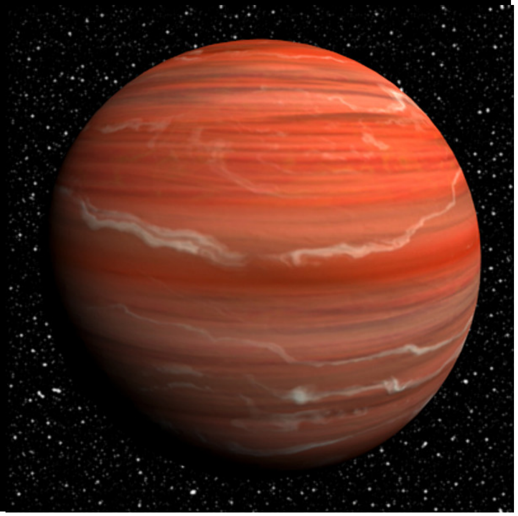
Giant Planet Formation & Internal Structure

Ravit Helled

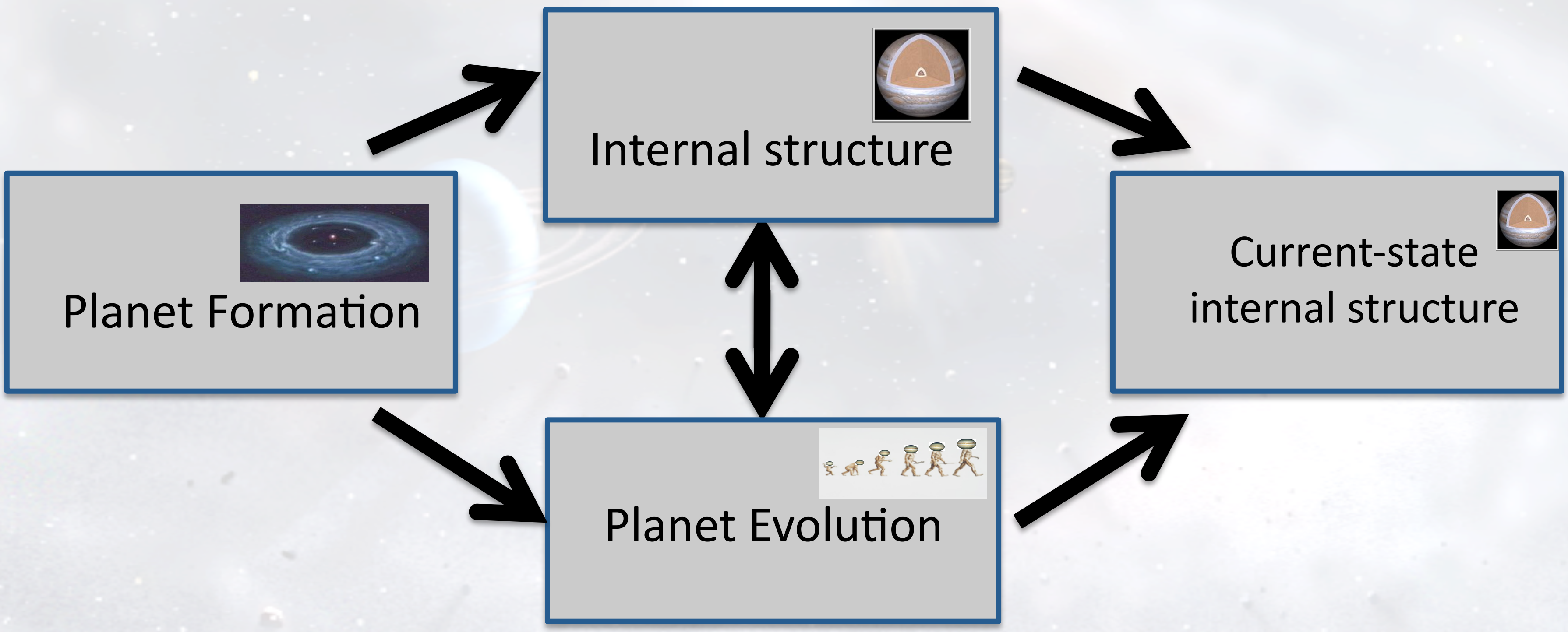
Tel-Aviv University

The Astrophysics of Planetary Habitability, Vienna, Feb. 2016

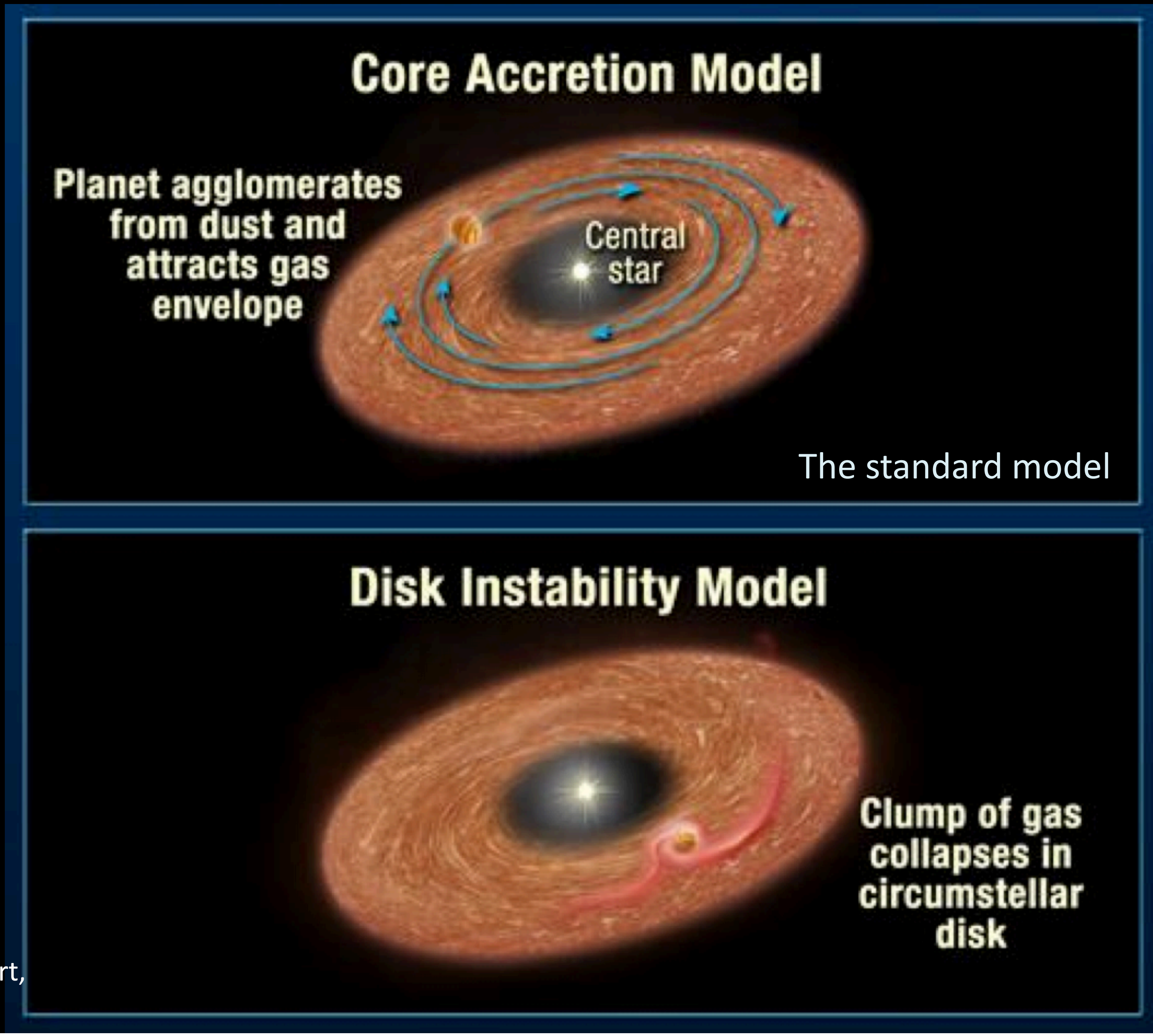


Linking planet formation and internal structure is not easy

Need to combine planet formation, evolution, and internal structure self-consistently

