The Thermal State of Giant Planets Formed by Core Accretion

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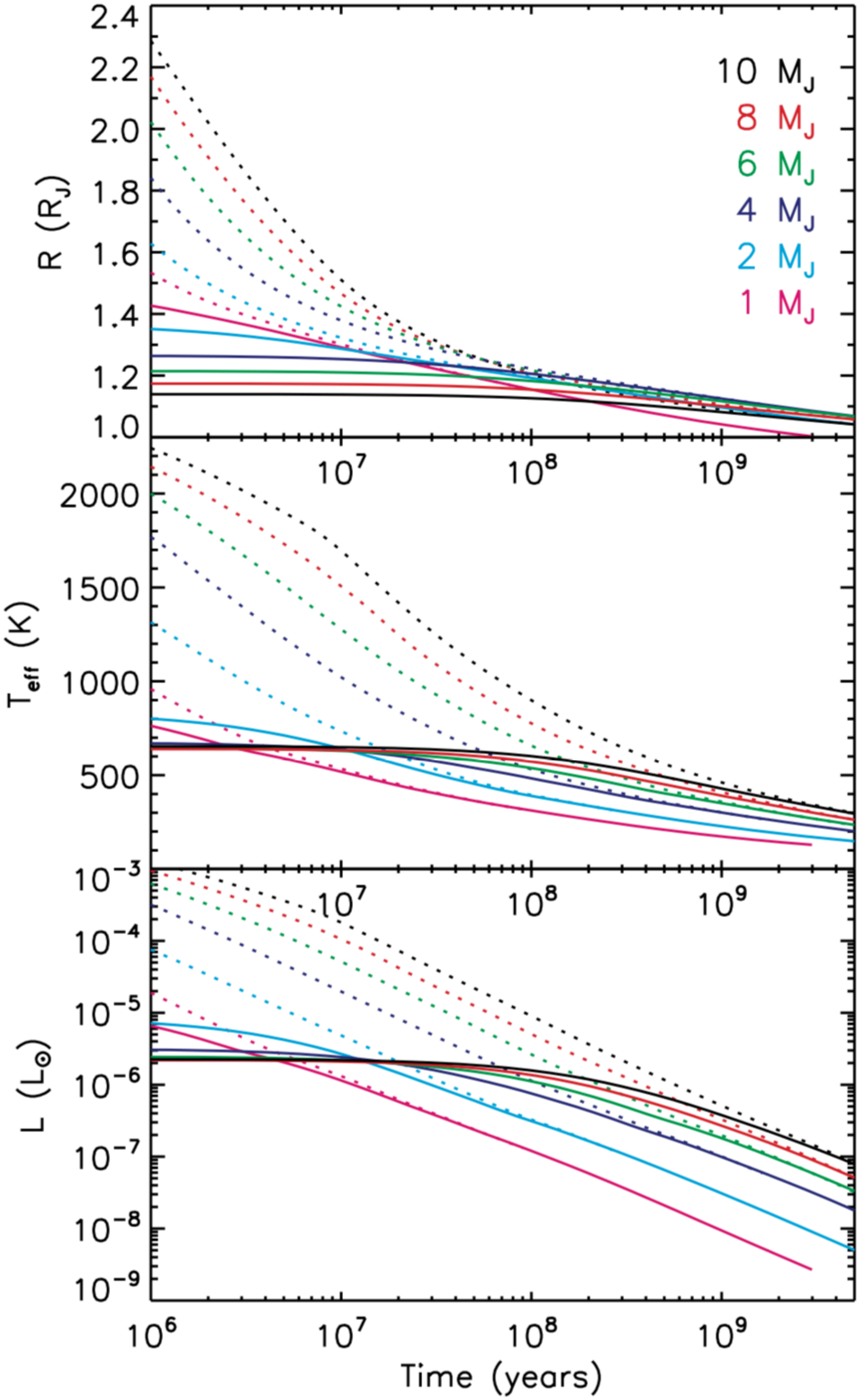
Marley et al. (2007) :

- core accretion models make cold starts (S~8-9 k_B/m_p) not hot starts (S~10-12 k_B/m_p)

- important for interpreting directly-imaged gas giants

What is it that sets the entropy of a giant planet produced by core accretion?

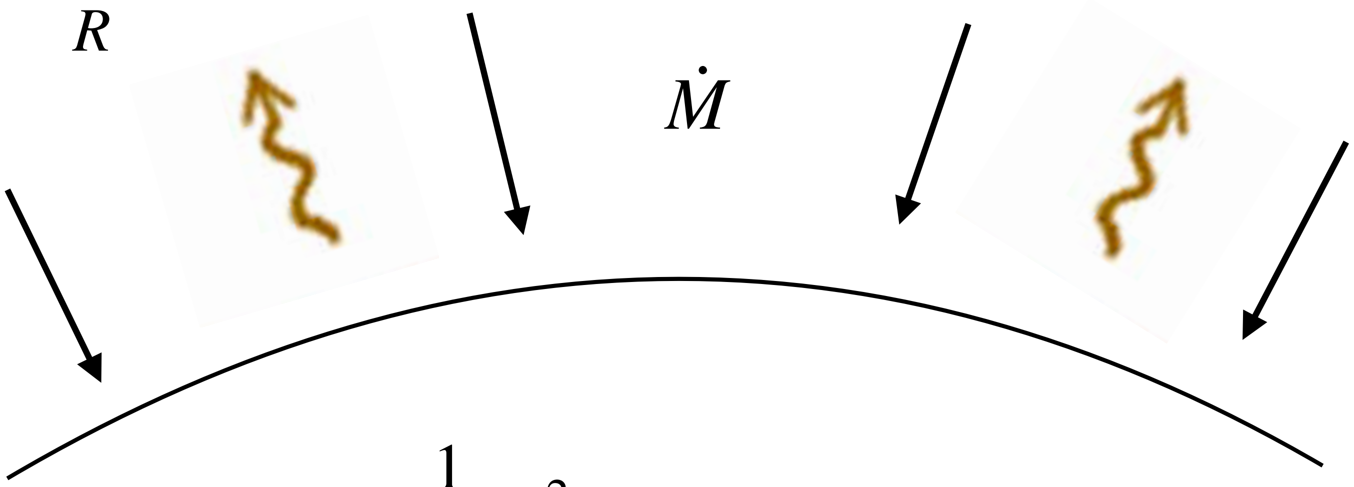
(Is entropy a good number to describe giant planet interiors, i.e. are they fully-convective?)



Marley et al. (2007)

Key ingredient: efficiency of the accretion shock during runaway accretion

Marley et al. 2007, Mordasini et al. 2012, Chabrier et al 2014 PPVI



$$L_{\mathrm{accr}} = \eta \frac{GM\dot{M}}{R}$$

accreting gas

$$\dot{M}$$

post-shock conditions

$$P_0 = \frac{1}{2}\rho v_{ff}^2$$

$$T_0 = ?$$

accretion shock (radiative, isothermal shock)

“Cold start” => shock radiates away all the gravitational energy

Different approaches to hot and cold accretion

- Lissauer, Bodenheimer et al. core accretion models: Integrate radiative diffusion through the flow

$$\frac{dT^4}{dr} = -\frac{3}{4\sigma}\frac{\kappa\rho_0 R_{\rm p}^{1.5}}{r^{1.5}}\frac{L_r}{4\pi r^2}$$

with $T = T_{\rm neb}$ on the outer boundary.

