Evolution of the Massive Protostar with the High Accretion Rate

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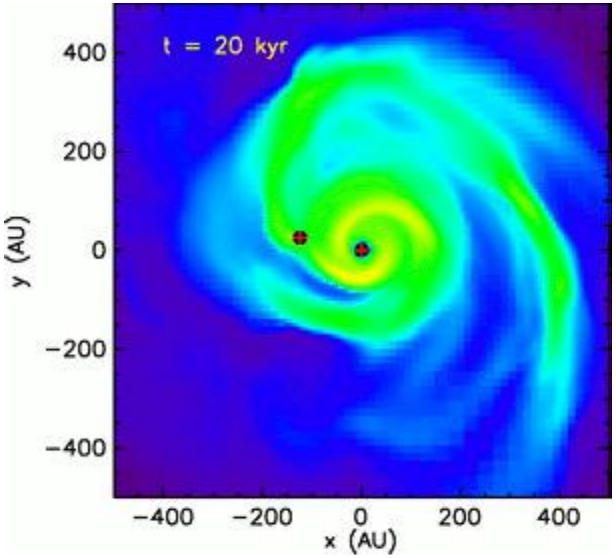
Accretion with high $\dot{M}$

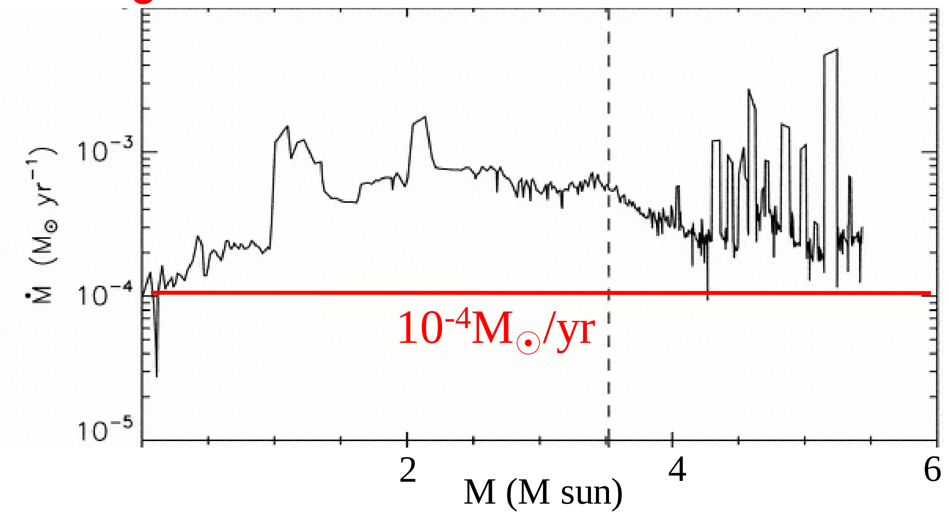
(e.g., Nakano '00, McKee & Tan '02)

- To overcome the radiation pressure barrier (Wolfire & Cassinelli '86)
- Some observational support (e.g., outflow, core SED)
- turbulent core model (McKee & Tan 02)

RHD calculation of the turbulent core collapse (Krumholz et al. '07)

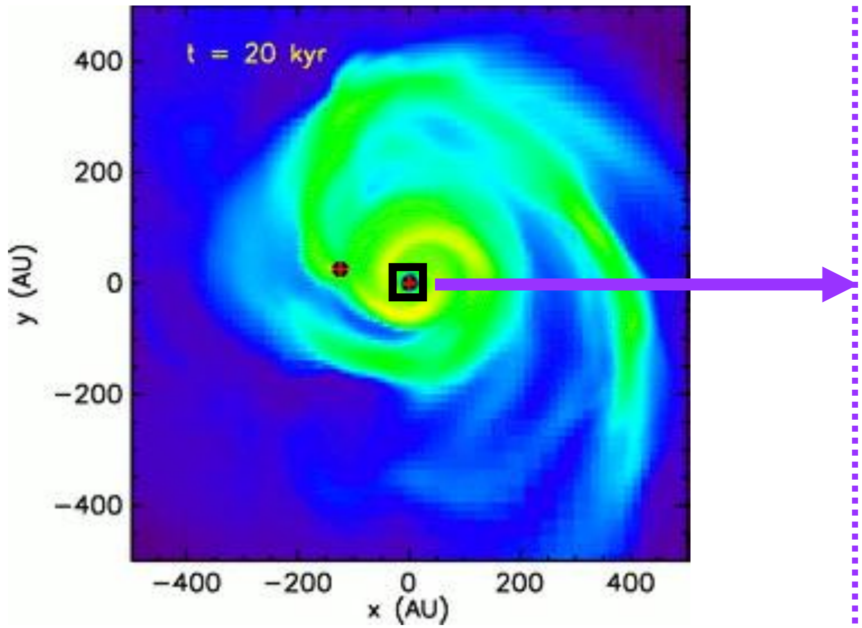


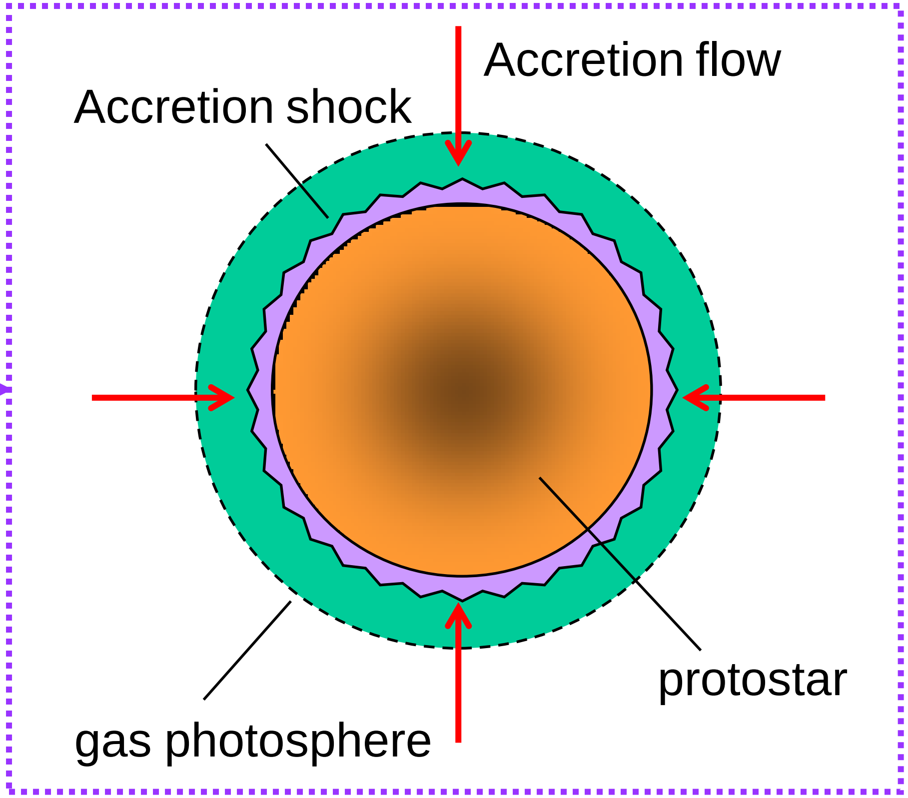
High Accretion Rate of $\dot{M} > 10^{-4} M_{\odot}/\mathrm{yr}$



