Melting in Super-Earths

Lars Stixrude
University College London

Super-Earth

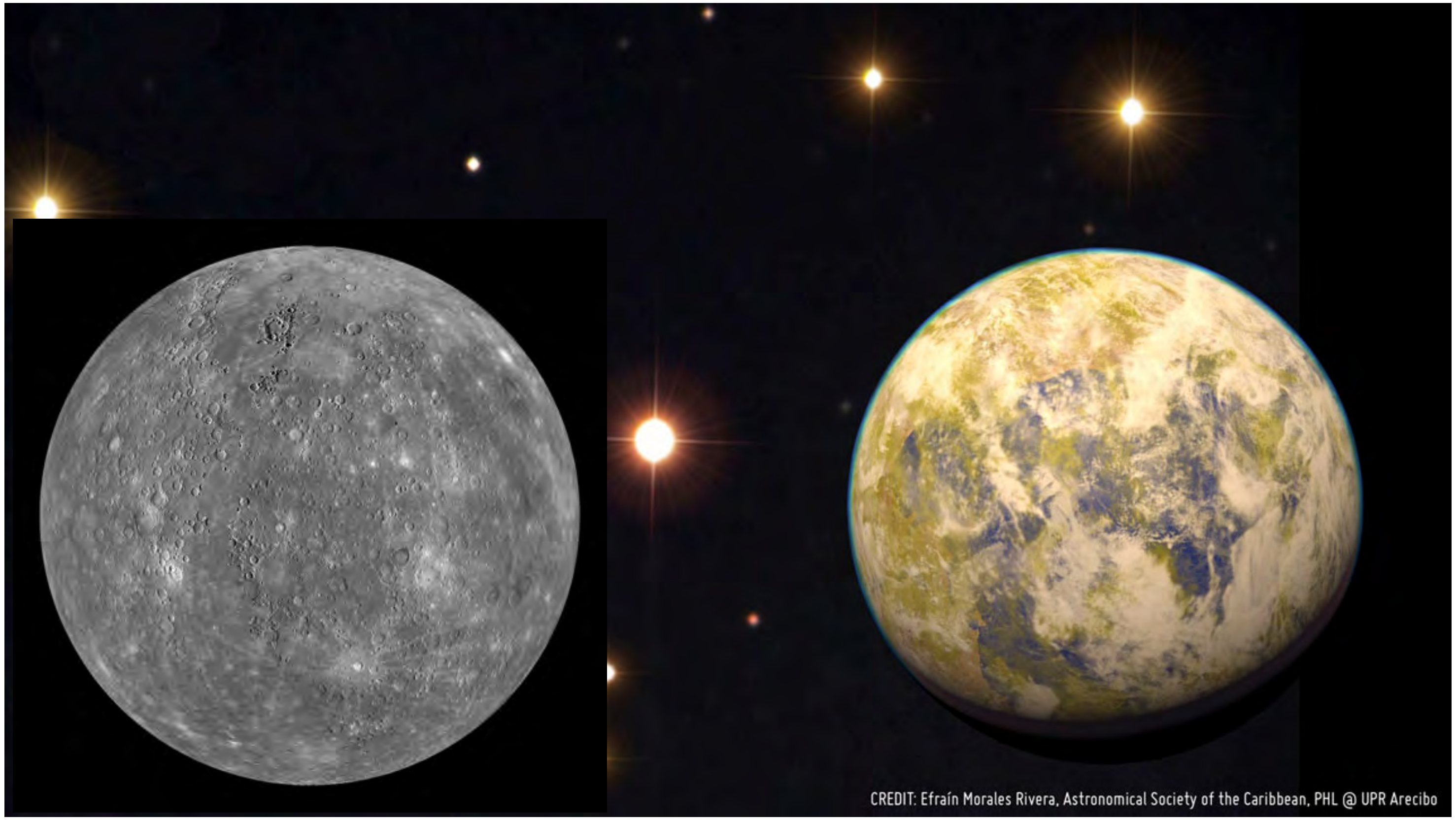
Gleise 832c

CREDIT: Efraín Morales Rivera, Astronomical Society of the Caribbean, PHL @ UPR Arecibo

Wittenmyer et al. (2014)

Super-Earth

Gleise 832c

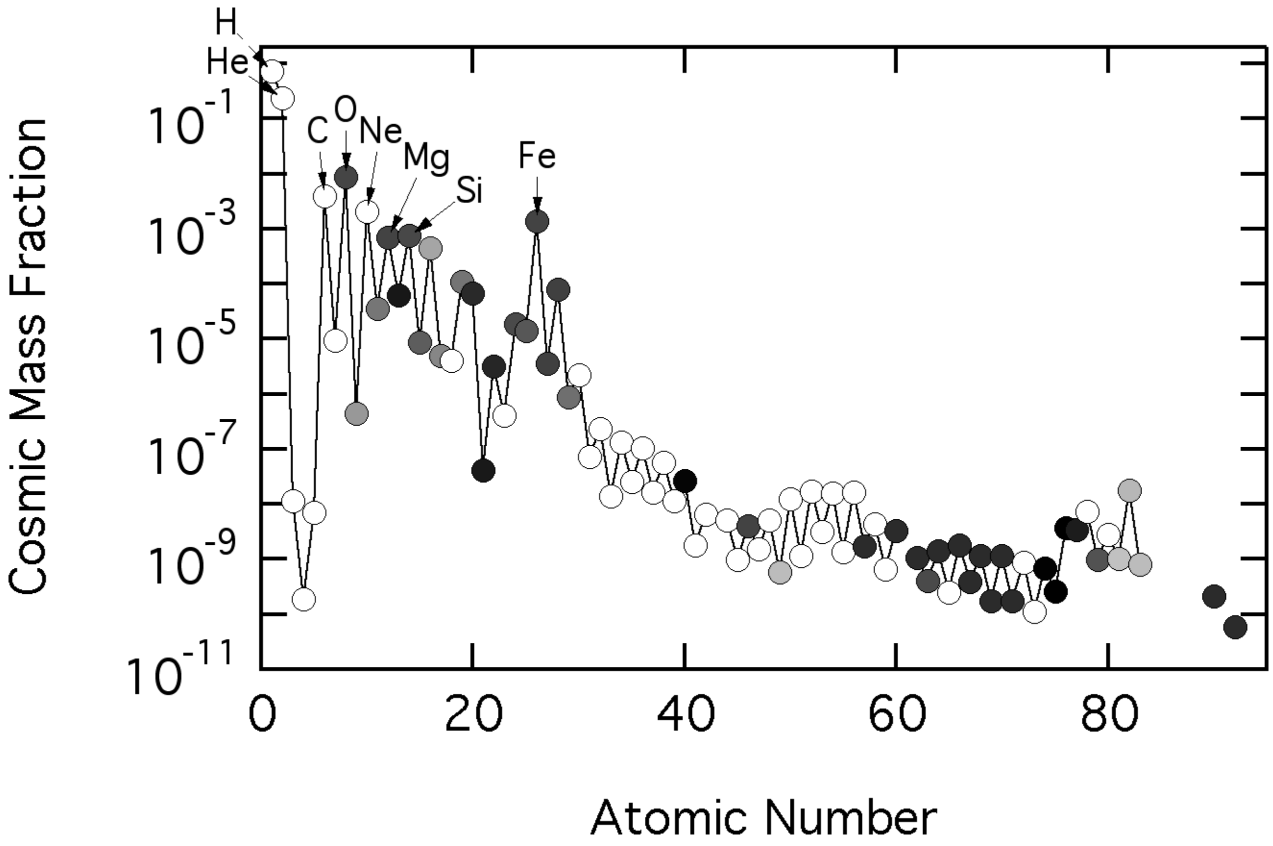


CREDIT: Efraín Morales Rivera, Astronomical Society of the Caribbean, PHL @ UPR Arecibo

Wittenmyer et al. (2014)

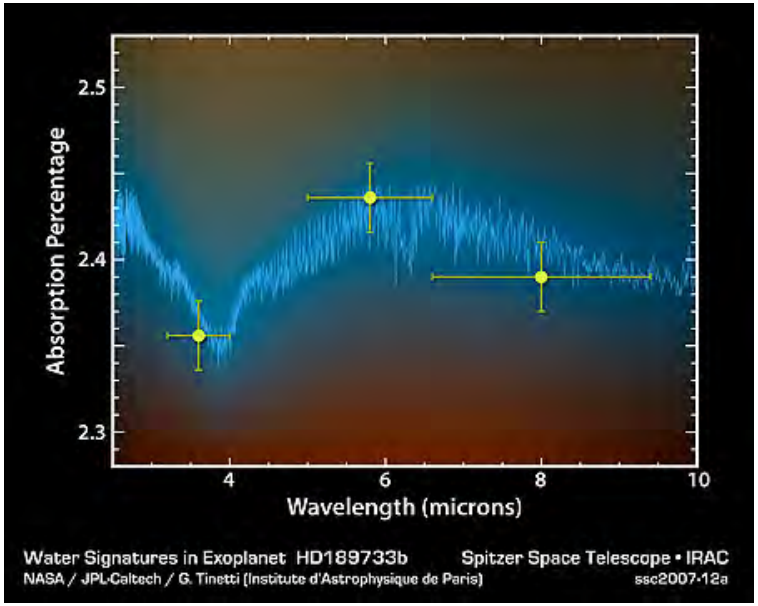
- Interior remembers formation and long term evolution
- Melting is a first order measure of interior state
- Melting produces external manifestations of internal processes that may be detectable

