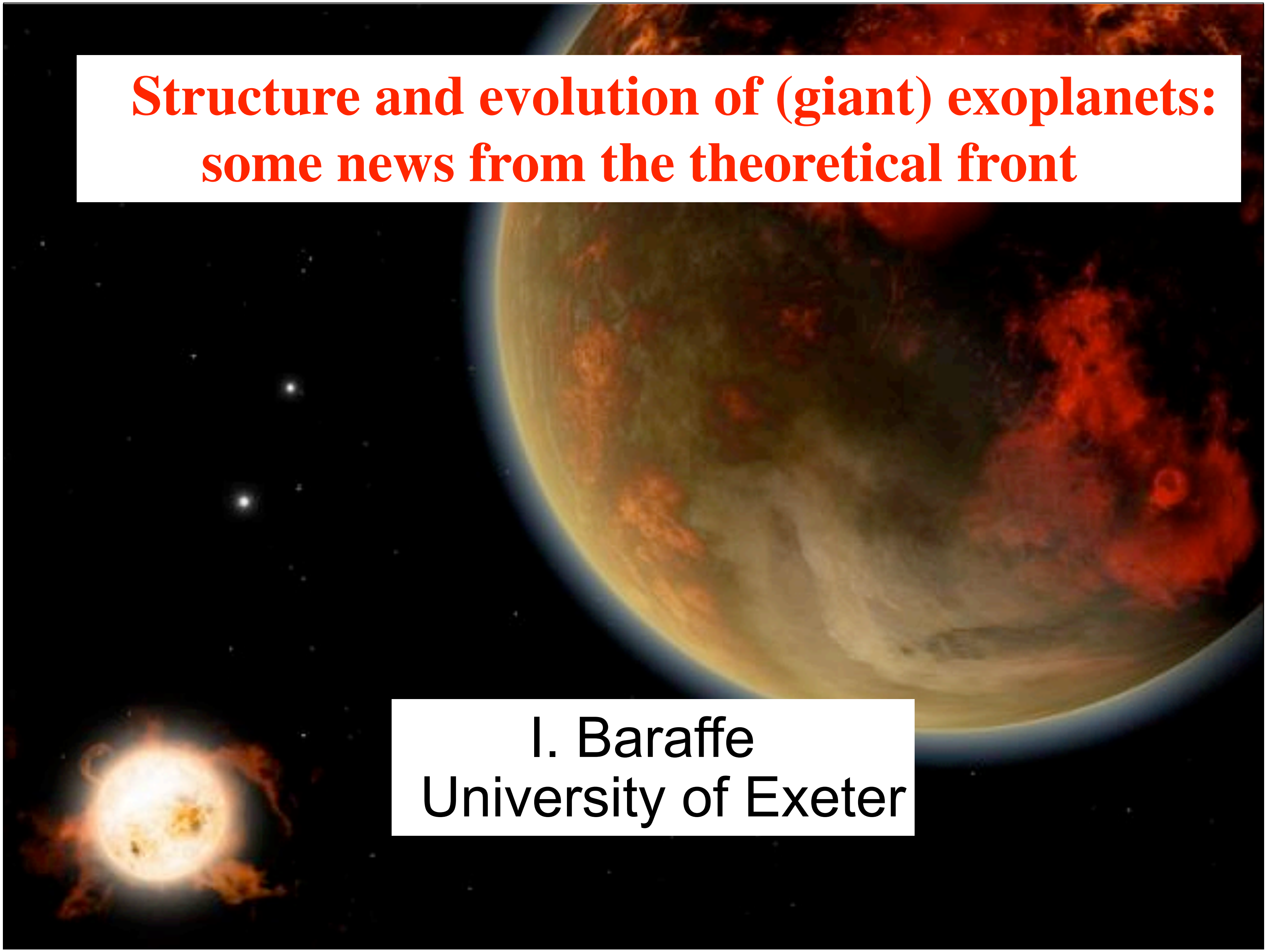
Structure and evolution of (giant) exoplanets: some news from the theoretical front



