Searching for Fly-by Encounters of Galaxies in Cosmological Simulations

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Abstract

Fly-by encounters of galaxies are believed to be far more frequent than direct mergers, playing an important role in galaxy evolution. Using cosmological N-body simulations, we have investigated the statistical properties of the fly-by interactions as functions of halo masses and ambient environments. We use a tree-particle-mesh code GOTPM, and discern impulsive fly-by pairs from eventual merger candidates based on the total energy of the two halos of interest. The results are summarized as follows: (1) Halos in the cluster environment experience more frequent mergers and fly-by encounters than those in the field region; (2) Both merger and fly-by fractions for the massive halos evolve more dramatically with time than those for dwarfs; and (3) The fly-by fraction decreases as approaching to z = 0, while the merger fraction increases.

I. Motivation

- Galaxies experience gravitational interactions
  - Mergers (Toomre & Toomre 1972; Barnes & Hernquist 1992; Moore et al. 1996; Springel et al. 2005; Cox et al. 2008)
  - Orbiting satellites (Weinberg & Blitz 2006)
  - Fly-by encounters (Gnedin 2003; Knebe et al. 2004; Sinha et al. 2012).
- Most studies have focused on direct mergers between galaxies to understand their formation and evolution. Recent observation and modeling, however, reveal the importance of impulsive (one-time) fly-by encounters between galaxies in making their detailed (sub)structures.
- In addition to mergers, fly-by interactions perturb galactic potential resulting in the formation of warps and/or spiral arms. Based on cosmological N-body simulations, we have quantified the fraction of fly-by interaction and compare it with the merger fraction.

II. The Fly-by Fraction (FBF)

- A fly-by between halos are defined by the total energy of the system. It has a positive value of the energy ($E_{12} > 0$) (while $E_{12} < 0$ for the merger)

$$E_{12} = -\frac{G(M_1+M_2)}{|\vec{R_1}-\vec{R_2}|} + \frac{1}{2}(\vec{V_1}-\vec{V_2})^2 > 0 \qquad (1)$$

(where G is the gravitational constant, M is the halo mass, R is the radial vector and V_1-V_2 is the relative velocity)

- We only count interactions located within the sum of virial radius of two halos.

$$|\vec{r_1}| + |\vec{r_2}| < R_{1,200} + R_{2,200} \qquad (2)$$

$$F_{fly-by} = \frac{2 \times N_{fly-by}}{N_{halo}} \qquad (3)$$

- Classification in estimating the fly-by fraction
  - Mass : Massive (0.333-3 MW) / Dwarf (0.1-0.333 MW)
  - Environment : Cluster / Field (They are classified based on the number of halos within 5 h^{-1} Mpc)

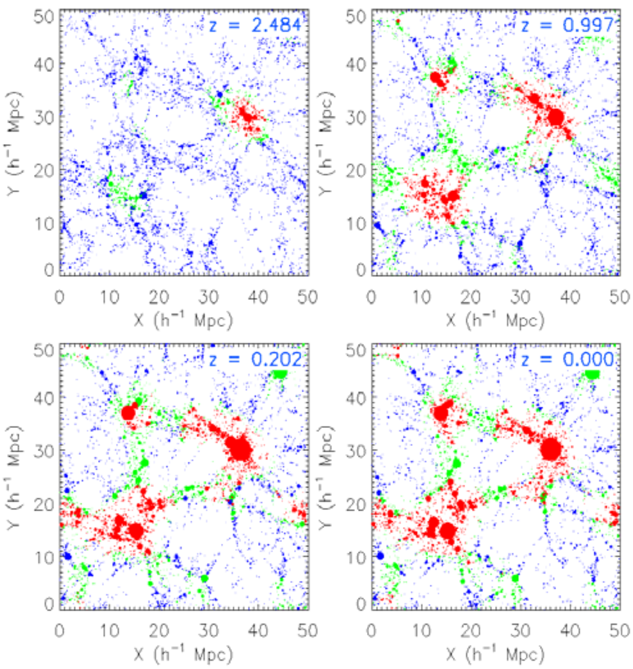

Figure 1. Environment determination. The distribution of halo environments; Field (blue) and Cluster (red) at redshift z=2.484 (top left), 0.997 (top right), 0.202 (bottom left) and 0.000 (bottom right)

