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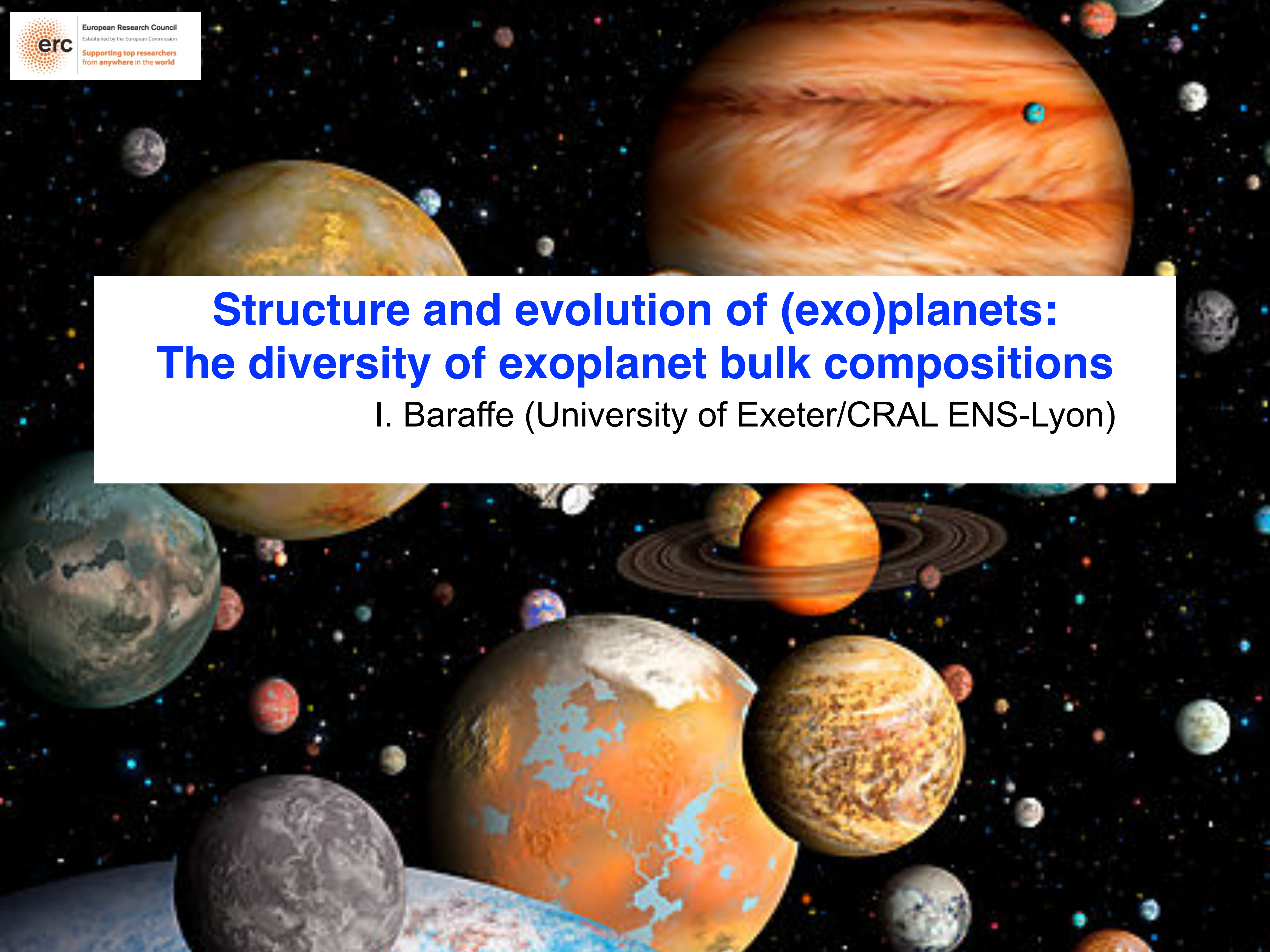
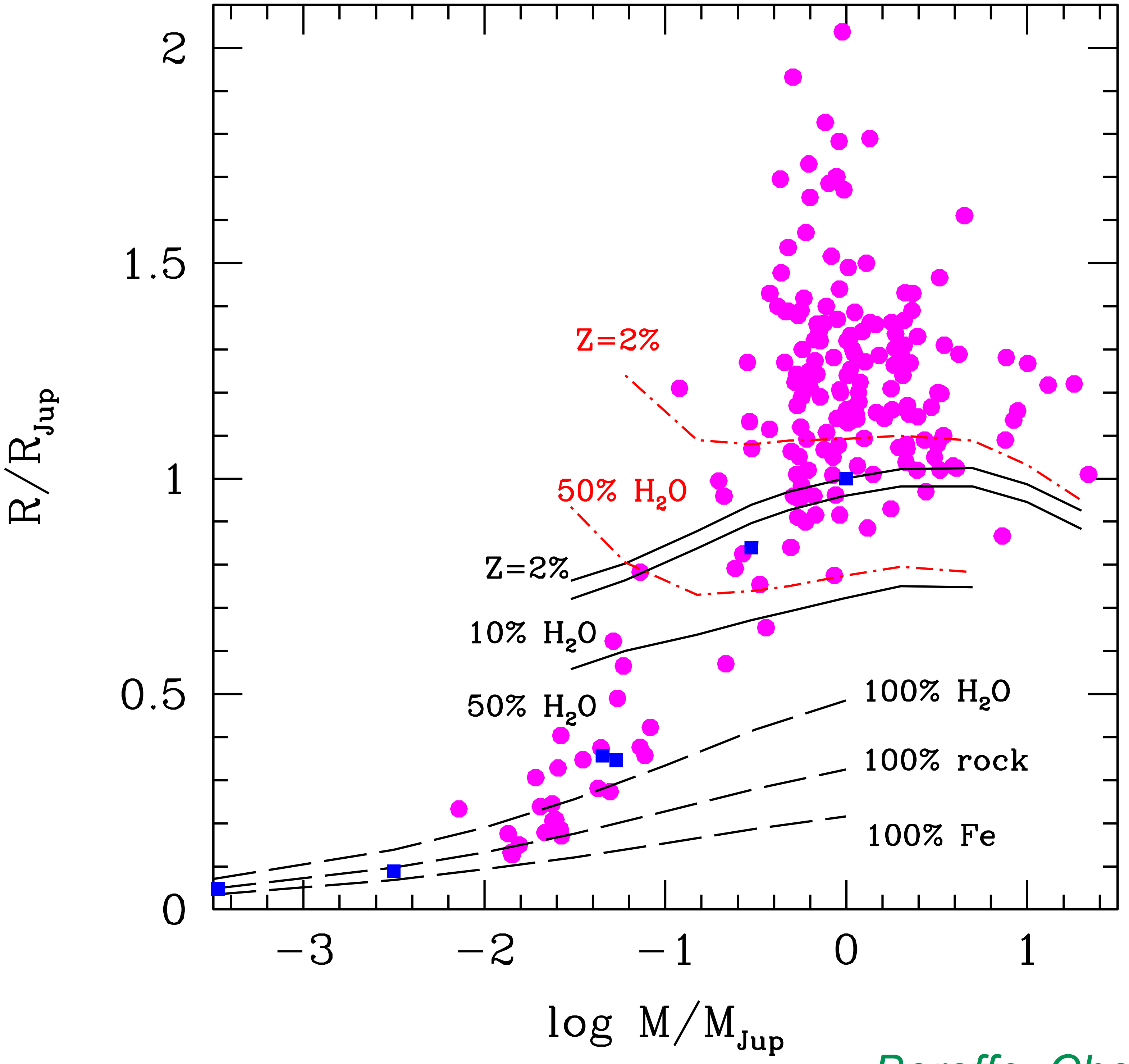


