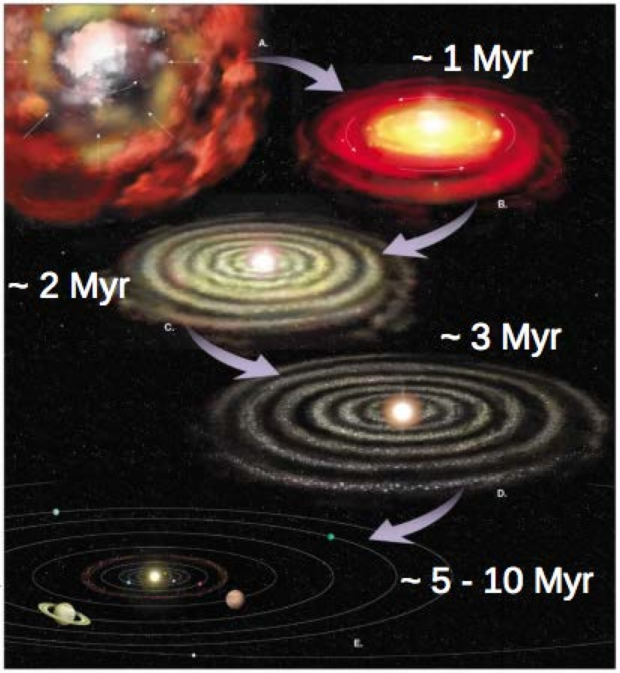
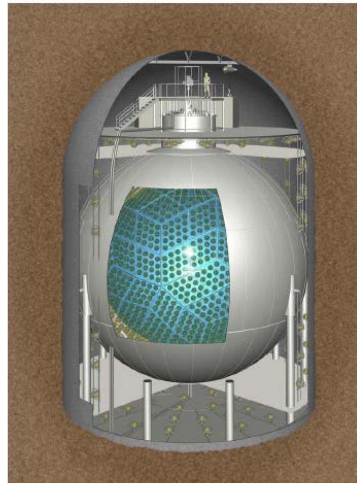
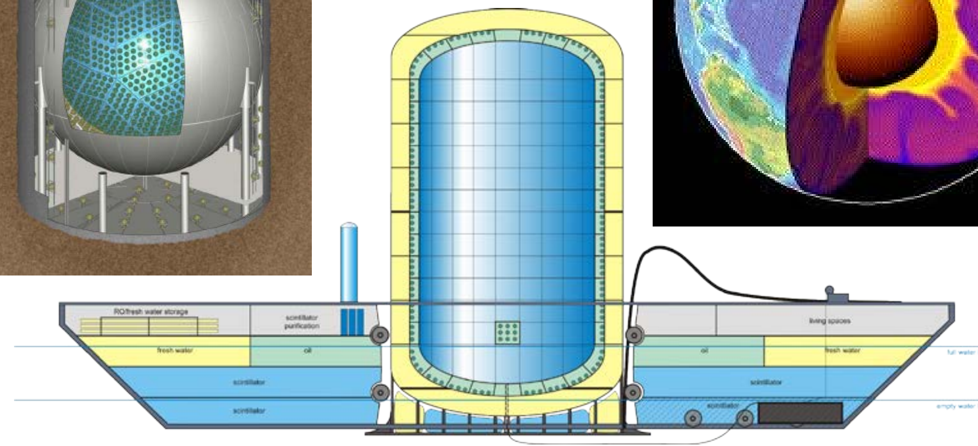
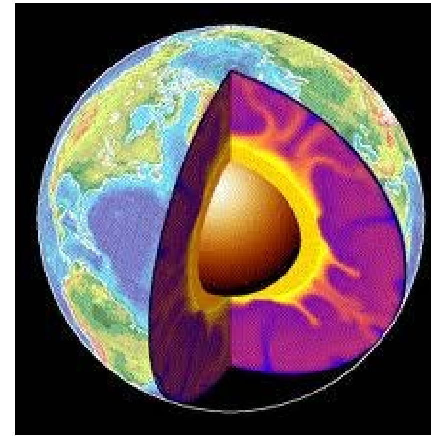
Grand Challenges in solid Earth Sciences

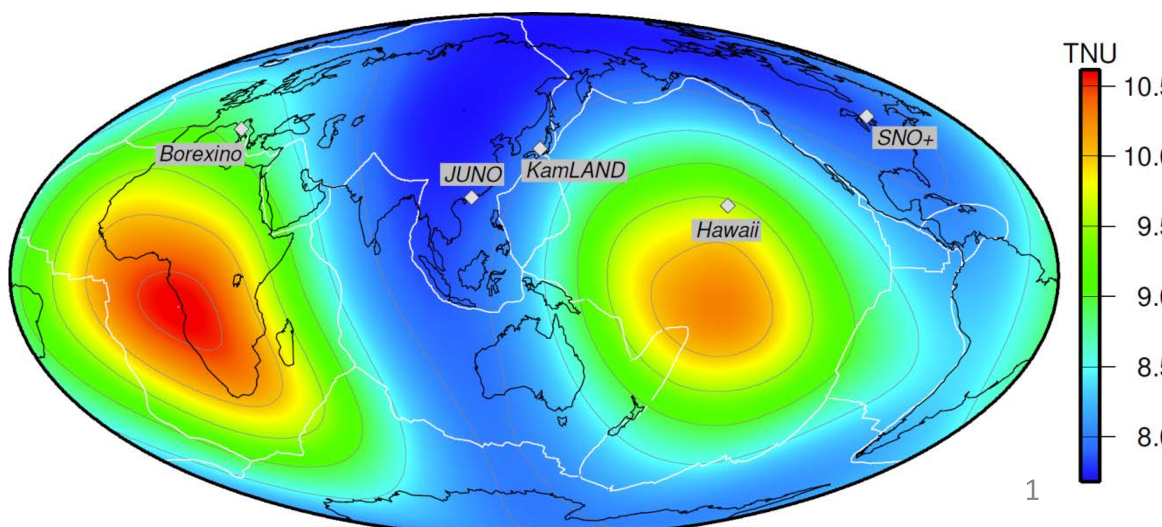








Bill McDonough
Geology, U Maryland

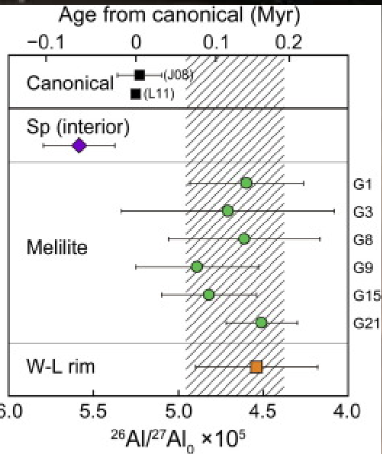


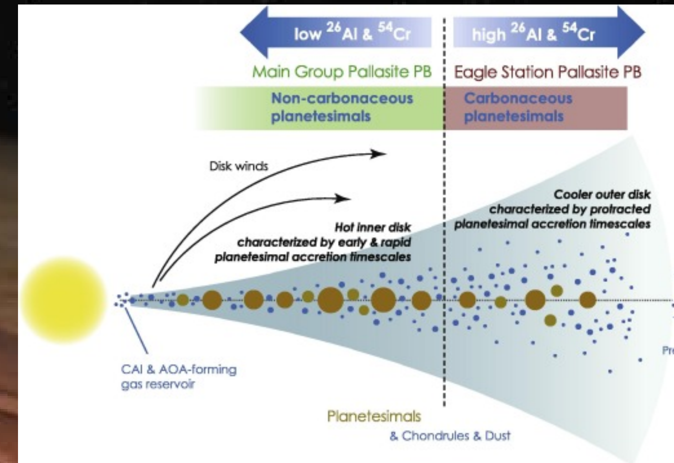
Observations about the mantle:

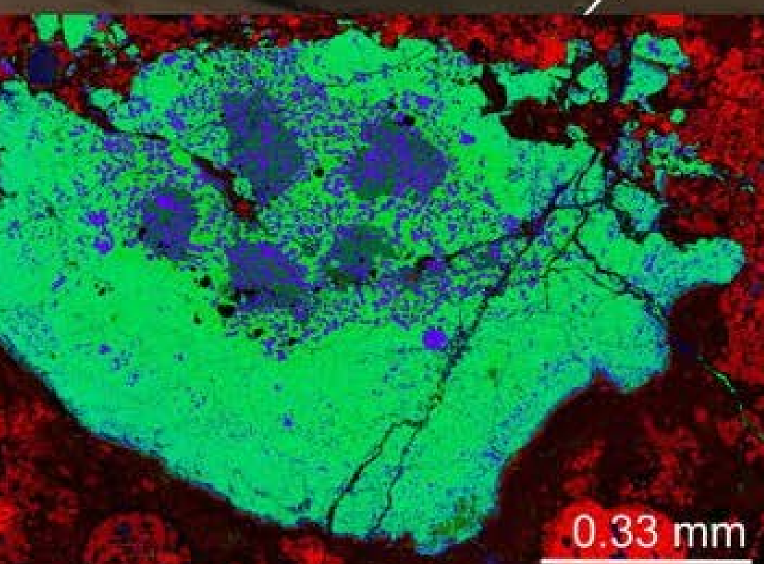
- ^{142}Nd controversy no longer exists – Earth is chondritic
- Mg/Si of Earth: accretion of olivine to pyroxene; Sun is heterogeneous
- Collisional erosion models are unnecessary and unfounded
- ^{182}W isotopes record early core-mantle separation
- Geoneutrino flux of Th & U: define building blocks & describes convective state

Challenges we face in understanding the mantle:

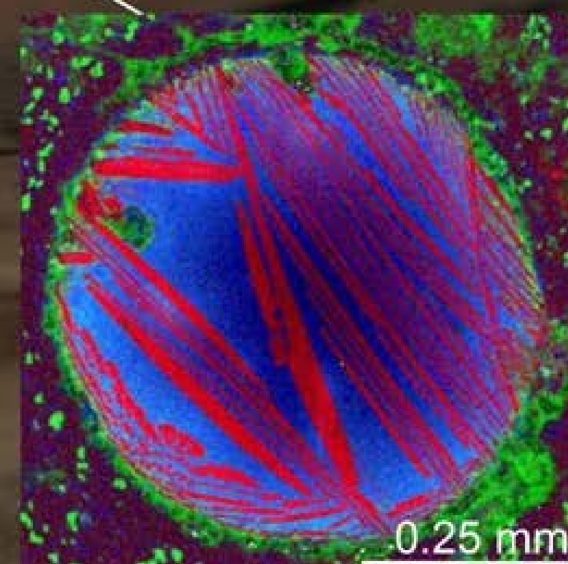
- **rate of heat loss is known to be between 50 and 150 K/Ga**
- Defining mineralogy of the mantle remains a challenge
- LLSVP origins is either primordial or subduction related – no resolution in sight
- Stirring efficiency of the mantle remains to be understood
- Core-mantle mass exchange might occur, but not geochemical evidence
- Primordial domains may remain from magma ocean conditions







