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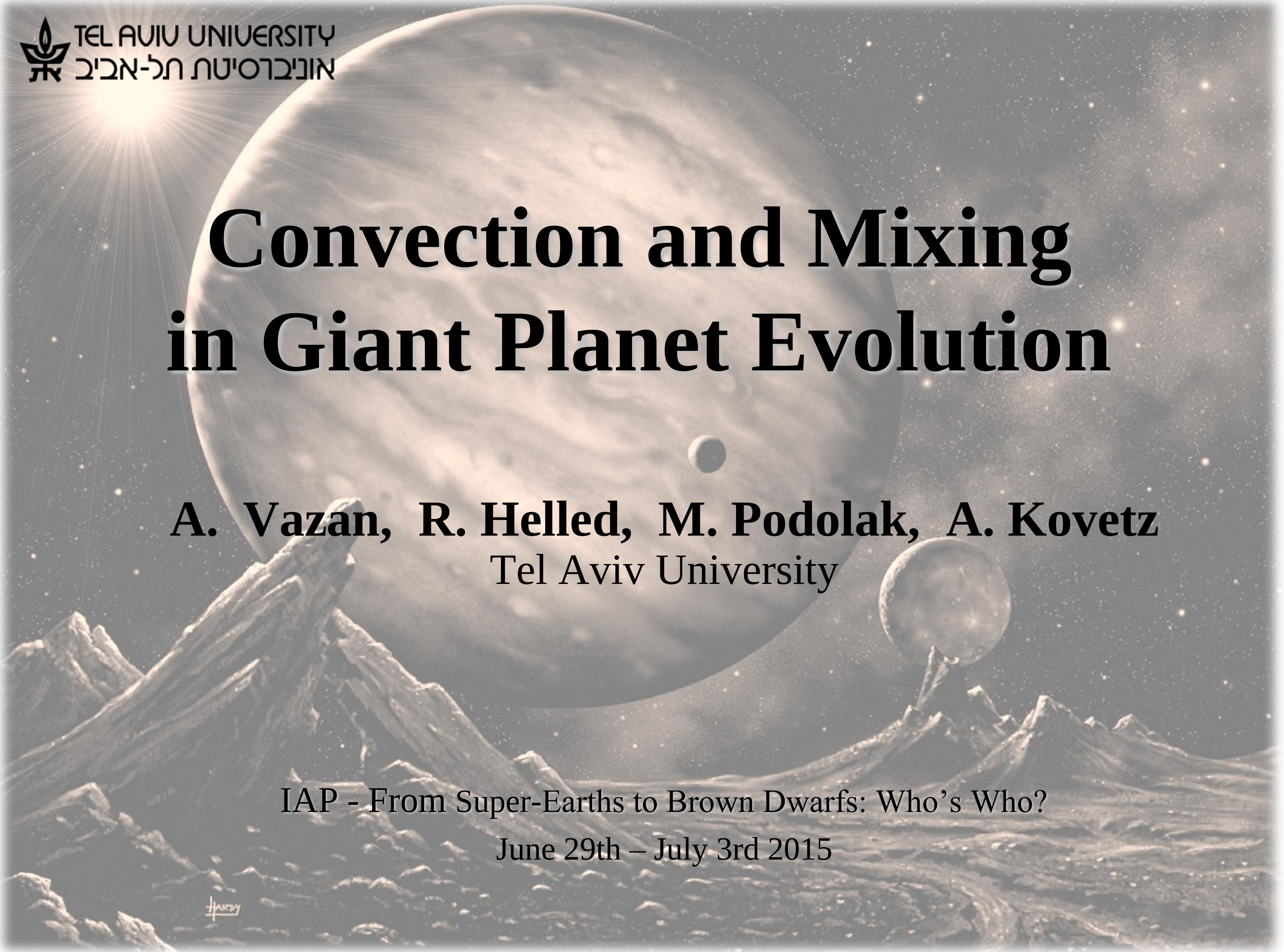

Convection and Mixing in Giant Planet Evolution

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IAP - From Super-Earths to Brown Dwarfs: Who's Who?

