大質量原始星の進化

細川 隆史 (東大)

- ❖ TH, Omukai, 2009, ApJ, 691, 823
- ❖ Smith, TH, Omukai, Glover & Klessen 2012, MNRAS, 424, 457

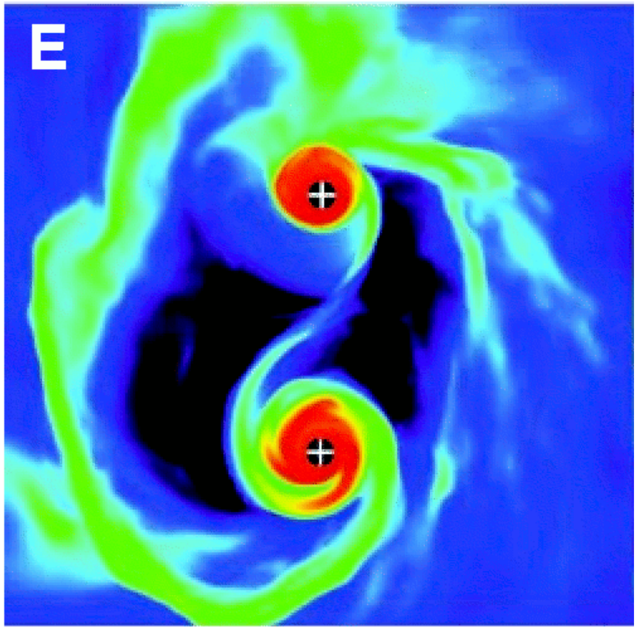
など

2013.3.8 “様々な変光現象とその観測的アプローチ”@ 茨城大学

大質量星形成 = rapid mass accretion

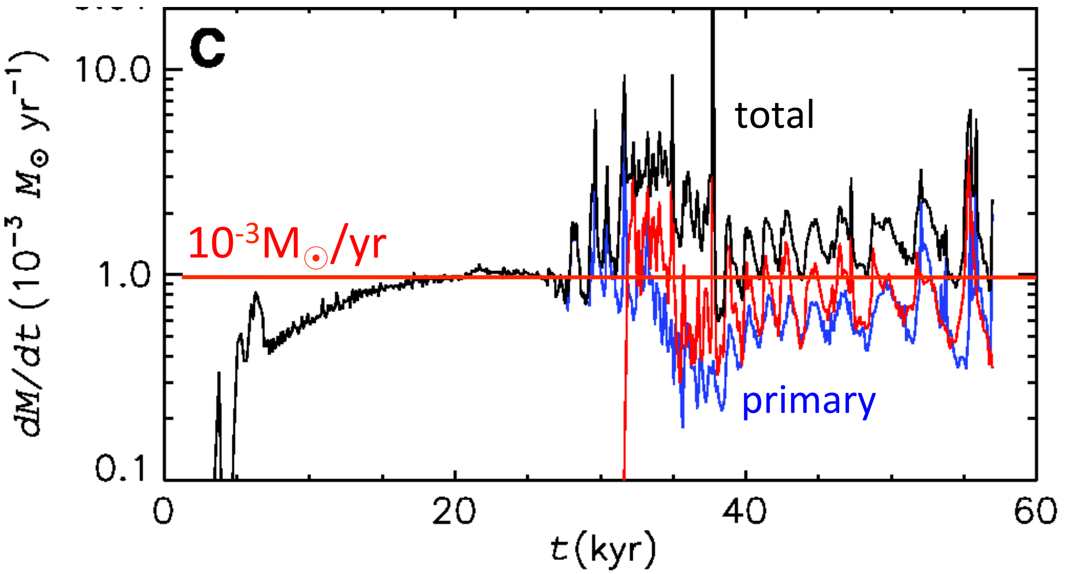
+ various observational supports: infall motion, outflow, SED fitting etc.
+ formation scenarios: monolithic collapse v.s. competitive accretion
(e.g., McKee & Tan 03)　　(e.g., Bonnell et al. 04)
rapid mass accretion is expected for the both

Krumholz et al. '09



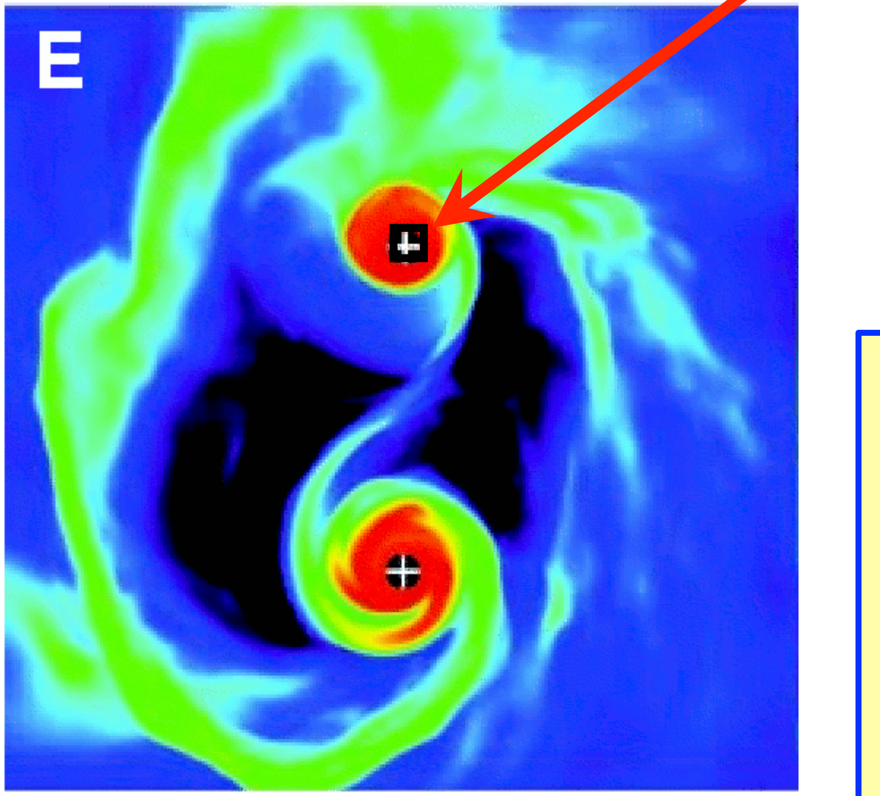
O型星同士のbinaryができた

降着率の時間進化



A “target”

Krumholz et al. ‘09



“Protostar”,
but just “sink” in simulations

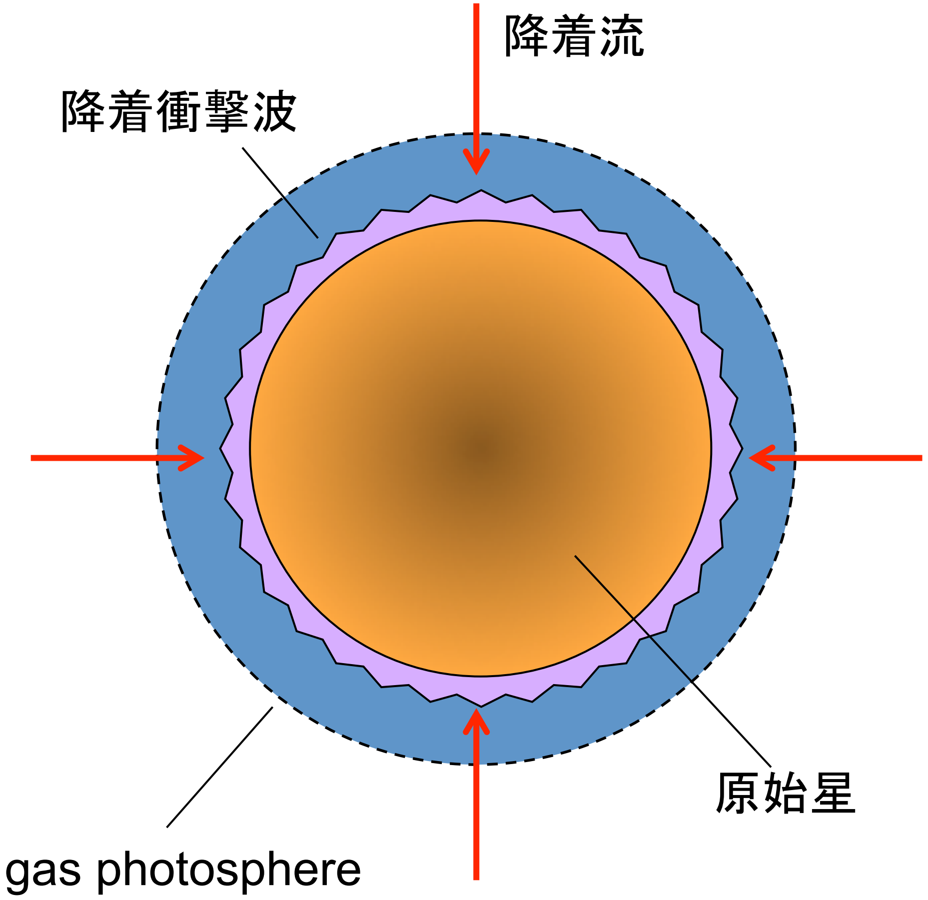
- ガス : in-going, 輻射 : out-going
- 星ごく近傍はtime stepを非常に短く取る必要があるため

