Formation of Massive Pop III Stars under Radiative Feedback

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< References >

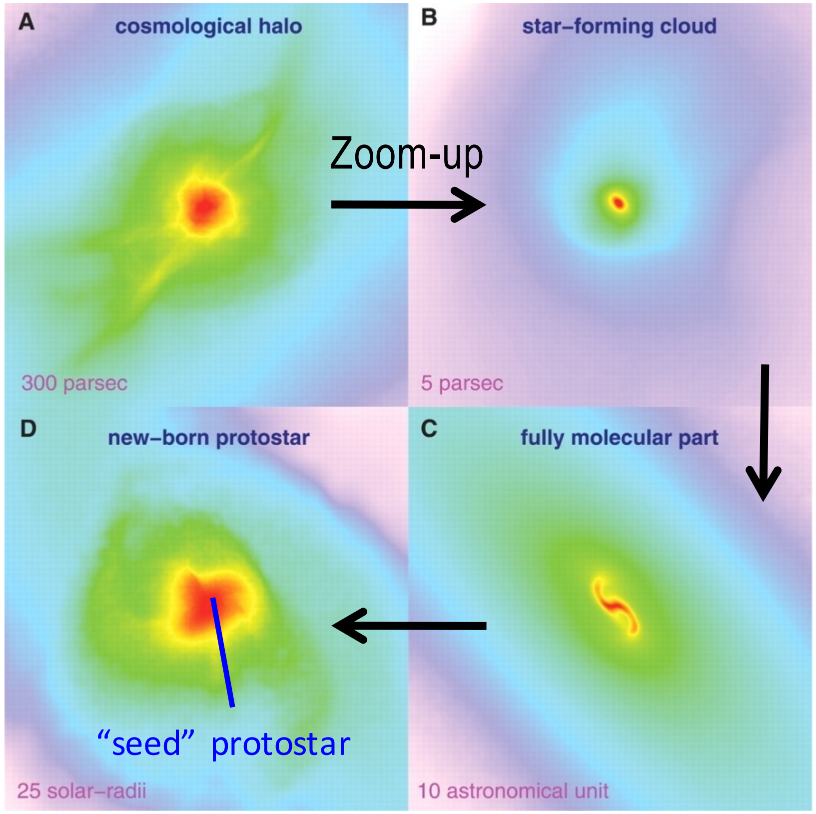
Hirano, TH, Yoshida et al. (2014) ApJ 781, 60, (2015) MNRAS, 448, 568
TH, Hirano, Kuiper, Yorke, Omukai & Yoshida, (2016), ApJ, in press
Sakurai, Vorobyov, TH, Yoshida, Omukai & Yorke, (2016), MNRAS, in press

⁂ 23.Jun.2016@KITP ⁂

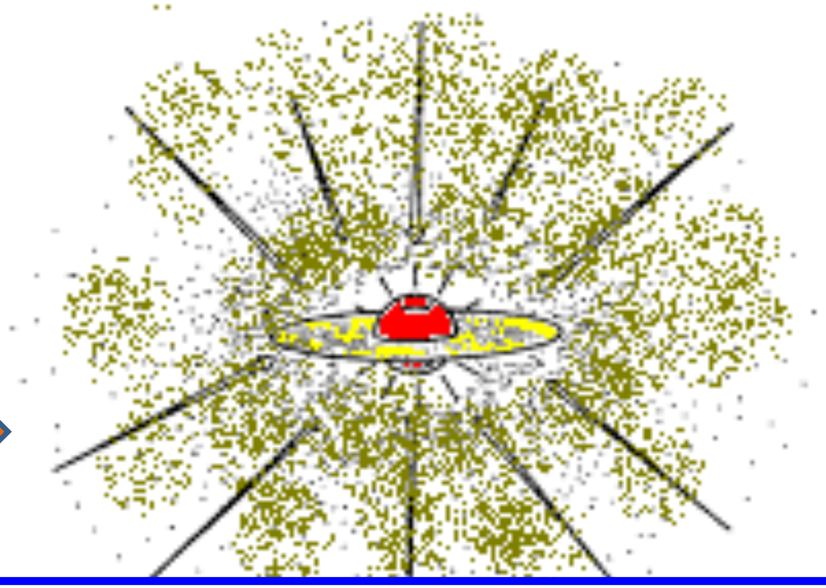
Pop III stars: How massive?

early collapse stage ⇒ late accretion stage

Yoshida, Omukai & Hernquist (2008)



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



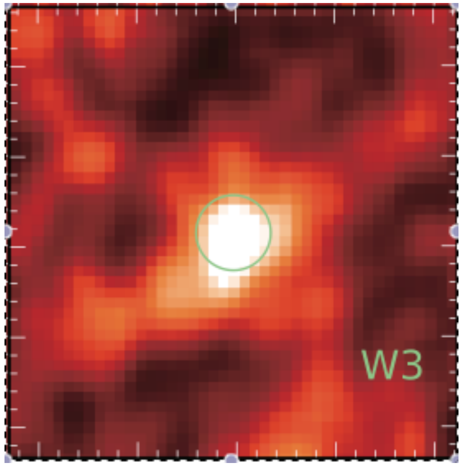
$$\dot{M} \sim \frac{M_{\rm J}}{t_{ff}} = \frac{c_s^3}{G} \sim 7 \times 10^{-4} M_{\odot}/{\rm yr} \left(\frac{T}{300\ {\rm K}} \right)^{3/2}$$

for stellar lifetime (∼Myr) → $\sim 1000 M_{\odot}$ star

The final stellar mass is fixed when the mass accretion ends

The first SMBHs?

A number (∼10) of very bright QSOs have been found beyond redshift 6



+ $M_{BH} \sim 2 \times 10^9 M_\odot$ @ z= 7.085
(Mortlock et al. 2011, Nature)

+ $M_{BH} \sim 1.2 \times 10^{10} M_\odot$ @ z=6.3
(Wu et al. 2015, Nature):

Age of the universe@z∼7: 0.77Gyr. Get them quickly before this

If a Pop III remnant BH (∼$100M_\odot$) grows via Eddington accretion…

$$t_{\rm grow} = 0.05 \log\left(\frac{10^9\ M_\odot}{10^2\ M_\odot}\right) \simeq 0.8{\rm Gyr}$$

But 100% of the duty cycle is needed (feedback prohibits this)

Key Questions

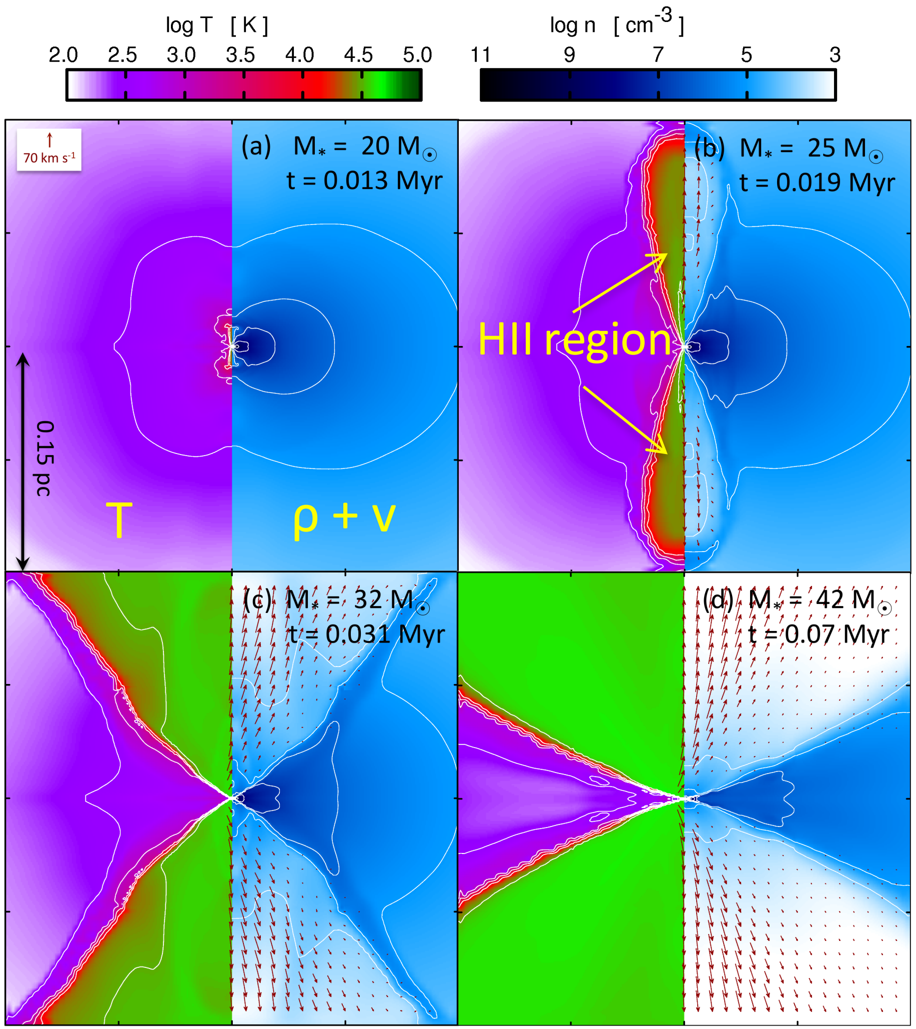
+ What is the final mass of the first stars, resulting from the evolution in the accretion phase?

