Formations of Compact Objects
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Waseda Univ.

Massive star formation in high-z and local universe

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Outline

I. Massive star formation in the local universe

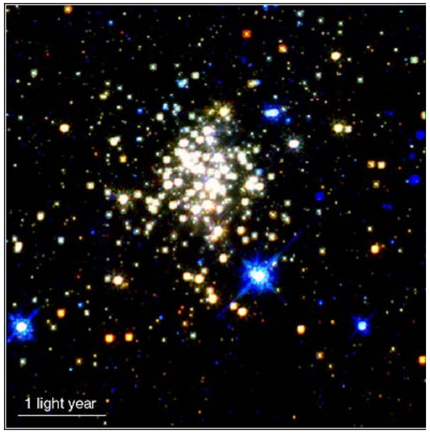
- Standard scenario of low-mass star formation
- Obstacles in forming massive stars
- Scenarios of massive star formation
- Accretion evolution of high-mass protostellar objects

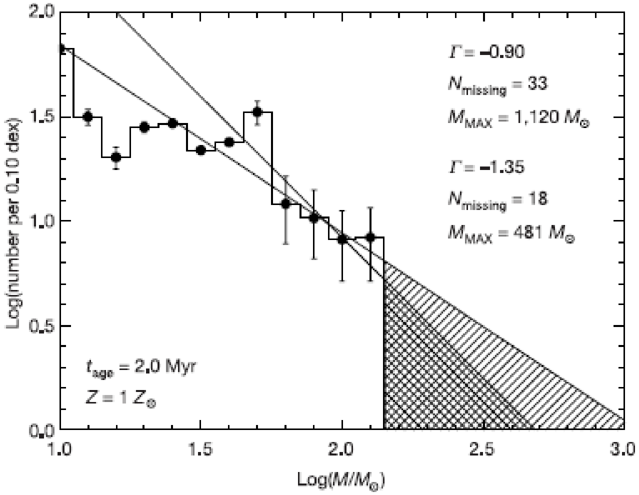
II. Massive star formation in the high-z universe

- Formation of First Stars in the universe
- Low-metallicity Stars:
  transition of characteristic fragmentation mass
- Super-massive Star Formation

Massive Stars in the Local Universe

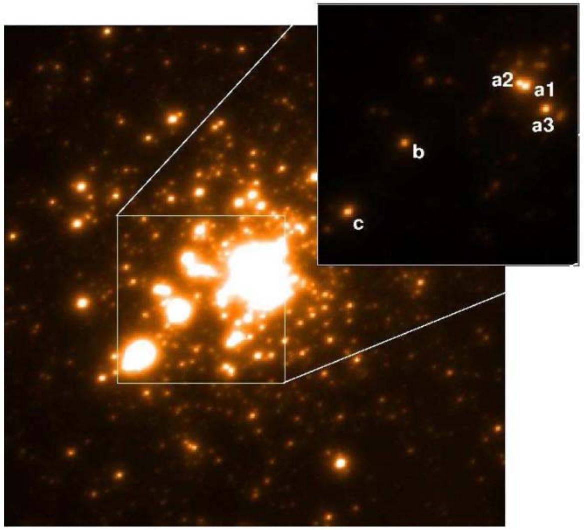
the Arches cluster in the Galactic Center Figer 2005



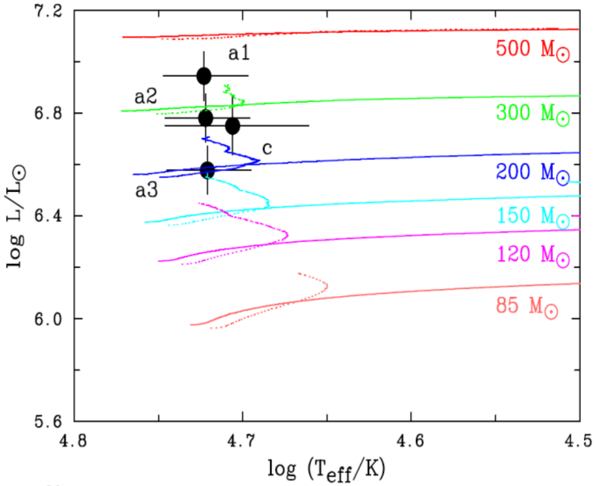


In our Galaxy upper mass limit ~150M_{sun}

R136 in 30 Dor



Crowther + 2010



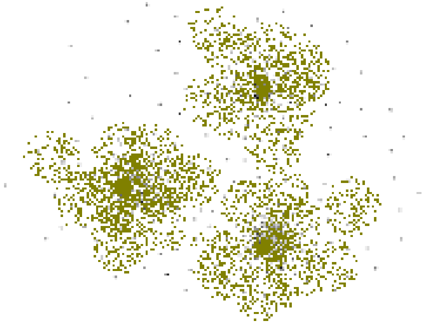
In LMC (~Z_{sun}/3) ~300M_{sun} stars ?

Standard scenario of low-mass star formation

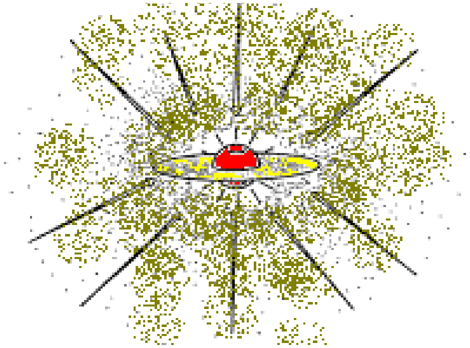
Established in 1980's

Shu, Adams & Lizano (1987)

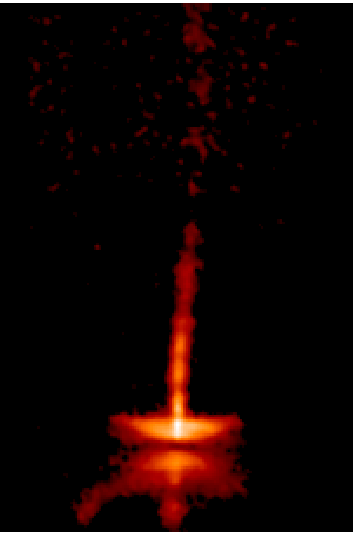
$$\dot{M} \sim \frac{M_{\rm J}}{t_{ff}} = \frac{c_s^3}{G} \sim 2 \times 10^{-6} M_\odot/\mathrm{yr} \left(\frac{T}{10K}\right)^{3/2}$$



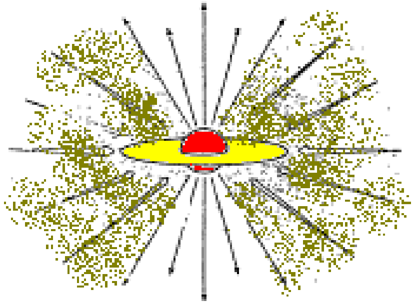
A. Dense cores form
within molecular clouds.



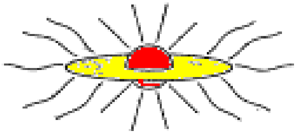
B. A protostar forms at the center
of a core, growing in mass
by accretion of ambient matter.



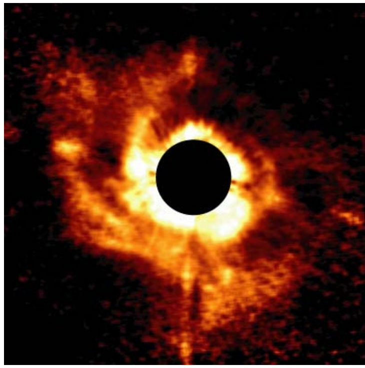
©HST



C. A stellar wind breaks out,
creating a bipolar flow



D. The infall terminates, revealing
a newly formed star with a disk.



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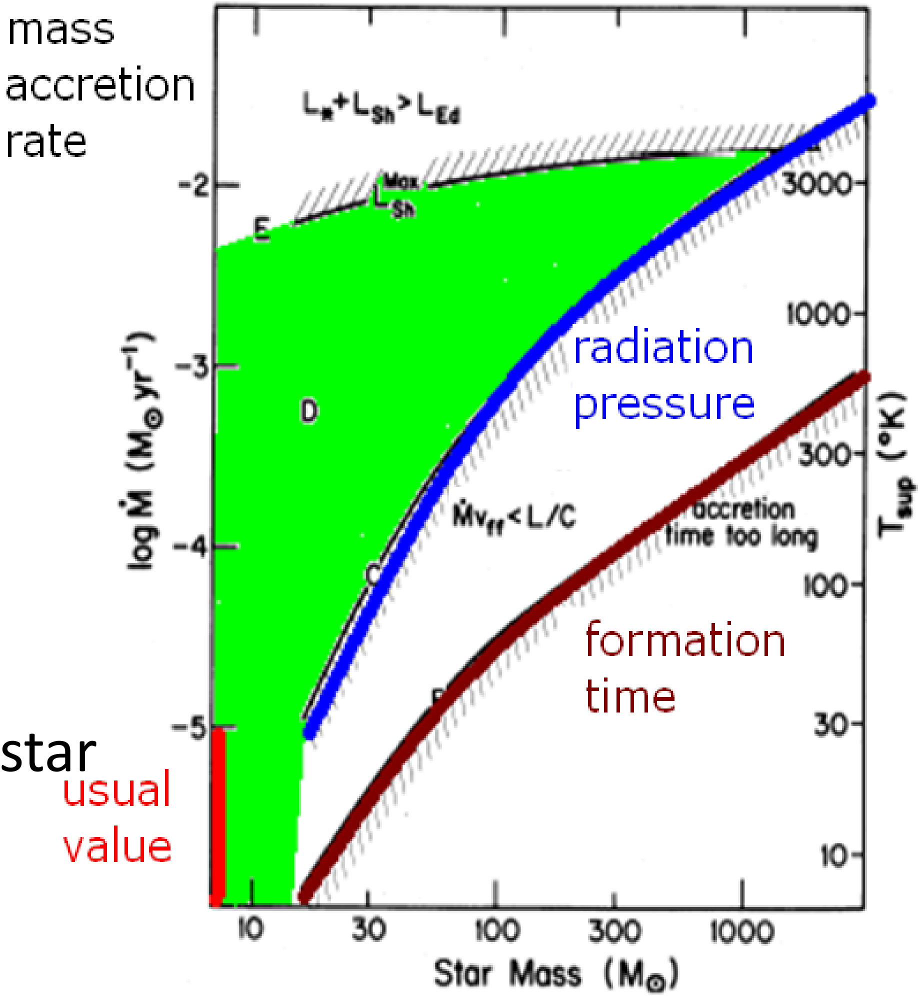
Obstacles in Forming Massive Stars

1. **Formation time problem**
   Time needed to form a massive star

$$t_{\rm acc} \equiv \frac{M_*}{\dot{M}_*}$$

   exceeds the stellar life time.

2. **Radiation barrier problem**
   Radiation pressure (on dust) by the star becomes too high for the matter to be accreted.



Radiation pressure barrier

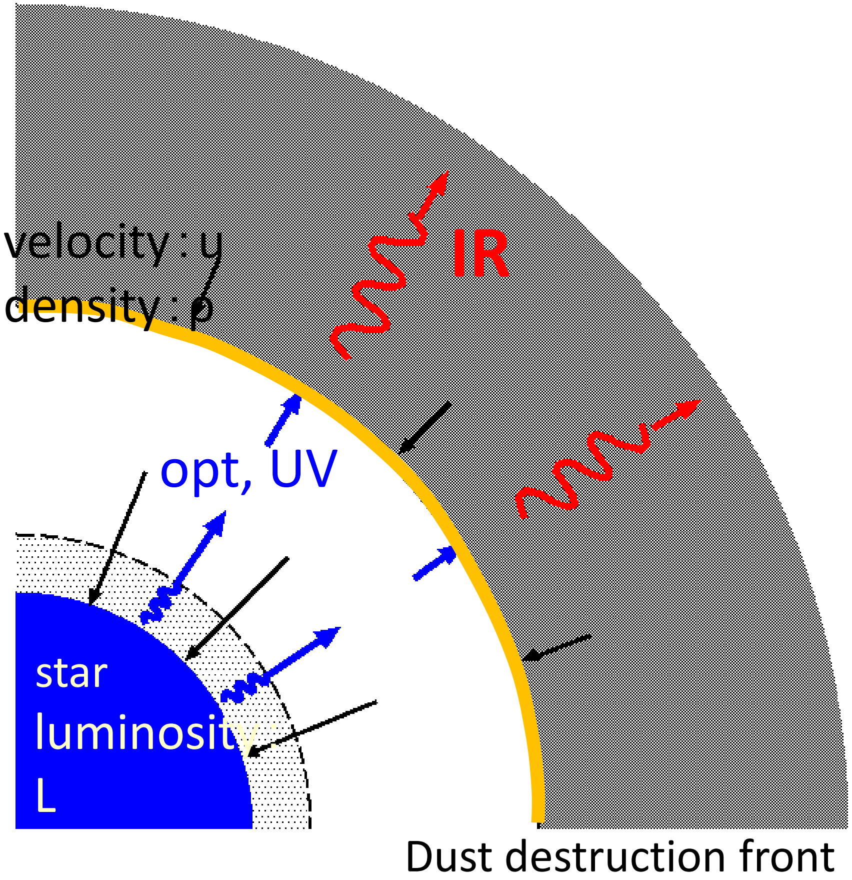
direct stellar light at dust destruction front

Most of the stellar（opt., UV) photos are absorbed at a thin layer just outside the dusc destruction front, to which large radiation force is imparted.

