Jornadas de Doctorandos 2020-21 Sesión de Primavera

Phase spirals in cosmological simulations of Milky Way sized galaxies

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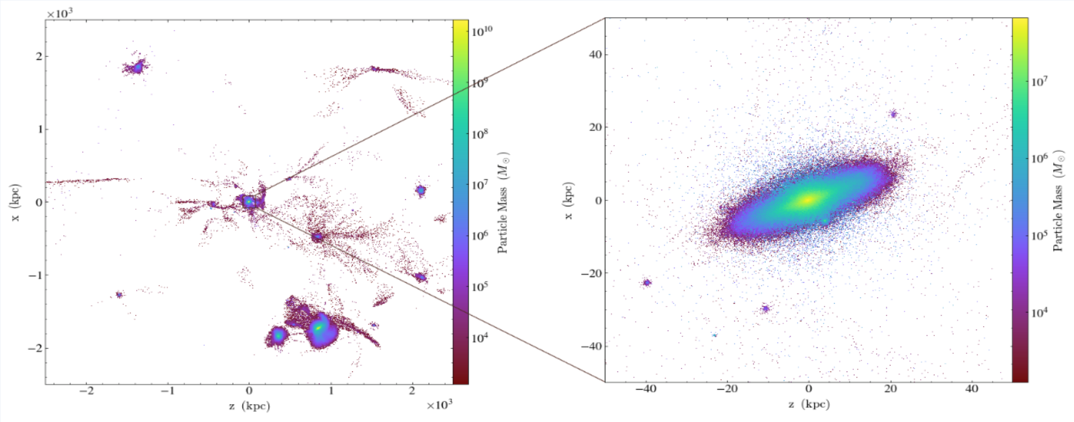

Introduction

- Which processes have given shape to the Milky Way?

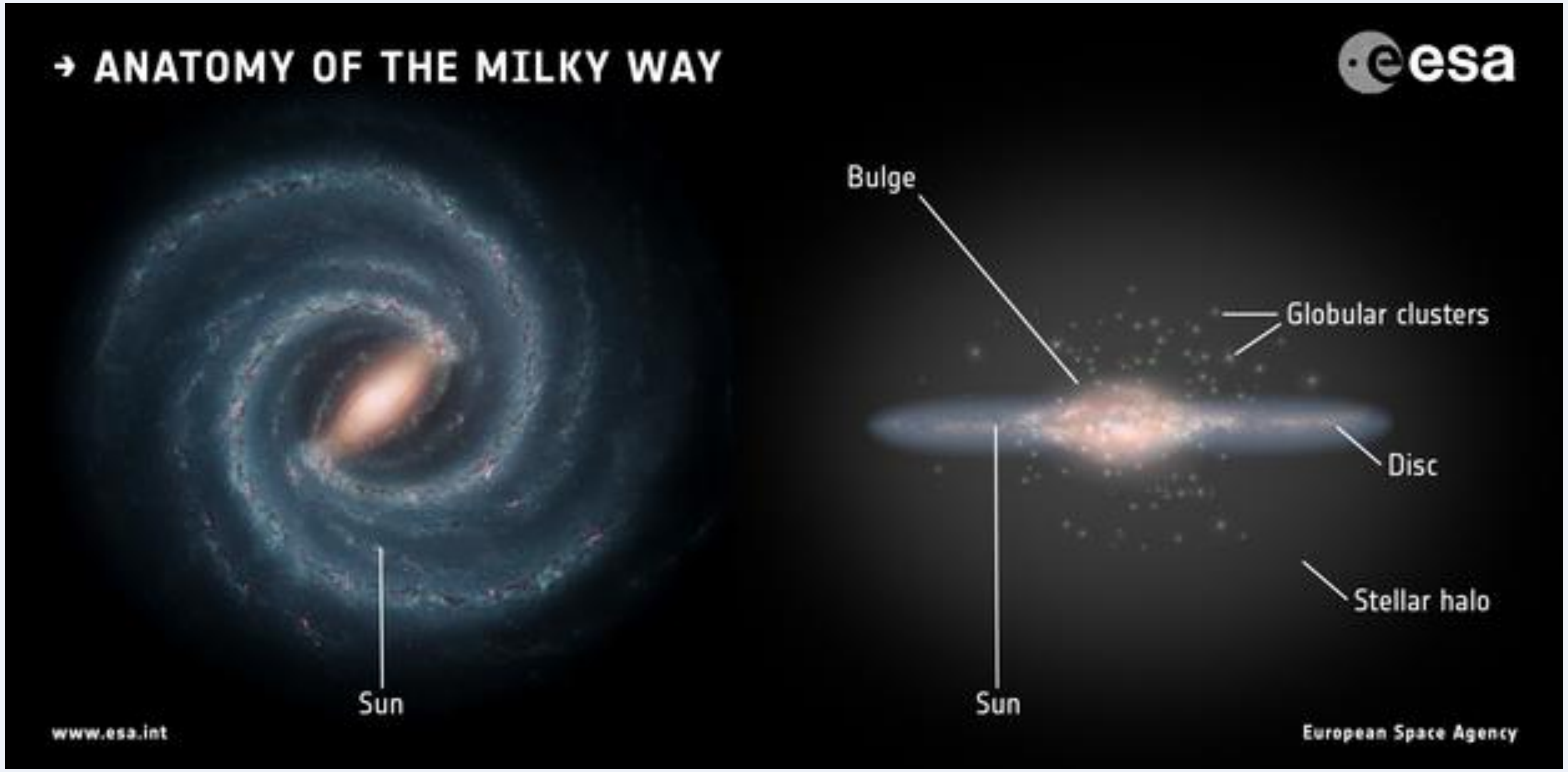

Figure 1: Schematic representation of the Milky Way (ESA)

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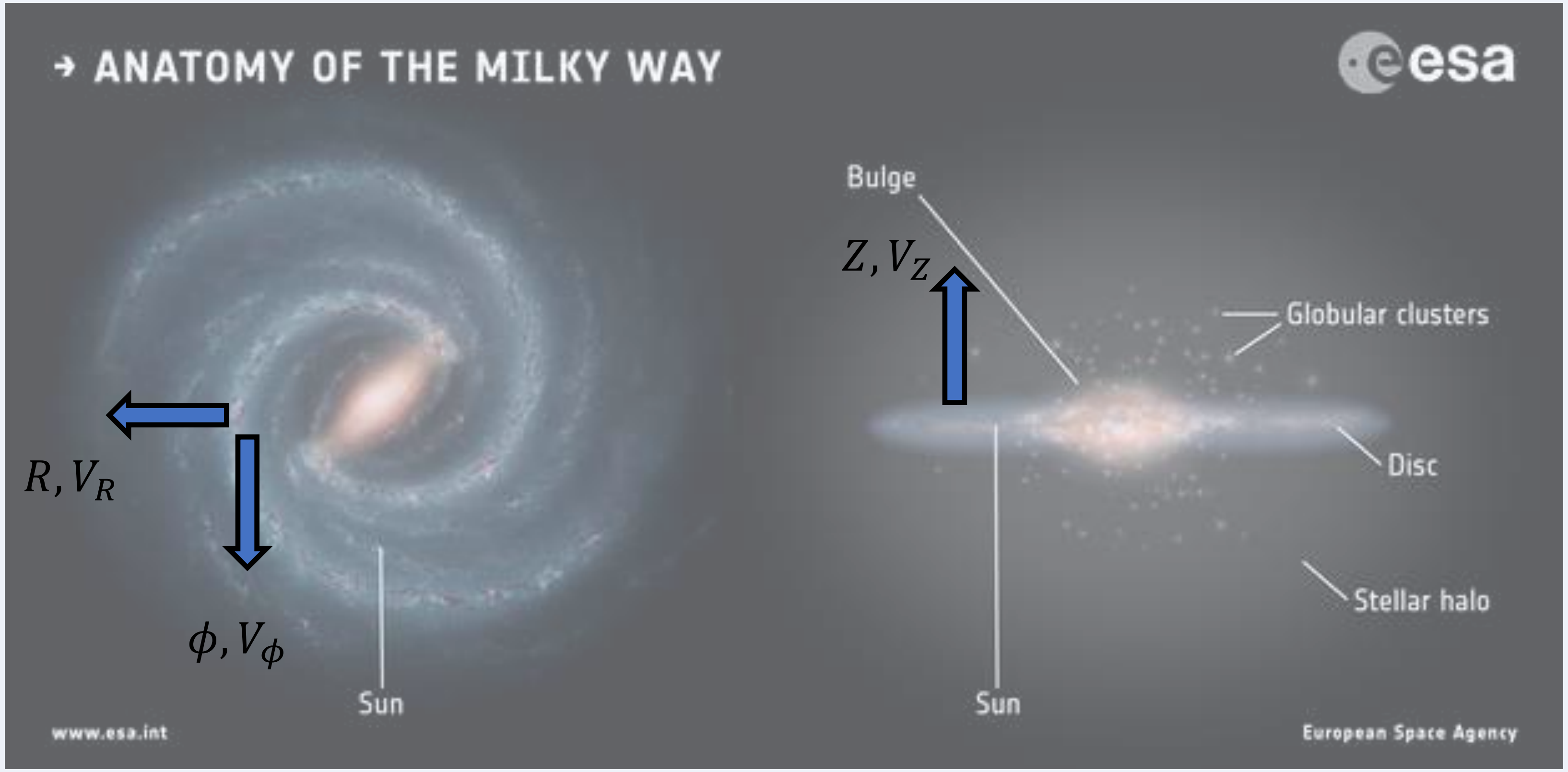

