FORMATION AND EVOLUTION OF SUB STRUCTURES AROUND DWARF GALAXY-SIZED HALOS

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Introduction

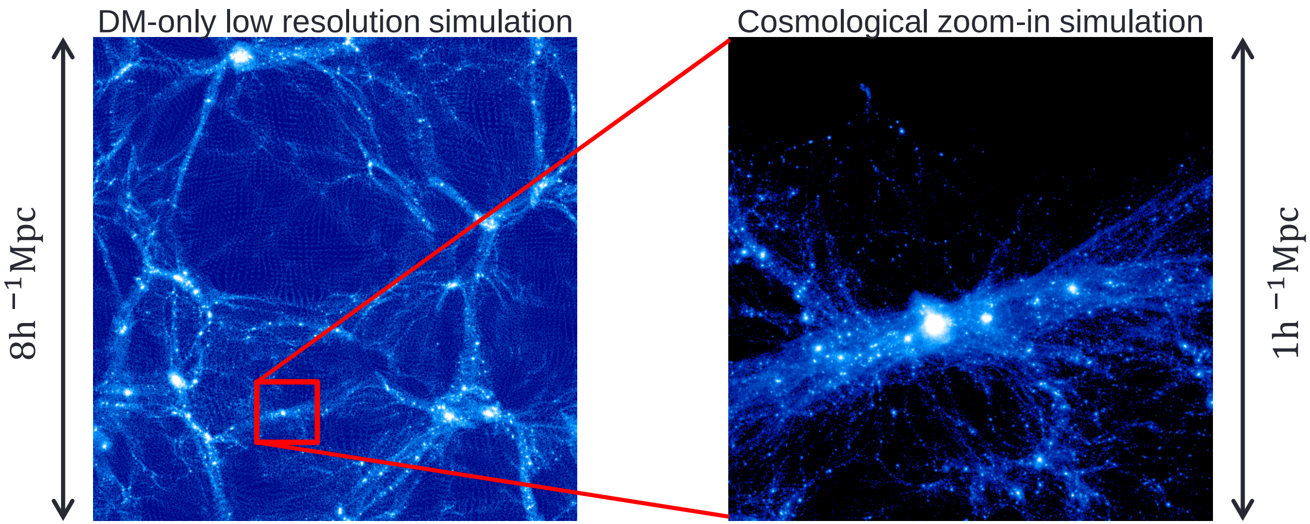
The stellar satellite structures

- Globular Cluster (GC)
- Ultra Compact Dwarf (UCD)
- Ultra Faint Dwarf (UFD)
- dwarf spheroidal (dSph)

→ They have similar luminosity, but, their other properties are different (e.g. dark matter mass fraction, size, density, metallicity, etc..).

Cosmological simulations

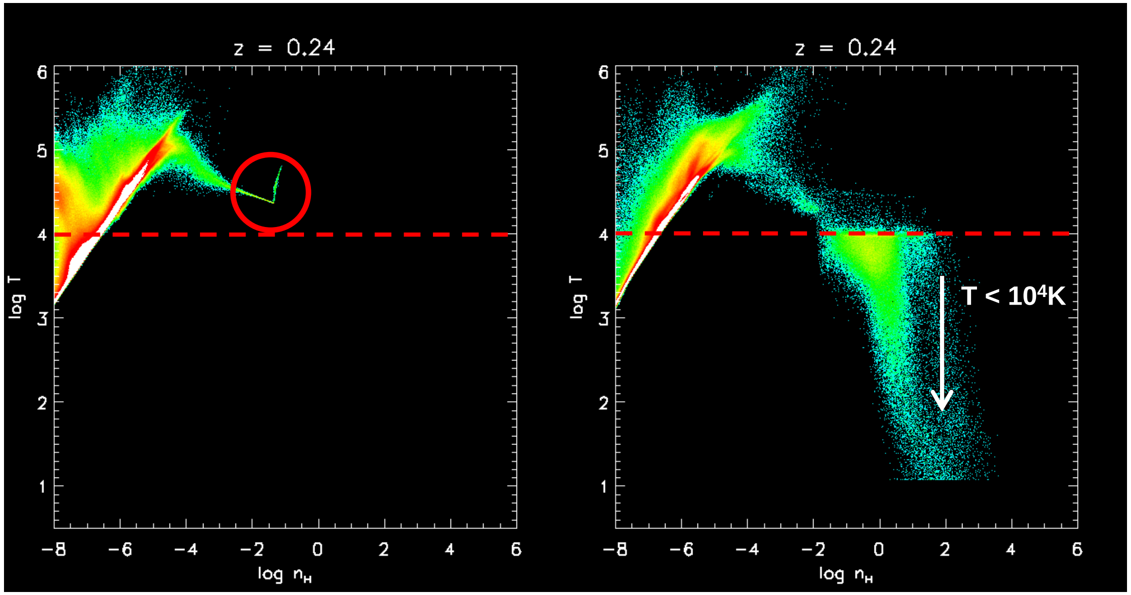
- Target : Three different isolated dwarf galaxies (~$10^{10} M_\odot$) and their sub halos
- Method : Cosmological hydrodynamic zoom-in simulation



