初代星初代銀河研究会
@札幌
2023年11月20日

宇宙初期の星形成

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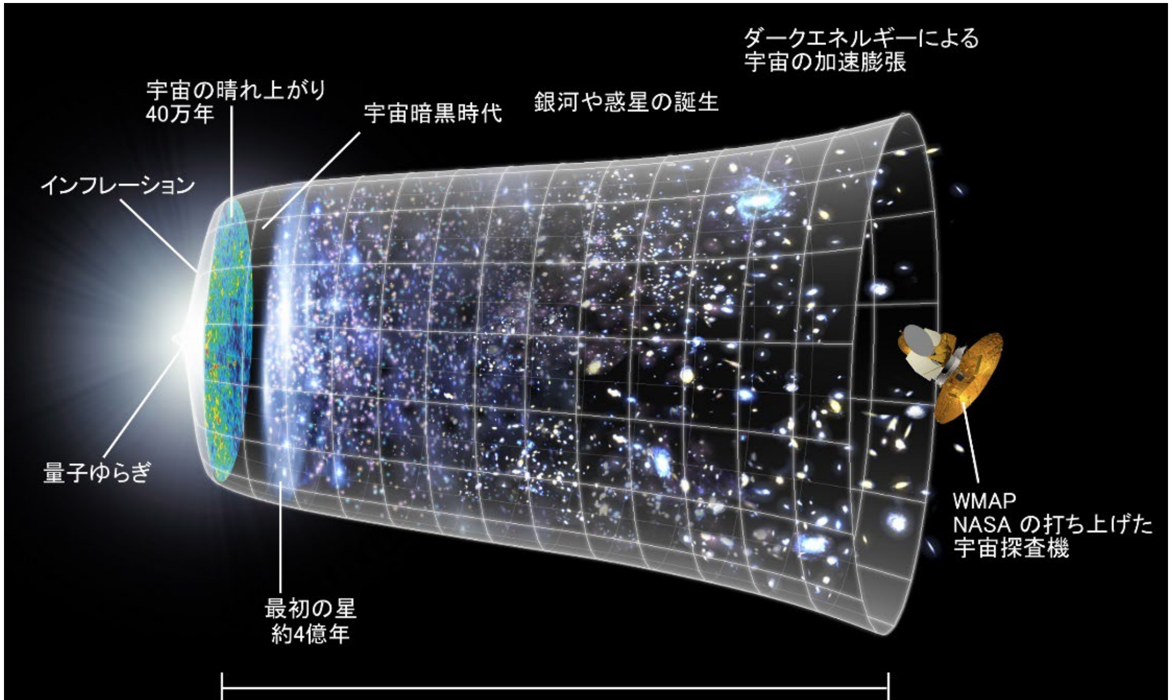
内容

- 背景
- 初代星形成
- 種族II星形成
- 超大質量星形成

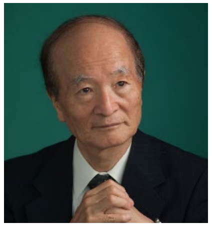
初代星（種族III星）

- 宇宙最初の重元素＆ダスト源
  - 以後の星間ガスの性質を変える
- 宇宙最初の輻射源
  - 宇宙再電離、IGM/ISMの加熱などフィードバック
- 観測的には、初期銀河、GRBなど遠方天体、銀河考古学による低金属度星との関連が話題。
- 重力波検出にともない大質量BH連星の起源としても注目
- 巨大ブラックホールの起源としても注目



初代星研究簡史

前史　種族II星中の重元素の起源として提唱された
(Schwarzschild & Spitzer 1953)


松田卓也 (1943-)


佐藤文隆 (1938-)

第一波　（60年代後半ごろから5年ほど）

Big Bang宇宙論の確立により、まじめに形成過程が考えられる始める
[平沢、会津＆武谷（１９６８）、松田、佐藤＆武田（１９６９）、米山（１９７２）など]
ビッグバン宇宙論、H_2形成・冷却の重要性

第二波　（80年代前半ごろから5年ほど）


吉井 譲　(1951-)

８０年代にもいくつか重要な研究がなされた。
[吉井&佐場野（１９８０）など]
CDMモデル、H_2形成の3体反応

第三波（90年代後半以後、もうすぐ30年）

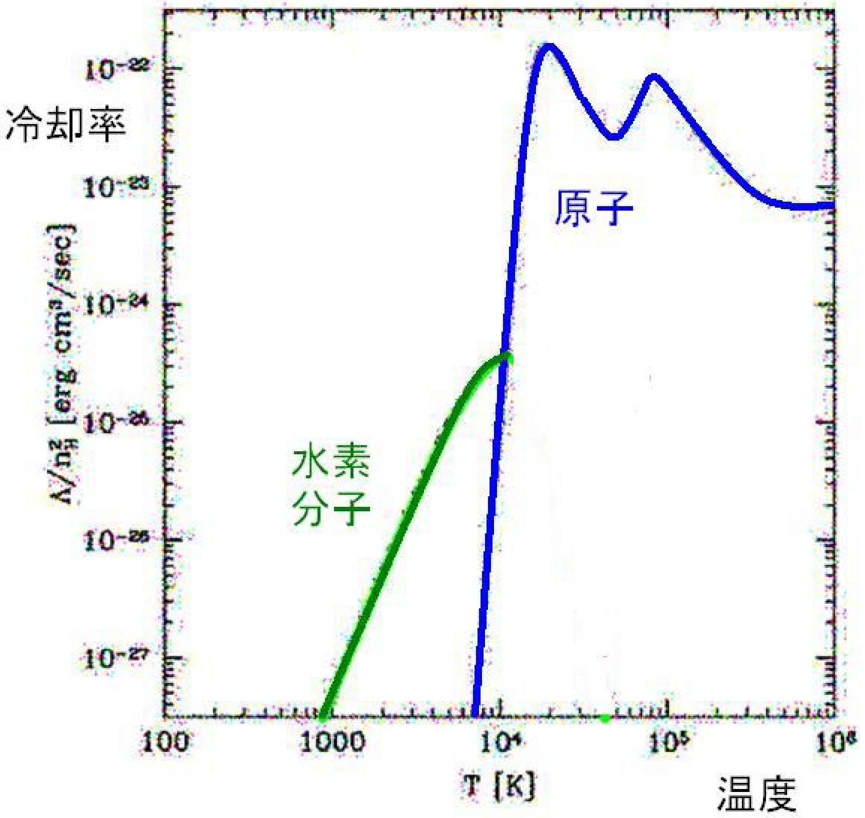
１９９０年後半（１９９６頃-）以後は宇宙論的シミュレーションの延長、また次世代観測プロジェクトのターゲットとして話題。
[今回もたくさんの研究が紹介されるでしょう！]
宇宙論的3次元計算によるコア形成、原始星コラプス、フィードバックによる降着の終了と質量の確定

国際会議 “First Stars”（4年ごと）: Munich(I, 1999), Penn State(II, 2003), Santa Fe(III, 2007), Kyoto(IV, 2012), Heidelberg(V, 2016), Cencepcion (VI, 2020), New York(VII, 2024)

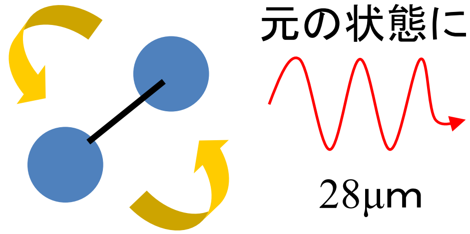
「初代星初代銀河研究会」 2006から毎年開催
（今回で18回目：前史もあります）

始原ガスの輻射過程

始原ガスの輻射冷却率



- 原子冷却: T>10^4K:
- H_2冷却 : それ以下



水素分子（H_2）
回転放射

光子（赤外線）を出して
元の状態に戻る

衝突により回転状態
が励起される
（第一励起エネルギー
0.044eV; ５１２K）

始原ガス中でのH_2 形成過程

低密度(<10^8cm^{-3})では、

H^- チャネル：e を触媒　(Peebles & Dicke 1968; Hirasawa+1969)

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

反応率はこっちが一桁ほど大

H_2^+ チャネル：H^+ を触媒　(Saslaw & Zipoy 1967)　初代星形成の記念碑的論文

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

輻射場が強い場合にこっちが
効くときもある

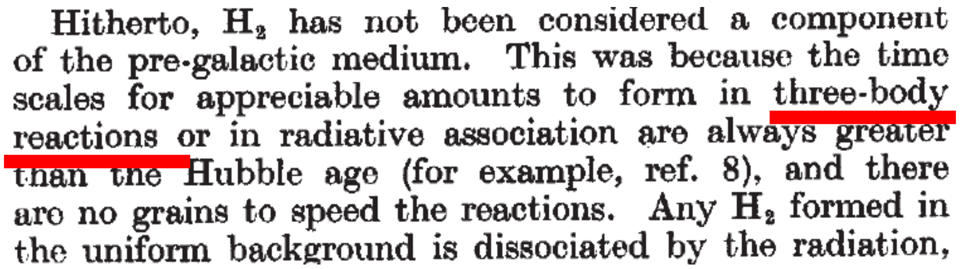
高密度(>10^8cm^{-3})では、

3体反応 (Palla, Salpeter & Stahler 1983)

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

高密度ではこれで全部分子になる

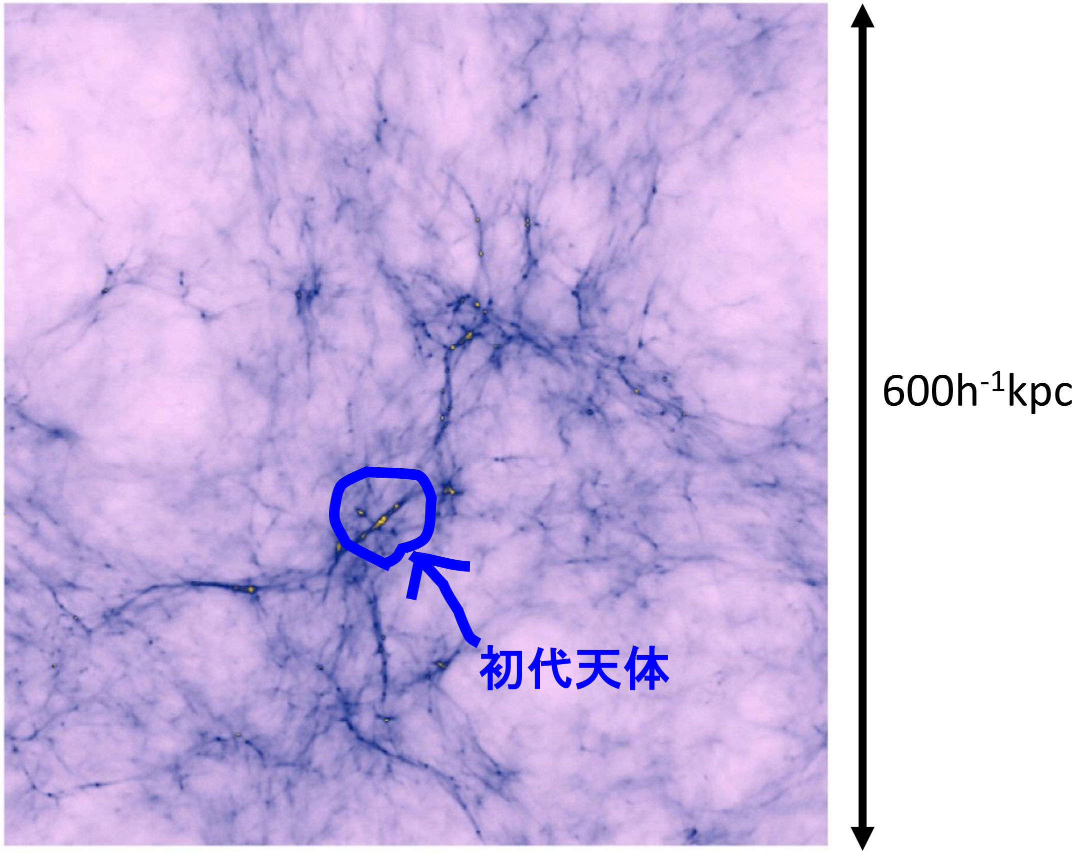
3体反応の存在自体は
Saslow&Zipoy (1967)も
既に認識していた



Hitherto, H_2 has not been considered a component of the pre-galactic medium. This was because the time scales for appreciable amounts to form in three-body reactions or in radiative association are always greater than the Hubble age (for example, ref. 8), and there are no grains to speed the reactions. Any H_2 formed in the uniform background is dissociated by the radiation,

初代天体の誕生

ΛCDMモデル
密度揺らぎから初代天体の形成までシミュレーション



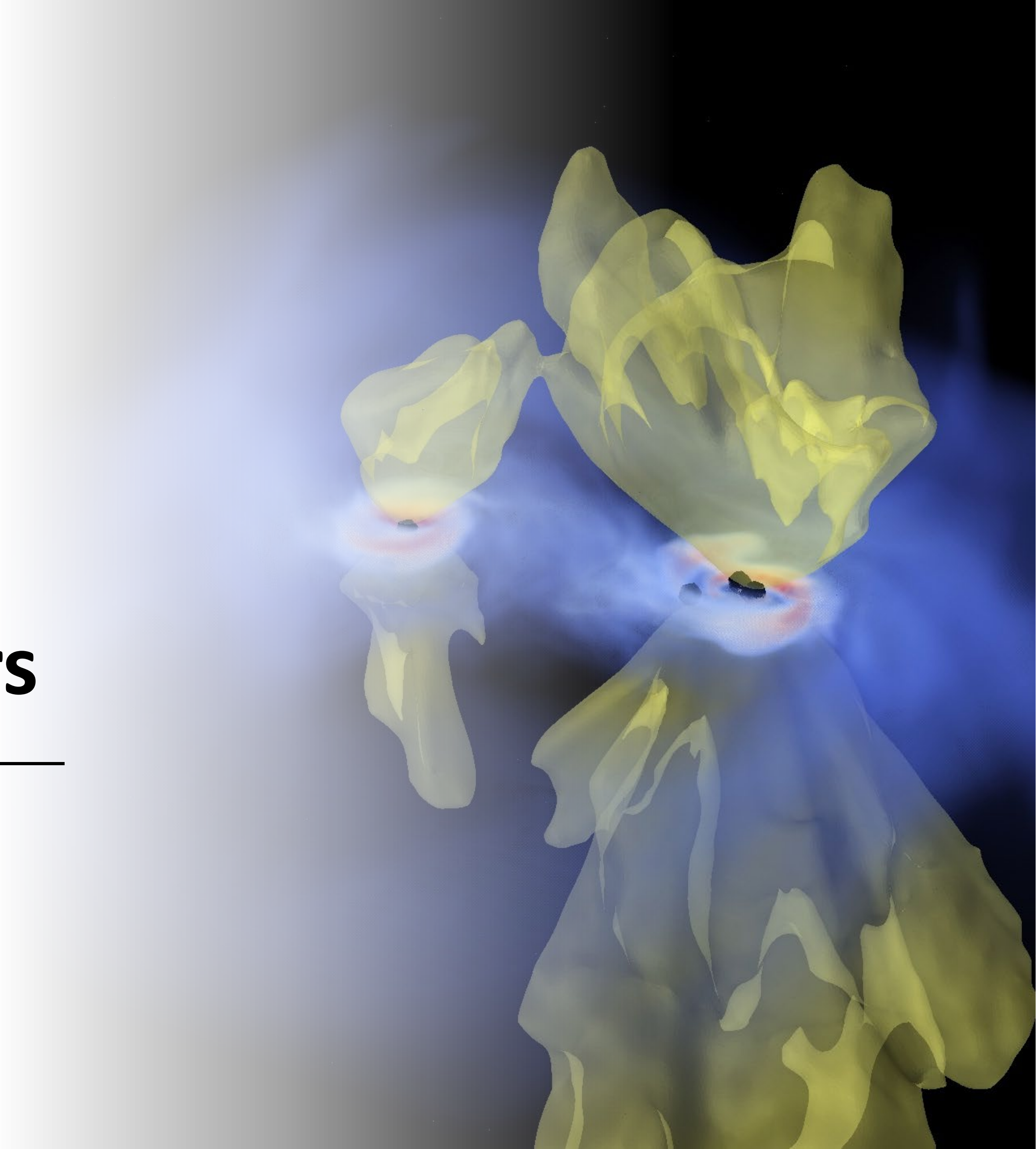
Yoshida, Abel, Hernquist & Sugiyama (2003)

