Geoneutrinos and the composition of the Earth

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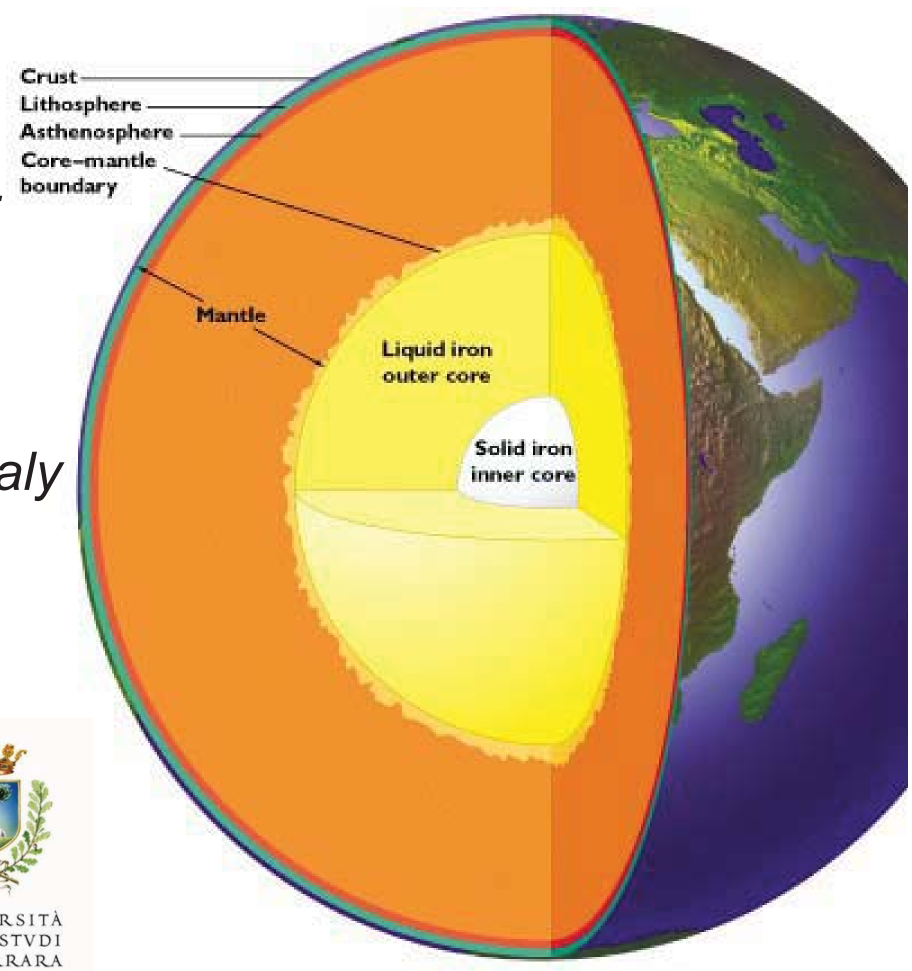


Earth Models Update: …just the last 11 months!

Murakami et al (May - 2012, *Nature*): "…the lower mantle is enriched in silicon … consistent with the [CI] **chondritic Earth model**."

Campbell and O'Neill (March - 2012, *Nature*): "Evidence **against a chondritic Earth**"

Zhang et al (March - 2012, *Nature Geoscience*): The Ti isotopic composition of the **Earth and Moon overlaps that of enstatite chondrites**.

Fitoussi and Bourdon (March - 2012, *Science*): "Si isotopes support the conclusion that **Earth was not built solely from enstatite chondrites**."

Warren (Nov - 2011, *EPSL*): "Among known chondrite groups, **EH yields a relatively close fit to the stable-isotopic composition of Earth**."

- Compositional models differ widely, implying a factor of three difference in the U & Th content of the Earth

Nature & amount of Earth's thermal power

radiogenic heating vs secular cooling

- abundance of heat producing elements (K, Th, U) in the Earth

  estimates of BSE from 9TW to 36TW

- clues to planet formation processes

  constrains chondritic Earth models

- amount of radiogenic power to drive mantle convection & plate tectonics

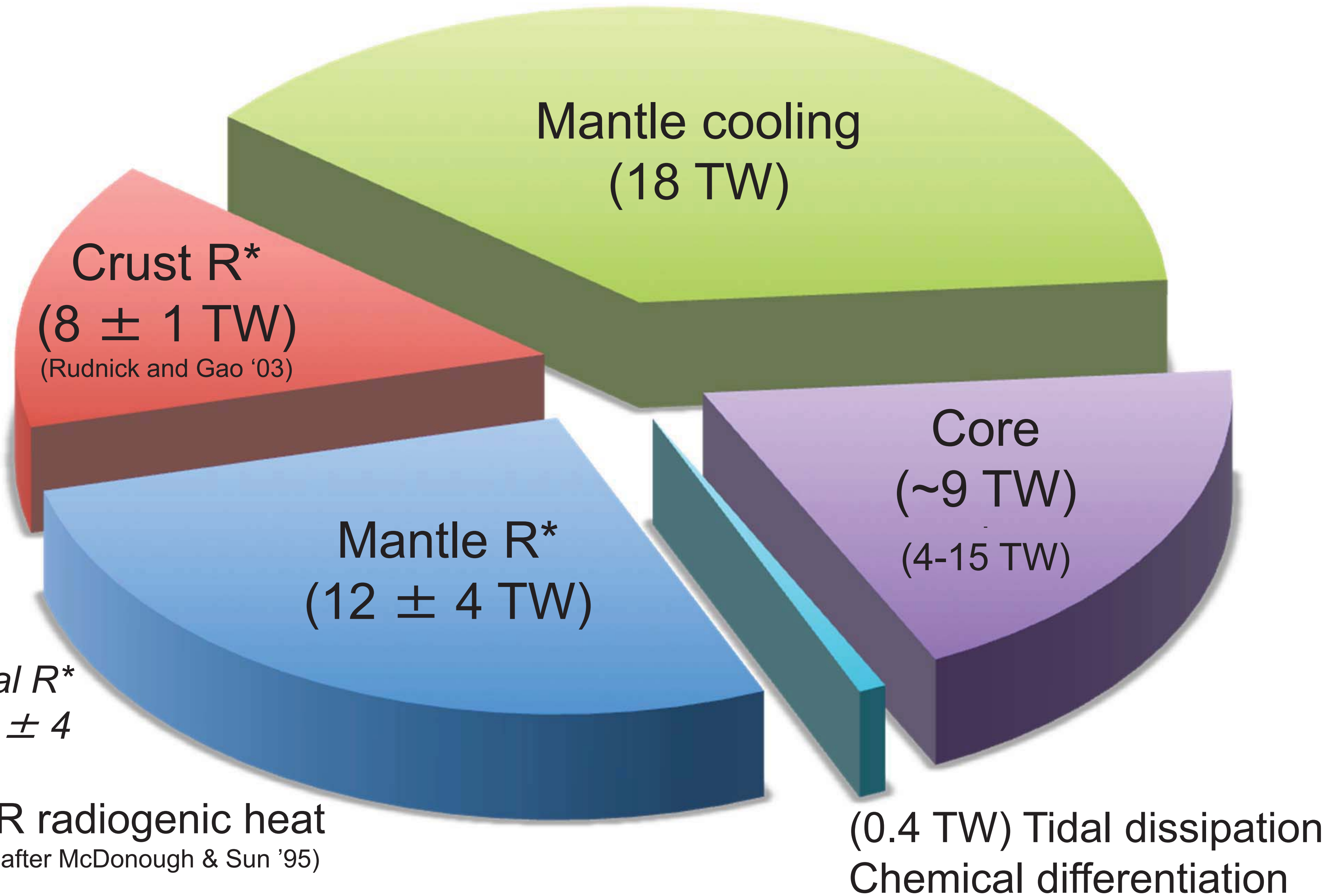
  estimates of mantle 1.3TW to 28TW

he mantle compositionally layered or have large structures?

layers, LLSVP, superplume piles

the future… *Geoneutrino studies*

Earth's surface heat flow 46 ± 3 (47 ± 2) 1σ

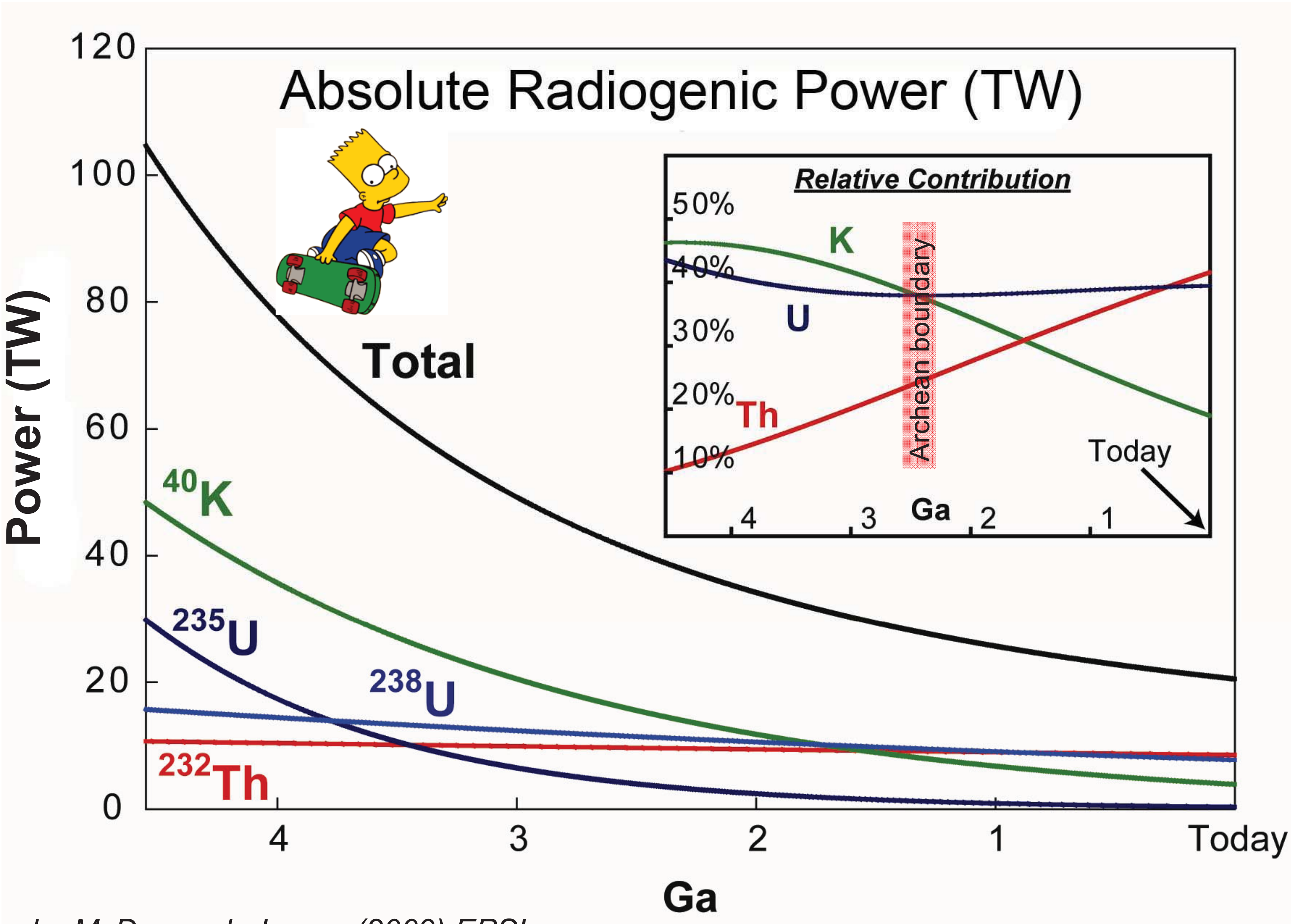


*total R**
20 ± 4

*R radiogenic heat
(after McDonough & Sun '95)

after Jaupart et al 2008 Treatise of Geophysics

Earth's thermal evolution: role of K, Th & U



Arevalo, McDonough, Luong (2009) EPSL

U content of BSE models

- Nucelosynthesis: U/Si and Th/Si production probability
- Solar photosphere: matches C1 carbonaceous chondrites
- Estimate from Chondrites: ~11ppb planet (16 ppb in BSE)
- Heat flow: secular cooling vs radiogenic contribution… ?
- Modeling composition: which chondrite should we use?

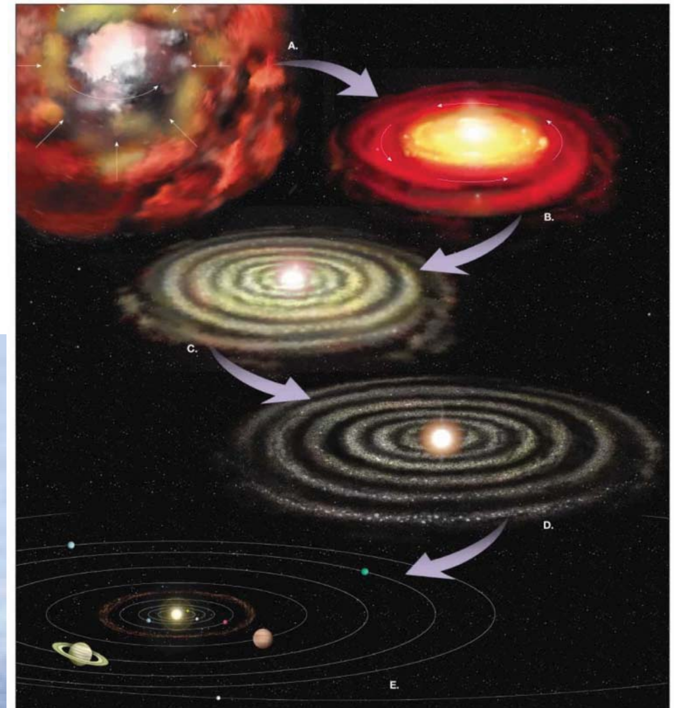
A brief (albeit biased) history of U estimates in BSE:

•Urey (56) 16 ppb
•Wasserburg et al (63) **33** ppb
•Ganapathy & Anders (74) 18 ppb
•Ringwood (75) 20 ppb
•Jagoutz et al (79) 26 ppb
•Schubert et al (80) **31** ppb
•Davies (80) 12-23 ppb
•Wanke (81) 21 ppb

Turcotte & Schubert (82; 03) **31** ppb
Hart & Zindler (86) 20.8 ppb
McDonough & Sun (95) 20 ppb ± 20%
Allegre et al (95) 21 ppb
Palme & O'Neill (03) 22 ppb ± 15%
Lyubetskaya & Korenaga (05) 17 ppb ± 17%
O'Neill & Palme (08) **10** ppb
Javoy et al (10) **12** ppb

What is the composition of the Earth? and where did this stuff come from?

