Neutrinos from Hell:

nature 436, 441–602 28 July 2005 www.nature.com/nature nature outlook: India no.7050 npg

28 July 2005 | www.nature.com/nature | $10

THE INTERNATIONAL WEEKLY JOURNAL OF SCIENCE

nature

NATUREJOBS
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BREAST CANCER
Gene signature for metastasis

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Everything has a fingerprint

INSIDE: INDIAN LIFE SCIENCES

nature outlook INDIA

EARTHLY POWERS

Geoneutrinos reveal Earth's inner secrets

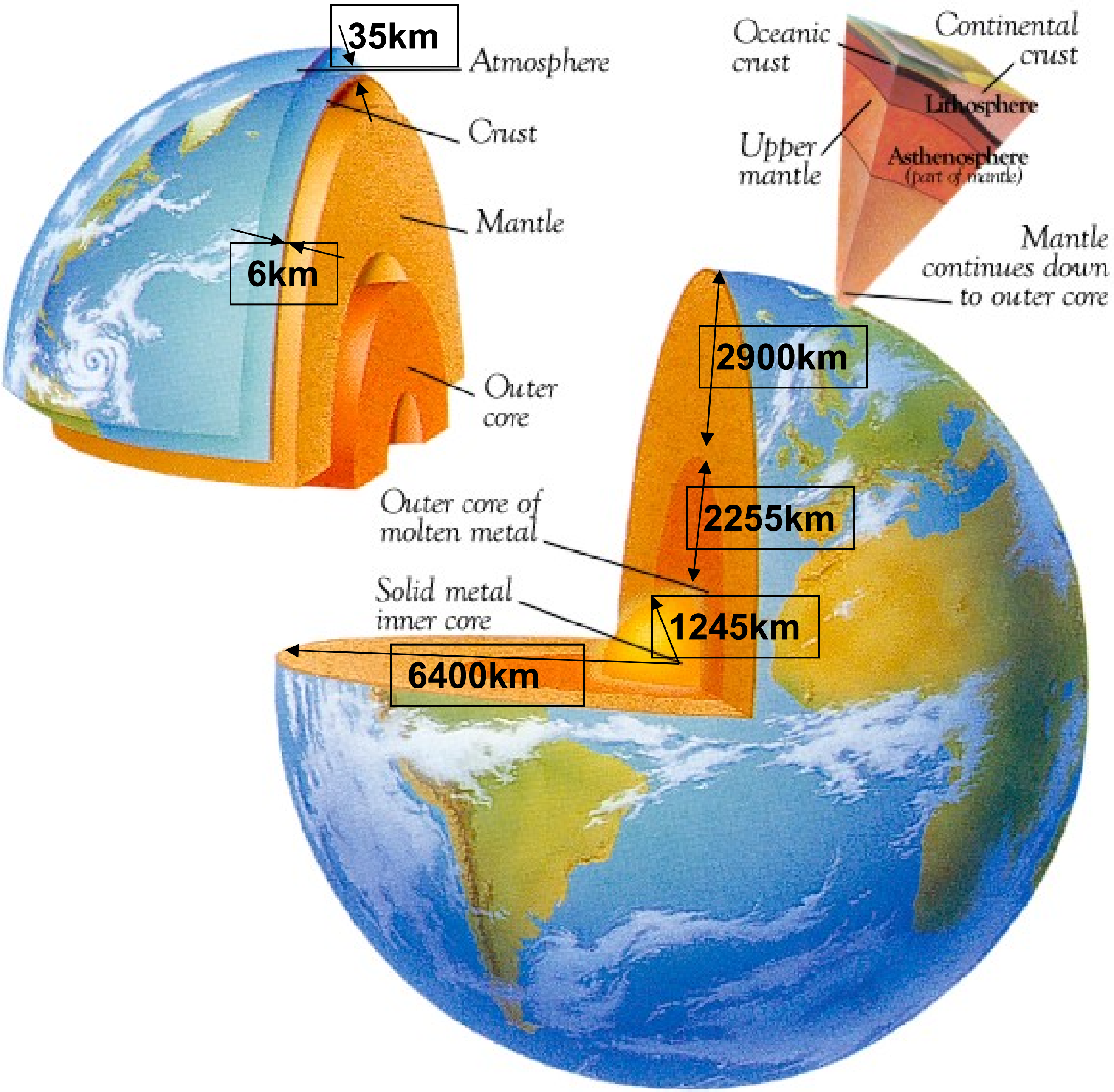
$10.00US $12.99CAN

the Dawn of Neutrino Geophysics

Giorgio Gratta

Physics Dept
Stanford University

Structure of the Earth: *a particle physicist's view*



- From seismic data 5 basic regions:
  - inner core,
  - outer core,
  - mantle,
  - oceanic crust,
  - continental crust and sediments

- All these regions behave like solids except the outer core.

Convection in the Earth

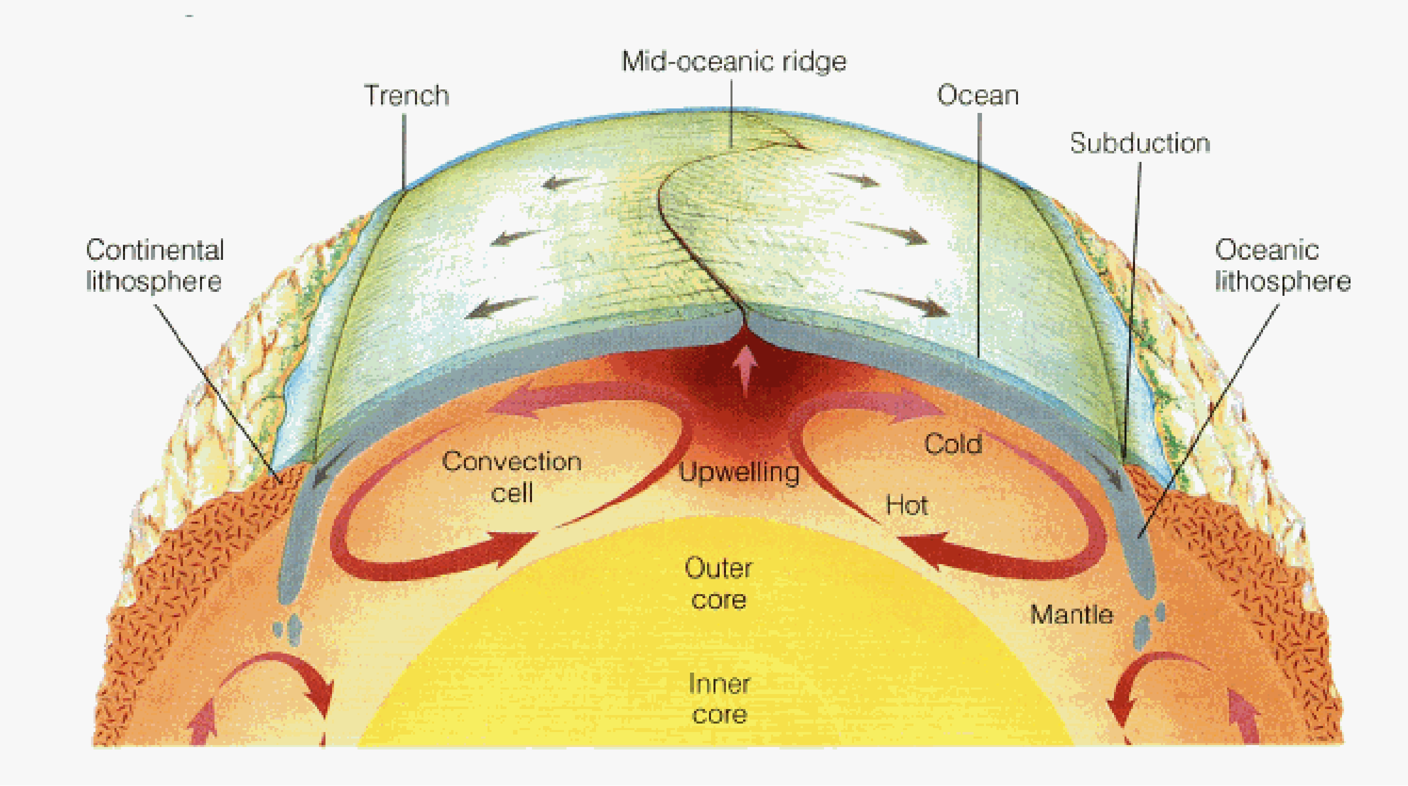


Image: http://www.dstu.univ-montp2.fr/PERSO/bokelmann/convection.gif

- The mantle appears to convect even though it is solid.
- This is responsible for plate tectonics and earthquakes.
- Oceanic crust is being renewed at mid-ocean ridges and recycled at trenches.

Francis Birch

J. Geophys. Res. 57 (1952) 227

"Unwary readers should take warning that ordinary language undergoes modification to a high-pressure form when applied to the interior of the Earth.
A few examples of equivalents follow:

High-pressure form	*Ordinary meaning*
certain	dubious
undoubtedly	perhaps
positive proof	vague suggestion
unanswerable argument	trivial objection
pure iron	uncertain mixture of all the elements

Very specific data on the Earth's interior is hard to collect

Historically, the only universal probe for the interior of the Earth has been seismology.

➔ But this is only sensitive to the elastic properties of the rocks.

Nomenclature derives from the seismic boundaries. Composition is then guessed for the different regions that are assumed homogeneous in composition.

Seismically motivated nomenclature is then used at times to signify a region of a certain composition.

This is sometimes confusing.

OK, let's say that the Earth probably has the same composition as the Solar System

→ How to average over the Solar System?

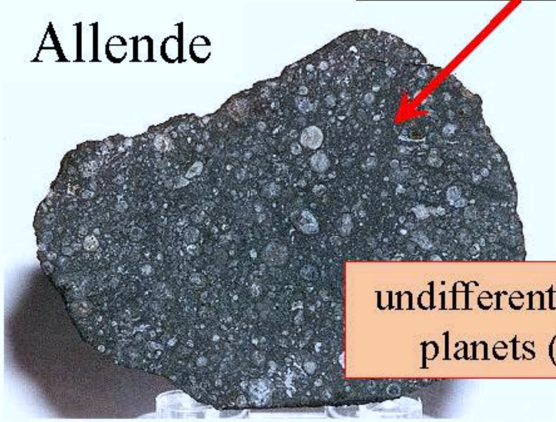
Meteorites

Achondrite, Ca-poor, Diogenite

Mantle-crust pieces (?)

chondrites

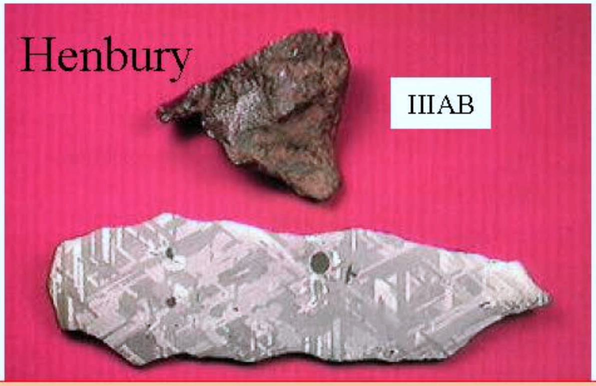
Allende



undifferentiated planets (?)

Carbonaceous chondrite (CV3)

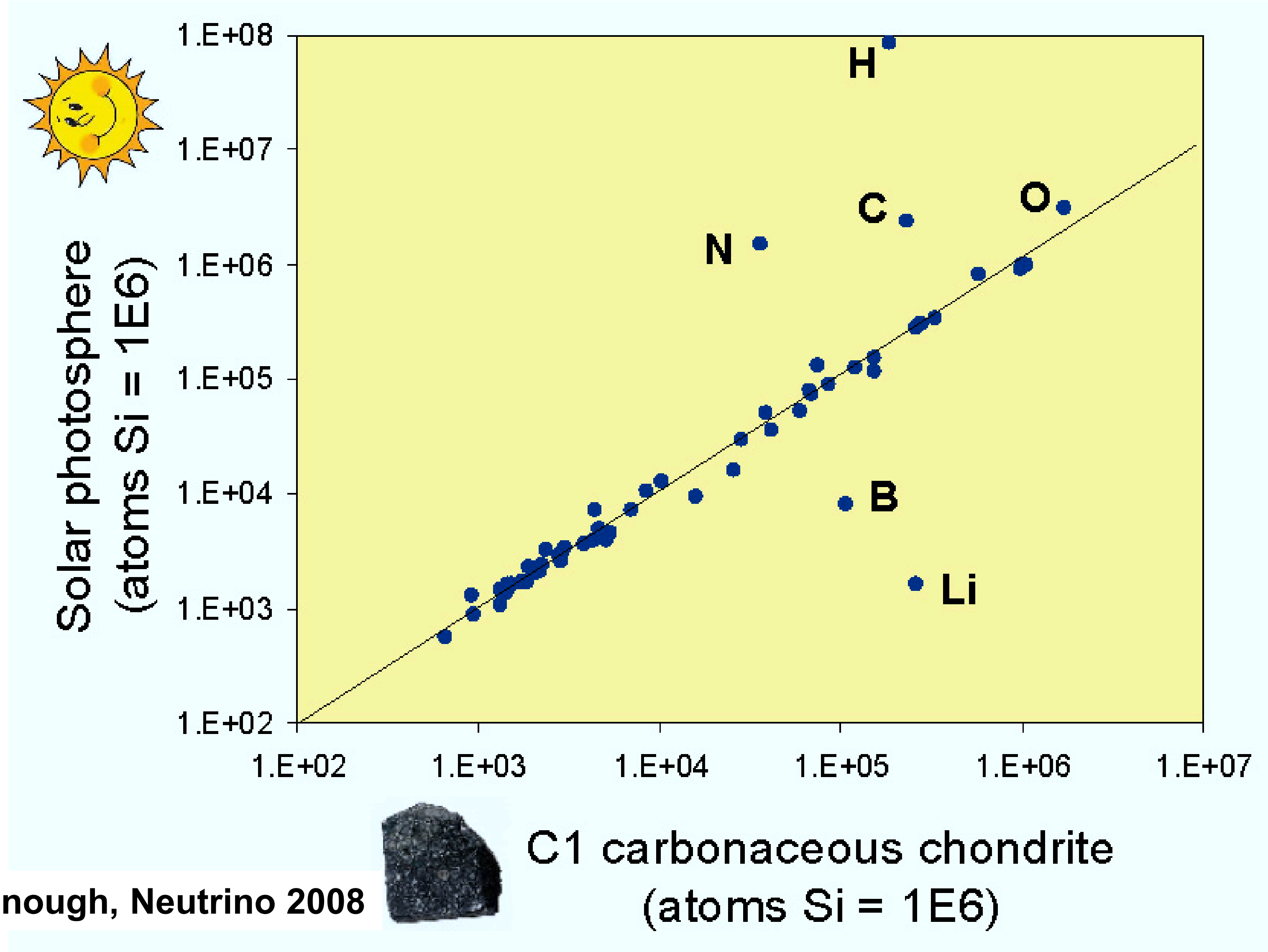
Pallasite: olivine and iron mixtures (CMB?)



Irons: pieces of core

McDonough, Neutrino 2008

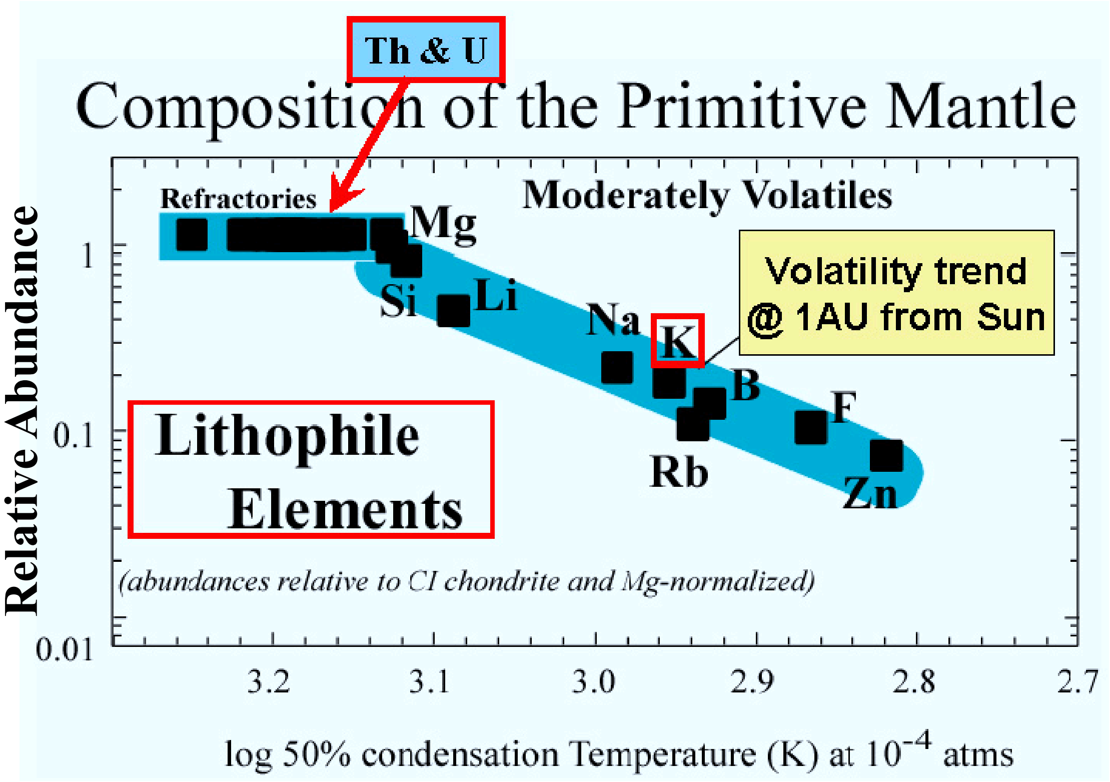
C1 chondrites have very similar composition to the solar photosphere (except for peculiar light elements that are expected to be anomalous around the Sun)



McDonough, Neutrino 2008

Next:

1) Correct for the loss of volatile elements during the Earth's formation



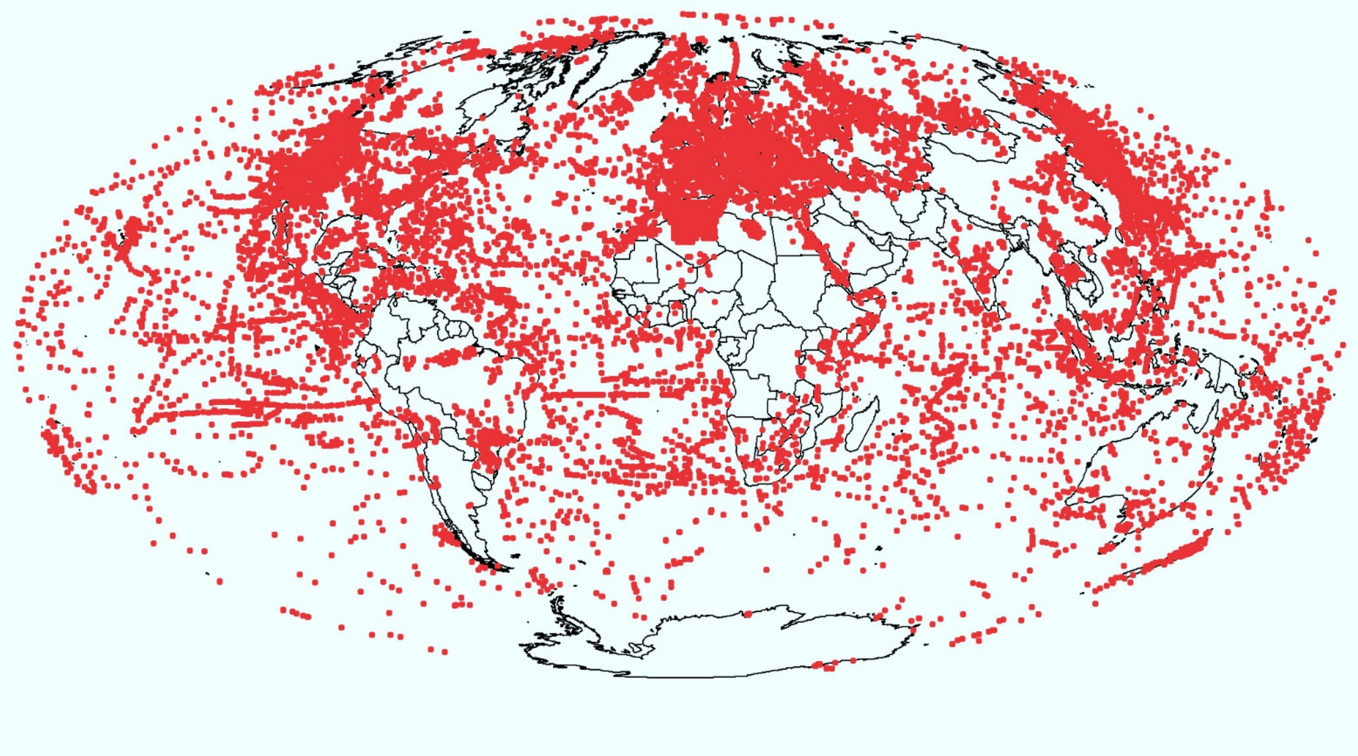
McDonough, Neutrino 2008

2) Based on chemical affinity estimate the composition of different regions

→ Core expected to have insignificant U, Th

→ Independently know that U, Th are ~1000x more common in the crust (ppm) than in the mantle (ppb)

Only a shallow layer has been sampled for chemical composition by drilling/sampling



Global distribution of heat flow data.
38,347 data points from Davies and Davies, 2010.

