Building-up Pop III IMF

in the Milky Way-like galaxies

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Simplified “RECIPE” of first star formation

+

Semi-analytic model: formation of MW-like galaxies (~10^{12} $M_\odot$ at $z=0$)

↓

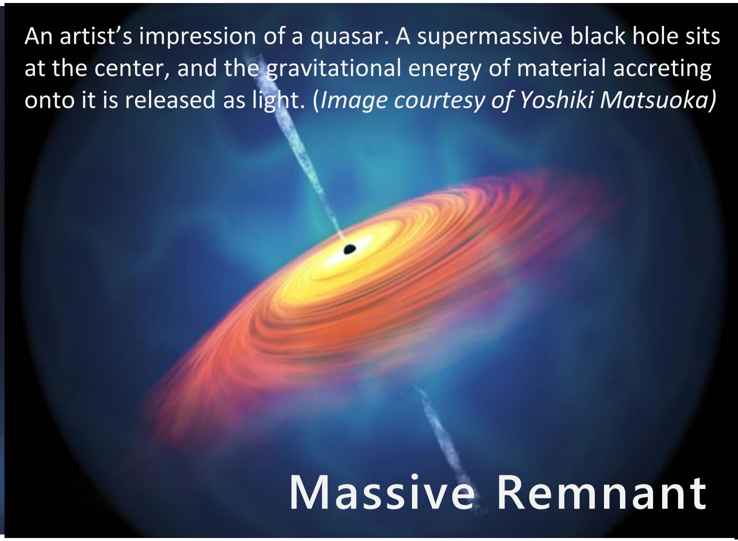
IMF construction: first stars formed during the galaxy formation

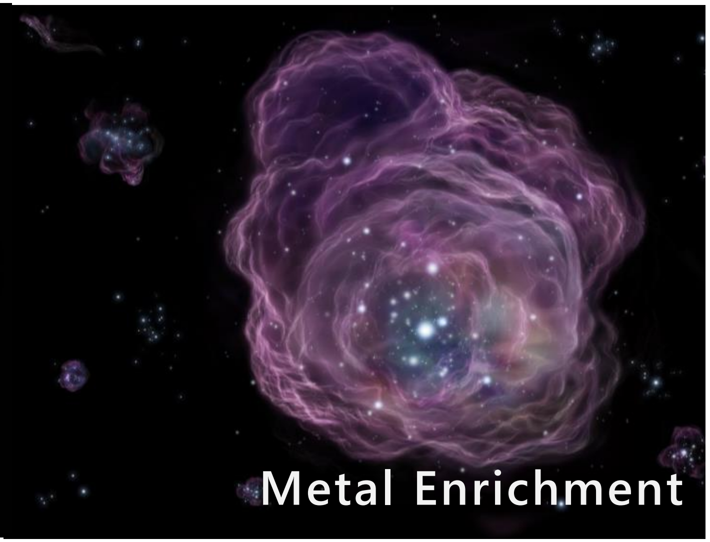
CEMP Stars as Probes of First-Star Nucleosynthesis, the IMF, and Galactic Assembly @ University of Geneva Sep. 9 – 13th, 2019

First Stars (1^{st}–generation stars)

mark the end of the “Cosmic Dawn”

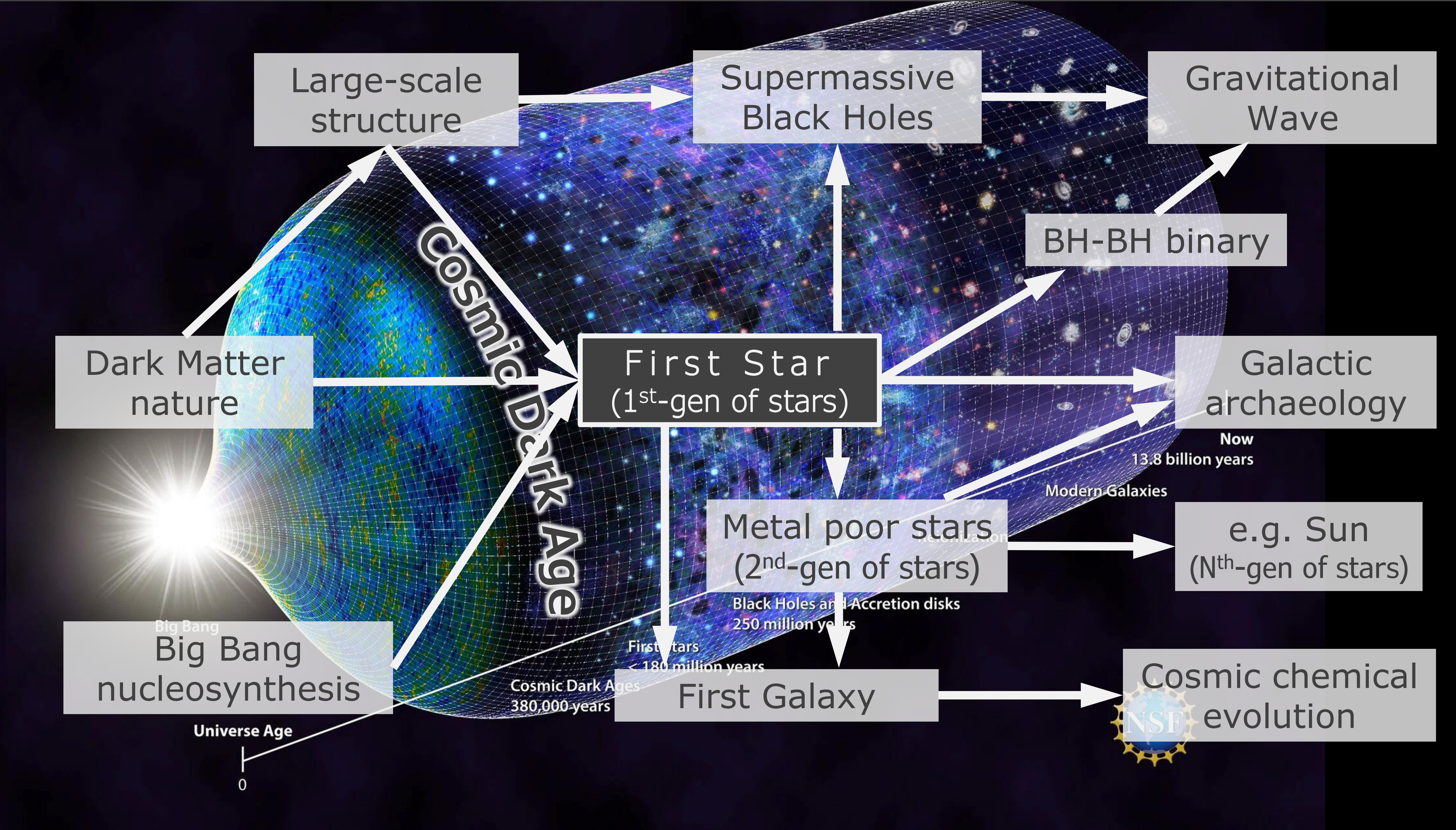
Pop III (zero-metallicity $Z/Z_\odot = 0$) stars formed
from the primordial gas (BBN elements: H, He, Li)
at $z \sim 20$ (from $z = 50$ to 15).


An artist’s impression of a quasar. A supermassive black hole sits at the center, and the gravitational energy of material accreting onto it is released as light. (*Image courtesy of Yoshiki Matsuoka)*



They have not directly observed yet.

An important hub of research in the early Universe



Large-scale structure

Supermassive Black Holes

Gravitational Wave

BH-BH binary

Cosmic Dark Age

Dark Matter nature

First Star
(1st-gen of stars)

Galactic archaeology

Metal poor stars
(2nd-gen of stars)

e.g. Sun
(Nth-gen of stars)

Big Bang nucleosynthesis

First Galaxy

Cosmic chemical evolution

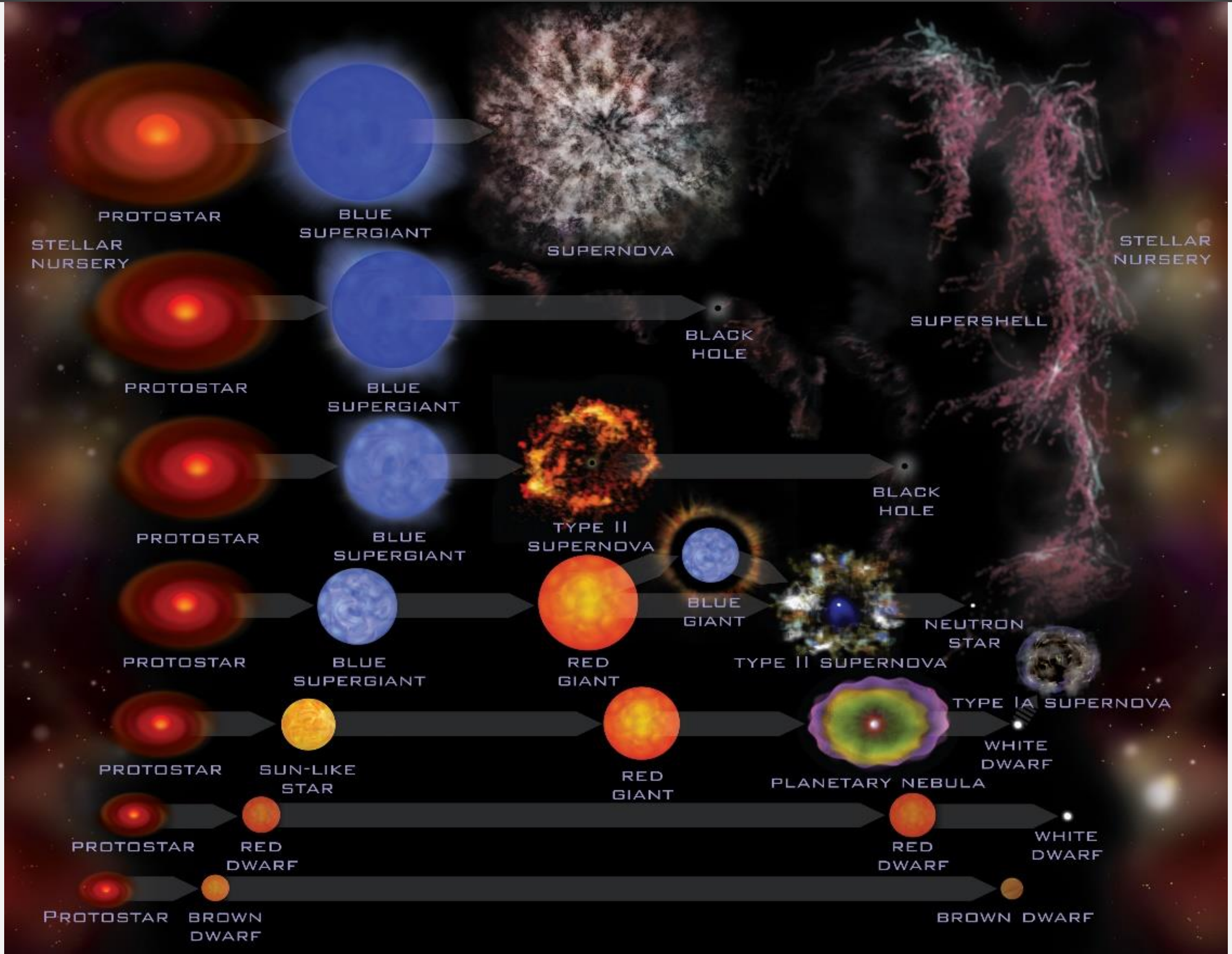
Formation scenario of first stars

can be verified indirectly by comparing with observations.

