銀河理論レビュー：
“Formation of the first stars & first galaxies”

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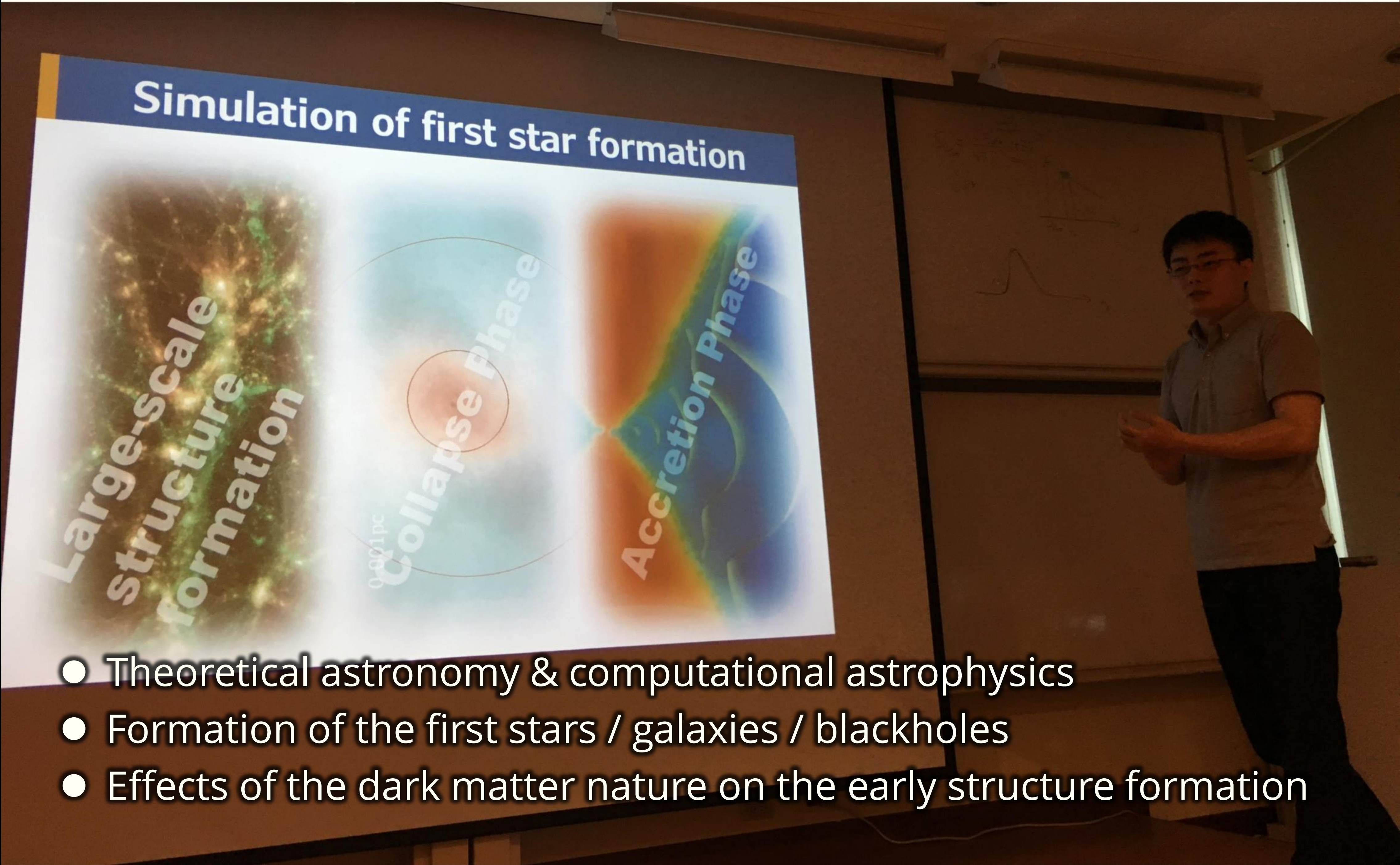
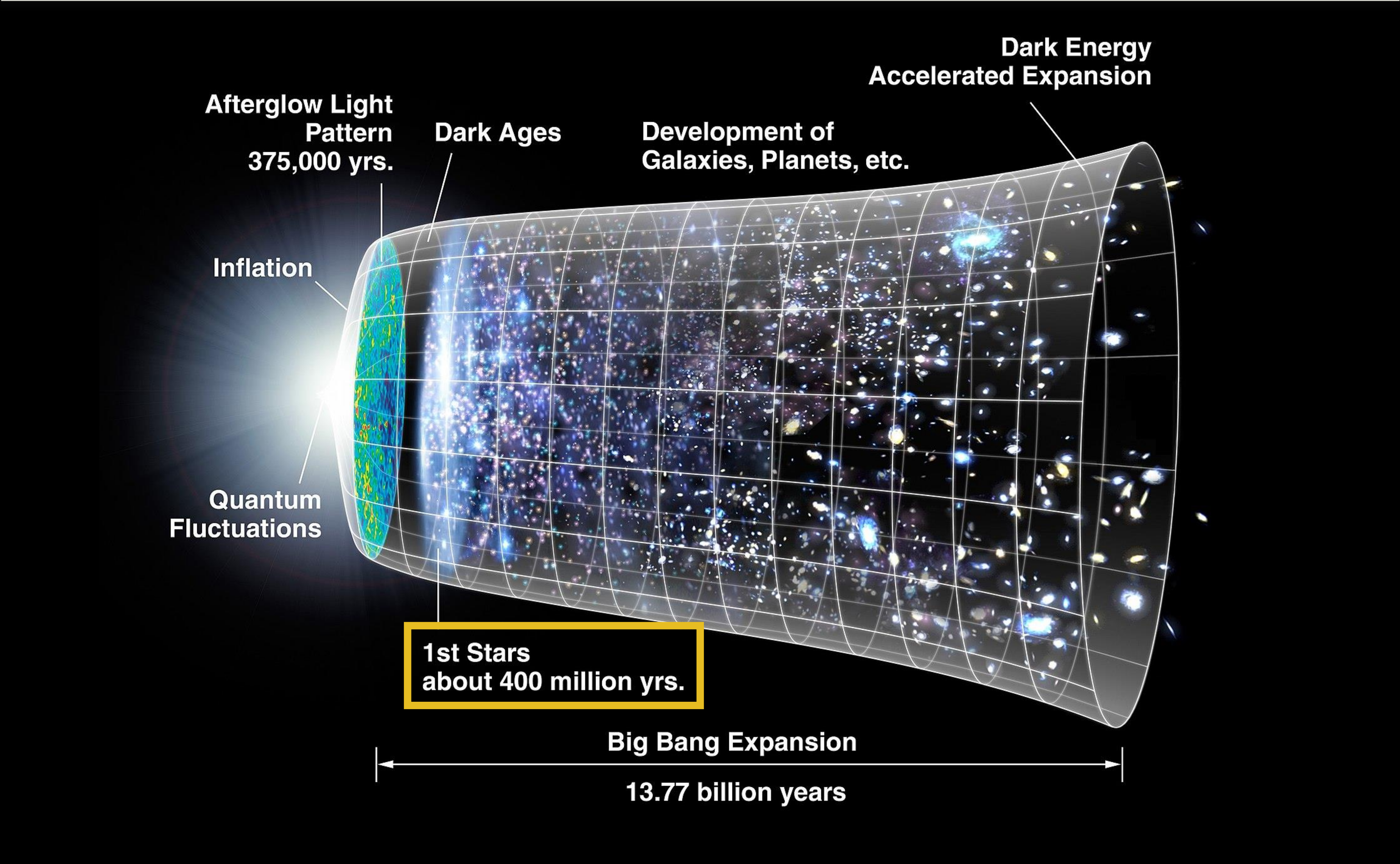


- Theoretical astronomy & computational astrophysics
- Formation of the first stars / galaxies / blackholes
- Effects of the dark matter nature on the early structure formation


Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
375,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.77 billion years

Hoyle (1946) first demonstrated that the heavy metal which cannot been generated by Big-Bang nucleosynthesis is produced from the hydrogen in the star.

Population (Pop) III stars

- They formed from the primordial gas (zero-metallicity $Z/Z_\odot = 0$) with the Big-Bang nucleosynthesis elements (H, He, Li) at $z \sim 20$ (from $z = 50$ to 15).
- They have not directly observed yet.

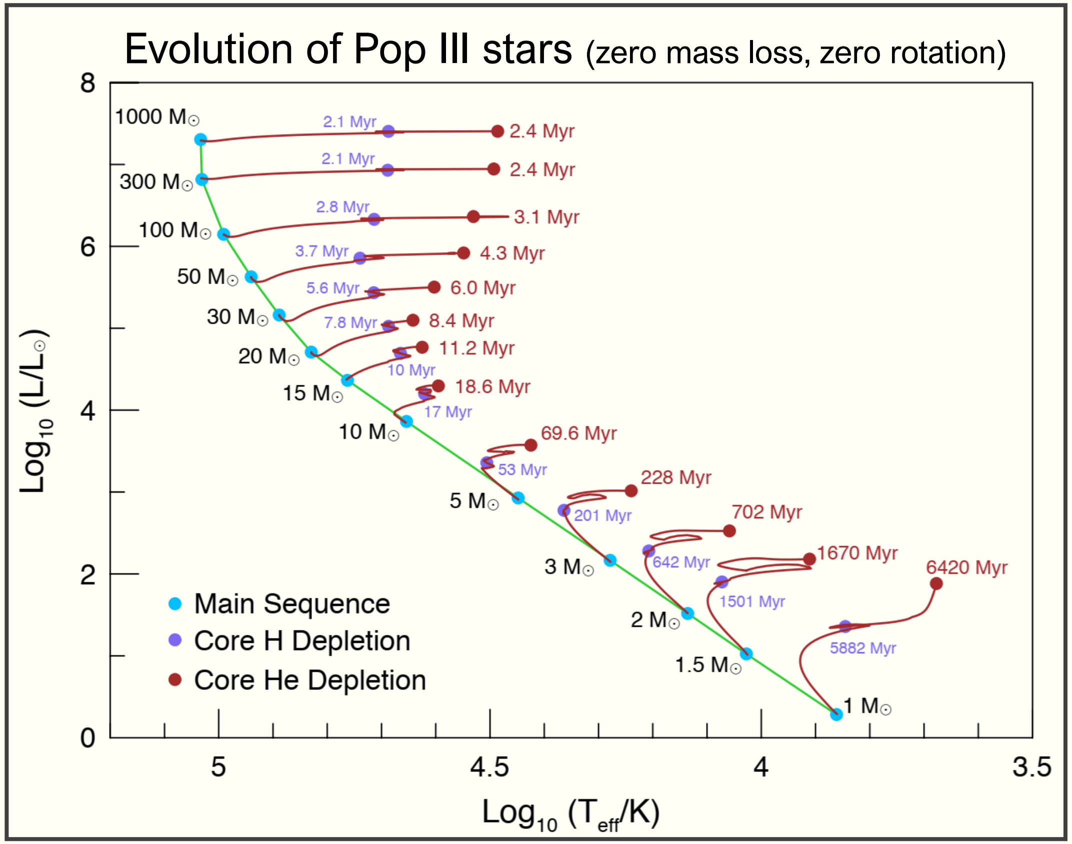
Vital player of the cosmic evolution in the early Universe

(1) Mass spectrum

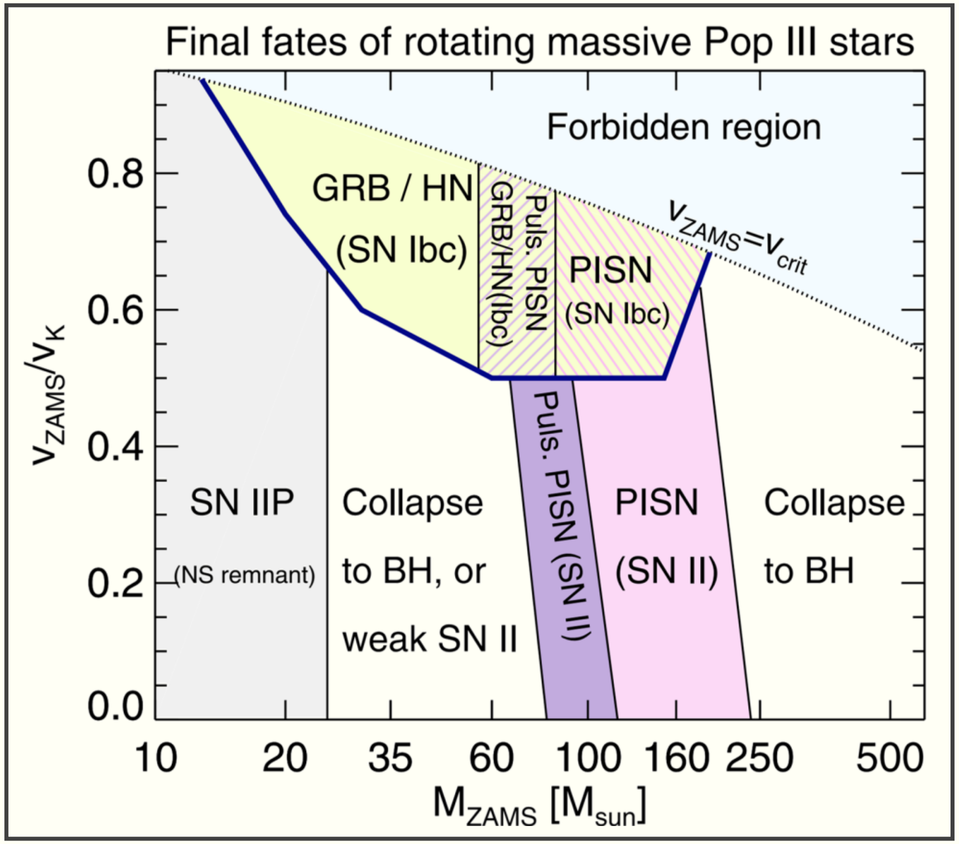
Typical mass, binarity, multiplicity

(2) Stellar spin

v_{rot}/v_{kep} < 0.5 or >0.5



(e.g., Heger & Woosley'02; Heger+'03, …)



(e.g., Chiappini+'11; Yoon+'12, Chatzopoulos&Wheeler'12, …)

「**初代星の質量（初期質量関数）**は宇宙初期の銀河形成を左右する重要なパラメータである。①初代星の形成過程においてその影響が未解明である物理過程について調べ、初代星質量に与える不定性を整理せよ。②また、将来どのような観測を行えばこの不定性を制限することができるか検討せよ」

“**The mass of the first star (or its initial mass function IMF)** is an important parameter that influences galaxy formation in the early universe. (1) Investigate the physical process whose influence is unclear in the formation process of the first star, and summarize the indeterminacy on the mass of the first star. (2) Also, consider what kind of observations can be made in the future to limit this indeterminacy.”

Any comments and suggestions are welcome!