+ What is the maximum mass of the first star?
Is it possible to seed SMBHs in the early universe?

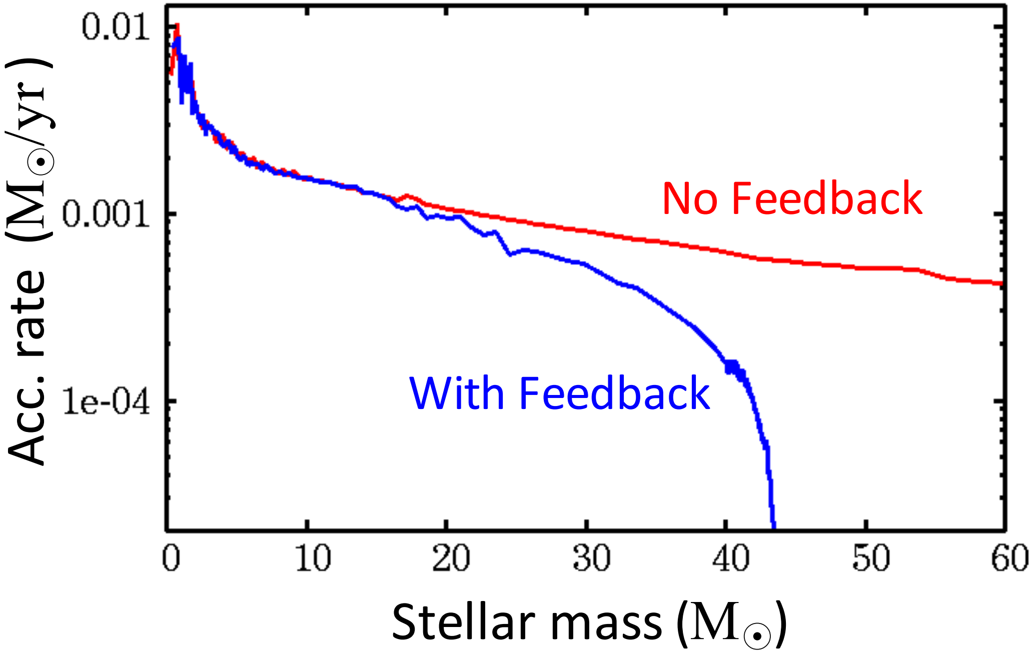
Study the late evolution in the accretion stage to answer these questions

But actually there are *two potential barriers* against formation of very massive stars:
① stellar UV feedback, ② fragmentation

① UV feedback



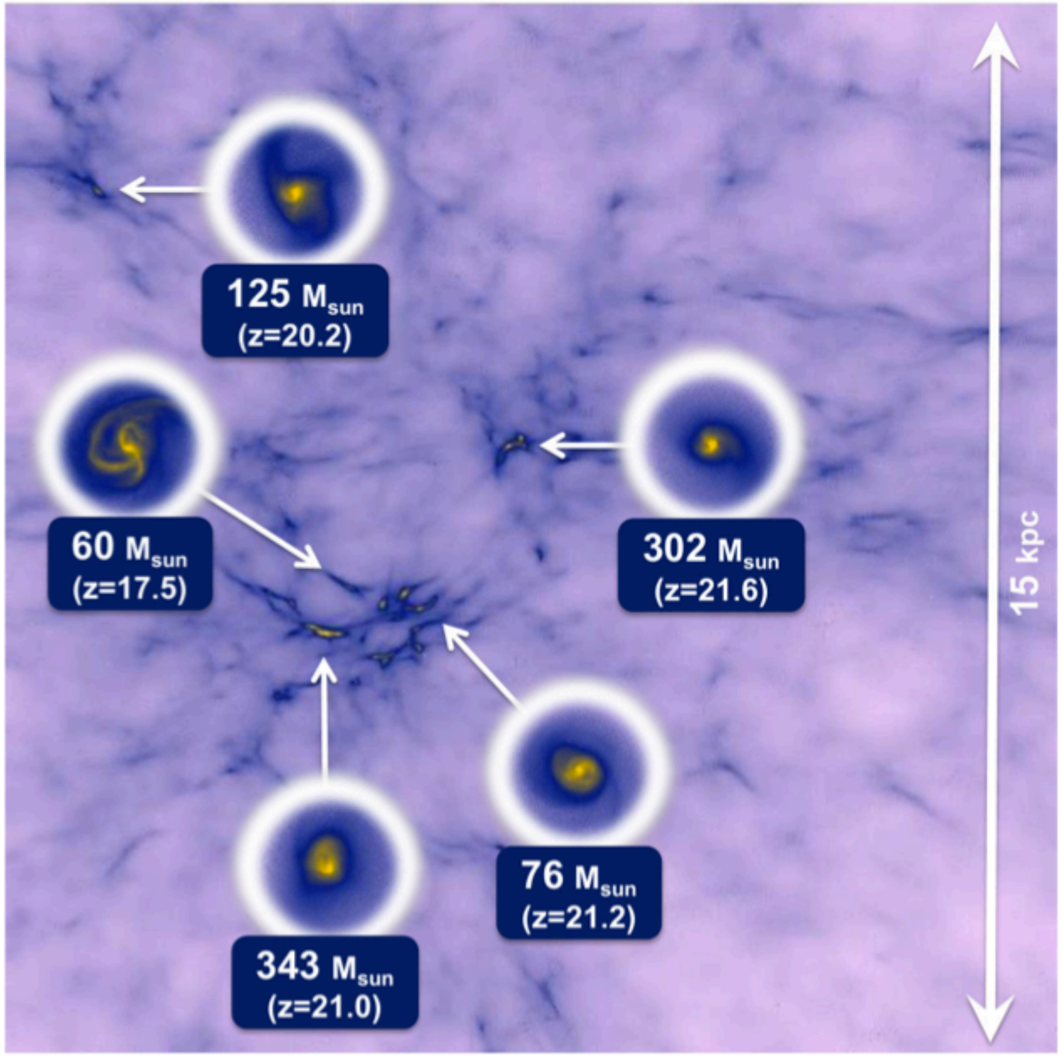
McKee & Tan 08, TH+11,
Stacy+12, Susa13 etc.

