Detecting Geoneutrinos

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

FORENSIC SCIENCE
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INSIDE: INDIAN LIFE SCIENCES

nature outlook INDIA

EARTHLY POWERS

Geoneutrinos reveal Earth's inner secrets

nature 436, 441–602 28 July 2005 www.nature.com/nature

nature outlook: India

no.7050 npg

Giorgio Gratta
Physics Dept
Stanford University

Plan for this talk

- Primer on Neutrinos
- A little history of Geoneutrino detection
- Basics of Neutrino detection
- Results from KamLAND and Borexino
- How to make further progress

  (from the point of view of detection)

Neutrinos occupy an important role in particle physics…

Particles

Antiparticles

ν_e	ν_μ	ν_τ
e	μ	τ

Leptons

ν_τ	ν_μ	ν_e
τ	μ	e

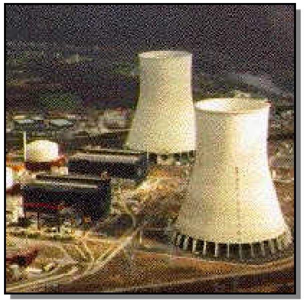
u	c	t
d	s	b

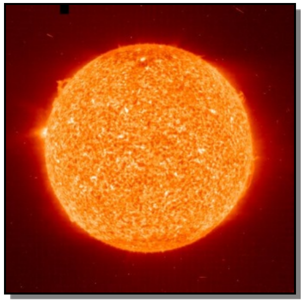
Quarks

t	c	u
d	s	b

Sources of neutrinos: artificial and natural

✓ Nuclear Reactors (power stations, ships)





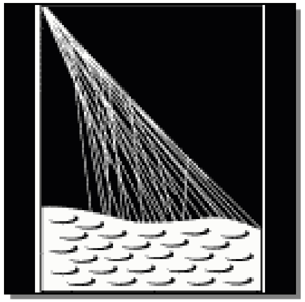
Sun ✓

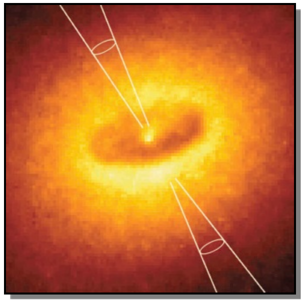
✓ Particle Accelerator

Supernovae (star collapse)

SN 1987A ✓

✓ Earth's Atmosphere (Cosmic Rays)

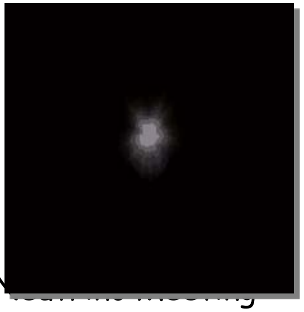




Astrophysical Accelerators

IceCube 2014? ✓

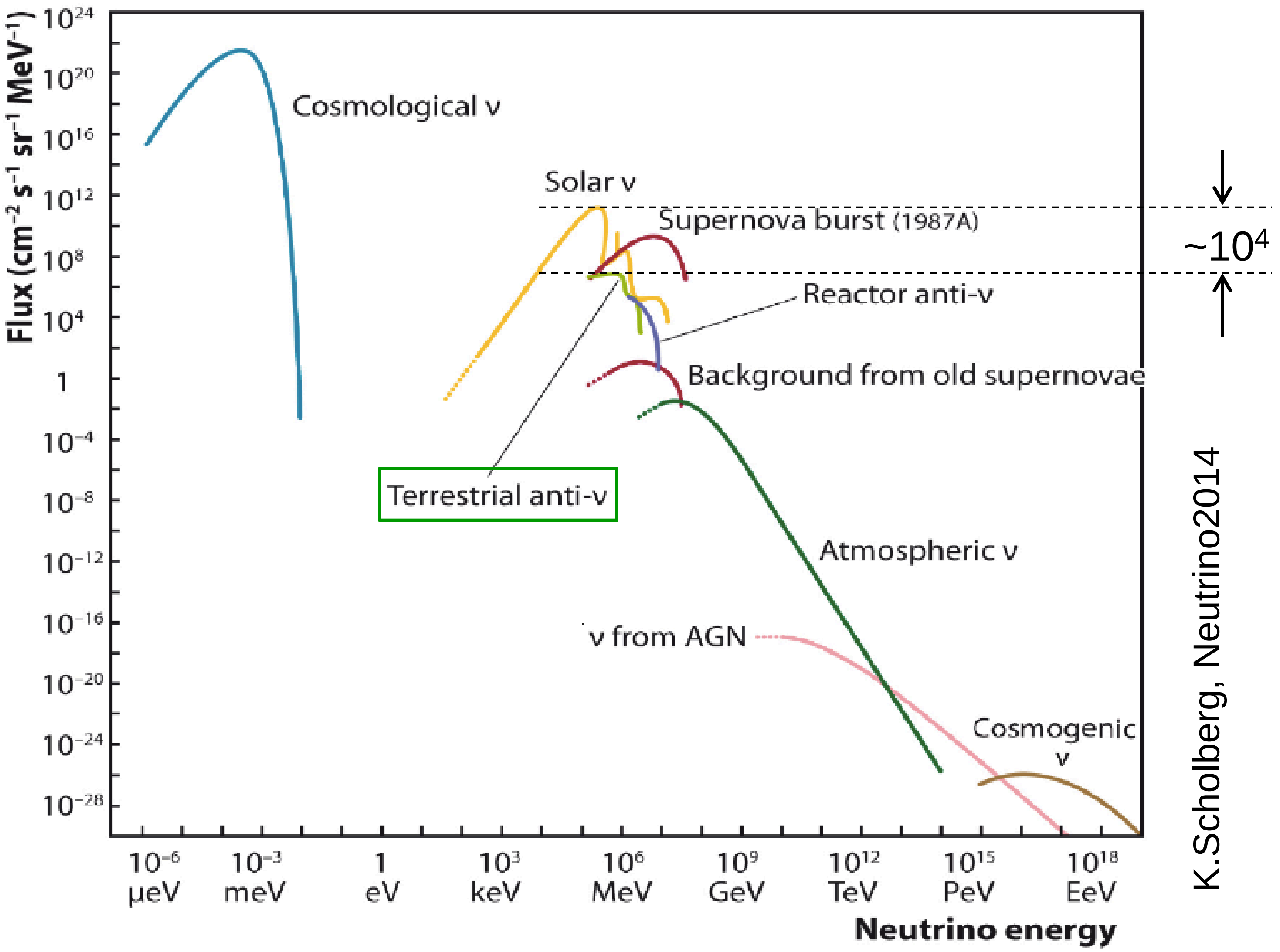
✓ Earth's Crust (Natural Radioactivity)



Big Bang (here 330 ν/cm^3)

Indirect Evidence

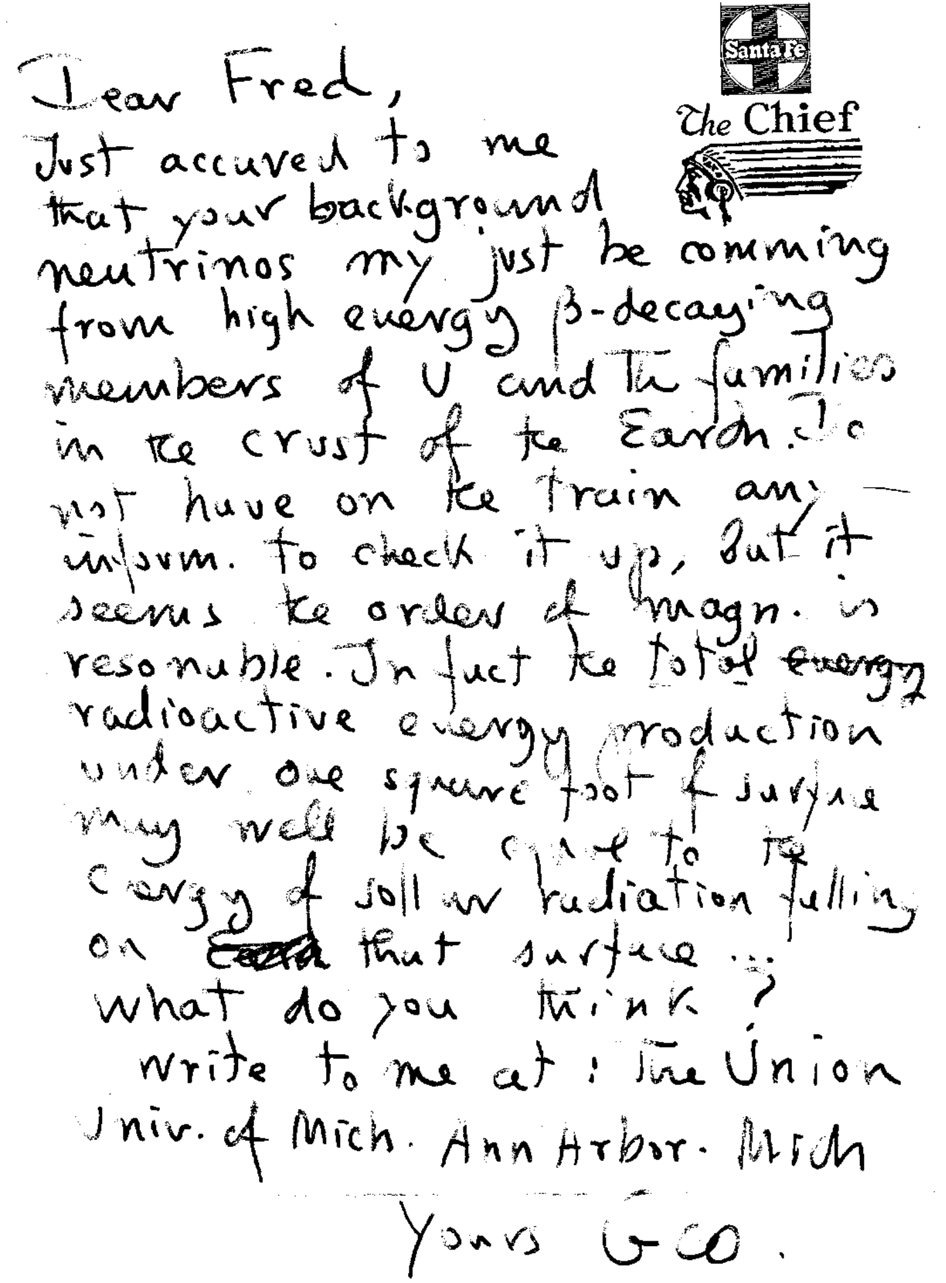
The (anti)neutrino flux on Earth greatly depends on their energy



K.Scholberg, Neutrino2014

Pre-history of Geoneutrinos

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



Santa Fe

The Chief

Dear Fred,

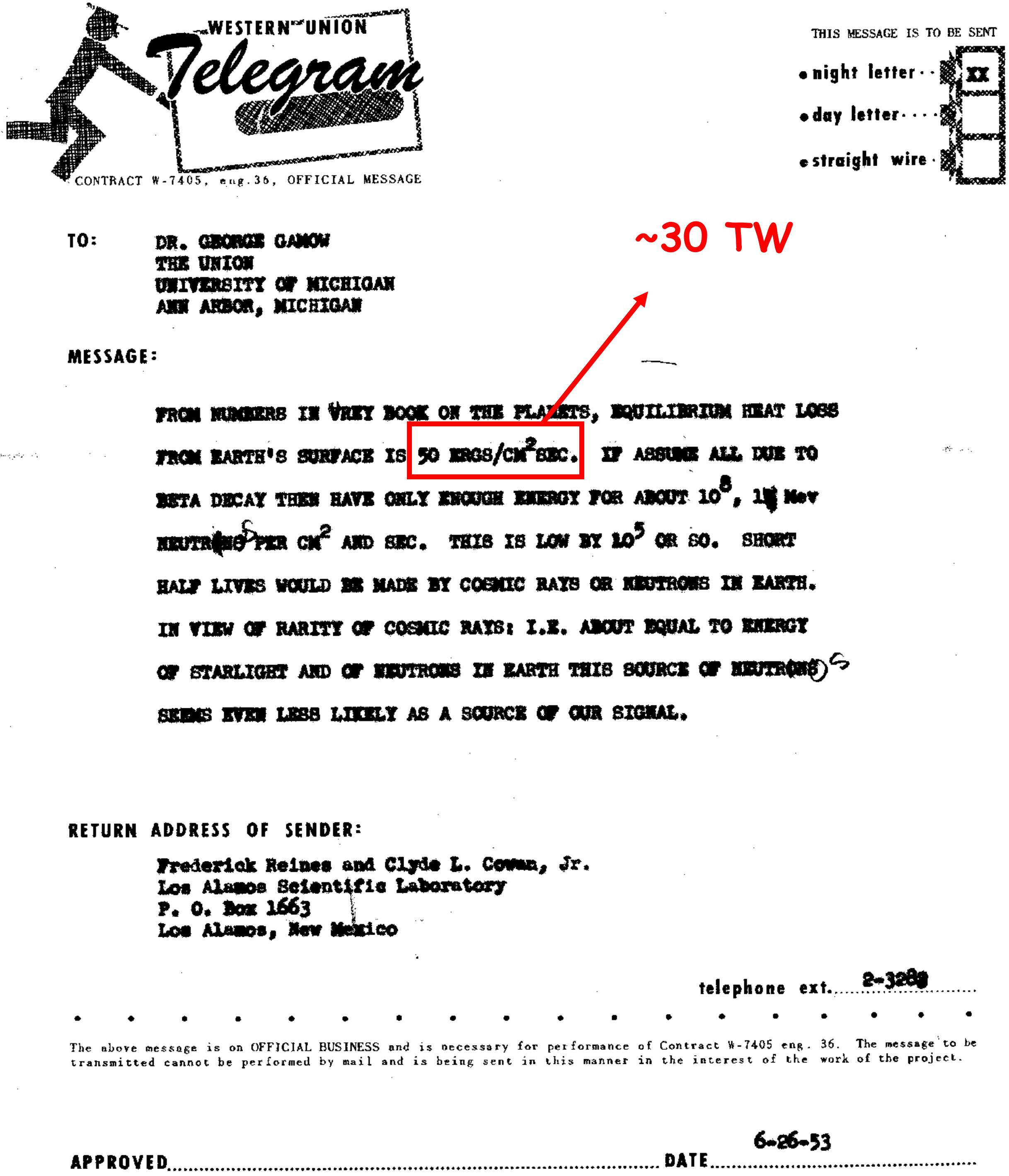
Just accured to me that your background neutrinos my just be comming from high energy β-decaying members of U and Th families in the crust of the Earth. I do not have on the train any inform. to check it up, but it seems the order of magn. is resonable. In fact the total ~~energy~~ radioactive energy 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



~30 TW

WESTERN UNION Telegram

CONTRACT W-7405, eng.36, OFFICIAL MESSAGE

THIS MESSAGE IS TO BE SENT

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

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

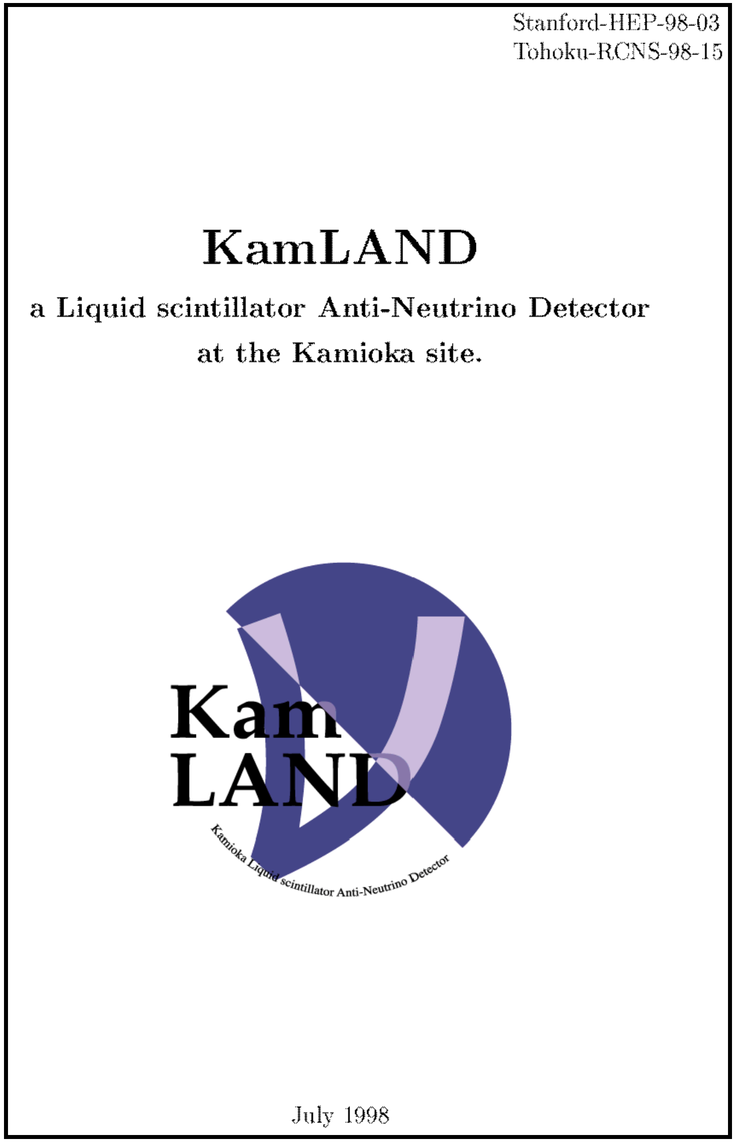
telephone ext. 2-3289

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, 30 Jun 2014

Fast forward 45 years…



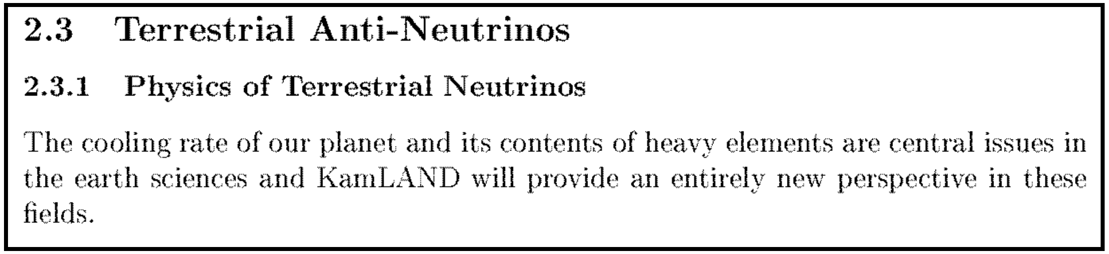
Stanford-HEP-98-03
Tohoku-RCNS-98-15

KamLAND

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

Kam
LAND
Kamioka Liquid scintillator Anti-Neutrino Detector

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.

