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高エネ研究会@蔵王温泉

宇宙初期天体の形成：
初代星＆初代BH

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First Stars

Before First Stars＝Simple Universe ？

- well-defined initial condition Cosmological Initial Condition

  Streaming motion(velocity difference between baryon and DM) was overlooked (Tseliakhovich& Hirata 2010)

- simple chemistry and thermal process

  Simple primordial gas (H, He,& slight amount of D, Li)
  no external radiation field other than CMB, no Cosmic Ray

  This is still OK
  (But: new missing process is sometimes found and added e.g., Li chemistry
  DM annihilation might have played a role in heating/ionization)

- simple dynamics weak magnetic field

magnetic fields may have been amplified by small-scale turbulent dynamo,
and may have played some role in dynamics and heating by ambipolar diffusion

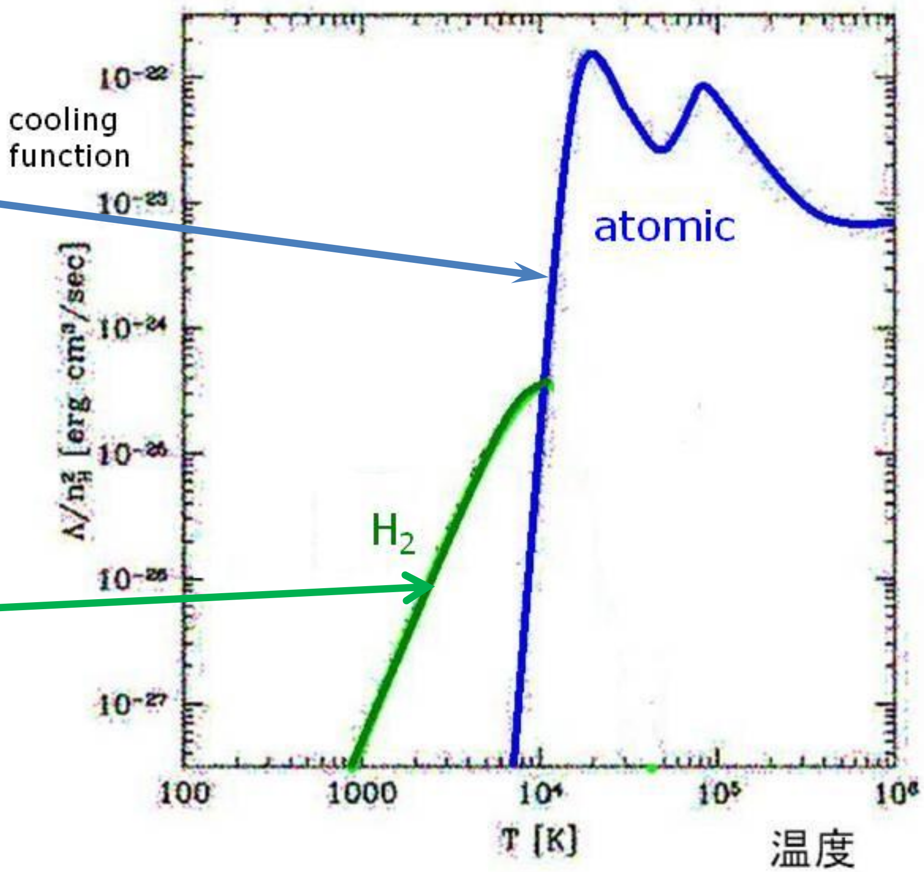
Except very early universe,
predictable theory is well established？？

Radiative cooling in primordial gas

Barkana & Loeb 2001

Atomic cooling
(H Ly a transition)
efficient only T>8000K

H_2 rovibrational cooling
is important
in lower temperature



H_2 is needed for
making the gas cold

H_2 formation in primordial gas

At low densities ($<10^8 cm^{-3}$)

H^- channel : e catalyzed (Peebles & Dicke 1968; Hirasawa+1969)

$$H + e \rightarrow H^- + \gamma$$
$$H^- + H \rightarrow H_2 + e$$

rate higher by an order of mag.

H_2^+ channel : H^+ catalyzed (Saslaw & Zipoy 1967)

$$H + H^+ \rightarrow H_2^+ + \gamma$$
$$H_2^+ + H \rightarrow H_2 + H^+$$

can be important in strong radiation fields.

At higher densities ($>10^8 cm^{-3}$)

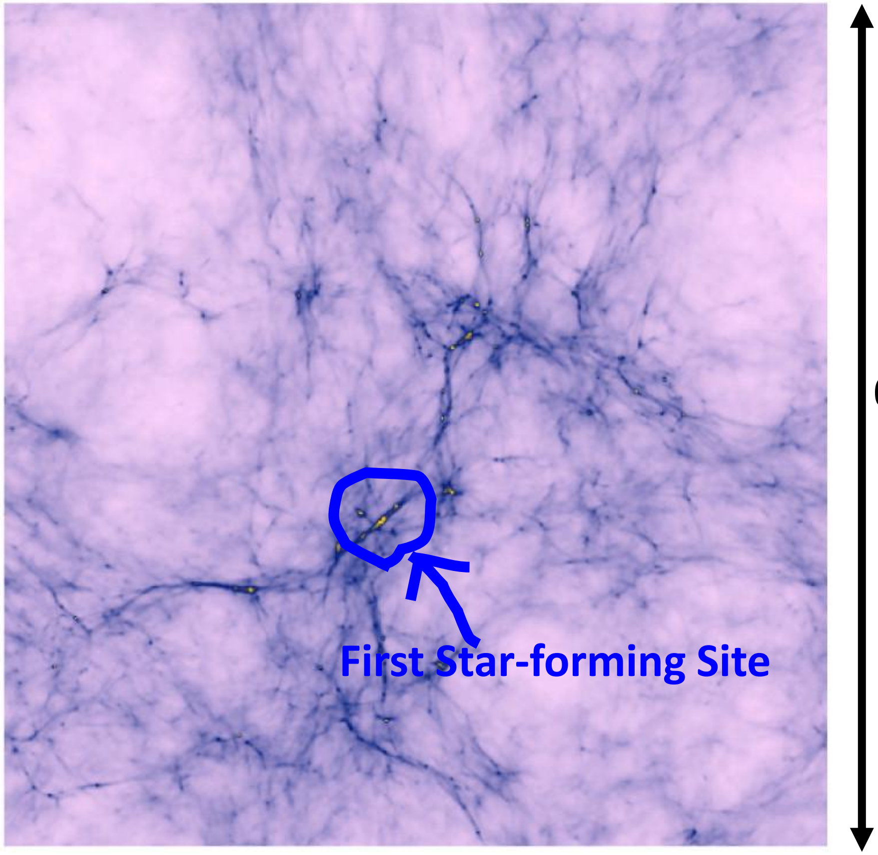
3-body reactions (Palla, Salpeter & Stahler 1983)

$$H + H + H \rightarrow H_2 + H$$
$$H + H + H_2 \rightarrow H_2 + H_2 .$$

Makes the gas fully molecular at $\sim 10^{11} cm^{-3}$

First Star Forming Sites

ΛCDM cosmology
Simulate starting from the density fluctuations up to the formation of first object



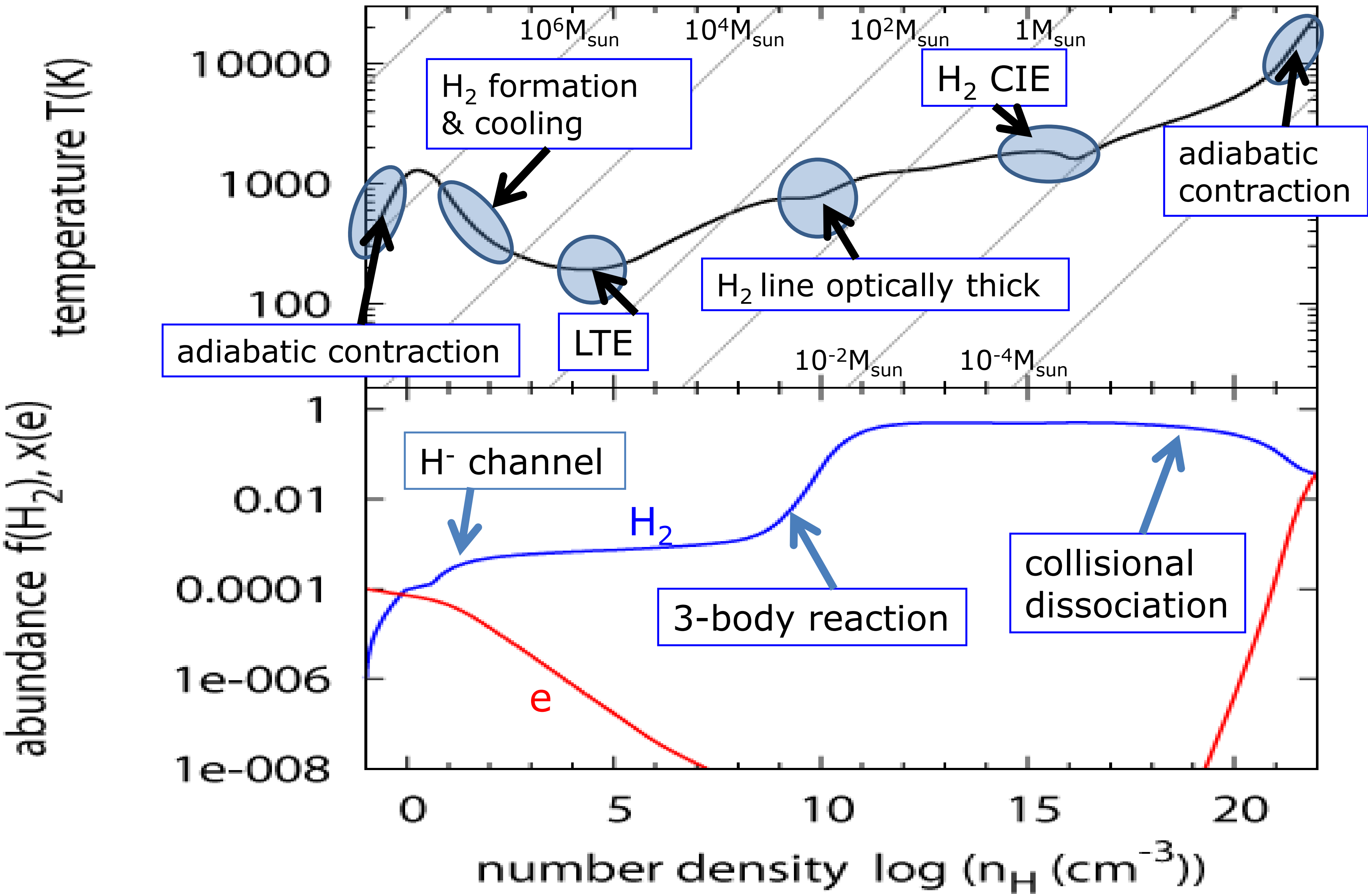
First Objects to form stars:
small halos with
virial temperature T_{vir} > 1000K
(minihalos ~$10^6 M_{sun}$, z~20-30)

the gas in which cools by
H_2 line emission and
become denser

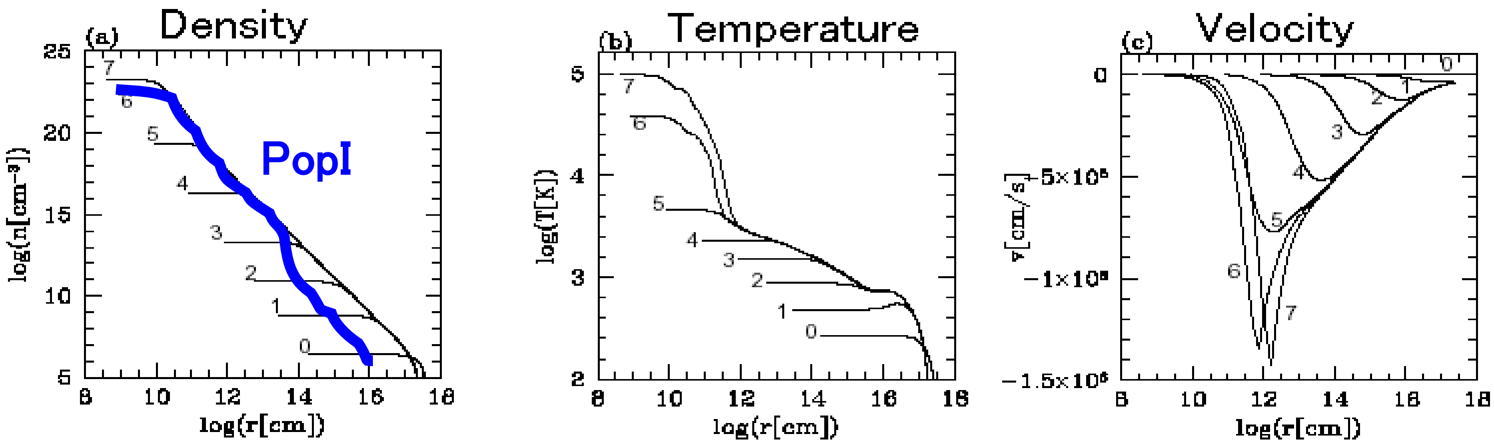
➔Star formation

Yoshida, Abel, Hernquist & Sugiyama (2003)

Thermal evolution of primordial gas



Runaway Collapse of Dense Cores to Protostars



(KO & Nishi 1998)

Self-similar Collapse
(up to $n \sim 10^{20} cm^{-3}$)

Density, temperature, velocity higher than in Pop I case

0—7 in Figure is time sequence

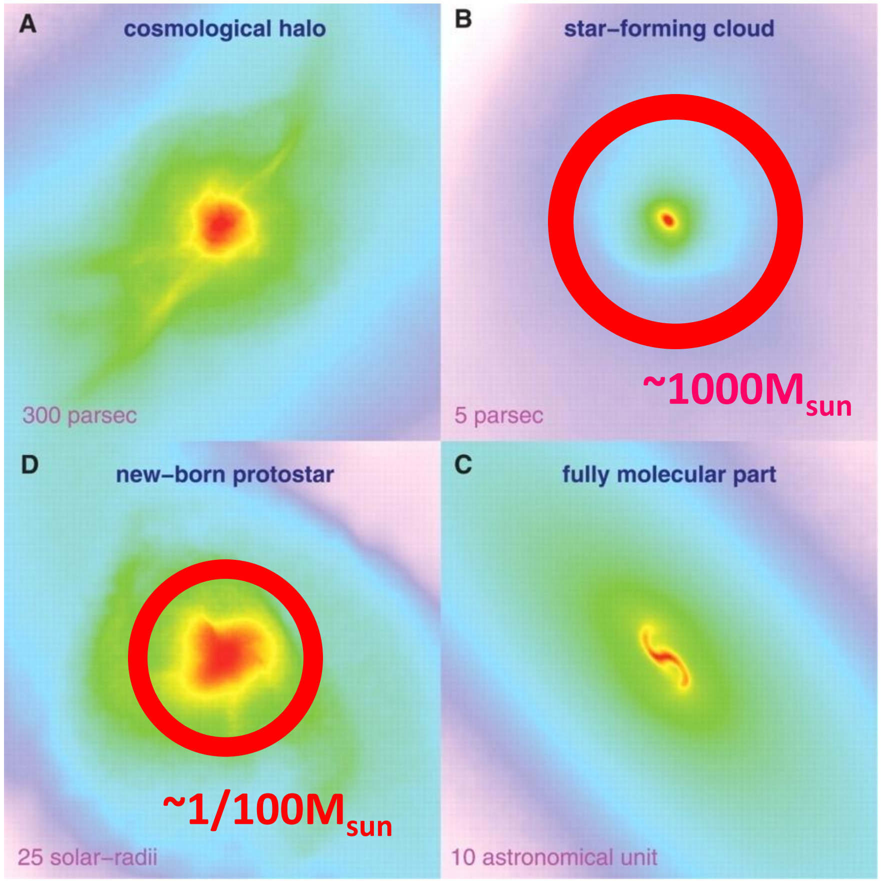
● protostar (＝hydrostatic core)

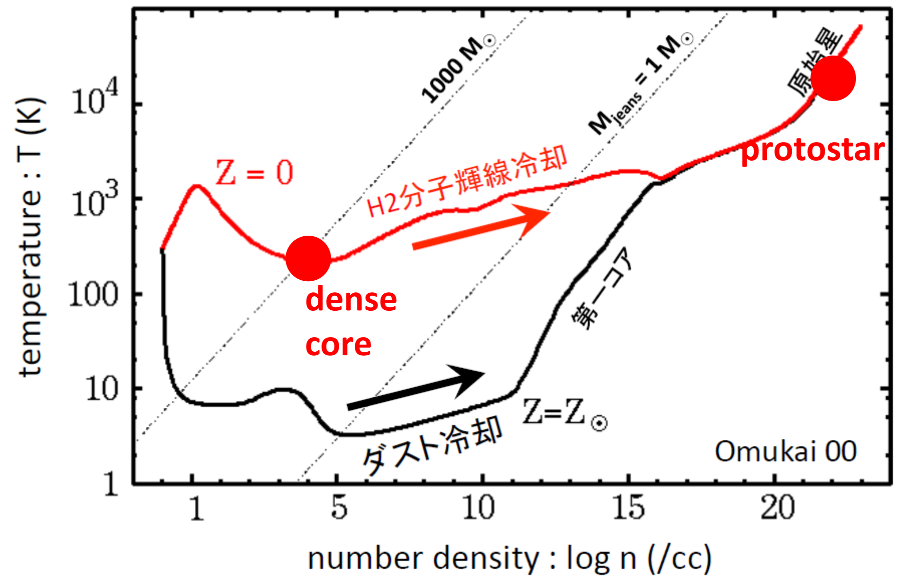
state 6; $n \sim 10^{22} cm^{-3}$, $M_{star} \sim 10^{-3} M_{sun}$

(similar to Pop I case)

● temperature and density in the envelope are higher than in Pop I case.

Birth of the first protostar



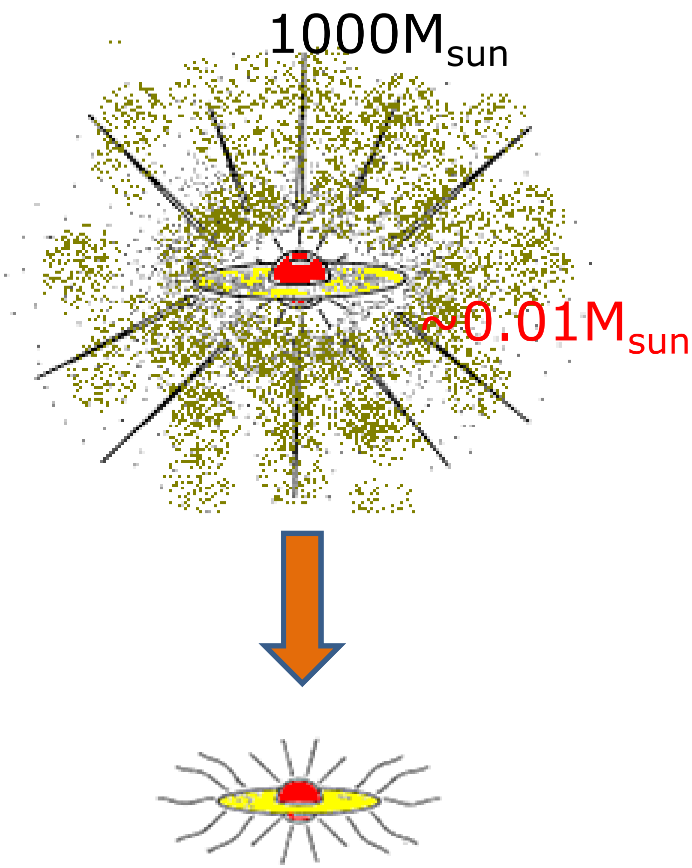


Yoshida, KO, Hernquist 2008

- **Dense core** (~1000M_{sun}) forms at ~10^4cm^{-3}

- **Hydrostatic protostar** (initial mass ~$10^{-2}M_{sun}$) forms at ~10^{21}cm^{-3}

Protostar grows by accretion



Accretion terminates
→ Final stellar mass

primordial gas (Z=0)

no dust, low opacity

⇒ lower radiation pressure

higher temperature (a few 100K)

⇒ 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 work to weaken the stellar feedback effect

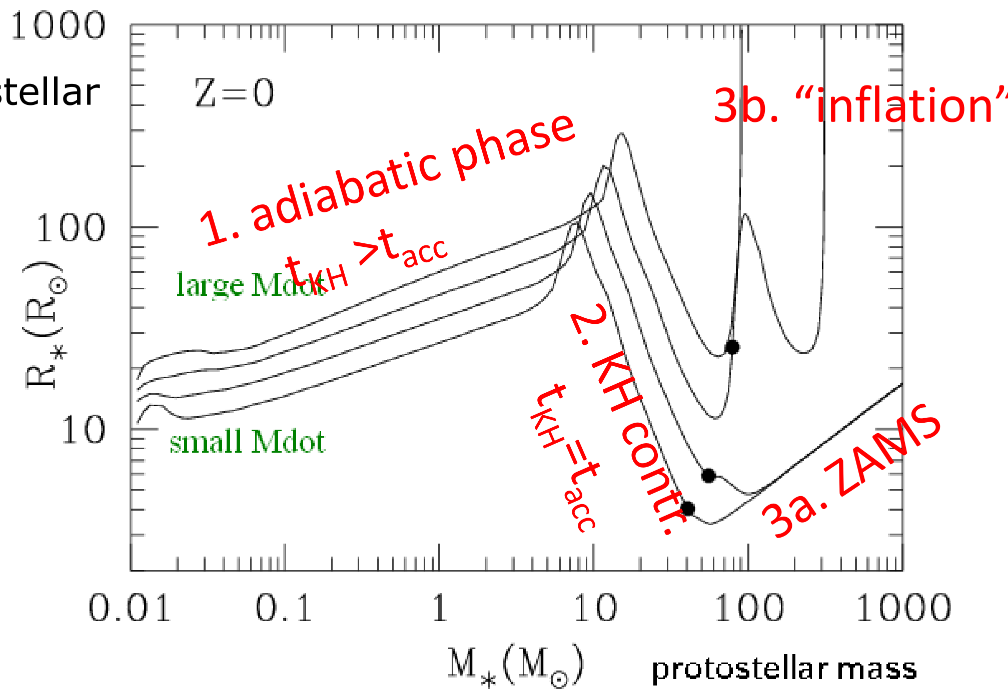
➔ Massive star will be formed.
How much?