To overcome the rad. force : $\rho u^2 > \dfrac{L}{4\pi r^2 c}$

Using $\dot{M} = 4\pi r^2 \rho u$

$$\boxed{\dot{M} > \frac{L}{cu}}$$



Two scenarios for massive star formation

1. Large accretion rate (e.g., Nakano et al. 2000 ; McKee & Tan 2002)

Observationally of High mass protostellar objects

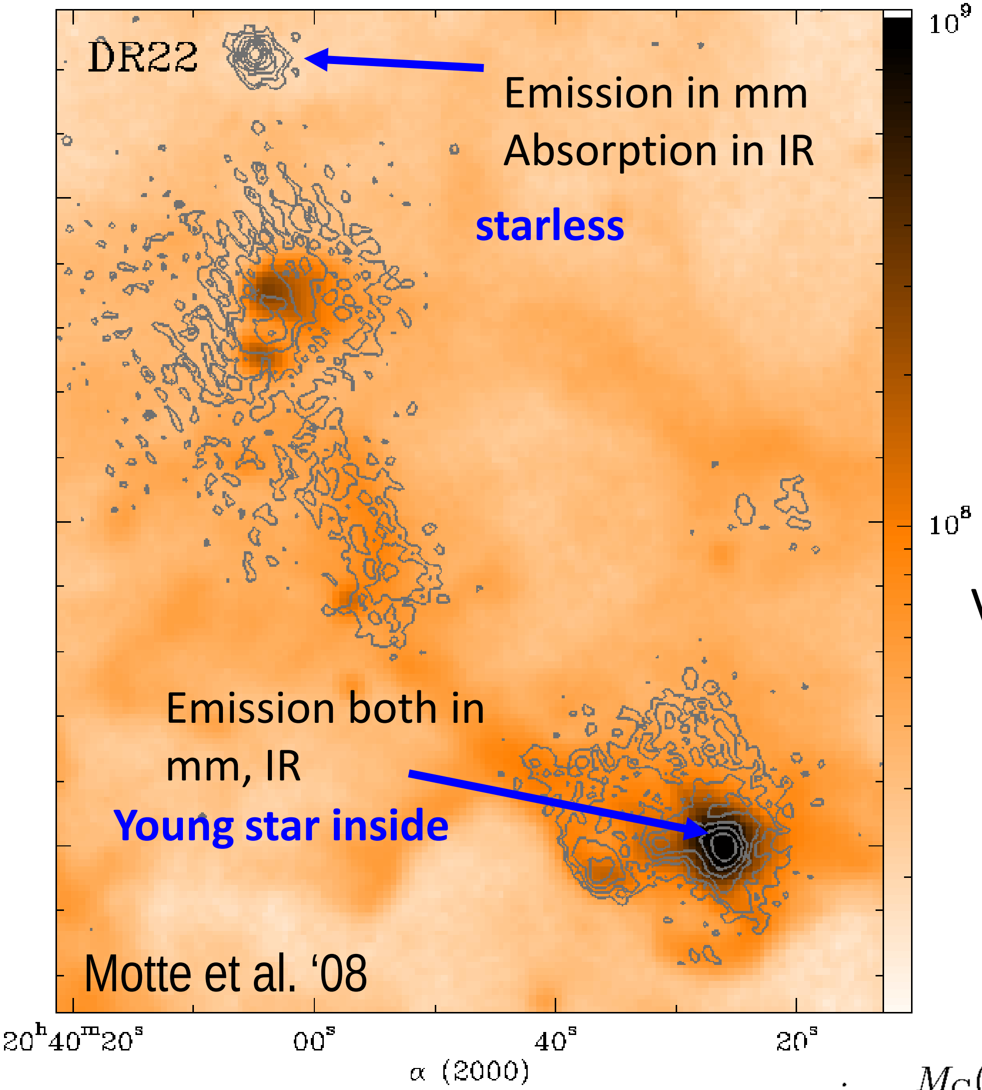
- **Infall motion** (e.g., Sollins et al. 05, Beltran et al. 06)
- **surrounding massive dense material** (e.g., Osorio et al. 99, Kumar & Grave 08)
- **large outflow rate** (e.g., Beuther et al. 02, Zhang et al. 05)

→All consistently suggest high ($>10^{-4} M_\odot$/yr)accretion rate.

2. Stellar merger (e.g., Bonnel et al. 1998; Stahler et al. 2000)

Massive stars tend to be formed at the center of dense clusters.
Mass segregation, gas drag make merger easier.
But ,the threshold stellar density ~10^{6-8} stars/pc3 is too high.

Monolithic Collapse of Massive Core



Emission in mm
Absorption in IR

starless

Emission both in mm, IR

Young star inside

Motte et al. '08

Image : MIR(warm dust)
contour: mm (cold dust)

Initial condition of massive star formation

Massive Molecular Core

radius : ~ 0.1pc
mass: ~ $10^{2\text{-}3}\ M_\odot$ ~ $10^{2\text{-}3}\ M_J$
line width : ~ 1 km/s

Very massive, dense and turbulent.

c.f.) low-mass core

radius : ~ 0.1pc
mass: ~ $1\ M_\odot$ ~ $1\ M_J$
line-width : ~ 0.1 km/s

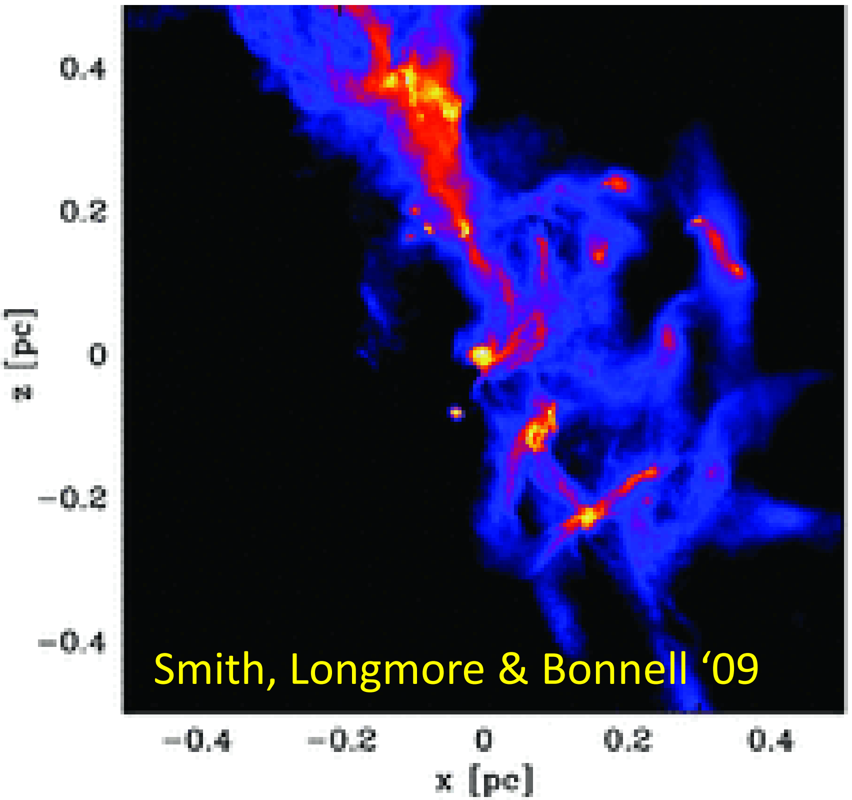
$$\dot{M} \sim \frac{M_{\rm C}(\text{coremass})}{t_{\rm ff}} \simeq 2 \times 10^{-4}\ M_\odot/\text{yr} \left(\frac{T}{10\ \text{K}}\right)^{3/2} \left(\frac{M_{\rm C}}{100\ M_{\rm J}}\right)$$

High accretion rate is realized

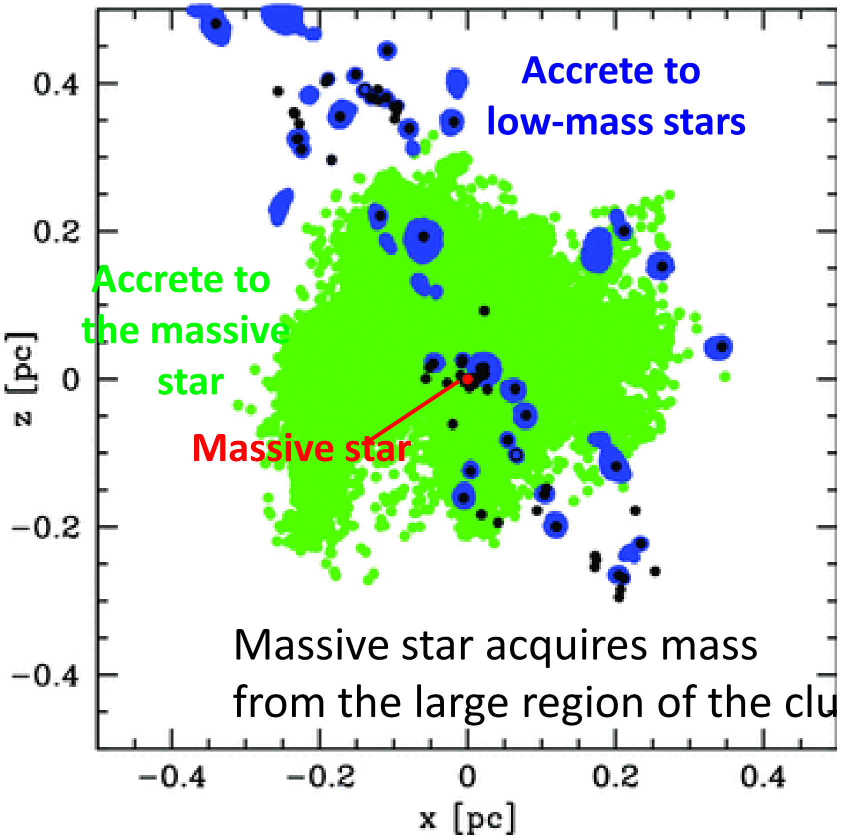
Alternative Scenario: Competitive Accretion

Fragments in to small pieces M_{core}~ M_{Jeans}

Accretion from the entire cluster scale (~pc) at Bondi accretion rate



Smith, Longmore & Bonnell '09



Accrete to low-mass stars

Accrete to the massive star

Massive star

Massive star acquires mass from the large region of the cluster

Feedback ⇒ outflow : Wang et al. '10 / UV radiation : Peters et al.

