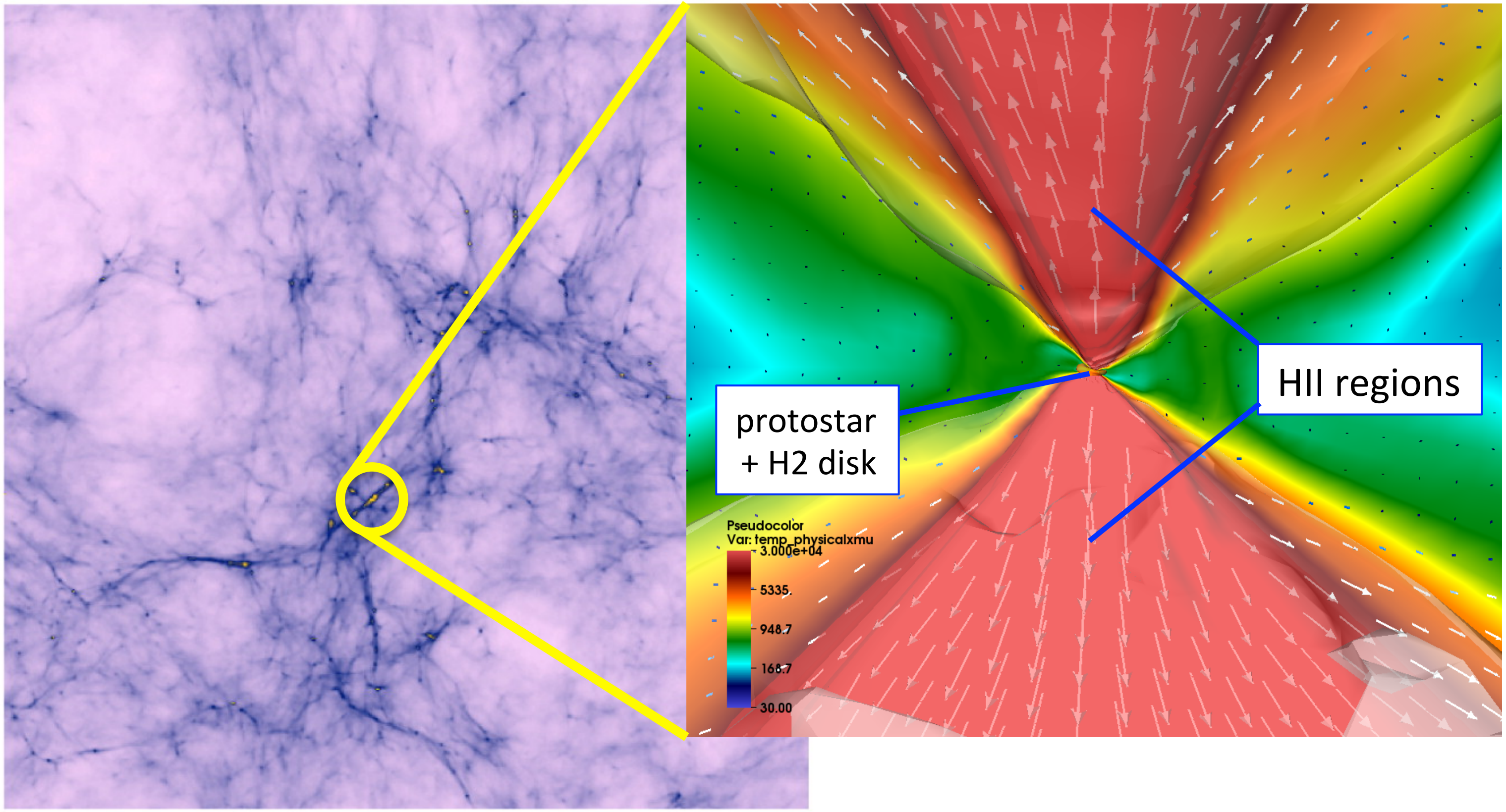
The First Stars (and SMBHs)



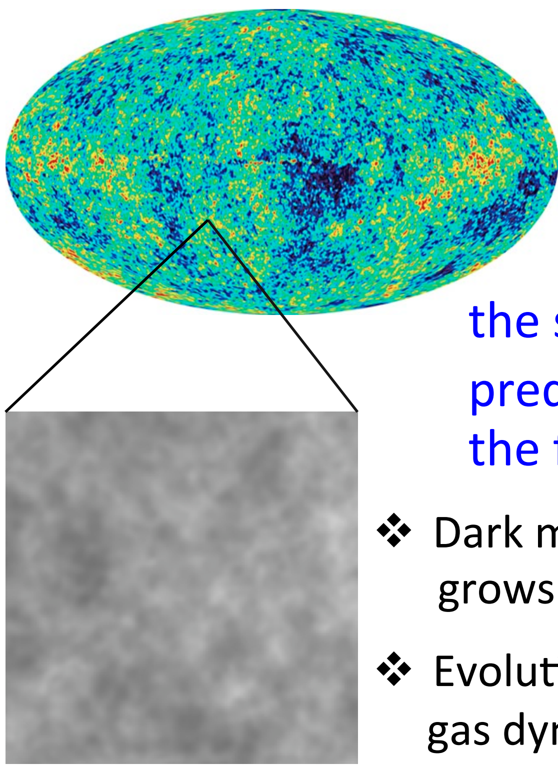
Takashi Hosokawa (Univ. of Tokyo)

15.Sep.2014 EANAM6 @Suwon

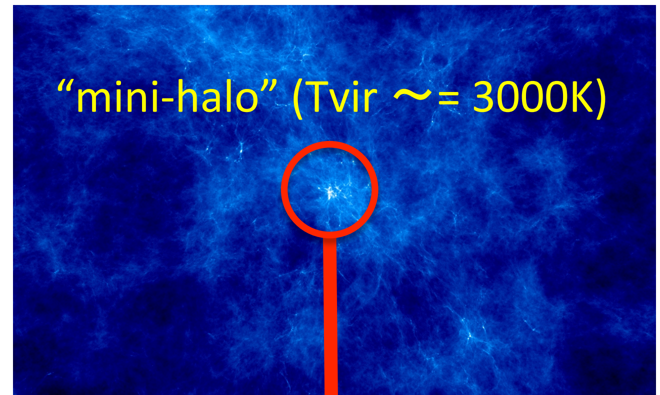
The First Star Formation

Form stars with the fixed initial conditions (well-defined problem!)

CMB → density fluctuation
in the early universe



Birth place of the first star



the standard cosmology
predicts when and where
the first stars should form

star formation
process

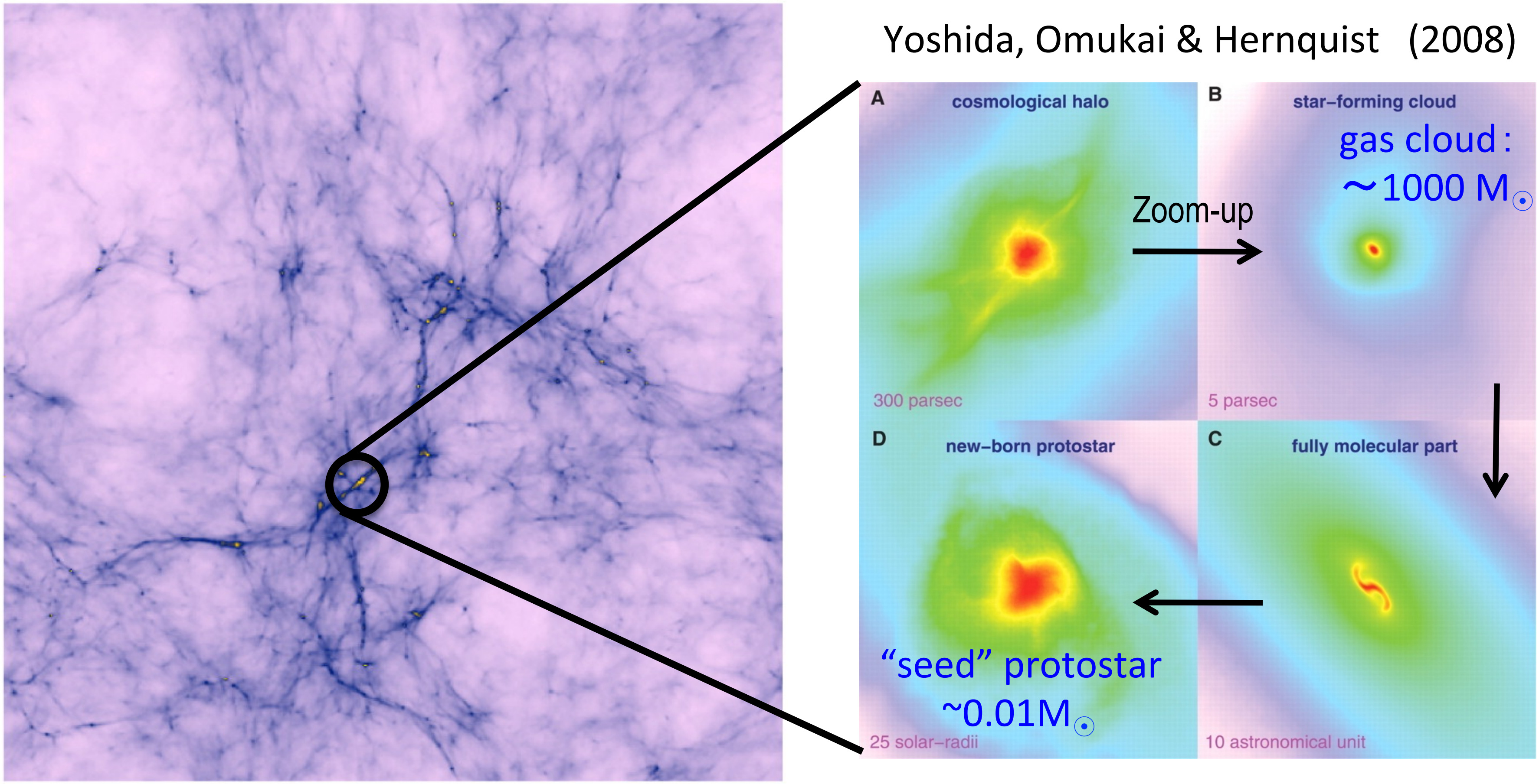
- ❖ Dark matter large-scale structure grows by gravitational instability.
- ❖ Evolution of baryons:
  gas dynamics, chemistry,
  radiative processes…

The first stars

Just Do it with Computers

Cosmological simulations show that the first star forms in less than 1 billion year after the Big-Bang, as a result of the large-scale structure formation.

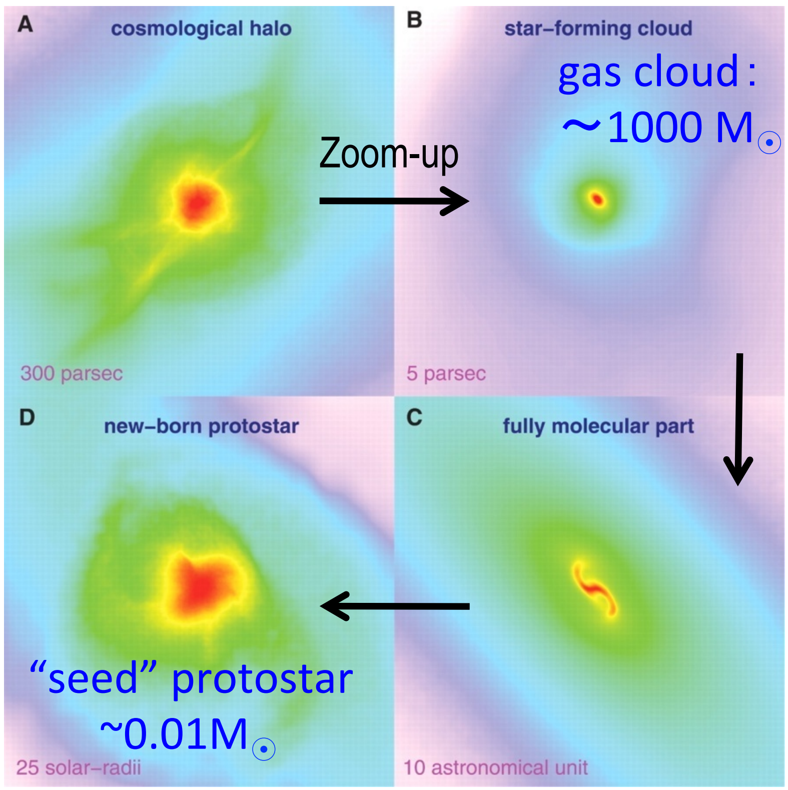
Yoshida, Omukai & Hernquist (2008)

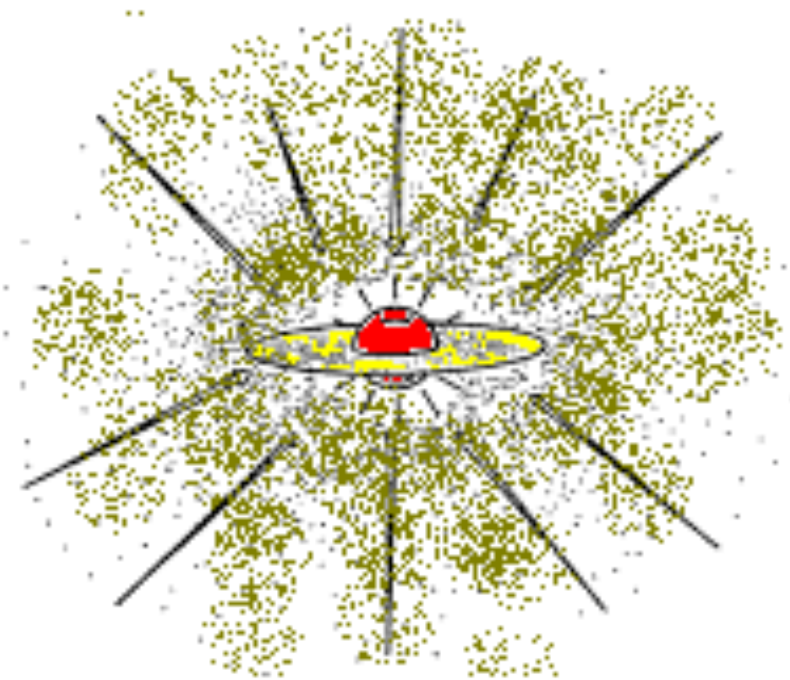


This is just beginning...

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.

Key Questions

What is the typical mass of the first stars,
resulting from the evolution in the accretion phase?
How massive are they? What is their mass distribution?

Study what happens in the accretion phase
to answer these questions.