lcium-Aluminum-Rich Inclusion

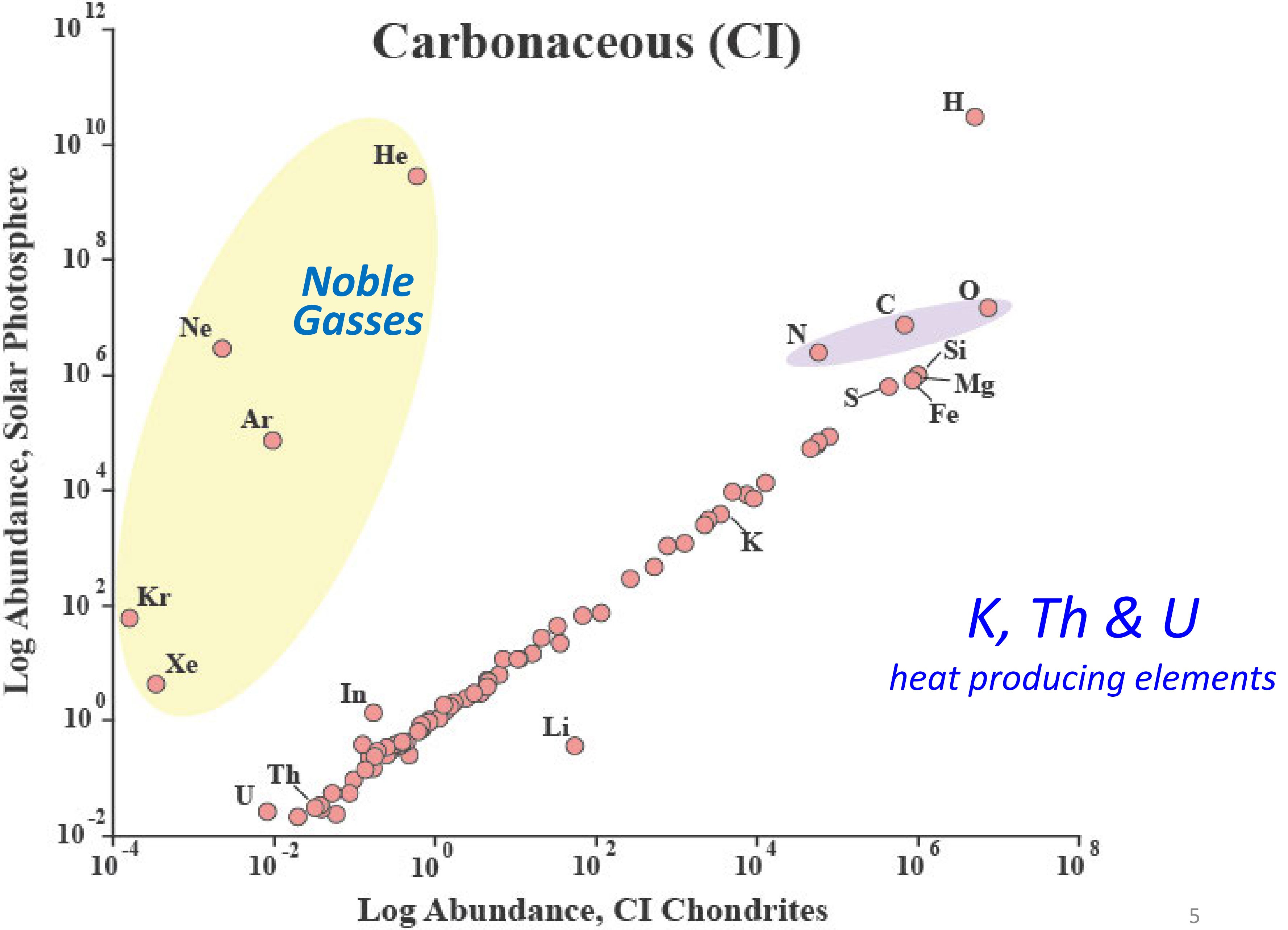


Chondrule

Early Solar System chronology

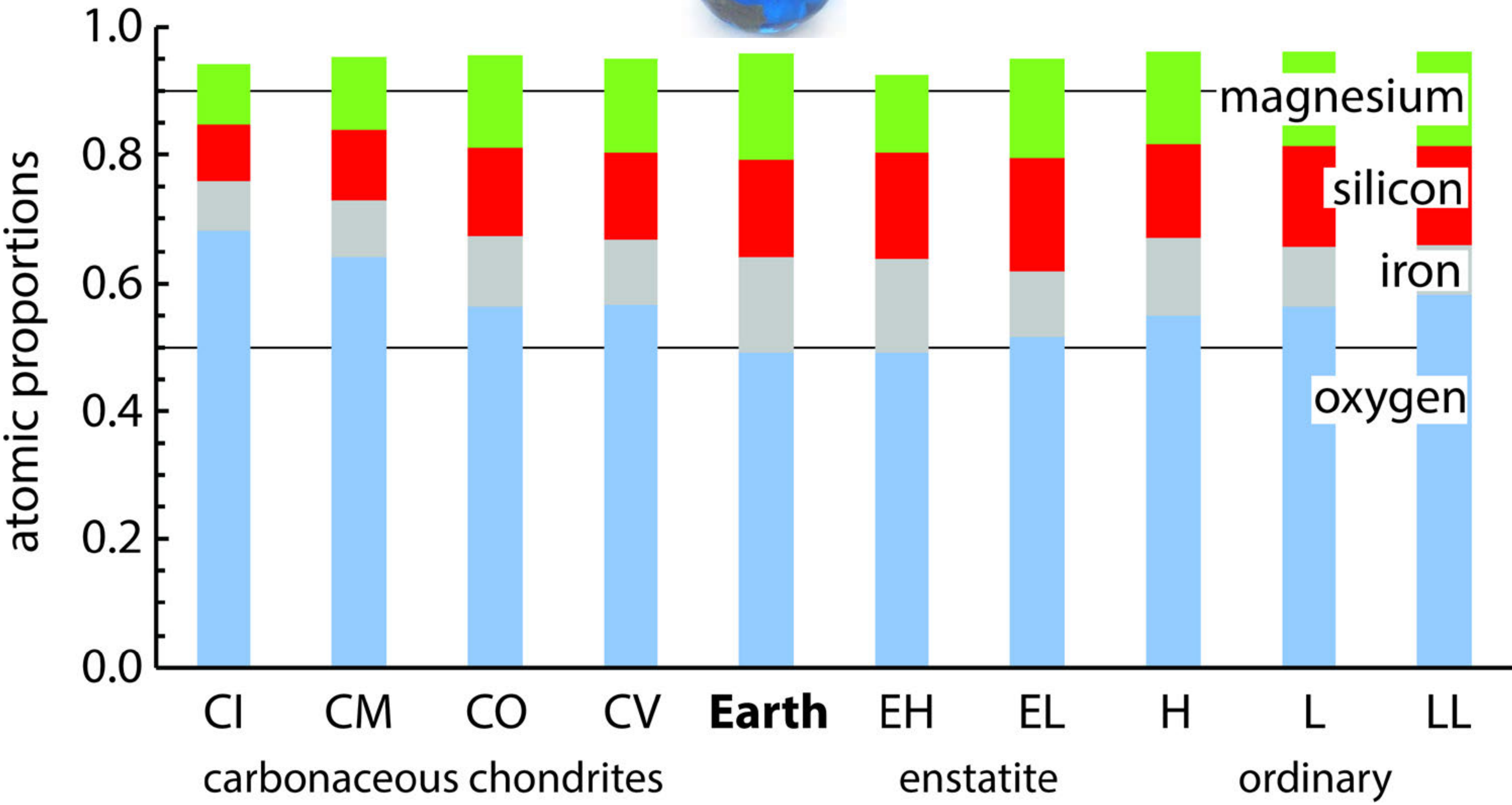
- **CAI** formed in ≤10^5 yrs at **4567.80 ± 0.16 ± 0.5** Ma (***t_{zero}***)
  stat. *syst.*
- Chondrules formed from 0.5 to ~5 Ma after t_{zero}
- Cores and mantles of small planets (10 to 1000 km) formed between t_{zero} + 0.5 Ma to t_{zero} + ~5 Ma
- Earth's core & Moon formed: t_{zero} +~30 to +~150 Ma
- Accretion models, consider **rapid** planetary growth

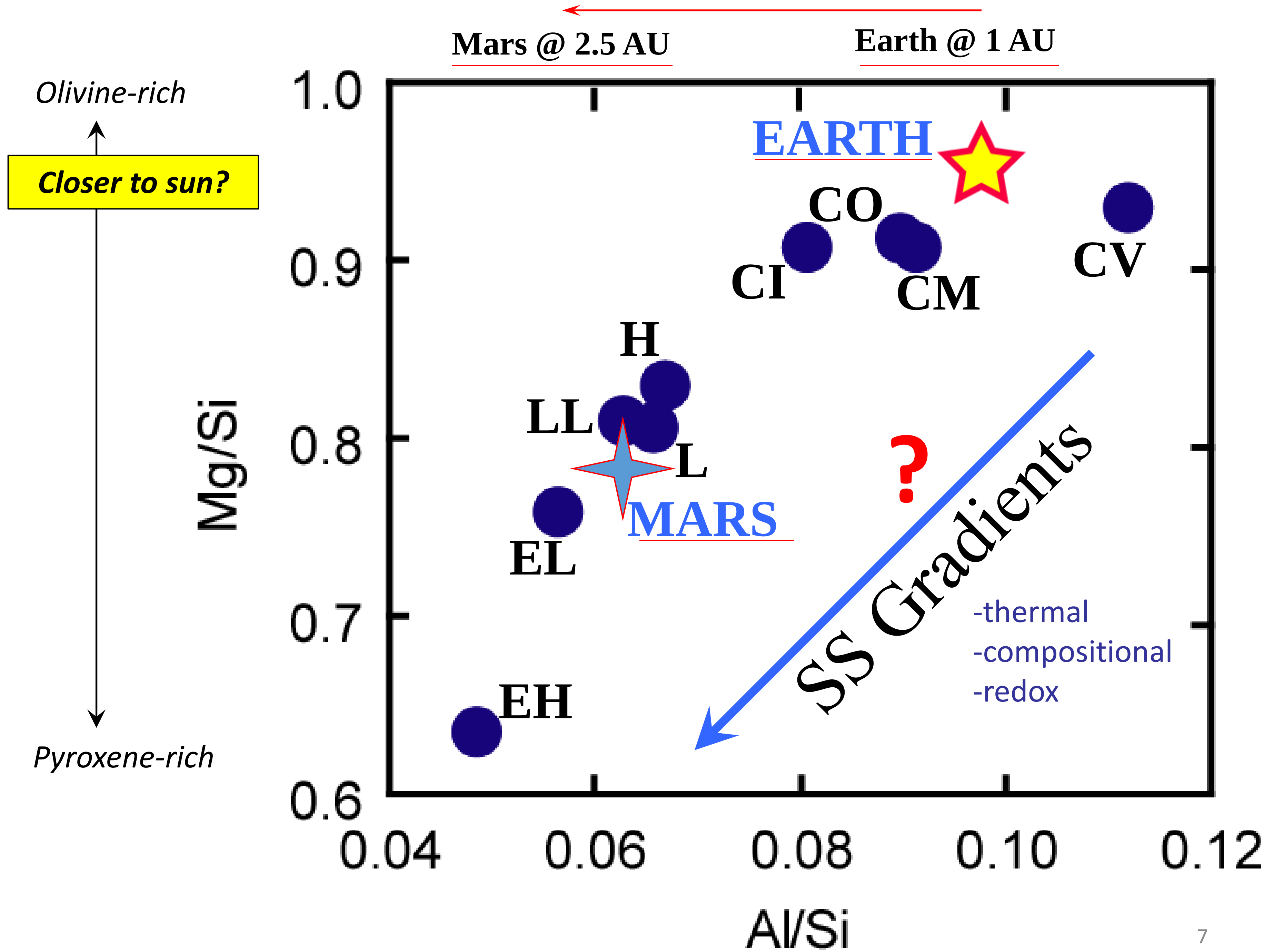
Sun and Chondrites are related



Compositional space where we "might" fit…

4 elements describe >90% of the Earth!





Mars @ 2.5 AU
Earth @ 1 AU
Olivine-rich
Closer to sun?
Pyroxene-rich
Mg/Si
Al/Si
1.0
0.9
0.8
0.7
0.6
0.04
0.06
0.08
0.10
0.12
EARTH
CO
CI
CM
CV
H
LL
L
MARS
EL
EH
?
SS Gradients
-thermal
-compositional
-redox

Mg/Si variation in a nebula disk

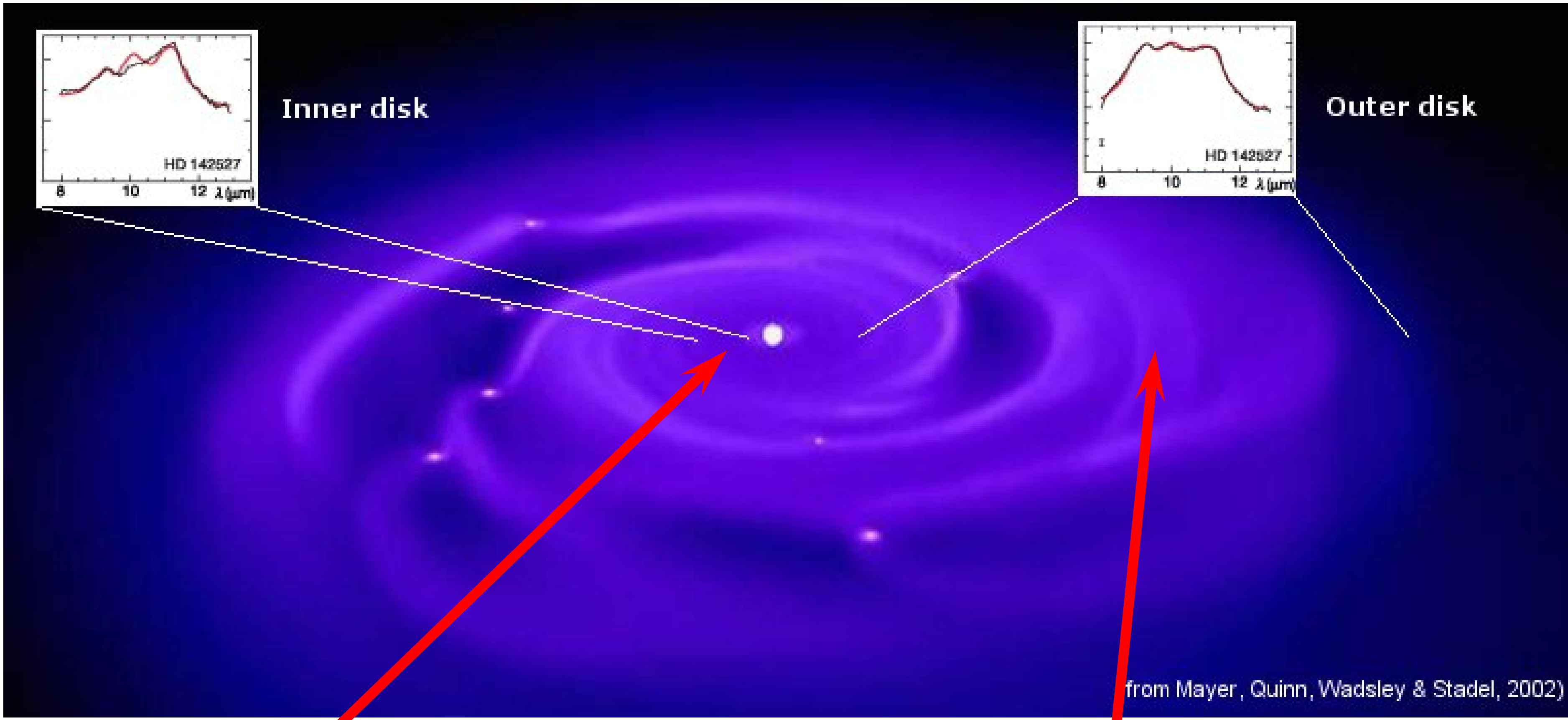
Olivine
-high temperature
-early crystallization
-high, Mg_2/Si
-fewer volatile elements

Pyroxene
-lower temperature
-later crystallization
-low, Mg/Si
-more volatile elements

Inner nebular regions of dust to be highly crystallized,

Outer region of one star has

- equal amounts of **pyroxene** and **olivine**
- while the inner regions are dominated by **olivine**.