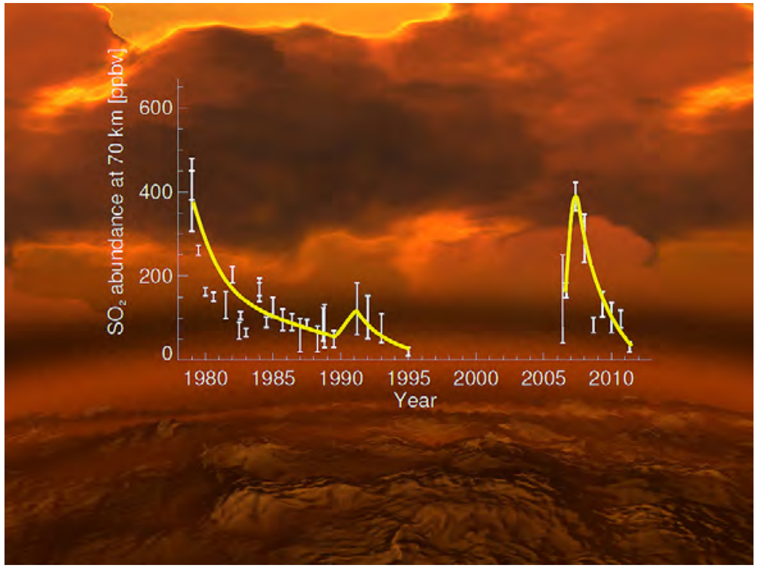
Earth-like Super-Earths



Silicate Melting

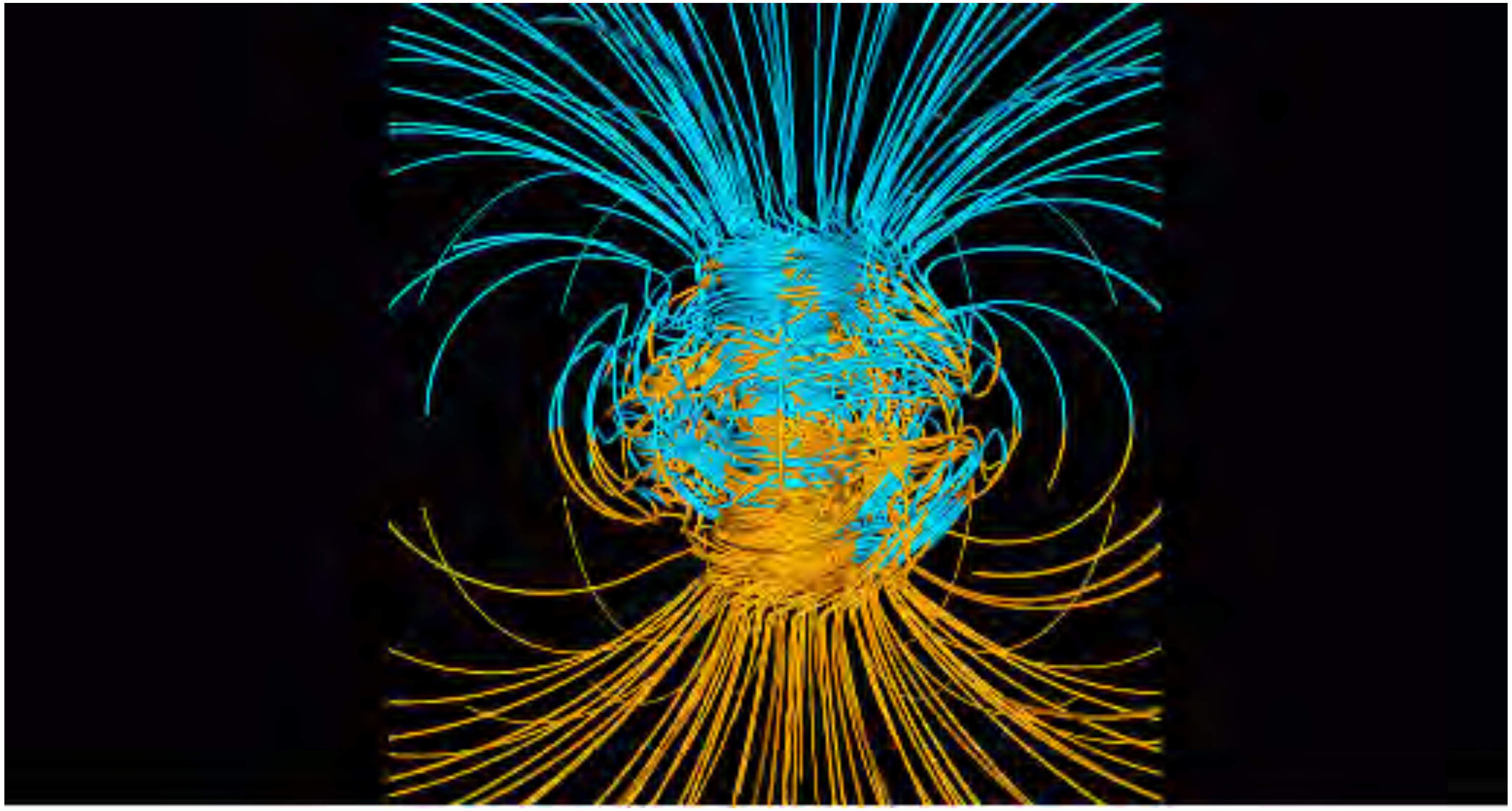
Atmospheric Spectroscopy





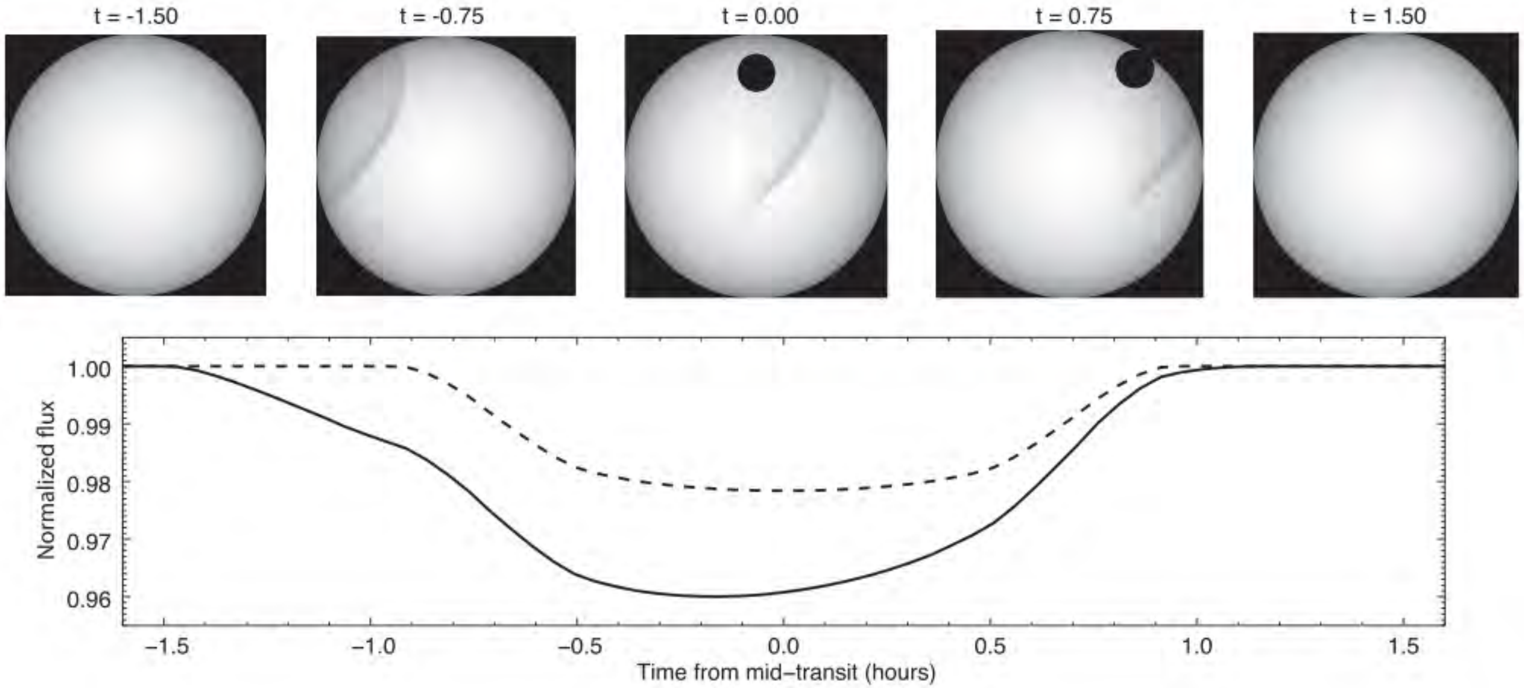
Tinetti et al. (2007) Nature
Marcq et al. (2012) Nat. Geosci.

