The First Stars: their diversity and beyond

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+ final mass of the first stars and radiative feedback
+ the mass distribution of the first stars
+ origin of the supermassive black holes in the early universe

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Rolf Kuiper, Harold Yorke

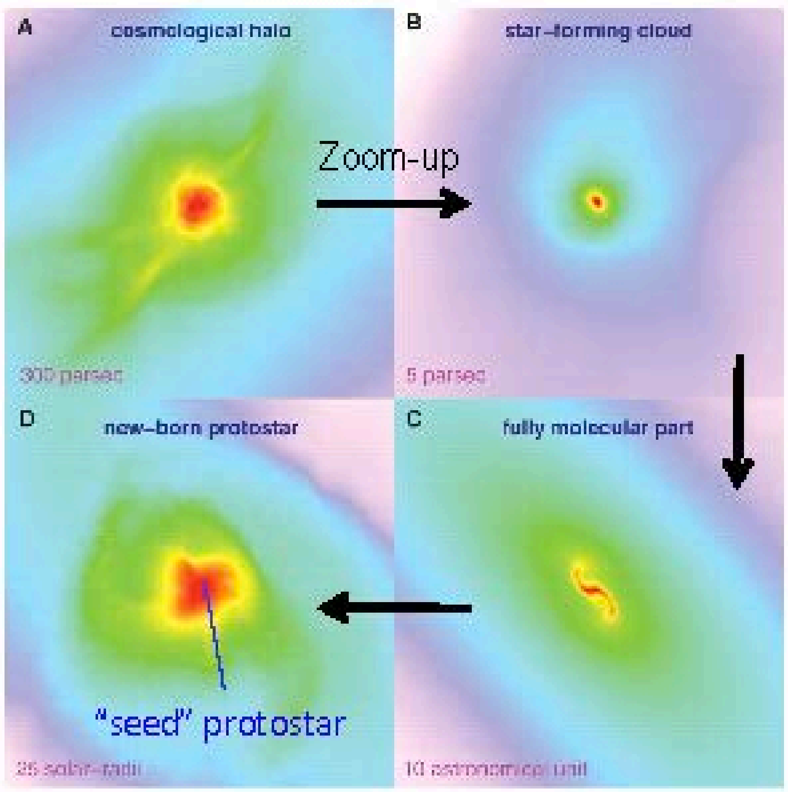
<References>

+ Hirano, Hosokawa et al. 2014, ApJ, 781, 60
+ Hosokawa et al. 2013, ApJ, 778, 178
+ Inayoshi, Hosokawa & Omukai, 2013, MNRAS, 431, 3036
+ Hosokawa, Yoshida, Omukai & Yorke, 2012, ApJ, 760, 37L
+ Hosokawa, Omukai & Yorke, ApJ, 2012, 756, 93
+ Hosokawa, Omukai, Yoshida & Yorke Sci, 2011, 334, 1250

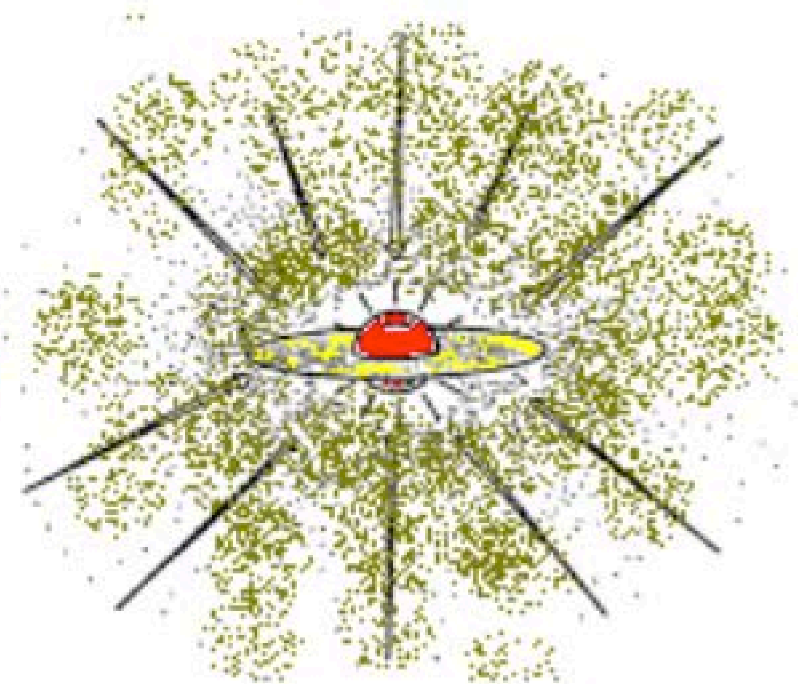
First Stars: How massive?

grav. collapse of gas cores ⇒ mass accretion onto the protostars

Yoshida, Omukai & Hernquist (2008)



10^{-2} $M_\odot$ protostar
surrounded by >10^3 $M_\odot$ gas envelope



The stellar final mass is fixed when the mass accretion ceases.

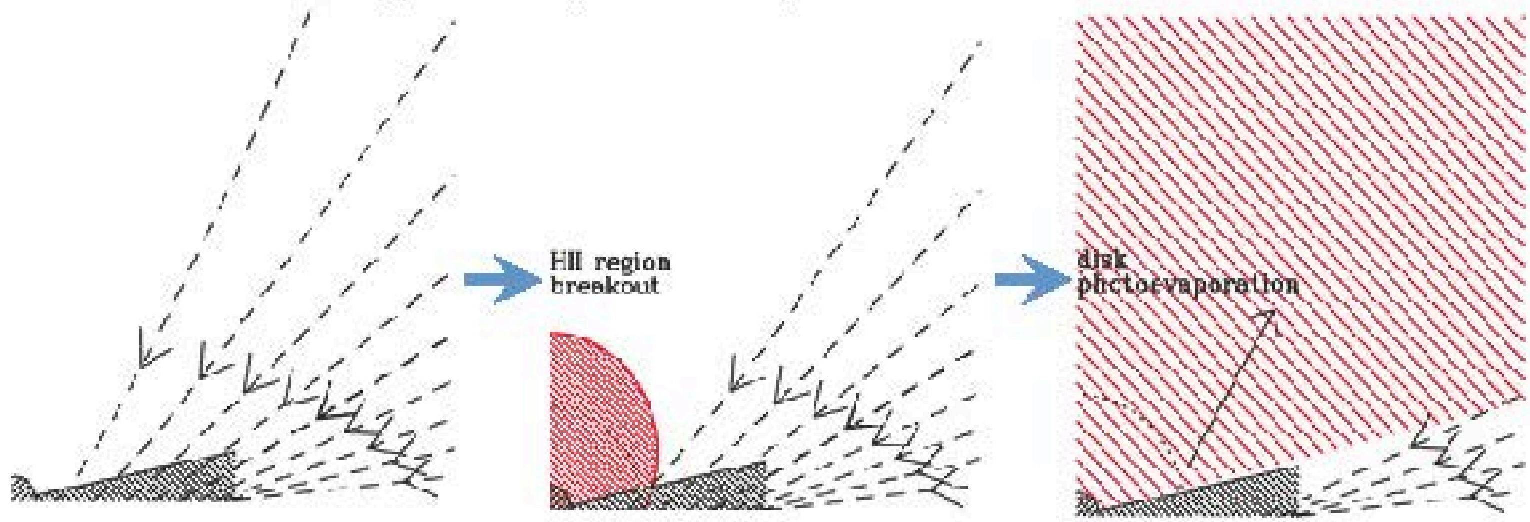
Evolution in Accretion Phase

Expected acc. rate : $\dot{M} \sim \frac{M_J}{t_{ff}} \sim \frac{c_s^3}{G} \sim 7 \times 10^{-3} M_\odot/\mathrm{yr} \left(\frac{T}{300\ \mathrm{K}}\right)^{3/2}$

With this rapid mass accretion, the entire cloud could accrete onto the star in its lifetime (～Myr) ⇒ $M_* \sim 1000 M_\odot$

UV stellar feedback (e.g., McKee & Tan 08)

Formation of an HII region + photoevaporation of the disk → $M_* \sim 150 M_\odot$?

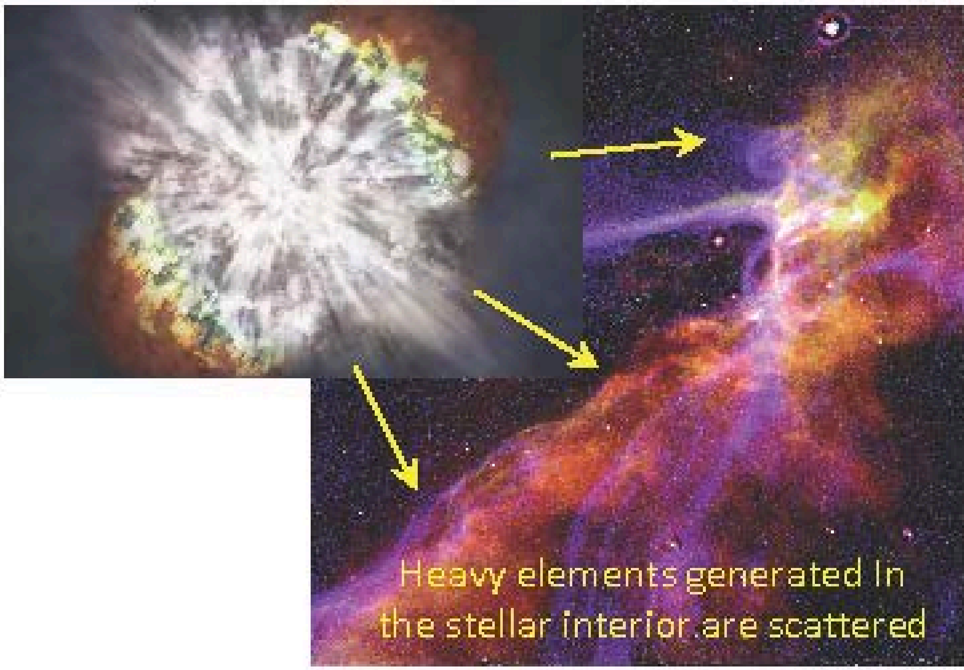


It has been postulated that the first stars were very massive (> 100 $M_\odot$)

Observational Challenge

Abundance patterns of the heavy elements generated in SN could be the observational signature of the first stars

The first stars end their lives with supernova explosion



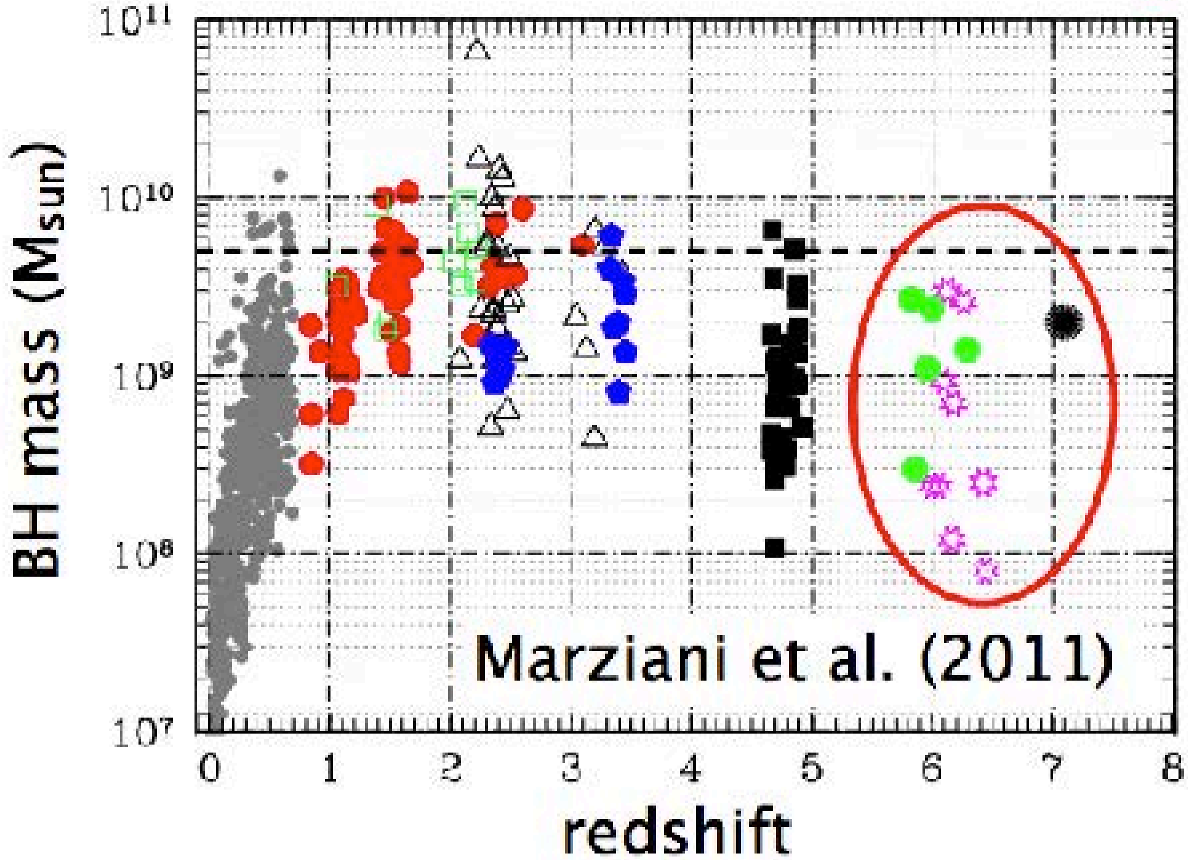
Stars born from the polluted gas have the same abundance patterns as the supernova progenitors

No signatures of PISNe (～a few x $100M_{\odot}$).

This prefers the ordinary massive stars which cause the CCSNe.

Very Very Massive Stars: still needed?

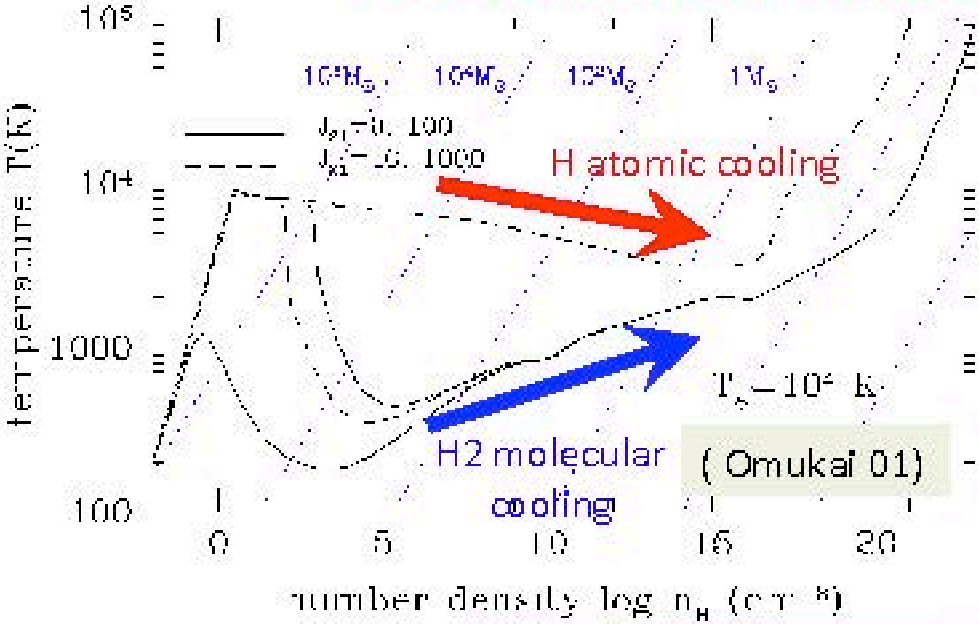
bright QSOs at z > 6 with SMBH of > 10^9 $M_\odot$

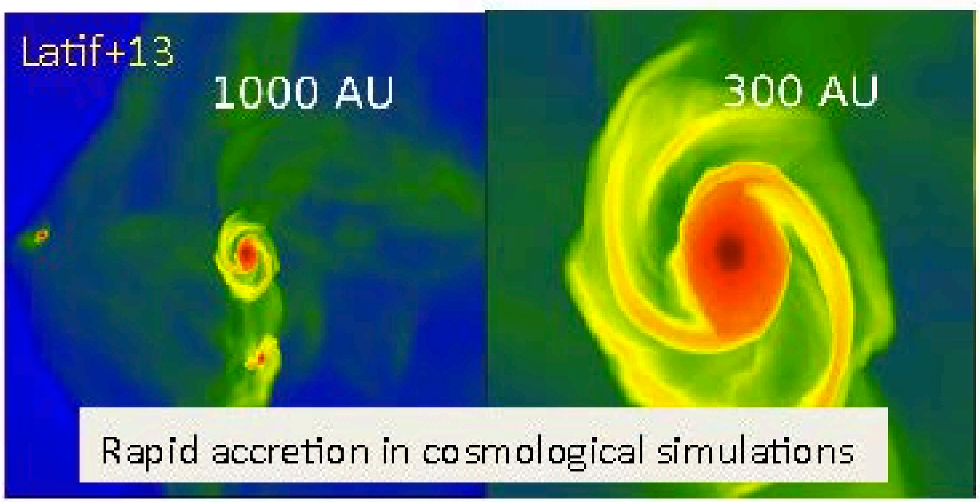


Age of the universe@z～7: 0.77Gyr. Get it before this.
Very very massive stars might be preferred to achieve this.