Figure 1: Schematic representation of the Milky Way (ESA)

- **Gaia Data Release 2** (2018): the Milky Way's disk is actually perturbed.
- New velocity substructures: (Antoja et al. 2018, Ramos et al., 2018), phase spirals in the Z - V_z plane, rigdes in R- V_ϕ and arches in the V_ϕ - V_R velocity plane.

Phase spirals:
They are present in the Z - V_z plane of a local region of the galactic disk and are the consequence of a **phase mixing process** triggered by external or internal perturbation which cause vertical and radial oscillations.

Spiral shape that winds up through time: Also can be seen when coloured by $V_\phi$and V_R .

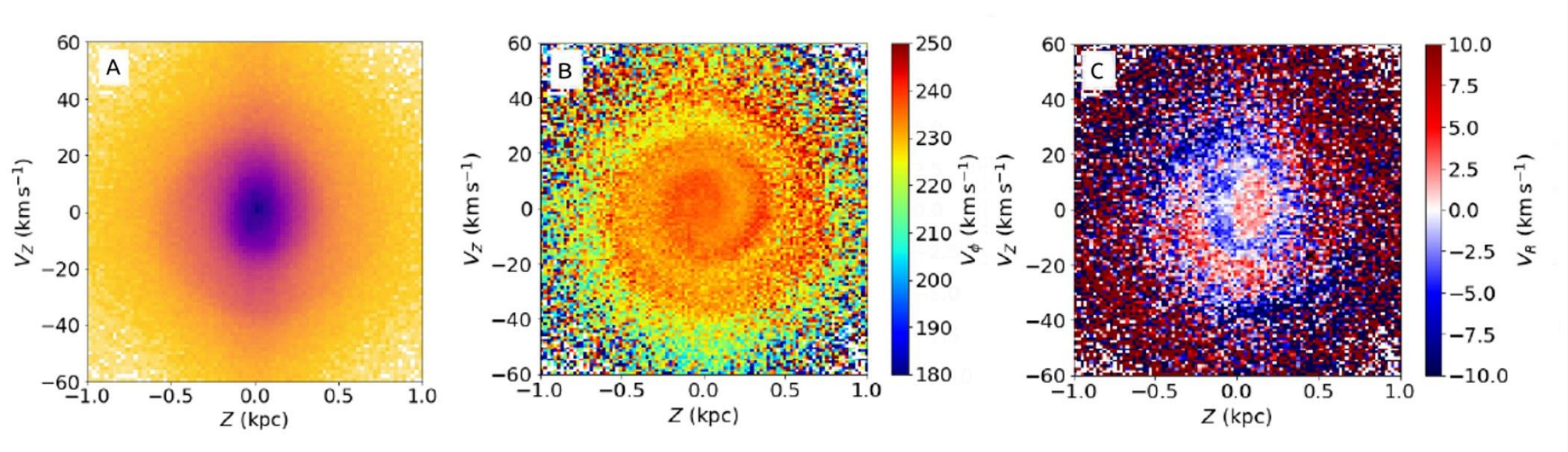

Figure 2: Phase spirals present in Gaia DR2 (Antoja et al 2018).

- An interacting satellite an induce a phase mixing event.

- Gaia data: the process of vertical phase mixing is **compatible with the last pericenter of the Sagittarius dwarf Galaxy** estimated at 500 Myr ago.

- Since this Gaia DR, the phase spirals as consequence of Sagittarius have been studied in isolated models (**N-body**) (Laporte et al. 2019, Khanna et al. 2019, Binney & Schönrich 2018).

- Other studies with isolated models also focus on **internal perturbations** such as the buckling of the bar (Khoperskov et al. 2019).

- A **cosmological simulation (N-body + hydrodynamics)** is self-consistent and provides:

    - Evolution of stellar populations and supernovae feedback.
    - Information of gas: inflows and outflows.
    - Several satellites with different masses.
    - Evolution through long periods of time.

Methodology

GARROTXA Simulation:

- Set of zoom-in cosmological simulations (Roca-Fabrega et al. 2016) with the ART code.
- Python's library yt (Turk et al. 2011).

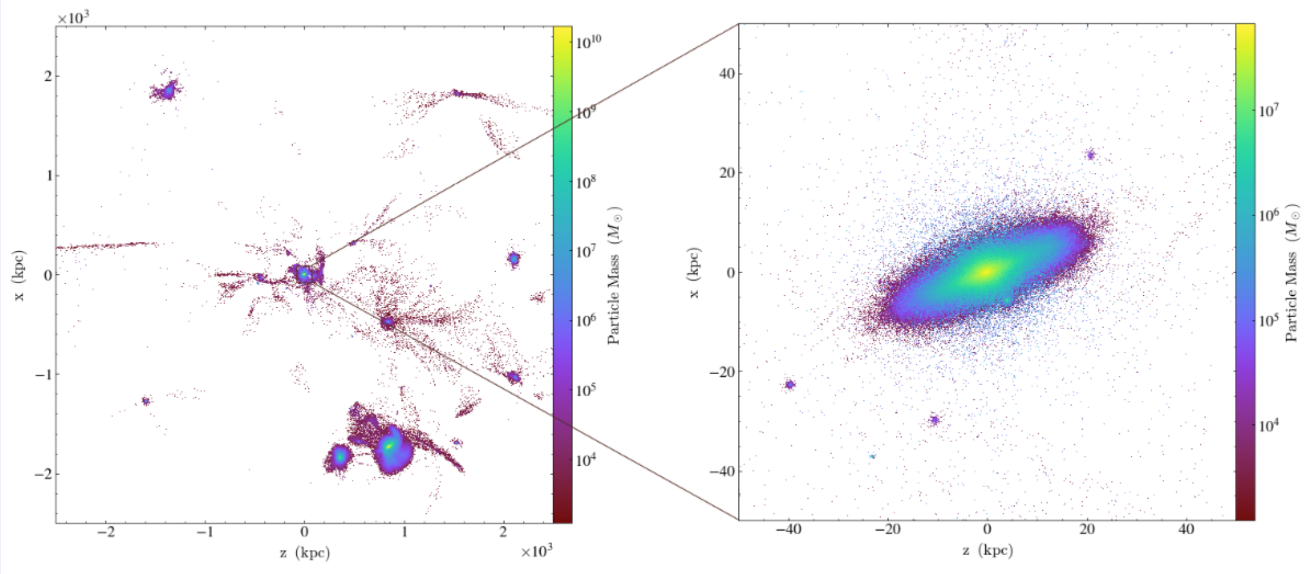

Figure 3: Model M003 Run 2.2 in GARROTXA.