Bodenheimer et al. (2000)

The cold limit is $T_0 \sim T_{\rm neb}$ ~ few 100 K

- Star formation: give the accreted material extra thermal energy $\alpha\frac{GM}{R}$

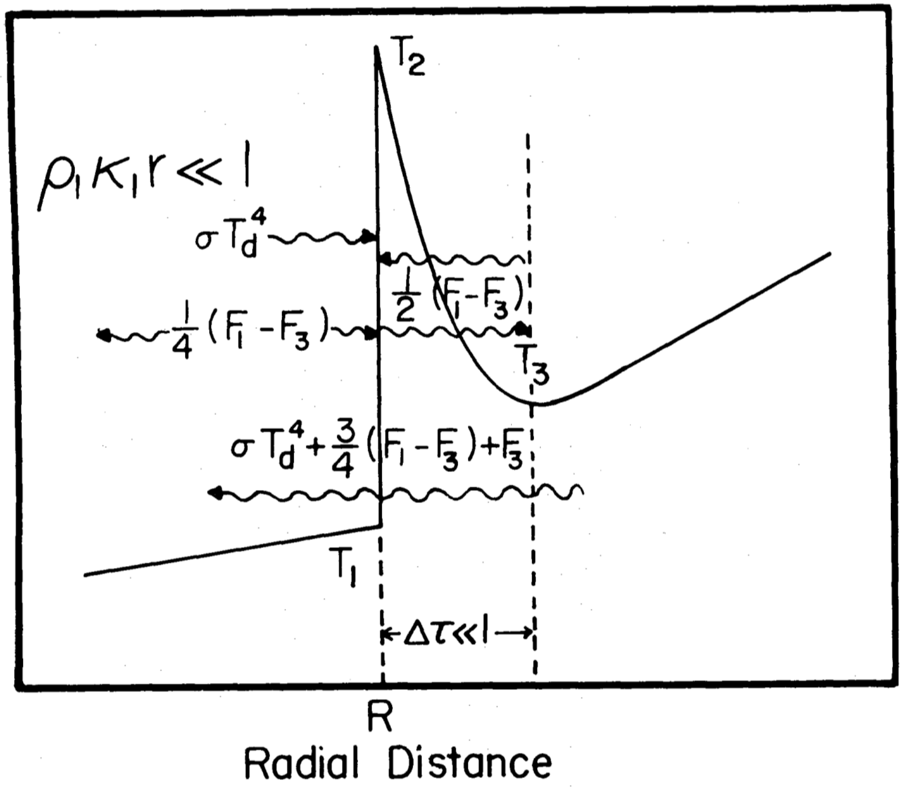
e.g. Prialnik & Livio (1985) Hartmann (1997)

In the cold limit $\alpha \rightarrow 0$, the planet just cools as usual $L \approx 4\pi R^2\sigma T_0^4$

=> $T_0 \gg T_{\rm neb}$ e.g. $T_0 \sim T_{\rm therm} \approx 1300\ {\rm K}$ for $L_{\rm int} = 10^{-4}\ L_\odot$

Different approaches to hot and cold accretion

- Shock models: the pre/post shock material has to heat up to be able to radiate the accretion luminosity



Stahler et al. (1980)

$$\sigma T_0^4 \approx \frac{3}{4}\frac{GM\dot{M}}{R}\frac{1}{4\pi R^2}$$

$$\Rightarrow T_0 \approx 3000\ \mathrm{K}$$

Marleau et al. (2017)

$$\sigma T_0^4 = \frac{1}{4}\frac{\eta_{\rm kin}}{\Delta f}\frac{GM\dot{M}}{4\pi R^3}$$

$$\Rightarrow T_0 \gtrsim 2000\ \mathrm{K}$$

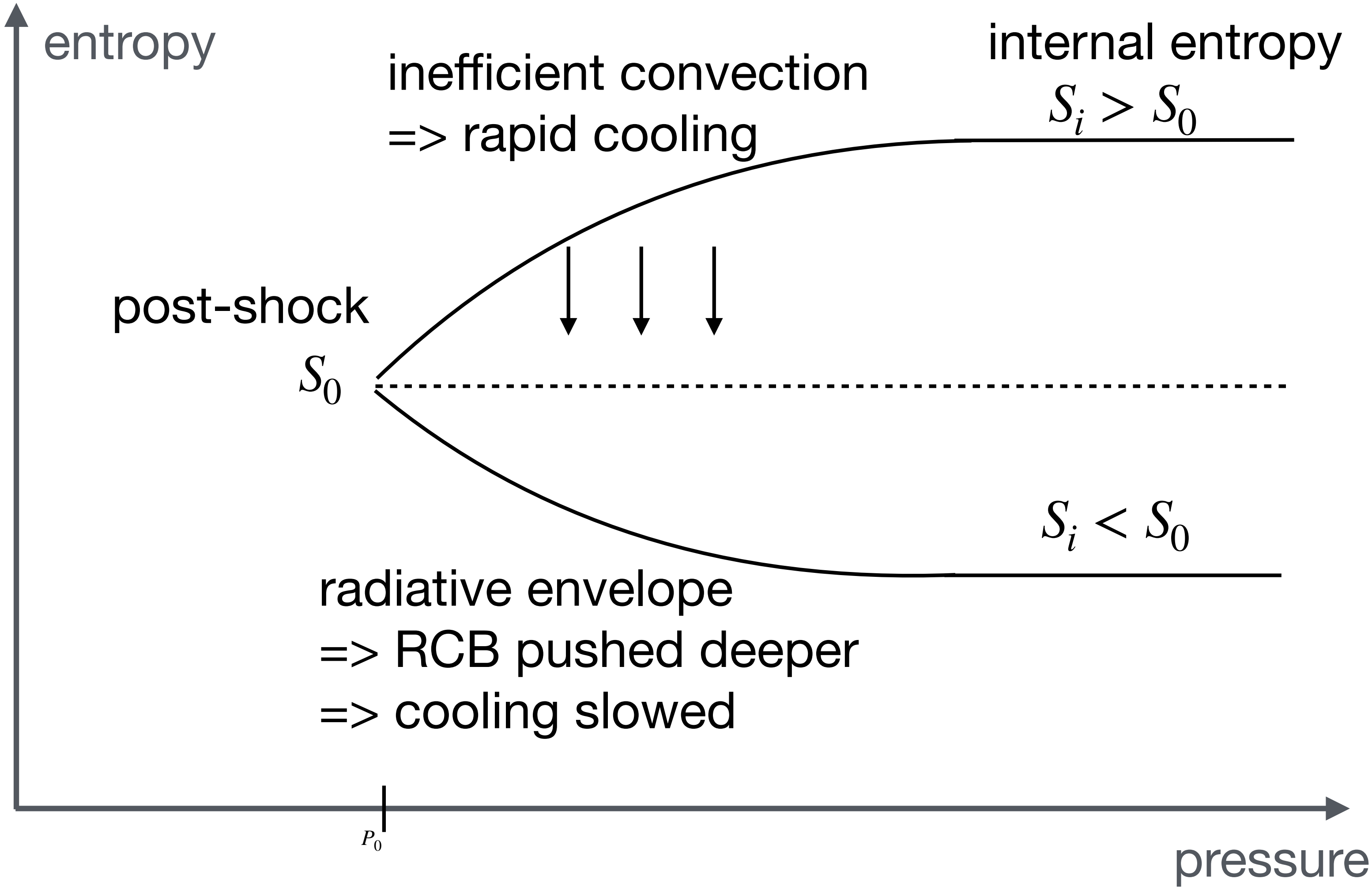
optically thin $\Delta f = 2$

optically thick $\Delta f \approx \dfrac{4}{3\Delta\tau}$

$$f_{\rm red} \equiv F_{\rm rad}/(cE_{\rm rad})$$

Structure of accreting envelopes

Very different behavior depending on whether the accreted gas has lower or higher entropy than the interior adiabat



inefficient convection
=> rapid cooling

radiative envelope
=> RCB pushed deeper
=> cooling slowed

“cooling regime”
(cold shower)

