# Vertical accelerations in cosmological simulations of Milky Way sized galaxies

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Cosmological simulations with high resolution are recently used to study the dynamics of the Milky Way. In our previous work we have analyzed the simulation GARROTXA and have found phase spirals in the $Z$- $V_Z$ plane. Such features are an indication of vertical perturbation of the galactic disk. To discern the cause of these phenomena and having such a complex disk with several satellites orbiting the system, we study how transient and non-axisymmetric structures in and around the main galactic system affect and perturb the disk. We calculate the accelerations that each of these components - both separately and as a whole- produce on the galactic plane. We find that satellites do not dominate the acceleration field, but the stars at radii from 10-15 kpc and gas in from 10-15 kpc. At recent times, the overall accelerations reaches its maximum as the combination of all components, shortly after several pericenters from the satellites of the system. We suggest that even though the satellites do not dominate the acceleration over the galactic plane, they produce perturbations in both the dark matter halo and the infalling gas that may have an impact on the galactic disk.

## Introduction

Galactic disks may present different signs of perturbations in the **vertical plane**: Warp, corrugations, north-south asymmetries in density and velocity, flares (*Widrow et al. 2012; Schönrich & Dehnen 2018; Nandakumar et al. 2022*), and more recently (in the case of the Milky Way), phase spirals (*Antoja et al. 2018; Bland-Hawthorn et al. 2019*). N-body simulations modeling have proposed several answers to understand this behaviour such as **interactions with satellites**, dark matter **wake** or **sub-halos**, **gas**, or **missalignment** of the plane of stars at different radii (*Laporte et al. 2018, Bennett & Bovy 2021*). However, none of these studies have the completeness or self-consistency of a cosmological simulation.

In this work we use one of GARROTXA simulation's Milky Way model and analyse the vertical behaviour of its galactic disk, motivated by the discovery of its phase spirals in the younger population *(García-Conde et al 2022*). We calculate the **acceleration applied onto its plane** (*z = 0*) by the different components of the simulation: dark matter, satellites, gas and stars and apply a Fourier decomposition to better visualize and quantify both disk vertical distribution ($Z$ and $V_Z$) and said accelerations ($a_Z$).

The disk in our model remains almost **permanently disturbed** by the many following interactions with the satellites, being the ones studied the three of higher mass (Arania, Grillo and Mosquito), between $10^8$ $M_{\odot}$ and $10^7$ $M_{\odot}$.

## Vertical behaviour of the disk

We divide the galactic disk in rings and apply a Fourier decomposition. The vertical behavior of the disk can be characterized with the **amplitude of mode 1** of the Fourier decomposition weighted by Z and $V_Z$.

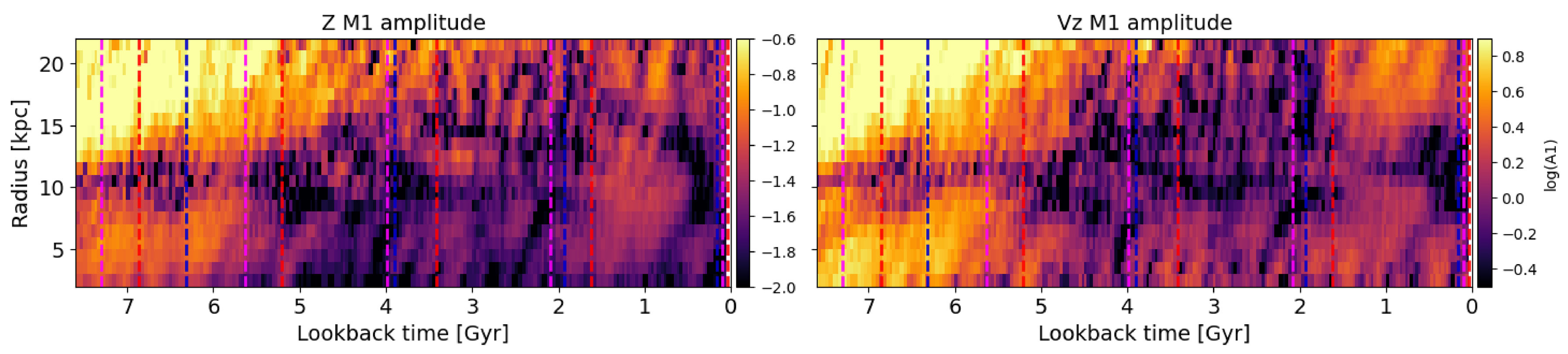


Figure 1. Fourier M1 amplitude of Z, $V_Z$ of the galactic disk from 7.5 Gyr to the present. The colored vertical lines mark the moment of the pericenters of the three main satellites, the blue corresponding to the most massive one.