- Deepest bore-hole (12km) is only ~1/500 of the Earth's radius
- Oceans and southern hemisphere substantially less studied

Q: What powers the Eyjafjallajökull?

Q: What powers the Eyjafjallajökull?

...more generally what powers plate tectonics that powers volcanoes?

Same boreholes can be used to measure the heat flow from the Earth's interior

- ΔT_{hole} is measured between 2 points far away along the borehole
- Thermal conductivity C_{rock} of the rock is measured in the lab
- $Q = \Delta T_{hole}\, C_{rock}$ (assuming pure conduction)
- But in addition have to account for mantle convection
- *Get a total 46±3 TW* (100 mW/m^2)
- Error is small BUT other analyses with different convection model gives 31±1 TW (61mW/m^2)…

Heat flow from the Earth

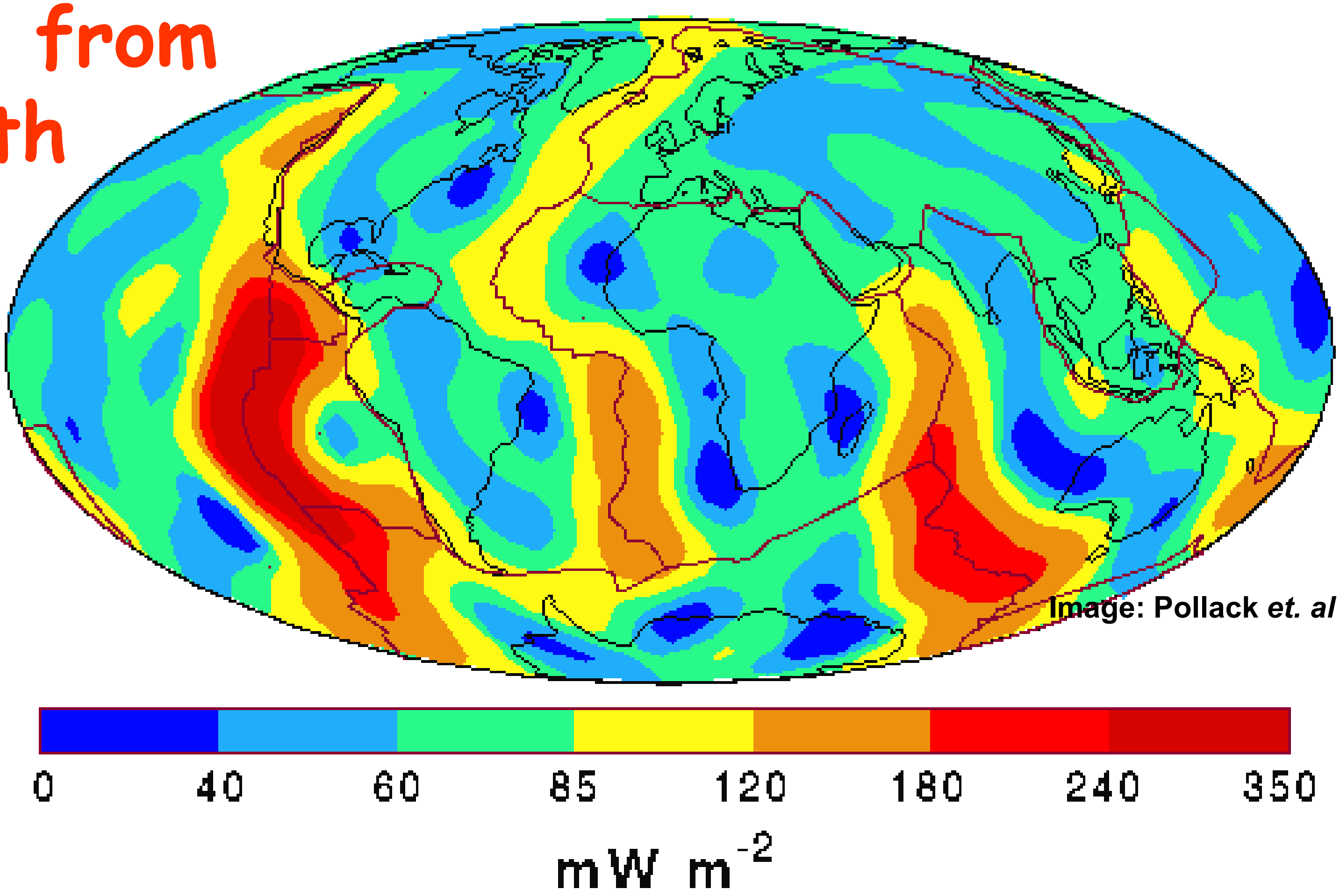


Image: Pollack *et. al*

Note the large emission under the mid ocean ridges (~83% of the total heat!): this is where mantle convects and this is also where the pure conduction model really does not work well.

Putting in context the 31-46TW produced by the planet

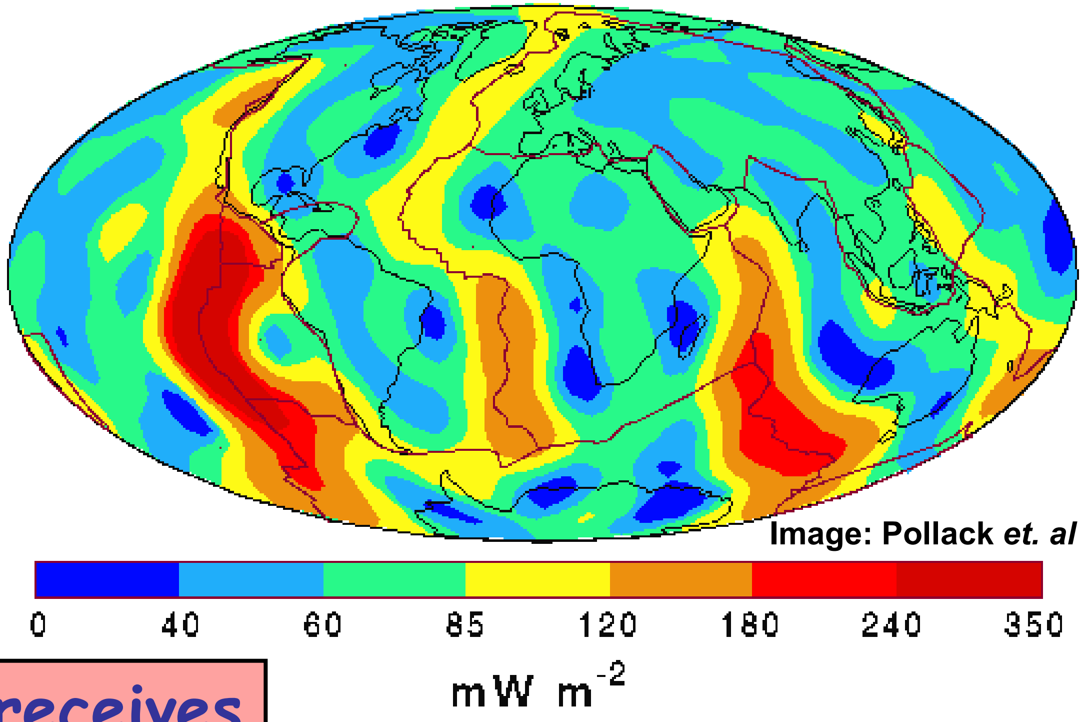
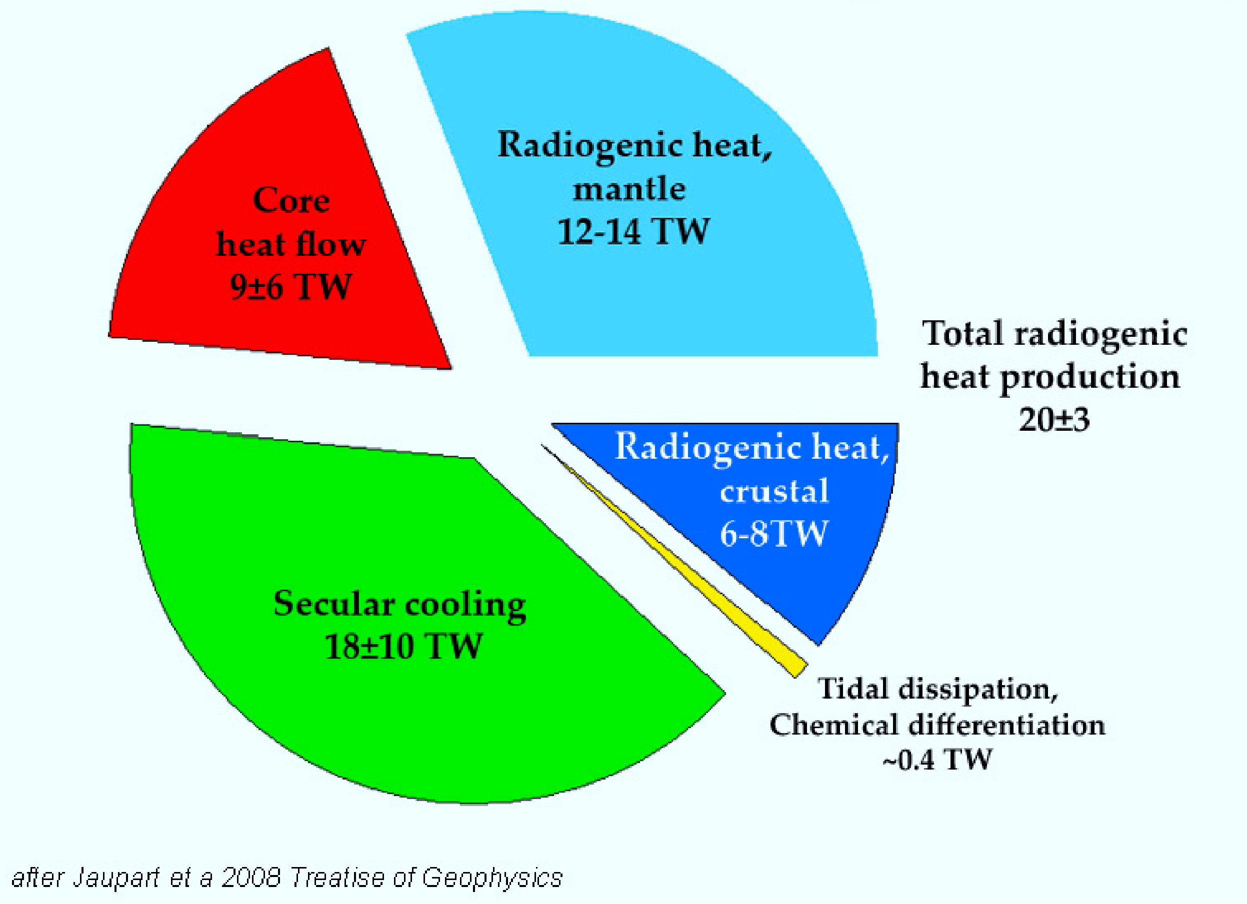


Image: Pollack *et. al*

From the Sun the Earth receives on average
1400W/m^2 at the top of the atmosphere and
400W/m^2 at the surface
→ the surface temperature has nothing to do with the heath produced inside.

We need 15 TW to run human society. This is sizeable compared to the total output from the planet!

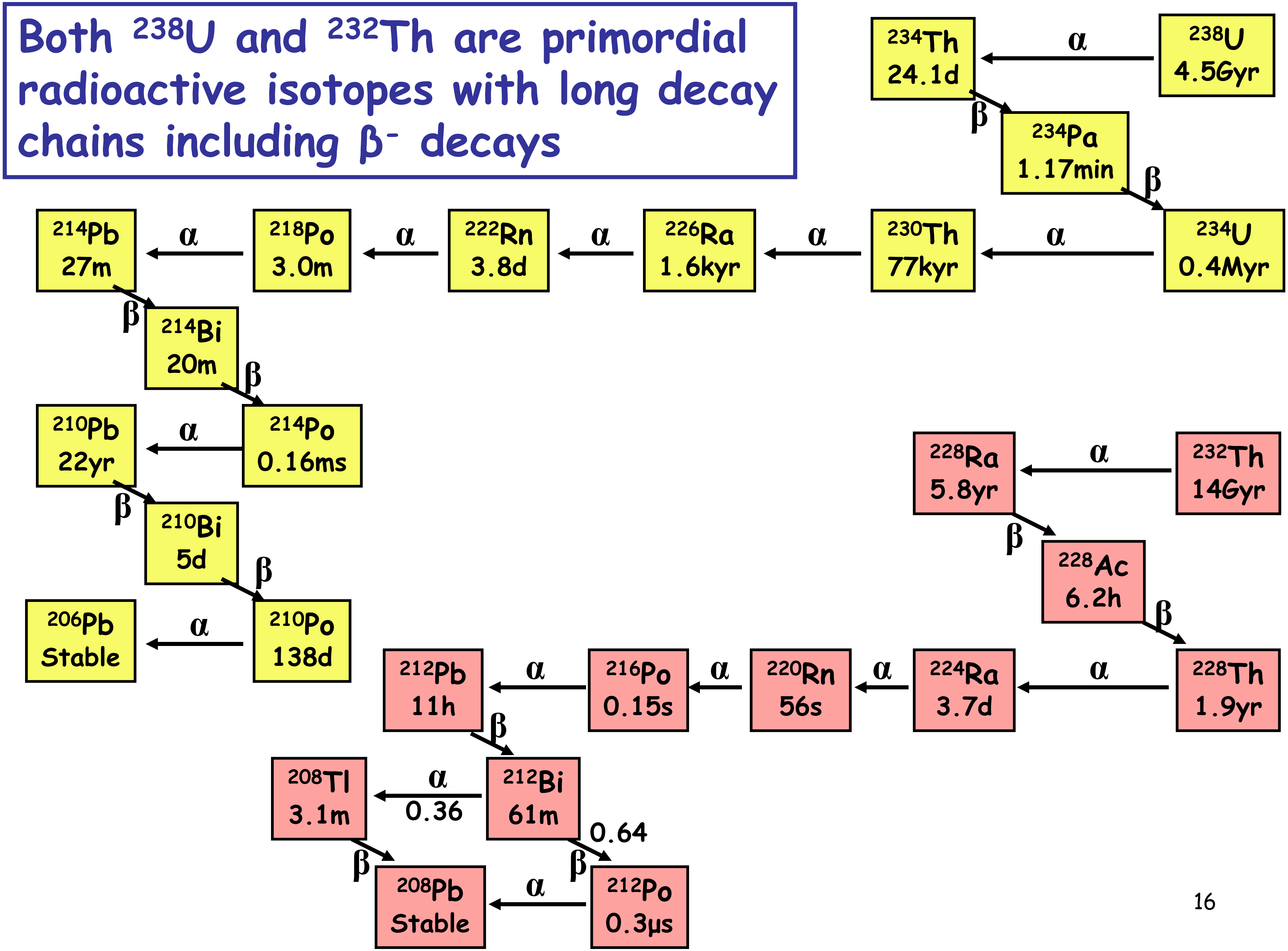
What produces the heat ?



after Jaupart et a 2008 Treatise of Geophysics

Radiogenic heat / Total heat
called "Urey ratio" → believed to be 0.3 to 0.7

Both ^{238}U and ^{232}Th are primordial radioactive isotopes with long decay chains including β^- decays



