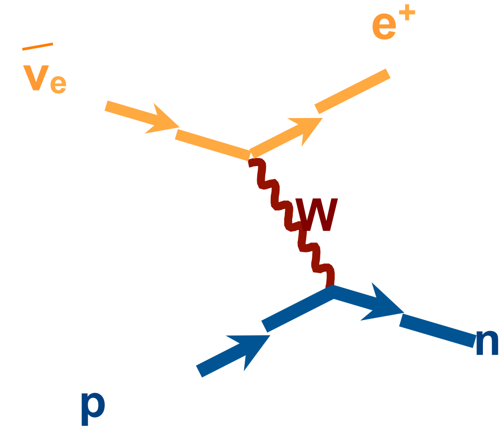


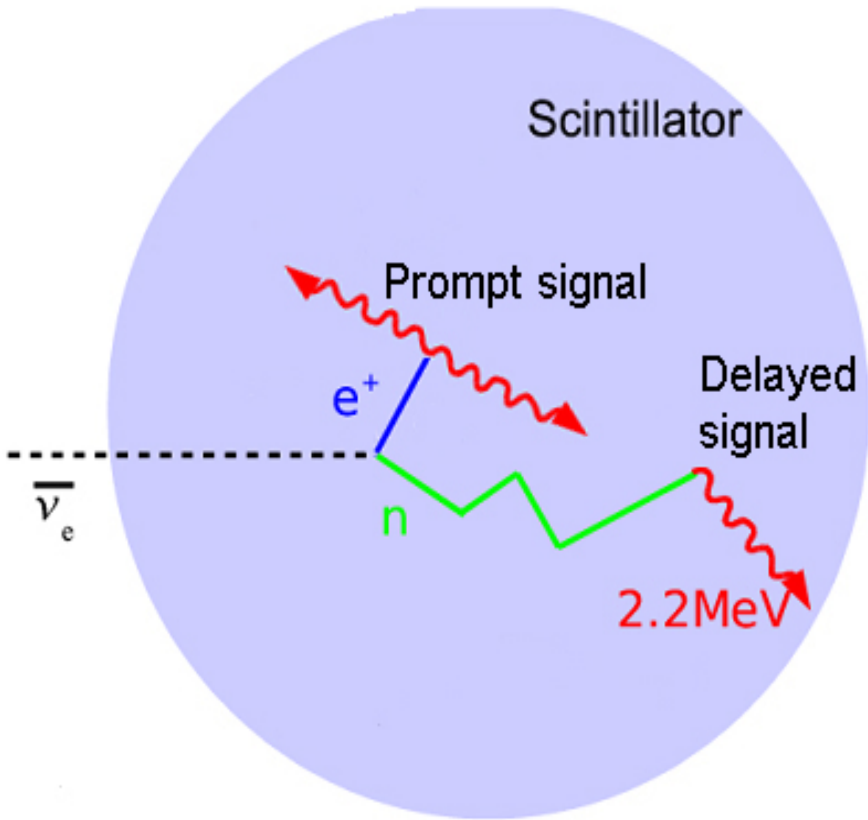


DETECTION PRINCIPLE

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

Inverse **B**eta **D**ecay





"prompt signal"

e^+: energy loss T_{e+} + annihilation (2 x 0.511 MeV)

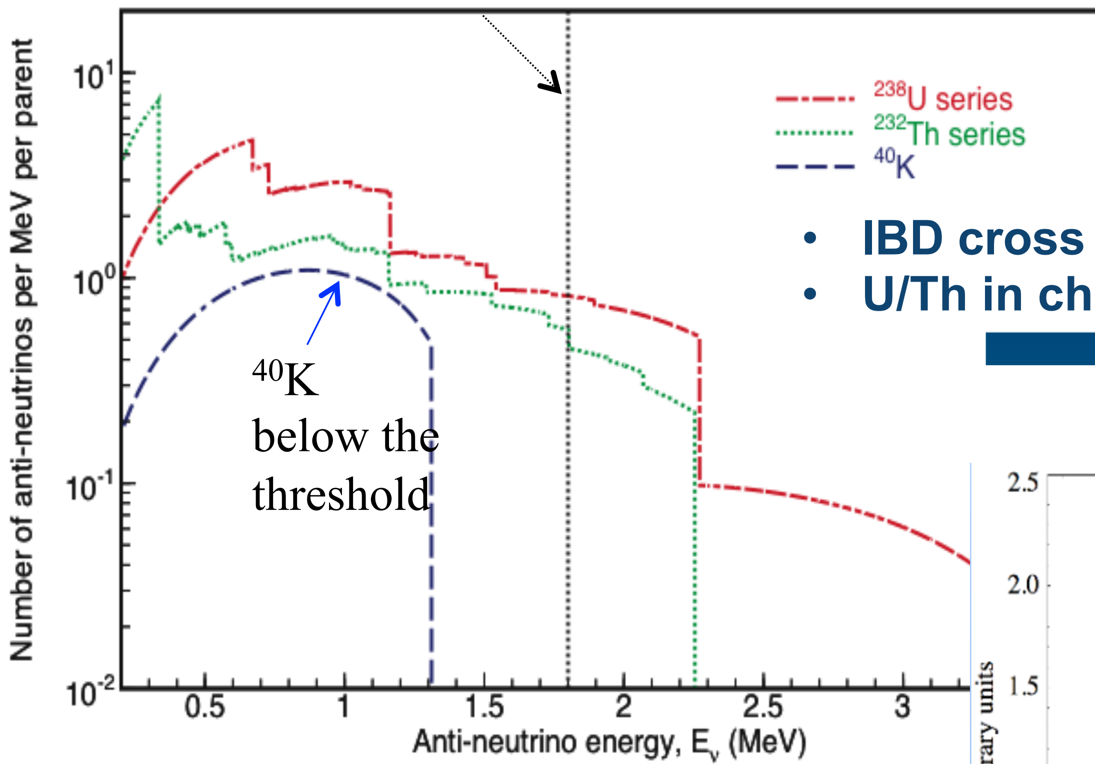
$\mathbf{E_{prompt} = E_{geonu} - 0.784\ MeV}$

"delayed signal"

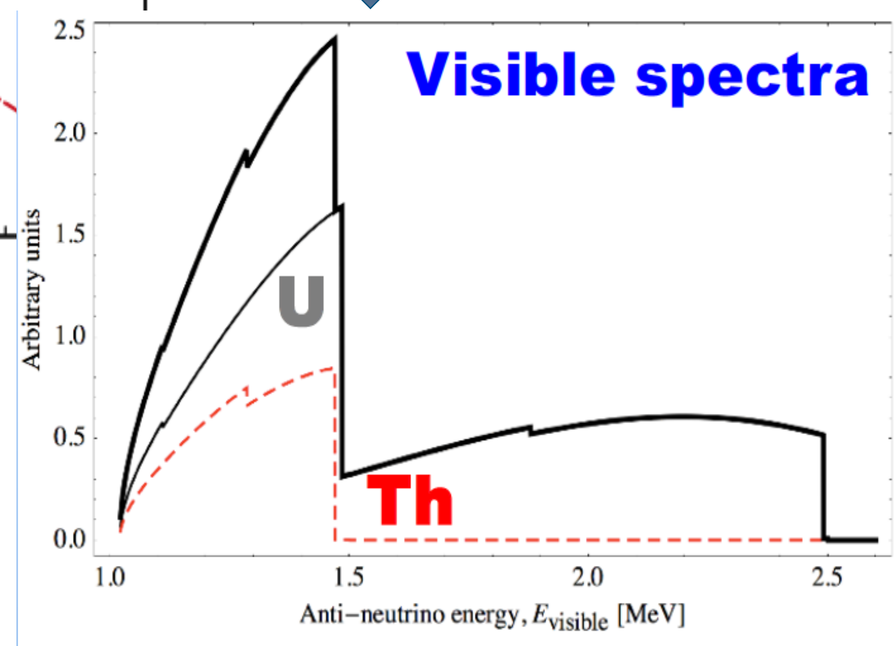
neutron thermalisation & capture on protons, emission of **2.2 MeV γ**

GEONEUTRINOS ENERGY SPECTRA

1.8 MeV kinematic threshold

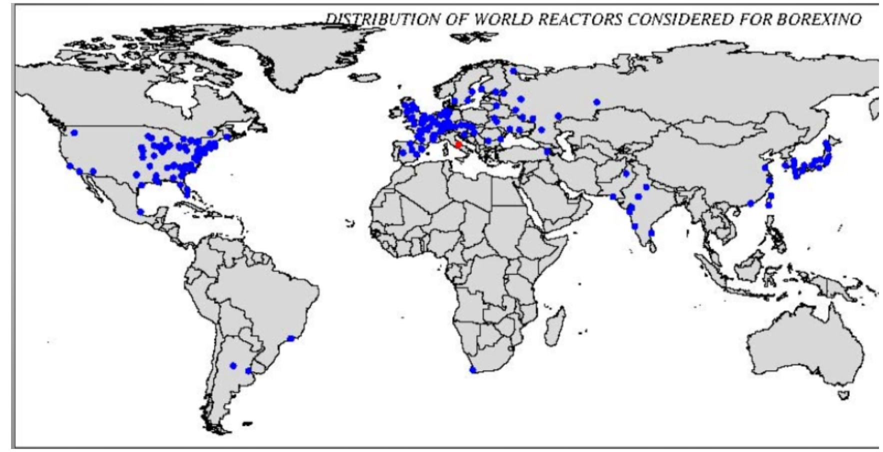


- IBD cross section
- U/Th in chondritic ratio



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;

