1 MATCHING HALOS

(How should I show the varification between 256^3 and 512^3 particles...?)

In this section, we investigate how the number of steps affects to halo properties. In order to compare halos in different simulations, it is required to identify the same halos in those samples. Since all the simulations use exactly the same initial conditions, if those approximated N-body simulations recover the halos well enough (compared to a full N-body simulation), we find the same halo at the same position with the same mass. In those simulations, we stored information of particle id and halo id besides particle's position and velocity. Particle id is an id to identify each particle and halo id is a tag for the halo where the particle belongs. Having the same particle id implies that those particles were initially at the same position. On the other hand, there is no correspondence for halo id, because halo id is assigned to each halo rather randomly. So, we need to match halo id in different samples to identify whether two halos are the same halo or not. By matching halos by halos, we can investigate the effect of step numbers on halo properties (i.e., halo mass, position, and velocity).

To find matched halos, we first identify particle ids in each halo. Note that we did all the matching with respect to the sample of 450/5. For each halo in 450/5, we identify particle id and find the corresponding particles in the other sample. Among those particles, we take a halo id that those particles share the most. Since the number of halos in the samples is different, there are some halos which match with two or more halos in 450/5. For those "double-booked" halos, we also checked the fraction of matched particles over the total number of particles in those halos and chose the one whose fraction is the largest. At last, we decided to make thresholds to check whether those macthed halos can be really identified as the same galos. We checked the fraction of matched particles over the total number and eliminated the ones whose fractions are below the threshold. Figure 1 and Table 1 show how matched (and unmatched) fractions are changed as a function of thresholds. We chose the threshold of 0.5 in the following section, because XXX.

At last, we show the fraction between number density of unmatched halos and the total number density at three different redshifts and with different number of steps in Figure 2. I need to check why z=0.8 behaves so differently for 450/5 (and whether the same thing is happened for matching with other samples). As shown in the right panel in Figure 2, the fractions are almost the same for different redshifts. On the other hand, the left panel in Figure 2 shows that global time steps actually affect to the fraction of unmatched halos on any halo mass while sub-cycles only affect on low-mass halos.

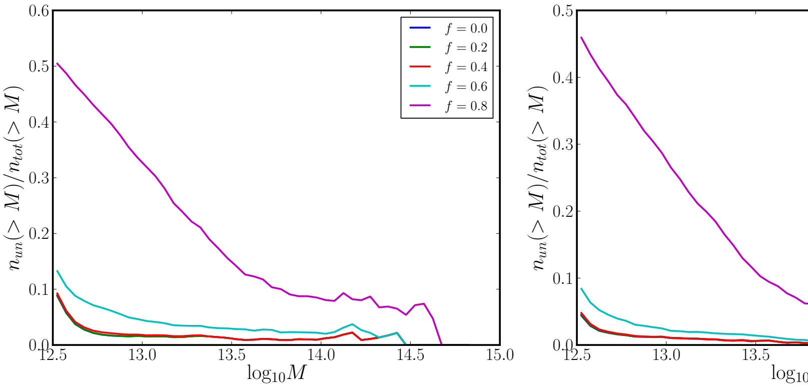

Figure 1. The fraction of unmatched halo number density and the total number of halos for the simulation of 300 global steps and 2 sub-cycles matching with 450 global steps and 5 sub-cycles at $z = 0.15$. Both are from 256^3 particle simulations. The right panel is the fractions for 450/5 and the left panel is the fraction for 300/2.

1.1 Time steps

In this section, we examine how global steps and sub-cycles affect to halo properties. The goal here is to know the smallest global steps and sub-cycles required to preserve necessary properties for mock catalogs.

Here, all the samples have the same mass resolution, 256^3 particles in the box of $(256h^{-1}\mathrm{Mpc})^3$. We use 450/5 (450 global steps and 5 sub-cycles) as a reference to other samples: 300/3, 300/2, 150/3, and 150/2.

Figure 3 shows halo mass differences for paired halos with respect to halos from 450/5. Global steps affect on overall distribution properties (i.e., mean and standard deviation shown in Table 2), while sub-cycles affect on their amplitudes. This is because sub-cycles changes small-scale dynamics and it can cause a difference on number of halos declared through FOF, whose linking length is fixed to $b = 0.2$. In general, smaller step sizes make distribution of DM par-

[p]

threshold\redshift	$z = 0.15$	$z = 0.5$	$z = 0.8$
0.25	0.973	0.973	0.972
0.5	0.955	0.953	0.952
0.75	0.709	0.662	0.638
1.0	0.0	0.0	0.0

Table 1. Fractions of matched halo for the sample of 450/5 when we compare a halo by halo for 300/2. Here, both simulations have the same mass resolution (i.e., 256^3 particles in the box of $(256h^{-1}\mathrm{Mpc})^3$). This table shows how the fraction is changed according to changing the thresholds.

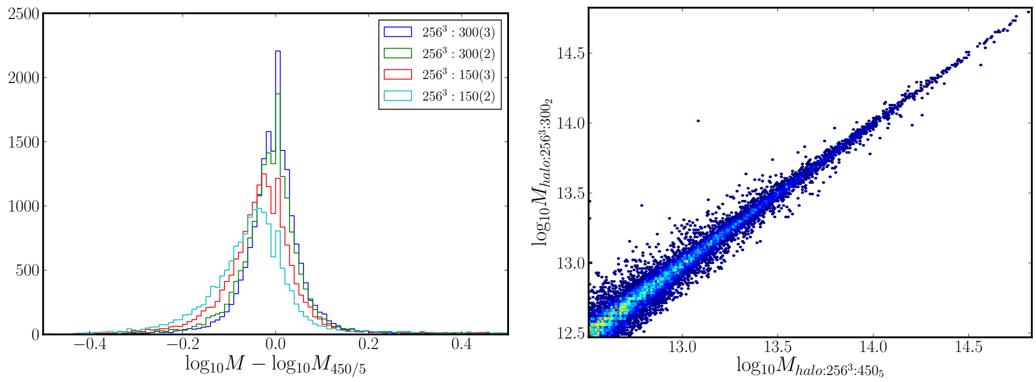

Figure 3. Right: Histograms of log-based mass difference of different simulation step sizes with respect to the one with 450 global steps and 5 sub-cycles. Histograms are not normalized and all halos are from the simulations with 256^3 particles. For each of simulations: 300 global steps with 3 sub-cycles (blue) and 2 sub-cycles (green), and 150 global steps with 3 sub-cycles (red). Left: A scatter plot of halo mass between 450/5 and 300/2 at $z = 0.15$. This scatter plot indicates that most of halo masses agree well except some halos (which I should investigate further).

