VI Astrobion – September 2026

Internal Structure and Formation of Rocky Planets

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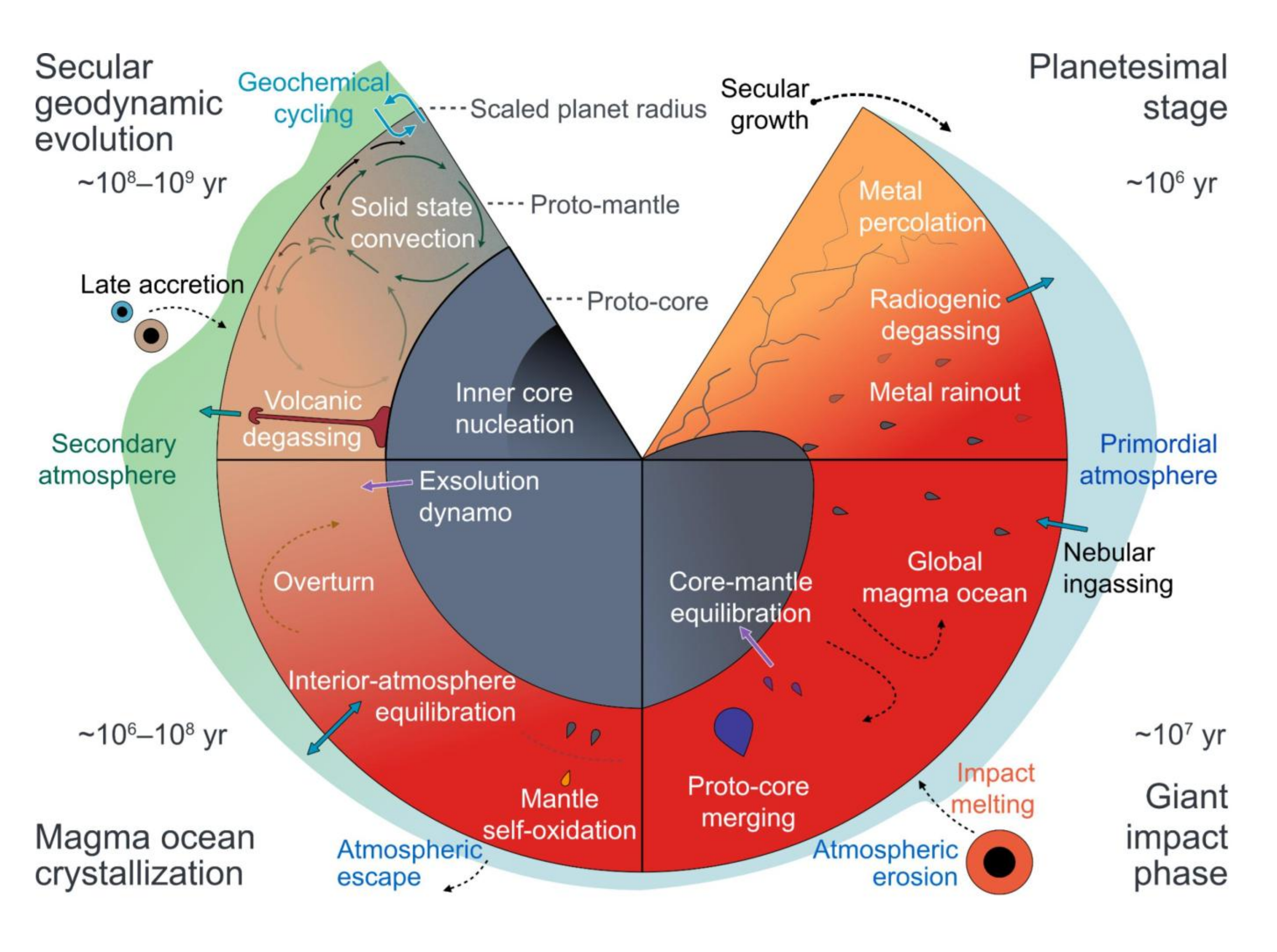
Atmosphere-Interior Evolution

Life-essential elements (CHNOPS) interact with all layers of a rocky planet during the process of planet formation and evolution.

The availability of these elements at the surface depends on the integrated history of the planet.



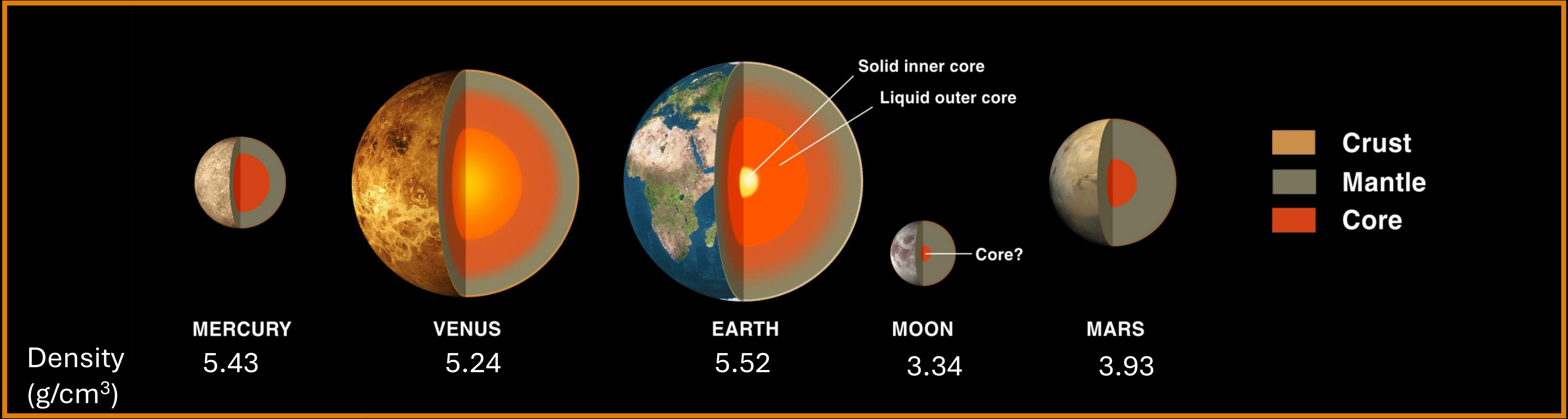
Lichtenberg et al. (2022) Protostars and Planets VII

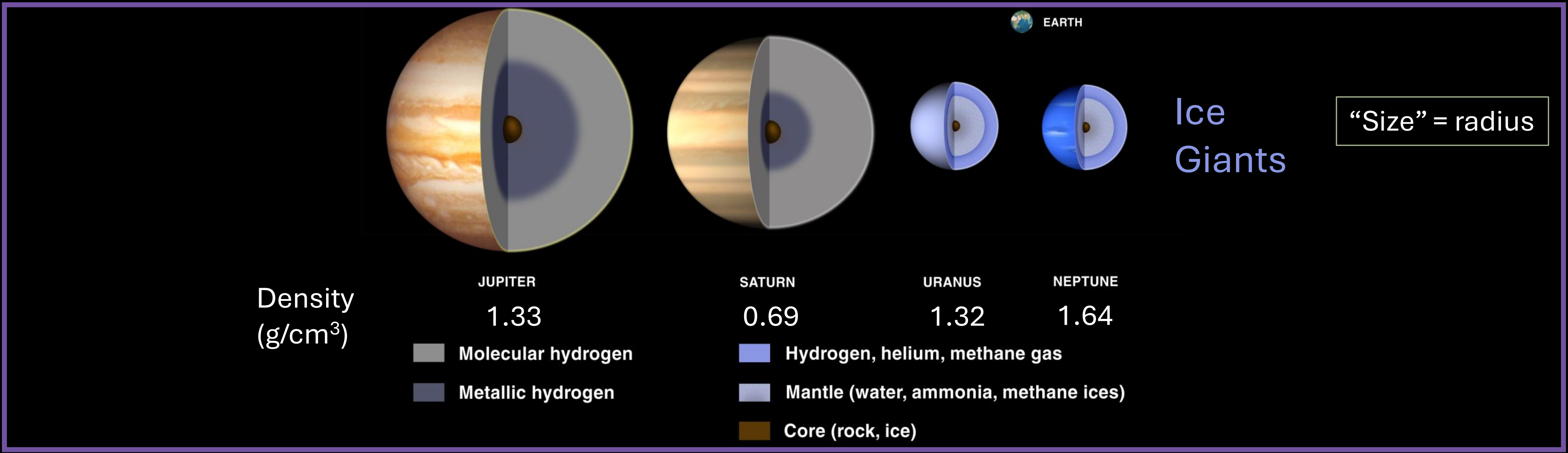
For This Week:

- Planetary Interiors and Formation
  - Delivery of volatiles to rocky planets, internal structure models
- Core Formation and Magma oceans
  - Setting the initial conditions for the planet
- Long-term tectonics
  - Deep volatile cycles and silicate weathering
- Everything else
  - Tidal effects, atmospheric escape, and impacts

For Today:

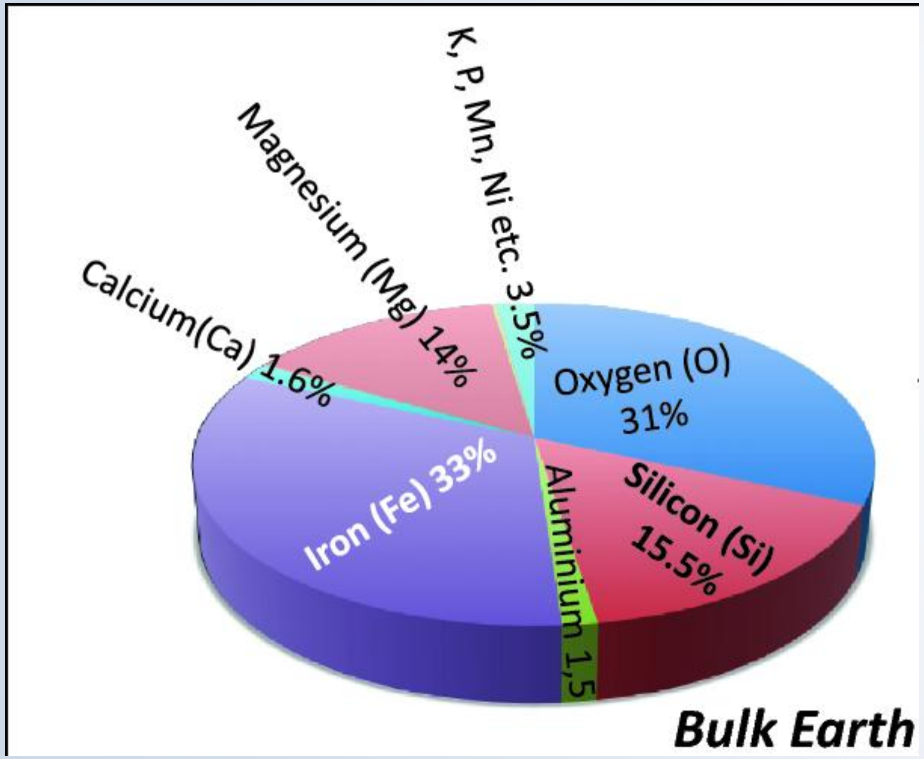
- Planet formation
    - Volatile delivery to the Earth
- Planet Interiors
    - Rocky planets
- Mass-Radius Diagrams
    - Equations of state
    - Degeneracies


Solid inner core
Liquid outer core
Core?
Crust
Mantle
Core
MERCURY
VENUS
EARTH
MOON
MARS
Density (g/cm³)
5.43
5.24
5.52
3.34
3.93

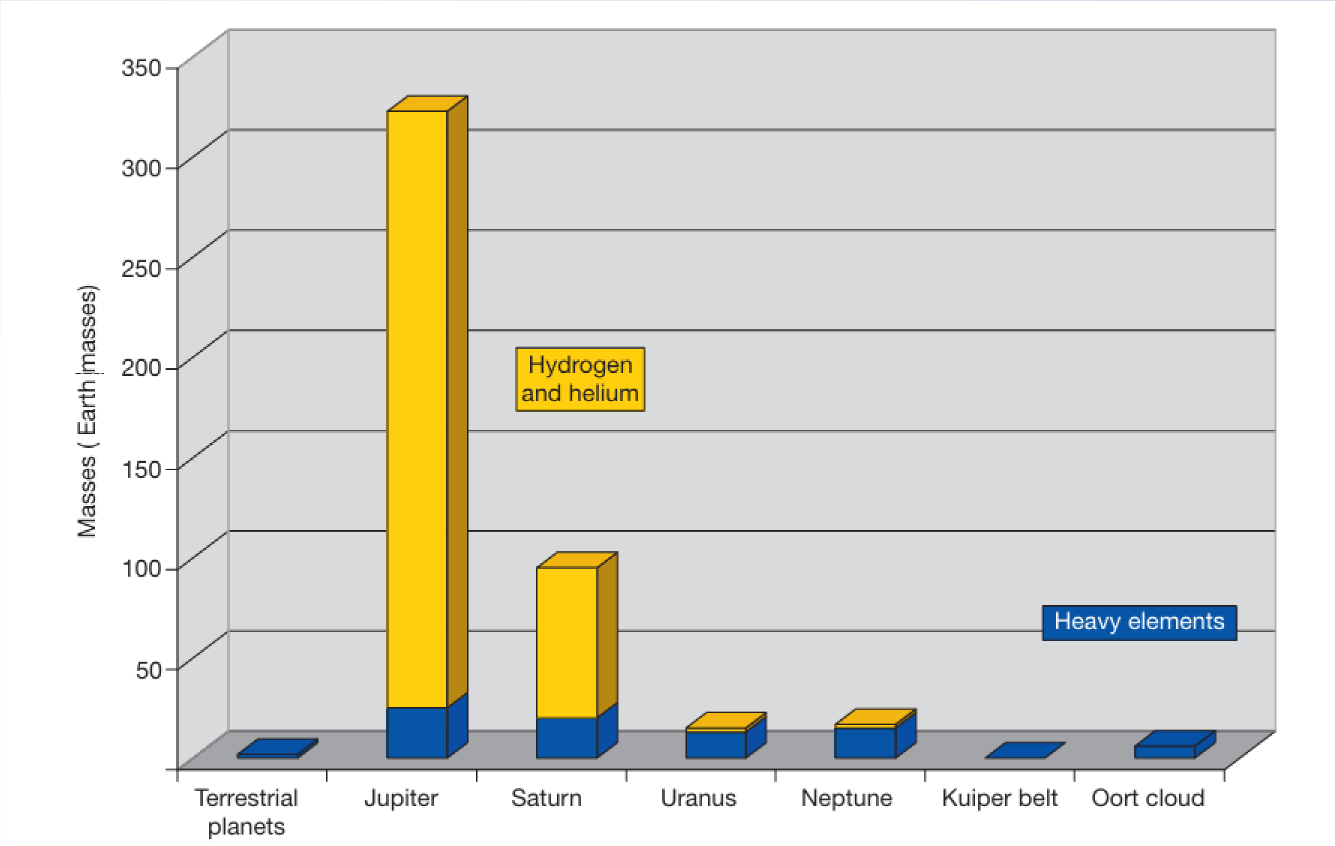

EARTH
Ice Giants
"Size" = radius
JUPITER
SATURN
URANUS
NEPTUNE
Density (g/cm³)
1.33
0.69
1.32
1.64
Molecular hydrogen
Metallic hydrogen
Hydrogen, helium, methane gas
Mantle (water, ammonia, methane ices)
Core (rock, ice)


Rocks: ρ ~3 g cm-3
Ices: ρ ~1 g cm-3
Metals: ρ ~8 g cm-3
Gas: ρ <~1 g cm-3

Compositions



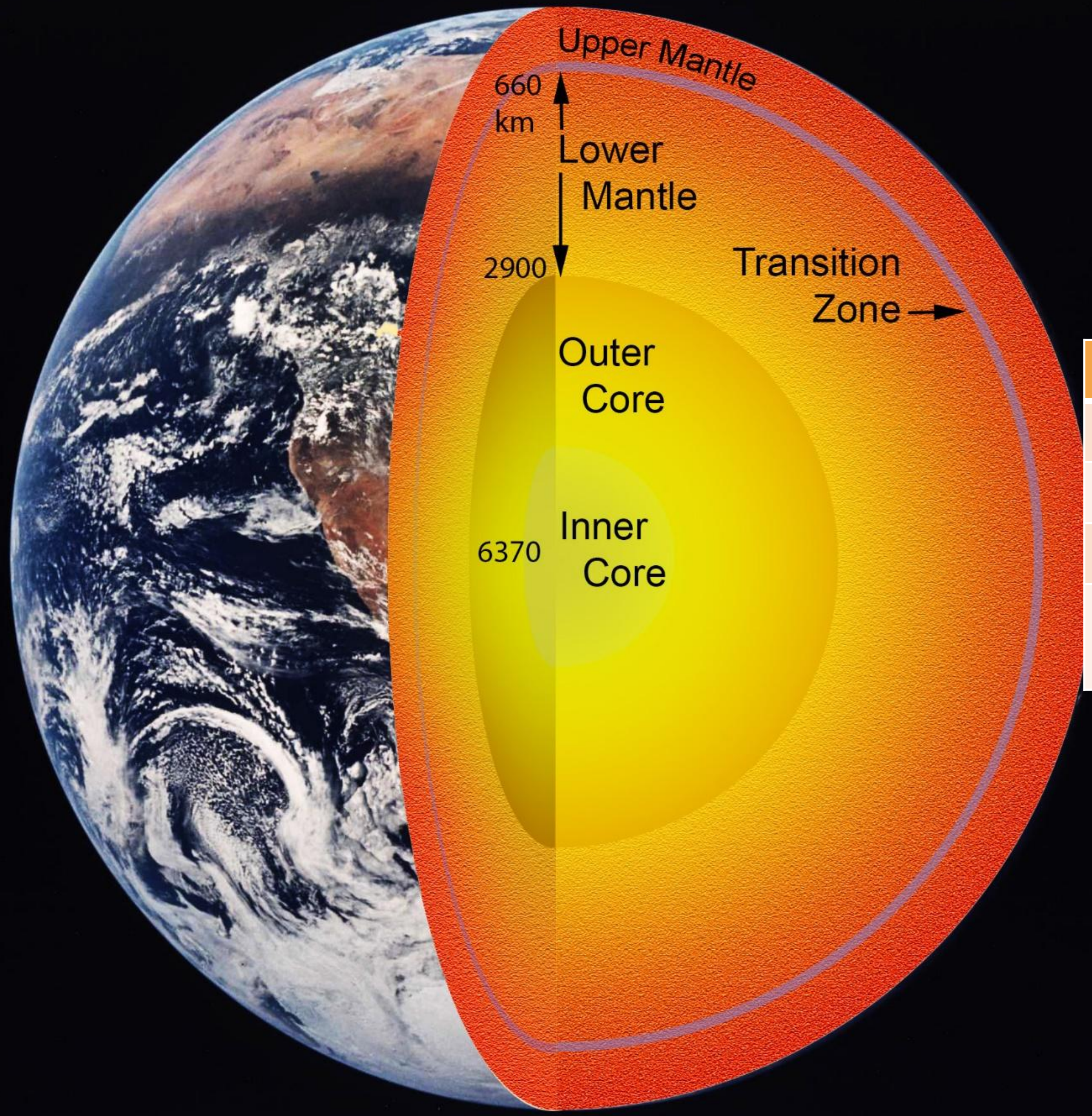
Earth is a mix of silicates (Mg + Si + O + other) and metal (Fe).



