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
Highlight India

GLOBAL CLIMATE
Vital CO_2 flux from Amazon vegetation

BREAST CANCER
Gene signature for metastasis

FORENSIC SCIENCE
Everything has a fingerprint

INSIDE: INDIAN LIFE SCIENCES

nature outlook INDIA

EARTHLY POWERS

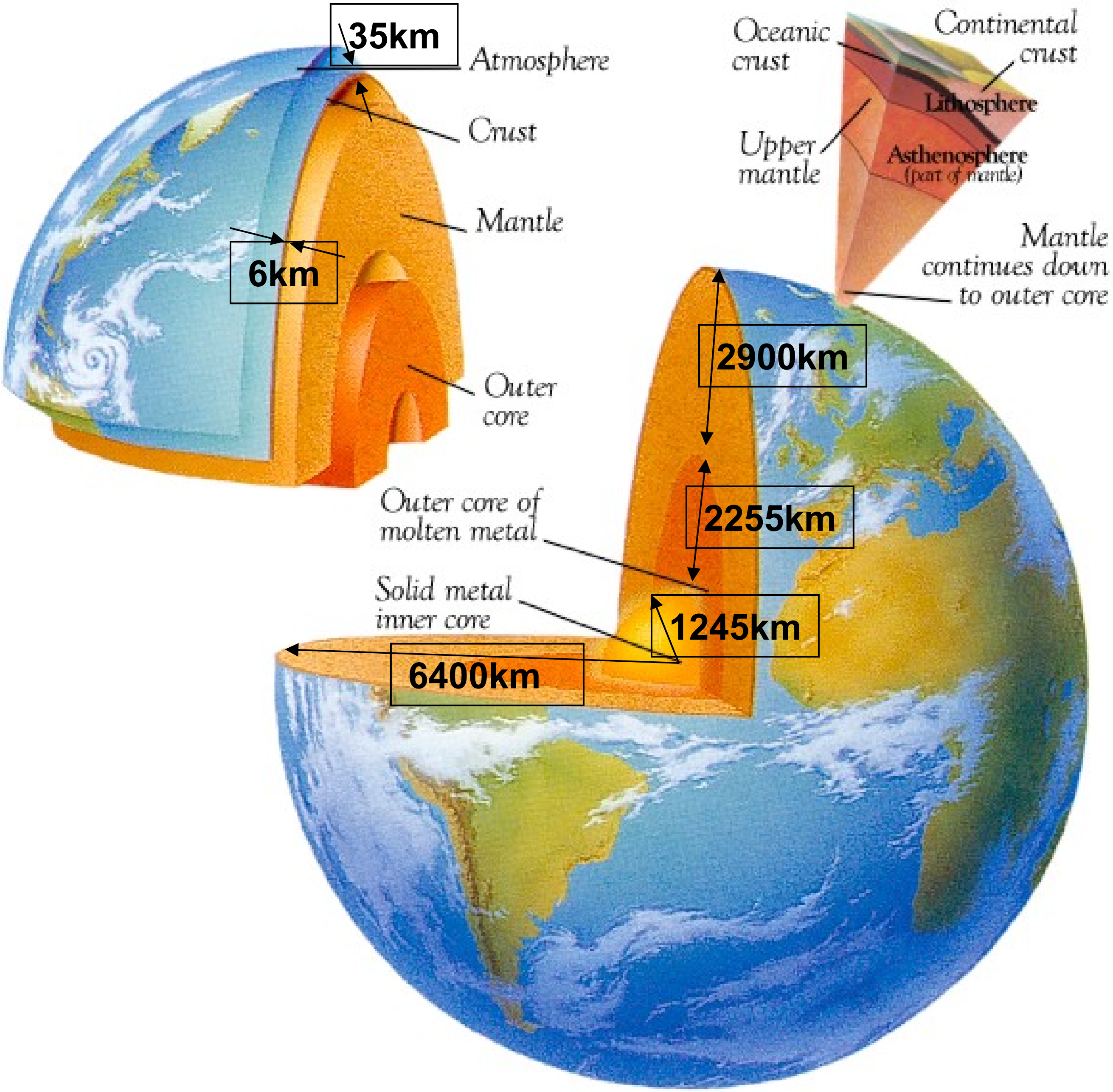
Geoneutrinos reveal Earth's inner secrets

$10.00US $12.99CAN

the Dawn of Neutrino Geophysics

G.Gratta
Physics Department
Stanford University

Structure of the Earth



- 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

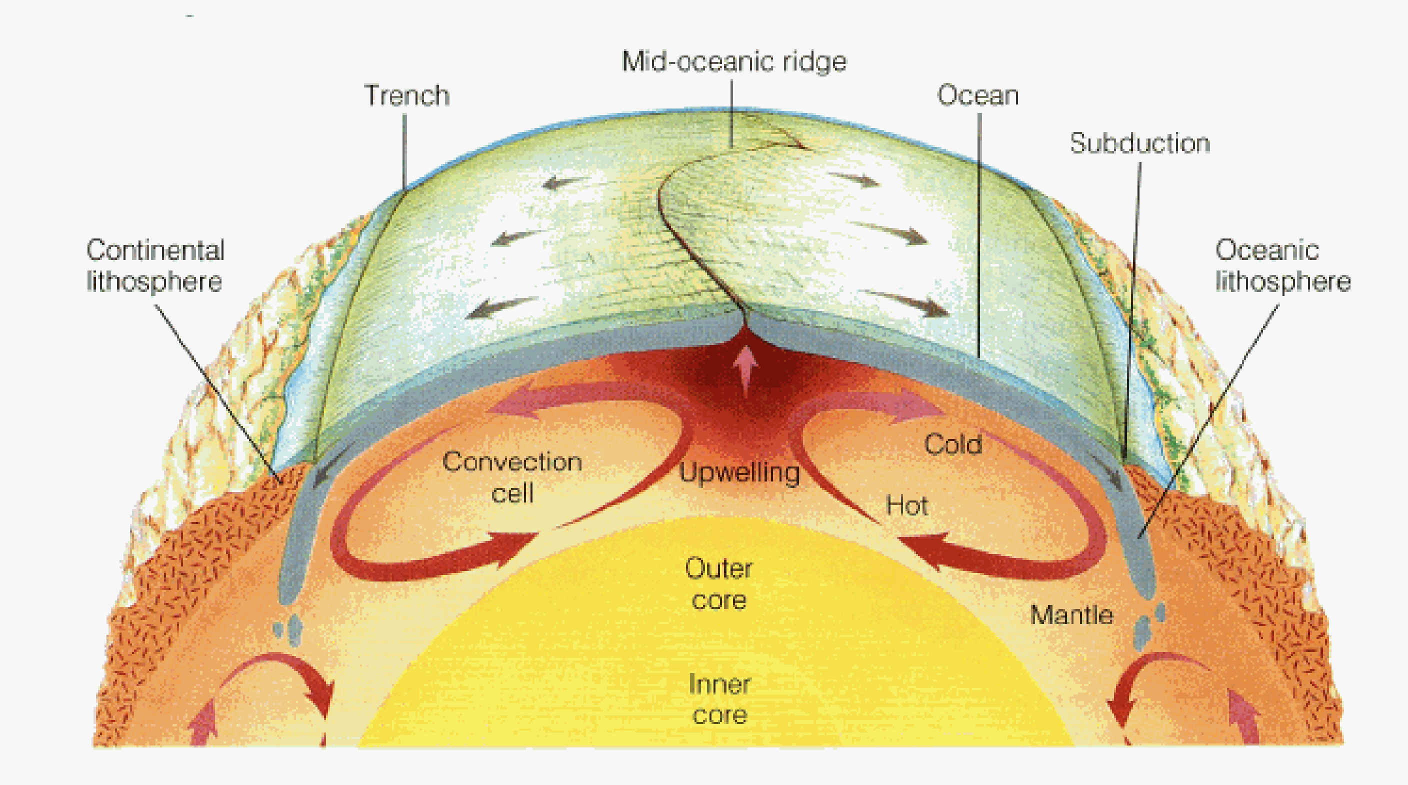


Image: http://www.dstu.univ-montp2.fr/PERSO/bokelmann/convection.gif

- 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.

Remember, always, the words of Francis Birch (1952)

"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

The only universal probe for the interior of the Earth is 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 not necessarily kosher.

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

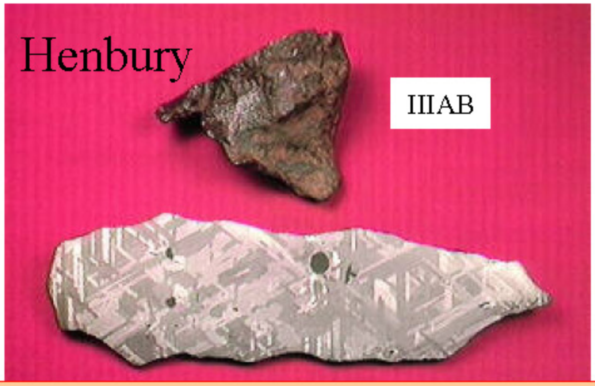
Mantle-crust pieces (?)

chondrites

undifferentiated planets (?)

Carbonaceous chondrite (CV3)

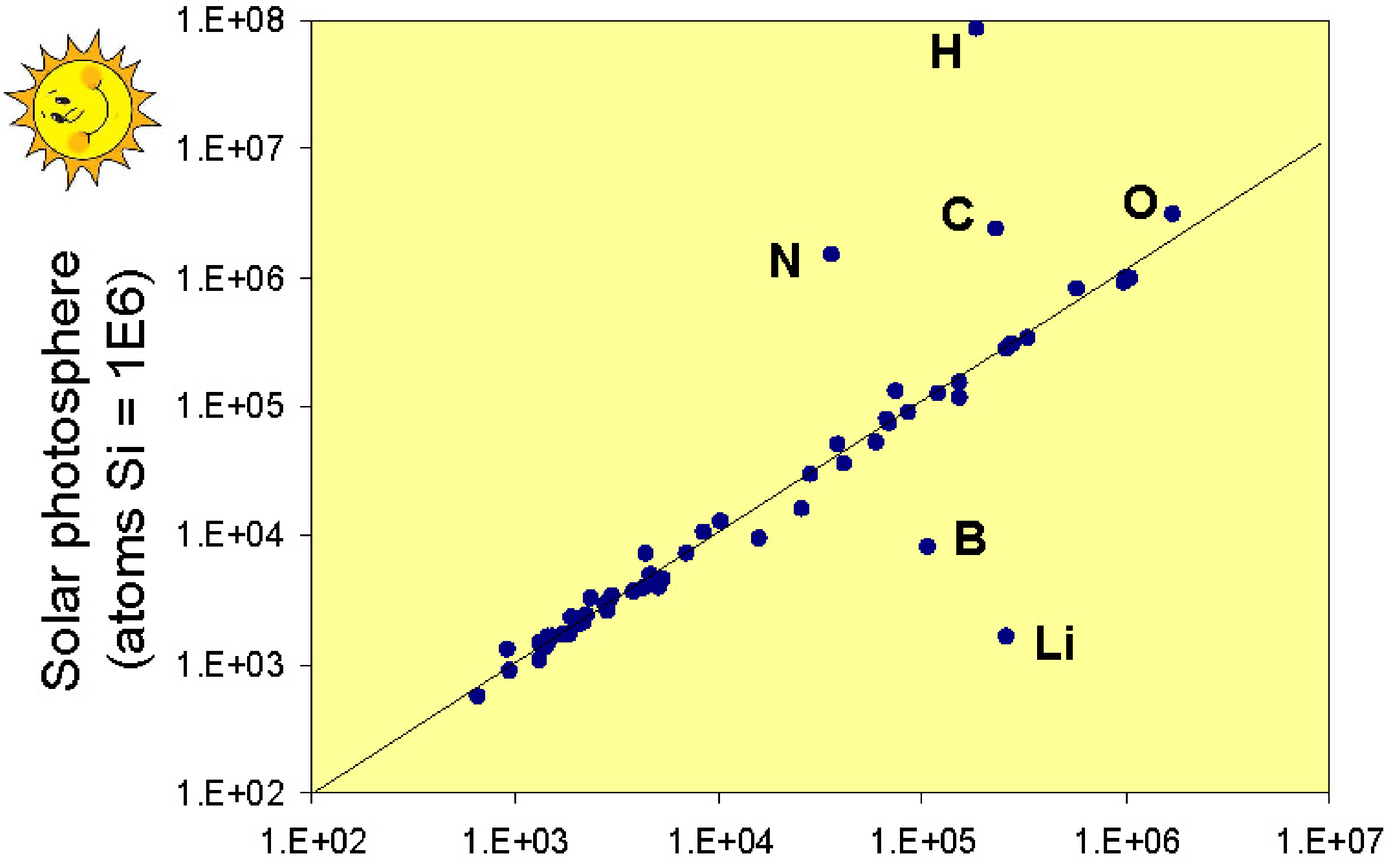
Pallasite: olivine and iron mixtures (CMB?)



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)

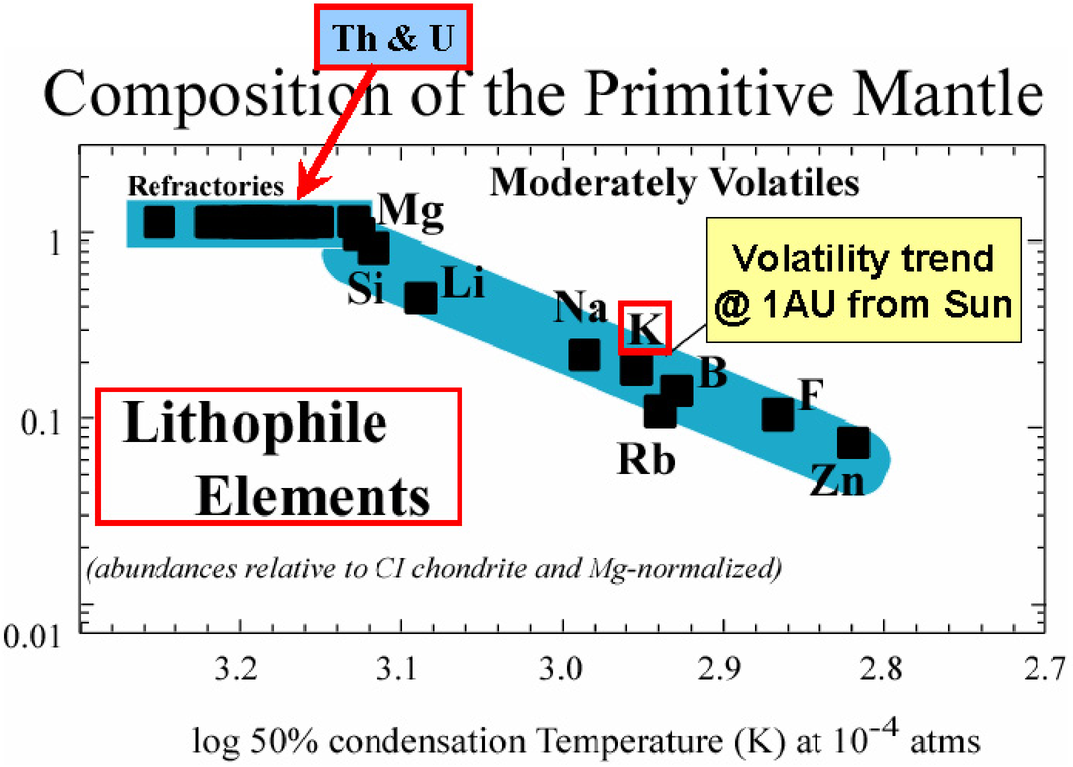


C1 carbonaceous chondrite
(atoms Si = 1E6)

McDonough, Neutrino 2008

Next:

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



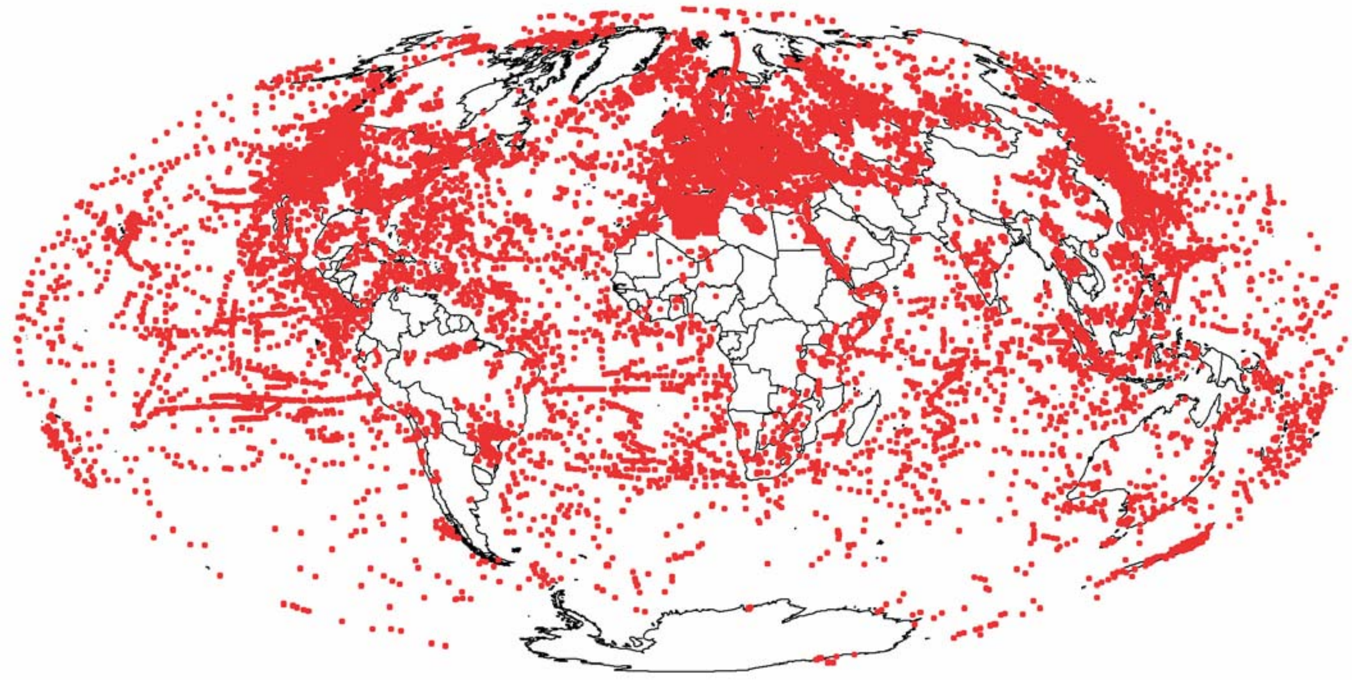
McDonough, Neutrino 2008

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 stidied

Q: What powers the Eyjafjallajökull?