ticles as halos more diffused (since bigger stepsizes cen't capture all the non-linearities that finer stepsizes can) and there is a possibility that some of gathered DM particles are not considered as halos. In Manera et al. 2012 which approximates N-body simulations by using the second-order Lagrangian Perturbation Theory, they solved this problem by changing the linking length for FOF., but one of our advantages in this approximated N-body simulations is that we can avoid tuning the linking length in order to get halos correctly.

Figure 4 shows positional differences for paired halos. This histogram indicates that global step has bigger effects on overall halo positions and the effect of sub-cycles is almost negligible. Most of halos for 300 global steps have their center positions within 100 kpc by comparing with halo center positions for 450/5, while the simulations for 150 global steps have more scatter in the figure. Means and standard deviations for the histograms are shown in Table 3.

For halo velocities, the results are shown in Figure 5. The histogram is a function of velocity magnitude differences. For 150 global steps, the means slightly deviate from 0 and have negative values. This means that magnitude of velocity for 150 global steps is smaller than that for 450 global steps. One way to explain this is that smaller time step halos are less dense, and the potential wells at center of halos may be less deeper than the ones for larger step sizes. We also examined differences on velocity direction. More than 98% of paired halos have angle differences (with respect to halos for 450/5) within 0.3 radians. This implies that orientation of velocities are well-preserved among the samples for different time steps.

z=0.15	mean	std
300/3	0.006	0.113
300/2	0.002	0.124
150/3	-0.021	0.118
150/2	-0.039	0.125

z=0.5	mean	std
300/3		
300/2		
150/3		
150/2		

z=0.8	mean	std
300/3		
300/2		
150/3		
150/2		

Table 2. Means and standard deviations for halo mass differences in log-based halo mass (with base 10) in Figure 3.

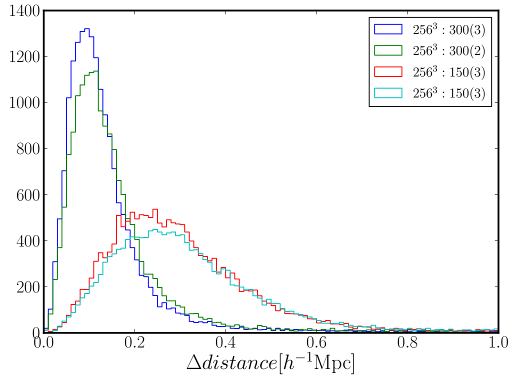

Figure 4. Histograms of distance difference for matched halos with respect to halos from 256^3 particles with 450 global steps and 5 sub-cycles. Different colors correspond to different simulation step sizes: 300 global steps with 3 sub-cycles (blue) and 2 sub-cycles (green), and 150 global steps with 3 sub-cycles (red) and 2 sub-cycles (cyan). All the simulations use 256^3 particles at redshift $z = 0.15$.

[H]

z=0.15	mean $[h^{-1}\mathrm{Mpc}]$	std$[h^{-1}\mathrm{Mpc}]$
300/3	0.172	2.674
300/2	0.235	4.312
150/3	0.458	6.348
150/2	0.509	7.118

z=0.5	mean $[h^{-1}\mathrm{Mpc}]$	std$[h^{-1}\mathrm{Mpc}]$
300/3		
300/2		
150/3		
150/2		

z=0.8	mean $[h^{-1}\mathrm{Mpc}]$	std$[h^{-1}\mathrm{Mpc}]$
300/3		
300/2		
150/3		
150/2		

Table 3. Means and standard deviations for positional differences in Figure 4.

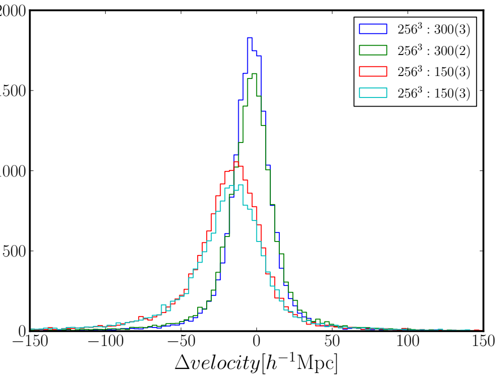

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Figure 5. Histograms of velocity magnitude difference for matched halos with respect to halos from 256^3 particles with 450 global steps and 5 sub-cycles. Different colors correspond to different simulation stepsizes: 300 global steps with 3 sub-cycles (blue) and 2 sub-cycles (green), and 150 global steps with 3 sub-cycles (red) and 2 sub-cycles (cyan). All the simulations use 256^3 particles at redshift $z = 0.15$. Note that angle difference of velocity vectors for 98% of matched halos are within 0.3 radians. Also, change the unit of velocity, which is wrong!!!!!

z=0.15	mean [km/s]	std [km/s]
300/3	-4.92	32.55
300/2	-5.53	36.58
150/3	-22.10	35.94
150/2	-20.82	38.44

z=0.5	mean [km/s]	std [km/s]
300/3		
300/2		
150/3		
150/2		

z=0.8	mean [km/s]	std [km/s]
300/3		
300/2		
150/3		
150/2		

Table 4. Means and standard deviations for halo velocity differences in Figure 5.

z=0.15	mean [km/s]	std [km/s]
300/3	0.993	0.054
300/2	0.992	0.057
150/3	0.992	0.052
150/2	0.992	0.052

z=0.15	fraction within 10 degree
300/3	0.951
300/2	0.938
150/3	0.928
150/2	0.923

Table 5. Means and standard deviations for halo velocity phase differences.