1st-gen. stars

formed with

- M_{star}
- V_{rot}
- M_{halo}

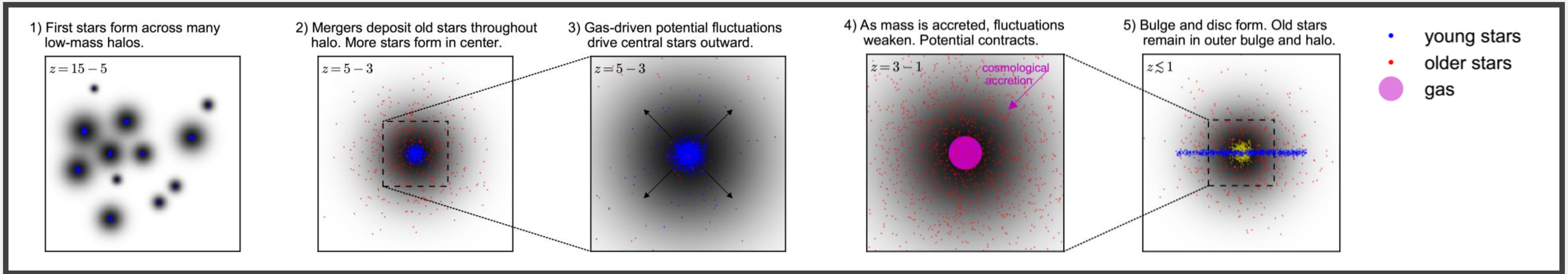


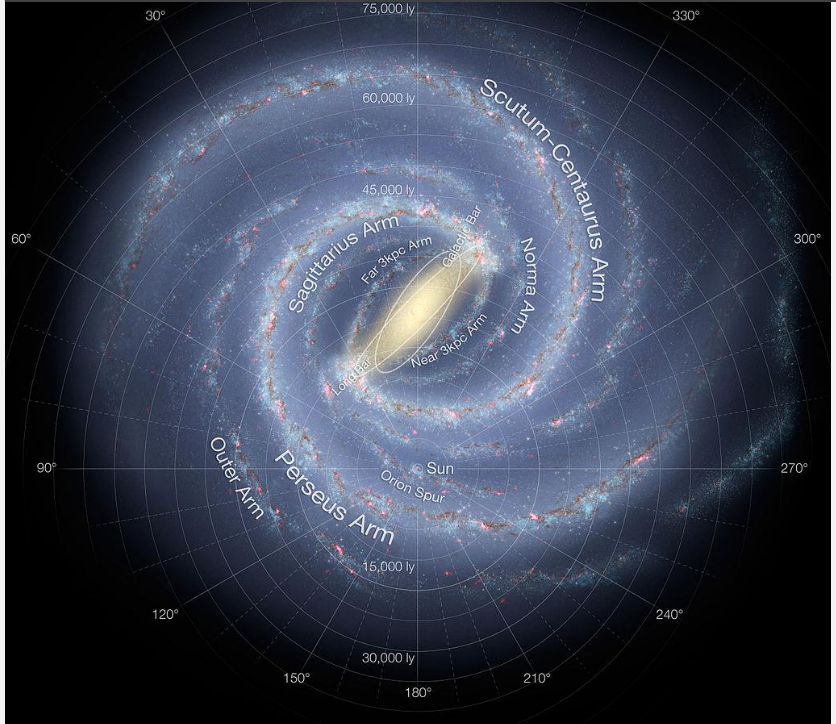
2nd-gen. star

Surviving star

First stars born in our Galaxy

Can we construct Pop III IMF in the MW-like galaxies?





Problem | **Computational cost** of the simulation of first star formation in a full consistent manner.

"# of first star formation in MW"

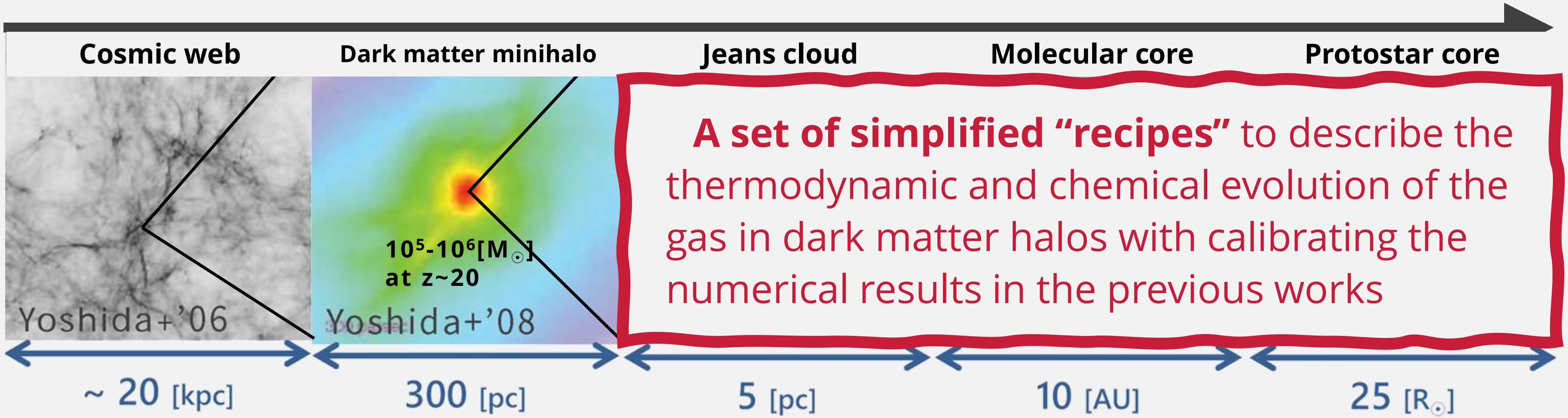
~ M_{MW} / $M_{minihalo}$ = 10^{12} / 10^{6} = **10^{6}** !

Simplified “RECIPE” of star formation

for the galaxy formation & evolution

Present-day case → IMF, star formation efficiency

Primordial case → Correlation between the stellar properties and the physical state of the star formation cite



Cosmic web

Dark matter minihalo

Jeans cloud

Molecular core

Protostar core

Yoshida+’06

Yoshida+’08

10^5-10^6[$M_\odot$] at z~20

A set of simplified “recipes” to describe the thermodynamic and chemical evolution of the gas in dark matter halos with calibrating the numerical results in the previous works

~ 20 [kpc]

300 [pc]

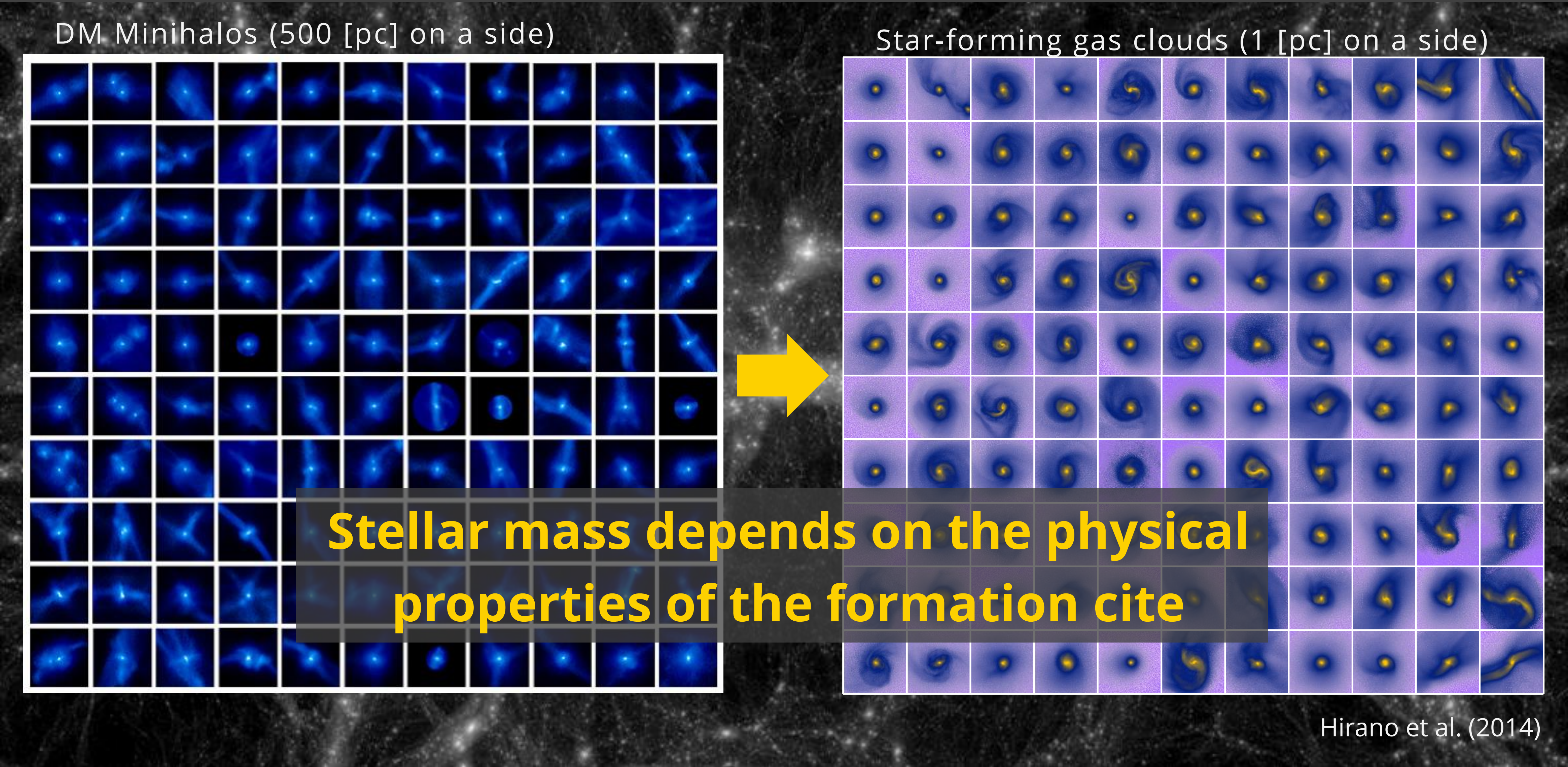
5 [pc]

10 [AU]

25 [$R_\odot$]