Q: What powers the Eyjafjallajökull?

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

Same boreholes 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 recent analysis with different convection model gives 31±1 TW (61mW/m^2)…

Heat flow from the Earth

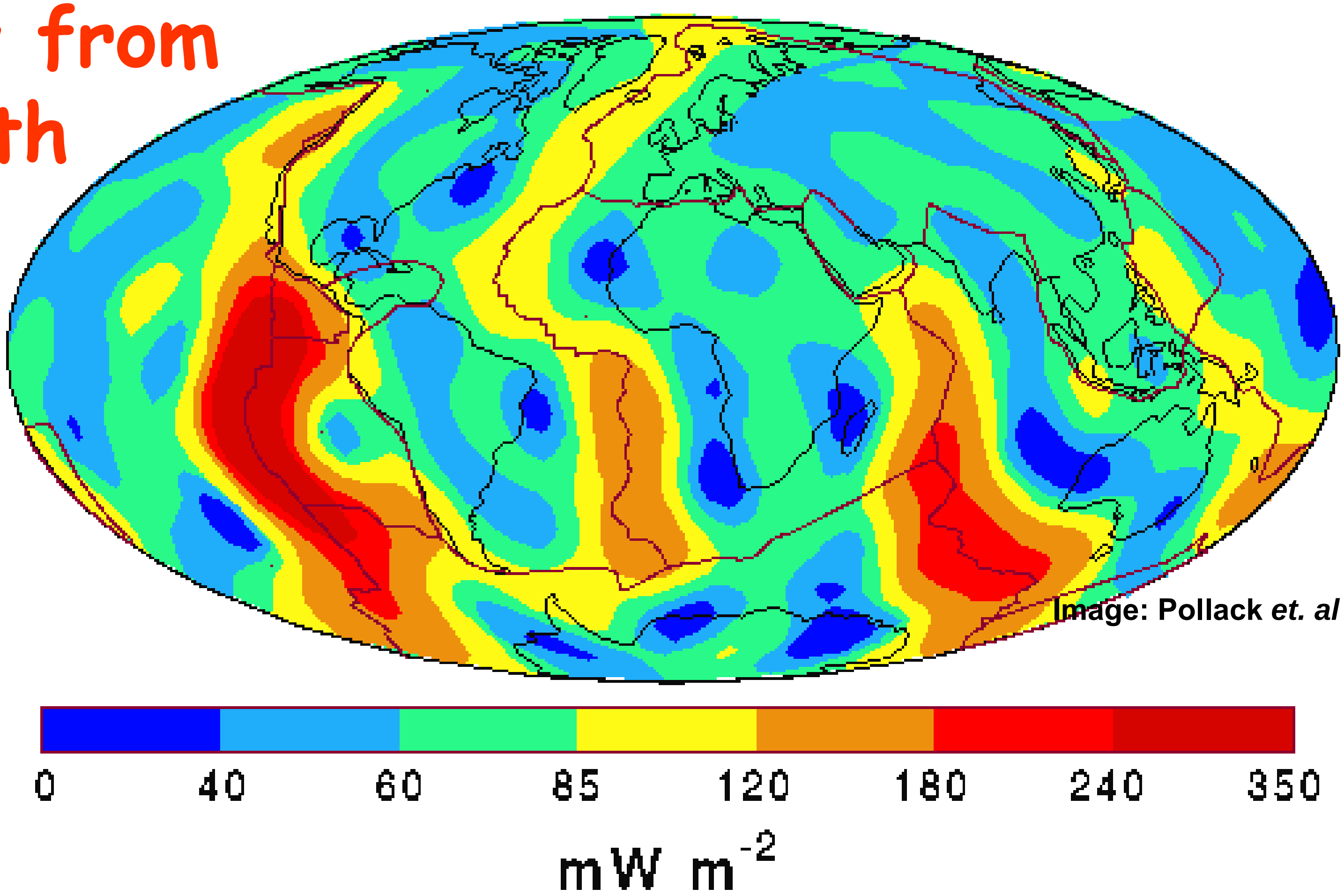


Image: Pollack *et. al*

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

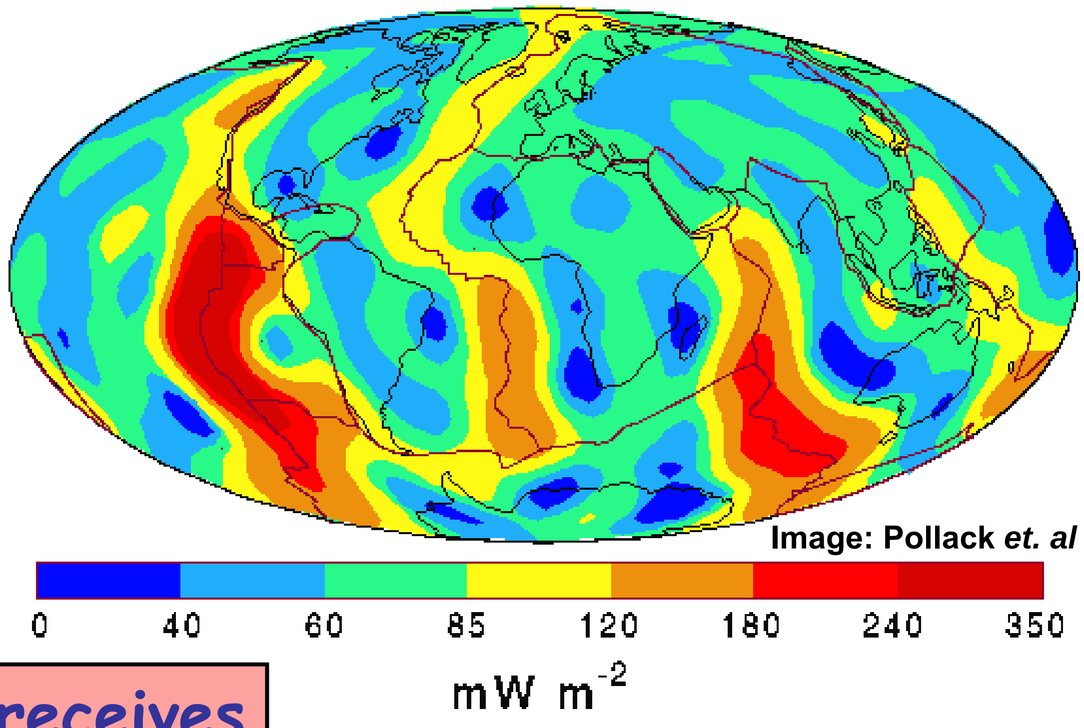
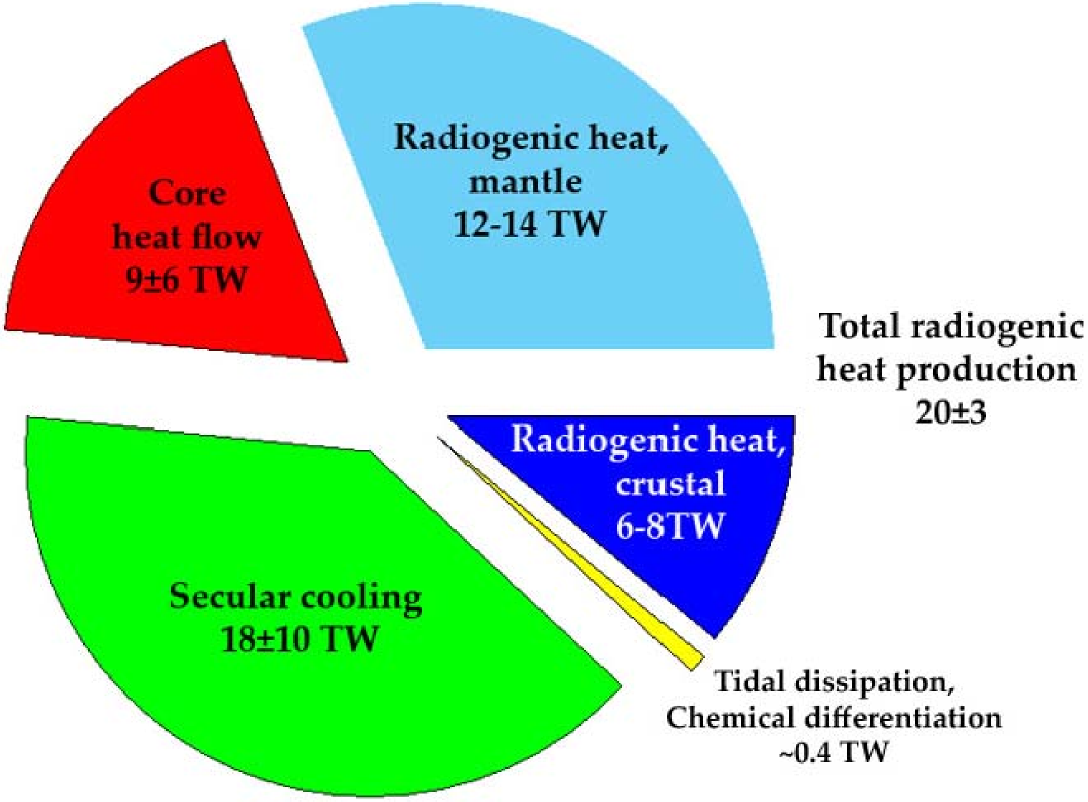


Image: Pollack *et. al*

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!

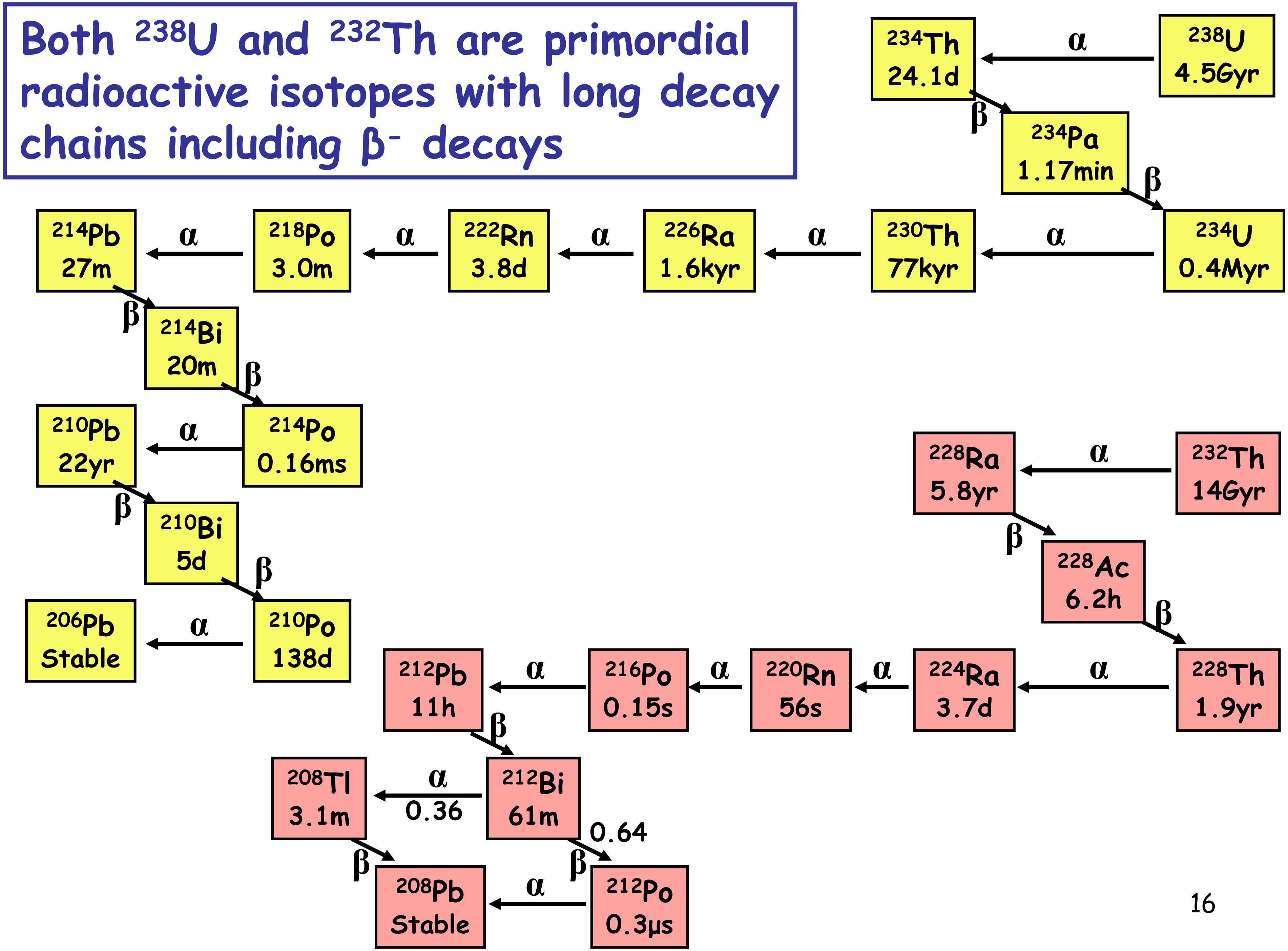
What produces the heat ?



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

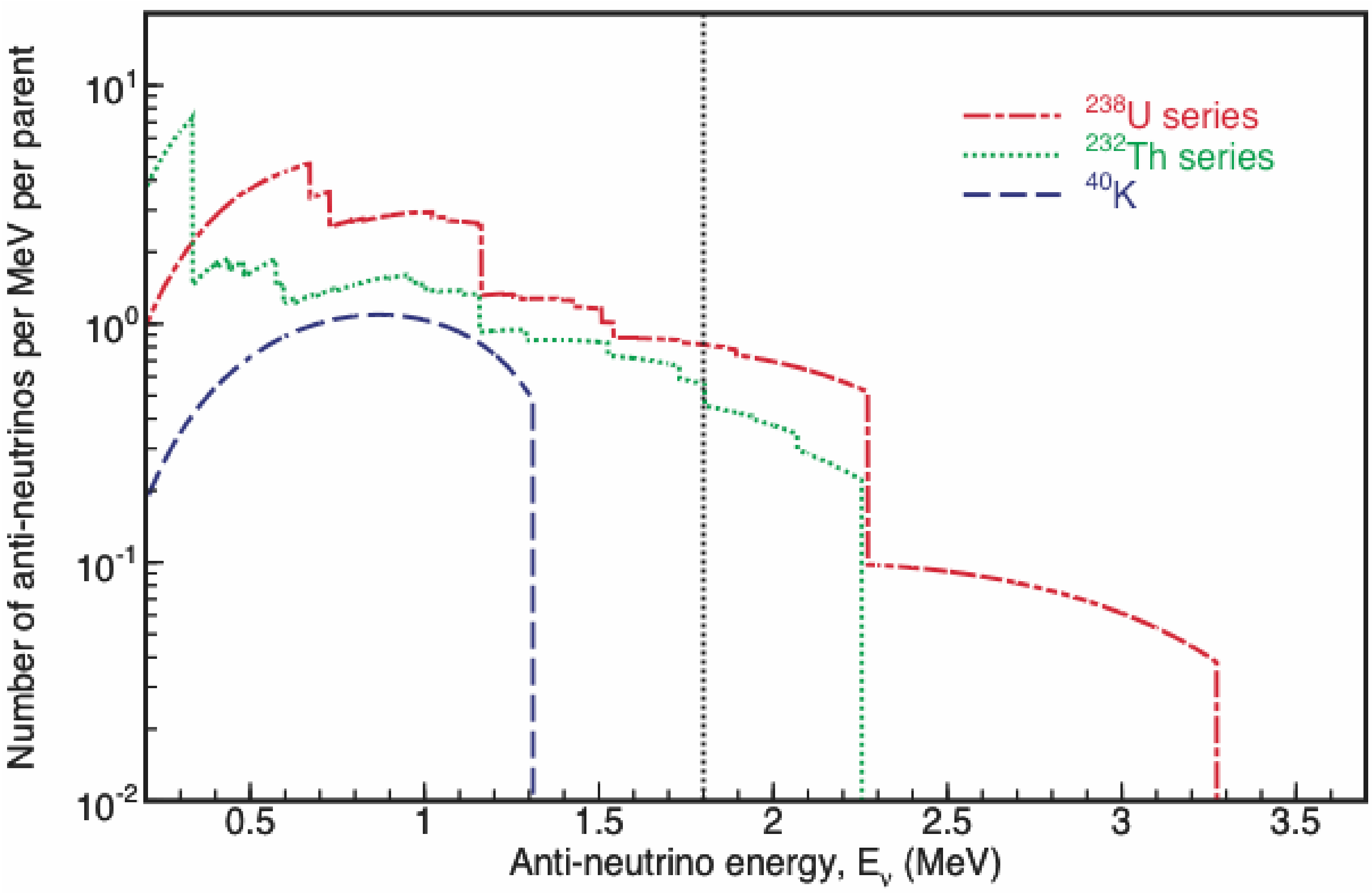
0.64 β

^{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)