Nebula



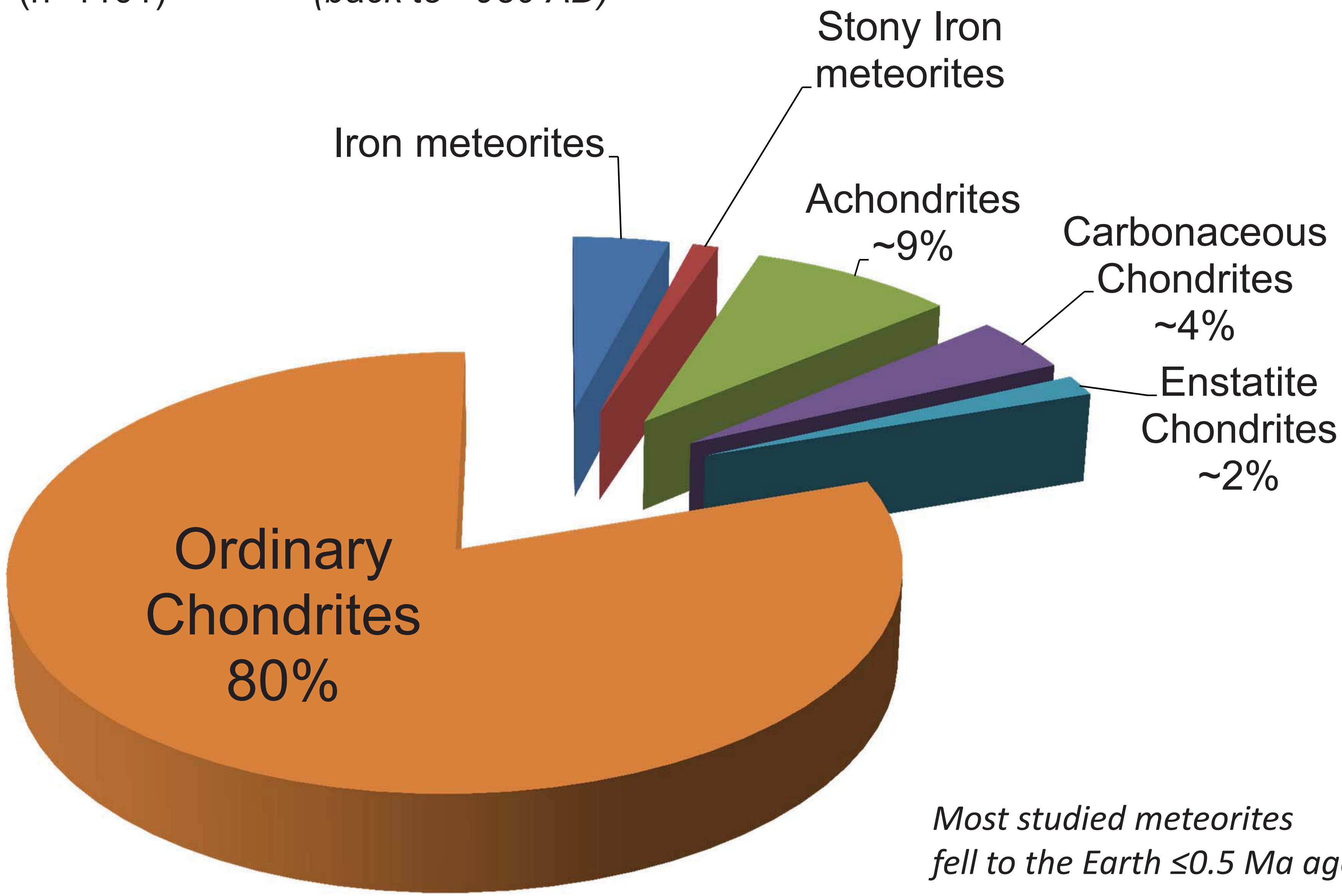
Meteorite

Heterogeneous mixtures of components with different formation temperatures and conditions

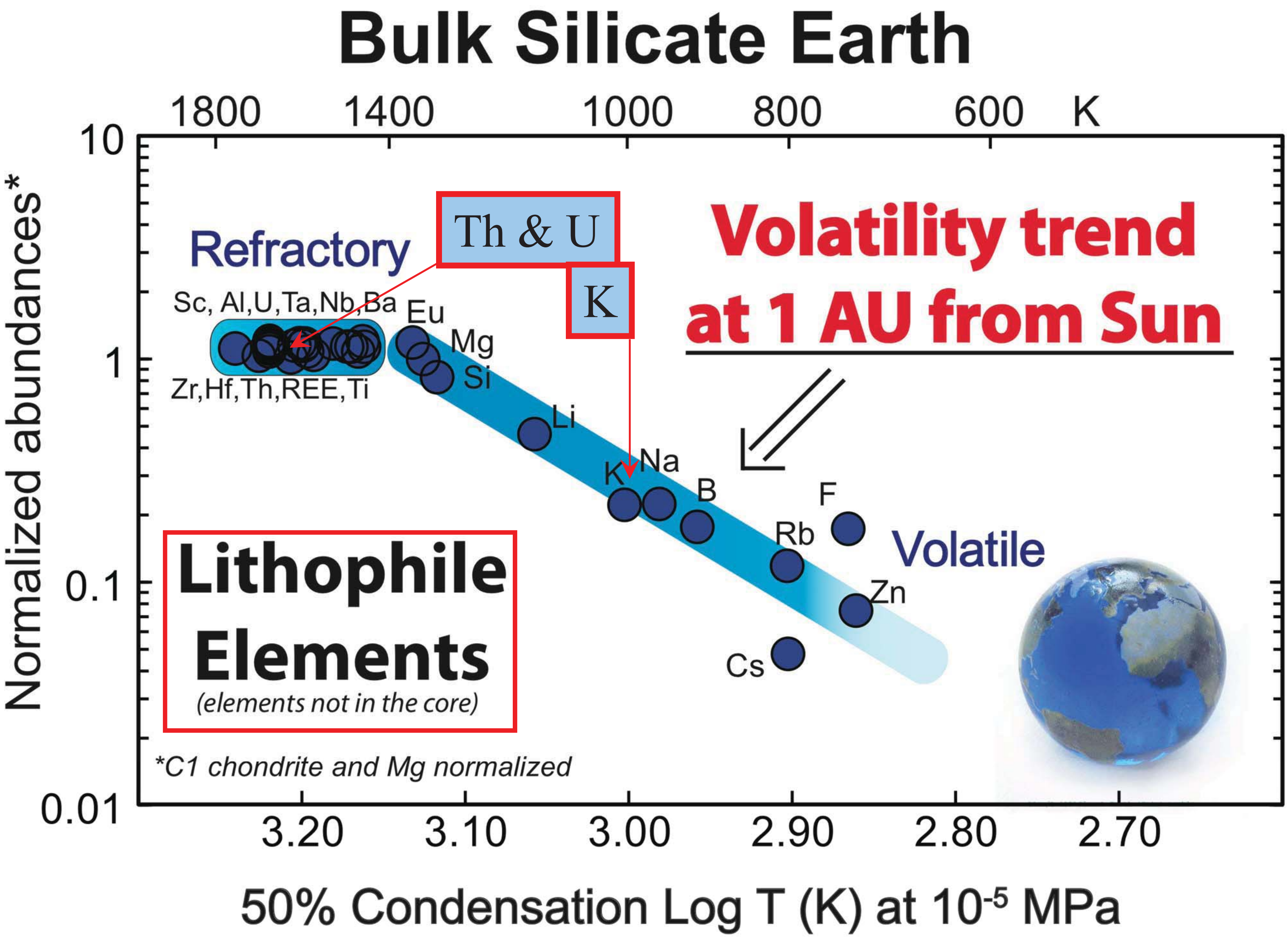
Planet:
mix of metal, silicate, volatiles

Meteorite: Fall statistics

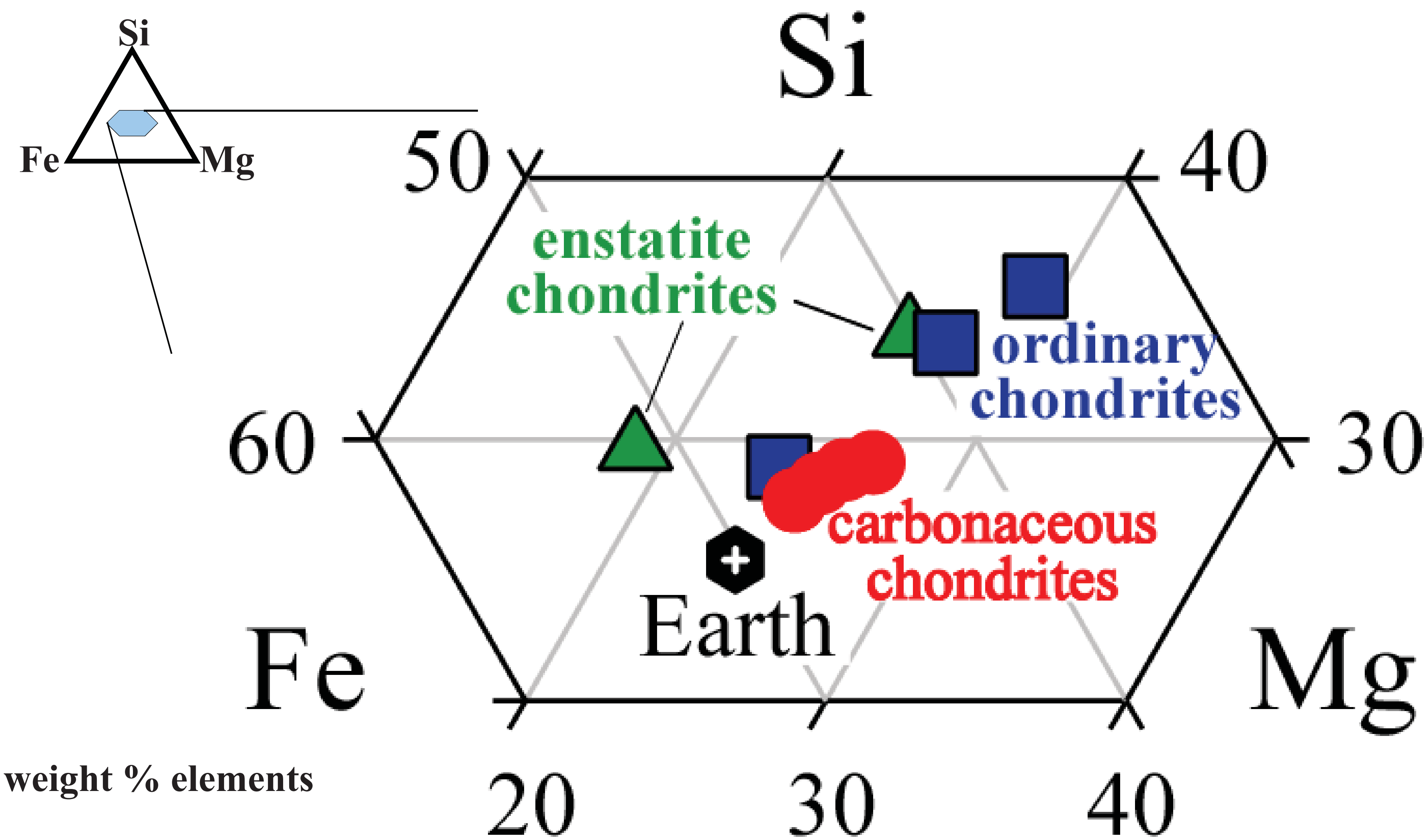
(n=1101) *(back to ~980 AD)*



Most studied meteorites fell to the Earth ≤0.5 Ma ago

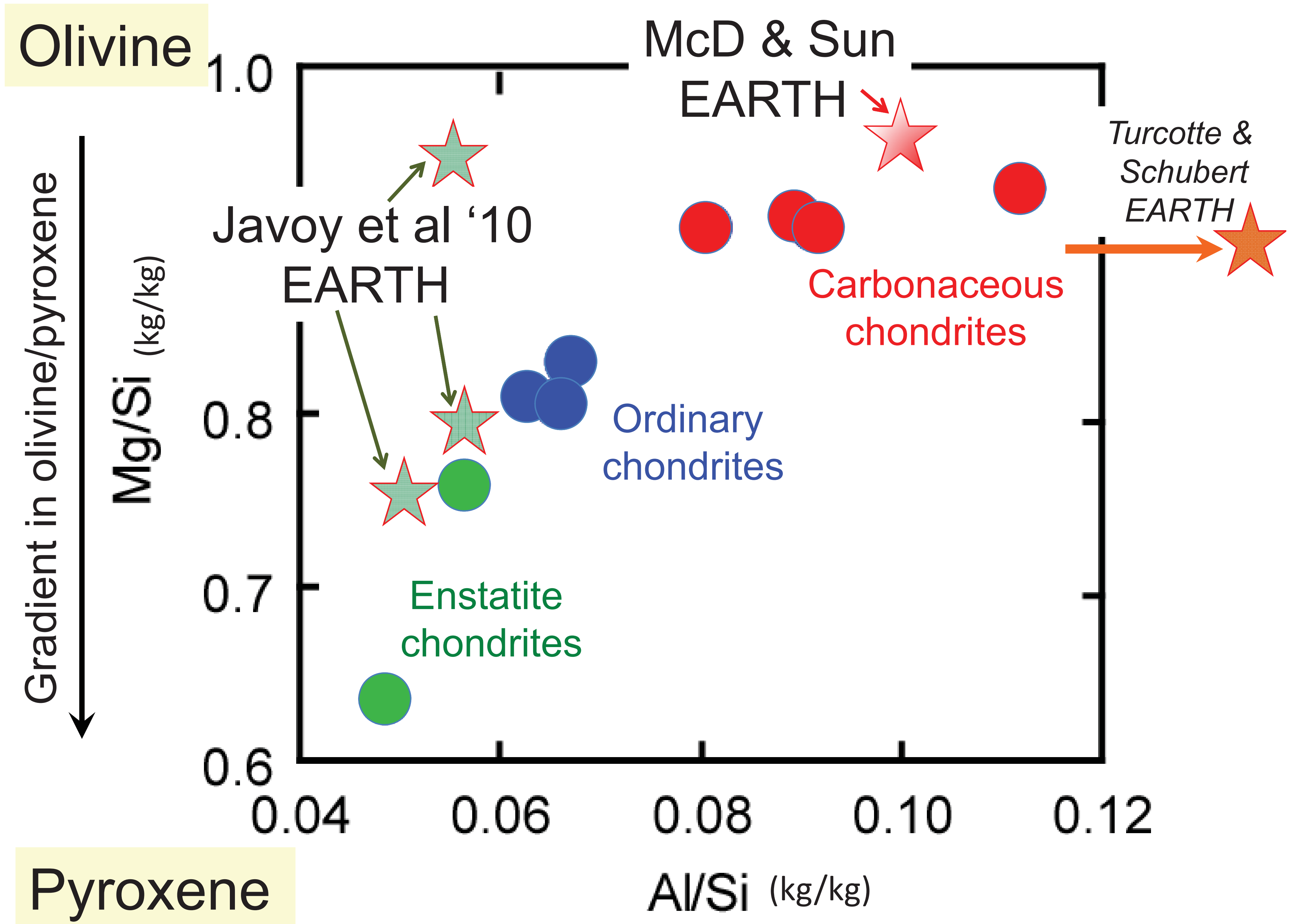


from McDonough & Sun, 1995



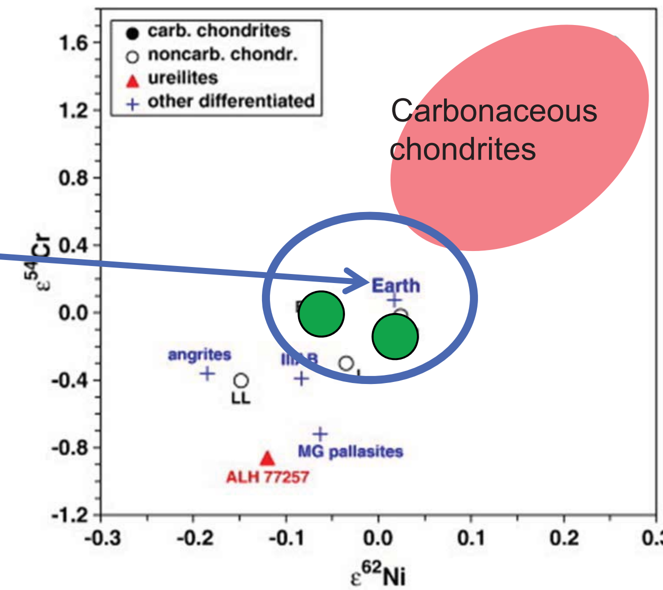
Moles Fe + Si + Mg + O = ~93% Earth's mass