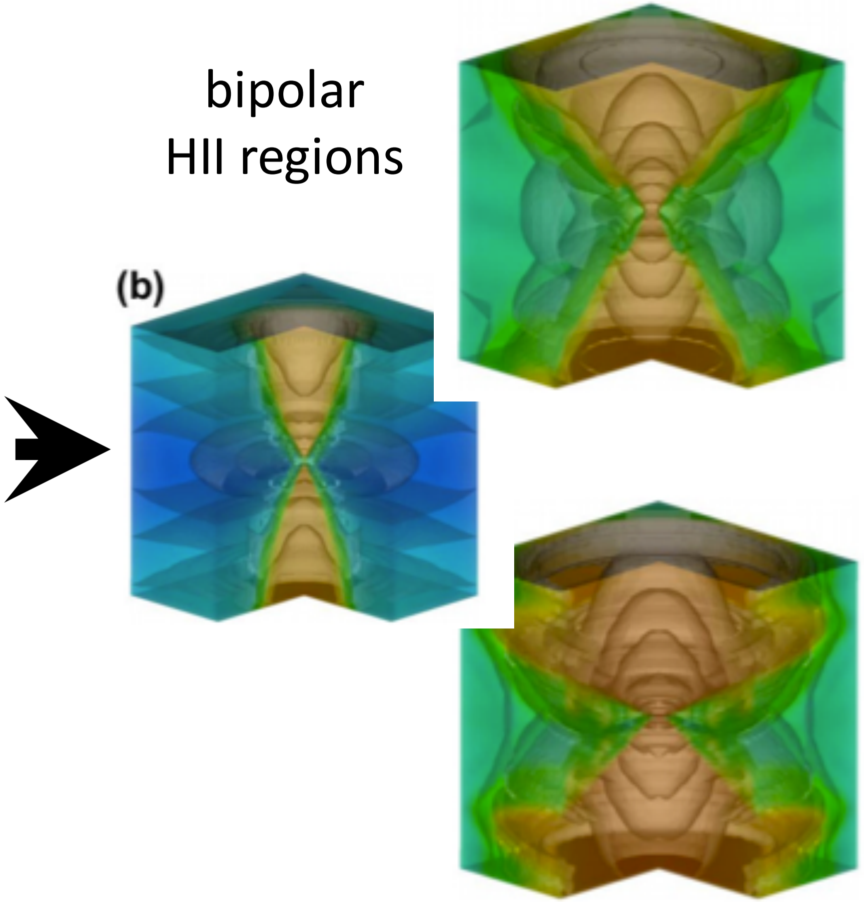


- ➢ Acc. rate is significantly reduced by the stellar UV feedback
- ➢ How possible to form very massive stars?

Forming >100 Pop III 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, Yoshida et al. 2014)



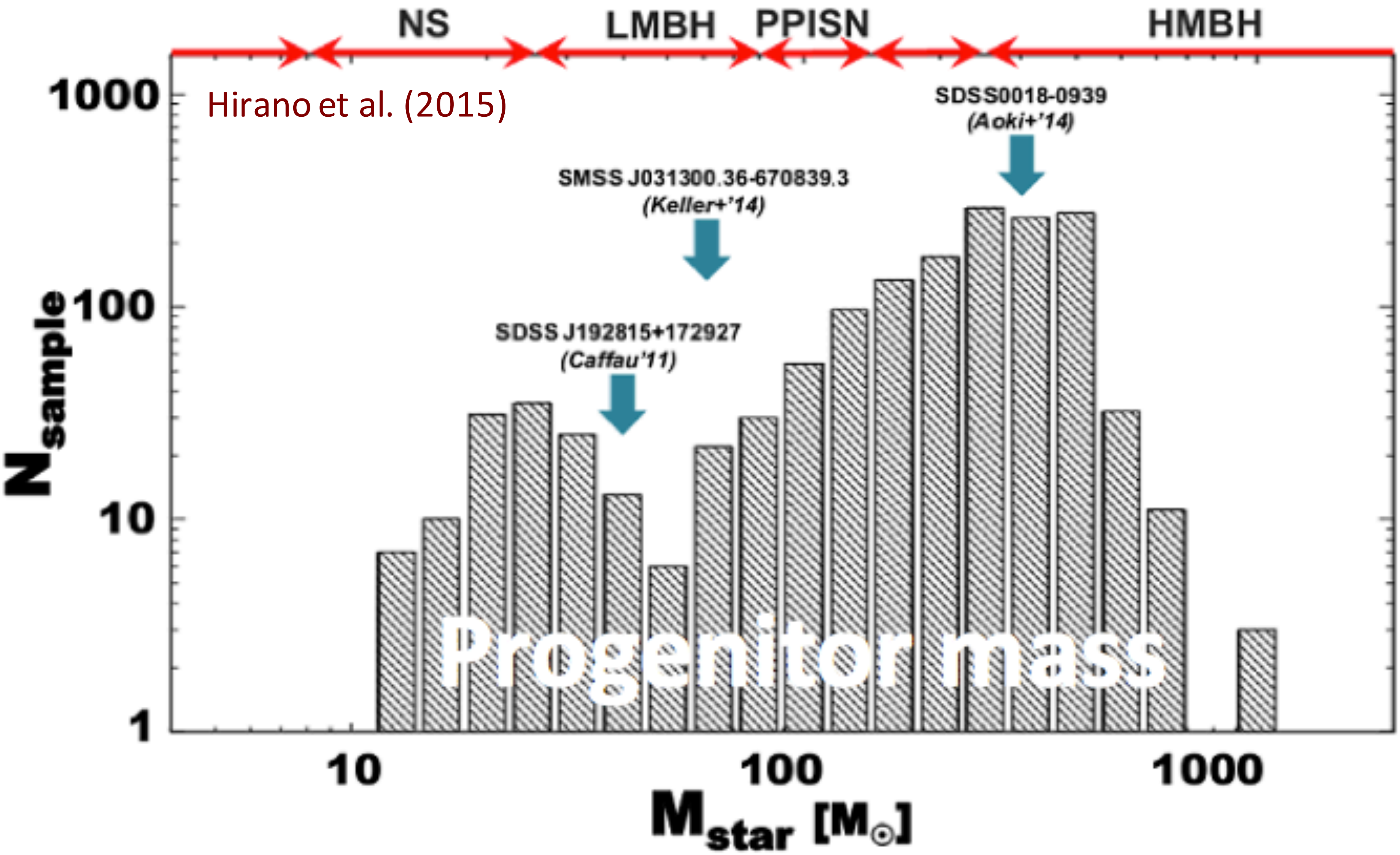


bipolar
HII regions

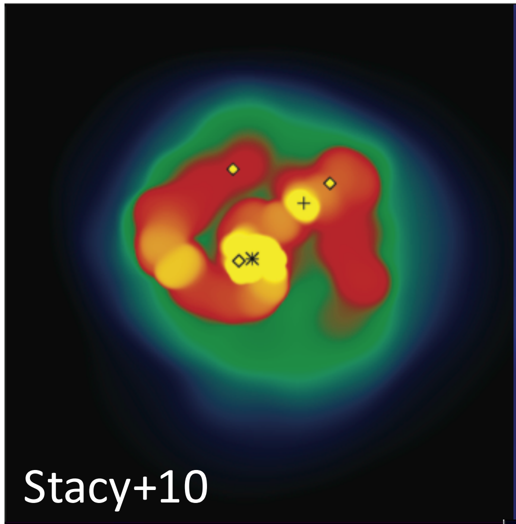
The UV feedback finally shuts off the mass accretion in all the cases

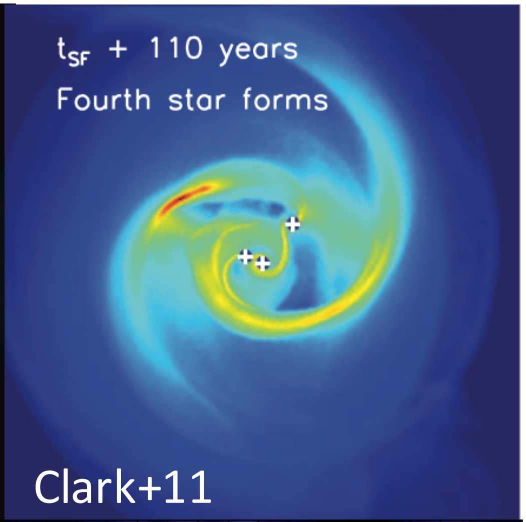
The “Mass Spectrum”

