Phase spirals in cosmological simulations

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Abstract: The Gaia DR2 has revealed several substructures in the phase space of the Milky Way's disk. These substructures, such as the phase spirals in the $Z - V_z$ plane, are been studied to determine whether they are caused by external or internal perturbations. Our goal is to analyze the origin of these phase spirals and their relation to perturbative phenomena in simulations to better understand the history and evolution of the Milky Way. In this work we use the cosmological simulation GARROTXA, which combines the N-body algorithms with hydrodynamical techniques to link the phase spirals to different perturbative processes such as pericenters of satellites. We find that phase spirals can be seen in cosmological simulations and are present in the main system through time.

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Introduction

Substructures in the pase space of the Milky Way:

One of the goals of modern astrophysics is to determine the processes which have given shape to the disk of the Milky Way. To study these phenomena is to understand the history of formation and evolution of our galaxy. Gaia Data Release 2 (2018) has shown that the Milky Way's disk is actually perturbed. Since this release, new stellar streams have been found (Malhan et al., 2018, Price-Whelan and Bonaca, 2018) and new velocity substructures have been discovered (Antoja et al. 2018, Ramos et al., 2018).

Phase spirals: They are present in the $Z - V_z$ plane and represent the vertical component of the process of phase mixing ocurring in the perturbed disk. They can be produced by external perturbation (such as satellites' pericenter: Purcell et al 2011 and Minchev et al 2009) and internal perturbations (bending waves casued by buckling instability of the bar).

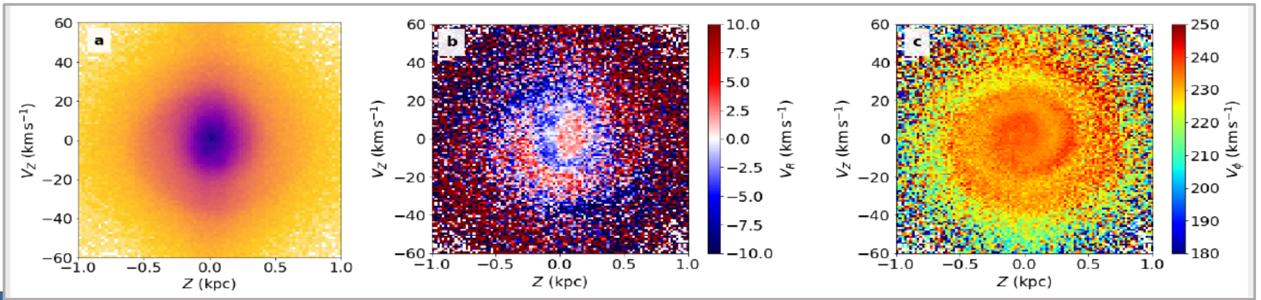


Figure 1: Phase spirals present in Gaia DR2 (Antoja et al 2018).

Like the phase spirals the diagonal **ridges** in the $R - V_\varphi$ can be induced by external perturbers (such as satellites) and internal perturbers and they can be a consequence of the phase mixing in the horizontal direction. The bar and the arms of the galaxy can produce these diagonal ridges due to the resonant orbital structures, creating stable and unstable orbits for the stars, which appear in the $R - V_\varphi$ as overdensities and underdensities.

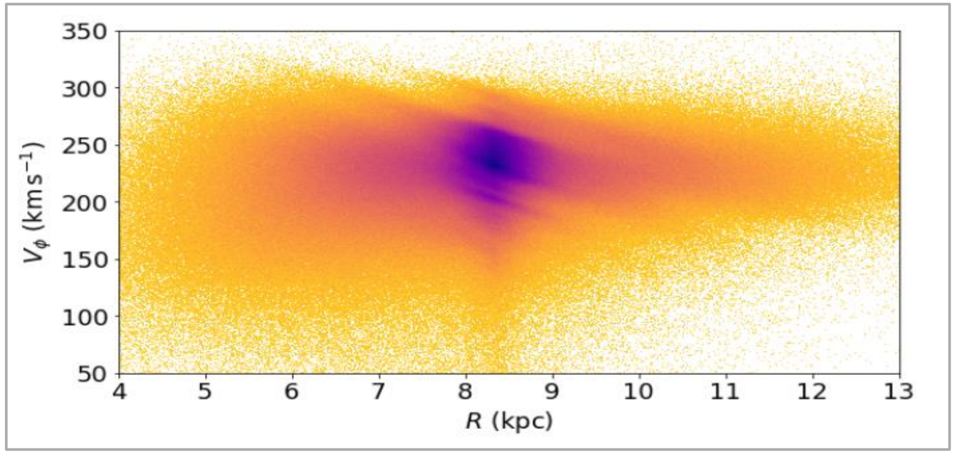


Figure 2: Diagonal ridges present in Gaia DR2 (Antoja et al 2018).

