Geoneutrinos: Motivations and Prospects

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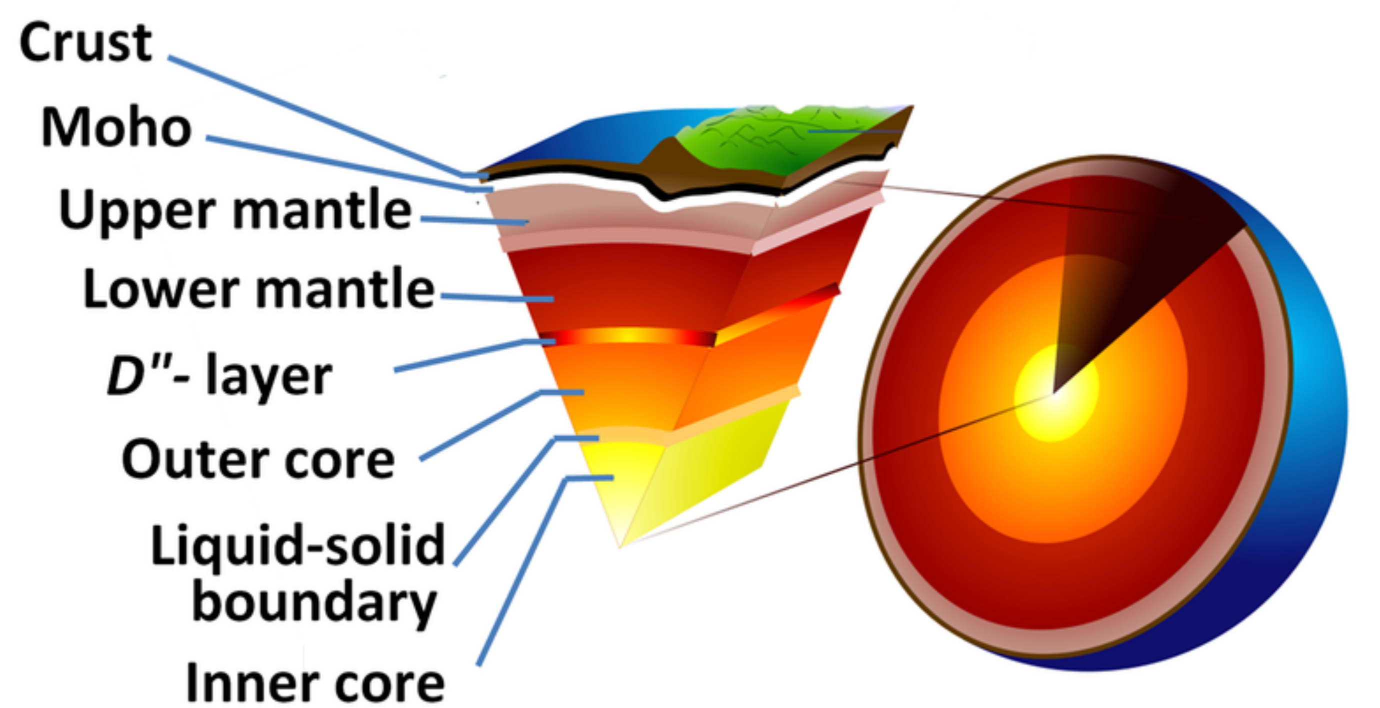
What are Geoneutrinos?

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)



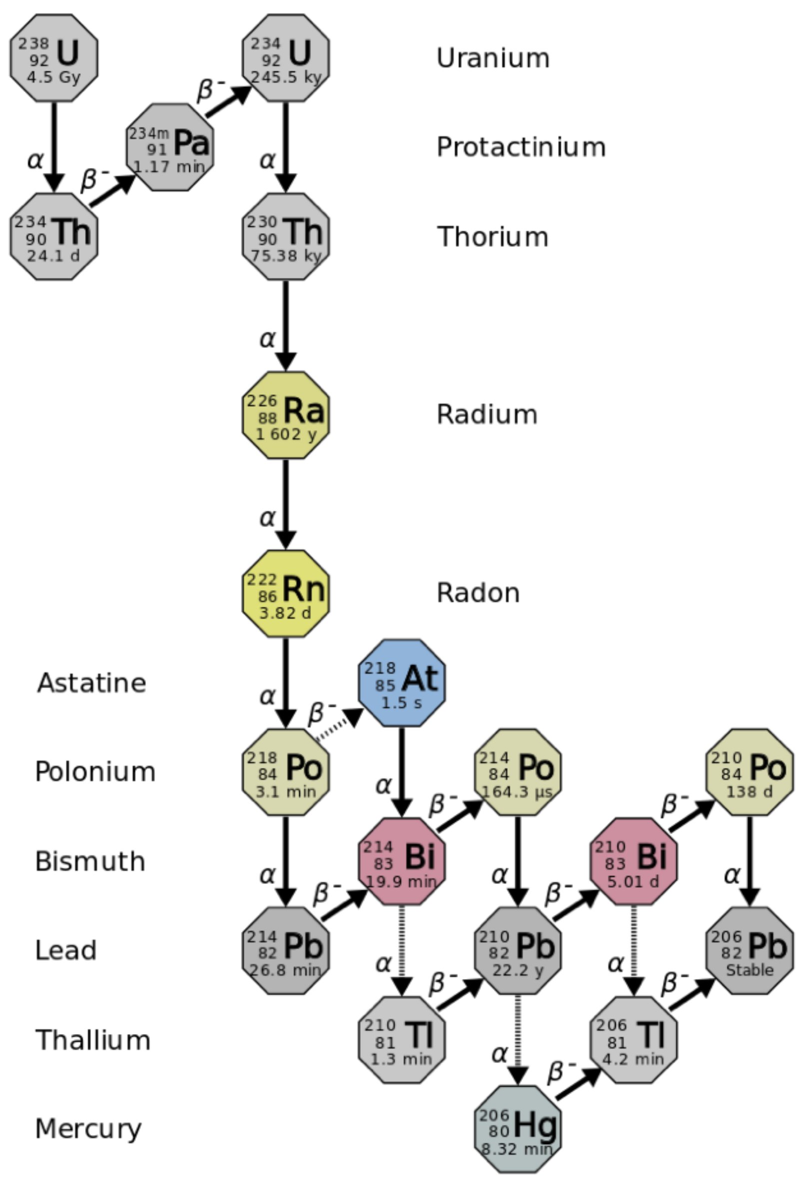
Decaying heat producing elements emit antineutrinos in direct proportion to their heating power

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

0th-order goal: assay the entire Earth by looking at its "neutrino glow"

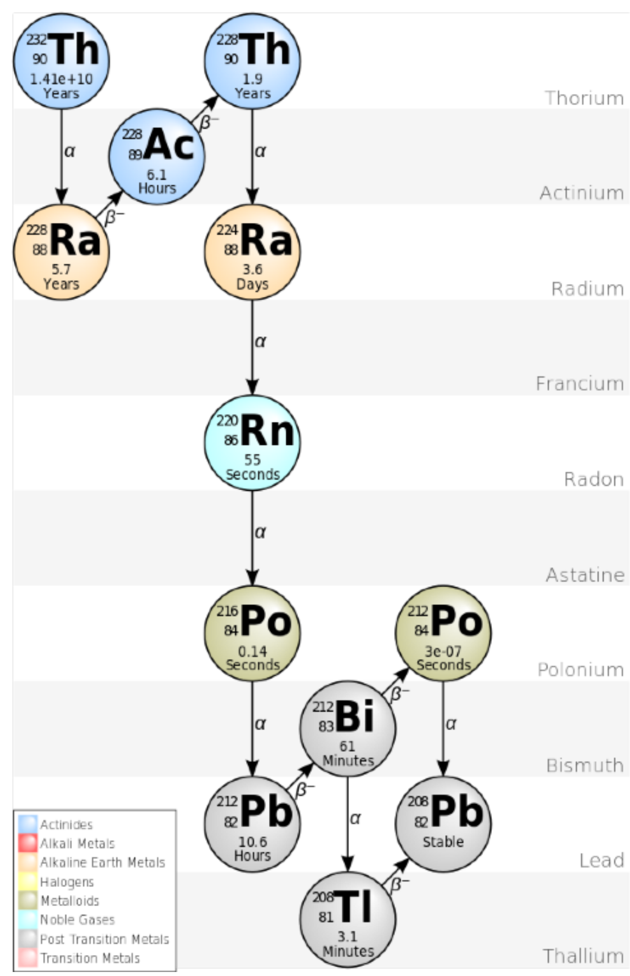
How much of Earth's heat is primordial (residual)?
How much heat is radiogenic?

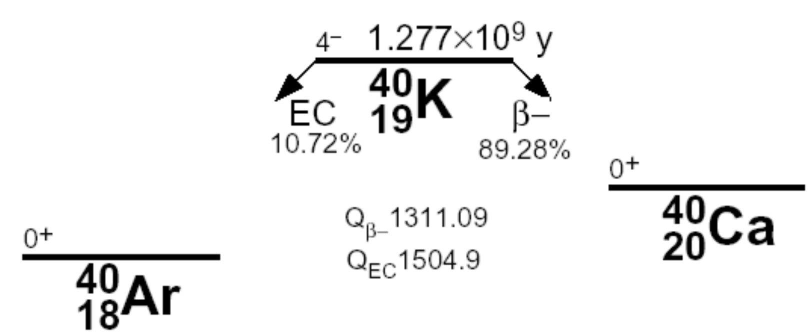
Uranium, Thorium and Potassium Decay



Decay	$T_{1/2}$ [10^9 yr]	$E_{\max}$ [MeV]	Q [MeV]	$\varepsilon_{\bar{\nu}}$ [$\mathrm{kg}^{-1}\mathrm{s}^{-1}$]	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 et al.





0.0117% isotopic abundance

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)

Important Questions in Geosciences

related to geoneutrinos

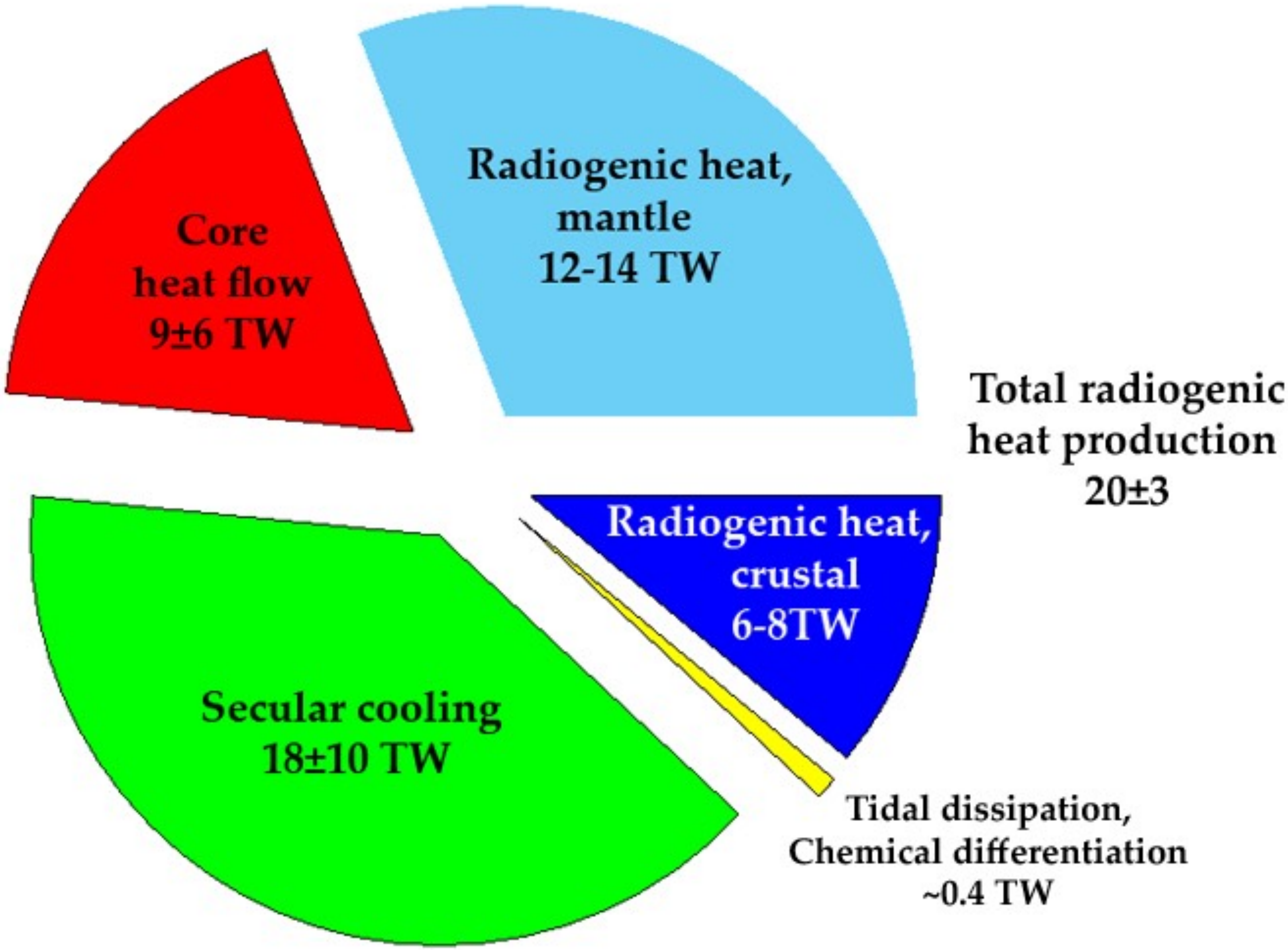
- what is the radiogenic contribution (U, Th, ^{40}K) to heat flow and energetics in the deep Earth? →otherwise inaccessible, estimates between 9-36 TW
  - how much is mantle convection driven by radiogenic heat? →1-28 TW
  - geoneutrinos can say something about this (U and Th)
- are the fundamental ideas about Earth's chemical composition and origin correct? →bulk Earth chemical composition based on chondrites correct?
- are the basic models of the composition of the crust correct?
  - geoneutrinos can test which models are consistent; →Th/U ratio (and K) important

