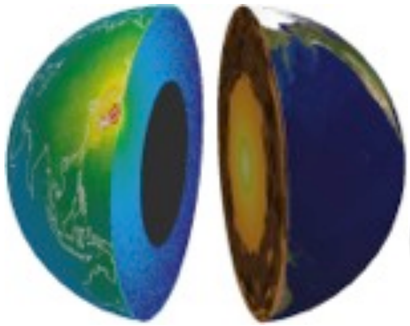
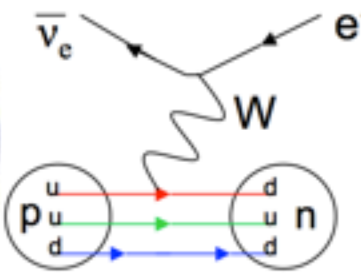
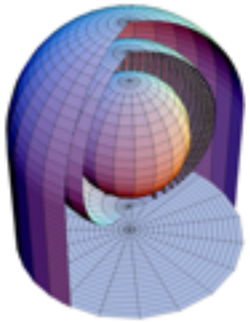
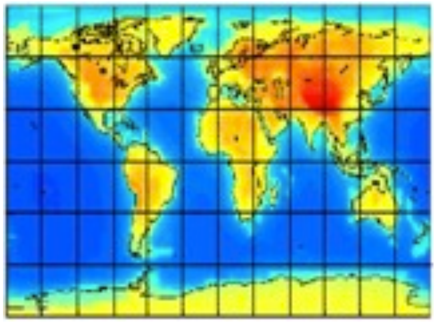
Geoneutrinos and the heat budget of the Earth







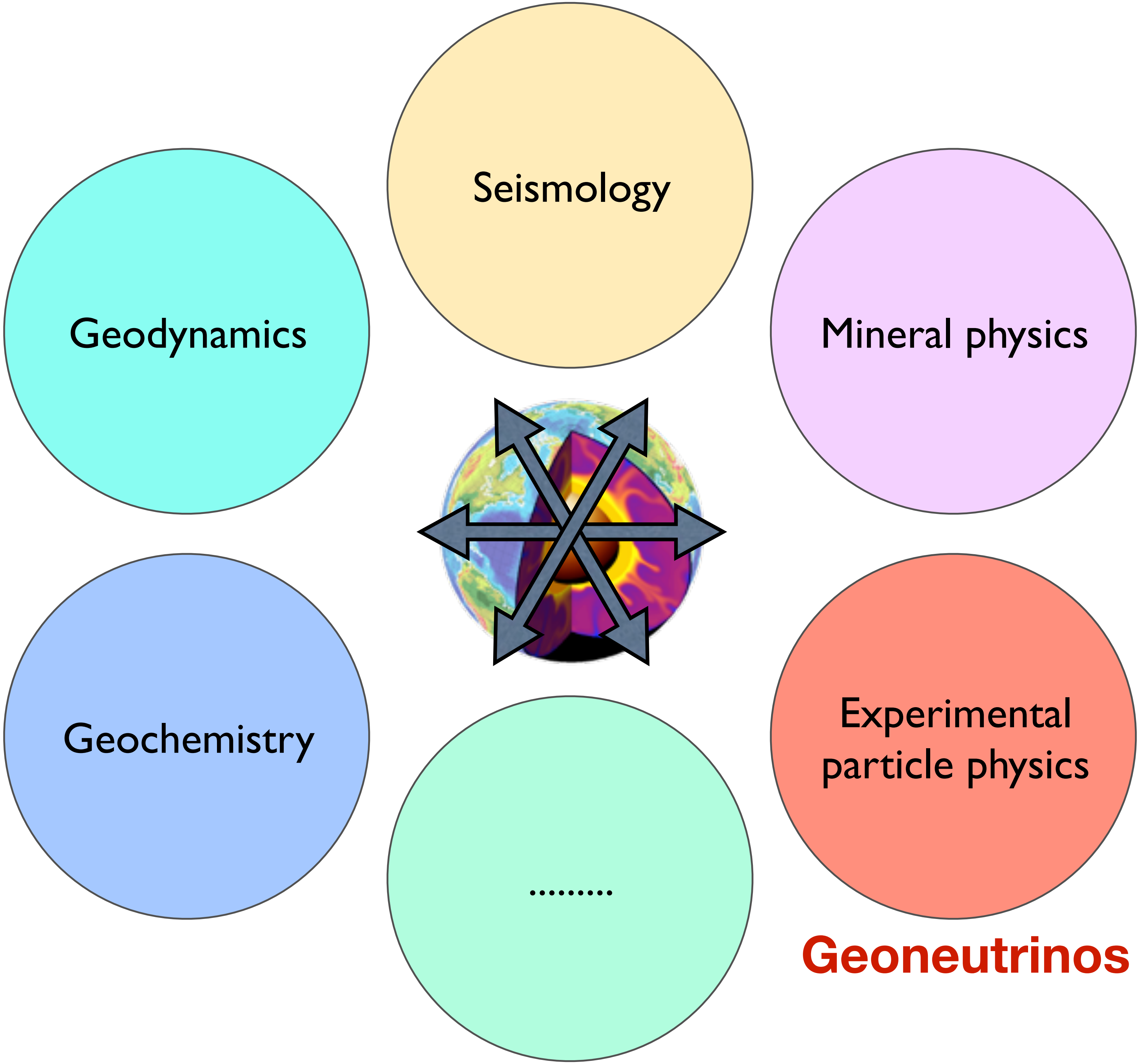


Ondřej Šrámek

University of Maryland

presented at Department of Geophysics, Charles University in Prague on 14 November 2012

Collaboration with Bill McDonough (UMD), Steve Dye (HPU), Shijie Zhong (UCB), Edwin Kite (Caltech), Vedran Lekić (UMD)



Seismology

Geodynamics

Mineral physics

Geochemistry

Experimental particle physics

....

Geoneutrinos

"Geoneutrinos" = electron anti-neutrinos emitted in β^- decays of naturally occurring radionuclides

$$\begin{aligned}
{}^{238}_{92}\mathrm{U} &\longrightarrow {}^{206}_{82}\mathrm{Pb} + 8\alpha + 6e^- + \boxed{6\bar{\nu}_e} + 51.698\,\mathrm{MeV} \\
{}^{235}_{92}\mathrm{U} &\longrightarrow {}^{207}_{82}\mathrm{Pb} + 7\alpha + 4e^- + \boxed{4\bar{\nu}_e} + 46.402\,\mathrm{MeV} \\
{}^{232}_{90}\mathrm{Th} &\longrightarrow {}^{208}_{82}\mathrm{Pb} + 6\alpha + 4e^- + \boxed{4\bar{\nu}_e} + 42.652\,\mathrm{MeV} \\
{}^{40}_{19}\mathrm{K} &\xrightarrow{89.3\,\%} {}^{40}_{20}\mathrm{Ca} + e^- + \boxed{\bar{\nu}_e} + 1.311\,\mathrm{MeV},
\end{aligned}$$

geo-ν's now detectable ... and have been detected

Measuring radioactivity of the Earth!

How much radiogenic heating in the mantle??

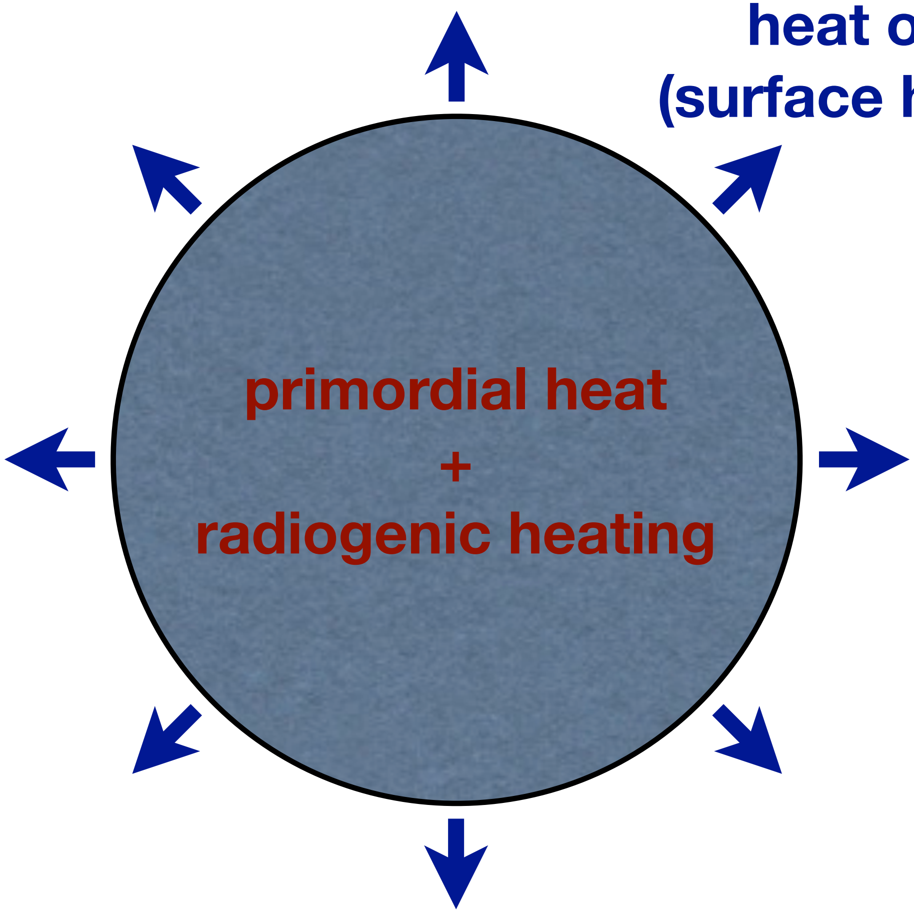
What is the Earth made of??

Chemical reservoirs in the mantle??

1. geophysical motivation
2. neutrino history
3. antineutrino production, propagation, detection
4. observations of geoneutrinos
5. predictions of geoneutrinos flux
6. perspectives

Radiogenic heating rate in the mantle...?

How do we know it...?

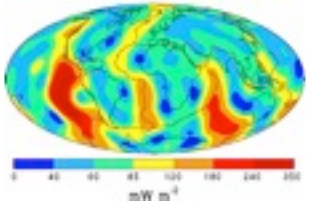


primordial heat

+

radiogenic heating

heat output
(surface heat flux)



^{238}U

^{232}Th

^{40}K

?

How much radiogenic heating in the Earth?
How is it spatially distributed?
... implications for geodynamics

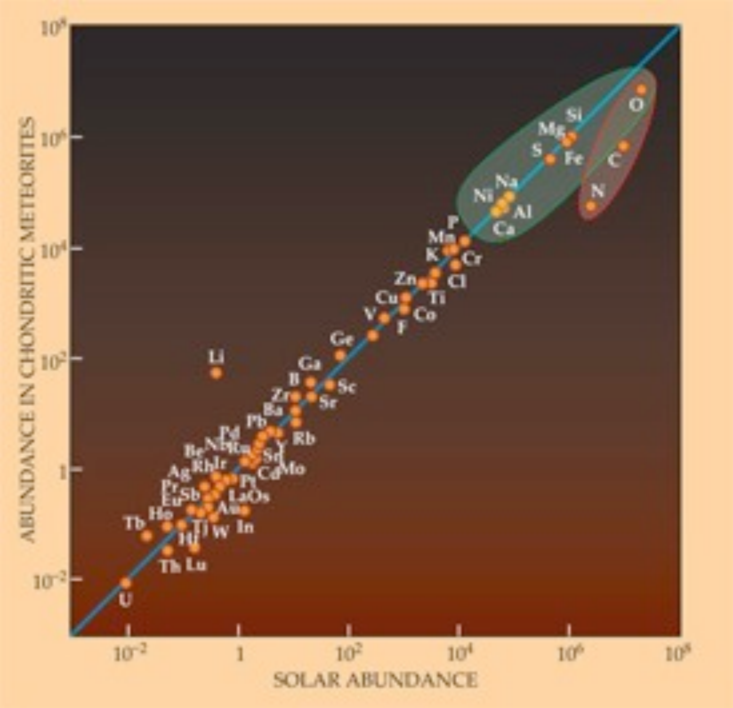
U Th K

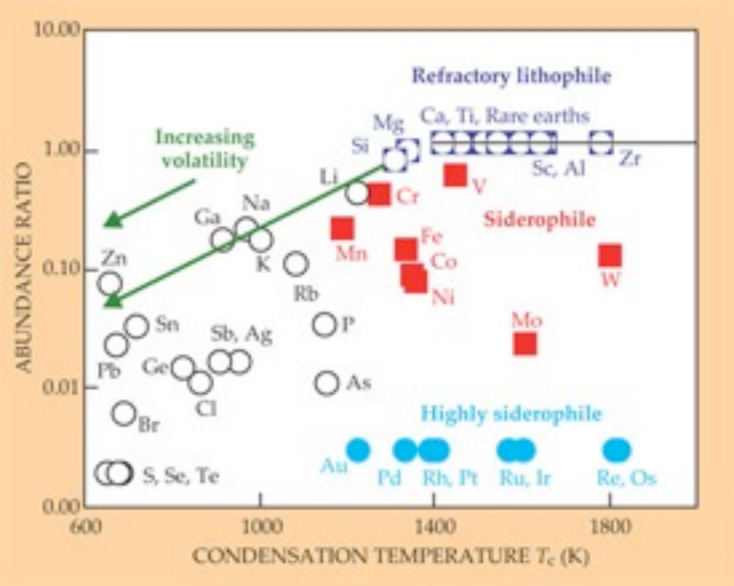
Composition of Silicate Earth

- U, Th, K are lithophile elements, strong arguments against presence in the core
- Composition of “Silicate Earth” (BSE) of interest,
  Silicate Earth = whole Earth minus the core
- [But: some unorthodox models even predicting natural nuclear reactor in Earth’s deep interior]
- Cosmochemistry and geochemistry: BSE compositional estimates
- Difficult. Usual problem in geophysics: rock samples only from shallow depths (uppermost mantle at most) but need average composition of the entire mantle + crust
- Meteorites ~ Solar System composition
- Several estimates for BSE composition exist, based of what observations are used and what assumptions made

U Th K

Composition of Silicate Earth





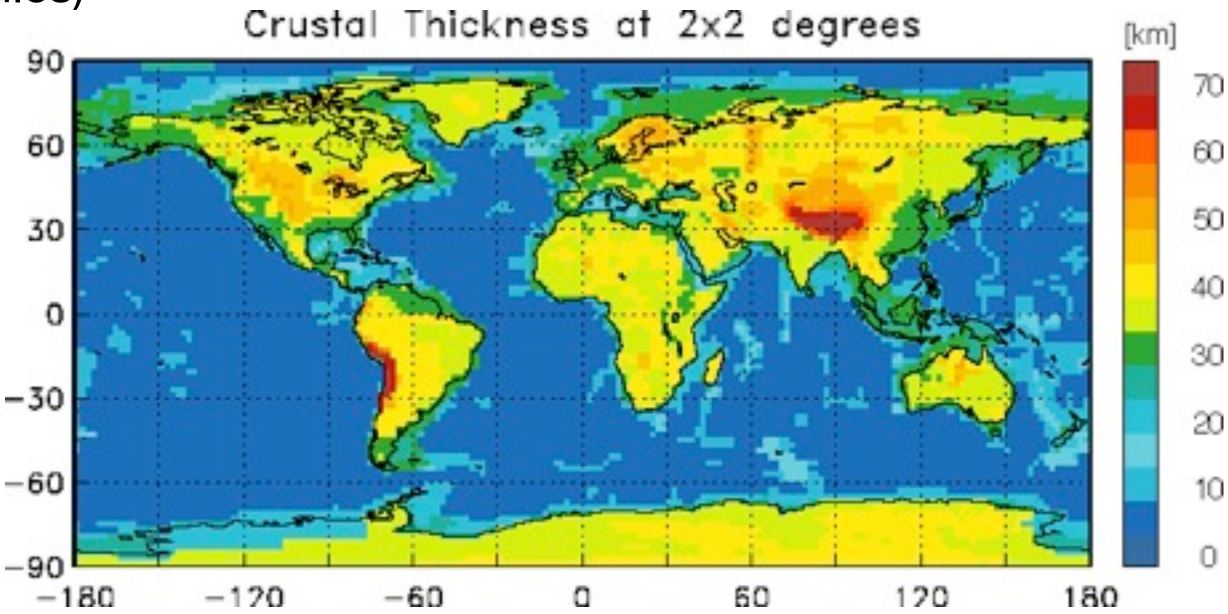
Wood 2011 Phys.Today 10.1063/PT.3.1362

- “**Geochemical**” estimate
  - – Ratios of RLE abundances constrained by C1 chondrites
  - – Absolute abundances inferred from Earth rock samples
  - – results in **~20 TW radiogenic power** in BSE
  - – McDonough & Sun (1995), Allègre (1995), Hart & Zindler (1986), Palme & O’Neill (2003)
- “**Cosmochemical**” estimate
  - – Isotopic similarity between Earth rocks and E-chondrides
  - – Build the Earth from E-chondrite material
  - – gives **~11 TW radiogenic power** in BSE (Javoy et al. 2010)
  - – also “collisional erosion” models (O’Neill & Palme 2008)

- Need uncertainty
- Crust vs. Mantle
- Surf. heat loss?

