

1 | Introduction

“Space (...) is big. Really big. You just won't believe how vastly, hugely, mindbogglingly big it is. I mean, you may think it's a long way down the road to the chemist's, but that's just peanuts to space” (Adams 1986). Although written in a work of fiction, this is correct: it's hard to imagine how vast the Universe really is. It takes light (which seems to move instantaneous to our eyes) more than two seconds to travel to the moon and back, a distance that would take over four months to travel at 120km/h. Yet, this distance is minute compared to other scales in the Universe. For instance, light from the nearest star (apart from the Sun) takes more than four years to reach us, and light from the galaxy nearest to us, Andromeda, takes 2.5 Myr to reach us. The current record holder for the furthest galaxy is about 12.5 Gyr away, nearly the age of the Universe itself.

Despite its huge size, the Universe is not static. It formed about 13.8 Gyr ago, and has been expanding ever since. Soon after the big bang, matter, which was initially distributed almost homogeneously, started clumping, forming the first stars. The first protogalaxies formed, which in time merged to form the galaxies we see nowadays in our region of space.

In our own galaxy, generations of stars formed and exploded before our own Sun and solar system formed from a giant molecular cloud. This cloud had been enriched with heavier elements such as carbon and oxygen, the building blocks for life, by these previous generations of stars. The Earth formed from remnants of this cloud around the Sun, and about 4.5 Gyr later, this thesis describing simulations of some of the mechanics in the Universe was complete.

1.1 Why simulate the Universe?

Since the distances are so large, timescales in astrophysics are often very long - on the order of millions to billions of years. While local stars can be measured to move, and while we can see variable stars and various stellar transients change on much shorter timescales, most of the far-away sky will remain completely unchanged during a human's lifetime. The process of forming galaxies and other large-scale structures in particular takes place over a very large amount of time.

In order to investigate how such structures form and evolve, we cannot resort to observing change in singular objects - this would simply take too long. To observe changes in objects of galactic scale, astronomers make the assumption that the Universe is homogenous and isotropic: on average, it looks the same in every direction. Galaxies that are far, far away - and therefore observed as they were a long time ago - can then be interpreted as the predecessors of modern close-by galaxies.

This still leaves a problem though: we cannot see the exact formation history of individual galaxies, only the evolution of galaxies in general. Even then, we observe local galaxies with much higher resolution than the faraway ones, so many details about these remain unknown.

In order to fill in these limitations, astronomers also try to investigate the Universe by modelling and simulating it. With simulations, we can investigate the formation of individual galaxies from very early on until now, and follow exactly what happens to it: how many other, smaller galaxies merge with it, when star formation occurs, etc.

1.2 Simulating gravity on a large scale

Such simulations to study galaxies can be done on various scales, from the size of the known Universe to the size of an individual galaxy. In order to model the formation of an individual galaxy though, we first have to know what the right initial conditions are - where was all the matter that ended up in this galaxy?

1.2.1 Finding the initial conditions

Finding the initial conditions of matter in the Universe is difficult, since we cannot just trace back the origin of all matter from current day observations. We can therefore roughly choose between two routes: either simulate a large environment with enough resolution to follow individual galaxies, or make assumptions about the composition of these galaxies.

As a starting point for the former (cosmological) type of simulations, we are fortunate enough to have a snapshot of the Universe when it was very young (only a few 100.000 years): the cosmic microwave background (CMB, see Figure 1.1 for a recent observation by the Planck satellite (Planck Collaboration et al. 2013)). From the CMB, we can obtain information about the distribution and type of matter in the Universe at that time, and we can use it to create large-scale initial conditions for cosmological simulations.

These initial conditions are only for a large scale though. Simulations of individual galaxies are not immediately possible, since we do not know which particles end up in one galaxy and which in another. So, we start with simulations of the large-scale Universe: the cosmic web. The cosmic web is a vast sponge-like structure that connects all galaxies with long filaments and walls. At the intersections of these filaments, galaxies are grouped in large clusters (see Figure 1.2).