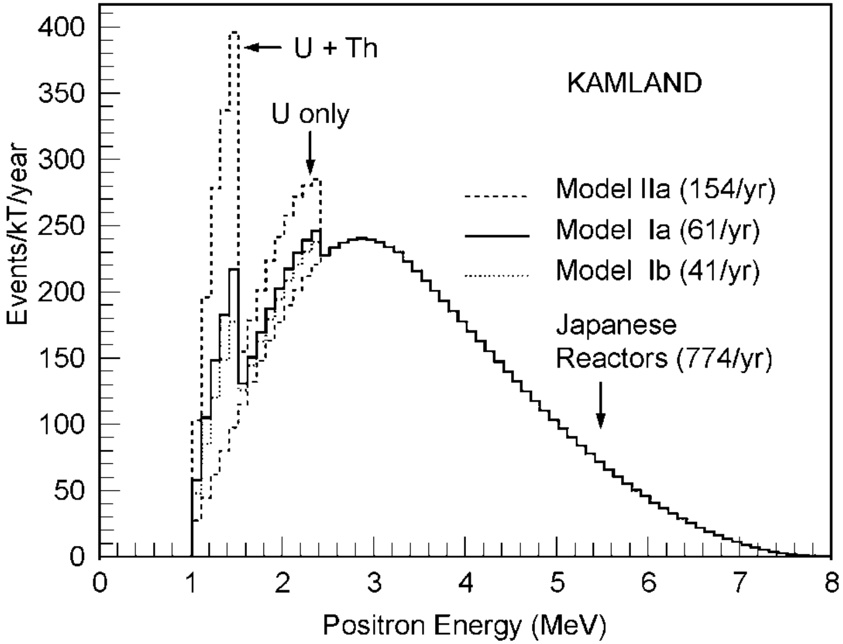


Figure 6: Energy spectrum from terrestrial anti-neutrinos compared with reactor signal as expected in KamLAND. Three different geophysical models [22] are shown for the terrestrial anti-neutrinos and no oscillations are assumed for all the spectra shown.

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.

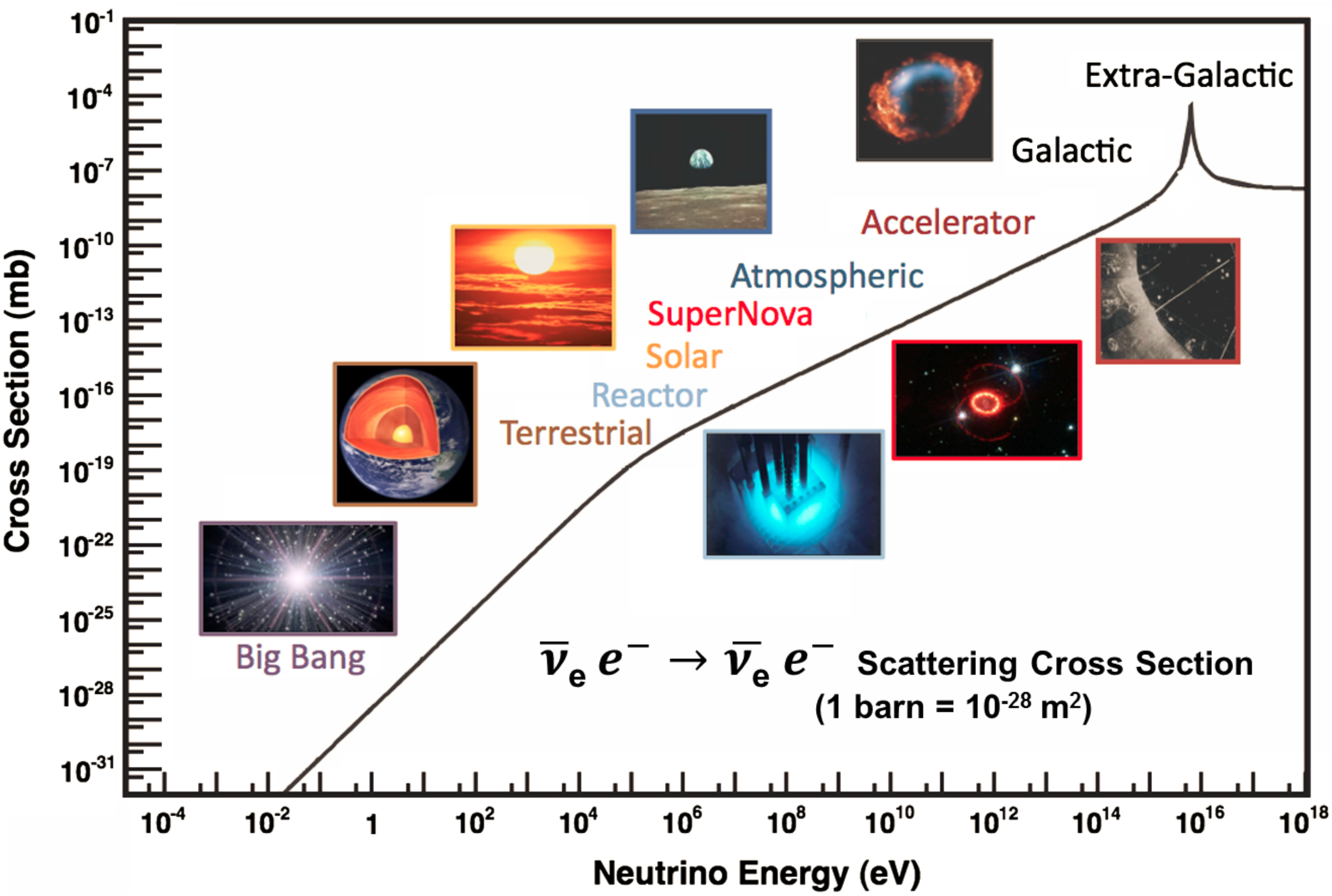
First experimental study (KamLAND): T.Araki et al., Nature 436 (2005) 499

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
G.Bellini et al., Phys. Lett. B 722 (2013) 295

…in addition there is now ample literature about the interpretation of the measurements (not covered in this talk)

The (anti)neutrino interaction cross section is tiny, particularly at low energy



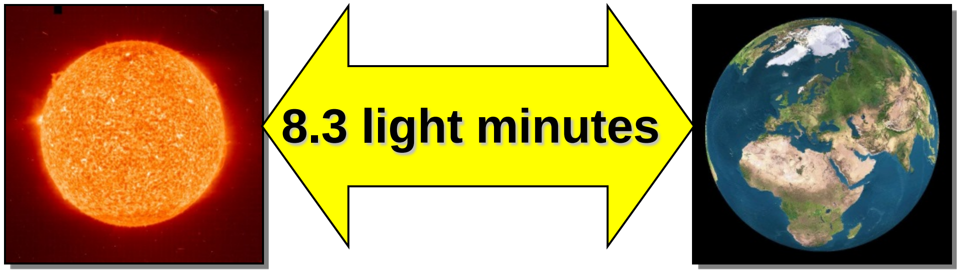
$\bar{\nu}_e e^- \rightarrow \bar{\nu}_e e^-$ **Scattering Cross Section**

(1 barn = 10^{-28} m^2)

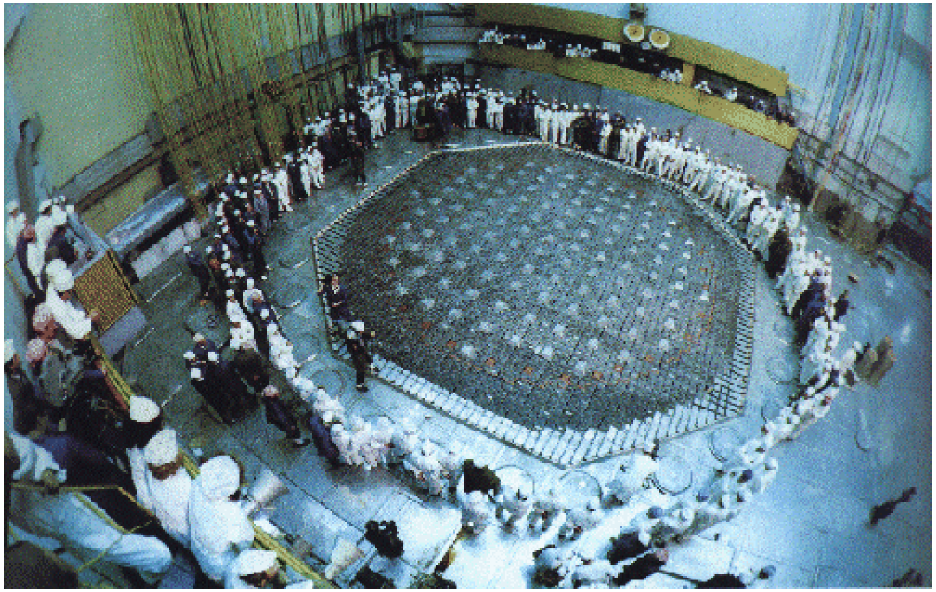
J.A.Formaggio & G.P.Zeller Rev Mod Phys 84 (2012) 1307

Examples:

- Mean free path of anti-neutrinos from a reactor in lead is ~0.3 light years !



- A large nuclear reactor makes 6×10^{20} neutrinos/s:
  at 20 meter distance
  (just outside the building)
  only one neutrino every
  3 sec interacts with
  our body !

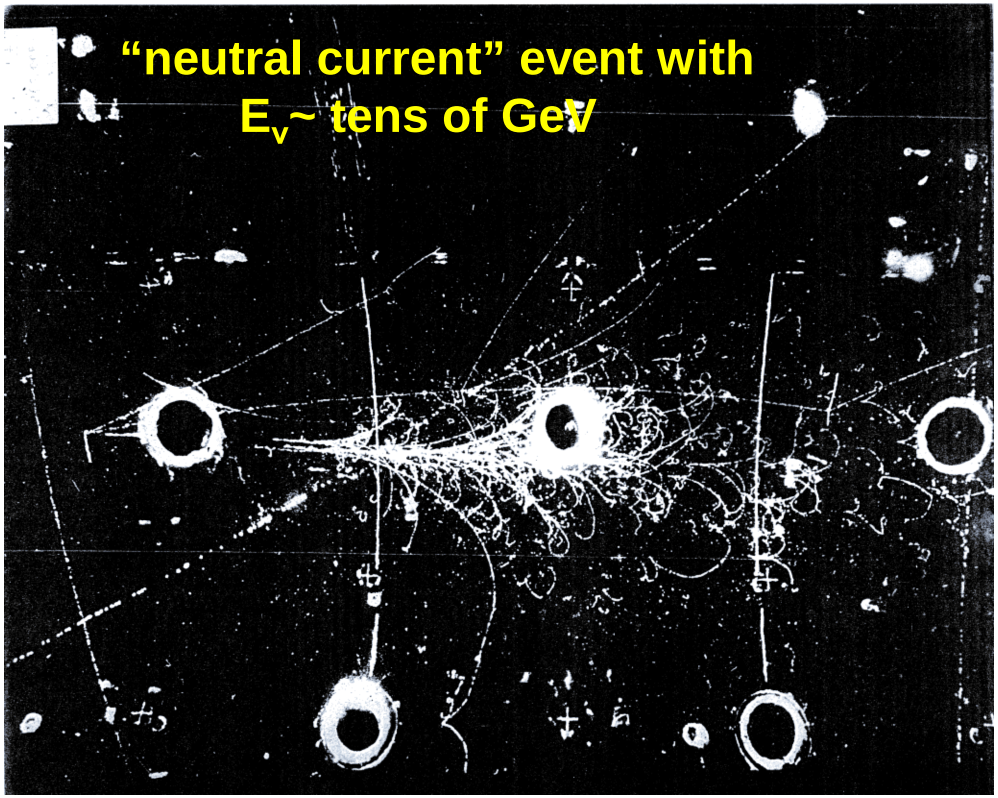


Neutrino detection always requires an interaction to produce some electromagnetic energy that is then detected

➔ Detecting neutrinos is hard!

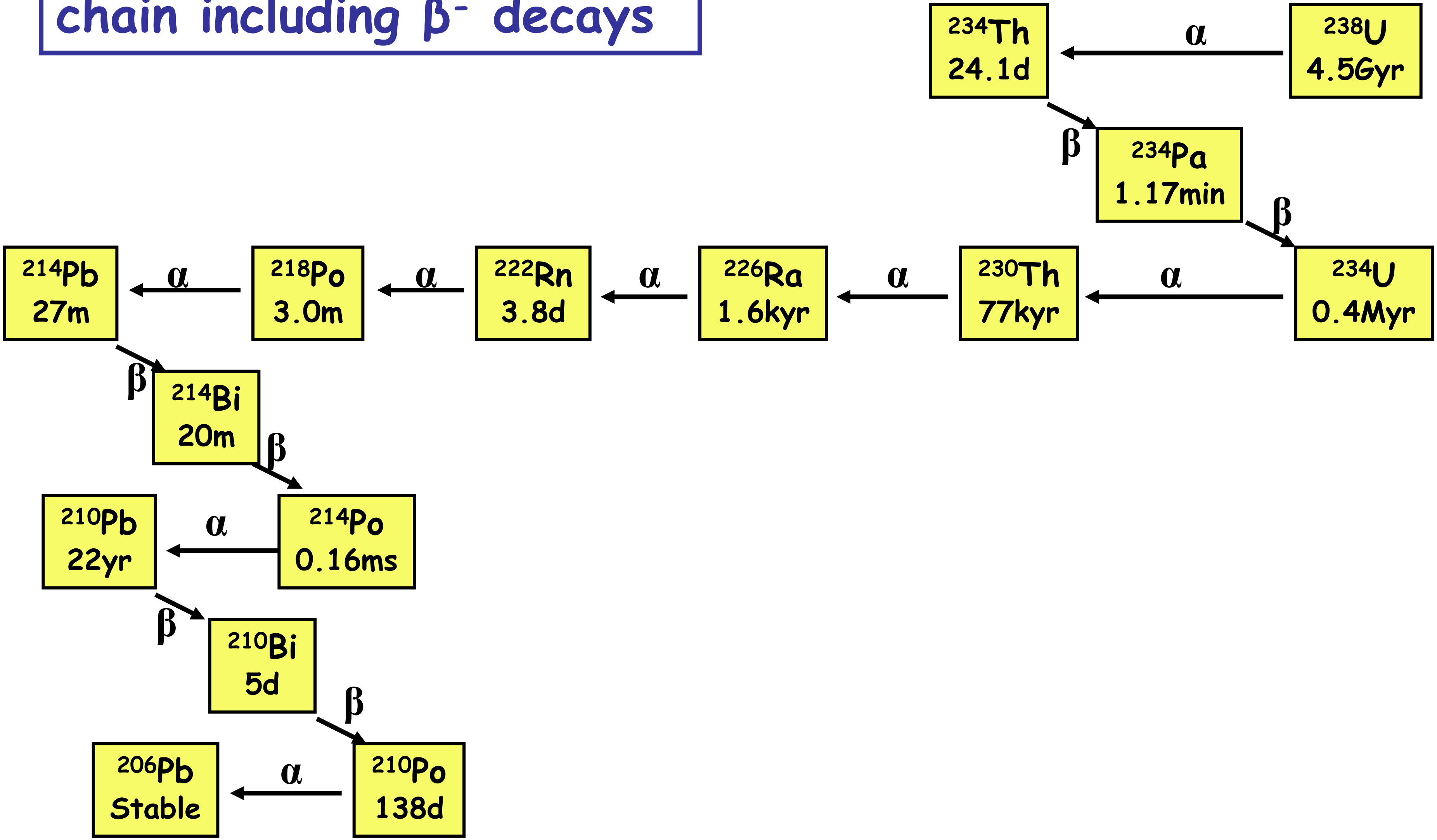
Energy affects detection in three main ways

