MODULE 3 | PROJECT
COSMOLOGICAL SIMULATIONS

The goal of this project is to create, on your own, a realistic simulation of the universe on cosmological scales, starting from an earlier time (redshift $z = 50$) and stopping at the current time ($z = 0$). You should write a paper describing your work, your results, and your conclusions, based on the tasks below.

A. A VERY BIG BOX

First, let's begin with the entire universe itself. Make a list of the currently accepted values for the following paramters: H_0, $\Omega_{m,0}$, $\Omega_{\Lambda,0}$, $\Omega_{0,\mathrm{tot}}$, and any others you think you might need. You should also calculate the crictical density of the universe (today) $\rho_{\mathrm{c},0}$, the matter density (today) $\rho_{\mathrm{m},0}$. Then calculate, in billions of years, the current age of the universe t_0 and the age, in millions of years, of the universe at the start of the simulation ($z = 50$). It's probably safe to neglect radiation as a component of the universe for the times we're simulating.

Next, consider a cubic section of the universe that today measures 50 Mpc by 50 Mpc by 50 Mpc. What is the total mass (of matter) inside this box? This is the volume of the universe we're going to simulate.

B. PARTICLE-MESH CODE

The notes we went over in class for cosmological simulations should be pretty complete, so build yourself a particle-mesh (PM) code. Your software should take an N-body file for initial conditions and output snapshots of the system at regular intervals. Since there's no softening to worry about, there's really only one parameter to worry about: the "timestep" Δa. Be sure you choose an appropriate value.

Test your PM code by using the following initial conditions:

1. A perfect grid of particles, evenly spaced. This grid should persist throughout the simulations, since there's no difference in density from the average value.
2. A box of randomly placed particles. This should form small structures where initially overdense regions are located, and void where initially underdense regions are.

Try varying your number of particles and grid cells (but you should probably have at least twice as many cells as particles along one dimension), and feel free to vary your universe and timestep, too. But these are not very realistic initial conditions, so once your code passes the test, move on.

C. A (SOMEWHAT) REALISTIC SIMULATION

I'll provide a more realistic set of initial conditions, although note that the box side length is 1 and the total mass is 1; the mass doesn't matter, but you should scale the box size up to what you need. The inital velocities of all particles are zero (this is particularly realistic, but no matter).

Run your code with my initial conditions.

D. SOME QUESTIONS

Here's some questions you can ponder:

1. What's the mass of the largest structures that form in your simulation? Try a "friend-of-friend" method to locate bound structures.

2. What happens if you change the box size (but keep the relative particle positions the same)? Is that what you expect?
3. What happens if you vary $\Omega_{m,0}$ or some of the other parameters?
4. What happens if you vary N_{grid}?
5. Try using a larger number of particles (and a corresponding larger number of cells). You can do this a couple of ways: try some already-existing code (e.g., music) or come see me and I can generate some for you.

E. Some Comparisons

One current popular cosmological N-body code is GADGET-2. It's a little hard to use, as it's very complex, and it one-ups our method here as it combines particle-mesh with a treecode. Download it, try it. It comes with some examples (one of which you might recognize). Then, try it with your initial conditions you used above and compare with your results. You can try pushing the particle number higher with GADGET, too, since it should be much faster than our code.

Lastly, what's the state of the art in terms of cosmological simulations? Do some background research on the largest, most detailed simulations to date. And, of course, compare with what you did.