I. Baraffe
University of Exeter

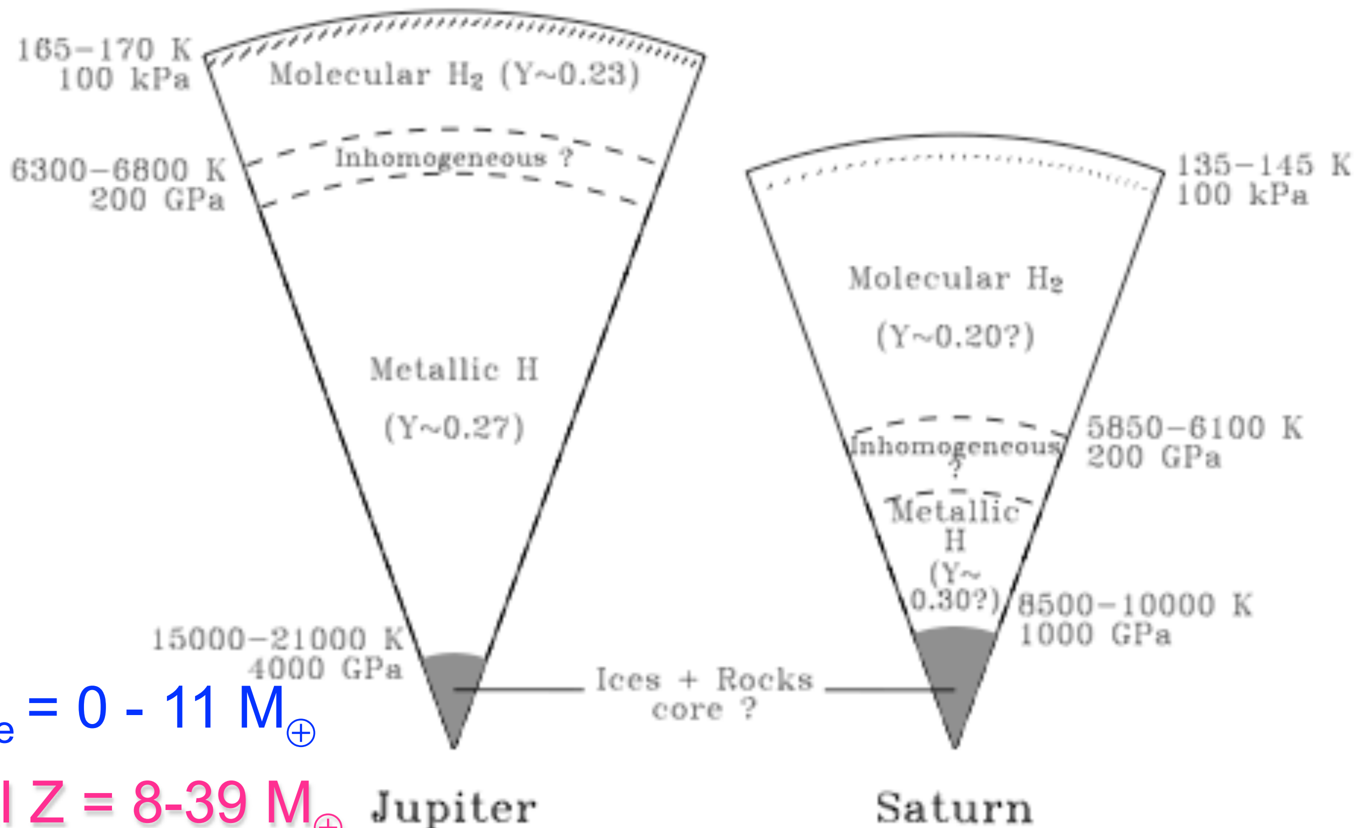
I) Structure of Jupiter and Saturn

II) Exoplanets: Interior structure and evolutionary models:

- *Heavy element enrichment*
- *Inflated exoplanets*

Internal structure of Jupiter and Saturn

*(the **standard** 3-layer picture)*



- $M_{core} = 0 - 11\ M_\oplus$
- Total Z = 8-39 $M_\oplus$

(Saumon & Guillot 2004)

Recent picture

- **Small core hypothesis** for Jupiter **challenged** by recent calculations based on first-principles EOS for H-He mixtures *(Militzer et al. 2008)*

