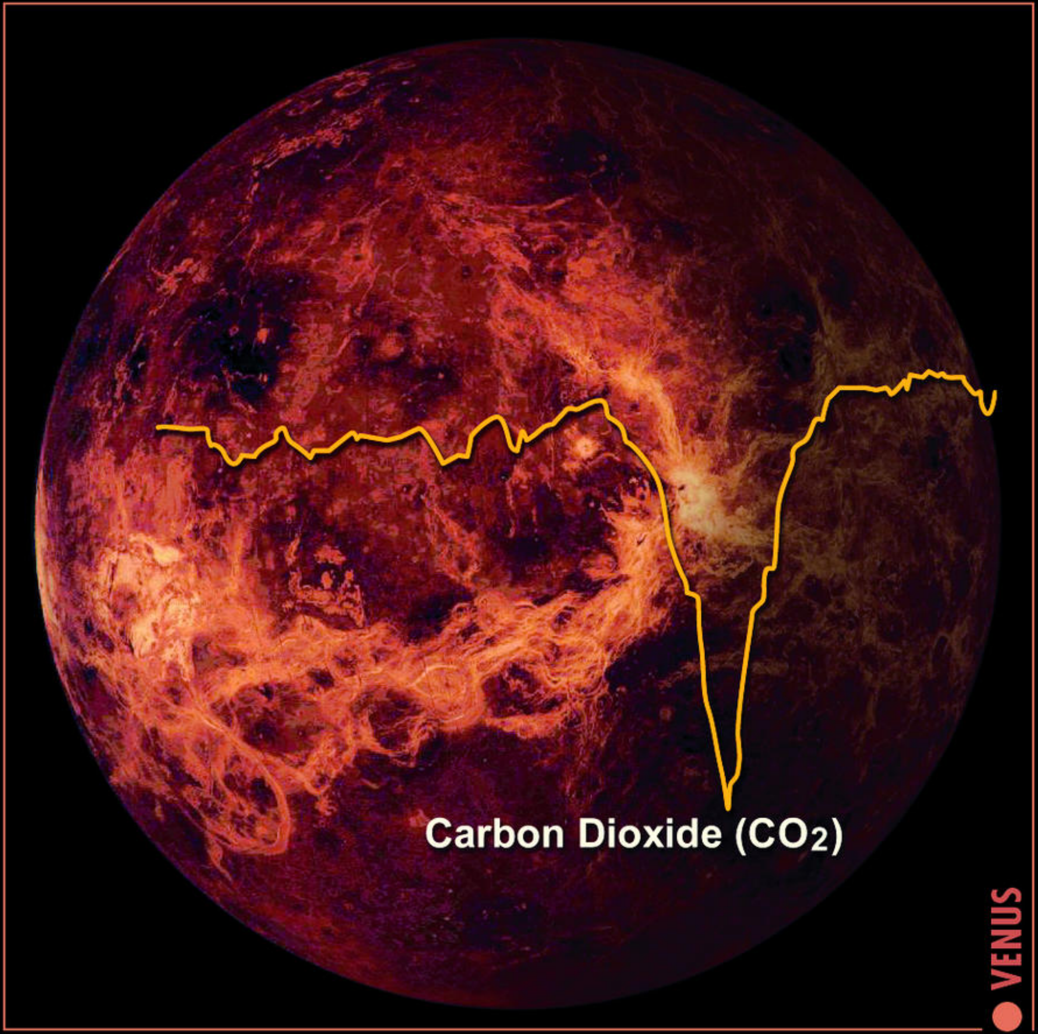
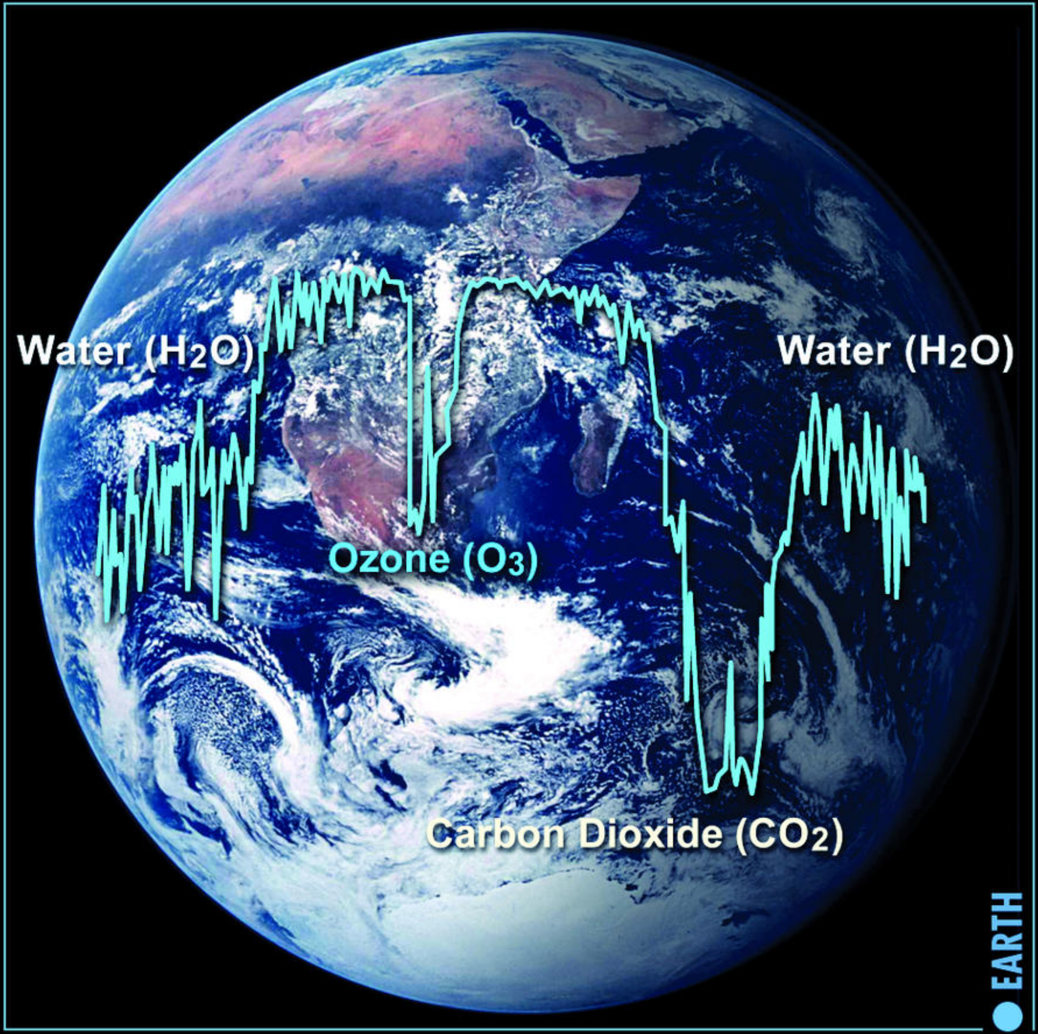
Planetary Habitability