ヴィリアル温度が
1000K以上のハロー
（**ミニハロー**；
$\sim 10^6 M_{sun}$, $z\sim 20$-30で誕生）

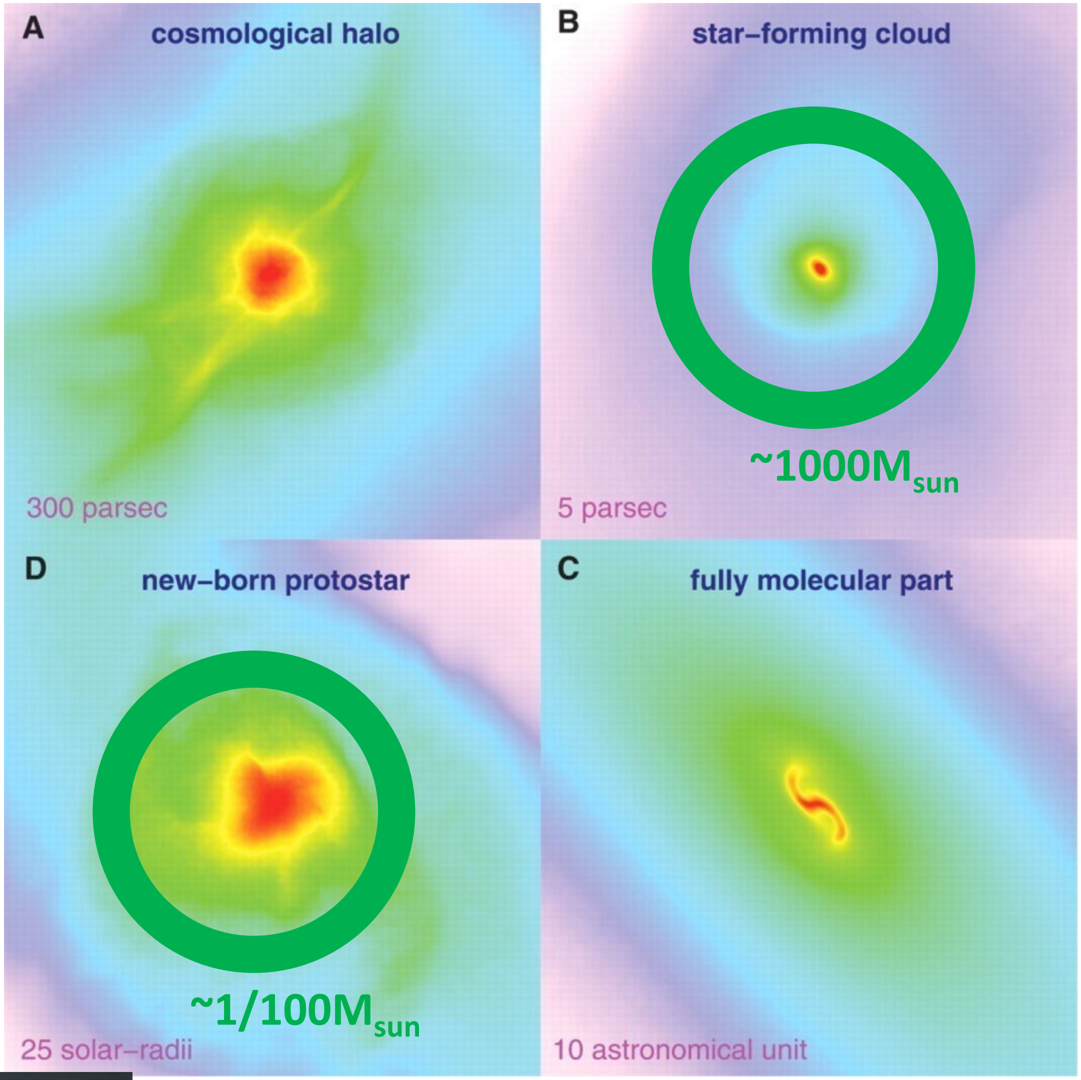
水素分子(H_2)の回転遷移
輝線放射により冷却、
重力収縮でより高密度に

➔初代星形成へ

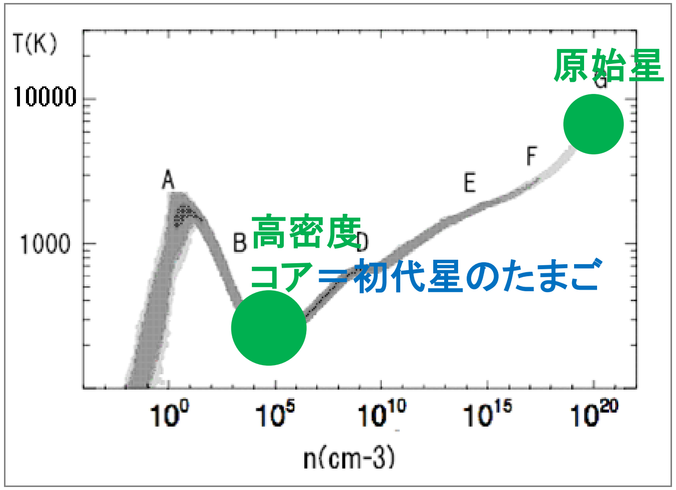
Part I: Formation of First Stars



重力収縮と原始星の誕生



温度進化

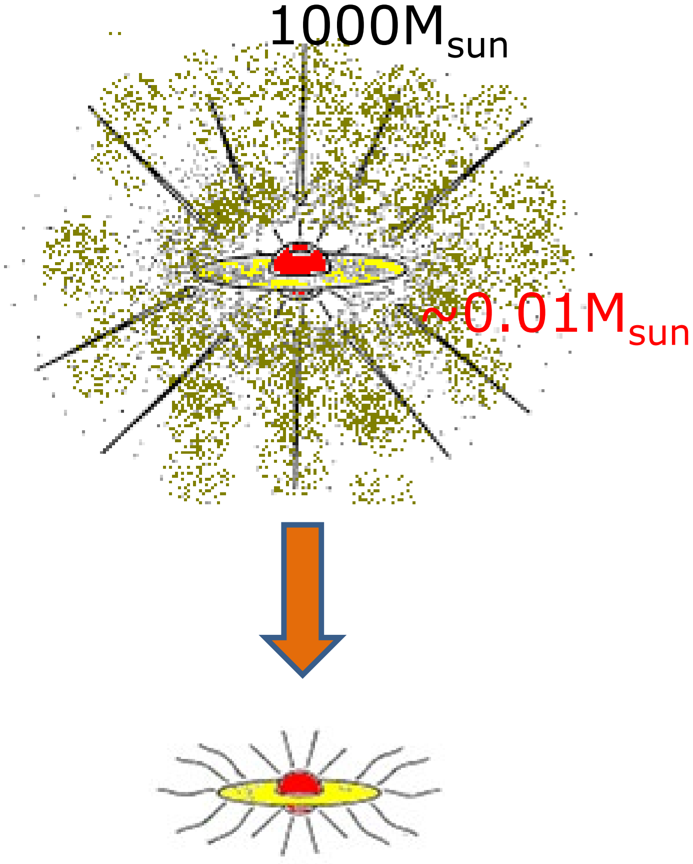


- H_2冷却により
数密度~10^4cm^{-3}で、
質量~1000M$_{sun}$
の高密度コアが形成

- その中で密度~10^{21}cm^{-3}時
原始星が誕生
(初期質量~10^{-2}M$_{sun}$)
これは現在の星形成と同じ

吉田、大向、
Hernquist 2008

原始星の降着成長



原始星降着の終了
→ 星質量が決まる

始原ガス (Z=0)

ダストなし, 低オパシティ
⇒ 輻射圧弱い
高いガス温度 (数100K)
⇒ 高い降着率

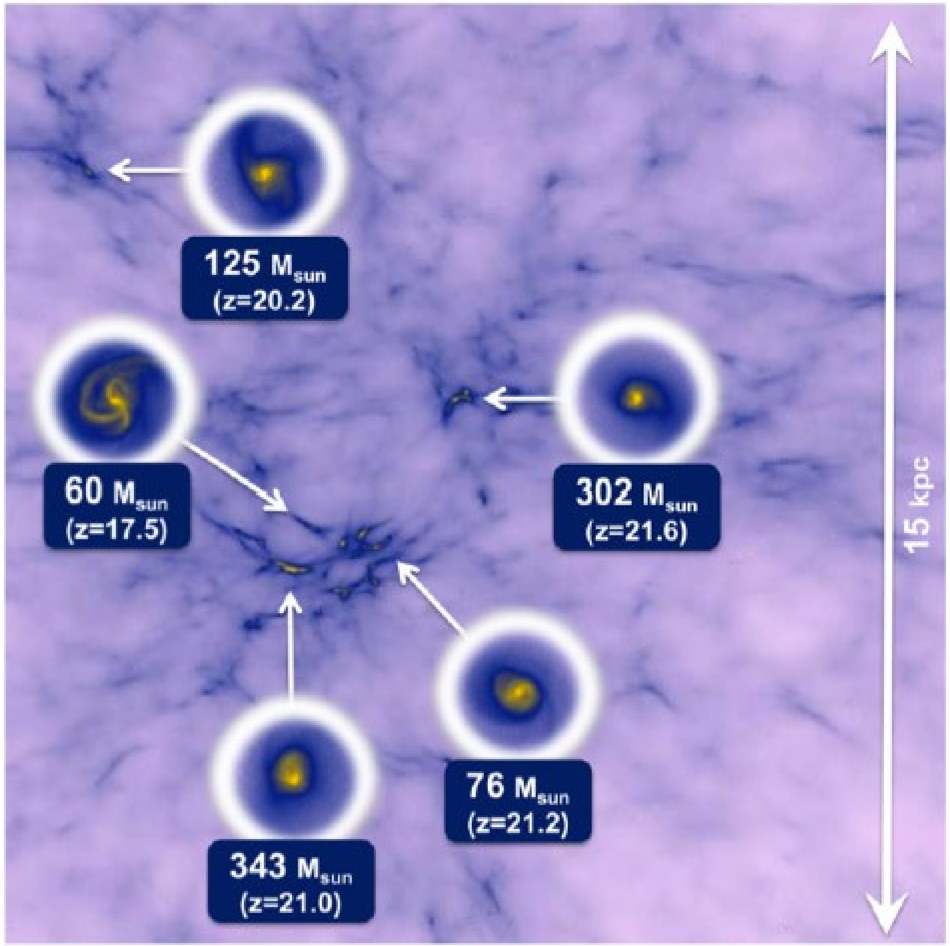
$$\dot{M} \sim \frac{M_{\rm J}}{t_{ff}} = \frac{c_s^3}{G} \sim 2\times 10^{-6} M_\odot/{\rm yr} \left(\frac{T}{10K}\right)^{3/2}$$

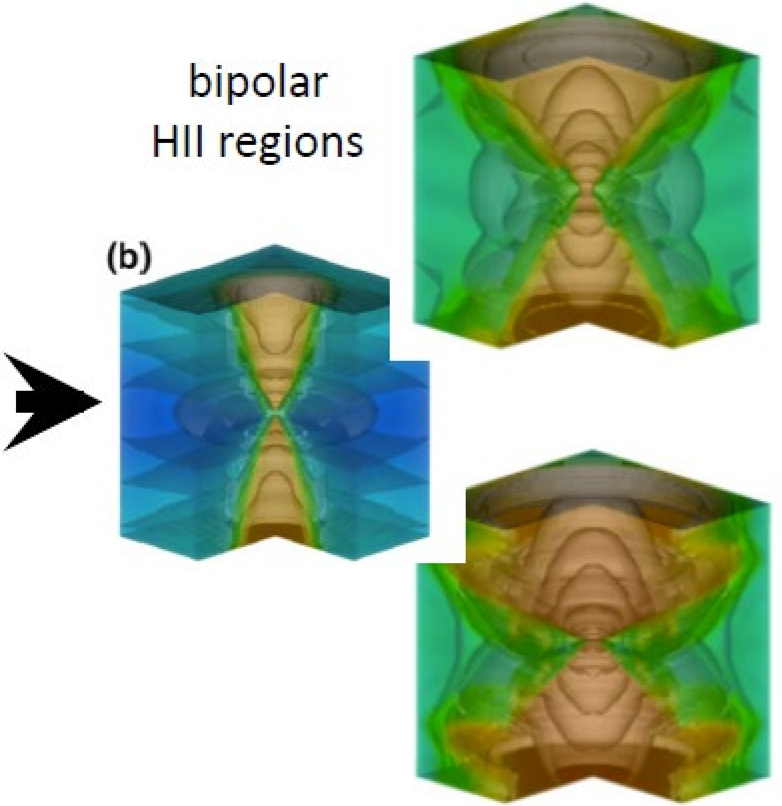
これらの効果
原始星フィードバックを弱める
➔ 大質量星の形成が期待
どれくらいか？

UV feedback sets the final stellar mass

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

Hirano et al. (+KO) 2014, 2015 studied hundreds of halos.

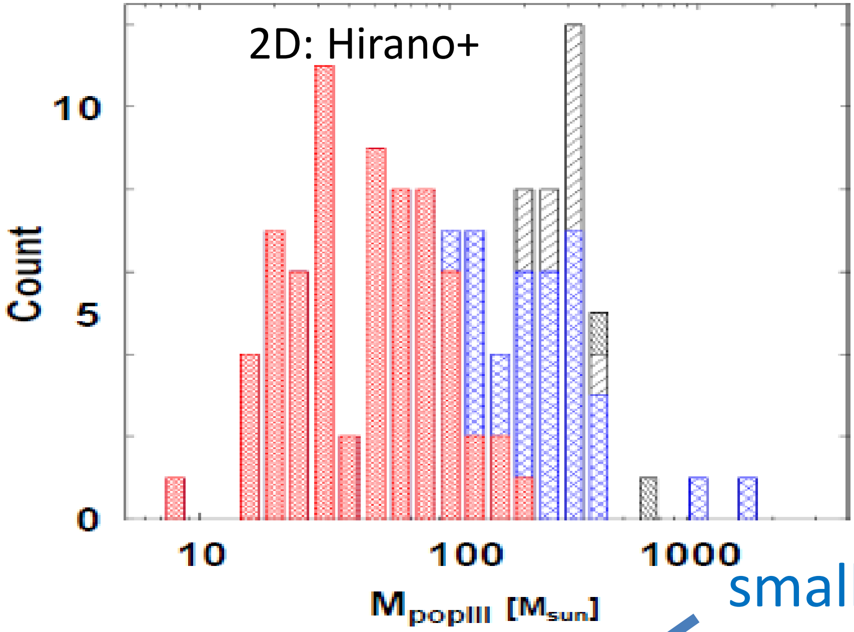




bipolar
HII regions

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

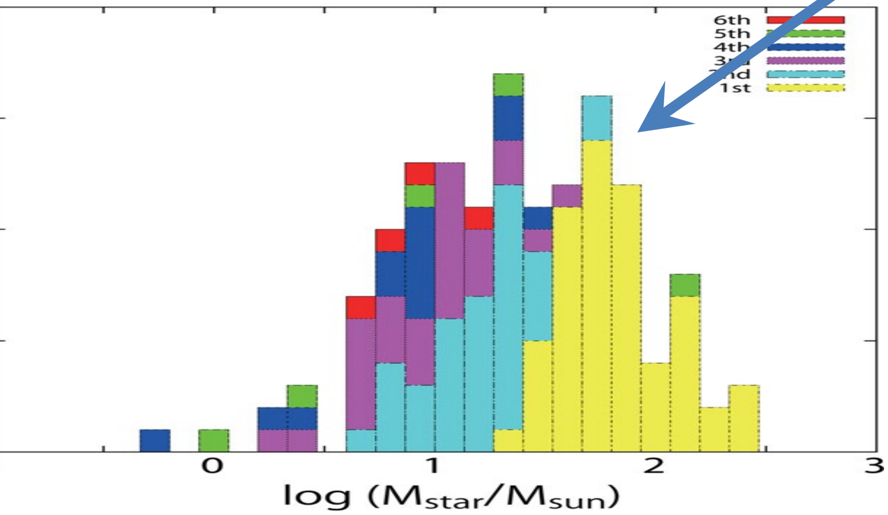
Pop III star IMF



Pop III stars
in a broad range of mass;
a few 10s- 100s M_{sun}

but
this was 2D simulation

3D: Susa+2014



smaller masses in
3D simulations (Susa+2014)
(but HII region propagation is
not accurately followed)

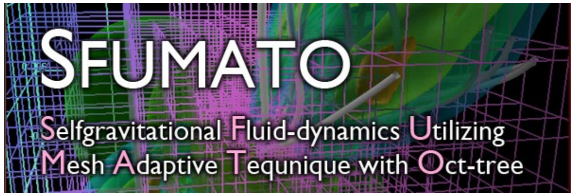
3D simulations with
multiple radiation sources
are needed.

multi-source hydro simulation

Sugimura +(KO). 2020 & 2023

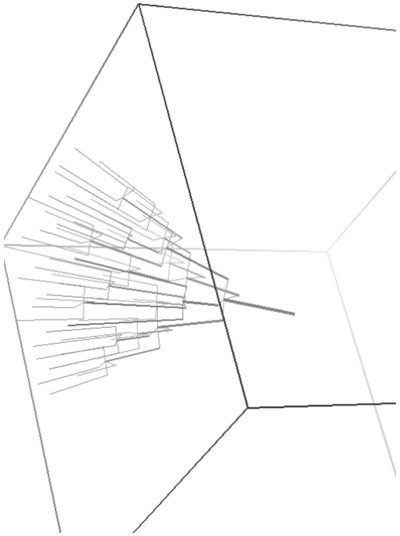
AMR hydrodynamics

+ stellar evolution (sink particles)
(Matsumoto 07 etc.)



