Death of Massive Stars
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NIKKO

Star formation in the early universe

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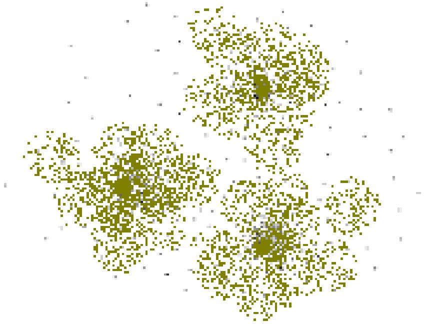
Outline

- Introduction : massive star formation in the local universe
- First stars: massive but not very massive
- Effect of metal-enrichment: pop III-II transition
- Super-massive stars ?: where and how

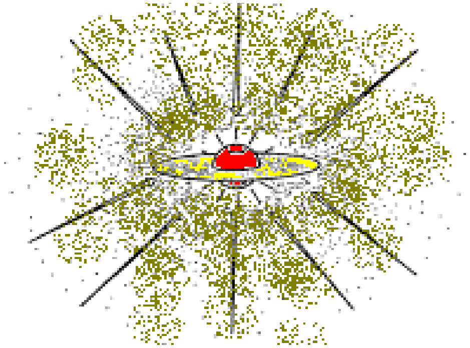
low-mass star formation

Shu, Adams & Lizano (1987)

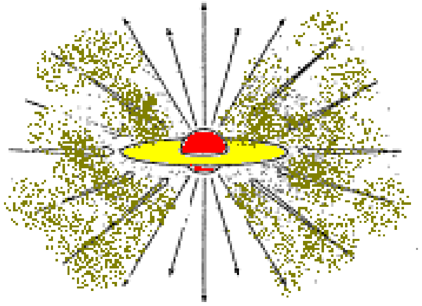
$$\dot{M} \sim \frac{M_{\mathrm{J}}}{t_{ff}} = \frac{c_s^3}{G} \sim 2 \times 10^{-6} M_{\odot}/\mathrm{yr} \left(\frac{T}{10K} \right)^{3/2}$$



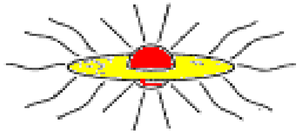
A. Dense cores form within molecular clouds.



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



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



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

Obstacles in Forming Massive Stars

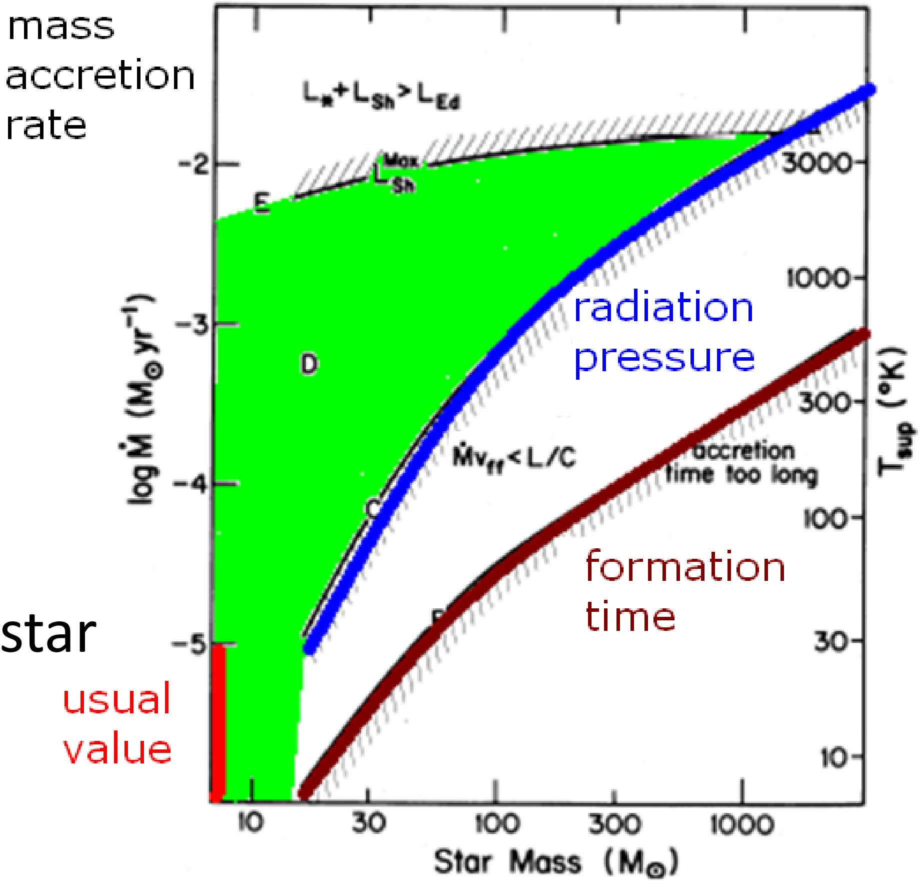
1. **Formation time problem**
   Time needed to form a massive star

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

   exceeds the stellar life time.

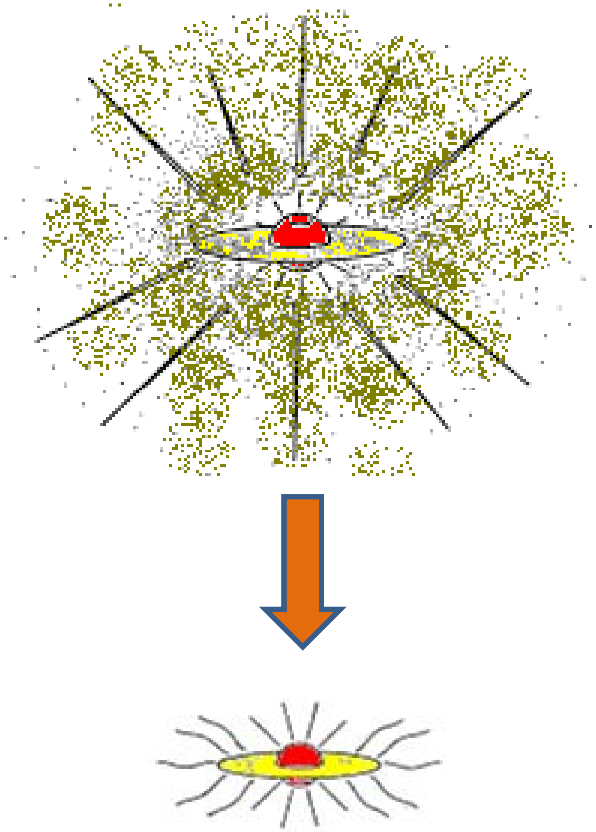
2. **Radiation barrier problem**
   Radiation pressure (on dust) by the star becomes too high for the matter to be accreted.

Wolfire & Cassinelli 1987



Rapid and non-spherical accretion is needed for massive star formation in local universe.