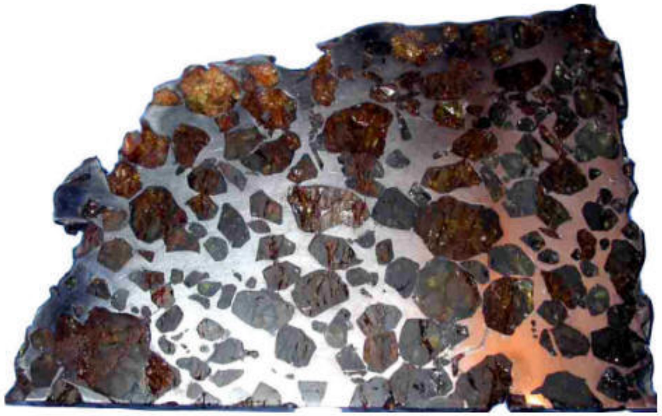


Olivine-rich

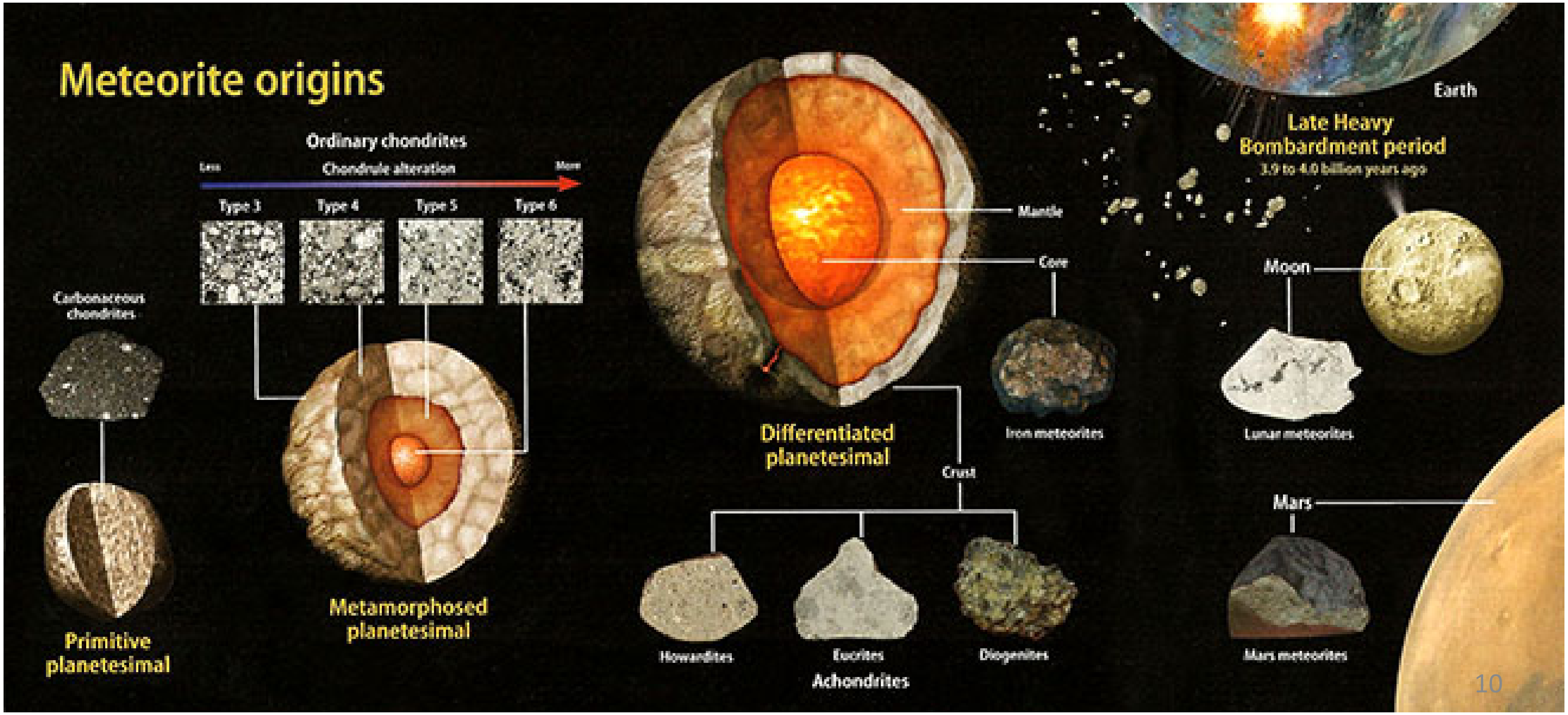
Ol & Pyx

STONY

IRON

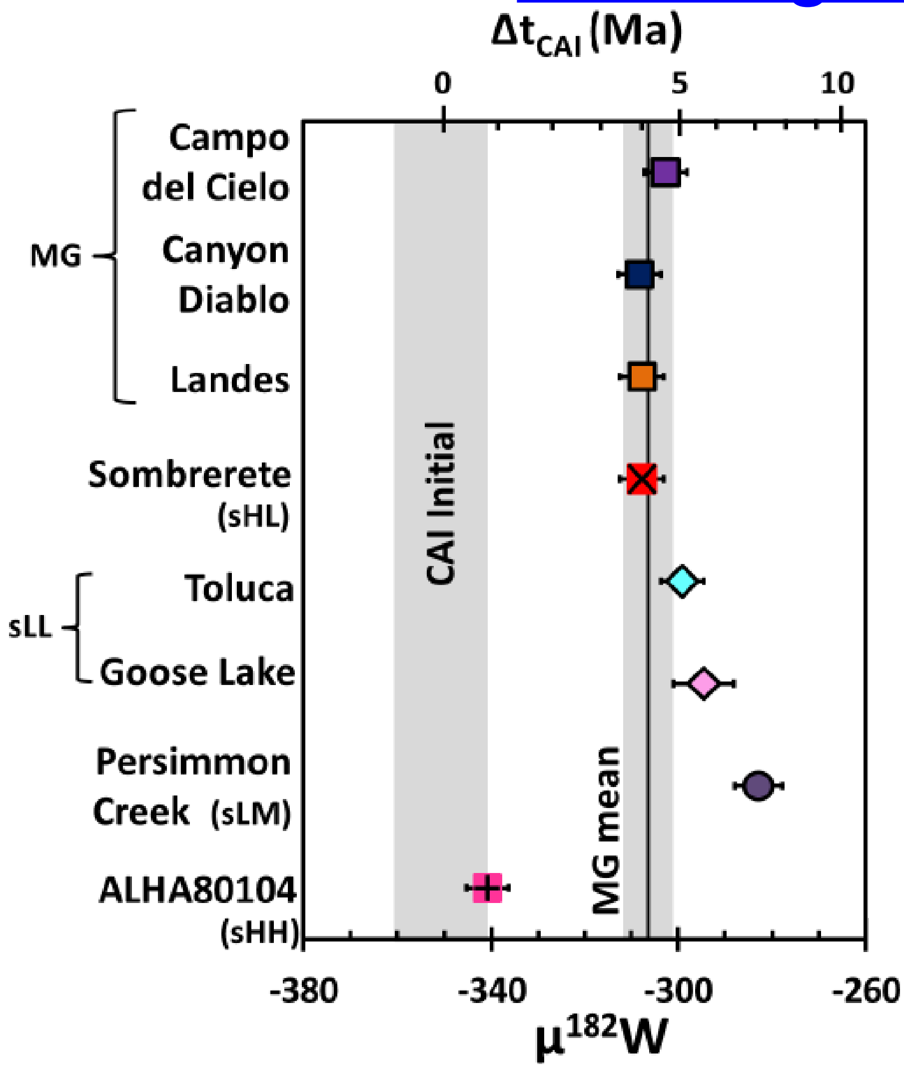


STONY-IRON



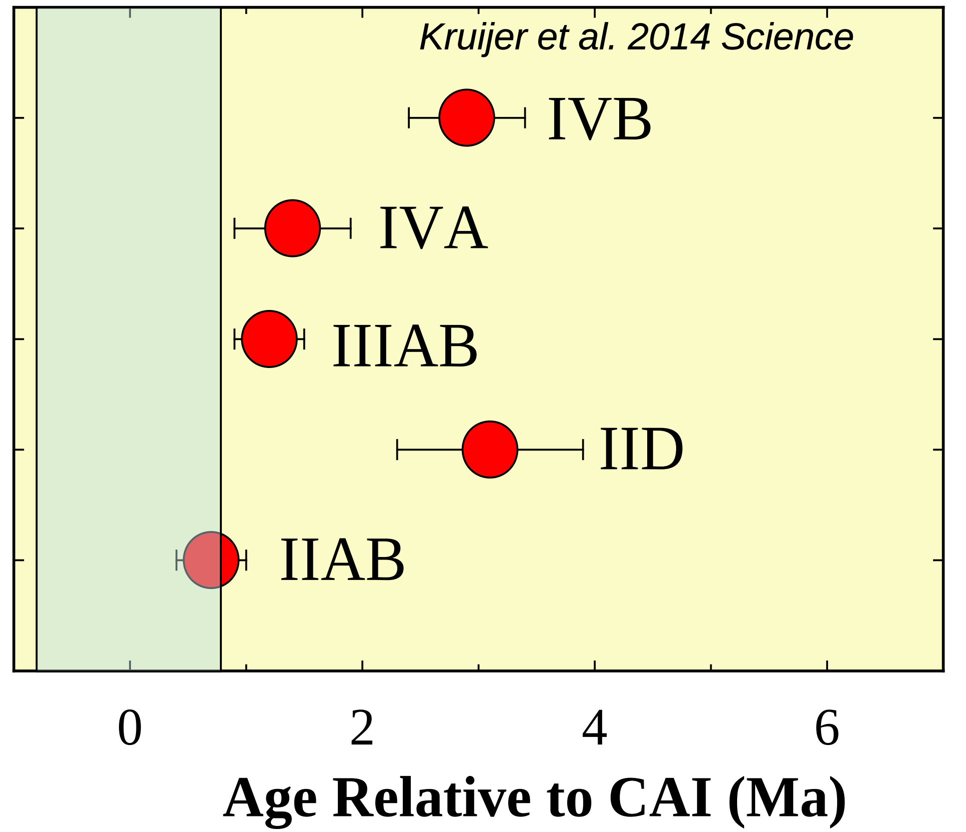
Small planet growth in just a few Myr

IAB irons : non-magmatic



Emily Worsham's unpublished data (UMd Ph.D. student)