Introduction

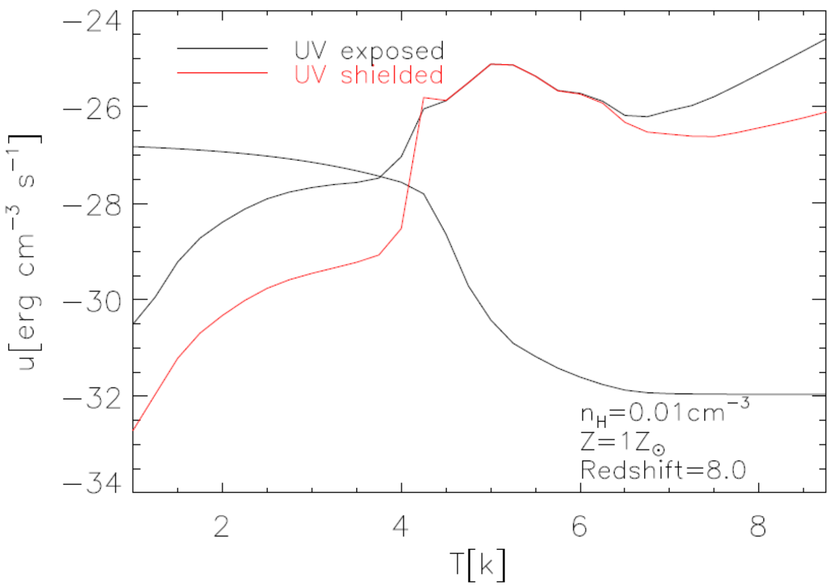
Code

- We **modified GADGET-3** to include realistic baryonic physics (Shin et al 2014).
  - We do not use the multi-phase model to describe **$T<10^4$K structures**.
  - Low temperature cooling is essential to trace the evolution of interesting objects ($10^4 \sim 10^{10}\ M_\odot$).



Original GADGET-3　　　Modifield GADGET-3

Radiative Heating & Cooling



- Radiative heating and cooling rates are measured using CLOUDY 90 (Ferland et al. 1998).
  - Cooling: Compton cooling, inverse Compton cooling, and atomic/molecular cooling
  - Heating: Compton heating, inverse Compton heating, and background UV heating
- Reionization is simultaneously occurred in the whole universe at $z_{re} = 8.9$ (Haardt & Madau 1996).
- UV Shielding is considered at dense gas cloud ($n_H \geq 0.014cm^{-3}$) (Sawala et al. 2010).

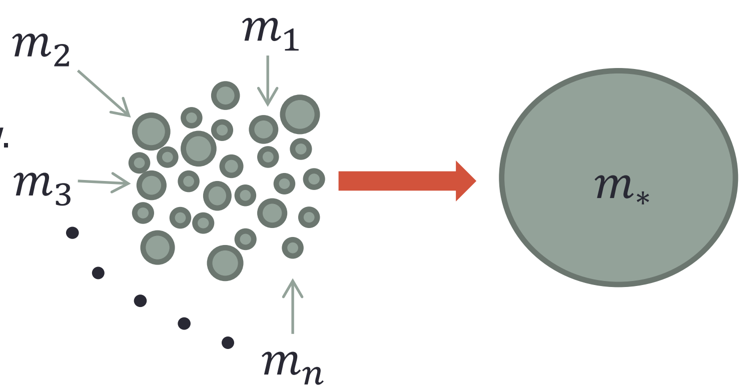
Star formation

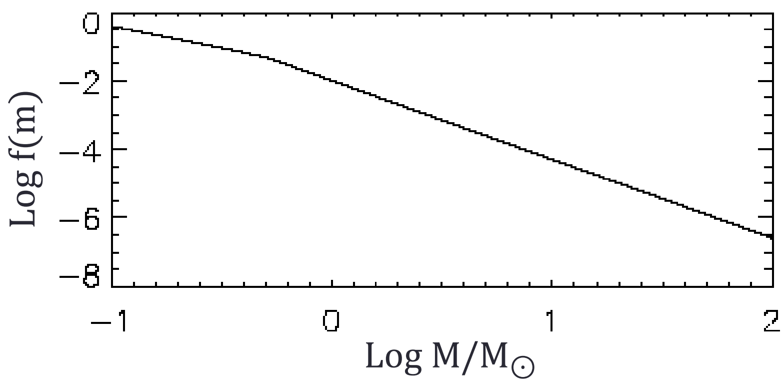
- Star formation criteria
  - (1) $n_H > 100cm^{-3}$ (2) $T < 10{,}000K$ (3) $\nabla \cdot v < 0$

- Star formation rate
  - Star particles are formed at a rate of the local Schmidt law.
  - $\frac{d\rho_*}{dt} = C_* \frac{\rho_{gas}}{t_{dyn}}$
  - C_* is the star formation efficiency.

- Star formation probability
  - $P_{SF} = \frac{m_{gas}}{m_*}\left[1 - \exp\left(-C_* \frac{dt}{t_{dyn}}\right)\right]$ (exponential law)
  - m_* is one third of the original gas particle mass.

- Single stellar population
  - Kroupa Initial Mass Function (Kroupa 2001).
  - Single stellar population (same age and metallicity.)





Kroupa Initial Mass Function

Supernova feedback

- $SN_{\rm II}$ explosion
  - Massive stars($> 8M_{\odot}$) explode as **Type II SNe**.
  - Energy of a supernova explosion is $\mathbf{10^{51}erg}$.
  - Stellar evolution model (Hurley, Pols, & Tout 2000).
  - Metal enrichment of $SN_{\rm II}$ (Woosley & Weaver 1995).
  - Energy, mass, and metal are distributed using Spline kernel.

- $SN_{\rm II}$ probability (Okamoto, Nemmen, and Bower 2008)
  - $P_{SN_{\rm II}}(Z) = \frac{\int_{t_{SSP}}^{t_{SSP}+dt} r_{SN_{\rm II}}(t', Z)dt'}{\int_{t_{SSP}}^{t_8} r_{SN_{\rm II}}(t', Z)dt'}$