星内部およびごく近傍の物理過程はほとんど調べられていない :

- **原始星進化**
- outflow噴出
- 近接連星形成

Our Study

大降着率のもとで原始星の進化 (e.g., 半径, 光度) がどうなるか
原始星の構造を解いて調べる　(e.g., Hosokawa & Omukai '09, ApJ)



Basic eq.: 4 stellar structure eqs.

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

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

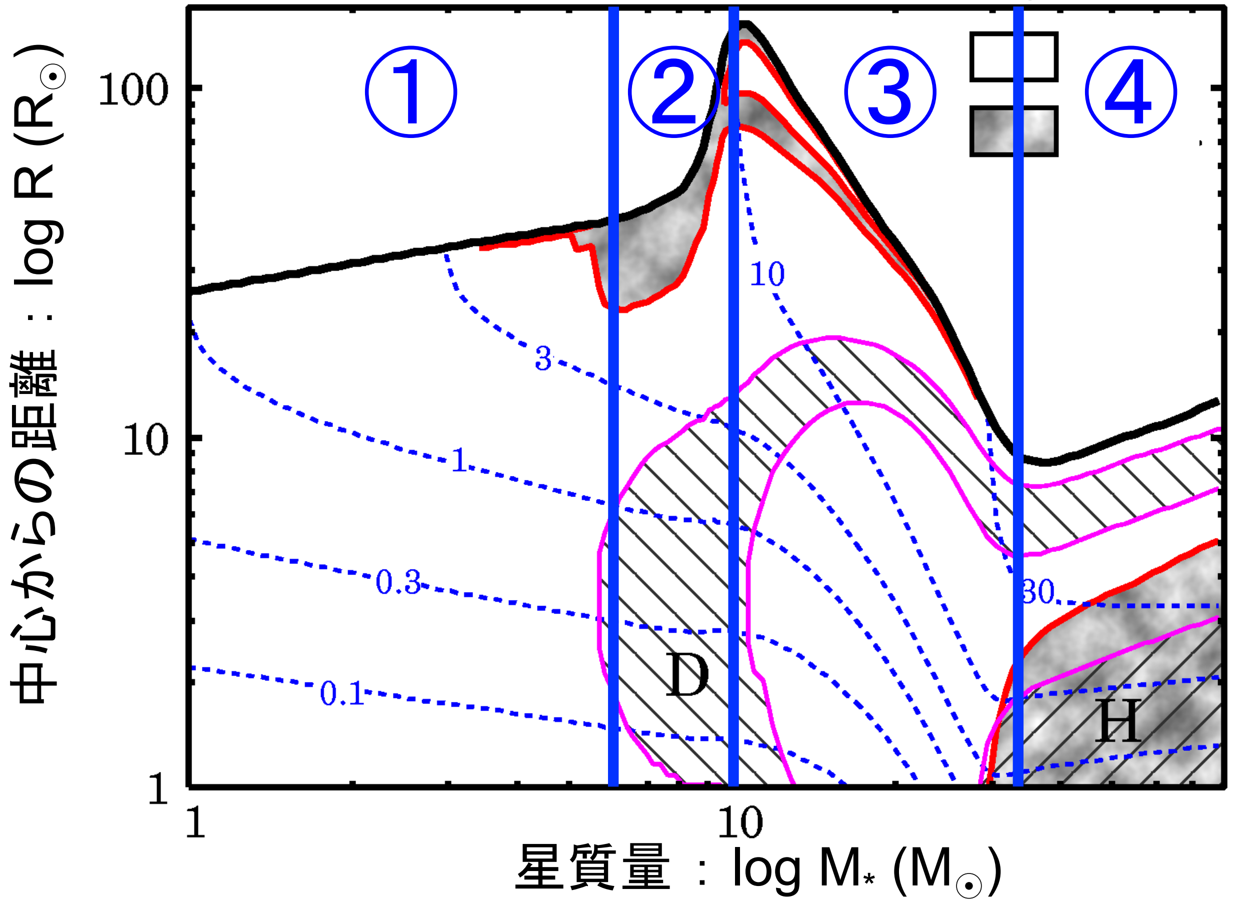
Energy : $$\frac{\partial l}{\partial m} = \epsilon_{\rm nuc} + T\left(\frac{\partial s}{\partial t}\right)_m$$