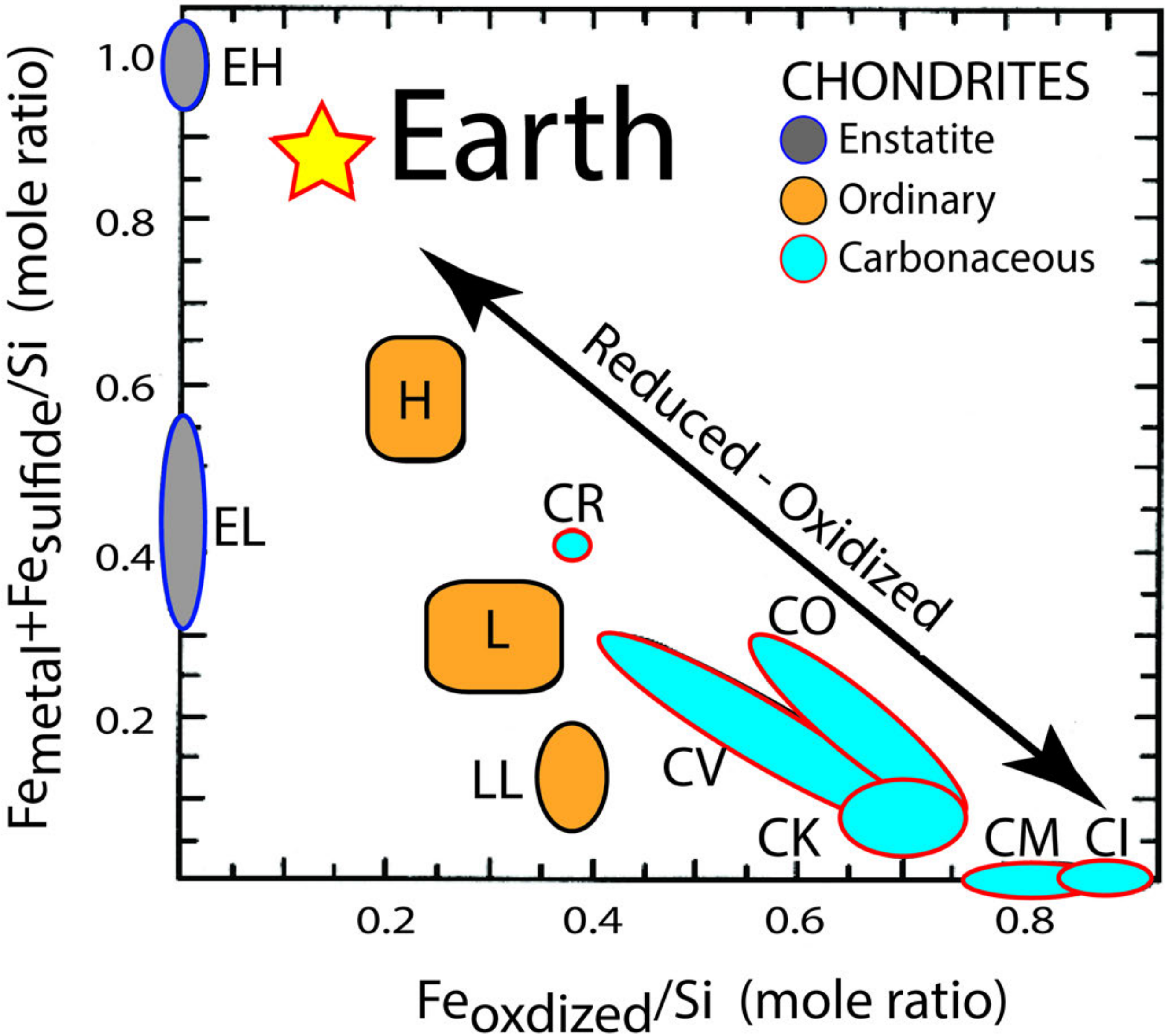
Magmatic irons



W isotope constrain these ages

from R. Walker 2015

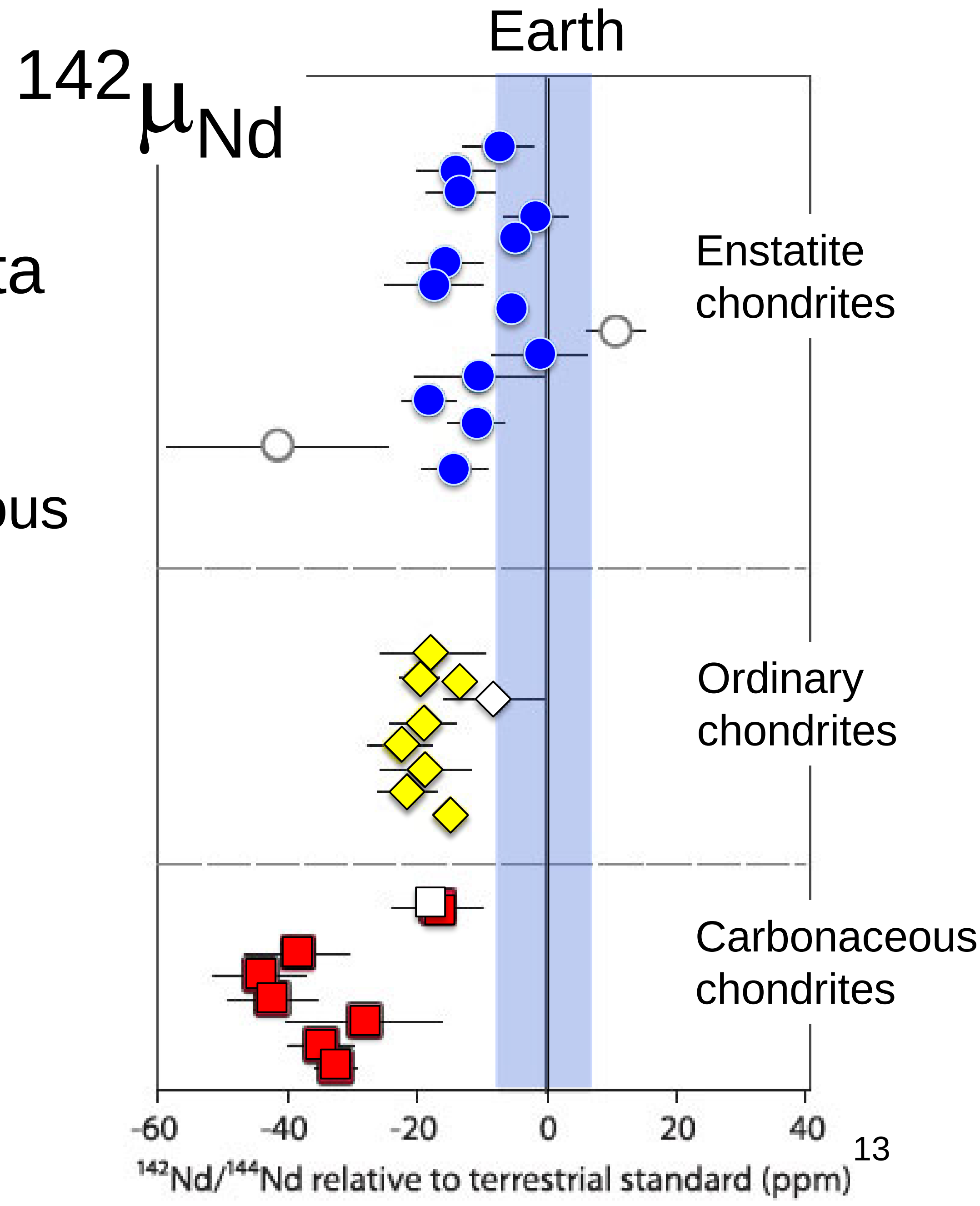
Redox state of the Earth



Which *chondrite* is the Earth?

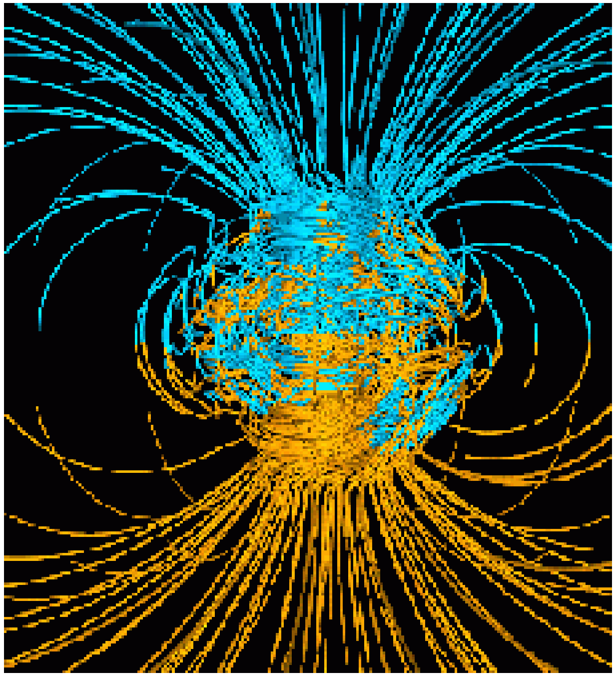
What does this Nd data mean for the Earth?

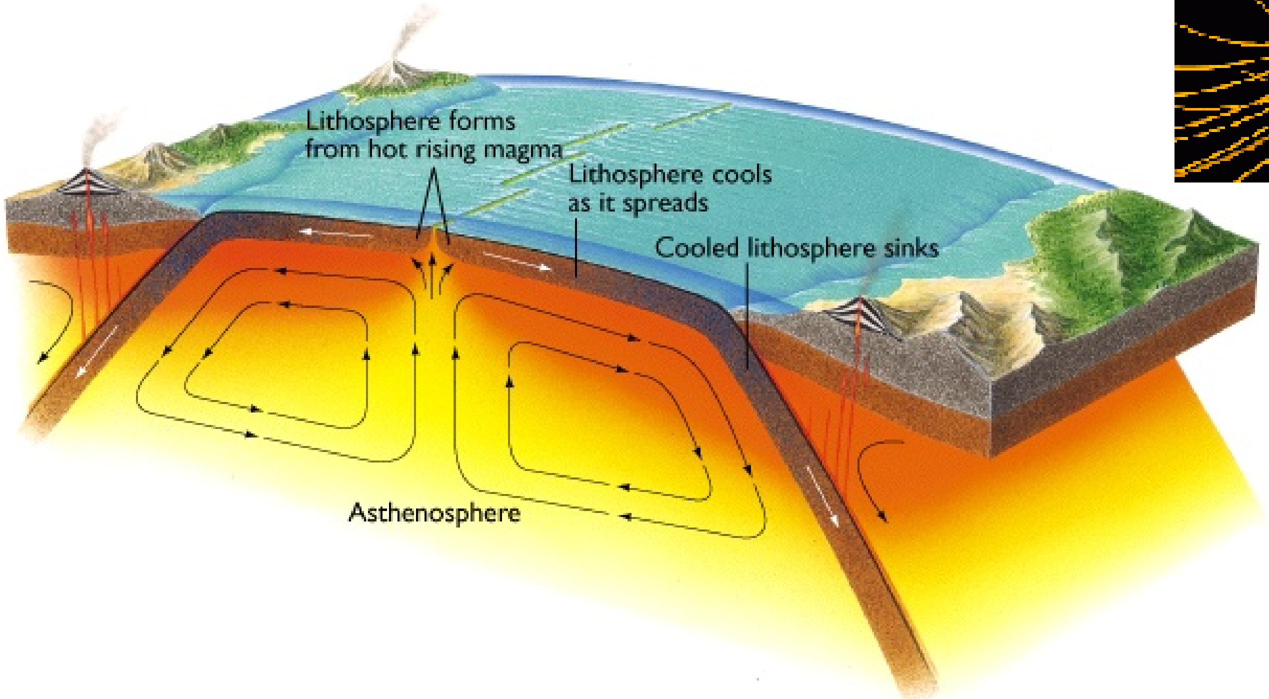
- Solar syst. heterogeneous
- Chondrites are a guide
- Planets ≠ chondrites ?

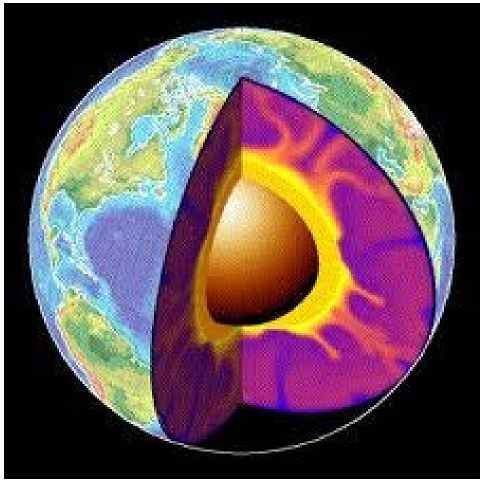


Data from:
Gannoun et al (2011, PNAS)
Carlson et al (Science, 2007)
Andreasen & Sharma (Science, 2006)
Boyet and Carlson (2005, Science)
Jacobsen & Wasserburg (EPSL, 1984)

Plate Tectonics, Convection, Geodynamo



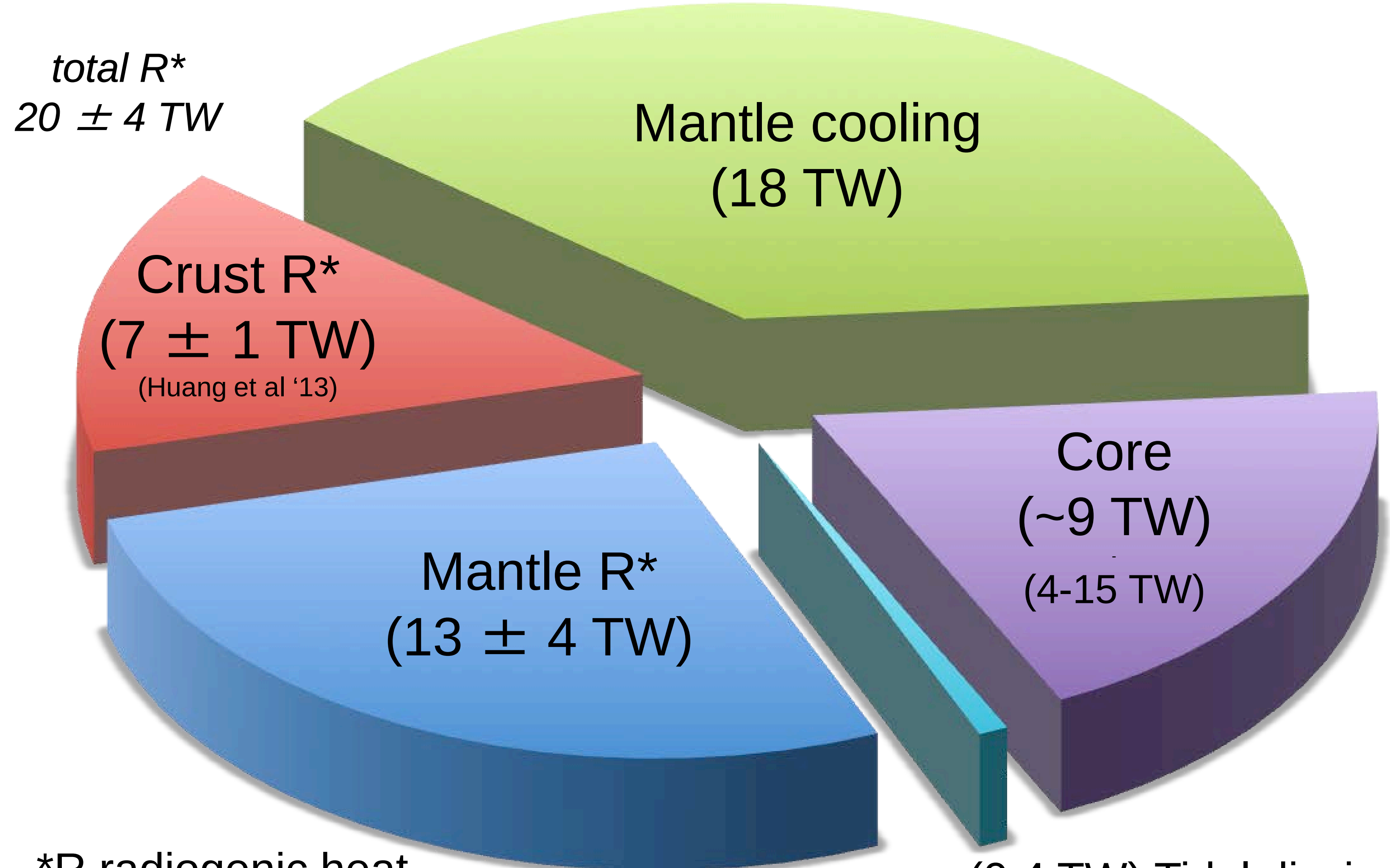




Radioactive decay driving the Earth's engine!