(with Ni, Al and Ca its >98%)

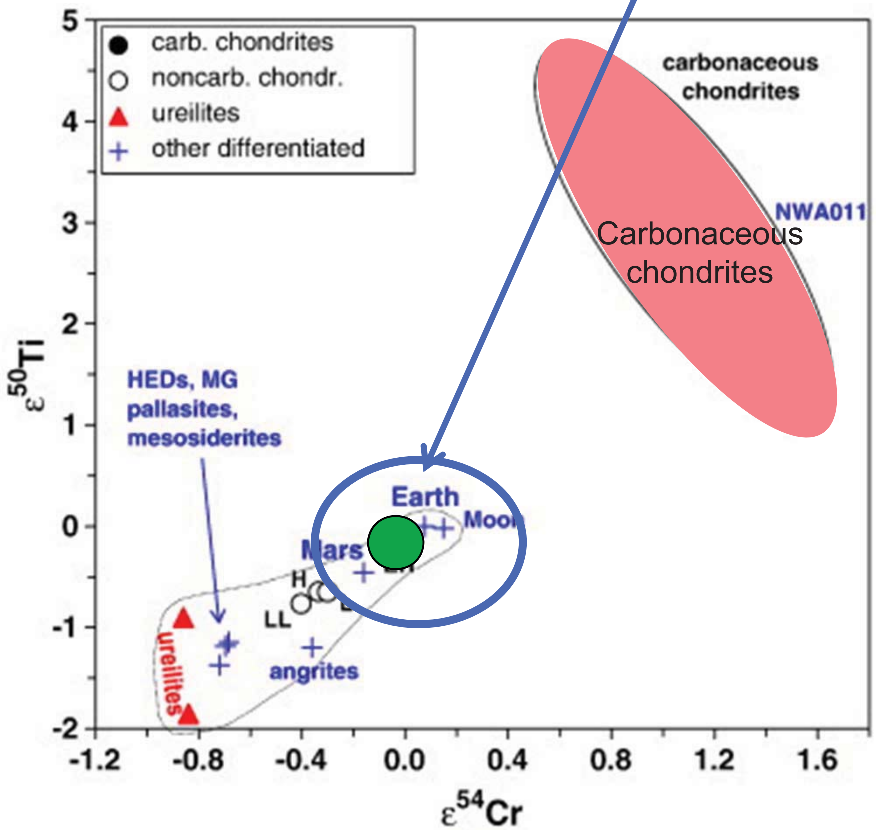


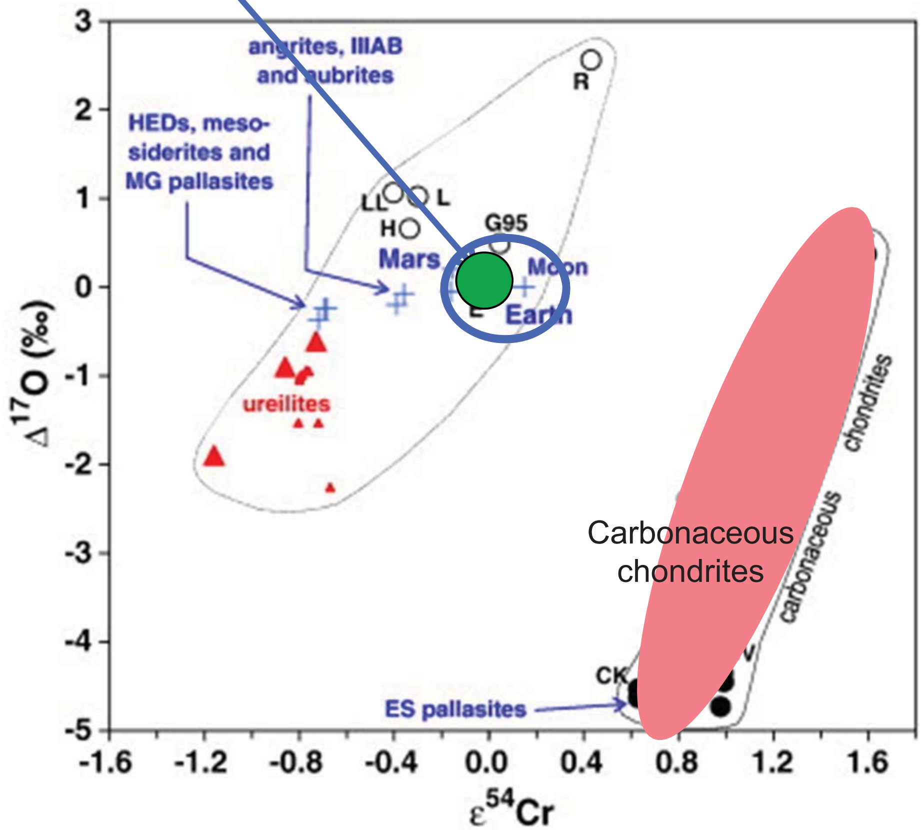
Olivine
Pyroxene
Gradient in olivine/pyroxene
Mg/Si (kg/kg)
1.0
0.8
0.7
0.6
0.04
0.06
0.08
0.10
0.12
Al/Si (kg/kg)
McD & Sun EARTH
Javoy et al '10 EARTH
Turcotte & Schubert EARTH
Carbonaceous chondrites
Ordinary chondrites
Enstatite chondrites

Enstatite chondrite vs Earth

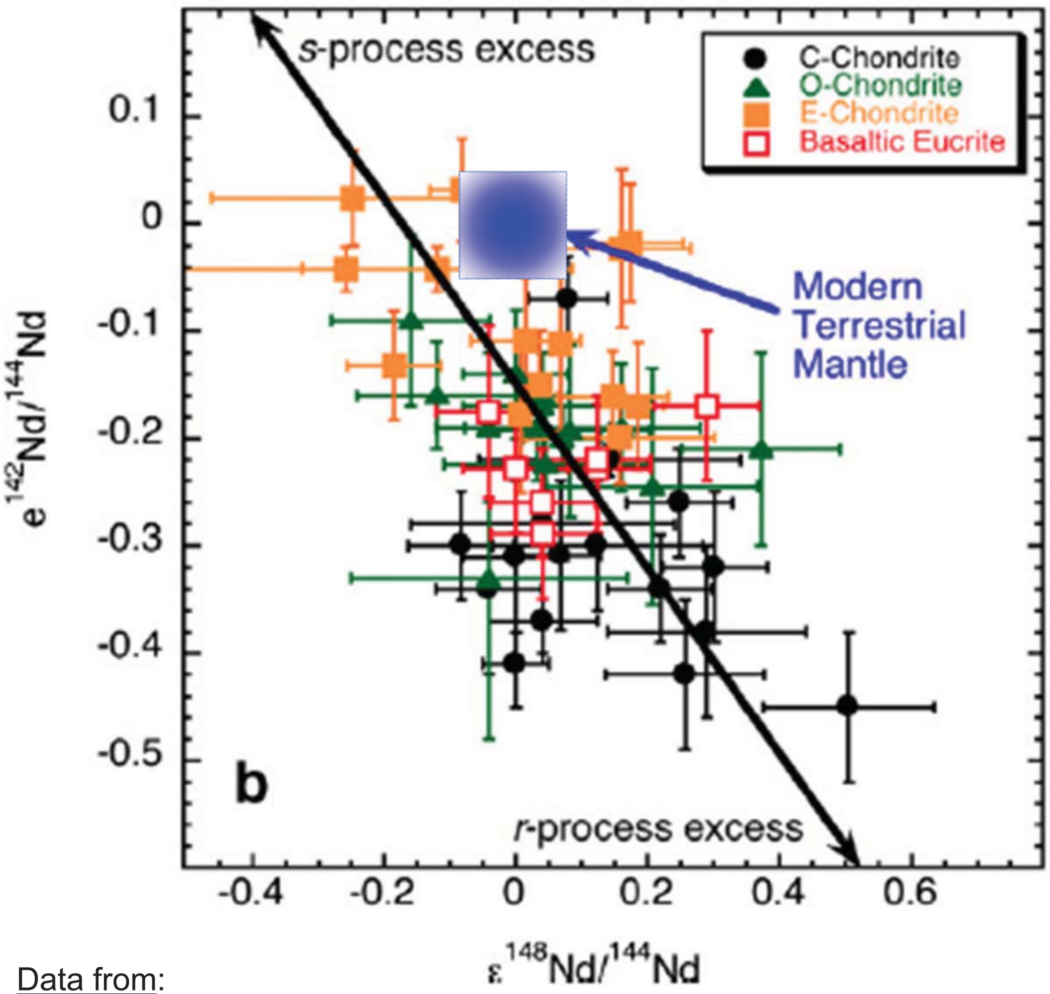


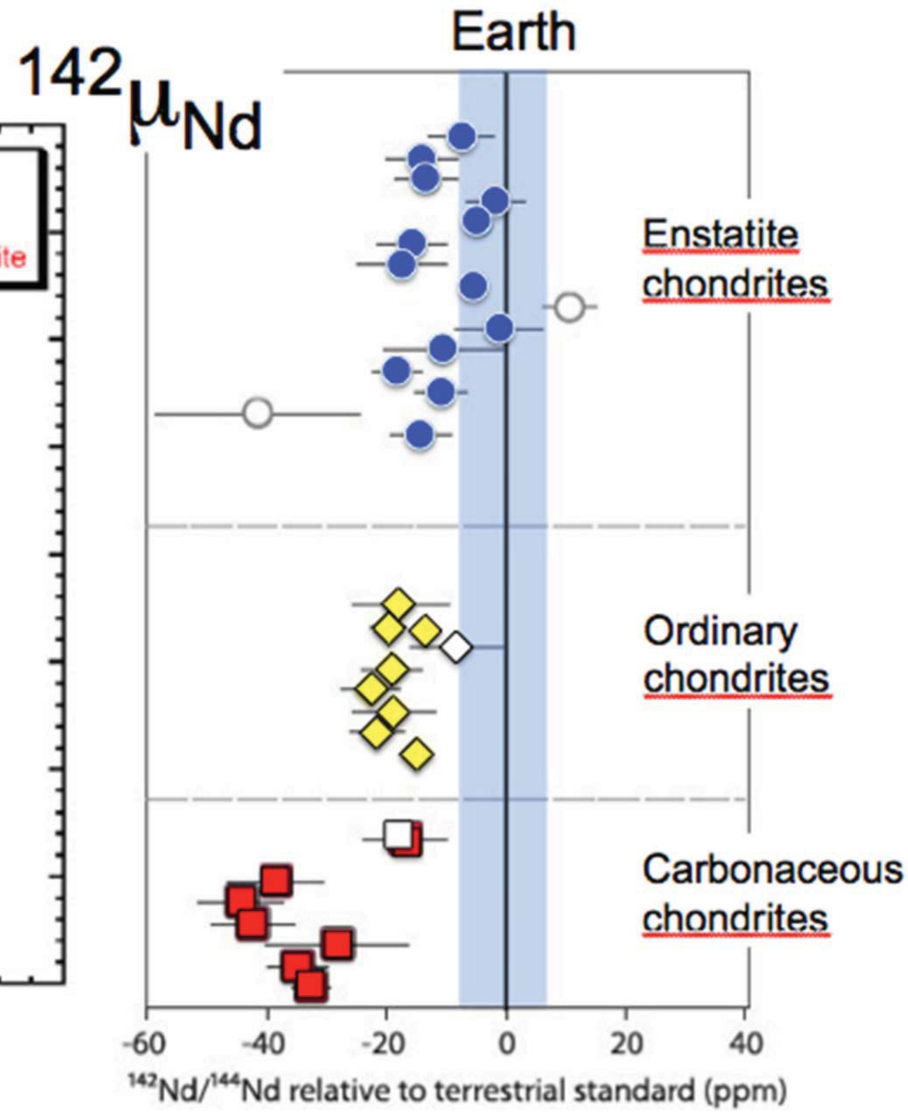
diagrams from Warren (2011, EPSL)





^{142}Nd: what does it tell us about the Earth and chondrites?

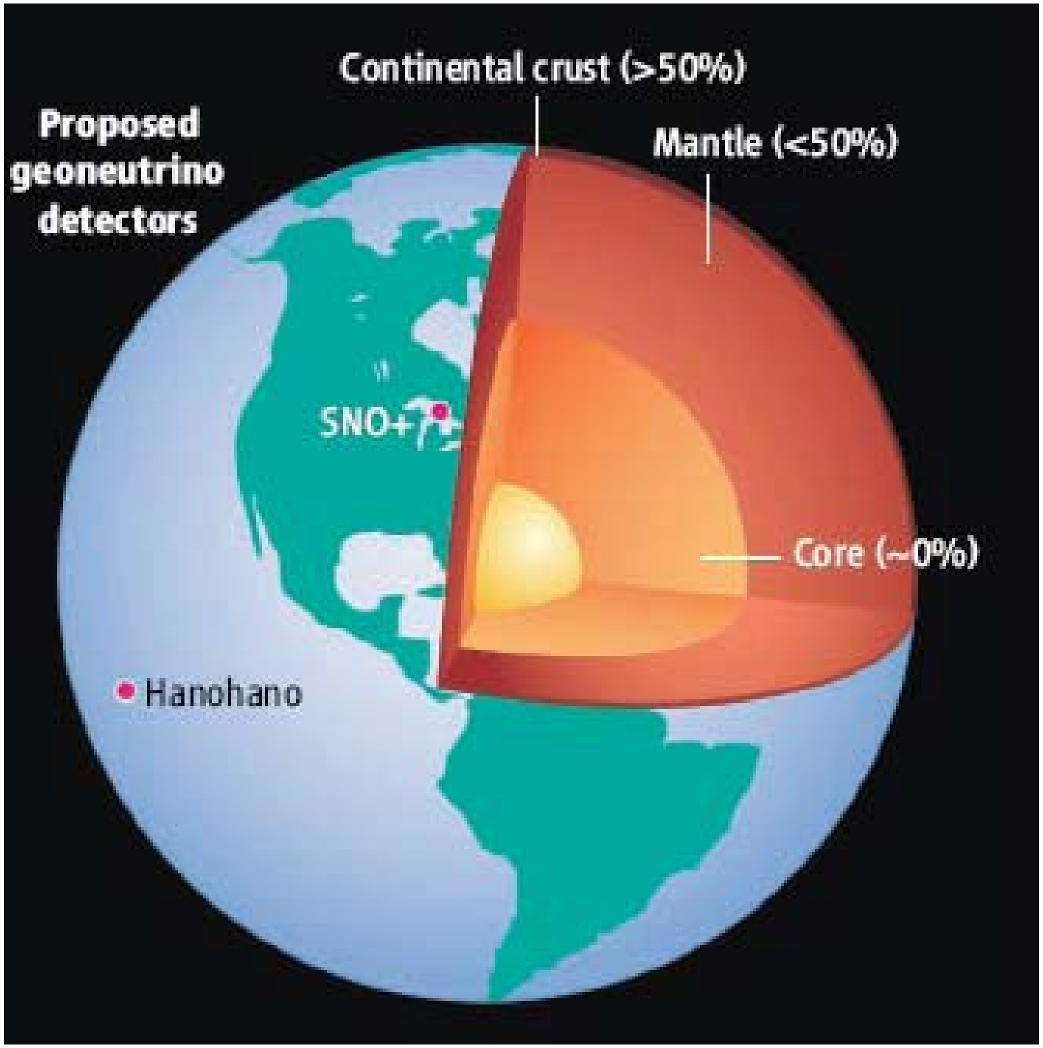




Data from:
Gannoun et al (2011, PNAS); Carlson et al (Science, 2007)
Andreasen & Sharma (Science, 2006); Boyet and Carlson (2005, Science);
Jacobsen & Wasserburg (EPSL, 1984); Qin et al (GCA, 2011)

U in the Earth:

"Differentiation"



~13 ng/g U in the Earth

Metallic sphere (core)
<<<1 ng/g U

Silicate sphere
20* ng/g U

**O'Neill & Palme (2008) 10 ng/g*
**Turcotte & Schubert (2002) 31 ng/g*

Continental Crust
1300 ng/g U

Mantle
~12 ng/g U

Chromatographic separation
Mantle melting & crust formation

Parameterized Convection Models *vigor of convection*

Thermal evolution of the mantle

$$Ra = \frac{\rho_0 g \alpha_v (T_1 - T_0) d^3}{\eta \kappa}$$

η = viscosity
ρ = density
g = accel. due gravity
α = thermal exp. coeff.
κ = thermal diffusivity
d = length scale
T = boundary layer T°

$Ra_{mantle} > Ra_{critical}$
mantle convects!

$$Q \propto Ra^{\beta}$$

Q: heat flux, Ra: Rayleigh number,

β: an amplifer - balance between viscosity and heat dissipation

At what rate does the Earth dissipate its heat?