+ Radiative transfer with multiple sources

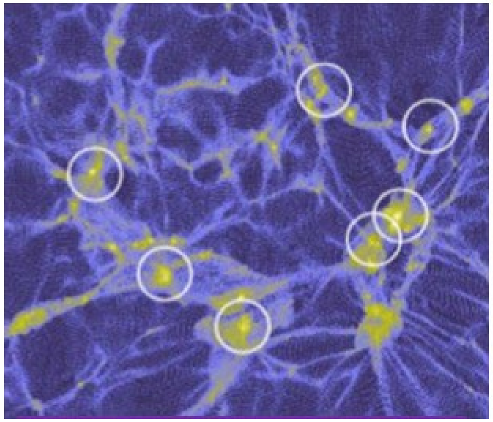
for EUV (H ionizing) & FUV (H_2 dissociating) radiation
by adaptive ray-tracing (ART) method
(e.g., Abel & Wandelt 02; Rosen et al. 2017)



+ Primordial gas microphysics

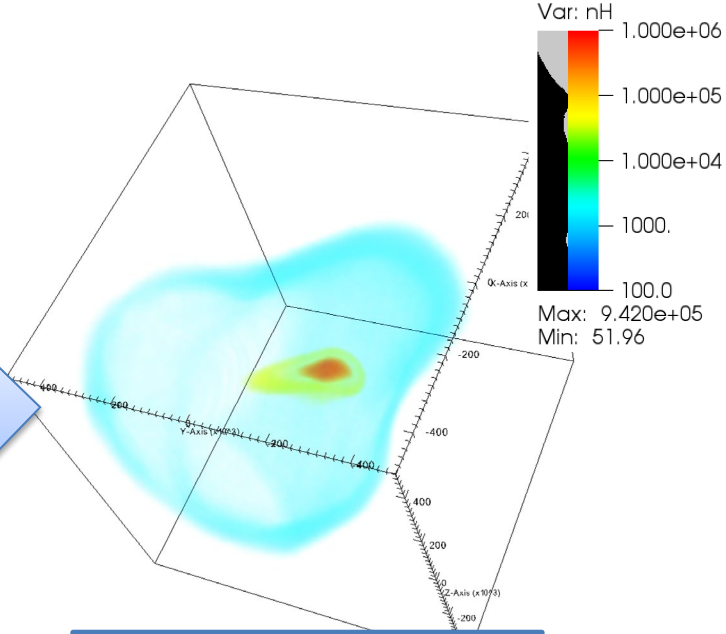
chemistry network & cooling/heating processes

initial conditions



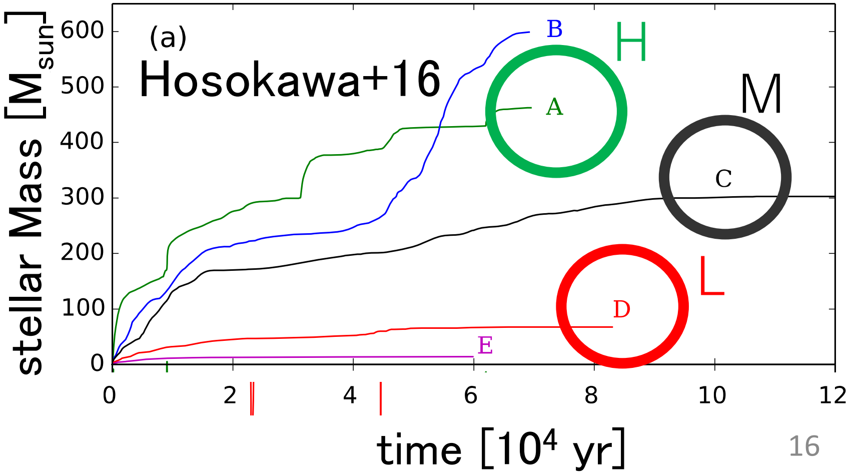
cosmological simulations with Gadget (Hirano+15)

minihalo@$n_{cen}=10^6 cm^{-3}$

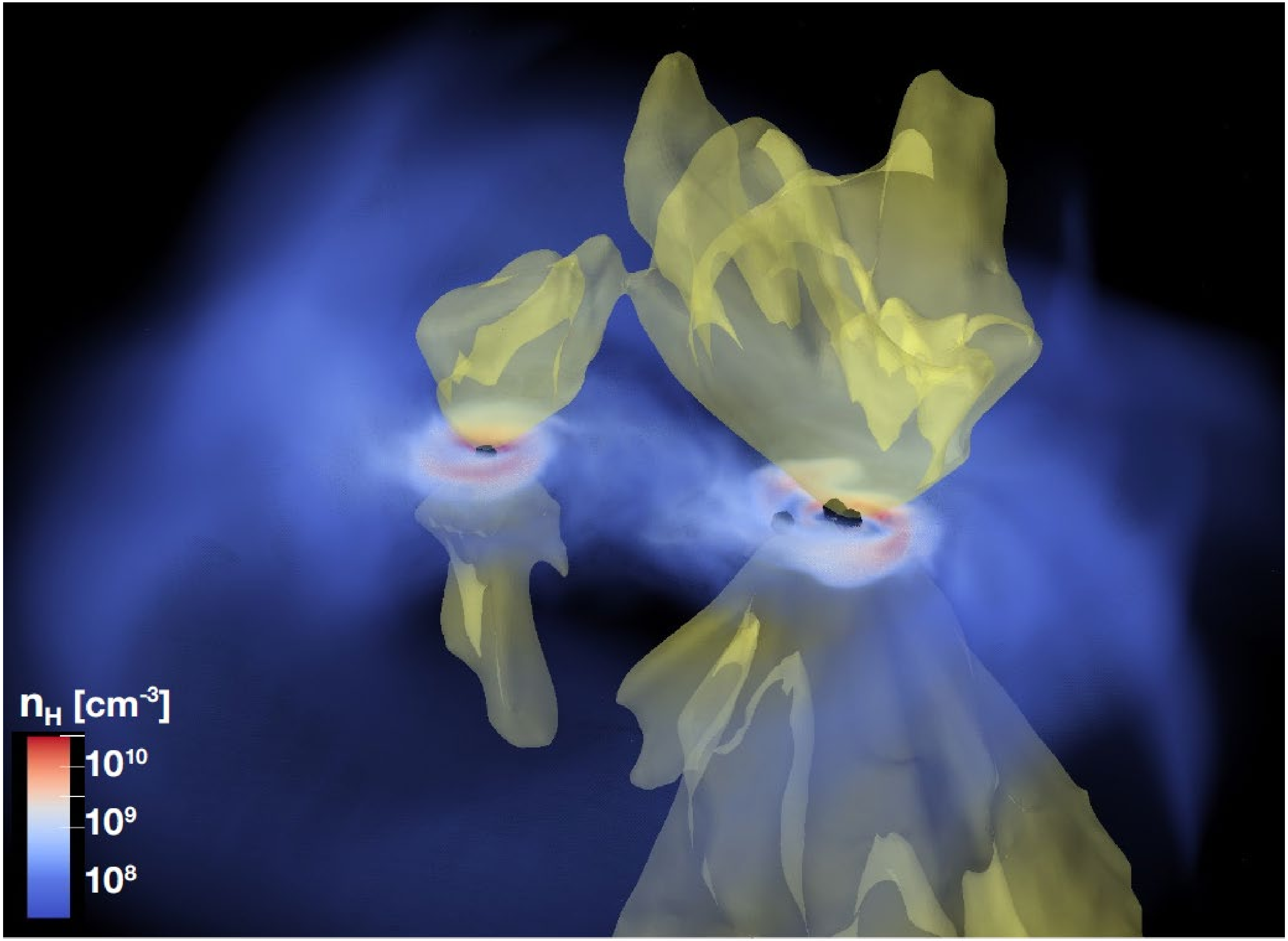


our initial condition

We pick up **3 minihalos** as the initial conditions, which hatched high-mass (H), **medium-sized (M)**, low-mass (L) stars in 3D simulation with only central UV source (Hosokawa+16)



初代星の連星形成（M case=70+60M_{sun}）



Evolution of Protostars

evolution stages

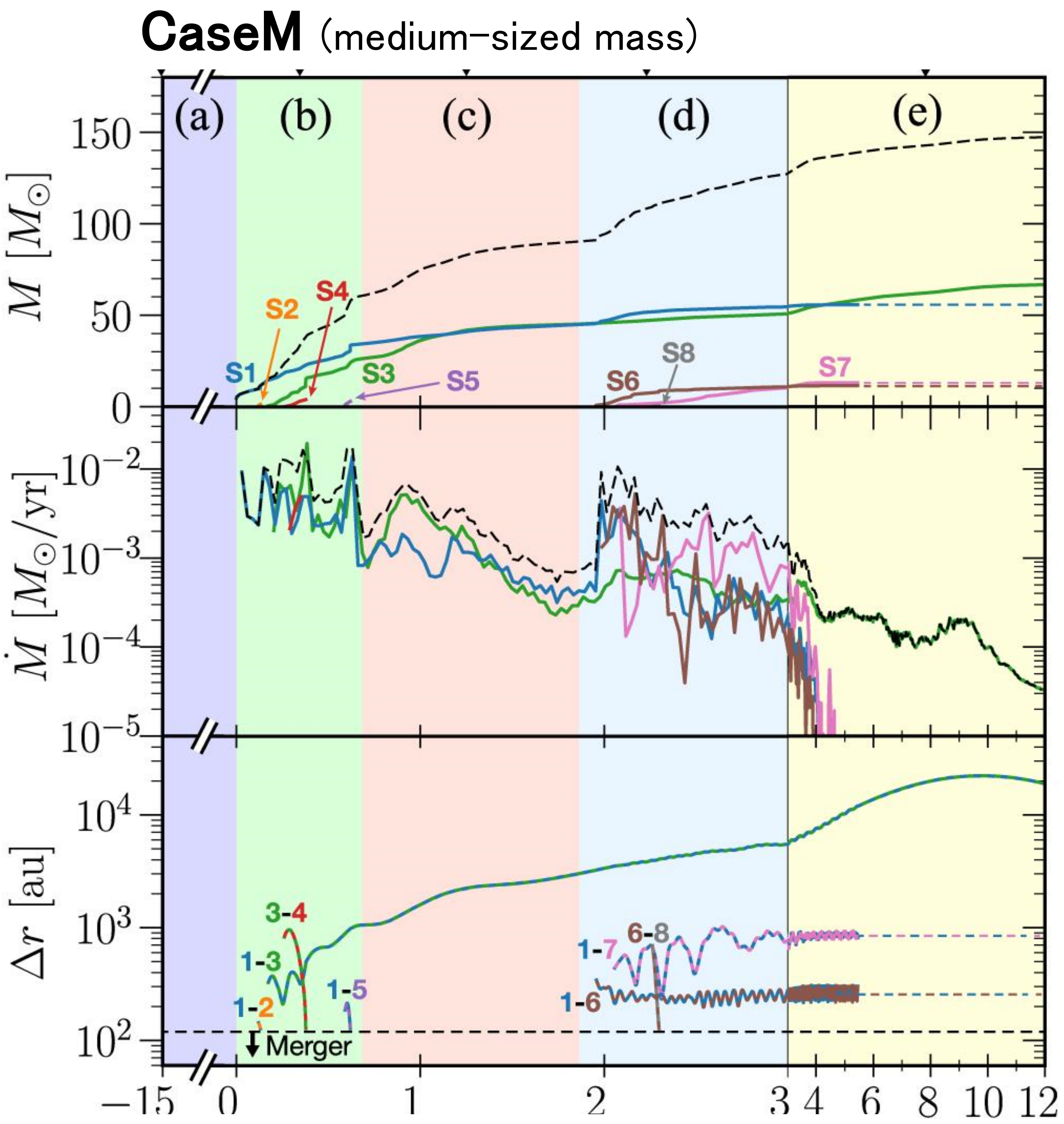
(a) gravitational collapse

(b) early fragmentation

(c) binary accretion

(d) late fragmentation

(e) photo-evaporation

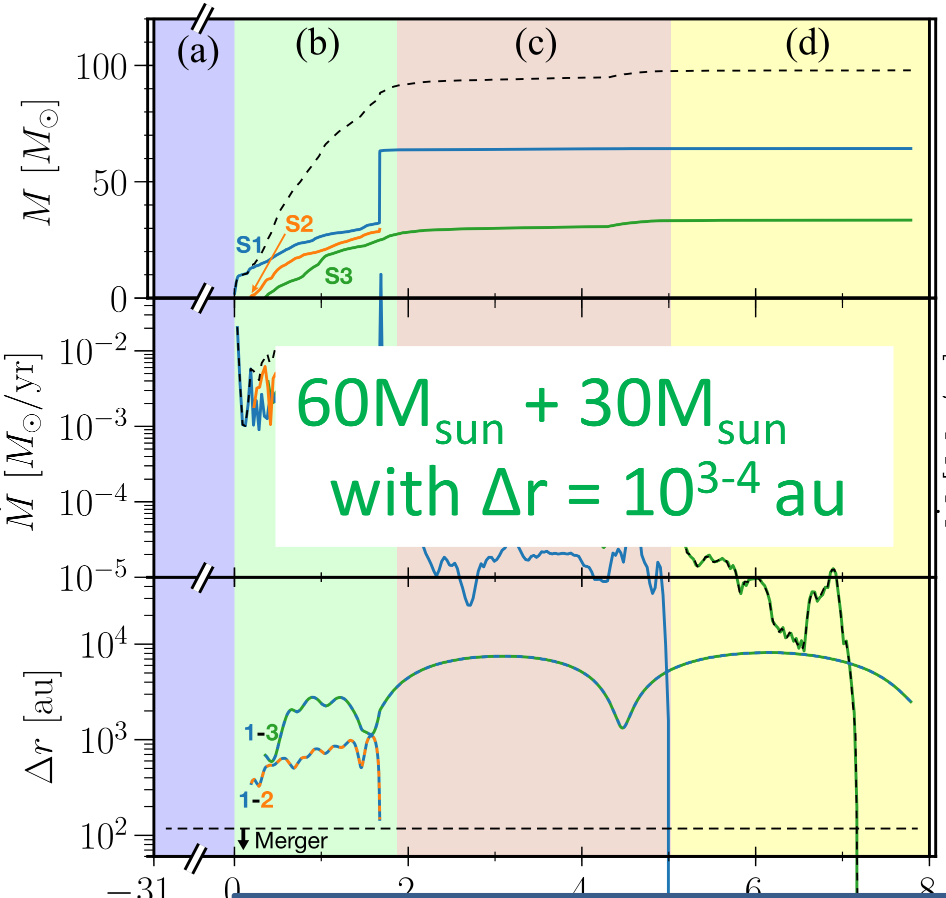

CaseM (medium-sized mass)

$70M_{sun} + 60M_{sun}$ with $\Delta r = 10^4$ au

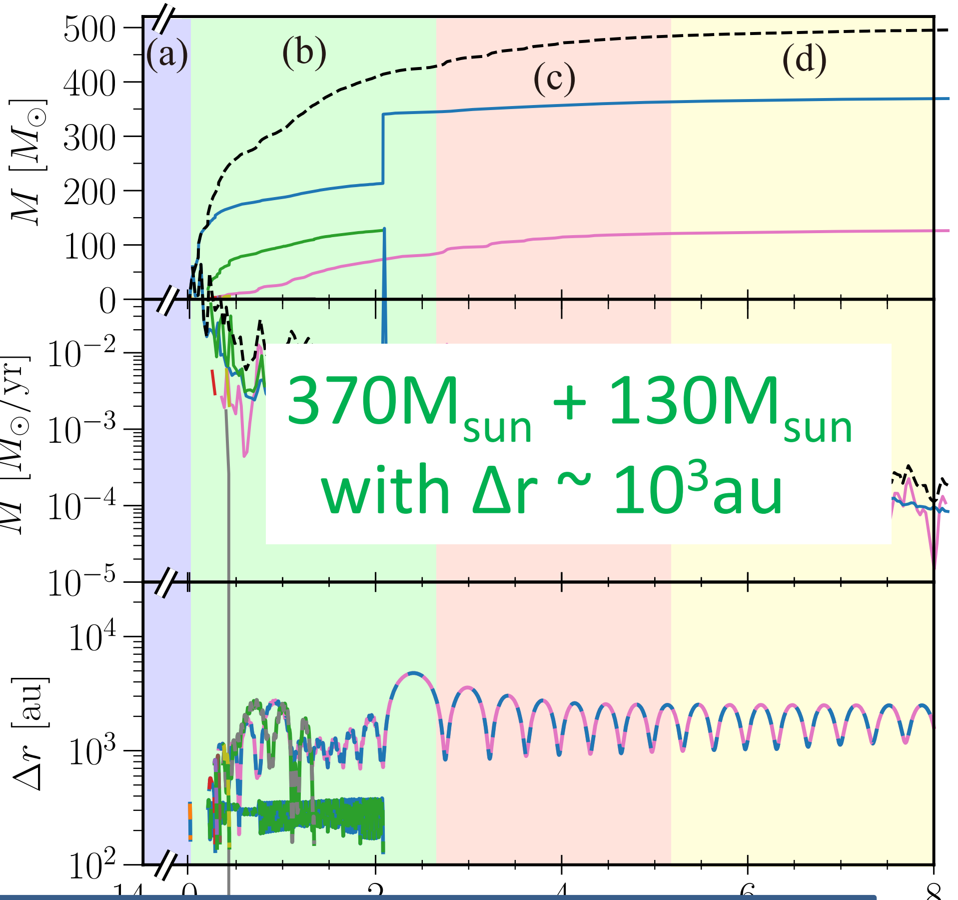
other cases

case L (low-mass)

case H (high-mass)



