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The diversity of exoplanet bulk compositions: Modelling structure and evolution of (exo)planets

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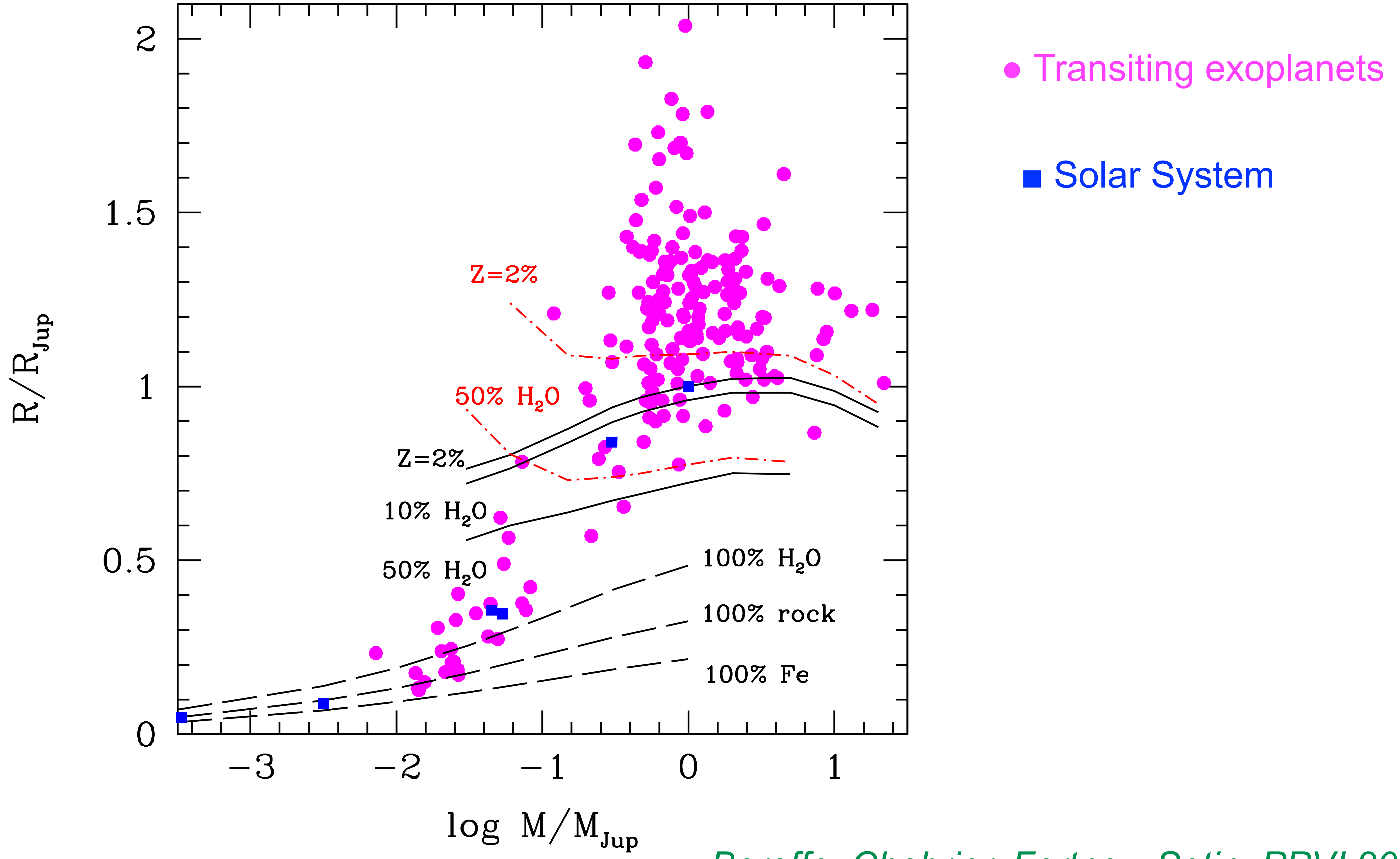
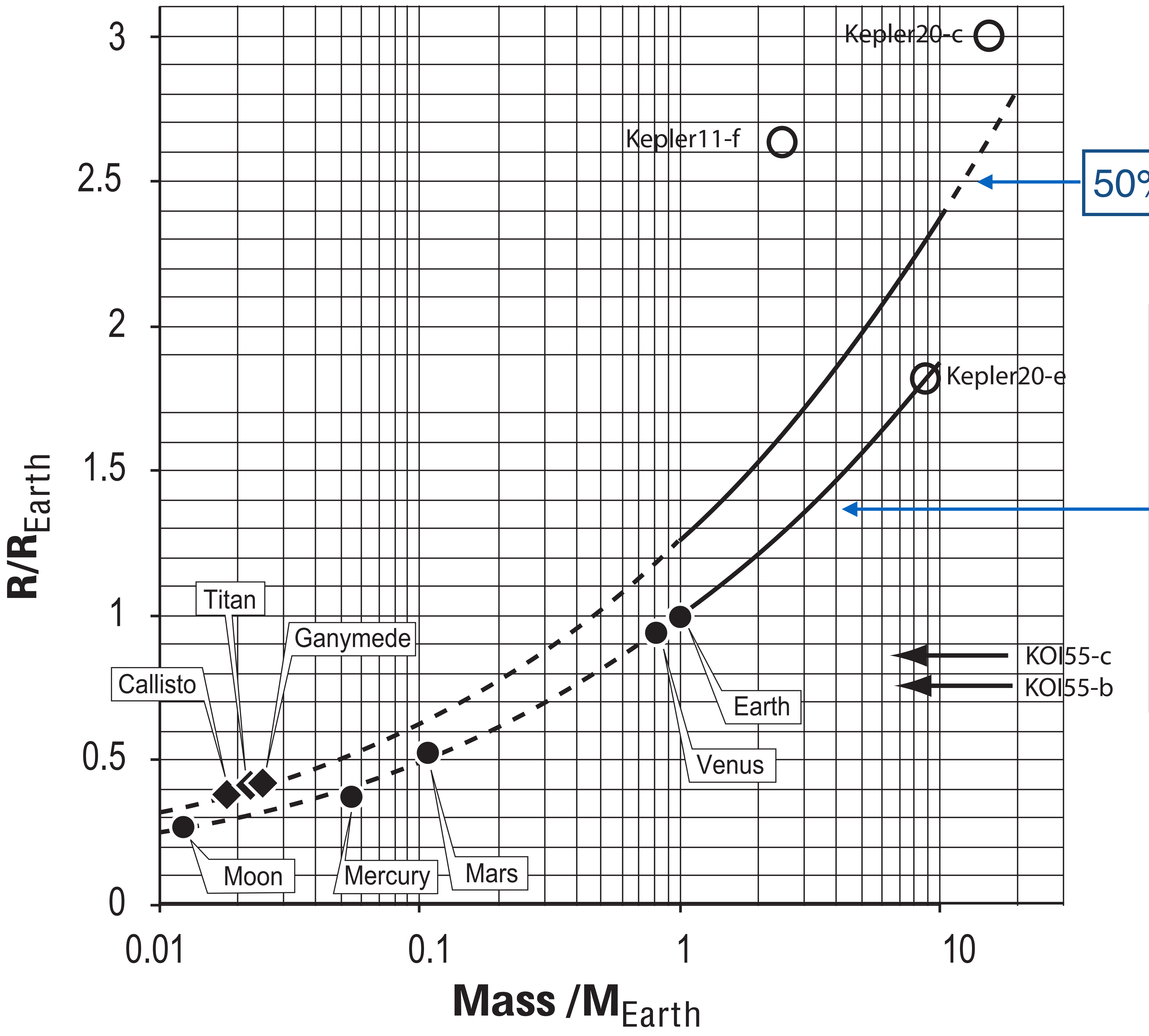
<u>The fact:</u> Huge diversity of bulk compositions according to the mass-radius relationship of known planets



Baraffe, Chabrier, Fortney, Sotin, PPVI 2013

In the realm of rocky planets: diversity seems to be also there



50% of H_2O

Terrestrial planets

$R \propto M^{0.274}$

(bulk composition fixed by amount of H_2O and ratios of Fe/Si and Mg/Si)