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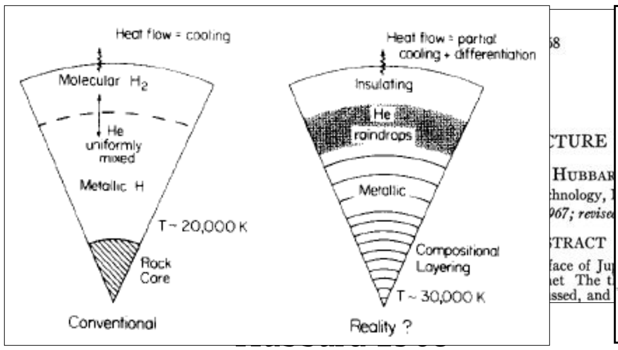
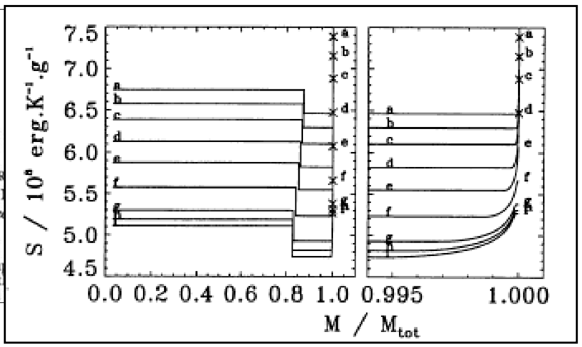
Giant Planet Evolution

Heat transport efficiency affects radius-mass-luminosity in time.

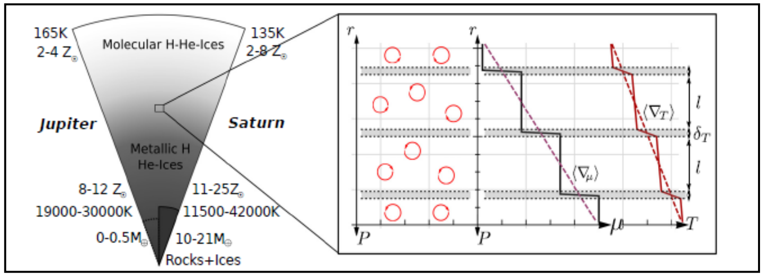


Stevenson 1985



Guillot et al. 1995

"The assumption of large-scale convection in planetary interiors has never been proven to be correct and even slightly inefficient convection can have a major impact on the planet's structure and evolution." (Chabrier & Baraffe 2007)

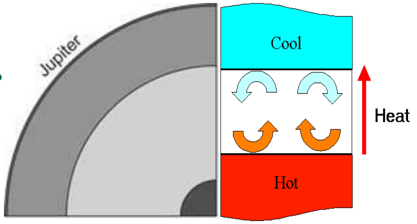


Leconte & Chabrier 2012

Internal Structure
Composition Distribution

Composition distribution affects the heat transport (Ledoux).

➢ Different internal structures have different cooling rates.



The primordial internal structure?

- Uniformly mixed / distinct homogeneous regions.
- Composition gradients:
  - ➢ Immiscibility of materials in hydrogen, helium phase separation (rain). *Stevenson & Salpeter 1977, Wilson & Militzer 2012*
  - ➢ Planetesimal dissolution in the envelope *e.g., Iaroslavitz & Podolak 2007*
  - ➢ Core erosion *Stevenson 1982, Guillot et al. 2004, Lissauer et al. 2007*
  - ➢ Rotation and magnetic fields effects *Chabrier et al. 2007*

Internal structure ➔ convection efficiency ➔ cooling rate

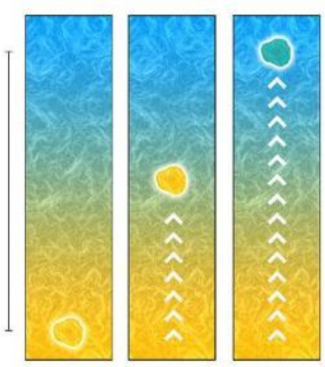
Convective regions ➔ mixing of materials

Modeling Convective-Mixing

Heat transport

$$\frac{\partial \ln T}{\partial m} = \nabla \frac{\partial \ln p}{\partial m}$$

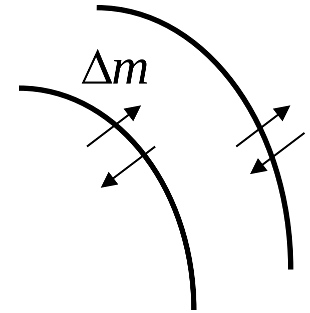
$$\nabla = \begin{cases} \nabla_R, & \nabla_R \le \nabla_A + \nabla_{Ledoux} \\ MLR, & \nabla_R > \nabla_A + \nabla_{Ledoux} \end{cases}$$