The disk is highly perturbed at the time of the first pericenter of the most massive satellite (6.3 Gyr). We also see vertical excitation between 2 and 0 Gyr, and a mild increase between 4 and 3 Gyr.

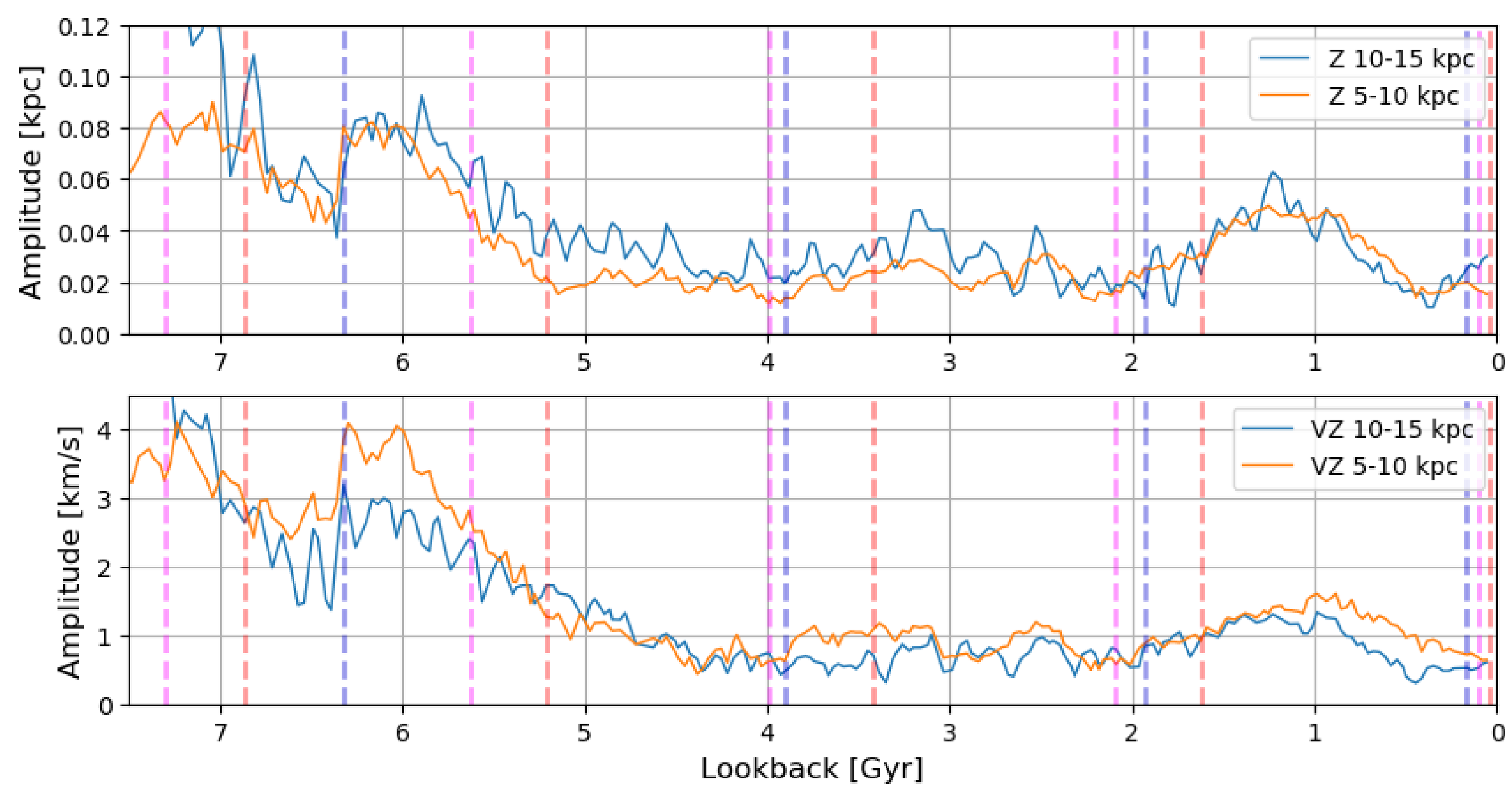


Figure 2. Average Fourier *m=1* amplitude of $Z$ (top), $V_Z$ (bottom) of the galactic disk from 7.5 Gyr to the present in radii intervals from 5-10 kpc and 10-15 kpc.