Methodology

GARROTXA Simulation:

- We analyse kinematic substructures in the GARROTXA simulation GAlaxy high Resolution Runs in a cOsmological conTeXt using ART (Roca-Fabrega et al. 2016) to compare to those of the Gaia DR2.
- For the analysis of the simulation, we will use Python's library yt (Turk et al. 2011). It is a tool that allows the analysis of numeric simulations with an extended variety of codes. Currently using yt-3 and soon will move to yt-4.

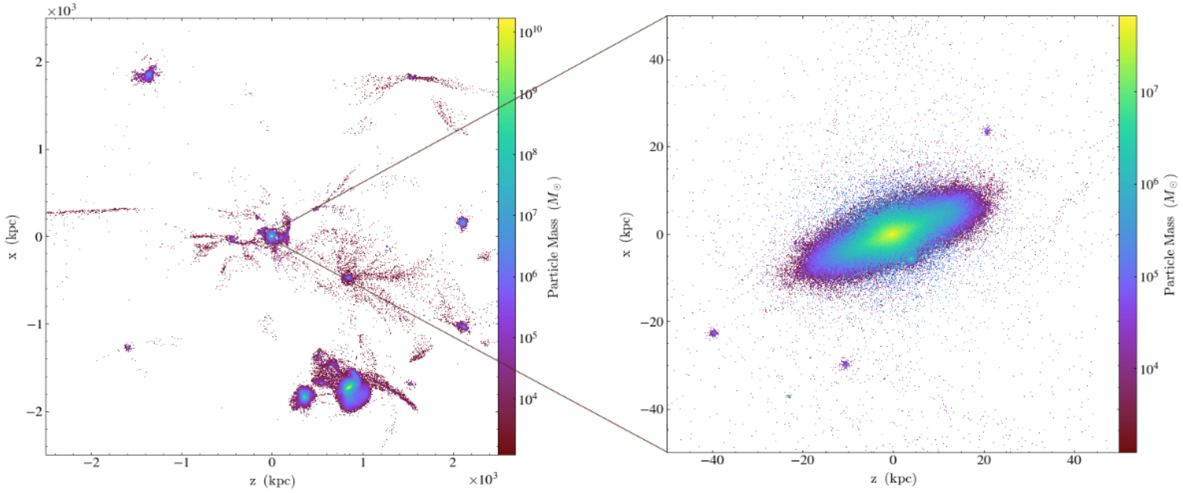


Figure 3: Model G.323 in GARROTXA.

- Spatial resolution of 108 pc.
- Resolution in mass of $6.3\ 10^3$ $M_\odot$ for star particles and $9.8\ 10^4$ $M_\odot$ for dark matter particles.
- Time resolution of 10^3 years.

Main analysis

- Identification of satellites and distance to the main system.
- Star formation history.
- Disk maps colored by <V_R> , <V_Z>, <V_ϕ> .
- Selection of a region.
- Phase spirals in said region.

Results

- Reconstruction of its **star formation history**. We detect several peaks in the SFH.

- We analyse then those **satellites** with stellar mass $> 10^{6.5}\ M_{\odot}$. We calculate their **distance** to the main galaxy.

- It is important to locate the **passage of nearby satellites** and their effects to estimate the moment where the phase mixing process may start, since these satellites can be the external perturbators.

- In the future we will use halo finder techniques (Rockstar, HOP) as this is a first approximation to the satellites' characteristics; satellites location presented here have been obatained by visual inspection.

- We select several snapshots at different lookback times to see if the phase spirals are present.