Characteristics:

- Spatial resolution of 100 pc.
- Minimum mass of $10^3\ M_\odot$ for star particles and $10^5\ M_\odot$ for dark matter particles.
- Minimum timestep 10^3 years.
- Mass assembling history similar to Milky Way.

Main analysis

Between 6.3 -1.5 Gyr in lookback time.

For each snapshot:

- Centering and alignment.
- Selection of regions (divided by azimuth and galactocentric radius).
- Groups of stars divided by age.
- Satellites: 4 satellites in this system.
- Other quantities: Star Formation efficiency and inflows of gas.

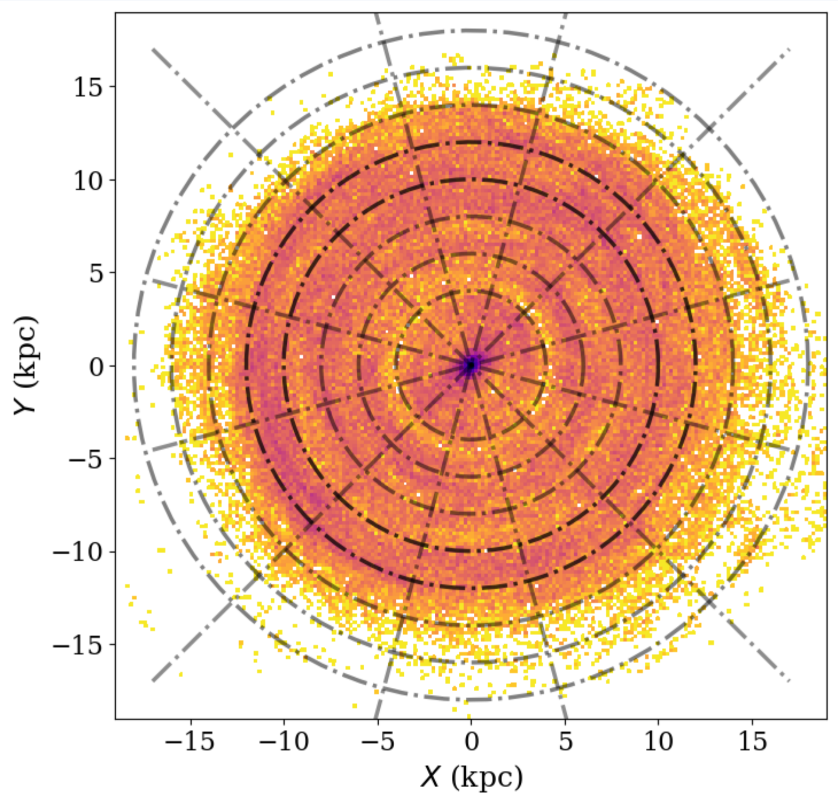

Figure 4: Disk divided by sections

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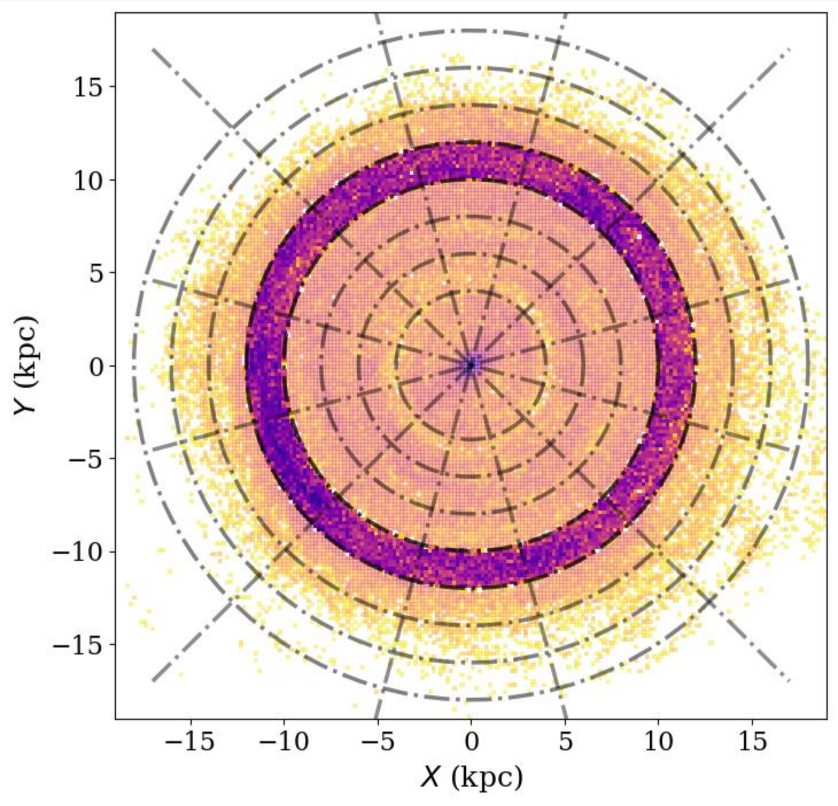


