Simulating Coulomb Interacting Dark Matter

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ABSTRACT

While Dark Matter (DM) is known to be the dominant form of matter in the universe through its gravitational effects on visible matter, the microscopic properties of DM are unknown. Astronomical observations and direct detection experiments suggest that DM may have self-interactions. We propose a numerical simulation of the cosmological formation of DM halos under the influence of Newtonian gravity and Coulomb-like self-interactions.

BACKGROUND

Direct interaction between DM and ordinary matter has not been detected. However, DM has been observed indirectly in a number of ways. The gravitational influence of DM was first noticed through observations of the rotation curves of galaxy clusters and eventually galaxies. Objects in a galaxy which are far from the galaxy's center are observed to orbit the galaxy faster than what is expected from standard Newtonian mechanics. The speed of the orbiting object $v(r)$, orbiting at distance r from the center of the galaxy is expected to be given by:

$$v^2(r) = \frac{M(r)}{r},$$

where $M(r)$ is the total mass inside the object's orbit. Since there are fewer objects toward the edge of galaxies the mass becomes essentially constant and it is expected that far from the center of the galaxy the gravitational force will weaken and the speed will begin to decrease. Observations indicate, however, that objects on the edge of galaxies travel just as fast as objects near the center (See Fig. 1). Since the radius is obviously increasing, the force of gravity must also be increasing. The simplest explanation of this is that there is mass, distributed throughout the galaxy, that cannot be seen, i.e. dark matter.
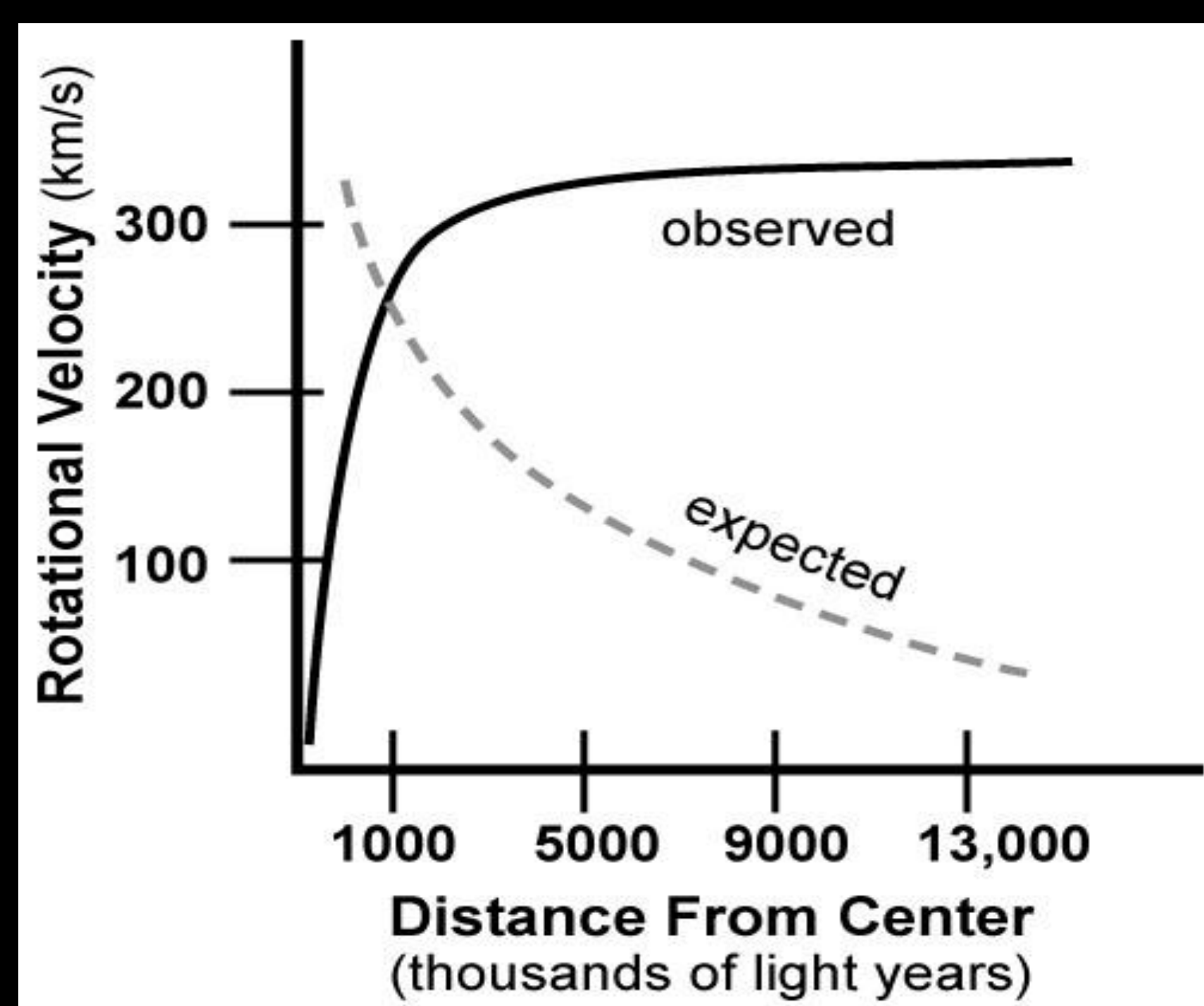