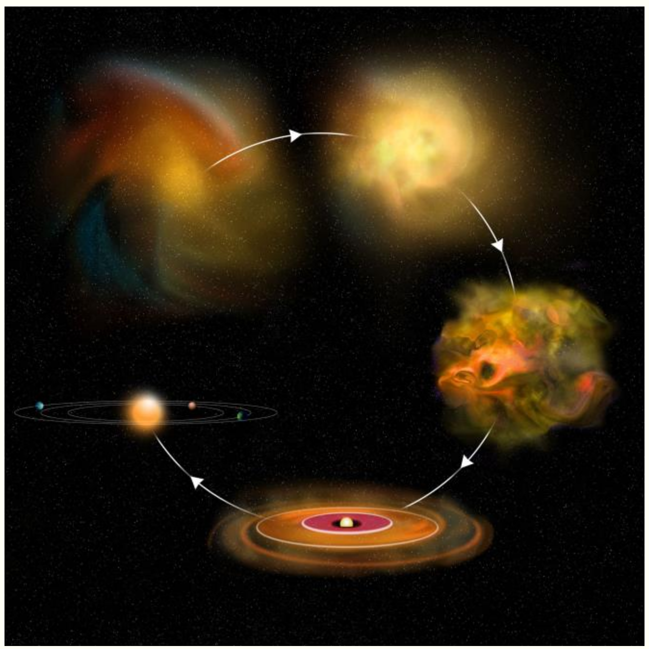
In especially, ideas related to galaxy-scale events and observations

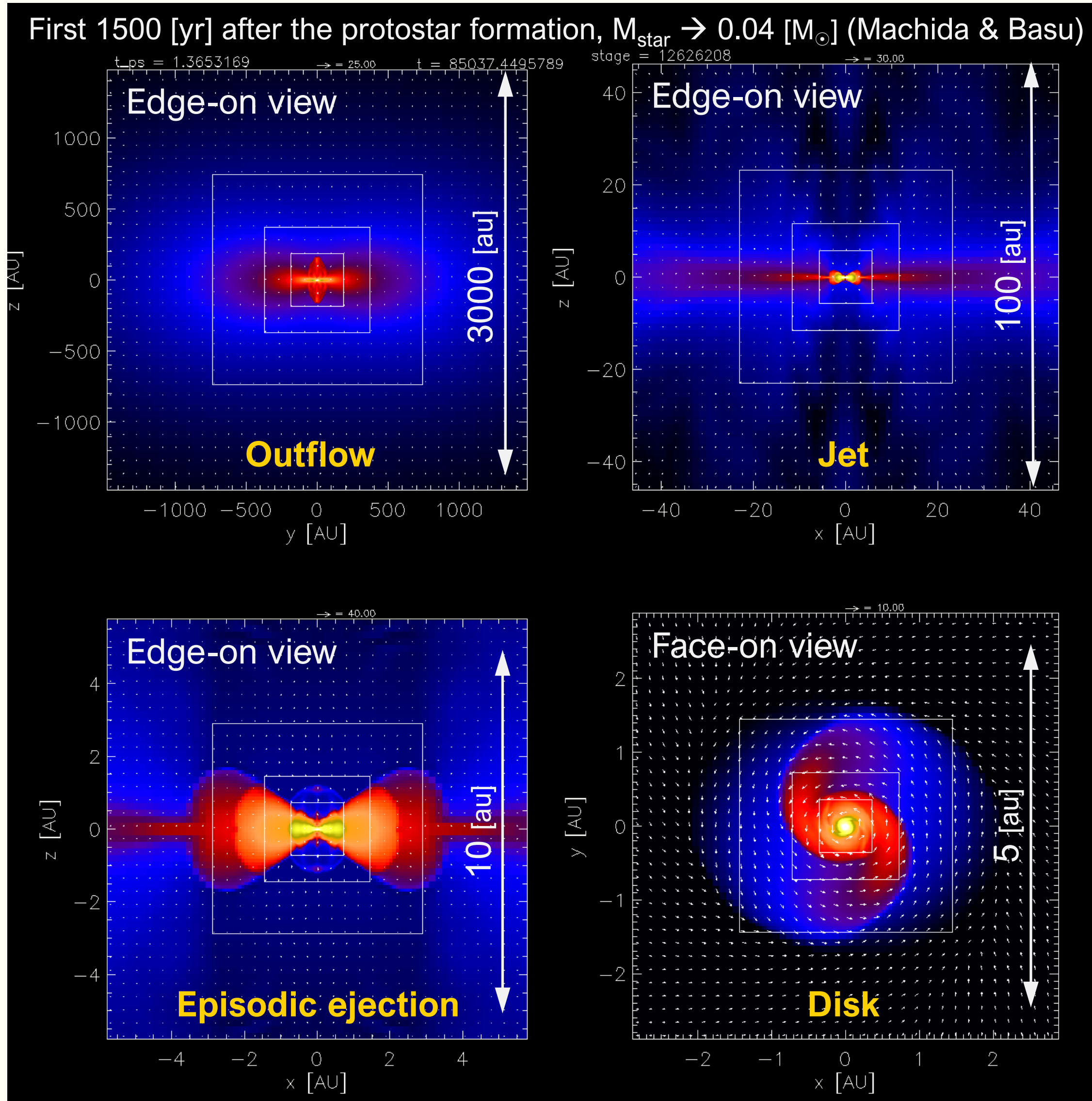
First stars in the early universe

- Mass spectrum → No obs.
- Star formation process → No obs.

(i.e.) Pop I stars in the nearby universe

- Mass spectrum → Obs.
  (e.g., Salpeter IMF)
- Star formation process → Obs.

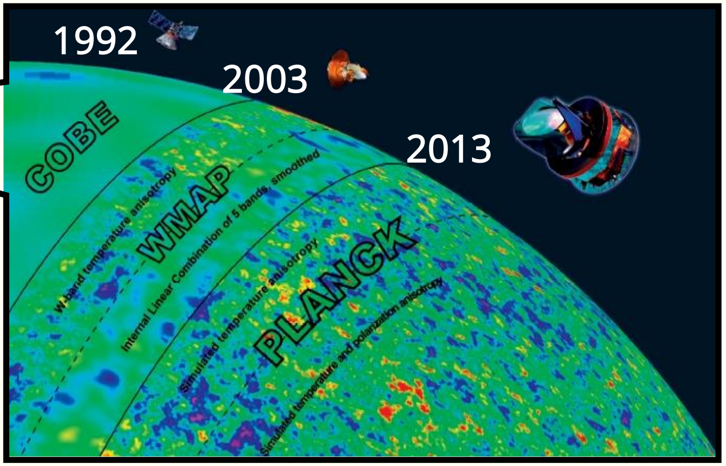




Ab initio computer modeling of the structure formation in the early universe

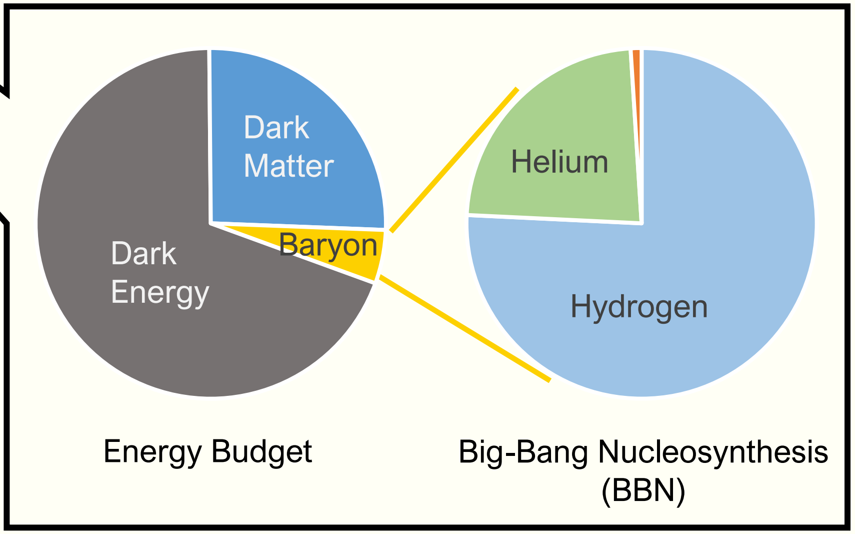
① Cosmological **initial condition** (z~1100) is given.

- Cosmic Microwave Background (CMB)
  ➔ Matter & velocity distributions
- Big-Bang nucleosynthesis
  ➔ Initial chemical abundances

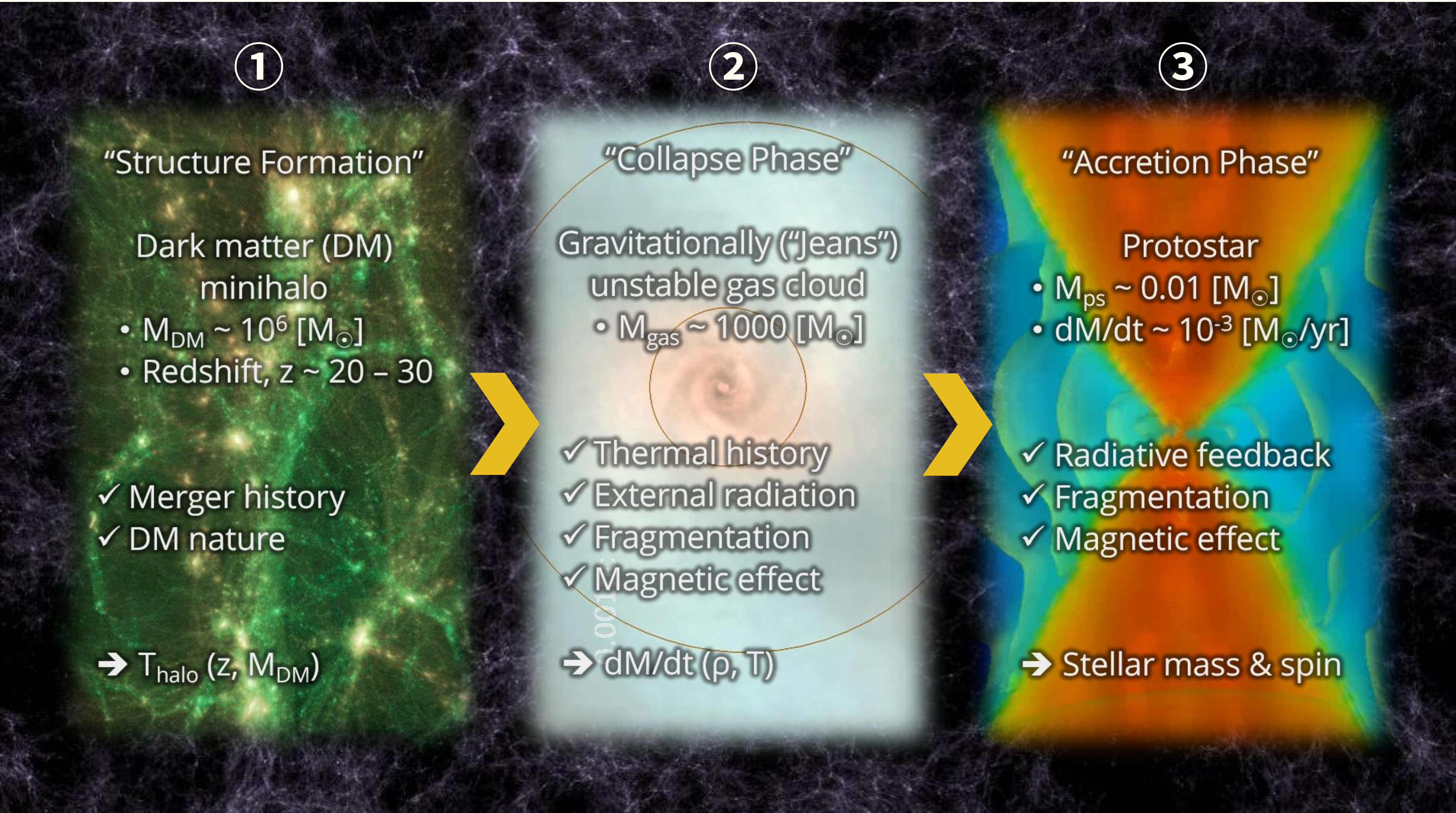


② **Physical processes** are known.

- Gravity
- (radiative-)(magneto-)hydrodynamic
- Chemical reactions

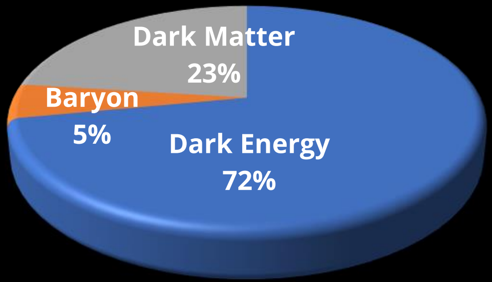


From the cosmological initial condition to the zero-age main sequence



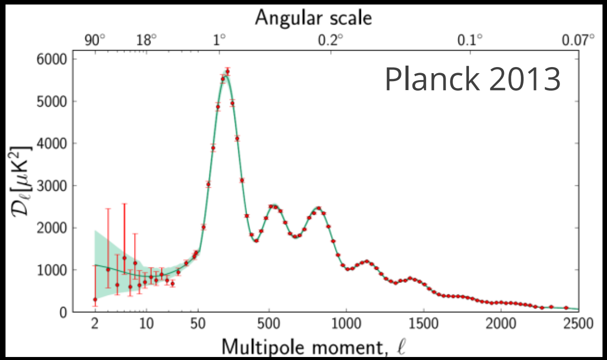
Cosmological initial condition

- Λ-Cold dark matter cosmology



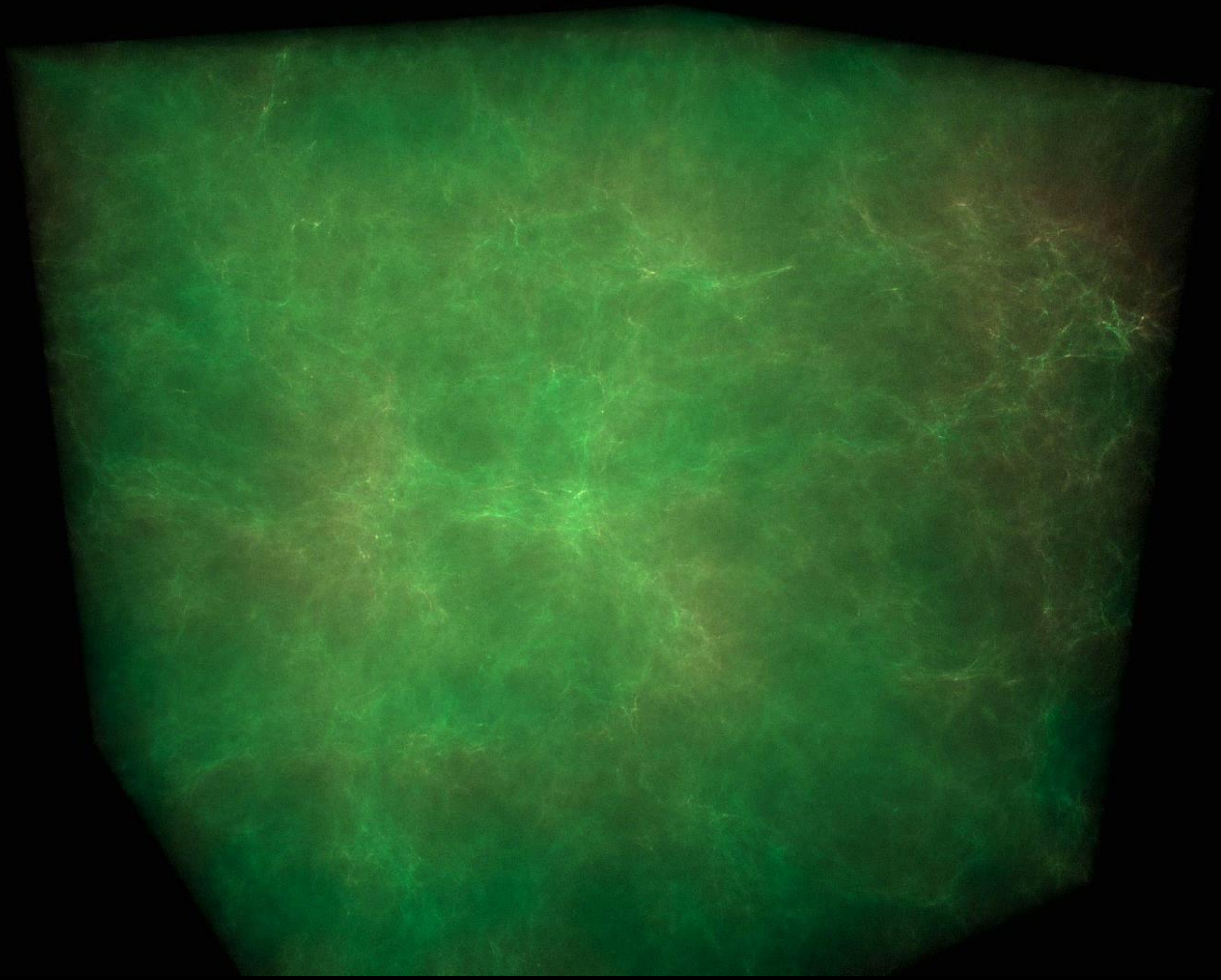
- Power spectral

→ Matter & velocity distributions



- Big-Bang Nucleosynthesis

→ Chemical abundance



(L_{box} = 1 cMpc/h)

Dark matter (mini)halo … Formation cite of the first stars

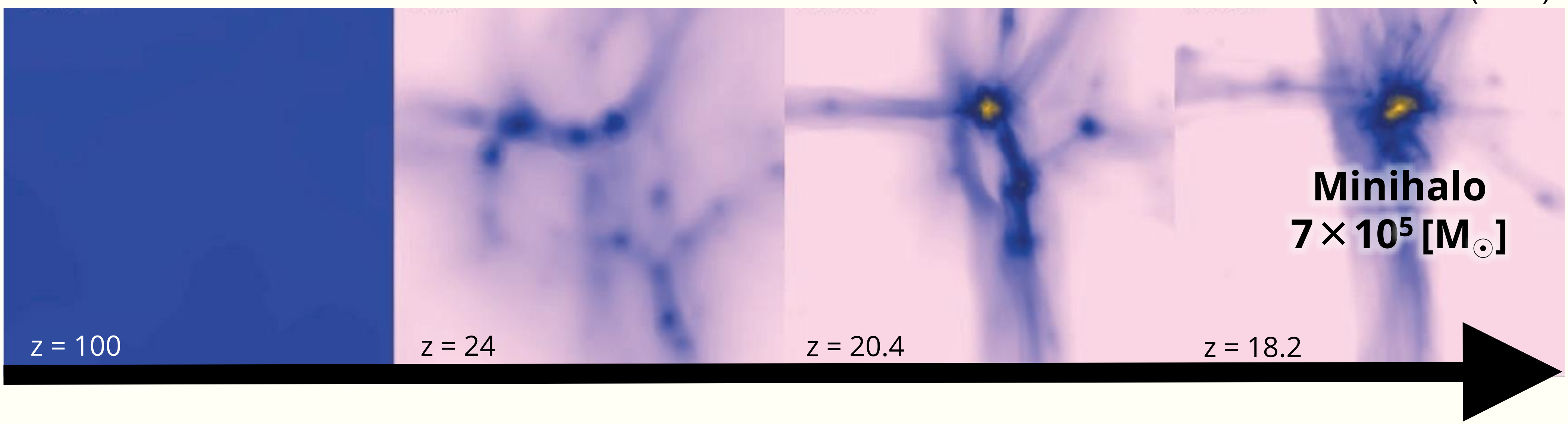
with 10^5 – 10^6 [$M_\odot$] at z = 20 – 30