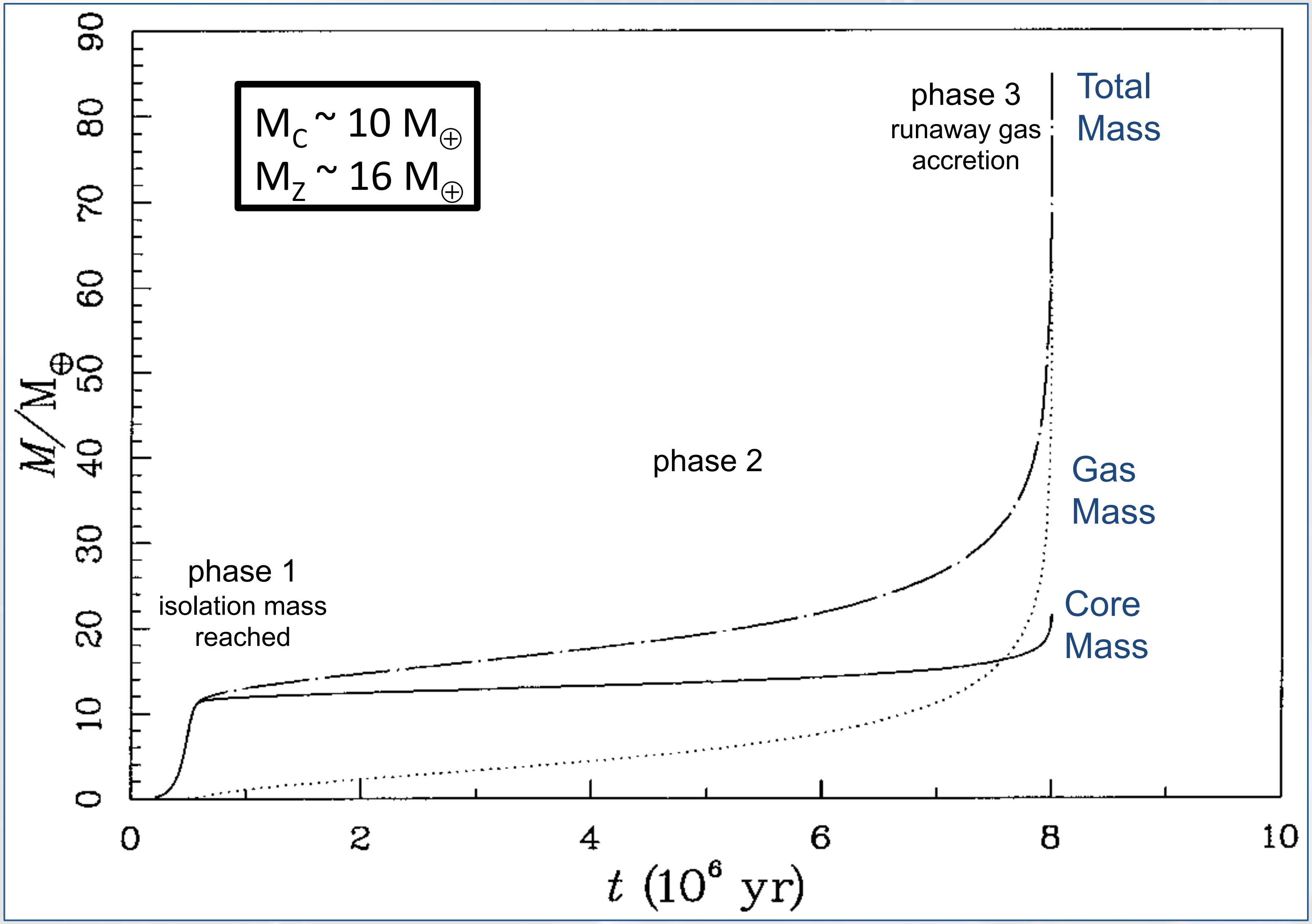


Two models for giant planet formation



Talks by Y. Alibert, E. Vorobyov

A standard core accretion model for Jupiter's formation



Pollack et al., 1996

$$d = 5.2\ \mathrm{AU} \qquad \sigma_{solids} = 10\ \mathrm{g\,cm^{-2}}$$

$$T_{neb} = 150\ \mathrm{K} \quad \rho_{neb} = 5 \times 10^{-11}\ \mathrm{gcm^{-3}}$$

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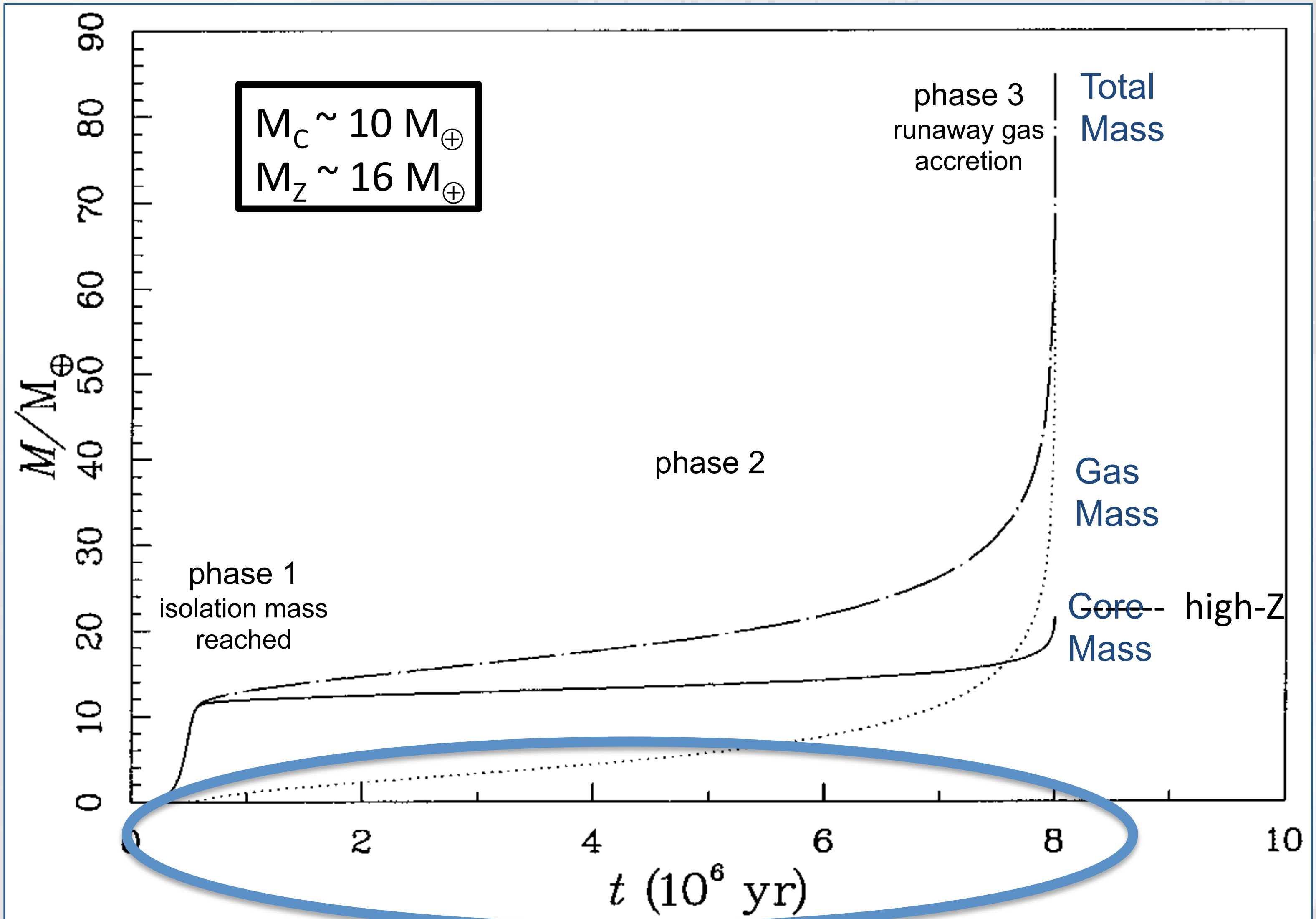