Cases with different accretion rates

KO & Palla (2003)

$dM_*/dt=8.8, 4.4, 2.2, 1.1 \times 10^{-3}\ M_{sun}/yr$

protostellar radius



KH time

$t_{KH}=GM_*^2/R_*L_*$

accretion time

$t_{acc}=M_*/(dM_*/dt)$

All protostars go through the adiabatic and the KH contraction phases.

Subsequent phase depends on the accr. rate.

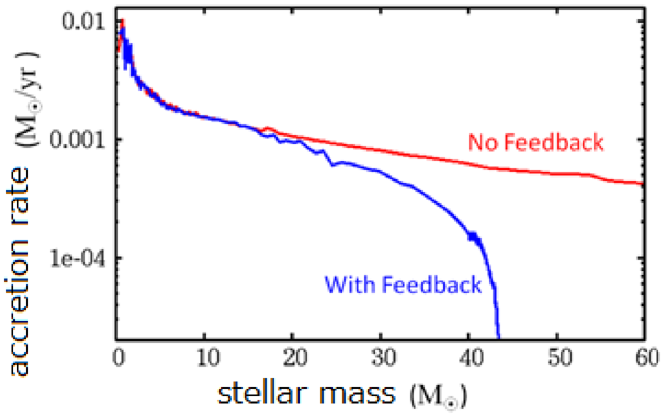
✓With low accretion rate ($<dM/dt_{crit}=4\ 10^{-3}M_{sun}/yr$):
→the star reaches ZAMS and accretion continues

✓With higher accretion rate ($>dM/dt_{crit}$) :
→the star starts inflating when L ($=L_*+L_{acc}$) becomes close to L_{Edd}.

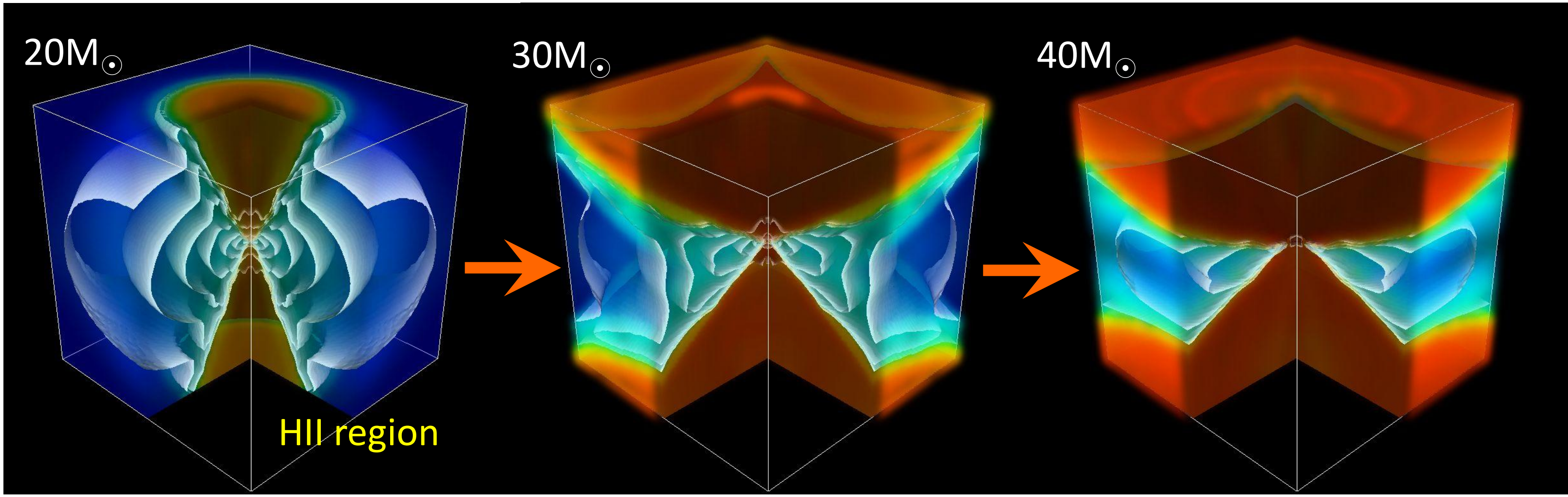
$L_{acc} \propto \dot{M}_*/R_*$

Feedback-limited mass of first stars

In non-spherical accretion:
mass of first stars is set by
the UV feedback
photoevaporation of disk
(McKee & Tan 08, Hosokawa+11/12,
Stacy+12, Hirano +14, Susa + 2014)



Accretion stops at ~40Msun



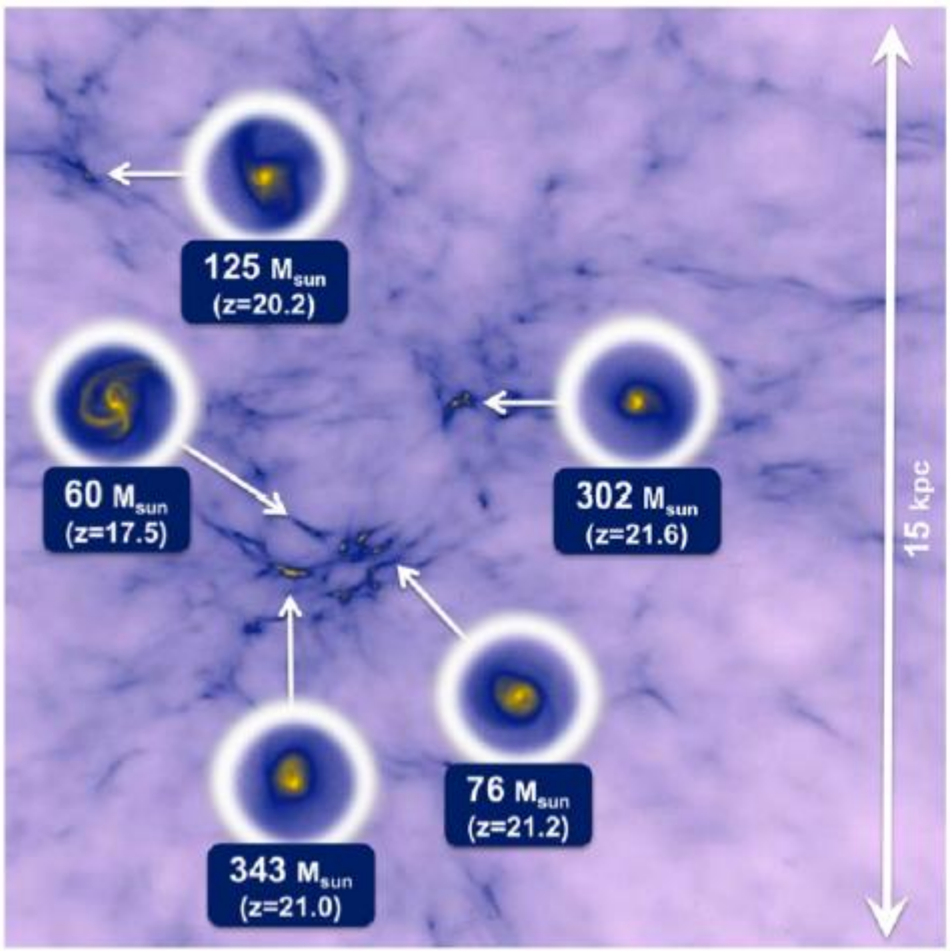
contour: density, color: temperature

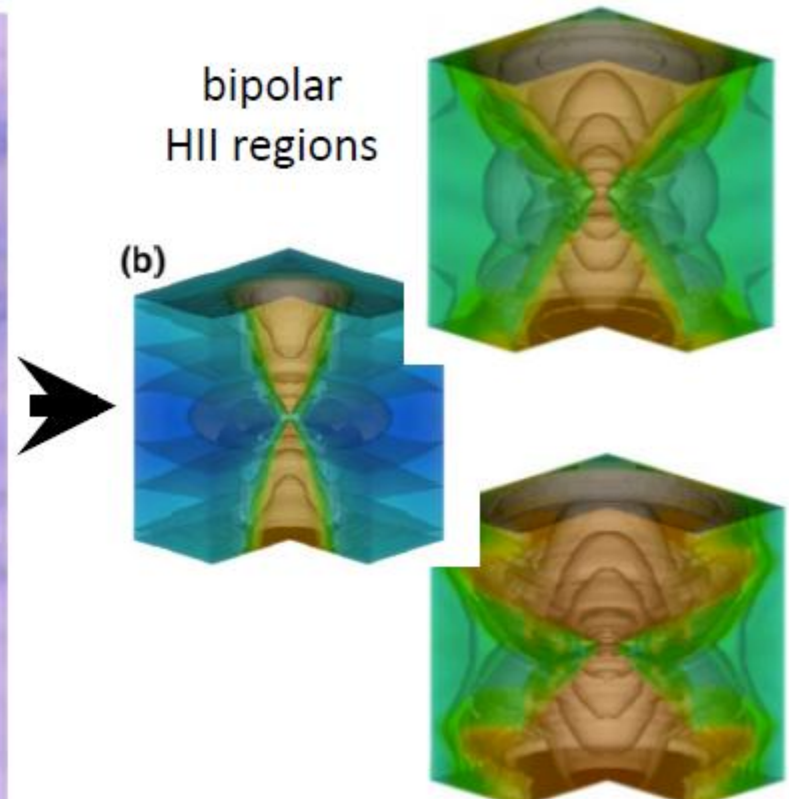
Hosokawa, KO, Yoshida, Yorke 2011, 2012

Statistical Study: toward IMF

3D cosmological simulation
+2D radiation hydro simulation
for star formation

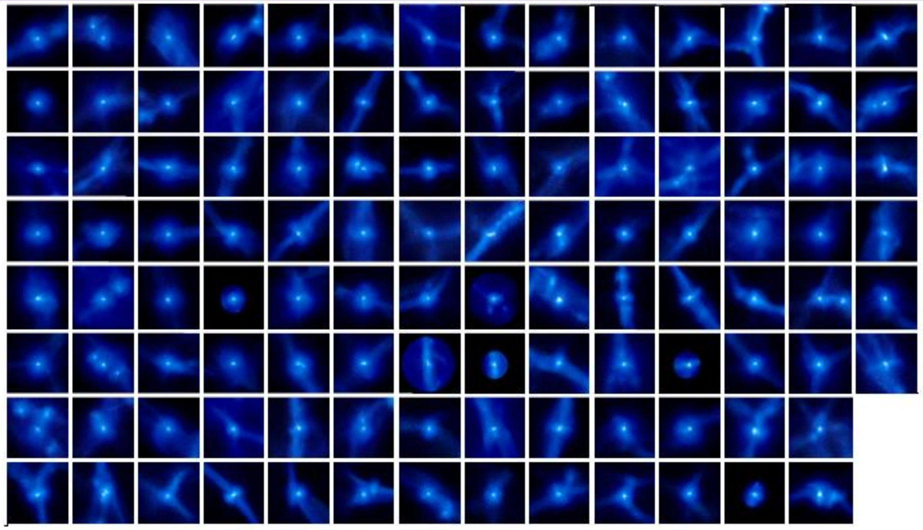
Hirano et al. (+KO)
2014, 2015
studied
>100-1000 halos



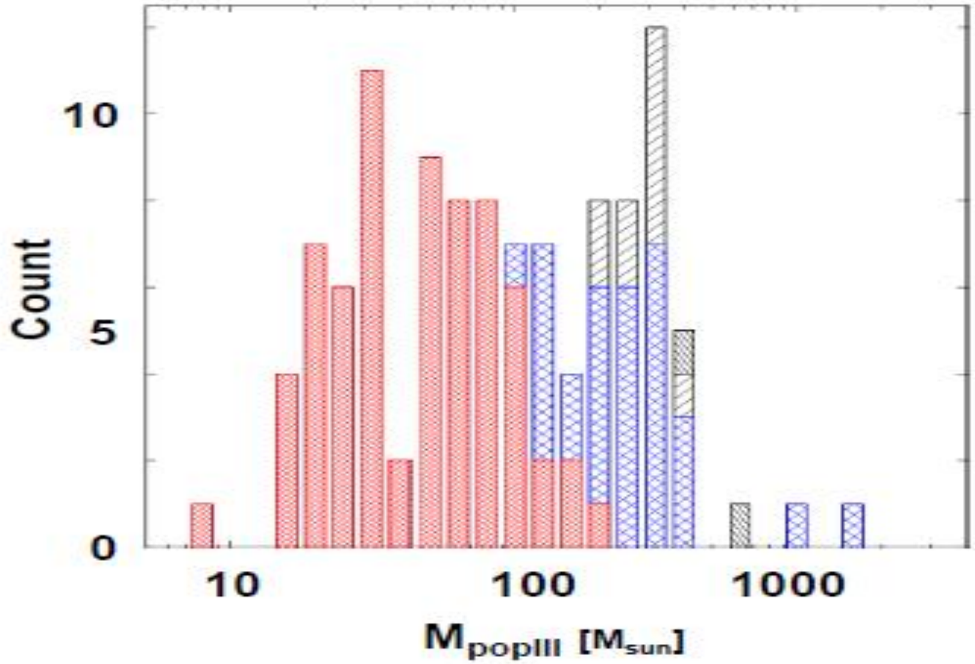


The UV feedback finally shuts off the
mass accretion in all the cases

mass distribution of first stars



Hirano+ (KO) 2014, 2015 studied >100-1000 halos



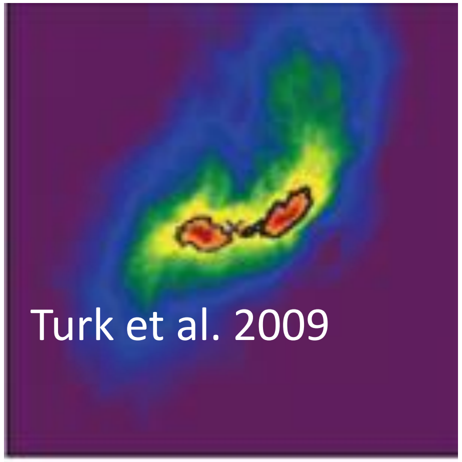
✓flat distribution in a wide mass range: a few 10-100 M_{sun}

✓even 1000M_{sun} first stars can be formed

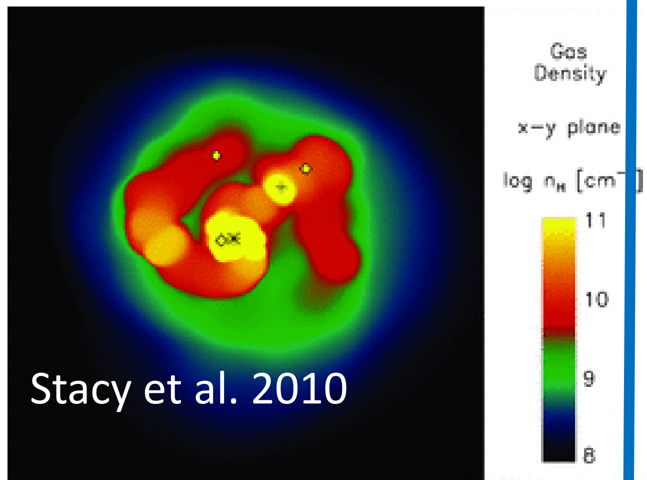
First Binaries ?

Some first stars were also binaries

fragmentation during the collapse
("turbulent fragmentation")

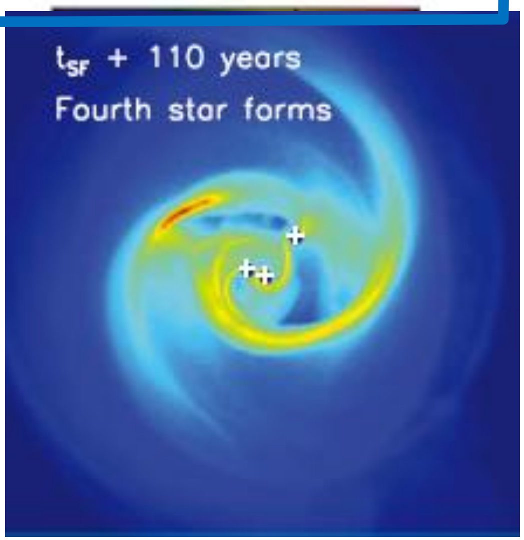


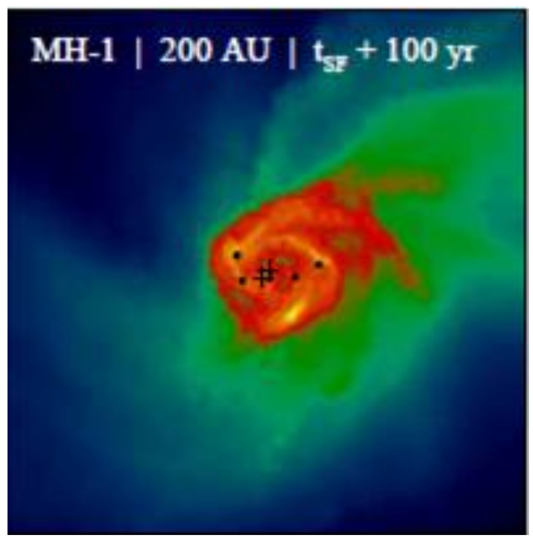
Turk et al. 2009



Stacy et al. 2010

From 2009 onward, it becomes known that binaries/multiples are formed in the first star formation.





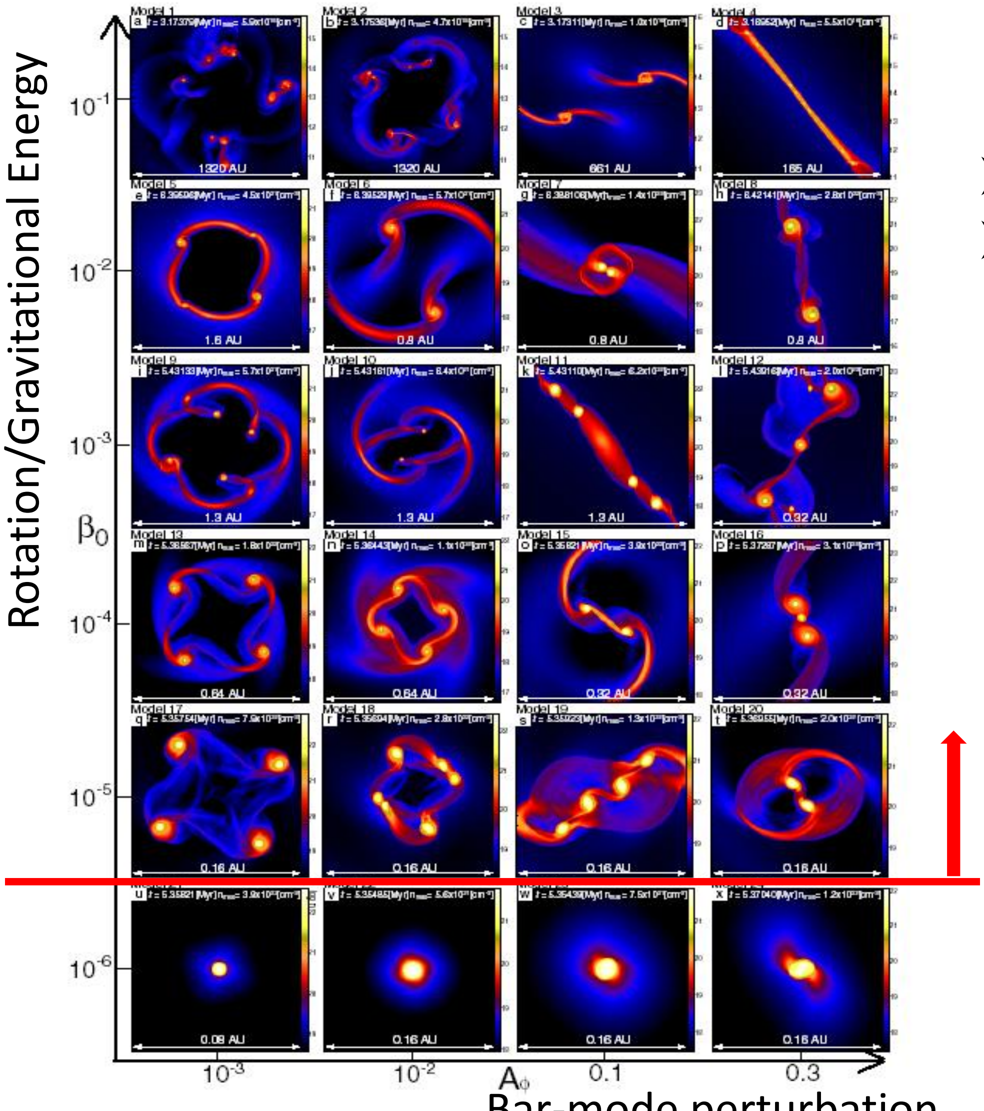
fragmentation
of circumstellar disk
after protostar formation
("disk fragmentation")

Clark et al. 2011

Greif et al. 2011

Earlier work on first binary formation

Machida, KO+ 2008



- ➢barotropic EOS from one−zone model
- ➢idealistic initial condition:
  - ➢BE sphere ($10^3 cm^{-3}$)
    density x 1.01 (α_0=0.83)
  - ➢Rotation β_0
  - ➢Perturbation (bar A_φ + m=3)

All the cores with some rotation (β_0> 10^{-6} - 10^{-5} fragment.