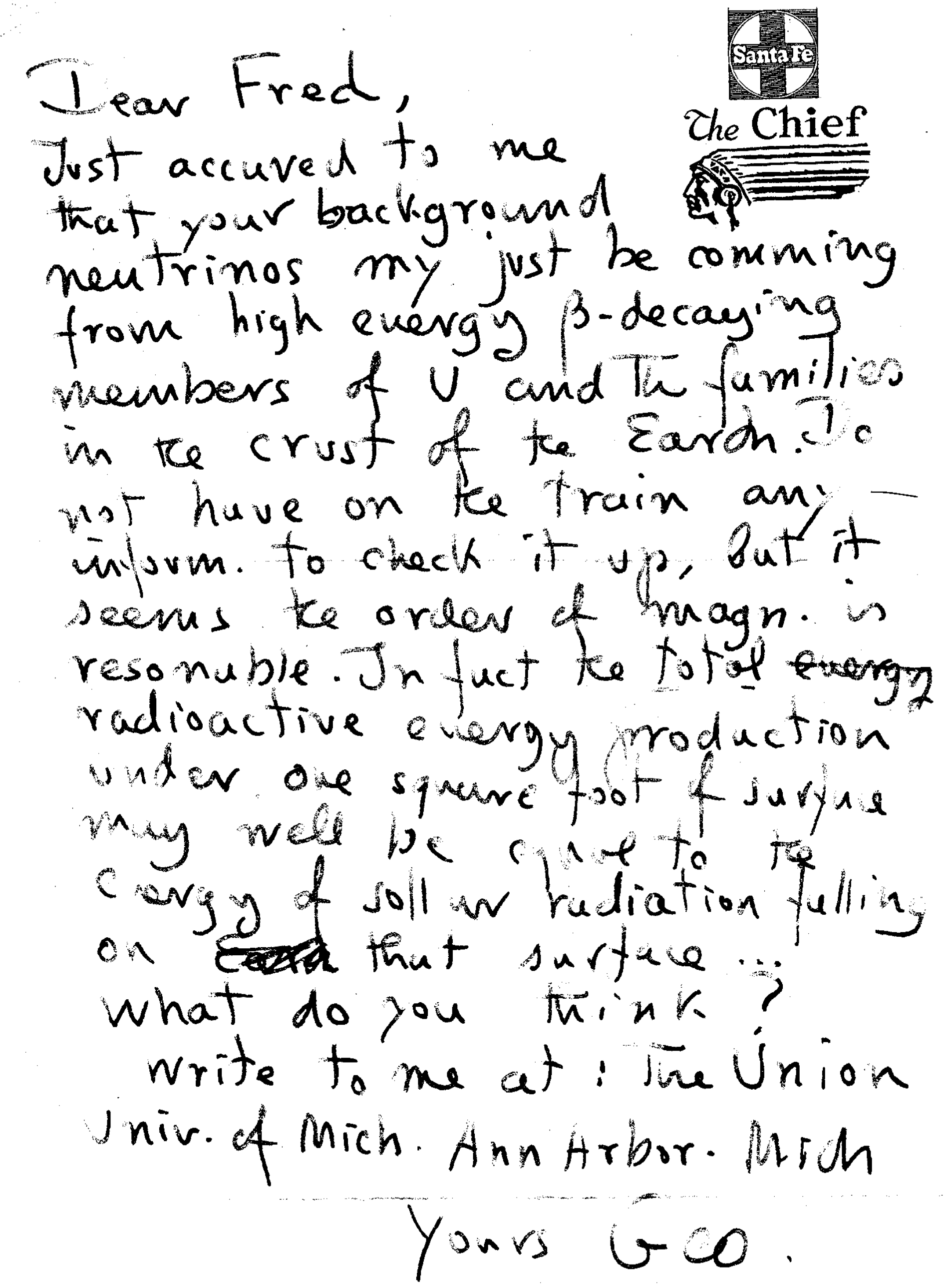


Geo-neutrinos are a rare witness of the chemical composition (at least for U, Th and K) of the Earth

Can they be detected?

Yesterday's background is today's signal…

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

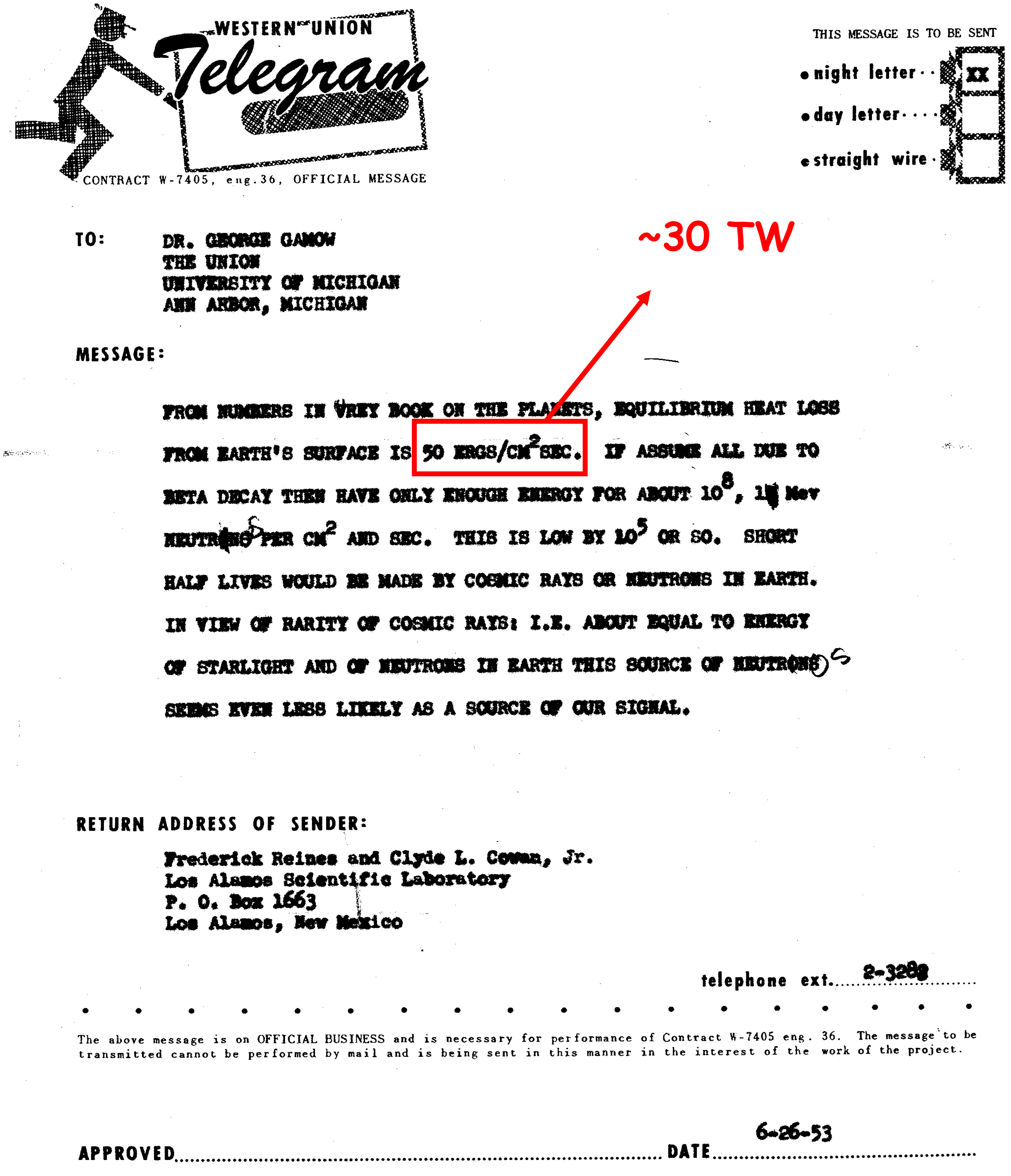


Santa Fe
The Chief

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. 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 solar 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 ☒
- day letter ☐
- straight wire ☐

~30 TW

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

MESSAGE:

FROM NUMBERS IN VREY 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 NEUTRONS S 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. 2-3289

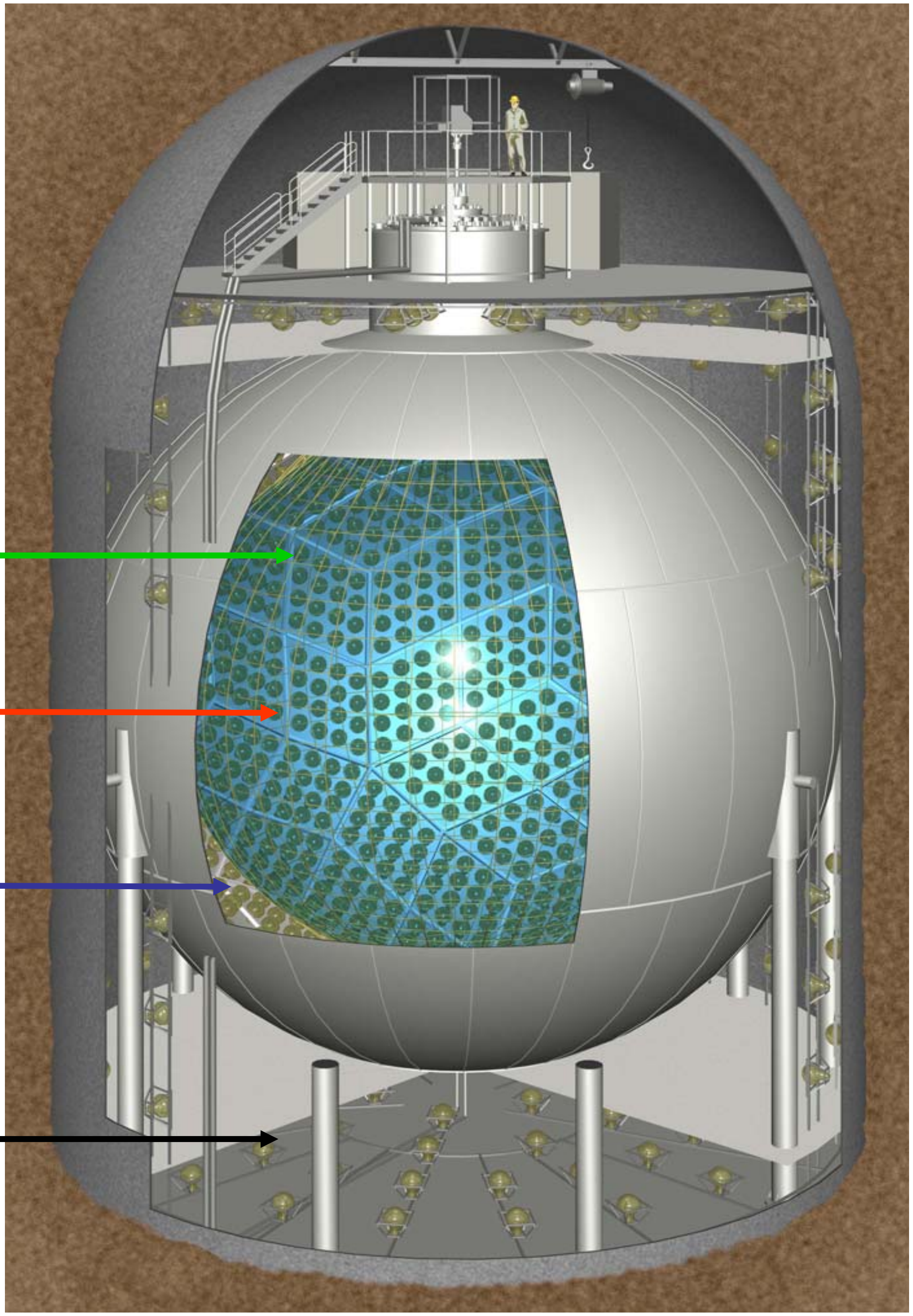
The above message is on OFFICIAL BUSINESS and is necessary for performance of Contract W-7405 eng. 36. The message to be transmitted cannot be performed by mail and is being sent in this manner in the interest of the work of the project.

APPROVED .... DATE 6-26-53

G.Gratta

Modern detectors are ~10^5 times larger !

Example: KamLAND



1km overburden

~2000 20" PMTs

1 kton liquid-scintillator

2.5 m-thick paraffin shielding

Water shield/Cherenkov veto

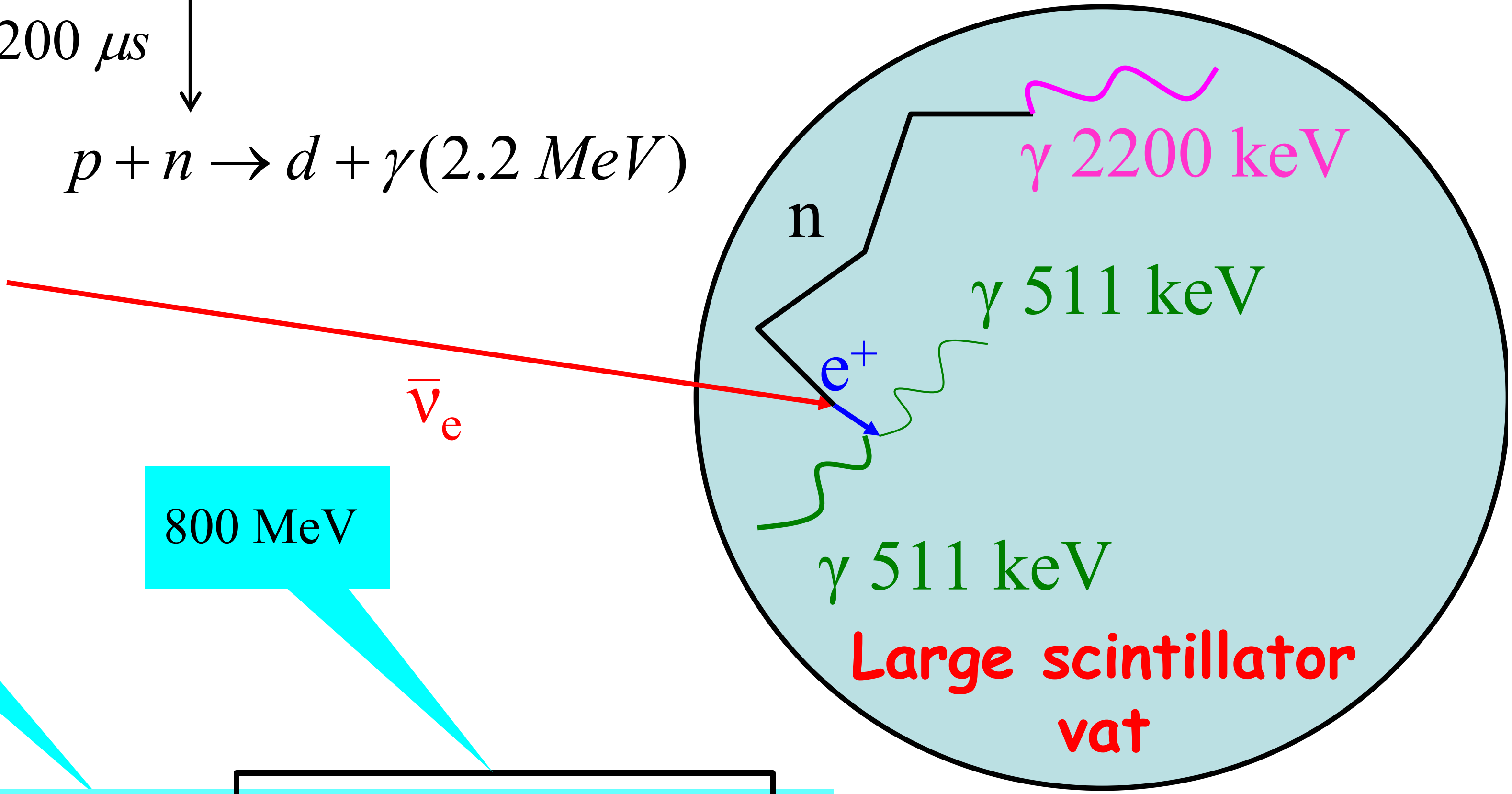
$\bar{\nu}_e$ are handy: can use inverse to suppress backgrounds

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

$$\Big\downarrow \; \tau \approx 200\ \mu s$$

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

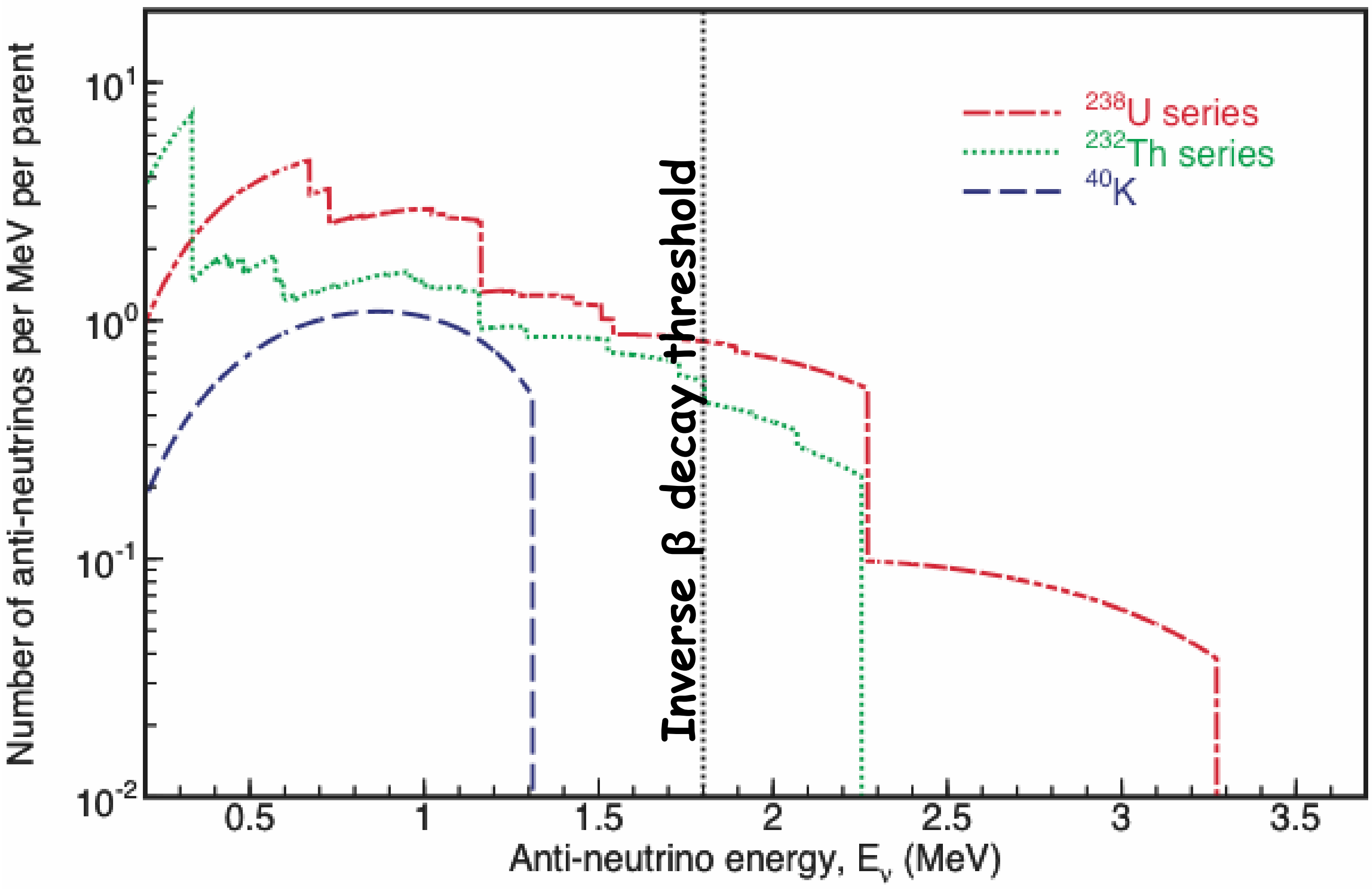
Event tagging by delayed coincidence in energy, time and space



