The Peculiar Acceleration of the Milky Way

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THESIS

submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE
in
PHYSICS

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Leiden, The Netherlands, July 19, 2023

Peculiar acceleration of the Milky Way

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July 19, 2023

Abstract

In our research project, we conducted an analysis of the impact of dark matter haloes on the motion of the Milky Way. Our study focused on dark matter haloes located within a radius of 200 Mega Parsecs (Mpc) from the Milky Way. The cosmological framework we implemented was the Lambda Cold Dark Matter model. Our primary objective was to determine the peculiar acceleration of the Milky Way and derive insights about its motion. To achieve this, we compared the peculiar acceleration to the Hubble rate, a significant parameter in cosmology, as a reference point. By means of our study, we aimed to determine whether the Milky Way would eventually reach the Great Attractor or undergo a change in its direction of motion. Additionally, we generated an all-sky structure map for the haloes to explore the density distribution within each region. This analysis allowed us to examine the concentration of dark matter throughout the universe inside the 200 Mpc from the Milky Way. In our research, we utilized data obtained from the SIBELIUS-DARK project, which provided a robust scientific basis for our study.

Contents

Chapter 1

Introduction

In our research project, we are implementing the Lambda Cold Dark Matter model ΛCDM of the universe, depending on which the universe contains three components: dark energy associated with the cosmological constant Λ, cold dark matter, and ordinary matter.

The global motivation of our research project is to try to test the ΛCDM model, see if it is possible for this model to evolve into the Universe, we have today. What can be the origin of the Cosmic Microwave Background (CMB) dipole? How can we get such a high peculiar velocity for our galaxy? Our specific focus lies in understanding the influence of dark matter on our galaxy, the Milky Way. For cosmological studies, CMB frame serves as the most suitable reference frame. Hence, we will use this frame for our calculations and estimations. Below, we will explain the terms mentioned in this paragraph in more detail.

The density fluctuations that originated in the early universe have evolved into the complex structures we observe today. These structures extend beyond individual galaxies and are referred to as large-scale structures, encompassing groups of galaxies, clusters, filaments, and voids. Unlike a random distribution, the matter within these large-scale structures exhibits correlations. This is where peculiar velocities come into play.

To comprehend the behavior of matter within these large-scale structures, one can use the concept of peculiar velocity. Peculiar velocity refers to the velocity of an object or collection of objects in relation to the cosmic expansion. It takes into account the local gravitational interactions and deviations from the overall cosmic expansion due to the influence of nearby matter concentrations. These peculiar velocities are a consequence of the gravitational pull exerted by neighboring structures and play a significant role in shaping the distribution and motion of matter on cosmic scales.

Peculiar velocity is defined as follows[1]:

$$\mathbf{v} = a\dot{\mathbf{x}} \tag{1.1}$$

Where $\mathbf{x}$ is comoving coordinates. Peculiar velocities describe the motion of element with respect to the fundamental observer (which is comoving with the background). Peculiar velocities are induced by density perturbations and in linear regime are proportional to the amplitude of density perturbations. Consequently, if peculiar velocities are not affected by non-gravitational processes, then by measuring the peculiar velocities it is possible to get constraints on the mass density fluctuations in the Universe.

By studying peculiar velocities, one can gain deeper insights into the complex interplay between gravity, dark matter, and cosmic expansion. They can observe the flow of matter along cosmic filaments and the gravitational interactions that give rise to the formation and evolution of large-scale structures. Peculiar velocities also provide crucial information about the distribution of dark matter, as its gravitational influence on visible matter can be indirectly inferred through the measurement of these velocities.

In summary, the study of large-scale structures and peculiar velocities allows us to unravel the intricate web of cosmic structure formation and evolution. By investigating the correlations and motion of matter on cosmic scales, we can better understand the fundamental processes that have shaped the universe from its early beginnings to its present state.

Also it is interesting to look at peculiar velocities from other point of view. As we already mentioned, peculiar velocity describes the motion of a galaxy as it is accelerated towards nearby regions of higher mass concentrations. Over long periods of time, these gravitational interactions result in peculiar velocities. So, it is very tempting to investigate if acceleration exerted on Milky Way is sufficient to get as high peculiar velocity as we observe in CMB dipole in a reasonable time (e.g. age of the Universe).

From this we could see, if the correlation observed in peculiar velocities extends to the accelerations experienced by galaxies on these large scales.

Now let us focus on our own galaxy, the Milky Way. It is known that, according to our cosmological model, the universe undergoes the Hubble expansion. Furthermore, we acknowledge the presence of a peculiar velocity of the Milky Way relative to the CMB [2], commonly referred to as the CMB dipole. As we already mentioned, peculiar velocity represents a velocity independent of the Hubble flow, arising from the gravitational attraction between celestial objects. By considering the combined effect of the Hubble flow and peculiar motion, we can express the velocity of our galaxy in the following manner:

$$v = Hd + v_{pec} \tag{1.2}$$

So the total velocity can be defined as the sum of the Hubble flow and the peculiar velocity. According to Hubble expansion, the universe is accelerated, and consequently so is the Milky Way, but our primary interest lies in examining the peculiar acceleration of our galaxy (acceleration with respect to CMB). What could cause the peculiar acceleration? The first possible answer can be the gravitational force. Given that dark matter constitutes a significant portion of the matter content, it is logical to explore the influence of dark matter on our galaxy. In this context, the most reasonable objects to examine are the gravitationally bound dark matter halos.

In this research project we are investigating the effects of dark matter halos on our Milky Way galaxy inside the radius of 200 Mpc distances from the Milky Way itself. For this, we are using the data from SIBELIUS-DARK[3][*]. The SIBELIUS-DARK simulations are scientific simulations that specifically focus on dark matter. In these simulations, only dark matter particles are modeled and simulated, neglecting the presence of baryonic matter (ordinary matter). We will explain how we use it in more detail later in Chapter "Methods & Data Analysis".

The primary objective of this thesis is to estimate the magnitude and direction of the Milky Way's acceleration relative to the CMB, which arises from the gravitational influence of dark matter halos located within a 200 Mpc radius. This acceleration is referred to as cosmic peculiar acceleration, representing the motion deviating from the expected cosmological expansion.

Once the cosmic peculiar acceleration is estimated, an in-depth analysis will be conducted. One aspect of interest is estimating the time required

[*]the link http://virgodb.dur.ac.uk:8080/MyMillennium/

for the Milky Way to reach the Great Attractor, a gravitational anomaly situated in the direction of the Centaurus and Hydra constellations.

Furthermore, we will examine the relationship between peculiar velocity and peculiar acceleration. Peculiar velocity characterizes the motion of an object in relation to cosmic expansion, while peculiar acceleration describes changes in velocity over time. Understanding the interplay between these two quantities will provide insights into the overall dynamics of our galaxy.

Finally, it is crucial to investigate whether our galaxy's motion will ever change direction. By considering the gravitational influences of the surrounding dark matter halos, we can ascertain the likelihood of a change in the Milky Way's direction of motion.

Finding the answers to these topics is very compelling and we will try to do that during this thesis work.

For simulations, we use the Python programming language, "Healpy" package, and "Mollview" projection to make all-sky plots.

Chapter 2

Formalism and Structure formation

As we already mentioned, our goal is to investigate the effects of different dark matter halos on the Milky Way. We are interested in finding the accelerations, which different halos give to Milky Way. Subsequently, we will calculate the cumulative acceleration experienced by the Milky Way due to all the halos within a 200 Mpc radius and assess its plausibility. To verify our results, we will compare the total acceleration with theoretical calculations, such as the ratio of the Milky Way's velocity to the age of the universe and the gravitational acceleration of the Milky Way with respect to the Great Attractor. If we get the approximately same numbers, then the acceleration we calculated can be considered reasonable.

Firstly, we want to generate an all-sky map of the galaxy halos and get a general imagination about their structure.

For this, we use the SIBELIUS-DARK simulation data[3]. Here is the table of redshift $z = 0$ Galform galaxy catalog from SIBELIUS-DARK.

Table 1: Galaxy data

column	type	UCD unit	description
GalaxyID	integer		Unique identifier of a galaxy
HOstHaloID	integer		Unique identifier of a galaxy's halo
redshift	real		Redshift of galaxy (z=v_r/c)
mstars_bulge	real	Msolar	Stellar bulge mass
mstars_disk	real	Msolar	Stellar disk mass
mbh	real		Mass of the central black hole in this galaxy
rank	integer		Rank order of galaxy in host halo (rank=0 is the central galaxy, rank $>$ 0 are satellites)
type	integer		Whether this is a central galaxy (0), satellite with resolved subhalo (1), or satellite with no resolved subhalo(2)
mbound	real	Msolar	Total mass bound to the subhalo. We refer to this as the subhalo mass, or Msub
nbound	integer		Number of particles bound to the subhalo
dist	real	Mpc	Distance from Milky Way
v_r	real	km/s	Radial velocity of the galaxy relative to Milky Way. This is the radial component of the galaxy's peculiar velocity plus the Hubble flow
x	real	Mpc	x coordinate of the galaxy's center of potential (equatorial)
y	real	Mpc	y coordinate of the galaxy's center of potential (equatorial)
z	real	Mpc	z coordinate of the galaxy's center of potential (equatorial)
v_x	real	km/s	x coordinate of the galaxy's velocity (CMB rest frame)
v_y	real	km/s	y coordinate of the galaxy's velocity (CMB rest frame)
v_z	real	km/s	z coordinate of the galaxy's velocity (CMB rest frame)
ra	real	degrees	Right Ascension (equatorial)
dec	real	degrees	Declination (equatorial)

From the data, we take the coordinates of all galaxies (galaxy halos) within the radius of 200 Mpc from the Milky Way, considering the galaxies with a combined stellar mass of $mstars\_bulge + mstars\_disk \geq 10^7 M_\odot$. This selection criterion encompasses nearly all galaxies in the region of interest. Then we are observing shell-by-shell structure formation, which means, we plot an all-sky map firstly for galaxy halos in a radius of 10 Mpc from the Milky Way, then in a radius of 20 Mpc, and so on we reach the 200 Mpc radius. We consider from 16 up to 32 shells, but here we plot only 6 for visualisation. The result is shown in Figure 2.1.

