Dobrý den

Introduction to Geoneutrinos

Vítejte

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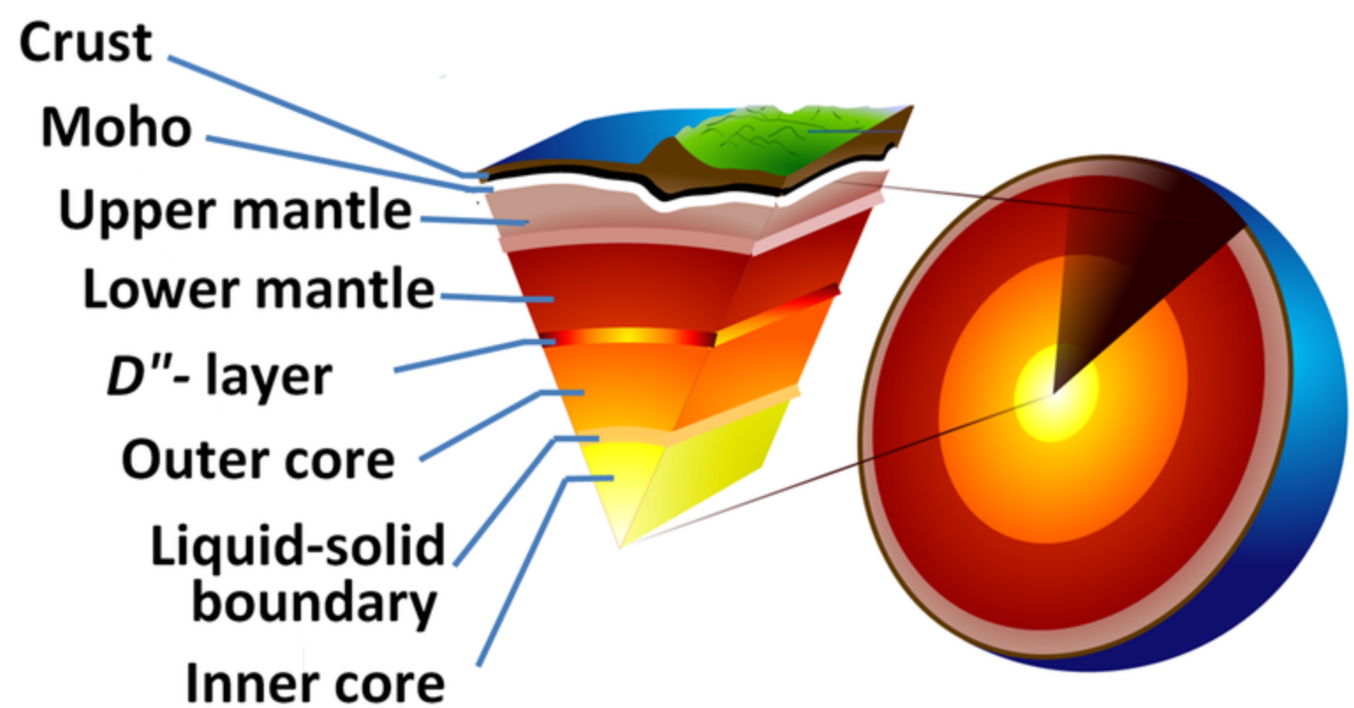
Outline

- Geoneutrinos – what are they?
- Why are they interesting?
- How to detect geoneutrinos?
  - R&D ideas: K-40 geoneutrinos, directionality
- Featuring @ Neutrino Geoscience 2019
  - KamLAND and Borexino new results
  - Future experiments: SNO+, JUNO, Jinping, Baksan

What are Geoneutrinos?

the antineutrinos produced by natural radioactivity in the Earth

Radioactive decay of
U, Th, ^{40}K
accounts for >99% of Earth's radiogenic heat (and a large fraction of the total heat flow)



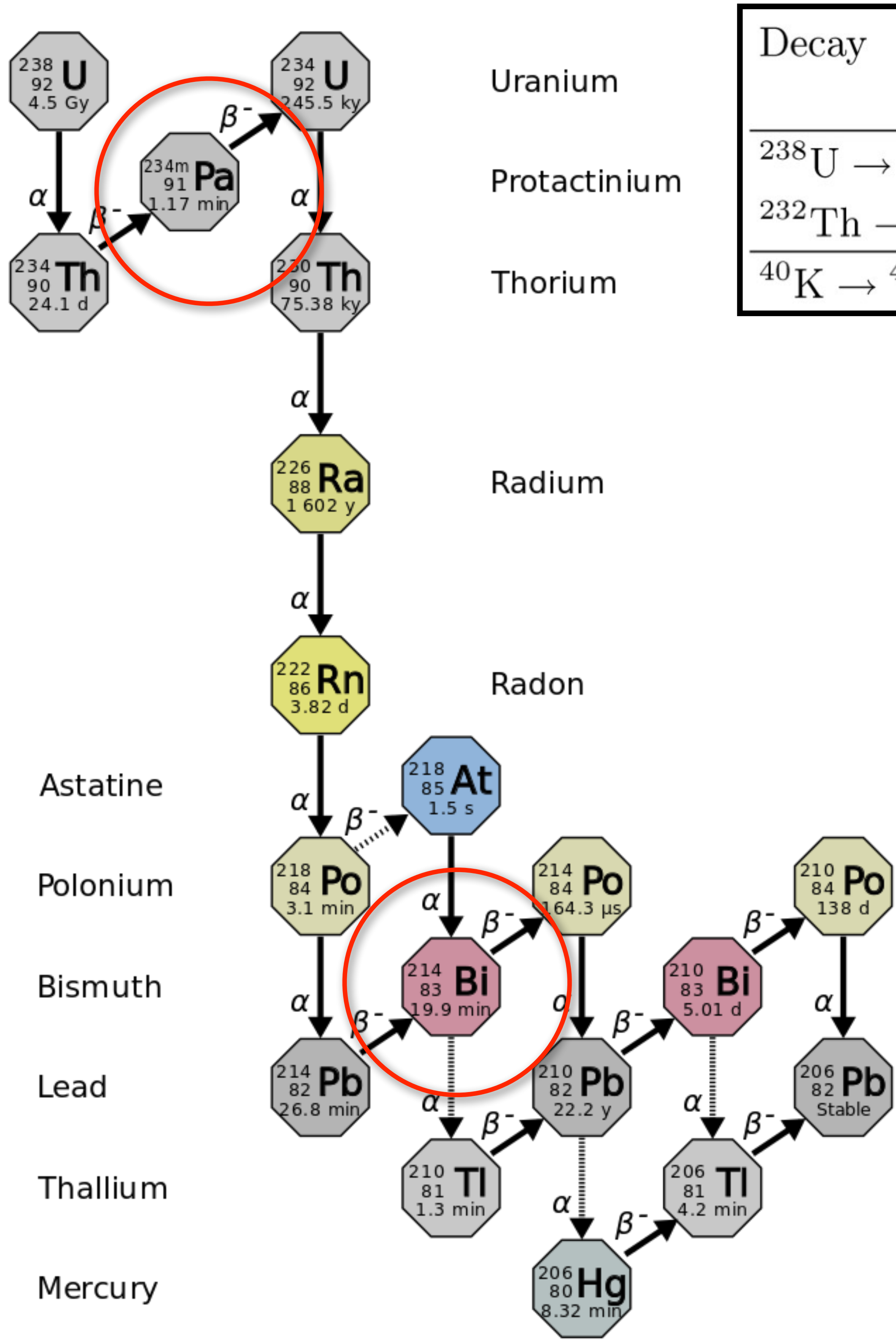
heat producing elements (HPEs)

Decaying HPEs emit antineutrinos in direct proportion to their heating power

$$N_{\bar{\nu}_e} \rightarrow \mathrm{TW}$$

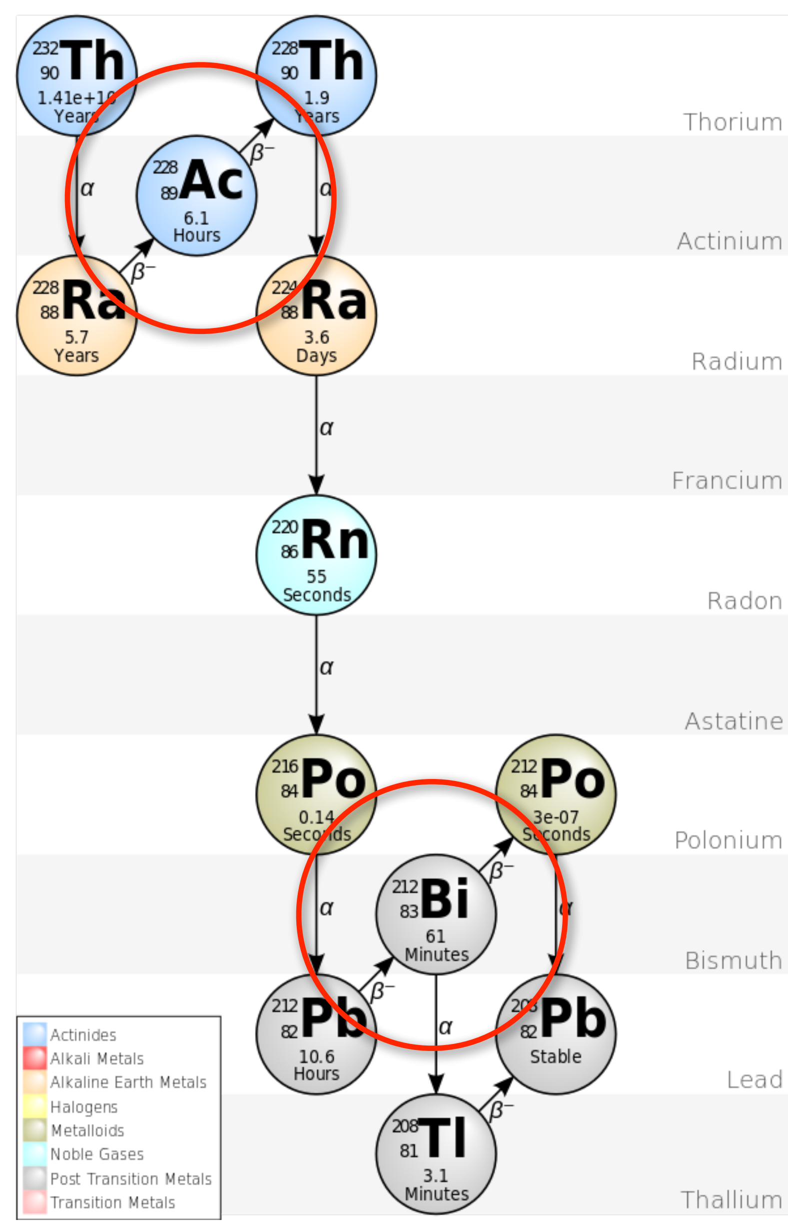
goal: assay the entire Earth by looking at its "neutrino glow"