Supermassive Stars (~$10^5 M_\odot$)

A special case in PopIII star formation





Rapid accretion in cosmological simulations

①strong FUV radiation
(destroying H2 molecules)

↓

②collapse via H atomic cooling
(almost isothermal at T~8000K)

↓

③growth of a protostar with very rapid accretion (> $0.1 M_\odot$/yr)

$$\dot{M} \sim \frac{M_J}{t_{ff}} = \frac{c_s^3}{G} \propto T^{1.5}$$

↓

④collapse of the star (GR effect)
→$10^5 M_\odot$ BH

Key Questions

+ What is the final mass of the first stars, resulting from the evolution in the accretion phase?
What is their mass distribution?

+ How does the stellar UV feedback halts the stellar growth via mass accretion? Does the feedback always operate?

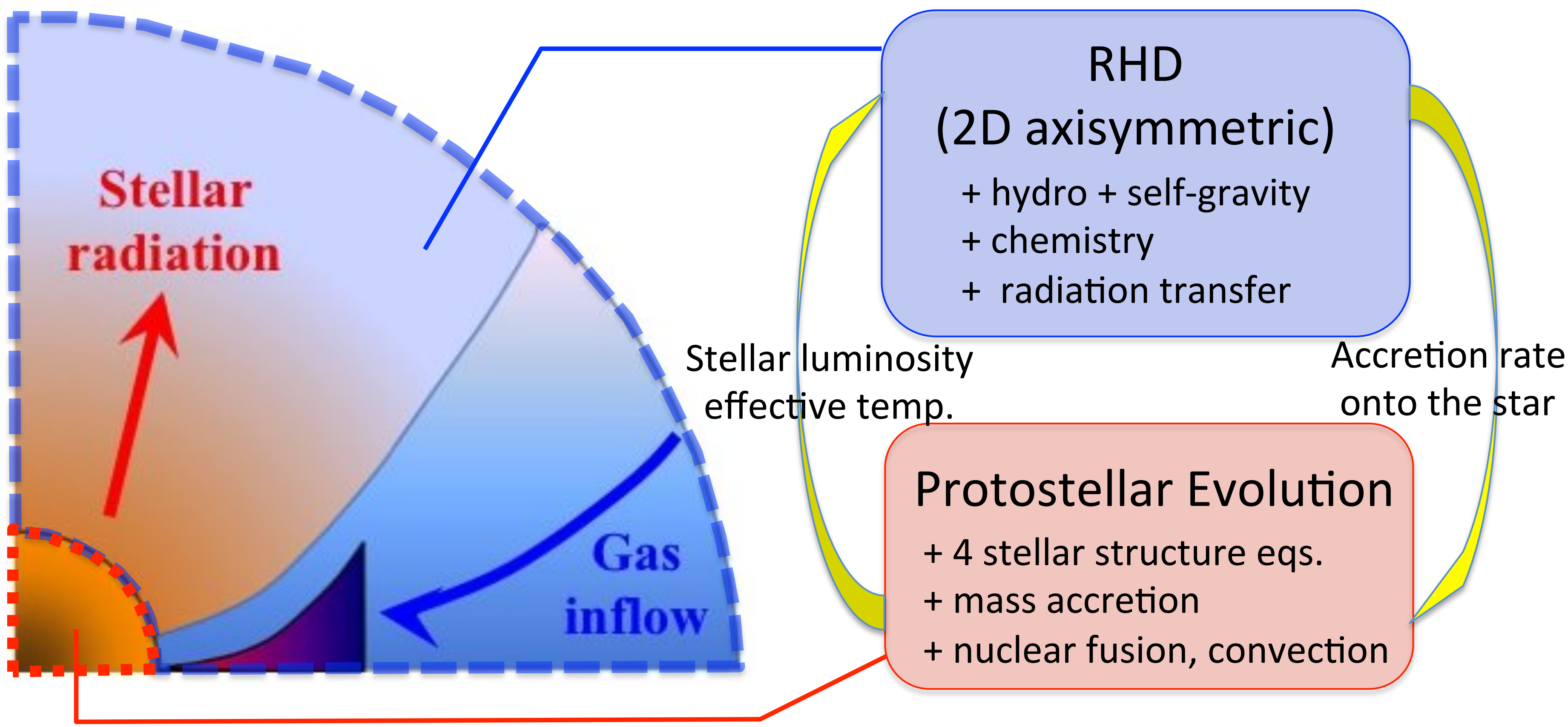
+ What is the maximum stellar mass?
Is the formation of supermassive stars possible?
Finally seeding SMBHs in the early universe?

Study evolution in the accretion phase
to answer these questions.

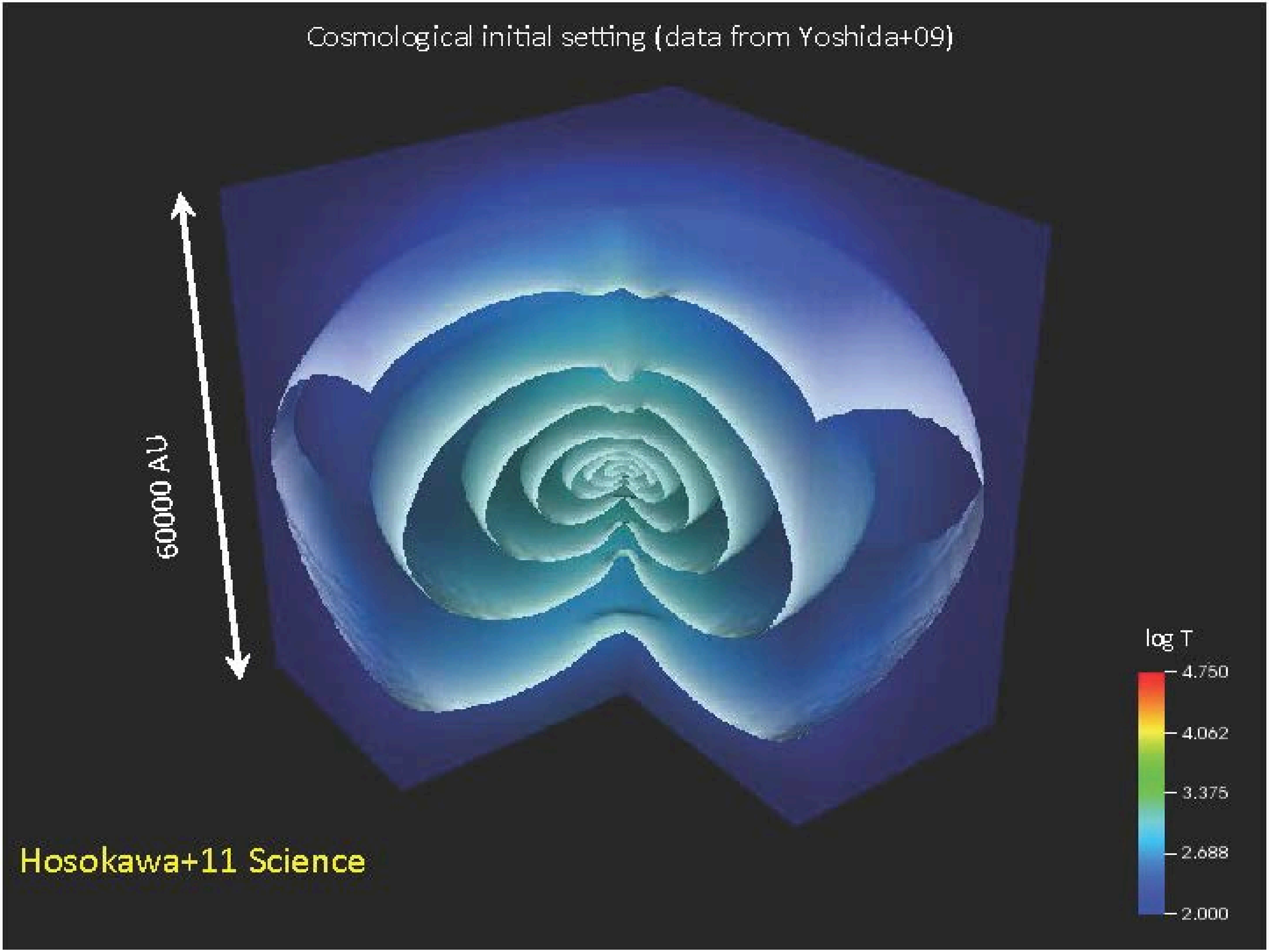
Our Approach

Direct numerical simulations

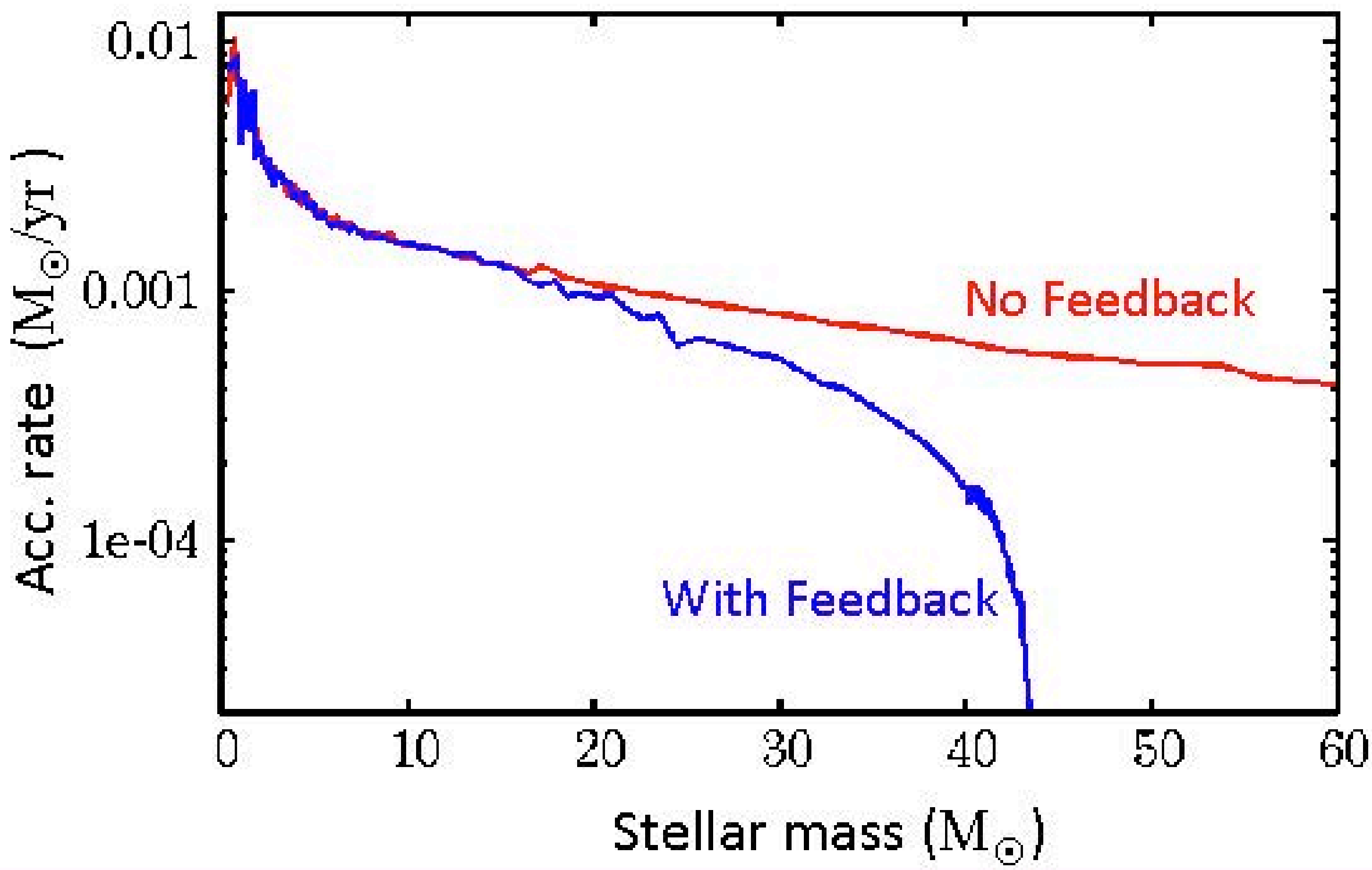
hybrid code : 2D radiation-hydro + stellar evolution



Evolution over 10^5 yrs after the birth of the protostar is followed

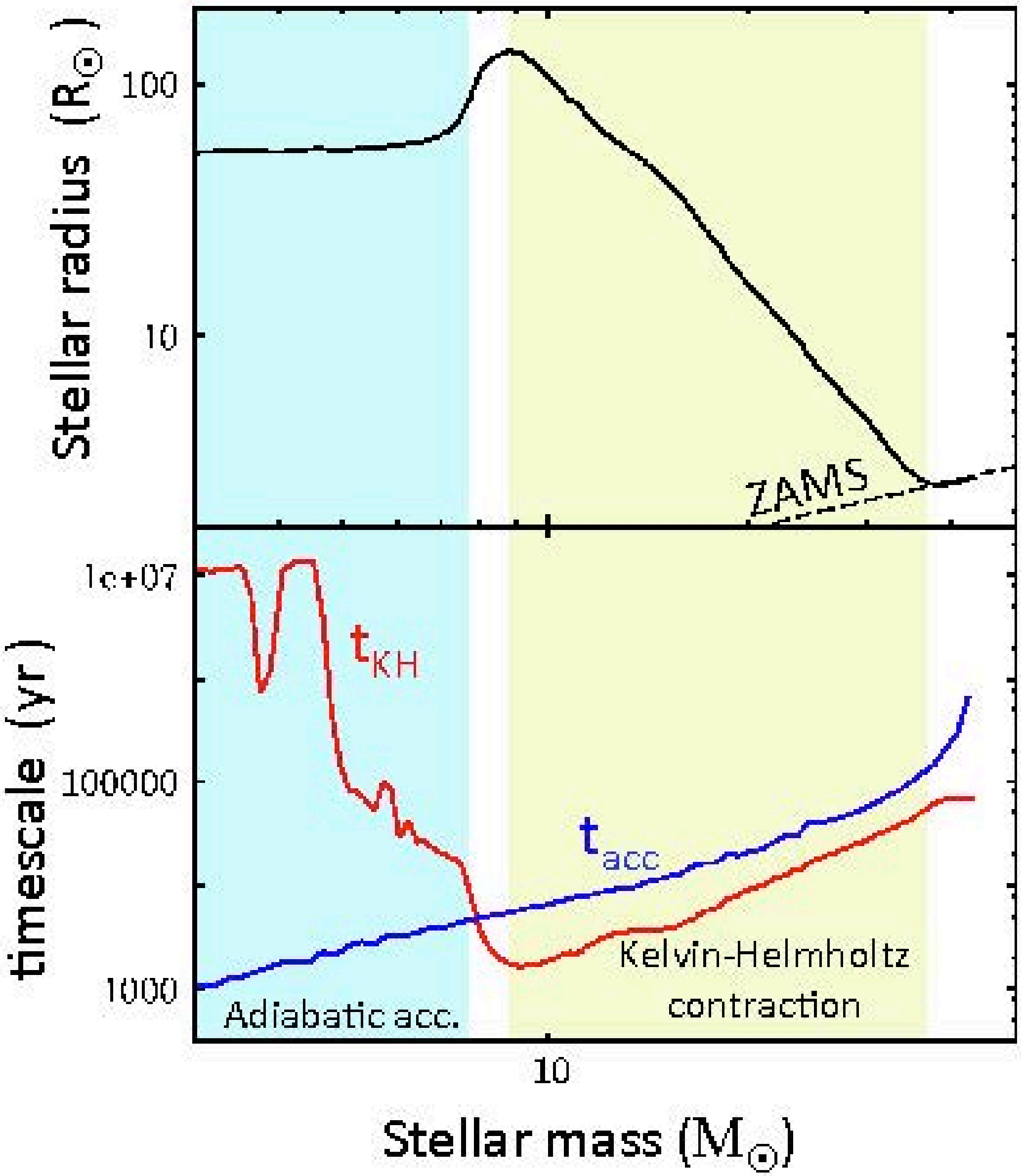

Cosmological initial setting (data from Yoshida+09)
60000 AU
log T
4.750
4.062
3.375
2.688
2.000
Hosokawa+11 Science