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Topics

- Lecture 1 – Introduction
- Lecture 2 – Habitability Factors
- Lecture 3 - Stars
- Lecture 4 – Planetary Atmospheres
- Lecture 5 – Planetary Interiors
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- Lecture 9 – Earth as a Living Planet
- Lecture 10 – Mars
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- Lecture 17 – Milankovitch Cycles
- Lecture 18 – Geological Cycles
- Lecture 19 – The Next Steps
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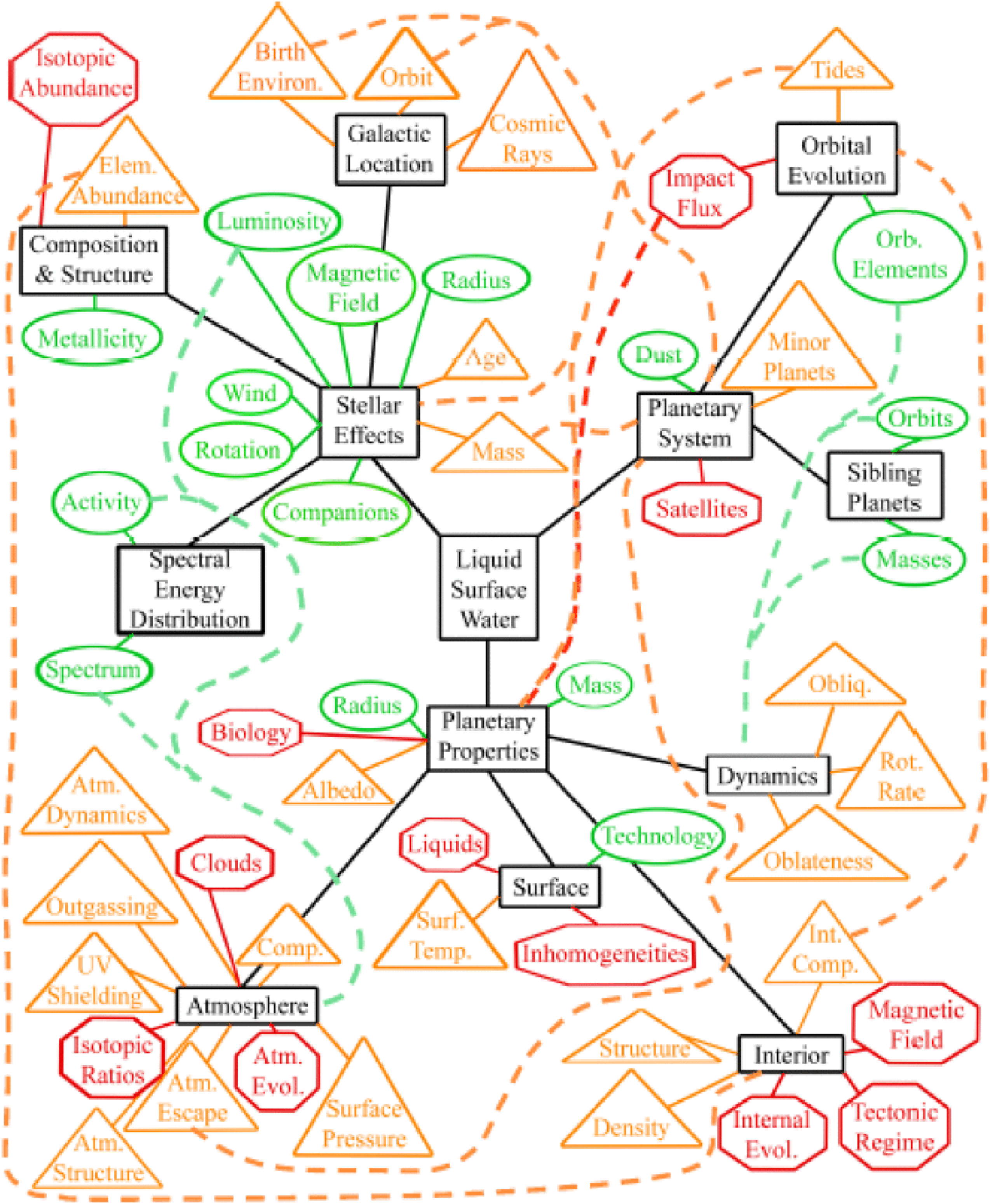
Isotopic Abundance
Birth Environ.
Orbit
Cosmic Rays
Galactic Location
Tides
