Statistical Study of Substructure Pair Histories

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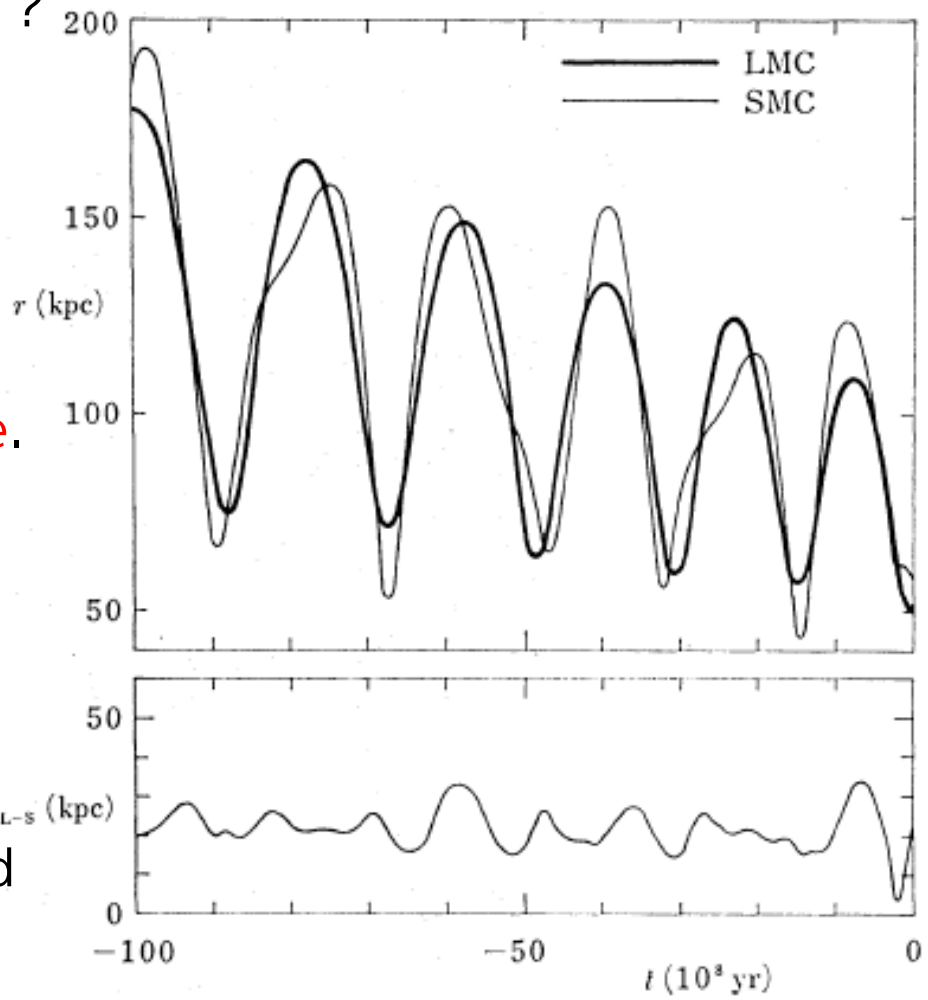
Motivation

- How do the Magellanic Clouds orbit ?
- Murai and Fujimoto (1980)
  - Modeling the orbits of the Clouds.
  - Motion of the Magellanic Clouds was integrated backward in time.
  - Initial condition is combinations of present position and velocity of the Clouds (more than 1000 in the range of observational error).
  - Magellanic Clouds could be bound orbit over the Hubble time.



The model of Murai and Fujimoto (1980)

$$\frac{d^2\boldsymbol{r_L}}{dt^2} = \frac{\partial}{\partial \boldsymbol{r_L}}\left[\phi_S(|\boldsymbol{r_L}-\boldsymbol{r_S}|)+\phi_G(|\boldsymbol{r_L}|)\right]+\boldsymbol{F_L}$$