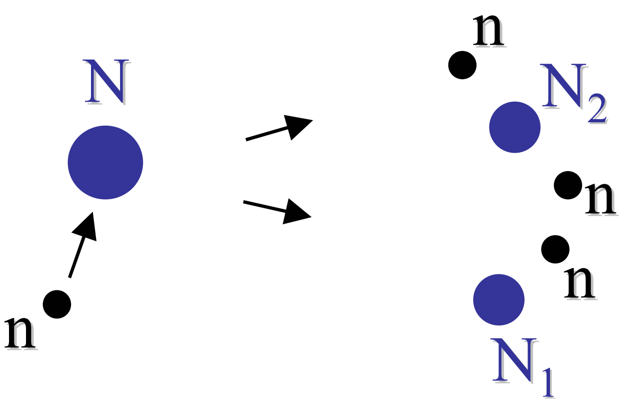
$$E_{\bar{\nu}} \cong E_{e^+} + \overset{\text{10-40 keV}}{E_n} + \overbrace{(M_n - M_p) + m_{e^+}}^{\text{800 MeV}}$$

⇒ E_ν measurement

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



Nuclear reactors are very intense sources of ν_e deriving from beta-decay of the neutron-rich fission fragments



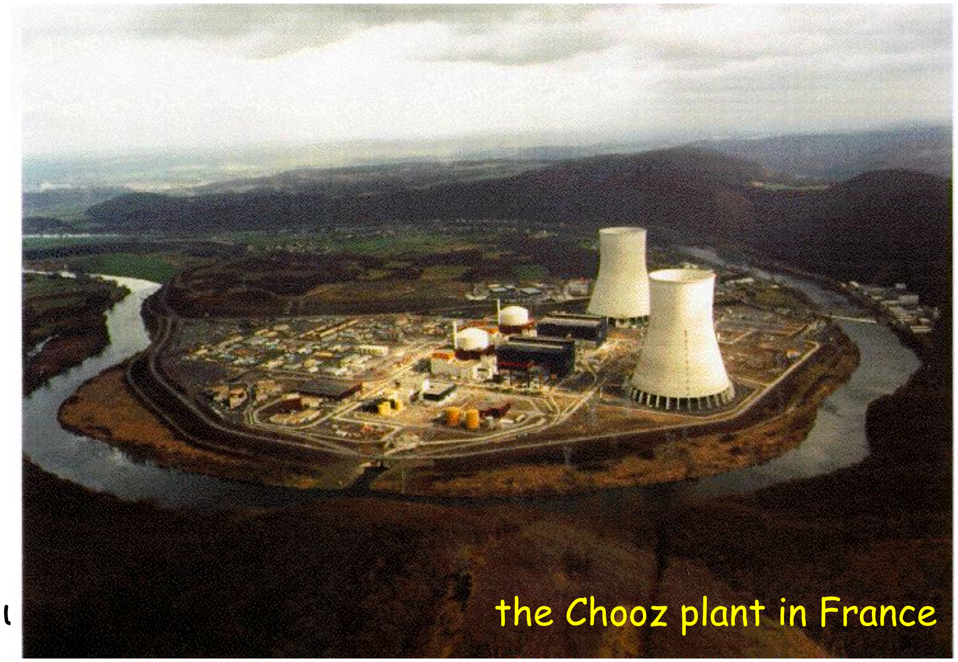
N_1 and N_2 still have too many neutrons and decay

$N_2 \rightarrow N_3 + e^- + \nu_e$

$$200 MeV / fission$$

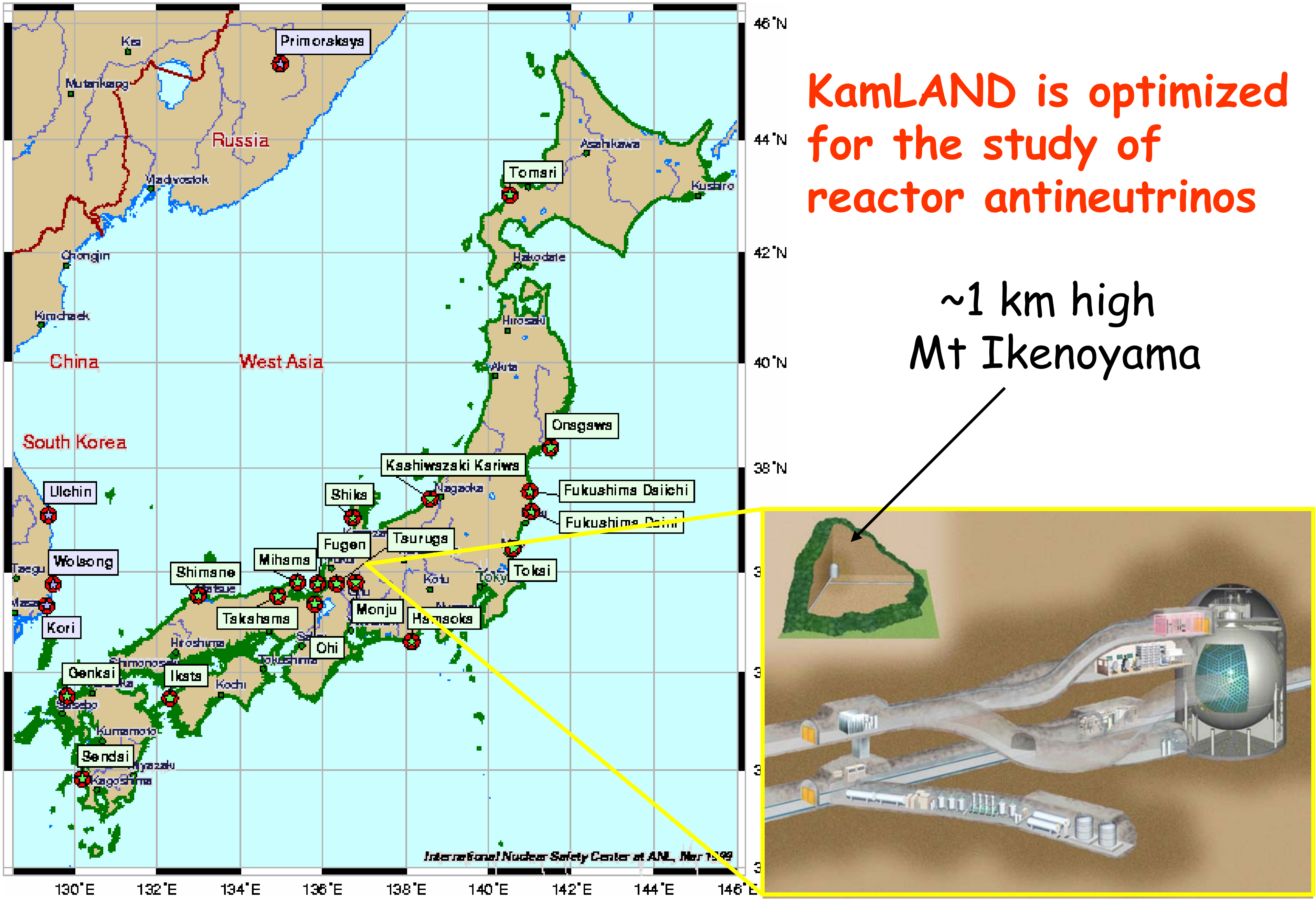
$$6 \overline{\nu}_e / fission$$

A typical large power reactor produces 3 $GW_{thermal}$ and $6 \cdot 10^{20}$ antineutrinos/s