Current work

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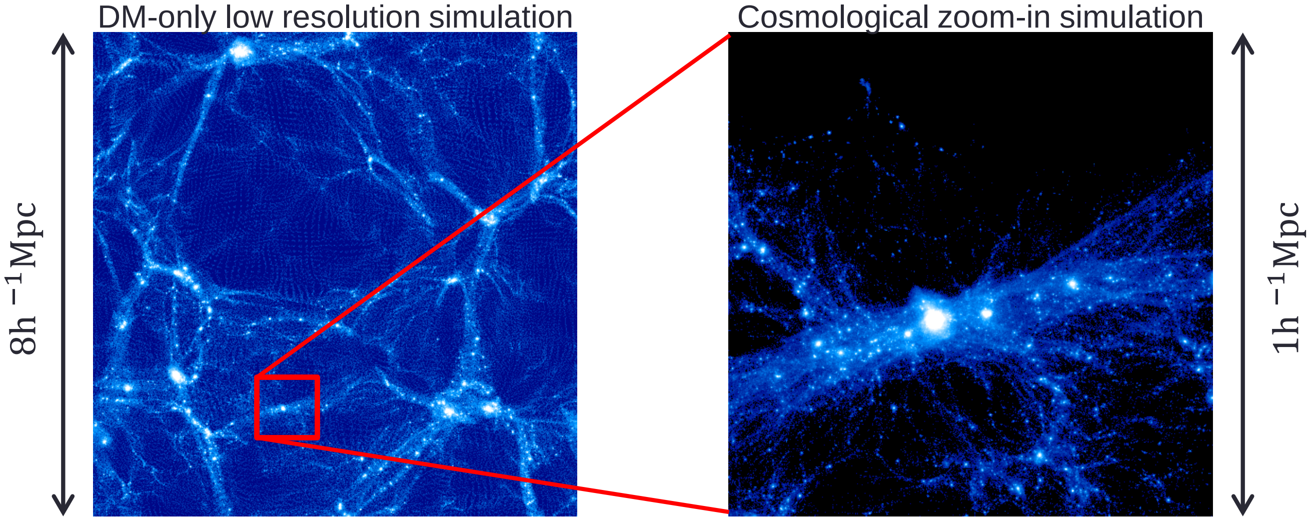


Simulation

Initial Condition

- **MUSIC** (Hahn & Abel 2011)
- $z_{init} = 49$
- Cosmological parameters: $\Omega_m = 0.3,\ \Omega_\Lambda = 0.7,\ \Omega_b = 0.048,$ and $h = 0.68$

Resolution

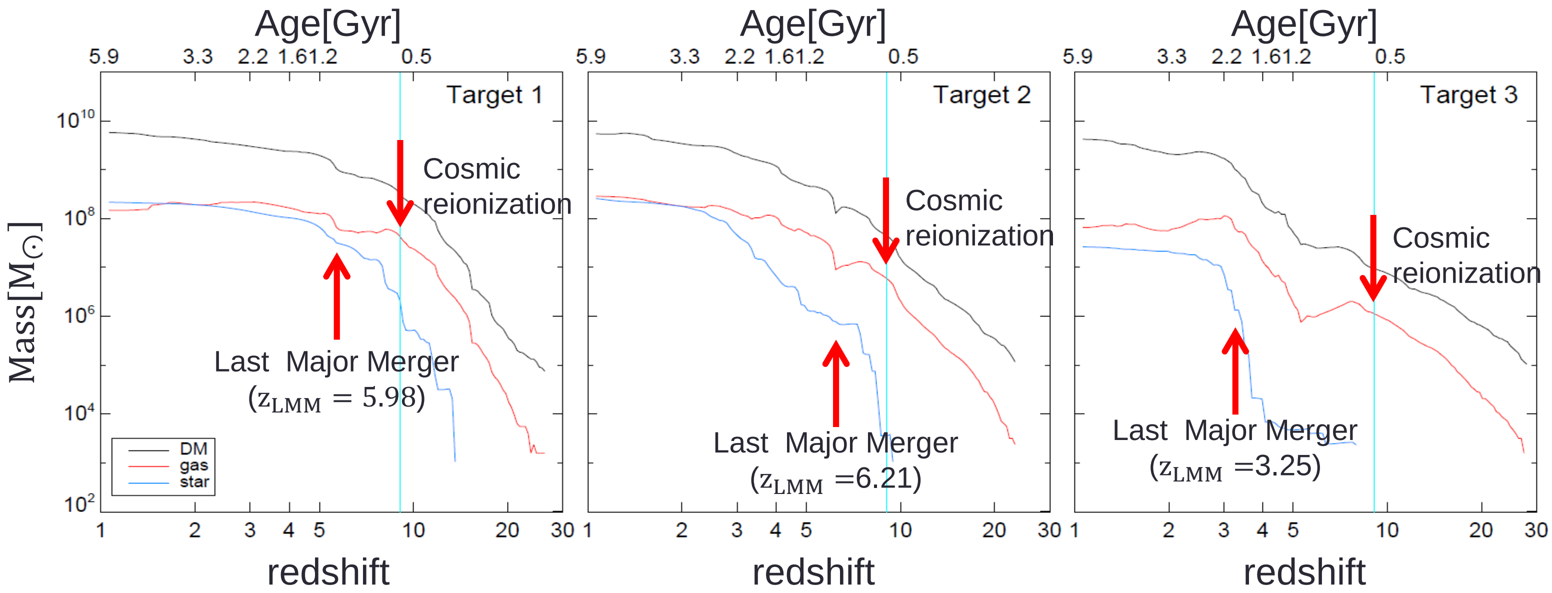
- Particles numbers: $N_{DM} = N_{Gas} = 1.7 \times 10^7$
- **Particles mass**: DM: $4.17 \times 10^3 M_\odot$, Gas: $7.92 \times 10^2 M_\odot$