Formation of the first stars

from the cosmological initial condition to the zero-age main sequence phase

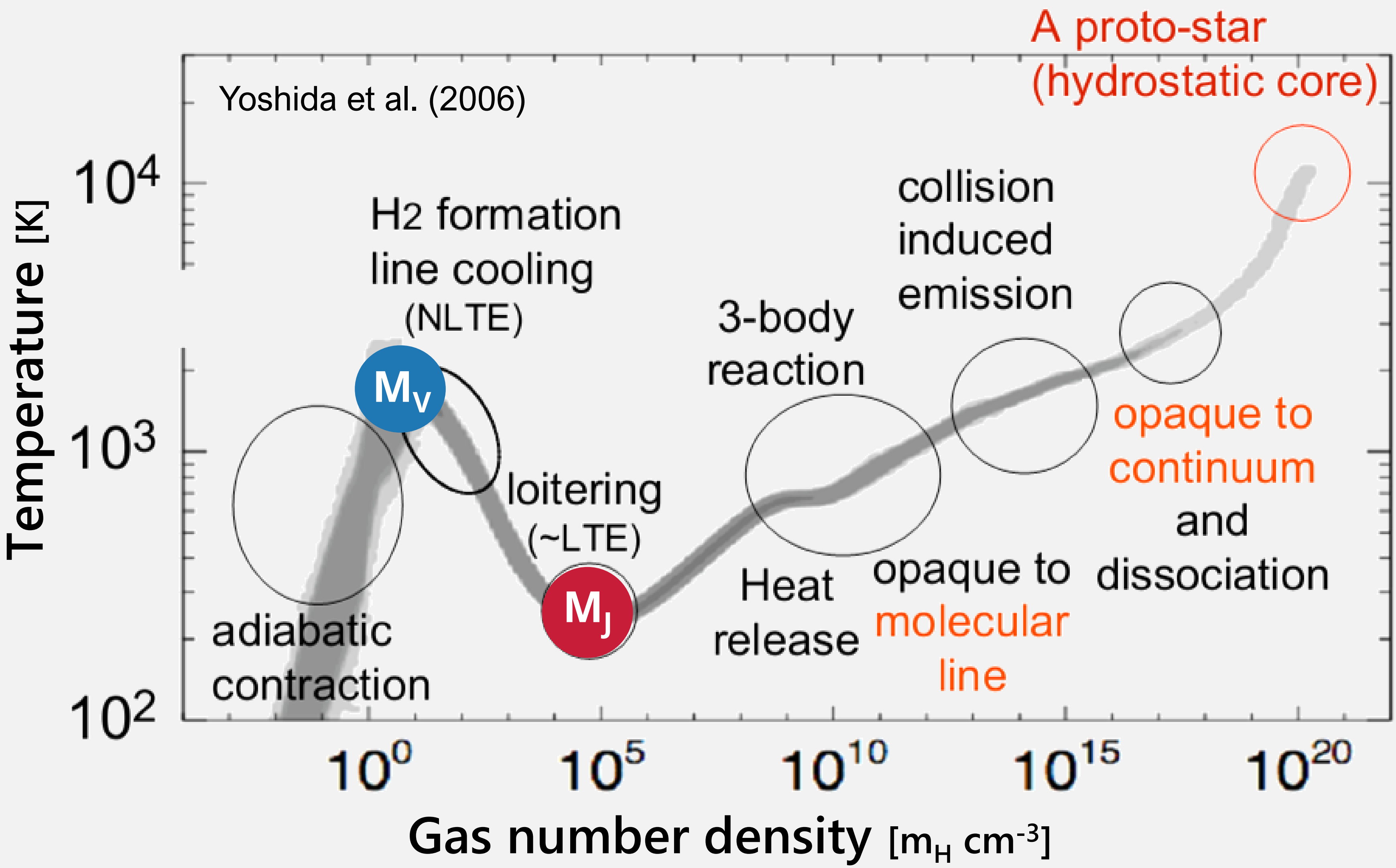


Stellar mass depends on the physical properties of the formation cite

Hirano et al. (2014)

How massive?

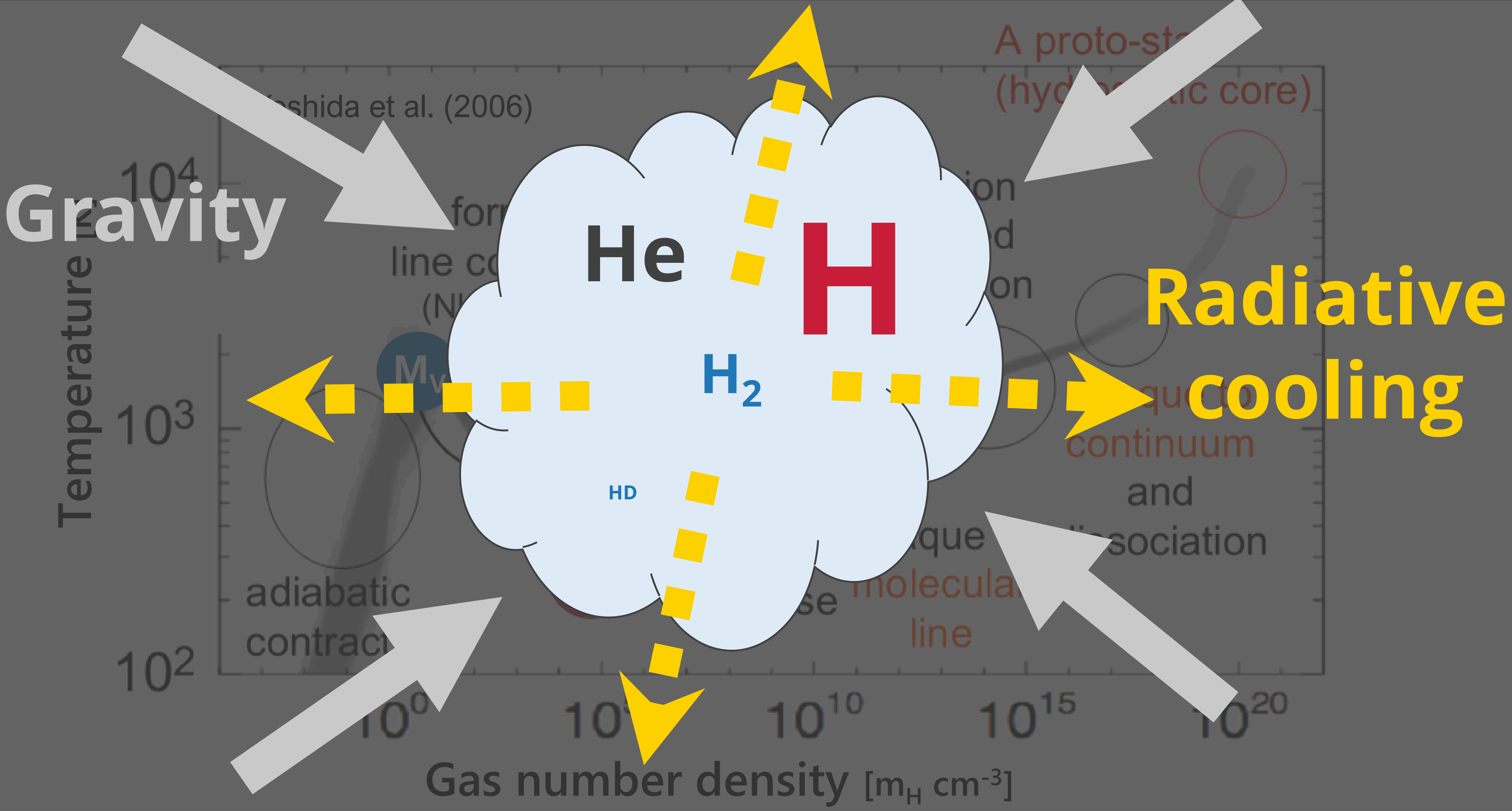
Jeans mass of the star-forming cloud



How massive?

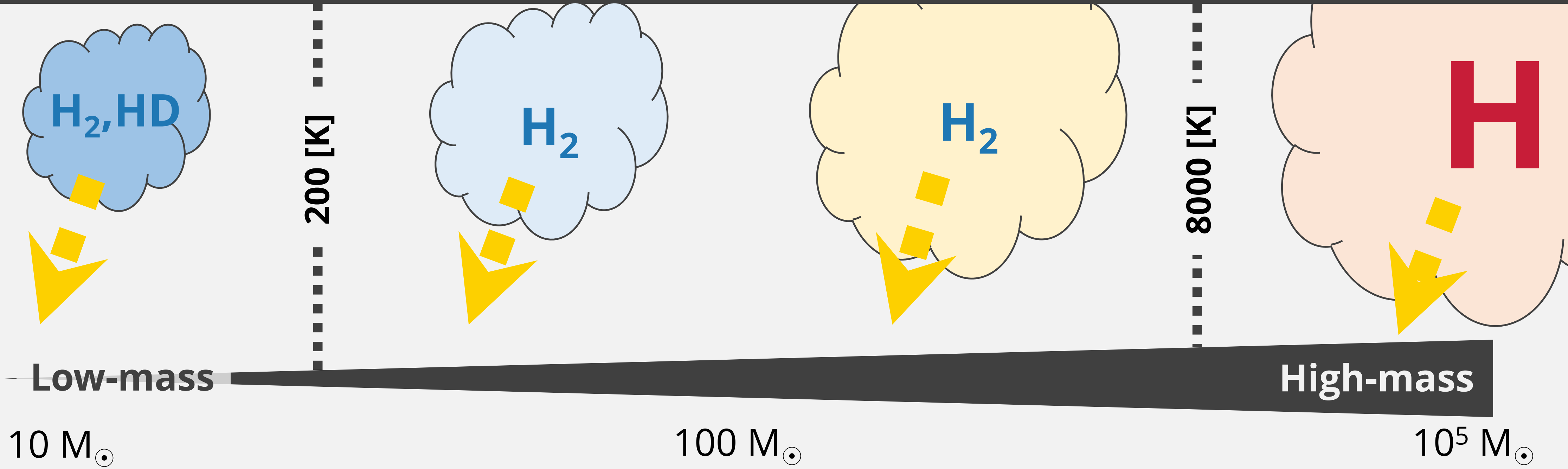
Jeans mass of the star-forming cloud

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



Low- / High-mass ends

Jeans mass of the star-forming cloud



Contraction speed

Statistical study
(e.g. *Hirano+'14; '15*)

External radiation

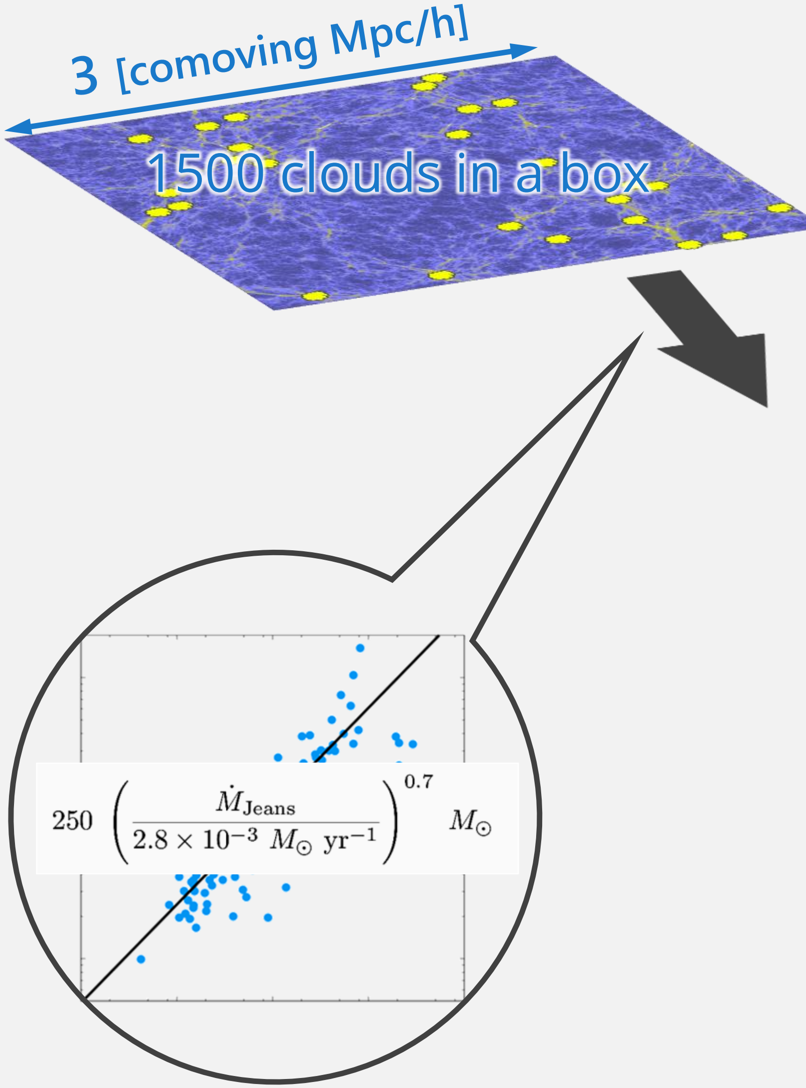
Ultra-violet radiation photo-dissociate H_2 molecules
(e.g. *Latif+'13; Chon+'16; Regan+'17*)