Structure and evolution of (exo)planets: The diversity of exoplanet bulk compositions

I. Baraffe (University of Exeter/CRAL ENS-Lyon)

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

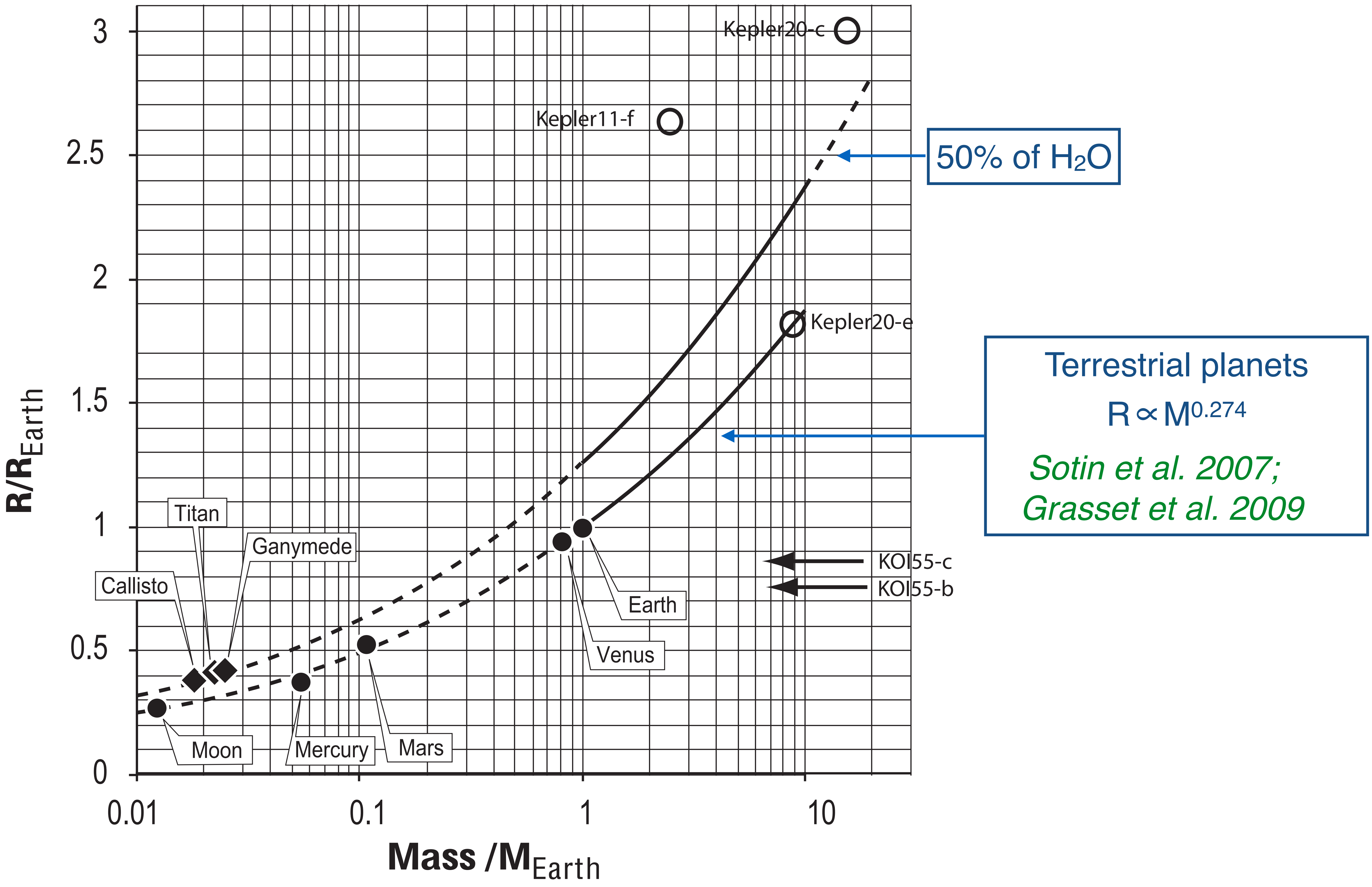


● Transiting exoplanets

■ Solar System

Baraffe, Chabrier, Fortney, Sotin, PPVI 2013

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



50% of H_2O

Terrestrial planets