Here we see that as we look farther structure becomes more and more uniform. This is just a galaxy halo distribution map. Now we want to see the effect (in the sense of acceleration) of the dark matter halos on the Milky Way. In order to investigate the effect of dark matter halos on the Milky Way's acceleration, we need to determine the coordinates of these halos. However, the available data provide us with the coordinates of galaxies rather than the halos themselves. To address this, we apply a filtering process to identify the halos for which our known galaxies act as central objects. Firstly, we filter the data based on rank, selecting only the galaxies with a rank value of 0. Then, to establish a correspondence between galaxies and their respective halos, we compare the ID values of the galaxies (GalaxyID) with the corresponding IDs of the halos (HostHaloID) in Table 1. By identifying matching IDs, we can determine the halos that correspond to the selected galaxies and treat the galaxy coordinates as corresponding halo coordinates. Having obtained the halo coordinates using this matching process, we can then calculate the acceleration exerted by these halos on the Milky Way using Newtonian Gravity. Newton's law of gravitation provides us with the formula to estimate the gravitational acceleration:

$$\mathbf{a} = -\frac{GM}{r^3}\mathbf{r}. \tag{2.1}$$

Using the approach described, we calculate the acceleration contributed by each dark matter halo to the Milky Way. Initially, we calculated the acceleration on a shell-by-shell basis, considering galaxy halos within a specific distance range from the Milky Way ($r_1 \leq dist \leq r_2$). However, upon further consideration, we determined that it would be more meaningful to plot the cumulative acceleration as the radius increases. This cumulative acceleration takes into account an increasing number of galaxy halos as the radius expands. Figure 2.2 displays the results of this cumulative acceleration analysis. The figure illustrates how the total acceleration experienced by the Milky Way evolves as we include more and more galaxy

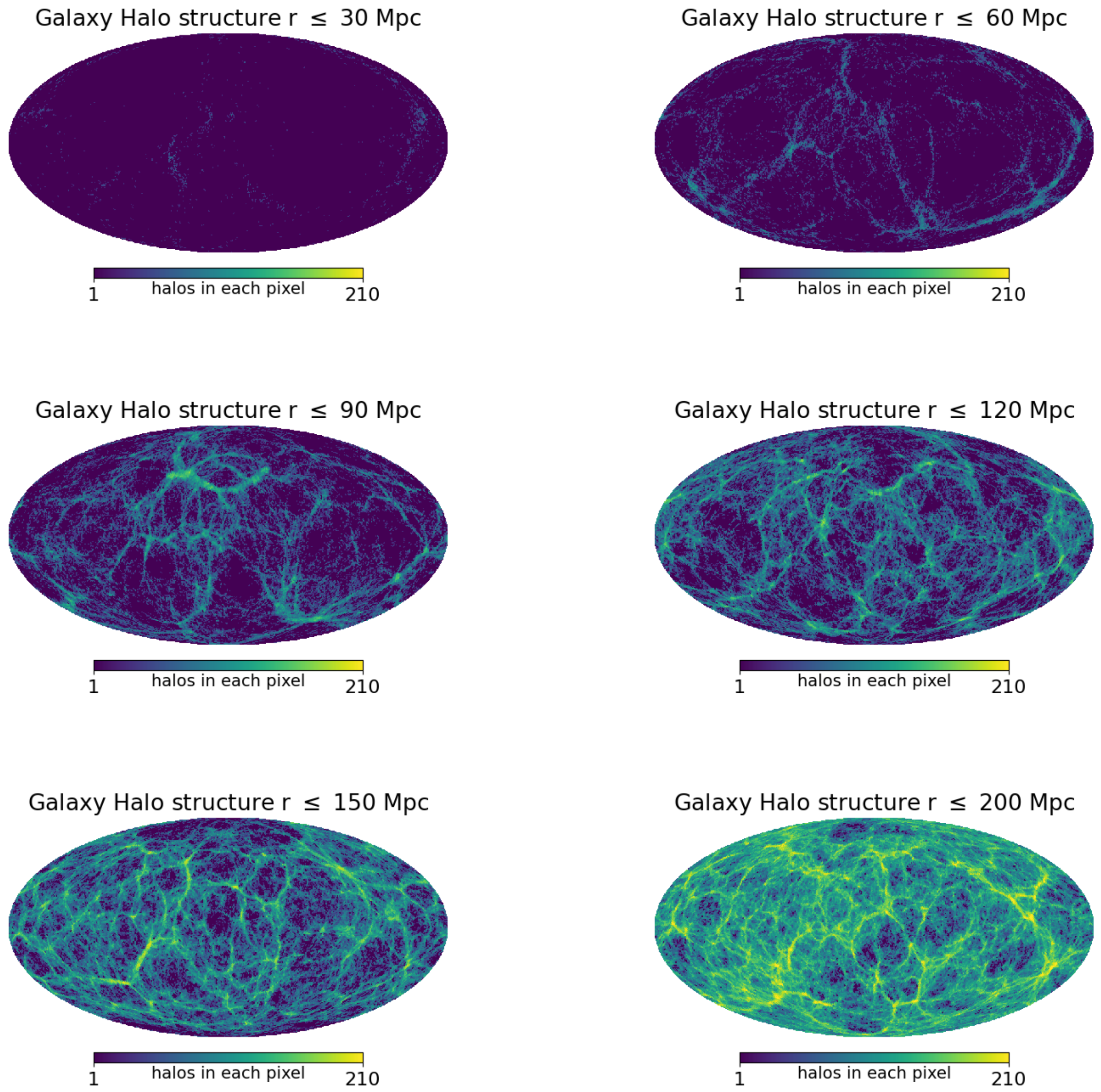

Figure 2.1: *The shell-like structure of the galaxy halos up to 200 Mpc radii from the Milky Way (halo coordinate plot depended on their central galaxy's coordinates).*

halos with increasing radii.