K, Th & U!

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

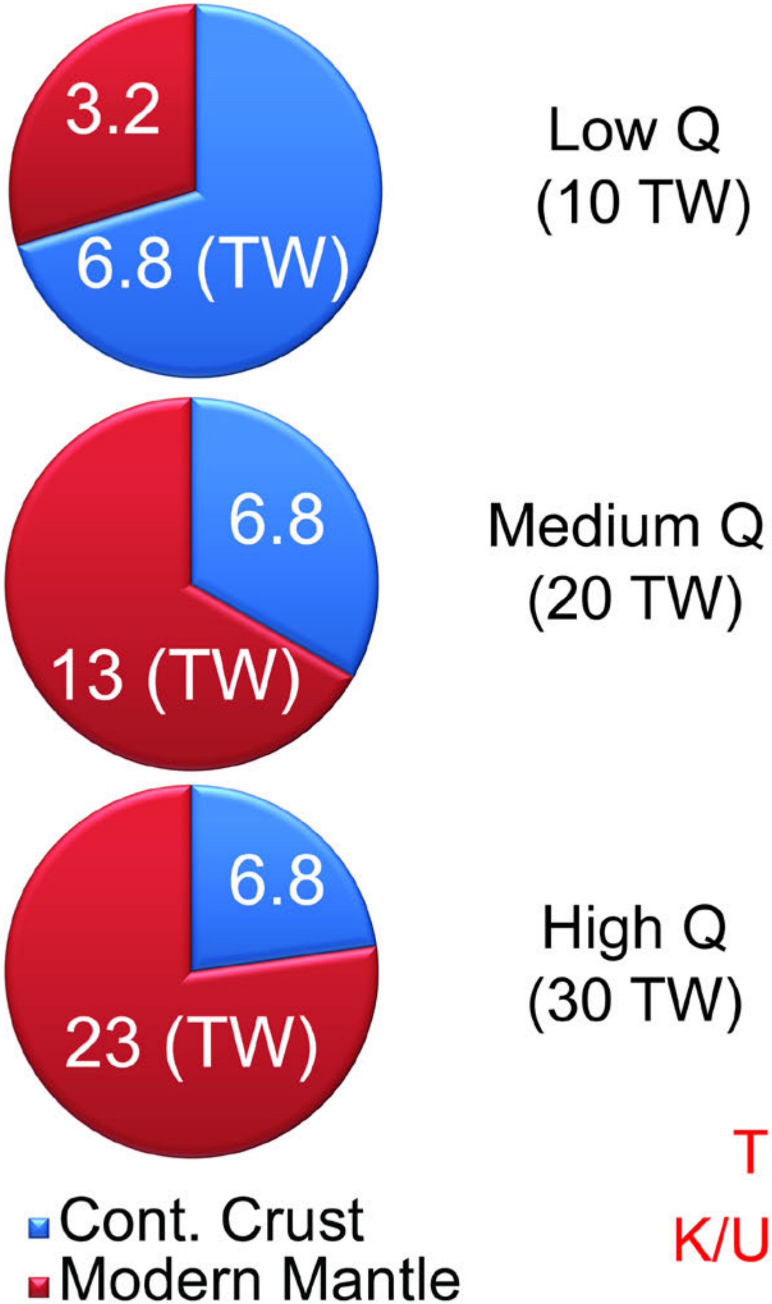


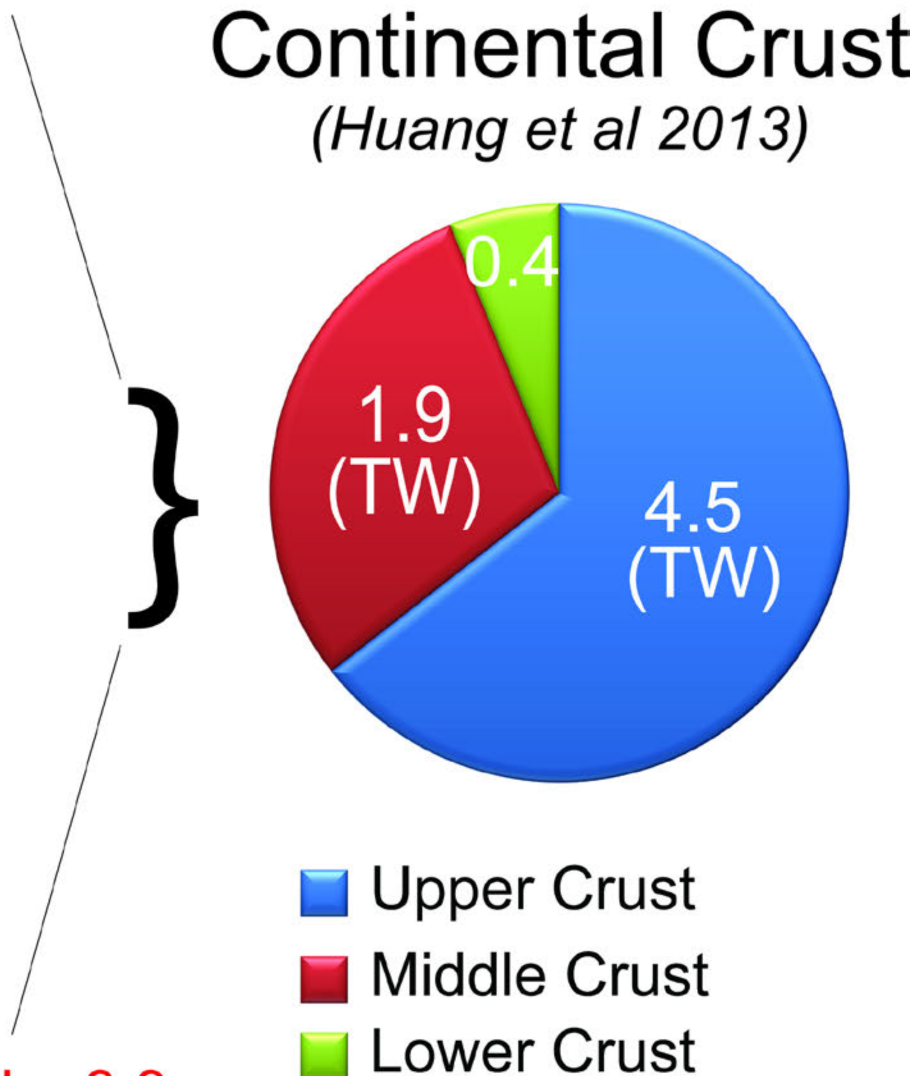
*R radiogenic heat
(after McDonough & Sun '95)