- Models with $\beta \sim 0.3$ --- Schubert et al '80; Davies '80; Turcotte et al '01
- Models with $\beta << 0.3$ --- Jaupart et al '08; Korenaga '06; Grigne et al '05,'07

Convection Urey Ratio and Mantle Models

$$\text{Urey ratio} = \frac{\text{radioactive heat production}}{\text{heat loss}}$$

- Mantle convection models typically assume:
  mantle Urey ratio: **~0.7**
- Geochemical models predict:
  mantle Urey ratio **~0.3**

Factor of 2 discrepancy

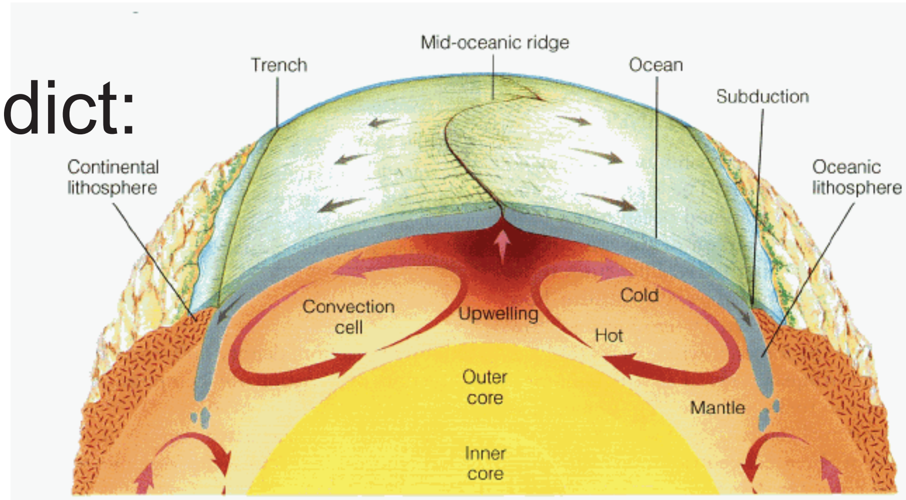
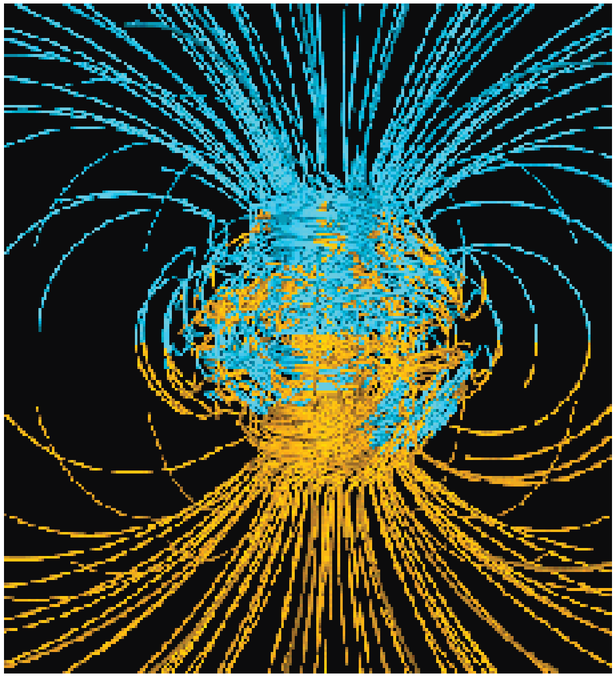
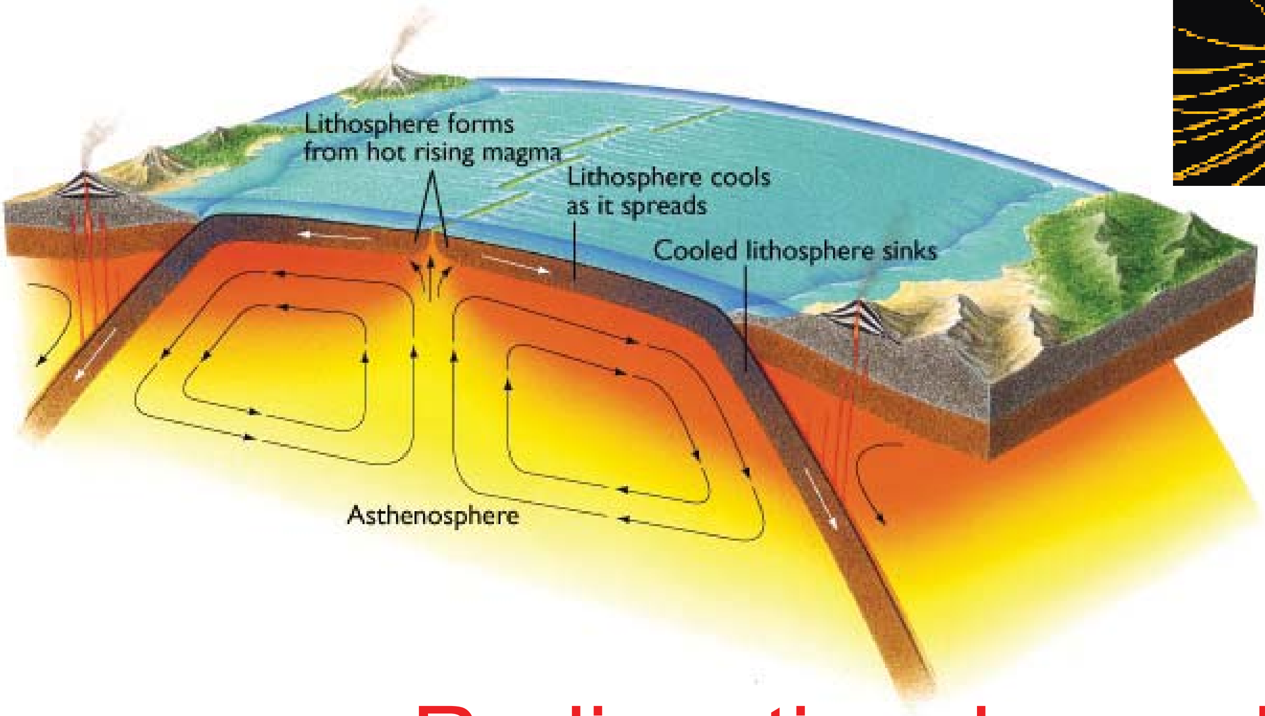
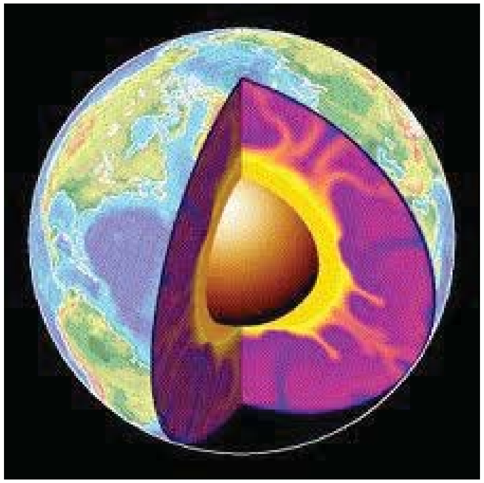


Plate Tectonics, Convection, Geodynamo







Radioactive decay driving the Earth's engine!

nature geoscience **2011** ARTICLES

PUBLISHED ONLINE: 17 JULY 2011 | DOI: 10.1038/NGEO1205

Partial radiogenic heat model for Earth revealed by geoneutrino measurements

The KamLAND Collaboration*

Detecting ***Geoneutrinos*** from the Earth

2005

Physics Letters B 687 (2010) 299–304

Contents lists available at ScienceDirect

Physics Letters B

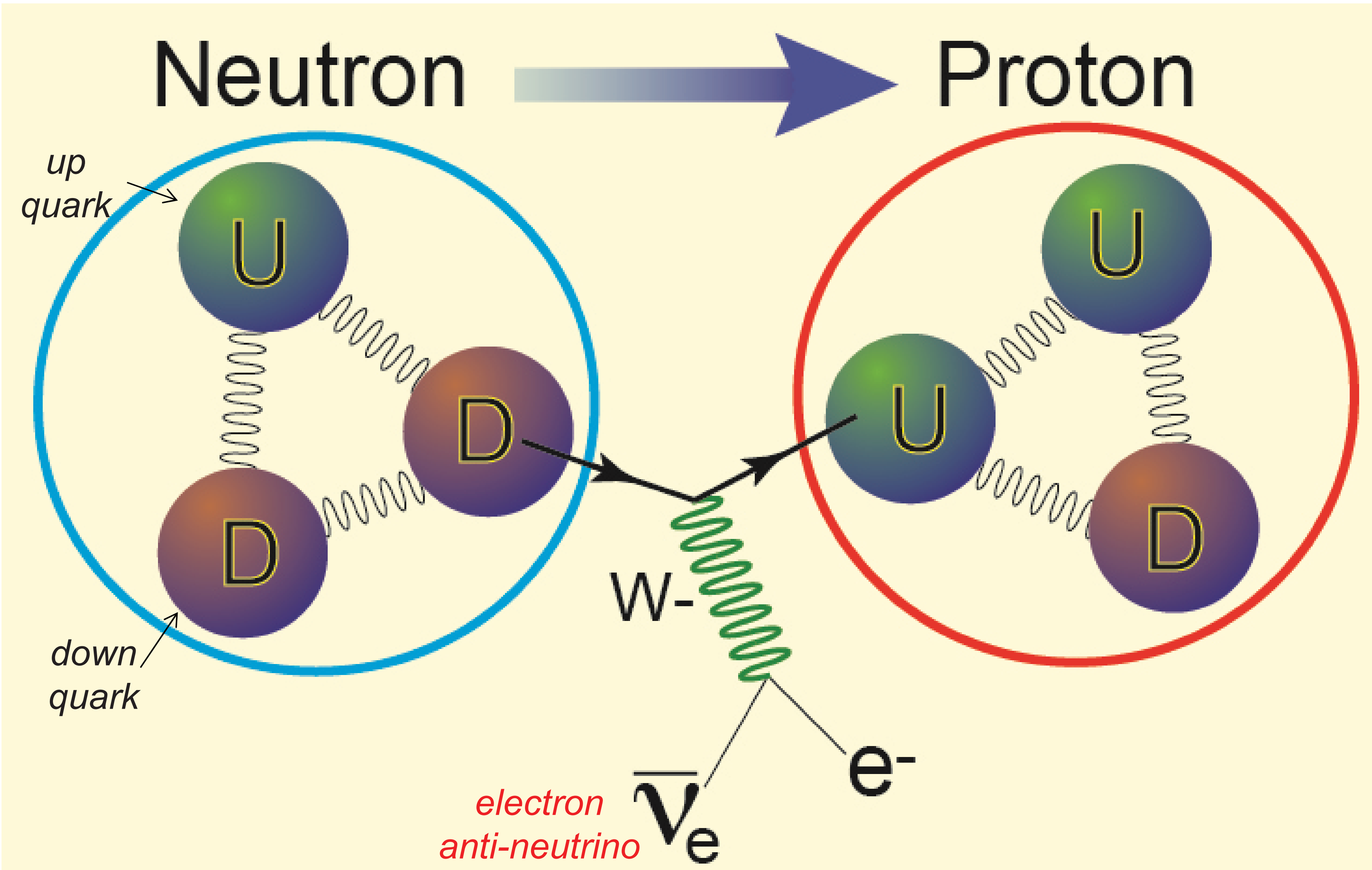
www.elsevier.com/locate/physletb

2010

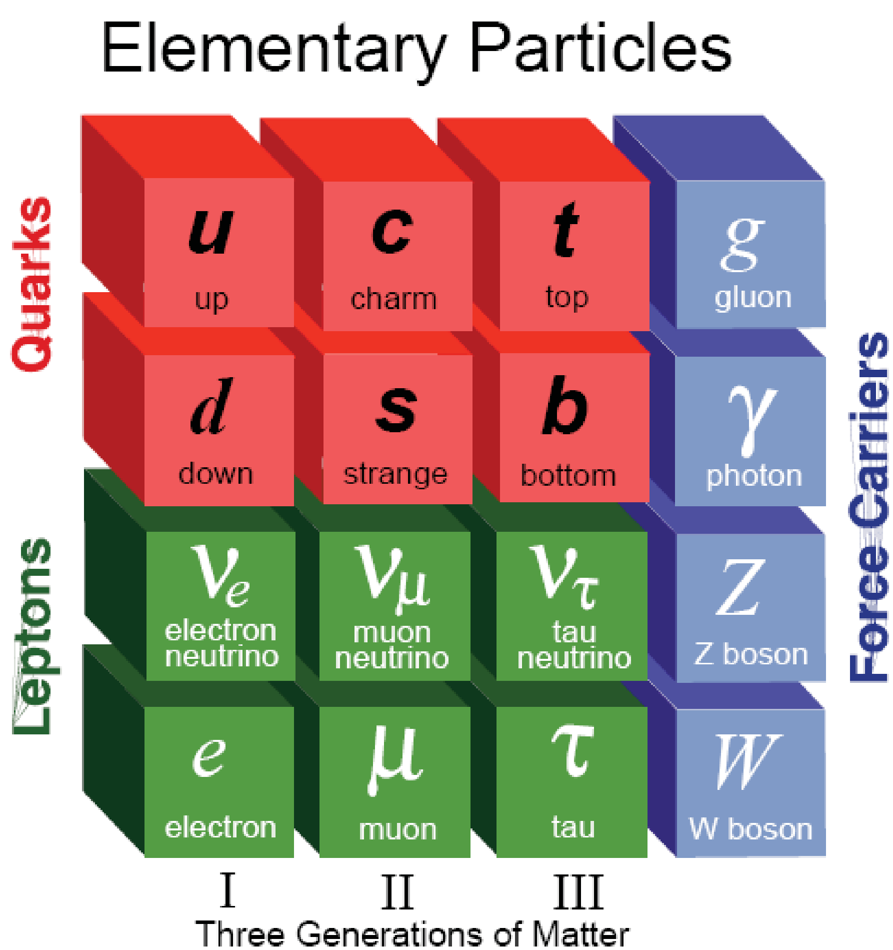
Observation of geo-neutrinos

Borexino Collaboration

β^- decay process (e.g., U, Th, K, Re, Lu, Rb)



What is Geoneutrino?



