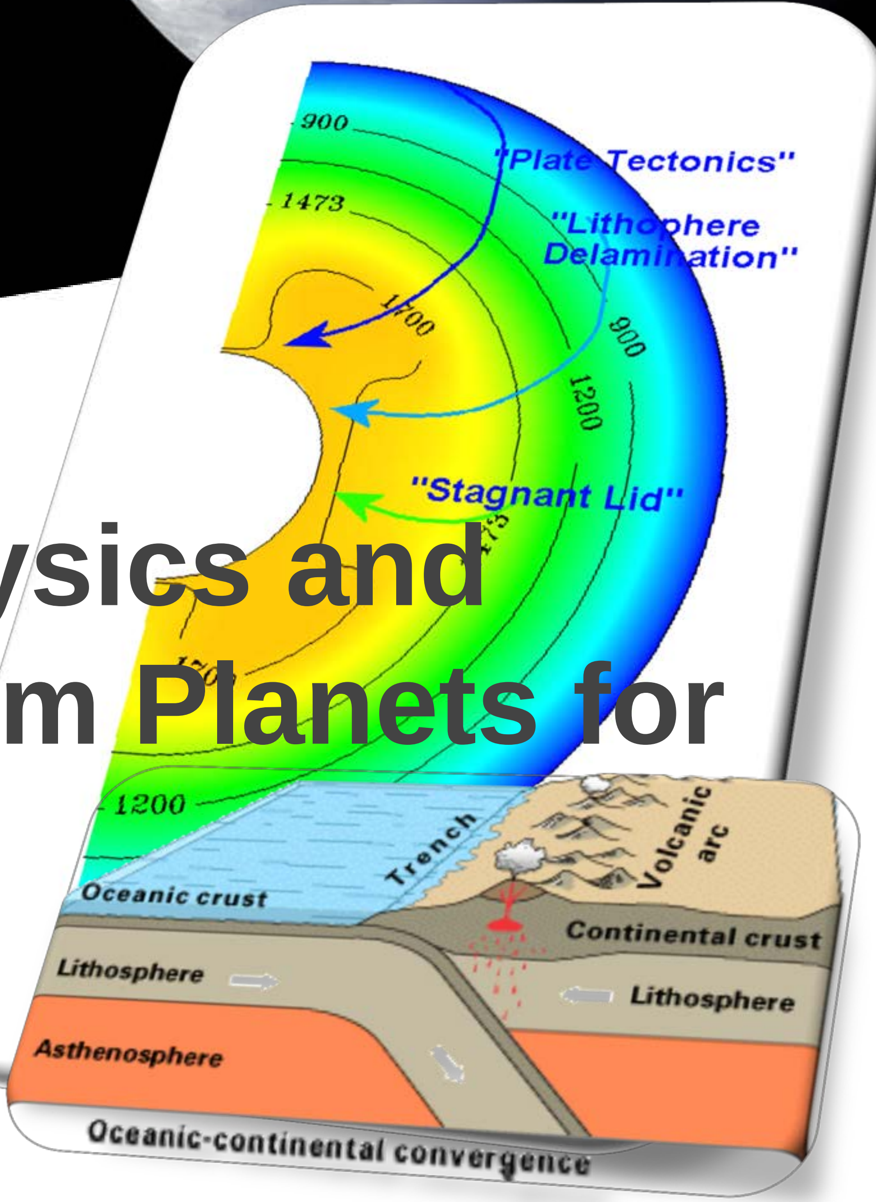


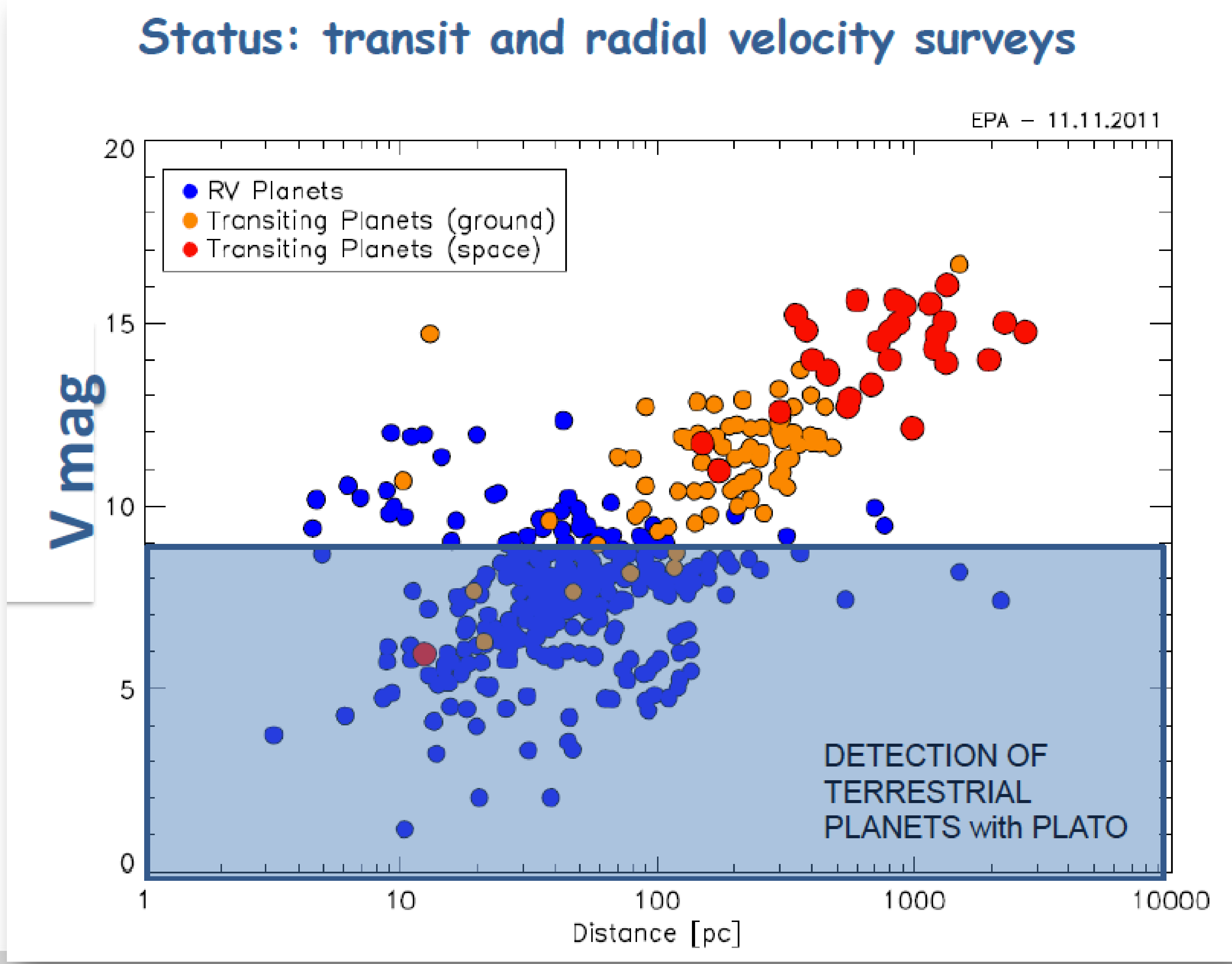
How Could Plato Serve Planetary Physics and What can we Learn From Solar System Planets for Terrestrial Exoplanets?

Tilman Spohn

DLR Deutsches Zentrum
für Luft- und Raumfahrt e.V.
in der Helmholtz-Gemeinschaft

PLATO – What we expect

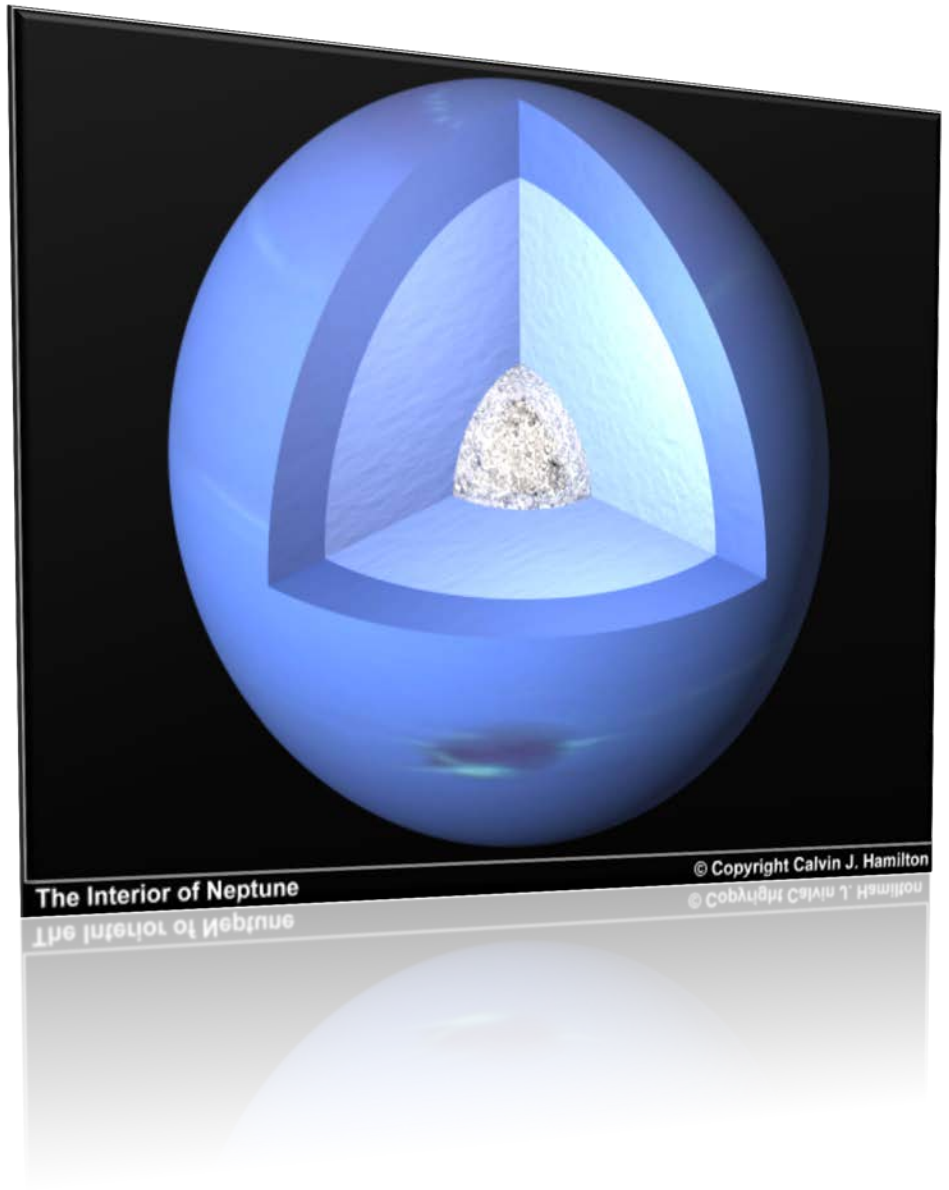
- ✓ Several thousand exoplanets with mass and radius (constraining composition) and age of the parent star!
- ✓ Statistics of planets and planetary systems
- ✓ Spectroscopy of the parent star to provide its composition? (From which we may infer the composition of the planets...see below)