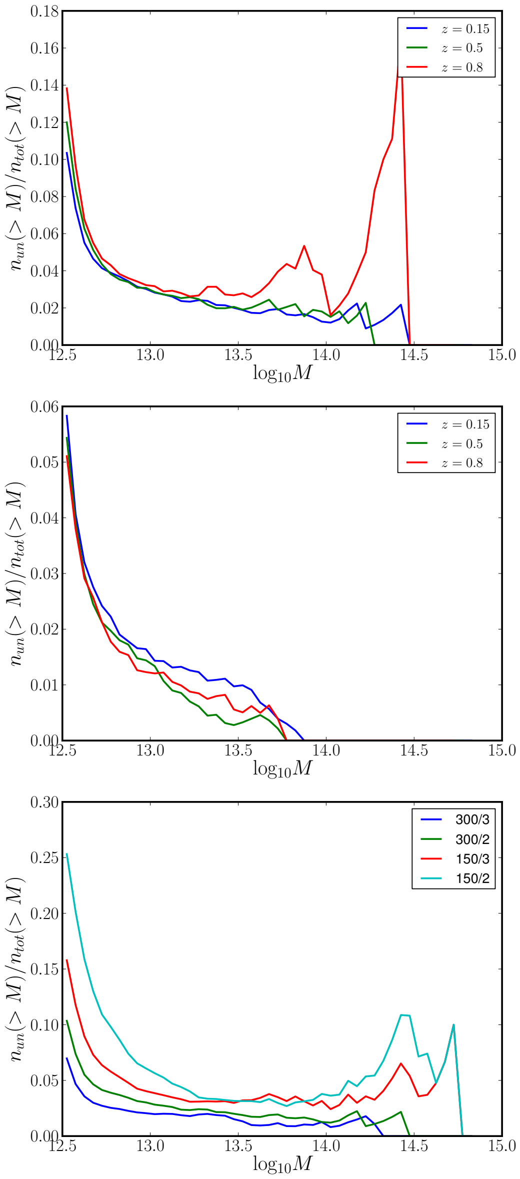


Figure 2. The fraction of unmatched halo number density and the total number of halos for the simulation of 300 global steps and 2 sub-cycles matching with 450 global steps and 5 sub-cycles. All the sample are 256^3 particle simulations. The right panel is the fractions between 450/5 and 300/2 as a function of redshift and the left panel is the fractions between 450 and various number steps at $z = 0.15$. Note that the middle plot is the same as the right plot but the fractions for 300/2.

2 OBSERVABLE/STATISTICS

Goal: To correctly describe the large-scale distribution of these galaxies. ⇒ Need to correctly locate DM halos in the simulations and estimate their masses.

2.1 Mass Function

* Why do we care about mass functions?: White 2002 "mass function is one of the most fundamental predictions of a theory of structre formation."

* If we have samples with different mass functions, what does it mean? and what kind of problems are caused by that?

* What does it physically (observationally?) mean to have the same mass function?

* I am not sure how Manera et al. assigned masses to halos...apparently, they were using analytic mass functions for this...:(

* relation between $n(M)$ and HOD.

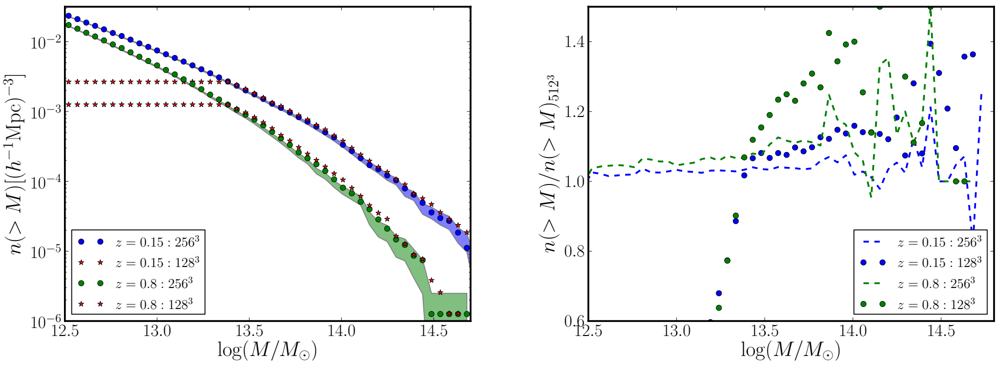
* ingredients of mass function: cosmology, initial conditions (how important is initial condition??), what other physical processes??

In this section, we examine how mass resolutions and time steps affect to mass functions. Note that all the number densities (as a function of halo mass) are mean of 100 samples generated through the bootstrap method.

2.1.1 Mass Resolution

* Analytic comparison

In this section, we investigate effects of mass resolutions on mass function and number density of halos (as a function of mass). For the case of 128^3 particles simulation, a mass of one particle is about $10^{12}\mathrm{M}_\odot$, which implies that we cannot have halos smaller than about $10^{13.5}\mathrm{M}_\odot$ through FOF. This is because FOF requires a certain number of particles clustered to declare a halo. The lowest mass halo for 256^3 particles simulations is about $10^{12.5}\mathrm{M}_\odot$. Figure 6 shows number densities as a function of halo mass at redshift $z = 0.15$ and $z = 0.8$. The colored regions indicate number densities for 512^3 particles with 450/5 with errors. The reason that number densities for 128^3 particles below $M_{halo} < 10^{13.5}\mathrm{M}_\odot$ are constant is because there are no halos smaller than $10^{13.5}\mathrm{M}_\odot$ for the case of 128^3 particles. Otherwise, all three simulations have almost the same number densities, though they start slightly deviating on large halo mass end.