Fig. 1 shows a plot of the distance of an object from the center of a galaxy cluster vs. the object's rotational velocity. The dashed line is what is expected based on Newtonian mechanics and the solid line is what is actually observed. This incongruity is the first evidence of the existence of DM.

Another phenomenon that supports the existence of DM is gravitational lensing. According to Einstein's theory of gravity (general relativity) massive objects bend space, so that even light – which is massless – feels the effects of gravity and follows curved paths around massive objects (See Fig. 2). The angle of deflection that the light experiences is directly proportional to the mass of the intervening object. This effect was originally observed for stars behind our own sun and has since been confirmed many times. When this principle is applied to clusters of galaxies, it is observed that the light is bending far more than it ought to be for the amount of *visible mass* present. Again, the simplest explanation for this is that a large fraction of the mass present on galactic and super-galactic scales is DM.
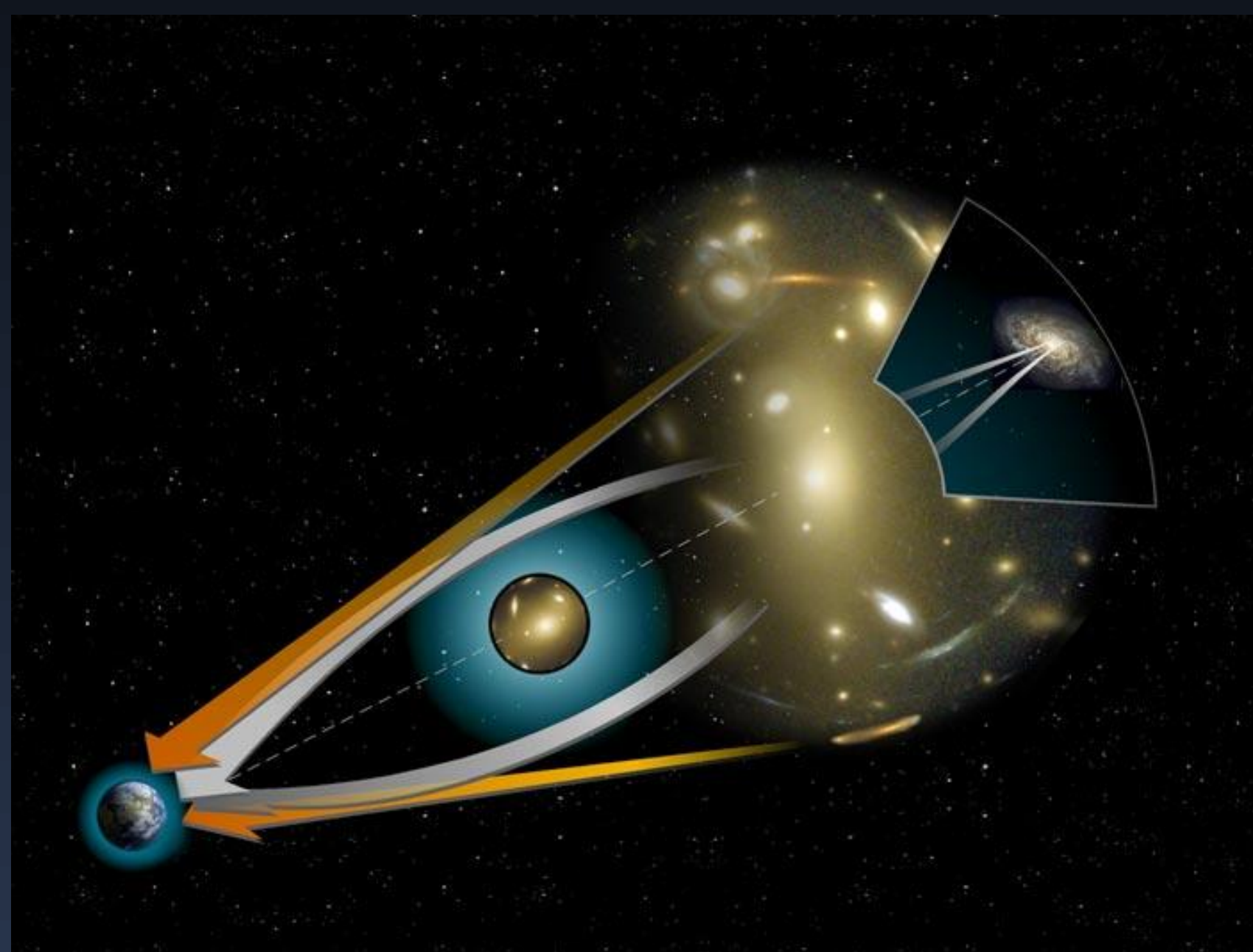