Another Radiation barrier

dust Eddington limit
by re-radiated IR light

IR dust opacity

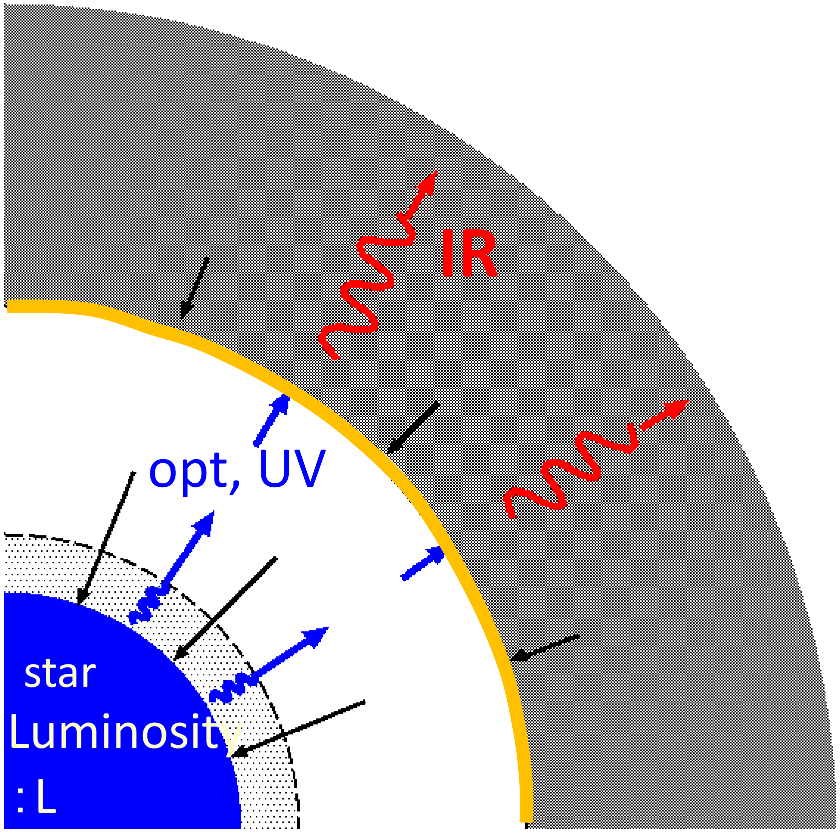
$$\kappa_{\rm IR} \simeq 8 \left(\frac{Z}{Z_\odot} \right) \ {\rm cm^2/g}$$

Eddington limit for dust

$$L_{\rm Edd,IR} = \frac{4\pi c G M_*}{\kappa_{\rm IR}}$$

For accretion to continue :

$$\boxed{L_{\rm tot} < L_{\rm Edd,IR}}$$



Dust destruction front

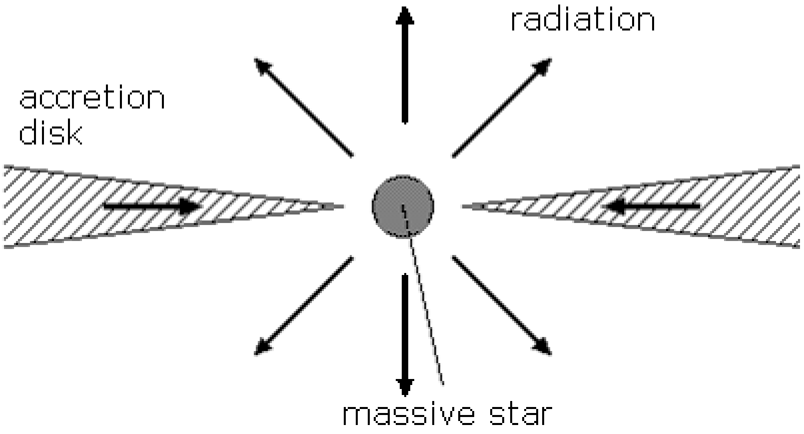
Overcoming the dust Eddington limit

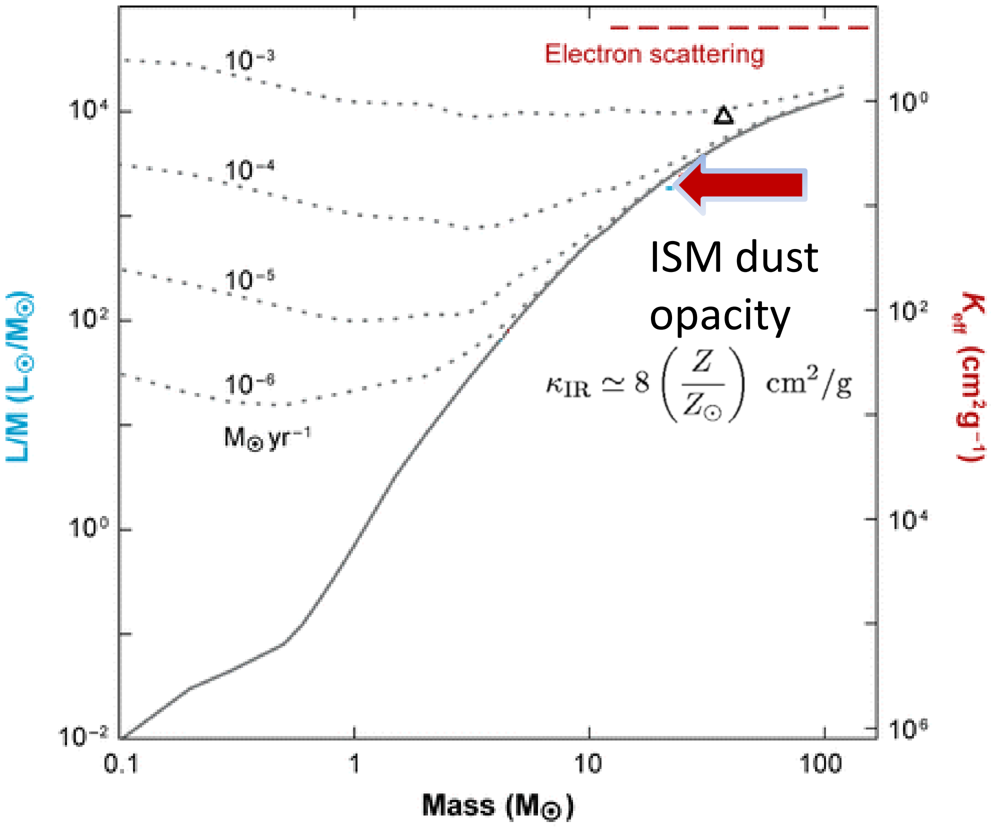
Cannot be overcome with
spherical symmetry and ISM dust amount
regardless of accretion rate.

- **Lower dust depletion**
  (Wolfire & Cassinelli ‘86)

- **Non-spherical accretion**
  (Nakano ’89 etc.)

disk accretion: flash light effect





ISM dust opacity

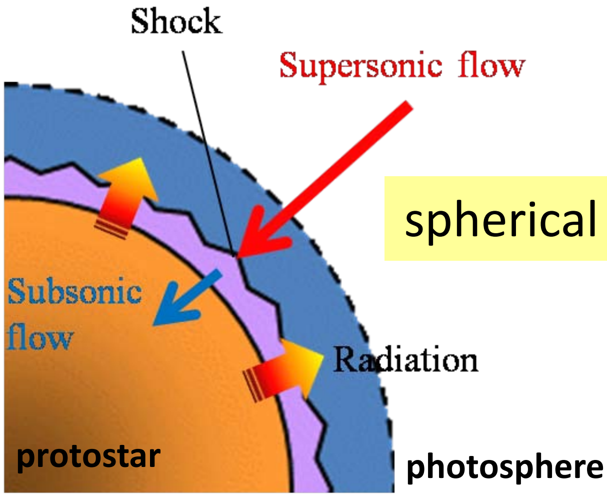
$$\kappa_{\rm IR} \simeq 8 \left(\frac{Z}{Z_\odot}\right)\ {\rm cm^2/g}$$

Zinnecker & Yorke(2007)

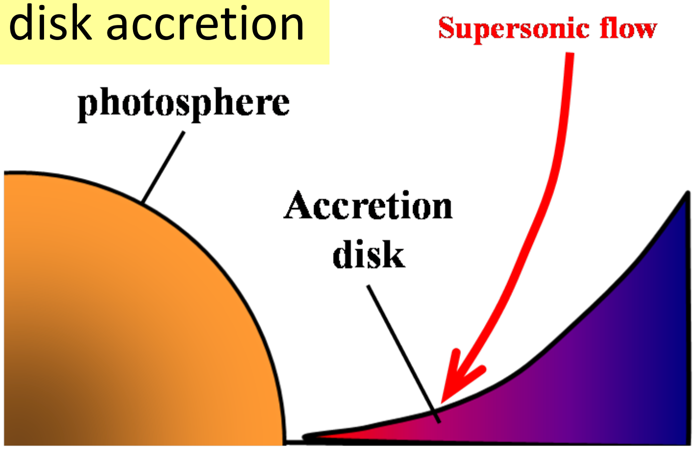
Protostellar evolution with rapid accretion

(Stahler et al. 1986)

spherical accretion



disk accretion



Protostar **hydrostatic**

Eq.s for Stellar Structure

+ [shock/ photospheric condition]

ENVELOPE

Stationary Accretion

radiative precursor(< R_{ph})
stationary hydro

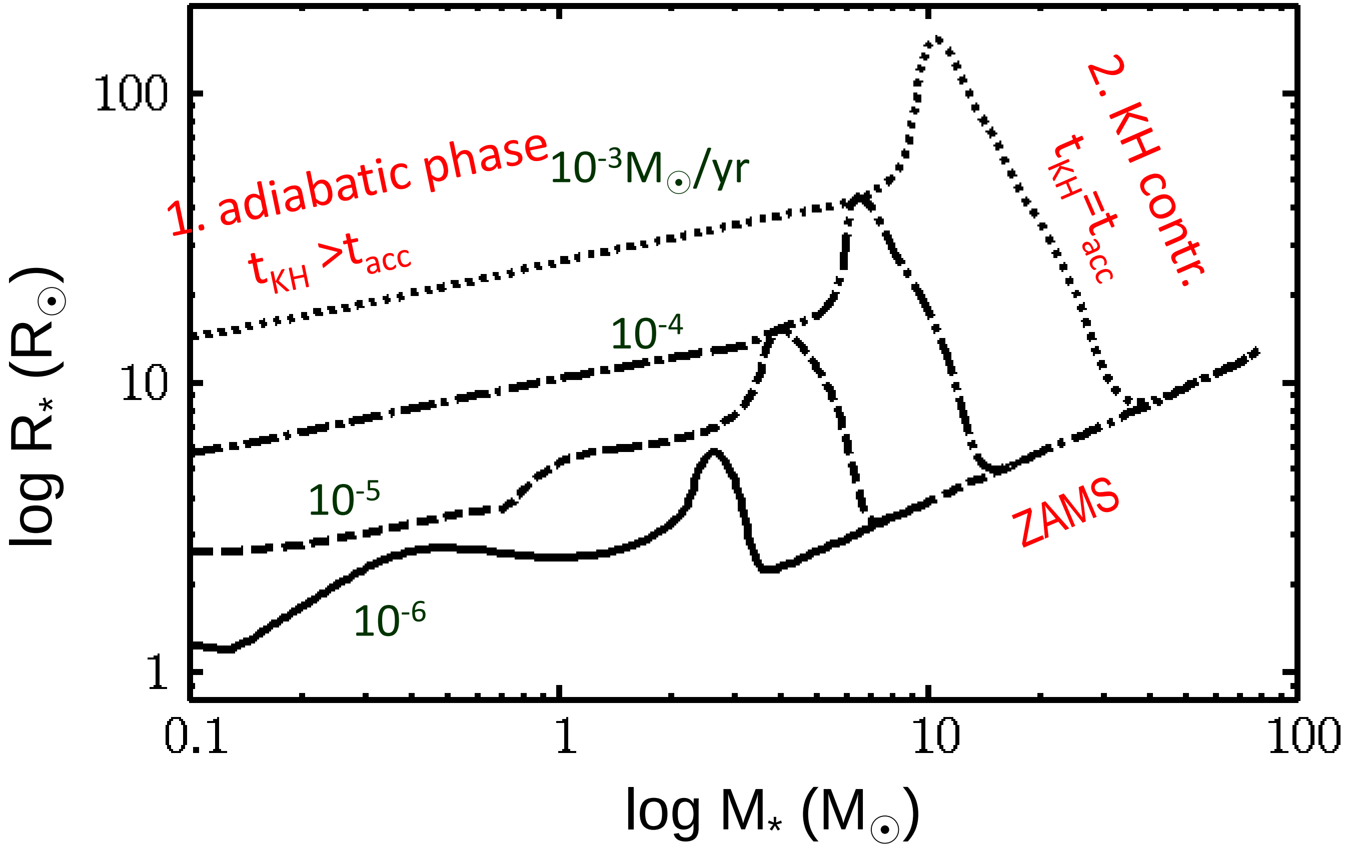
outer envelope

(>R_{ph}) free fall

Protostellar evolution with different accretion rate

Mass-radius relation

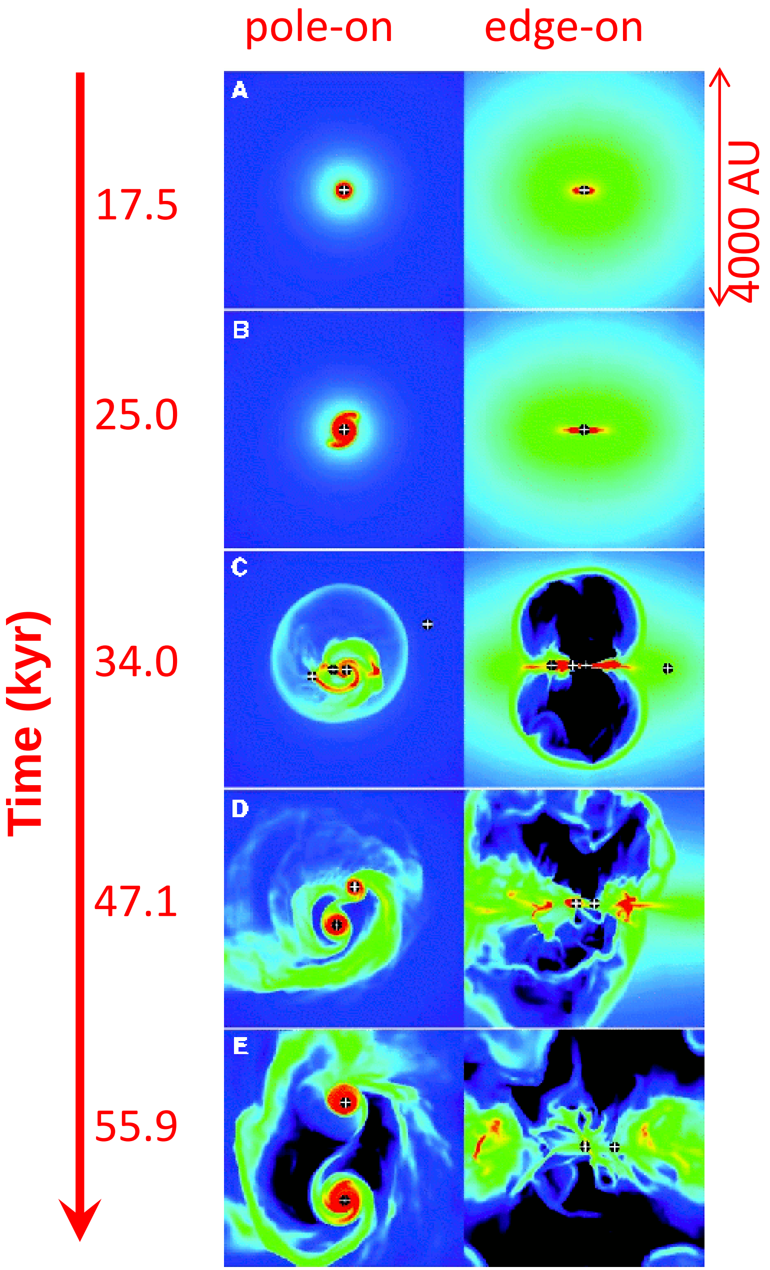
Hosokawa & KO ’09



With higher accretion rates,

- The stars have larger radii before ZAMS.
- The stars become more massive at the onset of H burning.

