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New Cosmological Hydrodynamic Code Developments

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Motivations – GCs as fossil records of galaxies

Globular star clusters (GCs)

- the oldest bound stellar system in the universe
- typical mass and size : $\sim 10^5\ M_\odot$ ($\sim M_V$=-5 to -10), a few parsecs
- The characteristics of GC systems are correlated with properties of their parent galaxies.

  : metal bimodality, specific frequency, size dist., radial dist., and so on

Motivations - GCs & Reionization

The previous studies on GCs & reionization

1. GC formation was suppressed by the reionization
   - Beasley et al. 2002, Santos 2003, Bekki 2005, Moore et al. 2006, Spitler et al. 2012

2. GCs reionized the universe
   - Ricotti 2002, Power et al. 2009, Schaerer & Charbonnel 2011, Griffen et al. 2012

3. GC formation was triggered by the reionization
   - Cen 2001, Hasegawa et al. 2009

4. GC formation rate using UV luminosity function
   - Katz & Ricotti 2012

Motivations

GCs to constrain the below

- the star formation and assembly histories of galaxies
- the nucleosynthetic processes governing chemical evolution
- the epoch and homogeneity of cosmic reionization
- the role of dark matter in the formation of structure in the early universe
- the distribution of dark matter in preset-day galaxies

Strategies

To simulate the sub-galactic scale structure formation in the Lambda CDM model,

we have developed a new cosmological hydrodynamic code.

- using the most efficient code (PM+tree) for the large scale structure, GOTPM (Dubinsky, Kim, & Park 2003),
- improved the hydrodynamics (SPH) into the GOTPM code (mainly by Juhan Kim)
- added the realistic baryonic physics (in preparation, Shin, Kim, & Kim 2013)

: Reionization process by UV background sources and UV shielding

: Radiative heating/cooling (T ~ reach to 100K)

: Star formation as single stellar population

: Metal, mass and energy feedback by SN_{II}

Targeted mass resolution is ~ 10^3 M_{sun}

: from globular clusters to galaxy groups (box size up to ~32 Mpc/*h*)

: using zoom-in technique and powerful computer resources

GOTPM (Dubinski, Kim, Park, & Humble 2003)

- based on a hybrid scheme using the particle-mesh (PM) and Barnes-Hut (BH) oct-tree algorithm
- used for recent large-volume simulations : Horizon Run 1, 2, 3 (7210^3 particles, 10.815 Gpc/h side length)

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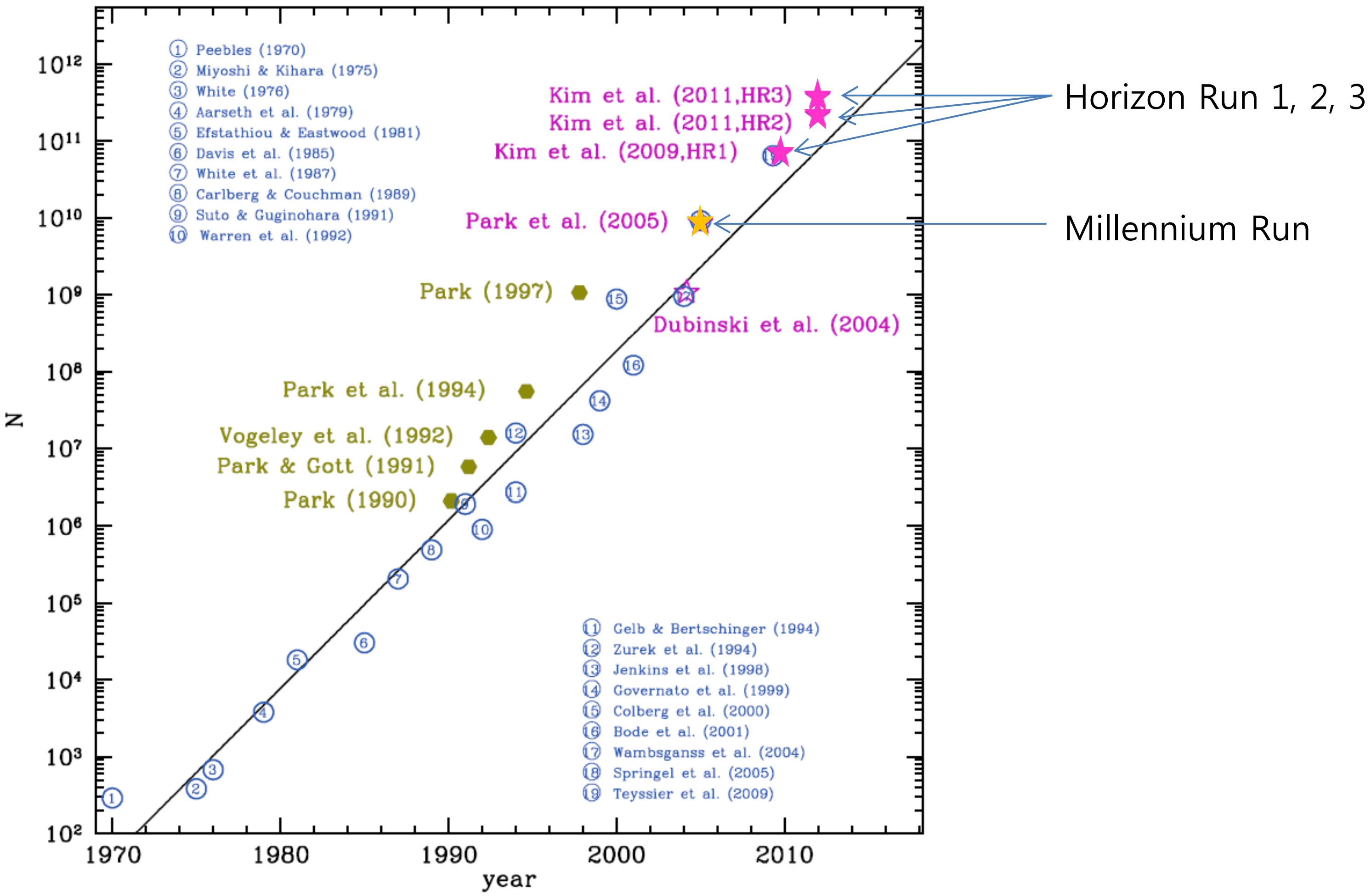


Kim et al. 2011

SPH (Smoothed-Particle Hydrodynamics)