^{238}U 4.5Gyr

α

^{234}Th 24.1d

β

^{234}Pa 1.17min

β

^{234}U 0.4Myr

α

^{230}Th 77kyr

α

^{226}Ra 1.6kyr

α

^{222}Rn 3.8d

α

^{218}Po 3.0m

α

^{214}Pb 27m

β

^{214}Bi 20m

β

^{214}Po 0.16ms

α

^{210}Pb 22yr

β

^{210}Bi 5d

β

^{210}Po 138d

α

^{206}Pb Stable

^{232}Th 14Gyr

α

^{228}Ra 5.8yr

β

^{228}Ac 6.2h

β

^{228}Th 1.9yr

α

^{224}Ra 3.7d

α

^{220}Rn 56s

α

^{216}Po 0.15s

α

^{212}Pb 11h

β

^{212}Bi 61m

α 0.36

^{208}Tl 3.1m

β

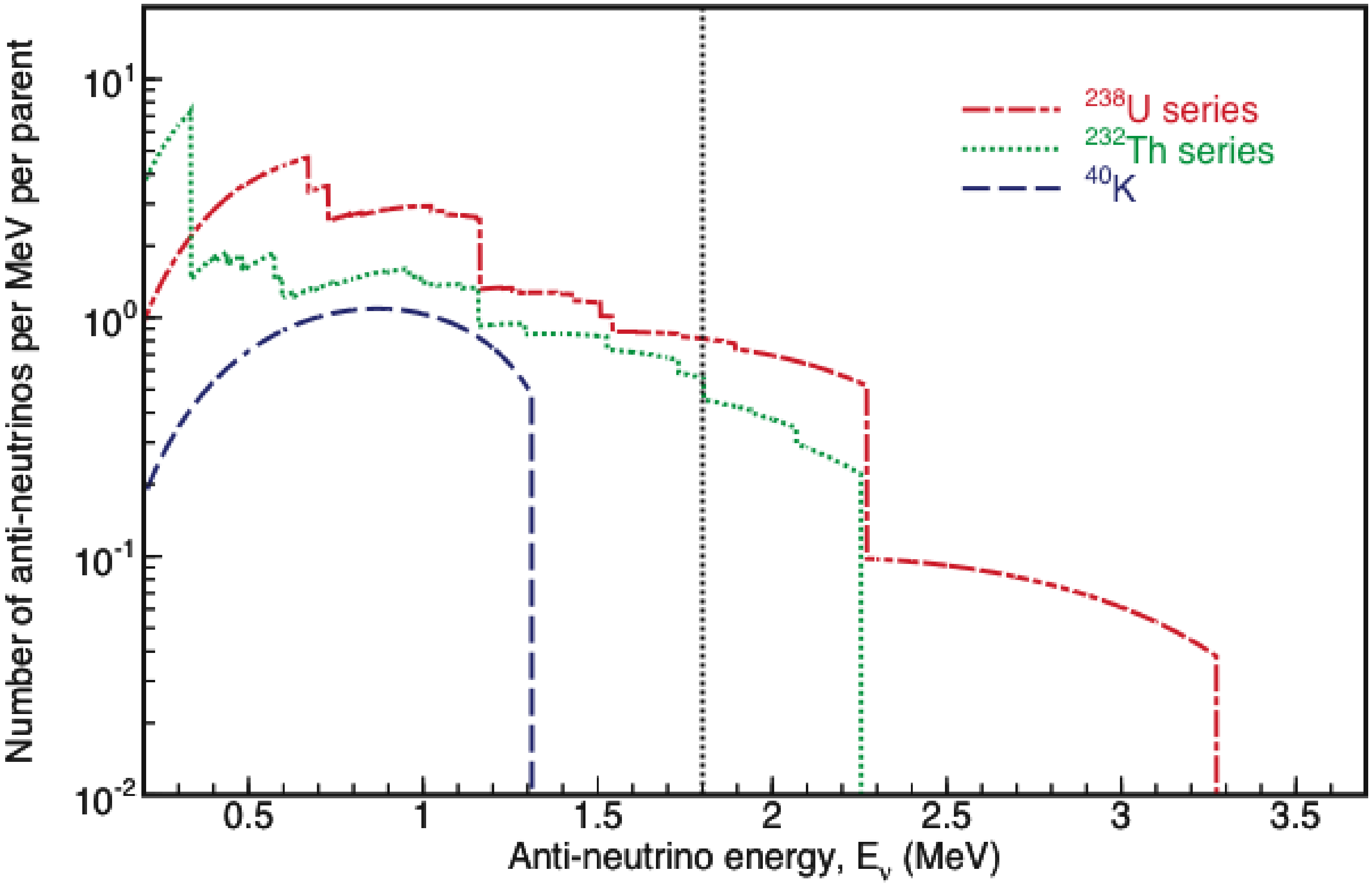
0.64 β

^{212}Po 0.3μs

α

^{208}Pb Stable

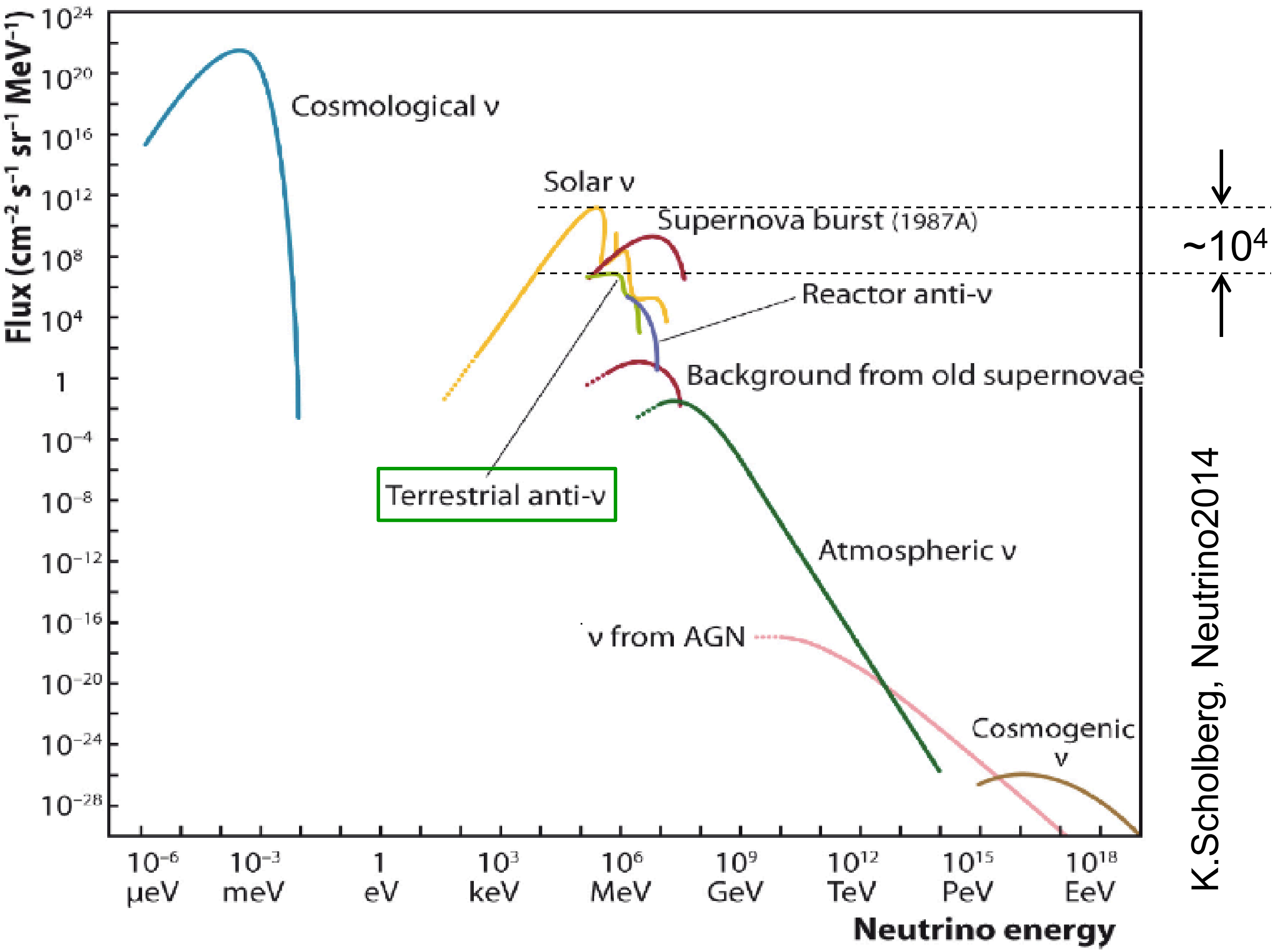
$\overline{\nu}_e$ of different endpoint energy are emitted at each β⁻ decay step producing characteristic spectra for ^{238}U, ^{232}Th (and ^{40}K)



Geo-neutrinos are a rare witness of the chemical composition (at least for U, Th and K) of the Earth

Can they be detected?

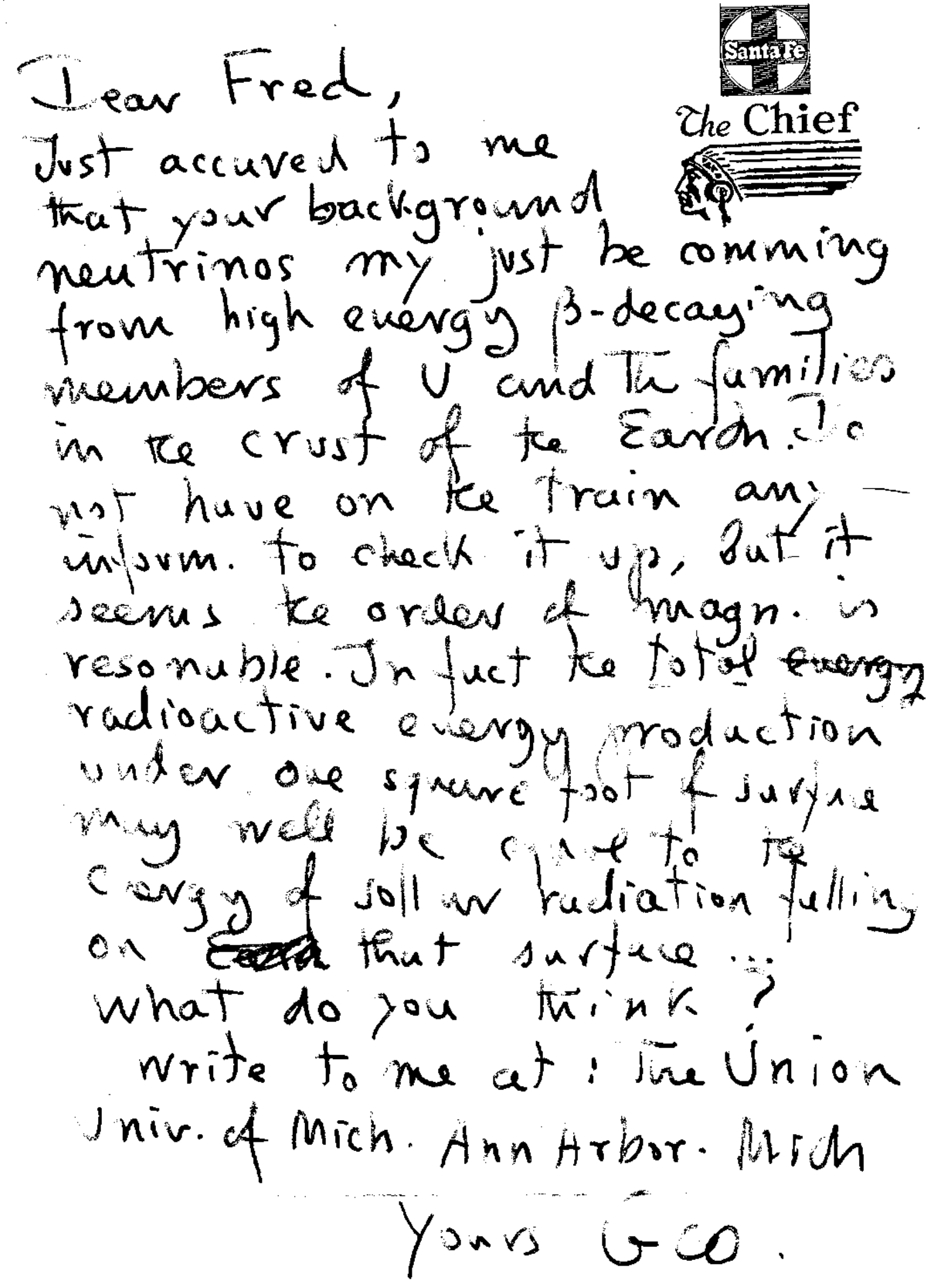
The (anti)neutrino flux on Earth greatly depends on their energy



K.Scholberg, Neutrino2014

Yesterday’s background is today’s signal…

Fred Reines (?) working at a neutrino detector (circa 1953)



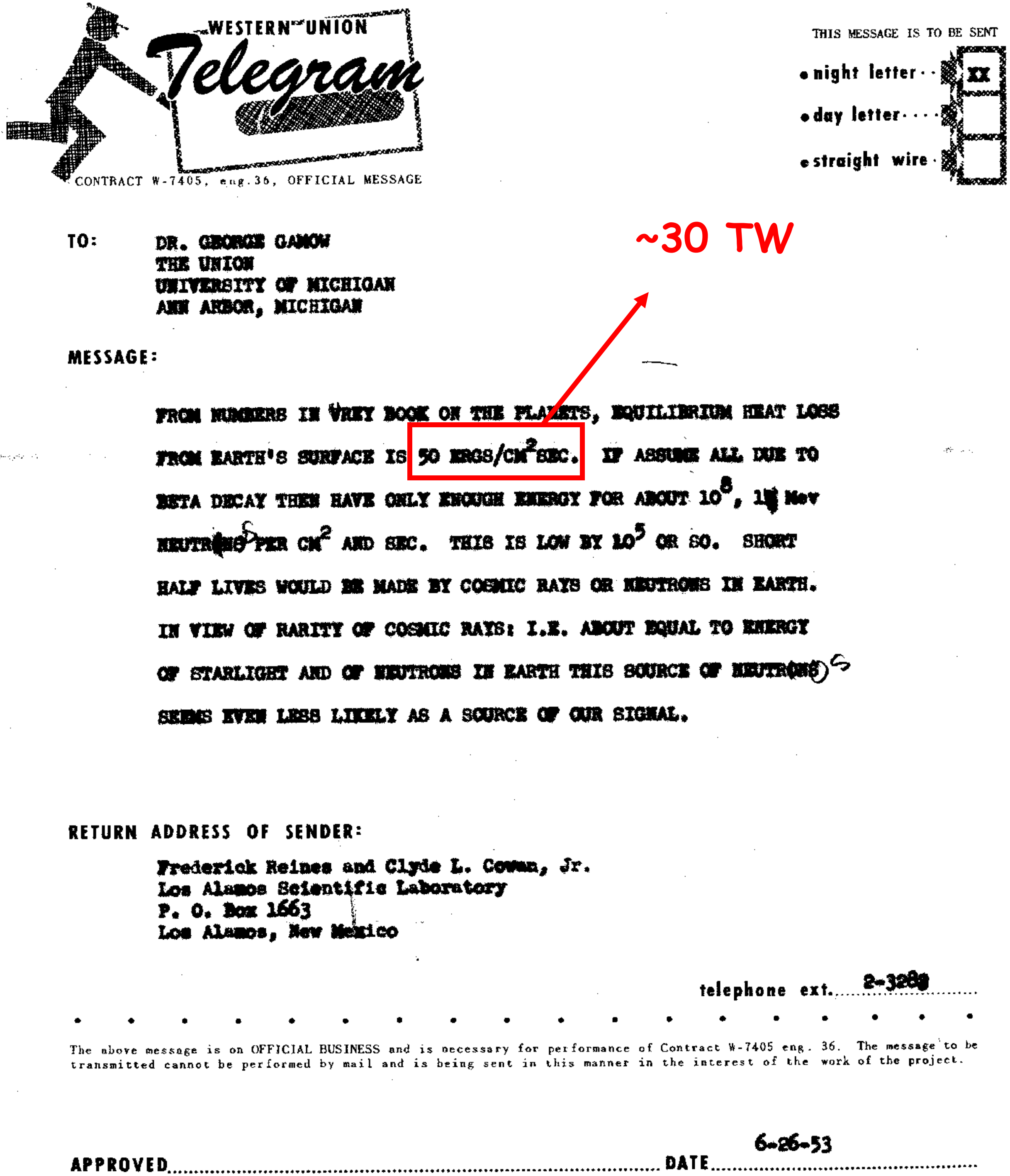
Santa Fe
The Chief

Dear Fred,
Just accured to me
that your background
neutrinos my just be comming
from high energy β-decaying
members of U and Th families
in the crust of the Earth. I do
not have on the train any
inform. to check it up, but it
seems the order of magn. is
resonable. In fact the total ~~energy~~
radioactive energy production
under one square foot of surface
may well be equal to the
energy of sollar radiation falling
on ~~earth~~ that surface...
What do you think?
Write to me at: The Union
Univ. of Mich. Ann Arbor. Mich

Yours Geo.

…Well… not quite !

That detector was some 5 orders of magnitude too small



WESTERN UNION Telegram

CONTRACT W-7405, eng.36, OFFICIAL MESSAGE

THIS MESSAGE IS TO BE SENT

- night letter ☒ XX
- day letter ☐
- straight wire ☐

~30 TW

TO:

DR. GEORGE GAMOW
THE UNION
UNIVERSITY OF MICHIGAN
ANN ARBOR, MICHIGAN

MESSAGE:

FROM NUMBERS IN UREY BOOK ON THE PLANETS, EQUILIBRIUM HEAT LOSS FROM EARTH'S SURFACE IS 50 ERGS/CM^2 SEC. IF ASSUME ALL DUE TO BETA DECAY THEN HAVE ONLY ENOUGH ENERGY FOR ABOUT 10^8, 1 Mev NEUTRINOS PER CM^2 AND SEC. THIS IS LOW BY 10^5 OR SO. SHORT HALF LIVES WOULD BE MADE BY COSMIC RAYS OR NEUTRONS IN EARTH. IN VIEW OF RARITY OF COSMIC RAYS: I.E. ABOUT EQUAL TO ENERGY OF STARLIGHT AND OF NEUTRONS IN EARTH THIS SOURCE OF NEUTRINOS SEEMS EVEN LESS LIKELY AS A SOURCE OF OUR SIGNAL.

RETURN ADDRESS OF SENDER:

Frederick Reines and Clyde L. Cowan, Jr.
Los Alamos Scientific Laboratory
P. O. Box 1663
Los Alamos, New Mexico

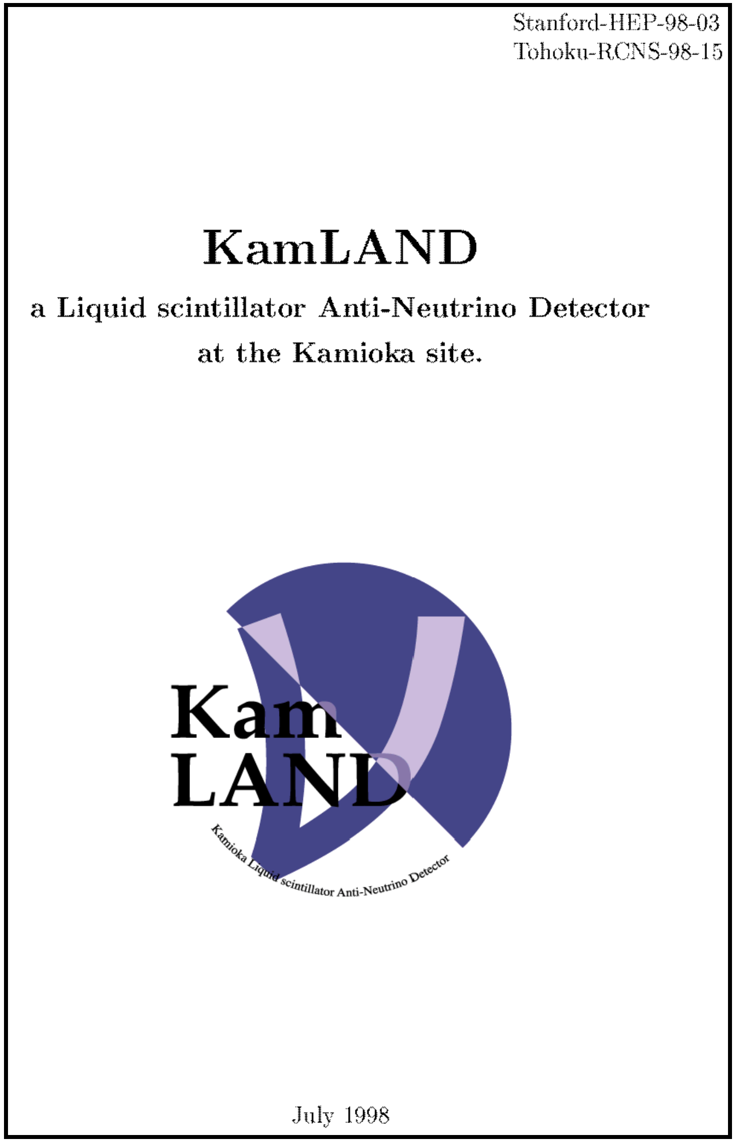
telephone ext. 2-3288

The above message is on OFFICIAL BUSINESS and is necessary for performance of Contract W-7405 eng. 36. The message to be transmitted cannot be performed by mail and is being sent in this manner in the interest of the work of the project.

APPROVED .... DATE 6-26-53

Fast forward 45 years…

1kton detector ~10^4 100kg detectors

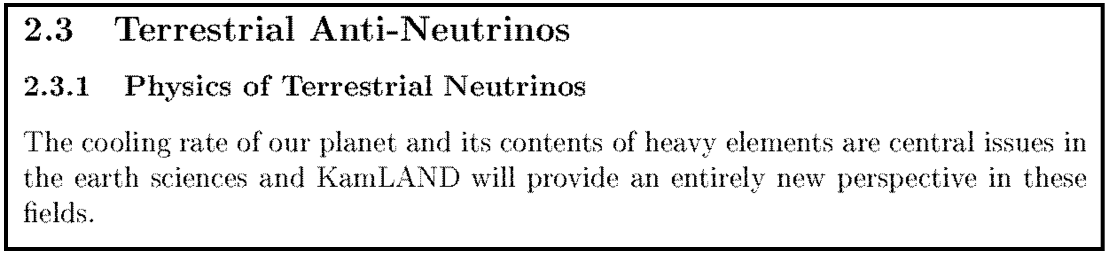


Stanford-HEP-98-03
Tohoku-RCNS-98-15

KamLAND

a Liquid scintillator Anti-Neutrino Detector
at the Kamioka site.

July 1998



2.3 Terrestrial Anti-Neutrinos

2.3.1 Physics of Terrestrial Neutrinos

The cooling rate of our planet and its contents of heavy elements are central issues in the earth sciences and KamLAND will provide an entirely new perspective in these fields.

