High Resolution Simulation of First Generation Star Formation

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FIRST
The Origin of FIRST Generation Objects

Mass of the First Stars

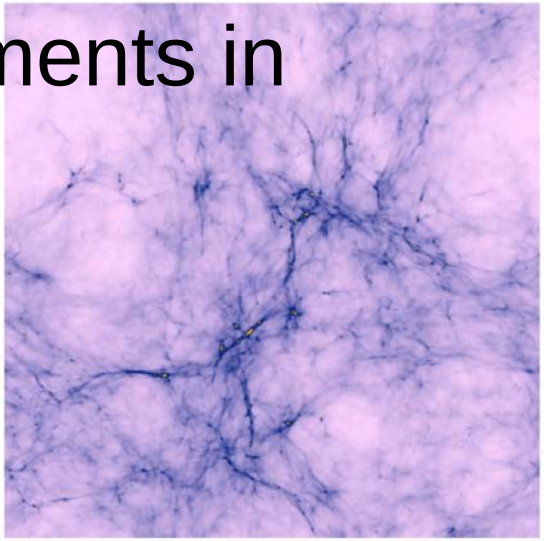
- Massive stars (≧100 $M_{\odot}$)
  - Bromm, Coppi, & Larson (2002)
    - Clumps of ~1000$M_{\odot}$ is formed
  - Yoshida et al.(2006)
    - M_{ZAMS}～100$M_{\odot}$
  - O'Shea & Norman (2007)
    - 12 simulations of adaptive mesh refinement (AMR)
    - Isolate core which suggest stellar mass of ~100$M_{\odot}$
- Low mass stars (～1$M_{\odot}$)
  - Low mass stars can be formed by fragmentation of dense ($n>10^5 cm^{-3}$) filament (Nakamura & Umemura 2001).

FIRST The Origin of FIRST Generation Objects

Problems

- What is the functional form of the primordial IMF?
- Whether or not low-mass star can be formed by fragmentation of filaments in realistic situation?

Yoshida et al. (2006)



This work

- Using uniformly high-resolution cosmological simulation, we investigate a density peak of our simulation box.

FIRST Cluster

- **Hybrid PC cluster system**
  - **256 (16 x 16) node 2U-size server PC**
    - **496 CPU ＋
16 Blade-GRAPE
224 Blade-GRAPE X64**
  - **Main memory:
240 x 6GB + 16 x 10GB
= 1.6 TB**
  - **Total performance (Host): 3.1 Tflops**
- **Each node equip a newly-developed board for gravity calculations, Blade-GRAPE**

Blade-GRAPE

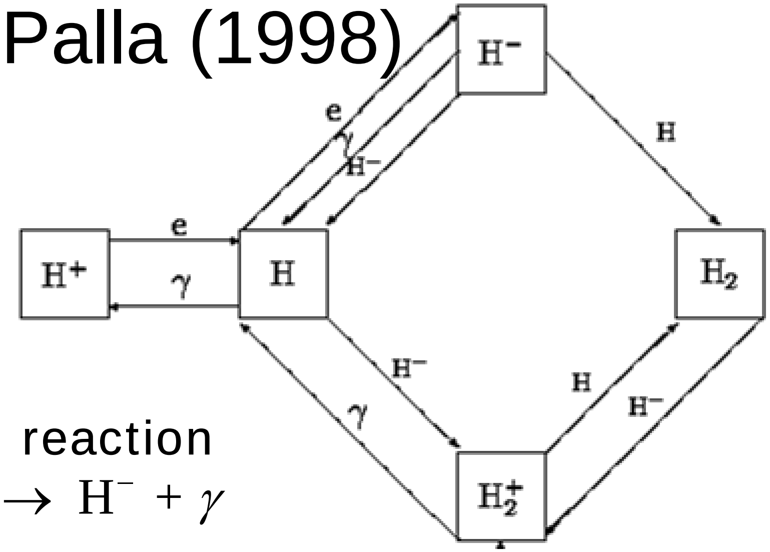
- Blade-GRAPE
  - Embedded Special Purpose Processor for Gravity
  - Each board has 16MB memory
    - Corresponds to 256K particles at the maximum
  - Theoretical peak performance: 136.8 GFlops
- Blade-GRAPE X64
  - **64 bit PCI-X version with FPGA**
  - newly developed in 2006
- Total performance:
  33 Tflops

P^3M + GRAPE+SPH

- Gravitational forces are solved by Particle-Particle-Particle-Mesh (P^3M) scheme
  - PP-part is accelerated by Blade-GRAPE
  - Calculation with GRAPE is about 10 times faster than that by host CPUs
- Hydrodynamic processes are solved by Smoothed Particle Hydrodynamics (SPH) scheme (Springel & Hernquist 2002)

Chemical reaction & heating/cooling

- 6 species of chemical elements are included (e^-, H, H^+, H^-, H_2, H_2^+)
  - Minimal model of Galli & Palla (1998)



- Main reaction
  - Low density ($n<10^8 cm^{-3}$)

Proton reaction

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

$$H_2^+ + H \rightarrow H_2 + p$$

Electron reaction

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

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

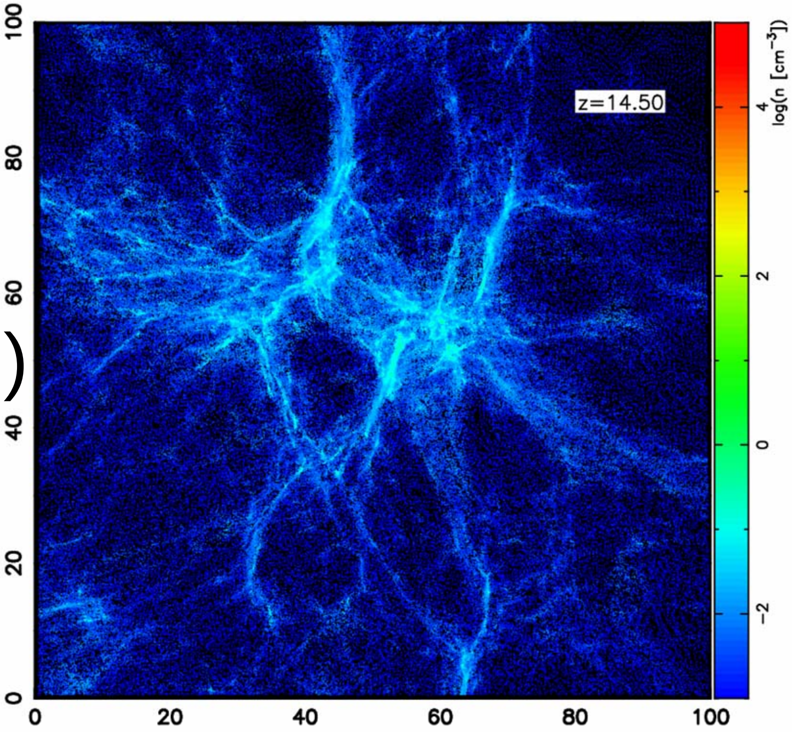
  - High density ($n>10^8 cm^{-3}$)