Iron Melting



Glatzmaier & Roberts (1995) Nature

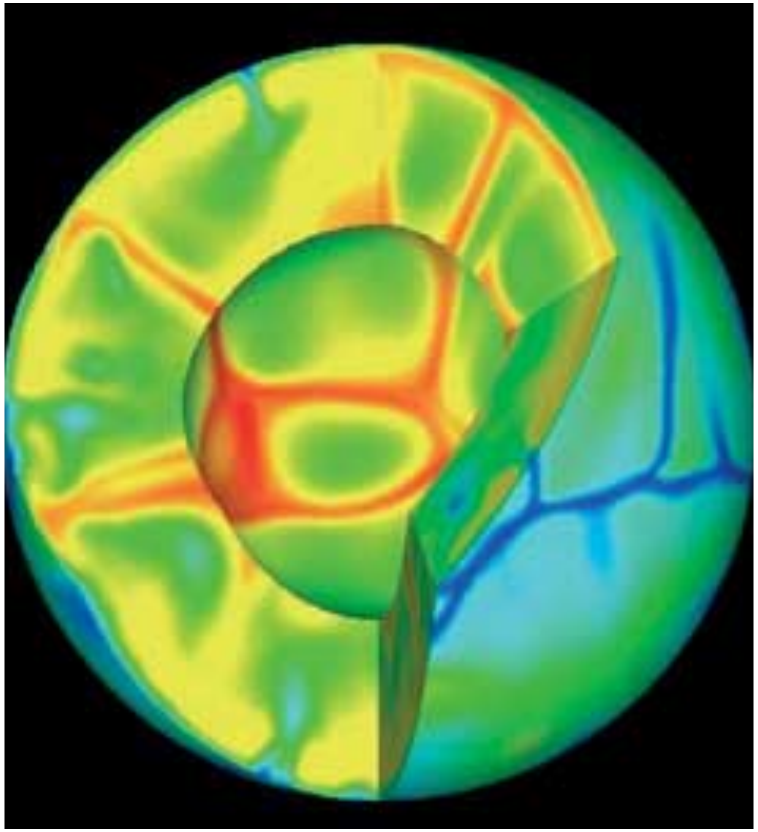
Exoplanet magnetic fields



Llama et al. (2013) MNRAS

Super Earth Magnetic Fields

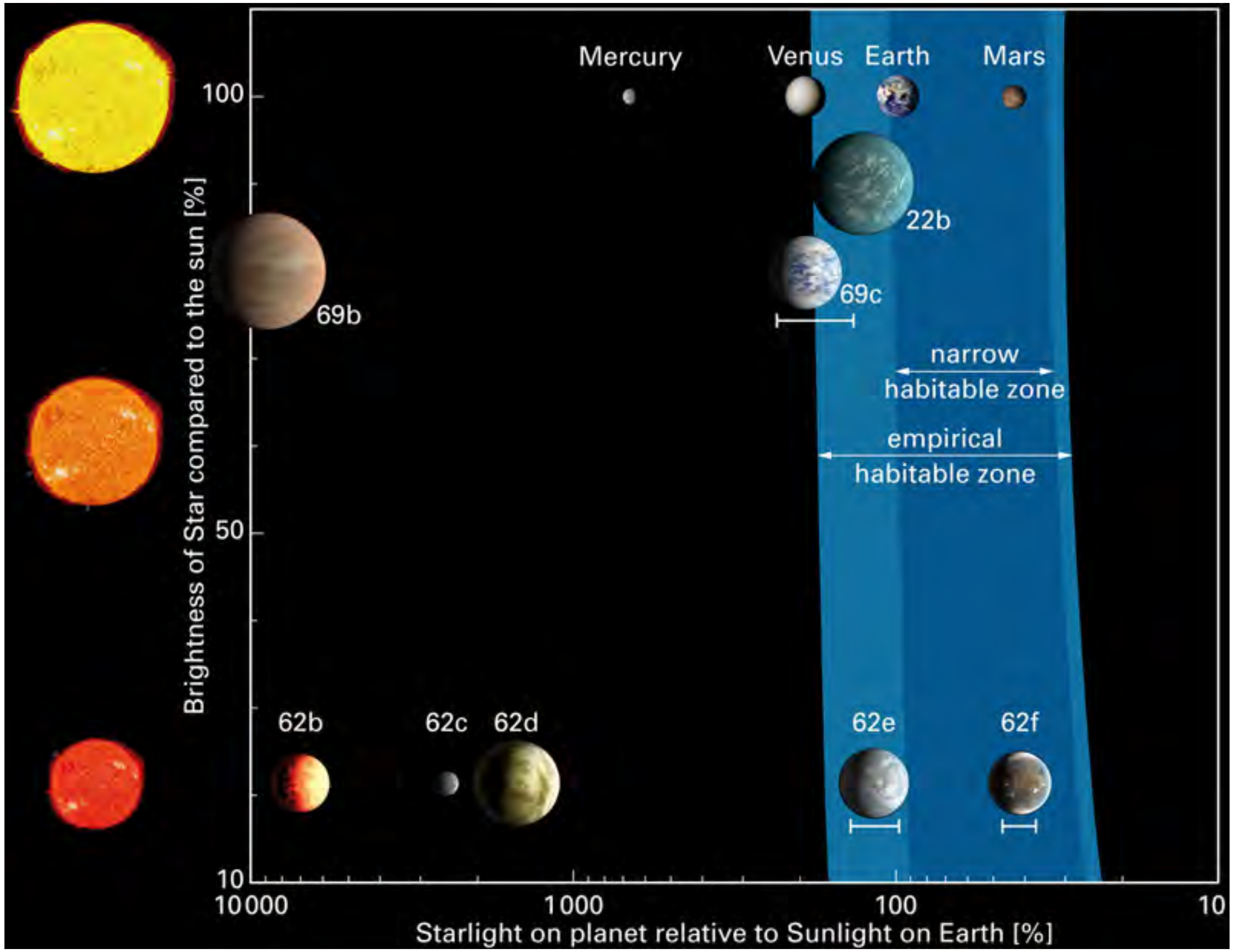
- Cooling is an important, perhaps essential energy source for a dynamo
- Rate of cooling depends on the overlying mantle
- Heat transported by convection
- Heat flux must exceed that conducted down the core adiabat
- ΔT across core-mantle boundary



Bunge et al. (1996) Nature

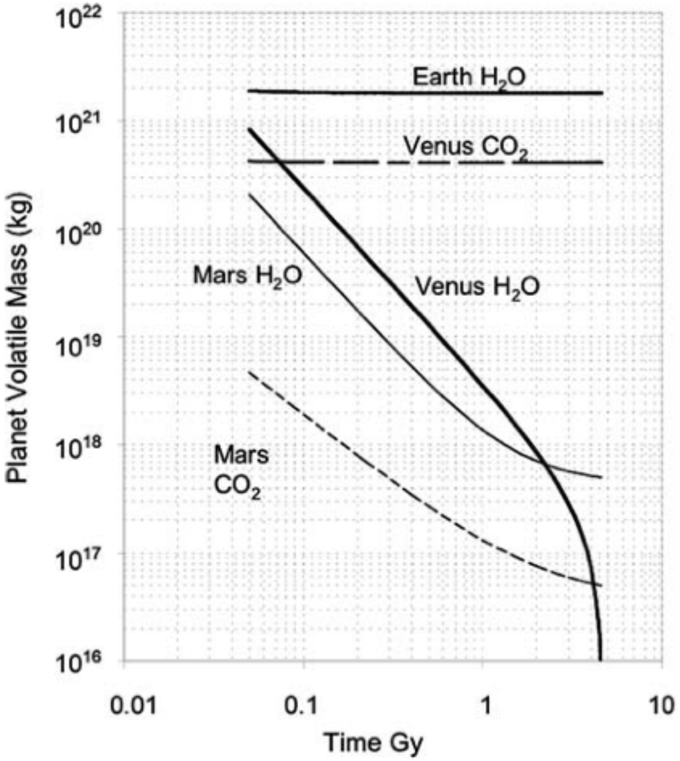
- Melting may be important for habitability of Super-Earths

Habitable Super-Earths



Borucki et al. (2013) Science

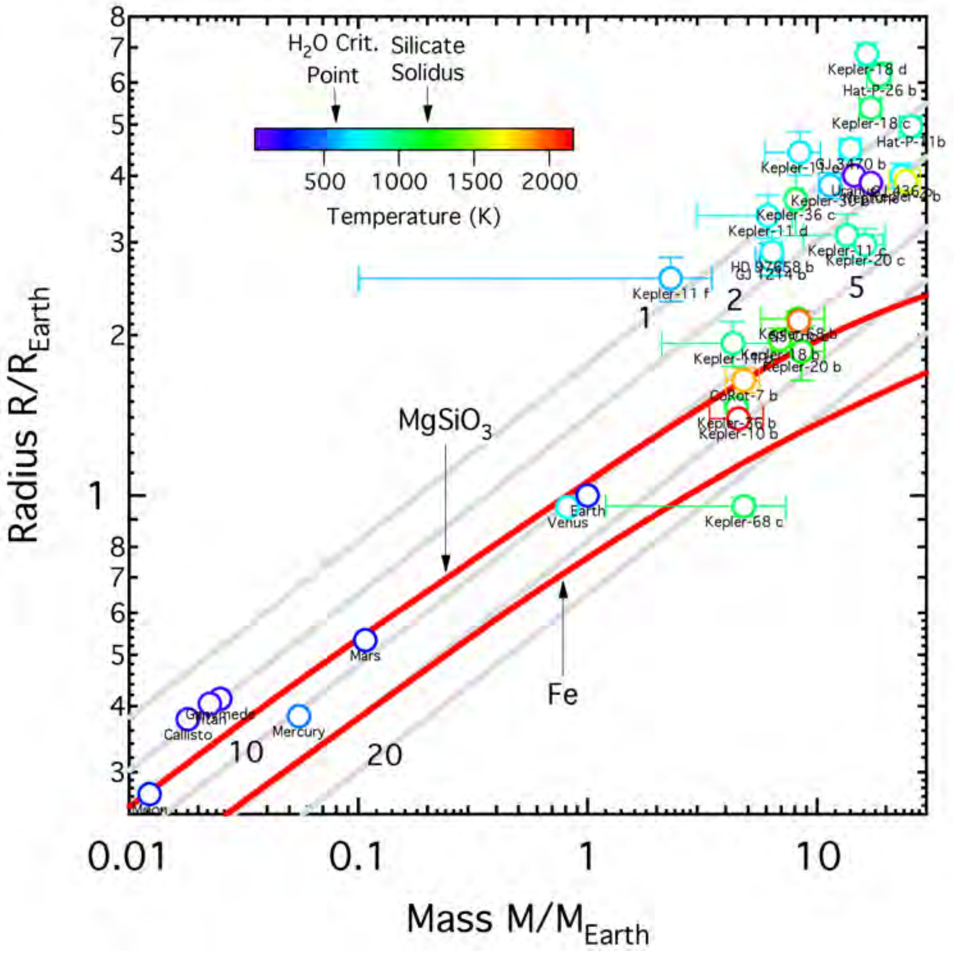
Melting and Habitability



Lundin et al. (2007) Space Sci. Rev.