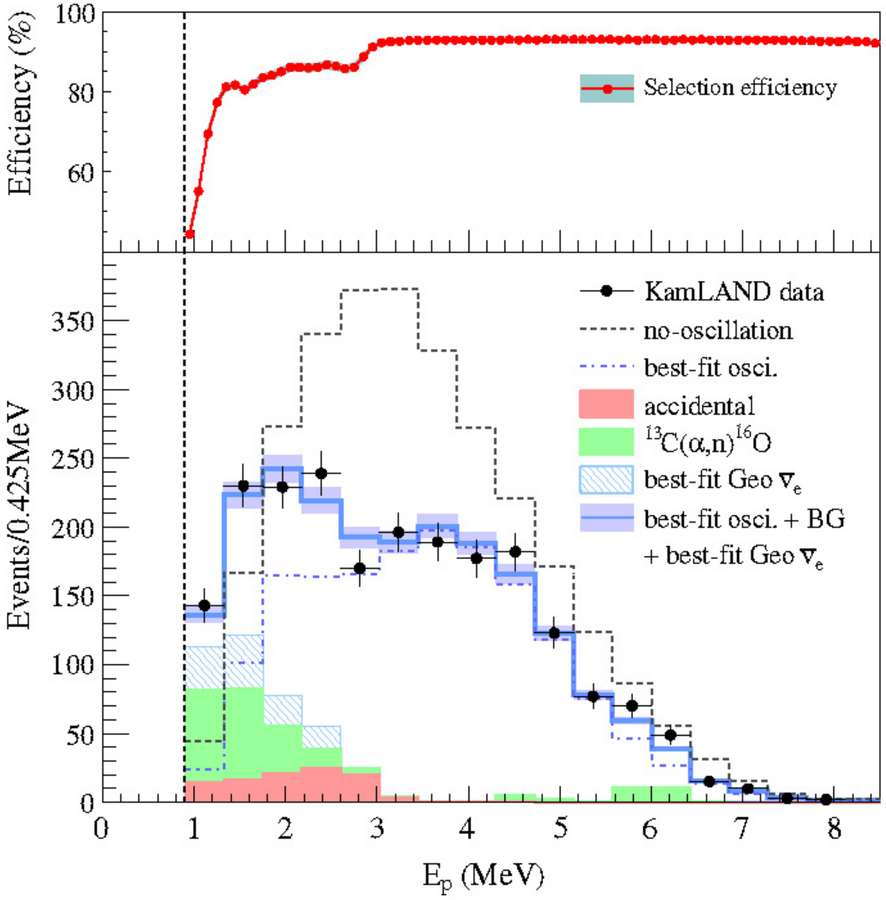
the Chooz plant in France

KamLAND is optimized for the study of reactor antineutrinos

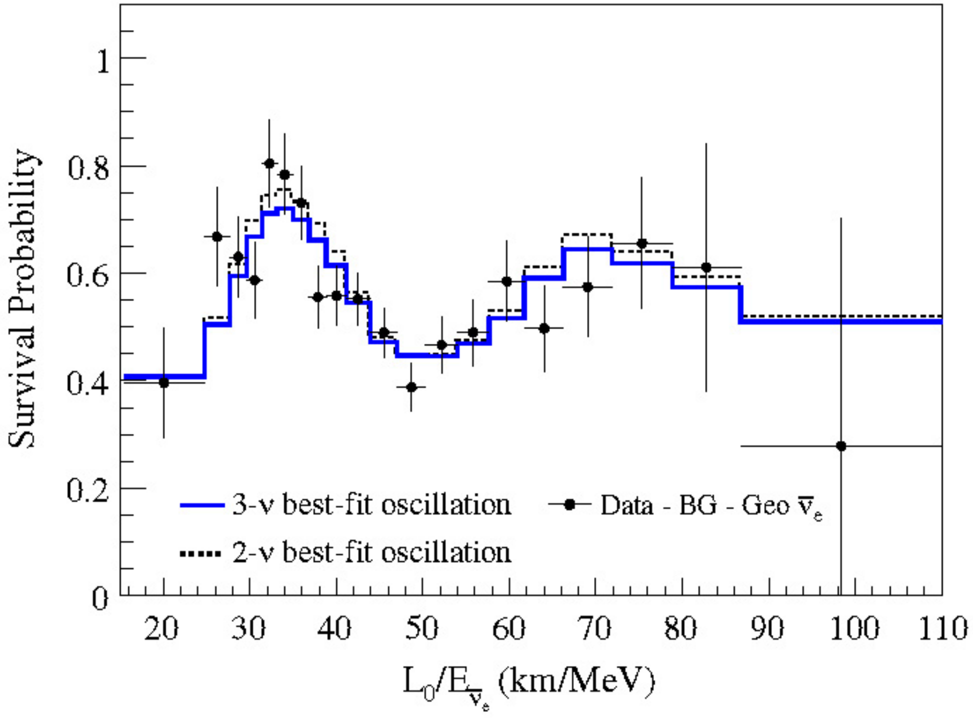


~1 km high
Mt Ikenoyama

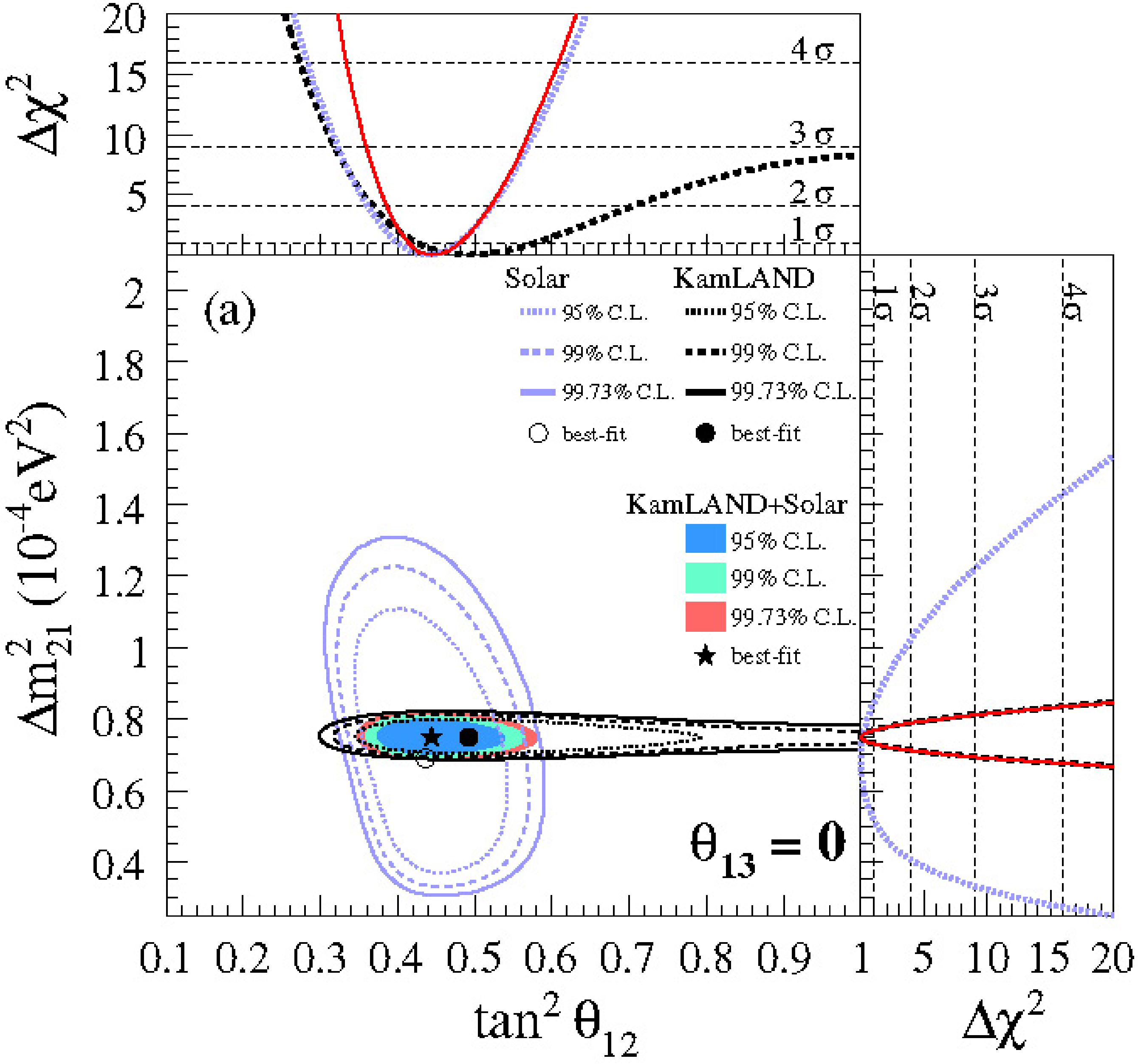
Oscillation measurements using reactors



A.Gando et al. arXiv:1009.4771
to appear on PRD



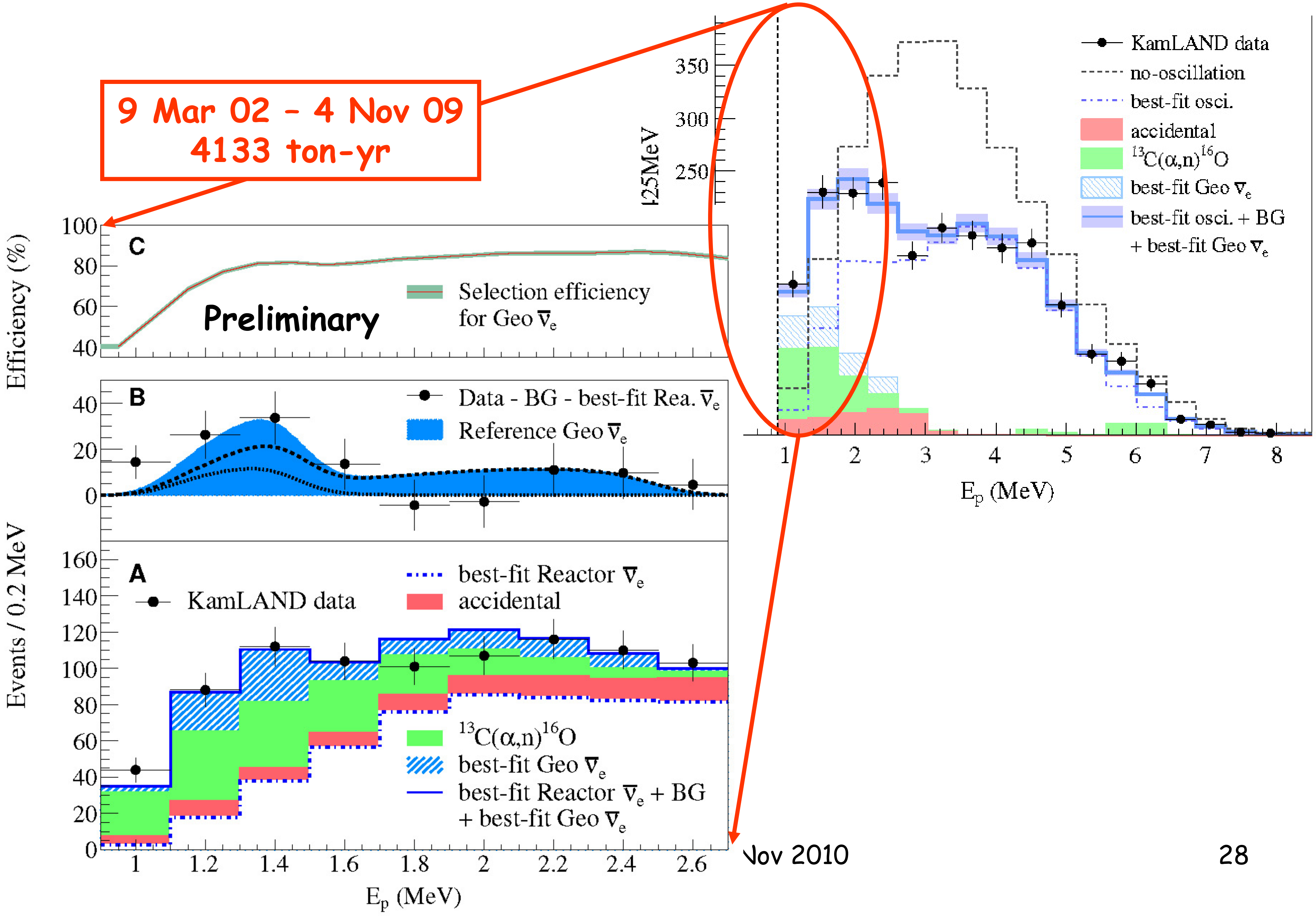
…that, combined with other results provide accurate values for Δm and θ_{12}



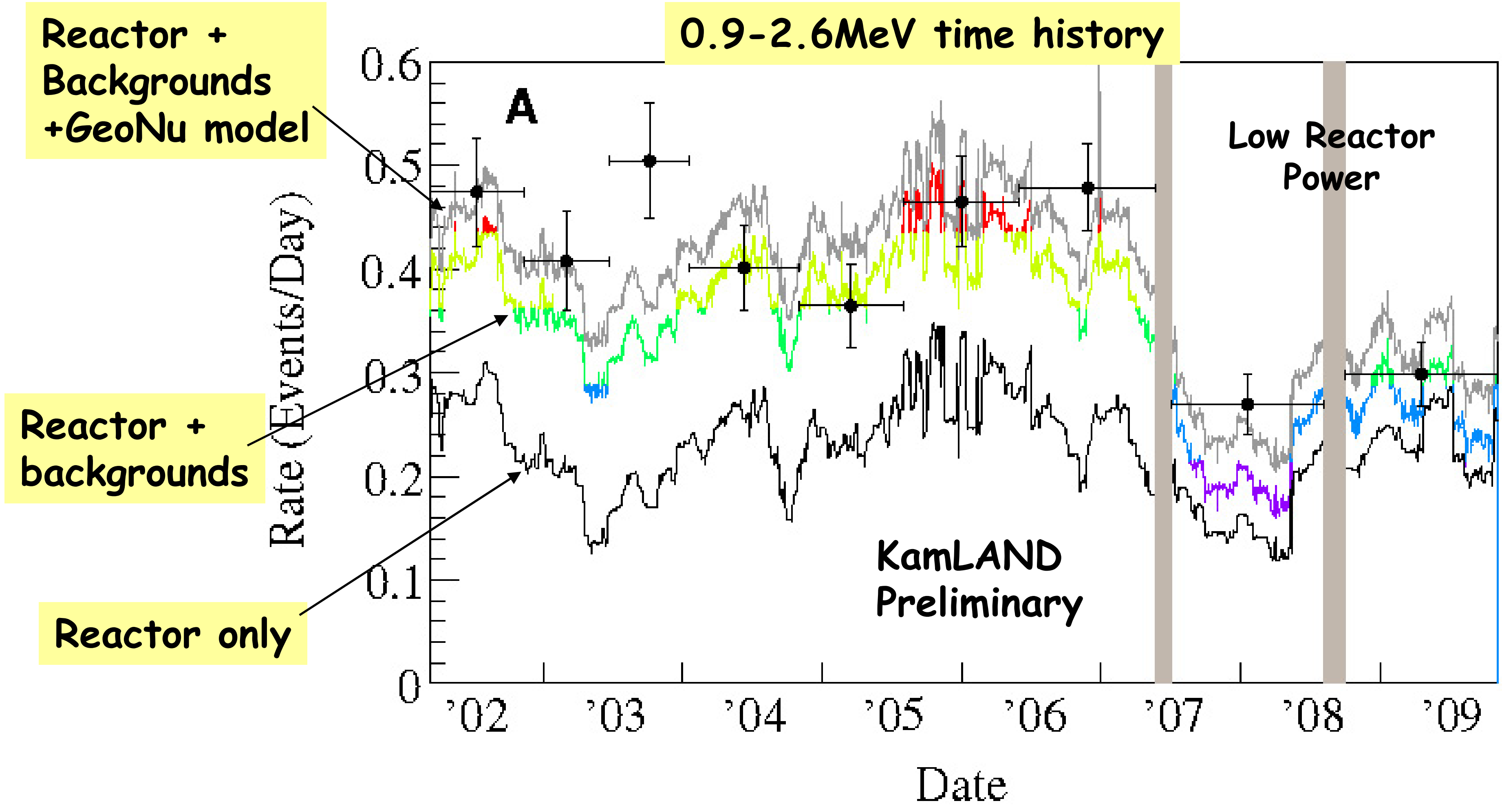
A.Gando et al. arXiv:1009.4771

But what about Geoneutrinos?

9 Mar 02 – 4 Nov 09
4133 ton-yr



Even in presence of large reactor background, power excursions can be used to separate the geoneutrino signal



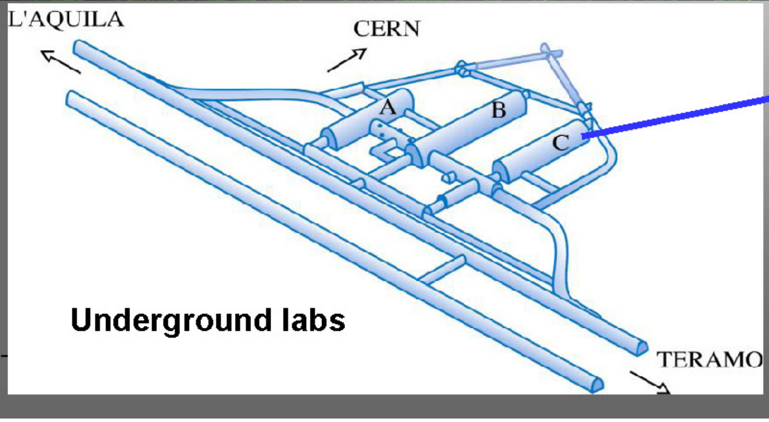
Null hypothesis for geoNu excluded at 99.997%CL

Borexino

Abruzzo
120 Km from Rome

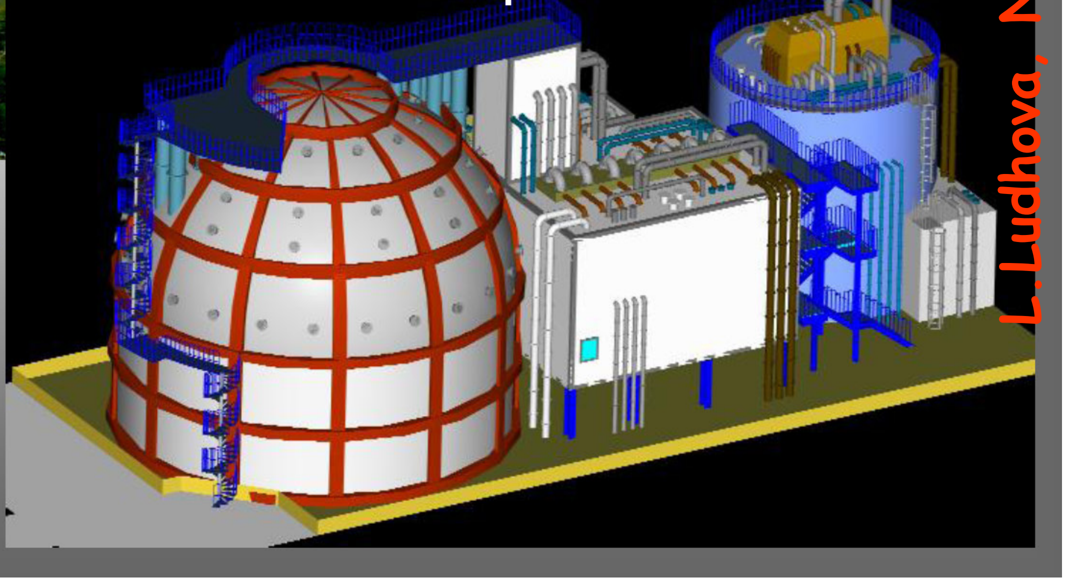
Laboratori
Nazionali del
Gran Sasso

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



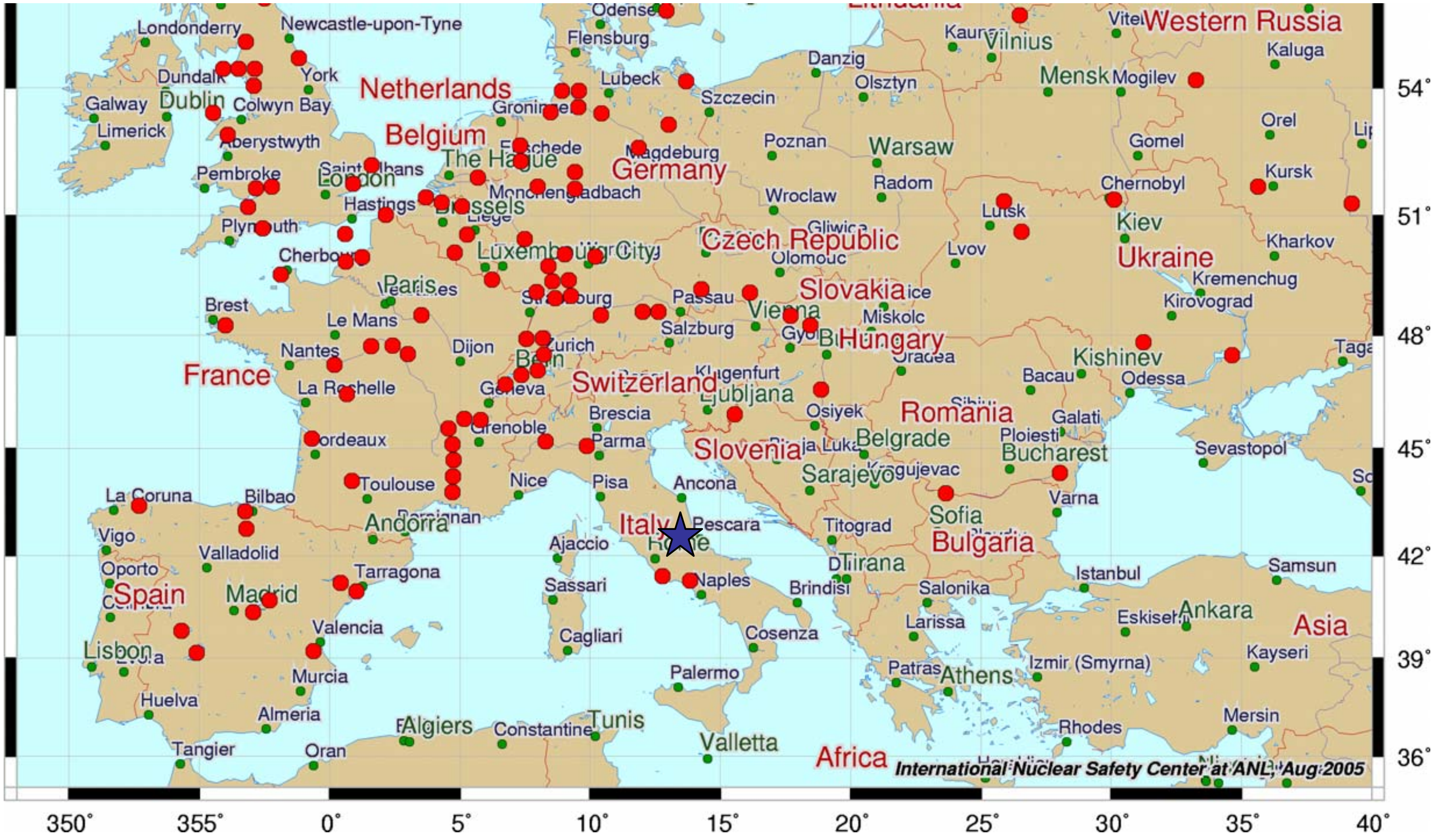
Underground labs

Borexino detector + fluid plants



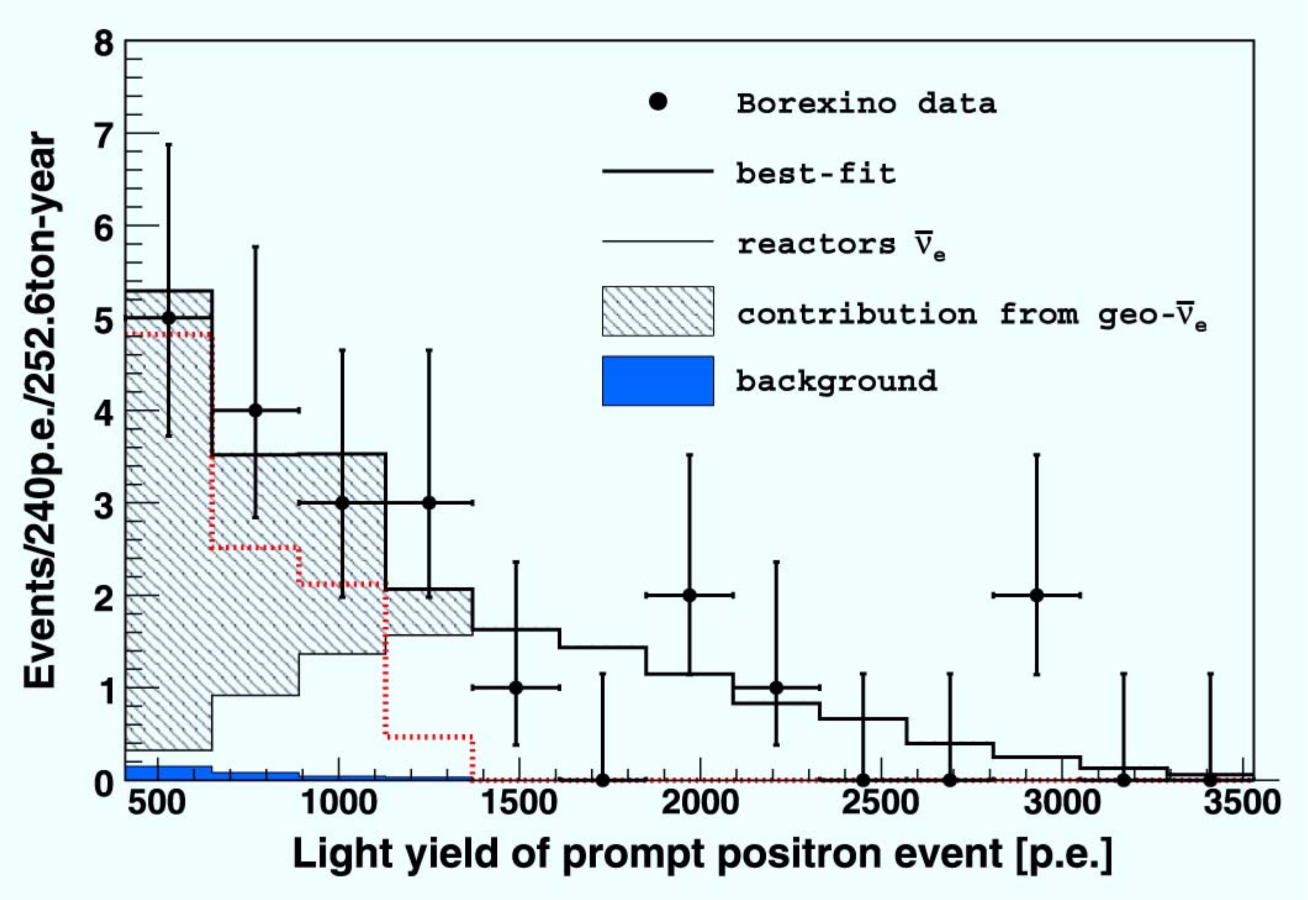
L.Ludhova, Neutrino Geoscience 2010

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



Null hypothesis excluded at 99.997%CL

- Borexino is ~3x smaller and run shorter time: exposure is 253 ton-yr (~6% of KamLAND)
- Borexino is substantially cleaner than KamLAND and they have very little "background" from nuclear reactors