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

} **neutrinos *might* probe**

- what is the planetary K/U ratio? if only we could detect ^{40}K geoneutrinos

Earth's surface heat flow 47 ± 3 TW



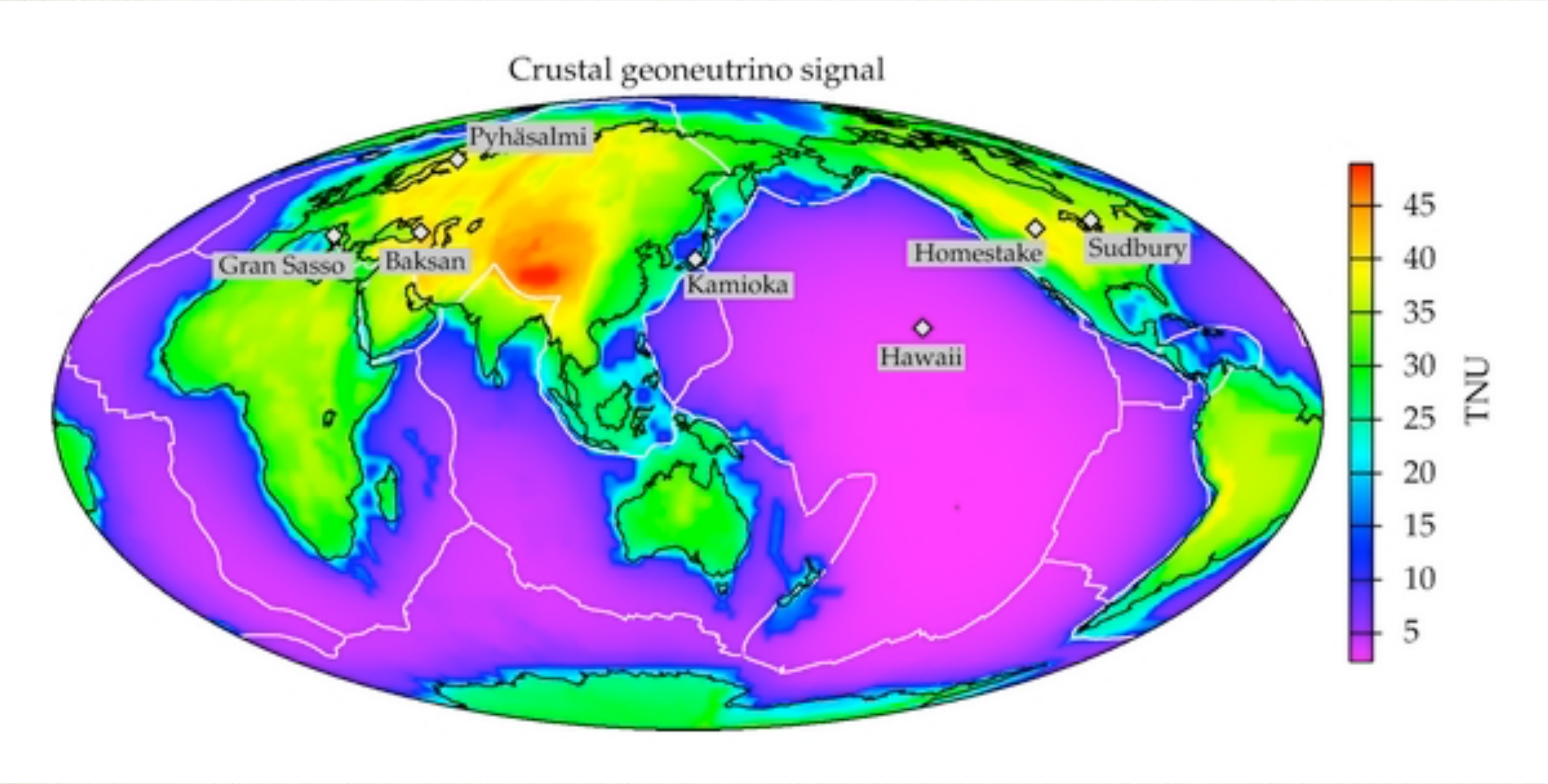
breakdown of what we think gives rise to the measured heat flow, **from Bulk Silicate Earth models**

figure from Bill McDonough

example of a model calculation

Expected Rates of Geoneutrinos

Primary driver of differences is continental crust thickness



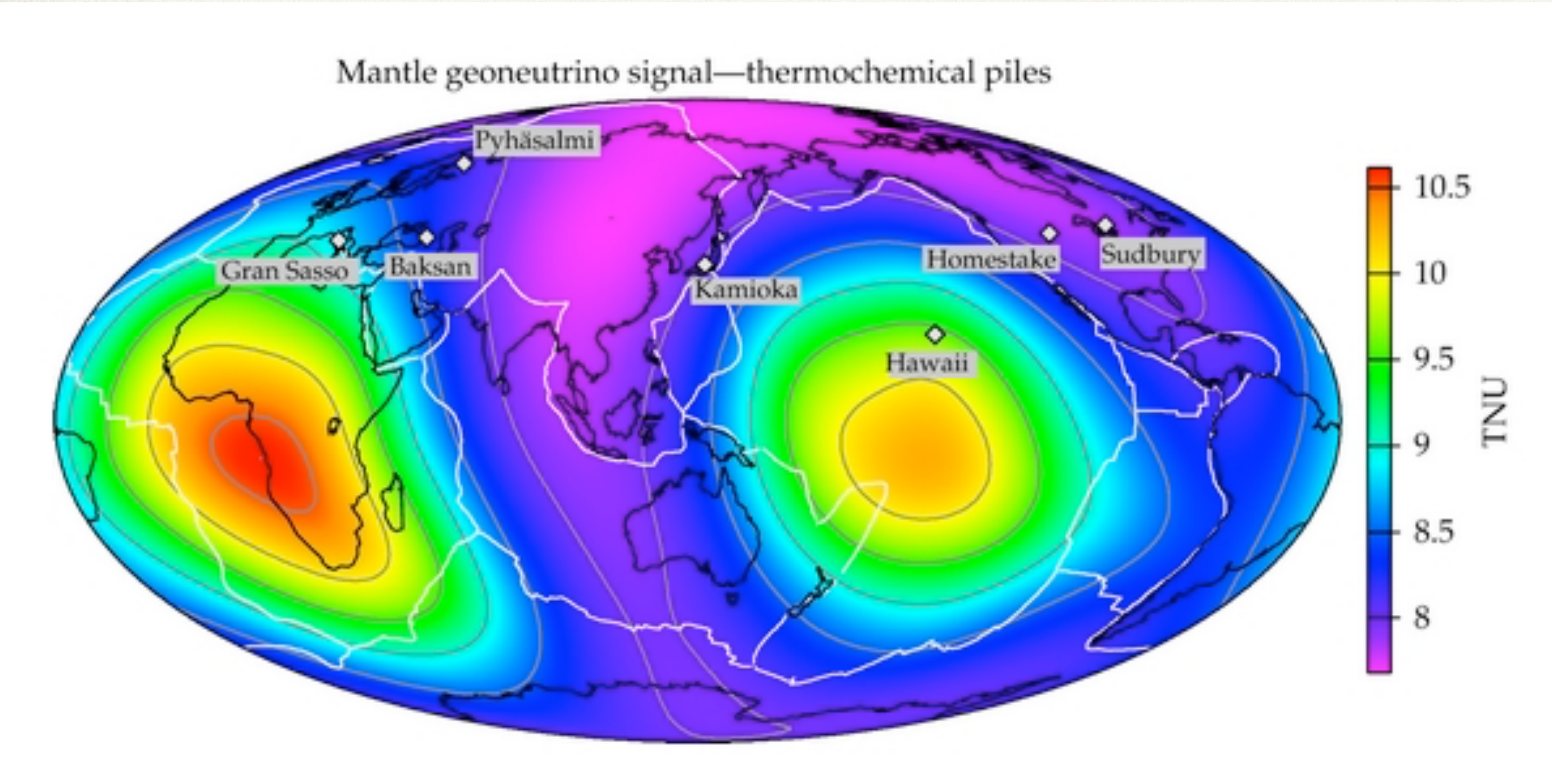
Šrámek, McDonough, Learned (2012)