Figure 4: Disk divided by sections

Phase spirals through space and time

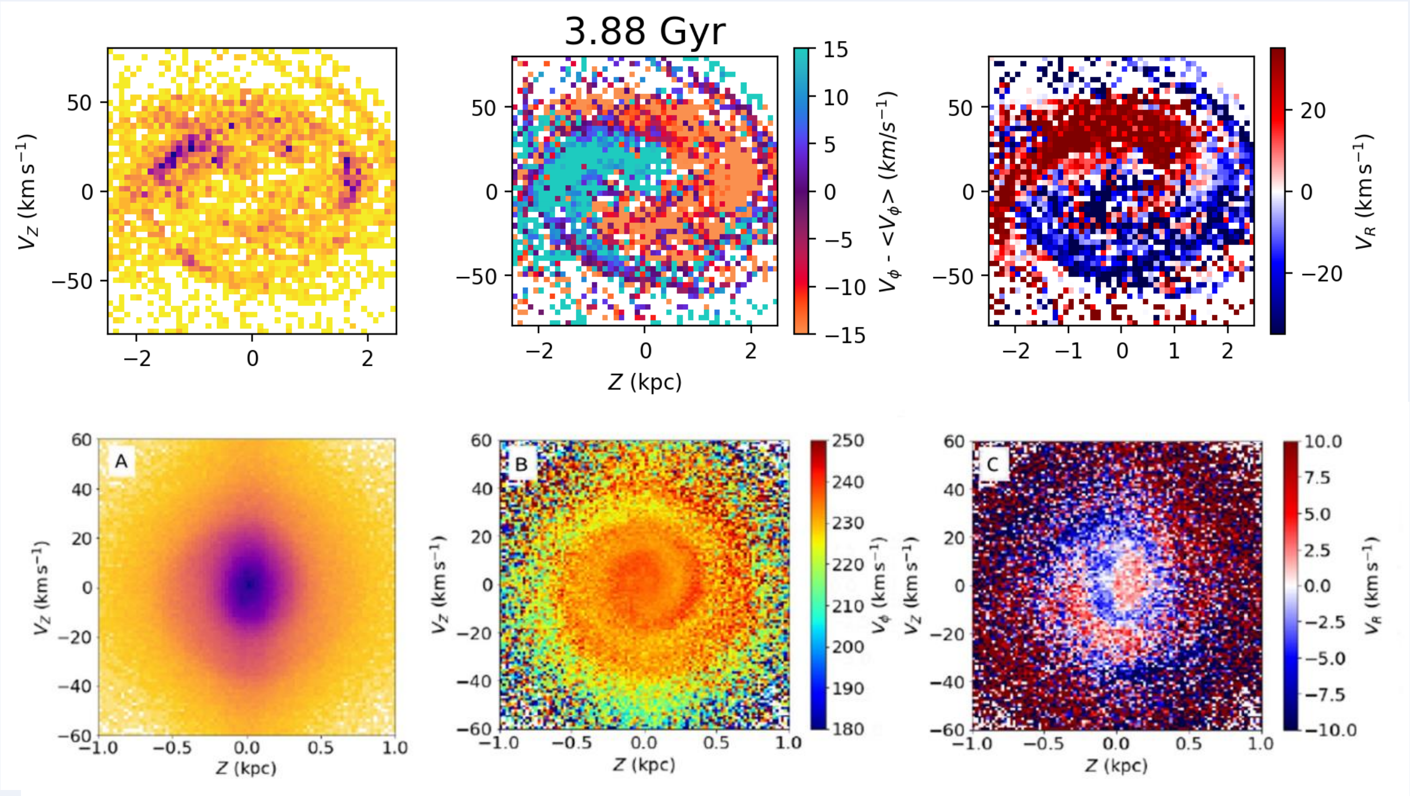
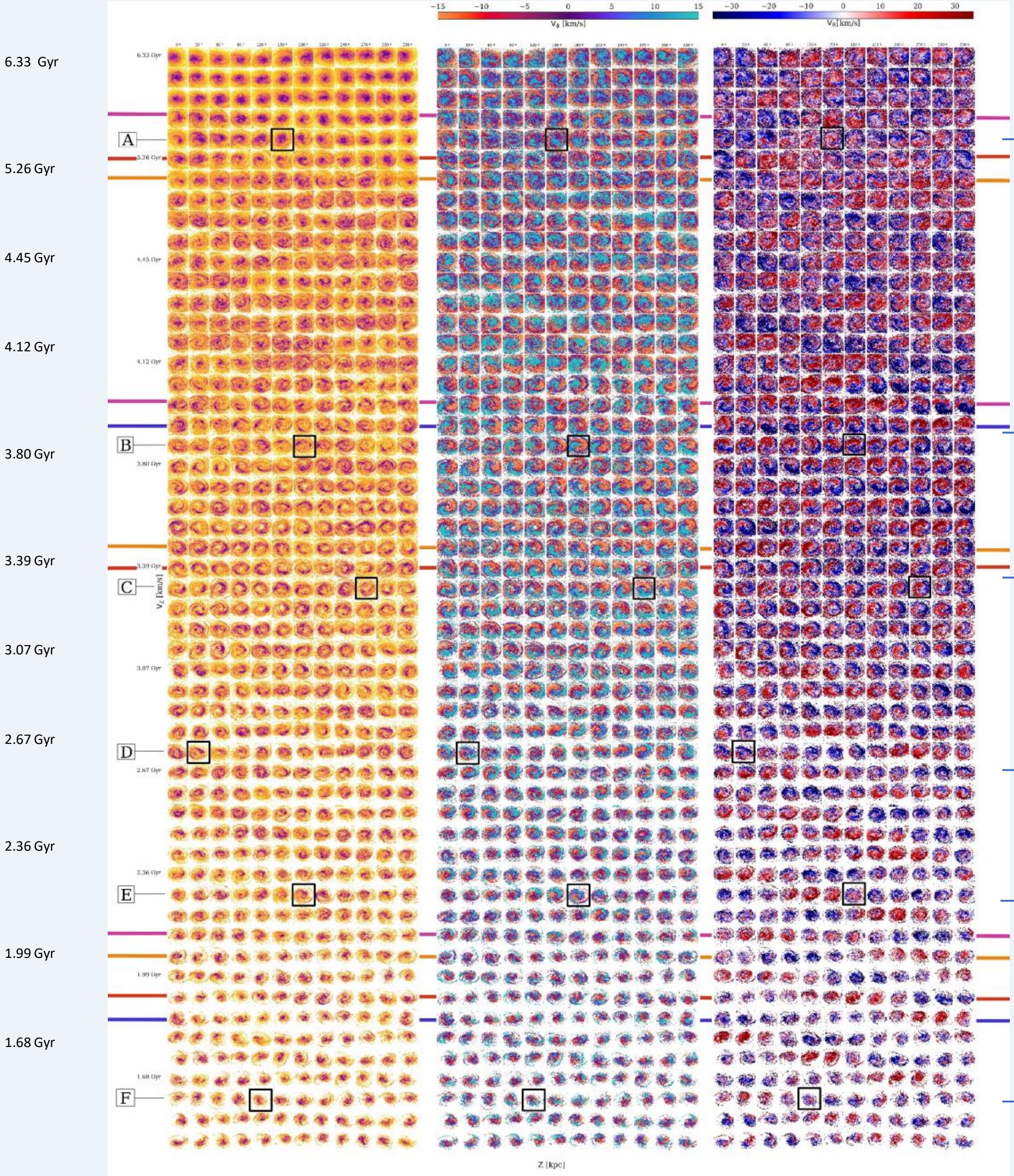


Figure 5: Exampe of phase spirals in GARROTXA model and comparison with Gaia data

- For the first time we observe **phase spirals in cosmological models**.
- The comparison with Gaia data is more complex due to the limitations in resolution of these kind of simulations.