Critical halo mass … Minimum mass to trigger the first star formation

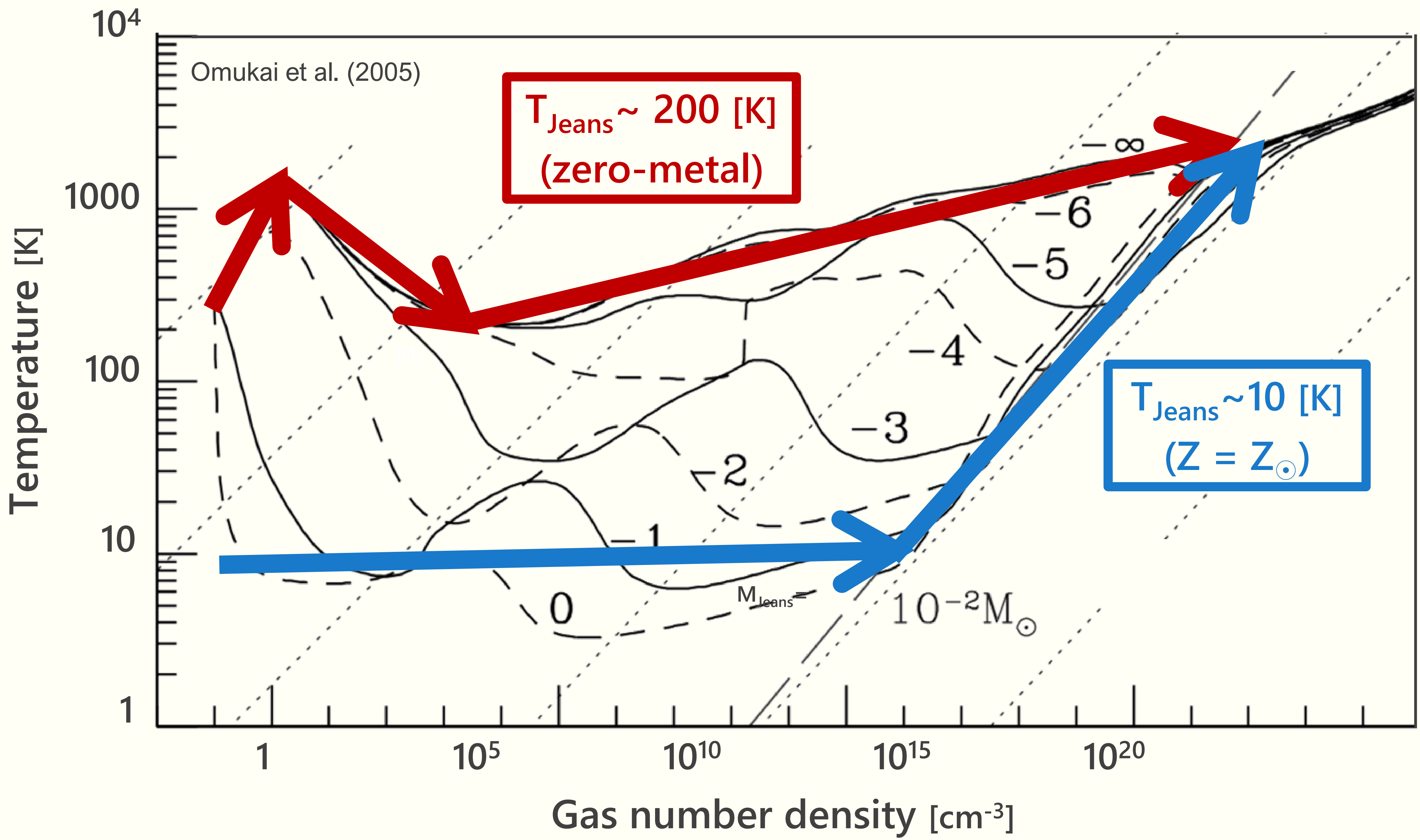
※ Important parameter for the sub-grid model

of the semi-analytical modelling

Abel et al. (2002)



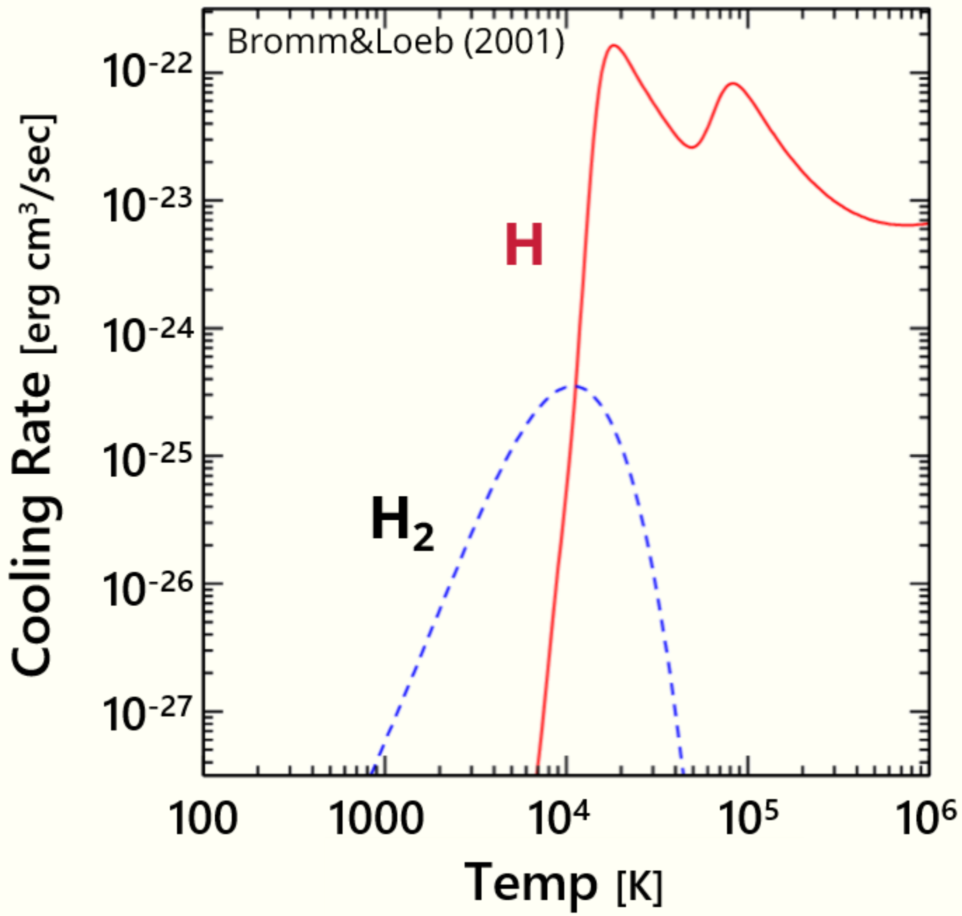
Collapse phase of the star formation

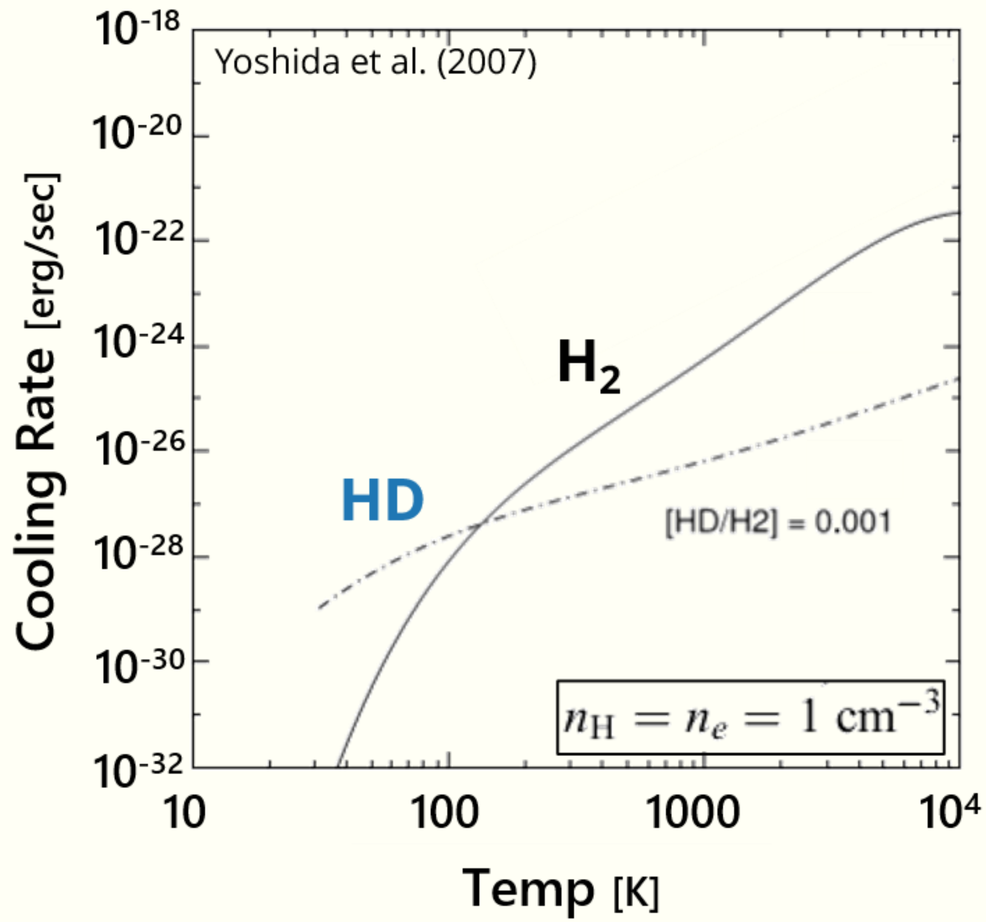


H : T_{gas} > 8000 [K] ➔ T_{gas} → 8000 [K]

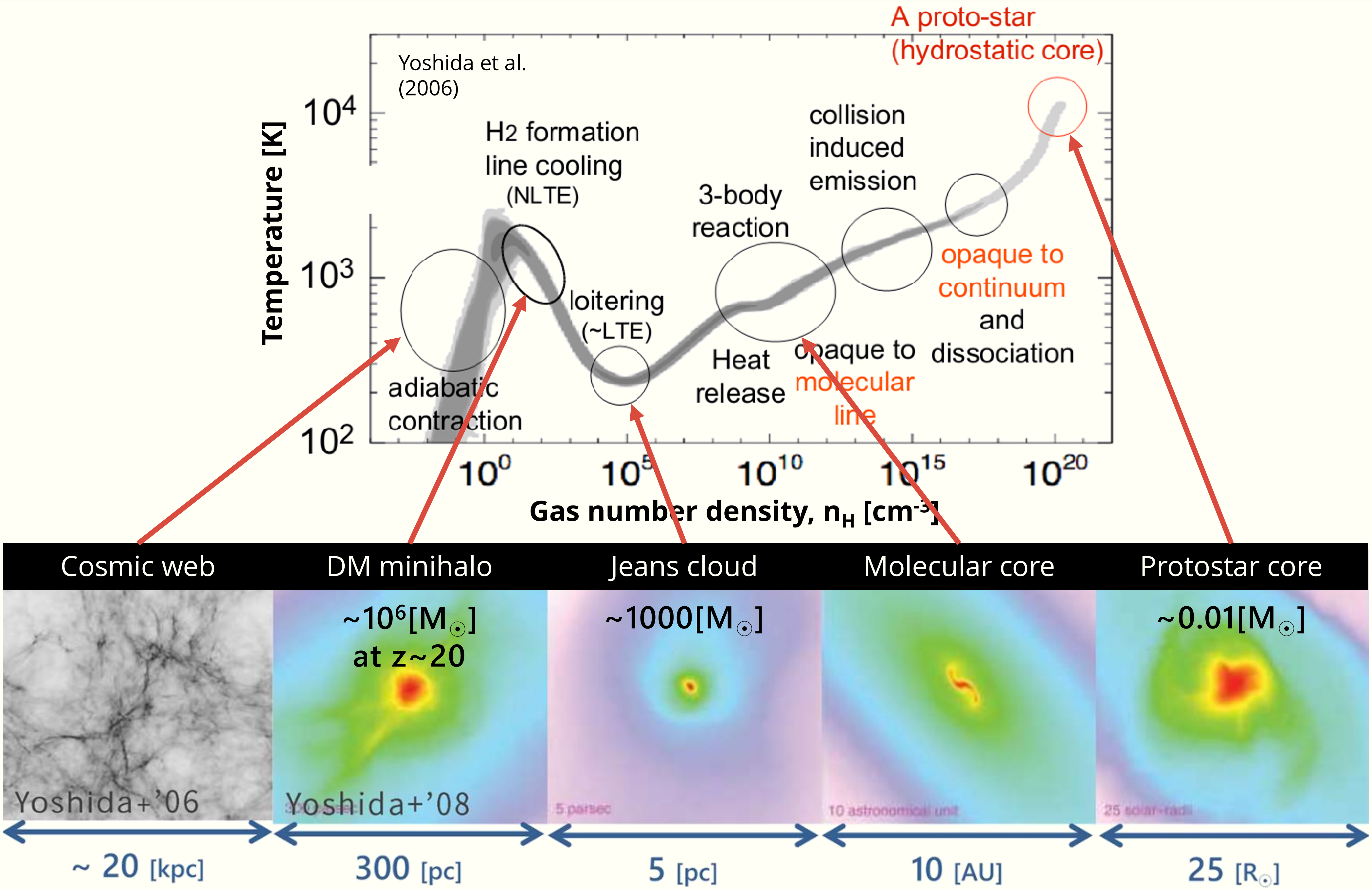
H_2 : ~ 200–1000 [K] ➔ T_{gas} → 200 [K]

HD : < 150 [K] ➔ T_{cgas} → T_{CMB} = 2.73(1+z) ~ 50 [K] (at z~20)

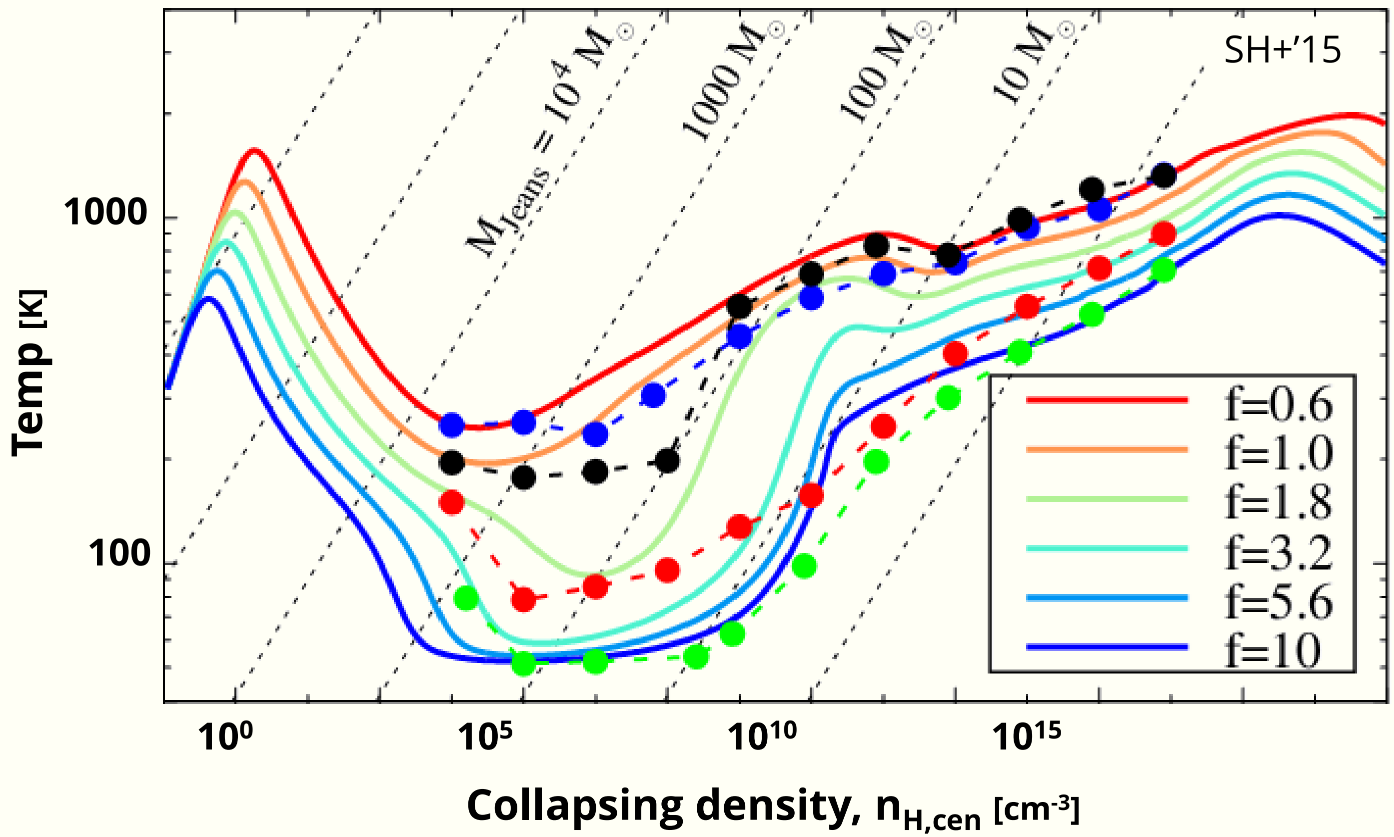




Thermal evolution of the primordial collapsing cloud



Dependence of the thermal evolution on the collapse speed



higher $M_{\rm cloud}$ & lower $v_{\rm rot}$

lower $M_{\rm cloud}$ & higher $v_{\rm rot}$

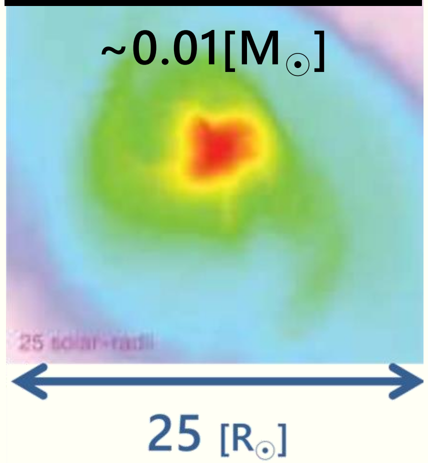
$$M_{\rm Jeans} = 1000 \left(\frac{T_{\rm Jeans}}{200\ [\mathrm{K}]}\right)^{1.5} \left(\frac{n_{\rm H}}{10^4\ [\mathrm{cm}^{-3}]}\right)^{-0.5} [\mathrm{M}_\odot]$$

$$\dot{M} \cong \frac{M_{\rm Jeans}}{t_{\rm freefall}} = 2\times 10^{-3} \left(\frac{T_{\rm Jeans}}{200\ [\mathrm{K}]}\right)^{1.5} [\mathrm{M}_\odot\ \mathrm{yr}^{-1}]$$

