Light-cone Simulations: Evolution of dark matter haloes

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1 The light-cone simulation

We present a new fast method for simulating pencil-beam type light-cones, using the MLAPM-code (Multi Level Adaptive Particle Mesh) by Knebe et al. [3] with light-cone additions.

We apply the method to simulate a 6 Gpc deep pencil-beam mock survey in the light-cone, similar to the contemporary observational deep surveys of galaxies. We use a simulation with 256^3 dark matter particles in a 256^3 grid in a "concordance" cosmological model, and follow the evolution of dark matter (DM) haloes with the cosmic epoch. Our simulation covers $2^\circ \times 0.5^\circ$ in the sky. We base the light-cone on periodic replicas of our simulation cube. Our light-cone is narrow and has oblique direction therefore we use different regions of the cube along the beam. In this way we avoid periodicities in pencil-beams. Our method to create a light-cone is rather efficient and allows to perform and analyse the simulation on single workstations.

We use friend-of-friend method to extract dark matter haloes from our light-cone. Our sample of rich haloes with more than 100 dark matter particles ($M_h \geq 3.6 \cdot 10^{12} h^{-1} \mathrm{M}_\odot$) includes 4088 haloes.

Figure 1 shows the projected (dark-matter) density fields of our light-cone simulation from $z = 0$ to $z = 6$ (for the cosmological model chosen $z = 6$ corresponds to 5981 h^{-1} Mpc. The density was calculated, using an Epanechnikov kernel of radii r 1.0 h^{-1} Mpc, 16.0 h^{-1} Mpc - i.e., for the characteristic scales of clusters and superclusters of galaxies. Figure 2 shows a snapshot from a fly-through movie of our light-cone. The movie is presented on Tartu Observatory web pages (`http://www.aai.ee/~maret/lc.html`) Figure 3 shows the placement of a light-cone in a cube.

2 The evolution of the halo mass function

Using light-cone we can follow the formation of first massive haloes. We plot the halo mass function for different redshift intervals in Fig. 4. The overall shape of the mass functions between $z = 0$ to $z = 1$ and $z = 1$ to$z = 2$ is quite similar to the mass function of the whole sample, for the mass interval $M \geq 10^{12}M_\odot$. The mass functions steepen with redshift, showing the dominance of small haloes at large redshifts. The characteristic halo masses decrease with redshift, with the maximum halo mass at the largest redshift interval $z = 5 \ldots 6$ being $1.5 \cdot 10^{12}M_\odot$.

The most easier objects to observe at any epoch are the most luminous (most massive) ones. In Fig. 5 we plot the masses of the most massive haloes for a given redshift. This figure shows that the masses of the most massive haloes increase exponentially with decreasing redshift, down to the redshift ~ 0.9, where the cosmic variance limit appears. This interesting trend, shown in the figure, can be approximated by a simple formula

$$M_{\max}(z) \approx 10^{15}M_\odot 10^{-0.5z} \approx 10^{15}M_\odot e^{-z}. \qquad (1)$$

This relation is shown by a dashed line in the figure Fig. 5.

3 Early haloes and black holes

As an example of an application of light-cone models, we discuss an interesting possibility that masses of super-massive black holes (BH) may correlate with masses of dark matter (DM) haloes.

Using a sample of 37 local galaxies Ferrarese [2] obtained a relation between the masses of BH and circular velocities of galaxy disks. If we assume that Ferrarese's M_{BH}/M_{DMhalo} relation also holds at high redshifts, and combine it with our mass relation for the most massive haloes (1), we obtain a simple relation for the BH masses likely to reside in the most massive dark matter haloes as a function of redshift:

$$\frac{M_{BH}}{10^{12}M_\odot}(z) = 10^{-0.83z}. \qquad (2)$$

We find that the most prominent quasars exist between the redshifts ~ 6 to ~ 2. Haloes massive enough to form super-massive black holes and hence quasars, either did not exist before the redshift $z \approx 6$, or they were very rare, with the number density $n_h < 10^{-7} Mpc^{-3} h^3$.

4 Perspectives

An important problem in simulating light-cones to compare with observational data is populating dark matter haloes with galaxies, and assigning the galaxies the features an observer sees. In fact, the MoMaF project (Blaizot et al. [1]) already gives galaxy populations in light-cones, using semi-analytic recipes. We plan to include such recipes in our code.

The algorithm we use to simulate light-cones is lightweight and fast. The code is in the public domain, included in the MLAPM package.