$$3H \rightarrow H_2 + H$$ 3-body

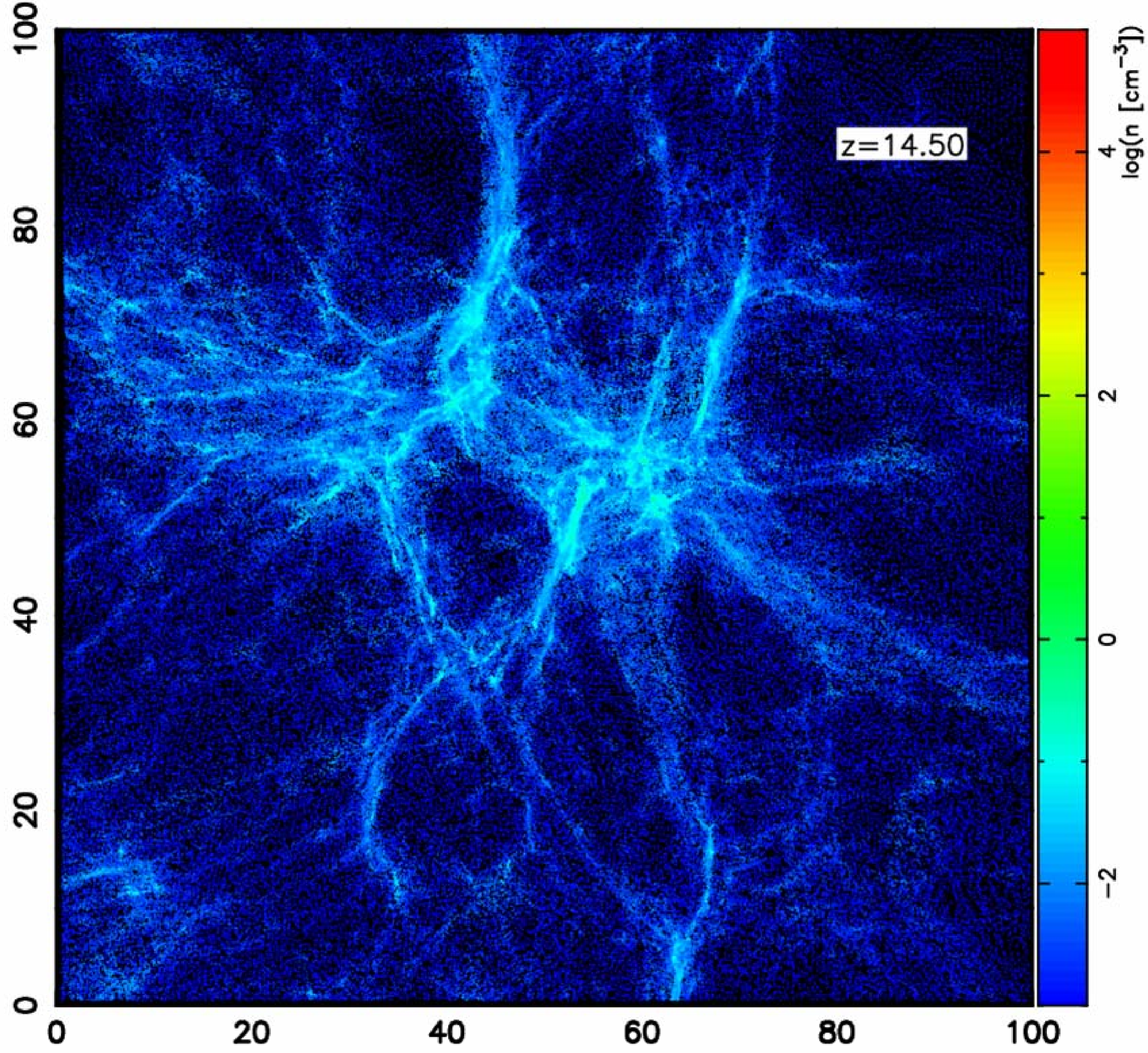
$$2H + H_2 \rightarrow 2H_2$$

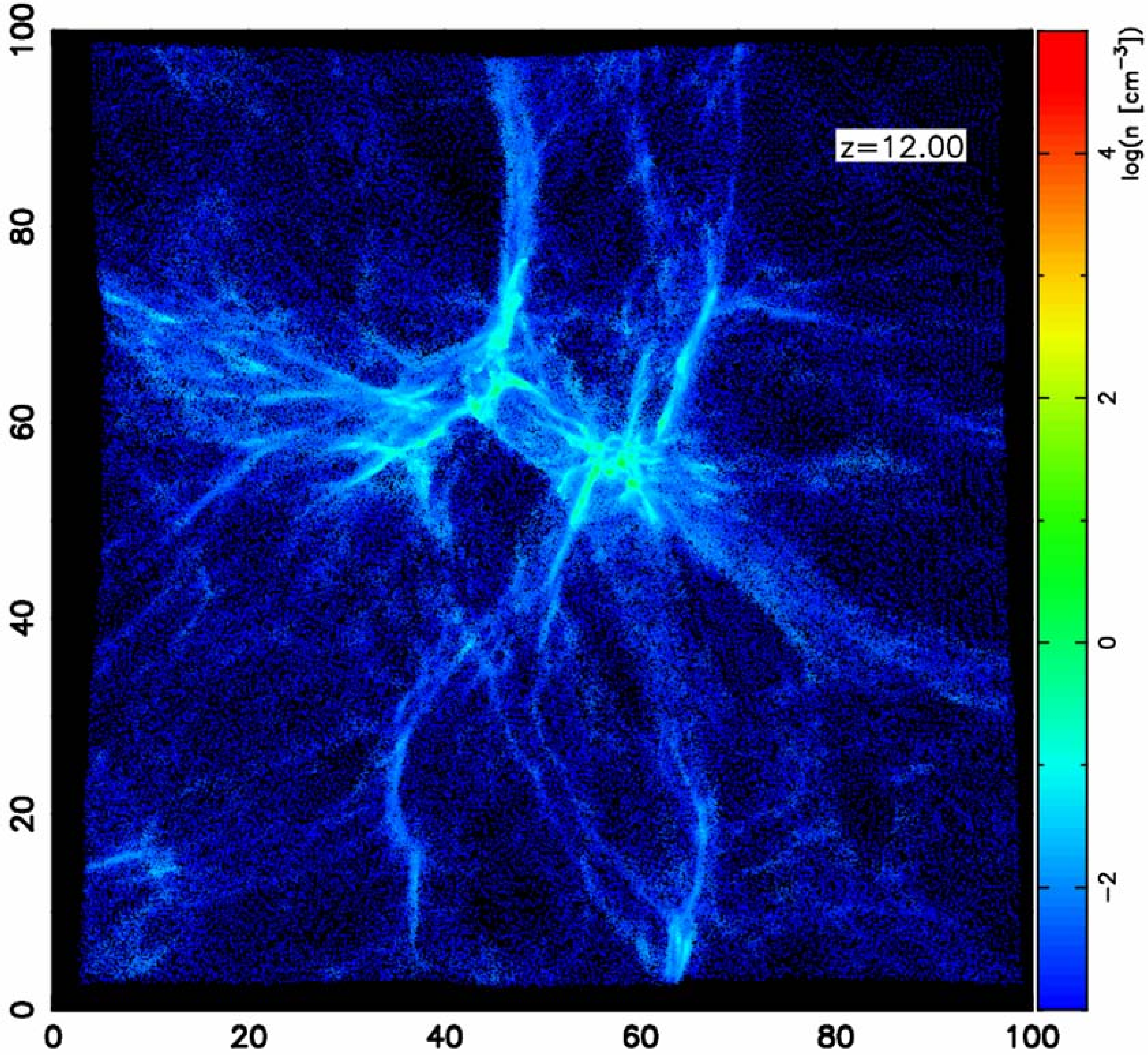
Simulation setup

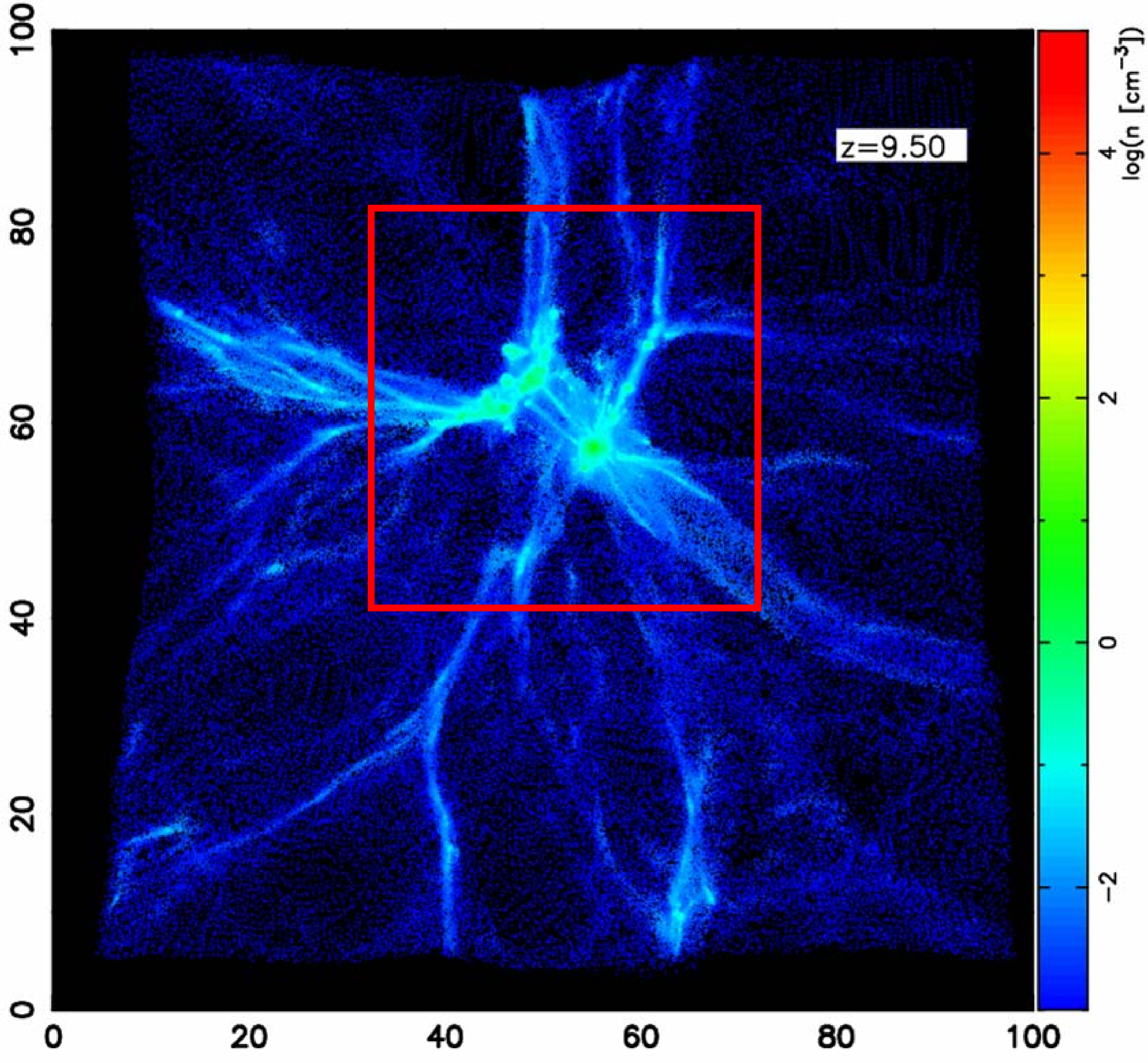
- # of particles: 2×30 million（DM＋SPH）
- Mass resolution:
  - 0.3M_O (SPH)
  - 1.5M_O (DM)
- Box size: 100kpc (comoving)
- Mesh Size: L_{box}/256
- Initial condition is generated at z=15 using truncated Zeldvich approx.