“stalling regime”
(hot jupiter)

Berardo, AC, Marleau (2017)

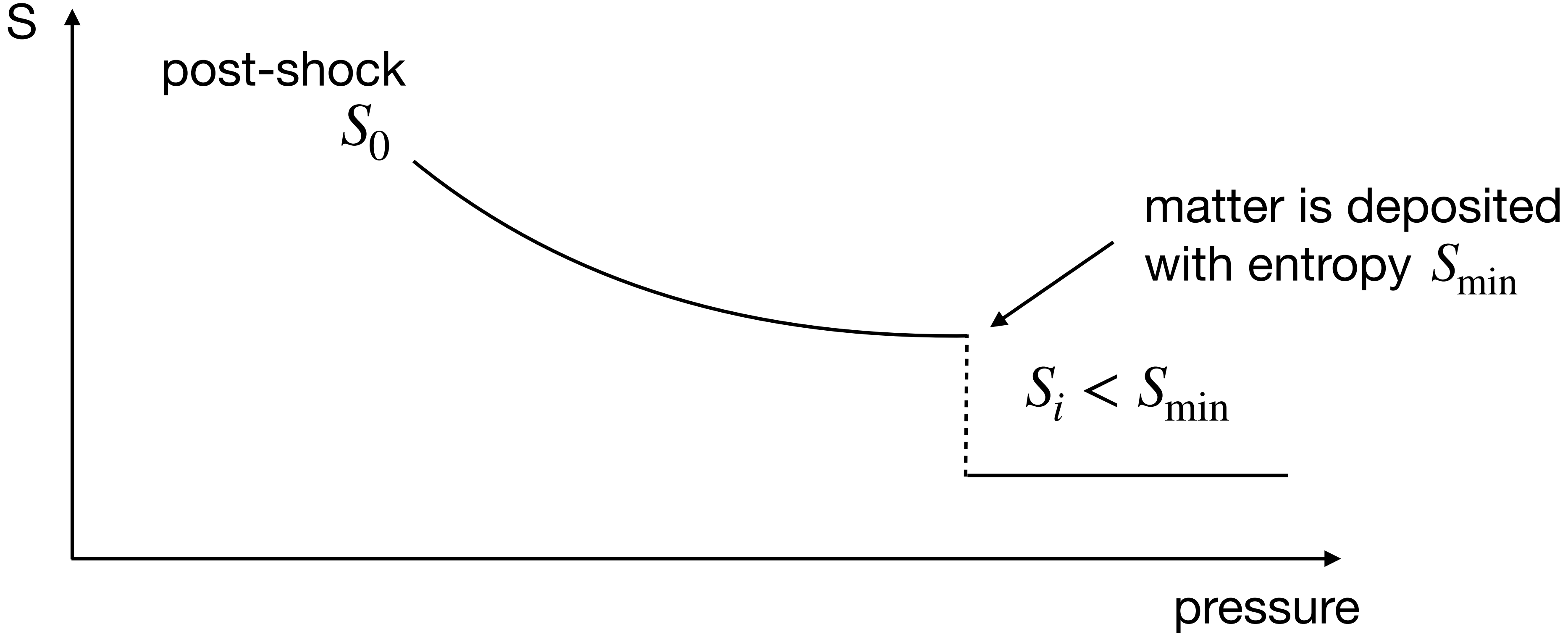
Accreting envelopes have a minimum entropy

Minimum entropy that can be reached in the envelope

$$S_{\rm min}(T_0, \dot{M}, M, R)$$

(see Stahler 1988 for SF case)

Arises because the envelope has to be hot enough to transport the compressional heating $L_{\rm comp} \approx \dot{M} T \Delta S$