Final condition of the collapse phase:

- Protostar with **0.01 [M☉]**
- surrounding by the collapsing gas with **1000 [M☉]**
- which accretes with $\dot{M} \cong \frac{M_{\rm Jeans}}{t_{\rm freefall}} = 2 \times 10^{-3} \left(\frac{T_{\rm Jeans}}{200\ [\mathrm{K}]}\right)^{1.5}\ [\mathrm{M}_\odot\ \mathrm{yr}^{-1}]$

Protostar core



Accretion Phase

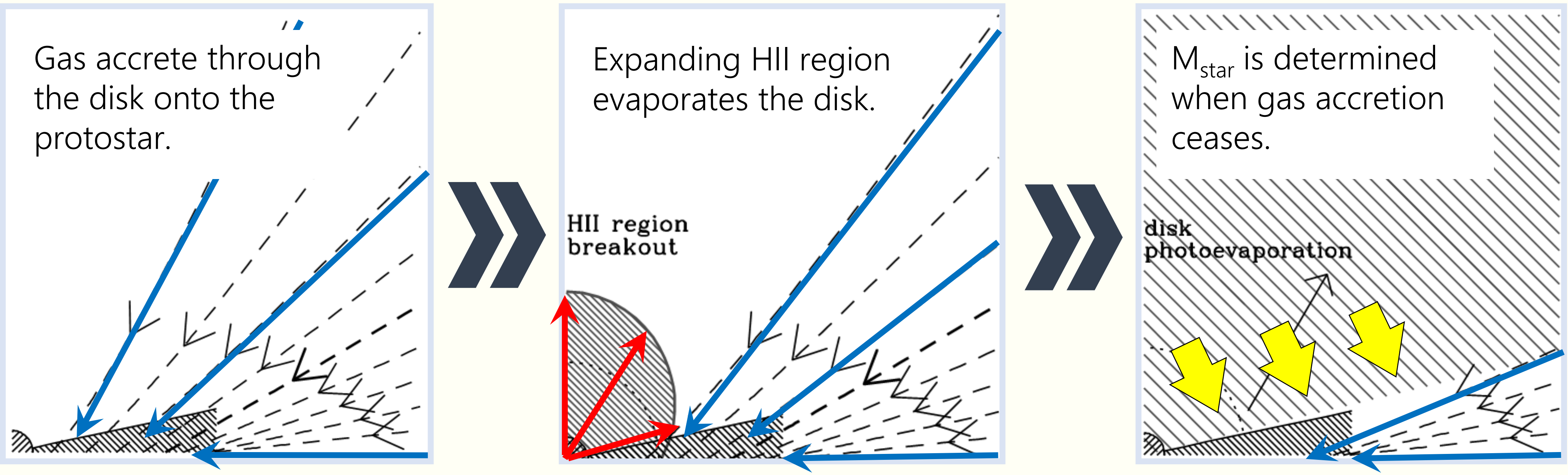
How massive can the protostar grow?

In the metal-free gas cloud,

× Radiation pressure

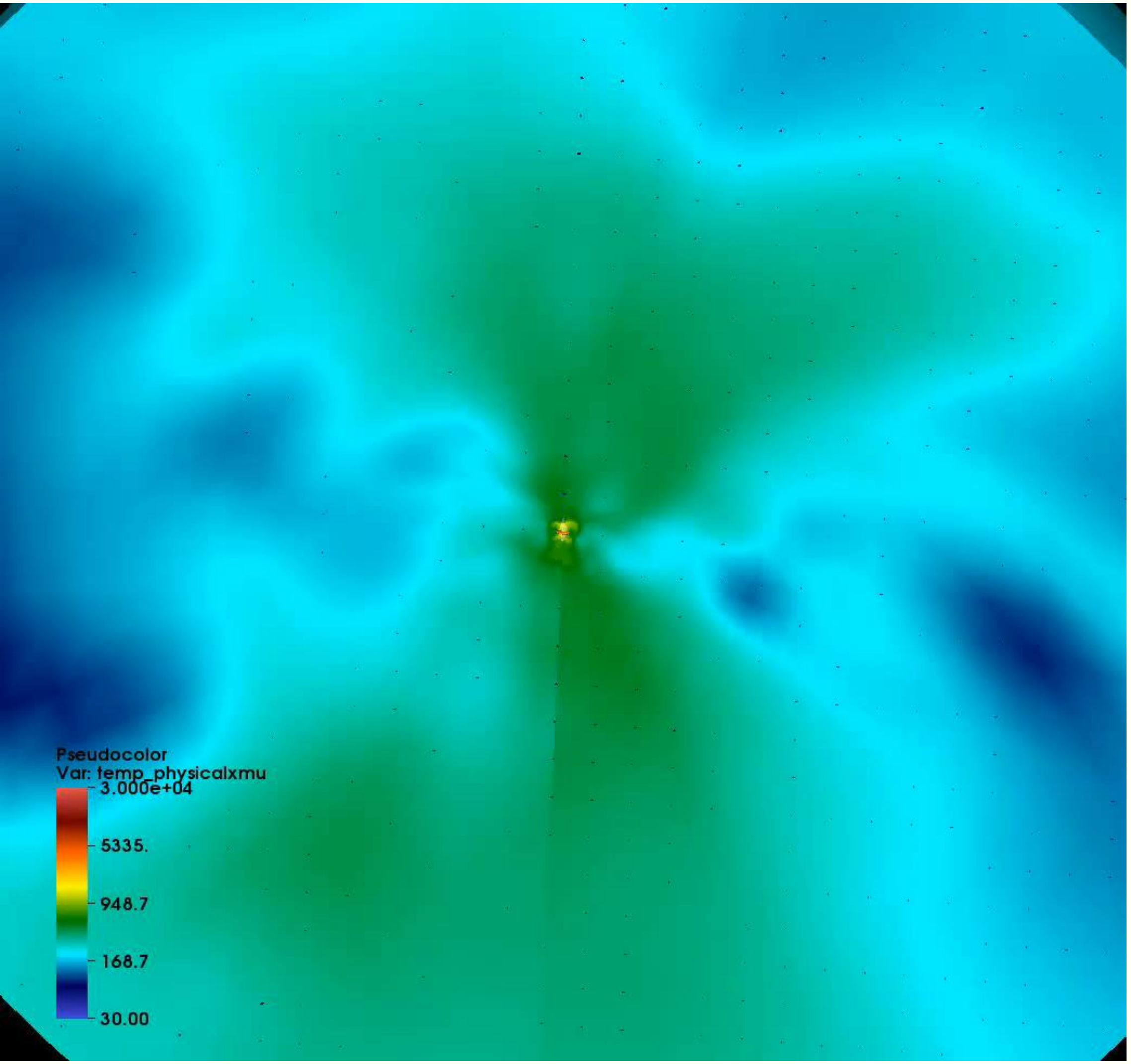
× MHD disk wind

○ **Ultra-Violet (UV) photo-evapolation** [McKee & Tan 2008]

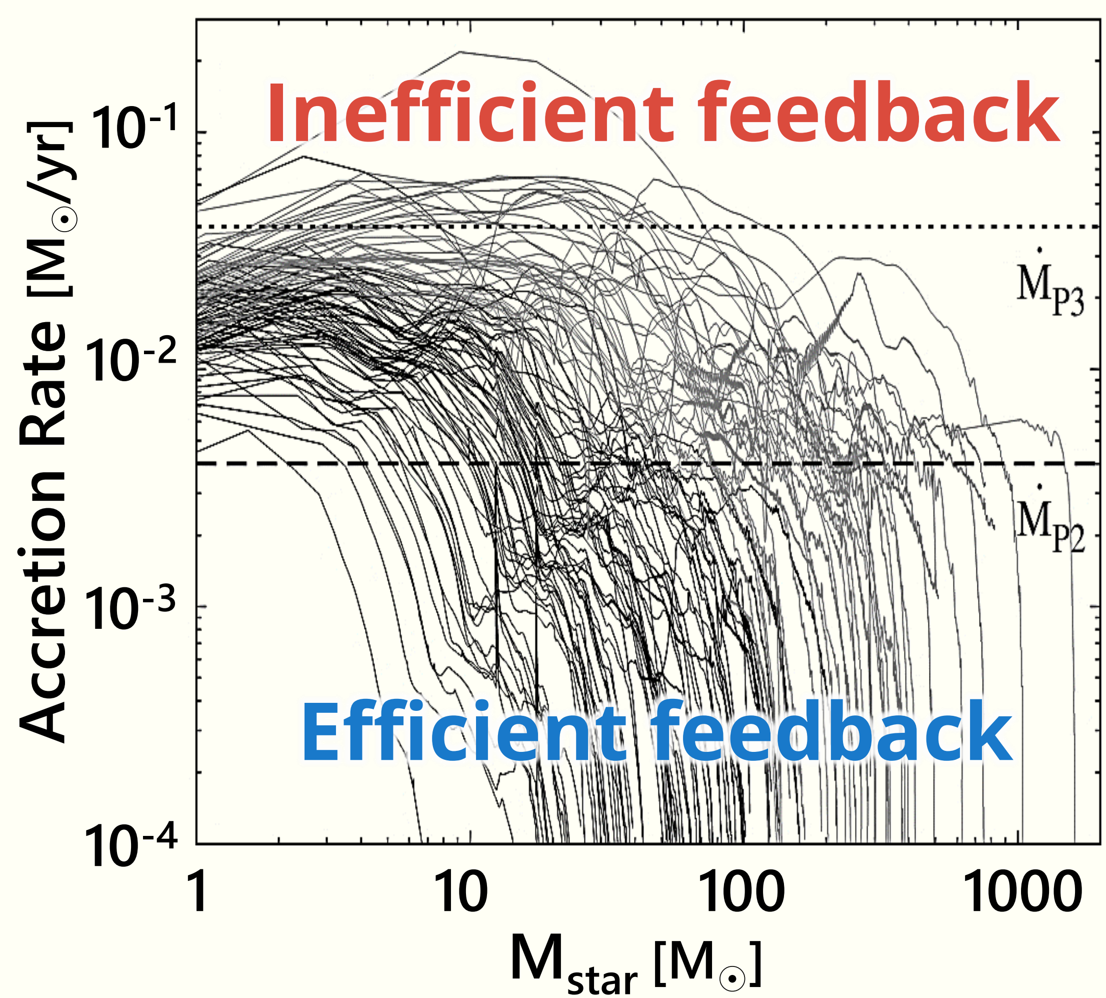


With $\dot{M} \geq 4 \times 10^{-3}$ [$M_\odot$/yr], the expanded protostar cannot emit UV photons from the low-T surface ($T_{eff} \propto R^{-2}$). ➔ UV feedback is inefficient [Omukai&Palla 2003]

Hosokawa et al. (2016)



SH+'14



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× MHD disk wind

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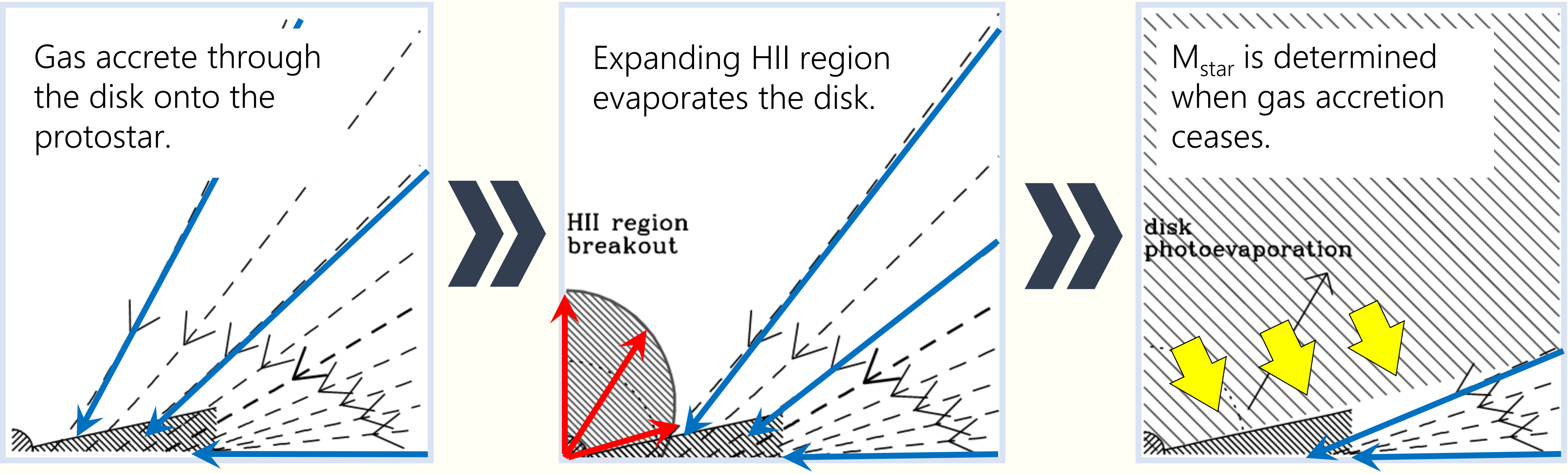