Orbital Evolution
Impact Flux
Elem. Abundance
Composition & Structure
Luminosity
Magnetic Field
Radius
Metallicity
Age
Orb. Elements
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Mass
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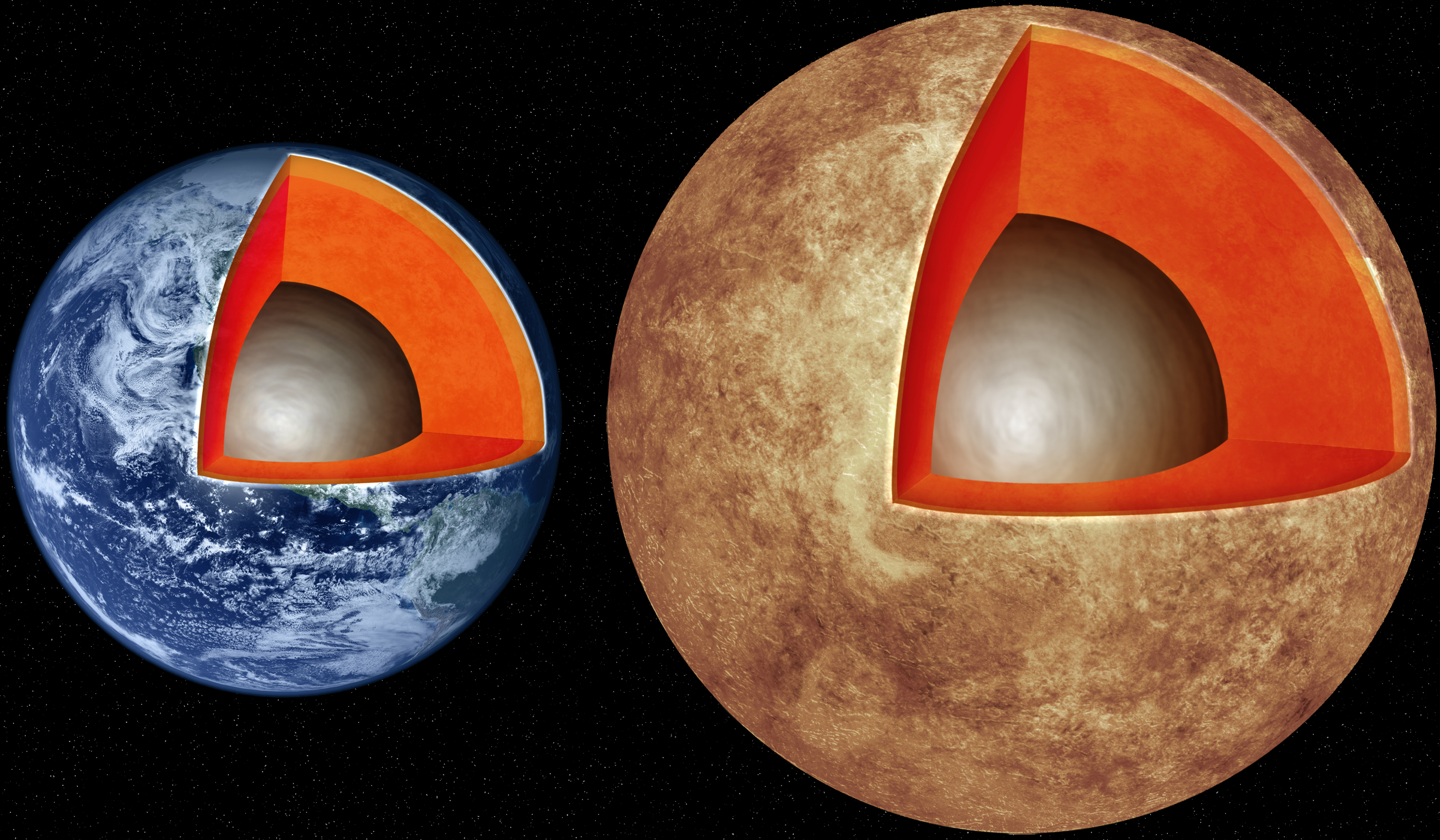
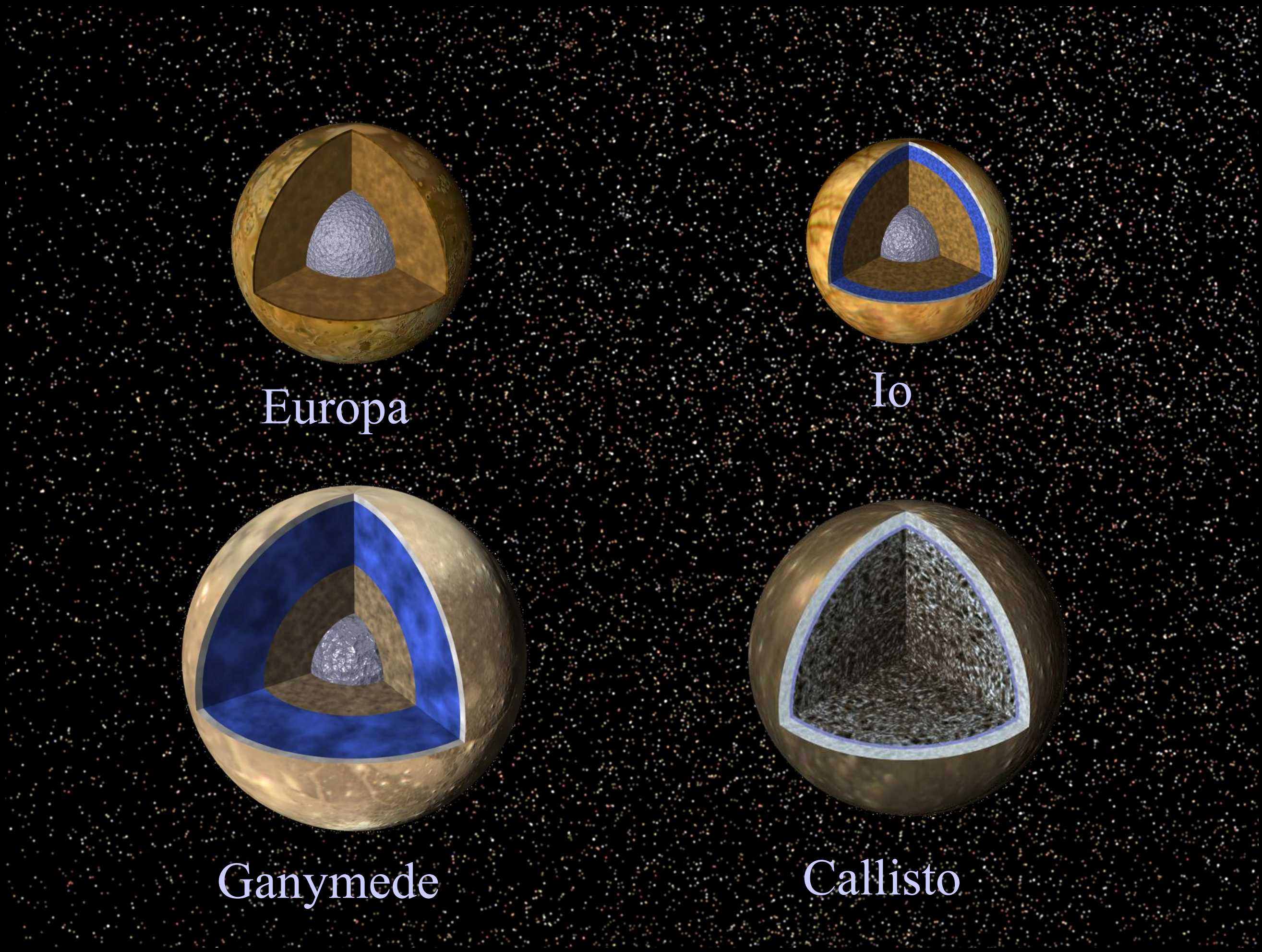
Planetary Properties
Rot. Rate
Albedo
Dynamics
Atm. Dynamics
Technology
Liquids
Oblateness
Clouds
Surface
Outgassing
Comp.
Surf. Temp.
Int. Comp.
UV Shielding
Inhomogeneities
Atmosphere
Magnetic Field
Structure
Interior
Isotopic Ratios
Atm. Evol.
Atm. Escape
Surface Pressure
Density
Internal Evol.
Tectonic Regime
Atm. Structure