Accretion Histories



- Acc. rate is significantly reduced by the stellar UV feedback
- Mass accretion is shut off when the stellar mass is ~43 $M_\odot$

Protostellar Evolution



Mass accretion ceases soon after the protostar's arrival to the zero-age main-sequence (ZAMS)

2 characteristic timescales

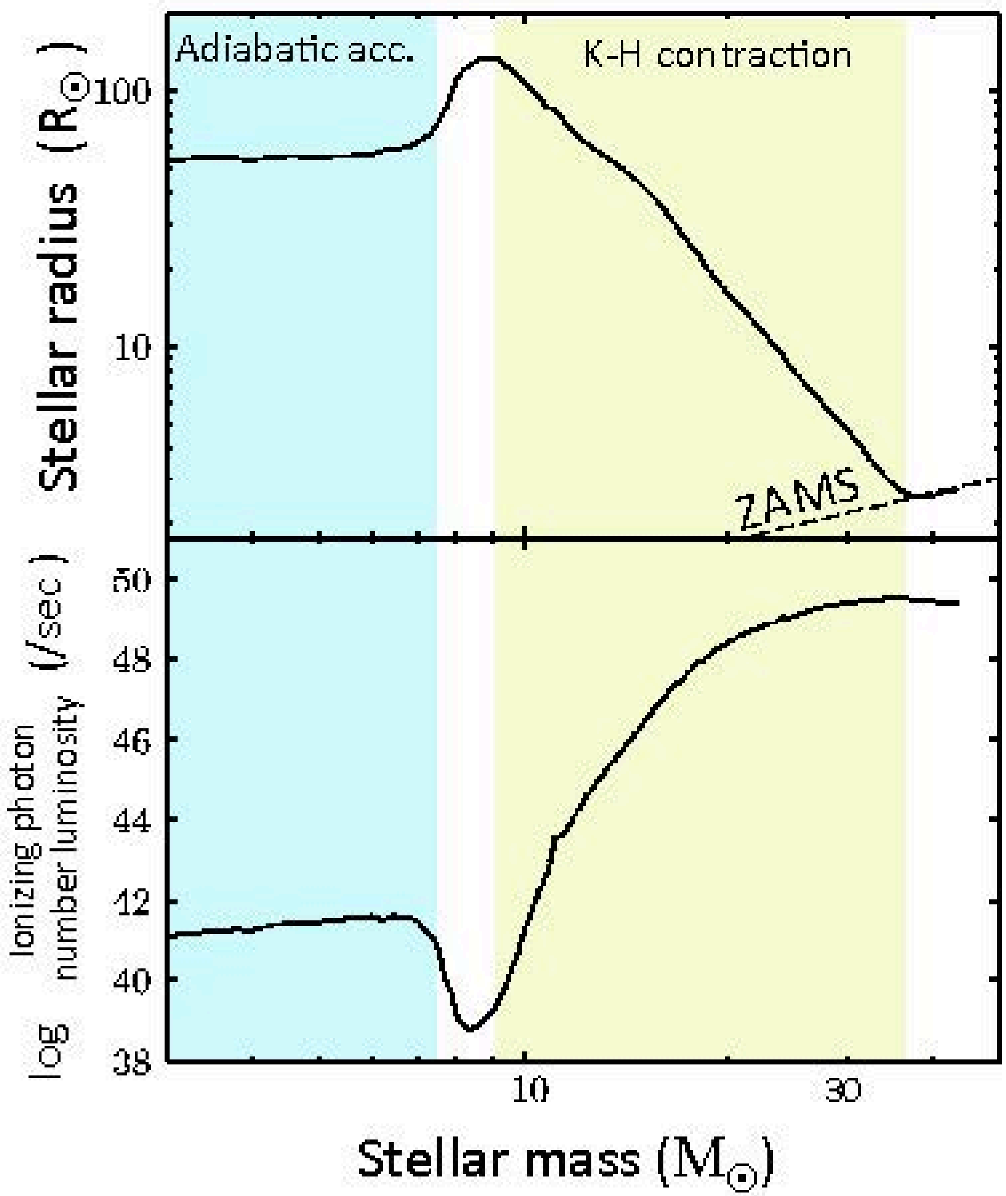
$$t_{\rm acc} = \frac{M_*}{\dot{M}}, \quad t_{\rm KH} = \frac{GM_*^2}{R_* L_*}$$

Early : $t_{KH} > t_{acc}$; adiabatic acc.

Opacity ↓ ⇒ L_* ↑
⇒ t_{KH} ↓

later: $t_{KH} < t_{acc}$; K-H contraction

Protostellar Evolution and feedback



K-H contraction stage

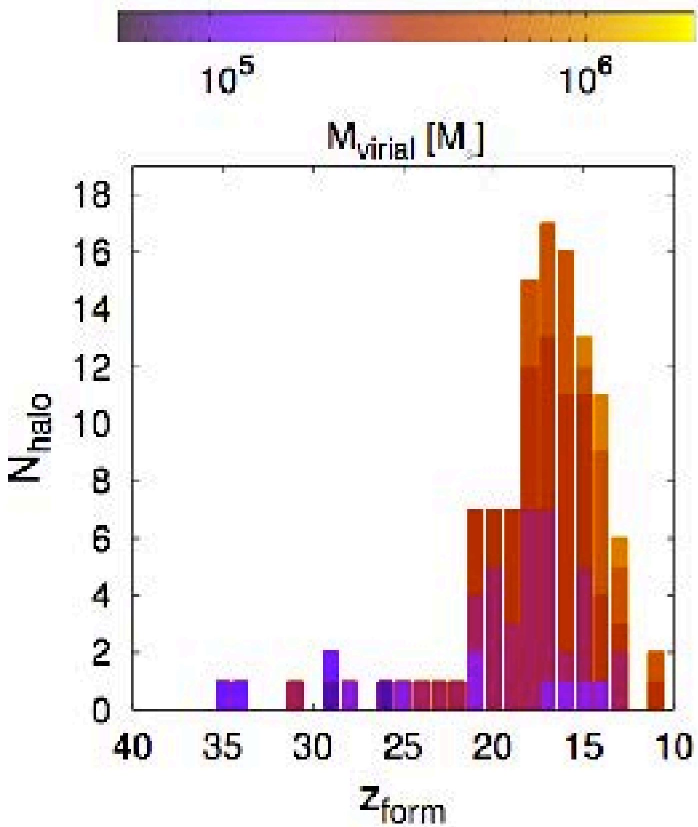
luminosity ↑
by releasing grav. energy of the star
+
contraction (radius ↓)

Effective temp. : Teff ↑
UV luminosity ↑

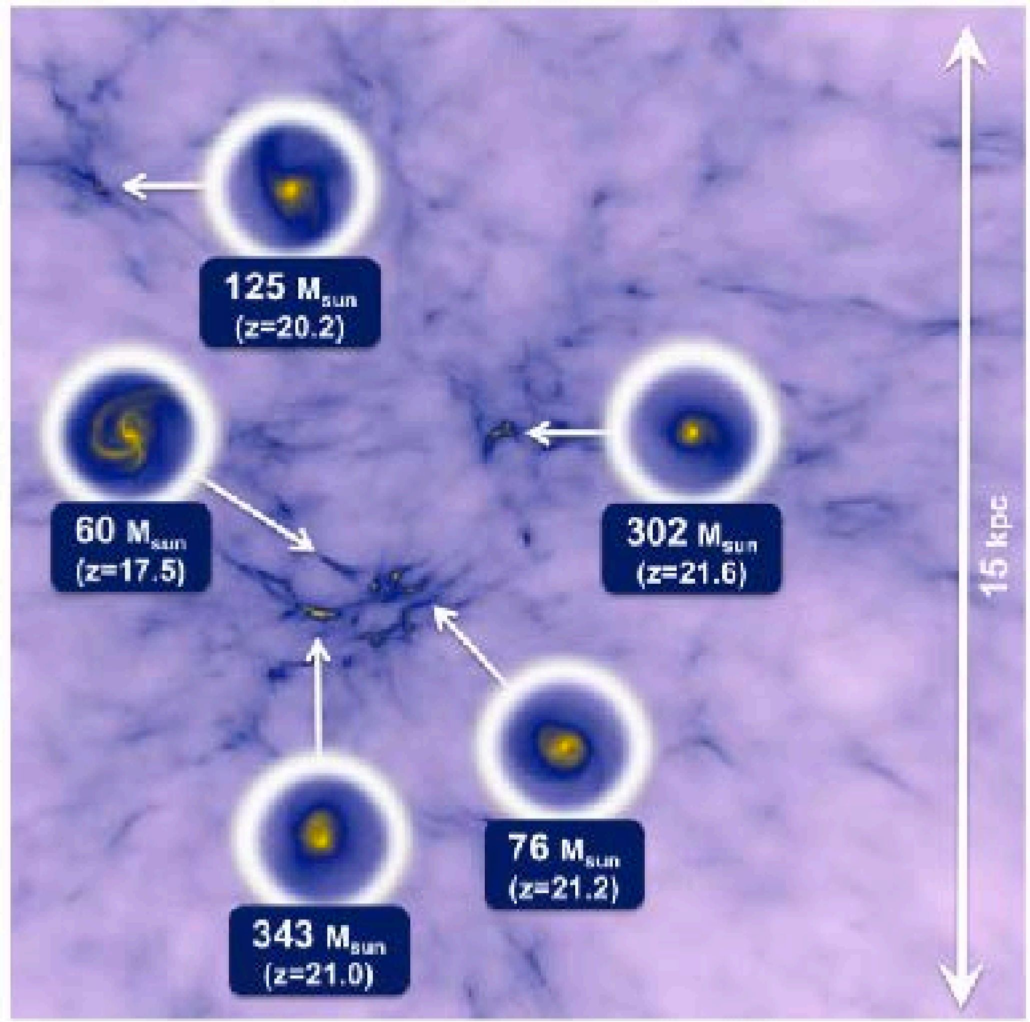
UV feedback operates over late KH contraction → ZAMS stages, and finally stops the mass accretion

Forming 100 First stars

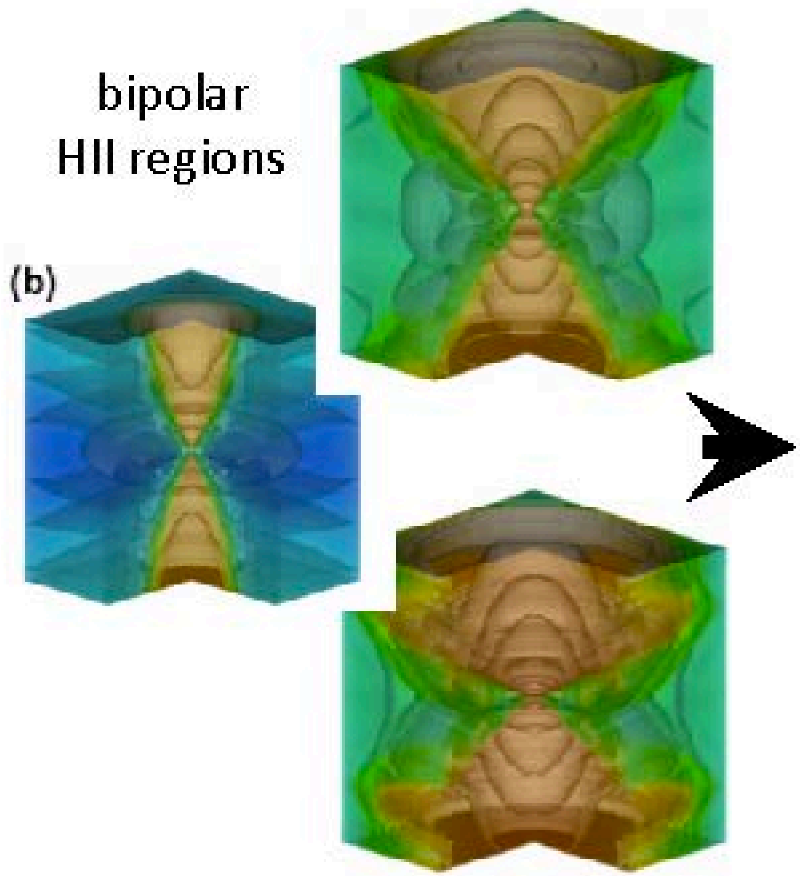
Derive the mass distribution of the first stars following the evolution with 100 different star-forming clouds. (Hirano et al. 2014)