Mixing Length Recipe

Material transport

$$\frac{\partial Y_j}{\partial t} = \frac{\partial F_j}{\partial m}$$



$$F_j = -\sigma \frac{\partial Y_j}{\partial m}$$

Mutual effect

$$\sigma = \left(\frac{dm}{dr}\right)^2 D_c$$

$$D_c = \begin{cases} K v_c l_c, & convective \\ 0, & radiative \end{cases}$$

Evolution Model

Continuity $$\frac{\partial}{\partial m}\frac{4\pi}{3}r^3 = \frac{1}{\rho}$$

Hydrostatic equilibrium $$\frac{\partial p}{\partial m} = -\frac{Gm}{4\pi r^4}$$

Energy transfer $$\frac{\partial \ln T}{\partial m} = \nabla \frac{\partial \ln p}{\partial m}$$

Energy balance $$\frac{\partial u}{\partial t} + p\frac{\partial}{\partial t}\frac{1}{\rho} = q - \frac{\partial L}{\partial m}$$

Composition balance $$\frac{\partial Y_j}{\partial t} = R_j - \frac{\partial F_j}{\partial m}; \qquad F_j = -\sigma_j \frac{\partial Y_j}{\partial m}$$

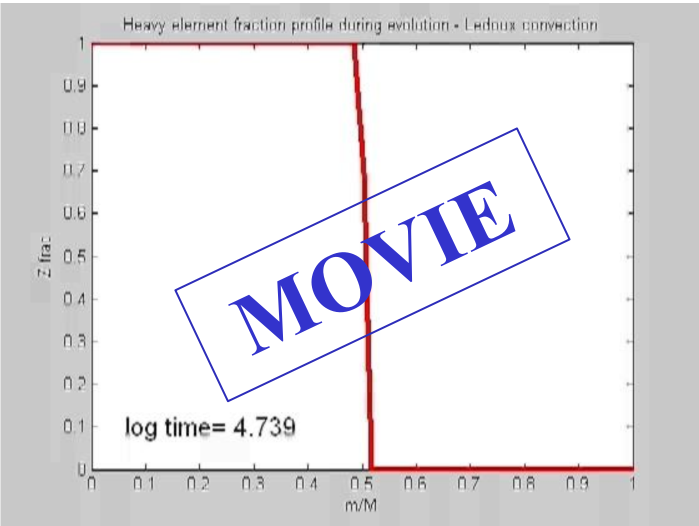
Adaptive mesh grid: $$f = \left(\frac{m}{M}\right)^{2/3} - c_2 \ln p - c_3 \ln\left(\frac{T}{T + c_4}\right) + c_5 \ln\left(r^2 + c_6\right)$$