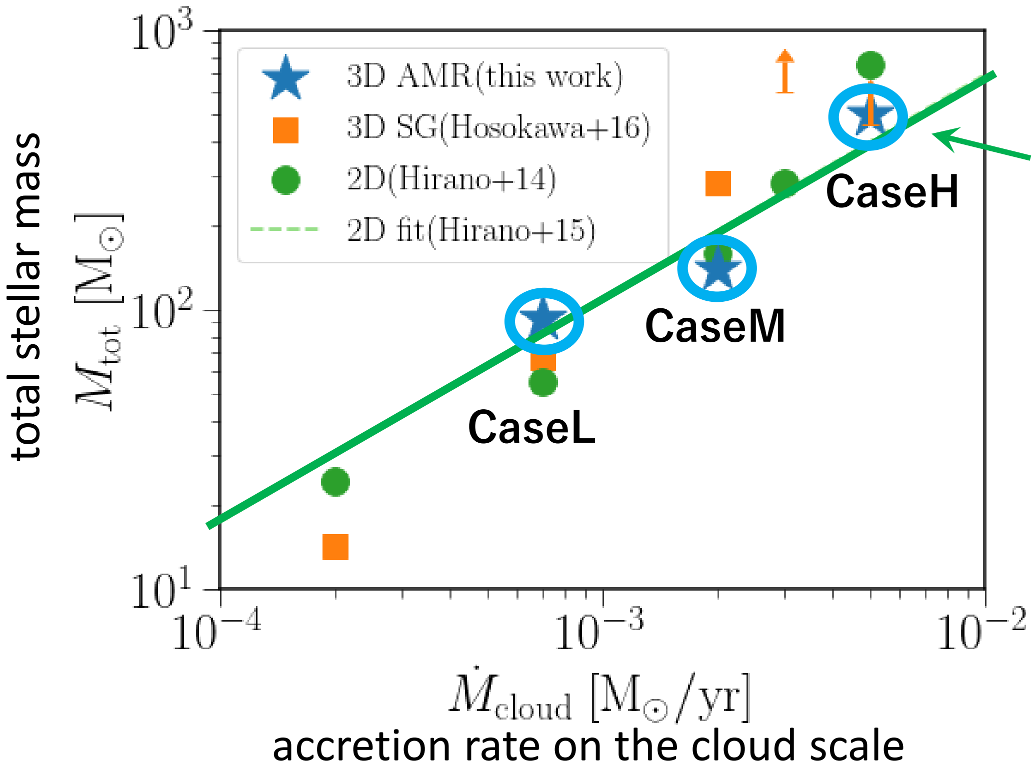
$60M_{sun} + 30M_{sun}$ with $\Delta r = 10^{3\text{-}4}$ au



$370M_{sun} + 130M_{sun}$ with $\Delta r \sim 10^3$au

Massive (& wide) binaries are common among first stars

comparison with 2D simulation



fitting for the 2D results of Hirano+15

$$M_* = 250\,M_\odot\left(\frac{\dot M_{\rm J}}{2.8\times10^{-3}\,M_\odot\,{\rm yr}^{-1}}\right)^{0.8}$$

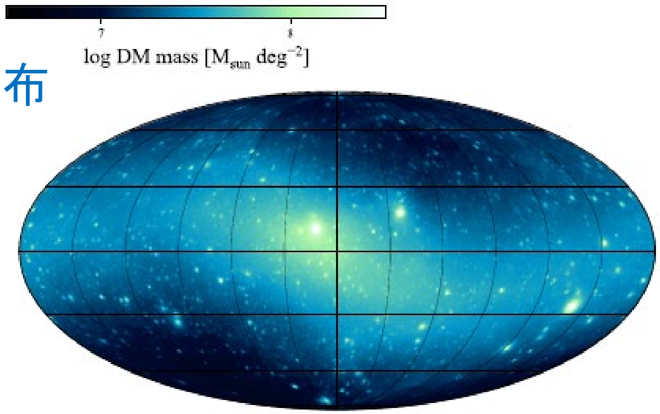
- 合計質量は2Dの場合とよく合っている
- 3Dの場合はこの質量はいくつかの星に分配（主に2個の星）

低質量種族Ⅲ星は本当に存在したか？

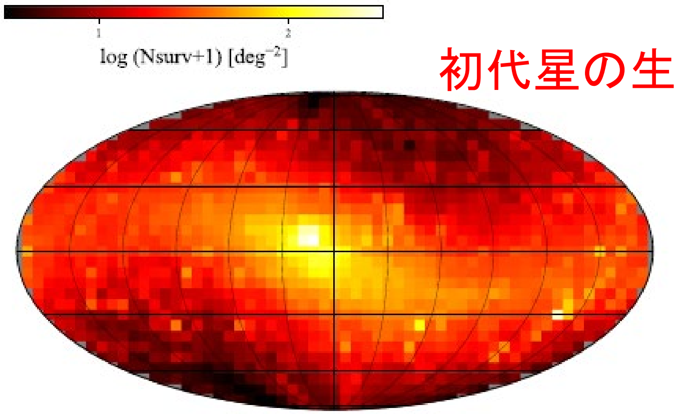
宇宙論的N体シミュレーション→銀河系中の低質量初代星分布

Ishiyama et al. (2016)

DM分布

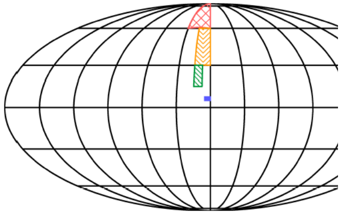


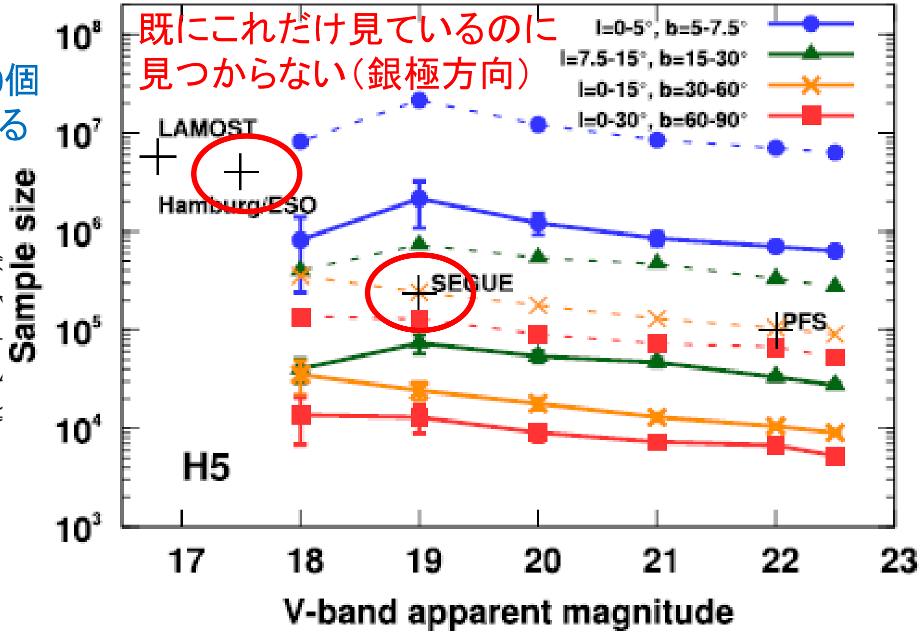
初代星の生き残り



種族III星を見つけるためには何個星を見ればいいか？

ミニハロー中に
破線：1個、実線：10個
低質量初代星出来る



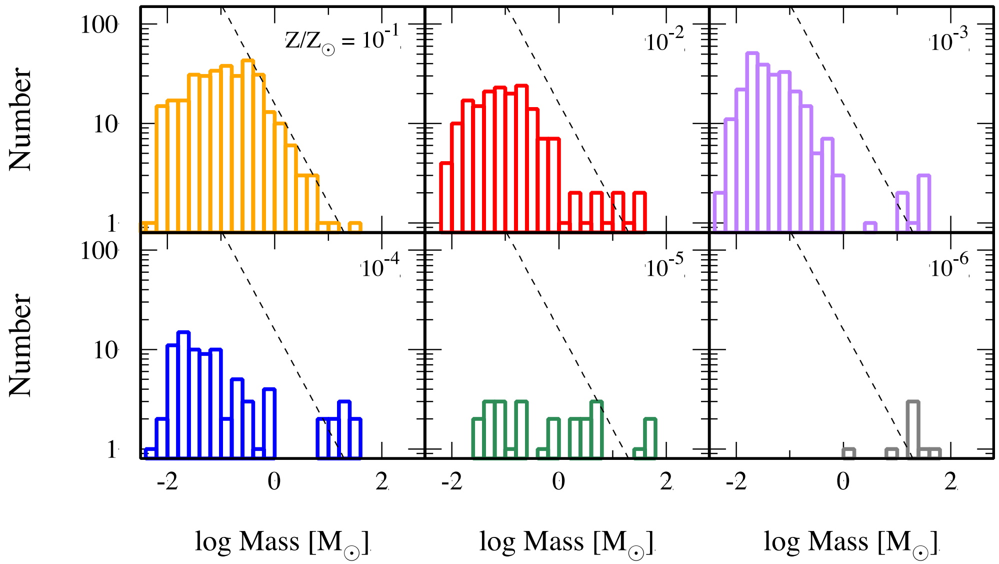


既にこれだけ見ているのに
見つからない（銀極方向）

ミニハローにつき
何個も初代星が出来るモデル
棄却される

Part II: Formation of Pop II Stars

IMF transition in cosmic history



stellar mass at different epochs

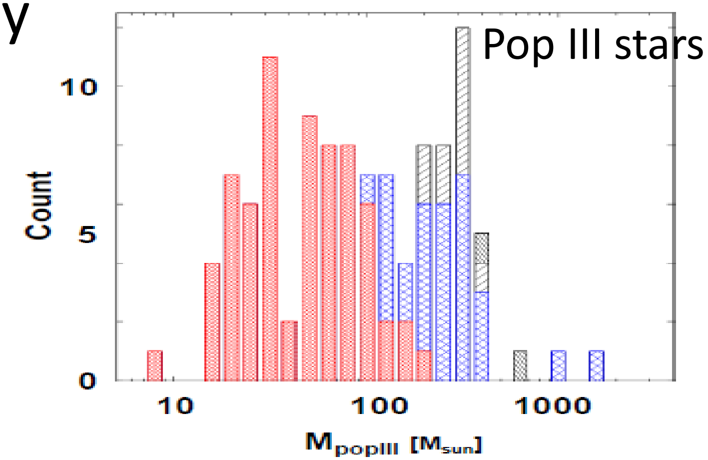
- **First Pop III stars**
  are massive ($\sim 100 M_{sun}$) according to theory

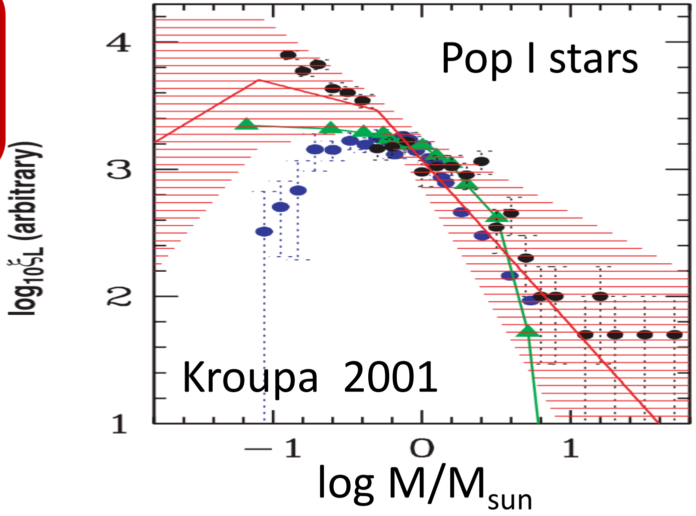
- Low-mass very-metal-poor **Pop II stars**
  are present in MW and other galaxies

- **Pop I stars** in the solar neighborhood
  are mostly low-mass ($0.1\text{-}1 M_{sun}$)

transition of characteristic stellar mass
in the cosmic history **"Pop III-II transition"**

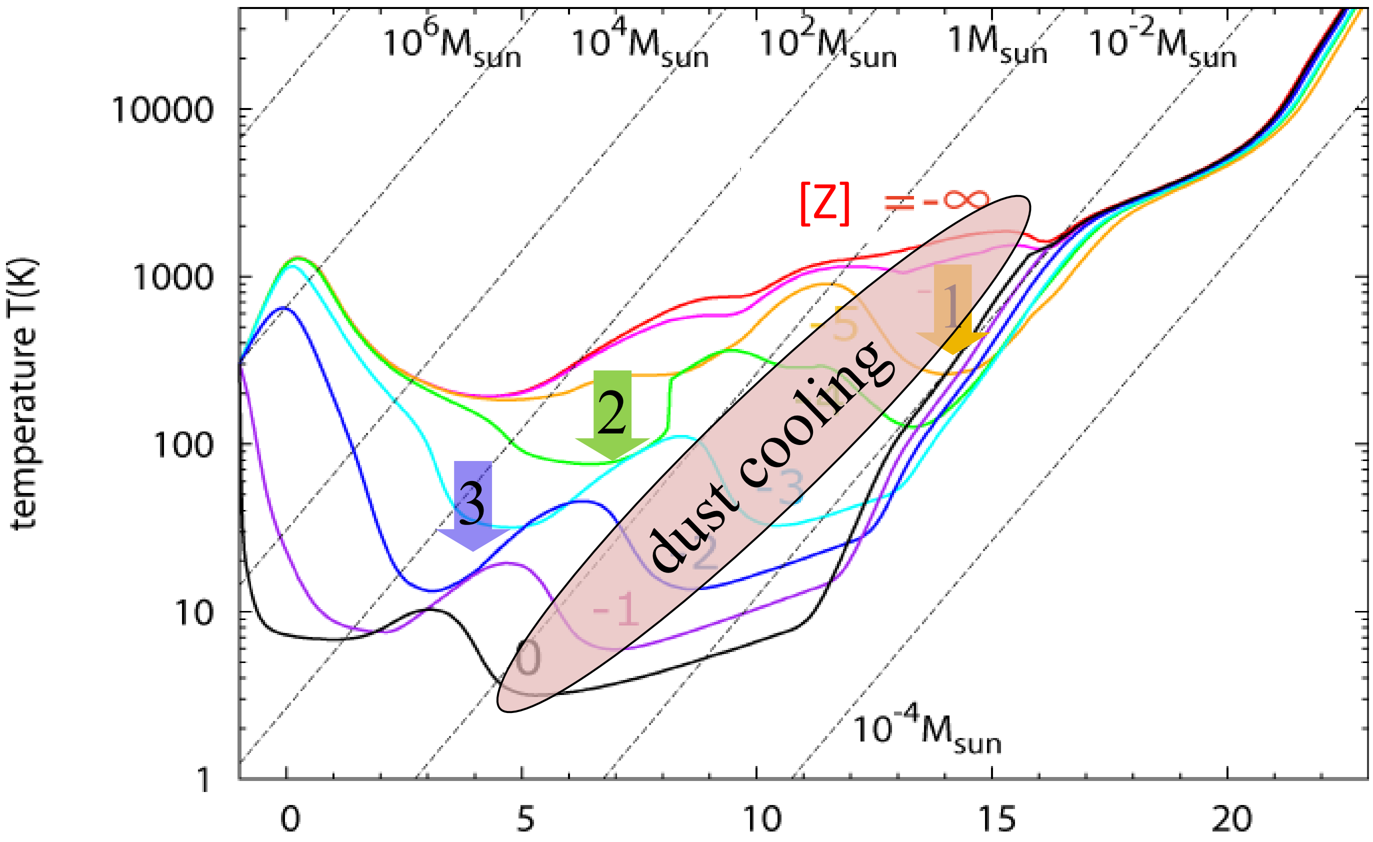
mechanism?
probably caused by accumulation of
metals and dusts in ISM





Thermal evolution of clouds with different metallicities

1) cooling by dust thermal emission: [Z] > -5
2) H_2 cooling formed on dust surface : [Z] > -4
3) cooling by metal lines (C and O): [Z] > -3



dust amount
scaled with
metallicity from
the MW value

KO+2005
input physics
updated
also KO(2000)
Schneider+(2003)

Rapid temperature drop causes fragmentation

→ dust cooling produces low-mass fragments

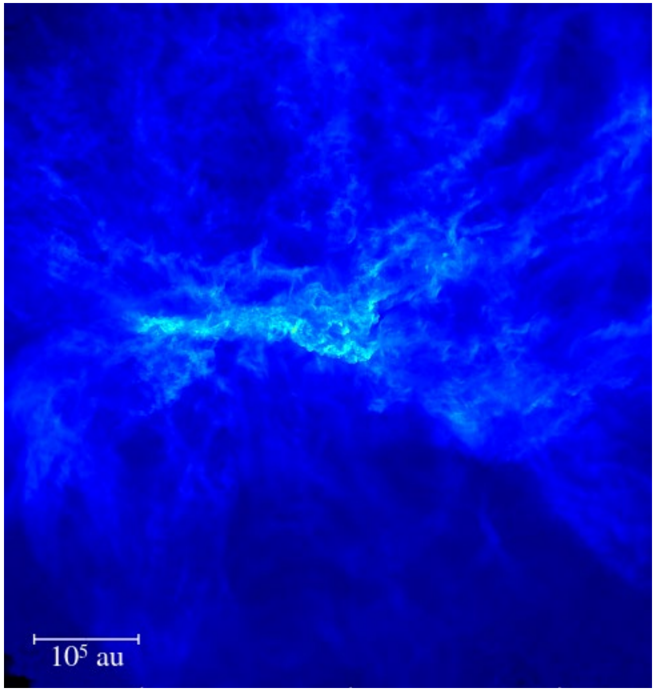
star cluster formation at low metallicities: hydro simulations

Chon, KO & Schneider (2021)

see also
Tsuribe & KO(2006),
Clarke+(2008),
Dopke+(2013)

numerical setup

- SPH + N-body simulation (by Gadget 3)
  - sink particle (at $n = 2\times10^{16}$ cm^{-3},radius：～1 au) merger
- low-metallicity gas microphysics
  - primordial-gas chemistry +dust (e^-,H,H^+,H_2,H^-,D,D^+,HD)
  - radiative process
    - primordial gas cooling
    - metal line cooling (CII, OI)
    - dust cooling