Motivation

Going to the much smaller scale …



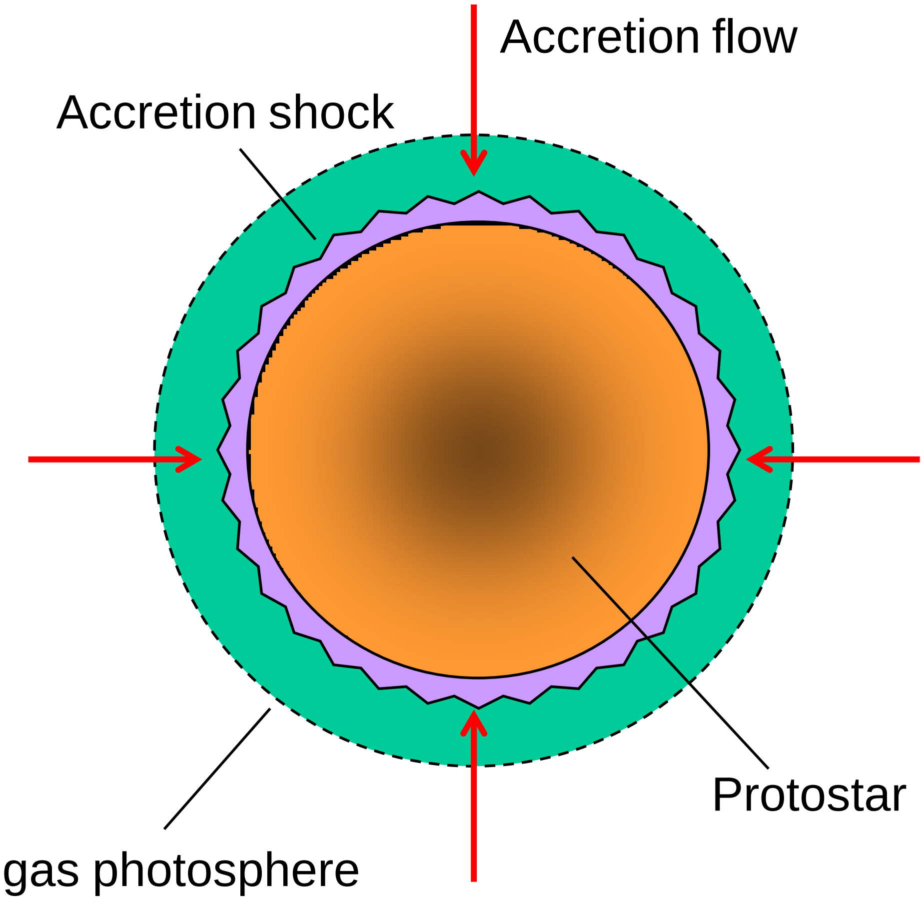


With the high acc. rate (10^{-4} -$10^{-3} M_{\odot}$/yr),

- How is the evolution of the protostar ? (e.g., radius, luminosity)
- How is the evolution different from the cases with low acc. rate?
- What causes the differences?

Problem Settings

(ref. Stahler, Shu & Taam '80, Palla & Stahler '90)



Basic eqs : 4 stellar structure eqs.

Continuity : $\frac{\partial r}{\partial m} = \frac{1}{4\pi\rho r^2}$

Momentum : $\frac{\partial P}{\partial m} = -\frac{Gm}{4\pi r^4}$

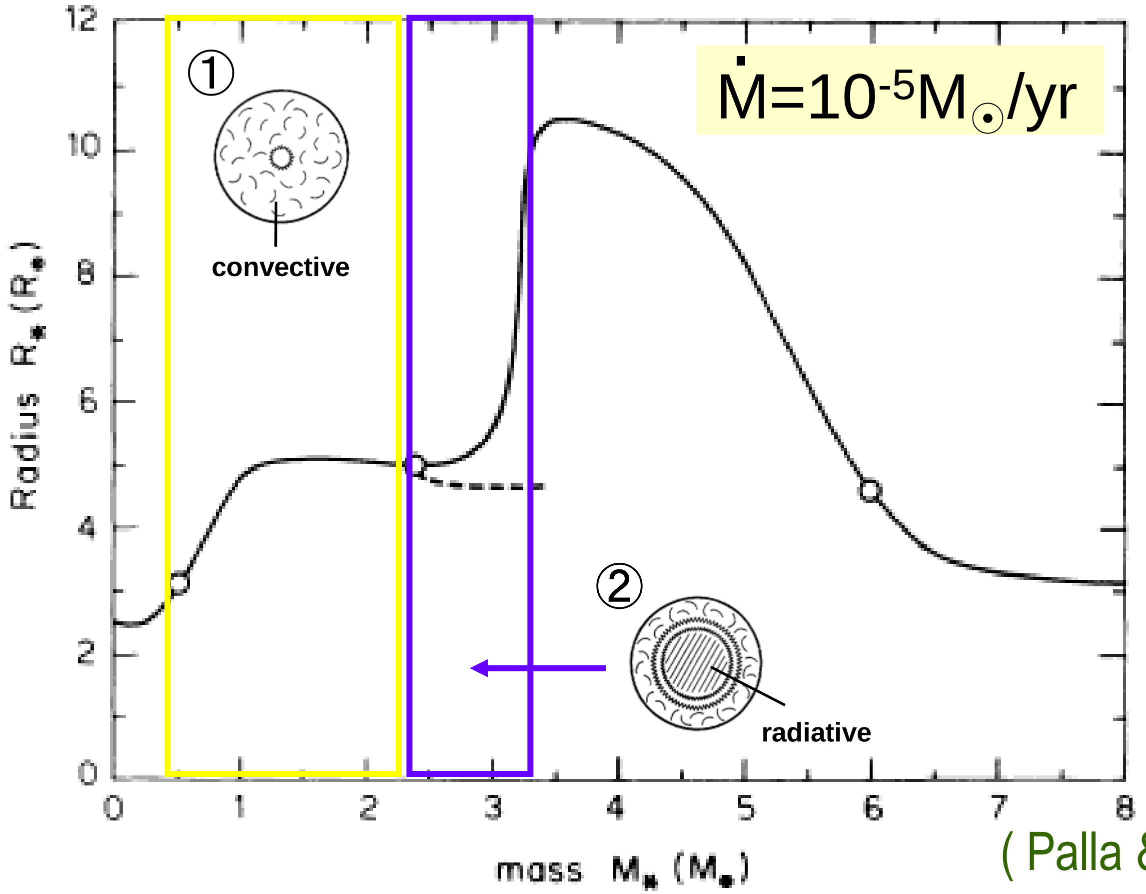
Energy : $\frac{\partial l}{\partial m} = \epsilon_{\rm nuc} + T\left(\frac{\partial s}{\partial t}\right)_m$

Heat transport : $\frac{\partial T}{\partial m} = -\frac{T}{P}\frac{Gm}{4\pi r^4}\nabla$

- under the constant acc. rate
- accretion shock boundary
- initial mass : 0.01, 0.05$M_\odot$

Previous works : Low Acc. Rate

Mass-Radius Relation



(Palla & Stahler '90)

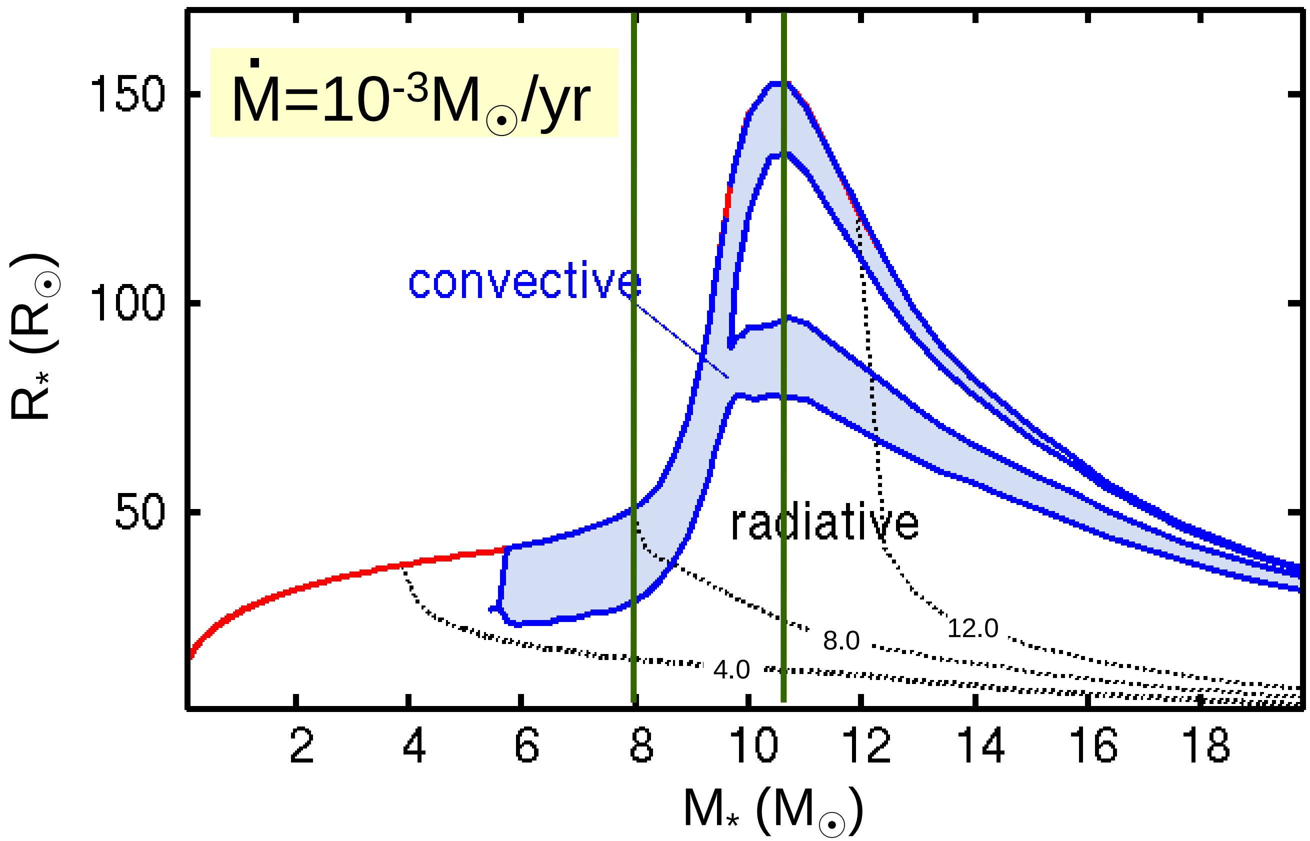
① D-burning $\Rightarrow -ds/dm > 0$ ⇒ fully convective

inner radiative region appears (T↑ ⇒ opacity↓)