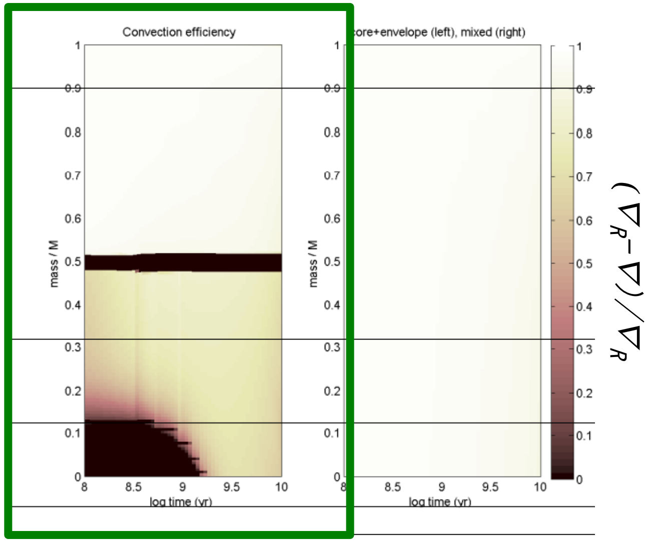
Opacity: radiative + conductive

EOS for a mixture

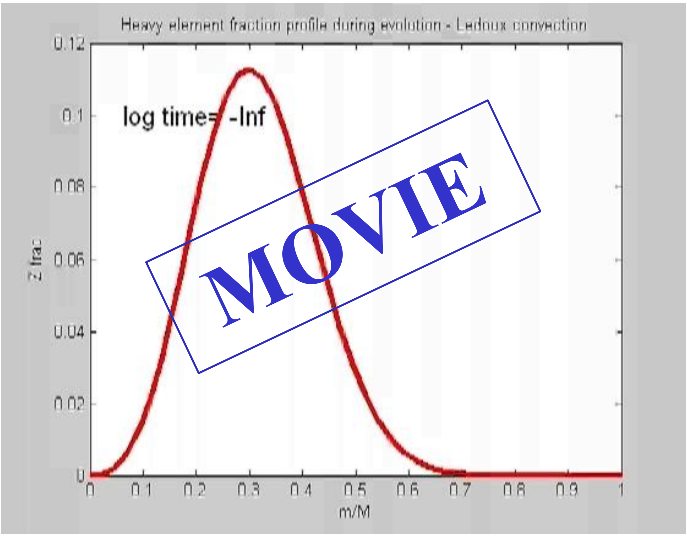
Internal structure

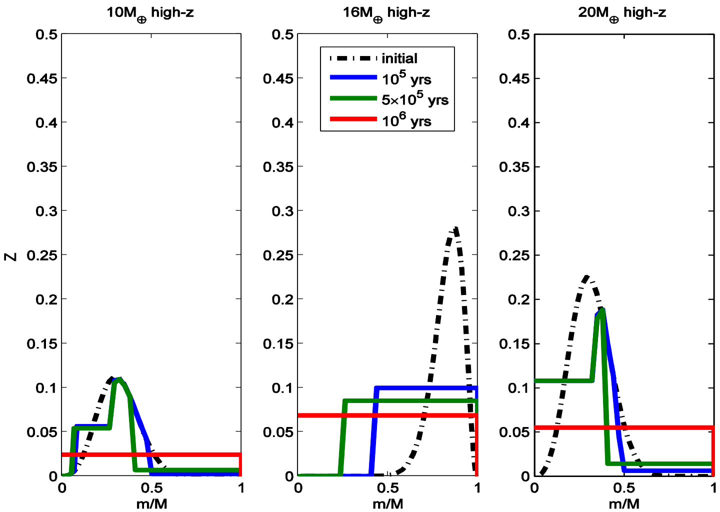
Heat transport





Core-envelope boundary prevents convection and convective-mixing.

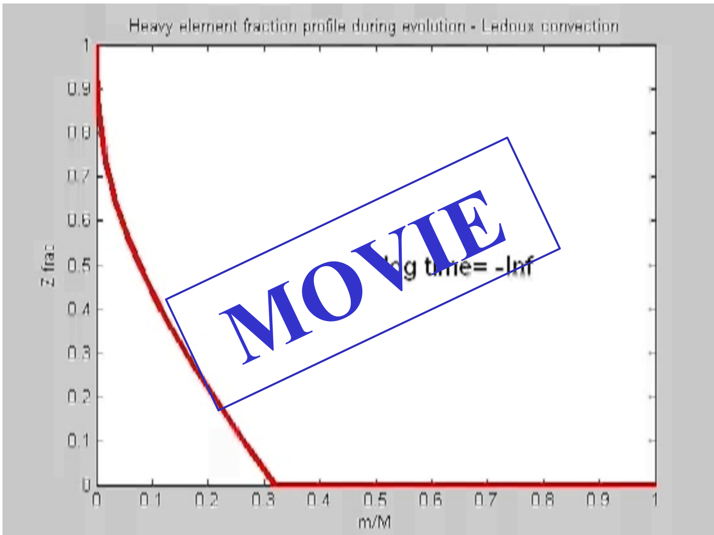


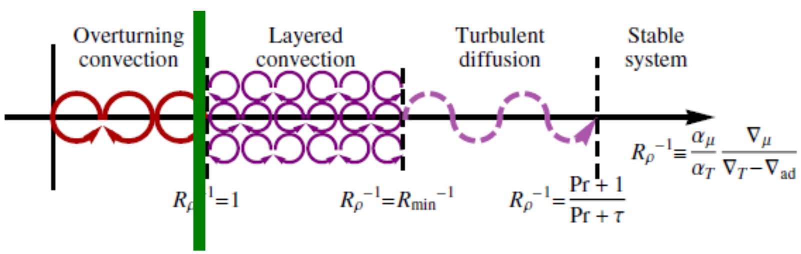


Local high-z concentration is mixed efficiently.