Collapse of Massive Molecular Core



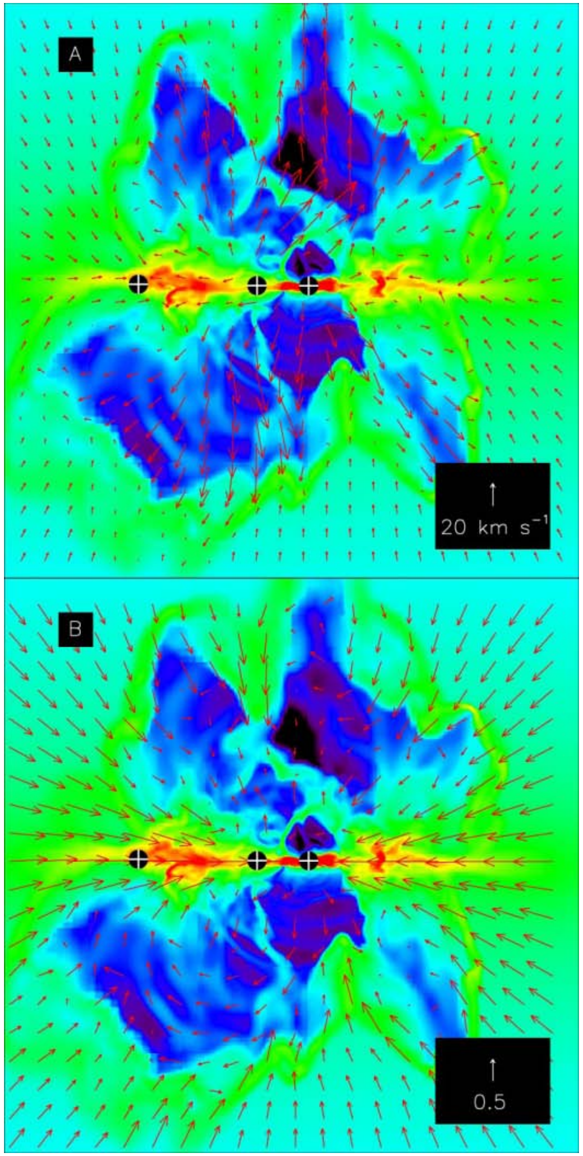
3D RHD simulation
Krumholz et al. '09

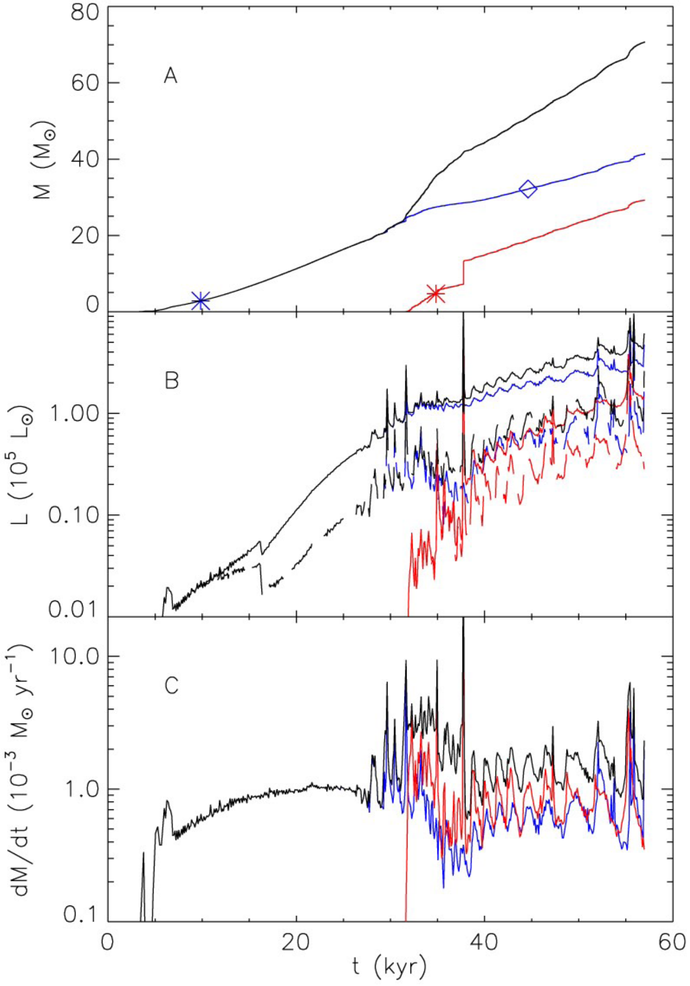
Massive Molecular Core
(100$M_\odot$, 20K, 0.1pc)
↓
Fragmentation of self-gravitating disk
↓
O-type star binary
(41.5$M_\odot$ + 29.2$M_\odot$)

- High accretion rate
- Non-spherical accretion via disk

→the accretion continues despite of strong radiation pressure.

Collapse of Massive Molecular Core & rapid protostellar accretion



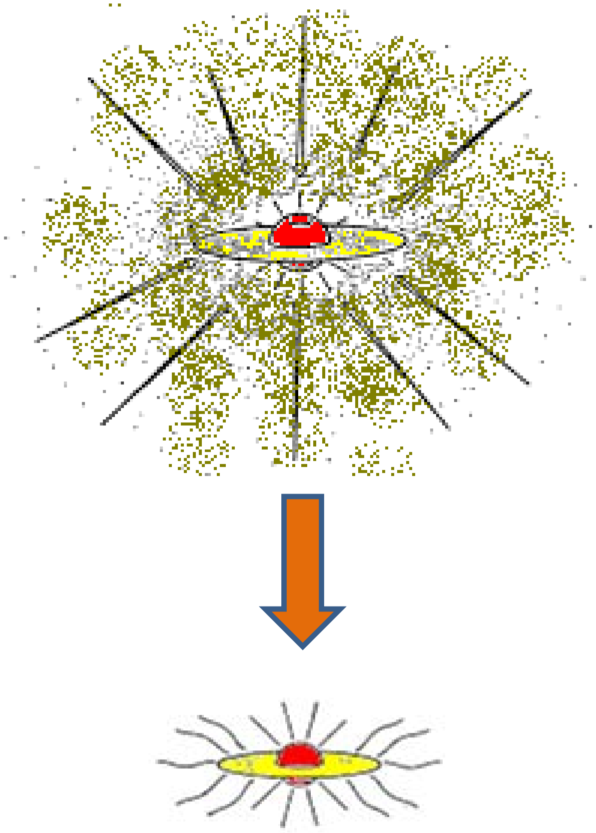


- Accretion continues intermittetly despite the strong radiation pressure.
- Average accretion rate does not change so much.

Krumholz + (2009)

II. Low-metallicity Star formation

Metallicity and Massive Stars

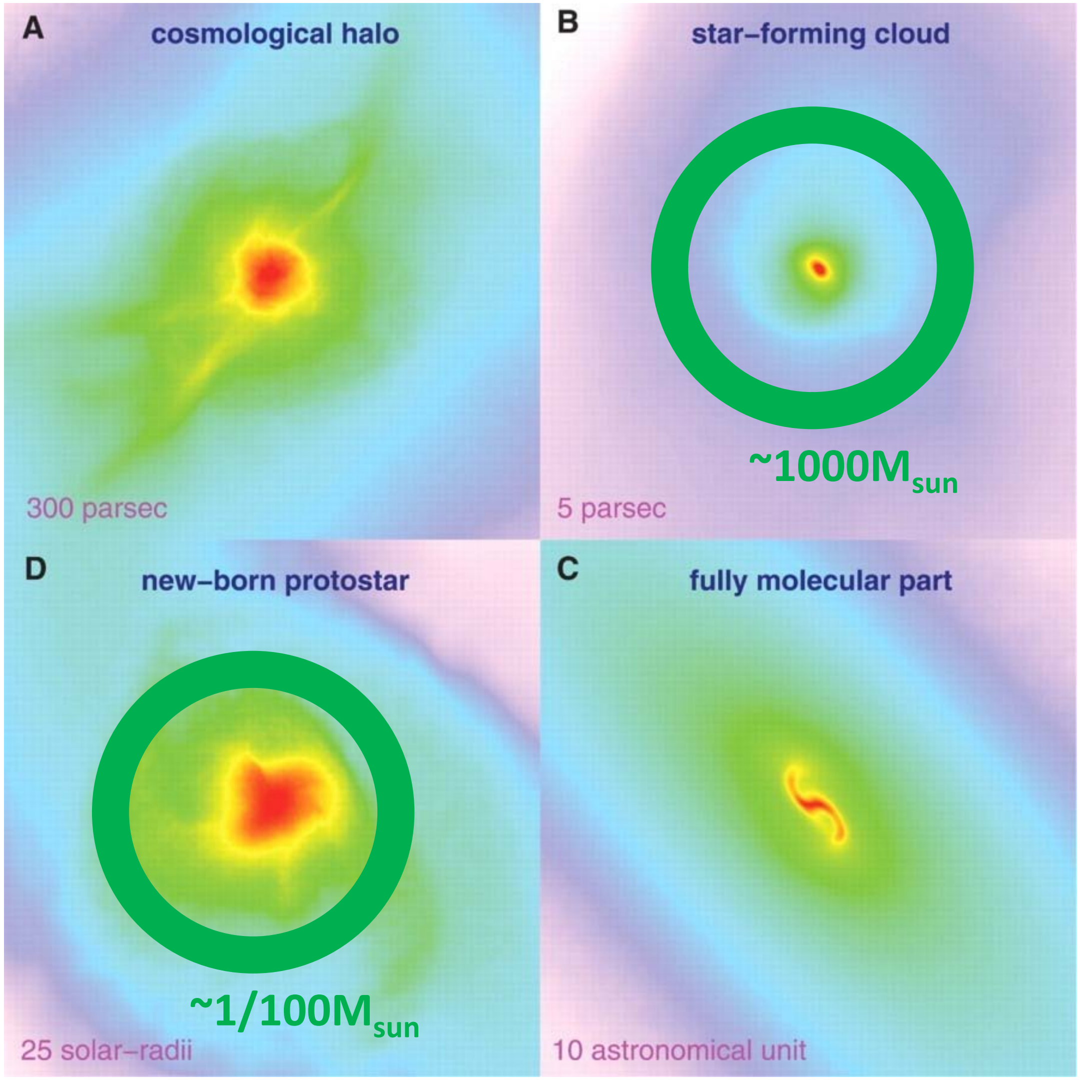


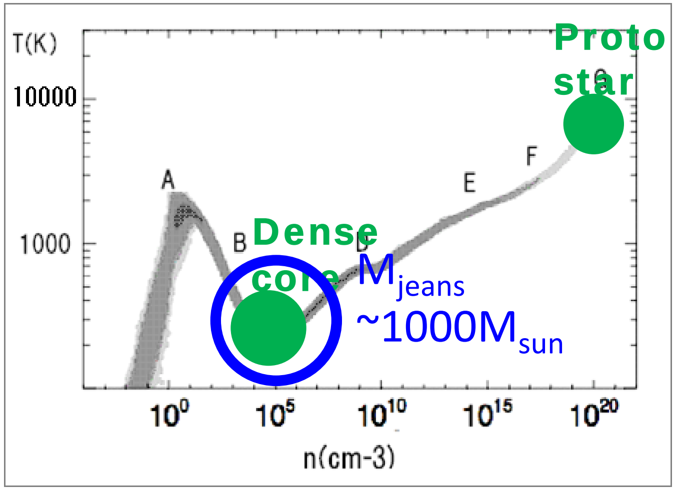
- Low-metallicity environment ($Z<<Z_\odot$)

lower dust depletion
⇒ lower radiation pressure
higher temperature
⇒ higher accretion rate

Weaker feedback
More massive stars?