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

外部の定常降着流とshock条件で接続

大降着率下での原始星進化

内部構造 ： $\dot{M}=10^{-3}M_{\odot}/\mathrm{yr}$

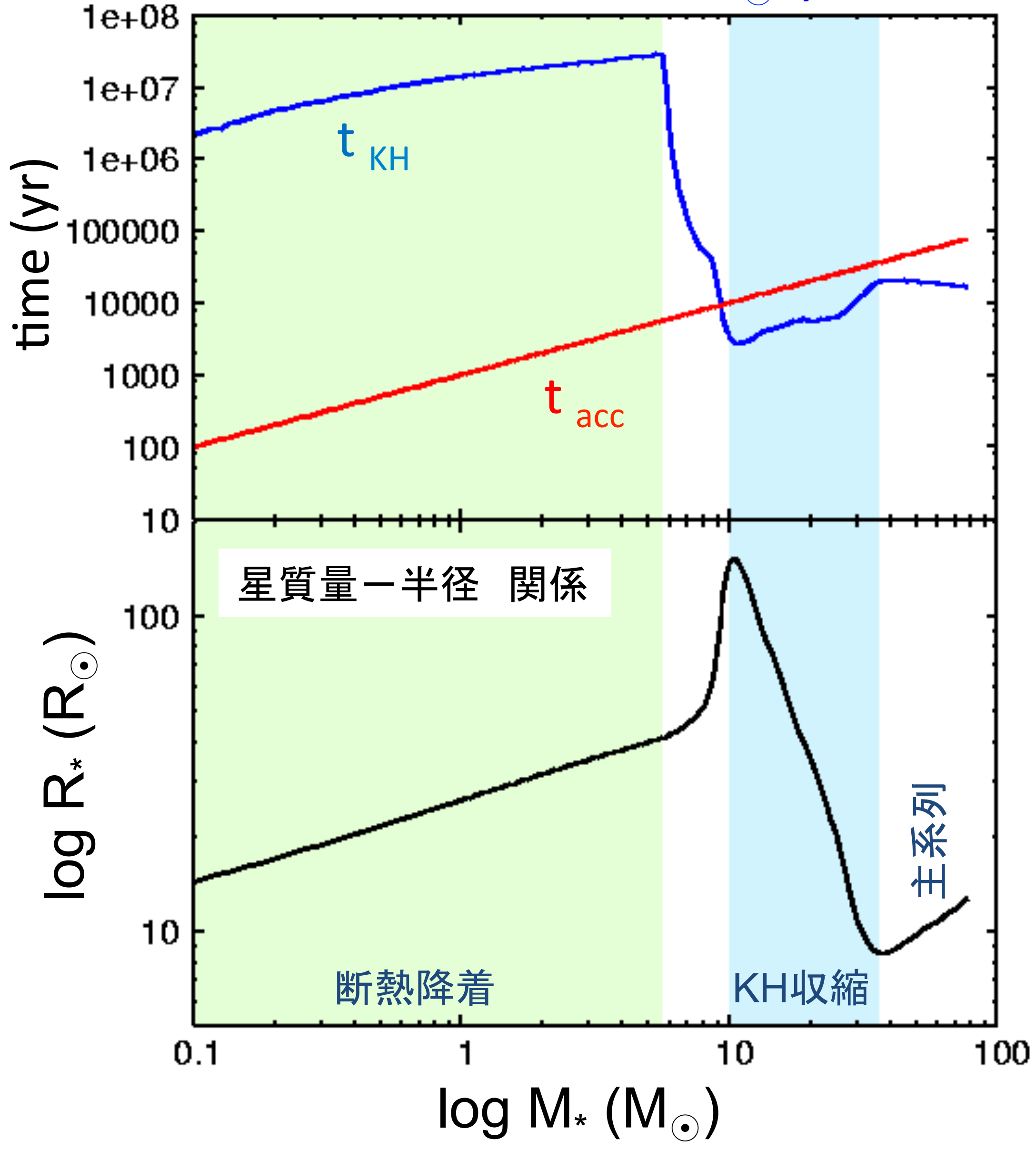


① はじめゆっくり膨張 ⇒ ② 急激に膨張

⇒ ③ 収縮 ⇒ ④ 水素燃焼（主系列）

Timescale Balance

質量降着率: $10^{-3} M_\odot$/yr



2つの重要時間スケール

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

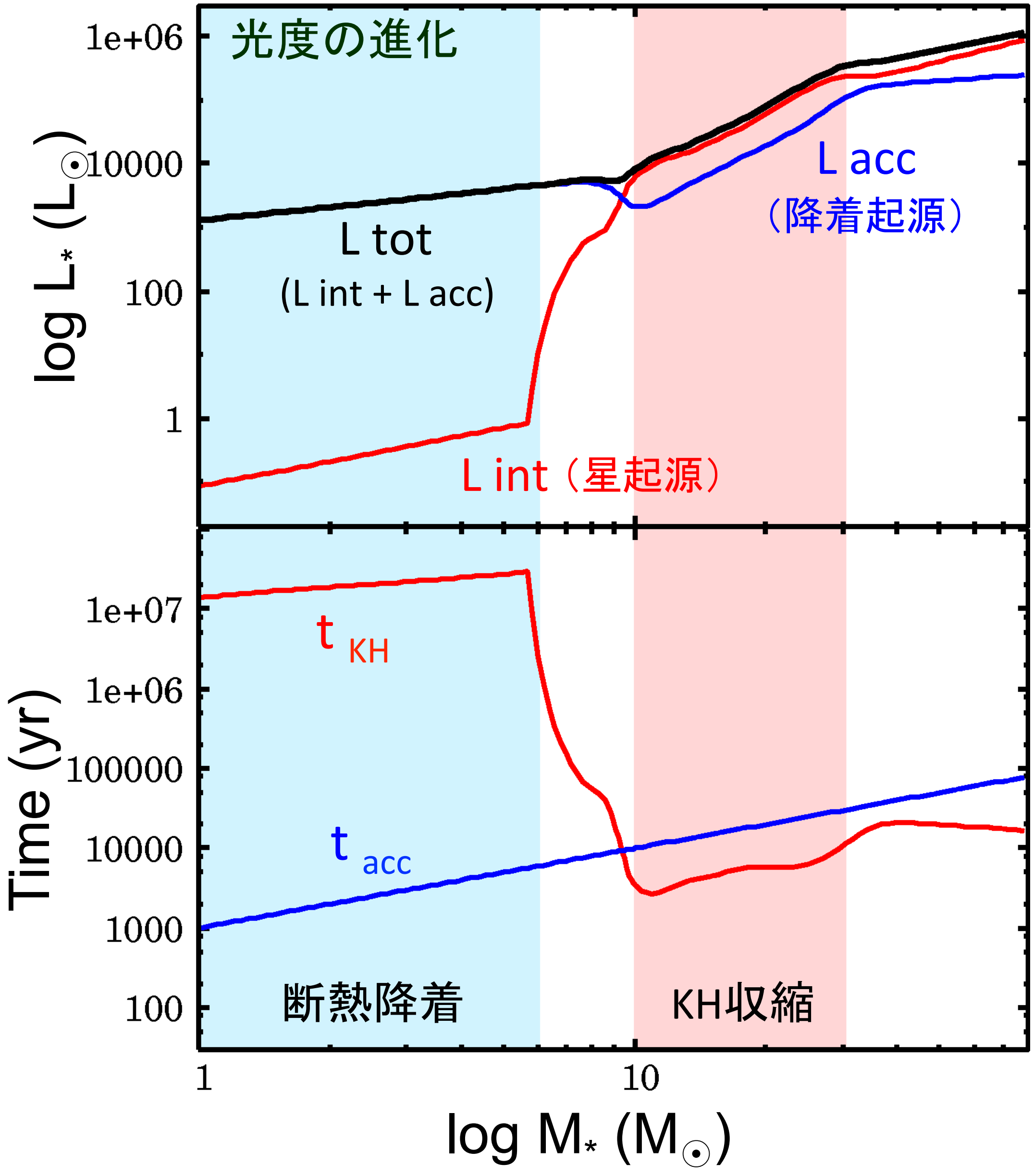
初期: $t_{KH}>t_{acc}$; 断熱降着
（徐々に膨張）

Opacity ↓ ⇒ t_{KH} ↓

後期: $t_{KH}<t_{acc}$; K-H 収縮

過渡期:　急激な膨張

Luminosity Balance



初期： $L_{int} < L_{acc}$; 断熱降着

↓

後期： $L_{int} > L_{acc}$; K-H 収縮

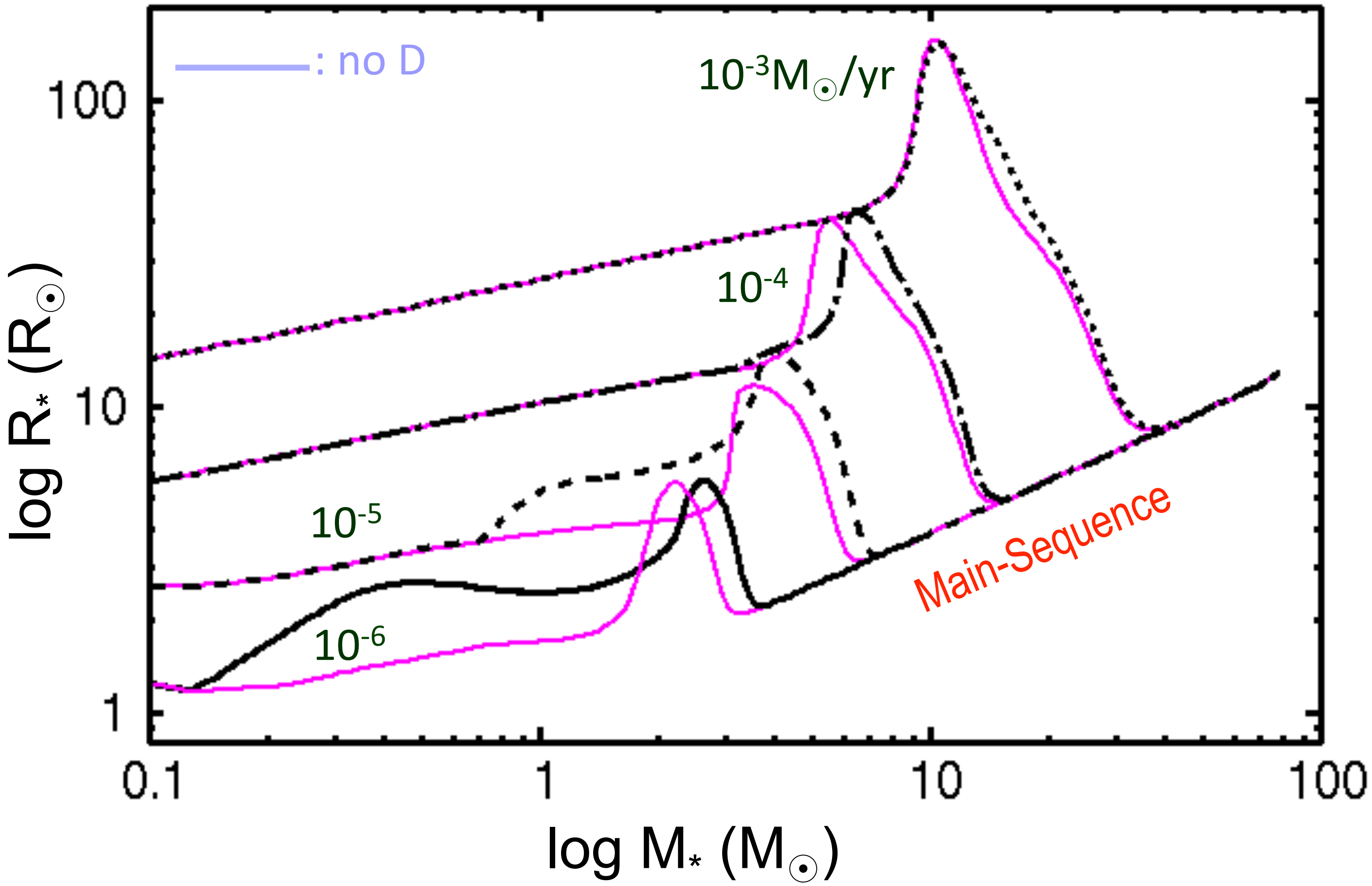
timescaleのバランスが入れかわる時点で光度のバランスも入れかわる

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

$$t_{KH} / t_{acc} = L_{acc} / L_{int}$$

原始星進化：降着率の依存性