References

[1] Blaizot, J., Wadadekar, Y., Guiderdoni, B. et al. 2005, MNRAS, 360, 159

[2] Ferrarese, L., 2002, ApJ, 578, 90

[3] Knebe, A., Green, A., Binney, J., 2001, MNRAS, 325, 845

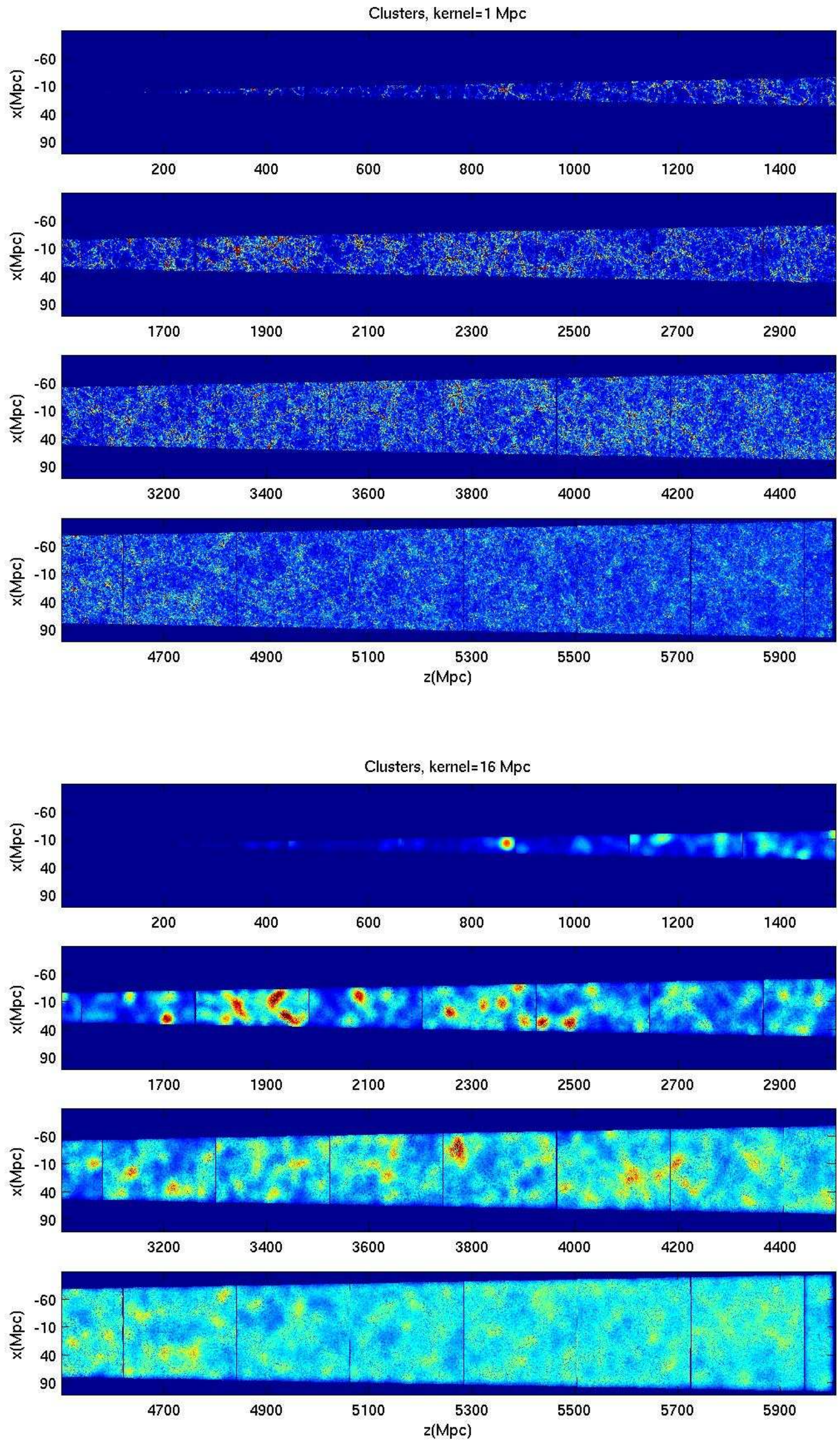

Figure 1: The density field of the 6 Gpc deep dark matter light-cone simulation smoothed with a $r = 1.0\ h^{-1}$ Mpc kernel (upper panels), and with a $r = 16.0\ h^{-1}$ Mpc kernel (lower panels).

