Fingerprints of merger events in galaxy groups

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Summary

Mergers of galaxy groups are very frequent during the galaxy formation period and continue to happen even at the present time. From observations it is very important to try to find fingerprints of recent merger events to interpret the underlying physical phenomena and processes behind the galaxy formation and group properties. We have used Millennium II cosmological simulations to evaluate how different techniques to find the signs of mergers and substructure function in realistic merger events. This is an important step to understand how merger events can actually be seen in real observational data and galaxy surveys that are always limited to a certain epoch of time.

1. Background

It is very well known fact that in the ΛCDM cosmology, structure grows hierarchically and mergers in all scales are very important elements in galaxy formation. Merger rates and detailed mechanisms, as a function of properties such as mass, number of galaxies, redshift, and mass ratio, are quantities of fundamental interest.

In our project we investigate theoretical possibilities to find signatures of recent merger events of galaxy groups in observational data. For example, the Sloan Great Wall provides a good laboratory to track down the merger events (*Einasto et al., 2010 A&A, 522, id.A92*). We use cosmological simulations to track realistic merger events for large **$M \geq 10^{13} h^{-1} M_{sun}$** dark matter halos that resemble galaxy clusters. For proper statistics we use a sample of **414 Fof-halos** in this mass range. The Millennium II simulation (*Boylan-Kolchin et al. 2009, MNRAS, 398, 1150B*) provides good data set for our study. One example of an ongoing merger event is shown in the following Figure 1.