Uranium, Thorium and Potassium Decay



Decay	$T_{1/2}$ [10^9 yr]	$E_{\max}$ [MeV]	Q [MeV]	$\varepsilon_{\bar{\nu}}$ [$\mathrm{kg^{-1}s^{-1}}$]	ε_H [W/kg]
$^{238}\mathrm{U} \to {}^{206}\mathrm{Pb} + 8\,{}^4\mathrm{He} + 6e + 6\bar{\nu}$	4.47	3.26	51.7	7.46×10^7	0.95×10^{-4}
$^{232}\mathrm{Th} \to {}^{208}\mathrm{Pb} + 6\,{}^4\mathrm{He} + 4e + 4\bar{\nu}$	14.0	2.25	42.7	1.62×10^7	0.27×10^{-4}
$^{40}\mathrm{K} \to {}^{40}\mathrm{Ca} + e + \bar{\nu}$ (89%)	1.28	1.311	1.311	2.32×10^8	0.22×10^{-4}

table from G. Fiorentini



when neutron-rich heavy elements undergo beta decay

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

antineutrinos (electron-flavour) are emitted

Uranium, Thorium and Potassium Decay

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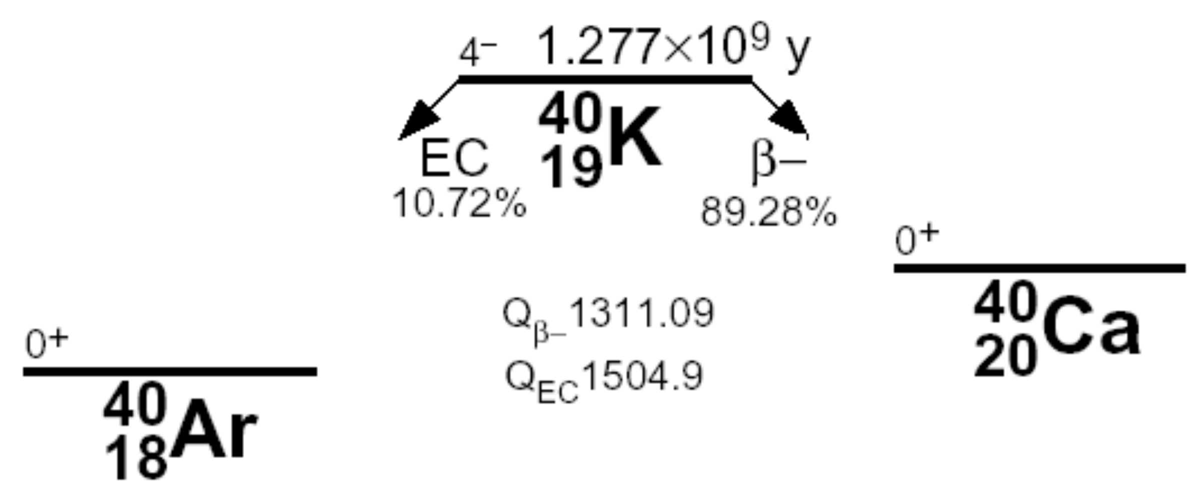
table from G. Fiorentini

- note: ^{40}K also has 10.72% EC branch

  thus also emits neutrinos as well as antineutrinos; but the ν_e are mostly inconsequential because they have much lower energy, 44 keV (EC to an excited state of ^{40}Ar, 10.67%) or very small branching ratio, 0.05% to the ground state



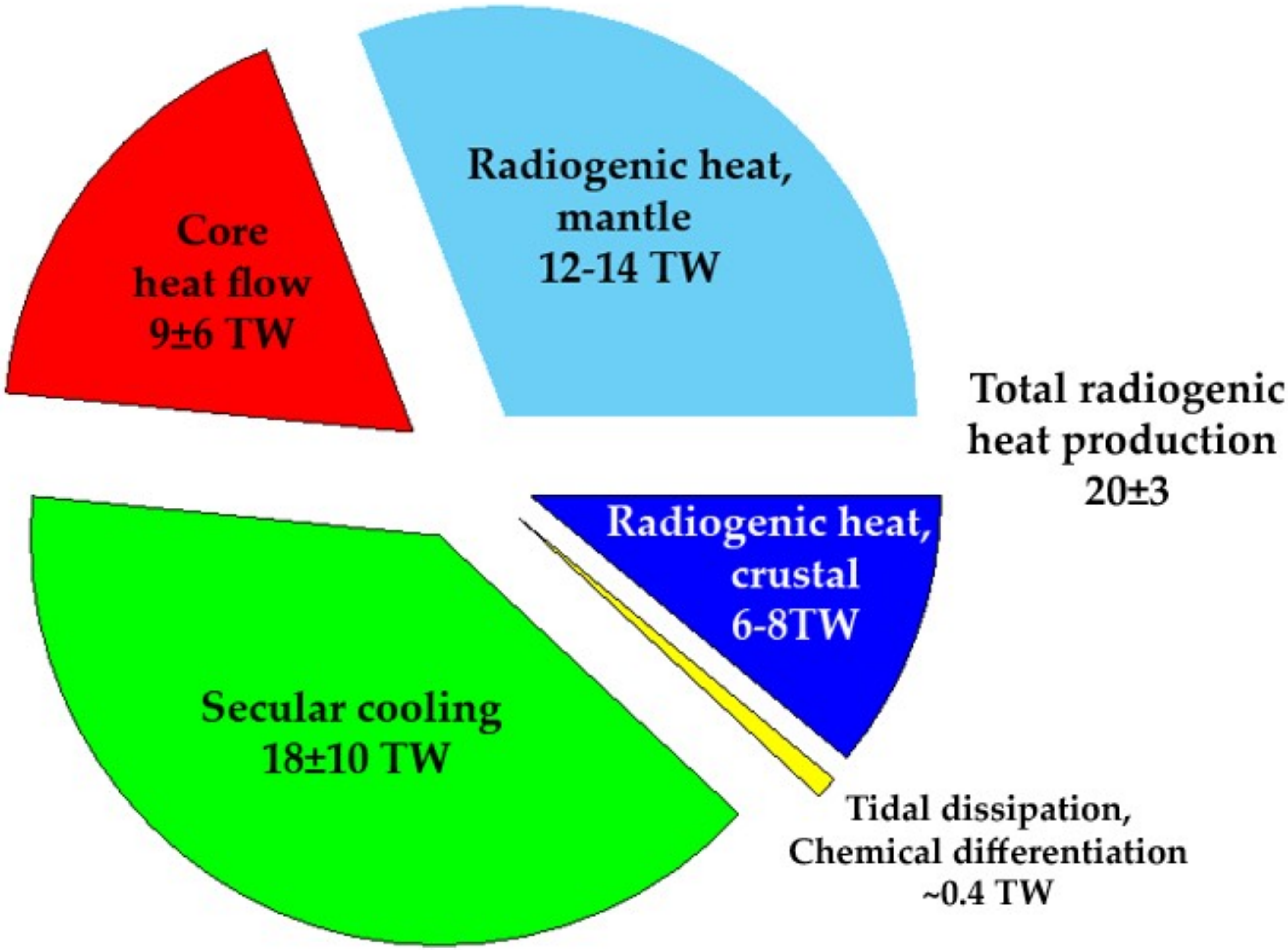
0.0117% isotopic abundance

Important Questions in Geosciences

related to geoneutrinos

- what is the radiogenic contribution (U, Th, ^{40}K) to heat flow and energetics in the deep Earth? – otherwise inaccessible
  - mantle: convective Urey ratio?
  - geoneutrinos can measure (U and Th for now)

Earth's surface heat flow 47 ± 3 TW



breakdown of what we think gives rise to the measured heat flow

figure from Bill McDonough

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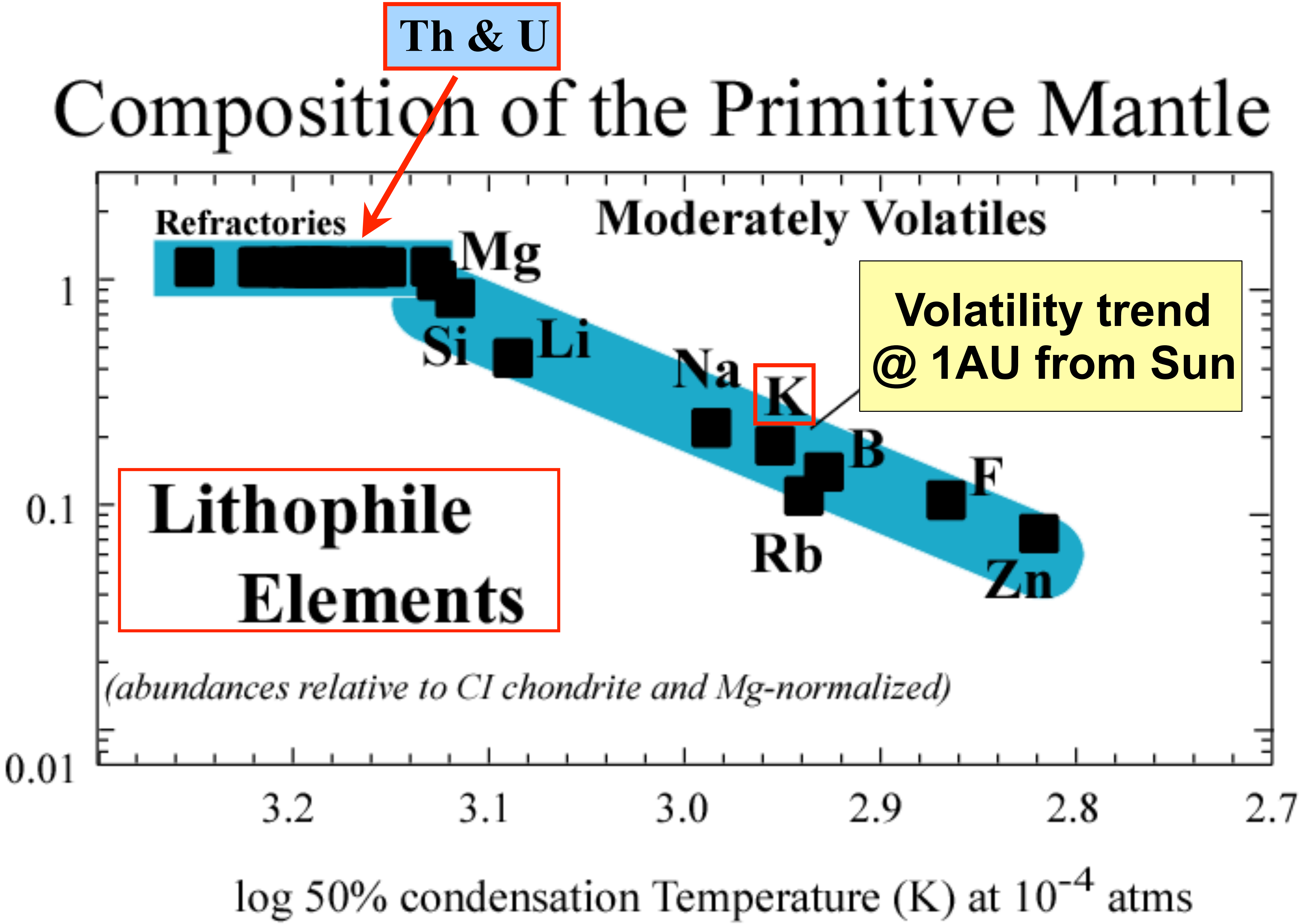
- are the fundamental ideas about Earth's chemical composition and origin correct?
- are the basic models of the composition of the crust correct?
  - geoneutrinos can test which ones are