First Star Formation: early phase





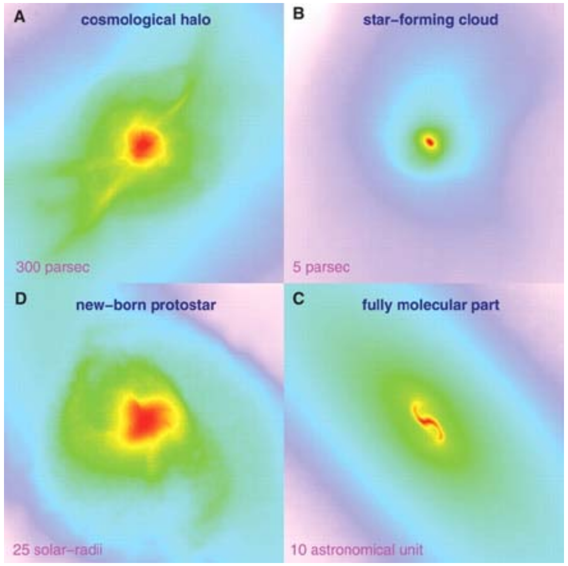
- At ~10^4cm^{-3}, dense core of ~1000M_{sun} forms by H_2 cooling
- Inside of it, a protostar forms at~10^{21}cm^{-3} with initial mass of ~$10^{-2}M_{sun}$

Yoshida, KO, Hernquist 2008

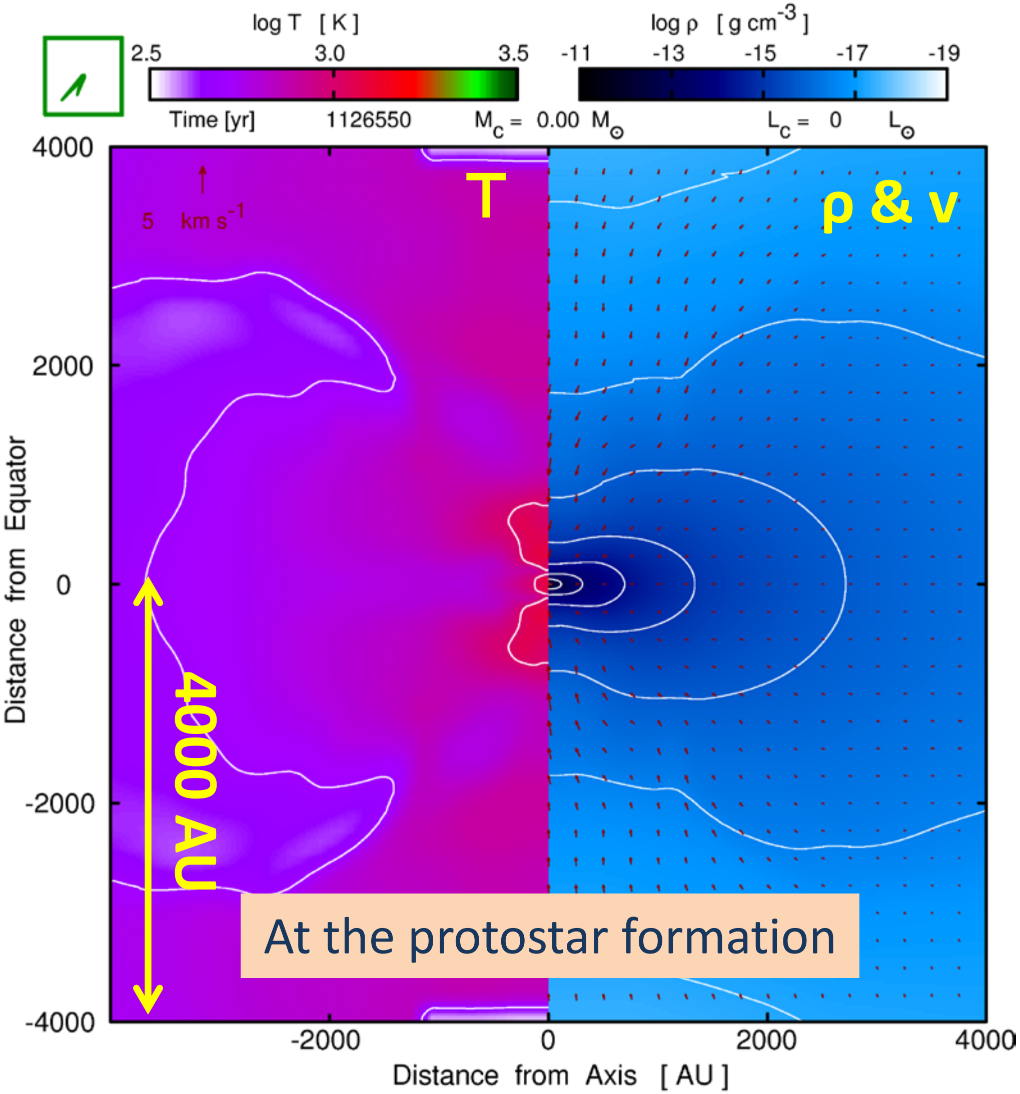
Accretion evolution of the first star

Hosokawa, KO, Yoshida, Yorke 2011

- Initial condition from the cosmological simulation
- 2D radiative-chemical hydro ＋protostellar evolution

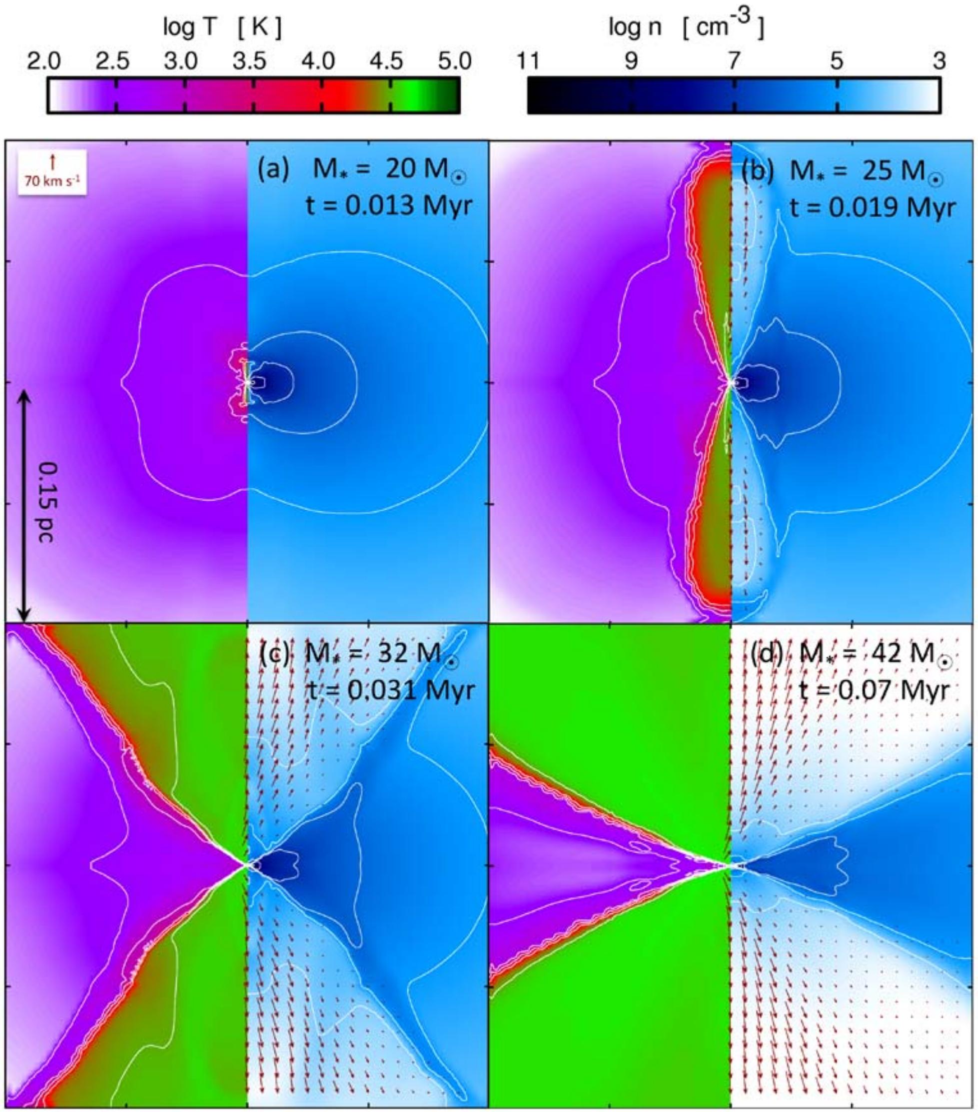


→



At the protostar formation

Development of HII region

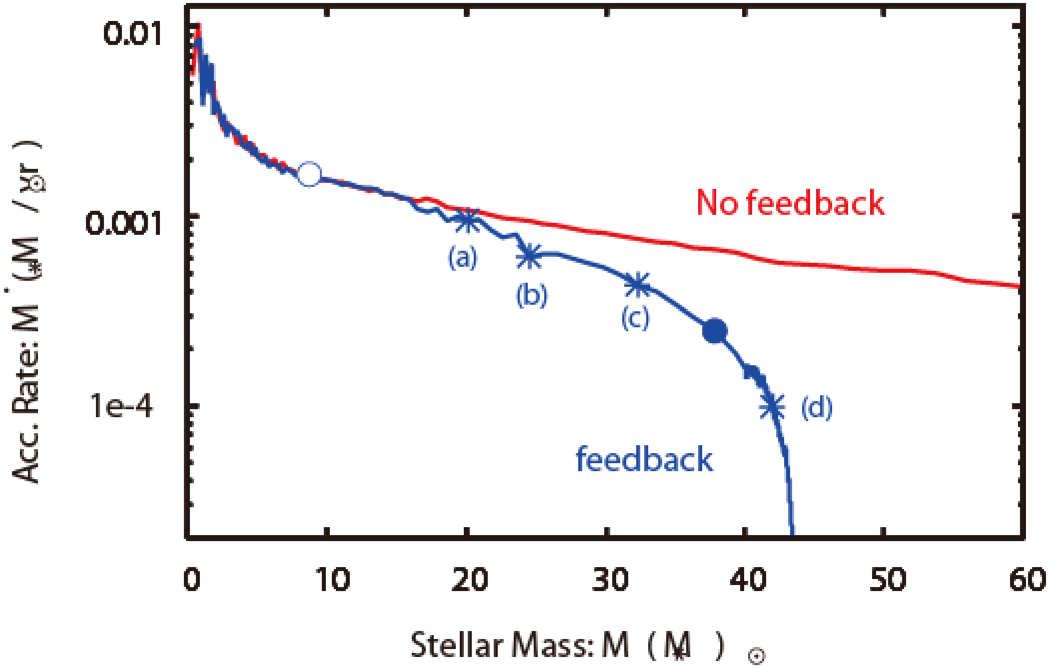


2D Radiation Hydro
+ protostellar evolution

- HII region
  - expands rapidly in the polar directions
  - becomes wider and expels the gas (except in the shadow of the disk)

- Disk photo-evaporation
  gas escapes in the polar directions with velocity of a few x 10 km/s

Accretion rate



- accretion rate is drastically reduced by protostellar UV feedback.
- the accretion terminates at 43 $M_\odot$

Massive (but not very massive) star forms
- ends its life as the core-collapse SN, instead of PISN

Pop III-II transition

✓**First stars** (Pop III stars)

theoretically predicted to be very massive(>100M_{sun})

✓**Stars in the solar neighborhood** (Pop I)

typically low-mass(0.1-1M_{sun})

Low-mass Pop II stars exist in the halo.

