Environmental Dependence of the First Star Formation

Shingo Hirano

JSPS Fellow / Kyushu Univ.

FAPESP-JSPS Workshop
"Cosmological challenges to dark matter, dark energy and galaxy formation"
@Physics Institute, University of Sao Paulo, Brazil
(Feb. 18 – 20, 2019)

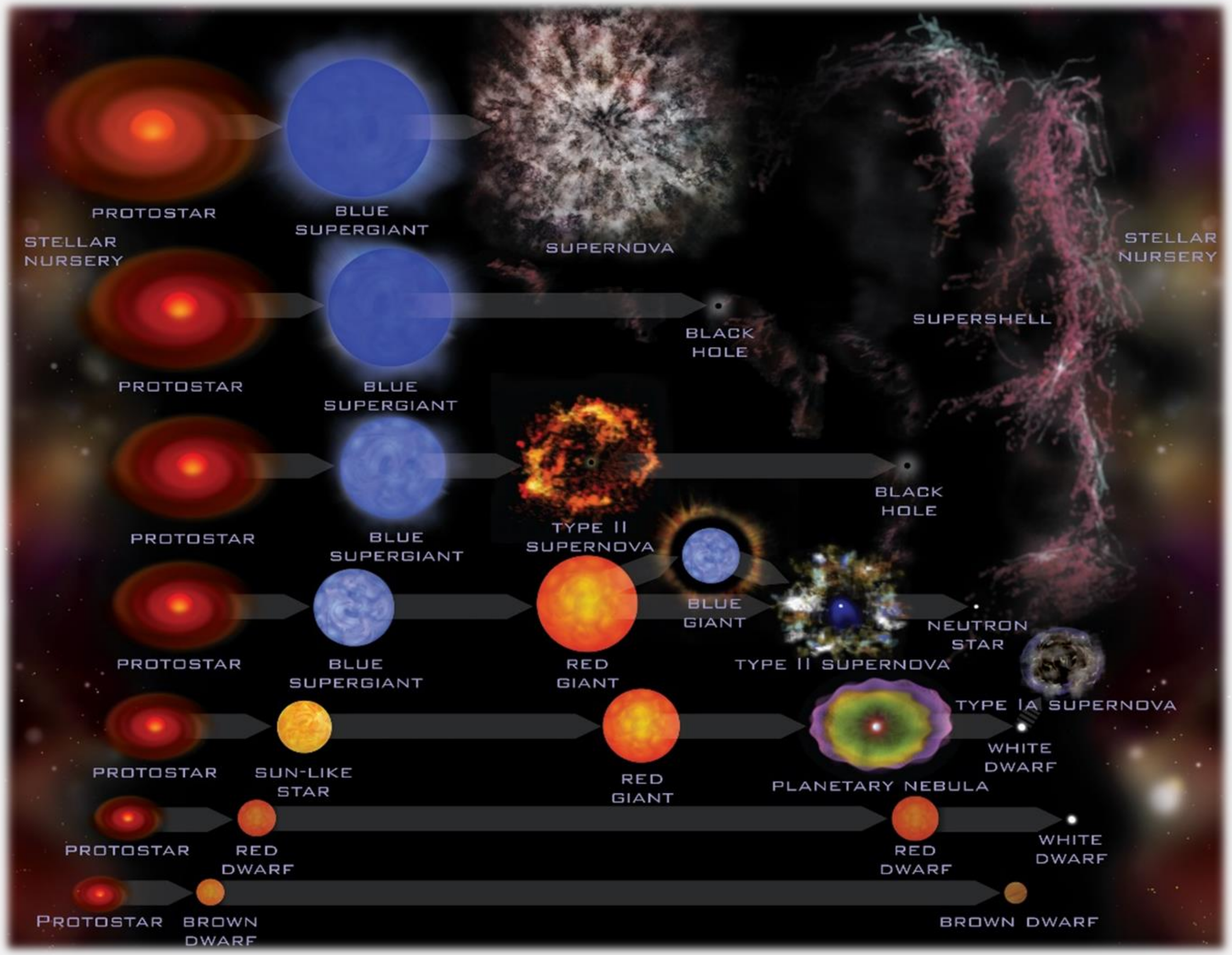
“Environmental Dependence of the First Star Formation”

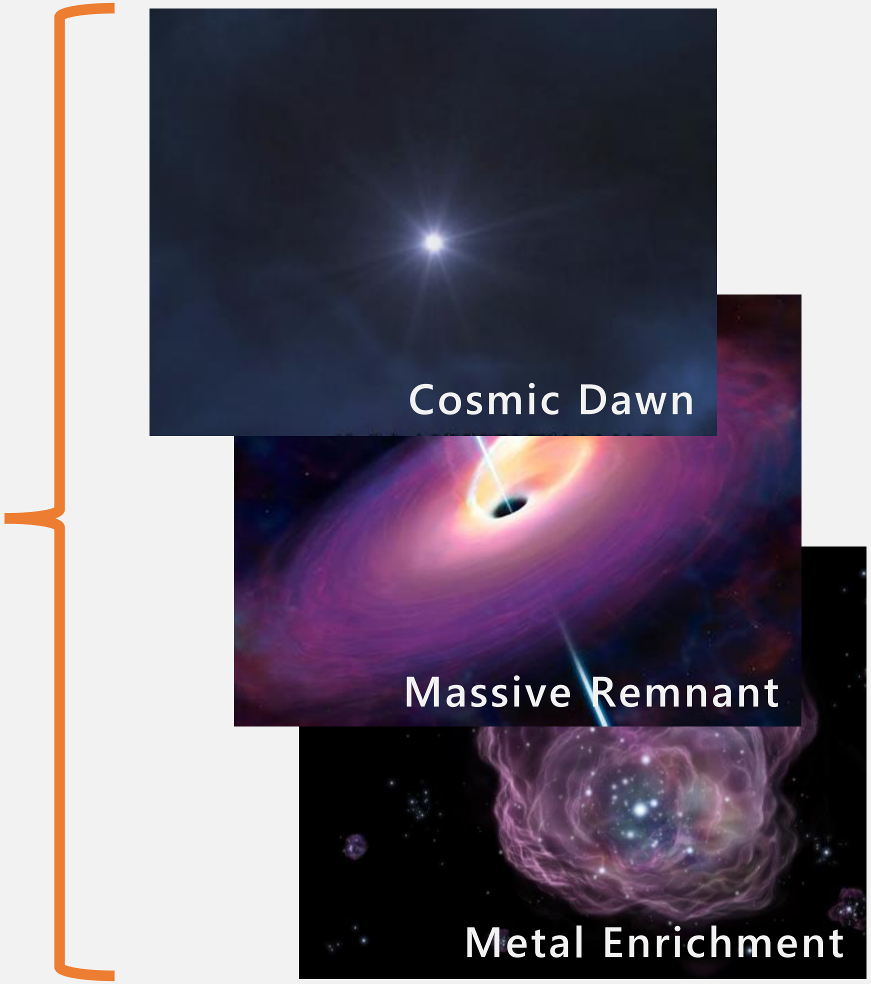
Shingo Hirano

S. Hirano, T. Hosokawa, N. Yoshida & R. Kuiper (2017) Science, 357 (1375)
“Supersonic Gas Streams Enhance the Formation of Massive Black Holes in the Early Universe”
S. Hirano, N. Yoshida, Y. Sakurai & M. S. Fujii (2018) Astrophysical Journal, 855 (17)
“Formation of the first star cluster and massive star binaries by fragmentation of filamentary primordial gas clouds”

First Stars (1st-generation stars)

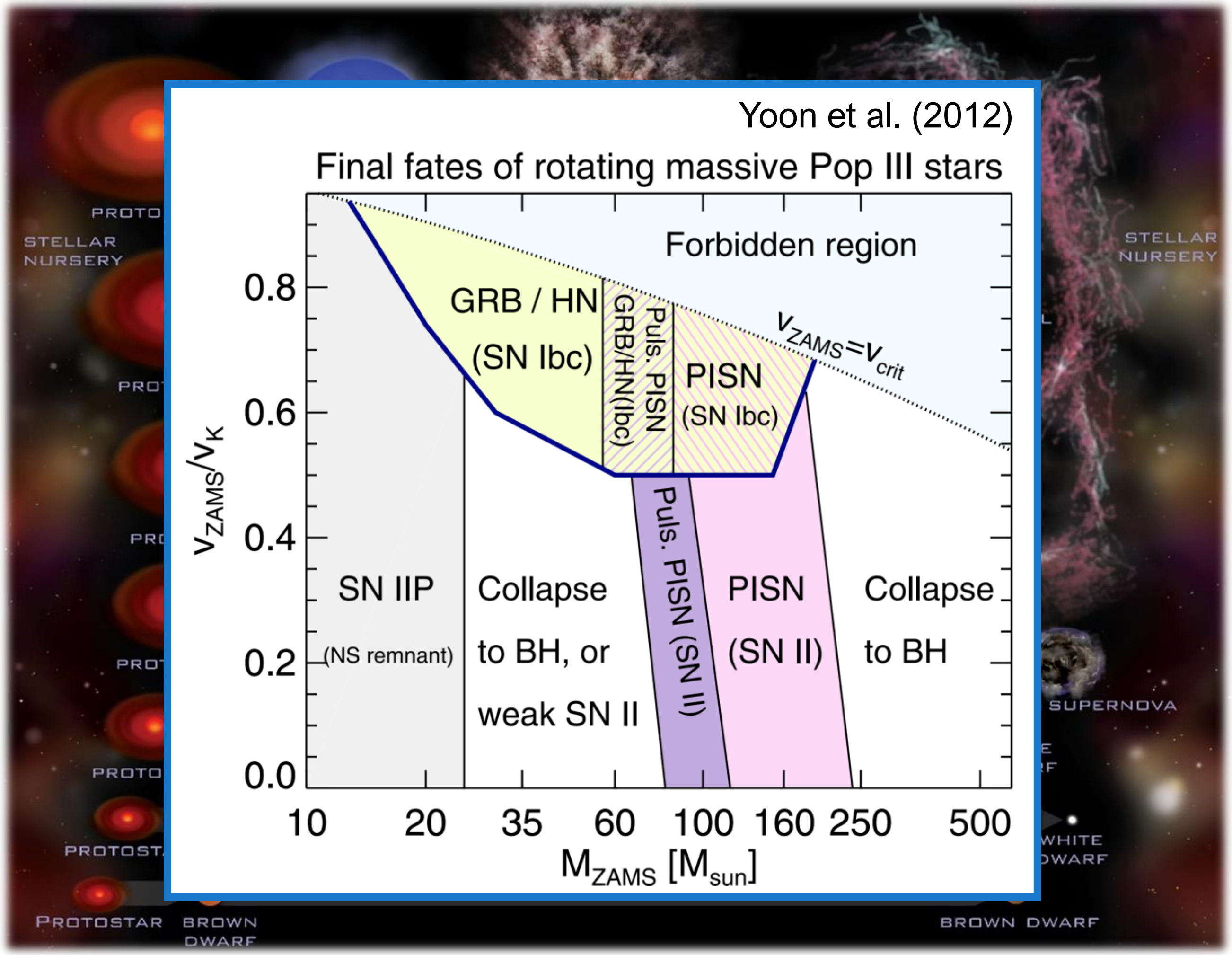
formed from the primordial gas (H, He, light atoms).