- A version of the Lagrangian scheme in the hydrodynamics
- Following the entropy-conservation method (Springel & Hernquist 2003)
- Efficient memory consumption : 104 byte/particle (152byte/particle, GADGET-2)
- Individual time-step based on the Kick-Drift-Kick scheme (Springel 2005)
- Glacial initial condition : random positioning of the baryonic matter $N_{baryon} = N_{total} \times (\Omega_{baryon}/\Omega_{matter})$
- $\rho_i = \sum_{j=1}^{N_{nbg}} m_j W(\vec{r_i} - \vec{r_j}, h_i)$, $P_i = A_i \rho_i^{\gamma} = (\gamma - 1)\rho_i u_i$,

$$\frac{d\vec{v}}{dt}| = -\sum_{i=1}^{N_{nbg}} m_j \left[f_i \frac{P_i}{\rho_i^2} \nabla_i W_{ij}(h_i) + f_j \frac{P_j}{\rho_j^2} \nabla_j W_{ij}(h_j) + m_j \Pi_{ij} \nabla_i \overline{W_{ij}} \right],$$

$$\frac{du_i}{dt} = f_i \frac{P_i}{\rho_i} \sum_{j=1}^{N_{nbg}} m_j (\vec{v_i} - \vec{v_j}) \cdot \nabla W_{ij}(h_i) + \frac{1}{2} \sum_{j=1}^{N_{nbg}} m_j \Pi_{ij} \overrightarrow{v_{ij}} \cdot \nabla W_{ij}(h_i),$$

$$\Pi_{ij} = -\frac{\alpha}{2} \frac{(c_i + c_j - 3\omega_{ij})\omega_{ij}}{\rho_{ij}},$$

$$\Delta t^{SPH} = \frac{C_{courant} h_i}{max_j (c_i + c_j - 3\omega_{ij})}.$$

Cooling/Heating

Including non-adiabatic process on the evolution of the baryons

Using the publicly available photoionization package CLOUDY 90 (Ferland et al. 1998)

- functions of density, temperature, metallicity and redshift

Tabulating the cooling/heating rates as existence of the uniform UV/X-ray background (Haardt & Madau 2001)

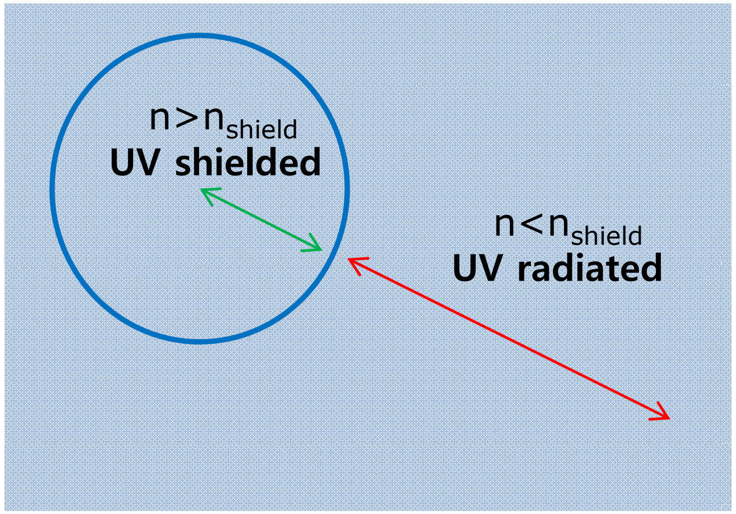
- Average thermal evolution before and after the reionization (z=8.9)

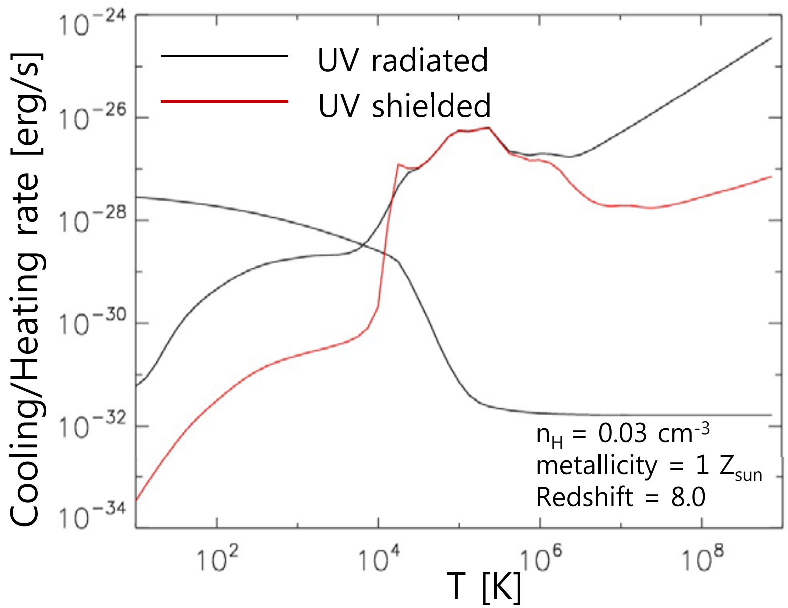
  : collisional ionization for z>8.9 and photoionization for z<8.9

- self-shielding from the UV background radiation (n_{shield}= 0.014 cm^{-3} following Tajiri & Umemura 1998)

  $n_H < n_{shield}$: UV radiated medium

  $n_H > n_{shield}$: UV shielded medium





Star Formation

Converting gas particles into star particles

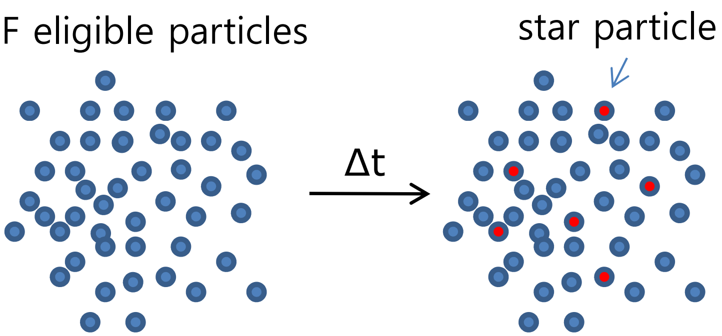
Star formation criteria :
(Katz et al. 1996)