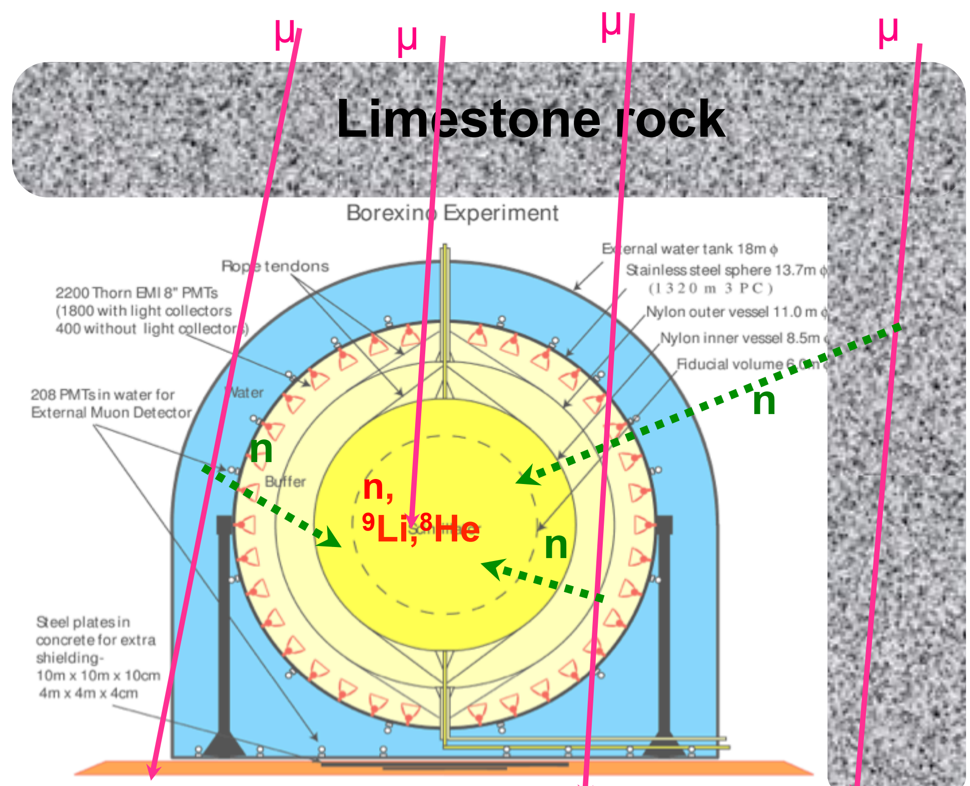
Estimated from OFF-time coincidences

3) Due to the internal radioactivity:

(α, n) reactions: ^{13}C(α, n)^{16}O

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

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



THE FIRST SEARCH BY KAMLAND IN 2005

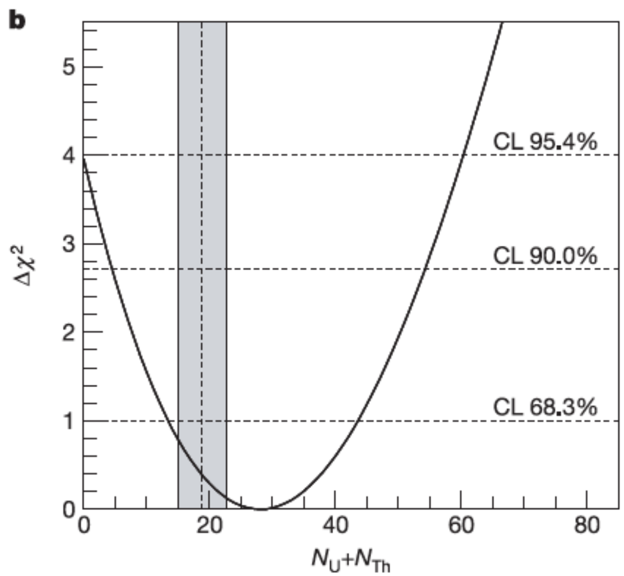
Vol 436|28 July 2005|doi:10.1038/nature03980 nature

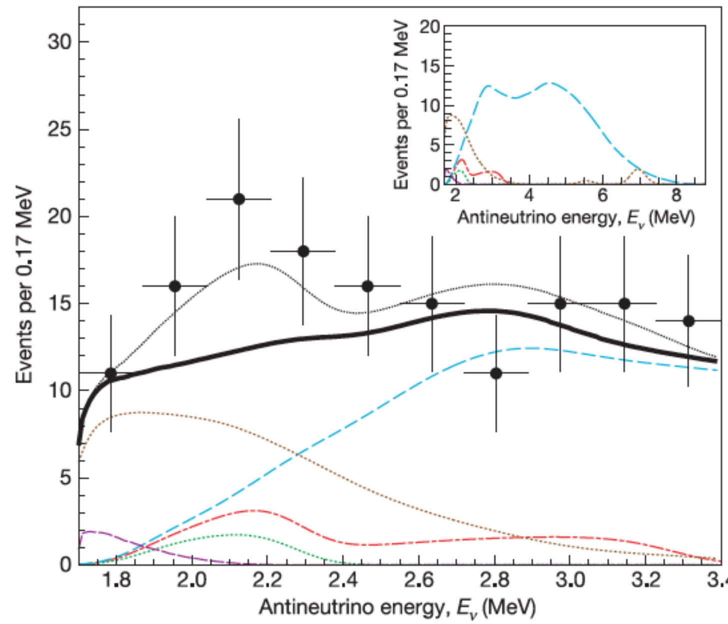
NATURE

ARTICLES

Experimental investigation of geologically produced antineutrinos with KamLAND

T. Araki[1], S. Enomoto[1], K. Furuno[1], Y. Gando[1], K. Ichimura[1], H. Ikeda[1], K. Inoue[1], Y. Kishimoto[1], M. Koga[1], Y. Koseki[1], T. Maeda[1], T. Mitsui[1], M. Motoki[1], K. Nakajima[1], H. Ogawa[1], M. Ogawa[1], K. Owada[1], J.-S. Ricol[1], I. Shimizu[1], J. Shirai[1], F. Suekane[1], A. Suzuki[1], K. Tada[1], S. Takeuchi[1], K. Tamae[1], Y. Tsuda[1], H. Watanabe[1], J. Busenitz[2], T. Classen[2], Z. Djurcic[2], G. Keefer[2], D. Leonard[2], A. Piepke[2], E. Yakushev[2], B. E. Berger[3], Y. D. Chan[3], M. P. Decowski[3], D. A. Dwyer[3], S. J. Freedman[3], B. K. Fujikawa[3], J. Goldman[3], F. Gray[3], K. M. Heeger[3], L. Hsu[3], K. T. Lesko[3], K.-B. Luk[3], H. Murayama[3], T. O'Donnell[3], A. W. P. Poon[3], H. M. Steiner[3], L. A. Winslow[3], C. Mauger[4], R. D. McKeown[4], P. Vogel[4], C. E. Lane[5], T. Miletic[5], G. Guillian[6], J. G. Learned[6], J. Maricic[6], S. Matsuno[6], S. Pakvasa[6], G. A. Horton-Smith[7], S. Dazeley[8], S. Hatakeyama[8], A. Rojas[8], R. Svoboda[8], B. D. Dieterle[9], J. Detwiler[10], G. Gratta[10], K. Ishii[10], N. Tolich[10], Y. Uchida[10], M. Batygov[11], W. Bugg[11], Y. Efremenko[11], Y. Kamyshkov[11], A. Kozlov[11], Y. Nakamura[11], H. J. Karwowski[12], D. M. Markoff[12], K. Nakamura[12], R. M. Rohm[12], W. Tornow[12], R. Wendell[12], M.-J. Chen[13], Y.-F. Wang[13] & F. Piquemal[14]





PHD THESIS

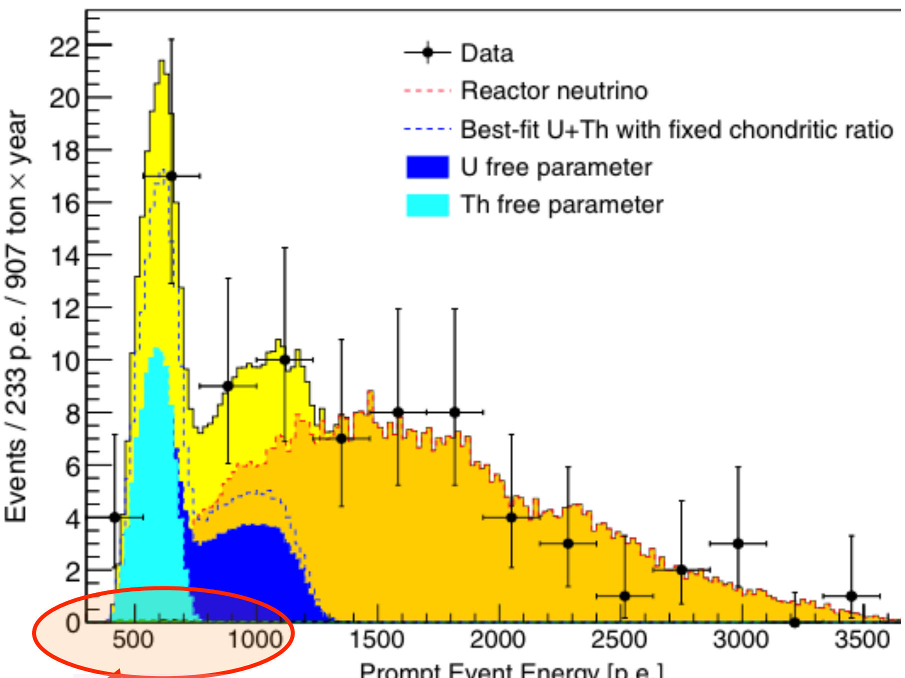
Neutrino Geophysics
and
Observation of Geo-Neutrinos at KamLAND

Enomoto Sanshiro
Tohoku University

JÜLICH Forschungszentrum

LATEST PUBLISHED RESULTS

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



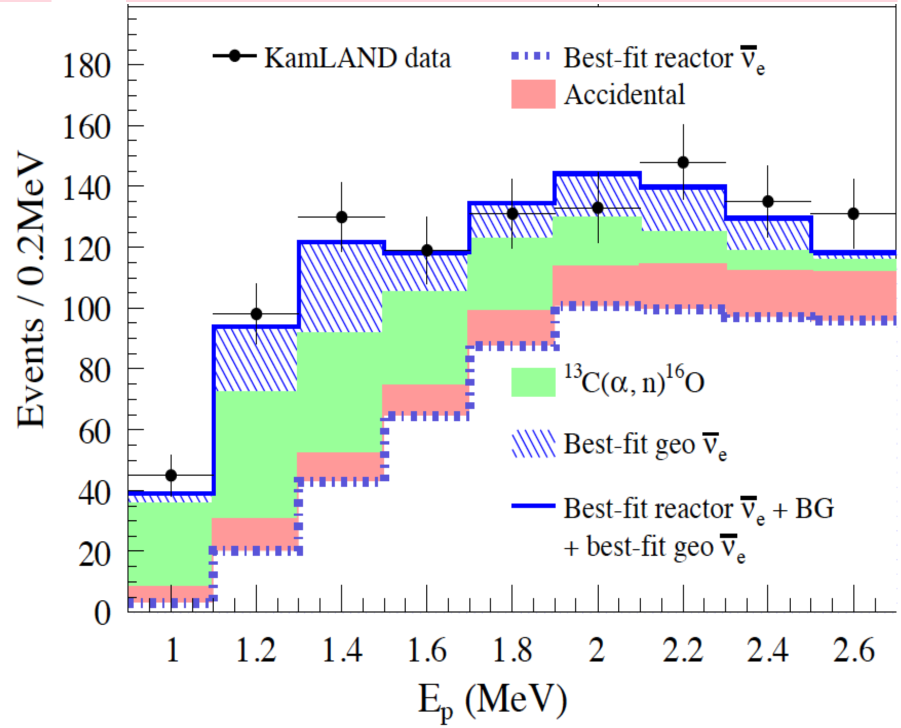
~1 MeV

~7 MeV

PRD 92 (2015) 031101 (R)