More prone to fragmentation than present-day

Radiative feedback in 3D

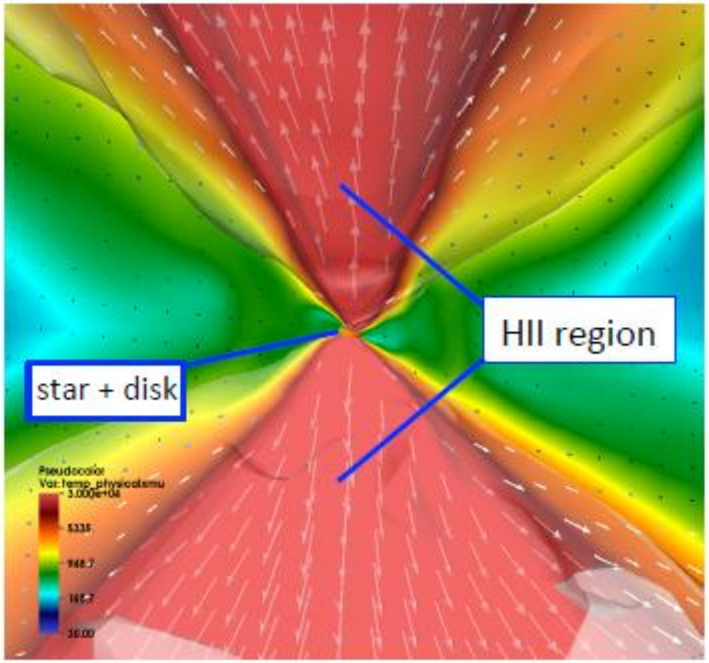
Hosokawa + (KO) 2016

Public multi-D MHD code: PLUTO (e.g., Mignone et al. 07)

A modified version developed for studying present-day high-mass star formation (R.Kuiper+10 etc.)
+ self-gravity + FLD solvers

+

- UV radiation transfer + chemistry
- Stellar evolution (Yorke & Bodenheimer 08)
- Cosmological initial condition (Hirano+14)



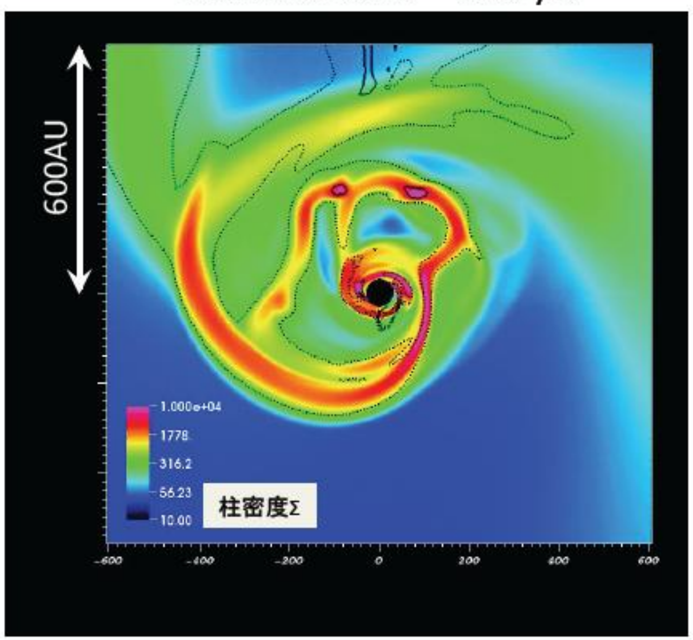
polar coordinate + central sink (radius of 30AU and spatially fixed)

Follow the long-term ($\sim 10^5$ yrs) evolution
with ionizing (EUV) and dissociating (FUV) feedback in 3D

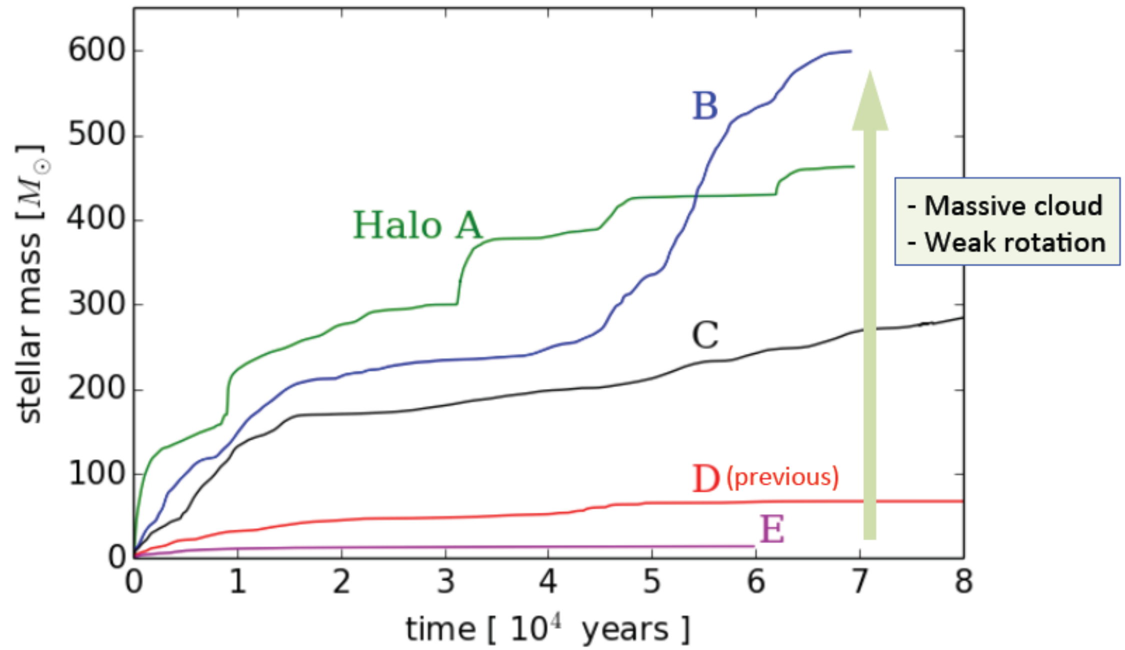
fragmentation and migration…

Hosokawa + (KO) 2016

Evolution over ～100 yrs



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

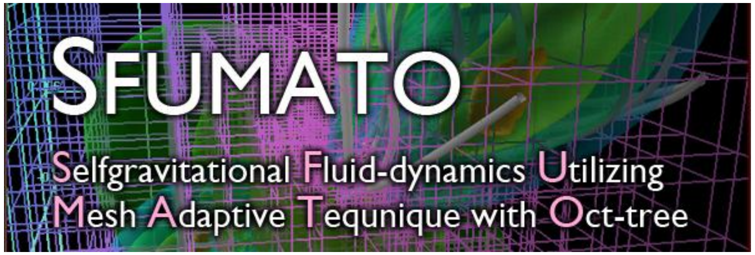


The central star grows very massive
before the UV feedback shut off the accretion.

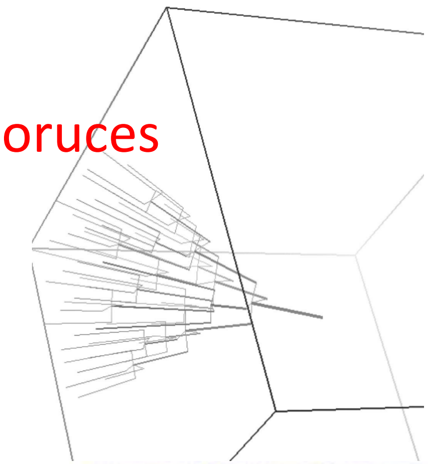
But, radiation comes only from the central source.
→ massive binary formation remains unexplored.

Multi-source simulation in AMR

Sugimura +(KO). in prep.



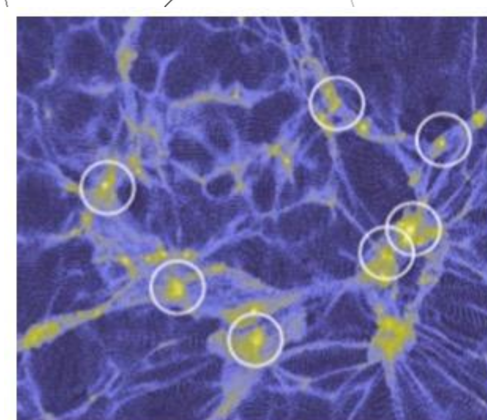
AMR + (M)HD + self-gravity
+ sink particle method
(Matsumoto 07 etc.)



+ adaptive ray-tracing (ART) method for multiple soruces
(e.g., Abel & Wandelt 02; Rosen et al. 2017)
of EUV (H ionizing) & FUV (H2 dissociating) rad.

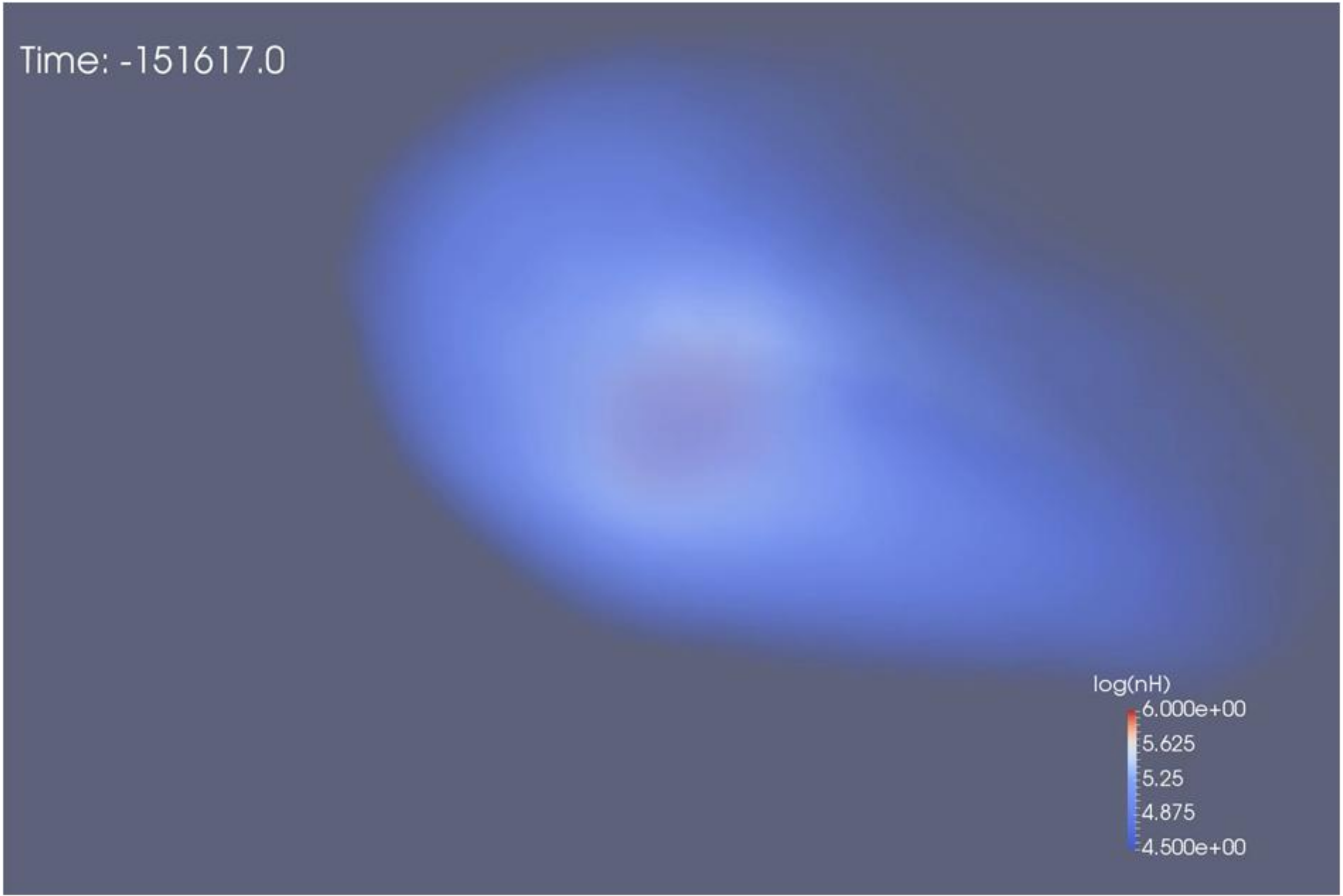
+ chemistry network & cooling/heating processes
w/ the primordial composition (zero metallicity)

+ Cosmological initial cond. (Hirano et al. 15)
Halos C & D of Hosokawa+ (2016)



3D movie

halo C, $rsin_{k=64}au$



sink particle evolution

minihalo C, r_{sink}=64au

Evolutionary phases

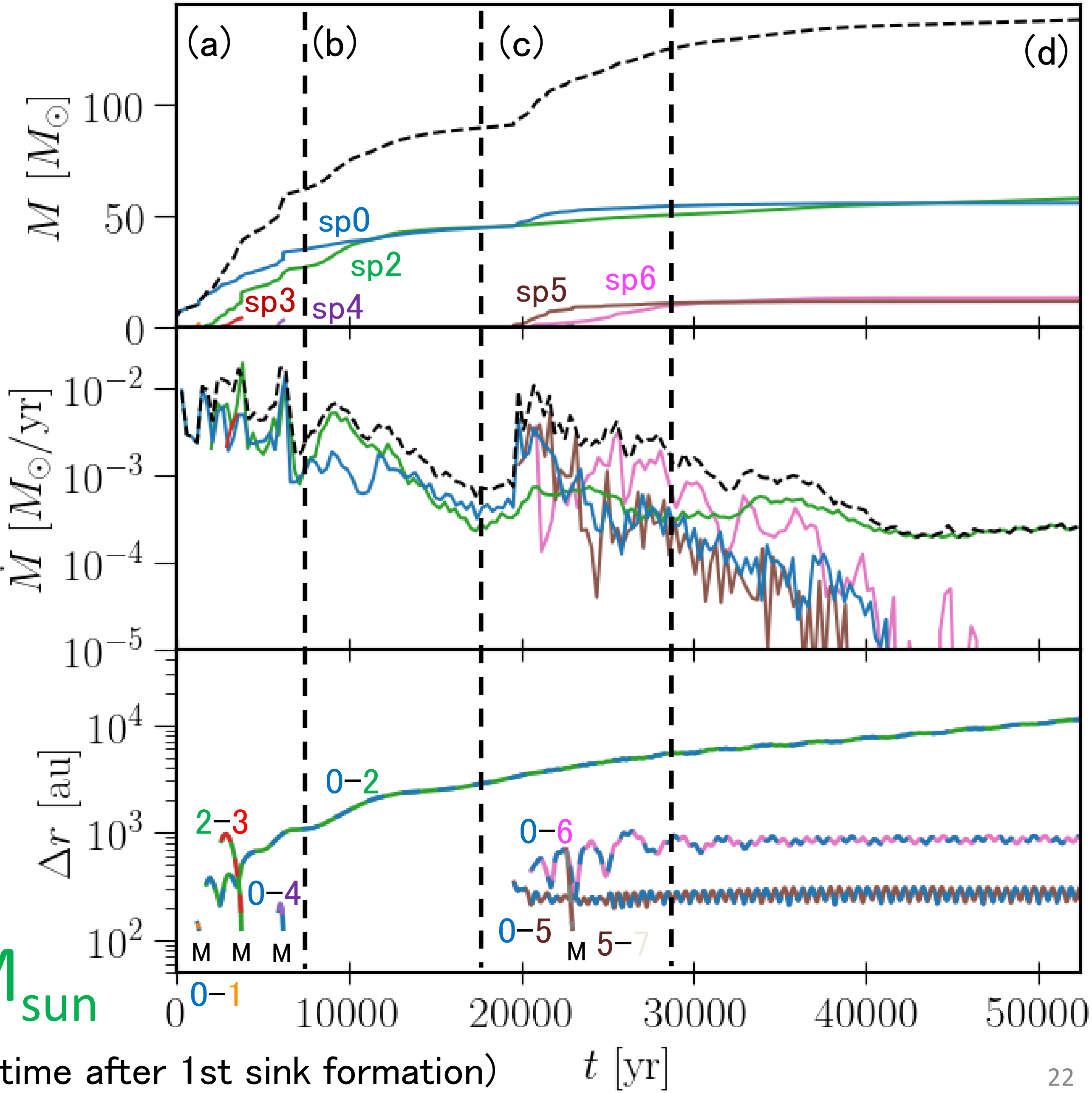
(a) initial frag.

(b) acc. binary

(c) late−time frag.

(d) photo−evap. of mini−multiple system

$50M_{sun} + 50M_{sun}$



(t: time after 1st sink formation)

sink particle evolution

Evolutionary phases

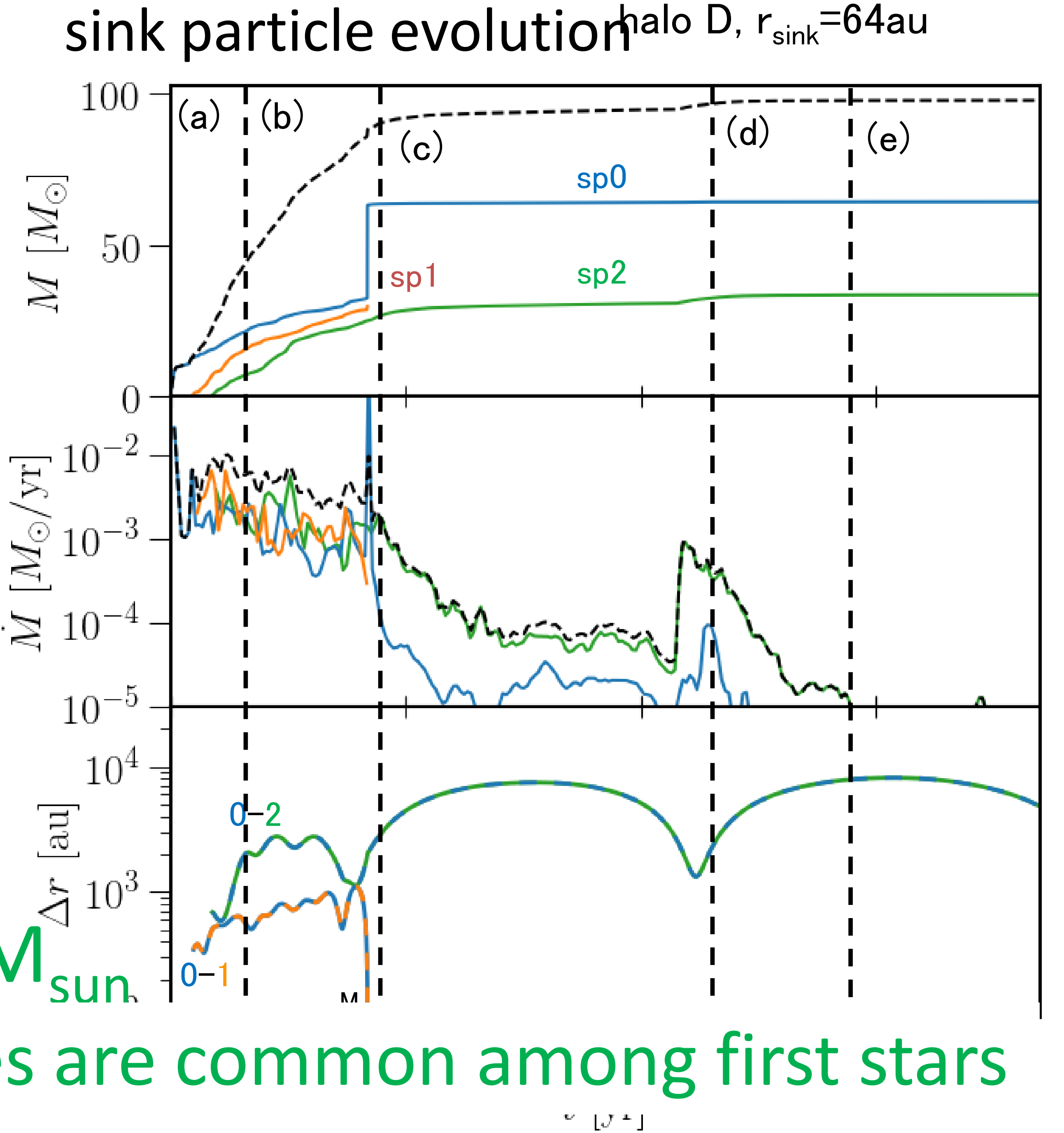
(a) initial frag.