Continental Crust

- Ancient, thicker (~40 km), low density, stratified and heterogeneous
- Highly enriched in U, Th, K (incompatible elements)
- CRUST2.0 structure (2°× 2° layered tiles)
- Rudnick & Gao (2003) composition
- **7.8 ± 0.9 TW**



http://igppweb.ucsd.edu/~gabi/crust2.html

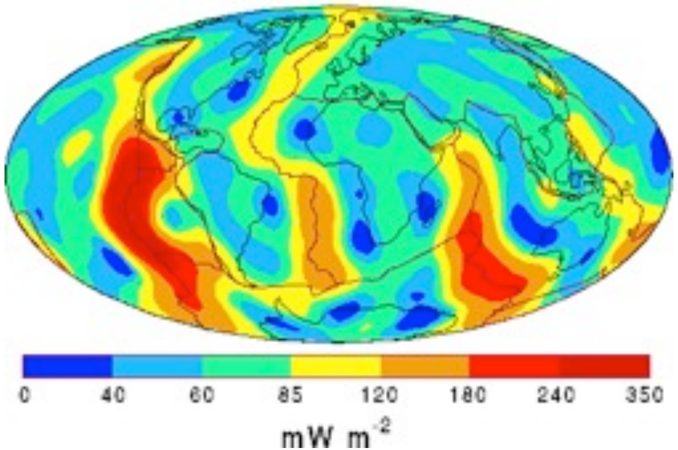
Oceanic Crust

- Young, thinner (~7 km), denser, basaltic
- Composition: White & Klein (2013), Plank (2013)
- **0.22 ± 0.03 TW**

Crust total (CC+OC): **8.0 ± 0.9 TW**

Surface heat flow

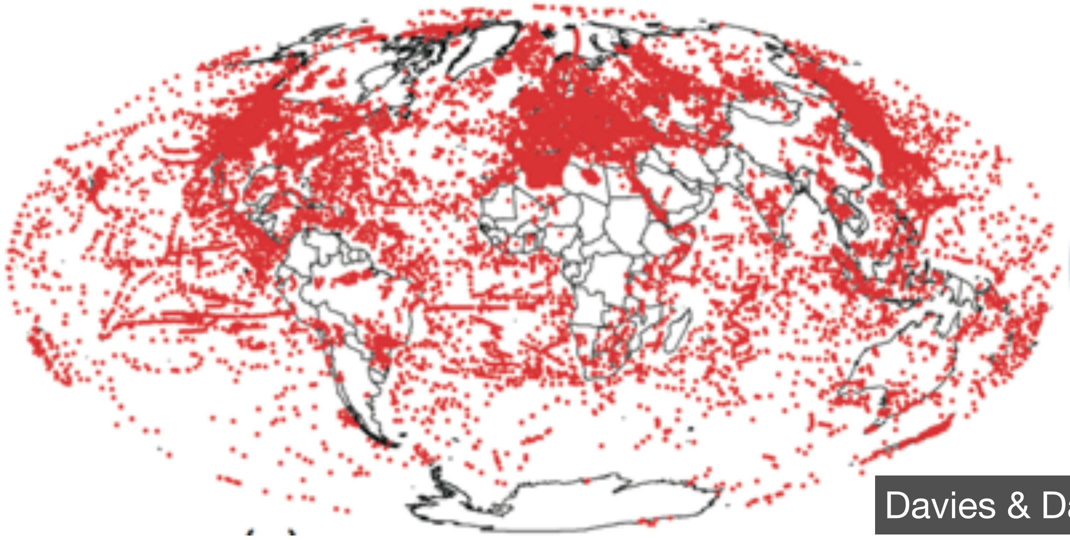
- Pollack et al. (1993): **44 TW**
- Jaupart et al. (2007): **46 ± 3 TW**
  - oceans: half-space cooling model, 32±2 TW
  - continents: 14±1 TW



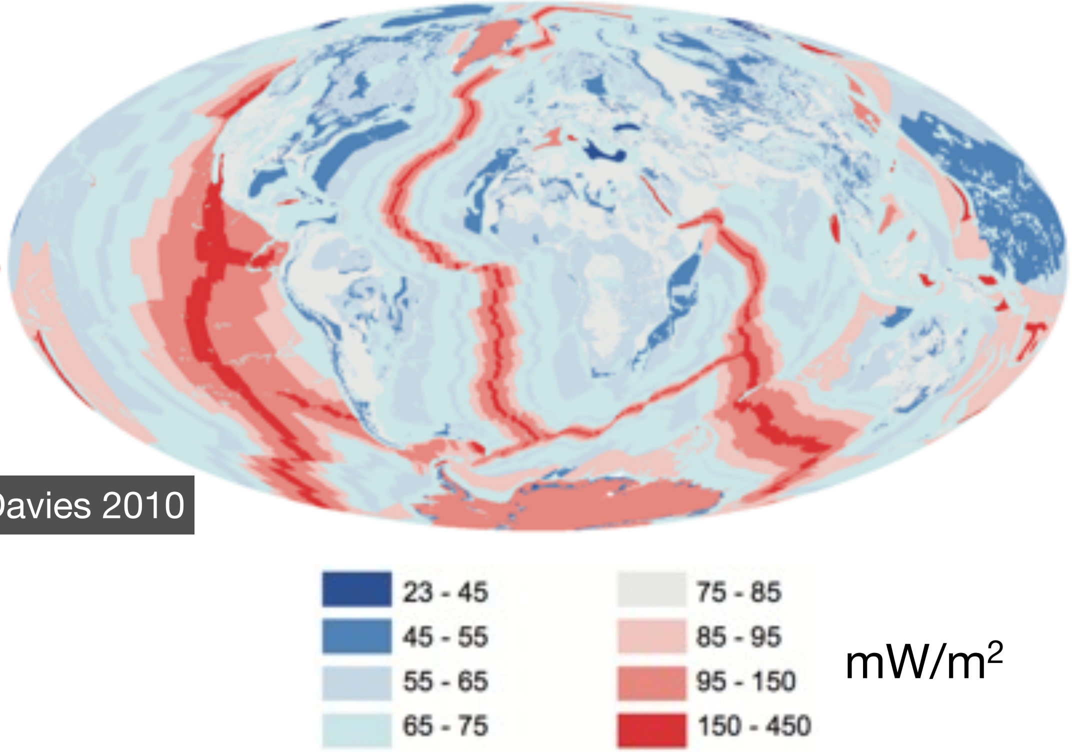
Pollack et al. 1993

- Davies & Davies (2010):

measurement sites (~40000)



heat flux



Davies & Davies 2010

- total: **47 ± 1(stat) TW**

- BSE heat prod. – Crustal heat prod. = Bulk Mantle heat prod.
- Surface heat flow – Crustal heat prod. = Mantle heat flow
- Mantle heat prod. / Mantle heat flow = Mantle Urey ratio

Cosmochemical: Urey ~ 0.1 (~11 TW in BSE)

Geochemical: Urey ~ 0.3 (~ 20 TW in BSE)

- "**Geodynamical**" BSE compositional model

Parameterized convection model: heat loss = radiogenic heating + secular cooling

Classical *Nu*–*Ra* scaling with exponent ~1/3

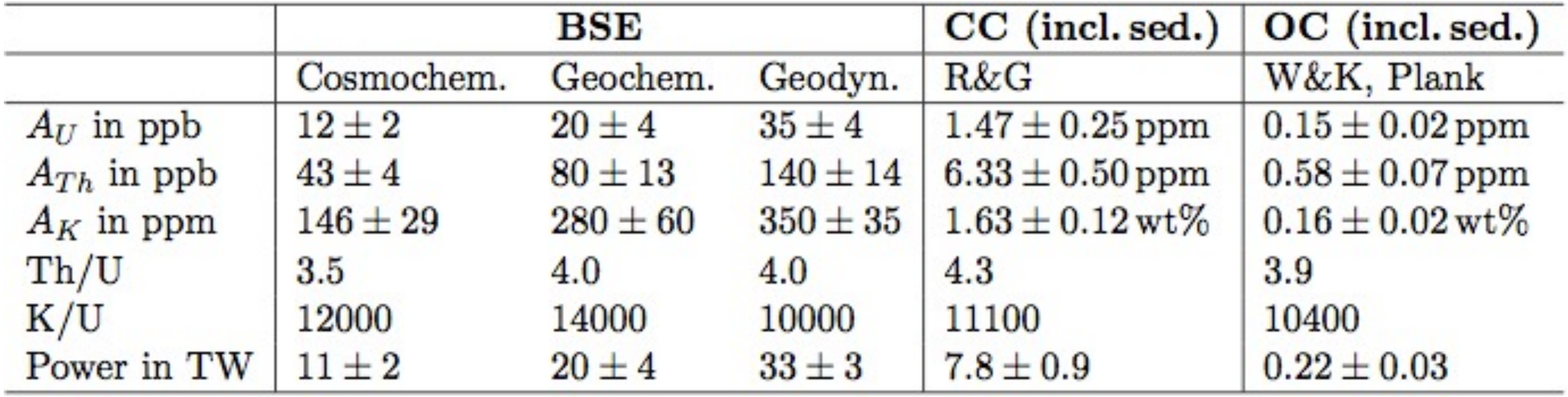
Need a large proportion of radiogenic heating to account for mantle heat flow, otherwise "thermal catastrophe" in the Archean

Requires Urey ≥ 0.6

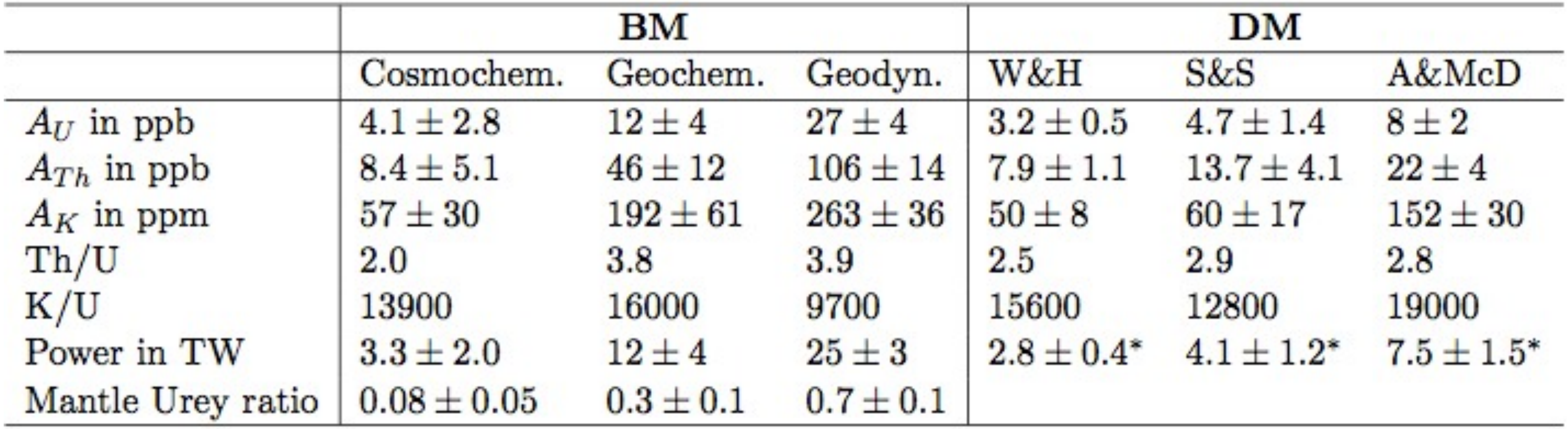
Therefore needs higher abundance of U, Th, K

Radiogenic heating **≥ 30 TW in BSE**

Summary of U, Th, K abundances



	BSE			CC (incl. sed.)	OC (incl. sed.)
	Cosmochem.	Geochem.	Geodyn.	R&G	W&K, Plank
A_U in ppb	12 ± 2	20 ± 4	35 ± 4	1.47 ± 0.25 ppm	0.15 ± 0.02 ppm
A_{Th} in ppb	43 ± 4	80 ± 13	140 ± 14	6.33 ± 0.50 ppm	0.58 ± 0.07 ppm
A_K in ppm	146 ± 29	280 ± 60	350 ± 35	1.63 ± 0.12 wt%	0.16 ± 0.02 wt%
Th/U	3.5	4.0	4.0	4.3	3.9
K/U	12000	14000	10000	11100	10400
Power in TW	11 ± 2	20 ± 4	33 ± 3	7.8 ± 0.9	0.22 ± 0.03



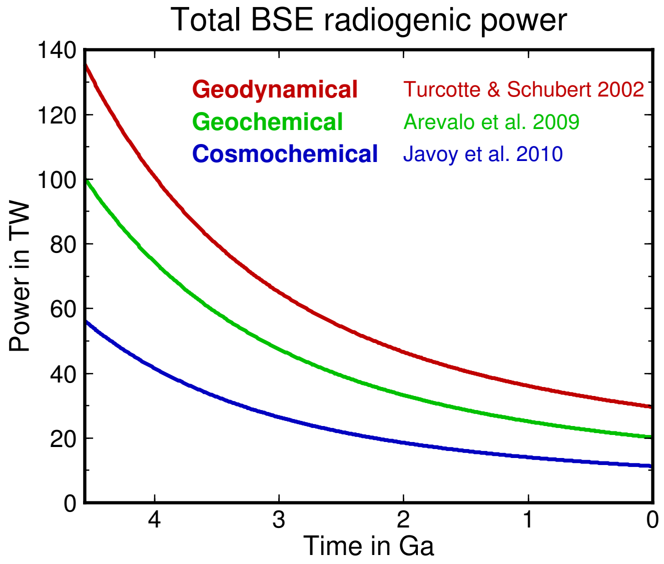
	BM			DM		
	Cosmochem.	Geochem.	Geodyn.	W&H	S&S	A&McD
A_U in ppb	4.1 ± 2.8	12 ± 4	27 ± 4	3.2 ± 0.5	4.7 ± 1.4	8 ± 2
A_{Th} in ppb	8.4 ± 5.1	46 ± 12	106 ± 14	7.9 ± 1.1	13.7 ± 4.1	22 ± 4
A_K in ppm	57 ± 30	192 ± 61	263 ± 36	50 ± 8	60 ± 17	152 ± 30
Th/U	2.0	3.8	3.9	2.5	2.9	2.8
K/U	13900	16000	9700	15600	12800	19000
Power in TW	3.3 ± 2.0	12 ± 4	25 ± 3	$2.8 \pm 0.4^*$	$4.1 \pm 1.2^*$	$7.5 \pm 1.5^*$
Mantle Urey ratio	0.08 ± 0.05	0.3 ± 0.1	0.7 ± 0.1			

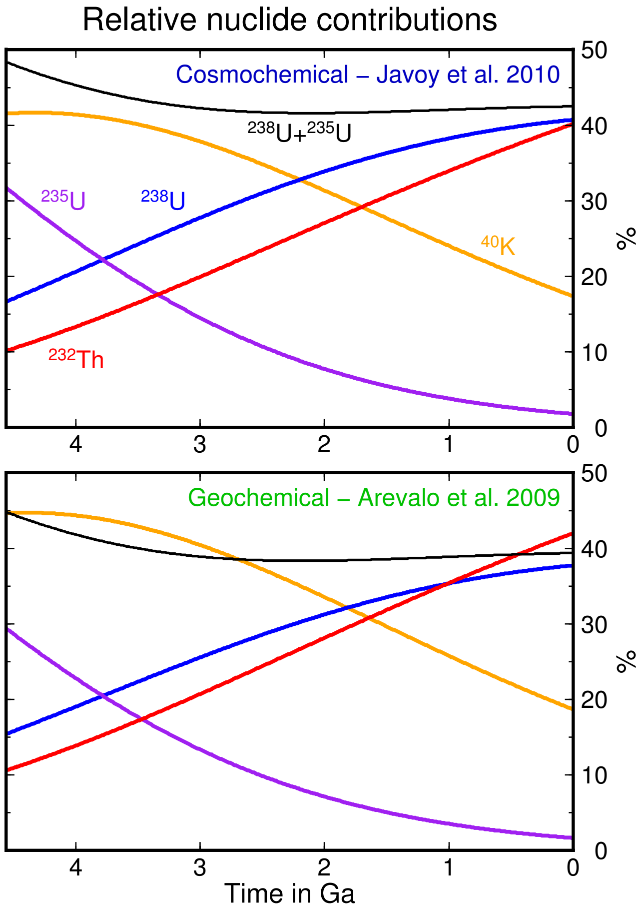
Q [$\times 10^{-9}$ W m^{-3}]	3.7±2.3	14±0.4	28±0.4
H [$\times 10^{-12}$ W kg^{-1}]	0.82±0.51	3.0±0.9	6.3±0.9

- shallow mantle composition
- from analysis of MORBs
- independent from BSE estimate

Is the mantle compositionally uniform?

BSE radiogenic power over time





- **Which BSE (BM) is the Earth?**
- **Is the mantle compositionally uniform?**
- **Enriched reservoir in the mantle? What geometry?**
- **... geoneutrinos!**

1. geophysical motivation
2. **neutrino history**
3. antineutrino production, propagation, detection
4. observations of geoneutrinos
5. predictions of geoneutrinos flux
6. perspectives

Short (and incomplete) history of (geo)neutrinos

1897 Henri Becquerel discovers mysterious radiation

Ernst Rutherford identifies 3 forms: α, β, γ

1914 James Chadwick: continuous energy spectrum β-radiation – energy conservation problem

Neils Bohr: perhaps energy is not conserved in β-decay

1930 Wolfgang Pauli proposes a new neutral particle

1932 Chadwick discovers neutron

1933 Fermi calls Pauli's proposed particle "neutrino"

1934 Fermi's theory of β-decay

1948 Bruno Pontecorvo proposed a neutrino detection mechanism

1956 Clyde Cowan & Fred Reines detect electron (anti-)neutrinos from nuclear reactor using \`inverse beta decay' reaction

1957 Pontecorvo: neutrino oscillations

1962 Lederman, Schwartz, Steinberger observe muon neutrinos

1968 solar neutrino flux is too low (Davis' experiments vs. Bahcall calculations) – neutrino oscillations? (Pontecorvo)

1987 detection of neutrinos from supernova SN1987A (Koshiba at Kamiokande)

...