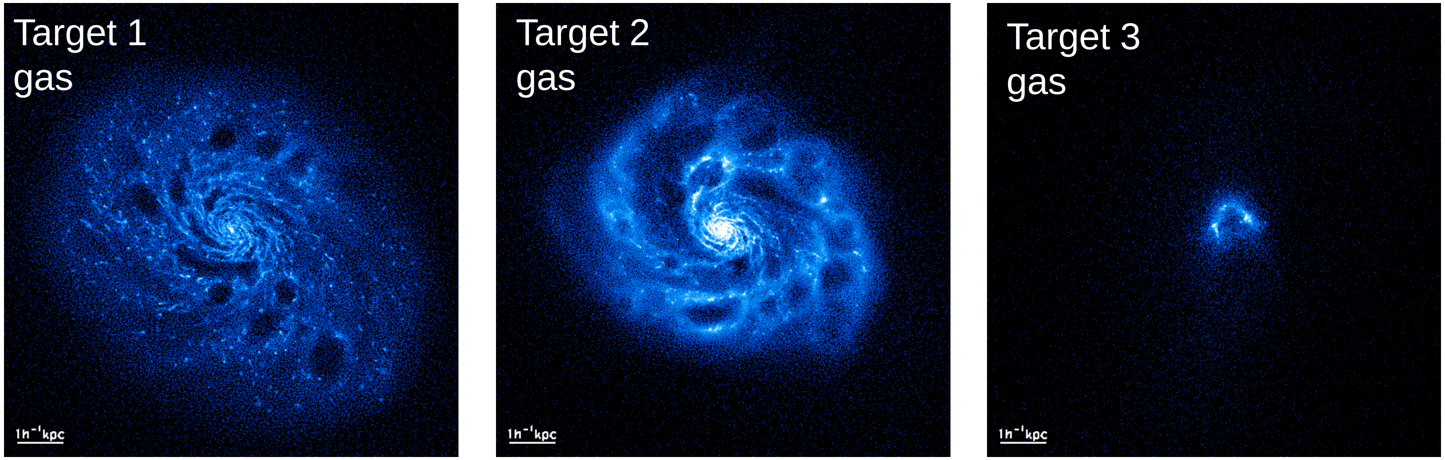
  → The satellite structures can be resolved using at least 100 particles.
- Gravitational softening: Maximum physical softening length: ~10pc

Halo finding

- **Amiga Halo Finder** (Knollmann & Knebe 2009)

Properties of main halos





Mass growth of mini halos

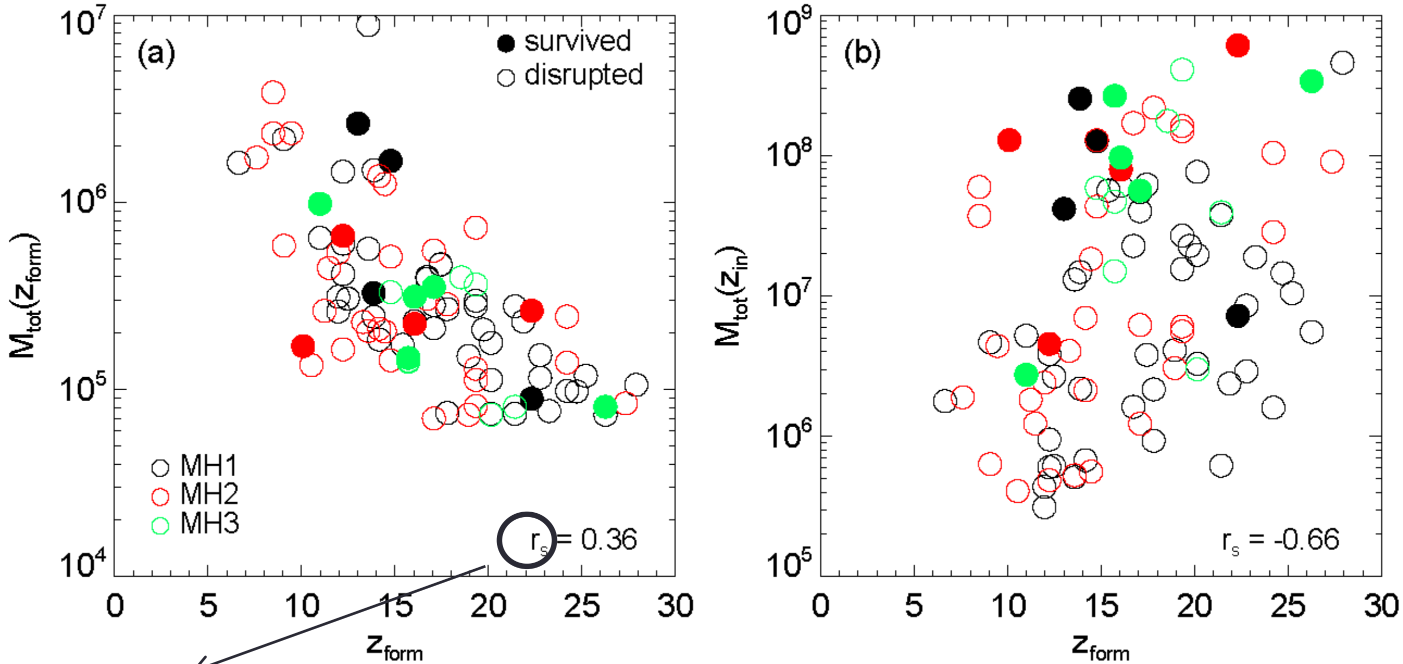
<u>Mini halos</u>

- **Candidates for stellar satellite structures (e.g. GC, UCD, UFD and dSph).**

  - Condition 1: The halos form outside of the main halos.