[p]

Figure 6. Comparison of mass functions (should I call this number density?) for different simulations at redshift $z = 0.15$ and $z = 0.8$. The shaded regions indicate the upper limit and the lower limit of mass functions for the simulation with 512^3 particles and 450 steps with 5 sub-cycles. The mean and standard deviations are calculated from bootstrap method. We compare them with the simulations of 256^3 particles with 450 global steps and 5 sub-cycles (described as 256^3 with circles in the figure) and 128^3 particles with 450 global steps and 5 sub-cycles (described as 128^3 with red stars in the figure).

2.1.2 Time Steps

Here, we check the same thing as 2.1.1 for varying time steps with a fixed mass reslution of 256^3 particles. Figure 7 compares 450/5 and 300/2 with 512^3 particles mass resolution and 450/5 time steps. The colored regions indicate number densities of 512^3 : 450/5 with errors. Both 450/5 and 300/2 for 256^3 particles are well within the errors. Figure 8 shows the ratios between 512^3 : 450/5 and 256^3 particles with different time steps. For the case of 450 and 300 global time steps, the agreement is better than 10%.

2.2 Halo power spectra

In this section, we examine how mass resolution and time steps change statistical observables (i.e., auto- and cross-power spectra). By calculating those quantities, we want to know what the smallest global steps and sub-cycles required to preserve enough properties on power spectra for observations.

2.2.1 Mass Resolution

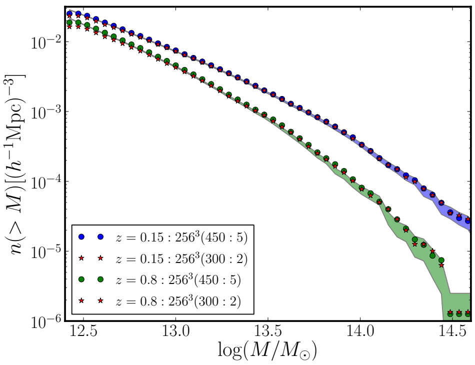
In this subsection, we calculate auto power spectra for two different mass resolutions, 512^3 and 256^3 particles in a $(256h^{-1}\mathrm{Mpc})^3$ cubic box. Halos used here are selected so that those halo masses are greater than $10^{12.5}\mathrm{M}_\odot$.

In Figure 9, we show various auto power spectra for 512^3 and 256^3 particles-simulations at redshift $z = 0.15$, $z = 0.5$, and $z = 0.8$ on the left panels and ratios of auto power spectra between those two samples on the right panels. Power spectra on the upper panels are subtracted a Poisson shot noise of $1/n$, where n is the nuber density of halos. The lower panels are the same as the upper panels without a Poisson shot noise subtraction. As shown in Figure 9, the agreement between 512^3 and 256^3 particles- simulations is within 10%.

2.2.2 Time Steps

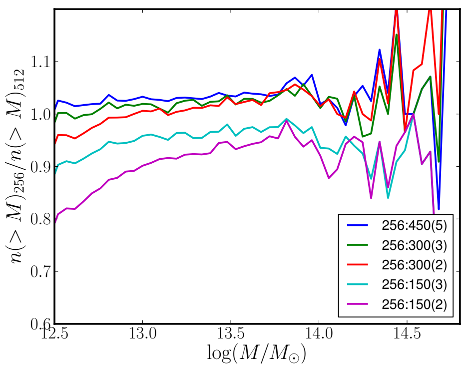
In this subsection, we examine effects of time steps on power spectra. While global steps is responsible for resolving the large scale structure, sub-cycles mainly afftes on the small scales and inner structure of halos. We want to evaluate qualitative effects of those differences on dynamics.

In Figure 10, we show various auto power spectra for 450/5 and 300/2 at redshift $z = 0.15$, $z = 0.5$, and $z = 0.8$ on the left panels and ratios of auto power spectra for different global steps and sub-cycles at redshift $z = 0.15$ on the right panels. Power spectra on the upper panels are subtracted a Poisson shot noise of $1/n$, where n is the nuber density of halos. The lower panels are the same as the upper panels without a Poisson shot noise subtraction. Note that halos selected here has a mass treshhold of $10^{12.5}\mathrm{M}_\odot$. As shown



[p]

Figure 7. Comparison of mass functions (should I call this number density?) for different simulations at redshift $z = 0.15$ and $z = 0.8$. The shaded regions indicate the upper limit and the lower limit of mass functions for the simulation with 512^3 particles and 450 steps with 5 inner(?) steps. The mean and standard deviations are calculated from bootstrap method. We compare them with the simulations of 256^3 particles with 450 global steps and 5 sub-cycles (described as $256^3(450 : 5)$ with circles in the figure) and with 300 global steps and 2 sub-cycles (described as $256^3(300 : 2)$ with red stars in the figure).



[p]

Figure 8. Ratios of mass functions of different time steps with 256^3 particles, compared to 512^3 particles with 450 global steps and 5 sub-cycles, at redshift $z = 0.15$. Different colors are corresponding to different time steps. The legend in the plot has the same format as the one in Figure 1. This plot shows that the simulations with 450 and 300 global steps agree well with the simulation with 512^3 particles.

in Figure 10, the agreement between 450/5 and other time steps is within 10%.