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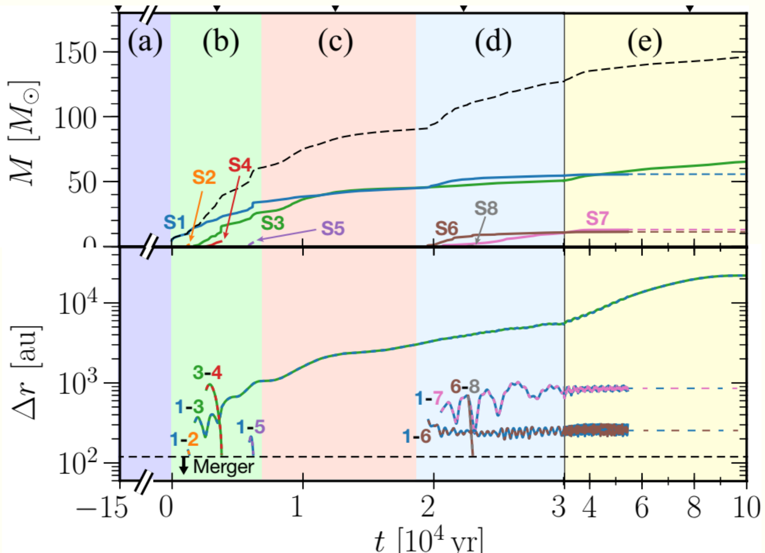
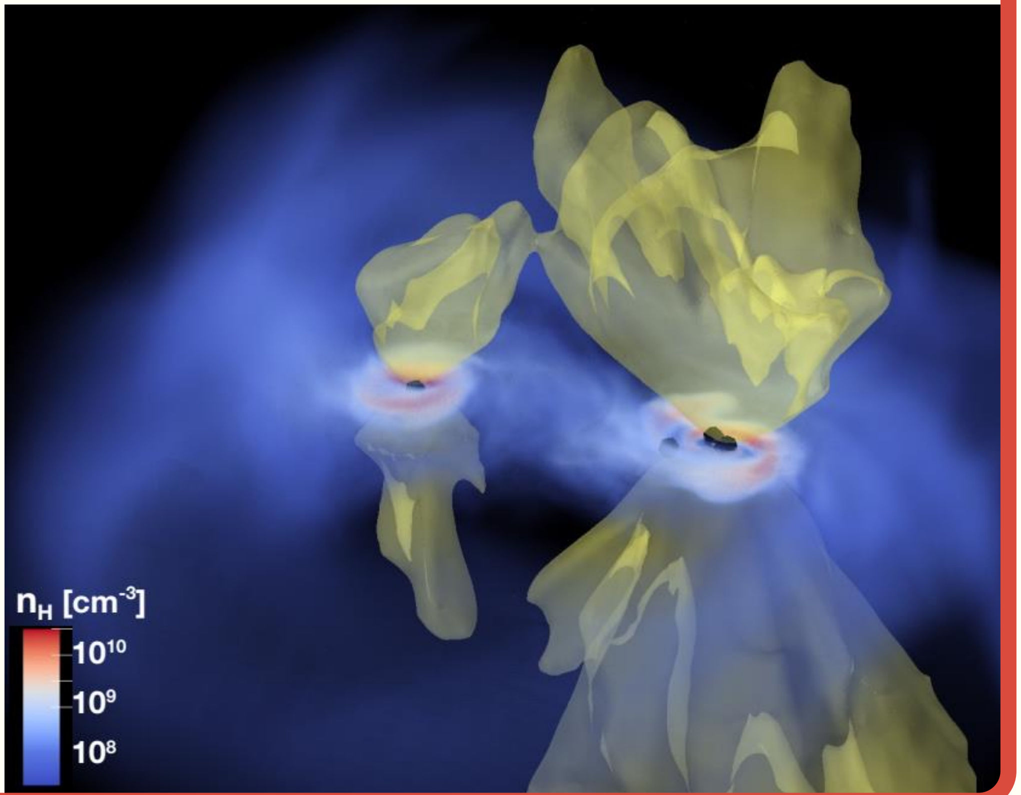
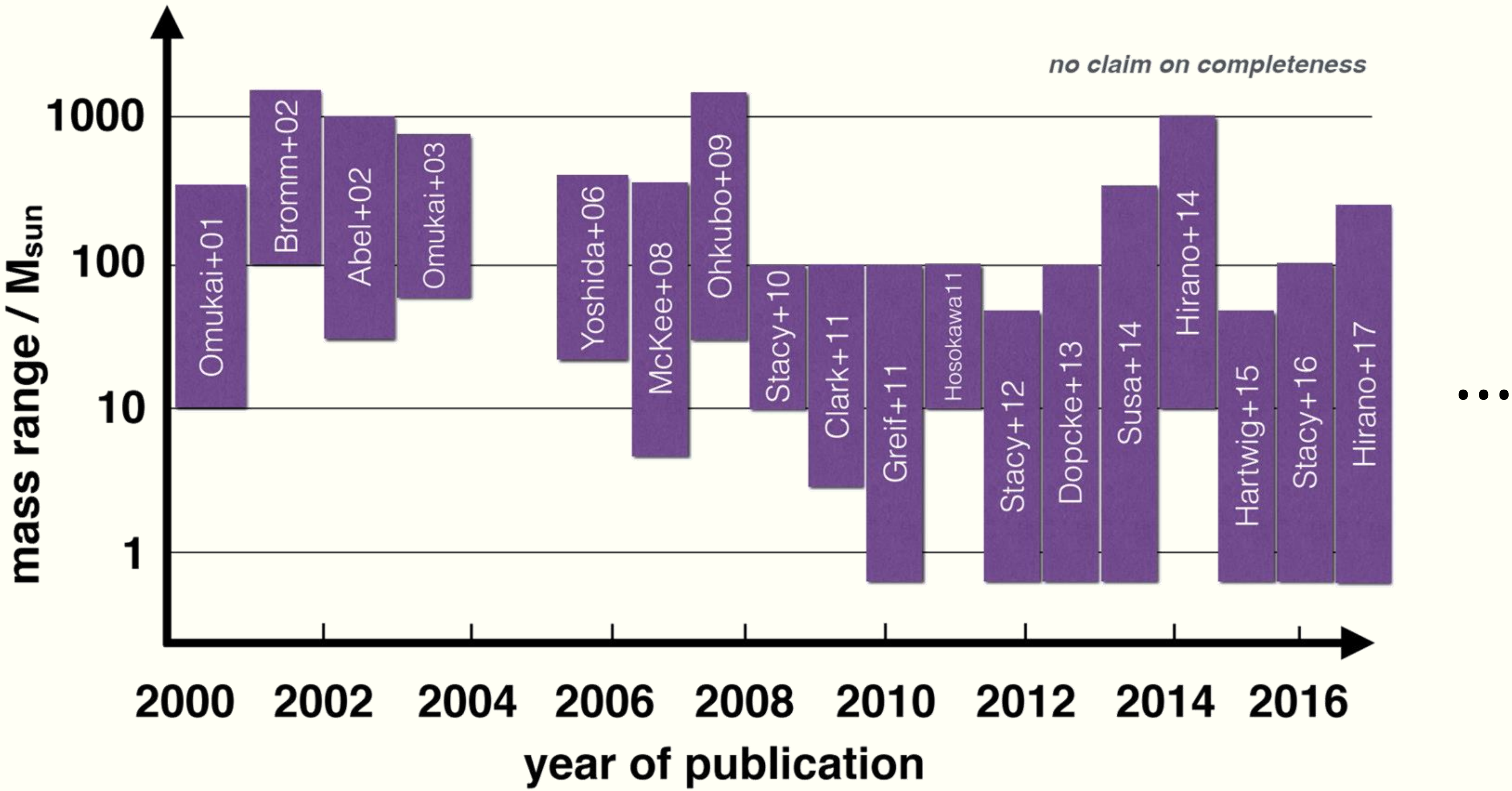
① Cosmological simulation → 10^5 – 10^6 [$M_\odot$] host DM minihalo at z = 20 – 30
② Collapse phase → 0.01 [$M_\odot$] protostar surrounding by 1000 [$M_\odot$] gas cloud
③ Accretion phase → radiative feedback determined the stellar mass ~100 [$M_\odot$]

e.g., Sugimura et al. (2020) *"The Birth of a Massive First-star Binary"*

Code : AMR RHD (SFUMATO-RT)
ICs : cosmological sample (SH+'14;15)
Result : 66 + 56 (+12+13) [$M_\odot$] system
orbiting at 2×10^4 [au] distance



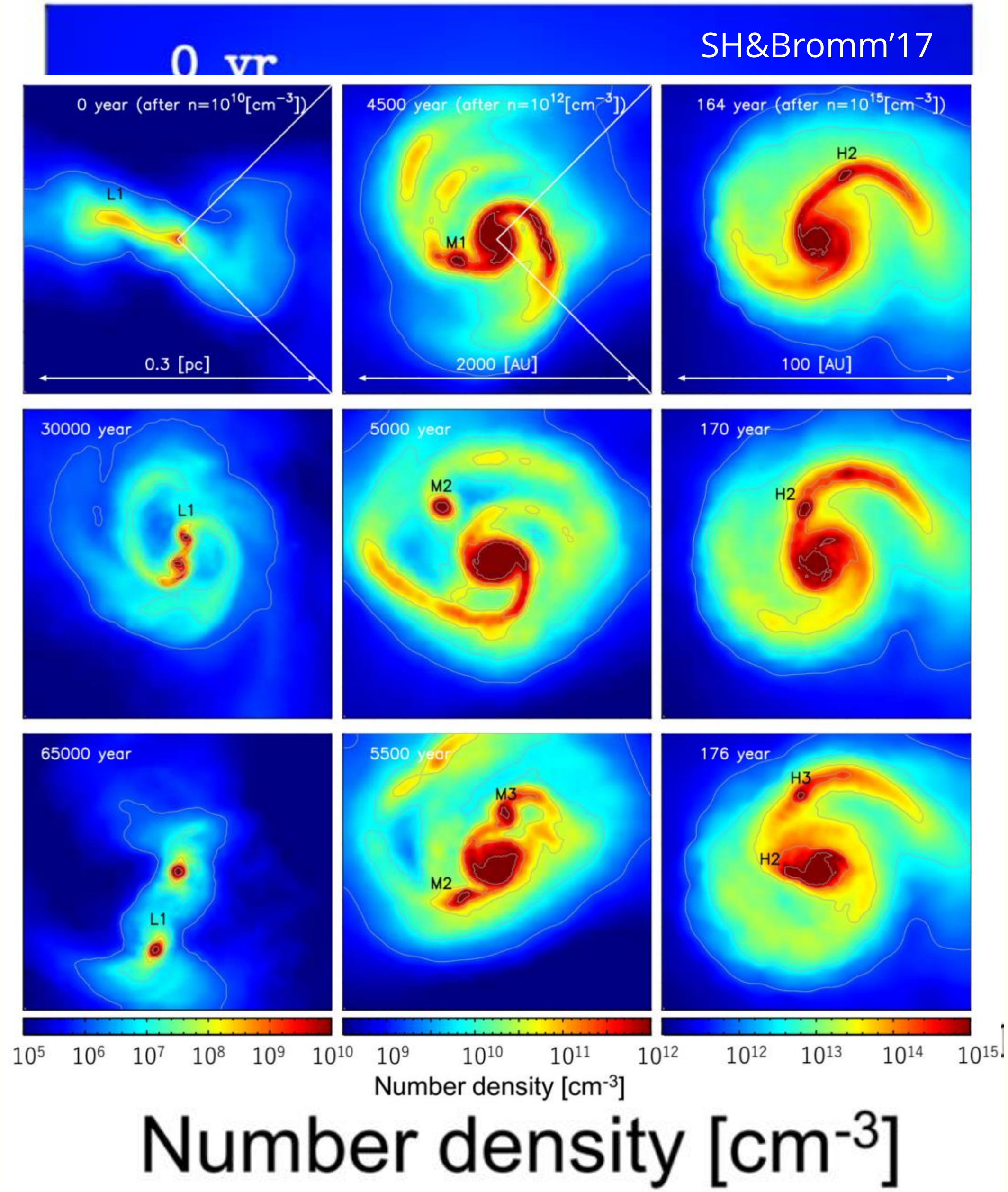



no claim on completeness
mass range / M_{sun}
1000
100
10
1
Omukai+01
Bromm+02
Abel+02
Omukai+03
Yoshida+06
McKee+08
Ohkubo+09
Stacy+10
Clark+11
Greif+11
Hosokawa11
Stacy+12
Dopcke+13
Susa+14
Hirano+14
Hartwig+15
Stacy+16
Hirano+17
2000
2002
2004
2006
2008
2010
2012
2014
2016
year of publication
...

Fate of fragments
(1) Merge → accretion burst
(2) Survive → binary/multiple
(3) Escape → low-mass first stars

To study the final mass spectrum, long-term (~0.1 Myr) simulation with high resolution is necessary.
→ **COMPUTATIONAL COST PROBLEM**

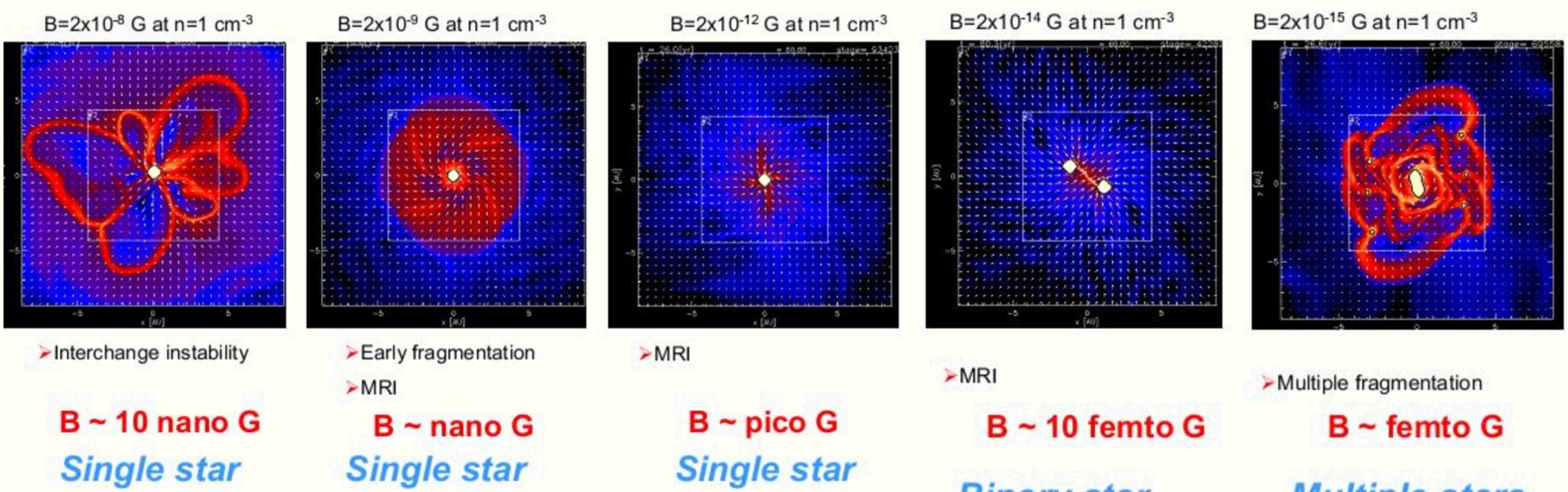
Simplification: sink, adiabatic EOS



Angular momentum transfer from the star-forming cloud via the magnetic freezing and outflow/jet

➔ Accretion rate increases, rotational disk diminish, fragmentation become suppressed, binary separation decreases, stellar spin decreases

➔ Totally, first star forms with higher mass and lower number.

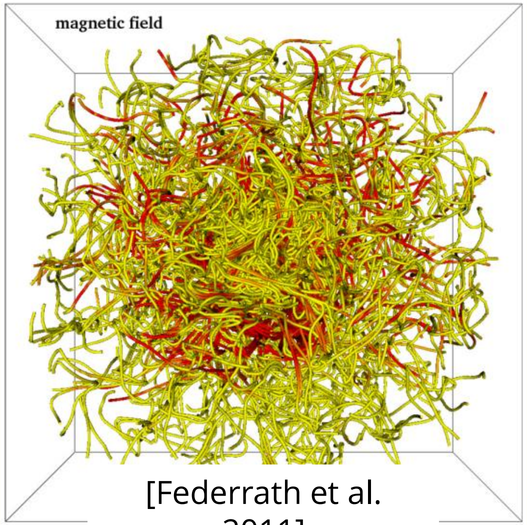


Machida&Doi13

The magnetic fields in the early Universe are **too weak** to have any dynamical impact. So **MHD effects are usually neglected**.

Small-scale turbulent dynamo can efficiently amplify the tiny seed magnetic field during the star-formation process.
[e.g., Sur et al. 2010; Turk et al. 2011; Schobar et al. 2012; Sharda et al. 2020]

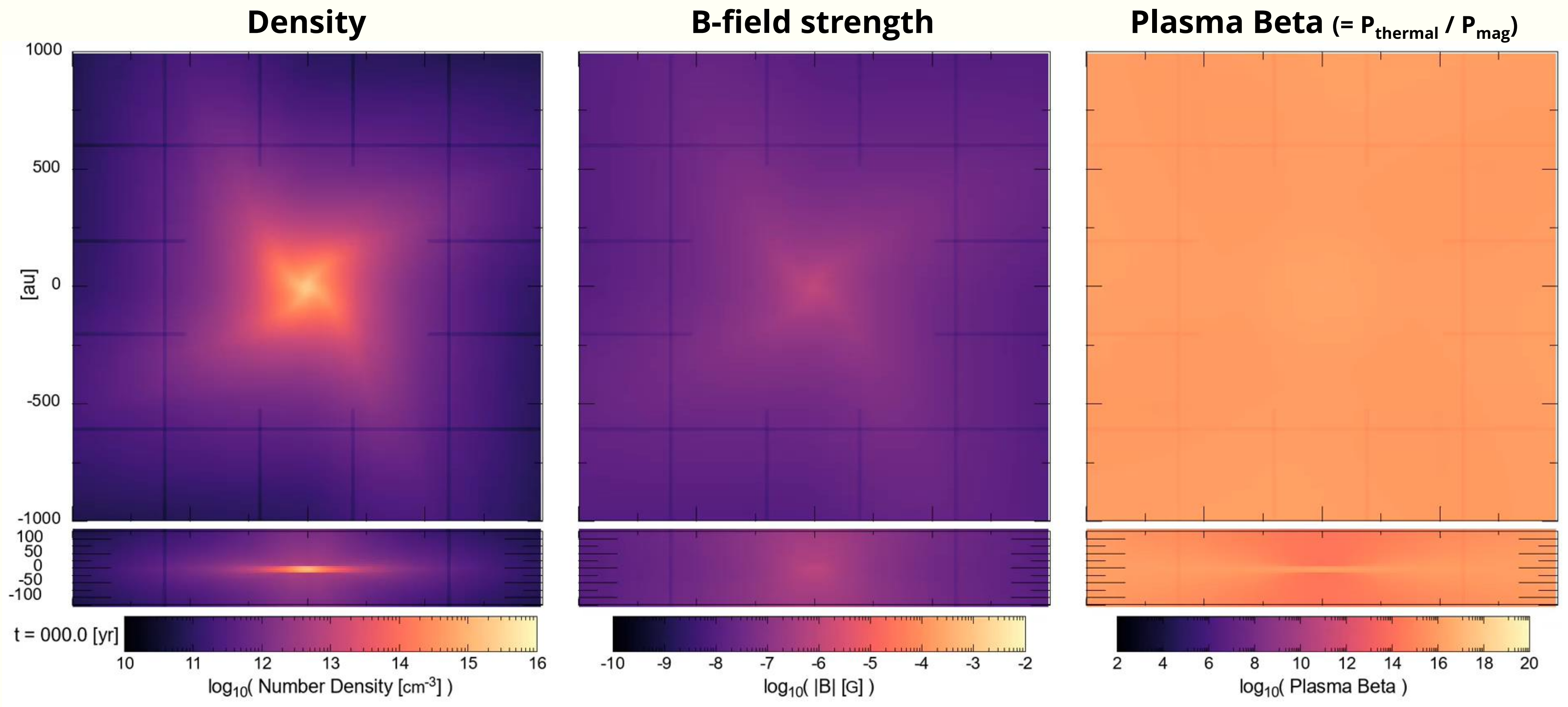
Dynamically significant magnetic fields can affect the **accretion history, fragmentation, and stellar mass**.
[e.g., Machida et al. 2008; Machida&Doi 2013; Latif et al. 2013]



[Federrath et al. 2011]

Grete et al. (2019)
Simulations of the **magnetized atomic-cooling halos** **during the collapse phase**.
They stopped all simulations when the maximum density reaches ~4.9×10^{14} [cm^{-3}].