- ✓ Non-antineutrino background almost invisible!
- ✓ 5.5 x 10^{31} target-proton year

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



PRD 88 (2013) 033001

- ✓ Largest sample!
- ✓ 4.9 x 10^{32} target-proton year

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
  15-17%
  (H. Watanabe @ Neut. Res. And Thermal Evol. Earth)

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**
  IMPROVED SELECTION, <20% PRECISION

FIRST GEOLOGICAL INTERPRETATIONS

- Measured **geoneutrino flux is in agreement with expectations**, but we cannot distinguish among various geological models.
- **U/Th ratio is compatible with chondritic ratio**, but the errors are too big.
- First **indications of the measured non-zero mantle signal.**
- 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)

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 1^{st} year!
- **JINPING** (China): 5 kton; deepest lab, far away from reactors, very thick continental crust at Himalayan region;
- **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.

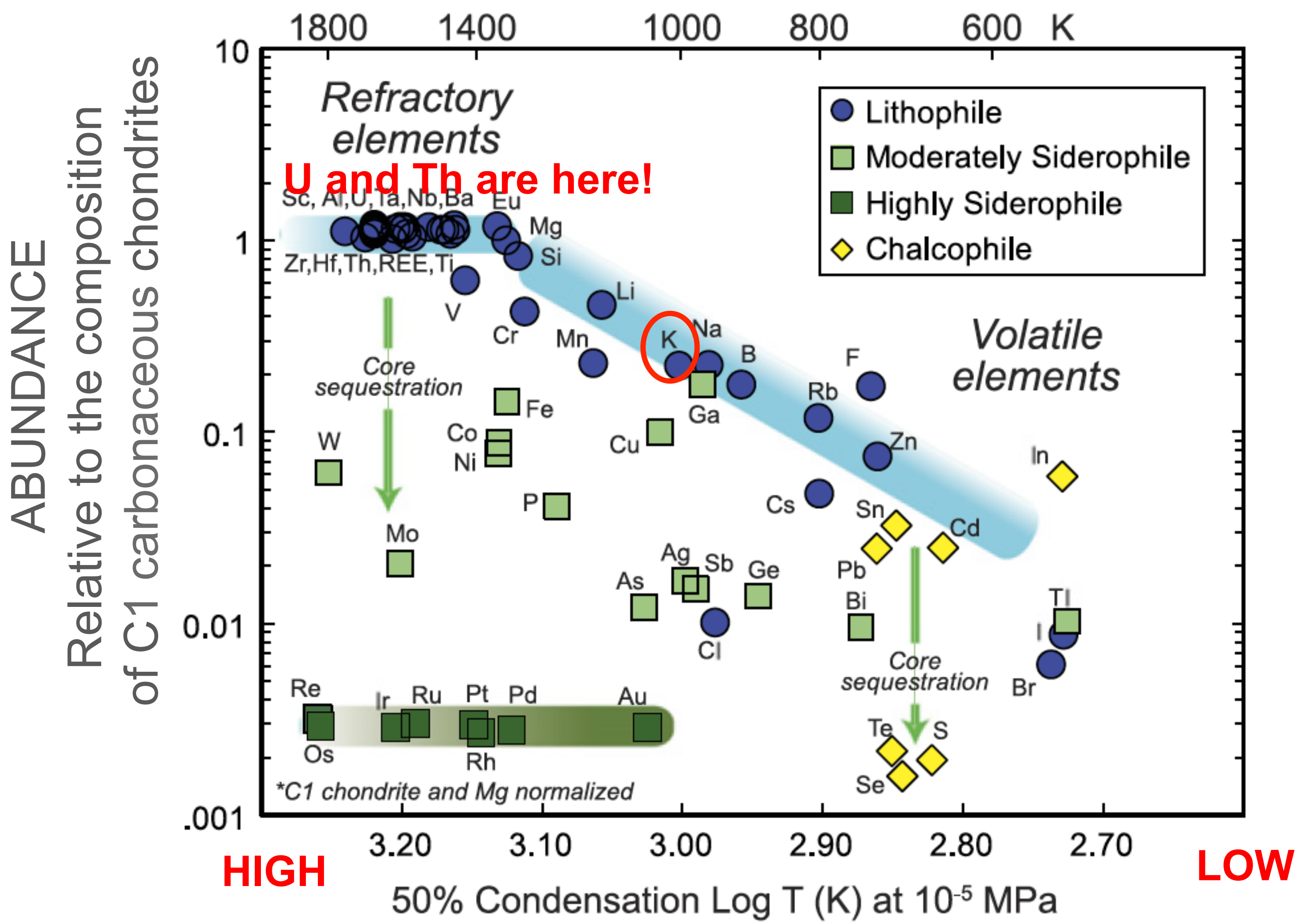
Geoneutrino summary

- The new interdisciplinary field is born and collaboration among geologists started **(Neutrino Geoscience conference series** since 2005 (last time in 2015 here in Paris!), **ISAPP Summer School**
  Using Particle Physics to Understand and Image the Earth 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