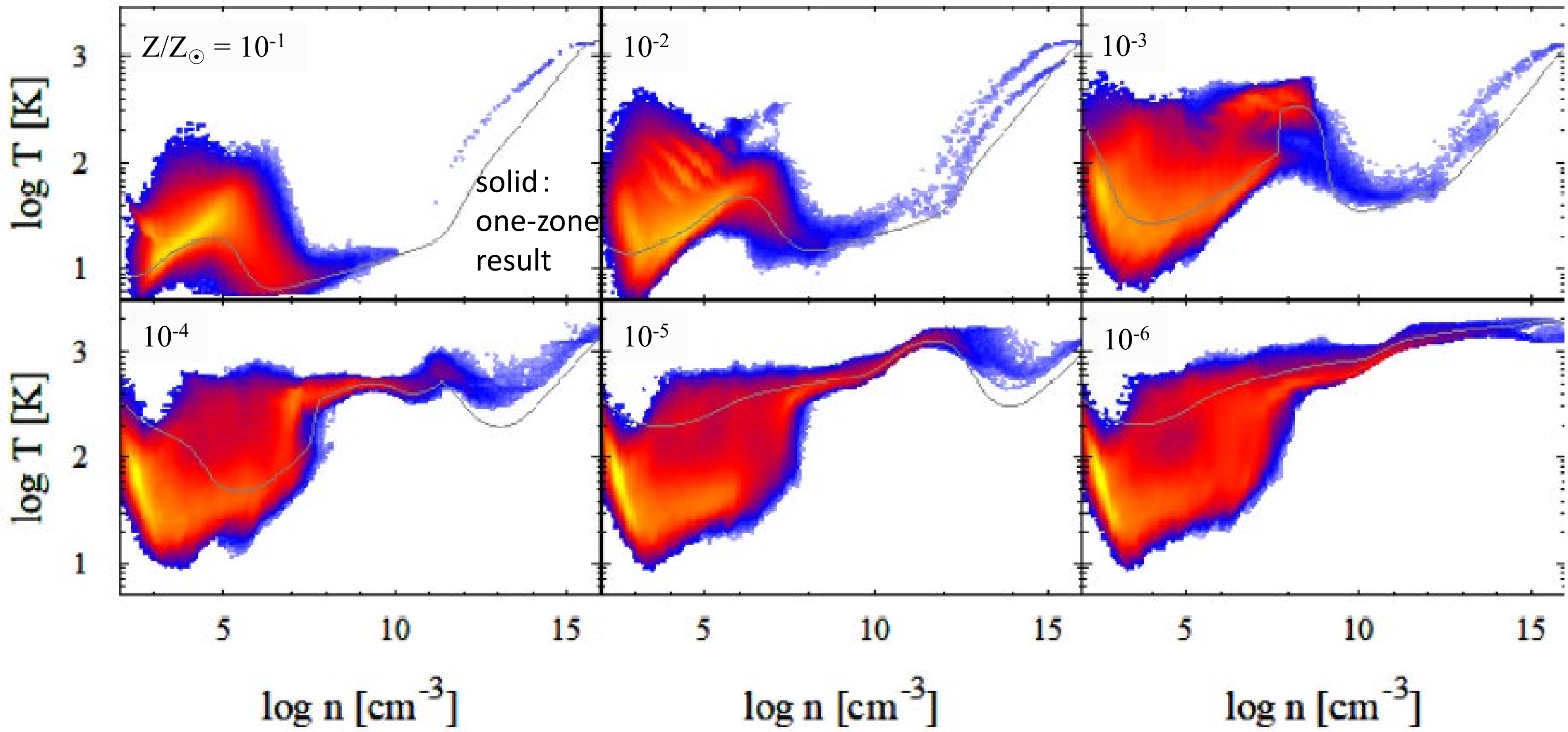
Cases studied:

- Metallicity $\log Z/Z_\odot = -1, -2, -3, -4, -5, -6$
- Initial condition：Bonnor-Ebert sphere with trans-sonic turbulence

$$E_{turb} / E_{grav} = 1,\ \ E_{th} / E_{grav} = 0.7,\ \ E_{rot}/E_{grav} = 0.001,\ \ P(k) \propto k^{-4}$$

$$M_{cloud} = 1950\ M_\odot,\ \ R_{cloud} = 10\ \mathrm{pc},\ n_{cloud} = 10^4\ \mathrm{cm}^{-3}\ ,\ T=200\mathrm{K}$$

Thermal evolution of collapsing clouds



solid : one-zone result

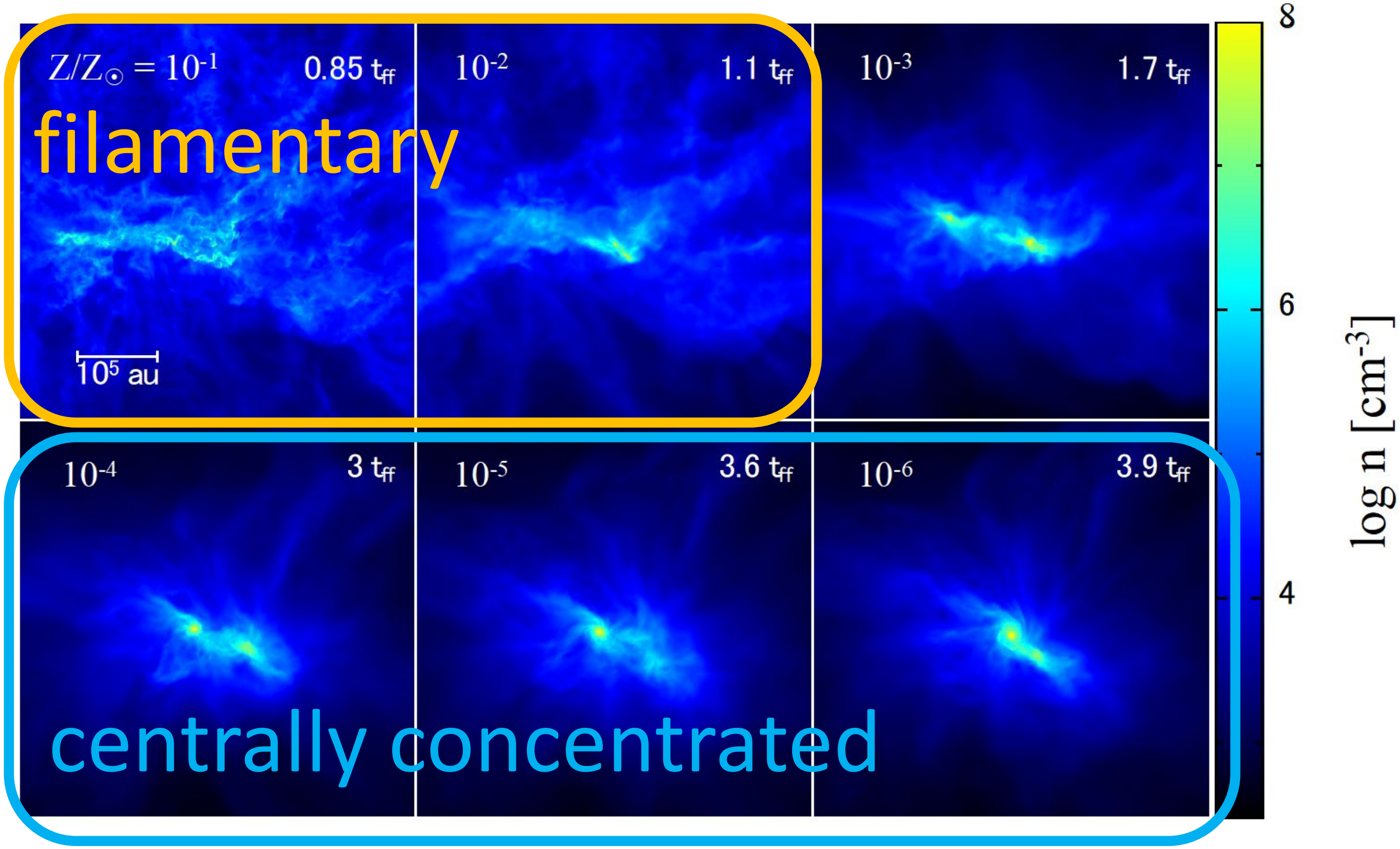
- Temperature evolution is similar to that in one-zone models.
- but somewhat lower (down to 10 K) at low densities.

← HD cooling due to delayed collapse by the turbulence

turbulence and cloud structure

log Z/Z_{sun}
= -1, -2, -3

log Z/Z_{sun}
= -4, -5, -6



filamentary

centrally concentrated

$Z/Z_\odot > 0.01 - 0.1$: more turbulent

→overall shape becomes filamentary

$Z/Z_\odot < 10^{-3}$: less turbulent

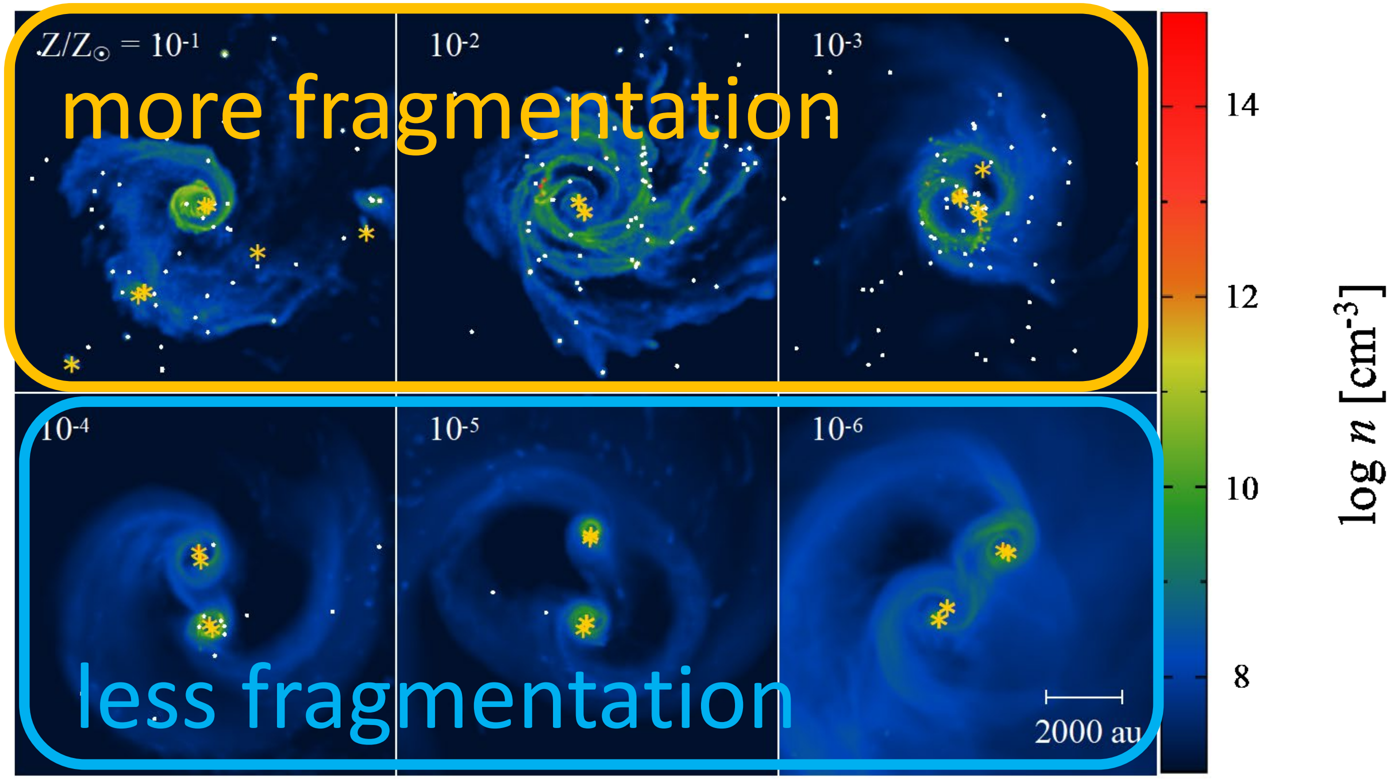
→cloud becomes centrally concentrated

Fragmentation in accretion phase

At total stellar mass of 150 $M_\odot$
(cloud mass 1950 $M_\odot$, Star formation efficiency = 8%)

log Z/Z_{sun}
= -1, -2, -3

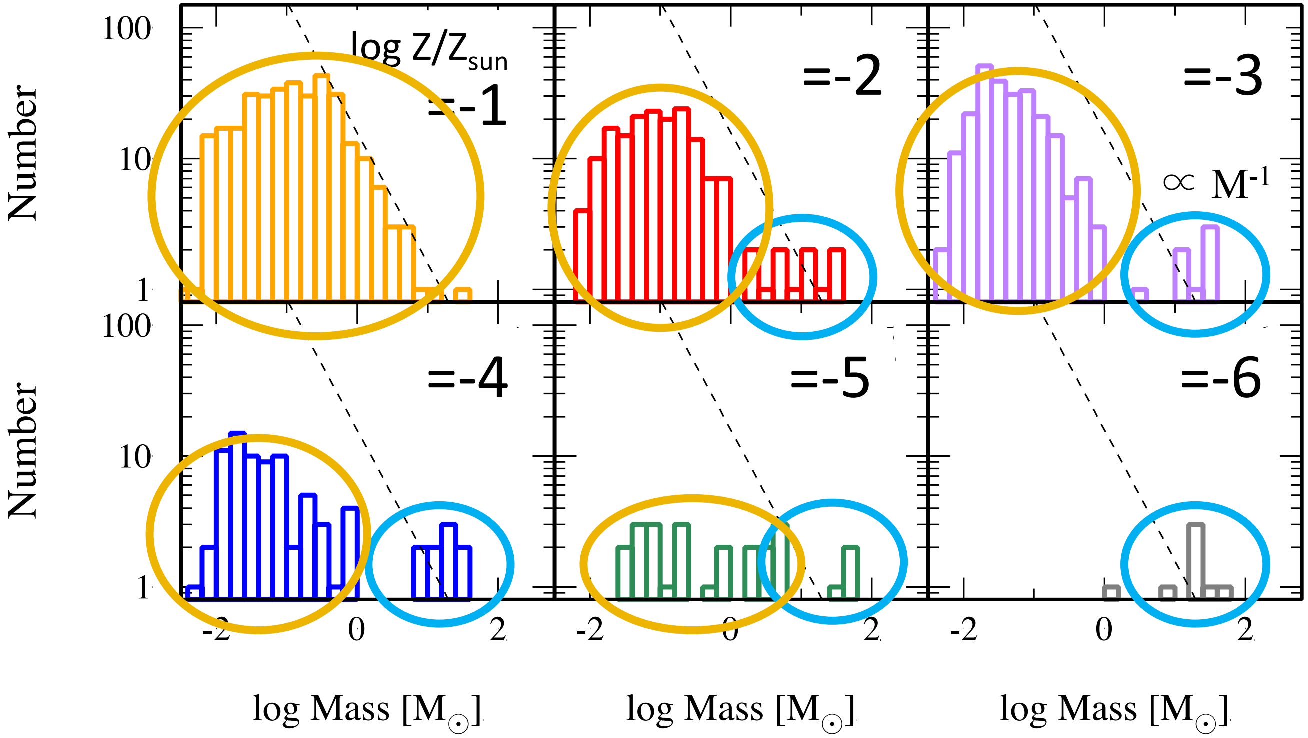
log Z/Z_{sun}
= -4, -5, -6



$Z/Z_\odot = 10^{-1}$: fragmentation of filaments rather than disk
$Z/Z_\odot = 10^{-3} - 10^{-2}$: disk vigorously fragments
$Z/Z_\odot < 10^{-4}$: disk is relatively stable

mass distribution at different metallicities

At total stellar mass of 150 $M_\odot$
(cloud mass 1950 $M_\odot$, Star formation efficiency = 8%)



massive and low-mass components in IMF

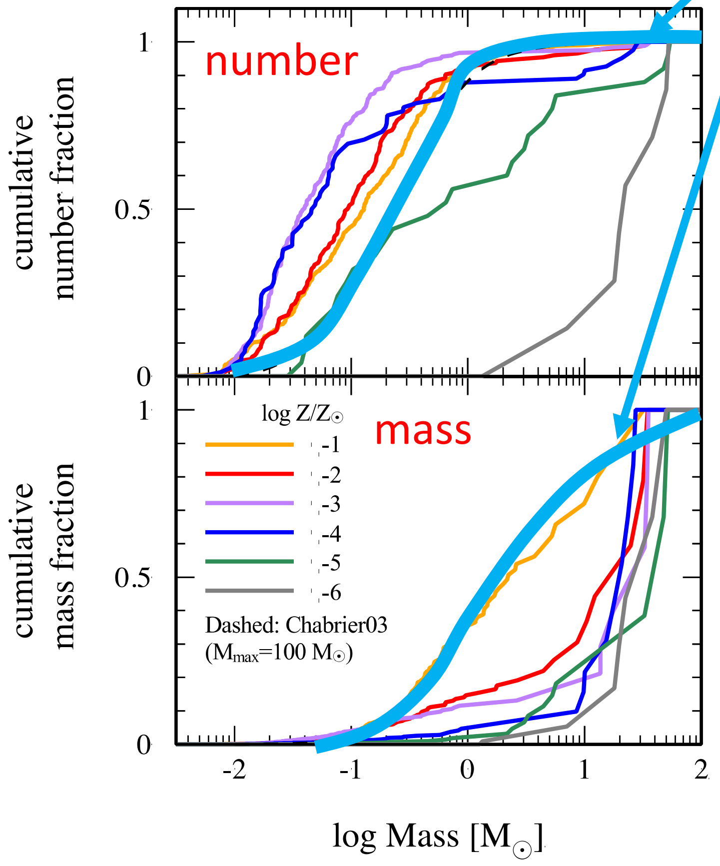
- at $10^{-6}Z_{sun}$, only massive component

IMF transition is not abrupt, rather proceeds gradually with metallicity.