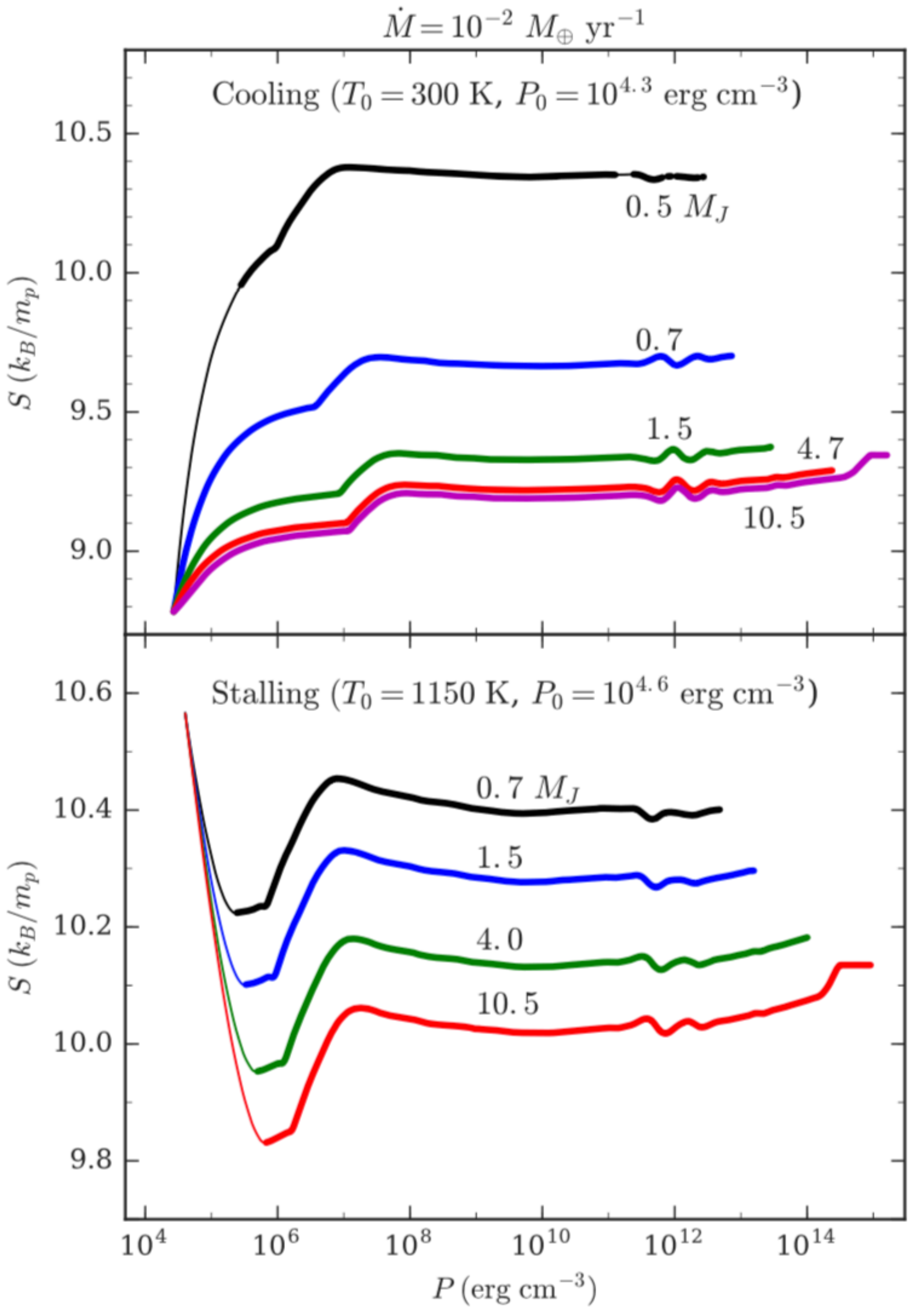


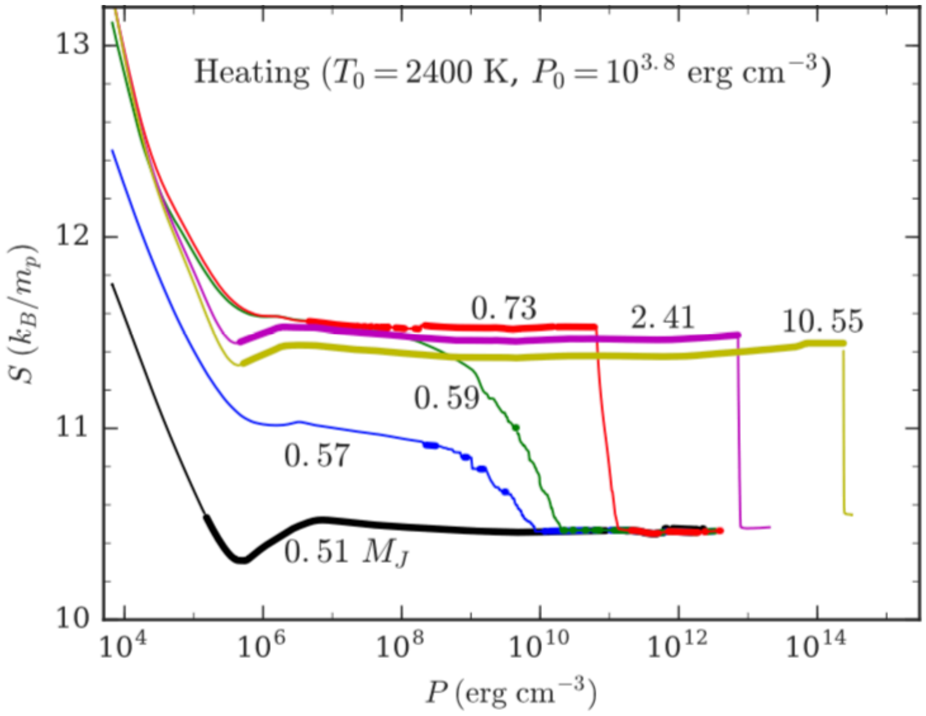
Berardo, AC, Marleau (2017)

Time-dependent calculations with MESA

Accrete $10M_J$ over 3×10^5 yrs
H/He only — no heavy elements

$T_0 = 300, 1150, 2400$ K



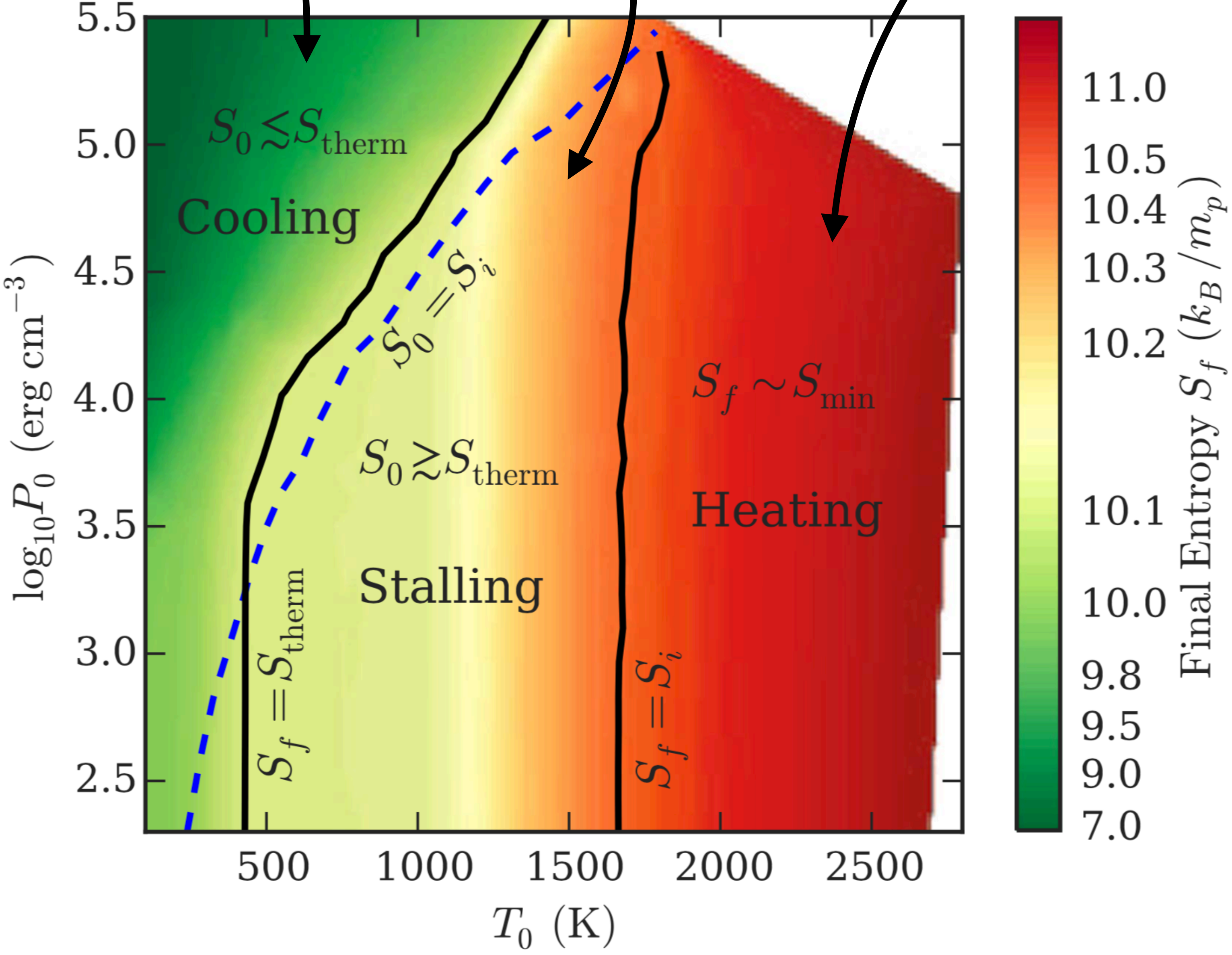


Berardo, AC, Marleau (2017)