Metallicity and Massive Stars



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

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

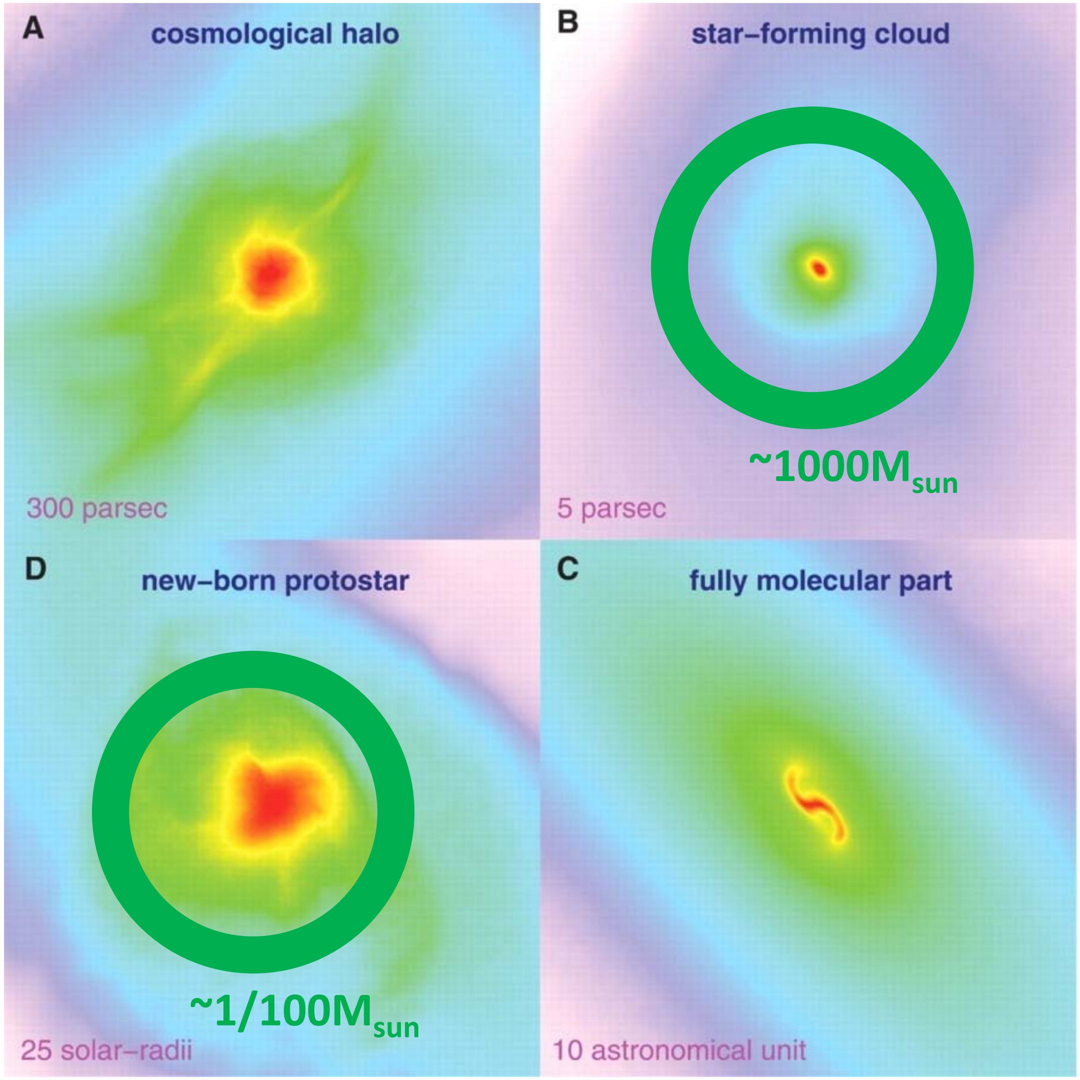
$$\dot{M} \sim \frac{M_{\rm J}}{t_{ff}} = \frac{c_s^3}{G} \sim 2 \times 10^{-6} M_\odot/{\rm yr} \left(\frac{T}{10K} \right)^{3/2}$$