2005 KamLAND observes geoneutrinos

2009 Borexino observes geoneturinos

1. geophysical motivation

2. neutrino history

3. **antineutrino production, propagation, detection**

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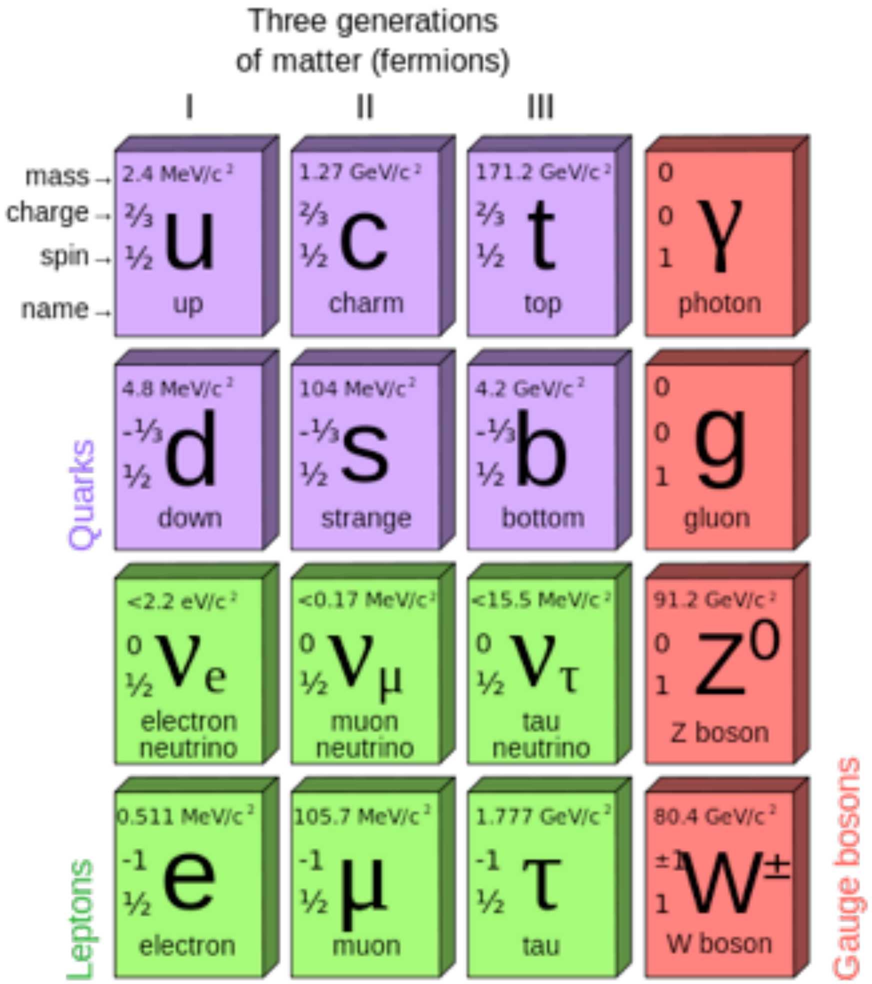
6. perspectives

Geoneutrinos

electron antineutrinos

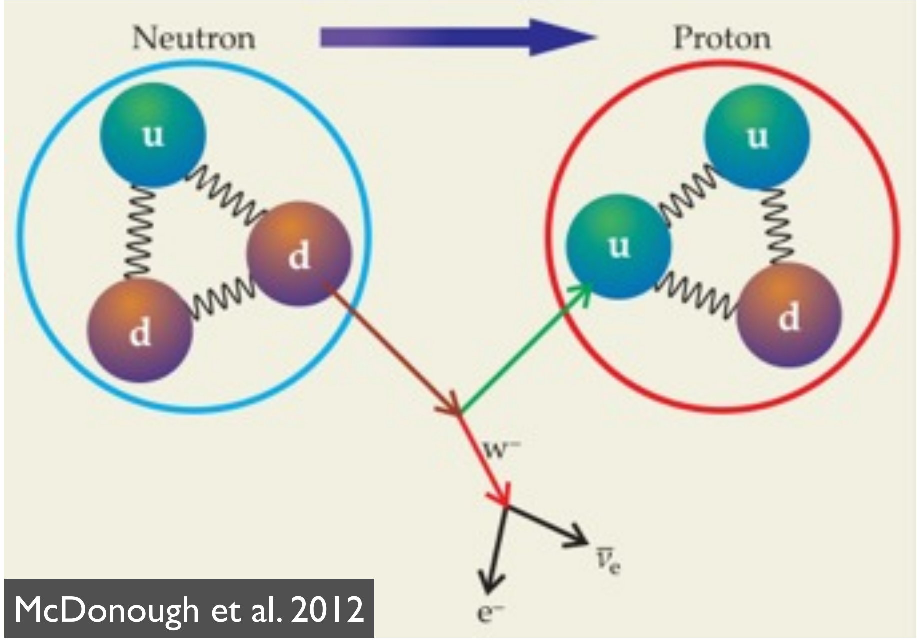
produced in β^- decays



Three generations of matter (fermions)

	I	II	III	
mass → charge → spin → name →	2.4 MeV/c² ⅔ ½ u up	1.27 GeV/c² ⅔ ½ c charm	171.2 GeV/c² ⅔ ½ t top	0 0 1 γ photon
Quarks	4.8 MeV/c² -⅓ ½ d down	104 MeV/c² -⅓ ½ s strange	4.2 GeV/c² -⅓ ½ b bottom	0 0 1 g gluon
	<2.2 eV/c² 0 ½ ν_e electron neutrino	<0.17 MeV/c² 0 ½ ν_μ muon neutrino	<15.5 MeV/c² 0 ½ ν_τ tau neutrino	91.2 GeV/c² 0 1 Z^0 Z boson
Leptons	0.511 MeV/c² -1 ½ e electron	105.7 MeV/c² -1 ½ μ muon	1.777 GeV/c² -1 ½ τ tau	80.4 GeV/c² ±1 1 $W^\pm$ W boson
				Gauge bosons

β^- decay (U, Th, K, ...)



McDonough et al. 2012

Typical geoneutrino flux:
10^7 cm^{-2} s^{-1} at Earth surface

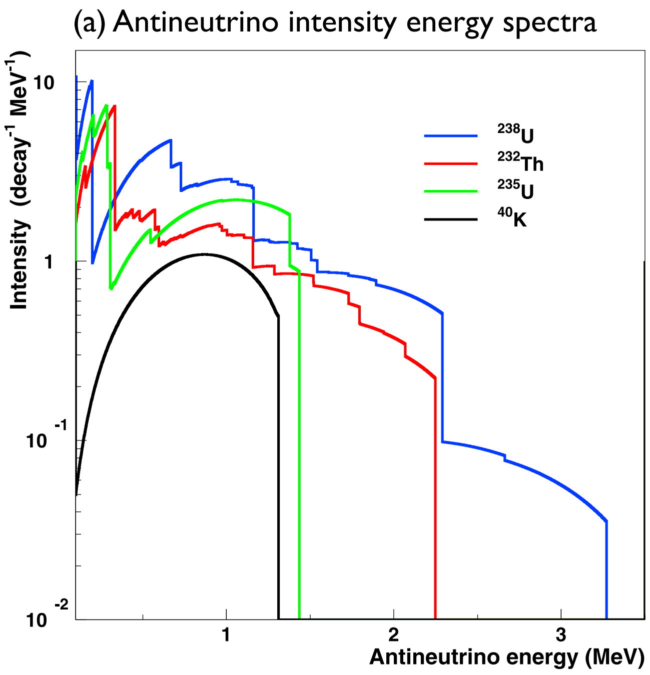
or ~10^{10} flying through each of you every second.

Only weakly interacting.

Carry the integrated information about radioactivity inside the Earth.

Geoneutrino production

- rate of antineutrino production proportional to local U, Th, K abundance


(a) Antineutrino intensity energy spectra

Dye 2012

Geoneutrino propagation

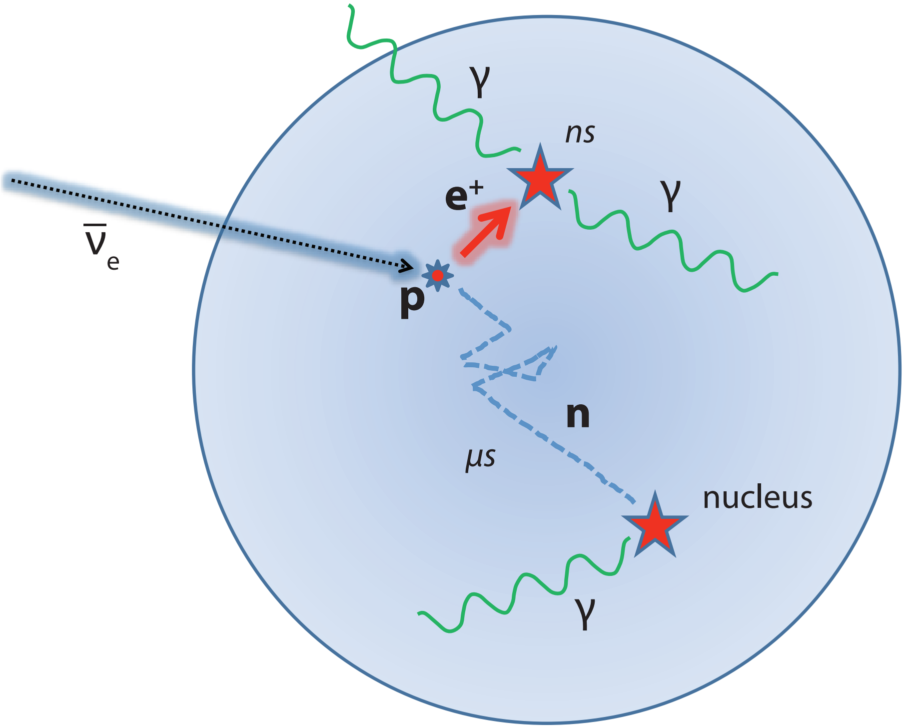
- flux from a point source scales as $1/R^2$
- neutrino oscillation
  - neutrino travels as a superposition of 3 mass eigenstates (ν_1, ν_2, ν_3)
  - consequently ν oscillates between 3 flavor states (ν_e, ν_μ, ν_τ) until detected
  - measured flux smaller than expected based on emission rate
  - oscillation length (E-dep.) much smaller than Earth radius, introduces a simple factor (“survival probability” $\langle P \rangle$~0.54)

Detection mechanism

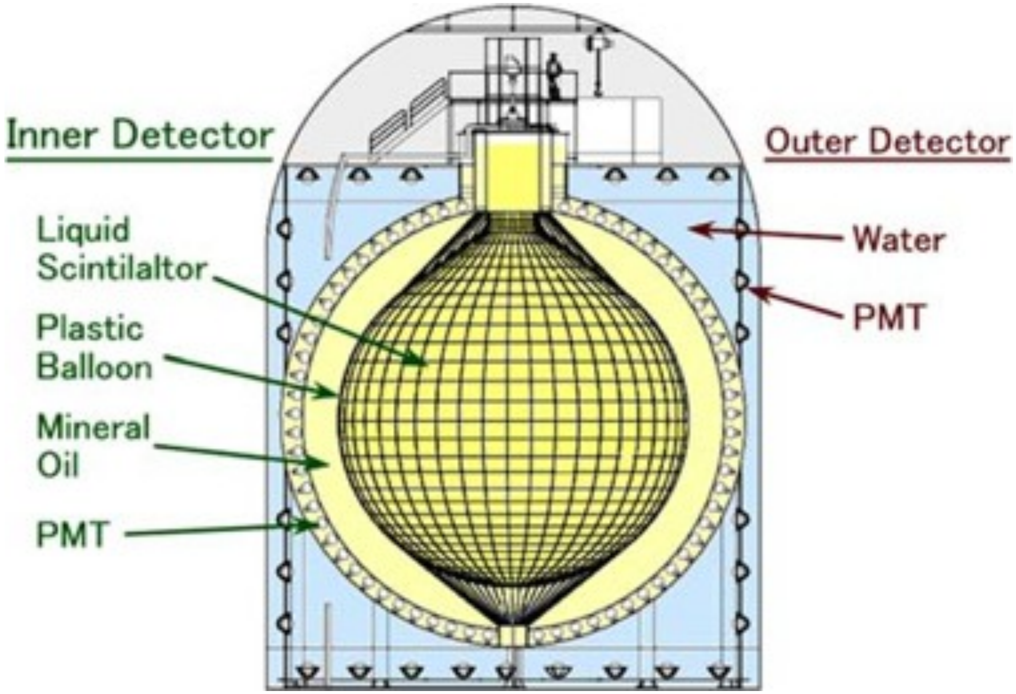
inverse β-decay reaction

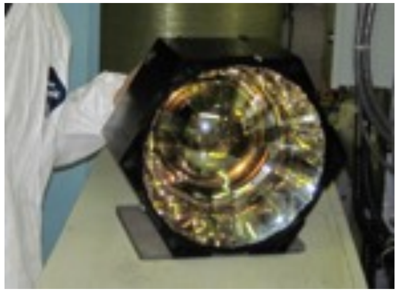
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

two flashes of light coincident in space and time

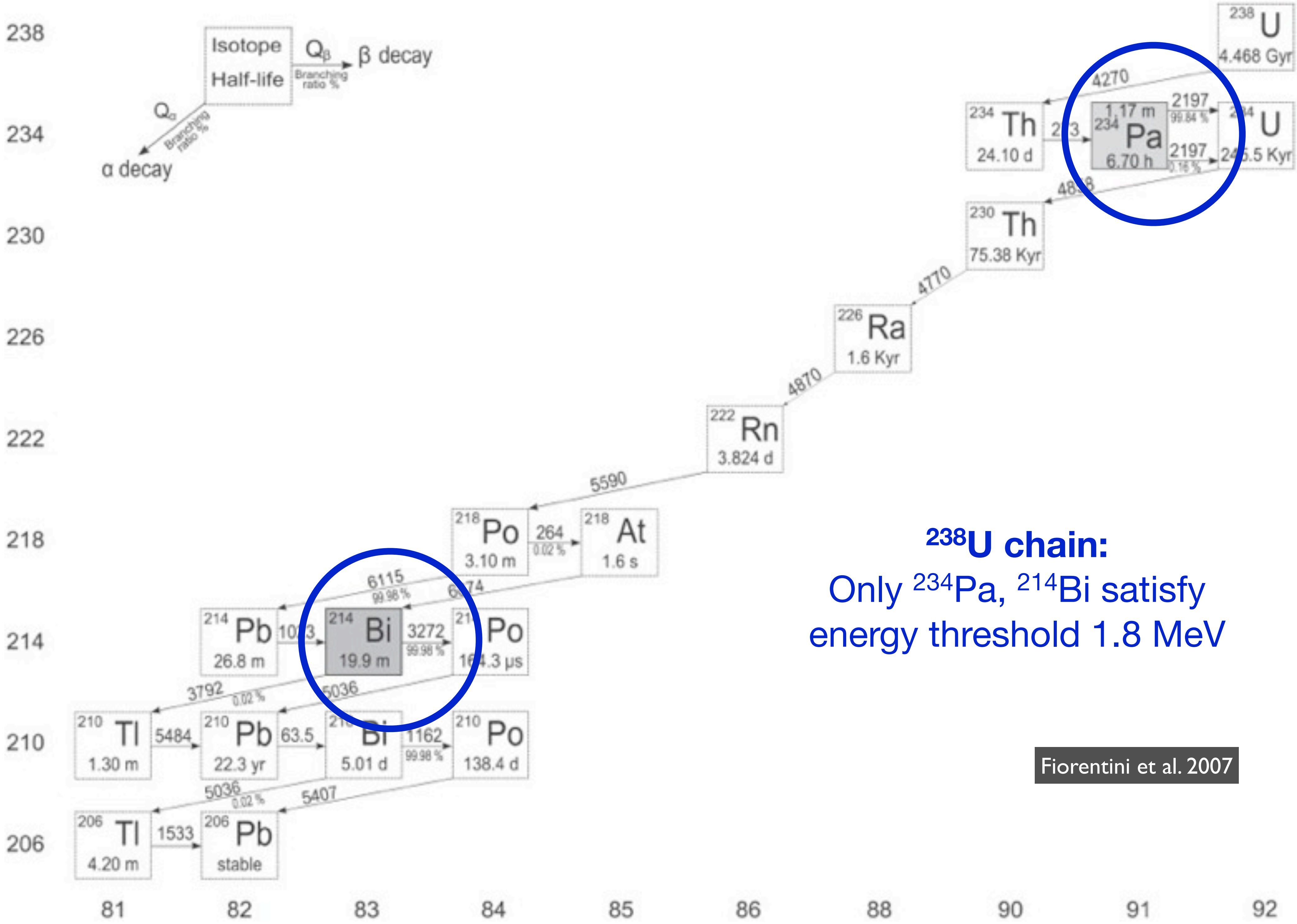


...energy threshold 1.8 MeV:
only the high-energy neutrinos from ^{238}U and ^{232}Th are detectable [no ^{40}K :( ]