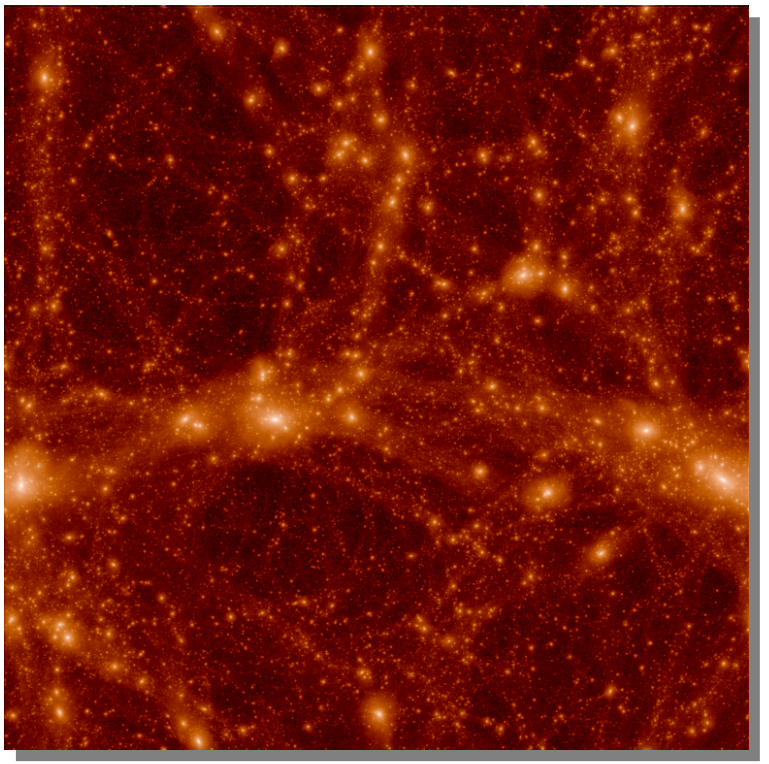
$$\frac{d^2\boldsymbol{r_S}}{dt^2} = \frac{\partial}{\partial \boldsymbol{r_S}}\left[\phi_L(|\boldsymbol{r_S}-\boldsymbol{r_L}|)+\phi_G(|\boldsymbol{r_S}|)\right]+\boldsymbol{F_S}$$

- Motion of the Magellanic Clouds is integrated backward in time.
- Similar Method : Gardiner et al. (1994), Yoshizawa and Noguchi (2003), Bekki and Chiba (2005), Connors et al. (2006)
- The equations do not include
  - dynamical friction between the Clouds
  - tidal-deformation and tidal-stripping of the Clouds
  - merger history of the Milky Way.

Cosmological N-body Simulation includes all of these effects.

Our Approach

- Cosmological N-body Simulation
  - Dark matter in phase space is represented by *N* particles.
  - Particles are evolved forward in time using Newton's law from the early Universe to present.
- Find host halos($> 10^{12}\,M_{\odot}$, >200km/s) and substructures ($> 10^{8}\,M_{\odot}$) from the simulation data and track these orbit from z=1 to z=0
- Investigate how many substructure close pairs exist at present and their histories.