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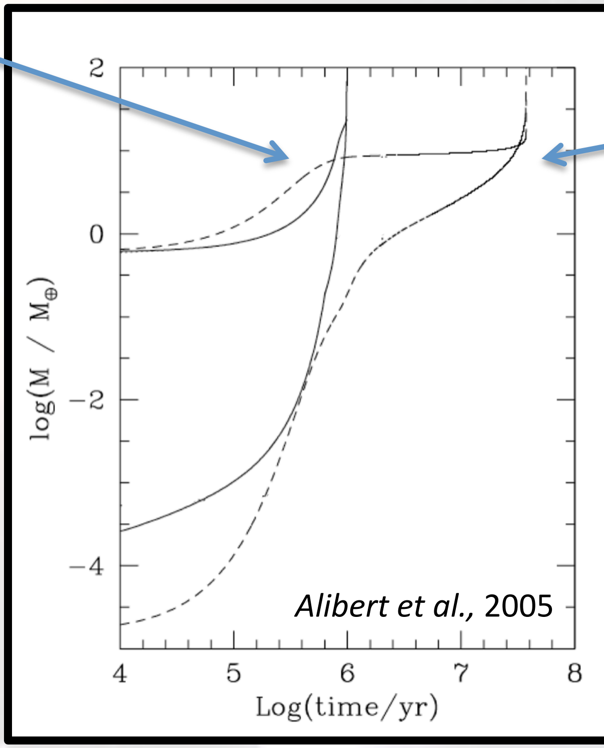
*** Reducing formation timescale by migration:**

a migrating planet starting at 8 AU (no gap)

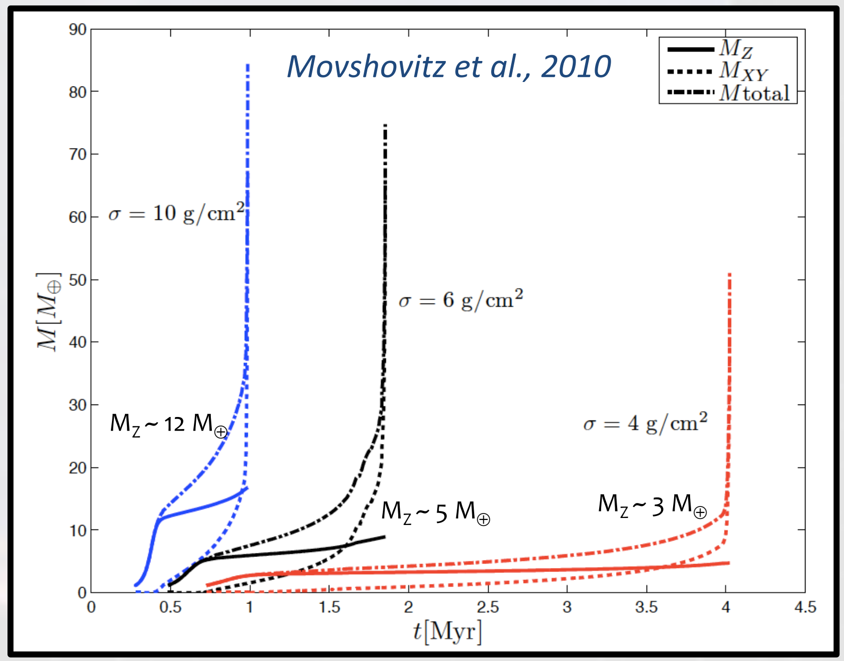
in situ formation 5 AU



A migrating Jupiter has $M_Z \sim 30\ M_\oplus$

Total heavy element mass (core+envelope) and gaseous (H/He) mass vs. time, until cross-over mass is reached.

*** Reducing formation timescale by grain settling (opacity reduction):**



Different final compositions;
High-Z mass can be very small!

Core Accretion: predicted composition

Giant planets formed by *CA* can have a large range of metallicities:

$$Z_{planet} = (M_c + M_{z\_env})/M_{tot}$$

$Z_{planet} < Z_\star$: accreted gas is metal-poor & core mass is small

$Z_{planet} \sim Z_\star$: accreted gas has stellar composition & core mass is small or accreted gas is metal-poor & core mass is large

$Z_{planet} > Z_\star$: accreted gas has stellar composition & core mass is large and/or much planetesimals are accreted during rapid gas accretion

… and of course other options are possible…

..the more massive the planet, the more metal-poor it is…

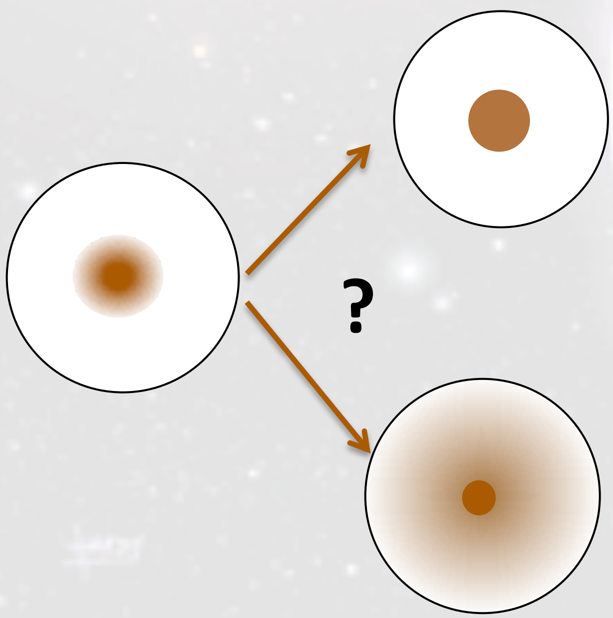
see Helled et al. 2011, 2014 for details

Core mass predicted from formation models

- Innermost region above a **~2 $M_\oplus$** core can have a very high heavy-element mass fraction but extremely high temperatures (10^4 K).
- Does this region join the core or does it mix with the gaseous envelope?
- What happens during runaway gas accretion?

	σ (g cm^{-2})	r_{pls} (km)	t_{cross} (Myrs)	Mz ($M_\oplus$)	$Mc_{,z=0.9}$ ($M_\oplus$)	$Mc_{,z=0.5}$ ($M_\oplus$)	Mc_{mix} ($M_\oplus$)
Case I	10	100	0.95	16	**15**	17.5	**1.66**
Case II	10	1	0.9	15.9	**15.1**	18.4	**2.33**
Case III	6	100	1.54	7.6	**5.6**	7.7	**1.03**

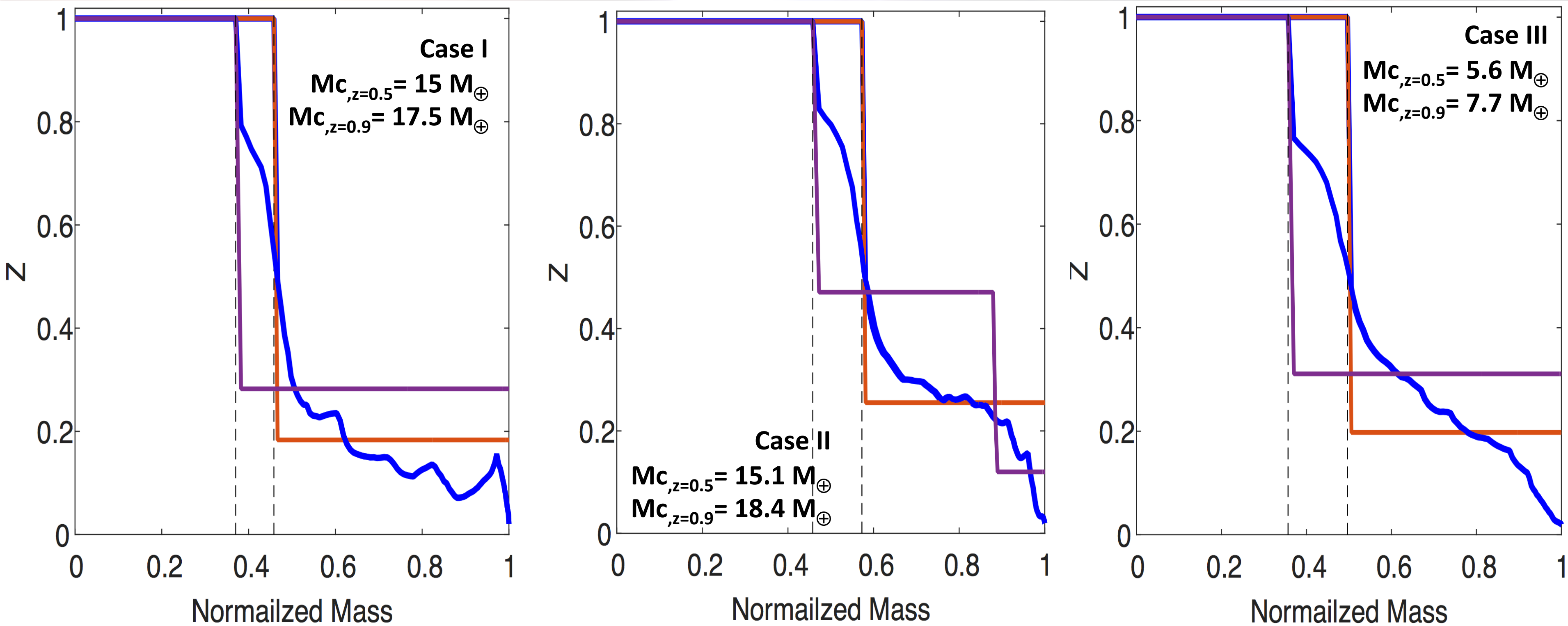
Core mass depends on the formation model, but also on the way we define the core….