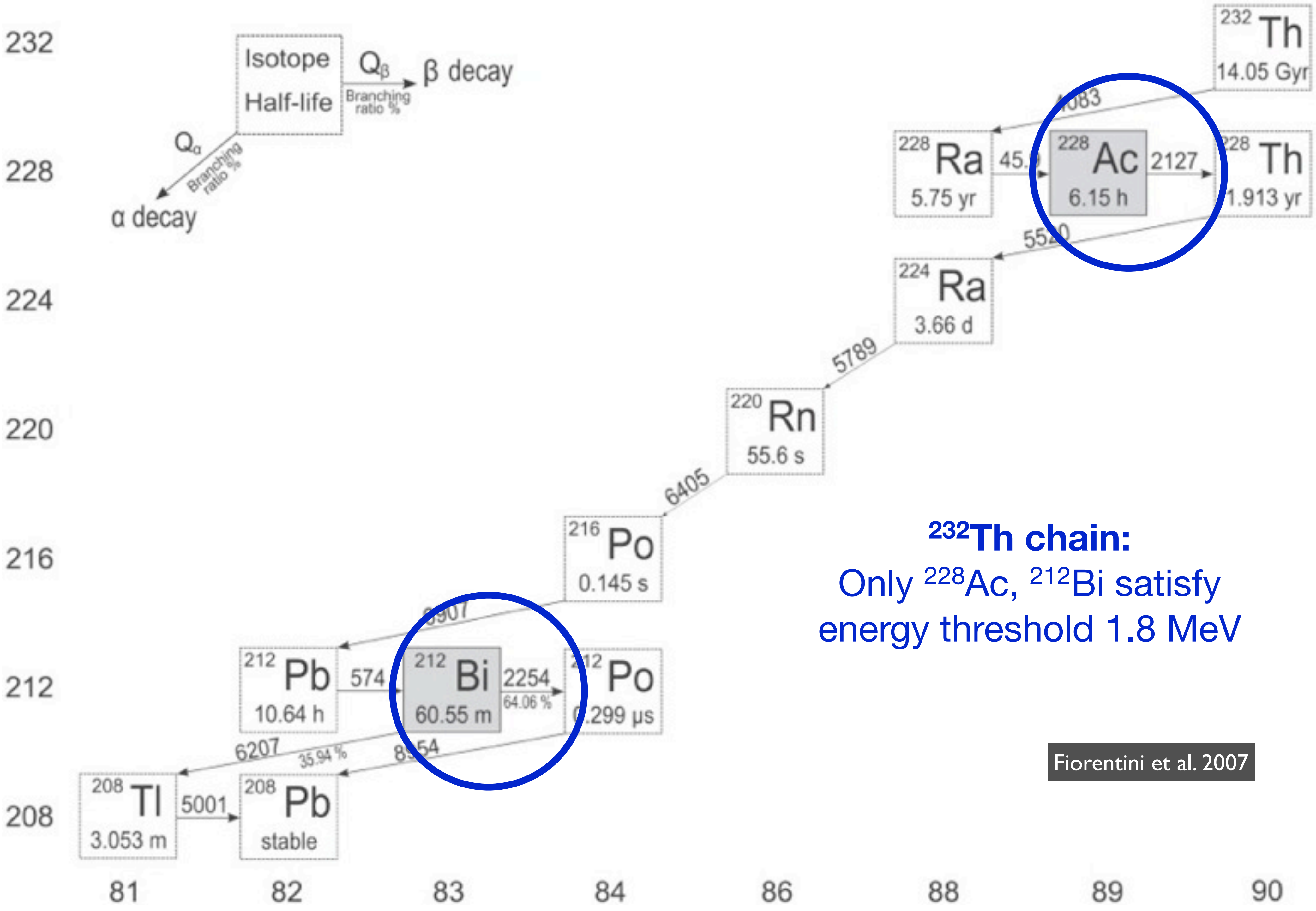
PMT



^{238}U chain:

Only ^{234}Pa, ^{214}Bi satisfy energy threshold 1.8 MeV

Fiorentini et al. 2007



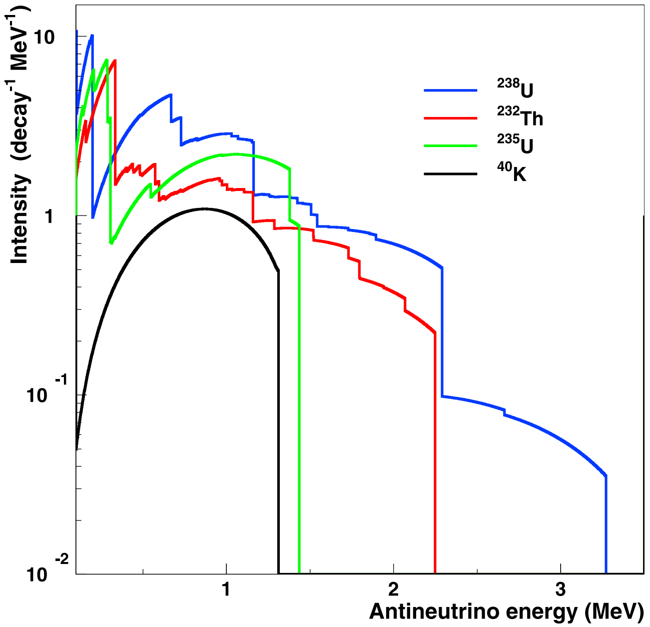
^{232}Th chain:

Only ^{228}Ac, ^{212}Bi satisfy
energy threshold 1.8 MeV

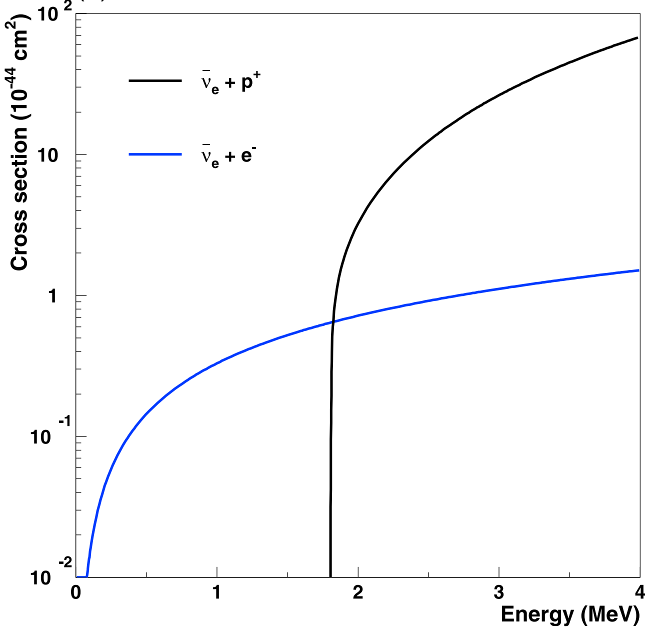
Fiorentini et al. 2007

Energy spectra

(a) Antineutrino intensity energy spectra



(b) Cross sections



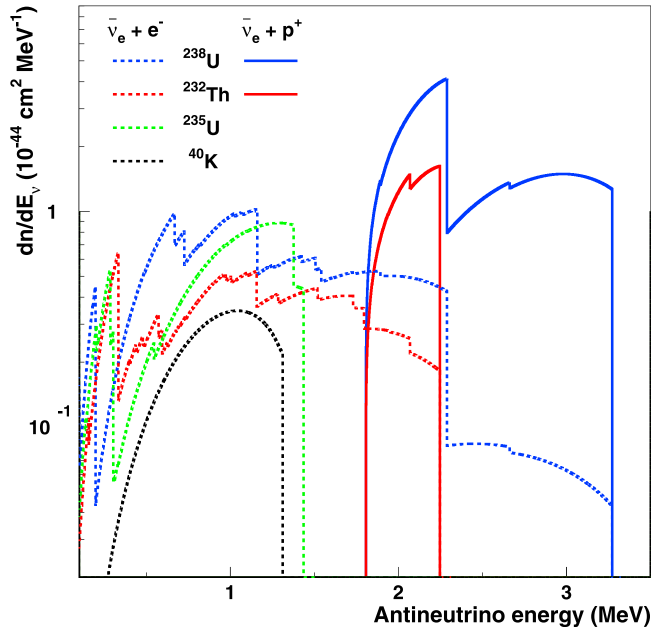
inverse β-decay
(currently used)

scattering on electrons
(on the wish list, K!)

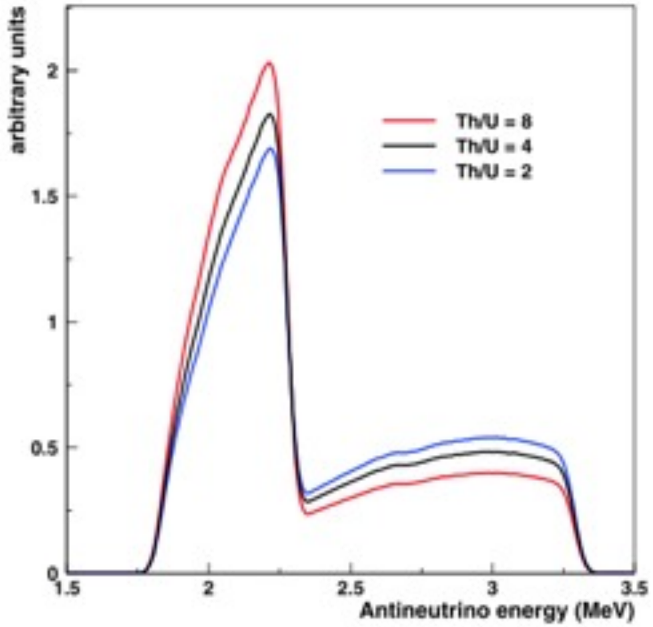
Dye 2012

intensity spectrum (a)
×
cross section (b)
=
interaction spectrum (c)

(c) Antineutrino interaction energy spectra

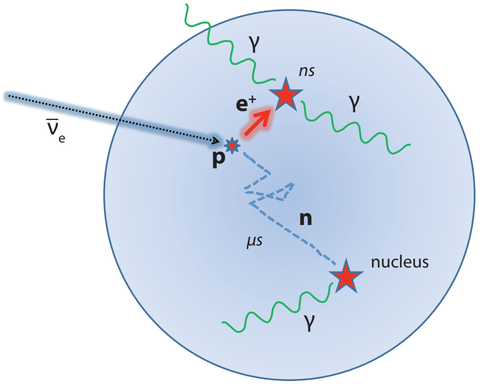


(d) Th+U antineutrino interaction energy spectra



Size requirement on detector

- weak interaction, small cross section
- need a lot of free protons (~10^{32}) to measure in reasonable time (few years)
- detector size ~1 kiloton

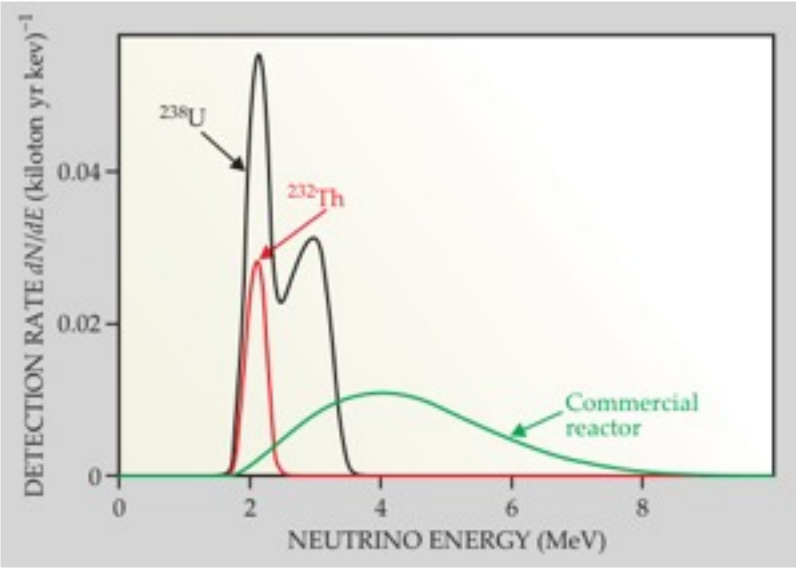


Flux in cm^{-2} s^{-1} ⟺ Signal rate in TNU

1 TNU (“Terrestrial Neutrino Unit”) =
= 1 event over a year-long fully efficient exposure on 10^{32} free protons

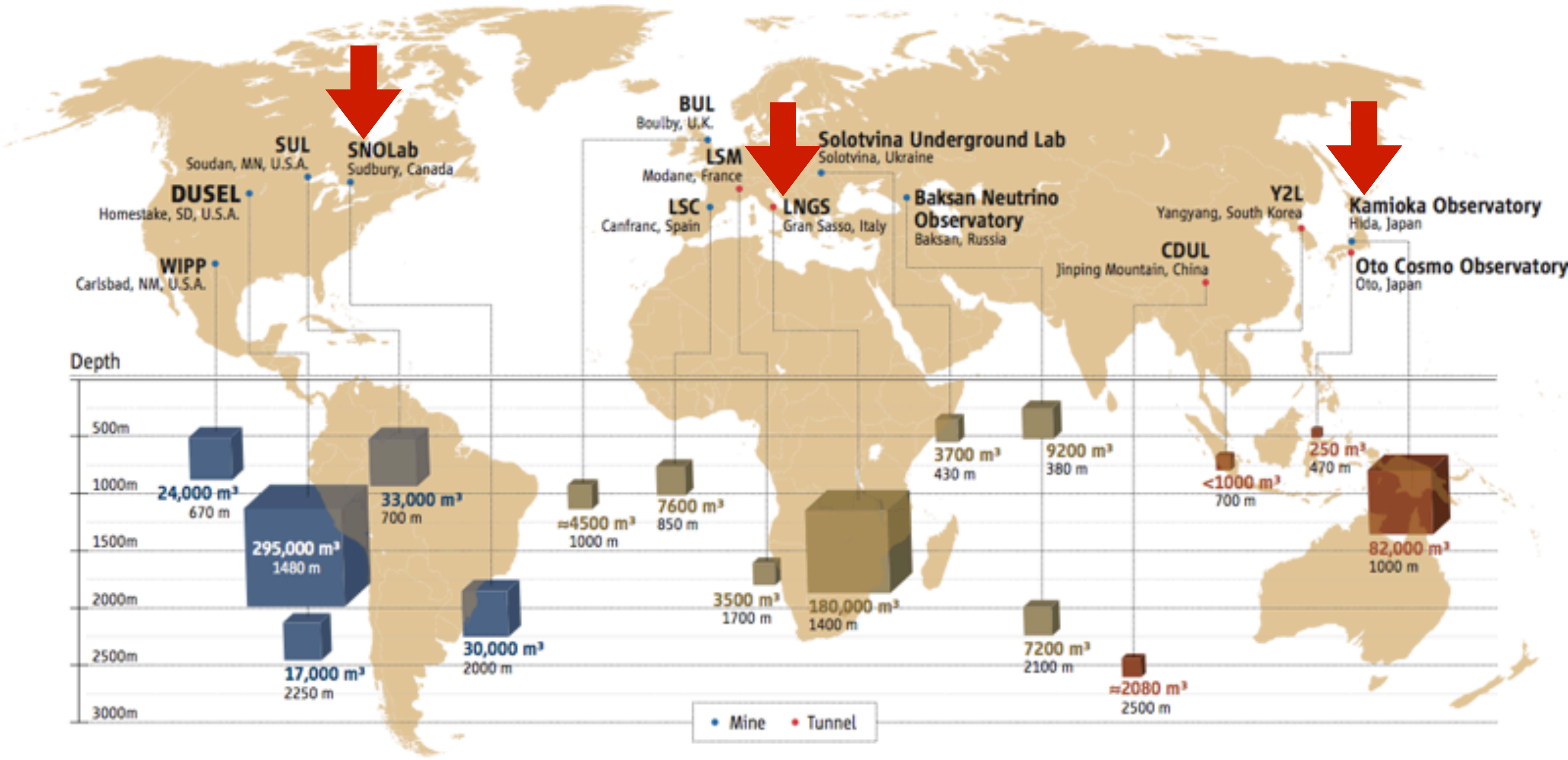
Antineutrino background

- reactor antineutrinos: proximity of nuclear reactors good for fundamental physics, bad for geophysics
- other:
  - impurity of scintillator
  - cosmic ray muon interactions in the atmosphere – **measure at depth**



McDonough et al. 2012

Underground physics laboratories



Cho 2010 Science 10.1126/science.330.6006.904

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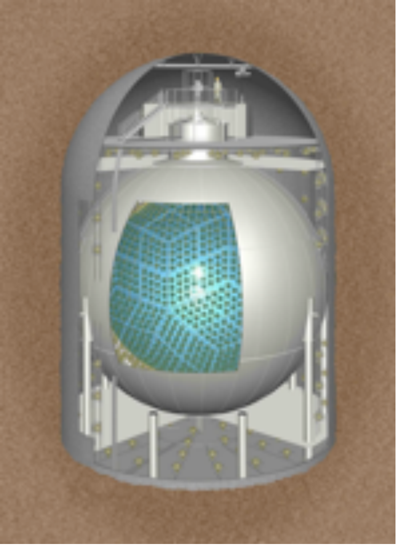

2005: KamLAND, Kamioka, Japan

Size ~1 kton

Live-time 749.1±0.5 days

Exposure 0.709±0.035 × 10^{32} proton years

First detection of geoneutrinos!

