CTA200H project for week 2: the distribution of Lyman Limit Systems around massive halos

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1 Motivation

Massive galaxies[1] often live together and are often surrounded by many other smaller galaxies. Between galaxies there are large-scale filaments, where the gas is denser than the cosmic mean.

As a result, when we take a spectrum of a high-redshift quasar located in a massive halo, there is a high likelihood of detecting some signature of dense gas in the surrounding area along the line of sight. This gas can either be associated with nearby galaxies or located in the cosmic filaments [2]. The gas can absorb significant amount of ionizing ("Lyman Limit") photons from the quasar if its density exceeds a certain value. Such gas systems are called Lyman Limit Systems (LLSs). These LLSs can shield the gas from the radiation emitted by the quasar. Studying these LLSs is crucial for interpreting the quasar proximity spectrum.

In this project, you will analyze a cosmological simulation and study the gas environment around massive halos. You will utilize two types of simulation products: 3D data cube and halo catalogue.

2 Explore a Cosmological Simulation

2.1 Explore Gas Properties

z-ifrit-a=0.1401.bin stores gas information of the simulation: neutral fraction of hydrogen x_{HI}, density contrast Δ(density in the unit of cosmic mean), and temperature T (in Kelvin). Each 3D datacube has 1024^3 cells, and the length of the simulation box is 40 comoving magaparsec (cMpc) / h, where $h = 0.68$.

Task 1: Use the script read_cube.py to read the datacube. It returns 3D array for x_{HI}, Δ and T. Choose one slice of them and visualize the 2D array for x_{HI}, Δ and T, respectively.

[1] Oftentimes bright, too! And quasars usually reside in the center of these galaxies.
[2] https://arxiv.org/abs/2212.07033

Task 2: Convert unit for gas density to g/cm^3. To do so, download python package astropy and use the cosmology module. Import WMAP9 as cosmo. Then use the function "critical_density" at redshift 6 in cosmo to calculate the critical density of the universe at that time. Then, multiply it by the contribute from baryon cosmo.Ob at the same redshift to get the mean density of the ordinary matter (mostly gas at that time). What is the mean density of gas at redshift 6 in units of g/cm^3?

Task 3: Calculate the Lyman α optical depth of the densest cell: the Lyman α optical depth is defined as

$$d\tau_{Ly\alpha} \equiv \sigma_{Ly\alpha} n_{\rm HI} ds$$

The cross-section of Lyman α line $\sigma_{Ly\alpha} = 4.48 \times 10^{-18}\mathrm{cm}^2$. $n_{\rm HI}$ is the number density of NEUTRAL hydrogen gas. Note that in the universe, about 76% of the baryon mass is in the form of hydrogen. ds is the PHYSICAL length of the cell, which is equal to the comoving length times the expansion factor at that time $a = 1/(1+z) \approx 0.14$.

Task 4: When light travels through a patch of gas and if we do not consider emission, the light will be dimmed by an exponential factor of $e^{-\tau}$. What is the percentage of Lyman α photons that remain after traveling through the densest cell in Task 3?

2.2 Explore the Halo Catalog

hlist_0.14005.list stores the information of dark matter halos (inside which galaxies form). It is a text file, so you can open it with command like less, vim, emacs, etc. It contains information like the position of each halo and their mass.

Task 5: Use python to load the halo catalog. Using the column of virial mass Mvir(10) and plot a histogram (number of halos for each mass bin). Choose logarithmic mass bins from $10^9 - 10^{13} M_\odot$. The number of halos in each mass bin is called "halo mass function" in literature. Briefly describe what this histogram looks like.

3 *if time allows:* Locate the Halos in the 3D Data Cube

The halo catalog also contains the position of each halo [x(17) y(18) z(19)]. To study the gas properties around halos, we need to match the positions between halos and gas cells in the two types of data products described in the section above.

To match the position, you will convert between comoving unit and code unit. It is a linear mapping between 40 cMpc/h to 1024 but with a small difference to account for[3]. In short, 40 cMpc/h linearly maps to 1024 times 0.98391.

[3]For cosmological simulations, each run is initiated with a random seed. The total mass inside each box can be a tiny bit different from the mean density of the universe. If it is

Task 6: Overlie the position of halos (within the same slice) in the figures you produced in Task 1. Zoom in to one of the halo (plot a 10×10 cMpc/h region around it).

4 *if time allows:* Draw a Sightline from a Halo

Task 7: Now that you can accurately locate the halos in the 3D datacube, draw a sightline (length 10 cMpc/h) starting from the halo along a random direction. Plot the density contrast as a function of distance. Are there any cells that have density contrast above 100?

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slightly denser, then the box does not follow exactly the expansion of the universe but become a tiny bit smaller. Somehow this is not coded in the halo finder so we need to manually correct for this.