The geo-neutrino flux due to a particular isotope accumulated at a particular distance $\vec{L}$ from the detector 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 the distance

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

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*
- *S. Enomoto et al. Earth Planet. Sci. Lett. 258 (2007) 147*

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 resolution description of the distributions in the nearby crust (because of the $1/L^2$ in the integral)

The expected rate at different world locations

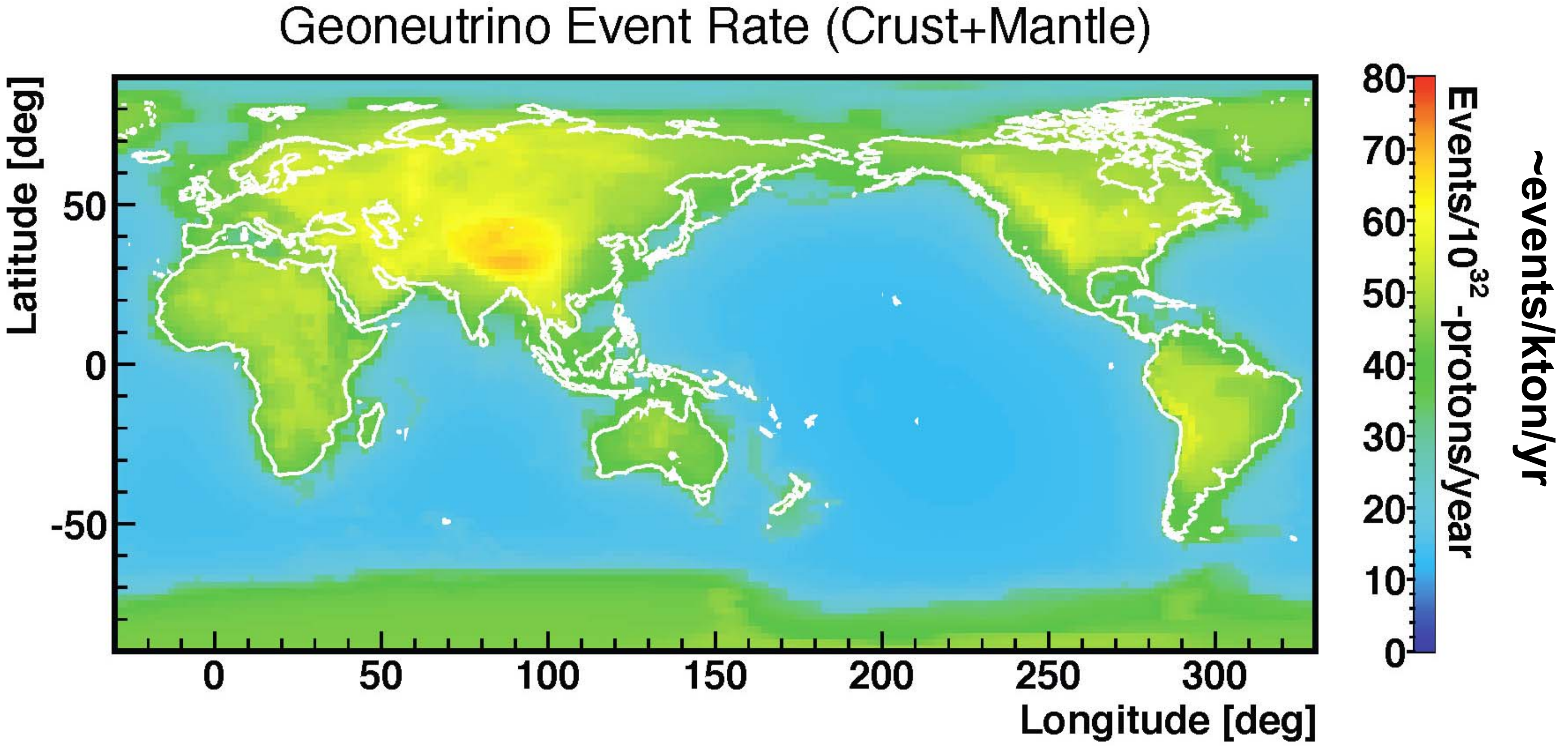


Image: S. Enomoto

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

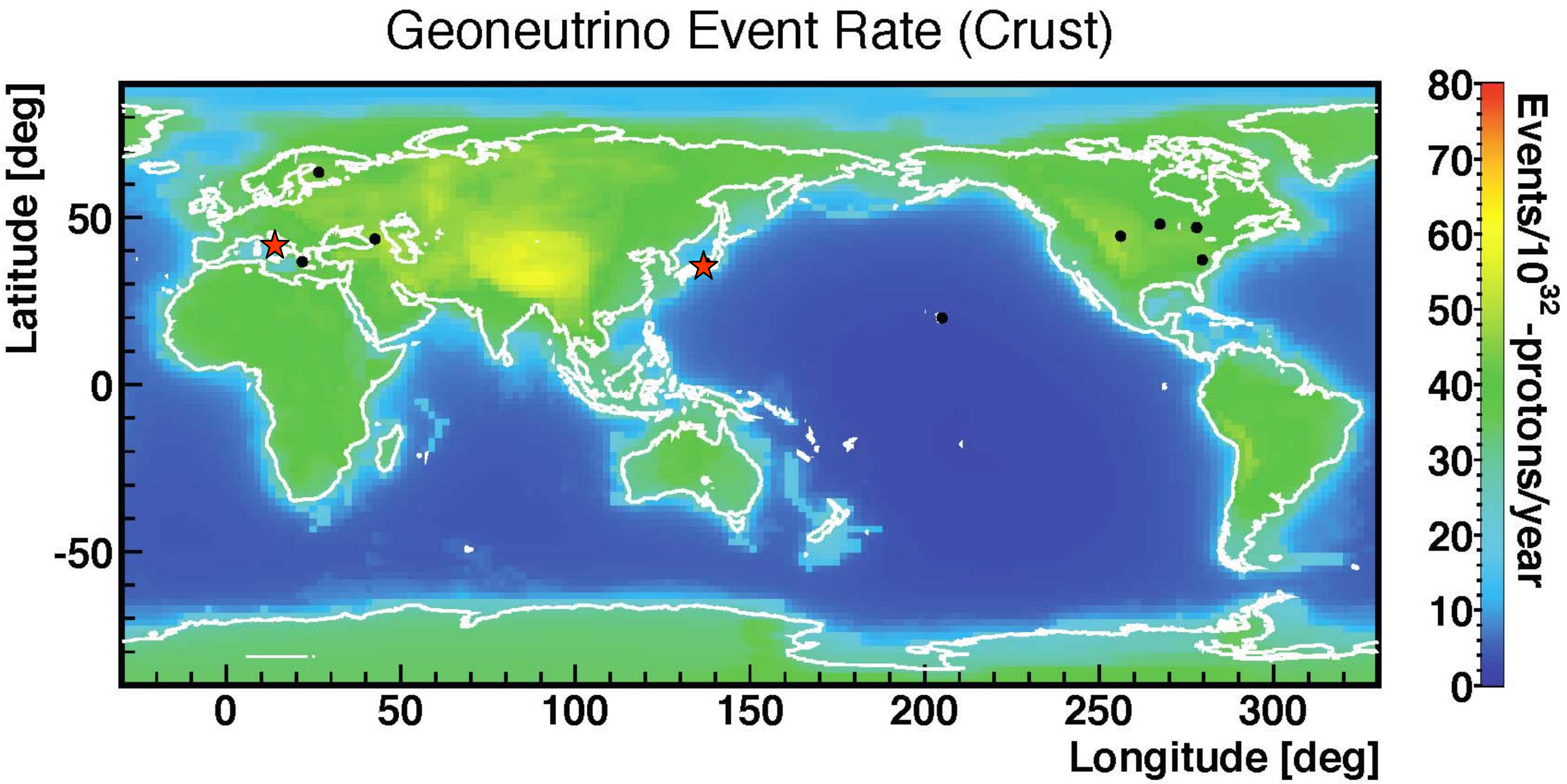
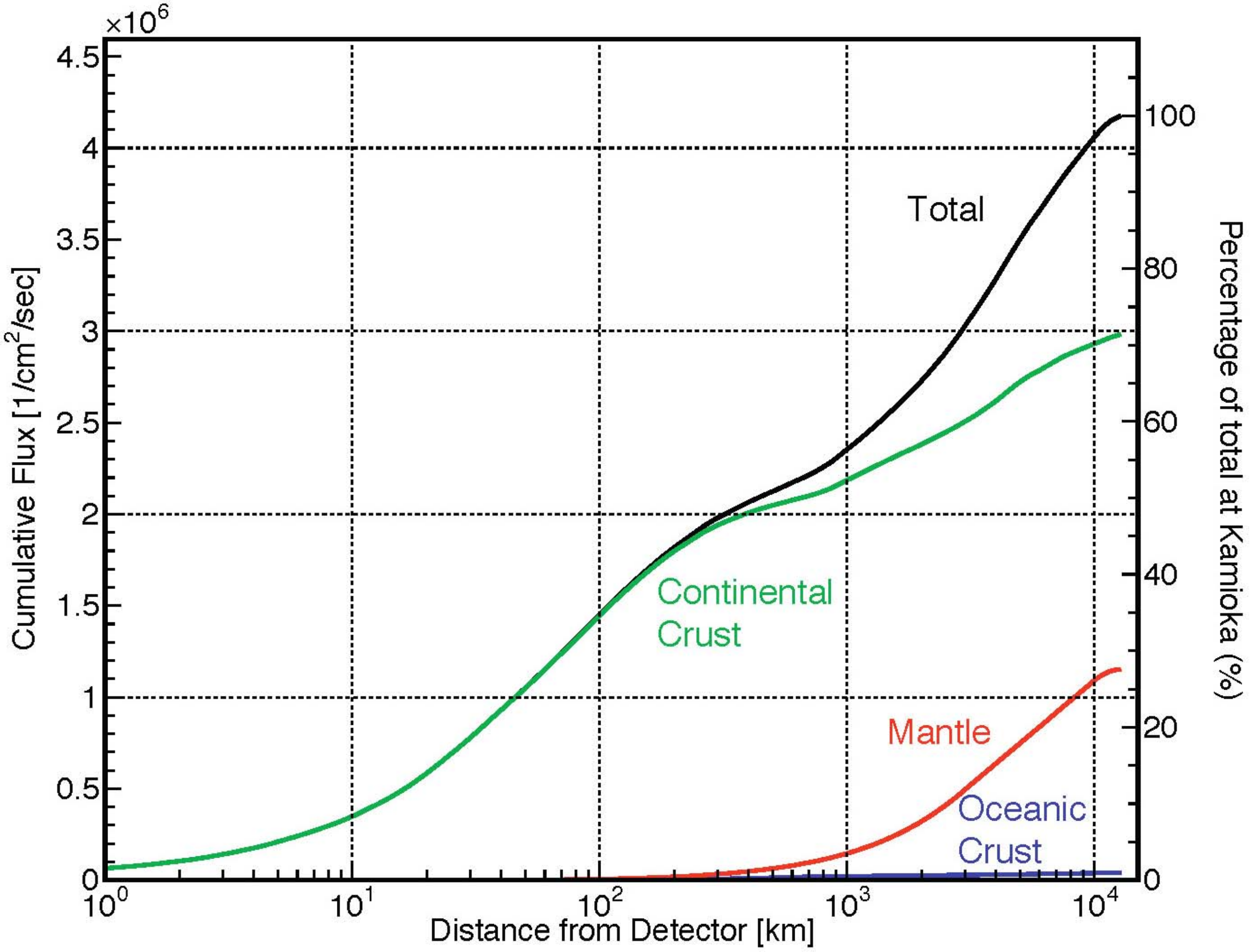