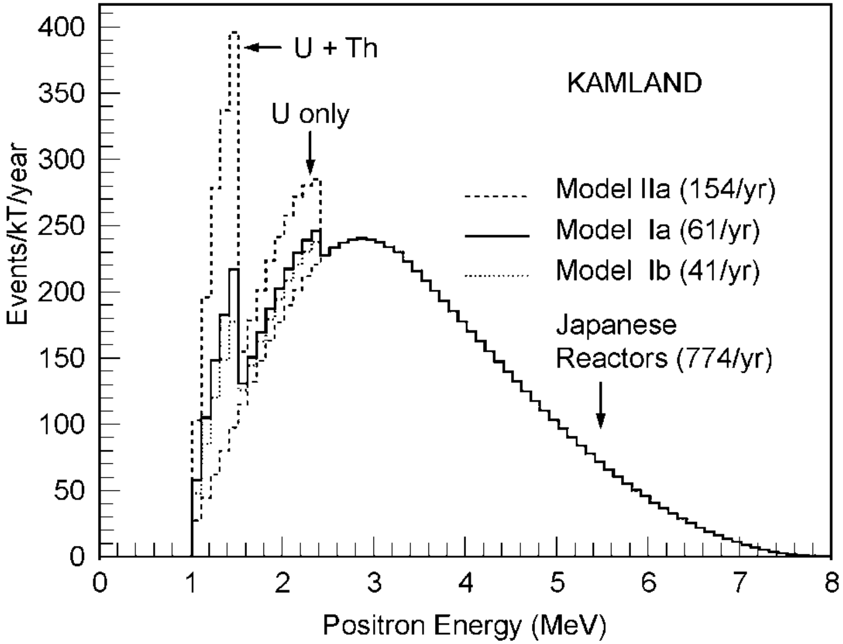
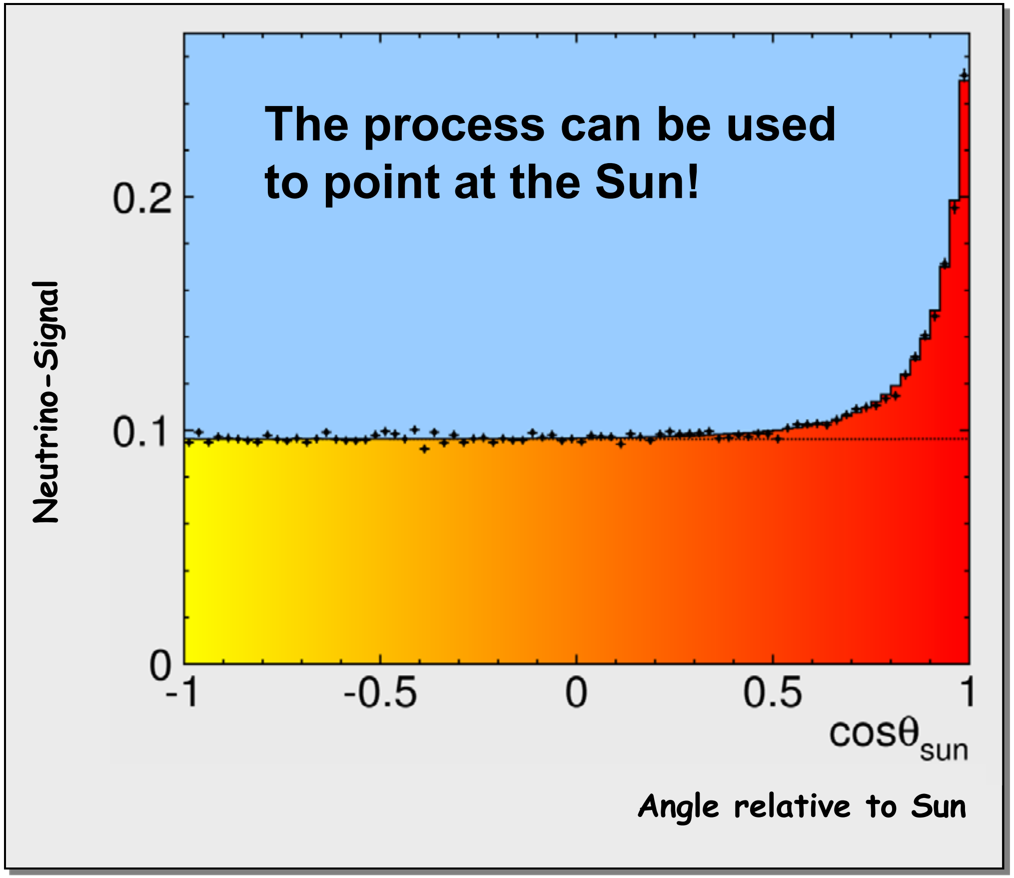


Figure 6: Energy spectrum from terrestrial anti-neutrinos compared with reactor signal as expected in KamLAND. Three different geophysical models [22] are shown for the terrestrial anti-neutrinos and no oscillations are assumed for all the spectra shown.

Candidate processes for Geo-$\overline{\nu}_e$ detection

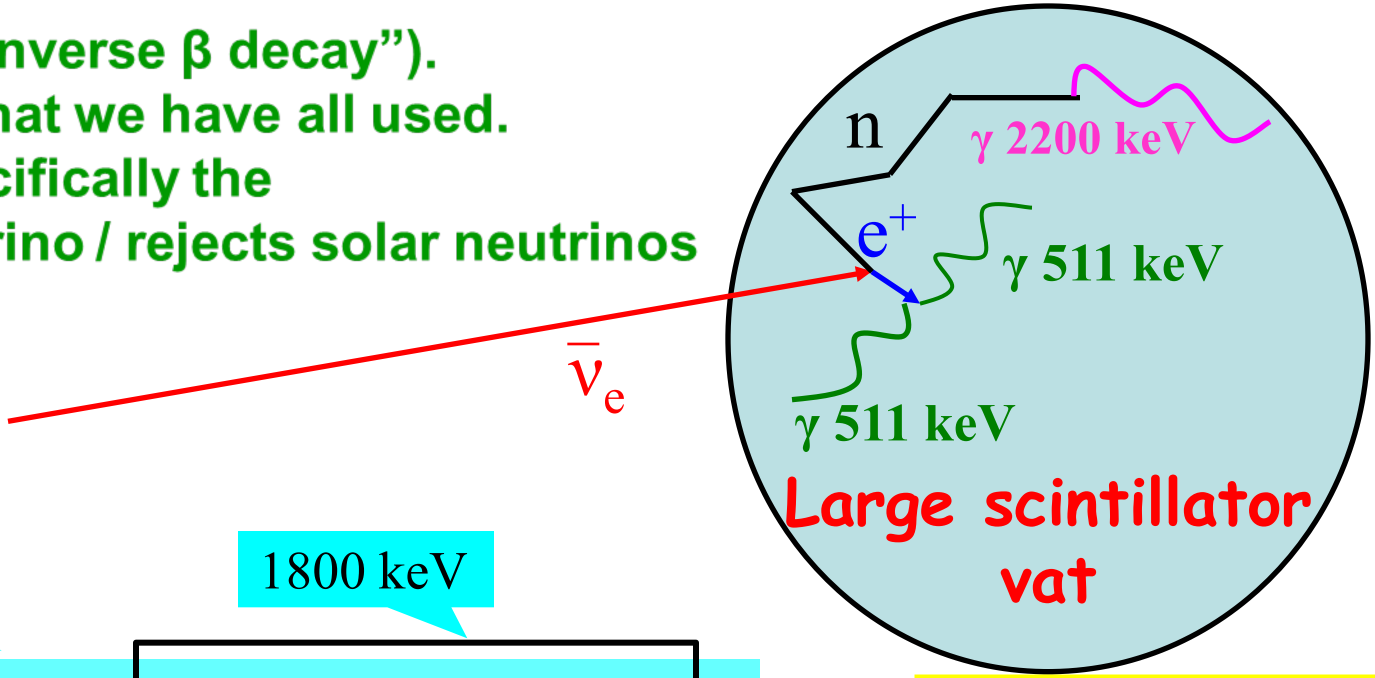
- $\overline{\nu}_e e^- \rightarrow \overline{\nu}_e e^-$: Too generic (e.g. solar neutrinos can do this too)
  Too bad because this has memory of the direction



Candidate processes for Geo-$\overline{\nu}_e$ detection

- $\overline{\nu}_e e^- \rightarrow \overline{\nu}_e e^-$: **Too generic (e.g. solar neutrinos can do this too)**
  Too bad because this has memory of the direction

- $\overline{\nu}_e p \rightarrow n e^+$ **("inverse β decay").**
  This is what we have all used.
  Tags specifically the
  anti-neutrino / rejects solar neutrinos



$$E_{\overline{\nu}} \cong E_{e^+} + \overset{10\text{-}40\text{ keV}}{E_n} + \overbrace{(M_n - M_p) + m_{e^+}}^{1800\text{ keV}} \Rightarrow E_\nu \text{ measurement}$$

The process has a 1.8MeV threshold:
➔ most of the flux is not accessible (no ^{40}K)

Candidate processes for Geo-$\overline{\nu_e}$ detection

- $\overline{\nu_e}\, N(A,Z) \rightarrow e^+ N'(A,Z-1)$

Threshold is Q_β+1022keV (^{40}K endpoint is 1311keV)

There are MANY nuclei to check for this and I have not done an Exhaustive search. However some of this (with some mistakes) was done by Krauss, Glashow and Schramm and more work was done by Mark Chen. Some examples:

- $\overline{\nu_e}\, {}^3He \rightarrow {}^3H\, e^+$ Q_β=18.6keV, $t_{1/2}$=12.3yr
  ~2000 atoms/kton yr, ~1/3 from ^{40}K
  - How to collect ~tons of ^{3}He?
  - How to detect the tritium? Wait 12yrs?

- $\overline{\nu_e}\, {}^{35}Cl \rightarrow {}^{35}S\, e^+$ Q_β=167keV, $t_{1/2}$=88d
  ~2 atoms/kton yr
  - How to extract the S from the Cl? Substantially more challenging than the solar neutrino experiment

Candidate processes for Geo-$\overline{\nu_e}$ detection

- $\overline{\nu_e}\, N(A,Z) \rightarrow e^+ N'(A, Z-1)$

Threshold is Q_β+1022keV (^{40}K endpoint is 1311keV)

More examples (M.Chen):

- $\overline{\nu_e}\; {}^{106}Cd \rightarrow {}^{106}Ag\; e^+$ Q_β=194keV, $t_{1/2}$=8.3d
  <10 atoms/kton yr (some from ^{40}K)
  - ^{106}Cd is only 1.25% of Cd
  - How to extract the Ag from the Cd? Again more challenging than the solar neutrino experiment

Candidate processes for Geo-$\overline{\nu}_e$ detection

- $\overline{\nu}_e e^- \rightarrow \overline{\nu}_e e^-$: Too generic (e.g. solar neutrinos can do this too)
  Too bad because this has memory of the direction

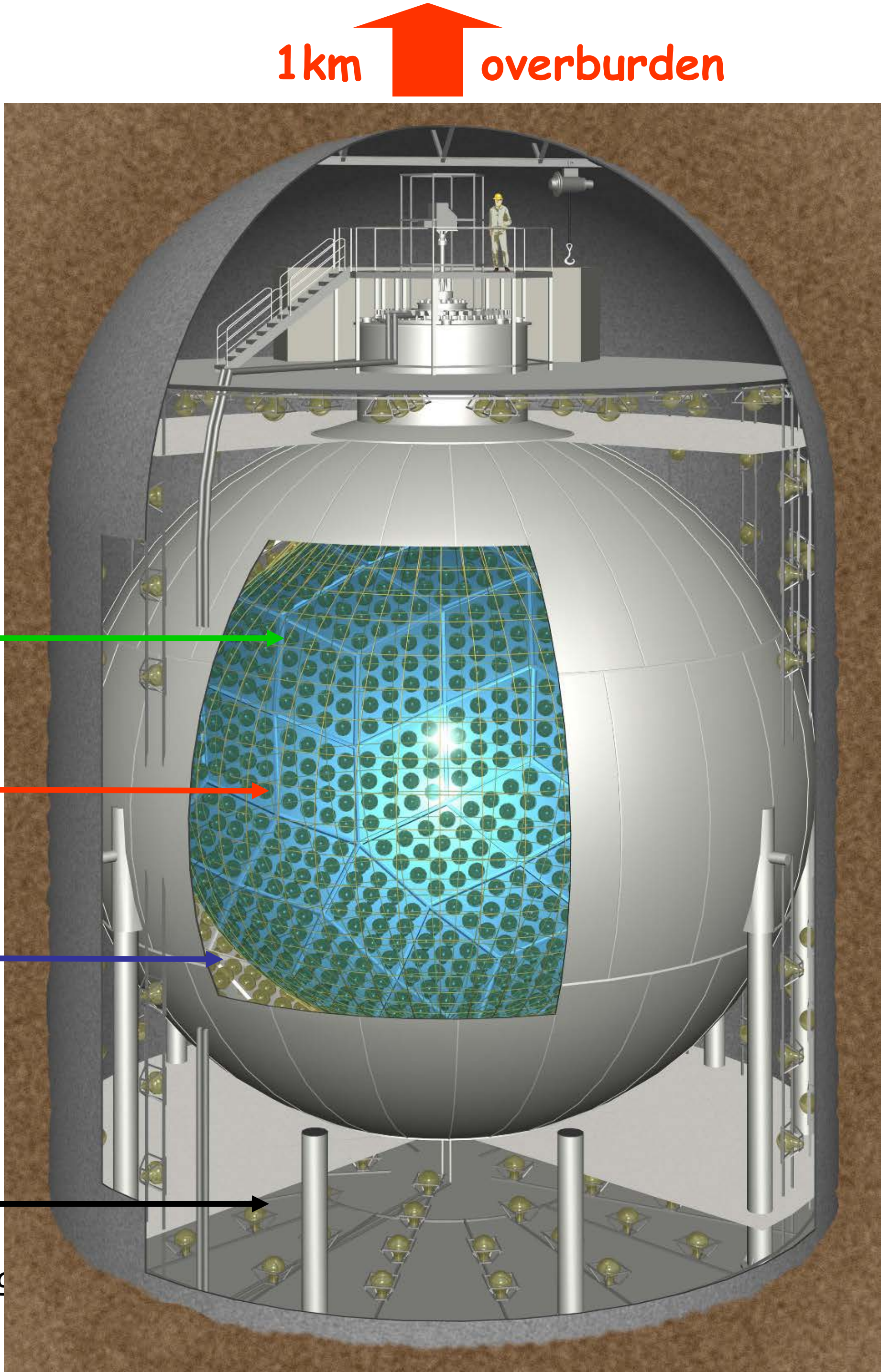
- $\overline{\nu}_e p \rightarrow n e^+$ ("inverse β decay"). This is what we have all used.
  Tags specifically the anti-neutrino / rejects solar neutrinos

- $\overline{\nu}_e N(A,Z) \rightarrow e^+ N'(A,Z-1)$ Also a sort of inverse β decay.
  Also antineutrino-specific.
  Can have lower threshold.
  Generally lower cross section.
  → No good candidates, but maybe worth another look

- $\overline{\nu}_e N \rightarrow \overline{\nu}_e N$ Coherent neutrino-neutron scattering.
  At E_ν~2MeV λ_ν~100fm. Since the nuclear size is <~10fm
  the neutrino wavefunction overlaps the entire nucleus.
  Gain a factor ~N in cross section but not specific
  (solar nu does this too!)

Inverse beta decay detection in liquid scintillator detectors

Example: KamLAND



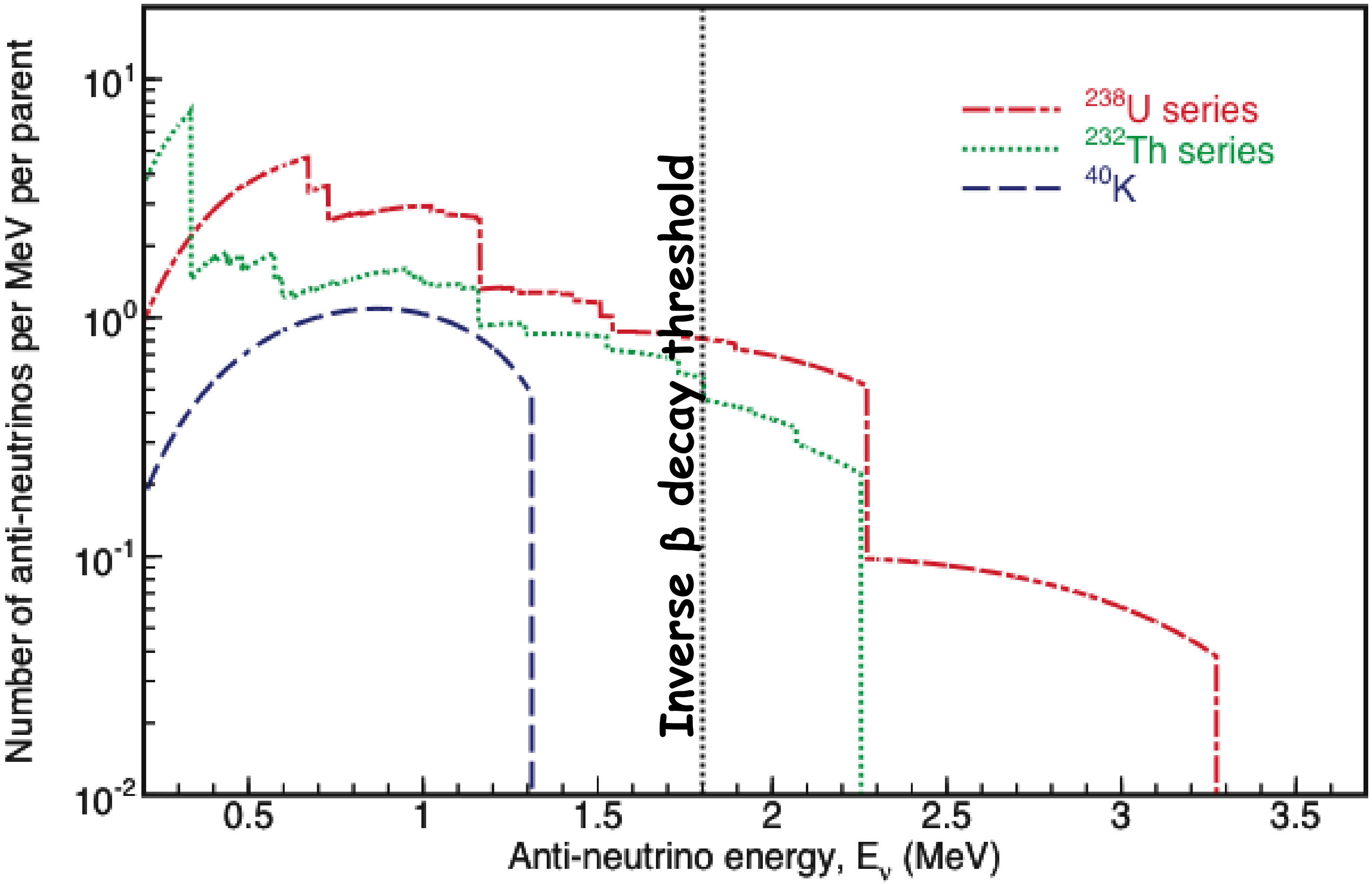
~2000 20" PMTs

1 kton liquid-scintillator

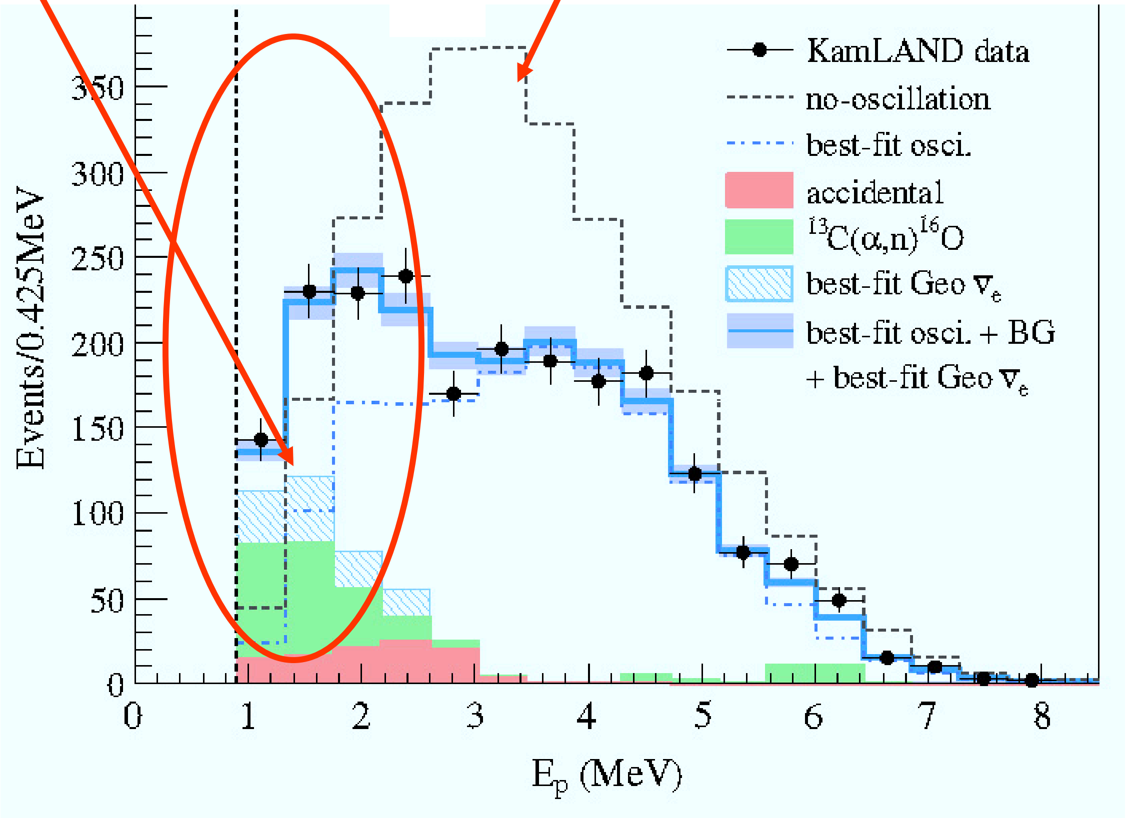
2.5 m-thick paraffin shielding

Water shield/Cherenkov veto

So there is a threshold for detecting neutrinos this way and ^{40}K $\overline{\nu}_e$ are all below threshold



So geo-(anti)neutrinos populate the bottom part of the reactor spectrum



GeoNeutrino Timeline

Pre-history: F.Reines' & G.Gamov's correspondence

Early ideas: G.Eder, Nucl. Phys. 78 (1966) 657
G.Marx, Czech. J. Phys. B19 (1969) 1471
L.M.Krauss, S.L.Glashow, D.M.Schramm, Nature 310 (1984) 191

KamLAND proposal: P.Alivisatos et al,
Stanford-HEP-98-03, Tohoku-RCNS-98-15, unpublished.