1. Detection processes vary with energy and produce very different signatures
2. Cross section increases with energy
3. Signatures become more distinctive at high energy, so that the background decreases


"neutral current" event with

E_ν~ tens of GeV

The ^{238}U long decay chain 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

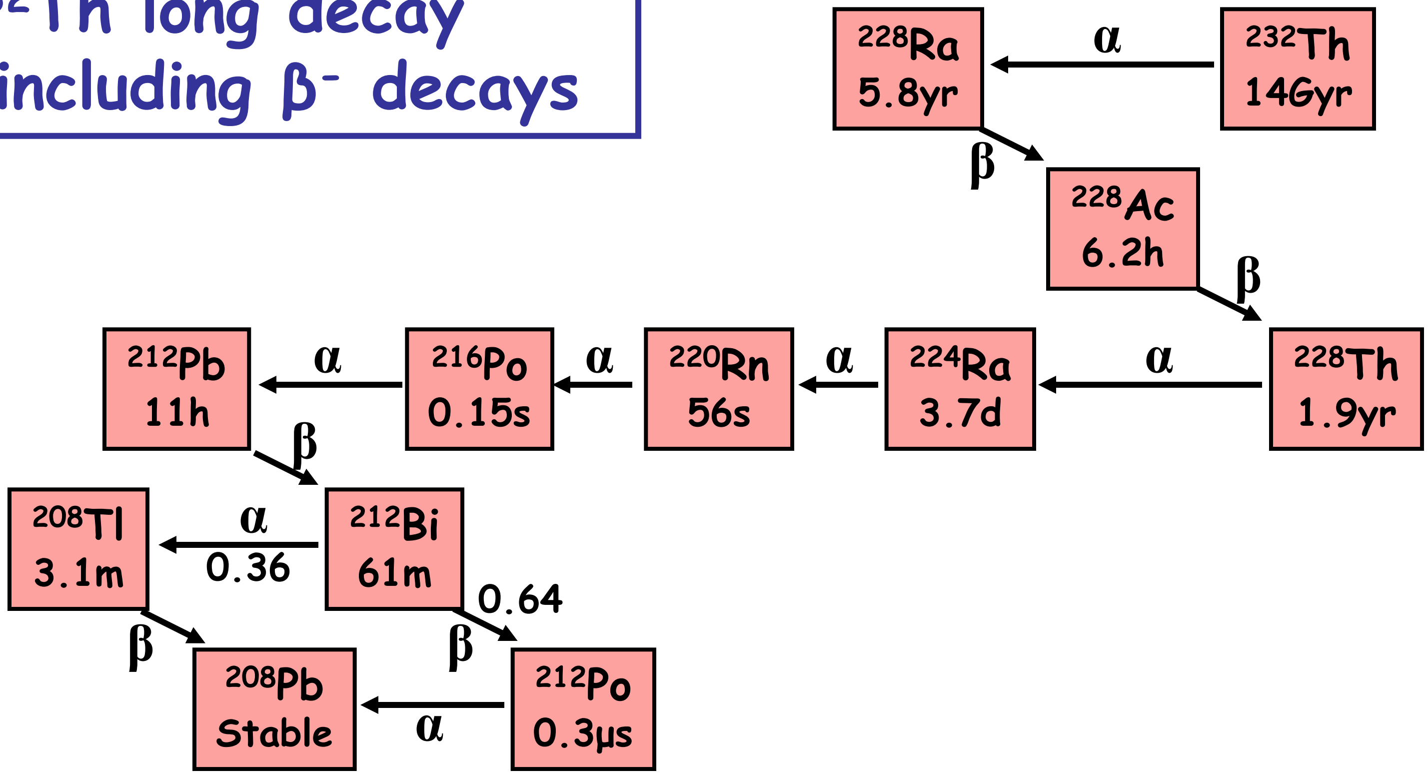
β

^{210}Po 138d

α

^{206}Pb Stable

The ^{232}Th long decay chain including β^- decays



^{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

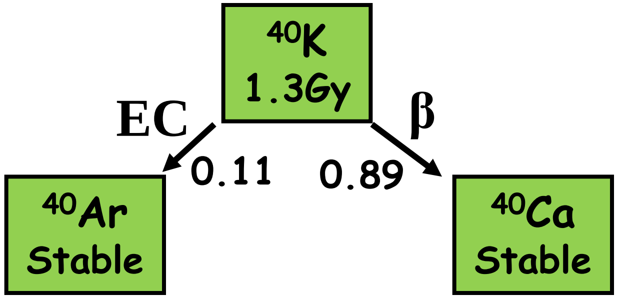
0.64 β

^{212}Po 0.3μs

α

^{208}Pb Stable

The ^{40}K β^- decay



^{40}K 1.3Gy

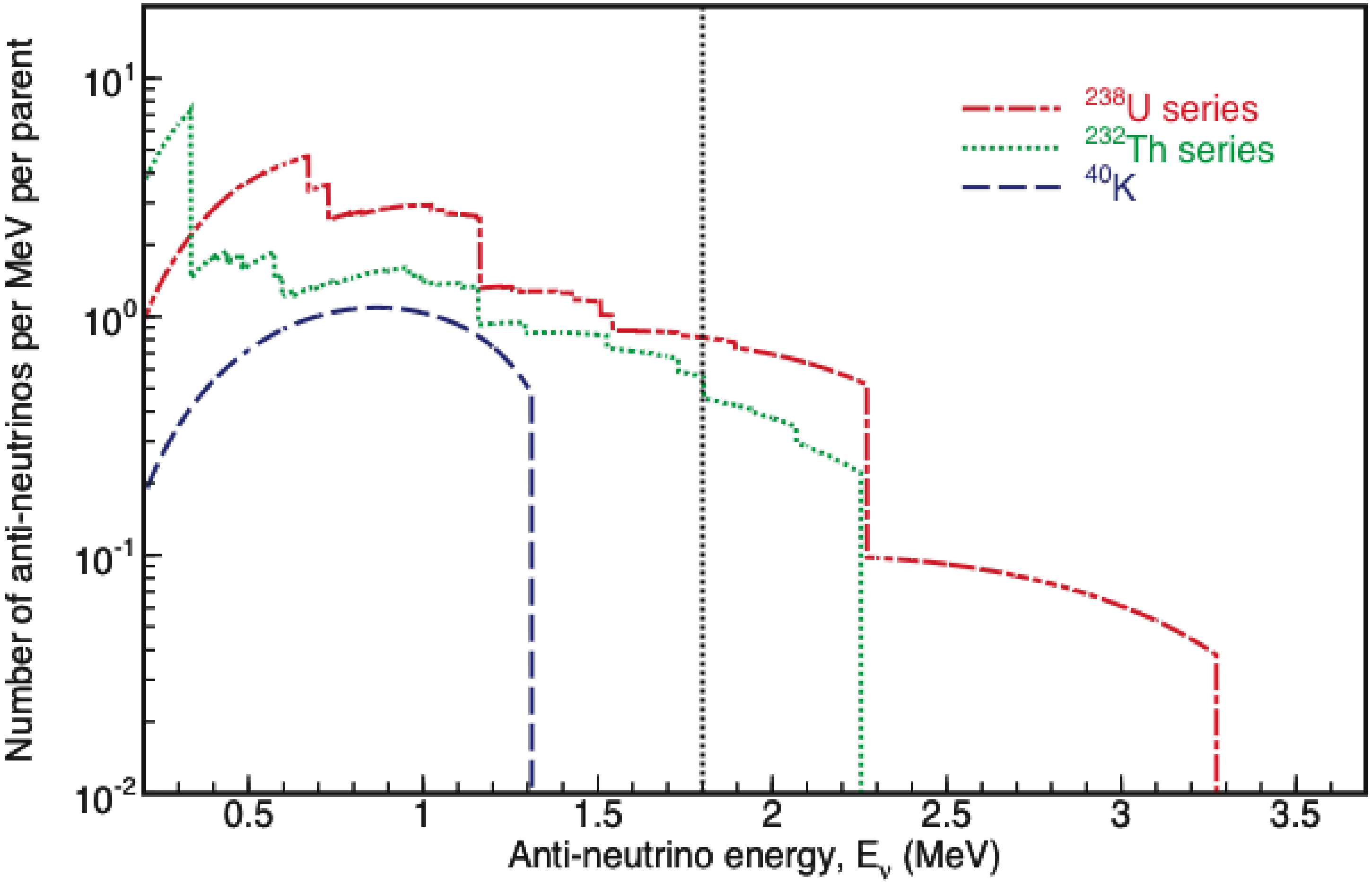
EC 0.11

^{40}Ar Stable

β 0.89

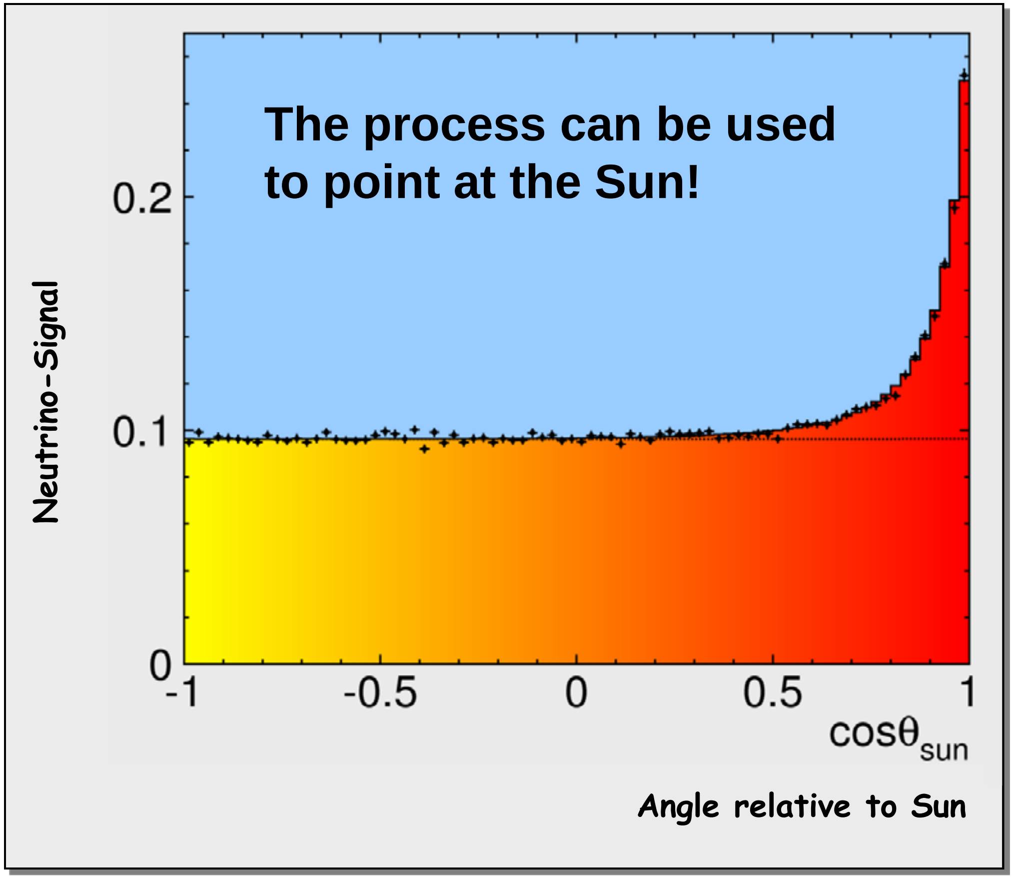
^{40}Ca Stable

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



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



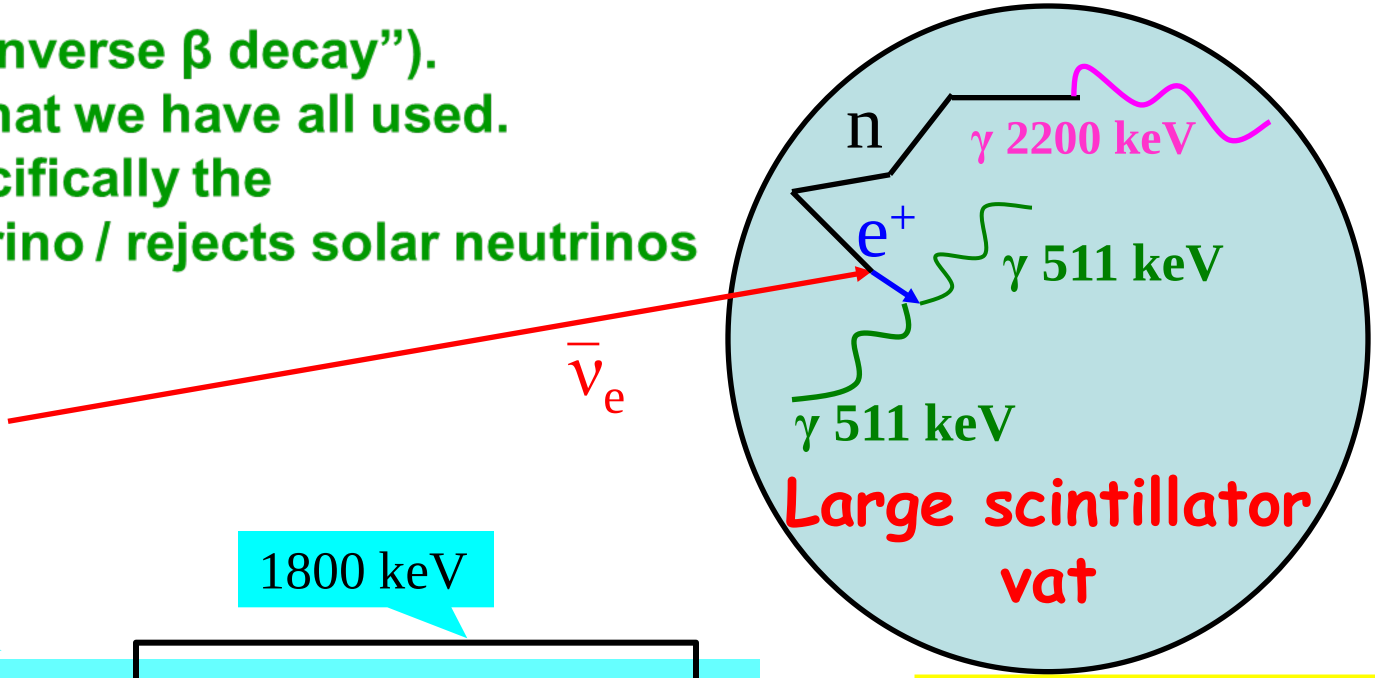
The process can be used to point at the Sun!

Angle relative to Sun

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

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

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



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

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

- $\overline{\nu_e}e^- \rightarrow \overline{\nu_e}e^-$: Too generic (e.g. solar neutrinos can do this too)
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- $\overline{\nu_e}p \rightarrow ne^+$ ("inverse β decay"). This is what we have all used.
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- $\overline{\nu_e}\, N(A,Z) \rightarrow e^+N'(A,Z-1)$ Also a sort of inverse β decay.
  Also antineutrino-specific.
  Can have lower threshold.
  Generally lower cross section.