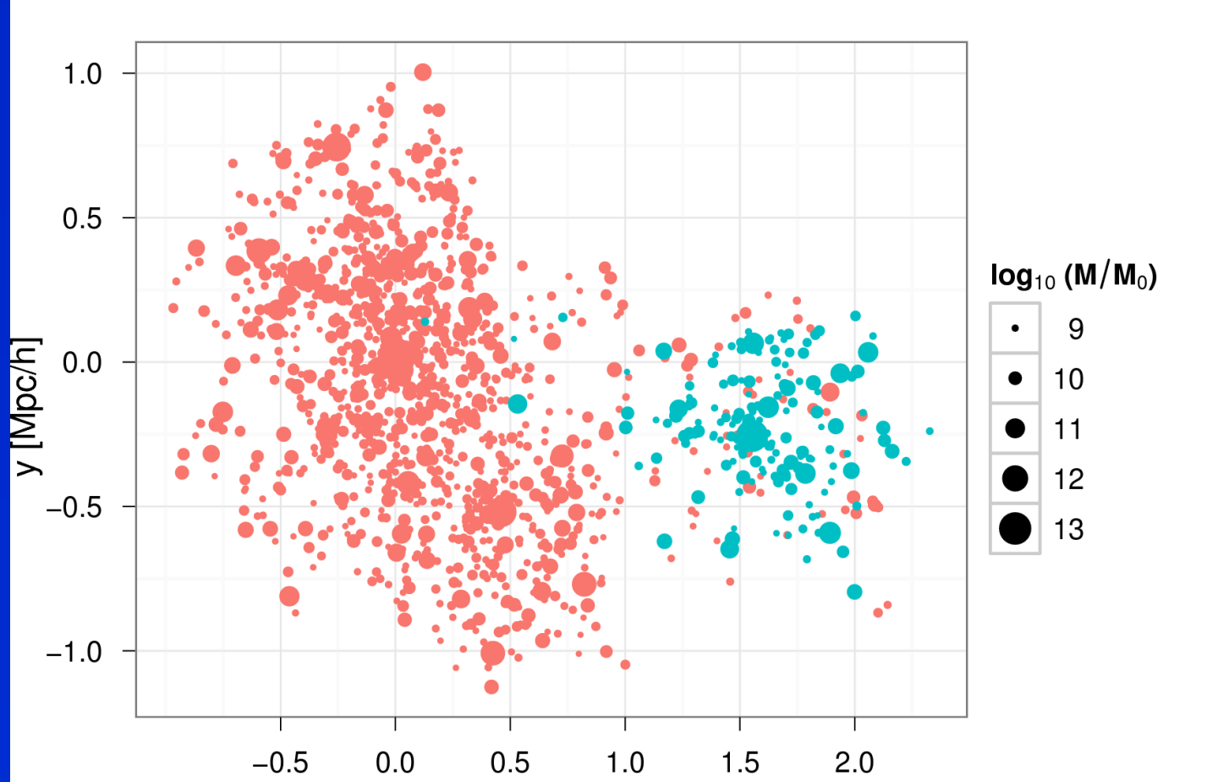

Figure 1: *An ongoing merger event of two separate galaxy groups in the Millennium II simulation. At redshift z = 0.1 has already occurred merger event (mass ratio 0.2) in the red group and it is still merging with blue group.*

In the following figure 2 we show the frequency of the merger events in different scales. **Red line** is for minor mergers, with **mass ratio >0.1** and **blue line** is for major mergers (**mass ratio >0.3**). Redshift z marks the latest merger event. As expected, minor mergers are very frequent and half of all halos have experienced the latest merger event at redshift 0.5 and for major mergers corresponding redshift is 1.0.