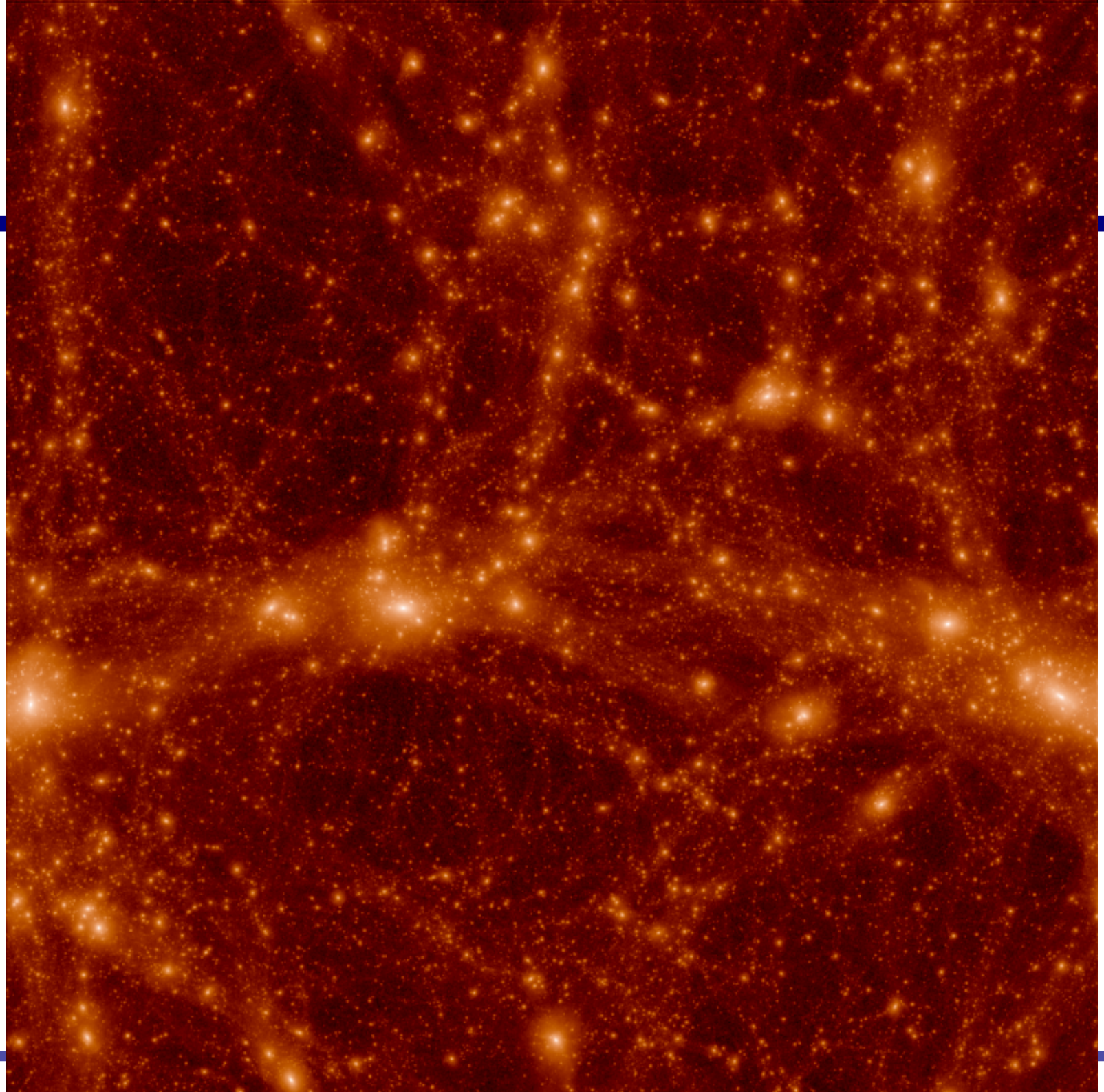


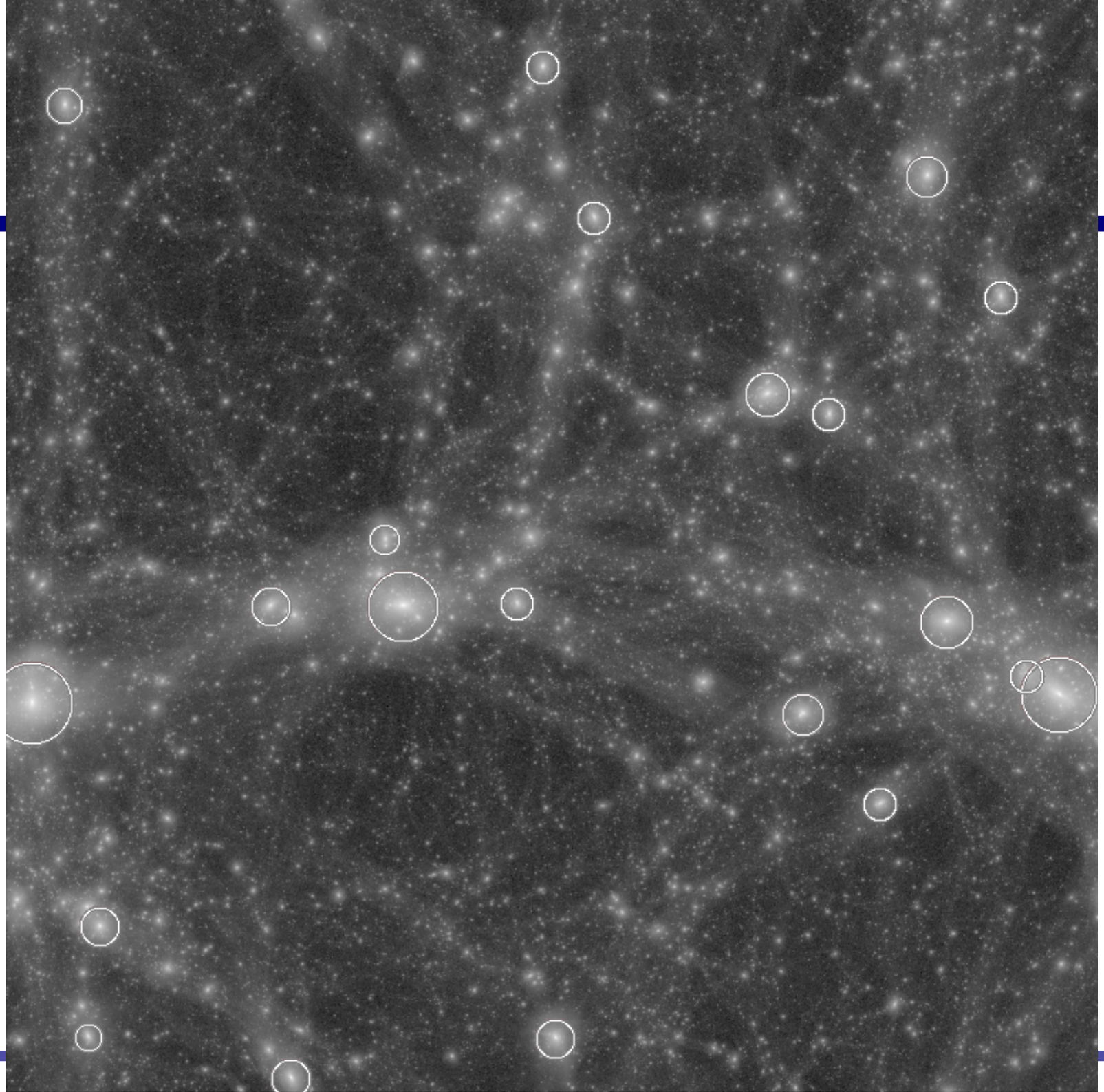
Cosmological N-body Simulation

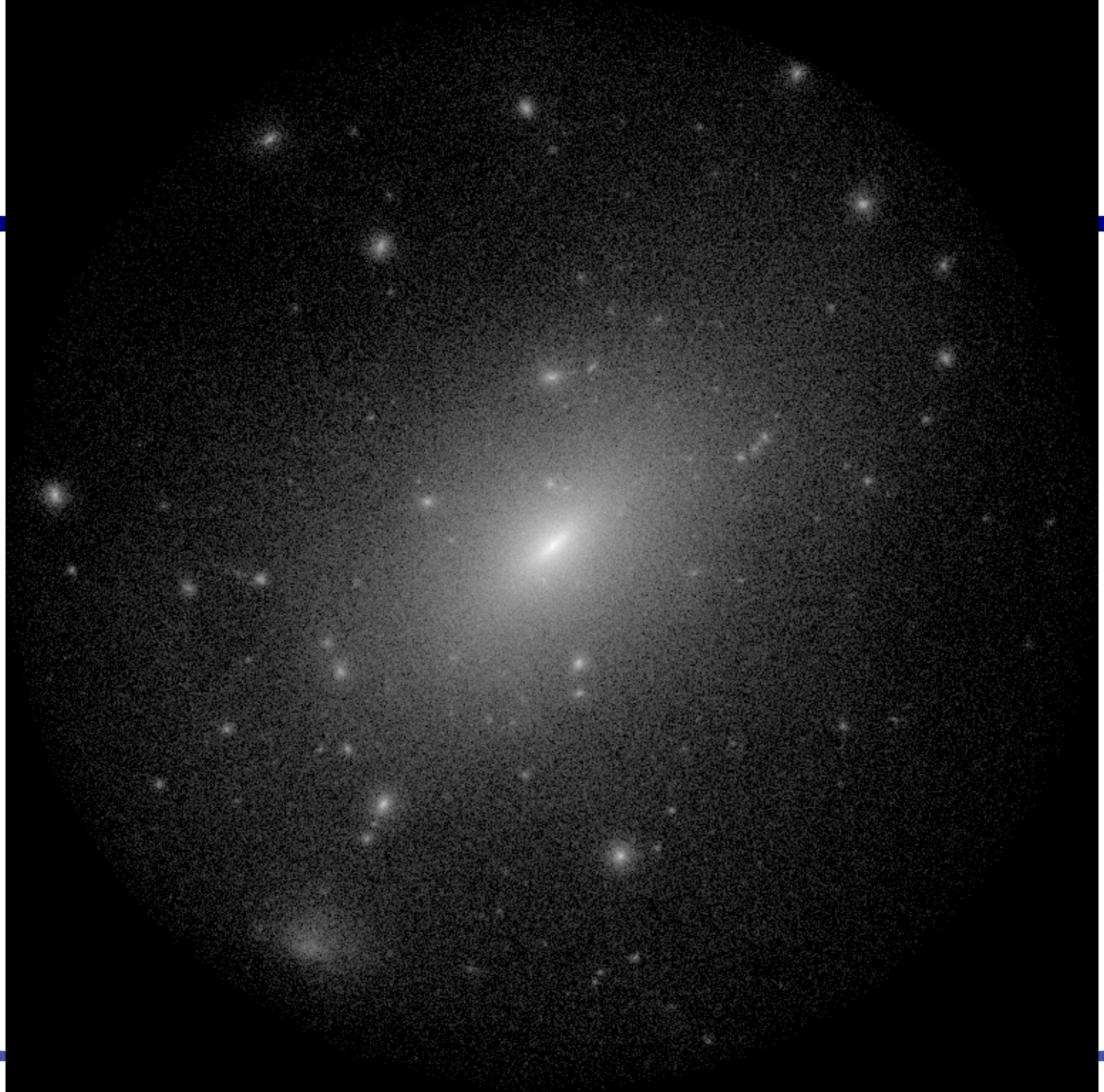
- Density fluctuation in the early Universe is generated by GRAFIC package (Bertshinger 2001) based on the ΛCDM model.
  - $N=512^3$ in 21.4Mpc cubic box.
  - $m=3.0\times10^6\,M_\odot$: mass per particle.

The SMC size substructures are resolved.

- The gravitational forces was computed using parallel TreePM code (Yoshikawa and Fukushige 2005) .
- Calculation of the gravitational forces was accelerated using GRAPE-6A, a special-purposed computer for gravitational N-body simulations.
- A leapfrog integrator was used with adaptive time steps.







Substructure Pair Histories