$T < 10^4$ K

$n_H > 0.1$ cm^{-3}

$\nabla \cdot v < 0$

$\rho > 57.7\rho_g(z)$

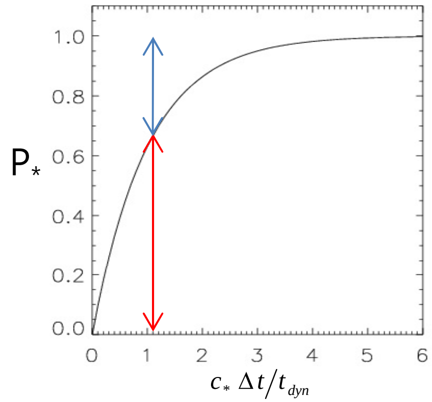


Star formation rate (c_*) : calibrated by the Schmidt-Kennicutt relation

$$\frac{d\rho_*}{dt} = c_* \frac{\rho_{gas}}{t_{dyn}}$$ (global star-formation properties, Kennicutt 1998)

Star formation probability : $$p_* = \frac{m_{gas}}{m_*}\left[1 - \exp\left(-c_* \frac{\Delta t}{t_{dyn}}\right)\right]$$

$$m_{gas} / m_* = 3, \ c^* = 0.033$$



Containing a single stellar population

: Location, velocity, mass, metallicity - inherited from the parent gas particles

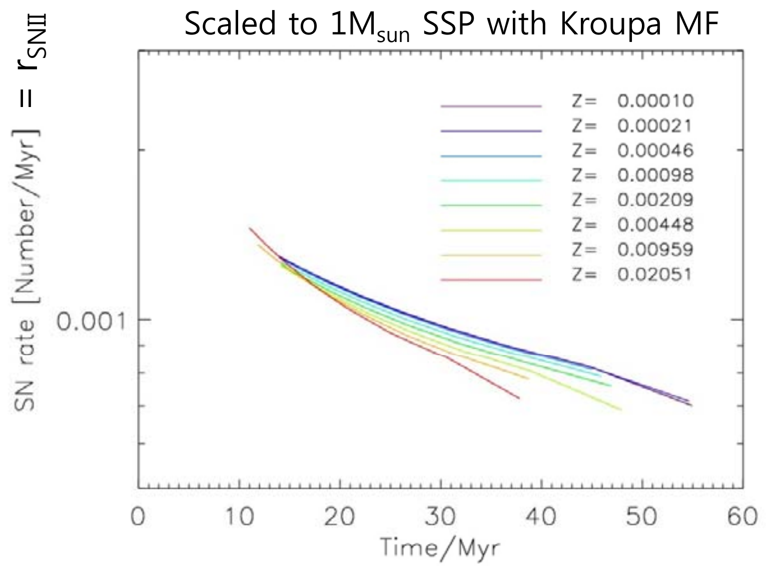
: Stellar mass function - Kroupa (2001) with range of 0.1 M_{sun}~100 M_{sun}

Feedback (SN_{II})

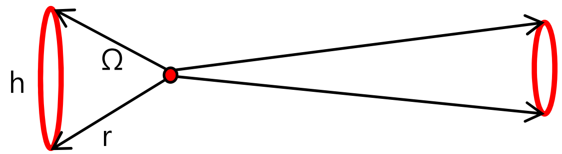
- Implementing feedback in a probabilistic manner

  (Okamoto, Nemmen, and Bower 2008)

$$P_{SN} = \int_{t_{SSP,i}}^{t_{SSP,i}+dt} r_{SNII}(t')dt' \bigg/ \int_{t_{SSP,i}}^{t_8} r_{SNII}(t')dt'$$



- Distributing feedback to neighbor gas particles
  1. energy feedback
     - ΔE of star particle : ~10^{51}erg/1 SN_{II}
     - overcooling problem : a new scheme of the individual time-step limiter (Saitoh & Makino 2009)
     - leading to a self-regulated cycle for star formation activity
  2. metal and mass feedbacks
     - released metal : $\Delta Z = \int \Psi(m) m_{ej,metal}(m,Z)dm / \Delta M_{SN}$, $m_{ej,metal}(m,Z)$ from Woosley & Weaver (1995)
     - proportional to solid angles of neighbors :



$$\Omega_i \propto h_i^2 / r_i^2 \propto n_i^{-2/3} / r_i^2$$

$$\Delta Z_{SN,i} = m_i n_i^{-2/3} r_i^{-2} \Delta Z_{SN} \bigg/ \sum_{j=1}^{N} m_j n_j^{-2/3} r_j^{-2}$$