(0.4 TW) Tidal dissipation
Chemical differentiation

after Jaupart et al 2008 Treatise of Geophysics

Bulk Silicate Earth Models





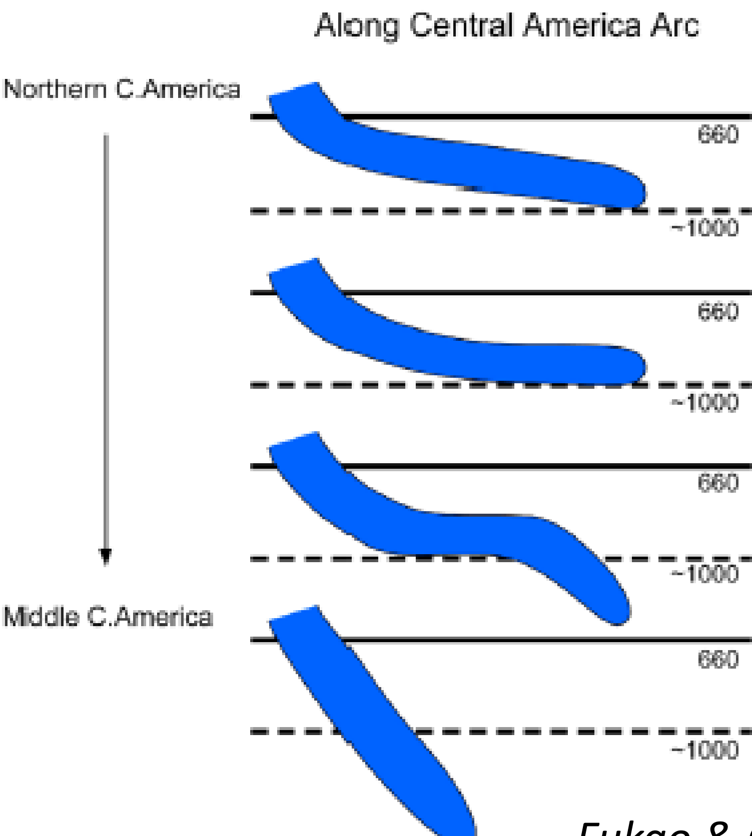
Th/U = 3.9

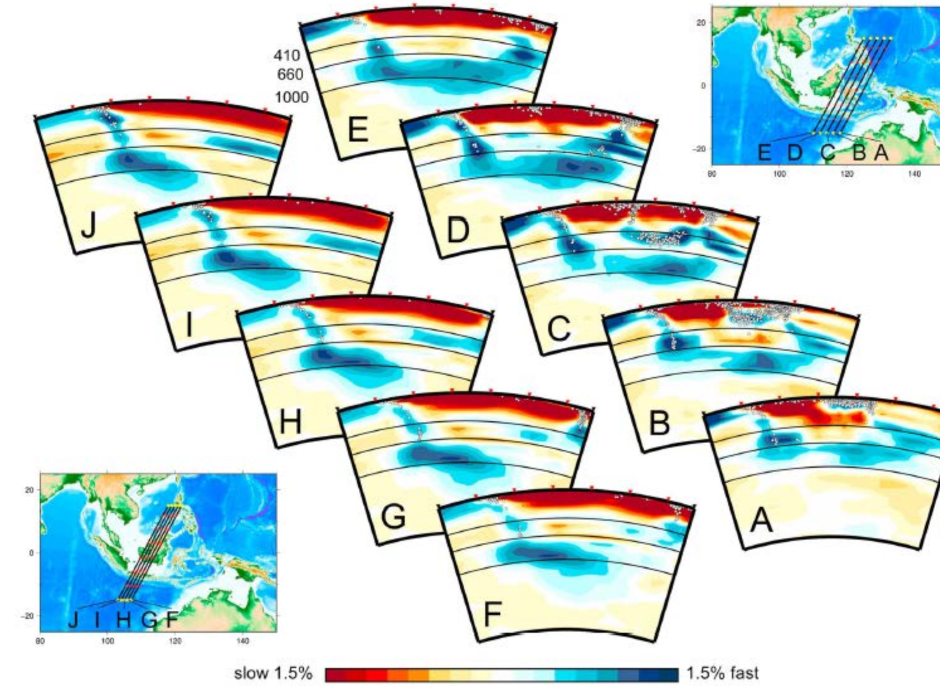
K/U = 1.4 x 10^4

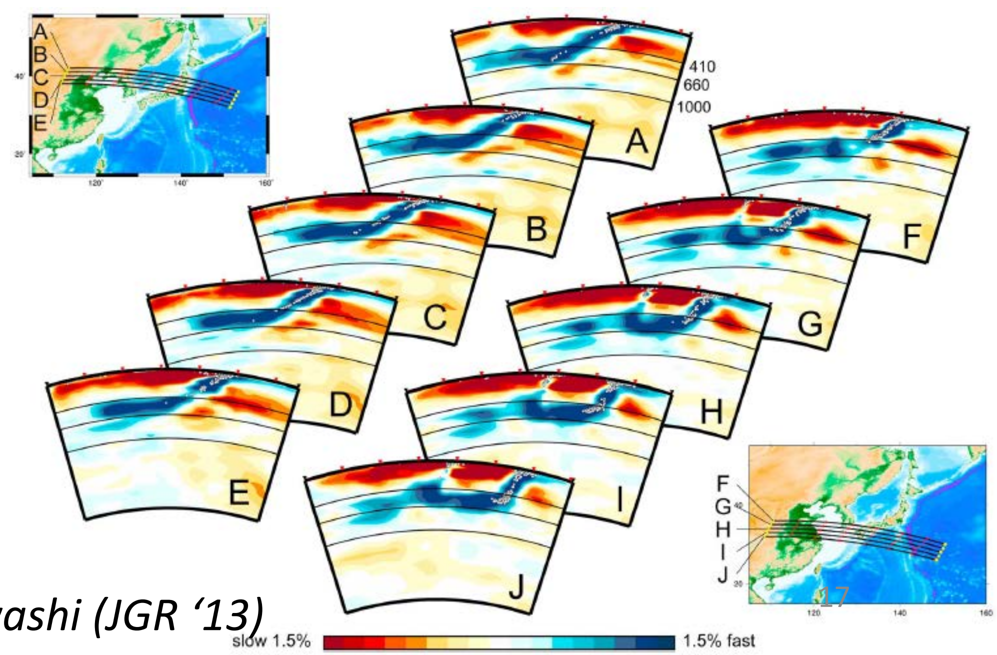
Oceanic Plate stagnation

- 660 km depth
- 1000 km depth

Understanding mantle viscosity structure



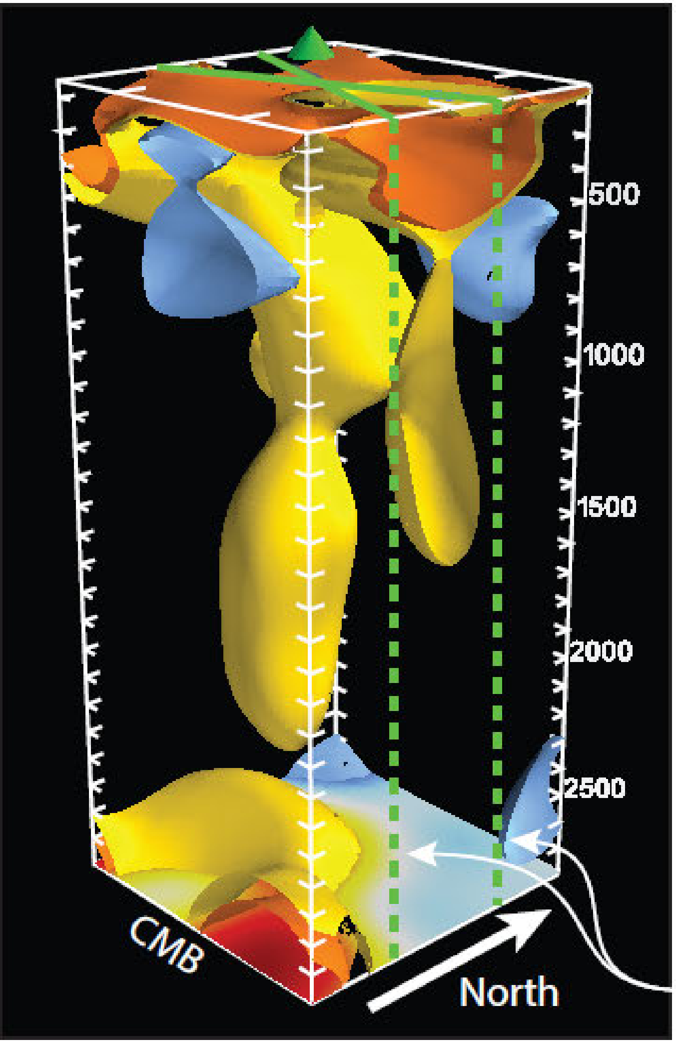


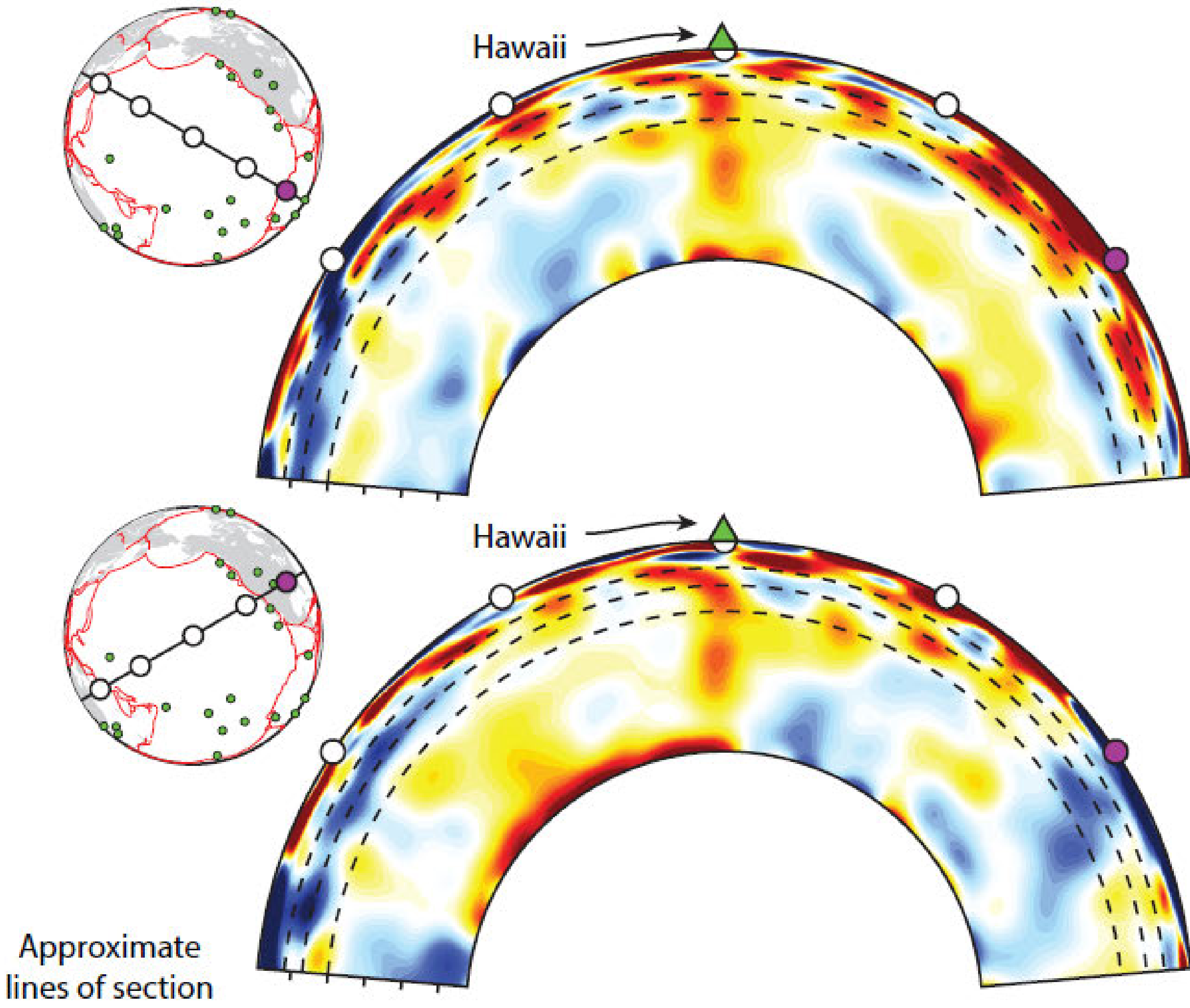


Fukao & Obayashi (JGR '13)

Hawaiian plume:

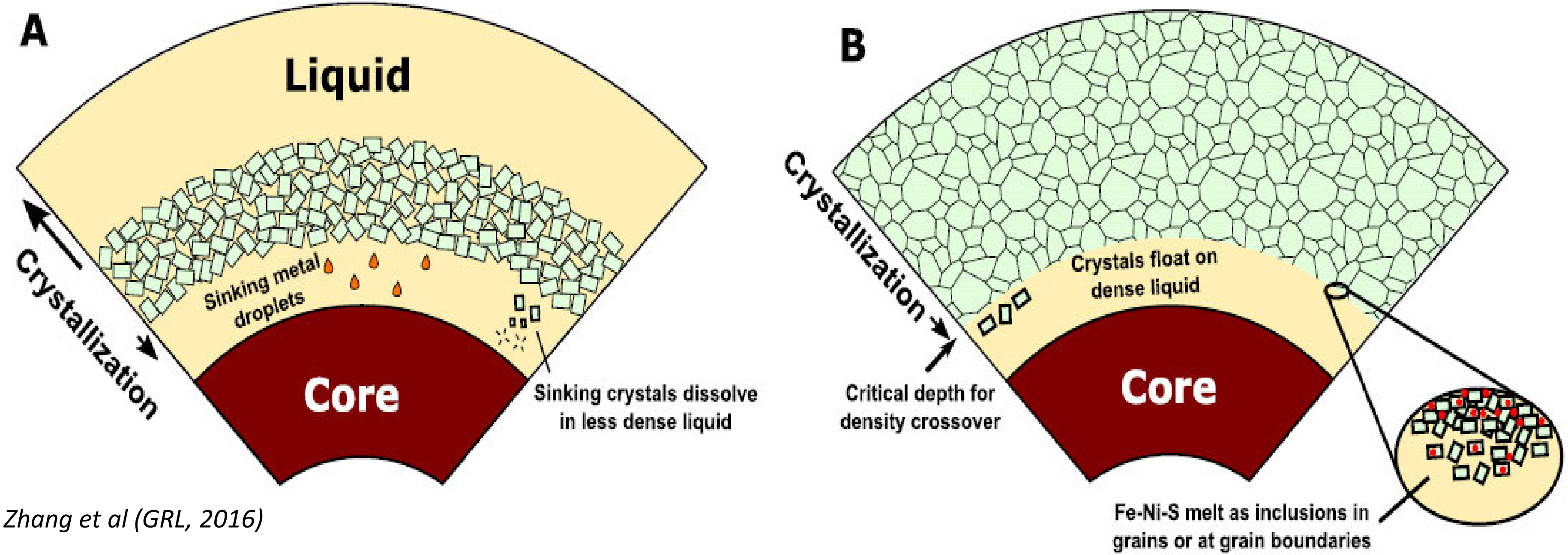
- extending from CMB
- rooted in **large ULVZ**





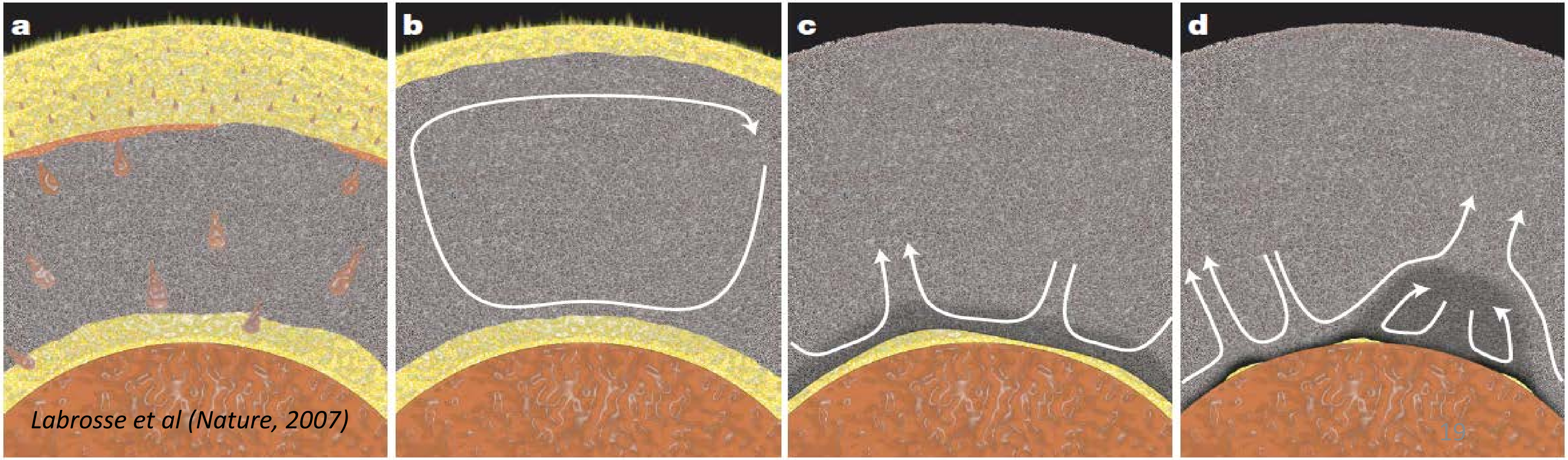
1st time: continuous connection between ULVZ's and mantle plumes

French & Romanowicz (Nature, 2015)



Zhang et al (GRL, 2016)