Image: S. Enomoto

The breakdown of various contributions at the Kamioka site



Background from reactors.
Note that in many locations this is a severe problem

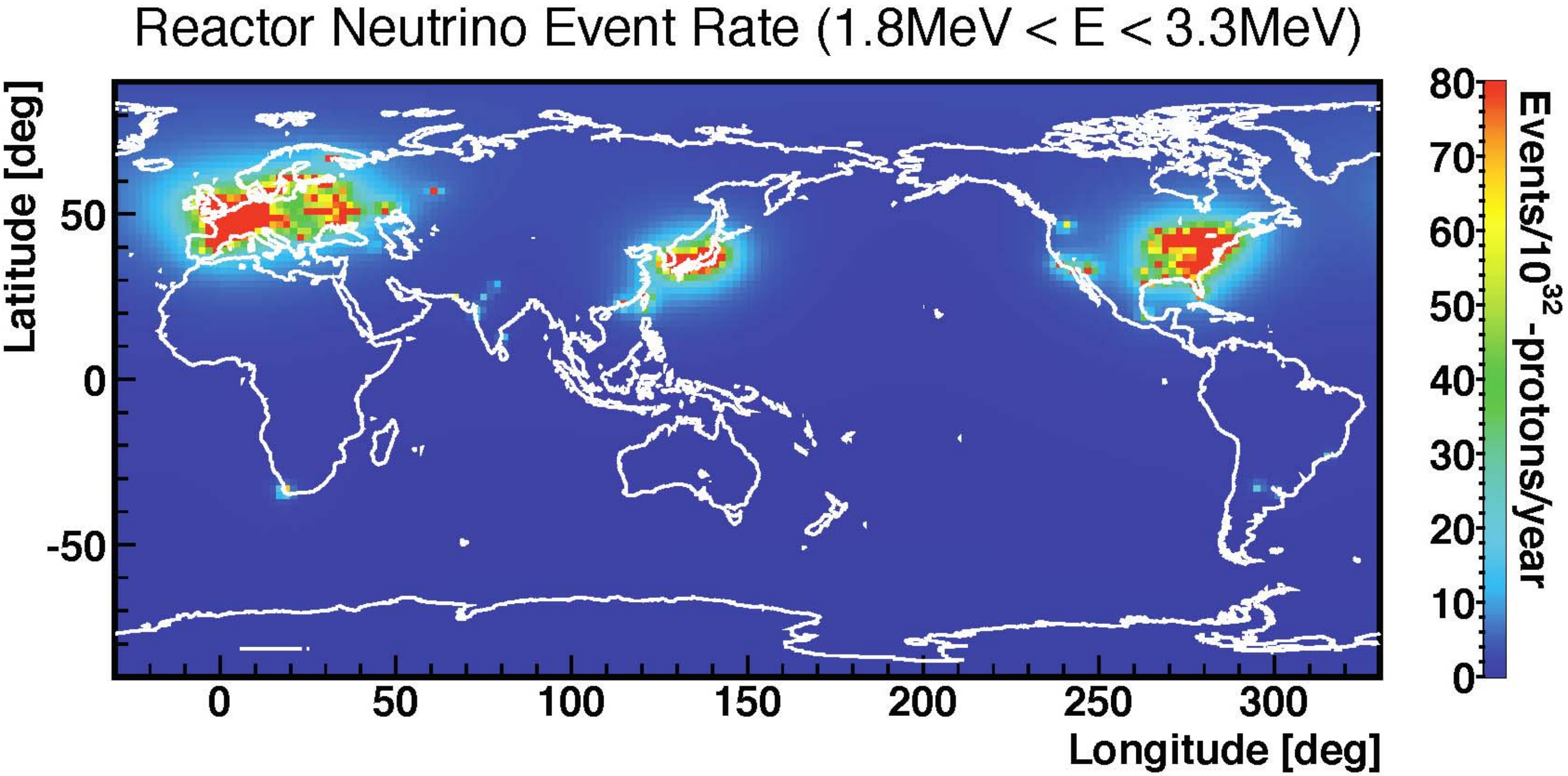


Image: S. Enomoto

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

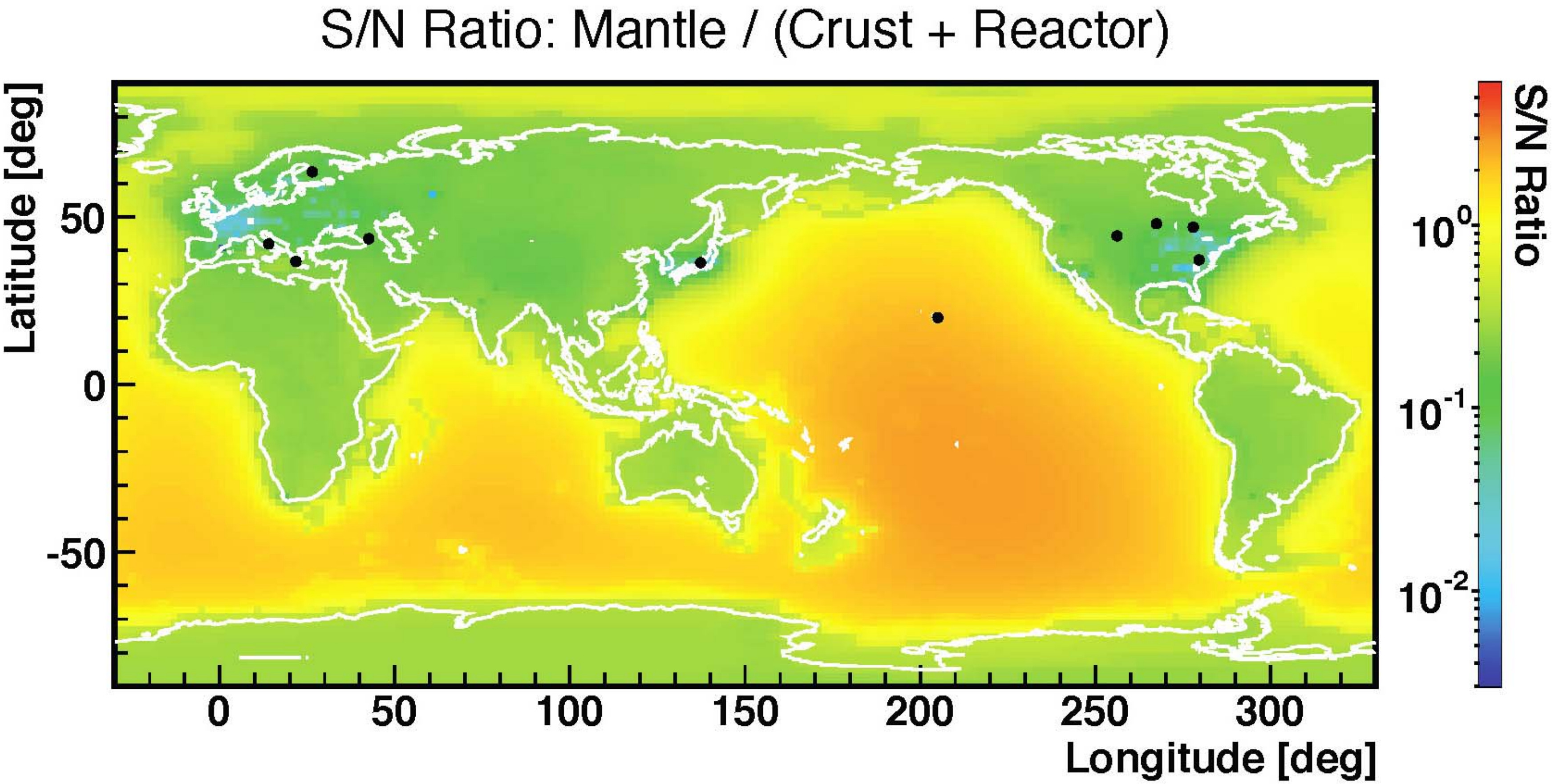
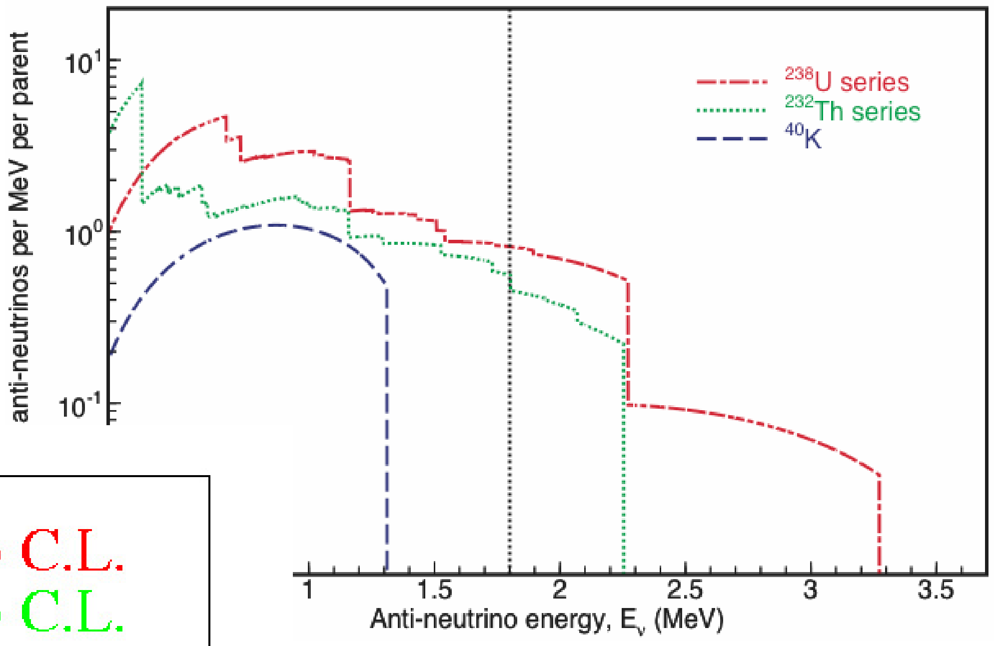
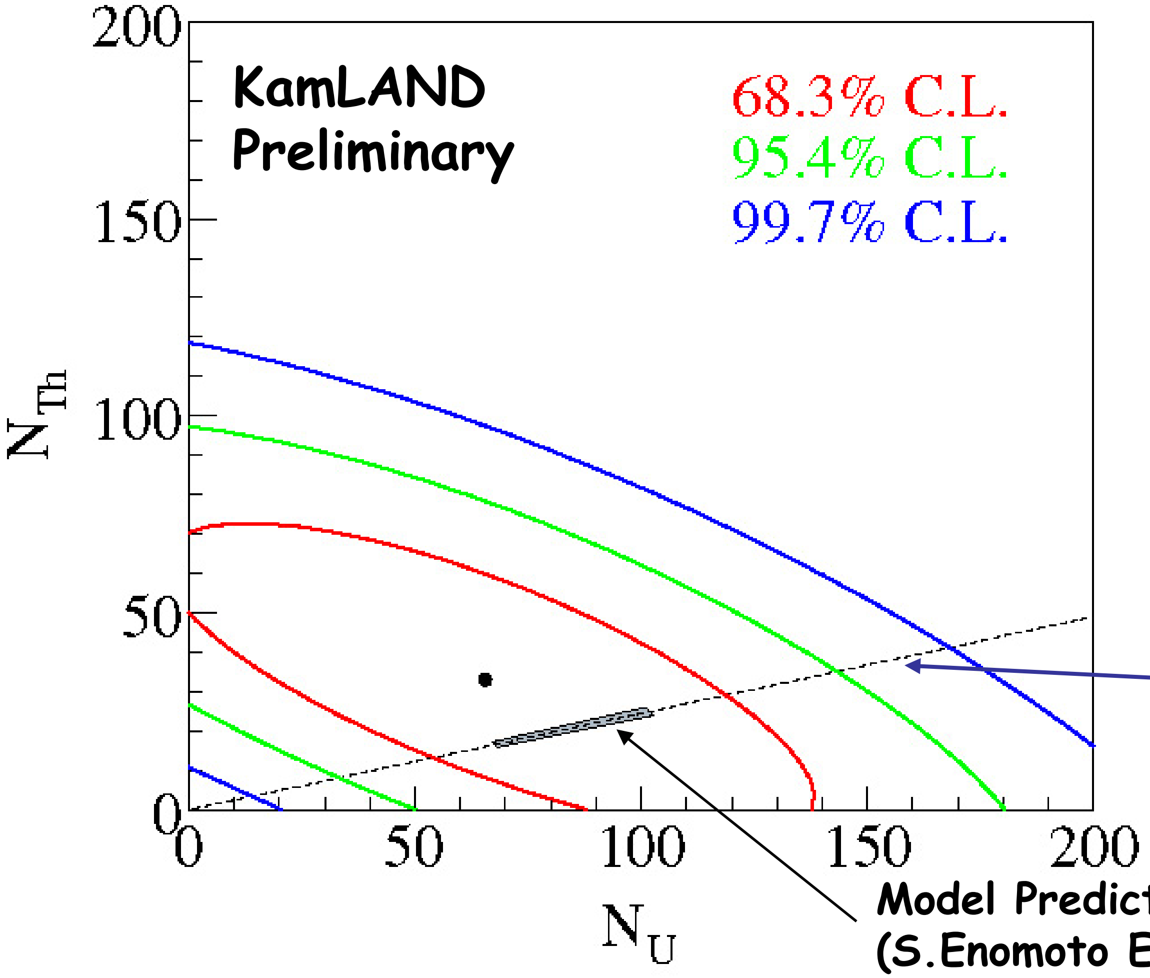


Image: S. Enomoto

Flux $[\times 10^6\ cm^{-2}\ s^{-1}]$			
Measured			Model (Enomoto / Mantovani et al)
KamLAND 2005*	$6.4^{+3.6}_{-3.4}$	Nature <u>436</u>, 499	4.4 / 4.0
KamLAND 2008	4.4±1.6	PRL <u>100</u>, 221803	4.4 / 4.0
Borexino 2010*	$7.1^{+2.9}_{-2.4}$	Phys Lett B<u>687</u>, 299	5.2 / 4.6
KamLAND 2010	$4.3^{+1.2}_{-1.1}$	Preliminary, Neutrino 2010	4.4 / 4.0

Data is still pretty insensitive to the U/Th ratio



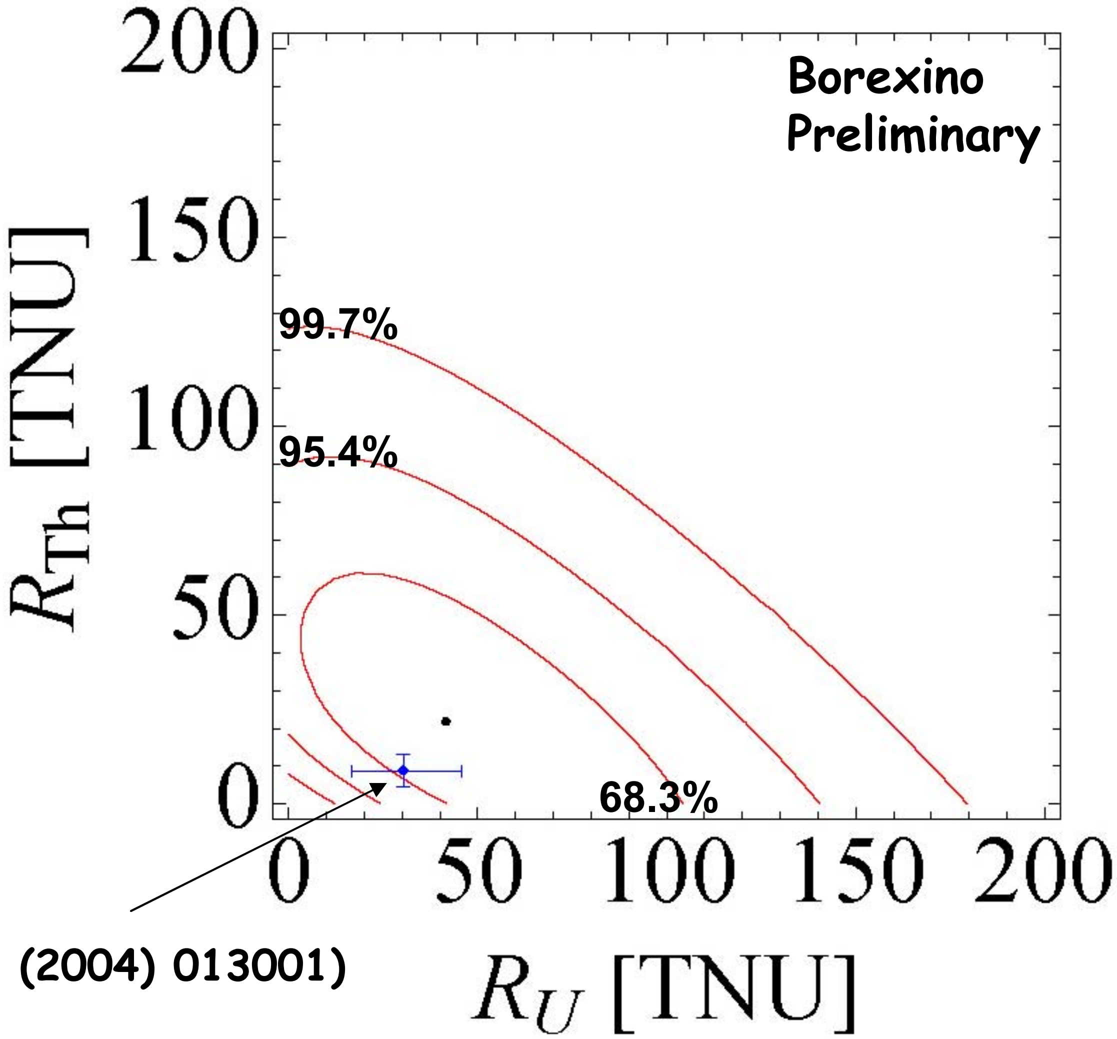


Best fit gives U/Th=65/33

U/Th ratio fixed by Chondrites (0.26)

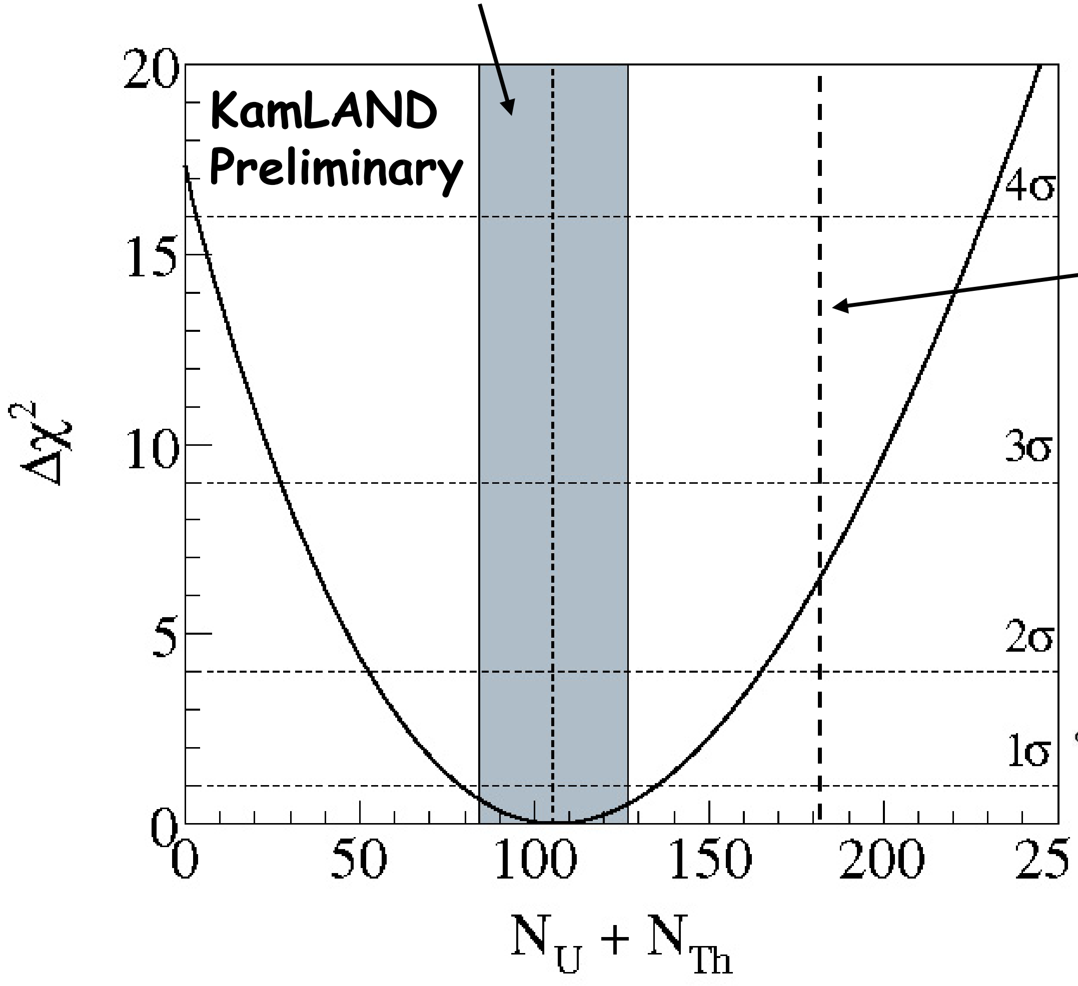
Model Prediction (S.Enomoto EPSL 258, 147 (2007))

Similar result for Borexino



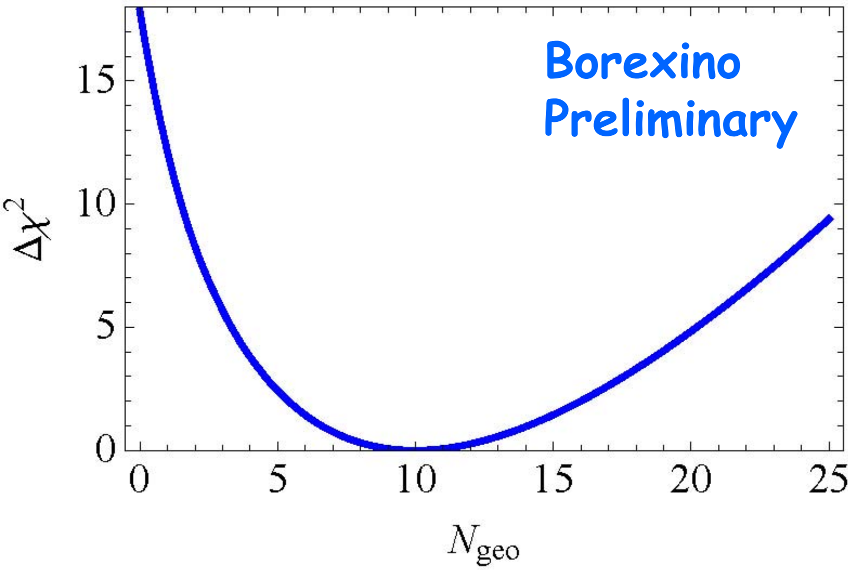
Model Prediction
(F.Mantovani et al. PRD 69 (2004) 013001)