Heavy-element distribution in giant protoplanets

The heavy elements are gradually distributed in proto giant planets.
The gradient in heavy depends on σ - the <u>higher</u> σ is, the <u>less gradual</u> is the distribution in heavy elements.

No mixing is allowed

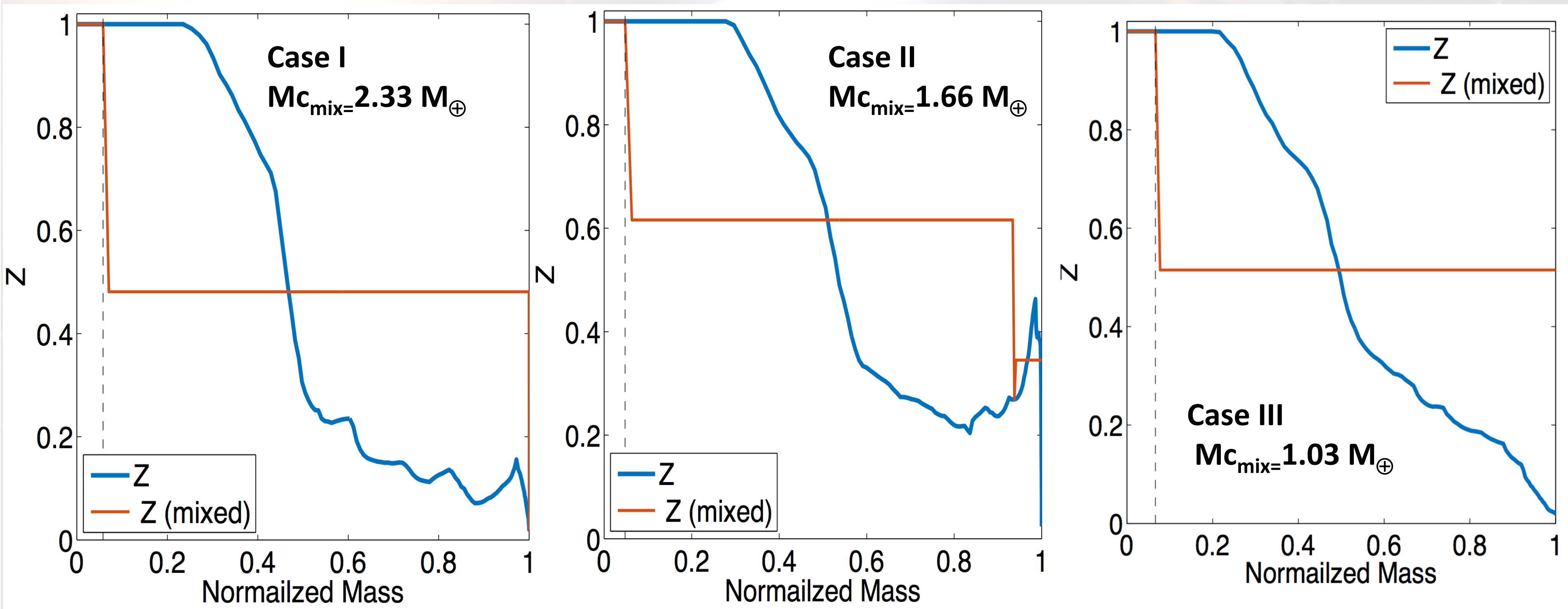


The distribution of heavy elements before (blue) and after mixing (red, purple) at crossover mass. The purple and red curves correspond to $Mc_{,z=0.5}$ and $Mc_{,z=0.9}$, respectively.

WORK IN PROGRESS

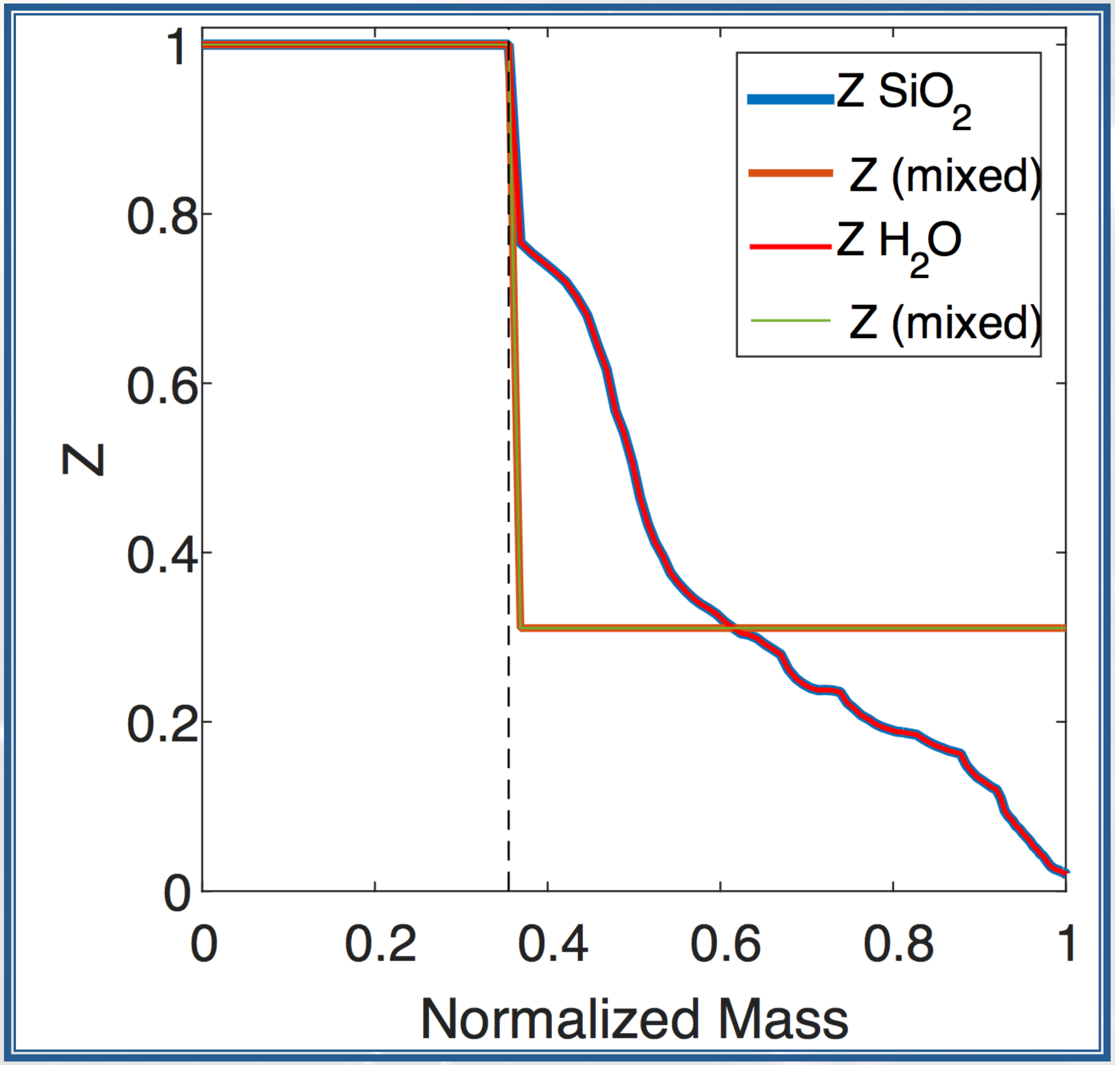
Defining the core according to convection (mixing) criterion

• The core mass (region) is defined as the innermost stable region in the planet, Mc_{mix}. In this case, Jupiter's core mass is found to be significantly smaller, **1--2.3 $M_\oplus$**.