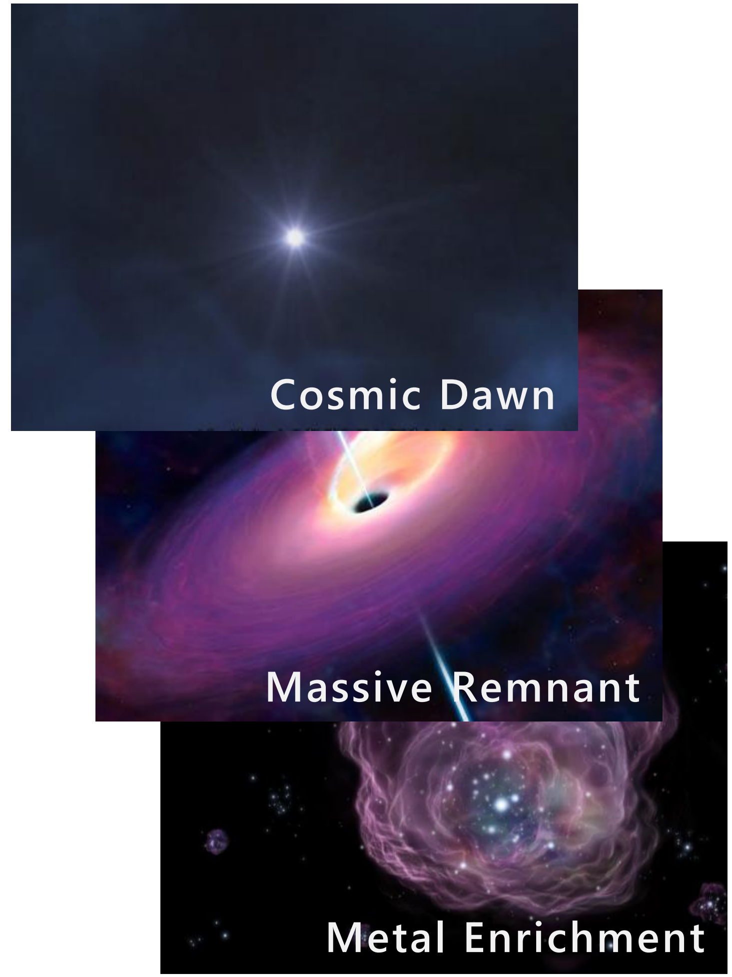




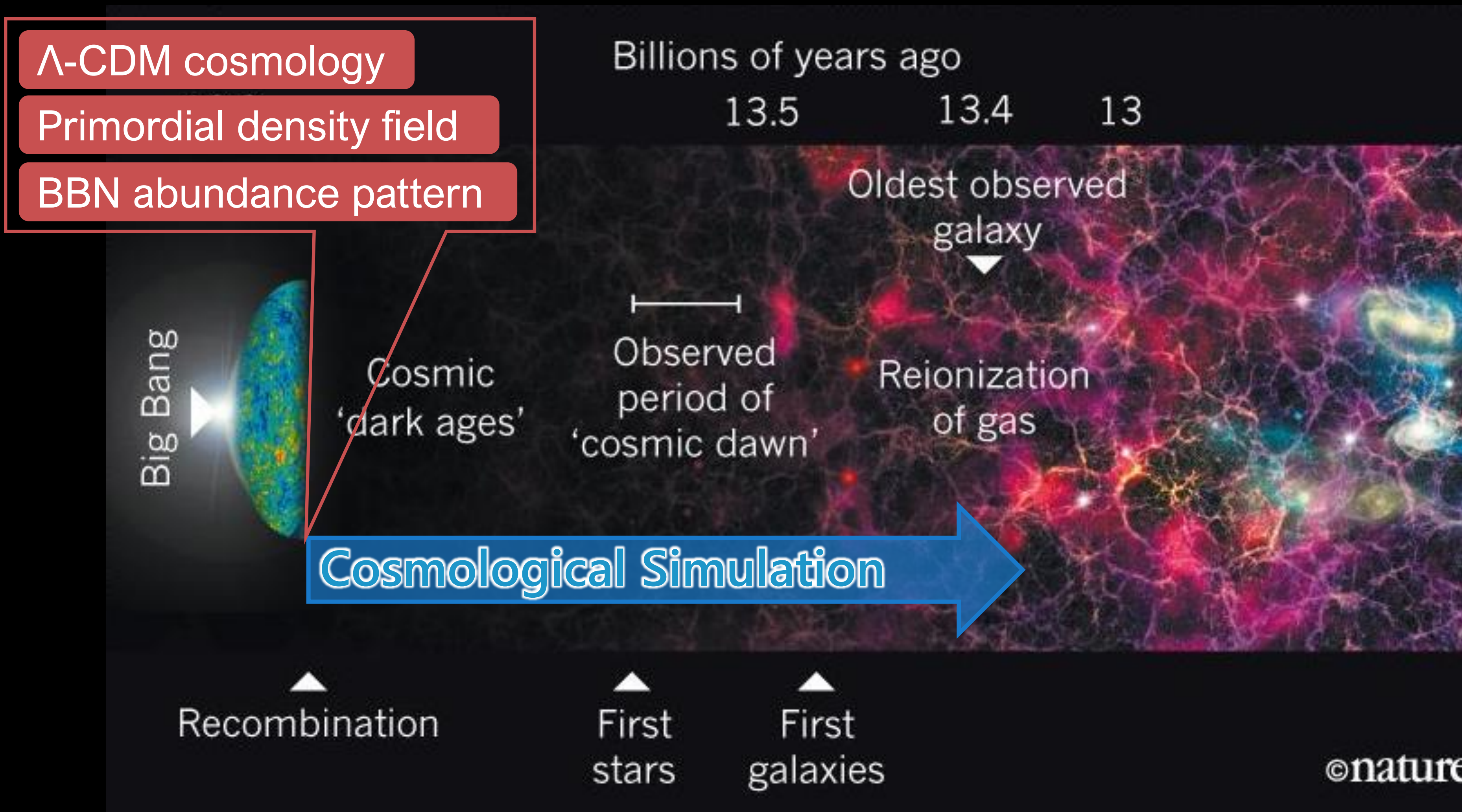
First Stars (1st-generation stars)

formed from the primordial gas (H, He, light atoms).