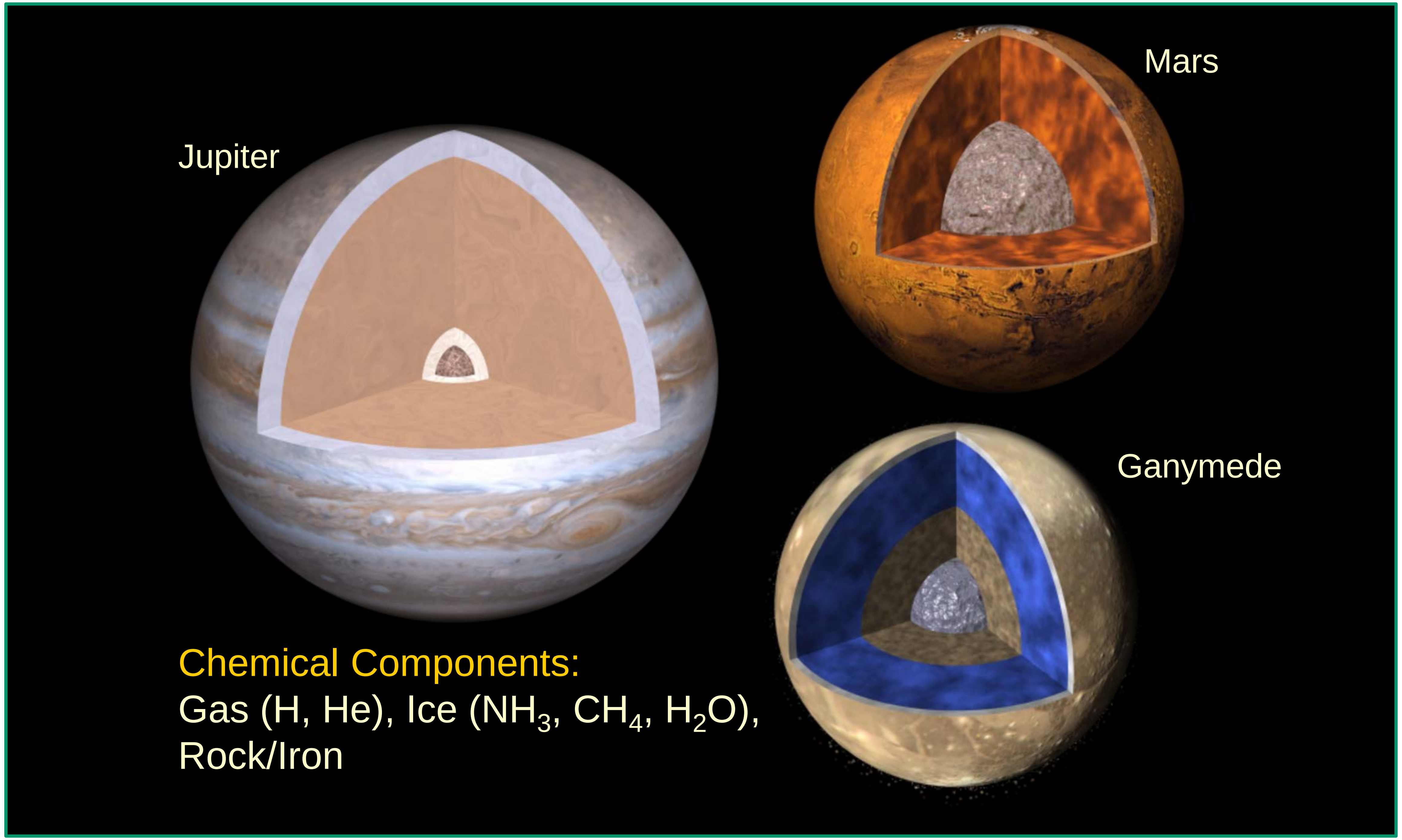

Status: transit and radial velocity surveys

EPA – 11.11.2011

DETECTION OF TERRESTRIAL PLANETS with PLATO

Simple Compositional Models of Planets

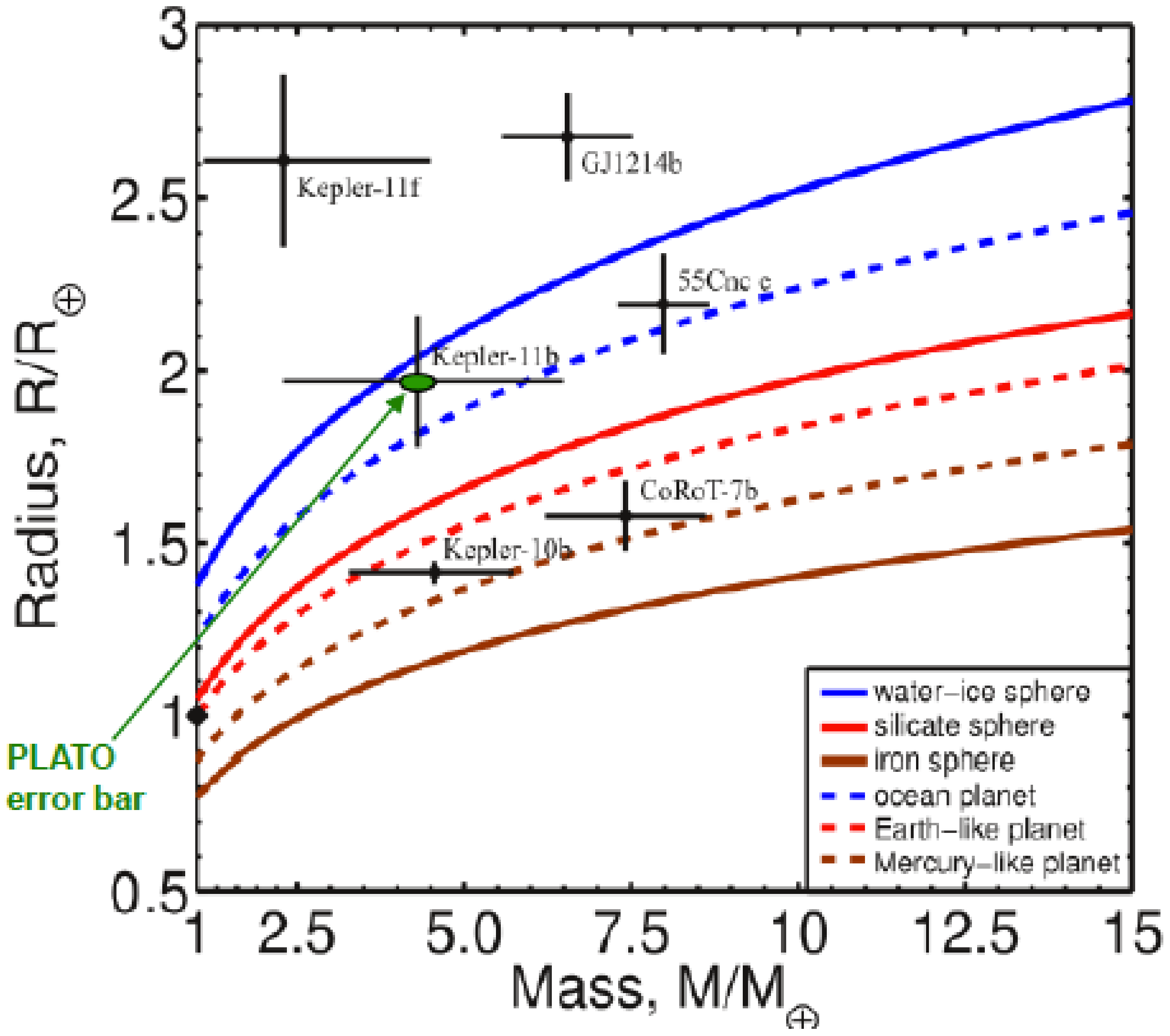




Chemical Components:
Gas (H, He), Ice (NH_3, CH_4, H_2O), Rock/Iron

Composition – What are the Planets made of?

- Densities need to be compared at standard values of T and P
- Decompress actual densities using EOS
- Densities of planetary components are clearly distinguishable
- Ice (275 K, 10^5 Pa) around 1000 kg/m^3; rock 3000-4000 kg/m^3; iron 5000 to 8000 kg/m^3; rock/iron 4000-5000 kg/m^3

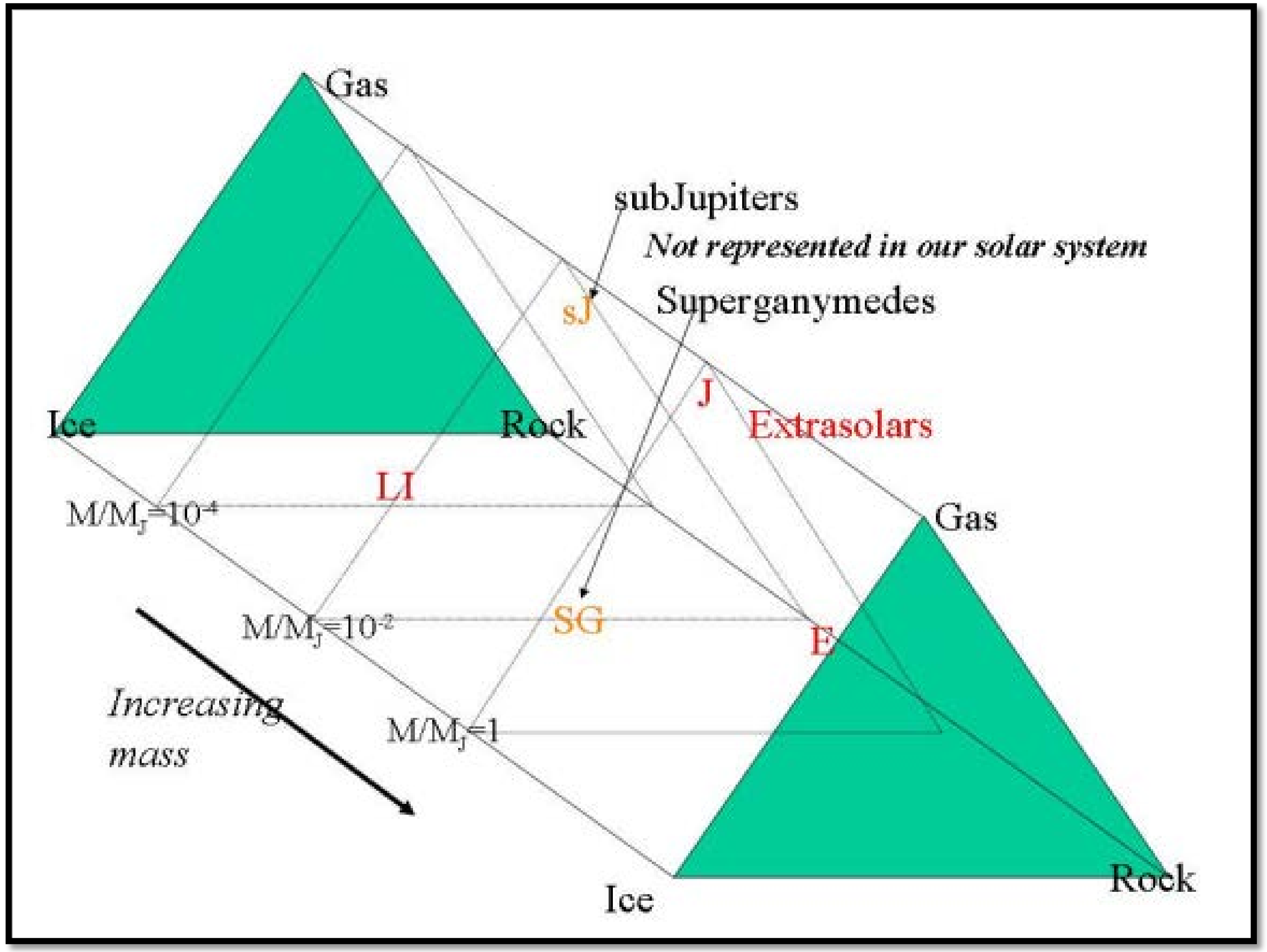


These EOS give the right trend but must be regarded as highly uncertain

Simple Compositional Models of Planets

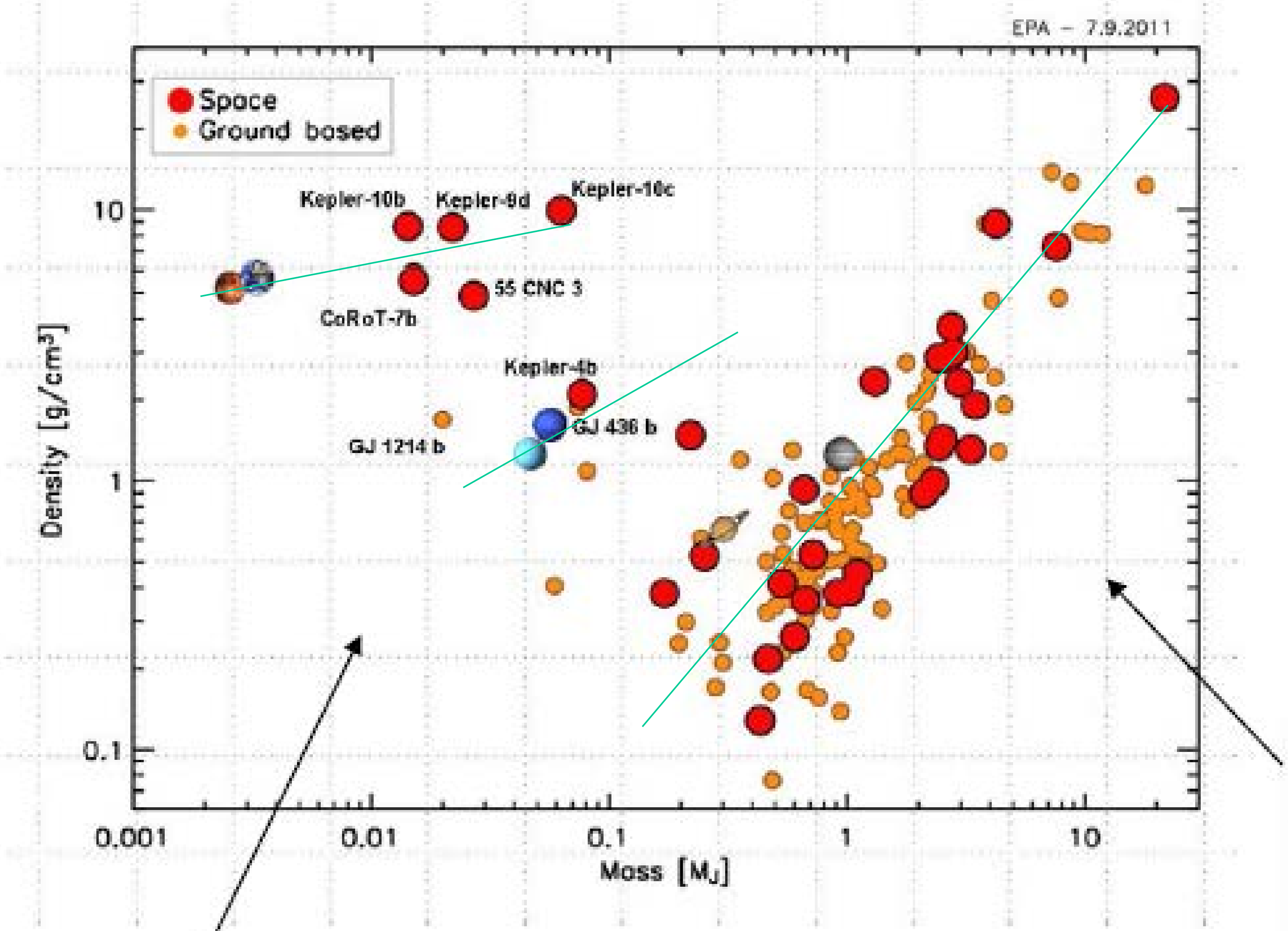
- Only a few of the cases one may think of are realized in the solar system
- PLATO, please fill the diagram!
- Is there a maximum mass (size) for rocky planets? (as H. Rauer suggests)
- What is the transition mass for super-Ganymedes to mini-Neptunes?
- Is there a minimum mass (size) for gaseous planets? Maximum mass according to EOS theory?
- There will – of course – be uniqueness problems