In Figure 11, we computed the cross power spectra between halos and the matter field at redshift $z = 0.15$. For the matter field, we used the one for 256^3 particles mass resolution with 450/5 time steps. On the left panel, we show three different mass bins and compare 300/2 (circles) and 450/5 (solid line) simulations. They agree remarkably well. On the right panel, we take ratios between the cross power spectrum for 450/5 time steps and the cross for other time steps. Halos selected for the right panel has a mass from $10^{12.5}\mathrm{M}_\odot$ to $10^{13.0}\mathrm{M}_\odot$. We see that all the ratios are within 5% accuracy except 150/2 simulations on small scales. Note that those ratios are equivalent to the ratios of the halo biases, which implies that biases for different time steps are almost the same.

3 OBSERVABLE BOX

What we want to check/know here are:

1) What redshift can we use linear-shifting?,

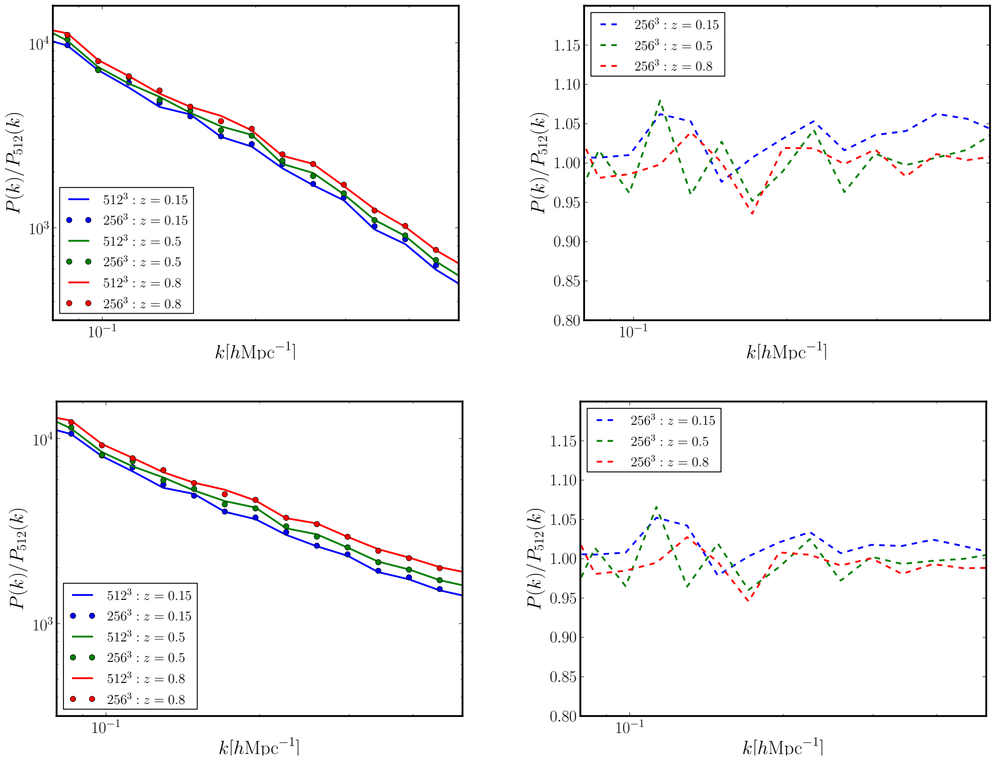


Figure 9. Halo auto power spectra for different mass resolutions (512^3, 256^3, and 128^3 particles in the box of $(256h^{-1}\mathrm{Mpc})^3$) with a fixed time step of 450/5. The sample of halos is equivalent to a mass thresholds of $M = 10^{13.5}\mathrm{M}_{\odot}$.

2) What redshift-step size is required to preserve dynamics in simulations?

Appendix A: snapshots for unmatched halos whose mass is greater than $10^{14}\mathrm{M}_{\odot}$. There is a weird case between 450_5 and 300_2

Appendix B: mass selected samples v.s. matched halo samples

- Comparison of matched halo samples and mass-sliced samples: what the comparison indicates is that corresponding halos don't have the same masses. -¿What kind of problems do we have by having this issue?-¿$b(M)$ may be diffrent for different simulations.

Appendix C: Extra Plots
Appendix D: Redshift-space distortion
D1: Mass Resolution
Fontsize

256^3	mean $[km/s]$	std $[km/s]$
$z = 0.15$	1.69	33.60
$z = 0.5$	7.09	49.94
$z = 0.8$	4.82	59.42

128^3	mean $[km/s]$	std $[km/s]$
$z = 0.15$	9.47	59.45
$z = 0.5$	16.18	74.44
$z = 0.8$	24.97	89.64

Table 1. Mean and standard deviations for the velocity magnitude difference histograms, which compares $256^3/128^3$ particles with 512^3 particles. I just felt wierd that deviations on means from 0.0 become bigger and the values of standard deviations become bigger as redshift goes higher. I feel that this should be opposite...

[t]