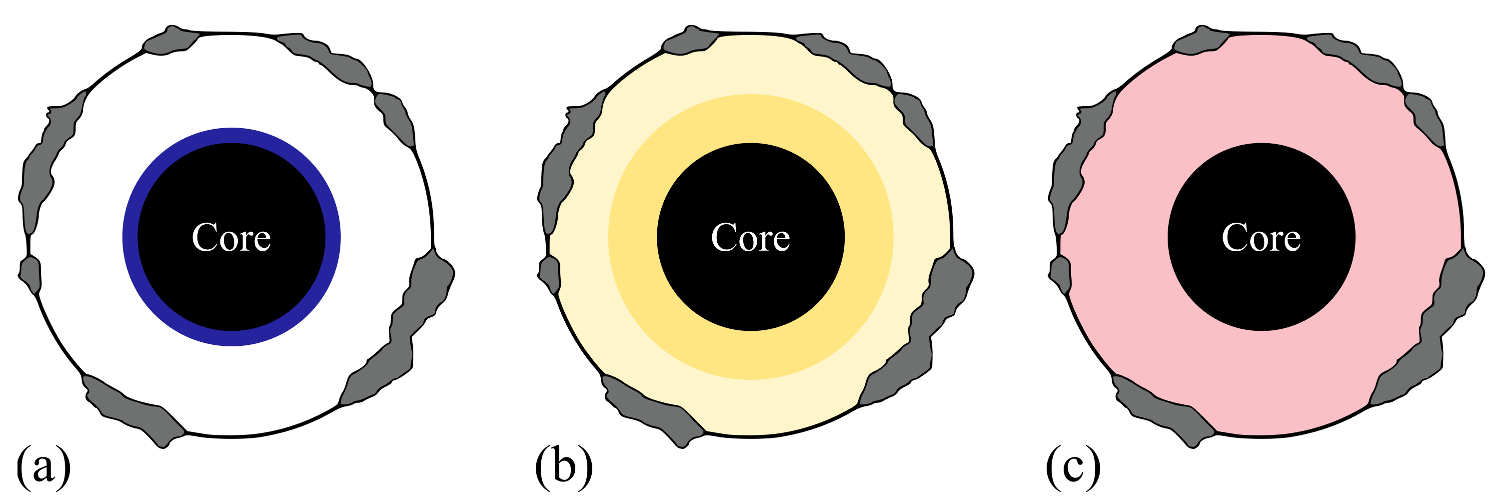
Composition of the Primitive Mantle



slide from Bill McDonough

Silicate Earth Models and Distribution of HPEs

- “Cosmochemical” models
  - EH enstatite chondrite (Javoy et al., 2010)
    - 11-14 TW radiogenic heat
- “Geochemical” models
  - CI chondrite (Rocholl & Jochum, 1993; McDonough & Sun 1995)
    - 17-19 TW radiogenic heat
- “Physical” or “Geodynamical” models
  - energetics of mantle convection (Turcotte & Schubert, 2002)
    - 27-35 TW radiogenic heat



illustrations of layered mantle HPE distributions from “Ferrara group”

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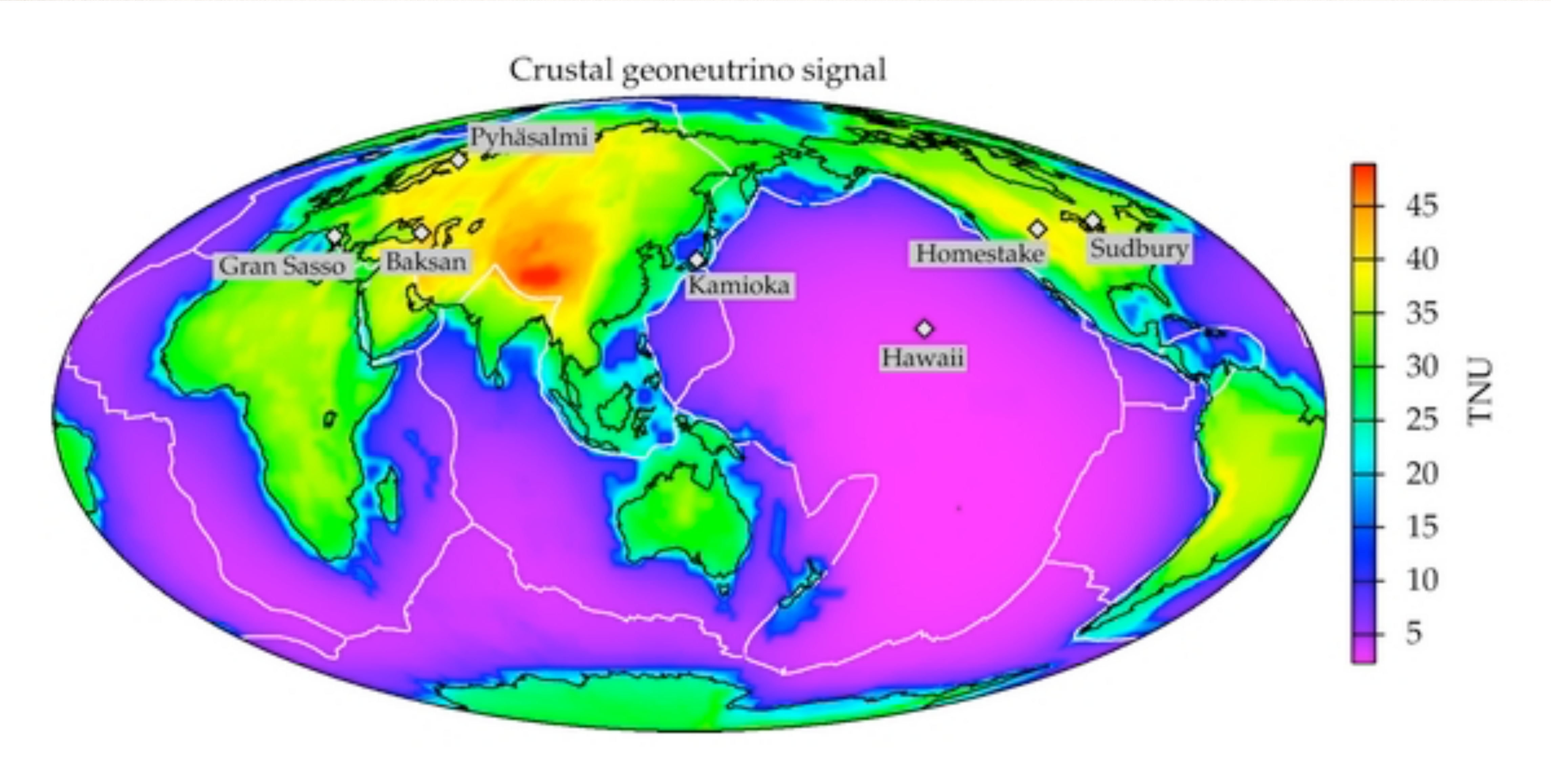
- distribution of reservoirs in the mantle?
  - homogeneous or layered?
  - lateral variability
- nature of the core-mantle boundary?

neutrinos *might* probe

example of a model calculation

Expected Rates of Geoneutrinos



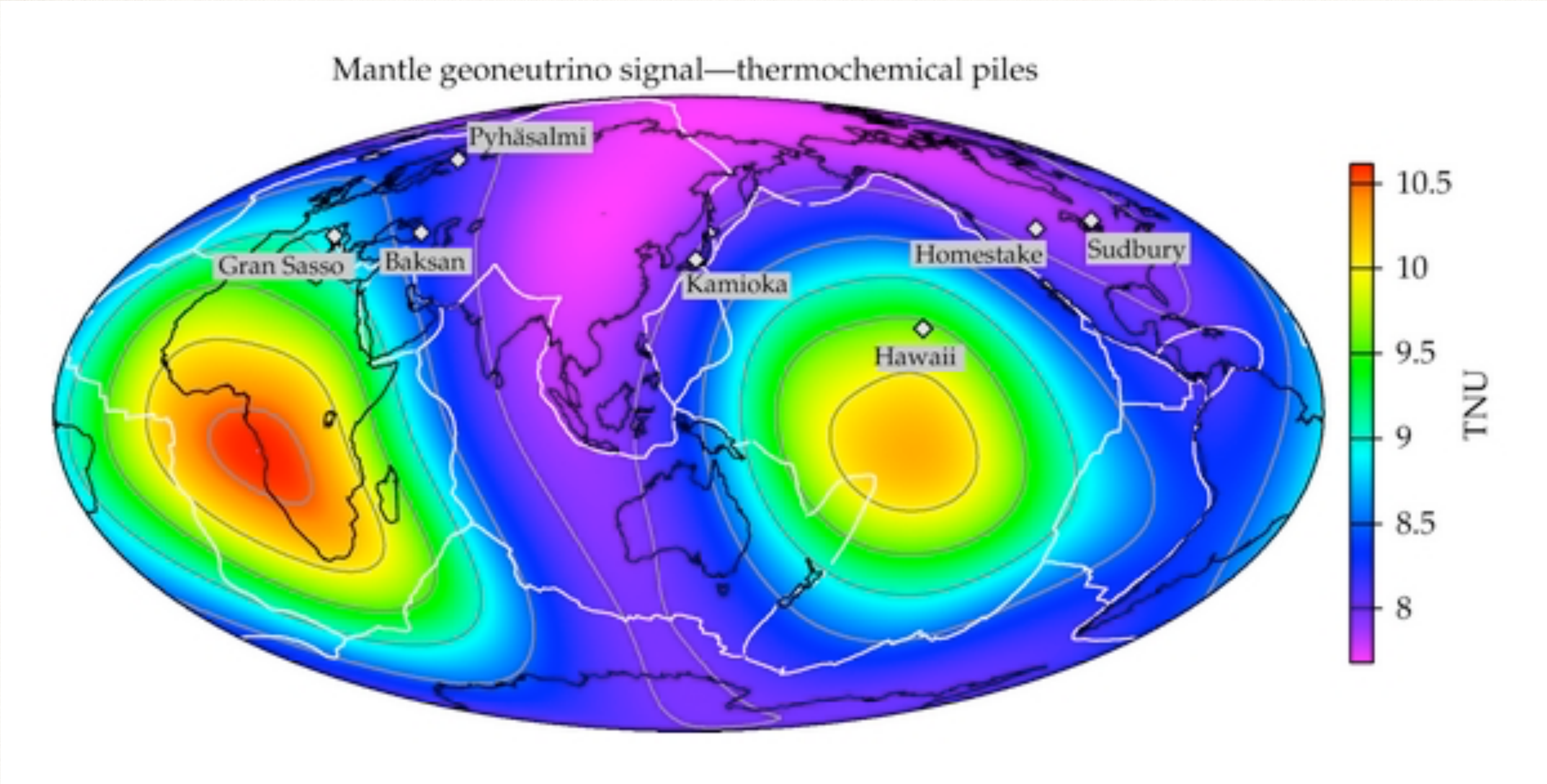
Šrámek, McDonough, Learned (2012)