Geo-neutrinos: electron anti-neutrinos from the Earth, products of natural radioactivities

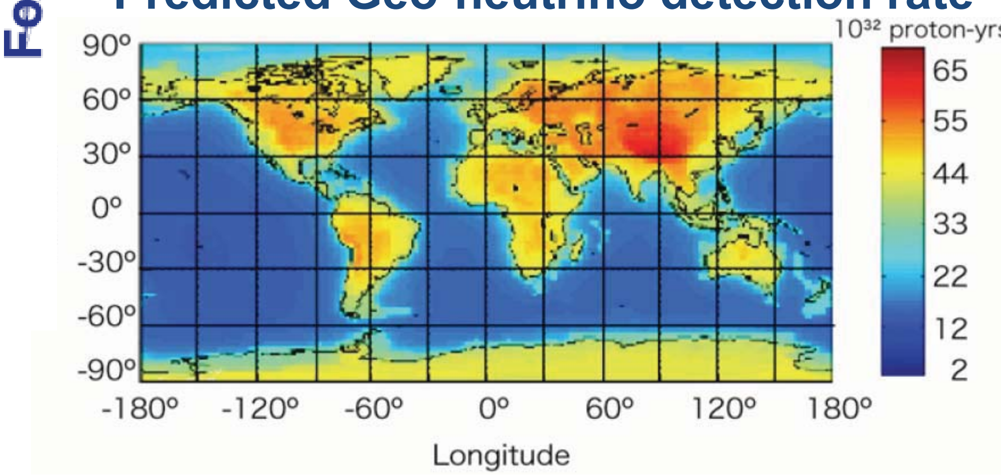
Geoneutrino flux

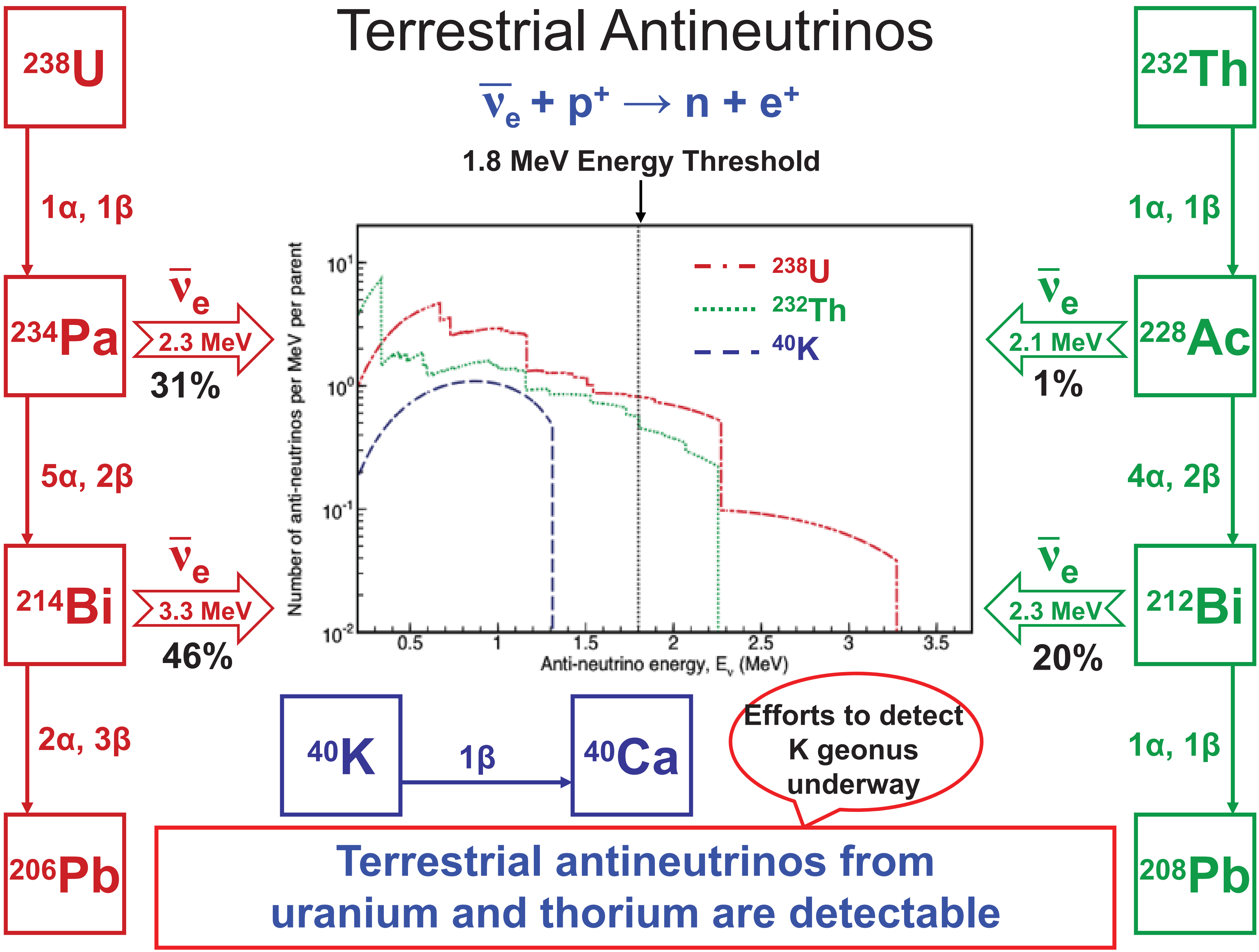
--typical flux $6*10^6$ cm^{-2} s^{-1}

Geoneutrino detection rate

--TNU: Terrestrial Neutrino Unit
-- 1 TNU = one geoneutrino event per 10^{32} free protons per year

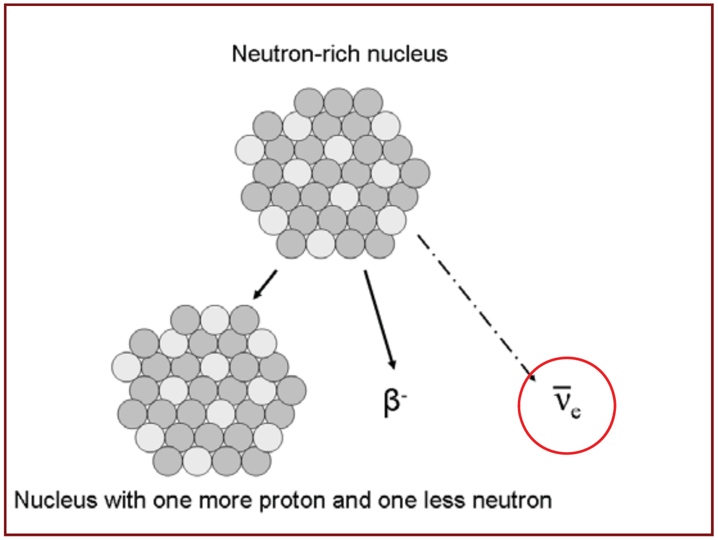
Predicted Geo-neutrino detection rate




Terrestrial Antineutrinos
$\bar{\nu}_e + p^+ \rightarrow n + e^+$
1.8 MeV Energy Threshold
^{238}U
1α, 1β
^{234}Pa
$\bar{\nu}_e$
2.3 MeV
31%
5α, 2β
^{214}Bi
$\bar{\nu}_e$
3.3 MeV
46%
2α, 3β
^{206}Pb
^{232}Th
1α, 1β
^{228}Ac
$\bar{\nu}_e$
2.1 MeV
1%
4α, 2β
^{212}Bi
$\bar{\nu}_e$
2.3 MeV
20%
1α, 1β
^{208}Pb
Number of anti-neutrinos per MeV per parent
10^{1}
10^{0}
10^{-1}
10^{-2}
0.5
1
1.5
2
2.5
3
3.5
Anti-neutrino energy, E_ν (MeV)
^{238}U
^{232}Th
^{40}K
^{40}K
1β
^{40}Ca
Efforts to detect K geonus underway
Terrestrial antineutrinos from uranium and thorium are detectable

MeV-Scale Electron Anti-Neutrino Detection

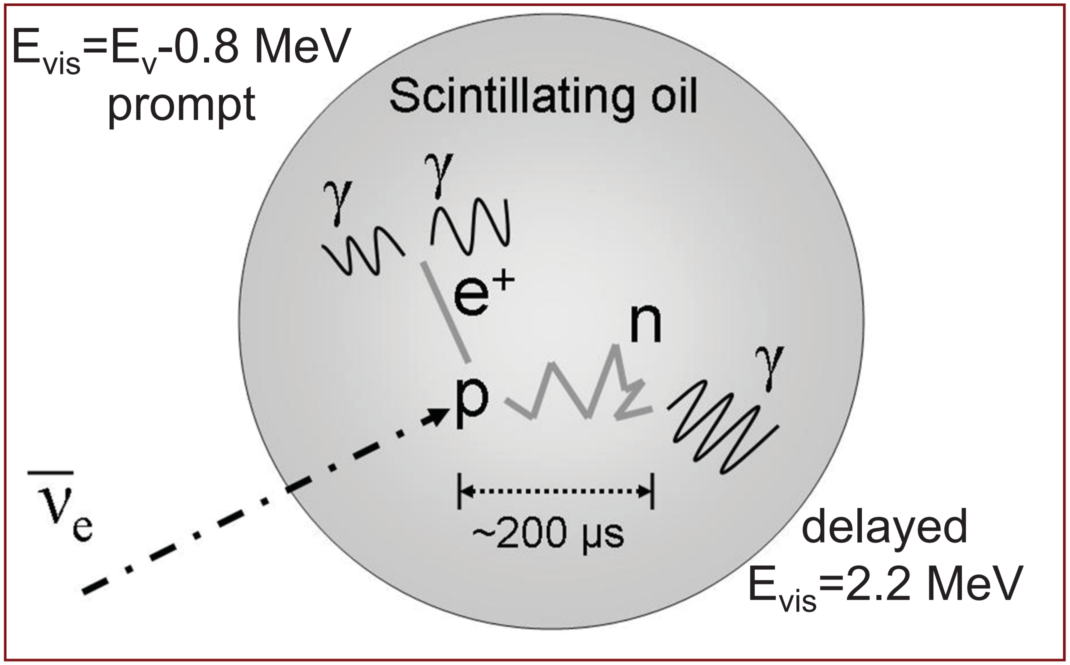
Production in reactors and natural decays



Reines & Cowan

Key: 2 flashes, close in space and time, 2nd of known energy, eliminate background

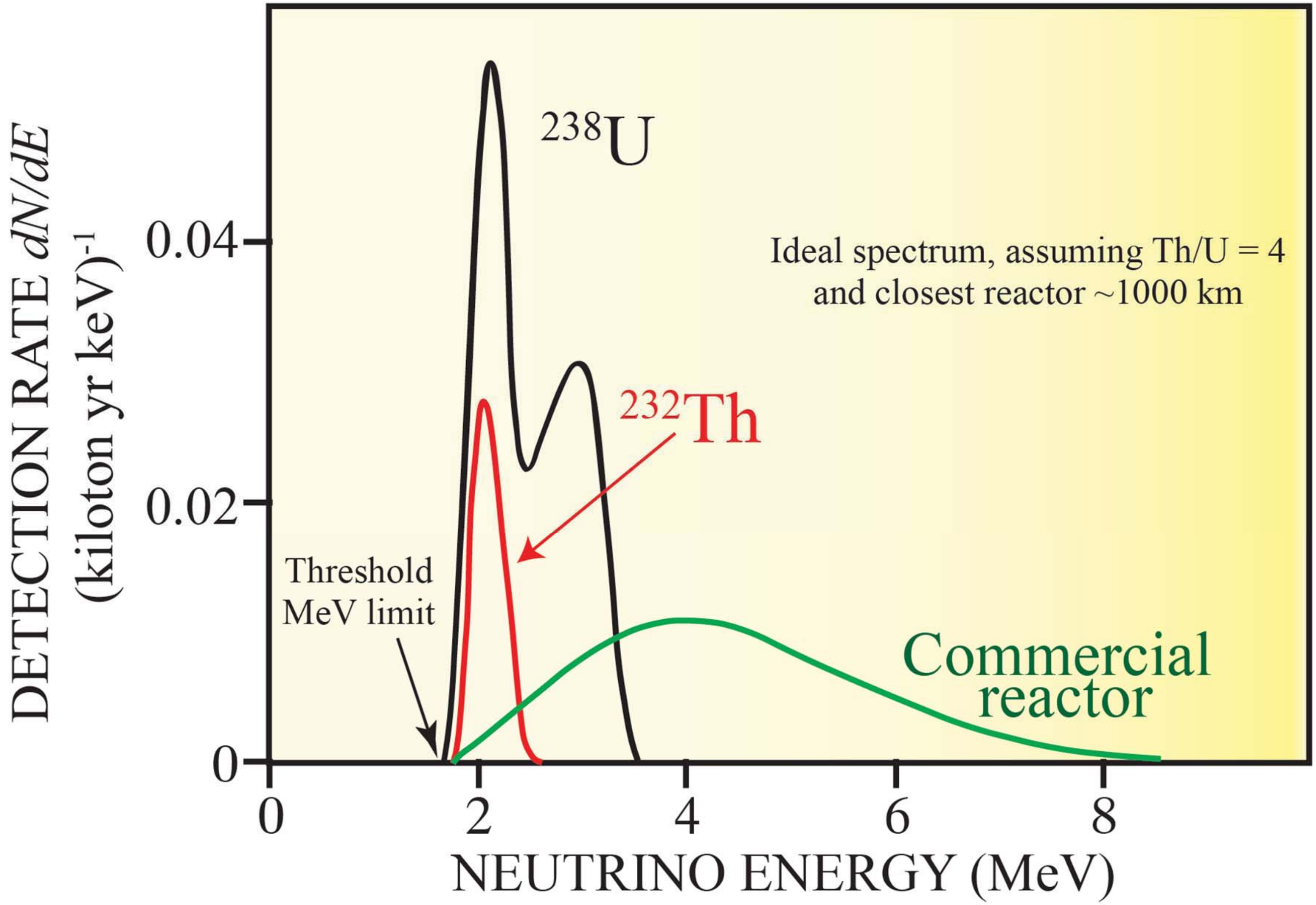
Detection



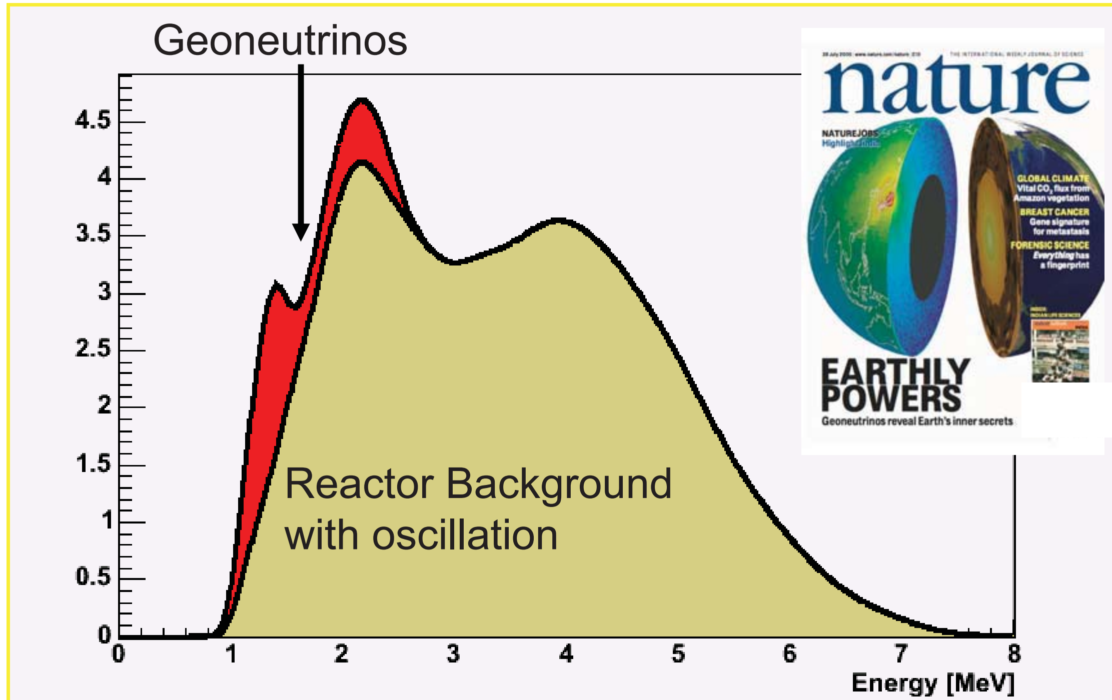
- Standard inverse β-decay coincidence
- $E_\nu > 1.8$ MeV
- Rate and spectrum - no direction

Antineutrinos - Geoneutrinos

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



Reactor and Earth Signal



- KamLAND was designed to measure reactor antineutrinos.
- Reactor antineutrinos are the most significant contributor to the total signal.