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

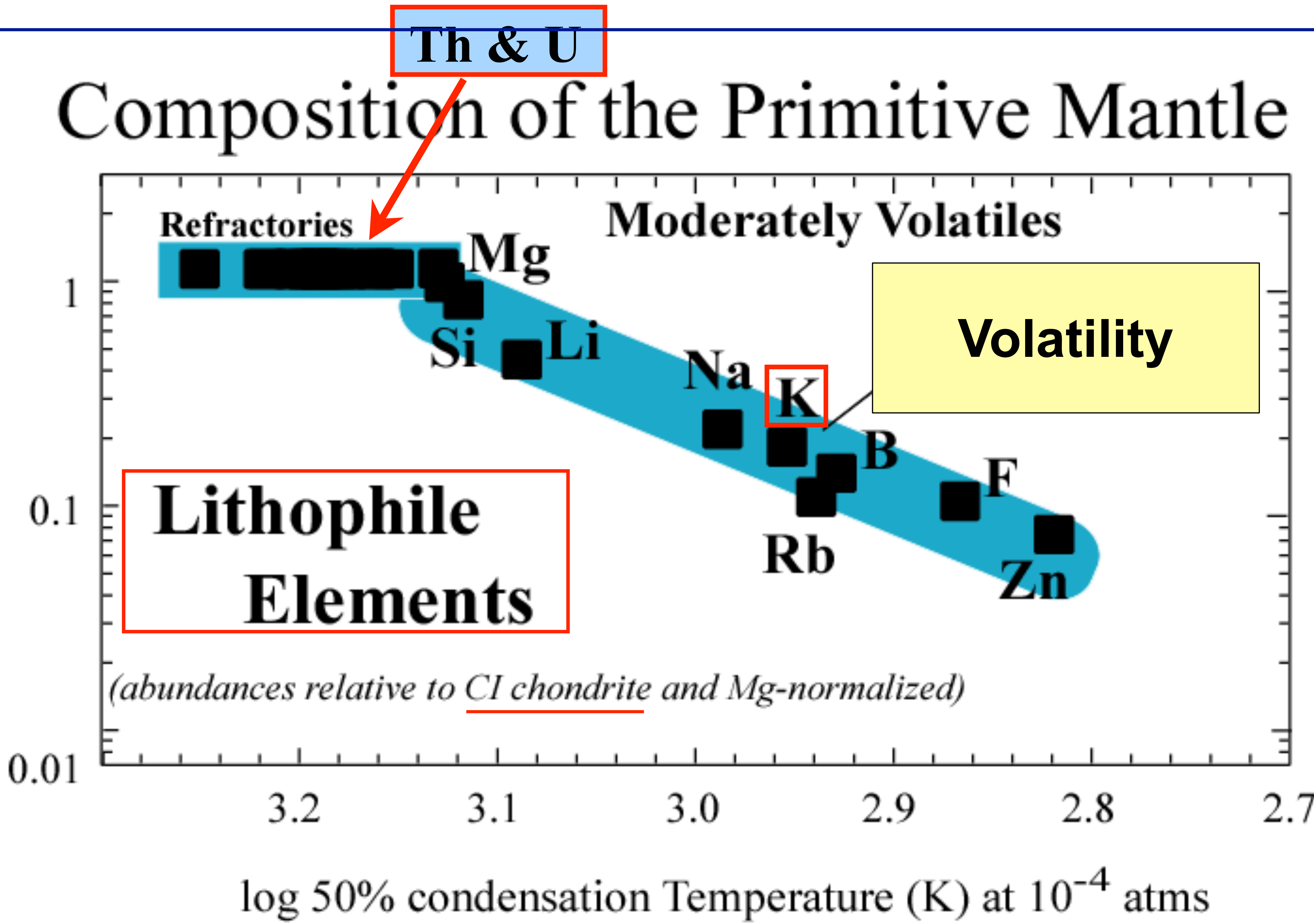
Mantle Composition Heterogeneity



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)

Bulk Earth Chemical Composition



slide from Bill McDonough

Motivation boils down to this…

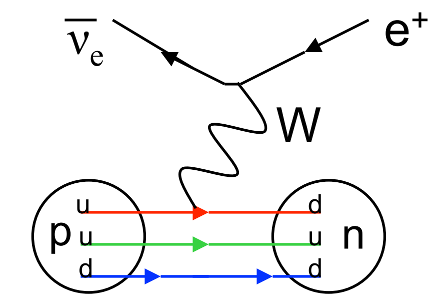
- geologists want to know more about the composition and energetics of the mantle (and core)
  - quantify energetics for *geophysical* models of mantle convection, Earth's formation thermal history, geodynamo
  - seismology reveals density; still need *geochemical* composition info

Objective: geoneutrino measurements aim to tell us about mantle U and Th content (can be related to other elements) and the Th/U ratio

- what about the crust?
  - even if rocks from the upper continental crust sample its composition, basic ideas about how the continents formed (enriched in certain elements, like U and Th) can be tested by geoneutrino *continental* measurements
  - just like the mantle, the full depth profile of the continental crust is not directly accessible

Detecting Geoneutrinos in Liquid Scintillator

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



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

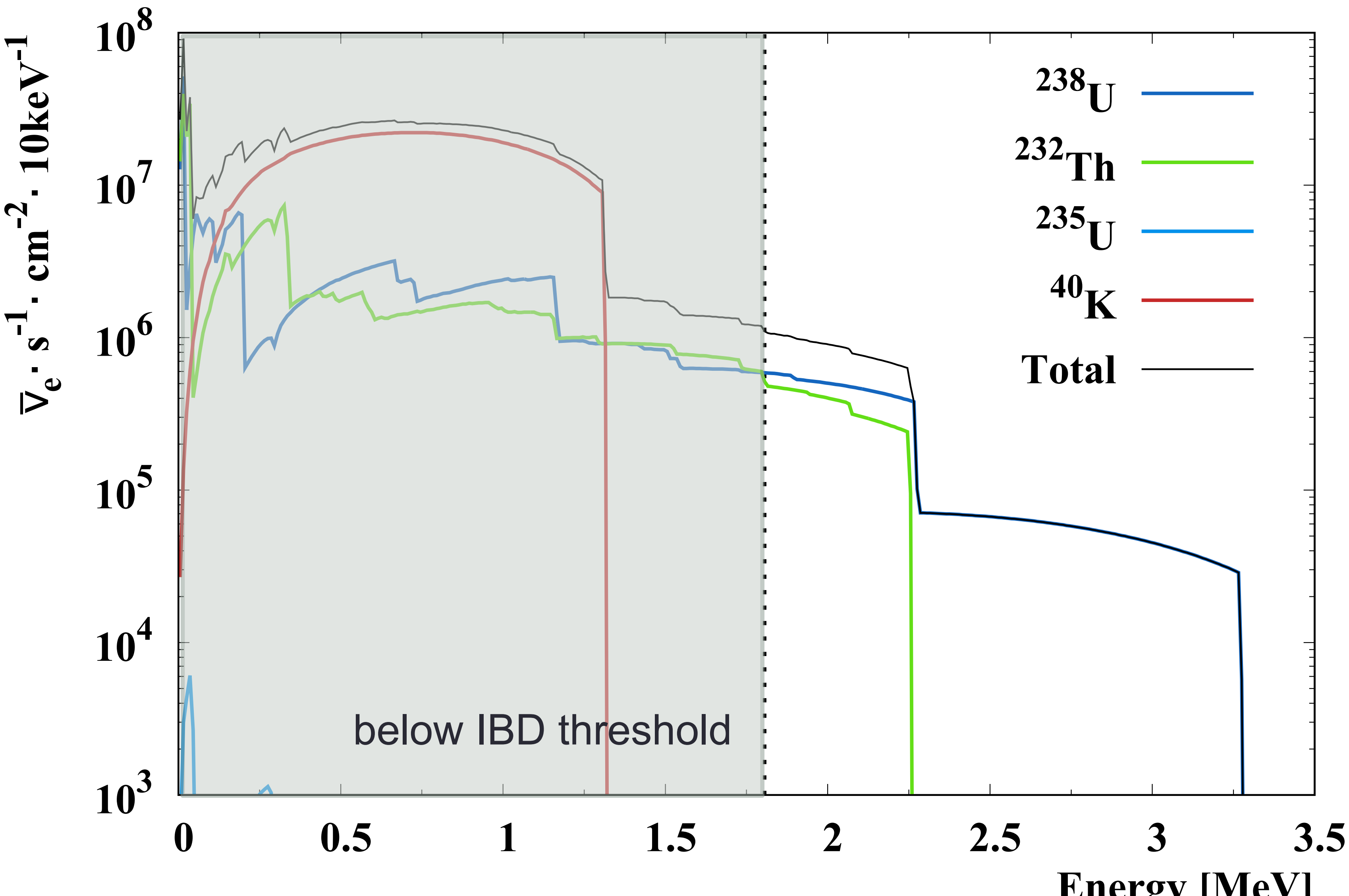


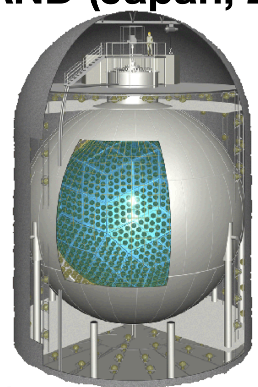
figure from Borexino 2019 paper

Present Status: KamLAND and Borexino

from H. Watanabe
talk @ Neutrino 2020

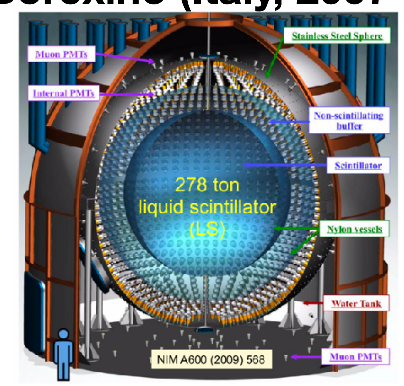
Two liquid scintillator (LS) experiments have measured geoneutrinos.

KamLAND (Japan, 2002~)



* LS : 1000 t
* Depth : 2700 m.w.e.
* expected event ratio
  reactor/geo ~**6.7** (up to 2010)
  ~**0.4** (2011~)
  w/o Japanese reactors

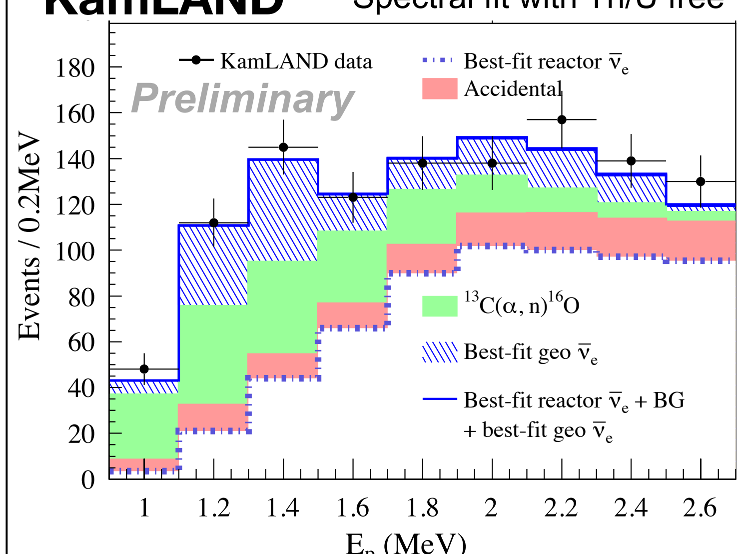
Borexino (Italy, 2007~)



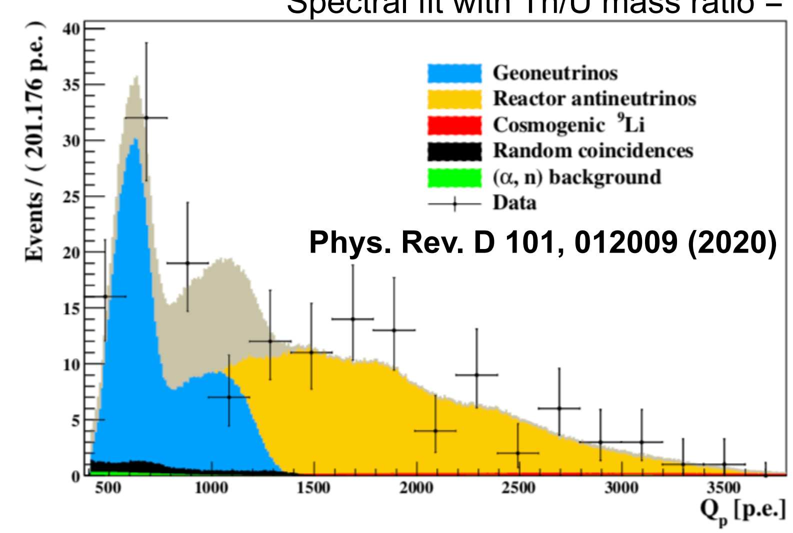
* LS : 278 t
* Depth : 3800 m.w.e.
* expected event ratio
  reactor/geo ~**0.3** (2007~)

