初代天体

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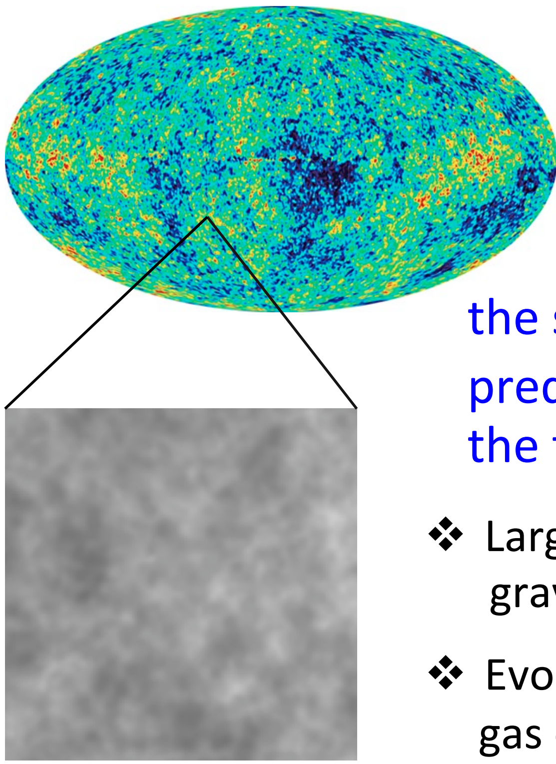
+ final mass of the first stars and radiative feedback
+ the mass distribution of the first stars
+ origin of the supermassive black holes in the early universe

23.March.2014 SKA研究会@東大本郷

初期宇宙での星形成

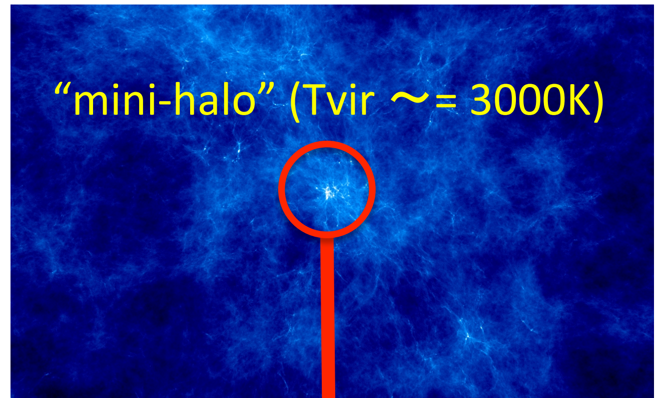
CMB → 初期密度ゆらぎ



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

- ❖ Large-structure forms via gravitational instability
- ❖ Evolution of baryons: gas dynamics, chemistry, radiative processes…

ダークマターの大規模構造



星形成過程

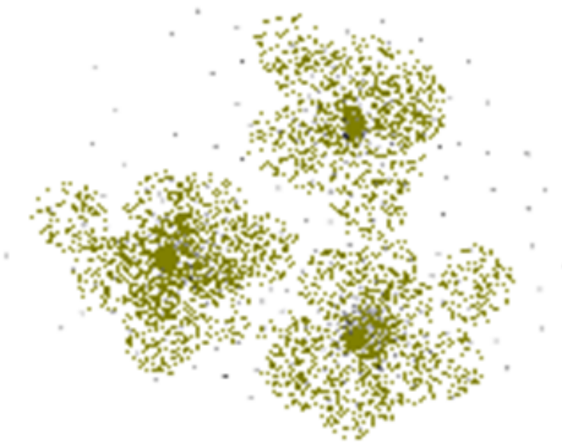
初代星

初代星形成は初期条件の定まった星形成の問題 (well-defined!)

星形成のながれ

Collapse(前期)段階

ガス雲が自己重力により収縮



ガス雲質量: $M_{\rm J} \propto \rho^{-1/2} T^{3/2}$

(free-fall time = sound crossing time)

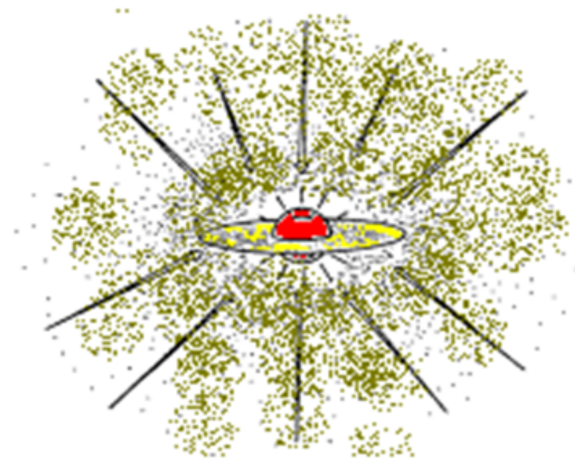
EOS: $P \propto \rho^{\gamma} \rightarrow M_{\rm J} \propto \rho^{(3\gamma-4)/2}$

$\gamma<4/3$のとき $\rho\uparrow \Rightarrow M_{\rm J}\downarrow$; 不安定→collapse

γは冷却過程による (初期宇宙ではH2分子線放射)

Accretion(後期)段階

原始星へ周囲からガスがふりつもる



冷却効率がさがり (γ>4/3)

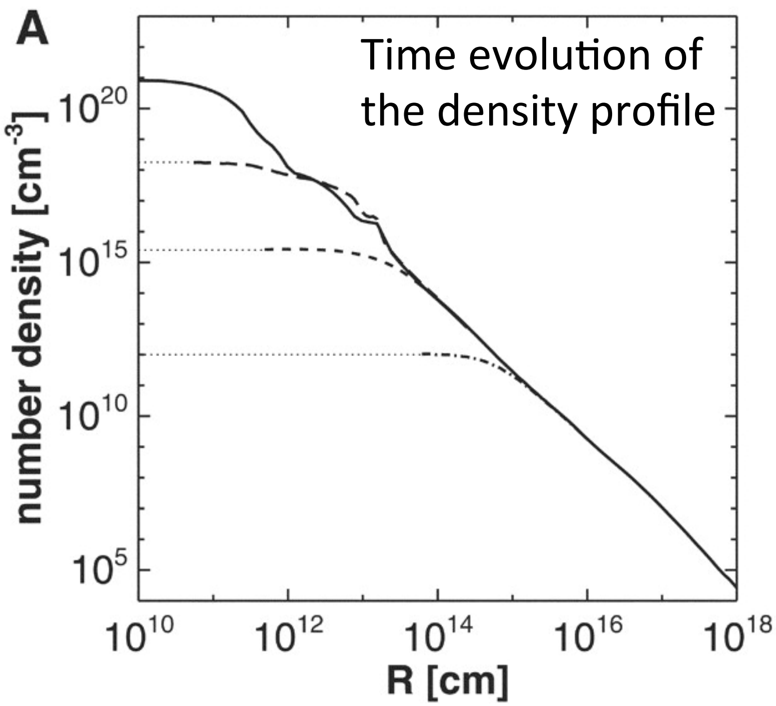
星の種(=原始星)が生まれる

原始星への降着率:

$$\dot{M} \sim \frac{M_{\rm J}}{t_{ff}} \propto T^{1.5}$$

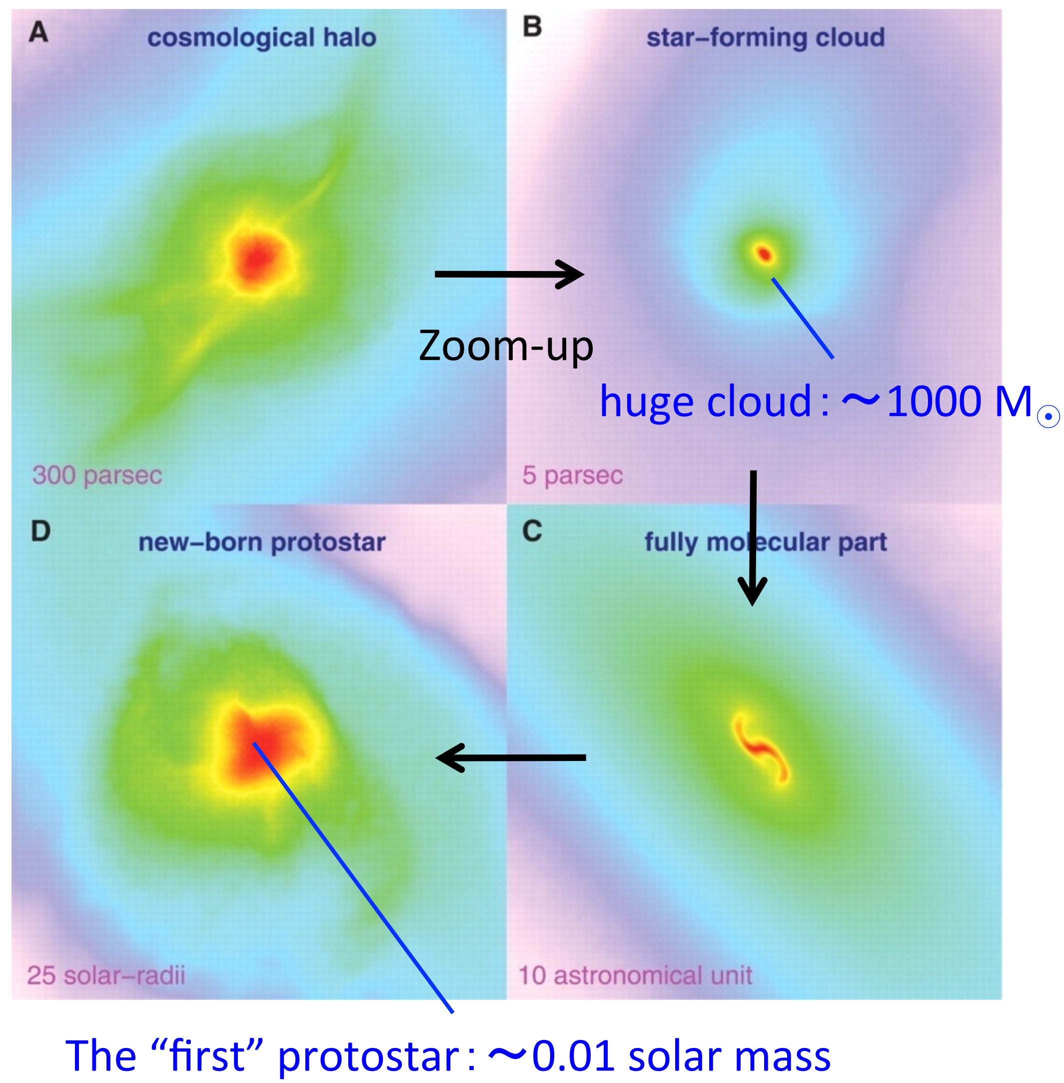
初代星形成の前期段階

始原ガス雲の重力崩壊
: self-similar “run-away “ collapse
(e.g., Omukai & Nishi 98, Abel et al. 02)



前期段階の進化は比較的
よく理解されている

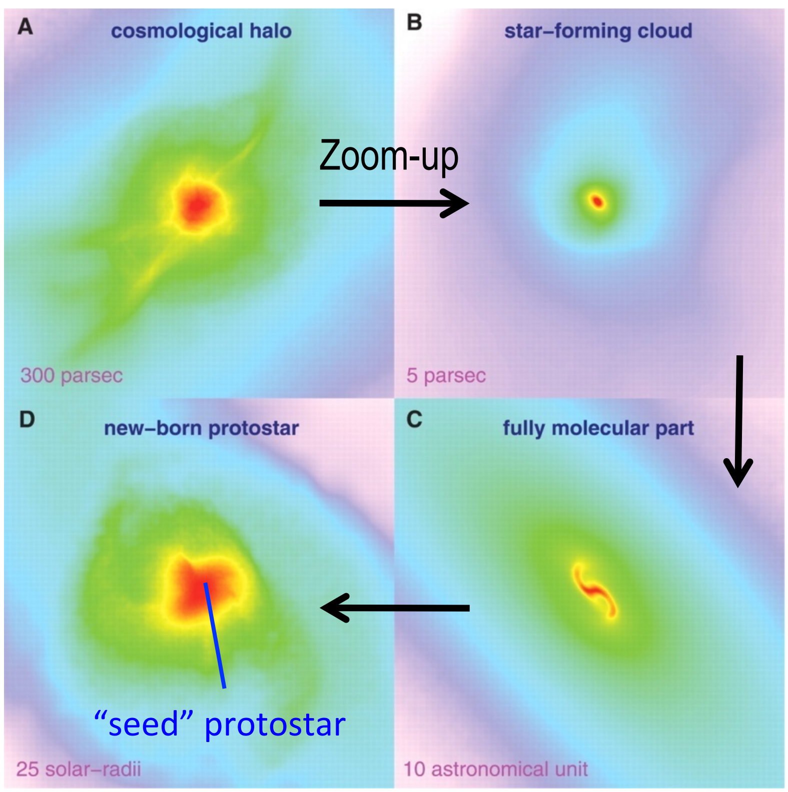
Yoshida, Omukai & Hernquist (2008), Science



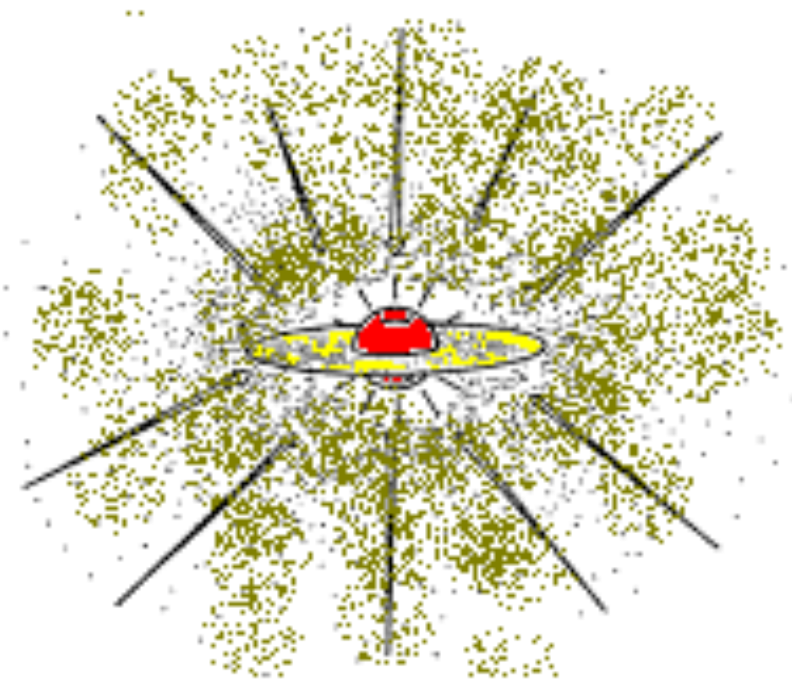
First Stars: How massive?