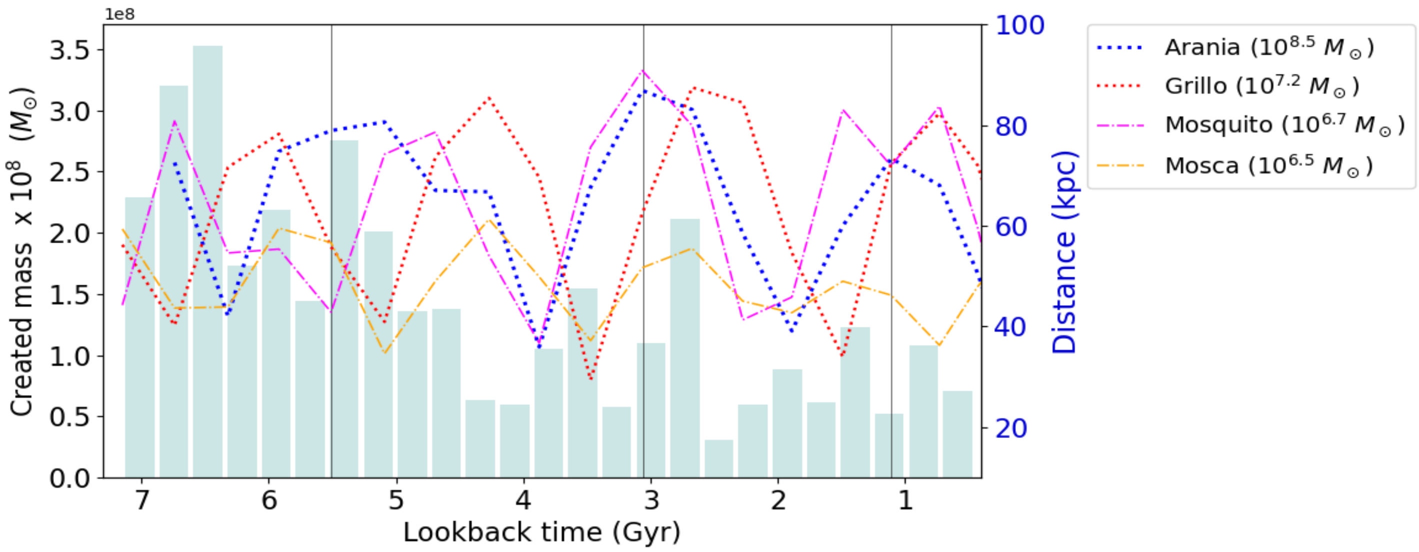


Figure 4: Star formation history in comparison to the distance of the satellites to the main system in GARROTXA. The black vertical lines correspond to the snapshots we are going to analyse.

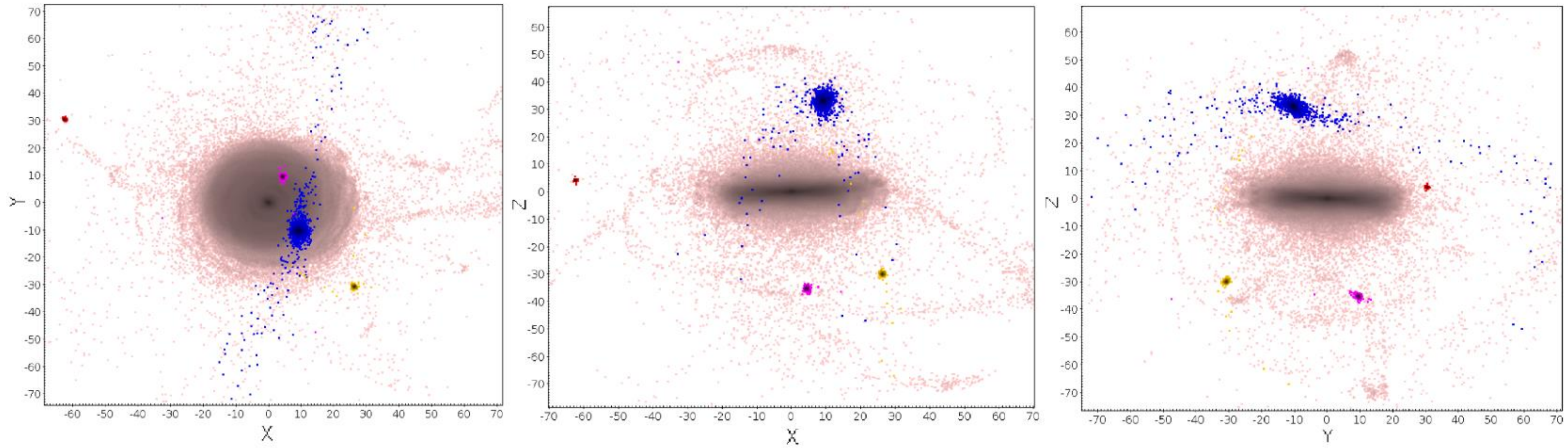
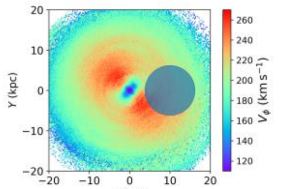