$R \propto M^{0.274}$

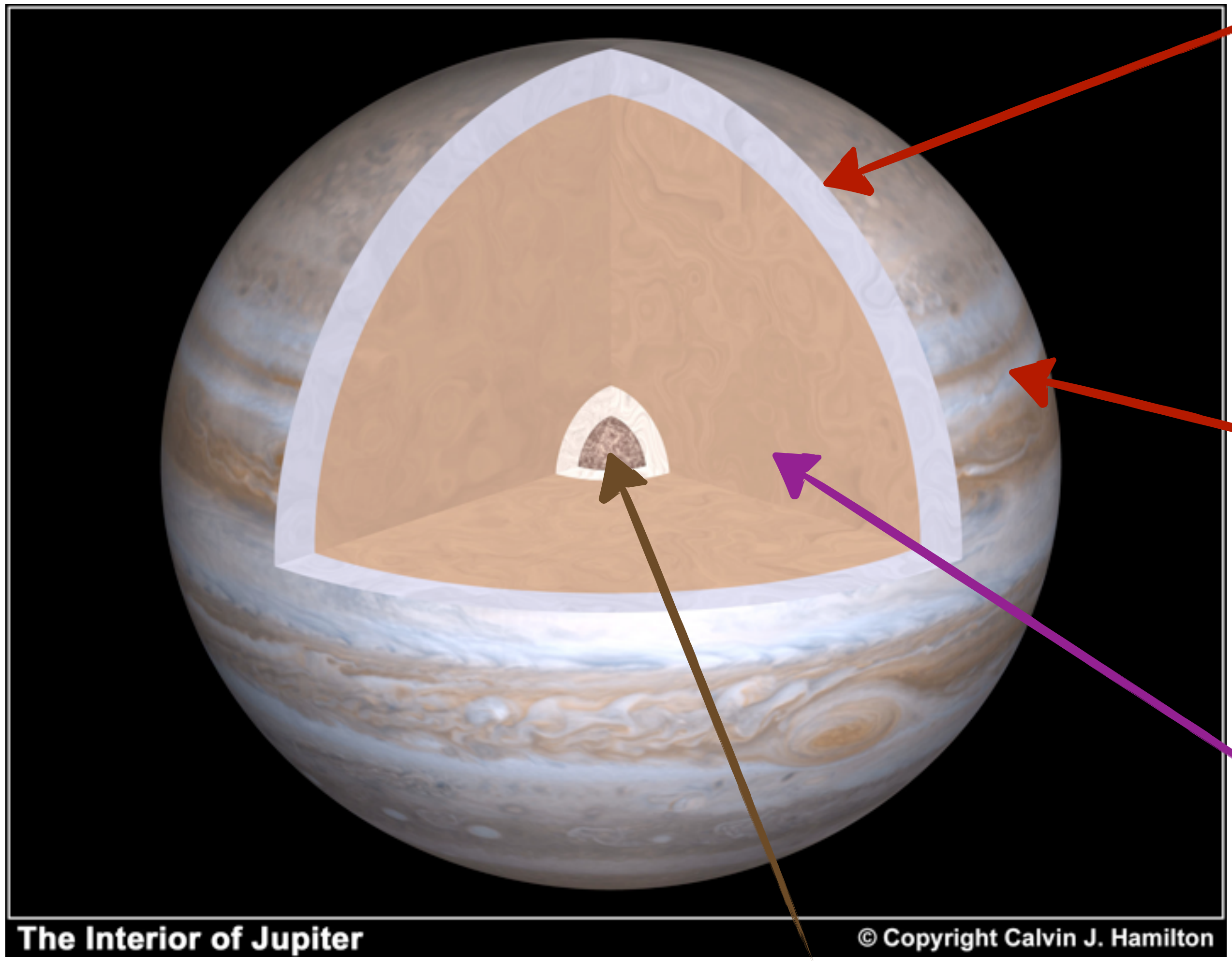
Sotin et al. 2007;

Grasset et al. 2009

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

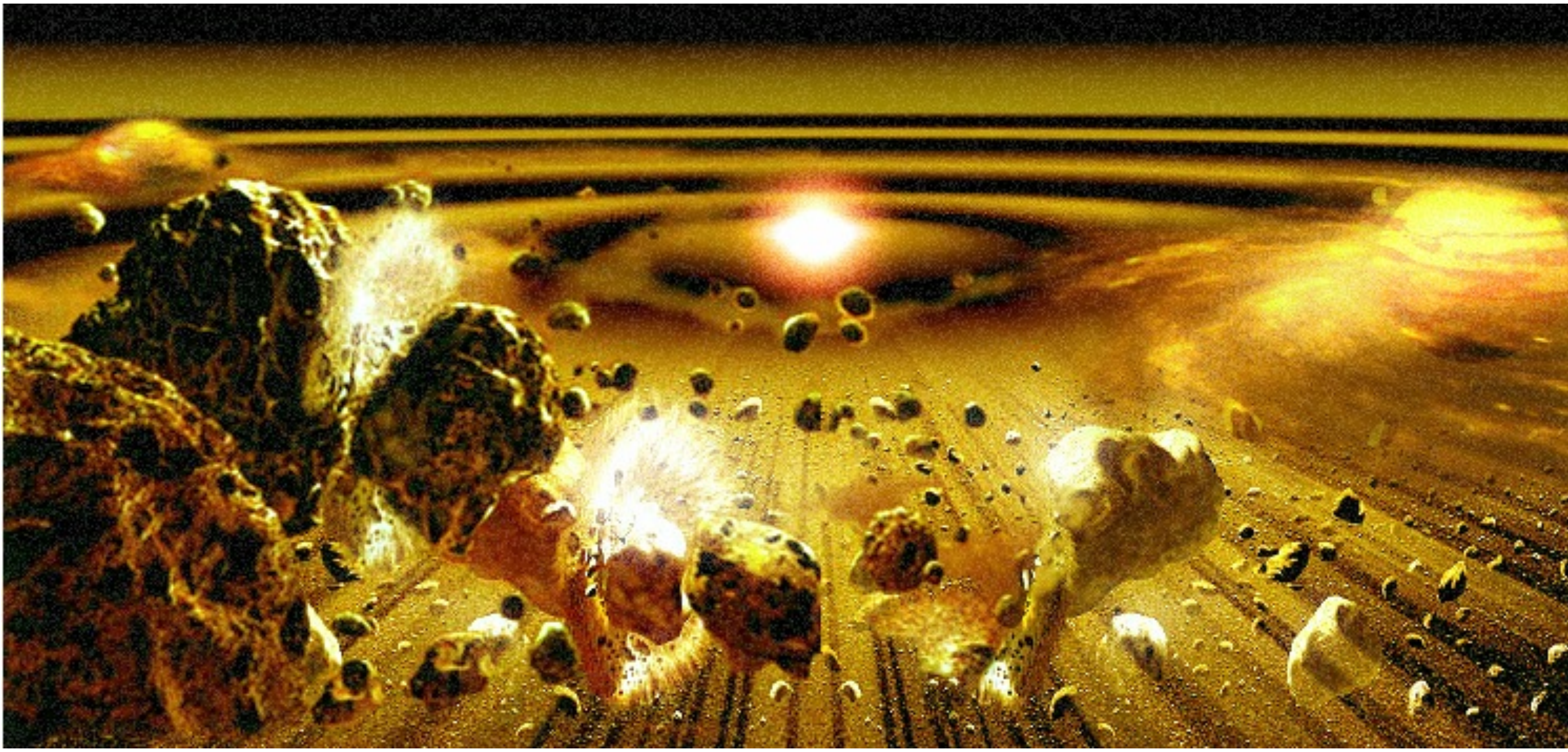
Jupiter:

- 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

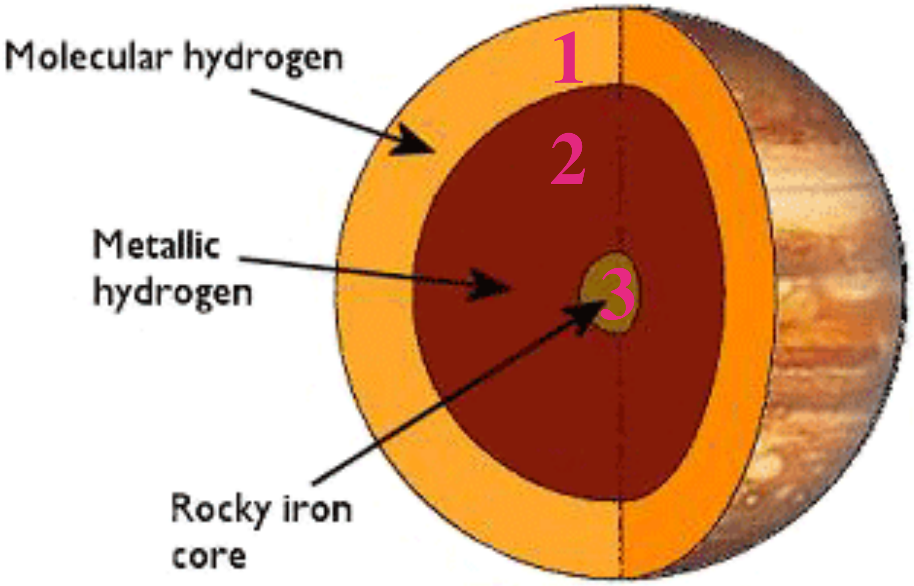
Metal enrichment expected because of the formation in a "dirty" proto-planetary disk →