Predicted core mass is small even for high σ cases, with a total high M_Z

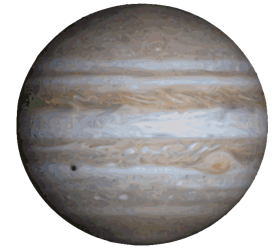
Dependence on heavy element composition



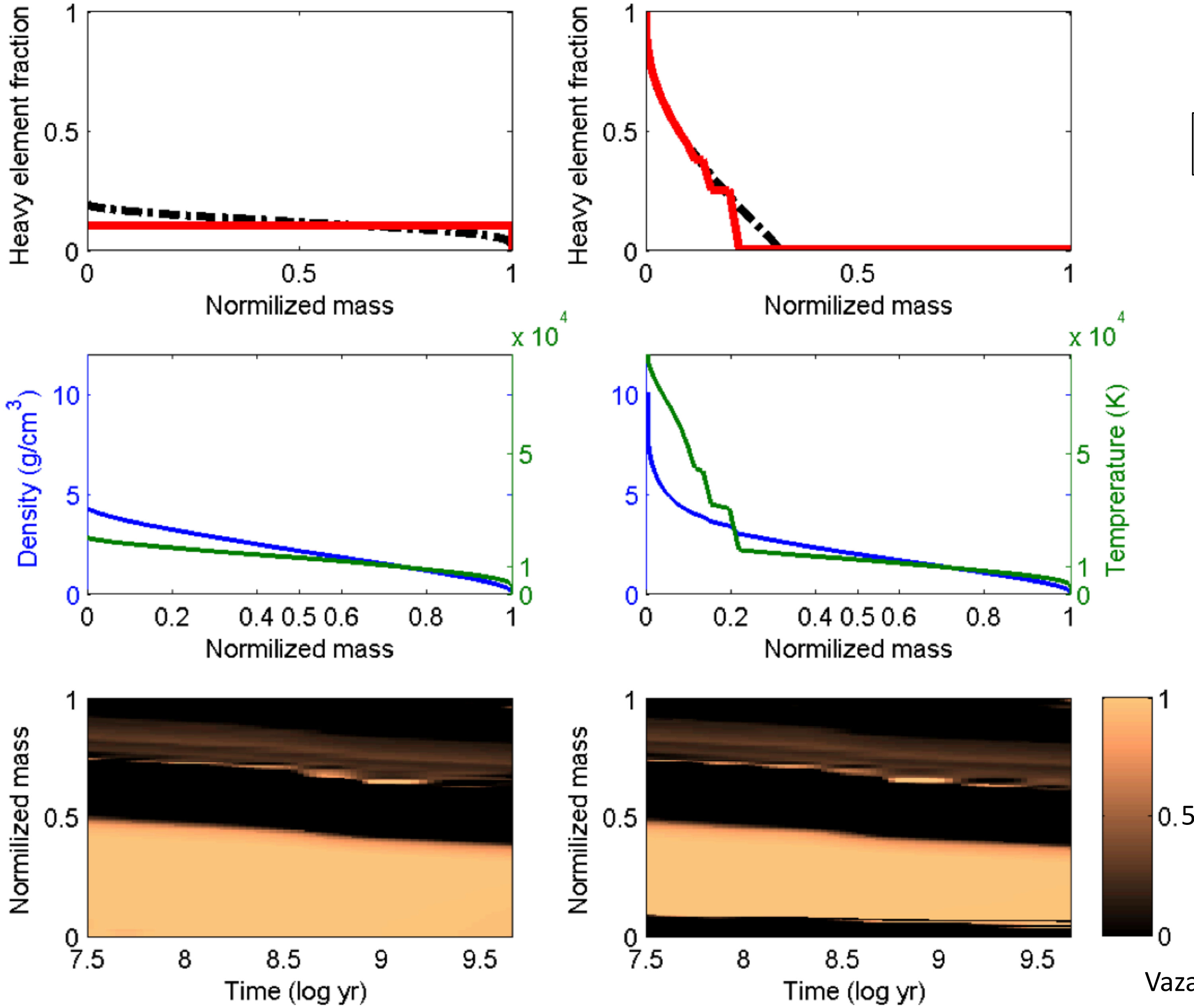
The distribution before and after mixing at crossover mass for Case I when the heavy elements are represented by SiO_2/H_2O.

The assumed high-Z material has a negligible effect on the stability-convection criterion, and therefore, on the derived distribution of heavy elements.

Jupiter's evolution for different primordial structure (but the same bulk composition)



$M_z = 33\ M_\oplus$



$T_{eff} = 124$ K

Vazan et al. in prep.

Advances in GP theory for interpretation of the M-R relation

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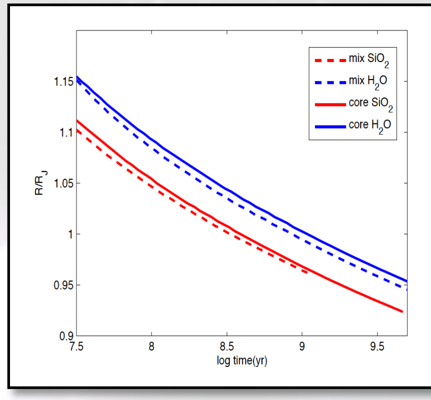
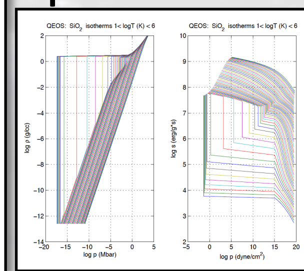
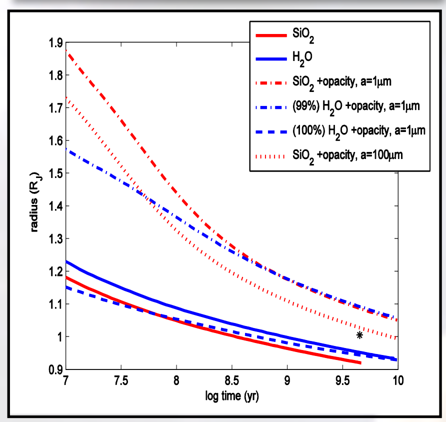
A better understanding of M-R (t)