Components of Planetary Interiors



- Core – contains metals (eg., iron, nickel).
- Mantle – intermediate layer with rocky (semi-molten) material.
- Crust – lowest-density rocks (surface).

Components of Planetary Interiors



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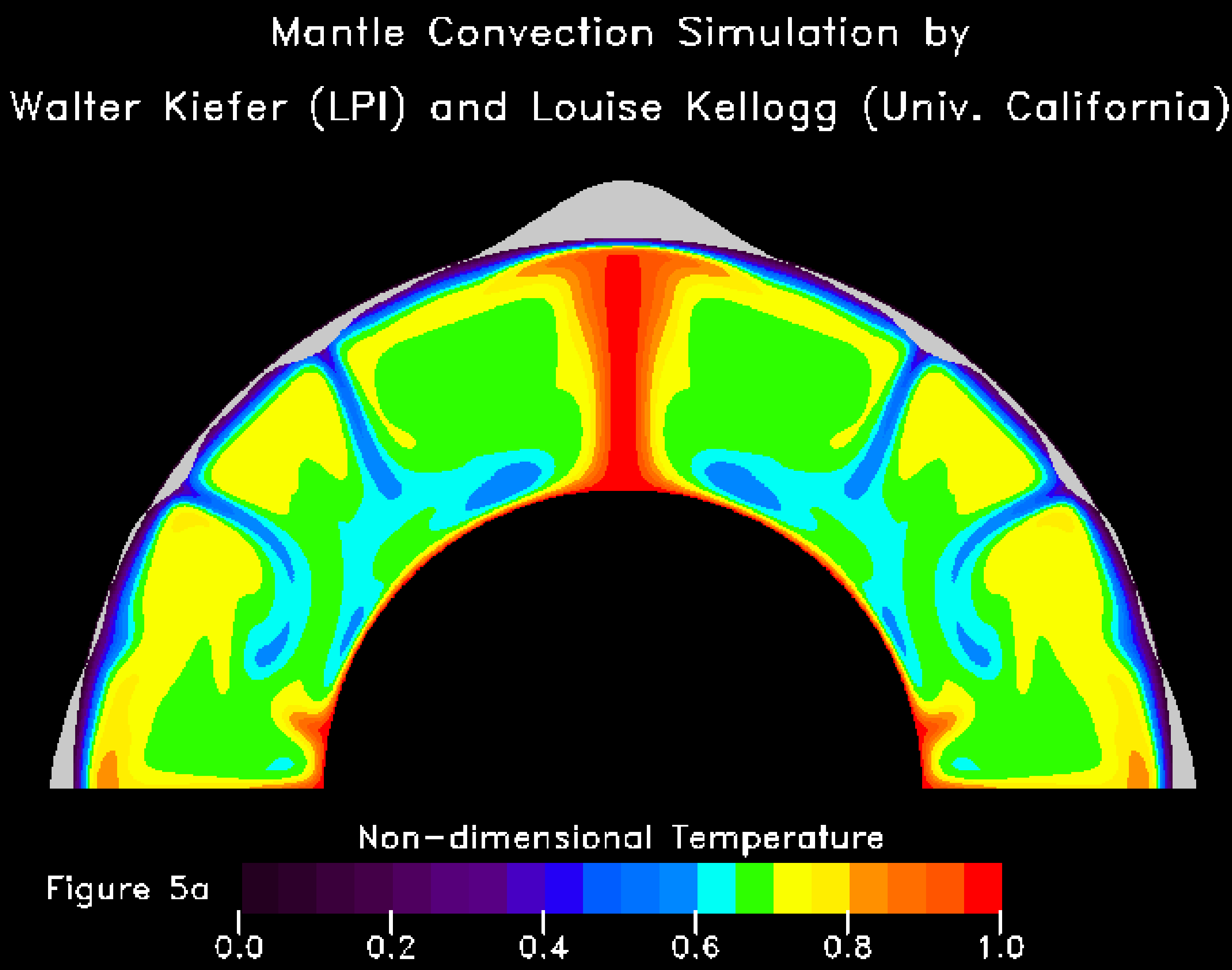
Planetary Interiors

Components of Planetary Interiors

All planets start in a molten state after the formation process. Differentiation is caused by gravity separating different materials where higher densities sink towards the center. This results in the formation of three distinct density zones within a terrestrial planet: core, mantle, and crust.

Convection transfers thermel energy from the interior to the crust via expansion and contraction of material. The process requires a temperature gradient (ΔT) between the core and the crust.

Components of Planetary Interiors



Modeling Planetary Interiors

Key observations yield a planet mass, size, and therefore an estimate for the average density. This can be used directly to derive first-order estimates of a planet's composition. A density $\rho < 1 g/cm^3$ implies an icy and/or porous object, whilst $\rho \approx 3 g/cm^3$ suggests a rocky object. Earth's density is $\sim 5.5 g/cm^3$.

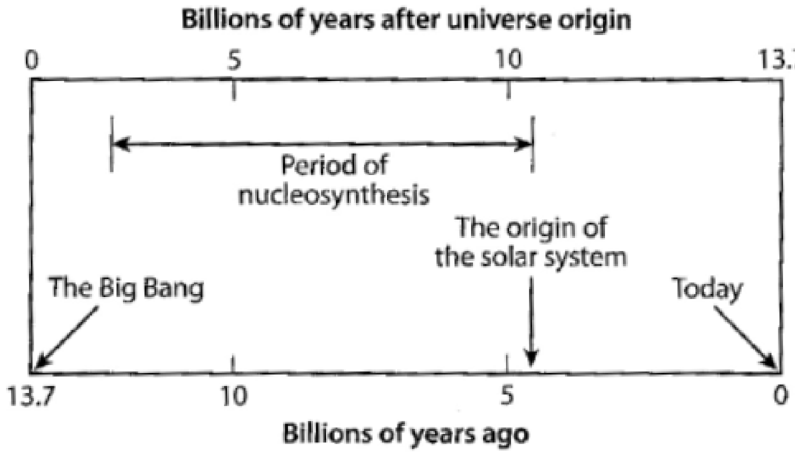
Bulk composition can be described using only a limited number of elements. For the Earth, O, Fe, Mg, and Si explain 95% of the mass. If Ni, S, Al, and Ca are added then 99.9% of the mass is taken into account.

TABLE 1. Mass fraction of the major elements contained in EH enstatite chondrites (values from *Javoy*, 1995).

Element	Enstatite Model Mass Fraction
O	30.28
Fe	33.39
Si	19.23
Mg	12.21
Total	95.11
Ni	2.02
Ca	1.01
Al	0.93
S	0.85
Total	99.92

This example shows that 8 elements account for more than 99.9% of the total mass.

Element Cooking: Abundance of Elements



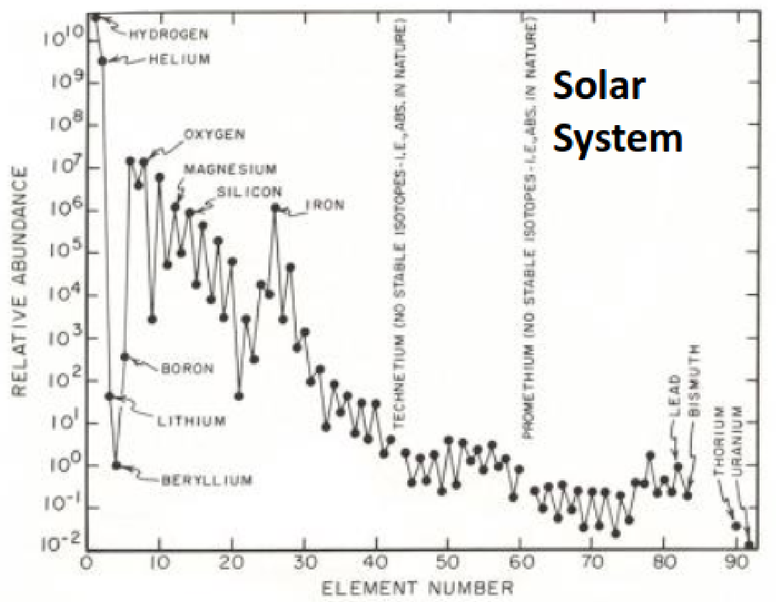


Figure 2-1. Relative abundances of the elements in our Sun.