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 layer 2 :

- **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)

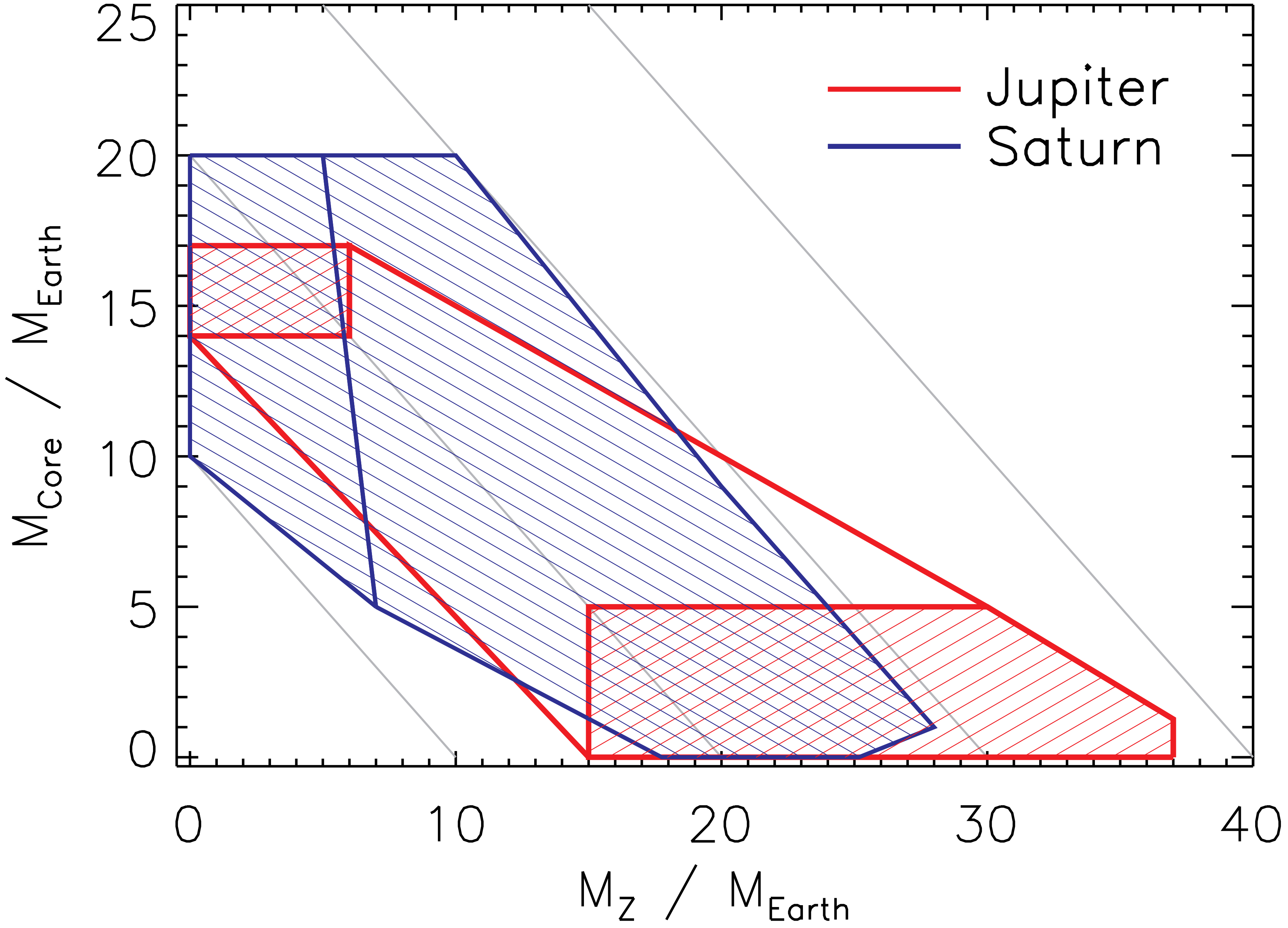
<u>Note:</u> better understanding of H/H_2 transition and of H-He demixing from first-principle EOSs is key to predict more accurate giant planet structures.

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)

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*)

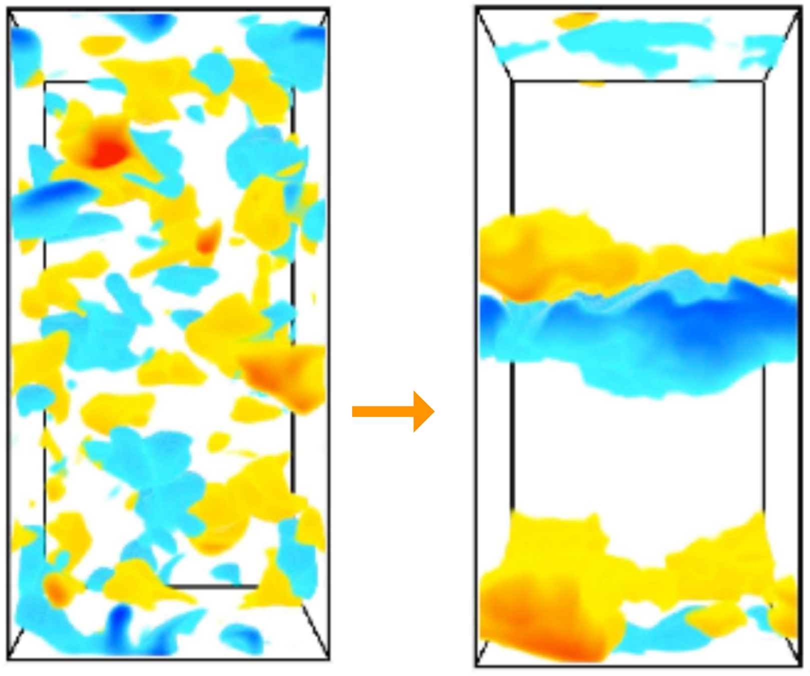
⇒ « layered convection » : system of convective layers + thiny diffusive layers

(double diffusive convection or semiconvection)

Layers formation are **observed** in oceans (Pr = 7) 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 miscibility 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:** Z_{tot} = 13% - 20% *(previous: Z_{tot} = 2.5% - 12%)*

- **Saturne:** 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.