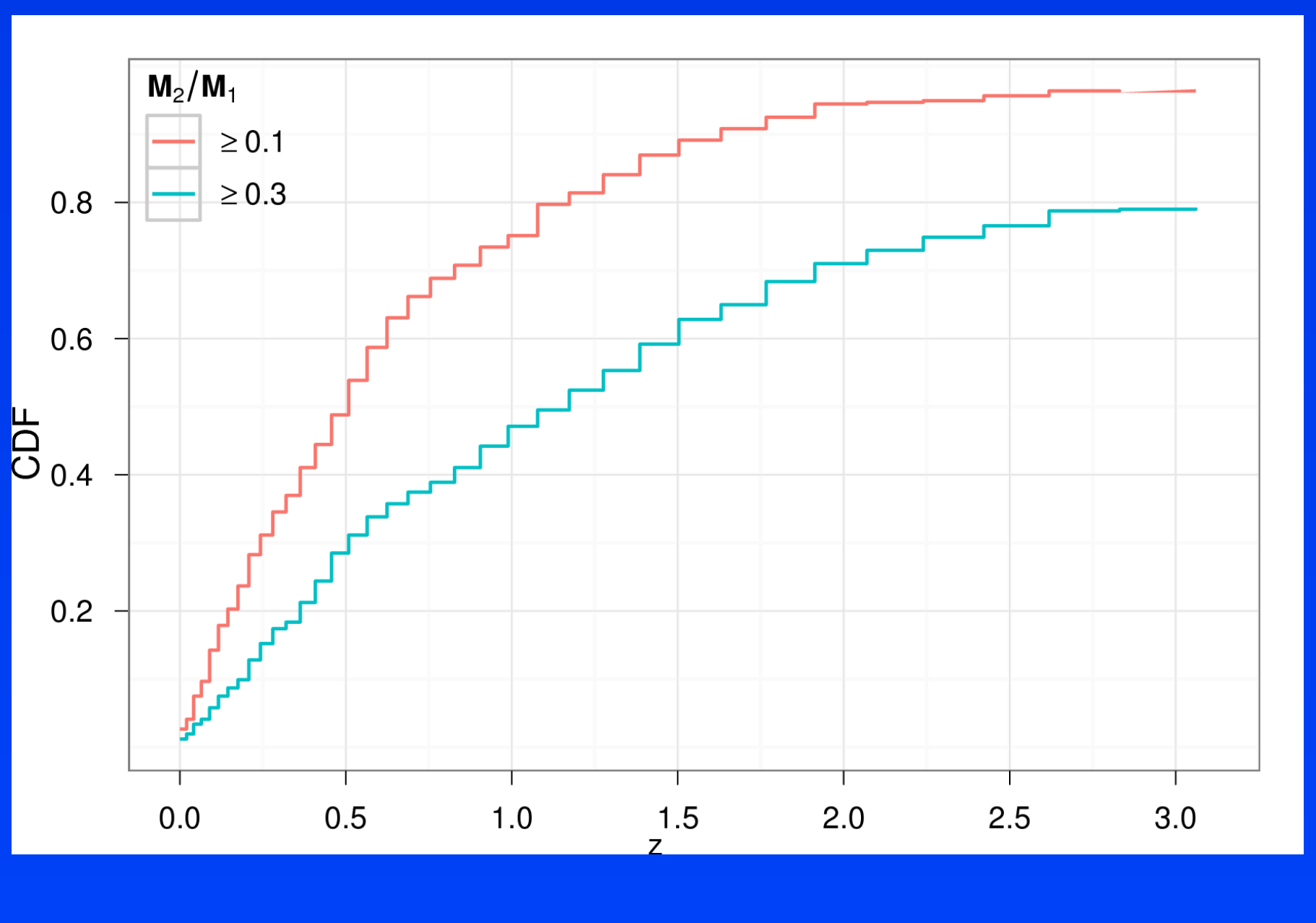

Figure 2. *Cumulative distribution for minor (mass ratio >0.1) mergers and major mergers (mass ratio >0.3) as a function of redshift z for the latest merger event. We see that ~50% of all large halos have no major mergers after redshift 1.*

2. Effectiveness of techniques

In the literature there are several different techniques to find substructure using different combinations of spatial and velocity co-ordinates. Different techniques were already compared by (*Pinkney et al, 1996 ApJSS, 104, 1). We* have used different approach applying techniques for cosmological simulations together with merger information. In our analysis we use normally two spatial co-ordinates and one velocity co-ordinate. In this way the test is very close to the observational situation.

To characterize the reliability of substructure we use $p \leq 0.05$ (in Table 1, Figure 3 and Figure 5), where p is the probability to get at least the same numbers for substructure detection from the algorithm for halos with no substructure by mixing the velocity and position information several times.

In table 1 we show the results of comparison for 7 different techniques to detect substructure (left column). Values in the table are percentages of positive detection for substructure (with $p \leq 0.05$). Either all subhaloes ($r \geq 0$) or only those inside $r \leq r_{200}$ are used in the analysis. Further we divide subhaloes to three different mass categories: $M \geq 10^{10} h^{-1} M_{sun}$ (minimum requirement is 30 subhaloes), 100 largest (m_{100}) or 300 (m_{300}) largest (if there are not that many, we use all that are available).

	$\mathbf{r \geq 0}$			$\mathbf{r \leq r_{200}}$		
	$10^{10} h^{-1} M_\odot$	m_{100}	m_{300}	$10^{10} h^{-1} M_\odot$	m_{100}	m_{300}
Δ	43%	55%	88%	16%	25%	41%
κ	38%	47%	80%	14%	20%	34%
α	42%	54%	80%	16%	23%	36%
β	25%	28%	52%	5.0%	5.0%	8.0%
SW	13%	15%	32%	13%	13%	24%
AD	15%	15%	32%	14%	14%	23%
Mclust	48%	48%	77%	14%	10%	15%
One test	73%	84%	98%	36%	46%	62%
All tests	12%	12%	38%	1.0%	0.0%	1.0%

Table 1: *This table collects the effectiveness of different techniques to find substructure in the simulation data. We use 2-D position information together with 1-D velocity co-ordinate for Δ, κ and α tests. β and Mclust use only positions, and SW and AD use only velocity. Percentage is for positive detection of substructure.*

The last two lines shows percentages of positive detection at least in one of the tests (One test) or positive detection in all tests (All tests). For these values SW and AD tests are ignored. The more subhaloes are included in the analysis, the more substructure is identified. This is quantified in the following figure 3.