Dynamical support

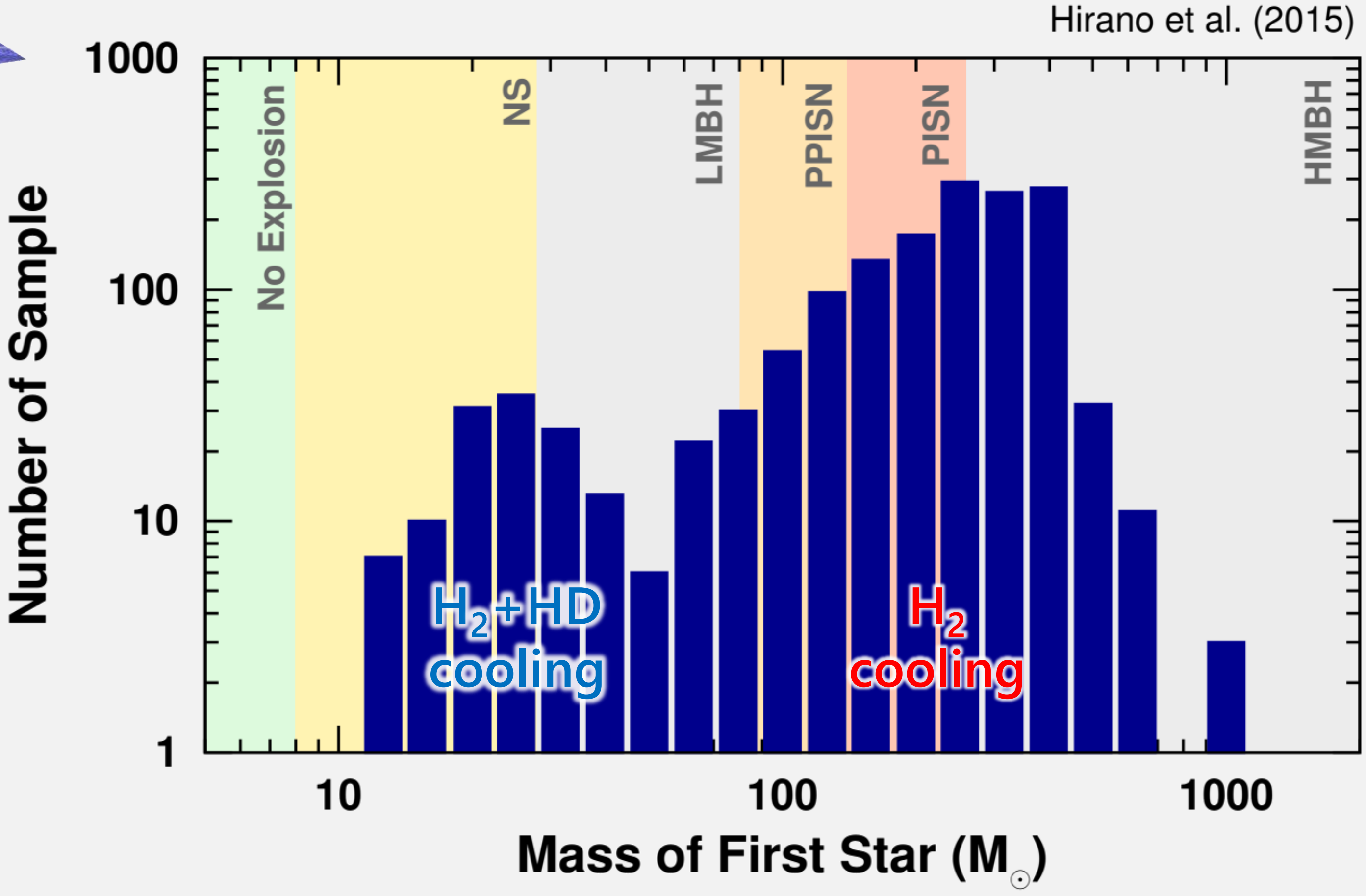
Later halo merger (e.g. *Schauer+'19; Wise+'19*)
Relative streaming motion (e.g. *Hirano+'17; '18*)

Mass prediction of (single) first star

depending on the physical properties of the formation cite

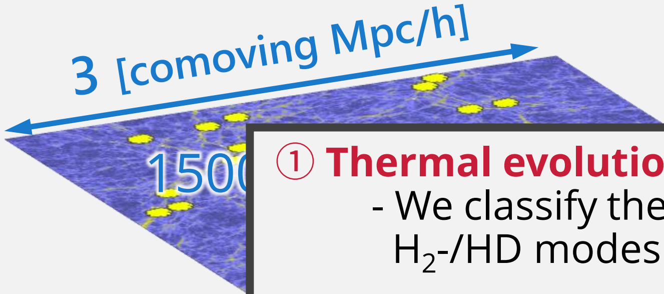


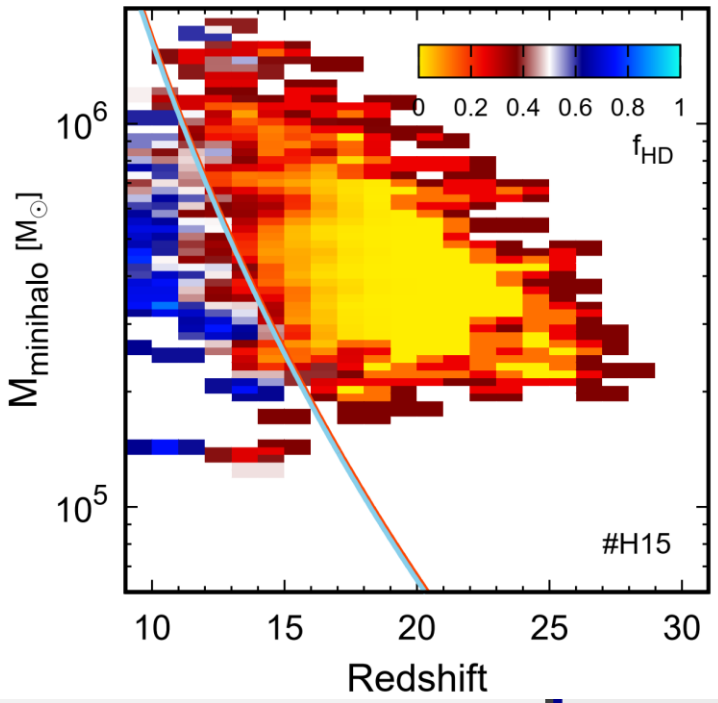
$$250\left(\frac{\dot{M}_{\rm Jeans}}{2.8\times10^{-3}\ M_\odot\ {\rm yr}^{-1}}\right)^{0.7} M_\odot$$



Mass prediction of (singl

depending on the physical properties of the formati





① **Thermal evolution of the collapsing gas cloud**

- We classify the minihalo into two thermal paths, H_2-/HD modes by using new criterion:

$$M_{\rm mh} \geq 3.5 \times 10^5 \left(\frac{1+z}{20}\right)^{-5} M_\odot$$

② **Mass contraction rate at Jeans scale**

- We calculate the mass contraction rate at the Jeans scale from two parameters, $\{z, M_{\rm mh}\}$, for two modes by using Equation (8) in H15:

$$\dot{M}_{\rm Jeans, H_2} = 3.0 \times \dot{M}_{\rm virial}$$

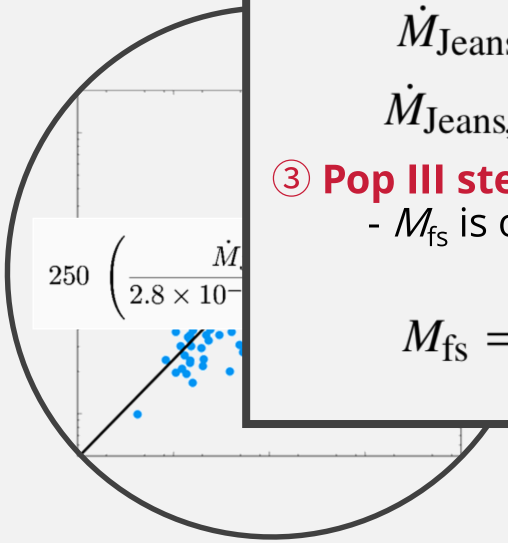
$$\dot{M}_{\rm Jeans, HD} = 0.3 \times \dot{M}_{\rm virial}$$

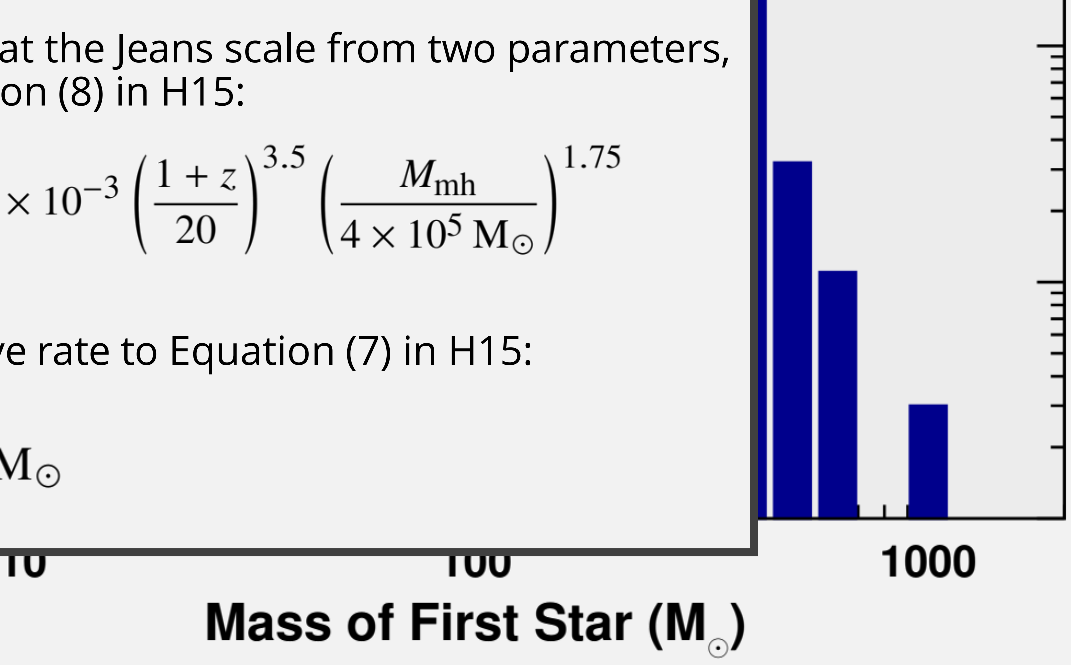
$$\dot{M}_{\rm virial} = 1.1 \times 10^{-3} \left(\frac{1+z}{20}\right)^{3.5} \left(\frac{M_{\rm mh}}{4 \times 10^5 \, M_\odot}\right)^{1.75}$$

③ **Pop III stellar mass**

- $M_{\rm fs}$ is obtained by substitution the above rate to Equation (7) in H15:

$$M_{\rm fs} = 250 \left(\frac{\dot{M}_{\rm Jeans}}{2.8 \times 10^{-3} \, M_\odot \, {\rm yr}^{-1}}\right)^{0.7} M_\odot$$





Merge of survive?

Clark+ 2011 O(10) sinks

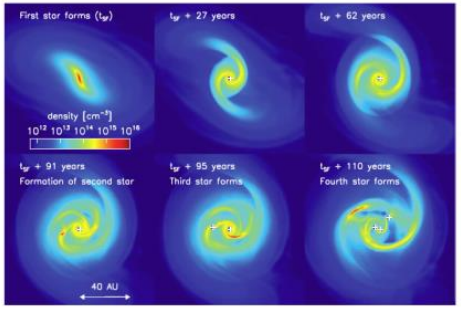
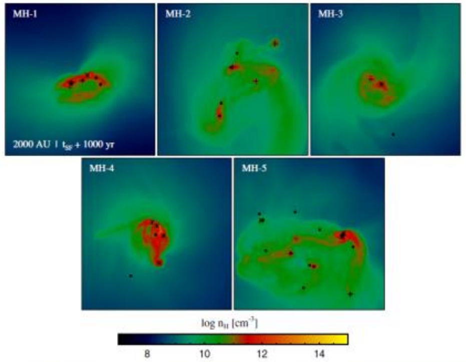
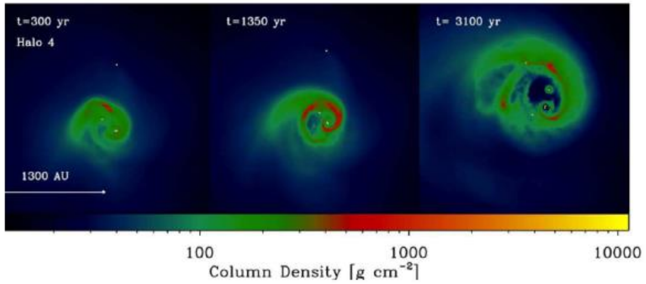


Fig. 1. Density evolution in a 120-AU region around the first protostar, showing the buildup of the protostellar disk and its eventual fragmentation. We also see "wakes" in the low-density regions, produced by the previous passage of the spiral arms.