1 Terrestrial Neutrino Unit (TNU) = 1 event per 10^{32} proton targets per year
(assuming 100% efficient detection)

roughly 1 per kilotonne CH_2 per year

example of a model calculation

Mantle Composition Heterogeneity



Šrámek, McDonough, Learned (2012)

"thermochemical piles" model responsible for lateral variation in the flux (motivated by Large Low Shear Velocity Provinces at the base of the mantle)

Important Questions in Geosciences

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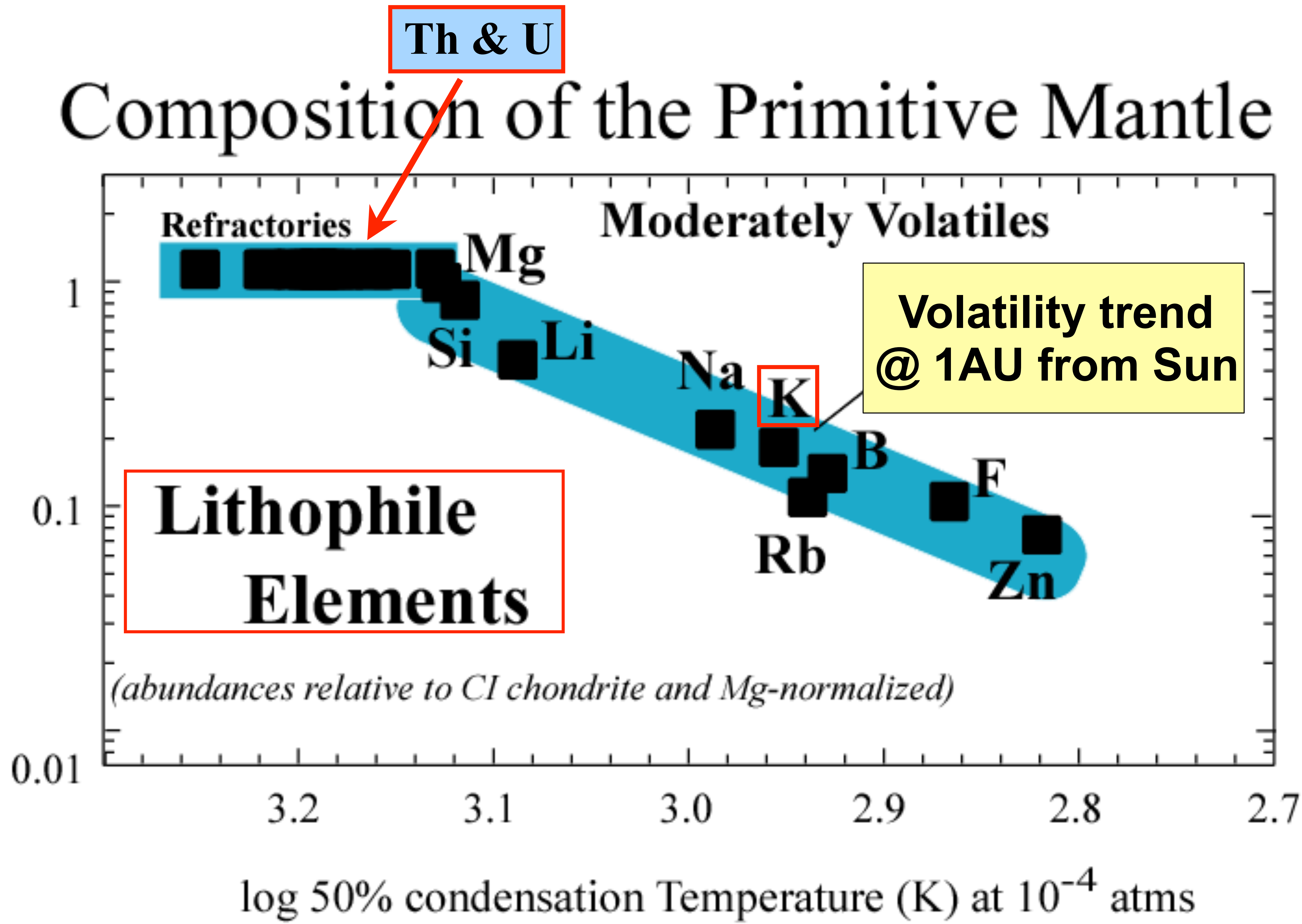
neutrinos *might* probe

- radiogenic elements in the core?
  - in particular potassium
- what is the planetary K/U ratio? if only we could detect ^{40}K geoneutrinos…

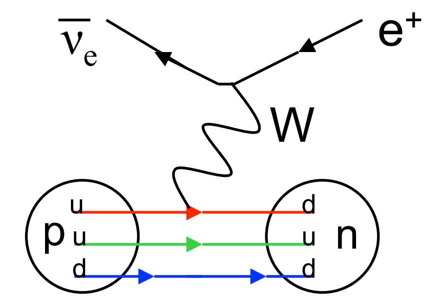
Composition of the Primitive Mantle



slide from Bill McDonough

Detecting Geoneutrinos

- inverse beta decay: $\bar{\nu}_e + p \rightarrow e^+ + n$



Geoneutrino Flux Prediction @ Gran Sasso
(two-layered mantle, "geochemical" model)

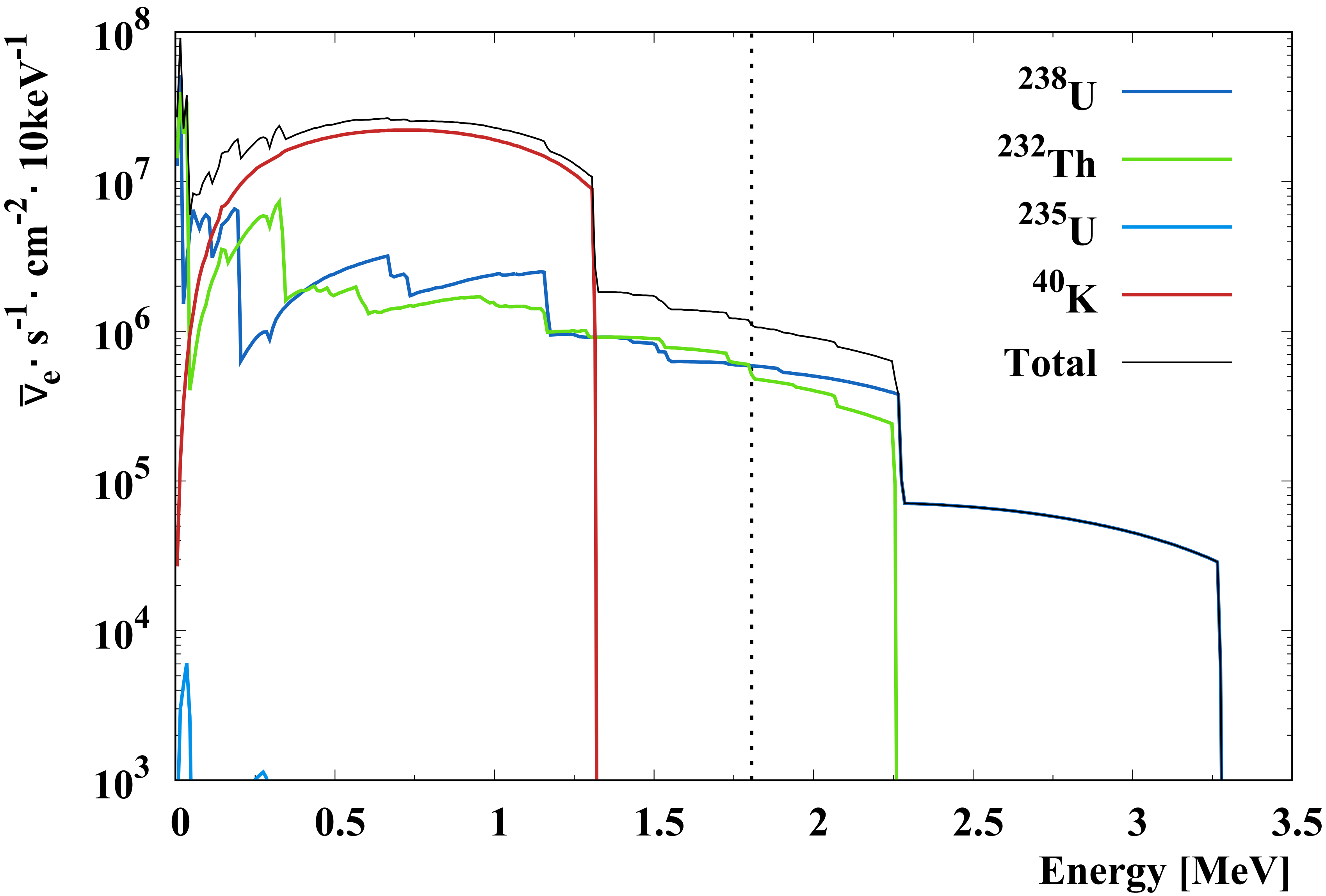
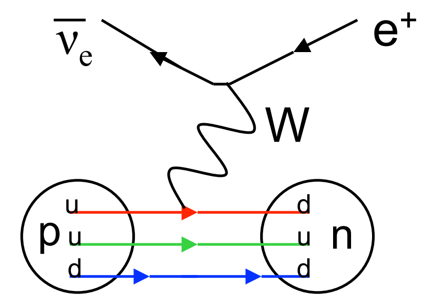


figure from Borexino 2019 paper

Detecting Geoneutrinos



- inverse beta decay: $\bar{\nu}_e + p \rightarrow e^+ + n$
  - "respectable" cross section on protons
  - energy threshold E > 1.8 MeV
  - liquid scintillator is ~CH_2 hence lots of protons
    - positron makes first scintillation
    - neutron captures on H
      - mean capture time ~0.2 ms
    - delayed 2.2 MeV gamma ray from neutron capture makes second scintillation
  - distinctive signature helps rejects background counts
    - e^+ and n correlated in time and in position in the liquid scintillator detector