  ☛ based on a 2-layer model: core of rock/H_2O and isentropic mantle of H/He

  ⇒ Find a core for Jupiter of $M_{core} = 14\text{-}18\ M_{\oplus}$

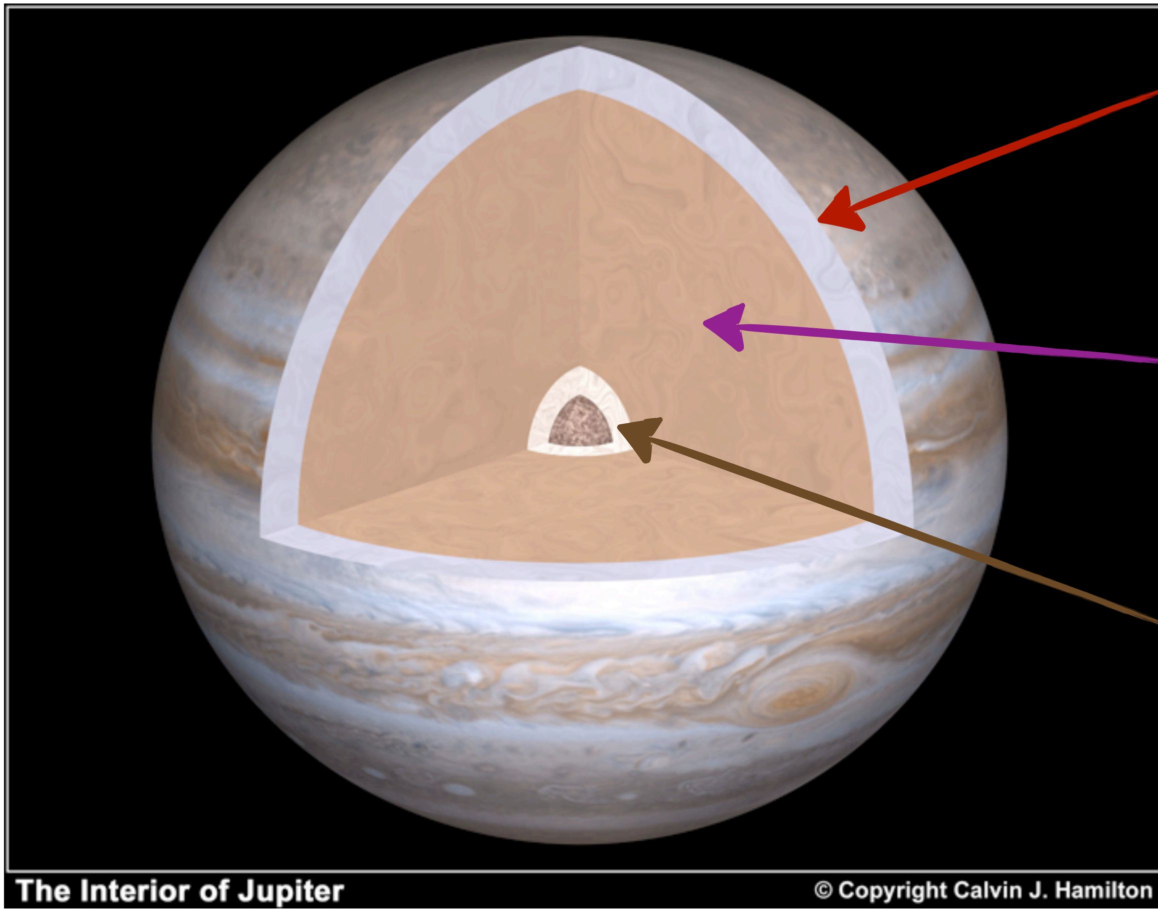
- **Strong disagreement** with another study also based on ab initio EOS calculations for H, He and H_2O *(Nettelmann et al. 2008)*

  ☛ 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 $M_{core} = 0\text{-}7\ M_{\oplus}$, $M_Z = 30\text{-}50\ M_{\oplus}$

II) Exoplanet modelling

(Baraffe et al. '06, '08, '10; Leconte et al. 2009, 10, 11)



Irradiated atmospheres
Barman et al. 2001;2005

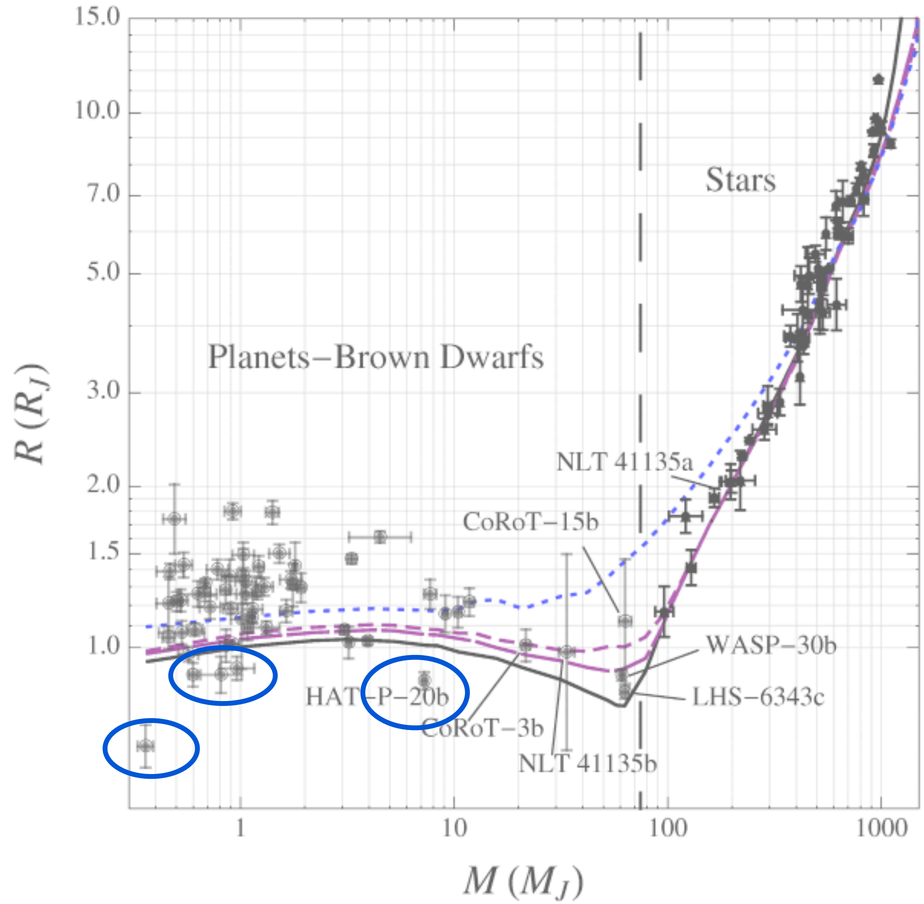
H/He envelope
Z=0 or Z=0.02
Saumon & Chabrier EOS