1.2.2 The Millennium run

One of the most famous simulations performed of this large-scale structure is the Millennium simulation (Springel et al. 2005). This simulation (see Figure 1.3) consists of a volume of $500 h^{-1}\text{Mpc}$, about 2 billion lightyears, with 10 billion particles. In this huge volume, we can see the evolution of a very large number of individual galaxies.

However, there are some limitations to this simulation. Because of its large volume, the Millennium simulation is limited in its accuracy on smaller scales. A galaxy like the Milky Way for instance, would only consist of about 100-1000 particles, which is not enough to investigate its structure and formation in detail.

Another limitation is that the simulation consists only of dark matter - a type of matter that has mass and therefore exerts gravity, but which doesn't interact with light and doesn't collide with other particles. This is the dominant form of matter in the Universe - there is about five times more of it than there is baryonic matter. Yet, all matter that we can see, including all stars and ourselves, consists of the 'other' type of matter: baryonic, which does interact with light and which does collide and interact with light. Therefore, the structures that form in dark matter simulations do not exactly correspond to visible structures. While a galaxy will form inside a dark matter halo, its shape and structure will be completely different.

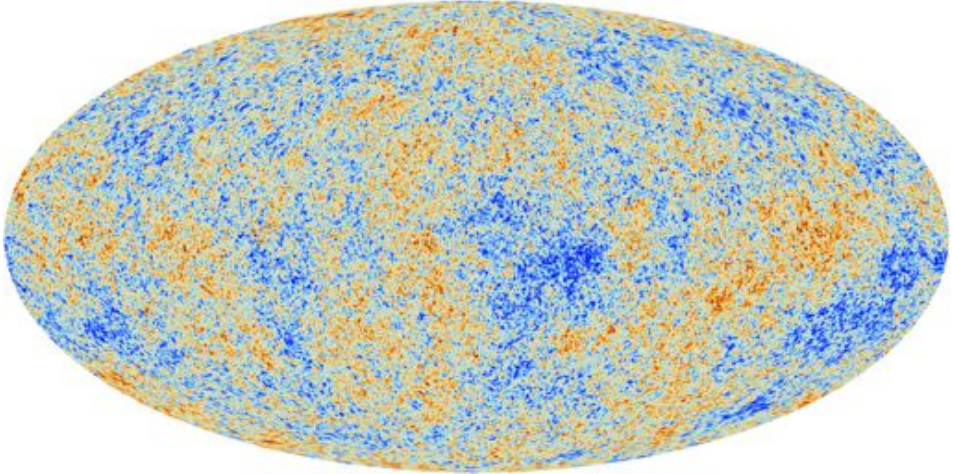


Figure 1.1: Projected image of the cosmic microwave background, the “initial conditions” of the Universe, as measured by the Planck mission (Planck Collaboration et al. 2013).