Both effects weakens the feedback

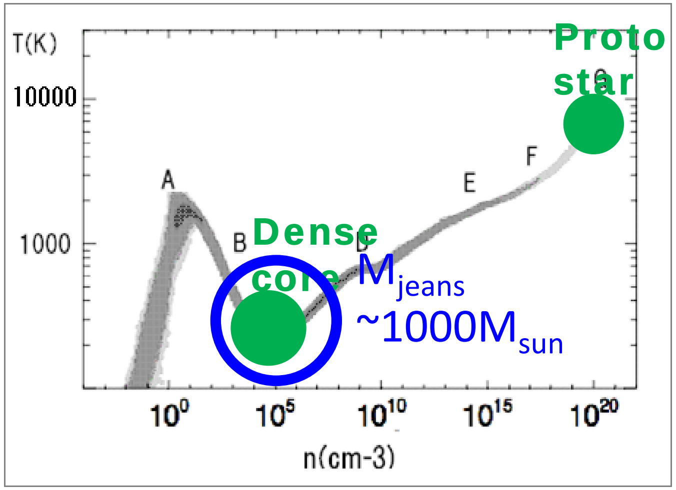
➔ More massive stars

1. Massive stars:
case of the first stars

First Star Formation: early phase



Yoshida, KO, Hernquist 2008

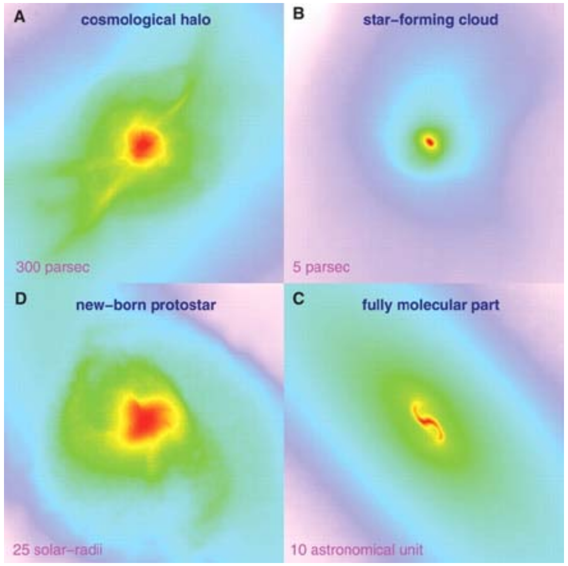


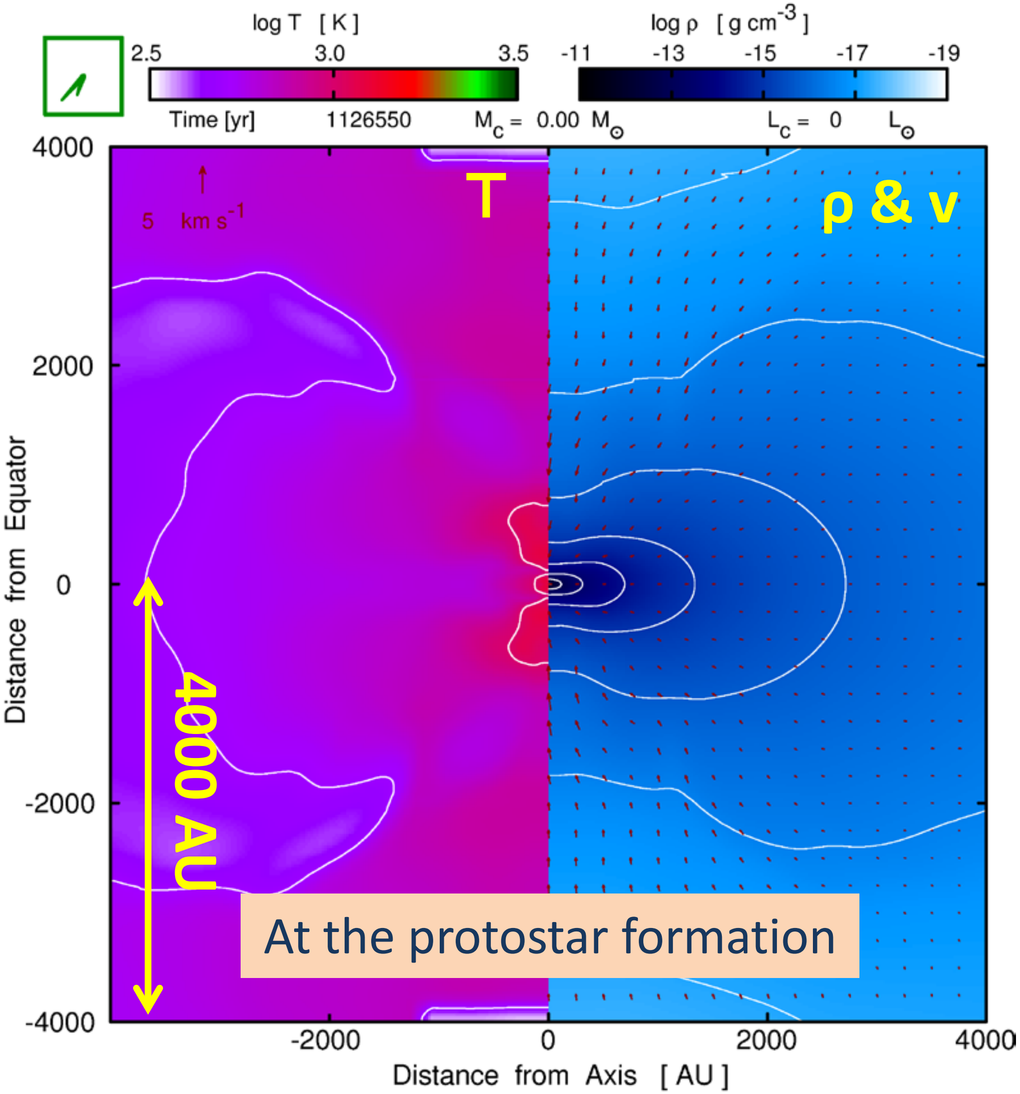
- At ~10^4cm^{-3}, dense core of ~1000M_{sun} forms by H_2 cooling
- Inside of it, a protostar forms at~10^{21}cm^{-3} with initial mass of ~$10^{-2}M_{sun}$
- The protostar grows with high accretion rate ~$10^{-3}M_{sun}$/yr

Accretion evolution of the first star

Hosokawa, KO, Yoshida, Yorke 2011

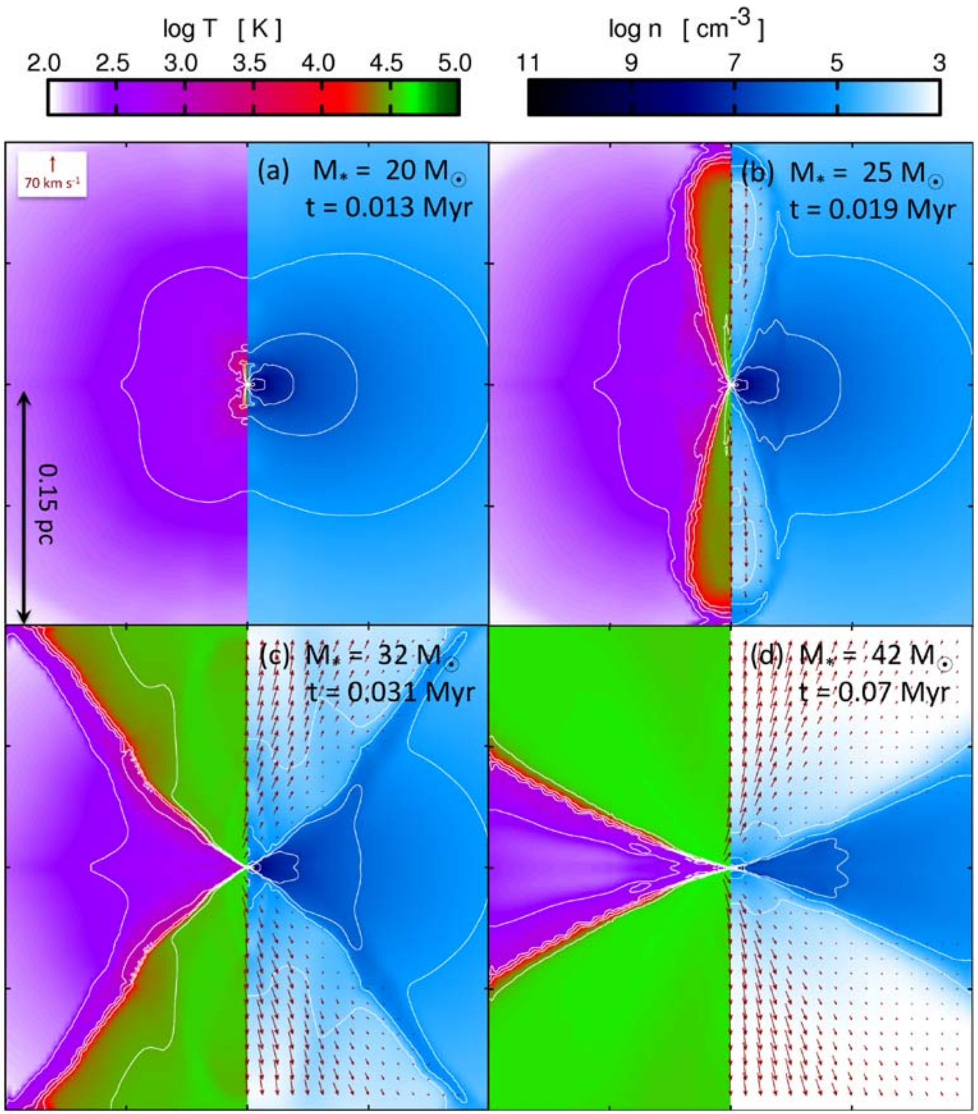
- Initial condition from the cosmological simulation
- 2D radiative-chemical hydro ＋protostellar evolution