Figure 5: Position of the satellites at 3.88 Gyr. The color codes for the satellites are the same as in Figure 4.

Results

Can we see the effects of the perturbations in the disk?

Selection of a region of the disk at different times



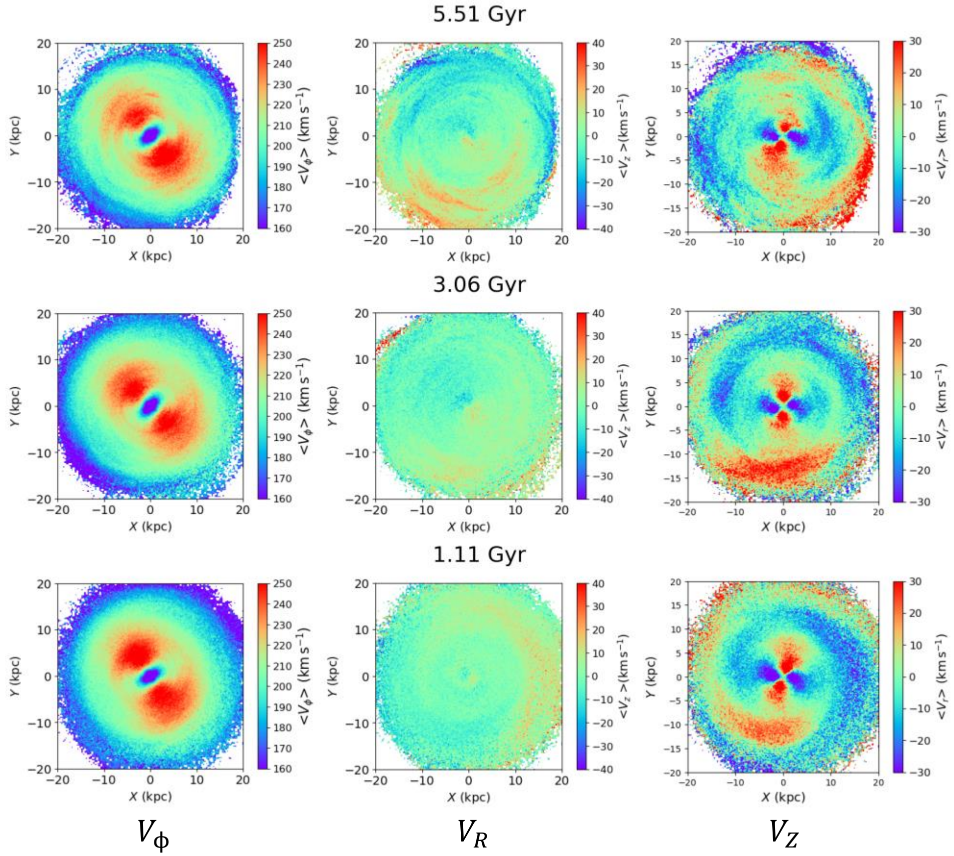


Figure 6: Main galaxy's disk in GARROTXA at different lookback times colour by V_ϕ(left panels), V_Z (central panels) and V_R (right panels).