cl : cluster / fd : field / ma : massive / dw : dwarf / mj : major

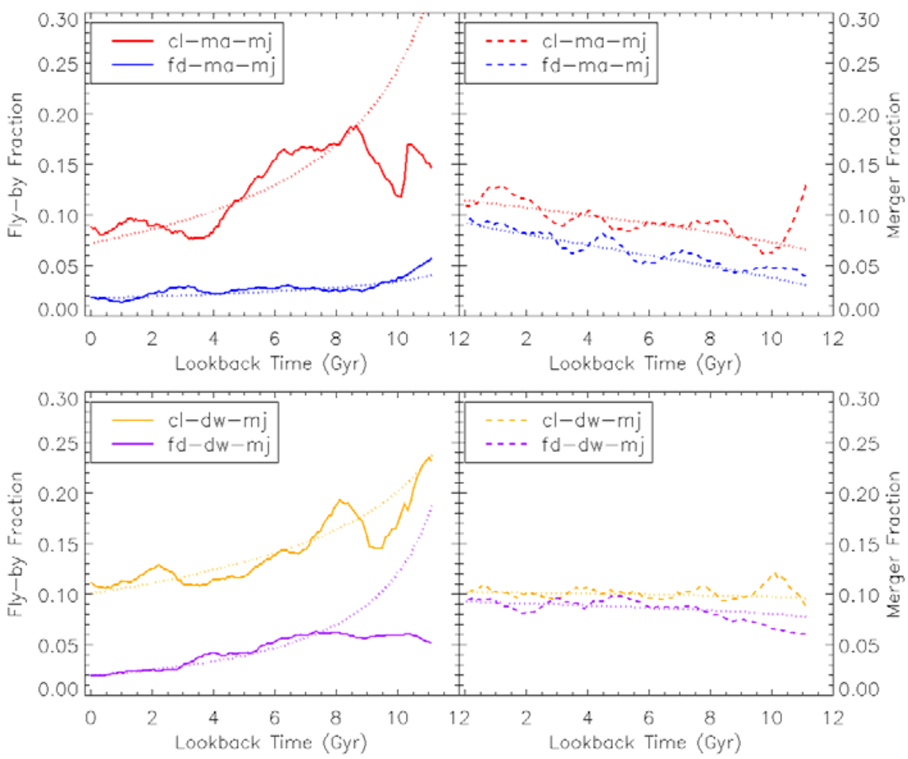

Figure 2. Comparison between fly-by fractions (left panels) and merger fractions (right panels).

III. Results

- Figure 2 shows the fly-by fraction (FBF) and merger fraction (MGF) as a function of redshift.
- As approaching the redshift z = 0, FBFs decrease while MGFs increase.
- In the cluster environment, more fly-bys and mergers occurs than in the low-dense region.
- Figure 3 presents $F(0)$ versus m which are two parameters of the fitting function,

$$F(z) = F(0)\,(1+z)^m \qquad (4)$$

where m is a power index and z is redshift.

- We apply the above equation (4) in order to generate the fitting curves (dotted lines in Figure 2) in the lookback time range of 0 to 8 Gyr.
- An m is an indicator that shows the change (increase or decrease) in the fraction of interactions with respect to redshifts.
- Massive halos are likely to have larger absolute values of m.