Rocky/icy core
«Ices»(H_2O, CH_4, NH_3)
silicates ($MgSiO_4$, $MgSiO_3$,...)
Iron (Fe)

II-a) Heavy element enrichment

Substantial fraction of exoplanets are enriched in heavy material :

(volatiles H_2O, CH_4, NH_3; silicates Mg_2SiO_4, $MgSiO_3$; Fe)



Models of Baraffe et al. for $Z_\odot$

(0.1 - 1 - 5 - 10 Gyr)

▪ Equations of state of heavy elements

10 $M_\oplus$ ---> 10 M_{Jup}**:** extreme pressure and temperature regime

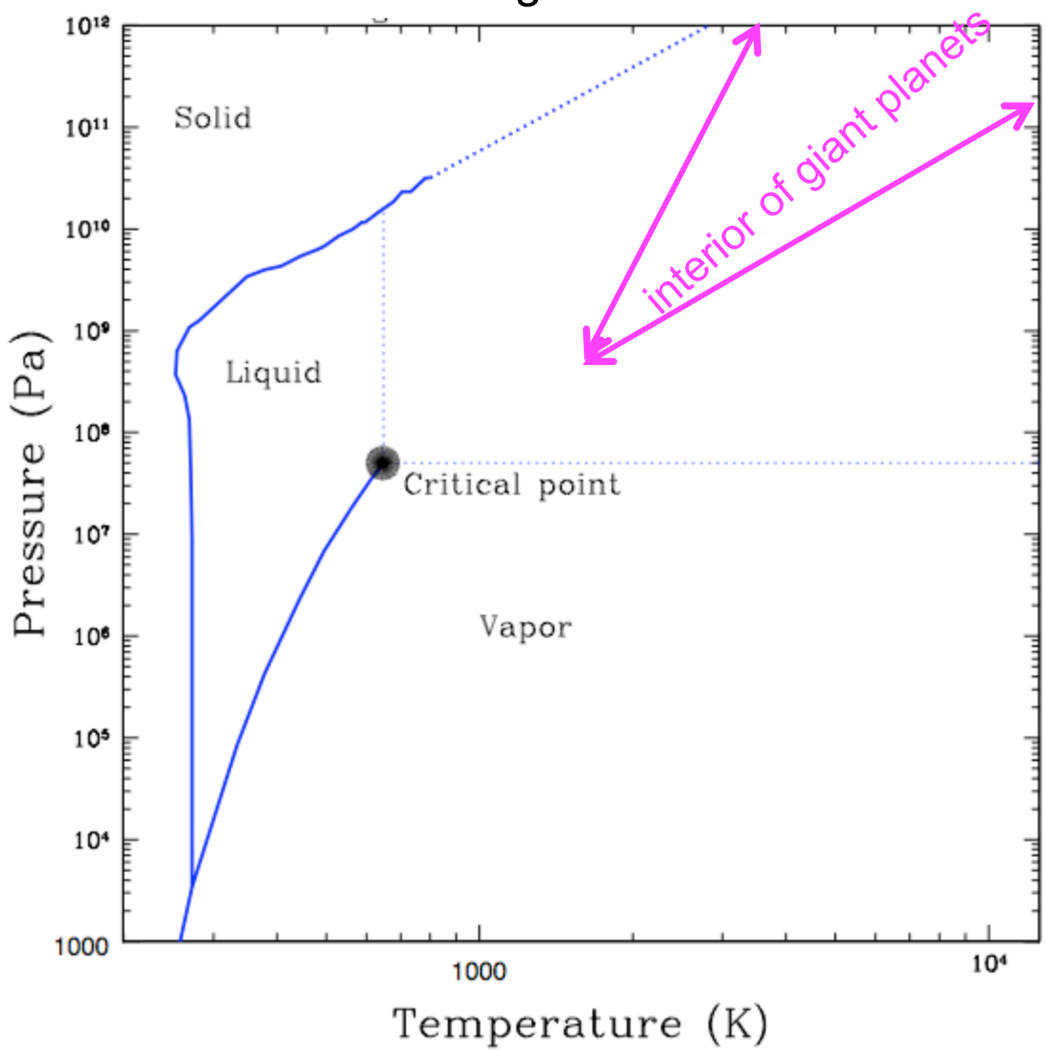
Mostly used EOS: ANEOS (Sandia) et SESAME (Los Alamos)

H_2O or « ice » (H_2O, CH_4, NH_3)

Rock ($MgSiO_4$, $MgSiO_3$, etc..)

Fe

Phase diagram of water



- **Distribution of heavy elements in planets**

---> 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?