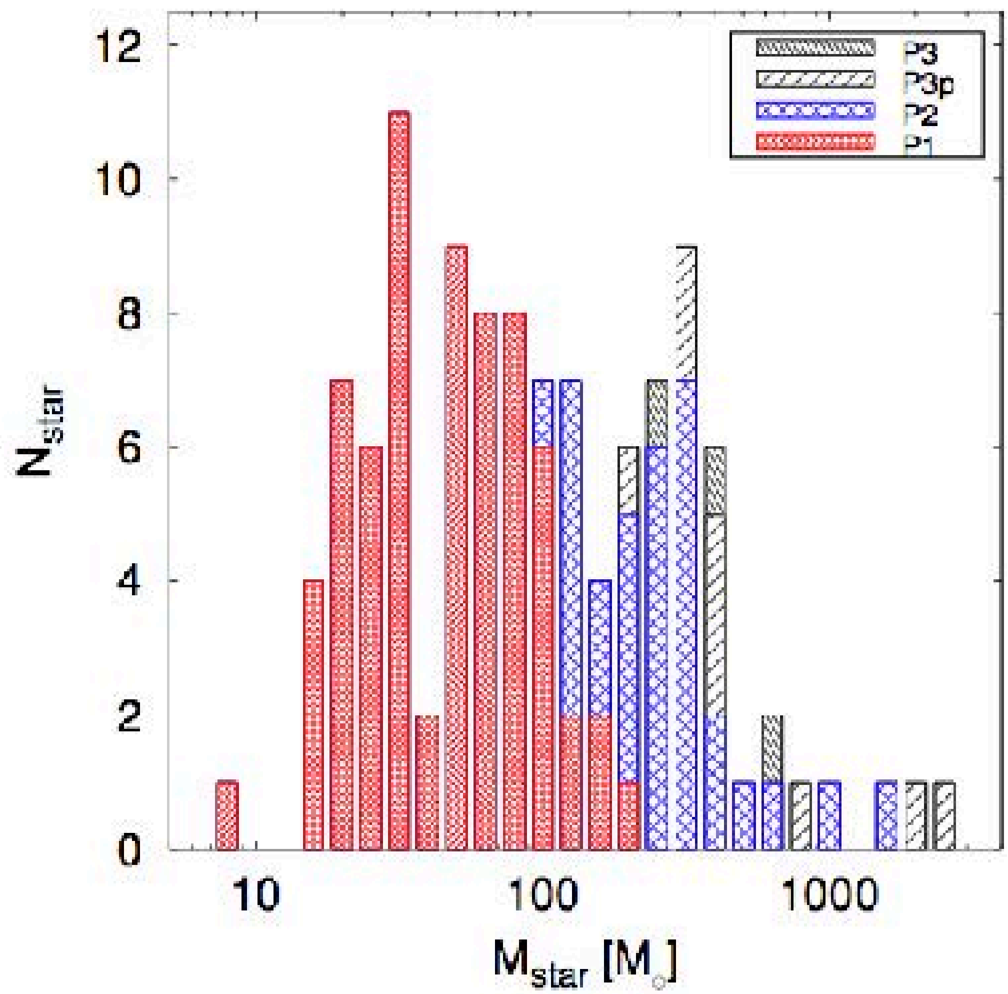


dark halo mass & formation redshift with primordial star-forming clouds



Mass Distribution

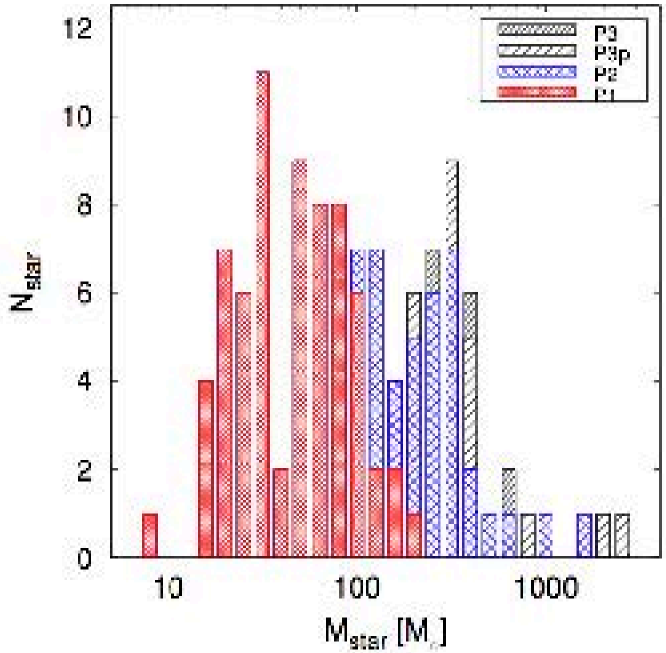


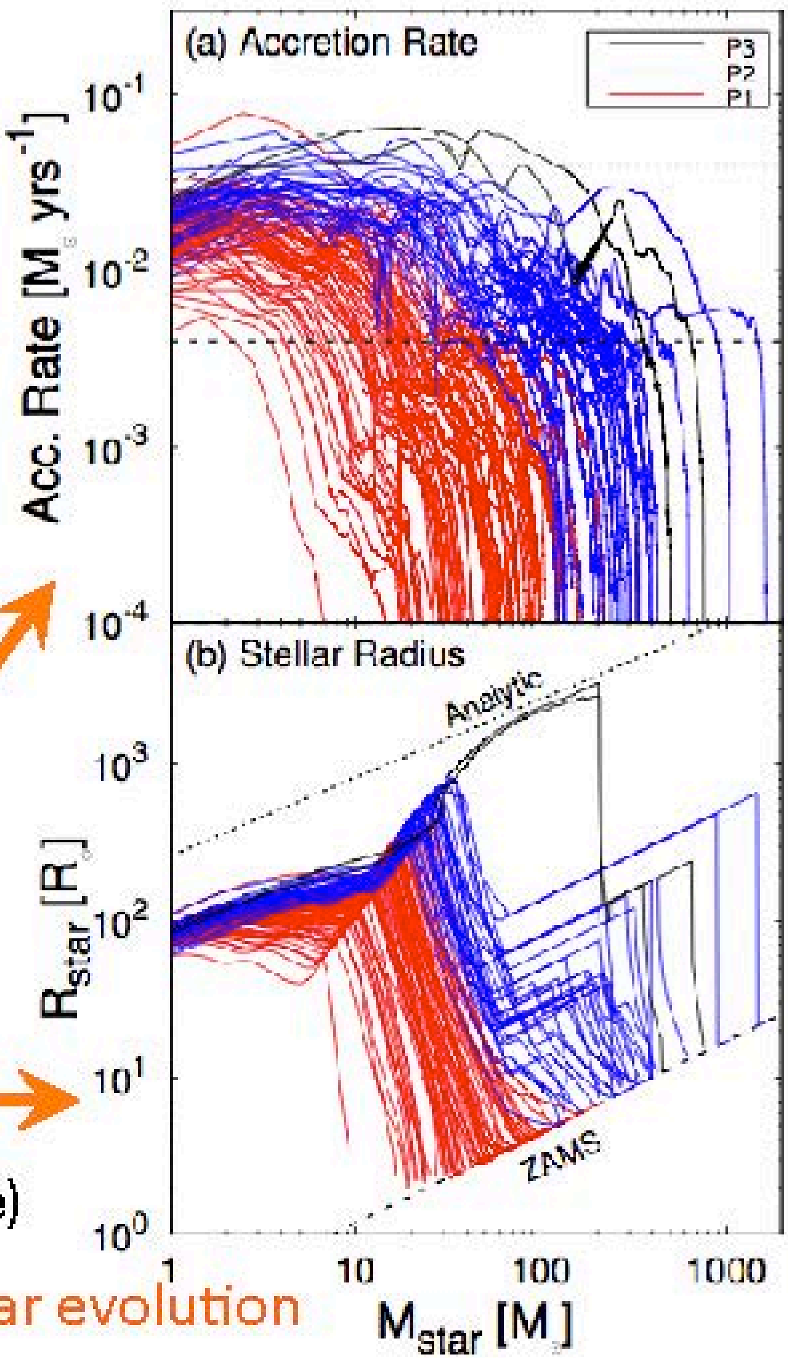


stellar mass is fixed after the stellar UV feedback shuts off the mass accretion

lots of $M_* < 100\ M_\odot$ stars, but also with $M_* > 100\ M_\odot$ stars

Diversity… why?





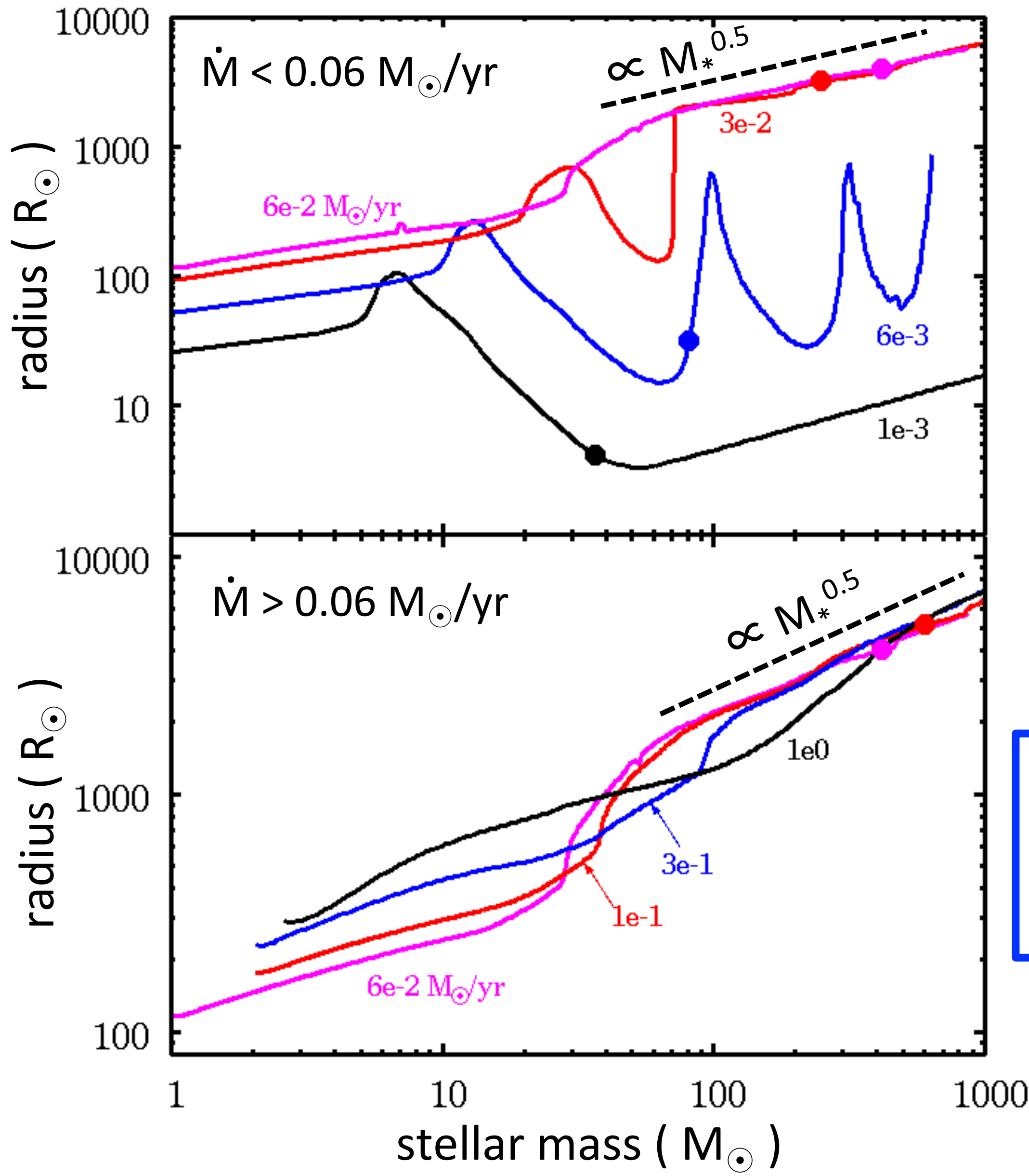
With the higher acc. rates,

+ the stellar mass is higher

+ the star approaches the ZAMS stage at the higher stellar mass
(UV feedback works near the ZAMS stage)

Rapid mass accretion changes the stellar evolution

With Very High Acc. Rates

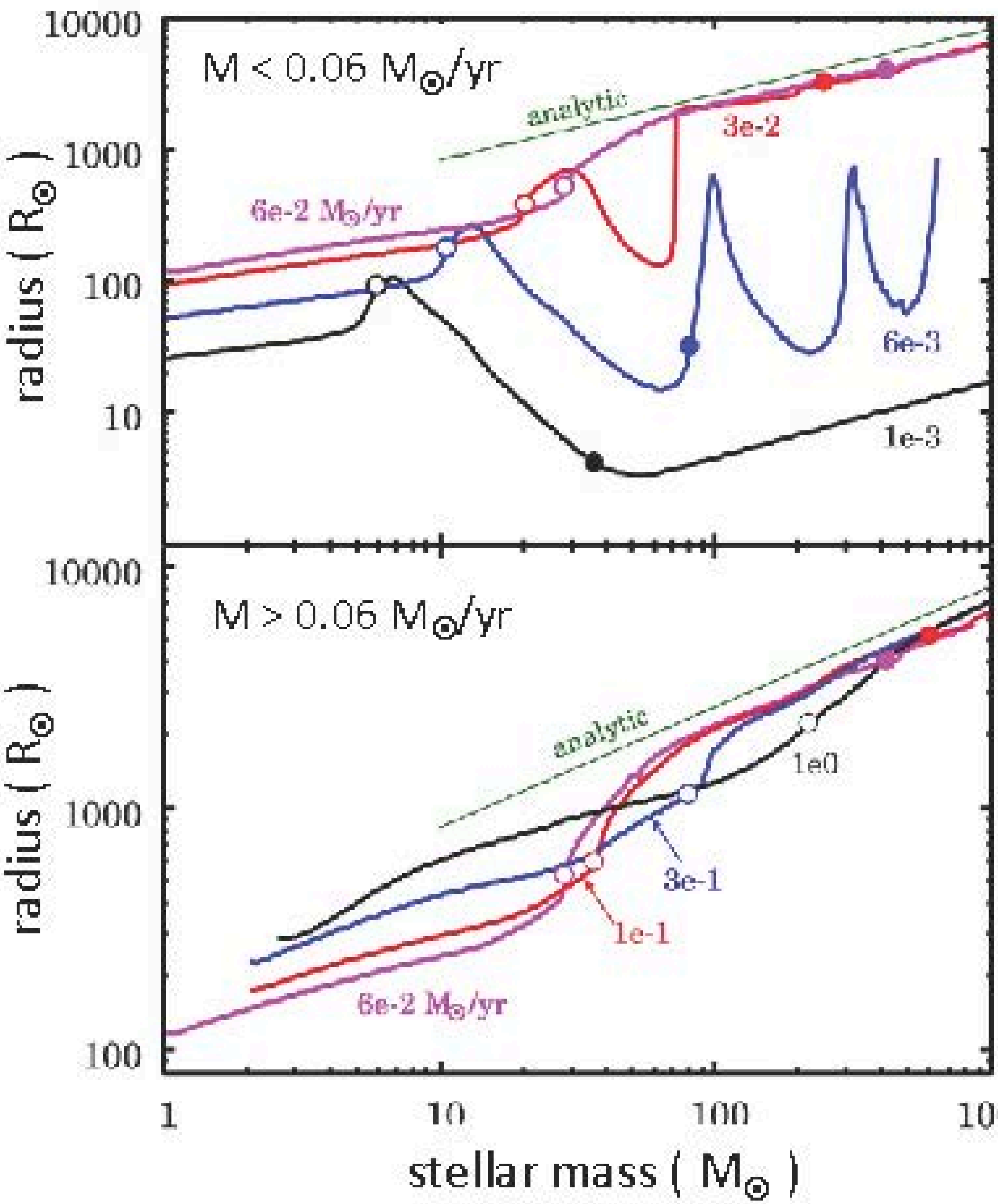


rather relevant to forming the supermassive stars

"supergiant protostar" stage with the rapid mass accretion of > 0.01 M$_\odot$/yr

mass-radius relation: $R_* \propto M_*^{0.5}$, which is independent of different mass accretion rates

Physics



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

+

stellar luminosity: L_*

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

+

nearly constant effective temperature

$T_{\rm eff} \sim 5000$K

(strong T-dependence of H- opacity)