●transition of characteristic stellar mass in the early universe from very massive to low-mass (**Pop III-II transition**)

●This transition is probably caused by accumulation of a certain amount of metals and dusts in ISM (**critical metallicity**)

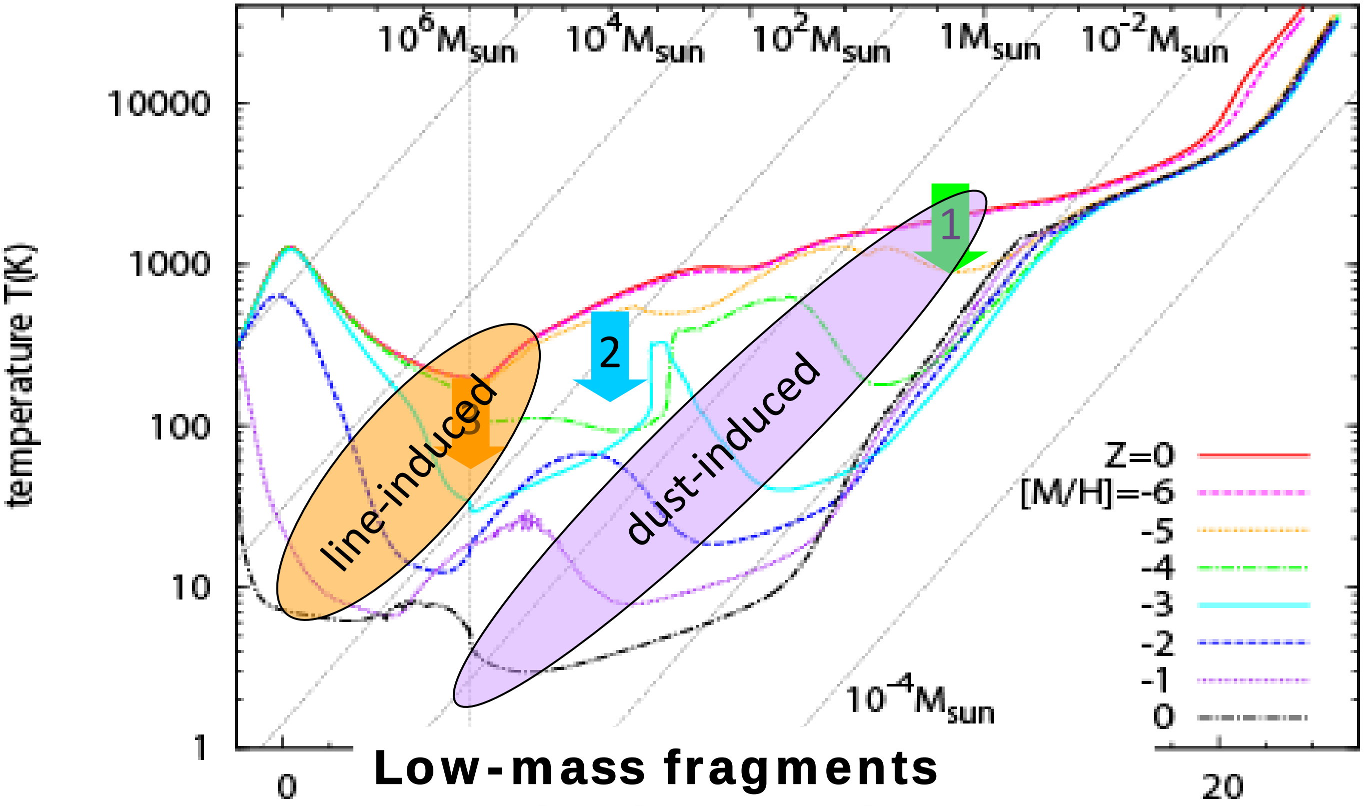
thermal evolution of low-metallicity clouds

1) Cooling by dust thermal emission: [M/H] > -5

2) H_2 formation on dust : [M/H] > -4

3) Cooling by fine-str. lines (C and O): [M/H] > -3

[M/H]
:= $\log_{10}(Z/Z_{sun})$



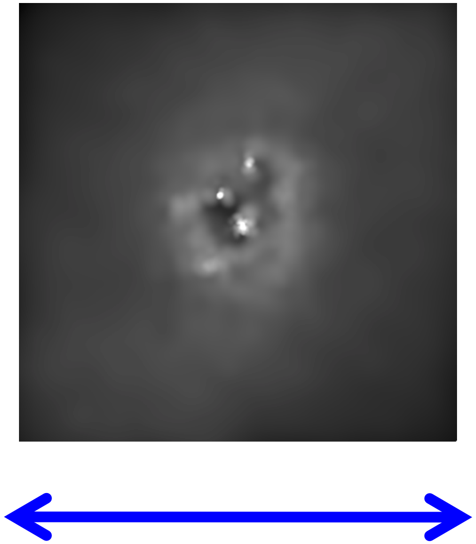
Low-mass fragments form by dust cooling

- 1D hydro (spherical)
- dust/metal ratio same as local ISM
- all the important cooling processes inclluded
- reduced H, D, C, O chemical network

KO et al. 2005;
KO, Hosokawa, Yoshida 2010

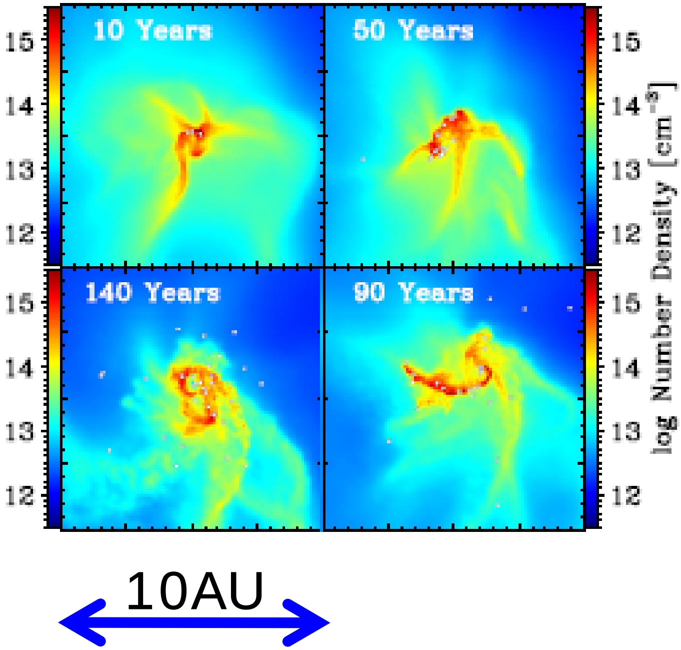
Dust-induced fragmentation

$[M/H]_{dust}=-5$



Yoshida, KO in prep.

$[M/H]_{dust}=-4$



Dopcke et al. (2011)

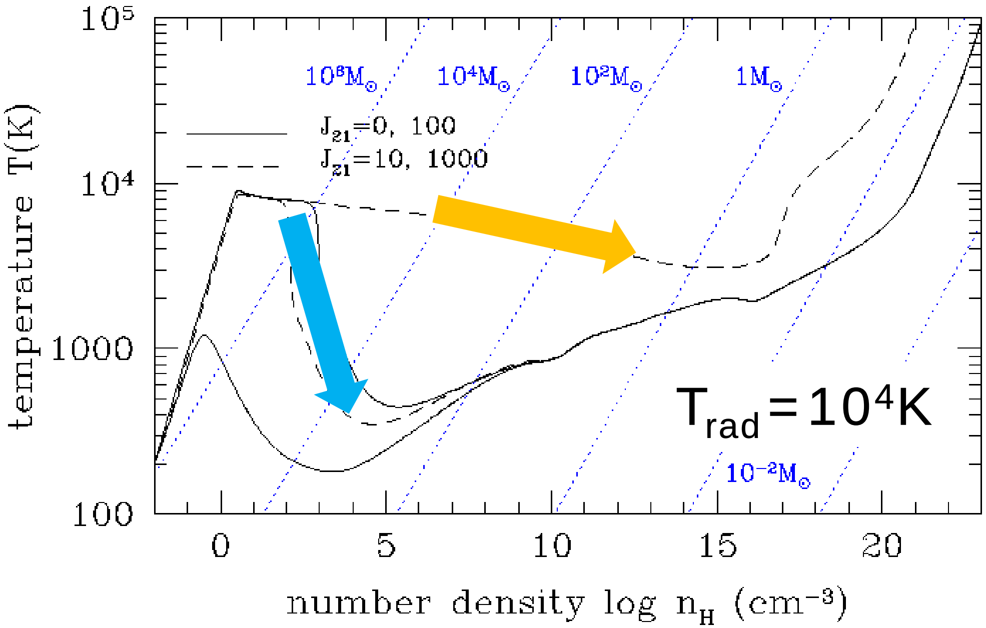
- Rapid cooling by dust at high density ($n \sim 10^{14}\mathrm{cm}^{-3}$) leads to core fragmentation. $M_{frag} \sim 0.1\ M_{sun}$
- With slight dust enrichment, characteristic stellar mass shifts to low-mass

Requirements for SMS formation by direct collapse

- Fragmentation suppressed
  - Rapid cooling → fragmentation
    Without such cooling → no fragmentation.
  - H_2 cooling is suppressed by FUV photodissociation, or by collisoinal dissociation.
- Formation timescale shorter than lifetime
  - High accretion rate
    $>M_*/t_* \sim 10^5 M_{sun}/2\mathrm{x}10^6 \mathrm{yr} \sim 0.05 M_{sun}/\mathrm{yr}$
  - If no H_2, $T \sim 10^4$K
    $dM^*/dt \sim c_s^3/G \sim 0.06 M_{sun}/\mathrm{yr}\ (T/10^4\mathrm{K})^{3/2}$

primordial gas with strong FUV field

Omukai 2001, Omukai & Yoshii 2003



FUV intensity

✓$J < J_{crit}$

→ at some density, H_2 cooling
and fragmentation

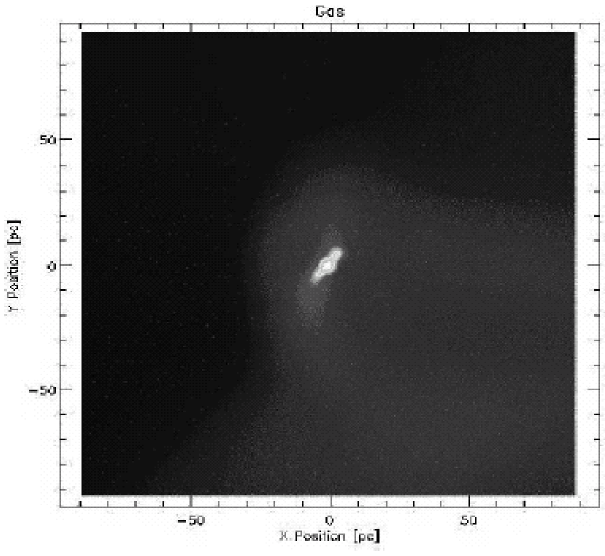
✓$J > J_{crit}$

→ isothermal collapse continues

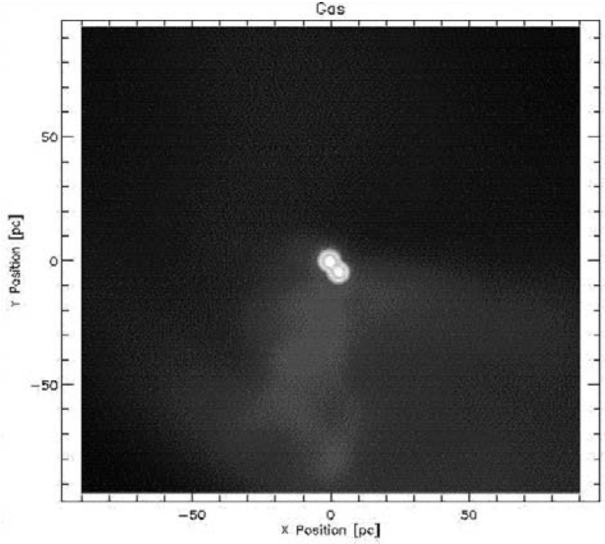
SMS formation by the isothermal collapse

