

Simulating Collisional Dark Matter

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Chapter 1

Objectives

1.1 General Objective

To simulate the phase space of a collisional dark matter fluid using a Lattice-Boltzmann method.

1.2 Specific Objectives

- To implement a Lattice-Boltzmann simulation using a 4-dimensional phase space and a varying collisional term.
- To implement a Lattice-Boltzmann simulation using a 6-dimensional phase space and a varying collisional term.
- To study the dynamical behavior of a dark matter fluid using different equilibrium distributions in the collisional term.
- To simulate the phase space of a collisional dark matter fluid using literature values for the thermally averaged cross-section and compare it with its collisionless version.

Chapter 2

Introduction

In this work, we simulate the phase space of a collisional dark matter fluid. In order to follow the ideas and developments of the upcoming chapters, it is essential to understand some concepts and computational techniques. In this chapter, we present all the necessary knowledge for the proper understanding of this work.

2.1 Dark Matter

Modern cosmology describes the universe as being composed of two fundamental types of energy: dark energy and matter¹, with dark energy being associated with a cosmological constant and matter being divided into two categories: dark matter and standard model matter². The energy density of the universe is 69% dark energy and 31% matter.

Standard model matter includes all the particles whose interactions can be properly described by the standard model, such as: Protons, Electrons, Atoms and naturally, any structure that they form, like Humans or Stars. On the other hand, dark matter is all the matter we measure from astrophysical sources which cannot be explained by baryonic matter. We know of the existence of dark matter entirely from astrophysical evidence, during this section we are going to do an historical review of such evidence.

2.1.1 The Cluster Missing Mass Problem

The traditional history of dark matter begins in the 1930s with the swiss astronomer Fritz Zwicky^[1] ^[2], who noticed an unusually high velocity dispersion between the galaxies of the Coma Cluster. To tackle the problem, Zwicky assumed that the Coma Cluster “had already reached a mechanically stationary state” ^[3] and such, the virial theorem could be applied. By counting galaxies, along with assuming that matter is distributed uniformly in the cluster and using Hubble’s estimate of the mean mass of a galaxy, Zwicky was able to estimate the potential energy of the Cluster. Using

¹In relativity, mass and energy are equivalent.

²Which is very often called “Baryonic matter” due to Baryons being the largest fraction of this mass.

his estimate of the visible mass and the virial theorem, Zwicky concluded that the velocity dispersion must be $\sqrt{v^2} = 80$ km/s. Nonetheless, the real measurement of the velocity dispersion was $\sqrt{v^2} = 1000$ km/s, implying a virial mass about 400 times larger than the visible mass³. Zwicky called the discrepancy between the luminous matter (in the form of visible galaxies which could simply be counted) and the virial matter (obtained from the virial theorem and the high velocity dispersion of the cluster) “Dark Matter”.

By the late 1950s similar calculations for different clusters had been published. Many of those calculations had very large values for the mass-to-light ratio[4], which were consistent with the mass-to-light ratio calculated from the Coma Cluster. The problem of the missing mass seemed to appear in almost every large scale structure in the universe, and by the early 1970s astrophysicist had already disregarded hot gas[5] and free hydrogen[6] as explanations for the missing mass in Clusters. Nonetheless, it was still possible that the missing mass problem could be in fact solved by a more refined model of the cluster kinematics, because so far, the missing mass problem had only been observed on Clusters and large scale structures.

2.1.2 Galaxy Rotation Curves

A galaxy rotation curve plots the orbital velocity of stars in a galaxy versus their distance to the galaxy centre. These curves became important thanks to the work of the Indian astrophysics Subrahmanyan Chandrasekhar, who proved that the mutual interactions of stars were negligible, so a galaxy could be modeled as a non-interacting system of stars. Such modeling allows to obtain mass profiles from galaxy rotation curves. Now, due to photometric measurements, astrophysicist believed that most of the mass was overwhelmingly concentrated in the galaxy centre, therefore, it was reasonable to model the galaxy similarly to the solar system. Consider a star in the galaxy disk with mass m at a distance r from the galaxy centre, given that we can disregard the interaction between stars, the sum of forces acting on the object is simply the gravitational attraction towards the galaxy centre:

$$m \frac{v^2}{r} = G \frac{mM}{r^2} \quad (2.1)$$

With M being the mass enclosed by the star orbit and v being the orbital velocity of the star. Finally, the galaxy rotation curve for such galaxy will be given by:

$$v(r) = \sqrt{\frac{GM}{r}} \quad (2.2)$$

Which means that for objects outside of the galaxy disk (but still under the influence of the galaxy gravitational pull), the enclosed mass will be constant regardless of the radius, and thus, the orbital velocity will be proportional to $r^{-1/2}$. With the advent of radio astronomy and the invention of the Image Tube Spectrograph, astronomers were able to measure orbital velocities way beyond the apparent end of the luminous galaxy disks, only to find that the orbital velocity did not decay proportionally to $r^{-1/2}$ but it stayed more or less constant[7] [8] [9]. This behavior can be seen more easily in the figure 2.1

³This ratio is often called the mass-to-light ratio.

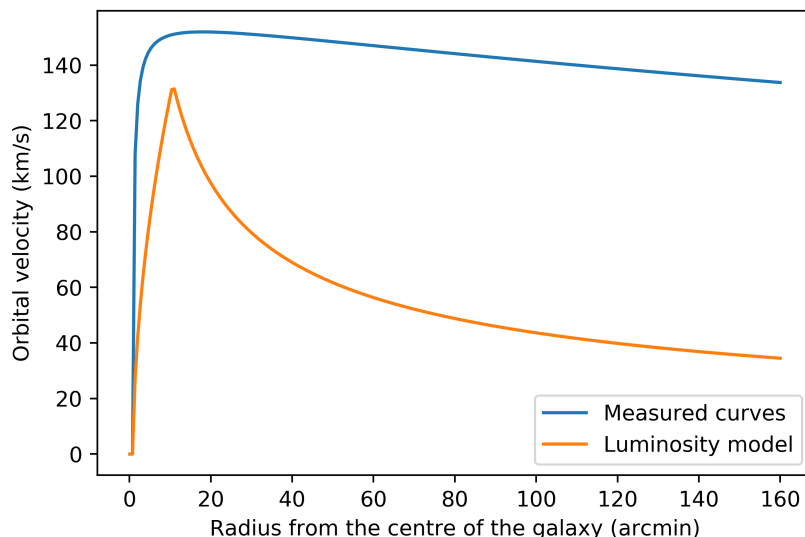


Figure 2.1: A comparison between the model from photometrical measurements and the curves measured. These curves are illustrative and do not correspond to a particular galaxy.

This unexpected velocity profile implied a mass-to-light ratio that increased with distance and the existence of mass beyond the visible galactic disk[10]. The overwhelming amount of high quality galaxy rotation curves measurements, led to the acceptance of the dark matter hypothesis in the astrophysical community.

Throughout the use of numerical simulations and the measurement of more galaxy rotation curves during the 1980s and the 1990s, it was concluded that the dark matter density in galaxies was well modeled by the Navarro-Frenk-White (NFW) profile[11][12]

$$\rho(r) = \frac{\rho_0}{r/r_s(1 + r/r_s)^2} \quad (2.3)$$

2.1.3 The Bullet Cluster

Galaxy clusters have three main constituents: dark matter, intracluster gas (which is almost in its entirety ionised hydrogen and helium), and the galaxy themselves.[13]

We can observe the intracluster baryonic matter in the x-ray band thanks to Bremsstrahlung radiation, therefore, by doing photometry to x-ray pictures it is possible to map the baryonic gas distribution in a cluster. In the case of dark matter, we infer its existence in clusters thanks to the work of Fritz Zwicky and the posterior work in the missing mass problem in galaxy clusters. Our current estimates place most of the cluster mass in the dark matter component. By analyzing the gravitational lensing effect (in particular the *weak* gravitational lensing effect), it is possible to map the mass distribution in a galaxy cluster. Given that most of the cluster mass is dark matter, weak

lensing mapping ends up creating a map of the dark matter distribution in a galaxy cluster. Lastly, we can observe the galaxies in the visual and the infrared band. They are the only component of a galaxy cluster that can be observed in the visual band. About 90 percent of the mass of a cluster is dark matter (this is not a surprise since Fritz Zwicky measured mass-to-light ratios of 50 during the 1930s). Of the remaining baryonic matter, the ionized gas mass can represent up to 90% of the mass, making galaxies responsible for about 1% of the cluster mass.