Guillot & Gautier 2015

Jupiter is ~70% H, ~20% He, and ~10% everything else.

That 10% of heavy elements is ~30x more mass than Earth.



layer	Mass %	Radius %	Pressure
Core	32.50%	54.6	330-132 GPa
Mantle	67.07%	99.9	132-0.3 Gpa
Crust	0.40%	100	3,000 - 1 bar
Atmosphere + ocean	0.03%	+0.3%	1 – 10^{-10} bar

1 bar = 10^5 Pa

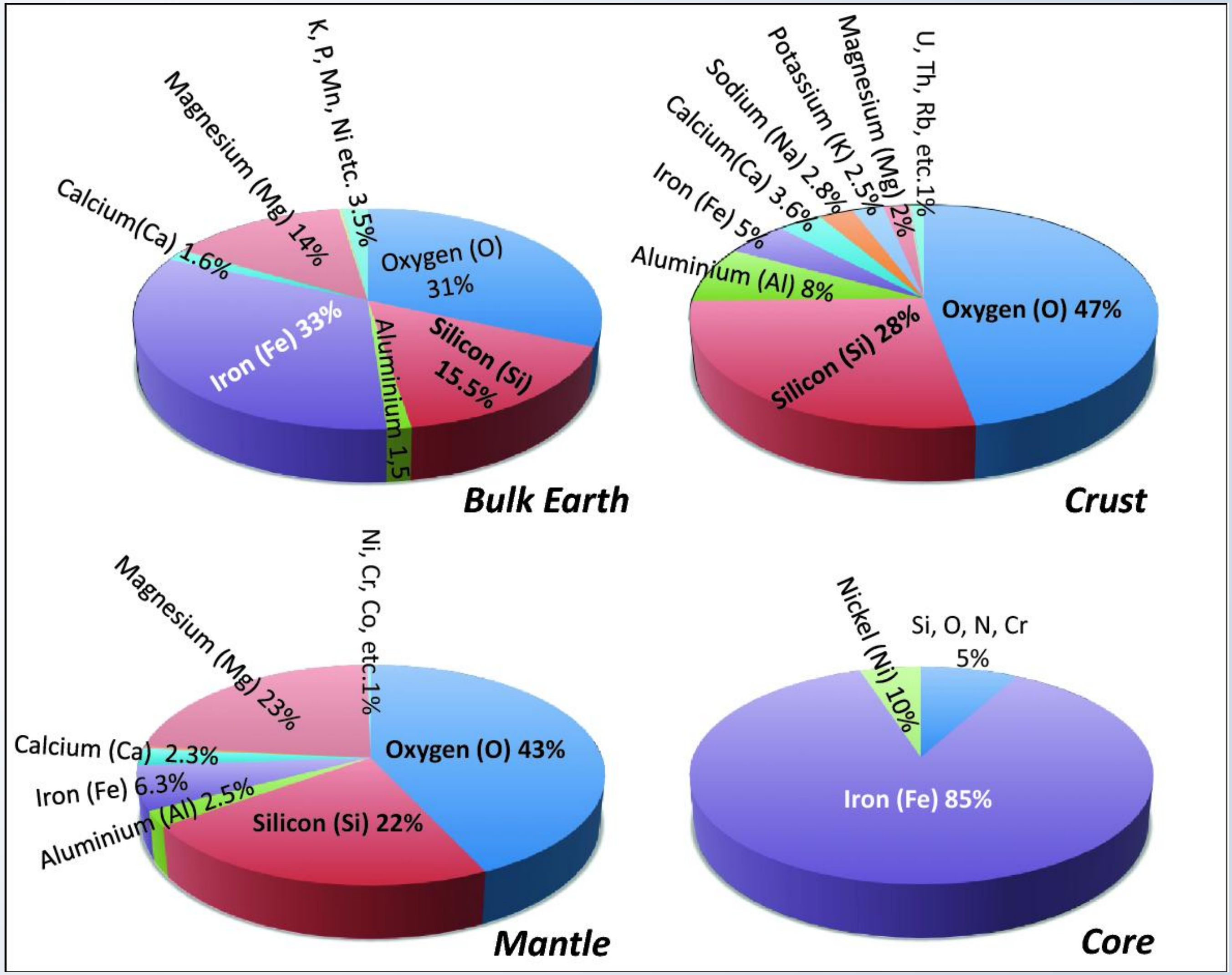
1 GPa = 10 kbar = 10^9 Pa

Earth Compositions

Earth separated into layers with different bulk compositions and density during the process of differentiation.

Differentiation of the core and mantle occurs during planet formation, when melting of metal allowed it to sink to the center of the planet.

Differentiation of the crust from the mantle is a continuous ongoing process, although much of it probably occurred early in our planet's history.

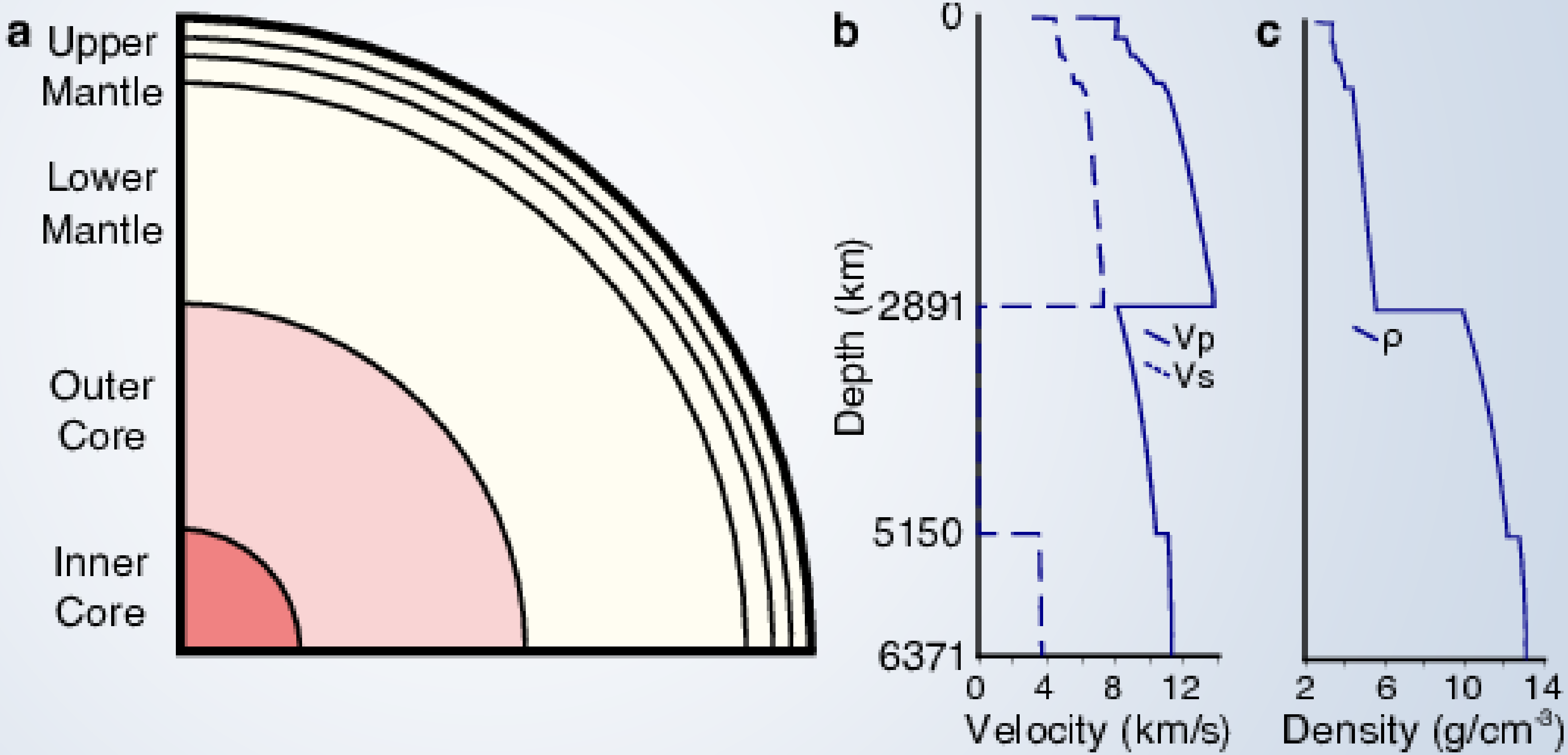


Preliminary Reference Earth Model (PREM)

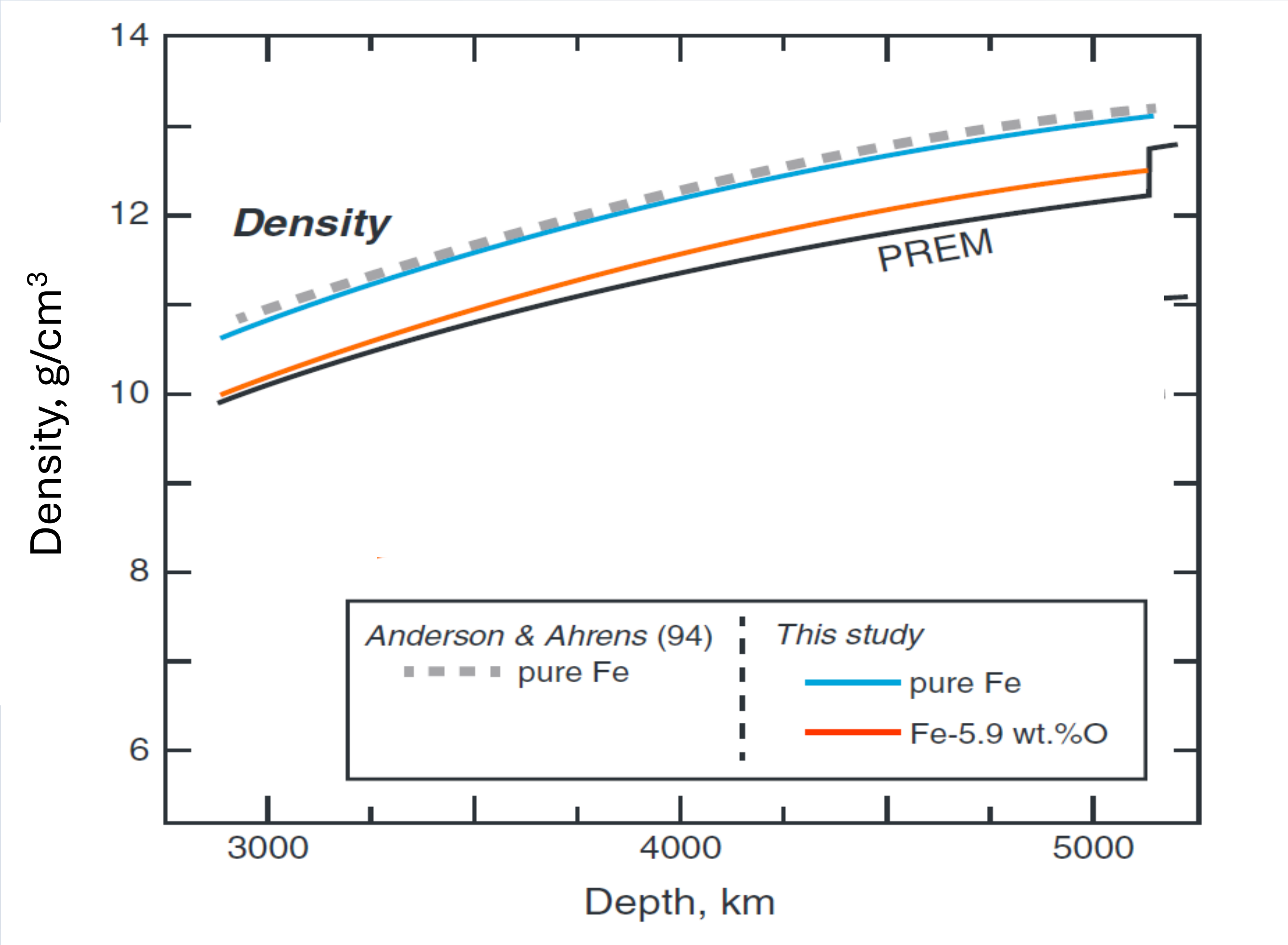
We have the best understanding of Earth's internal structure due to seismology.

Seismic velocities are sensitive to the material properties, including density.

PREM is a reference model for the internal structure of Earth.



Light elements in core

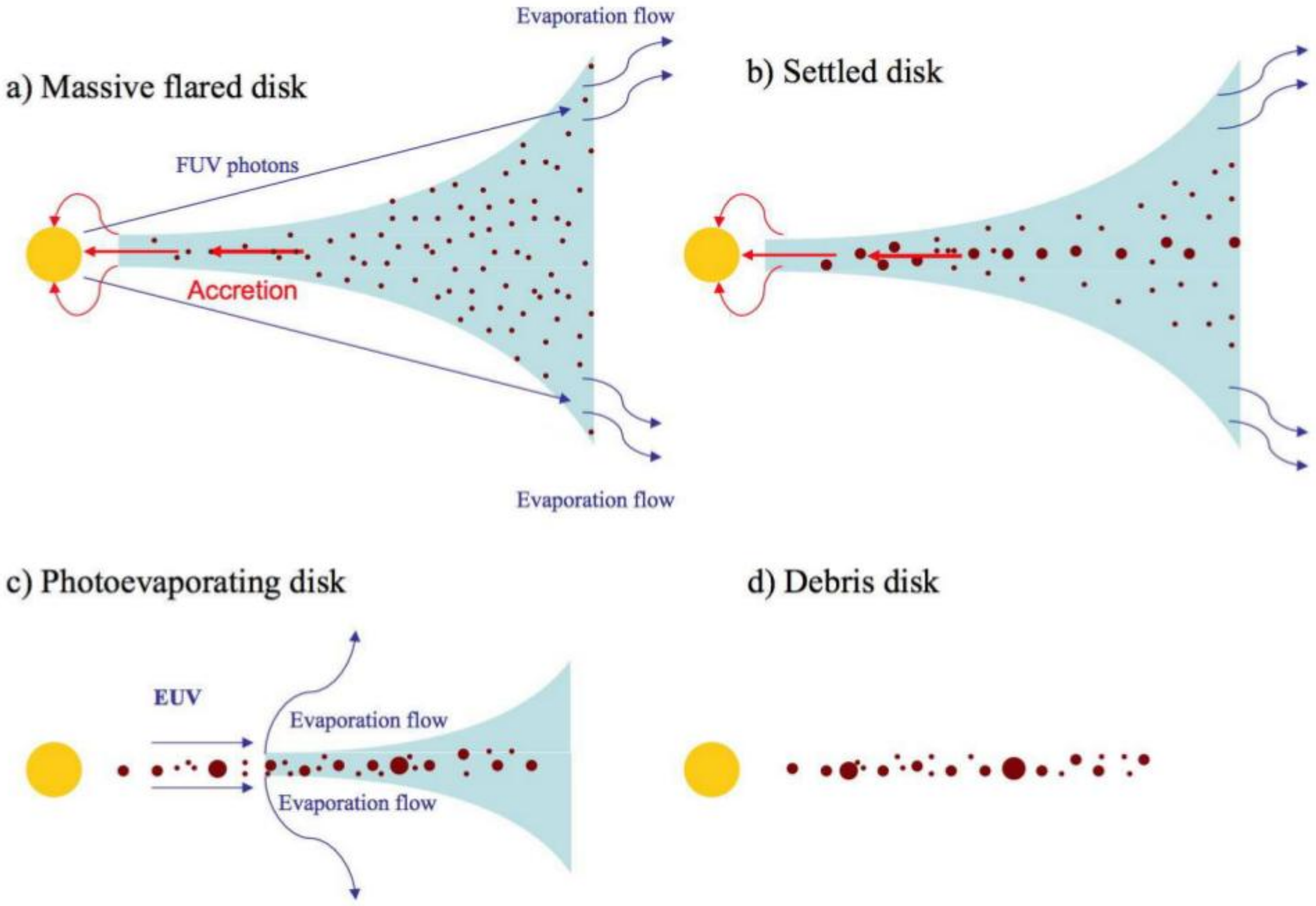


Komabayashi (2015)

PREM shows that the Earth's core is less dense than pure Fe. The core must contain up to 10 wt% of a lighter element (H, C, O, S, Si) to account for the deficit.

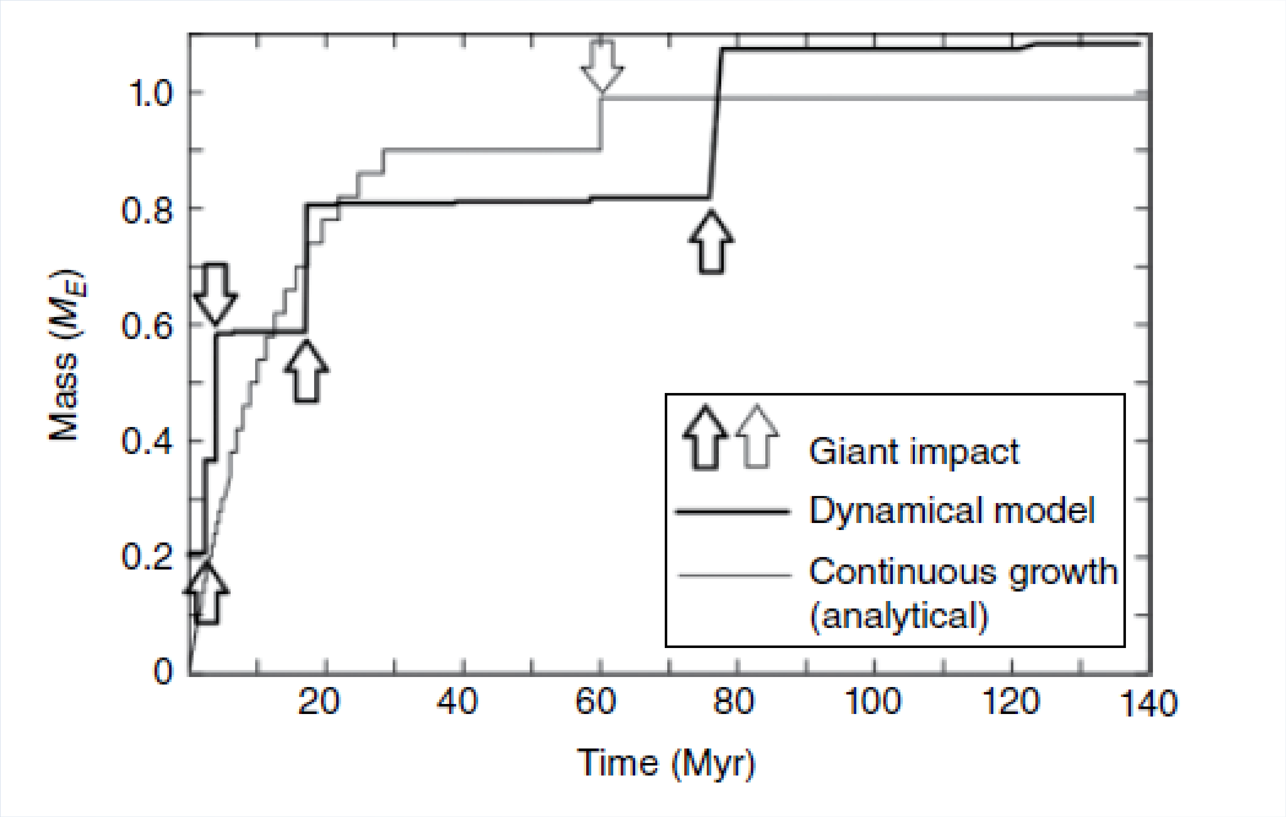
Observations of iron meteorites indicate that the cores also contain significant amounts of Ni and Co.