## Vertical accelerations

We analyze the vertical accelerations by the different components of the simulations by defining an imaginary mesh grid in the plane *z = 0*.

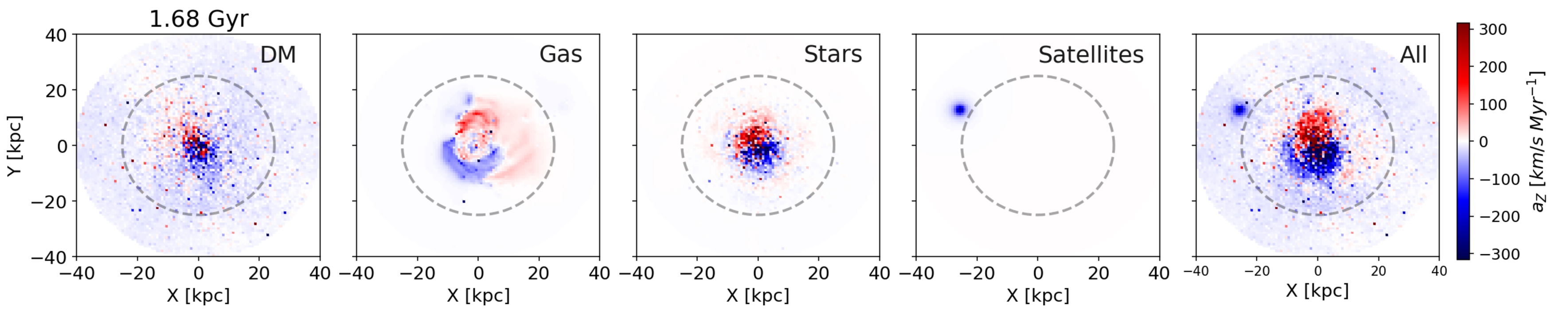


Figure 3. Example of vertical accelerations of the dark matter, gas, stars and satellites onto the plane z=0. The last panel shows the overall acceleration. The black line marks the radius of 25 kpc.

We apply Fourier decomposition and average the amplitude of *m=1* from radius of 5 to 10 kpc and 10 to 15 kpc. We see **sudden reactions** at 6.3 Gyr whereas the peaks at 1.3 Gyr are **more gradual**, which correlate with the curves in Fig.2.