② swelling by the D shell burning

High Accretion Rate

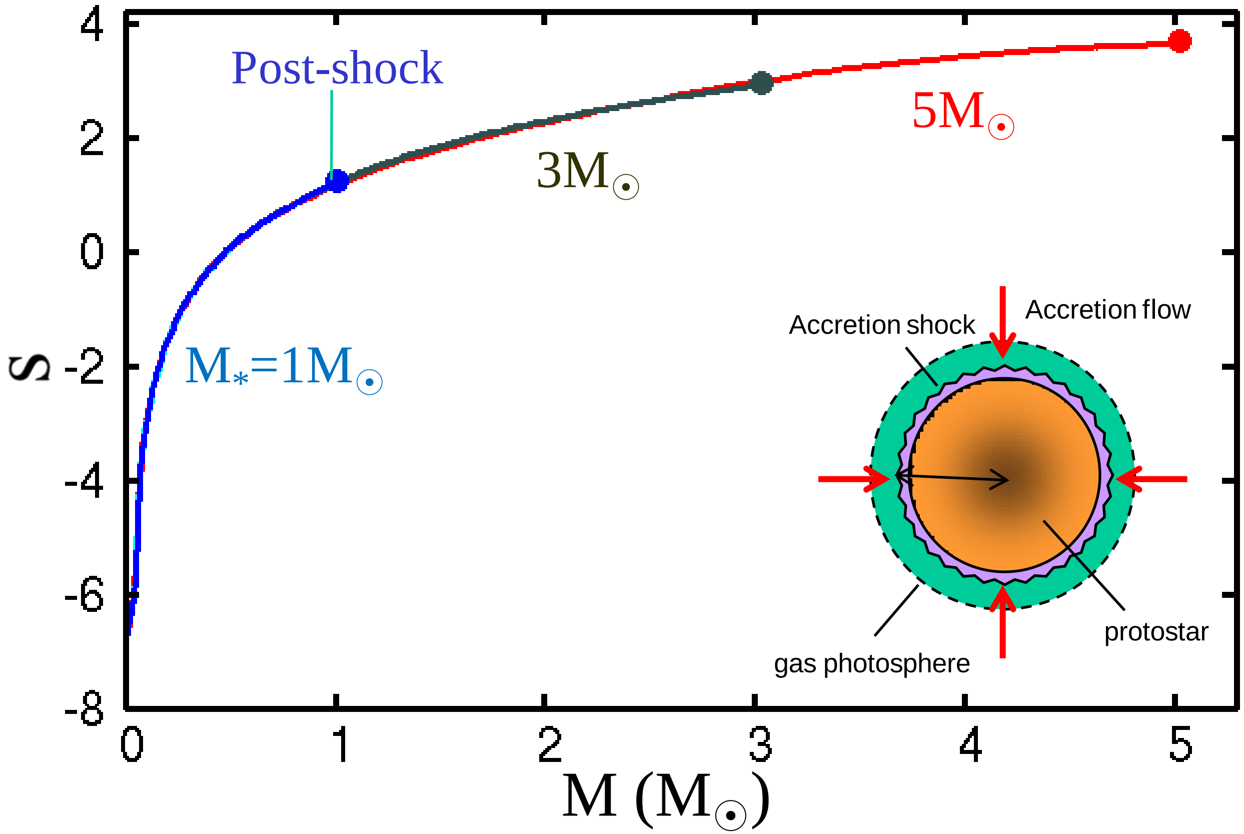
Mass-Radius Relation



- The radius is very large, and the protostar remains radiative.
- swelling at M_*~8-10$M_\odot$ → contraction at M_*>10$M_\odot$
- Without the D-burning, the evolution hardly change.

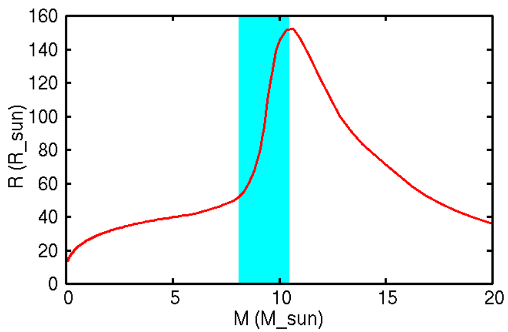
Adiabatic Accretion

entropy profile at M_*=1, 3, 5 $M_\odot$



- Stellar mass increases conserving the post-shock entropy
- High acc. rate → short acc. time : t_acc < t_cool ; adiabatic accretion
- high entropy → large stellar radius

Swelling



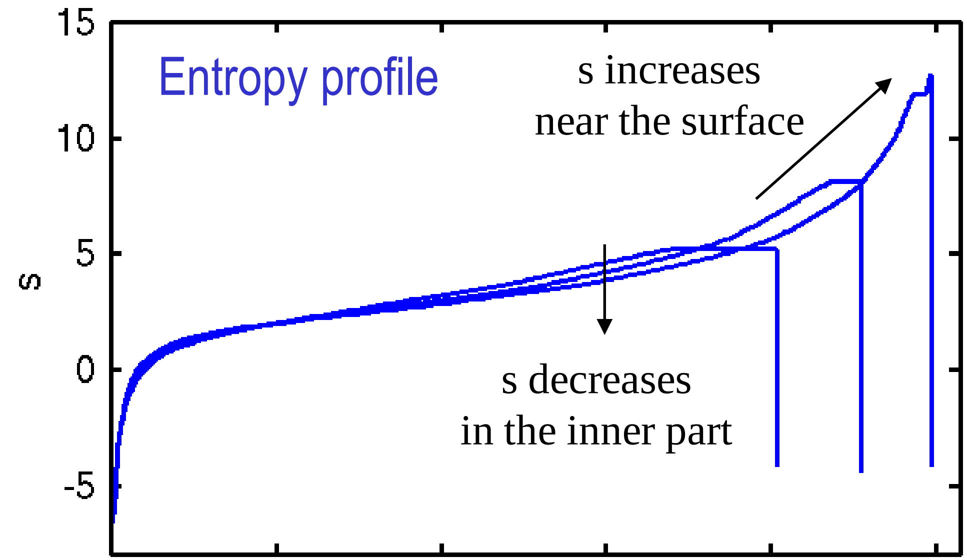
Radiative transport : L_{rad}
← limited by opacity

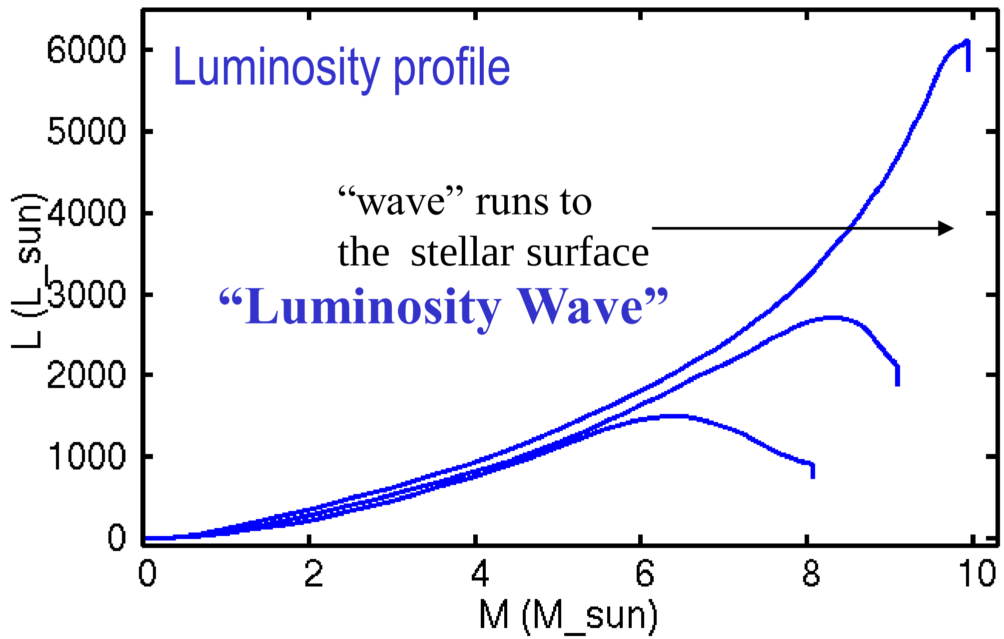
free-free opacity ;
$\kappa \propto \rho T^{-3.5}$