     - metallicity-dependent heating/cooling

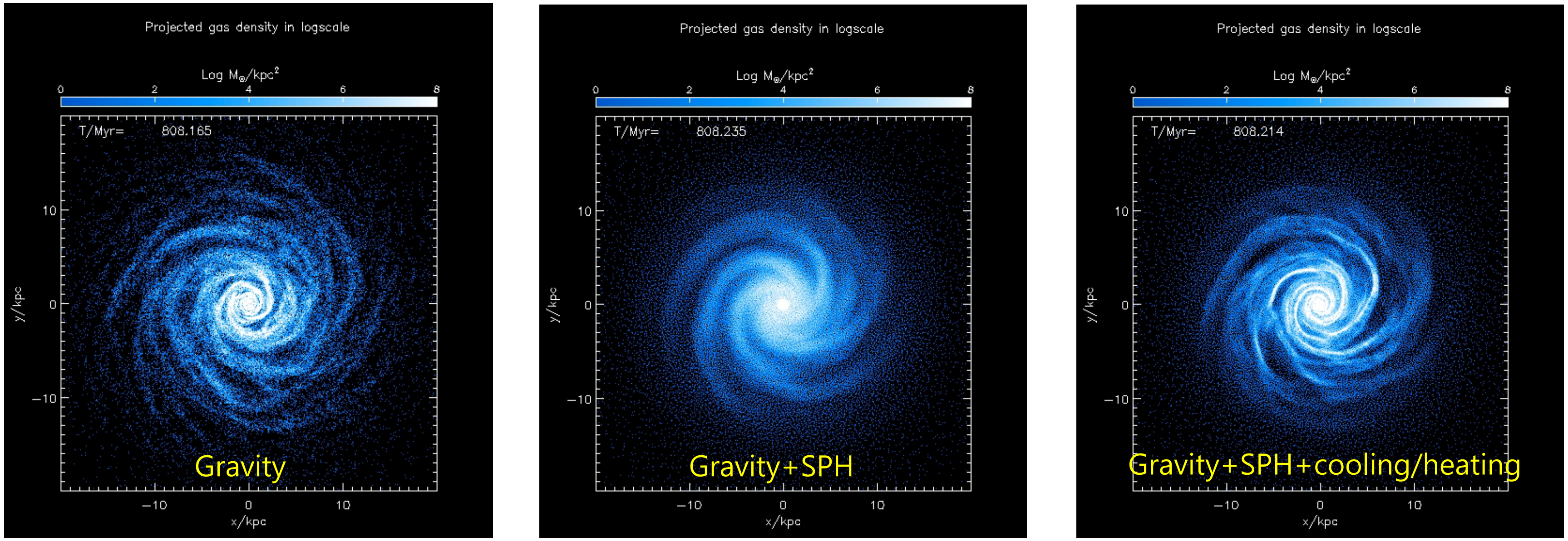
Test Run in Non-Cosmological Frame

Evolution of an isolated galaxy

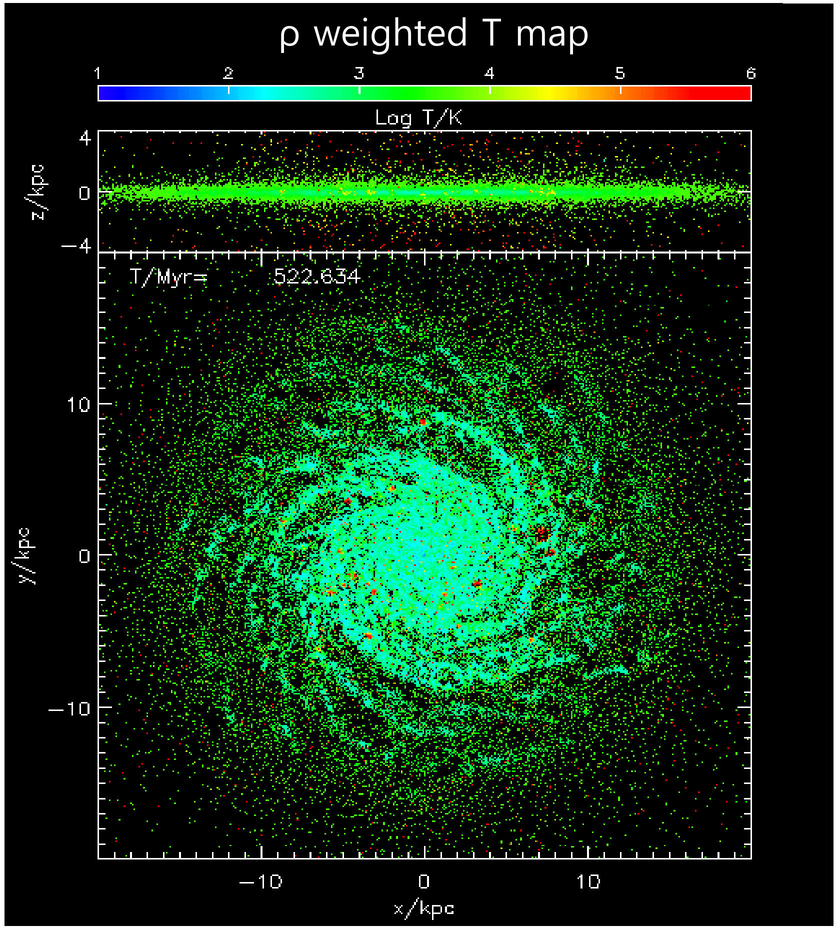
- to check how well the new implementation reproduce the Schmidt-Kennicutt law
- modified the GOTPM code to handle the non-expanding coordinate (scale length = constant)
- using a compound galaxy model as the initial condition for the test

	Particle number	Particle mass	Potential model	Parameter
Gas disk	98304	$4.196 \times 10^4\ M_{sun}$	Exponential Disk	$M=4.125 \times 10^9 M_{sun}$, z=0.3kpc, h=3.33kpc
Stellar disk	884736	$4.196 \times 10^4\ M_{sun}$	Exponential Disk	$M=3.715 \times 10^{10} M_{sun}$, z=0.3kpc, h=3.33kpc
Bulge	Fixed	-	Hernquist profile	$M=1.375 \times 10^{10} M_{sun}$, a=0.8kpc
Halo	Fixed	-	Hernquist profile	$M=2.2 \times 10^{11} M_{sun}$, a=10kpc