Mars

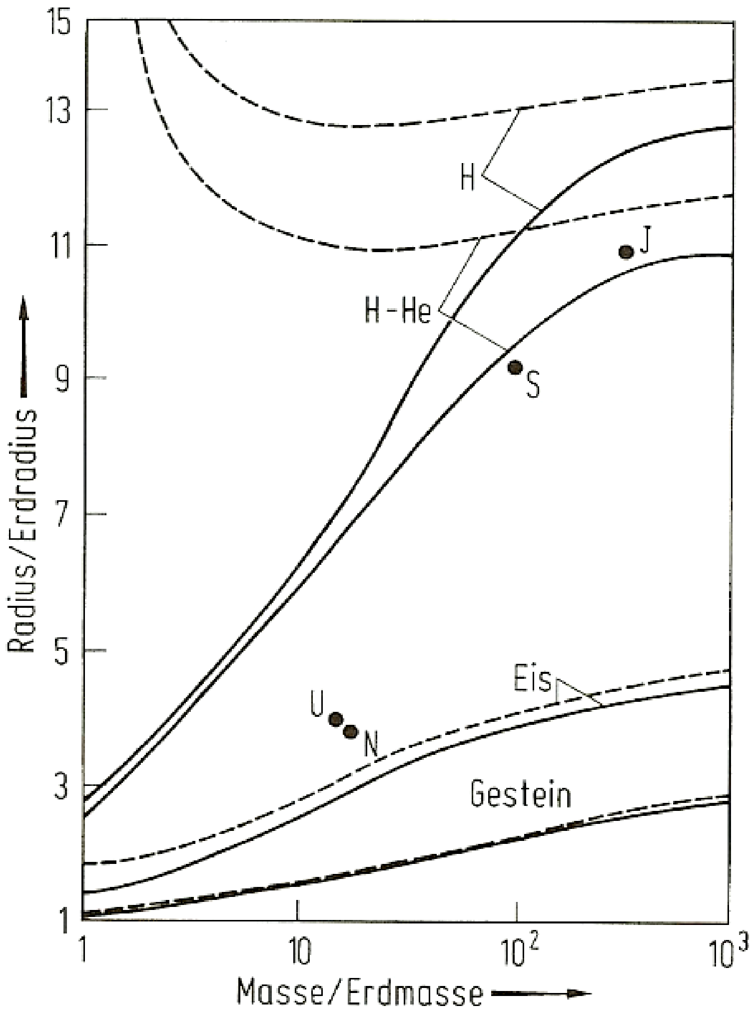


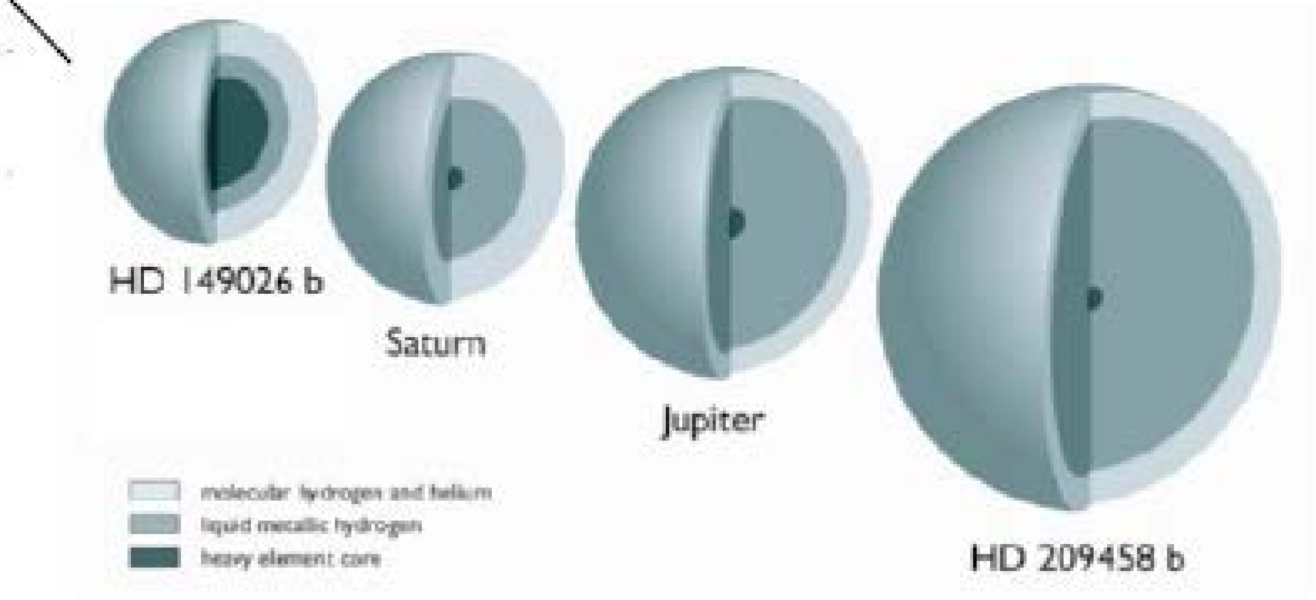
D. Stevenson‘s Toblerone Diagram

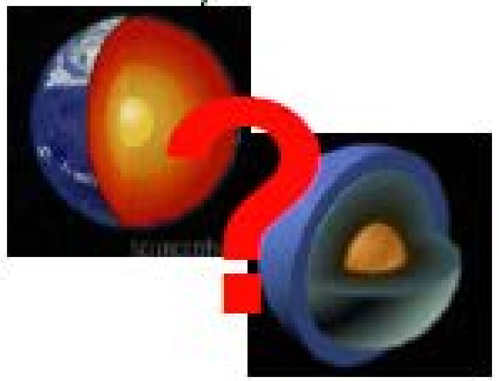
Maximum Masses



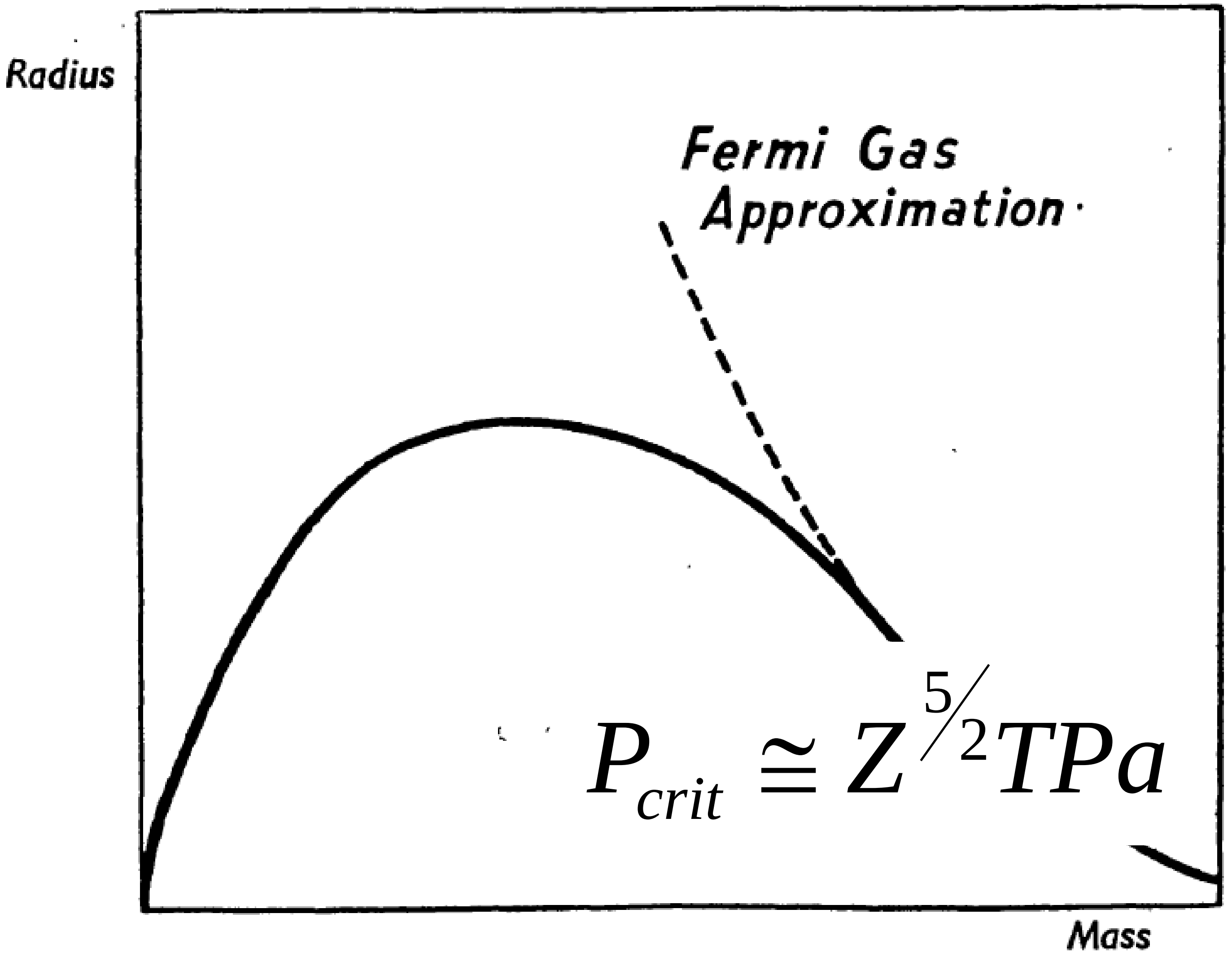
Modified from Rauer et al. 2012







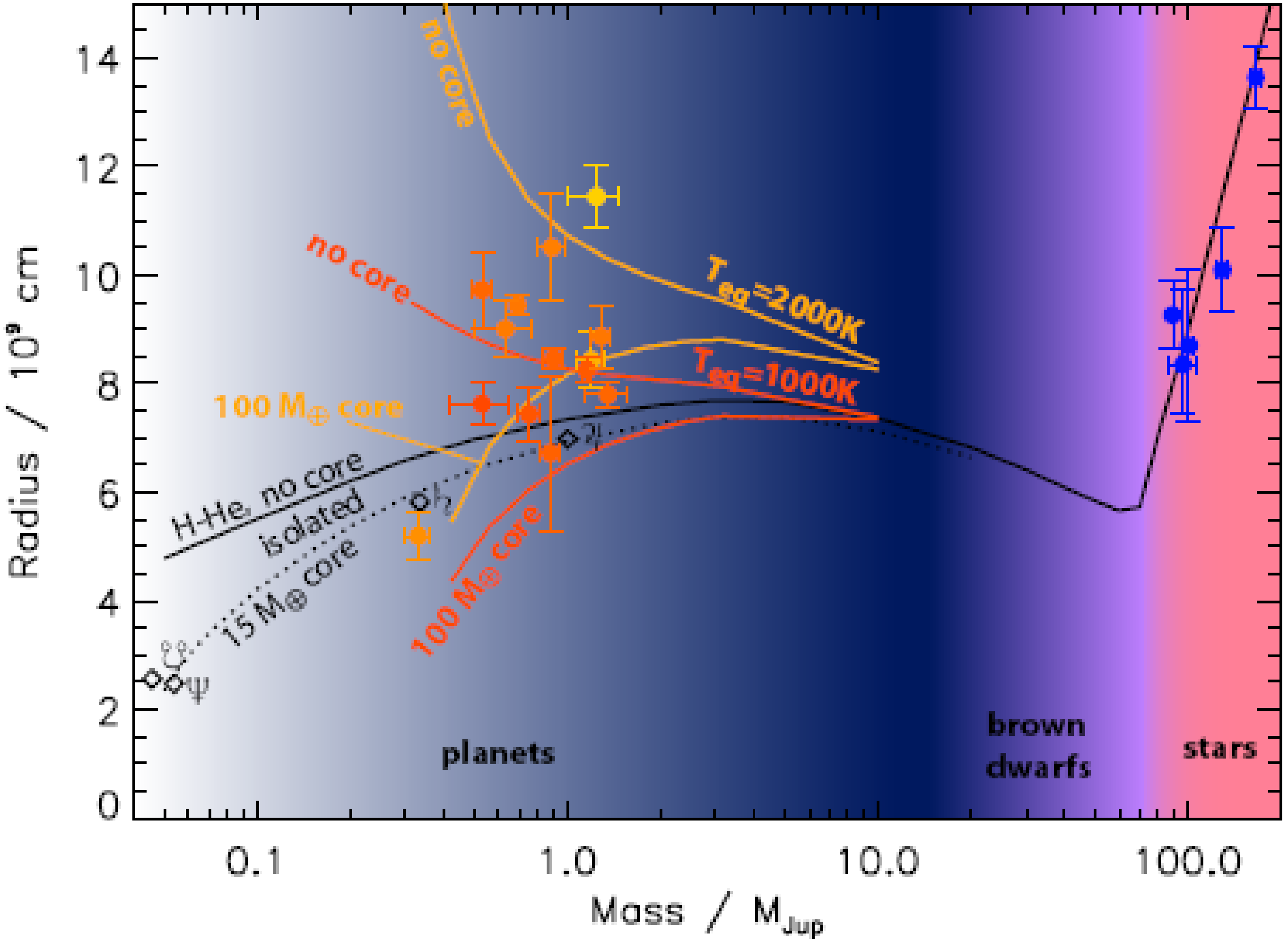
Mass-Radius Relation