Future missions in the Solar System to improve planetary models

- **Juno (2016) for Jupiter and final stages of Cassini (2017) for Saturn**
  - Mapping accurately gravitational moments up to J_{10} - J_{12}

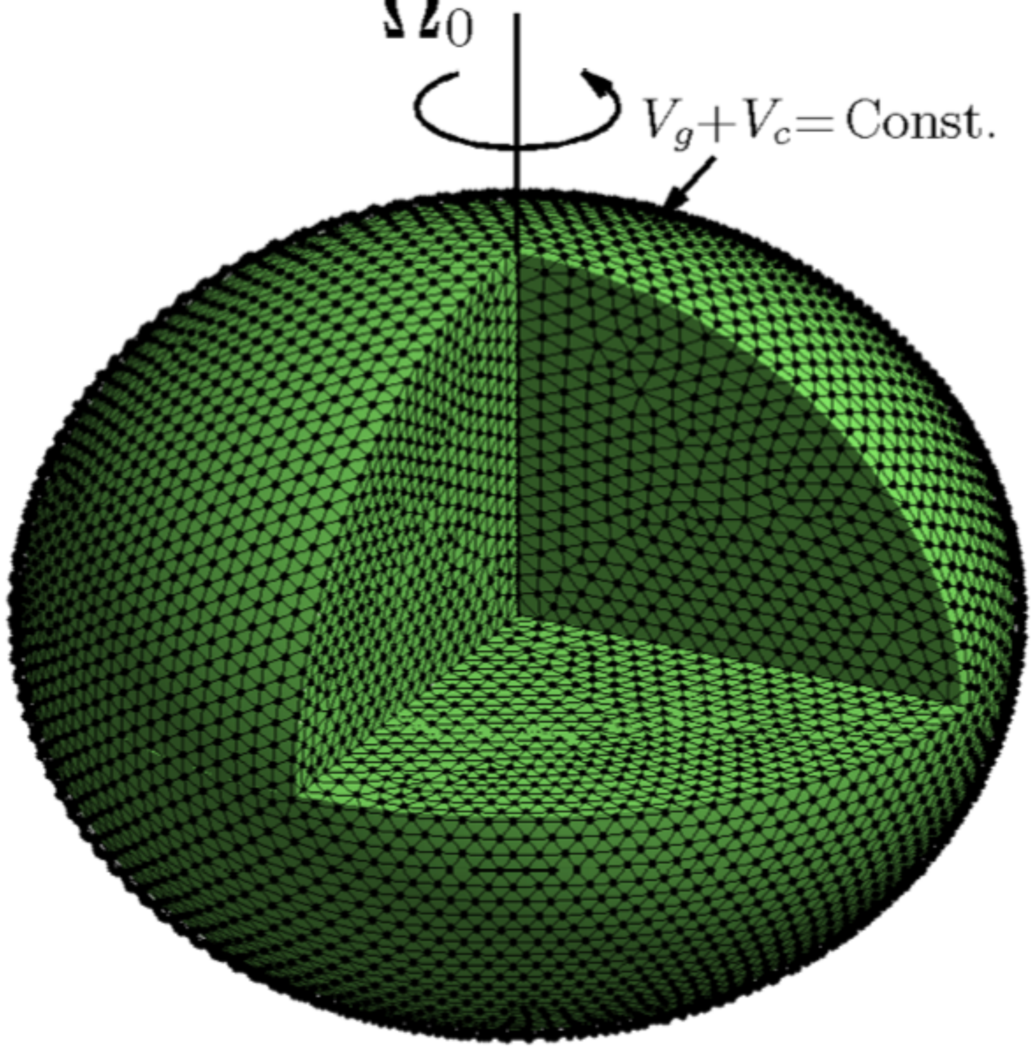
☛ constraint on the density distribution and internal structure

☛ constraints on differential or solid body rotation of the outer layers

Improved models are coming as well:

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

Interior structure models of giant exoplanets: Current status

- **Mostly used EOS:** **ANEOS (Sandia, 1972) et SESAME (Los Alamos, 1992)**

Relevant regime P ~ 1 Mbar - 100 Mbar: interpolated between experiments and asymptotic limits in the very high density, fully ionised limit.

(Only very preliminary applications of ab-initio EOS to exoplanets)

- **Distribution of heavy elements in exoplanets**

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

- All heavy elements located in the central core

- Metal-free or solar metallicity H/He envelope

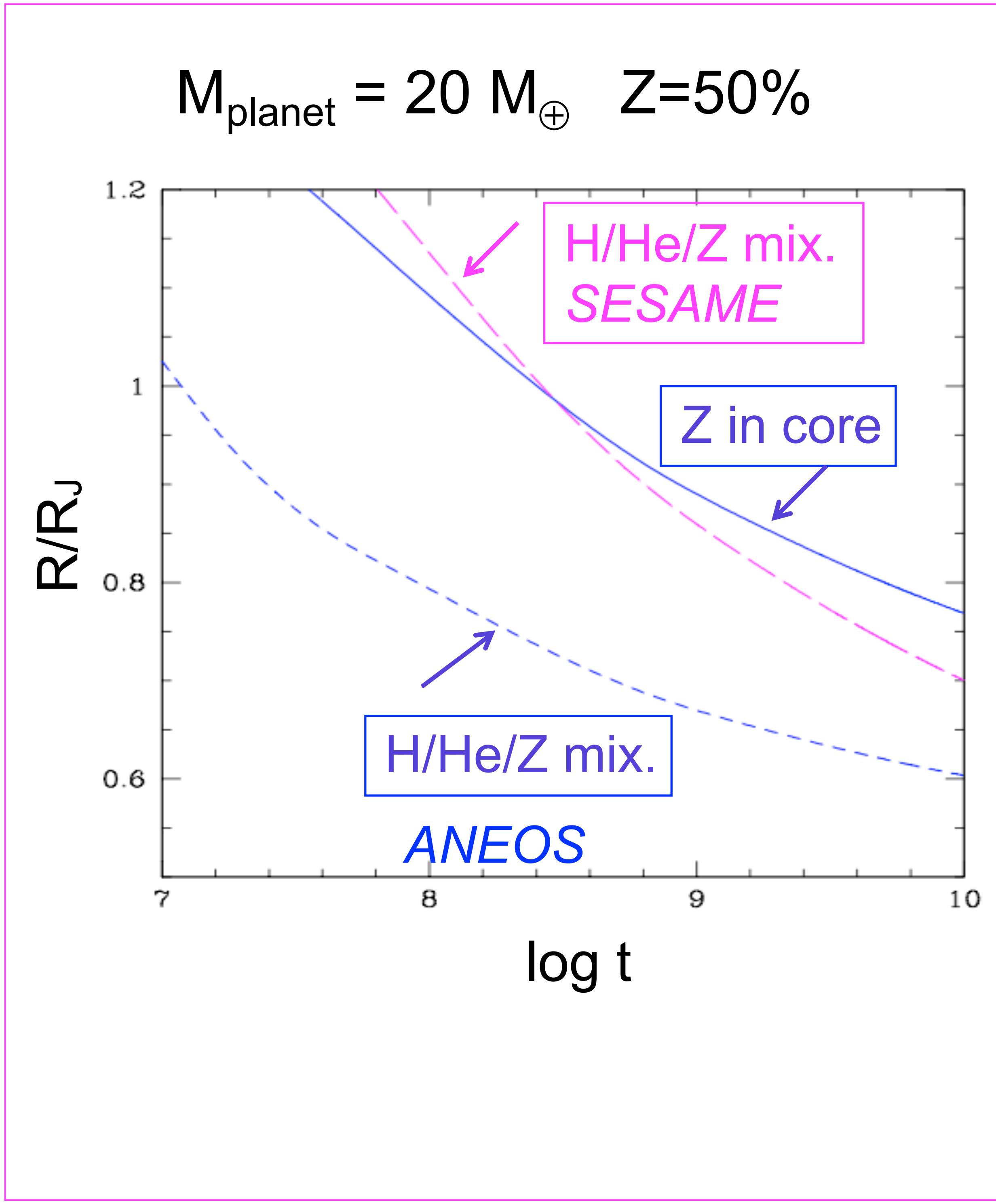
Equivalent to a distribution of Z over the entire planet?