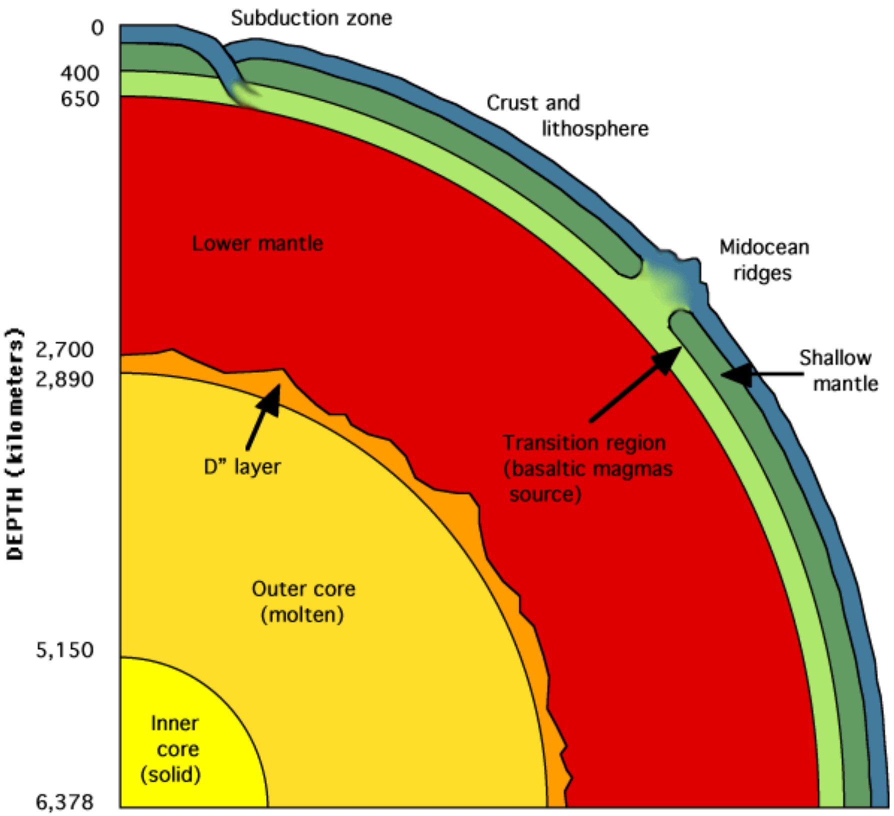
BACKUP

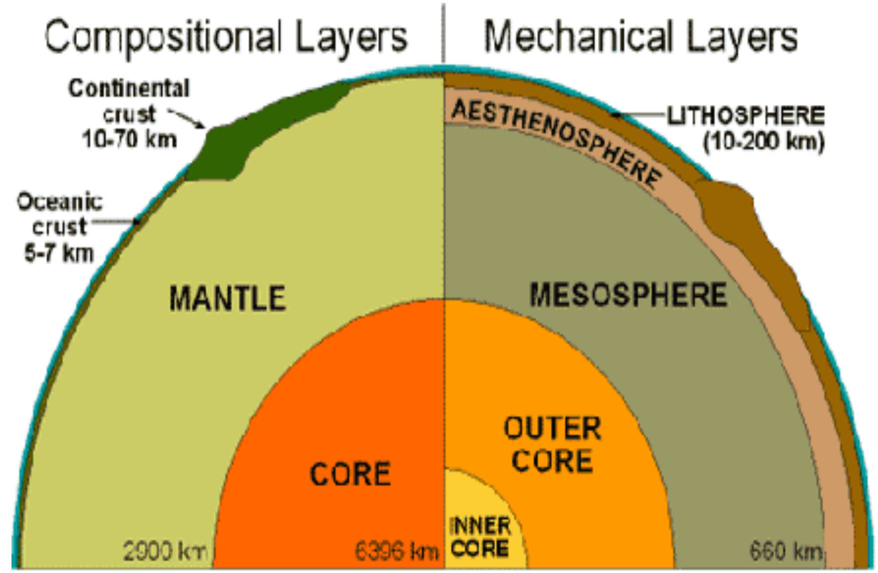
PRIMITIVE-MANTLE COMPOSITION

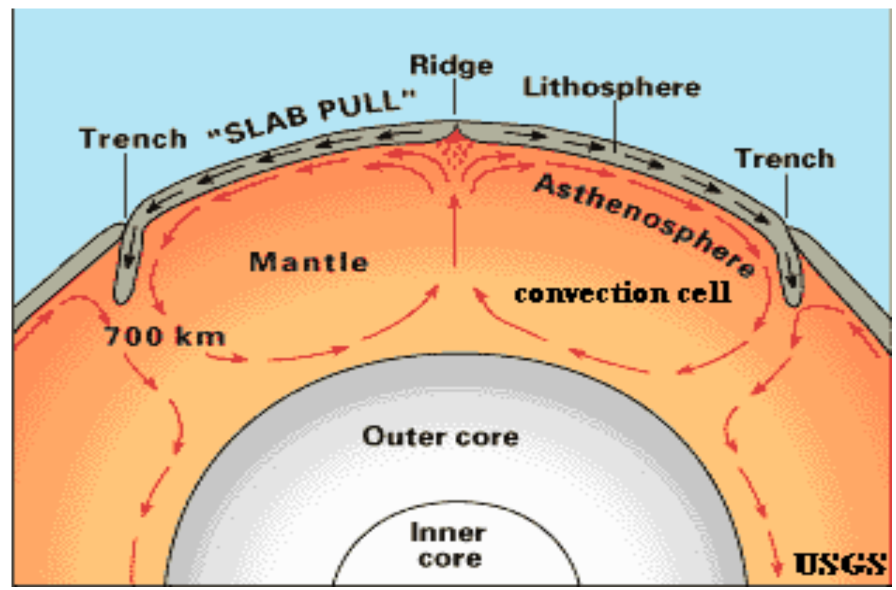


Progress in Particle and Nuclear Physics 73 (2013) 1–34

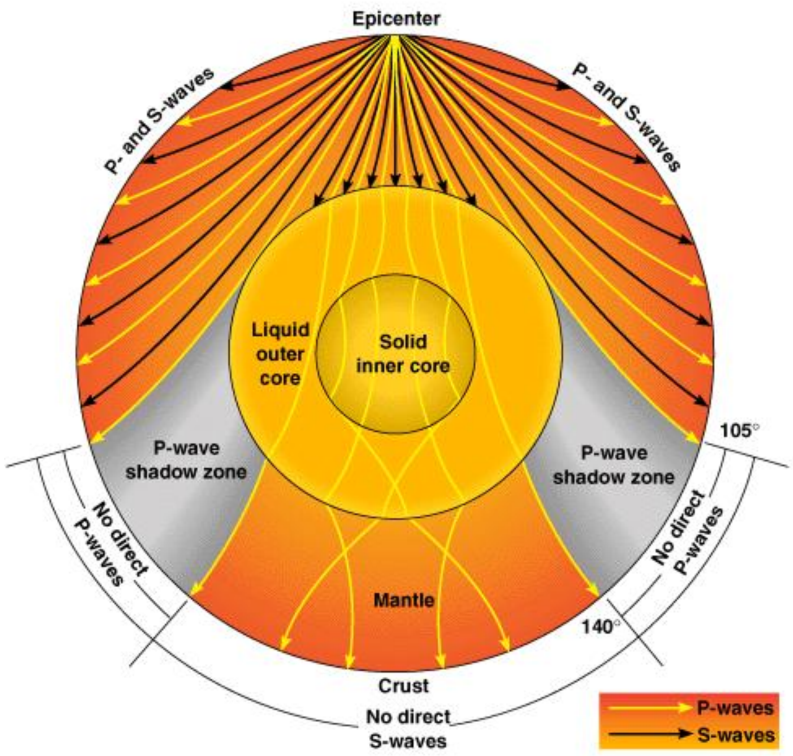
EARTH STRUCTURE

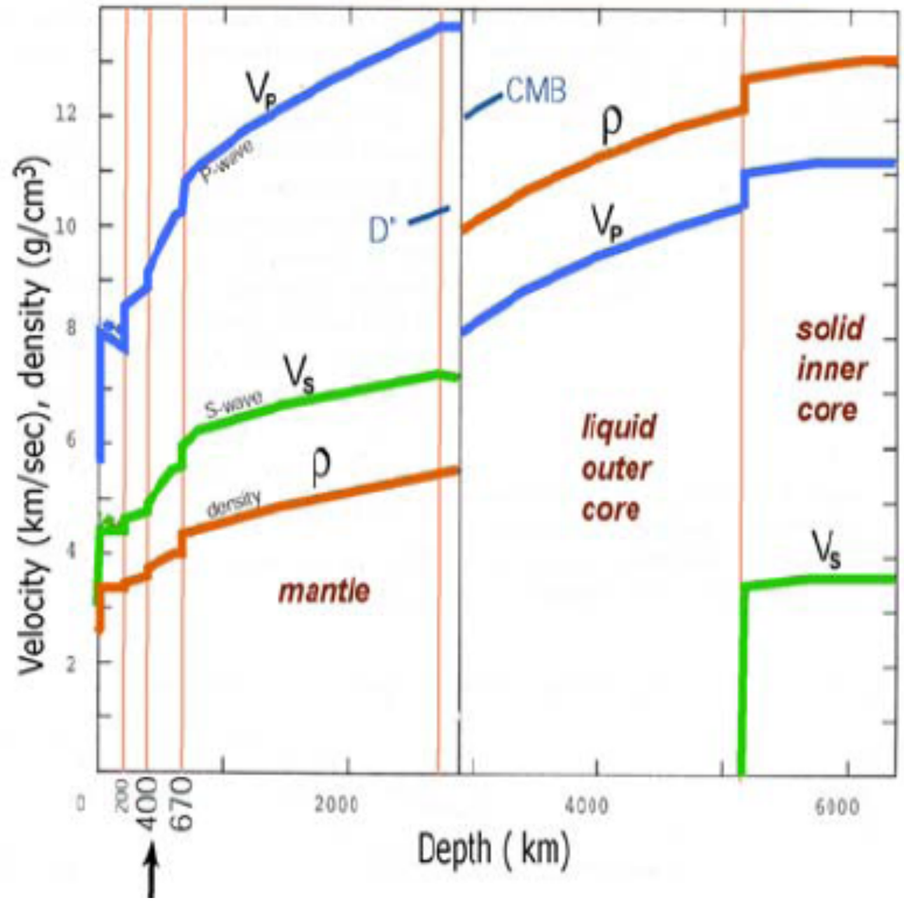






SEISMOLOGY





P – primary, longitudinal waves
S – secondary, transverse/shear waves

Discontinuities in the waves propagation and the density profile but no info about the chemical composition of the Earth

GEOCHEMISTRY

1) **Direct rock samples**

* surface and bore-holes (max. 12 km);

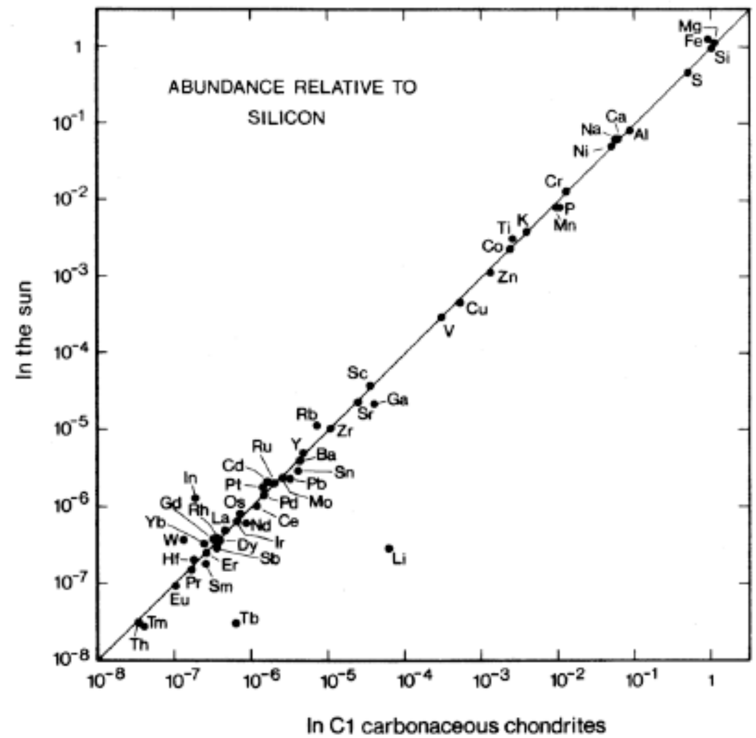
* mantle rocks brought up by tectonics and **vulcanism;**

BUT: POSSIBLE ALTERATION DURING THE TRANSPORT

2) **Geochemical models:**

composition of direct rock samples +
C1 carbonaceous chondrites meteorites +
Sun's photosphere;

Bulk Silicate Earth (BSE) models (several!):
medium composition
of the "re-mixed" crust + mantle,
i.e., primordial mantle before the crust differentiation and after the Fe-Ni core separation;



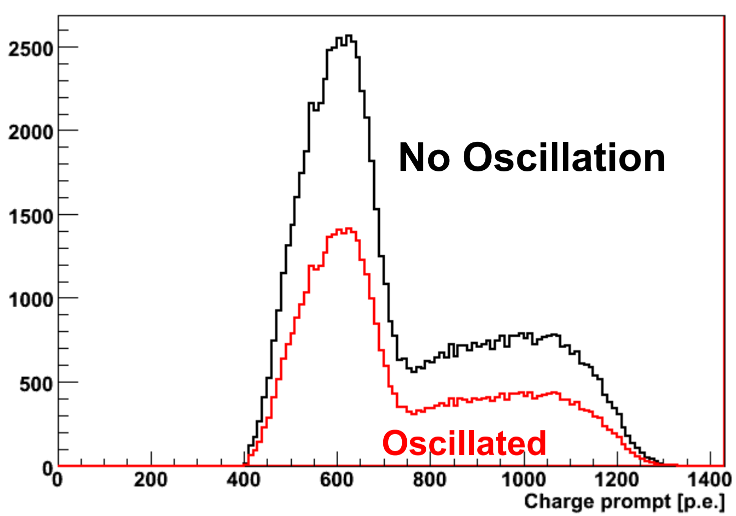
EFFECT OF NEUTRINO OSCILLATIONS

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

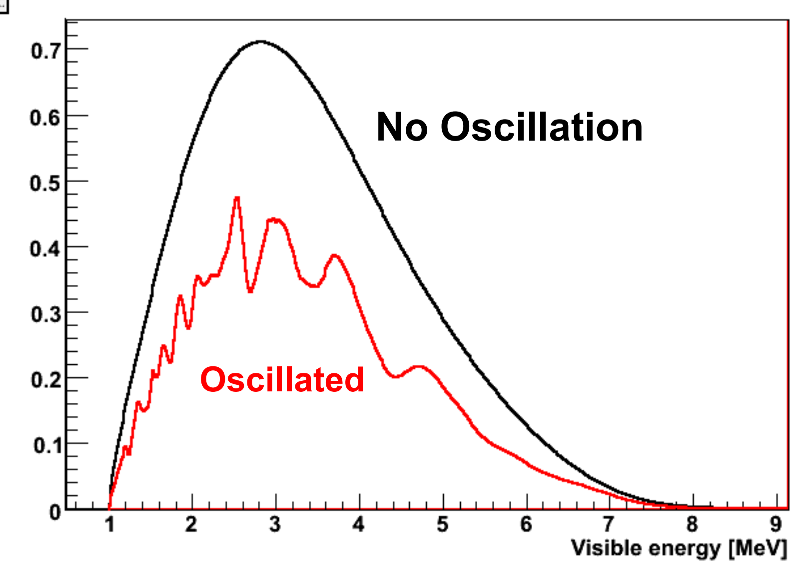
3 MeV antineutrino ..
Oscillation length of ~100 km