(b) merger induced by a–few–body effect

(c) accreting binary

(d) internal photo–evaporation

(e) external photo–evaporation



$60M_{sun} + 30M_{sun}$

Massive binaries are common among first stars

Toward MHD calculation:

accurate ionization degree modelling needed

Magnetic fields will change the picture ?

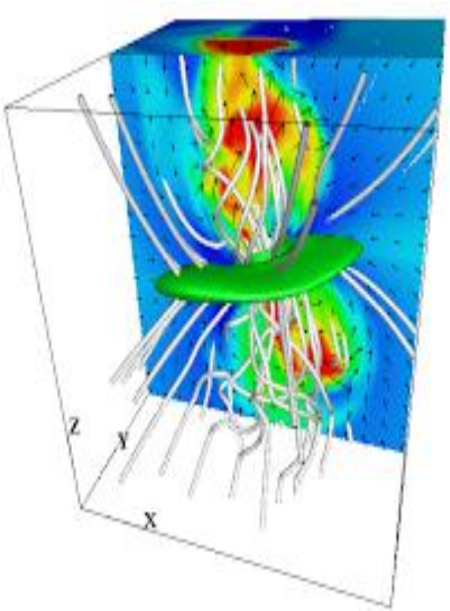
In Galactic ISM, B-fileds are almost in energy equi-partition:

$E_B \sim E_{kin} \sim E_{grav}$

Roles:

- Support against the collapse
- Jet/Outflow launching
- Angular momentum transport
  by magnetic braking, magneto-rotational instability
- Suppressing fragmentation of disk

→determines frequency of binary formation



(e.g., Machida & Doi '13)

Even in low-metallicity ISM, significant B-fields may be present
seed field ($\sim 10^{-19}$G) amplified by e.g., small-scale dynamo

Magnetic field dissipation

Ionization degree in star forming clouds is low → magnetic dissipation can occur

e.g., Wardle 2007

balance of Lorentz and drag forces for charged particles j

$$Z_j e \boldsymbol{E}' + Z_j e \frac{\boldsymbol{v}_j}{c} \times \boldsymbol{B} - m_j \gamma_j \rho \boldsymbol{v}_j = 0$$

Hall parameter

$$\beta_j = \frac{|Z_j| e B}{m_j c} \frac{1}{\gamma_j \rho}$$

$$\rightarrow \quad \boldsymbol{J} = \sum_j n_j e Z_j \boldsymbol{v}_j = \sigma_O \boldsymbol{E}'_{\parallel} + \sigma_H \hat{\boldsymbol{B}} \times \boldsymbol{E}'_{\perp} + \sigma_P \boldsymbol{E}'_{\perp}$$

with Ohmic, Hall, and Pedersen conductivities

$$\sigma_O = \frac{ec}{B} \sum_j n_j |Z_j| \beta_j \quad \sigma_H = \frac{ec}{B} \sum_j \frac{n_j Z_j}{1+\beta_j^2} \quad \sigma_P = \frac{ec}{B} \sum_j \frac{n_j |Z_j| \beta_j}{1+\beta_j^2}$$

$$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla \times (\boldsymbol{v} \times \boldsymbol{B}) - \nabla \times [\eta_{\mathrm{O}} \nabla \times \boldsymbol{B} + \eta_{\mathrm{H}} (\nabla \times \boldsymbol{B}) \times \hat{\boldsymbol{B}} + \eta_{\mathrm{A}} (\nabla \times \boldsymbol{B})_{\perp}]$$

Ohmic, Hall and ambipolar diffusivities

$$\eta_O = \frac{c^2}{4\pi \sigma_O} \qquad \eta_H = \frac{c^2}{4\pi \sigma_\perp} \frac{\sigma_H}{\sigma_\perp} \qquad \eta_A = \frac{c^2}{4\pi \sigma_\perp} \frac{\sigma_P}{\sigma_\perp} - \eta_O$$

$$\sigma_\perp = \sqrt{\sigma_H^2 + \sigma_P^2}$$

Ionization degree controls magnetic dissipation

new chemical network

107+107=214 reactions among 23 species.

H, H_2, e^-, H^+, H_2^+, H_3^+, H^-, He, He^+, He^{2+}, HeH^+, D, HD, D^+, HD^+, D^-, Li, LiH, Li^+, Li^-, LiH^+, Li^{2+}, Li^{3+}.

- all the reactions are reversed.

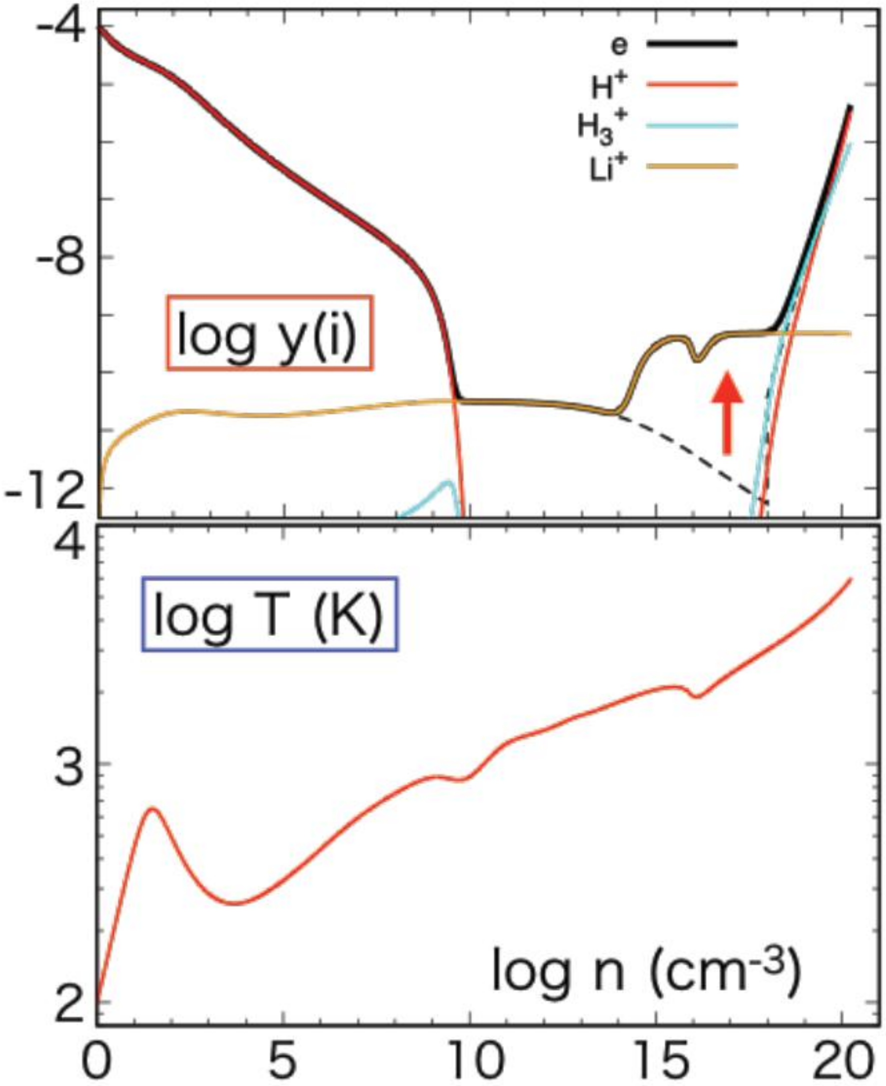
Rate coefficients for reverse reactions calculated from the detailed balance.

$$R_1 + R_2 \rightleftarrows P_1 + P_2 \qquad k_{\rm rev} = k_{\rm fwd} K_{\rm eq}(T)$$

$$K_{\rm eq}(T) = \left(\frac{2\pi k_{\rm B} T}{h_{\rm P}^2}\right)^{3(M-N)/2} \left(\frac{m_{\rm R_1} \ldots m_{\rm R_M}}{m_{\rm P_1} \ldots m_{\rm P_N}}\right)^{3/2} \left(\frac{z({\rm R_1}) \ldots z({\rm R_M})}{z({\rm P_1}) \ldots z({\rm P_N})}\right) e^{-\Delta E / k_{\rm B} T}$$

accurate treatment of ionization degree in primordial gas

Nakauchi, KO, Susa 2019



204 reactions (all reversed) among 23 species:

H, H_2, e^-, H^+, H_2^+, H_3^+, H^-, He, He^+, He^{2+}, HeH^+, D, HD, D^+, HD^+, D^-, Li, LiH, Li^+, Li^-, LiH^+, Li^{2+}, Li^{3+}.

major positive ions:

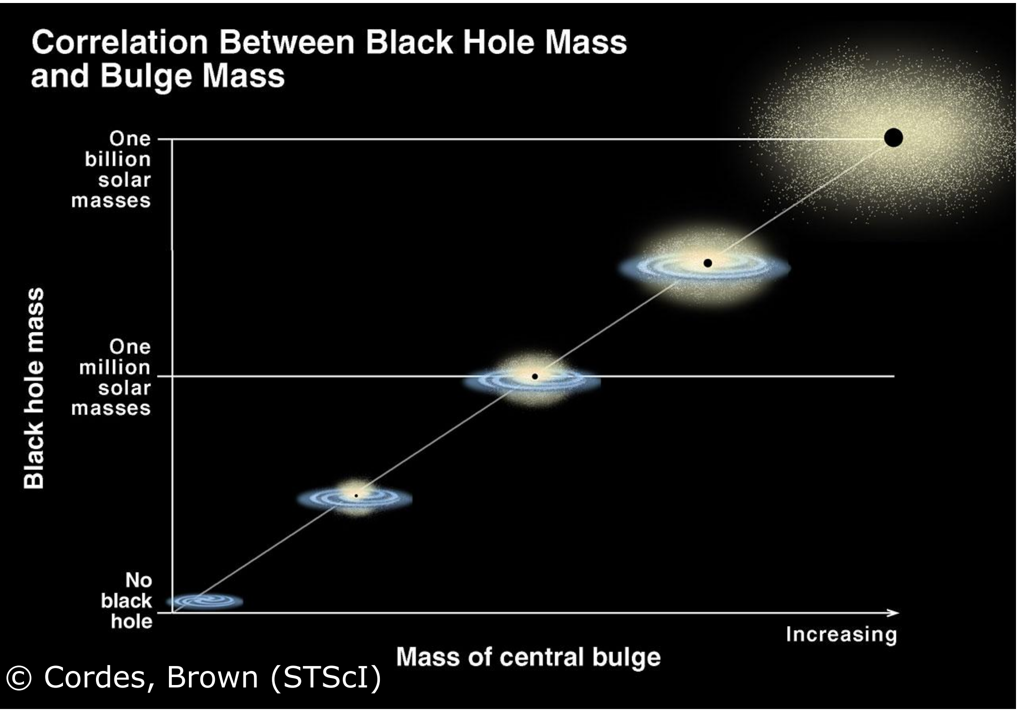
$H^+ \rightarrow Li^+ \rightarrow H_3^+ \rightarrow H^+$

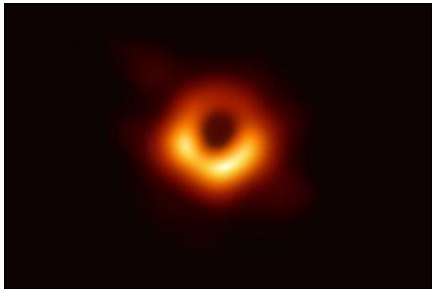
Li ionization by thermal photons enhances ionization degree at $>10^{14}$cm^{-3}

$$\mathrm{Li}^+ + e \rightleftharpoons \mathrm{Li} + \gamma$$

First Black Holes

Supermassive BHs





©EHT

- ubiquitously reside at the center of galaxies
- BH mass correlates with the bulge mass

Like train stations in Japanese cities

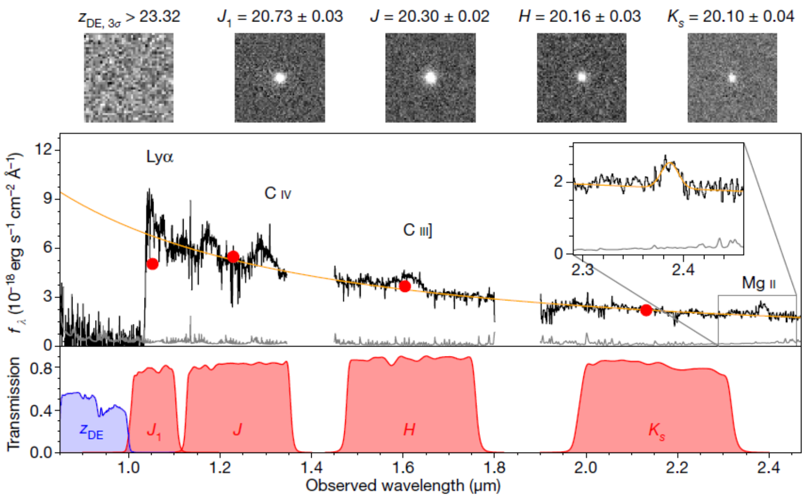
But its origin unknown

Highest-z SMBHs

SMBHs are already in existence in <Gyrs universe.

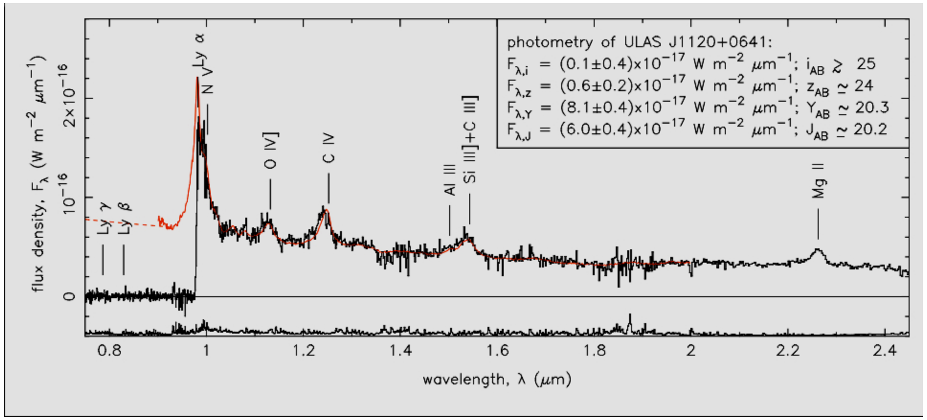
ULAS J1342 Banados+2017

M_{BH}=0.8x$10^9 M_{sun}$ z=7.54 (0.69Gyr)



ULAS J1120 Mortlock+2011

M_{BH}=2x$10^9 M_{sun}$, z= 7.085 (0.77Gyr)



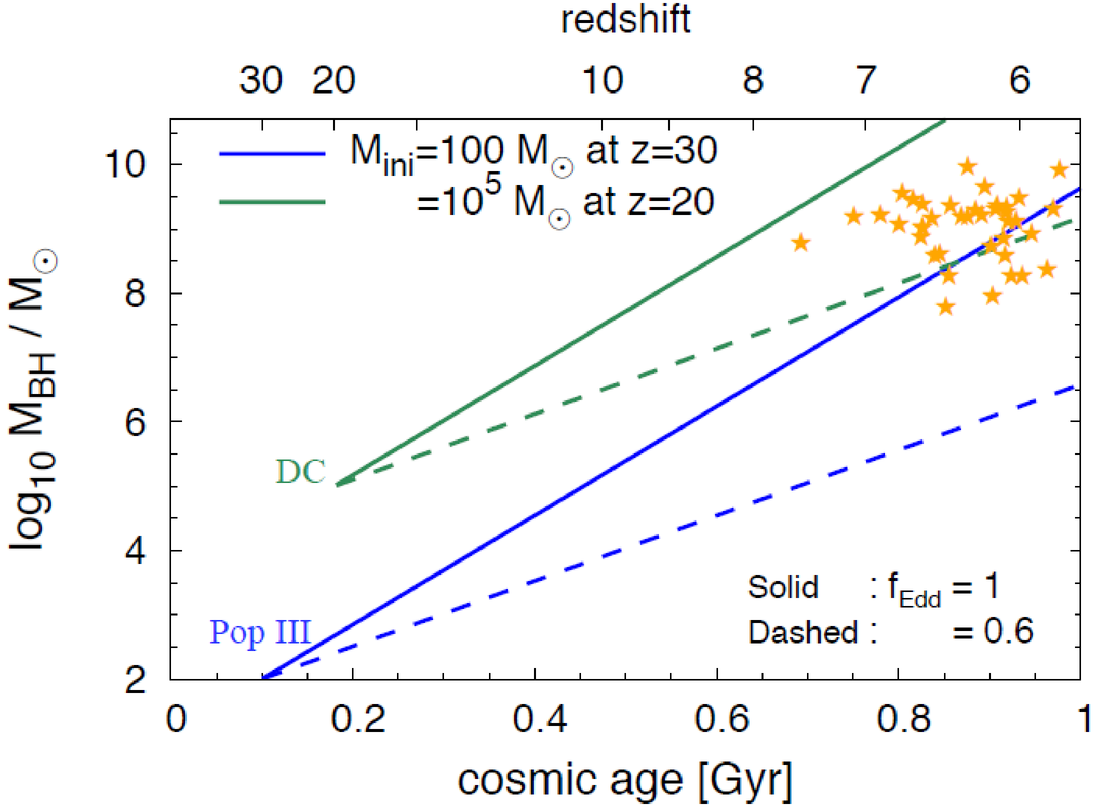
They are not alone:

・Dozens of quasars have been found at z>6.5

(Venemans +2014, Matsuoka+2017, 2018)

・Ultra-massive BH of 1.2x$10^{10}M_{sun}$ at z=6.3 (Wu+2013)

SMBH growth time problem



via Eddington-limited accretion:

$$M_{BH}=M_{ini}\exp(t/t_{Sal})$$

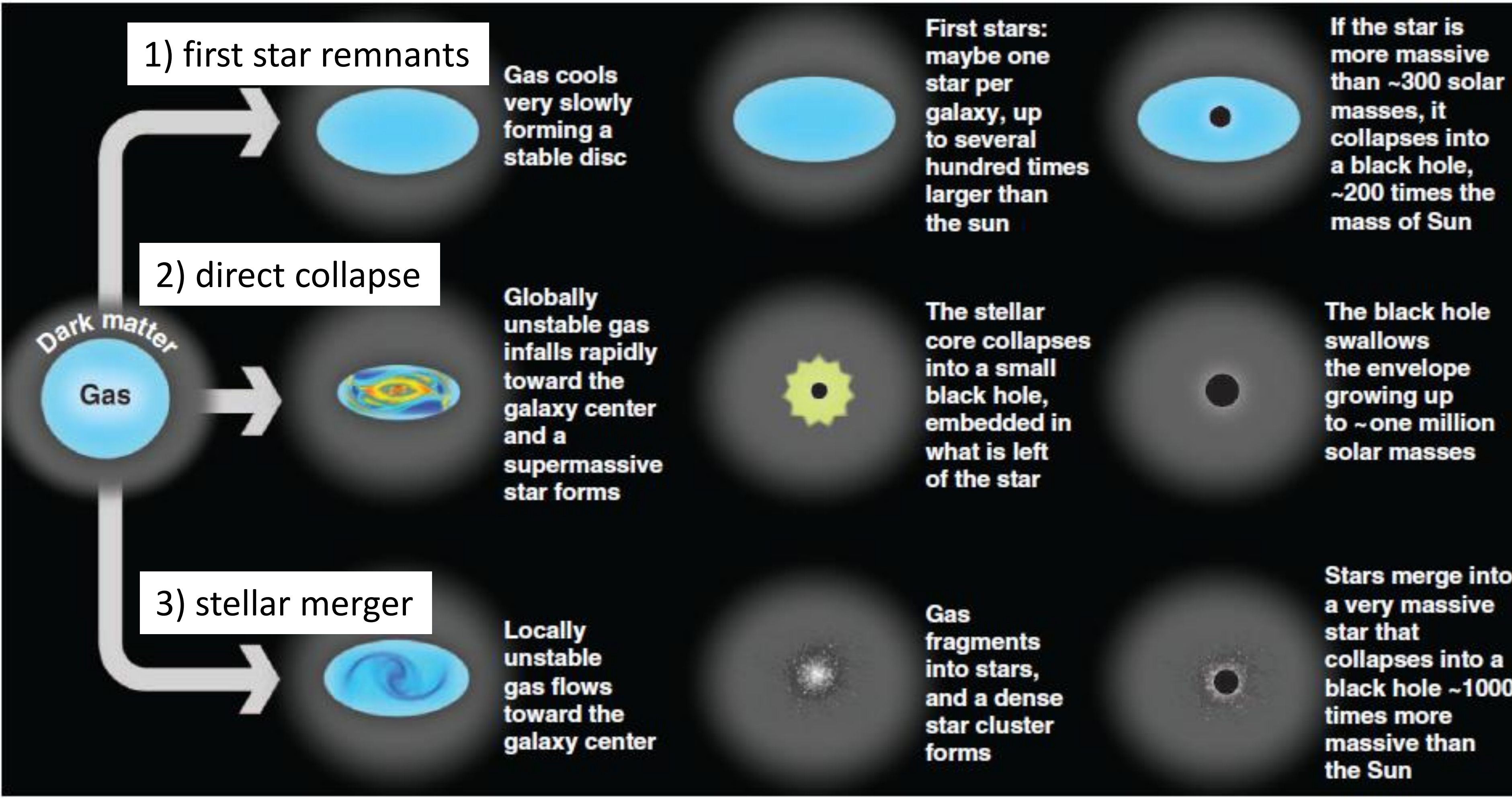
with Salpeter time

$$t_{Sal} = \varepsilon\sigma_T c/4\pi G m_H$$
$$=0.05\text{Gyr}\ (\varepsilon/0.1)$$

✓stellar-mass BH fails to reach supermassive by z~7.