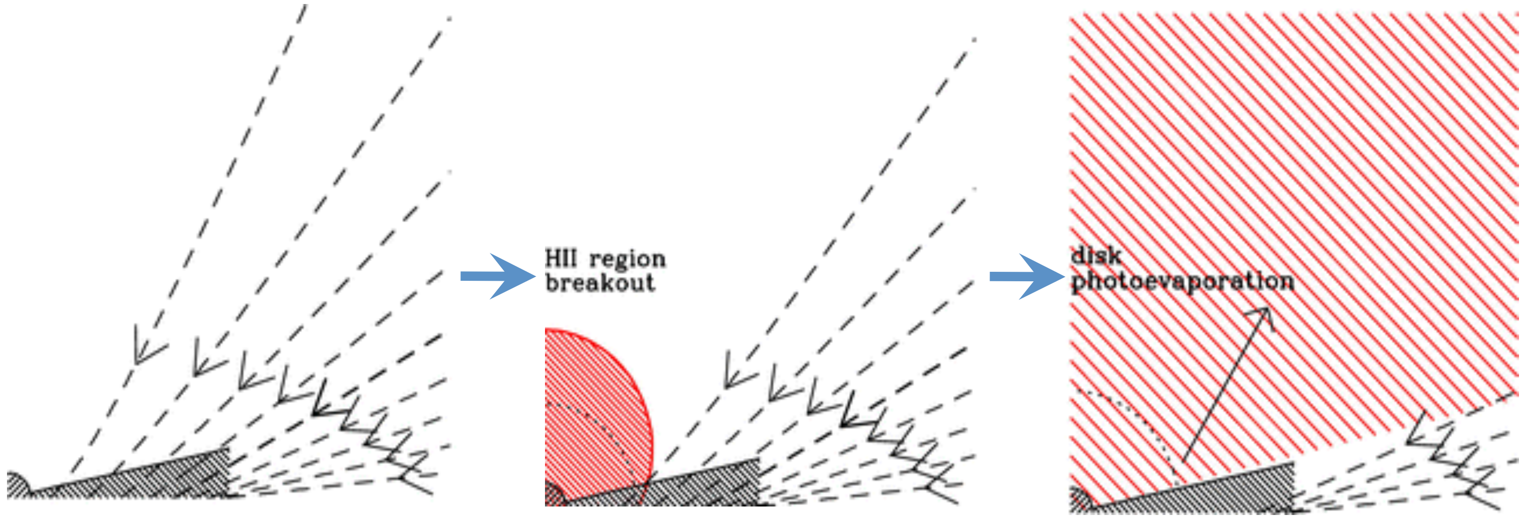
Evolution in Accretion Phase

Expected acc. rate : $\dot{M} \sim \frac{M_J}{t_{ff}} = \frac{c_s^3}{G} \sim 7 \times 10^{-4} M_\odot/\mathrm{yr} \left(\frac{T}{300\ \mathrm{K}} \right)^{3/2}$

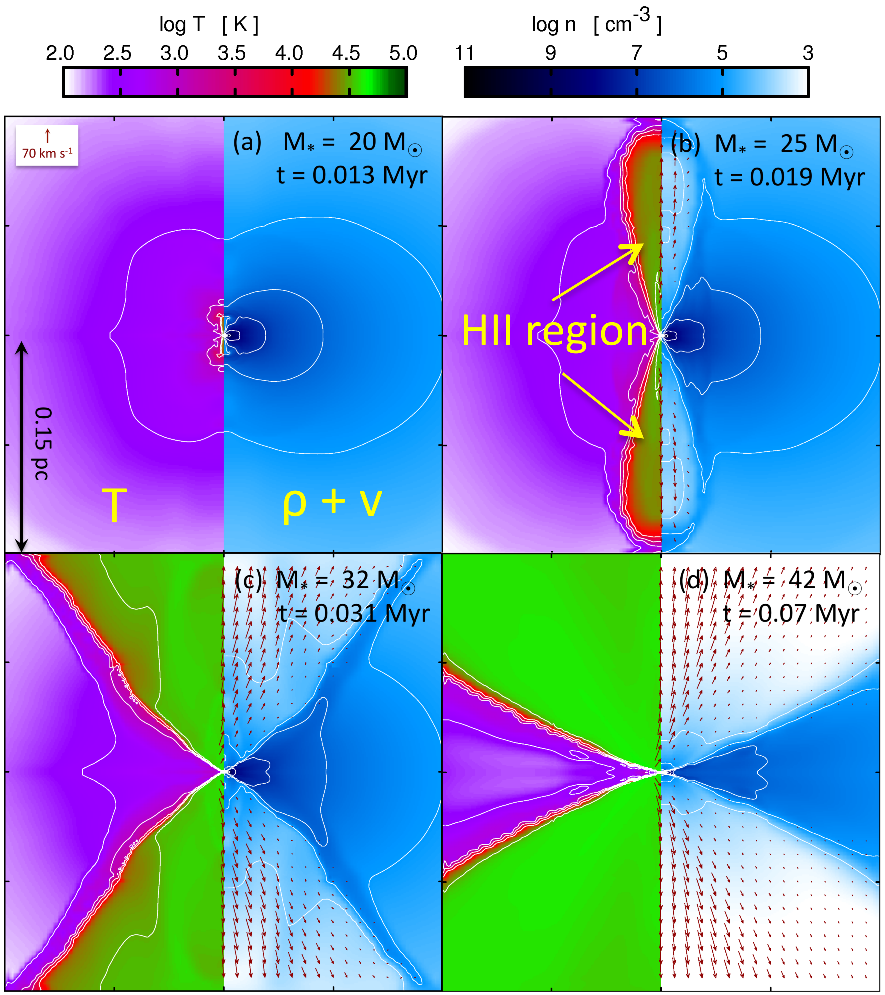
With this rapid mass accretion, the entire cloud could accrete onto the star in its lifetime (~Myr) ⇒ **$M_* \sim 1000 M_\odot$**

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

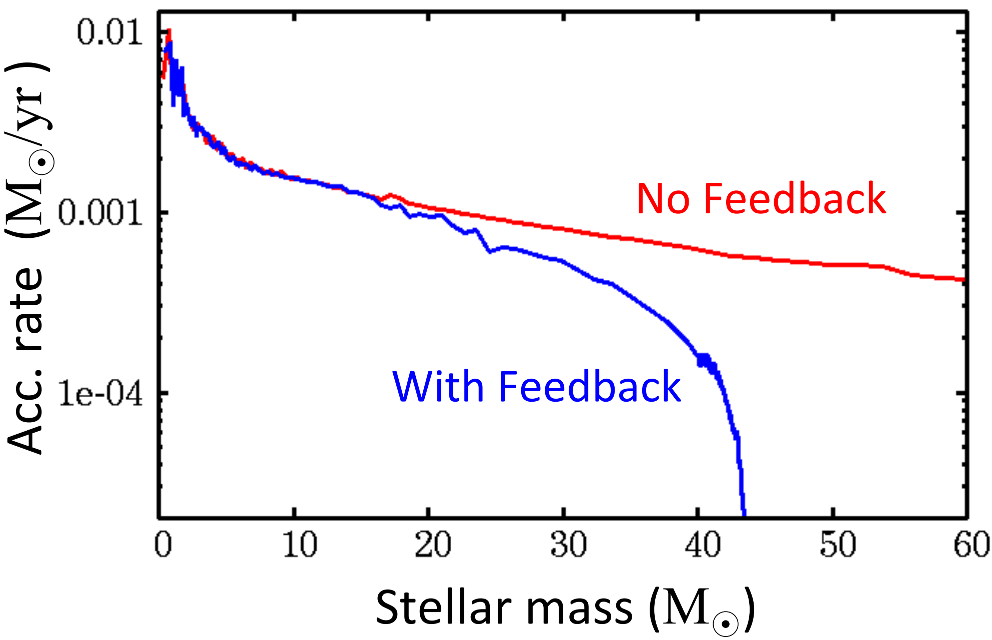
Formation of an HII region + photoevaporation of the disk → **$M_* \sim 150 M_\odot$?**



Direct Simulation in 2D



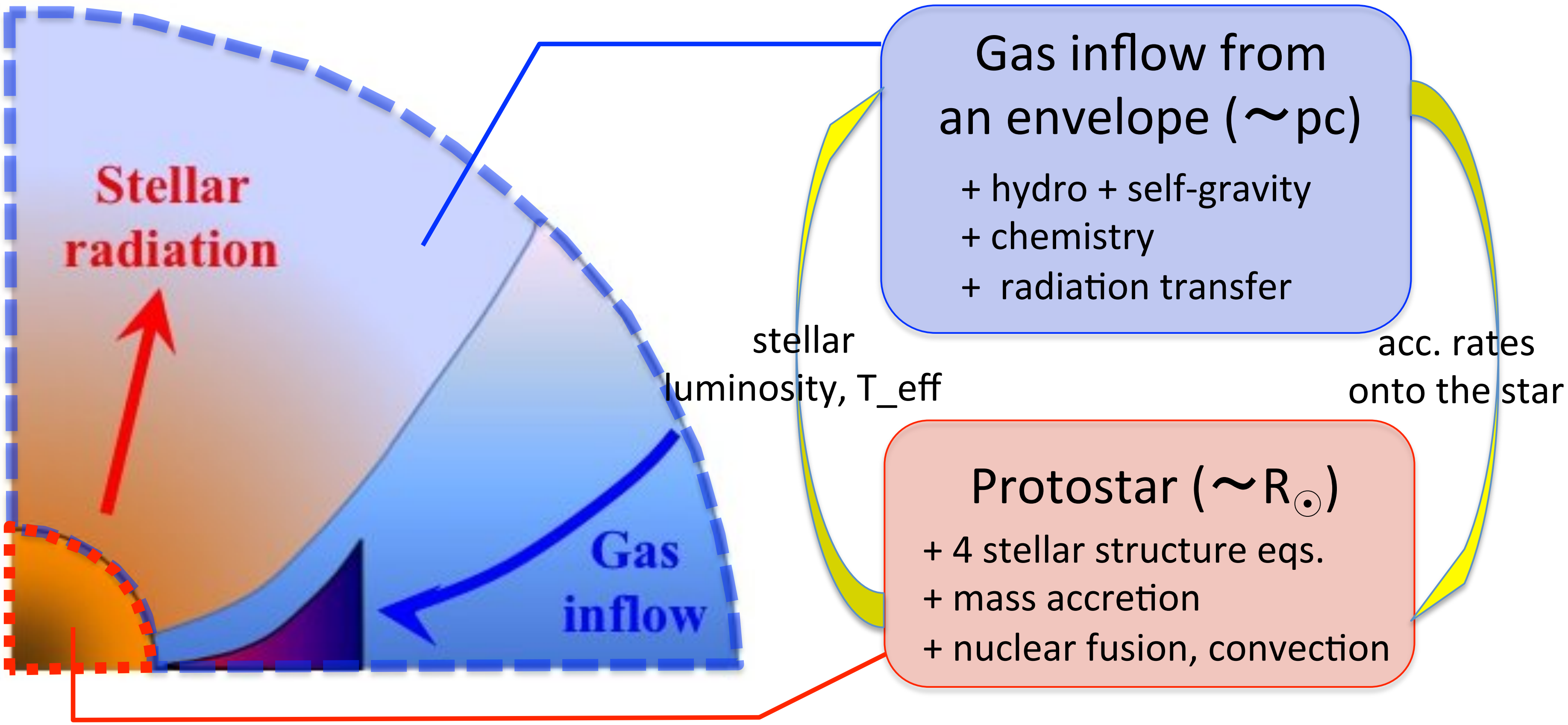
TH+11, 12; Hirano, TH et al. 14



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

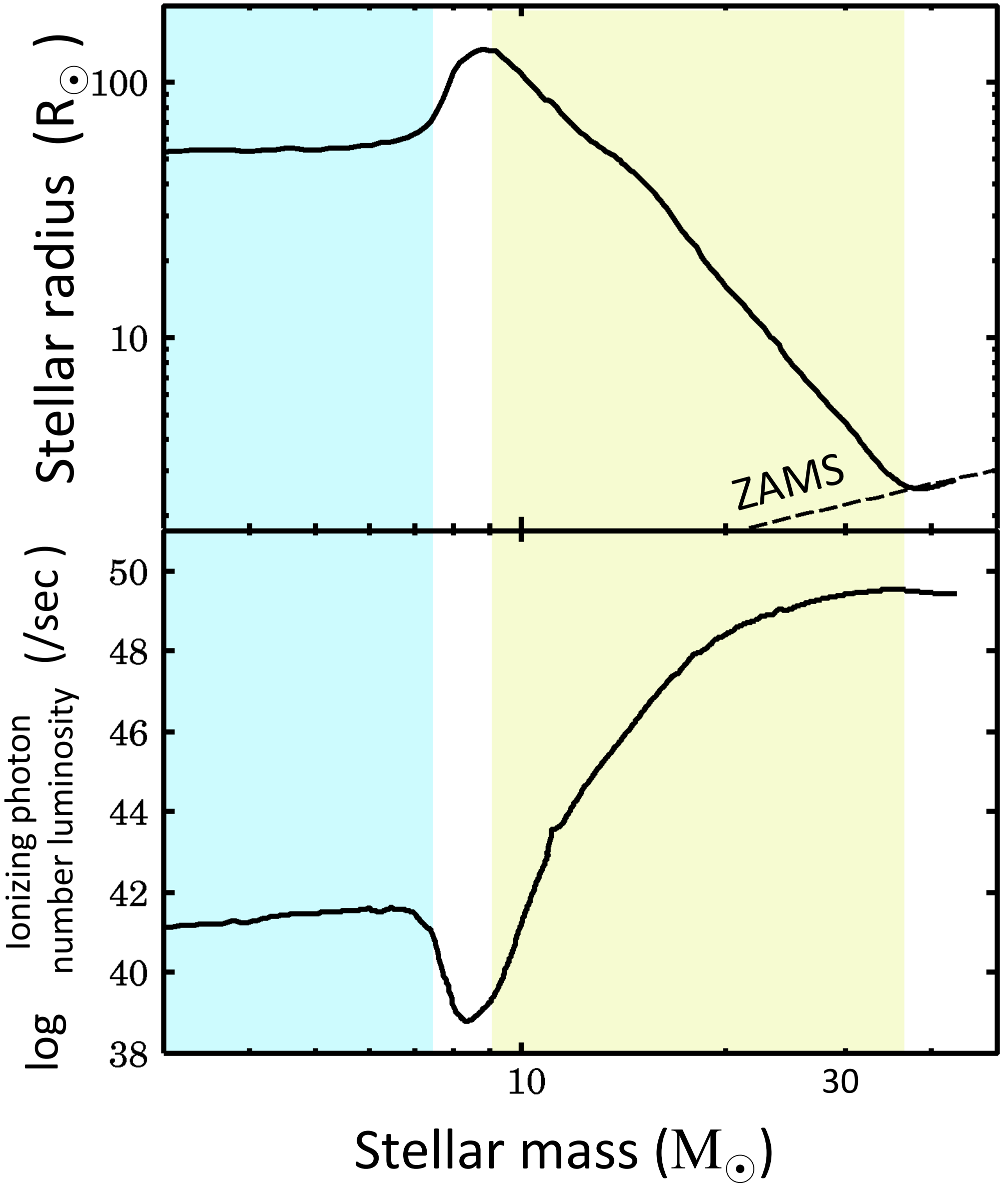
How Challenging?

You have to care about totally different scales simultaneously



Combining RHD simulations and stellar evolution calculations makes the problem solvable.