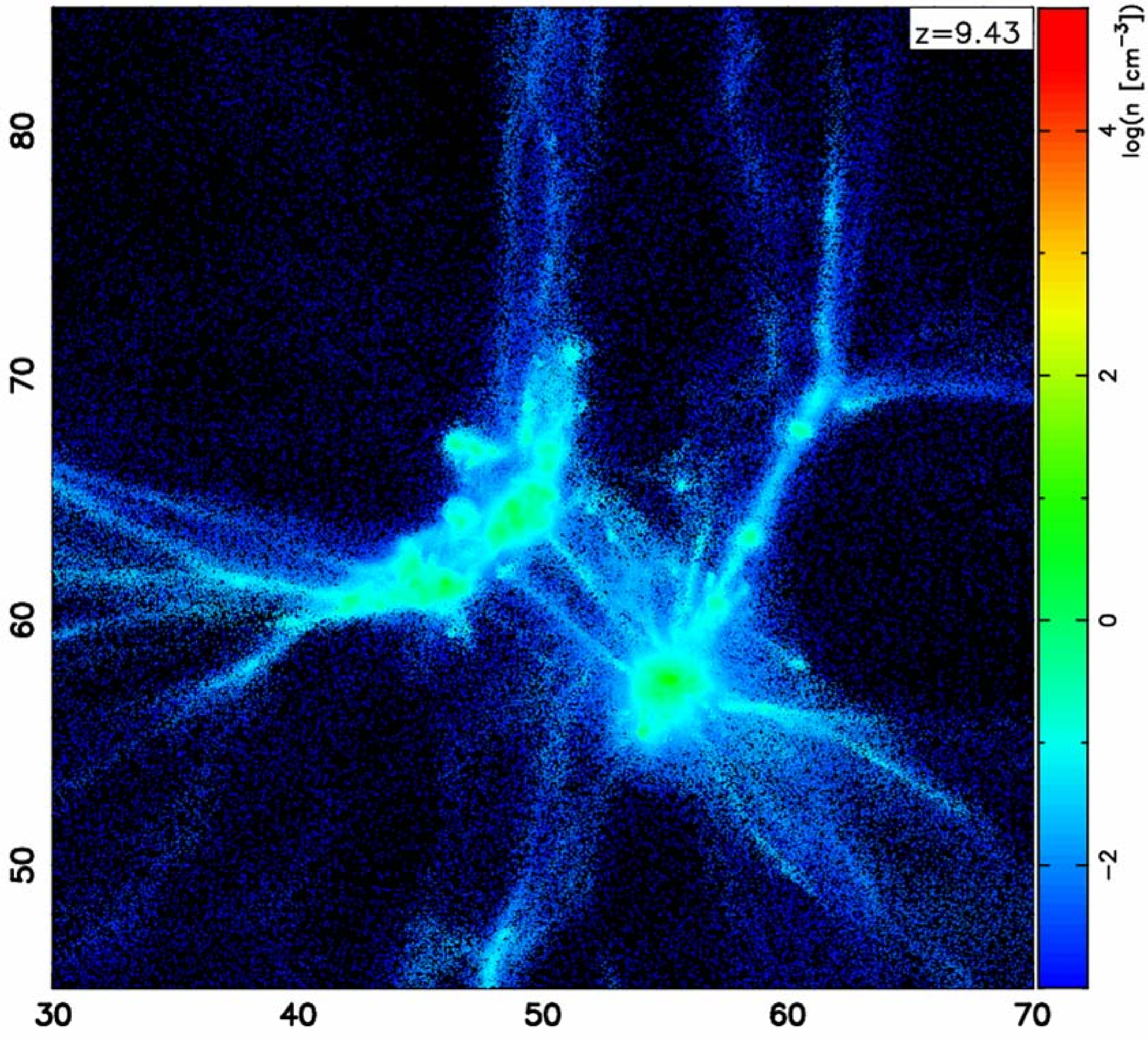


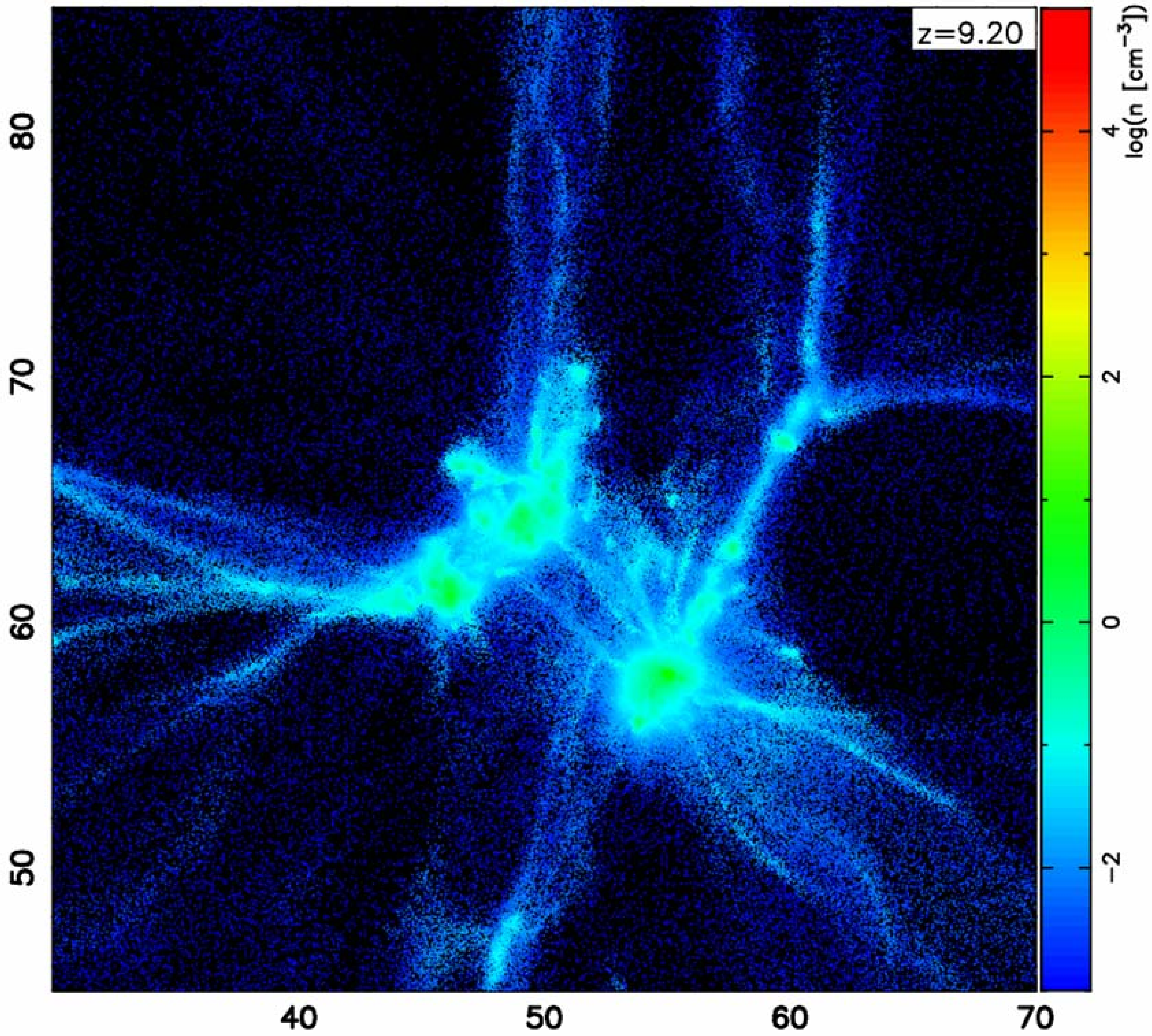
- Cosmological parameters:
  WMAP 3-year: **(Ω_0,Ω_b, h)=(0.24, 0.04, 0.73)**