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

THE INTERNATIONAL WEEKLY JOURNAL OF SCIENCE

nature

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INDIAN LIFE SCIENCES

EARTHLY POWERS

Geoneutrinos reveal Earth's inner secrets

Araki et al. 2005 10.1038/nature03980

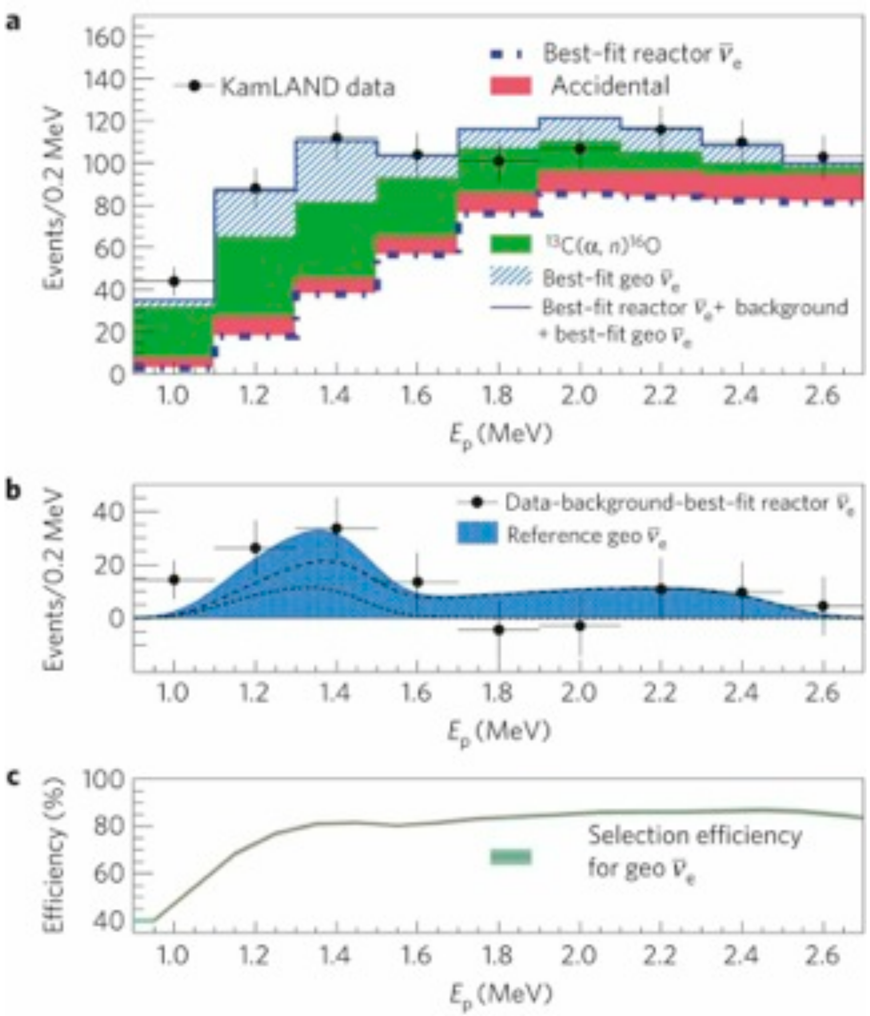
2011: KamLAND, Kamioka, Japan

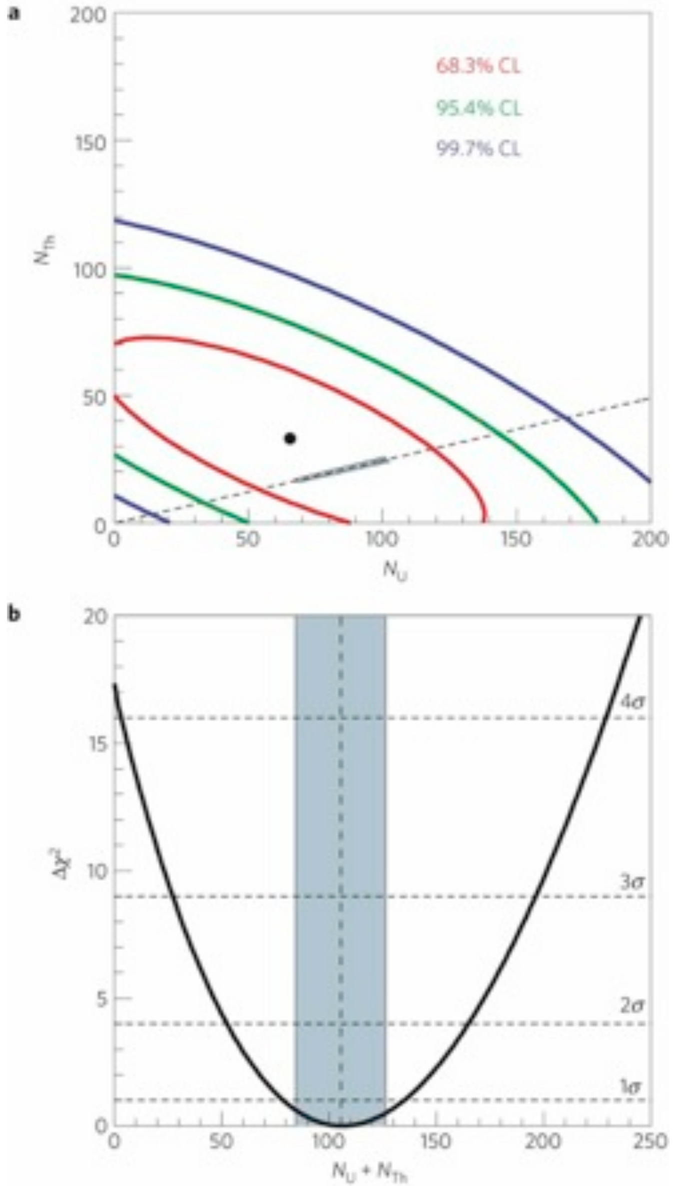
Live-time 2135 days

Exposure 3.49±0.07 × 10^{32} proton years

Events 841

- Background 729±32
- Geoneutrinos 111±43





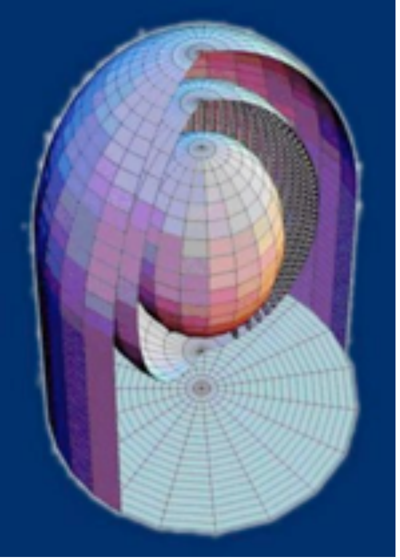
Unconstrained best fit:
Th/U~8
N_U=65, N_{Th}=33

But Th/U unresolved.

Constraining Th/U=3.9
N_{U+Th}=106±28

Geonu at 4σ C.L.

Gando et al. 2011

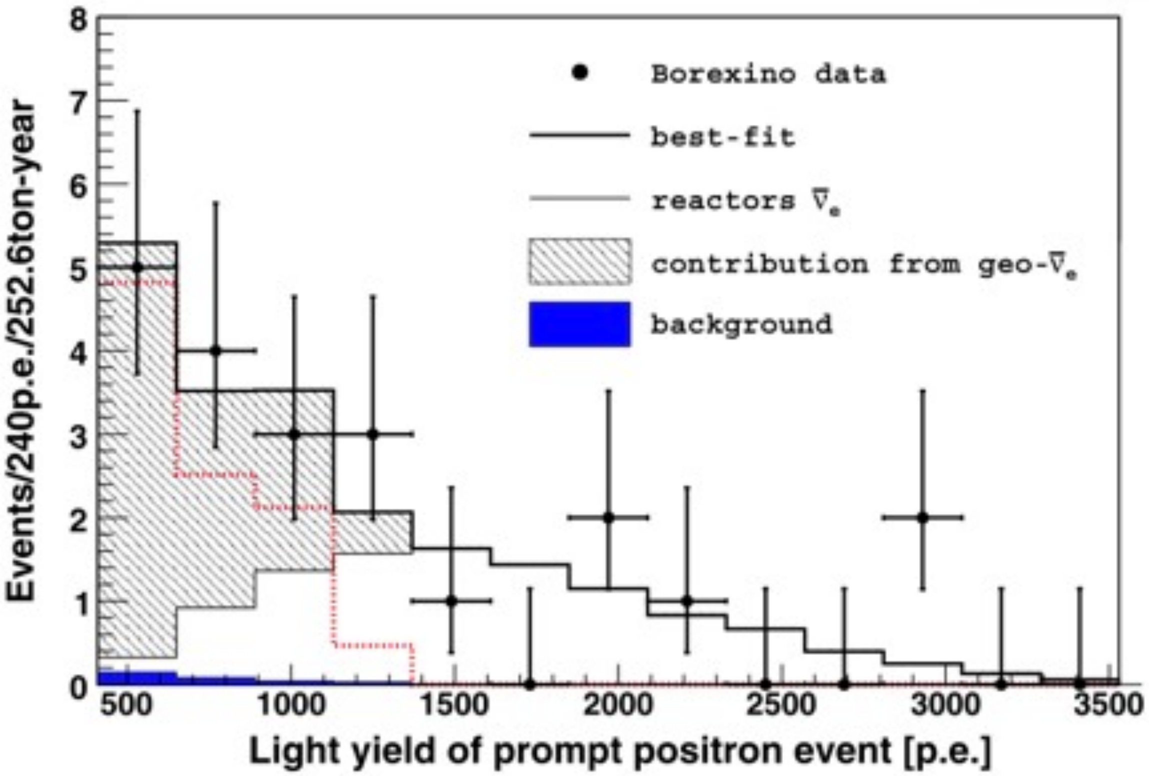


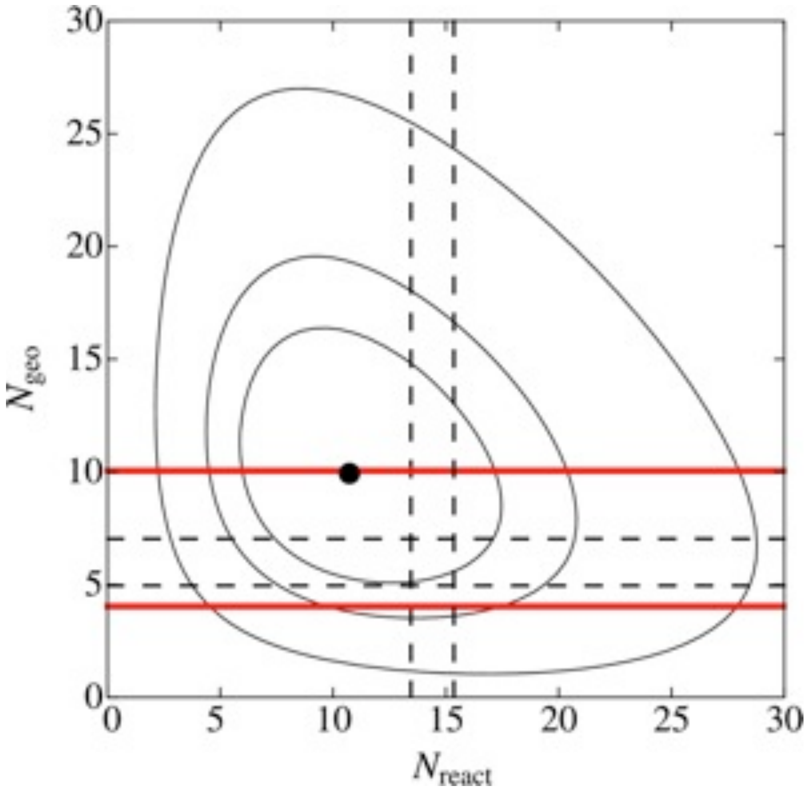
2010: Borexino, Gran Sasso, Italy

Size ~0.3 kton

Live-time ~537.2 days

Exposure ~0.152×10^{32} proton years



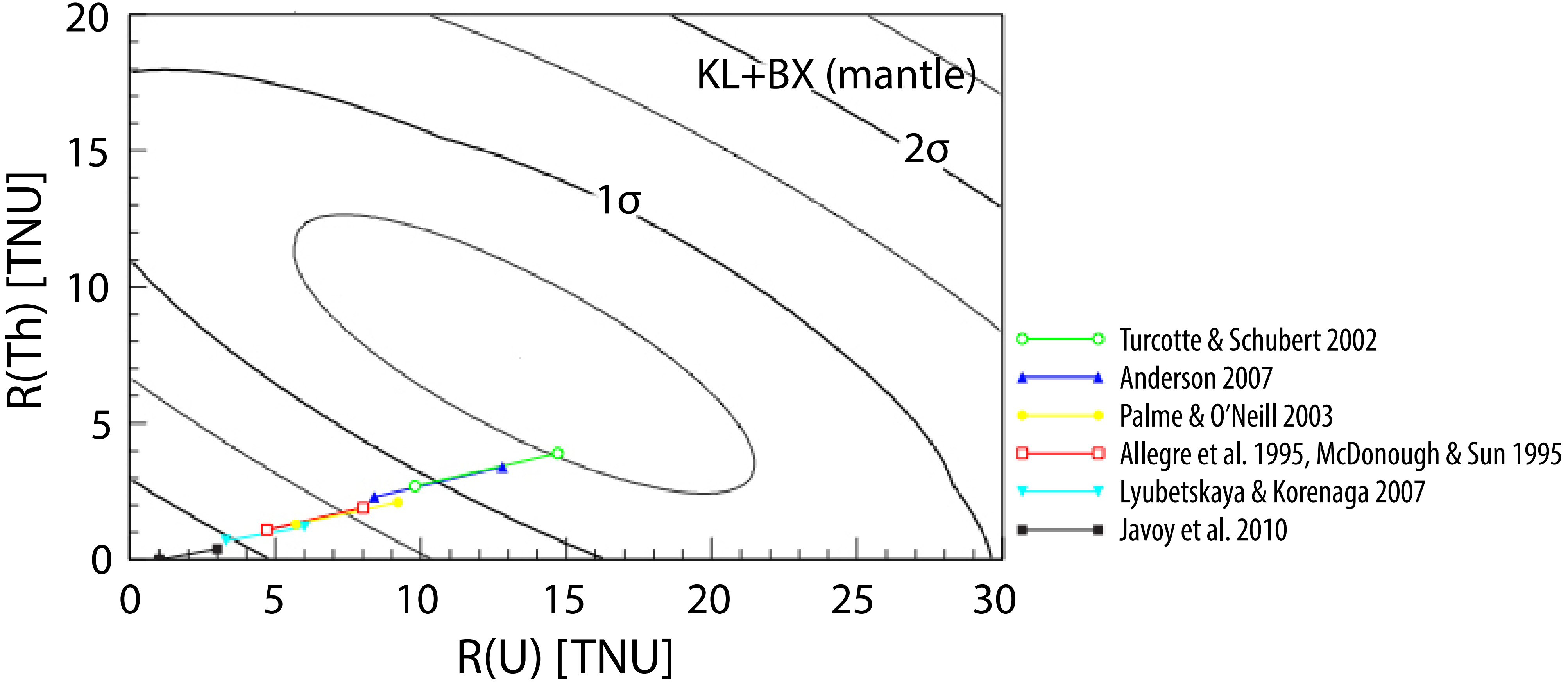


Bellini et al. 2010

Combined KL+BX analysis of mantle geonu flux

Fiorentini et al. 2012

Mantle signal rate from Th+U = **23 ± 10 TNU**
assuming Th/U between 1.7 and 3.9



1. geophysical motivation
2. neutrino history
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4. observations of geoneutrinos
5. predictions of geoneutrinos flux
6. perspectives

Prediction of geoneutrino flux

Calculate predictions for various compositional models & mantle architectures.

Compare with observed signal to test model.

Propose design of new detectors.