Stellar Evolution and Feedback



Early phase :
(accretion heating) > (radiation cooling)

rapid increase of L_*

Late phase:
(radiation heating) > (accretion heating)

Later contraction phase

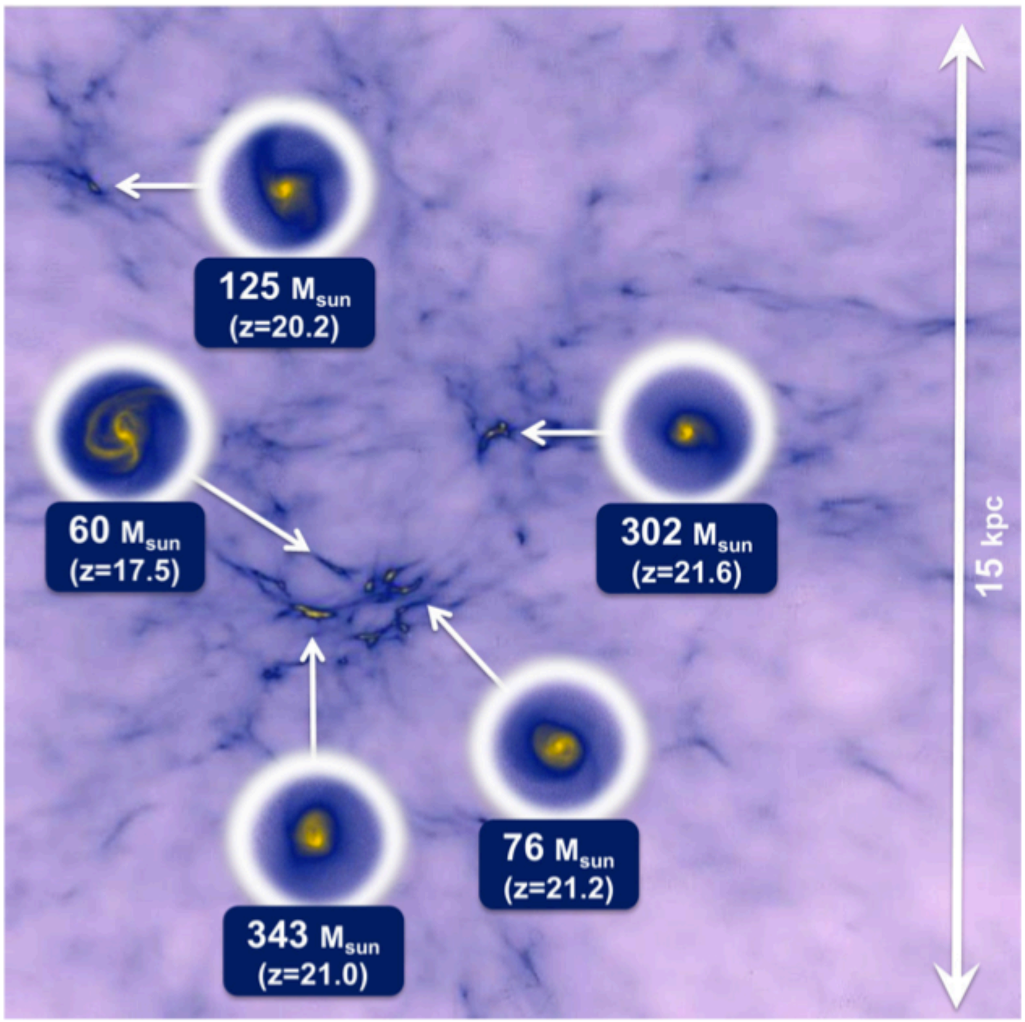
Stellar radius↓

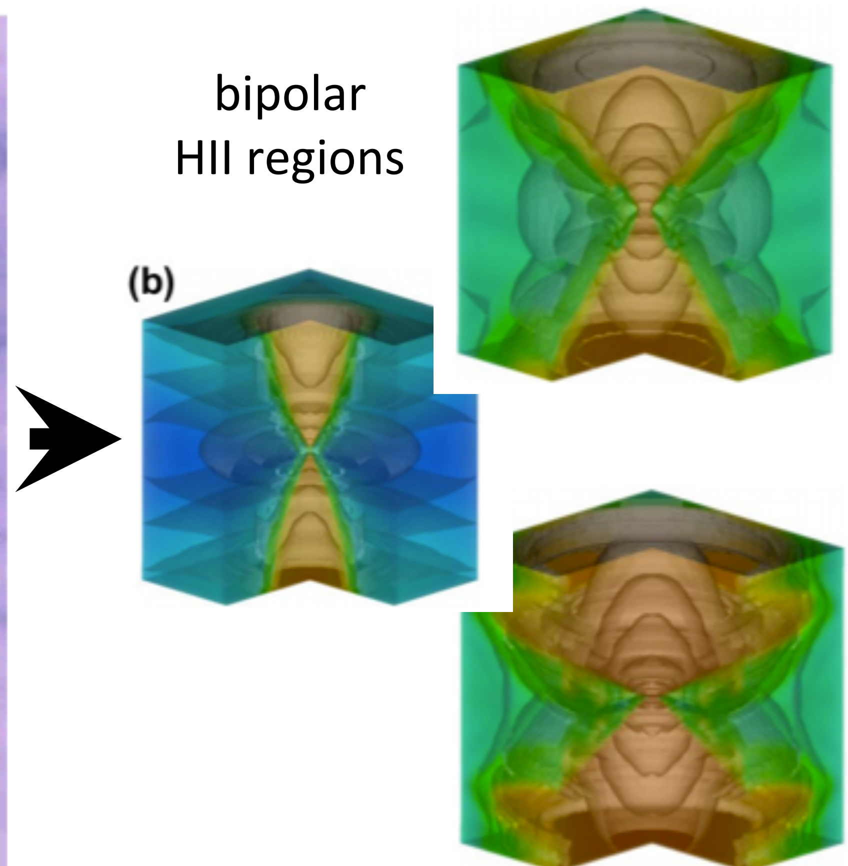
T_eff ↑ ・ UV emissivity ↑

Feedback operates when the stellar radius has sufficiently decreased.

Forming 100 First stars

Pick up a hundred of the star-forming clouds found in cosmological simulations. The later evolution until the stellar mass is fixed is followed by 2D RHD simulations (Hirano, TH et al. 2014)

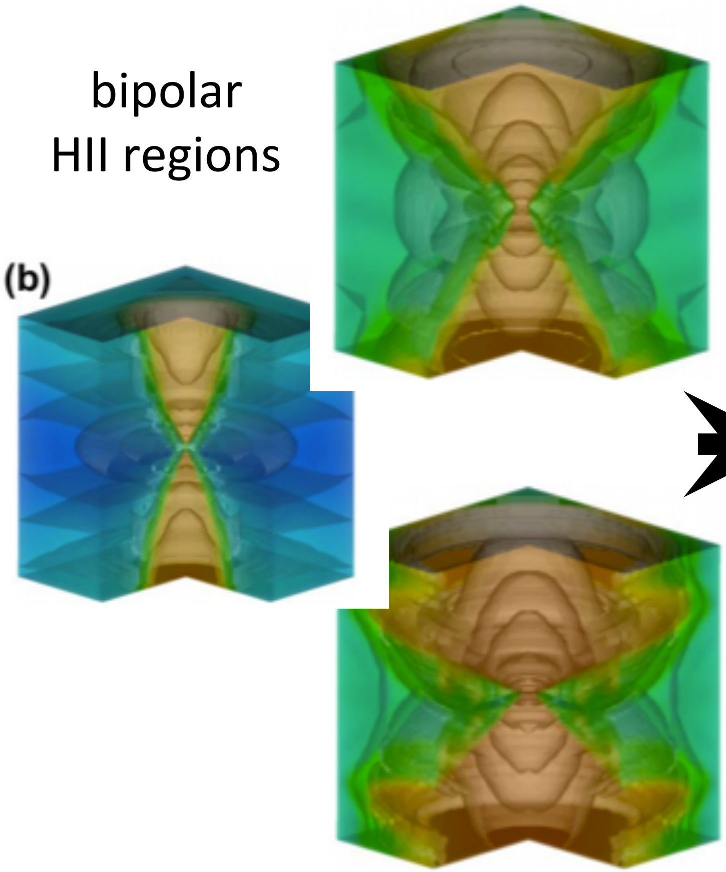


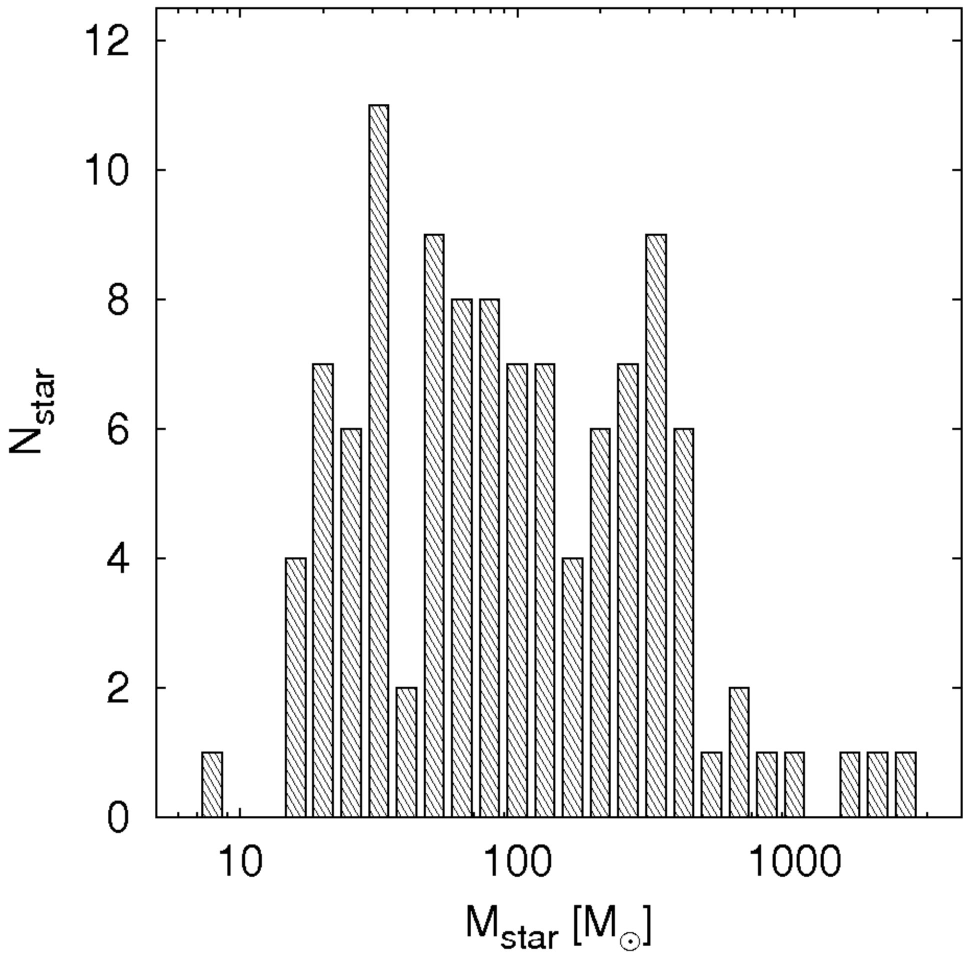


The UV feedback finally shuts off the mass accretion in all the cases

Mass Distribution

bipolar
HII regions





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

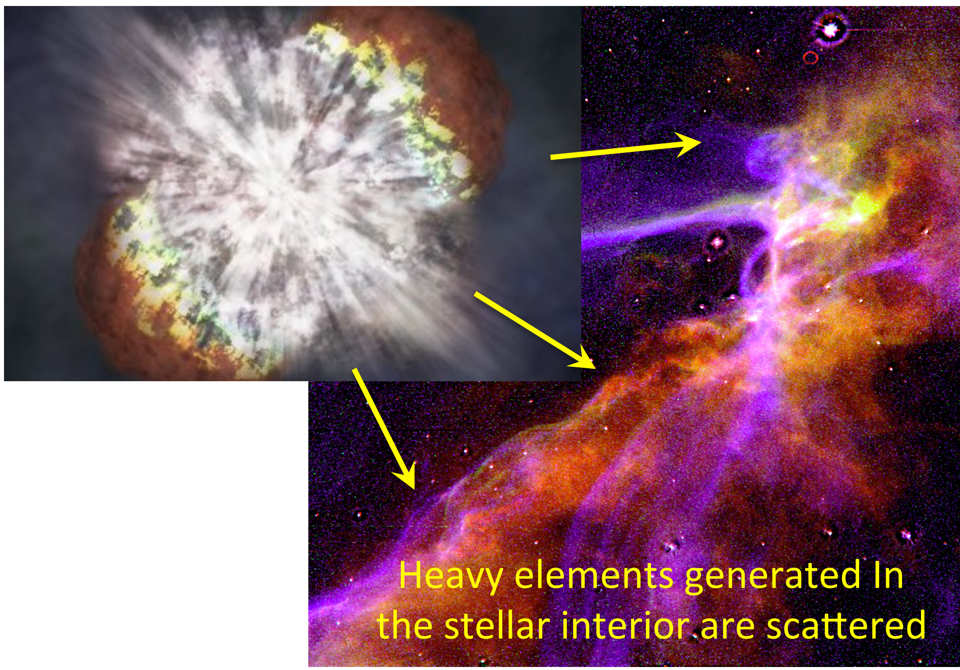
(also see Susa, Hasegawa & Tominaga 14)

Stellar mass is higher with weaker rotation and/or higher mass of the clouds.

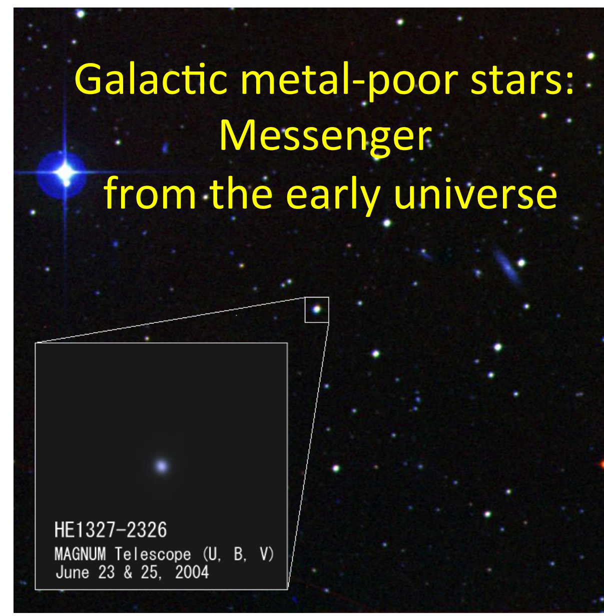
Observational Challenge

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

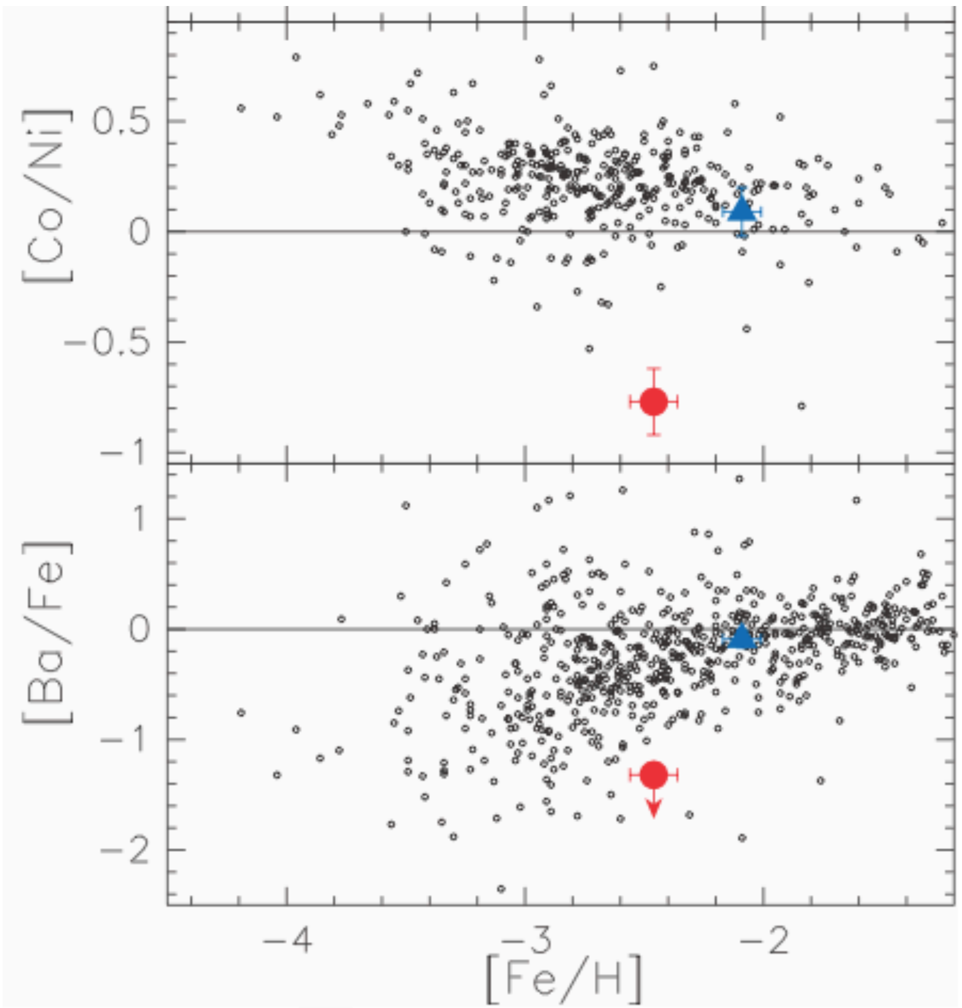


Stars born from the polluted gas have the same abundance patterns as the supernova progenitors



No signatures of PISNe (～a few x 100$M_\odot$).
This favors the ordinary massive stars which cause the CCSNe.