cold starts for low
boundary temperatures

in the stalling regime,
stay at the initial entropy

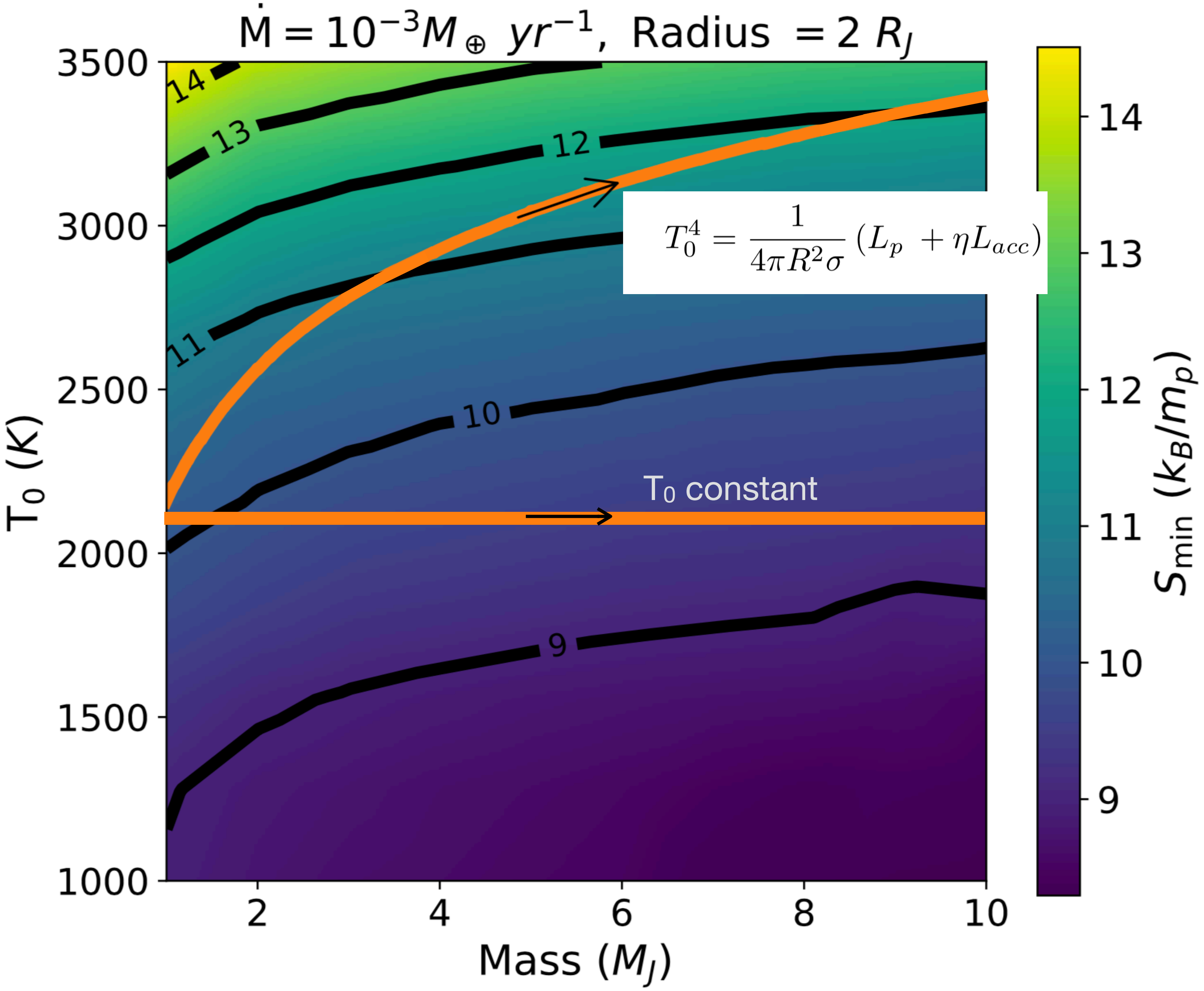
at high temperatures,
S_{min} determines the
entropy



Accretion from 0.5 -> 10 M_J
with starting entropy 10.4 k_b/m_p

Berardo, AC, Marleau (2017)

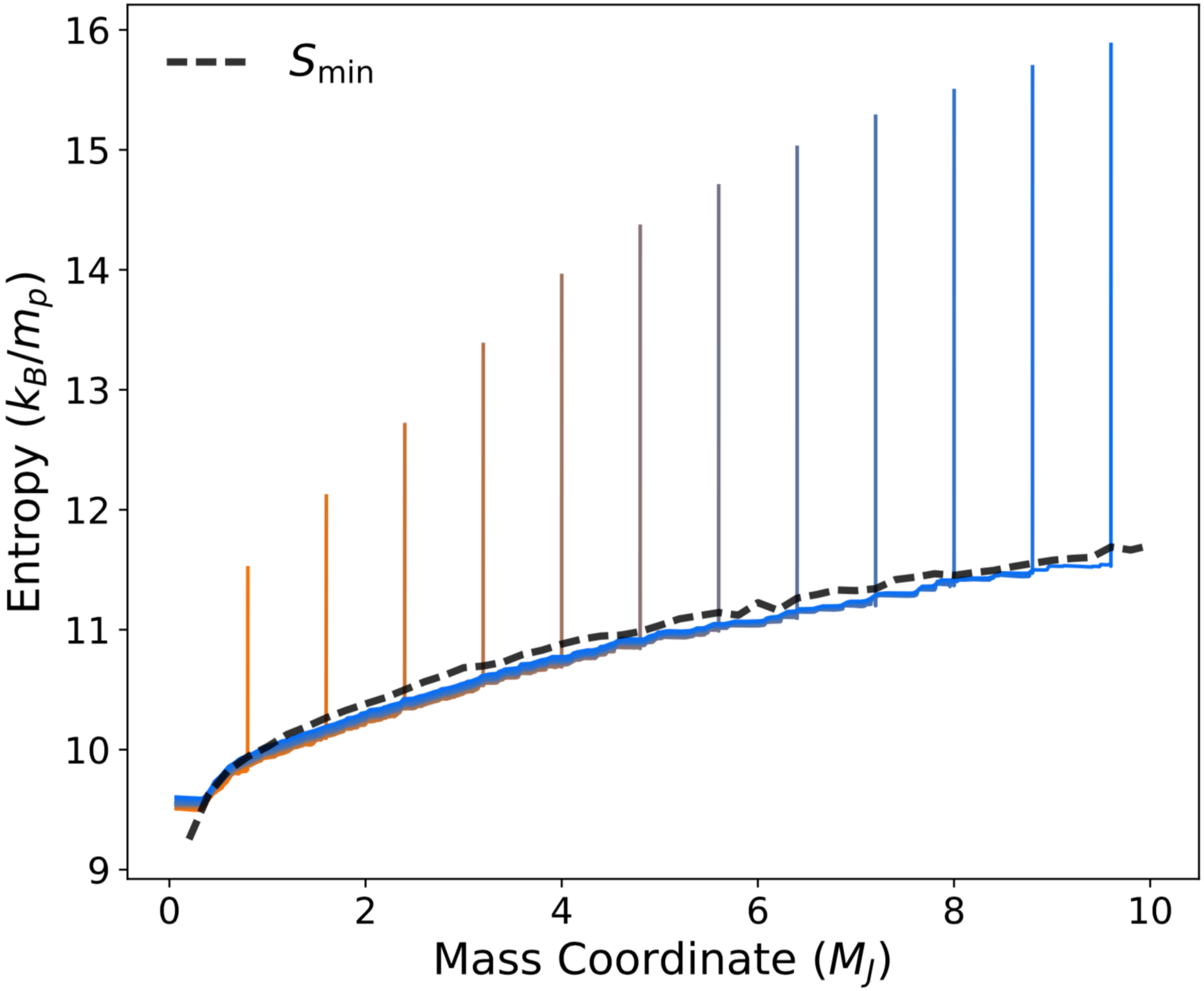
The entropy profile depends on the time history of the surface temperature



$$T_0^4 = \frac{1}{4\pi R^2 \sigma}\left(L_p + \eta L_{acc}\right)$$

Berardo et al. (2017b)