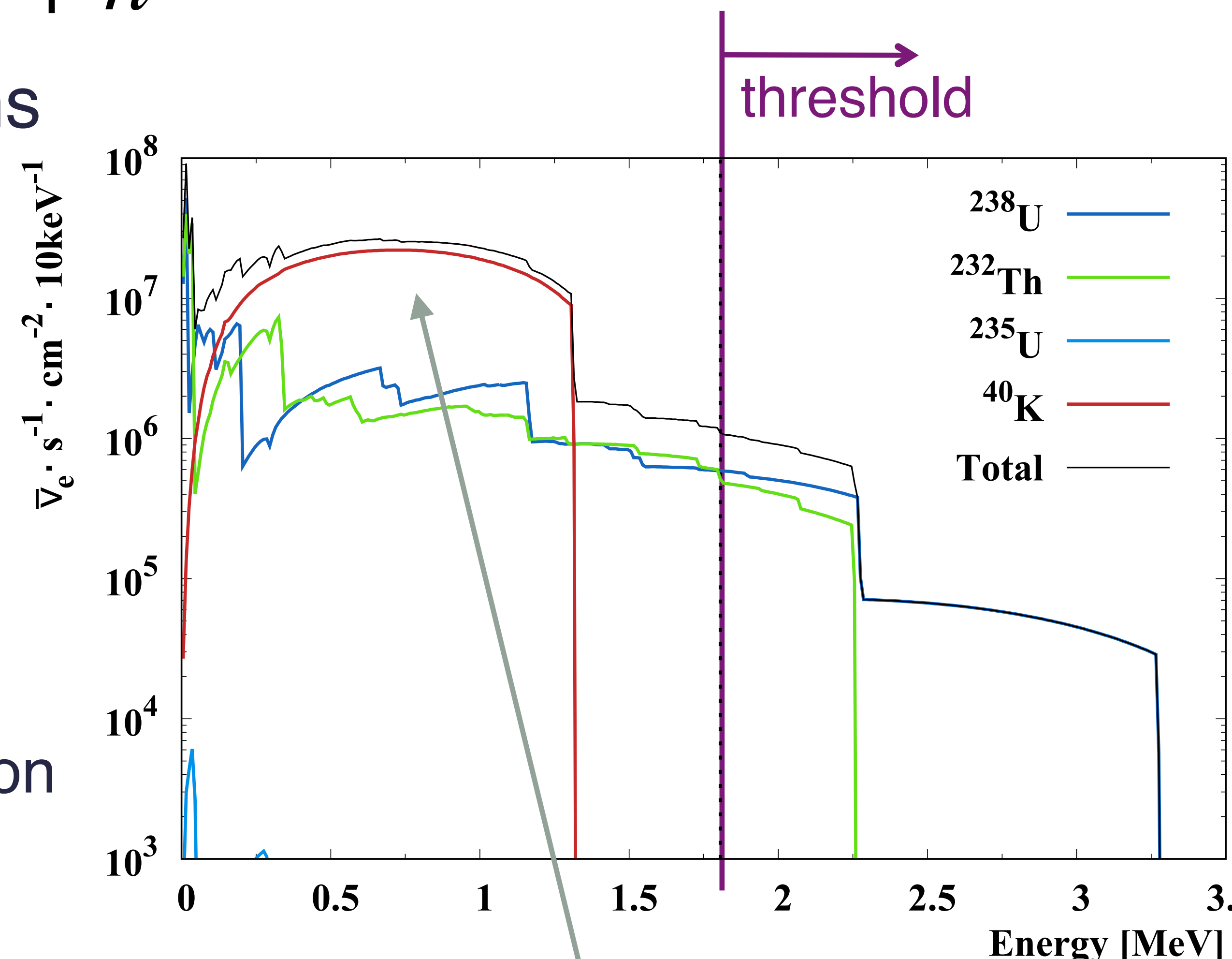
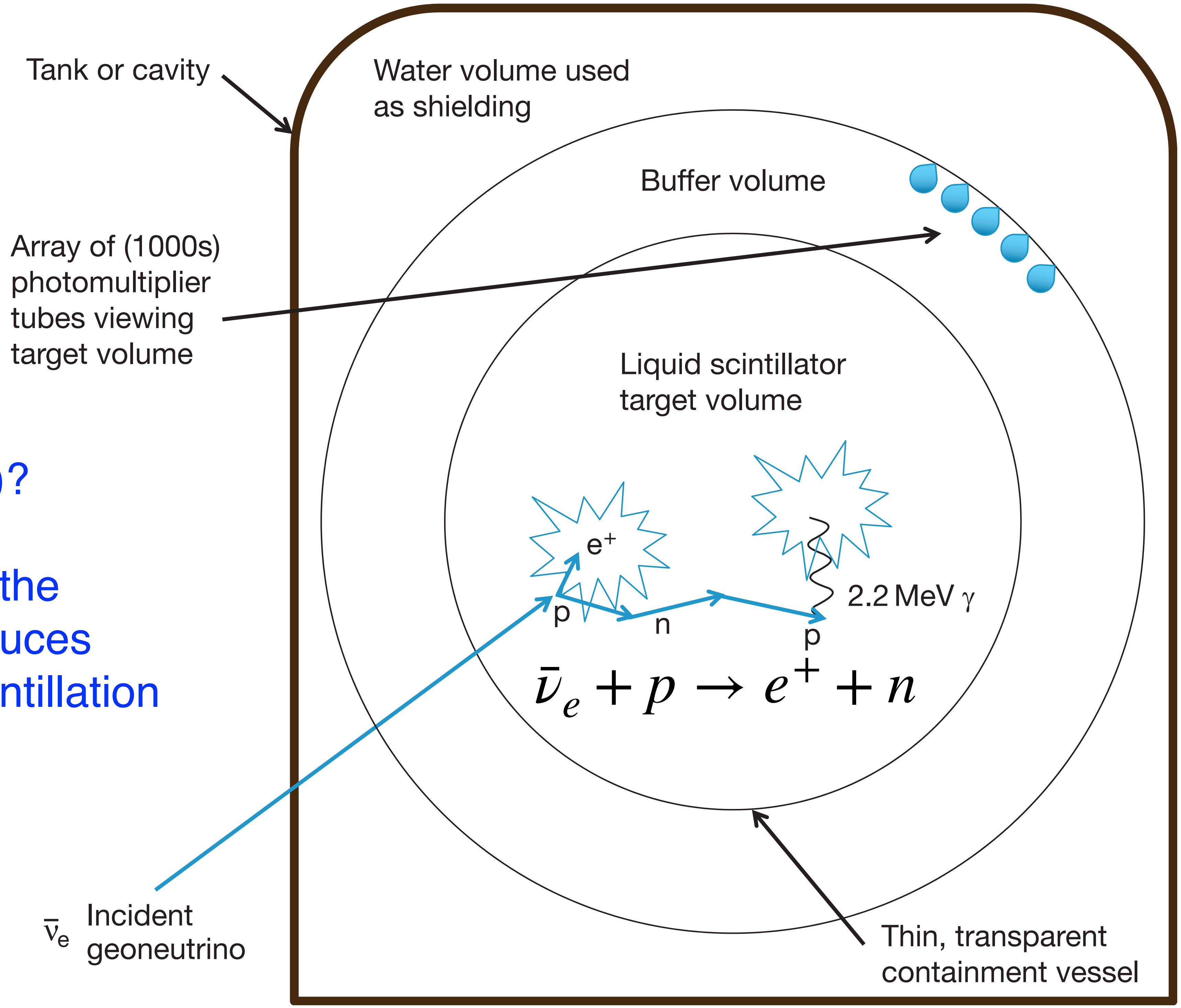


figure from Borexino 2019 paper

can't detect ^{40}K geoneutrinos with this reaction

Detecting Geoneutrinos with Liquid Scintillator



Q: can the detection medium be water (H_2O)?

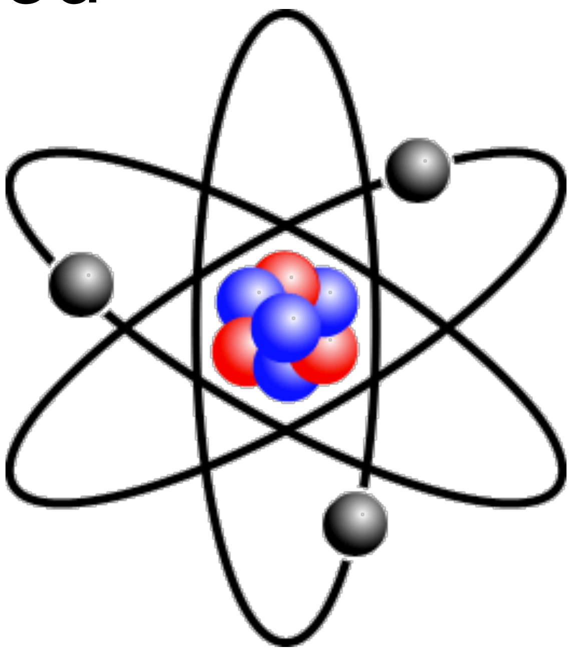
A: in principle, yes; but the Čerenkov process produces much less light than scintillation

Figure 1 The design or construction of a typical liquid scintillator antineutrino detector.

figure from MC, Treatise on Geochemistry, 2nd edition (2013)

Neutrino Detection

- to detect (anti)neutrinos, they must first interact to produce a charged particle which can then be observed
- possible targets in ordinary matter:
  - electrons
  - atomic nuclei
    - composed of nucleons (protons and neutrons)
      - composed of quarks



- (anti)neutrinos only undergo the weak interaction

CC: $\bar{\nu}_e + X \rightarrow e^+ + Y$ ← *Y has –1 charge compared to X*

NC: $\bar{\nu}_e + X \rightarrow \bar{\nu}_e + X'$

ES: $\bar{\nu}_e + e^- \rightarrow \bar{\nu}_e + e^-$

CC = charged-current weak
NC = neutral-current weak
ES = elastic scattering off electrons

All Possible Geoneutrino Detection Reactions

- NC neutrino-nucleus scattering (coherent)
  - detect the recoiling nucleus, *very* low energy, *many* backgrounds
- NC "excitation" of the nucleus
  - incoming neutrino excites the nucleus, then one can detect the gamma rays from nuclear de-excitation
- CC neutrino "absorption" $\bar{\nu}_e + X \rightarrow e^+ + Y$
  - detect the outgoing lepton **and/or** the modified nucleus
- ES neutrino-electron scattering
  - there is **directional information** – need to exploit – because *many* backgrounds

^{40}K Geoneutrinos via neutrino-electron scattering

Observing the Potassium Geoneutrinos with Liquid Scintillator Cherenkov Neutrino Detectors

Zhe Wang[a,b,*], Shaomin Chen[a,b]

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in arXiv:1709.03743 v3

ARTICLE

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Exploring the hidden interior of the Earth with directional neutrino measurements