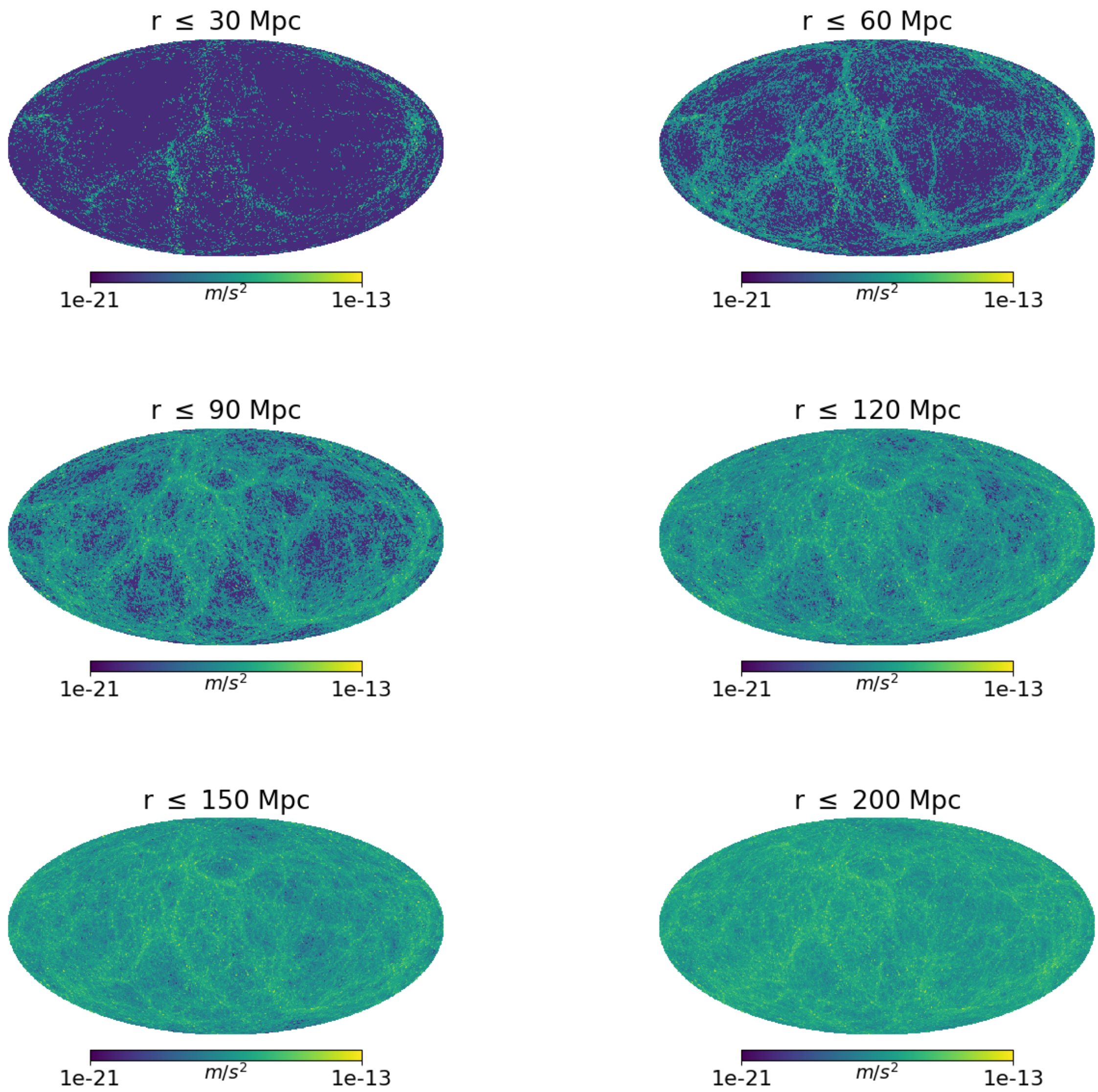

Figure 2.2: *The plot of cumulative acceleration of galaxy halos shell-by-shell up to 200 Mpc radius from the Milky Way.*

From our calculations and the plot, we can see, that the maximal acceleration halo can impart to the Milky Way is the order of $10^{-13} m/s^2$. Let us compare this value to the ratio of the Milky Way's velocity over the age of the universe. Peculiar velocity of Milky Way, $v_{MW} = 6.27 \cdot 10^5 m/s$, age of the universe $t_{age} = 4.37 \cdot 10^{17} s$. Therefore, the ratio v_{MW}/t_{age} is the order of 10^{-12}. Comparing this ratio with our calculated maximal acceleration, we find that the acceleration is approximately 10 times smaller, indicating a close agreement.

Additionally, considering that the Milky Way is moving toward the Great Attractor[2], we can use the theoretical calculations of acceleration toward the Great Attractor as another way to validate our peculiar acceleration results. The mass of Hydra cluster (Great Attractor) is $2 \cdot 10^{14} M\odot = 3.8 \cdot 10^{44} kg$, distance to it is approximately 58.3 Mpc, so the acceleration will be:

$$|a| = \frac{GM}{d^2} \approx 7.9 \cdot 10^{-15} m/s^2. \tag{2.2}$$

The total acceleration the Milky Way experiences from all considered galaxy halos is the order of $10^{-13} m/s^2$, acceleration calculated with the formula is only several (2) magnitudes smaller than then the acceleration we calculated, so we treat that as our result seems to make sense.

Now it is interesting to plot the total acceleration directions for each shell and see if acceleration vectors converge to one point. This expectation seems reasonable as we are summing up the total acceleration contributions from all shells. To accomplish this, we first determine the total acceleration vector for each shell. Depending on the magnitude of the total acceleration, we calculate the appropriate accession and declination angles for each vector. These angles represent the right ascension and declination coordinates on the celestial sphere. Next, we plot a point on the sky map corresponding to these calculated angles. This process is repeated for each shell, resulting in a set of total acceleration points distributed across the all-sky map for distances up to 200 Mpc from the Milky Way. As a result, we get Figure 2.3.

Now we can estimate how well acceleration vectors converge to the final distance-shell 200 Mpc acceleration vector. For this, we will divide our accelerations into two parts: angular difference and difference in magnitude, and see if both converge. For that, we are plotting the differences between each acceleration direction point and the final one. We do the same for magnitudes too. As a result, we get Figure 2.4

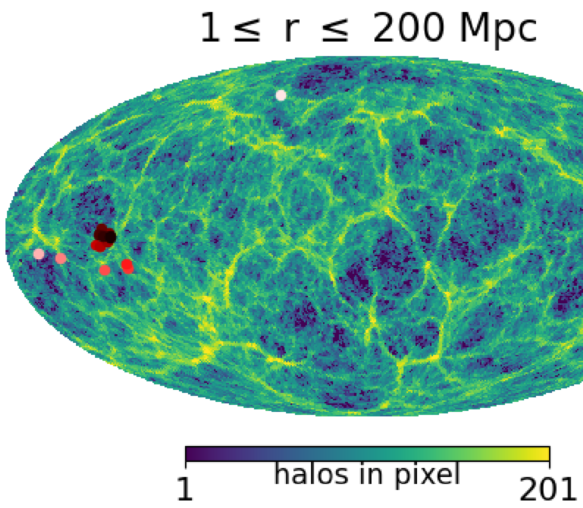

Figure 2.3: *Cumulative acceleration directions, dots represent the total acceleration for the relevant shell, getting darker indicates increasing the shell's radii.*

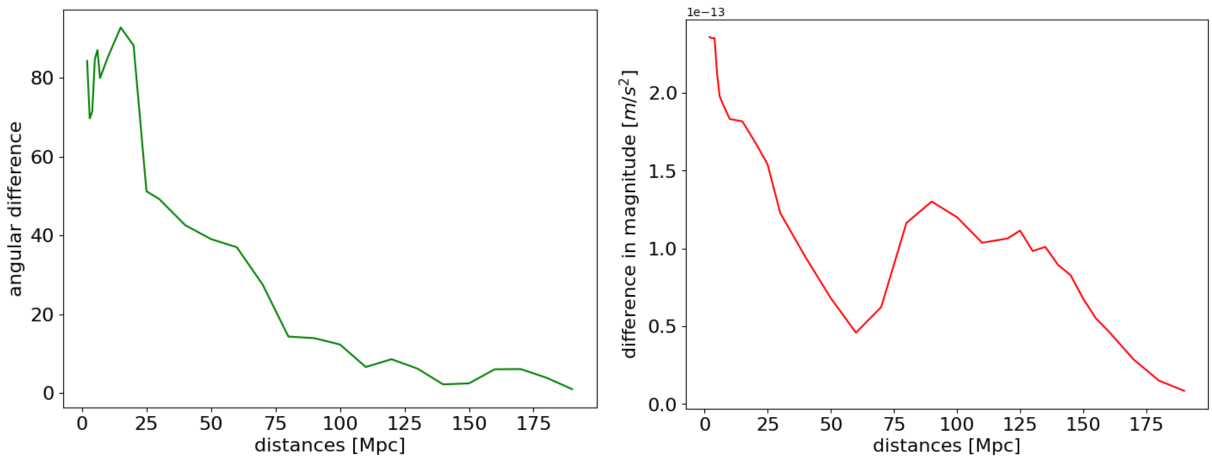

Figure 2.4: *Left: angular diameter distance between acceleration directions from different radii shell to the final one; right: difference in magnitude between different radii shell and final one.*

So, we can see that after some distance (approximately after 100 Mpc), the acceleration vectors' directions converge to the final one that serves as the clue, that our logic and calculations turn out to be right.

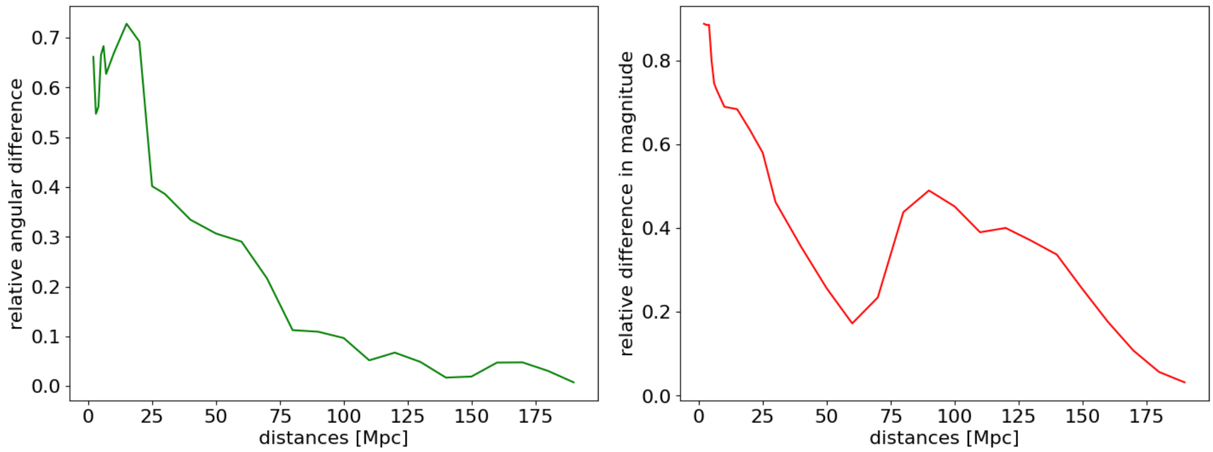

Figure 2.5: *Left: relative angular diameter distance between acceleration directions from different radii shell to the final one; right: relative difference in magnitude between different radii shell and final one.*

Now finally we can see, what is the total acceleration that all galaxies halos give to the Milky Way and where is it directed. This is given in Figure 2.6. Its magnitude is $2.66 \cdot 10^{-13} m/s^2$.
So, we found the value and the direction of the Milky Way's peculiar acceleration. In the next chapter, we will compare the directions of CMB dipole and peculiar acceleration and try to draw some conclusions about Milky Way motion.