Z=50%

----> « all Z in the core » versus

« H/He/Z mixture in the entire planet »:

up to ~ 30 % effect on R at a given age

Baraffe, Chabrier, Barman 2008, 2010

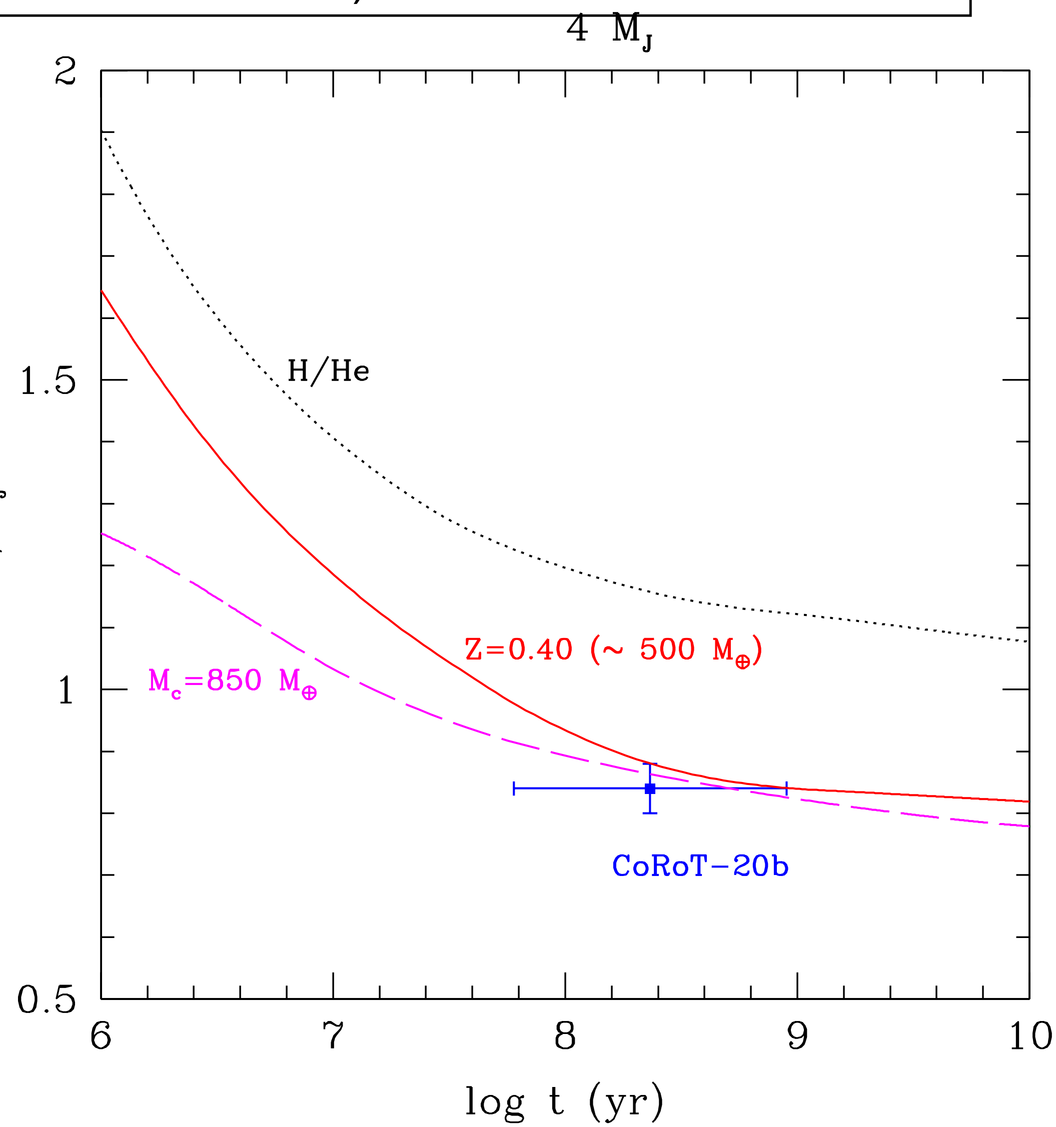
Bulk composition can provide a signature of the formation process (e.g. large heavy material content)

A very interesting case:
CoRoT20b
(4 M_{Jup} 0.8 R_{Jup})

Deleuil et al. 2012

Requires ***too massive core*** *of heavy material to explain its radius (maximum amount of heavy material in the disk ~ 800 M_{earth})*