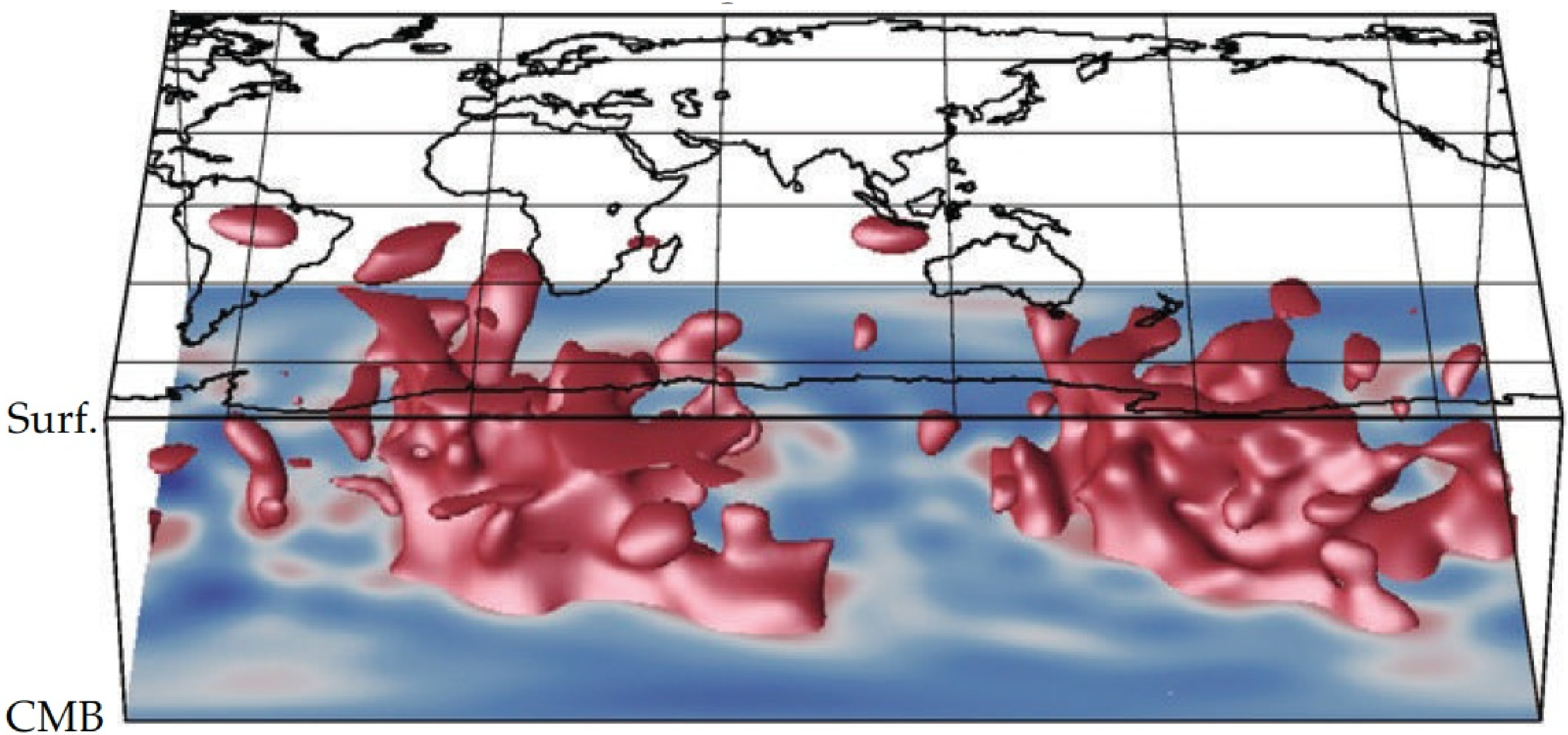
Deep mantle products(?) of an early magma ocean



Labrosse et al (Nature, 2007)

What's hidden in the mantle?

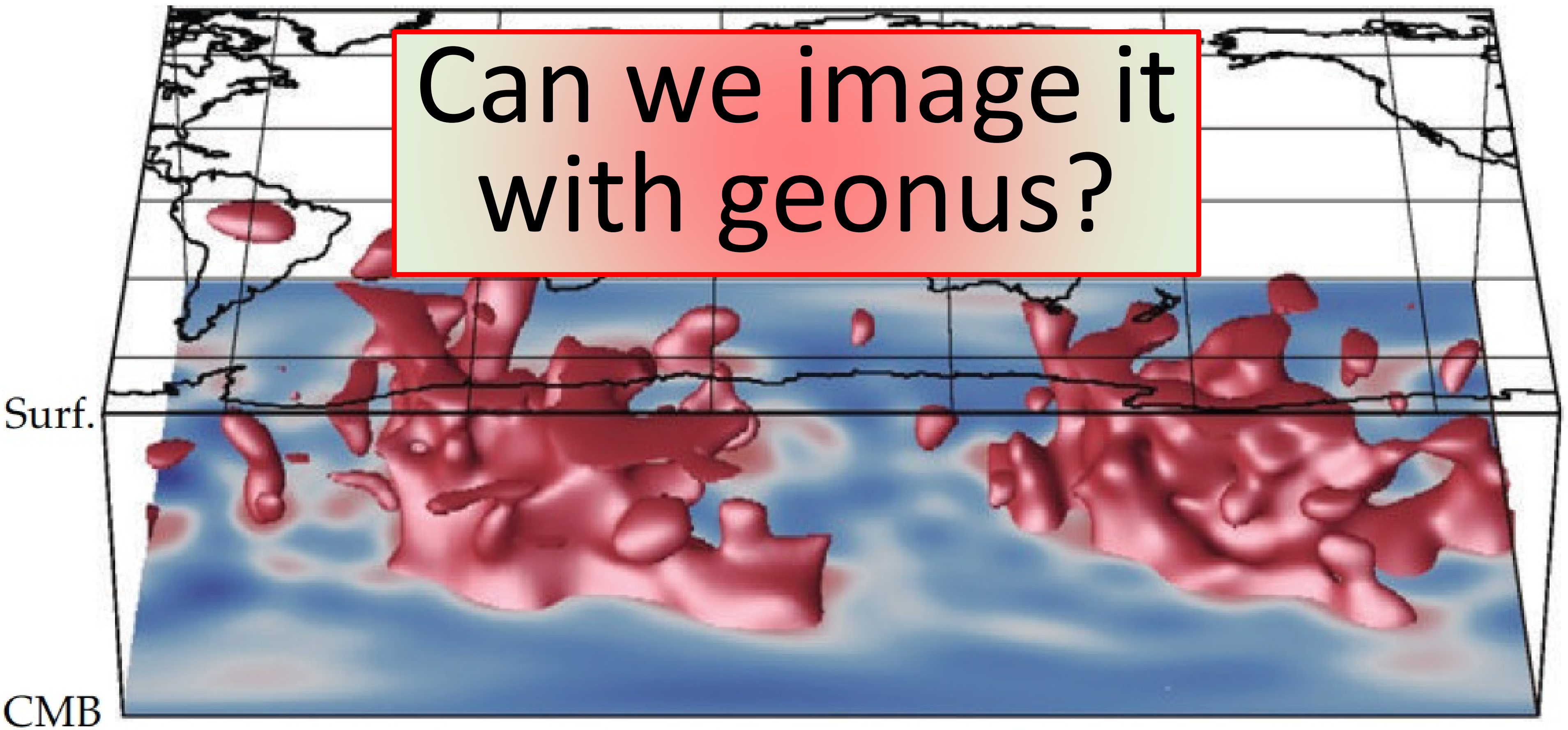
Seismically slow "red" regions in the deep mantle



From Alan McNamara after Ritsema et al (Science, 1999)

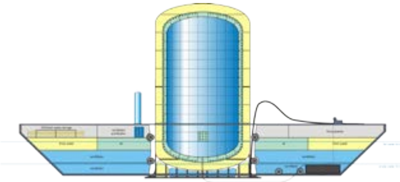
What's hidden in the mantle?

Seismically slow "red" regions in the deep mantle

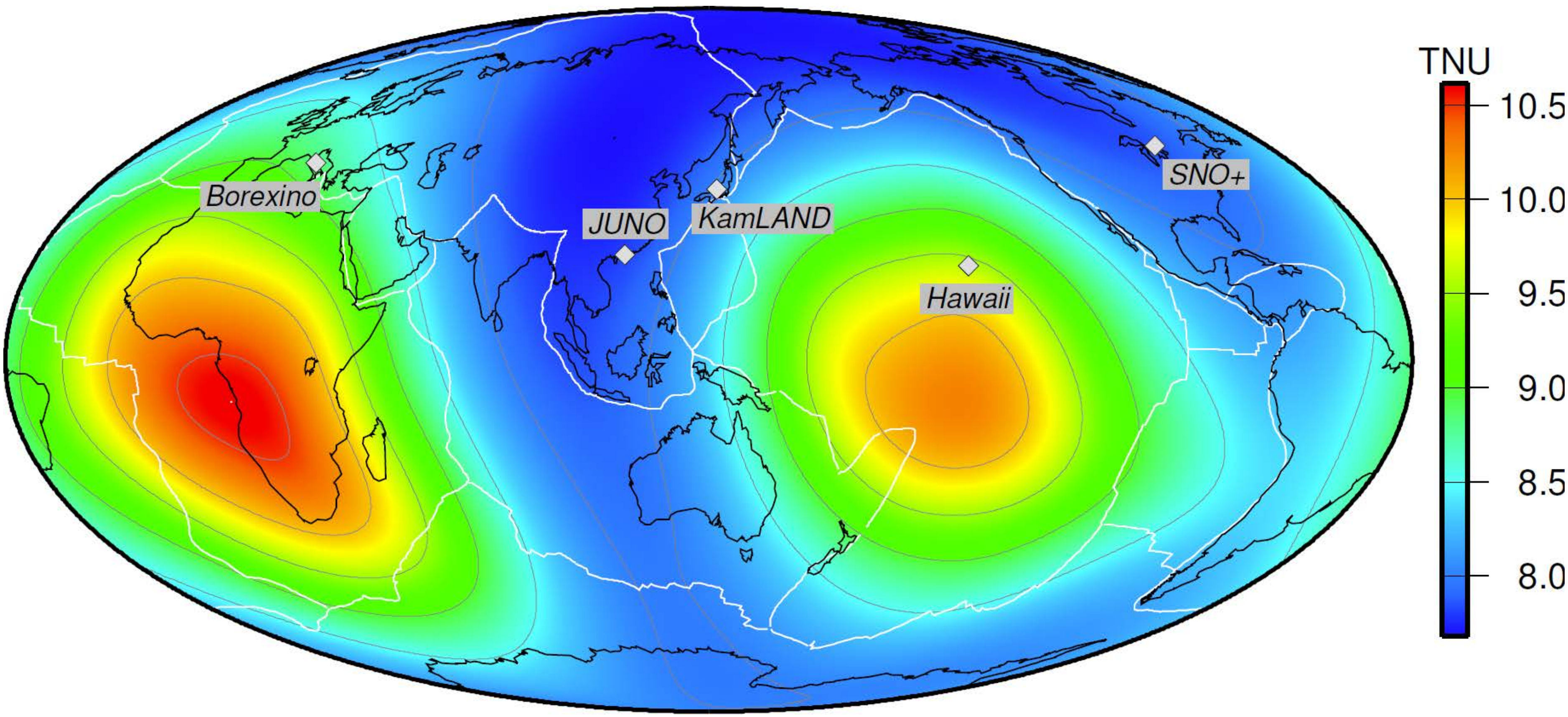


From Alan McNamara after Ritsema et al (Science, 1999)

Testing Earth Models

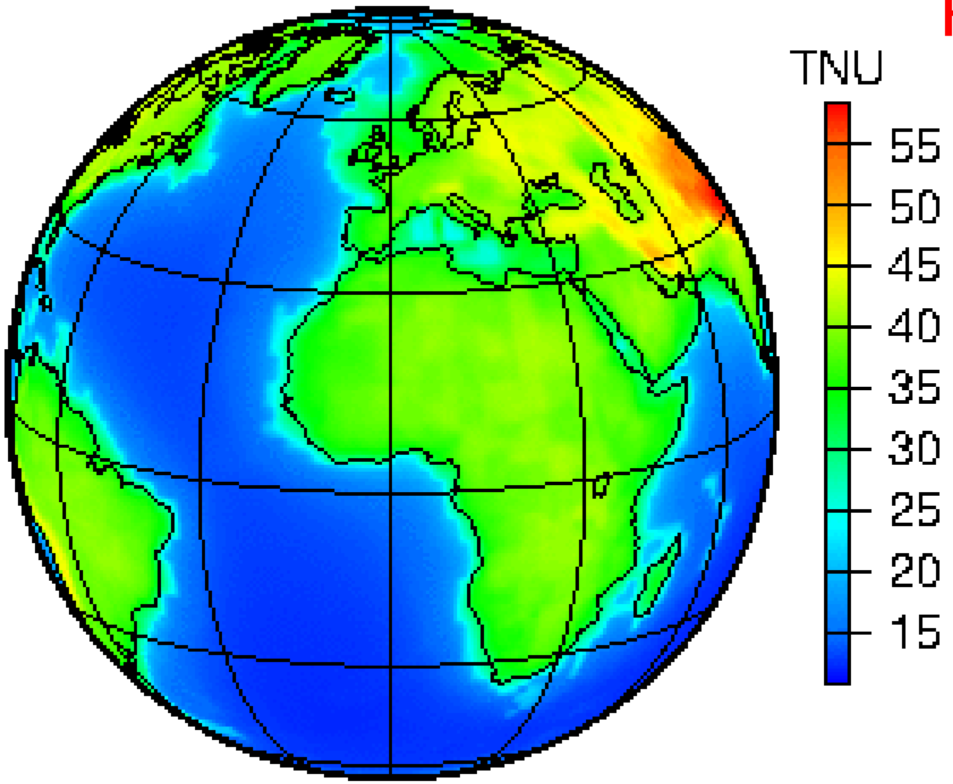


Mantle geoneutrino flux (^{238}U & ^{232}Th)



Šrámek et al (2013) EPSL, 361: 356–366, [10.1016/j.epsl.2012.11.001](https://doi.org/10.1016/j.epsl.2012.11.001)