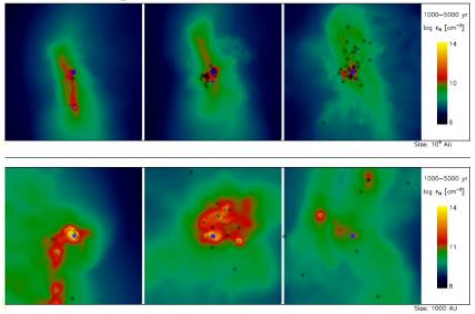
Greif+ 2011 O(10) sinks

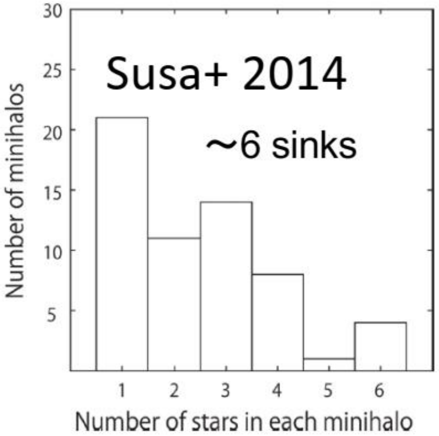




Smith+ 2011 O(10) sinks

Stacy+ 2016~50 sinks

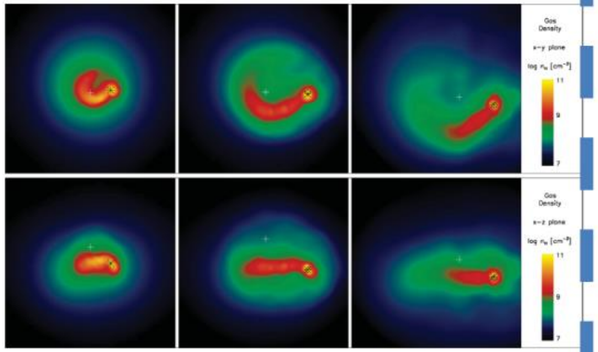




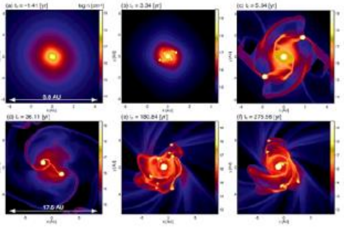
Susa+ 2014

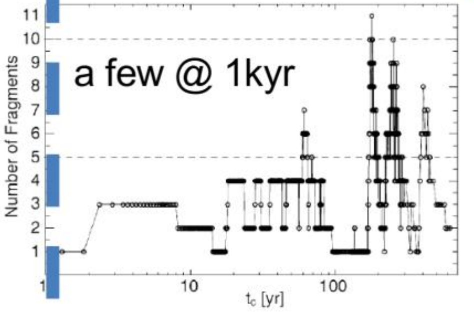
~6 sinks

Stacy+ 2012 a few sinks



Machida+2013

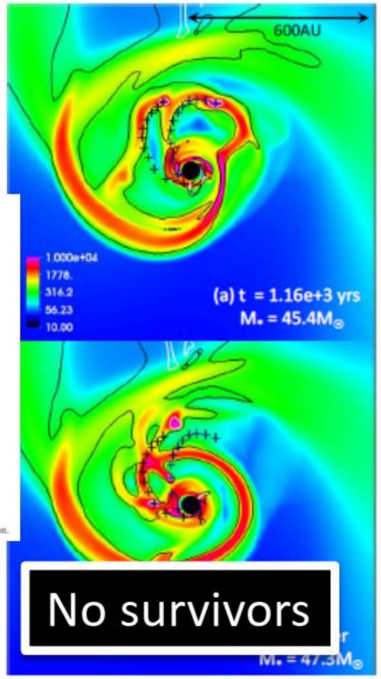




a few @ 1kyr

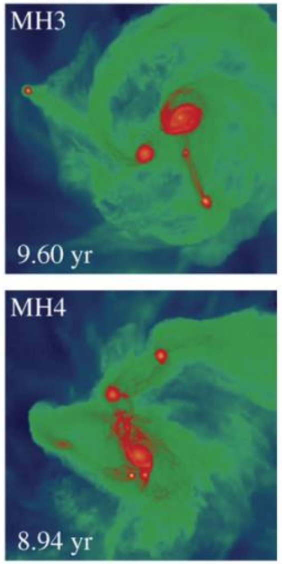
Figure 8. Number of clumps in the region of $r \leqslant 10$ AU against the elapsed time after protostar formation.

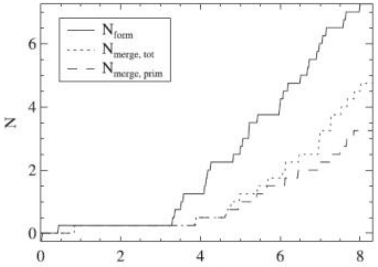
Hosokawa+2015



No survivors

Greif+2012

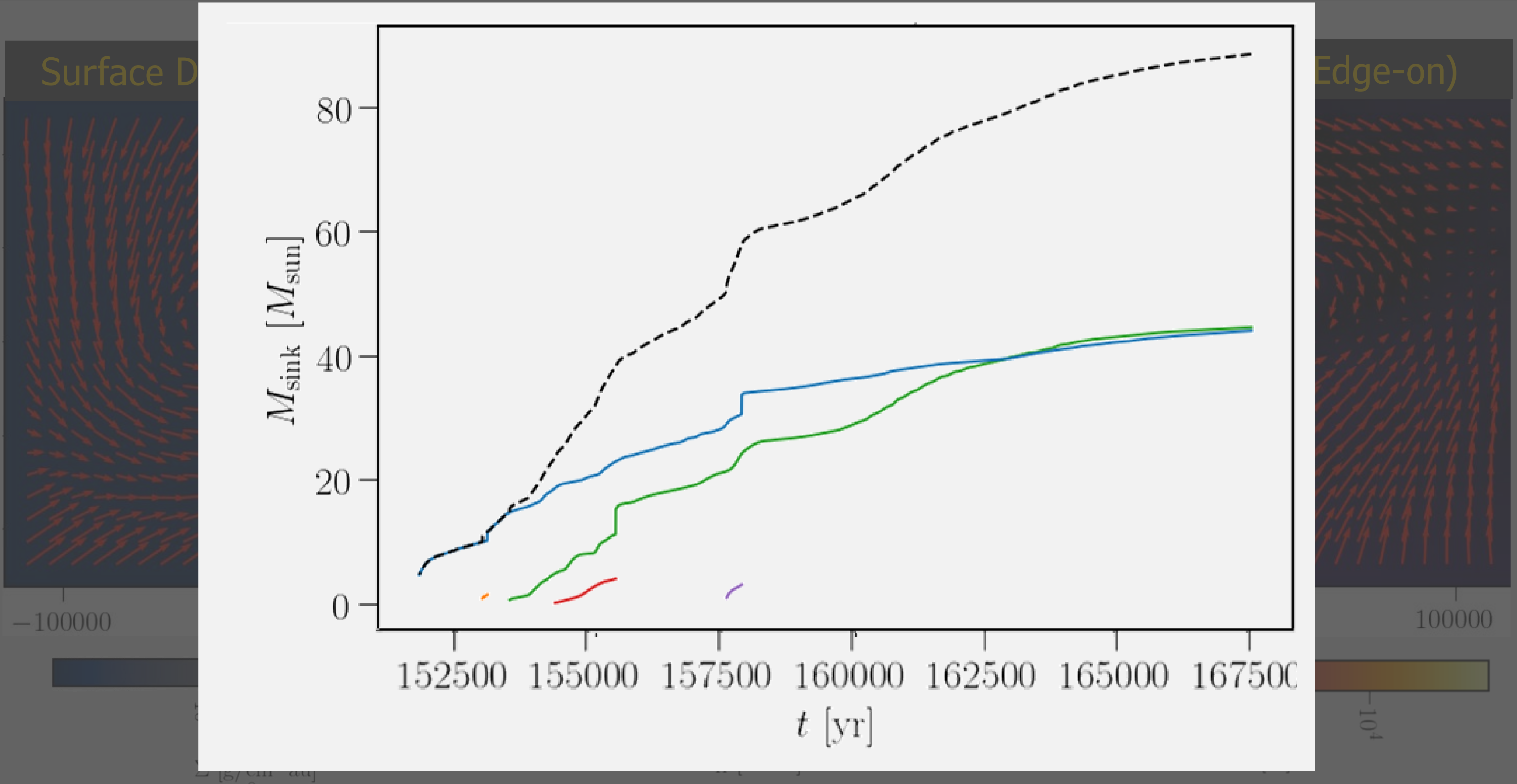




2/3 merge
within 10 yrs
(a few remains)

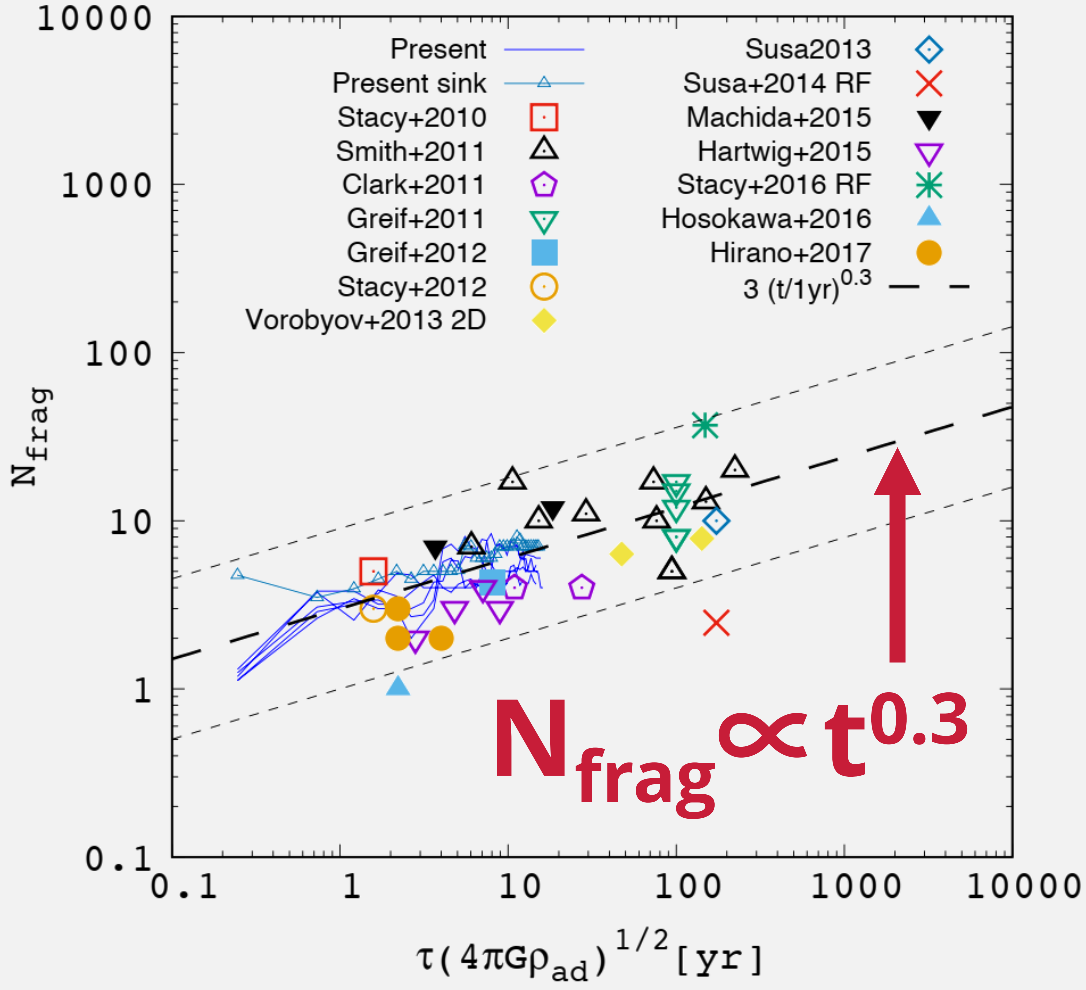
Fragmentation of accretion disk

3D AMR RHD simulation (Sugimura, SH et al., in prep)