The planet forms in layers of increasing entropy => fully radiative



Berardo et al. (2017b)

Now apply this to Jupiter:

- Use planet formation models (Venturini et al. 2016,2017) to get the initial conditions for the runaway accretion
- Accretion rate is not constant, in particular it likely ramps down at the end (e.g. Lissauer et al. 2009)
- Parameters:

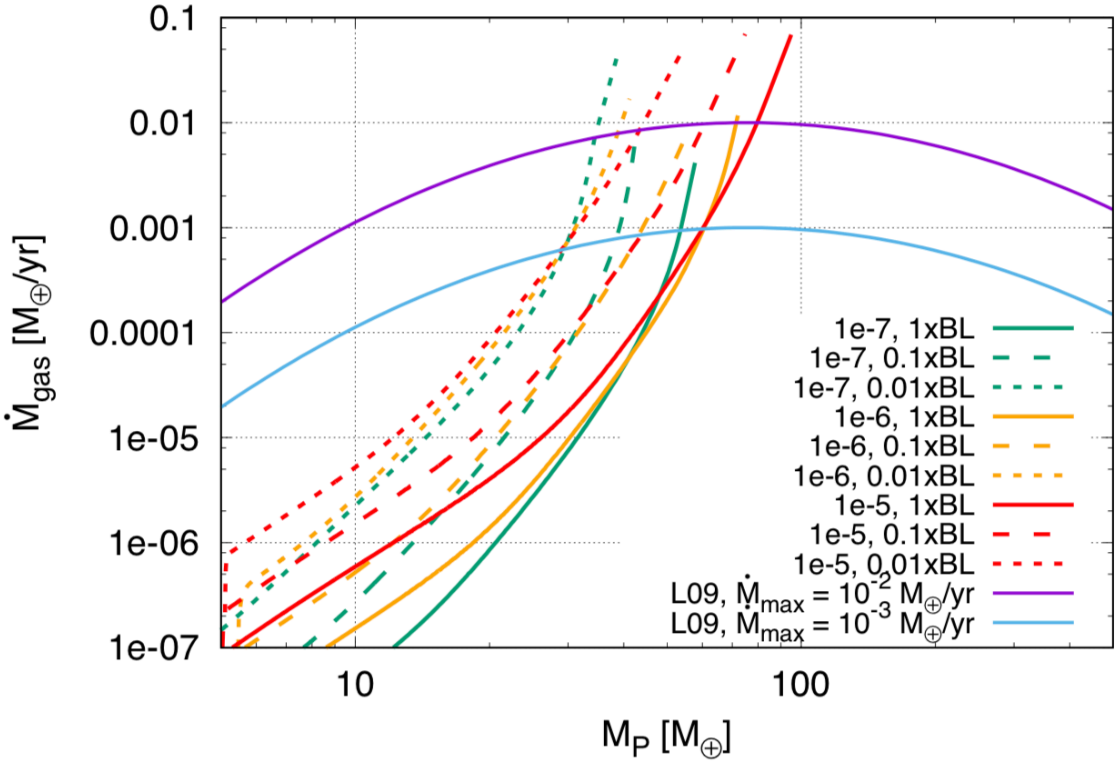
  opacity (scaled to Bell & Lin)