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:

- $\overline{\nu_e}\,{}^{3}He \rightarrow {}^{3}H\,e^{+}$ **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

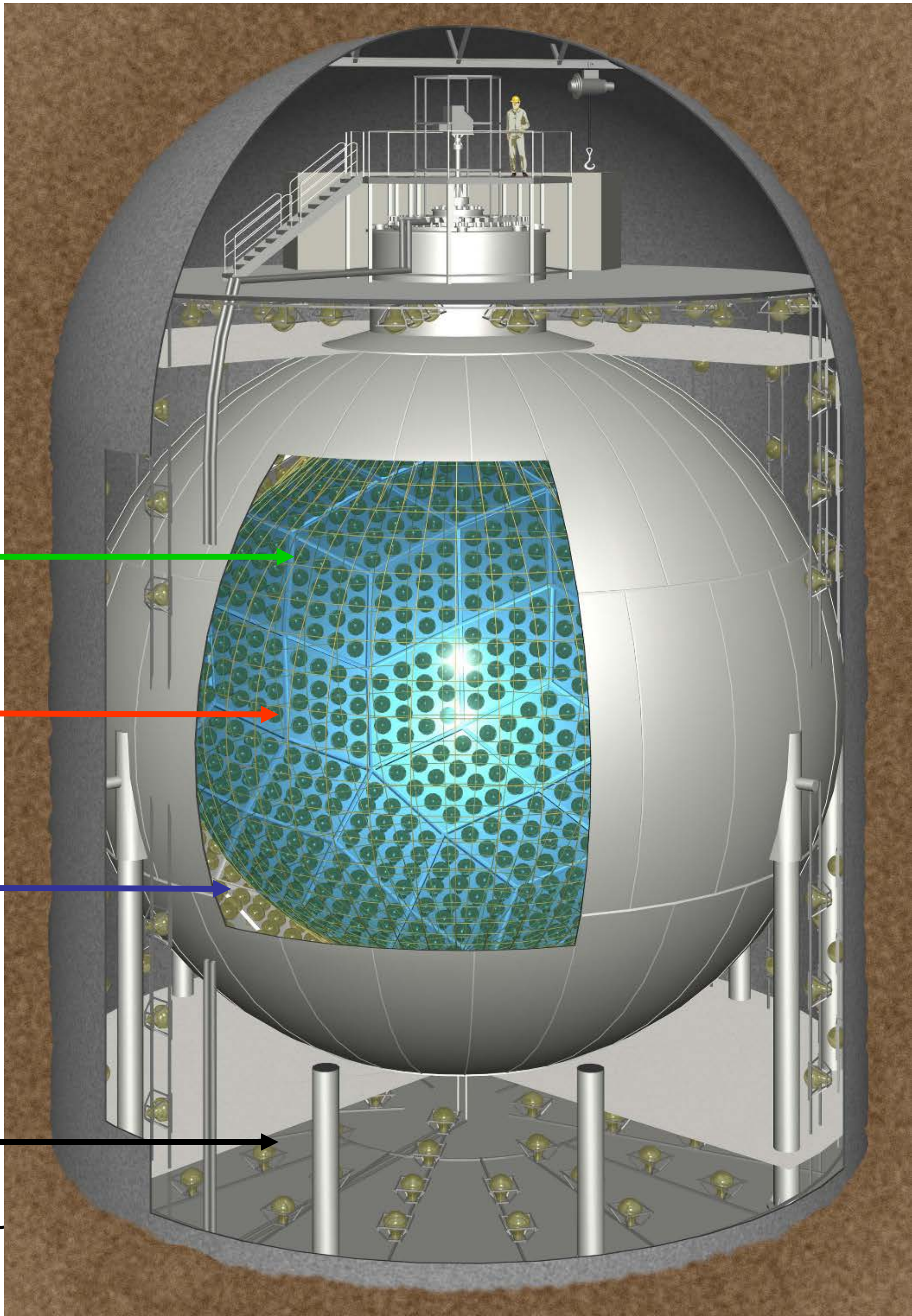
- $\overline{\nu}_e N(A,Z) \rightarrow e^+ N'(A,Z-1)$ Also a sort of inverse β decay.
  Also antineutrino-specific.
  Can have lower threshold.
  Generally lower cross section.
  → No good candidates, but maybe worth another look

- $\overline{\nu}_e N \rightarrow \overline{\nu}_e N$ 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

1km overburden

Example: KamLAND



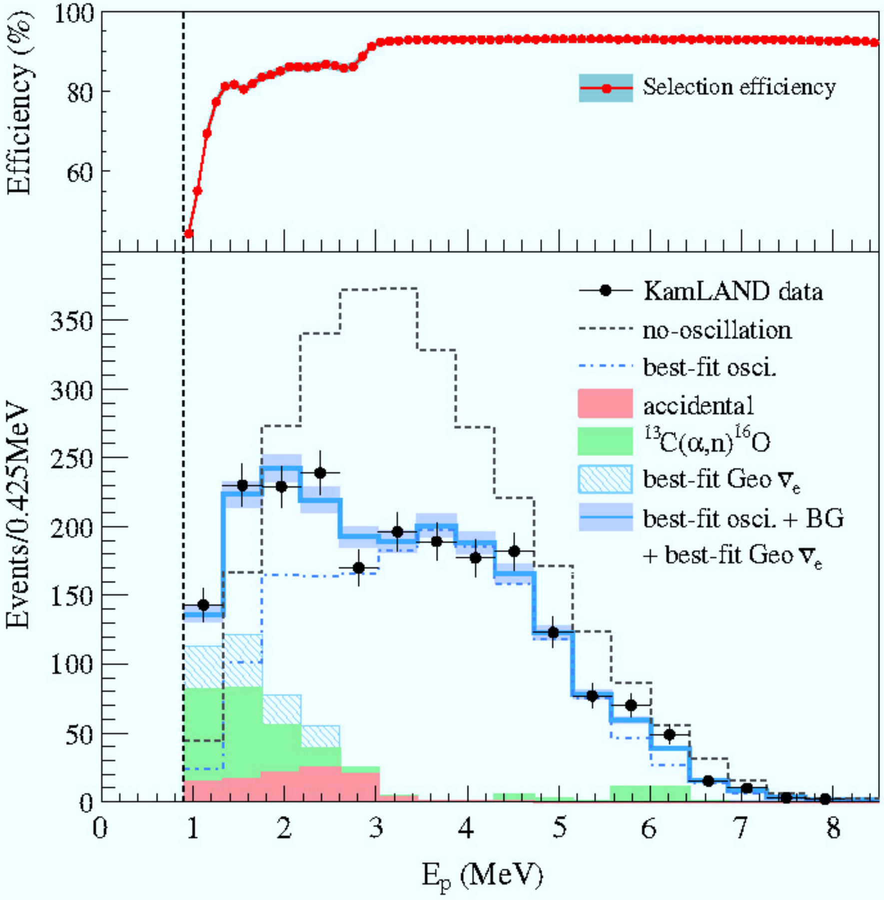
~2000 20" PMTs

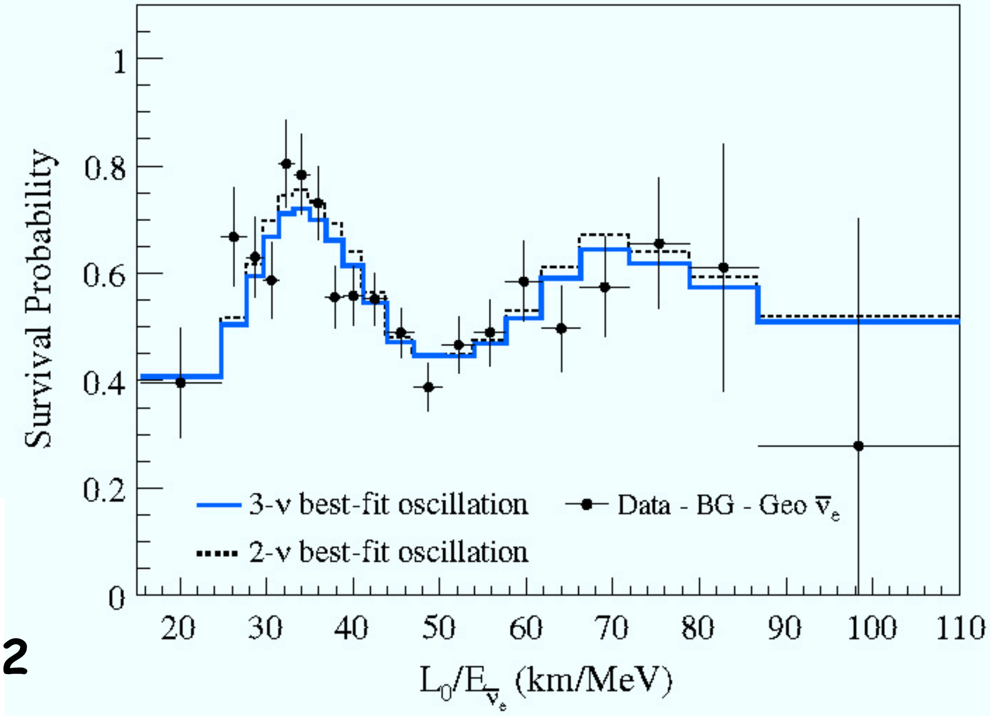
1 kton liquid-scintillator

2.5 m-thick paraffin shielding

Water shield/Cherenkov veto

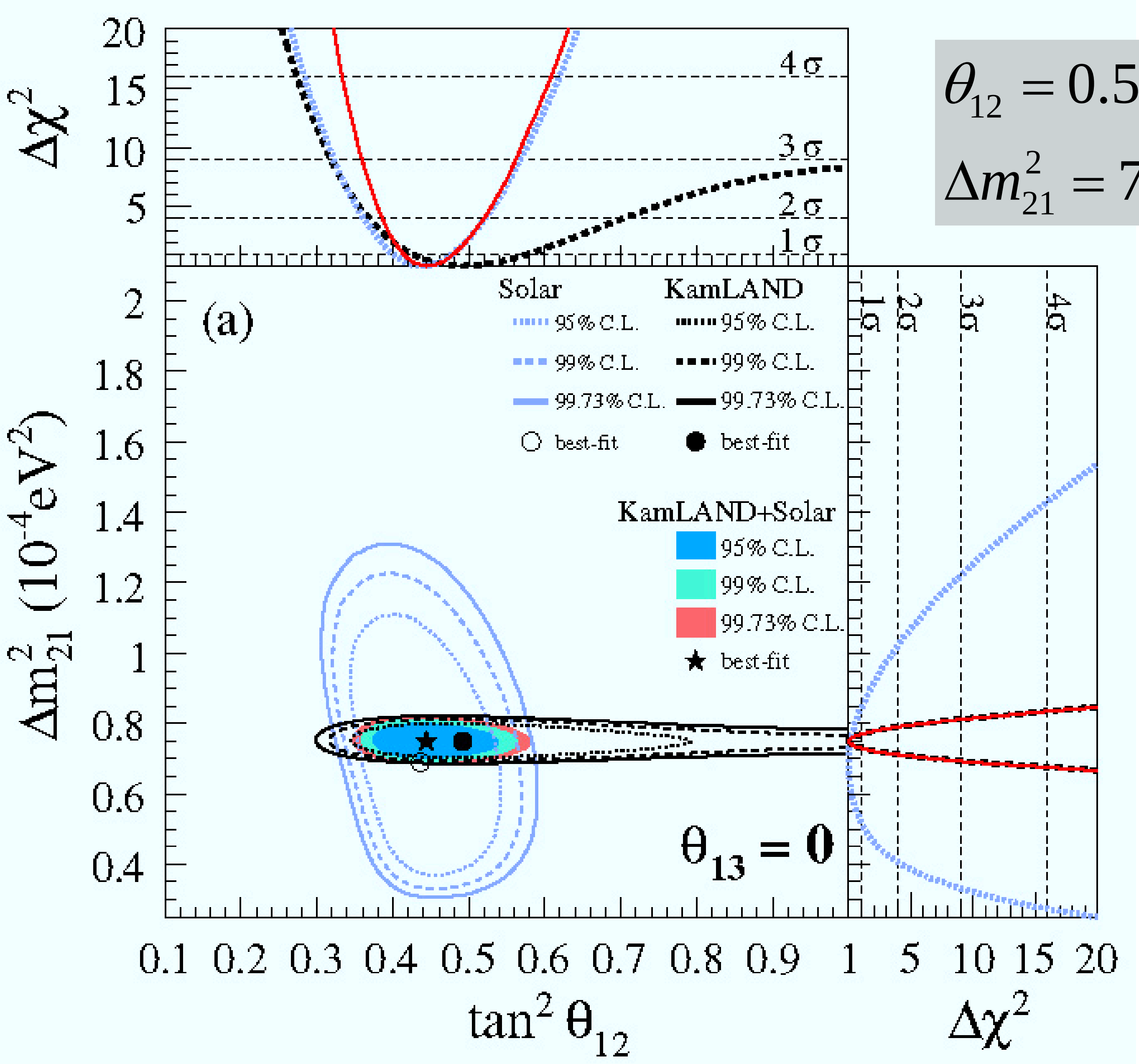
Oscillation measurements using reactors





A.Gando *et al.*
Phys Rev D 83 (2011) 052002

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

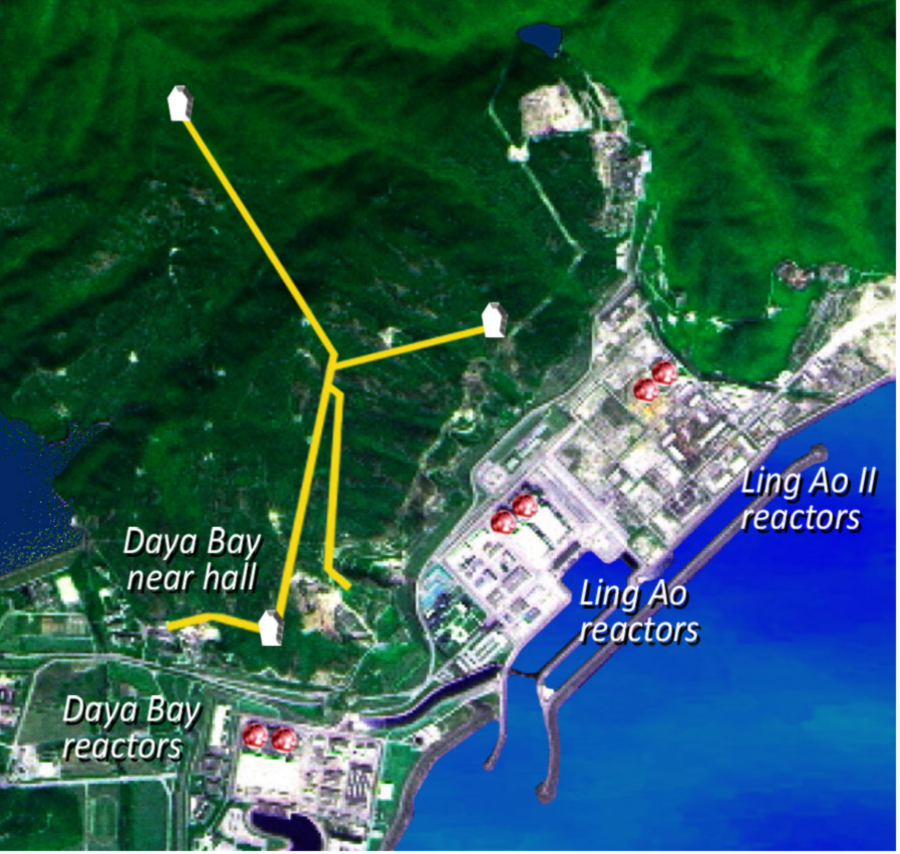


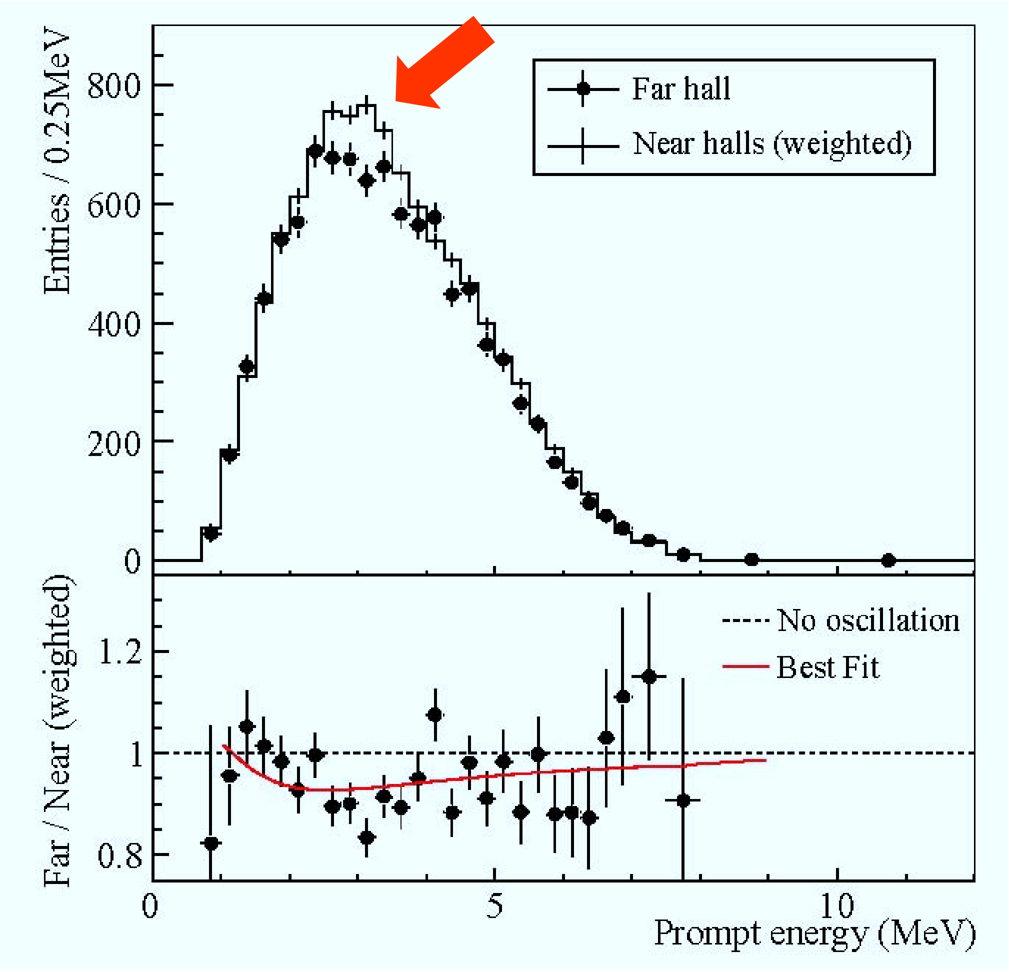
$$\theta_{12} = 0.588^{+0.018}_{-0.016}$$

$$\Delta m^2_{21} = 7.50^{+0.19}_{-0.20} \times 10^{-5}\,\mathrm{eV}^2$$

Most recently the small mixing angle, θ_{13} , has also been measured with the same technique

(DoubleChooz, Daya Bay, RENO)