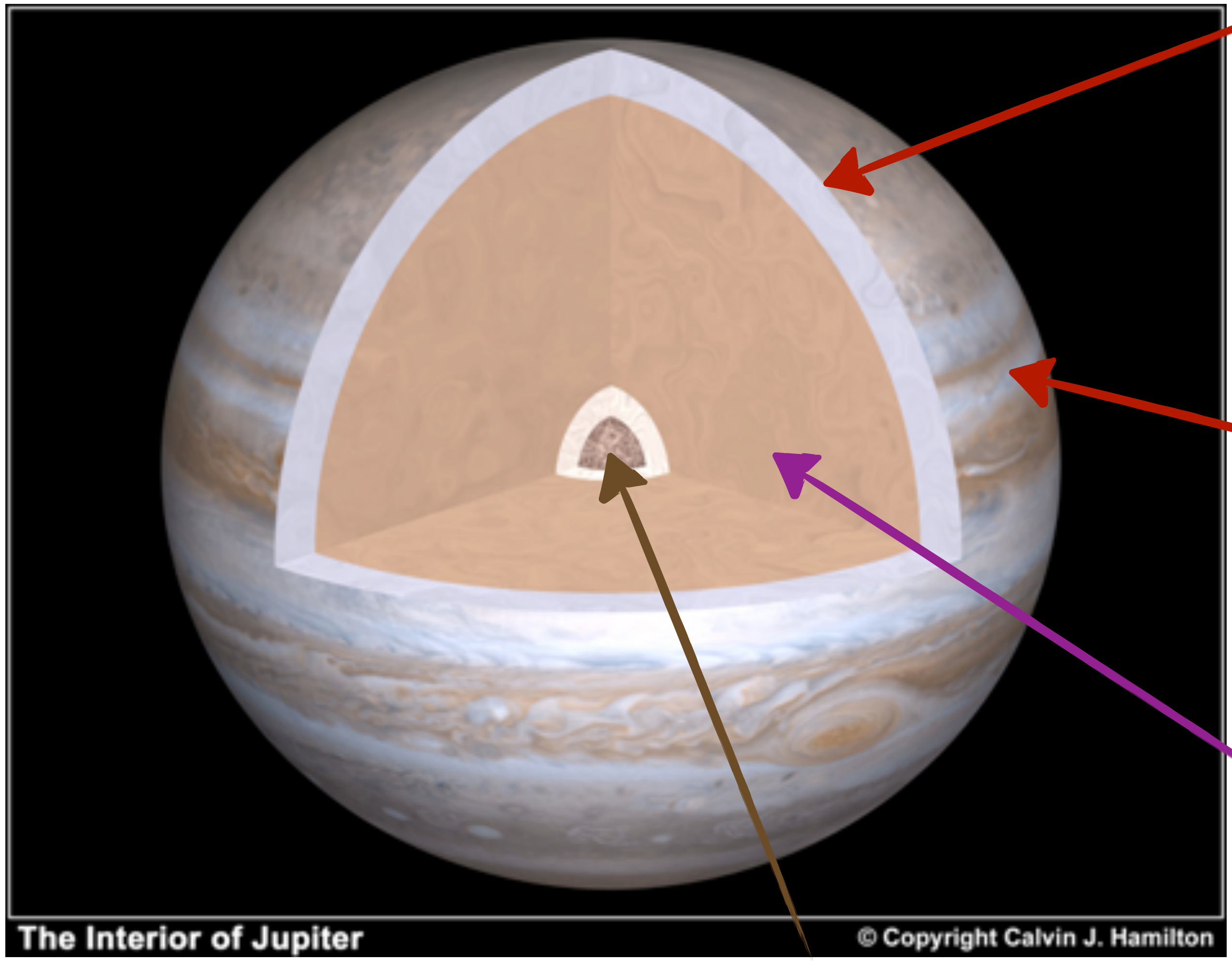
Sotin et al. 2007; Grasset et al. 2009

The big question: Are theoretical/numerical tools ready to interpret the observed diversity?

I) Some lessons from our solar system planets

II) Exoplanets: Interior structure and evolutionary models

The building blocks for modelling (exo)planets



The Interior of Jupiter

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Atmospheres (1D static, irradiated/non irradiated)
Boundary conditions for interior

Atmospheric dynamics (GCM)
Heating processes; Ohmic dissipation; Mixing

H/He envelope

Equation of State for H/He/Z
Evolutionary models
Tidal processes

Rocky/icy core

«Ices»(H_2O, CH_4, NH_3), silicates ($MgSiO_4$, $MgSiO_3$,…), Iron (Fe)

☛ Earth-like: internal dynamics (plate tectonics,volcanism, melting)

I) **Some lessons from our solar system planets**

II) Exoplanets: Interior structure and evolutionary models:

What do we learn from our own planets

Jupiter:

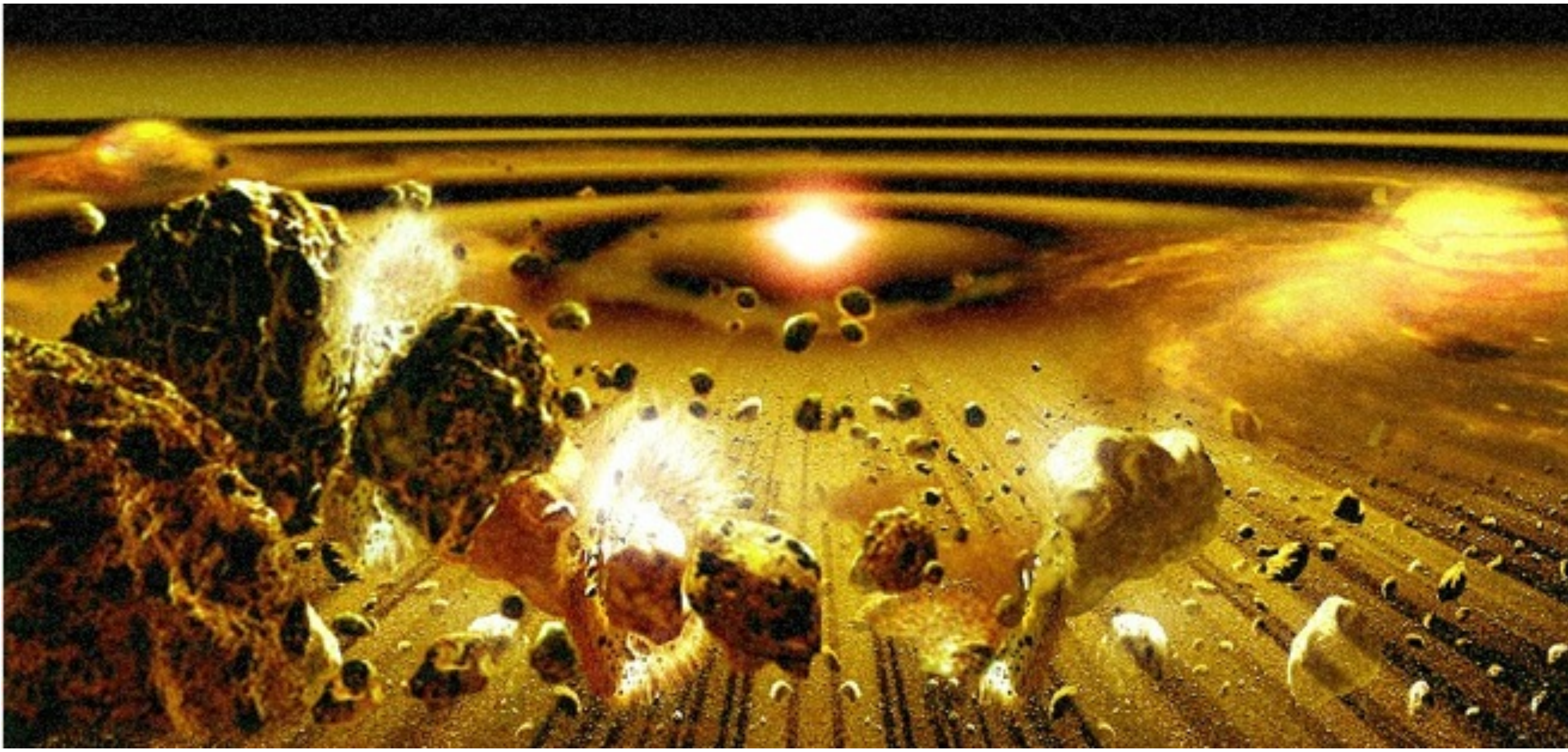
- Atmosphere depleted in He ($Y = 0.234$)
- Enrichment of Ar, Kr, Xe, C, N, S by a factor 2-4 over solar

Saturn:

- He depleted, but more uncertain ($Y = 0.18-0.25$)
- C ($CH4$) and N (NH_3) significantly enriched

Metal enrichment expected because of the formation in a “dirty” proto-planetary disk

➔



The standard picture for our giant planets:

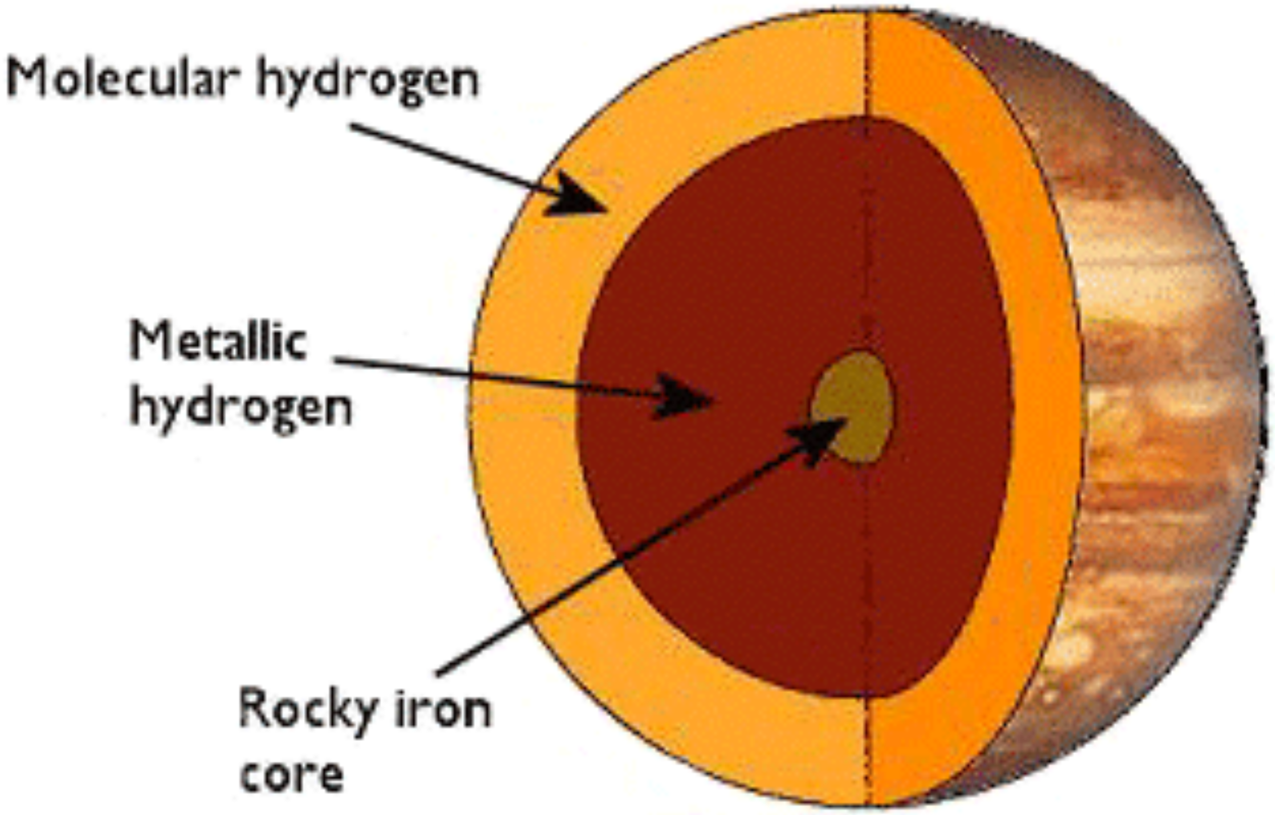
- Internal structure models commonly based on the "three-layer" picture

Layer 1: outer envelope with H_2, depleted He and Z_1
Layer 2: inner envelope with metallic H + He + Z_2
Layer 3: central core (rock/water)

Different composition between layer 1 and layer2 :

- First order transition metallic H - molecular H_2 (P ~ 1-2 Mbar) *Saumon & Chabrier*
- Phase separation between H and He (He droplets rain out) *Smolugovsky 1973; Salpeter 1973*

- Layers fully convective (i.e adiabatic)

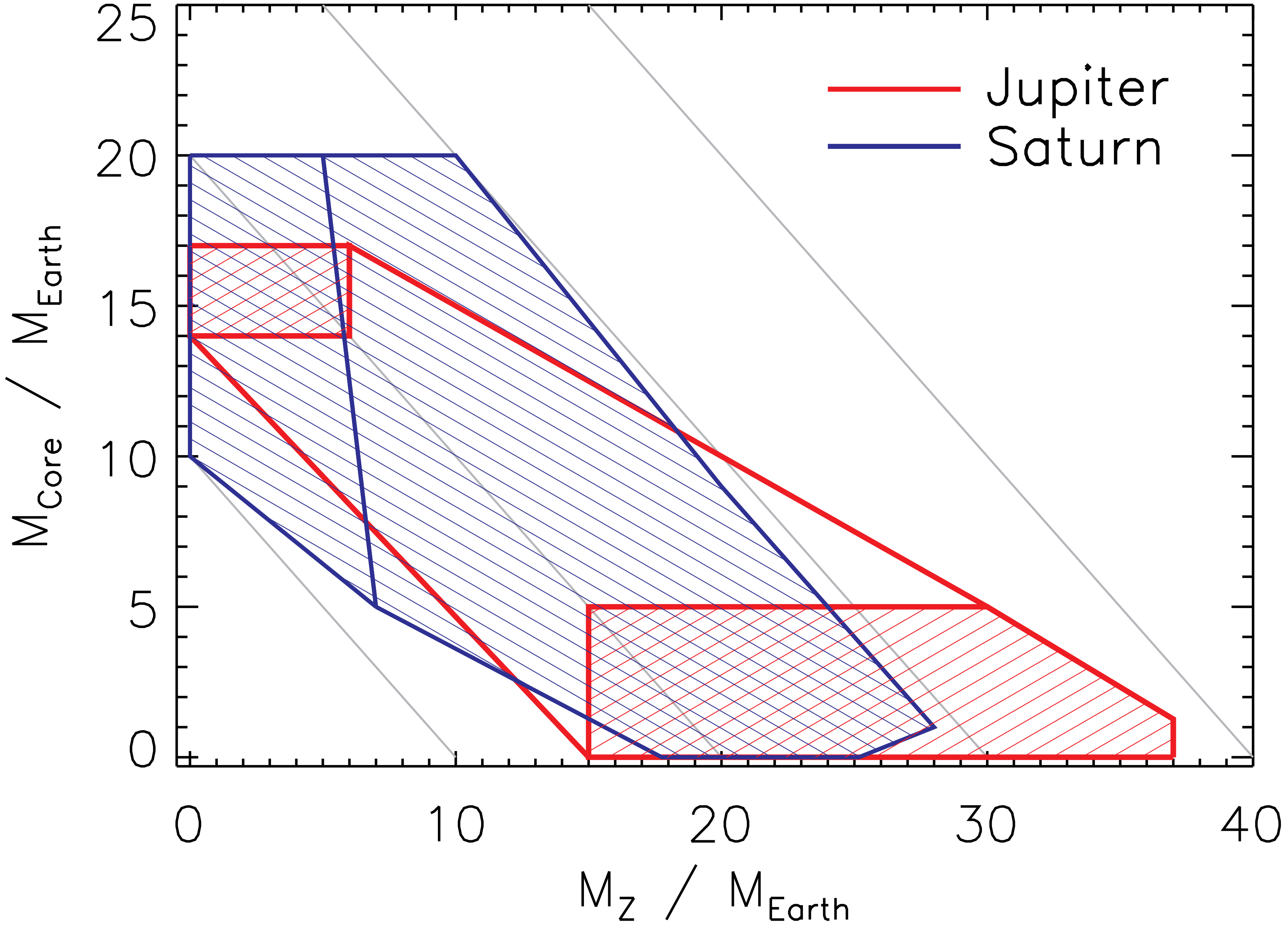


Compositions from various modern "adiabatic" models:

Based on improved EOS (first-principle) and two- or three-layers

(Militzer et al. 2008; Fortney & Nettelmann 2010; Helled & Guillot 2013)

Metals in the core versus metals in the envelope



(see PPVI review Baraffe et al. 2014)

Global enhancement in metals (compared to solar):

- Jupiter: factor ~ 3 to 8 (if solar composition ⇒ 4.5 $M_\oplus$ of metals)
- Saturn: factor ~ 12 to 21 (if solar composition ⇒ 1.3 $M_\oplus$ of metals)

An illustration of current uncertainties from EOS:

☛ Predictions based on first-principle EOS for H/He (continuous molecular to metallic H transition) and **a 2-layer** model
(core of rock/H_2O and isentropic mantle of H/He)

⇒ Find a core for Jupiter of **M_{core} = 14-18 $M_{\oplus}$** *(Militzer et al. 2008)*

⇒ Previous idea of a **small core** for Jupiter **challenged** by those recent calculations

☛ **Strong disagreement** with another study also based on ab initio EOS calculations for H, He and H_2O *(Nettelmann et al. 2008)*
based on a **3-layer** model: core of rocks/ice + inner isentropic envelop (Metallic H, He, Z_{met}) + outer isentropic envelope (molecular H_2, He, Zmol)

⇒ Find a core for Jupiter of **M_{core} = 0-7 $M_{\oplus}$**

Key takeaway: **better understanding of H/H_2 transition and of H-He demixing from first-principle EOSs is key to predict more accurate giant planet structures.**

Adiabatic interior (fully convective): revisiting the standard picture?