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

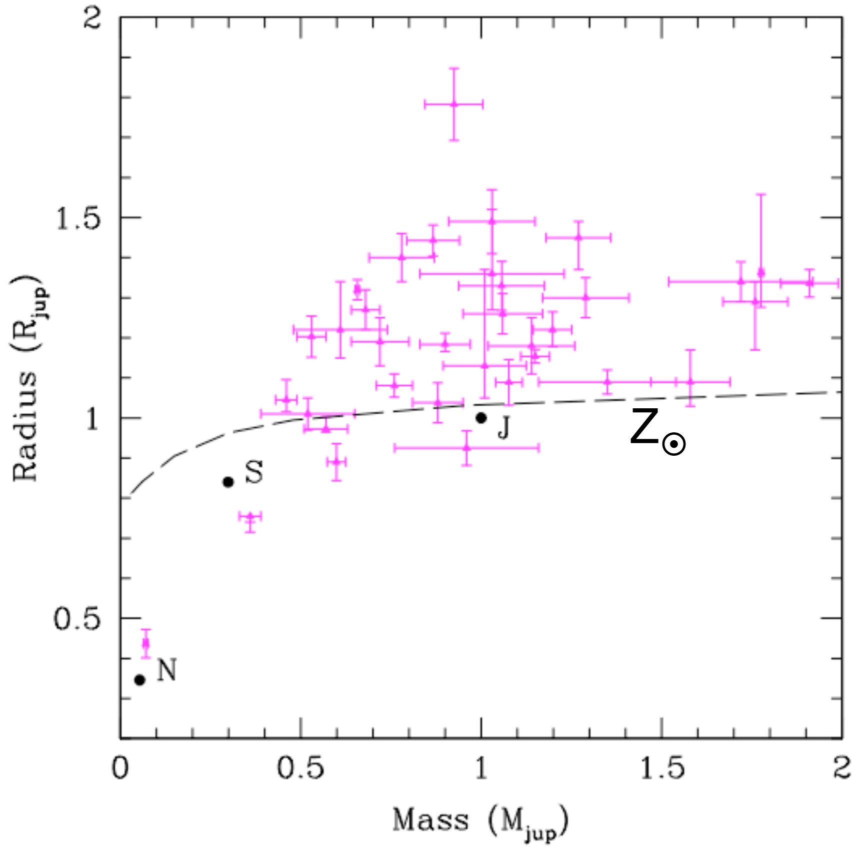


II-b) Inner structure models: inflated planets

Significant fraction of exoplanets with abnormally large radius

Missing physics in planetary interior models?

Several suggestions to explain this puzzle

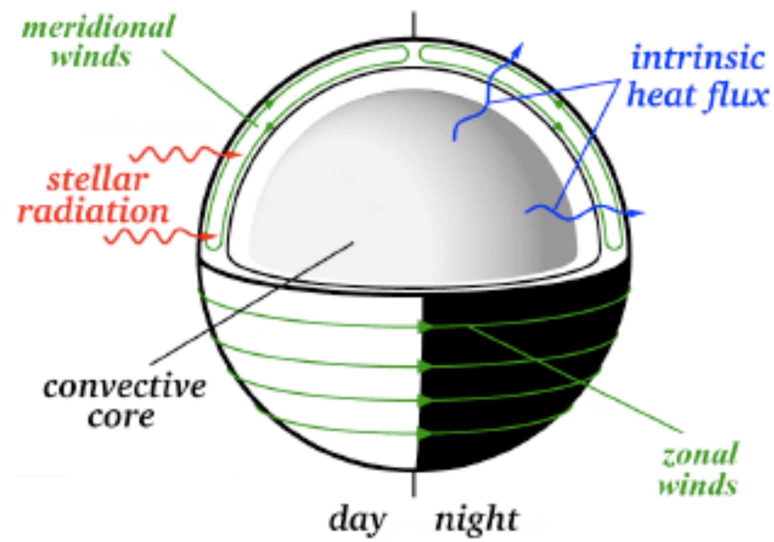


a) Atmospheric circulation: Showman & Guillot 2002

----> irradiation from the parent star
creates strong winds

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

→ *Heats the planet and slows down the contraction*



Atmospheric circulation models (GCM) *(Cho, Menou, Showman, etc....)*

☛ Adaptation of the **Exeter Met Office climate code** to exoplanets (can extend deeper than standard GCM codes, ***see poster D. Acreman***)

☛ **Study deep circulation pattern**

☛ **Effect of circulation on planet spectral signatures**
(link with observations: HST, ECHO)

b) Reduced heat transport: *Chabrier & Baraffe 2007*

- Phenomenological approach

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

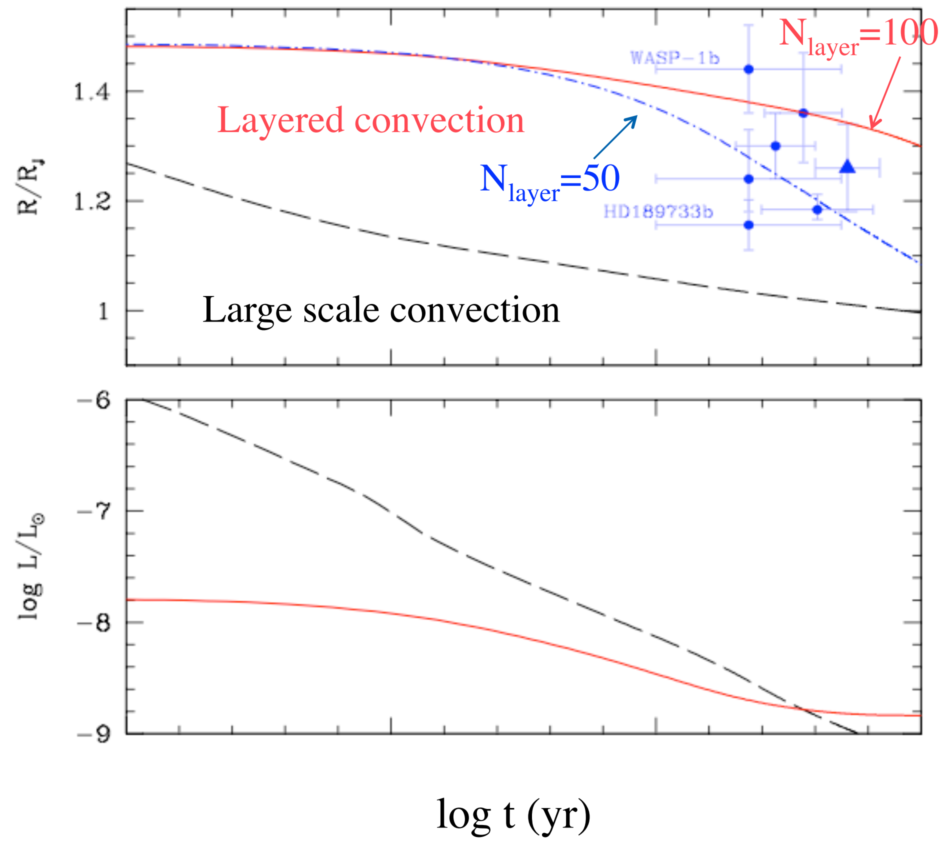
⇒ « layered convection » : system of convective layers + thiny diffusive layers