→ With the U/Th fixed by Chondritic Meteorites)

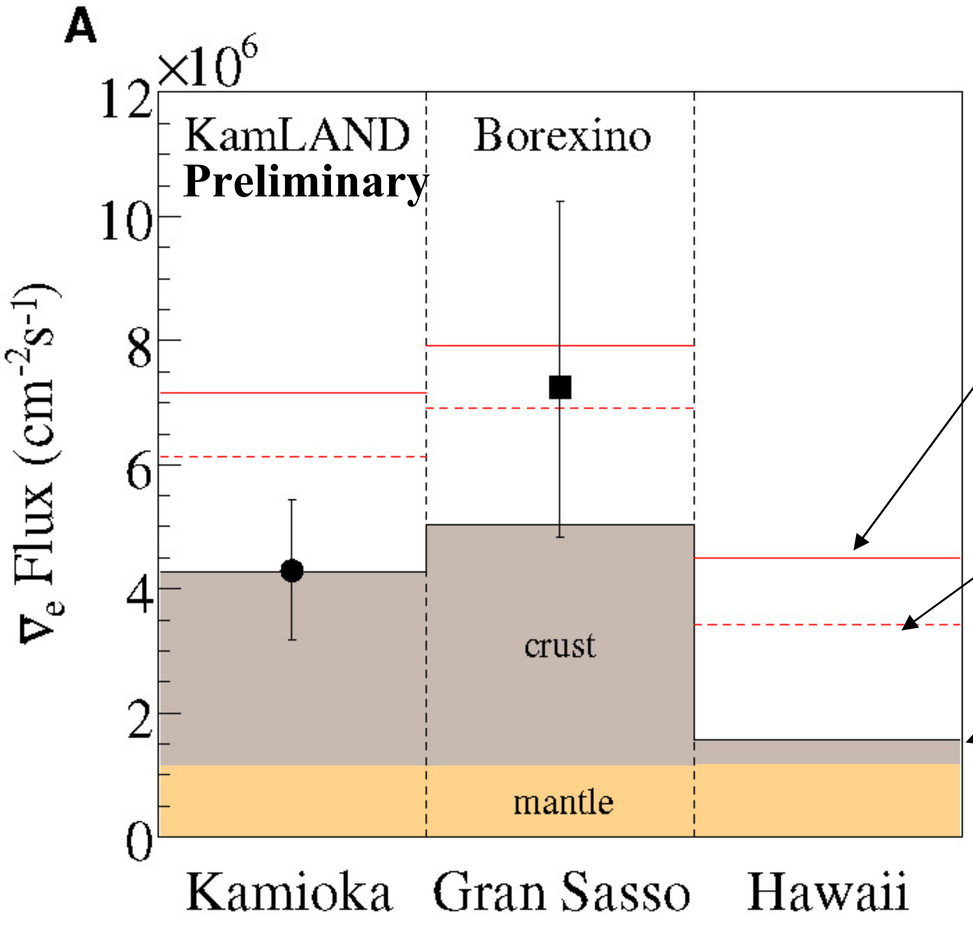


Model Prediction
(S.Enomoto EPSL 258, 147 (2007)

Best fit with
no oscillations
from reactors



Comparing the two sites/experiments



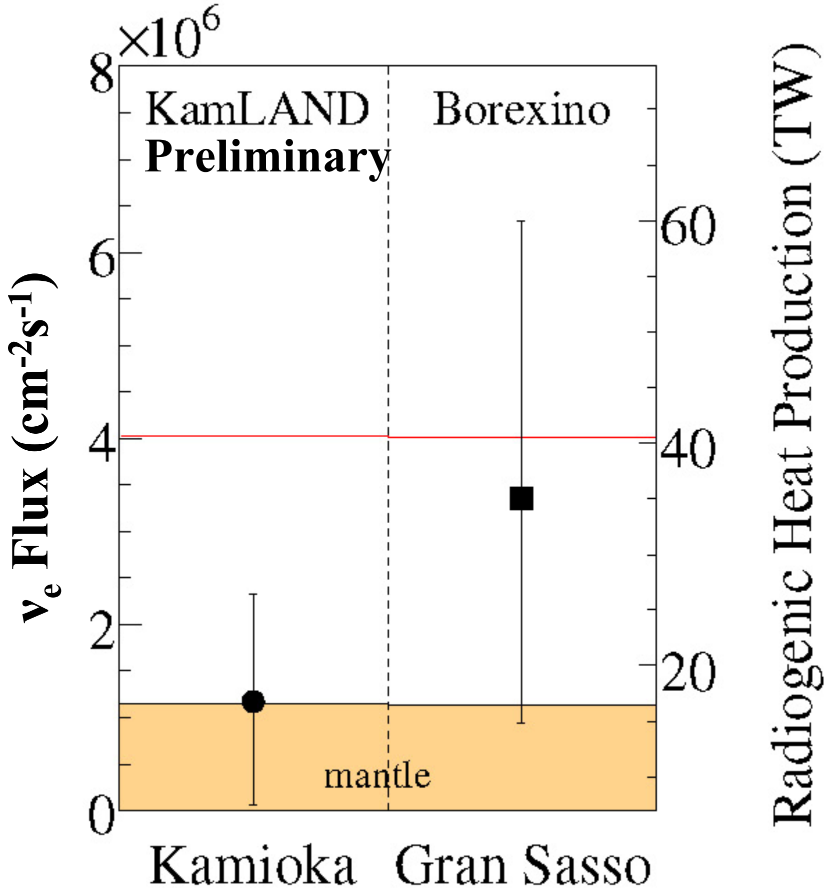
Fully radiogenic homogeneous mantle

Fully radiogenic mantle with U, Th at bottom

Standard Model
(S.Enomoto, EPSL 258, 147 (2007))

KamLAND data disfavor fully radiogenic mantle at 97.8%CL

Using model to subtract crustal contribution



Mantle contribution: 1σ contribution in KamLAND data

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 geochemists

The evidence for/against such a reactor is indirect and clearly controversial.

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

In this case Borexino is clearly in a better situation because of the low reactor background.

Both experiments have set limits that start probing the interesting regime

KamLAND $P_{reactor} < 5.2$ TW at 90% CL

Preliminary, Oct 2010

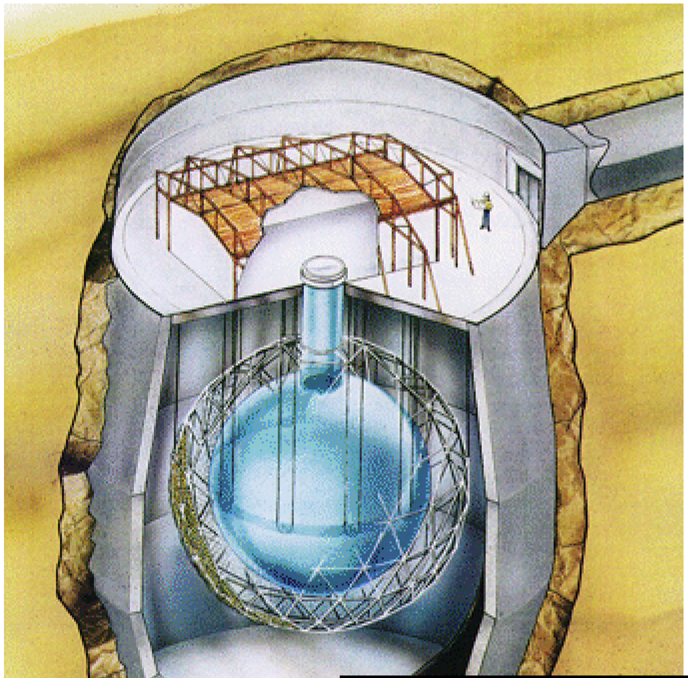
Borexino $P_{reactor} < 3$ TW at 95% CL

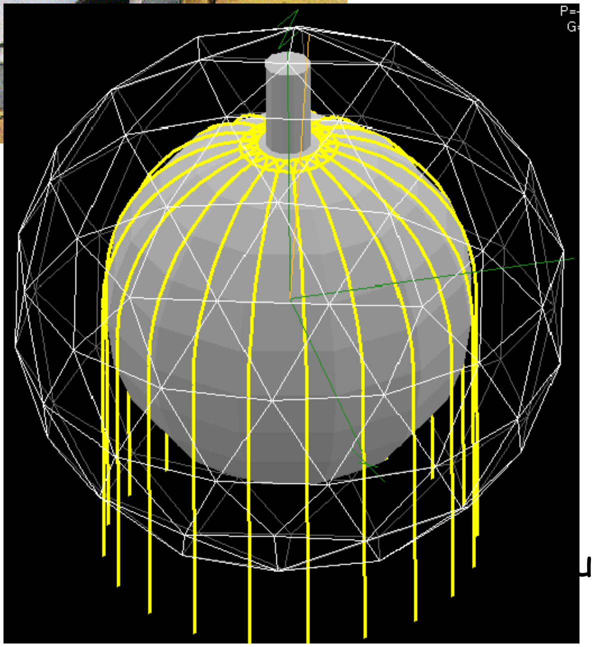
Phys.Lett. B687, 299 (2010)

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)

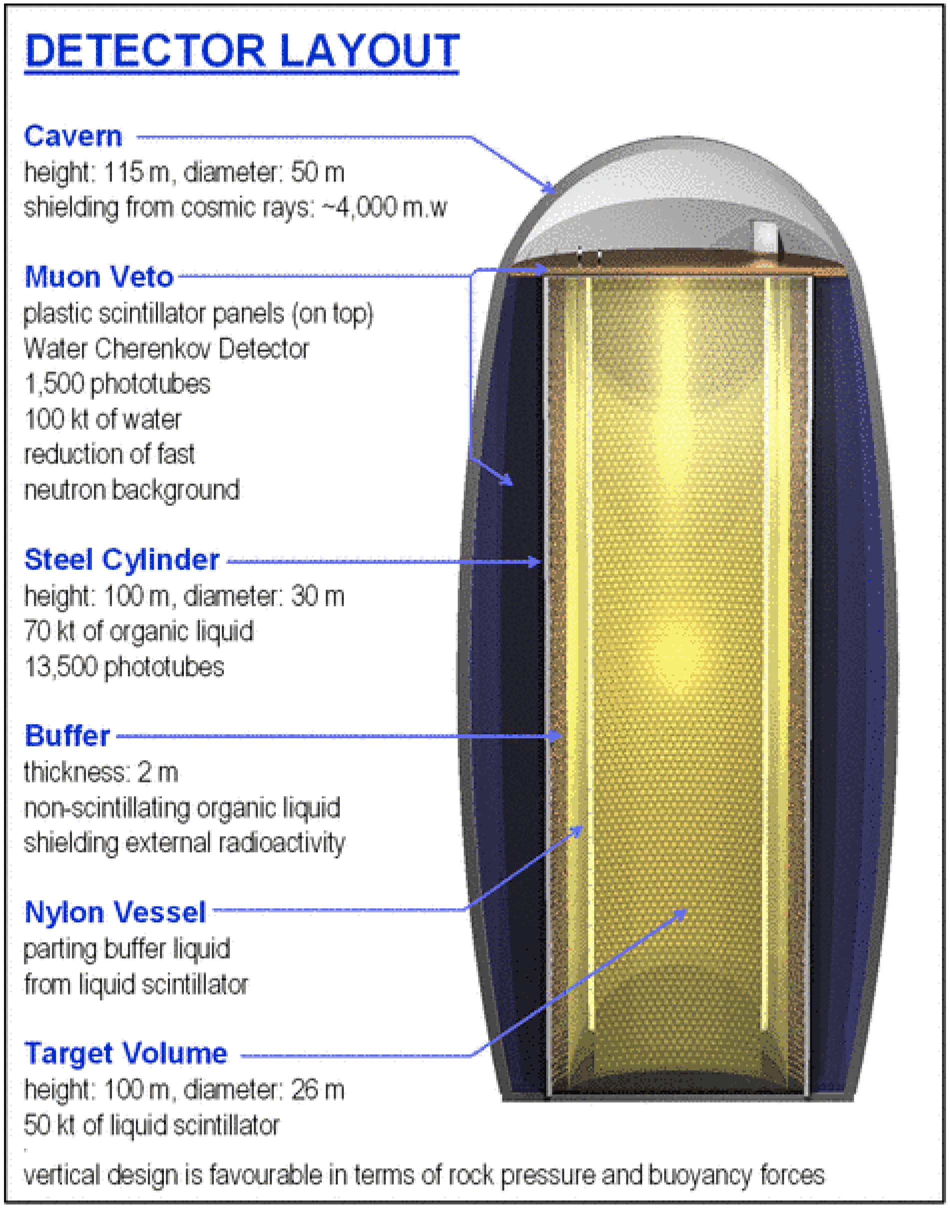
The near future: SNO+





~1kton
SNO site

Some more remote future: LENA



DETECTOR LAYOUT

Cavern
height: 115 m, diameter: 50 m
shielding from cosmic rays: ~4,000 m.w

Muon Veto
plastic scintillator panels (on top)
Water Cherenkov Detector
1,500 phototubes
100 kt of water
reduction of fast
neutron background

Steel Cylinder
height: 100 m, diameter: 30 m
70 kt of organic liquid
13,500 phototubes

Buffer
thickness: 2 m
non-scintillating organic liquid
shielding external radioactivity

Nylon Vessel
parting buffer liquid
from liquid scintillator

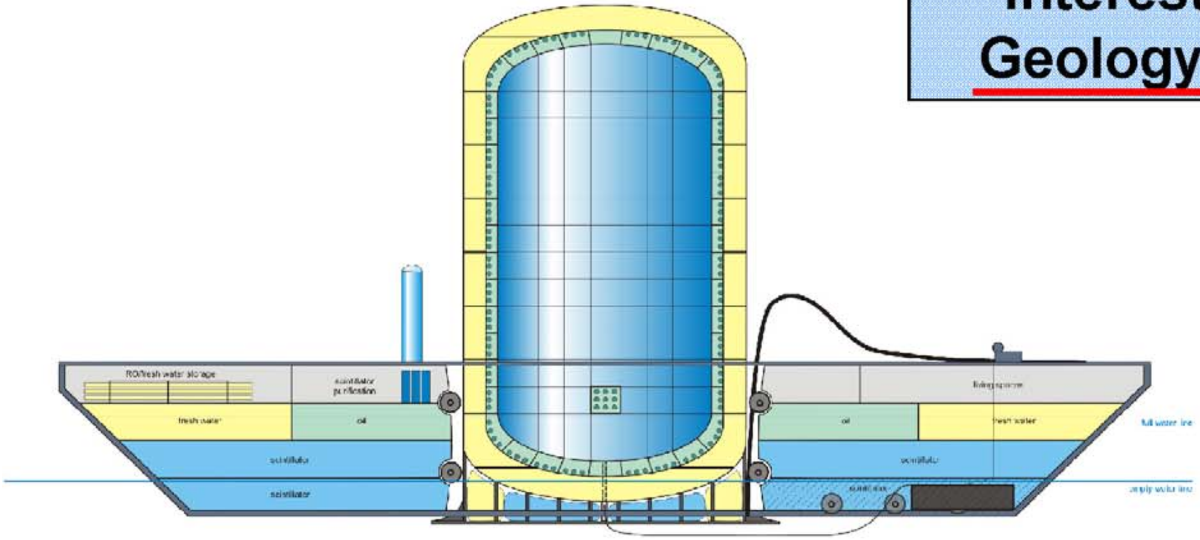
Target Volume
height: 100 m, diameter: 26 m
50 kt of liquid scintillator

vertical design is favourable in terms of rock pressure and buoyancy forces

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

Hanohano

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

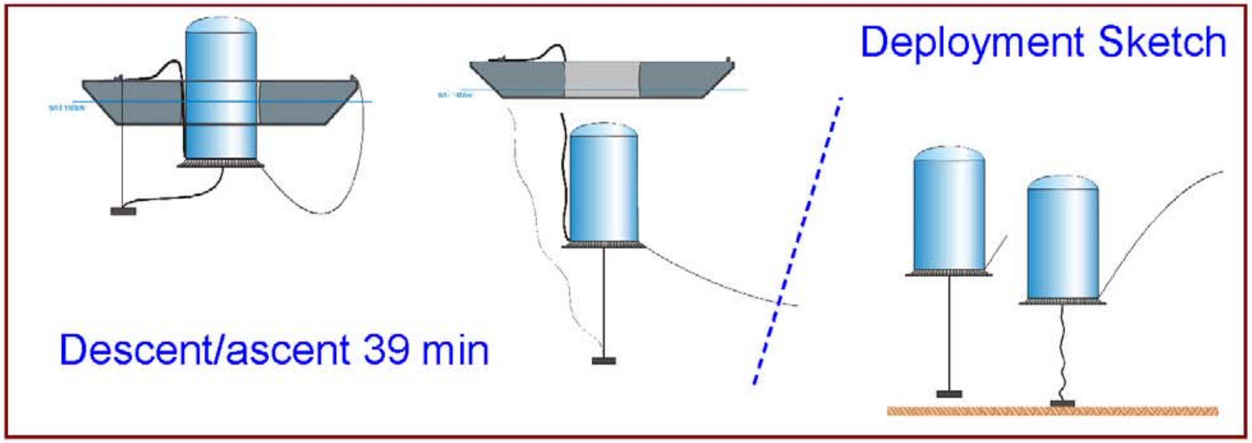


- multiple deployments
- deep water cosmic shield
- control-able L/E detection

Deep Ocean

$\bar{\nu}_e$

Observatory



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
- With data coming from two continents start constraining different models
- SNO+ to join the club soon
- A network of detector and an oceanic detector would drastically advance the knowledge of our planet