$M_* \uparrow \;\rightarrow\; \kappa \downarrow$

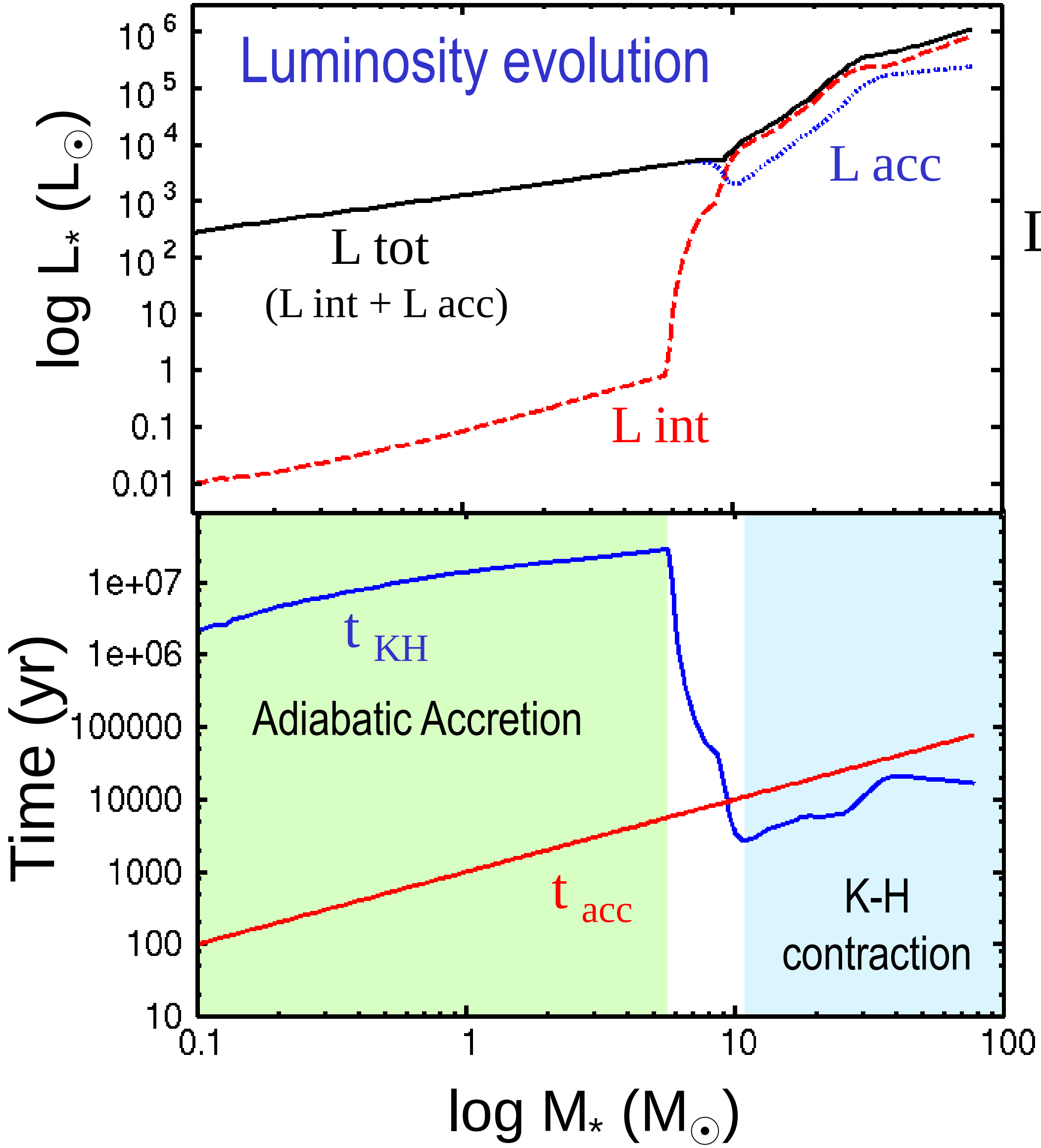
Embedded entropy can be radiatively transported to the stellar surface. → swelling

(Stahler, Palla & Salpeter '80)





K-H Contraction



L_{int} quickly increases at $M_*>5M_\odot$.
← opacity decrease

$$t_{acc} = \frac{M_*}{\dot{M}}, \quad t_{KH} = \frac{GM_*^2}{R_* L_{int}}$$

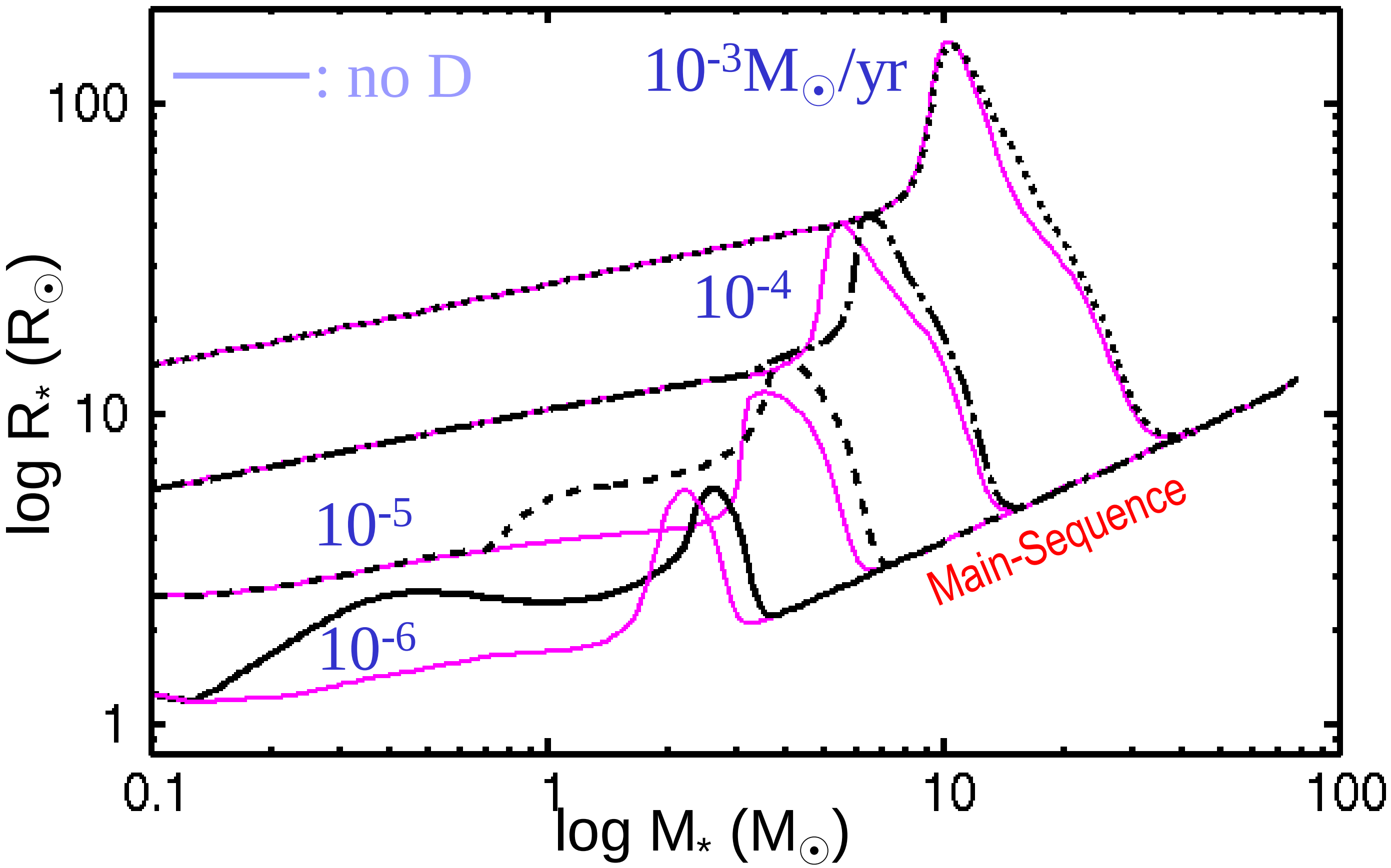
$t_{KH} < t_{acc}$ at $M_* > 10\ M_\odot$