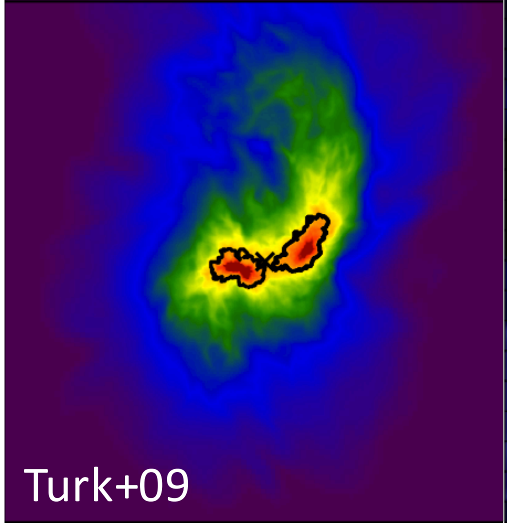
With more than 1000 (!) star-forming clouds taken from cosmological simulations

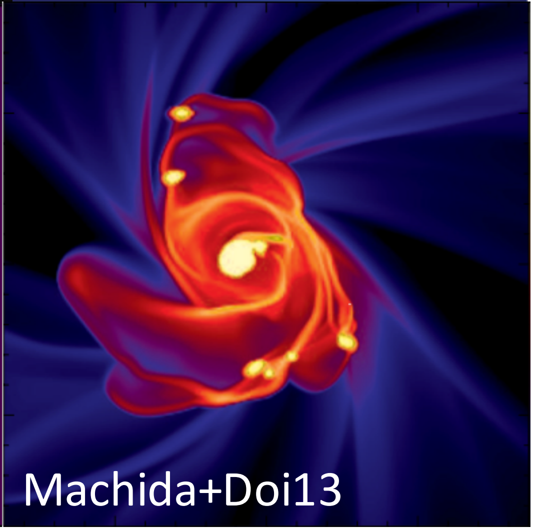


② Disk Fragmentation









caused by the gravitational instability

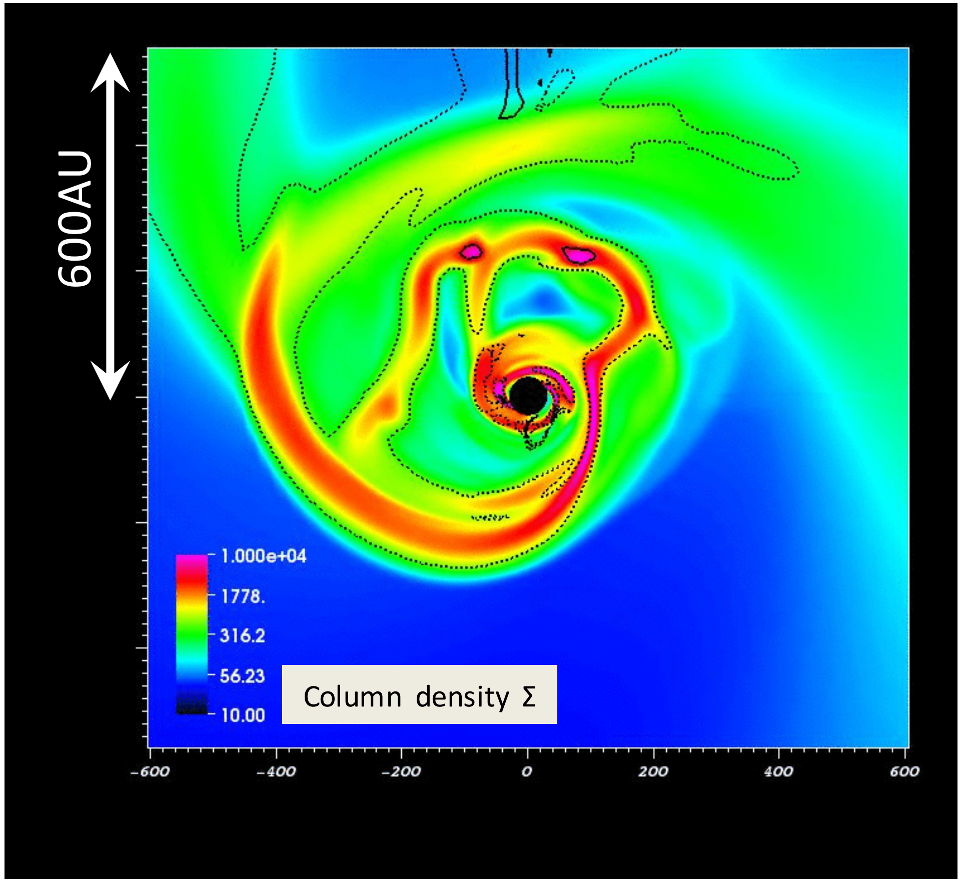
↓

A cluster of lower-mass stars instead of massive stars?

Let us move on to
3D simulations!

Fragmentation, and massive stars?

3D radiation hydro sims. (TH, Hirano, Kuiper et al. 2016, ApJ, in press)



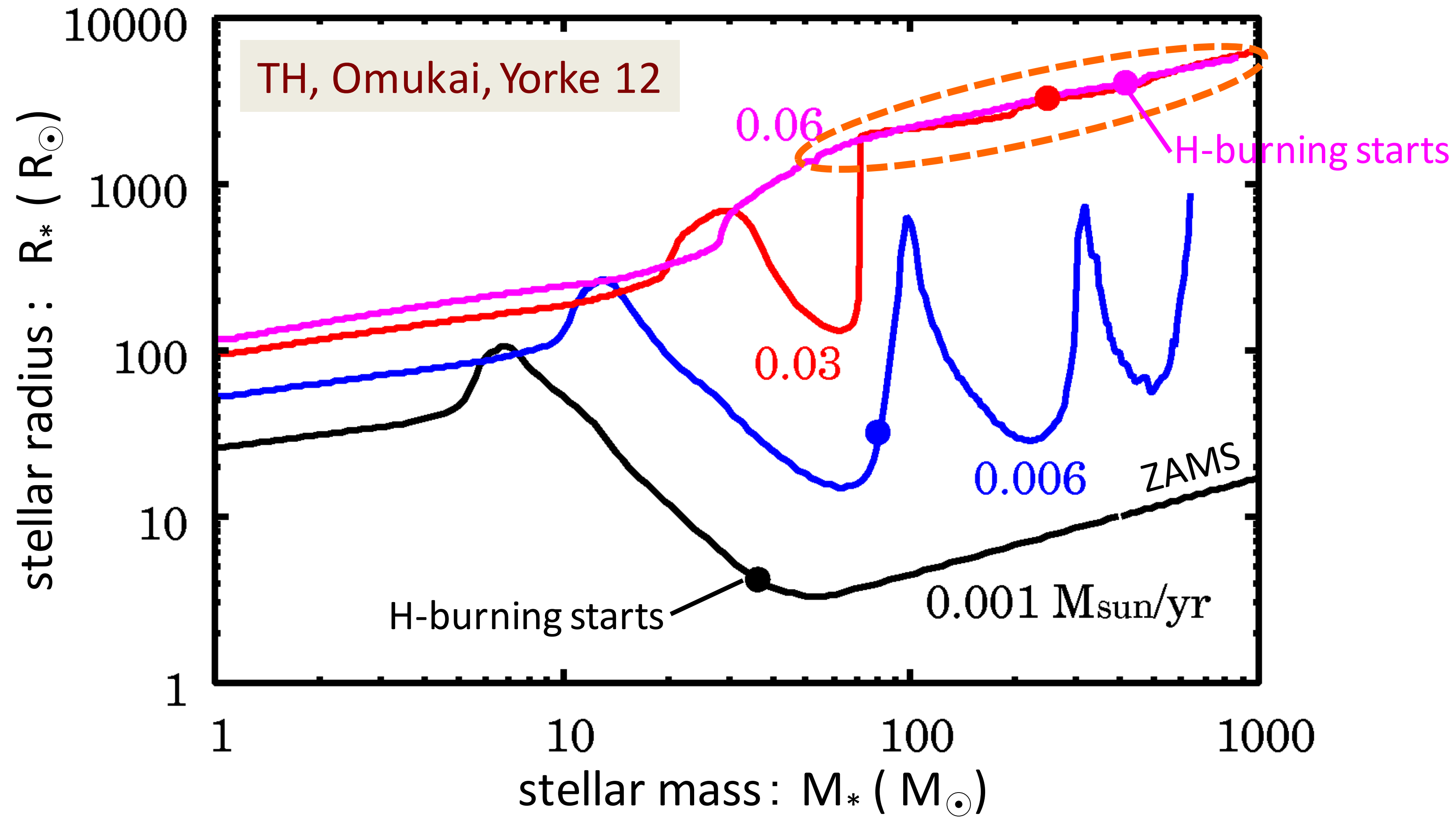
Evolution over ～100 yrs

Contour: Toomre Q parameter
solid: Q=0.1, dotted: Q=1.0

Fragments rapidly migrate inward toward the central star by gravitational torque
(type-I migration)