At the protostar formation

First Star Formation: late phase

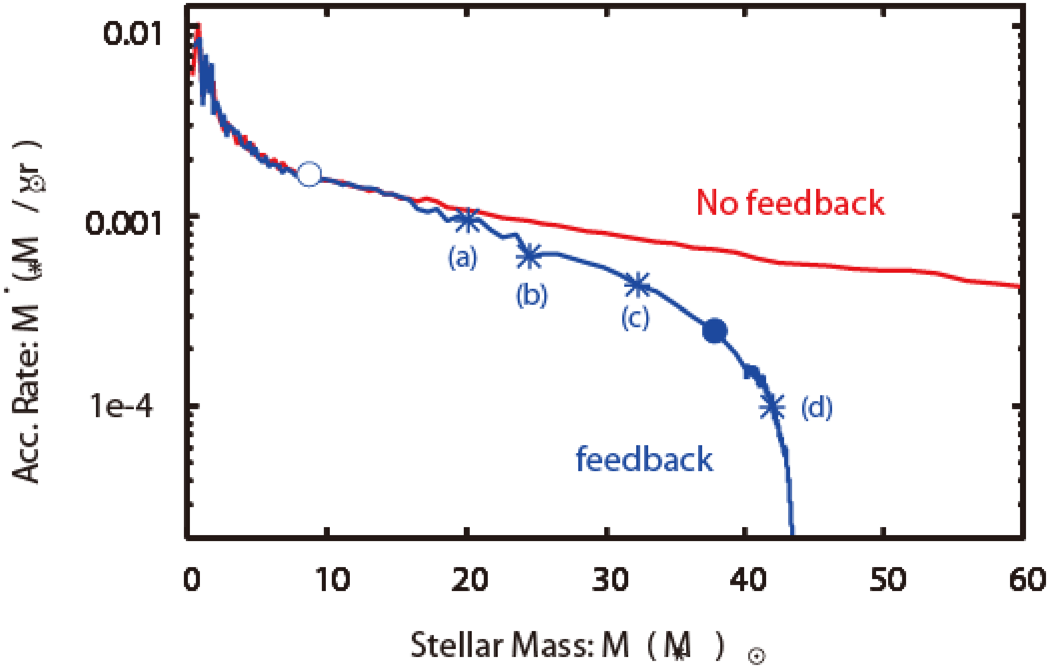


Hosokawa, KO, Yoshida, Yorke 2011

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

2. Low-mass stars: pop II-III transition by metal enrichment

Pop III-II transition

✓**First stars** (Pop III stars)

theoretically predicted to be massive(~ several 10M_{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 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**)

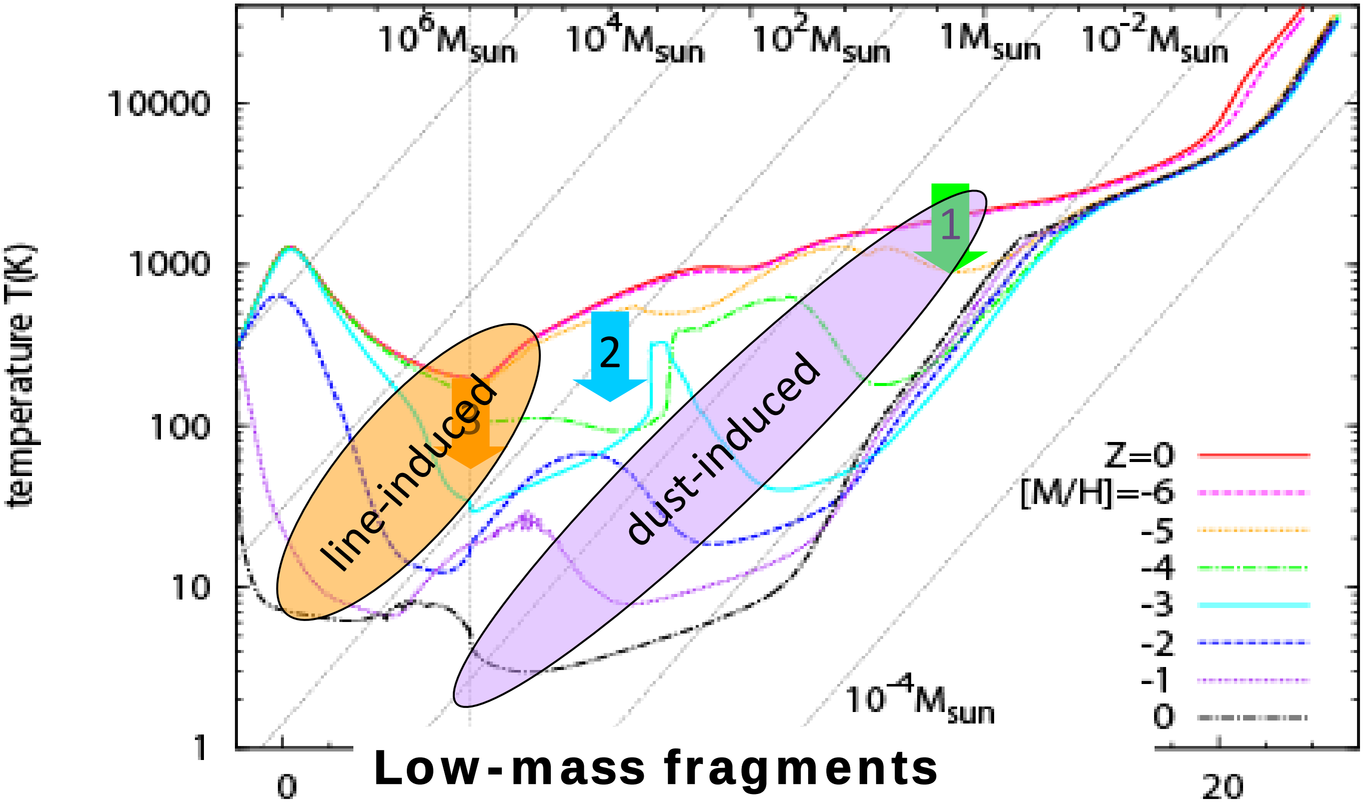
thermal evolution of low-metallicity clouds

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



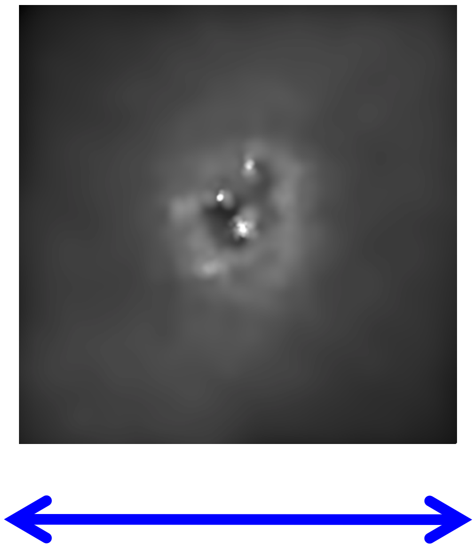
Low-mass fragments form by dust cooling

- 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

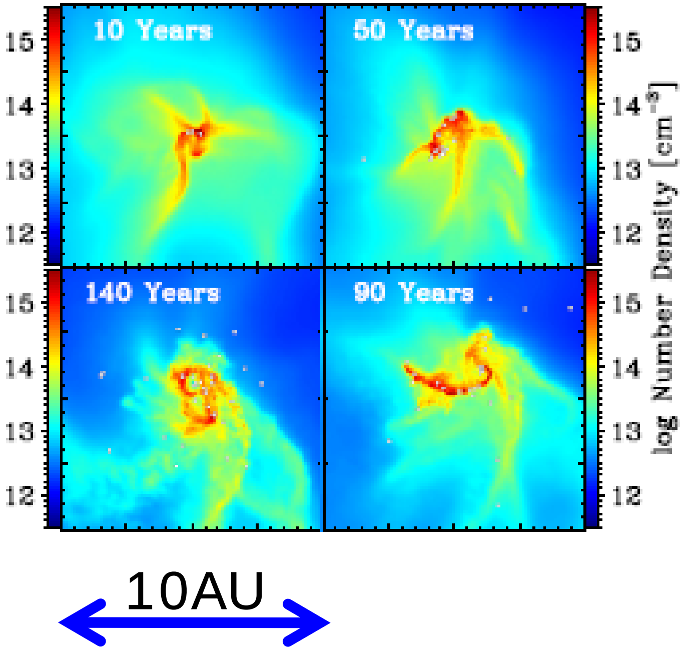
Dust-induced fragmentation

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



Yoshida, KO in prep.