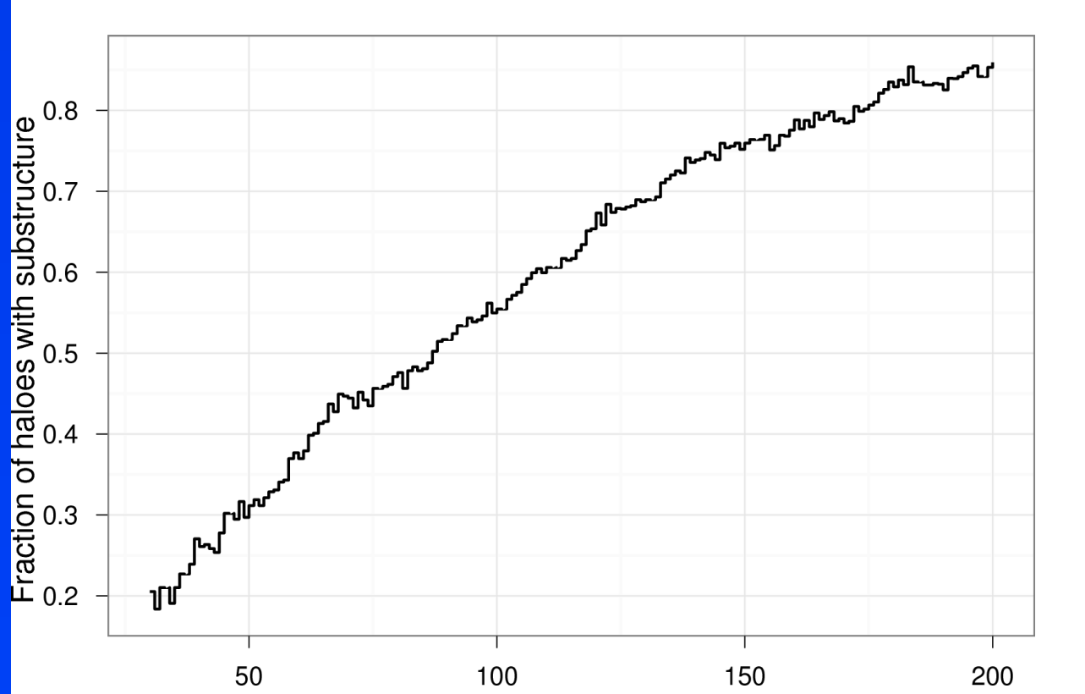

Figure 3: *The number of included subhaloes have crucial effect how well the substructure is identified. Here we have used all Fof-haloes, but the number of subhaloes included in the analysis is varied. We see that if we include ~80 largest subhaloes, then ~50% of Fof-halos have identified substructure.*

3. Mergers and their detectability

Furthermore, we are interested in the method that can find signatures of merger events ("dynamical" substructure) that have occurred in their near history. For this purpose we use the method that is the most reliable (Δ-test, see table 1). We divide the data to different groups and study the connection between the detection of substructure and merger event. In figure 4 red color is for halogroup that has experienced a recent merger (75% of halogroups have later merger) event.
Blue color is for groups with rather old mergers (75% have more recent merger). The trend is clear; high CDF for small p-values (reliability level) are for halos that have recent mergers, but there are still many positive detections for substructure without merger events. Evidently, there is a correlation between the merger time and detection of substructure, but it is weak.