Transitional metallicity for IMF

present-day IMF (Chabrier03)

cumulative fraction



in terms of number:

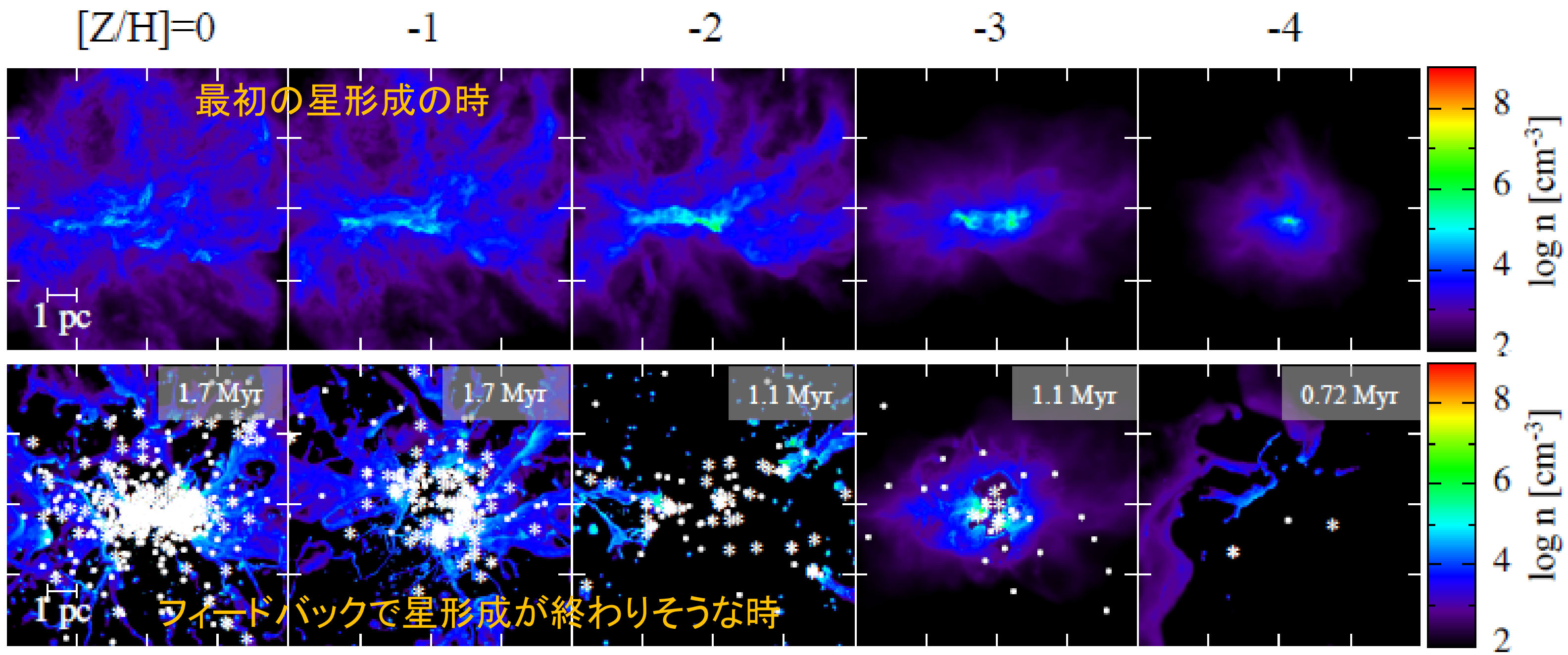
large number of low-mass stars start forming $>10^{-5}...10^{-4}$Zsun

in terms of mass:

- large fraction of mass is still in massive stars at $<10^{-2}Z_{sun}$ (top-heavy IMF)
- IMF becomes Salpeter-like at $0.1Z_{sun}$

IMF transition is not abrupt, rather proceeds gradually with metallicity.

輻射フィードバックの効果

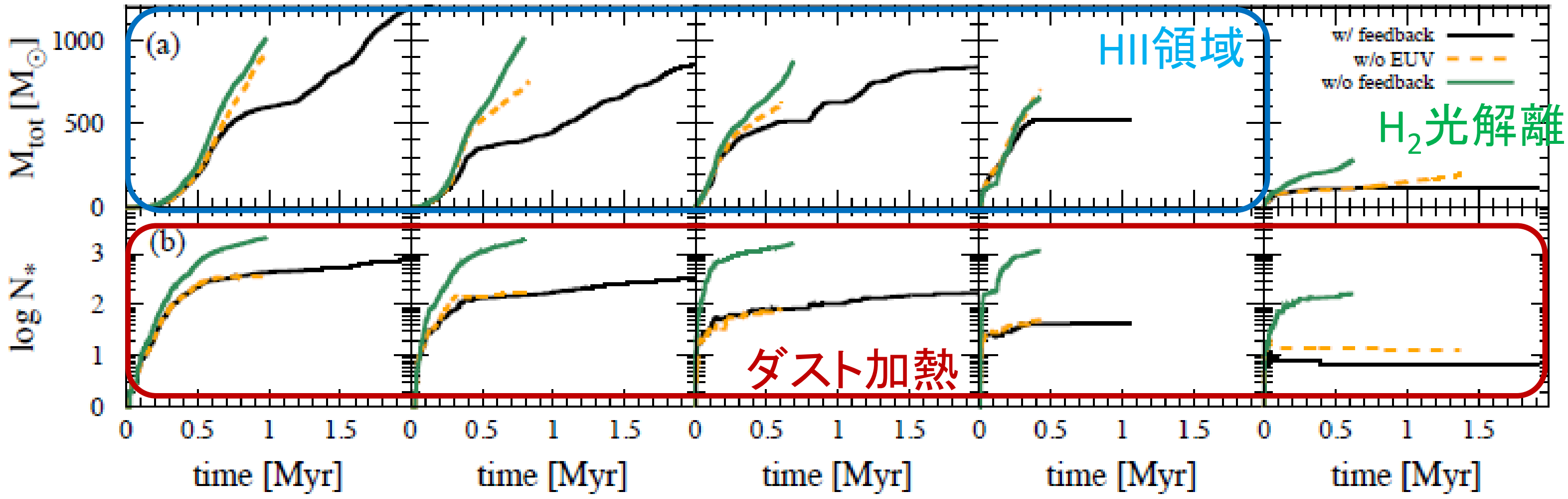


最初の星形成の時

フィードバックで星形成が終わりそうな時

中心に集中して分布、全星質量大

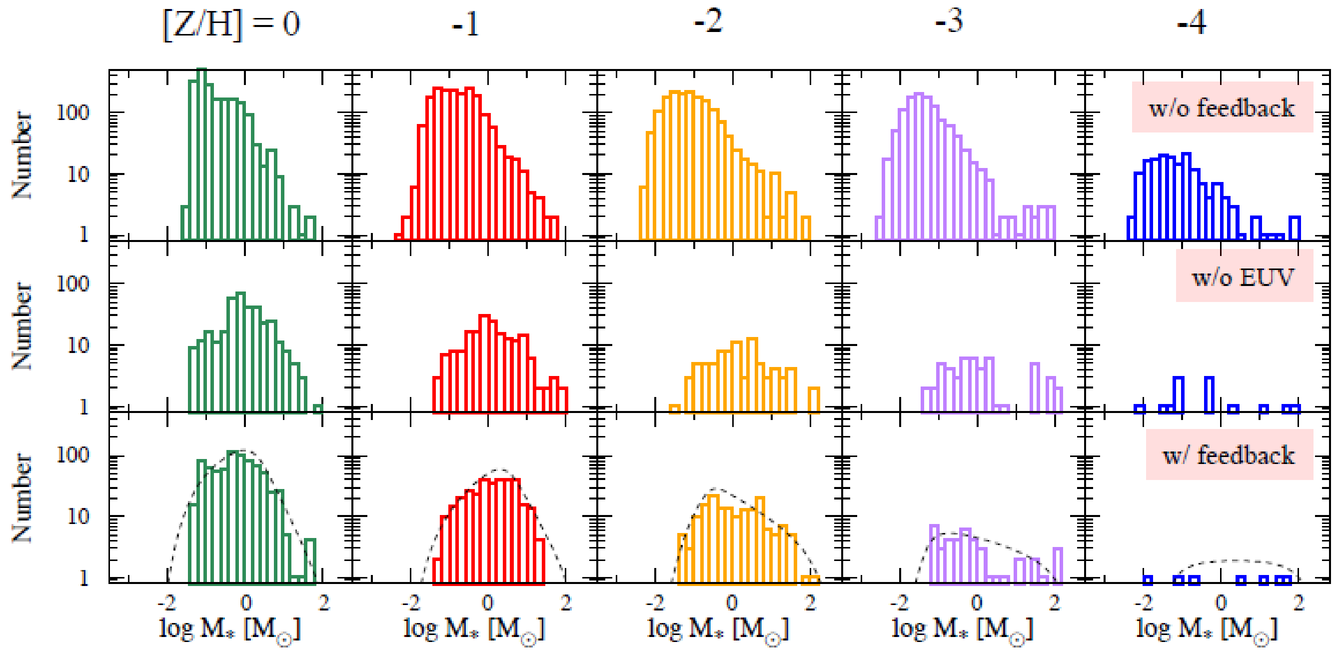
分散して分布、全星質量小



HII領域

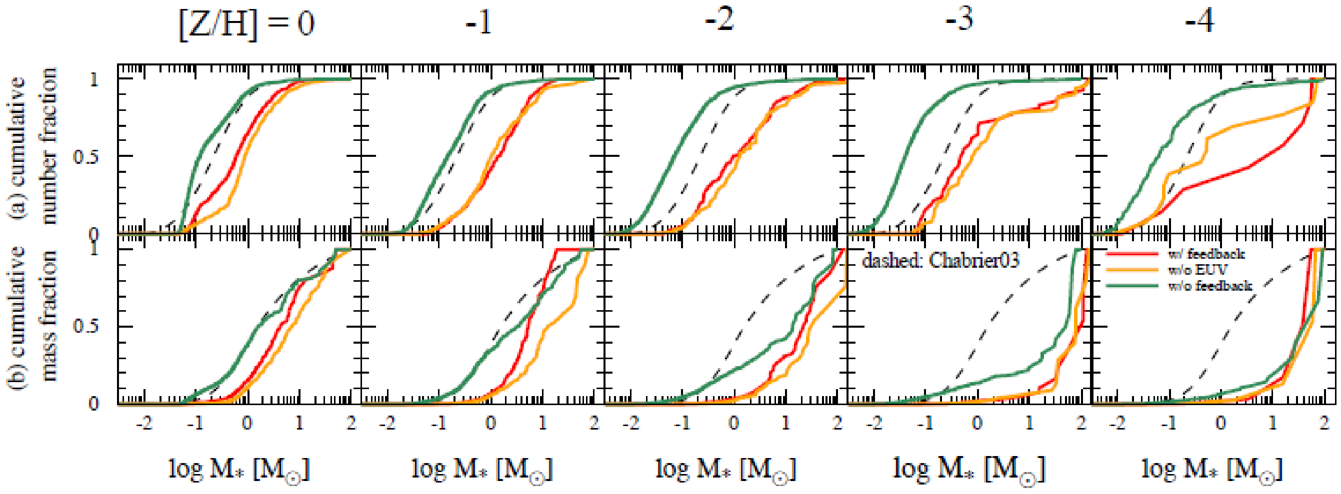
H_2光解離

ダスト加熱



ダスト加熱により
低質量星は消滅

大質量星は電離
フィードバックで減少

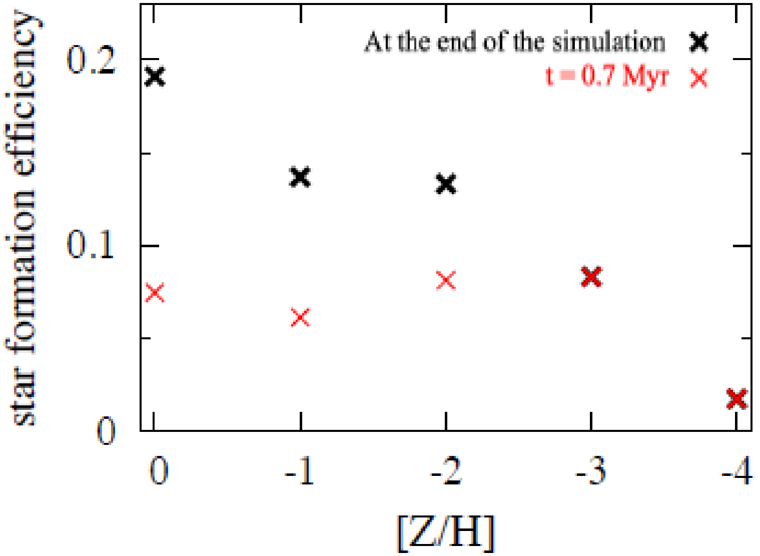


Chabrier IMFに似てくる

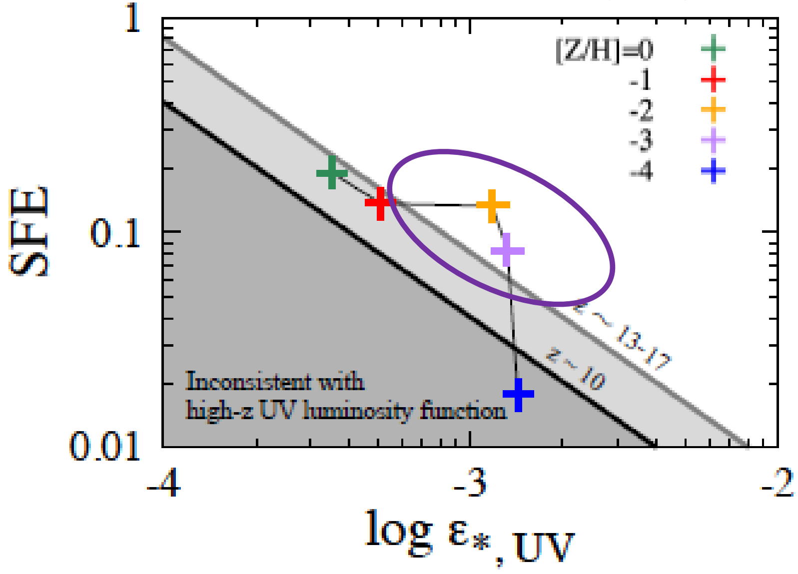
ほぼlog-flat的なIMF

星形成効率

重元素量と星形成効率



JWSTによるUVで明るい銀河数との比較

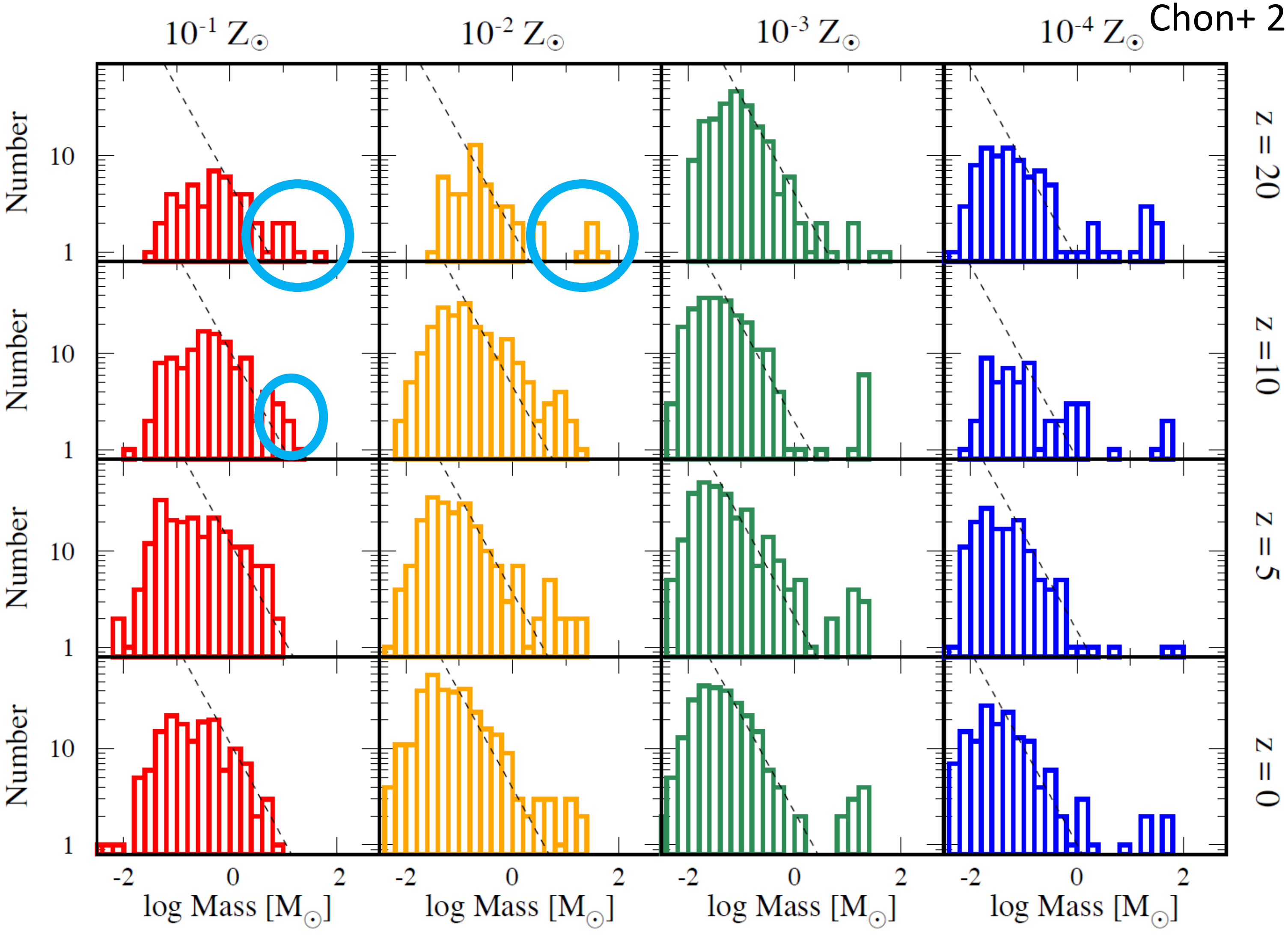


- 低金属度ほど星形成効率は下がる
- 輻射フィードバックが始まる前(t=0.7Myr)
はさほど重元素量によらない
- [Z/H]=-4では、SFEが非常に低い