星質量ー半径 関係



降着率が大きいと、 - 同質量で原始星の半径が大きい
- 主系列に達する質量が大きい

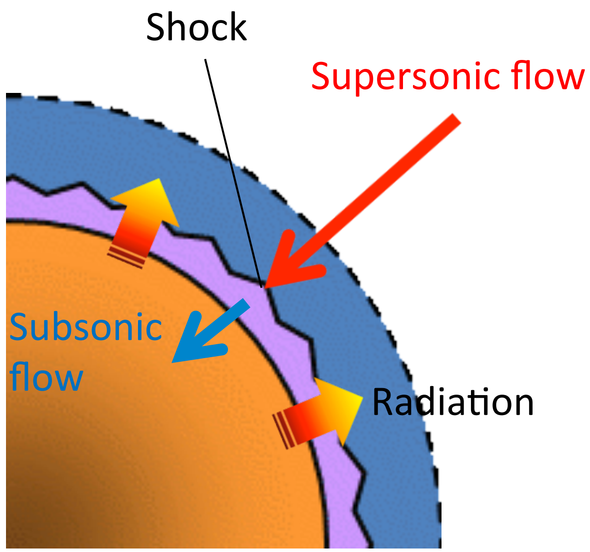
Why large R_* with high $\dot{M}$?

星内の典型的密度、圧力: $\rho \sim \frac{M}{R^3} \quad P \sim G\frac{M^2}{R^4}$

単原子理想気体の単位質量あたりエントロピー: s

$$s = \frac{3\mathcal{R}}{2\mu}\ln\left(\frac{P}{\rho^{5/3}}\right) + s_0 \longrightarrow R \propto M^{-1/3}\exp\left[\frac{2\mu}{3\mathcal{R}}(s - s_0)\right]$$

(同一質量で) エントロピーが大きいと半径が大きい



エントロピー生成 @ Accretion shock

降着率大 → t_acc << t_cool @post-shock

降着率大 → エントロピー大 → 半径大

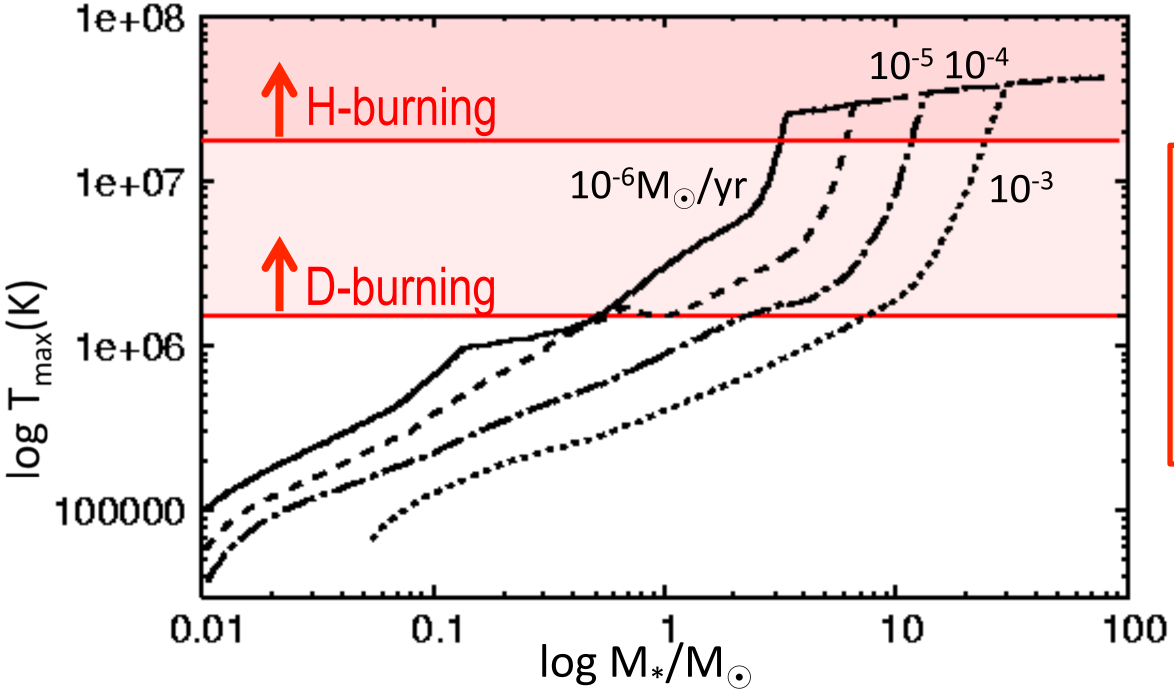
Why late fusion with high $\dot{M}$?

星内の典型的密度、圧力: $\rho \sim \frac{M}{R^3}$ $P \sim G\frac{M^2}{R^4}$

→ 星内の典型的温度: $T = \frac{\mu}{\mathcal{R}}\frac{P}{\rho} \sim \frac{G}{\mathcal{R}}\frac{\mu M}{R}$