Number of first stars per minihalo

Susa (2019)

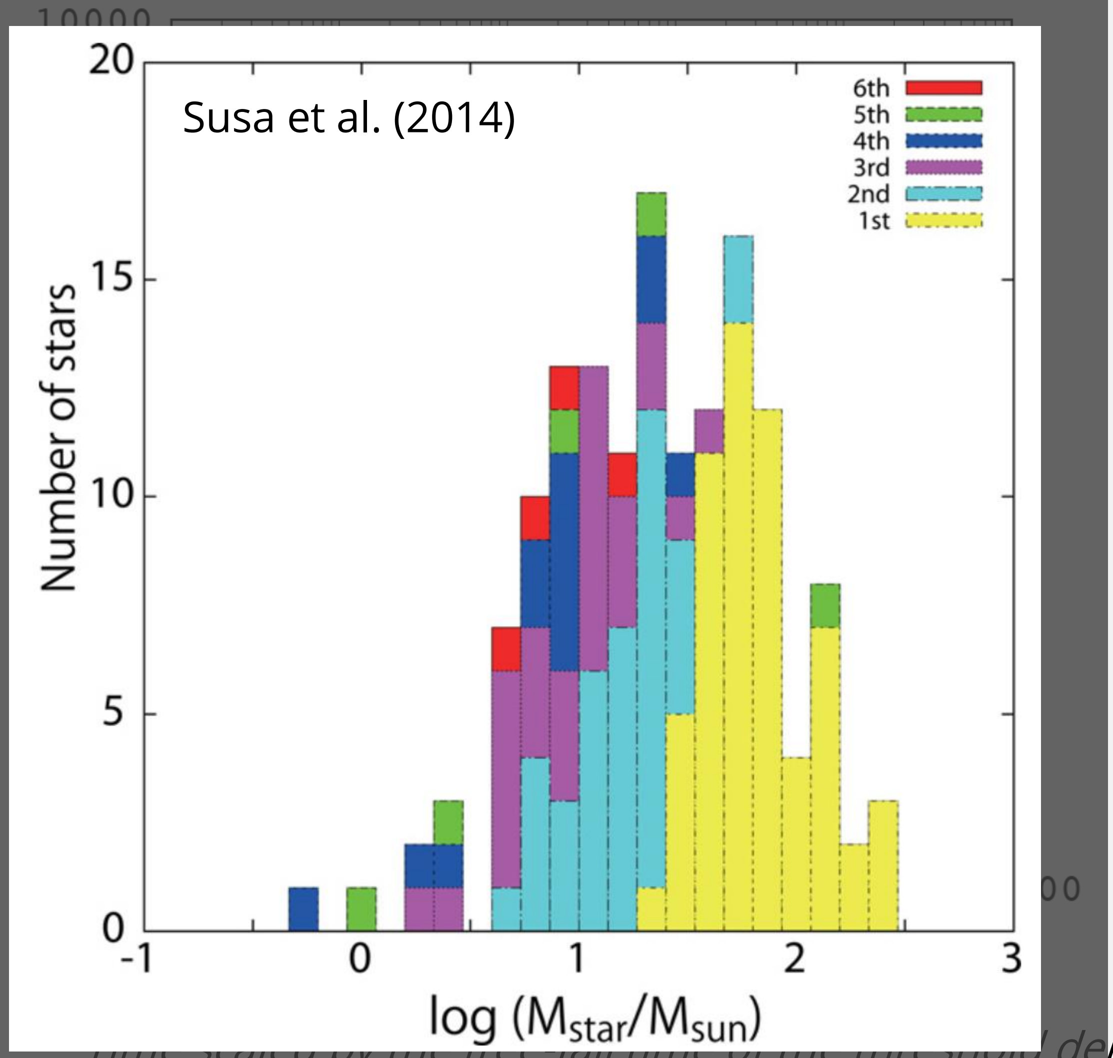


"Time scaled by the free-fall time of the threshold density"

N_{frag} = 10 – 100
at the beginning of the radiative feedback from massive protostars.

Number of first stars per minihalo

Susa (2019)



Time scaled by the free-fall time of the threshold density”

N_{frag} = 10 – 100
at the beginning of the radiative feedback from massive protostars.

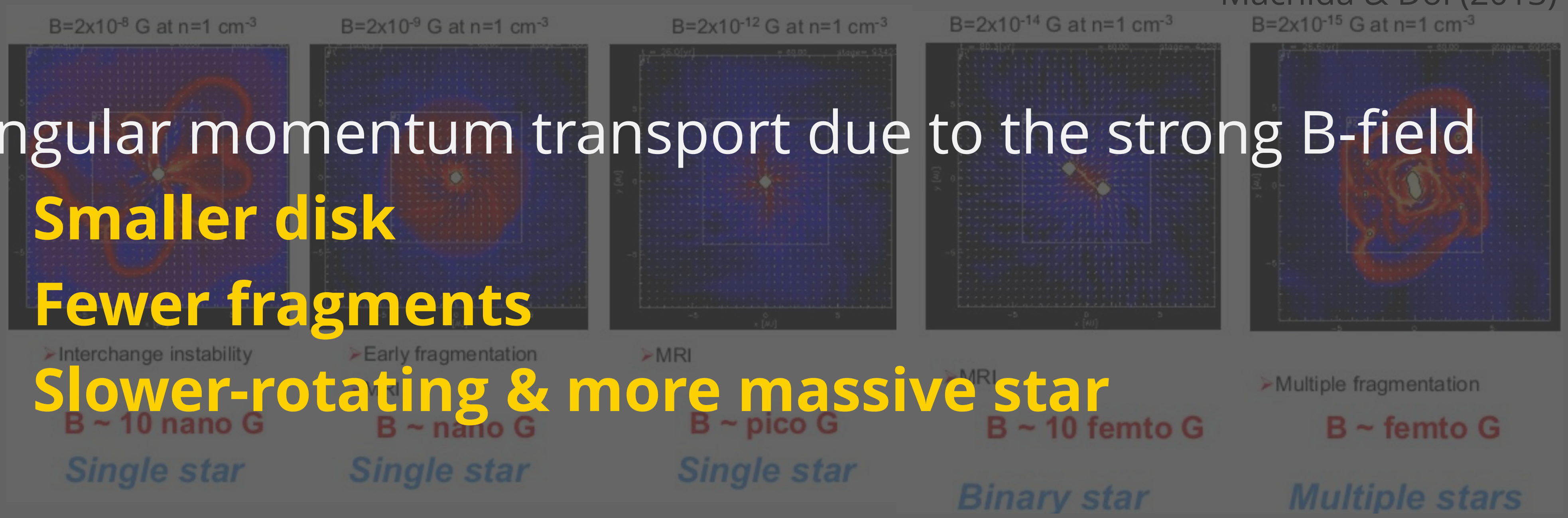
Recipes of multiple stars:
① $M_{total} = M_{star,single}$
② Log-normal mass spectrum (Susa et al. 2014) with N_{frag} = 10 – 100.

Stellar rotation

Influence on the stellar evolution and final state

Pristine star-forming cloud is a rapid rotator ($v_{rot}/v_{kep} \sim 0.5$)

If the tiny seed magnetic field (10^{-9} [G] in the host halo; Xu+’08) can be highly amplified during the cloud collapse, the magnetic braking effect transports angular momentum.



Machida & Doi (2013)

Angular momentum transport due to the strong B-field

- **Smaller disk**
- **Fewer fragments**
- **Slower-rotating & more massive star**

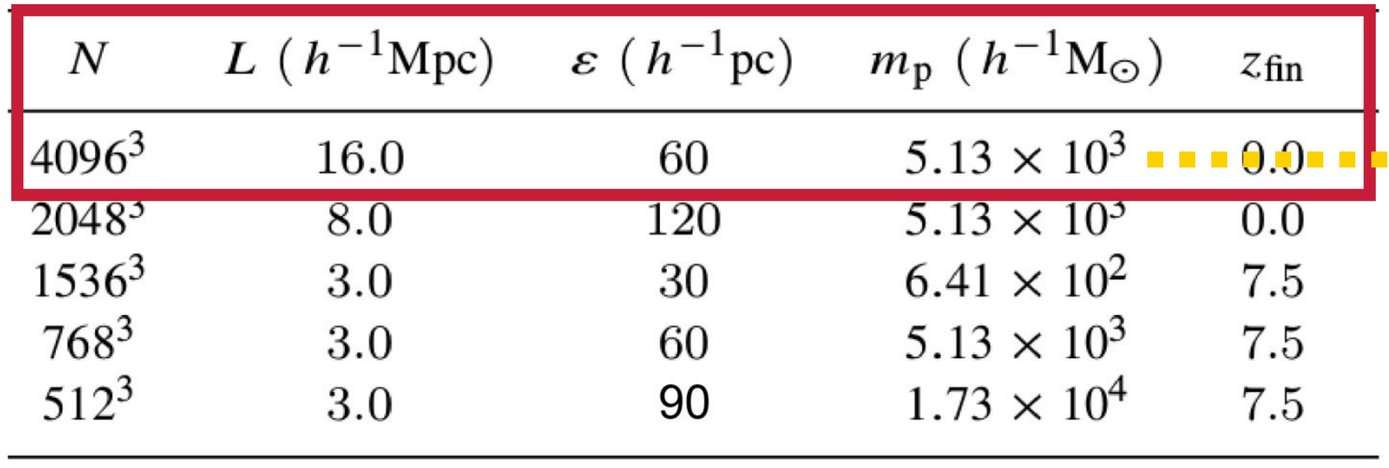
First stars formed in the MW-like galaxies

N-body data with resolving the host DM minihalo

Computed by Tomoaki ISHIYAMA (Chiba Univ., Japan)

*If you are interested to use our simulation data, please contact us (ishiyama@chiba-u.jp)

- All simulations are conducted by GreeM code (Ishiyama+'09; '12)
- DM halos/subhalos are identified by Rockstar halo finder (Behroozi+'13)
- Merger trees are constructed by consistent merger trees code (Behroozi+'13)