Test on a Neptune-mass 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)



High sensitivity of R_P:

→ differences in **entropy** behaviour

- S of metals whether in core or envelope
- between ANEOS and SESAME

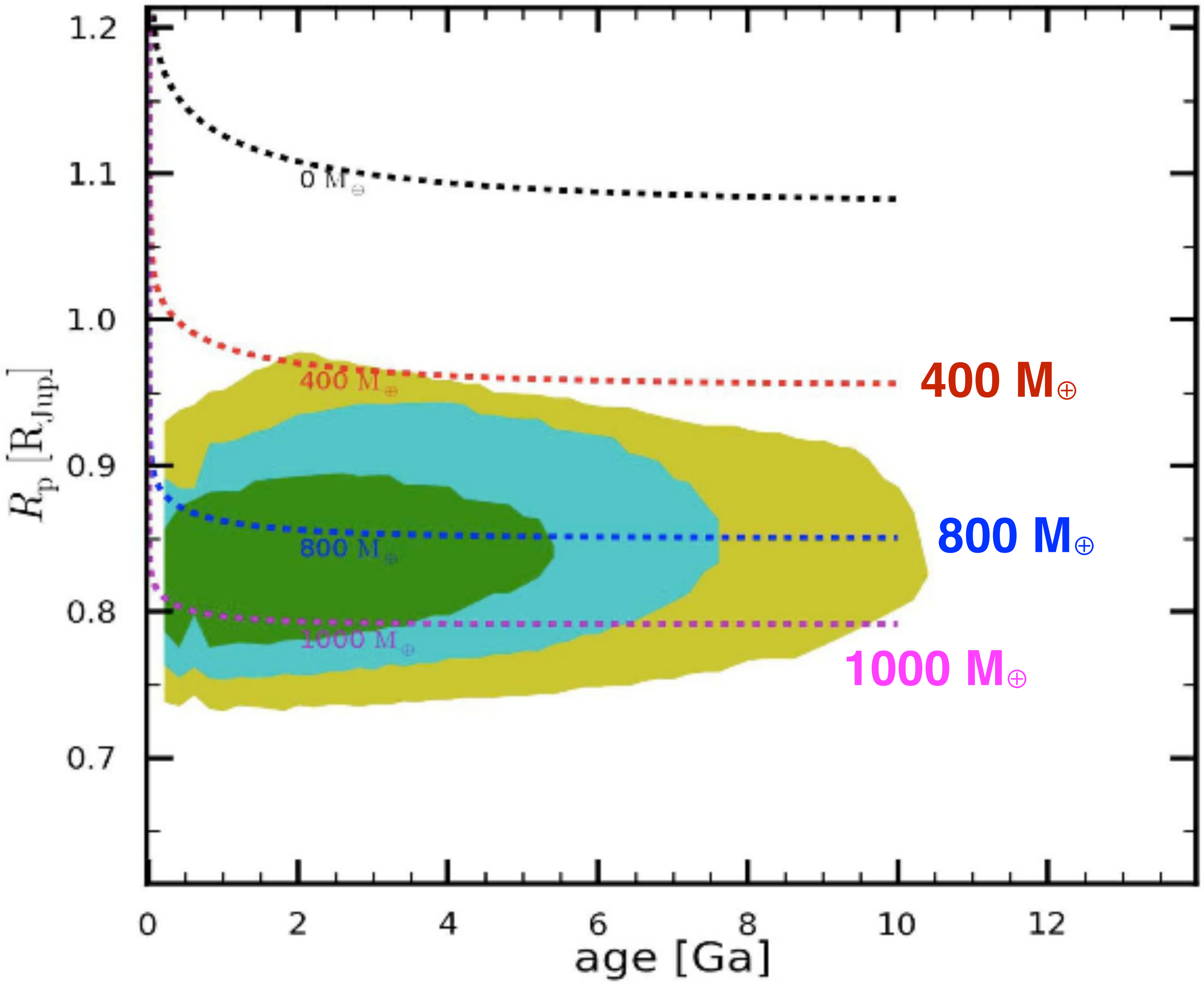
☛ evolution driven by $L(t) = \int_M -T\, \mathbf{dS/dt}\, dm$