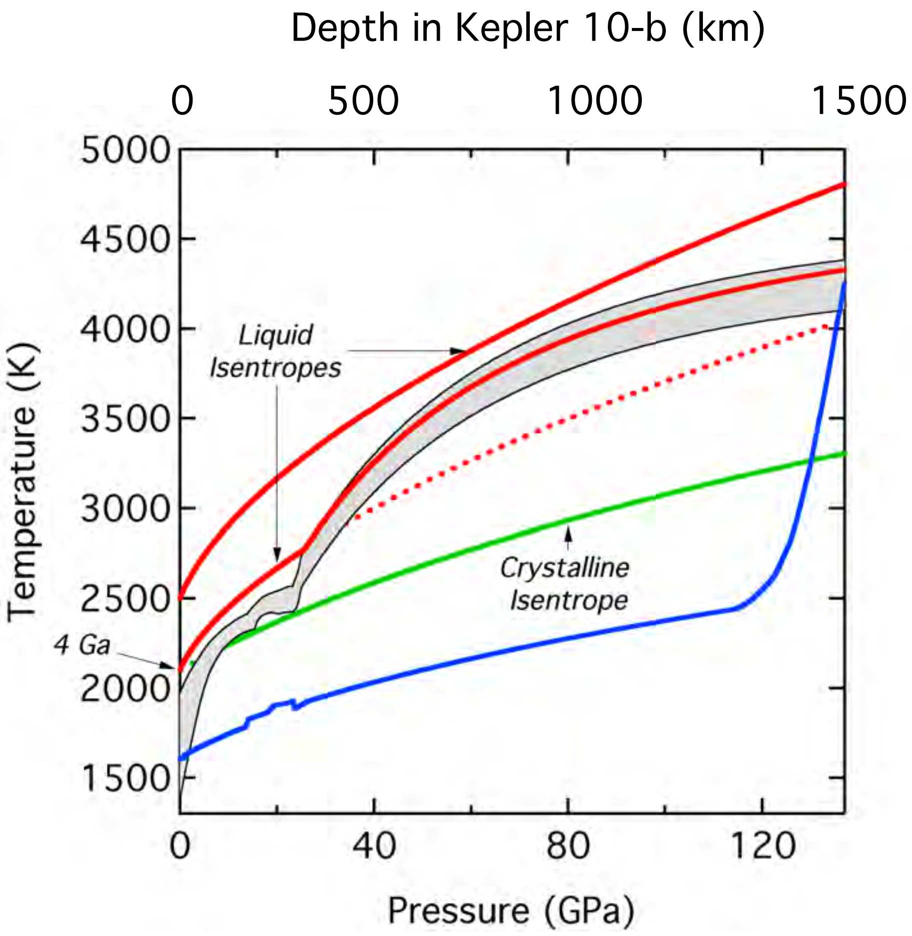
Hoffmann et al. (1998) Science

Super-Earths



$$R \propto M^{\beta}$$
$$\beta \simeq 0.27$$

Deep Melting Today

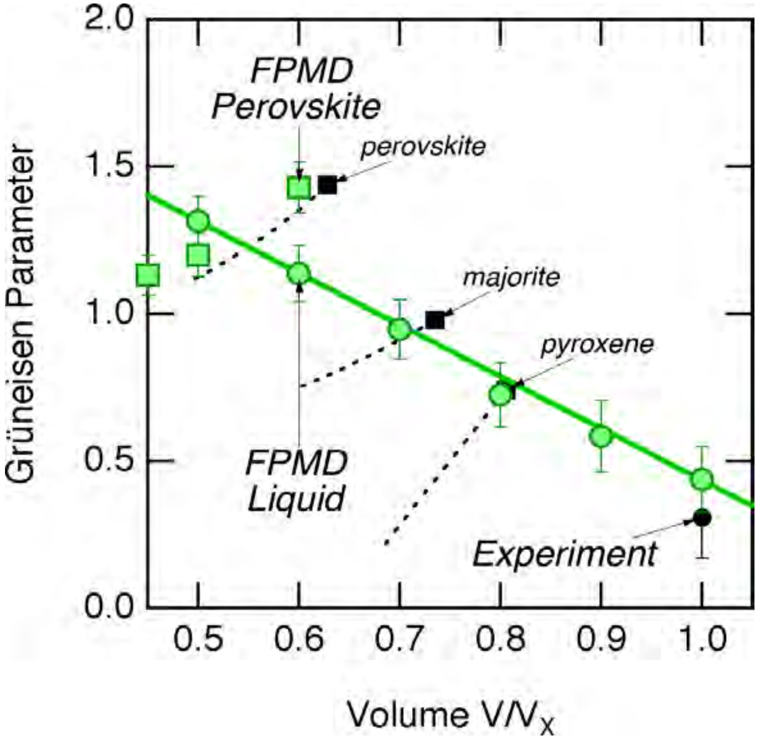


Stixrude et al. (2009) EPSL

Grüneisen Parameter

- Increases on compression
- Differs from crystalline phases
- Caused by change in liquid structure

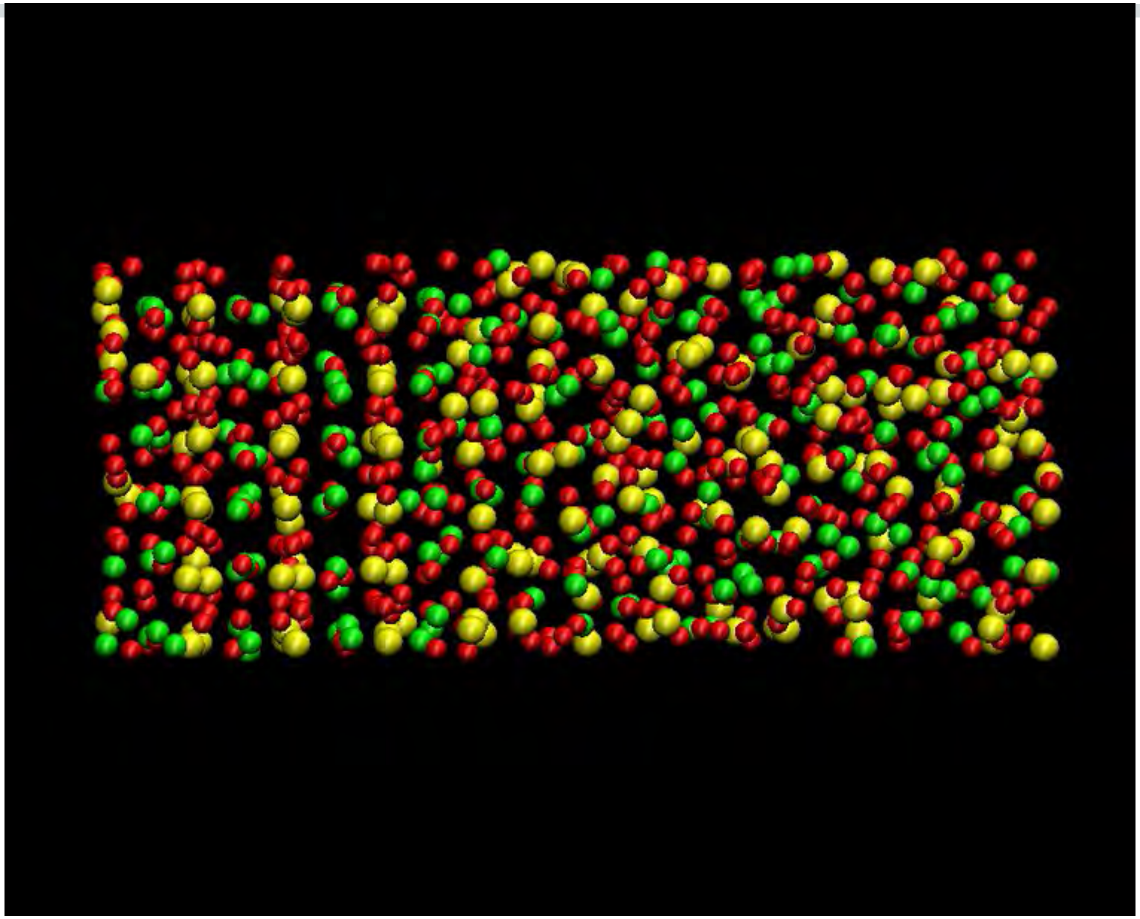
$$\gamma = \left(\frac{\partial lnT}{\partial ln\rho}\right)_S$$



$MgSiO_3$

Stixrude & Karki (2005) Science

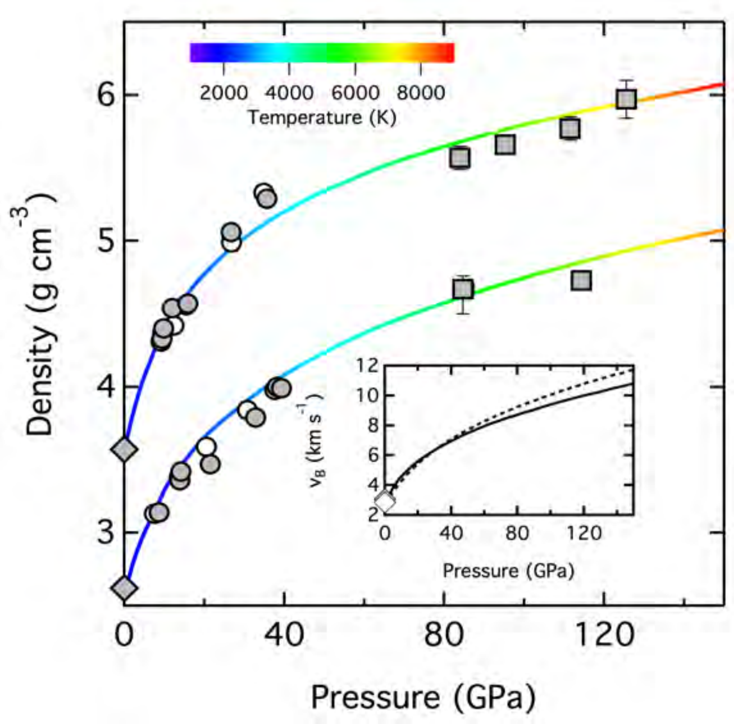
First Principles Molecular Dynamics



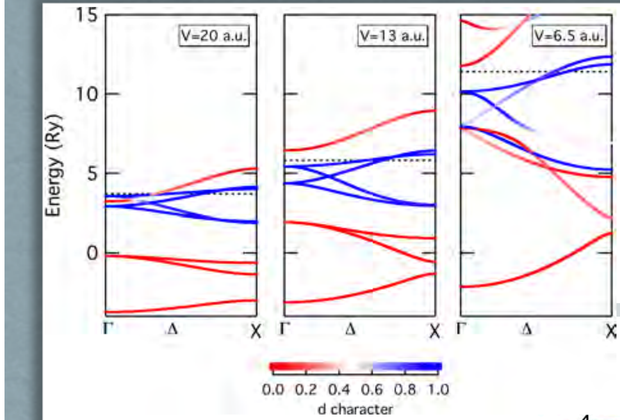
John Brodholt, UCL

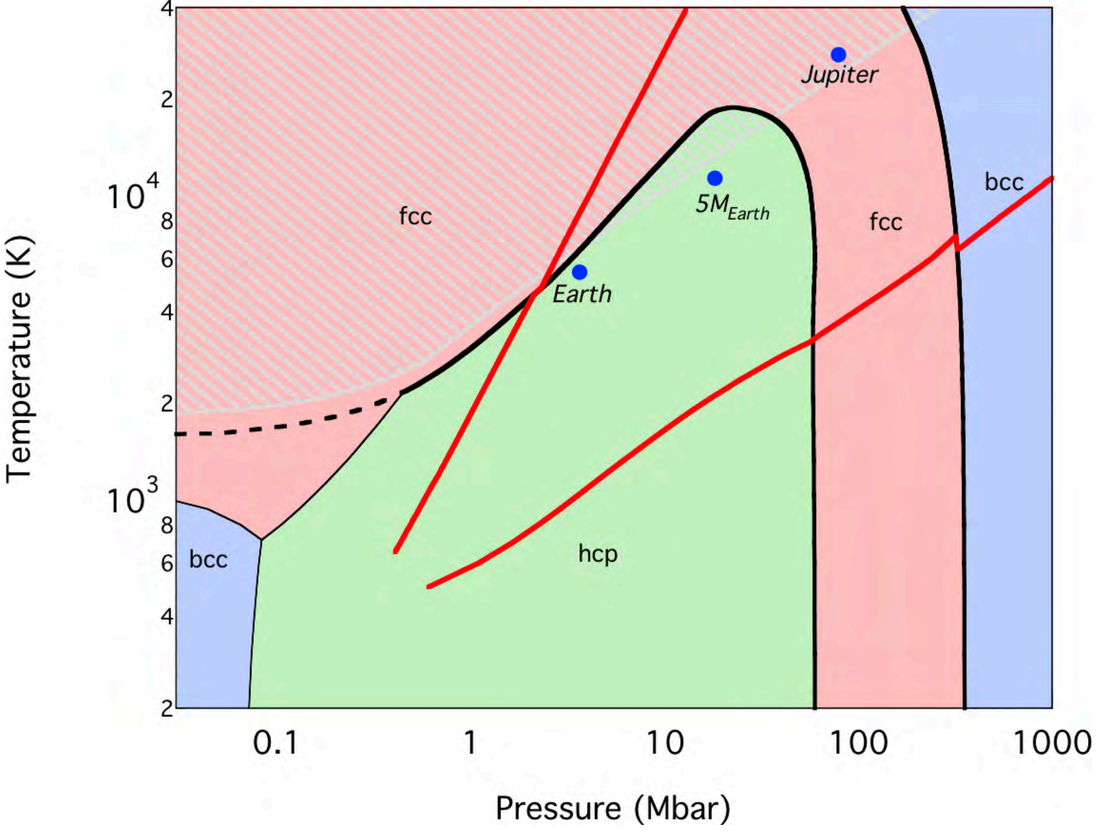
Density Functional Theory

- Predictive power
  - No free parameters
  - No *a priori* assumptions regarding shape of charge density or nature of bonding
- Scope
  - Entire pressure-temperature range of planets (and stars)
  - Entire periodic table
- Accuracy
  - Tested via comparison with experimental data