(double diffusive convection or semiconvection)

<u>Main effect:</u> **slow down** the evolution because of reduced heat transport in the interior

☛ planets with larger R

☛ Luminosity at young ages (< a few Gyr) **much lower** *(testable with Sphere, Gemini Planet Imager)*



1 M_J irrradiated by a Sun at a=0.05AU

- **Double-diffusive convection in Jupiter and Saturn?**
  (Leconte & Chabrier 2012,A&A, in press)

☛ 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 $M_\oplus$
  M_{env}(heavy) = 41 - 64 $M_\oplus$ ⇒ Z_{tot} = 13% - 20%

- Saturne: M_{core}= 12 - 21 $M_\oplus$
  M_{env}(heavy) = 10 - 24 $M_\oplus$ ⇒ Z_{tot} = 28% - 44%

Inhomogeneous models for Jupiter and Saturn are significantly more enriched in heavy material (30%-60% more) than previously thought ☛ change our standard picture of "homogeneous" layers

Rosenblum, Garaud, Traxler, Stellmach 2011: 3D numerical simulations

➡ Layers can form in low-Pr (< 1) double diffusive convection

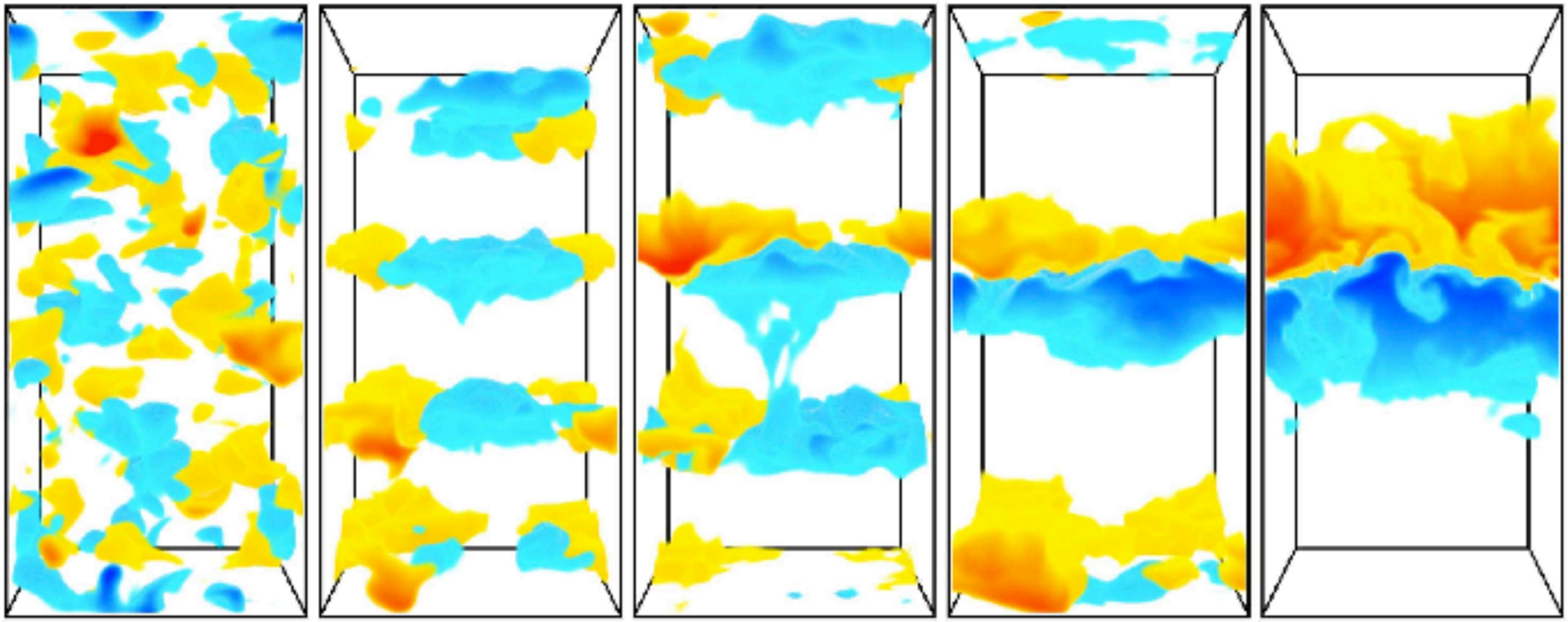


Fig. 5.— Volume-rendered visualization of the mean molecular weight perturbation, for

Question: do all layers merge or do the mergers stop and equilibrium layers form with height << size of system??