Energy Spectrum

KamLAND Spectral fit with Th/U free



Borexino Spectral fit with Th/U mass ratio = 3.9

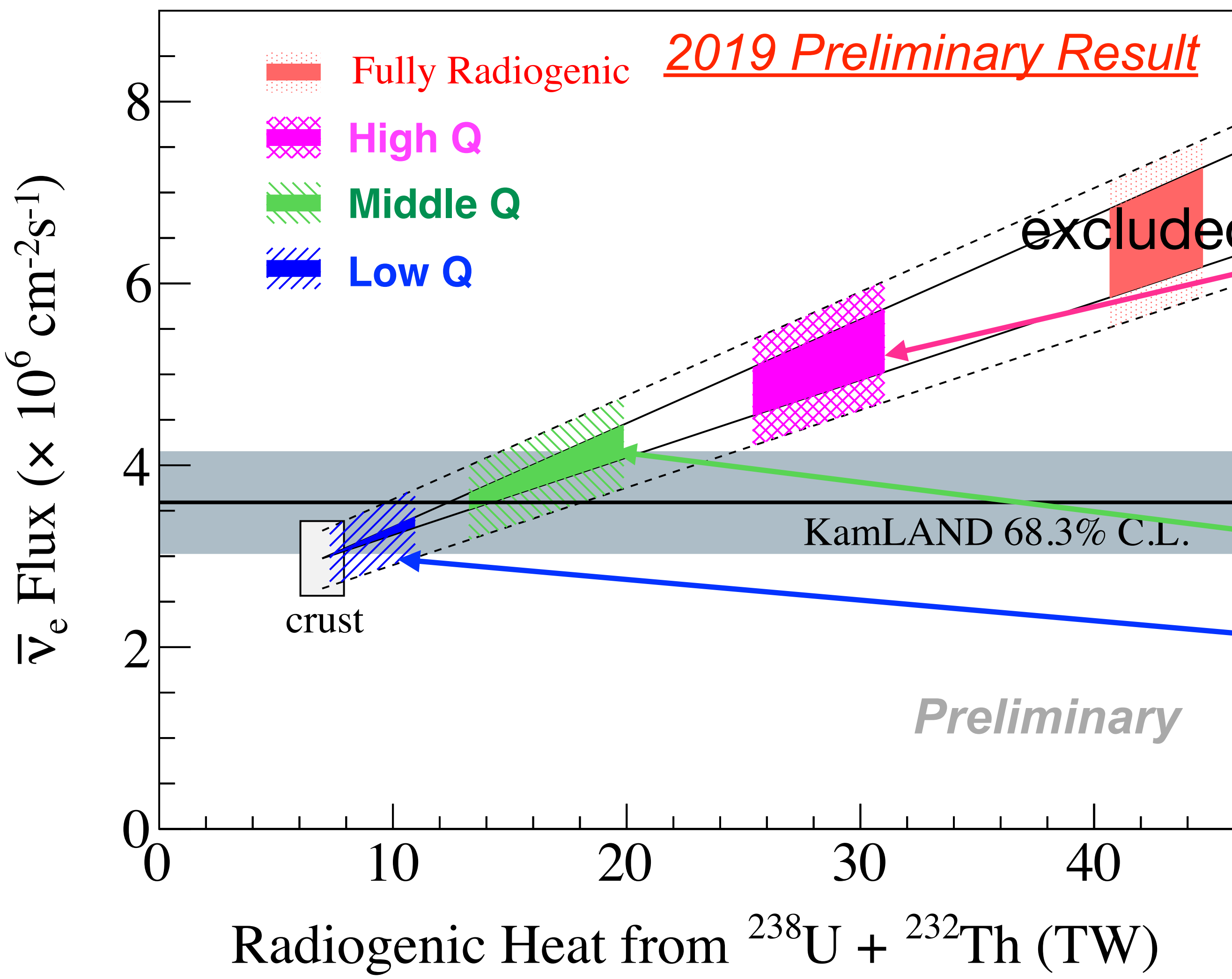


	KamLAND	Borexino
Livetime	4397 days (Mar 9, 2002 - Apr 15, 2018)	3263 days (Dec 9, 2007 - Apr 28, 2019)
Exposure	7.20×10^{32} proton-year	1.29×10^{32} proton-year
Candidates	1167 events	154 events
Geo-neutrino	168.8 +26.3/-26.5 events (Th/U=3.9)	52.6 +9.4/-8.6(stat) +2.7/-2.1(syst) events (Th/U=3.9)
Uncertainty	+15.6/-15.7 %	+18.3/-17.2 %

☑ Measurement uncertainty gets close to uncertainty of Earth model prediction (~20%).

KamLAND radiogenic heat interpretation

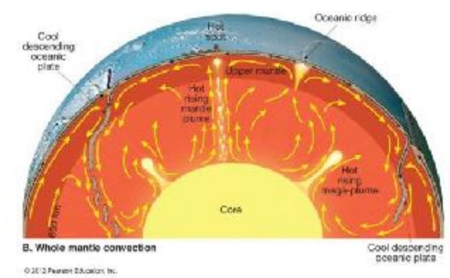
from H. Watanabe
talk @ Neutrino 2020



☑ Radiogenic Heat : **12.4 $^{+4.9}_{-4.9}$ TW**
(Mantle+Crust, U+Th)

ref) Crust (U+Th) ~7 TW [Enomoto et al. EPSL 258, 147 (2007)] → Mantle (U+Th) ~5.4 TW

High Q



whole mantle convection model

☑ **rejected with >2 σ**

Middle Q
Low Q
Different types of primordial meteorite

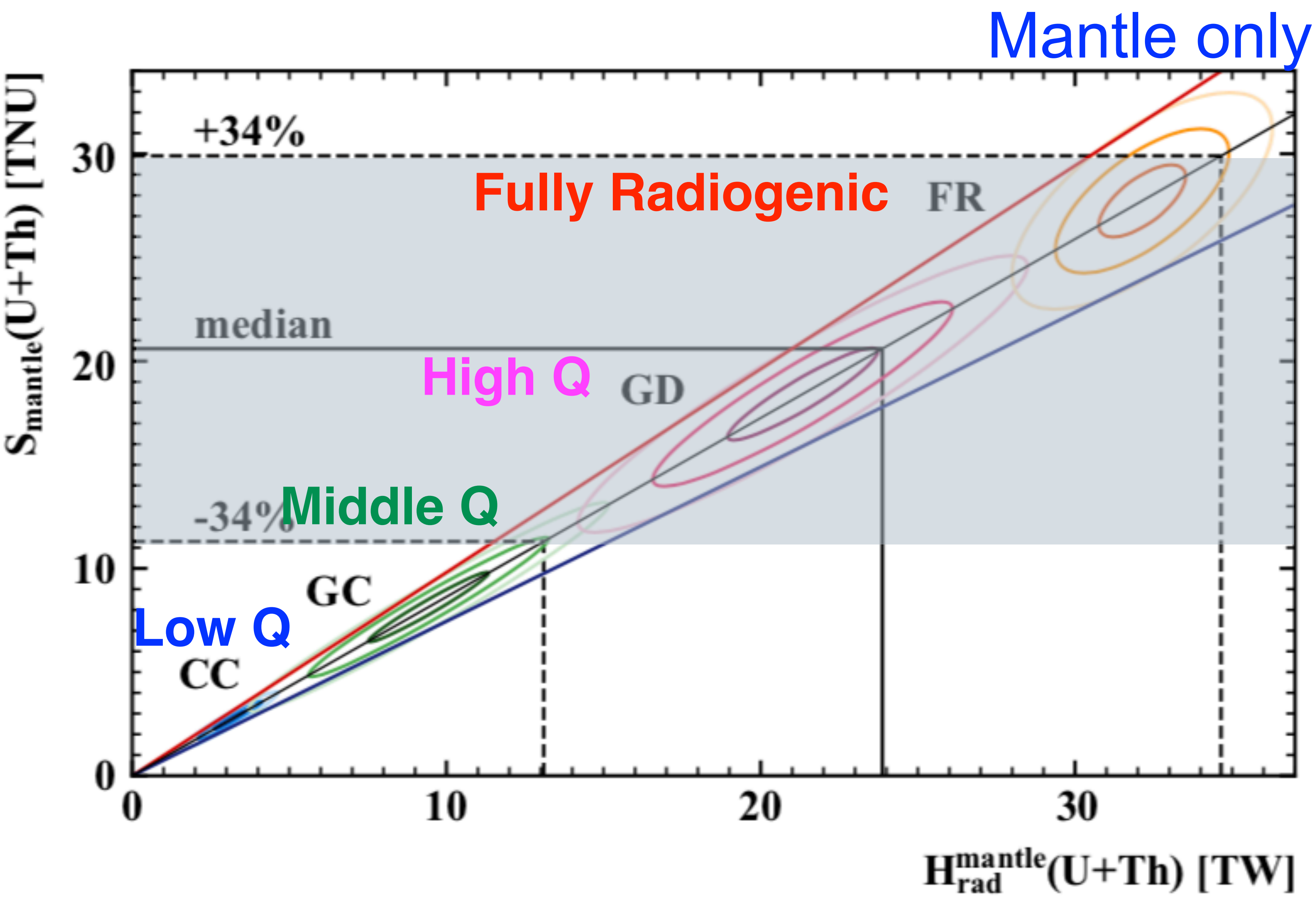
☑ **can be selected by geo-ν measurement**

[BSE models]

High Q	based on balancing mantle viscosity and heat dissipation
Middle Q	based on mantle samples compared with chondrites
Low Q	based on isotope constraints and chondritic models