$$P_{crit} \simeq Z^{5/2} TPa$$

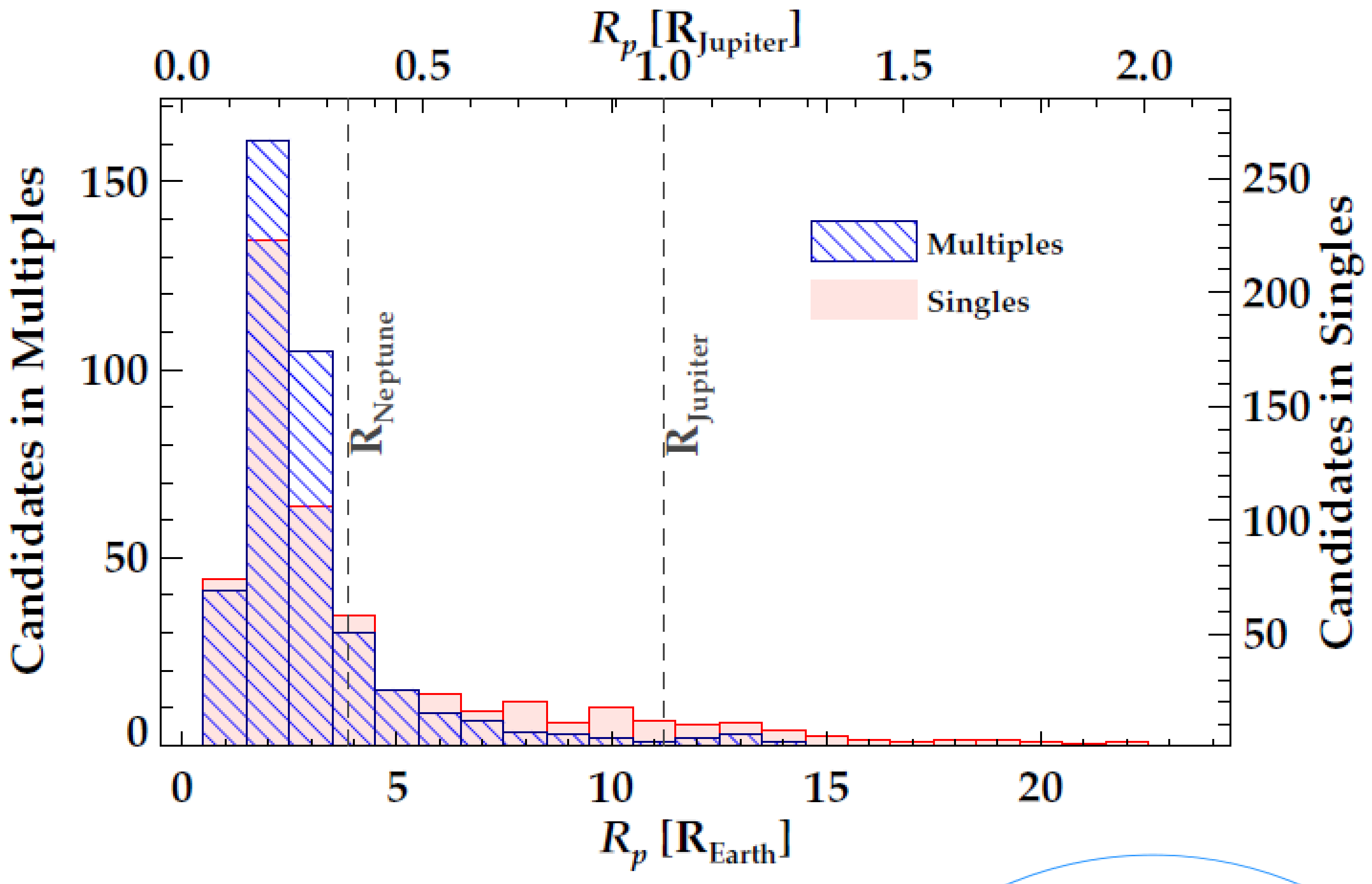
FIG. 2.—*A schematic mass-radius diagram.*

Russel, 1935; Ramsey, 1950

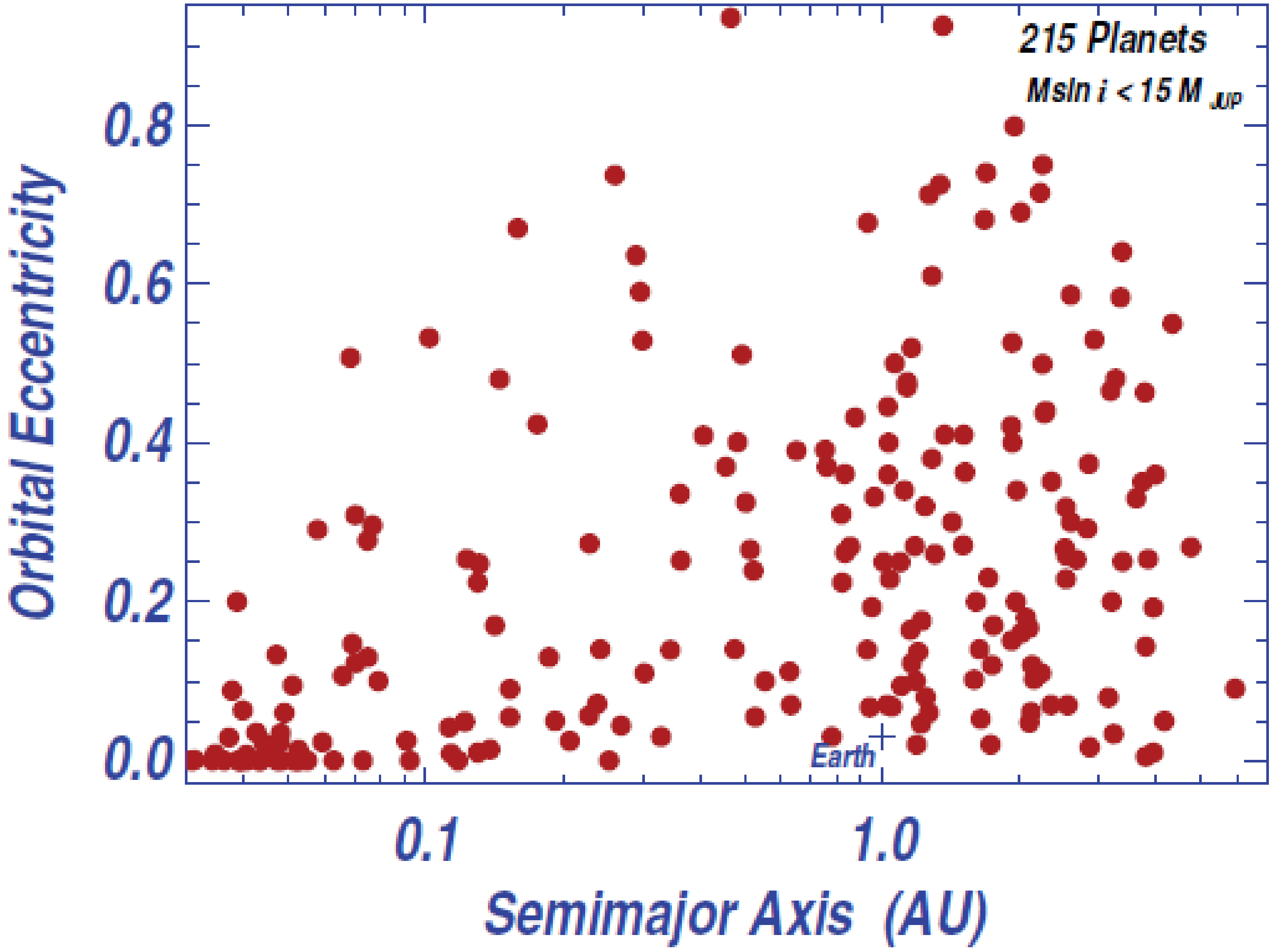


Guillot and Gautier, 2007

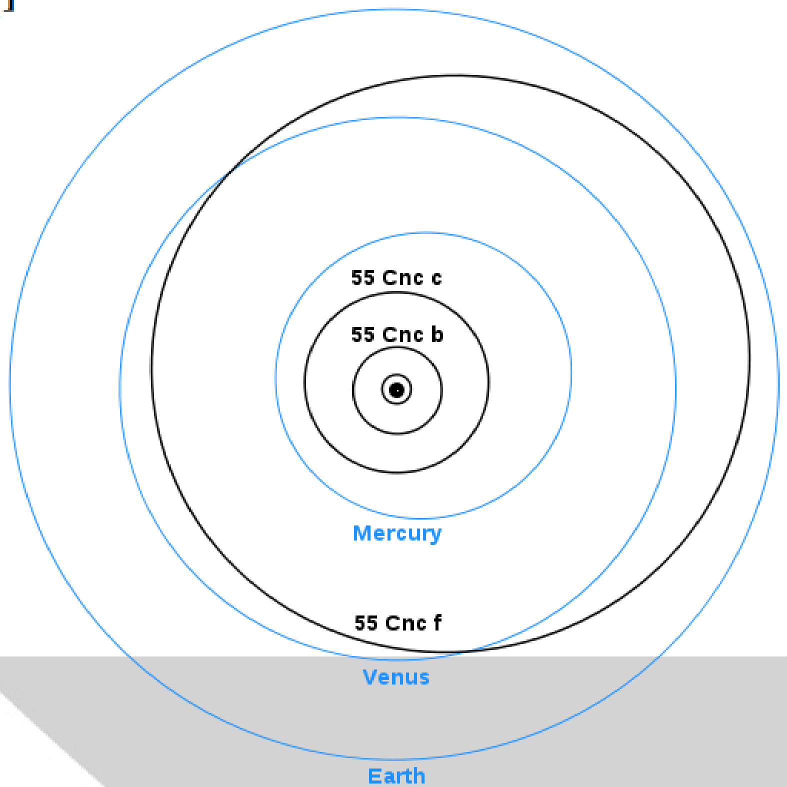
A planetary scientists interest in exoplanets…