Latest results

106 $^{+29}_{-28}$

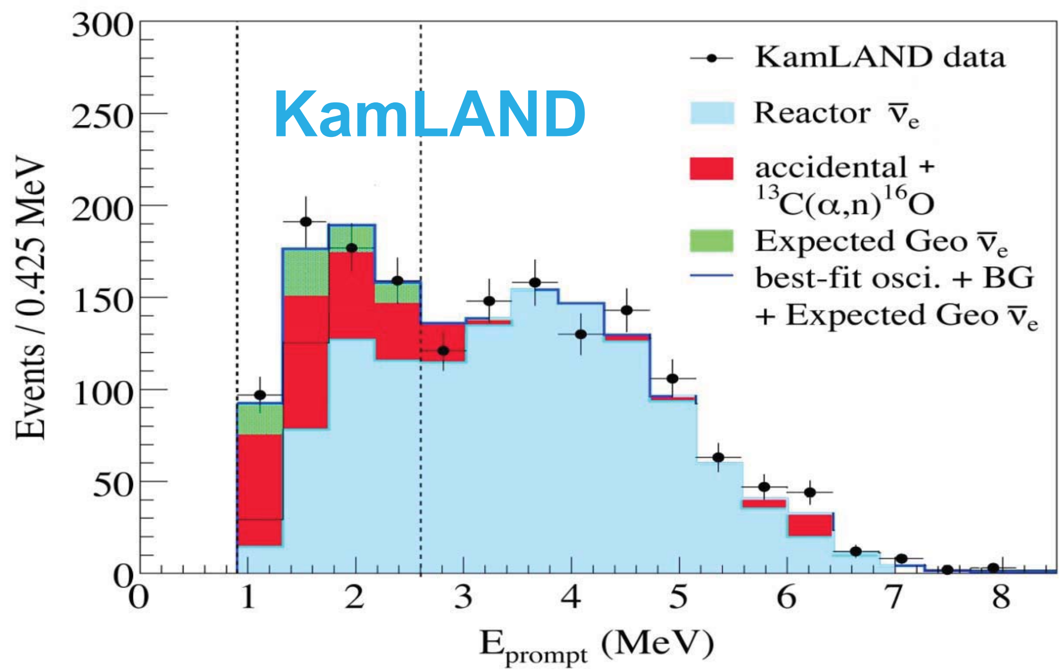
from 2002 to Nov 2009

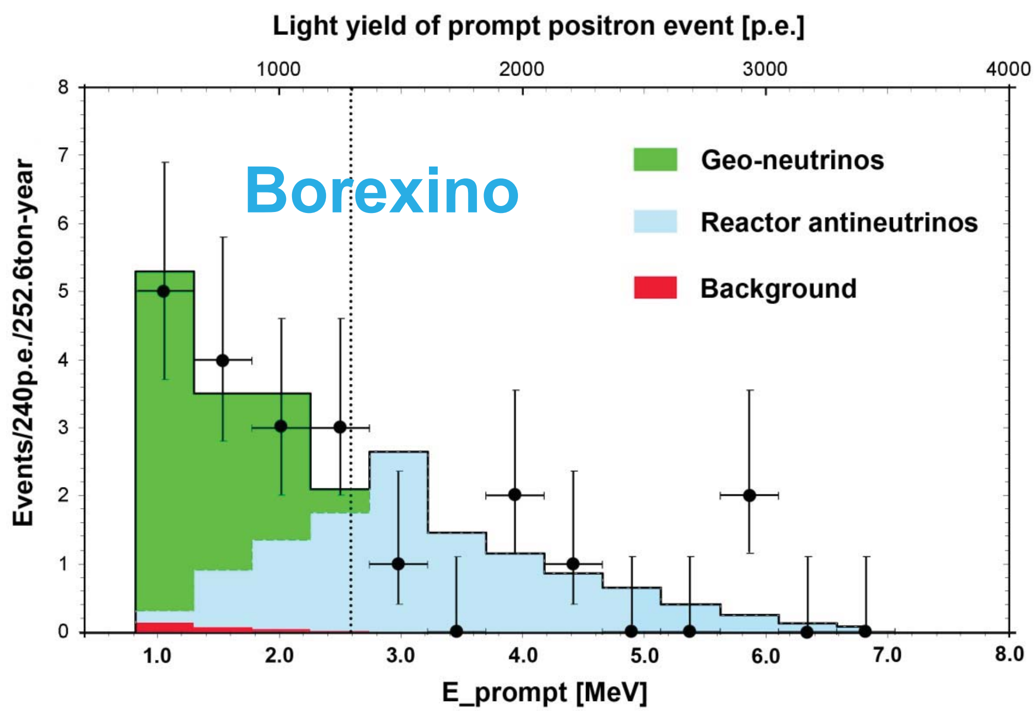
Event rates

9.9 $^{+4.1}_{-3.4}$

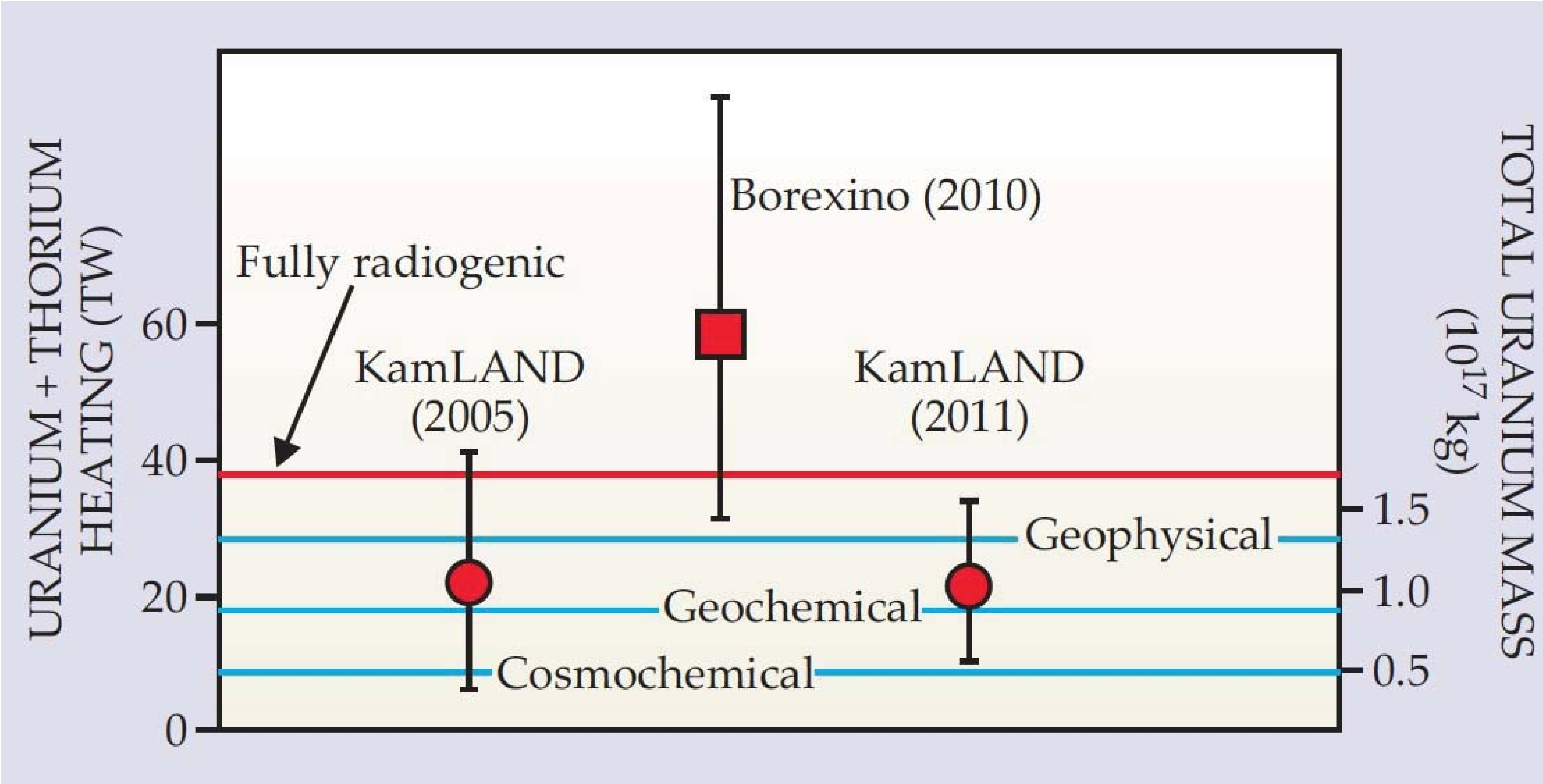
from May ‘07 to Dec ‘09

under construction





Summary of geoneutrino results



MODELS

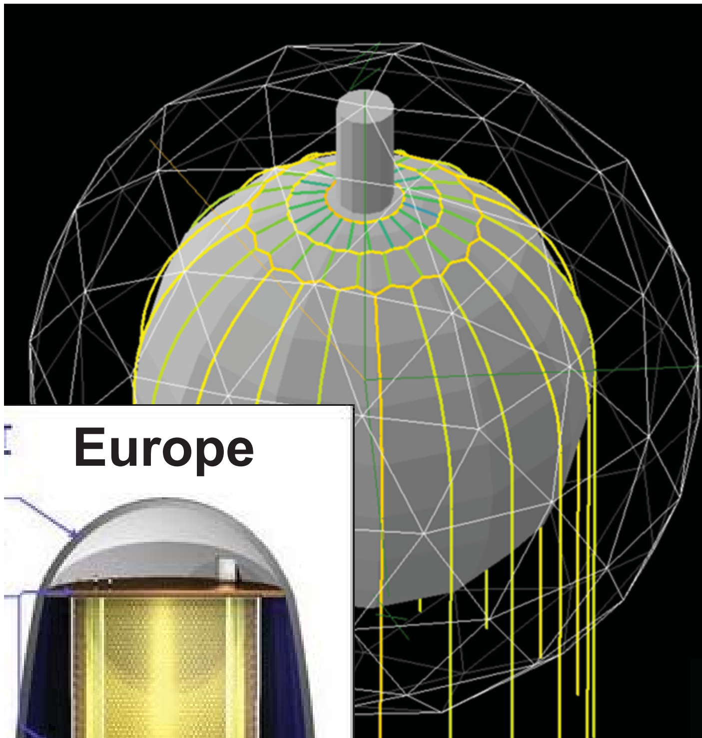
Cosmochemical: uses meteorites – *O'Neill & Palme ('08); Javoy et al ('10); Warren ('11)*

Geochemical: uses terrestrial rocks – *McD & Sun '95; Allegre et al '95; Palme O'Neil '03*

Geophysical: parameterized convection – *Schubert et al; Davies; Turcotte et al; Anderson*

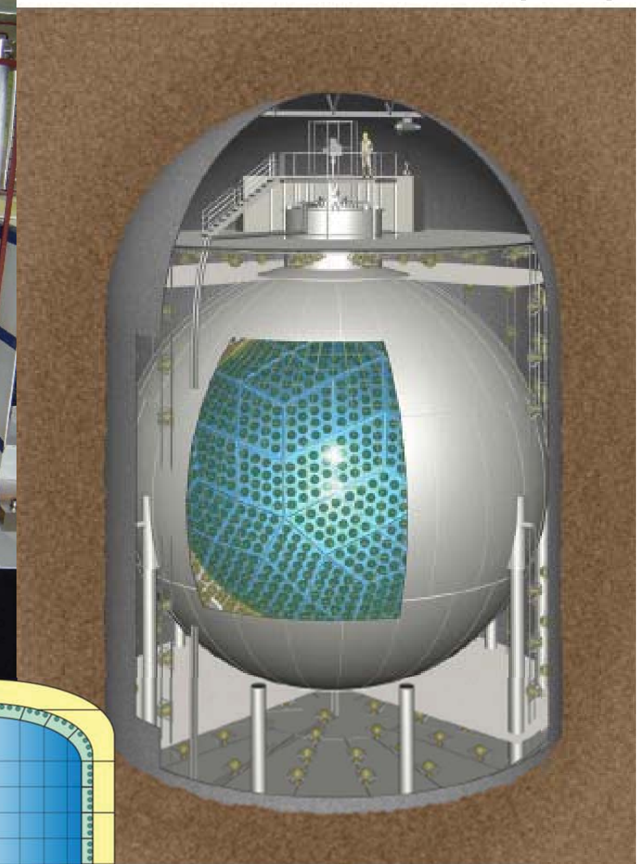
Present and future LS-detectors

SNO+, Canada (1kt)



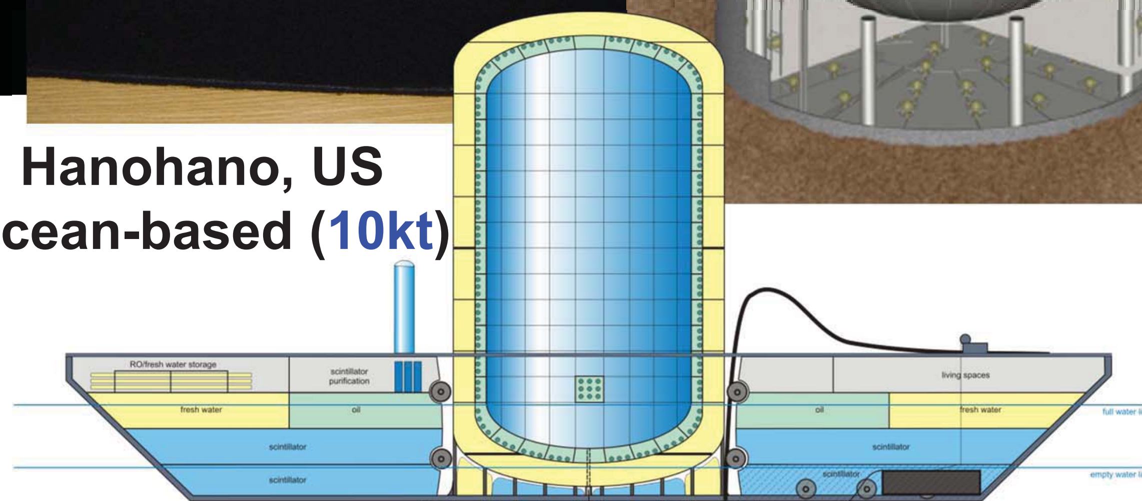
Borexino, Italy (0.6kt)

KamLAND, Japan (1kt)



LENA, EU (50kt)

Hanohano, US ocean-based (10kt)