Signature of Very Massive First Stars?



Aoki+14, Science

low-mass metal-poor star
SDSS J1820.5-093939.2

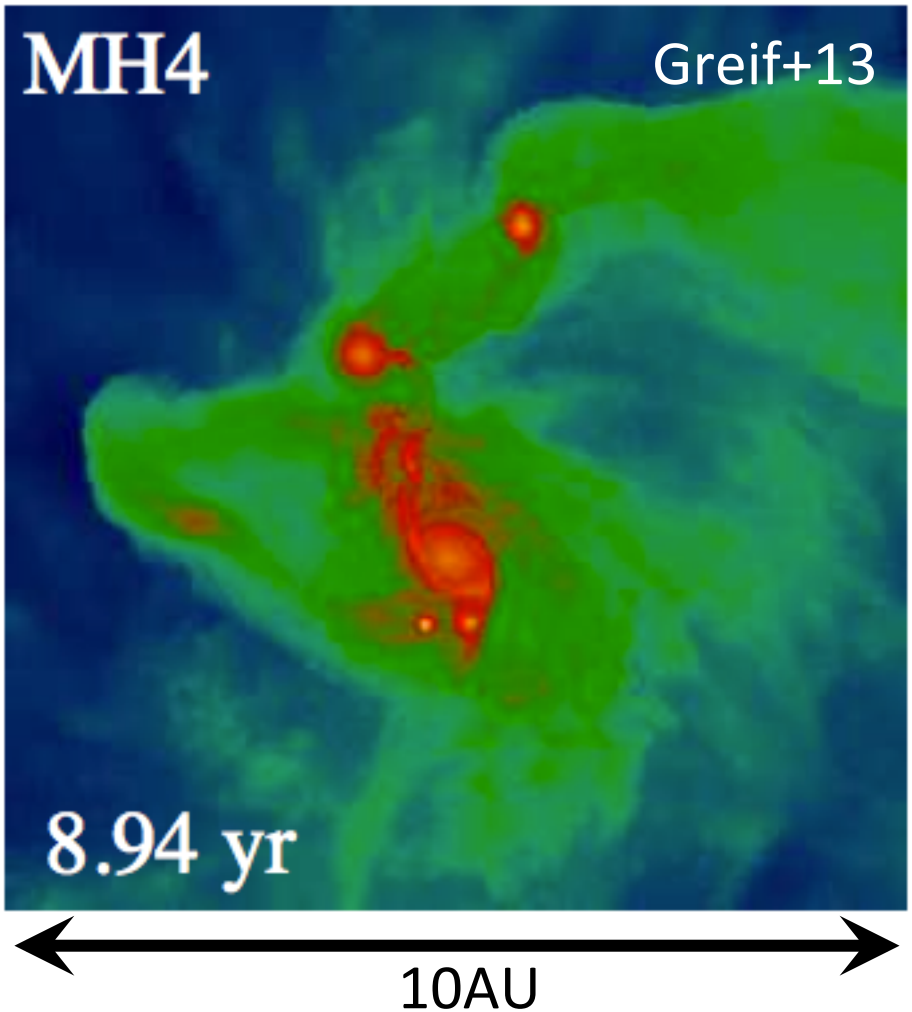
+ abundance pattern very different from other metal-poor stars

+ CCSN cannot explain the pattern

+ a very massive star causing PISN (> 140 $M_{\odot}$) is rather favored as a progenitor

More Challenges in 3D

The circumstellar disk becomes gravitationally unstable and fragments.



Multiple protostars could form

↓

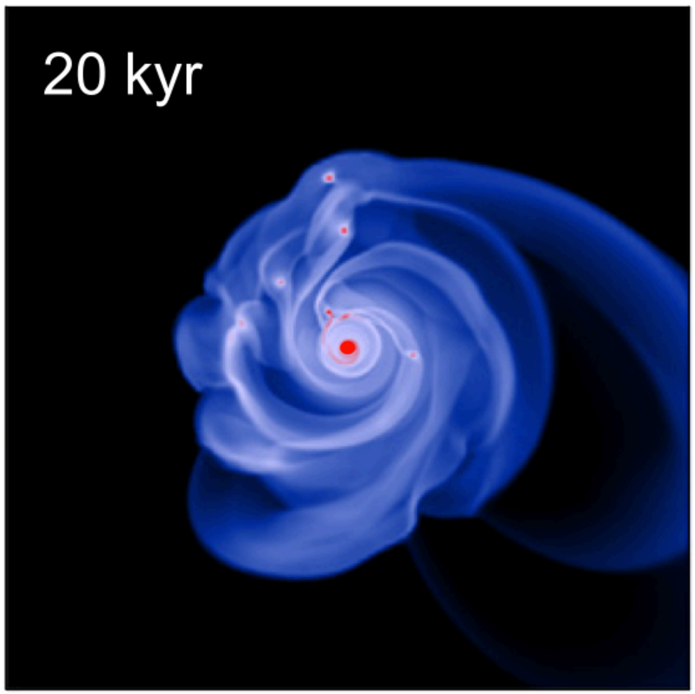
Accretion rate onto each protostar: reduced (?)

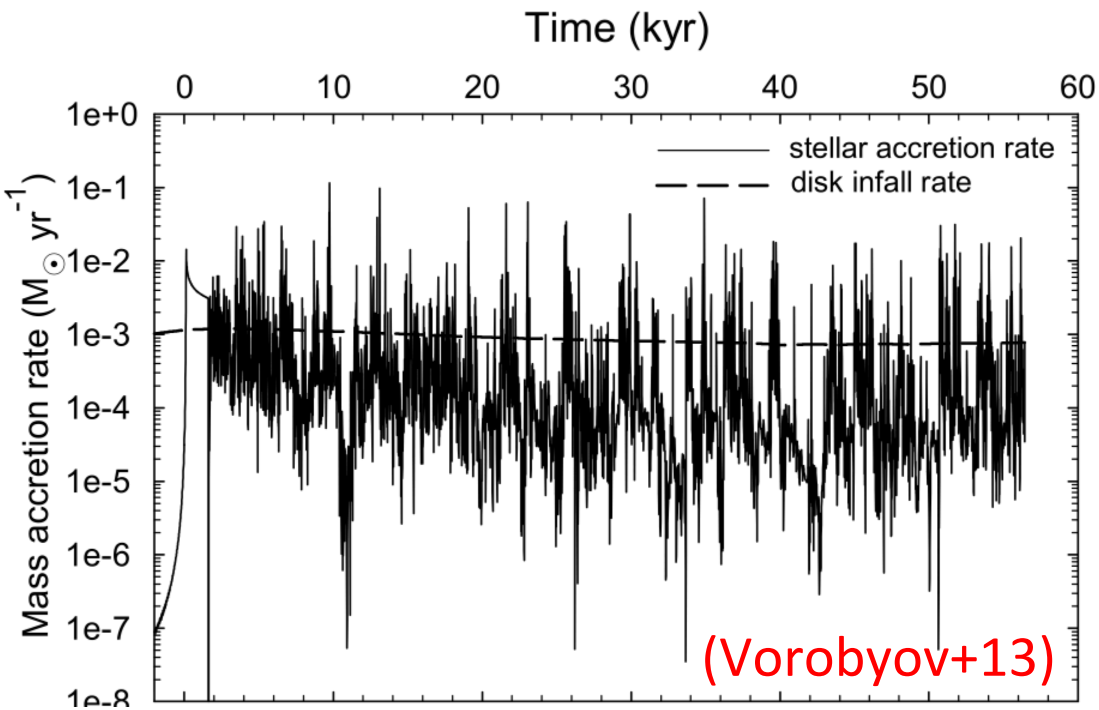
↓

Final stellar masses: reduced (?)

Another 3D effect: Episodic Accretion

Mass accretion through the gravitationally-unstable disk is very time-dependent. Even if the disk suffers from fragmentation, the fragments rapidly migrate inward and merge with the central star.

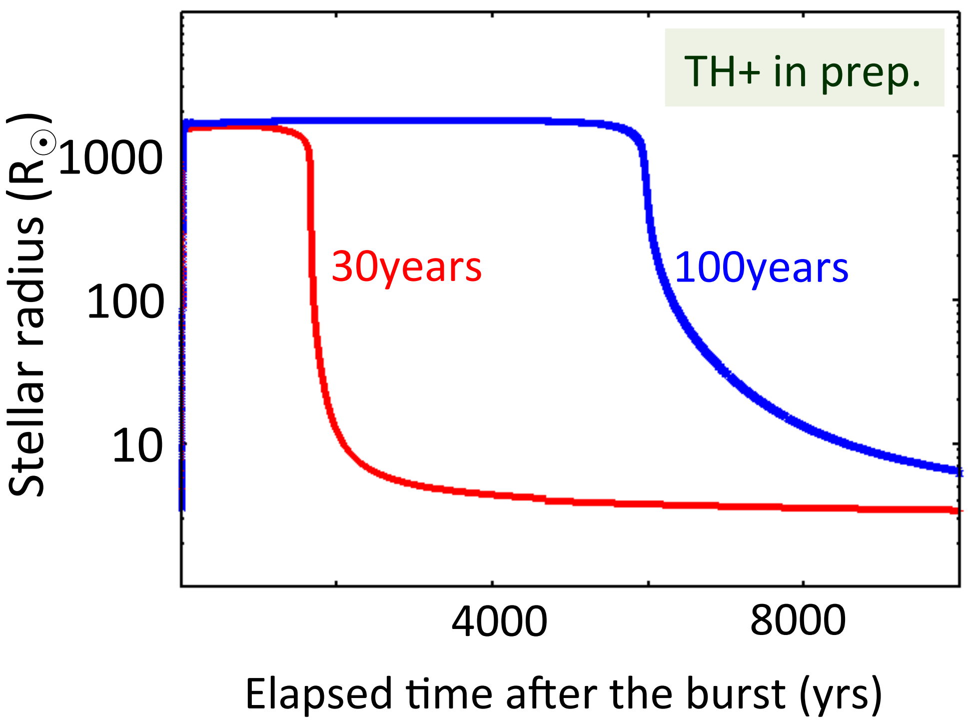




How this effect affects the final stellar mass?

Accretion Burst Makes A Protostar Swell

An experiment : put a short accretion burst on a $40M_{\odot}$ star.
$0.1M_{\odot}$/yr for 30/100 years, $10^{-3}M_{\odot}$/yr after that



The star swells up with the short accretion burst (R_{*}～10AU). It takes long time (thousand years) for contraction.

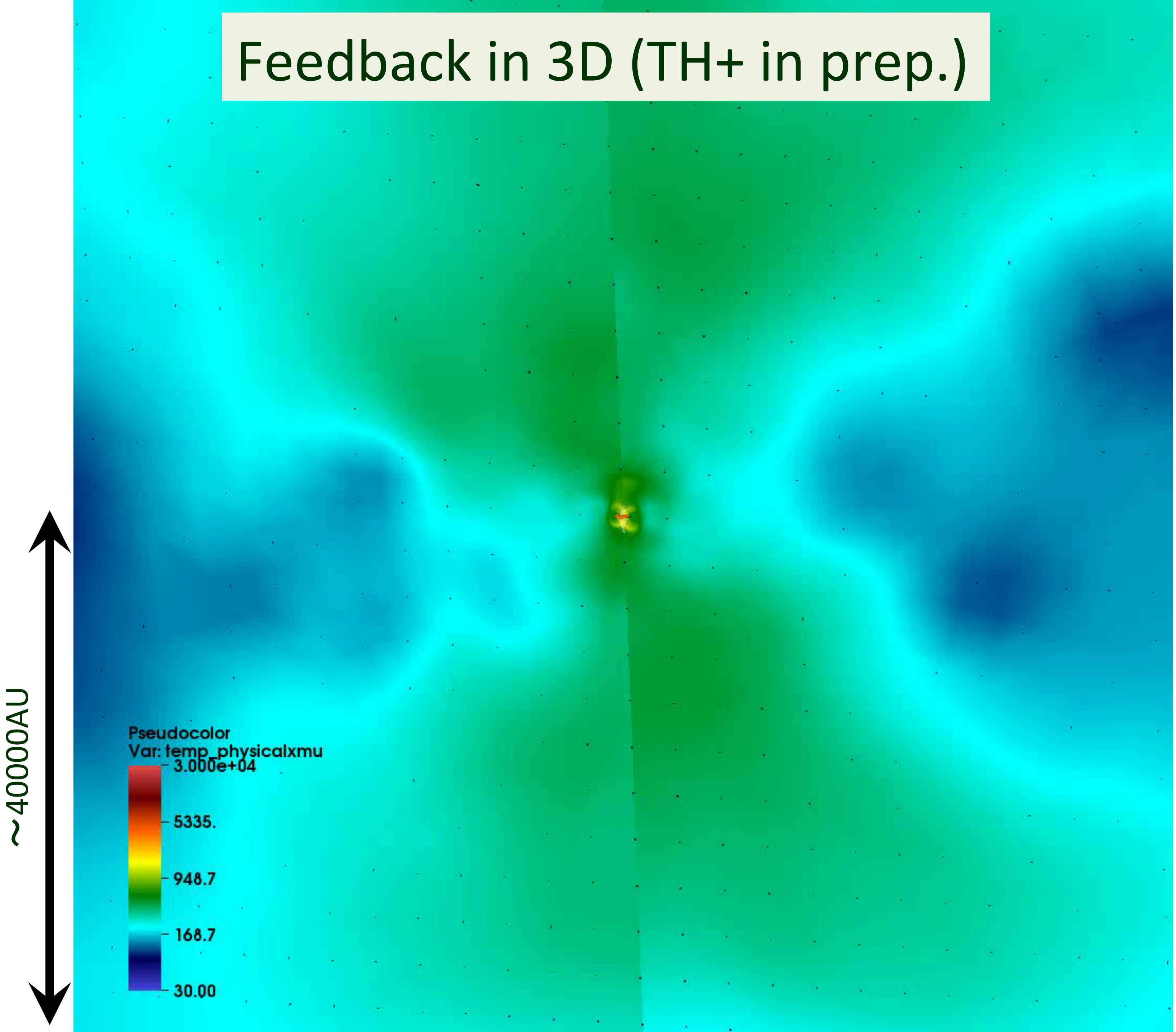
↓

+ reduce the UV emissivity
  (weaken the UV feedback)
+ make the stellar merger easy