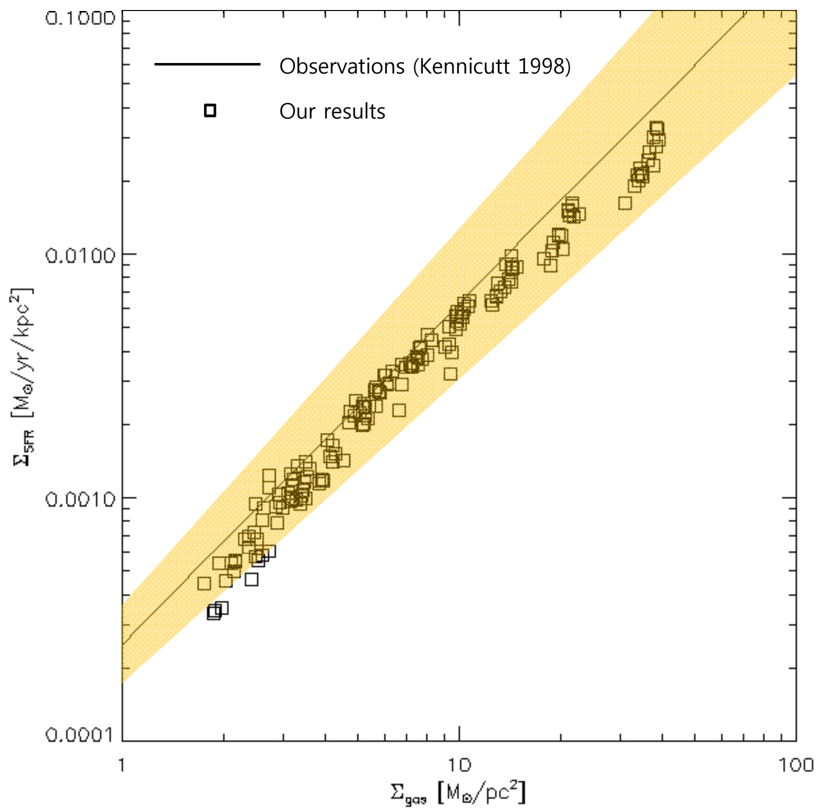
Initial conditions from ZENO by Barnes



Gravity + SPH + Cooling/Heating + SF + SN feedback

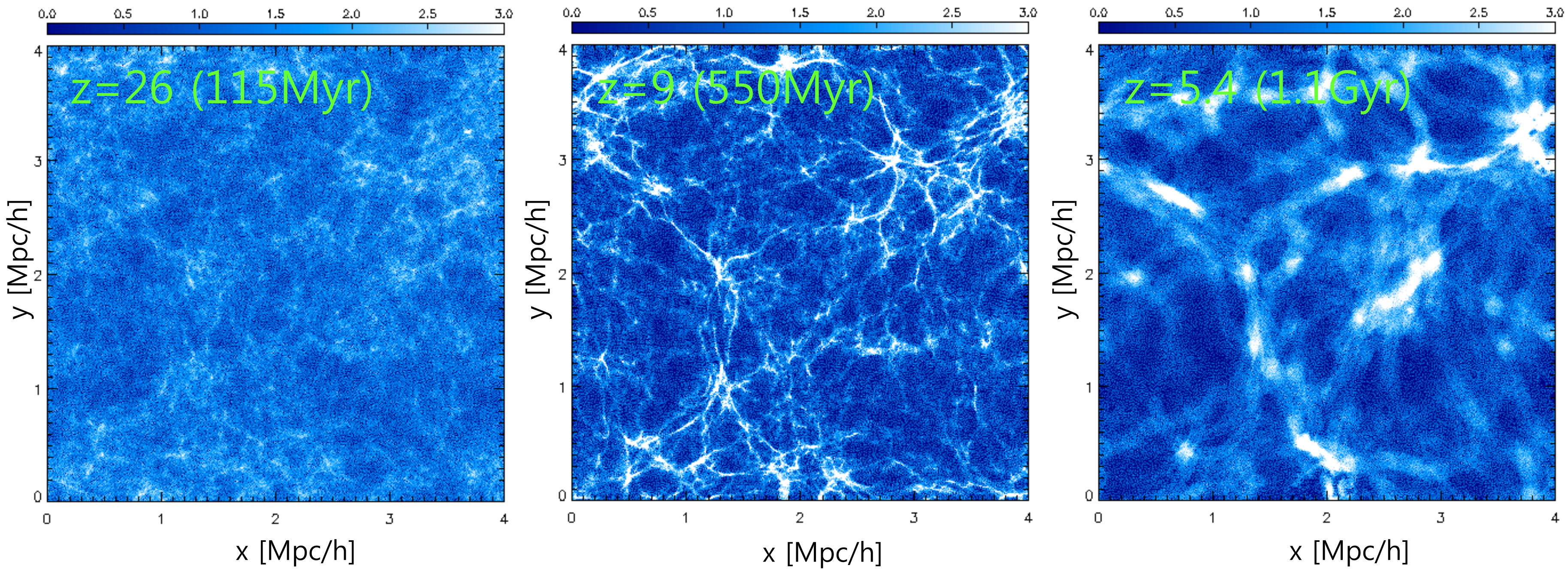


Schmidt-Kennicutt law



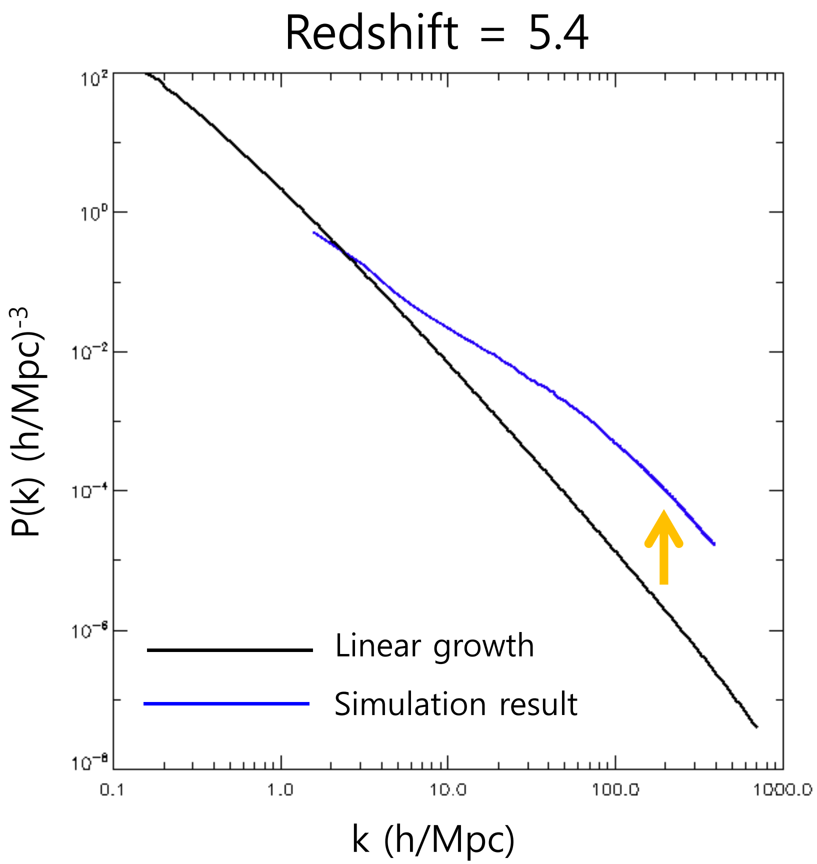
Test Runs in the Cosmological Frame

- We have performed a cosmological hydrodynamic simulation with the new code.
  - a cubic box with a side length of 4 Mpc/h with 512^3 (130 million) particles
  - mass resolution ~ 3.4 x 10^4 $M_\odot$ (sub-galactic halos are resolved with more than hundred particles)
  - initial condition : p(k) at z = 150 (CAMB package) and initial displacement (Zel'dovich's approximation)
  - ΛCDM cosmology : WMAP-5^{th} yr parameter (Ω_m=0.26, Ω_Λ =0.26, Ω_b=0.044, σ_8=0.76, h=0.72)
  - used 64 cores for one month down to z=5.4