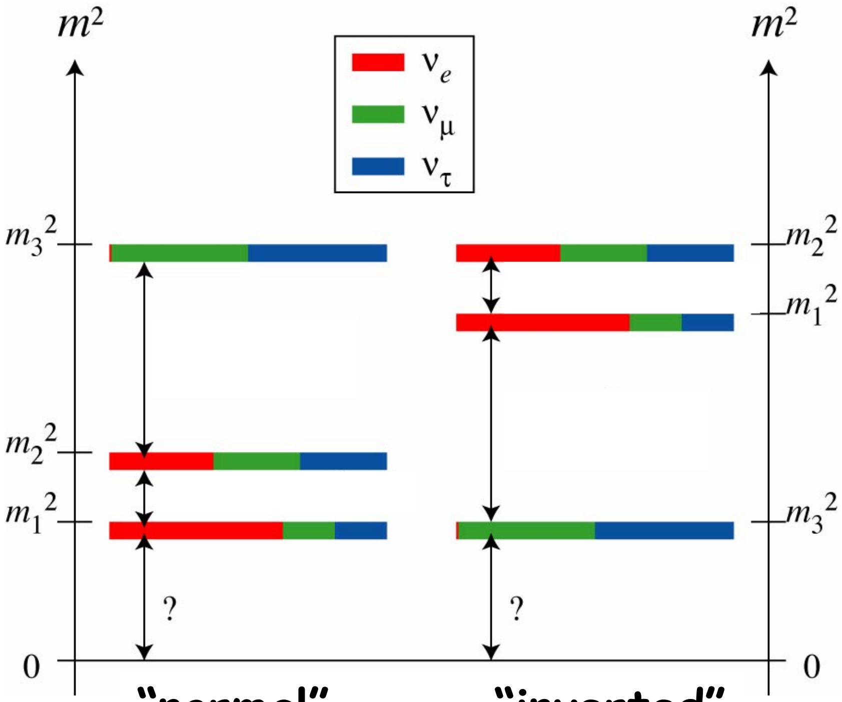


Daya Bay (China)

$\theta_{13}=0.154\pm0.015$

F.P. An et al.
Phys Rev Lett 108 (2012) 171803

The last 15 years have seen huge progress in our understanding of neutrino masses and mixing



“normal” “inverted”
hierarchy

Parameter	Value
$\sin^2\theta_{12}$	0.306 ± 0.017
$\sin^2\theta_{23}$	0.42 ± 0.05
$\sin^2\theta_{13}$	0.023 ± 0.003
Δm^2	$(2.35\pm0.10)^{-3}$ eV^2
δm^2	$(7.58\pm0.24)^{-5}$ eV^2
δ_{CP}	$(0.90\pm0.38)\pi$

(Errors have been symmetrized for simplicity and contain parts due to hierarchy uncertainty and parts due to reactor flux uncertainties)

The last 15 years have seen huge progress in our understanding of neutrino masses and mixing

$$\mathbf{U} = \begin{pmatrix} \mathbf{U}_{e1} & \mathbf{U}_{e2} & \mathbf{U}_{e3} \\ \mathbf{U}_{\mu 1} & \mathbf{U}_{\mu 2} & \mathbf{U}_{\mu 3} \\ \mathbf{U}_{\tau 1} & \mathbf{U}_{\tau 2} & \mathbf{U}_{\tau 3} \end{pmatrix} =$$

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \bullet \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{-i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \bullet \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \bullet \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{-i\alpha/2} & 0 \\ 0 & 0 & e^{-i\alpha/2+i\beta} \end{pmatrix}$$

Parameter	Value
$\sin^2\theta_{12}$	0.306±0.017
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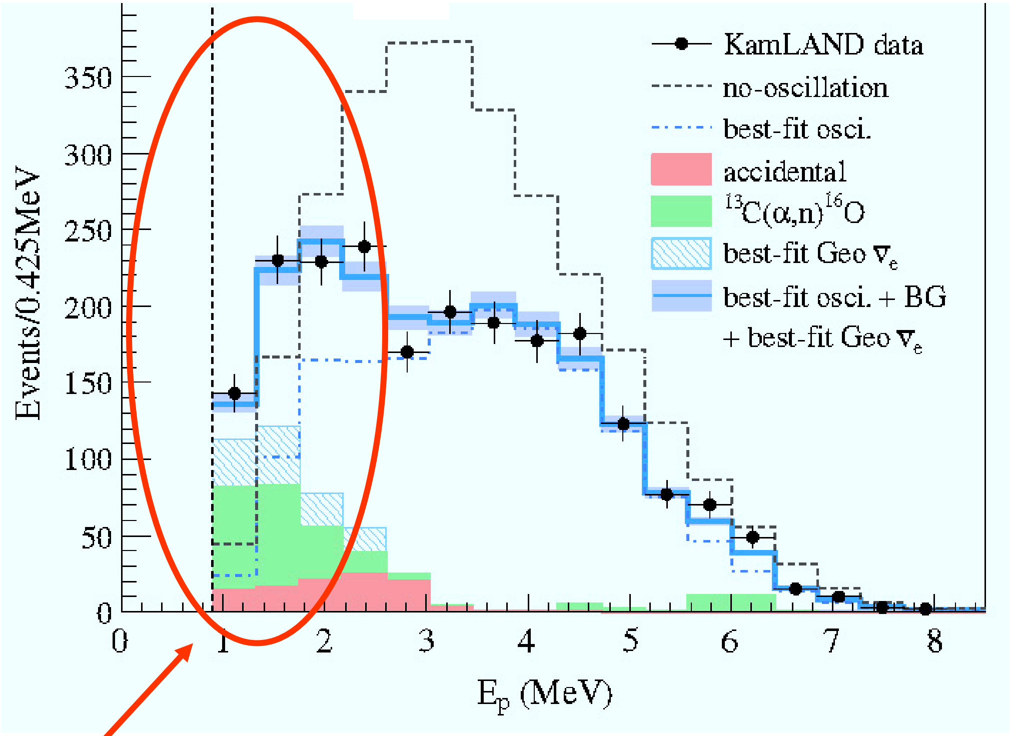
δ_{CP}	$(0.90\pm0.38)\pi$

(Errors have been symmetrized for simplicity and contain parts due to hierarchy uncertainty and parts due to reactor flux uncertainties)

But what about Geoneutrinos?

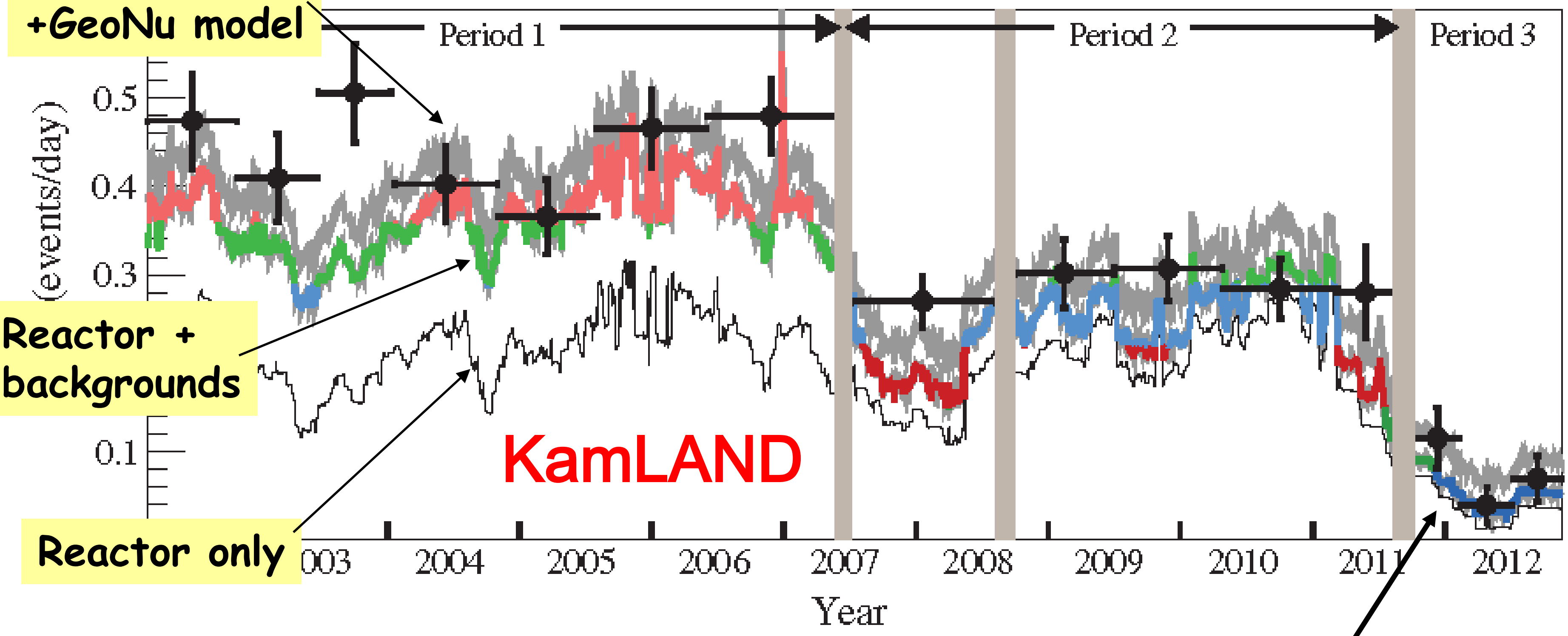


They are contained in the low energy part of the spectrum.

➔ Reactors here are a nuisance

Nuclear reactors traditionally have been a substantial "background" to the Geoneutrino measurement in KamLAND

0.9-2.6MeV time history



Reactor + Backgrounds +GeoNu model

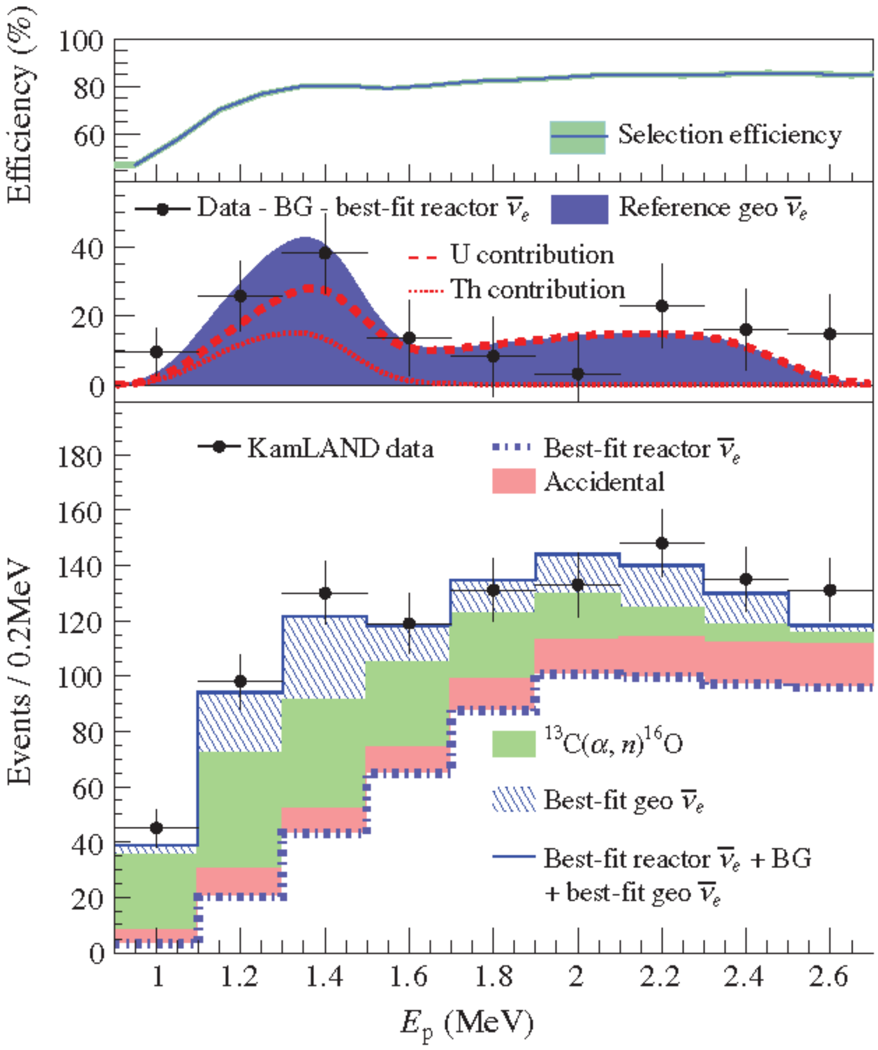
Reactor + backgrounds

Reactor only

After the Fukushima accident this background has gone away

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

The fit knows also of the reactor power excursions



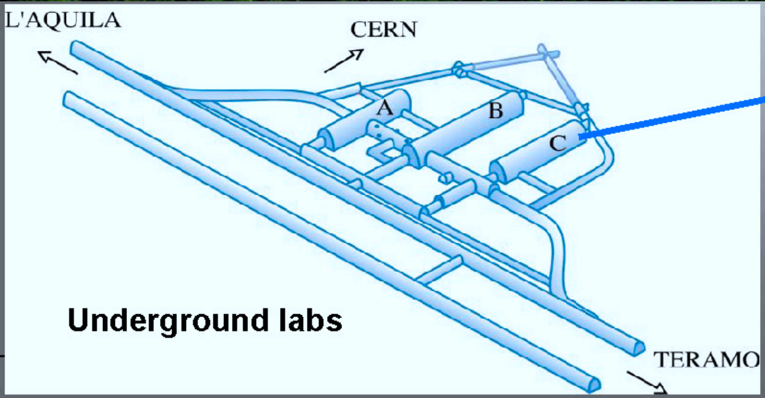
Null hypothesis for geoNu has a probability of $2\cdot10^{-6}$