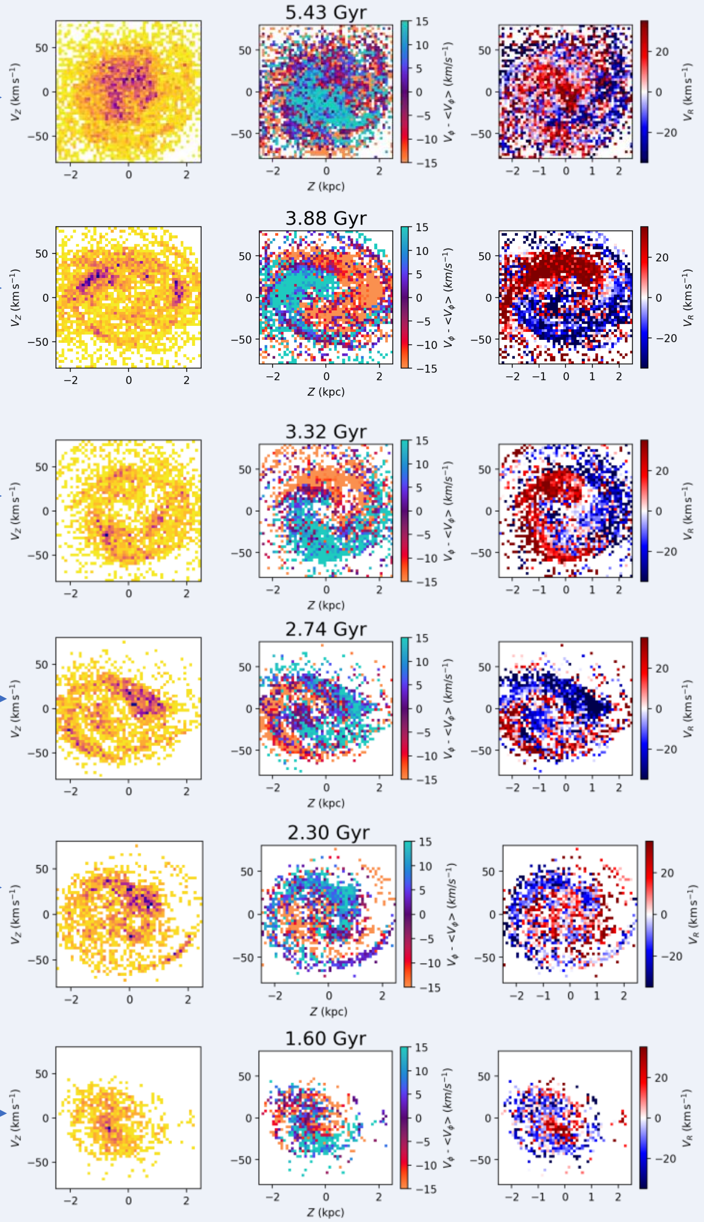


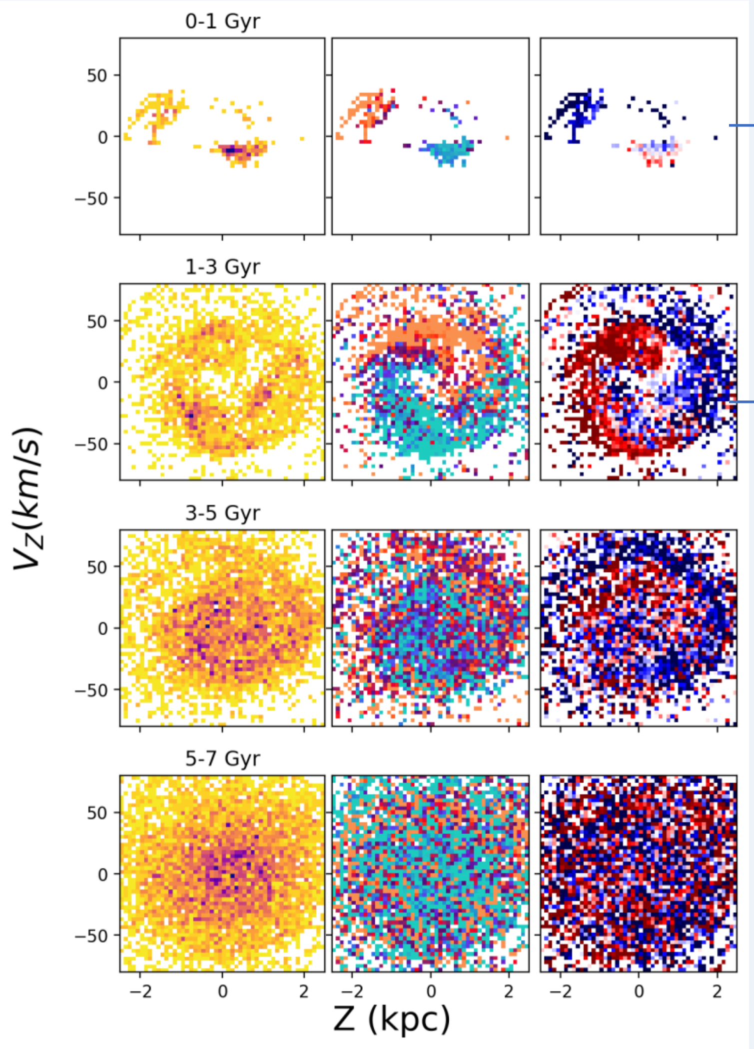
Figure 6: Phase spirals in GARROTXA model.

Non uniform structure **becoming a spiral** at certain times, where the disk might be perturbed.

Substructures moving diagonally.

Groups of different ages

3.32 Gyr



Simple structures

Prominent spiral structure

Hints of spiral structure

No structure

2.30 Gyr

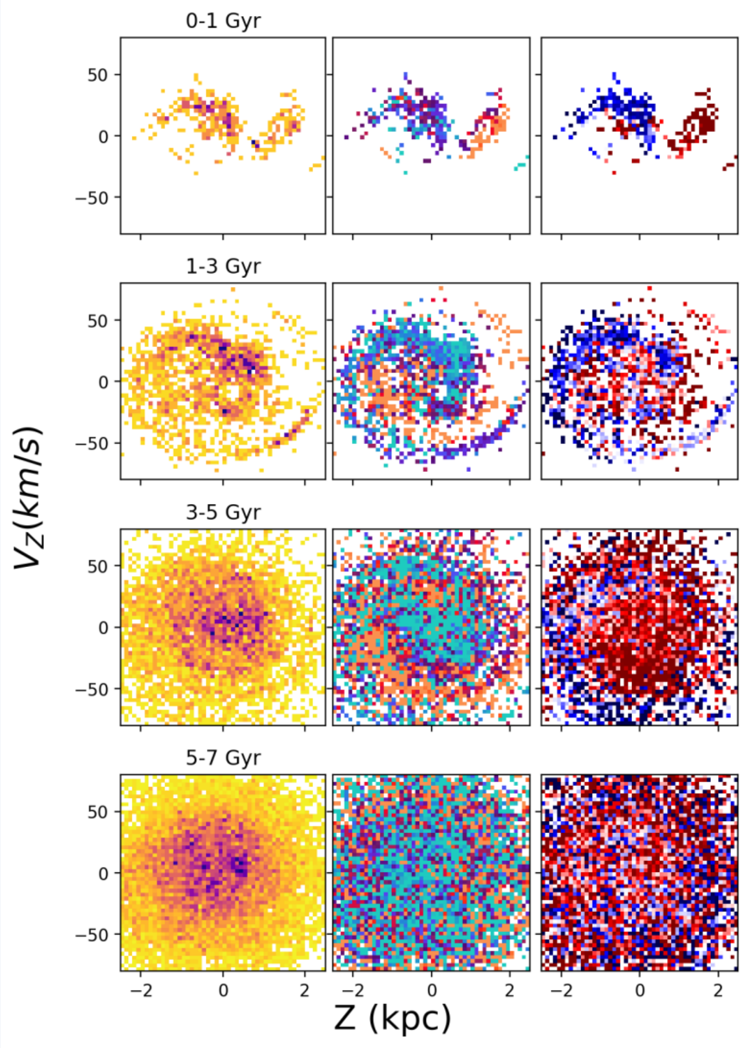


Figure 7: Phase spirals in GARROTXA model divided by age groups

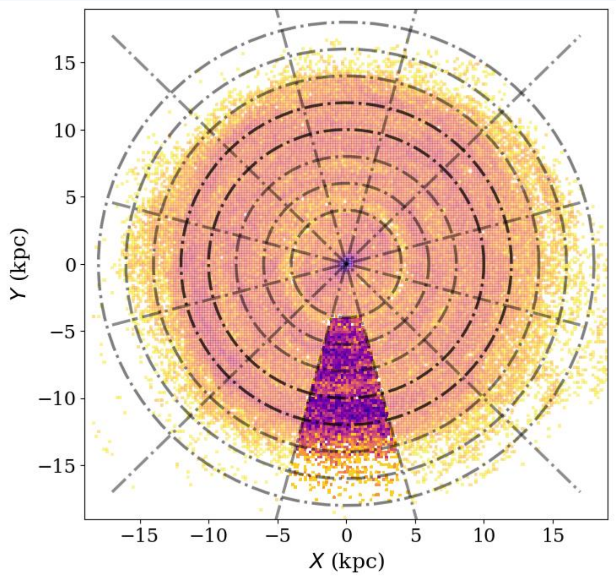


Figure 8: Selection of the regions with the same azimut.