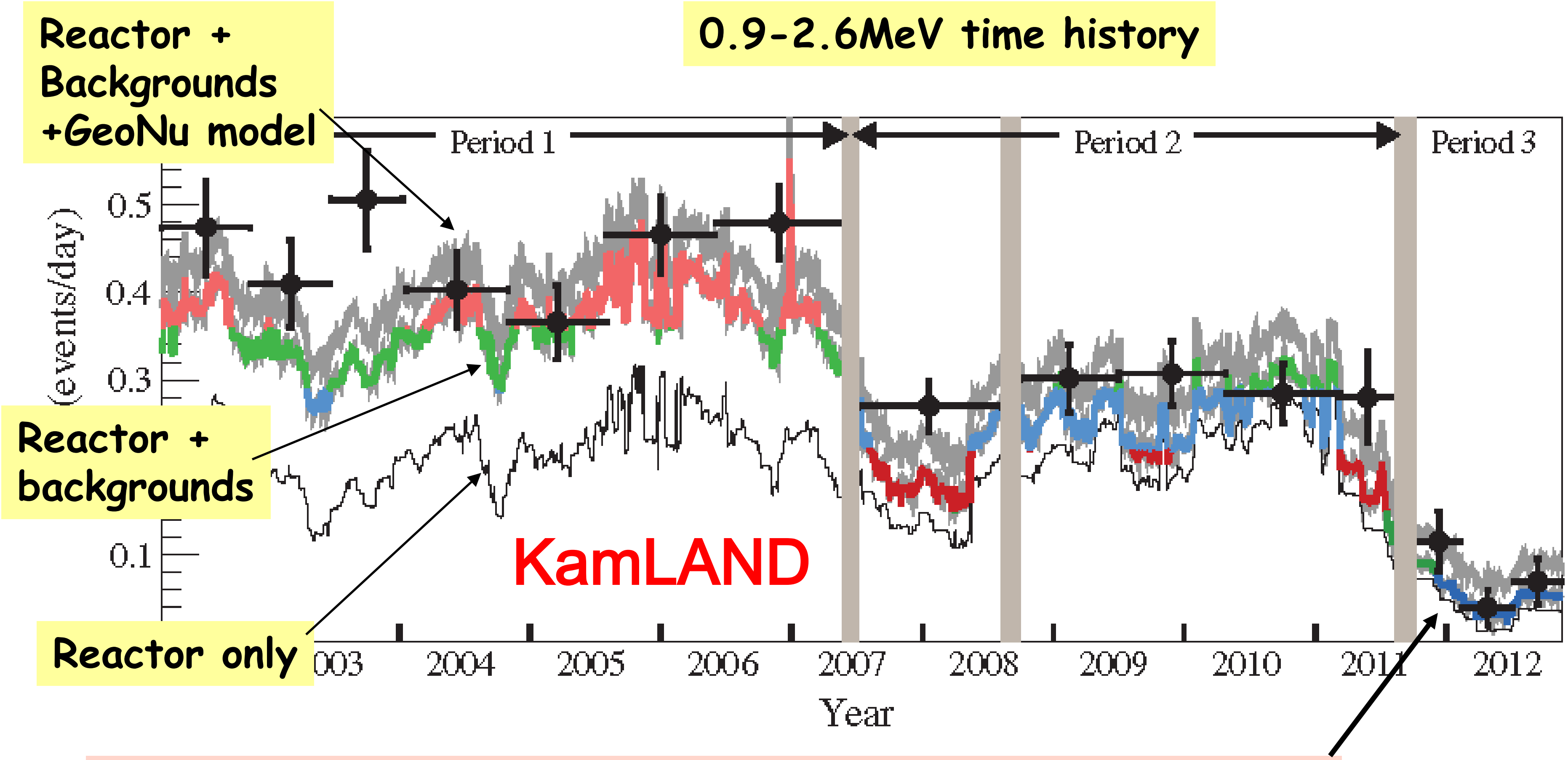
First experimental study (KamLAND): T.Araki et al., Nature 436 (2005) 499

Borexino enters the scene: G.Bellini et al. Phys. Lett. B687 (2010) 299

Latest experimental results: A.Gando et al., Phys. Rev. D 88 (2013) 033001
M.Agostini et al., Phys. Rev. D 92 (2015) 031101(R)

…in addition there is now ample literature about the interpretation of the measurements

For KamLAND nuclear reactors are a substantial "background" to the Geoneutrino measurement.

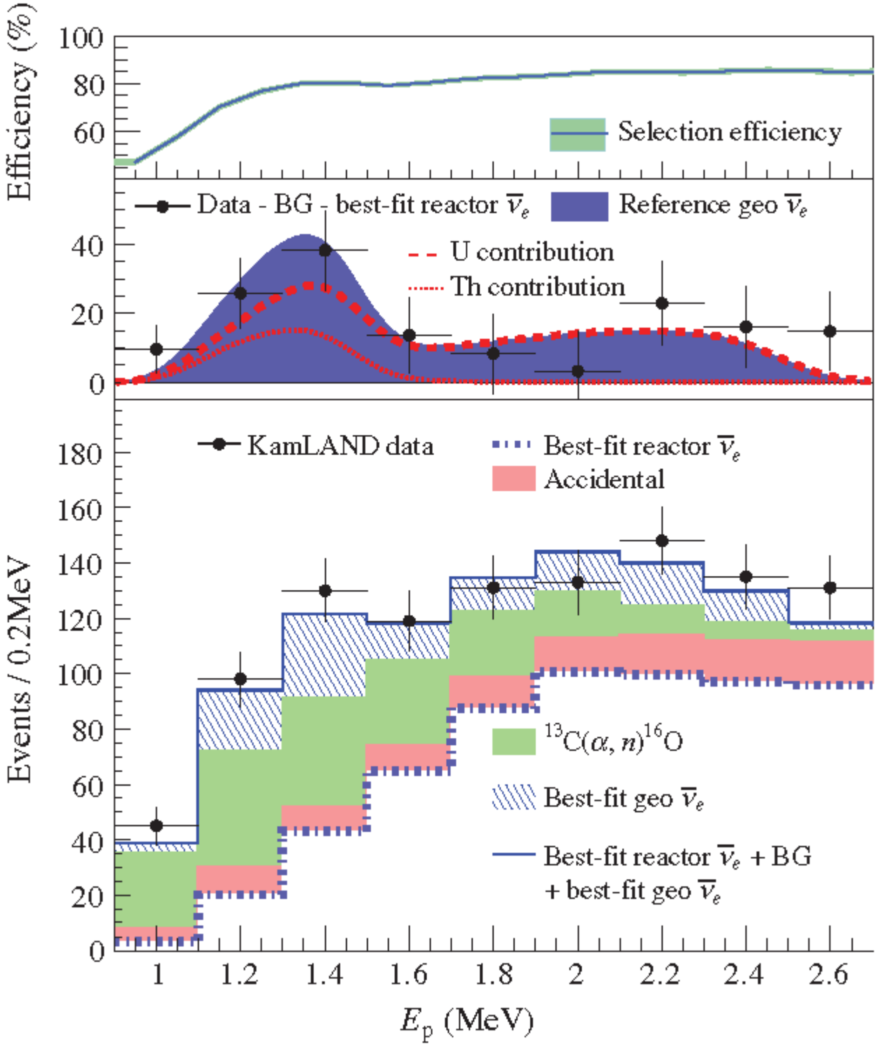


After the Fukushima accident this background has gone away

A. Gando et al. Phys. Rev. D 88, 033001 (2013)

The cumulative spectrum shows a clear excess where the geoneutrinos are supposed to be.

The fit knows also of the reactor power excursions



A. Gando et al. Phys. Rev. D 88, 033001 (2013)

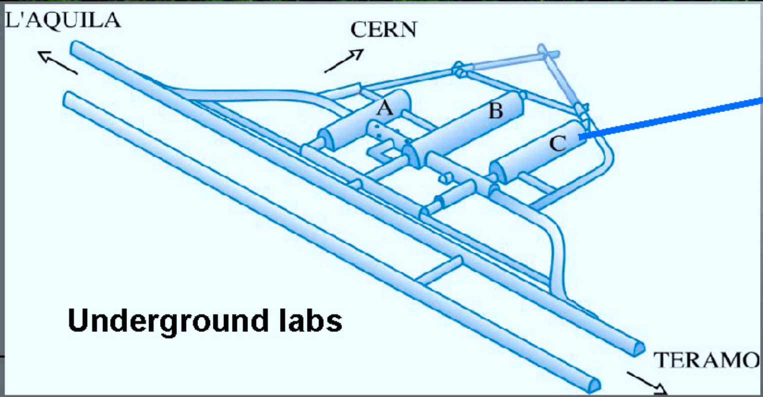
Null hypothesis for geoNu has a probability of $2 \cdot 10^{-6}$

Borexino

Abruzzo
120 Km from Rome

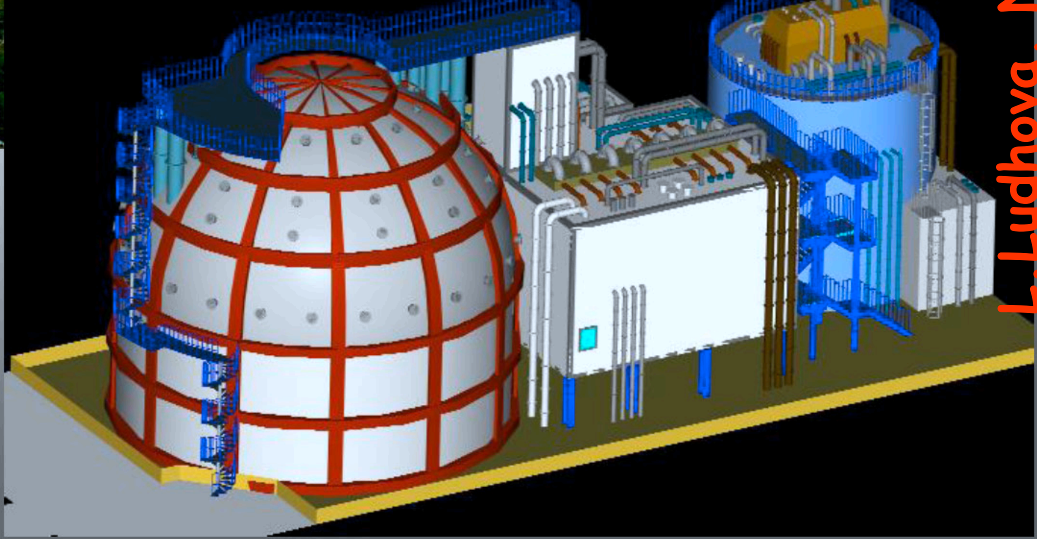
Laboratori
Nazionali del
Gran Sasso

Assergi (AQ)
Italy
~3500 m.w.e



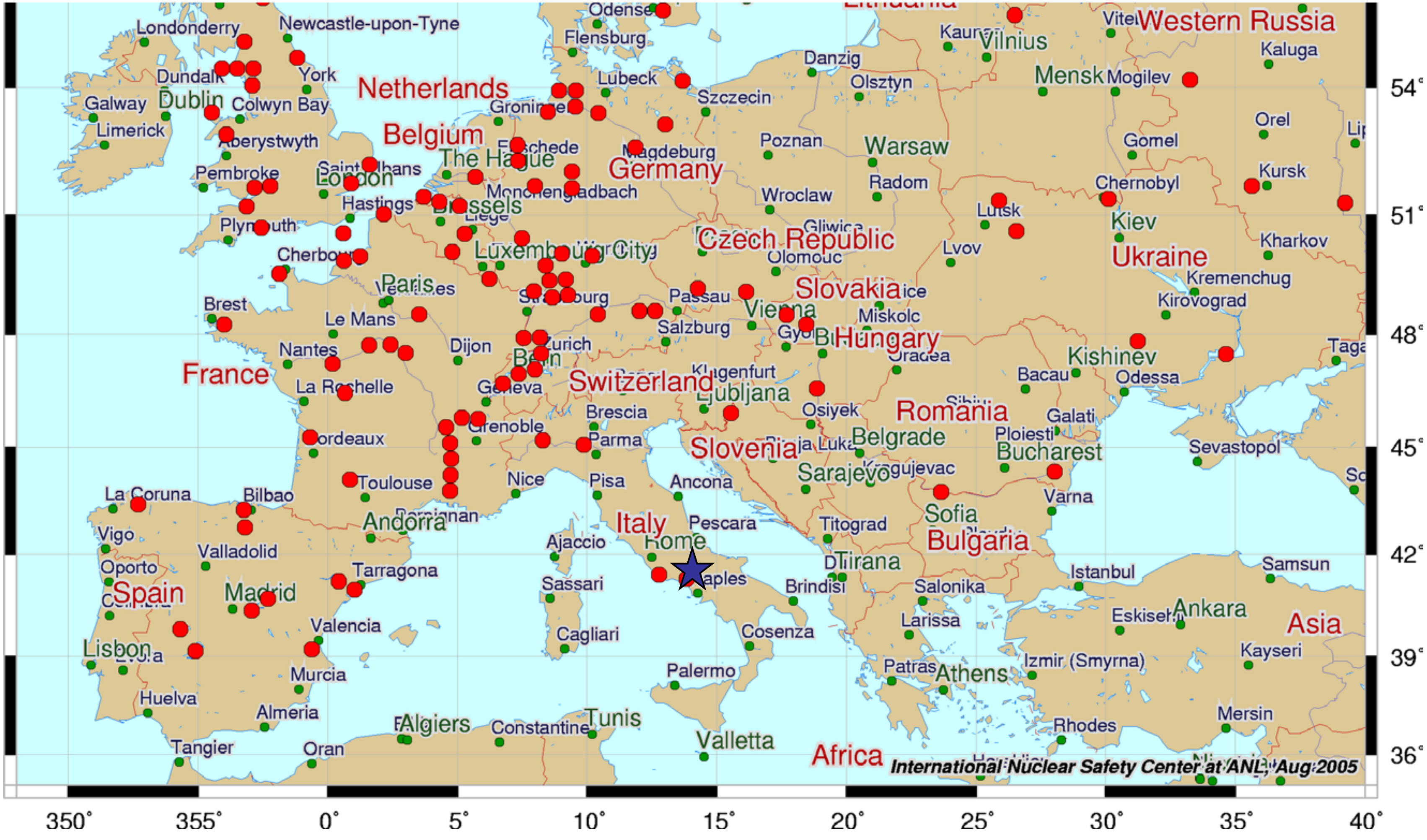
Underground labs

Borexino detector + fluid plants



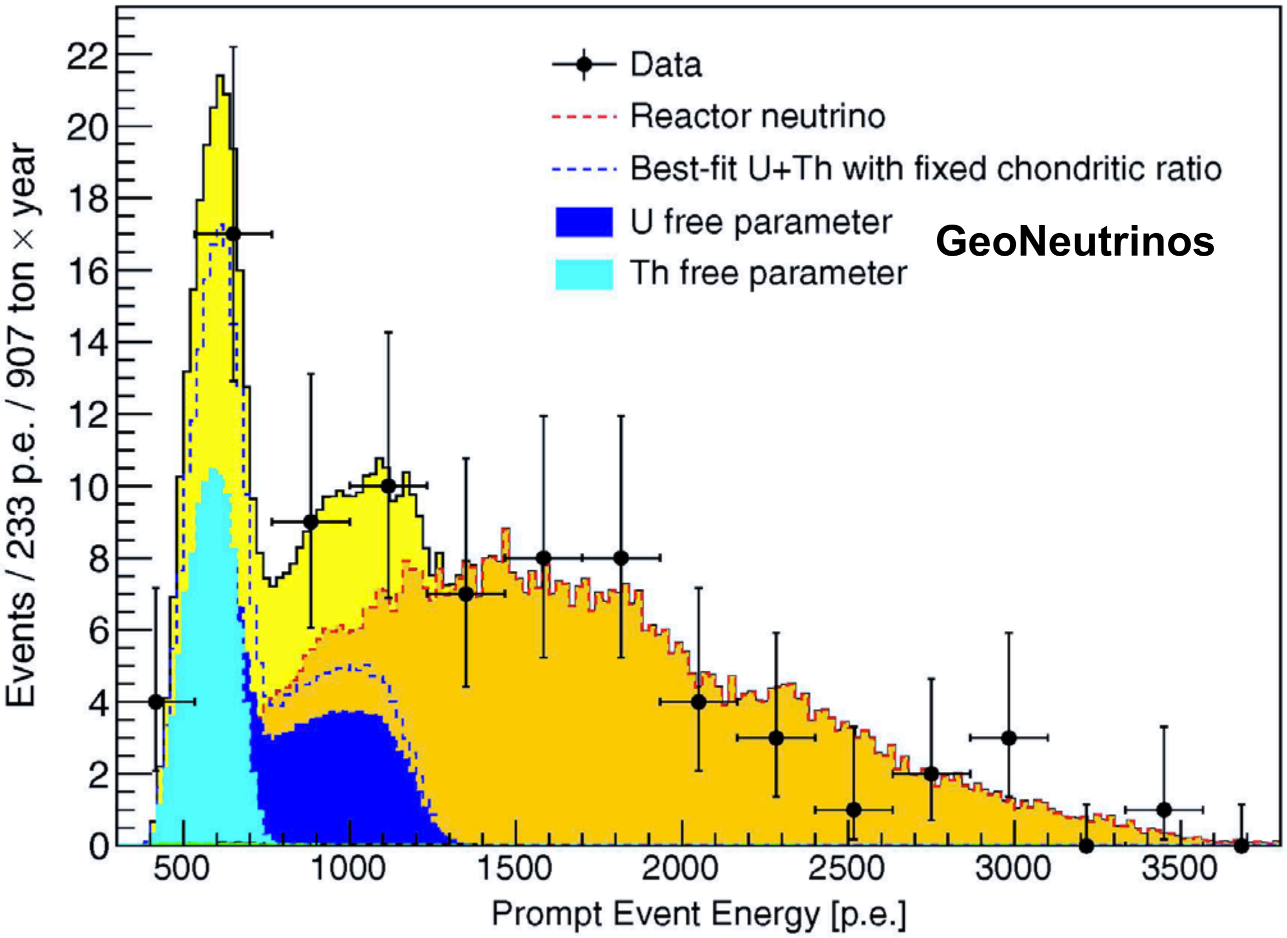
L.Ludhova, Neutrino Geoscience 2010

In order to help science and facilitate the study of GeoNeutrinos, Italy decided not to build new nuclear power plants and shut down the few they had!