Reduced heat transport in planetary interiors:

(Stevenson & Salpeter 1977; Stevenson 1979; Chabrier & Baraffe 2007)

- **Idea:** reduced heat transport in planetary interior due to **molecular weight gradient**

Presence of ∇_μ ---> Stabilizing effect against convection

$\nabla_{ad} > \nabla_T + \nabla_\mu \chi_\mu / \chi_T$ (*Ledoux criterion*)

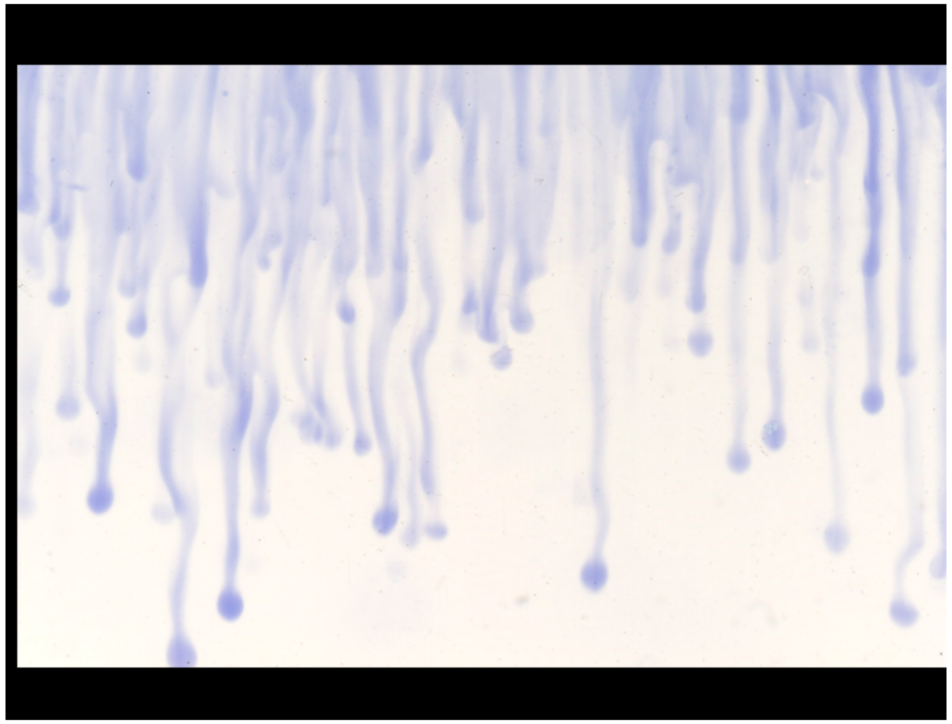
⇒ « layered convection » : system of convective layers + thiny diffusive layers

(double diffusive convection or semiconvection)

Process which may occur in a medium where two substances diffuse at a different rate

- When the fastest diffusive substance is stabilizing

-----> salt fingers

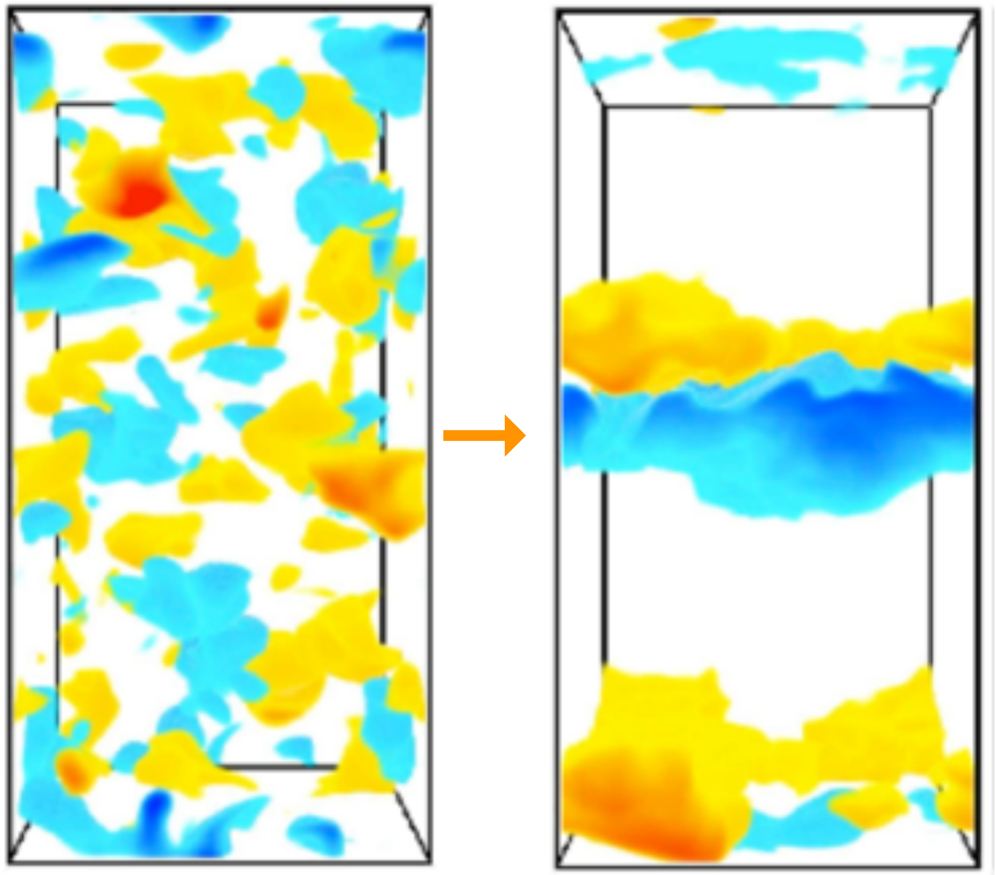


- When the fastest diffusive substance is destabilizing

----> formation of diffusive layers

In ocean, planets and stars:
heat is the fastest diffusive substance

Layers formation are **observed** in oceans and laboratory experiments



3D numerical simulations:

➡ Layers can form in low-Pr (< 1) double diffusive convection *(Rosenblum et al. 2011)*

- Origin of the molecular weight gradient:

- **Formation process:** during accretion of planetesimals in the gaseous envelope
But can such a gradient survive few Gyr?
May affect the luminosity of young planets (the GPI & SPHERE targets)
☛ much fainter planets

- **Core erosion:**
recent Molecular Dynamics simulations suggest immiscibility effects at T-P relevant to the core-envelope boundary of jovian planets *(Watson & Millitzer 2012)*
☛ H_2O and MgO (e.g rocky material) are soluble in hydrogen

Double-diffusive convection in Jupiter and Saturn?

(Leconte & Chabrier 2012, 2013 Nature Geosc.)

☛ Non conventional interior model for J and S

core + inhomogeneous, **“semiconvective”** envelope

☛ Reproduce the gravitational moments J_2 and J_4

- **Jupiter:** $M_{core} = 0 - 0.5\ M_\oplus$

  $Z_{tot} = 13\% - 20\%$ *(previous: $Z_{tot} = 2.5\% - 12\%$)*

- **Saturne:** $M_{core} = 12 - 21\ M_\oplus$

  $Z_{tot} = 28\% - 44\%$ *(previous: $Z_{tot} = 13\% - 29\%$)*

☛ **Layered convection** could explain Saturn’s luminosity anomaly

(anomalously high intrinsic flux that adiabatic models cannot reproduce)