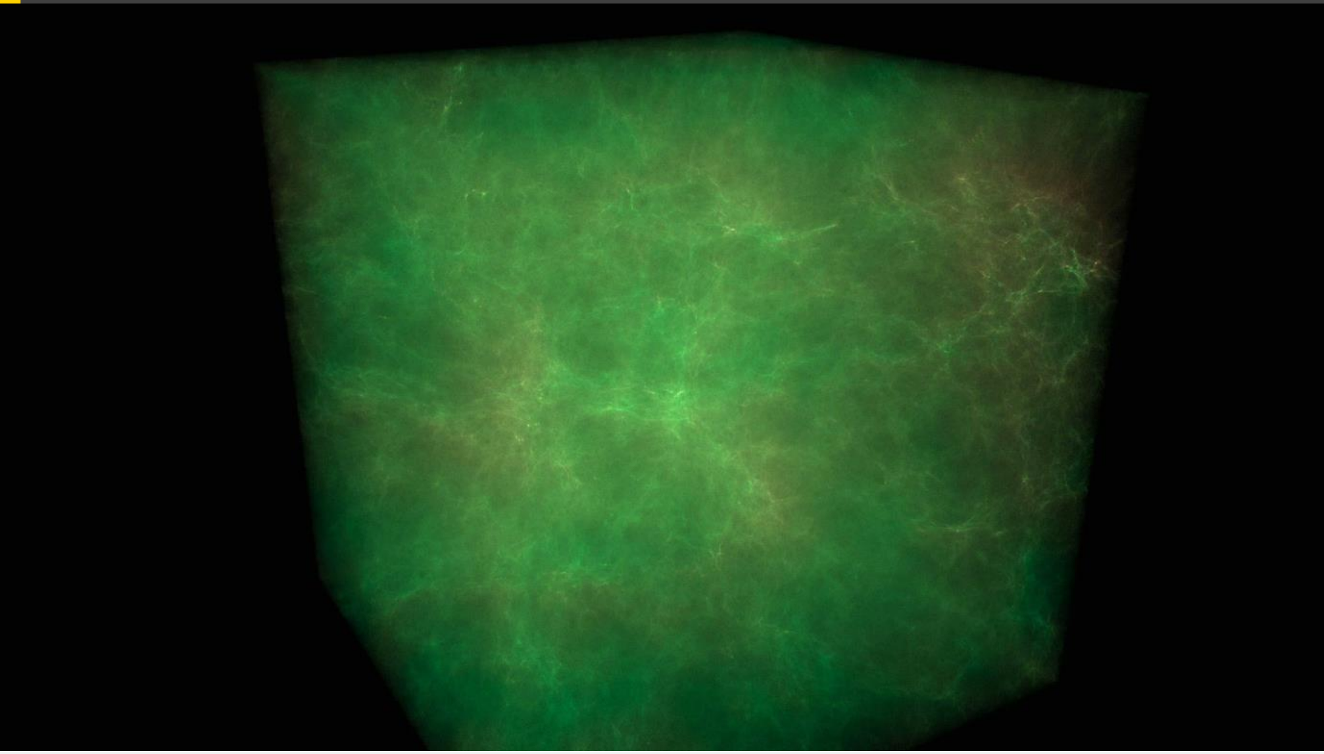


Ab initio Cosmological Simulation



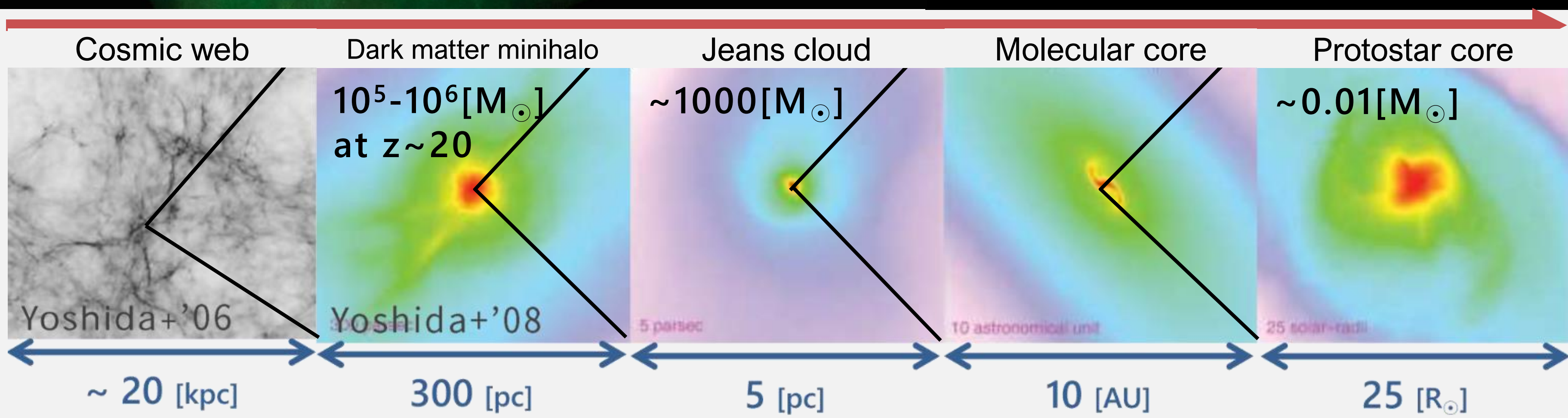
Physical properties of the primordial star-forming cloud can be reproduced theoretically & numerically by performing the cosmological simulation

Formation Path of the First Stars



Cosmological hydro simulation
by Gadget-3 (Springel'05)
N-body (DM) + SPH (Gas)
+Primordial chemistry
+Hierarchical zoom-in
+Particle splitting (L_{Jeans}/L_{sph} > 15)

Simulation by SH
Visualization by Takaaki Takeda (VASA)



Star-forming Gas Cloud

FS formation is a collaborative work between the cosmology and astrophysics.

First Star Formation Process

Λ-Cold Dark Matter Cosmology
→ Primordial density perturbation
→ Large-scale structure
→ Dark matter minihalo
→ Molecular gas cloud
→ Tiny protostellar core
→ First Star

Dark Matter dominated

Baryon (gas) dominated

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

$$= 0.01\left(\frac{T_{\rm Jeans}}{10\ [{\rm K}]}\right)^{1.5}\left(\frac{n_{\rm H}}{10^{10}\ [{\rm cm}^{-3}]}\right)^{-0.5} [{\rm M}_\odot]$$ **Solar-metallicity**

Star-forming Gas Cloud

FS formation is a collaborative work between the cosmology and astrophysics.

First Star Formation Process

Λ-Cold Dark Matter Cosmology

→ Primordial density perturbation

→ Larg

→ Dark

→ Mole

→ Tiny

→ First

Dark Matter

$$M_{\mathrm{Jeans}} \propto c_s^3$$

$$\rightarrow (c_s^2 + v^2)^{3/2}$$

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

$$= 0.01 \left(\frac{T_{\mathrm{Jeans}}}{10\ [\mathrm{K}]}\right)^{1.5} \left(\frac{n_{\mathrm{H}}}{10^{10}\ [\mathrm{cm}^{-3}]}\right)^{-0.5} [\mathrm{M}_\odot]$$ **Solar-metallicity**

1 | Formation of the First Stars

Ab initio cosmological simulation ➔ Stellar mass

Star-forming gas cloud = Jeans scale

2 | Baryon-DM Relative Motion

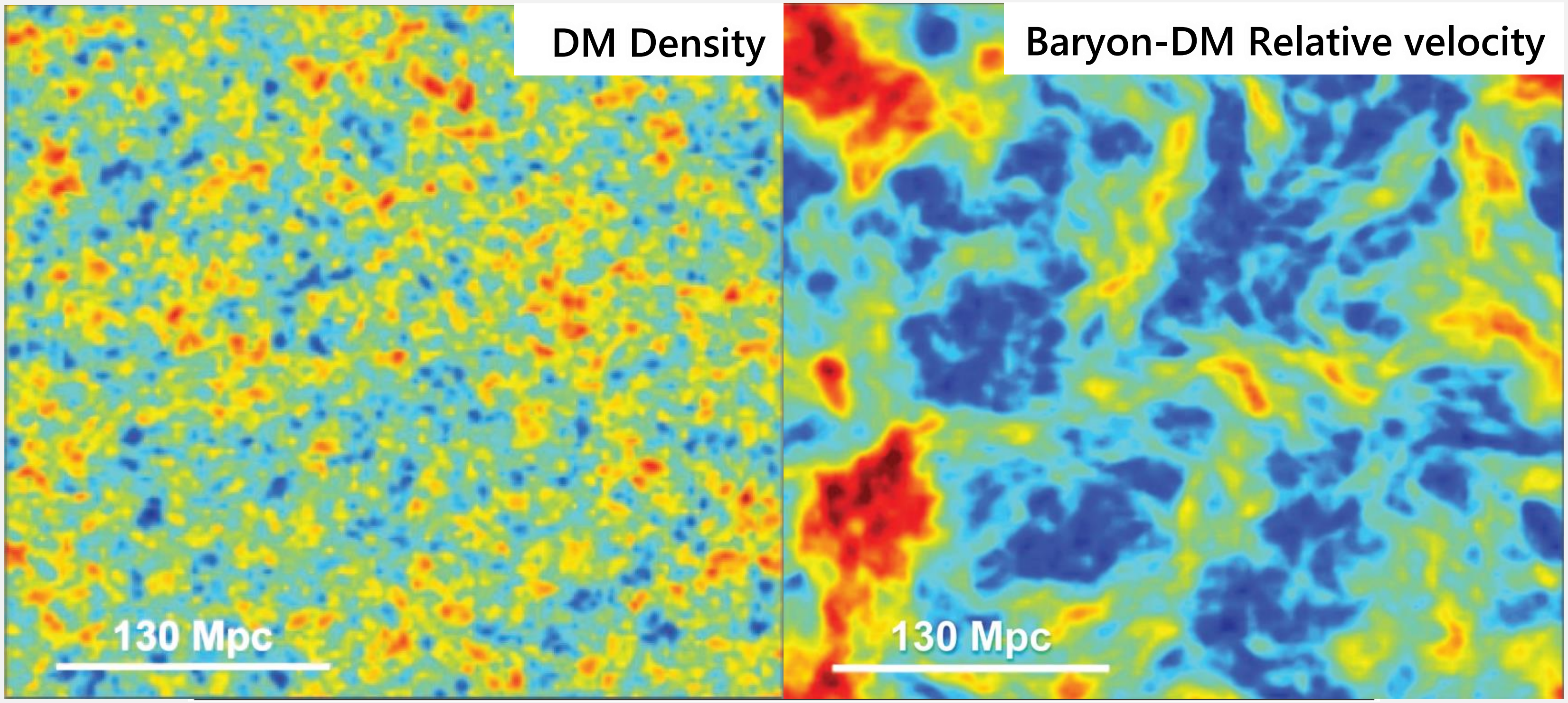
3 | Dependence of the First Star Formation

4 | Observational Counterpart

5 | Summary

Baryon-DM Relative Motion

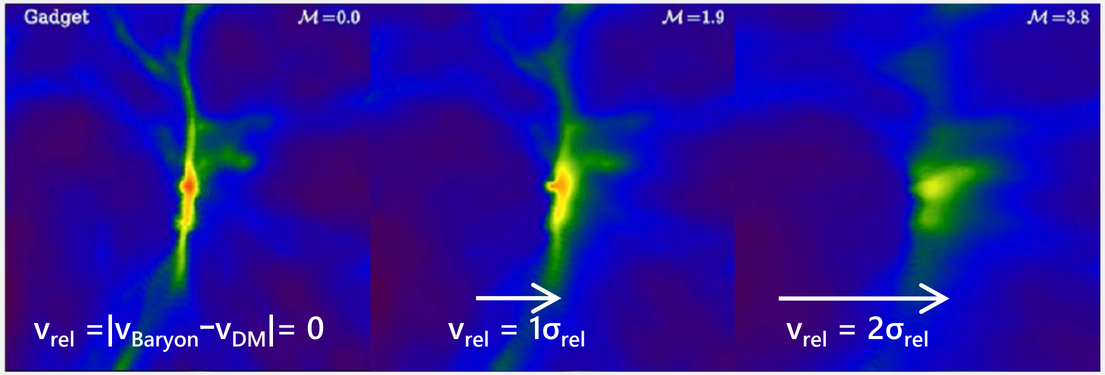
Supersonic coherent (~ a few Mpc) flows of the baryons relative to the underlying potential wells created by DM at z_{rec}.