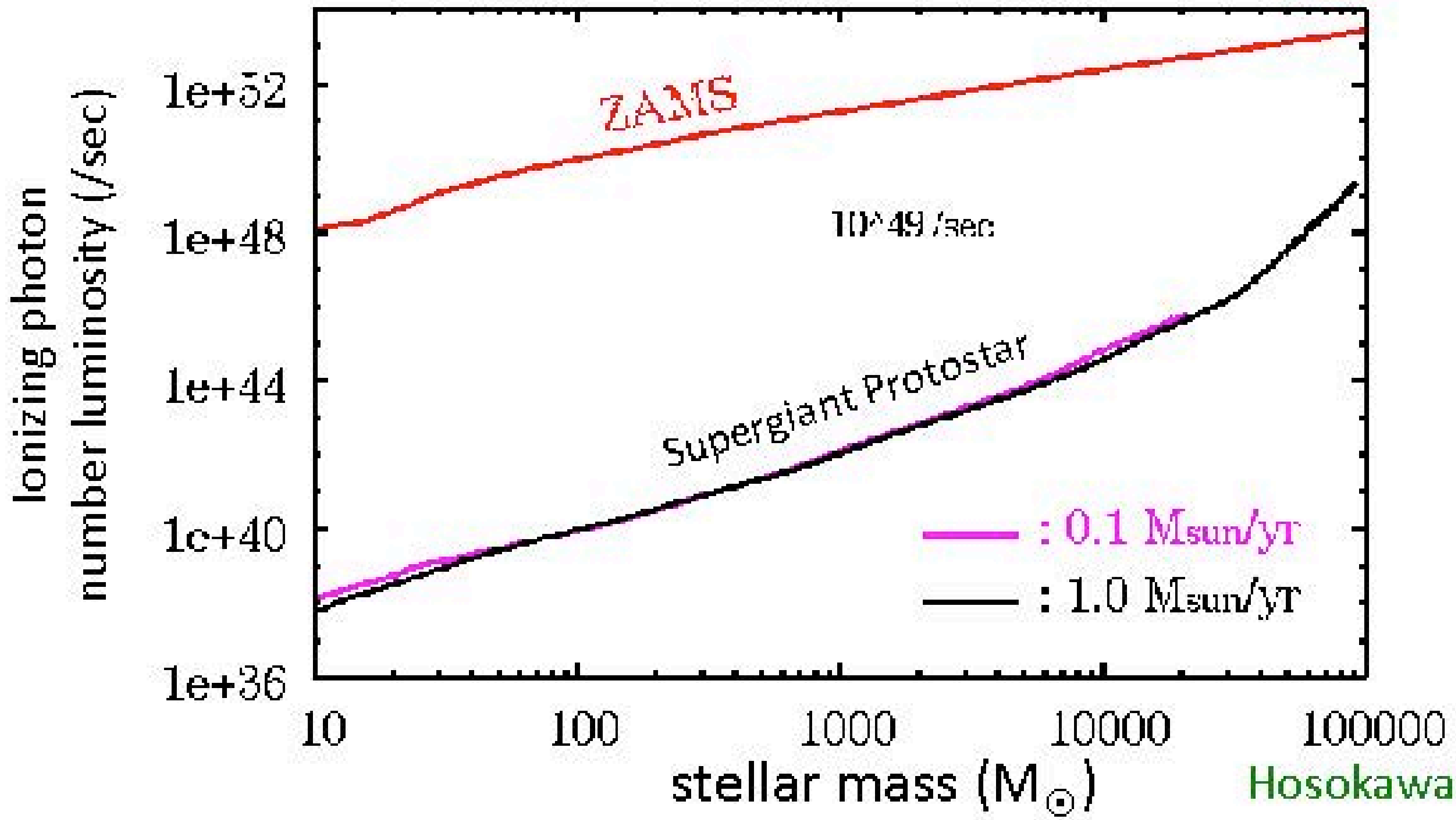
(ref. Hayashi track)

↓

$$R_* \simeq 2.6 \times 10^3 R_\odot \left(\frac{M_*}{100\ M_\odot} \right)^{1/2}$$

good agreement with the numerical results

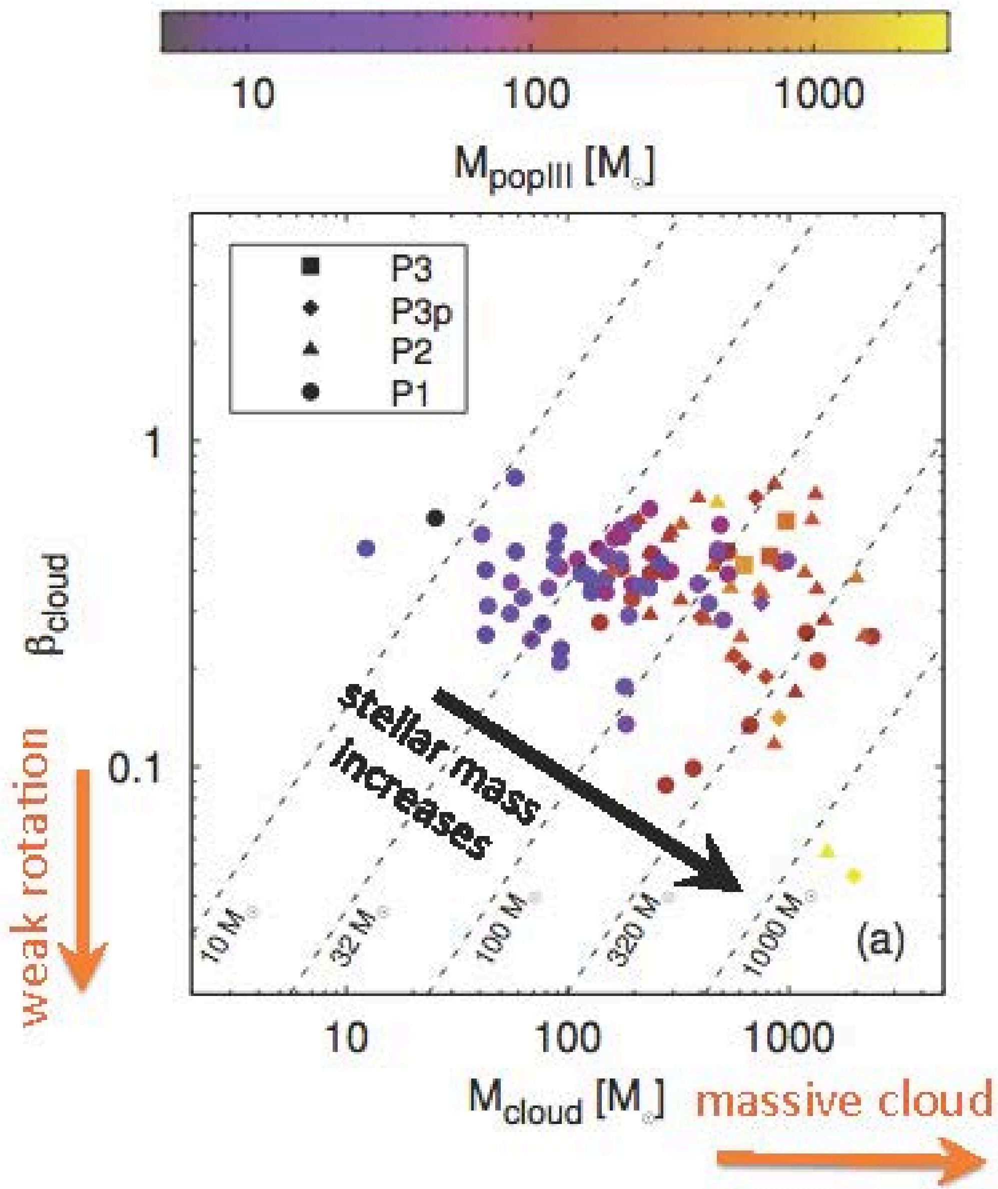
NO UV feedback



Hosokawa et al. 2013

- low effective temperature of < 10^4K → low UV luminosity
- UV radiative feedback would not disturb the formation of supermassive stars

What controls $\dot{M}$?: cloud mass & spin



- Weaker rotation
- More massive gas cloud

↓

More rapid mass accretion

↓

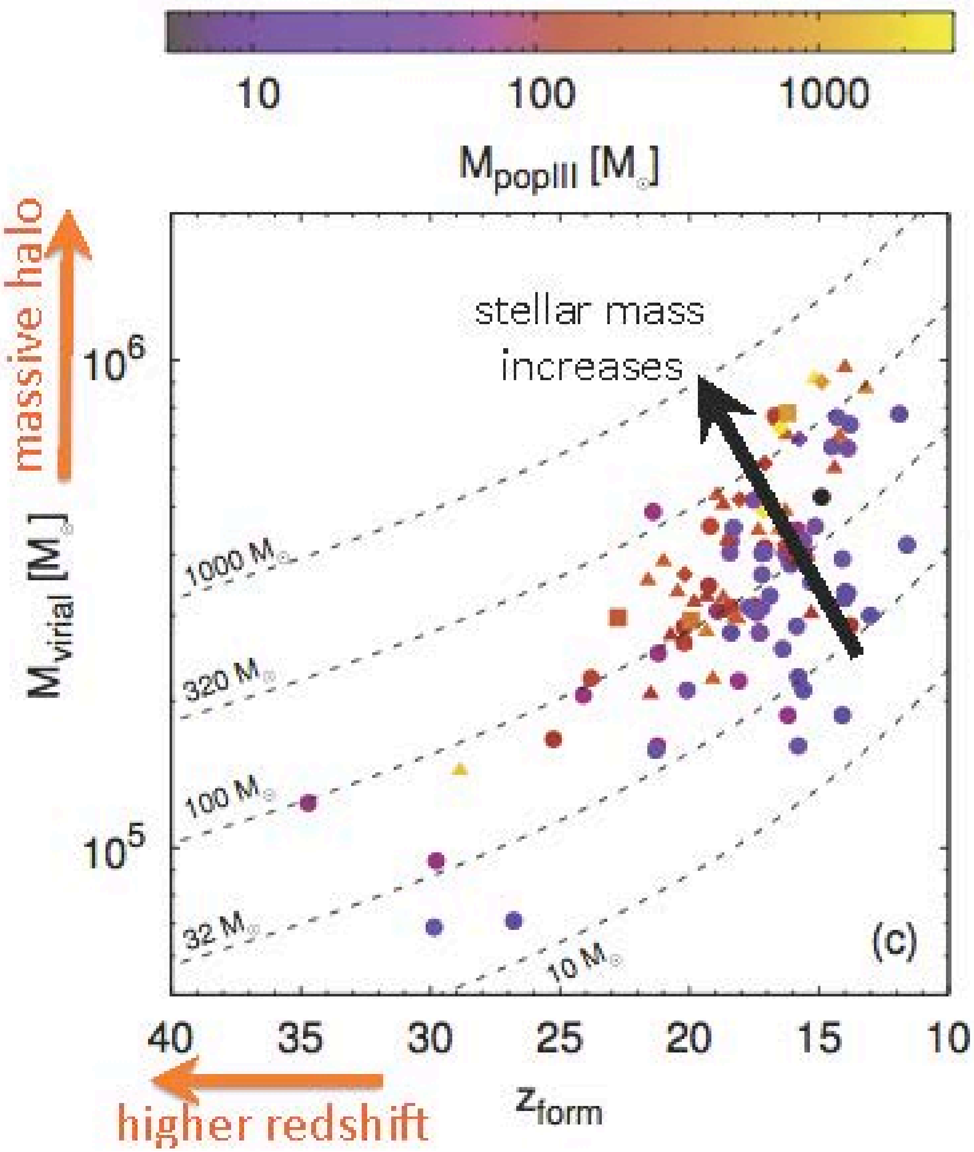
Higher stellar mass

Diversity of the stellar masses comes from that of the gas clouds.

Diversity of the gas clouds comes from... what?

Diversity from Cosmology

(large-scale structure formation)



Stellar mass (weekly) depends on the properties of dark halos.

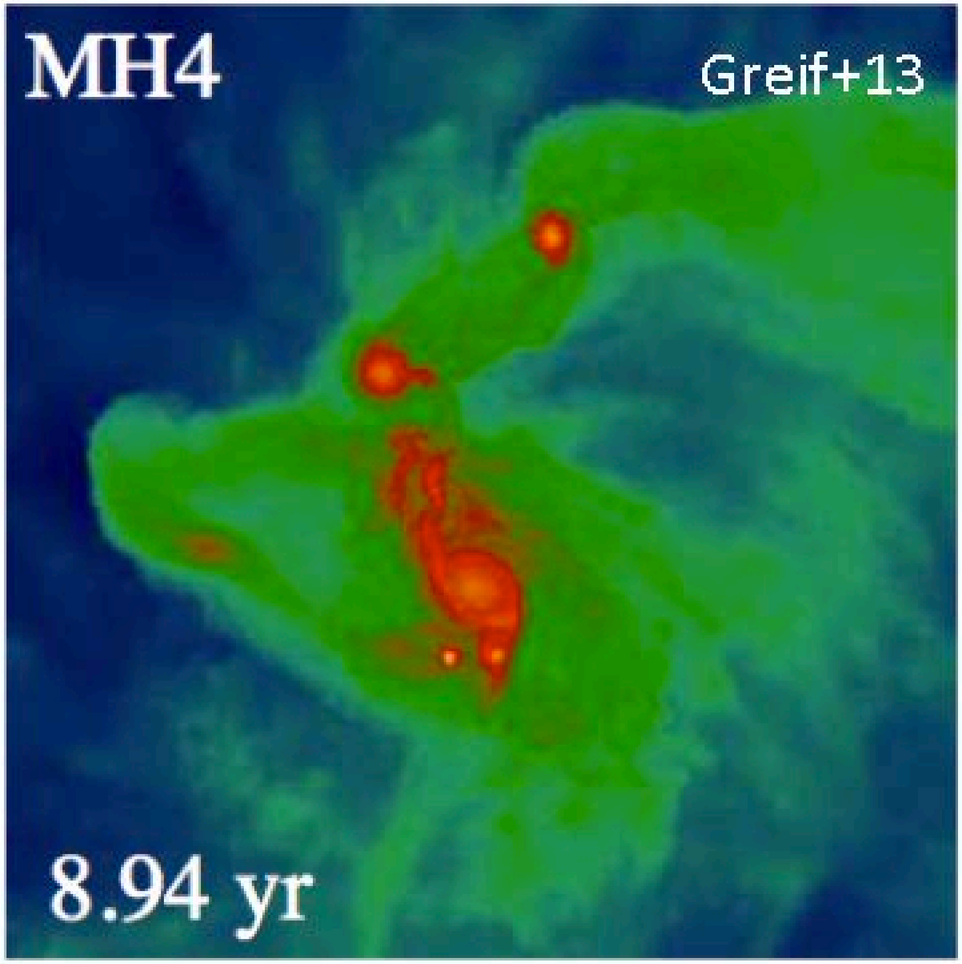
- higher redshift
- more massive dark halo

↓

higher stellar mass

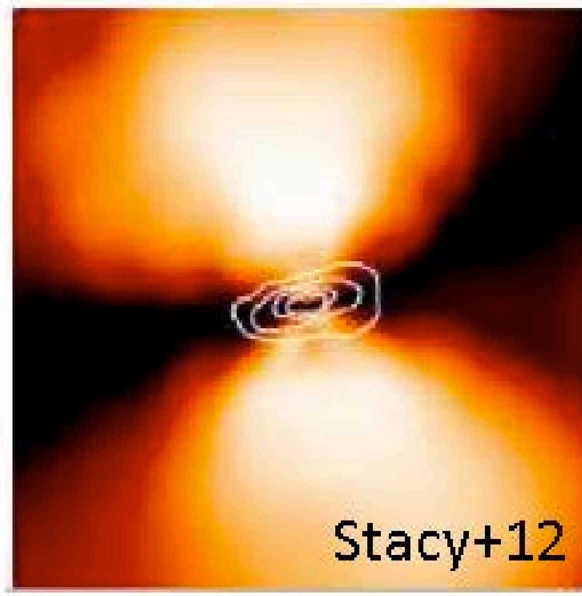
Cosmology sets the different conditions for forming the primordial gas clouds.

Fragmentation Matters?