Latham et al. 2011

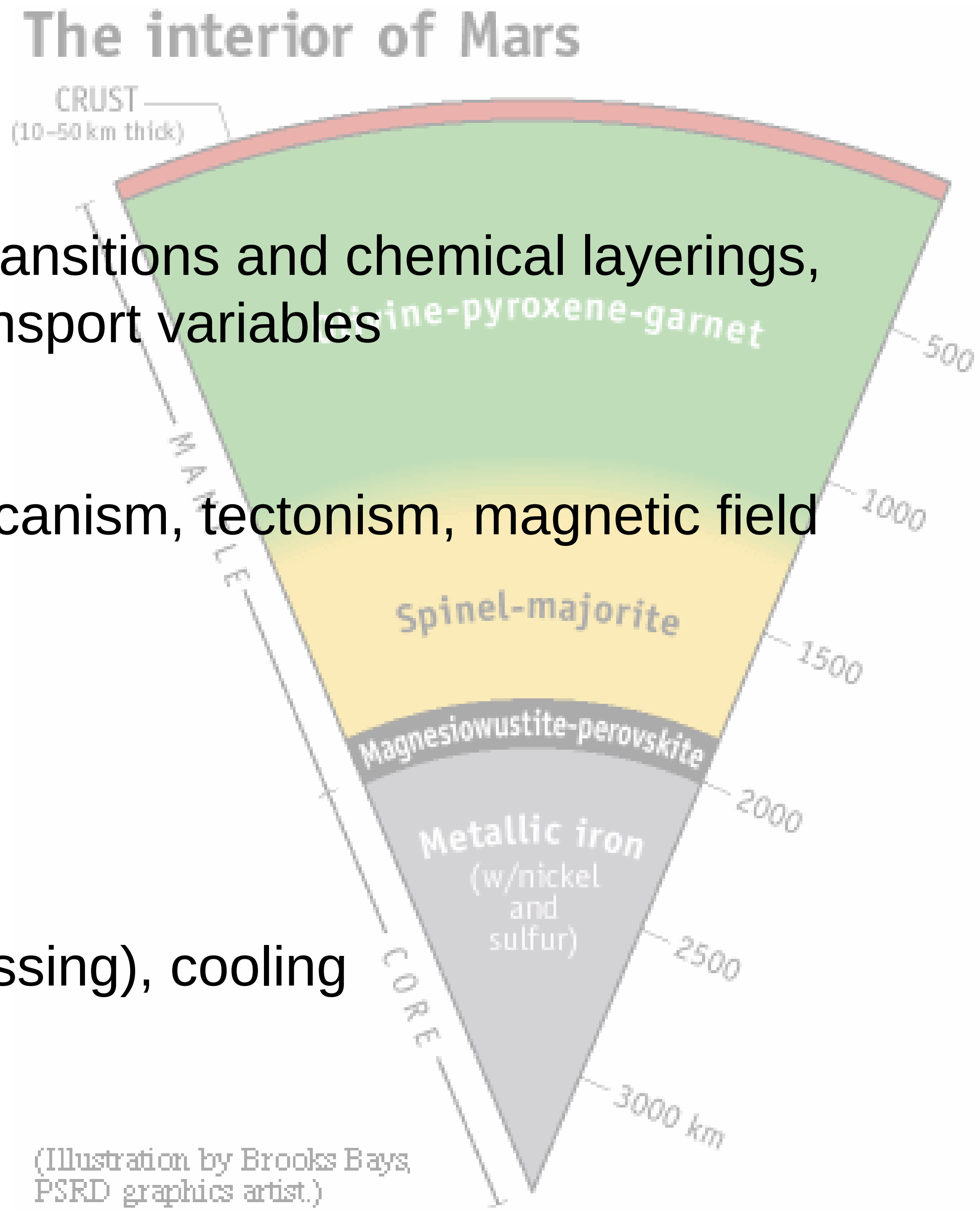


Courtesy G. Marcy



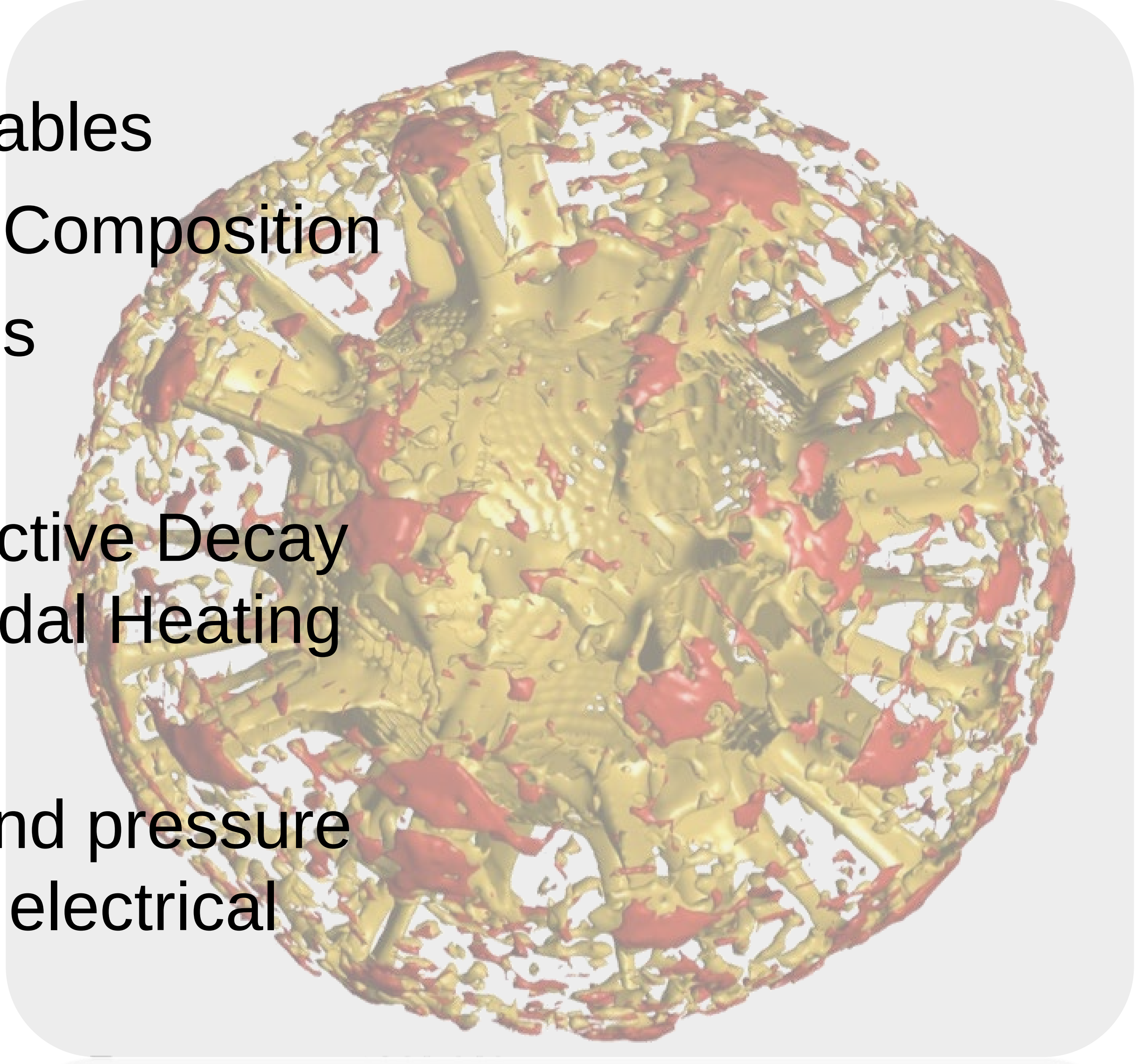
Theory of Terrestrial Planets (Thermodynamics)

- Interior Structure
  - Iron-rich core, rocky mantle and crust, phase transitions and chemical layerings, variations with depth of thermodynamic and transport variables
- Interior Dynamics
  - Core and mantle convection (heat transfer), volcanism, tectonism, magnetic field generation
- Rotation and Tides
  - Tidal dissipation
- Evolution
  - Accretion, differentiation (core formation, outgassing), cooling
- Habitability and Life
  - Feedback?



(Illustration by Brooks Bays, PSRD graphics artist.)

Important Elements of the Theory

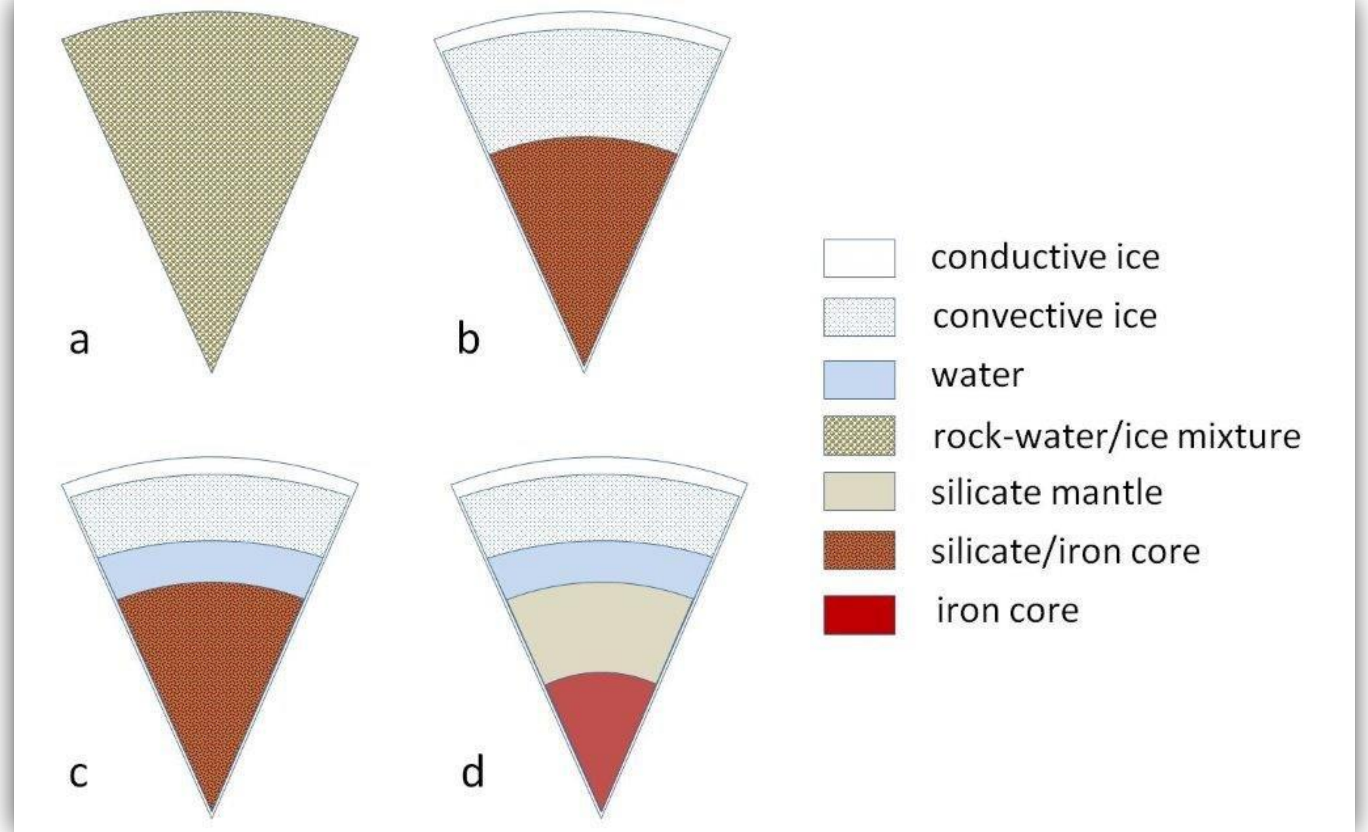


- Thermodynamic Properties, State variables
  - Density, Temperature, Pressure, Composition
- Chemical Reactions, Phase Transitions
- Energy Sources
  - Accretion, Differentiation, Radioactive Decay ($^{235,\,238}$U, ^{232}Th, ^{40}K, ^{26}Al, ^{60}Fe), Tidal Heating
- Transport Properties
  - Viscosity (strongly temperature and pressure dependent), thermal conductivity, electrical conductivity

Courtesy A. Plesa

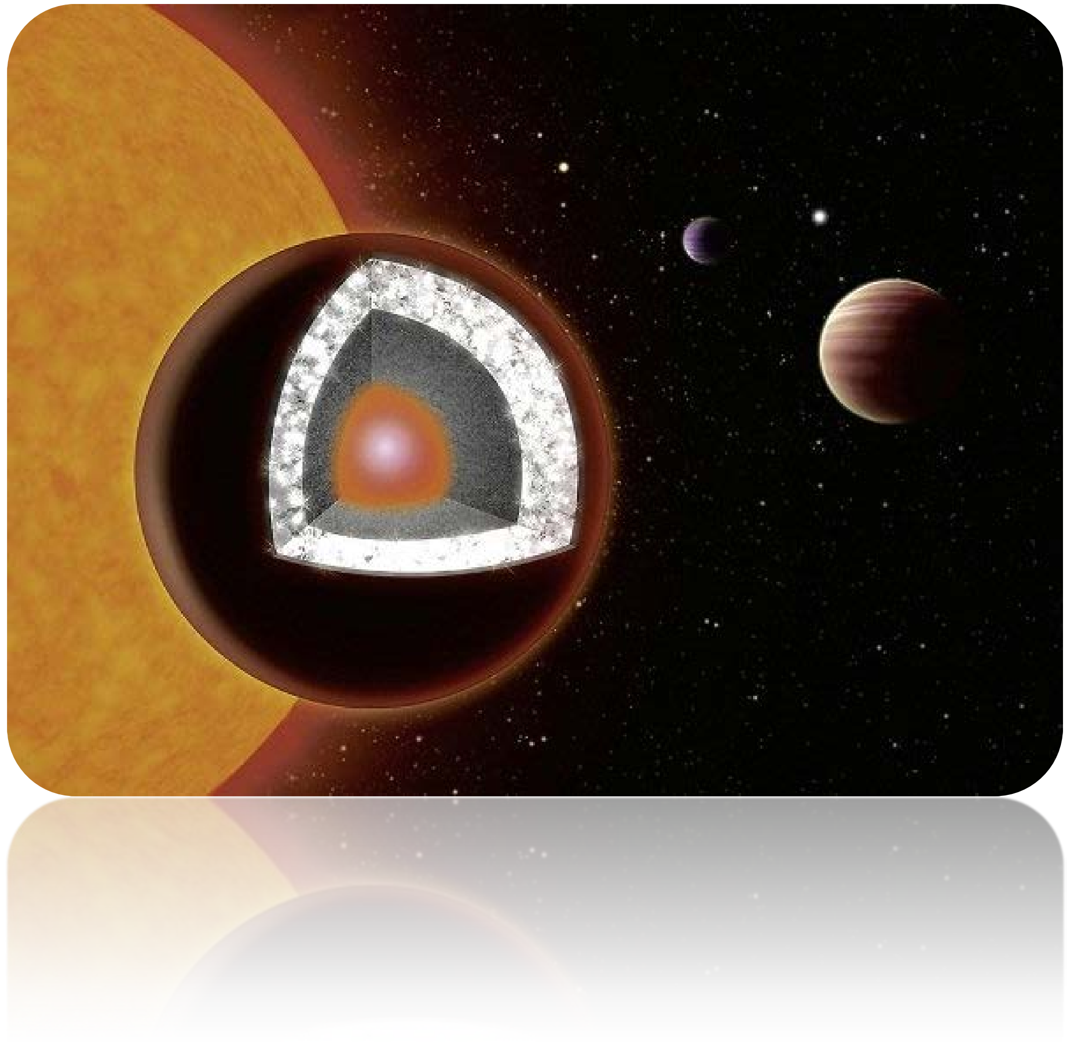
Interior Structure

- In principle, we cannot be certain about the interior structure of terrestrial exoplanets even if we accurately measure mass and radius
- The problem of calculating interior structure models even of solar system terrestrial planets is fraught with non-uniqueness issues, the only remedy being (planetary) seismology.
- But cosmochemistry can help! It also helps to note that in the solar system most bodies (of which we have sufficient data) larger than a few 100km are differentiated. Key issue: heating by radioactive decay