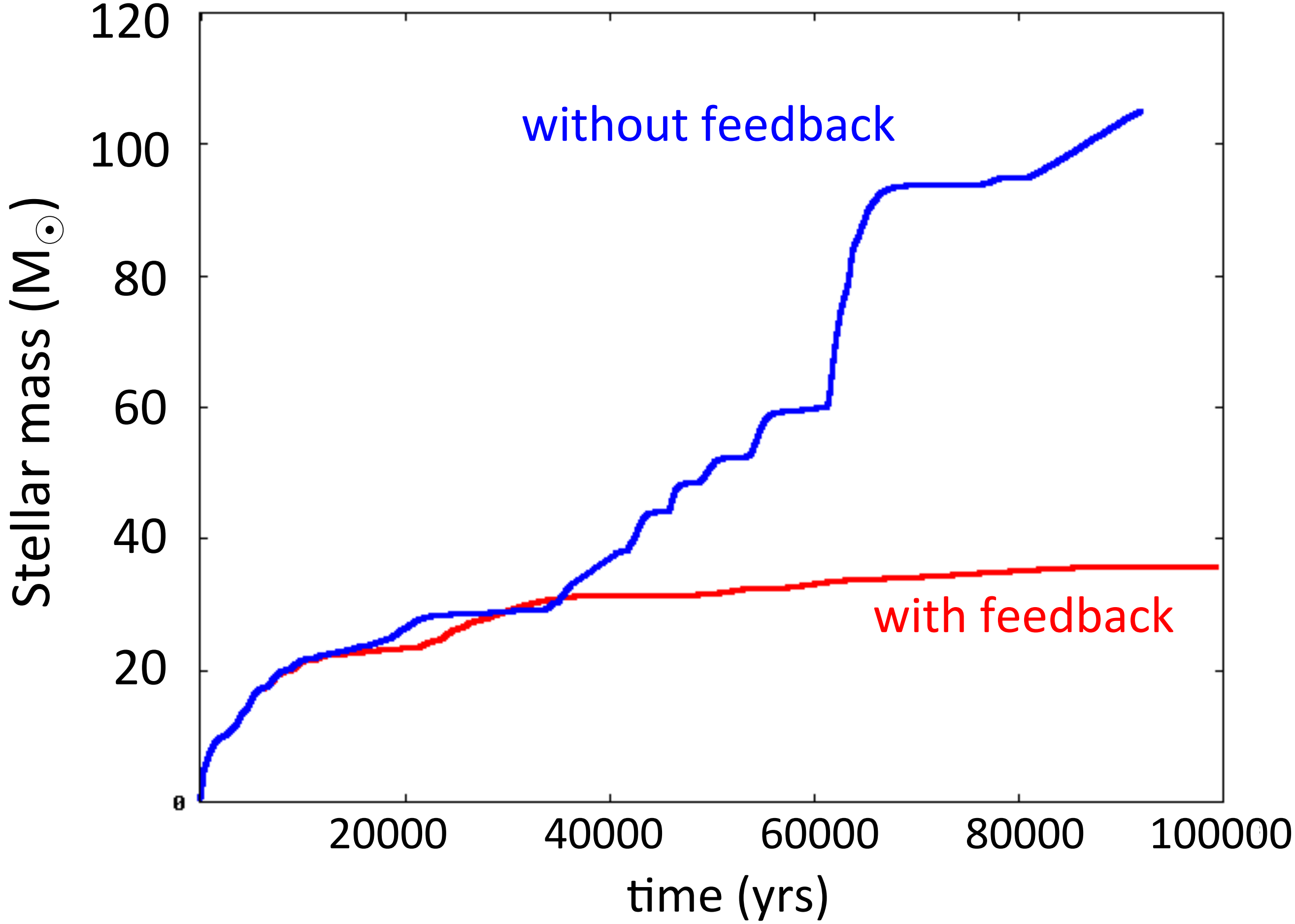
↓

The final stellar mass is increased(?)

Feedback in 3D (TH+ in prep.)



Stellar Mass Growth



UV feedback (formation of an HII region + photoevaporation) does operate in 3D and shuts off the stellar growth in mass.

(also see Stacy+12; Susa 13)

Summary

How massive were the first stars?

+ Stellar radiative feedback regulates the mass accretion and determines the final stellar mass

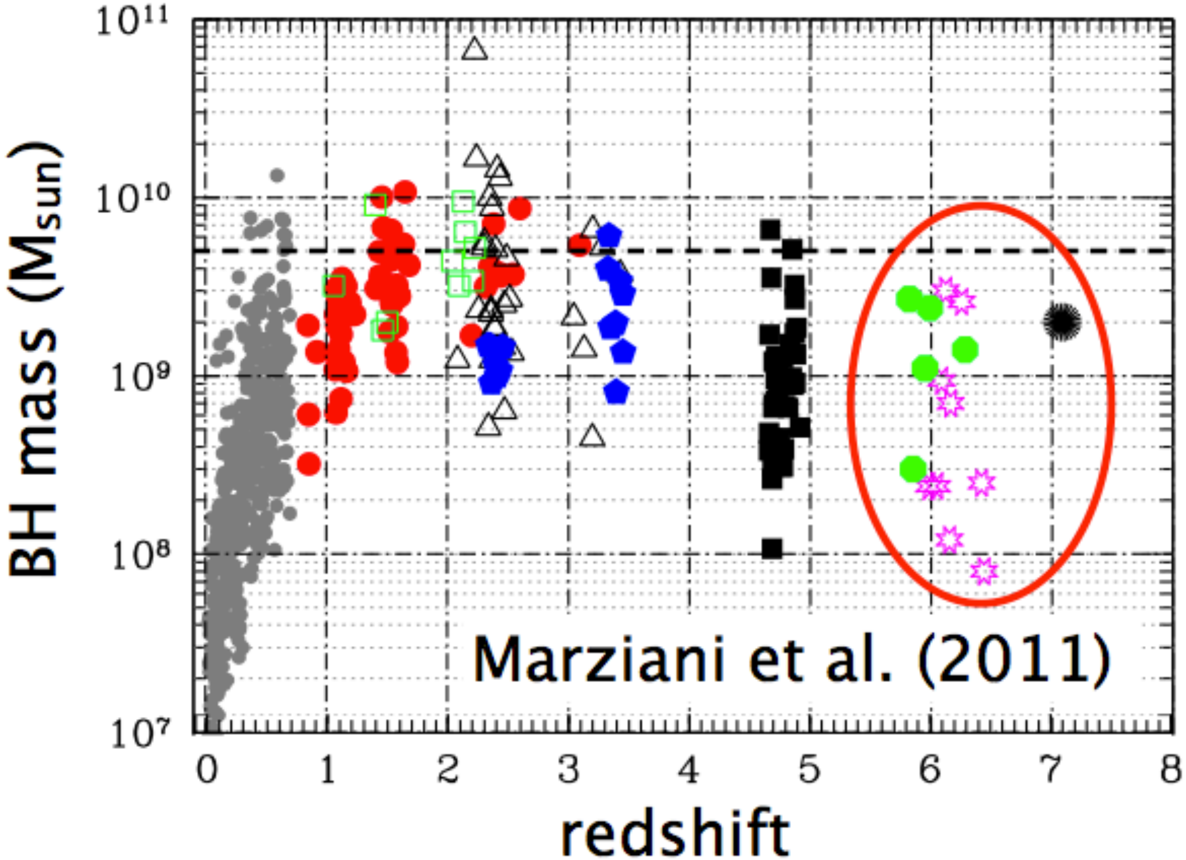
+ Lots of "ordinary" massive stars ($M_* < 100\ M_\odot$)
but still with a number of very massive ($M_* > 100 M_\odot$) stars
→ seeding SMBHs in the early universe?

+ 3D effects reduce or increase the final stellar mass?
(fragmentation, mergers, episodic accretion, and UV feedback)

Additional pages

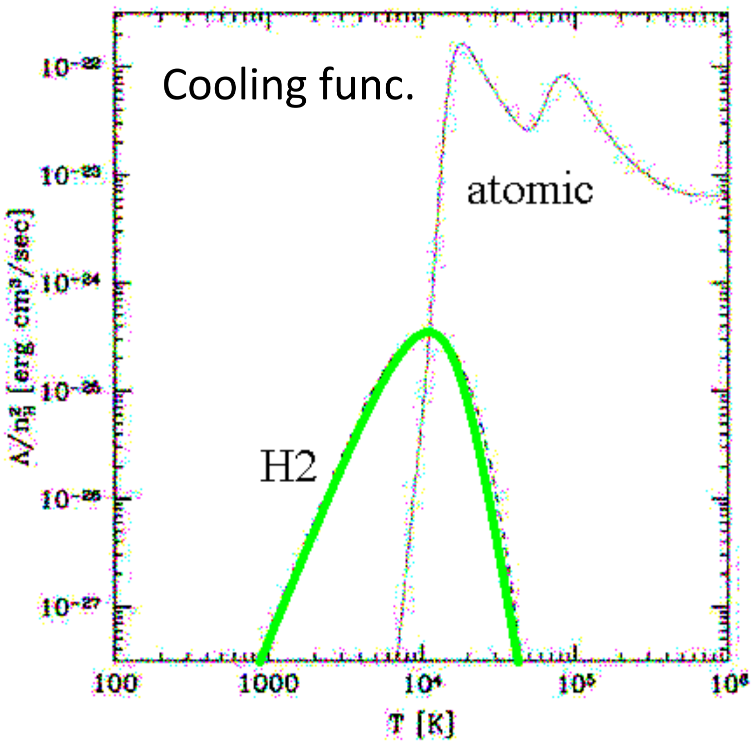
Very Very Massive Stars: still needed?

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.

Differences from the Galaxy



Zero metallicity (NO metal and dust) : different thermal / chemical processes

(e.g., Palla et al. 83, Galli & Palla 98)

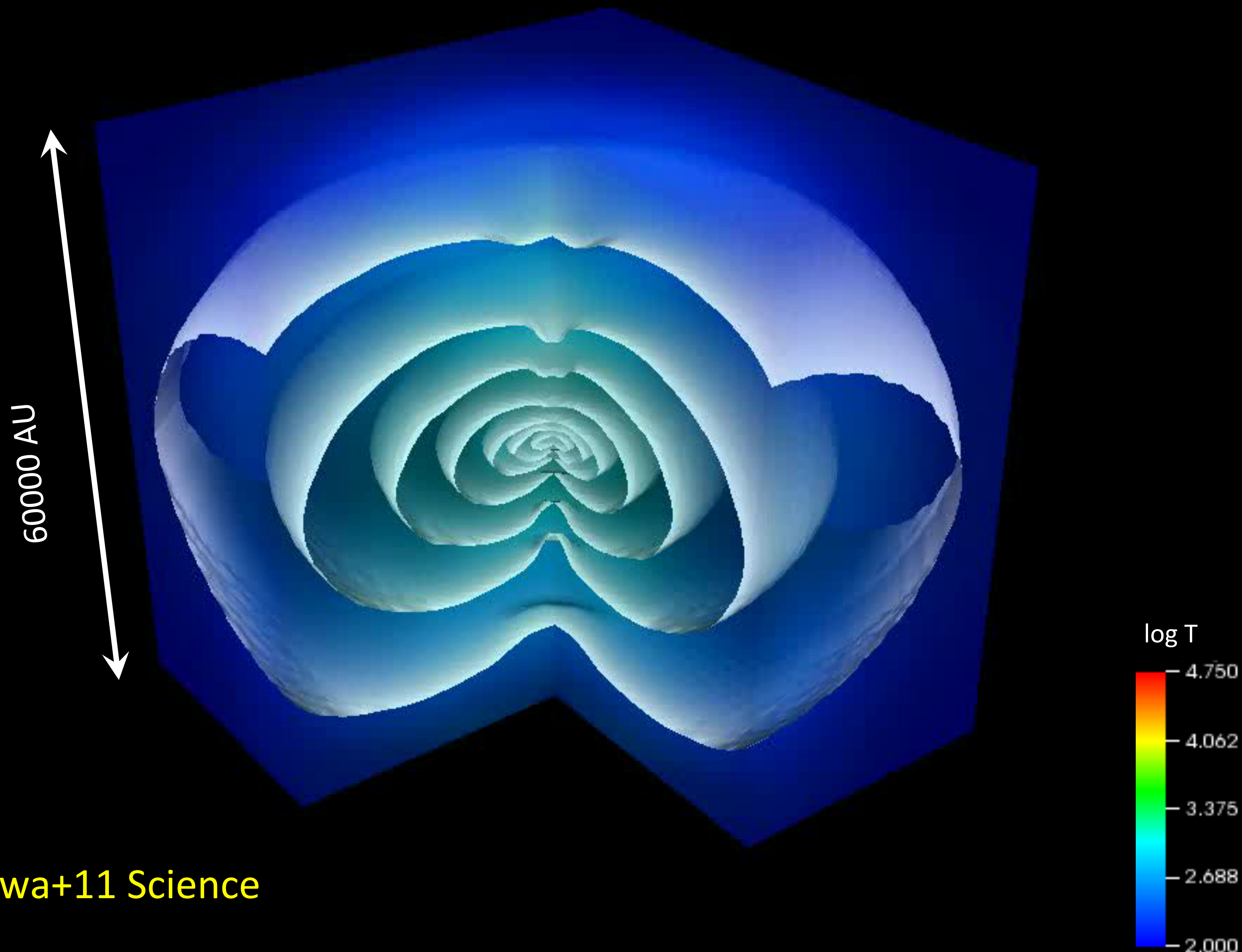
← gas cooling processes
H2 line cooling at T < 10000 K

(CII,OI,CO, dust cooling etc.@ Galaxy)

H_2 formation
- **H^- channel** : e catalyst ($n < 10^8 cm^{-3}$)
  $H + e \rightarrow H^- + \gamma$, $H^- + H \rightarrow H_2 + e$
- **3-body reaction** ($n > 10^8 cm^{-3}$) $3H \rightarrow H_2 + H$

(formation on dust grain surface @ Galaxy)

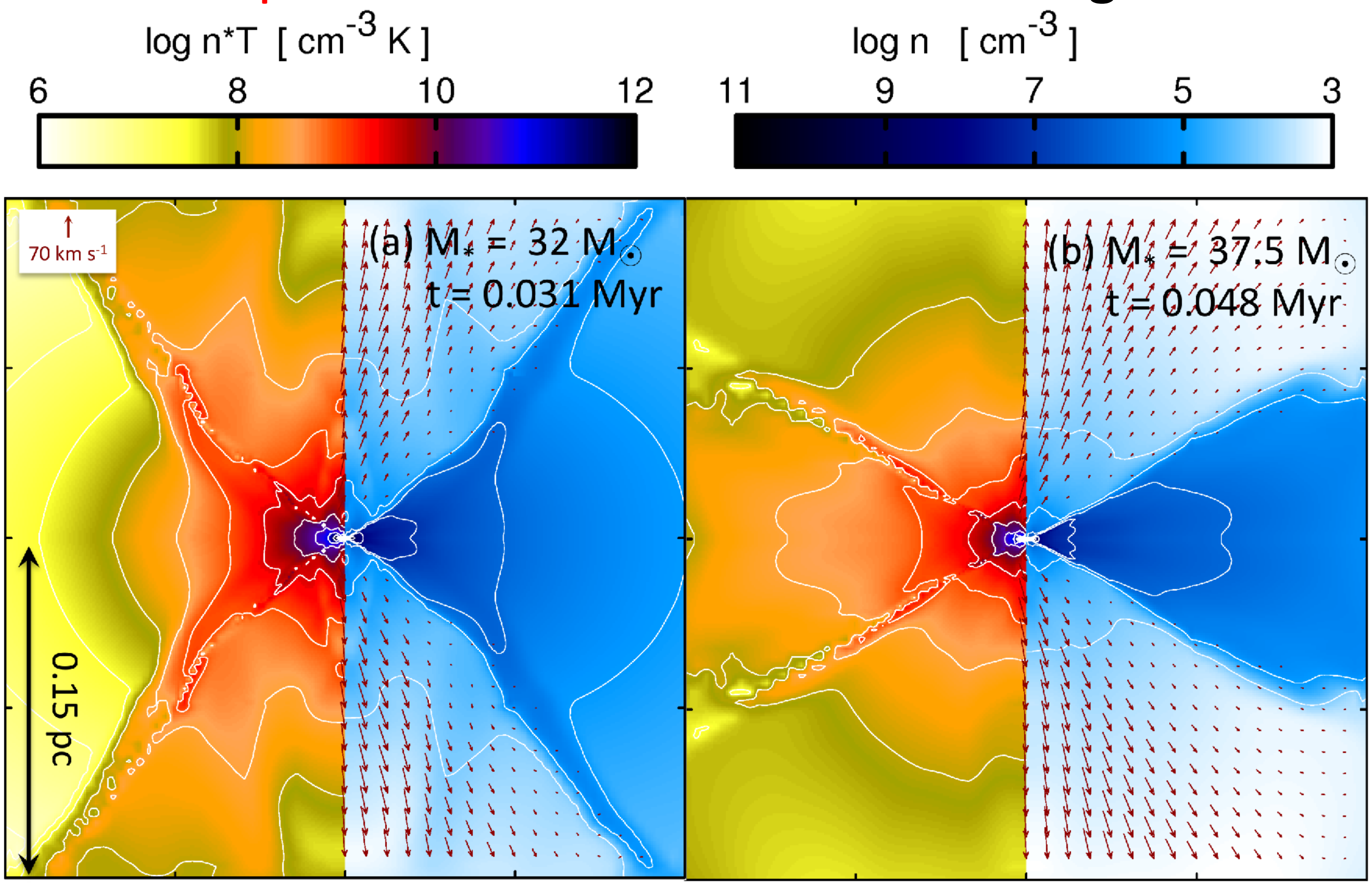
Cosmological initial setting (data from Yoshida+09)