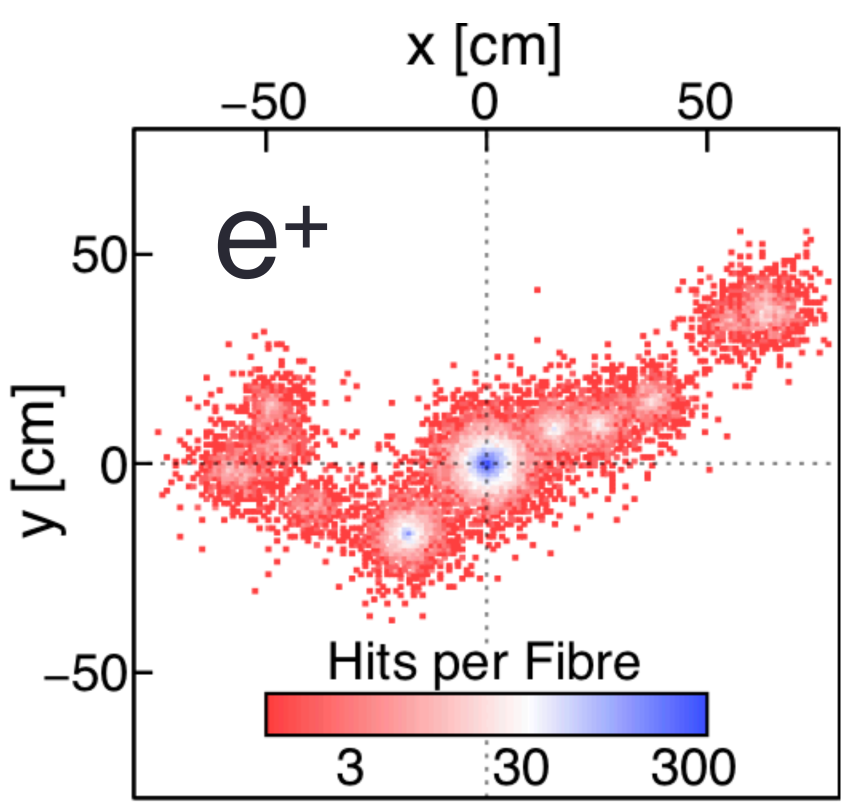
Michael Leyton[1,2,3], Stephen Dye[4] & Jocelyn Monroe[2,3,5]

in Nature Communications 8:15989

^{40}K Geoneutrinos via charged-current neutrino absorption

$$\bar{\nu}_e + X \to e^+ + Y$$

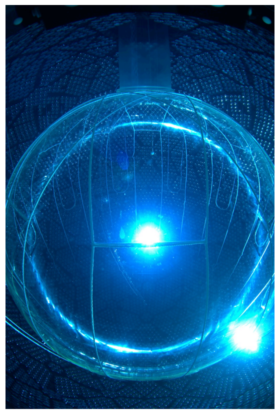
Could a single positron signal be used for ^{40}K geoneutrino detection?
What possible nuclear targets? Which one is best?
(expanding on MC's ^{106}Cd idea)



Andrea Serafini to present work of the Ferrara group + MC + A. Cabrera + S. Wagner…*paper to be submitted soon!*

Probing Earth's potassium content with a new technique for geoneutrino detection

Geoneutrino Projects around the Globe



SNO+

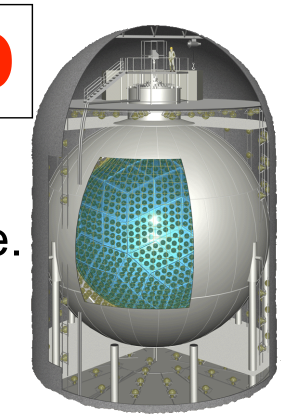
1 kt, LS+, 5.4 km.w.e.
Liquid scintillator filling is in progress!

Baksan

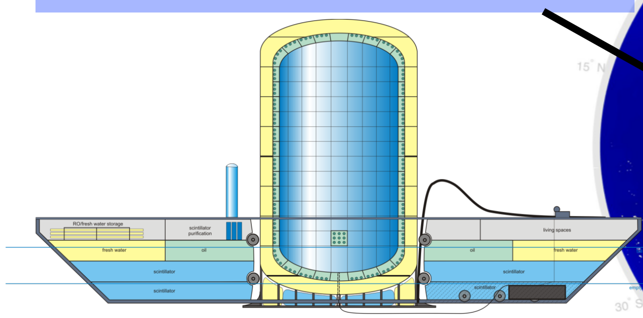
~10 kt, LS
4.8 km.w.e.
R&D

KamLAND

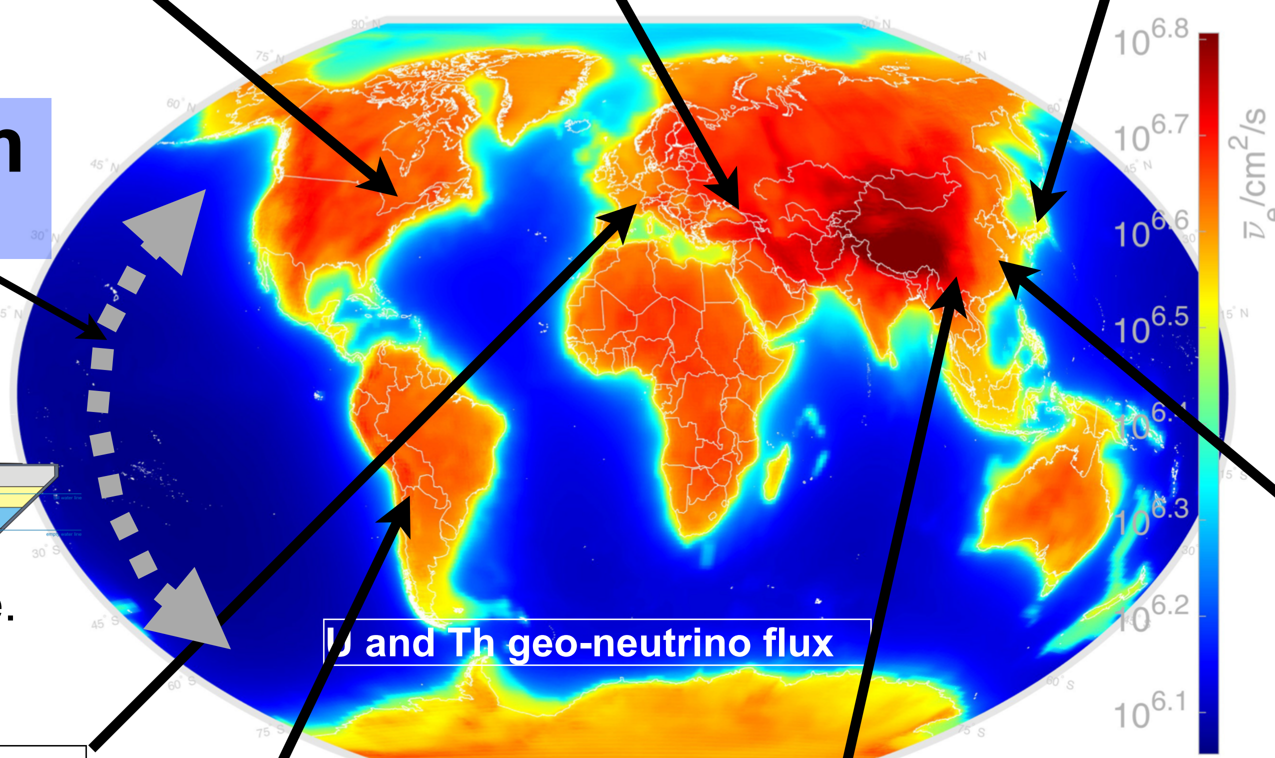
1 kt, LS
2.7 km.w.e.
running



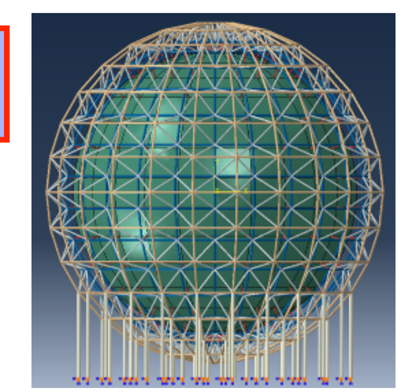
Ocean Bottom Detector

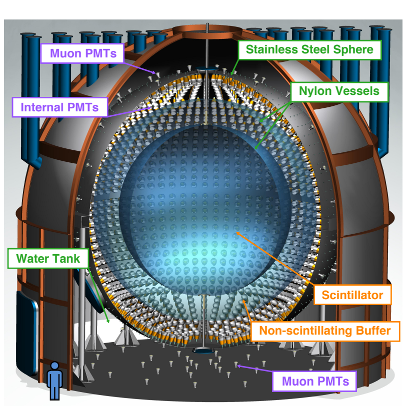


10-50 kt, LS, ~5 km.w.e.
movable, R&D



JUNO





Borexino

0.3 kt, LS
3.8 km.w.e.
running

ANDES

~3 kt, LS
4.5 km.w.e.
R&D

Jinping

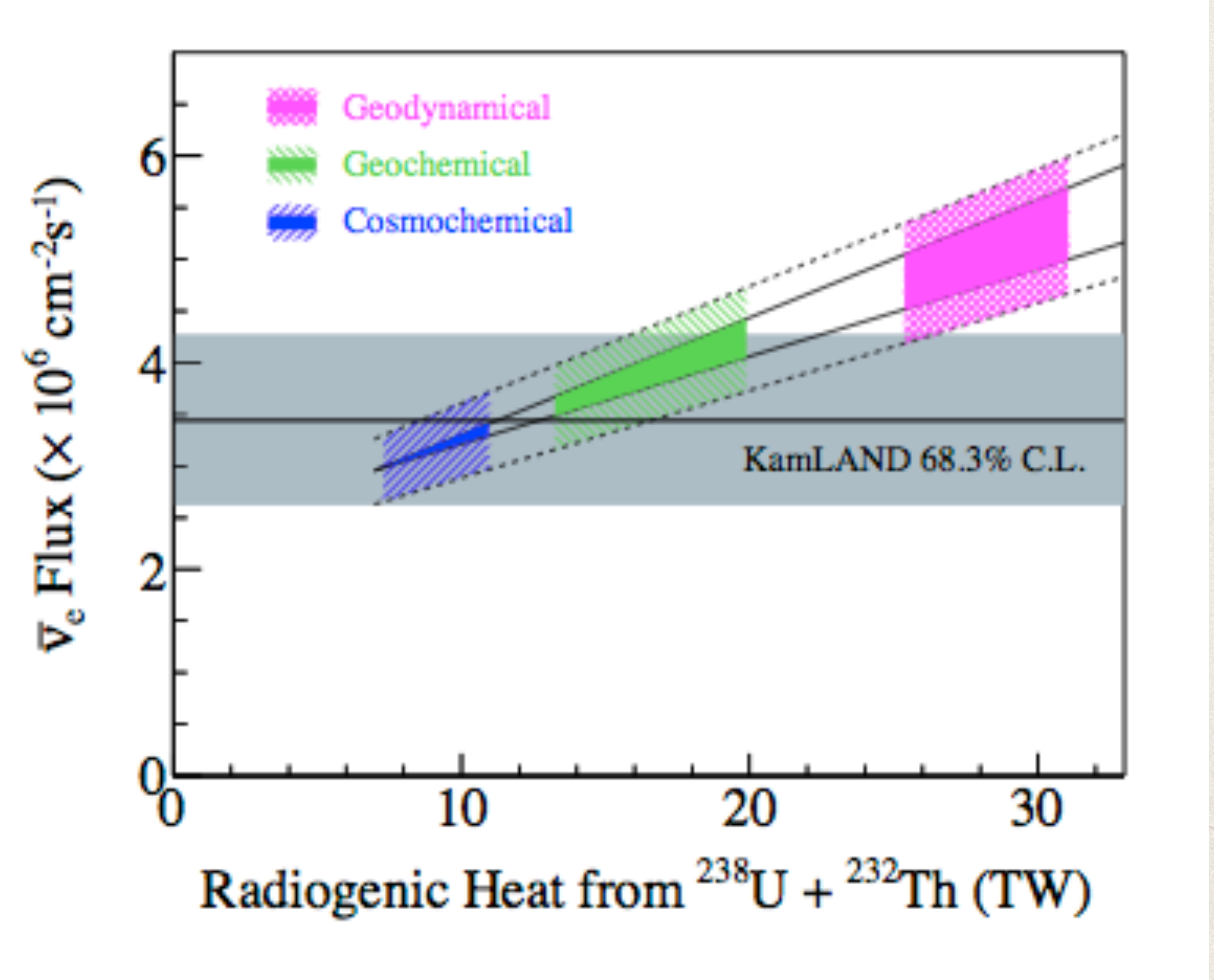
1 kt, LS
7.5 km.w.e.
Scheduled

20 kt, LS
1.5 km.w.e.
undue construction
(2021~)