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

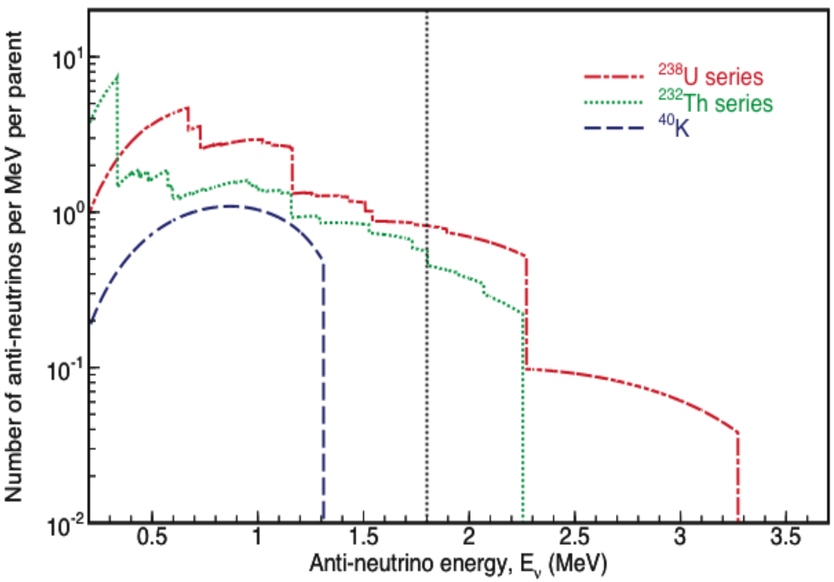
Geoneutrinos

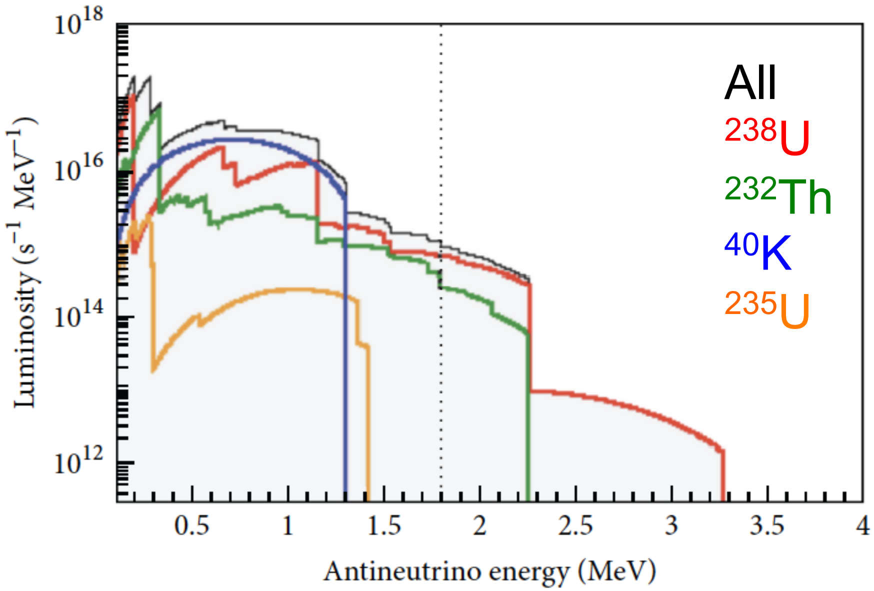


Reactor antineutrinos at LNGS



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]
$^{238}\mathrm{U} \rightarrow {}^{206}\mathrm{Pb} + 8\,{}^{4}\mathrm{He} + 6e + 6\bar{\nu}$	4.47	3.26	51.7	7.46×10^7	0.95×10^{-4}
$^{232}\mathrm{Th} \rightarrow {}^{208}\mathrm{Pb} + 6\,{}^{4}\mathrm{He} + 4e + 4\bar{\nu}$	14.0	2.25	42.7	1.62×10^7	0.27×10^{-4}
$^{40}\mathrm{K} \rightarrow {}^{40}\mathrm{Ca} + e + \bar{\nu}$ (89%)	1.28	1.311	1.311	2.32×10^8	0.22×10^{-4}



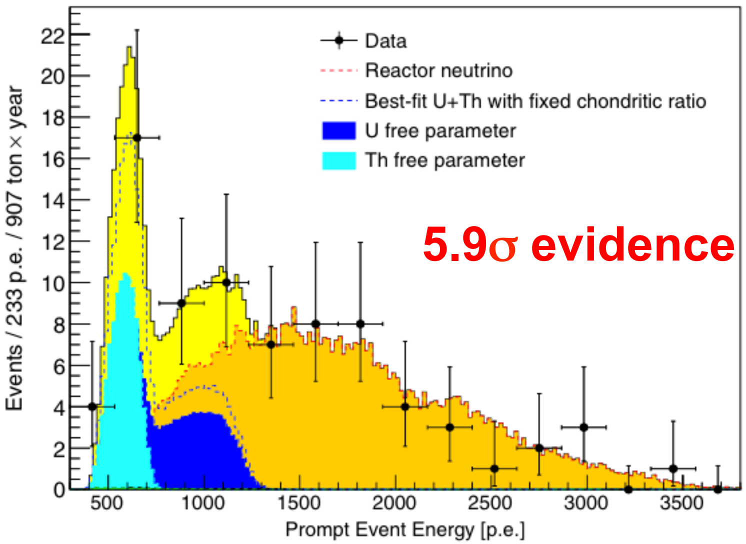


•Radiogenic heat is related to the neutrino flux:

$$H_R = 9.5\,M(U) + 2.7\,M(Th) + 3.6\,M(^{40}K)$$

$$L_\nu = 7.4\,M(U) + 1.6\,M(Th) + 27\,M(^{40}K)$$

2015 Borexino geoneutrino results



Period	Dec.07 – Mar15 (5.5 ± 0.3) 10^{31} prot*y
Tot ev [full sp.]	77
Reactors ev.	$52.7_{-7.7}^{+8.5}$ (stat) $_{-0.9}^{+0.7}$ (sys)
Background ev.	$0.78_{-0.10}^{+0.13}$
Geo-ν ev.	$23.7_{-5.7}^{+6.5}$ (stat) $_{-0.6}^{+0.9}$ (sys))
Geo-ν signal (TNU)	$43.5_{-10.4}^{+11,8}$ (stat) $_{-2.4}^{+2.7}$ (sys)

Two types of fits

1) $m(^{232}Th)/m(^{238}U) = 3.9$ (CI chondrites)