The object Bullet Cluster (also known as 1E 0657-558) is the aftermath of the collision of two galaxy clusters. Before the collision, each cluster had its own galaxies, baryonic gas and dark matter, and the center of mass of each constituent coincided with the center of mass of the whole cluster. During the collision, each constituent reacts differently to the situation. Galaxies, given that they occupy a minuscule volume in the cluster, are essentially collisionless. Two galaxy clusters can collide without any galaxy (or very little galaxies) colliding per se.

2.2 Types of Dark Matter

2.3 The Boltzmann Equation

2.4 Lattice Automata and Lattice Boltzmann

2.5 BGK Approximation

Chapter 3

The Lattice Boltzmann Algorithm

3.1 General Description

As previously asserted, the heart of the Lattice-Boltzmann Algorithm lies on its discretization of the phase space[14] [15]. To discretize the phase space, one must first choose the region to simulate. In this work, we name the extremal values in the w axis of the phase space W_{min} and W_{max} . Then, one has to fix either the size of the grid or the size of the lattice. We named the size of the grid in the w axis N_w (i.e. N_x or N_{vz}). The size of the lattice in the w axis (which we are going to name dw) and the extremal values are related by:

$$dw = \frac{W_{max} - W_{min}}{N_w} \quad (3.1)$$

In this work we are going to use the phase-space density, which means that $f(\mathbf{r}, \mathbf{v}, t)d\mathbf{r}d\mathbf{v}$ is the density of dark matter whose position is between \mathbf{r} and $\mathbf{r} + d\mathbf{r}$, and its velocity is between \mathbf{v} and $\mathbf{v} + d\mathbf{v}$. Now that we have properly defined the phase space grid, we can proceed to initialization. For simplicity, we choose gaussian initial conditions given by:

$$f(\mathbf{r}, \mathbf{v}, 0) = A \exp \left\{ -\frac{\mathbf{r}^2}{\sigma_r^2} - \frac{\mathbf{v}^2}{\sigma_v^2} \right\} \quad (3.2)$$

Where $f(\mathbf{r}, \mathbf{v}, 0)$ is the initialization of the phase space density, A is an indirect measure of the total mass in the system, \mathbf{r} is the vector (x, y, z) , \mathbf{v} is the vector (vx, vy, vz) , and σ_r and σ_v are a measure of the width of the gaussian profile in the given axis. After initialization, the system evolves by classical mechanics and the modelling of the collisional step, which can be seen more easily in figure 3.1

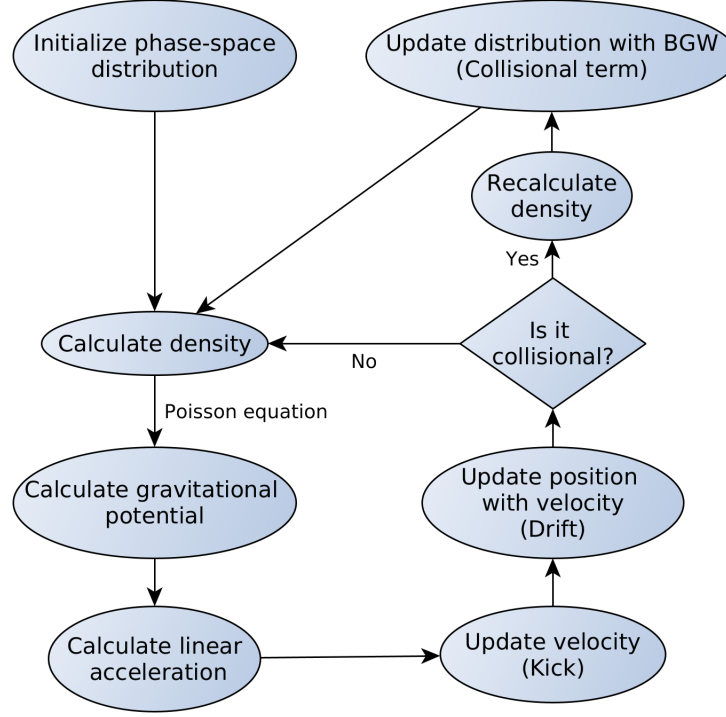


Figure 3.1: Flowchat of the algorithm.