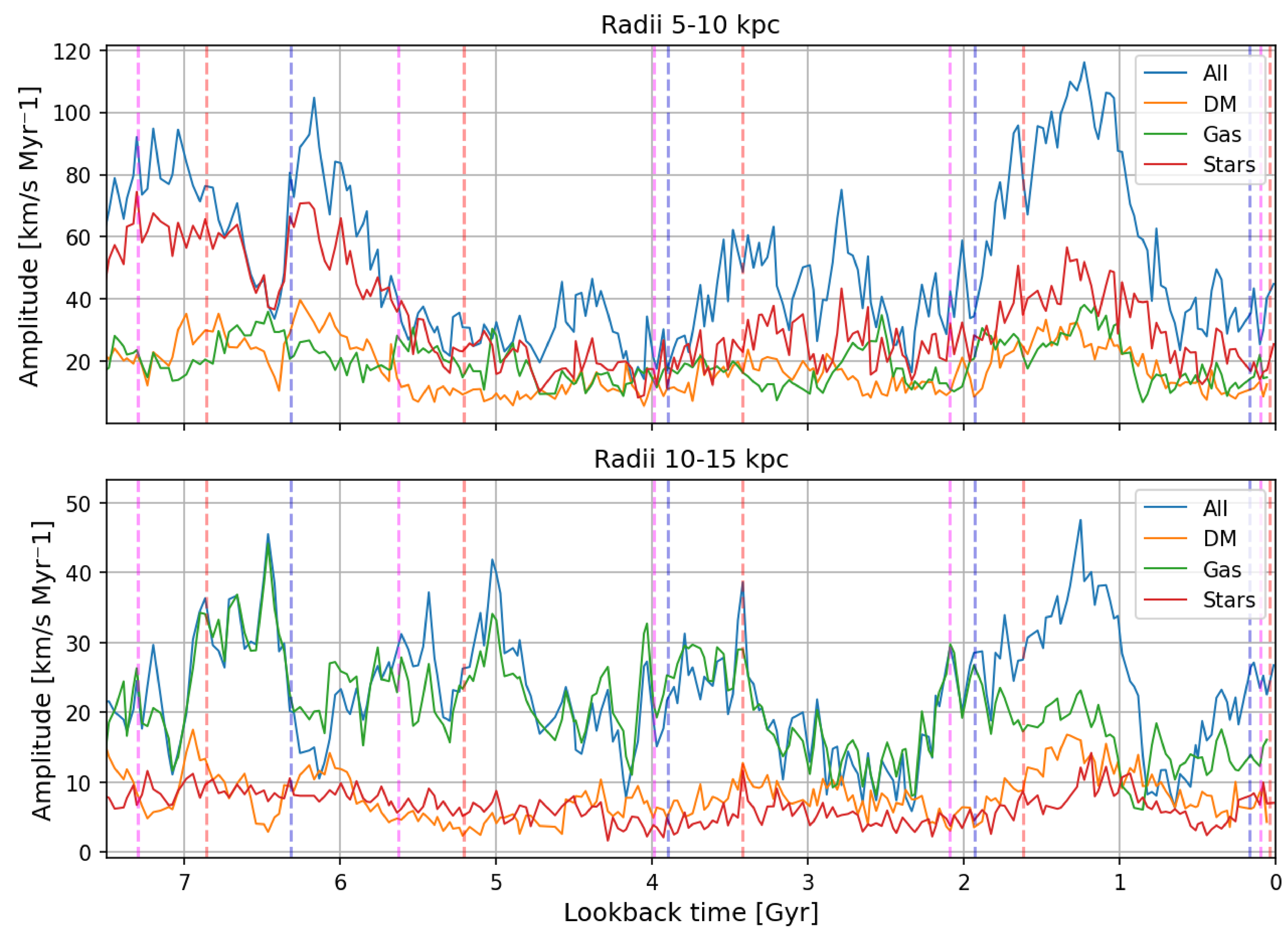


Figure 4. Average *m=1* accelerations between 5-10 kpc (top) and 10-15 kpc (bottom).

We observe that at radii from 5 to 10 kpc the acceleration of the stars dominates in the overall vertical acceleration, whereas through most time up until 2 Gyr, the gas dominates between 10-15 kpc. The sum of the accelerations reaches a maximum at 1.3 Gyr.

## Conclusions

- The **satellites** in this model belong to a **low mass regime**, adding up to $10^9$ $M_{\odot}$ by the time of the 2 Gyr pericenters. The acceleration exerted by the satellites onto the studied parts of the disk are minimal in comparison to the dark matter halo, gas and stars. However, the satellites may have an impact on these components which can be reflected on their vertical structure.
- There are **differences between "peaks" in acceleration**. While at 6.3 Gyr the interaction with Arania is more impulsive and generates a sudden reaction on the disk, at 2 Gyr the reaction is slower and "builds up" over time.
- Between 2 and 1 Gyr the total acceleration is a **combination between all components**, which contribute to a m=1 acceleration higher than the first impact of Arania.
- A strong mode one in all components can be attributed to a **tilting** of angular momentum in different directions as a reaction to perturbations.
- It is still no clear the relation with phase spirals (*García-Conde et al 2022*).

## Future work

- The quantification of the **dominant cause** of acceleration would clarify the causes producing the vertical perturbations at each moment in time and relation to satellites' pericenters.
- Our future aim is to **quantify the correlation** between the vertical accelerations (causes) with the peaks in $Z$ and $V_Z$ (effects).
- In addition to this, we want to establish the direct relation to the apparition of the **phase spiral**.
- We will have a better characterization of the satellites and sub-halos with **halo finder algorithms** such as rockstar. We can track the orbits of dark satellites and see their possible interaction with the galactic disk.

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