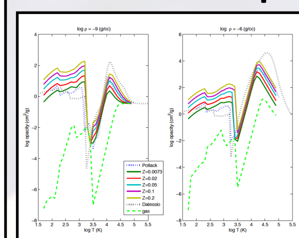


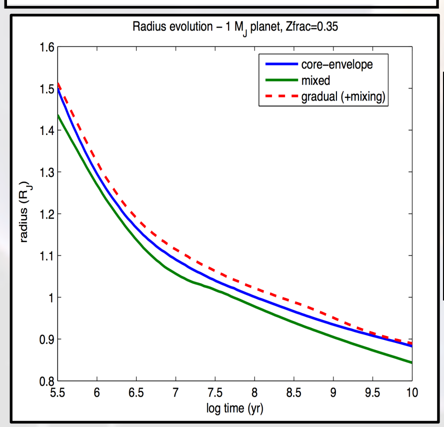
Equation of state



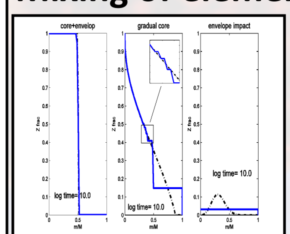


Gas and dust opacity





Mixing of elements



Vazan et al., 2013, 2014

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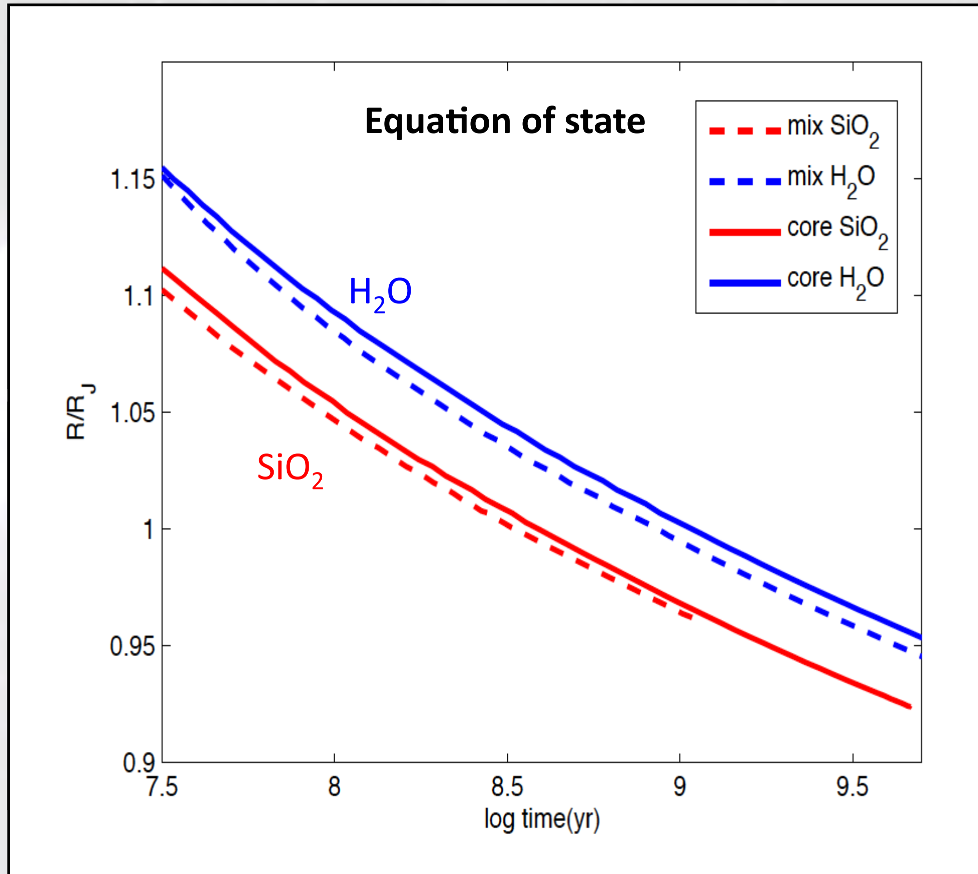

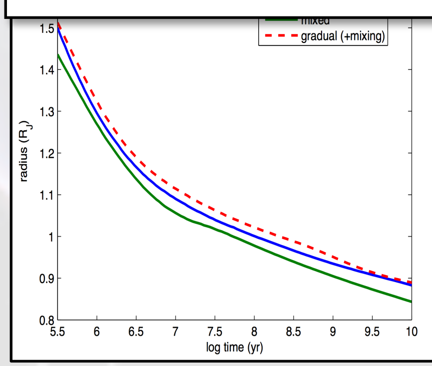

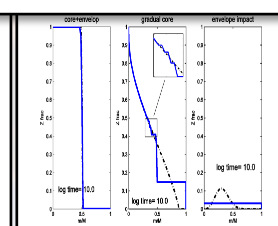

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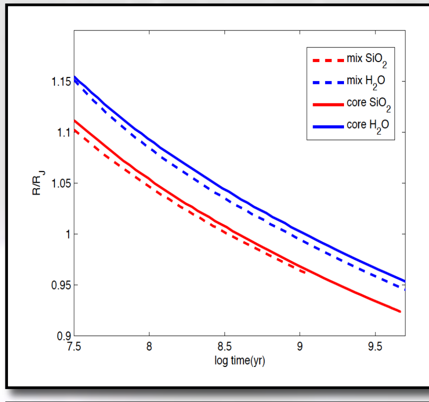

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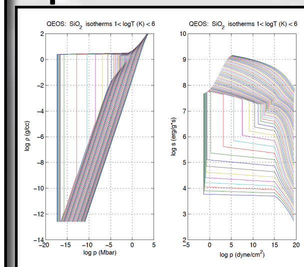
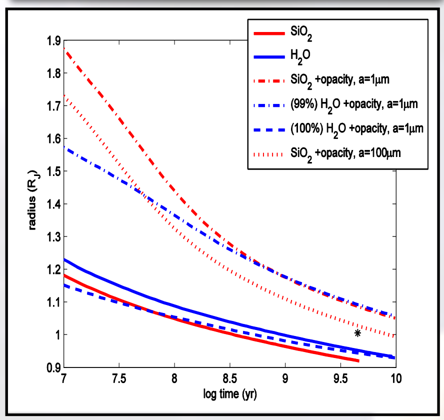
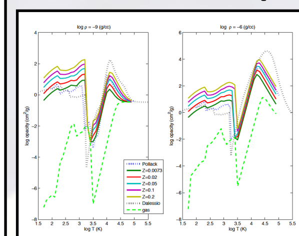
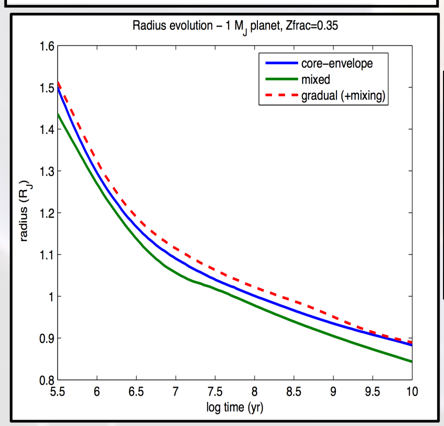




Gas and dust opacity





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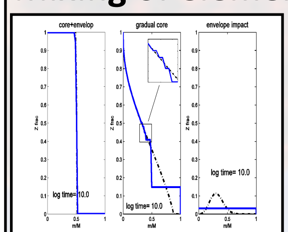

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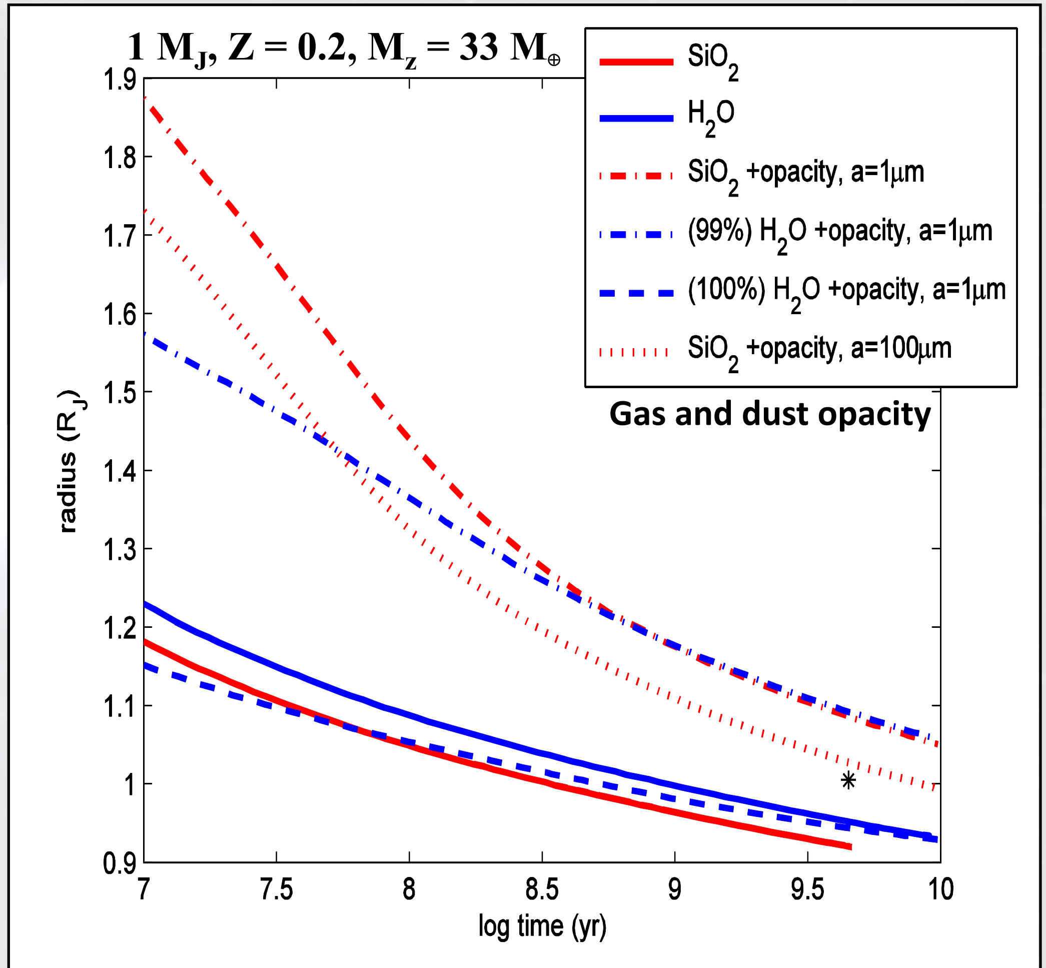