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



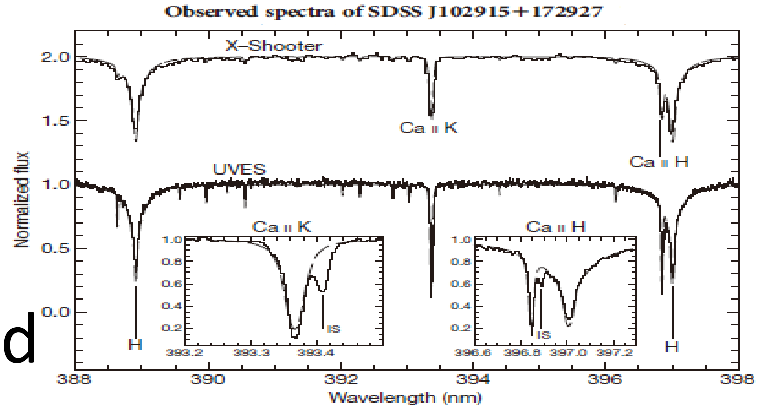
Dopcke et al. (2011)

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

Recent discovery in support of the dust fragmentation theory

An extremely primitive star in the Galactic halo

Elisabetta Caffau[1,2], Piercarlo Bonifacio[2], Patrick François[2,3], Luca Sbordone[1,2,4], Lorenzo Monaco[5], Monique Spite[2], François Spite[2], Hans-G. Ludwig[1,2], Roger Cayrel[2], Simone Zaggia[6], François Hammer[2], Sofia Randich[7], Paolo Molaro[8] & Vanessa Hill[9]



Caffau + 2011

- Lowest metallicity (including C and O) star ever found $4.5\times10^{-5}Z_{sun}$
- Fine-str. Line theory fails to explain its formation.

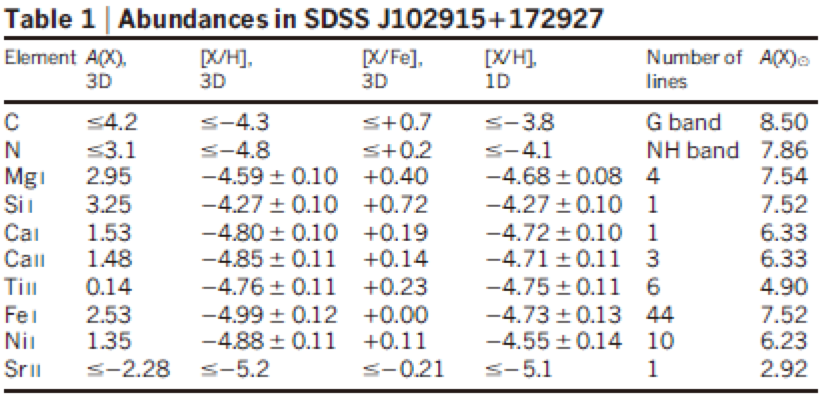
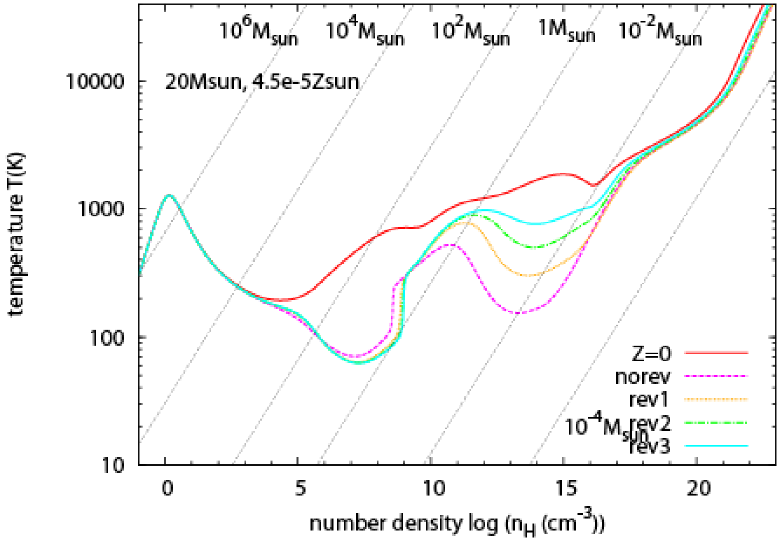


Table 1 | Abundances in SDSS J102915+172927

Element	*A*(X), 3D	[X/H], 3D	[X/Fe], 3D	[X/H], 1D	Number of lines	*A*(X)$_\odot$
C	≤4.2	≤−4.3	≤+0.7	≤−3.8	G band	8.50
N	≤3.1	≤−4.8	≤+0.2	≤−4.1	NH band	7.86
Mg I	2.95	−4.59 ± 0.10	+0.40	−4.68 ± 0.08	4	7.54
Si I	3.25	−4.27 ± 0.10	+0.72	−4.27 ± 0.10	1	7.52
Ca I	1.53	−4.80 ± 0.10	+0.19	−4.72 ± 0.10	1	6.33
Ca II	1.48	−4.85 ± 0.11	+0.14	−4.71 ± 0.11	3	6.33
Ti II	0.14	−4.76 ± 0.11	+0.23	−4.75 ± 0.11	6	4.90
Fe I	2.53	−4.99 ± 0.12	+0.00	−4.73 ± 0.13	44	7.52
Ni I	1.35	−4.88 ± 0.11	+0.11	−4.55 ± 0.14	10	6.23
Sr II	≤−2.28	≤−5.2	≤−0.21	≤−5.1	1	2.92