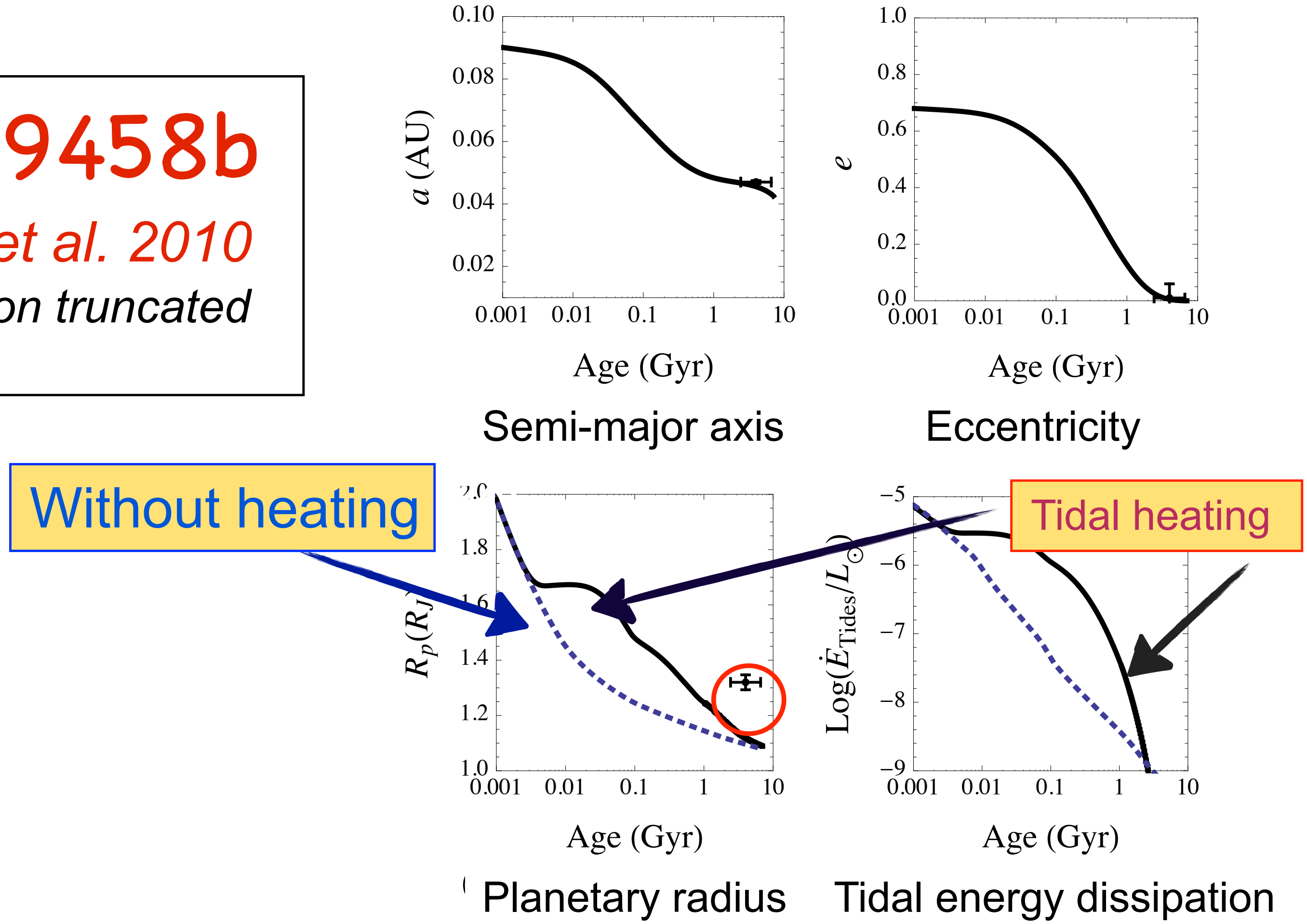
c) Tidal heating

(Bodenheimer et al. 01; Jackson et al. 08; Miller et al. 2009; Leconte et al. 2010)

HD 209458b

Leconte et al. 2010

(tidal model non truncated in eccentricity



☛ **Difficult to explain with tidal effects alone properties of most inflated planets**

The future: *(some future developments)*

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

Progress are coming!

- Ongoing and future high-pressure experiments (Livermore, Sandia in the US; LIL and Laser Megajoule in France)
- First principle numerical methods (DFT, path integral, quantum molecular dynamics)

• Development of **numerical simulations** to confirm the existence and stability 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!

• Development of **dynamical atmospheric models** (heating/cooling + circulation + radiative transfer)

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

☛ Effect on spectral signatures