前期段階: collapse ⇒ 後期段階: accretion

Yoshida, Omukai & Hernquist (2008)



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



最終的な星の質量は質量降着がいつまで続くかで決まる。

後期段階進化の研究が重要

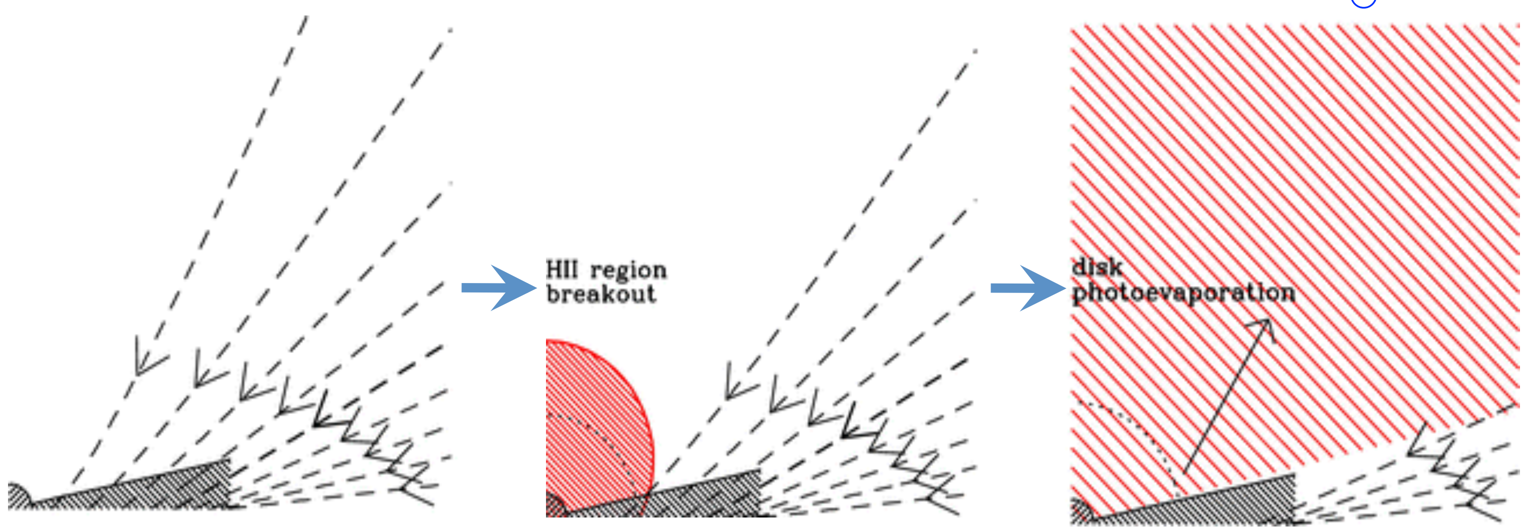
後期段階の進化

予想される降着率: $\dot{M} \sim \frac{M_J}{t_{ff}} = \frac{c_s^3}{G} \sim 7 \times 10^{-4} M_\odot/\mathrm{yr} \left(\frac{T}{300\ \mathrm{K}}\right)^{3/2}$

この降着率が維持されれば、星の寿命(～Myr)間にもとのガス雲の質量全部が星に降り積もれる ⇒ $M_* \sim 1000 M_\odot$

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

電離領域の形成 + 星周円盤の光蒸発 → $M_* \sim 150 M_\odot$?

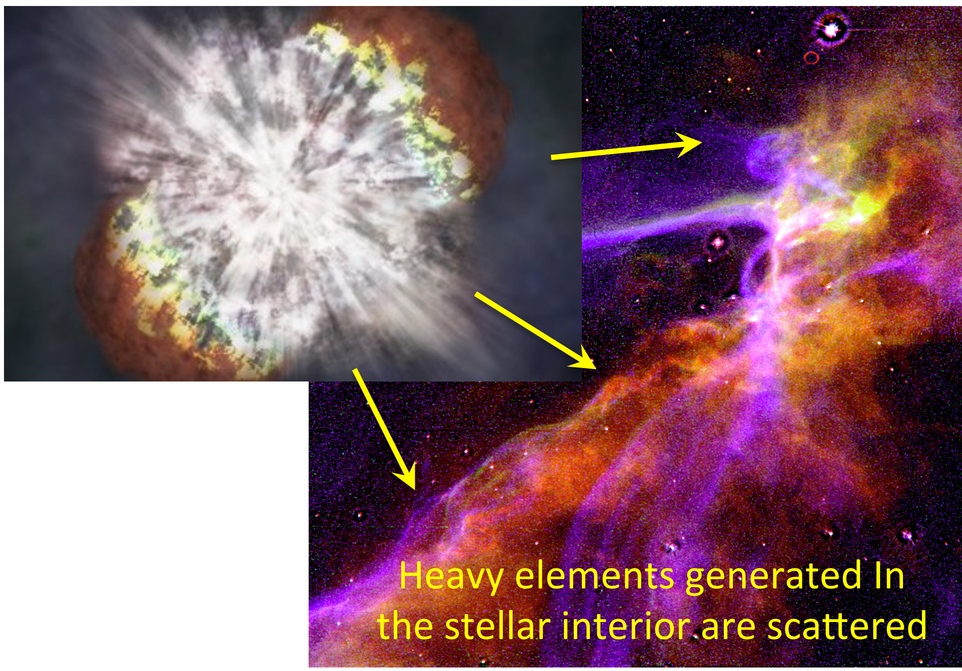


It has been postulated that the first stars were very massive (> 100 $M_\odot$)

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

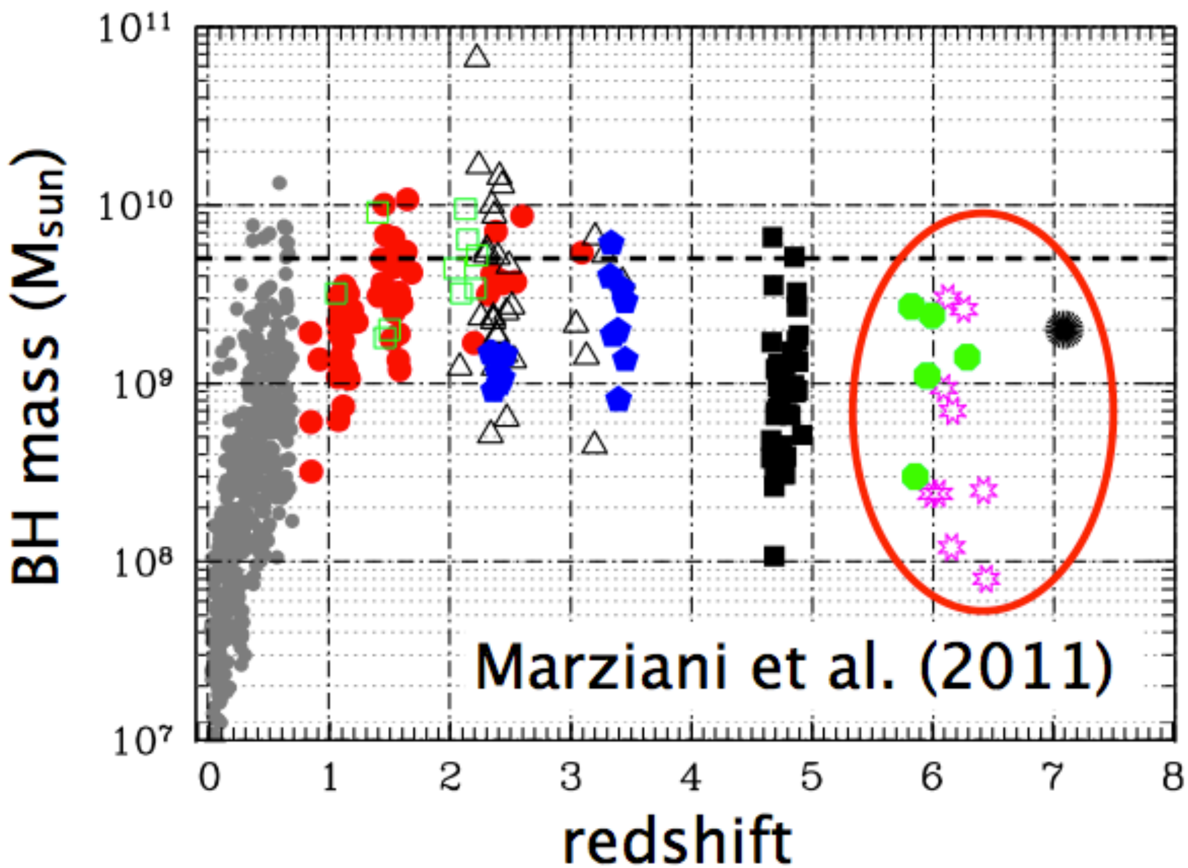


Stars born from the polluted gas have the same abundance patterns as the supernova progenitors

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

Extremely Massive Stars: still needed?

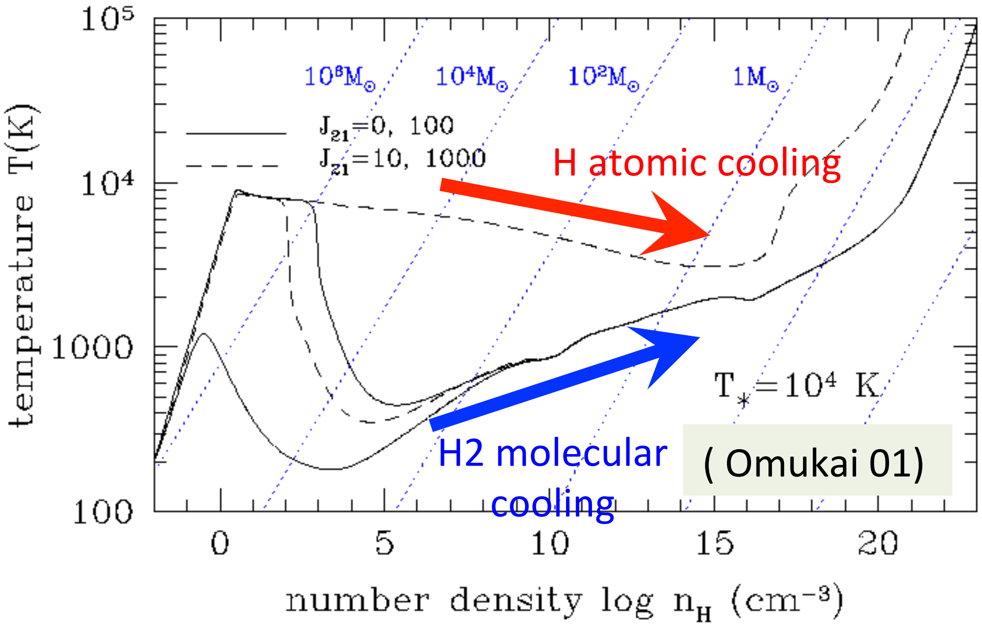
bright QSOs at z > 6 with SMBH of > 10^9 $M_\odot$

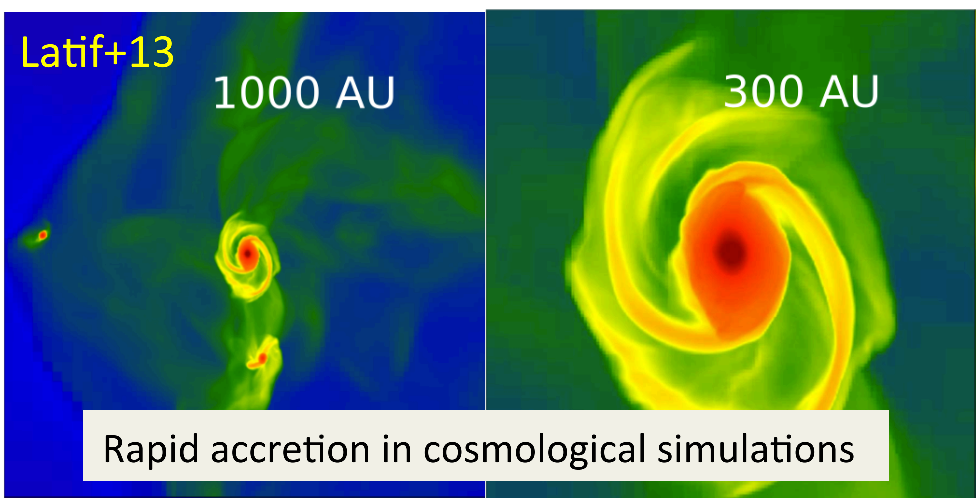


Age of the universe@z～7: 0.77Gyr. これまでに作る必要がある
非常に重い星が残す種BHから出発する方が都合がよい

超大質量星形成 (～$10^5 M_\odot$)