Hosokawa+11 Science

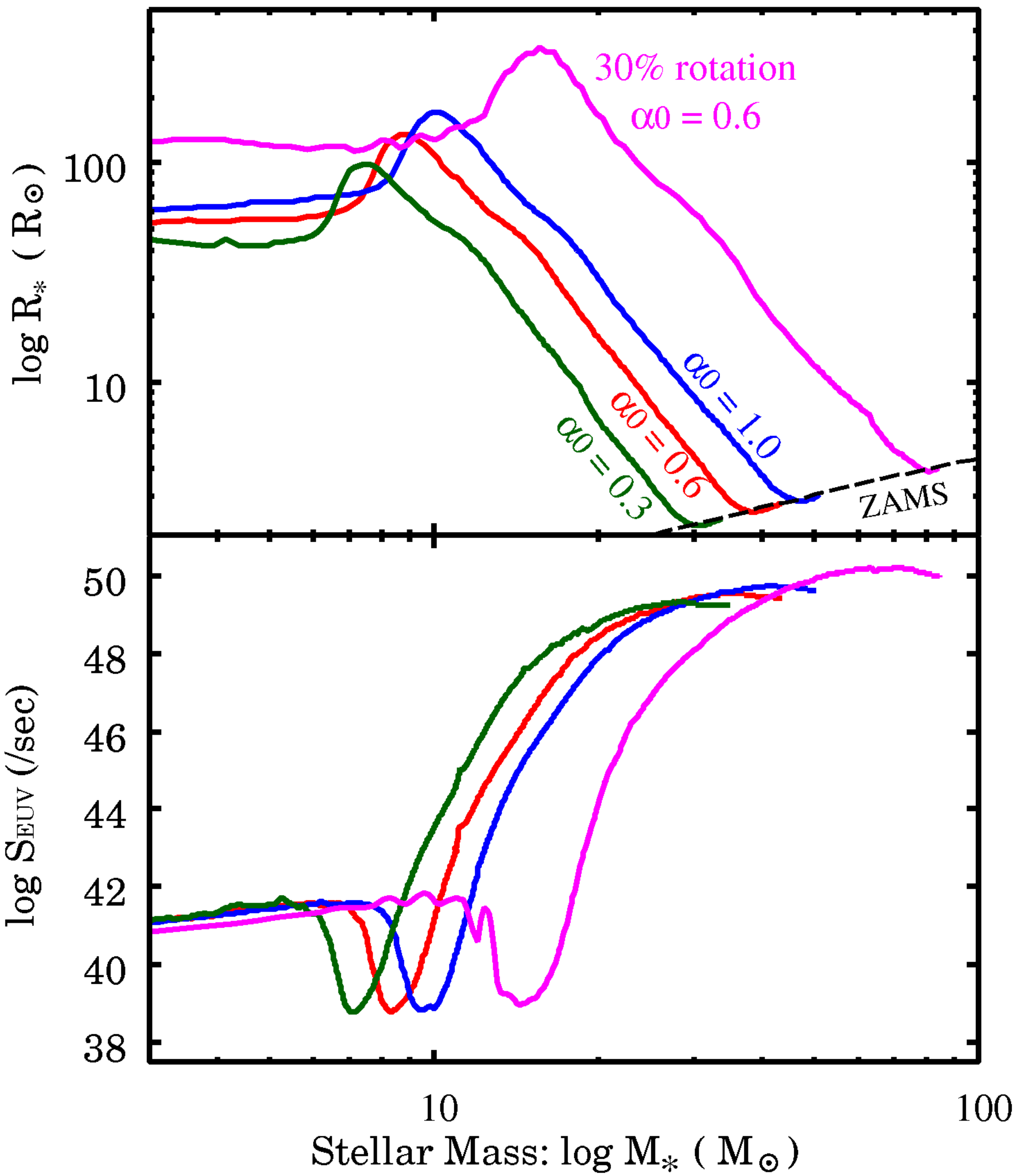
Why mass accretion ceases

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

More Massive Stars?

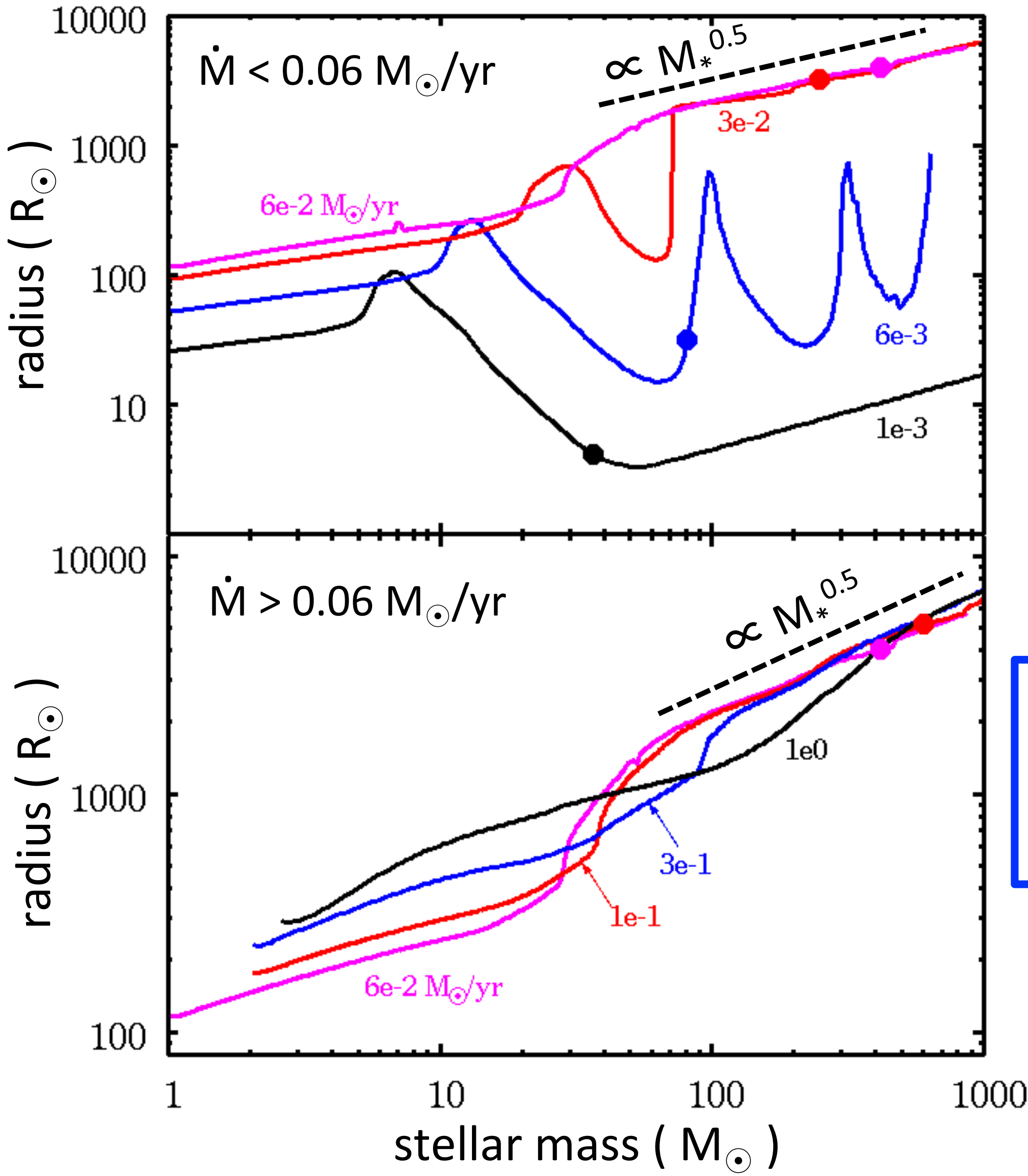


Stellar UV feedback operates after the late KH contraction stage.

↓

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

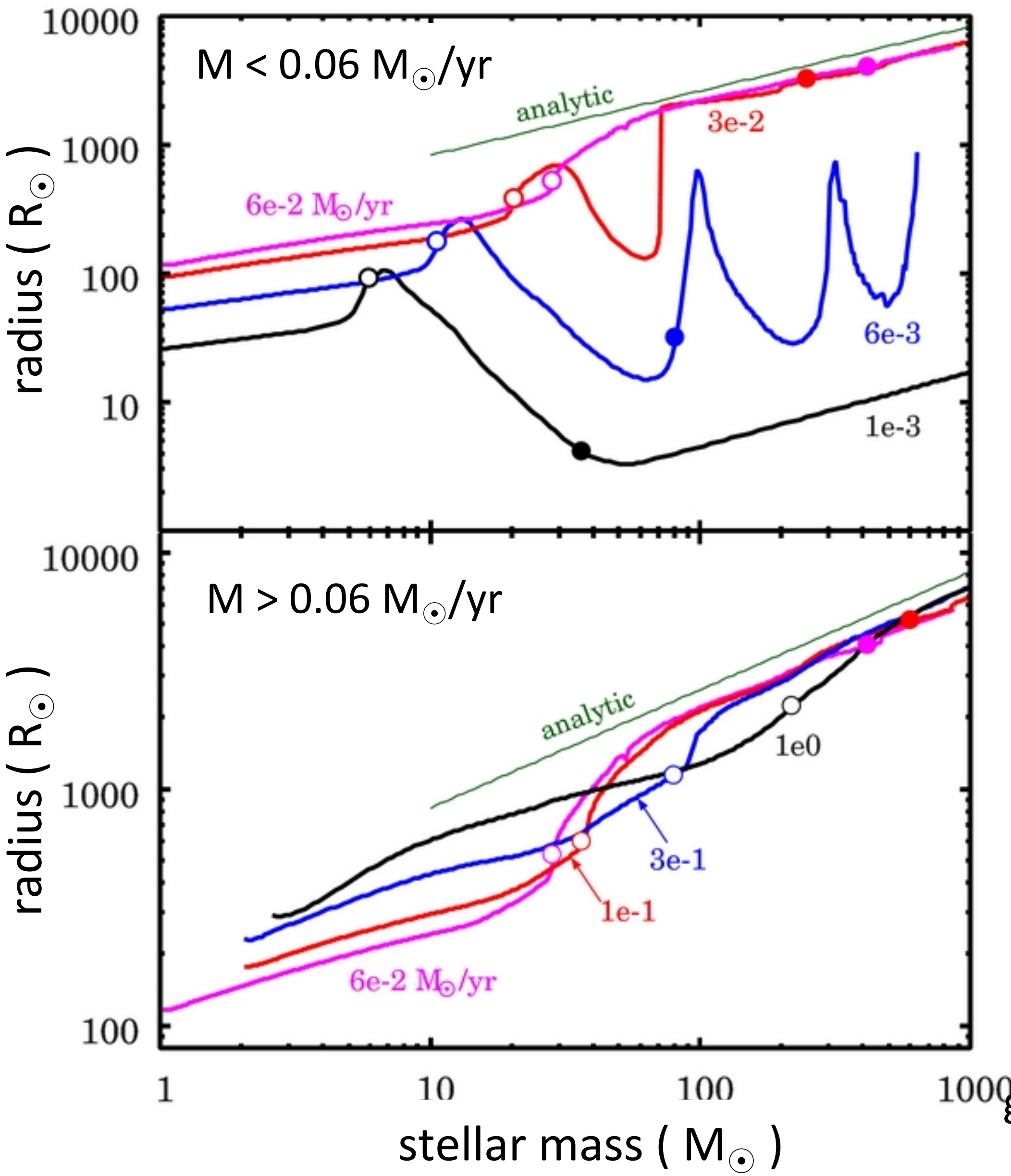
With Different Acc. Rates



"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)

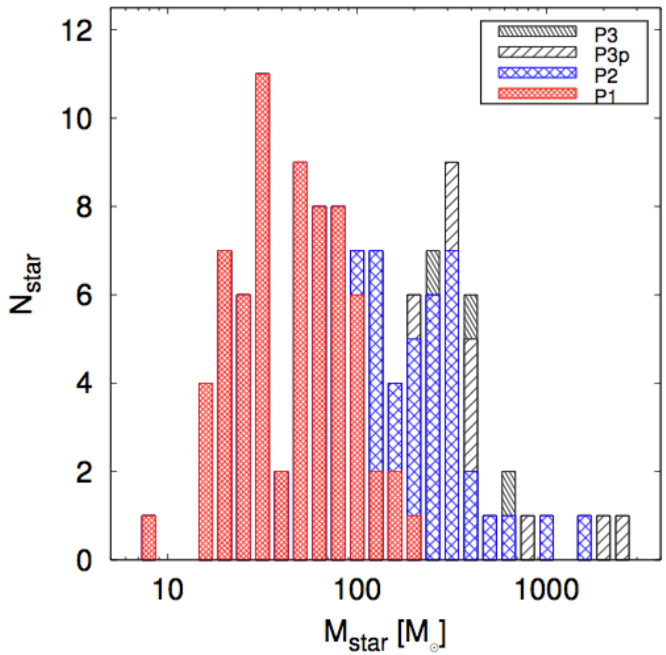
(ref. Hayashi track)

↓

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

good agreement with the numerical results

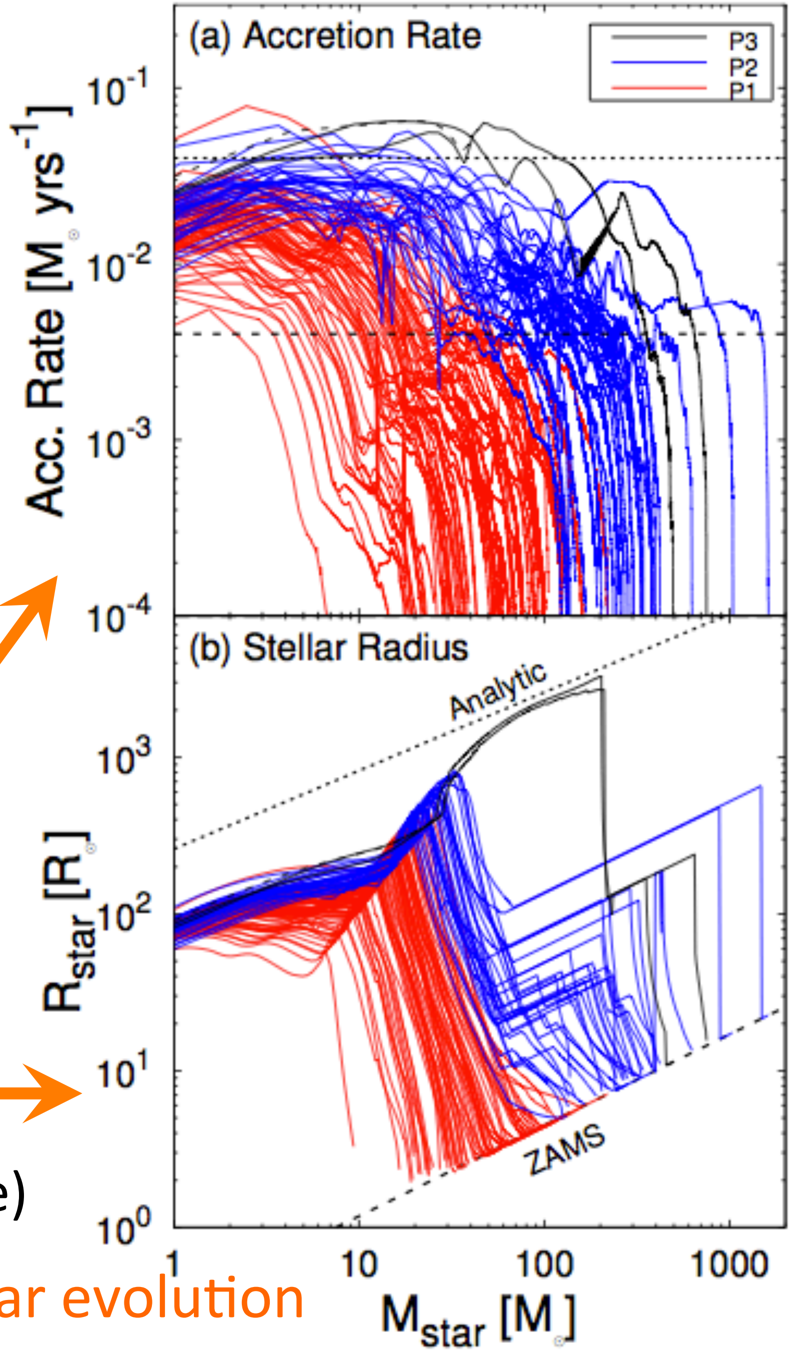
Diversity… why?