Models for exoplanets often neglect light elements in the cores of rocky planets because of the small effect on overall planetary radius.



a) Massive flared disk
Evaporation flow
FUV photons
Accretion
Evaporation flow
b) Settled disk
c) Photoevaporating disk
EUV
Evaporation flow
Evaporation flow
d) Debris disk

Accretionary models



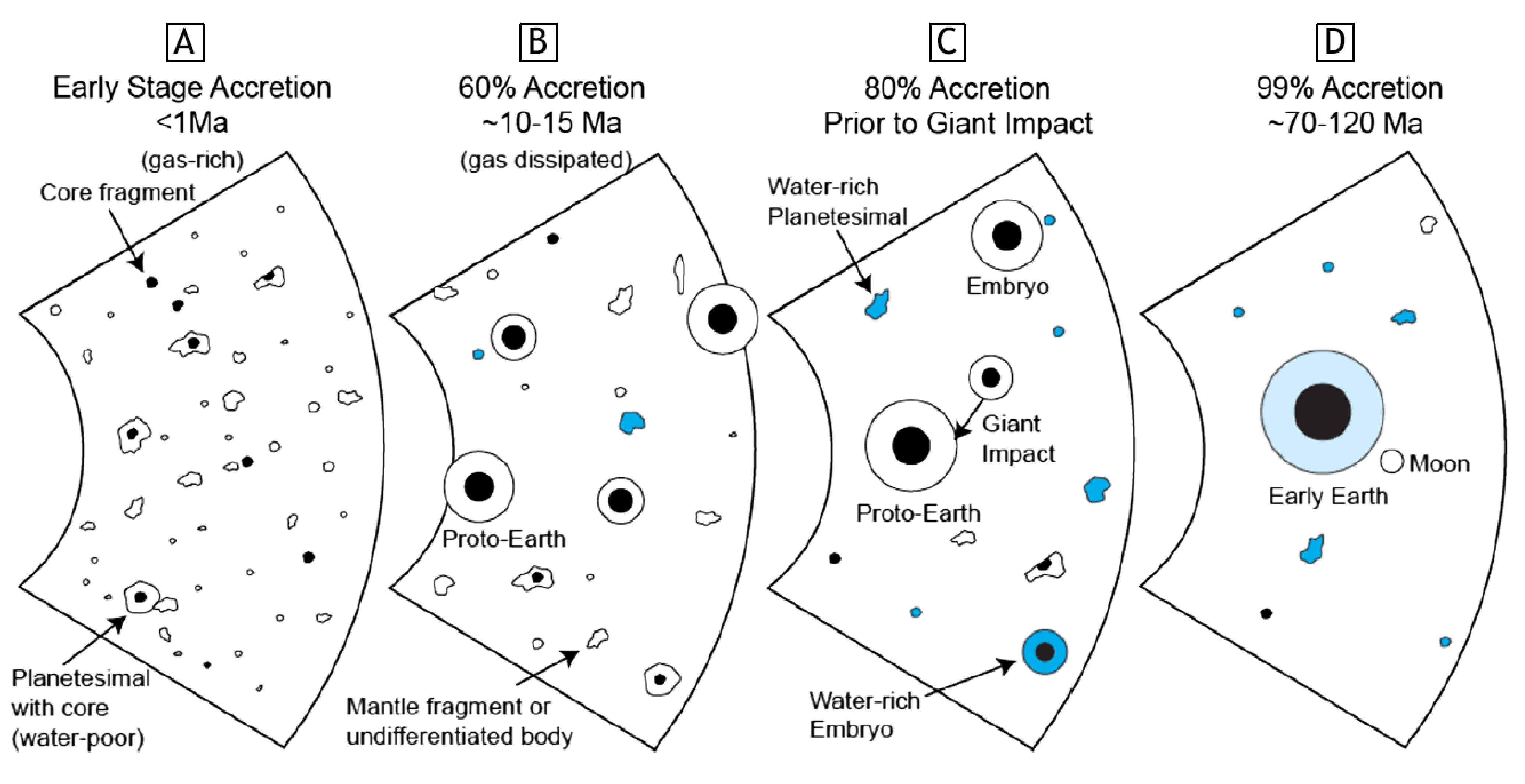
Continuous growth: planets grow continuously with an exponentially decaying rate of growth

Stochastic growth: early growth characterized by continuous planetesimal impacts, late stage growth characterized by a few really large impacts

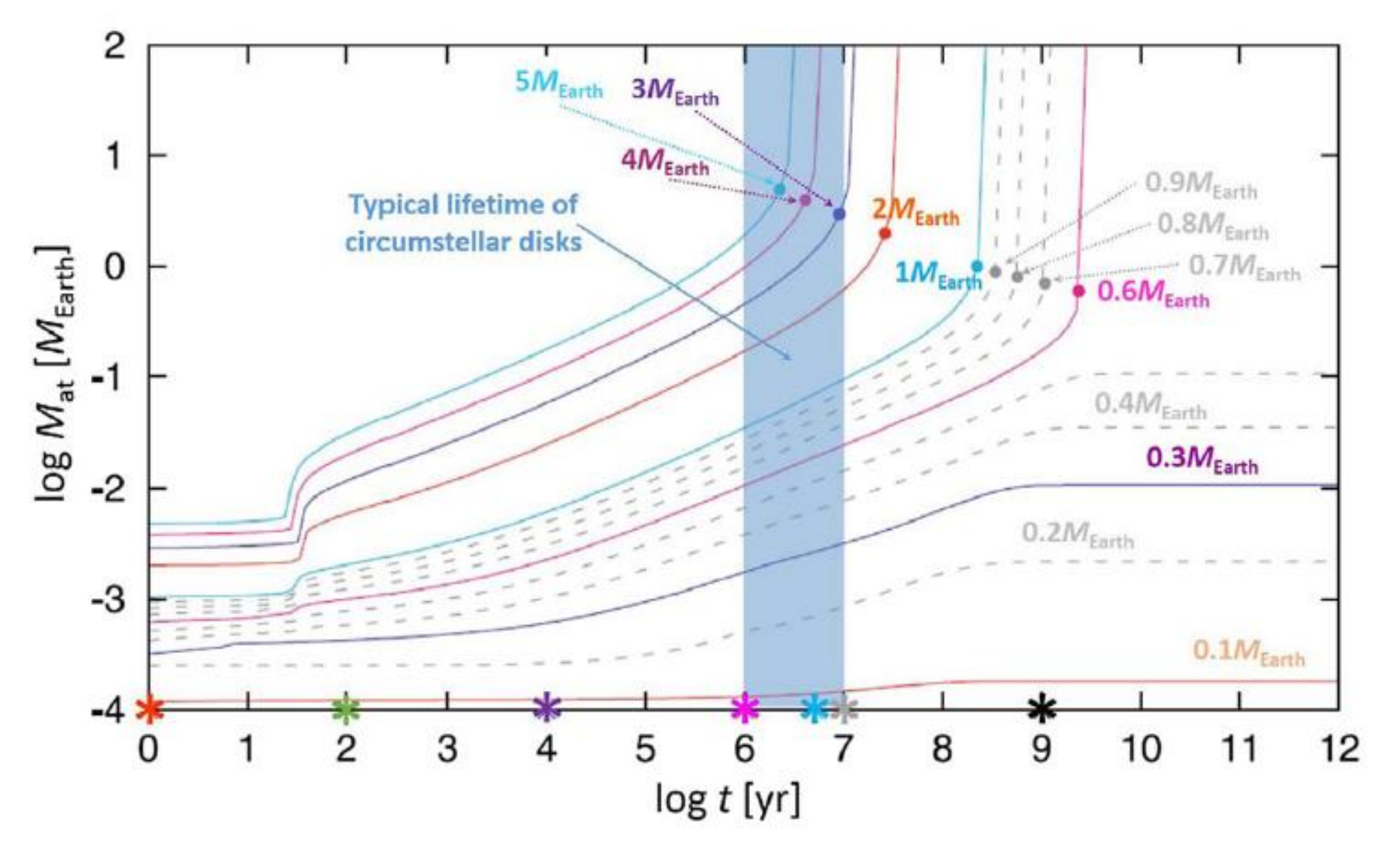
Volatile sources

Sources of volatiles to the rocky planets include:

- Volatiles in gas
  - disk gas with solar composition
- Volatiles in solid phases
  - Hydrated silicates
  - Organic material
  - Ices


A
Early Stage Accretion
<1Ma
(gas-rich)
Core fragment
Planetesimal
with core
(water-poor)
B
60% Accretion
~10-15 Ma
(gas dissipated)
Proto-Earth
Mantle fragment or
undifferentiated body
C
80% Accretion
Prior to Giant Impact
Water-rich
Planetesimal
Embryo
Giant
Impact
Proto-Earth
Water-rich
Embryo
D
99% Accretion
~70-120 Ma
Moon
Early Earth

Primary Atmosphere



Lammer et al. (2018)

Primary atmospheres are gas accreted directly from the protoplanetary disk, and therefore should have compositions similar to stellar abundances (i.e. H_2 + He).

Atmospheric escape of H and He could leave an atmosphere composed of otherwise solar composition, with CH_4, NH_3, H_2O. Oxidation of CH_4/NH_3 to CO_2/N_2 by hydrogen loss could produce an atmosphere of ~60% CO_2, 20% Ne, 10% N_2.

Embryos will accrete gas prior to gas dispersal at 3-5 Myr, depending on their size (gravity). Final assembly of rocky planets occurs during the giant impact stage, but embryos may reach up to roughly Mars-size before gas dispersal.

Earth could have accreted 10-100 bars of solar gas.

Tracking compositions

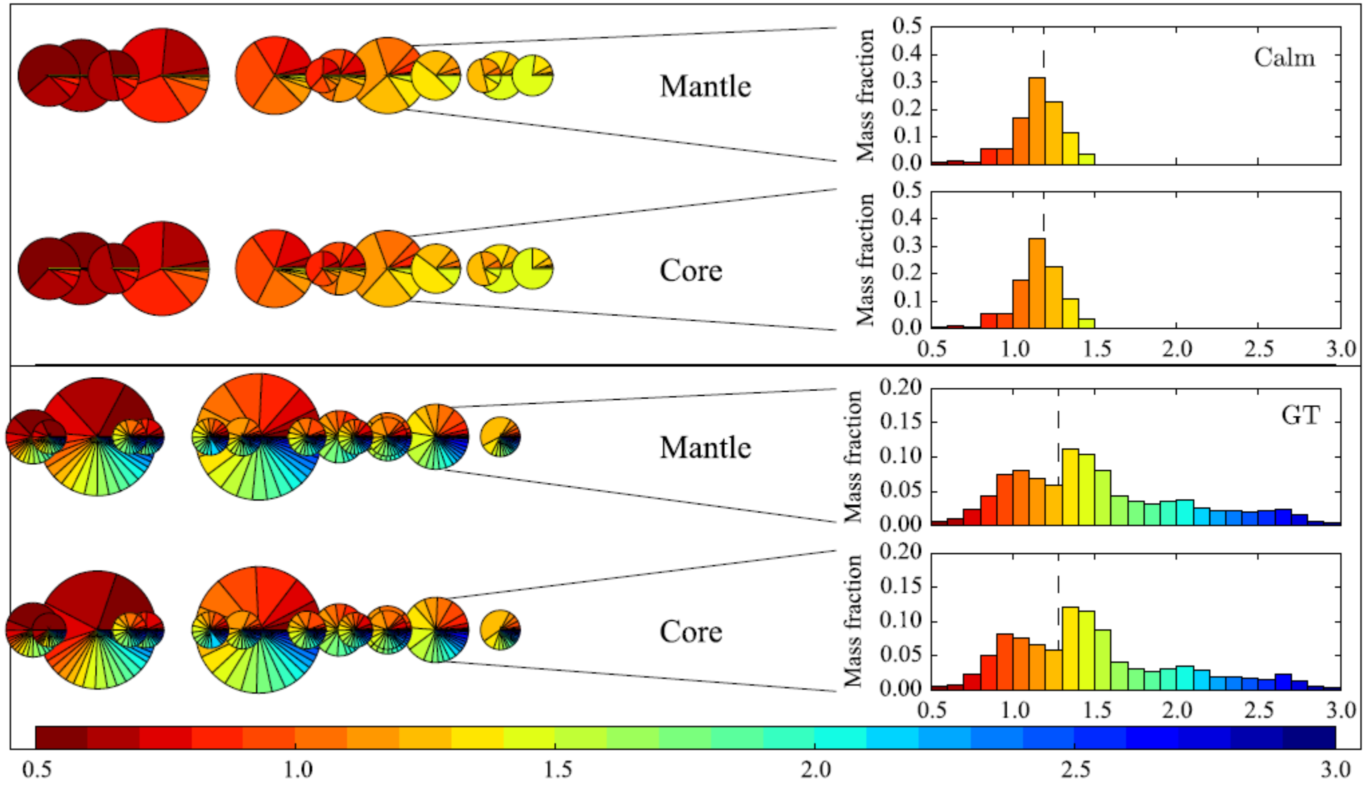


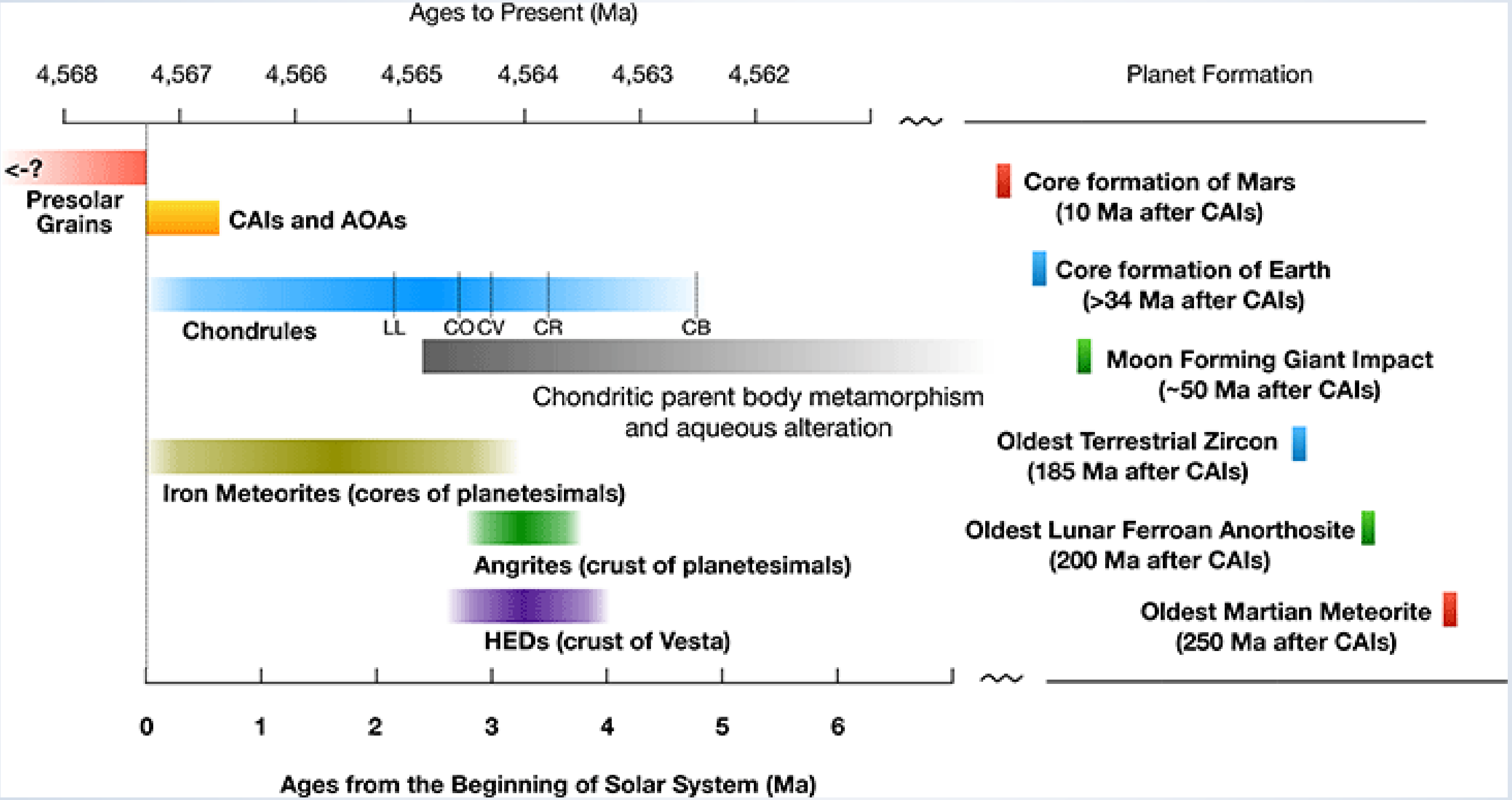
Figure 14. Composition pies for each planetary embryo at the end point of a calm disk simulation without gas drag (5, upper) and a Grand Tack simulation with fast, early migration (21, lower). The embryos are shown at their instantaneous semimajor axis, with the size of each pie proportional to the object's radius. Each sector of a pie shows the mass fraction of the embryo's mantle or core originating from the region indicated by the color bar. The histograms on the right show this breakdown for the indicated embryo, the dashed line showing its location.