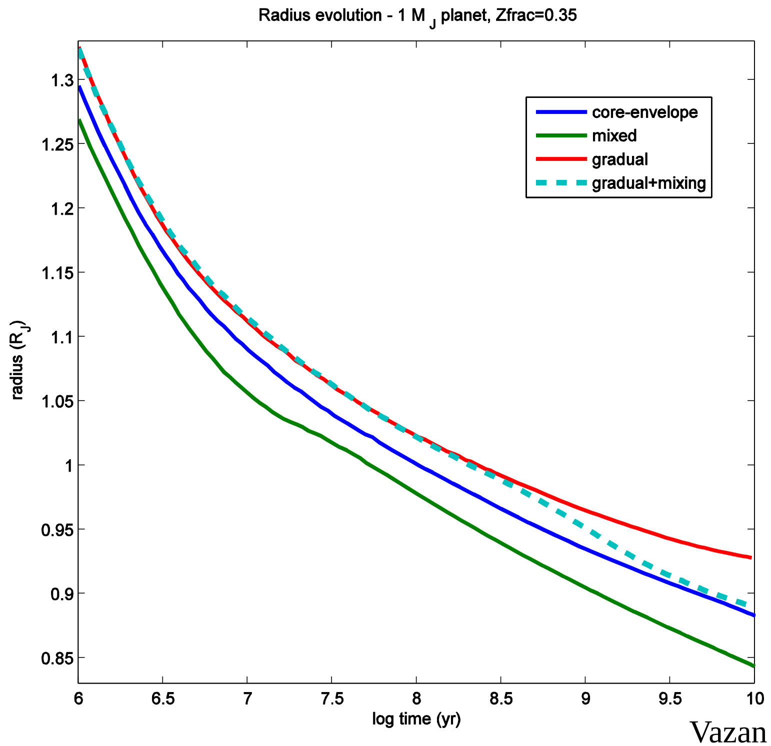
Composition Gradients

Convective-Mixing





Leconte & Chabrier 2012, Mirouh et al. 2012



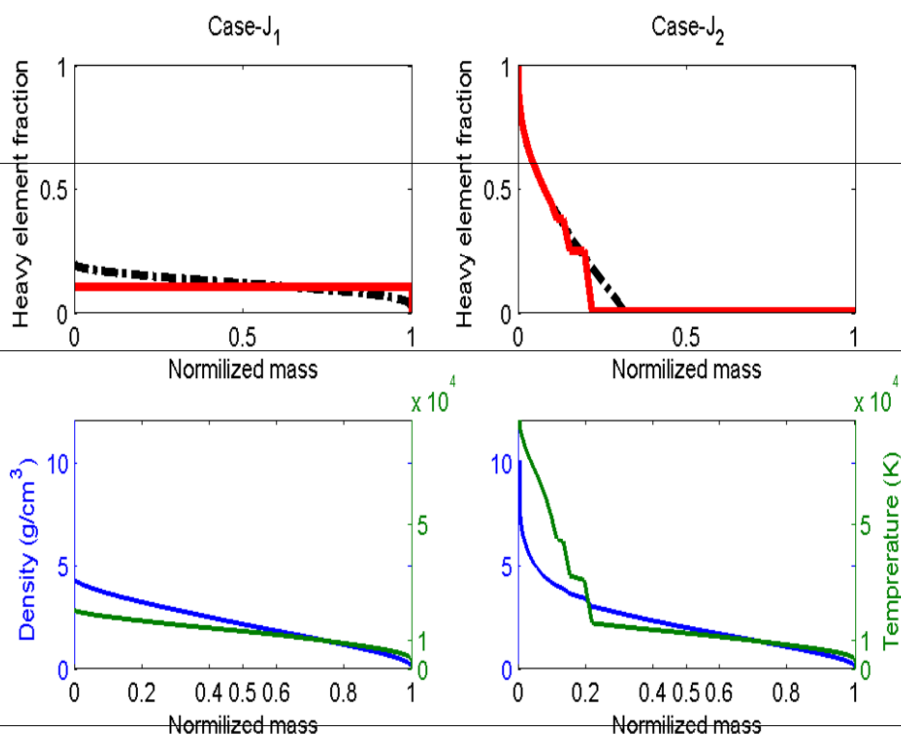
Vazan et al. 2015

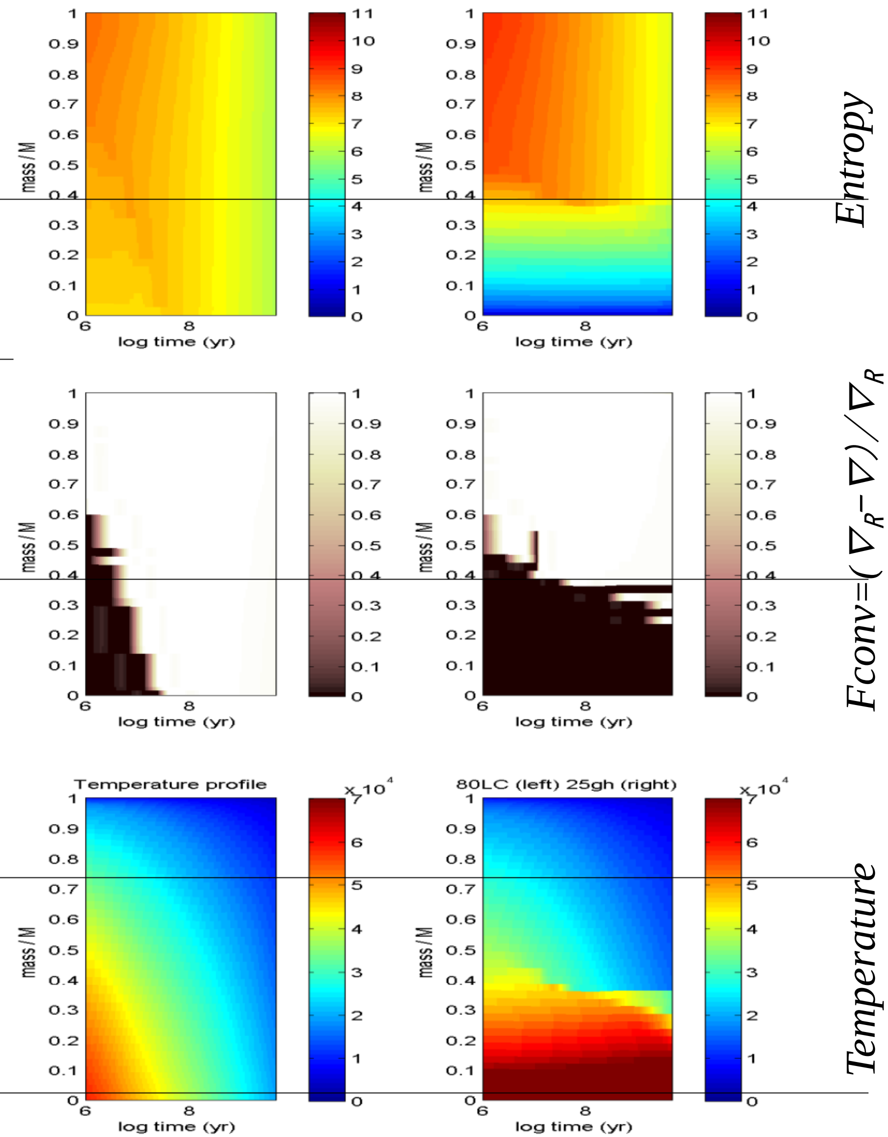
Composition gradients decrease the heat transport rate.

Convective-mixing enriches the envelope in high-Z material.

Jovian Planets

Convective Mixing





Heavy element distribution for the non-adiabatic model:

- ➔ 4% in radius.
- ➔ hotter interior.

Conclusions

- The primordial internal structure has an important effect on the long term evolution of giant planets.
- Internal structure can evolve, the current-state structure is not always the initial.
  - Steep composition gradient reduces the cooling rate of the planet. **R** ↑
  - Convective regions can evolve (expand) inward during evolution.
  - Mixing enriches the planetary envelope with heavy materials. **R** ↓

➔ **Characterization of planets by observed parameters can have greater ambiguity than expected.**

➔ **Giant planet modeling requires linking of formation, evolution, and internal structure self-consistently.**

Thank you!