With the higher acc. rates,

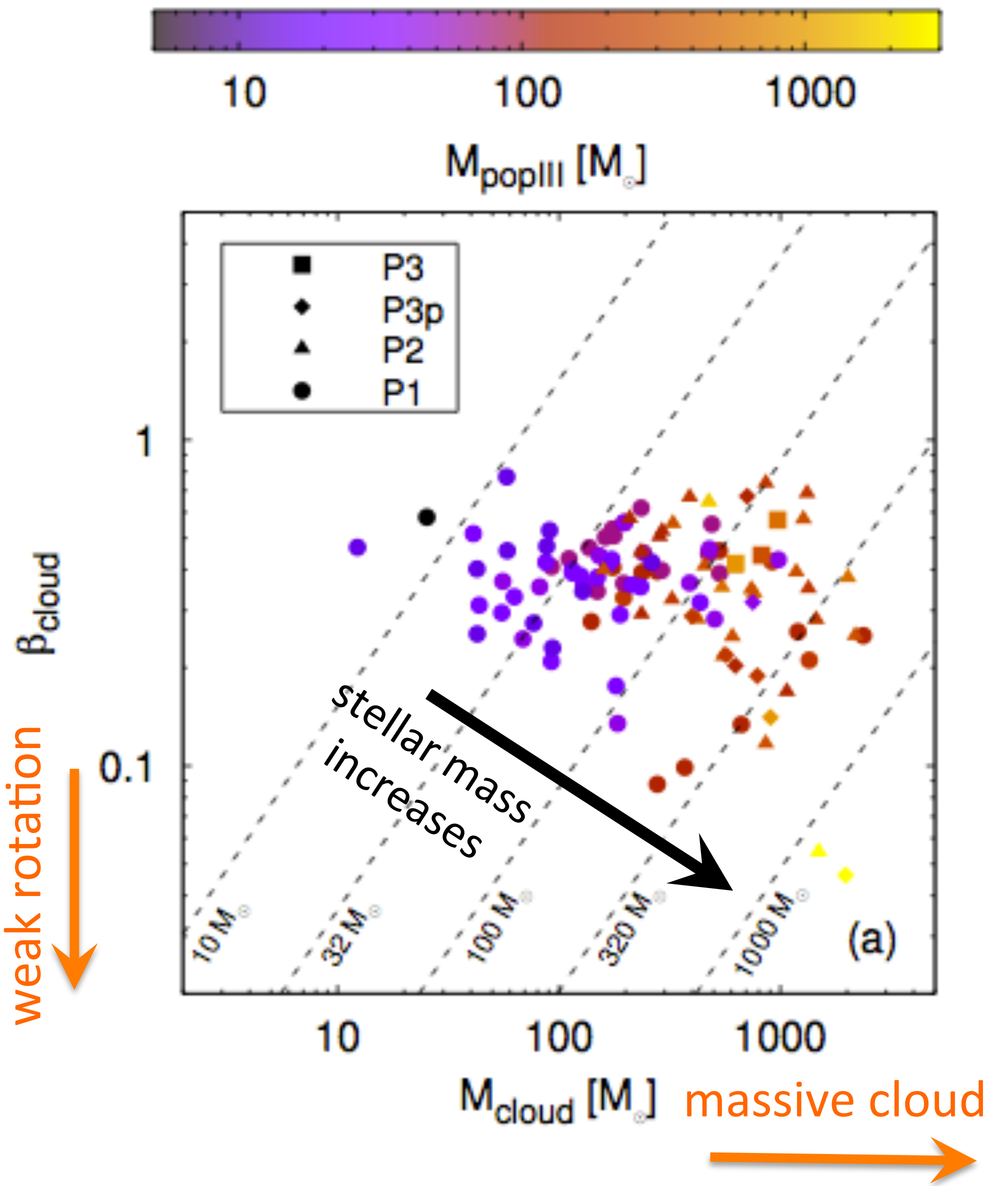
+ the stellar mass is higher

+ 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

Key parameters: cloud mass & spin



- Weaker rotation
- More massive gas cloud

↓

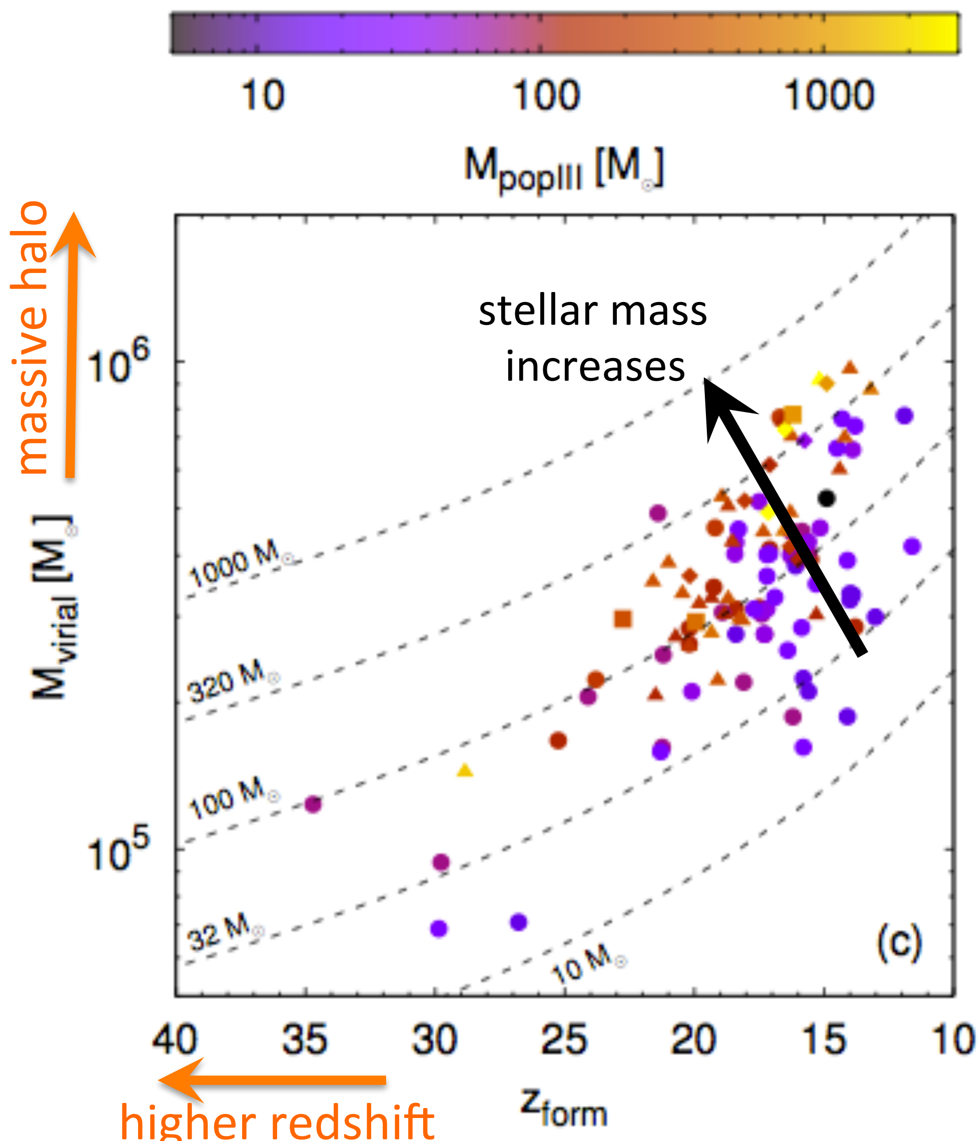
Higher stellar mass

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

Diversity of the gas clouds comes from cosmology

Diversity from Cosmology

(large-scale structure formation)



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

- higher redshift
- more massive dark halo

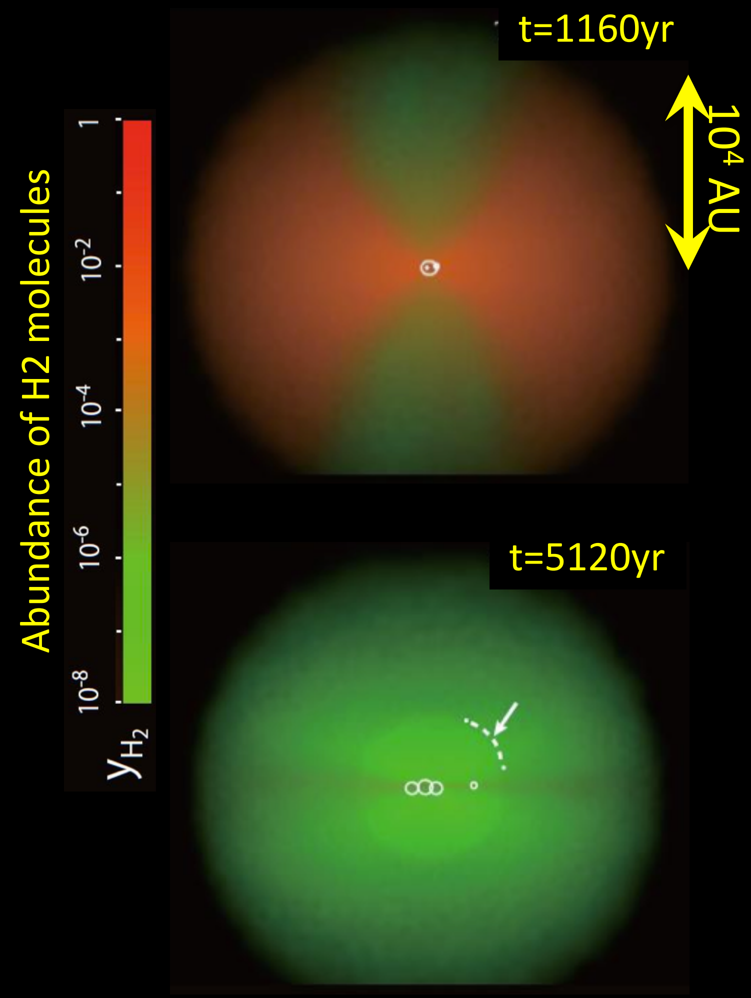
↓

higher stellar mass

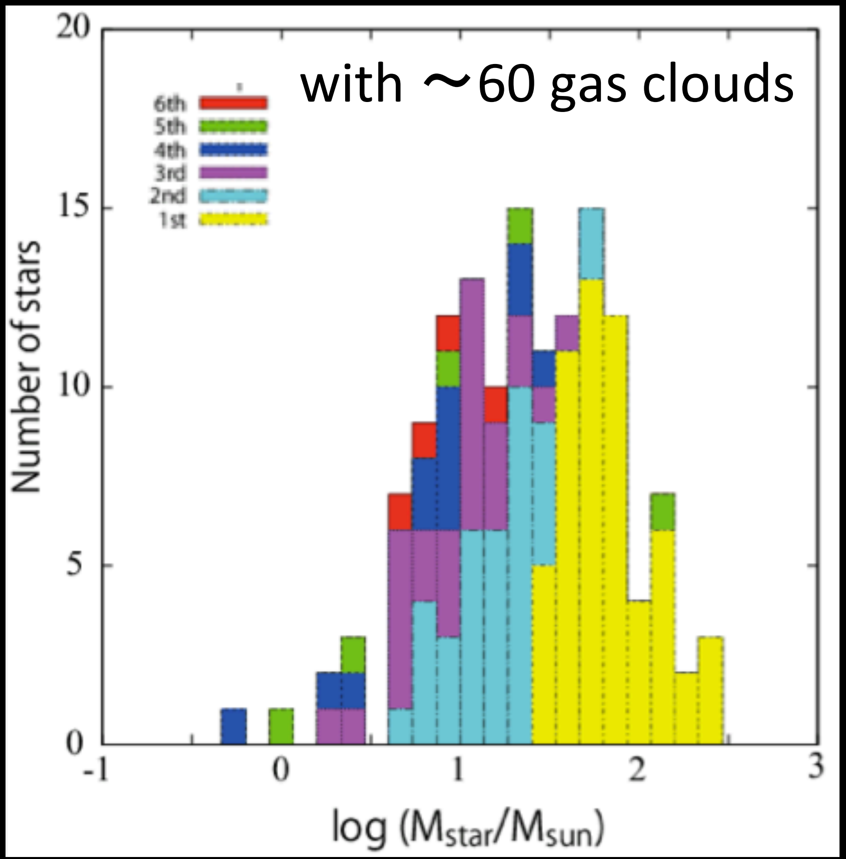
Cosmology sets the different conditions for forming the primordial gas clouds.