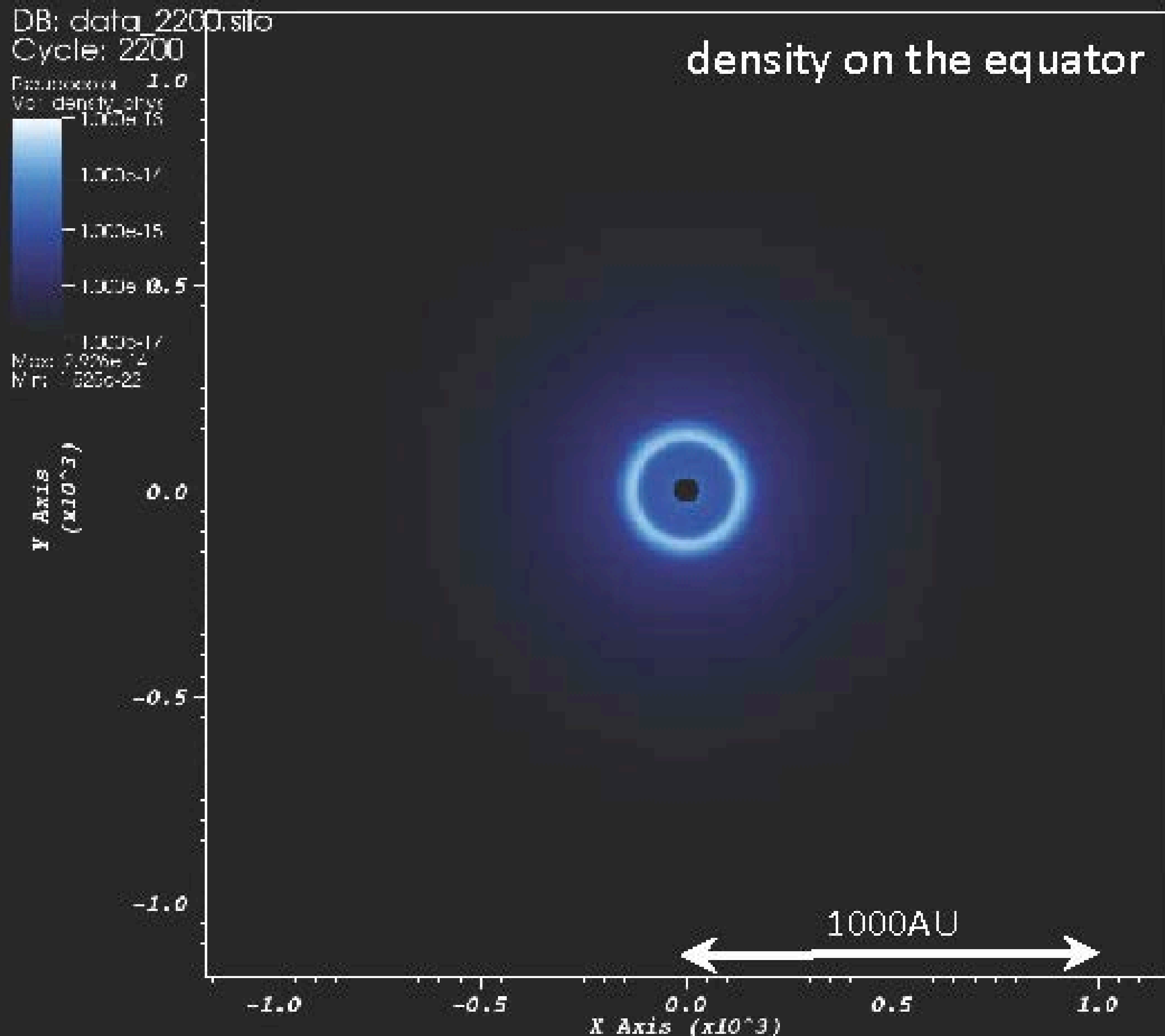


3D simulations show the disk fragmentation

final stellar mass reduced or increased?

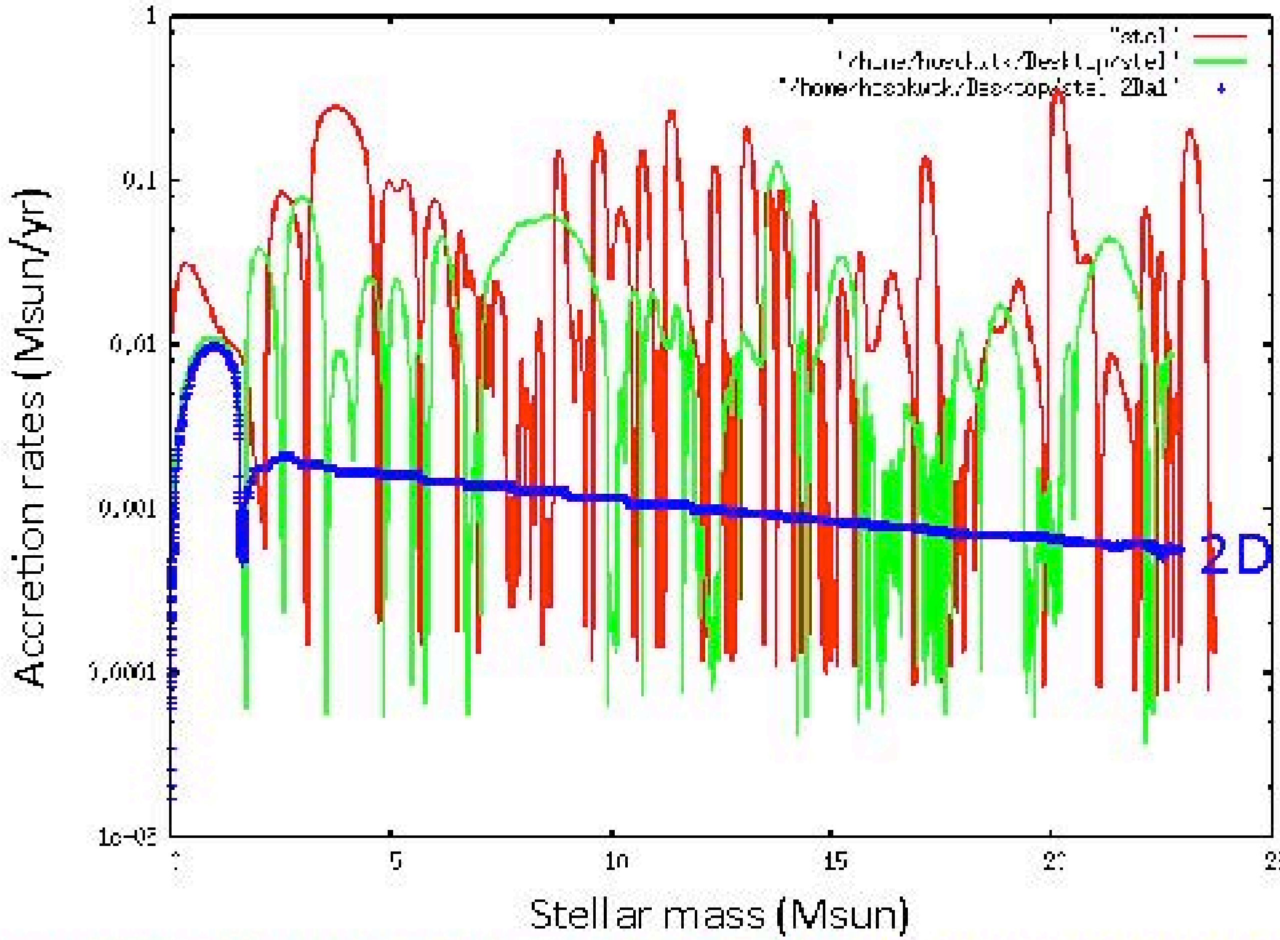


Stacy+12, Susa 13 show the stellar UV feedback should operate in 3D as well.



3D test case (TH in prep.)

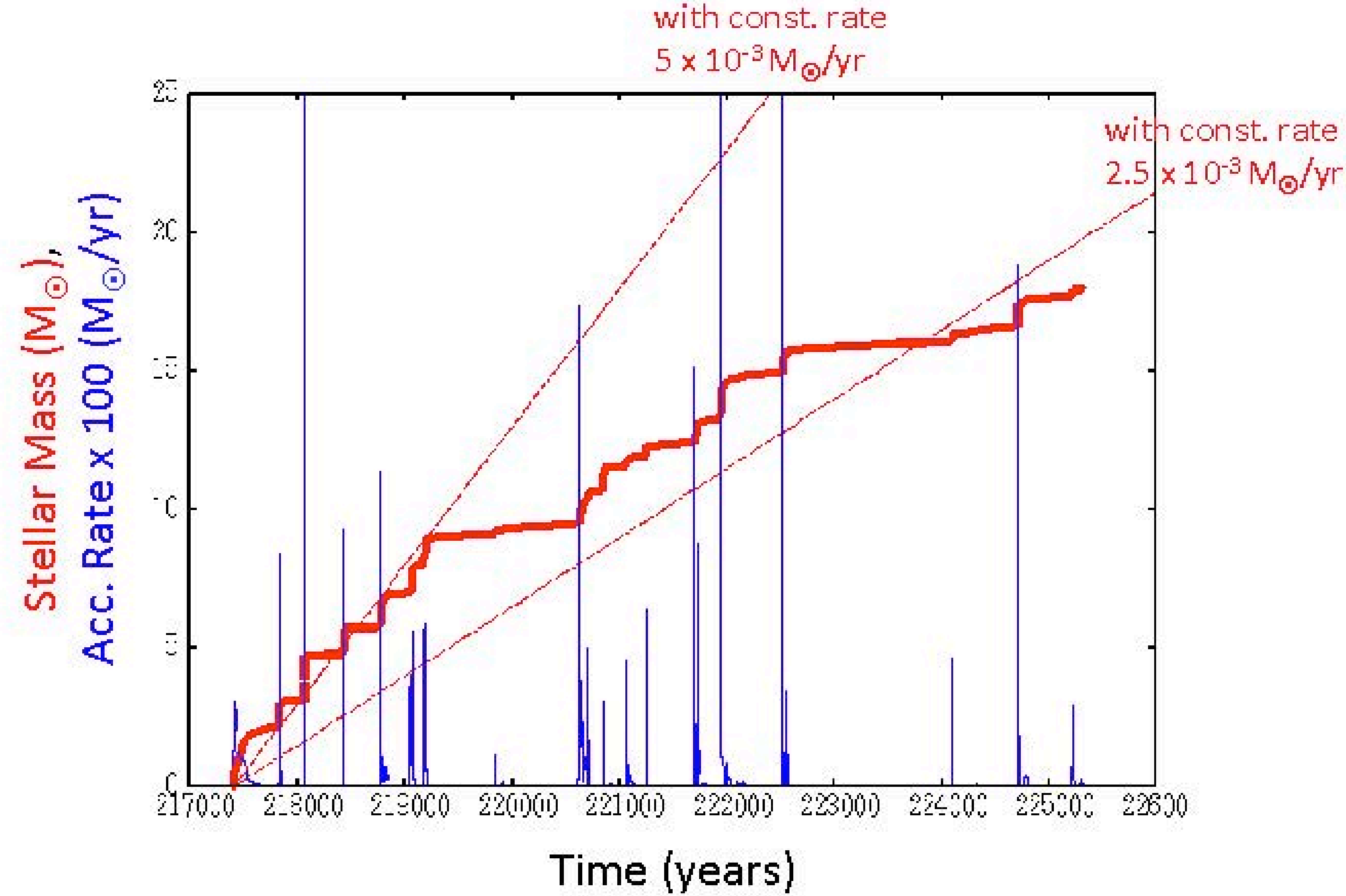
Accretion History



red: current case, green: lower res. (1/2 grids), blue: 2D with α=1 (lower res.)

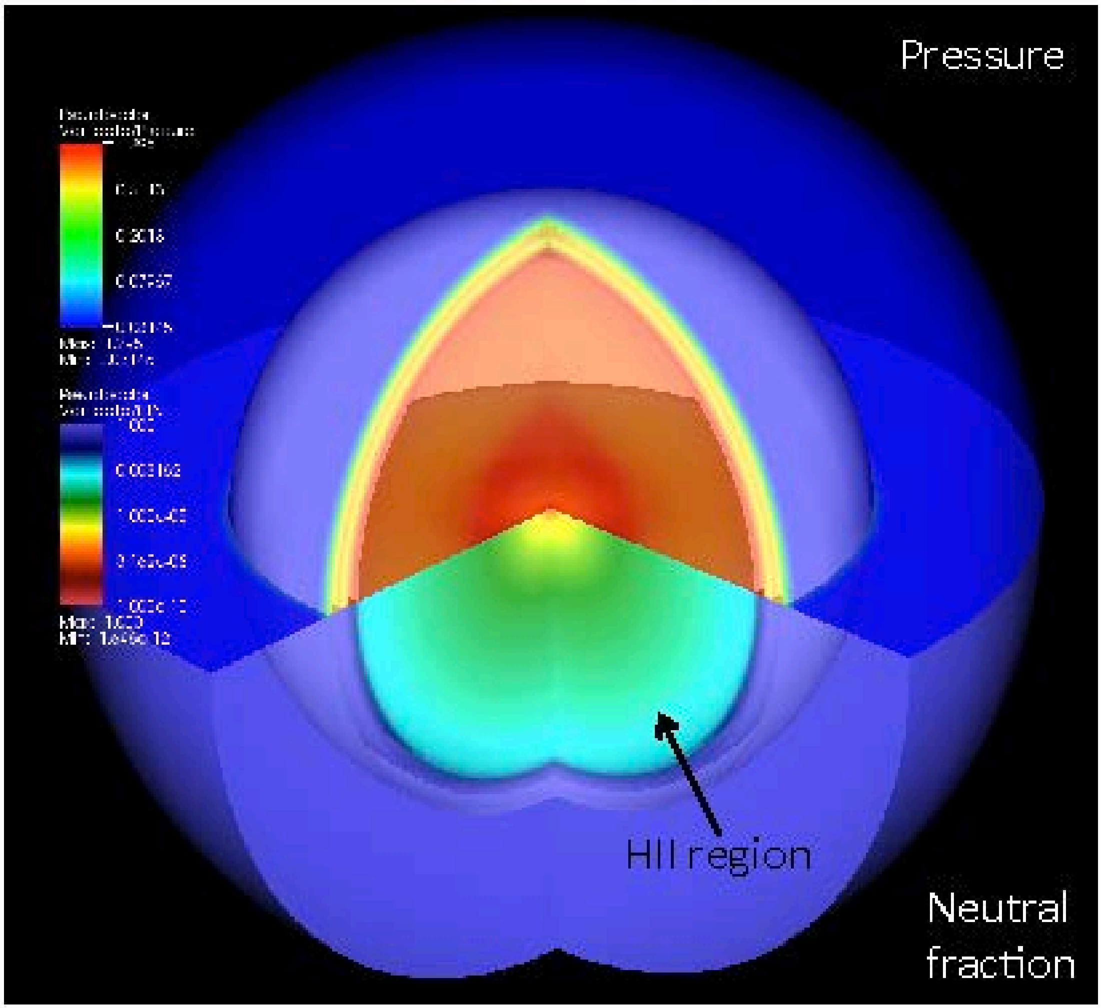
More fragmentation with the higher resolution
All of the fragments are falling into the central sink cell.

Mass Growth History



UV Feedback in progress

TEST: spherical expansion of an HII region in 3D



EUV/FUV transfer is being implemented.

Summary

How massive were the first stars?

+ Lots of "ordinary" massive stars, which are $M_* < 100\ M_\odot$ but still with a number of $M_* > 100 M_\odot$ stars
+ Rapid mass accretion changes the protostellar evolution, which is helpful for forming very massive stars.

Future Work

+ 3D effects (e.g., disk fragmentation) reduce or increase the final mass?
+ interaction between the fragmentation and UV feedback: in progress, and stay tuned for updates!