(同一質量で) 半径が大きいと温度が低い

星内最高温度の進化



降着率大 → 半径大
→ 温度低
→ D,H点火遅

Signature of high $\dot{M}$? ①

形成中の大質量星　Orion KL

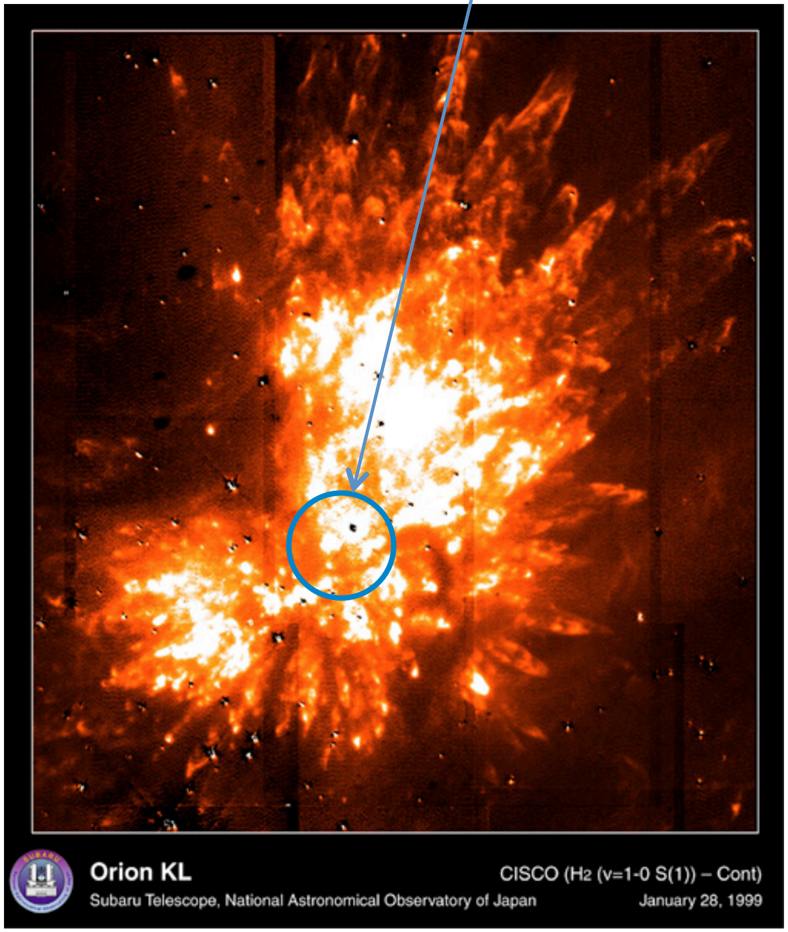
Morino et al. 1998, Nature

この領域のダスト反射
(2μ) を観測

- T_{eff} = 3000 – 5500 K
  (CO, metal の吸収線から）
- 全光度 : $L > 4 \times 10^4 L_\odot$

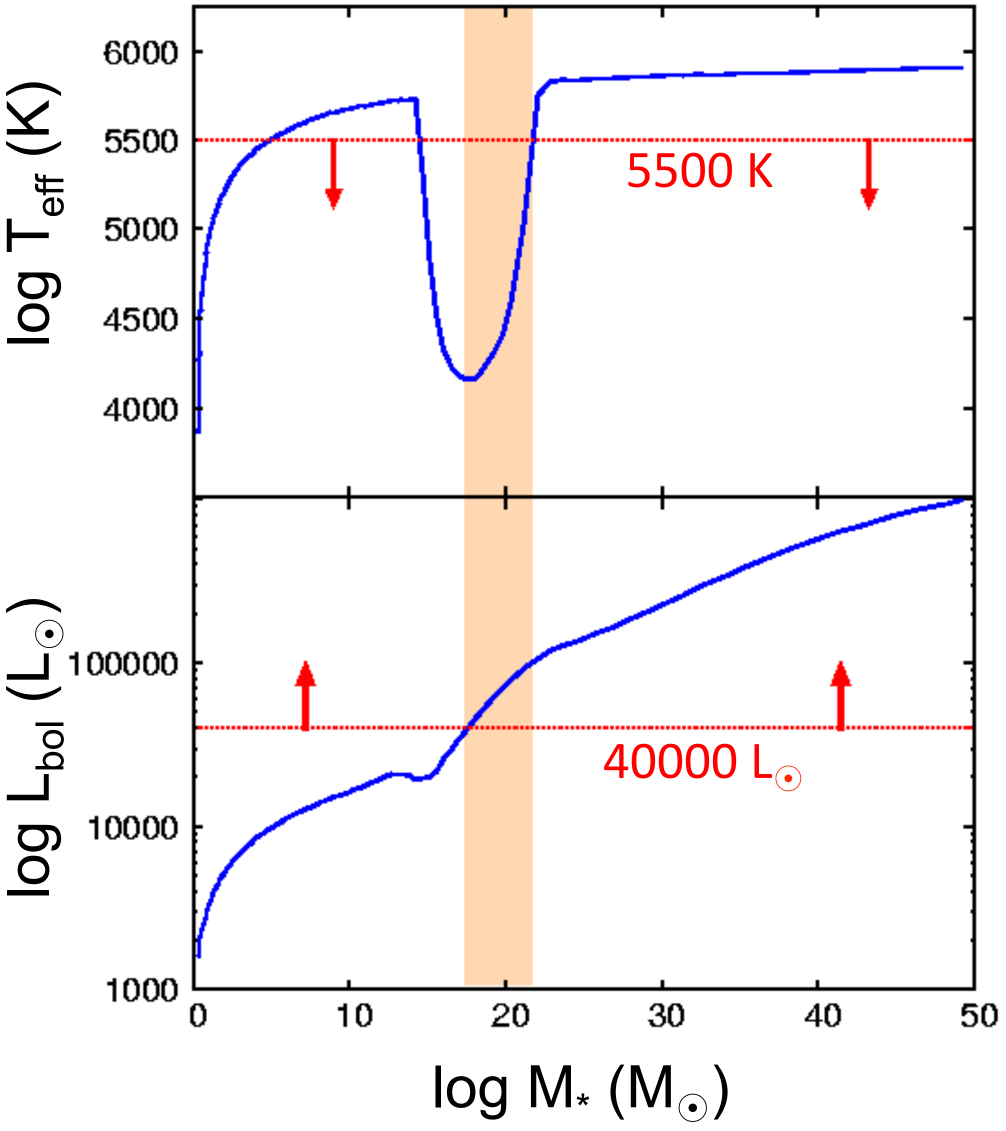
(cf. ZAMS
$L \sim 4 \times 10^4 L_\odot$のとき$T_{eff} \sim 35000$K)

Embedded high-mass protostar(s)



Signature of high $\dot{M}$? ②

（例）質量降着率：$4.5\times10^{-3}M_\odot$/yr



条件

有効温度：**T_{eff} < 5500 K**

全光度　：**L > 4 x 10^4 $L_\odot$**

計算結果と比べると、降着率 $4\times10^{-3}M_\odot$/yr　以上でOK

大光度 + 低輻射温度が大質量原始星の特徴

another signature→ 稲吉くん’s talk

Accretion in reality…

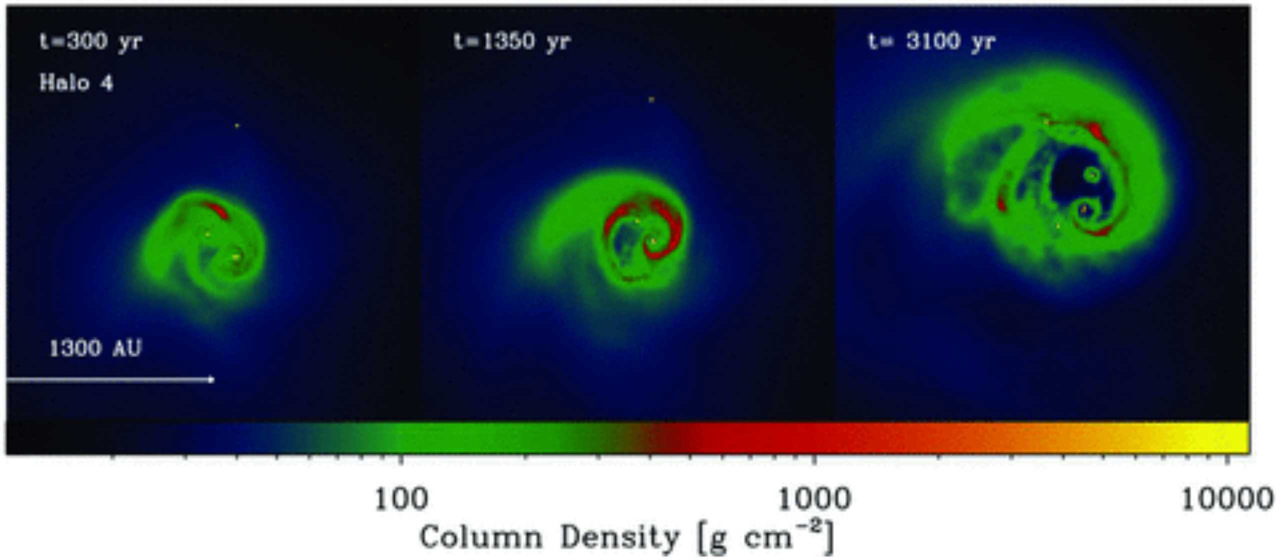
In reality, mass accretion onto the protostar should be more complex, e.g., accretion rates would be variable (time-dependent).