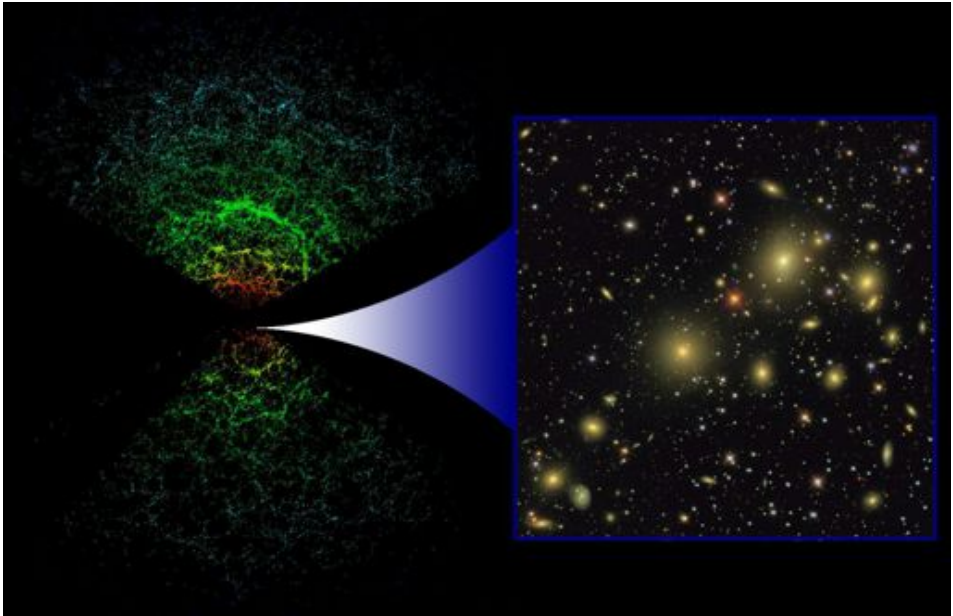


Figure 1.2: Image of galaxies at small and large distances, showing the web-like pattern in which they are distributed (left) and how they appear to us (right). Image from the SDSS.

1.3 Work in this thesis

1.3.1 The CosmoGrid project

In this thesis we mostly address the first of these limitations. In chapters 2-5, we discuss the CosmoGrid simulation and results obtained with it. CosmoGrid, like Millennium, is a dark matter-only simulation. However, it contains a much smaller volume, with an almost equal (8.5 billion) total number of particles. A Milky Way-size halo in CosmoGrid contains about 10 million particles, and will give us the much higher resolution needed to investigate internal properties of the halo and track mergers with small satellites.

A calculation like CosmoGrid is computationally very expensive. The computation time for direct gravity calculations scales with the square of the number of particles, and quickly becomes too large to be feasible. To do cosmological calculations, we therefore use approximations to direct calculation, like the TreePM method. This method calculates large-scale gravity using a particle mesh method, while a Barnes and Hut (1986) Tree code (which scales with $N \log N$) calculates gravity on smaller scales. This way, it becomes possible to do gravity calculations even with large numbers of particles.

1.3.2 Obtaining computational power (Chapter 2)

To compute such simulations, we use supercomputers, which consist of a large number of nodes with several CPU cores each. But, as the number of particles is increased, so are the computational requirements. At a certain point, it becomes rather difficult to perform a calculation, due to the limited amount of resources available.

A solution to this is either to find and obtain time on a larger supercomputer, or to combine multiple smaller supercomputers into one large computational machine. For CosmoGrid, we took the latter approach. We developed the `GreenM` (Ishiyama et al. 2009b) code into the multi-site enabled `Sushi` (Groen et al. 2011) code, which uses the `MPWide` (Groen et al. 2010) message passing interface to connect supercomputers at large physical distances, regardless of the locally installed software. We used the `Sushi` code in combination with a fast, dedicated network to combine supercomputers from all over the world, from Amsterdam to Japan, Finland and Scotland (see Figures 1.4 and 1.5). When limitations due to scheduling were met, this allowed us to combine all these machines efficiently into one large machine. In chapter 2, we discuss the performance of such a set-up.

Figure 1.3: Final snapshot of the Millennium simulation (at $z = 0$), showing the large scale structure as it forms in dark matter simulations. The image shows a slice of $15 h^{-1} \text{Mpc}$ thick.

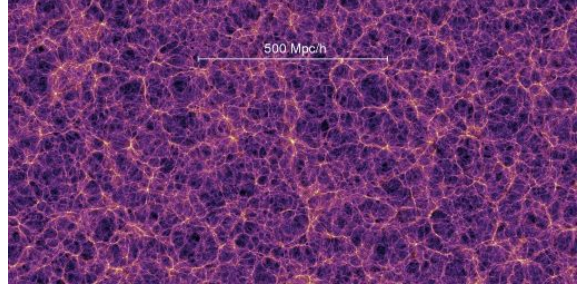


Figure 1.4: Locations of the supercomputers used in the CosmoGrid and GBBP projects.