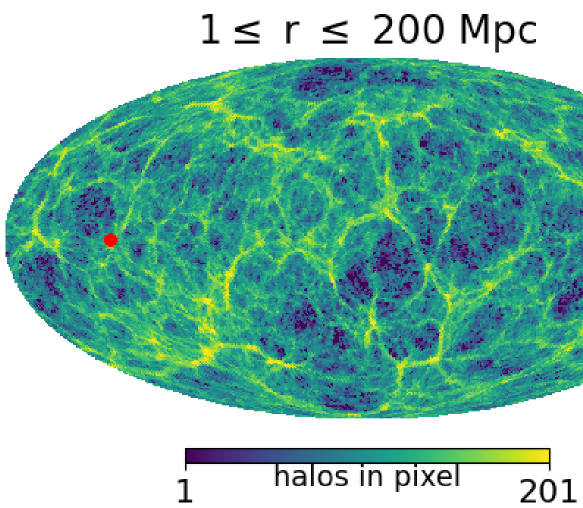

Figure 2.6: *The red dot shows the direction of the acceleration that all the galaxy halos inside radius 200 Mpc exert to the Milky Way.*

Chapter 3

Peculiar Velocity & Peculiar Acceleration, All-sky halo structure

In the previous chapter, we calculated and showed the direction of the peculiar acceleration of the Milky Way. Now we aim to compare the directions of the peculiar acceleration and peculiar velocity. To determine the direction of peculiar velocity on the plot, we use results from [3] presented in Table 2:

Table 2: Peculiar velocity

From observation	From simulation
$l = 271 \pm 2^\circ$ $b = 29 \pm 1^\circ$	$l = 232^\circ$ $b = 7^\circ$

In Figure 3.1, we present an all-sky map depicting the peculiar acceleration of the Milky Way due to the gravitational influence of all surrounding galaxy halos, as well as the peculiar velocity of our own galaxy. To represent these quantities visually, we use different symbols: with the symbol ”X” we denote velocity, and with a little circle - the acceleration of the Milky Way.

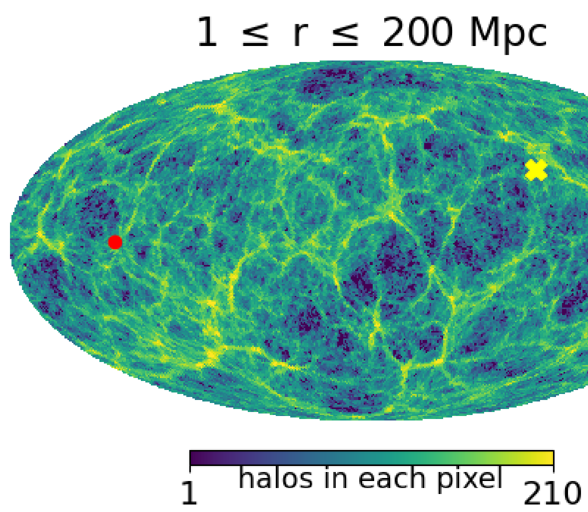

Figure 3.1: *The peculiar velocity vs peculiar acceleration. The red dot is acceleration, the yellow "X" is for velocity from observations, and the blue "X" is the velocity from simulations.*

The comparison between the directions of the peculiar acceleration and peculiar velocity reveals that they are "quite opposite" to each other. The angle between them is 104.5 degrees. This implies that the Milky Way is experiencing a deceleration in its peculiar motion (excluding the influence of the Hubble flow). Furthermore, based on the information provided in [3], we know that the Milky Way is moving towards the Great Attractor. Considering our result about the acceleration of the Milky Way, several interesting aspects arise for further investigation:

- When (if ever) will Milky Way turn back, that means considering negative acceleration, when will the galaxy's velocity become 0?
- If that happens, how far will have Milky Way gone by that time?
- Will we ever merge with the Great Attractor, and if so, when?
- How significant is the peculiar acceleration we calculated?

Another very interesting asset was to classify these galaxy halos into "clusters", "filaments", and "voids"*, and observe the structure of peculiar acceleration each part gives to the Milky Way separately. We will start by investigating the last thing and then try to classify the answers to above-mentioned 4 questions.

*under "cluster here we mean a cluster of halos", same for filaments and voids too.

3.1 Clusters, Filaments, Voids

From the beginning, why are we interested in classifying halos in clusters, filaments and voids? Firstly, we want to see the distributions of accelerations coming from each part. This can be used to check our assumption about our sources of acceleration. We were calculating acceleration from only dark matter halos, but there is more dark matter in the Universe. So, is our approximation about considering only halos valid? As we will see later, the acceleration coming from smaller objects will be distributed more uniformly, that means in total acceleration it will not take much part. So neglecting that part definitely will be the good approximation.

With our mass constraint of the combined stellar mass $mstars\_bulge + mstars\_disk \geq 10^7 M_{\odot}$, we have a dataset of approximately 2 million galaxies, considering only central galaxies for halos to avoid counting one halo multiple times. To classify our galaxy halos into clusters, filaments, and voids, we decided to create a 3D grid, spanning from $-200Mpc$ to $200Mpc$ on each side, representing the region within the radius of $200Mpc$ from the Milky Way. Then we divided this large cube into smaller, $4Mpc$ side cubes and histogramed the galaxy halos in these cubes. As a result, we got a 3D grid, where each cube contained a certain number of galaxy halos (of course, there could be empty cubes as well). Next, we assigned to each galaxy halo the density number, based on the number of the galaxy halos in its own cube. So, we created a density array for our galaxy halo array. With this logic, the minimal density value was set to 1, since each galaxy halo included at least itself in its own cube.

Now, the main question lies in determining the thresholds that define clusters, filaments, and voids based on the density numbers. To address this, we made different cut arrays for density numbers considered as clusters and analyzed the standard deviation of the pixels. The "Methods and Data Analysis" section provides a detailed explanation of this process. By altering the density numbers for clusters and filaments, we observed the corresponding changes in the standard deviation. However, we maintained a fixed density value for voids, less than or equal to 5. With this set up, we got the Figure 3.2.

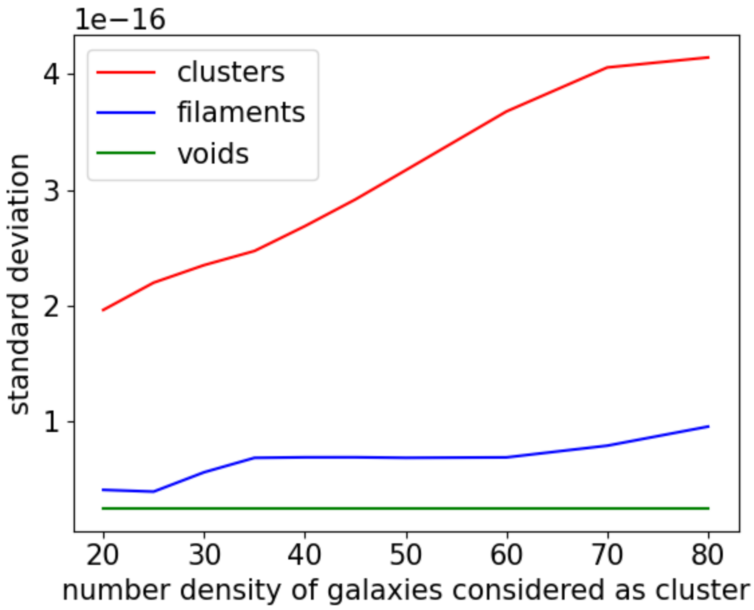

Figure 3.2: *The standard deviation as a function of the number density of galaxies considered as a cluster.*

Here we can observe that when considering the cluster density greater than approximately 25 (which means considering filament density less than or equal to 25), the standard deviation of filament becomes nearly constant (in the context of cut number). This suggests that the filaments exhibit homogeneity under a density of 25.

So, we decided, that the galaxy halos with a density number of less than or equal to 5 should have been treated as void regions, and halos with a density number of more than 25 we would consider as clusters (the check for density function is shown in Appendix 1), and everything between should have been considered as the filaments.

Now it would be very interesting to provide an all-sky structure of halos, from which we will be able to distinguish where are the clusters, filaments, and voids of the halos. As we mentioned earlier:

- density number > 25 - cluster
- $5 <$ density number≤ 25 - filament
- density number ≤ 5 - void.