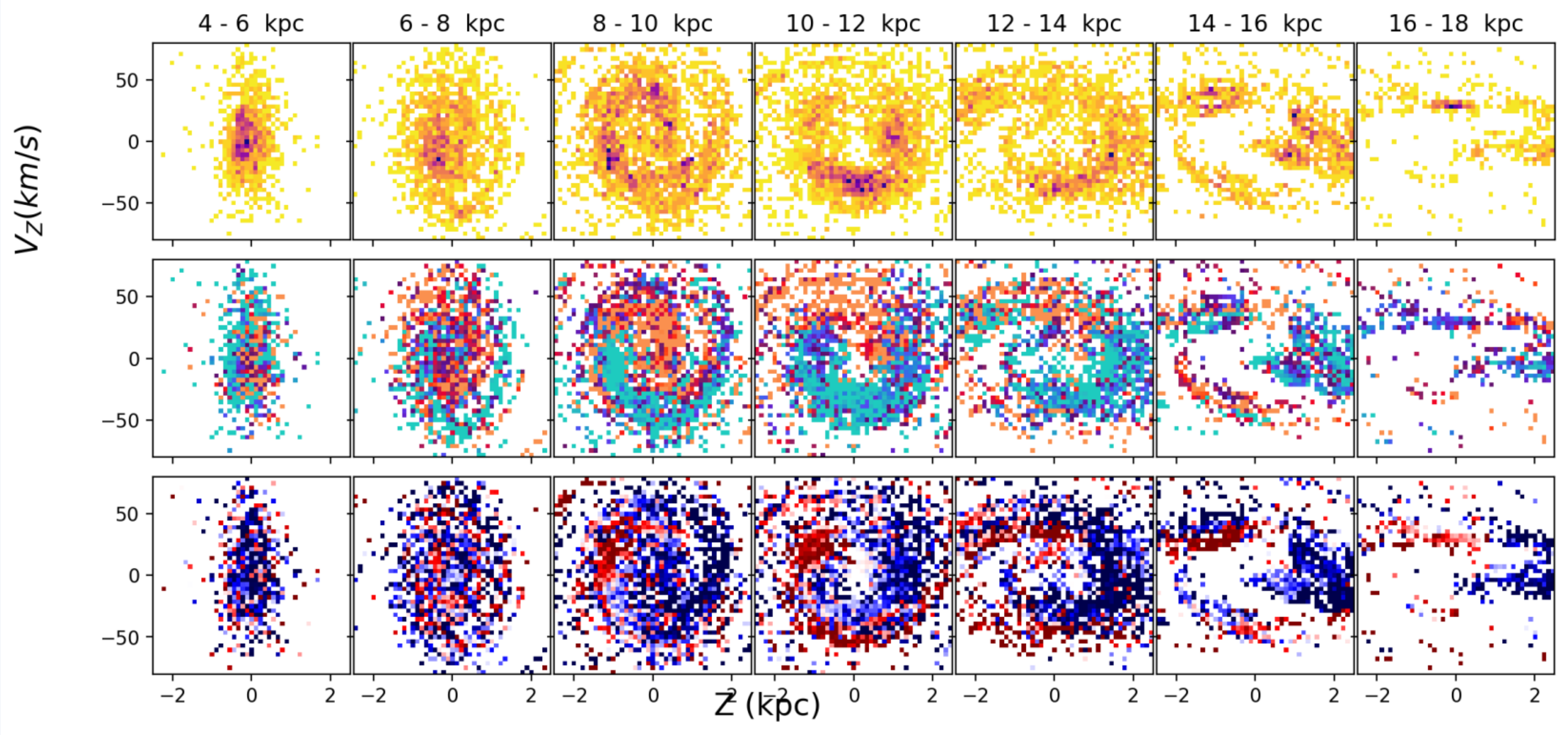


Figure 9: Phase spirals thrugh galactic radius.

Spiral pattern becomes noticeable

Splitted spirals

Satellites

Which phenomena have caused the phase spirals?

Satellite	Tidal radius (kpc)	Total mass ($M_\odot$)	Stellar mass ($M_\odot$)
Arania	1.59	4.31×10^8	2.058×10^8
Grillo	1.69	2.14×10^8	1.51×10^7
Mosca	0.47	3.014×10^7	2.75×10^6
Mosquito	1.34	6.75×10^7	4.06×10^6

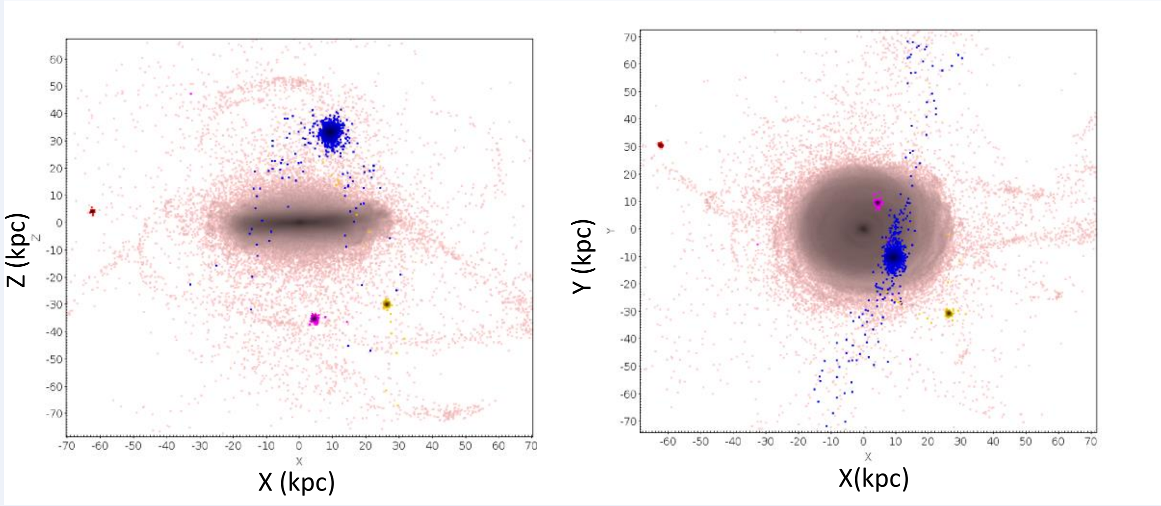


Figure 10: Satellites in the GARROTXA system.

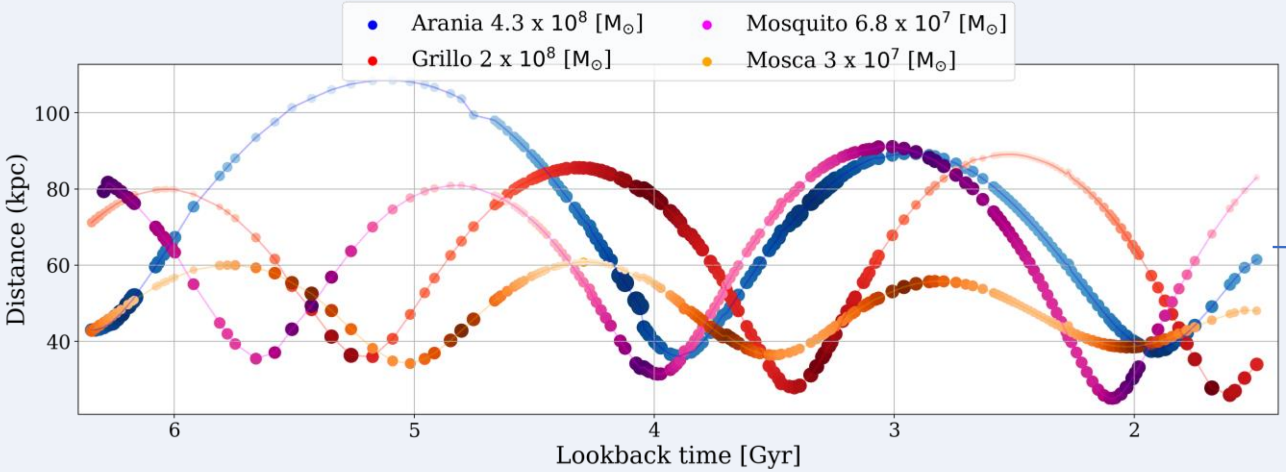


Figure 11: Distance to the center of the center of the galaxy of the four satellites.

- Distance to the center of galaxy.

Fourier analysis

Not trivial to discern the apparition and development through time and space.

We need a more **objective measurement** of the intensity of these substructures.

We build an estimator based on the amplitude of the Fourier modes of the particles on the vertical plane:

- Plane Z - V_z : modes from 0 to 6.
- Mode 1 dominating over high order modes.
- Variability in angle.