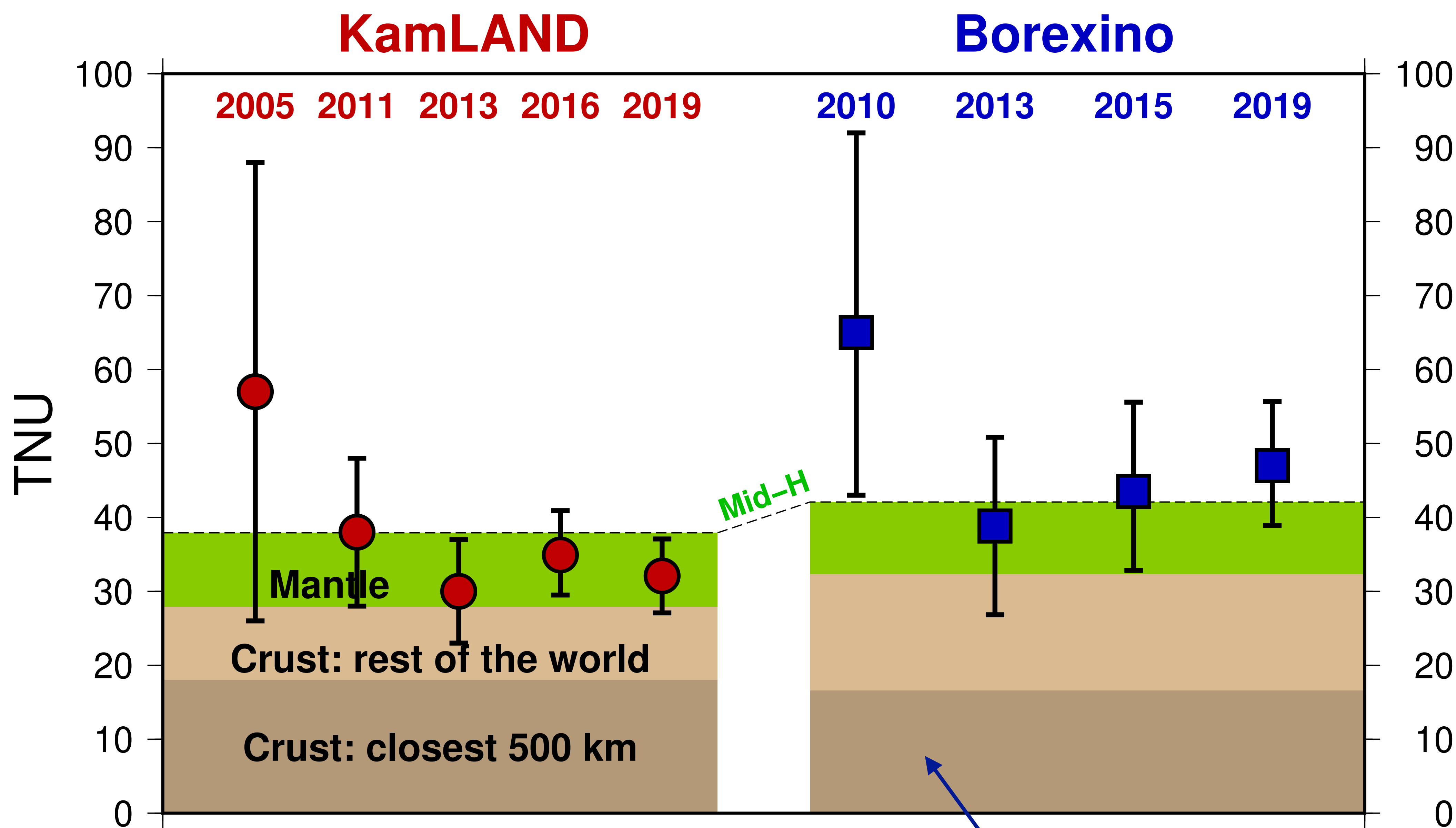
Borexino radiogenic heat interpretation

from L. Ludhova



(Mantle, U+Th) 24.6 +11.1/-10.4 TW

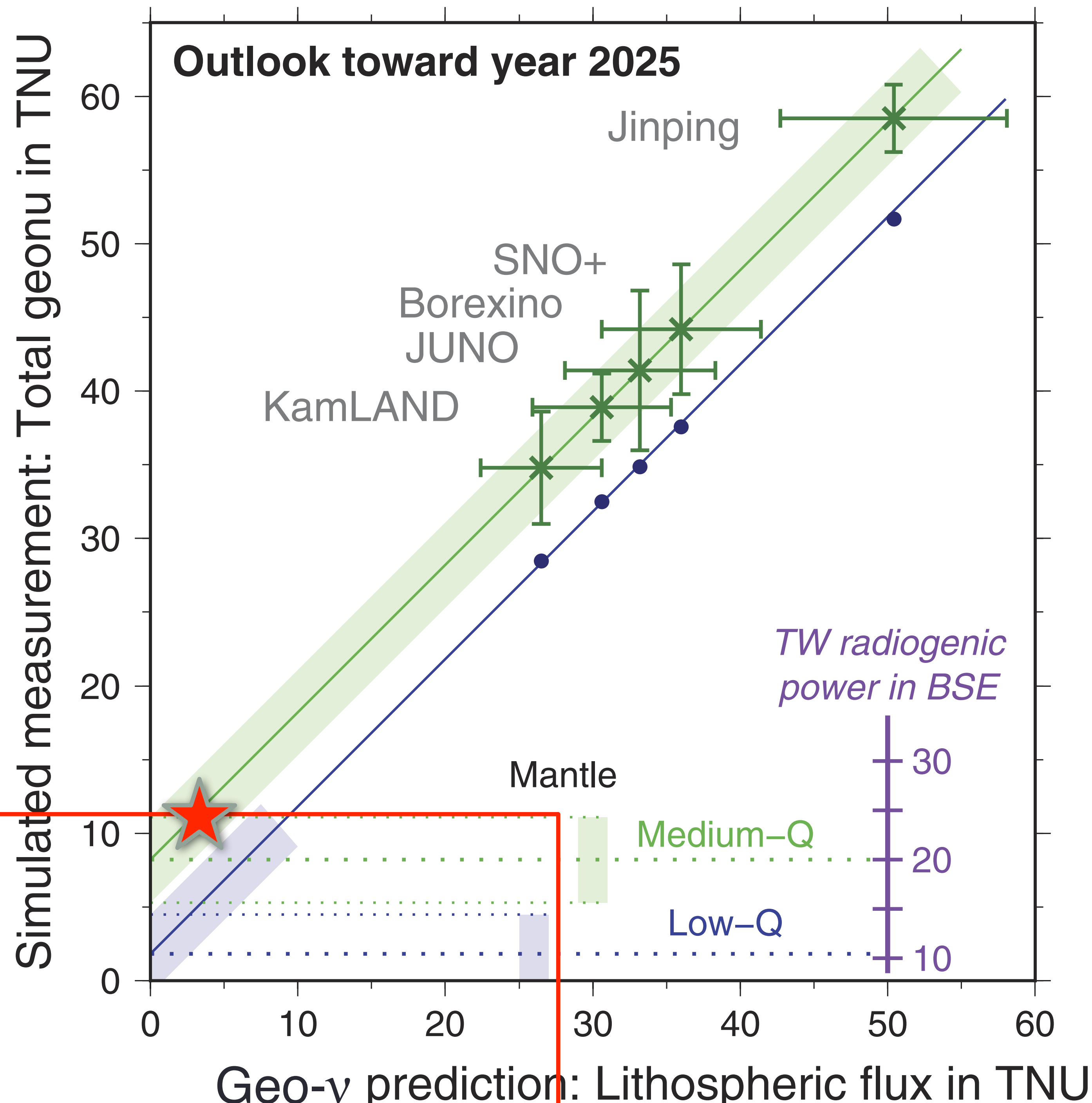
Comparison: Depends on Crustal Model



Geoneutrino prediction from Wipperfurth et al. 2020 JGR doi:10.1029/2019JB018433

Lithospheric model *not* the one used by Borexino in their analysis

Future Combined "Global" Analysis
with more experiments



- each experiment needs local crust geology characterized
- combined analysis yields the common mantle component

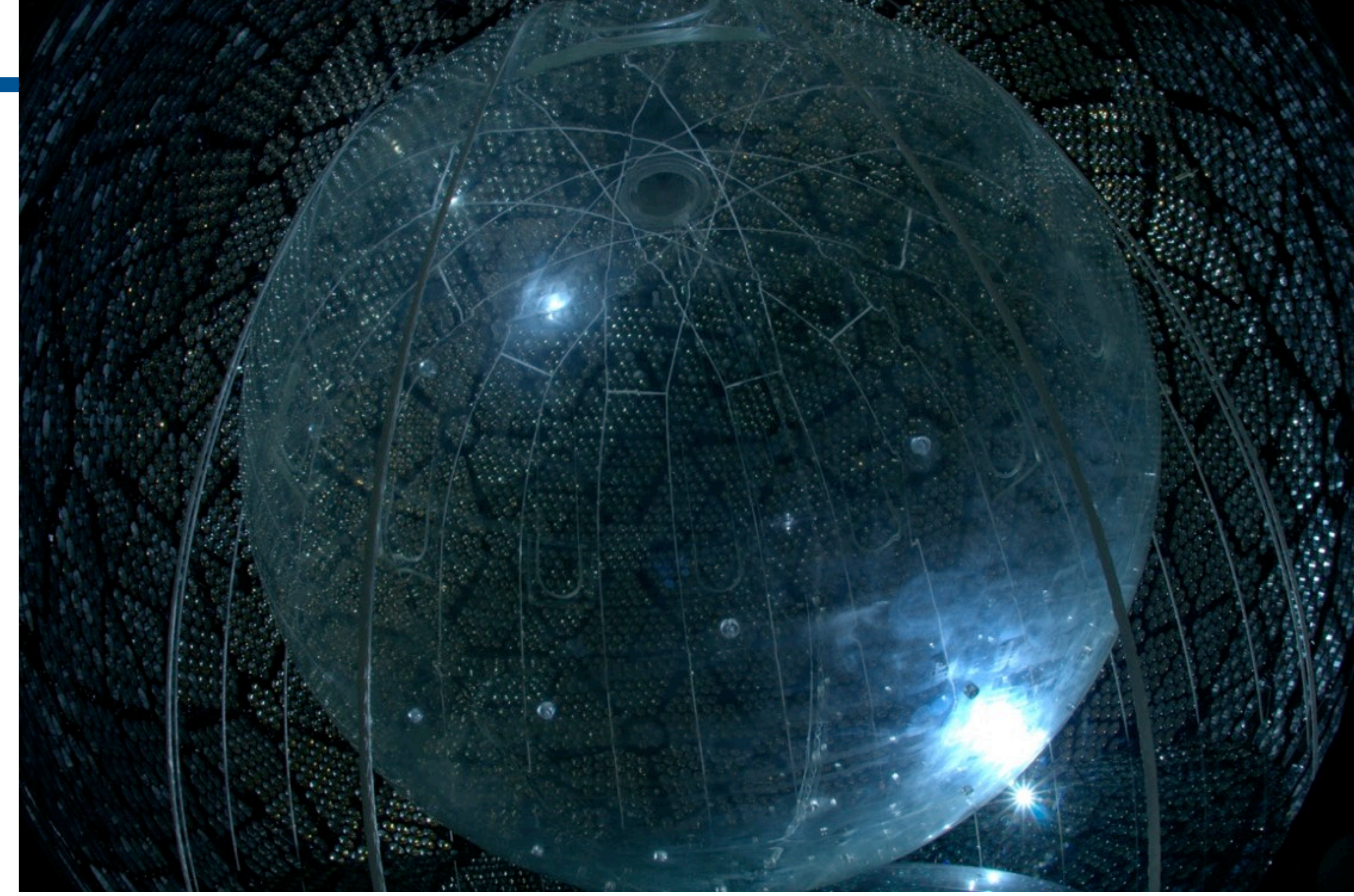
or

- reveals hidden reservoirs = mantle lateral inhomogeneity

An experiment in the ocean would measure predominantly the mantle component…see OBD next talk by Hiroko

from O. Šrámek et al. Scientific Reports (2016)

SNO+



780 tons liquid scintillator
- LS filling resumed in late Oct 2020 after being paused for >6 month due to pandemic lockdown restrictions
- soon to completed!
- even when Te loaded for DBD, IBD signal allows geoneutrino measurements to continue

Perceiving the Crust in 3-D: A Model Integrating Geological, Geochemical, and Geophysical Data

Virginia Strati[1,2], Scott A. Wipperfurth[3], Marica Baldoncini[2,4], William F. McDonough[3,5], and Fabio Mantovani[2,4]

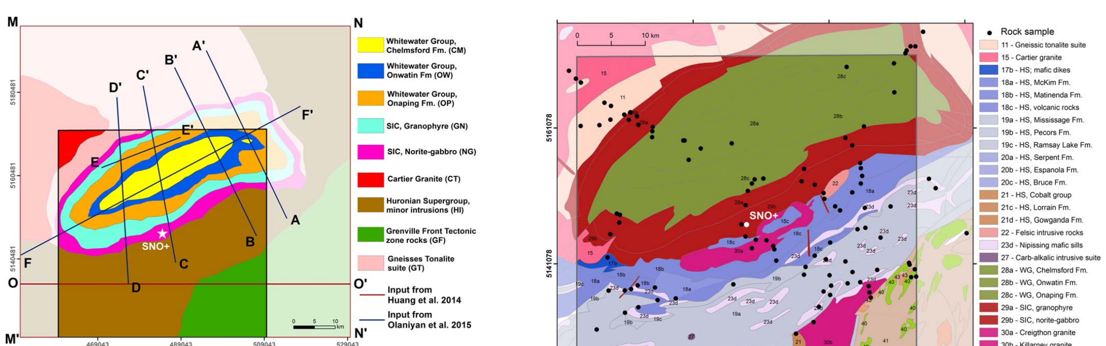


Figure 4. Geophysical inputs used for the construction of the 3-D model. The six cross sections derived from Olaniyan et al. (2015) (AA′, BB′, CC′, DD′, EE′, FF′) and the five cross sections extracted from the H14 model (MM′, M′N′, NN′, MN, OO′) are projected on the simplified geological map. The inner box represents the CUC. (Cartographic reference system NAD1927 UTM Zone 17N).