Carter et al. (2015)

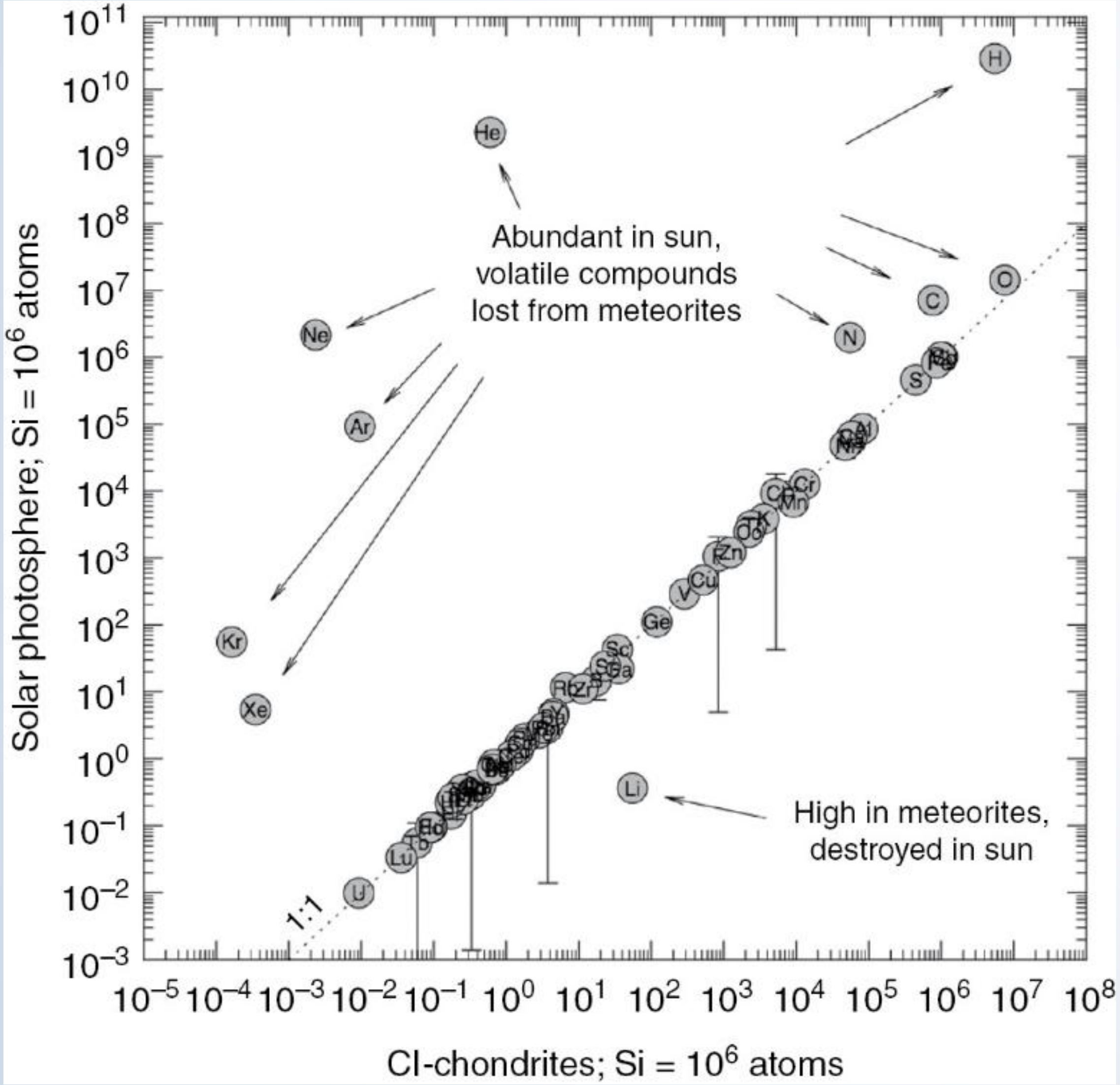
Simulations of planet formation show that accretion does not occur in narrow "feeding zones".

Planets formed in the inner solar system can accrete material from the outer disk due to chaotic scattering of objects by the gas giant planets and their migration.

Timing of Solar System formation



Meteorites as solar analog

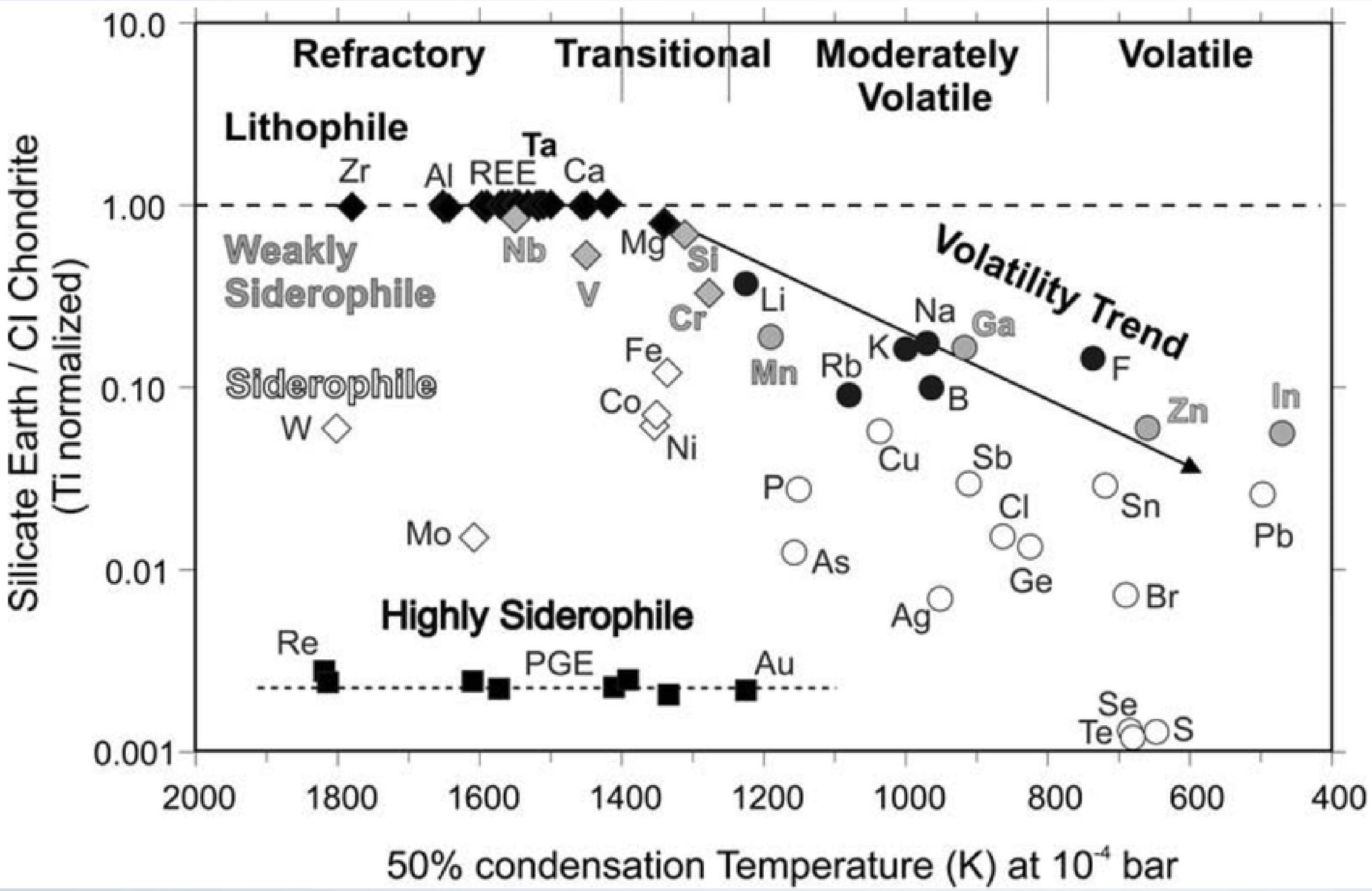


The most primitive type of meteorite (CI chondrite) has nearly solar abundances of many elements.

The exceptions are highly volatile elements (H,C,N, noble gases) that don't condense (or are volatilized and lost) in the region these meteorites formed.

Accretion of chondrites of different types could also provide the Earth with its volatile compliment.

Earth’s abundances



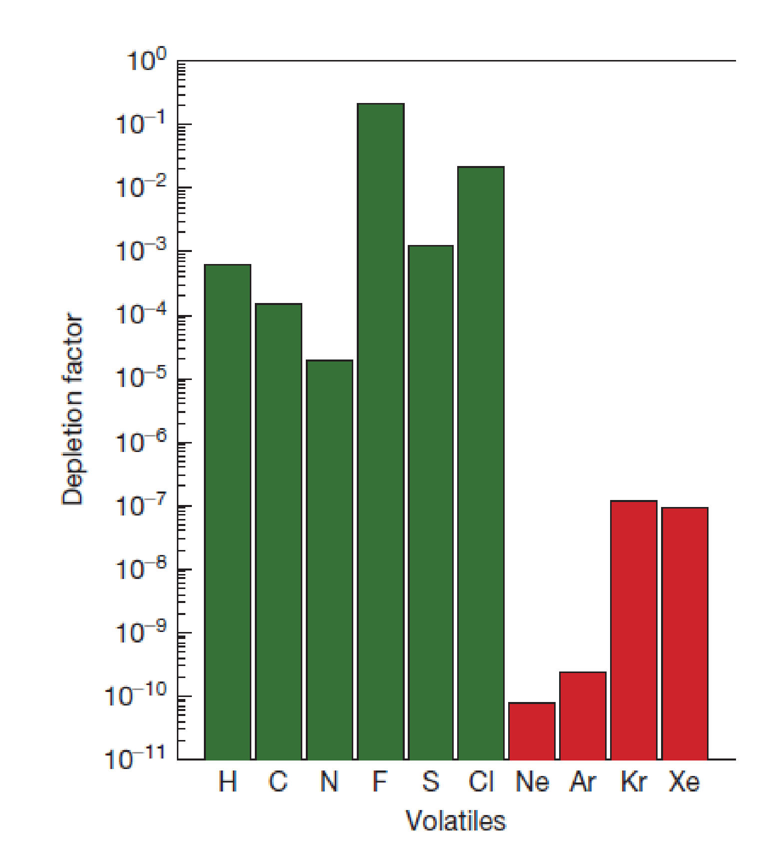
Mann et al. 2009

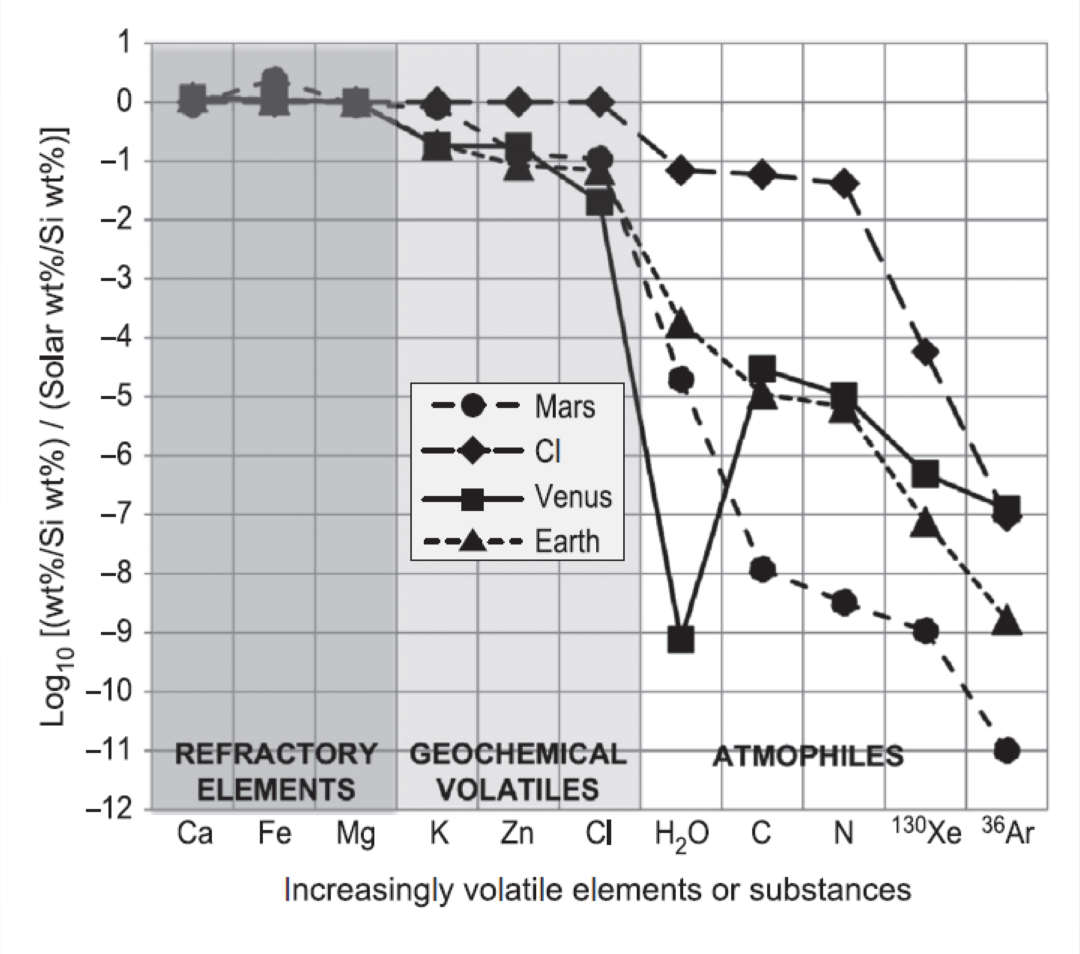
Models of planet formation suggest that objects made of rocky elements should have similar compositions to their star, because all of these elements condense within the protoplanetary disk.

Earth’s elemental abundances are not all solar, although many of them are close to solar.

Elements that condense at colder temperatures seem to be more depleted in the Earth.

Volatile depletion





Volatiles that more readily get incorporated into mineral phases (e.g. F, S, Cl) are less depleted. Noble gases, which form no solid phases, are the most depleted.

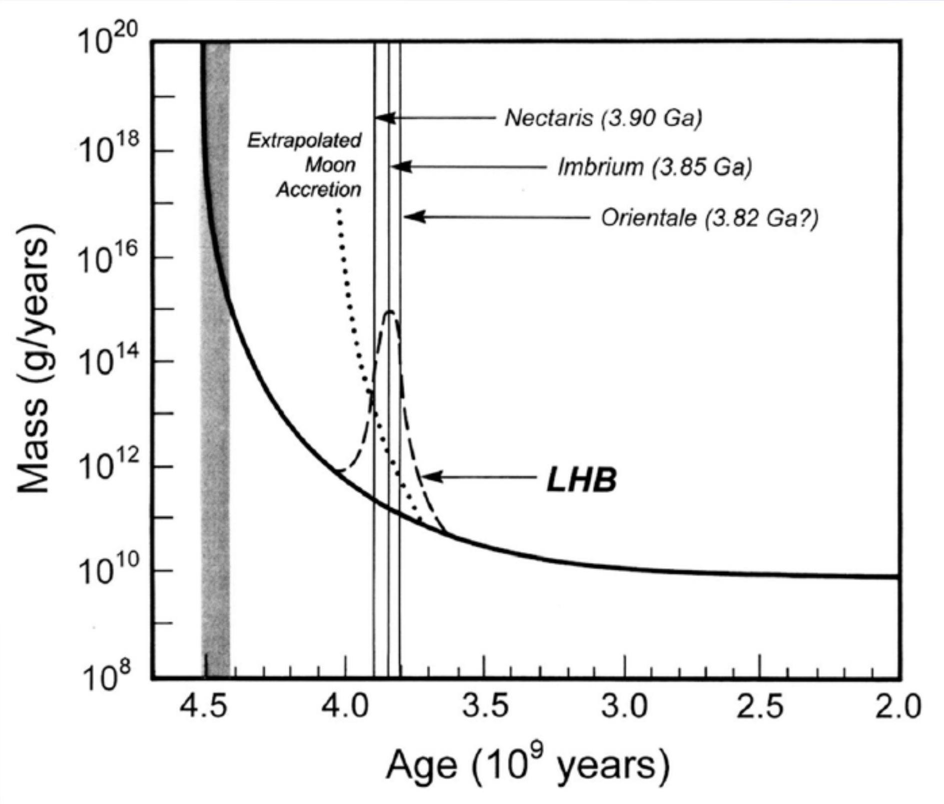
All rocky planets and meteorites are depleted in volatiles relative to solar composition. This includes C, H, N, S and the noble gases

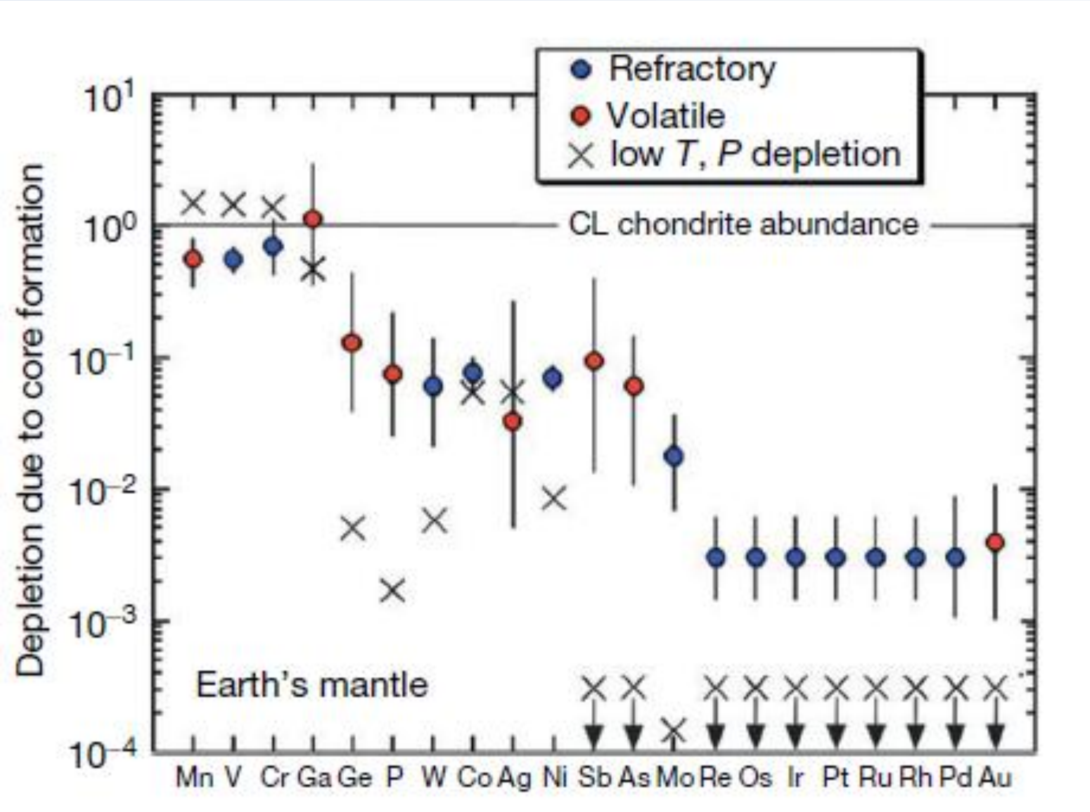
Late Veneer / Late Heavy Bombardment

Accretion was largely complete with the Moon-forming impact, but additional impacts, up to ~2-5% of the Earth's mass, accreted afterwards.

The exponential tail of accretion is referred to as either the later veneer or late accretion.