"The relative motion suppresses the abundance of the first objects"
(Tseliakhovich & Hirata 2010)

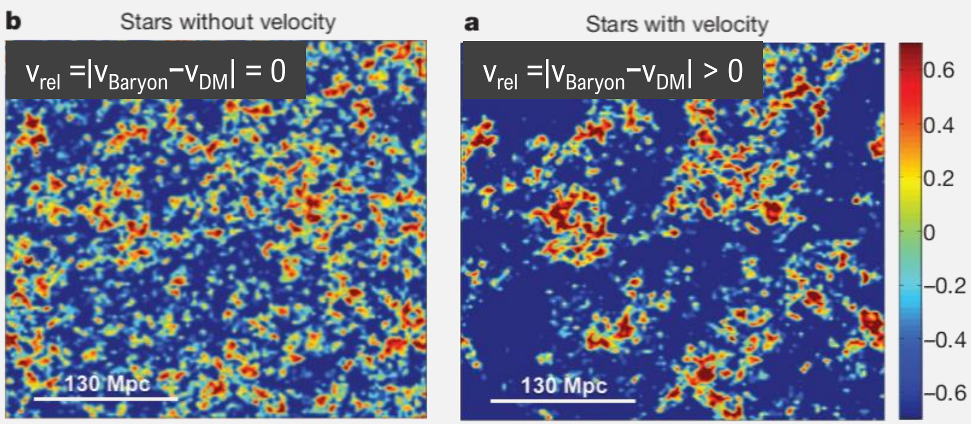
Suppression of the Early Structure Formation

Small-Scale



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

Large-Scale



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

Suppression of gas condensation:

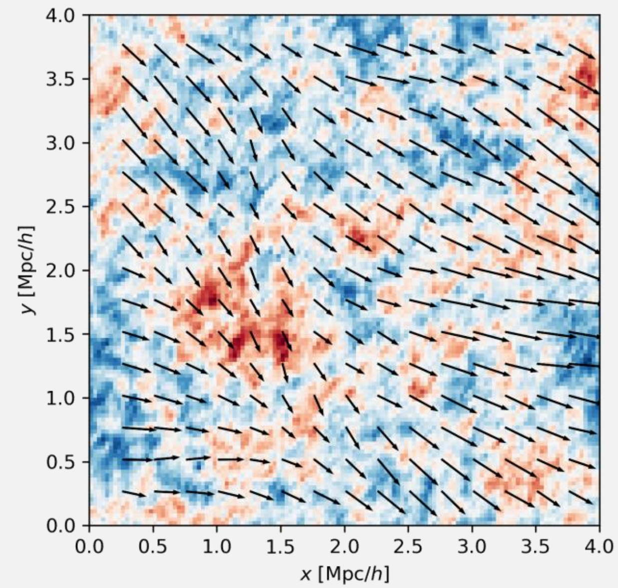
- Abundance of DM halo
- Baryon fraction
- Subsequent star formation
- Stellar/galactic feedbacks
- …

Inhomogeneous influence on large-scale structure:

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

Influence on the FS Formation

$L_{coherent}$ ~ a few cMpc >> $L_{1st\text{-}object}$ (~10 kpc)



$v_{bc}(z) = |v_{baryon} - v_{CDM}| = v_{bc,rec}\,(1+z)/(1+z_{rec})$

$M_{Jeans} \propto (c_s^2 + v_{bc}(z)^2)^{3/2}$

- c_s ~ 1 [km/s] for the FS formation
- σ_{bc} = 30 [km/s] … RMS value of v_{bc} at $z = z_{rec}$

$c_s \sim v_{bc}(z=30)$ for $v_{bc,rec} = 1.17\sigma_{bc}$
$c_s \sim v_{bc}(z=20)$ for $v_{bc,rec} = 1.73\sigma_{bc}$
$c_s \sim v_{bc}(z=10)$ for $v_{bc,rec} = 3.30\sigma_{bc}$

$$P_{vbc}(v) = \left(\frac{3}{2\pi\sigma_{vbc}^2}\right)^{3/2} 4\pi v^2 \exp\left(-\frac{3v^2}{2\sigma_{vbc}^2}\right)$$

$v_{bc}/\sigma_{v_{bc}}$	$P(> v_{bc})$
4	2.1×10^{-10}
3	5.9×10^{-6}
2	7.4×10^{-3}
1	0.392
0	1

Simulation of FS Formation

[0] **Initial Condition** (with the Λ-CDM cosmology)

by "MUSIC" (hierarchical zoom-in technique; Hahn & Abel 2011)

+ Coherent, relative motion between baryon and DM

MODEL PARAMETERS	
	$v_{bc} = |v_{baryon} - v_{CDM}| = X\sigma_{bc}$ (X = 0, 1, 2, 3) σ_{bc} = 30 [km/s] … root-mean-square value of v_{bc} at $z = z_{rec}$

[1] **Collapse Phase** (until $n_{H,cen} = 10^{13}$ [cm^{-3}])

by parallel N-body + SPH code "Gadget-3" (Springel 2005)

+ Primordial chemistry (Yoshida et al. 2006; 2007; SH et al. 2015)

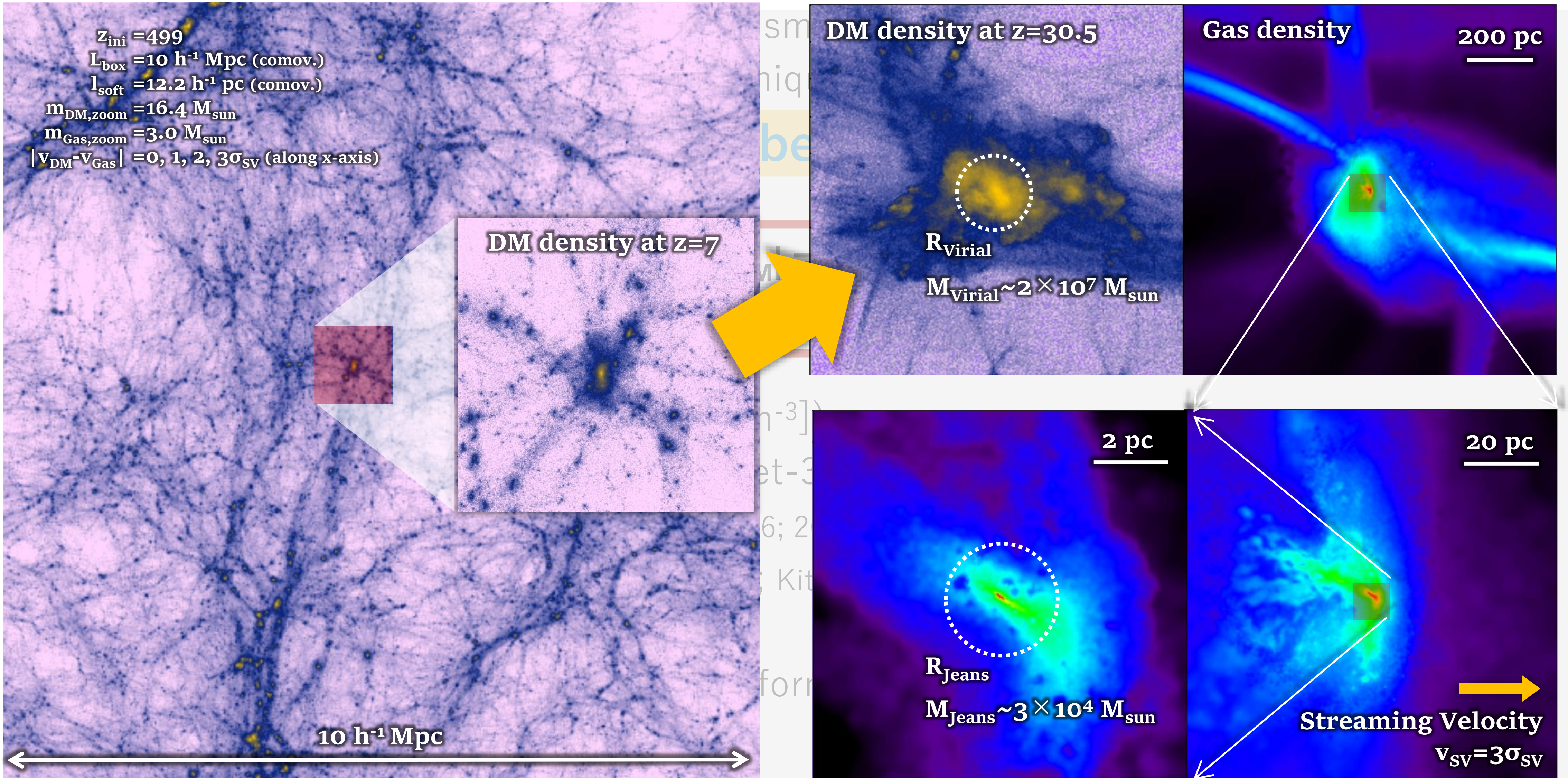
+ Particle splitting ($L_{HSML} / L_{Jeans} > 10$; Kitsionas&Whitworth 2002)

[2] **Accretion Phase** (after the protostar formation)

by 3D-RHD code "PLUTO"