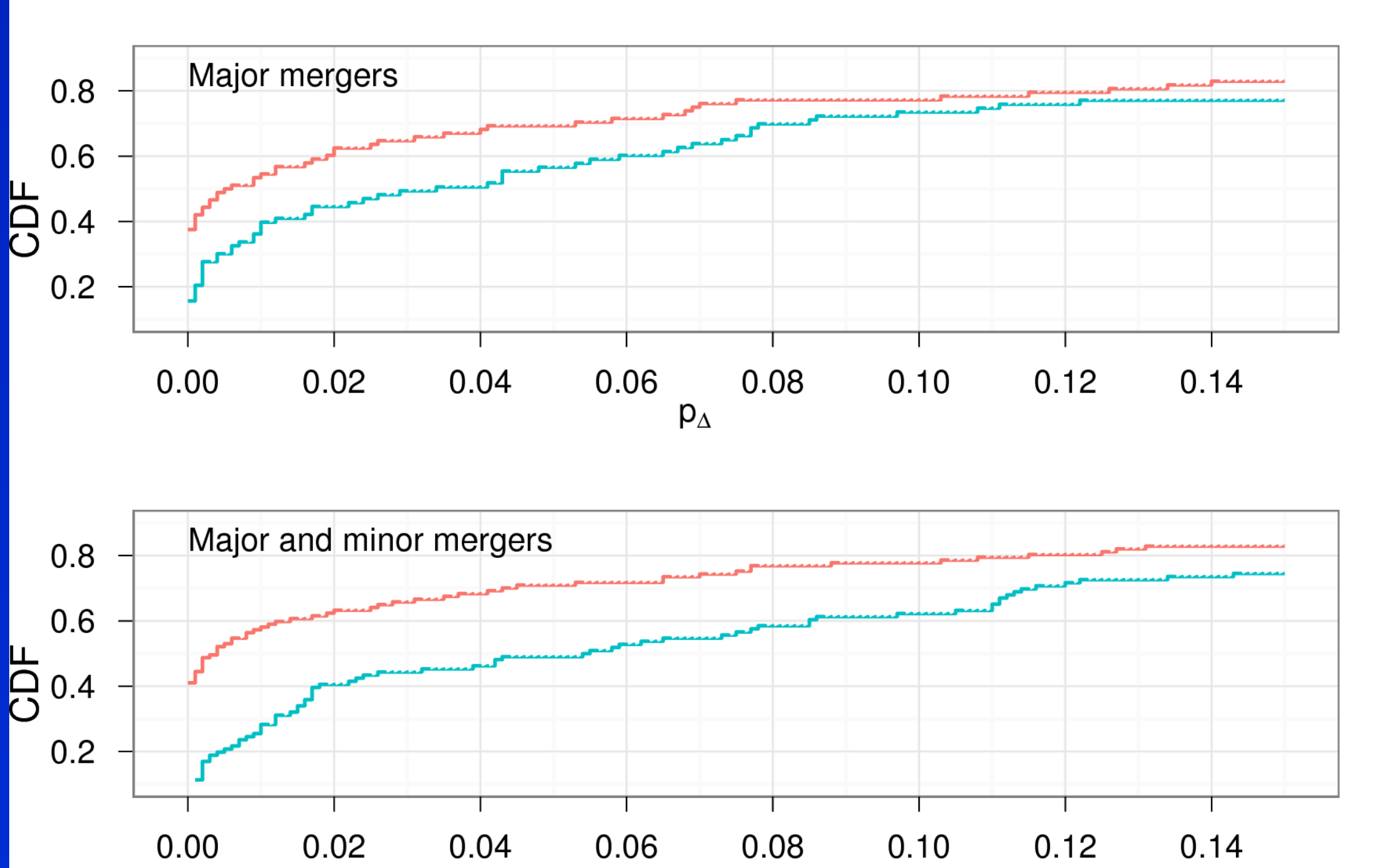

Figure 4: *Cumulative distribution for merger detection as a function of reliability (p-value) of the test. Upper panel is for major (mass ratio 0.3) mergers and lower panel is for all those mergers with mass ratio larger that 0.1.*

Another way to track the merger events is to search for the positive correlation between the fraction of substructure and redshift that must be a signature of cluster evolution (figure 5).