Given the phase-space density, the spatial density of matter is given by the integral:

$$\rho(\mathbf{r}, t) = \int_{-\infty}^{\infty} f(\mathbf{r}, \mathbf{v}, t) d\mathbf{v}. \quad (3.3)$$

When evaluating in the lattice the integral becomes a sum over the entire velocity space:

$$\rho(\mathbf{r}, t) = \sum_{\mathbf{v}_{min}}^{\mathbf{v}_{max}} f(\mathbf{r}, \mathbf{v}, t) d\mathbf{v} \quad (3.4)$$

and during initialization:

$$\rho(\mathbf{r}, 0) = \sum_{\mathbf{v}_{min}}^{\mathbf{v}_{max}} f(\mathbf{r}, \mathbf{v}, 0) d\mathbf{v} \quad (3.5)$$

Once we have calculated the density, we can use the Poisson equation to obtain the potential due to gravitational interaction: [15]

$$\nabla^2 \Phi(\mathbf{r}, t) = 4\pi G \rho(\mathbf{r}, t) \quad (3.6)$$

Where $\Phi(\mathbf{r}, t)$ is the gravitational potential and G is the gravitational constant. To solve the Poisson equation we use the Fourier pseudo-spectral method, which allows for very fast numerical

solutions by making use of the Fast Fourier Transform algorithm. The idea is simply to apply a Fast Fourier Transform (FFT), then solve the equation in the Fourier space, and then apply an inverse transform (IFFT). In the phase space the Poisson equation is given by[16] [17]

$$\lambda_{\mathbf{k}}^2 \hat{\Phi}(\mathbf{k}, t) = 4\pi G \hat{\rho}(\mathbf{k}, t) \quad (3.7)$$

Where $\hat{g}(\mathbf{k}, t)$ is the Fourier transform of $g(\mathbf{r}, t)$, and $\lambda_{\mathbf{k}}$ is a constant that depends on the size of the lattice and the wavevector \mathbf{k} . $\lambda_{\mathbf{k}}$ is calculated according to the approximation scheme used to solve the equation. In the pseudo-spectral approximation, $\lambda_{\mathbf{k}}$ is given by:

$$\lambda_{\mathbf{k}}^2 = \left(\frac{2\pi k_x}{X_{max} - X_{min}} \right)^2 + \left(\frac{2\pi k_y}{Y_{max} - Y_{min}} \right)^2 + \left(\frac{2\pi k_z}{Z_{max} - Z_{min}} \right)^2 \quad (3.8)$$

Therefore, solving the Poisson equation in the Fourier space is reduced to very simple numerical operations. Thanks to the highly efficient implementations of the Fast Fourier Transform Algorithm available nowadays, solving the Poisson equation takes very little time and computational resources. In this work we use the Fastest Fourier Transform of the West[18] subroutine to handle the Fast Fourier Transforms.

Once we have calculated potential, obtaining the acceleration is straight-forward:

$$\mathbf{a}(\mathbf{r}, t) = -\nabla \Phi(\mathbf{r}, t) \quad (3.9)$$

Which, in the context of the lattice can be calculated simply with a central difference numerical derivative.

Now, in order to update the phase space, we must first define the time interval to simulate: we name N_t the number of time intervals to simulate and dt the length of each of such intervals. After calculating the acceleration and defining dt , we can update our phase space, the subtlety here is that we will only use integer arithmetic, which means that we do not exactly care for the change in velocity during a time dt but for how many cells in the phase space that change represents. This is modeled by:

$$\mathbf{v}_{n+1} = \mathbf{v}_n + \lfloor \mathbf{a}_n dt \rfloor \quad (3.10)$$

With $\lfloor x \rfloor$ representing the operator “to nearest integer”, so that \mathbf{v} and $\lfloor \mathbf{a} dt \rfloor$ are vectors of integers and n represents the time instant. The update of the velocity is known as “kick”. Analogously, the update of the position is known as “drift”, and is given by:

$$\mathbf{r}_{n+1} = \mathbf{r}_n + \lfloor \mathbf{v}_n dt \rfloor \quad (3.11)$$

Using only integer arithmetics allows for the elimination of the rounding error but introduces lattice noise. Regardless, this method creates a one to one map with the continuous solution.[14] [15]

The “kick” and “drift” together are known as the “Streaming” step, and it represents the classical movement of particles under a potential but without considering the collision of particles. If we want a collisionless simulation, we can just calculate again the density and continue the algorithm from there. If we want a collisional simulation, we must define a collisional step.