- [Z/H]=-3..-2くらい
top-heavy IMFかつ高いSFEで
JWSTのhigh-z　UV-bright 銀河数を
説明可能
- ここでのSFEは初期の雲と
出来た星の質量の比（クランプスケール）
なので、おそらく銀河スケールより大きい

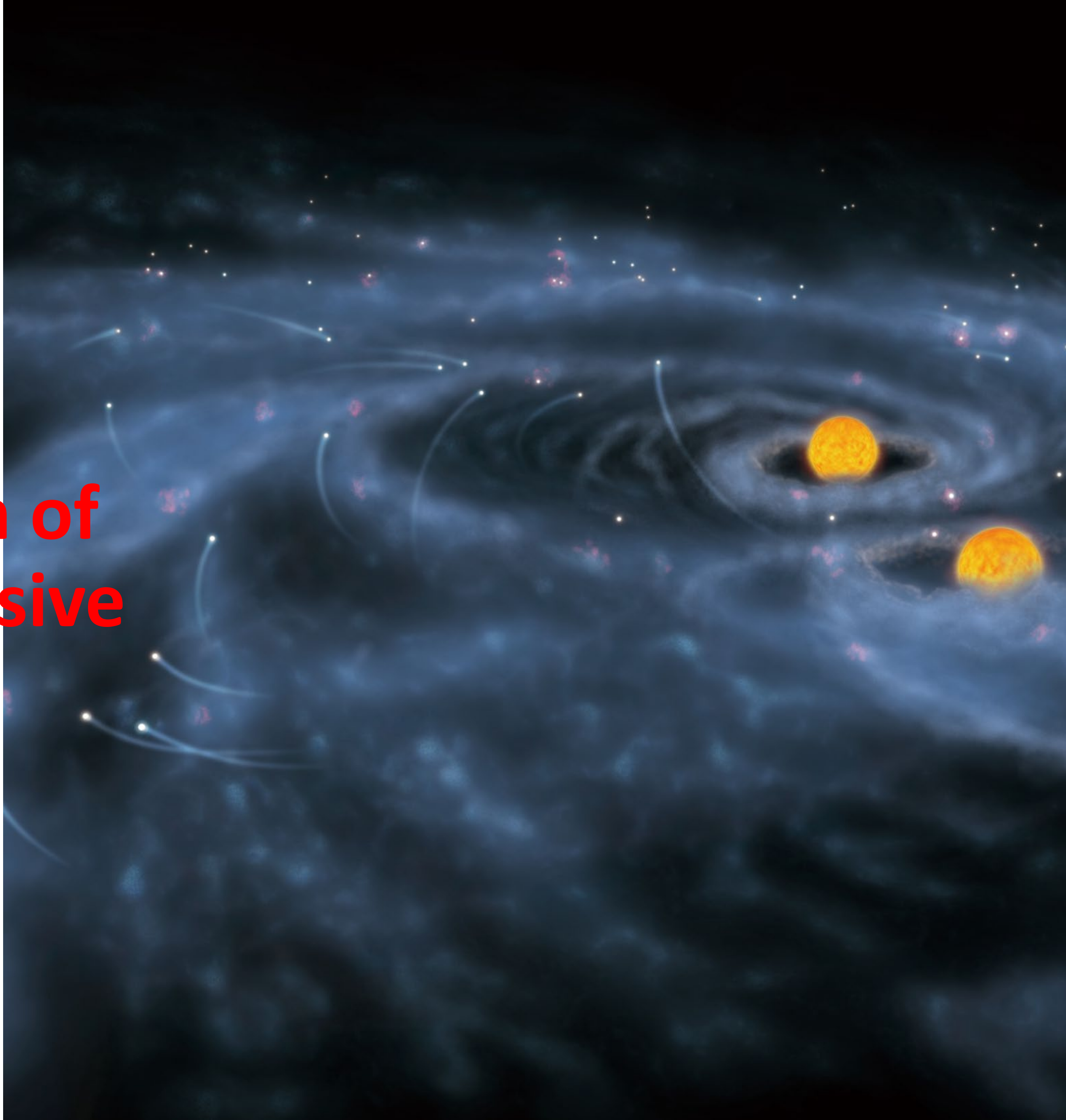
high-z CMB effect

Chon+ 2022



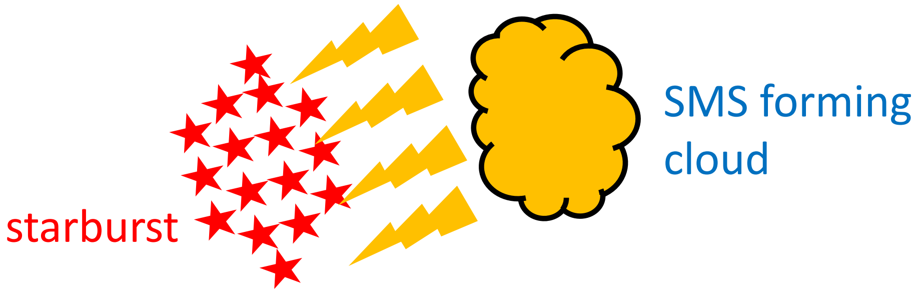
enhancement of massive stars at high-z (>~20)
in the cases of >0.01Zsun

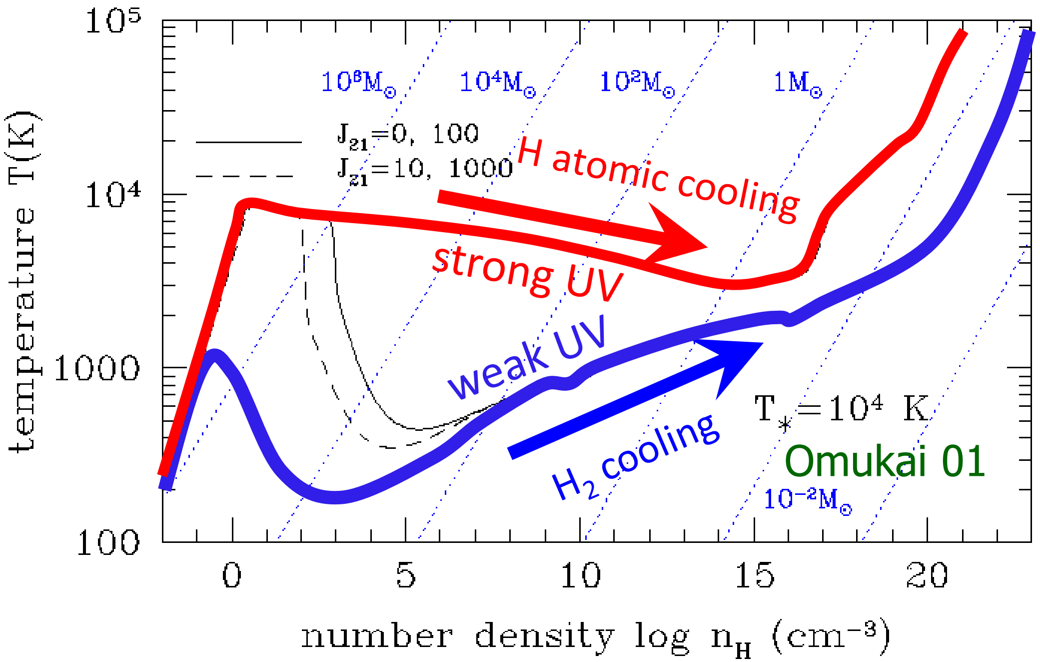
Part III: Formation of Supermassive Stars



How are super-massive stars formed ?

Collapse of a massive primordial cloud in strong FUV field





It cools solely by atomic cooling and collapses isothermally at ~8000K.

- No rapid cooling phase
  →monolithic collapse without fragmentation

- high temperature during the collapse
  →rapid accretion in protostellar phase

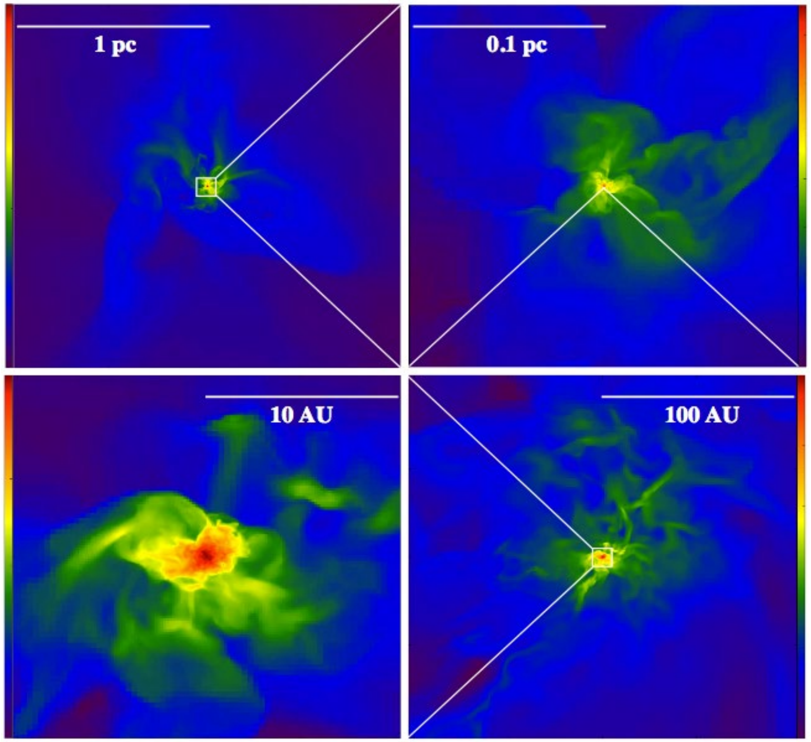
$dM_*/dt \sim c_s^3/G$
$\sim 0.1 M_{sun}/yr\ (T/10^4 K)^{3/2}$

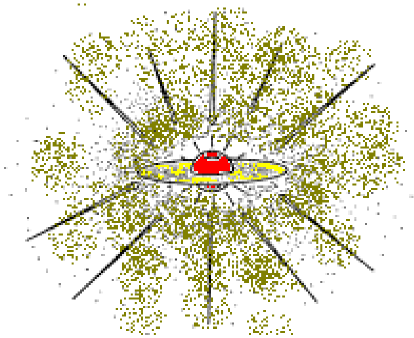
Supermassive stars ($>10^5 M_{sun}$) may form

Monolithic collapse of atomically cooling cloud

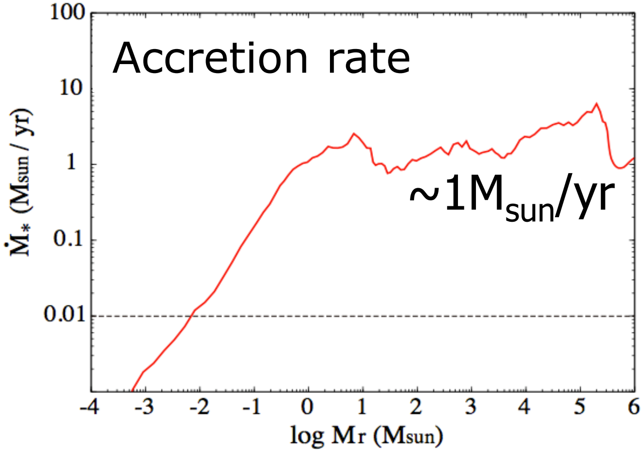
e.g., Bromm & Loeb 2003, Regan +2009

Inayoshi, Omukai & Tasker (2014)





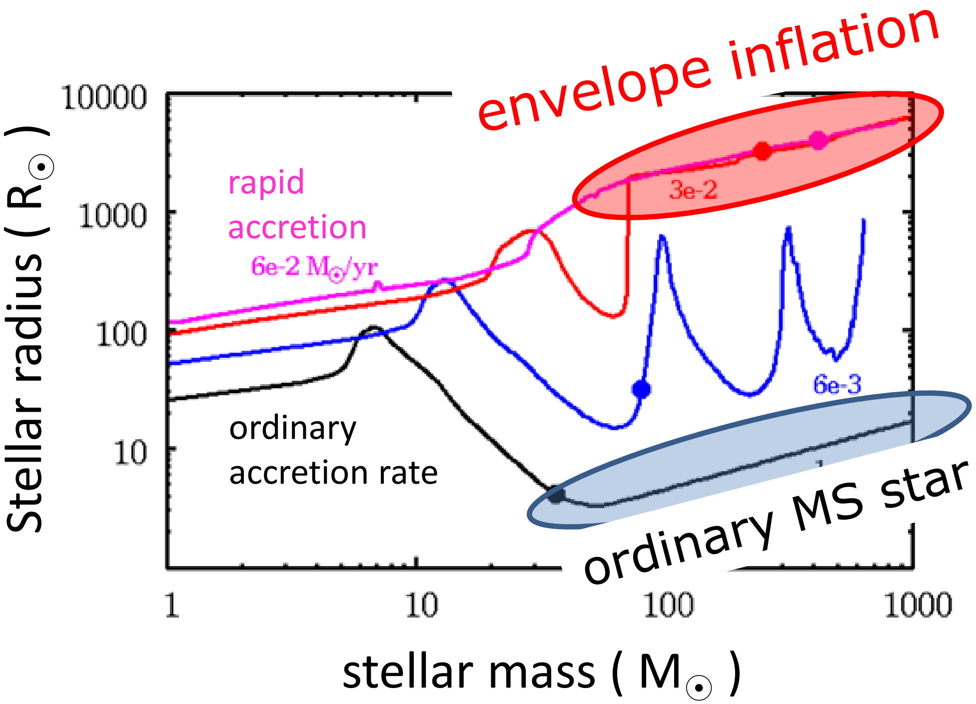
massive envelope $\sim 10^6 M_{sun}$



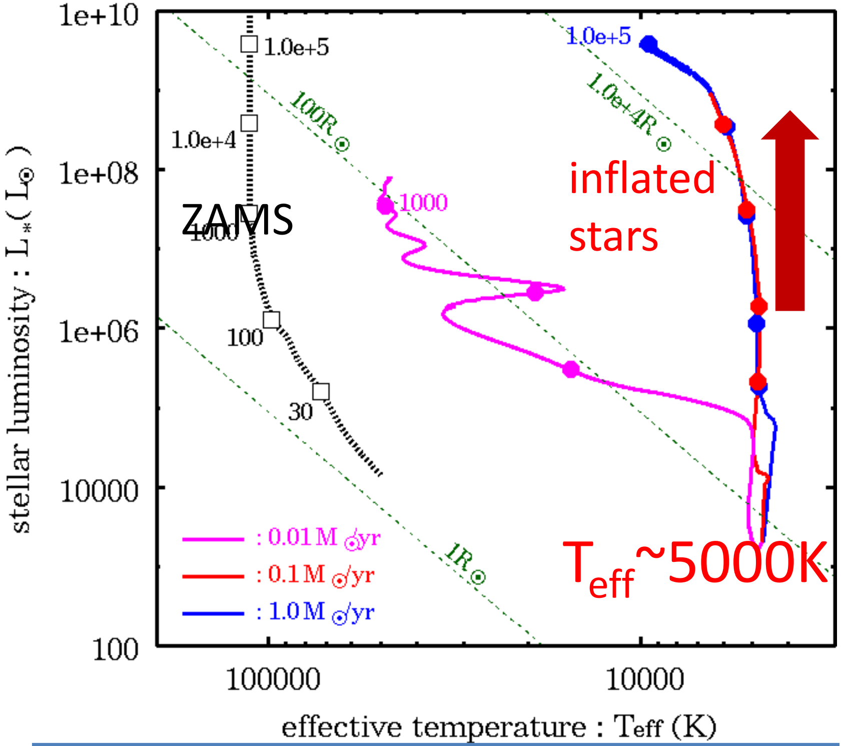
✓A single massive object forms with no major eposode of fragmentation

✓protostar grows rapidly ($\sim 1 M_{sun}$/yr) by accretion

envelope inflation by rapid accretion



Hosokawa, Yorke, KO +(2012,13)



