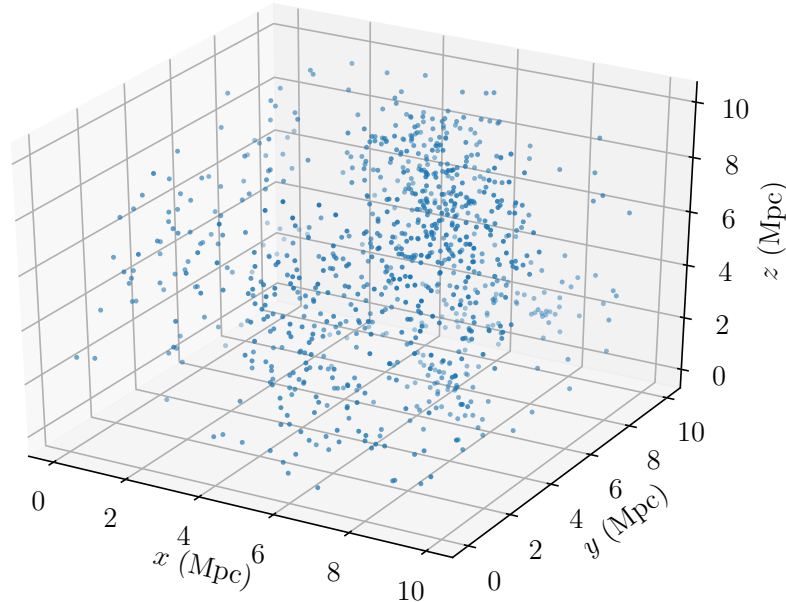


ASTP 720 - Homework 4 - Universe in a Box

Due March 24th, 2020

Your goal is to study the dynamics of a cluster of galaxies similar to the Virgo Cluster. In the file `galaxies0.npy` is an array representing the x , y , and z coordinates of 908 simulated galaxies and `galaxies1.npy` is an array representing the same galaxies 1000 years later (you need not choose this value as your timestep though). You may assume each galaxy has the same mass, which you can take to be $10^{12} M_{\odot}$.

The simulation at $t = 0$ looks like this:



This homework will be a little more free form than previous ones. It should be in the format of a mini paper, which includes:

- a short introduction, e.g., if you had to describe what galaxy clusters are and what you were doing to a first-year physics undergraduate student
- a section describing your methods, and
- a section describing your results.

You may wish to use `aastex` but you shouldn't feel required to. Plots are necessary!

Your tasks:

- Using the Barnes-Hut algorithm, evolve the system into the future, at least enough for particles to move of order Mpc if not more. You should include force softening. Make sure when you describe your method that you describe your parameters.
- Simulate a new particle at the position (1, 5, 5) Mpc with a very small random error on top of that. Performing this several times, estimate the Lyapunov exponent and timescale ($t = 1/\lambda$).
- You want to understand the crude potential of this cluster to understand how a new galaxy might interact with it. Pretend that all 908 galaxies are in an idealized cluster centered at (7, 5, 5) Mpc and uniformly distributed in a sphere with radius 2 Mpc (i.e., imagine a uniform density ball). Calculate the gravitational potential and make a 2D plot of a slice at $z = 5$ Mpc. Note that at the boundaries of the cube, the potential should be zero.