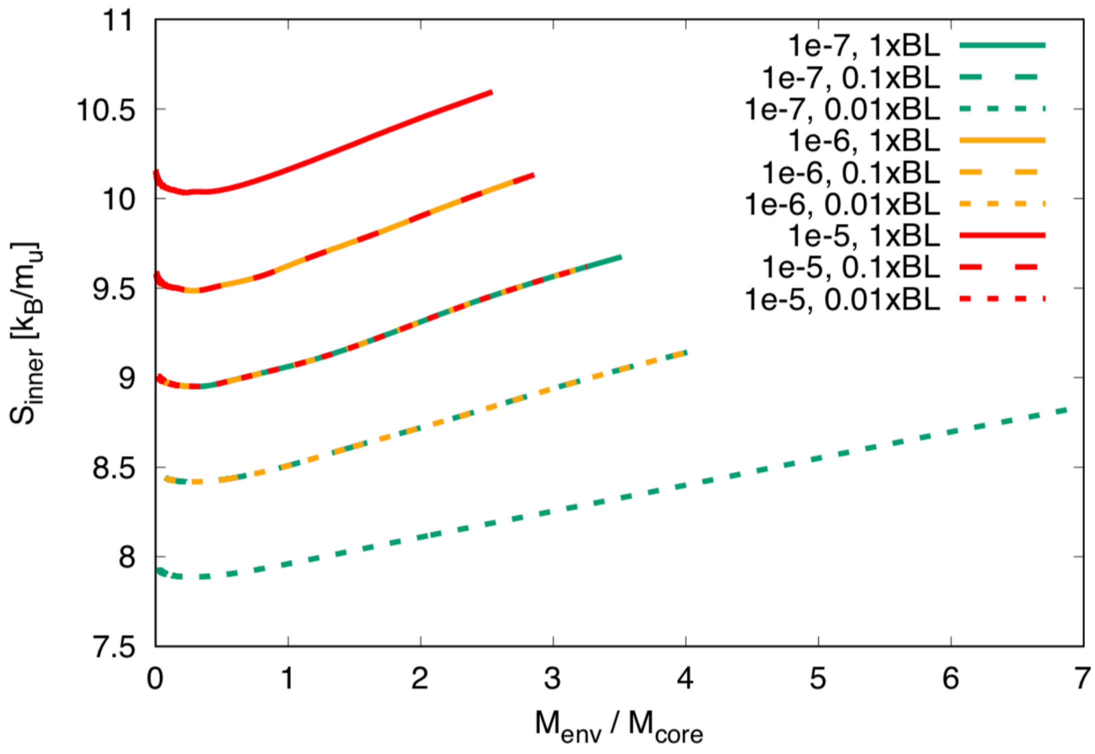
  $$\kappa/\kappa_{BL}$$

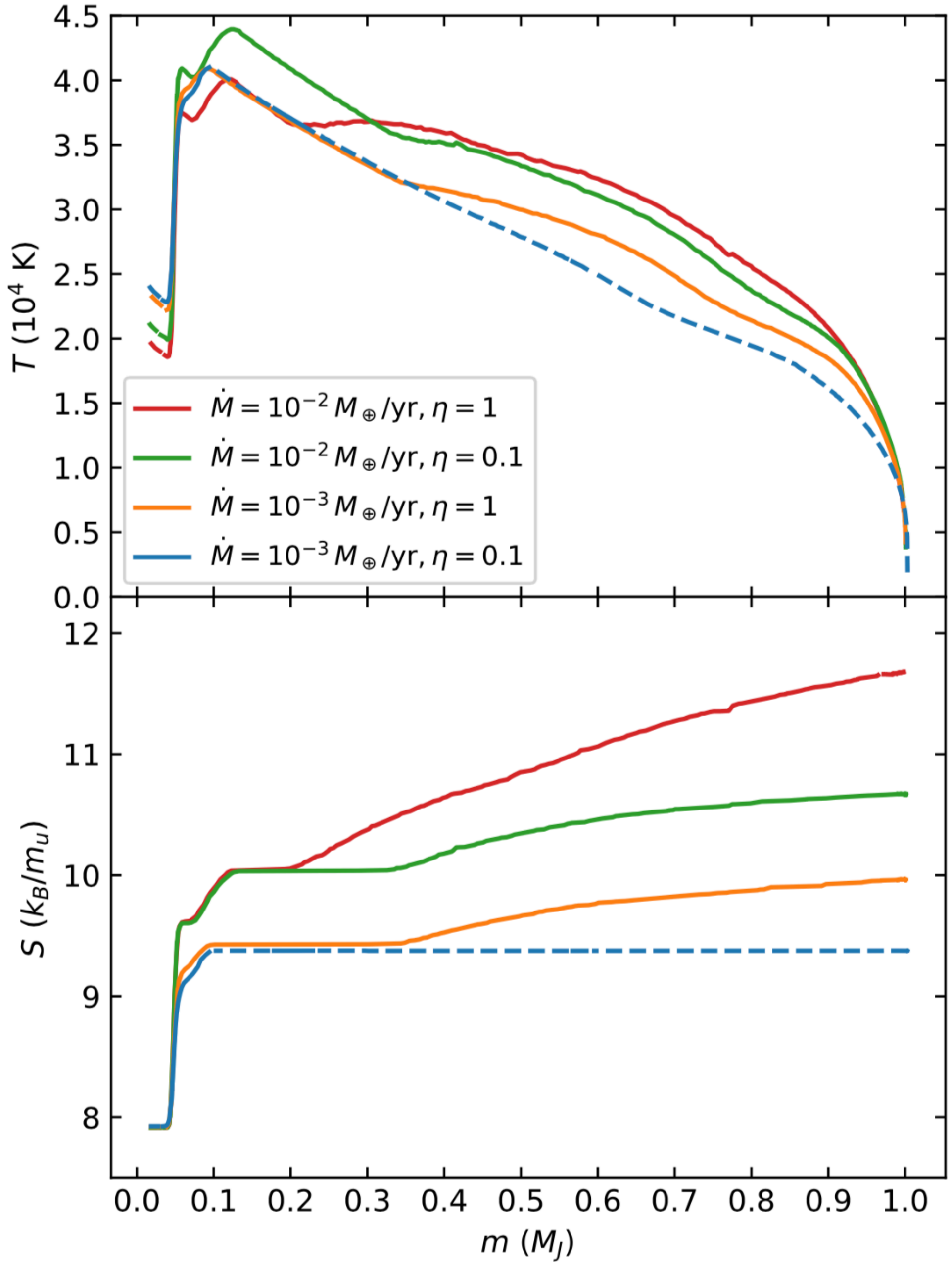
  solid accretion rate

  $$\dot{M}_Z$$

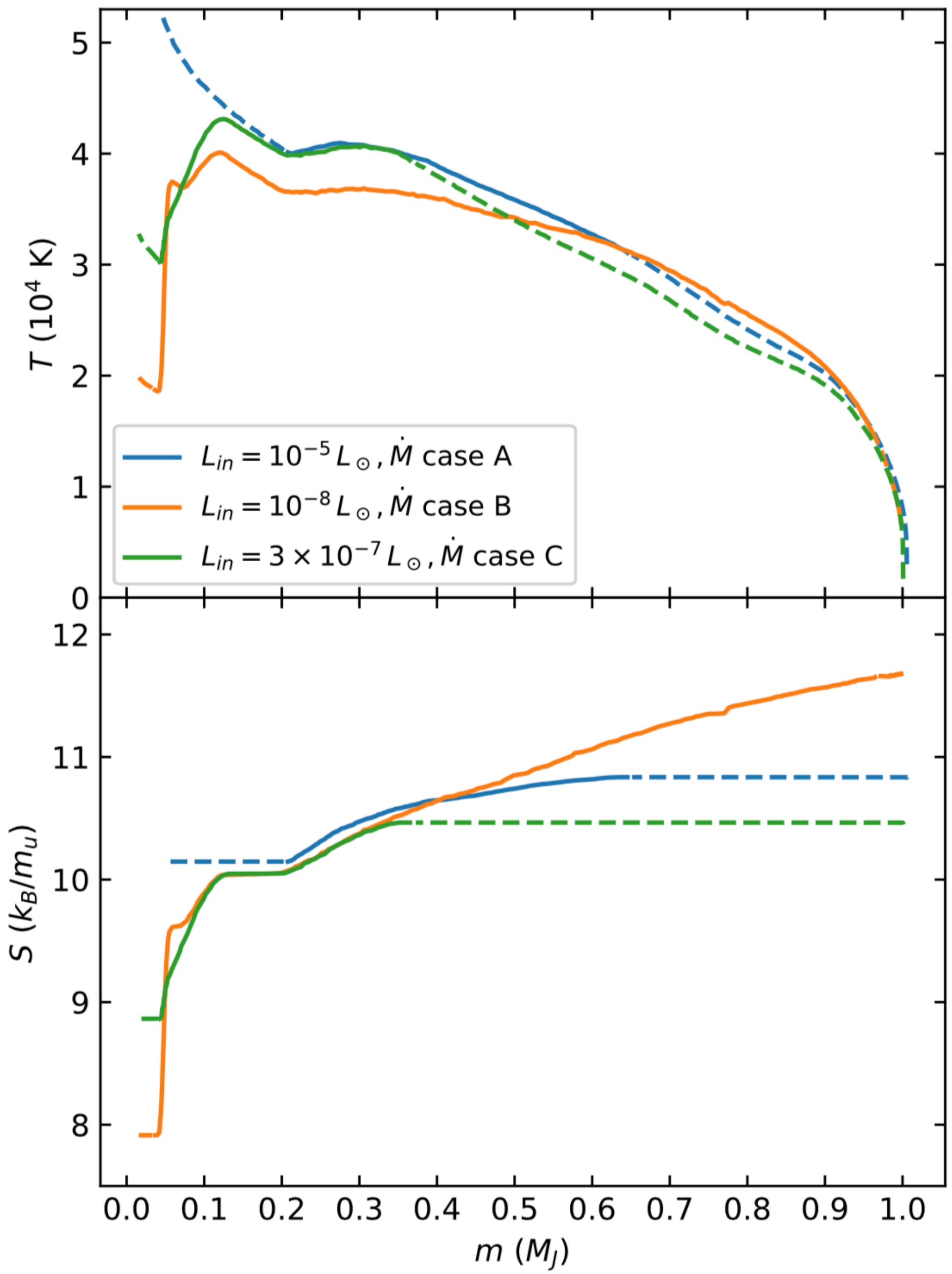
AC, Helled, Venturini (2018)