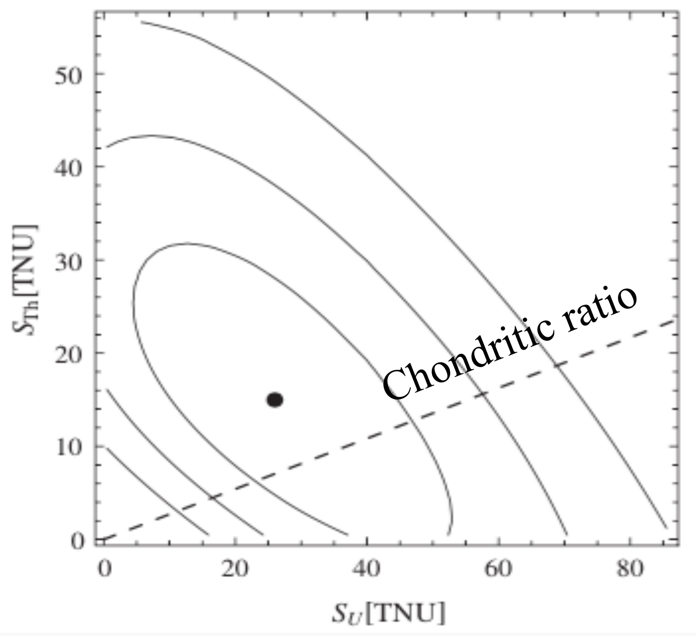
$S(^{232}Th)/S(^{238}U) = 0.27$

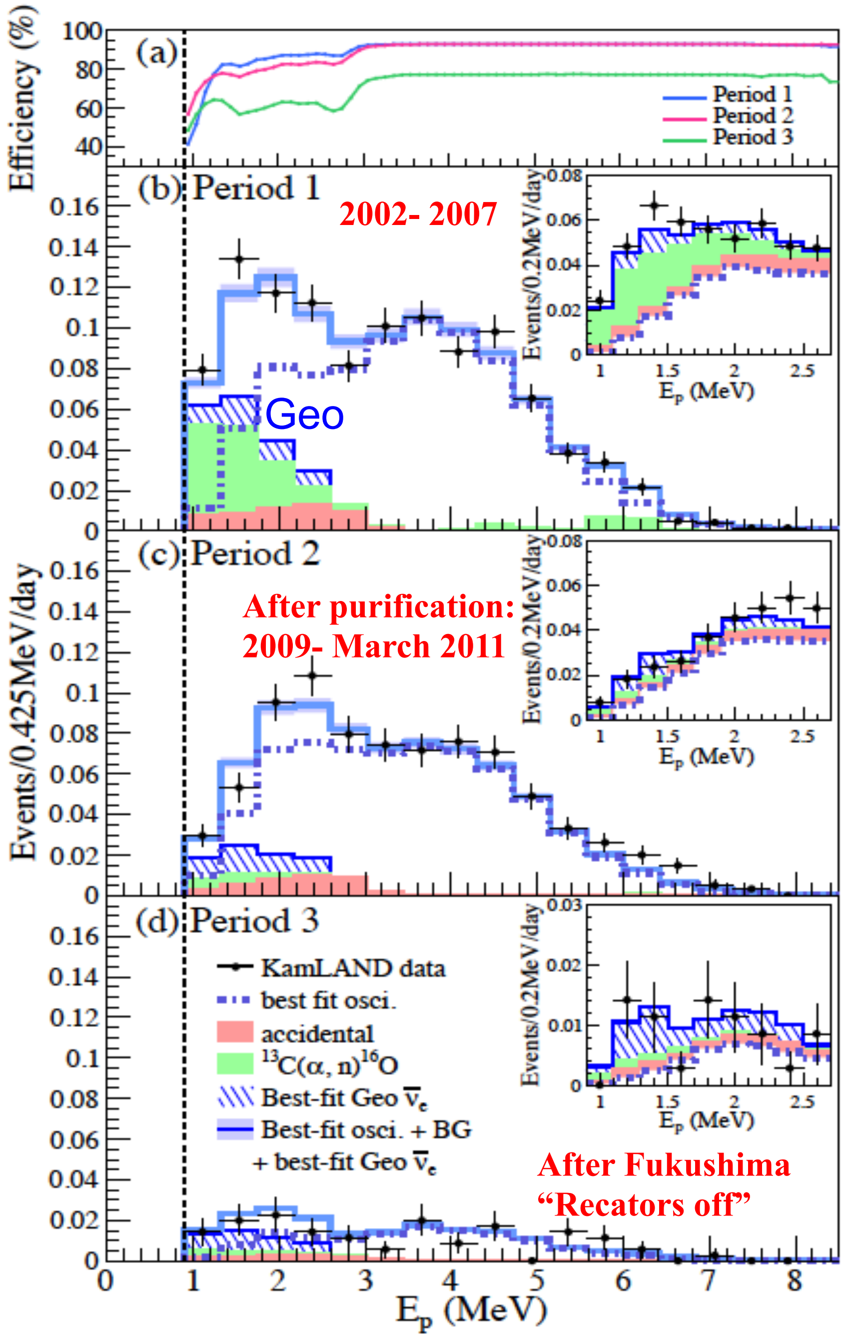
$S(^{238}U)/S(^{232}Th) = 3.7$

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

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

2) U and Th free fit paramters





KamLAND-Phases

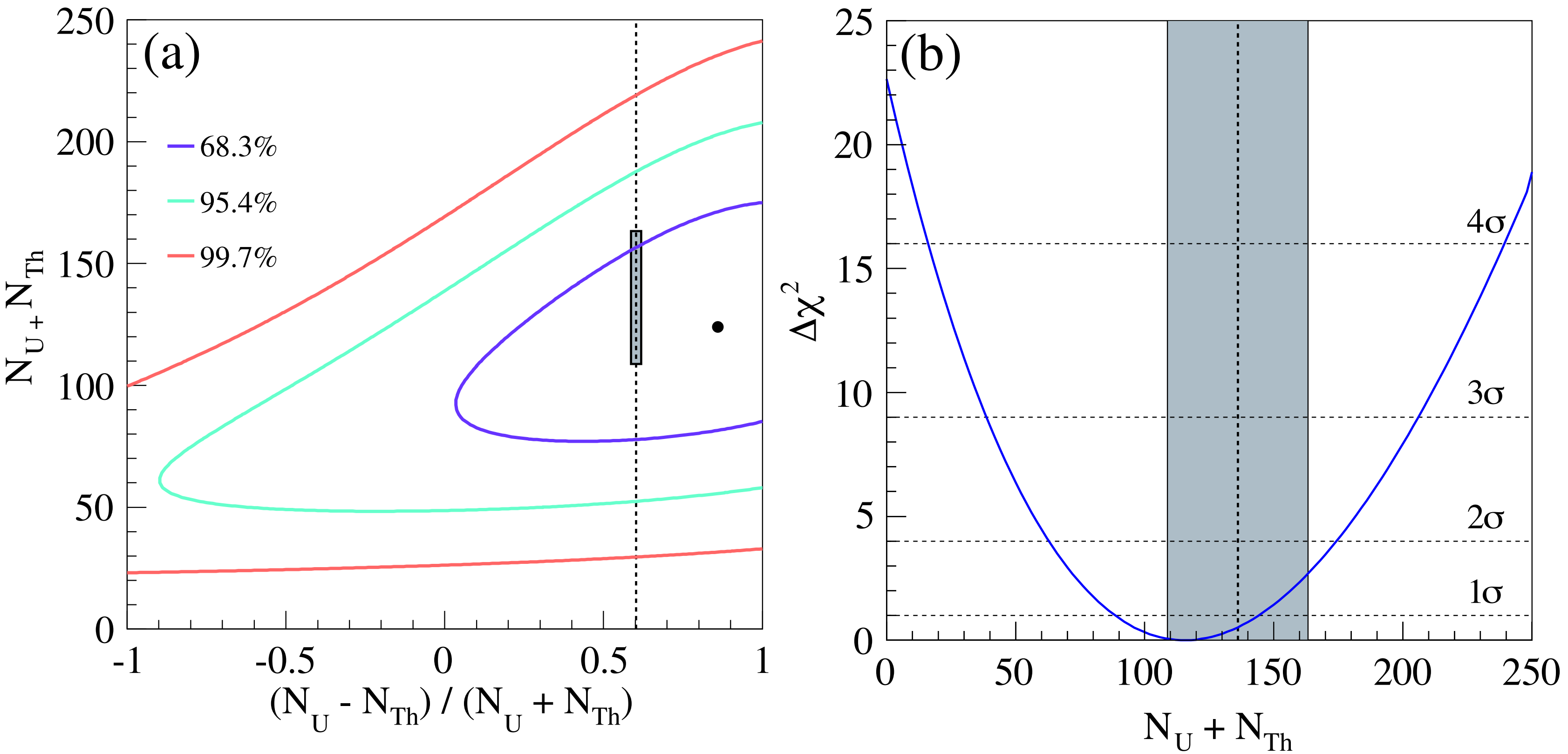
- ✓Period 1: 2002 – 2007
- ✓Period 2 (After a long purification campaign) 2009 – March 2011 (Fukushima disaster)
- ✓Period 3 – After Fukushima when many of the nuclear reactors were switched off

2013 results

PRD 88 (2013) 033001

▸Analysis - Rate+Shape+Time Analysis (2)

$N_U + N_{Th}$



best-fit $N_U+N_{Th} = 116^{+28}_{-27}$

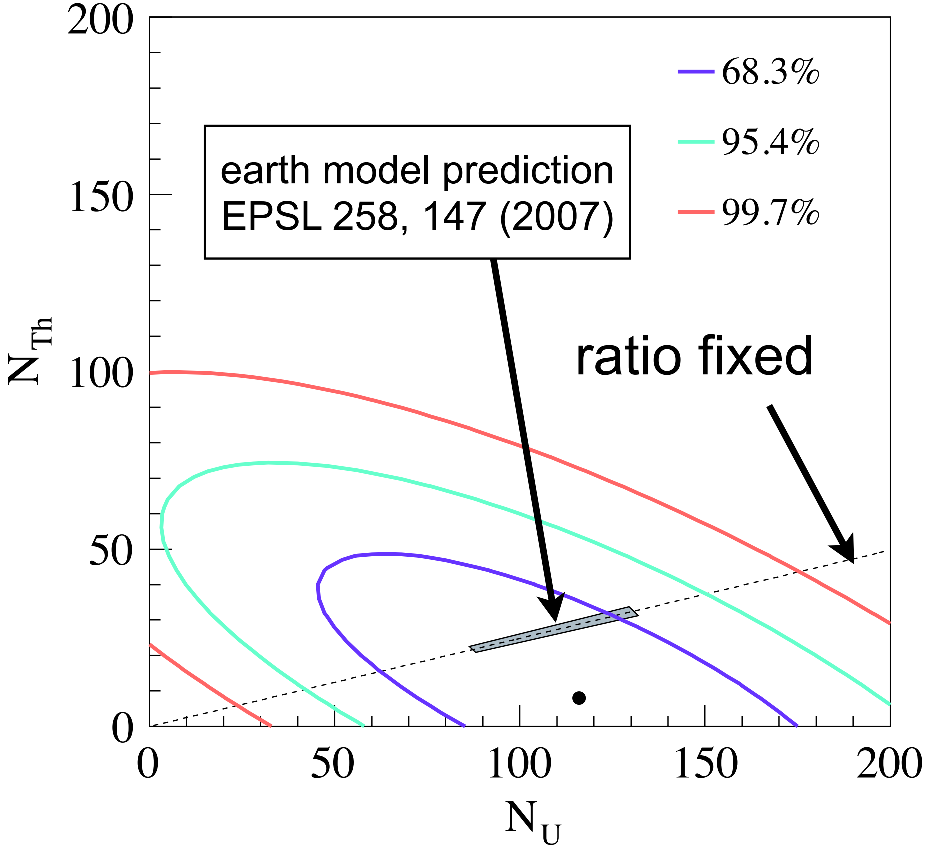
Flux : $3.4^{+0.8}_{-0.8} \times 10^6$ cm^{-2}s^{-1}