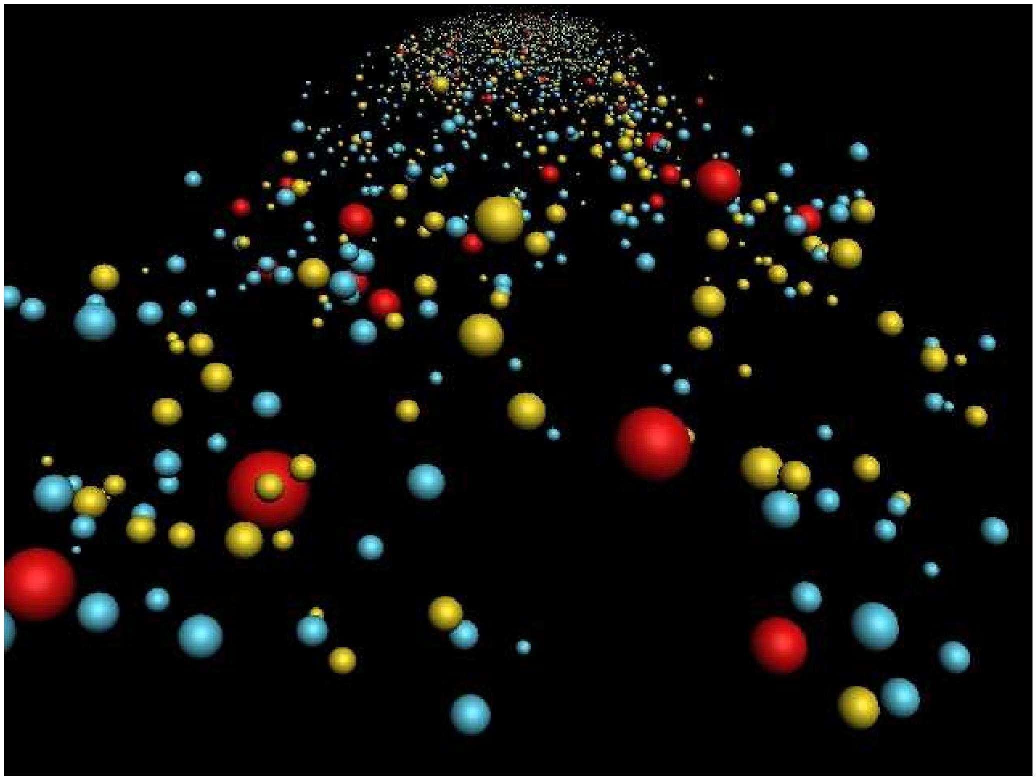

Figure 2: DM haloes of different mass in the light-cone. Red color correspond to most massive haloes (mass $M \geq 10^{14}\mathrm{M}_{\odot}$) yellow, blue and gray to haloes with mass in decreasing order ($M \geq 10^{13}\mathrm{M}_{\odot}$ etc).

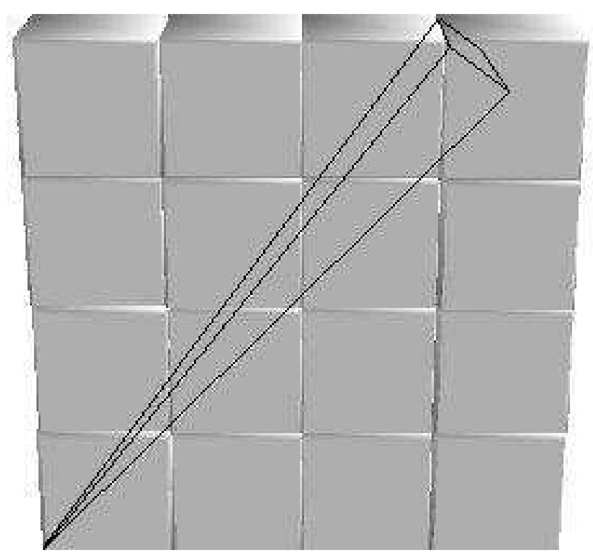

Figure 3: Figure shows the placement of a light-cone in a cube.