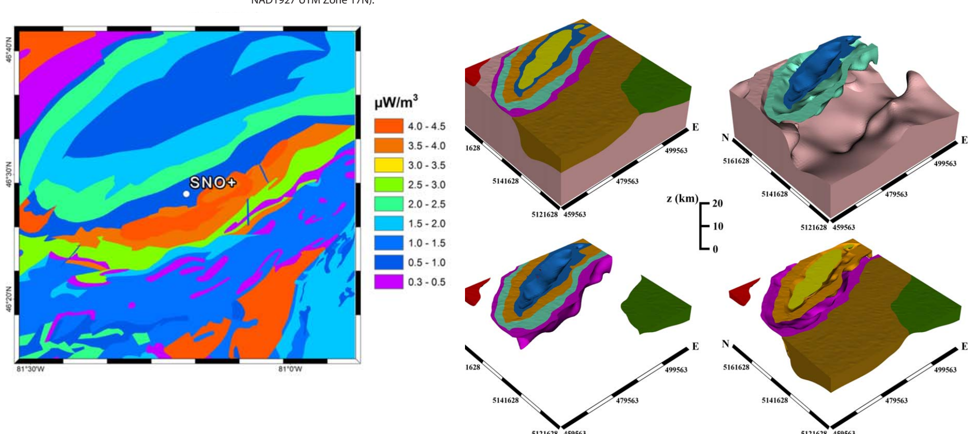
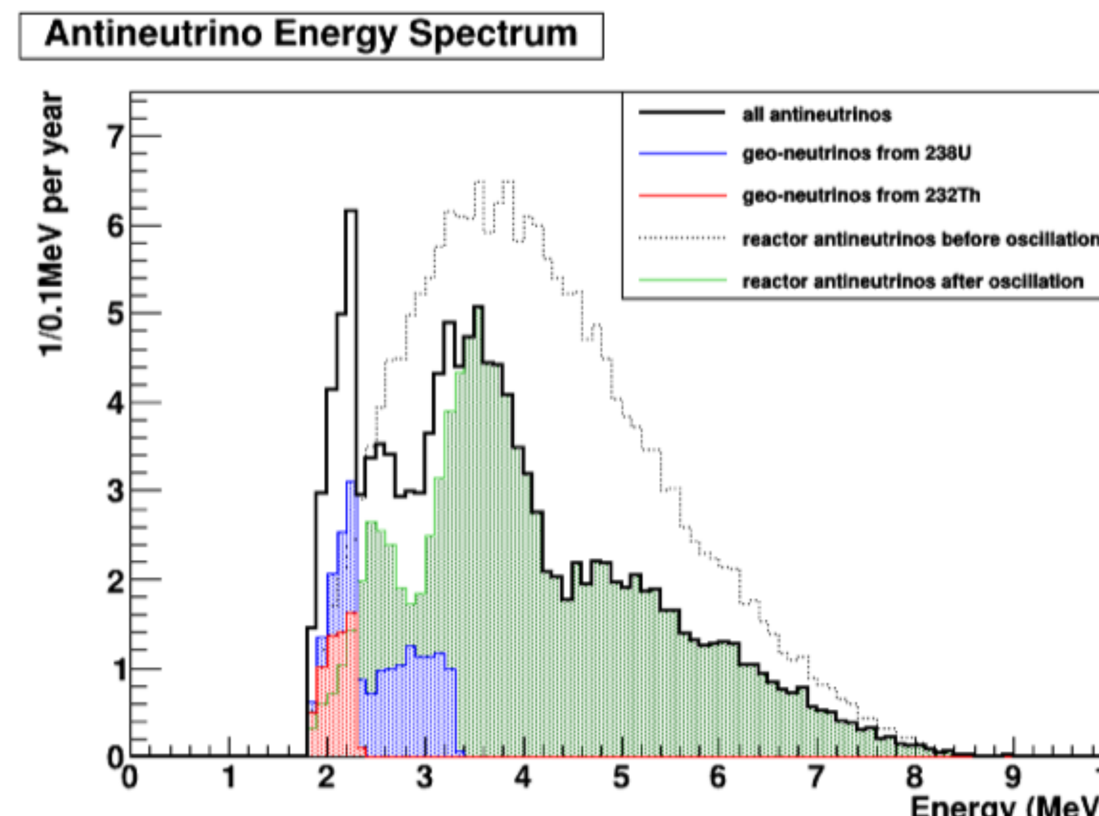


Figure 3. Rock sample of lapilli tuff (Geocode 28c, Onaping Fm.). (a) Each sample was collected from fresh outcrop and (b) then crushed and sealed in polycarbonate box of 180 cm^3 of volume.



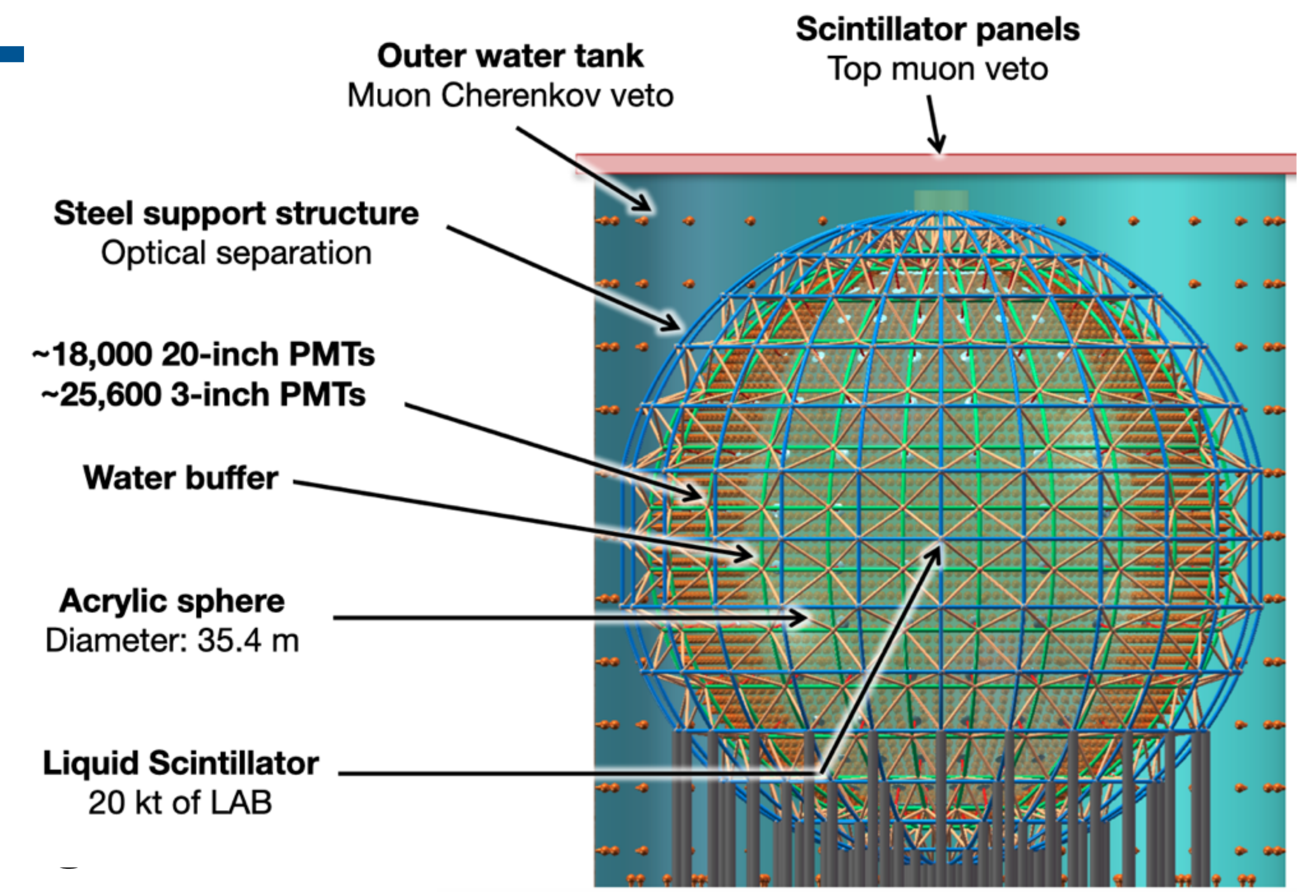
~25-30 events/year
geo:reactor signal is 1:1
well-studied local geology

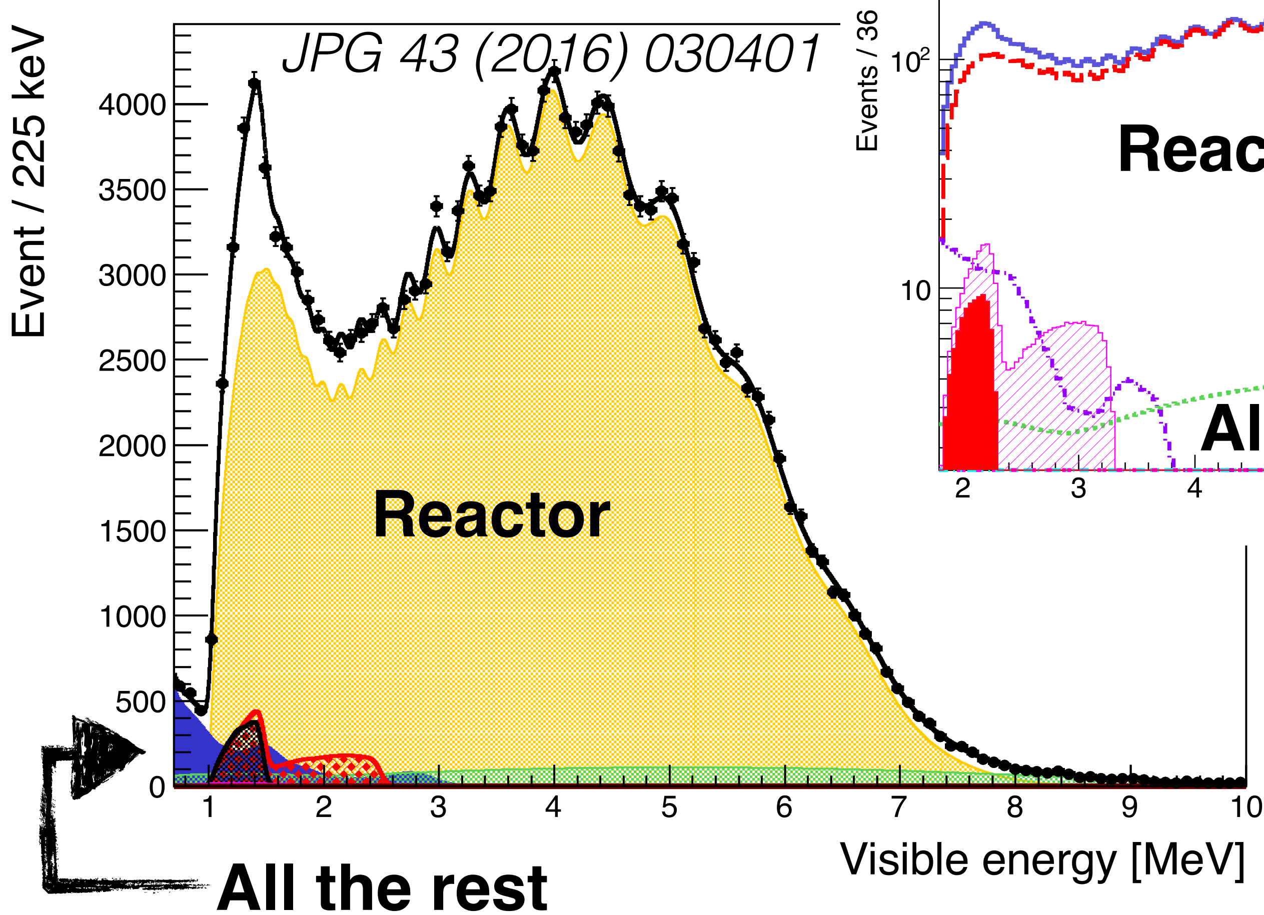
JUNO

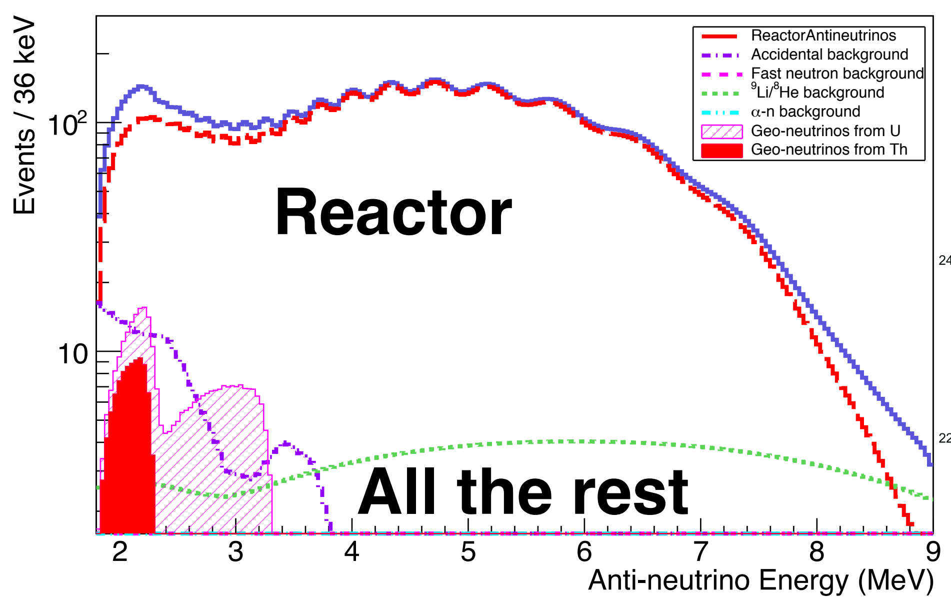
20 ktons liquid scintillator
- physics program starts 2022