Star loses the energy
→ contraction occurs

"K-H contraction"

Dependence on Accretion Rate

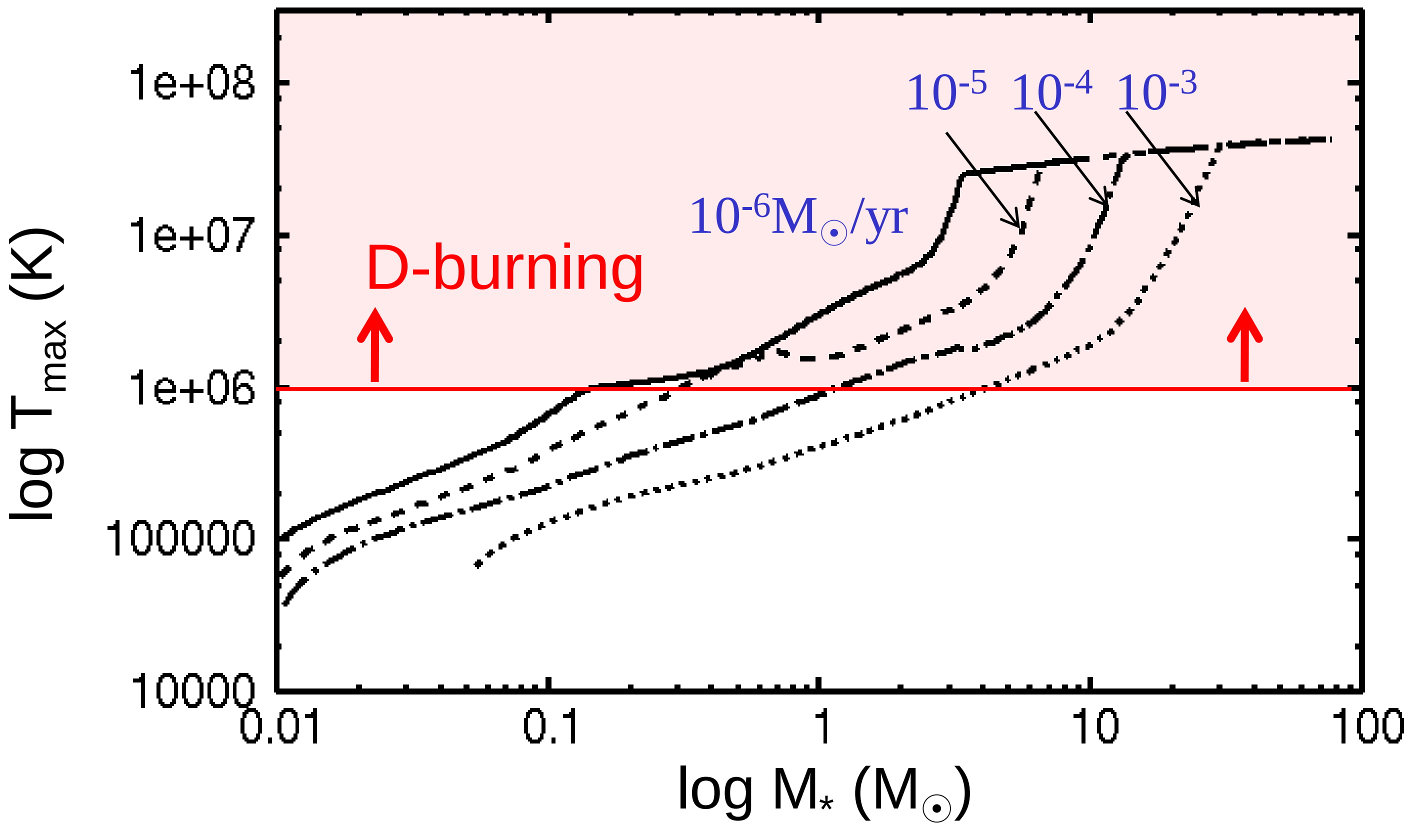
Mass-Radius Relation



- The stellar radius is larger, and protostar reaches M-S later with the higher acc. rate.
- The effect of D-burning appears later and becomes minor with the higher acc. rate.

Timing of D-ignition

Evolution of the maximum T in the star



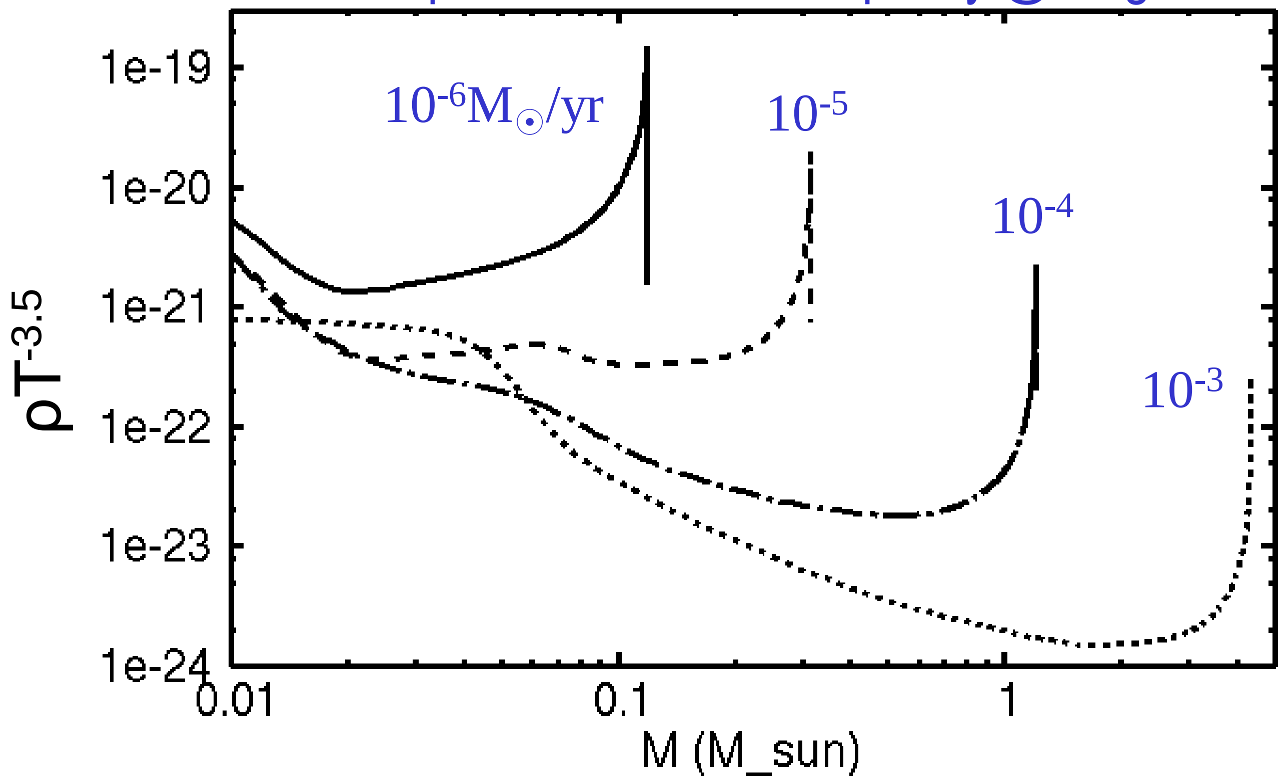
With the higher acc. rate, T_{max} is lower at the same stellar mass,
which delays the ignition of D .

Why radiative with high $\dot{M}$?

Entropy is generated by the D-burning, but if this is efficiently transported to the outer part *only by the radiation,* the star remains radiative.