- Formation of spiral arms in the disk
- Gravitational Fragmentation of the disk

(e.g., 3D numerical simulations: Krumholz+09, Kuiper+11 etc…)

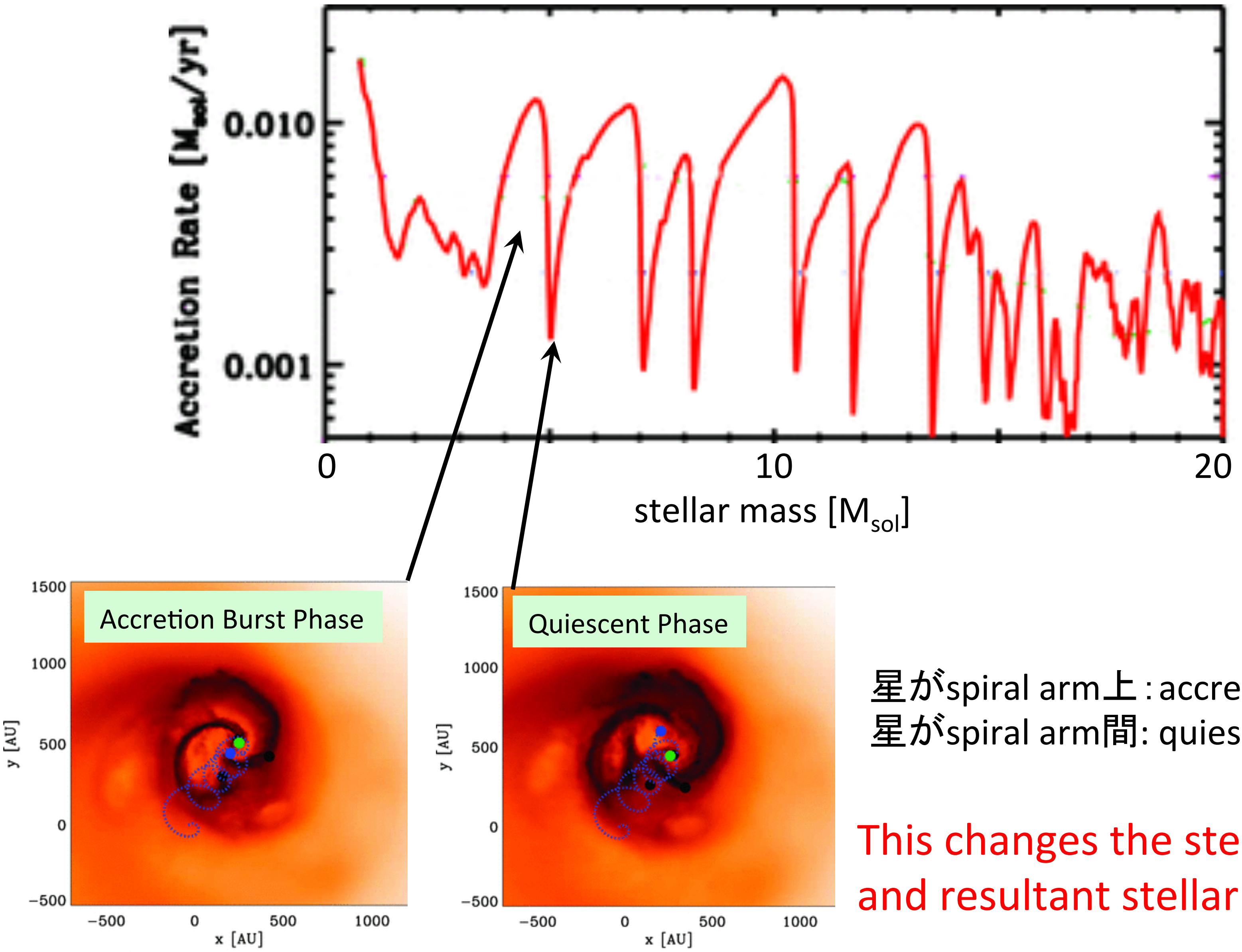
Smith et al. 11: 3D SPH simulations following the early several x 1000 yrs after the birth of the protostars (初代星形成)

time



Episodic Accretion

An accretion history taken from Smith+11

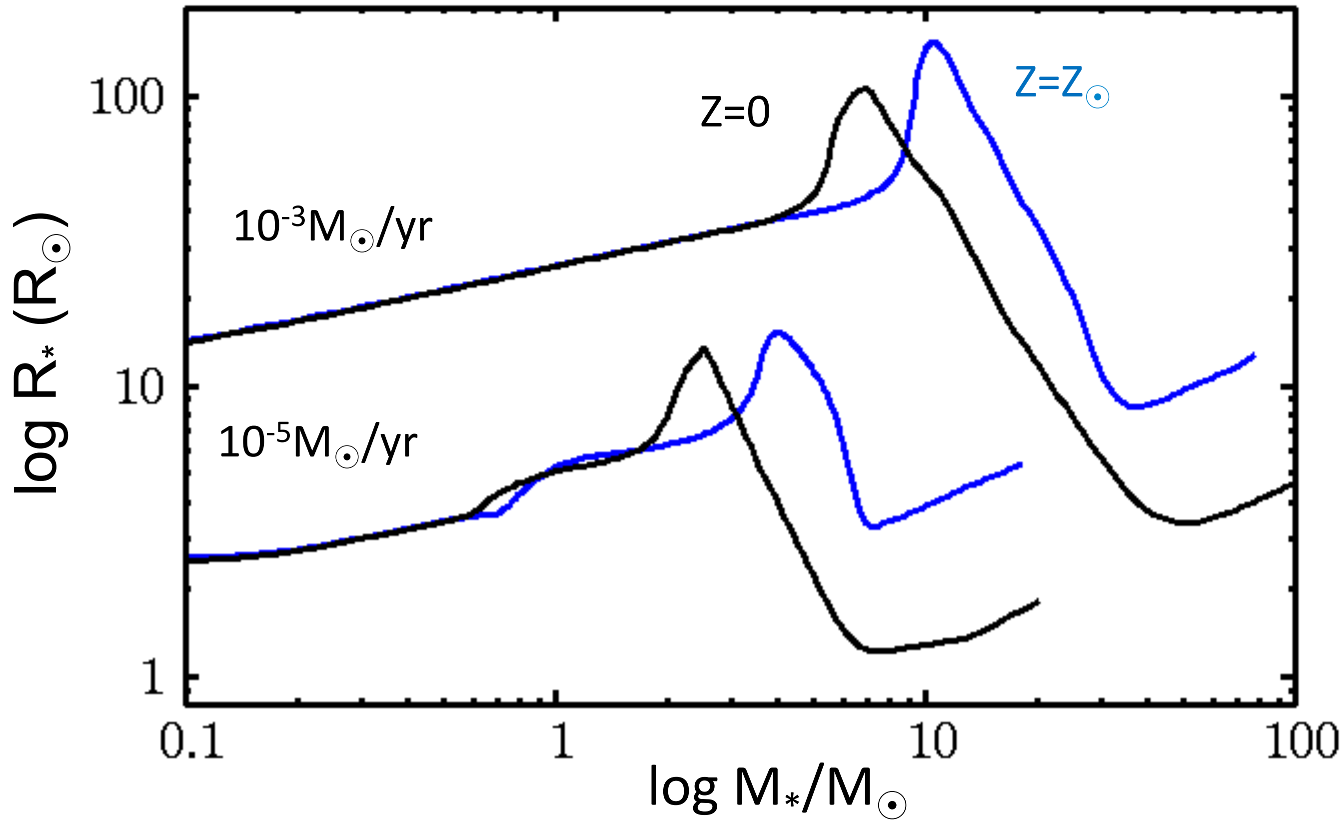


星がspiral arm上 : accretion burst phase
星がspiral arm間: quiescent phase

This changes the stellar evolution and resultant stellar feedback?