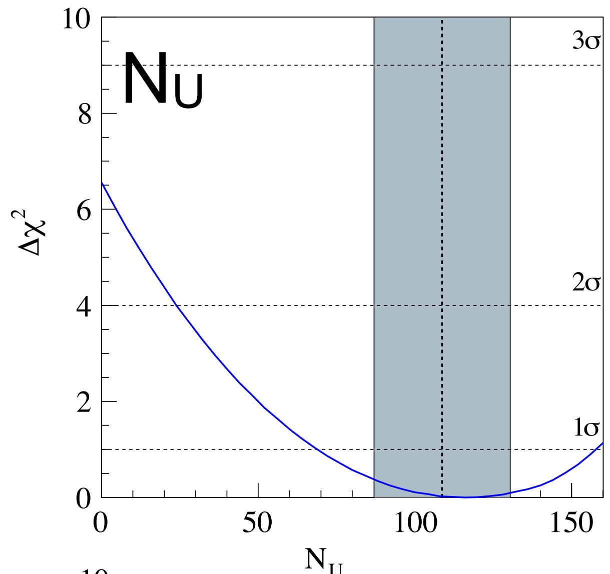
0 signal rejected at 99.9998% C.L. (2×10^{-6})

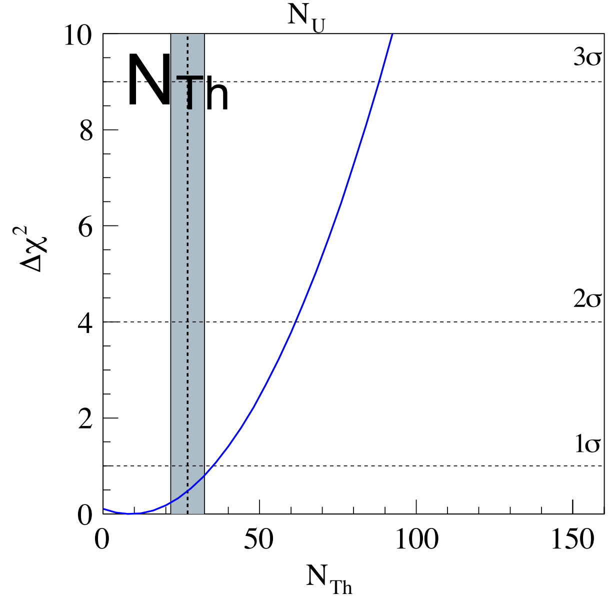
From KamLAND talk of H. Watanabe @ Neutrino Geoscience 2013

Analysis - Rate+Shape+Time Analysis (1)

N_U vs N_{Th}







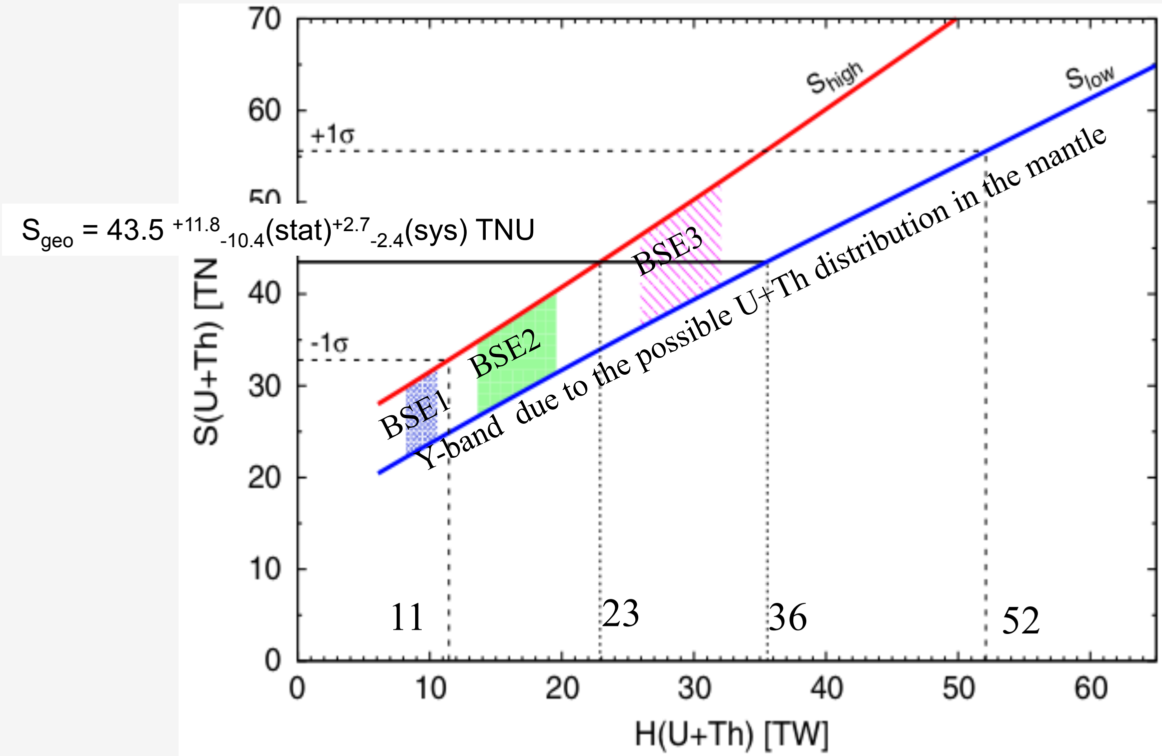
best-fit $(N_U, N_{Th}) = (116,8)$

N_U 0 signal : rejected at 2.6σ (99.0%)

From KamLAND talk of H. Watanabe @ Neutrino Geoscience 2013

Geological implications of the 2015 Borexino results

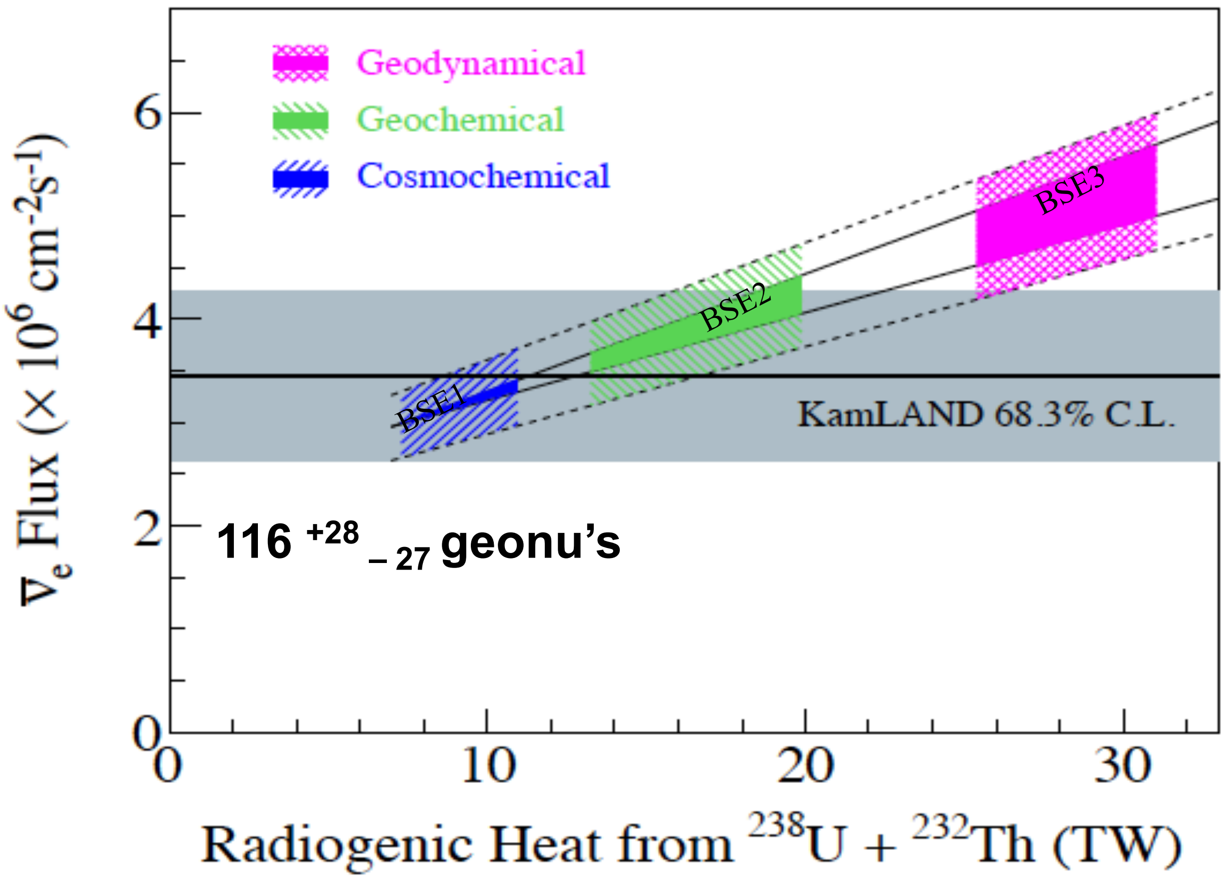
Radiogenic heat



- 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
  to be compared with 47 ± 2 TW of the total Earth surface heat flux (including all sources)

PRD 88 (2013) 033001

Geological interpretaion of the KamLAND geoneutrino results



Geological implications of the 2015 Borexino results

Mantle signal

- $S_{Mantle} = S_{measured} - S_{crust}$
- $S_{measured} = 43.5\ ^{+11.8}_{-10.4}(stat)^{+2.7}_{-2.4}(sys)$ TNU
- Crustal signal at LNGS "known"

ROC (Huang at al.) + LOC (Coltorti at al.)