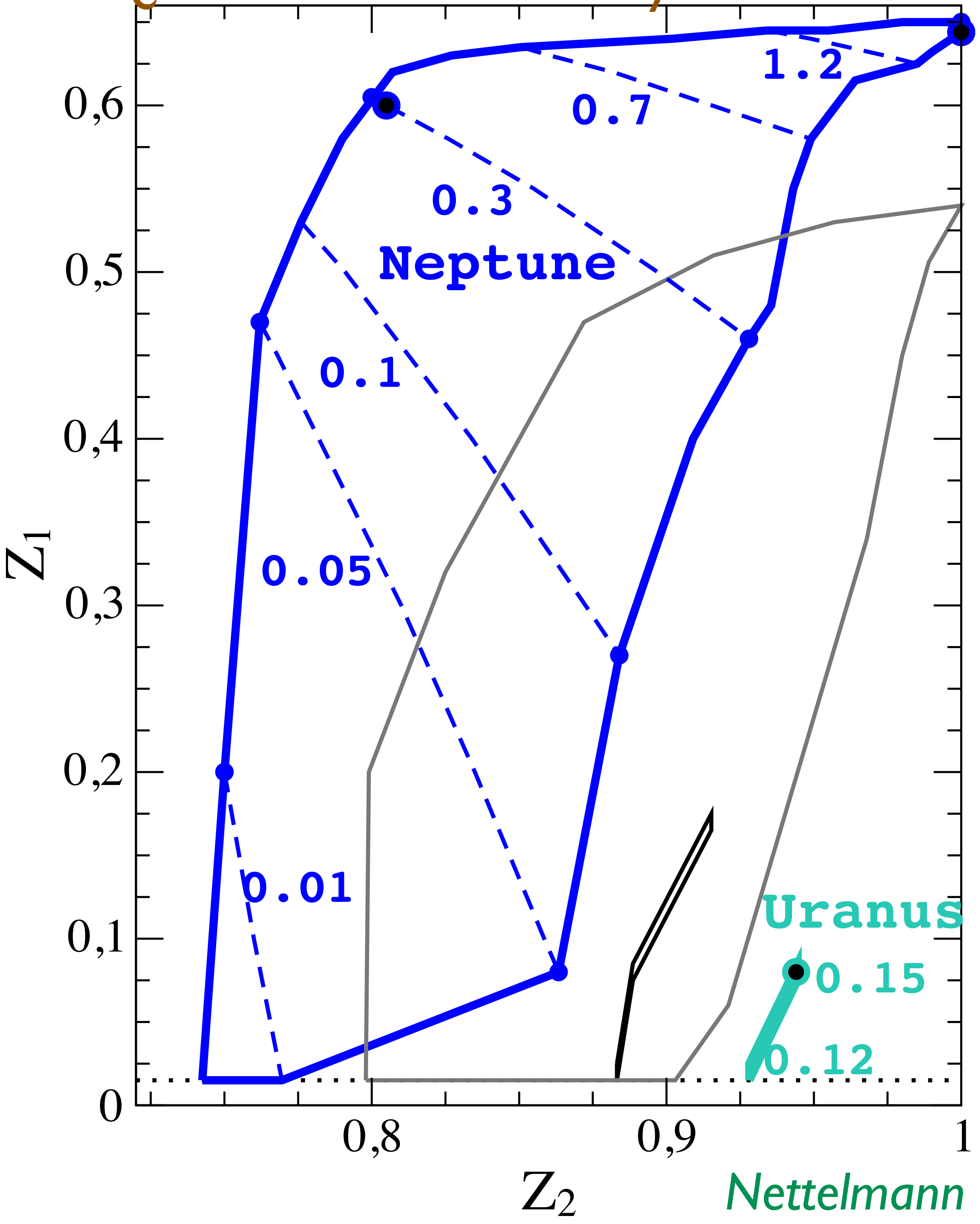
Inhomogeneous models for Jupiter and Saturn would be significantly more enriched in heavy material (30%-60% more) than adiabatic models.

Recent models for Uranus & Neptune:

Recent models by Nettelmann et al. 2013: constraint the metallicity of the "water-rich" inner envelope with Z_2 and the H-He rich outer envelope with Z_1

(water EOS of French et al. (2009) based on Quantum Molecular Dynamics simulations)

- Improved gravity field data (long term observations of planet's satellite motions)
- Modified shape and rotational periods compared to Voyager data



Nettelmann et al. 2013

First conclusions of planetary interior structures:

☛ Remaining uncertainties on interior structure models of our own giant planets (EOS, amount of heavy elements, size of core)

⇒ large uncertainties on the determination of exoplanet internal compositions from observed mass-radius

☛ Progress are coming with **improved EOS** of H/He and heavy materials (water, silicates, etc) at high pressure and high temperature *(see next talk by S. Mazevet)*

- ☛ **First applications to our Solar System Planets**
- ☛ **Preliminary application to exoplanets**

Future missions in the Solar System to improve planetary models

- **Juno (2016): for Jupiter**
  - Mapping accurately gravitational moments up to J_{12}
    ☛ constraint on the density distribution and internal structure
    ☛ constraints on differential or solid body rotation of the outer layers

  - Mapping of the magnetic field

  - Spectroscopy of thermal emission down to 100 bars
    ☛ measure of H_2O and NH_3 mixing ratios

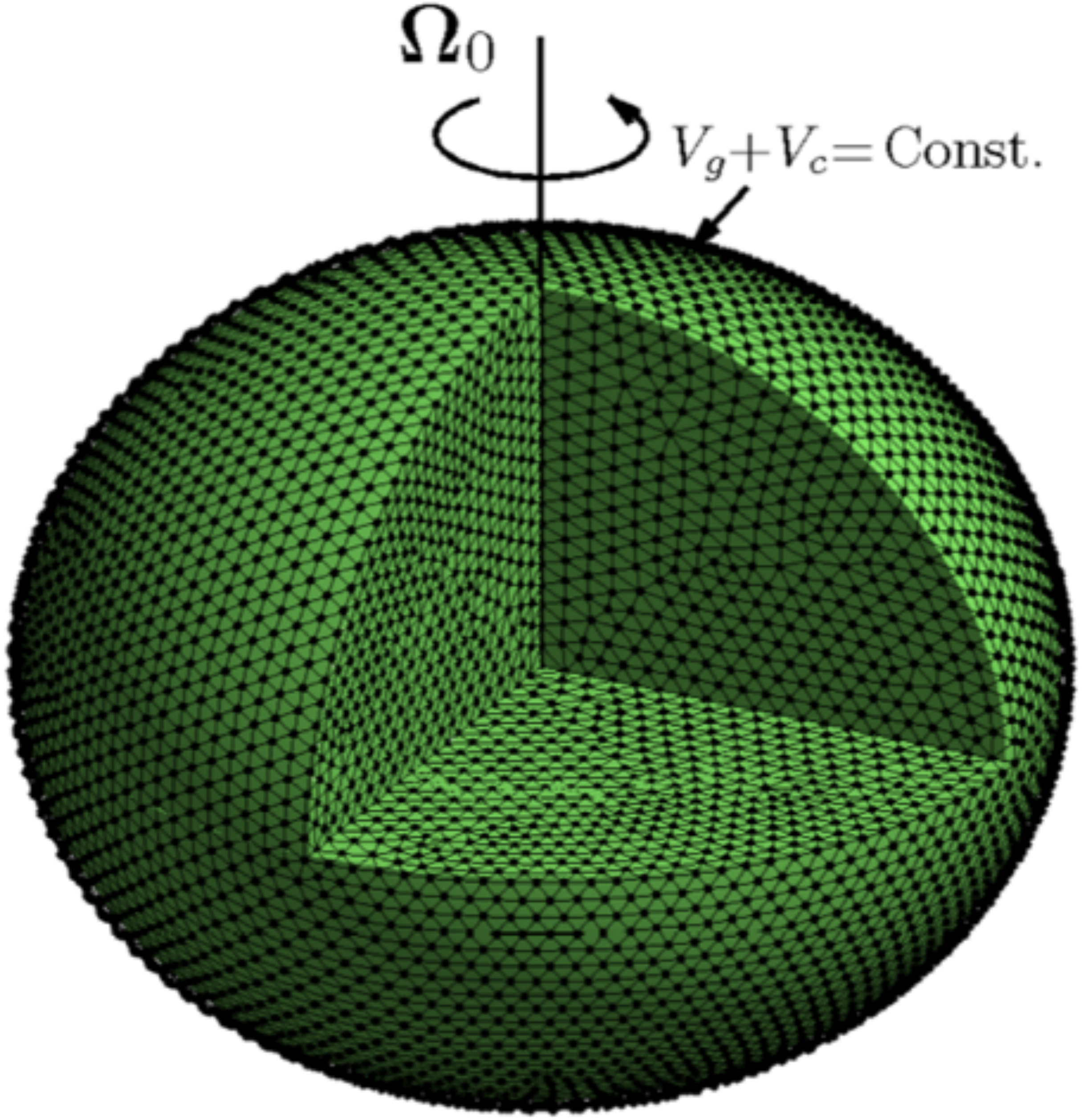
- **Final stages of Cassini (2017): for Saturn**
  - Precision mapping of gravitational moments (up to J_{10}) and magnetic fields
  - Possible in situ sampling of atmospheric mixing ratios
    (heroic death with the craft manoeuvred down in the atmosphere)

- **Seismology:**
  - First detection of Jupiter's oscillations by SYMPA *(Gaulme et al. 2011)*
  - Detection by Cassini of spiral structures in Saturn's ring which could be due to perturbations from Saturn's free oscilations
    ☛ seismology studies should be pursued!