z=14.50
log(n [cm^-3])
100
80
60
40
20
0
20
40
60
80
100
4
2
0
−2


z=12.00
log(n [cm^{-3}])
4
2
0
−2
0
20
40
60
80
100
0
20
40
60
80
100


z=9.50
log(n [cm⁻³])
0
20
40
60
80
100
−2
0
2
4


z=9.43
log(n [cm^-3])
80
70
60
50
30
40
50
60
70
4
2
0
−2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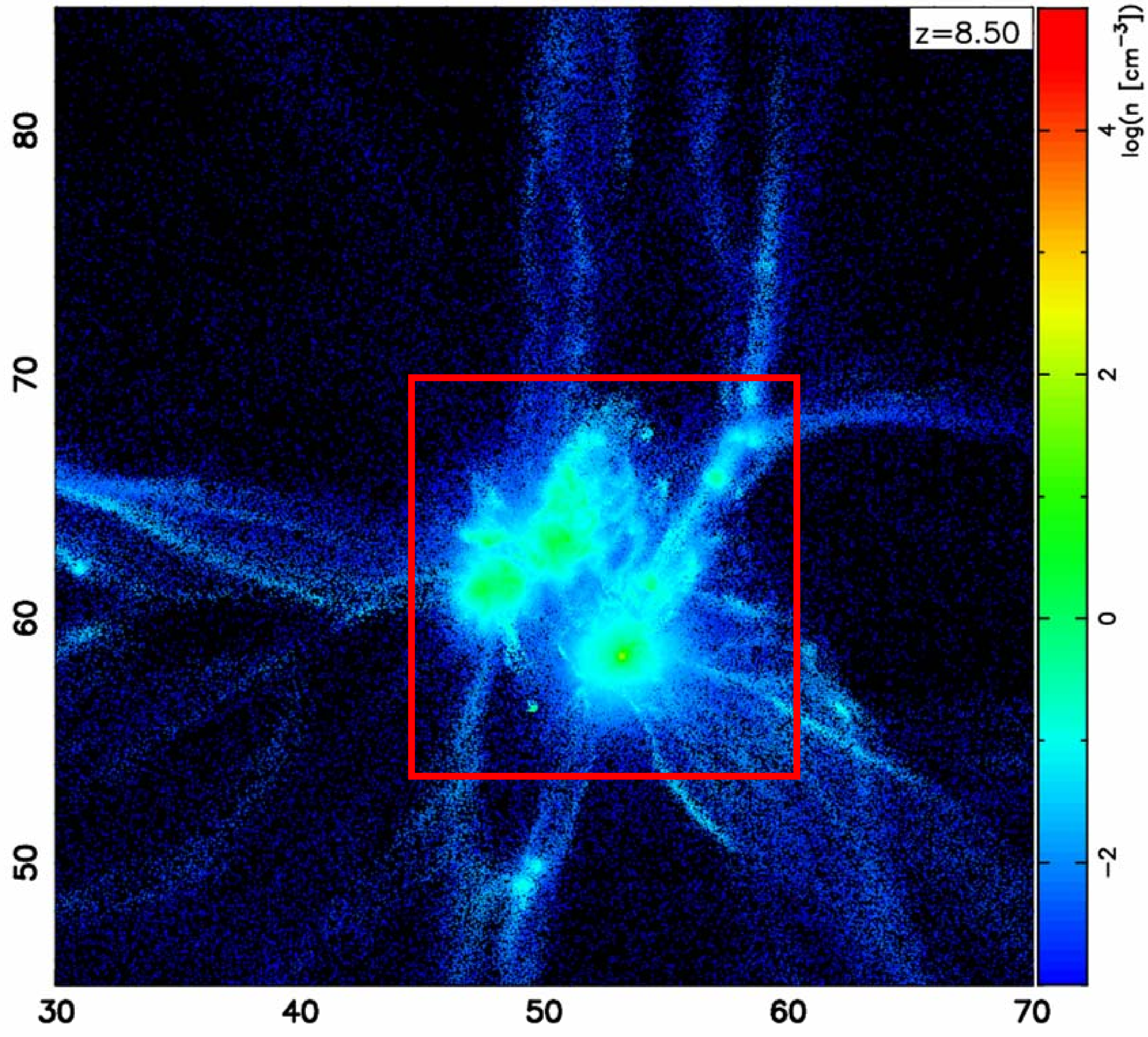