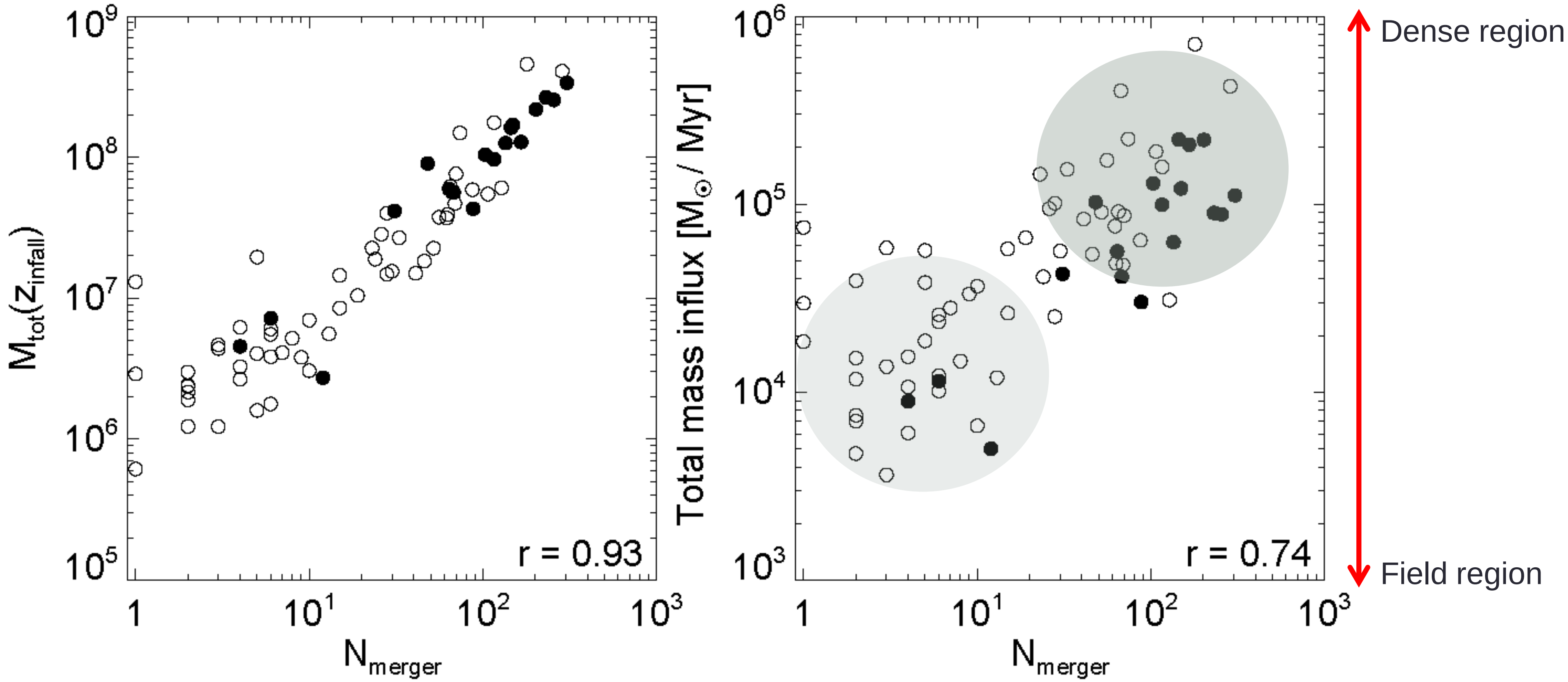
  - Condition 2: $10^4 M_{\odot} < M_{\mathrm{baryon\ (infall)}}$

→ **<u>Number of candidates: 93</u>**



r: Spearman's rank correlation coefficient ($-1 \leq r_s \leq 1$)