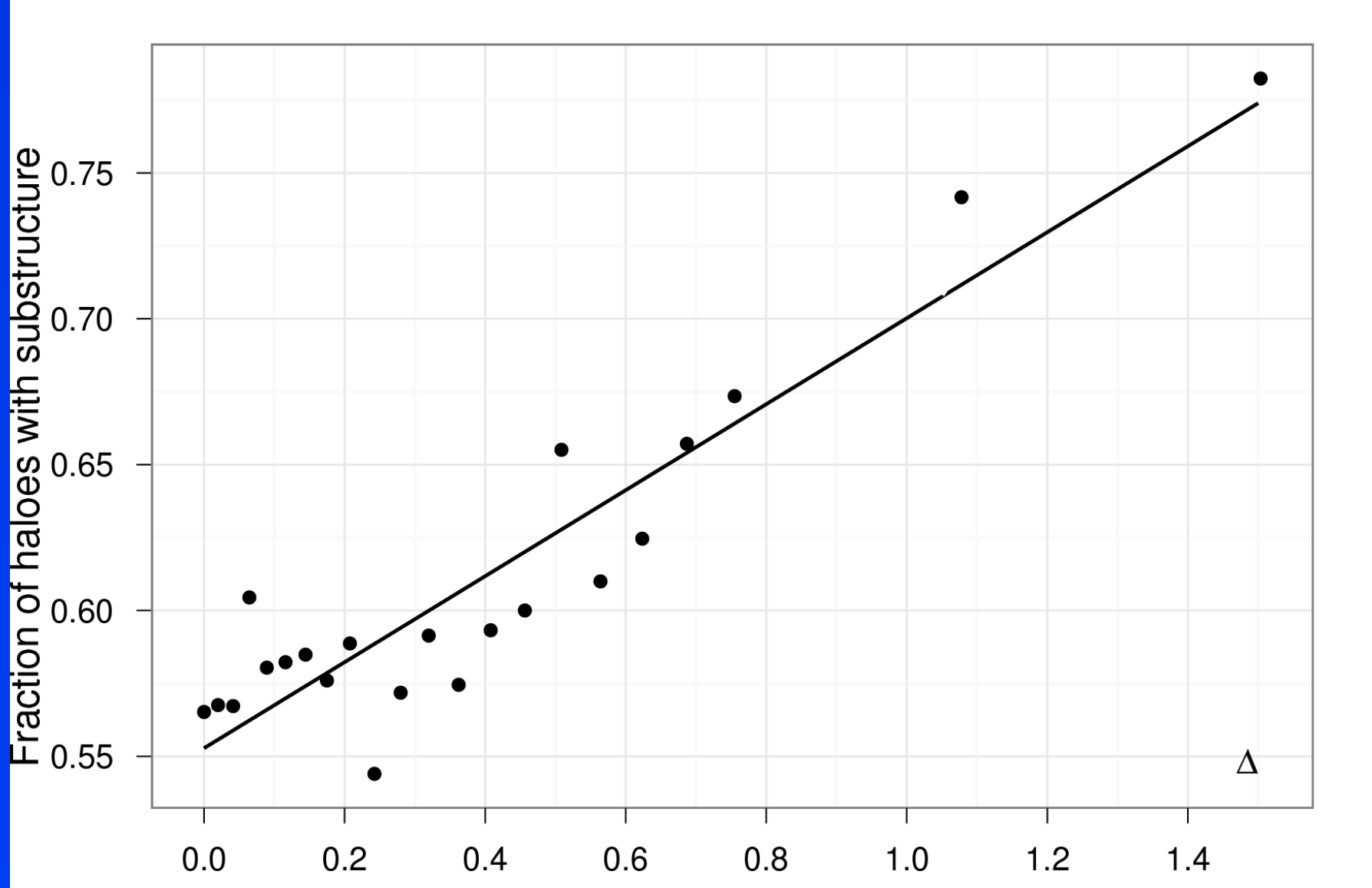

Figure 5: *The fraction of haloes with substructure increases together with redshift due to the merging history of haloes. This is clearly seen in this figure that uses the most reliable Δ-test.*