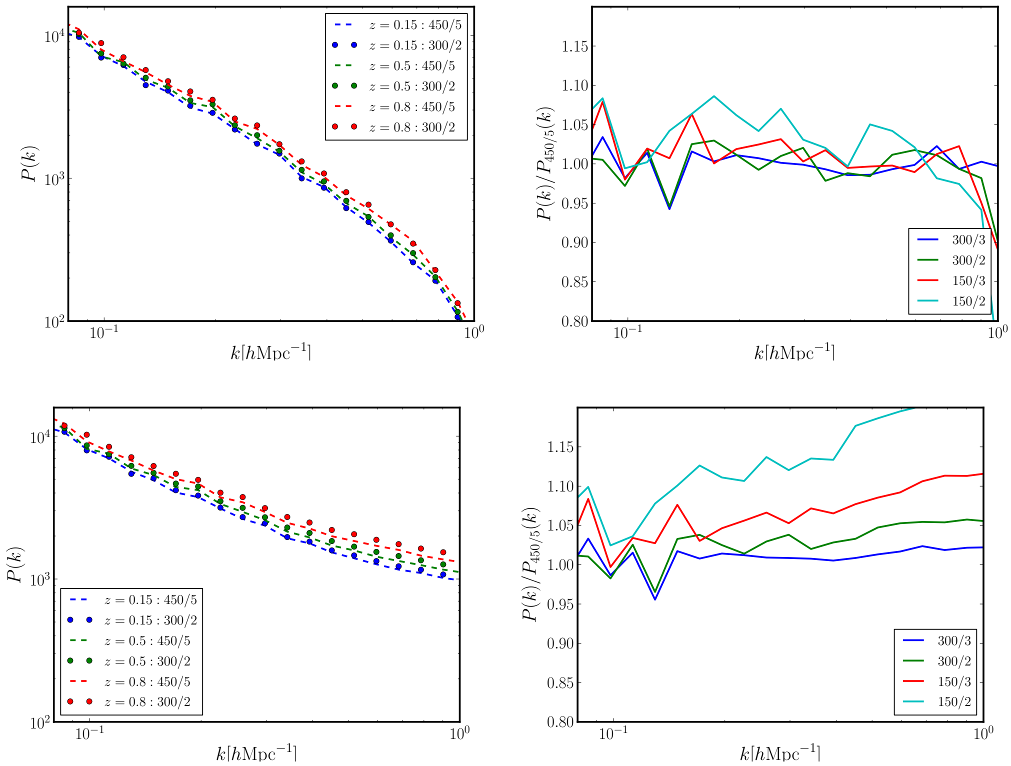
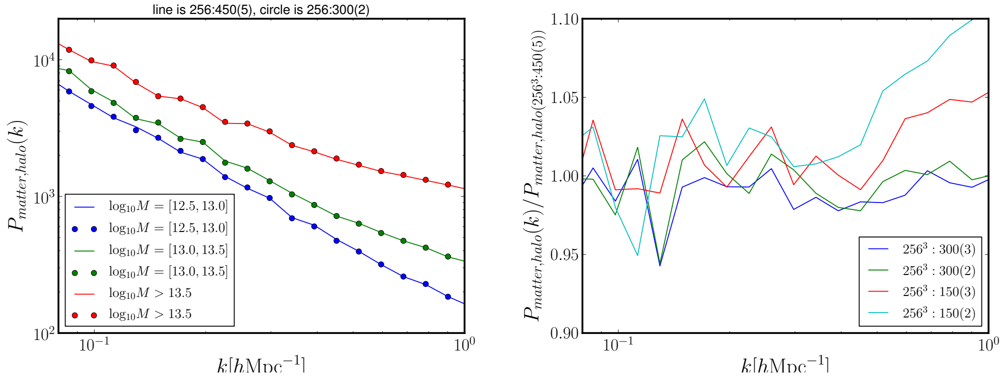


Figure 10. Left: Halo auto power spectra for different redshift $z = 0.15$ (blue), $z = 0.5$ (green), and $z = 0.8$ (red), which compare 450/5 (dashed line) and 300/2 (circles). Right: Ratios of halo auto power spectra between 450/5 and other time steps at redshift $z = 0.15$. All the samples used here has the same mass resolution, 256^3 particles in a $(256h^{-1}\mathrm{Mpc})^3$ cubic box. The upper panels are subtracted a Poission shot noise, while the lower panels are without a Poisson shot noise subtraction. The sample of halos is equivalent to a mass thresholds of $M = 10^{12.5}\mathrm{M}_{\odot}$.



[p]

Figure 11. Left: Cross power spectra between halos and DM particles at redshift $z = 0.15$. DM particles are taken from the simulation of 256^3 particles with 450 global steps and 5 sub-cycles. Different colors indicate different halo mass slices: $\log_{10}\mathrm{M} \in [12.5, 13.0]$ (blue), $\log_{10}\mathrm{M} \in [13.0, 13.5]$ (green), and $\log_{10}\mathrm{M} > 13.5$ (red). Lines are the simulations with 450 global steps and 5 sub-cycles, and circles are the ones with 300 global steps and 2 sub-cycles. Right:Ratios of cross power spectra for different simulations with respect to the cross power spectra with 450 global steps and 5 sub-cycles.

[t]

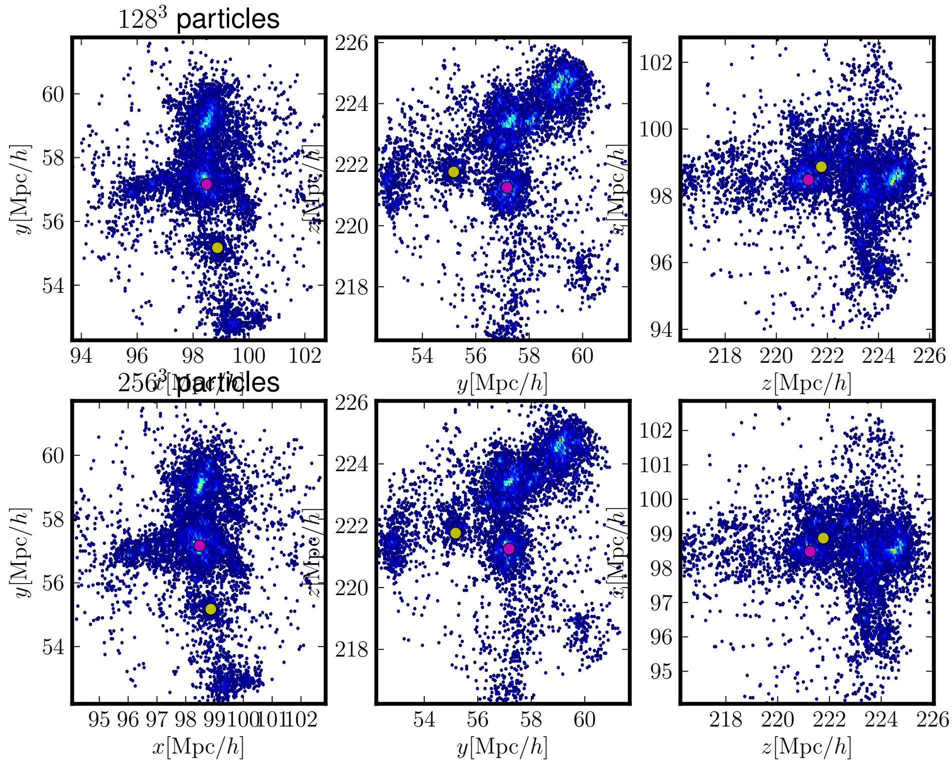


Figure 1. Snapshot of halos between 450/5 and 300/2 which don't agree completey. All the surrounding halos in 300/2 have distance more than $2h^{-1}$Mpc from an unmatched halo in 450/5.