$$M = \frac{4}{3}\pi[\rho_C R_c^3 + \rho_m(R_m^3 - R_c^3)]$$

Chemistry of the Solar System



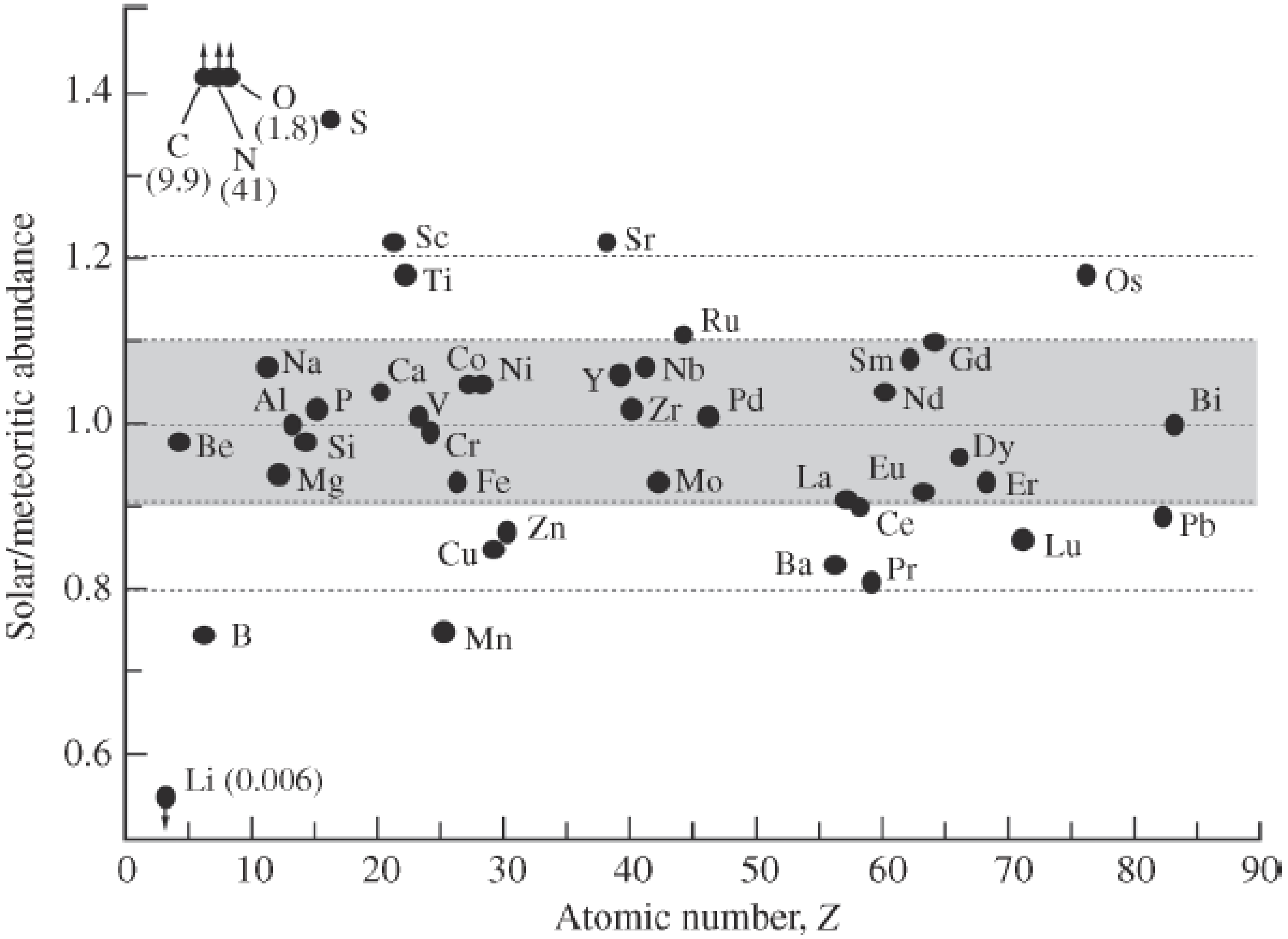


Figure 5 Comparison of solar and meteoritic abundances (see Table 1). The elements C, N, and O are incompletely condensed in meteorites. Li is consumed by fusion processes in the interior of the Sun, but not Be and B. Solar and meteoritic abundances agree in most cases within 10%. Only the four elements S, Mn, Sc, and Sr differ by more than 20% from CI abundances. The difference is below 10% for 27 elements. Only elements with uncertainties of less than 25% in the photosphere are plotted.

Rock/Iron Chemistry

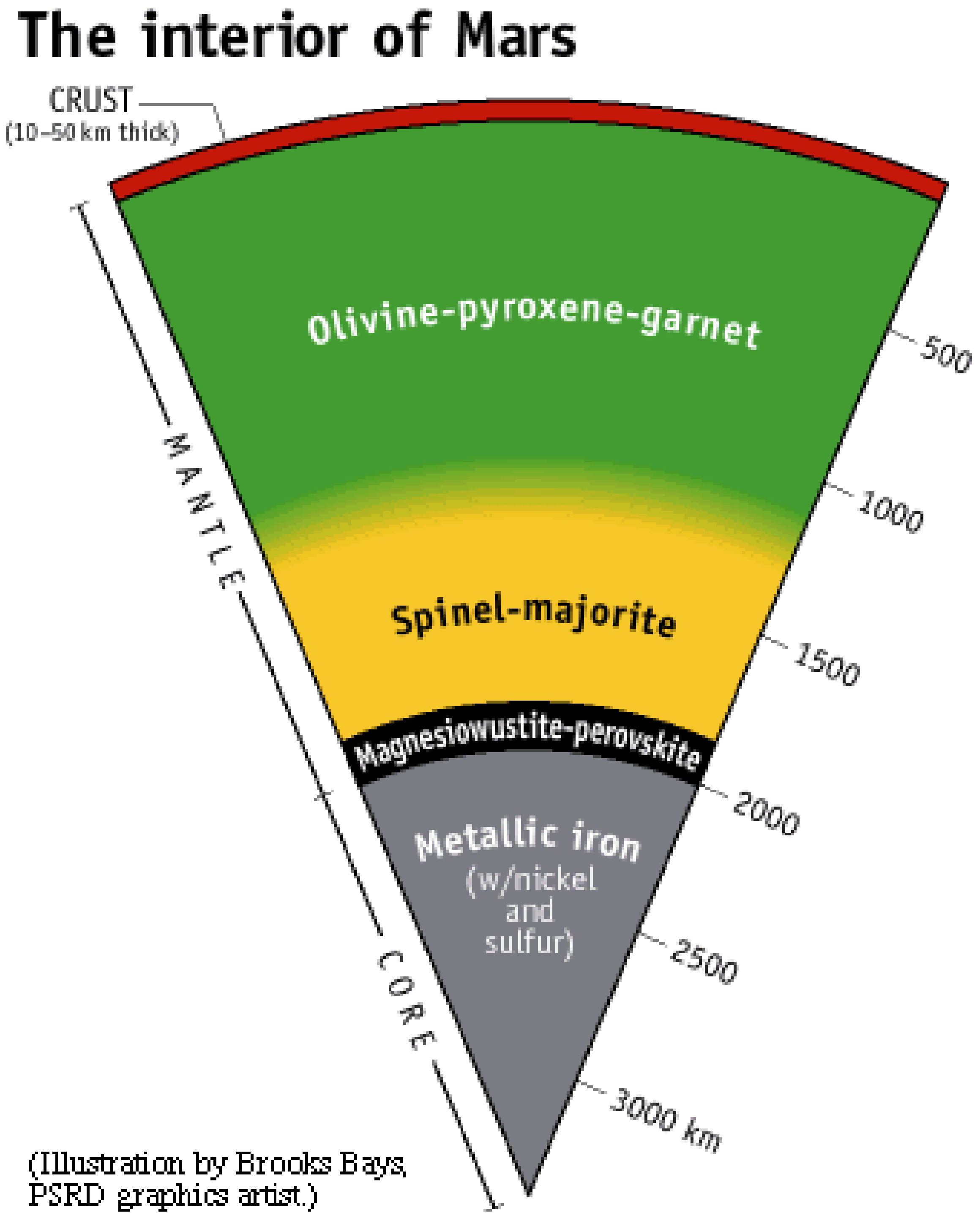
- Chondritic ratio Fe/Si = 1.71
- Mg_2SiO_4 (olivine) mantle and Fe core

$$\frac{M_c}{M_m} = \frac{Fe}{Si} * \frac{Si}{Mg_2SiO_4} \approx 1{,}71 * \frac{30}{150} \approx \frac{1}{3}$$

$$\frac{M_c}{M_m + M_c} \approx \frac{1}{3+1} = 0.25$$

Terrestrial Planets vs Super-Earth Planets

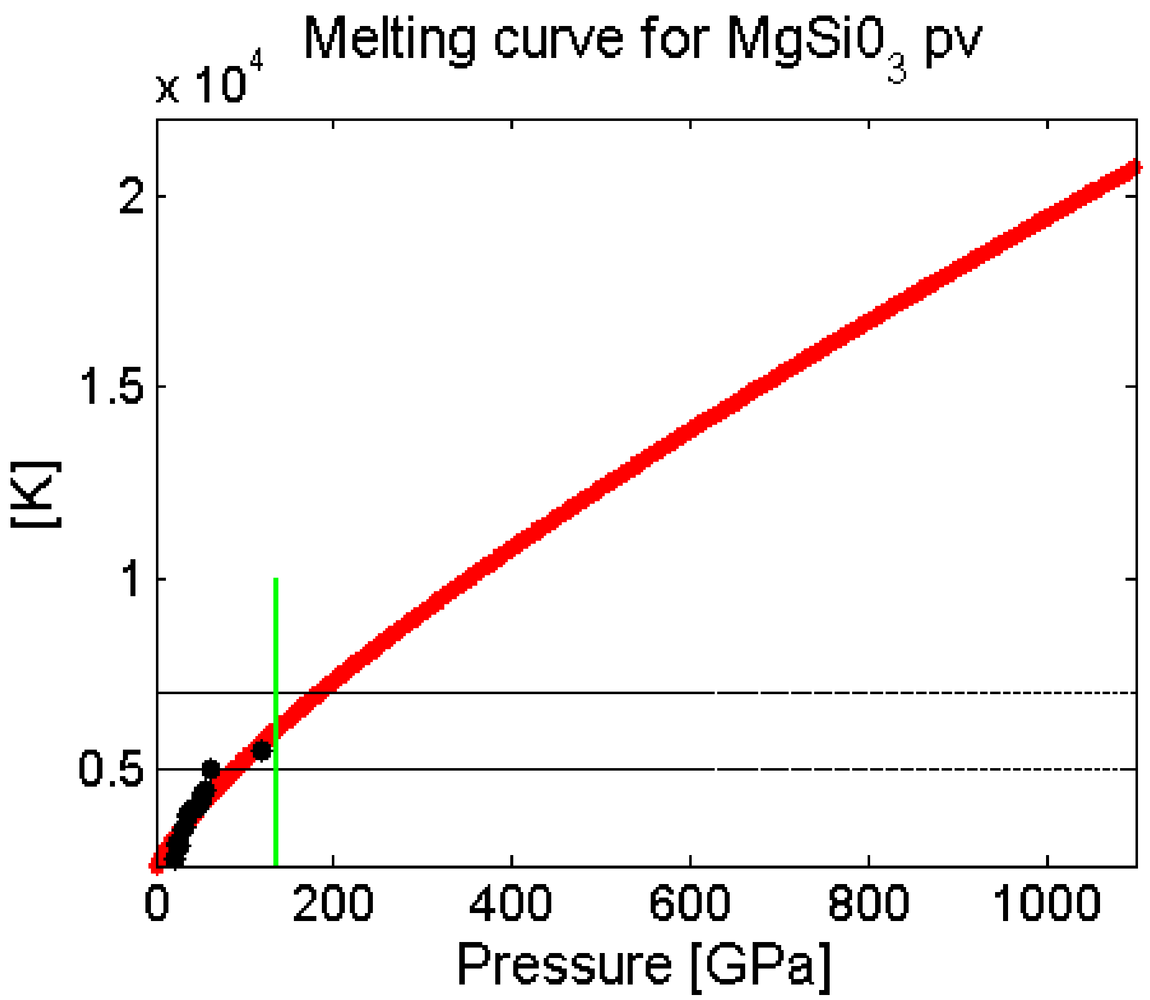
- Terrestrial Planets are relatively well understood (although Earth’s plate tectonics still poses many questions)
- Pressure and compression are low, much smaller than the critical pressure for degenerating into a Fermi gas
- Pressure range is largely accessible to experiment and the interpretation of geophysical data allows insights into the workings of the interior
- Rheology of rock is highly nonlinear and complex (e.g., as it depends on the presence minor constituents such as water)



(Illustration by Brooks Bays, PSRD graphics artist.)