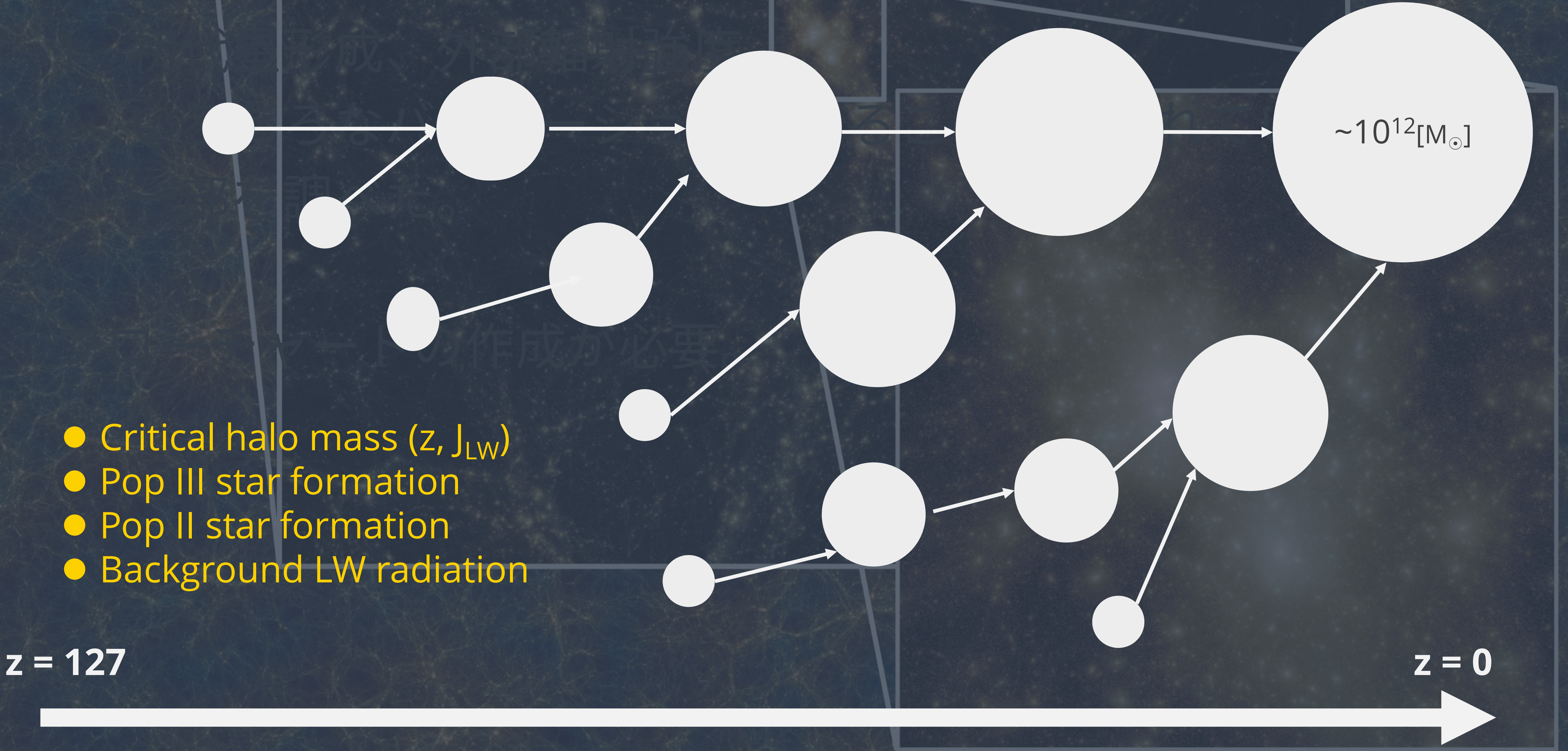
N	L (h^{-1}Mpc)	ε (h^{-1}pc)	$m_{\rm p}$ (h^{-1}M$_\odot$)	$z_{\rm fin}$
4096^3	16.0	60	5.13×10^3	0.0
2048^3	8.0	120	5.13×10^3	0.0
1536^3	3.0	30	6.41×10^2	7.5
768^3	3.0	60	5.13×10^3	7.5
512^3	3.0	90	1.73×10^4	7.5

→ **Resolving the minimum halo mass (~10^5 M$_\odot$)**

→ **27 Milky Way size halos ($M_{\rm halo}$ ~ 10^{12} [M$_\odot$] at z = 0)**

Merger tree of MW-like galaxies

Semi-analytical modeling of the galaxy formation (modified of Ishiyama+’17)



- Critical halo mass (z, J_{LW})
- Pop III star formation
- Pop II star formation
- Background LW radiation

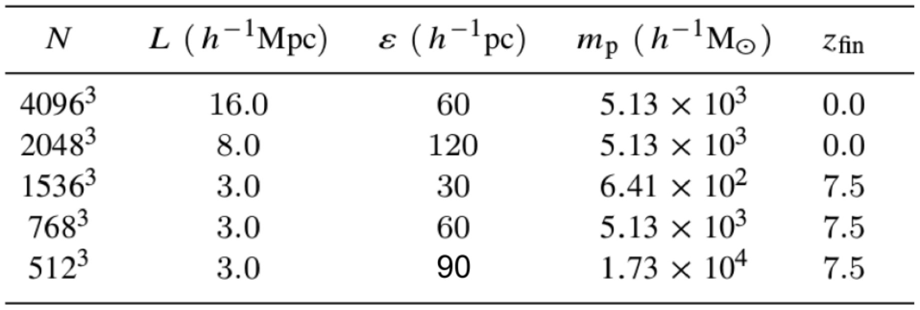
Consistency check

Previous works, box size effect, and resolution effect

- SFRD in the case with the same models in the previous works:

This work | L_{box}=16 [cMpc/h] , M_{DM}=5130 [$M_\odot$/h]
Visbal+'18 | L_{box}=5 [cMpc] , M_{DM}= 4600 [$M_\odot$]
Agarwal+'12 | L_{box}=3.8 [cMpc/h] , M_{DM}=6500 [$M_\odot$/h]

- Box size dependence
- Resolution dependence



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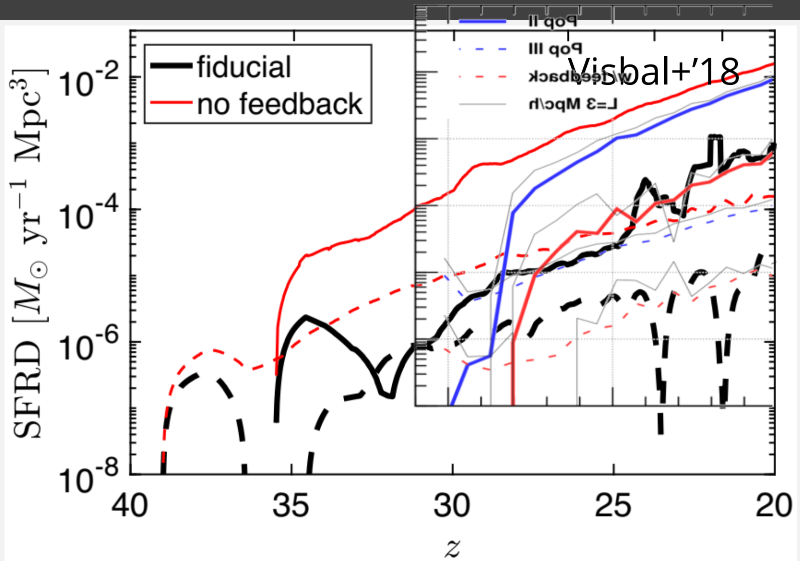
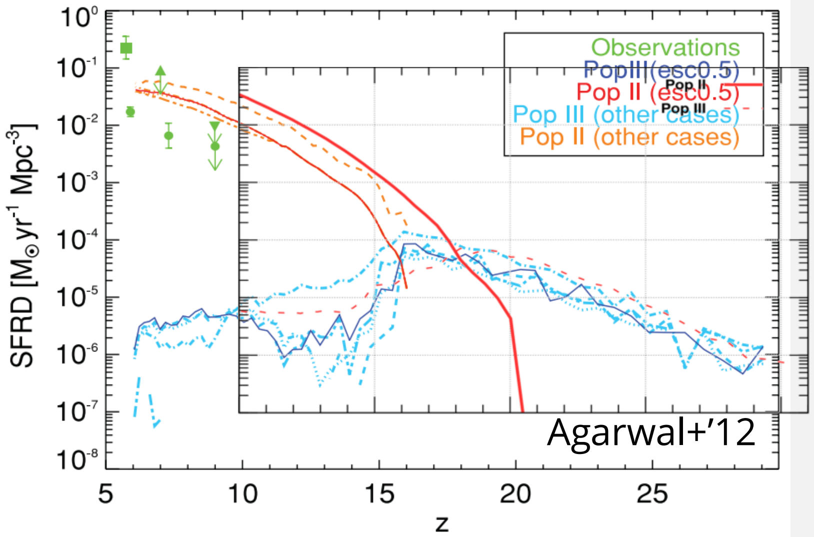
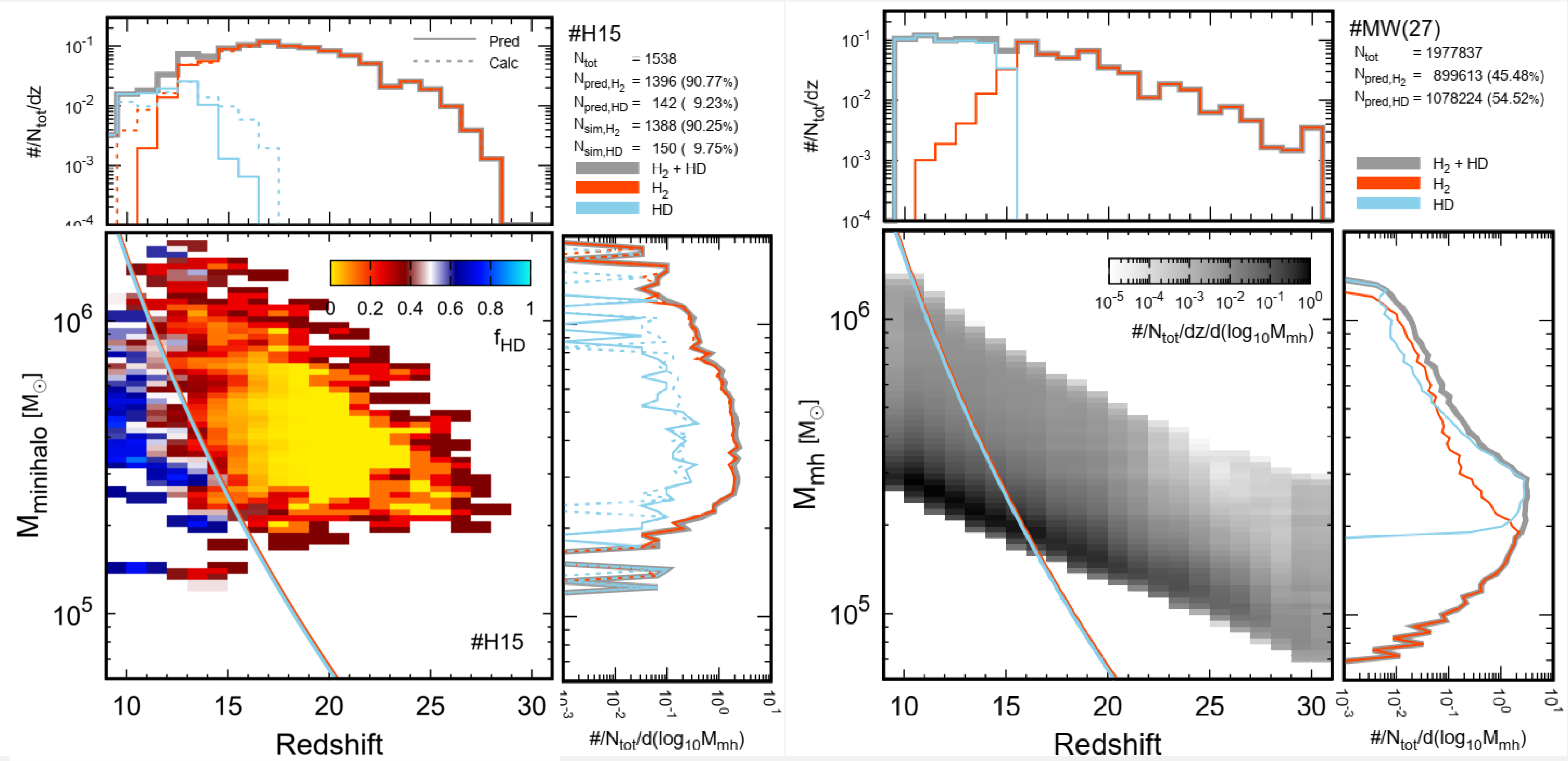