Magnetic effects during the early accretion phase?

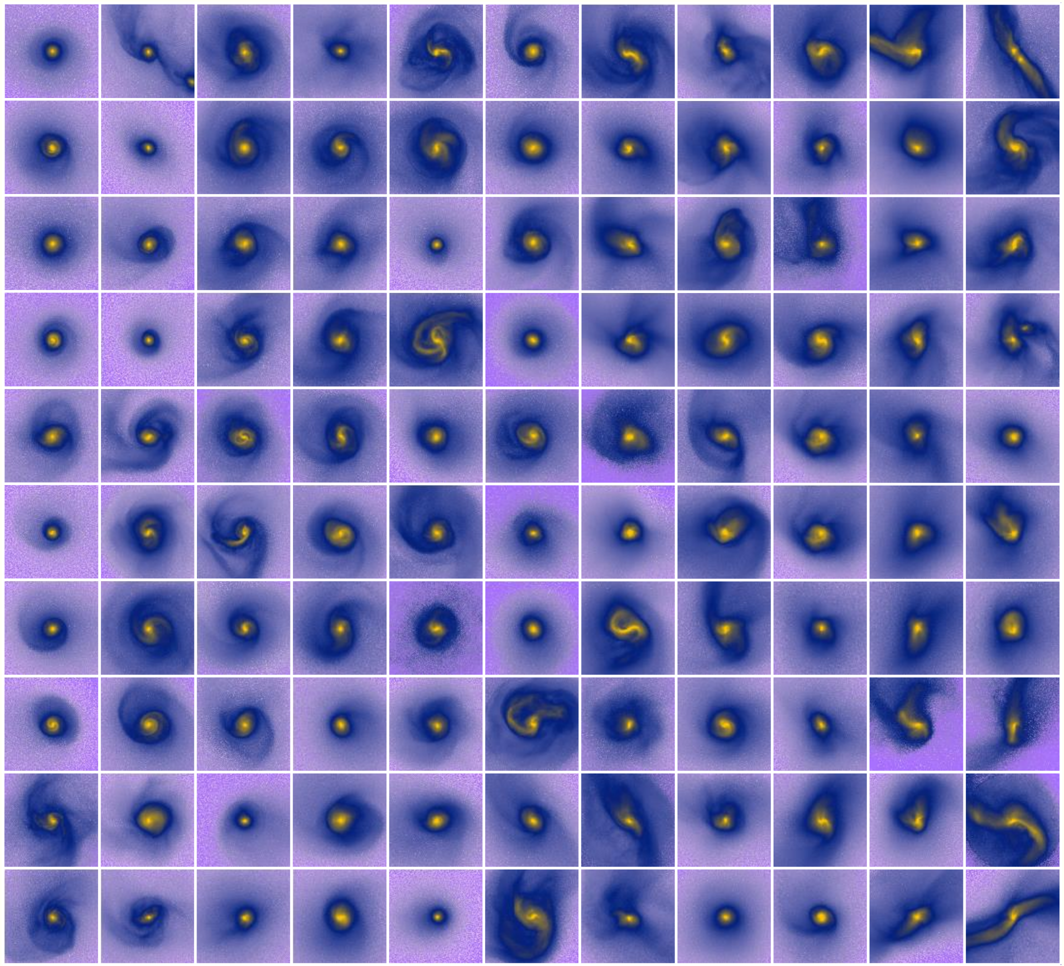


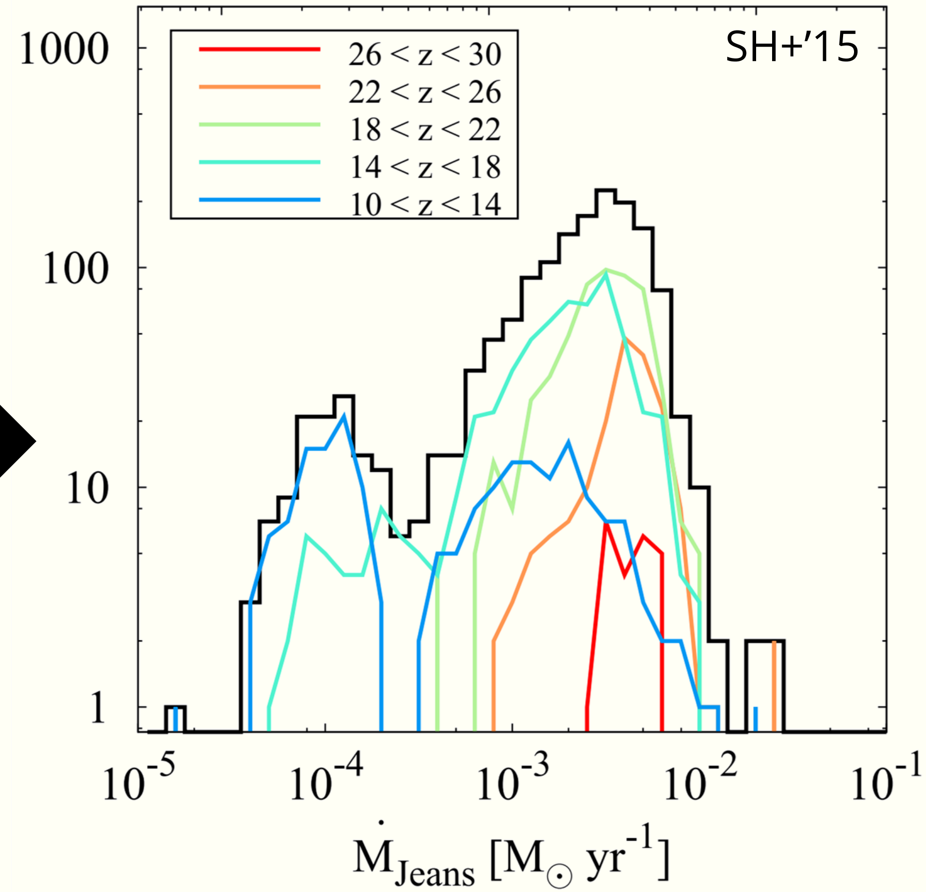
① Dense cores fragments and coalesces repeatedly.

② B-field around the dense cores quickly amplifies during the accretion phase.

③ Magnetic effects begins to affect the dynamics.

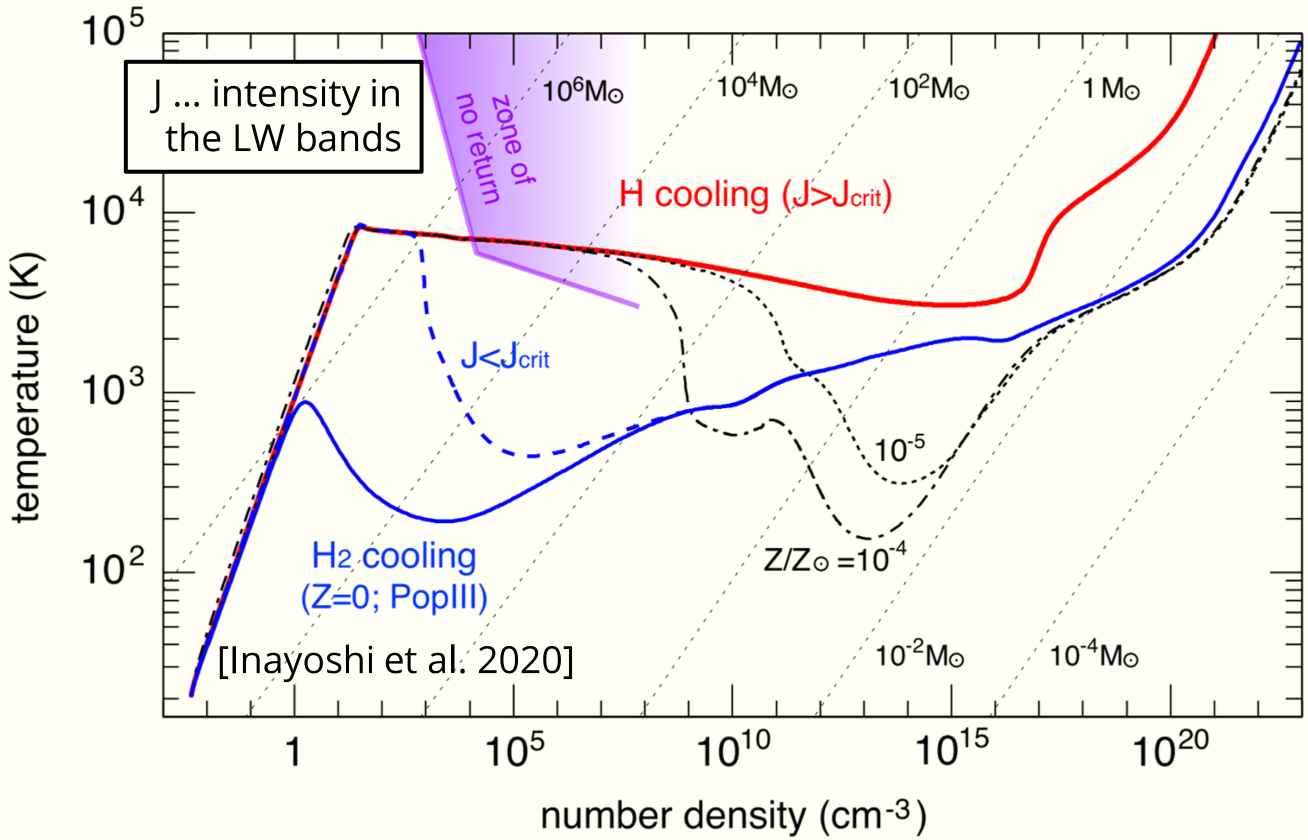
Thermal evolution depends on the cloud's properties, in especially, the mass accretion rate at the Jeans scale differs among clouds.





External radiation can change the thermal property of the cloud, which results in the different cloud mass, accretion rate, and stellar mass.

$$\dot{M} \cong \frac{M_{\mathrm{Jeans}}}{t_{\mathrm{freefall}}} = 2 \times 10^{-3} \left(\frac{T_{\mathrm{Jeans}}}{200\ [\mathrm{K}]}\right)^{1.5} [\mathrm{M}_{\odot}\ \mathrm{yr}^{-1}]$$

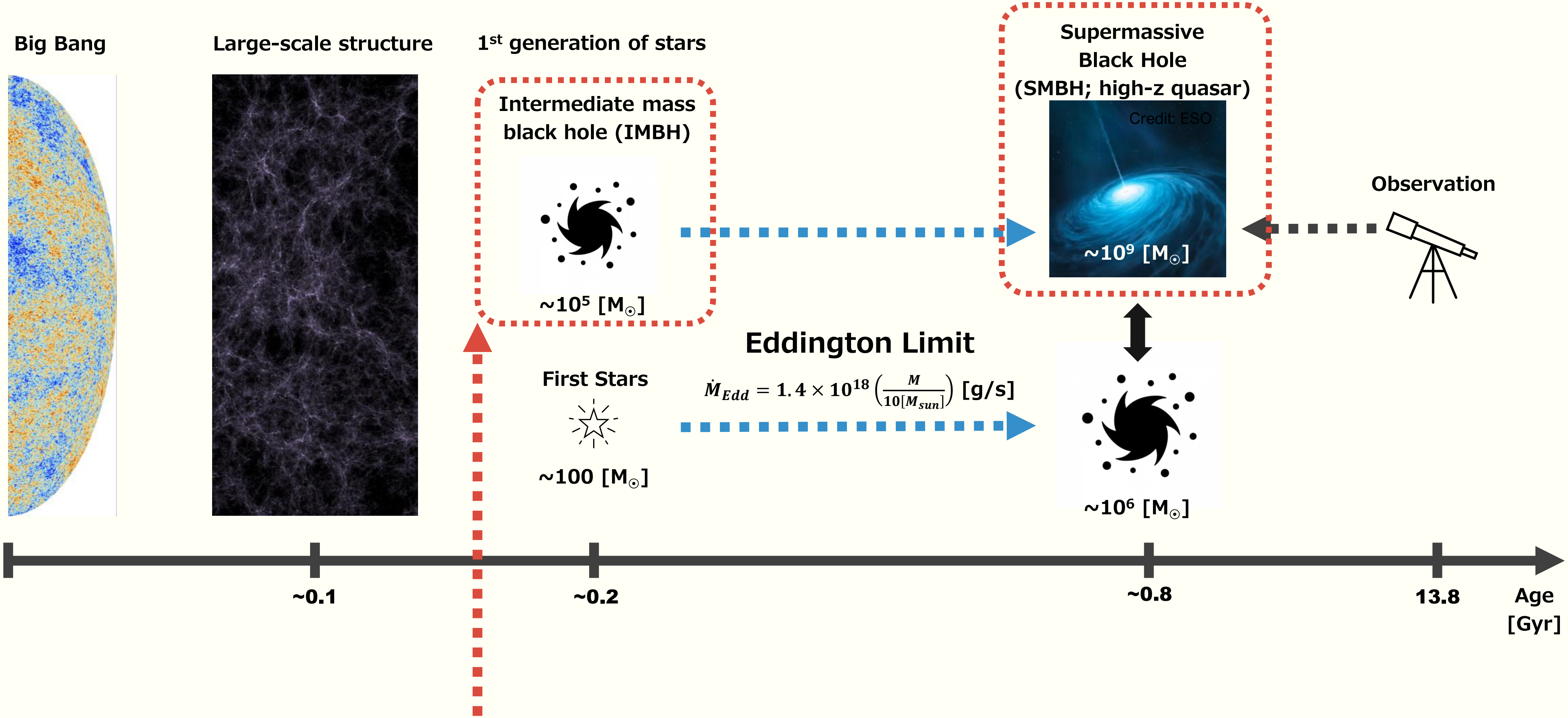


(e.g.) H_2 photo-dissociation by FUV photons with 11.2 < hν/eV < 13.6 in the Lyman-Werner (LW) bands

Solomon process

$$\mathrm{H}_2 + \gamma \rightarrow \mathrm{H}_2^* \rightarrow 2\mathrm{H}$$

Atomic H cooling halo, with massive $M_{\mathrm{cloud}} = 10^5\ [M_{\odot}]$, appears with $J > J_{\mathrm{crit}}$.



Massive seed BH formation channel

Rapid collapse of chemically pristine primordial gas forms a ~10^5 [$M_\odot$] supermassive star, which collapse to a BH with a similar mass (“direct collapse black hole” scenario).

[see Woods et al. 2019; Inayoshi et al. 2020, as review]

Formation site: atomic-cooling halo

- Large accretion rate of the protostar
- Avoiding fragmentation of the gas cloud

Necessary condition for the atomic-cooling halo

- H_2 dissociating UV radiation [e.g., Omukai 2001; Latif et al. 2013]
- High-velocity collisions [Inayoshi et al. 2015]
- Baryon-DM streaming velocities [Tanaka&Li 2014; Hirano et al. 2017]
- Dynamical heating due to the violent merger [Wise et al. 2019]
- Metal-enriched halo [Omukai et al. 2008; Chon&Omukai 2020]

Formation rate of SMBH seed ⟺ **Observational rate of the high-z quasars** **about a few [Gpc^{-3}]**

First star formation process

Dark matter dominated

1. Λ-Cold Dark Matter Cosmology
2. Primordial density perturbation
3. Large-scale structure
4. Dark matter minihalo

Baryon (gas) dominated

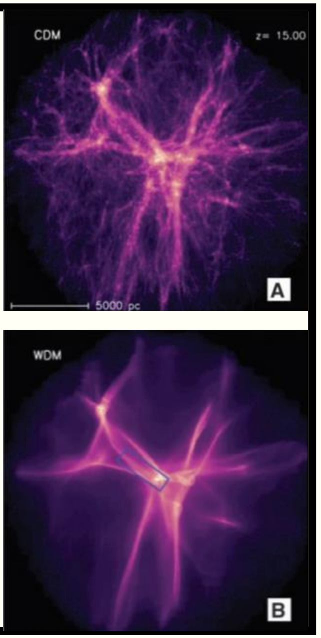
5. Molecular gas cloud
6. Tiny protostellar core
7. First Star

~ 1 [pc]
~ 10^3 [cm^{-3}]
~ 10^3 [$M_\odot$]

Λ-**Cold Dark Matter** (Λ-CDM) cosmology is basically adopted, and the DM is considered as only the gravity source.