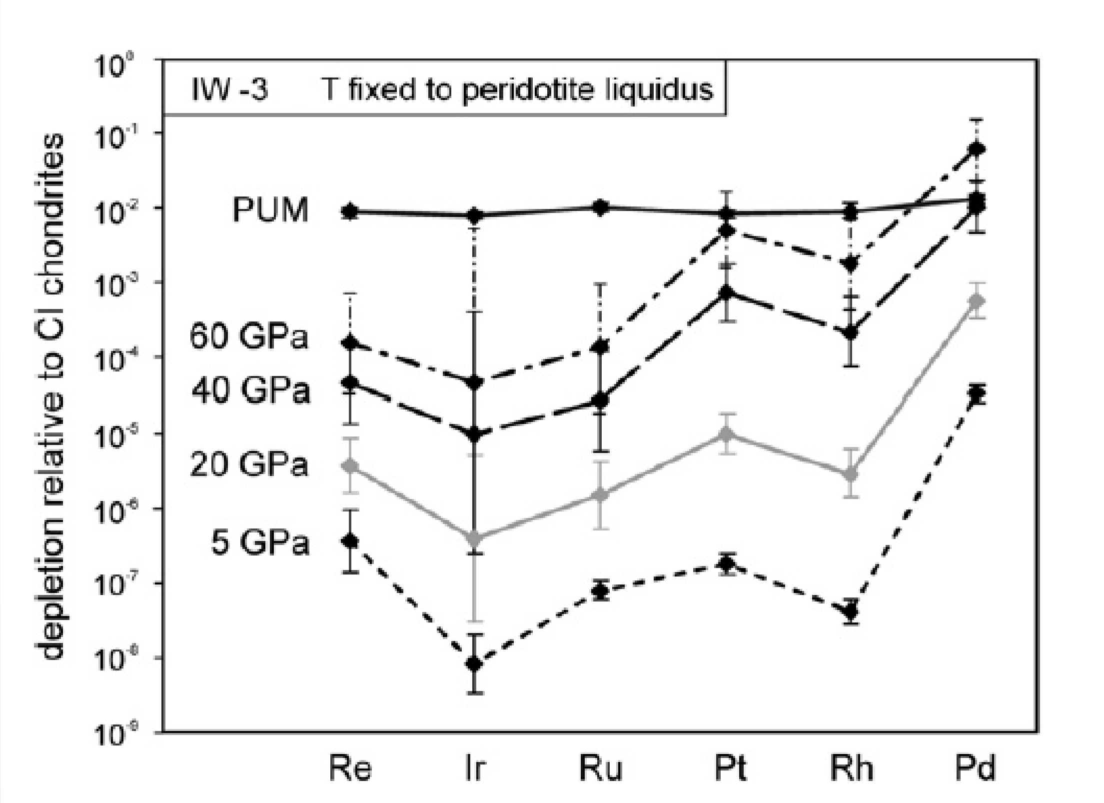
A possible spike in impacts may have occurred around 4 Gyr due to a late instability in the giant planets. This theory is based on the number of large impact basins on the Moon and a cluster in the dating of lunar samples associated with them. This is disputed as potentially being skewed by a single large impact basin.





Highly siderophile elements are less depleted in the Earth's mantle than predicted by partitioning models.

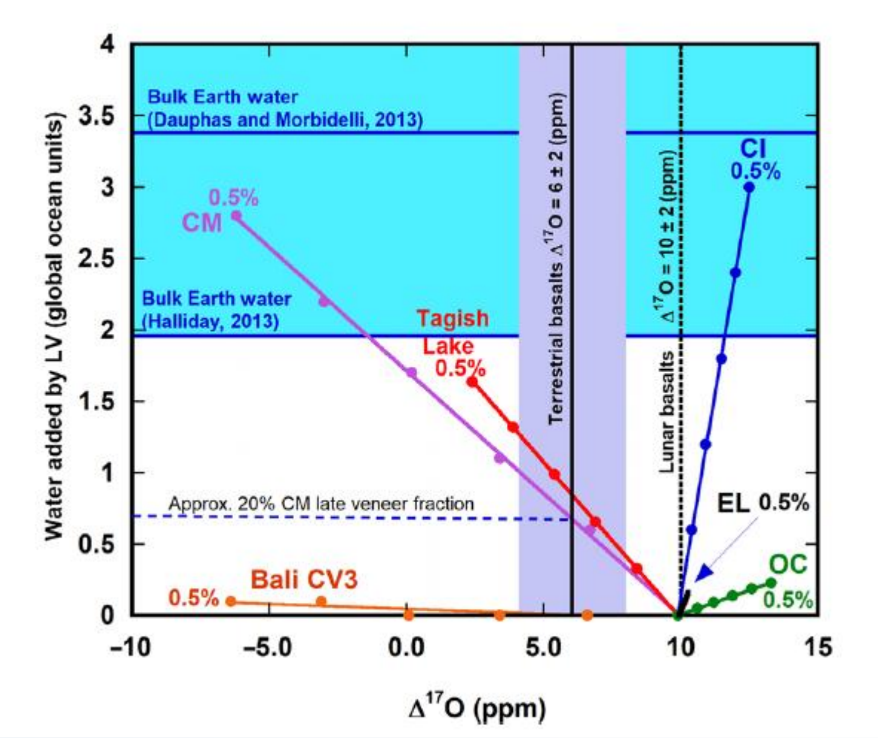
They also exist at chondritic relative abundances to one another.



Partitioning models even at high pressures and different fO_2 cannot match the observed chondritic relative abundances.

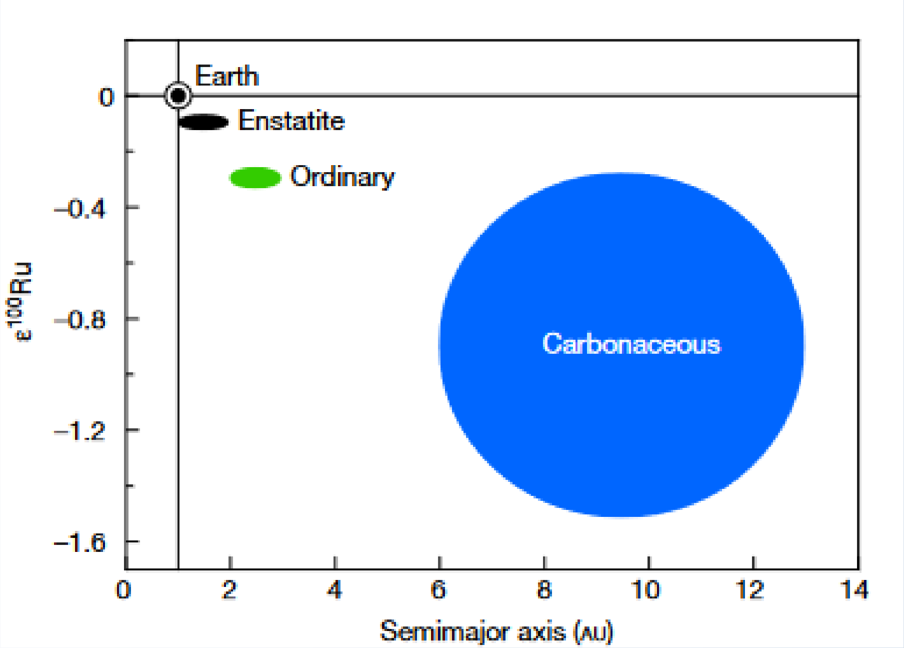
This is used as evidence for delivery of additional chondritic material after core formation has finished.

Timing of volatile delivery



Greenwood et al. (2018)

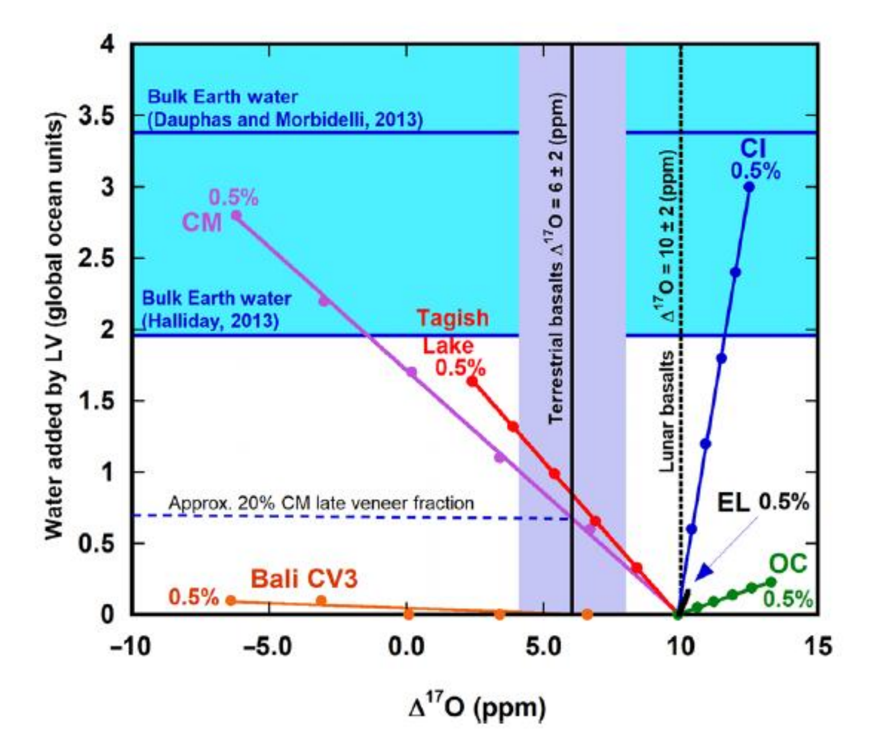
The late veneer would have caused deviations in the relative oxygen isotope compositions of the Earth and the Moon, depending on materials accreted.



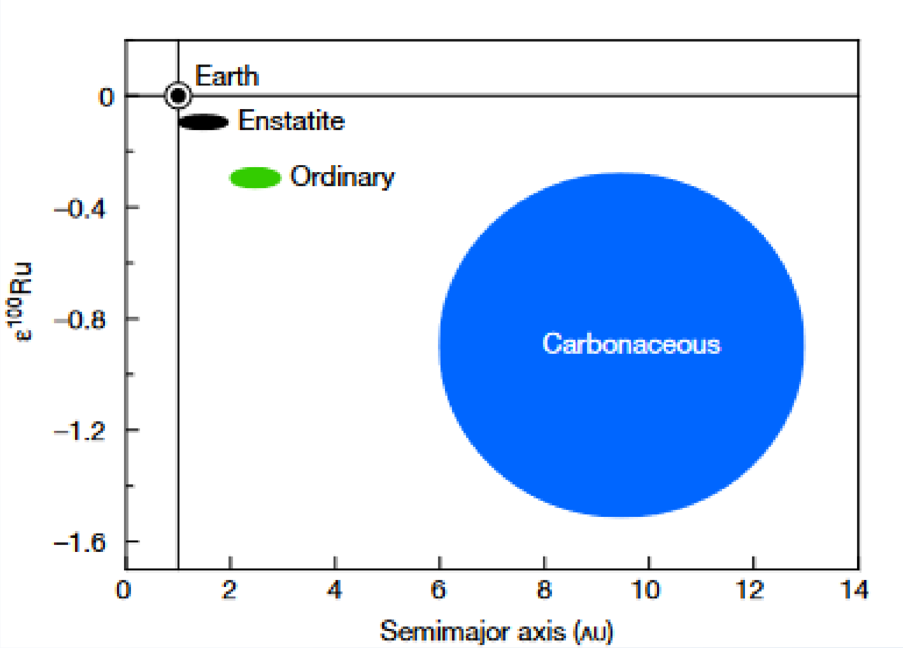
Fischer-Godde & Kleine (2017)

Ruthenium derived from the late veneer has very different isotopic composition from carbonaceous chondrites and is more consistent with an inner solar system source (e.g. enstatite chondrites).

Timing of volatile delivery



Greenwood et al. (2018)

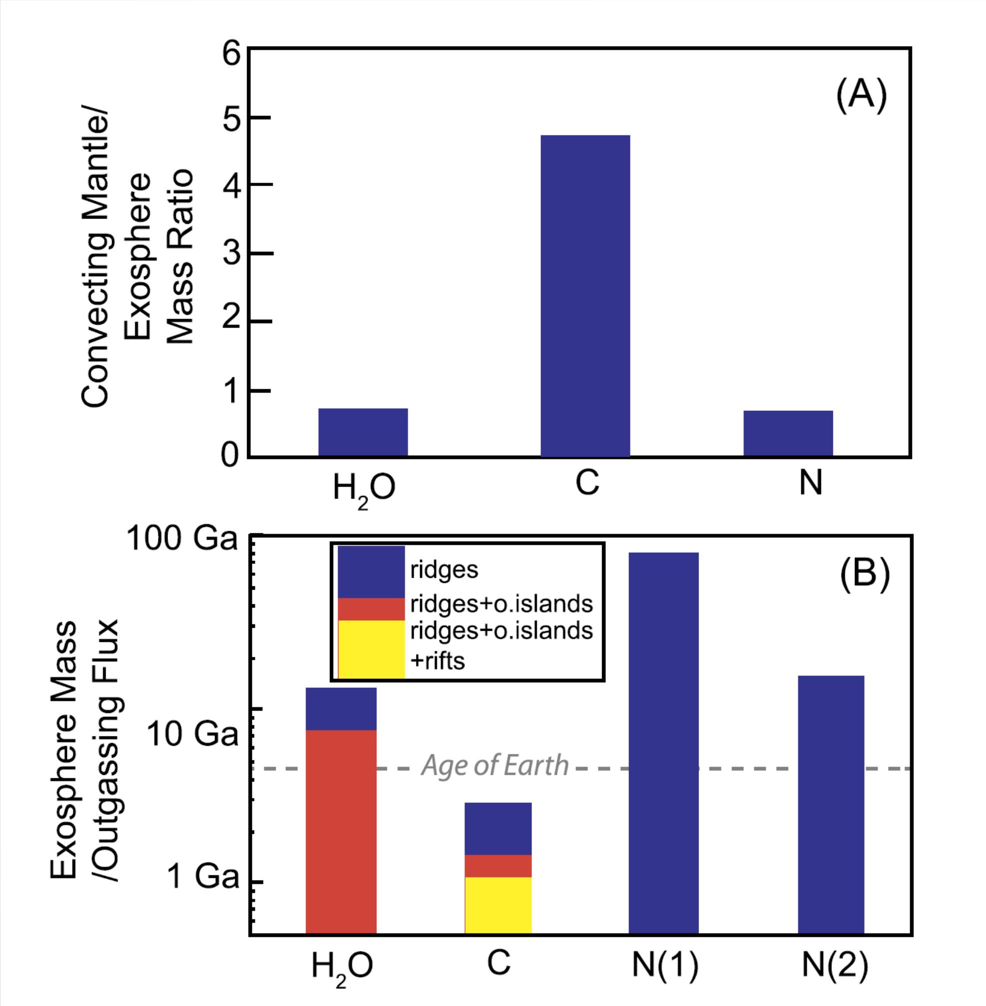


Fischer-Godde & Kleine (2017)

Both lines of evidence suggest that the late veneer cannot be composed of only carbonaceous chondrites and therefore cannot be the primary source of Earth's volatiles.

Based on combined constraints, **at most ~30% of Earth's water** could have been delivered after the Moon-forming impact.

Present-day Earth mantle volatiles

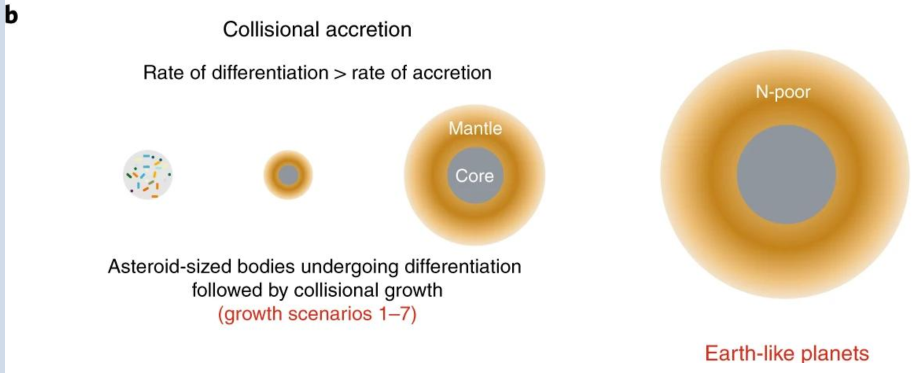


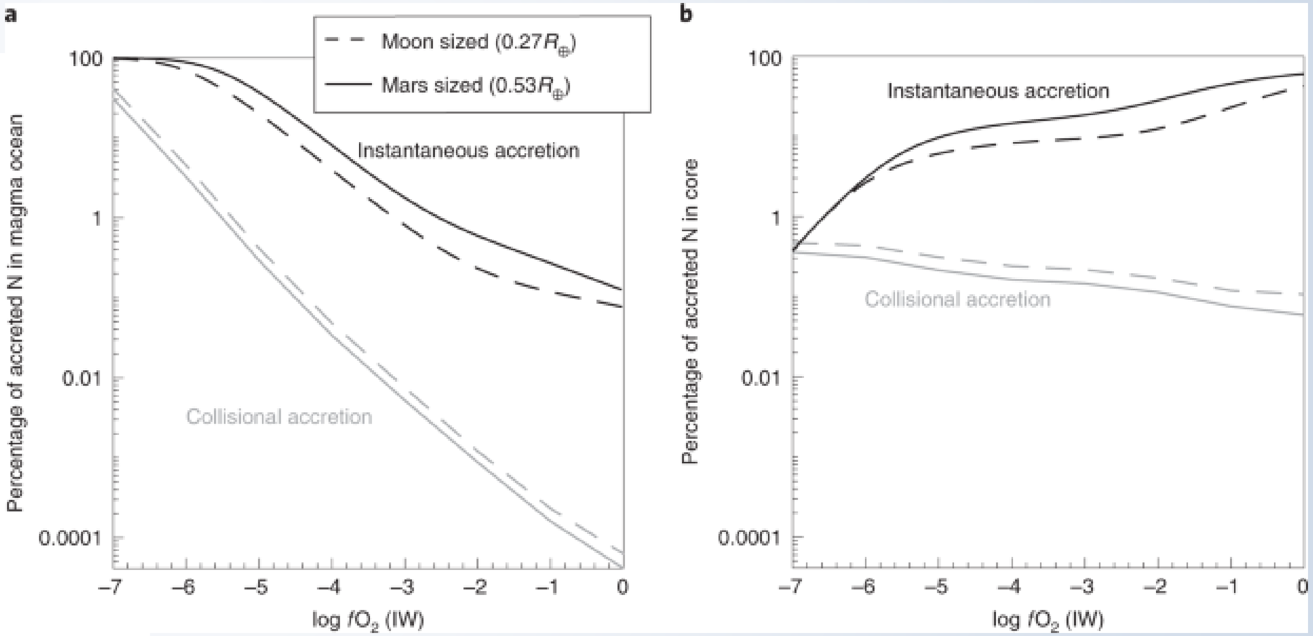
Estimates of surface/mantle inventories suggest that most of Earth's carbon is in the mantle, but most H_2O and N are at the surface

Based on current outgassing rates, the inventories require significant ingassing of C, but early large surface inventories of H and N

Hirschmann (2018)

Timing Matters!