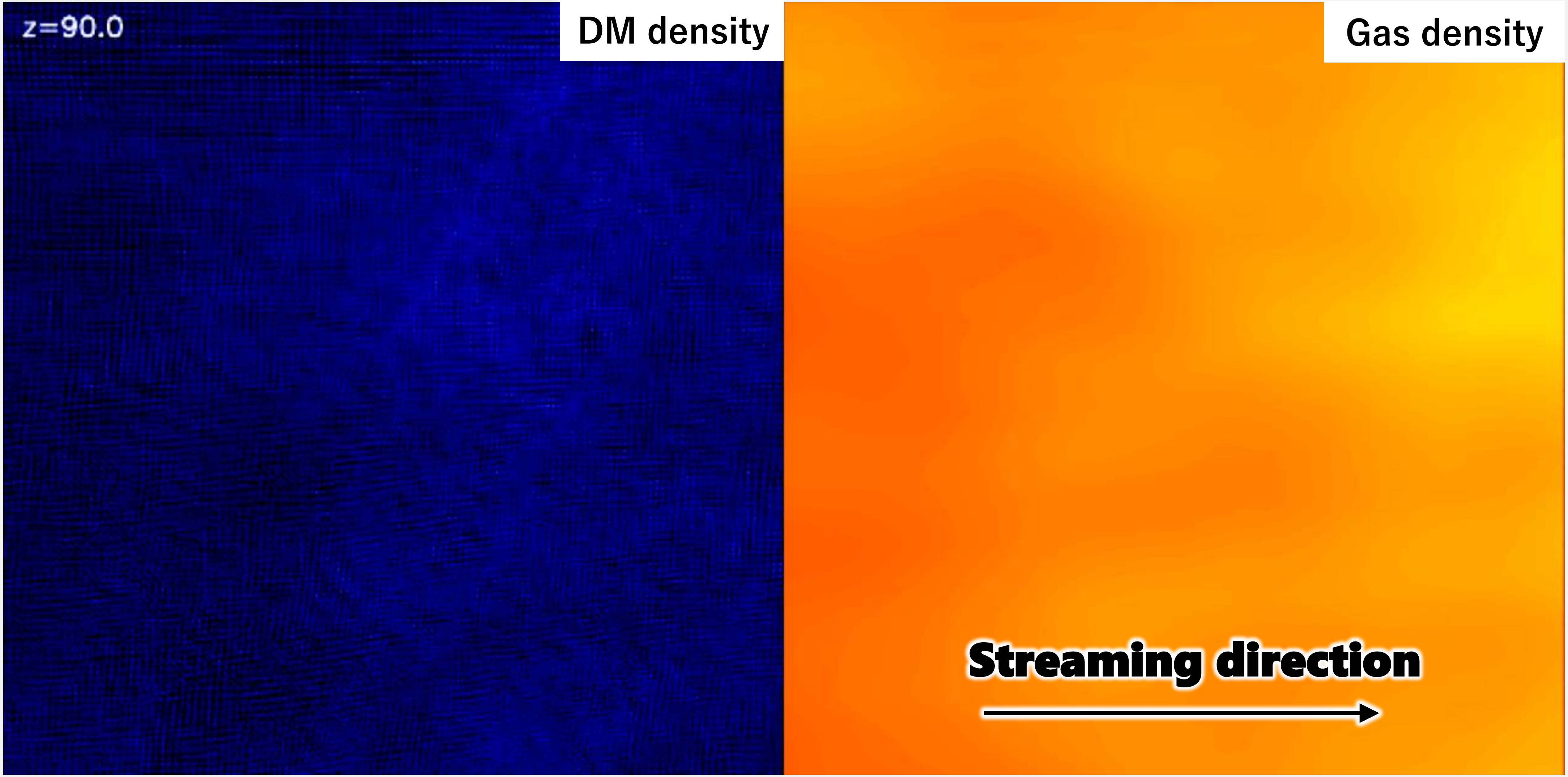
+ stellar evolution code "STELLAR"

Simulation of FS Formation



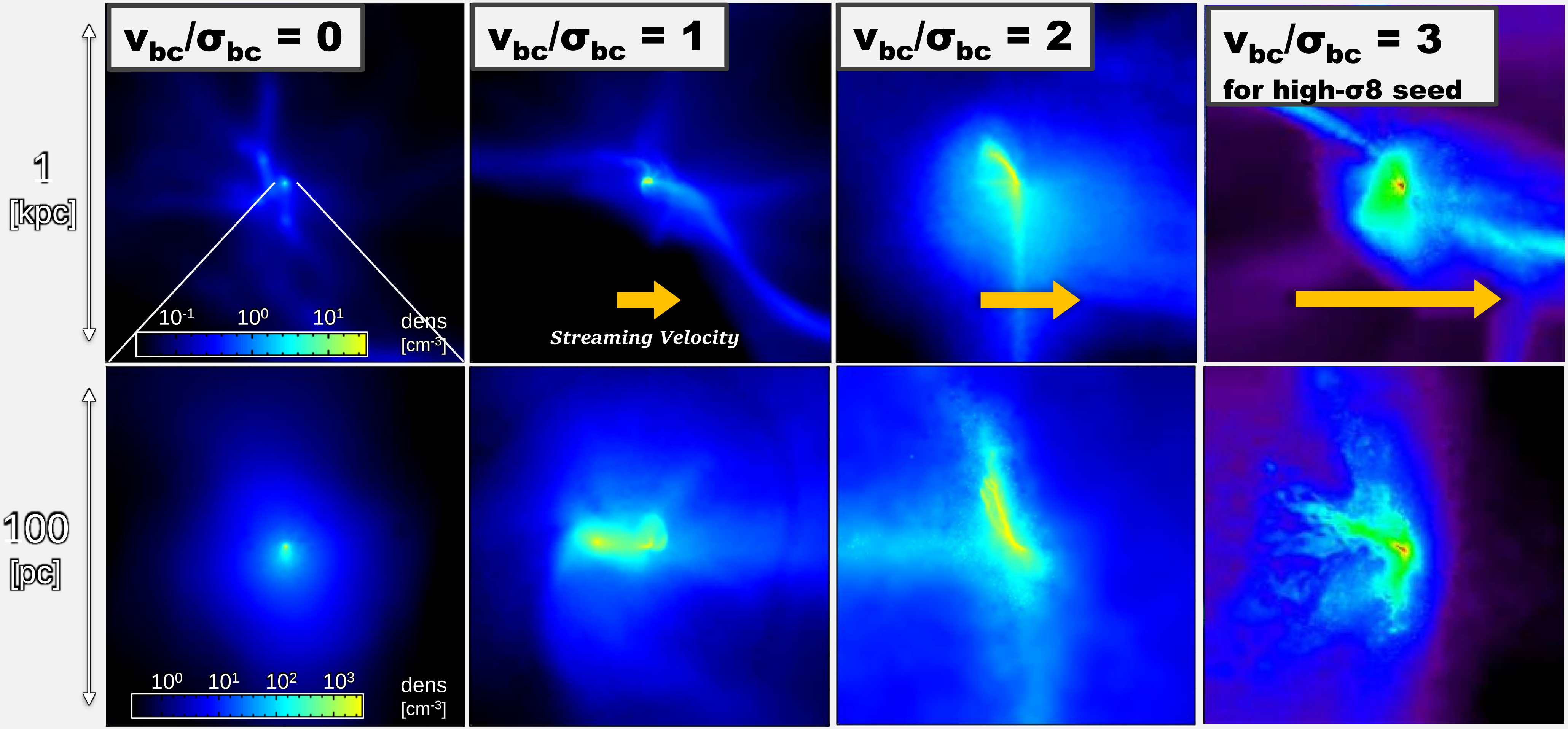
+ stellar evolution code "STELLAR"

Example | $v_{bc}/\sigma_{bc} = 3$



Baryon-DM relative velocity decreases with time as $v_{bc}(z) = v_{bc,rec}(1+z)/(1+z_{rec})$

Density map | v_{bc} / σ_{bc} = 0, 1, 2, 3

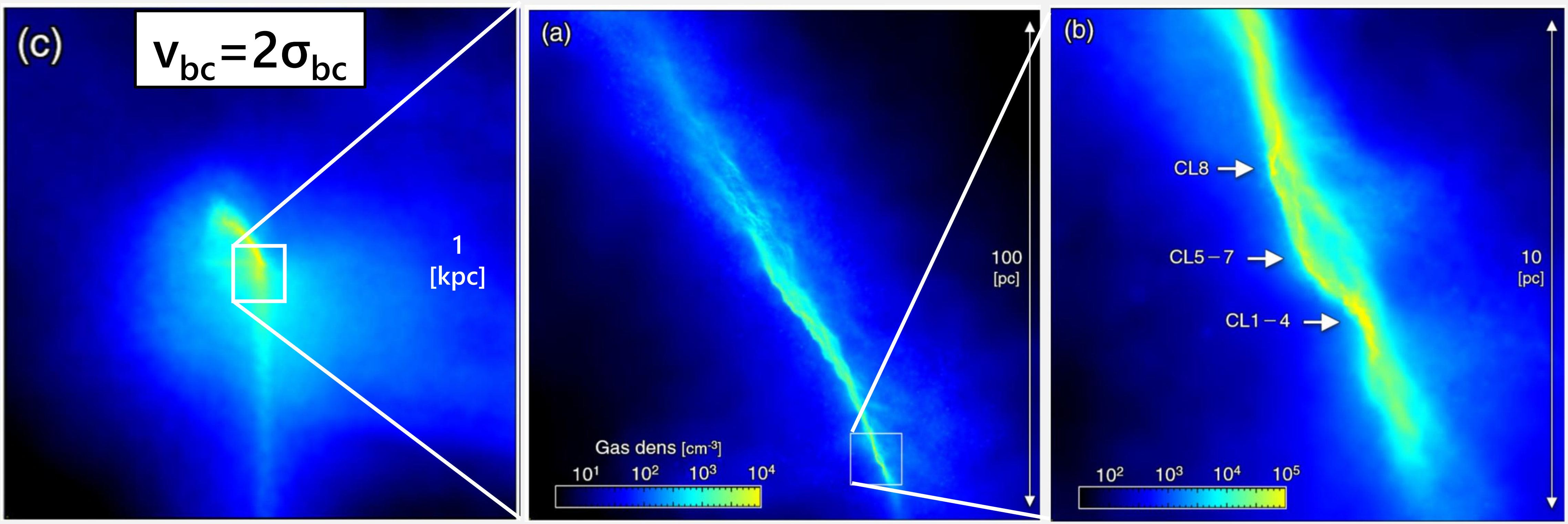


M_{halo} [$M_\odot$]	1.6×10^5	2.2×10^6	3.4×10^7	2.2×10^7
M_{Jeans} [$M_\odot$]	360	1,000 (twin)	200-400 (multiple)	26,000