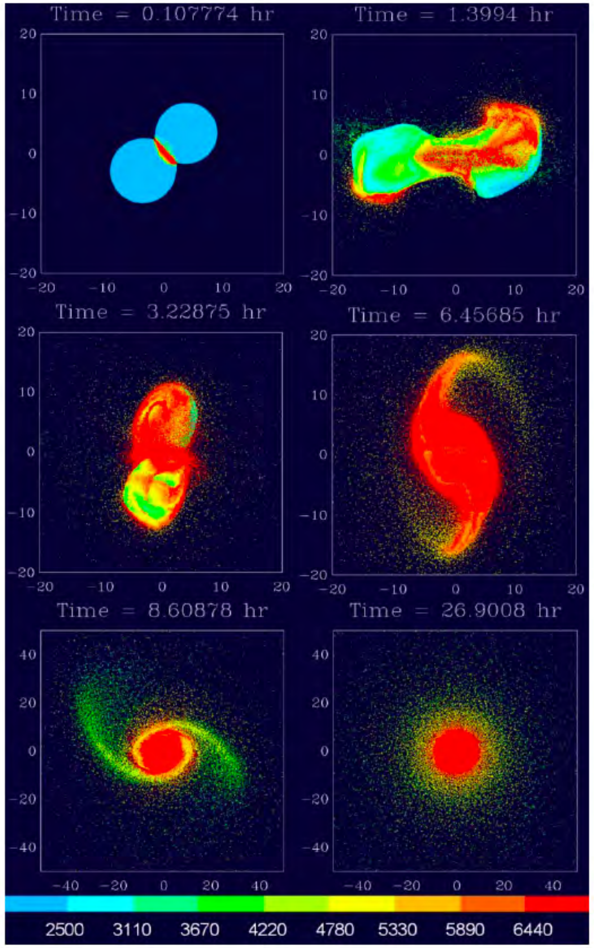
Sun et al. (2011) GCA
Karki et al. (2012) Am. Min.

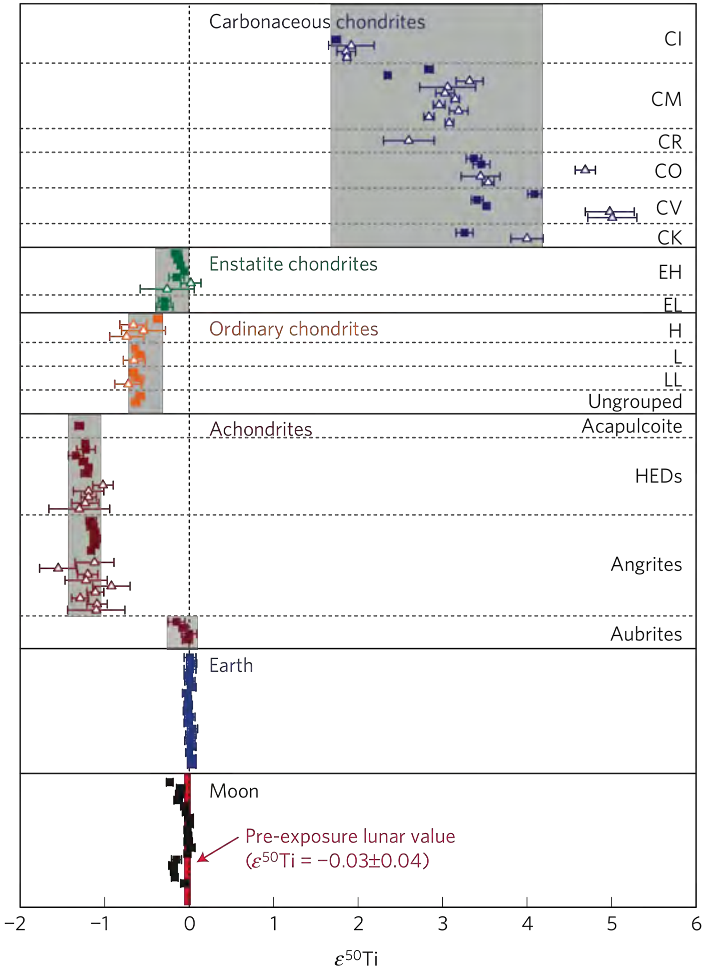




Stixrude (2012) PRL
Jeanloz et al. (2007) PNAS

Accretional Heating

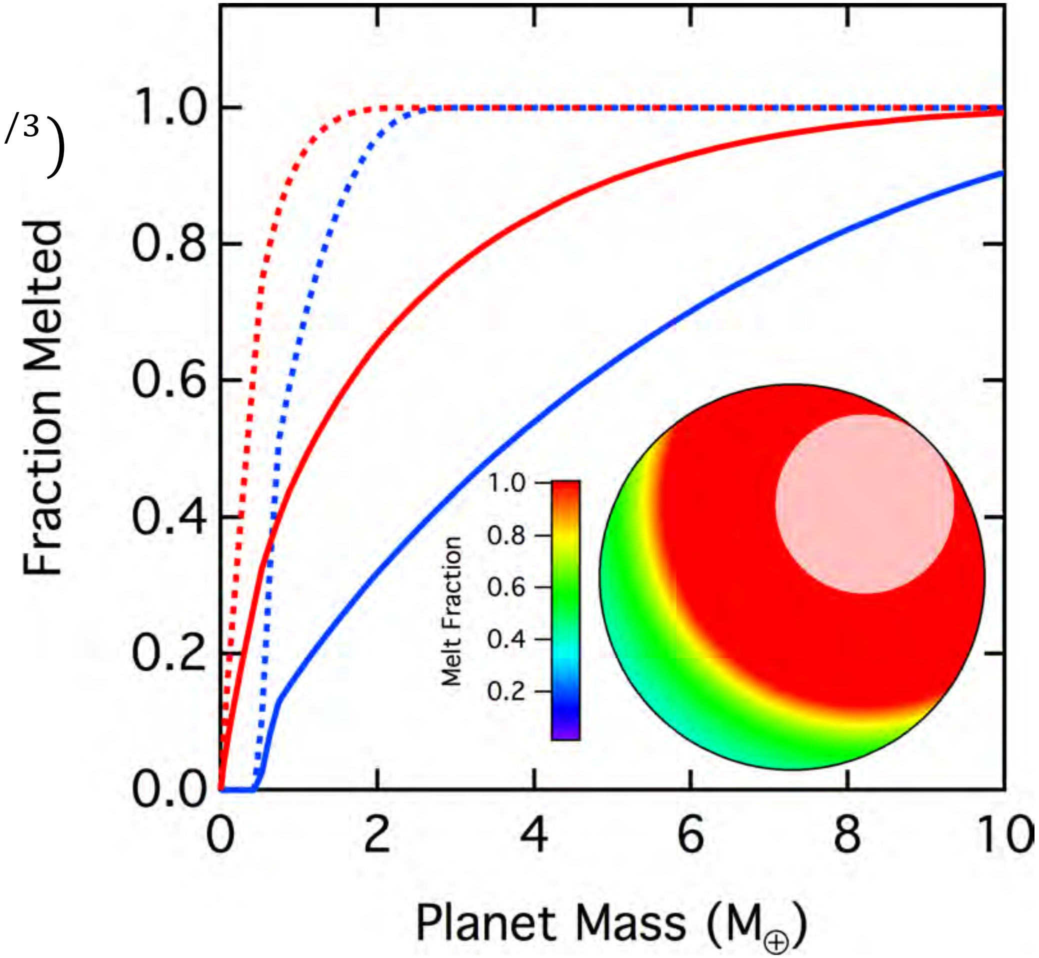




Canup (2012) Science; Zhang et al. (2012) Nature Geo.

Accretional Heating

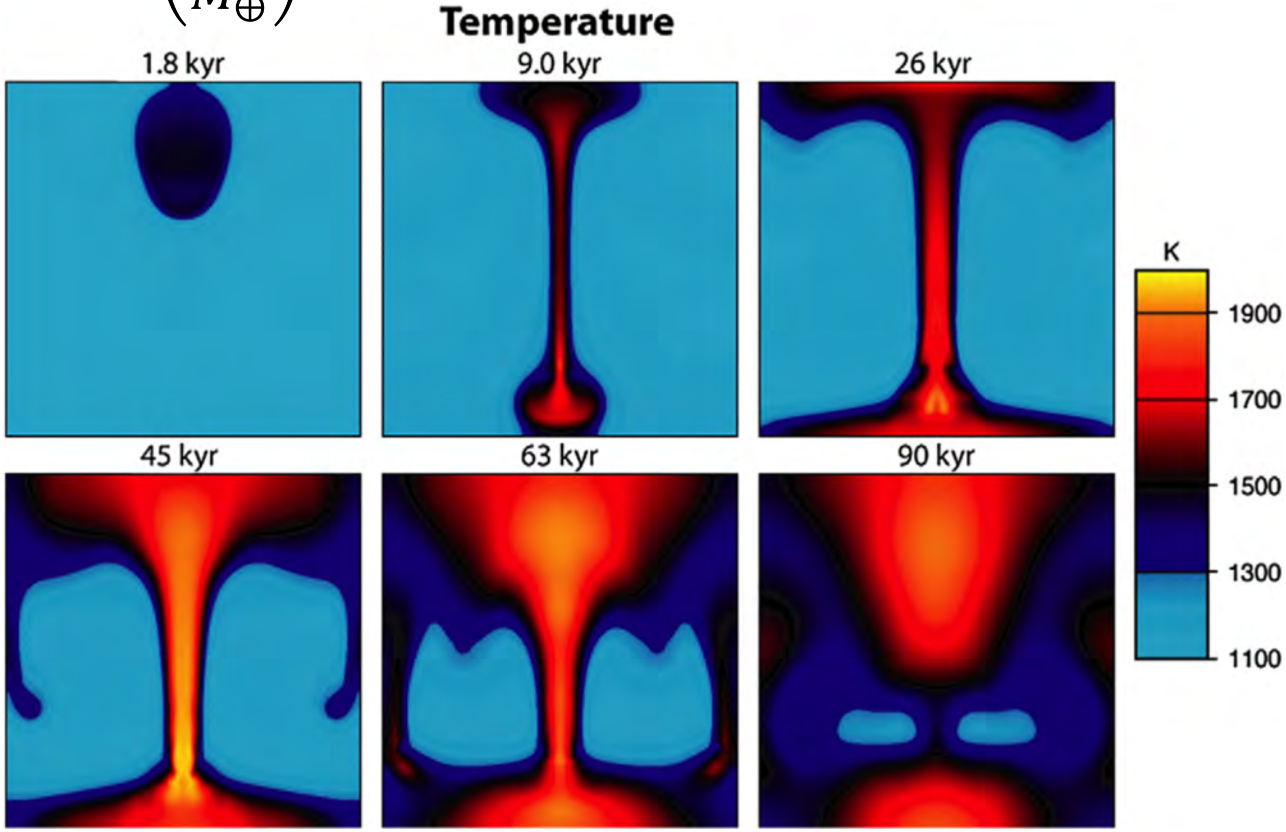
$$T_P = T_S + \frac{1}{5c'}\left(\frac{M_i}{M_P}\right)\left(GM_P^{2/3}\right)$$