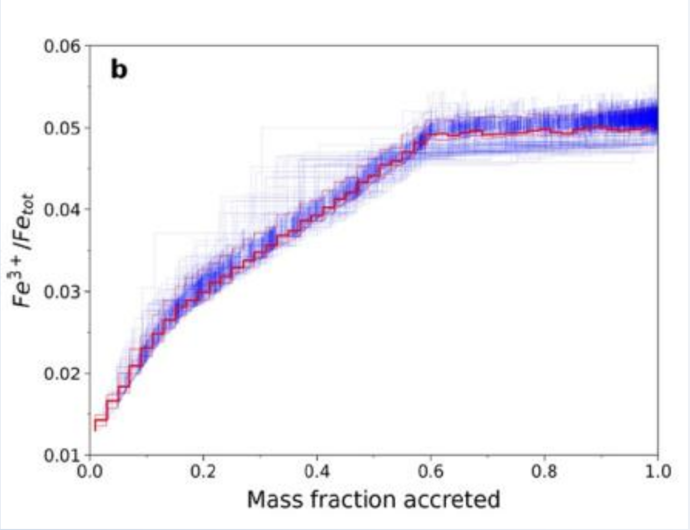


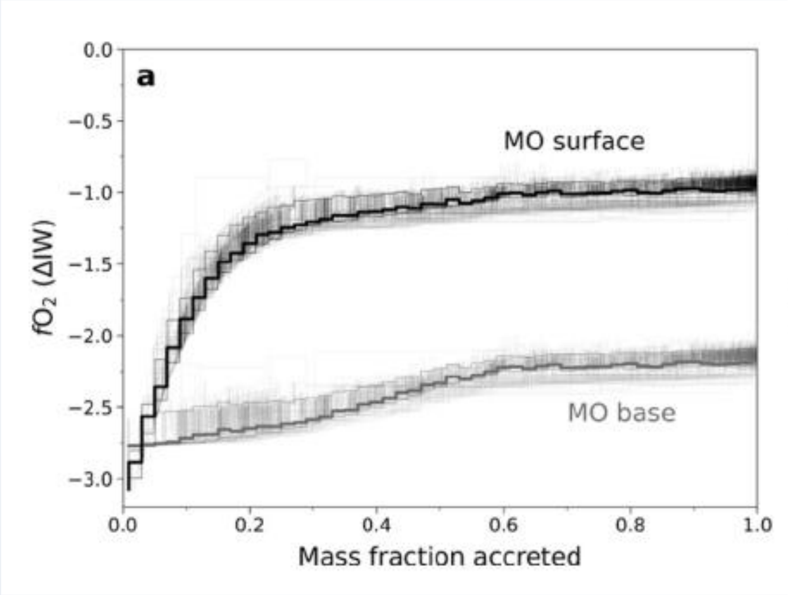
The fraction of N a protoplanet retains depends on whether the rate of accretion or differentiation is faster.

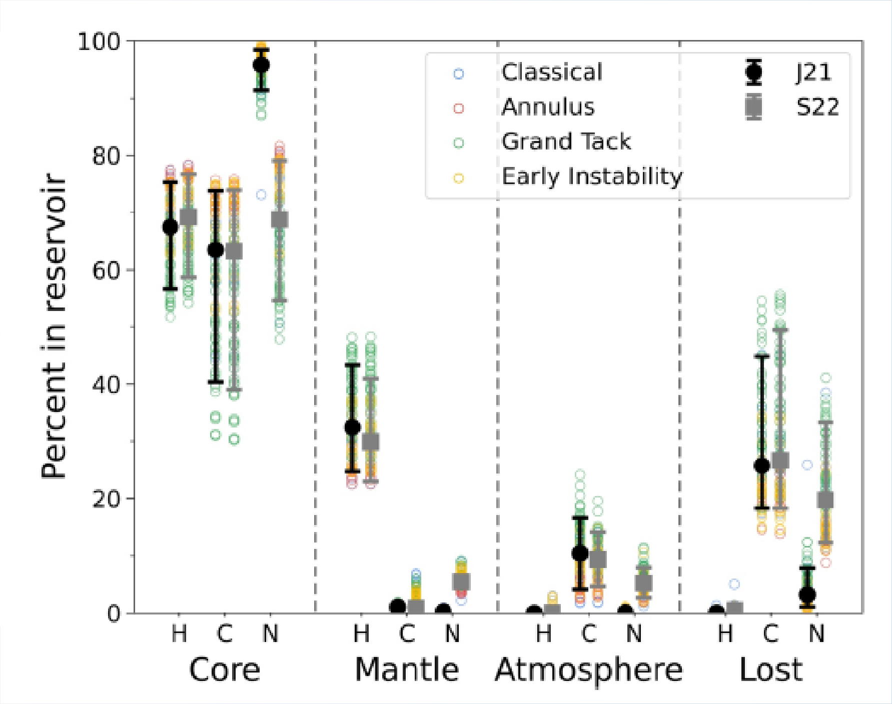
This model assumes any atmosphere layers that form during intermediate steps are lost.

Grewal et al. (2021)

Evolution of Fe^{3+} and volatile budgets during accretion







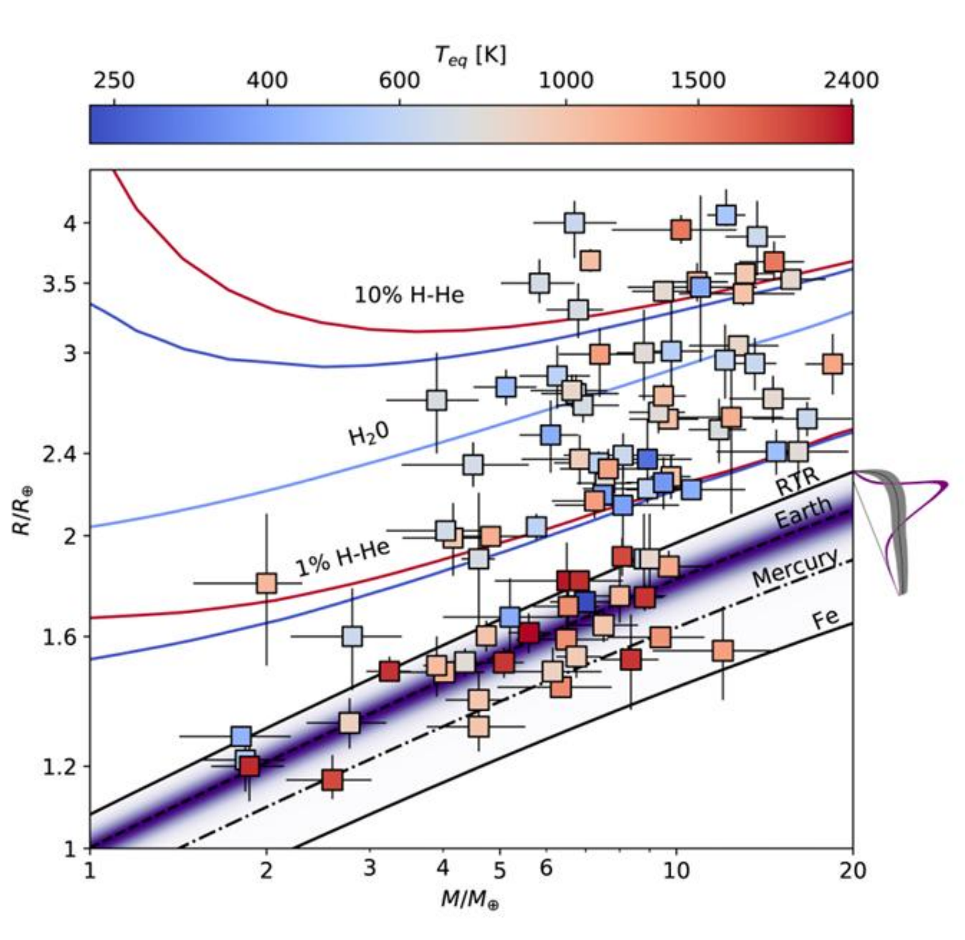
Nbody simulation that simultaneously tracks volatile accretion, mantle oxidation state, and impact erosion.

To match the BSE requires volatile-depleted planetesimals compared to CI.

The core is the largest volatile reservoir.

Gu et al. 2024

Exoplanet Mass-Radius Diagram



Nettelmann & Valencia (2020)

For exoplanets with both a mass and a radius measurement, we can estimate bulk composition by comparison to bulk density, and more detailed models of internal structure.

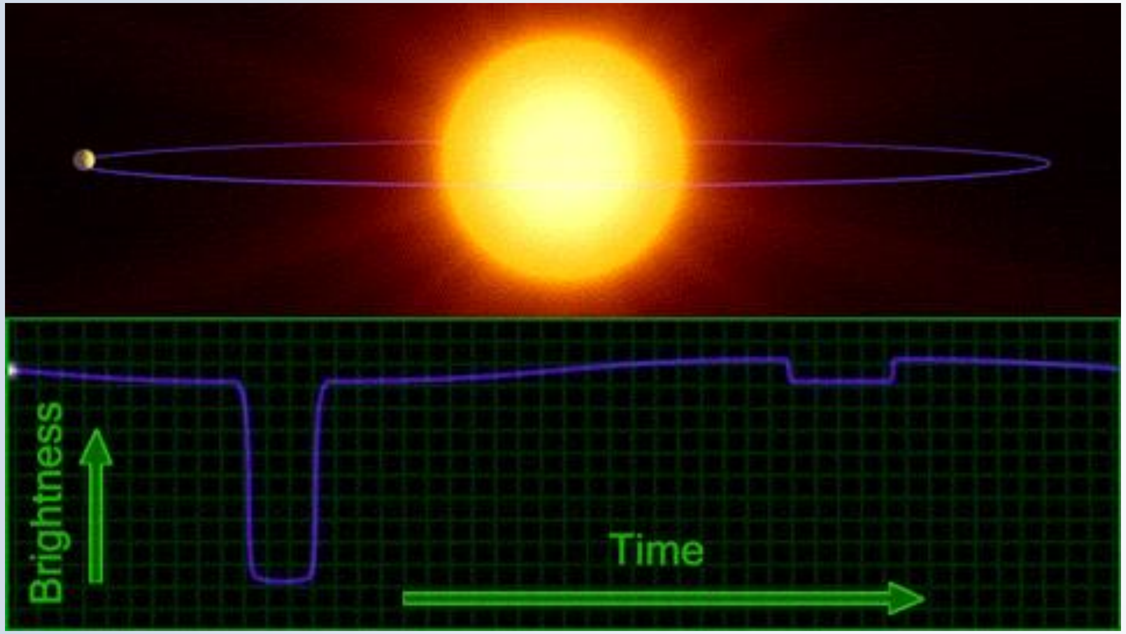
Internal structure equations

$$\frac{dm(r)}{dr} = 4\pi r^2 \rho(r)$$

$$\frac{dP(r)}{dr} = \frac{-Gm(r)\rho(r)}{r^2}$$

$$P(r) = f(\rho(r), T(r))$$

Measuring Planet Radius



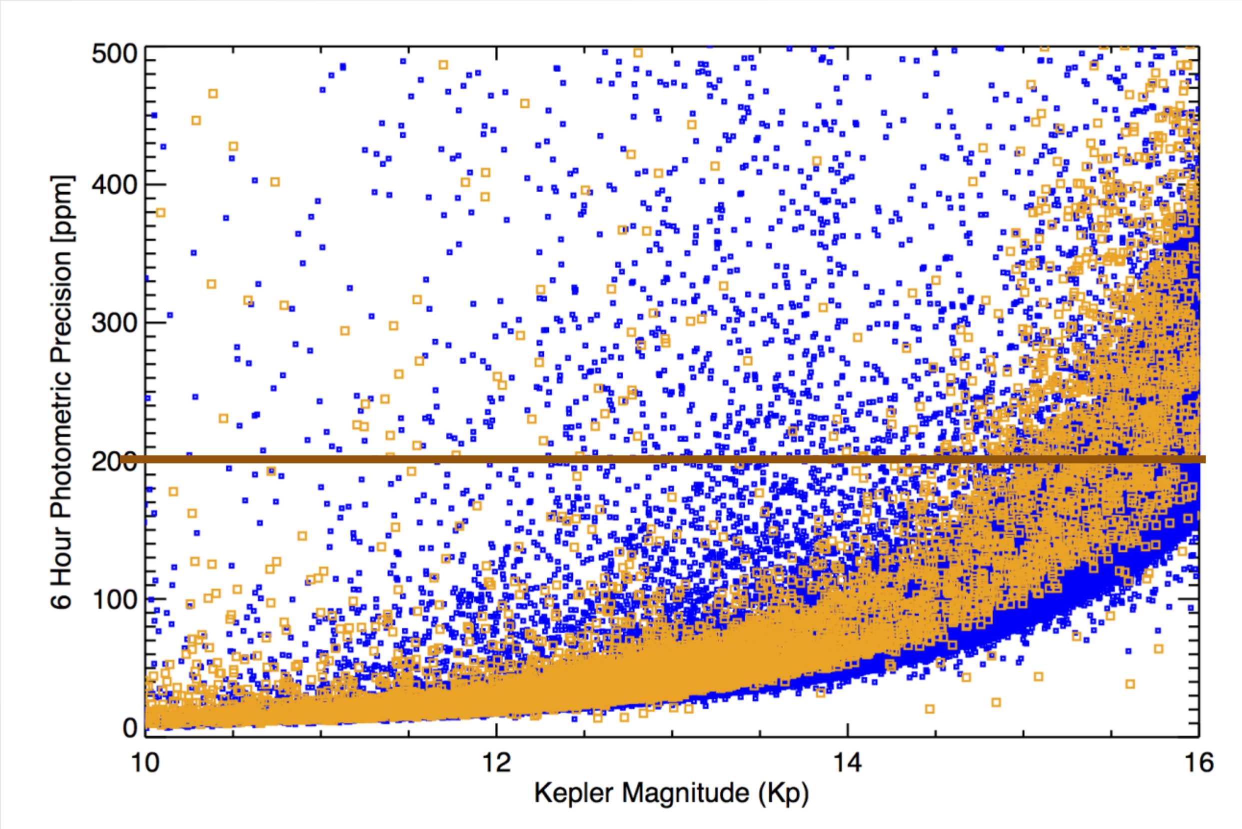
Transit depth $= \dfrac{area\ of\ planet}{area\ of\ star} = \dfrac{4\pi R_P^2}{4\pi R_S^2}$

How well can we measure the radius?

Most of the uncertainty comes from the uncertainty on the stellar radius, which we typically don’t know better than 10%.

For small planets, we may be limited by the photometric precision of our telescope.

Measuring Planet Radius



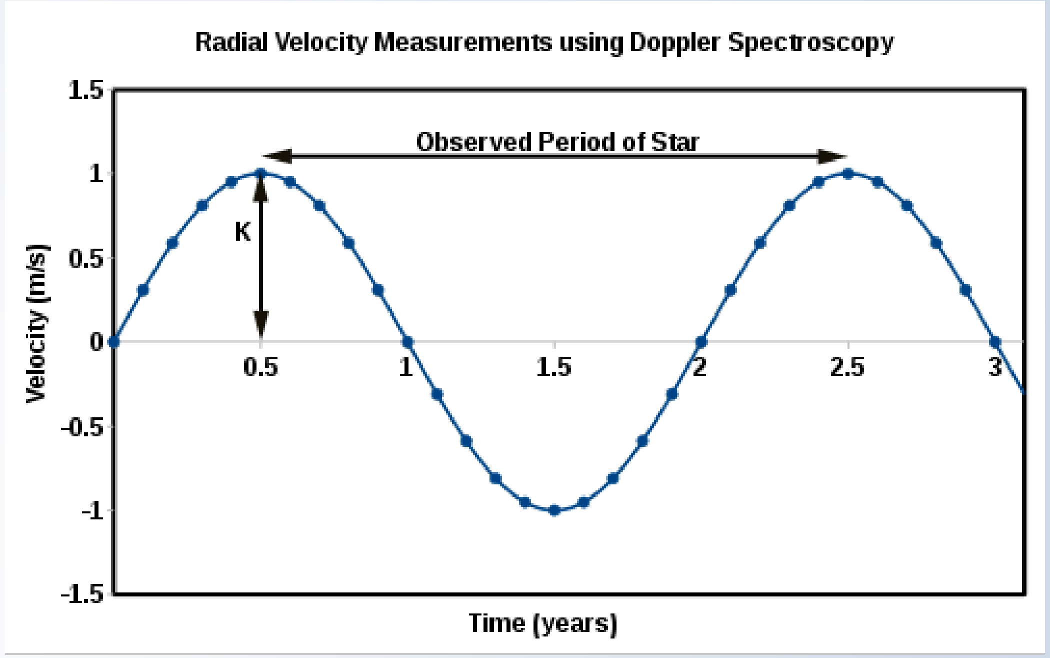
$$\delta_{\oplus} = \frac{(6371)^2}{(695950)^2} = 8.3 \times 10^{-5} = 83 \text{ ppm}$$

$$\delta_{2\oplus} = \frac{(2 \times 6371)^2}{(695950)^2} = 335 \text{ ppm}$$

So to tell the difference between a 1 and 2 Earth radii planet, we need a photometric precision better than ~200 ppm.

Kepler's precision depended on the **apparent magnitude** of the star. For brighter stars (*Kp* < 12), the precision was ~20-30 ppm, but for stars fainter than *Kp* = 16, the precision was ~500 – 1000 ppm.

Measuring Planet Mass



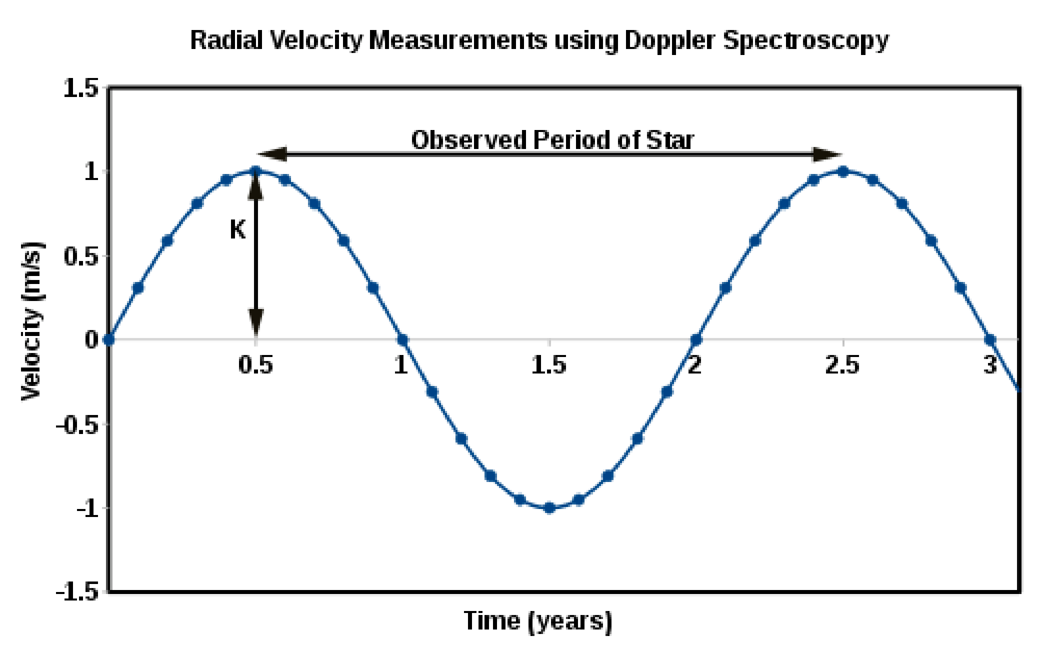
$$K = 0.6395 \text{ m s}^{-1} \left(\frac{P}{1 \text{ year}}\right)^{-1/3} \left(\frac{M_p \sin i}{M_\oplus}\right) \left(\frac{M_*}{M_\odot}\right)^{-2/3} \frac{1}{\sqrt{1-e^2}}$$

Using radial velocities, we can only calculate the absolute mass if we know the inclination of the planet.