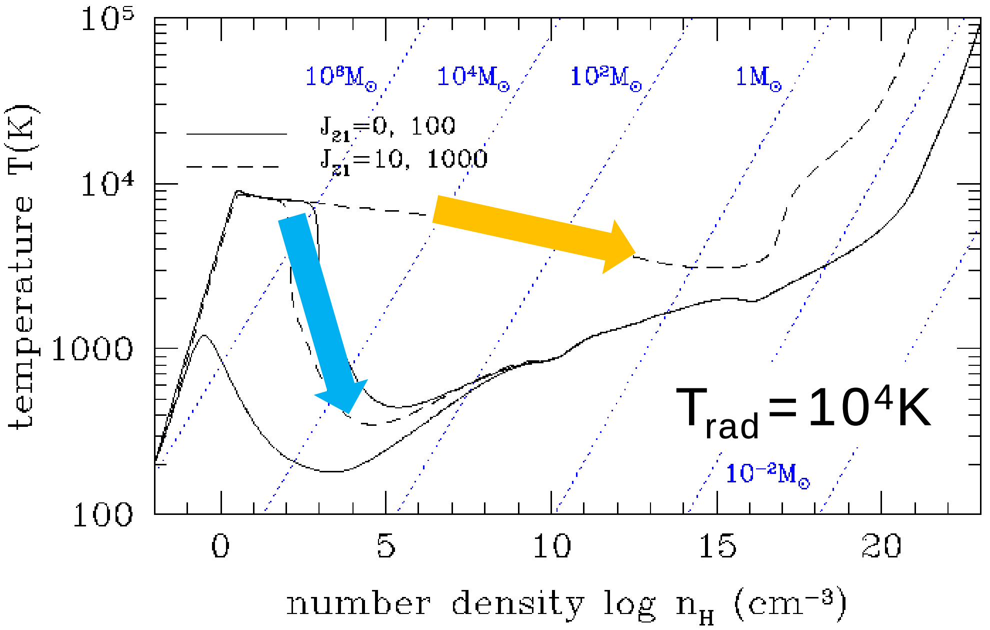
3. Supermassive stars: where and how ?

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
- Formation timescale shorter than lifetime
  - High accretion rate
    $>M_*/t_* \sim 10^5 M_{sun}/2x10^6 yr \sim 0.05 M_{sun}/yr$
  - If no H2, $T \sim 10^4 K$
    $dM^*/dt \sim c_s^3/G \sim 0.06 M_{sun}/yr\ (T/10^4 K)^{3/2}$

primordial gas in strong FUV field

Omukai 2001, Omukai & Yoshii 2003



FUV intensity

✓$J<J_{crit}$

→ at some density, H_2 cooling and fragmentation

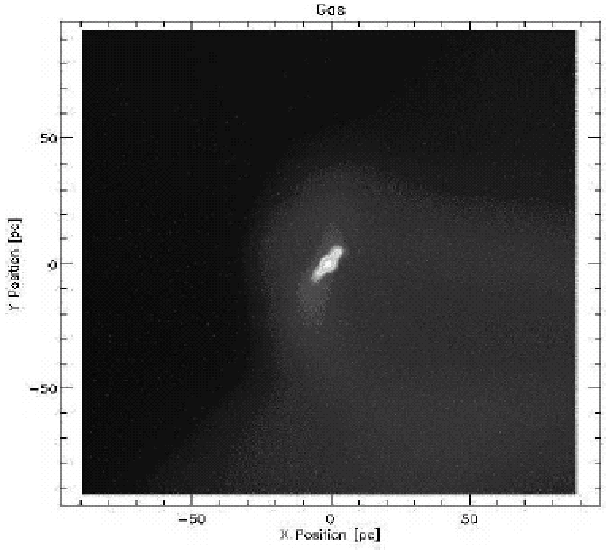
✓$J>J_{crit}$

→ isothermal collapse continues

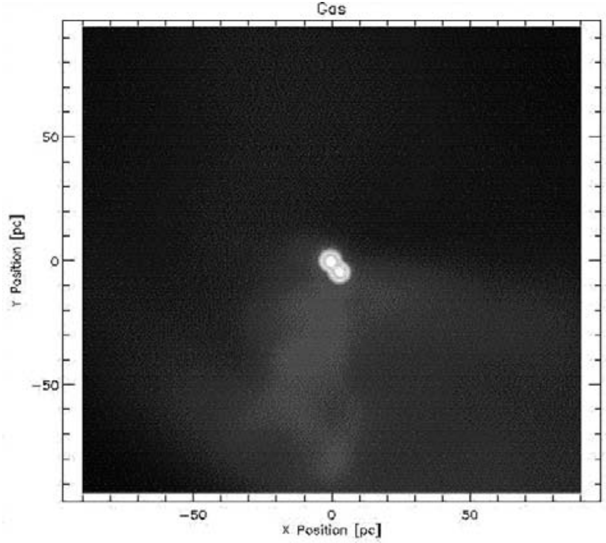
SMS formation by the isothermal collapse

Bromm & Loeb 2003

non-rotating



rotating

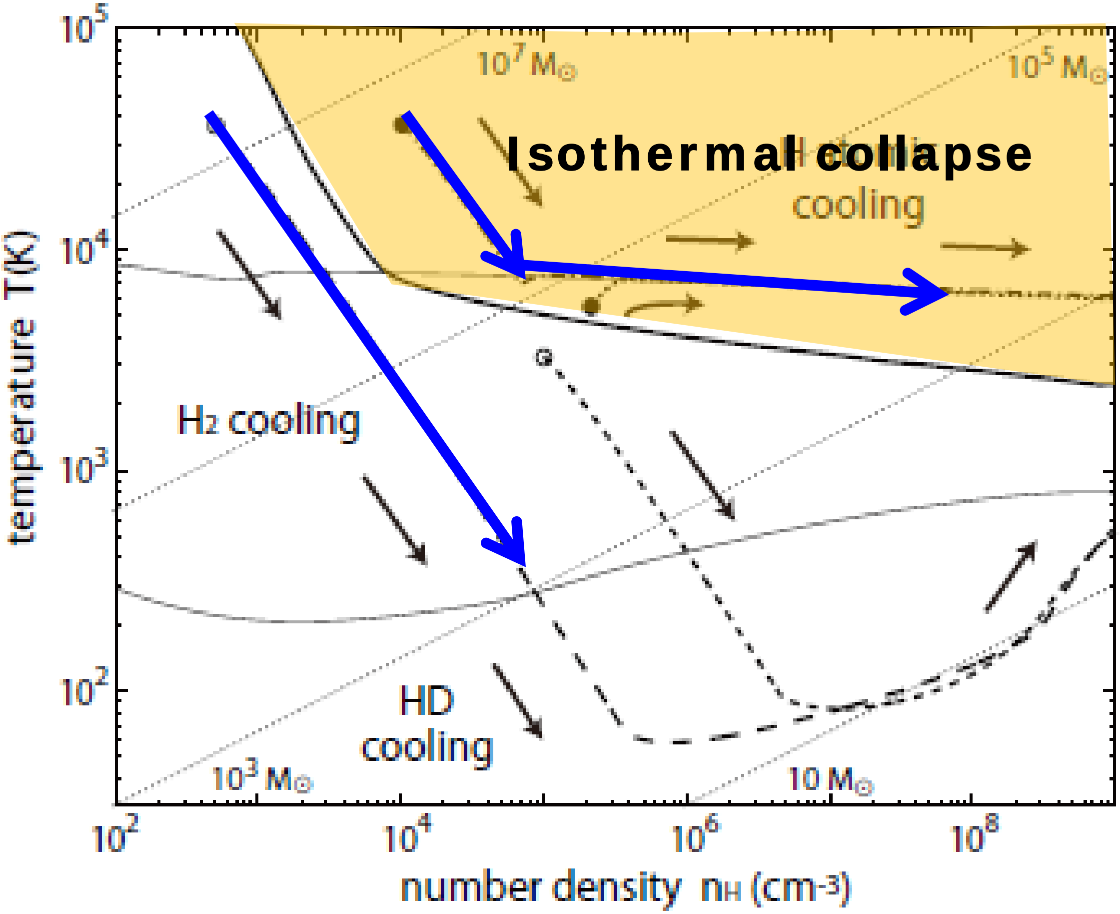


✓$M\sim10^8M_{sun}$ halo virializing at $z\sim10$ (2σ over-density) with strong FUV $J_{21}\sim4000$