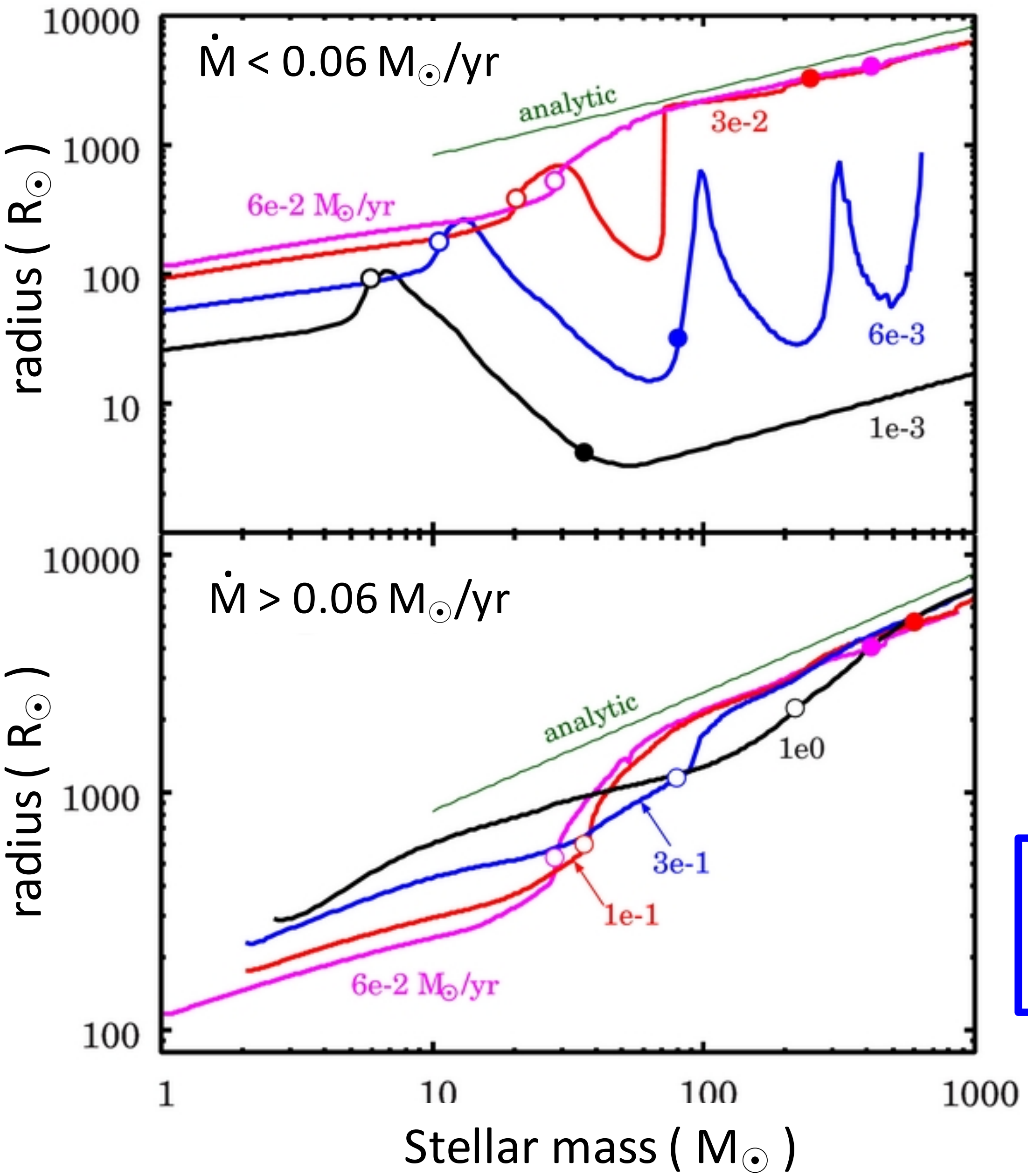
Accretion bursts
with disk fragmentation
↓
Very rapid mass accretion
for short durations
↓
Stellar structure changes

“Supergiant Protostar”



- The protostar never contracts to reach the ZAMS stage, but largely expands with very rapid accretion, > 0.01 M⊙/yr.
- large radius → low effective temperature → weak UV feedback