Earth's geoneutrino flux

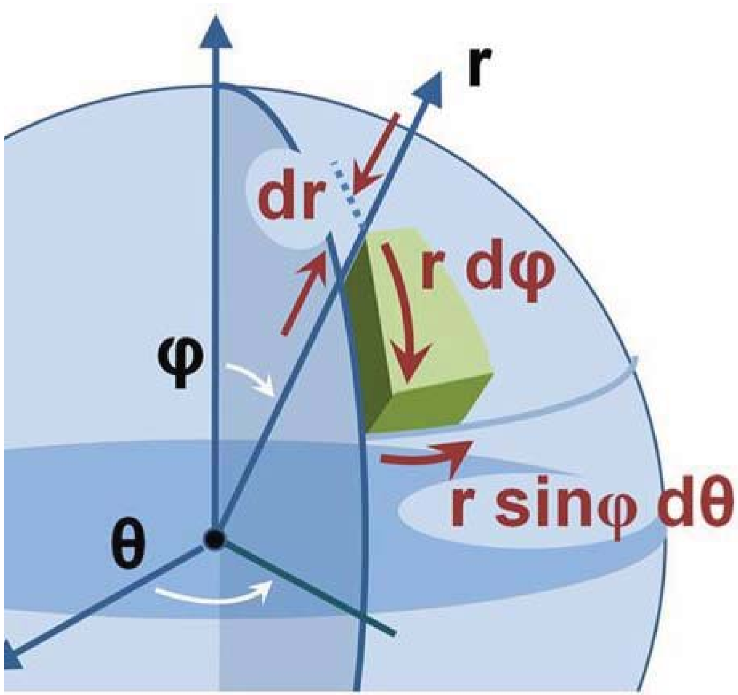
$$\Phi_X(\vec{r}_0) = \left(\frac{A_X \cdot N_X}{2R_\oplus}\right)\frac{R_\oplus}{2\pi}\int_\oplus dV \frac{a_X(\vec{r})\cdot\rho(\vec{r})}{\left|\vec{r}-\vec{r}_0\right|^2}$$

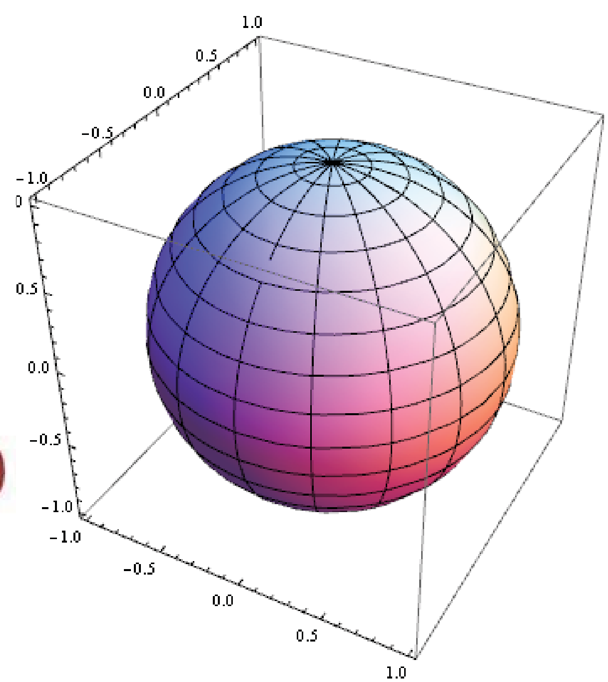
X	U or Th
$\Phi_X(r_0)$	Flux of anti-neutrinos from X at detector position r_0
A_X	Frequency of radioactive decay of X per unit mass
N_X	Number of anti-neutrinos produced per decay of X
$R_\oplus$	Earth radius
$a_X(r)$	Concentration of X at position r
$\rho(r)$	Density of earth at position r

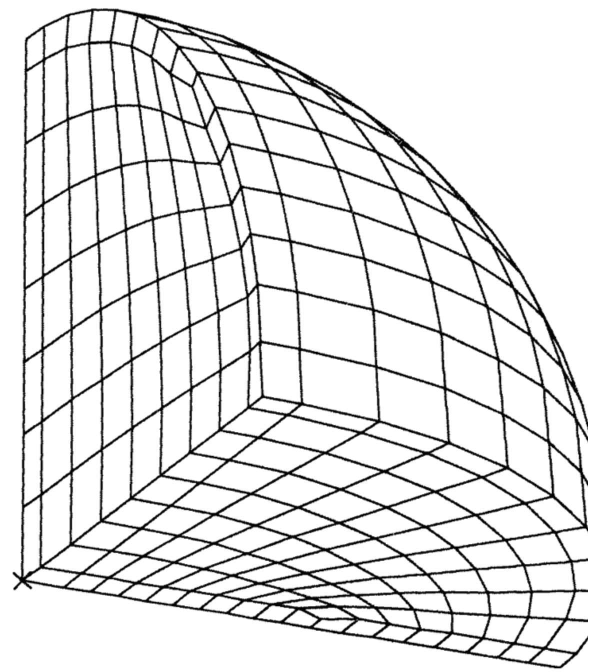
Interrogating the composition of the continental crust and "thermo-mechanical pile" (super-plumes?) in the mantle …

Constructing a 3-D reference model Earth

assigning chemical and physical states to Earth voxels

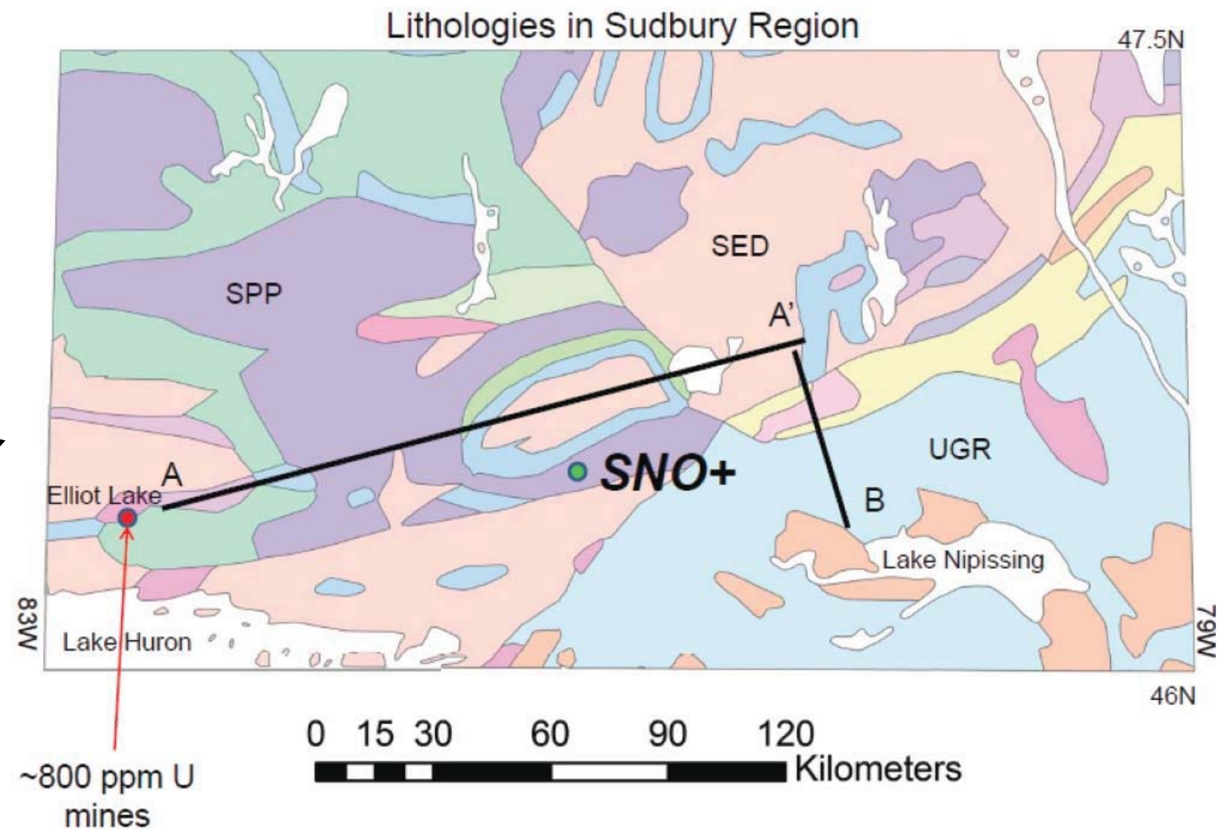






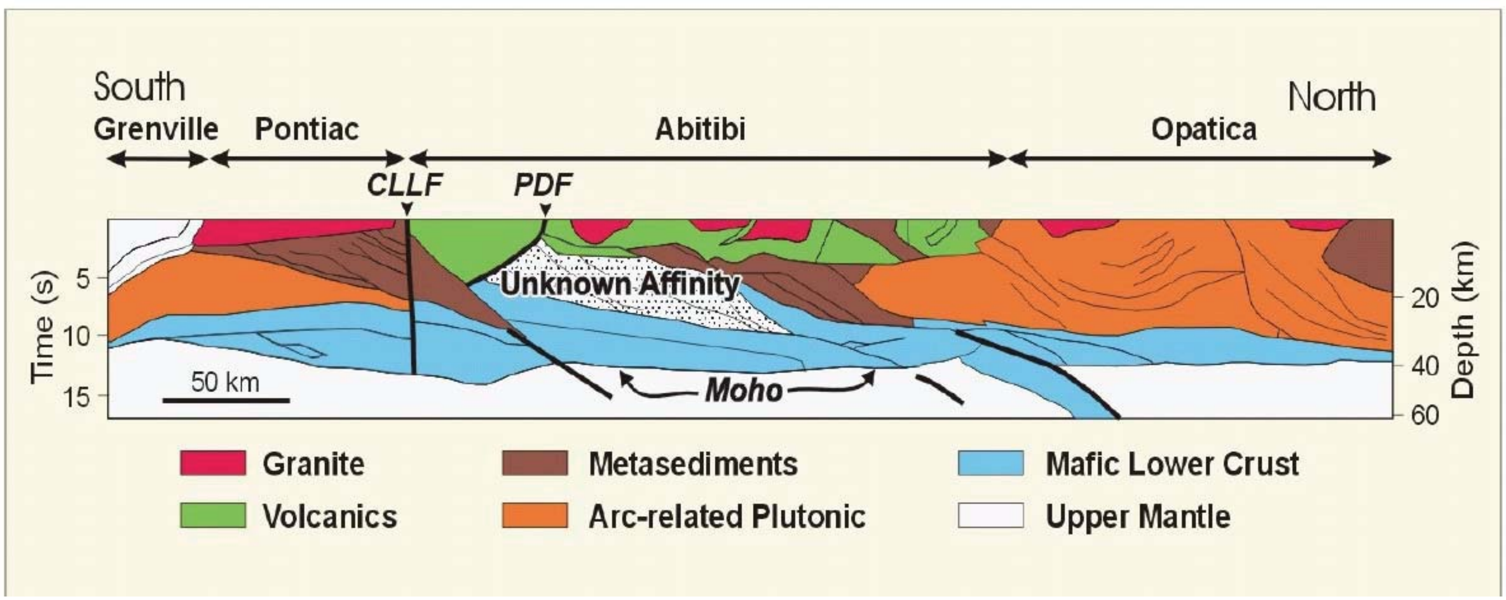
Estimating the geoneutrino flux at SNO+

- Geology



- Geophysics

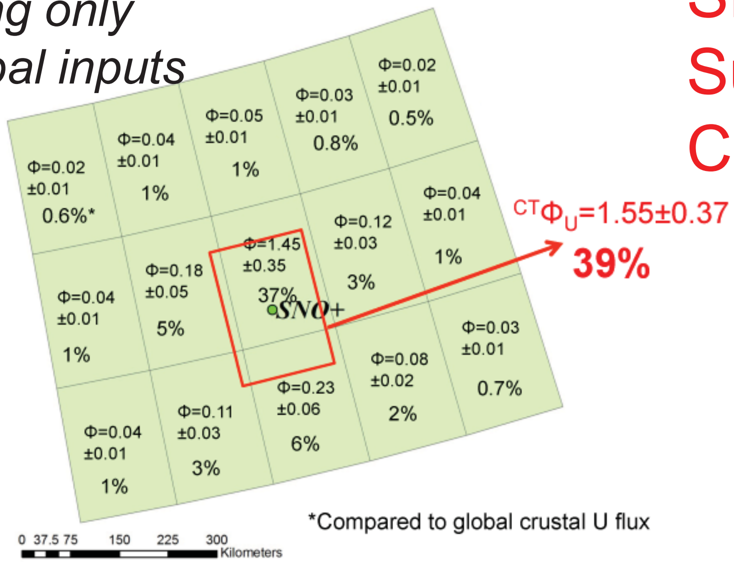
seismic x-section



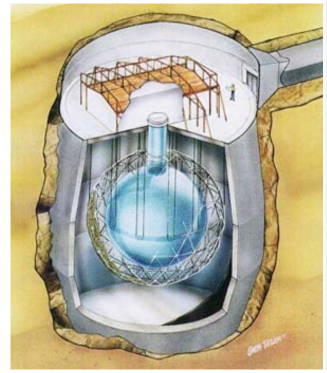
Global to Regional RRM

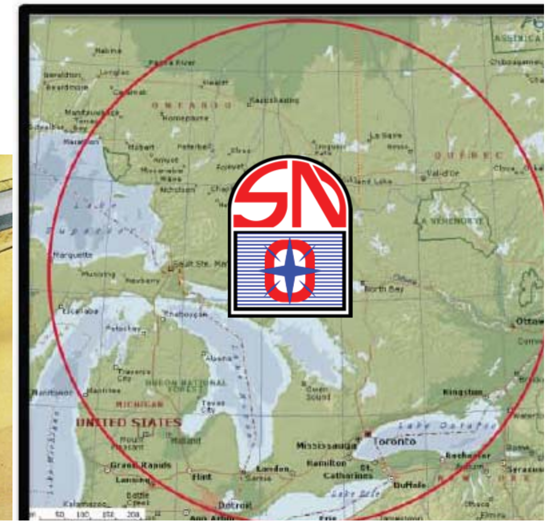
Regional Uranium Flux

using only global inputs



SNO+
Sudbury
Canada

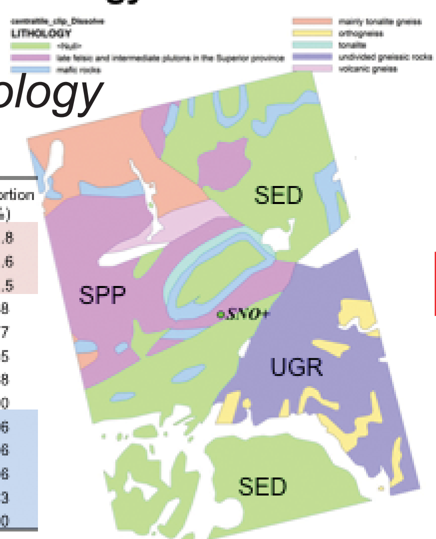




Central Tile Lithology

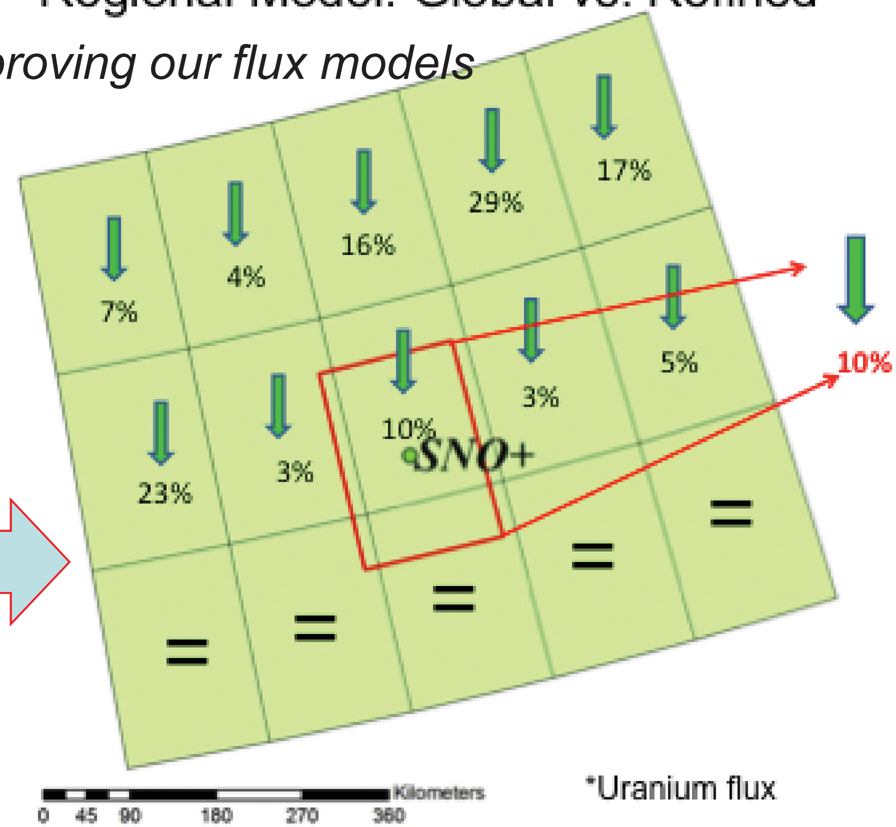
adding the regional geology

LITHOLOGY	AREA (10^9 m^2)	Proportion (%)
Sediments (**SED**)	11	40.8
Superior province felsic and intermediate plutons (**SPP**)	5.1	18.6
undivided gneissic rocks (**UGR**)	4.8	17.5
mainly tonalite gneiss	2.1	7.8
mafic rocks	1.8	6.7
orthogneiss	1.0	3.5
volcanic gneiss	0.5	1.8
tonalite	0.3	1.0
felsic rocks	0.2	0.6
gabbro-anorthosite	0.2	0.6
paragneiss	0.2	0.6
undivided granitic rocks	0.09	0.3
undivided volcanic rocks	0.01	0.0