International Nuclear Safety Center at ANL, Aug 2005

Borexino GeoNu data is cleaner but statistics not as good as KamLAND (smaller detector)



M.Agostini et al., Phys. Rev. D 92 (2015) 031101(R)

Null hypothesis excluded (3.6×10^{-9} or 5.9σ)

The geo-neutrino flux due to a particular isotope accumulated at a particular position $\vec{L}$ can be calculated as

$$\frac{d\Phi}{dE} \approx A \frac{dn}{dE} \Delta(E_\nu, \vec{L}) \int_{\oplus} d\vec{L} \frac{a(\vec{L})}{4\pi |\vec{L}|^2}$$

Where:

- A is the decay rate per unit mass for the isotope decay chain
- dn/dE is the anti-neutrino energy spectrum for the decay chain
- $\Delta(E_\nu, \vec{L})$ is a correction accounting for neutrino oscillations
- $a(\vec{L})$ is the amount of isotope at position $\vec{L}$

So from the measurement of $d\Phi/dE$ the amount of isotope $a(\vec{L})$ can be extracted by inverting this relationship

The integral over the volume of the Earth introduces substantial degeneracy for a measurement done at a single site.

So, for the time being we'll use the flux measured at 2 sites to test models of U and Th distributions

A number of models have been developed over the last few years:

- *R.S. Raghavan et al. Phys. Rev. Lett. 80 (1998) 635.*
- *C. Rothschild et al. Geo. Res. Lett. 25 (1998) 1083.*
- *F. Mantovani et al. Phys. Rev. D 69 (2004) 013001.*
- *G. Fiorentini et al. Phys. Rev. D 72 (2005) 033017.*
- *K.A. Hochmuth, Prog. Part. Nucl. Phys. 57 (2006) 293.*
- *G.L. Fogli et al. Earth, Moon, and Planets 99 (2007) 111.*
- *G. Fiorentini et al., Phys. Rep. 453 (2007) 117.*
- *S. Enomoto et al. Earth Planet. Sci. Lett. 258 (2007) 147.*
- *G. Fiorentini, et al., Phys. Rev. D 86 (2012) 033004.*
- *Y. Huang, et al., Geochem., Geophys., Geosyst. 14 (2013) 2003.*
- *O. Šramek, et al., Earth Planet. Sci. Lett. 361 (2013) 356.*

Aside from the "interesting" part of estimating the global distributions of U and Th in core, mantle, continental and oceanic crusts, models require a more mundane, hi res description of the distributions in the nearby crust (because of the $1/L^2$ in the integral)

The expected rate at different world locations

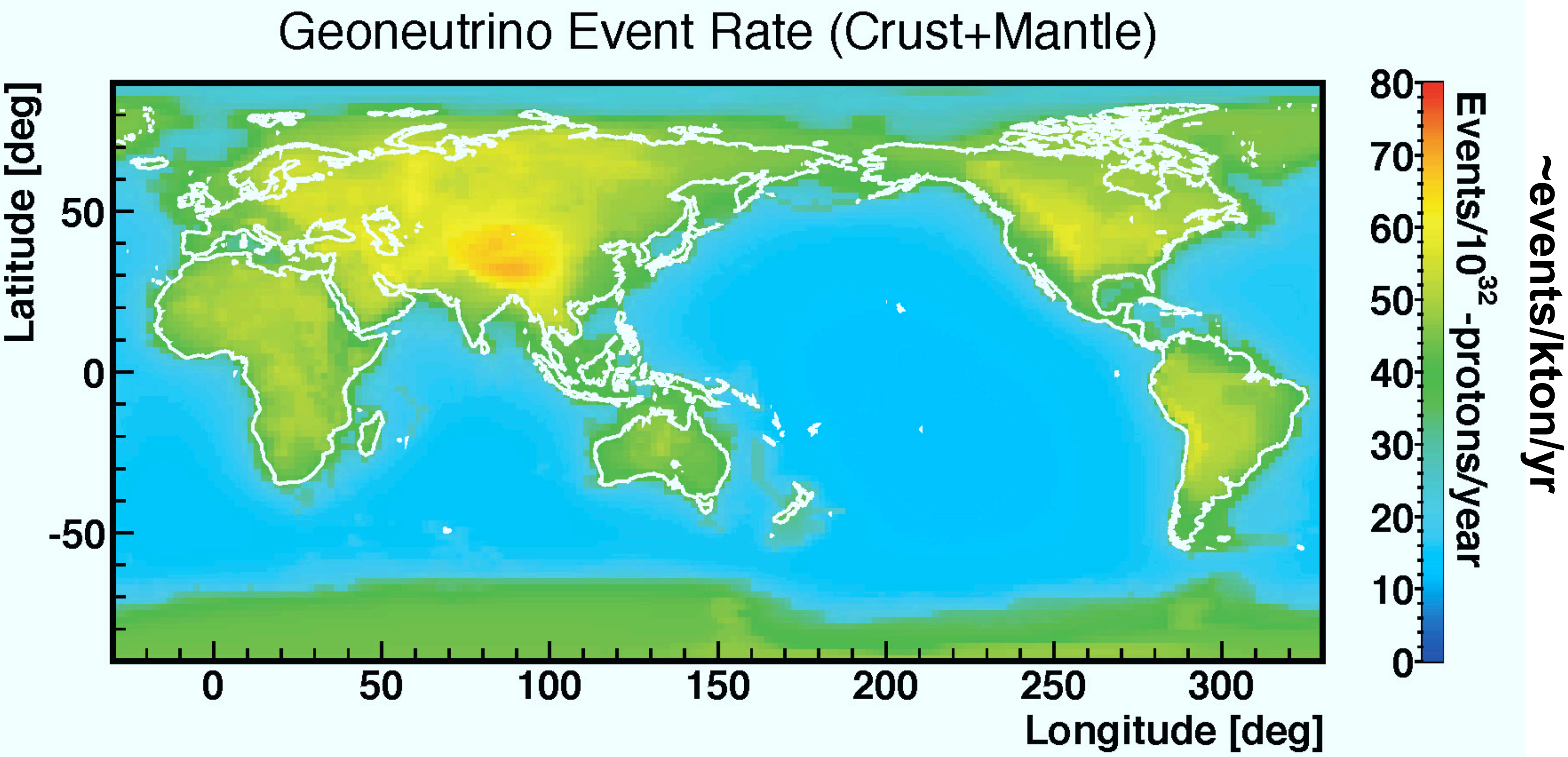


Image: S. Enomoto

Note the rate scale:

in most places expect 4 events/month in a 1kton detector!

Unfortunately where underground labs are this rate is mostly due to the crust

Crust is less interesting as it can be sampled directly

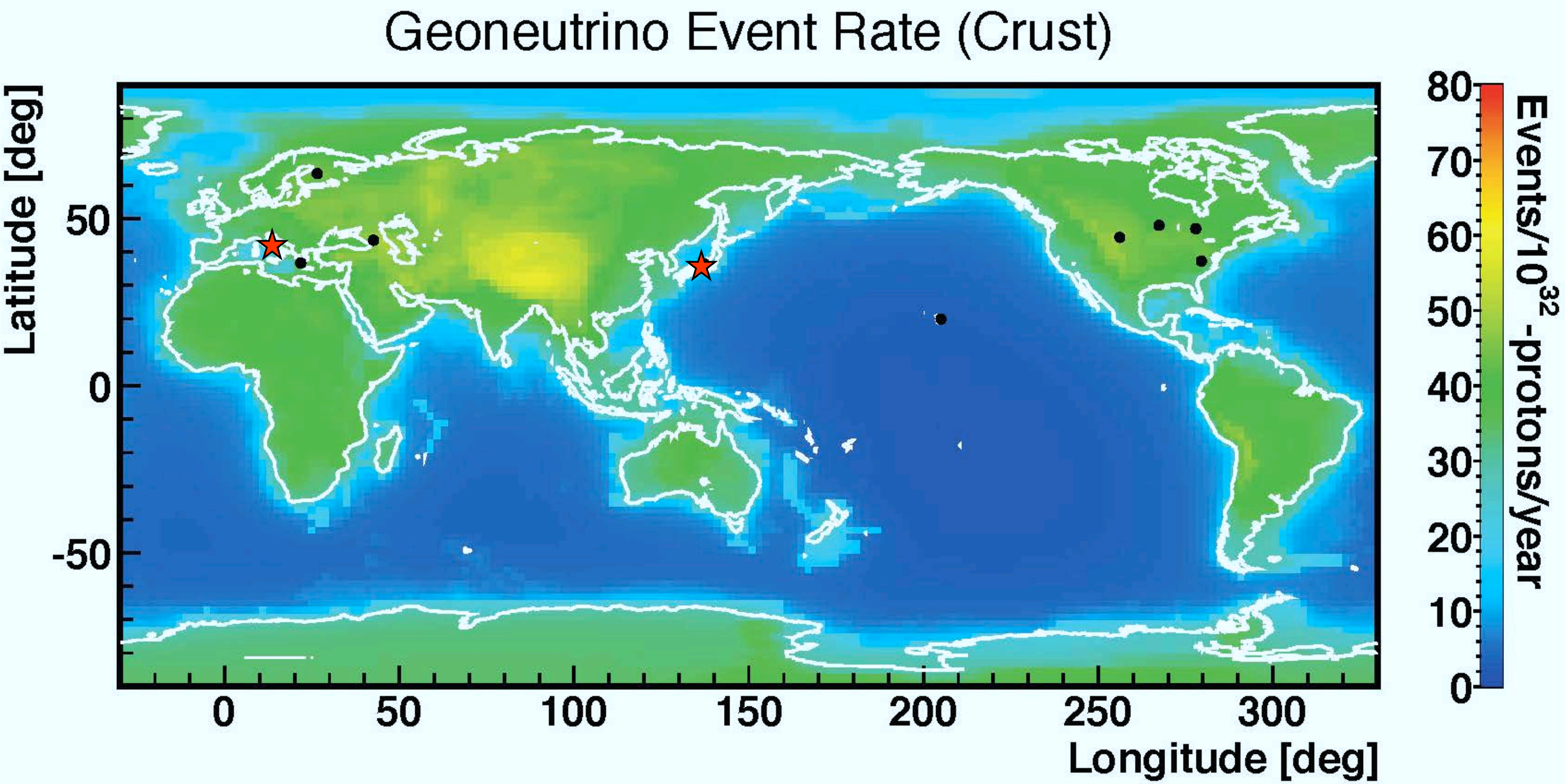
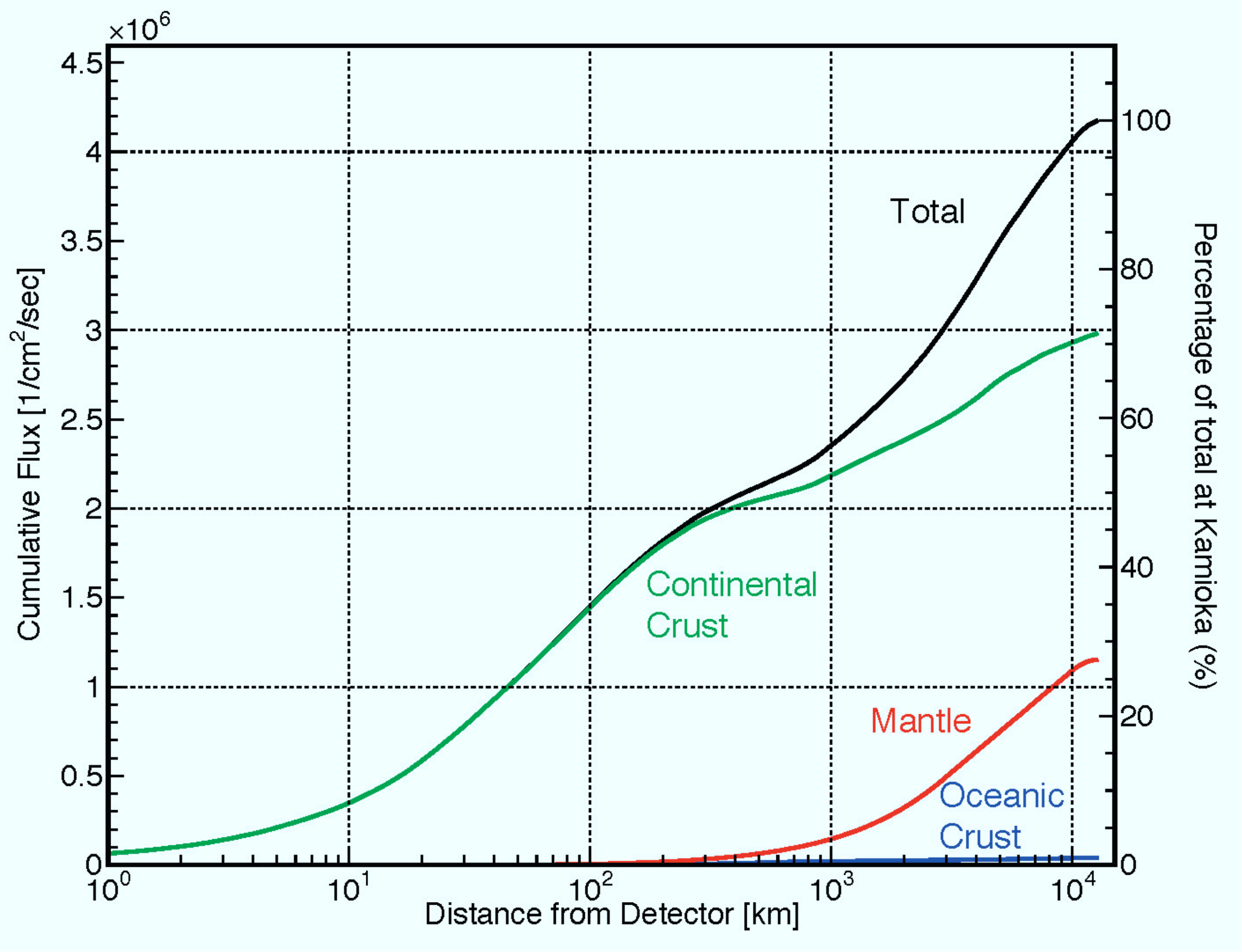


Image: S. Enomoto

The breakdown of various contributions at the Kamioka site



Background from reactors.

Note that in many locations this is a severe problem (although reactors are ~off today in Japan)

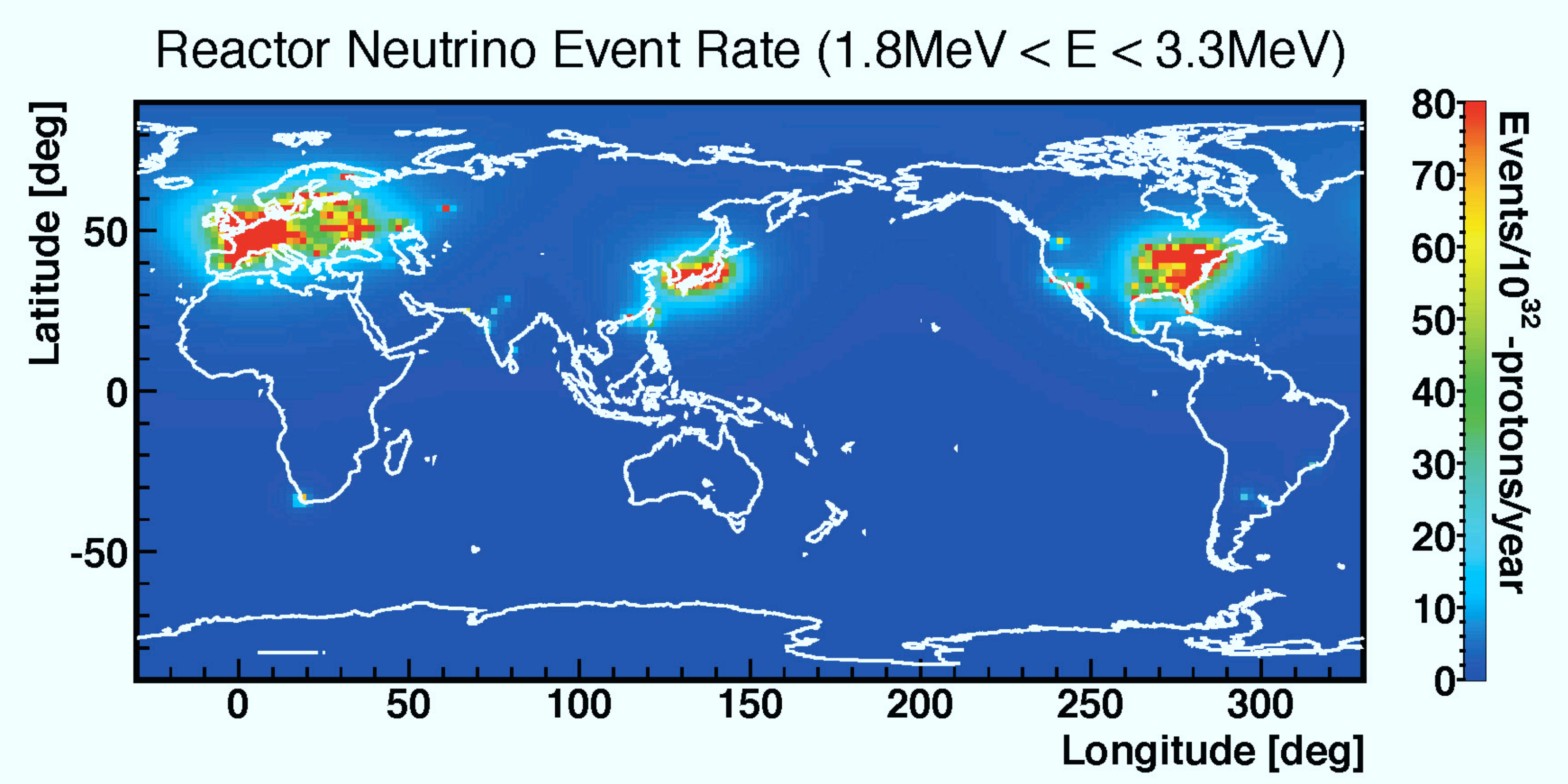


Image: S. Enomoto

The ideal location to study the Earth's mantle is the middle of an ocean, where there are no reactors and the crust is thinnest and depleted of Th & U