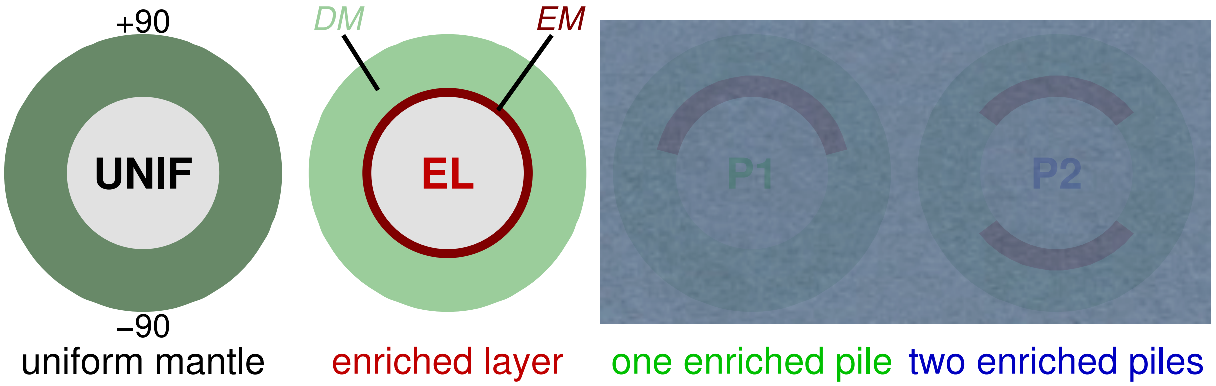
$$\Phi_X(\mathbf{r}) = \frac{n_X \lambda_X \langle P \rangle}{4\pi} \int_\Omega \frac{a_X(\mathbf{r}')\rho(\mathbf{r}')}{|\mathbf{r}-\mathbf{r}'|^2} \mathrm{d}\mathbf{r}' \qquad a_X = \frac{A_X X_X}{M_X}$$

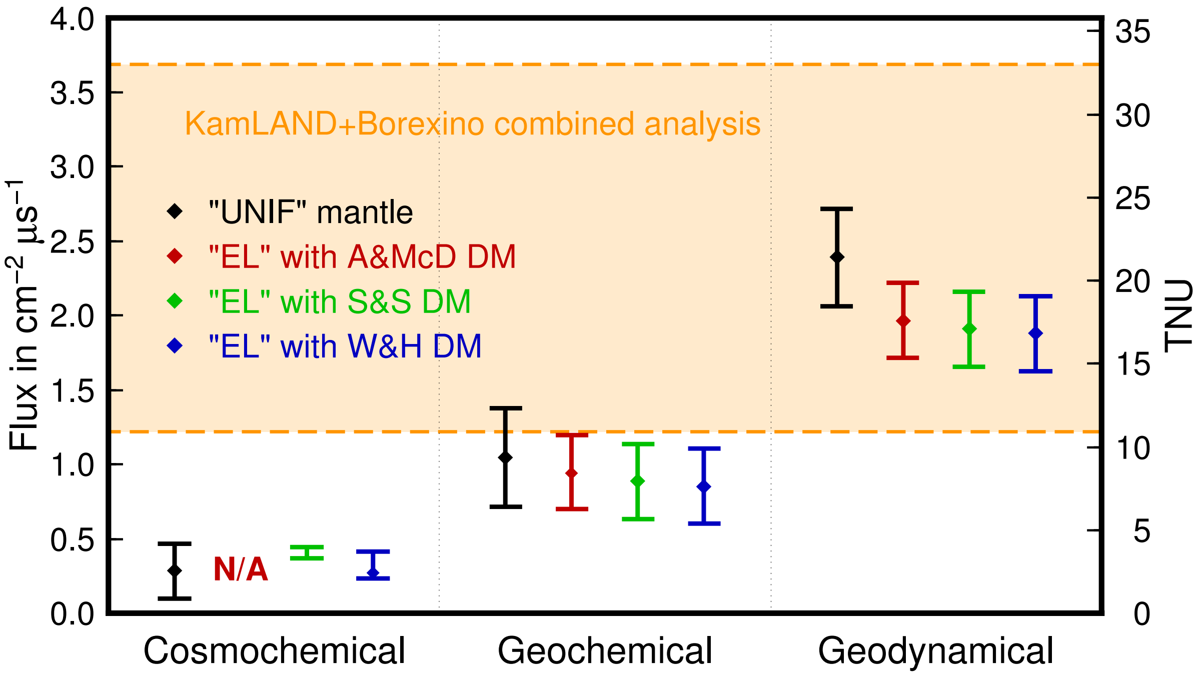
Flux at position ***r*** from radionuclide *X* distributed with elem. abundance *A* in domain *Ω*

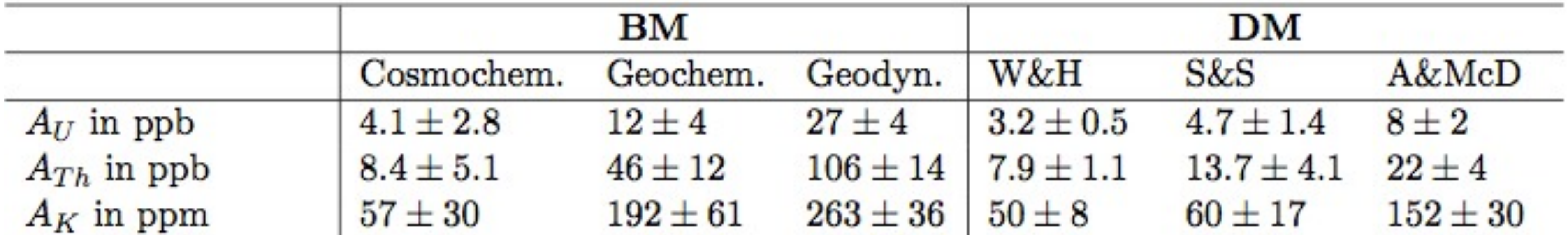
- **inputs from geoscience:**
  - chemical abundances *A* – large uncertainty
  - density *ρ* (PREM)
- **inputs from nuclear/particle physics:**
  - *n*, *λ*, ⟨*P*⟩, *X*, *M*
  - relatively well known

- Which BSE (BM) is the Earth?
- Is the mantle compositionally uniform?
- Enriched reservoir in the mantle?
  What geometry?

Prediction for spherically symmetrical mantle

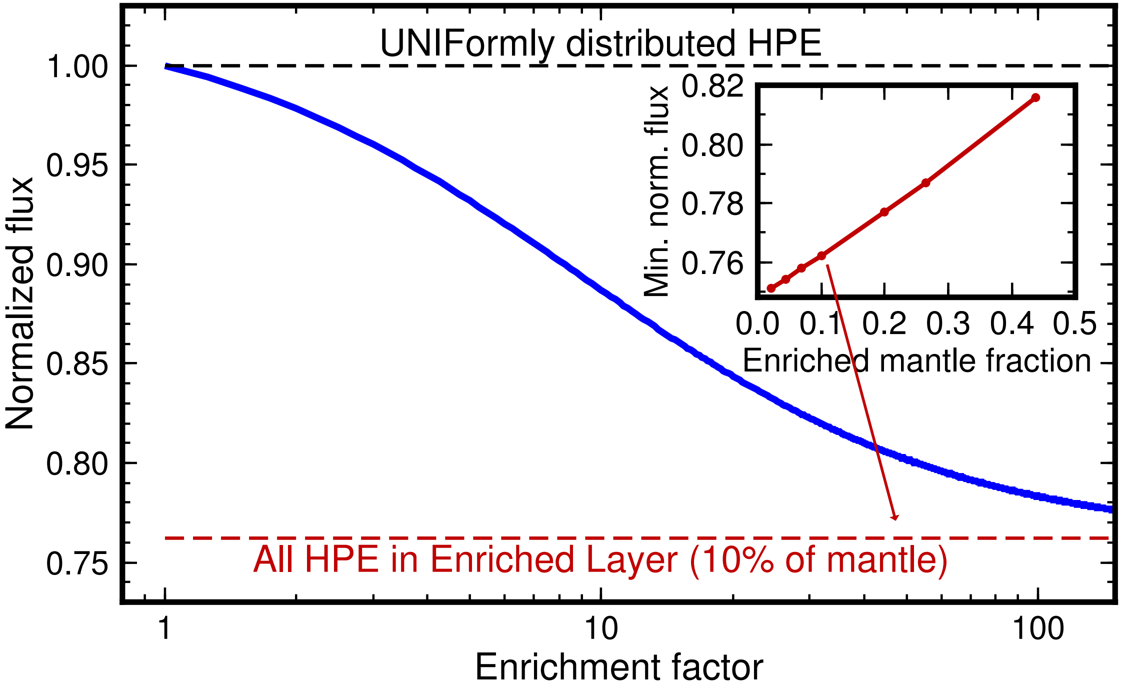






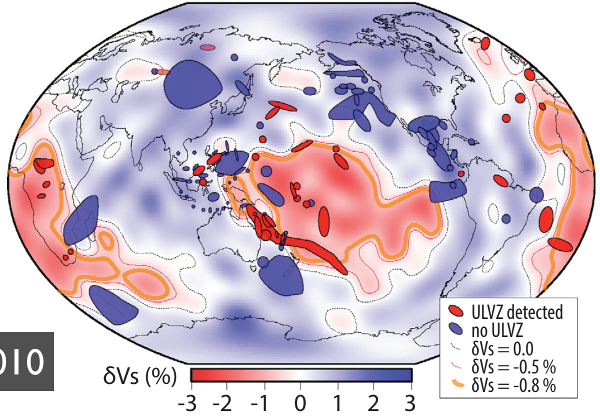
	BM			DM		
	Cosmochem.	Geochem.	Geodyn.	W&H	S&S	A&McD
A_U in ppb	4.1 ± 2.8	12 ± 4	27 ± 4	3.2 ± 0.5	4.7 ± 1.4	8 ± 2
A_{Th} in ppb	8.4 ± 5.1	46 ± 12	106 ± 14	7.9 ± 1.1	13.7 ± 4.1	22 ± 4
A_K in ppm	57 ± 30	192 ± 61	263 ± 36	50 ± 8	60 ± 17	152 ± 30

How much can surface flux be reduced by segregation of heat-producing elements in a uniform-thickness layer at the bottom of the mantle?



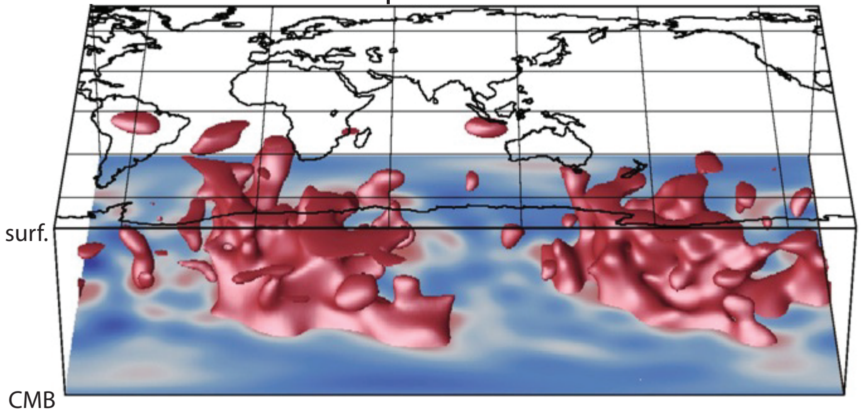
But an enriched reservoir may not be of uniform thickness...

LLSVPs – enriched reservoir?



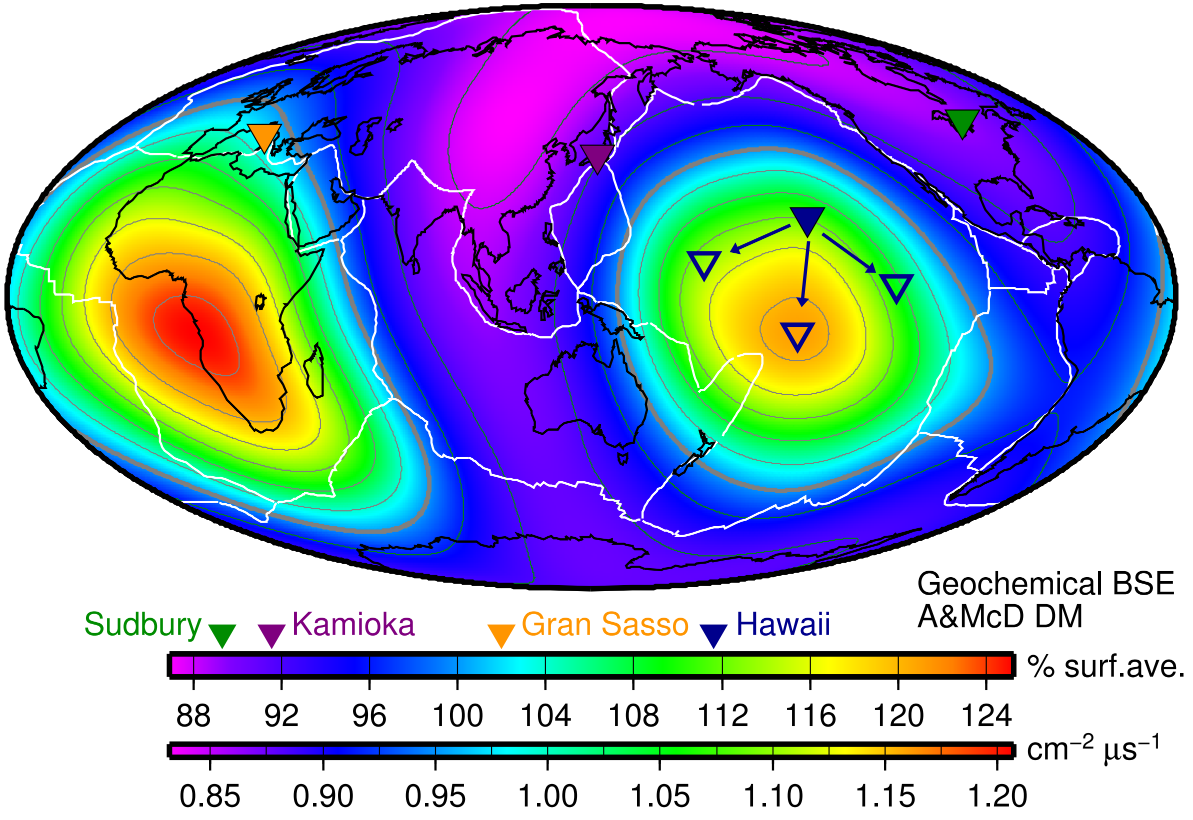
ULVZs and shear wave speed anomaly

McNamara et al. 2010



Shape of LLSVPs

Bull et al. 2009



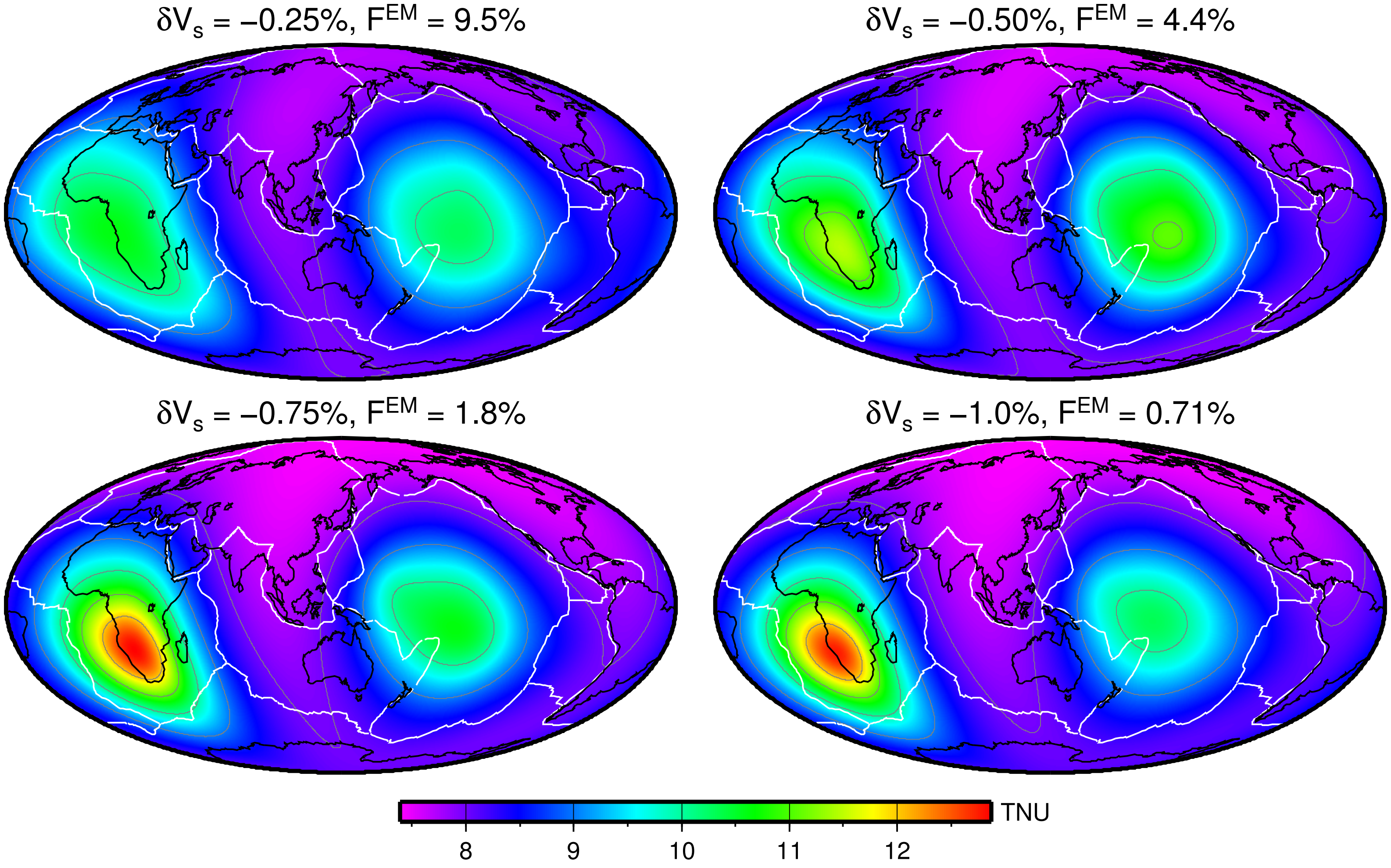
Mantle geoneutrino flux (^{238}U+^{232}Th)

Issue of dynamic stability

Size of the piles

Flux dependence on size of piles

Trade-off between size and enrichment for a given choice BM & DM compositional estimate