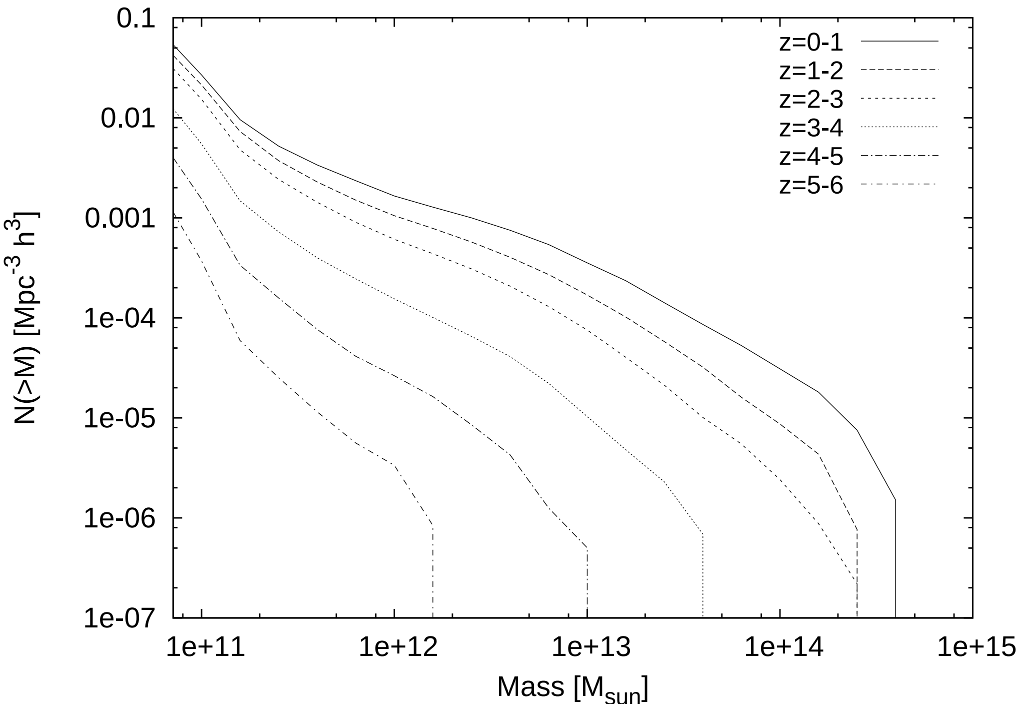

Figure 4: Halo mass functions for different redshift intervals.

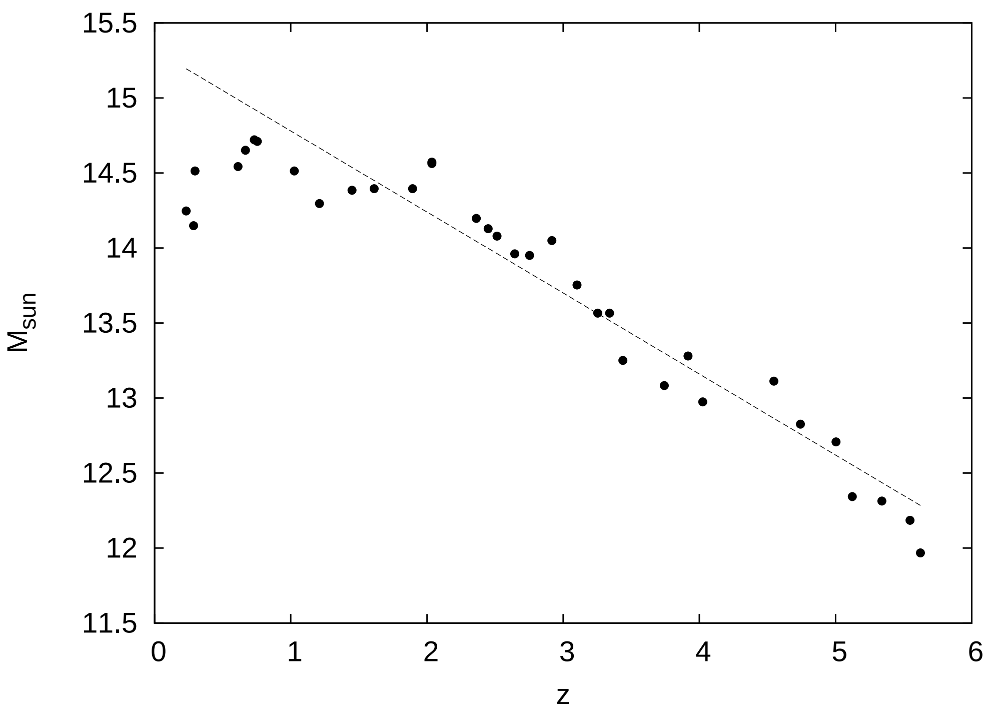

Figure 5: Masses of the most massive haloes for different redshifts