Bromm & Loeb 2003

non-rotating



rotating

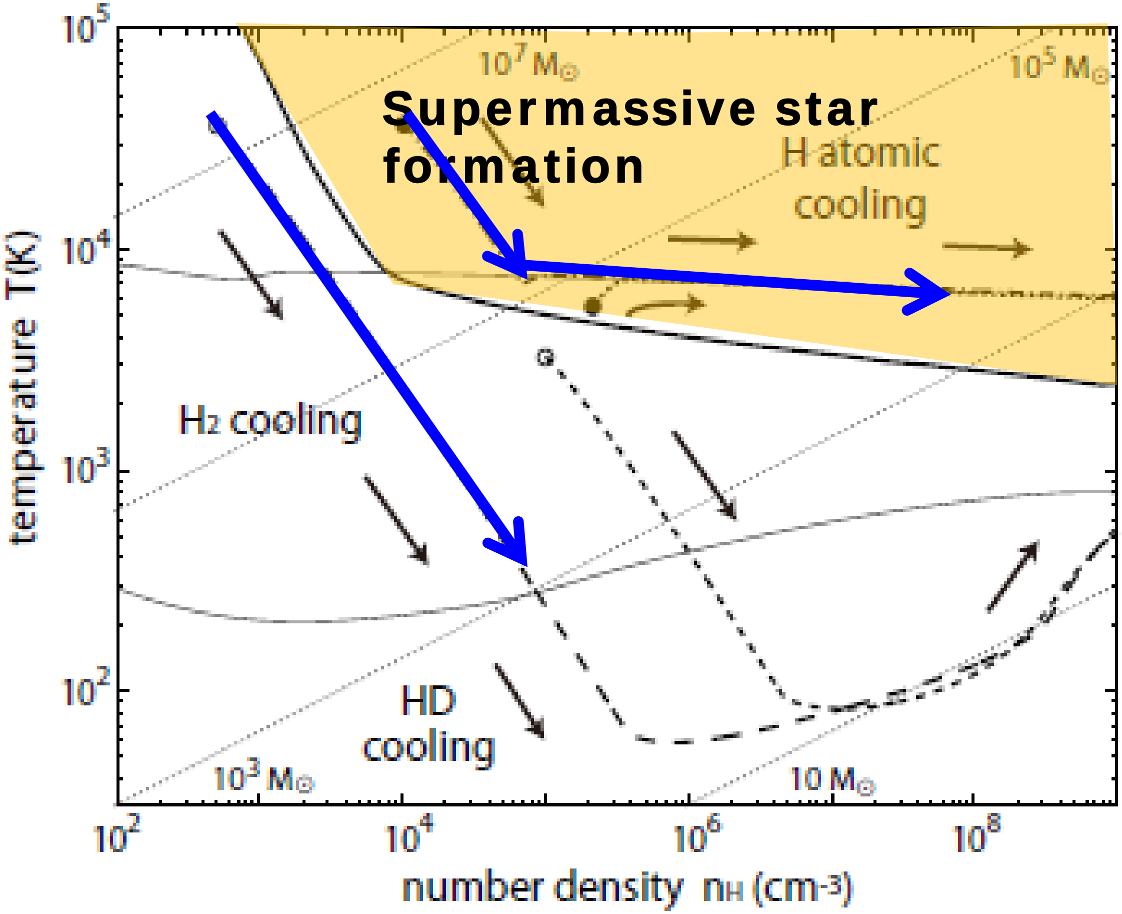


✓$M\sim10^8M_{sun}$ halo virializing at $z\sim10$ (2σ over-density) with strong FUV $J_{21}\sim4000$

✓Fragmentation is inefficient

→direct collapse to 10^6M_{sun} supermassive star

Collisional dissociation by high-density shock in primordial gas



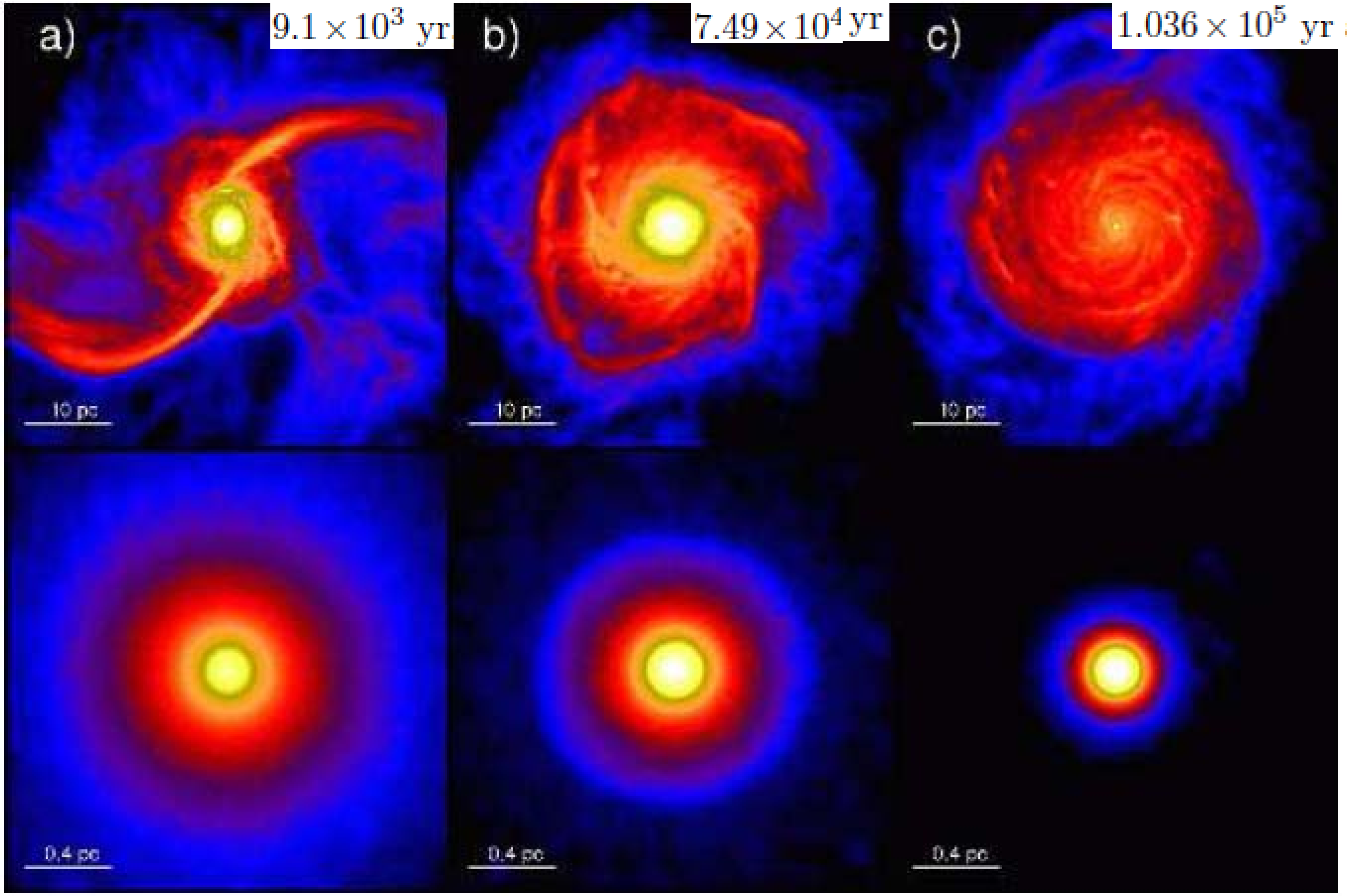
Supermassive star formation

- shocks at $>10^{3\text{-}4}$/cc, with> several 10^3K
  - H_2 collisionally dissociated
  - Fragments at 8000K with $>\sim10^5M_{sun}$
  - Isothermal collapse thereafter

Inayoshi & Omukai 2012

Possible sites of high-density shocks

- Galaxy merger driven inflow
(Mayer et al. 2010) ← probably metal-rich

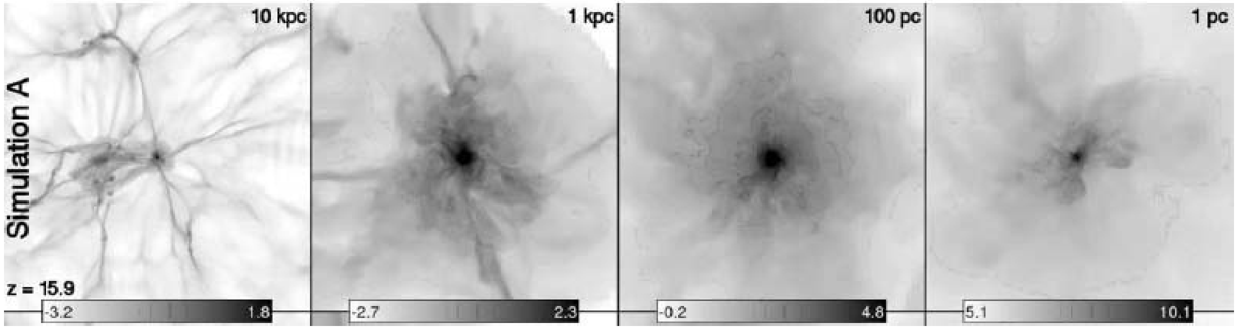


Large scale

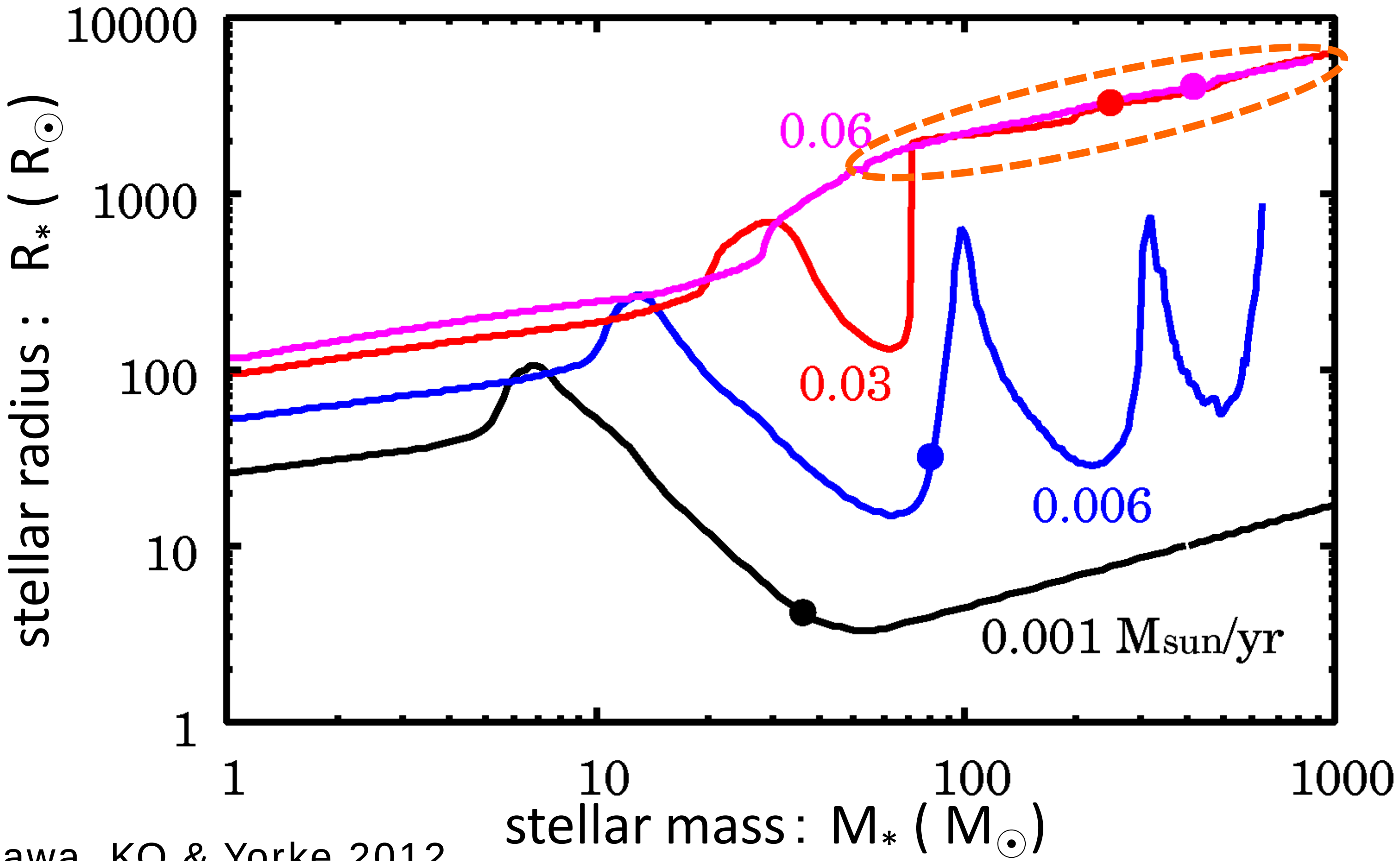
Enlargement

Possible sites of high-density shocks

- Cold-accretion-flow shock in the central ~10pc region of the first galaxy
  (Wise, Turk & Abel 2008)