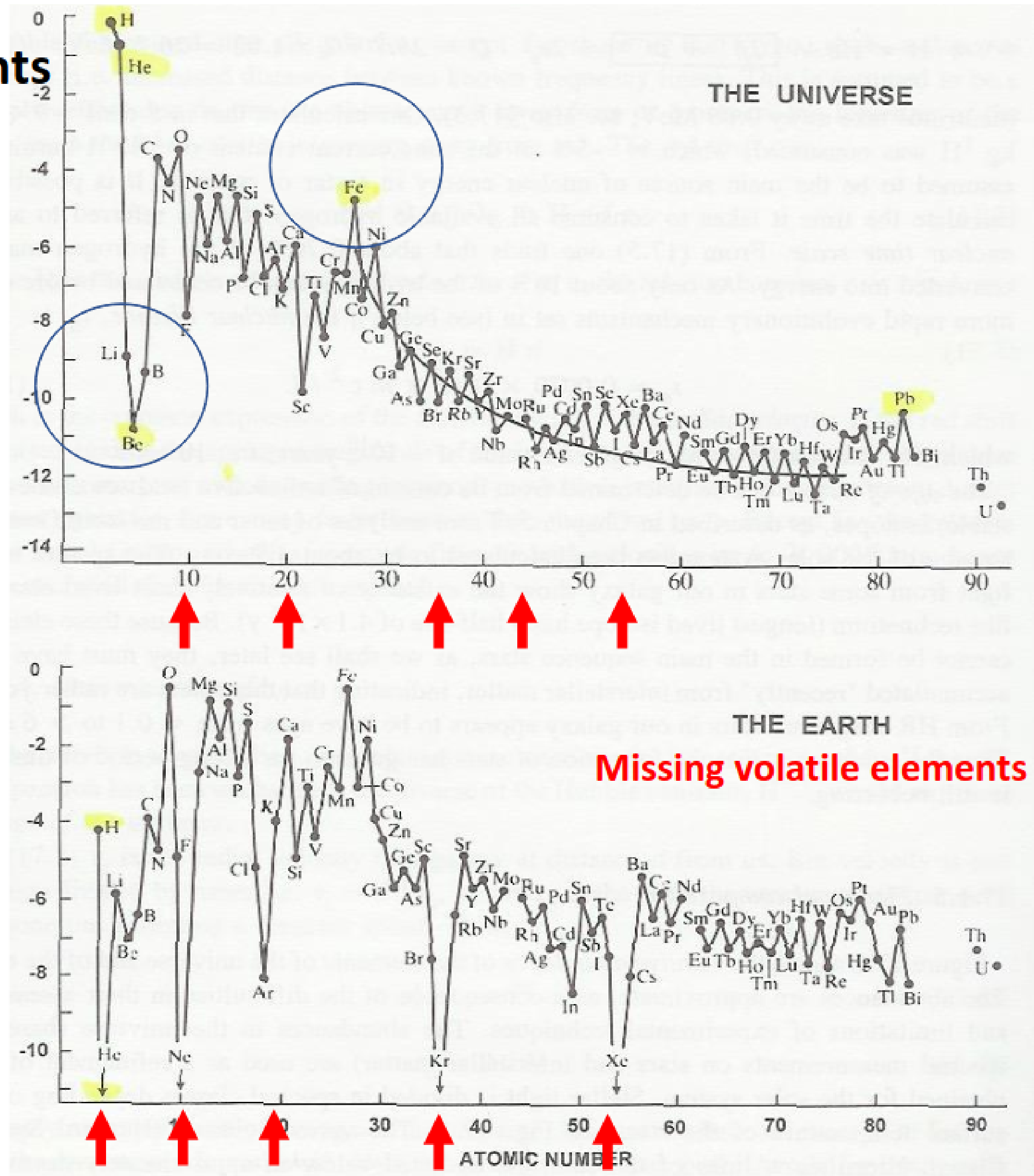
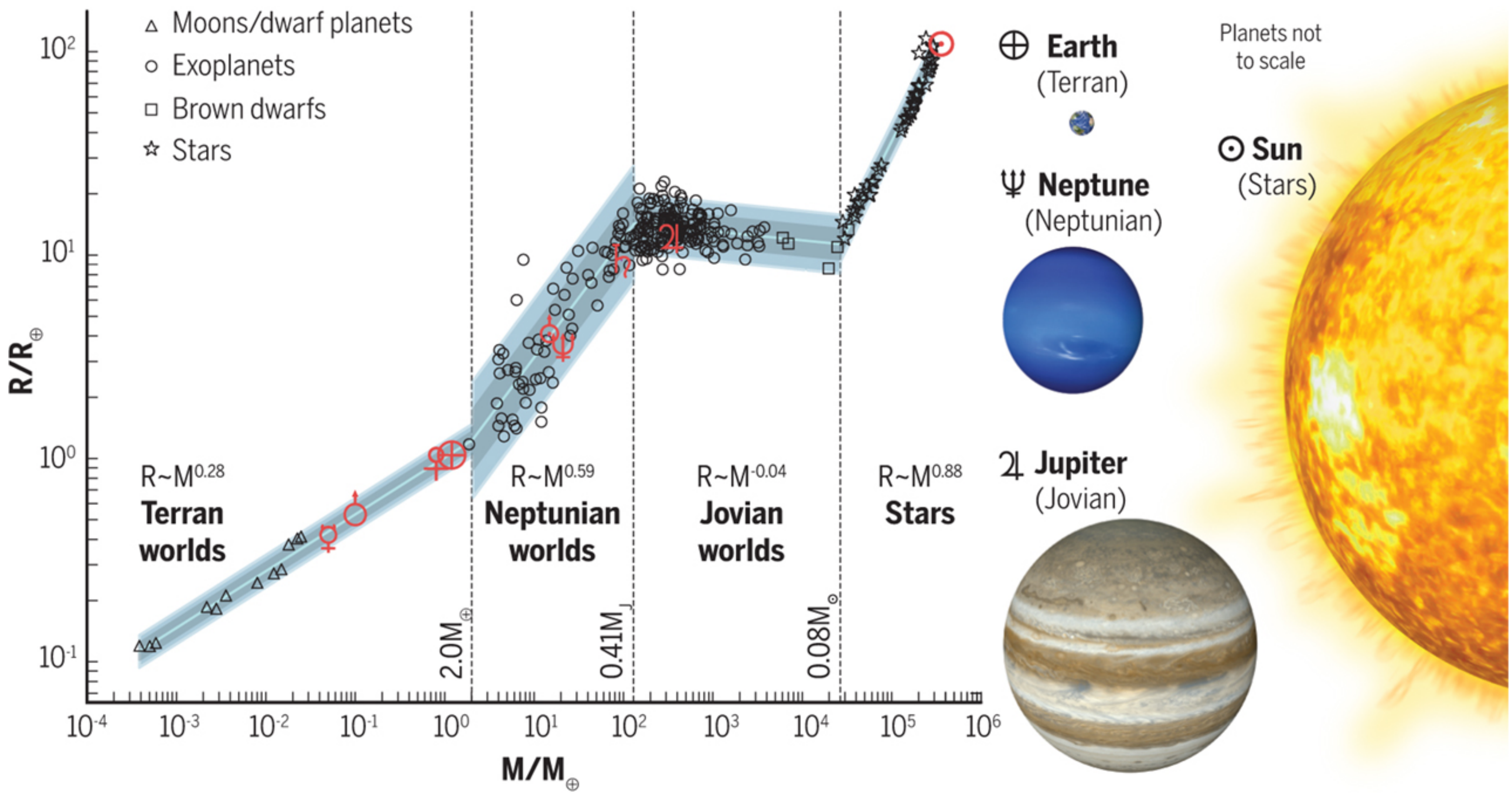