Future improvement:

Beyond the standard approach of the theory of figures (Zharkov & Trubitsyn 1978) based on an expansion around spherical geometry:
development of 3D numerical solutions for the shape of rotationally distorted planets

☛ higher accuracy for high order gravitational moments J

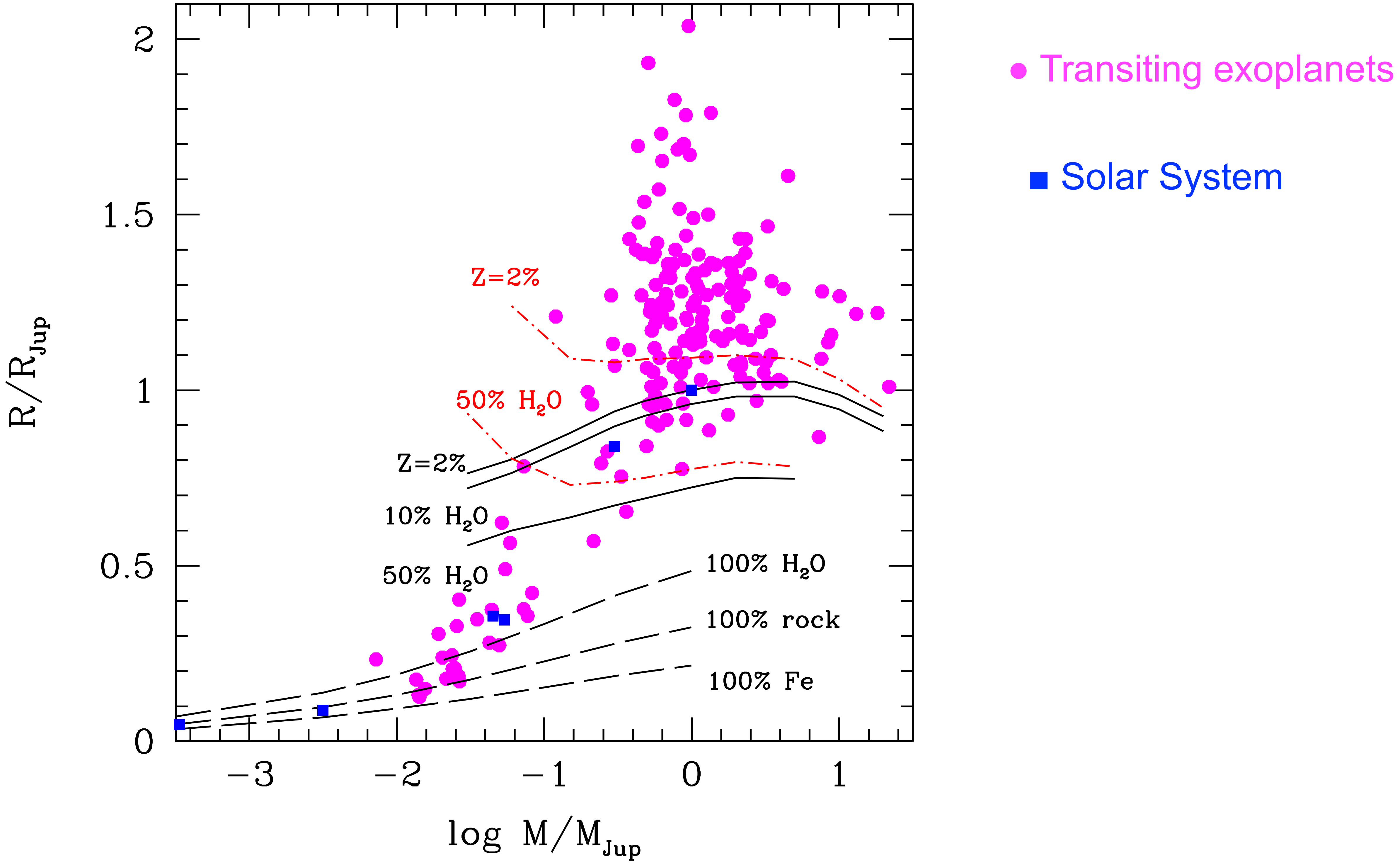


Sketch of a 3D tetrahedral mesh for oblate spheroidal Jupiter/Saturn *Kong et al. 2013*

I) Some lessons from our solar system planets

II) Exoplanets: Interior structure and evolutionary models

Knowledge of Solar System necessary to understand the huge diversity of planetary structures from the mass-radius relationship of exoplanets



Distribution of heavy elements in exoplanets

---> Current assumptions (Fortney et al. ; Burrows et al. etc...):

- **All heavy elements located in the central core**
- **Metal-free or solar metallicity H/He envelope**

Equivalent to a distribution of Z over the entire planet?

Planet with Z=50%
----> Comparison between planet with
Z in a core versus planet with **no core**:
up to ~ 30 % effect on R at a given age

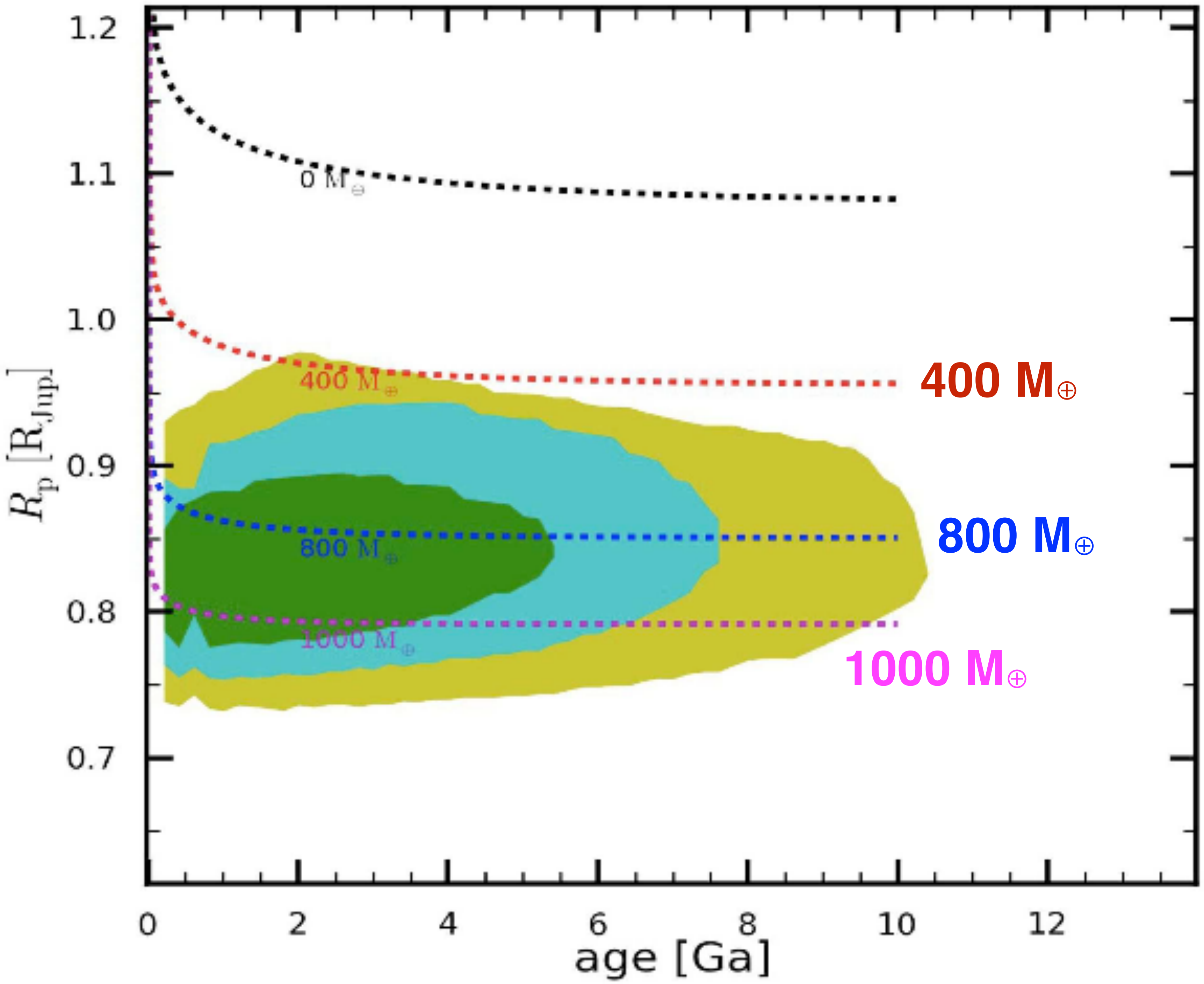
Baraffe, Chabrier, Barman 2008, 2010

EOSs ANEOS (Sandia) /SESAME (Los Alamos):
Relevant regime P ~ 1 Mbar - 100 Mbar:
interpolated between experiments and asymptotic limits in the very high density, fully ionised limit)