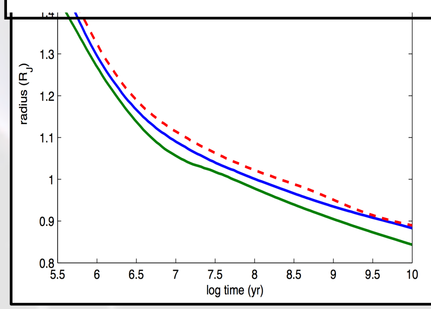

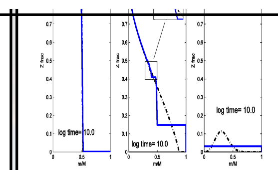

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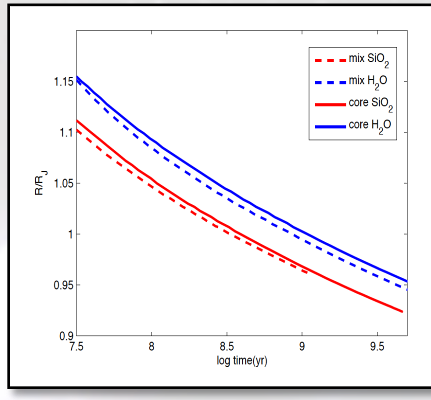

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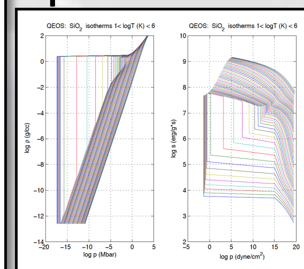

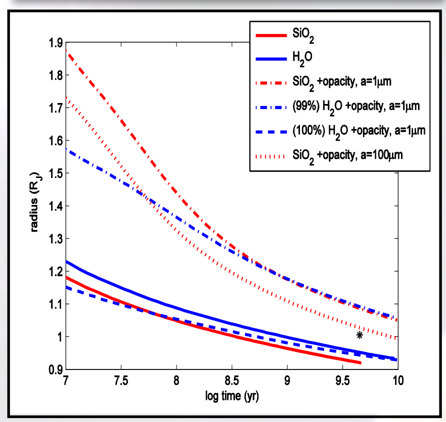

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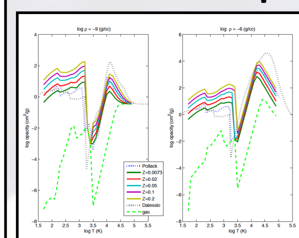

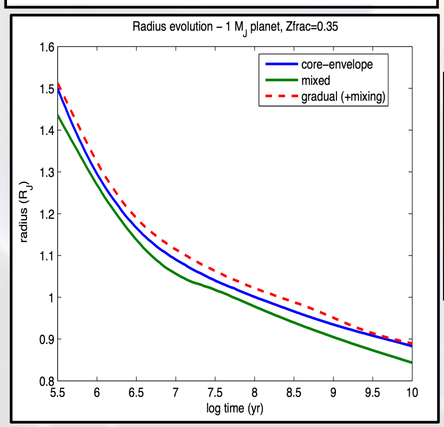

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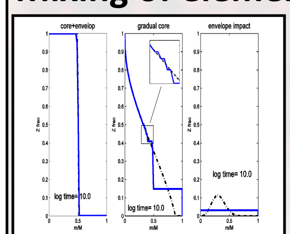

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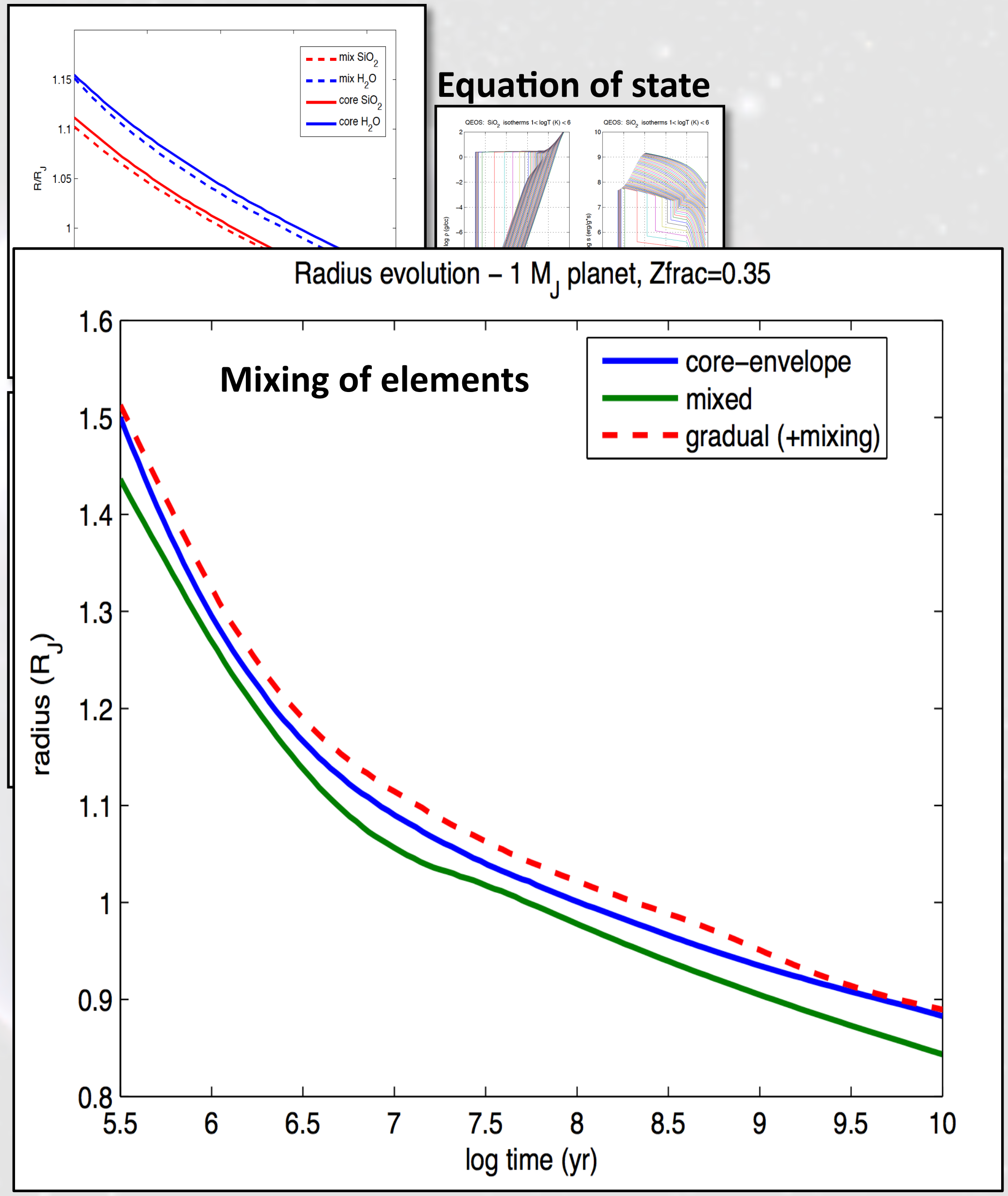
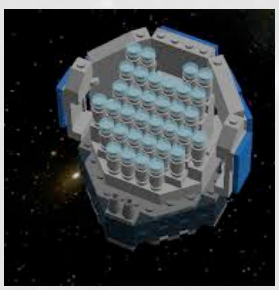


The Importance of planetary evolution & age

- Giant planets may have compositional gradients that can affect their cooling rate.
- Planetary internal structure (and even composition) can change with time!
- Planetary evolution cannot be neglected – it can affect the radius and the distribution of materials within the planet. The mass-radius diagram is time dependent, M-R (time).



We need to constrain the stellar/planet age

Conclusions and future work

- There is no unique composition predicted from the CA model, and the core mass is not well-defined. The bulk compositions of giant planets depend on their birth environment.

- Processes such as differentiation, mixing, accretion, outgassing, core erosion, atmospheric loss, impacts & collisions should be consider in planetary formation and evolution models.