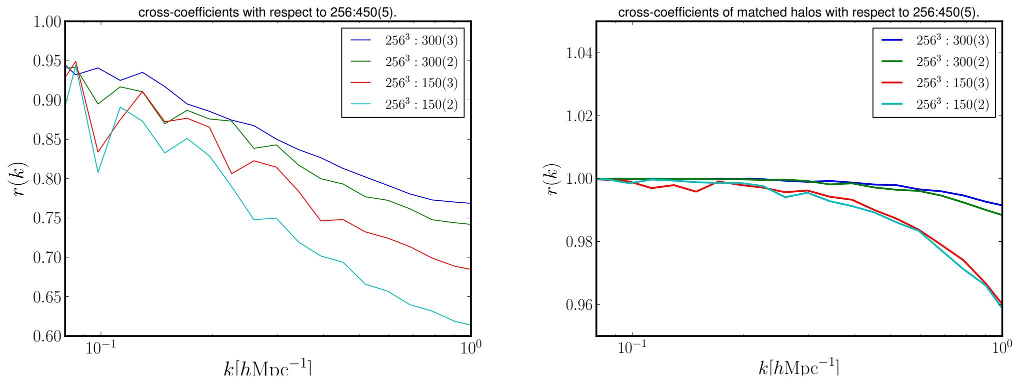


Figure 1. Cross-power coefficients for mass-selected halos (left) and for matched halos (right) at redshift $z = 0.15$. Both cross power coefficients compare the 450/5 simulation and other time steps. Halos for 450/5 have a mass from $10^{12.5}\mathrm{M}_{\odot}$ to $10^{13.0}\mathrm{M}_{\odot}$.

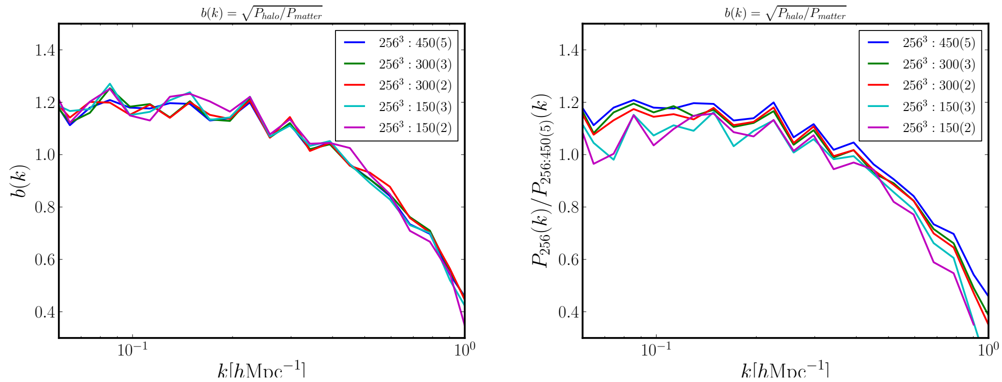


Figure 2. Halo Biases for different stepsizes with 256^3 particles at redshift $z = 0.15$. Left panel is halo biases for samples which are selected based on mass, and right panel is for samples which are corresponding to halos of 450 global steps and 5 sub-cycles. Different colors indicate different stepsizes and mass range for halo samples is from $10^{12.5}\mathrm{M}_{\odot}$ to $10^{13.0}\mathrm{M}_{\odot}$.

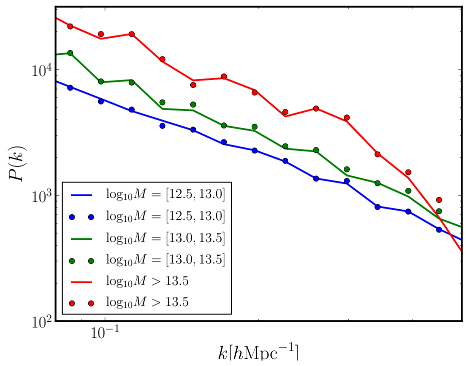


Figure 1. Auto power spectra for different halo mass bins, which compare 450/5 (solid line) and 300/2 (circles) at redshift $z = 0.15$.

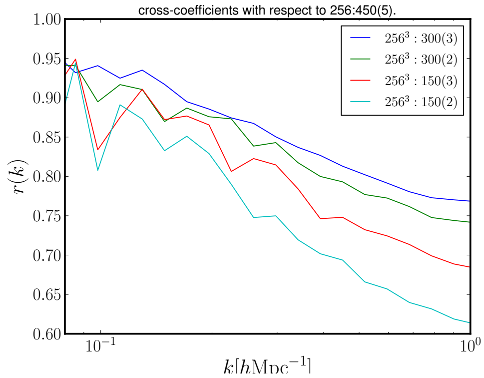


Figure 2. Cross power coefficients between 450/5 and other time steps at redshift $z = 0.15$. Halos used here have a mass from $10^{12.5}\mathrm{M}_{\odot}$ to $10^{13.0}\mathrm{M}_{\odot}$.