FIG. 17.2. Relative abundances of the elements in the universe and the earth. (From Cox.)

Equations for the Interior

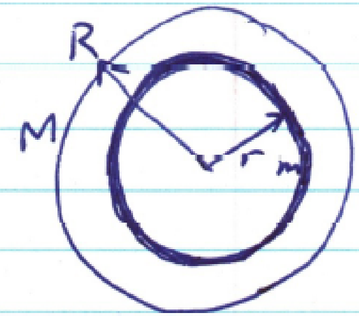
The relation between the mass of a planet (M) and its radius (R) is derived from four equations:

1. Mass conservation
2. Energy transport
3. Hydrostatic equilibrium
4. Equation of state



Chen & Kipping, 2017, ApJ, 834, 17

For conservation of mass, consider a shell of width dr, mass dm, and density $\rho(r)$. The mass interior to r is:



$$dm = 4\pi r^2 \rho(r)\, dr$$

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

and the total mass is

$$M = 4\pi \int_0^R r^2 \rho(r)\, dr$$

<u>Hydrostatic equilibrium</u> is the balance between gravity and pressure that determines the relationship between temperature, pressure, and density.

The change in pressure dP across width dr is:

$$dP = -g\,\rho(r)\, dr \qquad \text{where} \quad g = \frac{Gm}{r^2}$$

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

Boundary conditions imply $P = 0$ when $r = R$. For constant density, the pressure at the center is given by:

$$P_c = \frac{3GM^2}{8\pi R^4}$$

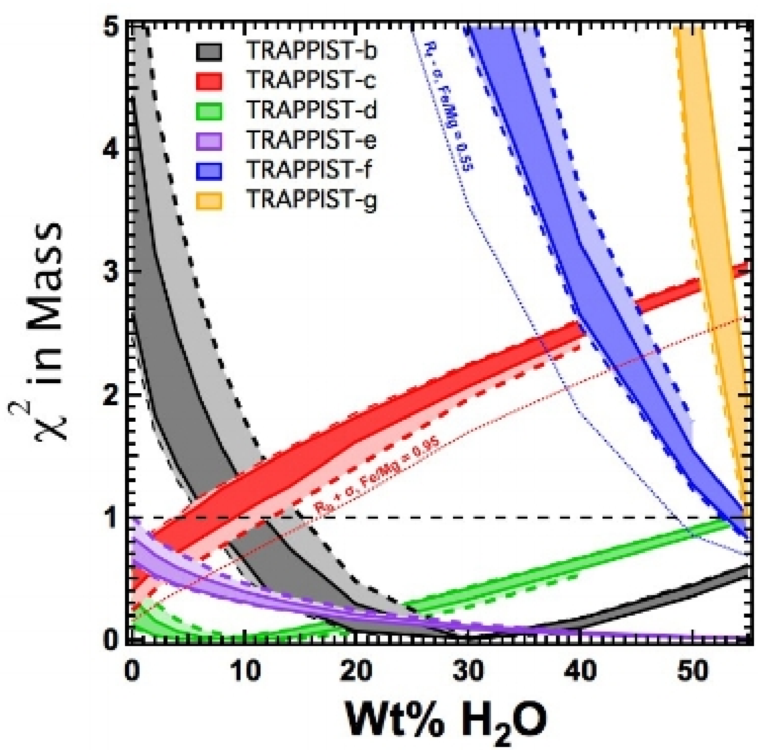
Equation of State

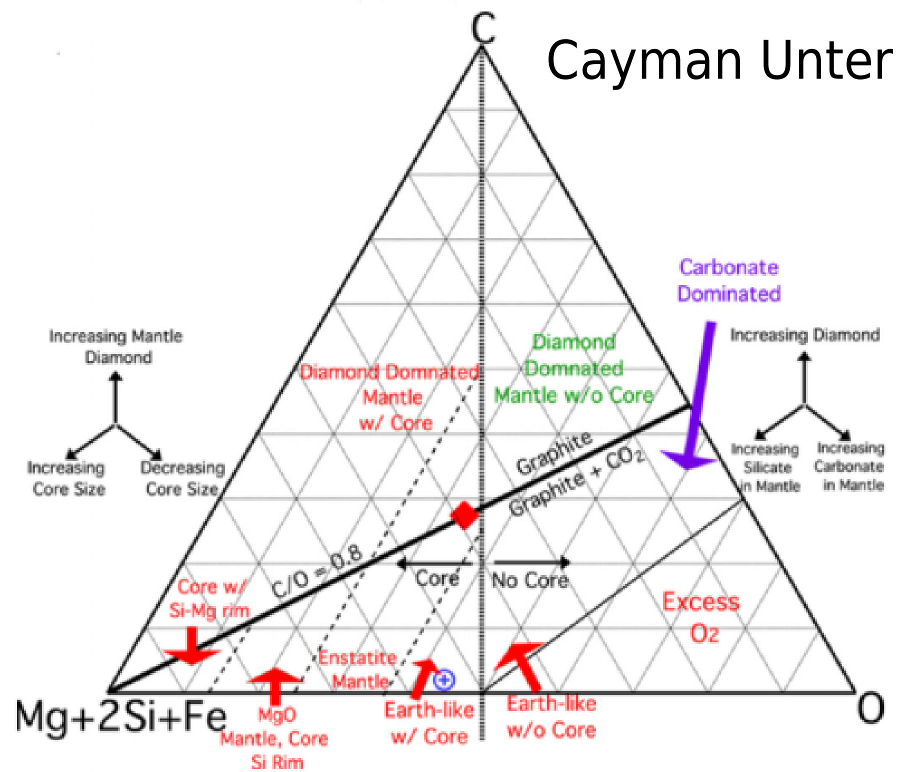
We need to consider the phases of materials in a planet as a function of temperature and pressure. The equation of state is an expression that relates pressure, density, temperature, and composition: $P = P(\rho, T, f)$.