PopIII星形成の特殊なケース





①水素分子が破壊されたハロー
(e.g., 近くの星からの紫外光)

↓

② H原始冷却による崩壊
(almost isothermal at T～8000K)

↓

③急速なガス降着 (> 0.1$M_\odot$/yr)
による原始星の成長

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

↓

④ GR不安定による星の崩壊
→$10^5 M_\odot$ BH

Key Questions

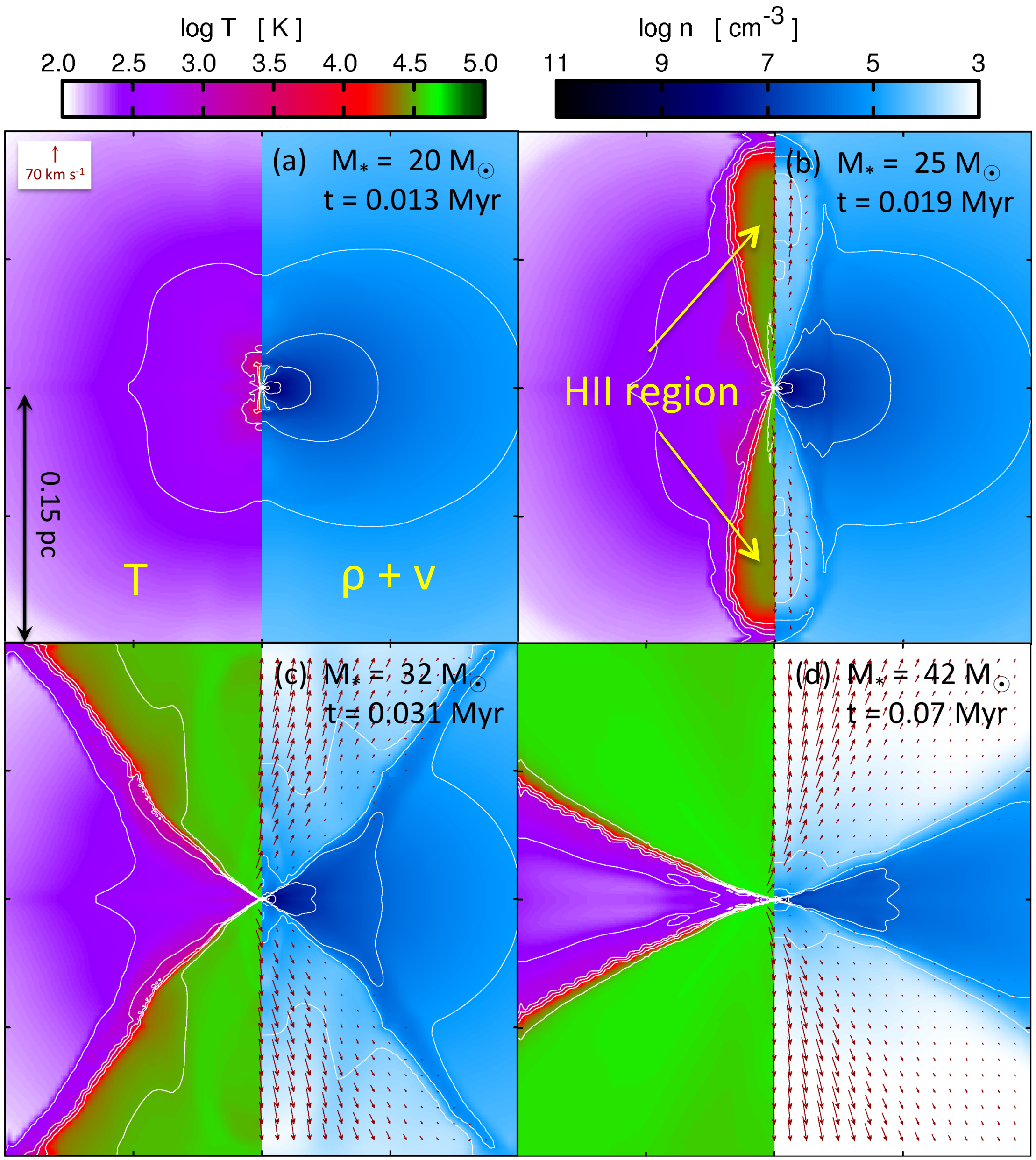
\+ What is the final mass of the first stars, resulting from
the evolution in the accretion phase?
What is their mass distribution?

\+ 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?

これらに答えるためには特に星質量が決まる後期段階の
進化研究が重要

2D輻射流体 + 星の進化計算



Hosokawa+11, 12

Breakout of bipolar HII region toward polar directions

↓

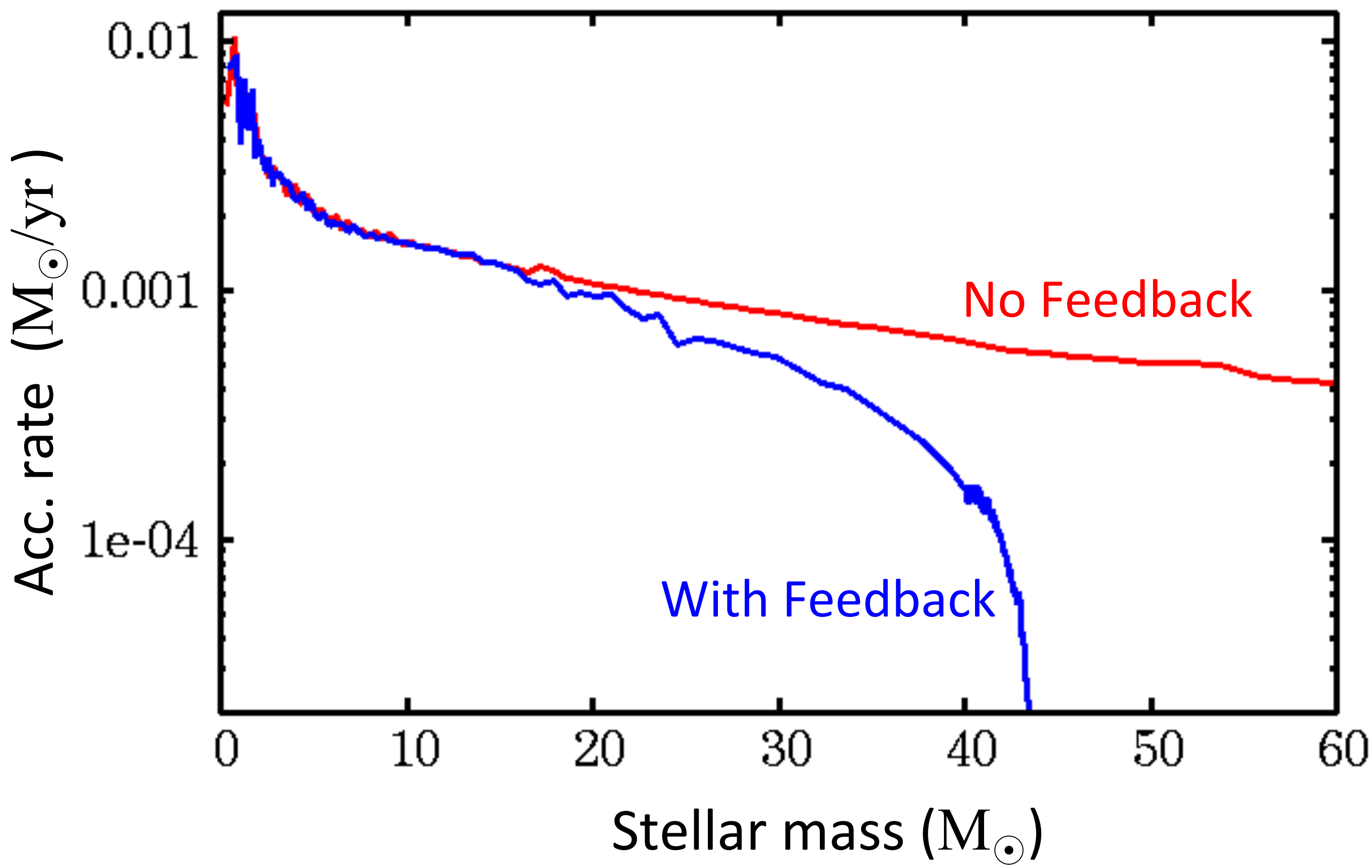
Dynamical expansion of the HII region

↓

Photoevaporation of the disk

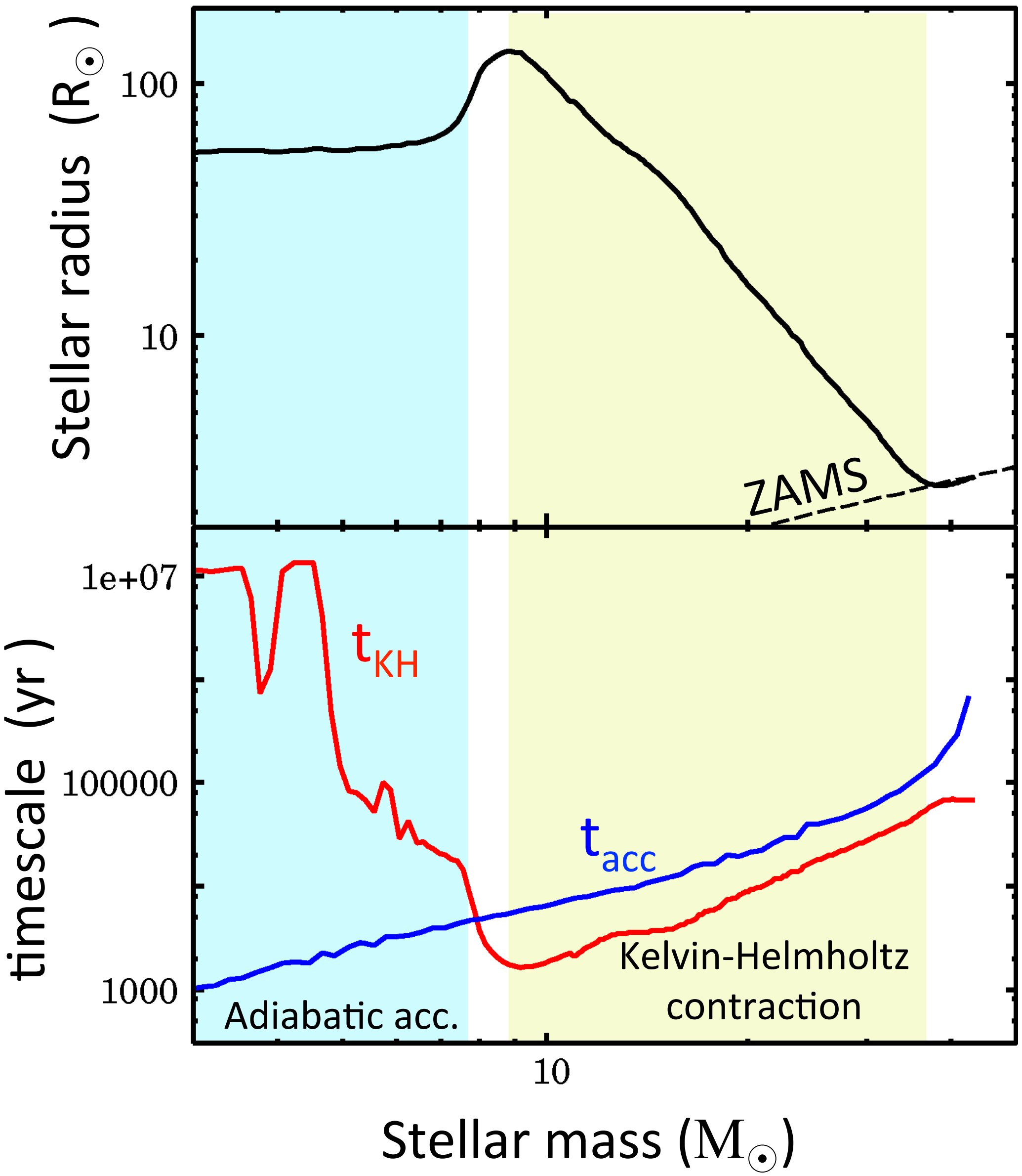
（0.1Myr since the birth of the protostar）