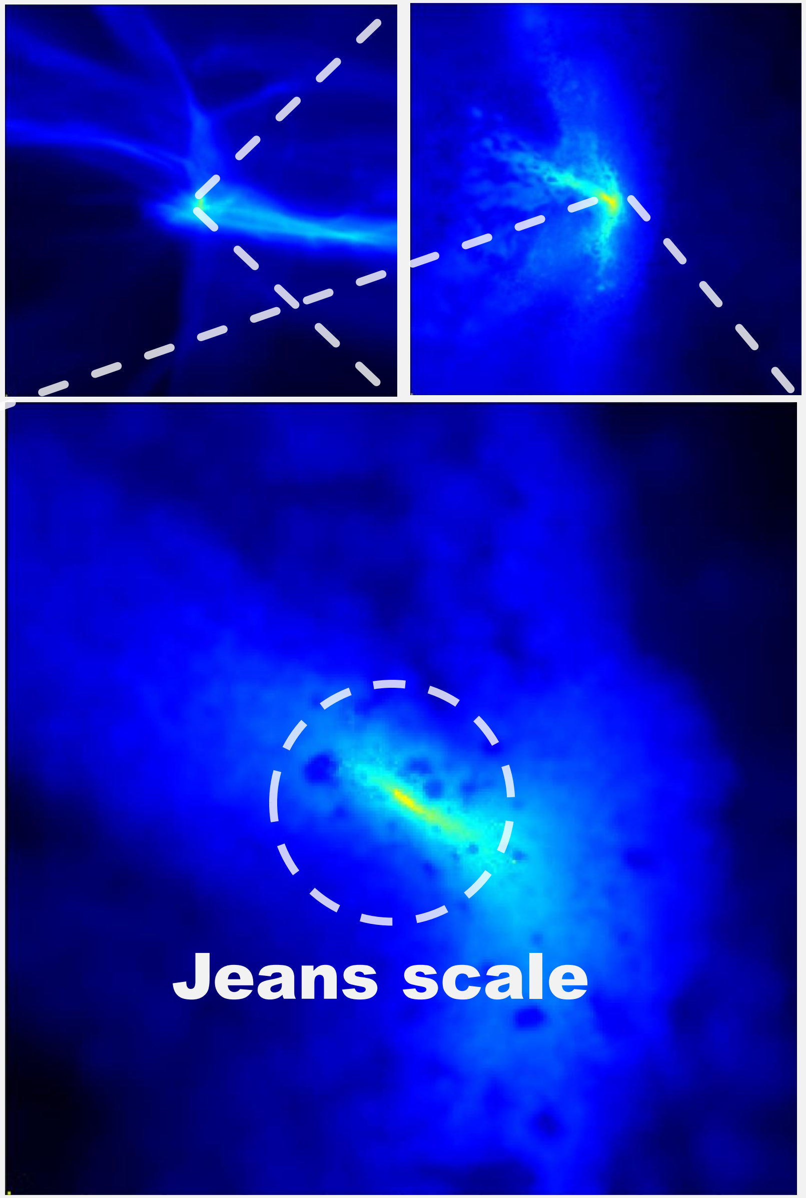
$v_{bc} / \sigma_{bc} = 2$ | Cluster of the First Stars

Large filamentary structure (with ~10^4 [$M_\odot$]) fragments to 8 clouds with ~200 – 400 [$M_\odot$] (filamentary instability)

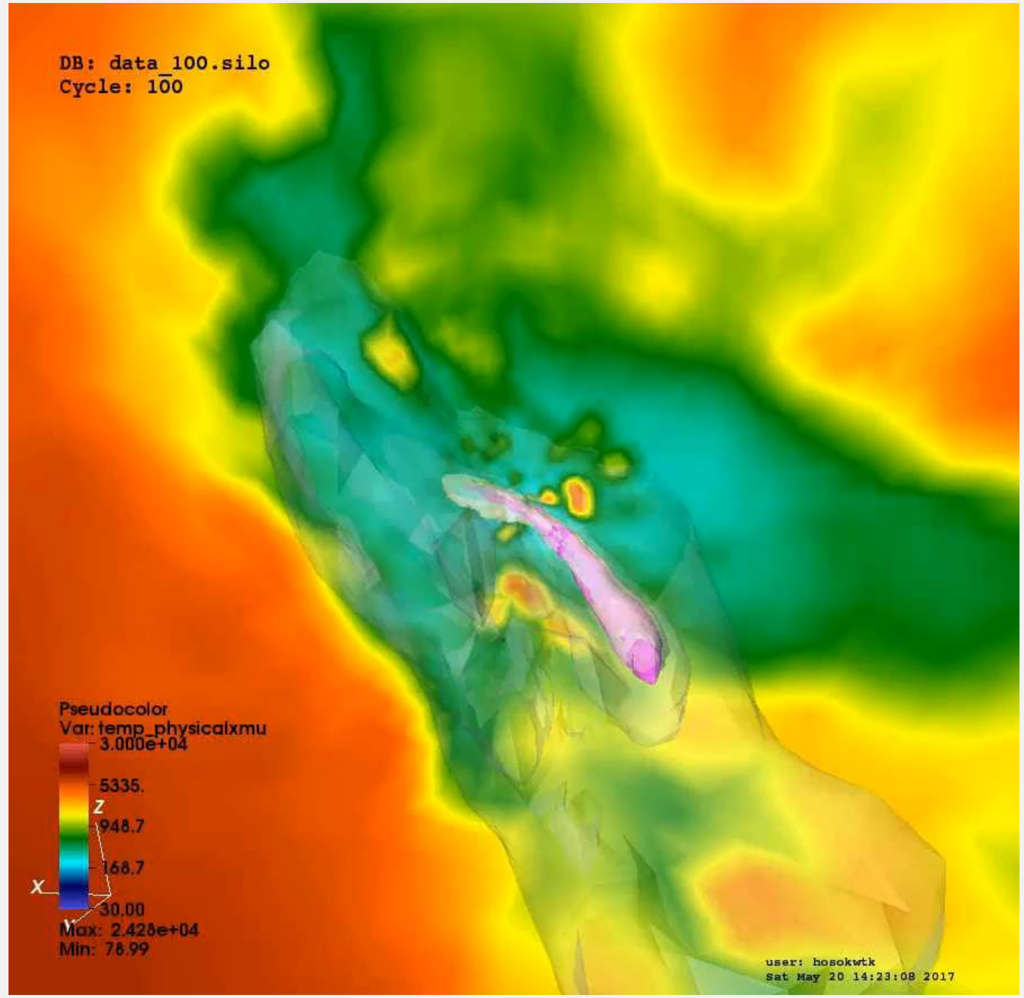
➔ First stars with 50 – 120 [$M_\odot$]