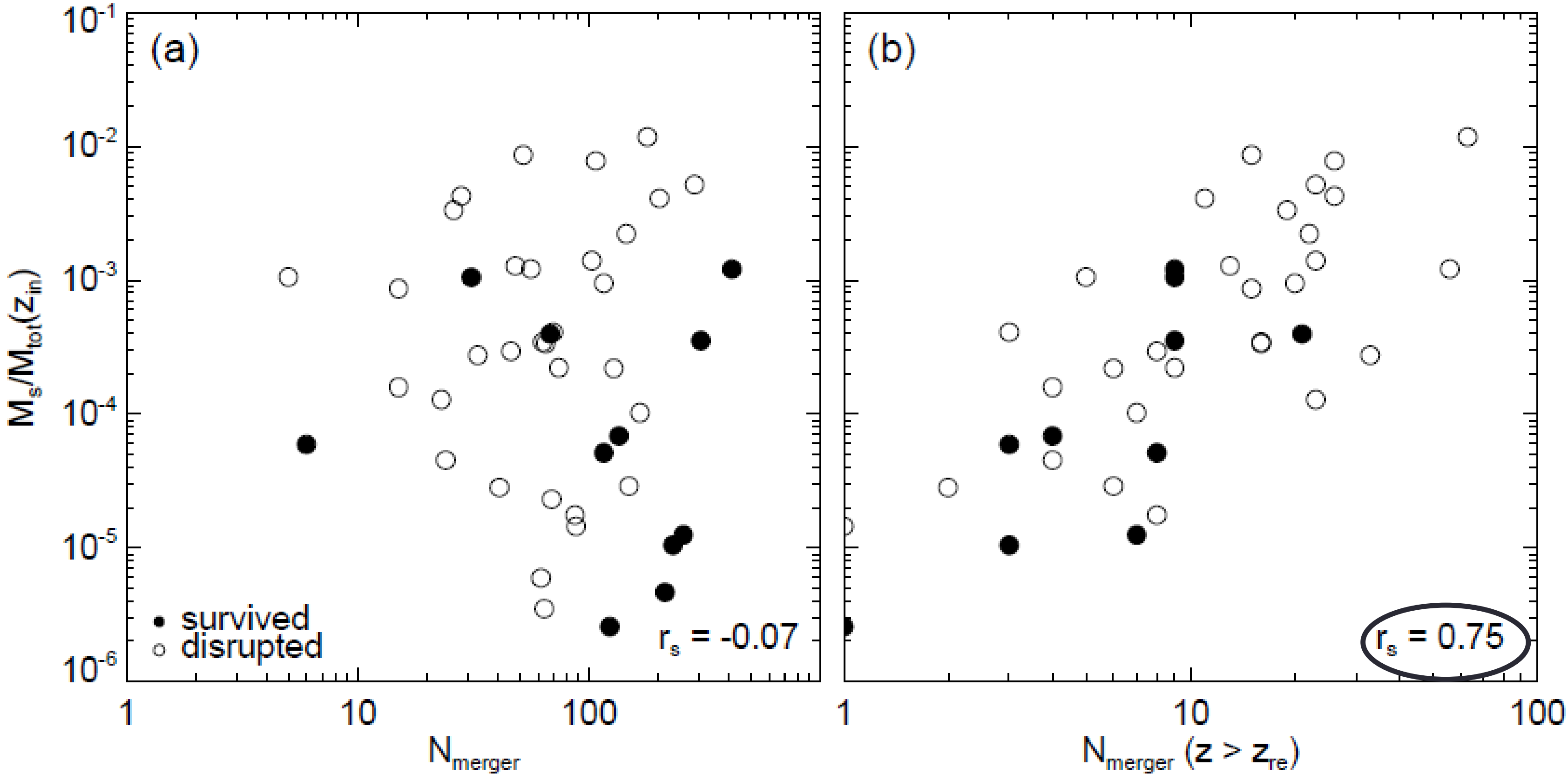
Mass growth of mini halos



The mass growth is related to
the surrounding environments of the mini halos.

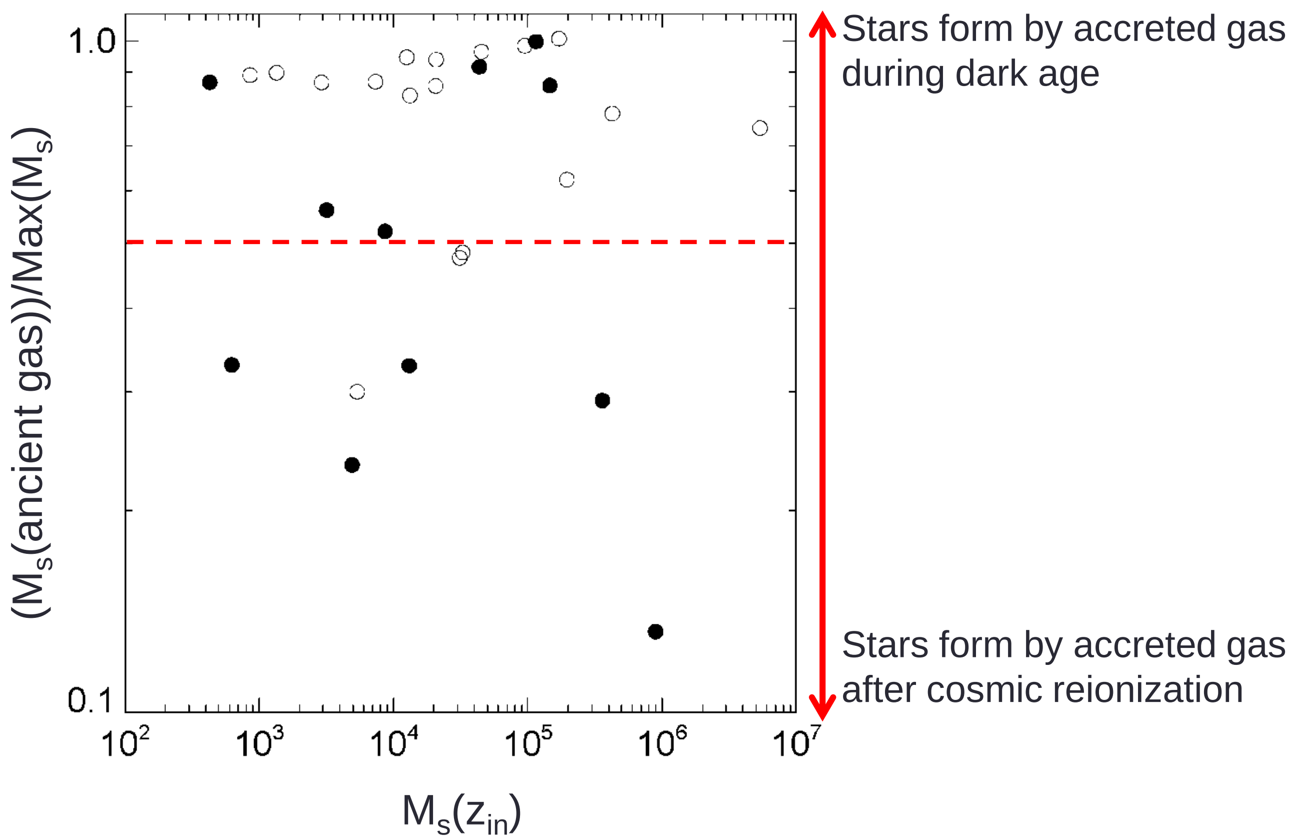
N_{merger}: The total number of merging with other halos before falling into the main halo