Stixrude (2014) Phil. Trans.; Tonks & Melosh (1993) JGR

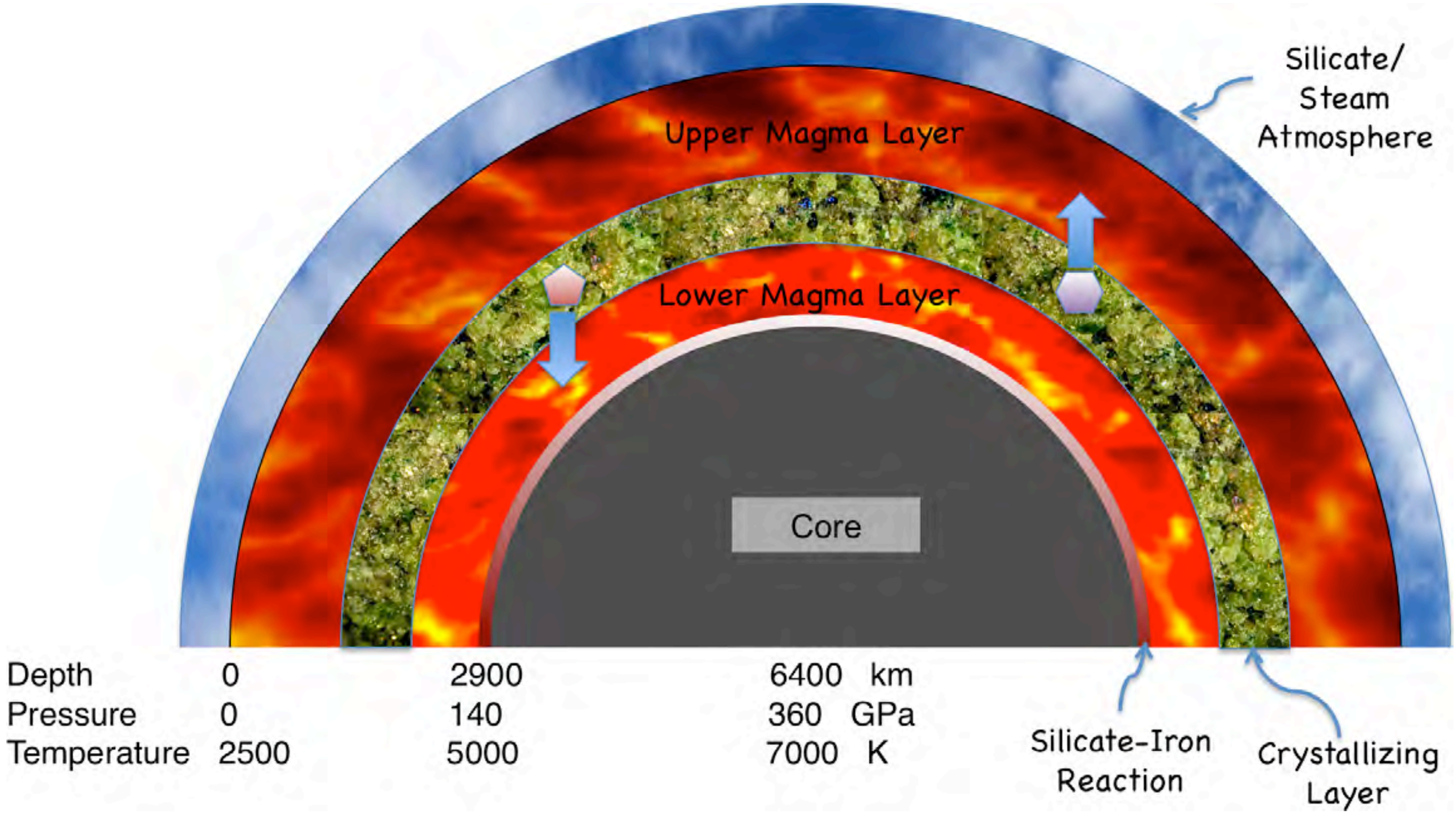
Gravitational Heating

$$\Delta T_P \approx 2300\ K \left(\frac{M_P}{M_\oplus}\right)^{1-\beta}$$



Ricard et al. (2009) EPSL

Molten Planet



Upper Magma Layer

Lower Magma Layer

Core

Silicate/
Steam
Atmosphere

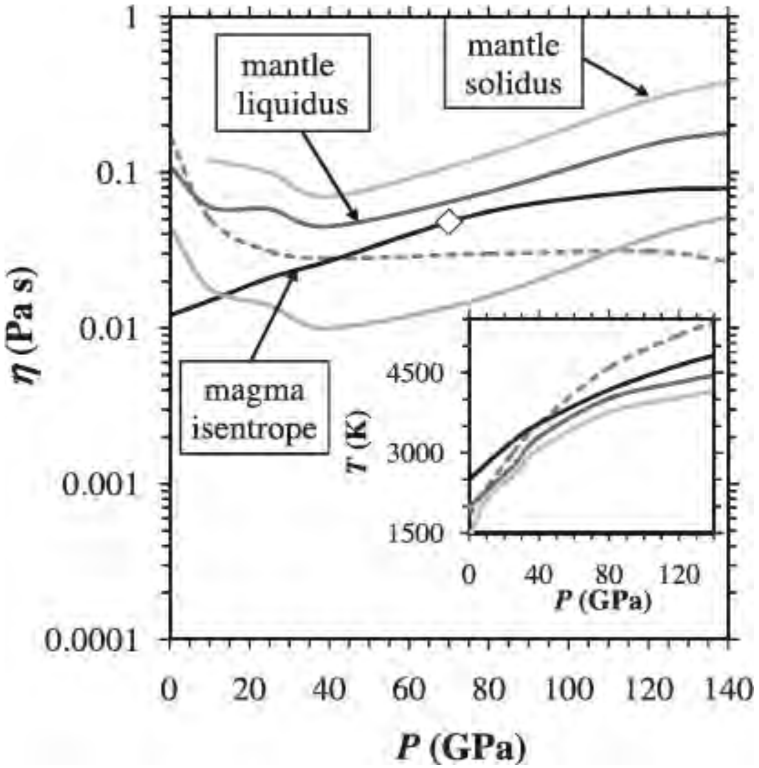
Silicate-Iron
Reaction

Crystallizing
Layer

Depth	0	2900	6400	km
Pressure	0	140	360	GPa
Temperature	2500	5000	7000	K

Viscosity

- Increases by factor of ~10 from surface to base of mantle
- Silicate liquids remain mobile throughout mantle
- Vigorous convection



$MgSiO_3 \pm H_2O$

Karki & Stixrude (2010) Science

Magma Ocean Dynamics

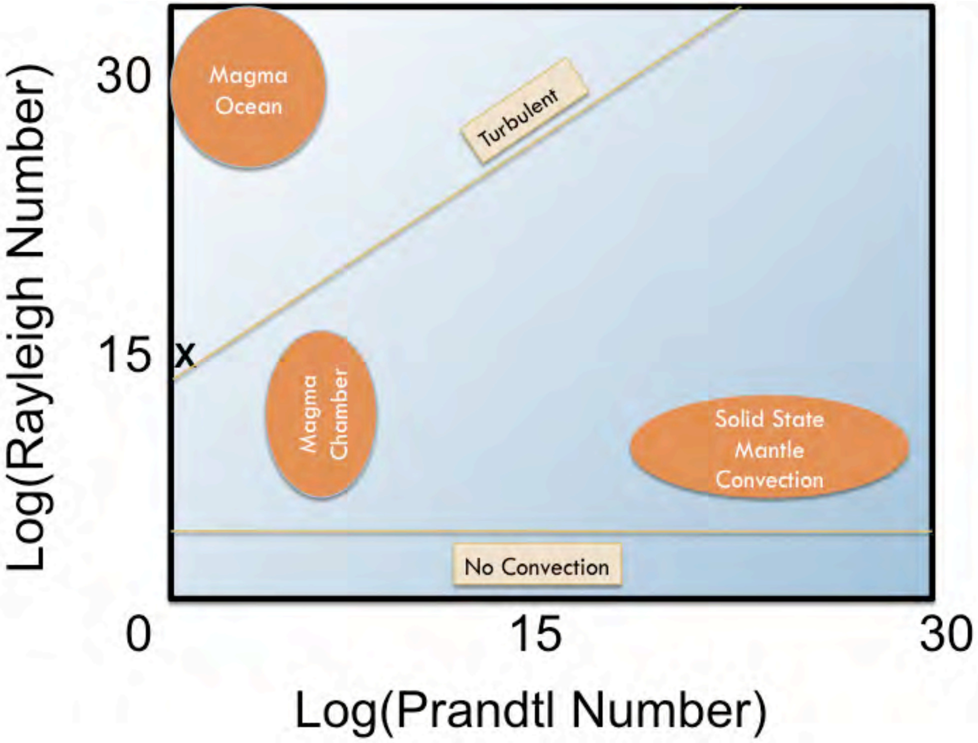
Flow is super-turbulent

Heat flux exceeds incoming stellar

$$\mathrm{Ra} = \frac{\alpha\rho g(T_M - T_S)L^3}{\kappa\eta} \approx 6\times10^{30}$$