Regional Model: Global vs. Refined*

improving our flux models

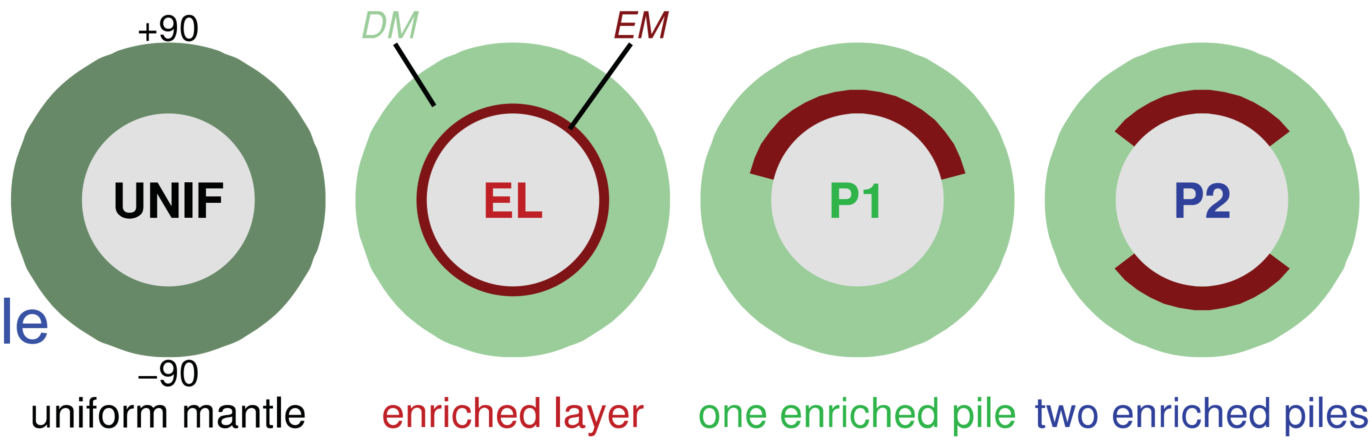


*Uranium flux

Models for understand Th & U in the Modern Mantle

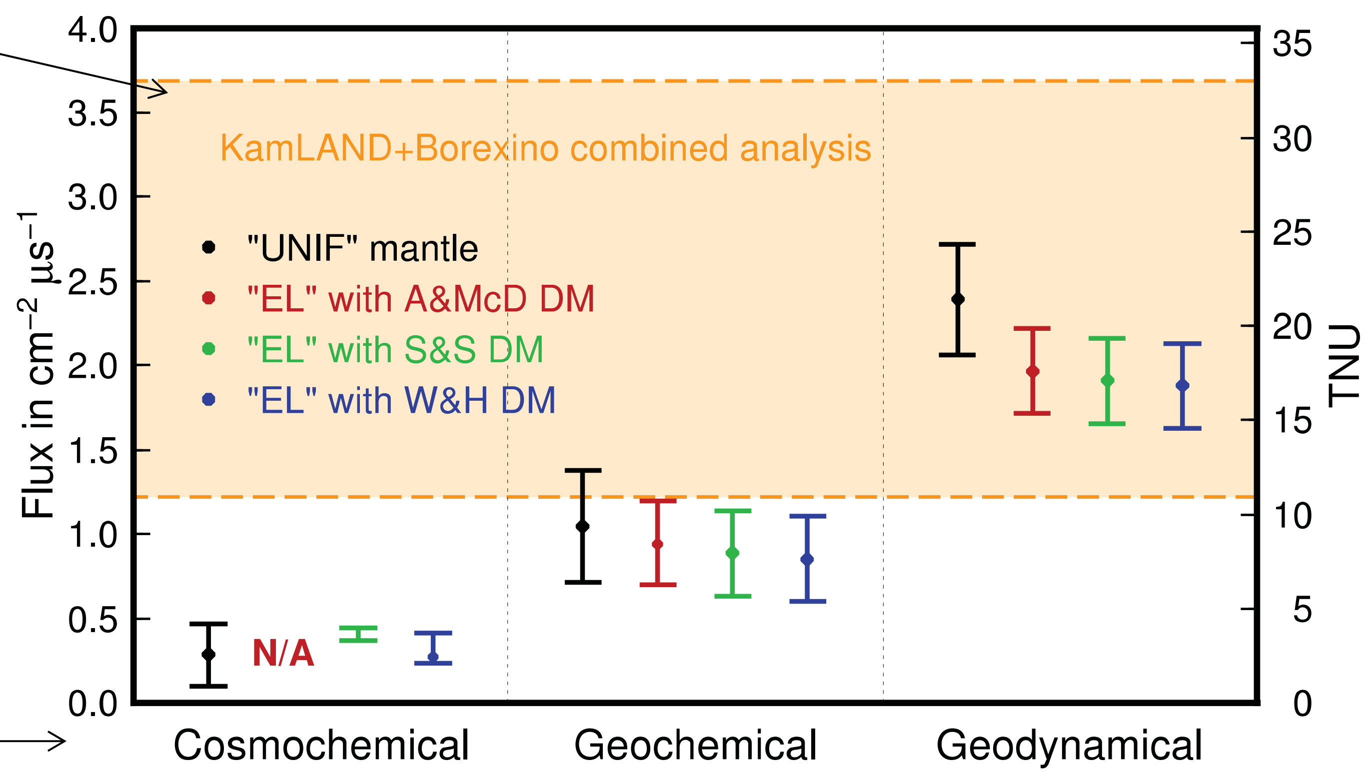
Inputs

- Bulk Sil. Earth
- Cont. Crust
- Depleted Mantle



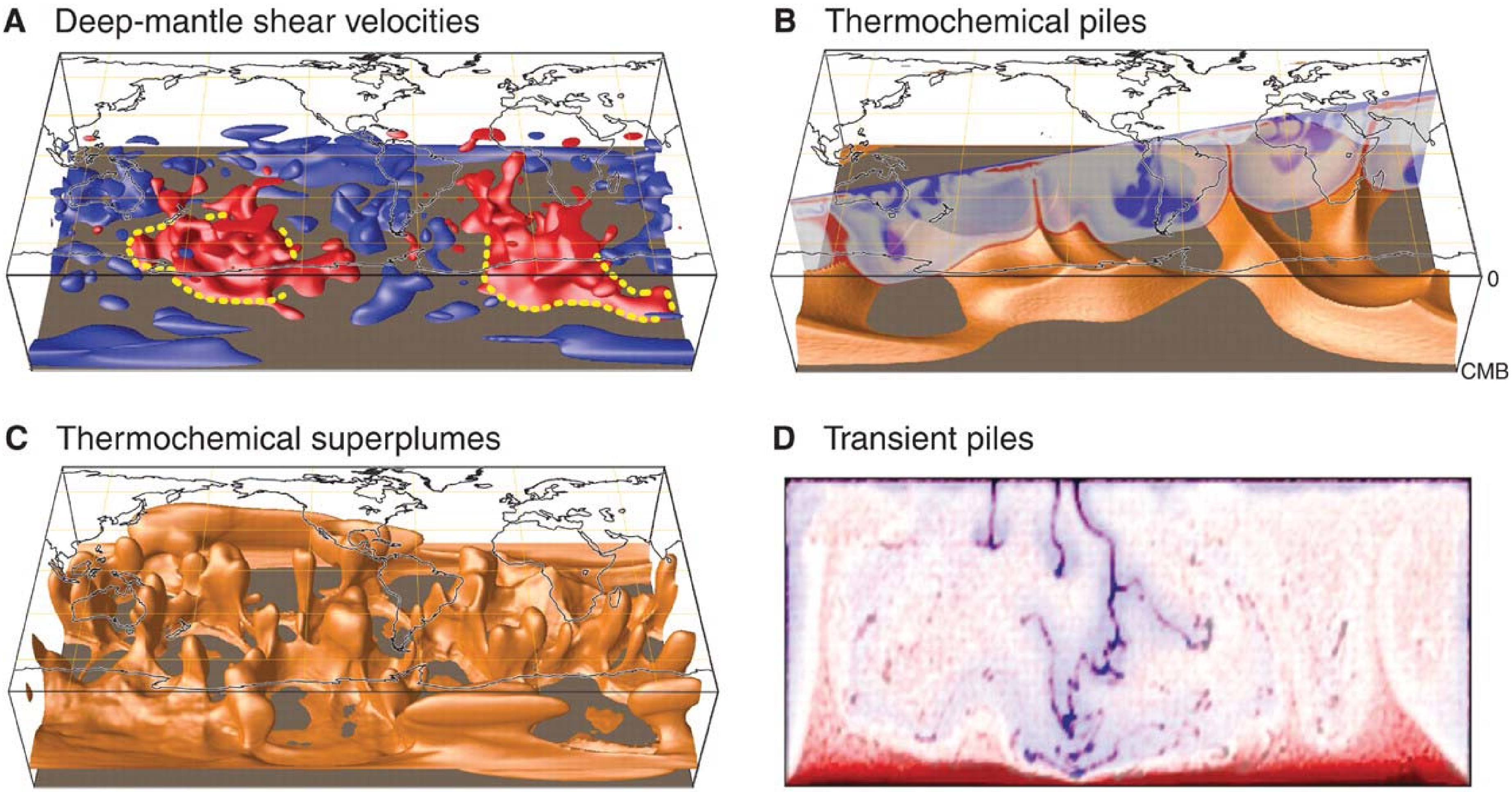
Geonu data

Data vs Models

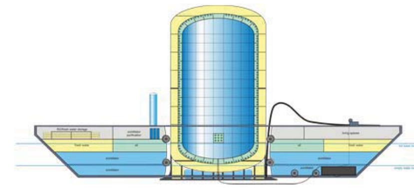


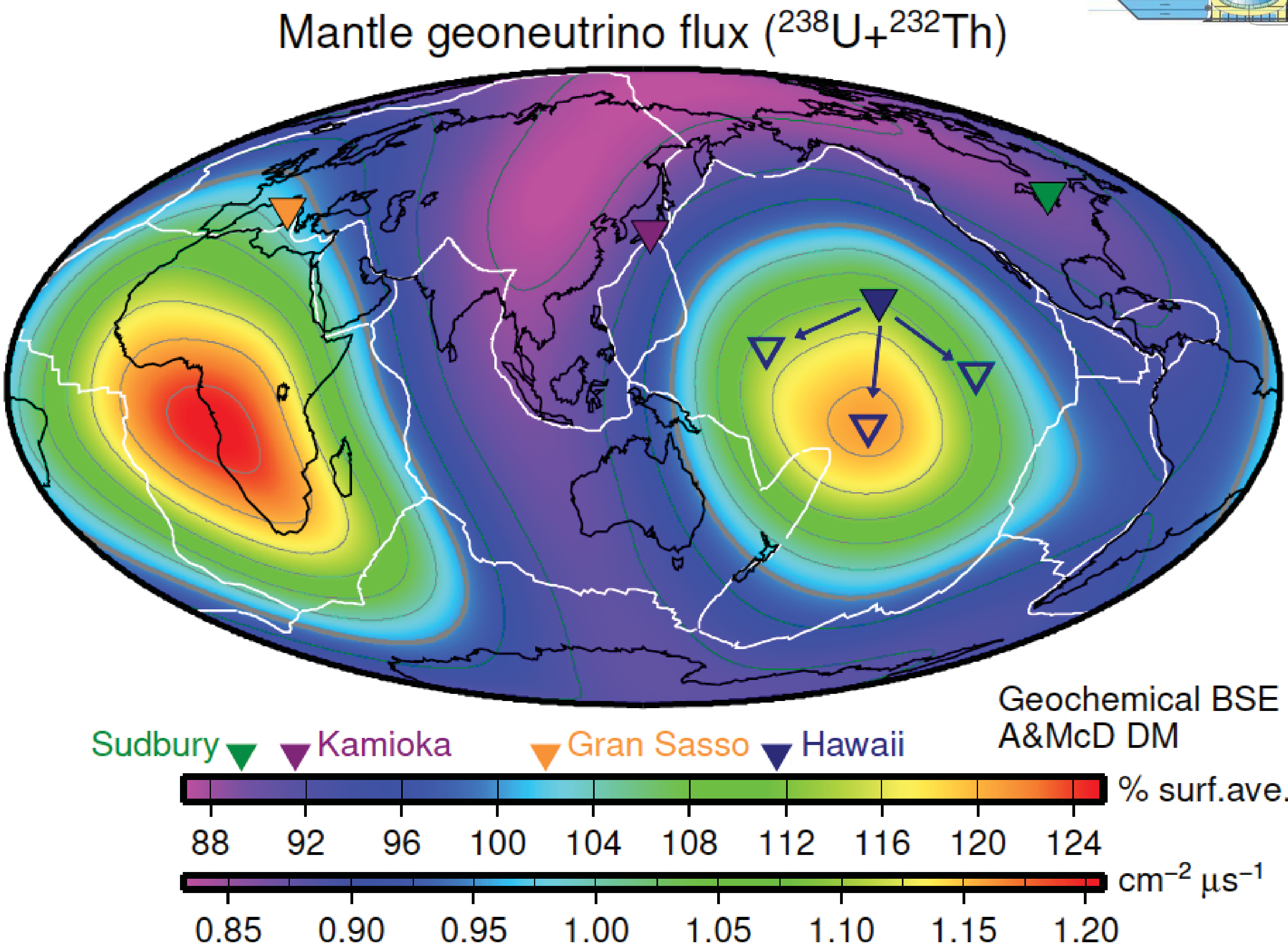
BSE Models

Structures in the mantle



Testing Earth Models





Šrámek et al, 2012, EPSL

SUMMARY

Earth's radiogenic (Th & U) power **20 ± 9 TW*** (23 ± 10)

Prediction: models range from **11 to 28 TW**

Future: -SNO+ online mid-2013

…2020…??
- Daya Bay II
- LENA
- Hanohano?

- Neutrino Tomography… ☺