$S_{Crust} = (23.4 \pm 2.8)$ TNU

- Non-0 mantle signal at 98% CL

$S_{mantle(Borexino)} = 20.1^{+15.1}_{-10.3}$ TNU

(taking the central values: 23.7 events distributed as ~13 from the crust and 11 from the mantle)

KamLAND preliminary update in 2016

Preliminary From H. Watanabe

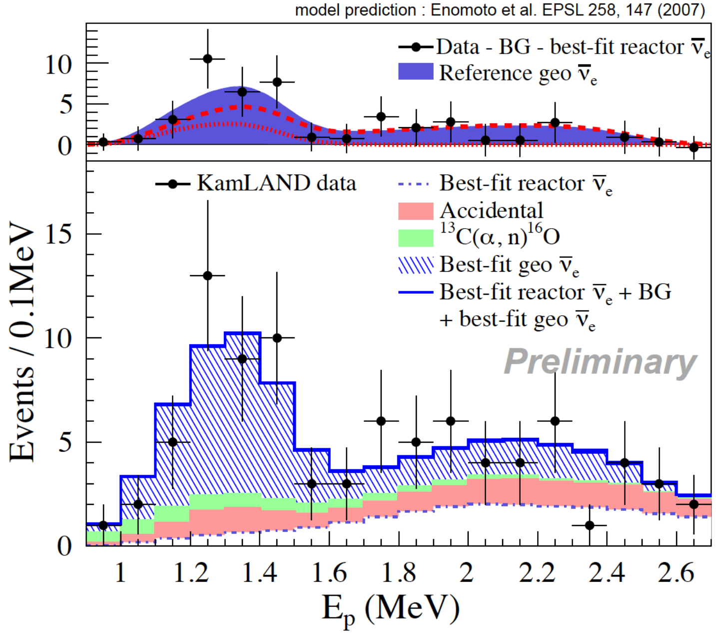
PRD 88, 033001 (2013)

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

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



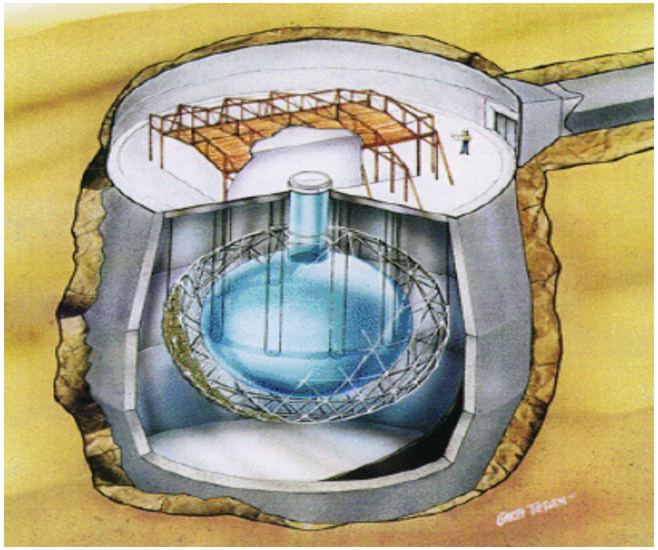
Beautiful spectrum, waiting for final results!

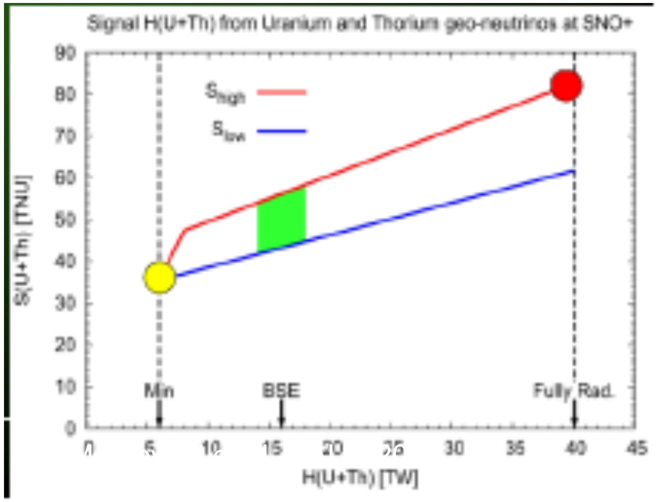
model prediction : Enomoto et al. EPSL 258, 147 (2007)

ratio fixed

	[event]	[TNU]	Flux [$\times10^6$ 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**

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)

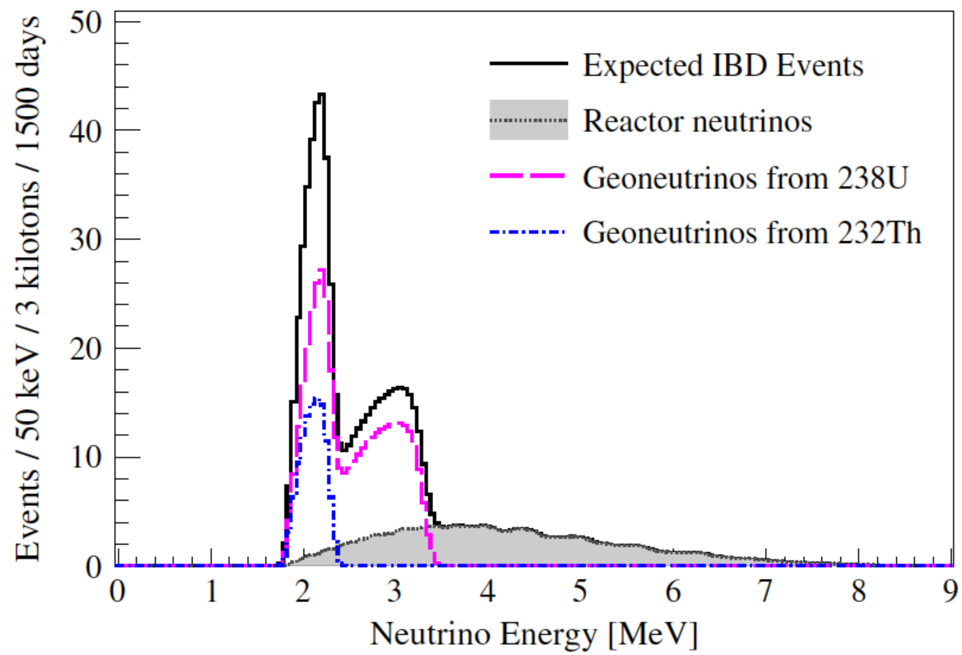
BSE: 28-38 events/per year

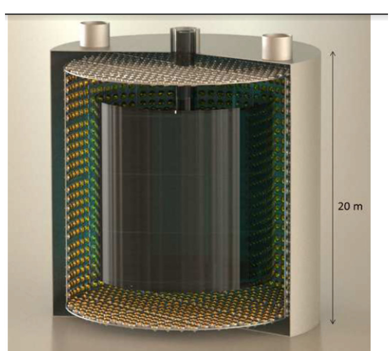
JINPING: THE DEEPEST LAB IN THE WORLD

Lab under excavation

5 kton liquid scintillator detector

PHYSICAL REVIEW D **95,** 053001 (2017)



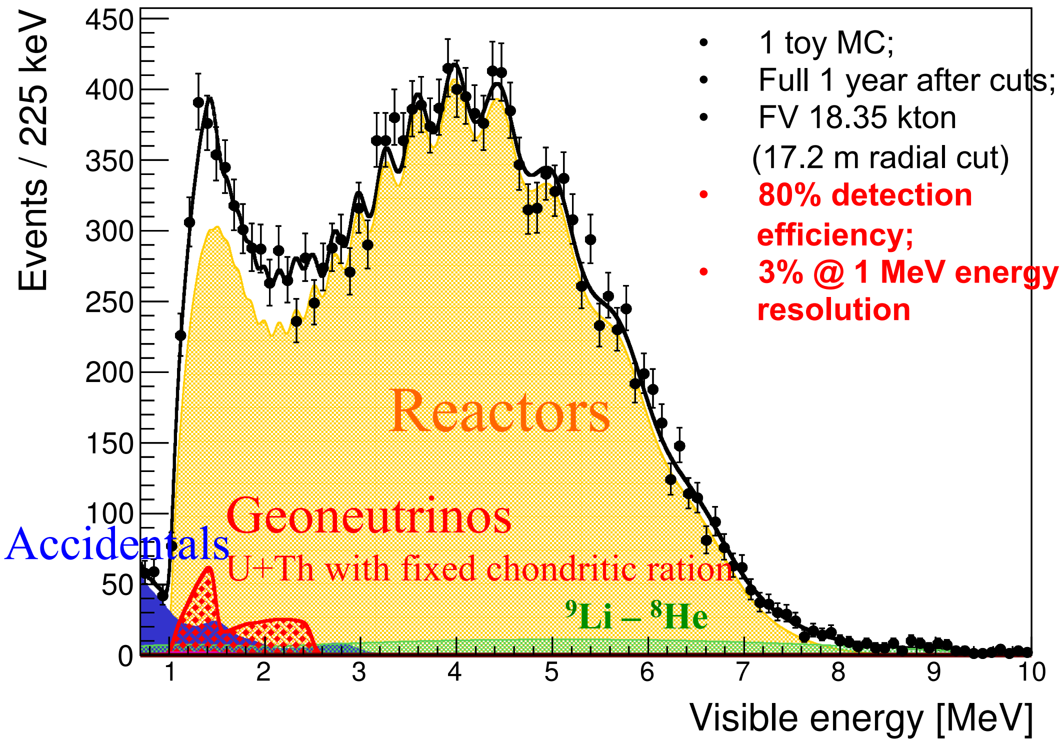


Expected IBD spectrum:
Far away from reactors!!!

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

Big signal from the continental crust

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;

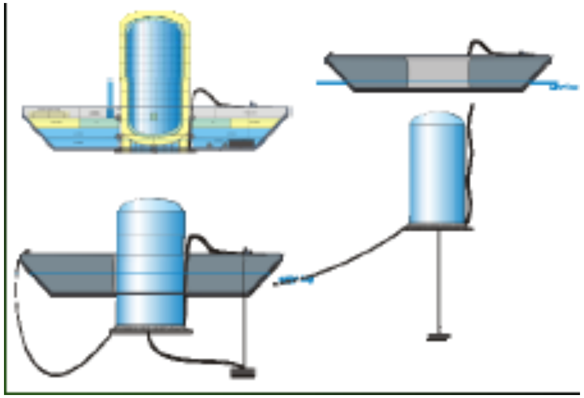
Critical:

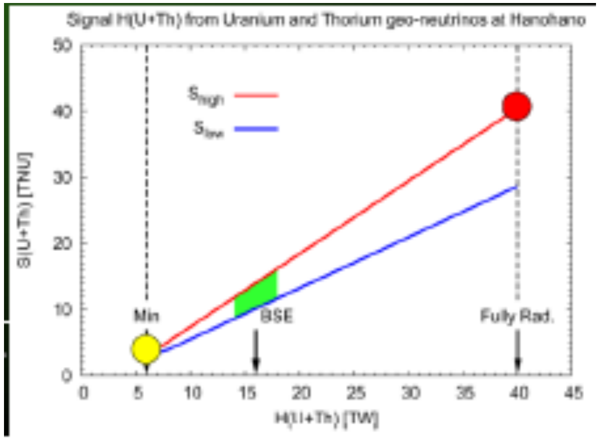
- ✓ Keep other backgrounds (^{210}Po contamination!) at low level and under control;

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;

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!