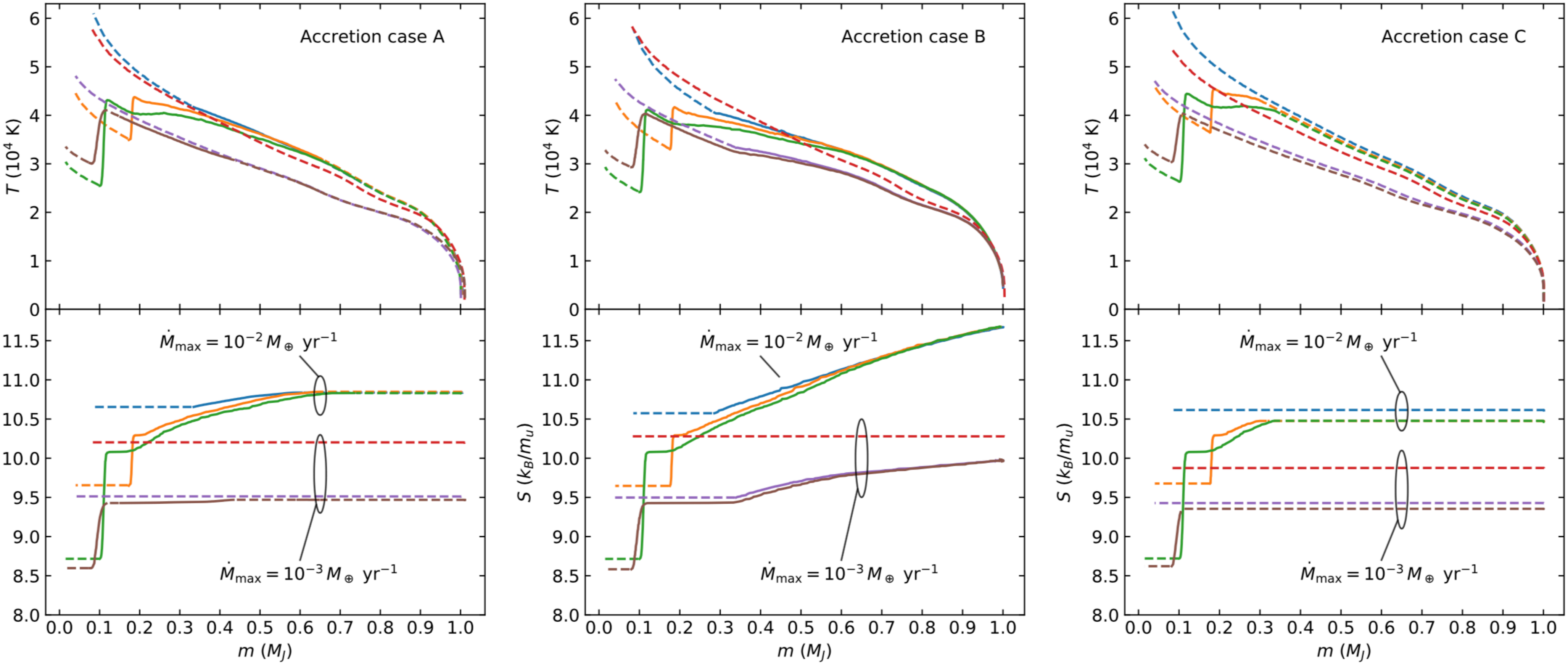




Accretion rate and shock η

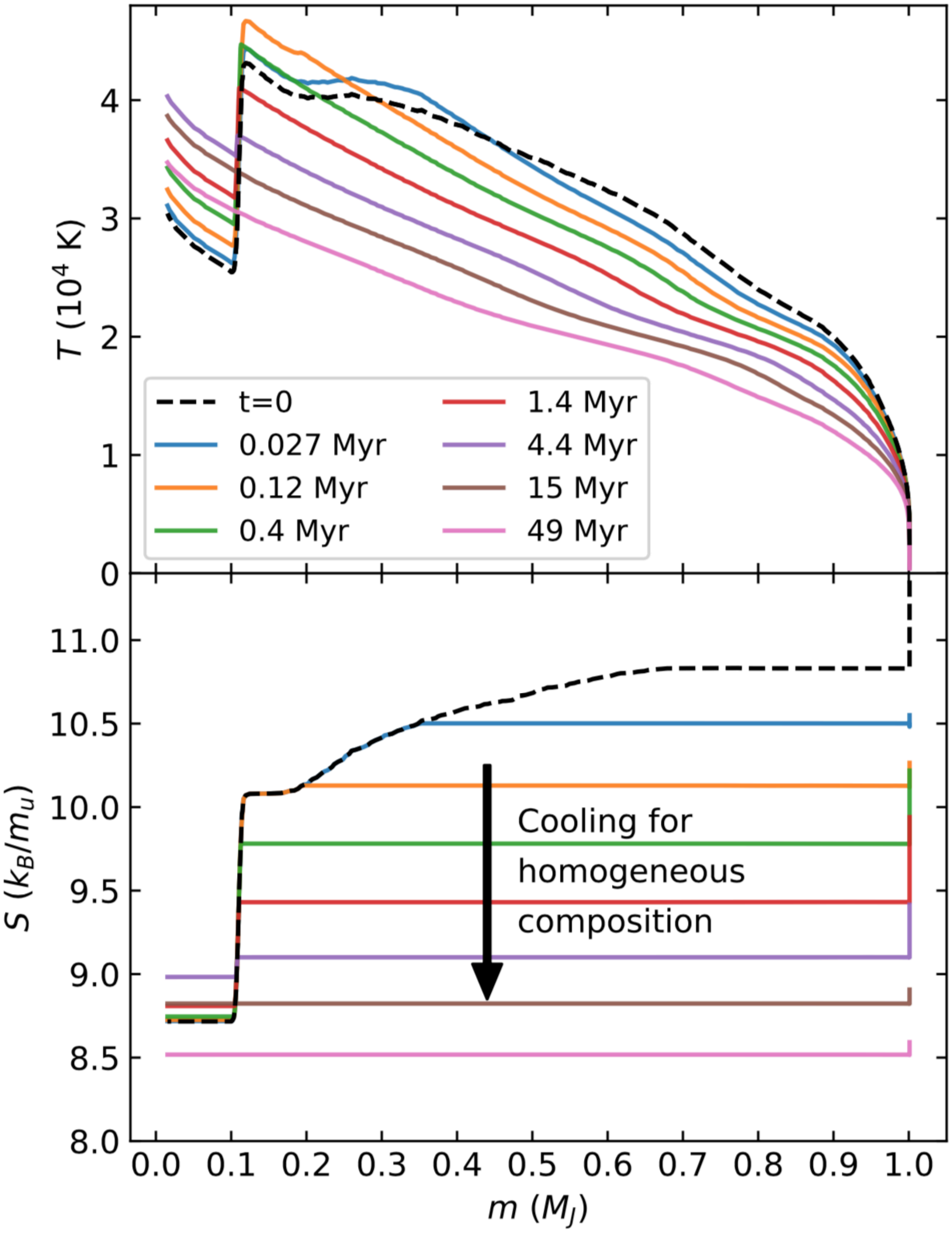


Starting entropy and Ṁ ramp down



$(\dot{M}_Z/M_\oplus\,{\rm yr}^{-1}, \kappa/\kappa_{BL}) = (10^{-7}, 0.01), (10^{-6}, 0.1)$ and $(10^{-5}, 1.0)$

For a homogeneous composition, cooling leads to a fully-convective interior in 10's of Myrs



Conclusions / Questions

* Core accretion gives warm to hot starts rather than cold starts

* Depending on how the temperature of the accretion shock evolves, gas giant planets can form with significant radiative regions

* Low mass cores / low opacity / low solid accretion rate
=> higher entropy contrast, more likely to be radiative

* The time-dependence of gas accretion rate is important:
a ramp down in accretion rate => outer layers convective

* Consequences of radiative regions:
- could persist until today if stabilized by composition gradients ?
- change the distribution of heavy elements laid down during formation ?