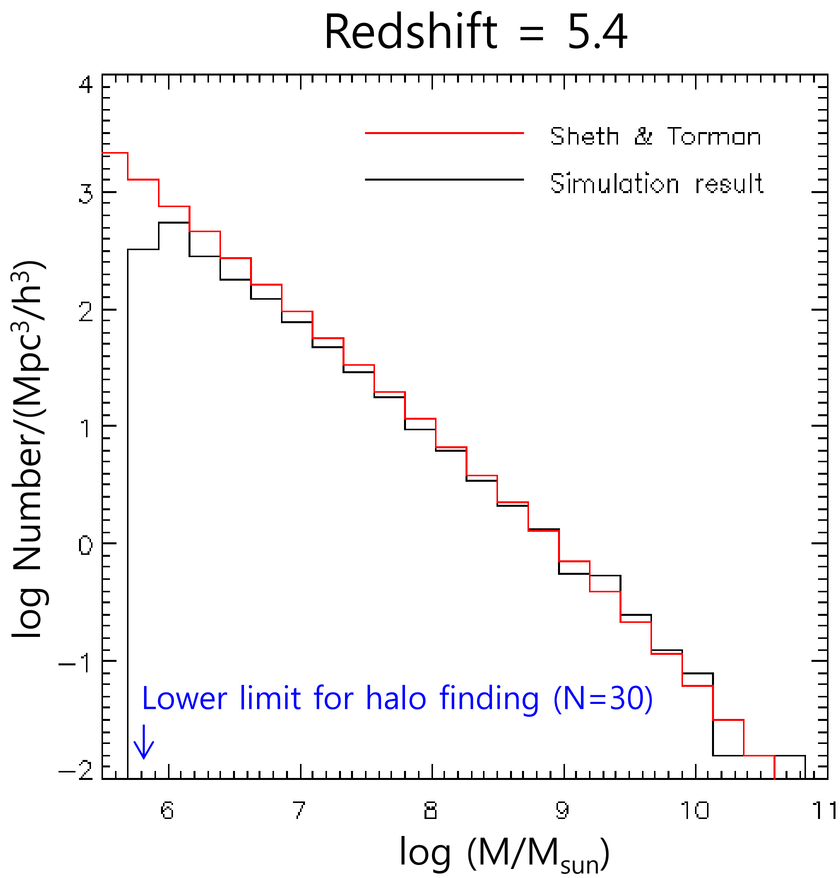


Projected gas density in logscale [Log $M_\odot$/kpc^2] at three different epochs