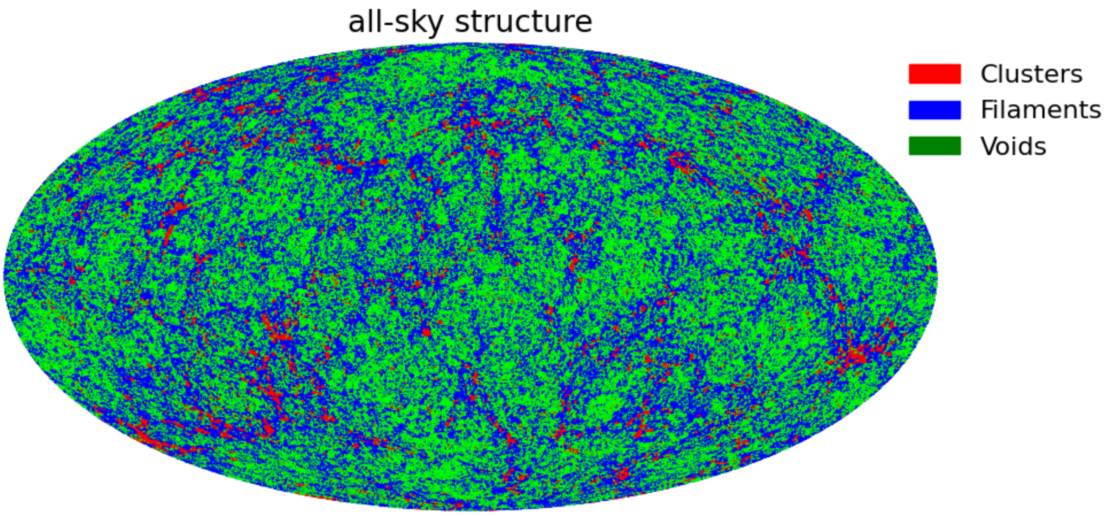

Figure 3.3: *The all-sky structure of dark matter halo distribution.*

So, the all-sky structure in this setup will look like Figure 3.3.

To visualize these structures in more detail, we plotted the cumulative acceleration for voids, filaments, and clusters. The result is demonstrated in Figure 3.4.

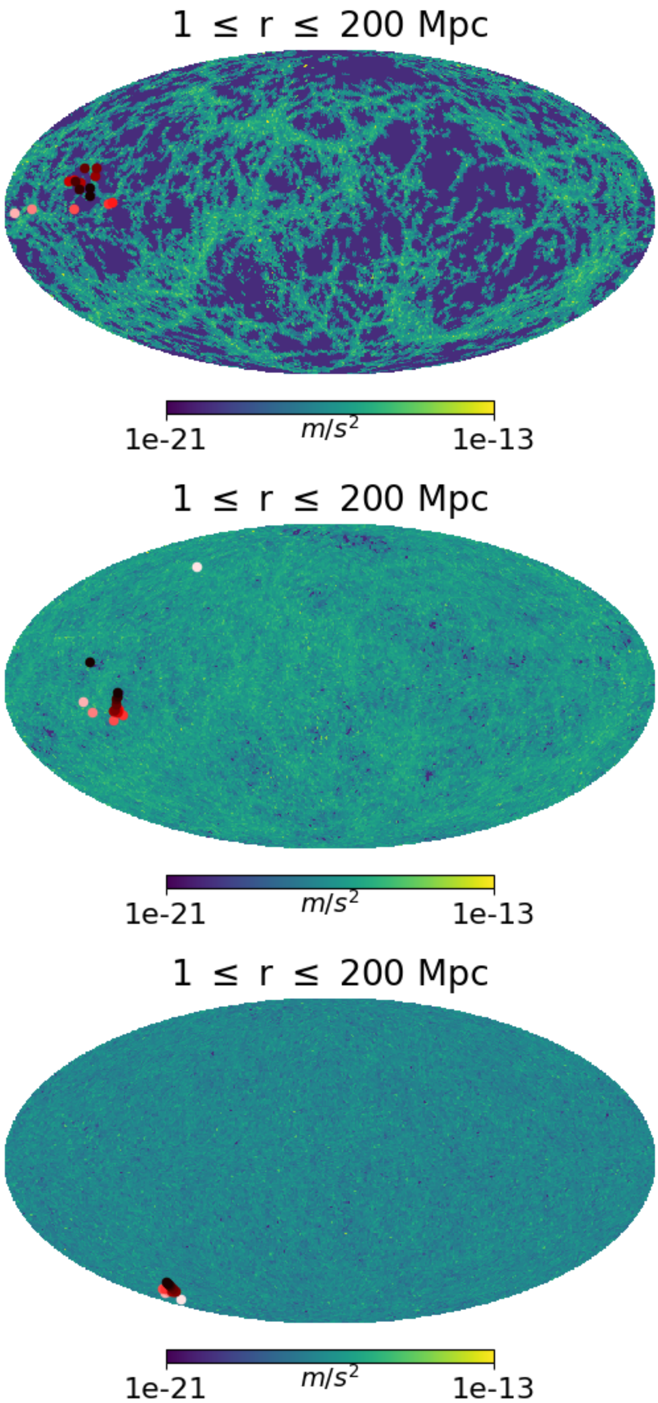

Figure 3.4: *The cumulative acceleration points for the clusters* $\approx 1.09 \cdot 10^{-14} m/s^2$*, filaments* $\approx 3.31 \cdot 10^{-15} m/s^2$*, and voids* $\approx 7.9 \cdot 10^{-16} m/s^2$*. Getting darker indicates considering the larger radius shell and finally reaching the* $200 Mpc$ *from the Milky Way.*

Furthermore, we can generate an all-sky map that encompasses all galaxies, including clusters, filaments, and voids, in order to visualize the distribution of acceleration points. Intuitively, we expect that the clusters should be the main contribution. Initially, this assumption is based on the understanding that clusters are the densest regions among the three cosmic structures. However, upon investigation, it became clear that the primary factor influencing the prominence of clusters is not only their mass but rather their distribution. Also, we find that clusters exhibit a significantly more inhomogeneous distribution compared to filaments and voids (we will see this later as well). The plot is shown in Figure 3.5.

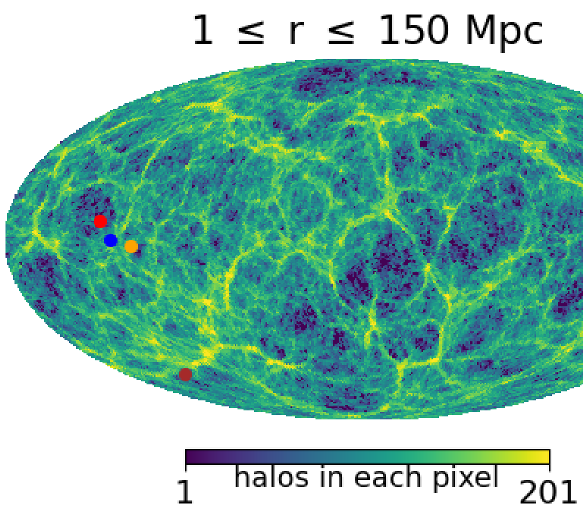

Figure 3.5: *Peculiar acceleration from clusters - red dot, from filaments - orange dot, from voids - brown dot, from all of them - blue dot.*

Figure 3.5 makes sense because it shows main acceleration coming from clusters ad filaments - red and orange dots are very close to blue dot - as was expected.

Now let us make clear, that the total acceleration point is closest to the clusters' and filaments' one not only because of the mass but because of the distribution too. To show this, we will divide the total mass of galaxy halos into three equal pieces and show that these three give different accelerations, although they have the same mass. For this, we follow the next steps:

1. Order the galaxy halos with respect to the density number so, that the density number was increasing;

2. Calculate the total mass of all halos and divide it by three;
3. Start from the beginning of our new galaxy halo array (ordered by density number increasing) and take all galaxy halos until their total mass reaches one-third of the total mass. This will be a contribution from the ”void” regions, as we are taking the lowest-density halos.
4. Then we do the same but start from the end of our ordered array. This will be the contribution from the ”cluster” region, as we are taking the highest-density halos.
5. Remaining part in between will be the contribution from the ”filament” region.

Then we plot the all-sky map for all three pieces and see if acceleration is the same (remembering that all three pieces have the same mass). The plot is shown in Figure 3.6.