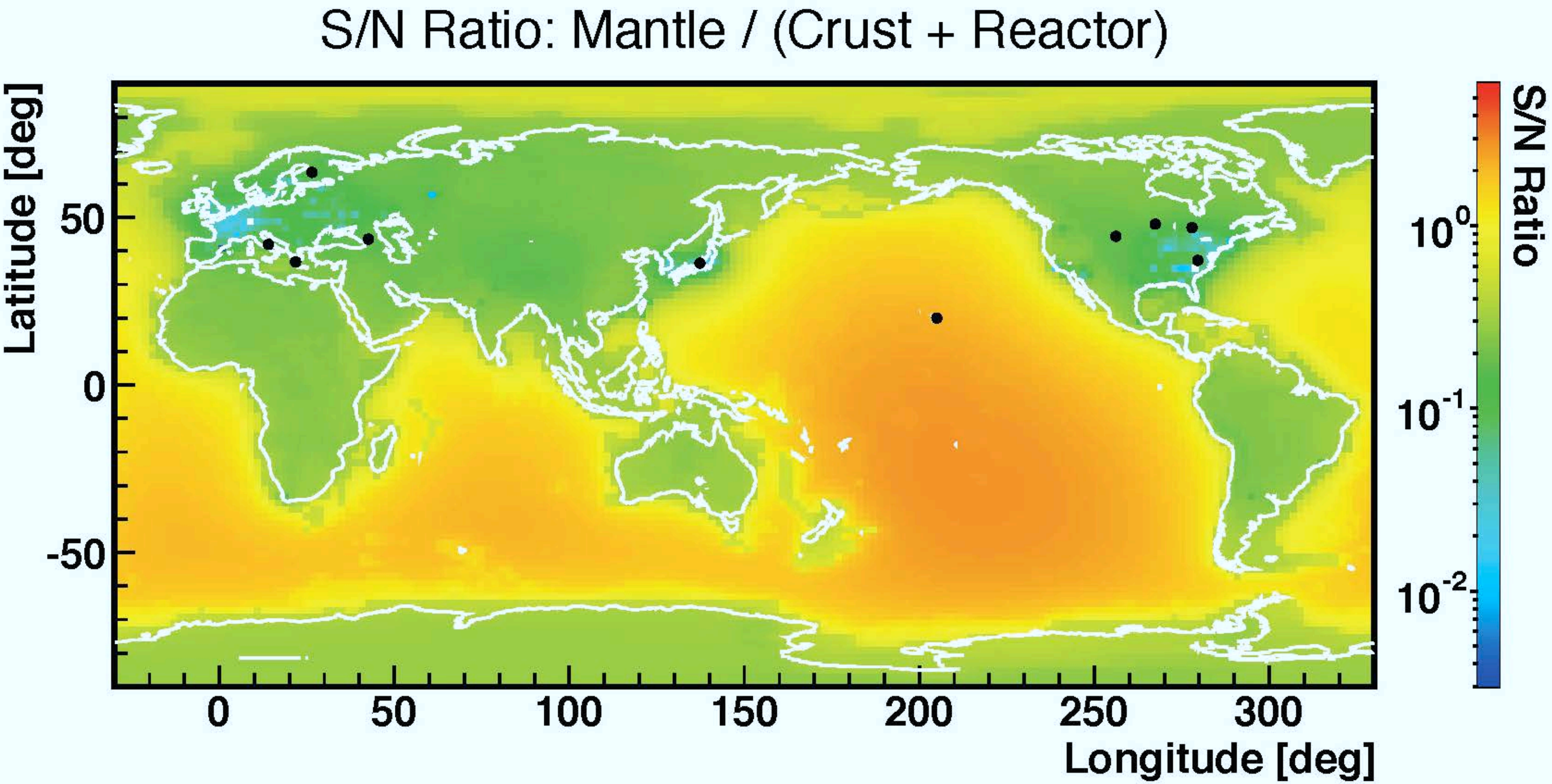
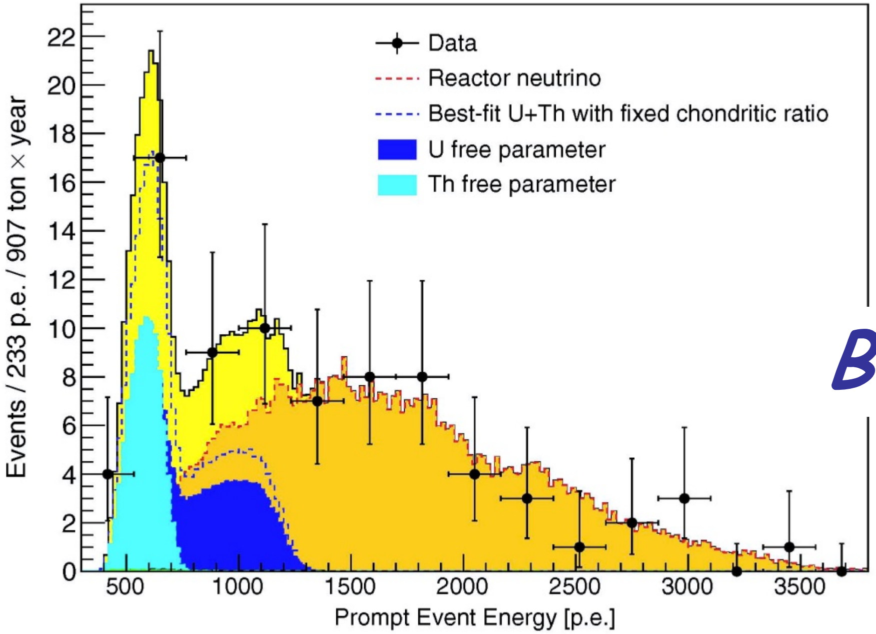
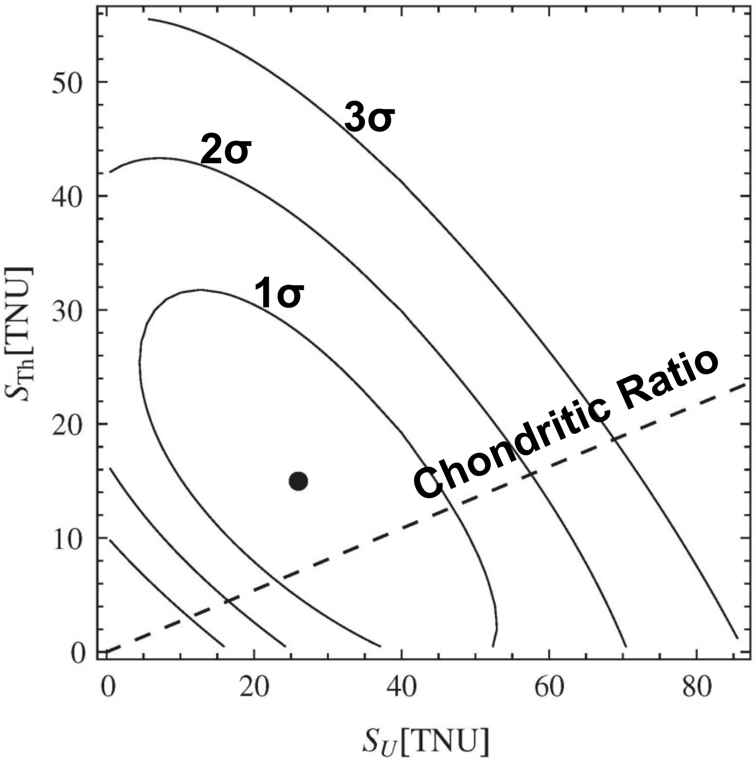


Image: S. Enomoto

In principle data could derive the Th/U ratio



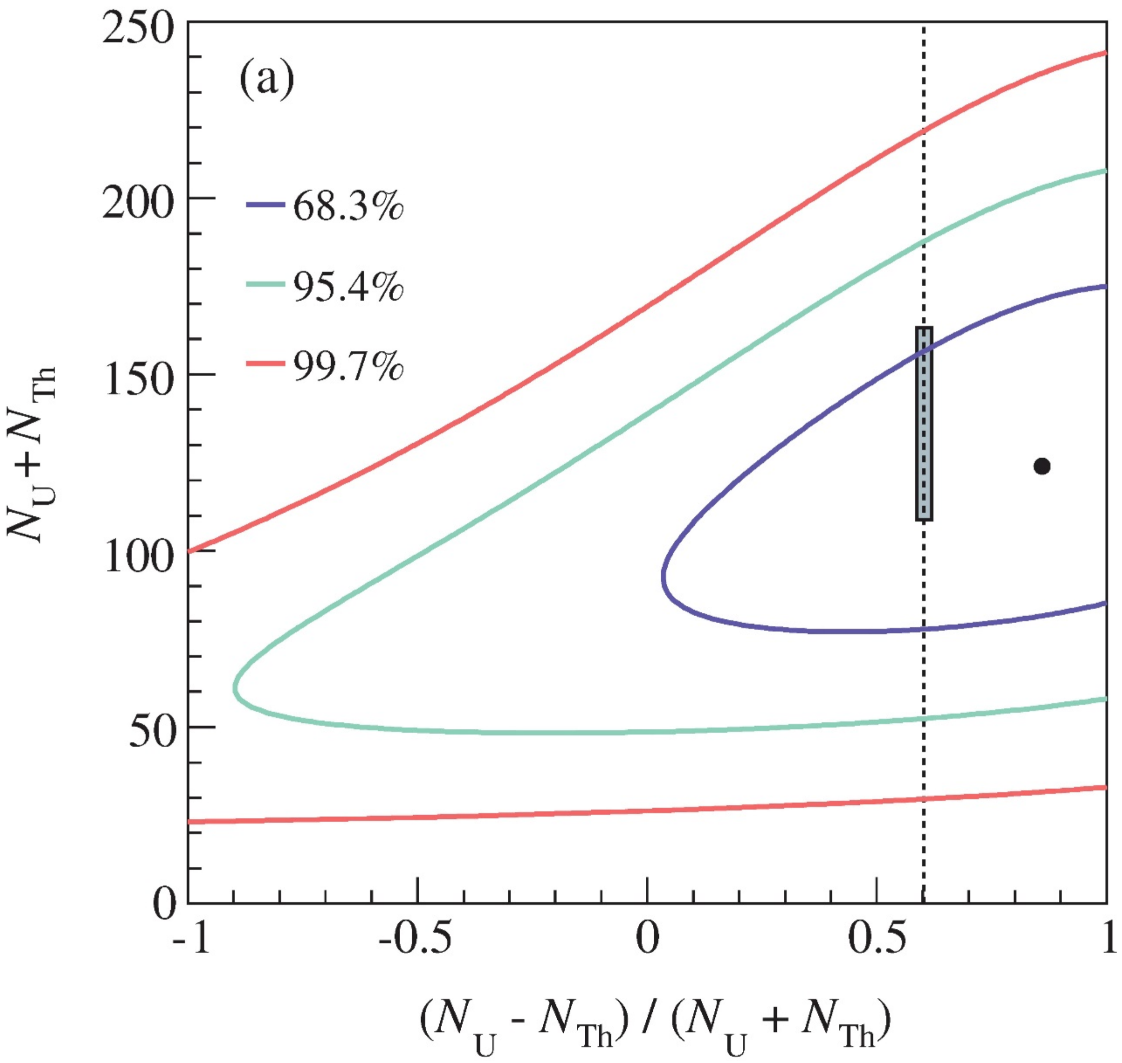
Borexino



But the uncertainty is still large and this is compatible with the C1 chondritic meteorite ratio mass ratio=3.9

Similar result for KamLAND

Again, the error is large, and the result compatible with C1 chondritic meteorite mass ratio of 3.9



How does the model compare with data for the total U + Th rates?

	Borexino flux (TNU)	KamLAND flux (TNU)
Local crust (local geology)	9.7 ± 1.3	17.7 ± 1.4
Remote crust (global property)	$13.7^{+2.8}_{-2.3}$	$7.3^{+1.5}_{-1.2}$
Total crust	$23.4^{+3.1}_{-2.6}$	$25.0^{+2.1}_{-1.8}$
Continental Lithospheric Mantle	$2.2^{+3.1}_{-1.3}$	$1.6^{+2.2}_{-1.0}$
(Homogeneous) Mantle	8.7	8.8
Total model	$34.3^{+4.4}_{-2.9}$	$35.4^{3.0}_{-2.1}$
Measurement	$\mathbf{38.8 \pm 12.0}$	$\mathbf{30 \pm 7}$

1 TNU = 1 interaction/(yr 10^{32} target protons) ~ 1 interaction/(yr kton)

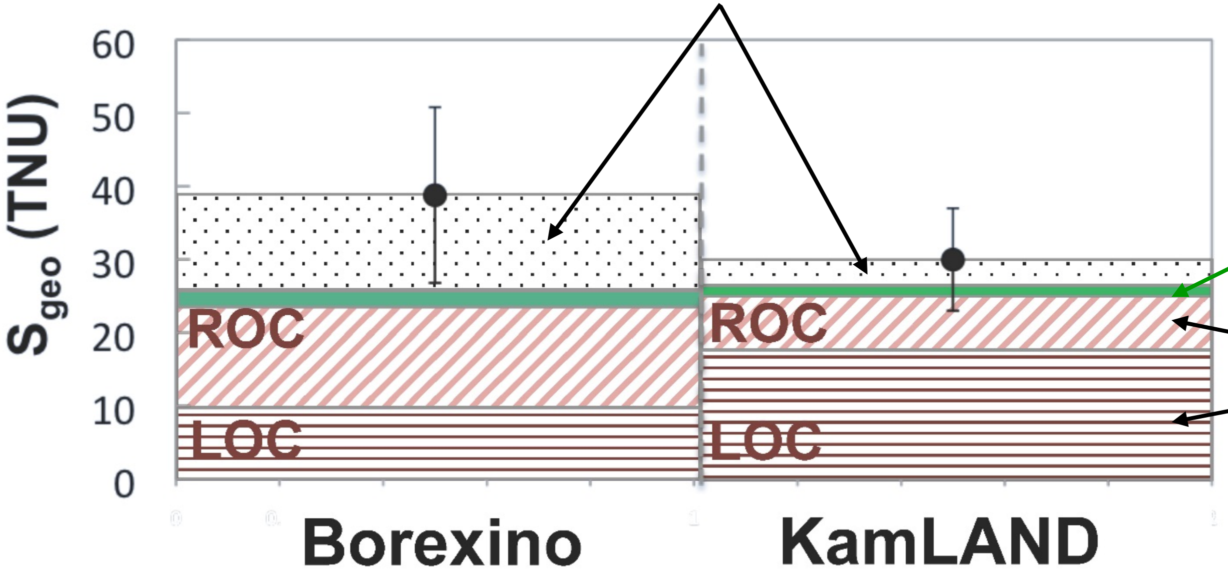
For ^{232}Th: Flux[10^{-6} cm^{-2}s^{-1}] = Rate[TNU]/4.07

^{238}U: Flux[10^{-6} cm^{-2}s^{-1}] = Rate[TNU]/12.8

from L.Ludhova and S.Zavatarelli, arXiv:1310.3961 (15 Oct 2013)

➔ With the U/Th fixed by Chondritic Meteorites

Remaining mantle contributions



Continental lithospheric mantle

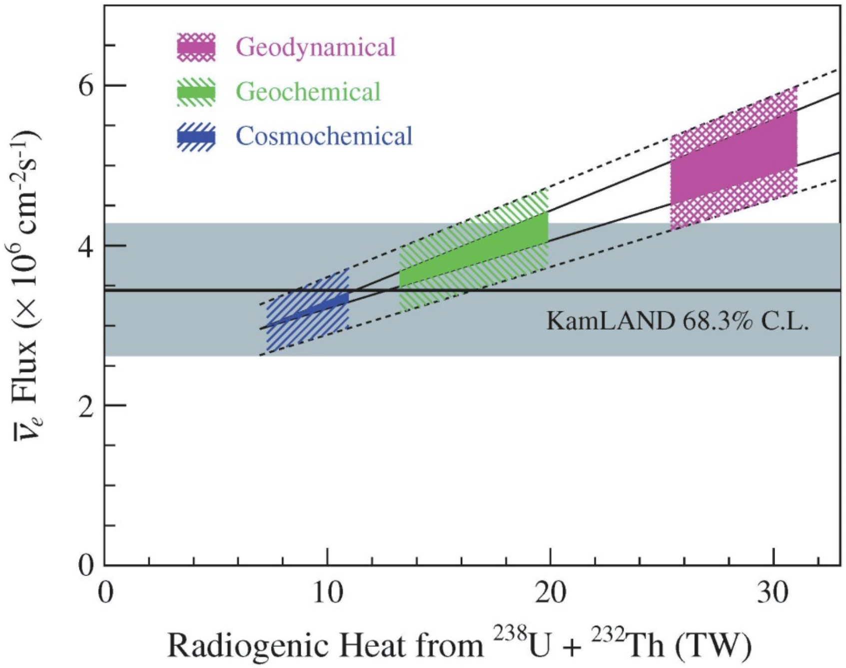
Crustal contributions

from L. Ludhova and S. Zavatarelli, arXiv:1310.3961 (15 Oct 2013)

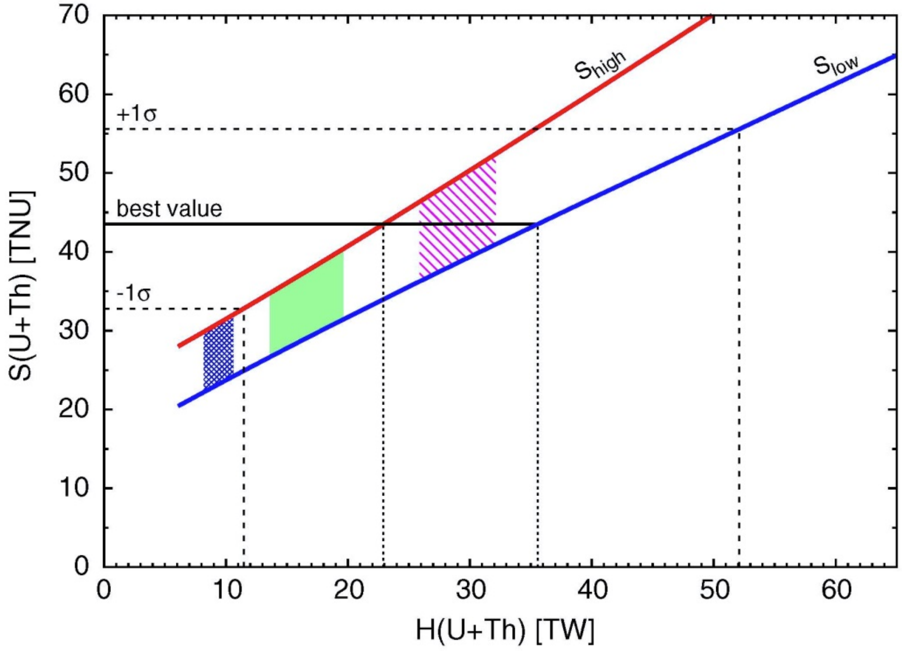
From PRD 92 (2015) 031101(R) Borexino detects mantle neutrinos @98% CL

The experiments start having some ability of discriminating between Earth models (except for the time being they don’t quite agree)