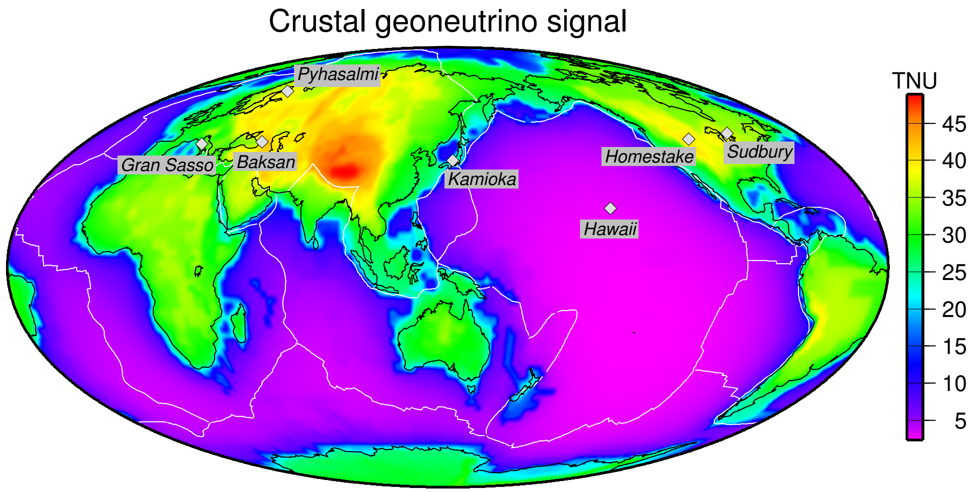
$\delta V_s = -0.25\%$, $F^{EM} = 9.5\%$

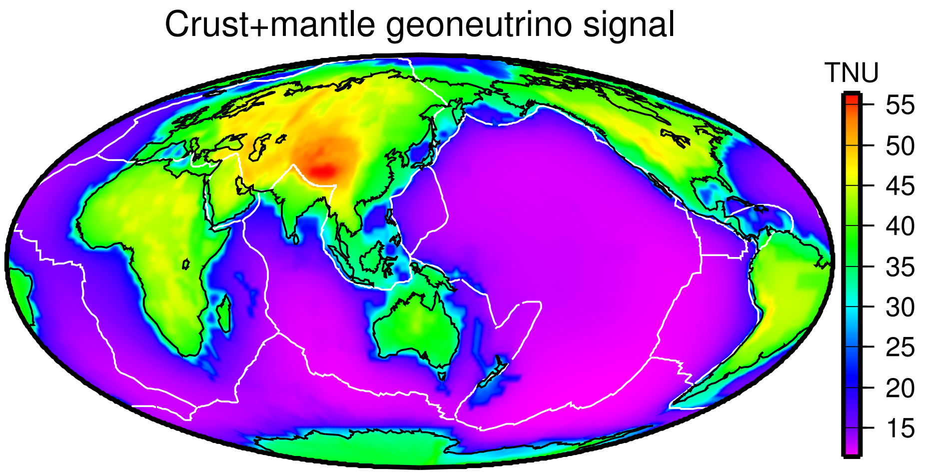
$\delta V_s = -0.50\%$, $F^{EM} = 4.4\%$

$\delta V_s = -0.75\%$, $F^{EM} = 1.8\%$

$\delta V_s = -1.0\%$, $F^{EM} = 0.71\%$

Do we have any chance of seeing this with geoneutrinos?


Crustal geoneutrino signal

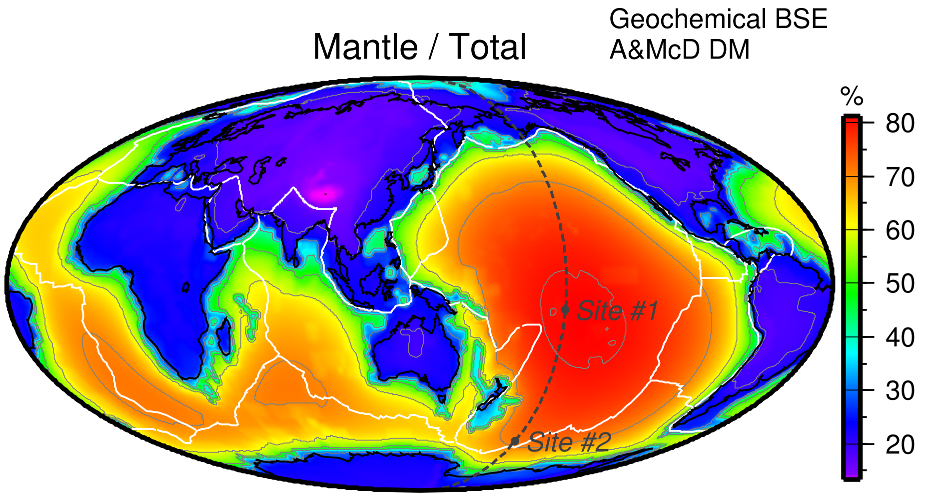

Crust+mantle geoneutrino signal

Continental crust dominates the geoneutrino signal:

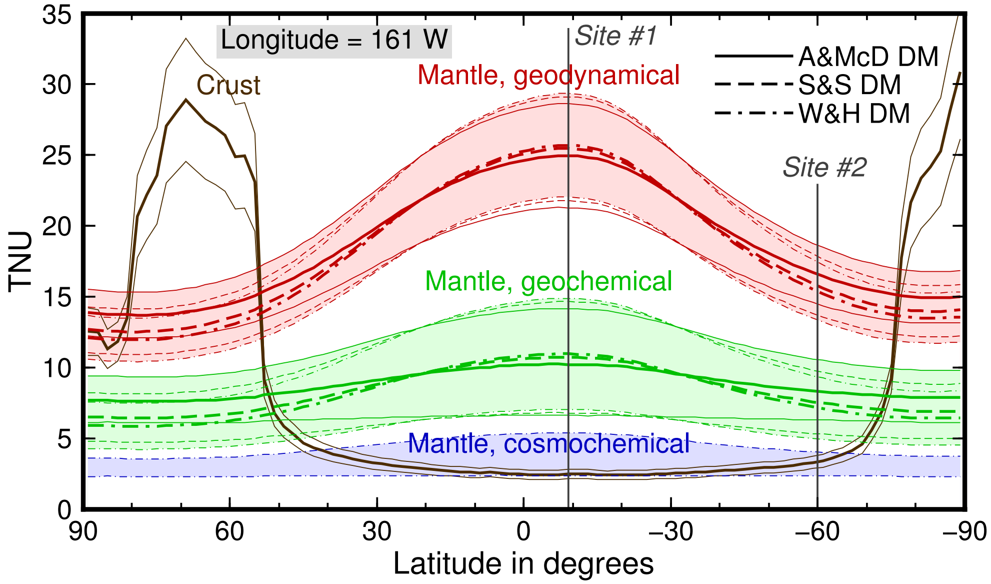
- highly enriched in U, Th, K
- source closest to detector

But we are interested in measuring the mantle.

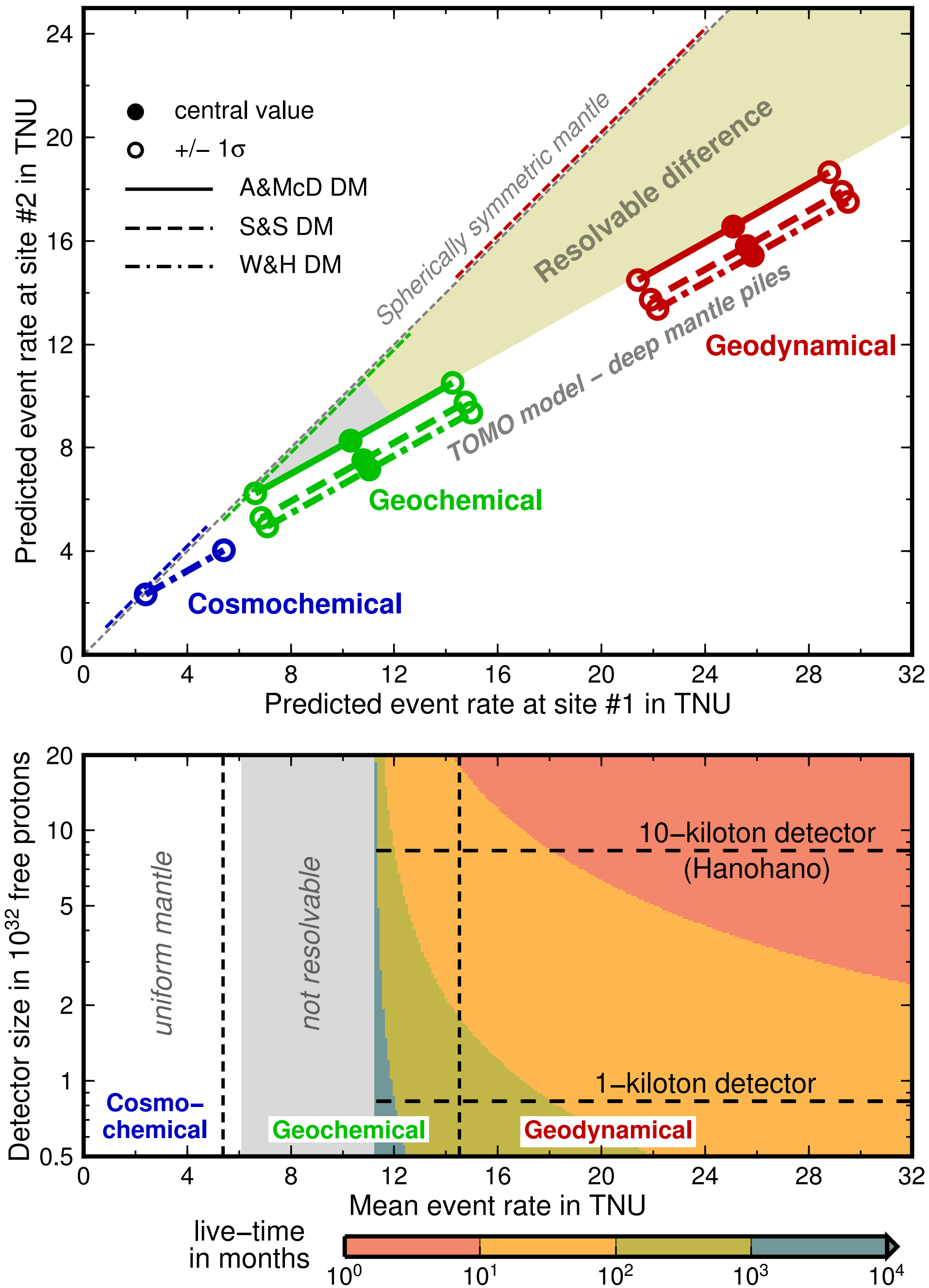
We need to go in the ocean.


Mantle / Total

Geochemical BSE
A&McD DM



Can we resolve the predicted lateral variation?



Yes, and we need a two-site measurement in the ocean!

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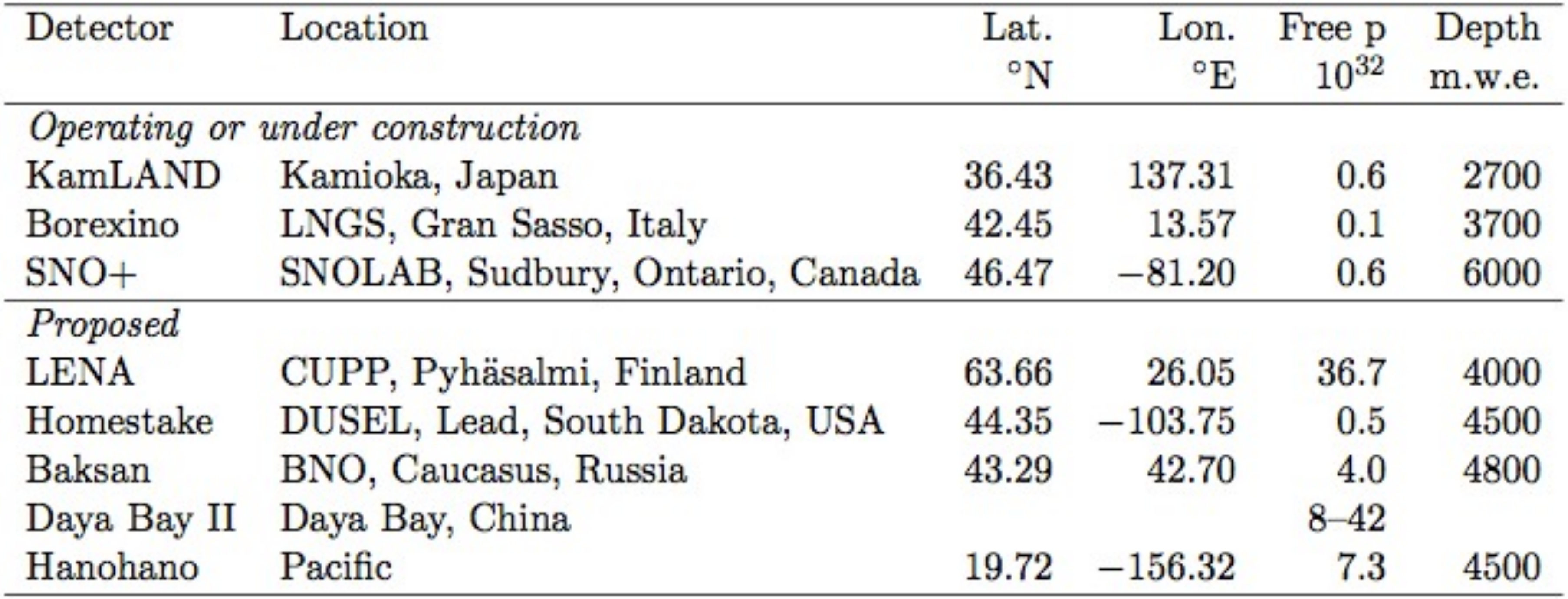
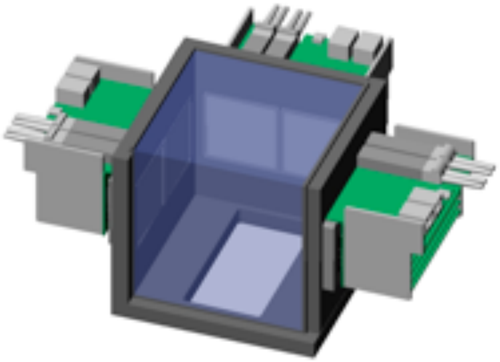
More geoneutrino detectors



Detector	Location	Lat. °N	Lon. °E	Free p 10^{32}	Depth m.w.e.
Operating or under construction					
KamLAND	Kamioka, Japan	36.43	137.31	0.6	2700
Borexino	LNGS, Gran Sasso, Italy	42.45	13.57	0.1	3700
SNO+	SNOLAB, Sudbury, Ontario, Canada	46.47	−81.20	0.6	6000
Proposed					
LENA	CUPP, Pyhäsalmi, Finland	63.66	26.05	36.7	4000
Homestake	DUSEL, Lead, South Dakota, USA	44.35	−103.75	0.5	4500
Baksan	BNO, Caucasus, Russia	43.29	42.70	4.0	4800
Daya Bay II	Daya Bay, China			8–42	
Hanohano	Pacific	19.72	−156.32	7.3	4500

Potential for geoneutrino tomography...

Small portable detectors?



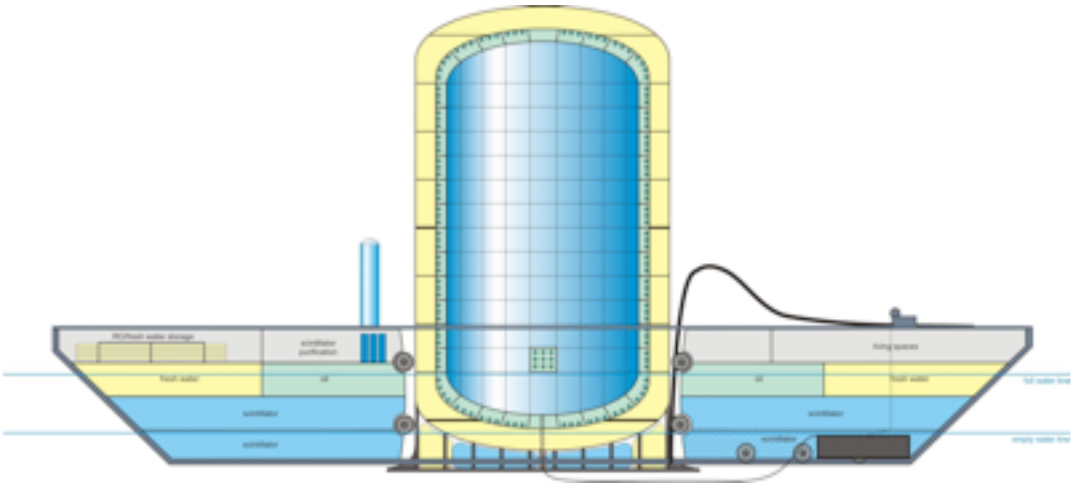
mini TimeCube ... John Learned’s group, U.Hawaii

Interest in clandestine nuclear reactor monitoring.

Hanohano ??

A proposed transportable geoneutrino detector designed for ocean deployment

http://www.phys.hawaii.edu/~sdye/hanohano.html



Directional antineutrino detection ??