Fig. 2 shows the effects of gravitational lensing. The gravity of the object in the center bends the light (white arrows) from the galaxy on the right so that it appears, to the observer on the left, that the light is coming from another direction (yellow arrows).

THEORY and MOTIVATION

Since its interactions are primarily gravitational, predictions of the distribution of DM particles in the universe are made using N-body particle simulations. In an N-body simulation, a large number (N) of bodies are assigned an initial position and momentum. Then, the forces on the particles (gravity, etc.) are calculated. The computer then updates, time step by time step, the position and momentum of each particle based on the acceleration the forces cause on them. The positions and momenta can be stored and the evolution of the DM galactic "halo" can be studied as a function of time. See Figure 3 for an example of what an N-body simulation looks like.

The microscopic properties of the DM particles should affect the DM distribution. In particular, non-gravitational DM interactions will change the *morphology* or *shape* of the DM distribution. Cold DM (CDM) only interacts gravitationally and results in an elliptical halo. If DM interacts with a force other than gravity, the morphology of the halo will deviate from elliptical. In principle, DM self-interactions as strong as ordinary matter could result in a dark disk! It is not known exactly how, if at all, DM interacts with itself or other matter. To date, simulations have been done with CDM and with DM particles having contact "billiard-ball" self-interactions.

Observations of dwarf galaxy populations suggest that DM does in fact self-interact. More precisely, *the lack*, of dwarf galaxies suggests that DM interactions are able to supply a form of pressure that prevents gravitational collapse from forming these small objects. This last fact motivates the present study.