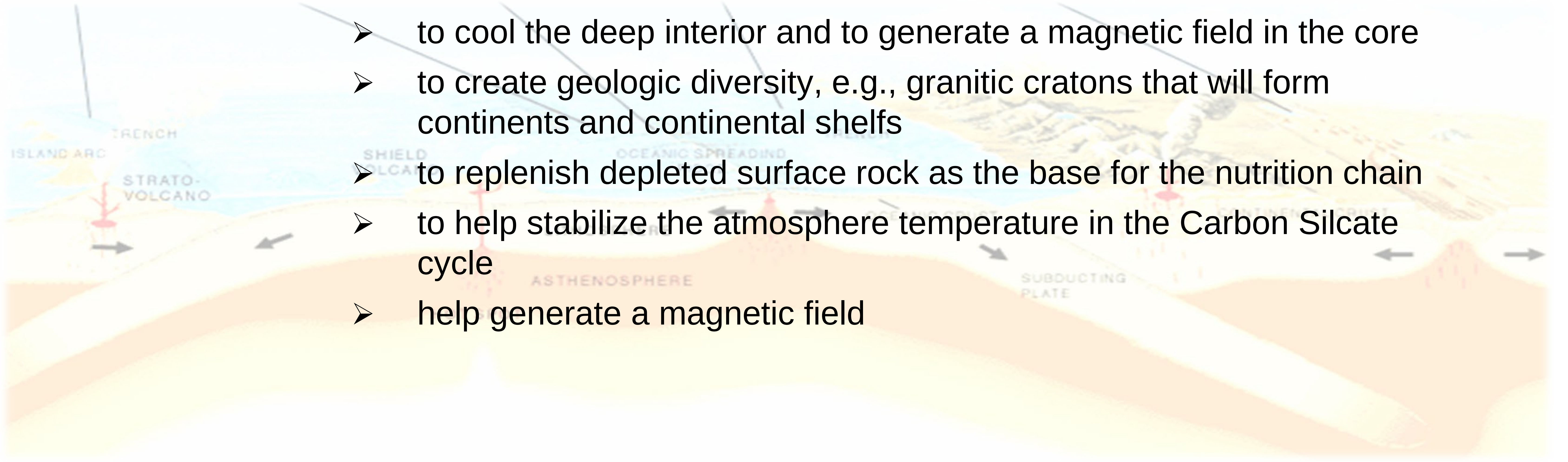
Terrestrial Planets vs Super-Earth Planets

- The pressure range in the Earth covers only the outer shell of a > 10 ME super-Earth
- The post-perovskite phase has been postulated for the lowermost Earth mantle but is not very well studied
- There may be more phase transformations and because the pressure becomes close to the critical pressure, it is not clear that iron and rock would not dissolve into each other and that the cores and mantles are not well separated, may be just like in the cores of the giant planets
- Extrapolations are substantial



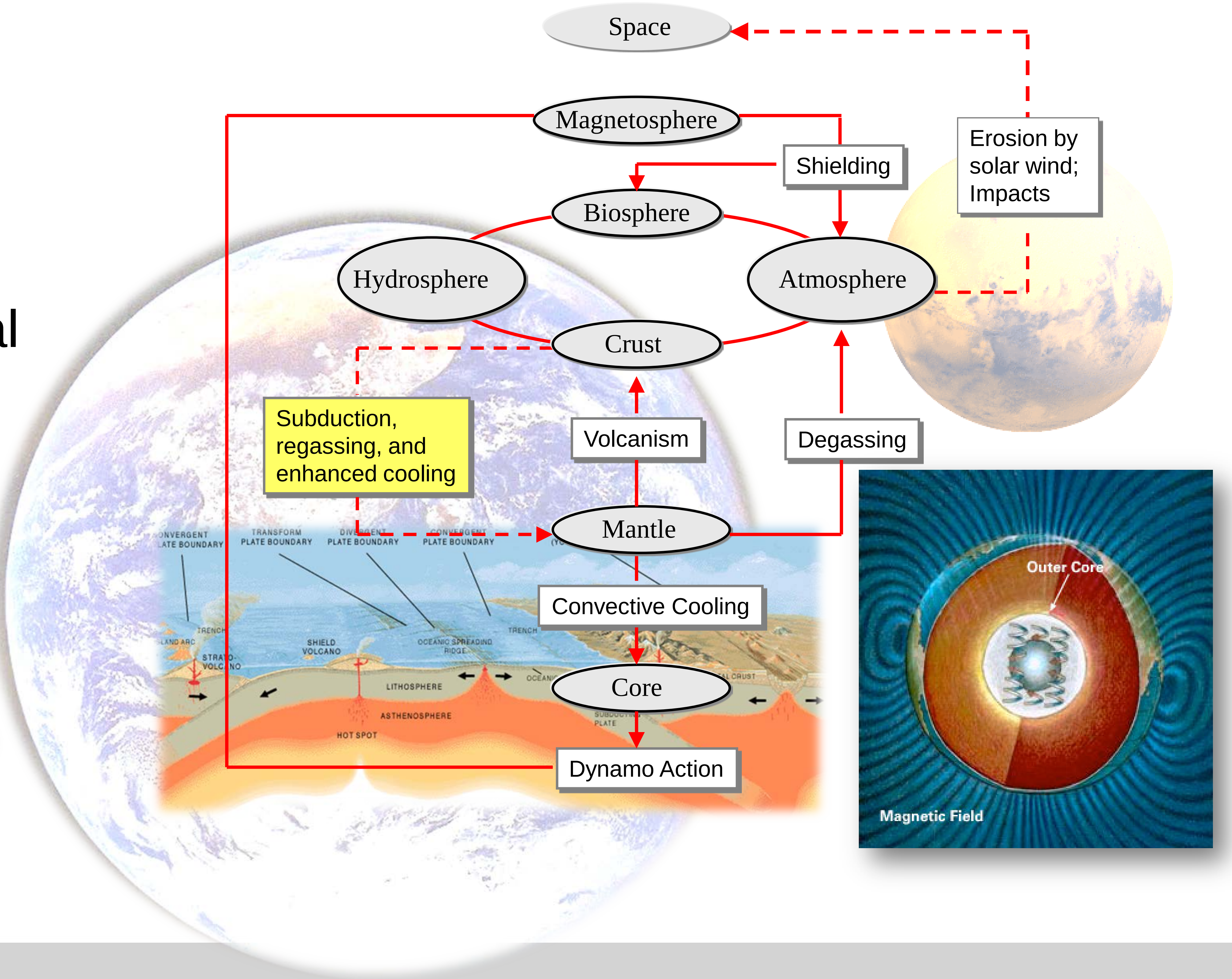
Habitability and Plate Tectonics

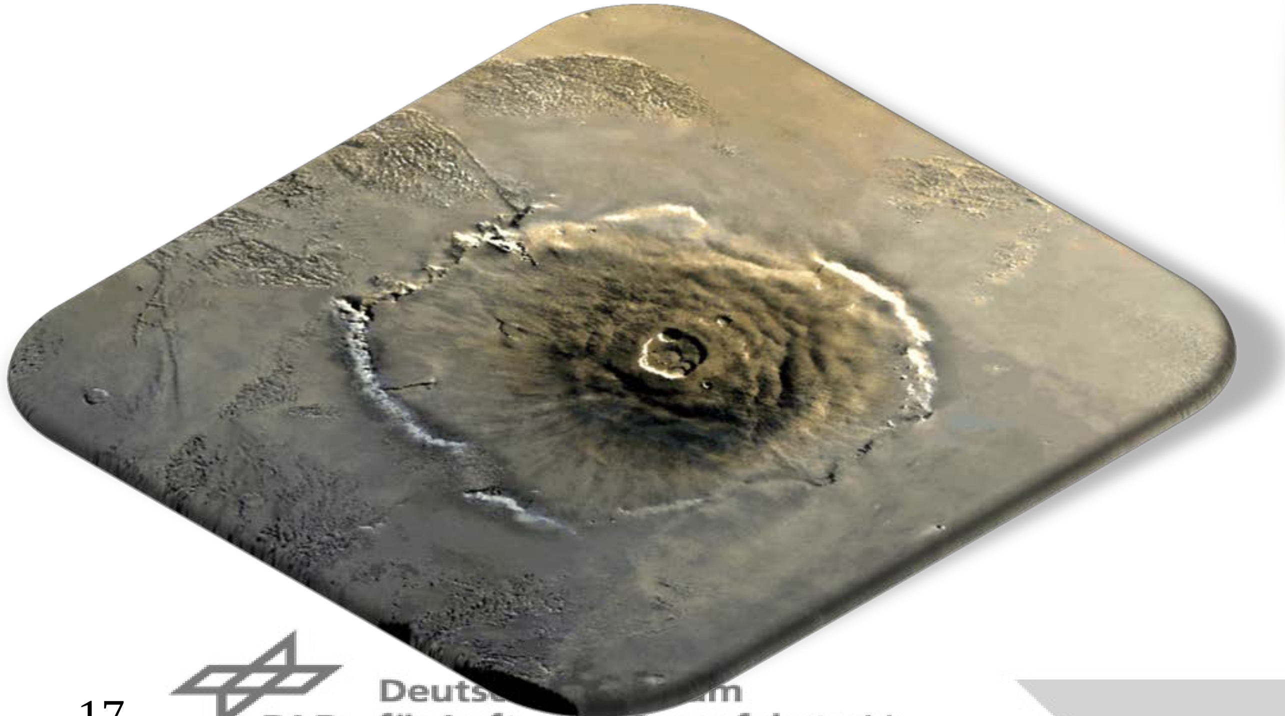
- Many believe that (complex, evolved) life requires plate tectonics to operate
  - Plate tectonics recycles near surface rock and volatiles with the planet’s interior through subduction. This helps
    - to cool the deep interior and to generate a magnetic field in the core
    - to create geologic diversity, e.g., granitic cratons that will form continents and continental shelfs
    - to replenish depleted surface rock as the base for the nutrition chain
    - to help stabilize the atmosphere temperature in the Carbon Silcate cycle
    - help generate a magnetic field



Planets are Heat Engines

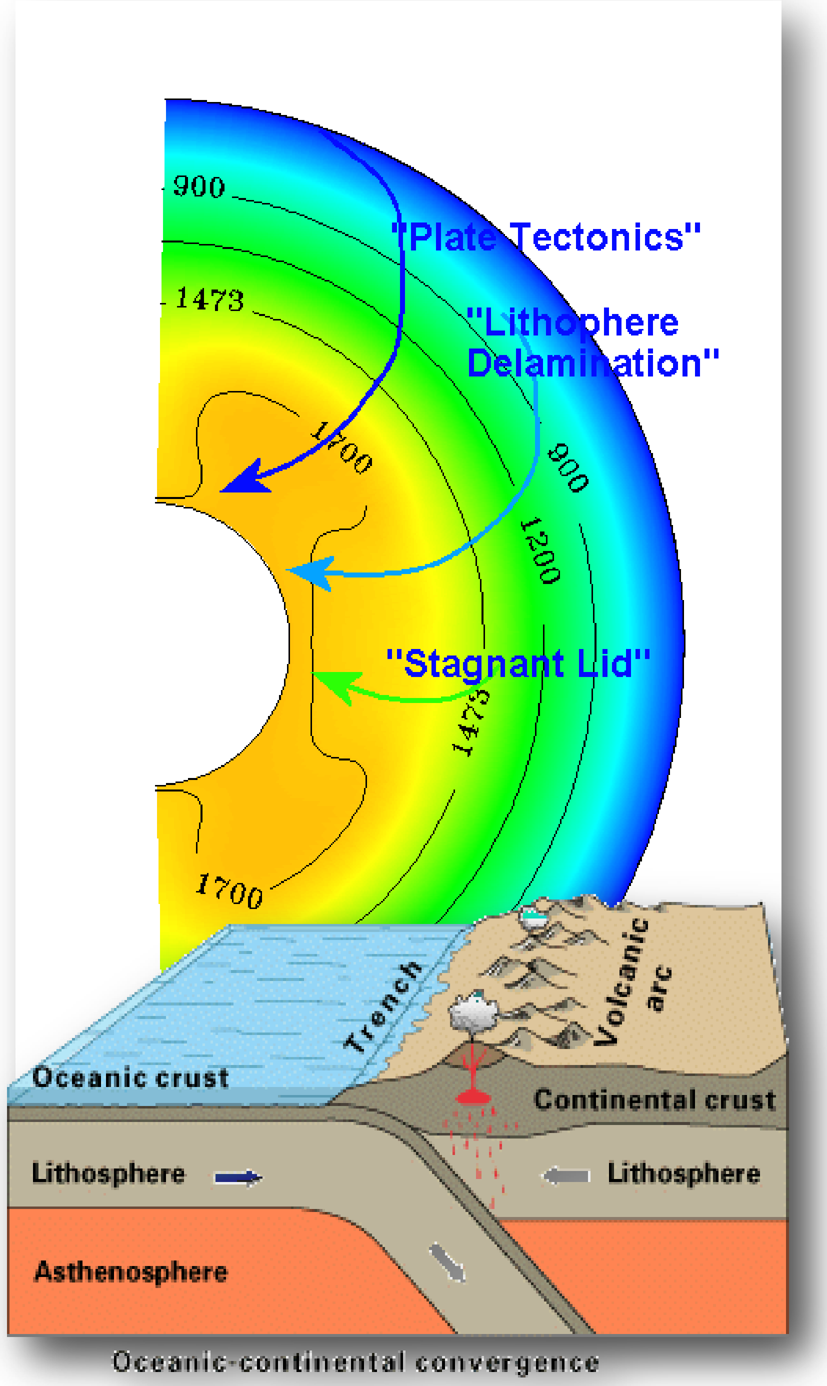
..that convert thermal into gravitational, deformational and magnetic field energy