This can usually be found for planets that transit, since their inclinations must be close to 90°, but there is still some uncertainty.

Measuring Planet Mass

$$K = 0.6395\ \mathrm{m\ s^{-1}} \left(\frac{P}{1\ \mathrm{year}}\right)^{-1/3} \left(\frac{M_p \sin i}{M_\oplus}\right) \left(\frac{M_*}{M_\odot}\right)^{-2/3} \frac{1}{\sqrt{1-e^2}}$$



For a quiet Sun-like star (best case scenario), stellar "jitter' can produce velocities of ~1-3 m/s.

Assuming a circular orbit, and a period of 10 days, how much mass uncertainty would this signal produce?

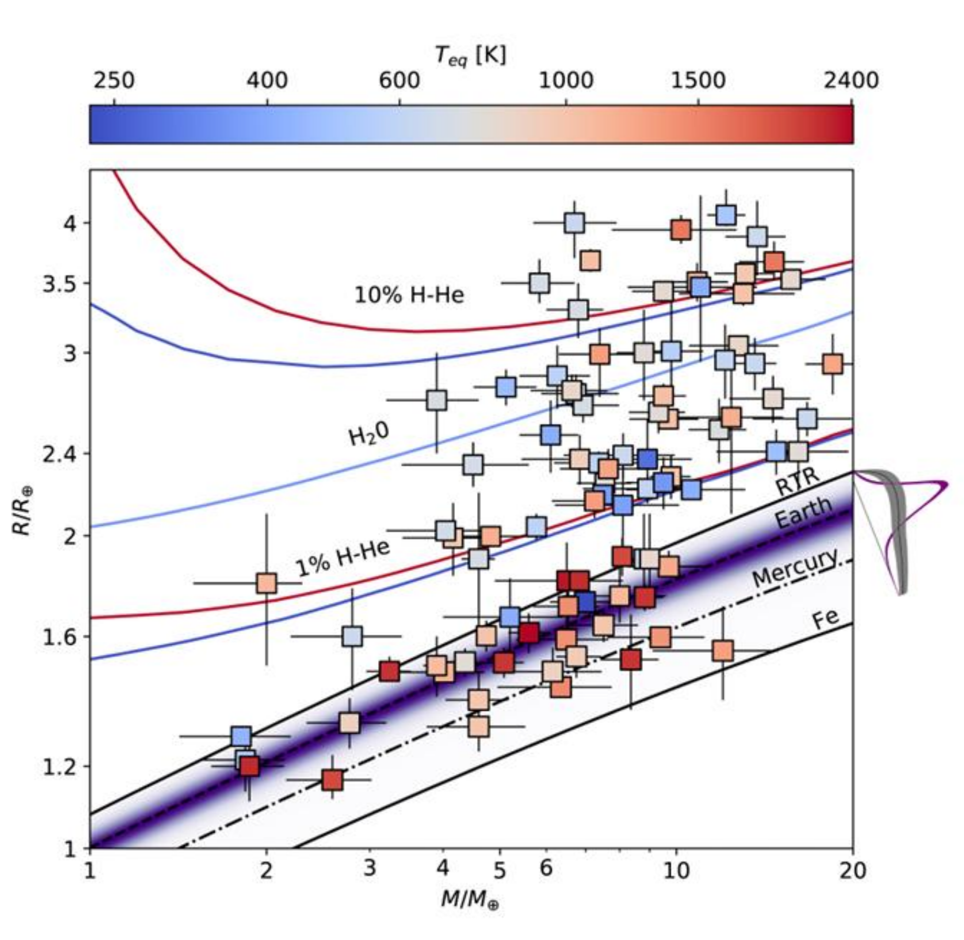
$$1\ \mathrm{m\ s^{-1}} = 0.6395\ \mathrm{m\ s^{-1}} \left(\frac{0.0274}{1\ \mathrm{year}}\right)^{-1/3} \left(\frac{M_p \sin i}{M_\oplus}\right)$$

$$\left(\frac{M_p \sin i}{M_\oplus}\right) \cong 0.5$$

This would be a 50% error in the mass measurement of an Earth-mass planet from one measurement. This would improve with more measurements.

Typical Uncertainty:
Hot Jupiter ~3-10%
Neptune ~10-20%
Super-Earth ~15-30%
Earth-like ~30-50%

Exoplanet Mass-Radius Diagram



Nettelmann & Valencia (2020)

Internal structure equations

Enclosed mass: $$\frac{dm(r)}{dr} = 4\pi r^2 \rho(r)$$

Hydrostatic equilibrium: $$\frac{dP(r)}{dr} = \frac{-Gm(r)\rho(r)}{r^2}$$

Equation of state (EOS): $$P(r) = f(\rho(r), T(r))$$

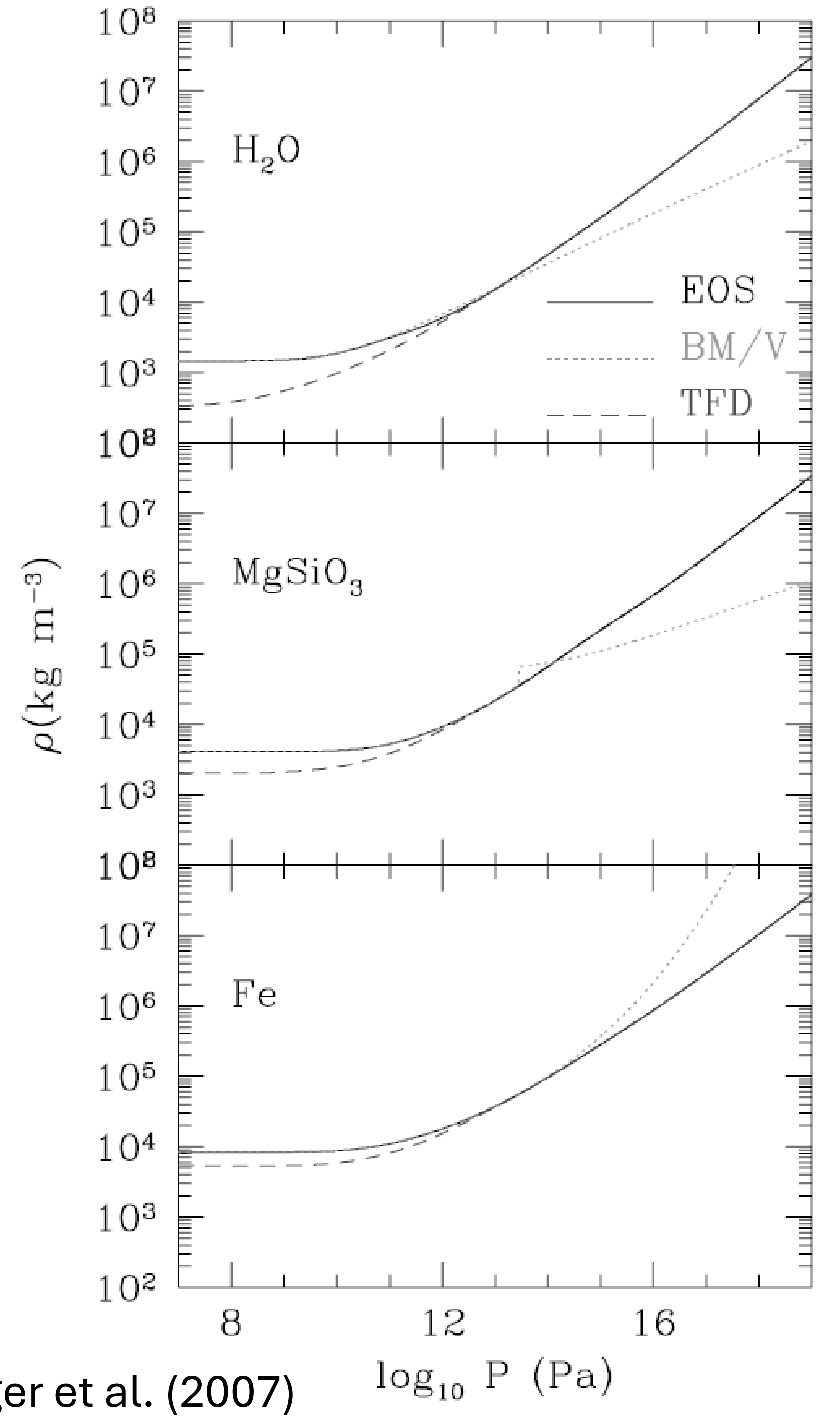
Equations of state

$$P = -2\left(\frac{9}{2}K_{T_0}V_0\right)\frac{1}{2}\left[\left(\frac{V_0}{V}\right)^{\frac{2}{3}} - 1\right]\left\{-\frac{1}{3V_0}\left(\frac{V_0}{V}\right)^{\frac{5}{3}}\right\} \times\left\{1 + \frac{3}{2}(K'_{T_0} - 4)\frac{1}{2}\left[\left(\frac{V_0}{V}\right)^{\frac{2}{3}} - 1\right]\right\}$$

3rd order Birch-Murnaghan EOS

An **equation of state (EOS)** relates how pressure, volume (or density), and temperature change within a given material.

The equation of state depends on **the bulk compressibility** of the material (K_T), which describes how much the volume changes with a change in pressure at constant temperature.

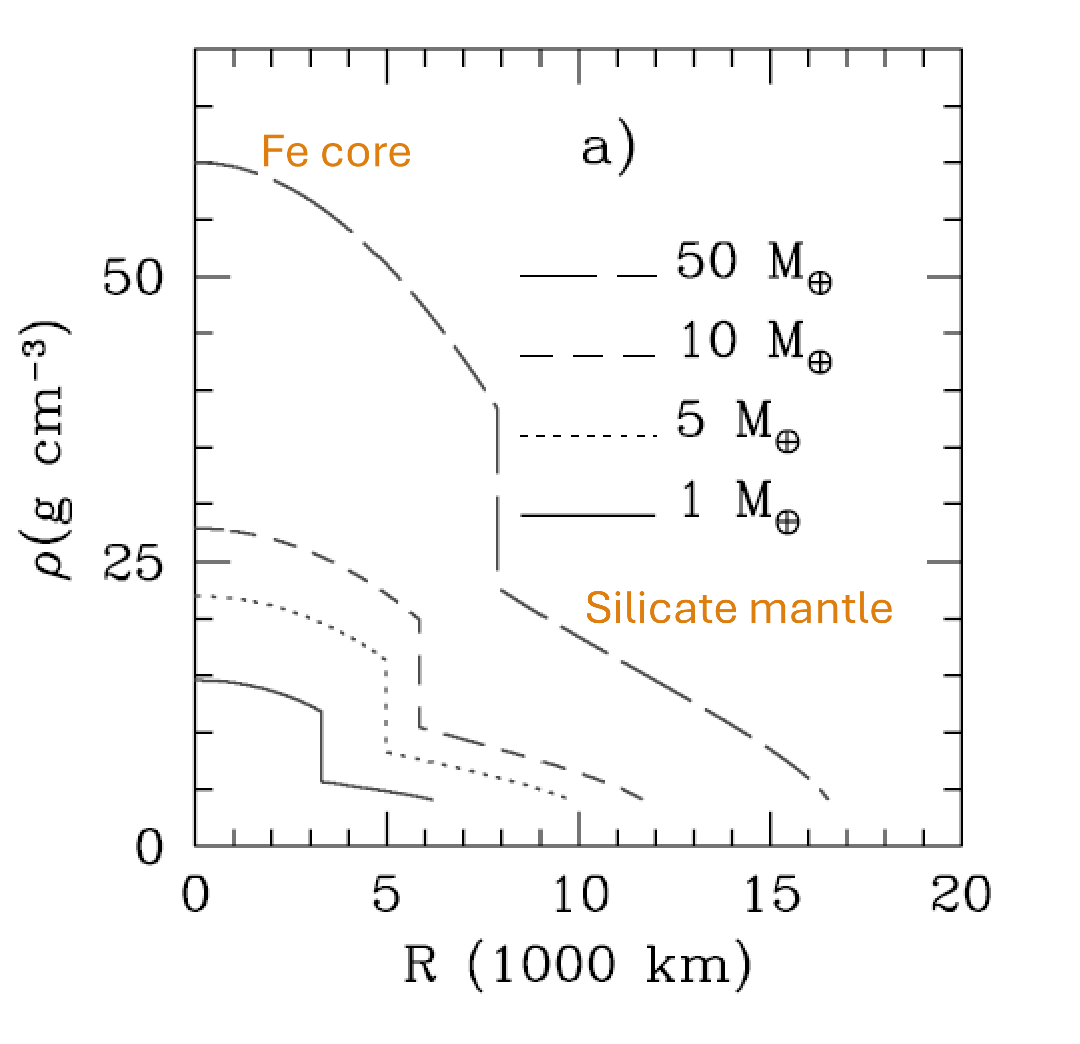


Seager et al. (2007)

Interior Models

An internal structure model integrates the equations for mass, gravity and pressure from the center of the planet to the surface.

They use different EOSs for the different layers of the planet, switching when they reach the appropriate enclosed mass for a given layer.

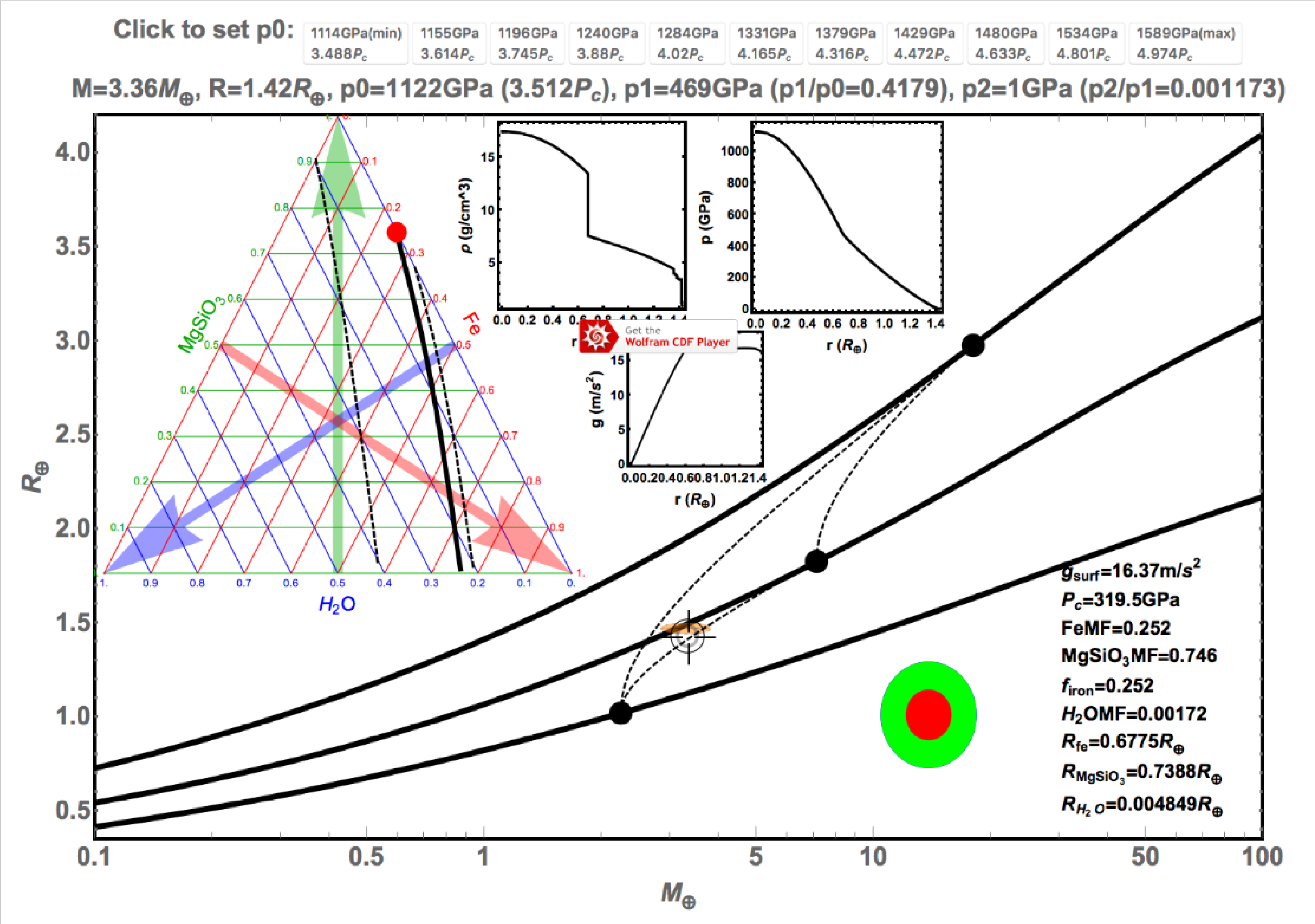


Seager et al. (2007)

Degeneracies

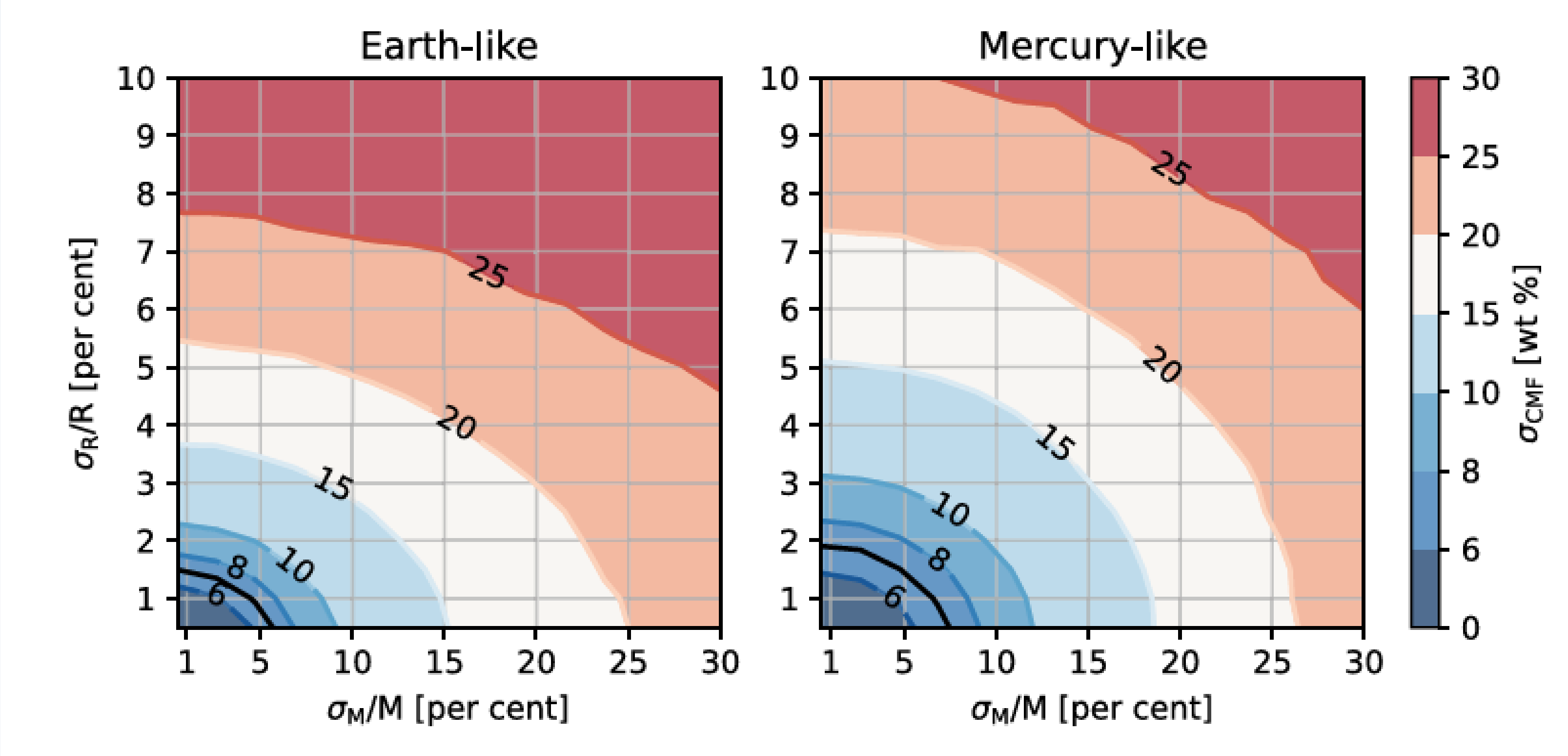
If a planet has more than two layers of different materials, we cannot uniquely solve for the thickness of each layer if all we know is the bulk density. We need additional constraints.