Physics



Stellar luminosity: L_*

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

+

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

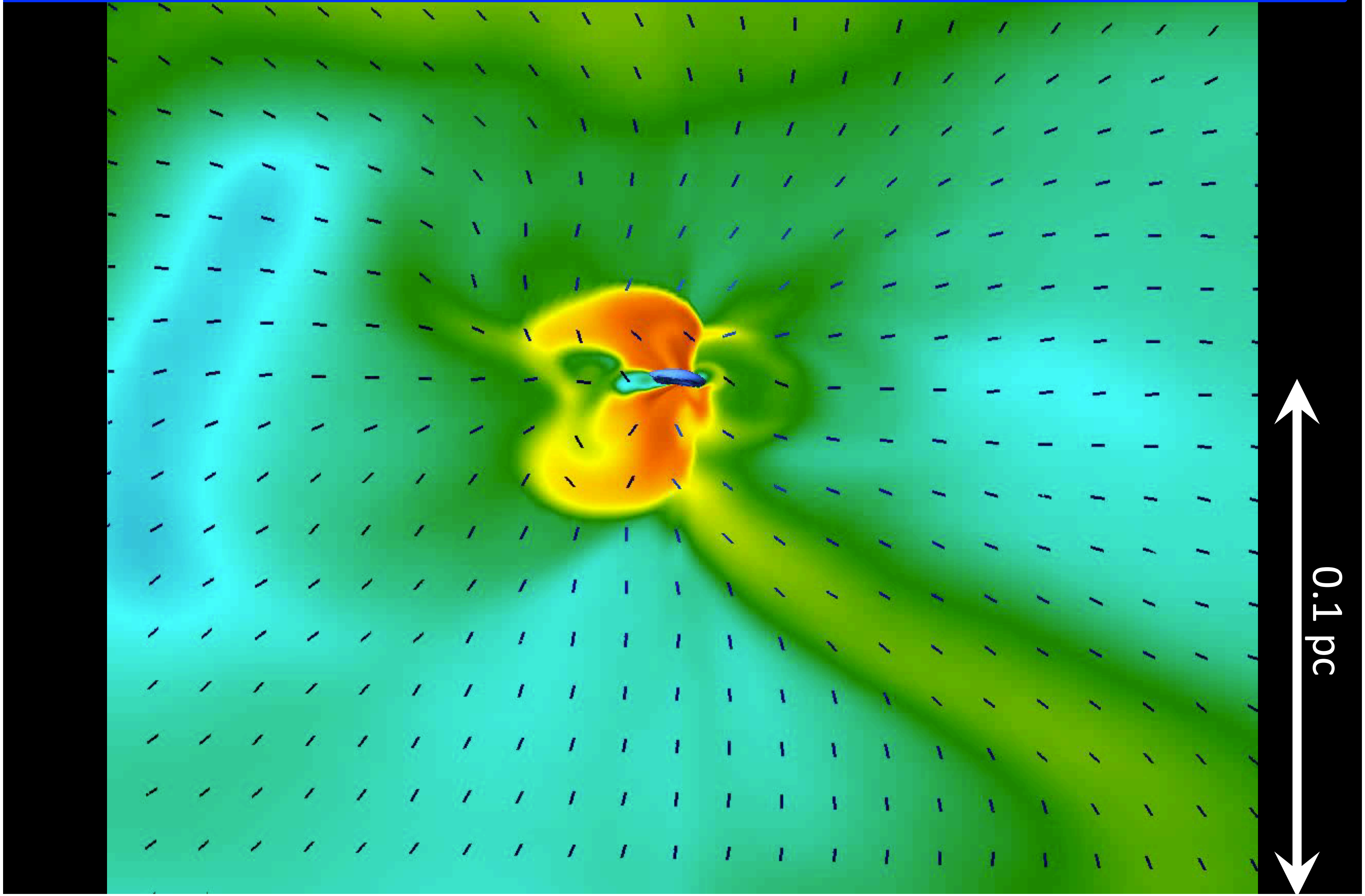
+

Effective temperature is almost locked around 5000 K.
(due to strong T-dependence of H- opacity) c.f. Hayashi track

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

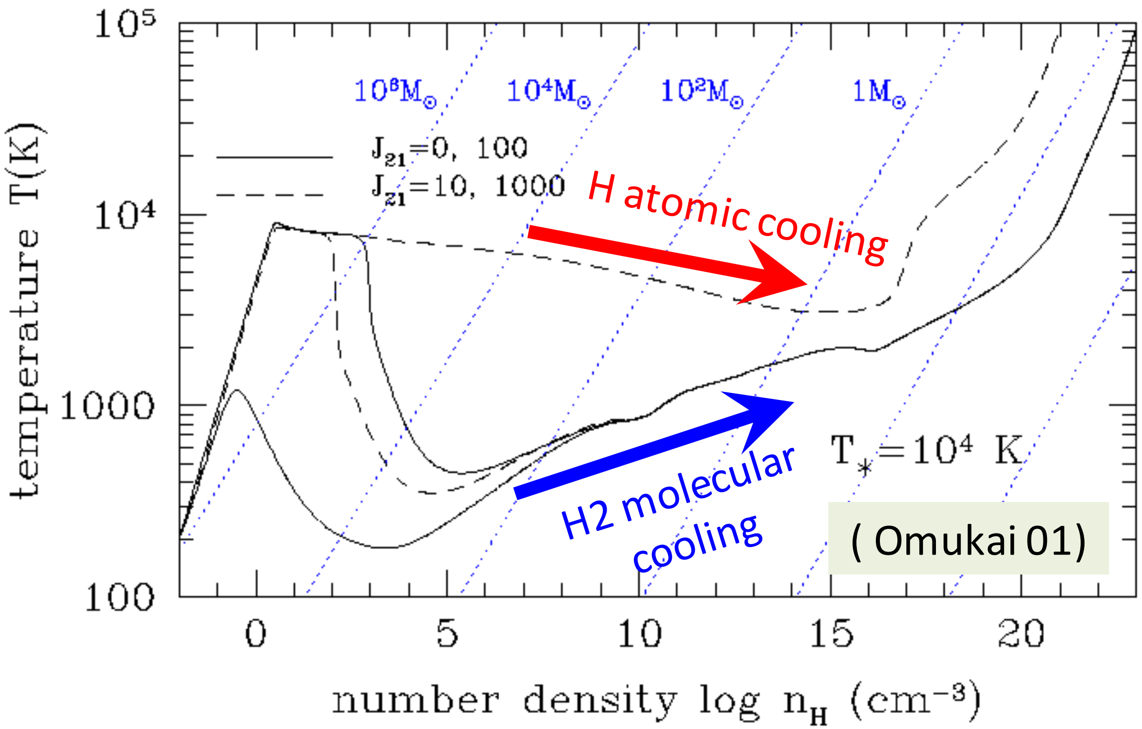
agrees well with the numerical results

Extinction and re-formation of HII regions are repeated.
Mass accretion is not efficiently stopped by such intermittent feedback



Supermassive Stars ($\sim 10^5 M_\odot$) !?

A special case among Pop III star formation (Direct Collapse)



① primordial cloud exposed by strong UV radiation from nearby stars (destroying H2 molecules)

② collapse via H-atomic cooling (nearly isothermally at T～8000K)

③ stellar growth via very rapid mass accretion (> $0.1 M_\odot$/yr)

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

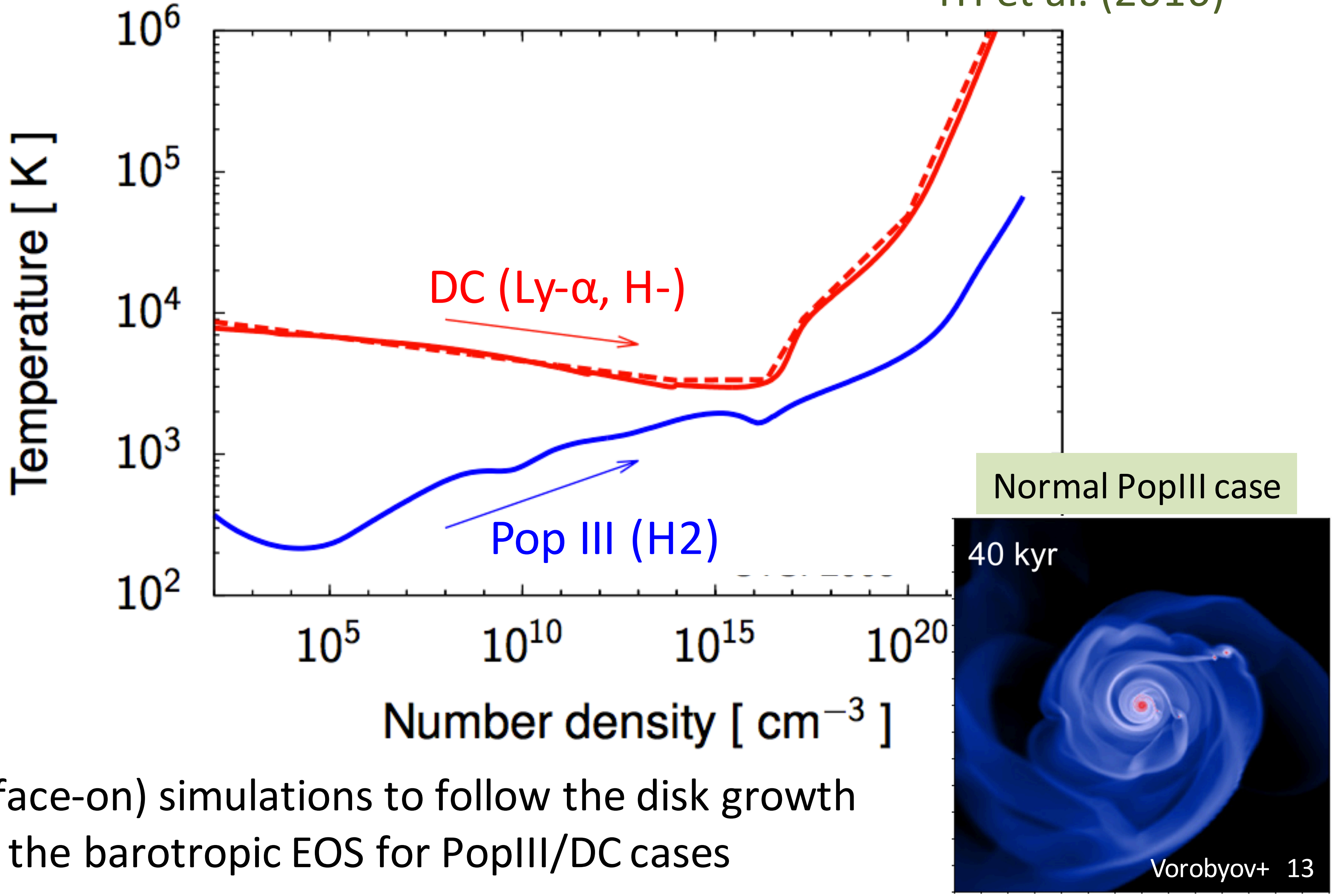
- Is this really possible？
- UV feedback + disk fragmentation do not prevent the stellar mass growth?