Work in progress on directional detector

Geoneutrinos: crust vs. mantle, uniform vs. layered mantle

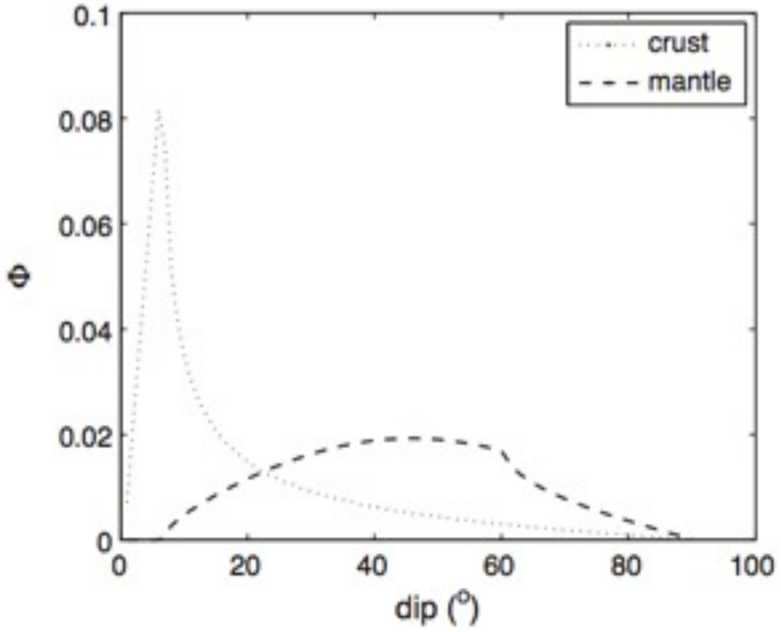


Fig. 11. Neutrino flux from the crust (a thin spherical shell with radius $0.994 < r/a < 1$) and the mantle ($0.5 < r/a < 0.994$) as a function of the inclination. The flux of crustal geoneutrinos exhibits a sharp maximum at near horizontal inclination. The flux of mantle geoneutrinos shows a distribution spread over a much wider range of dip angles, with a maximum near 50°.

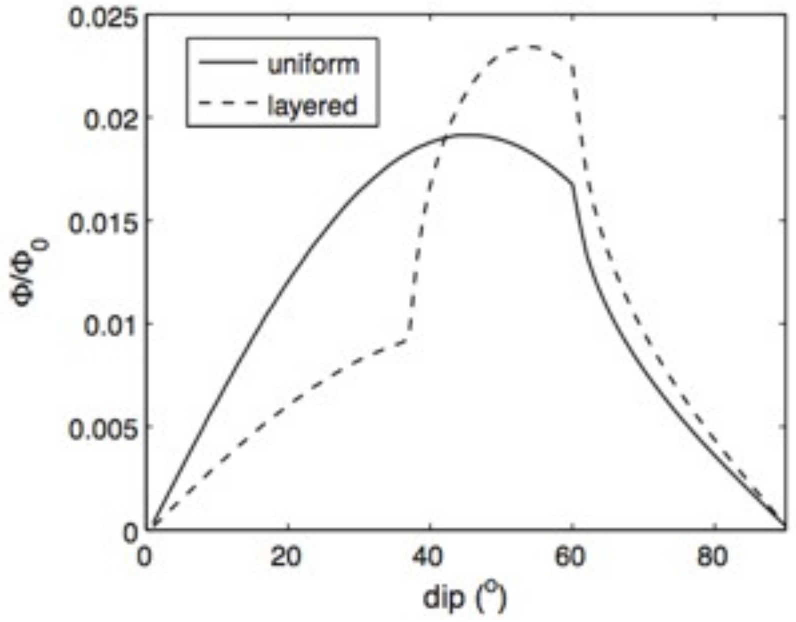


Fig. 12. Variations of the mantle neutrino flux with inclination for two different radial distributions of U and Th in the mantle. flux per unit dip angle is relative to the total integrated flux Φ_0, and both radial distributions are compared to the total integrated flux Φ_0 for the uniform distribution a uniform distribution. The differences between the two distributions are marked with the flux spread over a much wider range of inclinations for the homogeneous than the two reservoirs mantle. Note that the mantle flux is low (relative to the effective cross-section) and that it is one order lower than the crustal flux. It translates in low event yield per unit angle.

Mareschal et al. 2010

Some geoneutrino references

Popular articles:

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Fiorentini, G., M. Lissia, and F. Mantovani, Geo-neutrinos and earth's interior, *Phys. Rep.*, *453*(5-6), 117–172, doi:10.1016/j.physrep.2007.09.001, 2007.

Dye, S. T., Geoneutrinos and the radioactive power of the Earth, *Rev. Geophys.*, *50*(3), eid:RG3007, doi:10.1029/2012RG000400, 2012.

Šrámek, O., W. F. McDonough, and J. G. Learned, Geoneutrinos, *Adv. High Energy Phys.*, accepted to Special Issue on Neutrino Physics, 2012b (**preprint**).

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Other research literature:

Krauss, L. M., S. L. Glashow, and D. N. Schramm, Antineutrino astronomy and geophysics, *Nature*, *310*(5974), 191–198, doi:10.1038/310191a0, 1984.

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Enomoto, S., E. Ohtani, K. Inoue, and A. Suzuki, Neutrino geophysics with KamLAND and future prospects, *Earth Planet. Sci. Lett.*, *258*(1-2), 147–159, doi:10.1016/j.epsl.2007.03.038, 2007.

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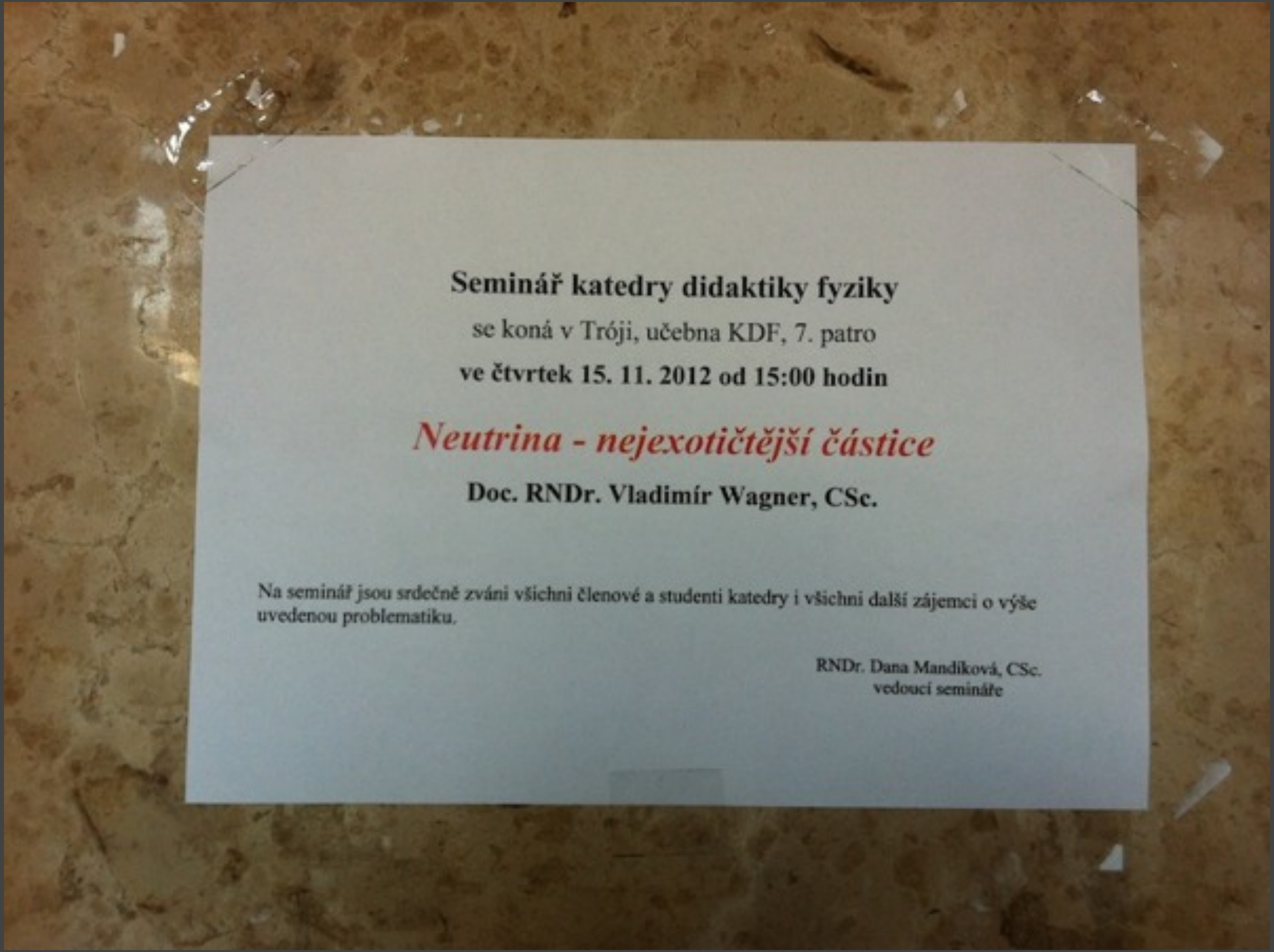
Šrámek, O., W. F. McDonough, E. S. Kite, V. Lekić, S. T. Dye, and S. Zhong, Geophysical and geochemical constraints on geoneutrino fluxes from Earth's mantle, *Earth Planet. Sci. Lett.*, accepted, doi:10.1016/j.epsl.2012.11.001, **arXiv:1207.0853**, 2012a.



Seminář katedry didaktiky fyziky

se koná v Tróji, učebna KDF, 7. patro

ve čtvrtek 15. 11. 2012 od 15:00 hodin

Neutrina - nejexotičtější částice

Doc. RNDr. Vladimír Wagner, CSc.

Na seminář jsou srdečně zváni všichni členové a studenti katedry i všichni další zájemci o výše uvedenou problematiku.

RNDr. Dana Mandíková, CSc.
vedoucí semináře

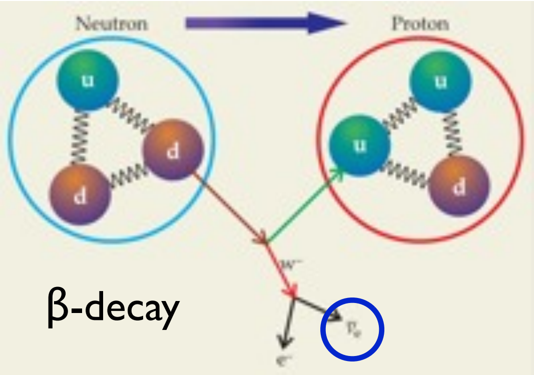
visit of SNOLAB, Ontario, Canada (photos)

How much radiogenic heating in the mantle⁇

What is the Earth made of⁇

Chemical reservoirs in the mantle⁇

^{238}U, ^{232}Th, ^{40}K

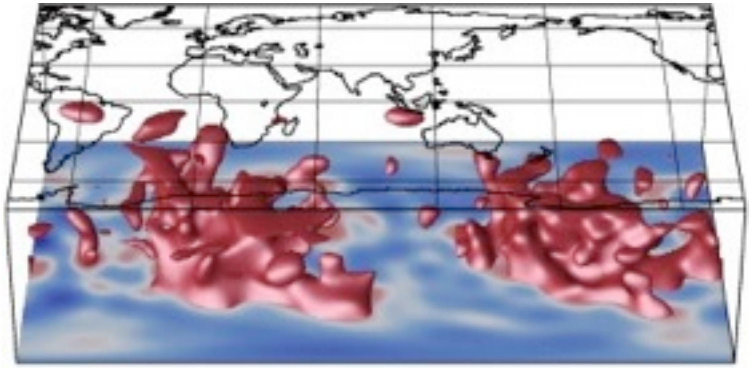


β-decay

Geoneutrinos:
electron antineutrinos emitted in β-decays of natural radionuclides

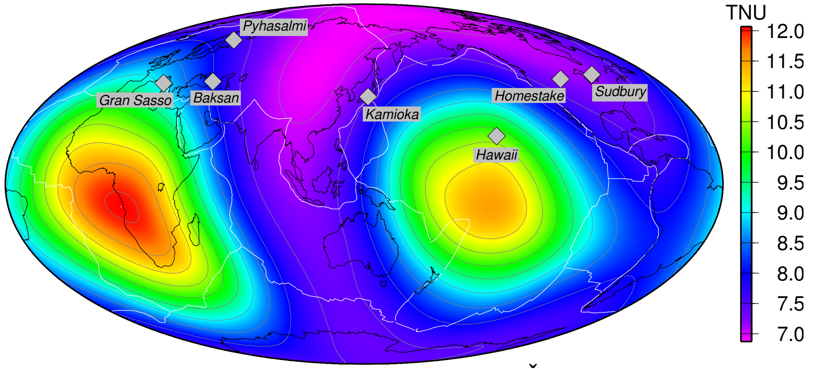
$$^{238}_{92}\mathrm{U} \longrightarrow {}^{206}_{82}\mathrm{Pb} + 8\alpha + 6e^- + 6\bar{\nu}_e + 51.698\ \mathrm{MeV}$$
$$^{235}_{92}\mathrm{U} \longrightarrow {}^{207}_{82}\mathrm{Pb} + 7\alpha + 4e^- + 4\bar{\nu}_e + 46.402\ \mathrm{MeV}$$
$$^{232}_{90}\mathrm{Th} \longrightarrow {}^{208}_{82}\mathrm{Pb} + 6\alpha + 4e^- + 4\bar{\nu}_e + 42.652\ \mathrm{MeV}$$
$$^{40}_{19}\mathrm{K} \xrightarrow{89.3\,\%} {}^{40}_{20}\mathrm{Ca} + e^- + \bar{\nu}_e + 1.311\ \mathrm{MeV},$$

LLSVPs may represent material enriched in U, Th, K



from Bull et al. 2009

Predicted mantle geoneutrino flux

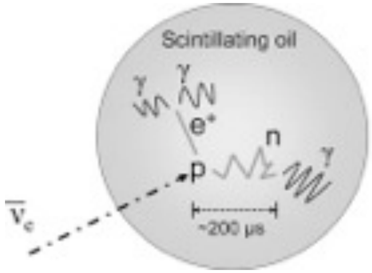


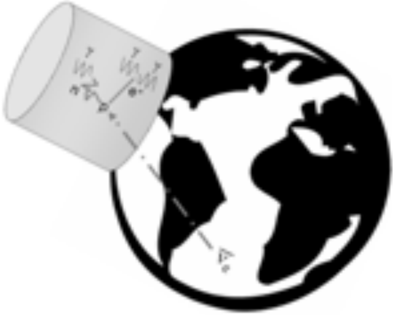
Šrámek et al. EPSL 2012

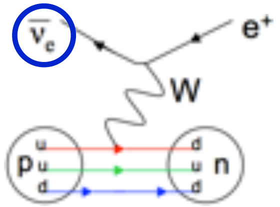
Geo-ν detection possible:

Large liquid scintillator detectors

Direct information on Earth's deep-seated radioactivity!

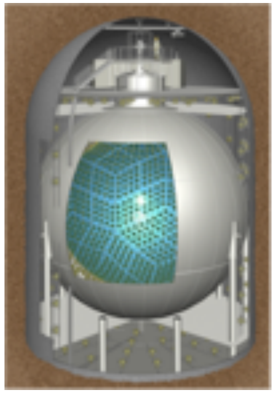


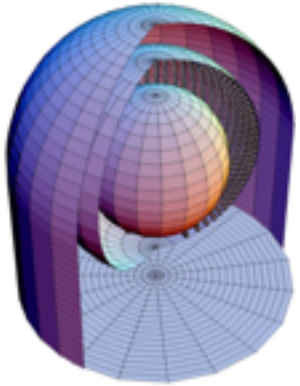




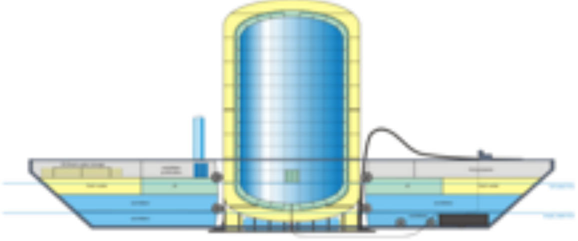
KamLAND (Japan)

Borexino (Italy)



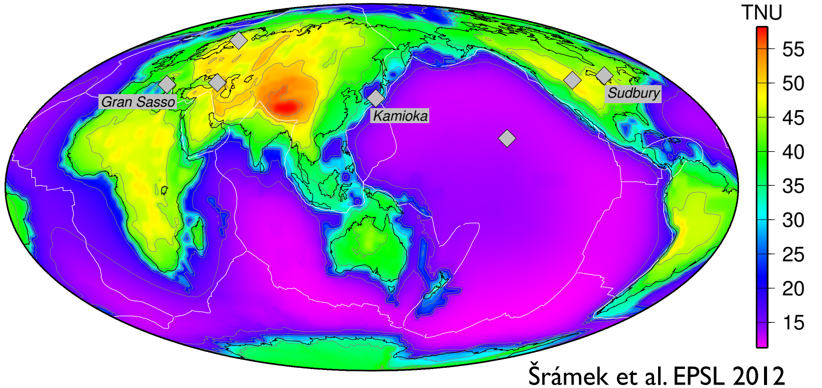


Hanohano, proposed ocean deployment



Mantle: detectable variations!
Must measure in the ocean...

Crust + mantle geoneutrino flux



Šrámek et al. EPSL 2012