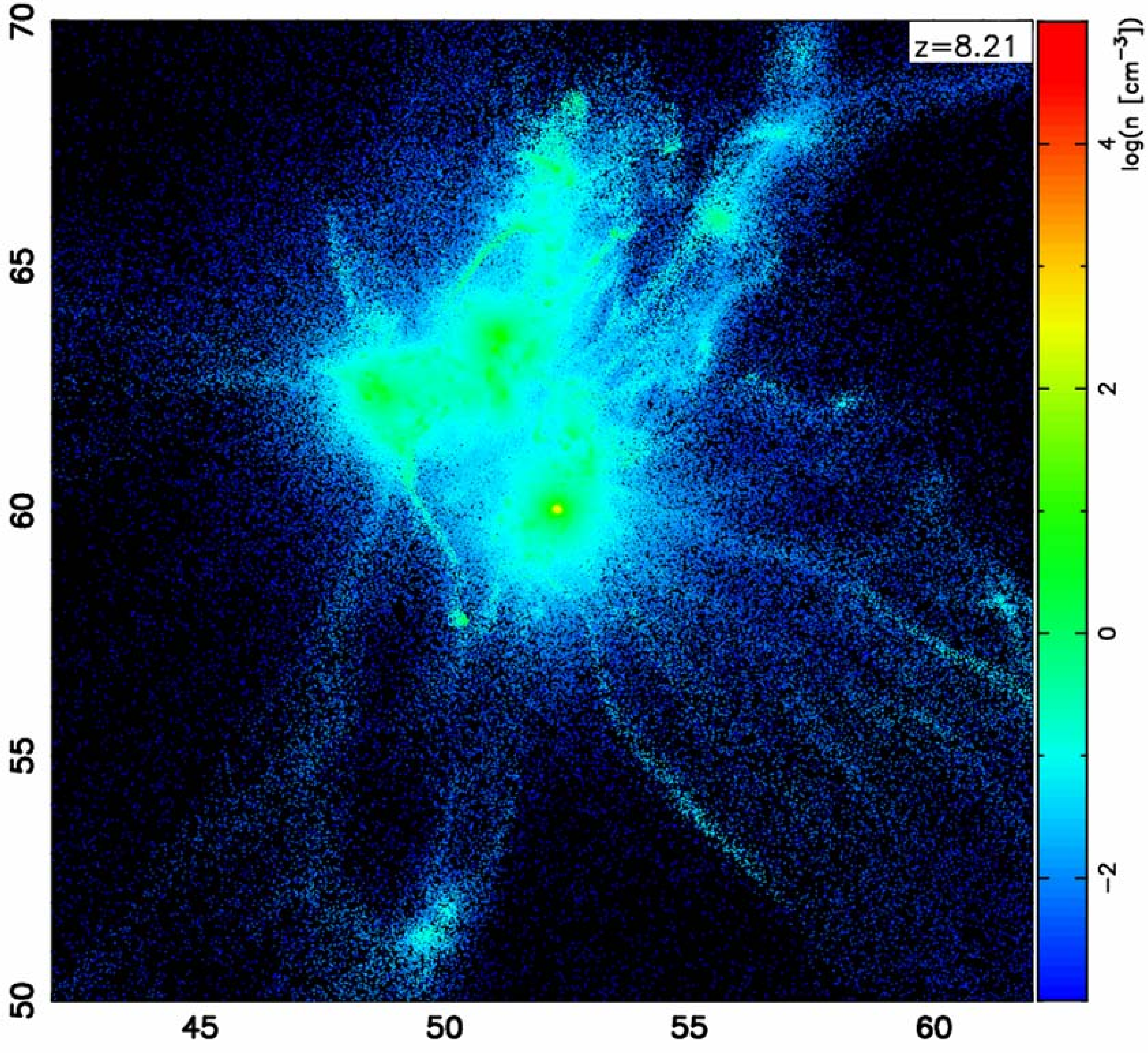
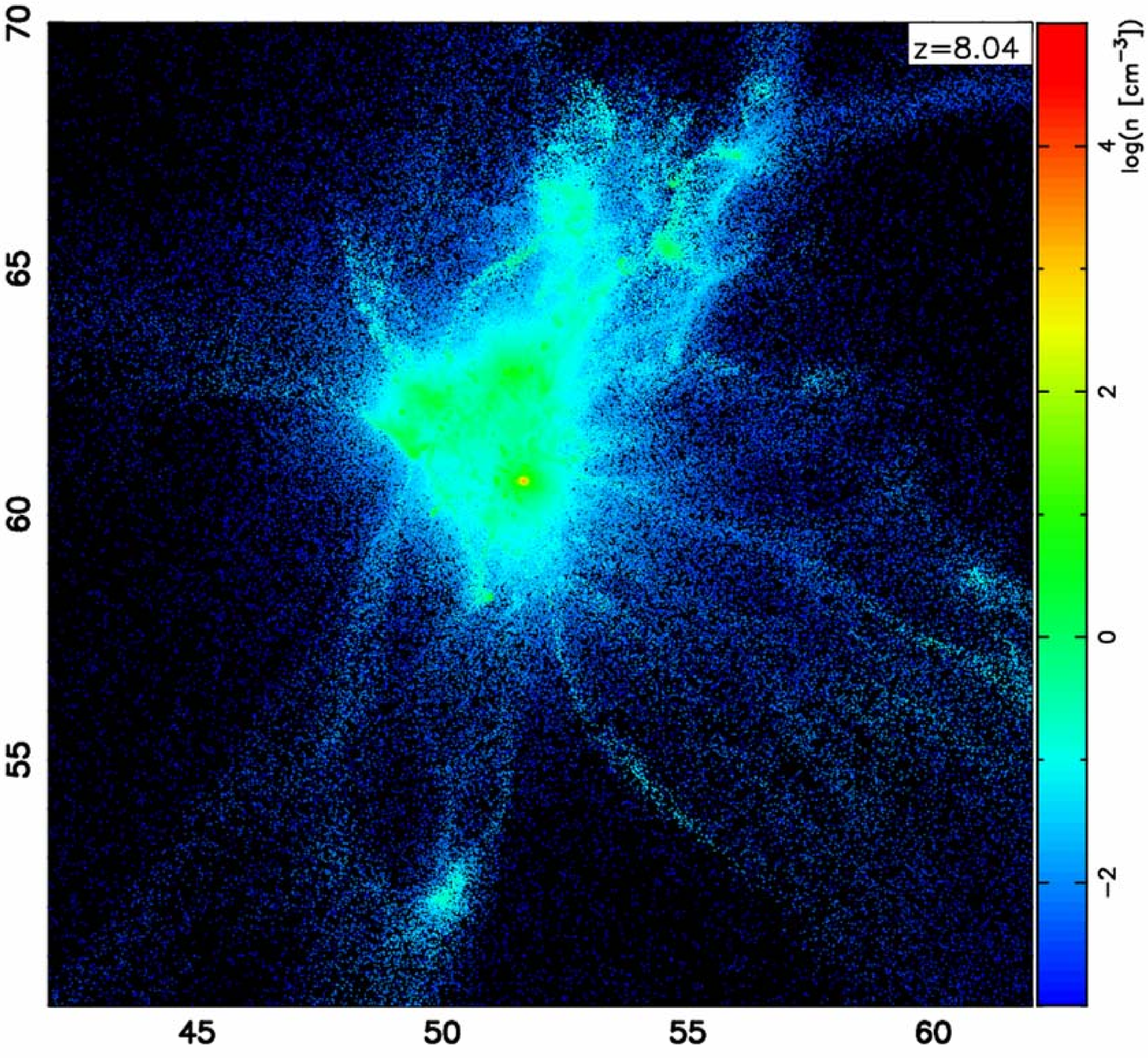
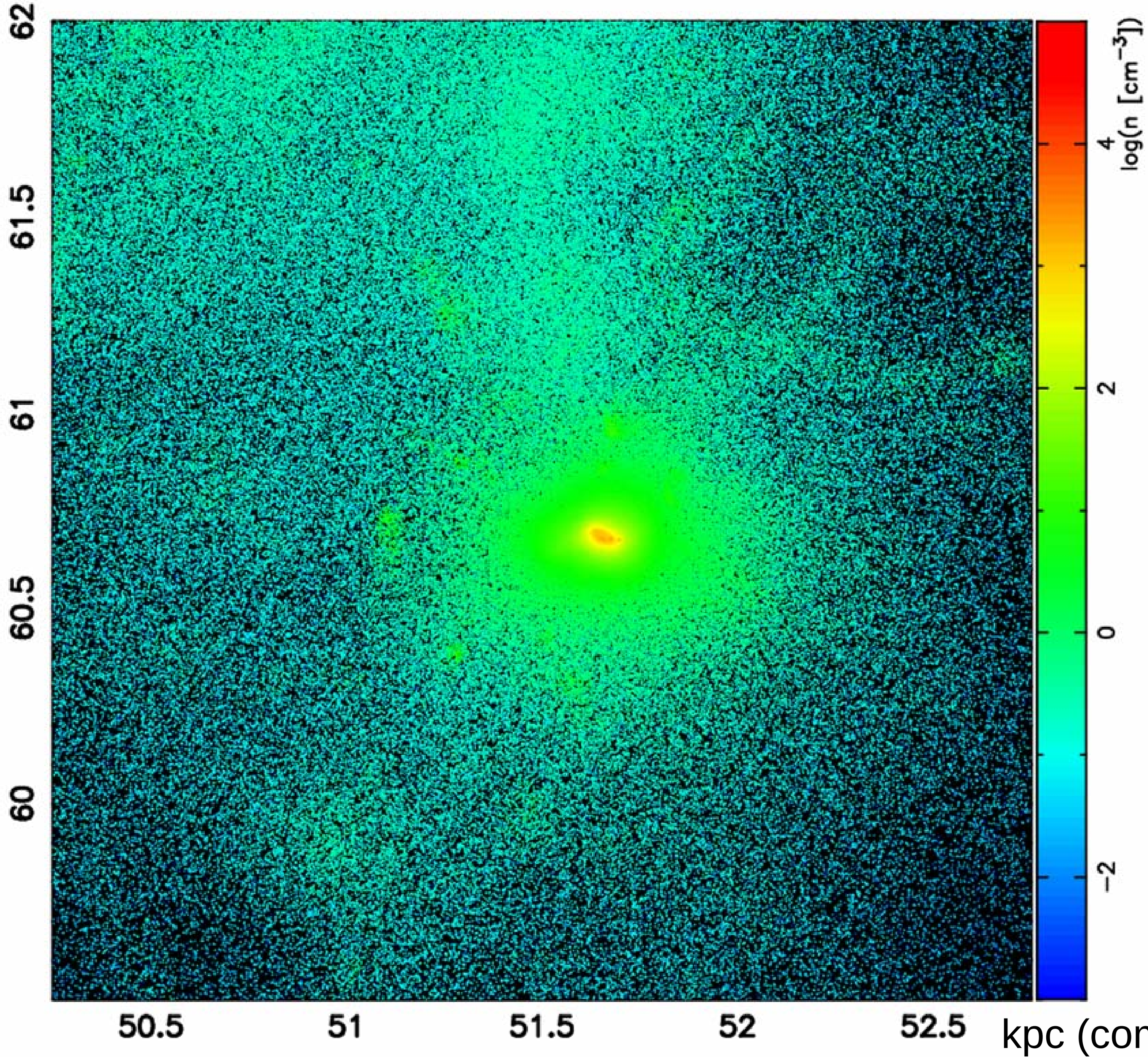
4
2
0
−2
80
70
60
50
40
50
60
70