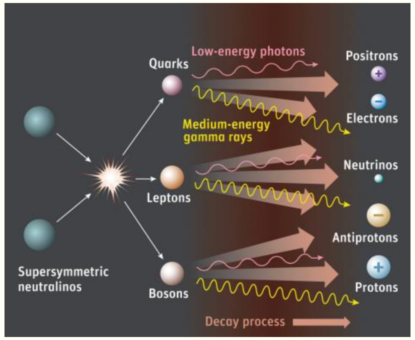
Small-scale problems associated with the Λ-CDM model: "missing satellites", "core-cusp", and "too big to fail" problems.

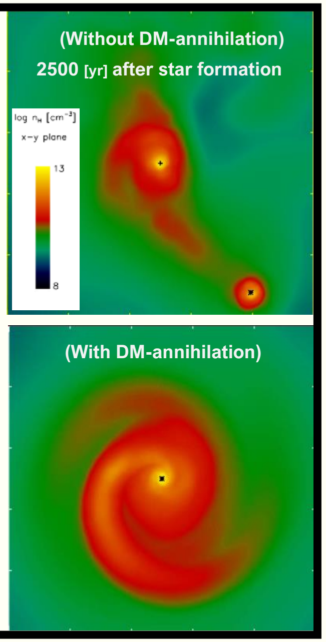
"**Warm DM** have intrinsic thermal velocities, and these motions quench the growth of structure below a free-streaming scale." (Gao & Theuns 2007)



WIMPs (Weakly Interacting Massive Particle)

- One of the most motivated CDM candidate
- Two WIMPs can self-annihilate to standard-model particles.
- The annihilation heating change the thermal evolution of the collapsing cloud.

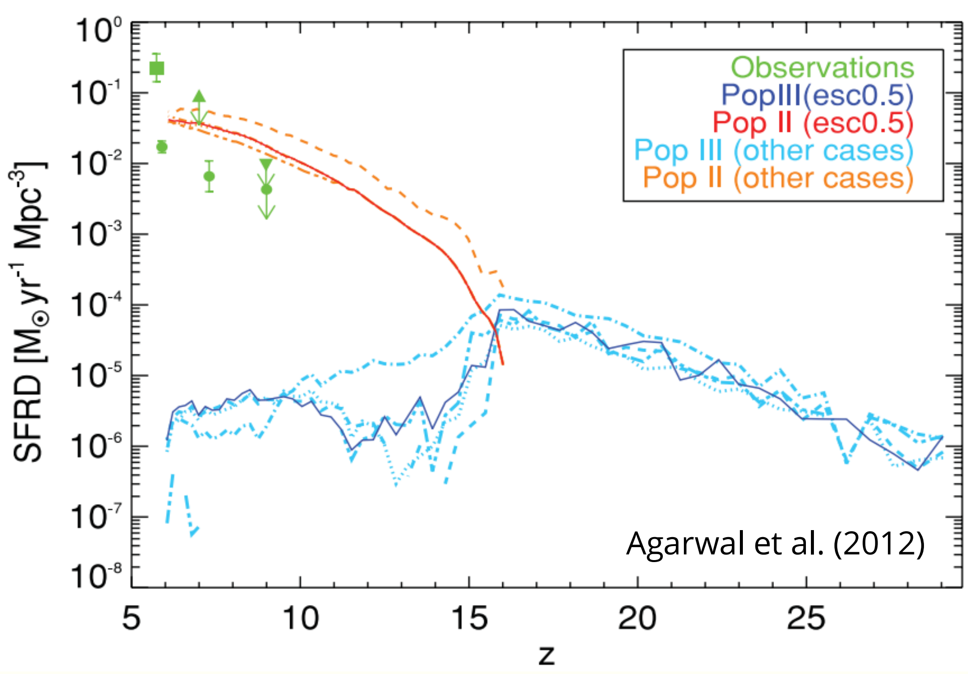




The formation process of the first stars depends on the nature of the DM.

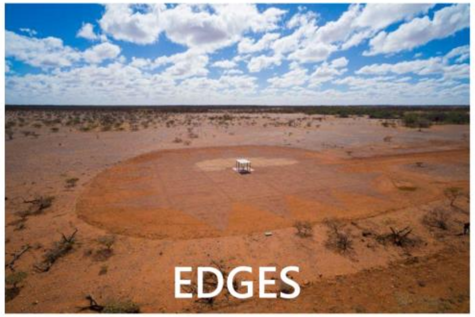
- ☐ Formation epoch
- ☐ Stellar mass

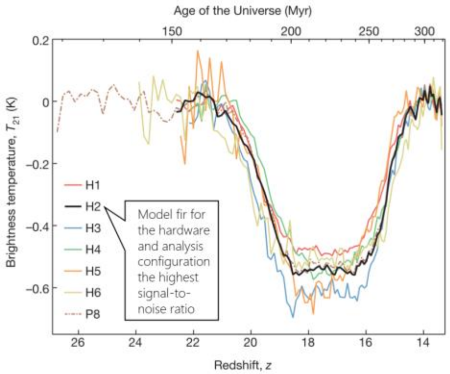
➔ These sensitivities can be used to constrain the particle nature of the DM.



By EDGES[1] (Experiment to Detect the Global Epoch of reionization Signature)

- at frequency : ν=78.1±1 [Mhz] (redshift z = 17.2)
- with brightness temperature : T_{21} = -500^{+200}_{-500} [mK]

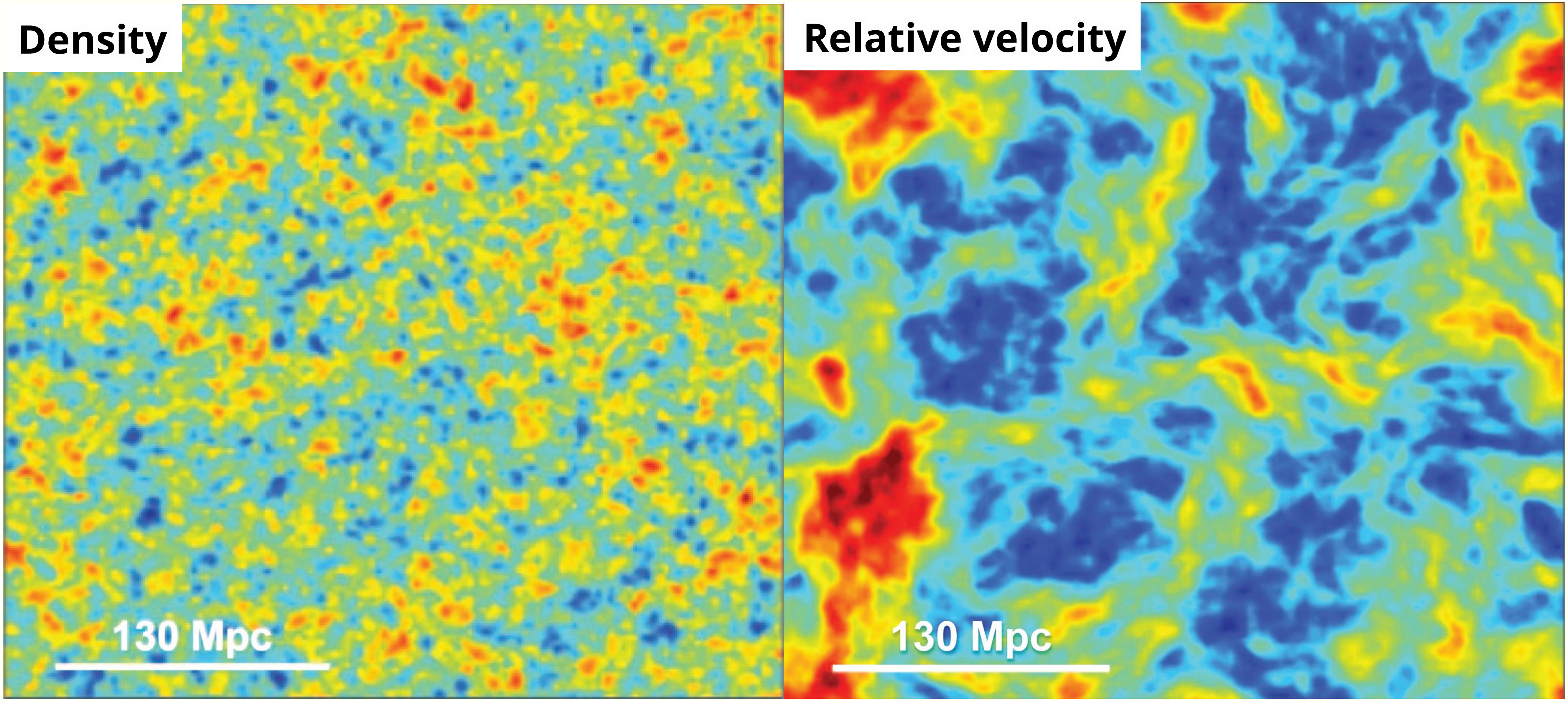




"Astronomers detect light from the Universe's first stars"
(28 Feb. 2018; Nature News)

Supersonic coherent (~ a few Mpc) flows of the baryons relative to the underlying potential wells created by DM at z_{rec} ~ 1100.

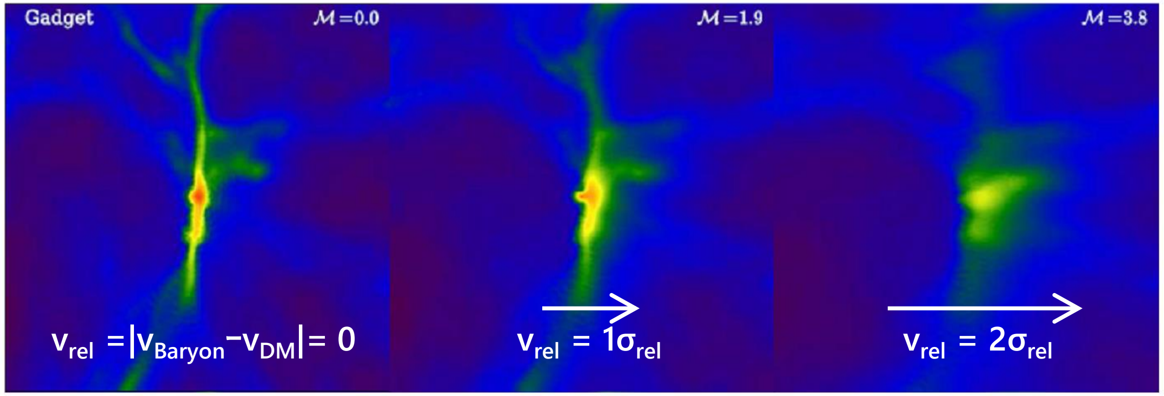
Visbal et al. (2012)



“The relative motion suppresses the early structure formation” [Tseliakhovich & Hirata 2010]

Suppression of gas condensation:

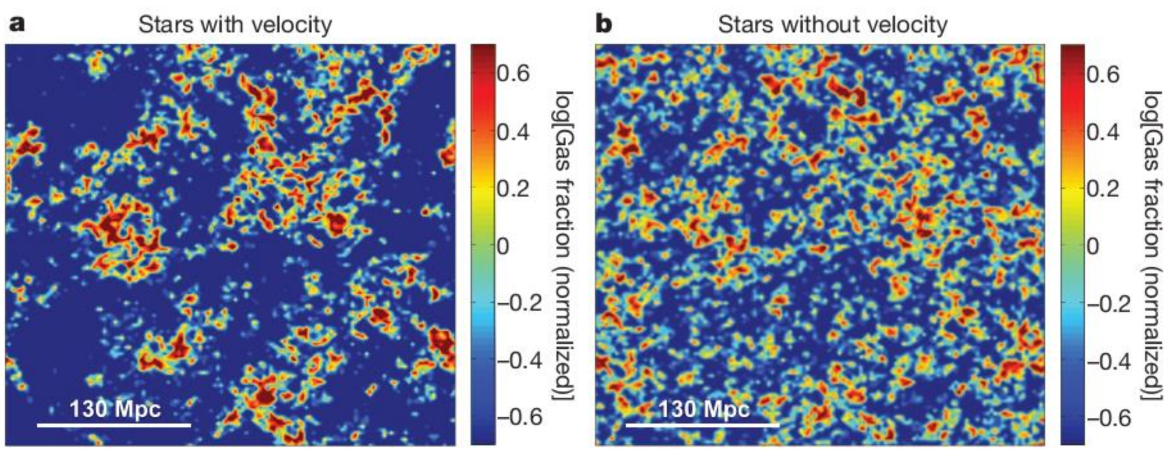
- Abundance of DM halo
- Baryon fraction
- Subsequent star formation
- Stellar/galactic feedbacks



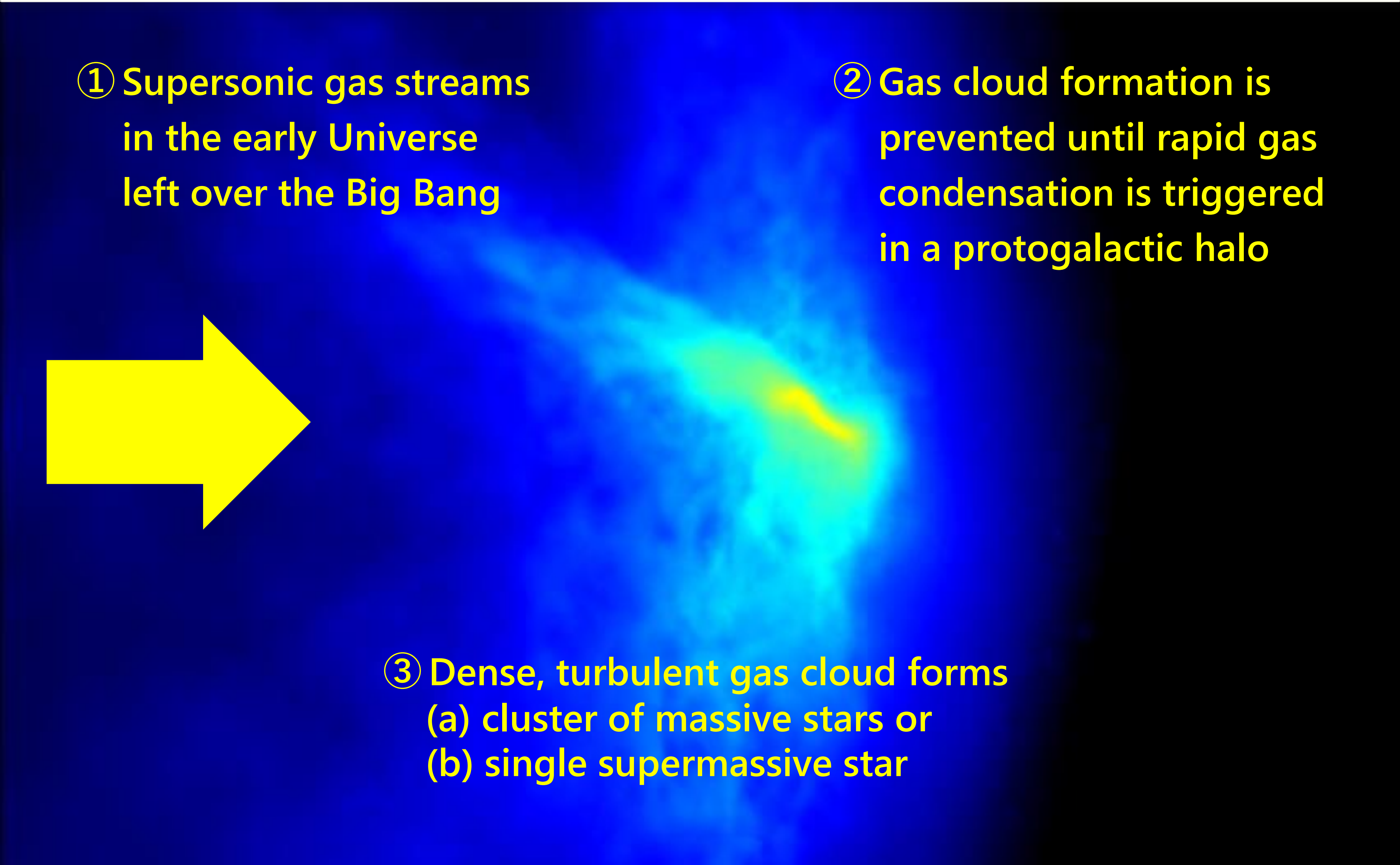
Gas density distributions of width 50 kpc/h at z=20
(O'Leary & McQuinn 2012)

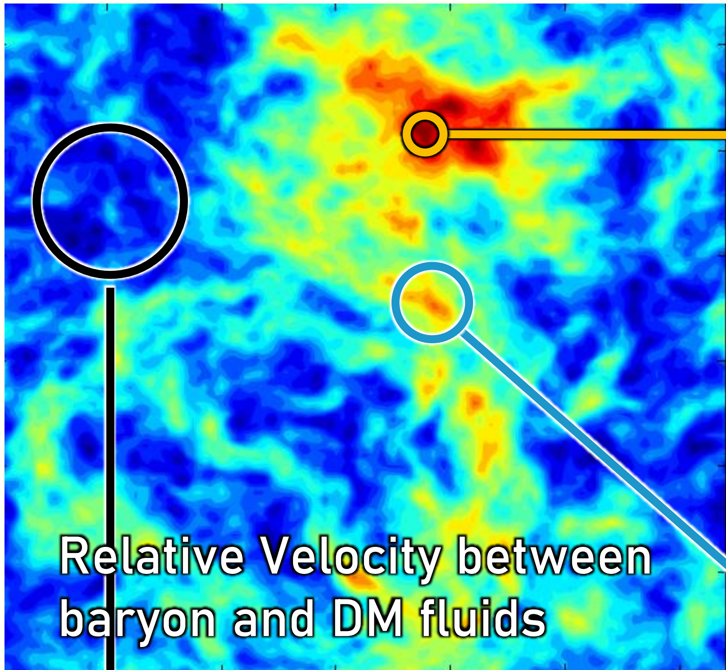
Inhomogeneous influence on large-scale structure:

- Cosmic reionization
- 21-cm intensity distribution
- B-mode polarization of CMB
- Missing satellite problem

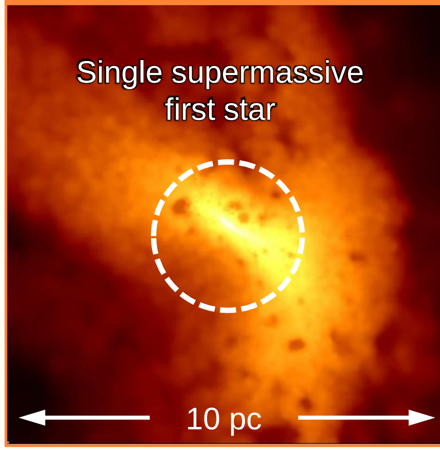


Gas fraction in star-forming halos at z=40
(Visbal et al. 2012)


① Supersonic gas streams
in the early Universe
left over the Big Bang
② Gas cloud formation is
prevented until rapid gas
condensation is triggered
in a protogalactic halo
③ Dense, turbulent gas cloud forms
(a) cluster of massive stars or
(b) single supermassive star



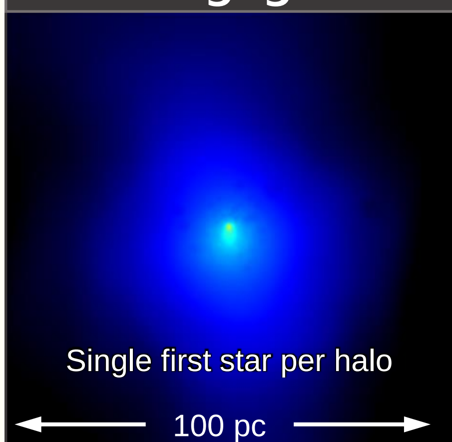
Rapid Relative Vel.