→ low opacity enables this (Stahler'88)

Profile of $\rho T^{-3.5}$ ∝ free-free opacity @ D-ignition



Opacity is lower with the higher acc. rate at the D-ignition

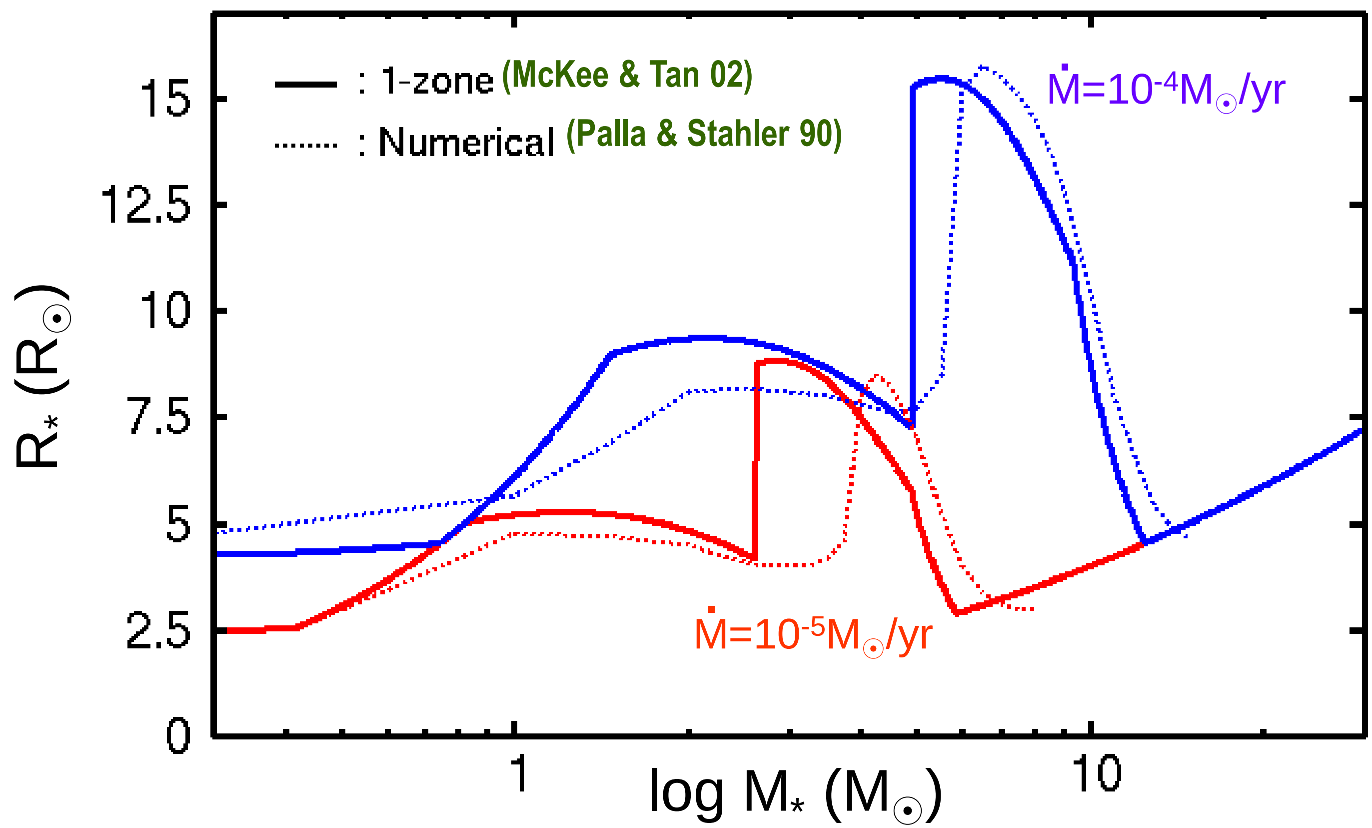
1-zone Polytrope Model

(ref. Nakano et al.'00, McKee & Tan '02)

Total energy of star: $$E = \underbrace{-a_{\rm E}\frac{GM_*^2}{R_*}}_{\text{grav. energy}} + \underbrace{\phi_{\rm I}\frac{M_*}{m_{\rm H}}}_{\text{Ionization dissociation}} - \underbrace{\phi_{\rm D}\frac{f_{\rm D}M_*}{m_{\rm H}}}_{\text{D-burning}}$$

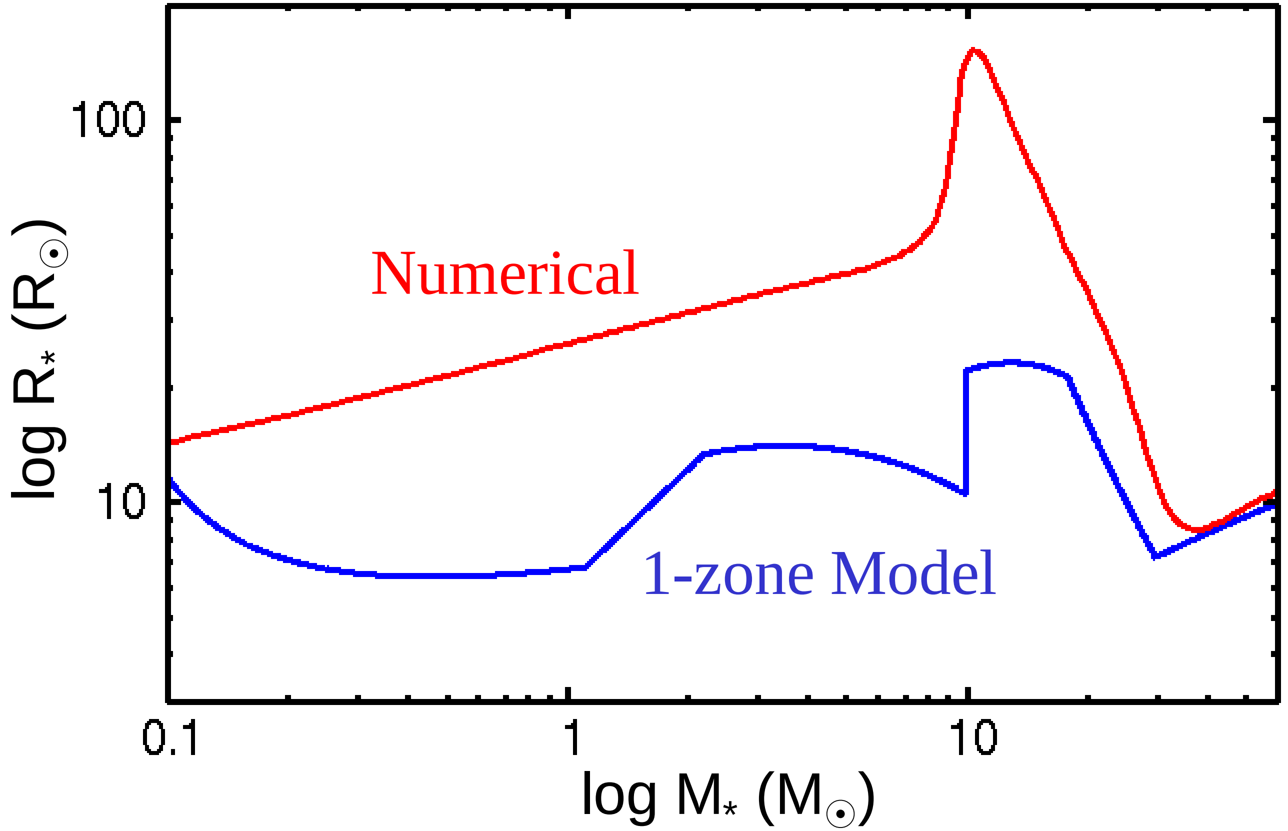
$$\frac{dE}{dt} = L_{\rm int} + L_{\rm acc} \sim L_{\rm MS}(M_*) + \frac{GM_*\dot{M}}{R_*}$$

$$\rightarrow \frac{d\log R}{d\log M}$$



Numerical *v.s.* 1-zone Model

$\dot{M}=10^{-3}M_{\odot}/yr$



Simple extrapolation of the 1-zone model can lead to the qualitatively different evolution at high acc. rate.

← our results are available for the better calibration

Summary

We have studied the detailed evolution of the accreting protostar focusing on cases with the high accretion rate of $10^{-4\sim-3} M_{\odot}$/yr.

- The evolution with high accretion rate is fairly different from that with the low accretion rate ($10^{-6\sim-5} M_{\odot}$/yr) .

adiabatic accretion → swelling by luminosity wave → K-H contraction

- High entropy in the star ⇒ very large radius (~10-100 $R_{\odot}$)
- D-burning hardly affect the evolution of the protostar. The protostar remains almost fully radiative until it reaches the M-S.

- Dependence on the accretion rate

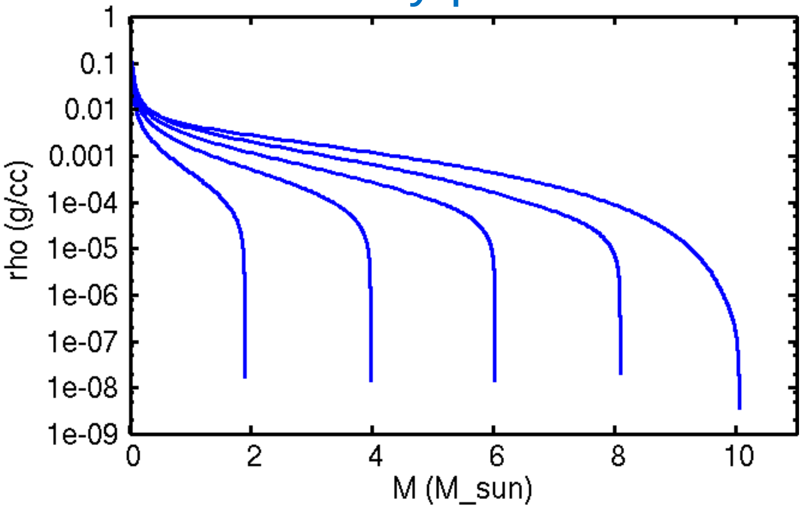
- R_* is larger, and protostar reaches M-S later with the higher acc. rate.
- The effect of D-burning appears later and becomes minor with the higher acc. rate; Free-free opacity at the D-ignition is important

- Our results are available for the better calibration of the 1-zone model.