z=8.50
log(n [cm^-3])
4
2
0
−2
80
70
60
50
30
40
50
60
70

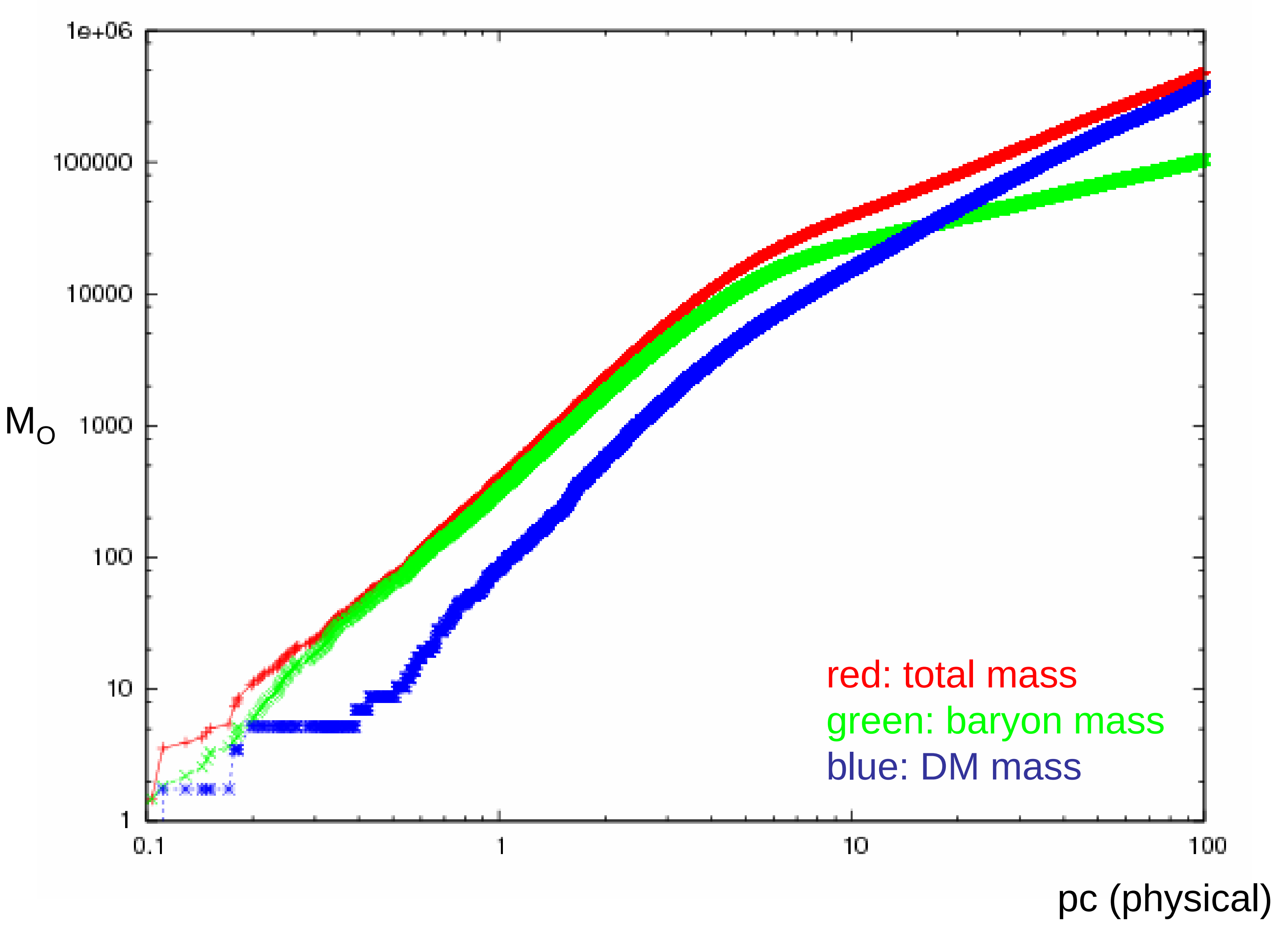

z=8.21
log(n [cm^{-3}])
4
2
0
−2
70
65
60
55
50
45
50
55
60


z=8.04
log(n [cm^{-3}])
4
2
0
−2
70
65
60
55
45
50
55
60

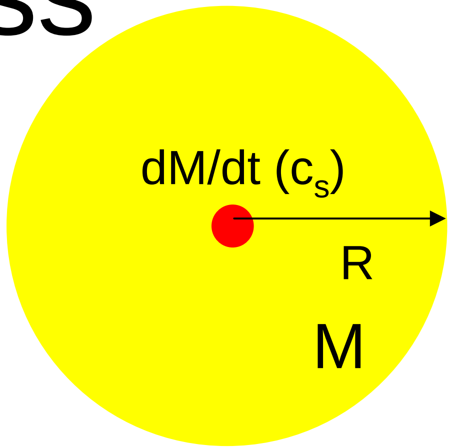


kpc (comoving)

Mass profile of the peak



Estimation of stellar mass

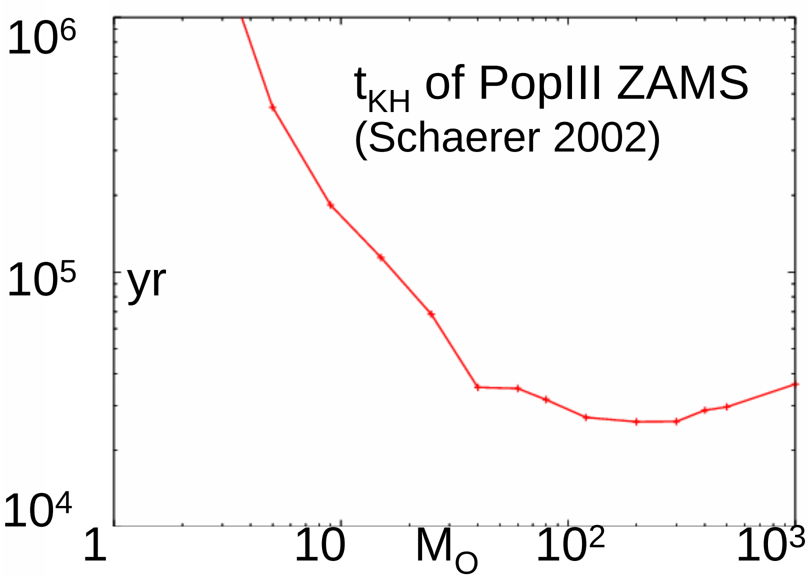


- We estimate the stellar mass

$$\dot{M}(c_s)t_{KH}(M) = M$$

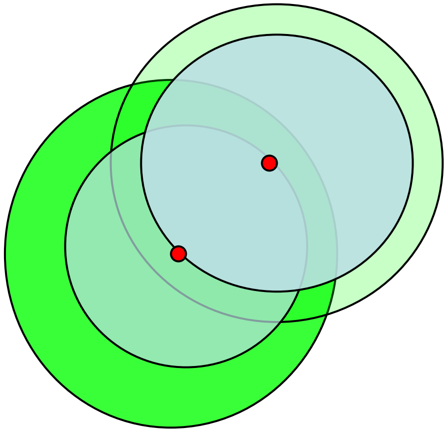
- M : Mass in a radius R
- t_{KH}: Kelvin-Helmholtz time determined by mass
- dM/dt (= c_s^3/G): Mass accretion rate

- Estimated mass of the first star at the peak is $M \sim 25 M_O$



Discussion

- This low-mass is due to low-temperature (~120 K) at the center of the peak
- The reason might be under estimation of SPH gravitation
  - Weak contraction force may not balance radiative cooling



Summary

- We perform a cosmological simulation of first star generation with FIRST cluster.
- Baryon mass resolution is 0.3 $M_{\odot}$ all over the simulation box.
- Estimated stellar mass at the center of the densest peak is 20～30$M_{\odot}$.
  - This low-mass is due to low-temperature (~120 K) at the center of the peak.
  - Physical validity of such temperature is still controversial.