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}

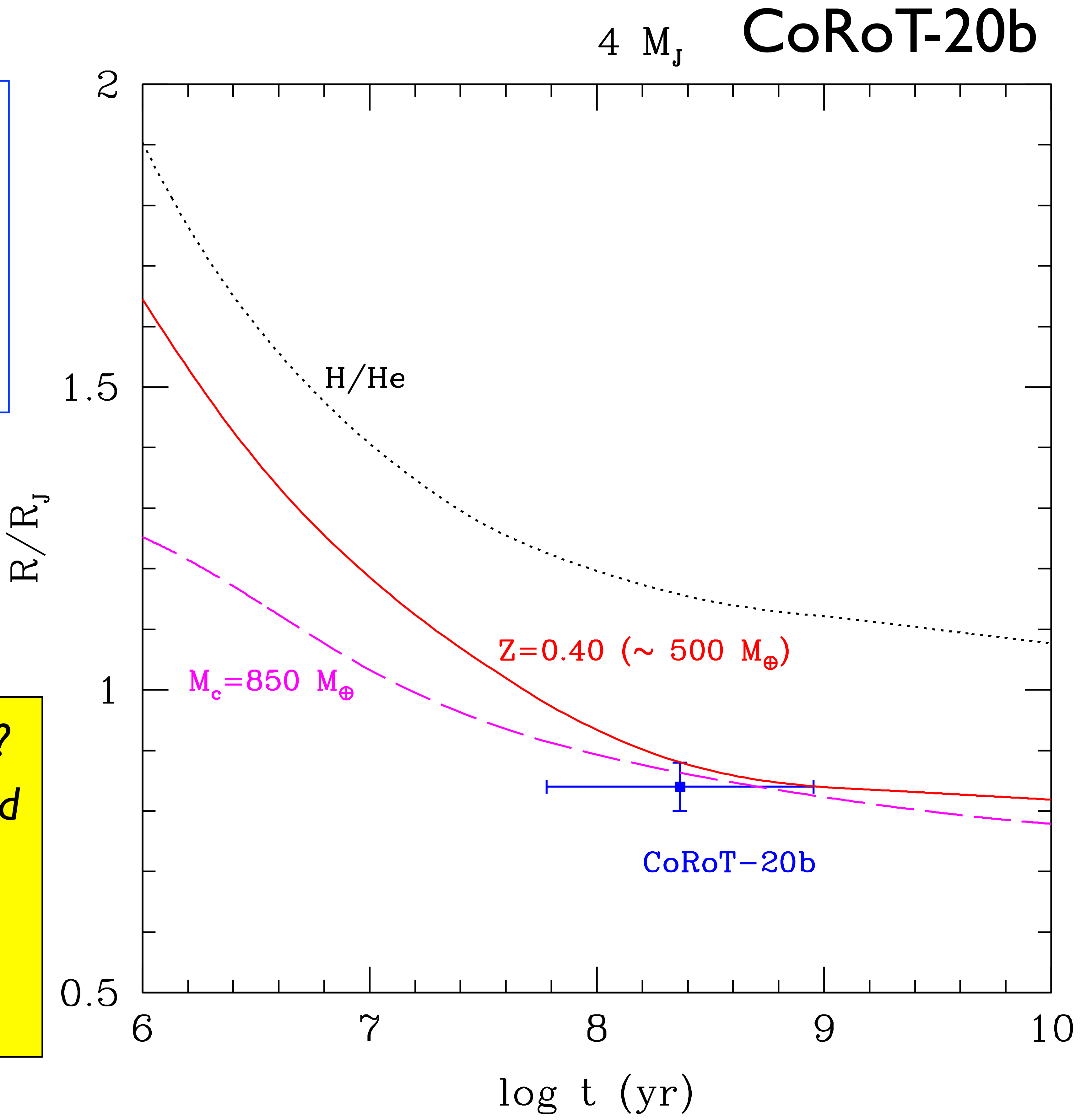
Requires ***too massive core*** *of heavy material to explain its radius (maximum amount of heavy material in the disk ~ 800 $M_\oplus$)*



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)*

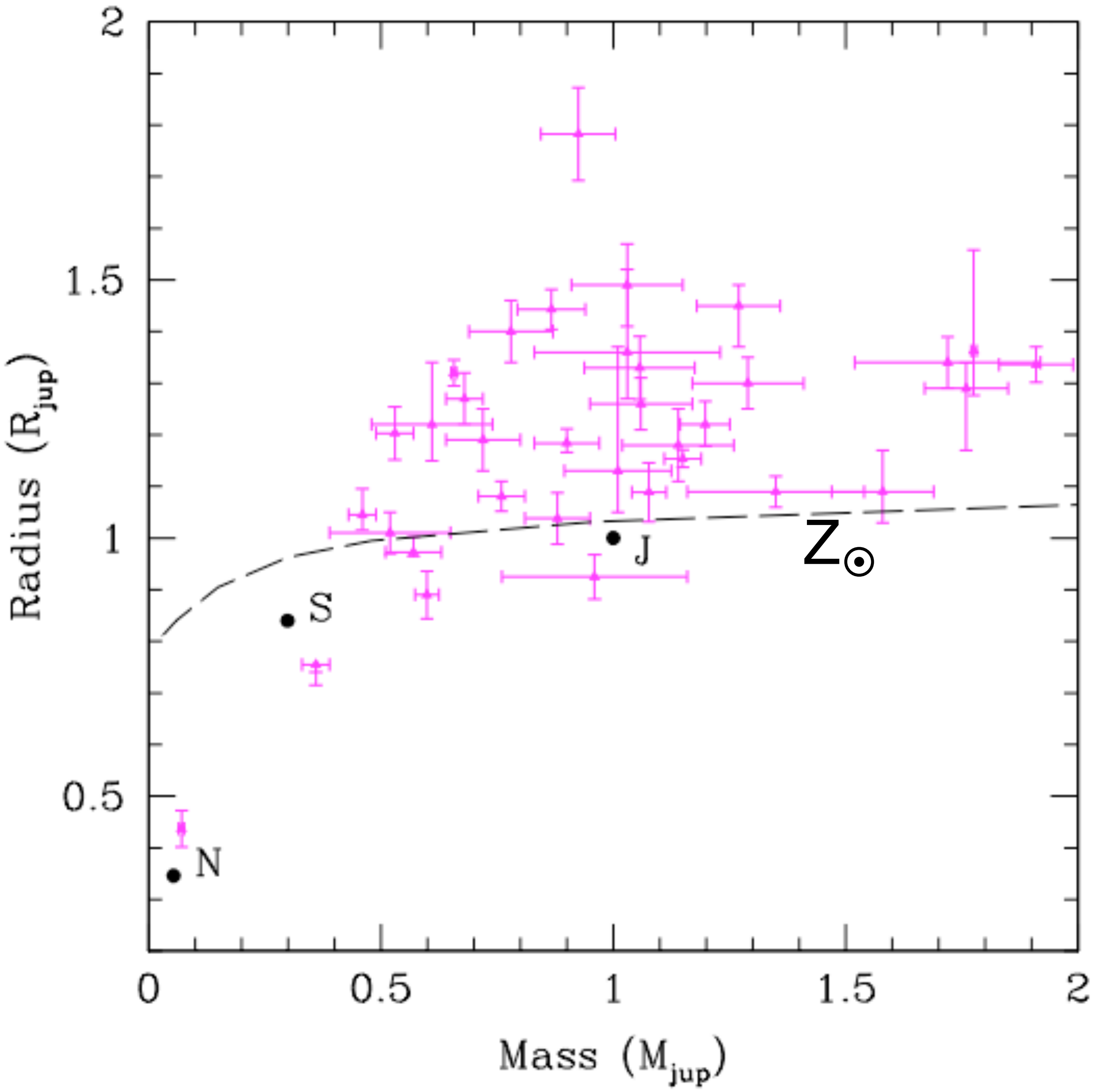


- ☛ *Wrong estimate of radius?*
- ☛ *Heavy material distributed all over the planet?*
- ☛ *Pb with EOS used (could ab-initio EOS improve that?)*

The problem of inflated planets

Significant fraction of exoplanets with abnormally large radius

Missing physics in planetary interior models?