星の進化と金属量

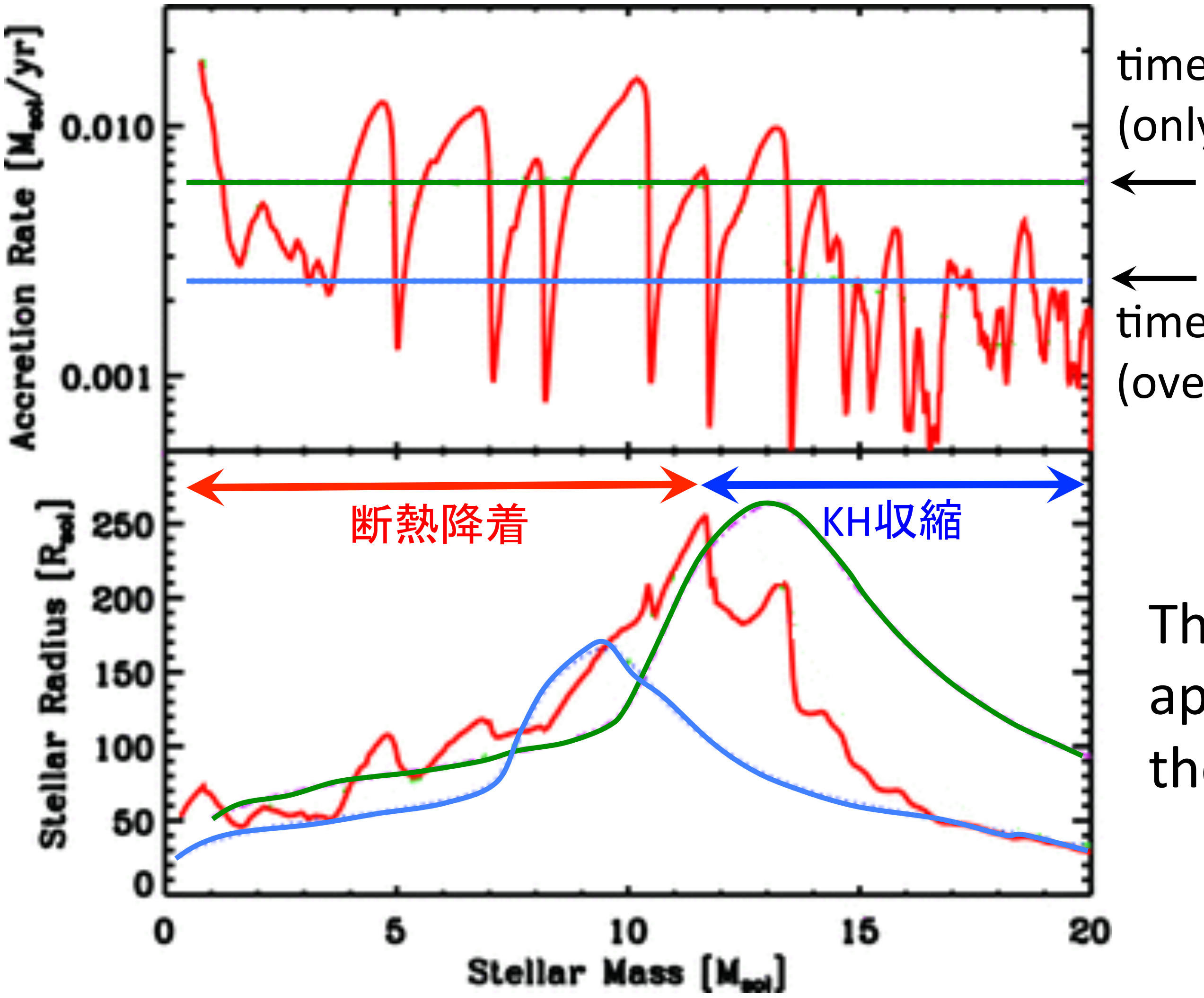
Mass-Radius relation



+ 定性的進化は金属量0でも同じ

+ 金属量が低い方が - 早くK-H収縮が始まる ← low opacity
 - より小さい半径でZAMSに至る

Stellar Evolution



time-averaged constant rate ①
(only for $M < 10M_\odot$)

←

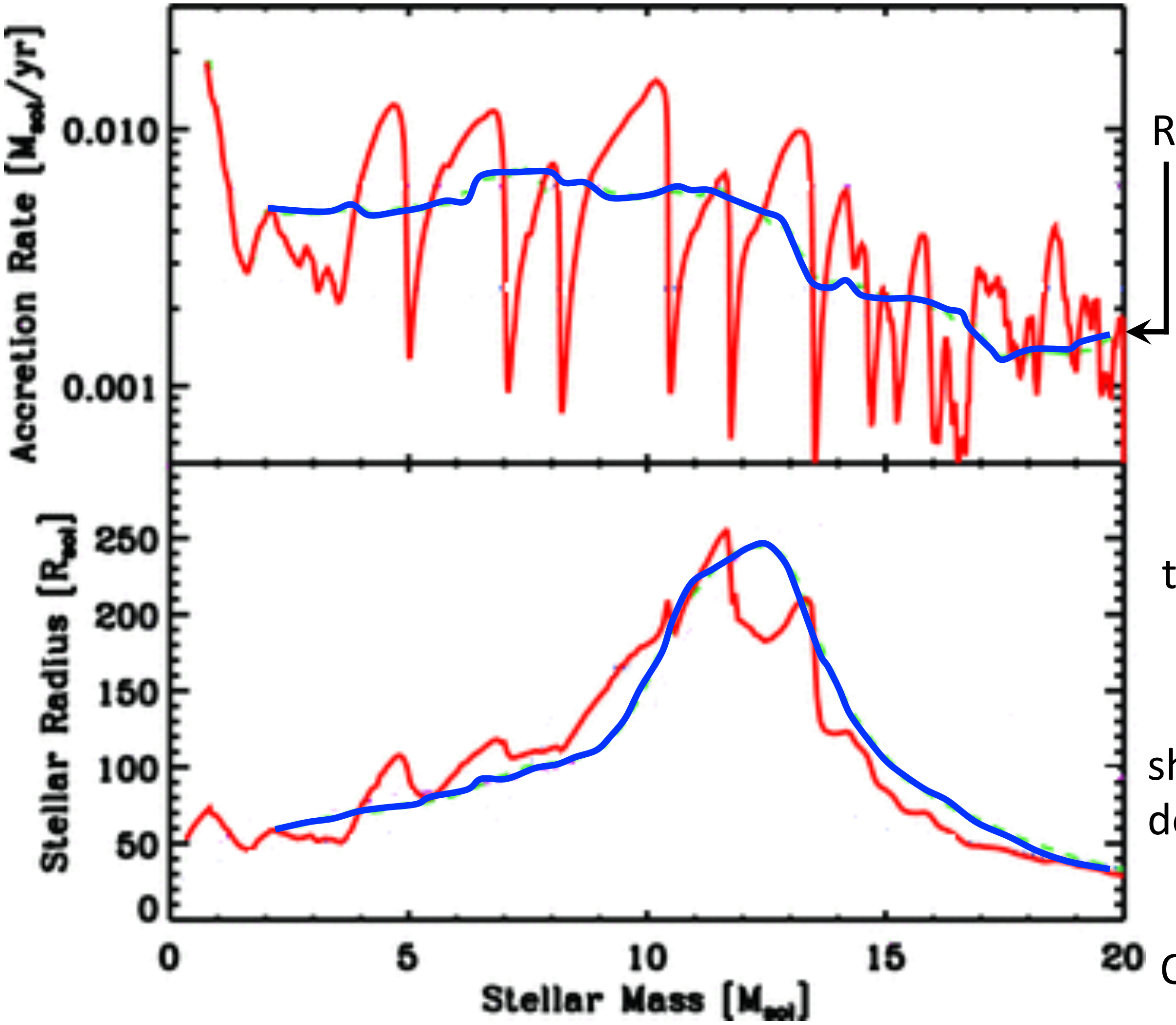
←

time-averaged constant rate ②
(over the entire evolution)

The evolution is poorly approximated with the constant rates.