Predicted geoneutrino flux



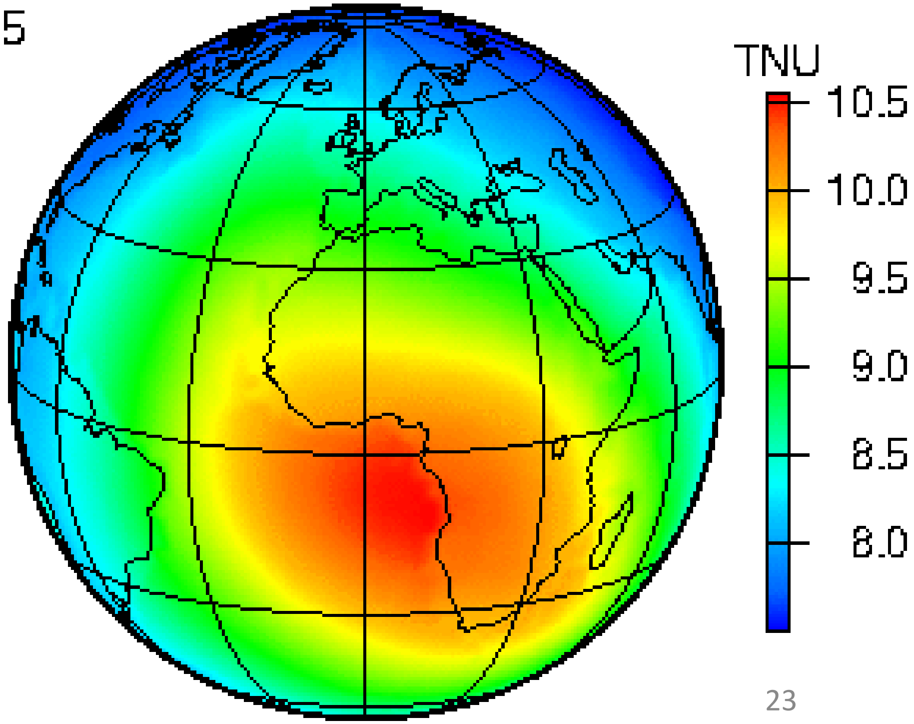
Total flux at surface

dominated by Continental crust

Yu Huang et al (2013) G-cubed ***arXiv:1301.0365***
10.1002/ggge.20129

Mantle flux at the Earth's surface

dominated by deep mantle structures



Šrámek et al (2013) EPSL 10.1016/j.epsl.2012.11.001; arXiv:1207.0853

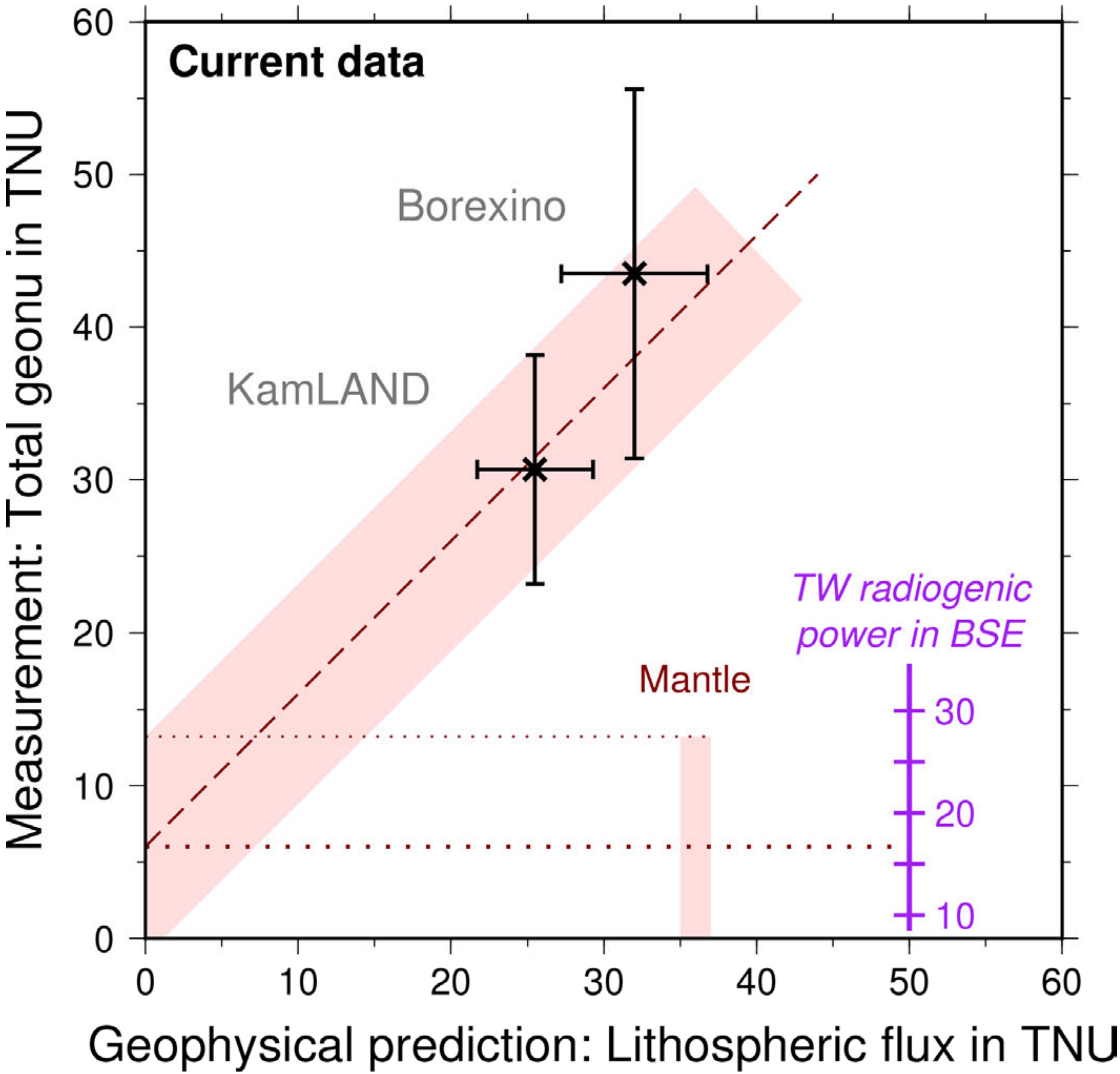
Today, looks bleak, but..

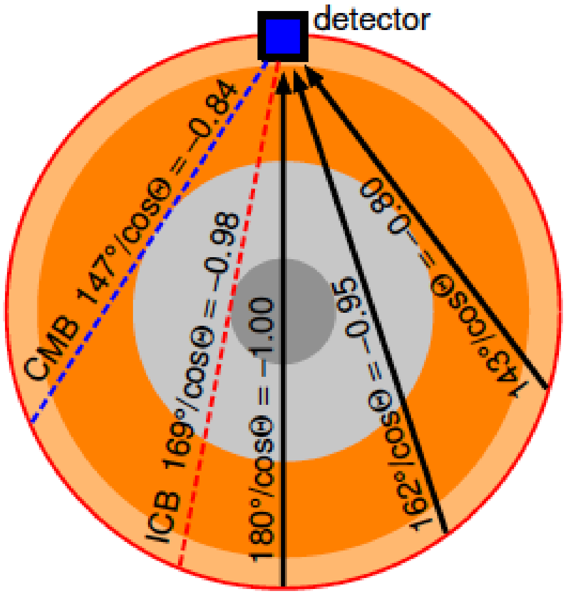
In 8 years, 2025…

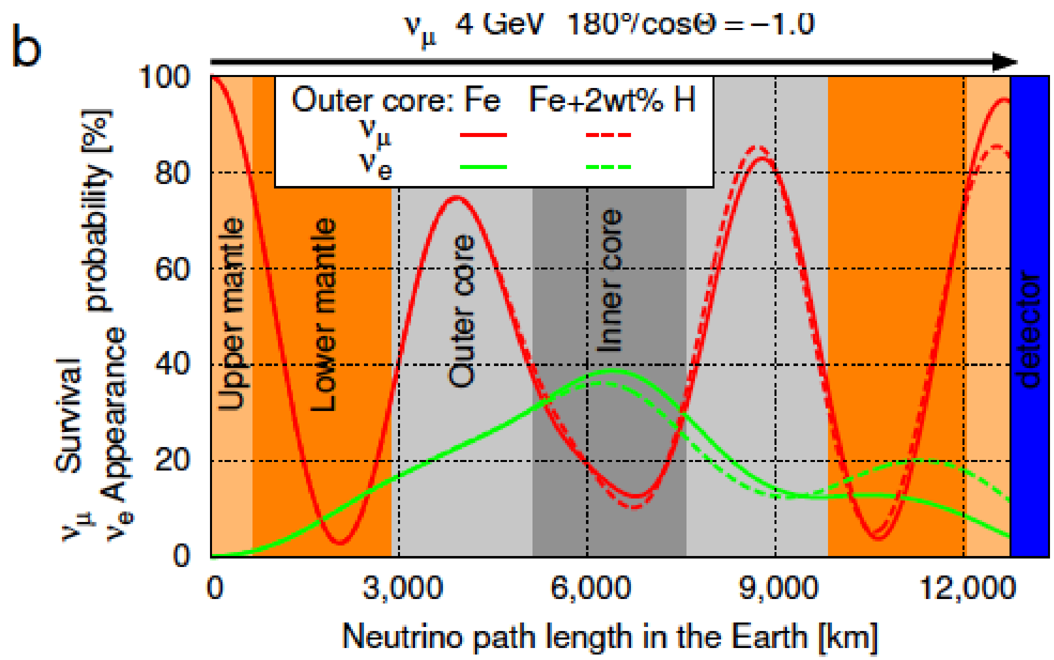
see Sramek talk tomorrow

Watanabe's talk today?...

Tomorrow?

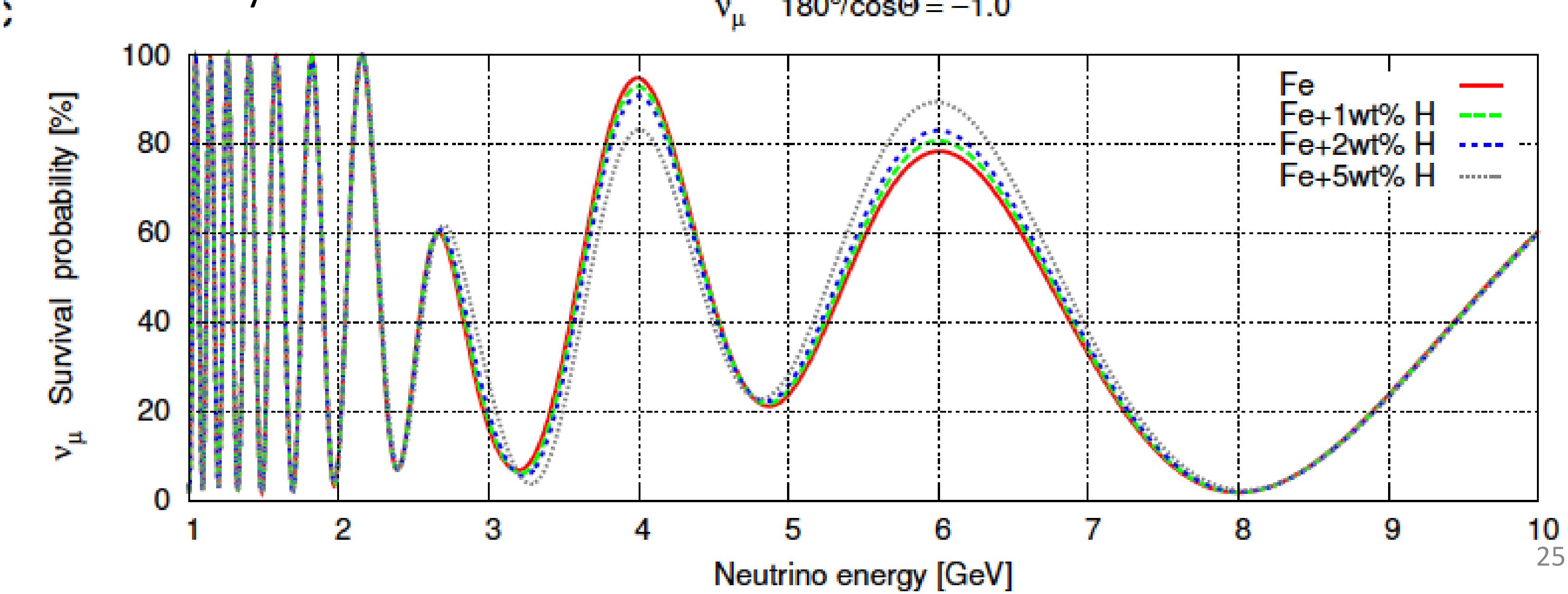






Carsten Rott’s talk

Electron density and neutrino oscillation



- Big Unknowns:
  - Composition of silicate Earth (Mg, Si, Fe, O)
    - Amount of recycled basalt in the mantle
  - Mineralogy of the Lower mantle
  - geothermal gradient Mantle and Core
  - Composition of Core (Fe-Ni + H, C, O, Si, S, ..)
  - Radioactive elements in Mantle and Core
  - Core – Mantle exchange *(do we see it?)*
  - Timing & rate of Inner Core crystallization