Reduction of those uncertainties are expected from improved EOSs

A very interesting case: CoRoT-20b *(Deleuil et al. 2012)*

$4\ M_{Jup}$ $0.8\ R_{Jup}$

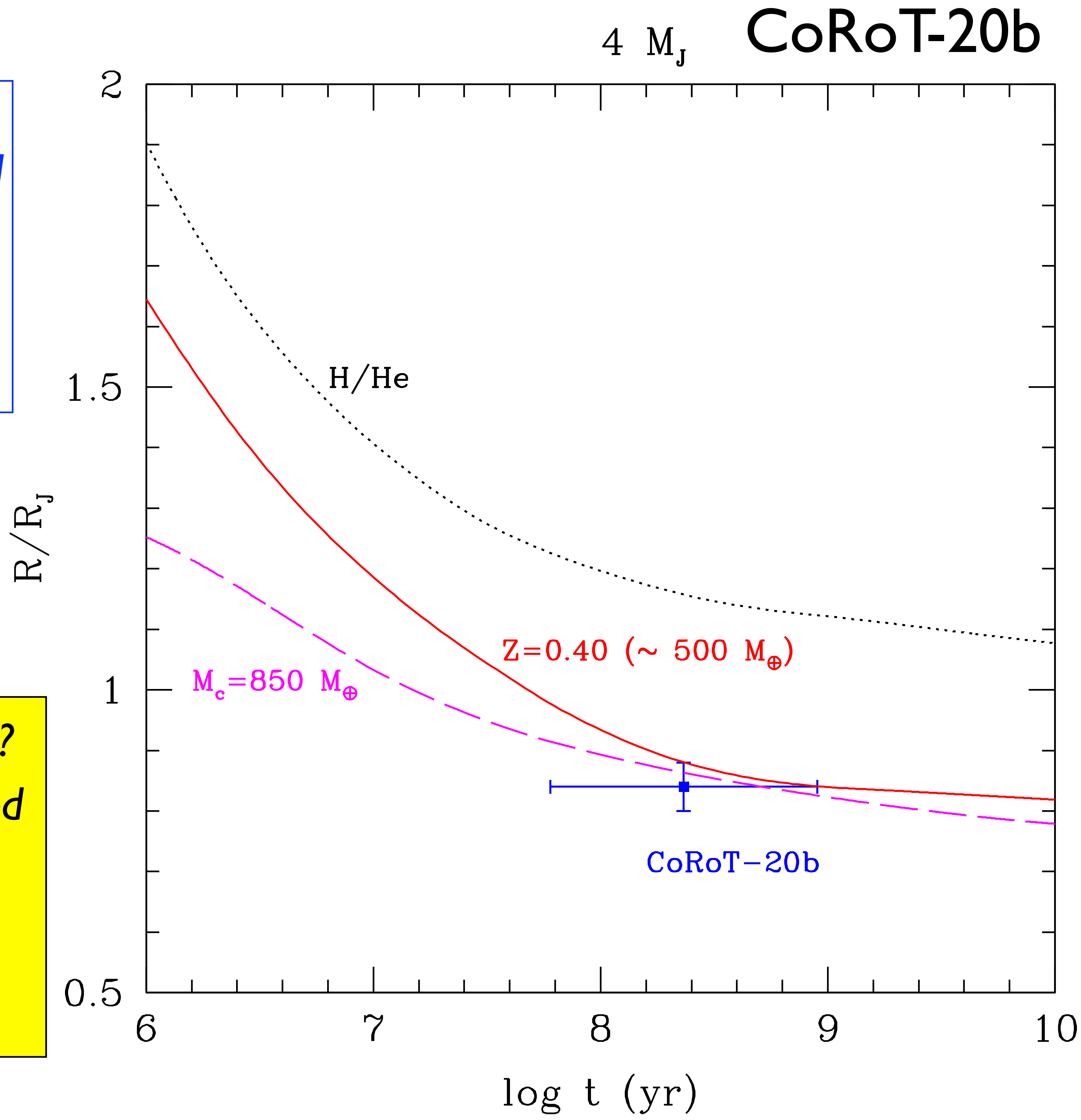


Requires ***too massive core*** *of heavy material to explain its radius (maximum amount of heavy material in the disk ~ 800 $M_\oplus$)*

Uncertainty ellipse within ***1sigma**, **2sigma**, **3sigma***

Effect of heavy element distribution?

Requires a ***smaller amount*** *of heavy material if distributed in the whole planet (~ 500 M*$_{earth}$*) (models of Baraffe et al. 2008)*



☛ *Wrong estimate of radius?*

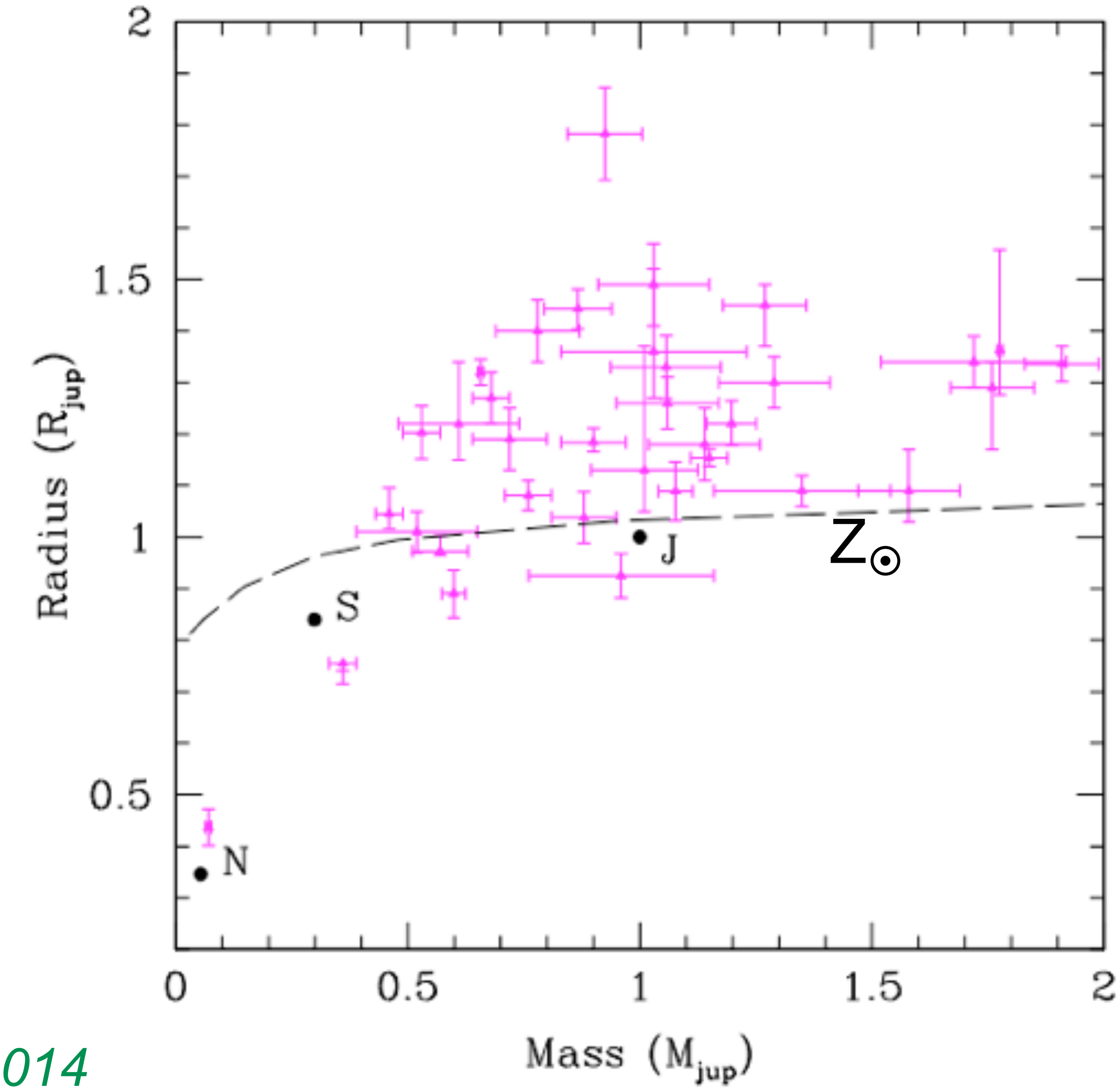
☛ *Heavy material distributed all over the planet?*