Additional pages

Approach

Radiation-hydro (2D axisymmetric) + stellar evolution

- **Hydro + self-gravity**

  nested grid technique (e.g., Yorke & Bodenheimer 98)

- **Chemistry**

  simplified network (15 reactions) with H, H+, H2, e, H-

- **Radiation transfer**

radiative cooling
- continuum cooling (via H^- free-bound opacity) **FLD**
- H2 line cooling (with trapping effect) **Sobolev approx.**

Yoshida et al. 06

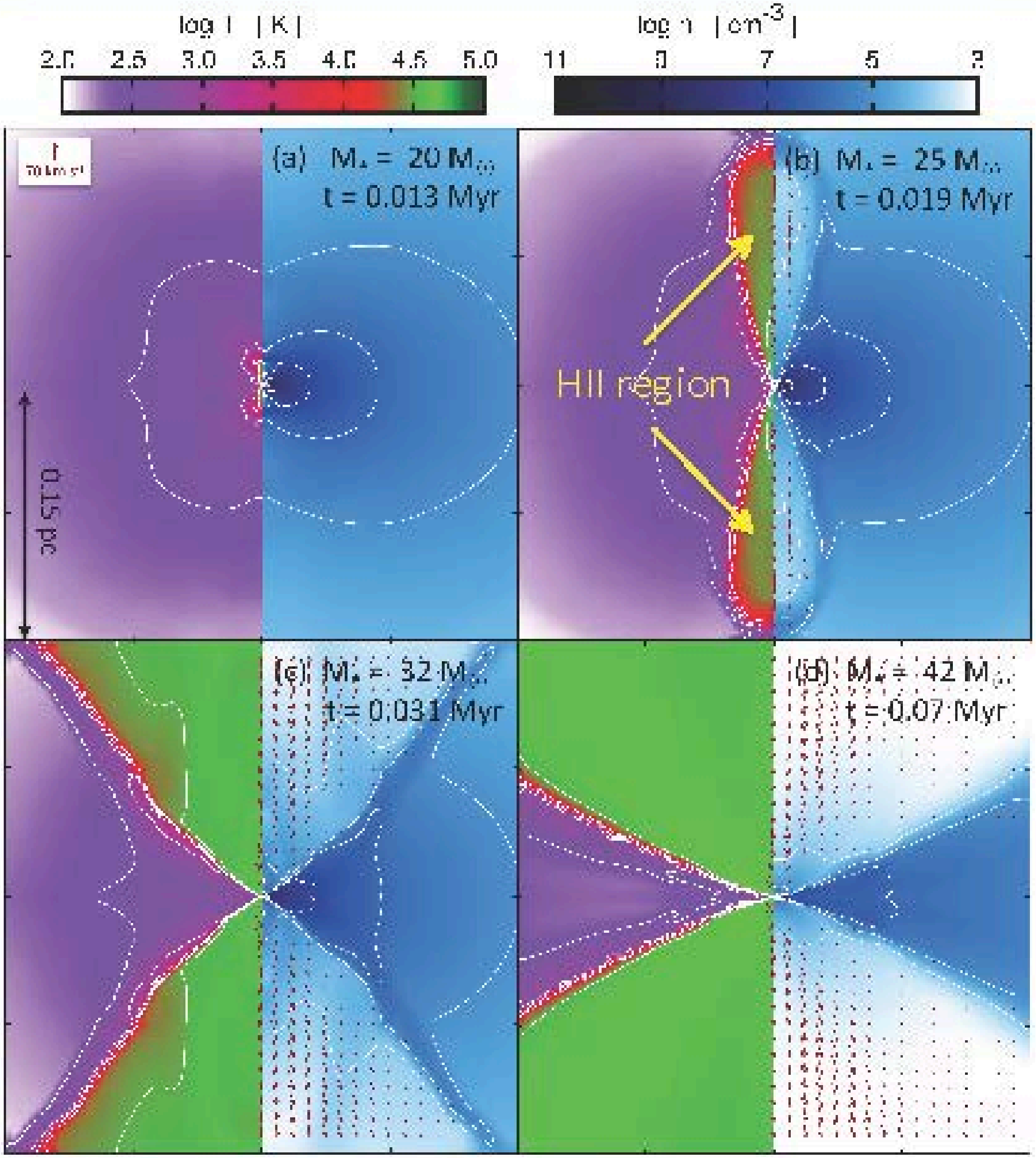
stellar feedback
- photoionization ($H+\gamma \rightarrow H^+ + e$) **ray-tracing + FLD**
- photodissociation ($H_2+\gamma \rightarrow 2H$)

Yorke & Welz 96
TH & Inutsuka 06

- **Protostellar Evolution** numerically solving the interior structure

TH & Omukai 09

What's going on?



Breakout of the HII region toward polar directions

↓

Dynamical expansion of the HII region through the accretion envelope

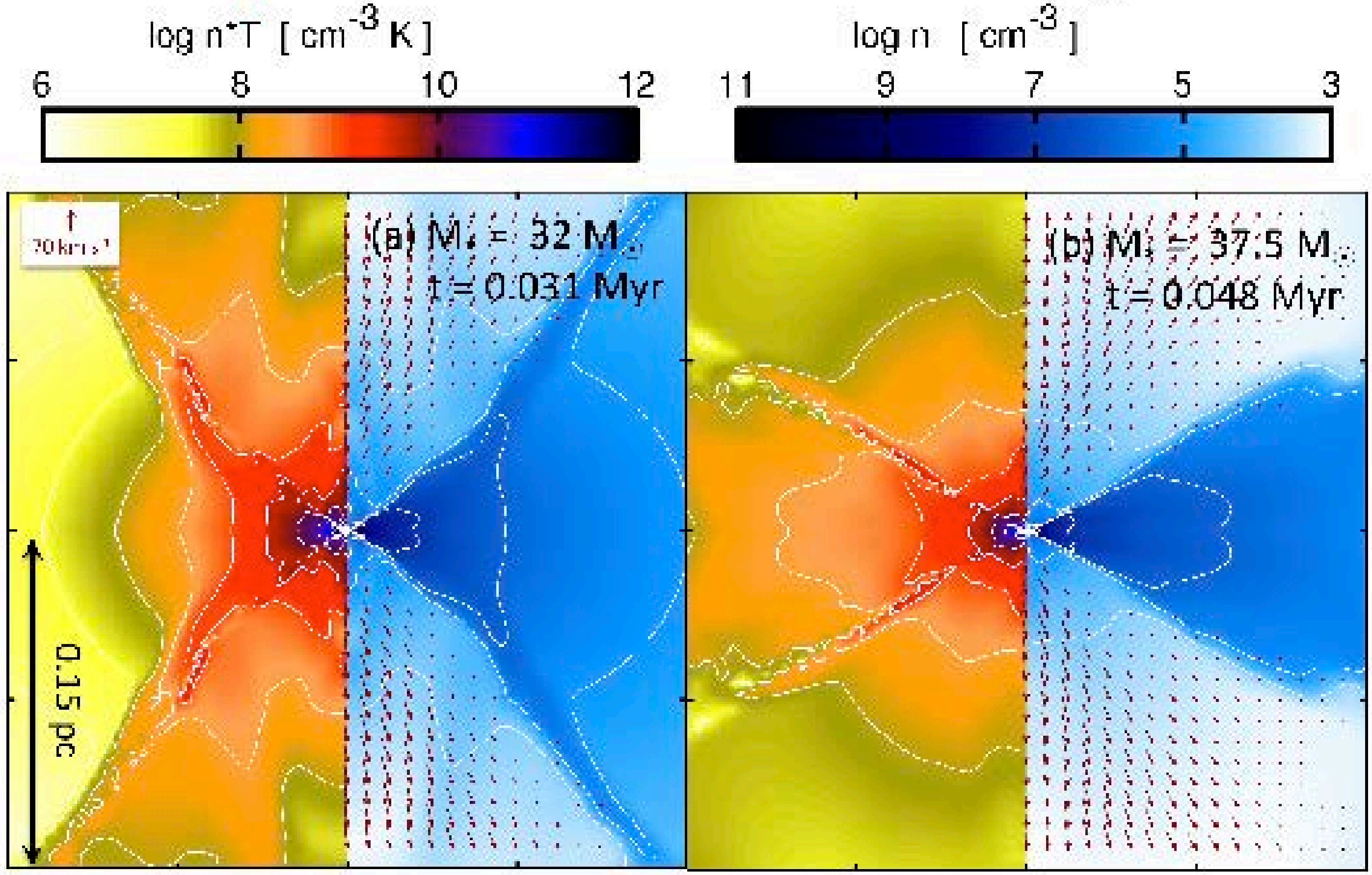
↓

Photoevaporation of the disk

Why not in the present-day high-mass star formation?

Why mass accretion ceases

Gas pressure excess within the HII region



outward pressure gradient within the HII region (due to the evaporating flow)

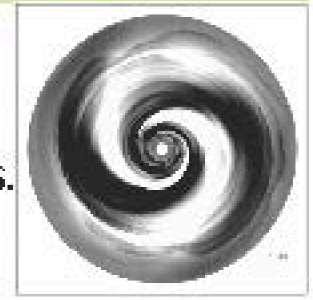
→ the same pressure gradient forms even behind the disk

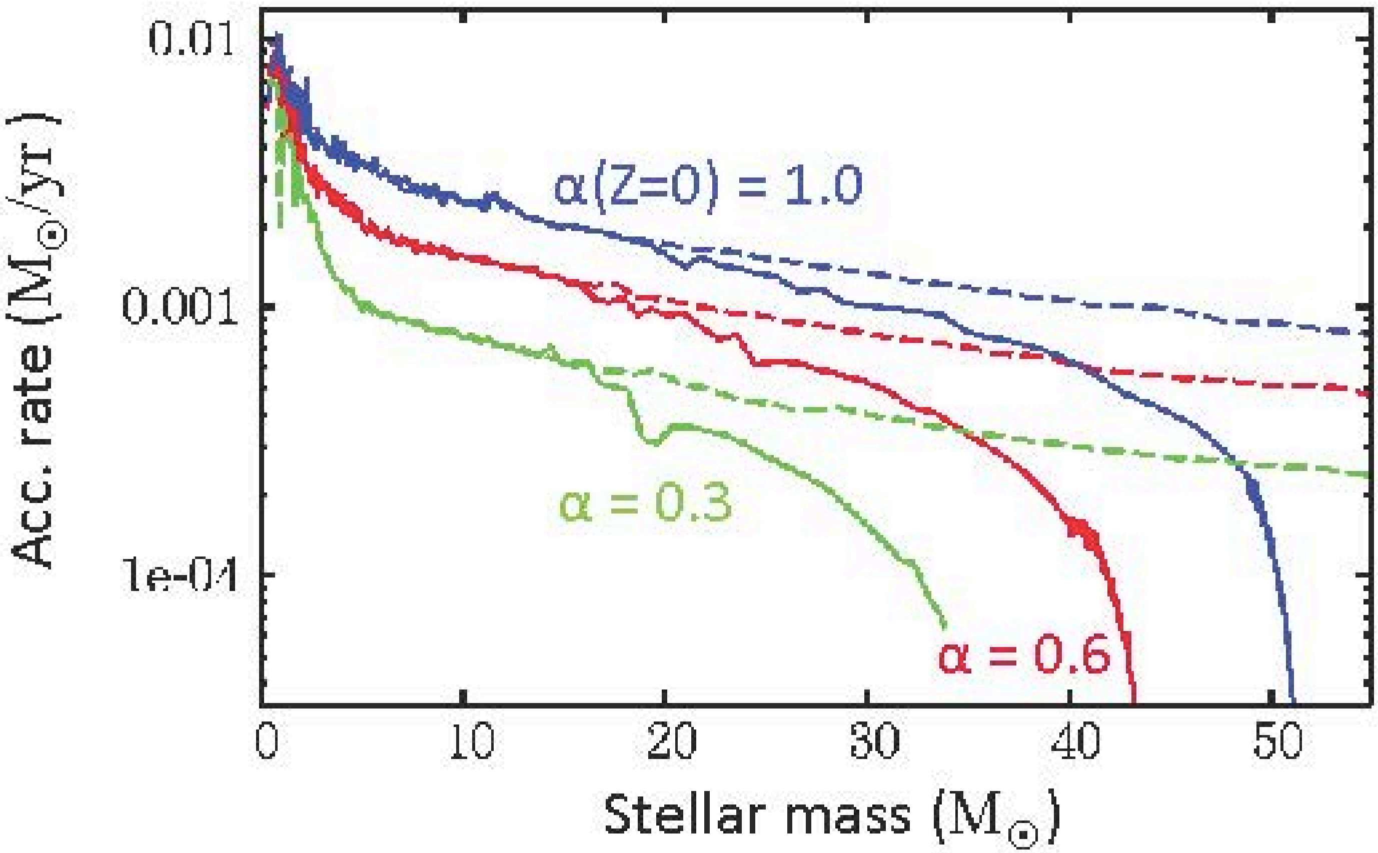
→ shutting off the gas supply from the envelope to the disk

→ photoevaporation of the isolated disk

α-parameter dependence

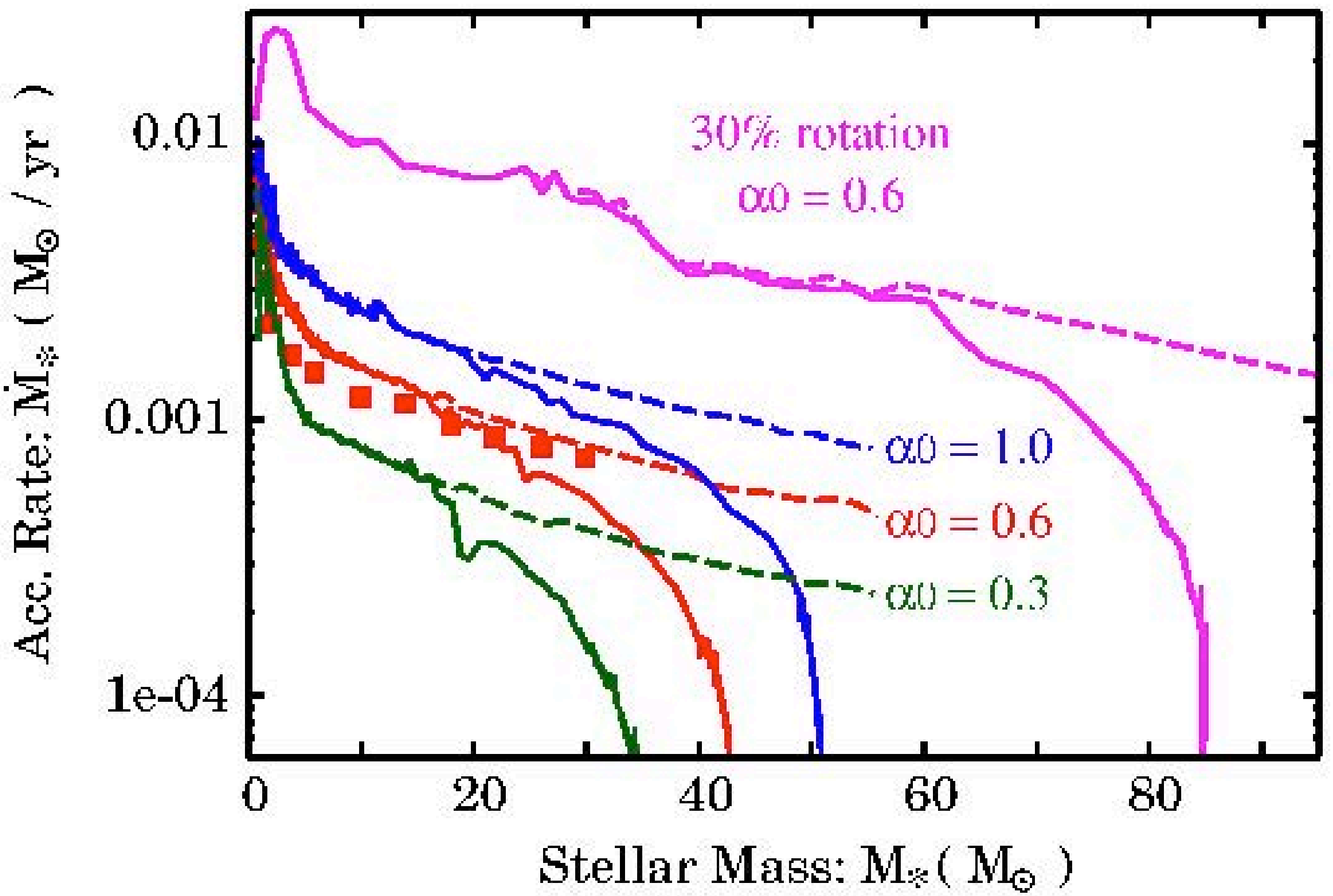
In reality, angular momentum transport would be due to the torque exerted by non-axisymmetric spiral arms.
In our 2D calculations, we employ the α-viscosity to mimic this.