Timescale of Variability

But this does not mean that all of the accretion variability affects the stellar evolution.



Running average of the variable rate

Smear out the short-term (< a few 100 yr) variability

Well approximated!

the stellar evolutionary timescale is min(t_acc, t_KH)～10^3 yrs.

↓

short-term episodic mass accretion does not change the stellar structure

↓

Only the overall trend is important

Summary

- **Evolution of (rapidly) accreting high-mass protostars**
  - **large stellar radius** (> $100R_\odot$ at maximum)
  - nuclear fusion is postponed (> a few x $10M_\odot$)
- **Orion KL**

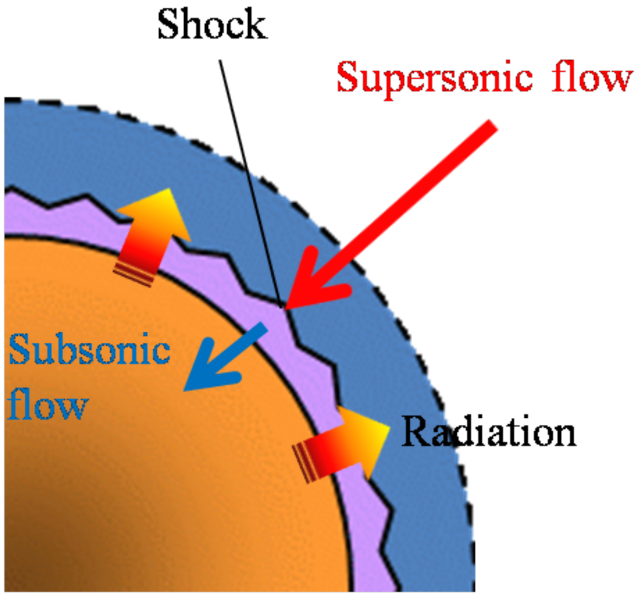
  low Teff + high L could be explained with a rapidly accreting protostar
- **Variable mass accretion**

  the short-term variability (< 10^3 yr) **does not change** the stellar evolution and resultant feedback.

Additional pages

“Hot” or “Cold” Accretion?

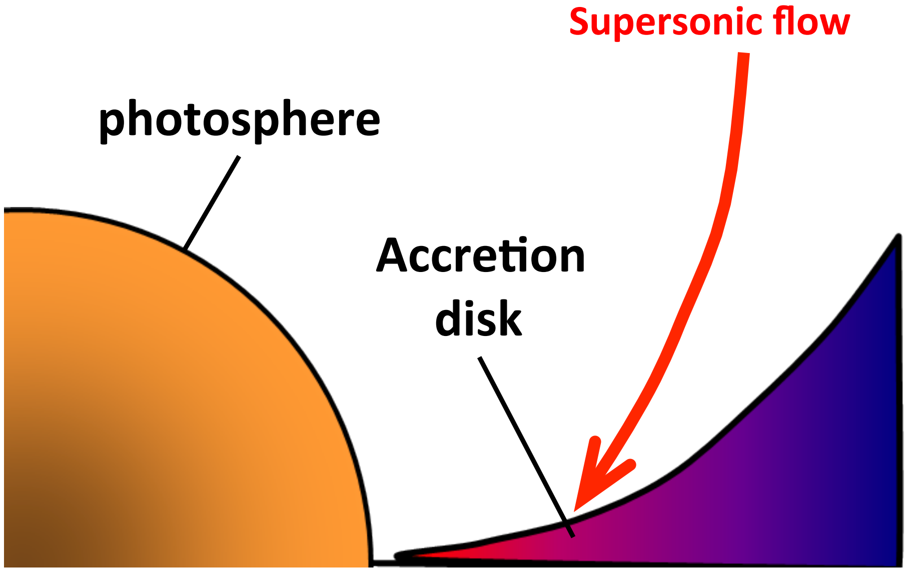
“HOT” mass accretion



Accretion flow directly hits the stellar surface. A part of the entropy generated at the shock front is taken into the stellar interior.

This is expected for the rapid mass accretion.

“COLD” mass accretion

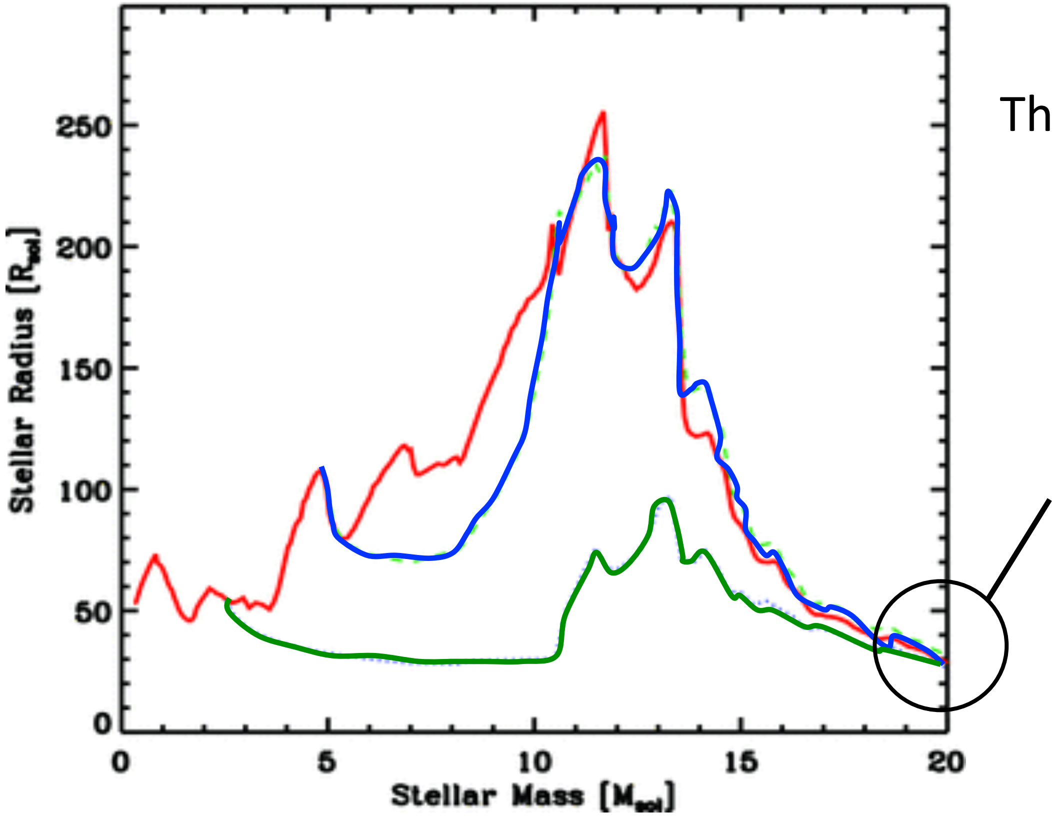


Gas softly accretes to the protostar through the disk. Accreting materials join the star with the same entropy as in the stellar atmosphere.

Cold Accretion?

The thermal properties of mass accretion (e.g., hot / cold accretion) are more important than the variability of the accretion rates.

The hot accretion is switched to the cold accretion for M > 2.5 / 5 $M_\odot$



The cold accretion reduces the average entropy in the stellar interior

↓

smaller stellar radius

But the timing of the protostar's arrival to the ZAMS is the same

(this is given by t_acc = t_KH,ZAMS)

The UV stellar feedback should be turned on at the same epoch.