Comparison with theoretical predictions



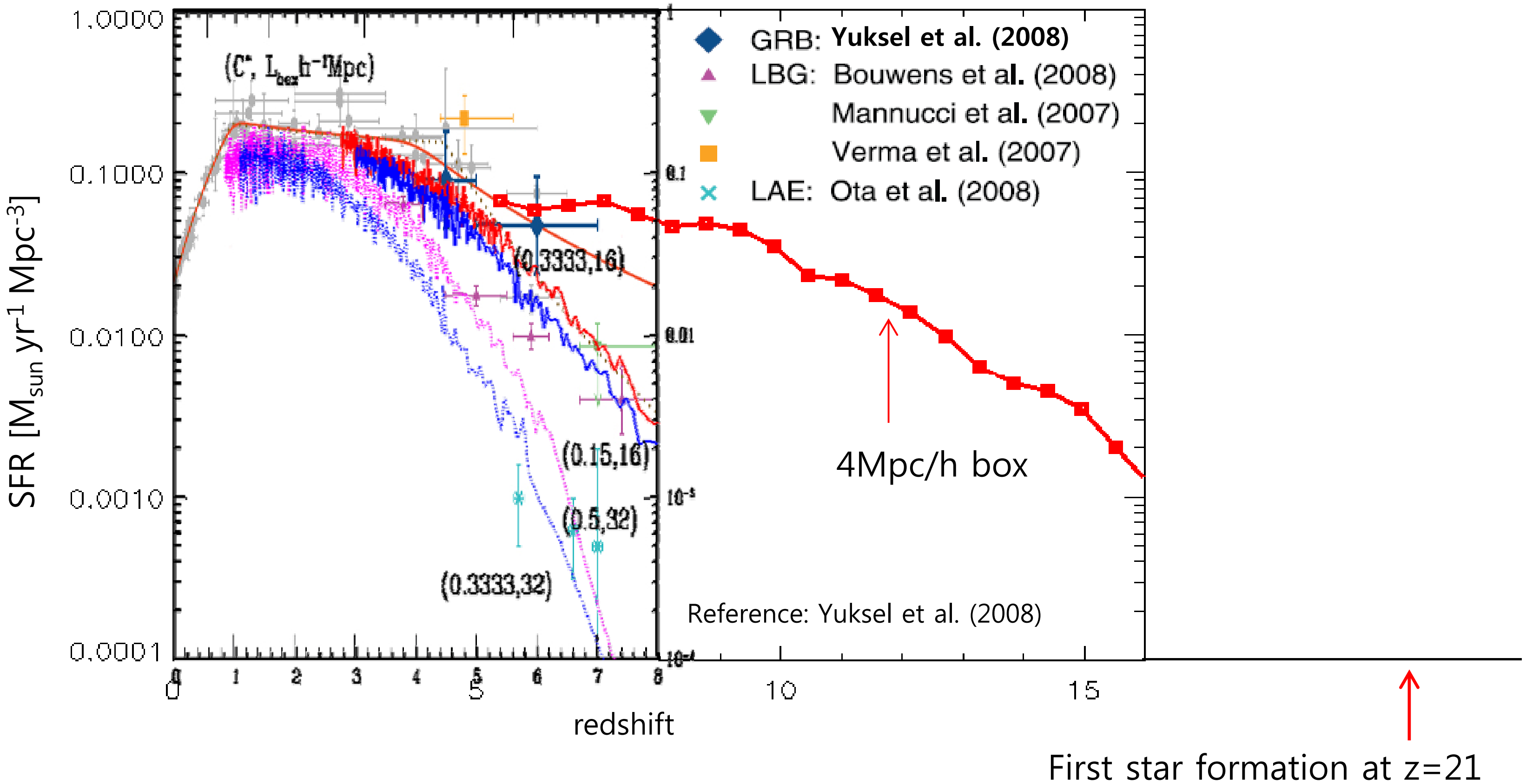
Power spectrum of cold dark matters



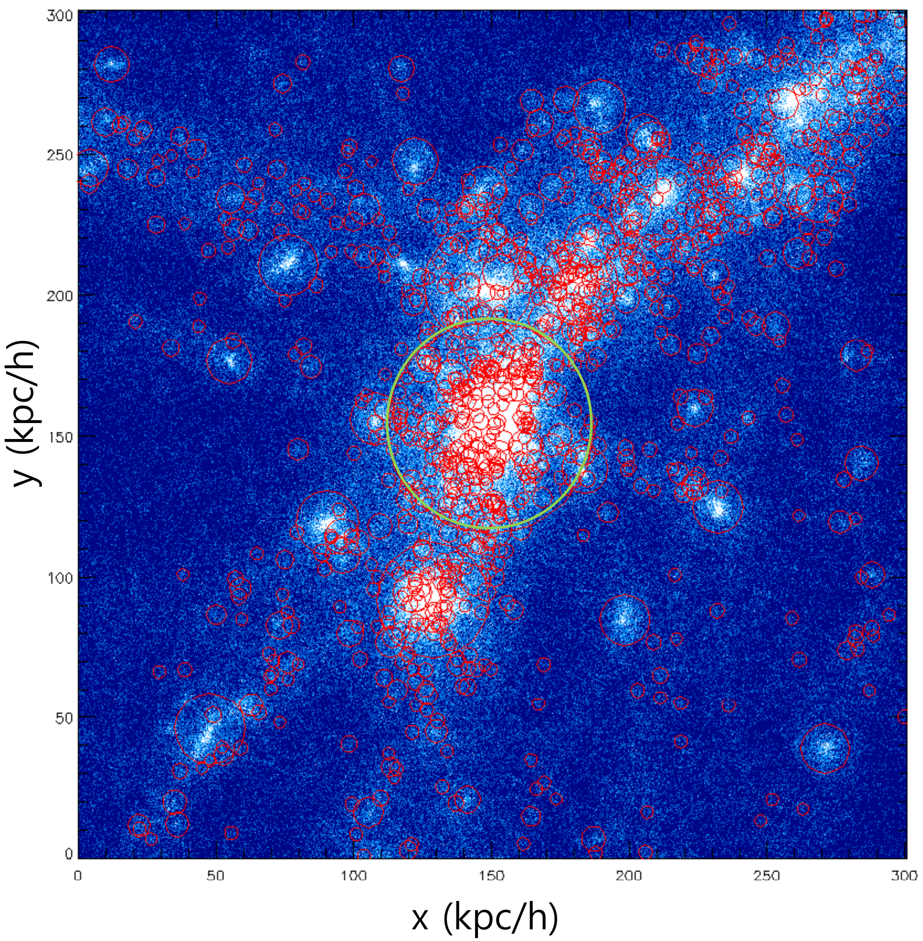
Dark matter mass function

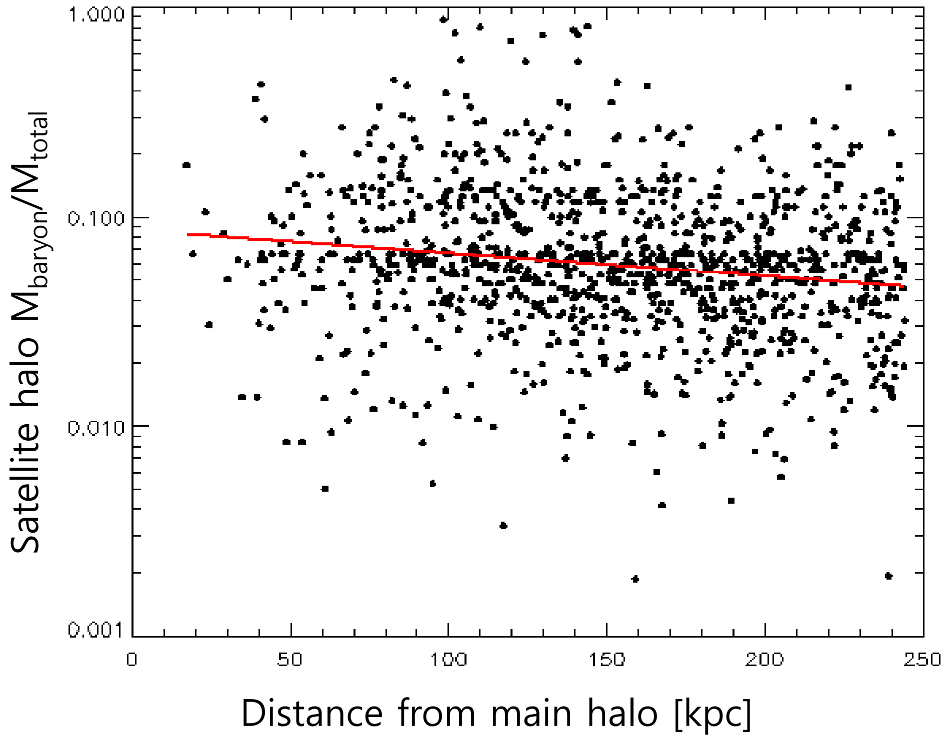
Halo finding : Friend-of-Friend (FoF) & hierarchical FoF