3.2 The Collisional Step

As previously mentioned, solving the collisional integral $C[f]$ is not straight-forward, as it depends on the modeling of the short range interactions that we decide to assign to the dark matter particle. Given that the short range interaction of dark matter is unknown, we avoid using an specific description of the microscopic interactions and choose to use a mesoscopic approach, as discussed in section 2.5. The BGK collisional operator is given by:

$$C[f] = -\frac{1}{\tau}(f(\mathbf{r}, \mathbf{v}, t) - f_e(\mathbf{r}, \mathbf{v})) \quad (3.12)$$

Which in the context of the direct integration scheme used in the simulation becomes:

$$f(\mathbf{r} + \mathbf{v}dt, \mathbf{v}, t) = f(\mathbf{r}, \mathbf{v}, t) - \frac{dt}{\tau}(f(\mathbf{r}, \mathbf{v}, t) - f_e(\mathbf{r}, \mathbf{v})) \quad (3.13)$$

The idea behind this approach is to recover the macroscopic description of the fluid without committing to a particular microscopic description. In this scenario, the macroscopic effects of the collisions is a local relaxation towards equilibrium, which the BKG operator models using a relaxation time τ and a local equilibrium distribution $f_e(\mathbf{r}, \mathbf{v})$.

In order to implement a collisional operator we add a collisional step after the streaming step, in which the system performs a relaxation with characteristic (relaxation) time τ towards the local equilibrium distribution $f_e(\mathbf{r}, \mathbf{v})$. It is important to notice that the BGK collisional operator is a *scattering* operator and does not includes annihilation or creation of particles.

After defining the collisional term, we have to choose a distribution fuction $f_e(\mathbf{r}, \mathbf{v})$. We claim that the phase space distribution relaxes towards equilibrium, which means a displacement in the phase space and not the introduction or annihilation of mass. Therefore, the equilibrium distribution must be perfectly *normalized* in order to enforce particle number conservation. We normalize this equilibrium distribution by using macroscopic quantities obtained by integrating the velocity part of the phase space. This macroscopic quantities are: the volumetric density $\rho(\mathbf{r}, t)$, the macroscopic velocity $\mathbf{u}(\mathbf{r}, \mathbf{v})$ and the internal energy $e(\mathbf{r}, \mathbf{v})$.

The volumetric density is the same density we have been using so far defined by the integral of equation 3.3. The macroscopic velocity $\mathbf{u}(\mathbf{r}, \mathbf{v})$ is defined by the integral:

$$\mathbf{u}(\mathbf{r}, \mathbf{v}) = \int_{-\infty}^{\infty} f(\mathbf{r}, \mathbf{v}, t) \mathbf{v} d\mathbf{v}. \quad (3.14)$$

When evaluating in the lattice the integral becomes:

$$\mathbf{u} = \sum_{\mathbf{v}_{min}}^{\mathbf{v}_{max}} f(\mathbf{r}, \mathbf{v}, t) \mathbf{v} d\mathbf{v} \quad (3.15)$$

And the internal energy is defined by the integral

$$e(\mathbf{r}, \mathbf{v}) = \frac{1}{2} \int_{-\infty}^{\infty} f(\mathbf{r}, \mathbf{v}, t) (\mathbf{v} - \mathbf{u})^2 d\mathbf{v}. \quad (3.16)$$

Which also becomes a sum when evaluating in the lattice.

$$e(\mathbf{r}, \mathbf{v}) = \frac{1}{2} \sum_{\mathbf{v}_{min}}^{\mathbf{v}_{max}} f(\mathbf{r}, \mathbf{v}, t) (\mathbf{v} - \mathbf{u})^2 d\mathbf{v} \quad (3.17)$$

3.3 Systems to Simulate

Chapter 4

Results

4.1 No Collisional

4.2 Collisional with reported $\langle \sigma v \rangle$

4.3 Different Equilibrium Distributions

Chapter 5

Conclusions

5.1 A Numerically Stable Simulation

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