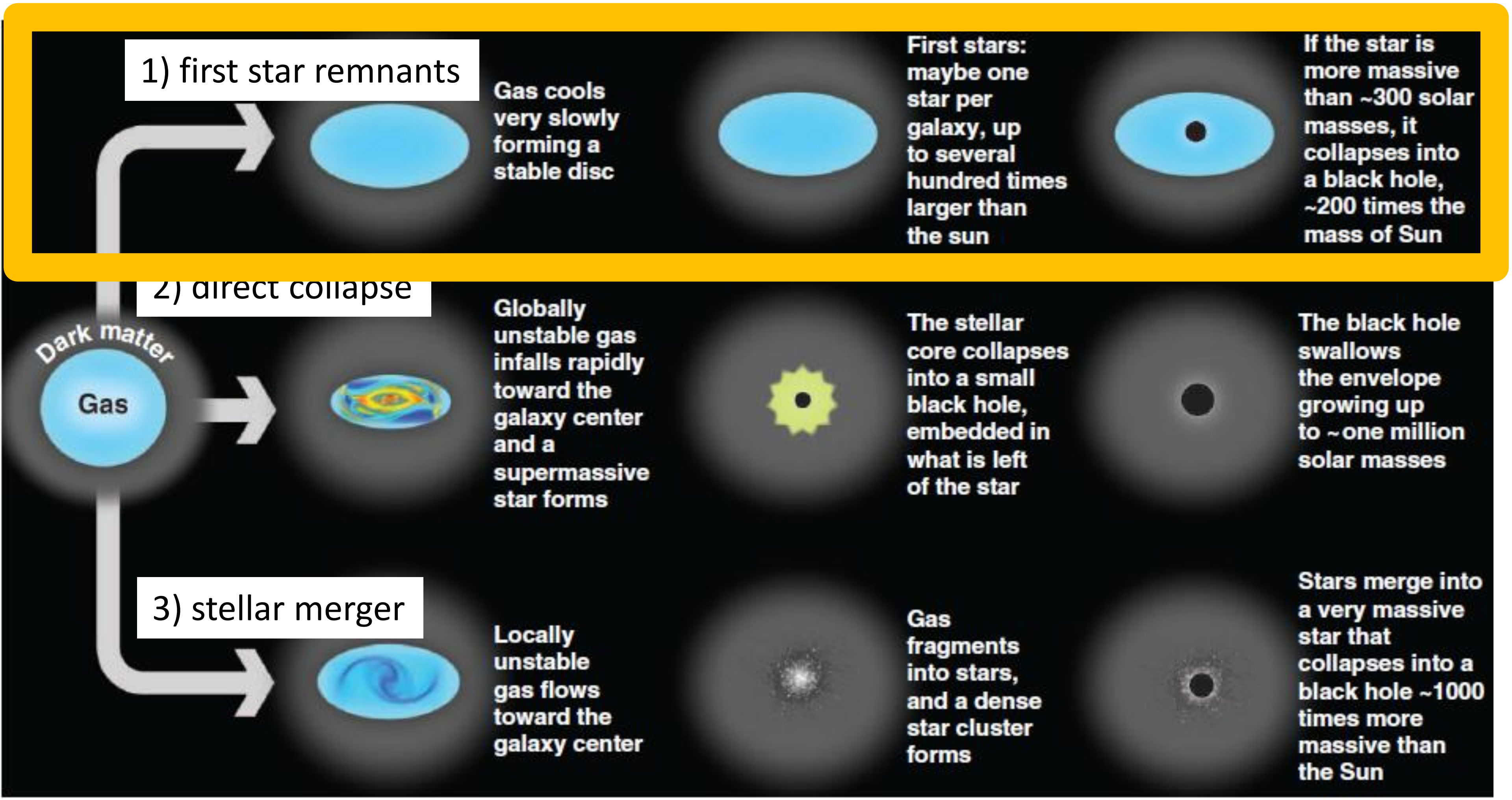
✓More massive seeds or more rapid growth required.

seed BH formation scenarios



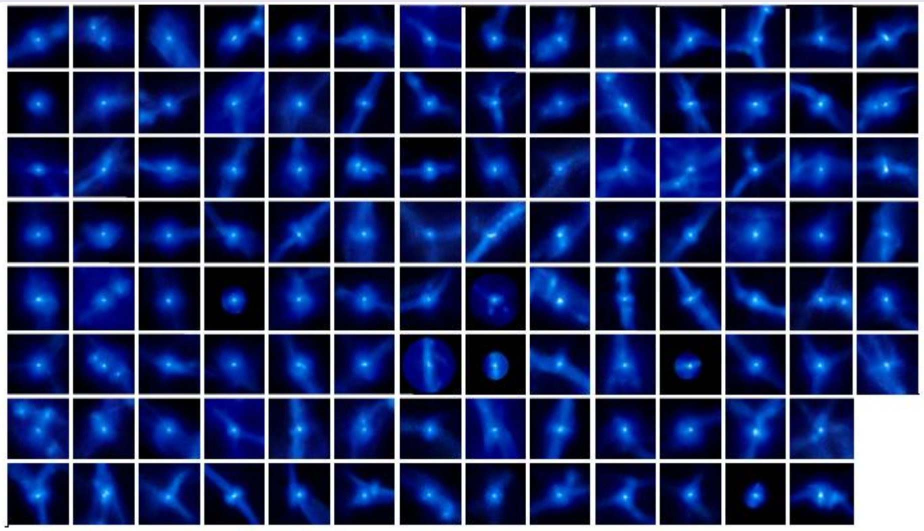
Volonteri 2012

1) first star remnant BHs

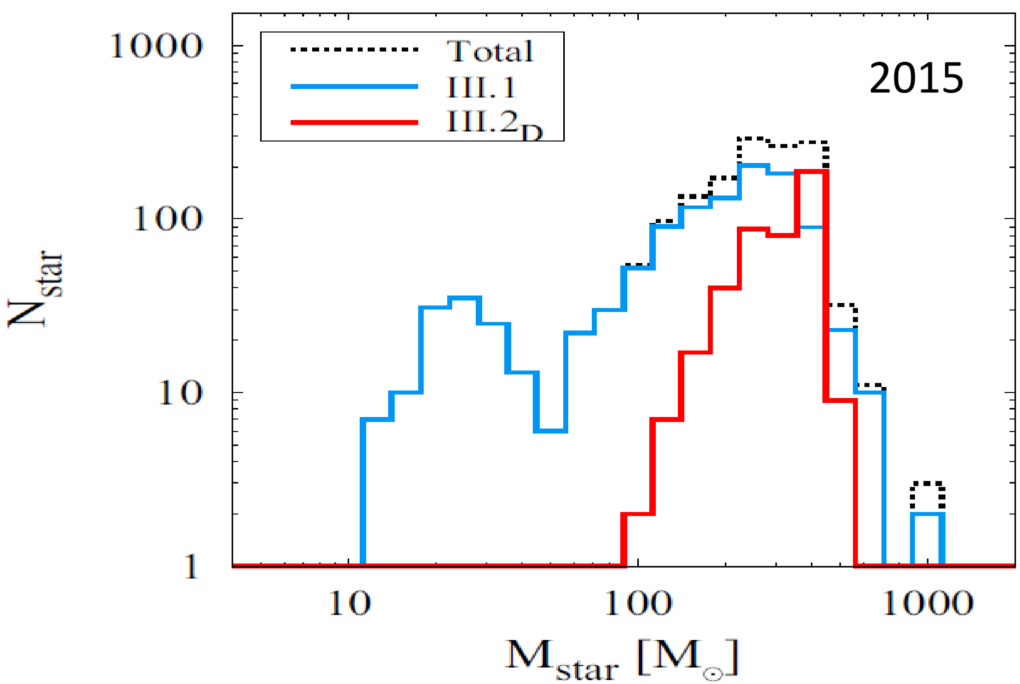


Volonteri 2012

getting more massive in recent years …



Hirano+ (KO)
2014, 2015
studied
>100-1000 halos

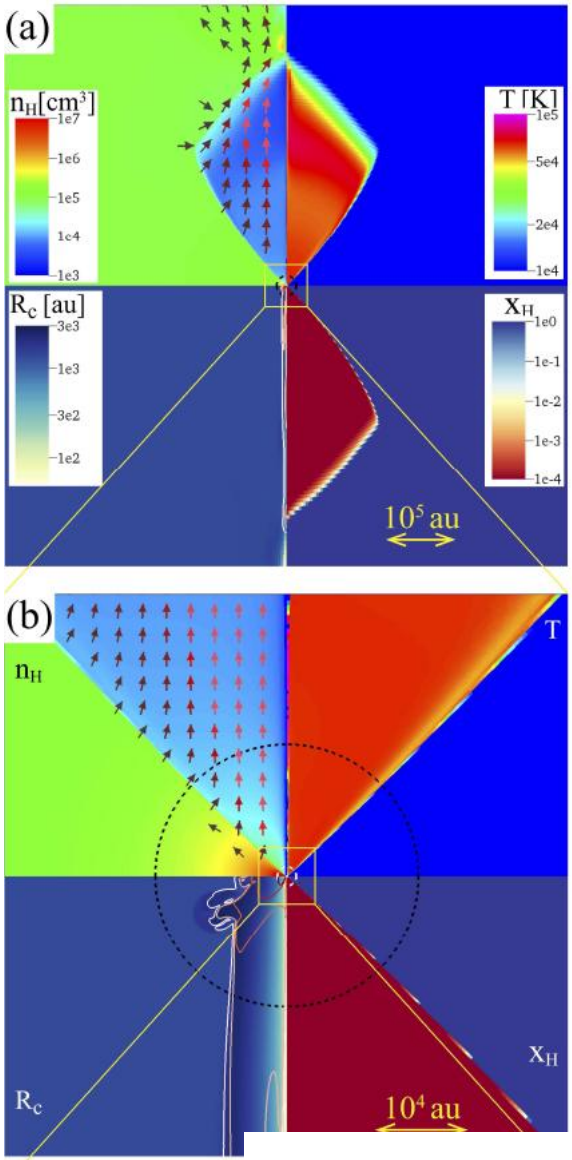


✓flat distribution in a wide mass range:
a few 10-100 M_{sun}

✓even 1000M_{sun} first stars can be formed

Super-critical growth feasible?

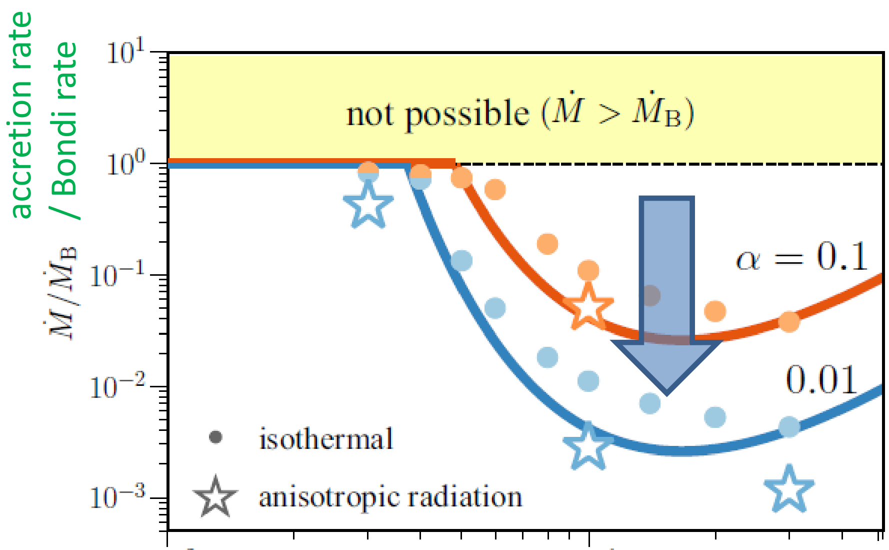
Sugimura+ (KO) 2017, 2018



- accretion flow in the shadow can be protected from radiative feedback.

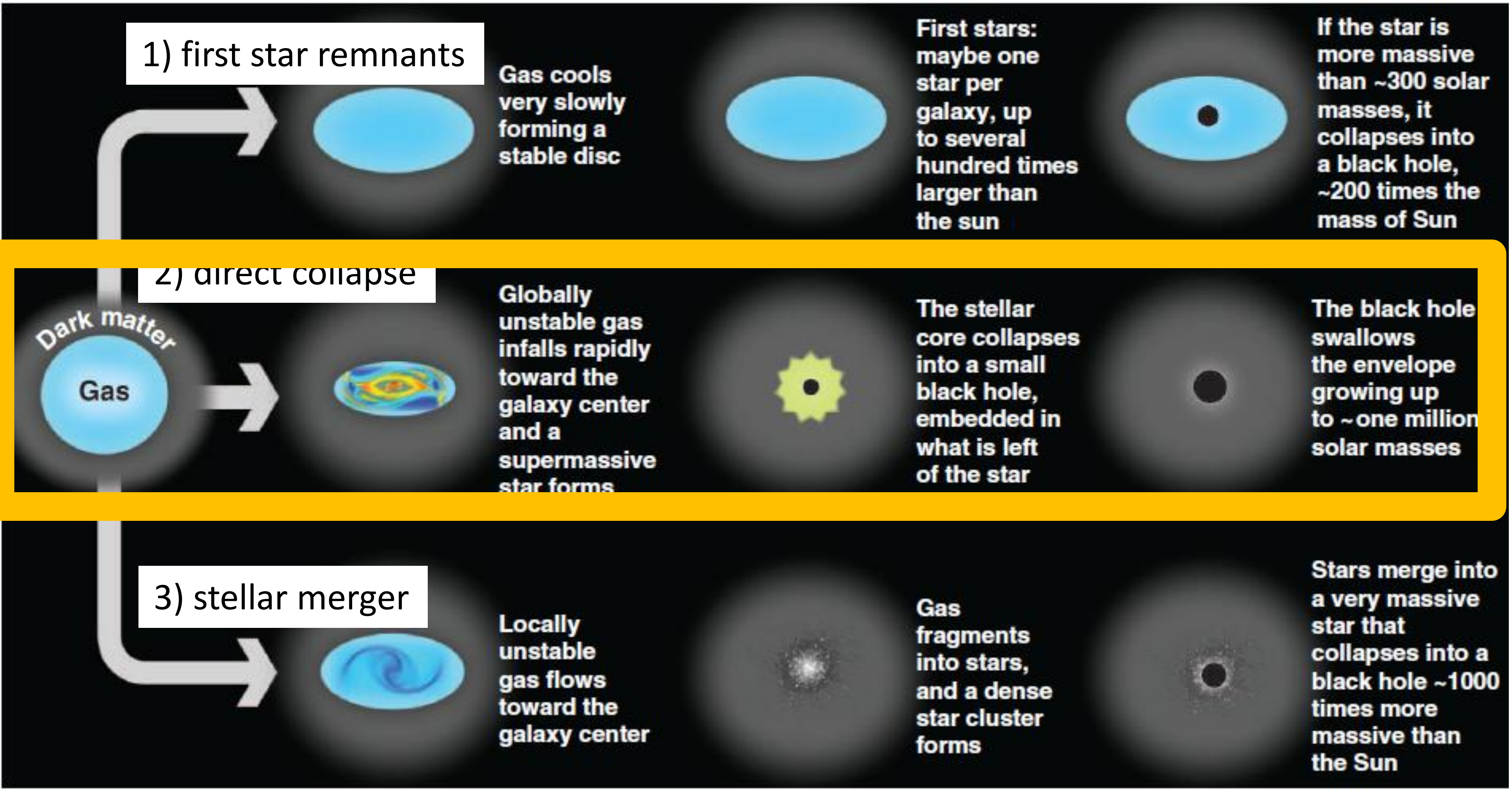
But

- angular momentum reduces the accretion rate unless
  centrifugal radius < ~5% Bondi radius



Rapid accretion growth is not so easy

2) direct collapse BHs



Volonteri 2012

Requirements for SMS formation by direct collapse

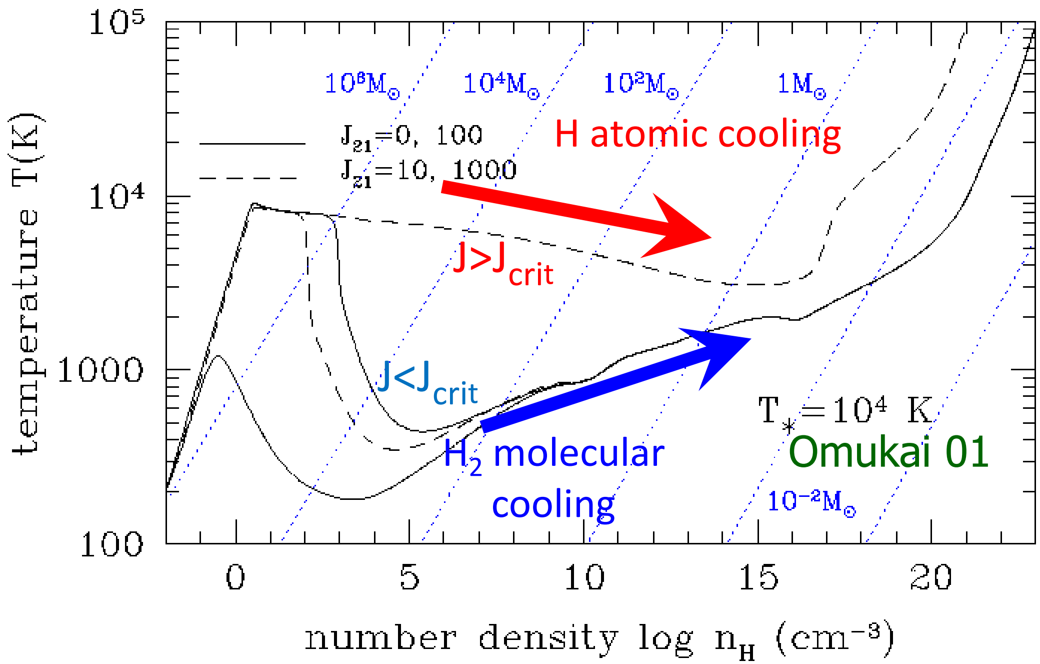
Collapse phase:

- Monolithic collapse without fragmentation
  - Rapid cooling → fragmentation
    Without such cooling → no fragmentation.

Accretion phase:

- Formation timescale shorter than lifetime (~2Myrs)
  - High accretion rate
    $>M_*/t_* \sim 10^5 M_{sun}/2x10^6 yr \sim 0.05 M_{sun}/yr$
- Protostellar Feedback suppressed

Cloud collapse in intense FUV field



If FUV radiation is more intense than the critical value J_{crit}, the cloud cools solely by atomic cooling.