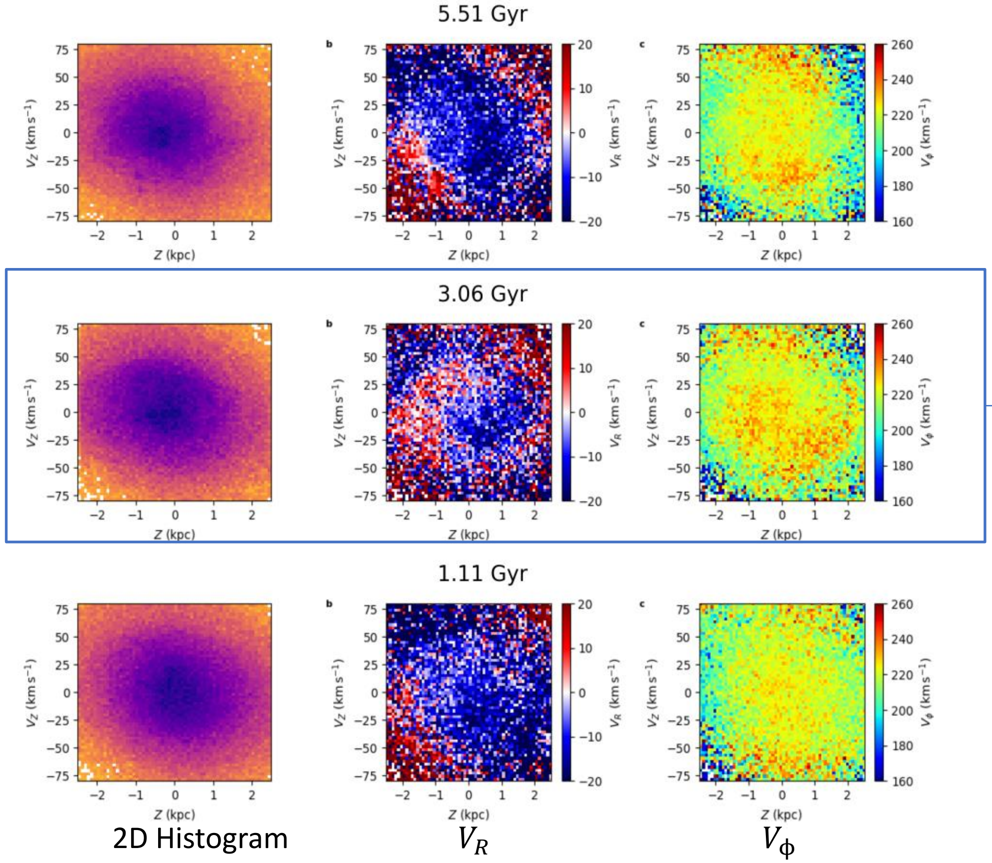
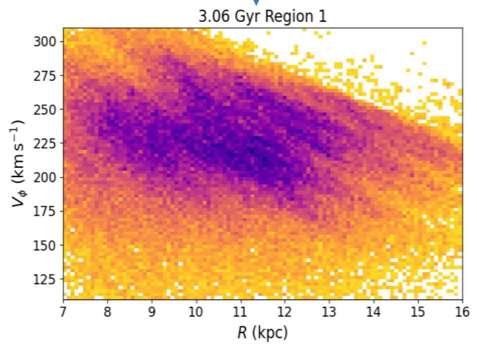


Figure 7: Selected regions for the disks shown in the previous figure in the plane Z-Vz. These phase spirals are a 2D histogram (left panels), coloured by Vr (central panels) and Vphi (right panels).

The phase spirals are especially prominent on the center panels where they are coloured by Vr.

These spirals are visible in other azimuts of the disk at the same galactocentric radius.



Conclusions and future work

Conclusions

- Presence of phase spirals in a **cosmological simulation** (N-body + hydrodynamics).
- These spirals can be seen through time, but **fade at more recent times**. Possibly due to the aging of stars, they become kinematicly hot and thus less prone to suffer the effects of perturbations.
- The phase spirals are also visible in different regions of the disk.
- Still not clear if the nature of these pase spirals is directly linked to satellites' pericenter.

Future work

- Start a detailed analysis of the nature of the phase space spirals and their **connection with external and internal perturbations.**
- Select different samples of stars by age and study the stelalr age dependence of the phase spiral.
- Are the diagonal ridges related with the observed phase spirals? Does a selection of stars that belong to the same ridge have a spiral pattern in the Z-V_Z plane?
- Undertake a similar study as the one presented here but using independent simulations obtained using different codes and physical prescriptions.
- Generate a new set of N-body simulations with unpreceded resolution (5 x 10^7 particles in the disk) and study the dependence of our results on the numerical resolution.