Borexino

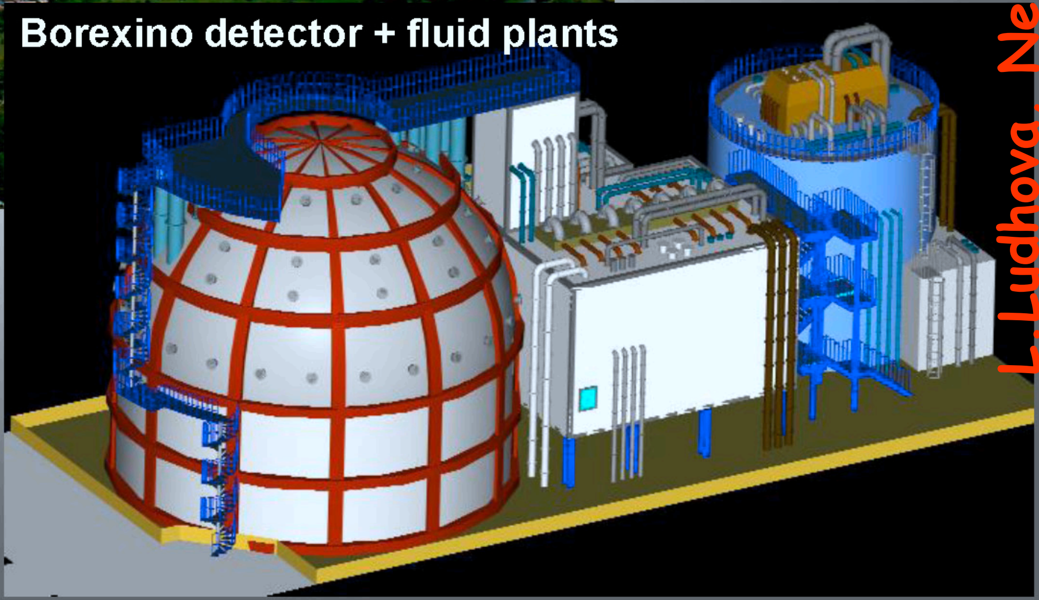
Abruzzo
120 Km from Rome

Laboratori Nazionali del Gran Sasso

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



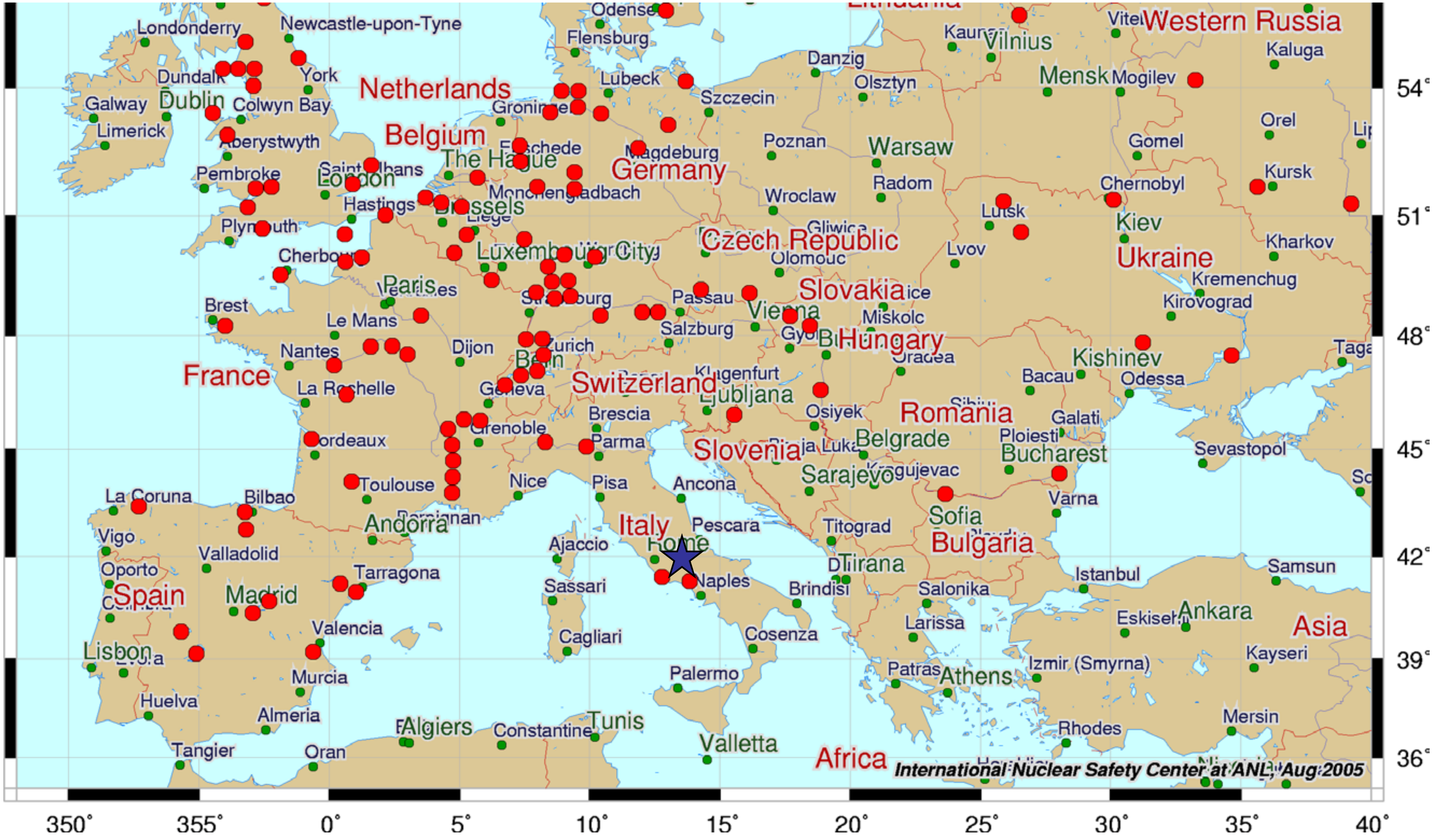
Underground labs



Borexino detector + fluid plants

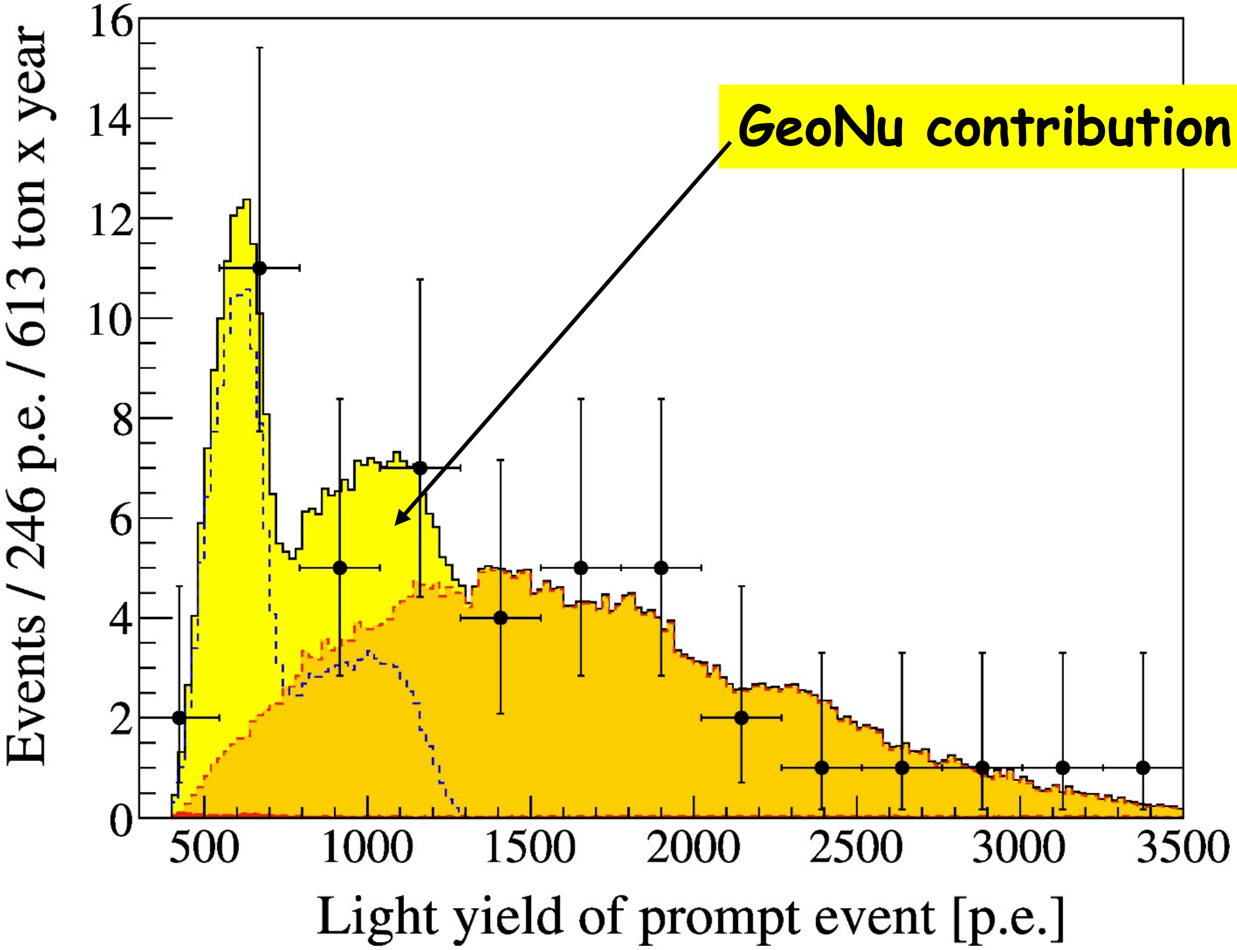
L. Ludhova, Neutrino Geoscience 2010

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 and shorter run)



GeoNu contribution

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

The expected rate at different world locations

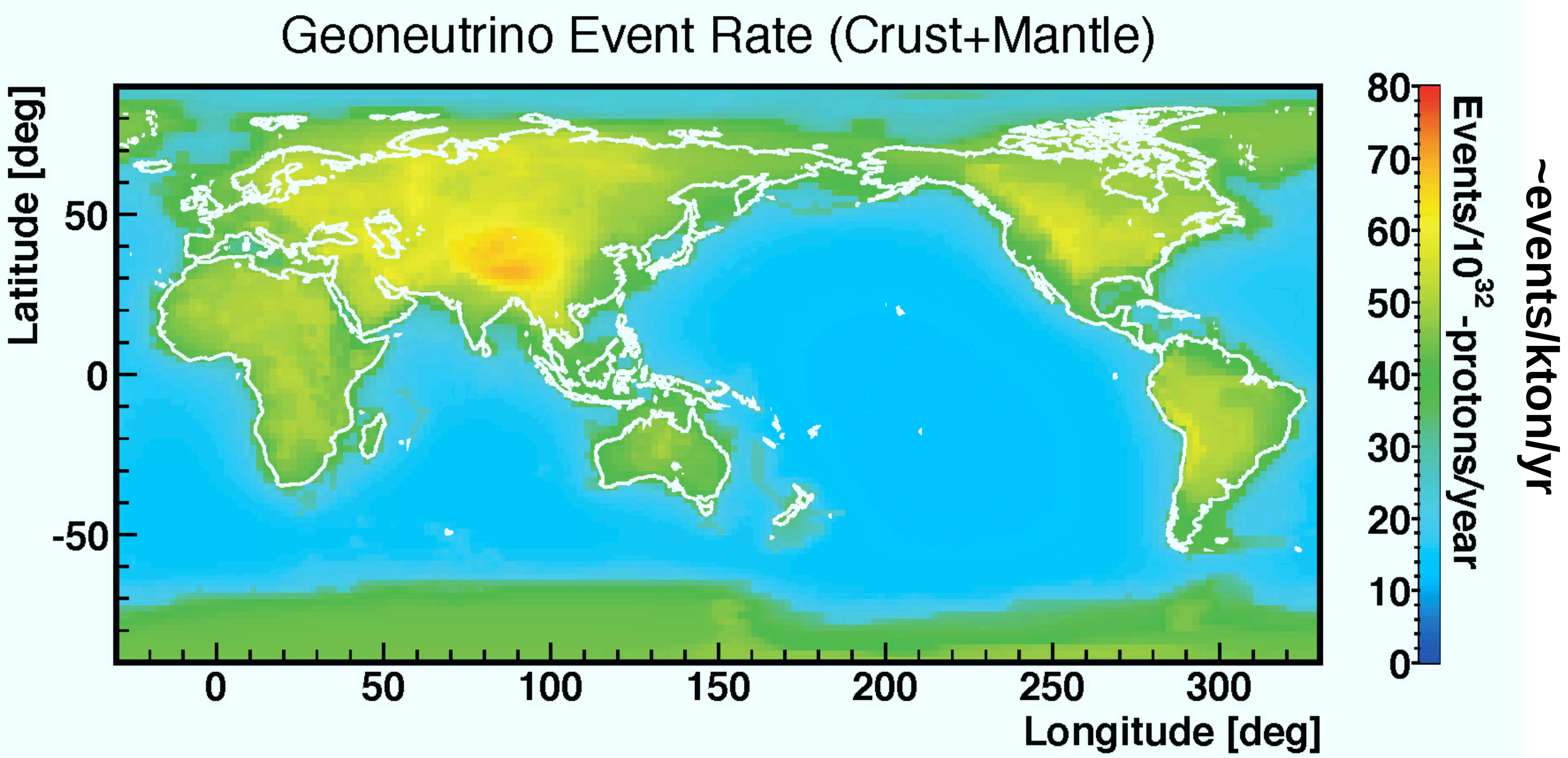


Image: S. Enomoto

Note the rate scale:

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

Background from reactors.