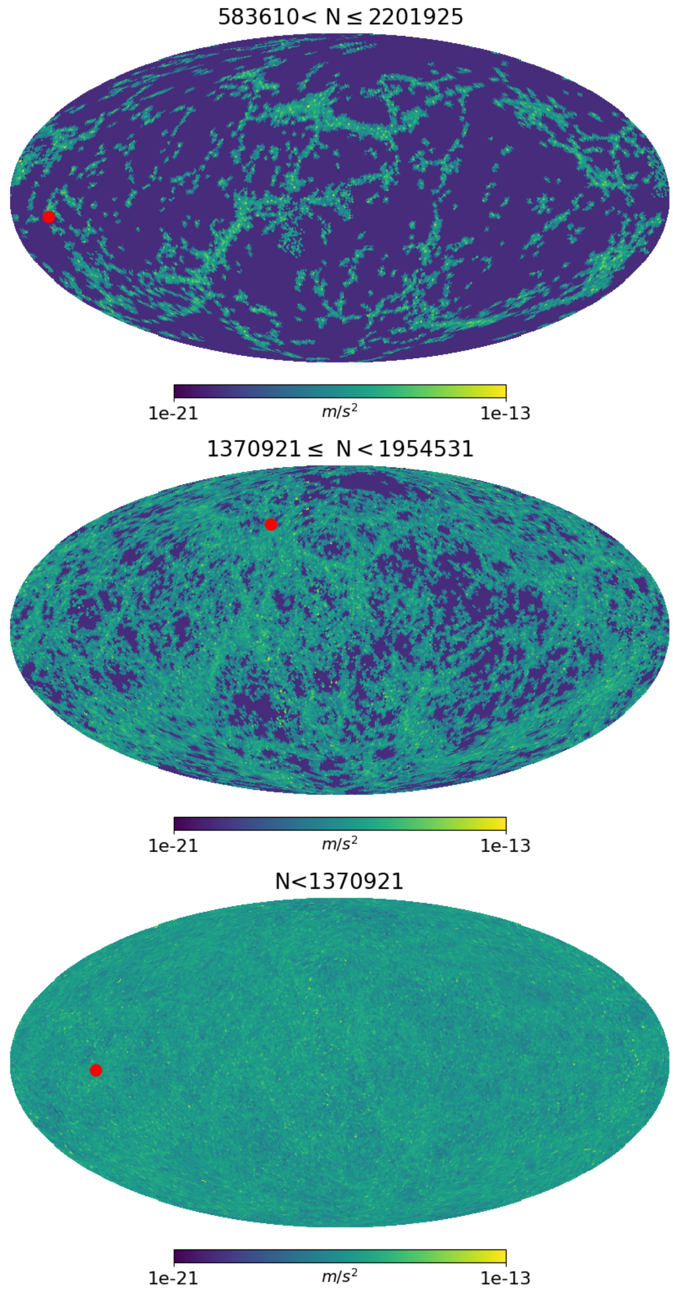

Figure 3.6: *The cumulative acceleration points for the 3 equal mass parts.*

We can see that the accelerations have different directions. The values of total acceleration are:

- for clusters: $\approx 1.14 \cdot 10^{-13} m/s^2$
- for filaments: $\approx 7.72 \cdot 10^{-13} m/s^2$
- for voids: $\approx 1.24 \cdot 10^{-13} m/s^2$.

So we see, that they have approximately the same order but still, they are different. So, we proved our idea, that the fact that cluster contribution is main, is not only due to the mass but due to the distribution.

Also, from Figure 3.5 it is clearly visible that clusters are less homogeneous than filaments, and filaments are less homogeneous than voids.

3.2 Analysis, calculations, and timing

Now let us try to answer the 4 questions stated above in the introduction of Chapter 3. For this, we will project the acceleration on the velocity vector. Then we will get:

$$a_v = a \cdot cos(\alpha). \tag{3.1}$$

Where α is the angle between the peculiar velocity and peculiar acceleration. Then:

$$a_v = a \cdot 0.24 = 2.66 \cdot 10^{-13} m/s^2 \cdot 0.24 = 0.64 \cdot 10^{-13} m/s^2. \tag{3.2}$$

Turn around point. In Fig. 3.1 we saw that the peculiar acceleration of the Milky Way is directed with angle $\alpha = 104.5^\circ$ relative to its velocity, indicating that the galaxy is decelerating. To calculate the time of turnaround point, we use the magnitude of the peculiar velocity of the Milky Way, which is $\approx$ 627 km/s[2]. For the peculiar acceleration, we obtained a magnitude order of $10^{-13} m/s^2$. Using the simple formula and plugging velocity and acceleration, we will get:

$$\begin{aligned}
&\mathbf{v} = \mathbf{v_0} + \mathbf{a}t \\
&\mathbf{0} = \mathbf{v_0} + \mathbf{a}t \\
&0 = v_0 - a_v t \\
&t = \frac{v_0}{a_v} = \frac{627km/s}{0.64 \cdot 10^{-13} m/s^2} \approx 9.95 \cdot 10^{18} s \approx 3.2 \cdot 10^{11} y.
\end{aligned} \tag{3.3}$$

We can also calculate the time using the peculiar velocity from simulations, which is $2.25 * 10^5 m/s$[3]. Then:

$$t_s = \frac{v_s}{a_v} = \frac{225km/s}{0.64 \cdot 10^{-13} m/s^2} \approx 3.5 \cdot 10^{18} s \approx 1.11 \cdot 10^{11} y \tag{3.4}$$

We get that the time that is needed to turn back for both cases (considering peculiar velocity from observation and from simulation) is more than the age of the universe, which is $1.37 * 10^{10} y$ (Here we consider only peculiar motion, not the Hubble flow).

How far will have gone our galaxy by the time of turn around point? Using the simple formula, from observations we get:

$$\begin{aligned}
&\mathbf{x} = \mathbf{v_0}t + \frac{\mathbf{a}t^2}{2} = \\
&6.27 \cdot 10^5 m/s \cdot 9.8 \cdot 10^{18} s - 0.32 \cdot 10^{-13} m/s^2 \cdot (9.8 \cdot 10^{18})^2 s^2 = \\
&= 3.07 \cdot 10^{24} m = 3.07 \cdot 3.24 * 10 \approx 99.5 Mpc.
\end{aligned} \tag{3.5}$$

From simulations we get:

$$\begin{aligned}
&\mathbf{x} = \mathbf{v_0}t + \frac{\mathbf{a}t^2}{2} = \\
&2.25 \cdot 10^5 m/s \cdot 3.5. \cdot 10^{18} s - 0.32 \cdot 10^{-13} m/s^2 \cdot (3.5 \cdot 10^{18})^2 s^2 = \\
&= 4 \cdot 10^{23} m = 4 \cdot 3.24 \approx 12.8 Mpc
\end{aligned} \tag{3.6}$$

Will we ever merge with the Great Attractor? The distance from the Milky Way to the Great Attractor is about $45.3 Mpc$ [4]. From formulas (3.3) and (3.5) we can already say that our galaxy could merge with the Great Attractor, as the distance the Milky Way will have gone until the time of turning point is greater than the distance to the Great Attractor. However, from simulations point of view, it would never happen, because Milky Way would change its direction earlier (from formula (3.6)). For exact timing results, let us calculate the time our galaxy would need to merge with the Great Attractor. We think that the Great Attractor may also be moving away from the Milky Way, indicating it also has a peculiar velocity with respect to CMB. However, for the purpose of our calculations, we choose to focus on the best-case scenario where the only factor influencing the change in distance is our own movement toward the Great Attractor (why this is the best case for our calculation, we will see later). Now, with the same simple formula we used in eq. (3.3), we get the following rom observation: (all quantities in equations which do not have units (in order to be better visible) are written in SI):

$$
\begin{aligned}
45.3Mpc &= 6.27 \cdot 10^5 \cdot t - 0.32 \cdot 10^{-13} t^2 \\
t_1 &\approx 2.56 \cdot 10^{18} s \approx 8.1 \cdot 10^{10} y \\
t_2 &\approx 1.75 \cdot 10^{19} s \approx 5.4 \cdot 10^{11} y
\end{aligned} \tag{3.7}
$$

From simulation:

$$
45.3Mpc = 2.25 \cdot 10^5 \cdot t - 0.32 \cdot 10^{-13} t^2 \tag{3.8}
$$

Here we can compare the merging time with the Great Attractor and the Merging time with the Andromeda Galaxy. We know, that Andromeda is only $0.7Mpc$ away from the Milky Way and the merging time is around $4 \cdot 10^9$ years. The Great Attractor is about 64 times farther, and it is expected that it would take much more time to merge with the Great Attractor.

From simulation we see that determinant is negative, so Milky Way is not going to merge with the great attractor.

From our results, calculated in eq.-s (3.3), (3.4), (3.5), we can see that if we considered peculiar velocity from observation, Milky Way could merge with the Great Attractor, as the turn round point time is greater than the time Galaxy needs to merge with the Great Attractor. It is important to note that our analysis does not take into account the influence of the Hubble flow or the peculiar motion of the Great Attractor. Considering these factors would only further extend the time required to reach the Great Attractor, reinforcing the validity of our chosen "best" case. The next interesting question is: Will our galaxy really merge with the Great Attractor and/or ever change its direction? Will turnaround really happen? The answer to this is quite complicated but in the ΛCDM model in several billion years, that is an order of 10^9 years, dark energy becomes dominant leading to the eventual splitting of the Universe. Upon closer examination, we find that the merging would theoretically occur in $\approx 8.1 \cdot 10^{10}$ years and turnaround even later, but the universe will be split up until that time. Consequently, because of the timing, we can conclude that our galaxy will neither merge with the Great Attractor nor change its direction in a reasonable time.

How significant is acceleration we calculated? We could conclude, that peculiar acceleration is tiny, it is not sufficient for changing the direction of the Milky Way in a reasonable time. We also wanted to compare our acceleration to some theoretical value. As the theoretical value for peculiar acceleration is not estimated yet, we decided to compare it with the Hubble expansion rate value today. The value of Hubble expansion rate today is $H_0 = 70km/s/Mpc = \frac{70 \cdot 10^3}{3.08 \cdot 10^{22}} \frac{m}{s \cdot m} \approx 2.27 \cdot 10^{18} s^{-1}$ that is 5 orders less compared to our peculiar acceleration, which value is $\approx 2.66 \cdot 10^{-13} m/s^2$. So, we could suppose that peculiar motion has more effect on the motion of the Milky Way Galaxy than the Hubble flow.