- Average number of pair per host halo at z=0.
  If the separation of two substructures is less than 50kpc,
  we define them pair.
  - galaxy group scale halo 55.7
  - giant galaxy scale halo 7.1
  - galaxy scale halo 3.7

- Average number of pair formed before z=0.33 per host halo.
  - galaxy group scale halo 1.0
  - giant galaxy scale halo 0.13
  - galaxy scale halo 0.0

Evolution of the Magellanic Clouds

- If the host halos and substructures similar to the Milky Way and the Magellanic Clouds were picked out.....
  - Pair formed before z=0.33 was not found.
  - Average number of pair formed after z=0.33 per host halo
    - top 2 massive substructures 0.0
    - top 5 massive substructures 0.10
    - all substructures 3.1

- A galaxy close pair like the Magellanic Clouds can exist in the ΛCDM context, but it might have formed recently (z<0.33).

Recent study

- The 3D velocities of the Magellanic Clouds are higher than previously estimated (Kallivayalil et al. 2006a,b).
- Besla et al. (2007) calculated the orbital evolution of the Clouds using these proper motion.
- They suggested a first passage scenario, which is the Clouds are currently on their first passage about the Milky Way.

Our result is consistent with their results.

Summary

- We followed dark matter halos formation using cosmological N-body simulation, and the evolution of the halos and substructures from z=1 to z=0
- A galaxy close pair like the Magellanic Clouds can exist in the ΛCDM context, but it might have formed recently (z<0.33).