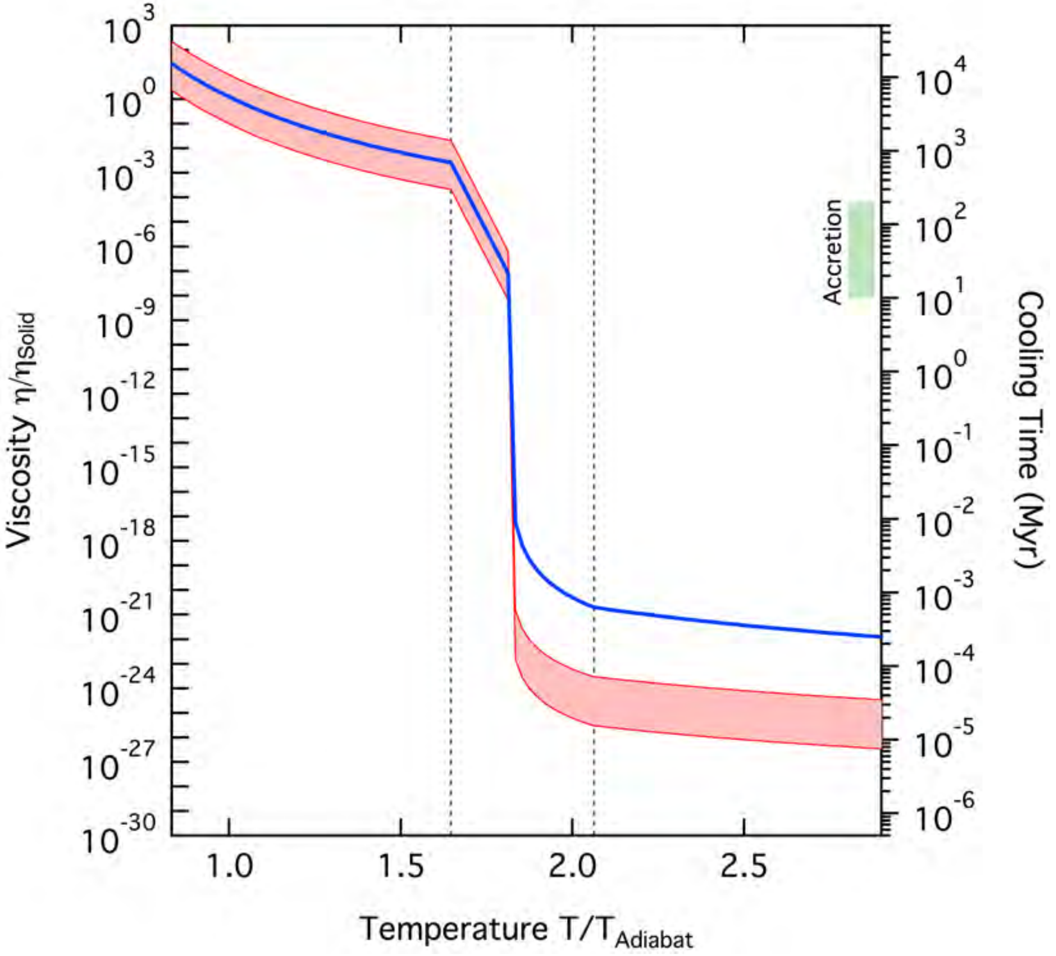
$$\mathrm{Pr} = \frac{\eta}{\rho\kappa} \approx 60$$

$$F = 0.22\frac{k(T_M - T_S)}{L}\mathrm{Ra}^{2/7}\,\mathrm{Pr}^{-1/7} \approx 6\times10^{4}\ \mathrm{W\ m^{-2}}$$



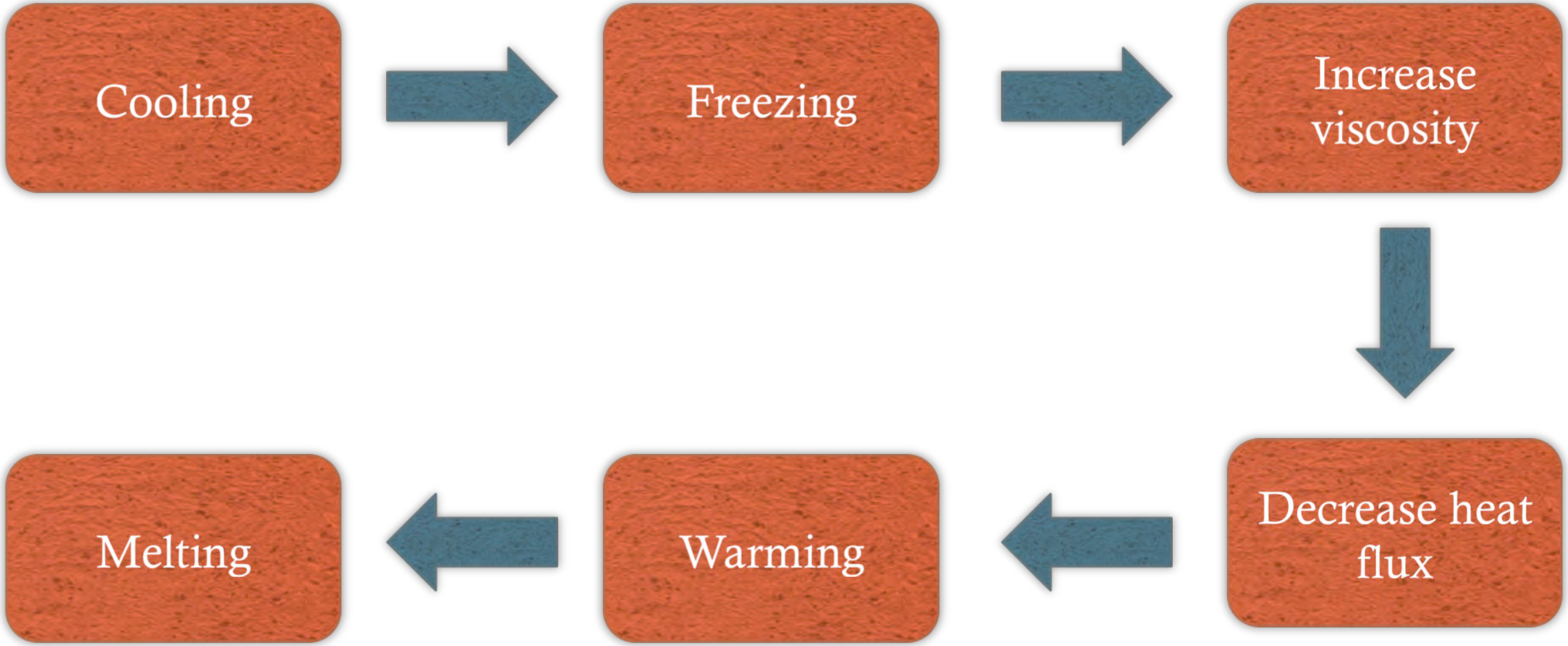
Karki & Stixrude (2010) Science

$$\tau = 3.9\ \mathrm{Gyr}\left(\frac{M_P}{M_\oplus}\right)^{1-2\beta}\left(\frac{\eta_0 e^{-\alpha\phi}}{1\times10^{21}\ \mathrm{Pa\ s}}\right)^{1/3}\left(\frac{T_P - T_S}{1300\ \mathrm{K}}\right)^{-1/3}$$



Stixrude (2014) Phil. Trans.

Thermal Regulation



Cooling

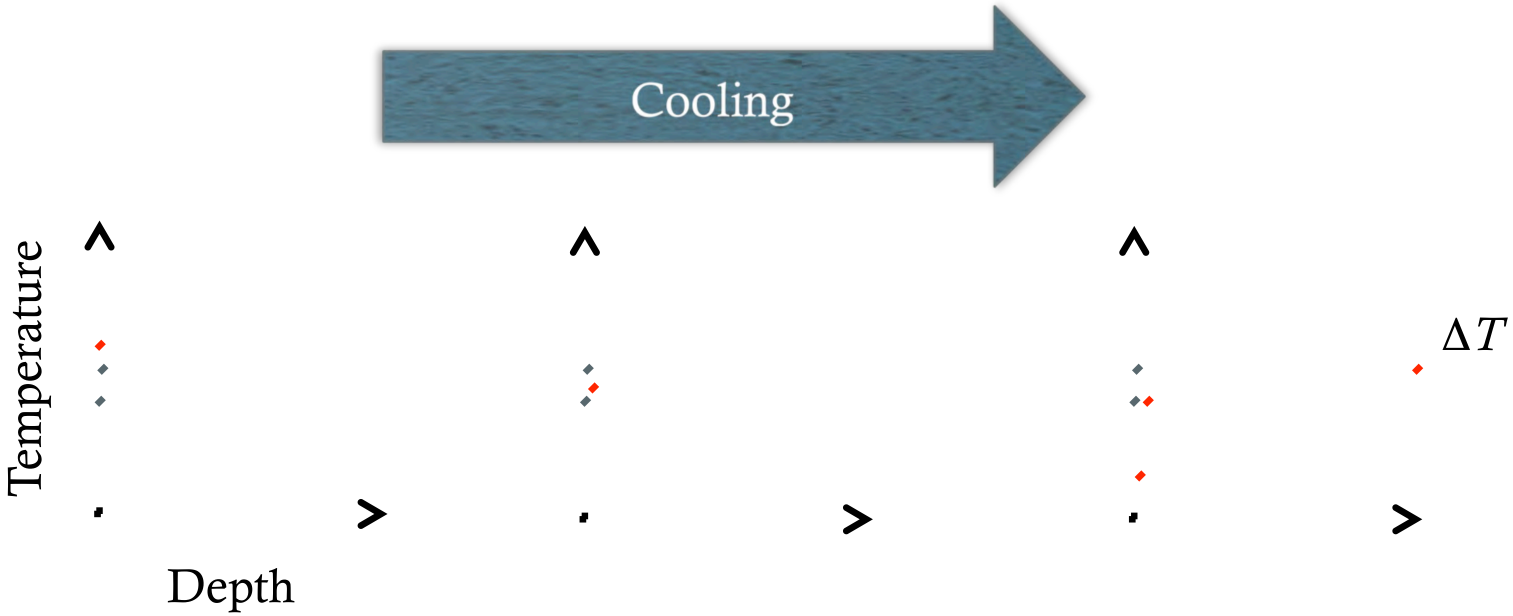
Freezing

Increase viscosity

Decrease heat flux

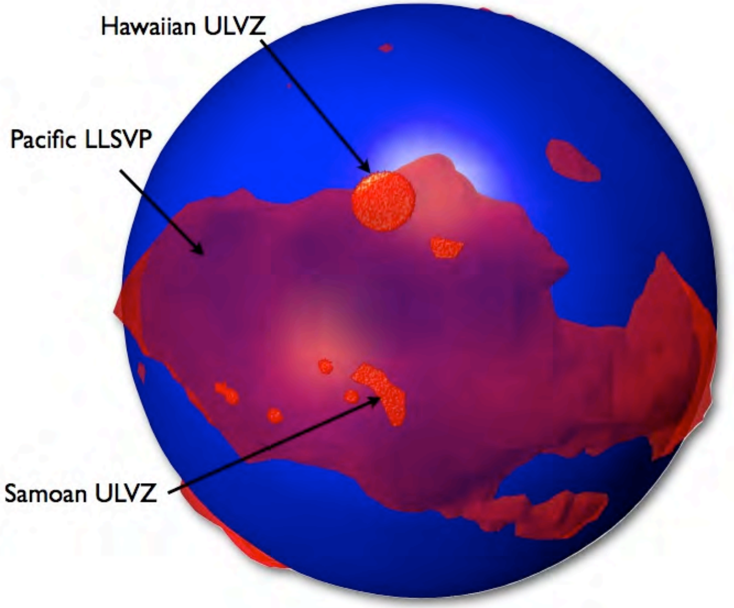
Warming

Melting



$$\Delta T = \left(\frac{\eta}{\rho^2 \alpha g c k^2}\right)^{1/4} F^{3/4}$$

Boundary Layer Melting



Grüneisen parameter γ controls
    slope of melting curve (Lindemann Law)
    slope of adiabat