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

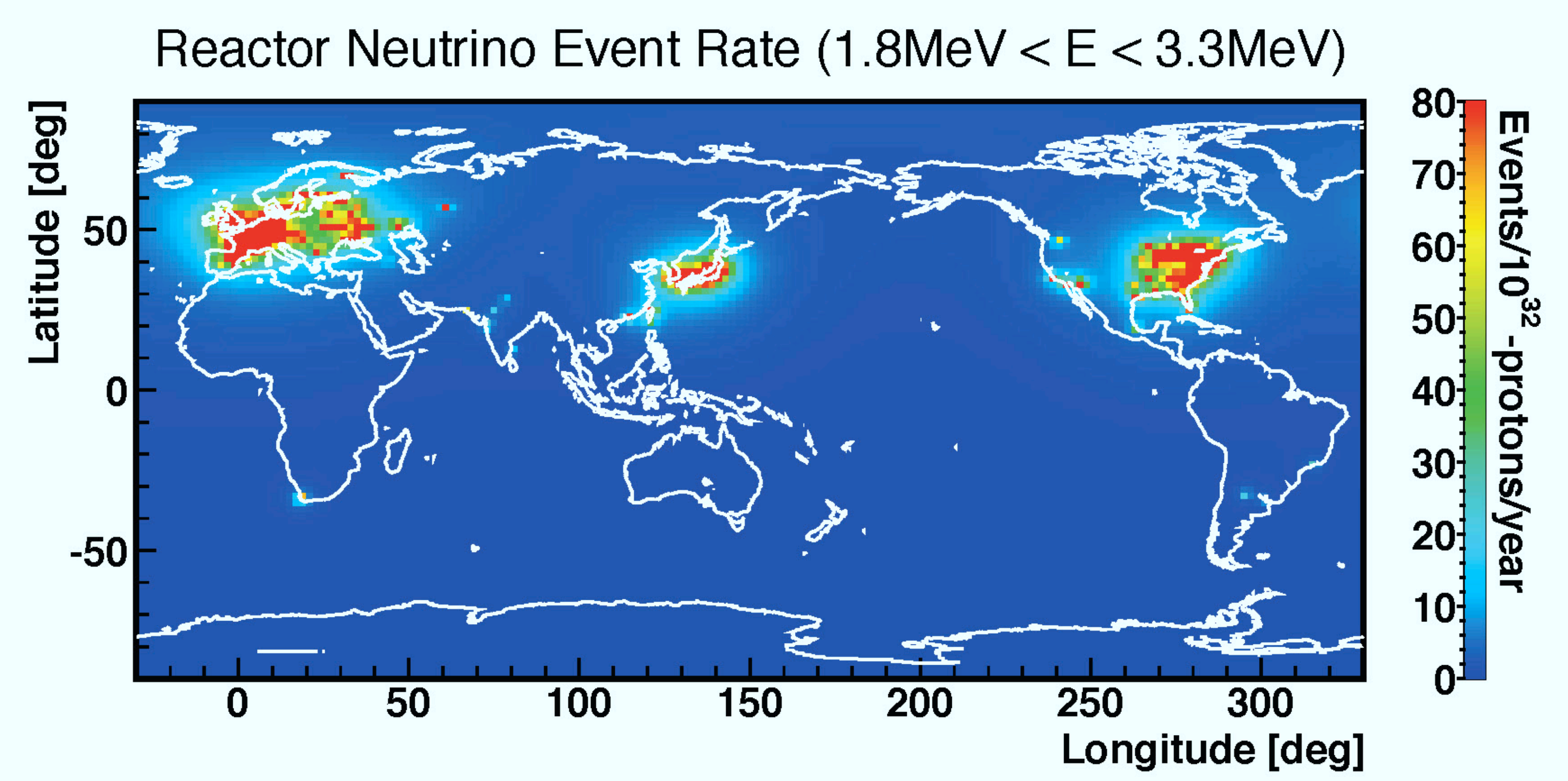


Image: S. Enomoto

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

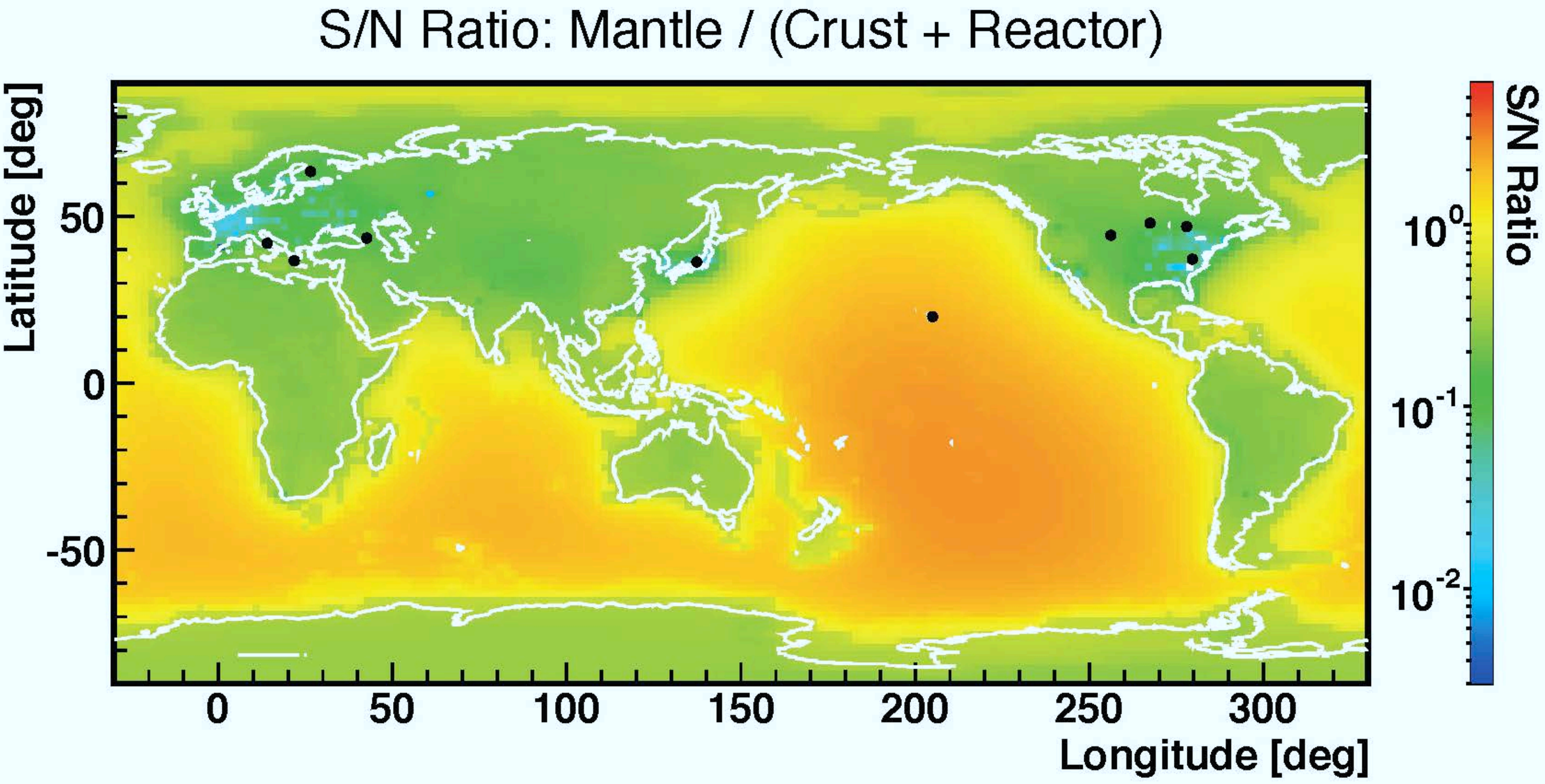
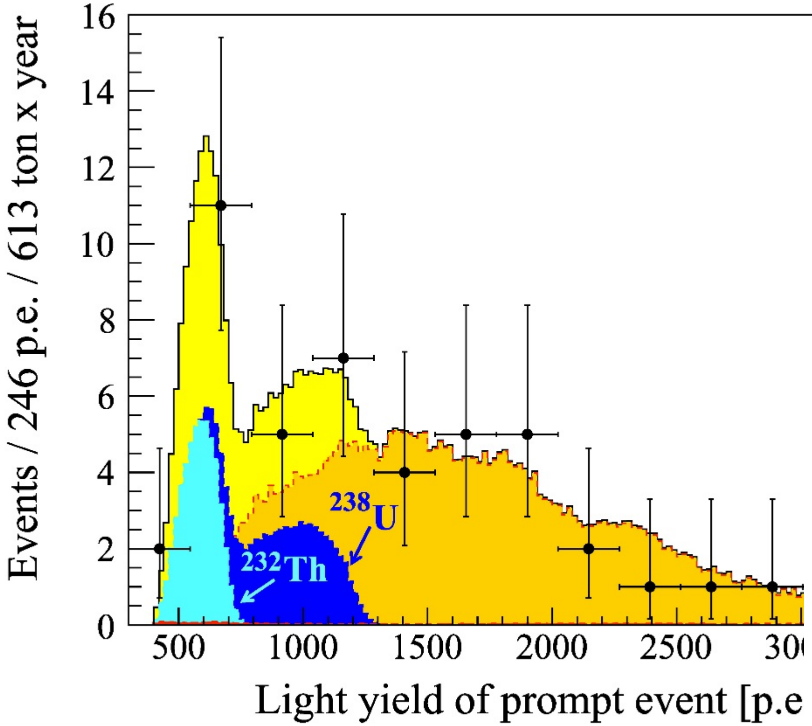
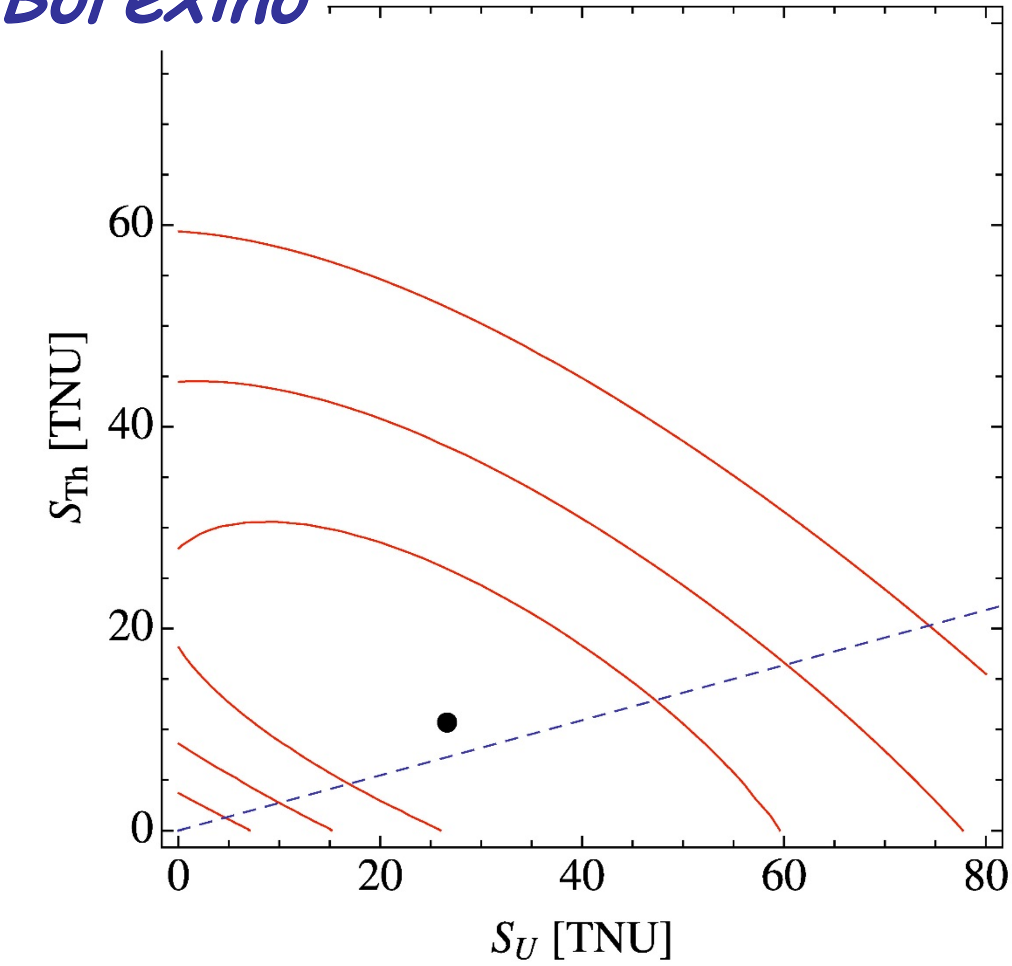


Image: S. Enomoto

In principle data could derive the Th/U ratio



Borexino



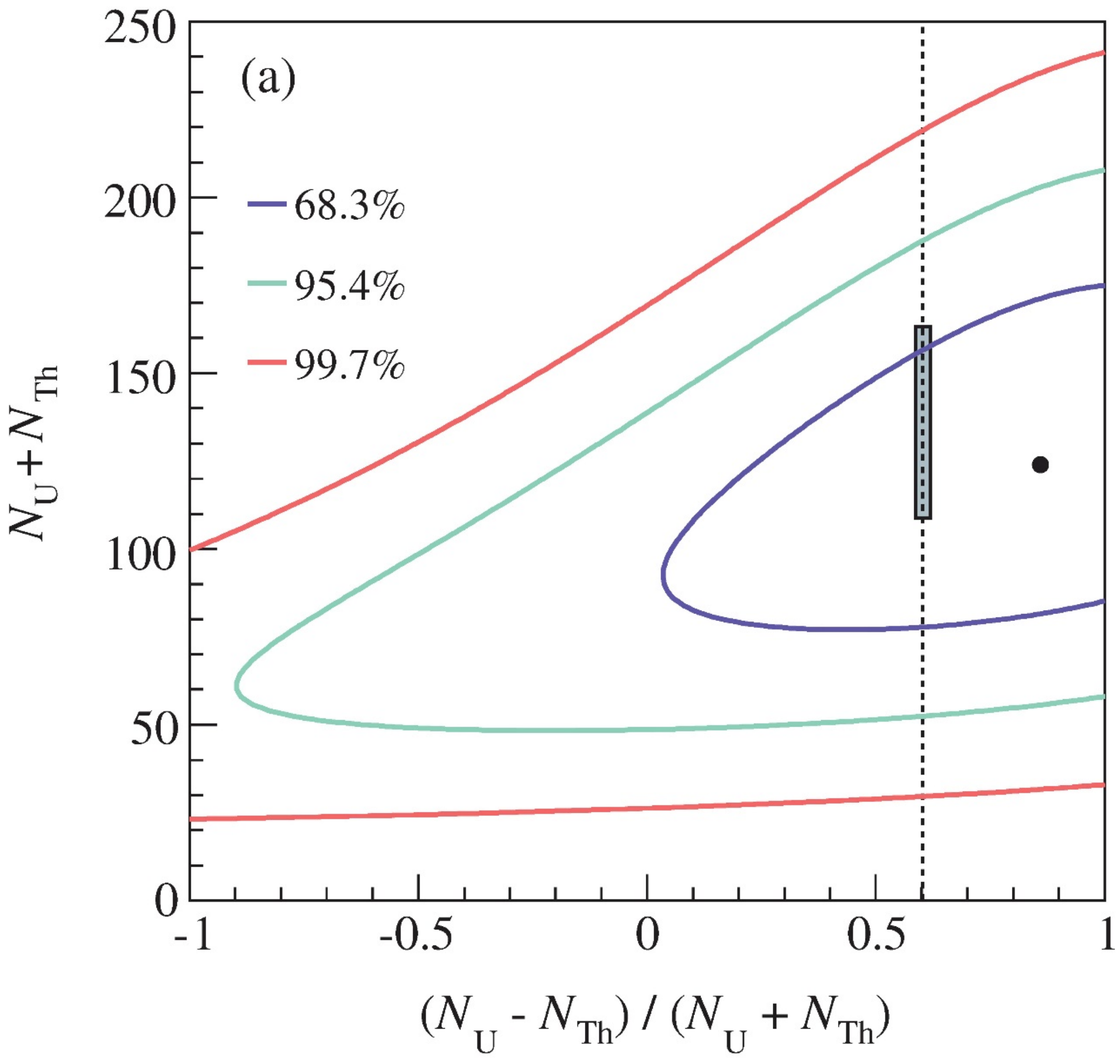
Best fit gives
N_{Th}/N_U = 0.4 for Borexino

But the error is huge and this is compatible with the C1 chondritic meteorite ratio 0.85 (mass ratio=3.9)

Similar result for KamLAND

Th/U mass ratio
<19 at 90% CL

But, again, the error is huge, in the rest use C1 chondritic meteorite ratio of 3.9



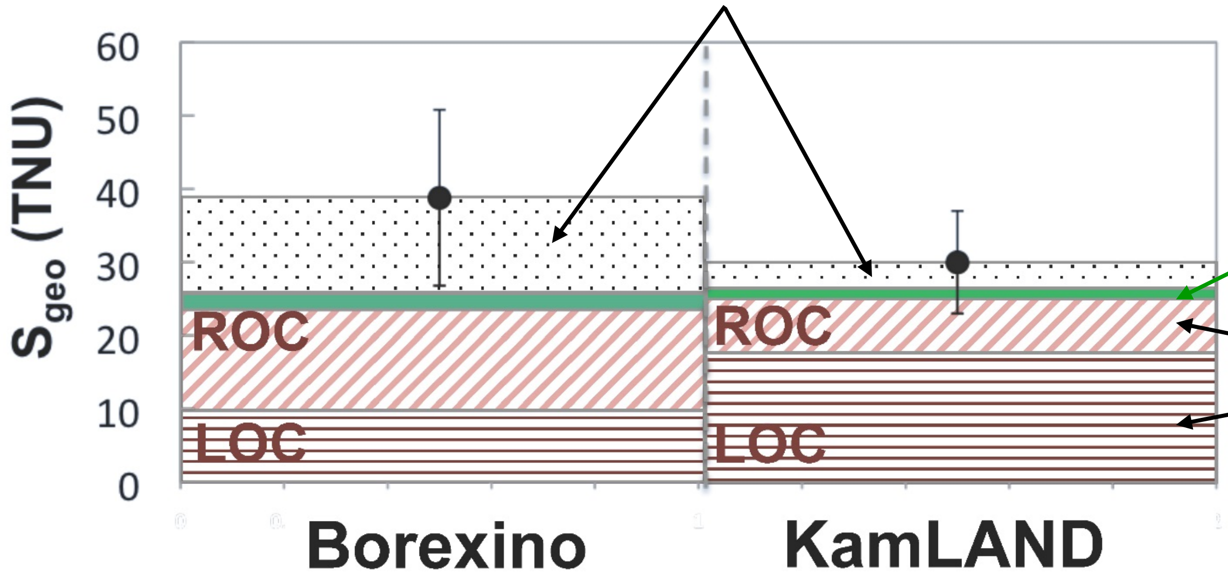
How does the model compare with data for the total U + Th rates?