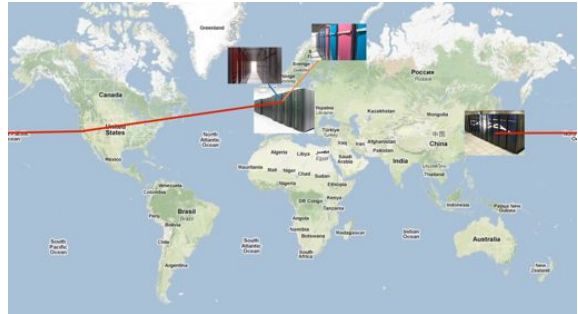
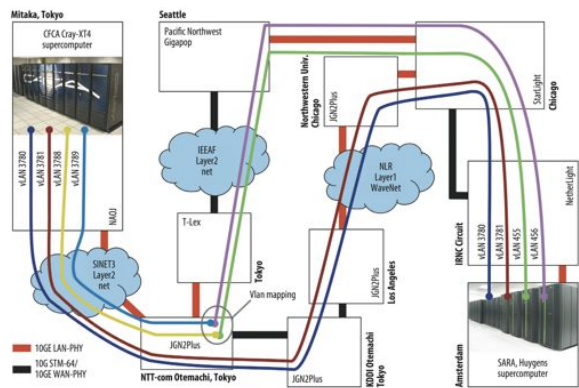


Figure 1.5: Schematic description of the network used in the CosmoGrid project to make the Tokyo-Amsterdam connection. Figure from Portegies Zwart et al. (2010a).



1.3.3 Results of CosmoGrid (Chapter 3)

The CosmoGrid simulation, as said, has very high spatial and mass resolution, uniquely suitable to investigate Milky Way- and dwarf-sized galaxies and groups of galaxies. In chapter 3, we discuss the properties of dark matter haloes found in this simulation, in particular we discuss how these properties change when we increase the resolution of the simulation.

1.3.4 Galaxies in the void (Chapter 4)

While dark matter is not directly observed, visible matter will follow its gravitational potential, and galaxies will form where dark matter haloes are. In chapter 4, we use this to describe the formation history of so-called void galaxies: galaxies that form in a seemingly empty region of space, where the amount of matter is much lower than in the surrounding environment. In a survey of galaxies in such voids, one particular system was found, consisting of three interconnected low-mass galaxies. Using the CosmoGrid simulation, we investigated how such a system can form, and what properties one may expect to observe.

1.3.5 Star clusters in a dark matter halo (Chapter 5)

Galaxies do not just have disks with loose stars, rather they contain a large number of star clusters. These are roughly divided into two types, although there is no physical difference: globular clusters, which are mostly old, massive systems that orbit the galaxy in the halo, and open clusters, which are generally much younger, extended objects in the stellar disk.

In chapter 5, we investigate the influence of the dark matter halo on star clusters resembling the globular clusters in the Milky Way. We use the CosmoGrid simulation to do this, by first finding two dark matter haloes, and then selecting particles at various distances from the galactic centre. We trace the orbits of these particles, and calculate the tidal forces exerted on them by the rest of the dark matter halo. We then combine these tidal forces to new simulations of star clusters in order to find how these disrupt.

1.3.6 Open clusters in a galaxy (Chapter 6)

One of the limitations of the project in chapter 5 was that star clusters formed at later age generally form in the disk of a galaxy, since all the gas is contained there, but that the CosmoGrid simulation does not contain any gas particles. We address this in chapter 6, where we use a re-simulation of a dark matter halo with

baryonic particles (gas and stars) as a large-scale environment. The result of this re-simulation is a galaxy that resembles our Milky Way.

In this chapter, we simulate a large number of open clusters from initial conditions chosen to match observed young clusters. We compare the surviving population of simulated clusters to open clusters observed in the solar neighbourhood, and investigate possible observable signatures in these clusters.