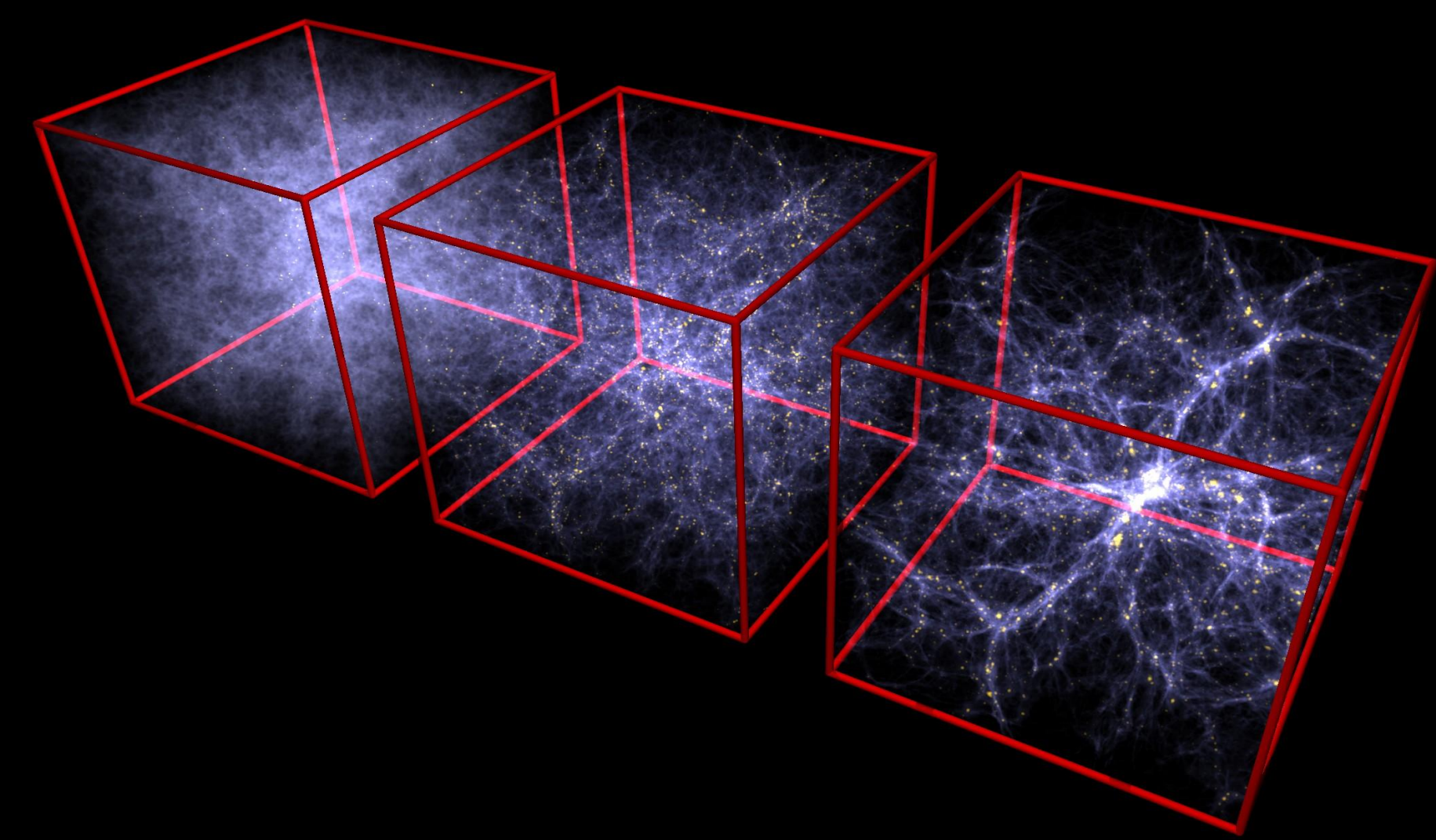

Fig. 3 shows three snapshots from an N-body simulation. The left box is the first step, when all the particles are randomly distributed, the middle box is several time steps after, and the right box is the final time step, when all the particles have grouped together due to the gravitational forces assigned to them.

PROJECT

We intend to run N-body simulations using GADGET2 (Galaxies with Dark matter and Gas intEracT), a publicly available set of algorithms for custom cosmological simulations. We will modify the code to include a Coulomb-like (electric charge) force to CDM. This force is proportional to r^{-2} and can be either repulsive or attractive. We will run simulations with 10^5 to 10^6 objects with a variety of interaction strengths in order to compare to state-of-the-art interactions with self-interacting DM.

PROGRESS

We have used GADGET2 to run test simulations of two galaxies colliding and have made videos of these simulations. We have also begun work building a computer cluster in the Houghton Digital Media and Communication Department's Learning Commons. To date, we have built a cluster of three computers processing in parallel and have successfully tested the cluster using Message Passing Interface (MPI) "ping-pong" algorithms; MPI is the basis of GADGET2's parallel processing functionality.

Fig. 4 is a picture of the Learning Commons. We are building a computer cluster using the iMacs in the Commons. The Mac OS is particularly well suited to major parallel processing on an ad hoc cluster.

OUTLOOK

The next step in the project is to modify GADGET2's code to include the Coulomb-like force. We will continue to build the computer cluster alongside the code modification. We hope to begin running simulations on the full Learning Commons cluster by Spring 2012.