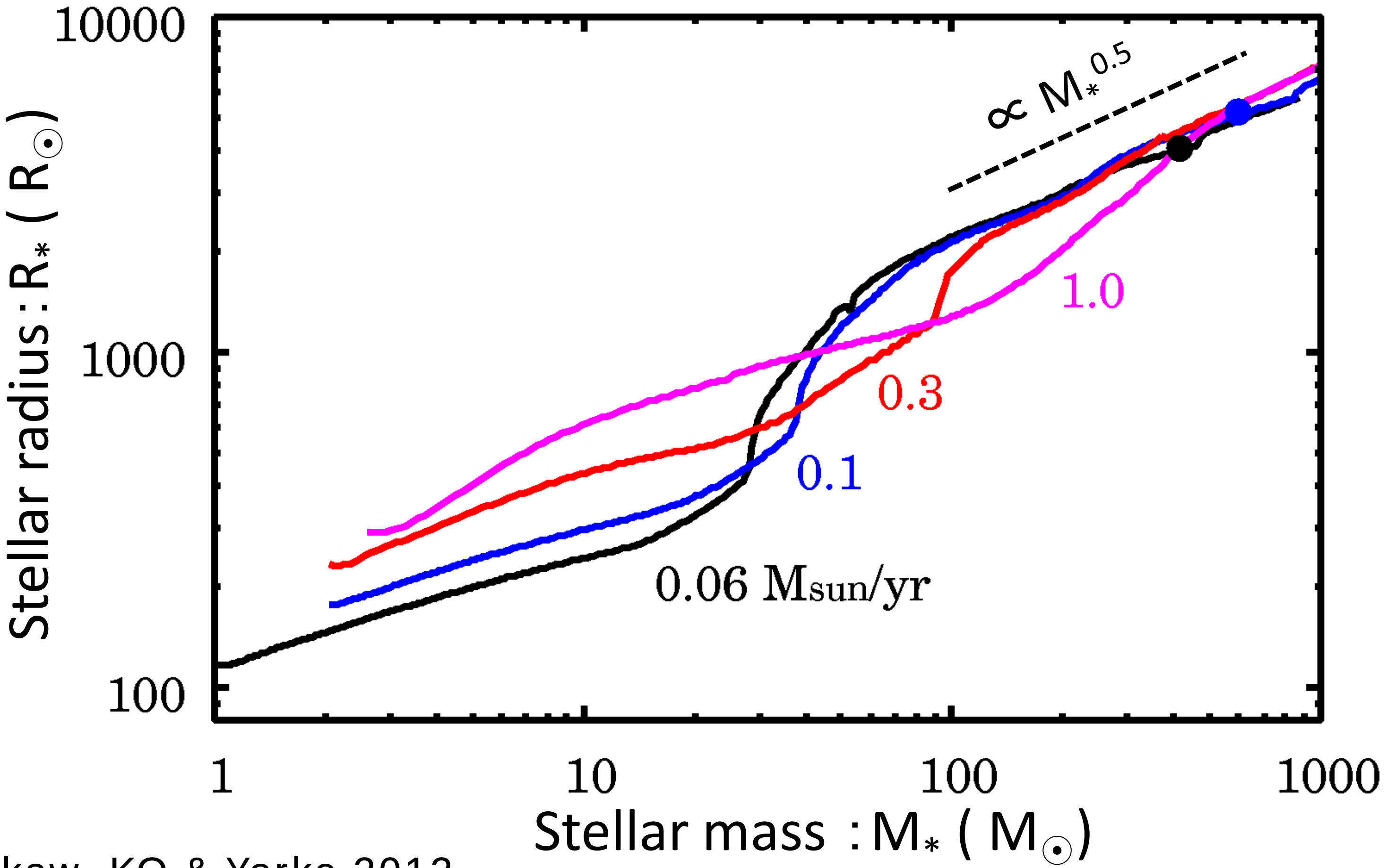
Protostars with very rapid accretion



Hosokawa, KO & Yorke 2012

- New evolutionary branch with higher rates of > 0.01 $M_\odot$/yr
- The star continues to expand, never contracting to the ZAMS

At even higher accretion rates



Hosokaw, KO & Yorke 2012

- ➢ Unique mass-radius relation: $R_* \propto M_*^{0.5}$, which is independent of mass accretion rates
- ➢ $7000R_{sun}$ ≒ 300 AU @ 1000 M_{sun} : “supergiant” protostars

Physics of MR relation

$$L_* = 4\pi R_*^2 \sigma T_{\rm eff}^4$$

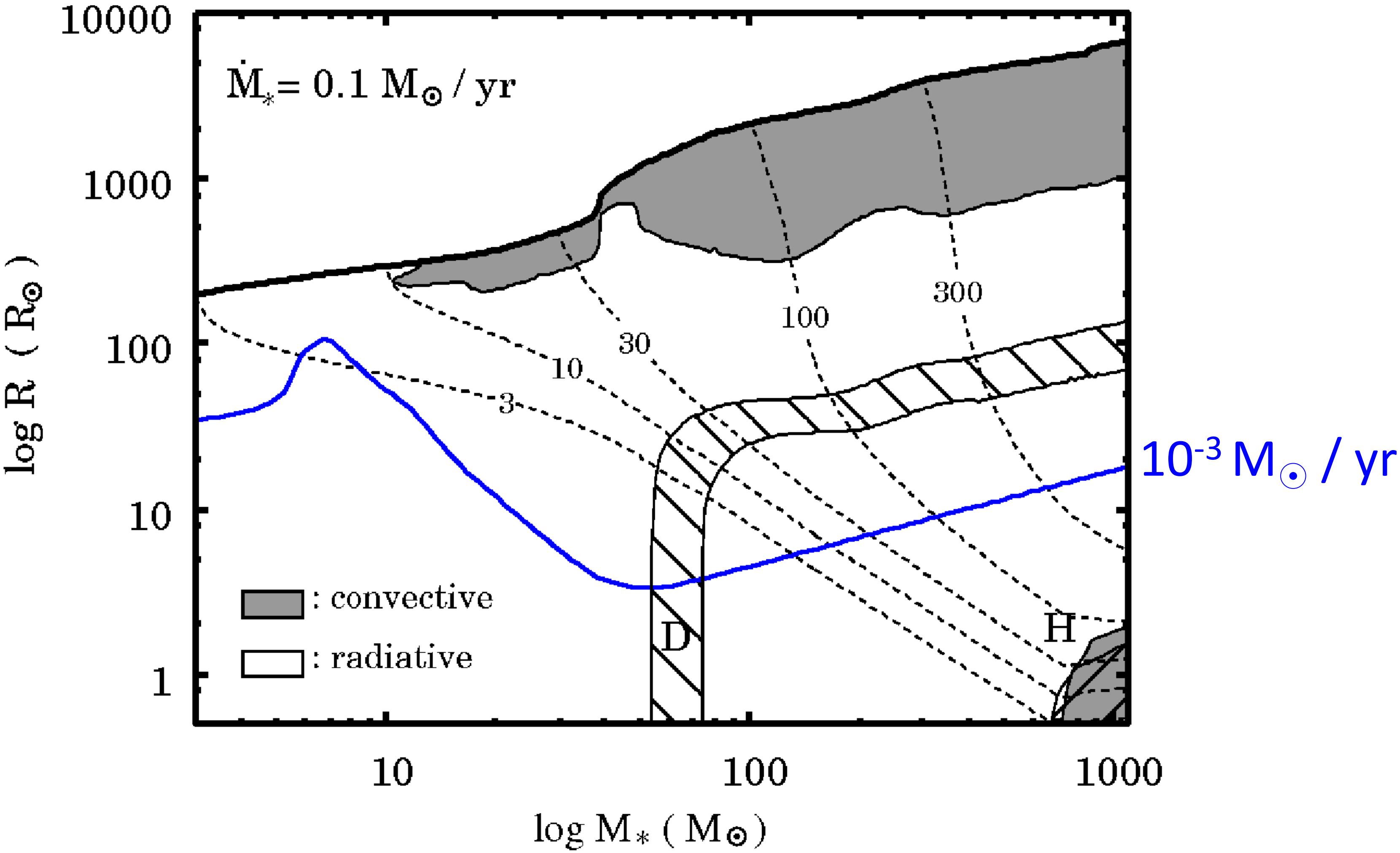
The stellar luminosity L_* is now close to the Eddington luminosity:

$$L_* \simeq L_{\rm Edd} \propto M_*$$

Constant $T_{\rm eff}$ at 5000 K ← strong T-dependence of H- opacity
(the Hayashi limit)

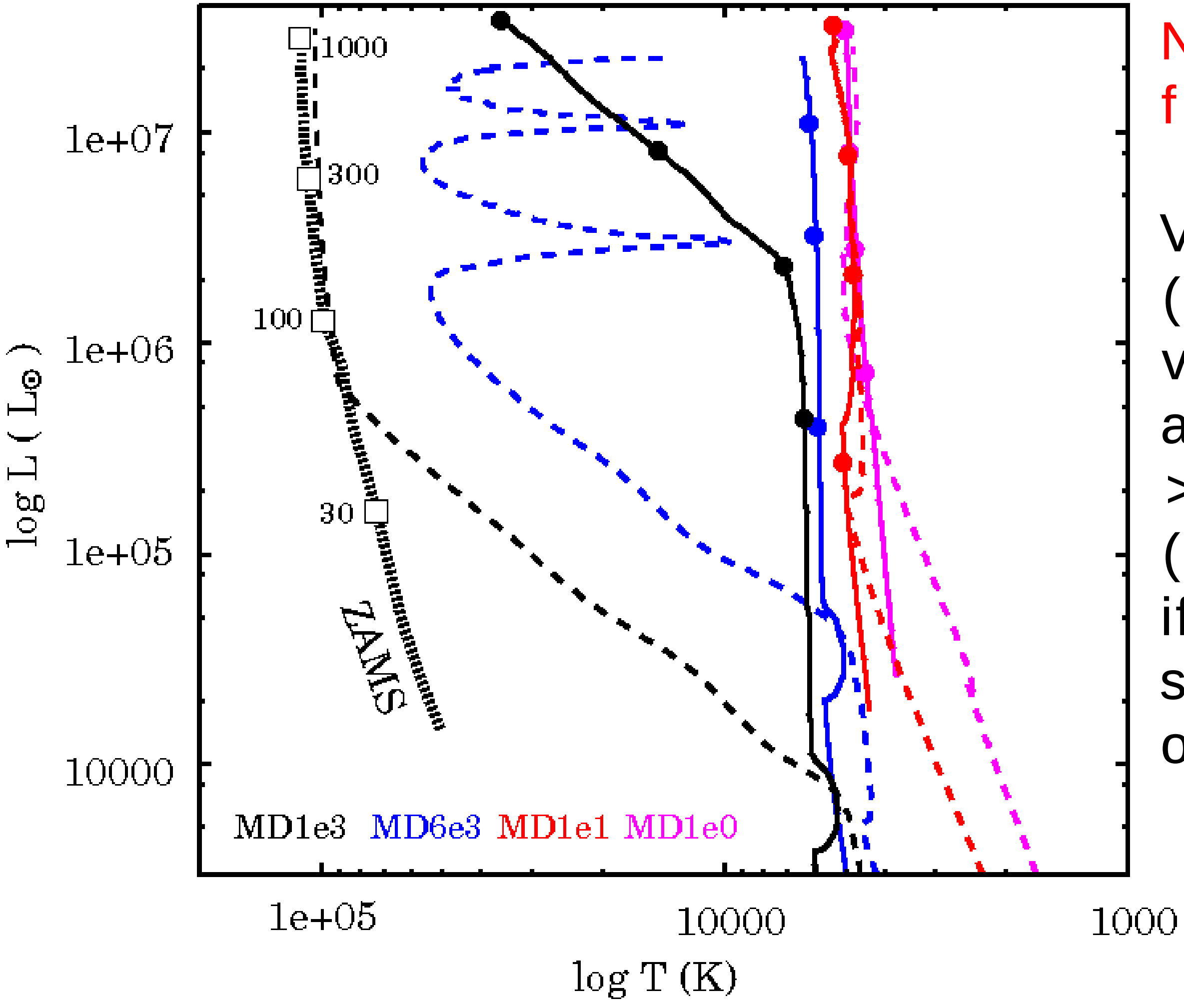
If $T_{\rm eff}$ takes the constant value, we get $R_* \propto M_*^{0.5}$

Interior Structure



Most part of the stellar interior contracts, and central temperature increases
H-burning begins at $700M_\odot$, but the star is still bloating (different from the ZAMS)

Evolution on the HR diagram



NO UV feedback
from bloated massive stars

Very massive stars ($> 100 M_{sun}$) could form via very rapid mass accretion with $> 0.01\ M_{sun}$ / yr. (but still unknown if the star becomes supermassive ($10^5\ M_{sun}$) or not)

SUMMARY (1/3)

Massive Star Formation in Local Universe

Radiation pressure barriers
- Not the scaled-up version of low-mass star formation
- Can be overcome by rapid, non-spherical accretion

Protostellar evolution with high accretion rate
- larger radius until ZAMS
- later onset of H burning

SUMMARY (2/3)

First stars: massive (but not very massive)

- dense core of 10^3M_{sun} forms at 10^4cm^{-3} by the H_2 cooling
- Protostellar radiative feedback sets the final stellar mass at ~40Msun

Pop III-II transition by dust cooling

- Dust cooling causes a sudden temperature drop at high density where M_{Jeans}~$0.1M_{sun}$, which induces low-mass fragmentation.
- The critical metallicity for dust-induced fragmentation is $[Z/H]_{cr}$~-5

SUMMARY (3/3)

Supermassive star formation

- New Scenario for SMS formation:
  Collisional dissociation in dense, cold accretion shocks in the first galaxy suppresses H_2 cooling, leading to SMS formation via isothermal collapse at 8000K.
- Accretion of SMS can continue at least ~$10^3 M_{sun}$, probably more.
  ➔Hopefully evolve to a SMBH seed.