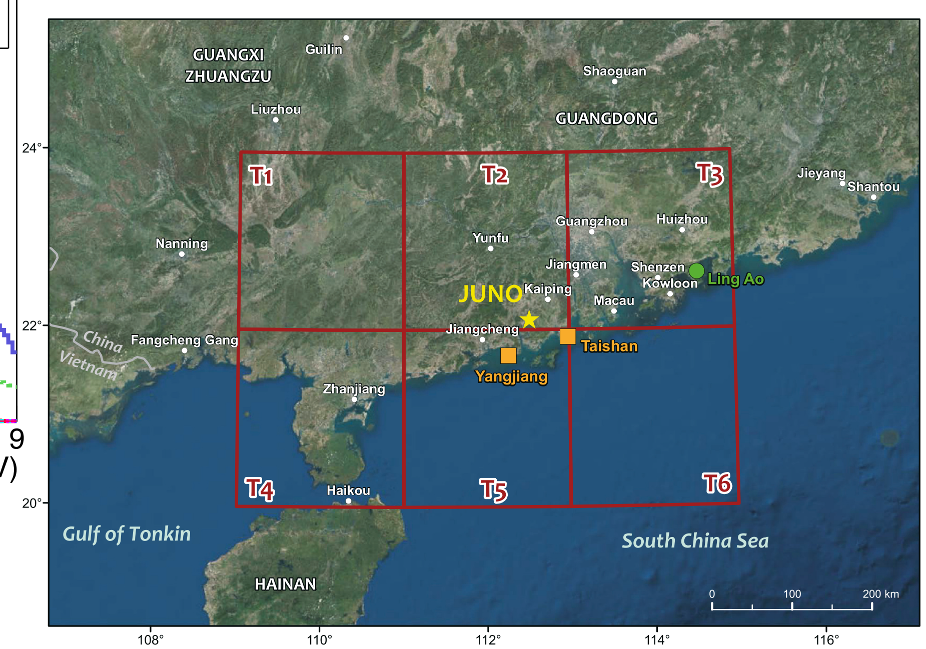
~400 geo ev/yr and 16000 reactor ev/yr
geo:reactor is 1:8 (geo energy range)

5% measurement precision in 10 yrs
±30% Th/U ratio









figures from Roskovec talk
@ Neutrino Geoscience 2019;
map in Strati et al., PEPS (2015)

Other Concepts for Geoneutrino Detection

as mentioned in the Snowmass LOIs and elsewhere

- OBD – Ocean Bottom Detector (see next talk)
- THEIA – 50 kton WbLS
- ^{6}Li doped liquid scintillator – good for IBD directionality
- coherent neutrino-nucleus scattering
  - CEνNS LOI (for geoneutrinos, see paper by G. Gelmini et al.)
  - CYGNUS LOI – gaseous detector for recoil direction
- LiquidO – low E_{thres} CC reaction based on single e^+ signal ID

- electron scattering
  - TPC – M. Leyton, S. Dye, J. Monroe paper
  - Cherenkov-scintillation separation – Z. Wang and S. Chen paper

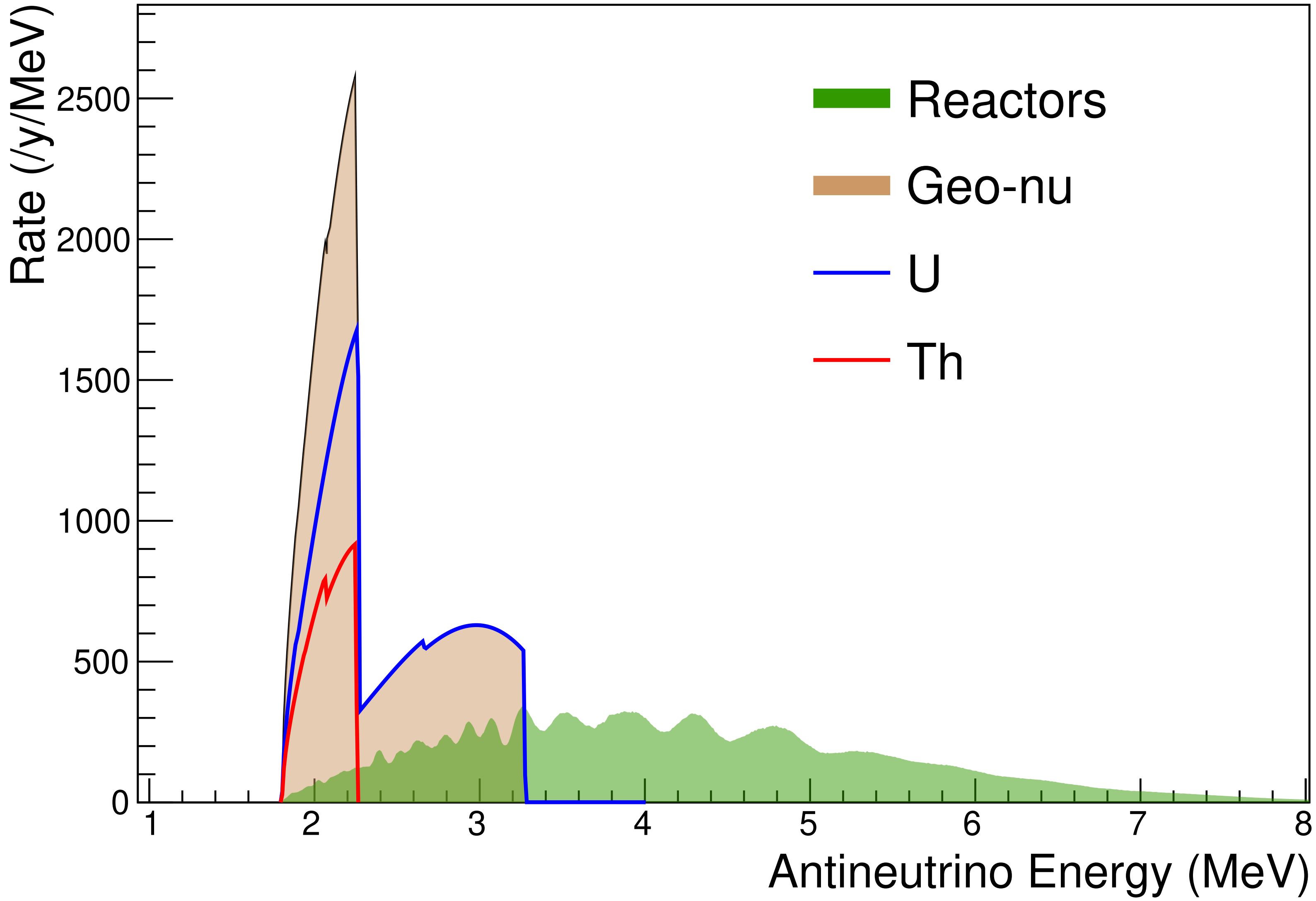
THEIA LOI

10-100 kton WbLS
Located at SURF

- Large statistics
- Excellent geo:reactor ratio
- Excellent prospects for measuring Th/U ratio
- Continental crust component dominates

Potential for Cherenkov signal in WbLS could help particle ID for positrons in the IBD reaction

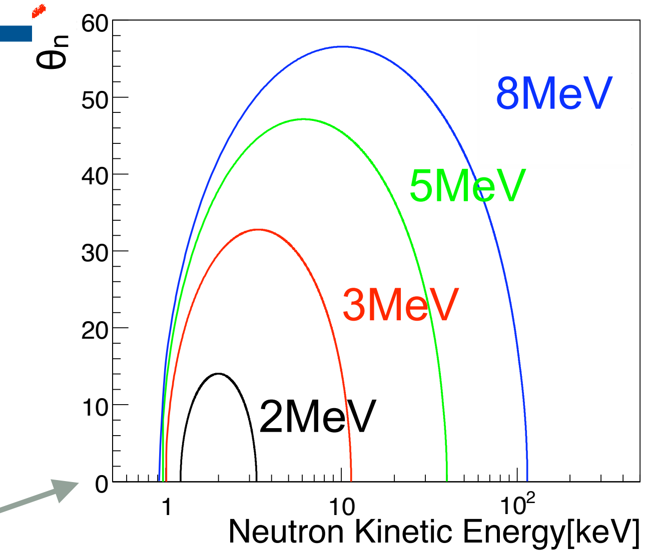
Note: directionality of IBD events does not come from Cherenkov…it's in the neutron recoil direction



Antineutrino IBD signal spectrum
(50 kton water target, no energy resolution)

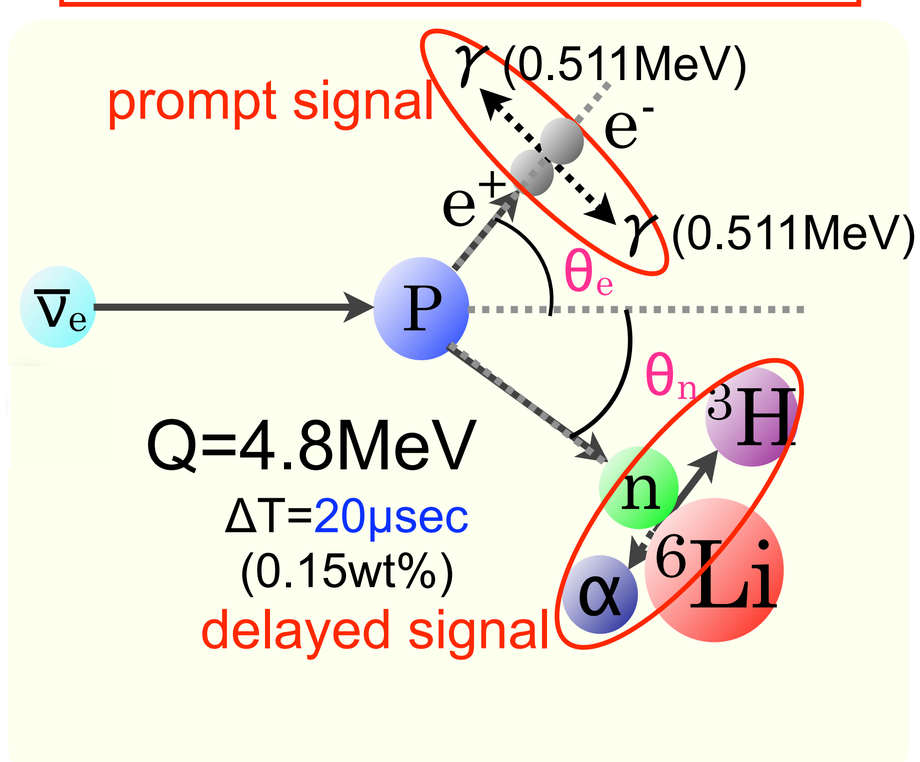
On the topic of directionality…

^{6}Li loaded LS development was an LOI (did not specifically mention geoneutrinos)