$v_{bc} / \sigma_{bc} = 3$ | Supermassive first star

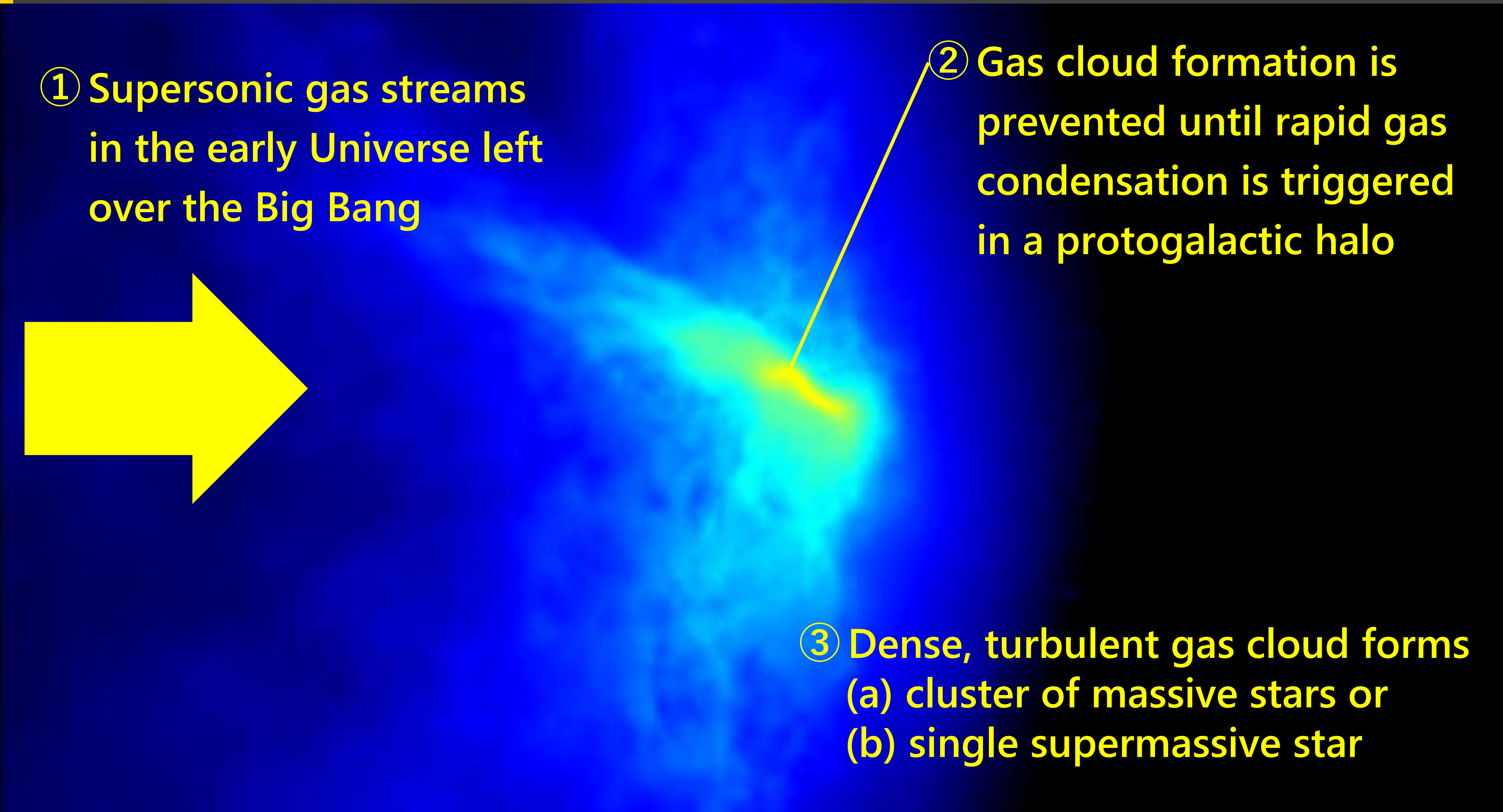


3D RHD Simulation of the mass growth of the protostar via mass accretion

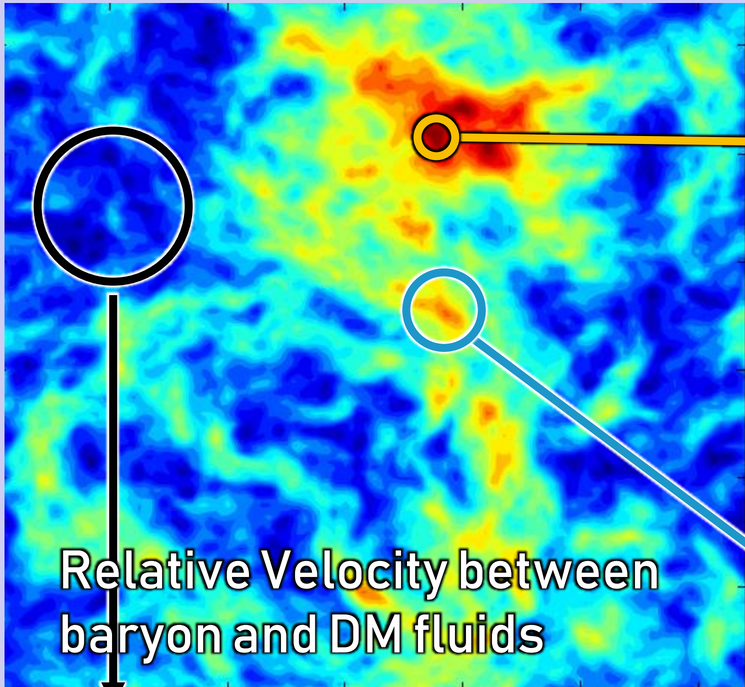


v_{bc} (σ_{bc})	σ_8	z	R_{virial} (pc)	M_{virial} ($M_\odot$)	V_{virial} (km s^{-1})	M_{Jeans} ($M_\odot$)	t_{acc} (10^6 yr)	M_{star} ($M_\odot$)
3	1.2	30.5	171	2.2×10^7	13.3	26,000	0.60	34,000

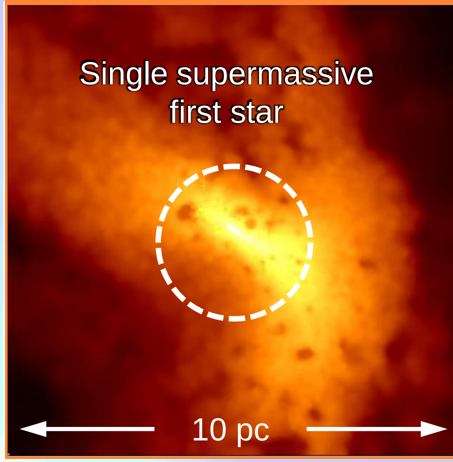
Dependence of the First Star Formation



Dependence of the First Star Formation



Rapid Relative Vel.

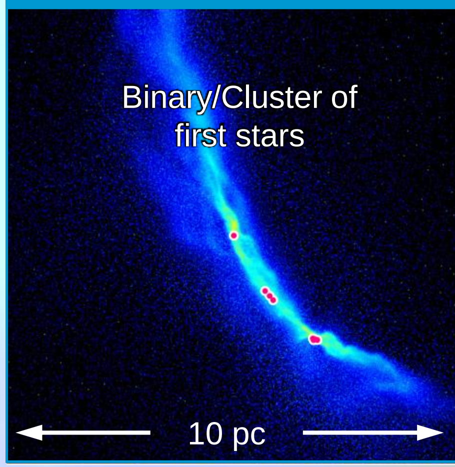


10^4-10^5[$M_\odot$] Pop III star at z~30

⬇

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

Slow Relative Vel.

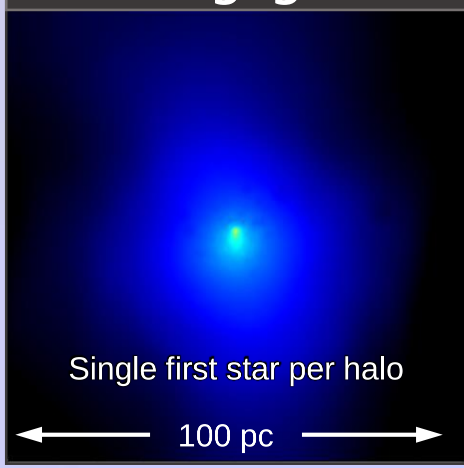


~10 Pop III stars with 100[$M_\odot$] at z~15

⬇

Massive BH binary (GW progenitor)

Negligible Relative Vel.

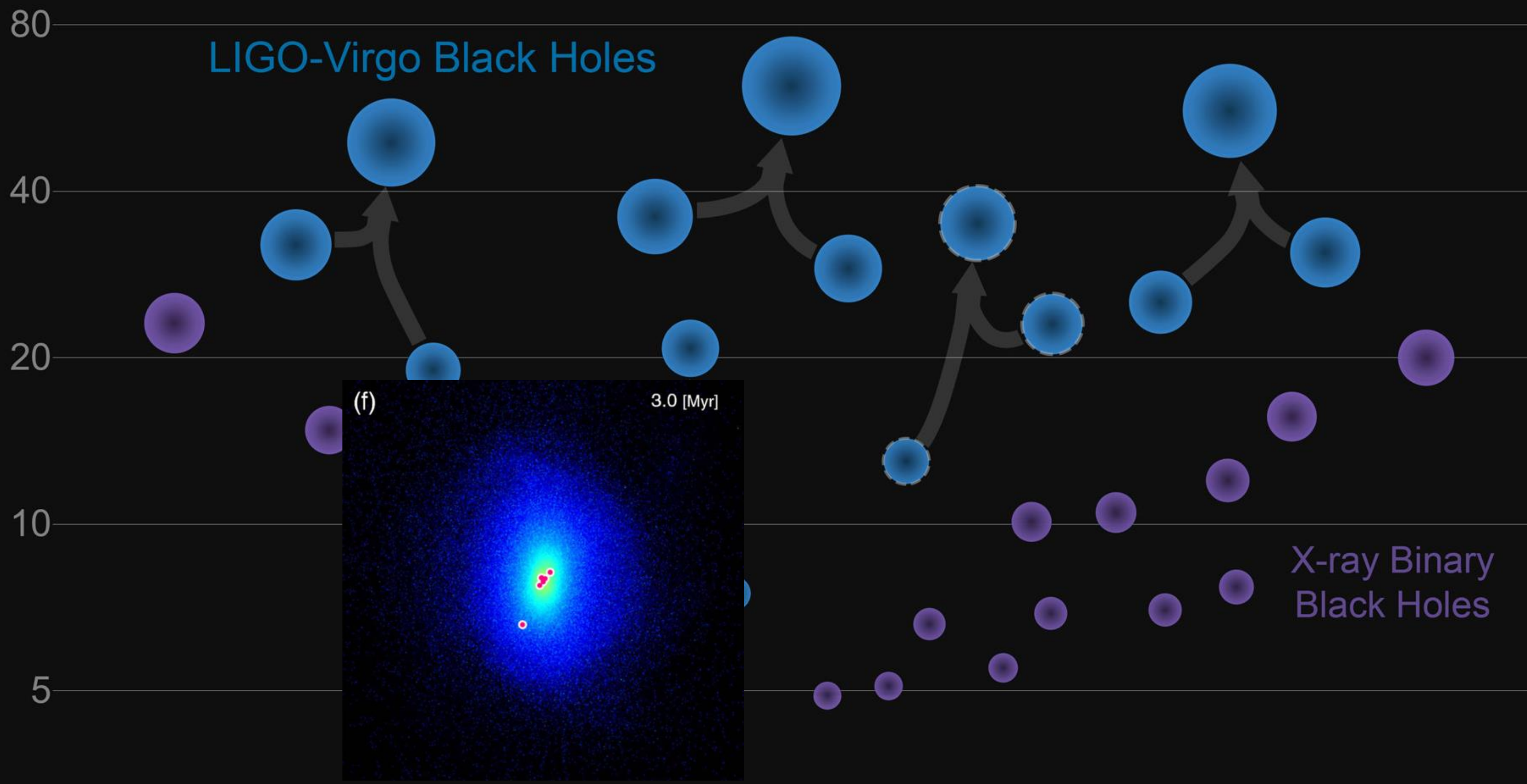


Pop III stars with ~100 [$M_\odot$] around z~15-25

⬇

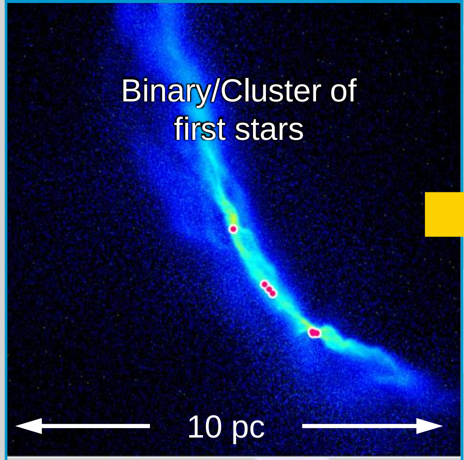
Parent stars of observed EMPs

Source of the Gravitational Wave Signal



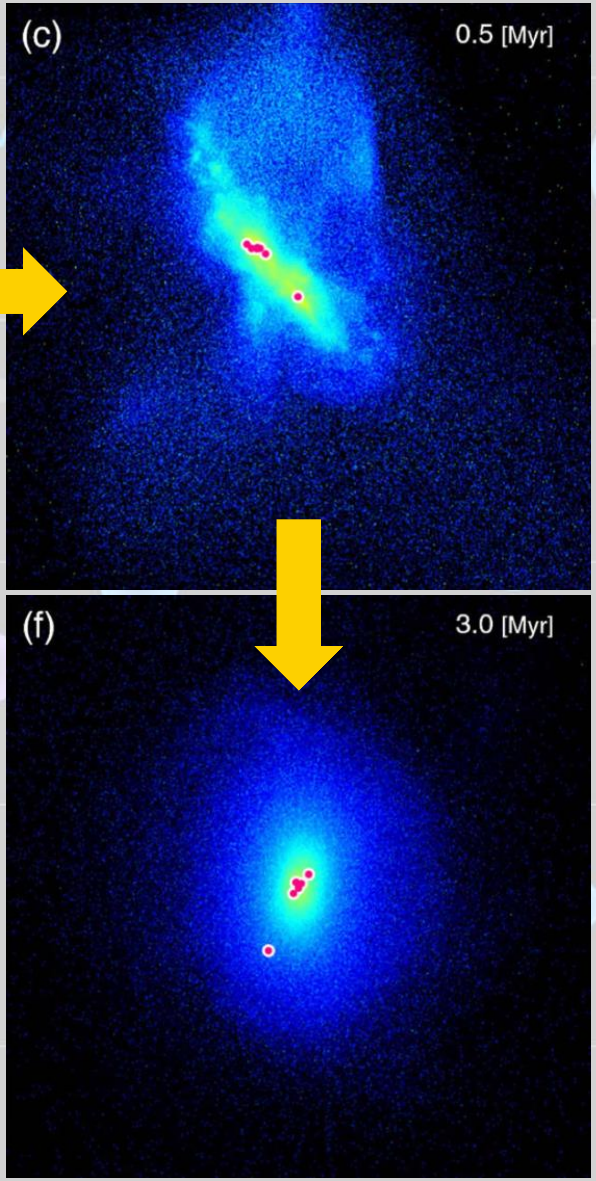
Source of the Gravitational Wave Signal

Slow Relative Vel.