✓Fragmentation is inefficient

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

Alternative: high-density shock in primordial gas

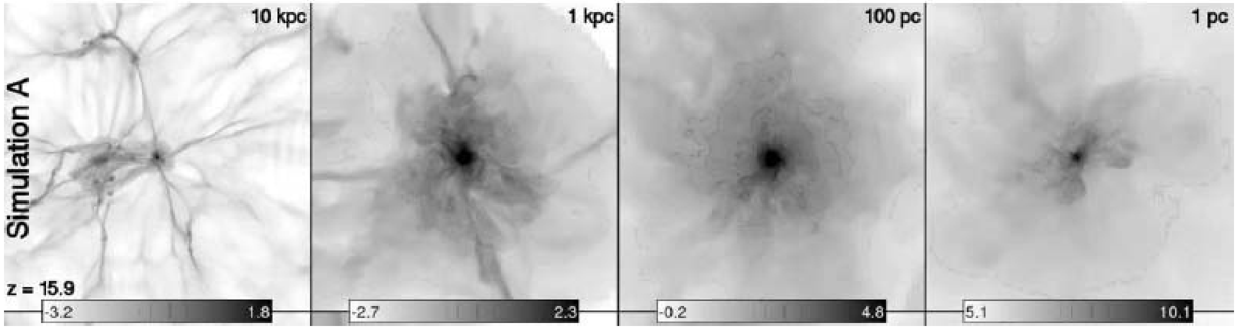


- shocks at $>10^{3-4}$/cc, with> several 10^3K
  - H_2 collisionally dissociated
  - Fragments at 8000K with $>\sim 10^5 M_{sun}$
  - Isothermal collapse thereafter