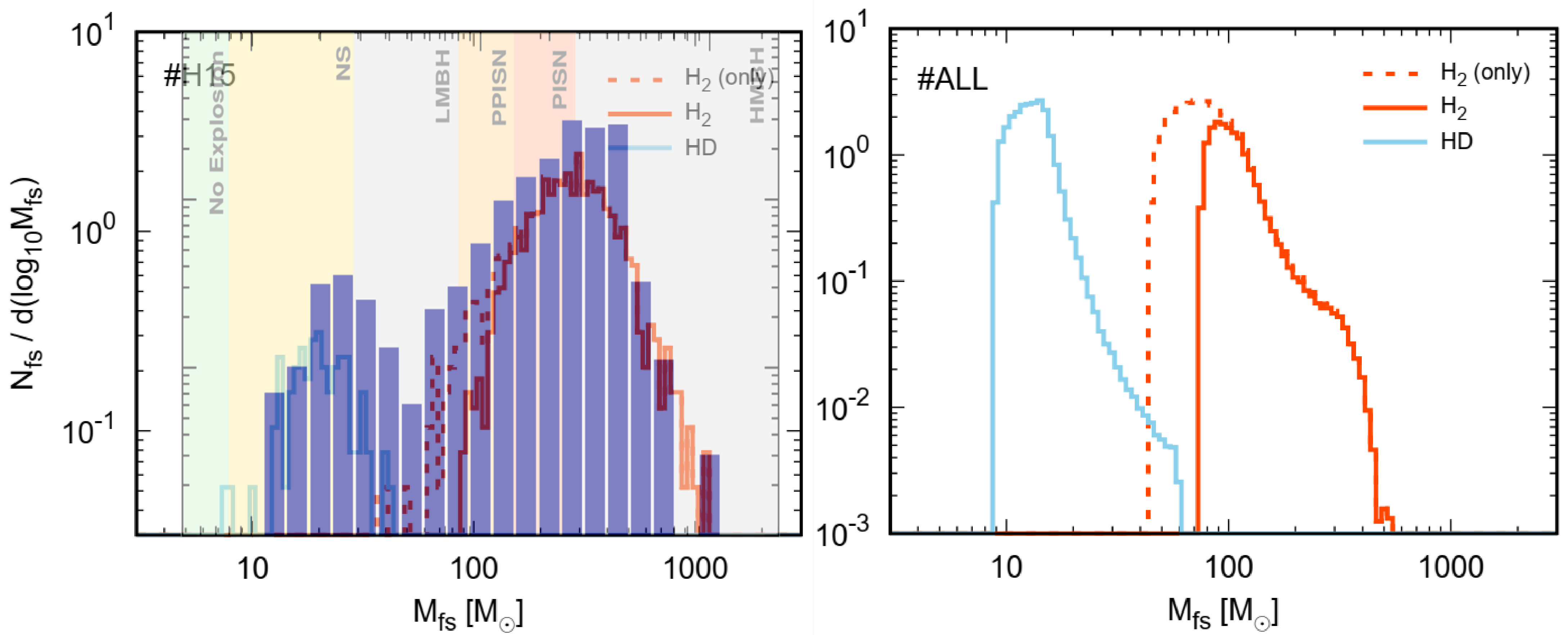
Host DM mihalos

We apply the semi-analytical model to two datasets



IMF of (single) first stars

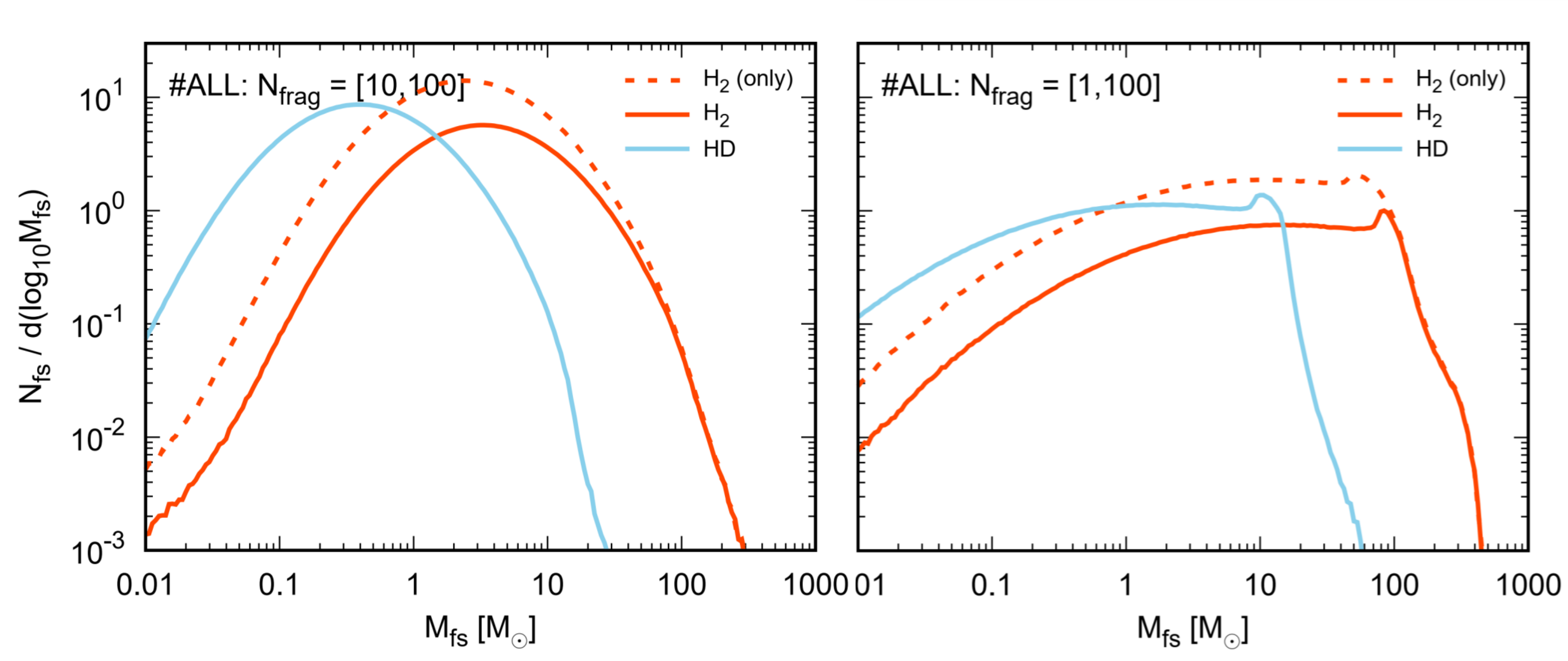
We apply the semi-analytical model to two datasets



IMF of (multiple) first stars

We apply the semi-analytical model to two datasets

Under Construction



Future plans

To compare with observations of the MW

- IMFs at different regions
  - In the center, outskirts, satellite
  - Numbers of surviving stars, massive BH (binary)

- MDF (Metallicity distribution function)
  - internal- / external-enrichments (yesterday Chiaki's talk)

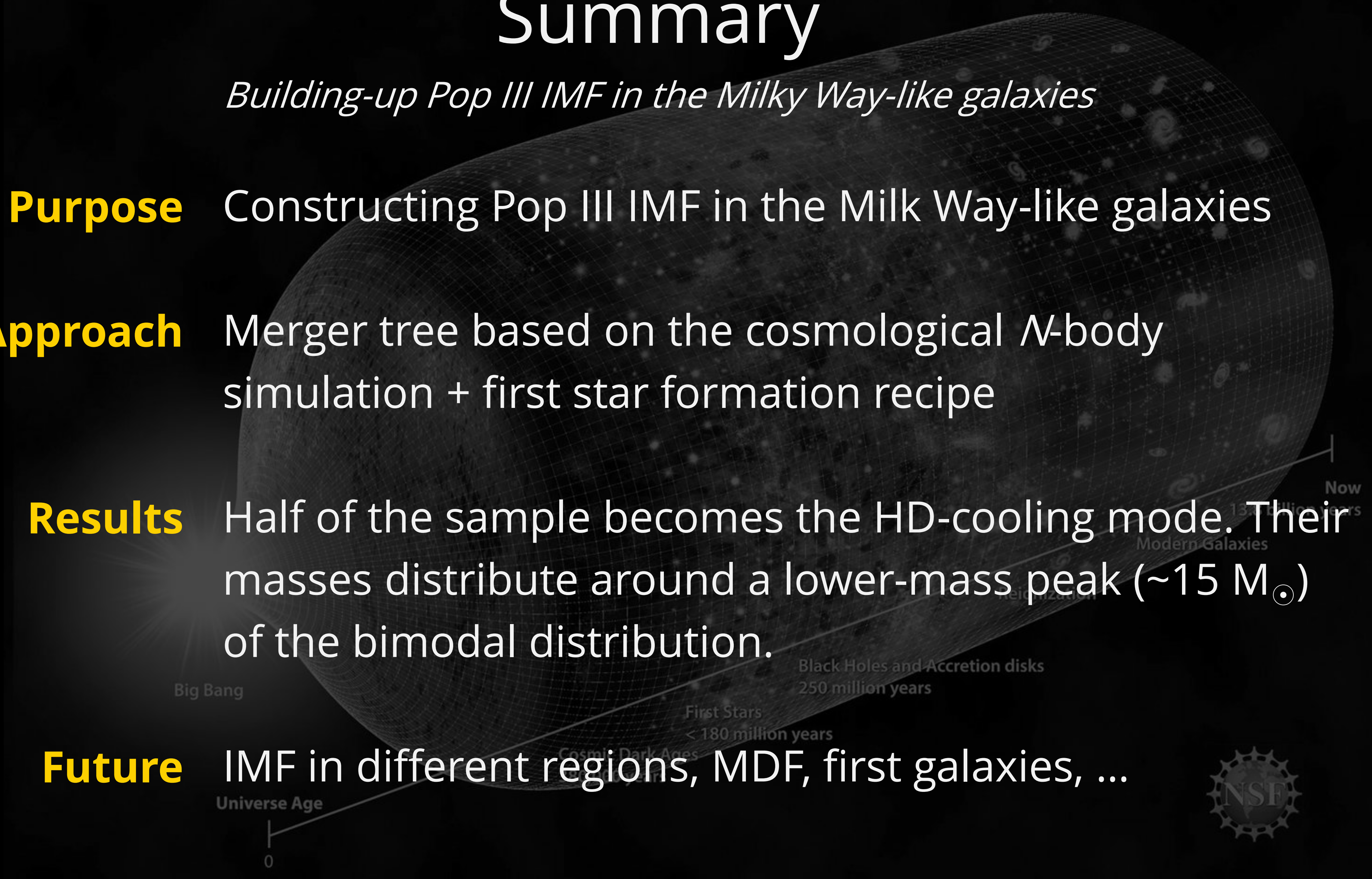
- IMF in the ancestral first galaxies
  - With different masses and formation epochs

- Effect of the local LW radiation (Pop III and II stars)

- We will reflect new simulation results on the star formation recipe.

Summary

Building-up Pop III IMF in the Milky Way-like galaxies



Purpose Constructing Pop III IMF in the Milk Way-like galaxies

Approach Merger tree based on the cosmological N-body simulation + first star formation recipe

Results Half of the sample becomes the HD-cooling mode. Their masses distribute around a lower-mass peak (~15 $M_\odot$) of the bimodal distribution.

Future IMF in different regions, MDF, first galaxies, ...