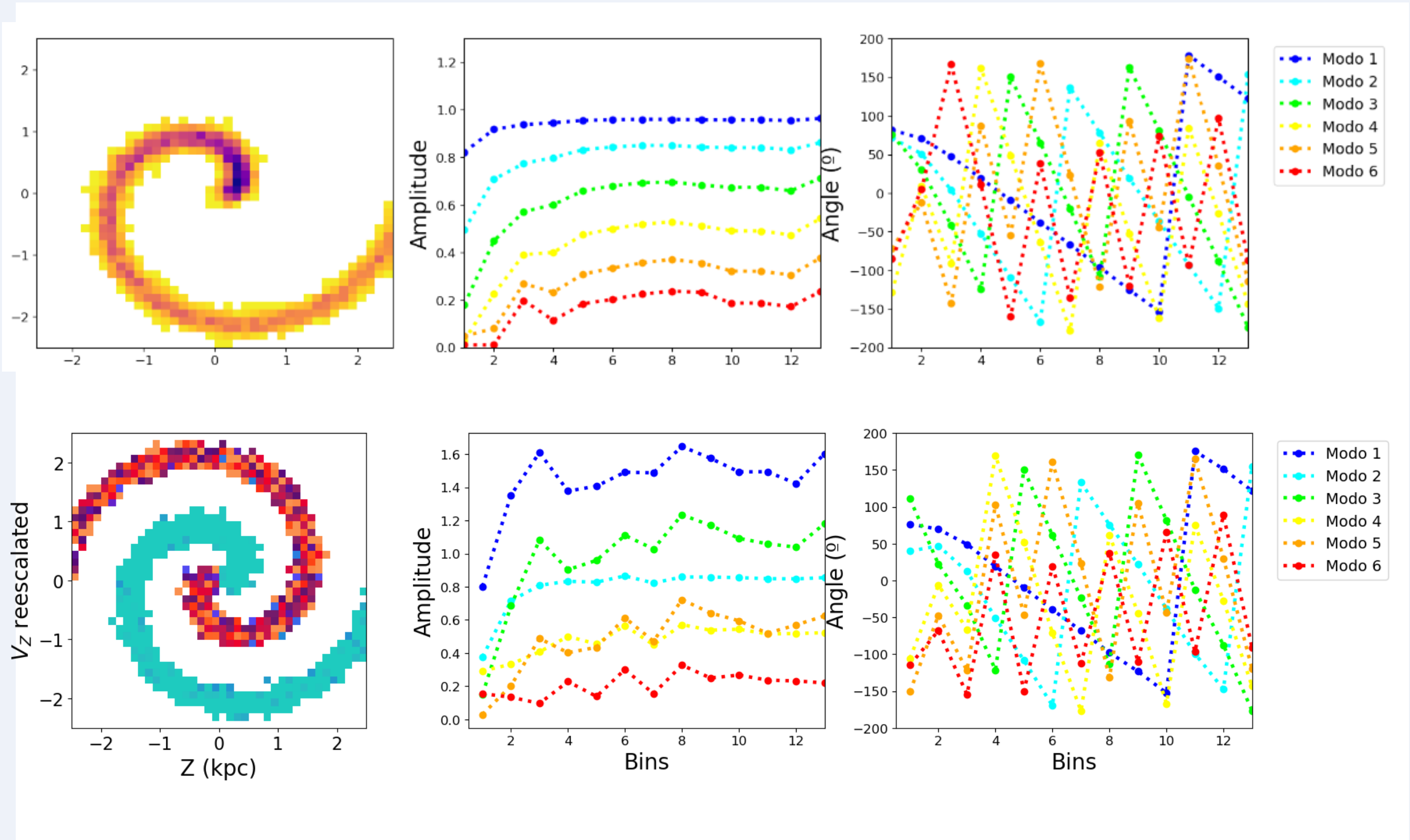


Figure 12: Toy model to test the estimator based on Fourier analysis.

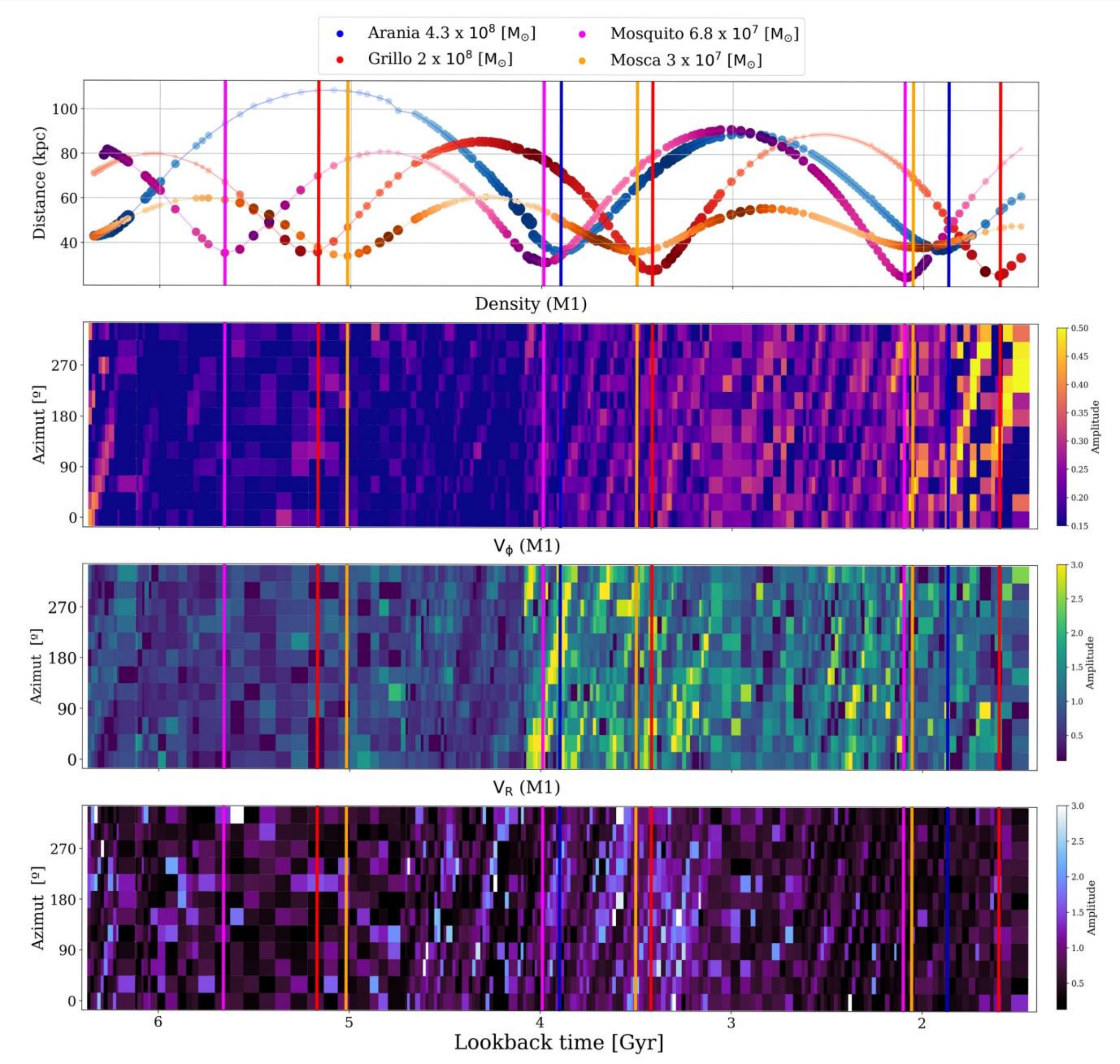


Figure 13: Satellites pericenters and Fourier estimator.

- Amplitude of the Fourier mode in different azimuts of the disk with star particles from 1 to 3 Gyr of age.
- Highlighted bins → more prominent spiral.
- **Correlation** between higher amplitudes and satellites pericenters.
- Multiple perturbers: **which satellite** has triggered certain response?
- Multiple perturbers: disk not reaching **state of equilibrium** before the next passage.

Conclusions

- For the first time we observe phase spirals in cosmological models of the Milky Way.
- The phase spirals are better observed when the stellar particles are younger.
- We develop techniques to objectively measure intensity of these substructures.
- We have found a visual correlation between pericenters and phase spirals.