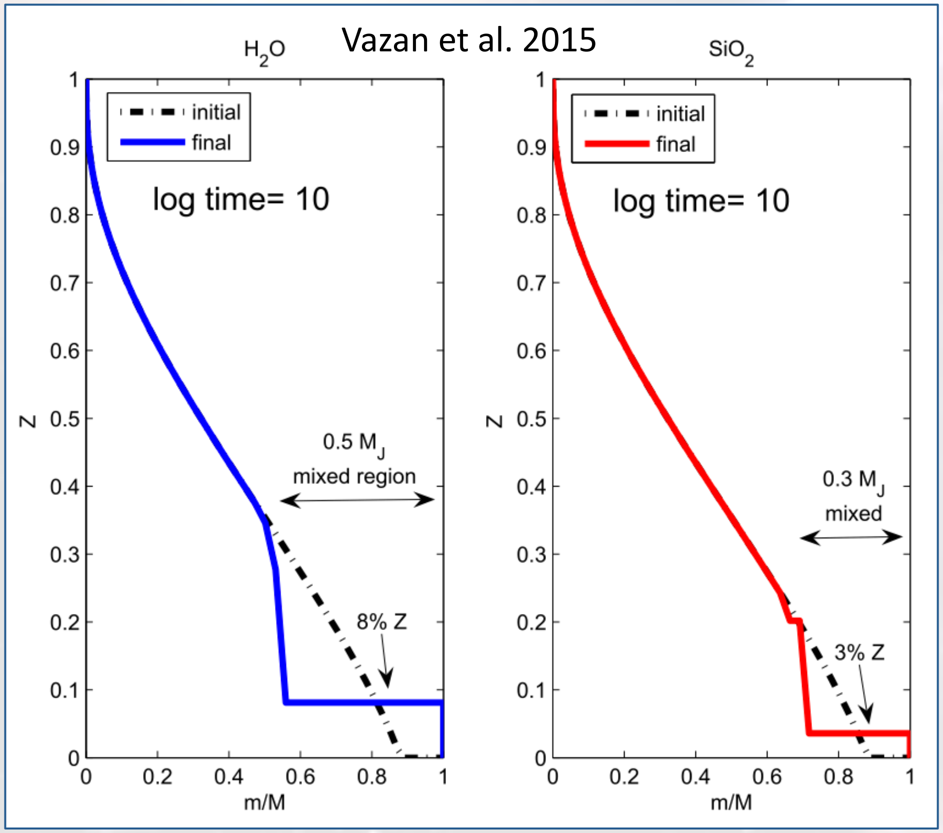
- In order to better characterize (giant) planets we need a new generation of planetary models combining: formation, evolution, and internal structure.


Thank you

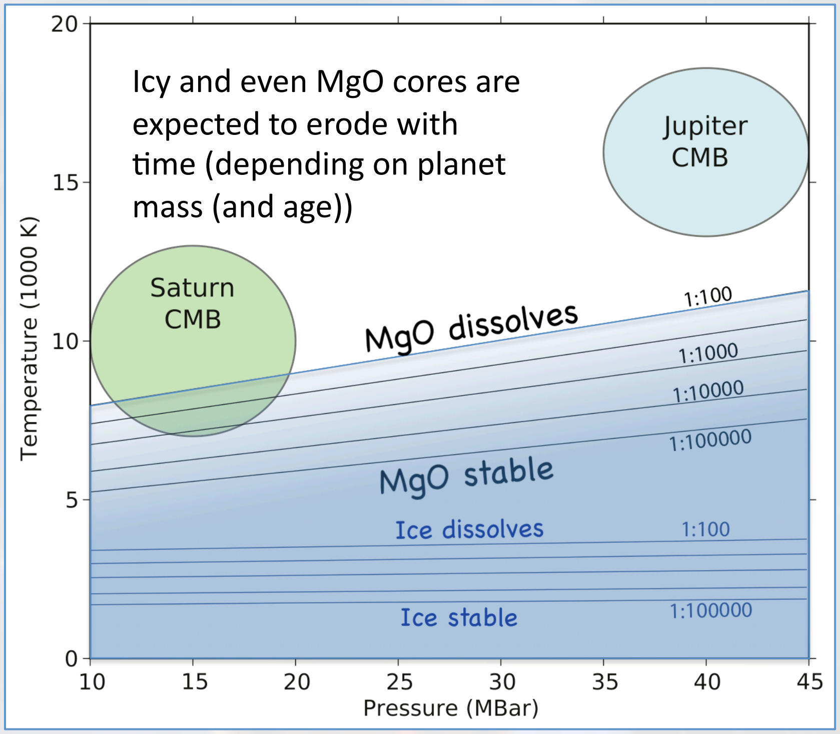
Extra slides

Re-distribution of heavy elements

The distribution of heavy elements can change with time due to **convective mixing,** while the core mass can decrease with time by **core erosion.**

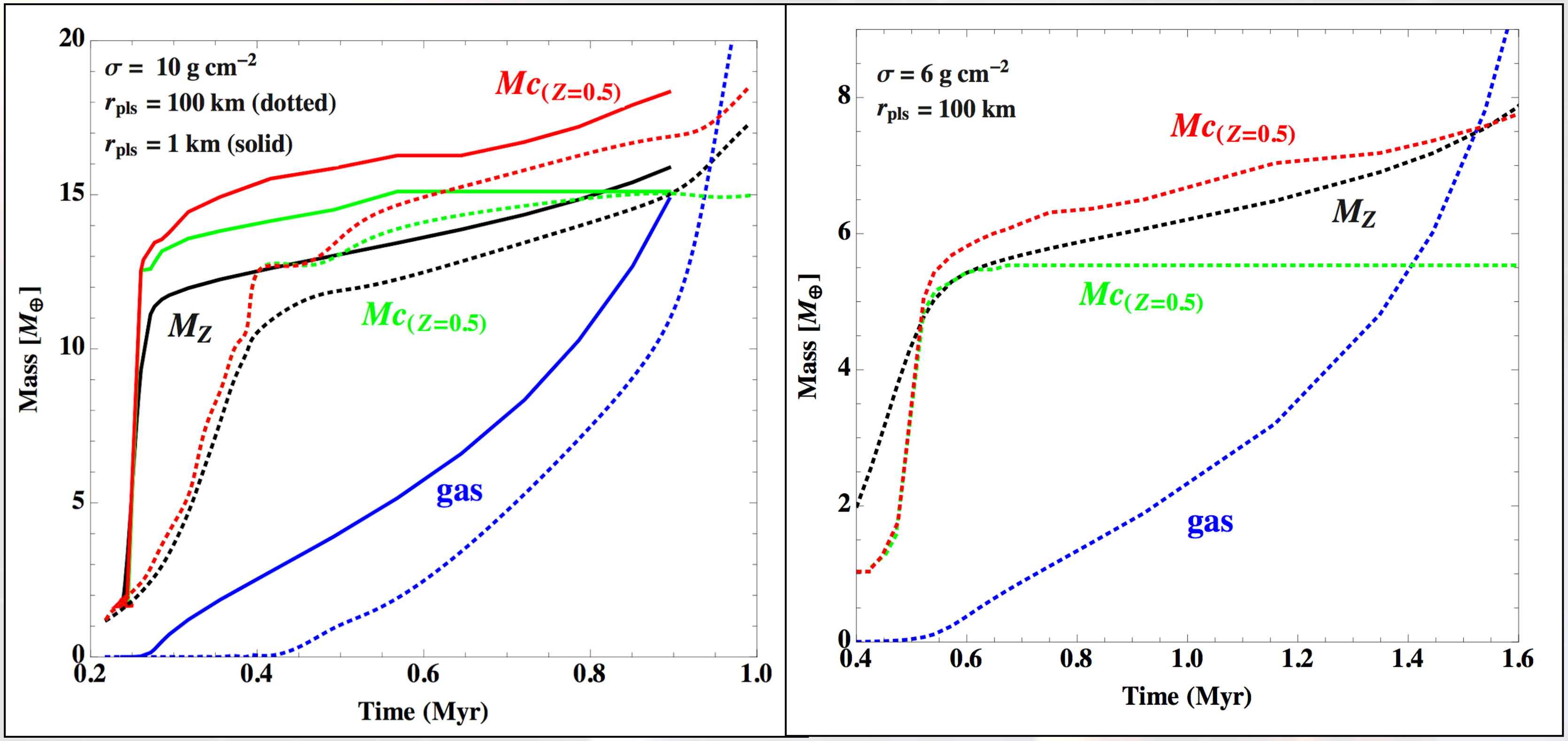


Convective mixing can change the heavy-element distribution as the planet evolves. Mixing efficiency depends on the composition and its distribution.



Simulations predict water ice is unstable above 3000 K when exposed to metallic hydrogen. Work by B. Militzer and collaborators…

Jupiter's growth – different CA formation models



The dotted and solid lines correspond to planetesimal sizes of 100 km and 1 km, respectively. The black and blue lines show the heavy-element and gaseous masses. The green and red lines correspond to calculated core masses when the "core region" is defined as the innermost regions with Z=0.5 and Z=0.9, respectively.