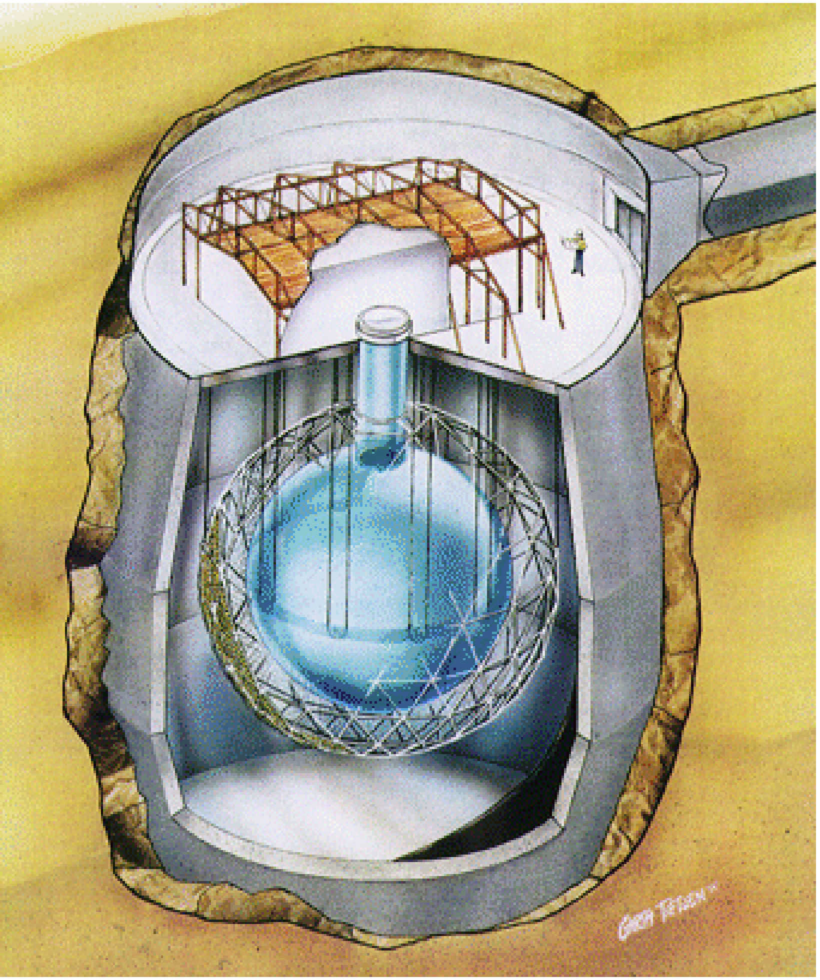
KamLAND: PRD 88 (2013) 033001



Borexino: PRD 92 (2015) 031101

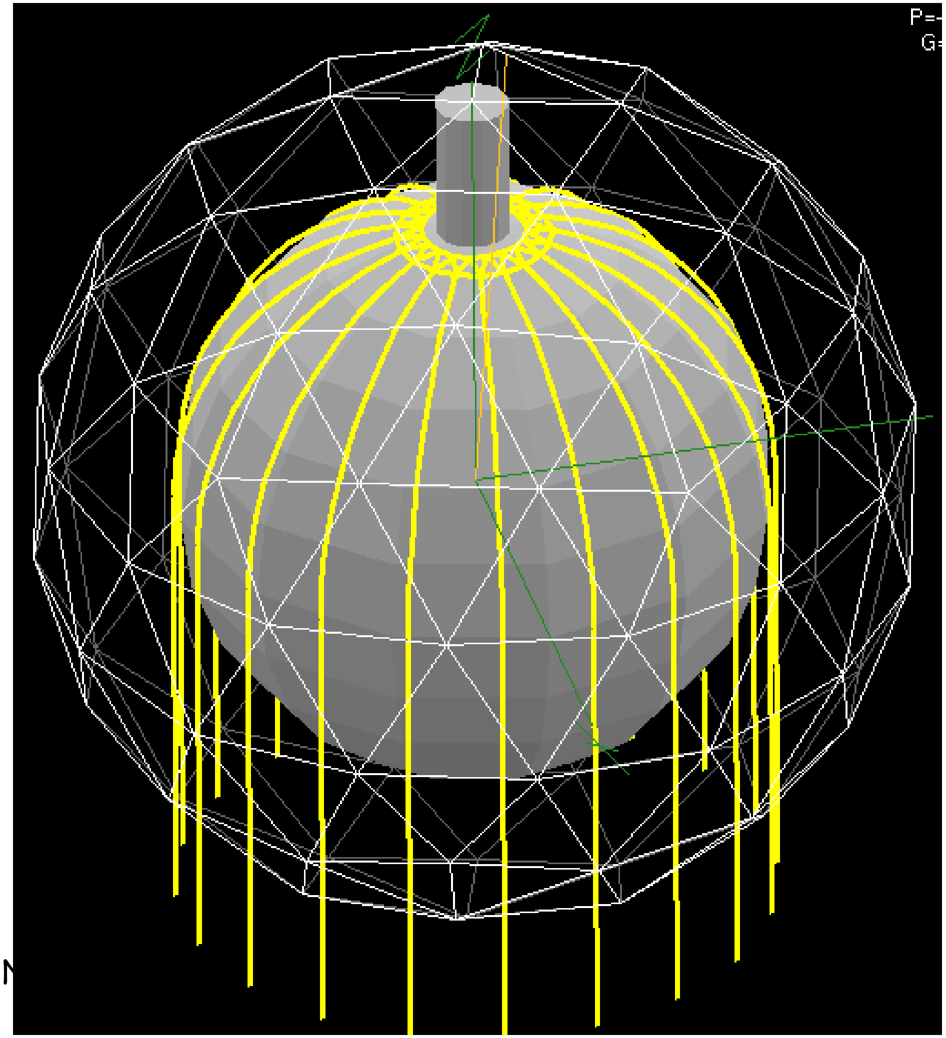


The near future: SNO+

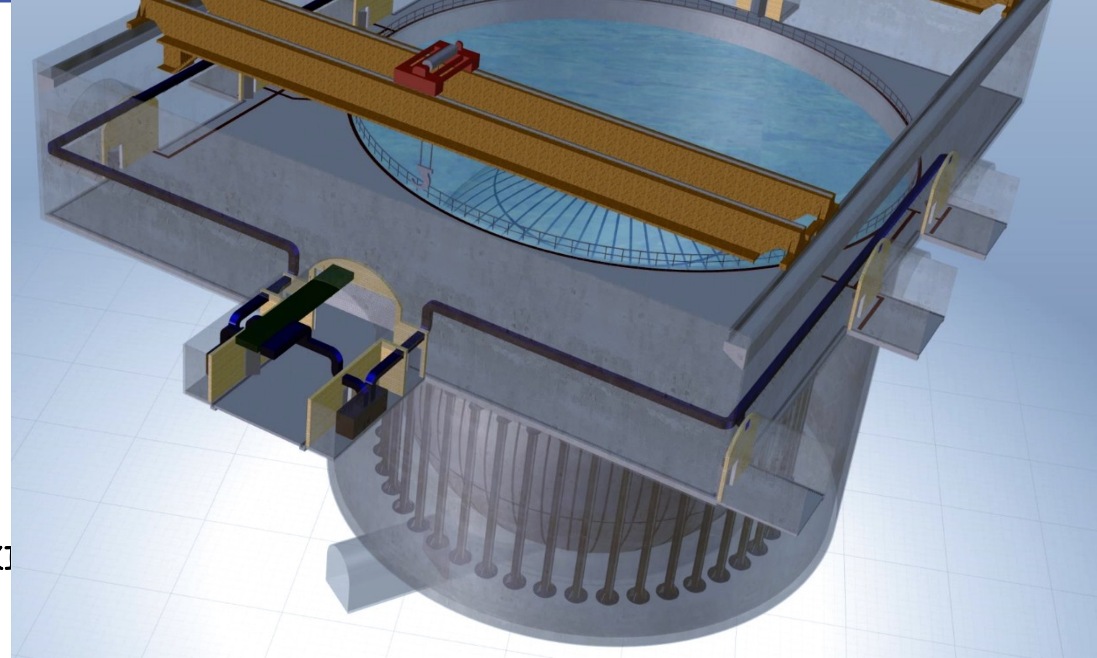


~1kton

SNO site



Slightly later: JUNO



20 kton
liquid scintillator
(~20x KamLAND
~60x Borexino!)

But, of course, the real killer would be an oceanic site

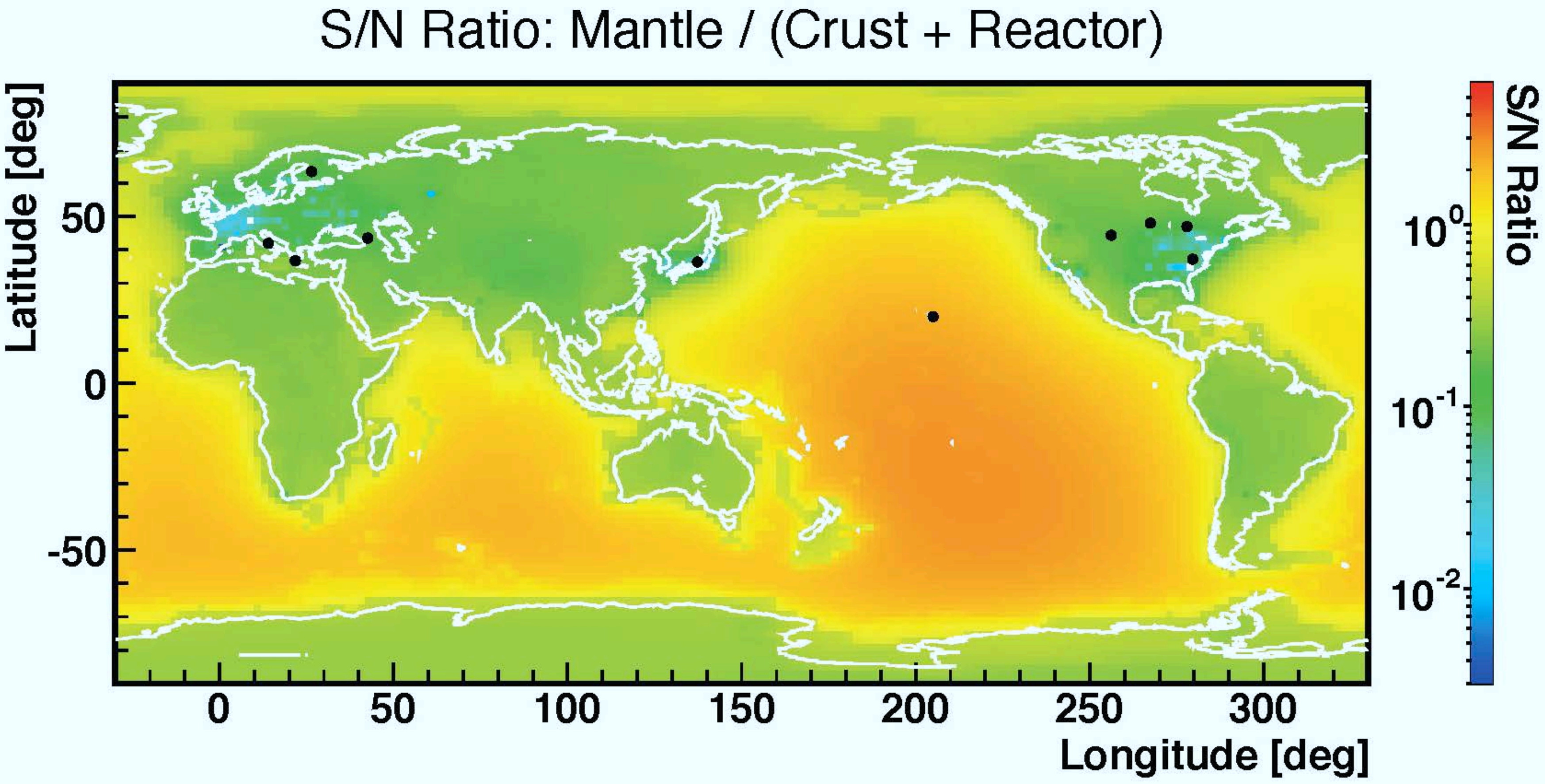
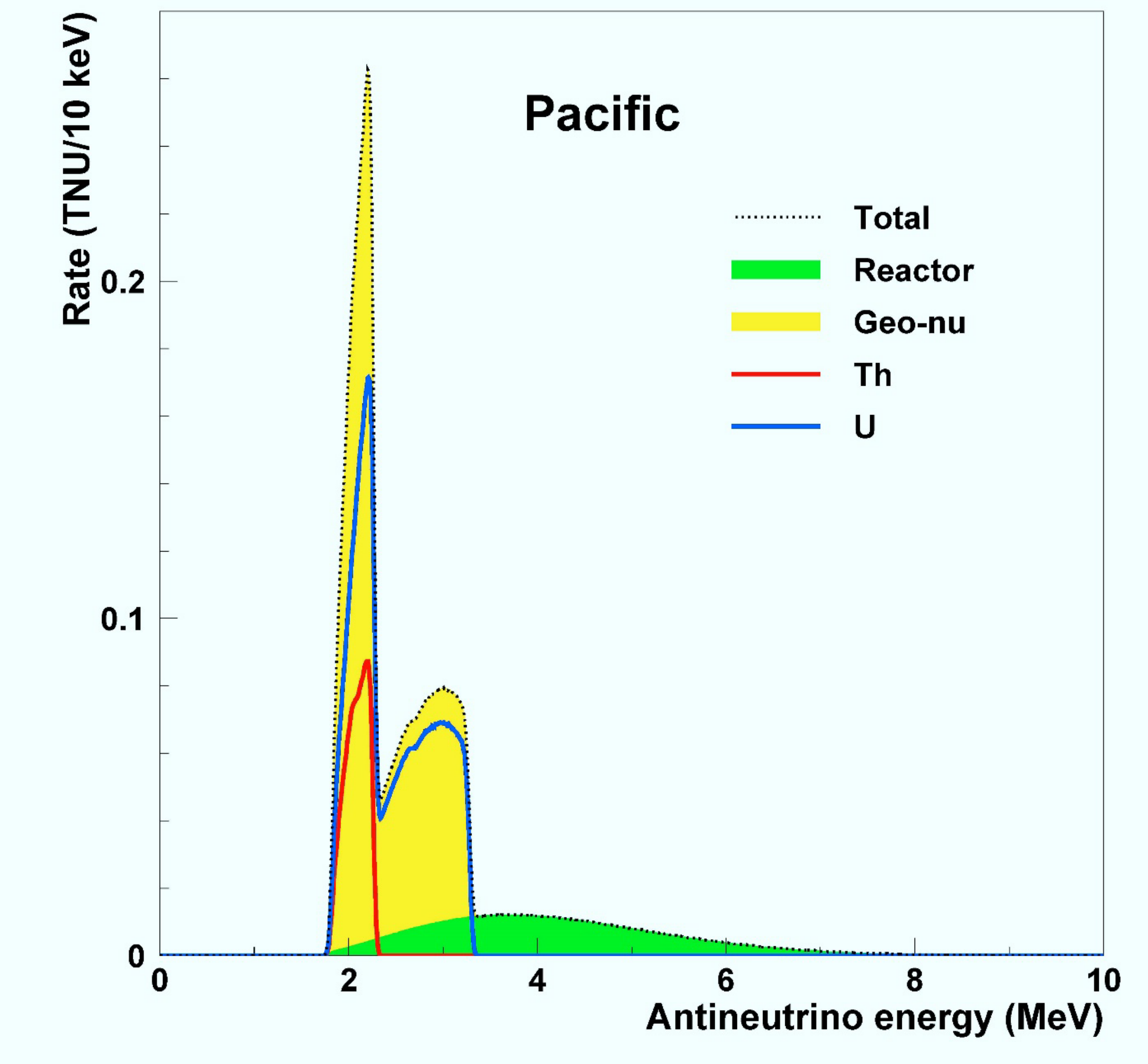


Image: S. Enomoto

Predicted Signals: Mid Pacific detector

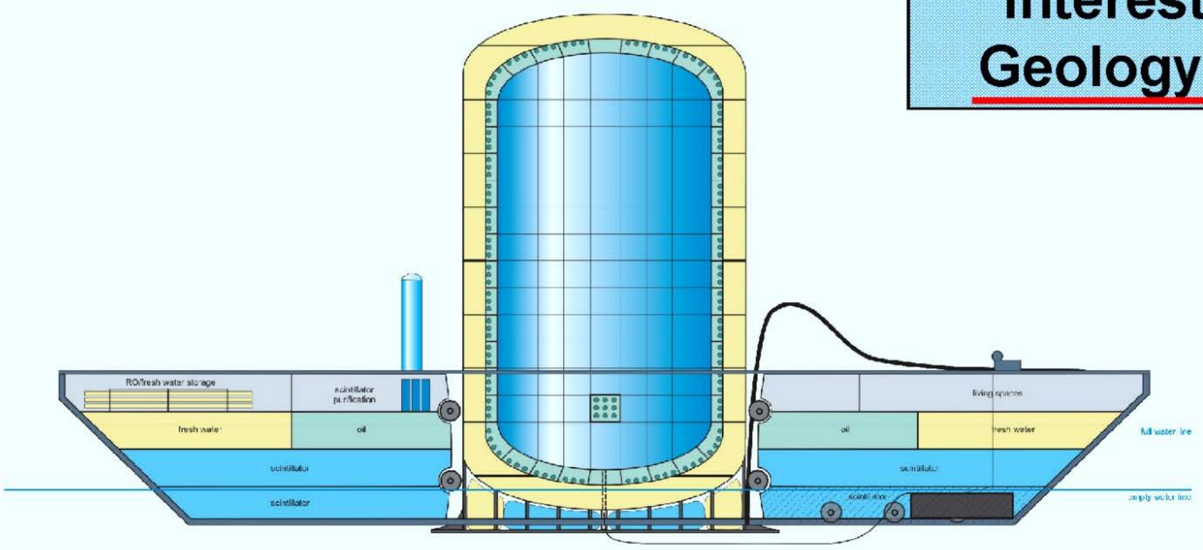


Steve Dye, AAP-2012, Honolulu Oct 2012

A 10kton dedicated detector that can be deployed in the ocean

Hanohano

An experiment with joint interests in Physics, Geology, and Security

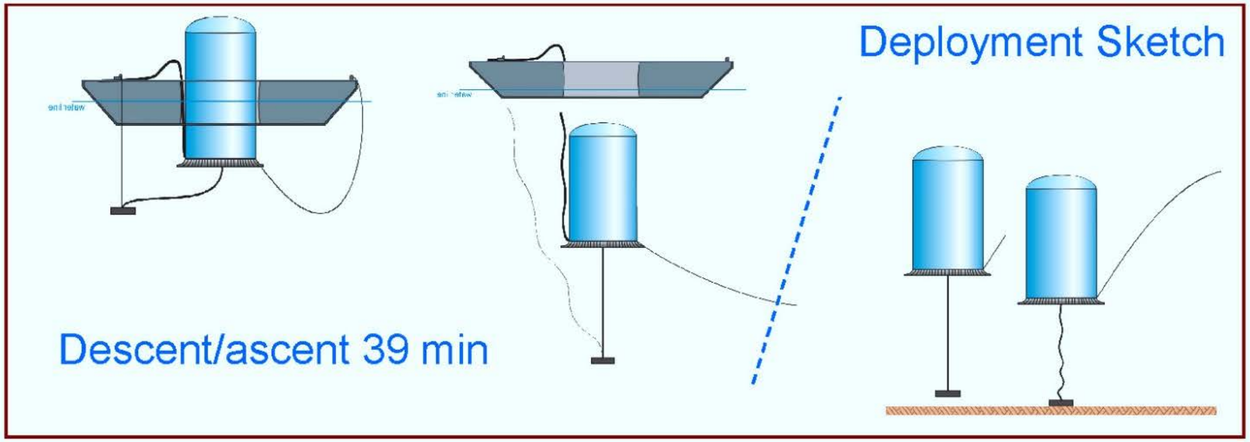


- multiple deployments
- deep water cosmic shield
- control-able L/E detection

Deep Ocean

$\bar{\nu}_e$

Observatory


Deployment Sketch

Descent/ascent 39 min

Neutrino Geoscience
2015 Paris

Fun conference, attended by neutrino physicists and Earth scientists! Learn a lot from each other!

Dec 2005	**Honolulu, HI**
Mar 2007	**Honolulu, HI**
Sep 2008	**SNOlab, ON**
Oct 2010	**Gran Sasso, I**
Mar 2013	**Takayama, JP**
Jun 2015	**Paris, F**

Is there a large nuclear reactor inside the Earth?

While natural reactors are known to have existed on Earth a natural reactor today presents a number of challenges because of the low concentration of ^{235}U

Nevertheless large natural reactors have been proposed

- In the core
  - *J.M. Herndon, PNAS USA 100, 3047 (2003)*
- Near core-mantle boundary
  - *V.D.Rusov et al. arXiv:0902.4092*
  - *R.J.deMeijer et al. Radiat.Phys.Chem. 71, 769 (2004)*

Part of the Oklo fossil reactor

A power of 5-10TW from fission may help explain heating, convection, ^{3}He anomaly and a number or other curiosities

Both models are strongly disfavored by mainstream geoscientists

The evidence for/against such a reactor is indirect and may be not iron-clad.

The detection of an excess of anti-neutrinos with reactor-like spectrum (hence at higher energy than that of geoneutrinos) would provide solid evidence

Both experiments have set limits that start probing the interesting regime

KamLAND $P_{reactor} < 3.7$ TW at 95% CL

Phys. Rev. D 88 (2013) 033001

Borexino $P_{reactor} < 4.5$ TW at 95% CL

Phys. Lett. B 722 (2013) 295

Wish list for future geoneutrino detectors:

- Better statistics (larger detectors)
- Multiple sites
- Oceanic site (this is very challenging but also very important)
- Pointing ability (very good position resolution)
- Lower threshold (^{40}K concentration is particularly interesting for mantle formation models)

Conclusions

- First example of "Applied Neutrino Physics" !!
- Clear detection of geoneutrinos by KamLAND and Borexino
- First chemical analysis of the mantle of the Earth
- Consistent with the current geological models
- SNO+ to join the club soon
- The much larger JUNO set to start in a few years
- A network of detector and an oceanic detector would drastically advance the knowledge of our planet