④ Gravitational collapse of the star via GR instability → $10^5 M_\odot$ BH

Hydro Simulations

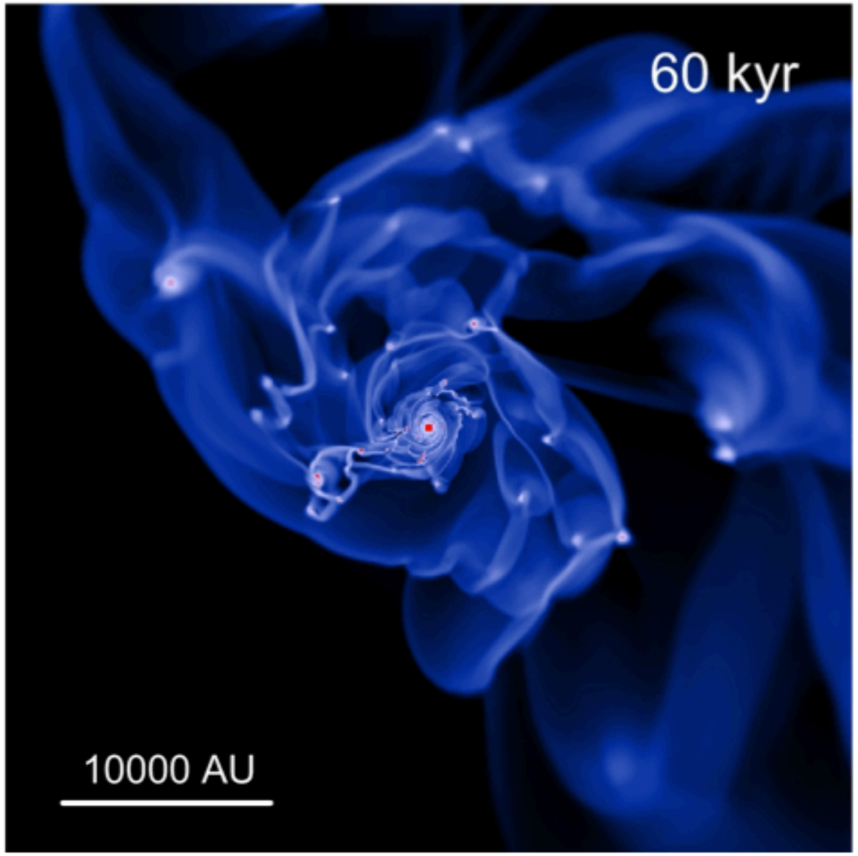
Normal Pop III *v.s.* Direct Collapse

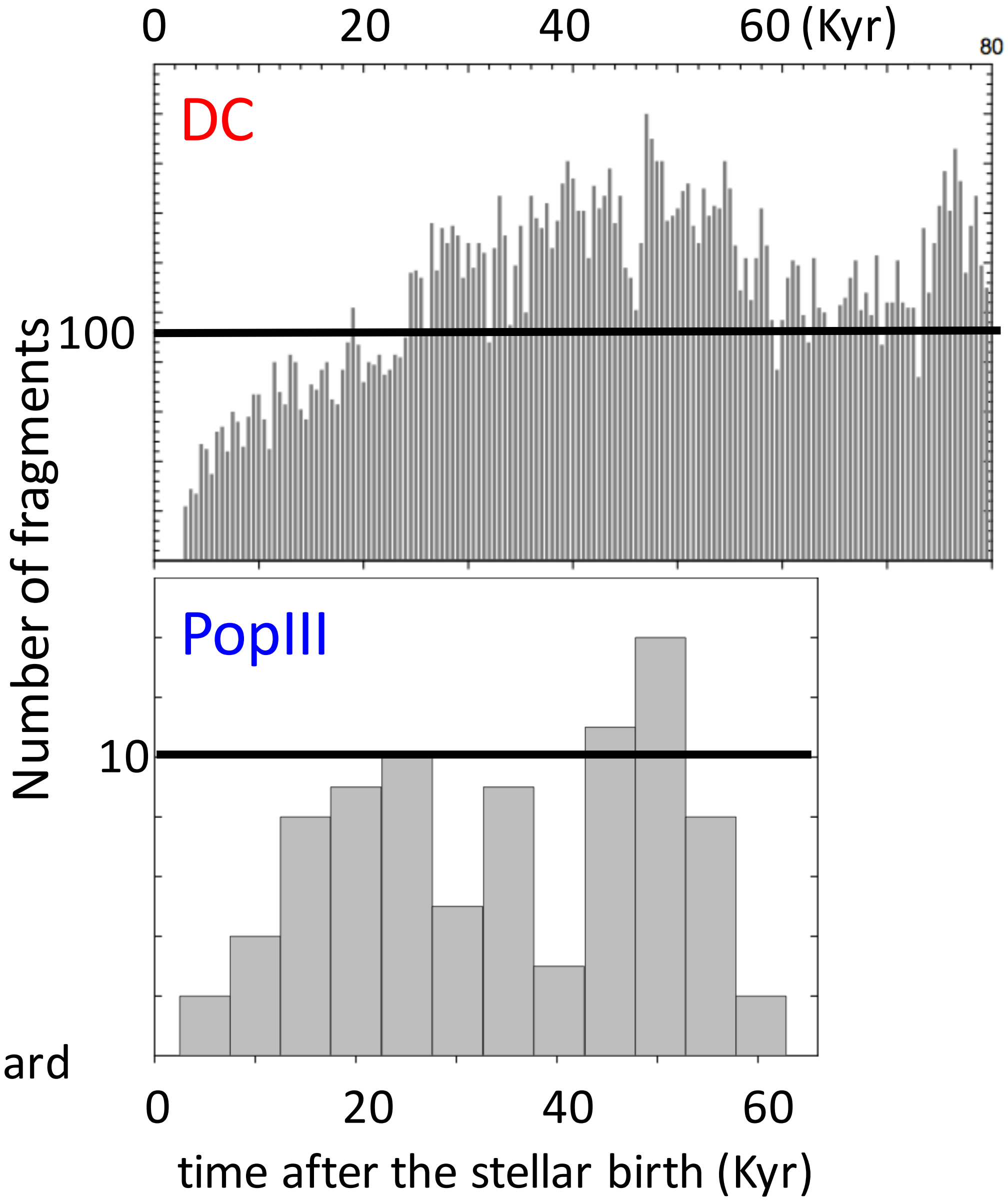
Sakurai, Vorobyov, TH et al. (2016)



2D (face-on) simulations to follow the disk growth with the barotropic EOS for PopIII/DC cases