☛ *Pb with EOS used (could ab-initio EOS improve that?)*

The problem of inflated planets

Significant fraction of exoplanets with abnormally large radius

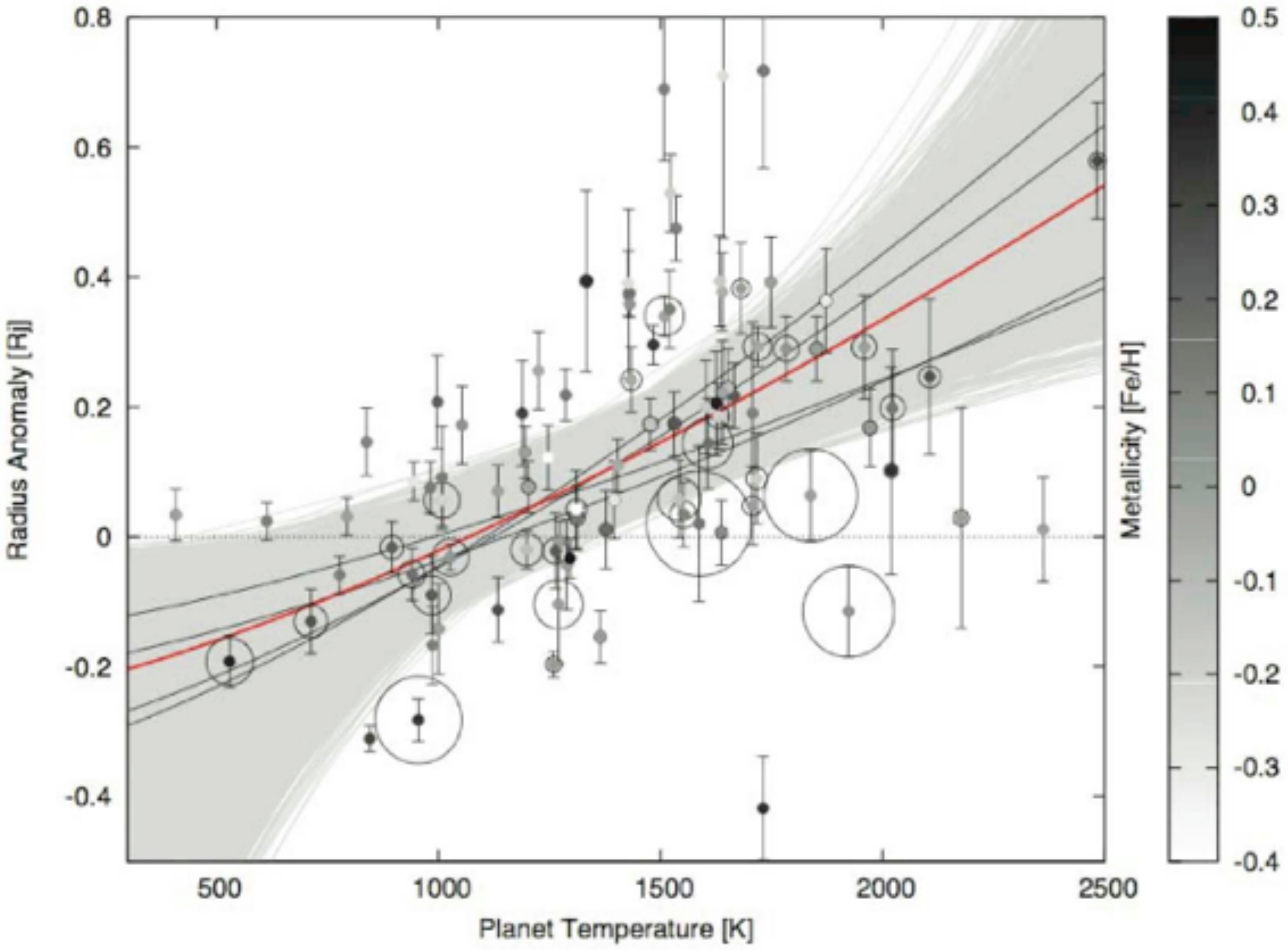
Missing physics in planetary interior models?



Summary in Baraffe et al. PPVI 2014

Correlation of the radius anomaly $R = (R_{obs} - R_{pred}) \propto T_p^{1.4}$

Laughlin, Crismani, Adams 2011



Similarly, Kepler data: reveal a lack of inflated radii for giant planets receiving modest stellar irradiation

(Miller and Fortney , 2011; Demory and Seager , 2011)

a) Incident stellar flux driven mechanism

😎😎 **Atmospheric circulation:** *(Showman & Guillot 2002)*

-----> downward transport of kinetic energy down to the internal adiabat

Heats the planet and slows down the contraction

😎 **Ohmic dissipation:** *(Batygin & Stevenson 2010; Perna et al. 2010)*

-----> Atmospheric winds produce currents penetrating in the interior

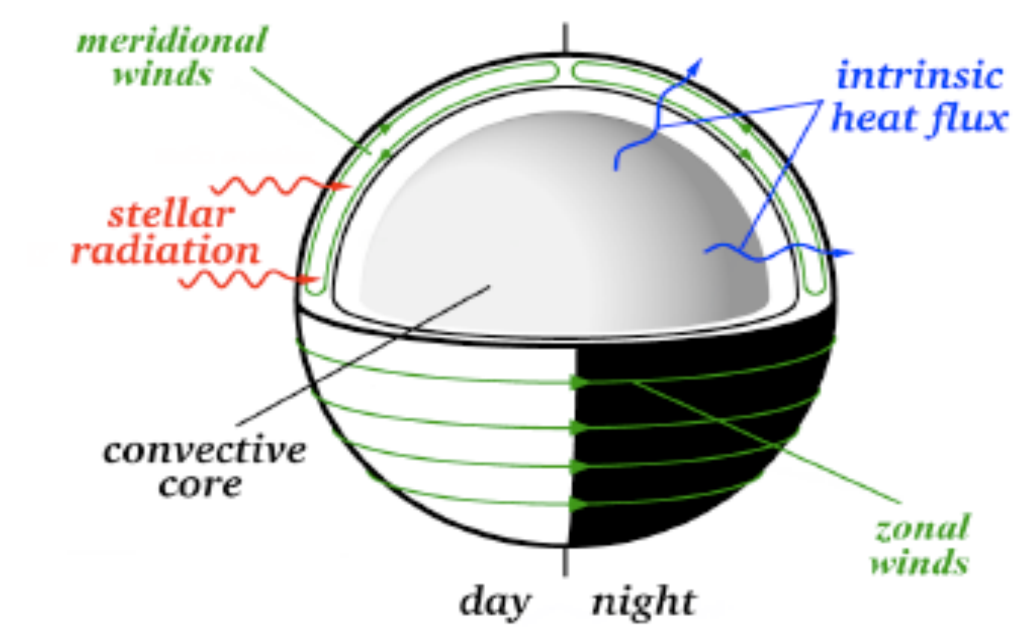
Ohmic heating in the interior $\dot{E} = J^2/(\varrho\sigma)$

Atmospheric circulation models (GCM: 3D hydrodynamics + radiative transfer + magnetic drag on a full sphere) *(Cho et al., Forget et al.; Heng et al., Mayne et al; Menou et al.; Showman et al.)*

☛ **Study the interaction between outer and deep circulation pattern**

☛ **Effect of circulation on planet spectral signatures**

(link with observations: HST, Spitzer, JWST, ELT)



b) Tidal mechanisms *(Bodenheimer et al. 2001)*

😔 *Difficult to explain with tidal effects alone properties of several inflated planets (HD209458b, WASP-12b, etc..)* *(Leconte et al. 2010)*

c) Delayed contraction

😩 **Enhanced atmospheric opacities:** *(Burrows et al. 2007)*

😢 **Double diffusive convection (semiconvection):** *(Chabrier & Baraffe 2007)*

The future:

- **Development of ab-initio EOS** of H/He and heavy materials (water, silicates, etc) at high pressure and high temperature

  ☛ **new generation of planetary models are coming**

- Development of **numerical simulations** to confirm the existence of **layered convection** in planetary interiors (*Rosenblum et al. 2011; Mirouh et al. 2012)*

  ☛ Planets are not necessarily fully adiabatic and homogeneous

  ☛ Important impact on our own giant planets!

  ➤ *Potential observable signature for young planets or discovery of an inflated giant exoplanet at a >> 0.1 AU)*

- Development of **sophisticated dynamical atmospheric models** (outer/deep circulation + radiative transfer + chemistry + magnetic drag)

  ☛ Solution for abnormally large radii of close-in planets?

  ☛ Effect on spectral signatures

  ➤ *Need for more observational constraints: wind velocity (cf Snellen et al.), shift of substellar point, heat redistribution.*

The big question: Are theoretical/numerical tools ready to interpret the observed diversity?

They are on the right track!

Because we know what to do….