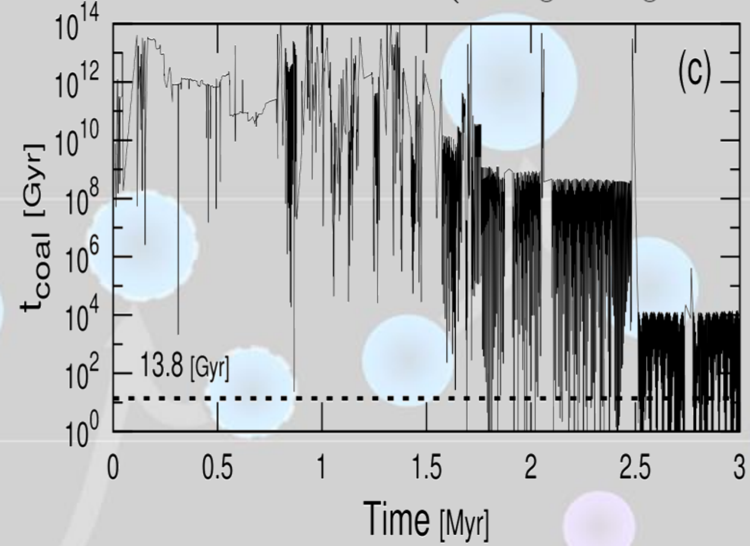


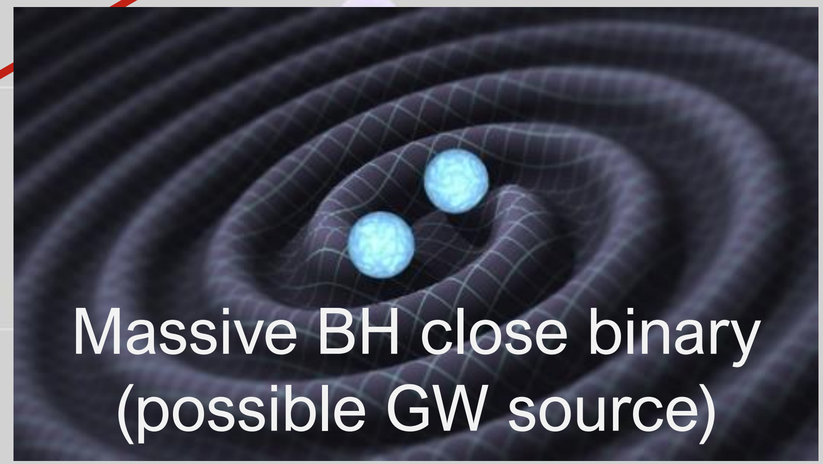
~10 Pop III stars with
100[$M_\odot$]
at z~15

Massive BH binary
(GW progenitor)



$$t_{\rm coal} \sim 10\,{\rm Gyr}\left(\frac{a_0}{0.2\,{\rm au}}\right)^4 (1-e_0)^{7/2}\left(\frac{M_1}{30\,M_\odot}\,\frac{M_2}{30\,M_\odot}\,\frac{M_1+M_2}{60\,M_\odot}\right)^{-1}$$

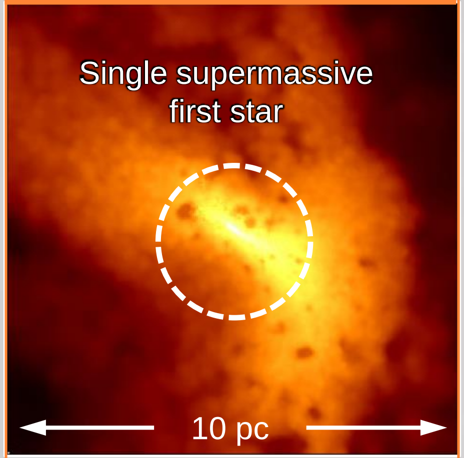




Seed of the SuperMassive Black Holes

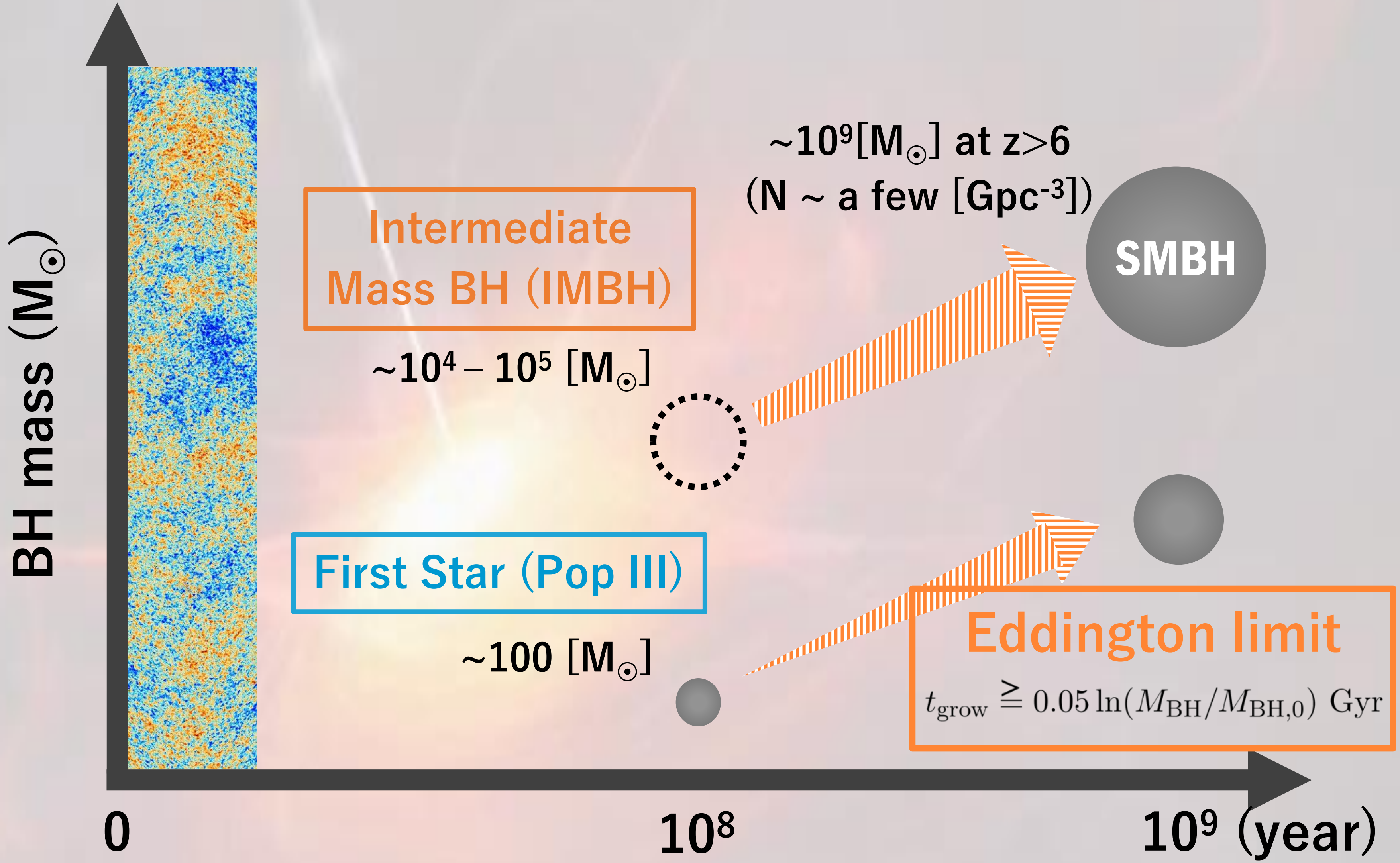
Seed of the SuperMassive Black Holes

Rapid Relative Vel.



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

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



Summary

Supersonic gas motions left over from the Big Bang are intrinsically generated in the early universe according to the standard model of structure formation.

The baryonic streaming motions prevent early gas cloud formation until rapid gas condensation is triggered in a protogalactic halo.

“Environmental Dependence of the First Star Formation”
➔ SINGLE, MULTIPLE, and SUPERMASSIVE first star(s) form depending on the degree of the streaming velocity.

Constraint DM Nature by FS Formation

Acceptable FS formation have to be realized.

- WIMPs DM self-annihilation

EVOLUTION OF PRIMORDIAL STARS POWERED BY DARK MATTER ANNIHILATION UP TO THE MAIN-SEQUENCE STAGE

Shingo Hirano[1], Hideyuki Umeda[1], and Naoki Yoshida[2]

- Not yet observationally constrained primordial power-spectrum

EARLY STRUCTURE FORMATION FROM PRIMORDIAL DENSITY FLUCTUATIONS WITH A BLUE, TILTED POWER SPECTRUM

Shingo Hirano[1], Nick Zhu[1,2], Naoki Yoshida[1,3], David Spergel[2], and Harold W. Yorke[4]

- Warm, Fuzzy, … DM(s)

First star formation in ultralight particle dark matter cosmology

Shingo Hirano ✉, James M Sullivan, Volker Bromm

- Baryon-DM cross-section (EDGES 21cm signal)
- …

Baryon-dark matter scattering and first star formation

Shingo Hirano ✉, Volker Bromm