Inayoshi & KO 2012

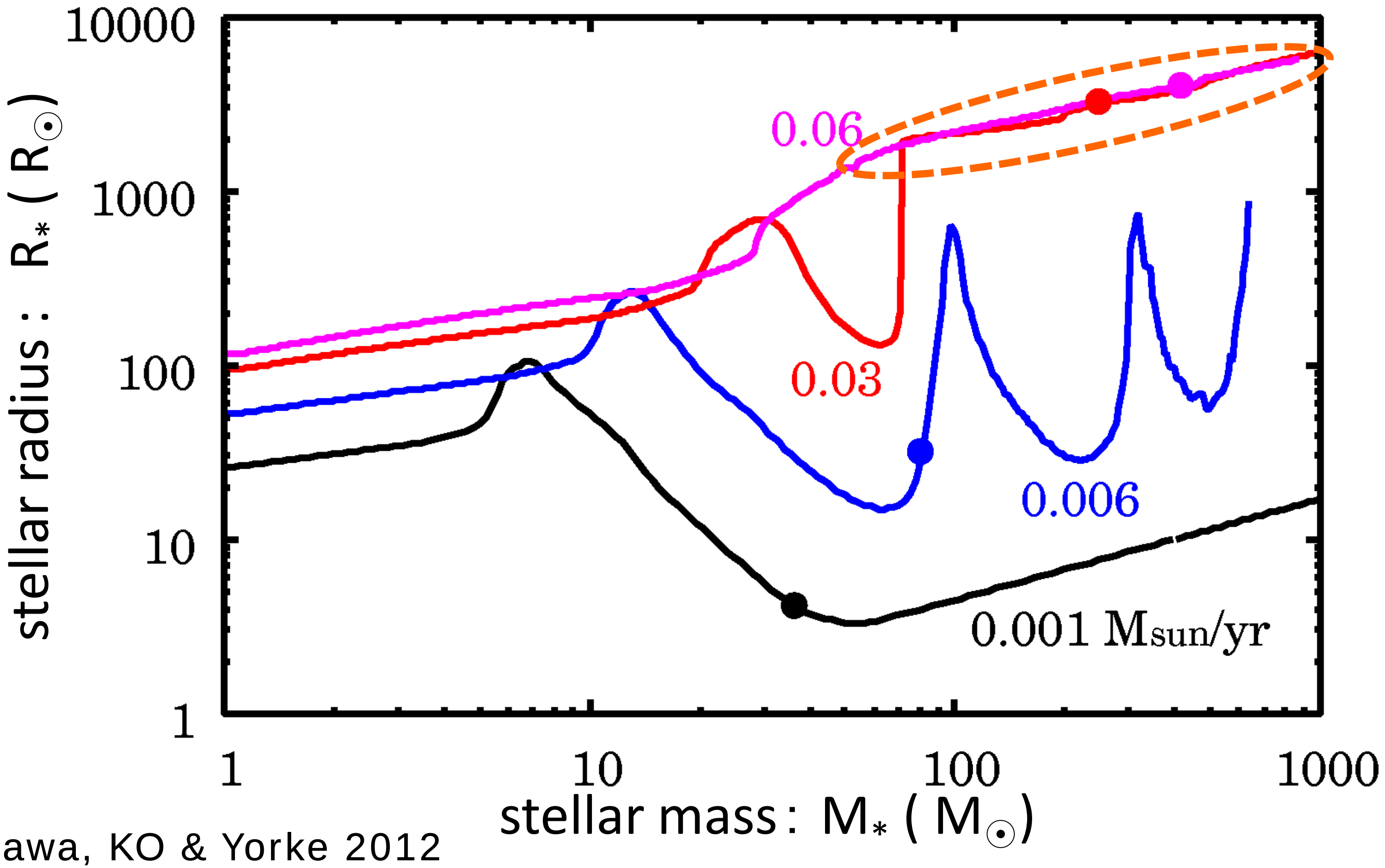
Possible sites of high-density shocks

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



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

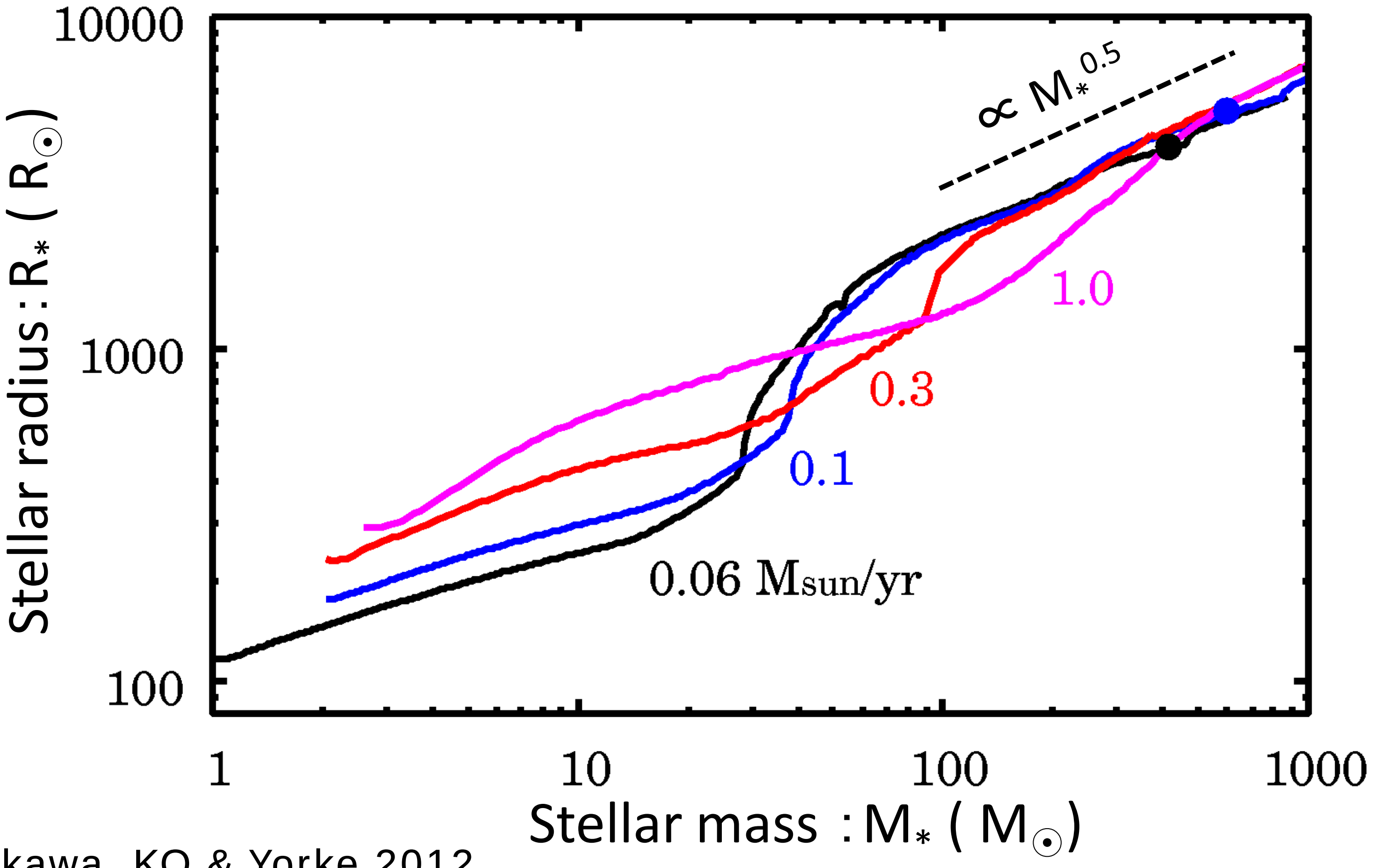
Protostars with very rapid accretion



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

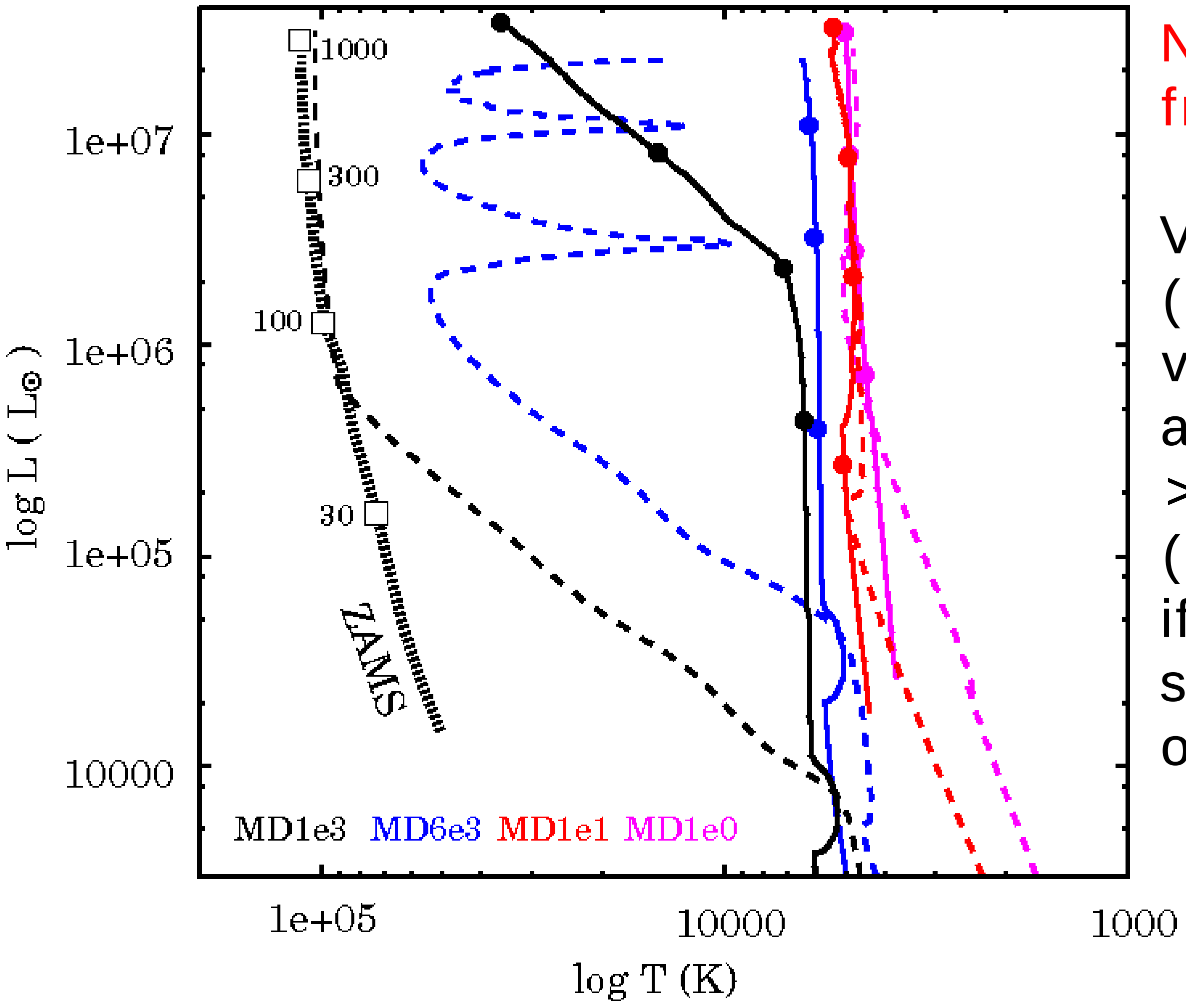
At even higher accretion rates



Hosokawa, KO & Yorke 2012

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

Evolution on the HR diagram



NO UV feedback
from bloated massive stars

Very massive stars ($> 1000 M_{sun}$) 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 (1/2)

First stars: massive (but not very massive)

- dense core of $10^3 M_{sun}$ forms at $10^4 cm^{-3}$ 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 (2/2)

Supermassive star formation

- Photodissociation/Collisional dissociation in dense, shocks suppresses H_2 cooling, leading to SMS formation via isothermal collapse at 8000K.

- Accretion of SMS can continue at least $\sim 10^3 M_{sun}$, probably more.
  ➔Hopefully evolve to a SMBH seed.