$$\frac{d\ln T_{\mathrm{melt}}}{d\ln\rho} = 2\left(\gamma - \frac{1}{3}\right)$$

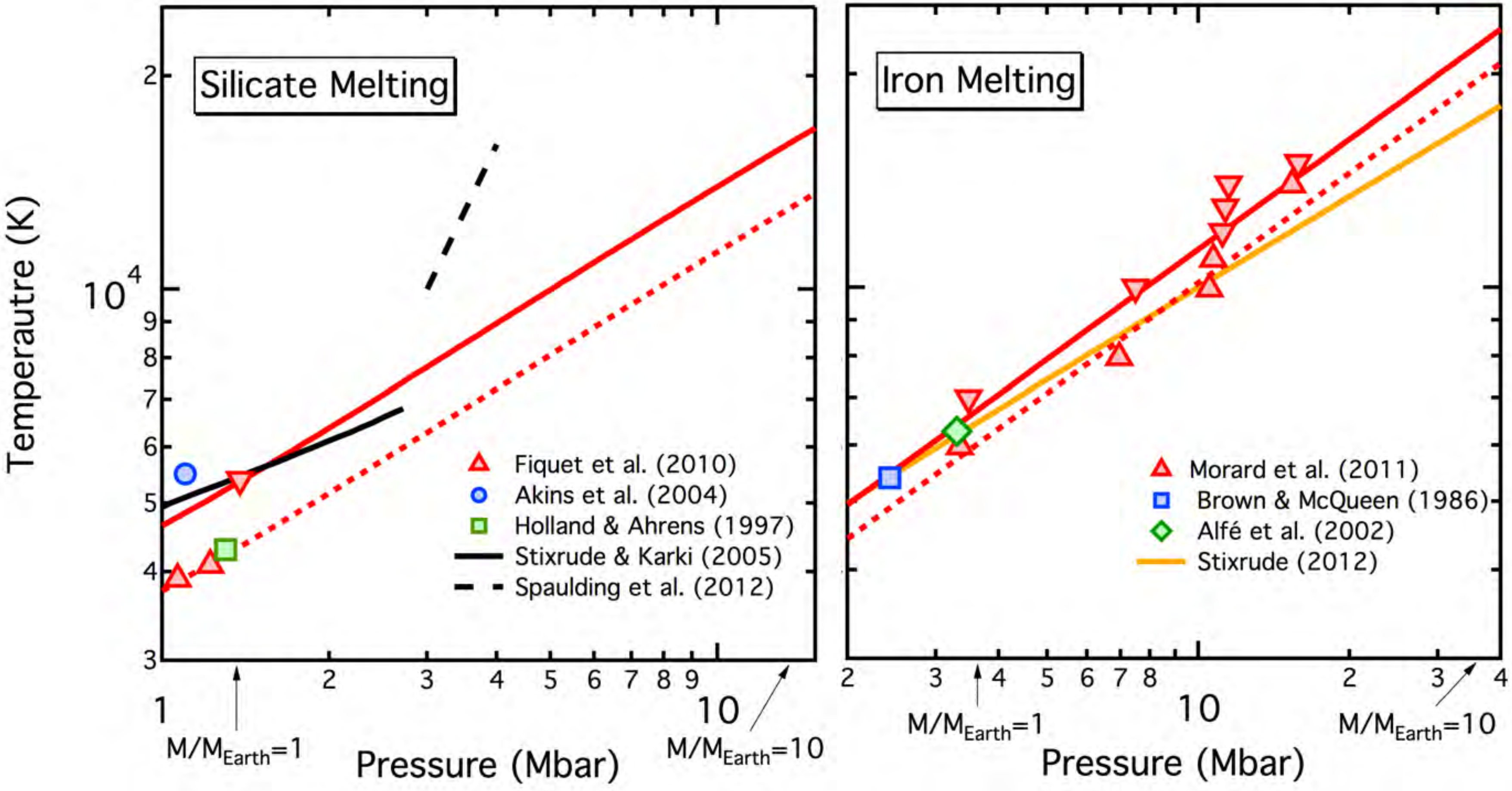
is greater than

$$\frac{dlnT_{\mathrm{adiabat}}}{dln\rho} = \gamma$$

$$\gamma \approx 1$$

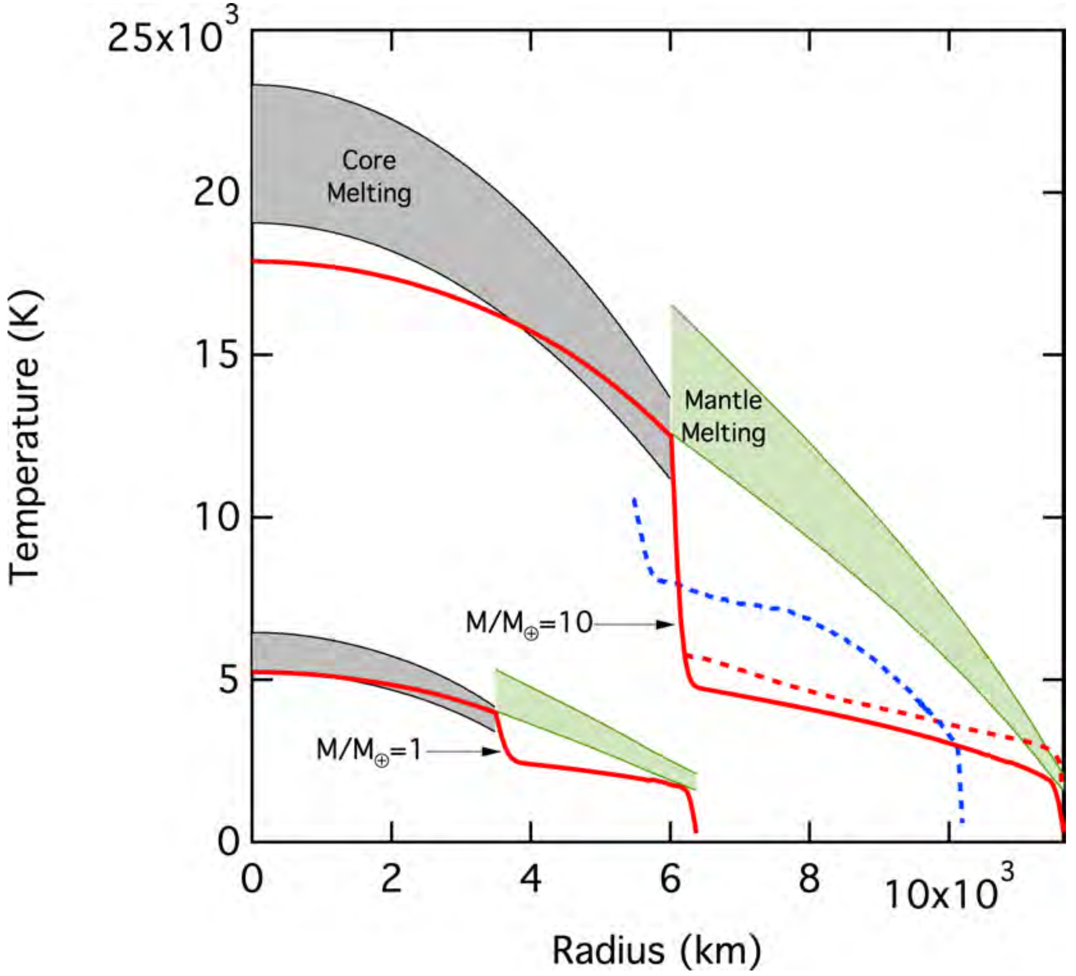
Stixrude (2014) Phil. Trans.

Planetary Melting



Stixrude (2014) Phil. Trans

Super-Geotherms



Stixrude (2014) Phil. Trans.

Super-Earth Magnetic Fields

$$F_{\mathrm{CMB}} \approx 80\ \mathrm{mW\ m^{-2}}\, \frac{M_P}{M_\oplus}$$

is greater than

$$F_{\mathrm{cond}} \approx 2k\frac{T_C}{R_C}\ln\frac{T_0}{T_C} = 60\ \mathrm{mW\ m^{-2}} \left(\frac{M_P}{M_\oplus}\right)^{1-\beta}$$

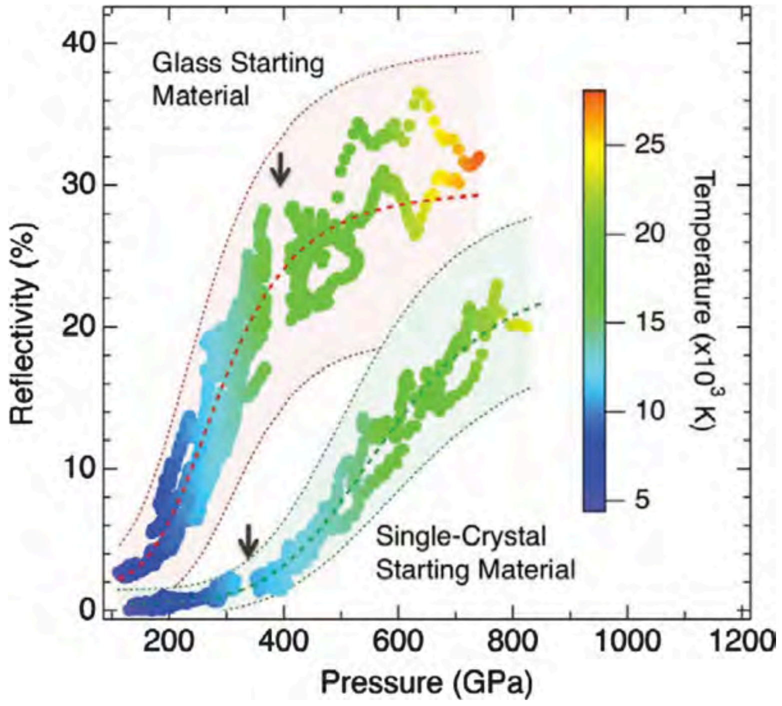
Stixrude (2014) Phil. Trans.

Conclusions

- Super-Earths began in a completely molten state
- Melt survives in upper and lower mantle boundary layers
- Volcanic activity increases with planetary mass
- Magnetic field strength increases with planetary mass
- Suprises in materials physics await…

Silicate Dynamos?

- Metallization of planet-forming materials at super-Earth conditions
- Molten silicate becomes metallic at super-Earth conditions
- Possible seat of dynamo activity



$MgSiO_3$

Spaulding et al. (2012) PRL