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

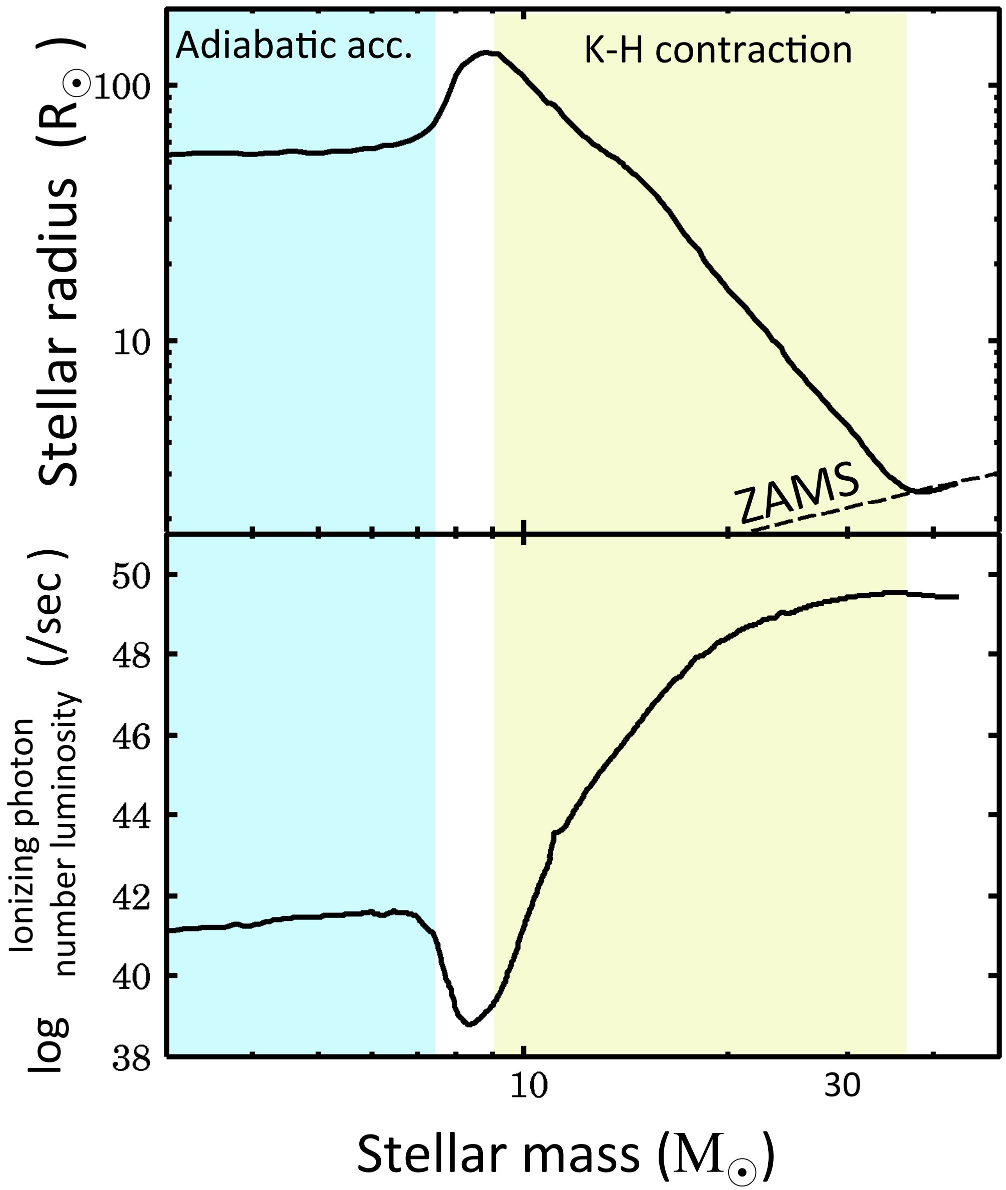
$$t_{\rm acc} = \frac{M_*}{\dot{M}}, \quad t_{\rm KH} = \frac{GM_*^2}{R_* L_*}$$

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 ↓)

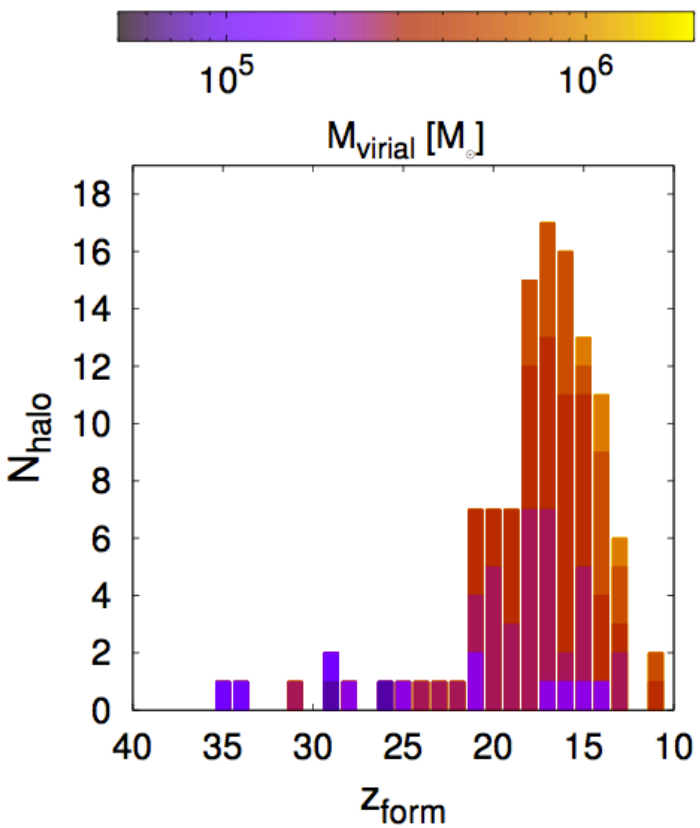
↓

Effective temp. : Teff ↑
UV luminosity ↑

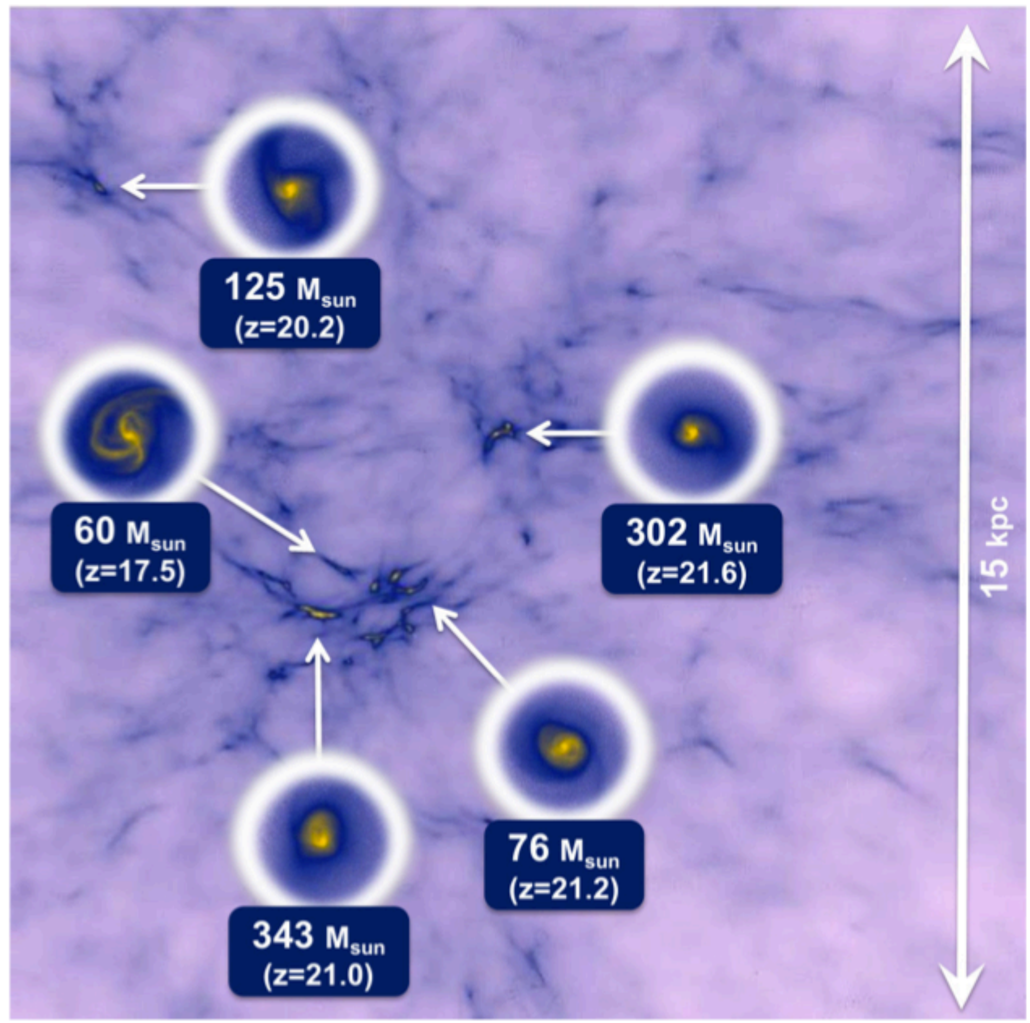
UV feedback operates over late KH contraction → ZAMS stages, and finally stops the mass accretion

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)

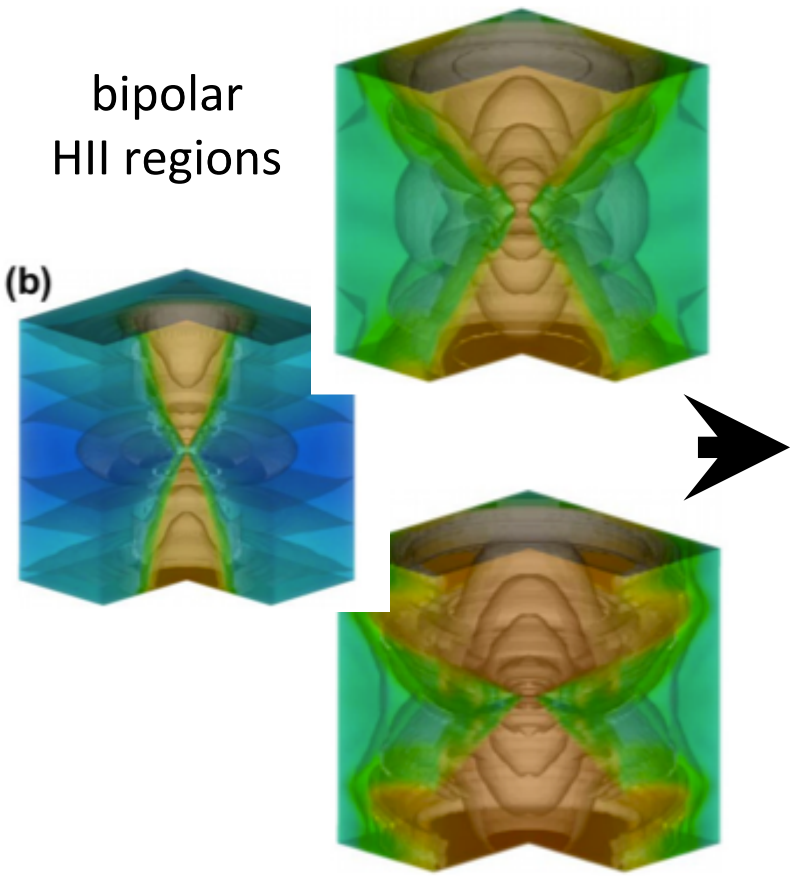


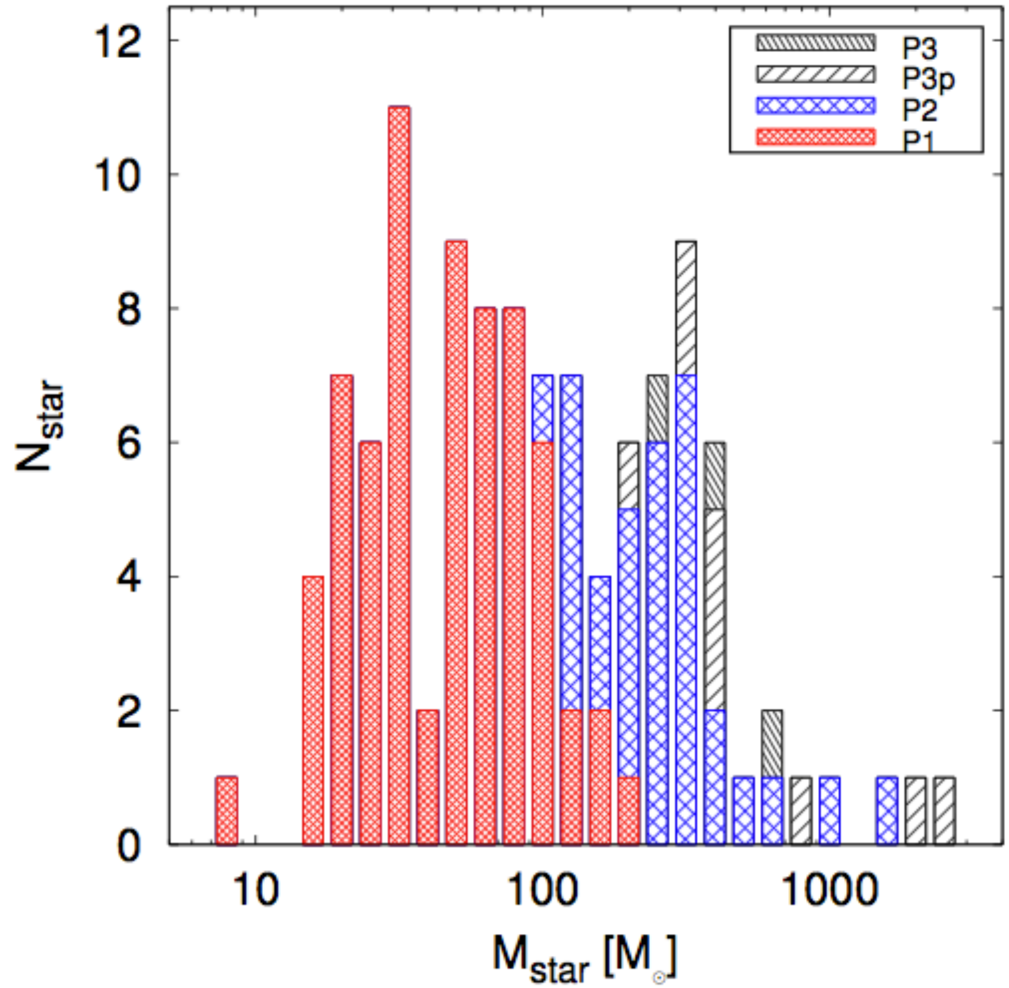
dark halo mass & formation redshift with primordial star-forming clouds