slide from Hiroko Watanabe

KamLAND 2013 Geoneutrino Published Result

- fixed Th/U ratio 3.9
- 116 ± 27 geo ν events
- oscillated flux
  $(3.4 \pm 0.8) \times 10^{6}\ cm^{-2}\ s^{-1}$



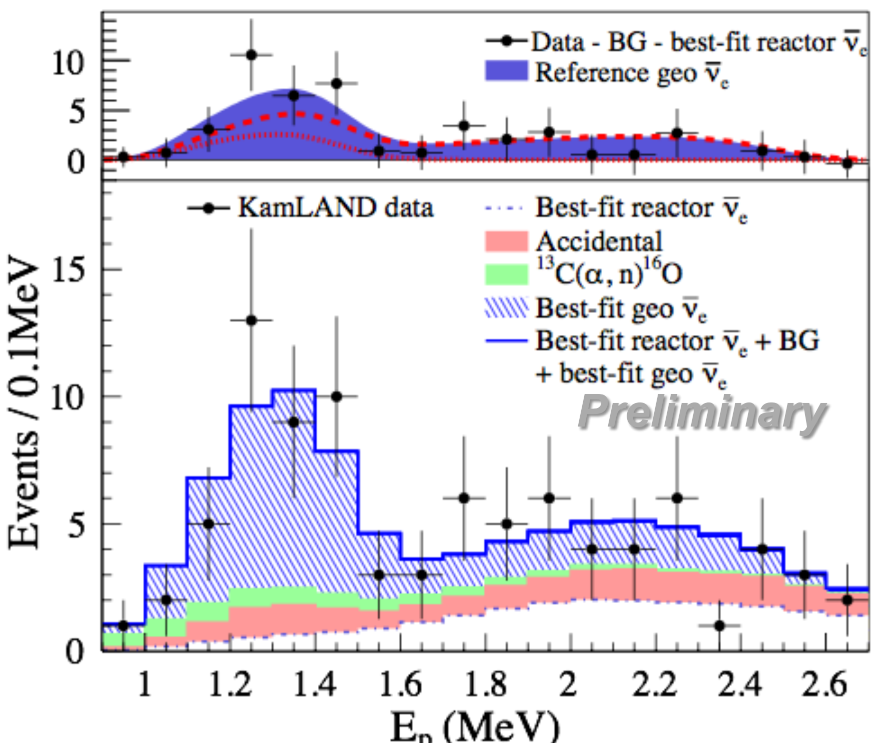
solid line – model band varies between homogeneous mantle and sunken-layer hypothesis

dashed line – incorporates crustal contribution uncertainty

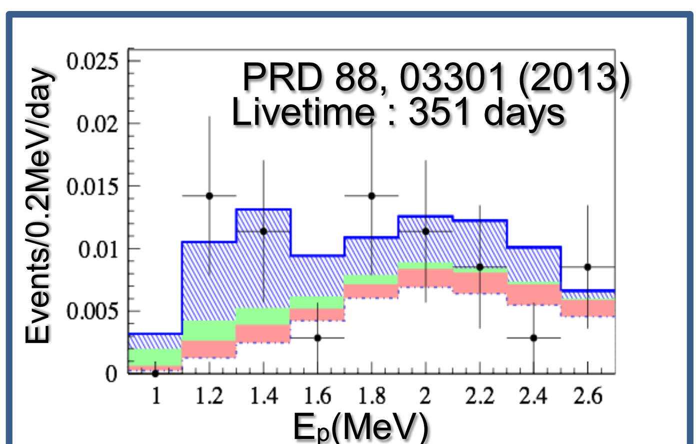
KamLAND 2016 Prelim Geo ν Result

Livetime : 1259.8 days 2016 Preliminary Result

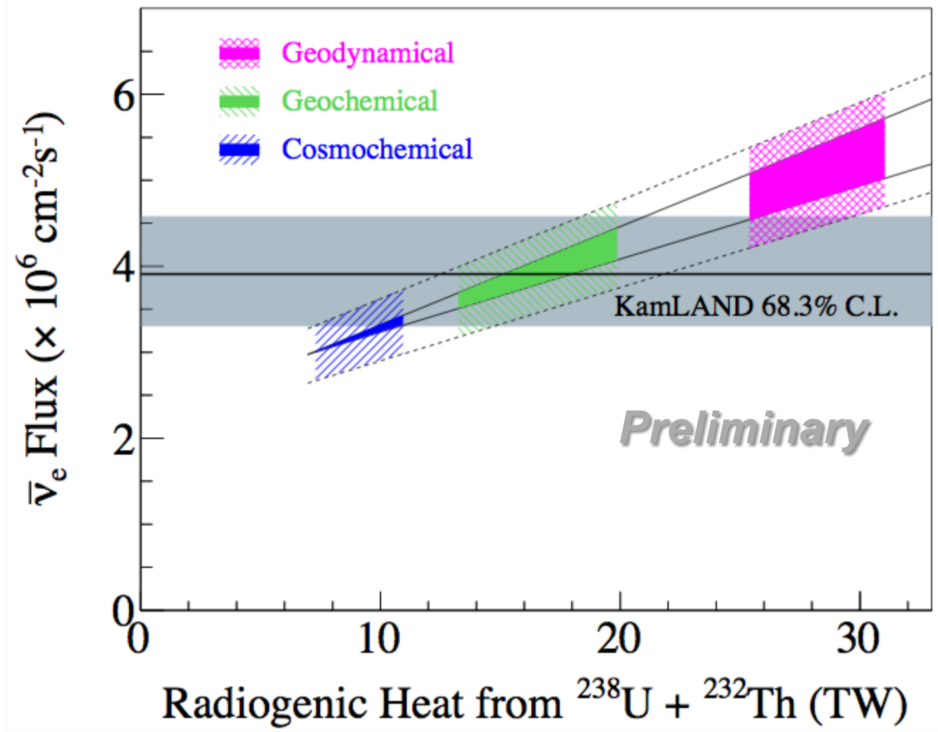
model prediction : Enomoto et al. EPSL 258, 147 (2007)



best-fit : Period 3 analysis



We measured clear distribution of geo-neutrino events!



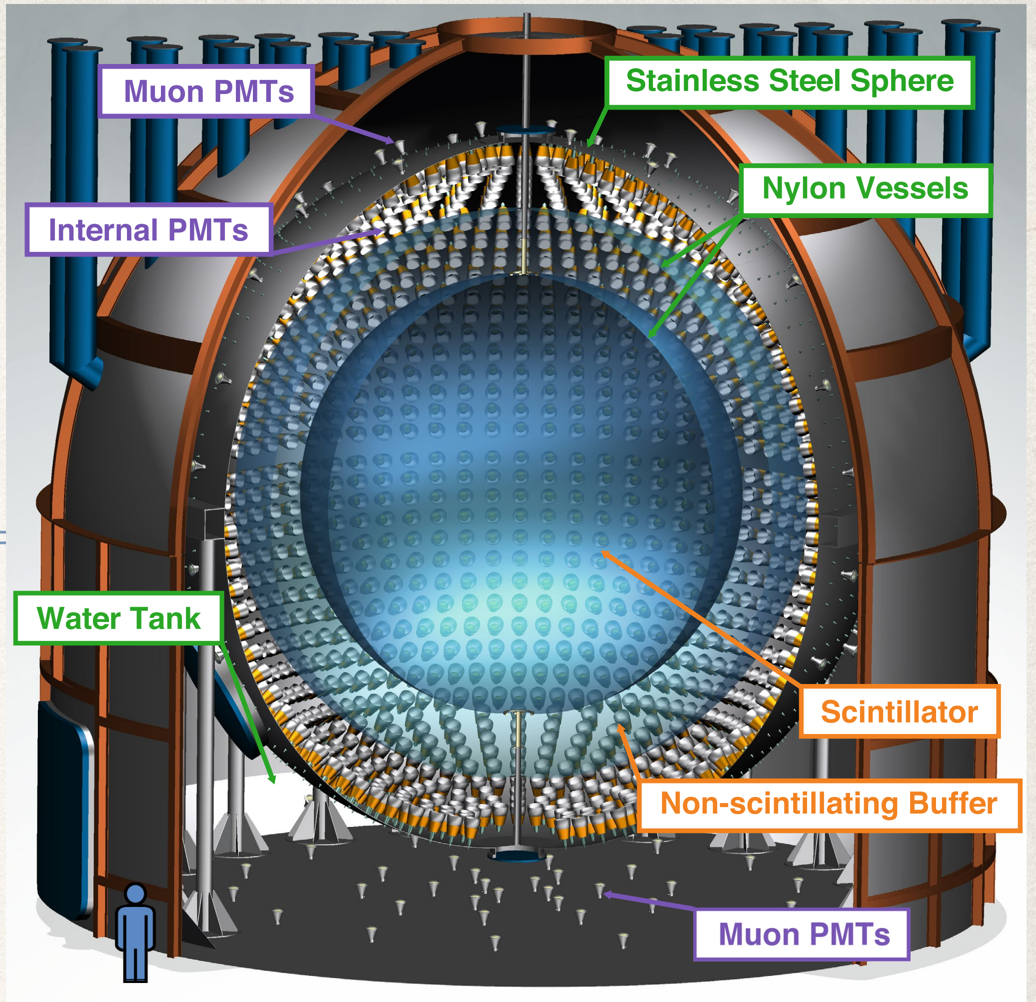
Rate+Shape+time analysis (ratio fixed)