higher α (or weaker initial rotation) → higher final stellar mass

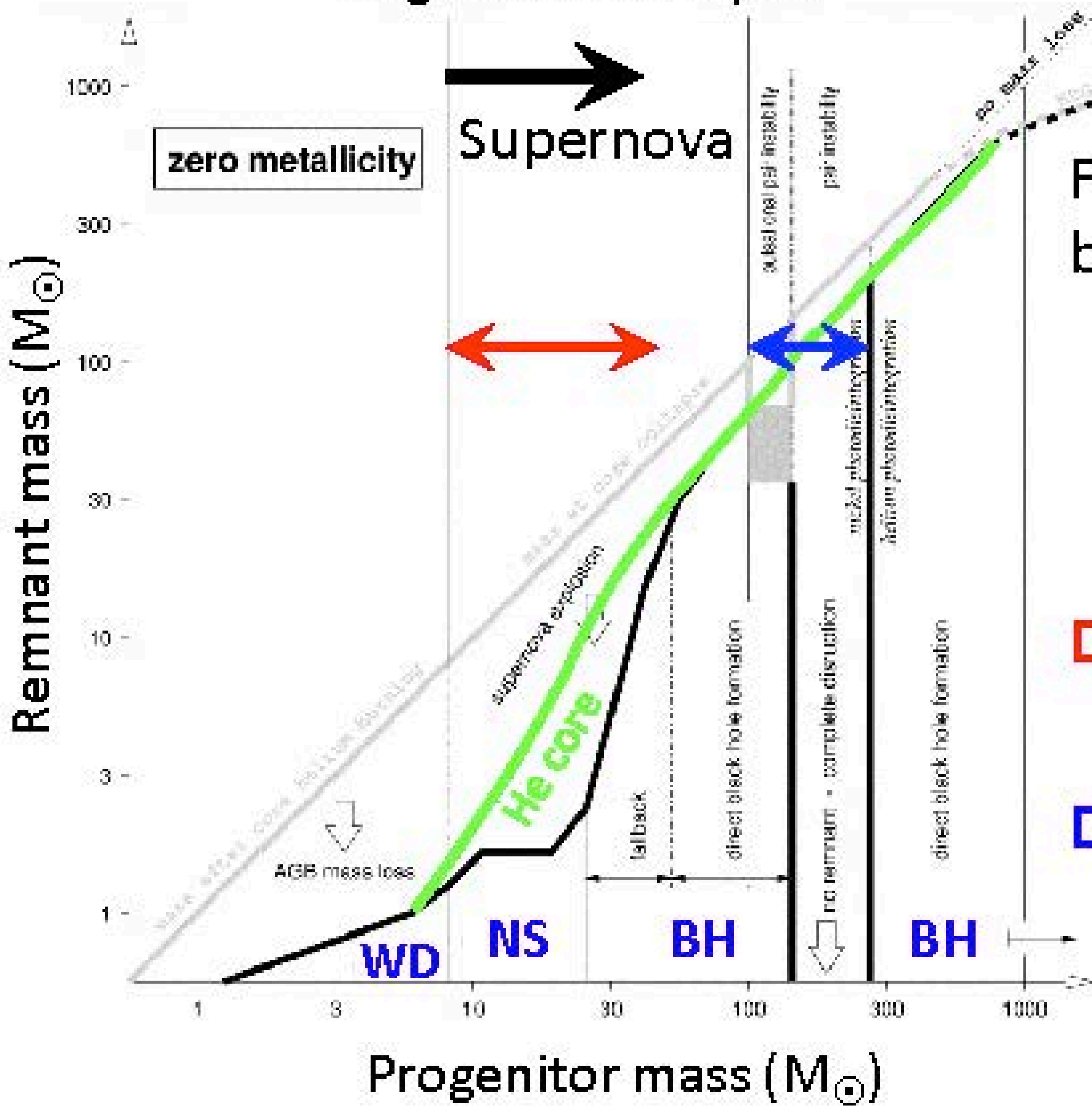
More Massive Stars?



Initial weak rotation of the gas cloud enables the formation of more massive stars

Stellar Mass and Fate

Heger & Woosley 02



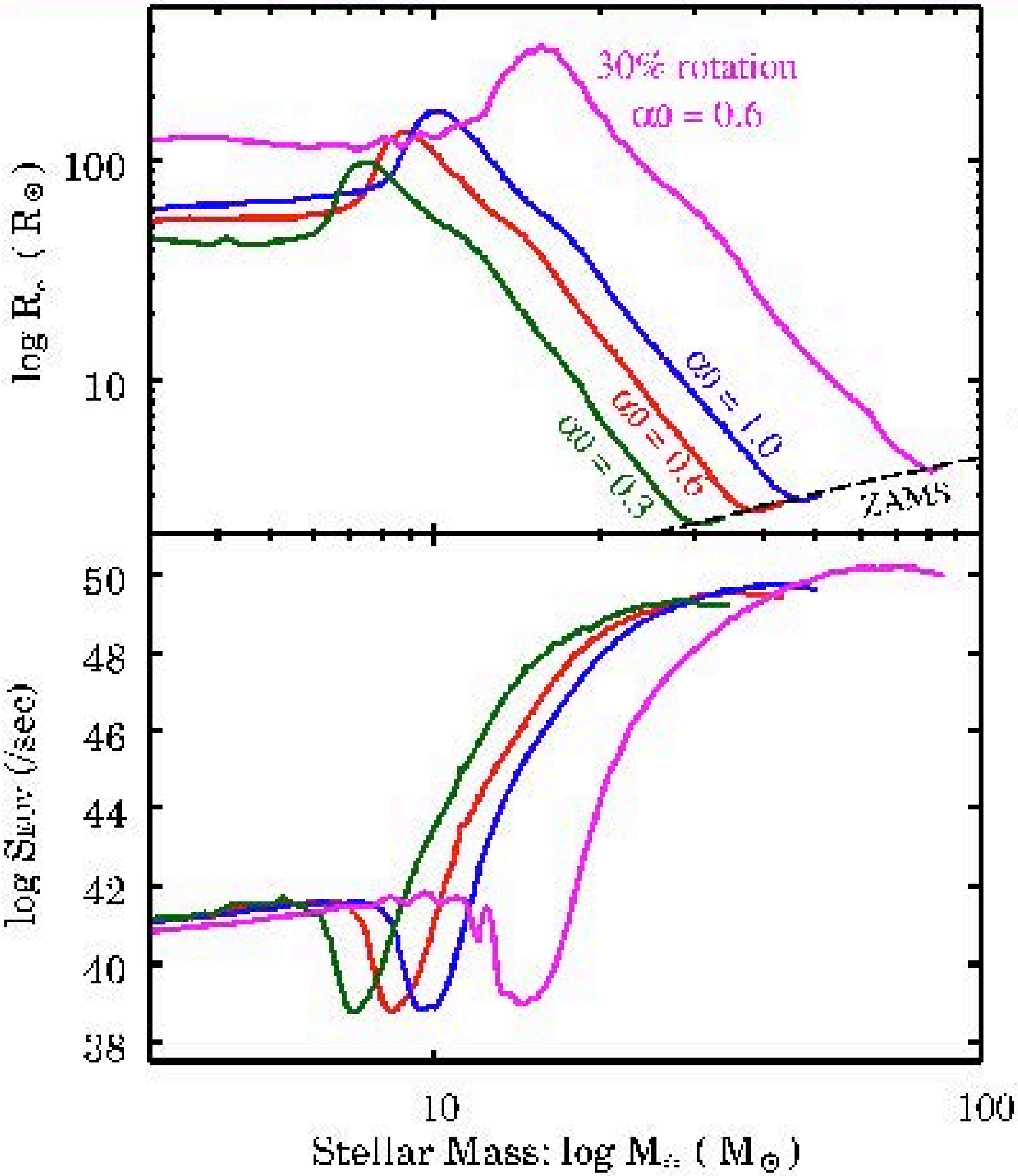
Fate of a star is determined by its mass.

Production of metals:
2 windows for generation

□ core collapse SN (CCSN):
$8M_\odot \leqq M_* \leqq 40M_\odot$

□ Pair instability SN (PISN):
$100M_\odot \leqq M_* \leqq 260M_\odot$

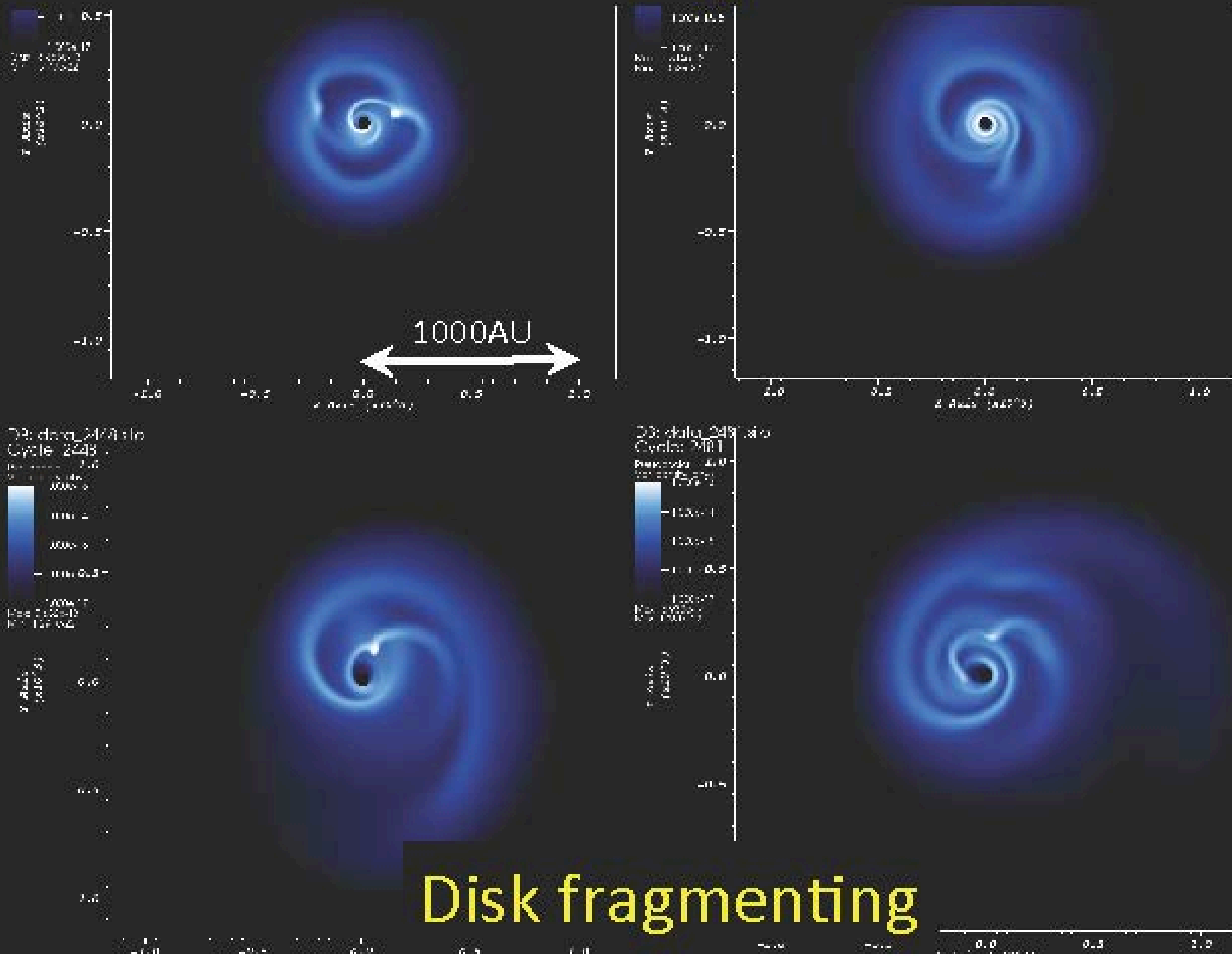
More Massive Stars?

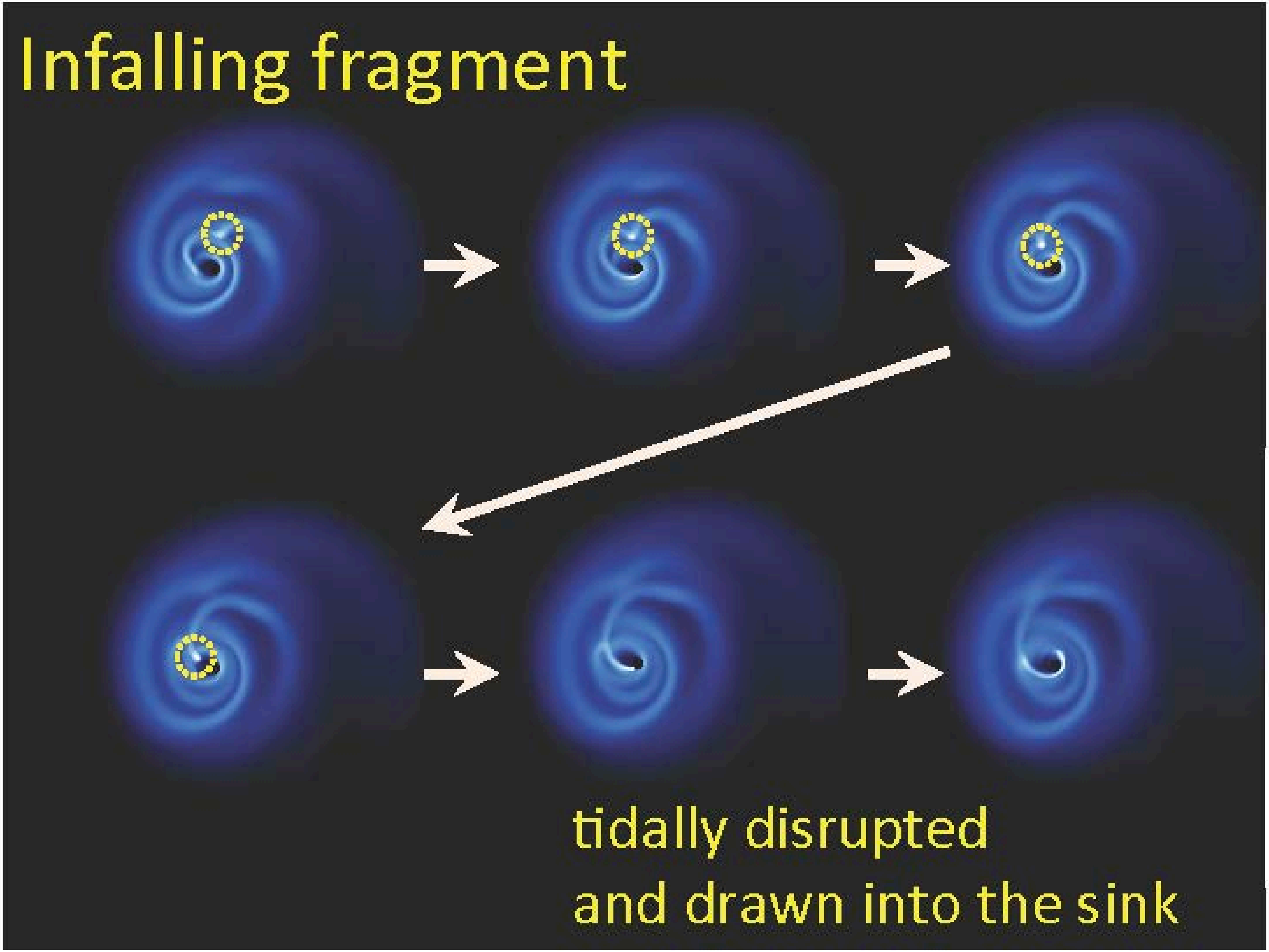


Stellar UV feedback operates after the late KH contraction stage.

In all the cases, the stellar final mass is fixed soon after the star arrives at the ZAMS stage

3D TEST: NR x Nθ x Nϕ = 128 x 32 x 128, feedback OFF
Core mass: ~$90M_{\odot}$, sink size: 30AU




Infalling fragment
tidally disrupted
and drawn into the sink

Temperature & H2