Mass Distribution

bipolar
HII regions

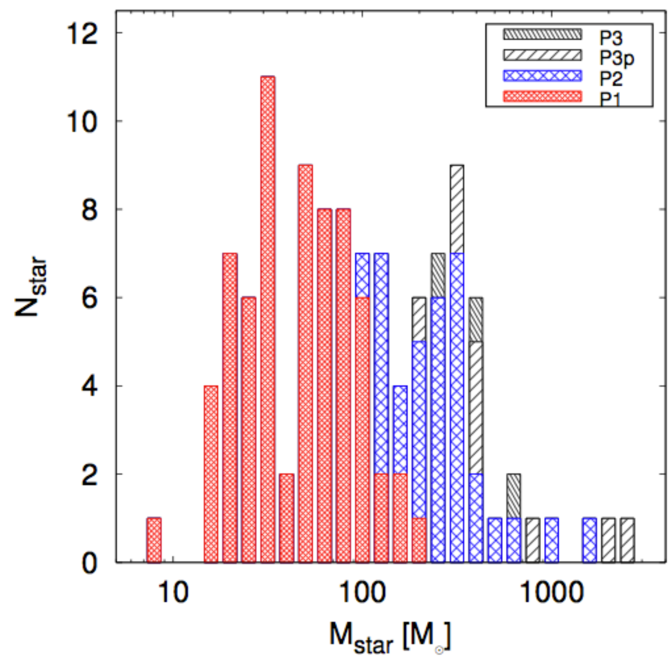


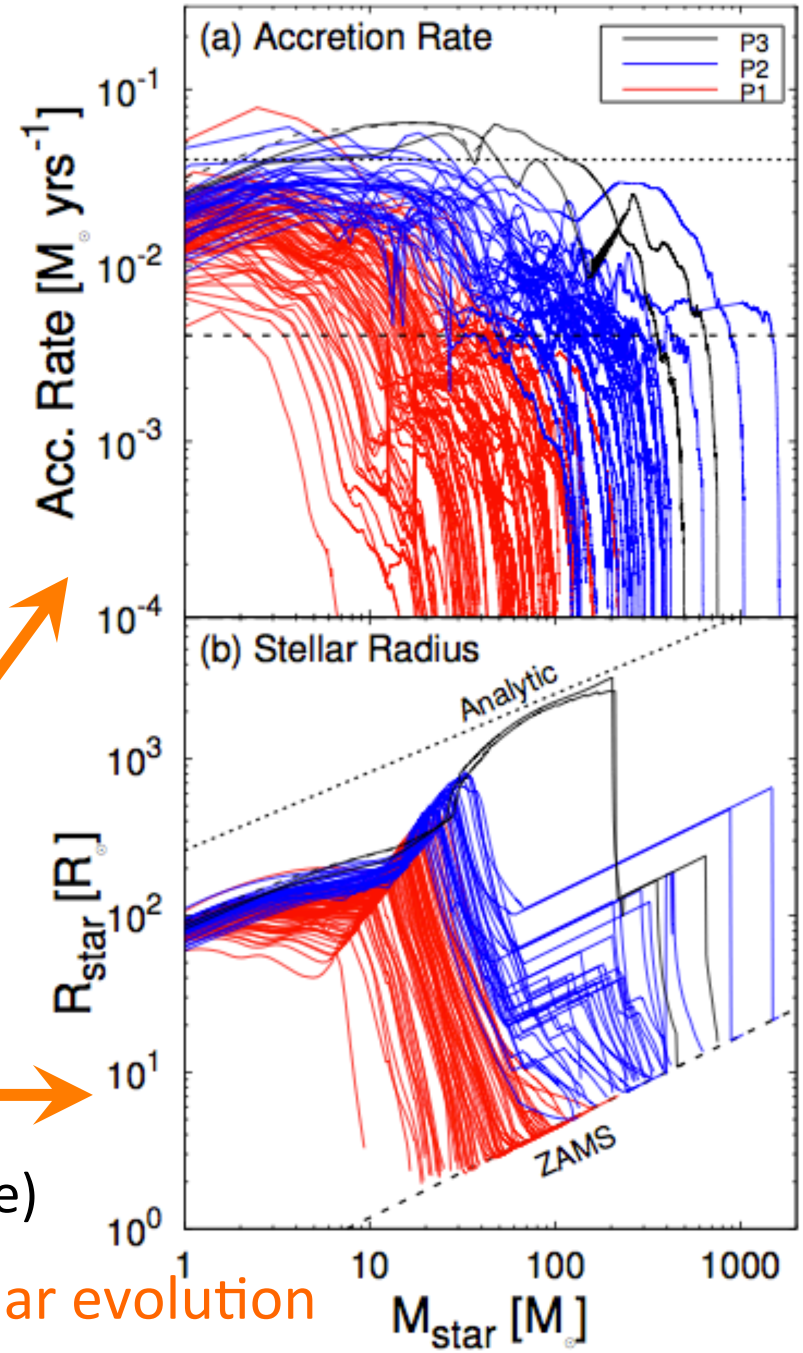


stellar mass is fixed after the stellar UV feedback shuts off the mass accretion

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

Diversity... why?





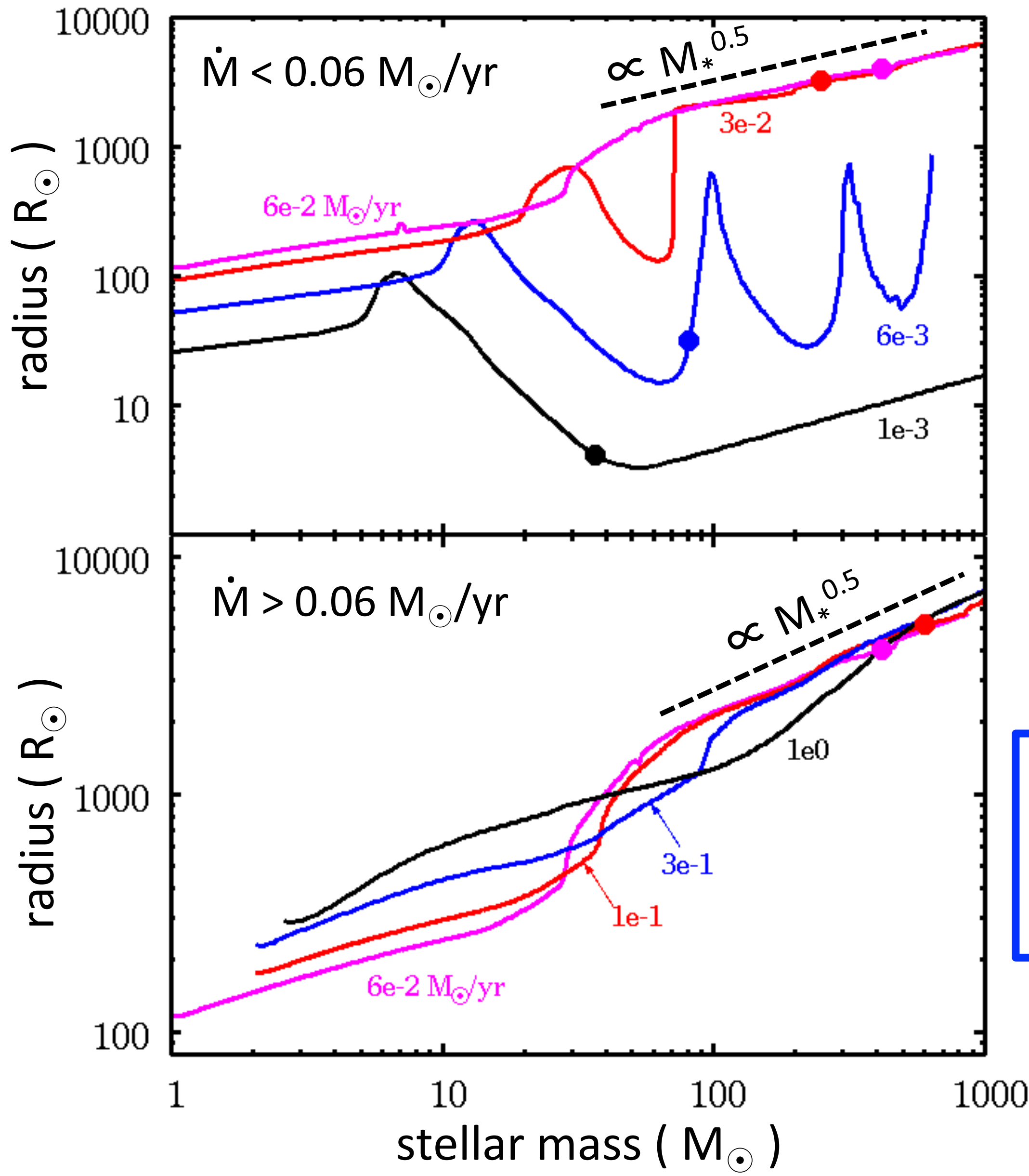
With the higher acc. rates,

+ 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

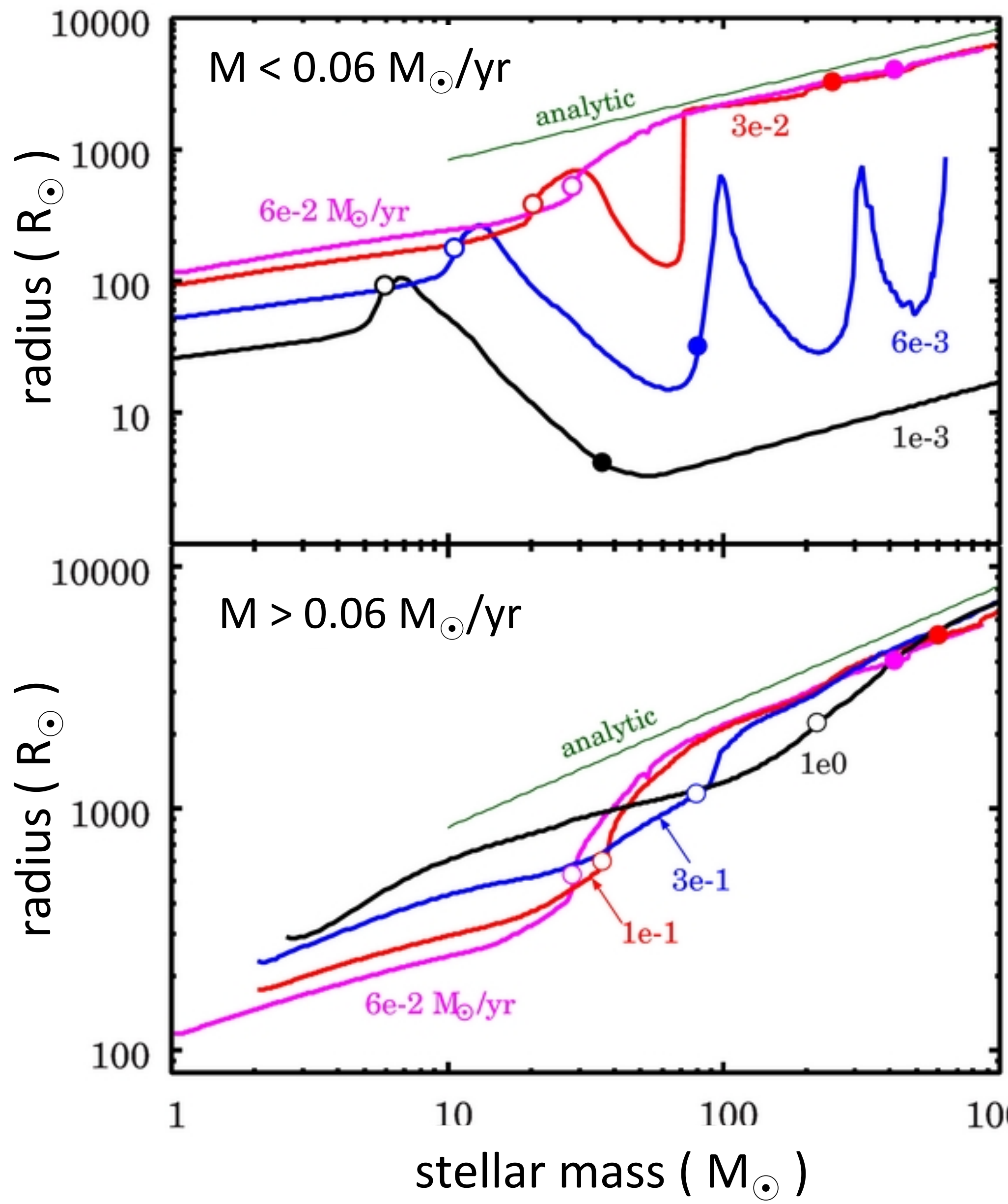


rather relevant to forming the supermassive stars

"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)