Comparison with observations



Distribution of satellite halos around a ~10^{10} $M_\odot$ main halo at z = 5.4

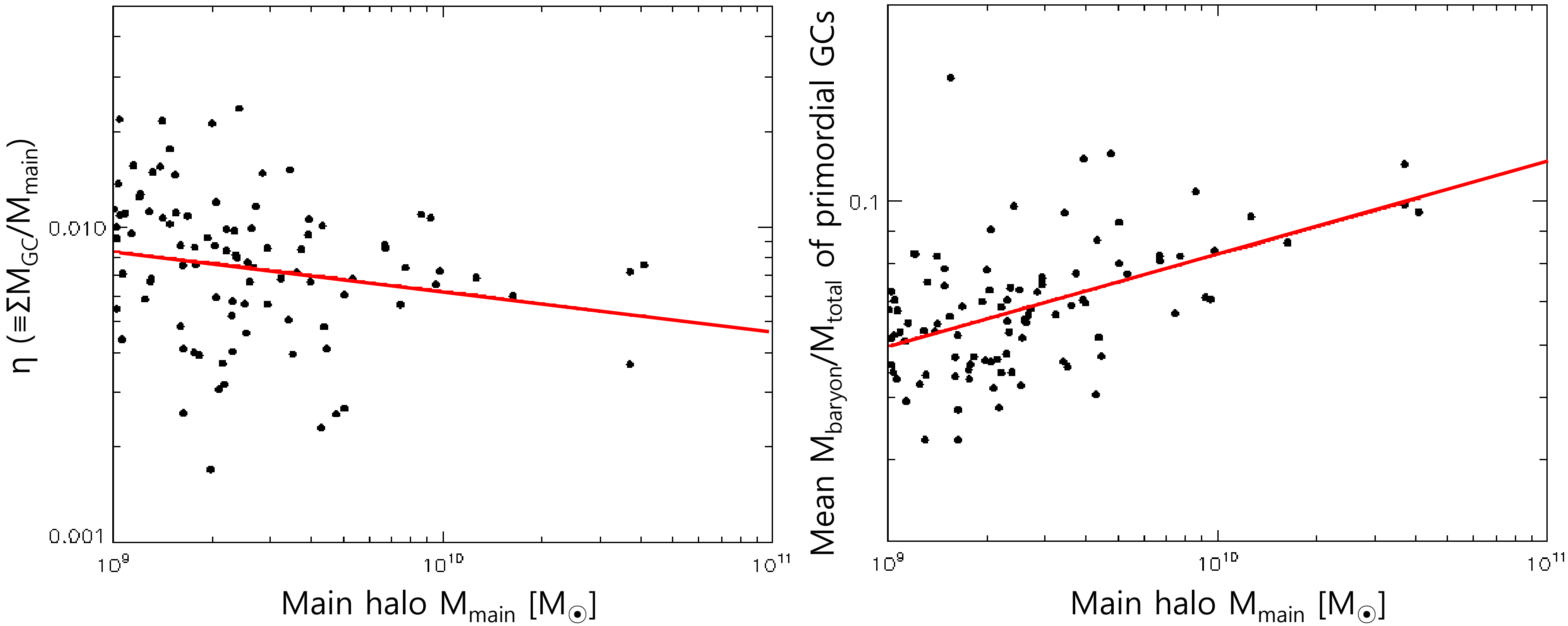




M_{baryon}/M_{total} of satellite haloes vs. their distances from the main halo

Properties of Globular Cluster Candidates

Specific mass and mean M_{baryon}/M_{total} of GC candidates at z=5.4

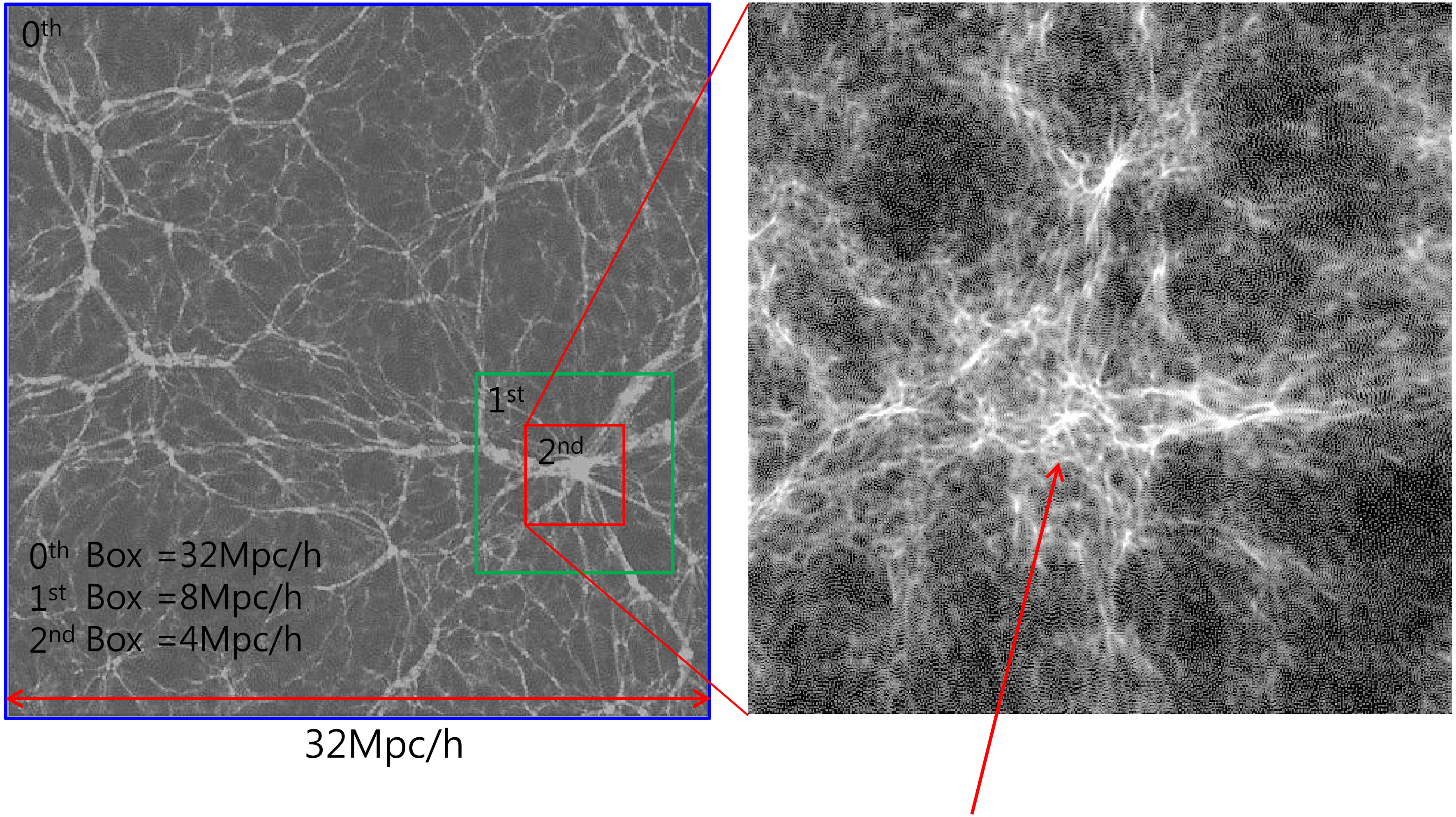


- η (≡ $\Sigma M_{GC}/M_{main}$: Specific GC formation efficiency) of the main halos at z=5.4 is ~2 orders of magnitude larger than the previous estimates of ~10^{-4}–10^{-5} (Blakeslee 1999; Kravtsov & Gnedin 2005; Spitler & Forbes 2009).

- A large fraction of GCs around the main halo at z=5.4 will be disrupted during the continuous accretion into the main halo and constitute the main halo.

Zoom-in Simulation

We just finished applying zoom-in technique into the our new GOTPM+SPH code



Formation site of the Milky Way sized halo at z=0

GCs & Reionization

The previous studies on GCs & reionization

1. GC formation was suppressed by the reionization
   - Beasley et al. 2002, Santos 2003, Bekki 2005, Moore et al. 2006, Spitler et al. 2012

2. GCs reionized the universe
   - Ricotti 2002, Power et al. 2009, Schaerer & Charbonnel 2011, **Griffen et al. 2012**
     = Aquarius DM halo + C^2-Ray

3. GC formation was triggered by the reionization
   - Cen 2001, Hasegawa et al. 2009

4. GC formation rate using UV luminosity function
   - Katz & Ricotti 2012

To do : ray tracing method + our code

Future work

1. Complete the code developments
   - zoom-in technique, especially the boundary particles
   - multi-phase model, H2 cooling, and H2 dependent star formation
   - stability and performance tests
   - using GPU

2. Perform the high resolution simulation
   - formation of GCs around the Milky-Way like galaxy
   - relations between properties of GCs and that of the host galaxies
   - GCs as tracers for the history of galaxies

3. Correlation between GCs and the cosmic reionization
   - implementing ray-tracing
   - origin of the bimodal distribution of globular clusters

Thank you very much