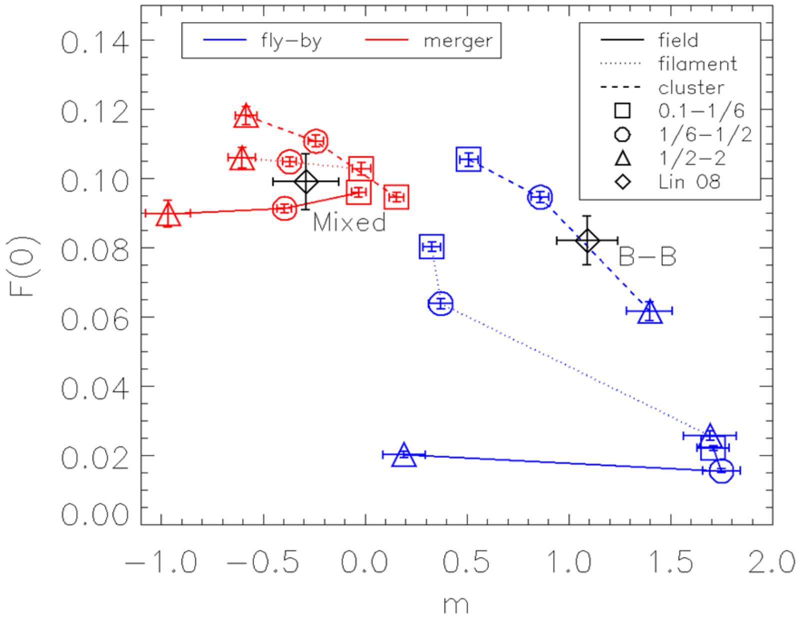

Figure 3. $F(0)$ and a power index m in fitting functions. We compare values of fly-by encounters (blue) and mergers (red) as functions of halo masses (shape) and ambient environments (line style).

IV. Discussion and Conclusion

- We present FBFs and MGFs in terms of redshifts, halo masses and environments with our classification scheme, which is primarily based on the total energy of two interacting halos.
- In principle, we are predicting the fate of galaxies at each snapshot since FBFs and MGFs are estimated at certain points, not the exact moments of interactions, therefore, the sum of those values should be treated as the probability of finding galaxy-pairs at certain points.
- In addition, our classification method might over-estimate the fraction of interaction between halos because a halo can possibly experience more than one interaction with multiple counterparts.
- We find three obvious results of halo interaction fractions;
  - ➢ FBFs (MGFs) increase (decrease), as redshift increases.
  - ➢ Halos in the high-dense region undergo more frequent fly-bys and mergers than those in the field region.
  - ➢ The power index m of equation (4) is greater in more massive halos than in less massive halos.

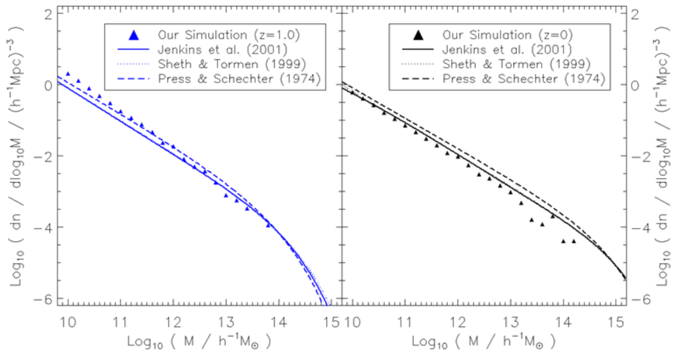

Figure 4. Halo mass functions at redshift z = 1 (left) and 0 (right).

Appendix A. Simulation

- The cosmological simulations, Grid-of-Oct-Tree-Particle-Mesh (GOTPM) (Dubinski, 2004)
- The boxsize is 50 h^{-1} Mpc including 512^3 particles with WMAP5 parameters.
- From redshift z=63 to 0 and 173 snapshots (the time resolution is 0.06-0.1 Gyr)
- The halo finding algorithm, Physically Self-Bound (PSB) (Kim & Park, 2006)
- We use a friends-of-friends linking length $l = 0.2$ and require at least 10 particles to define a halo.

Figure 5. Samples of fly-by interactions (left and middle) and mergers (right). They shows trajectories, distance, energy, relative velocity and mass of two interacting halos