	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



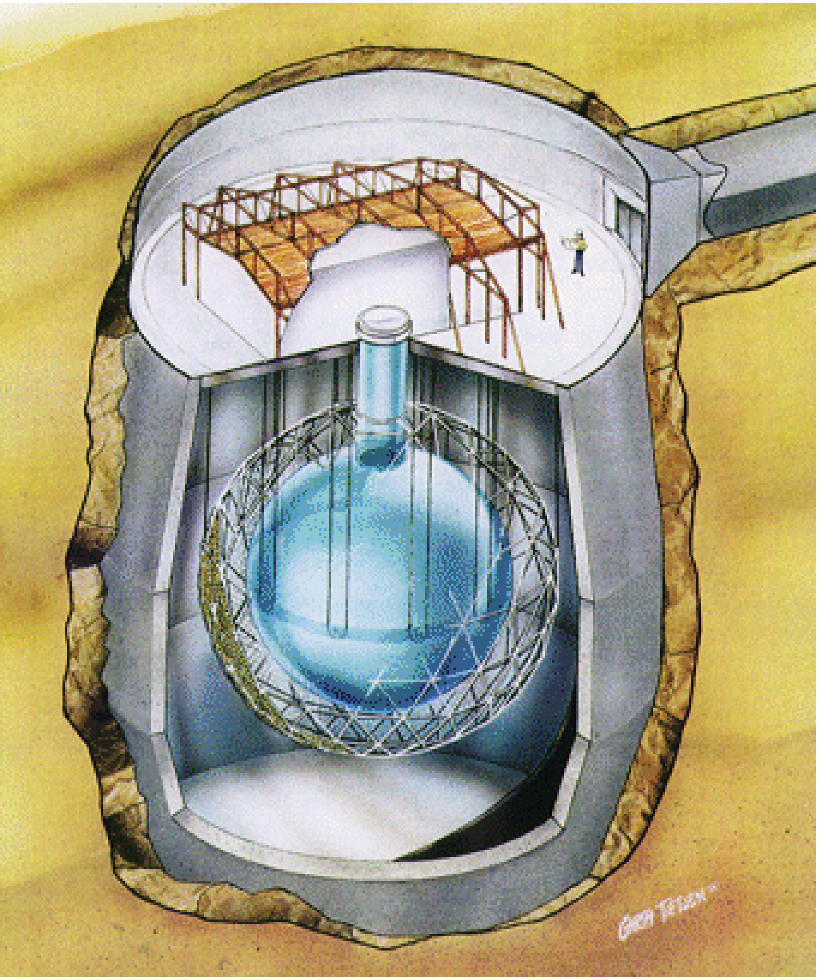
Remaining mantle contributions

Continental lithospheric mantle

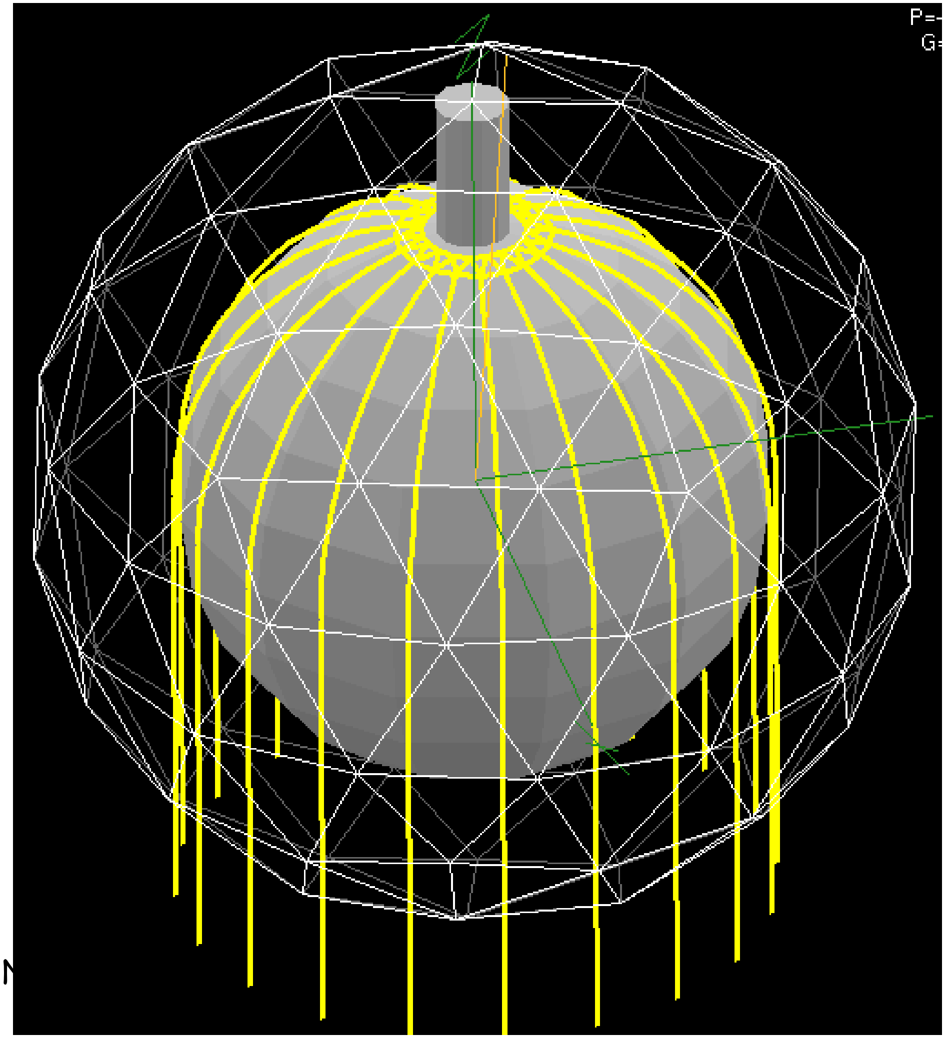
Crustal contributions

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

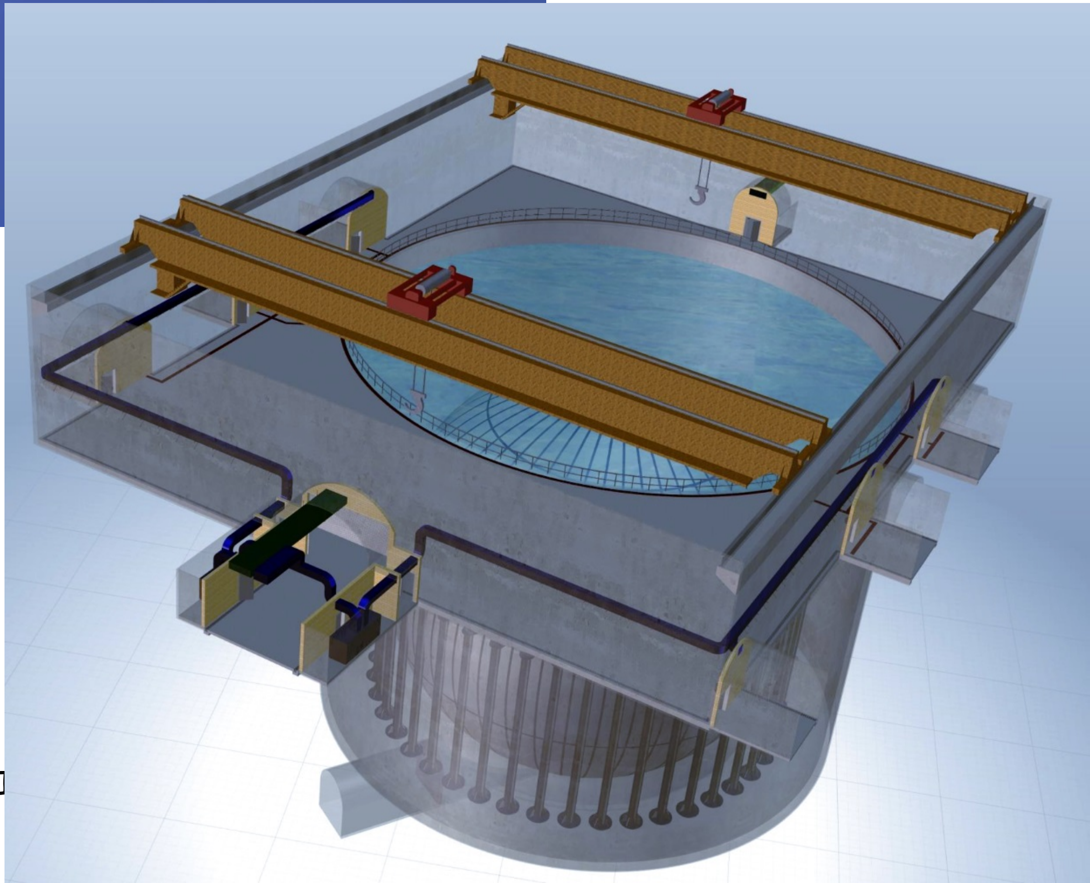
The near future: SNO+



~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

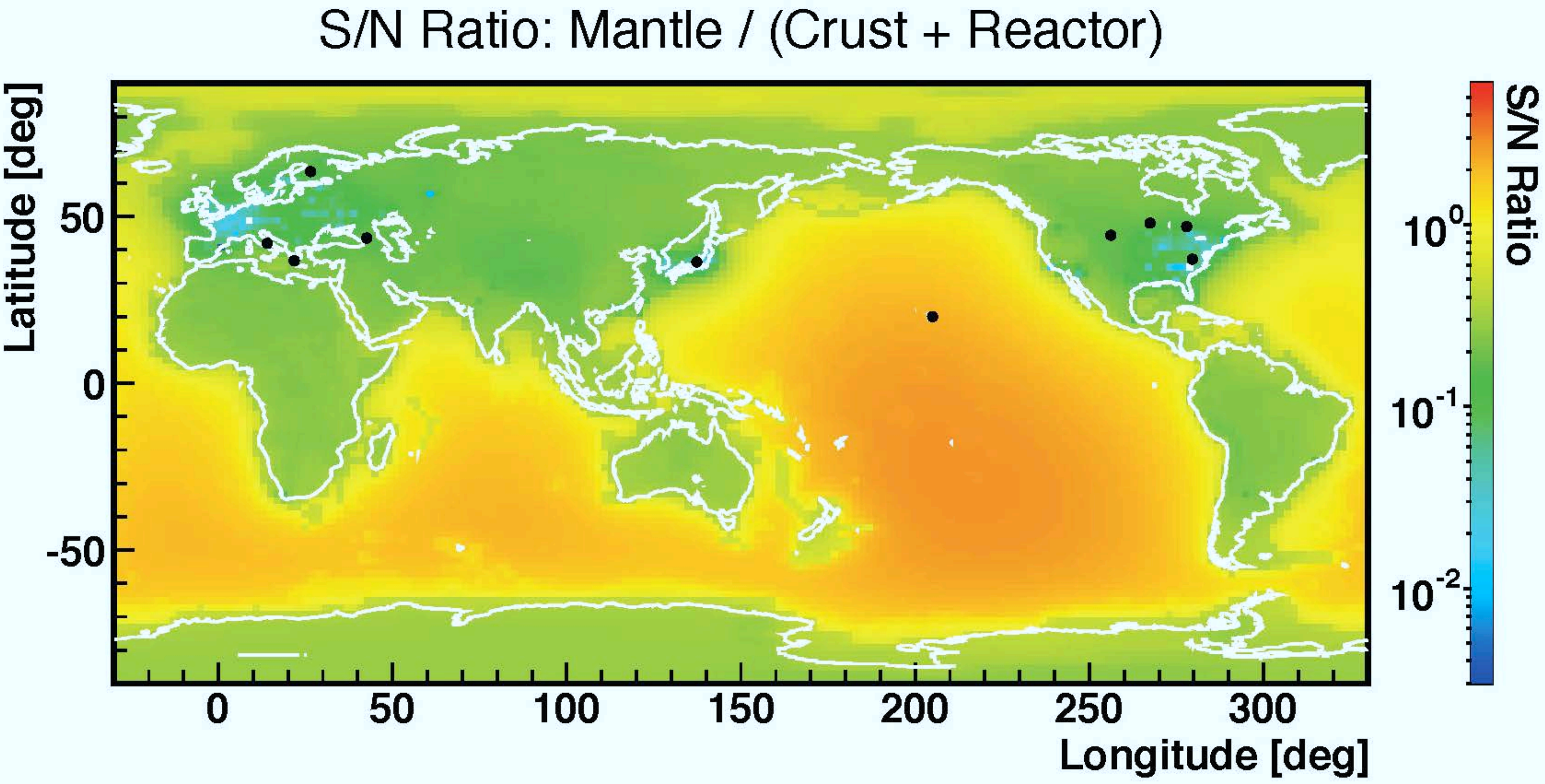
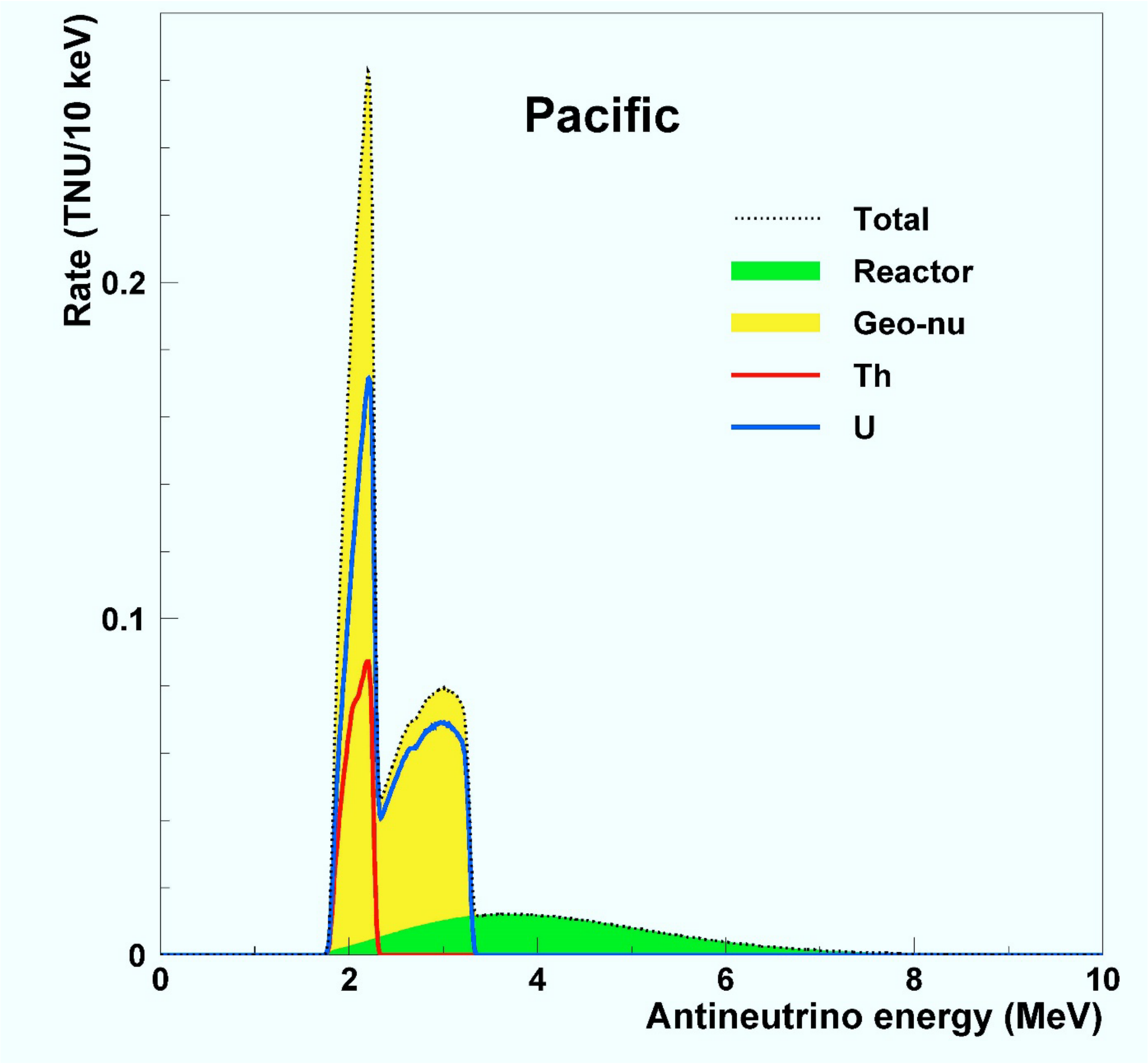


Image: S. Enomoto

Predicted Signals: Mid Pacific detector

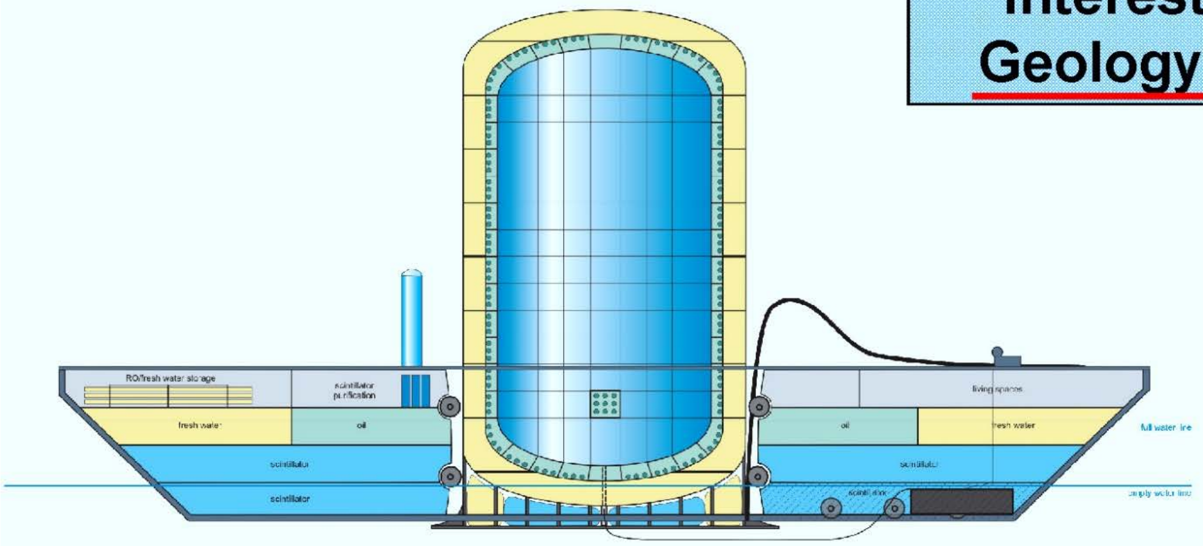


Steve Dye, AAP-2012, Honolulu Oct 2012

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

Hanohano

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

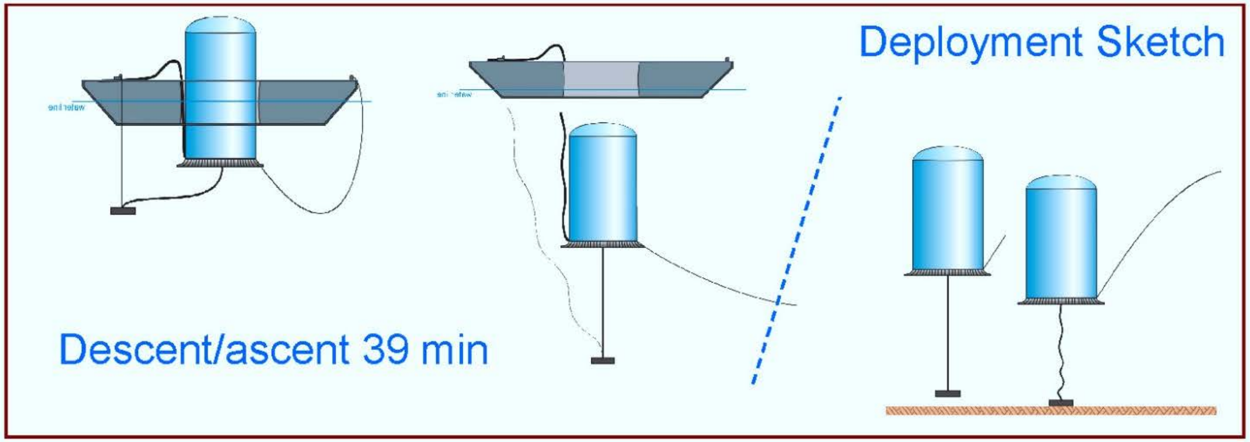


- multiple deployments
- deep water cosmic shield
- control-able L/E detection

Deep Ocean

$\bar{\nu}_e$

Observatory


Deployment Sketch

Descent/ascent 39 min

(my) wish list:

- **Better statistics** (larger detectors)
- Oceanic site
- Multiple sites
- Pointing ability
- Lower threshold (^{40}K)

Liquid scintillator technology is a limiting factor

With more light one may be able to image events

A typical organic scintillator (eg liquid scintillator) has energy efficiency of few% (~1 photon/100eV). Very hard to imagine doing better.

➔ Maybe energy can be stored in a material and its release triggered by ionization

➔ Maybe ionized trails can produce fluorescent sites, then imaged

…tried and failed, until now

Liquid scintillator technology is a limiting factor

If water-based was possible everything would be cheaper/larger

No one has been able to make this work

(liquid scintillators were invented in the 30's and are amazingly subtle/sophisticated things!)

Photodetector technology is a limiting factor

Photomultiplier Tubes (PMTs) are:

Bulky
Clumsy/delicate (vacuum)
Radioactive (glass)
Small/non-scalable
Expensive
Low quantum efficiency devices

No one has been able to find a replacement

(PMTs were invented in the 30's and are amazingly subtle/sophisticated things!)

Concluding…

- KamLAND and Borexino will continue taking data (for a while), but statistics accumulates linearly with time, further improvements are painful (the reactor-off period in Japan helps)
- SNO+ and JUNO will happen ("for free")
- JUNO will be quite a bit larger than anything else:

  will probably be the next highlight of the field

…and then…

- Hanohano should happen, it is "just matter of money"
- Beyond this we are lacking the technology to make further progress:
  - Should do R&D on scintillators
  - Should do R&D on photodetectors