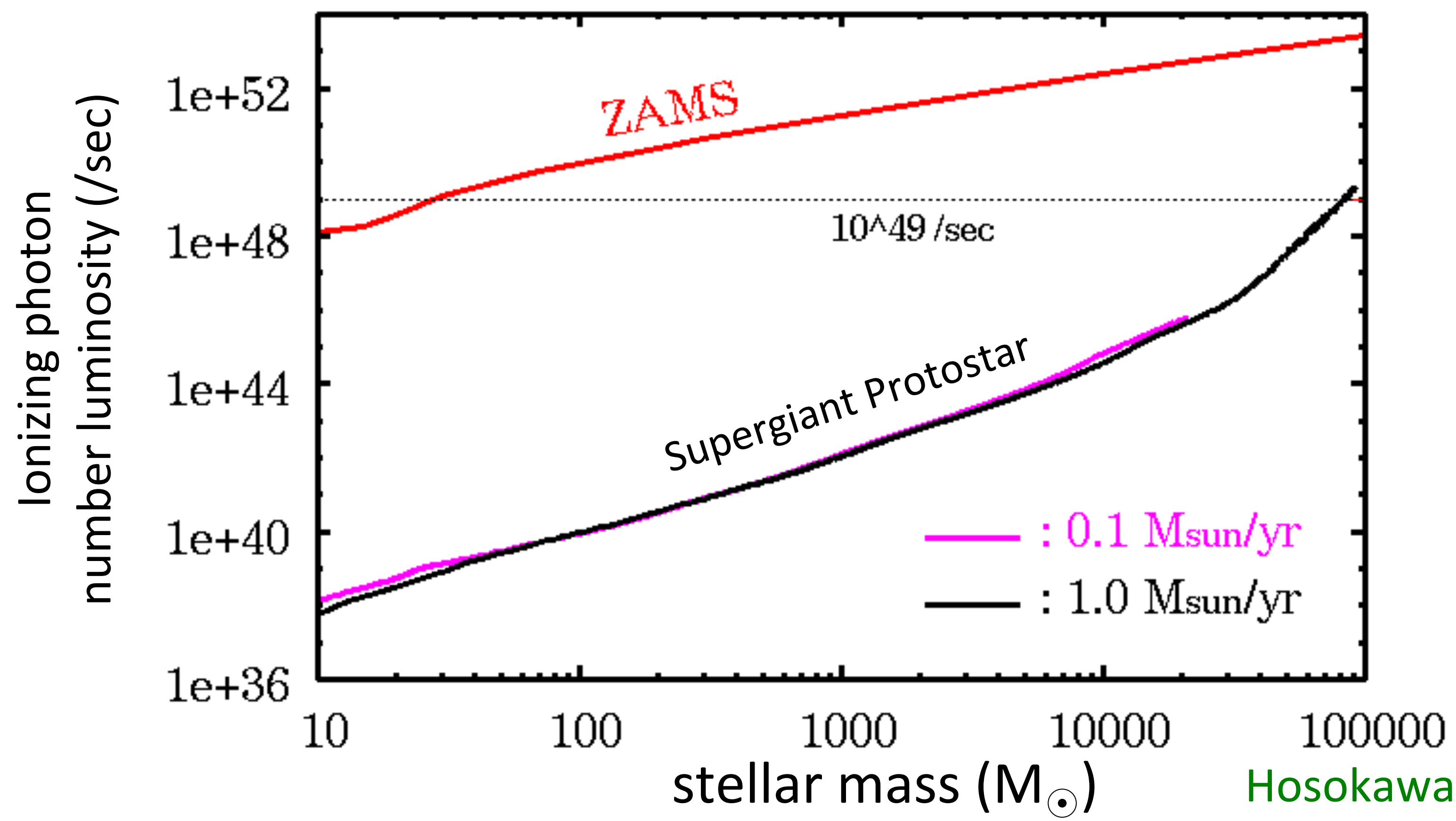
(ref. Hayashi track)

↓

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

good agreement with the numerical results

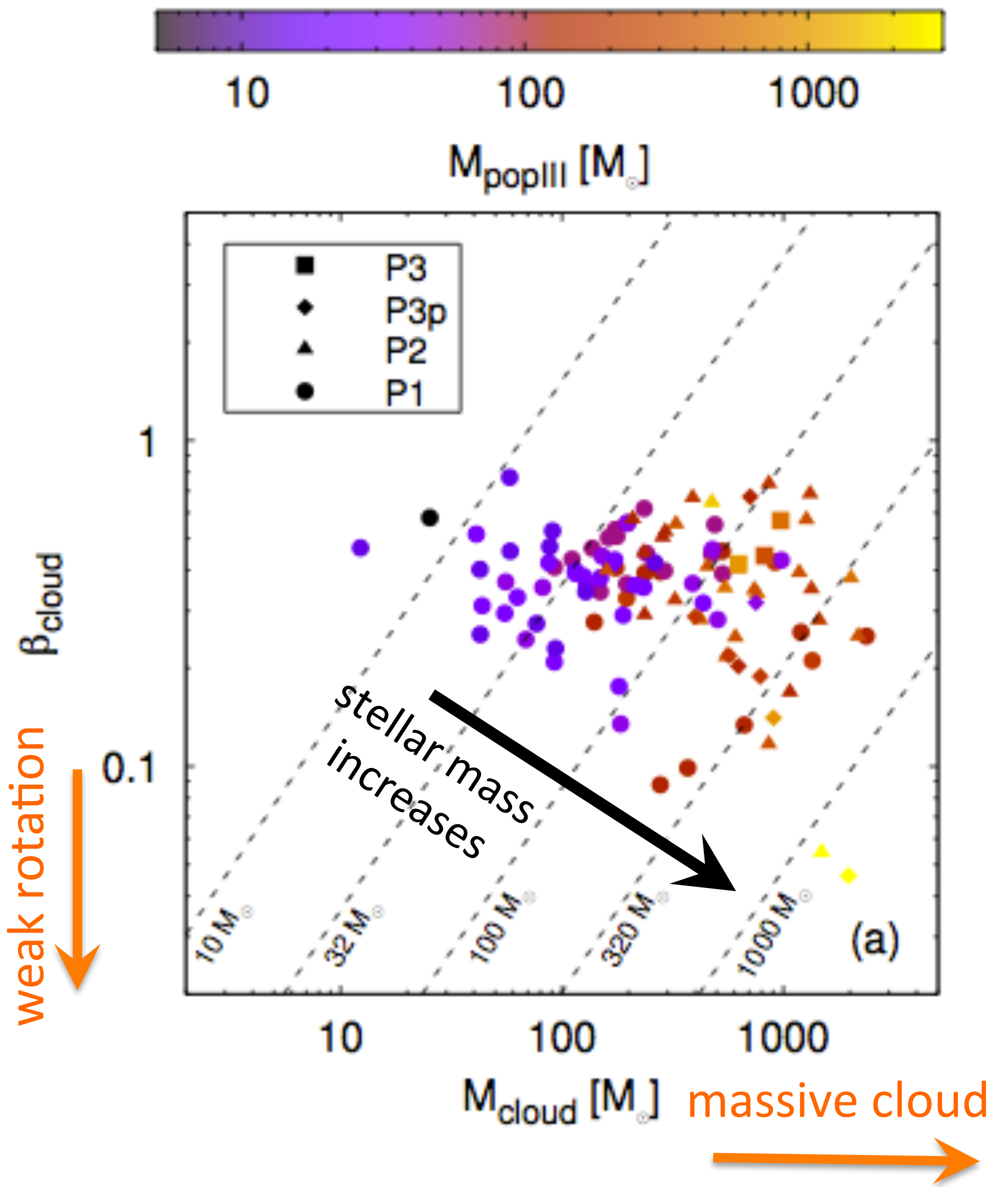
NO UV feedback



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

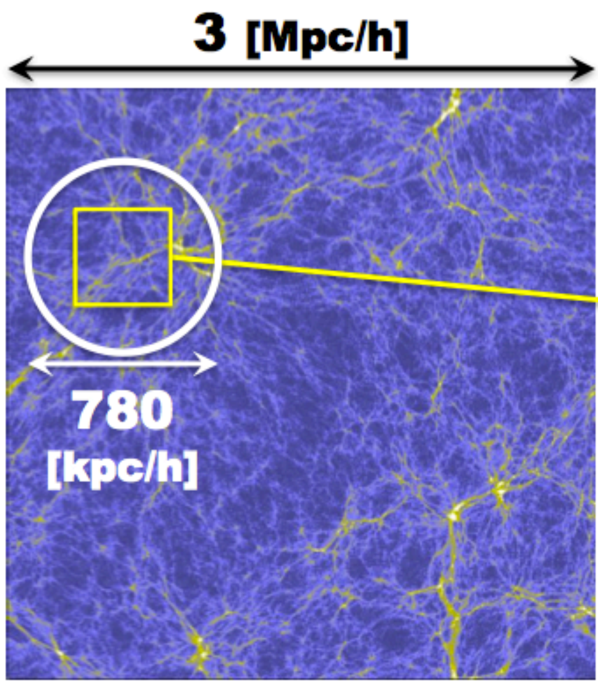
↓

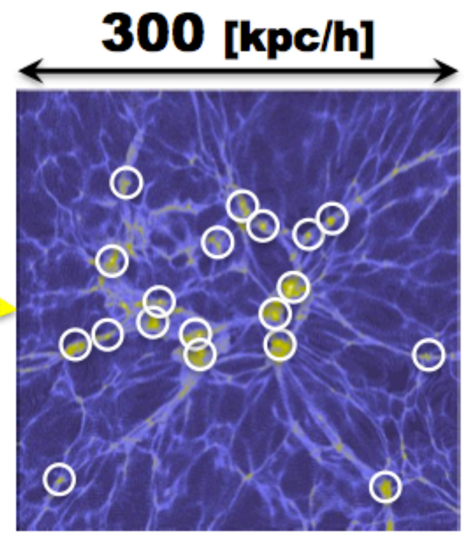
Higher stellar mass

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

Diversity of the gas clouds comes from cosmology

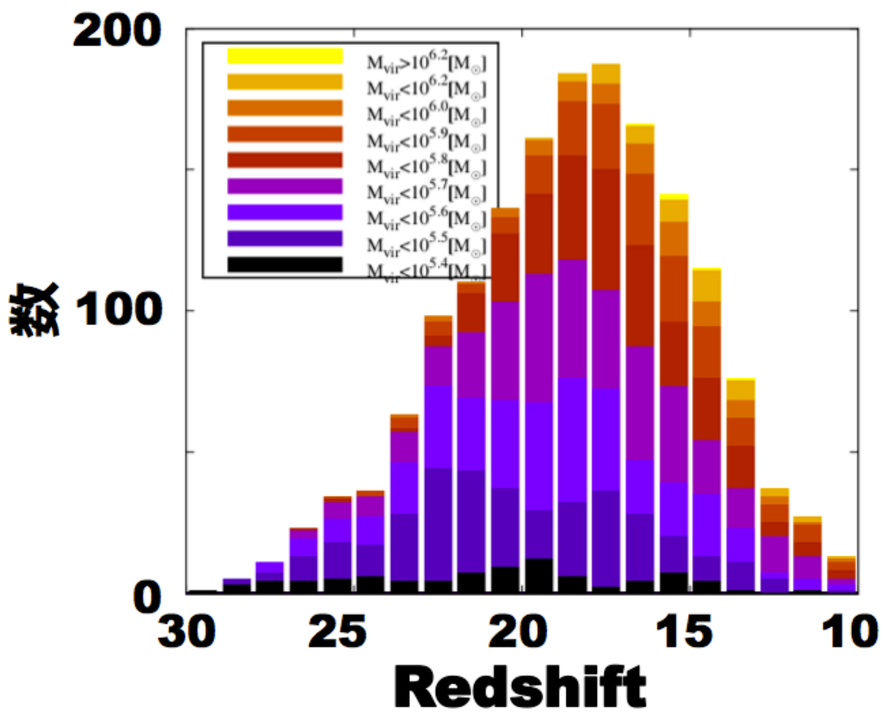
Hirano+14 in prep.