Stars of mini halos



$N_{merger}(z>z_{re})$: The total number of merging before cosmic reionization

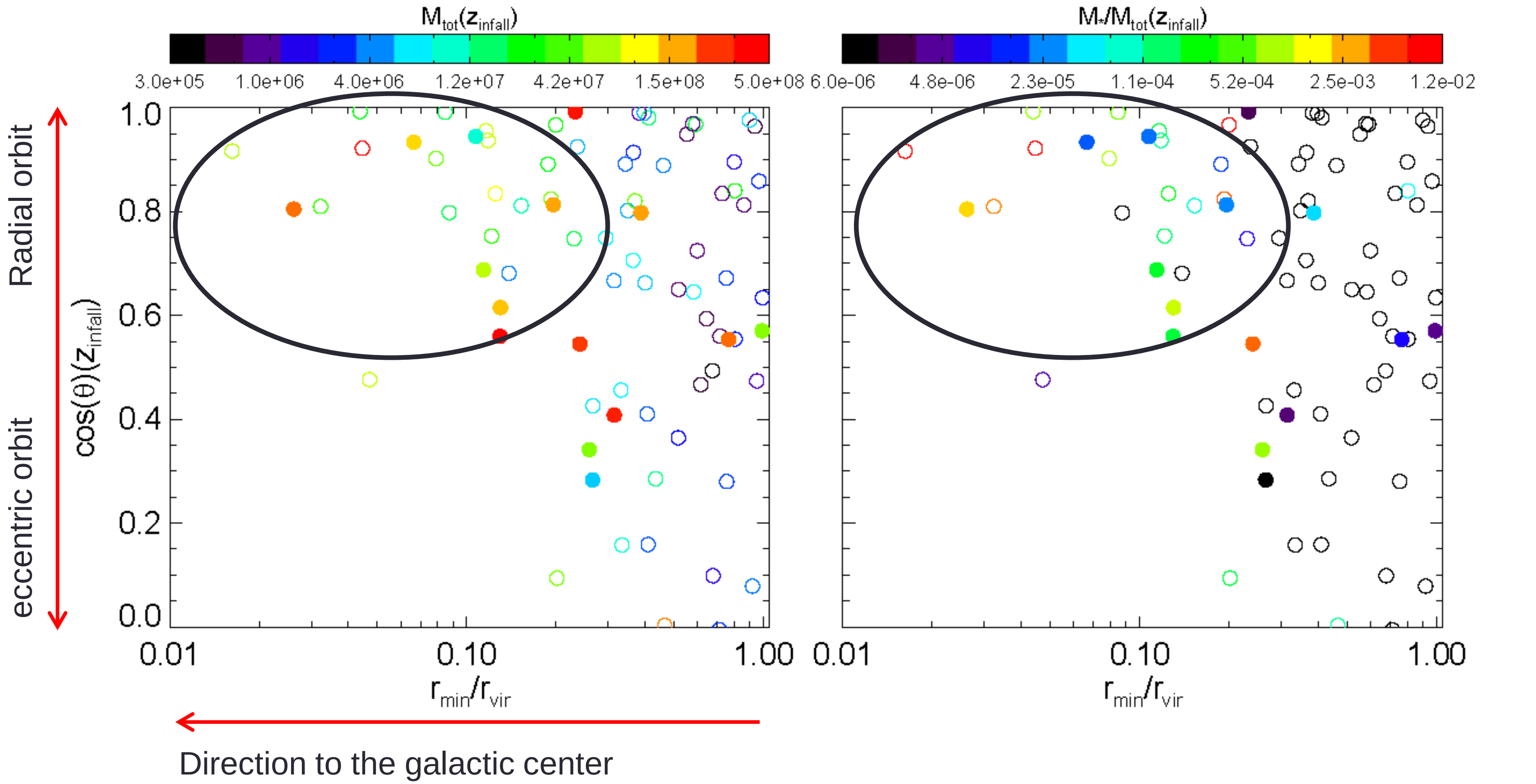
Stars of mini halos



Most halos generate stars by accreted gas during dark age.

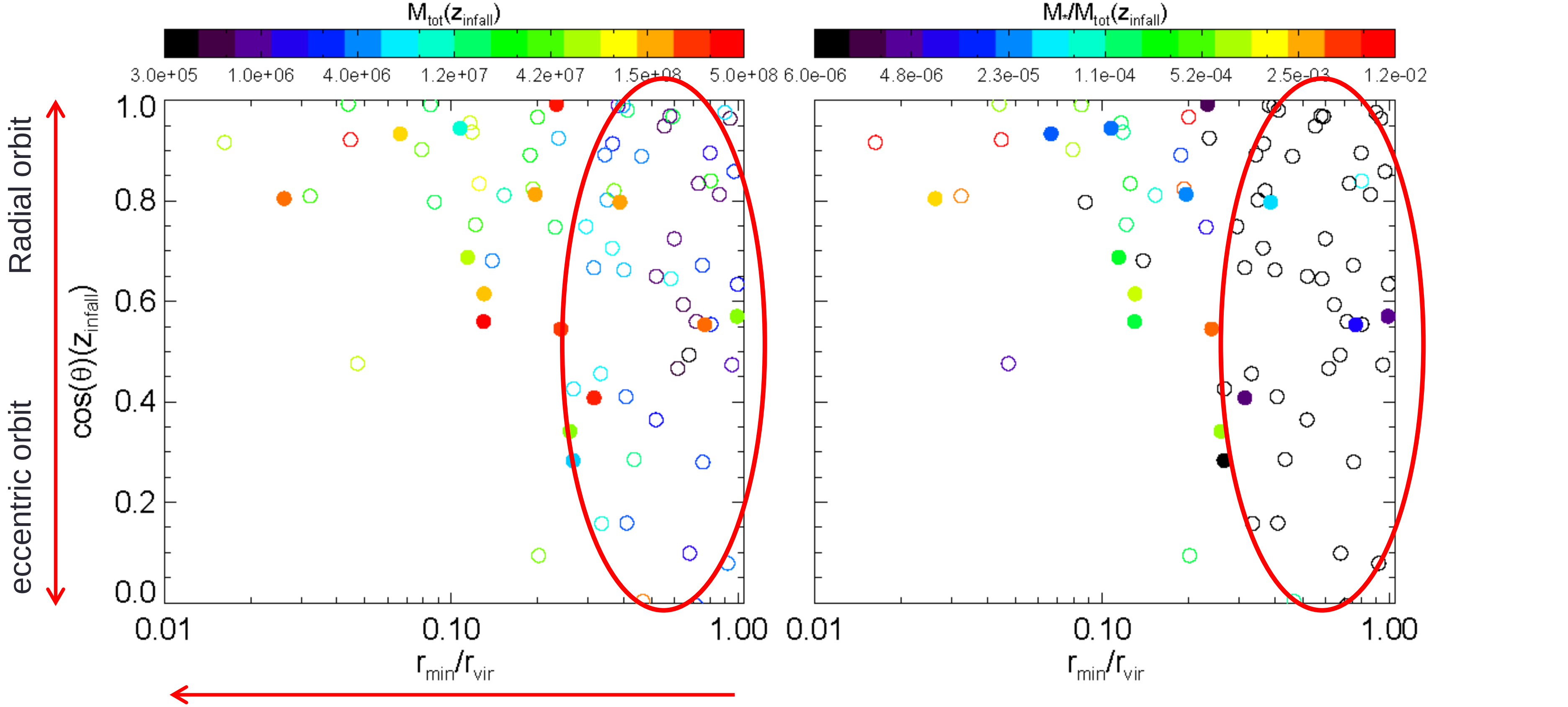
M_s(ancient gas): Stellar mass form by accreted gas during dark age