- No rapid cooling phase
  → monolithic collapse

- high temperature (at ~8000K) during the collapse
  → high accretion rate in protostellar phase

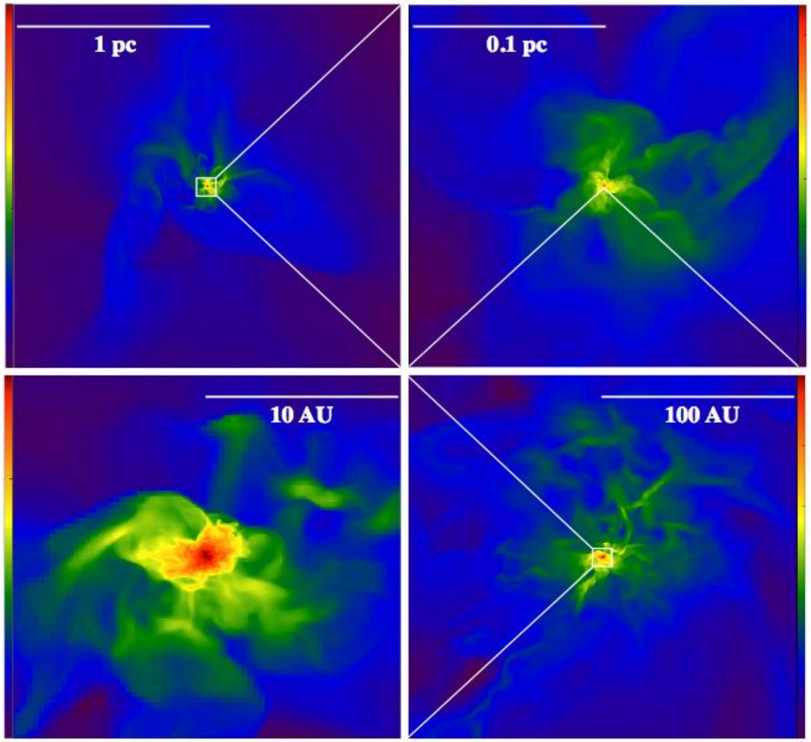
$dM_*/dt \sim c_s^3/G$
$\sim 0.06M_{sun}/yr\ (T/10^4K)^{3/2}$

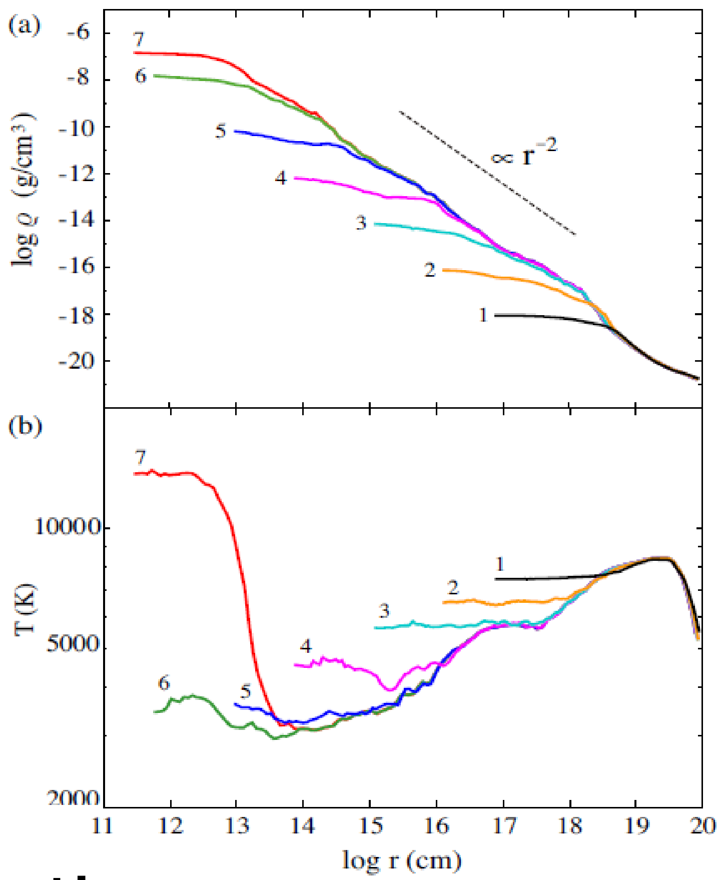
Supermassive stars ($>10^5M_{sun}$) will form

Monolithic Collapse of Atomically Cooling Cloud

e.g., Bromm & Loeb 2003, Latif +, Regan +

Inayoshi, Omukai & Tasker (2014)





✓No major eposode of fragmentation

✓small protostar (~$0.1M_{sun}$) is formed

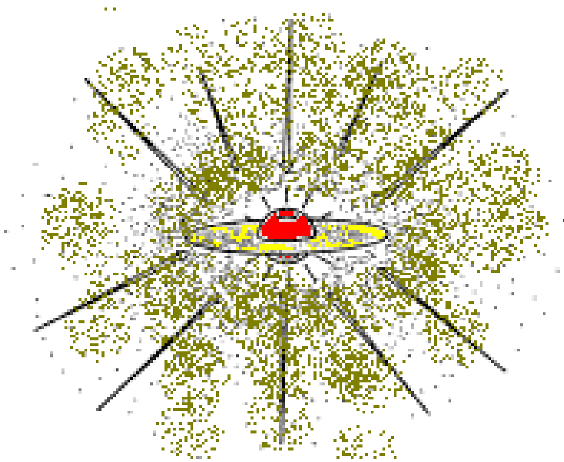
Accretion evolution to supermassive stars

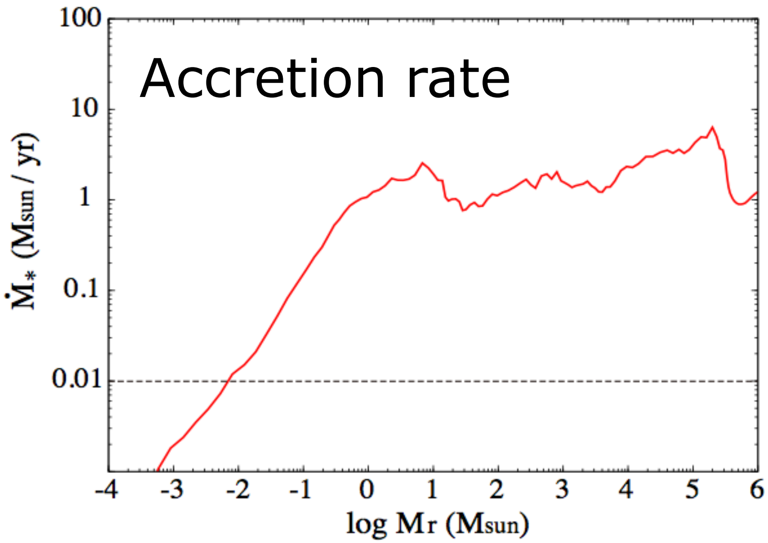
End product of the collapse phase:

protostar of 0.1 M_{sun}

surrounded by gas envelope of 10^{5-6} M_{sun},

accreting with $1 M_{sun}/yr$

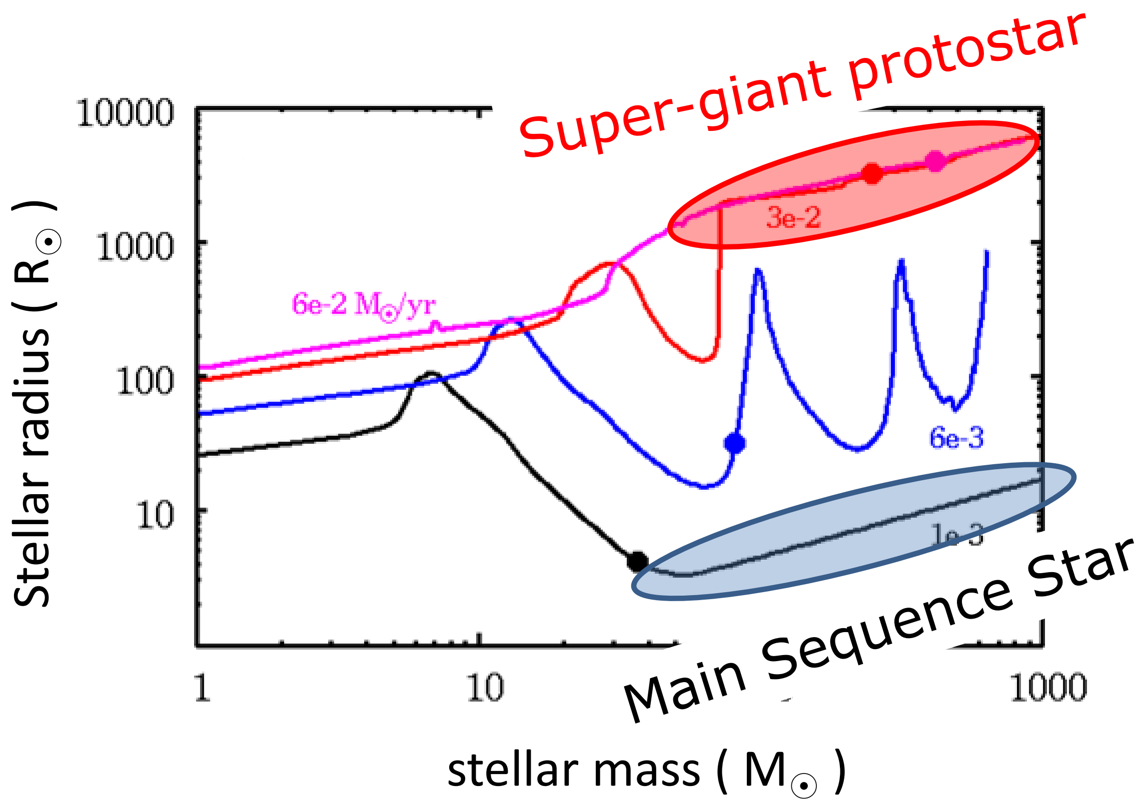




Does the star becomes super-massive without feedback stopping its growth?

"Stellar Inflation" by rapid accretion

Hosokawa, Yorke, KO (2012)

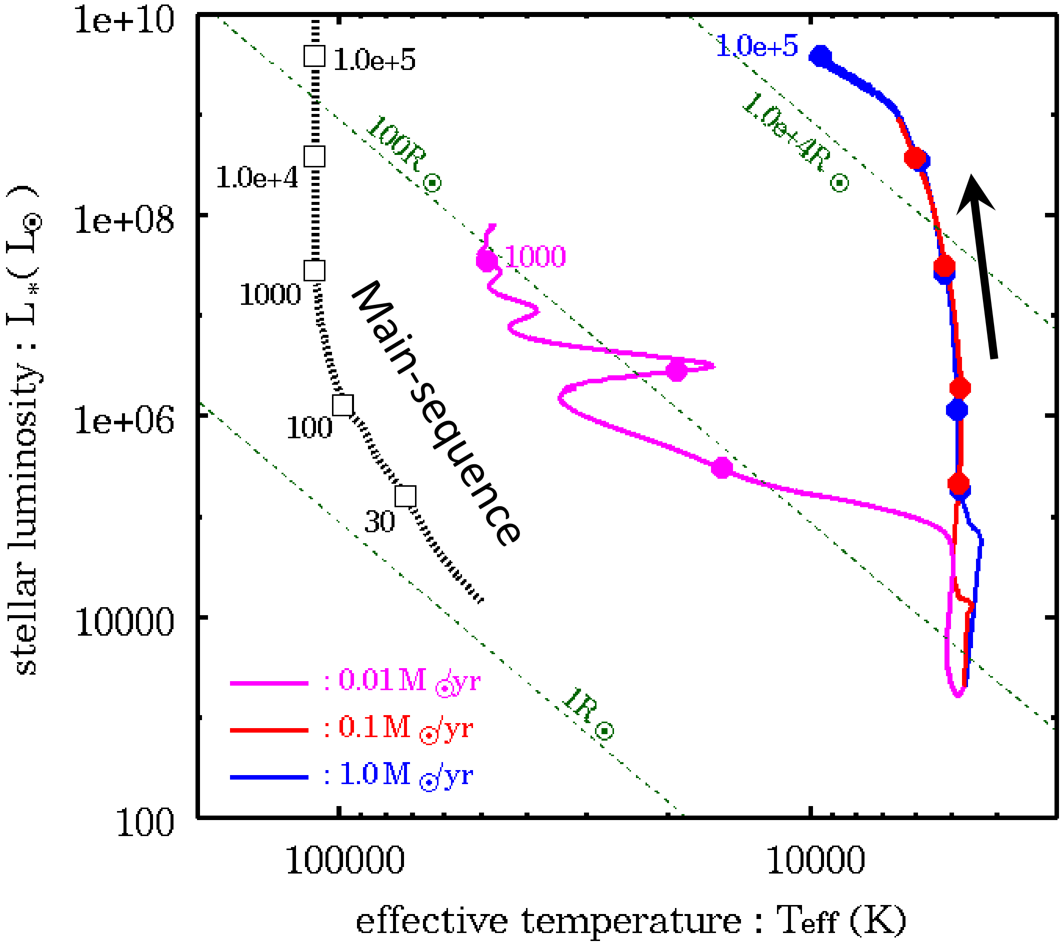


With rapid mass accretion ($> 0.01\ M_{sun}/yr$), protostar does not reach the main sequence.

Instead, its radius inflates enormously to ~10AU.

Super-giant protostar on HR diagram

Hosokawa+(KO) (2013)



low effective temperature at several 10^3K (looks like a red-giant star)

→negligible UV luminosity and feedback

→accretion continues unhindered and the star becomes supermassive

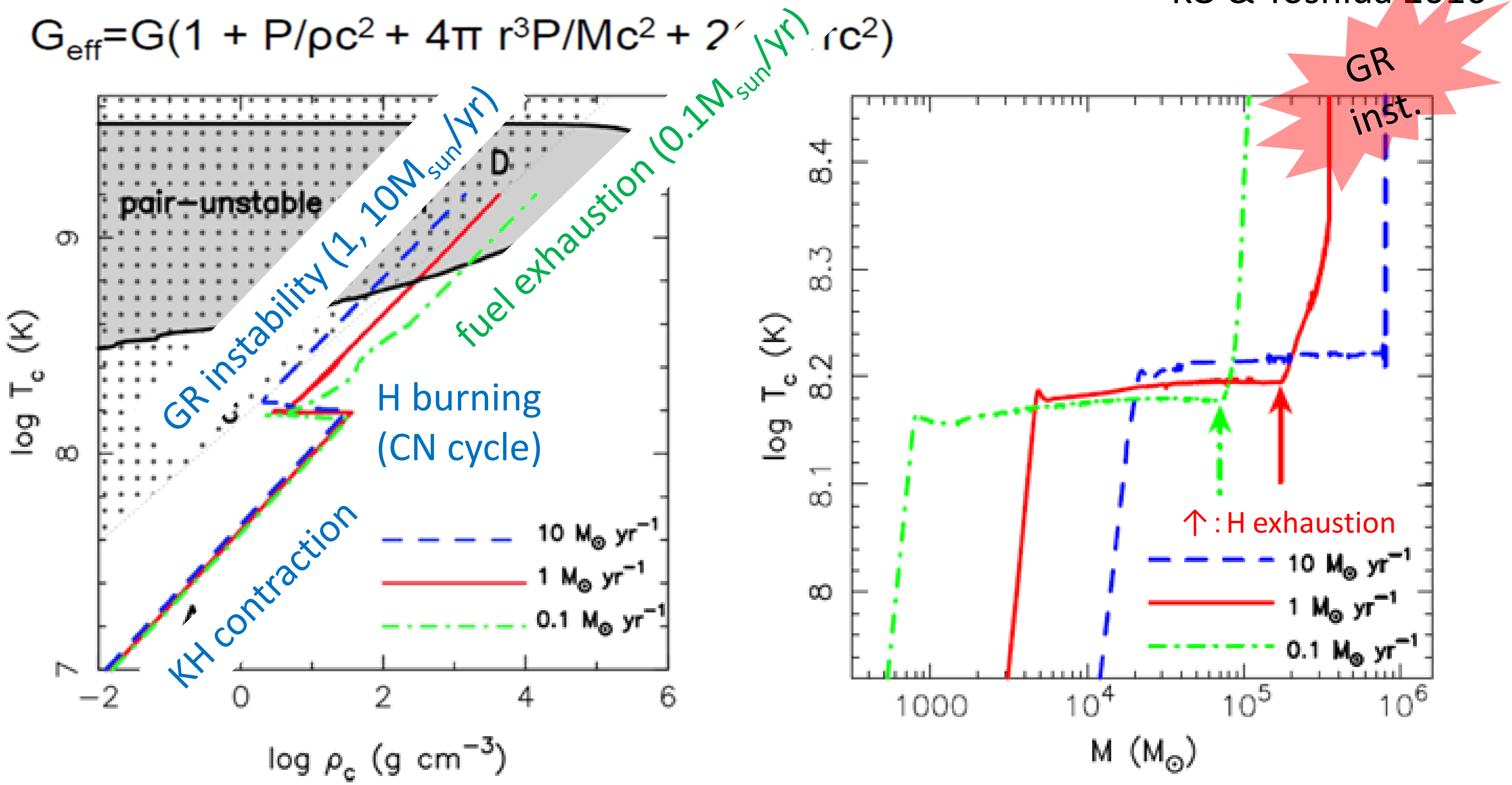
General relativistic collapse

stellar evolution caluculation with rapid accretion

Post Newtonian Gravity

G_{eff}=G(1 + P/ρc² + 4π r³P/Mc² + 2… rc²)

Umeda, Hosokawa, KO & Yoshida 2016



SMS collapses to BH at 10^5-$10^6 M_{sun}$ depending on its accretion rate

Final Stellar Mass and Composition of the Inner Core

$\dot{M}$ ($M_\odot$ yr^{-1})	0.1	0.3	1.0	10
M_f ($M_\odot$)	1.2×10^5	1.9×10^5	3.5×10^5	8.0×10^5
Y (or X)	0.00	0.99	1.00	(0.51)

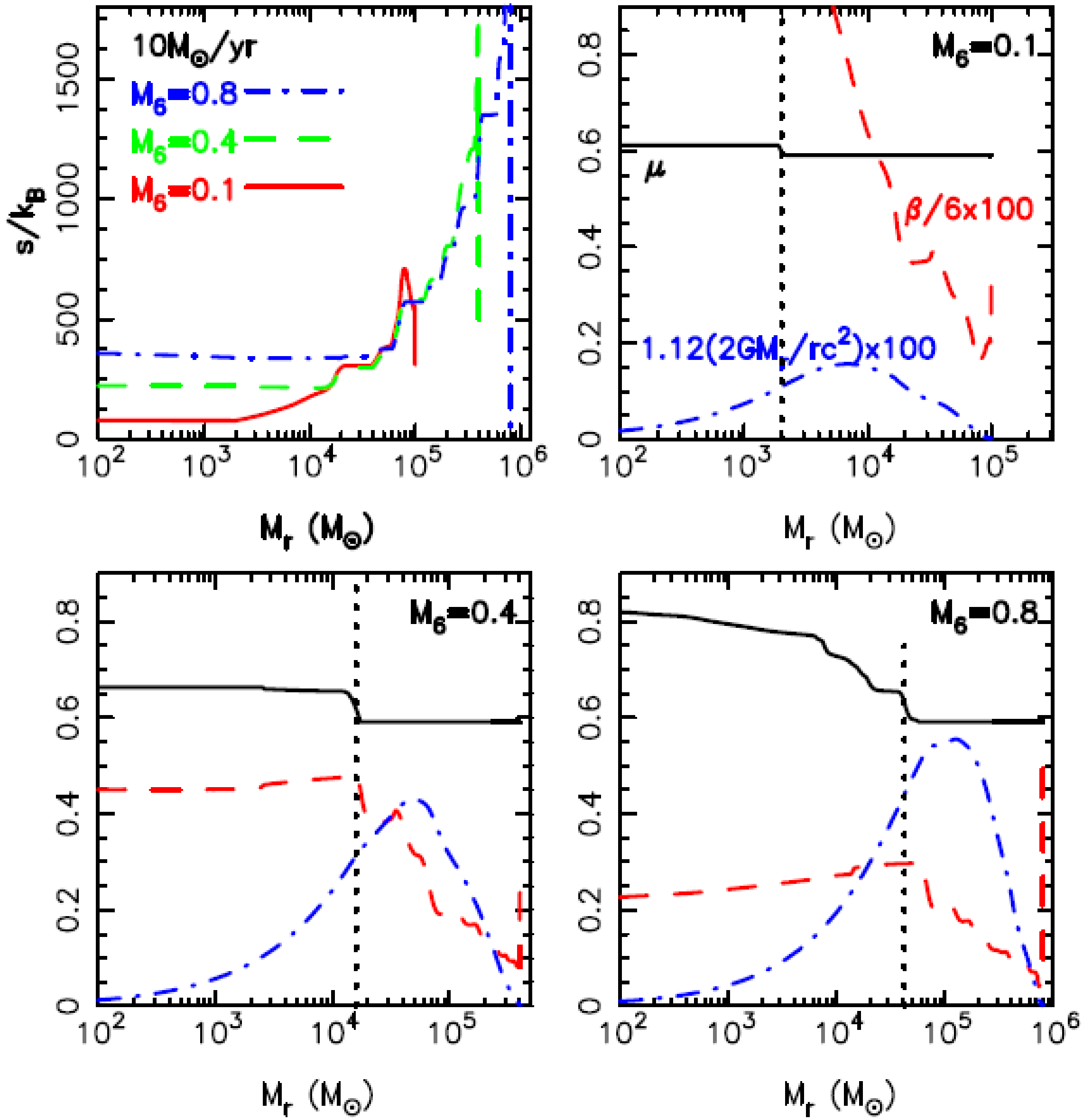
fuel exhaustion

general relativistic instability

✓The onset of GR instability at $1.4 \times 10^5 M_{sun}$ was predicted from n=3 polytrope model
→BUT the collapse starts at somewhat later (more massive) in reality