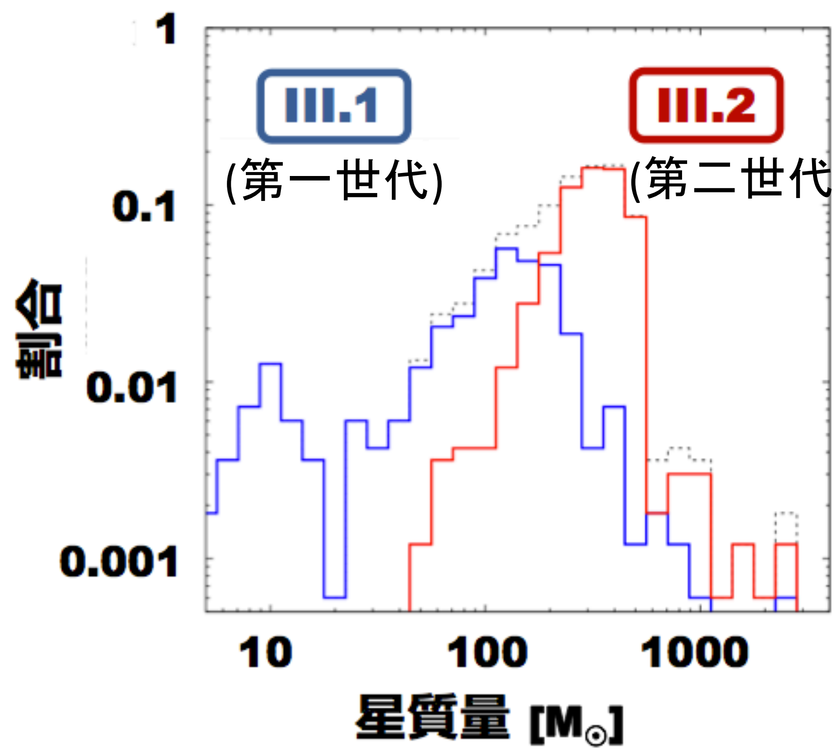




×55 Regions

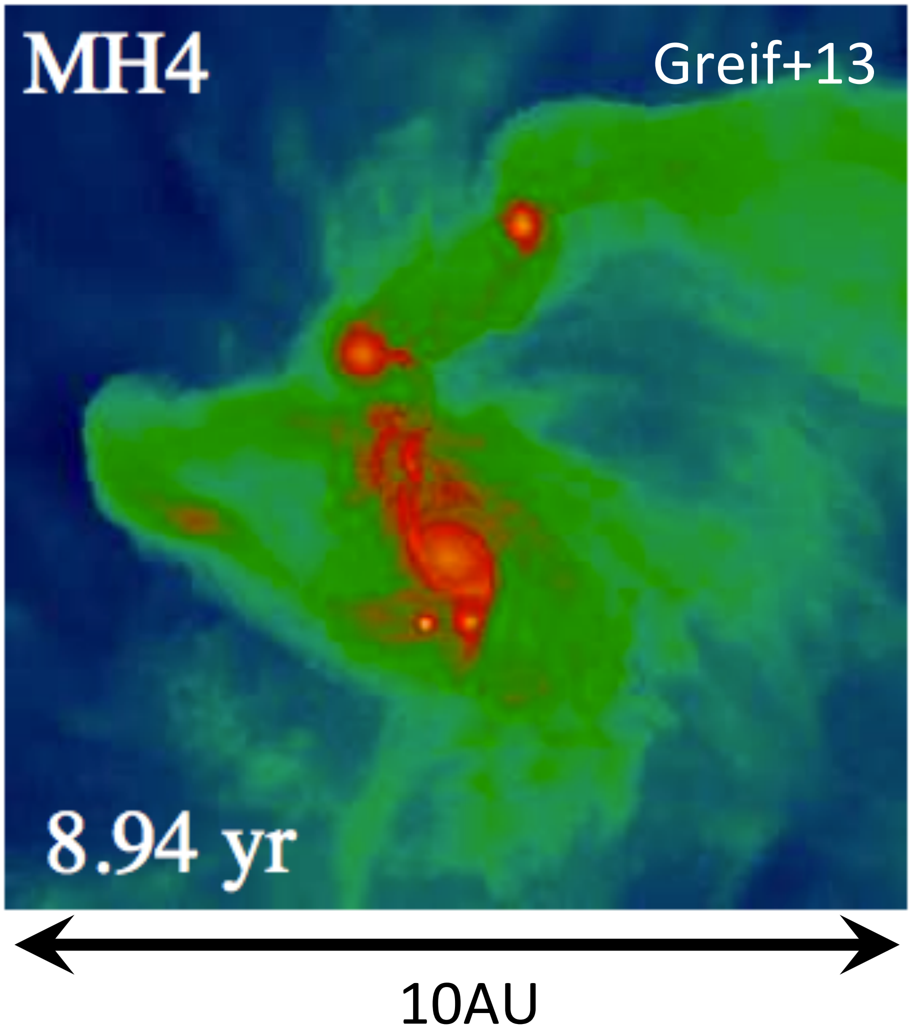
~ 1660 Clouds (！)





This is just beginning...

3D計算では重力不安定による円盤分裂も起こる



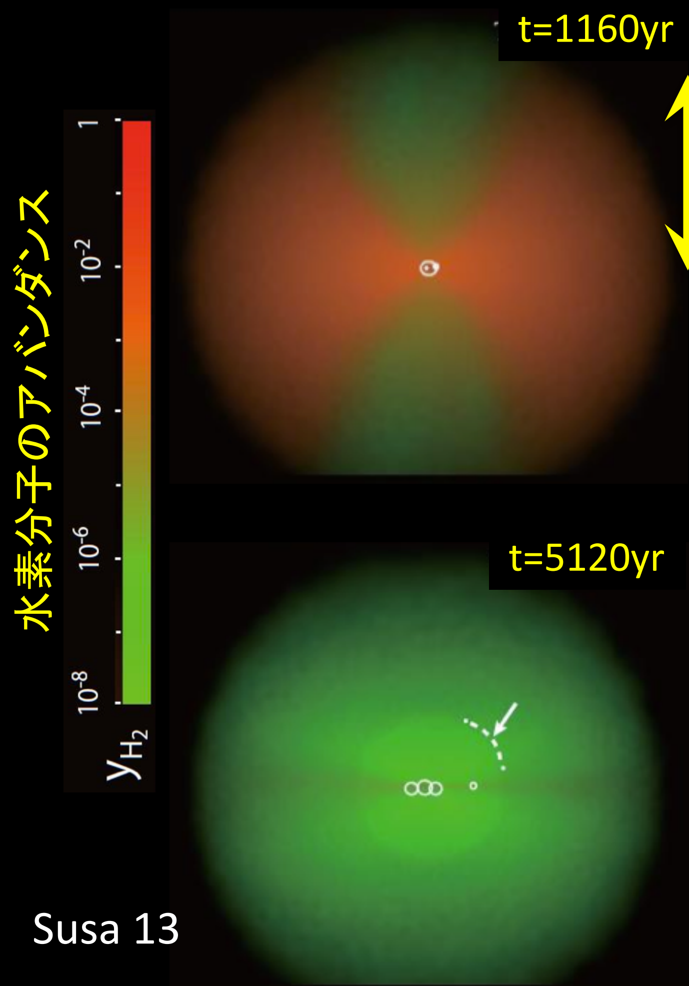
円盤分裂により原始星
が複数できる
↓
各々の原始星への降着率低下
(ガス雲の質量を分け合う)
↓
最終的な星質量低下(?)

どこまで高い分解能で長時間
進化を追えるかがchallenge

(※分裂強度は分解能依存)

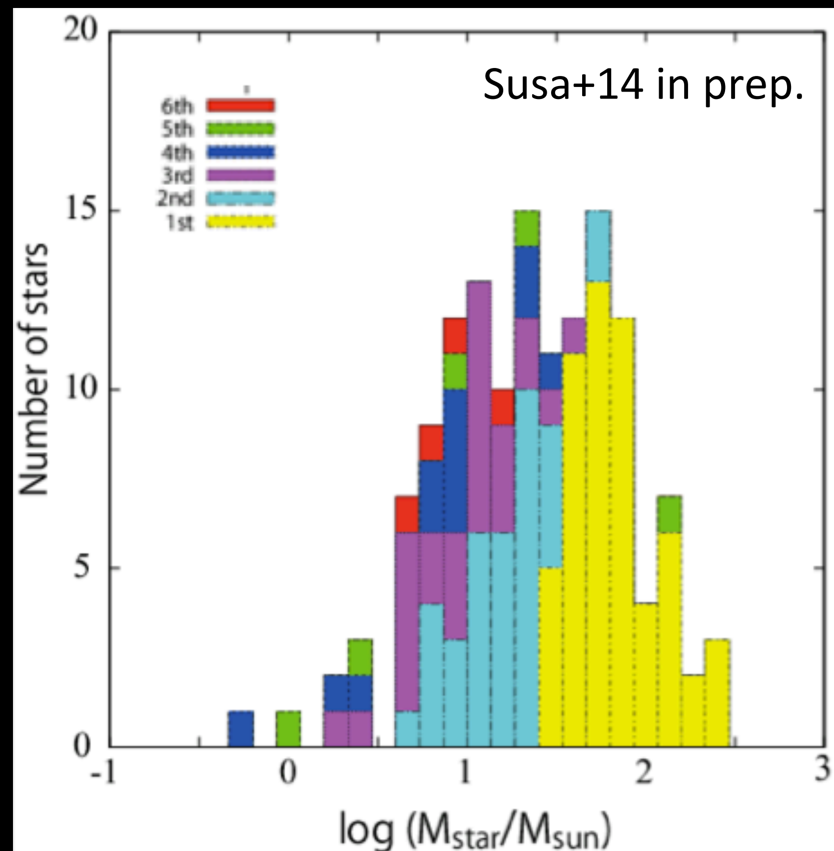
須佐計算

3D radiative SPH + 原始星進化tracks (Hosokawa & Omukai 09)