Uncertainties in the mass and radius measurements make the problem even more degenerate.



Li Zeng, astrozeng.com

This figure quantifies some of the degeneracies in composition that mass and radius uncertainties lead to.



Plotnykov & Valencia (2024)

The figures show how uncertainties in planet radius (y-axis) and planet mass (x-axis) translate into uncertainties on the core-mass-fraction (CMF) for planets with either an Earth-like (CMF=0.33) or Mercury-like (CMF = 0.74) core size.

Temperature-effect on radius

Internal structure equations

hydrostatic
$$\frac{\partial P}{\partial r} = -\rho g$$

mass
$$\frac{\partial m}{\partial r} = 4\pi r^2 \rho$$

Energy
$$\frac{\partial L}{\partial r} = 4\pi r^2 \rho \left(\dot{\varepsilon} - t\frac{\partial S}{\partial T} \right)$$

Temperature
$$\frac{\partial T}{\partial r} = \frac{\partial P}{\partial r}\frac{T}{P}\frac{d(lnT)}{d(\ln P)}$$

For planets that have thick gas layers, we have to add two additional equations to solve for the internal structure.

The first is energy transport, and the second is the internal temperature structure.

Temperature has a small effect on rocky planet M/R (~3-5%), but a much larger effect on the structure of gas-dominated layers.

The “radius gap”

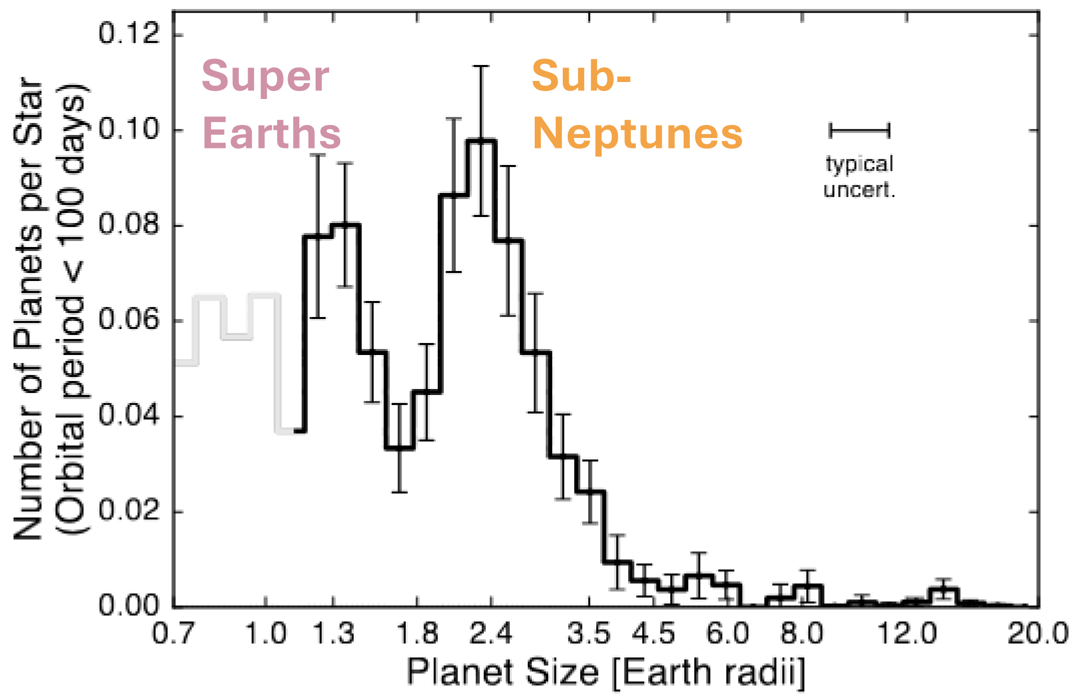


Fig. 5 From Fulton et al. (2017). Occurrence as a function of radius based on *Kepler* data, for planets with orbital periods shorter than 100 days. There is a “valley” in the occurrence rate density between about 1.5-2 $R_{\oplus}$, possibly the result of the erosion of planetary atmospheres by high-energy radiation from the star.

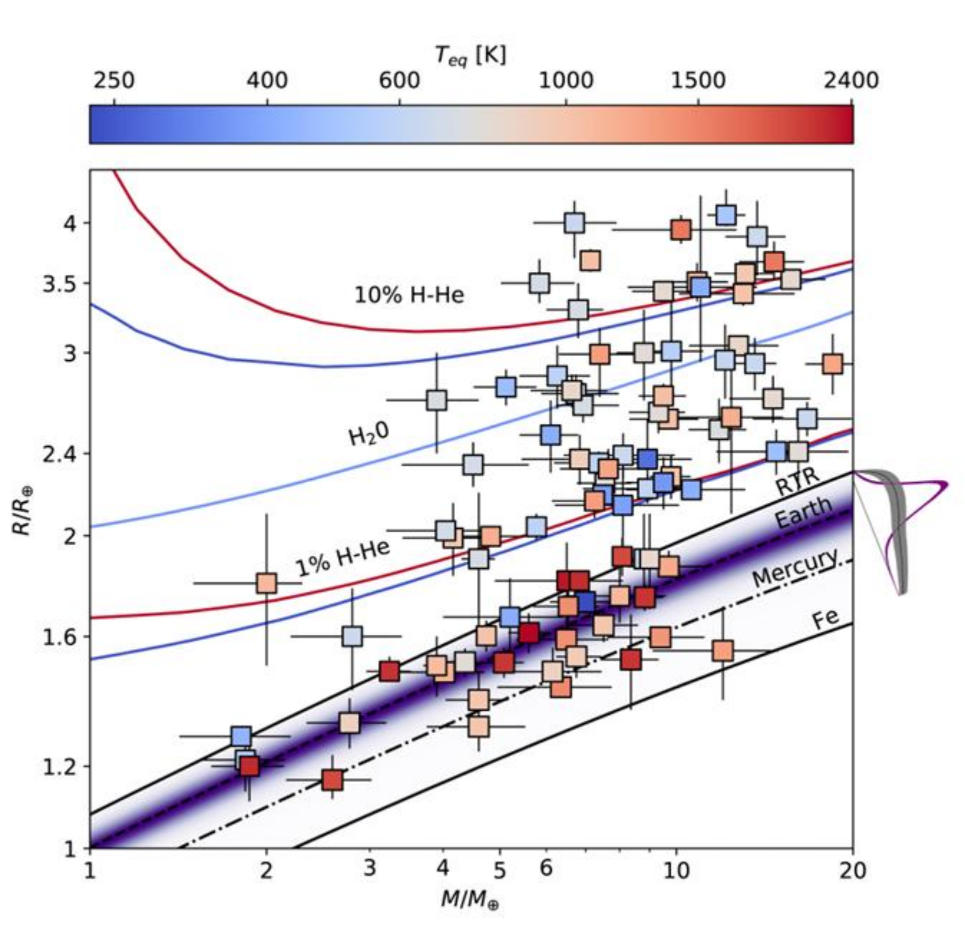
Fulton et al. (2017)

Small planets are the most common, but there seem to be two populations.

These two populations may have started out as a continuous distribution that was sculpted by atmospheric erosion.

We don’t have an example of either of these types of planets in our Solar System.

Exoplanet Mass-Radius Diagram



Nettelmann & Valencia (2020)

Many small planets are consistent with a dominantly rocky composition and internal structures similar to the Earth.

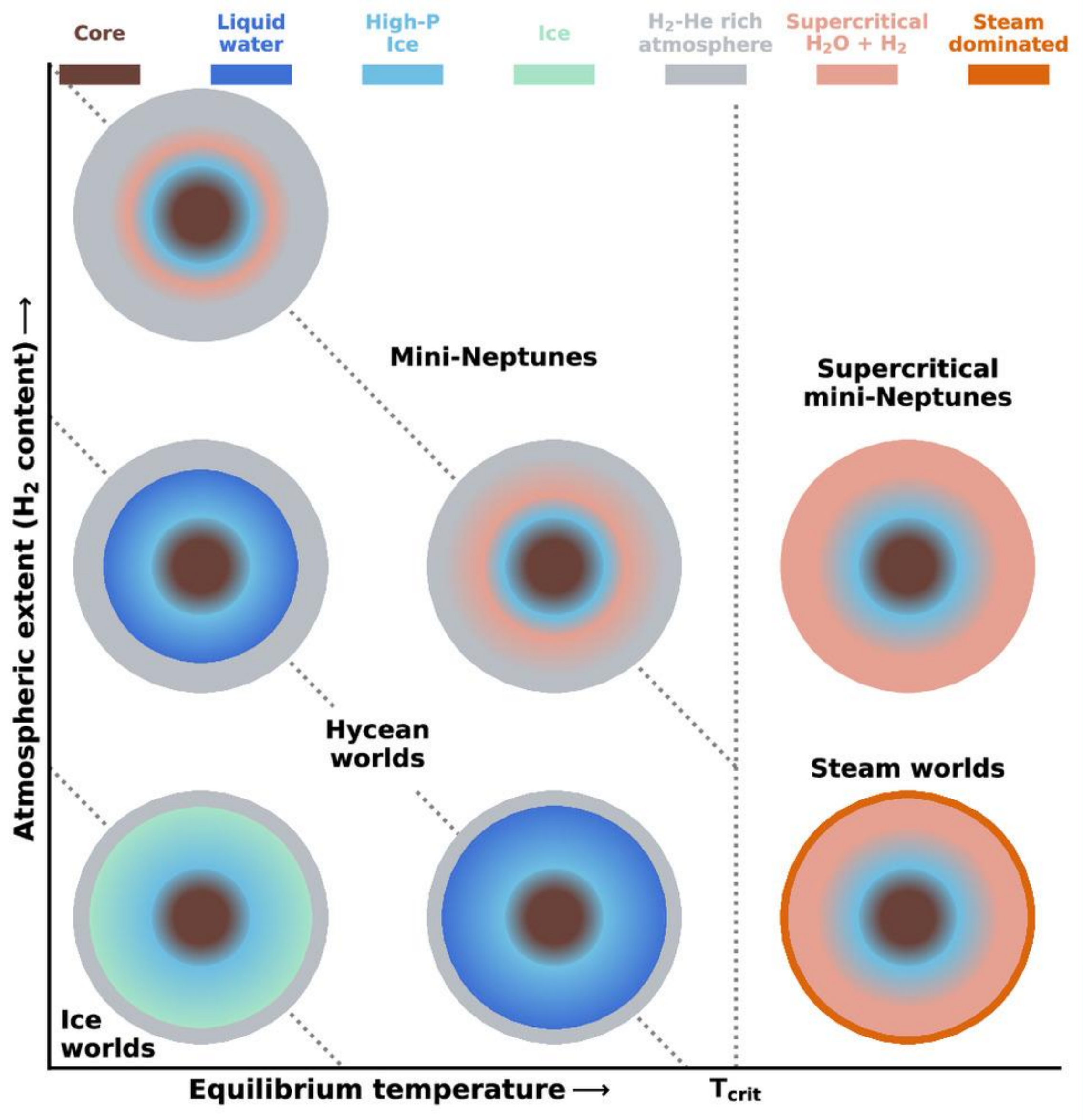
A large group of planets appears to require an additional low density layer: either water or a H-He gas layer. These planets have larger radii and therefore lower densities than the rocky planets.

Sub-Neptune internal structure

Sub-Neptunes are a common type of exoplanet which are missing from the solar System.

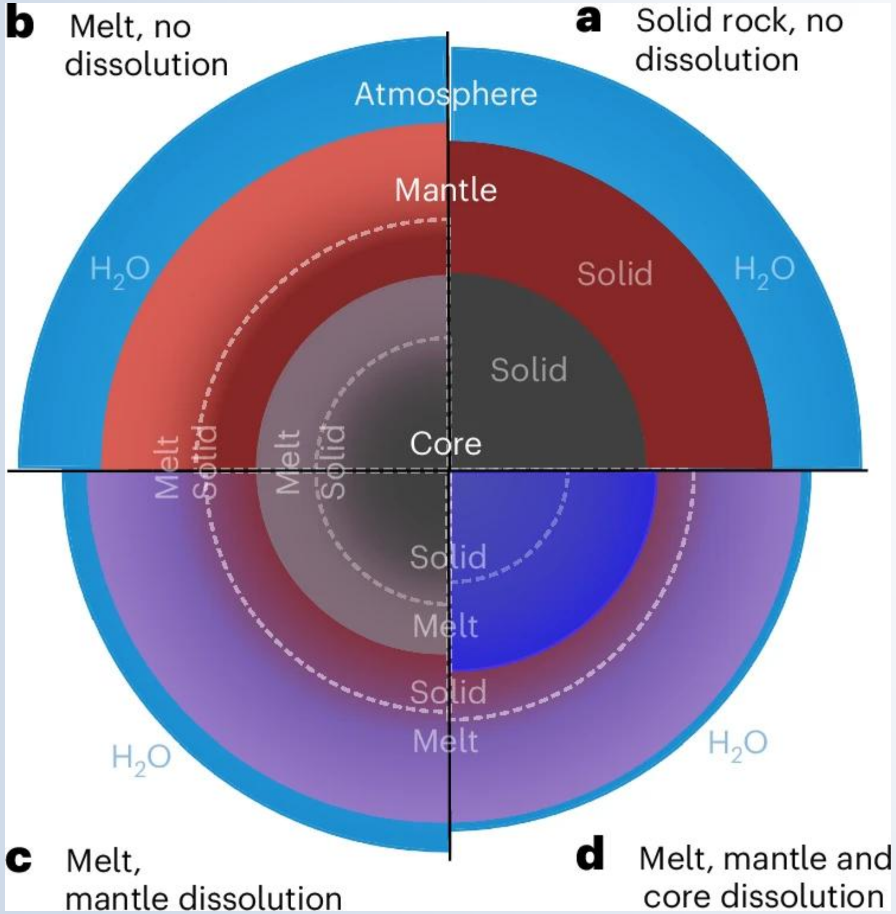
Their internal structure is a puzzle, due to the inherent degeneracies. Their low density could be explained by different fractions of either a water or H_2 dominated atmosphere on top of a rock+metal core. Or they could have significant ice/ocean layers beneath a thick atmosphere.

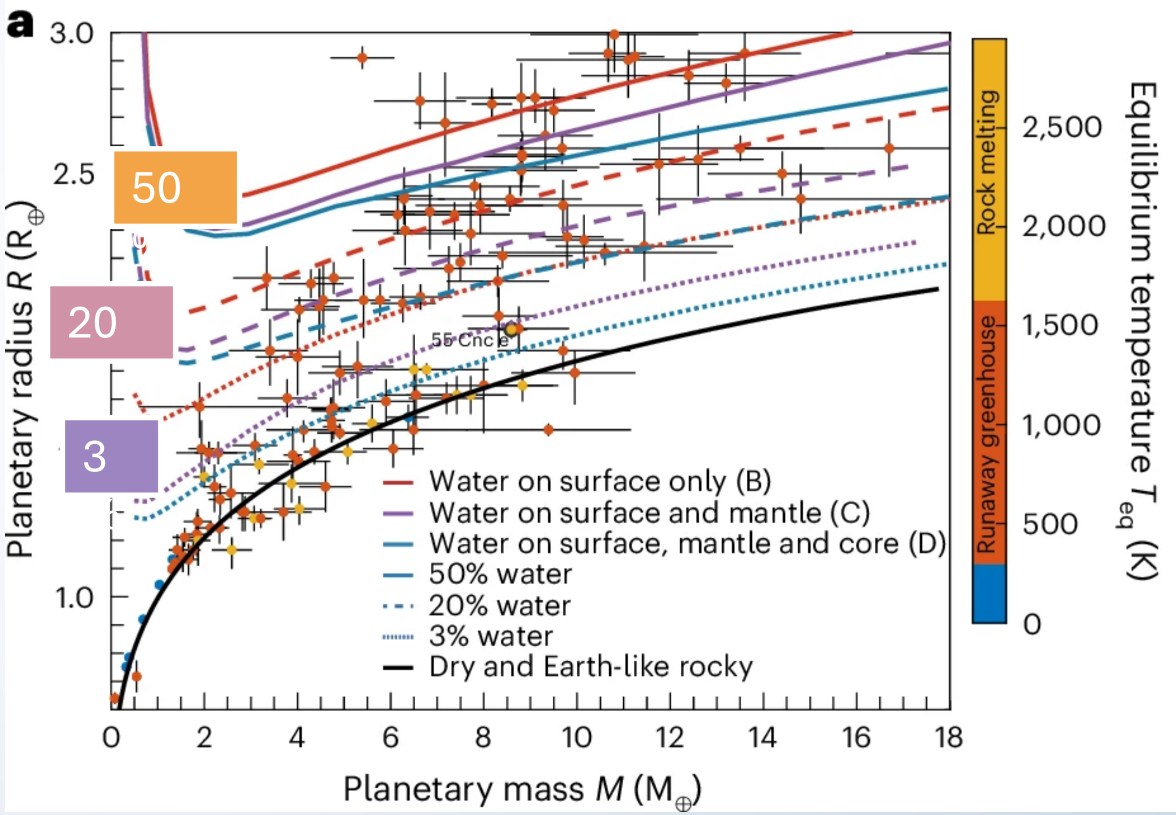
Atmospheric spectroscopy may be able to help distinguish between the H_2 vs. H_2O-dominated atmosphere models.



Madhusudhan et al. 2025

Water in super-Earth and sub-Neptune interiors





Luo et al. (2024)

Recap

- Small planets are made of rocks + metals (+ gas?)
- Volatiles can be delivered by gas or by solids (e.g. meteorites) during planet formation
  - Timing of delivery matters -> can determine where volatiles end up: core, mantle or atmosphere
- Exoplanet mass-radius measurements determine bulk density, but internal structure models have multiple solutions