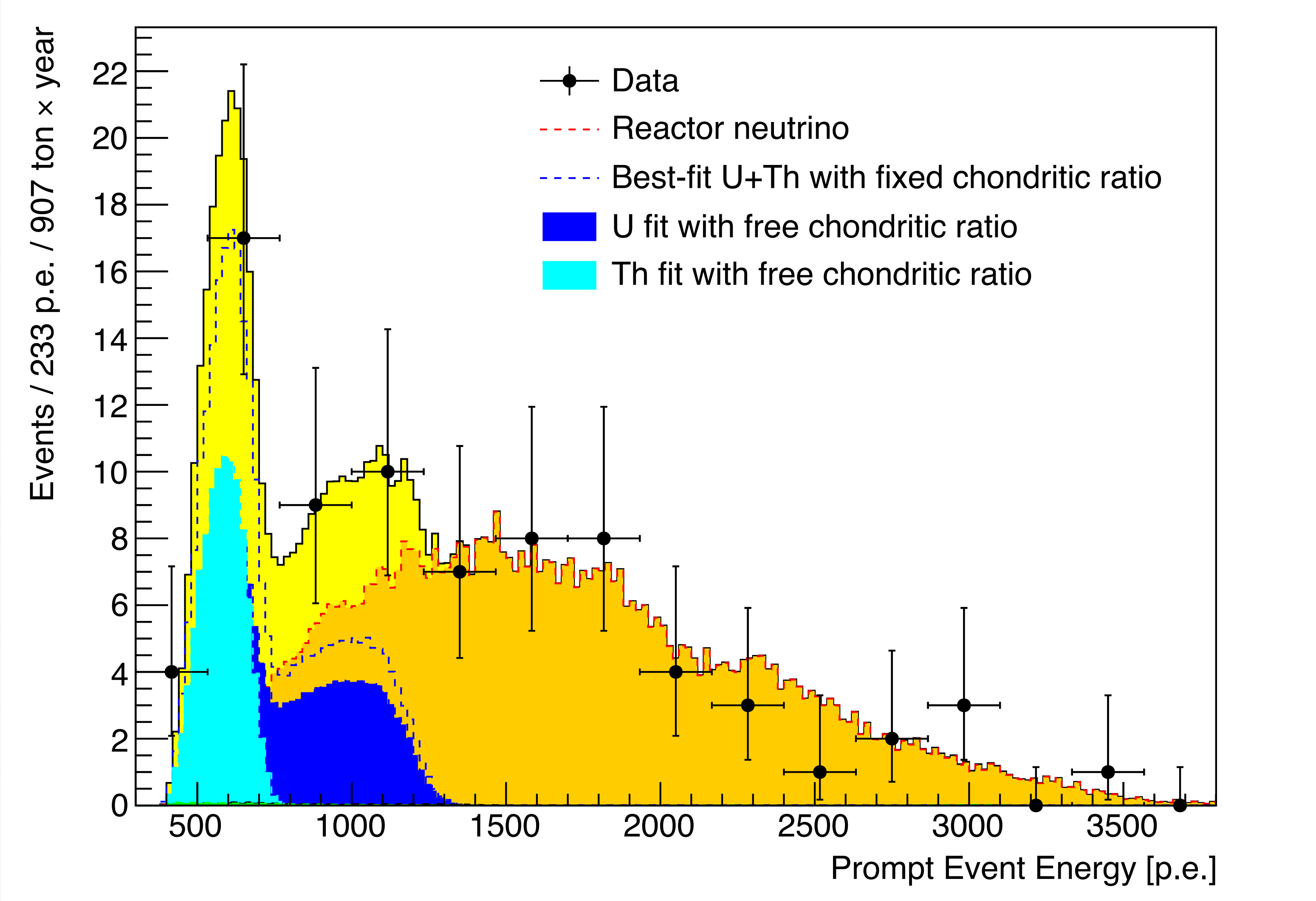
	[event]	[TNU]	Flux [$\times 10^6$ cm^{-2}s^{-1}]		0 signal rejection
			best-fit	model	
U+Th	164 +28/-25 (17%)	34.9 +6.0/-5.4	3.9 +0.7/-0.6	4.1	7.92σ

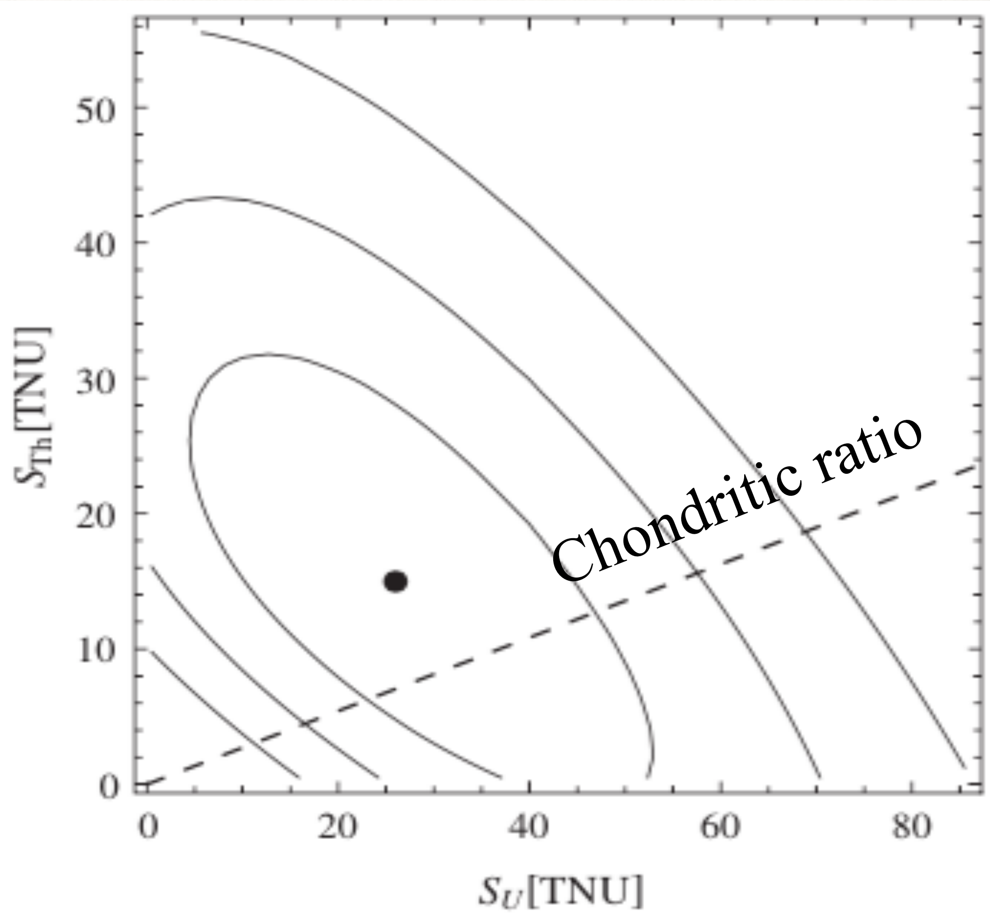
slide from Hiroko Watanabe

Borexino 2015

- 2056 days of data
- 23.7 ± 6.5 geo ν events

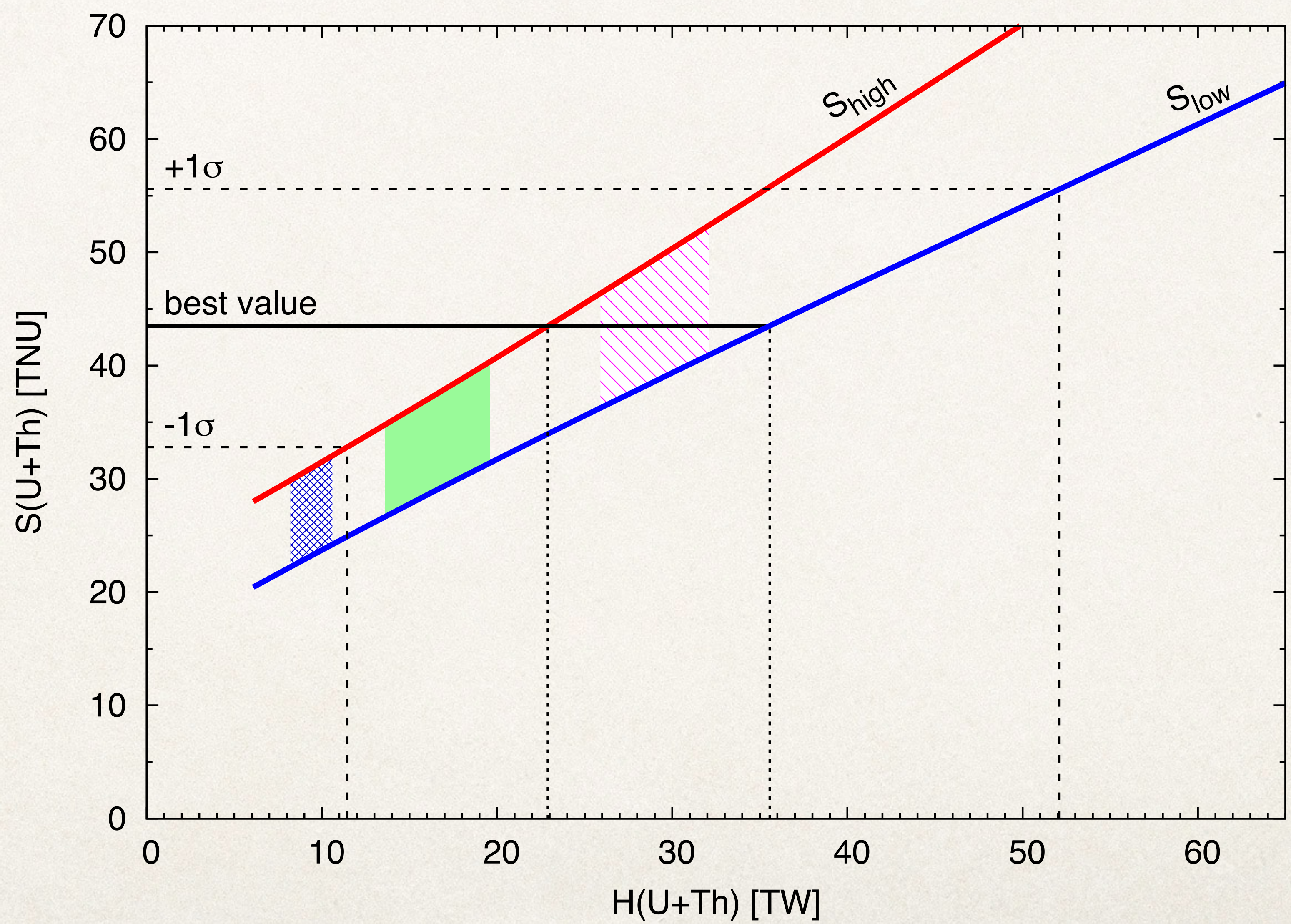






Borexino Geoneutrino 2015 Result Radiogenic Heat

- already favoured a higher value than KamLAND (note: all error bars are large)



Let’s Start the Meeting!