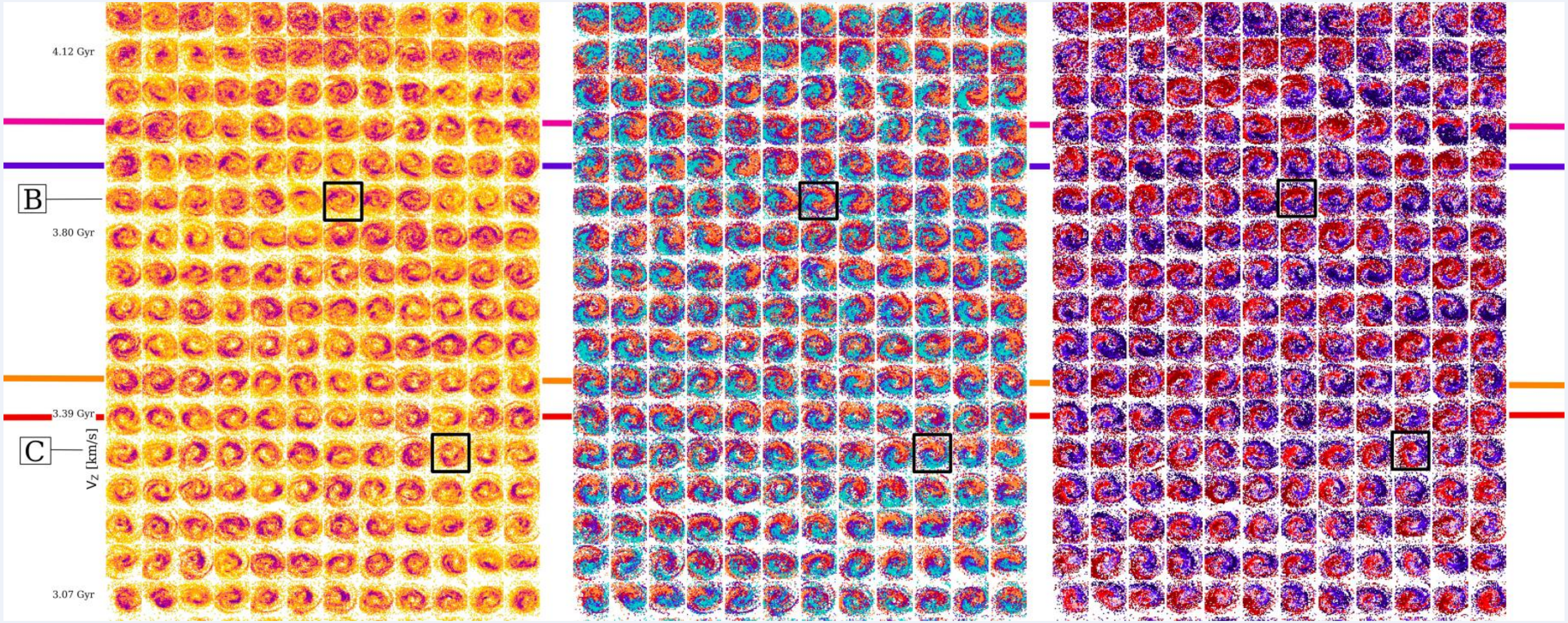
Open questions

- In a complex system such as a cosmological simulation, the link between the apparition of phase spirals and pericenters may not be that direct.
- What is the impact of multiple perturbers with different masses and orbits?

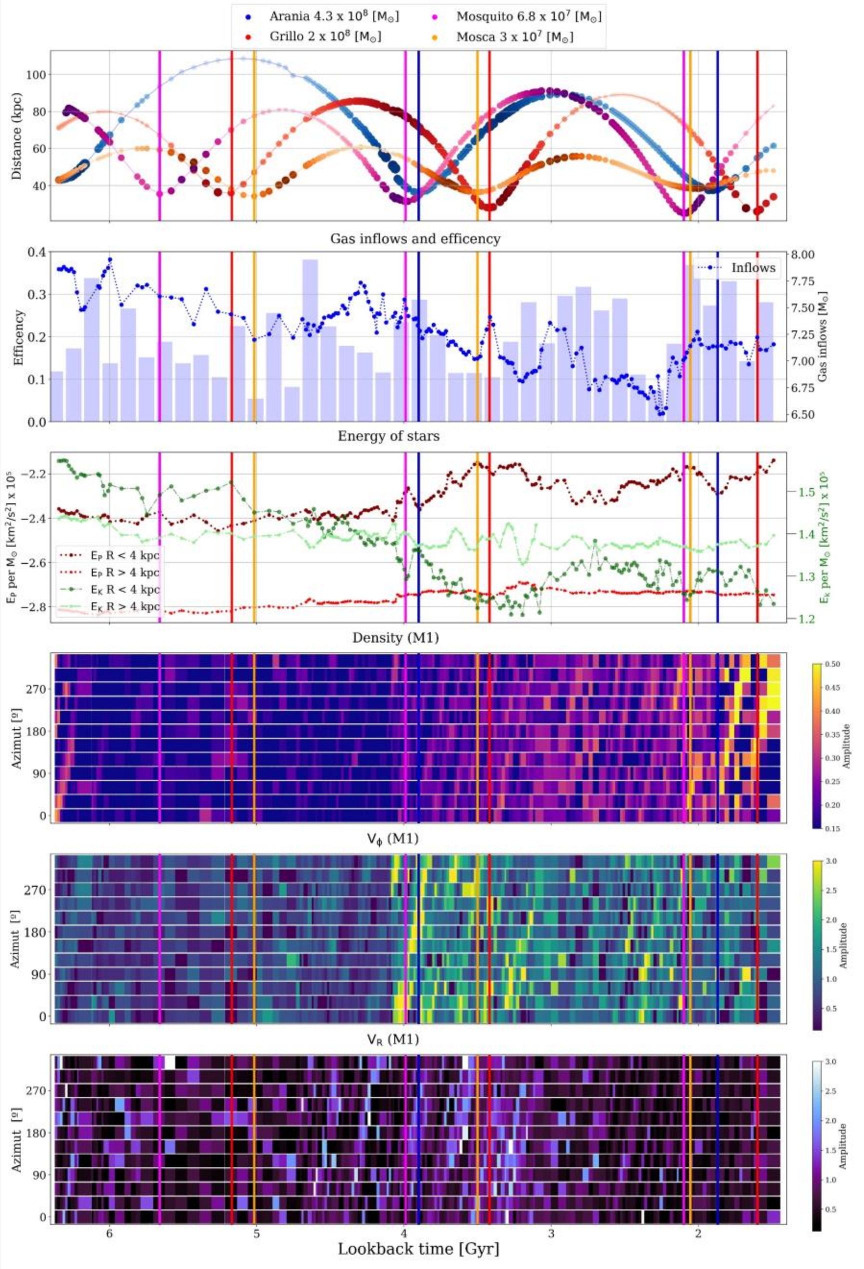
Future work

- Better characterisation of satellites: evolution through time, halo finders software…
- Multiple perturbers: Acceleration maps of the disk.
- Quantify the correlation between pericenters and the apparition of the phase spiral.
- Further explore this model: internal perturbations? Bar? Strong spiral arms?
- Use other cosmological models with other codes (RAMSES…) and compare.

Appendix



4.12 Gyr
B
3.80 Gyr
3.39 Gyr
C
v_z [km/s]
3.07 Gyr



Arania 4.3 x 10^8 [M⊙]
Grillo 2 x 10^8 [M⊙]
Mosquito 6.8 x 10^7 [M⊙]
Mosca 3 x 10^7 [M⊙]
Distance (kpc)
Gas inflows and efficency
Efficency
Inflows
Gas inflows [M⊙]
Energy of stars
E_P per M⊙ [km²/s²] x 10⁵
E_K per M⊙ [km²/s²] x 10⁵
E_P R < 4 kpc
E_P R > 4 kpc
E_K R < 4 kpc
E_K R > 4 kpc
Density (M1)
Azimut [º]
Amplitude
V_ϕ (M1)
V_R (M1)
Lookback time [Gyr]