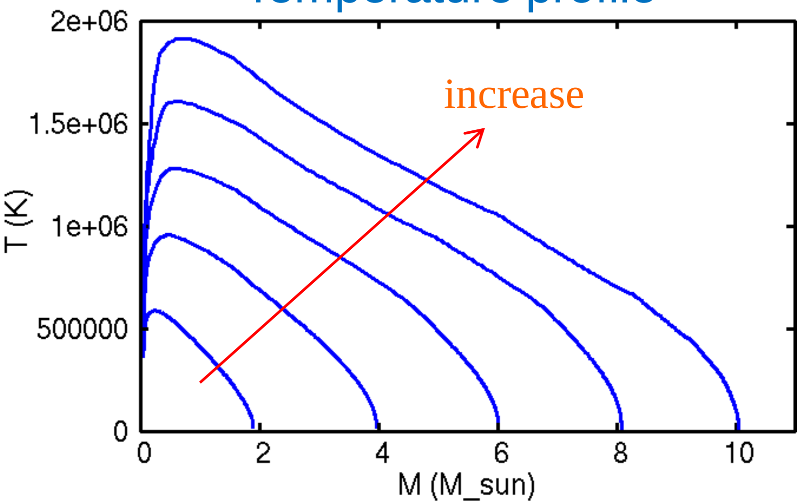
Supplement files

Opacity decrease

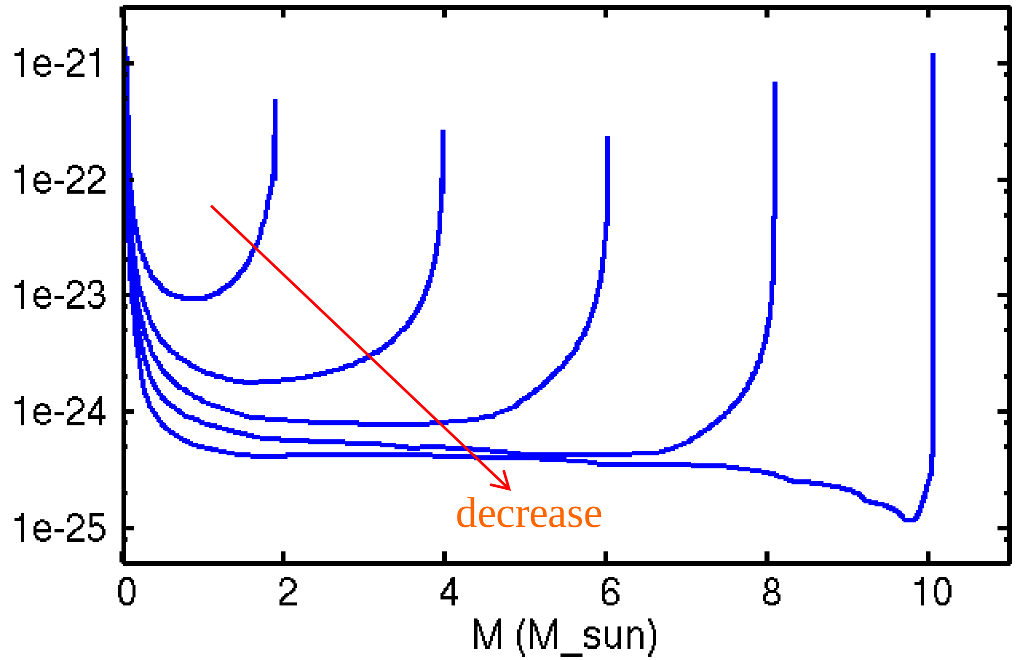
Density profile



Temperature profile



Profile of $\rho T^{-3.5} \propto$ free-free opacity



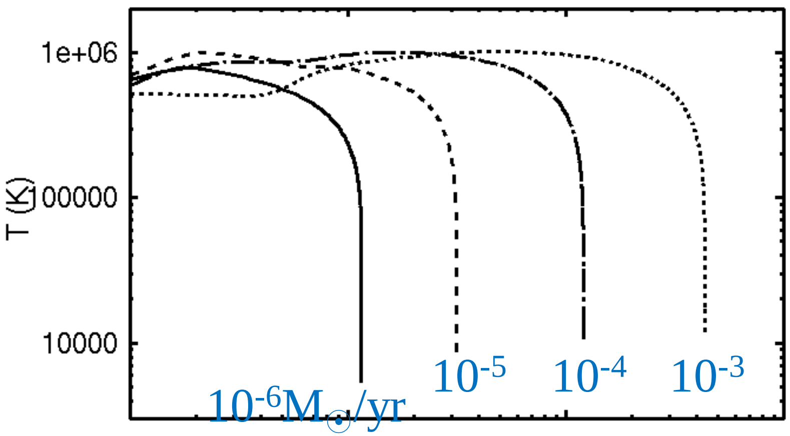
With increasing the stellar mass, free-free opacity within the star **decreases** owing to its T-dependence.

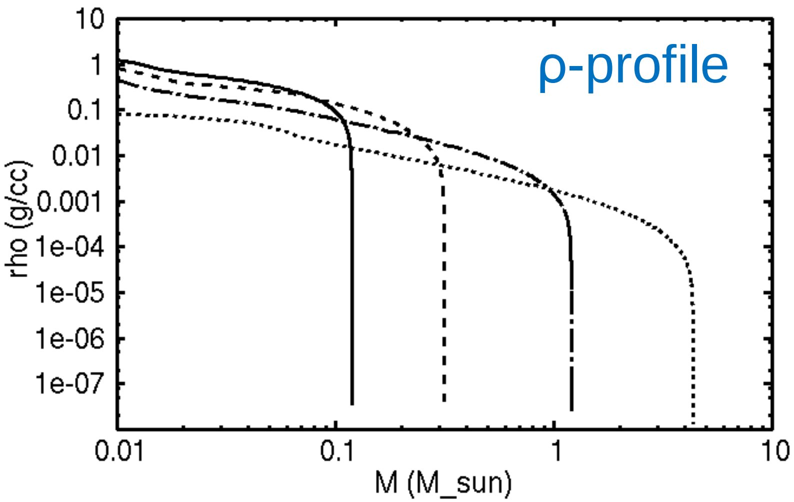
Why radiative with high $\dot{M}$?

Entropy is generated by the D-burning, but this is efficiently transported to the outer part *only by the radiation,* the star remains radiative