Susa 13

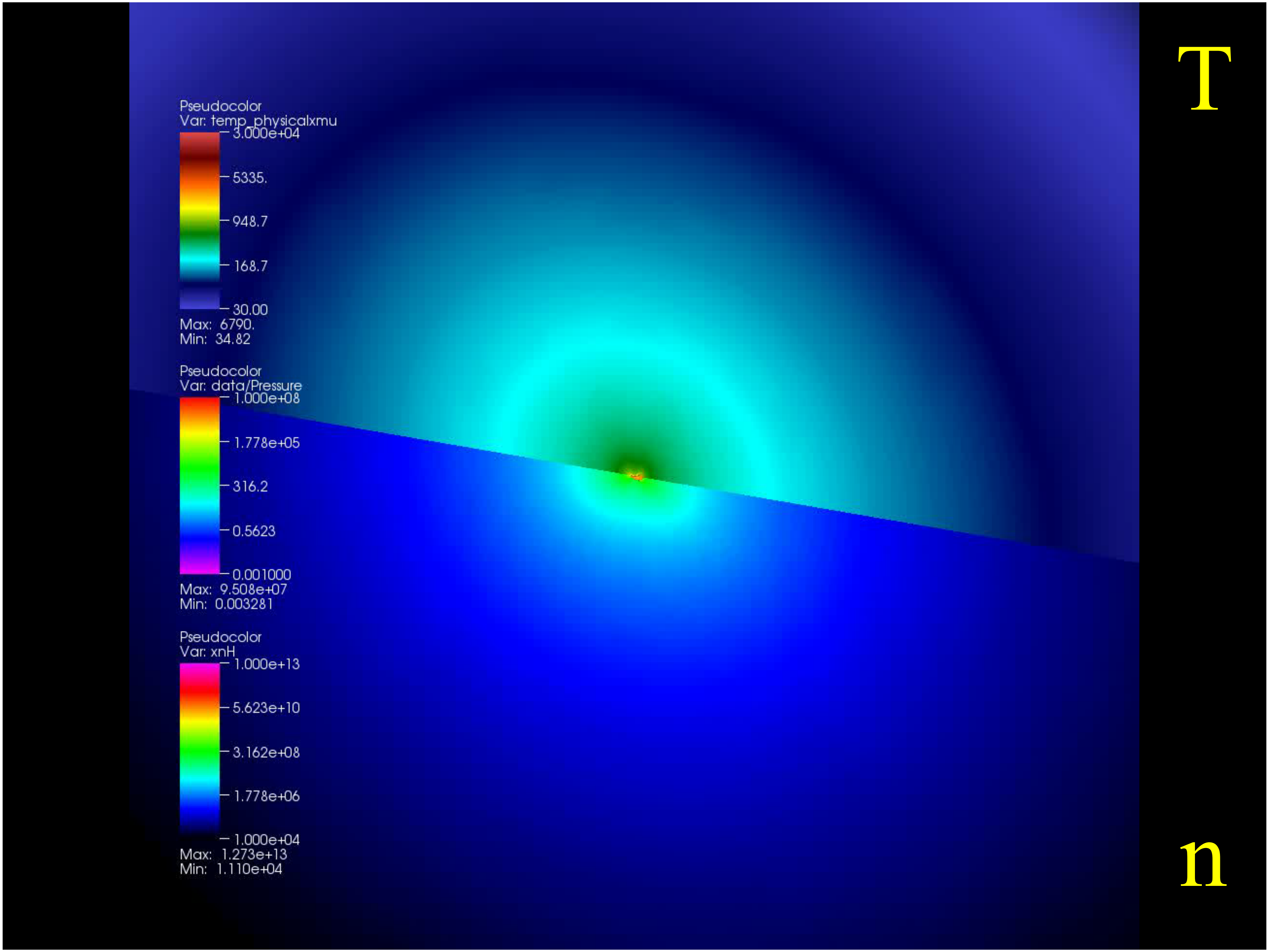
星のFUV光による水素分子破壊のfeedback



おそらく円盤分裂の効果により
Hirano+14よりやや低質量側にシフト

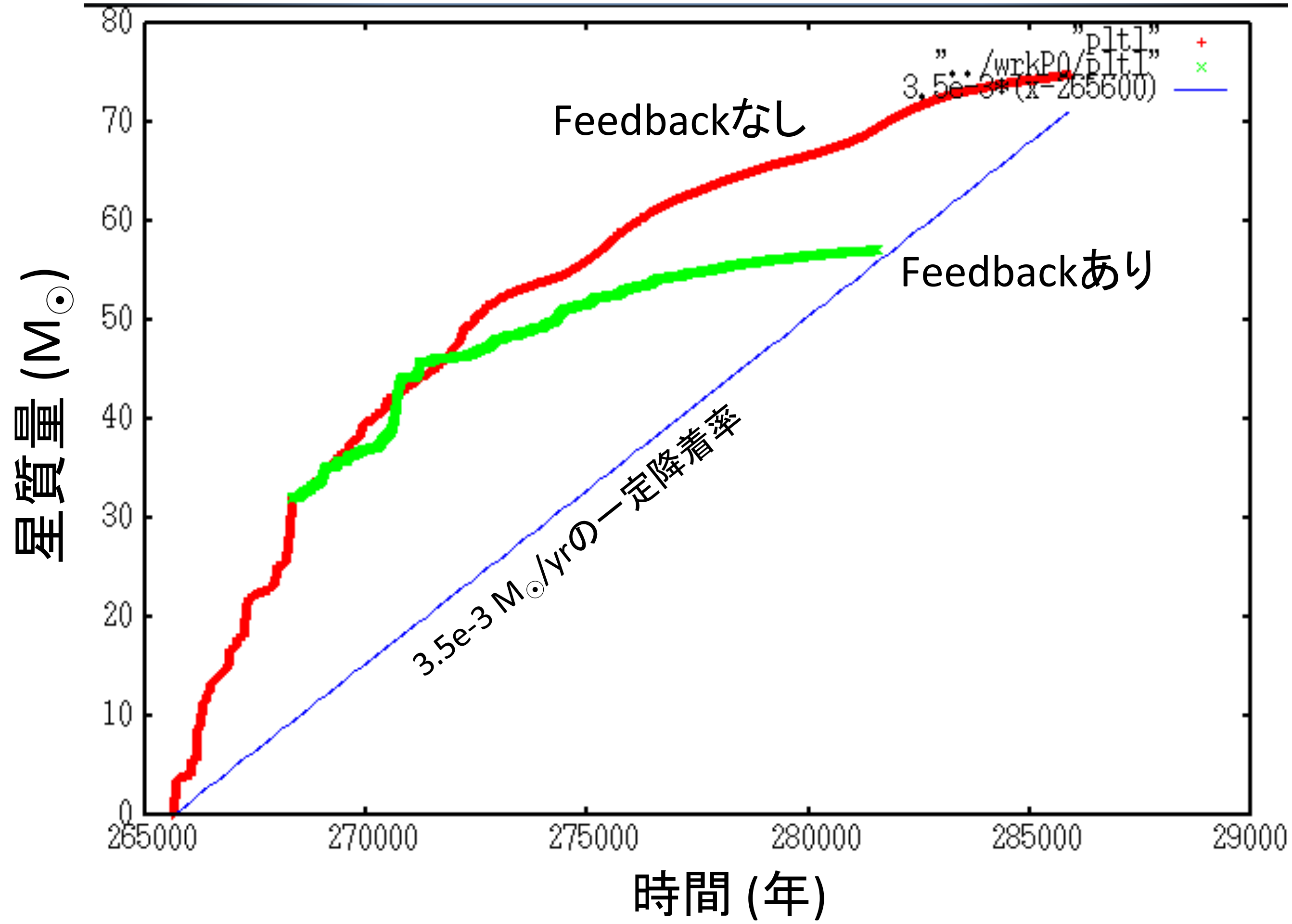
My 3D test case

+ UV feedback (星の進化は今回はcoupleせず)
星質量が$30M_{\odot}$に達したら$T_{eff}=10^5K$, $L_*=10^6L_{\odot}$で光らせる



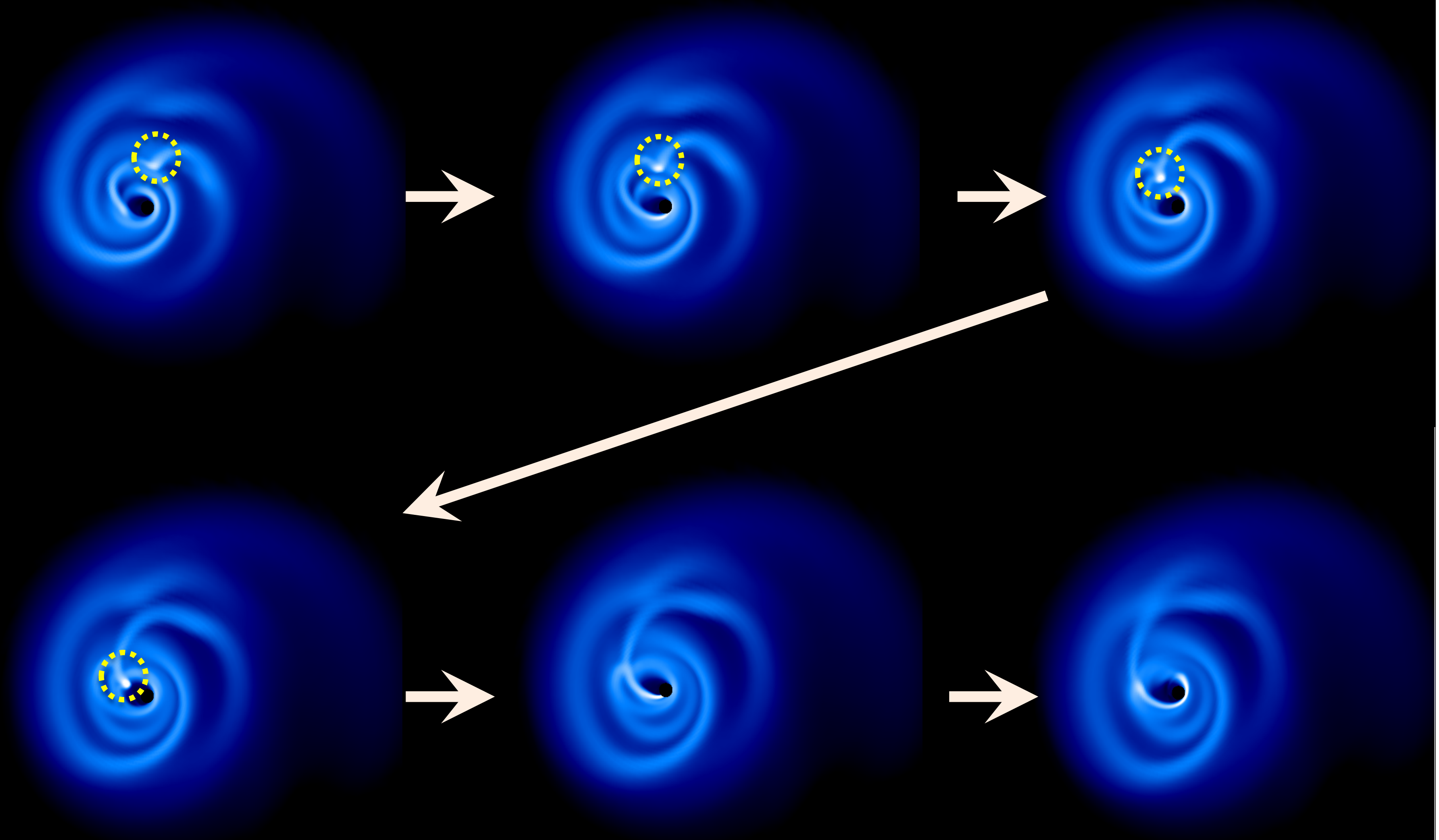
Pseudocolor
Var: temp_physicalxmu
3.000e+04
5335.
948.7
168.7
30.00
Max: 6790.
Min: 34.82
Pseudocolor
Var: data/Pressure
1.000e+08
1.778e+05
316.2
0.5623
0.001000
Max: 9.508e+07
Min: 0.003281
Pseudocolor
Var: xnH
1.000e+13
5.623e+10
3.162e+08
1.778e+06
1.000e+04
Max: 1.273e+13
Min: 1.110e+04
T
n

星質量増加



+ Feedbackによりじょじょに質量降着が阻害されている (光蒸発)
+ 星がちゃんと光れば3Dでも光電離によるfeedbackが起こる
+ このケースは円盤分裂は起こらず

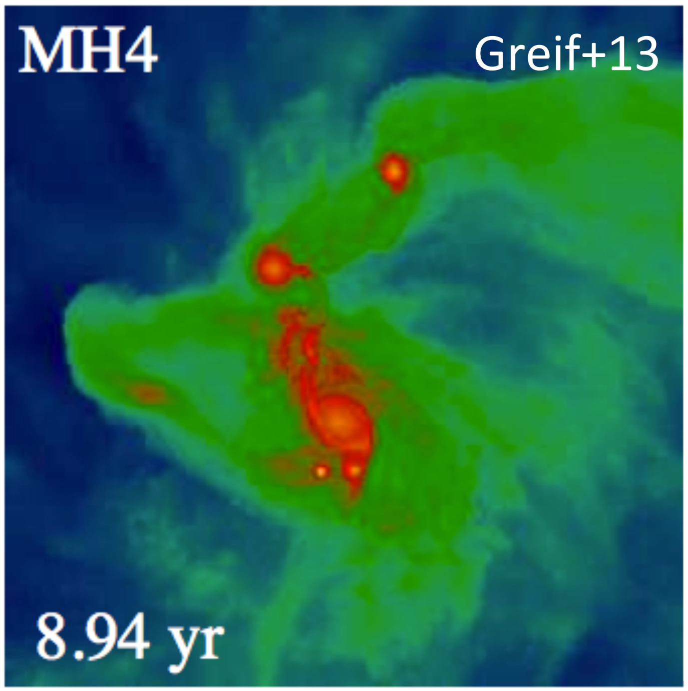
円盤分裂が起きた別ケース

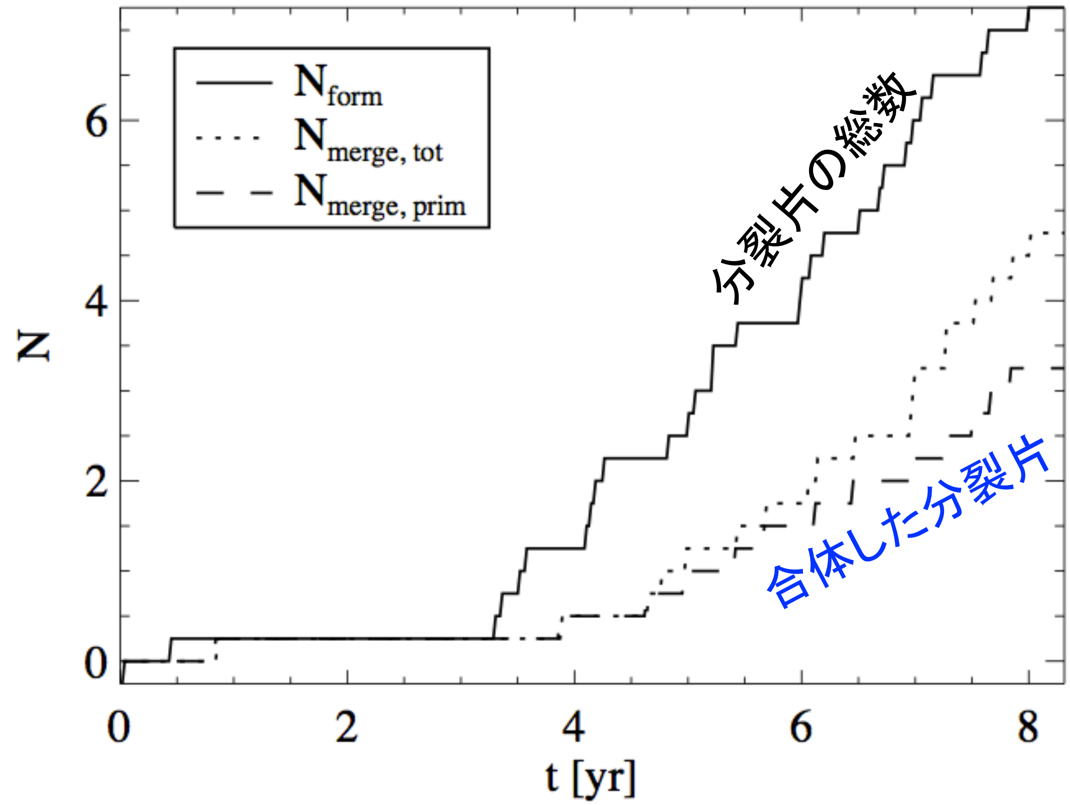


+ 中心星に落下して合体
+ 分裂が起きても必ずしも星質量が下がるとは限らない

円盤分裂と星最終質量

一度分裂した後、再度の合体がどのくらいの頻度で起きるかが鍵





およそ2/3程度の分裂片は合体
残りはejectionされるなどで生存

(※この例は分解能が高いかわりに最初の10年間だけ)

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 Prospects

+ 3D effects (e.g., disk fragmentation v.s. stellar merger)
  reduce or increase the final mass?

+ what about second or later generations of Pop III stars?
  (e.g., Hosokawa+12; Hirano+14 in prep.)