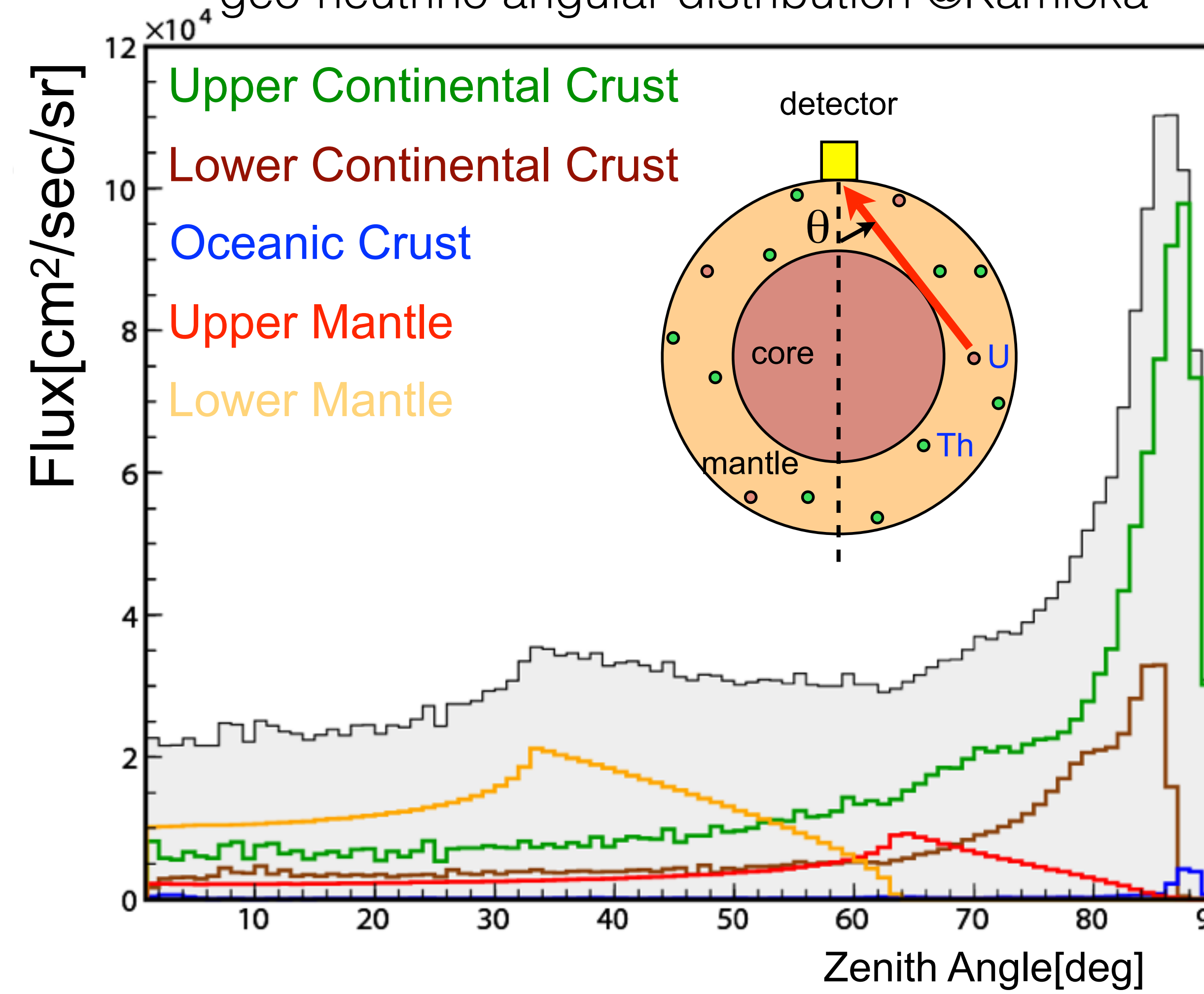


$E_{\bar{\nu}e}$ <3MeV→θ_n<35°

There has been research into ^{6}Li IBD directionality for geoneutrinos by H. Watanabe et al.



geo-neutrino angular distribution @Kamioka



Solutions

- large neutron capture cross section
  (^{6}Li 940 barns vs ^{1}H 0.3 barns)
- α does't travel far

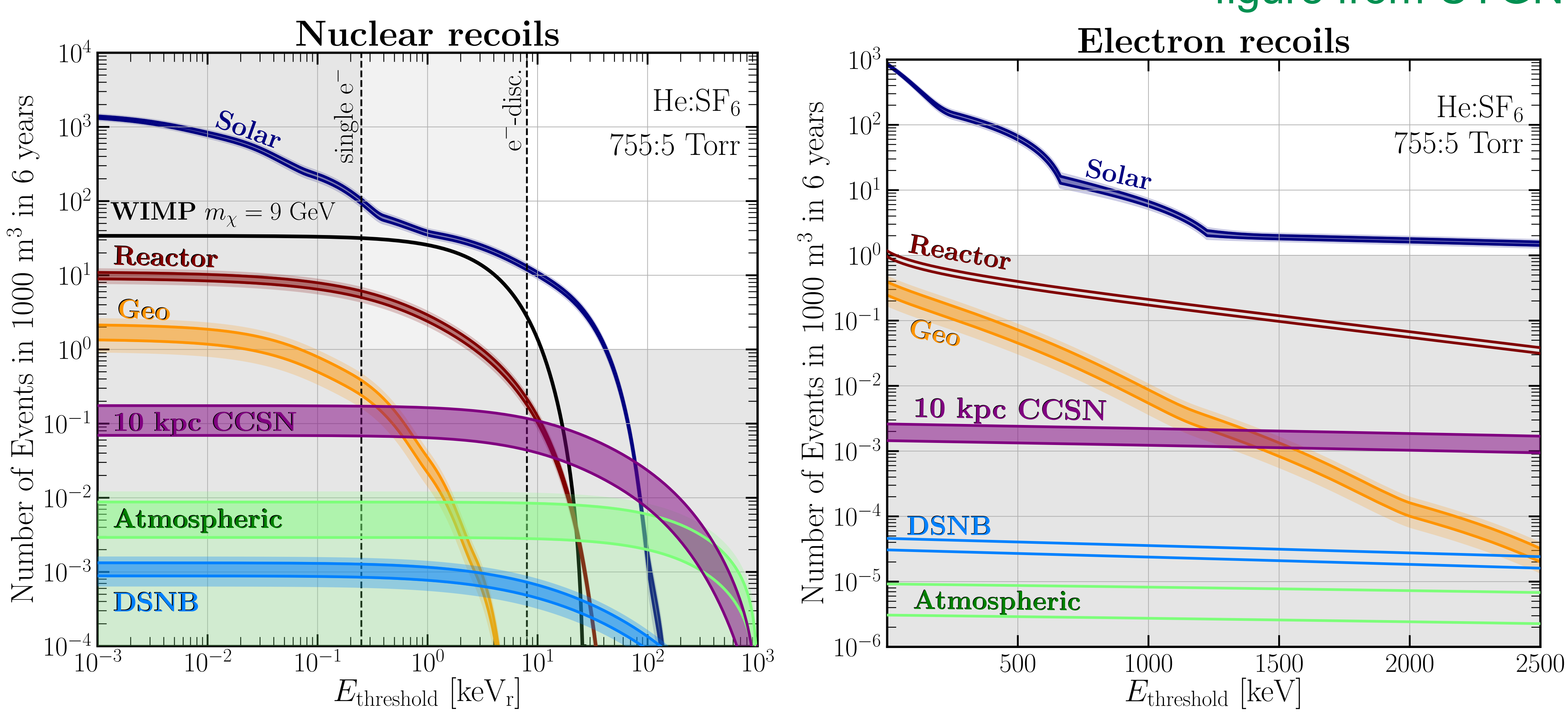
directional info separates mantle from crust and rejects background events from reactors

Nuclear Recoil and Electron Recoil Detection

- CEνNS and CYGNUS LOIs
- nuclear recoil (dark matter direct detection)
  - Gelmini et al., PRD 99, 093009 (2019)
- electron scattering
  - LDM, Nature Comm 8, 15989 (2017)
  - Wang and Chen, CPC 44, 033001 (2020)

- solar + reactor backgrounds are huge!
- directionality proposed to reject (in a TPC or Cherenkov-scintillation LS)
- …and then there are other electron recoil backgrounds!
- nuclear recoil directionality? at very low recoil energies…and other backgrounds!

figure from CYGNUS LOI



^{40}K geoneutrino via charged-current reaction with lower threshold than IBD(p)

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

"Probing Earth's missing potassium using the unique antimatter signature of geoneutrinos"
paper to be submitted

Could a single positron signal be used for ^{40}K geoneutrino detection?
What possible nuclear targets? Which one is best?
What are possible single e^+ backgrounds? →fewer than single e^-

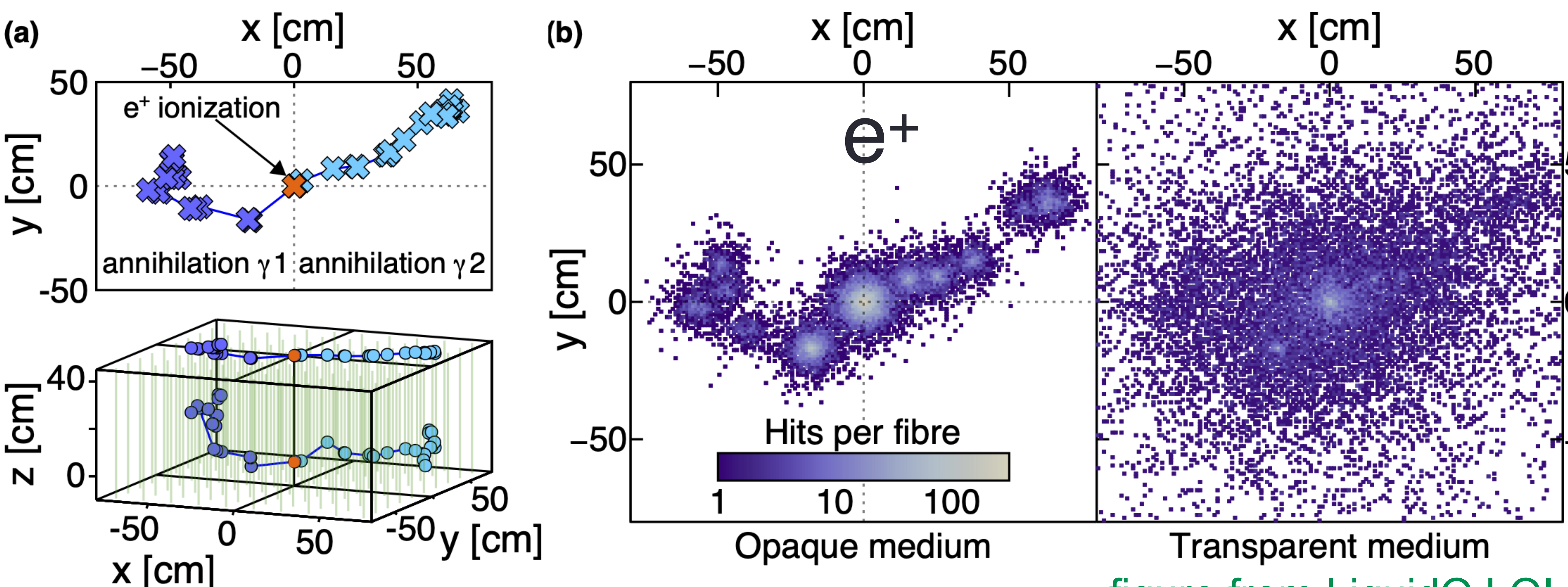


figure from LiquidO LOI

Thanks very much for your attention!

I tried to motivate the study of geoneutrinos and summarize what's happening in the field in this talk. I didn't mention every experiment – notable omission is a large LS detector in Jinping – apologies that I couldn't fit in all! I tried to cover the current developments and mention new ideas for geoneutrino detection, related to the LOIs that were received.