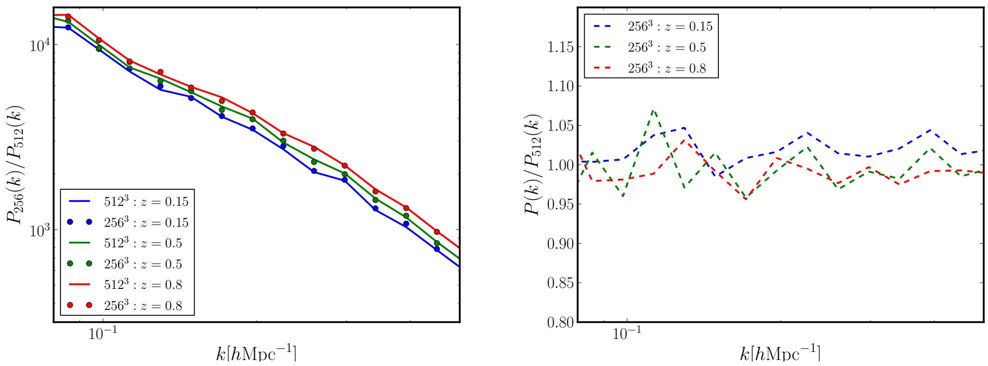


Figure 1. Halo auto power spectra in redshift-space for different mass resolutions (512^3 and 256^3particles in the box of $(256h^{-1}\text{Mpc})^3$) with a fixed time step of 450/5. The sample of halos is equivalent to a mass thresholds of $M = 10^{12.5}\mathrm{M}_{\odot}$.

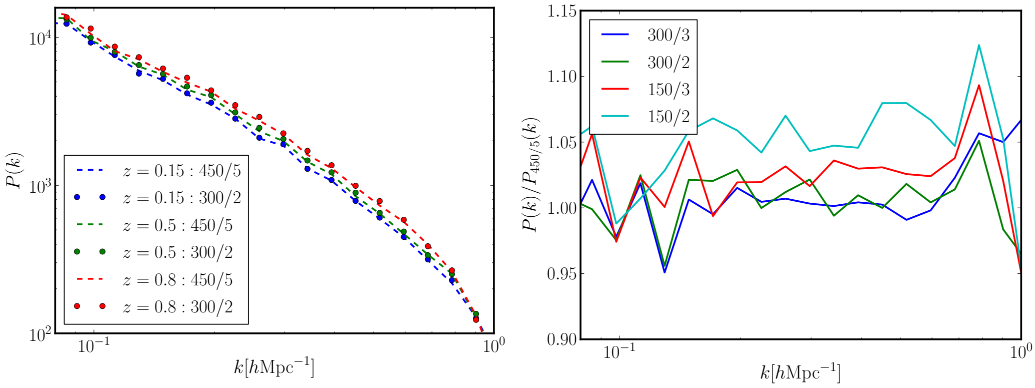


Figure 2. Halo auto power spectra in redshift-space for different redshift $z = 0.15$ (blue), $z = 0.5$ (green), and $z = 0.8$ (red), which compare 450/5 (dashed line) and 300/2 (circles). Right: Ratios of halo auto power spectra between 450/5 and other time steps at redshift $z = 0.15$. All the samples used here has the same mass resolution, 256^3 particles in a $(256h^{-1}\mathrm{Mpc})^3$ cubic box.

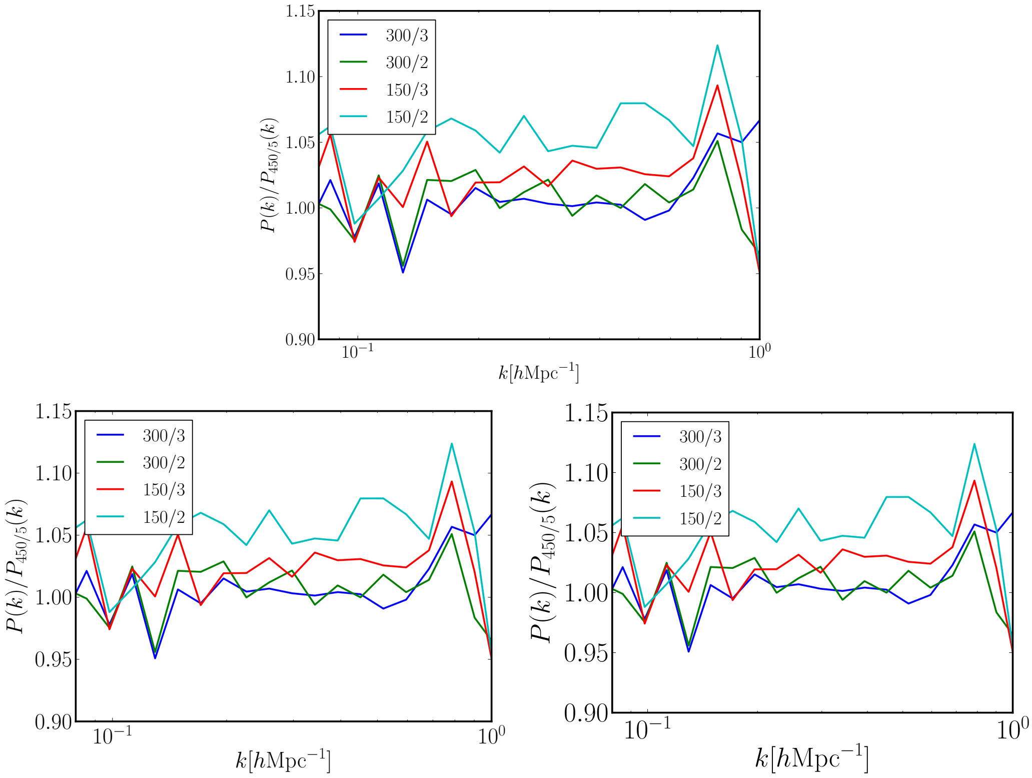


Figure 3. Check for fontsize 20,25,30...