Chapter 4

Methods & Data Analysis

In this chapter, we will delve into the details of the methods and references we utilized to obtain the desired results and create visually appealing plots. Although some of these methods have already been touched upon while explaining the underlying theory, I have chosen to gather them in separate sections for clarity and completeness.

It is worth noting that this project has been a valuable learning experience for me, as I have honed my programming skills and gained expertise in analyzing vast amounts of data. Consequently, a significant portion of my time was dedicated to mastering the intricacies of data analysis.

4.1 Data Analysis

We use the data from the SIBELIUS-DARK database, the data from McAlpine2022a [3], the exact link is the following:
http://virgodb.dur.ac.uk:8080/MyMillennium/Help?page=databases/mcalpine2022a/database.

The SIBELIUS_DARK is a simulation of the local volume at a distance of 200 Mpc from the Milky Way. The goal of this project lies in embedding a model Local Group-like system within the correct cosmic environment. Simulation is Dark-Matter only, and it also matches well with observational data.

Table 1: Galaxy data

column	type	UCD unit	description
GalaxyID	integer		Unique identifier of a galaxy
HOstHaloID	integer		Unique identifier of a galaxy's halo
redshift	real		Redshift of galaxy (z=v_r/c)
mstars_bulge	real	Msolar	Stellar bulge mass
mstars_disk	real	Msolar	Stellar disk mass
mbh	real		Mass of the central black hole in this galaxy
rank	integer		Rank order of galaxy in host halo (rank=0 is the central galaxy, rank >0 are satellites)
type	integer		Whether this is a central galaxy (0), satellite with resolved subhalo (1), or satellite with no resolved subhalo(2)
mbound	real	Msolar	Total mass bound to the subhalo. We refer to this as the subhalo mass, or Msub
nbound	integer		Number of particles bound to the subhalo
dist	real	Mpc	Distance from Milky Way
v_r	real	km/s	Radial velocity of the galaxy relative to Milky Way. This is the radial component of the galaxy's peculiar velocity plus the Hubble flow
x	real	Mpc	x coordinate of the galaxy's center of potential (equatorial)
y	real	Mpc	y coordinate of the galaxy's center of potential (equatorial)
z	real	Mpc	z coordinate of the galaxy's center of potential (equatorial)
v_x	real	km/s	x coordinate of the galaxy's velocity (CMB rest frame)
v_y	real	km/s	y coordinate of the galaxy's velocity (CMB rest frame)
v_z	real	km/s	z coordinate of the galaxy's velocity (CMB rest frame)
ra	real	degrees	Right Ascension (equatorial)
dec	real	degrees	Declination (equatorial)

We want to get halo coordinates to calculate the acceleration exerted by them on the Milky Way, but we only have galaxy coordinates in the database. For this reason, we use a particular selection criterion to associate these galaxies with their corresponding halos. To accomplish this, we choose the central galaxies of halos, which can be identified by their rank value of 0. By designating the GalaxyID and HostHaloID equal, we establish a connection between the central galaxy and its host halo. In this scenario, we can treat the coordinates of the central galaxy as the coordinates of the halo itself. Also, it is worth noting that this table gives us the data at a specific redshift, namely $z = 0$. Having determined the coordinates of the halos, we calculate the gravitational acceleration each halo exerts on the Milky Way using the mass and coordinates of the halo.

For simulations, we use Python programming language and more exactly, the "Healpy" package and "Mollview projection" to make all-sky plots. In our maps we take everywhere Nside=64, so the total number of pixels on the sphere is:

$$Npix = 12 \cdot Nside^2 = 49152. \tag{4.1}$$

For pixel area, we have:

$$A_{pix} = 4\pi/Npix = 41252.9612 sqdeg/Npix = 0.84 sqdeg. \tag{4.2}$$

4.2 Density array limiting numbers for clusters, filaments, voids

Another technique that is worth mentioning is the idea of creating a density array. We generated a density array for galaxy halos with a 3D grid. Upon observation, we determined the maximal number of galaxy halos within any given cube of the grid was 201. Consequently, the maximal density a galaxy halo could have was 201. However, the question arises: how do we establish the thresholds to classify the halo with a certain density as a cluster? To address this, we decided to construct an array with various cut-off numbers, denoted by $t_c = [20, 25, 30, 35, 40, 45, 50, 60, 70, 80]$. Each element in this array represents a specific density threshold starting from 20 and increasing up to 80. We considered halos exceeding these densities are clusters.

To determine the optimal density threshold for identifying clusters, we performed further analysis. Specifically, we calculated the standard deviation for each density threshold and plotted it as a function of the density number considered as a cluster. This analysis allowed us to examine how the standard deviation varied with different density thresholds. Notably, our findings indicated that at a number density of 25, the standard deviation for filaments reached a nearly constant value. The result is shown in Figure 4.1 below (the same as Figure 3.2):

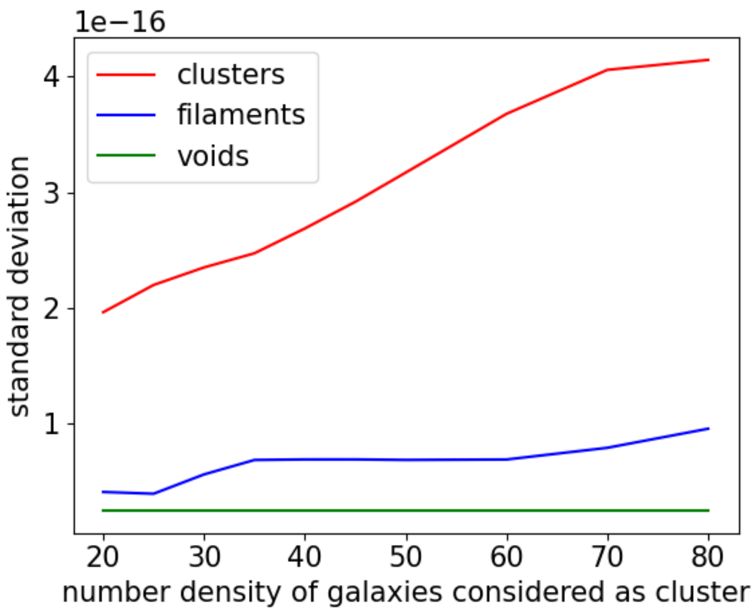

Figure 4.1: *The standard deviation as a function of the number density of galaxies is considered as a cluster.*

Therefore, appropriate limits would be 25, and 5 which means halos with a density number more than 25 would be considered as a cluster, and halos with a density number less than or equal to 5 would be voids, and everything between - filaments. The check for the density function is given in Appendix A.

Chapter 5

Results and Conclusion

In our research project, we looked at dark matter halos within a 200 Mpc radius of the Milky Way and investigated their impact on the motion of the Milky. Through our analysis, we found that the peculiar acceleration of the Milky Way with respect to CMB is on the order of $10^{-13} m/s^2$. This value is 5 orders of magnitude greater than the Hubble expansion rate today. Moreover, the peculiar acceleration is directed with angle 104.5° to the peculiar velocity of the Milky Way, indicating that our galaxy is decelerating on its way toward the Great Attractor. The plot for the peculiar velocity and peculiar acceleration is shown in Fig. 5.1.

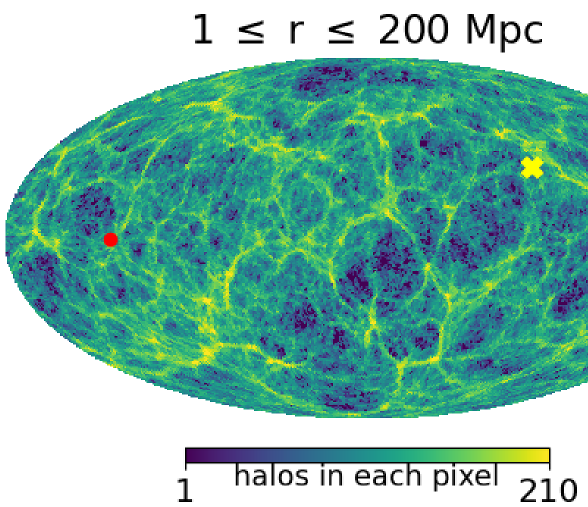

Figure 5.1: *The peculiar velocity vs peculiar acceleration. The red dot is acceleration, the yellow "X" is for velocity from observations, and the blue "X" is the velocity from simulations.*

Based on our calculations and observed value of peculiar velocity, the peculiar acceleration of the Milky Way would cause it to change direction in $\approx 3.1 \cdot 10^{11}$ years. However, the estimated time required for the Milky Way to merge with the Great Attractor is $\approx 8.1 \cdot 10^{10}$. This implies, that our galaxy could theoretically reach the Great Attractor. If we consider peculiar velocities from simulations we have another picture. this case change of the direction happens in $\approx 1.11 \cdot 10^{11} y$ and the distance covered by the Milky Way by that time is less than the dstance between MW and GA, what means our galaxy is not going to merge with the Grate Attractor.

However, considering the ΛCDM model, an interesting insight arises. The dark energy component in this model causes the universe to expand at an accelerated rate. This expansion will lead to the splitting of the universe on the order of 10^9 years. Consequently, even if peculiar acceleration could potentially change the direction of motion of the Milky Way, the splitting by the dark energy would occur earlier, preventing the change in direction.