✓It was believed that the collapse begins before the nuclear burning.
→BUT the hydrogen is exhausted in the $< 1 M_{sun}$/yr cases.

entropy distribution :
envelope not in n=3 polytrope



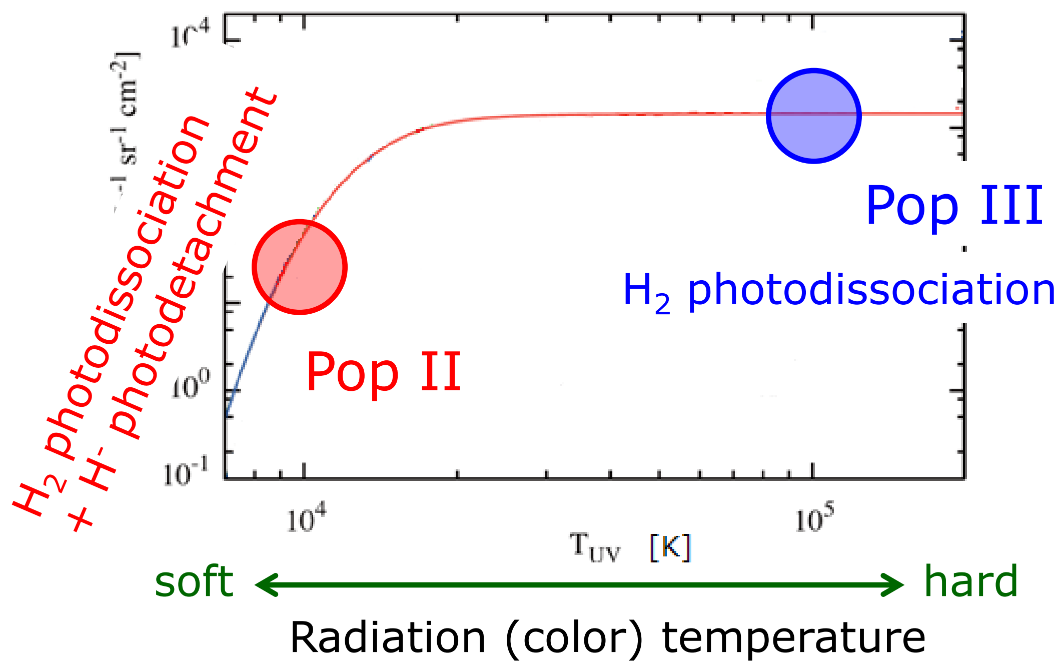
GR instability criterion for β=const. star

$$\beta/6 < 1.12\,(2GM/Rc^2)$$

Stringent condition for FUV channel

Sugimura, KO, Inoue 2014

J_{crit} : intensity at LW wavelenths (12.4eV) needed for atomic cooling.



✓J_{crit} increases with radiation temperature (i.e., hardness)

H^- photodetachment and H_2 formation

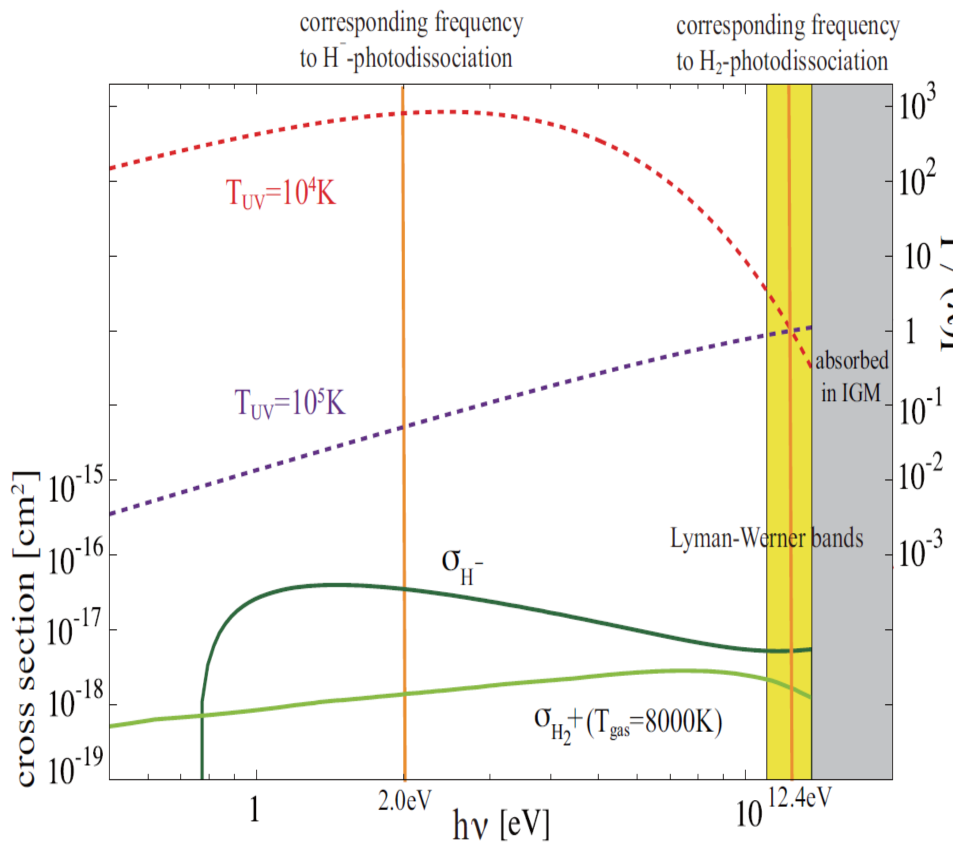
H_2 formation via H^- channel

$H + e \rightarrow H^- + \gamma$

H_2 formation: $H^- + H \rightarrow H_2 + e$

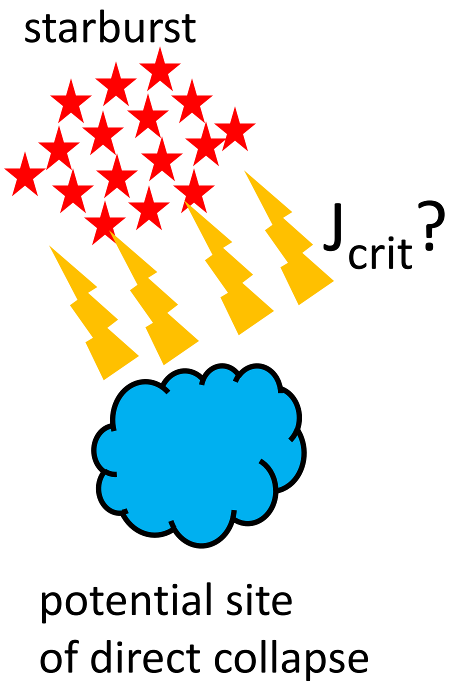
Photodetachment: $H^- + \gamma \rightarrow H + e$

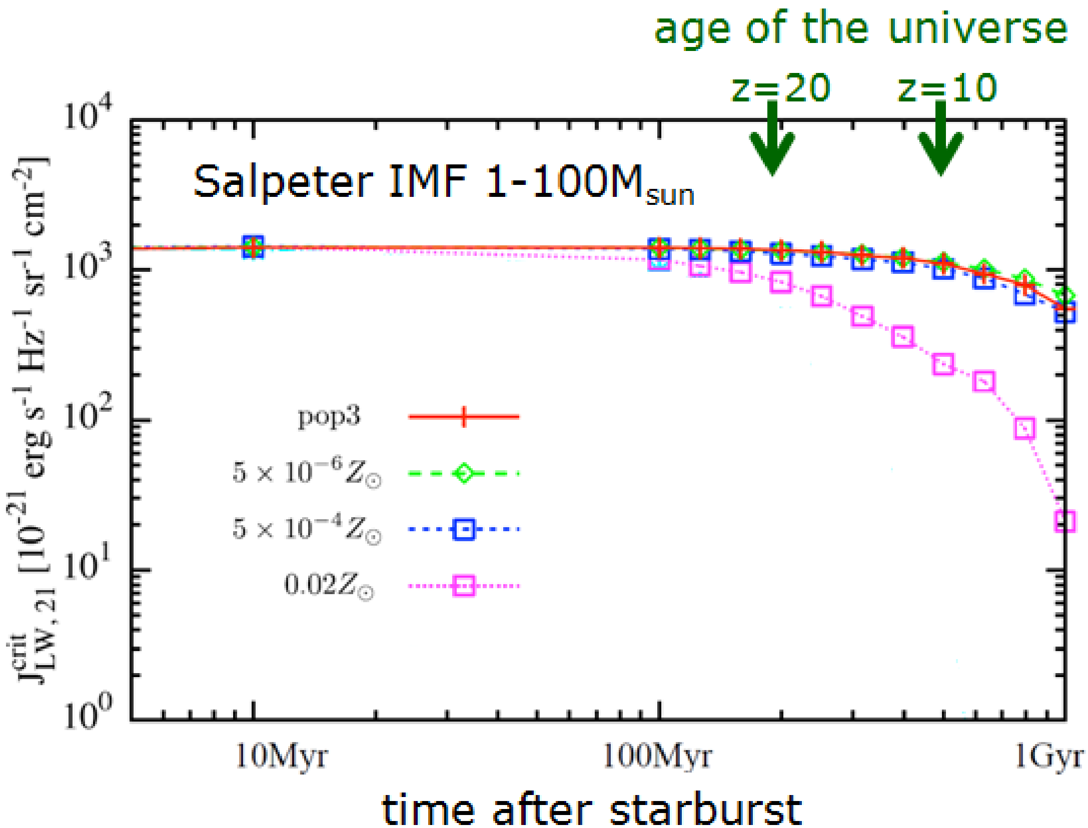
With the same J_{21},
softer (lower T_{UV})radiation is more effective in suppressing H_2 formation



J_{crit} for Starburst Galaxies

Using realistic spectra of starbursts...





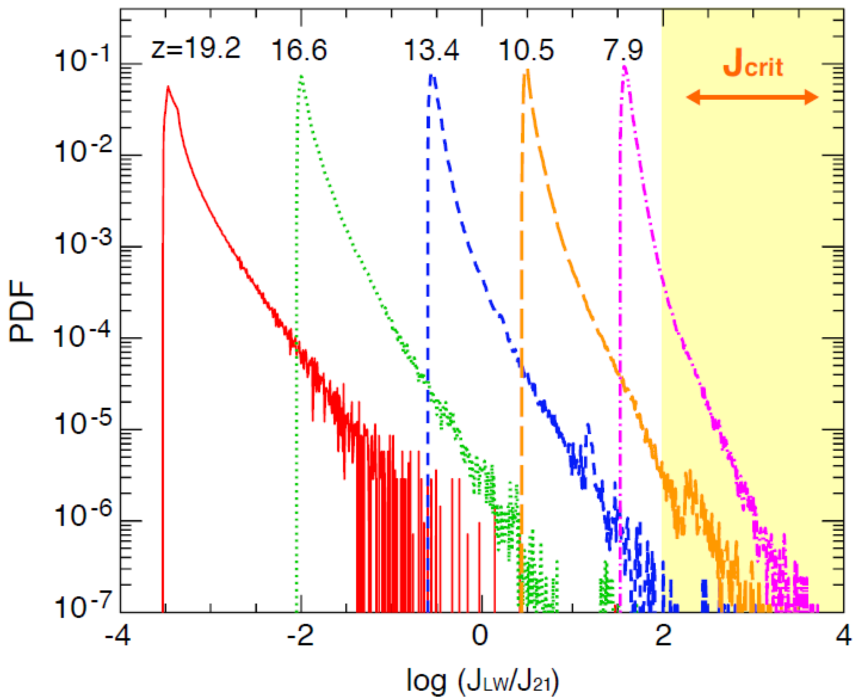
Required J_{crit} is very high (~1000)
even for PopII galaxies (unless >several 100Myr)

Only in rare environments ?

J_{crit}~1000 from our result

Ahn et al. (2009)

At high redshift
UV radiation are weaker
-> No/few direct collapse



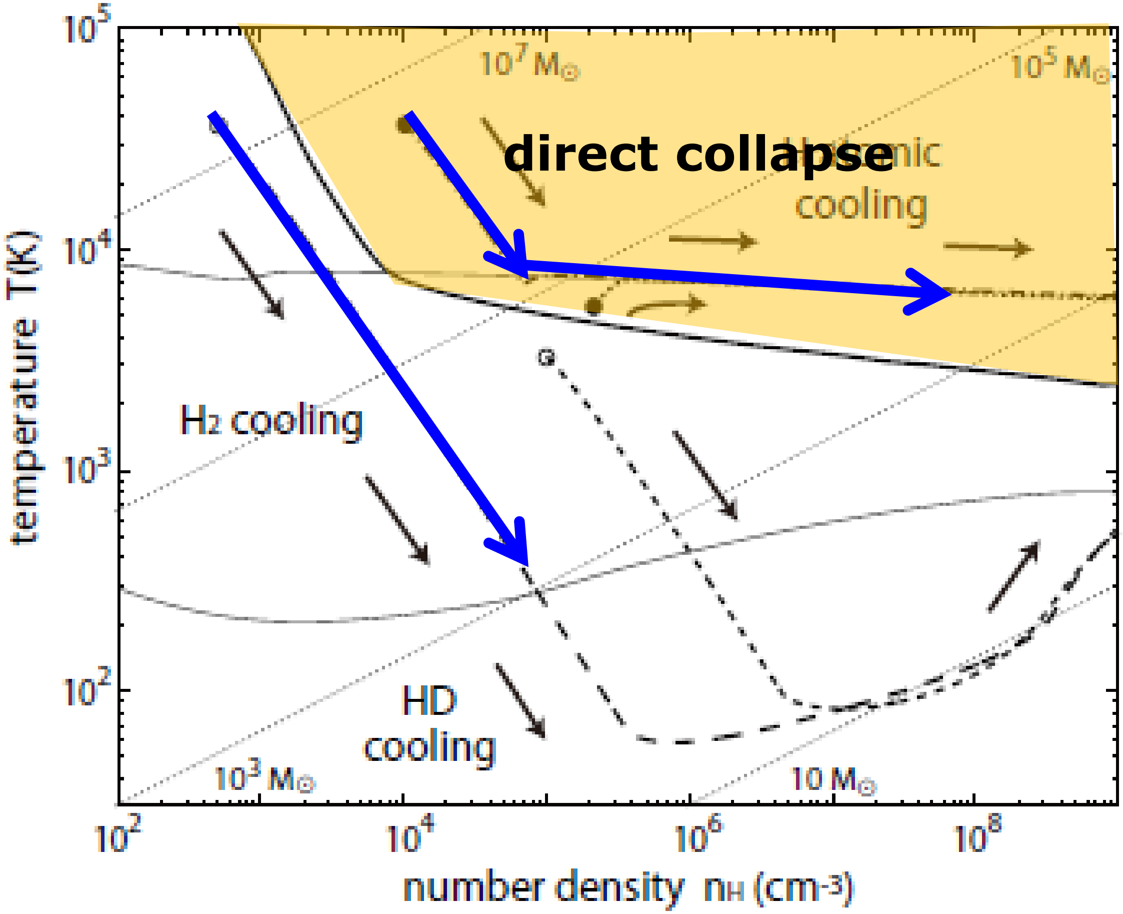
At lower redshift
halos are metal enriched
-> No /few direct collapse

- Direct collapse occurs only in very rare environments (~1Gpc^{-3}) .
- Direct collapse may still account for high-z SMBH.

Alternative channels?

shock heating in dense primordial gas

Inayoshi & KO 2012

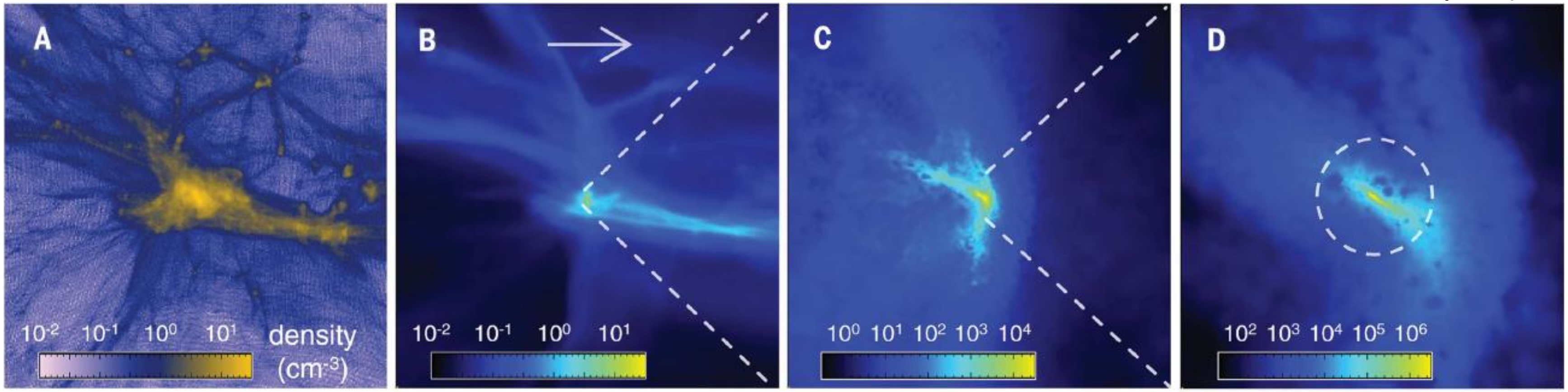


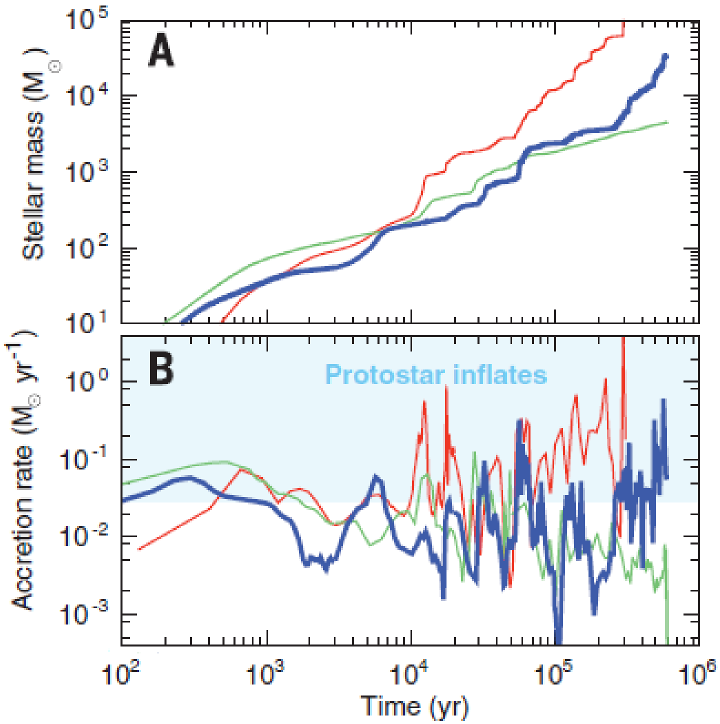
- shocks at $>10^{3\text{-}4}$/cc, with> several 10^3K
  - H_2 collisionally dissociated
  - Fragments at 8000K with $>\sim 10^5 M_{sun}$
  - Isothermal collapse thereafter

Alternative channels?

streaming motions of baryons

Hirano, Hosokawa, Yoshida & Kuiper (2017)



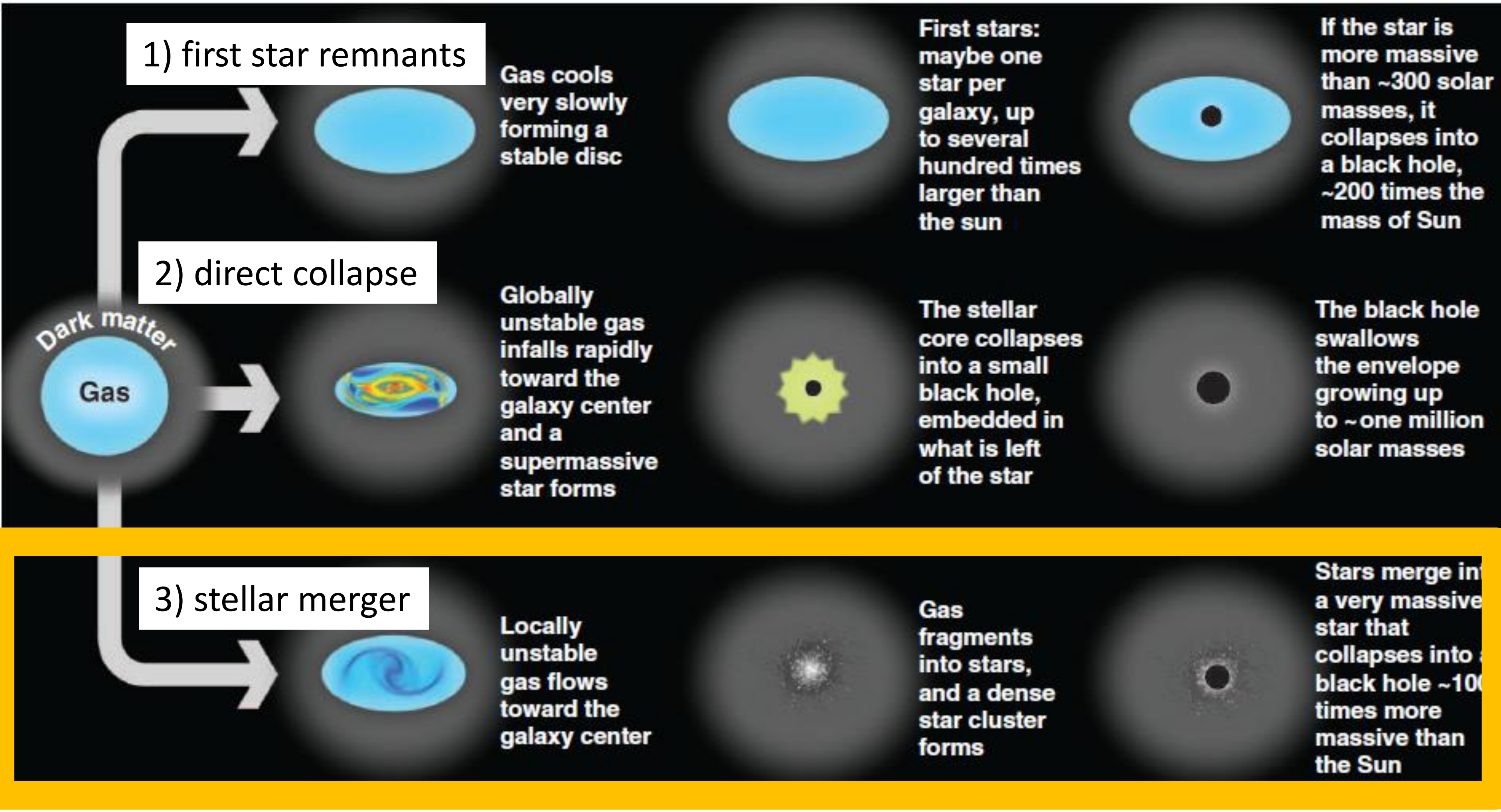


- In halos with large streaming motions, high accretion rate (~$0.1M_{sun}$/yr) is realized.