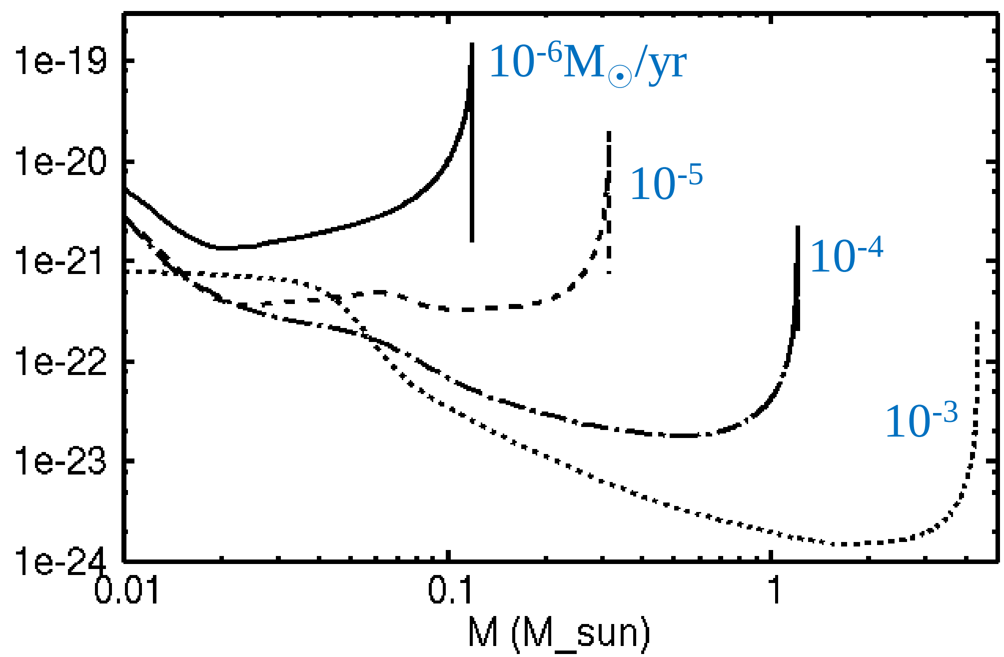
→ low opacity enables this

T profile @ D-ignition



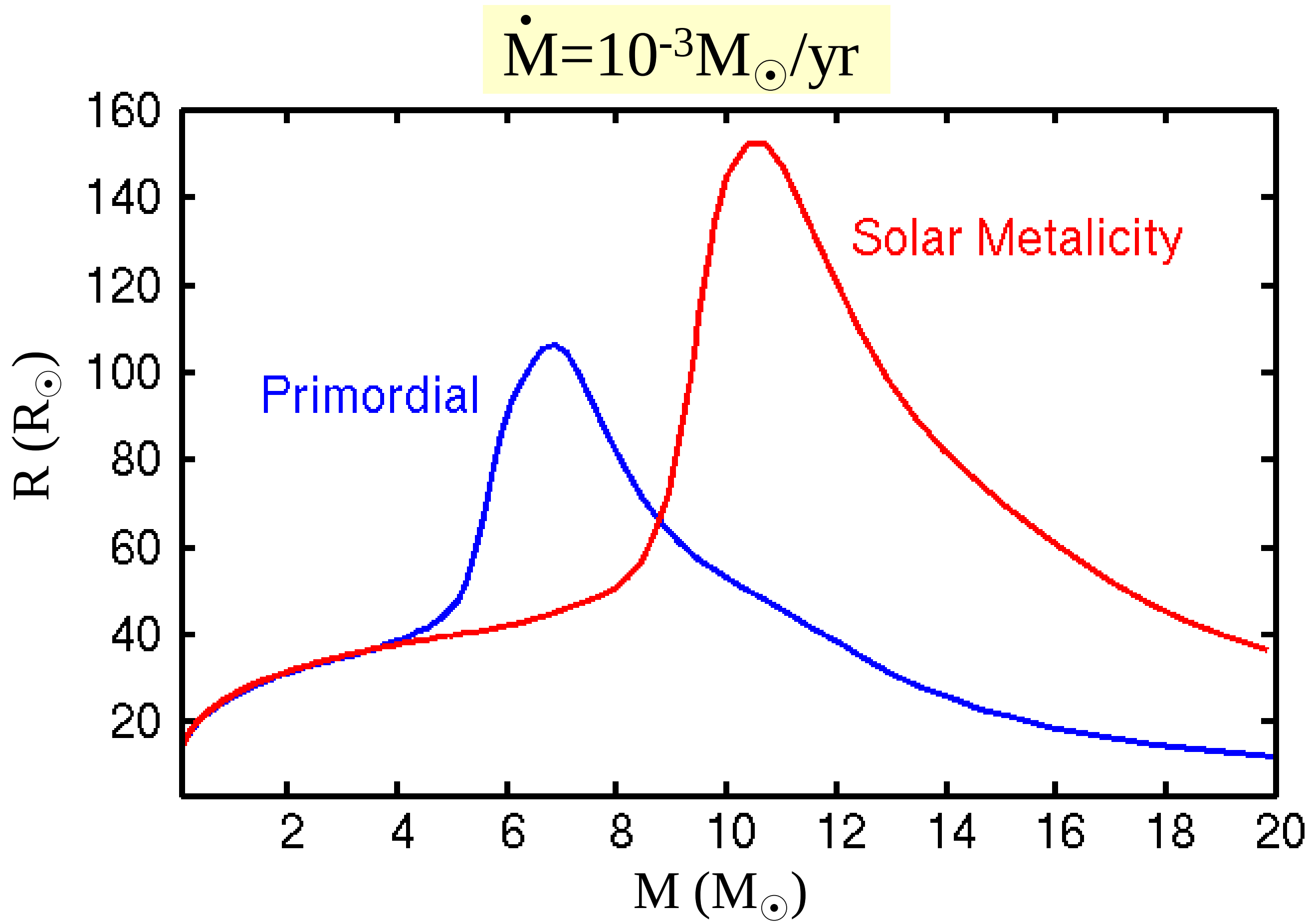


Profile of $\rho T^{-3.5}$



Opacity is low enough at the D-ignition with the high acc. rate.

Similarity to Primordial Protostar



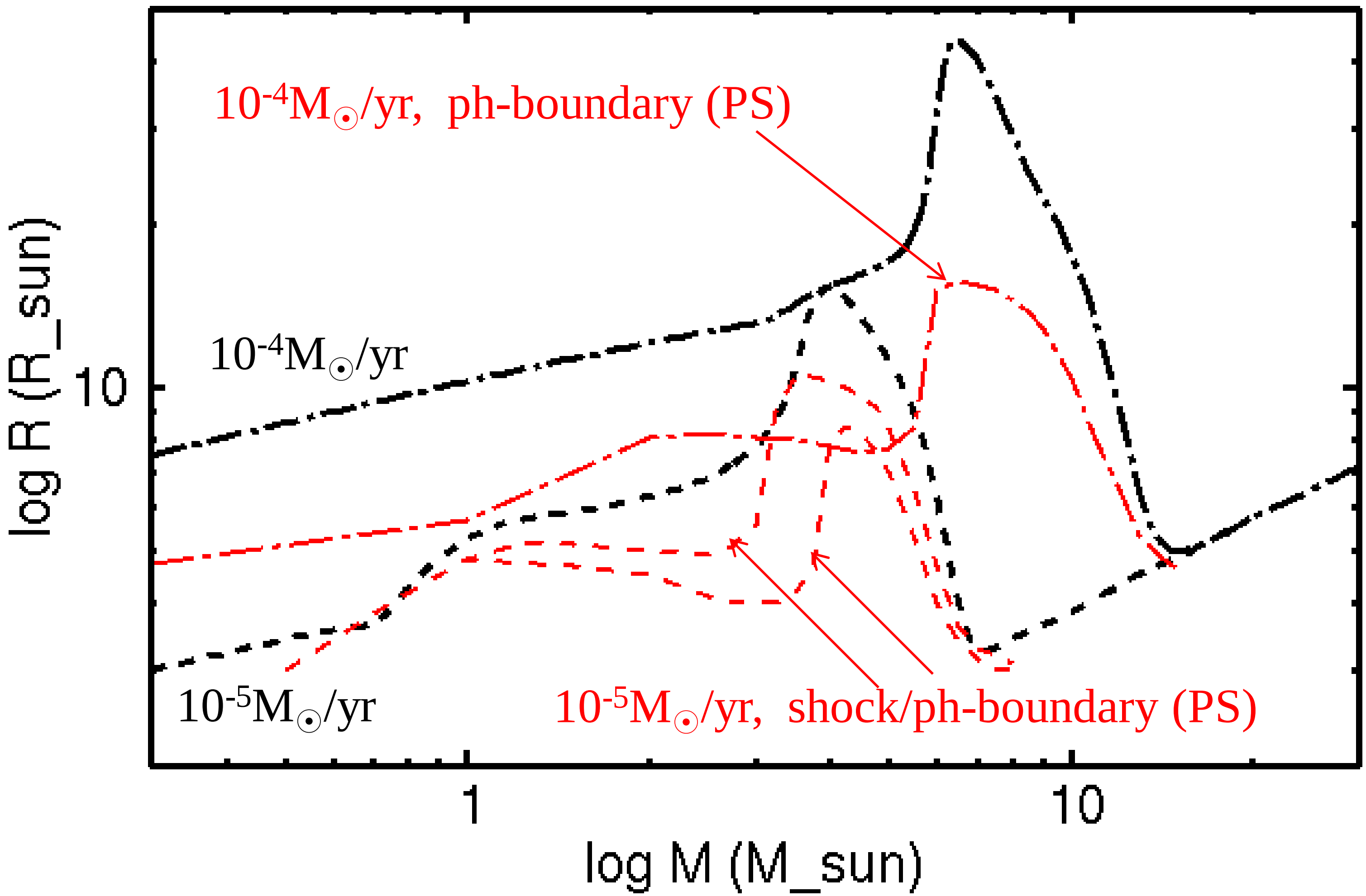
Star formation in the early universe

: formation of protostar with the high acc. rate

(e.g., Stahler, Palla & Salpeter '86, Omukai & Palla '01,03)

evolution is qualitatively similar with the present-day protostar with $\dot{M} \sim 10^{-3} M_{\odot}/\mathrm{yr}$

Comparison with Palla & Stahler ①



Comparison with Palla & Stahler ②