For atmospheres at pressures below ~50 bar we can use the ideal gas law, but at high temperatures and pressures this equation is not adequate. Over limited pressures, the equation of state can usually be approximated by a polytrope:

$$P = K_{po}\,\rho^{1+n_{po}} \qquad K_{po} = \text{polytropic constant}, \quad n_{po} = \text{polytropic index}$$

When $P \to 0$, $1/n_{po} \approx \infty$. For high pressure, $1/n_{po} = \frac{3}{2}$ and $P \propto \rho^{5/3}$.

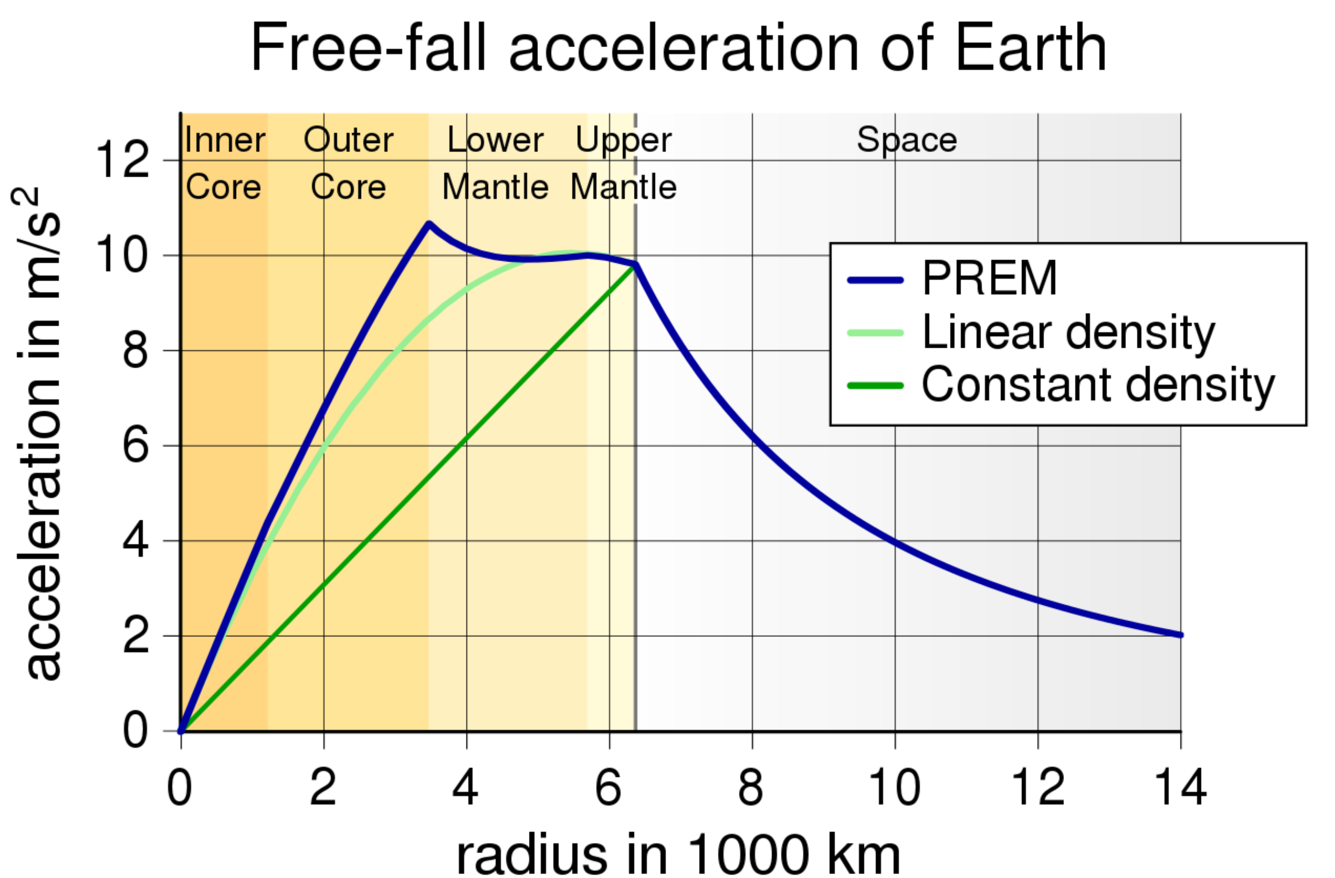




Cayman Unterborn

Gravity field: contains information on the internal density structure and can be determined by tracking orbits of spacecraft. This is particularly important for measuring the moment of inertia of the planet. Note, this is difficult for Venus due to the slow rotation rate.

Sources and losses of **internal heat** include: gravitational (mostly applicable to giant planets as a source of ongoing heat), radioactive decay (major source for terrestrial planets), and tidal and ohmic heat (dissipation of an induced electric current).



Application to Exoplanets

Significant focus is on establishing a robust mass-radius relationship for exoplanets. This can be written in the form:

$$\frac{M_p}{M_\oplus} = a\left(\frac{R_p}{R_\oplus}\right)^b$$

For $M \gtrsim 100 M_\oplus$ ($0.3 M_J$), the radii are more or less $1 R_J = 11.2 R_\oplus$ due to interior compression that occurs at high gravities.

The M-R relationship from Kepler planets was found to be:

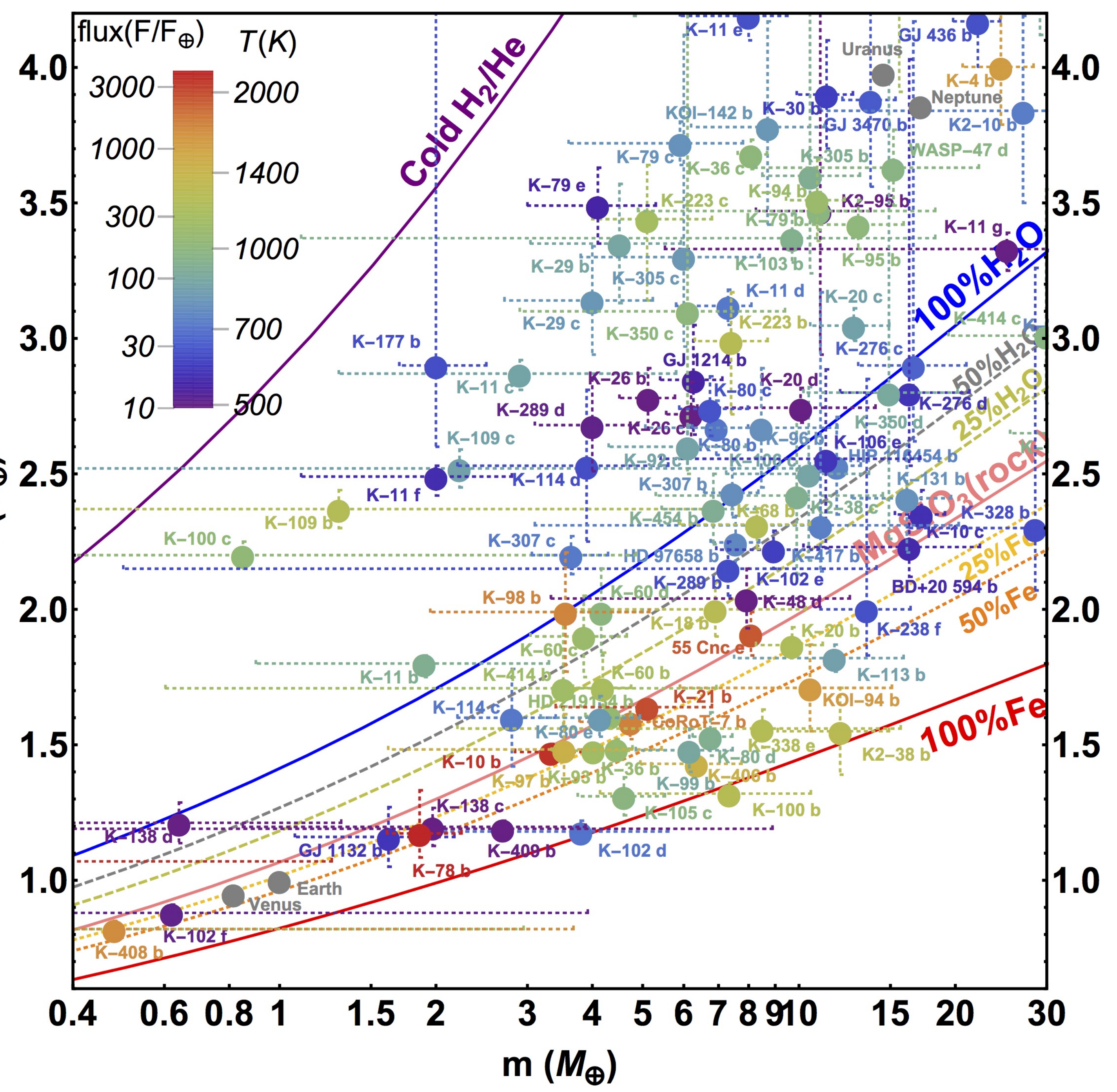
$$\frac{M_p}{M_\oplus} = 2.69\left(\frac{R_p}{R_\oplus}\right)^{0.93} \qquad 1.5 \leq \frac{R_p}{R_\oplus} < 4$$

$$\rho_p = 2.43 + 3.39\left(\frac{R_p}{R_\oplus}\right) \text{ g/cm}^3 \qquad \frac{R_p}{R_\oplus} < 1.5$$

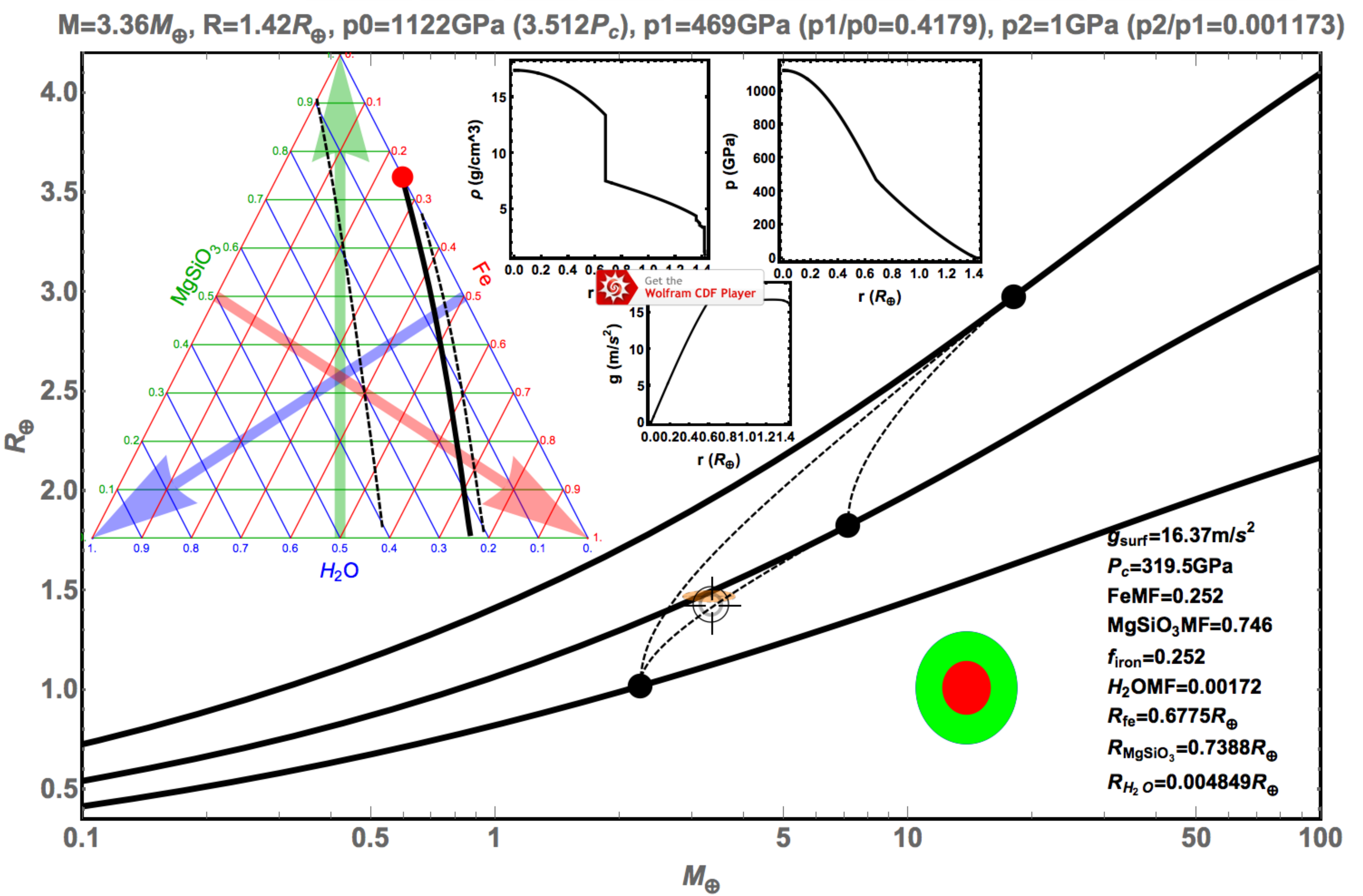
Weiss & Marcy, 2014, ApJ, 783, L6.

Masses & radii are often combined with compositional models using ternary diagrams, where three variables sum to a constant.

Note that, when either the radius or the mass are unknown, you're fitting the density as a free parameter.



Zeng et al., 2019, PNAS, 116, 9723



Zeng et al., 2019, PNAS, 116, 9723