- Formed star grows to ~$10^5 M_{sun}$.

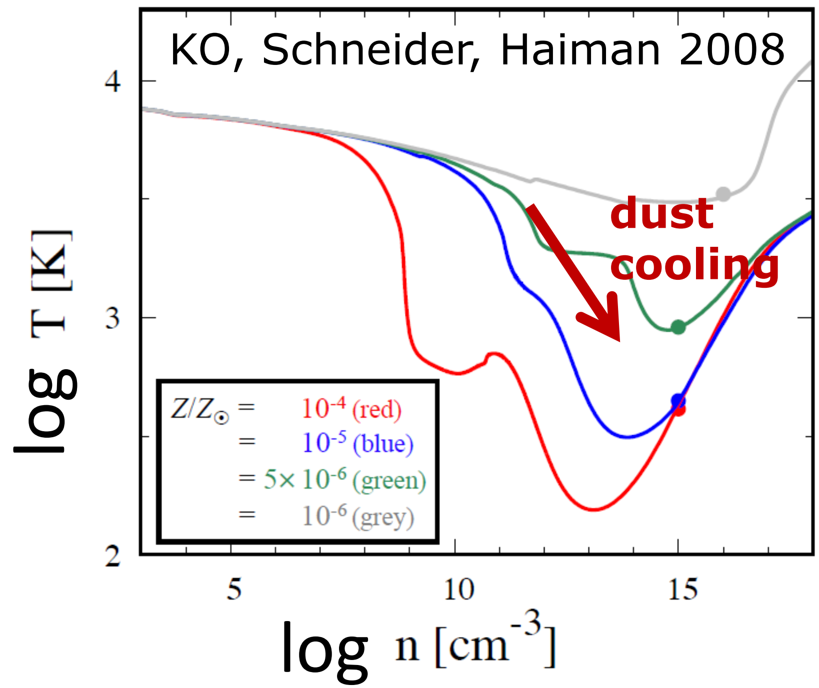
- Expected number ~1 Gpc^{-3}
  naturally account for highest-z SMBH
  (how about other SMBHs in less early universe?)

3) stellar merger in dense clusters



Volonteri 2012

What if there are some metals ?

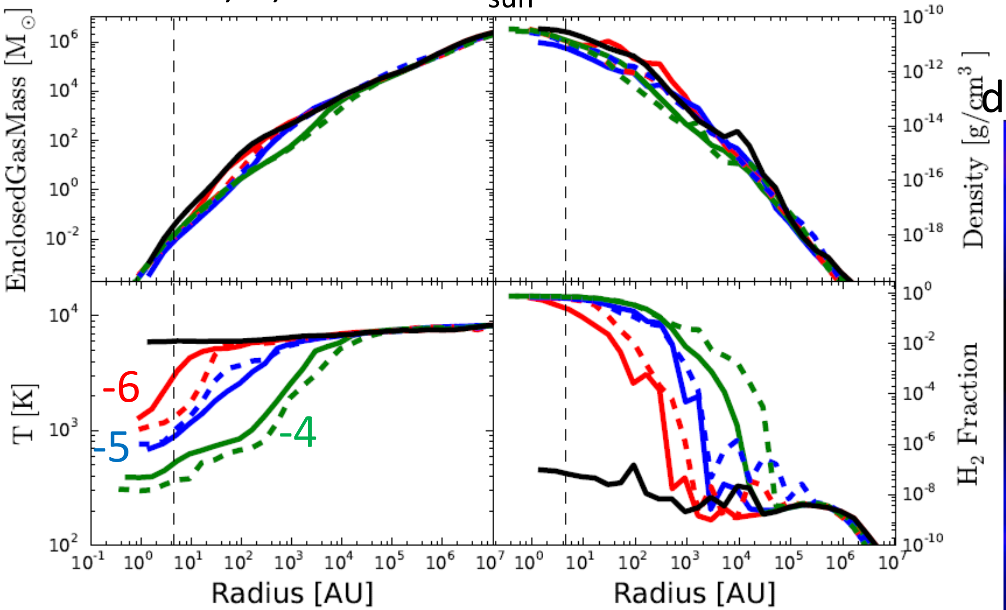


•For [M/H] > ~-5,
dust cooling causes rapid temperture drop

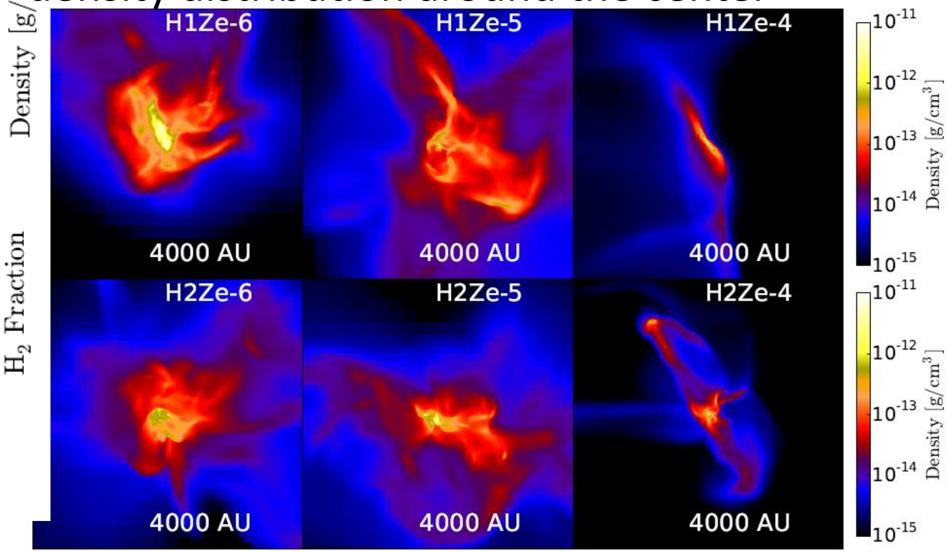
Fragmentation of metal-enriched clouds

Latif, KO, Habouzit, Schleicher, Volonteri 2015

radial distributions
（Halo 1, 2; Z=0~$10^{-4}Z_{sun}$）



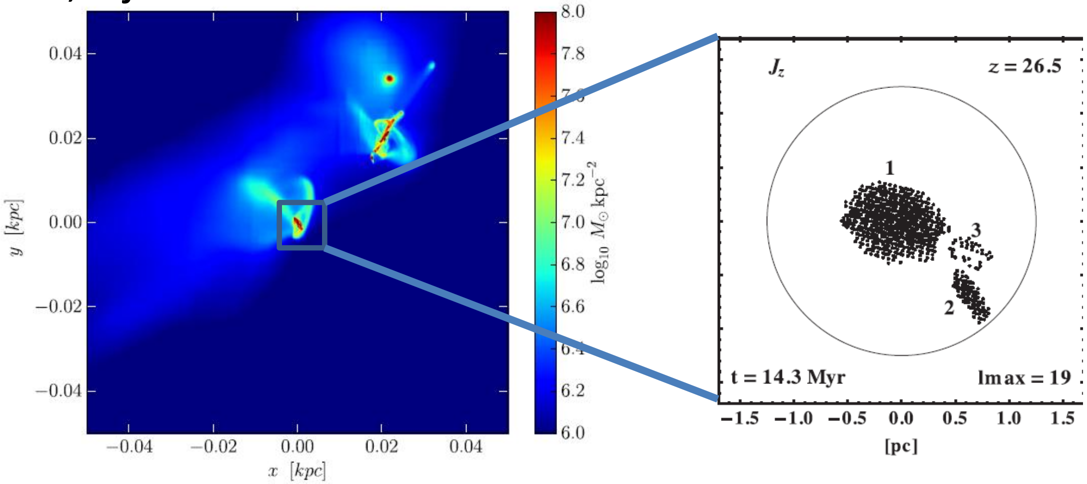
density distribution around the center

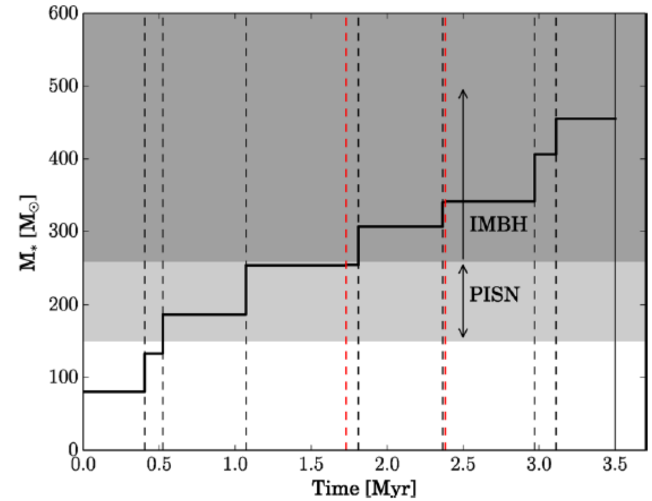


- Filament-like structure is formed and fragments due to sudden temperature drop in the case of Z~$10^{-4}Z_{sun}$
- dense star cluster formation?

Seed BH formation in dense clusters in cosmological simulations

Katz, Sijacki & Haehnelt 2015





pair halos where one is metal-polluted by wind from another .

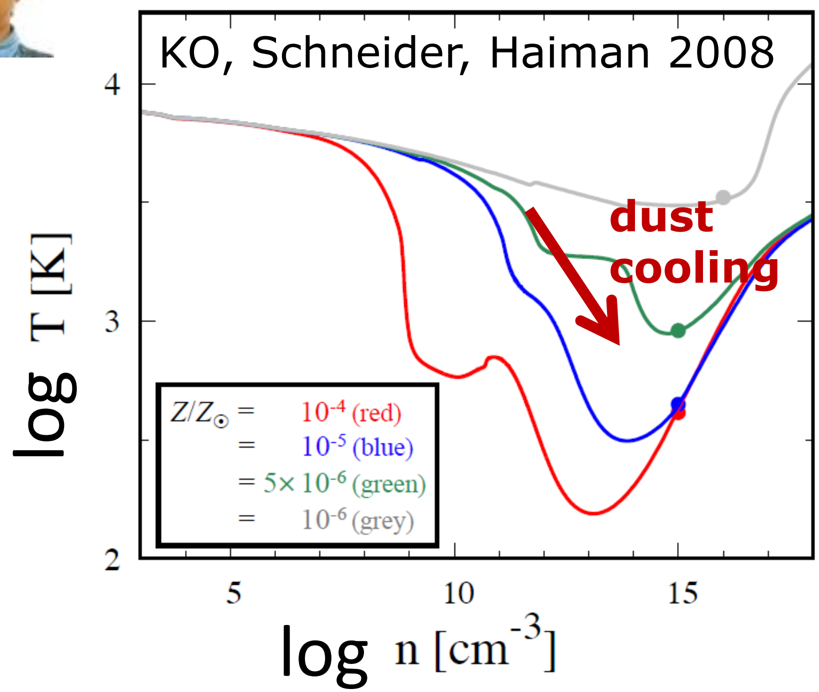
dense cluster at its center → N-body calculation

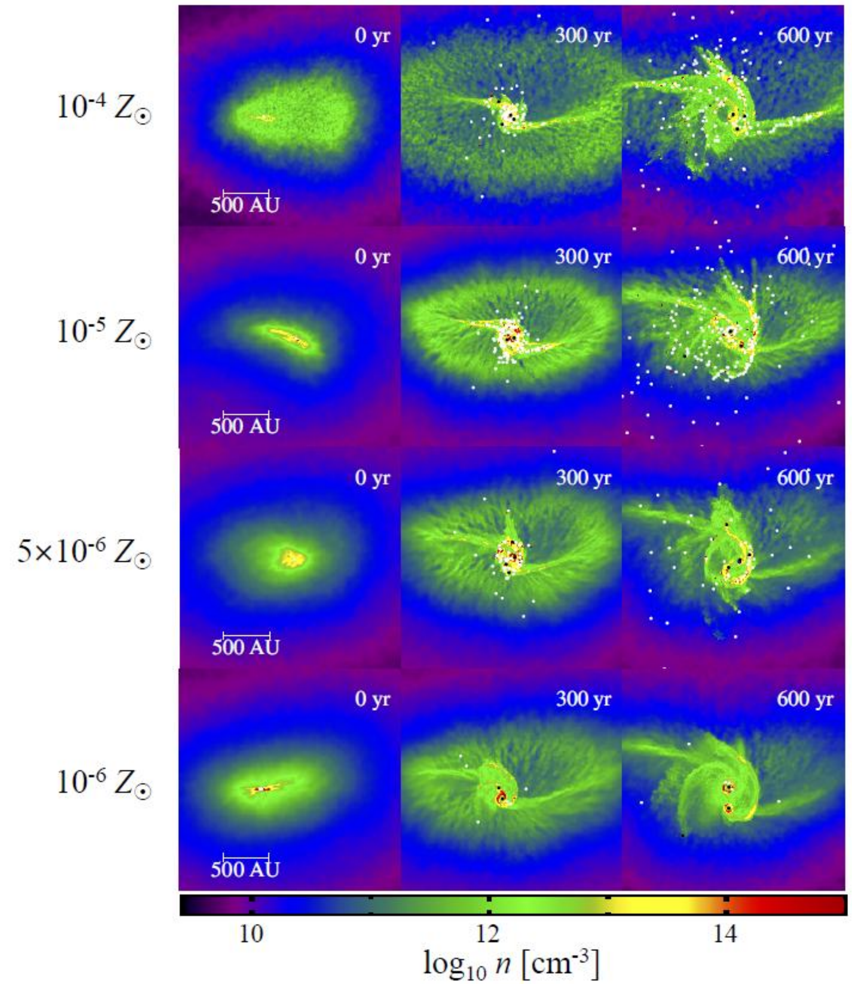
stellar mergers occur at the center of cluster

- stellar mergers occur in dense enough clusters
- merger product is at most ~1000M_{sun}, not more massive that first stars
- may loose some fraction of mass by stellar winds before collapse to BH

What if there are some metals ?

Chon & KO in prep.

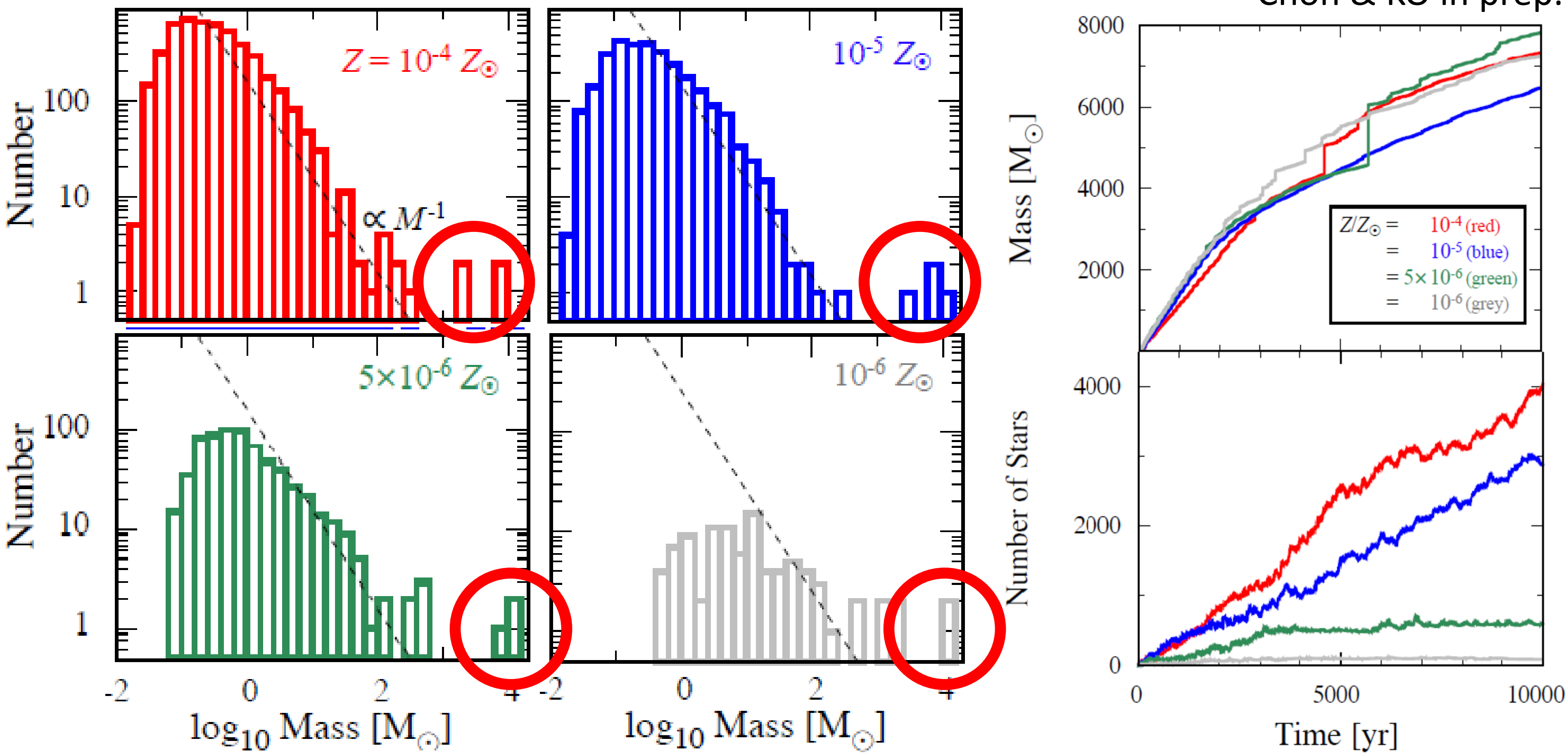




- For [M/H] > ~-5,
dust cooling causes rapid temperture drop
a ‘Super Competitive Accretion’

Runaway growth of the central star by Super Competitive Accretion

Chon & KO in prep.



- Cloud fragments into numerous objects
- Some grow supermassive by merger/accretion

Summary

First star formation

- Protostellar radiative feedback sets the final stellar mass at a few 10-100Msun
- Massive binaries are maybe common
- correct ionization model developed

Supermassive star as a seed BH

- Photodissociation (or collisional dissociation in dense, shocks) suppresses H_2 cooling, leading to SMS formation via isothermal collapse at 8000K.
- SMS grows by accretion up to $\sim 10^5 M_{sun}$, then collapses to BH by GR instability.
- Runaway formation of SMS by super competitive accretion in metal-enriched cluster seems viable.

ご清聴ありがとうございました。