<u>Clear observational trend:</u>
Correlation of the radius anomaly and the stellar flux
Laughlin, Crismani, Adams 2011, Miller and Fortney , 2011; Demory & Seager , 2011

Summary in Baraffe et al. PPVI 2014

☛ Need of 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

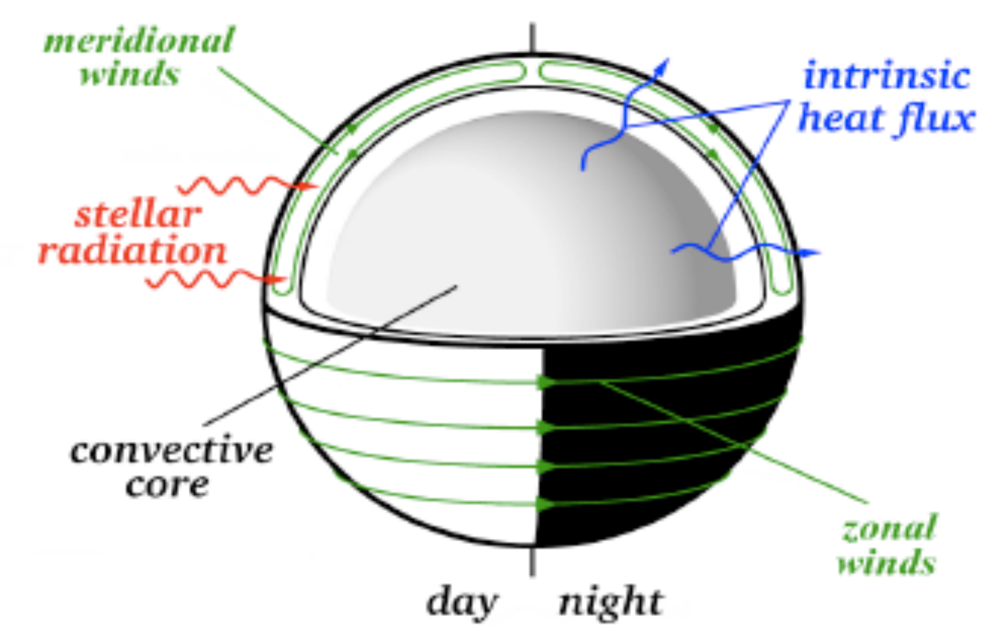
Ohmic heating in the interior $\dot{E} = J^2/(\varrho\sigma)$

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)



Recent developments: Adapting the Unified Model (UM) of the Exeter Met Office to Exoplanets *(Mayne, Baraffe et al. 2013, 2014)*

Main advantages compared to other GCMs *(LMD, MITg, Princeton, etc…)*

- Non hydrostatic deep-atmosphere equations of motions (3D full Euler equations)
  Usually hydrostatic equilibrium $\partial P/\partial r = -\rho g$

- No primitive equations or shallow-atmosphere approximation
  "shallow": $r \rightarrow R_p$ *and* $\partial/\partial r \rightarrow \partial/\partial z$

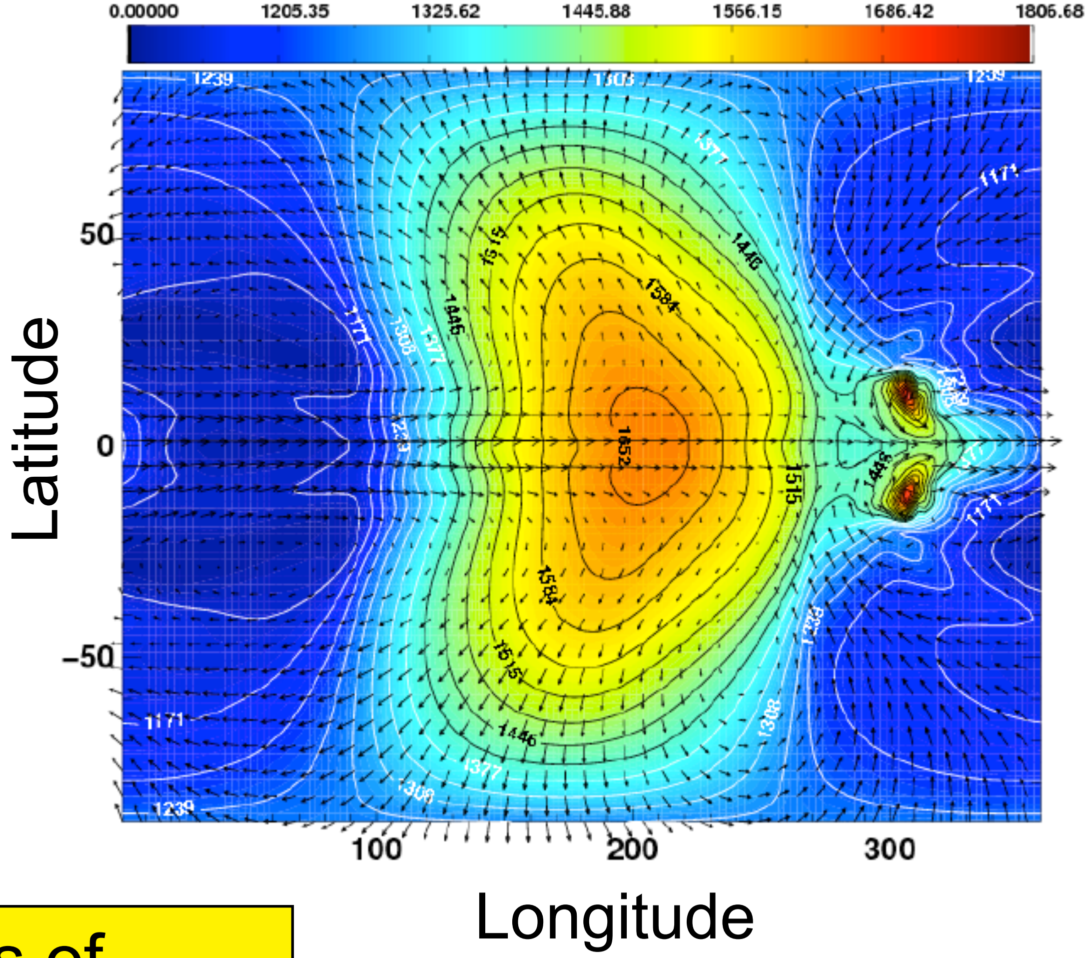
- Varying gravity
  Usually constant gravity $g(r) = g_p = GM_p/R_p^2$

☛ Can extend deeper than other GCM codes and better account for vertical motions

Observational constraints for GCMs:

☛ Phase curve observations of HD209458b suggest hot spot shifted eastward of the substellar point *(Knutson et al. 2007)*

☛ In agreement with previous GCMs results predicting equatorial super rotation *(Showman et al; Menou et al)*



Preliminary results with full dynamics: Properties of the zonal jet pattern could depend on
- assumed dynamical equations (e.g shallow versus full)
- the planet's gravity

(Mayne, et al, in preparation)

☛ Key to combine transit/RV data (planet's gravity) and phase curve (hot spot shift) observations

The future:

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

- ▪*Ongoing and future high-pressure experiments (Livermore, Sandia in the US; Laser Megajoule in France) (Eggert et al; Knudson et al)*
- ▪ *First principle methods (quantum molecular dynamics, DFT, path integral) (Mazevet, Chabrier, Soubiran et al.; Millitzer et al; French et al.)*

☛ **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: orbital phase curves, wind velocity (cf Snellen et al.)***