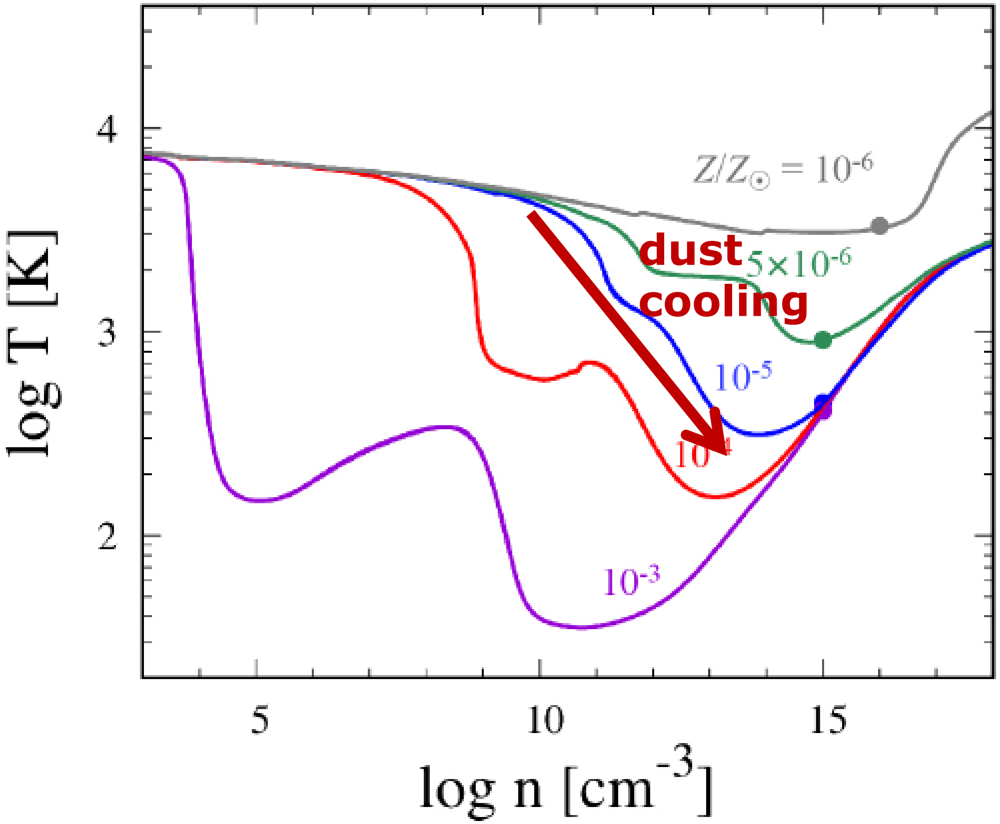
Rapid mass accretion
(> 0.01 M_{sun}/yr),
makes a protostar inflate to ~10au

Infrated stars emit no UV
(T_{eff} = 5000K, like red-giant stars)
→no UV feedback

Accretion continues unhindered.
The star becomes supermassive

What if there are some metals ?

Is it really impossible to form SMSs in metal-enriched case?

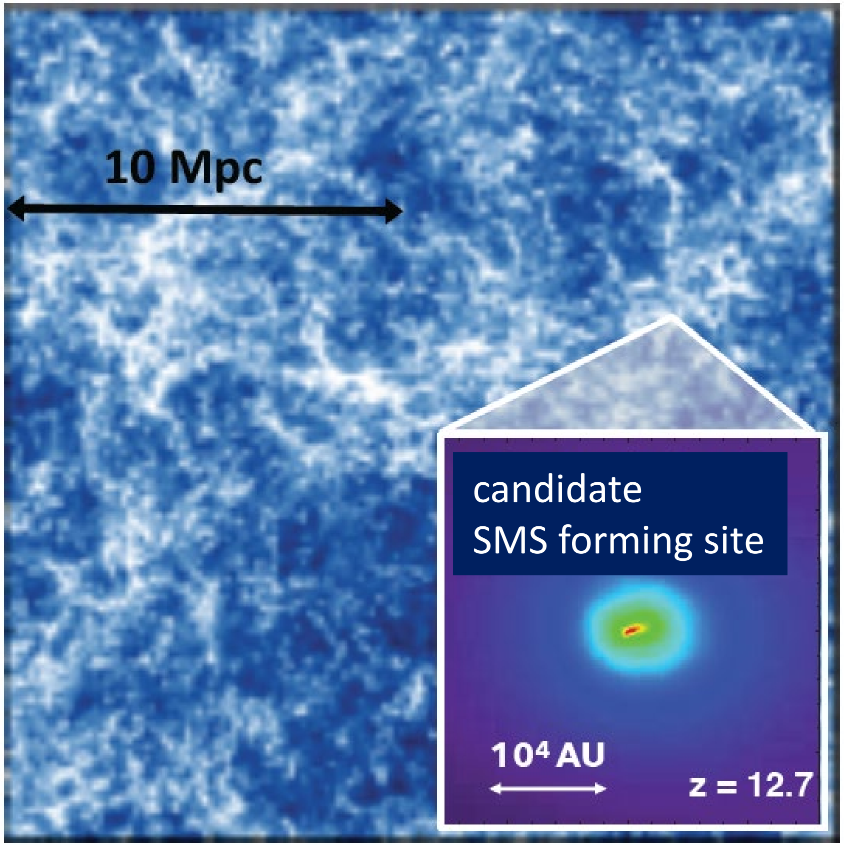


For [Z] > ~-5,
dust cooling causes rapid temperture drop

cloud fragments and forms a star cluster ?

Numerical Setup

Chon & KO 2020



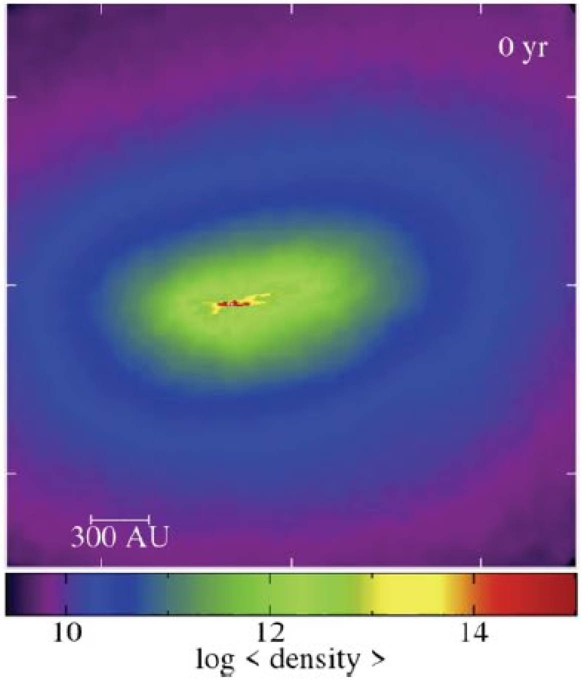
Initial condition:

a halo that is strongly irradiated in cosmological simulation of Chon et al. (2016, 18)

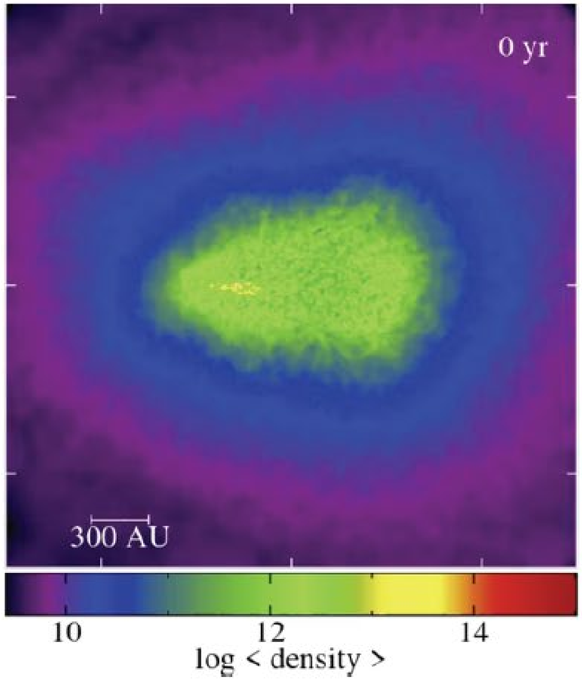
method

- SPH + N-body simulation (Gadget 2)
- use barotropic EoS
- sink formation at $2\text{x}10^{16}$-$2\text{x}10^{17}\text{cm}^{-3}$

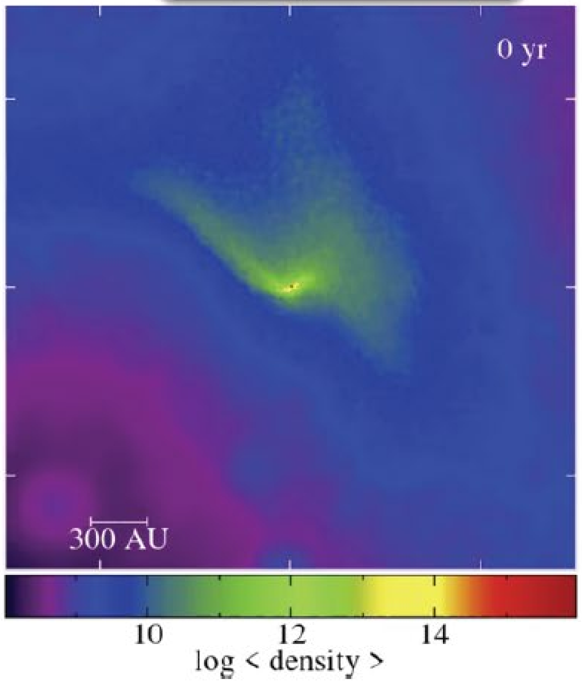
$Z/Z_{\odot} = 10^{-6}$ primordial



10^{-4} dust cooling



10^{-3} dust + metal-line cooling



black dots >$10M_{sun}$
white dots <$10M_{sun}$

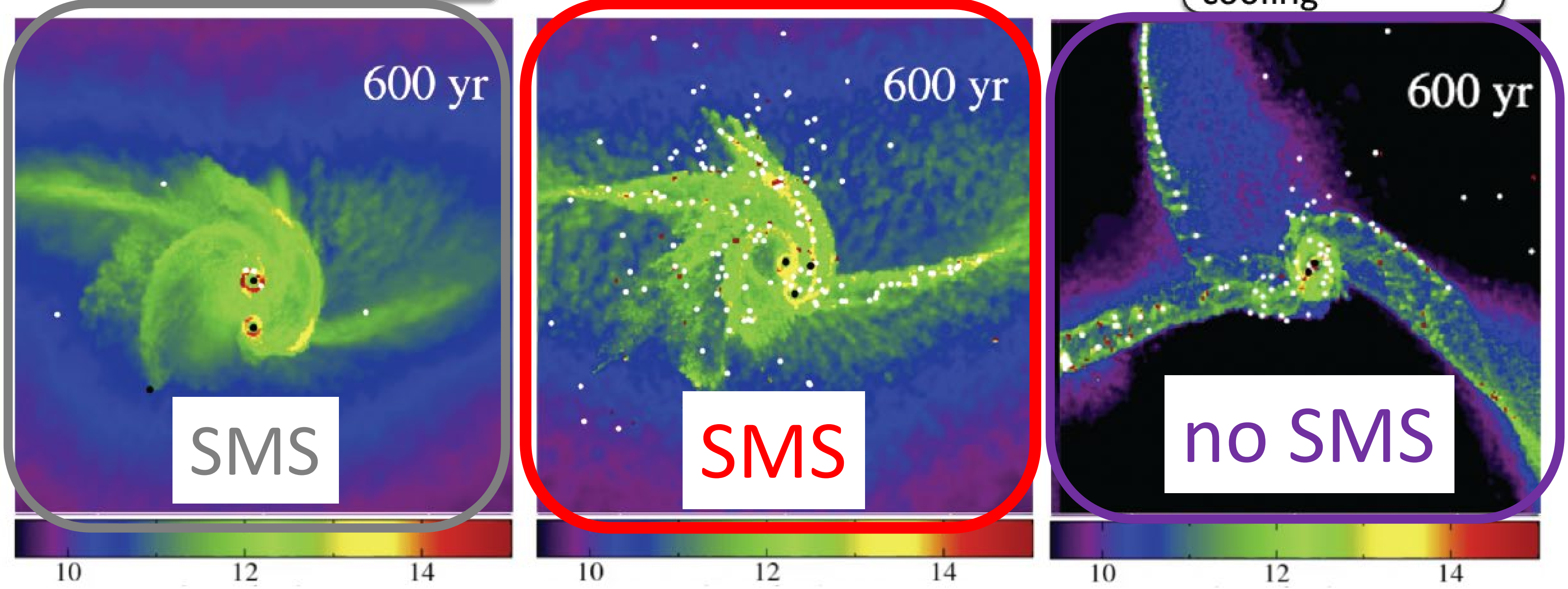
Conventional direct collapse

star cluster formation

$Z/Z_\odot = 10^{-6}$ primordial

10^{-4} dust cooling

10^{-3} dust + metal-line cooling



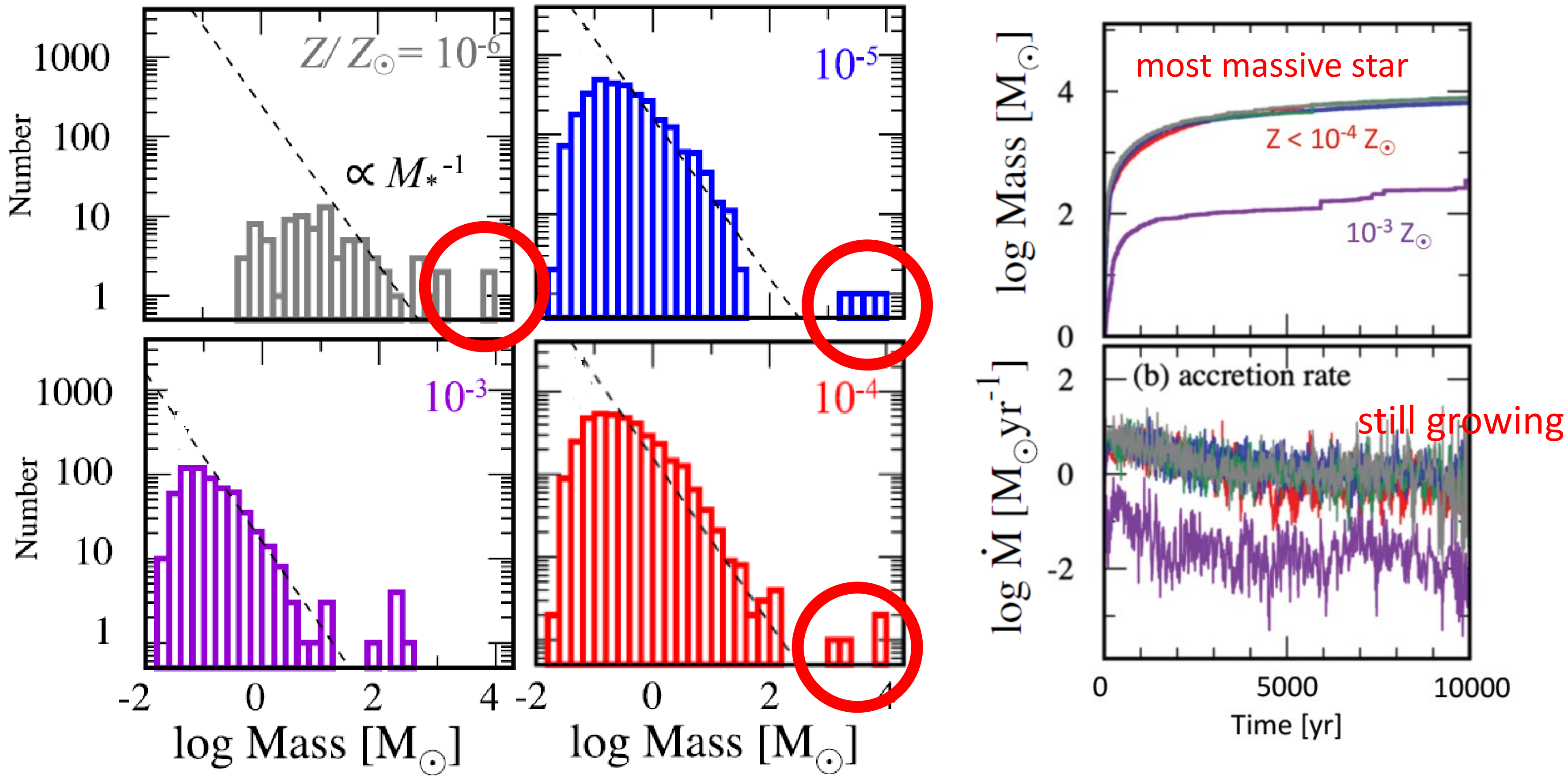
only little fragm
→ SMS formatio
at the center

numerous fragments
but the central star grows supermassive

oling
al flow
pattern
star cluster formation by fragmentation

Super Competitive Accretion

runaway growth of the central star



- central star accretes the gas exclusively and grows supermassive
- SMSs form along with a large number of low mass stars

SMS formation also from slightly metal-enriched gas

→ enhance the number of direct collapse BHs

Conclusion

- First stars are typically born as similar mass binaries of several 10's M_{sun}.

- IMF transition is not abrupt but proceeds gradually with increasing metallicity.
  - $\log Z/Z_{sun} > -5$:
    low-mass stars (Salpeter-like IMF) start to form.
  - $\log Z/Z_{sun} > -(1-2)$:
    massive star component disappears and IMF becomes Salpeter-like

- Supermassive stars are born in strong UV environments even with finite amount of metallicity ($\log Z/Z_{sun} < -3$) via super-competitive accretion.