So, we can conclude, that with the peculiar acceleration we found, our galaxy is neither going to merge with the Great Attractor, nor to change the direction of motion as the dark energy will split up the universe earlier.

With an acceleration we calculated that is $\approx 2.66 \cdot 10^{-13} m/s^2$, it is pretty difficult to get the peculiar velocity the Milky Way is observed to have today. That might be prompting about some wrong assumptions about the ΛCDM model.

During our research project, we also created an interesting all-sky structure map for halo distribution, which is shown in Fig. 5.2. We also analyzed the parts taken from clusters filaments and voids in total acceleration and concluded that the approximation that we consider the dark matter only from dark matter halos is valid.

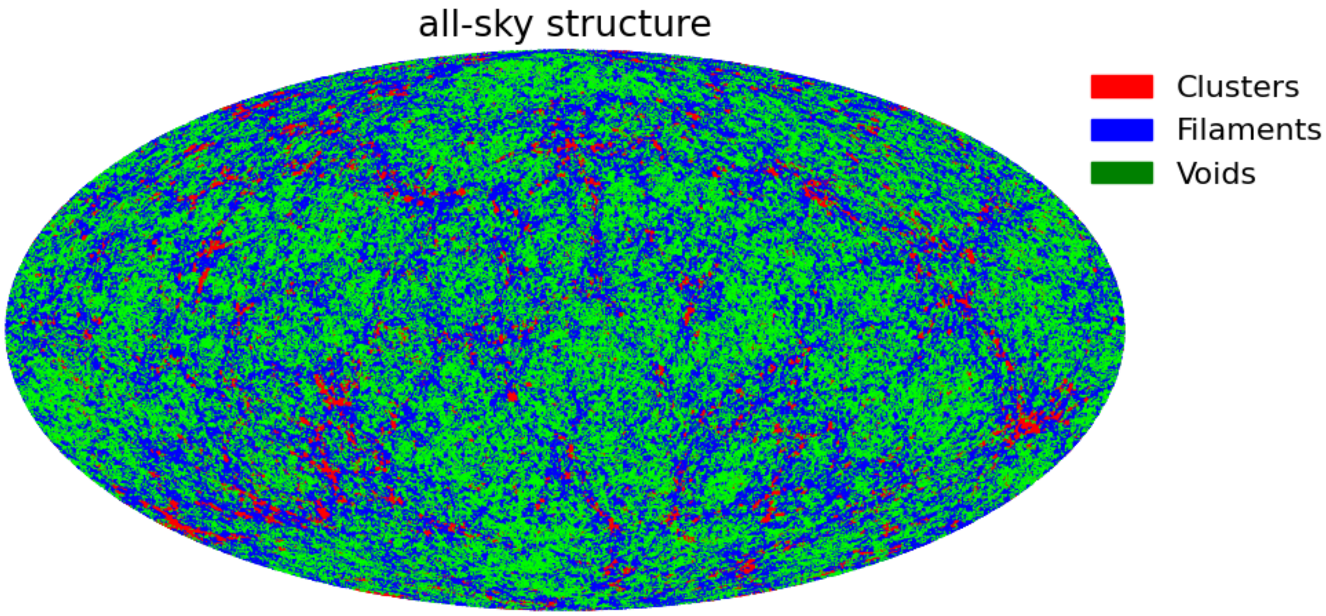

Figure 5.2: *The all-sky structure of dark matter halo distribution.*

Chapter 6

A chapter of gratitude

I would like to take this opportunity to express my heartfelt gratitude to Leiden University for granting me the invaluable chance to pursue my master's degree here. Without the generous scholarships provided by the Lorentz Fonds and Leiden Excellence Scholarship (LExS), I would never have been able to afford studying at such a prestigious institution. It is with immense appreciation that I extend my thanks to everyone who played a part in making this honorable opportunity possible!

Appendix A

Check for the density array

We mentioned that we generated a density array for galaxy halos with a 3D grid. Then we wanted to check if our function was working correctly. For this we fixed the third dimension in the grid and first plotted only the grid, which was colored by the histogramming of the galaxy halo points, then we plotted the dots for each galaxy and colored it depending on density value. If our calculation was right, these 2 plots should have coincided. We provide this in Figure A.1:

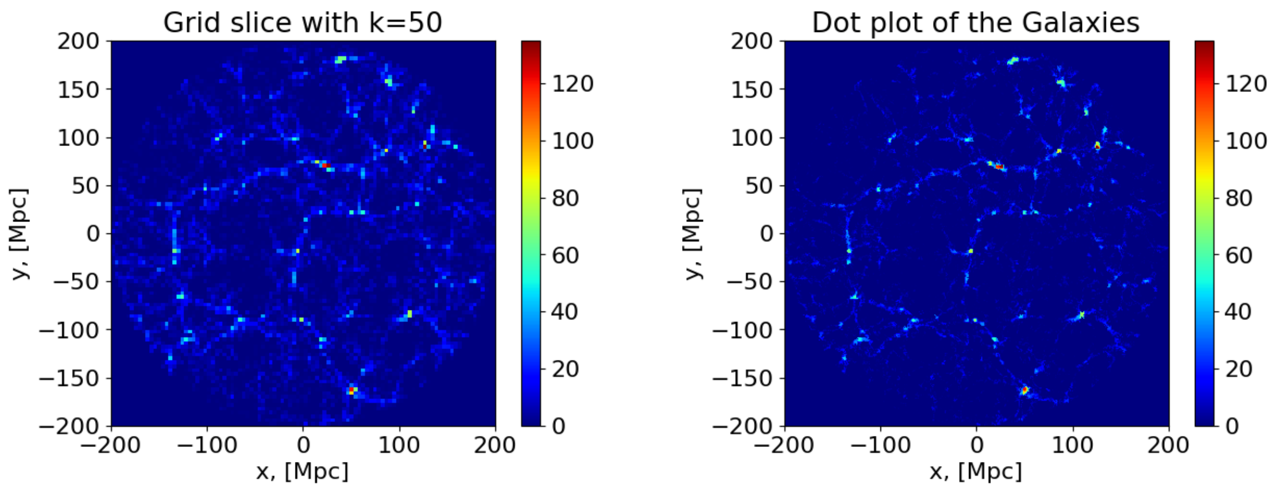

Figure A.1: *The comparison of 2D grid slice to the galaxy dot plot.*

We can see that the plots coincide. So, our density array works well.

Here is the code for finding the density array. First, we create the function, which forgiven coordinates can find the indices of these coordinates in our 3D histogram.

Indexfinder function 3D

```
def indexfinder(edges, x, y, z, M):
    s=0
    p=0
    q=0
    for i in range(M):
        if x<0:
            if x>=edges[0][i] and x<edges[0][i
               +1]:
                s=i
        elif x<edges[0][i+1] and x>=edges[0][i]:
            s=i
        if i==M-1:
            if x<=edges[0][i+1] and x>=edges[0][i
               ]:
                s=i
    for i in range(M):
        if y<0:
            if y>=edges[1][i] and y<edges[1][i
               +1]:
                p=i
        elif y<edges[1][i+1] and y>=edges[1][i]:
            p=i
    for i in range(M):
        if z<0:
            if z>=edges[2][i] and z<edges[2][i
               +1]:
                q=i
        elif z<edges[2][i+1] and z>=edges[2][i]:
            q=i
        if i==M-1:
            if z<=edges[2][i+1] and z>=edges[2][i
               ]:
                q=i
        return s, p, q
```

Then, we are using the number of halos in each cubic sell as the number density of halos, which are constrained in this cubic sell. So, we create the density number array, our galaxy (halo) array.

Density Array Creation

```
b=np.zeros(s3)
s=0
for i in range(s3):
    a=indexfinder(edges, dist[i][0], dist[i][1], dist[i][2], M
       )
    b[i]=hist[a[0], a[1], a[2]]
    if hist[a[0], a[1], a[2]]==0:
        s+=1
print(s)
```

Received array b is the density number for galaxy halo array we are using.

References

[1] H. Mo, F. Van den Bosch, and S. White, *Galaxy formation and evolution*. Cambridge University Press, 2010. [Online]. Available: https://doi.org/10.1017/CBO9780511807244

[2] C. H. Lineweaver, "The cmb dipole: The most recent measurement and some history," in *Proceedings of the XVIth Moriond Astrophysics Meeting, Gif-sur-Yvette publishers*, 1997, pp. 69–75. [Online]. Available: https://doi.org/10.48550/arXiv.astro-ph/9609034

[3] S. McAlpine, J. C. Helly, M. Schaller, T. Sawala, G. Lavaux, J. Jasche, C. S. Frenk, A. Jenkins, J. R. Lucey, and P. H. Johansson, "Sibelius-dark: a galaxy catalogue of the local volume from a constrained realization simulation," *Monthly Notices of the Royal Astronomical Society*, vol. 512, no. 4, pp. 5823–5847, 2022. [Online]. Available: https://doi.org/10.1093/mnras/stac295

[4] S. Mieske, M. Hilker, and L. Infante, "The distance to hydra and centaurus from surface brightness fluctuations: Consequences for the great attractor model," *Astronomy & Astrophysics*, vol. 438, no. 1, pp. 103–119, 2005. [Online]. Available: https://doi.org/10.1051/0004-6361%3A20041583