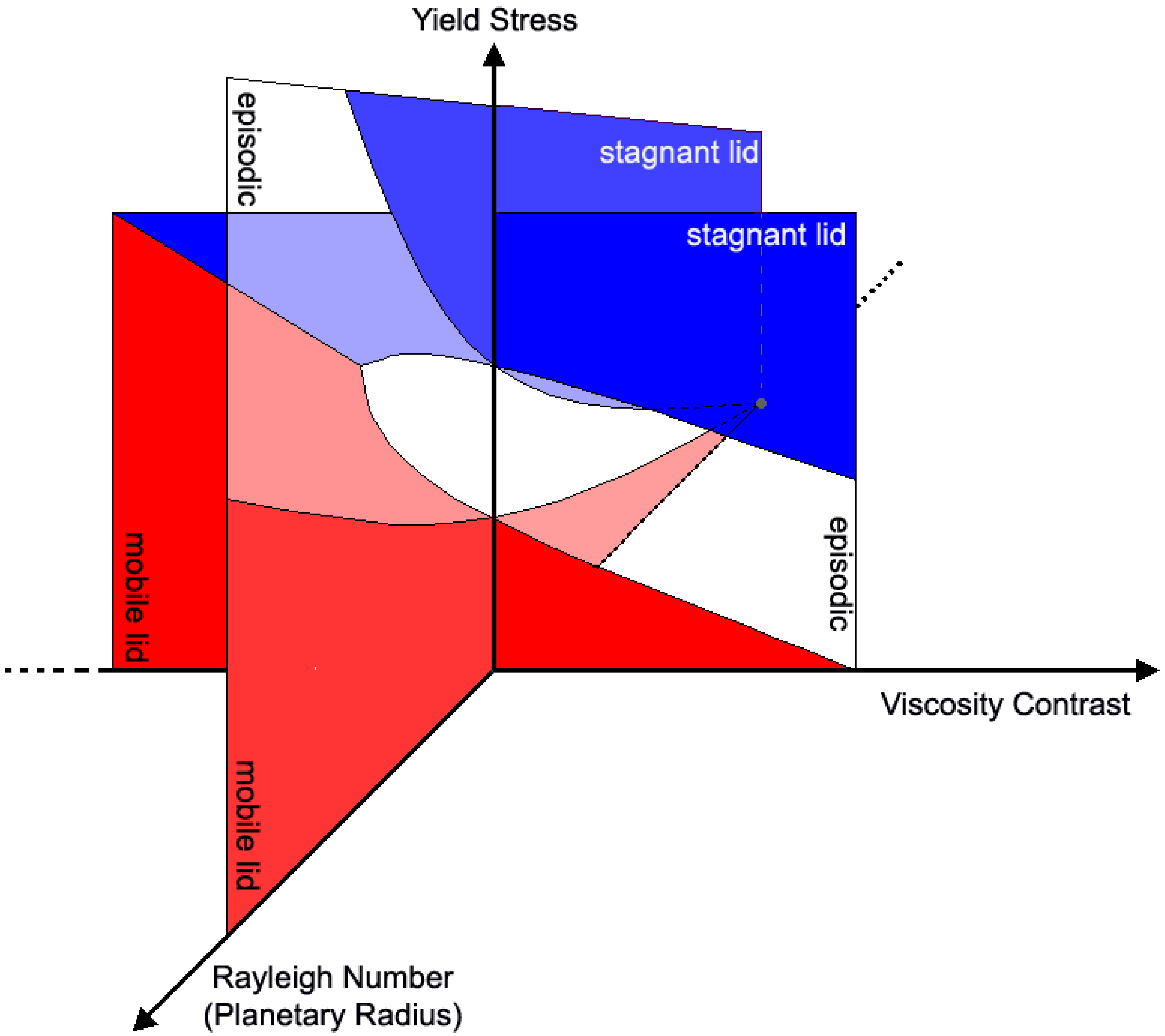


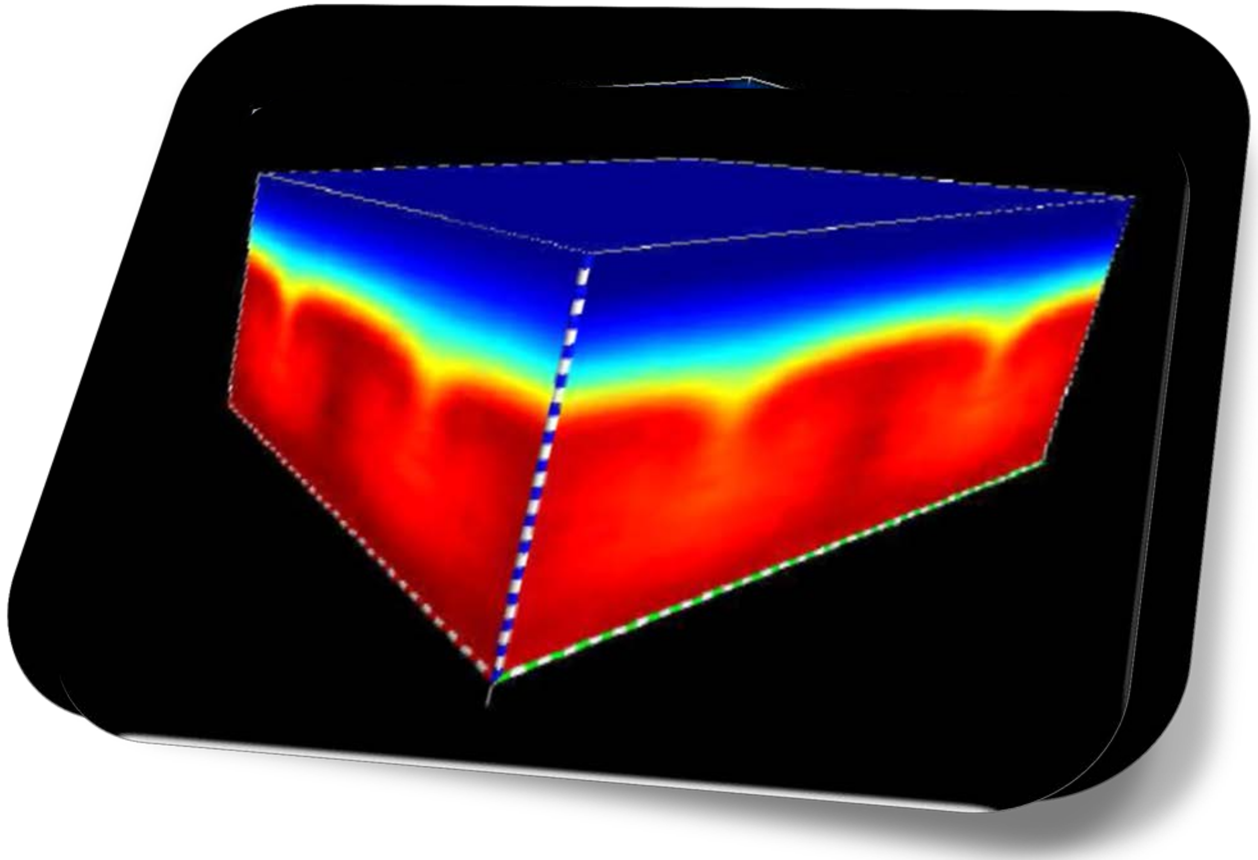
Mantle Convection

- Is the essential driver of the planet as a heat engine
- Drives surface tectonics ((conversion of heat into mechanical (deformational) energy
- Drives the dynamo through cooling the core
- Drives the long-term carbon silicate cycle
- A plate tectonics planet is more efficient at cooling the deep interior than a stagnant lid planet and therefore more effective at generating a magnetic field



Mantle Convection

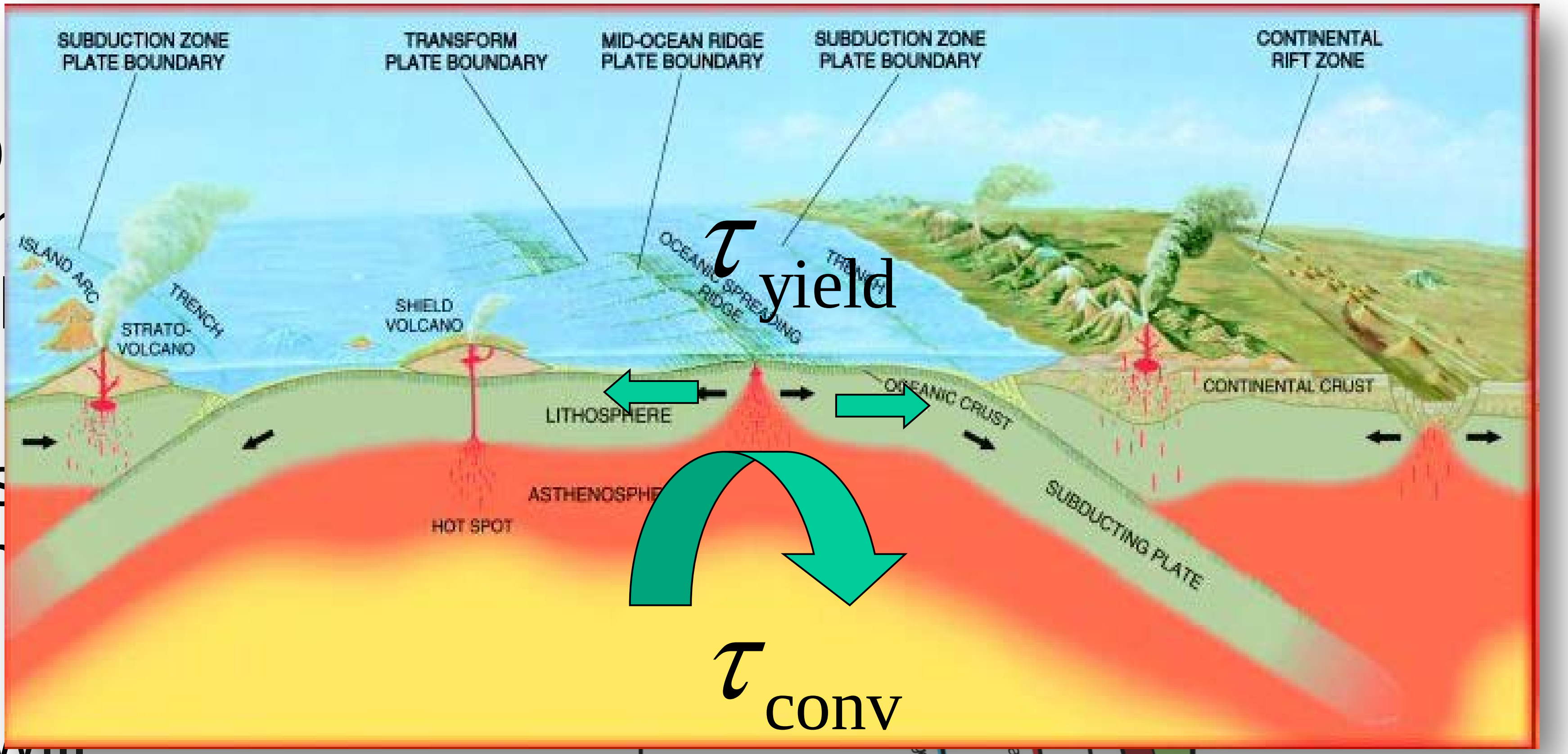


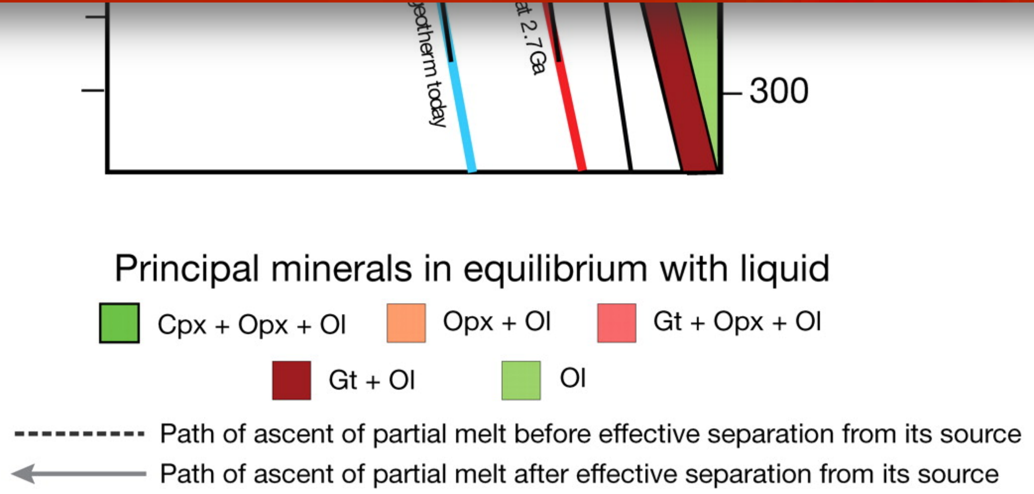


Stein and Hansen 2008

Atmospheres and Outgassing

- The origin of the Earth’s atmosp still debated. The mechanisms ir competition are outgassing and l accretion.
- Outgassing is comparatively eas planet is undergoing plate tector
- For one plate planets, the mass (gravity) may be important as it w affect the degree of partial melting in the interior (Noack et al., 2013)
- Interactions between the interior and the atmosphere/hydrosphere beyond simple volcanic outgassing are possible through lithosphere weakening





Conclusions, Take away messages

- Planetary scientists look forward to PLATO recognizing its potential to provide the most fundamental parameters for characterizing a large number of planets: mass, size, composition age. The database will increase from a few hundred to many thousands. For terrestrial exoplanets the increase will be even more substantial. The mission will greatly help to put the Earth in a perspective!
- PLATO would also contribute data about planetary systems and thereby allow to judge how peculiar the solar system is.
- The observations will provide a basis for more speculative work: Habitability, magnetic fields, plate tectonics, atmospheres.