Mass Distribution in 3D

Susa, Hasegawa & Tominaga 14

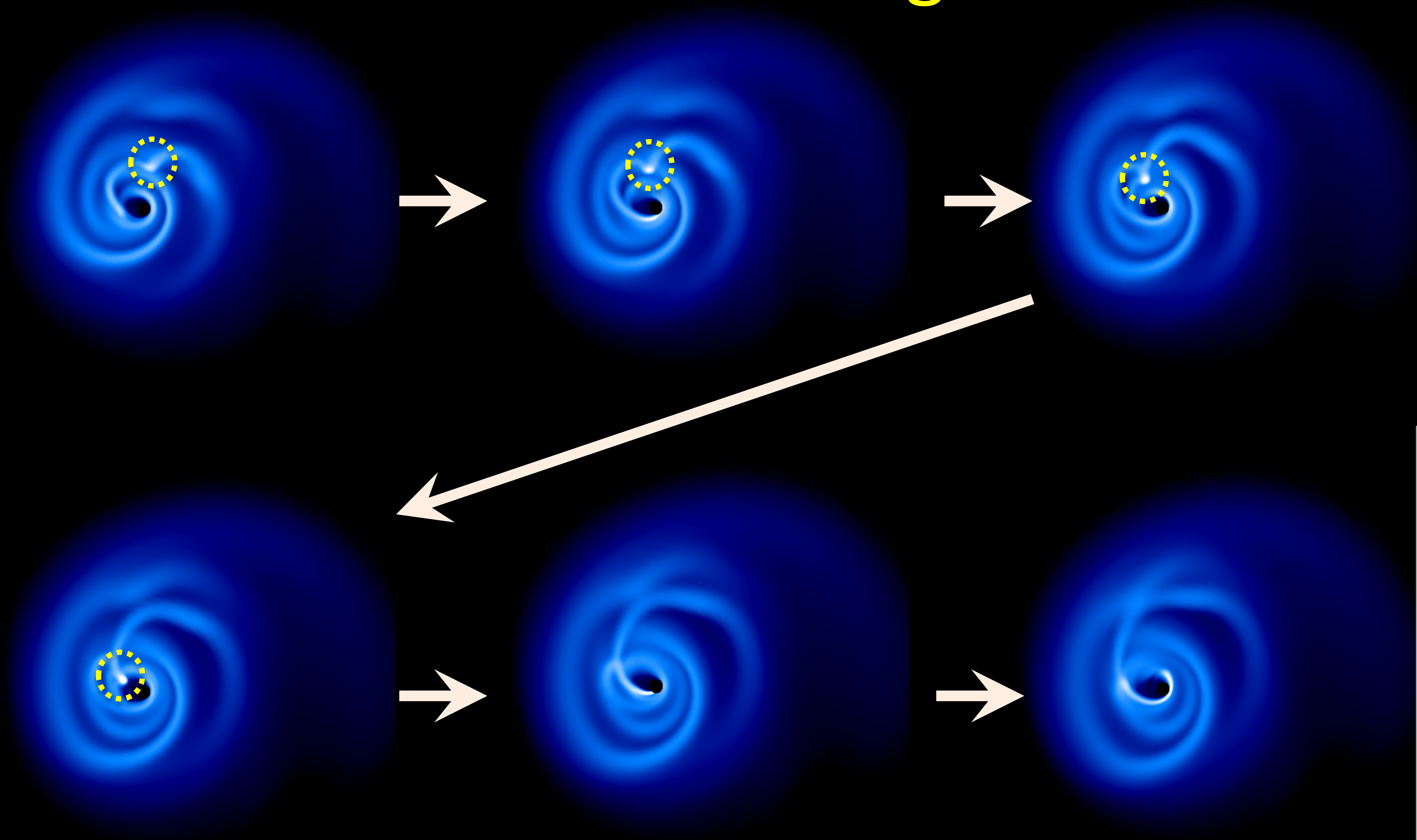


stellar FUV feedback:
destruction of H2 molecules



More lower-mass stars because of the disk fragmentation
(compared to Hirano+14)

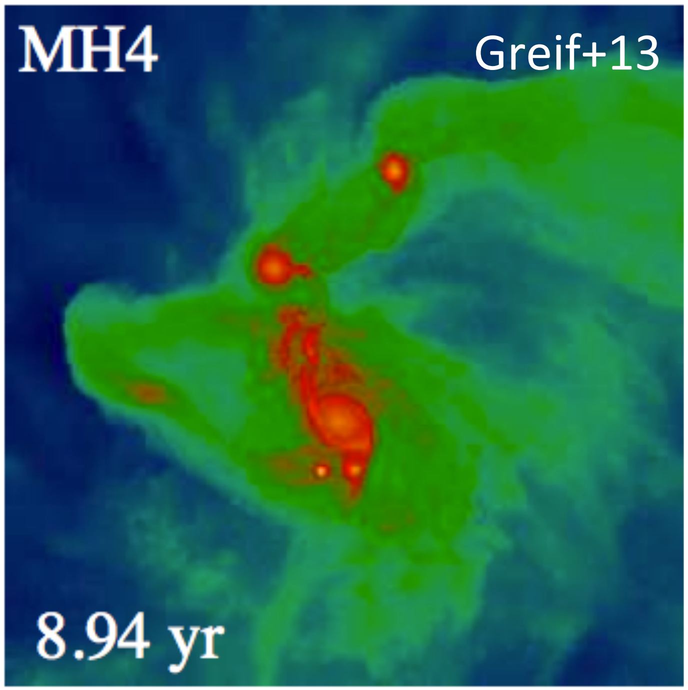
Another case with disk fragmentation

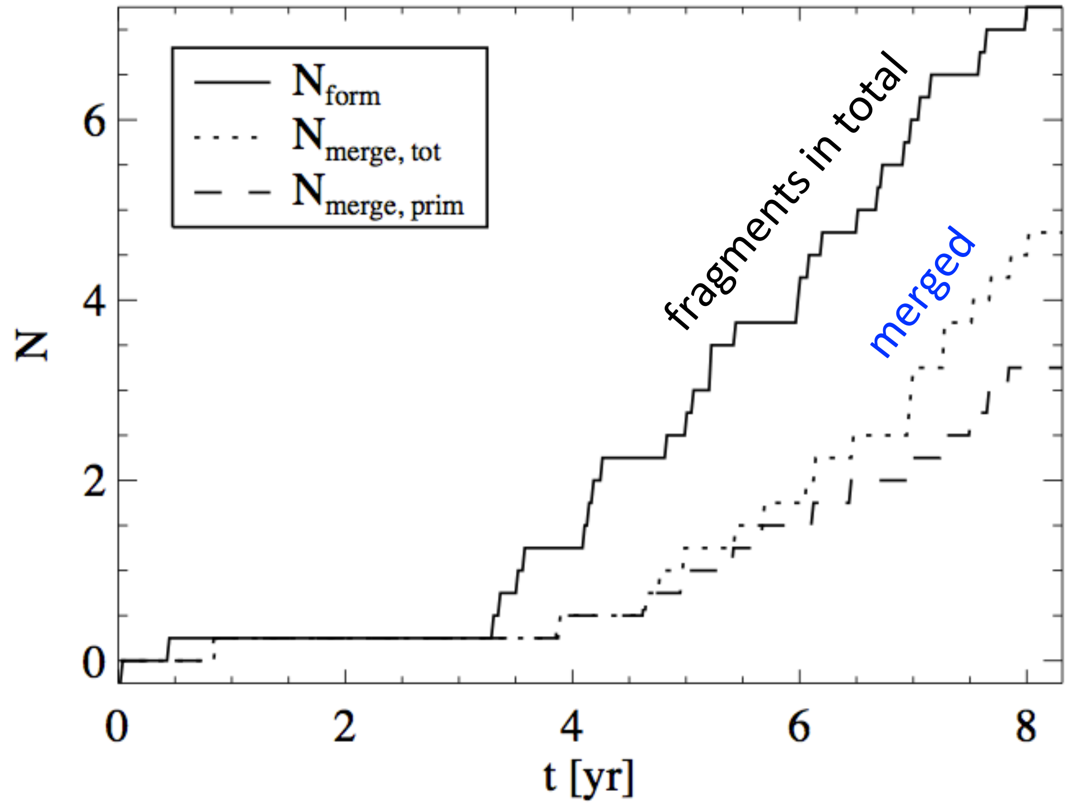


fragments rapidly falls onto the star (type-I migration)
→ the final stellar mass is not always reduced

Disk Fragmentation and Merger

frequent fragmentation, but followed by lots of mergers

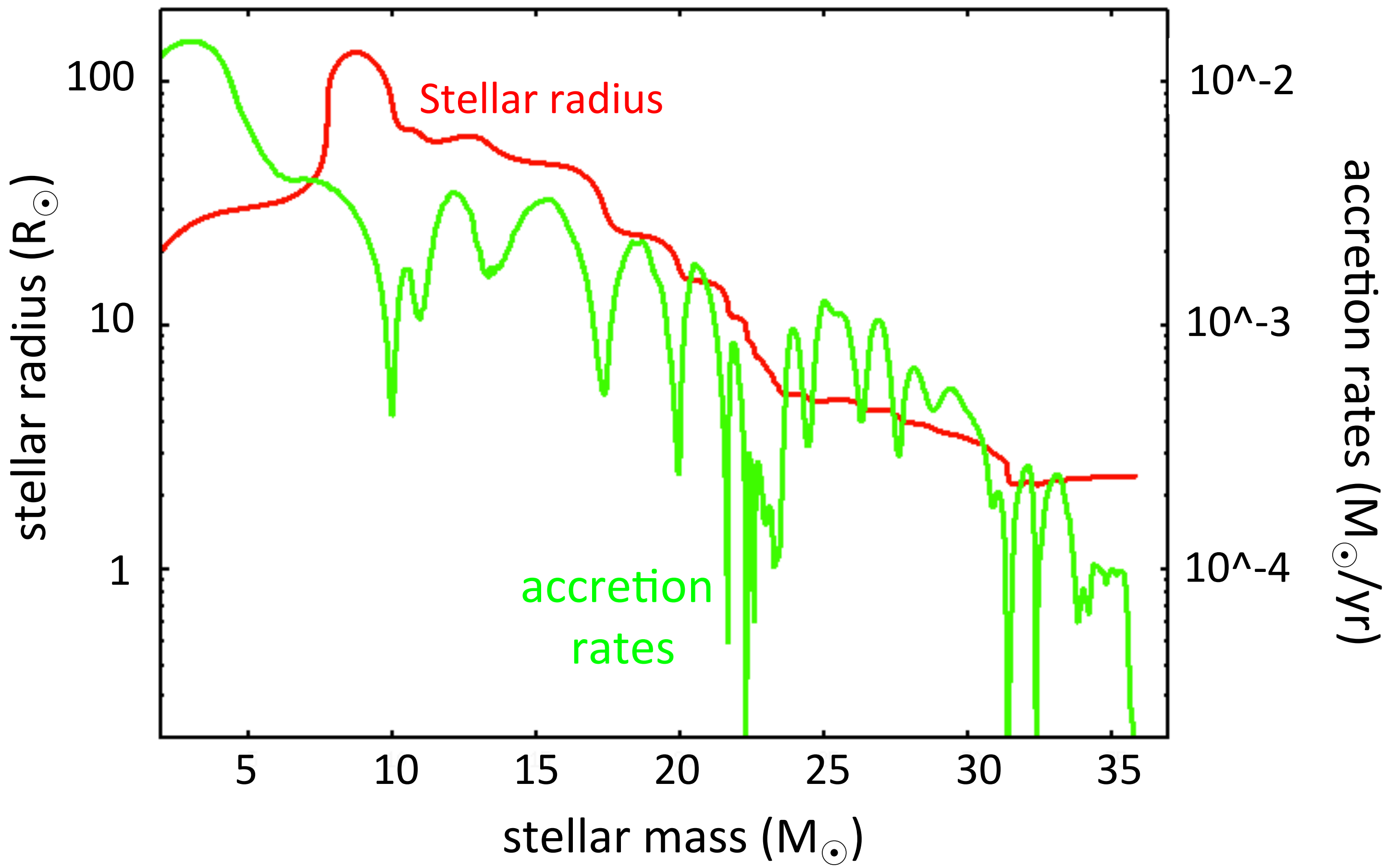




2/3: merged, 1/3: gravitational ejection

Final stellar mass should be determined with the balance between these competing effects (+UV feedback)

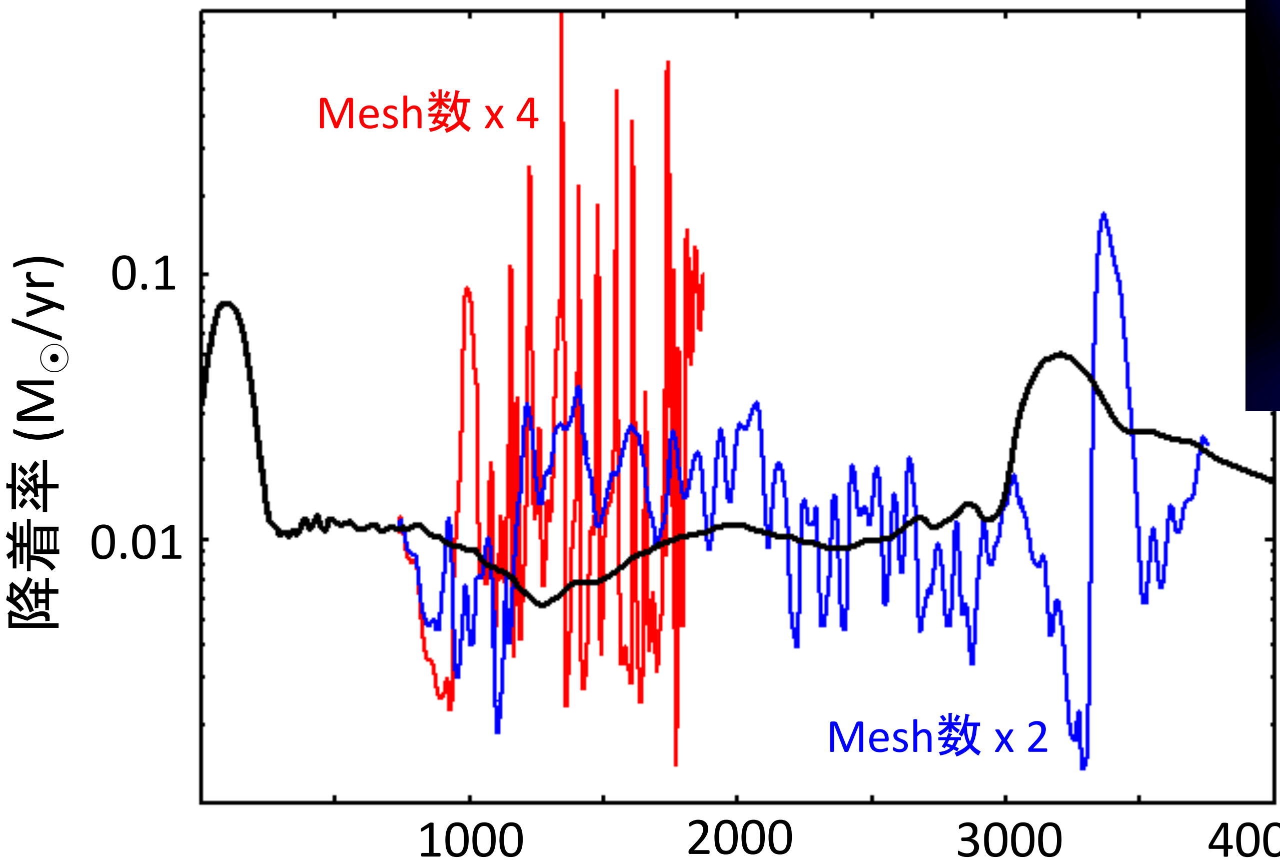
Stellar Evolution + Variable Accretion

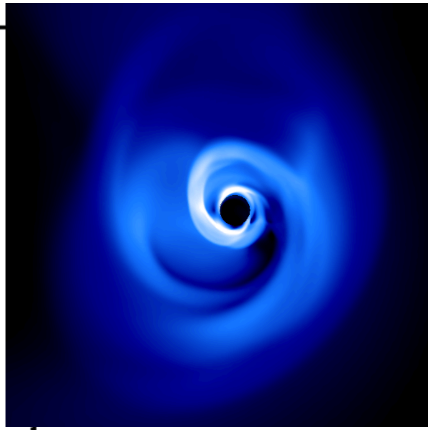


+ Very-time dependent mass accretion with the angular momentum transport in a gravitationally unstable disk

+ Stellar evolution is simultaneously solved with the variable mass accretion

3D効果: Episodic Accretion





赤道面密度分布
(mesh数x4の場合)

原始星へのガス降着率は、はげしく時間変動する (e.g., Vorobyov+13)
高分解能ではより激しい時間変動