Disk Fragmentation: DC *v.s.* Pop III



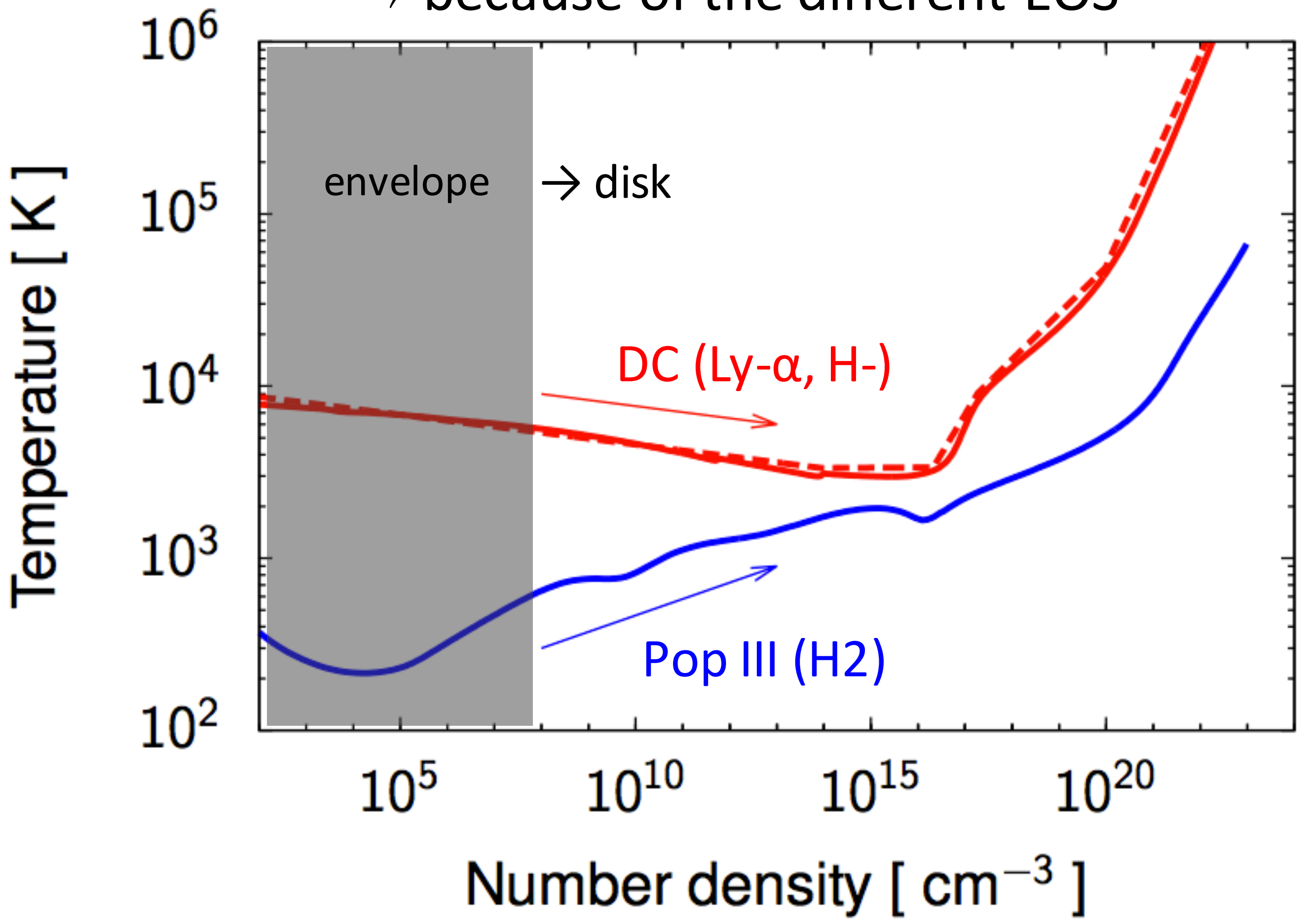


+ DC case shows more unstable disk with greater number of fragments

+ Most of the fragments rapidly migrate inward to feed the central star
(ejection also occurs, but much rarer)

Why so unstable disk?

⇒ because of the different EOS

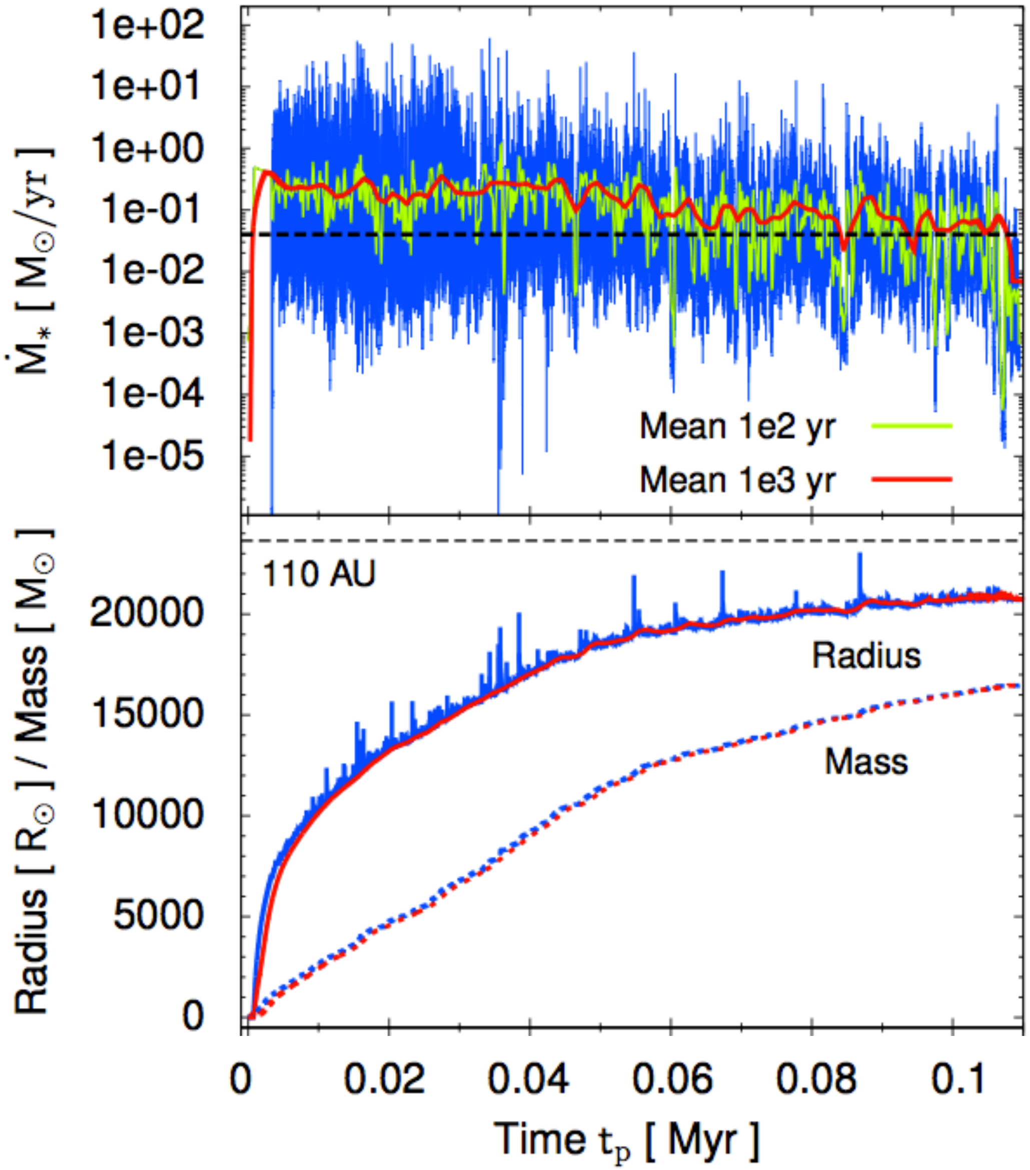


disk stability: mass transfer rate through the disk *v.s.* mass supply rate from the envelope to the disk

$$Q \sim \mathcal{O}(1) \times (T_{\rm disk}/T_{\rm env})^{3/2}$$

negative slope of N-T curve → smaller Q → more unstable disk

Stellar Evolution and Feedback



Much more variable accretion than in normal Pop III case

How is the stellar evolution with such very rapid and variable acc.?

Stellar evolution calculations (post-process)

→ The star never contracts because variability timescale is too short to modify the stellar structure

→ very week UV feedback

Summary

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

→ Ordinary massive ($M_* < 100\ M_\odot$) stars should form, but also with a number of $M_* > 100\ M_\odot$ stars

+ What is the maximum mass of the first star?
Is it possible to seed SMBHs in the early universe?

→ Some (rare) favorable conditions may allow the formation of extremely massive stars (even $> 10^3 M_\odot$), circumventing the UV feedback and disk fragmentation.