Properties of mini halos in the main halo



- Massive halos having star components
- Proper motion toward galactic center (from dense region)
- Active DM loss (by strong tidal field) → Star fraction ↑ (by self-gravity of stars)

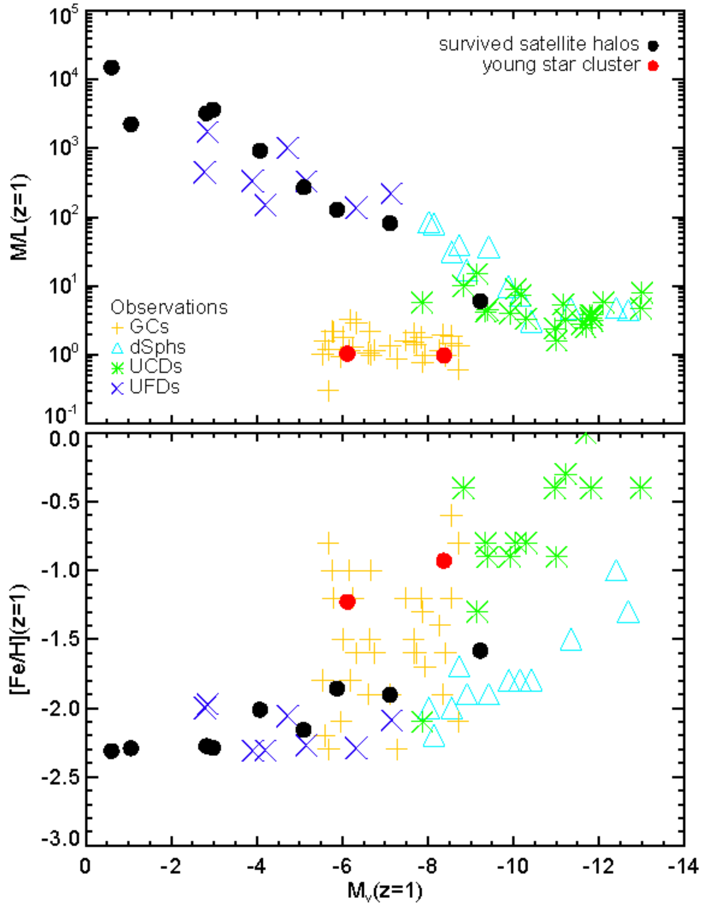
Properties of mini halos in the main halo



Direction to the galactic center

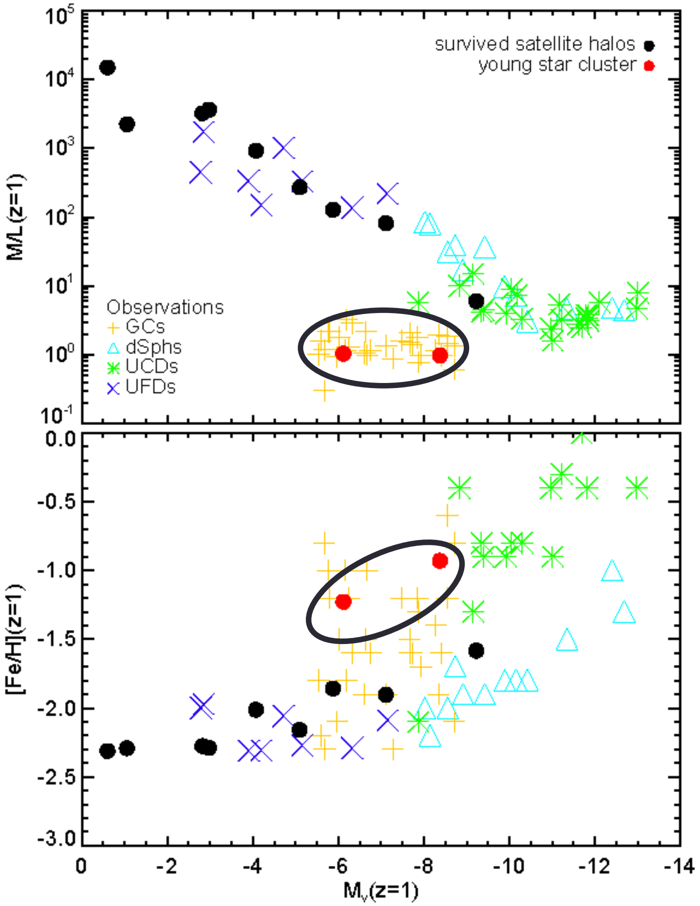
- Low mass halos without star components
- Random proper motion (from field or early infall)
- Destroyed by tidal force

Comparison with observation



- Surviving halos at z~1
  → candidates of UFDs or dSphs
- The objects formed in the main halo
  → candidates of red (metal-rich) GCs

Comparison with observation



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Summary & Future works

- The main factors determining the properties of mini halos
  - Total mass: surrounding environments
  - Star contents: the accreted gas during dark age
- The halos from dense region
  - Massive halos with star components
  - Halos reach the galactic center despite of strong tidal force.
- The halos from field region
  - Low mass halos without star components.
  - Halos stay in high r_{min}/ r_{vir} and are destroyed by tidal force.

→ **Growth process outside of the main halo is important to the evolution of the mini halo.**

- We are going to investigate the evolution of gas cloud in the mini halos with radiative transfer.
  - Our results are used as initial & boundary conditions.