10^4-10^5[$M_\odot$] Pop III star at z~30

Seed of high-z quasars with 10^9[$M_\odot$] at z>7

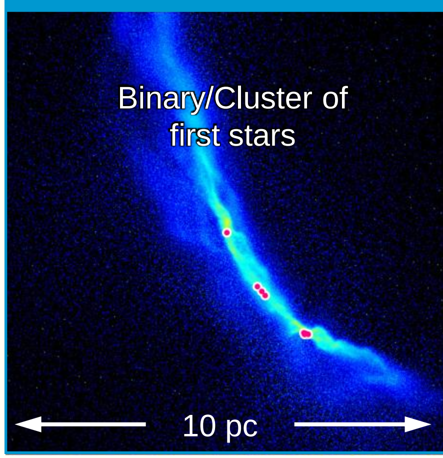
Negligible Relative Vel.



Pop III stars with ~100 [$M_\odot$] around z~15-25

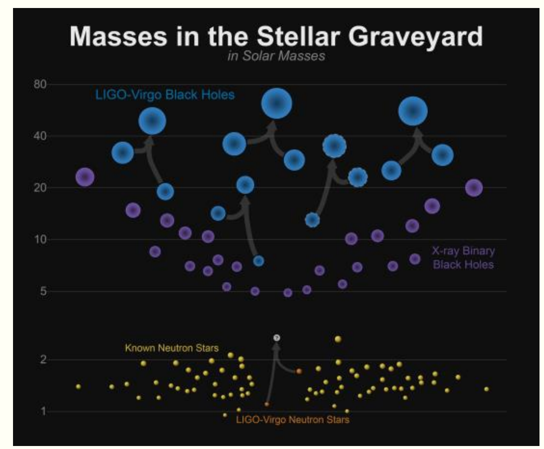
Parent stars of observed EMPs

Slow Relative Vel.

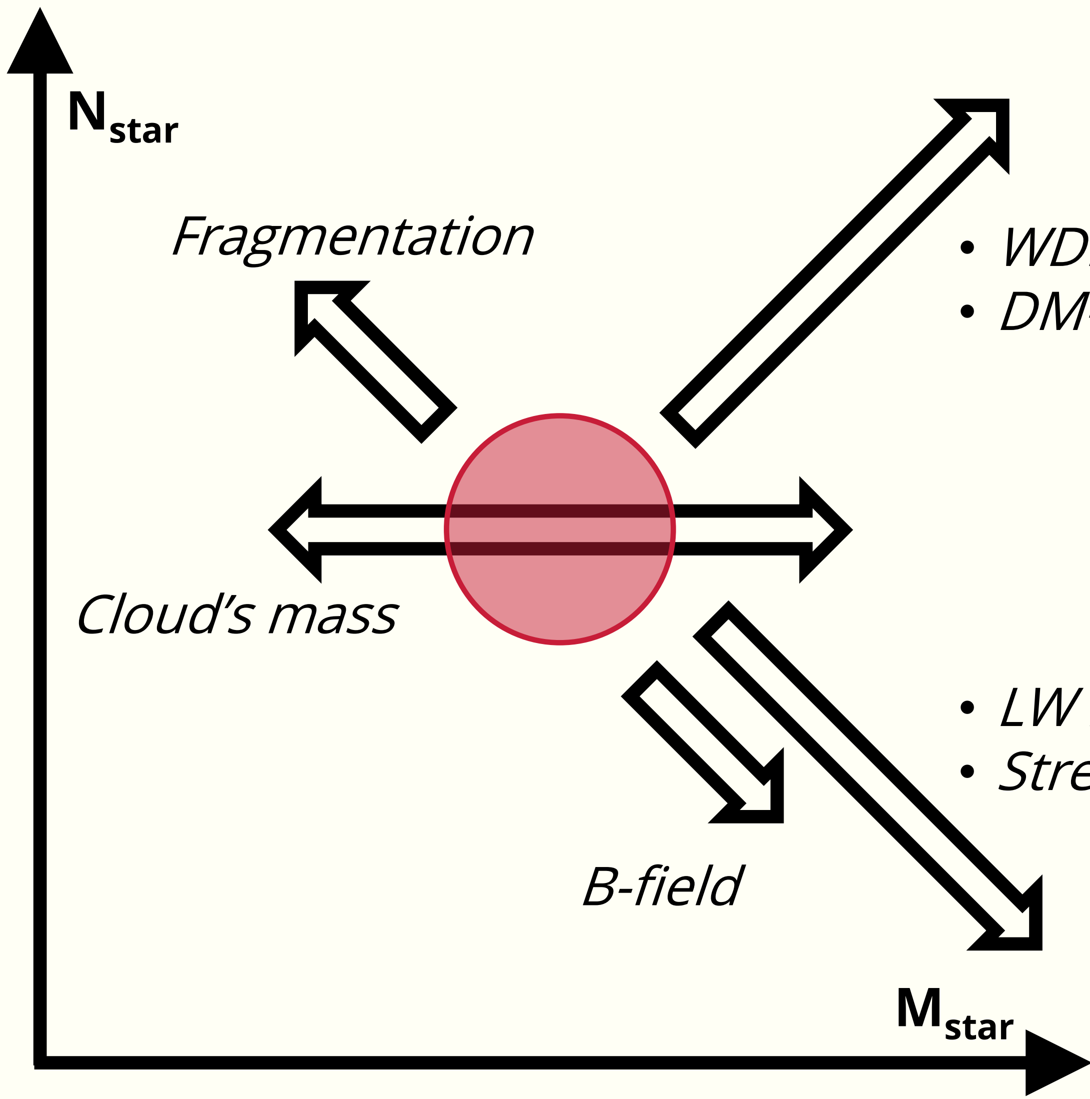


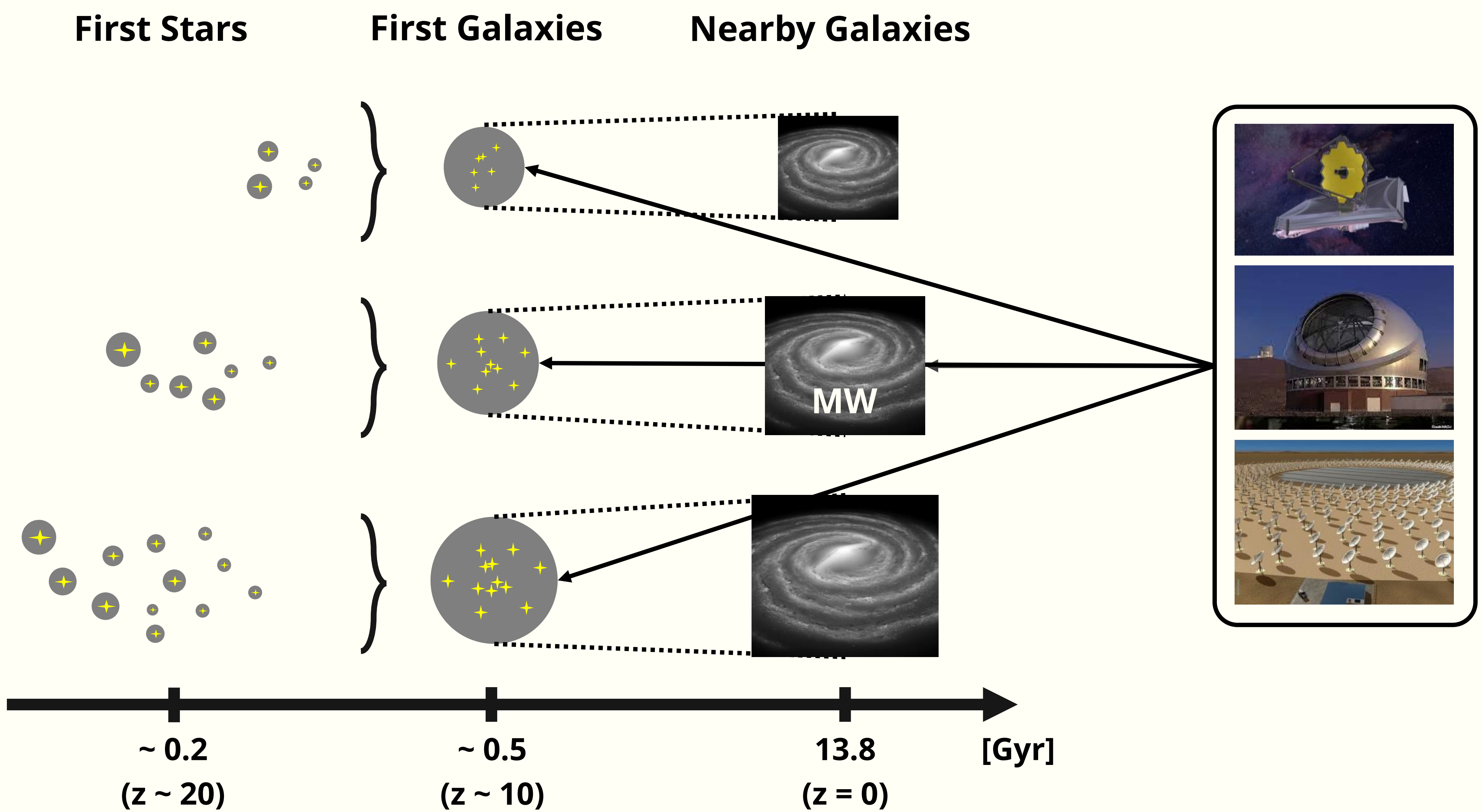
~10 Pop III stars with 100[$M_\odot$] at z~15

Massive BH binary (GW progenitor)

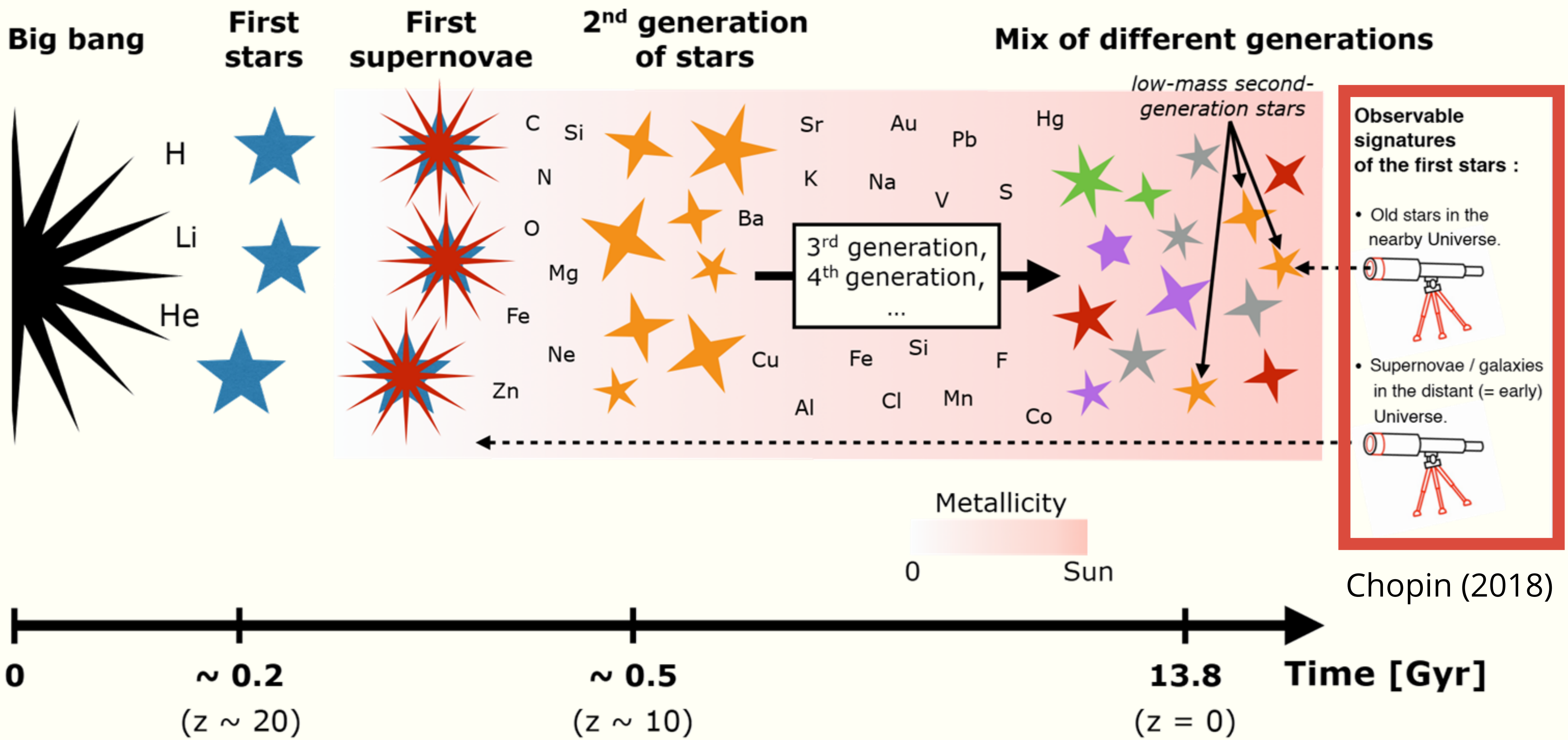


Mass spectrum of the first stars per one star-formation event




First Stars
First Galaxies
Nearby Galaxies
MW
~ 0.2
(z ~ 20)
~ 0.5
(z ~ 10)
13.8
(z = 0)
[Gyr]

The mass of the first star can be verified using the chemical abundance pattern in the 2nd generation of stars (extremely metal-poor stars).



Chopin (2018)

Zero-metallicity stars with less than 0.8 [$M_\odot$] in our galaxy

- Semi-analytical model estimates the number of the surviving first stars in MW (Hartwig+'15; Ishiyama+'16; Komiya+'18; Magg+'19)
- Until now, there is no detection of the surviving first stars in MW.

Gravitational-wave signal from the BH-BH merger event

- Estimation of the typical mass of merging Pop III binary BHs : 30 + 30 [$M_\odot$] (Kinugawa+'14)

Supermassive blackholes with 10^9 [$M_\odot$] in the distant universe ($z > 7$)

- Observational ratio = a few [Gpc^{-3}]

Standard scenario of the first star formation:

① Cosmological simulation → 10^5 – 10^6 [$M_\odot$] host DM minihalo at z = 20 – 30

② Collapse phase → 0.01 [$M_\odot$] protostar surrounding by 1000 [$M_\odot$] gas cloud

③ Accretion phase → radiative feedback determined the stellar mass ~100 [$M_\odot$]

Possible changes in the first star formation:

- Disk scale: fragmentation, magnetic effects
- Cloud scale: statistical properties of the clouds
- DM halo scale: external radiation, DM particle nature, streaming velocity

Observational constraints:

- First galaxies
- MW … relic abundance pattern in the extremely metal-poor stars
- MW … surviving first stars
- Gravitational-wave signal
- Supermassive stars in the high-z universe