Radial actions as tracers of Milky Way spiral arms:
evidence from Gaia DR3 observations and simulations

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Seminar GECO Group, LAM, 12th November 2025

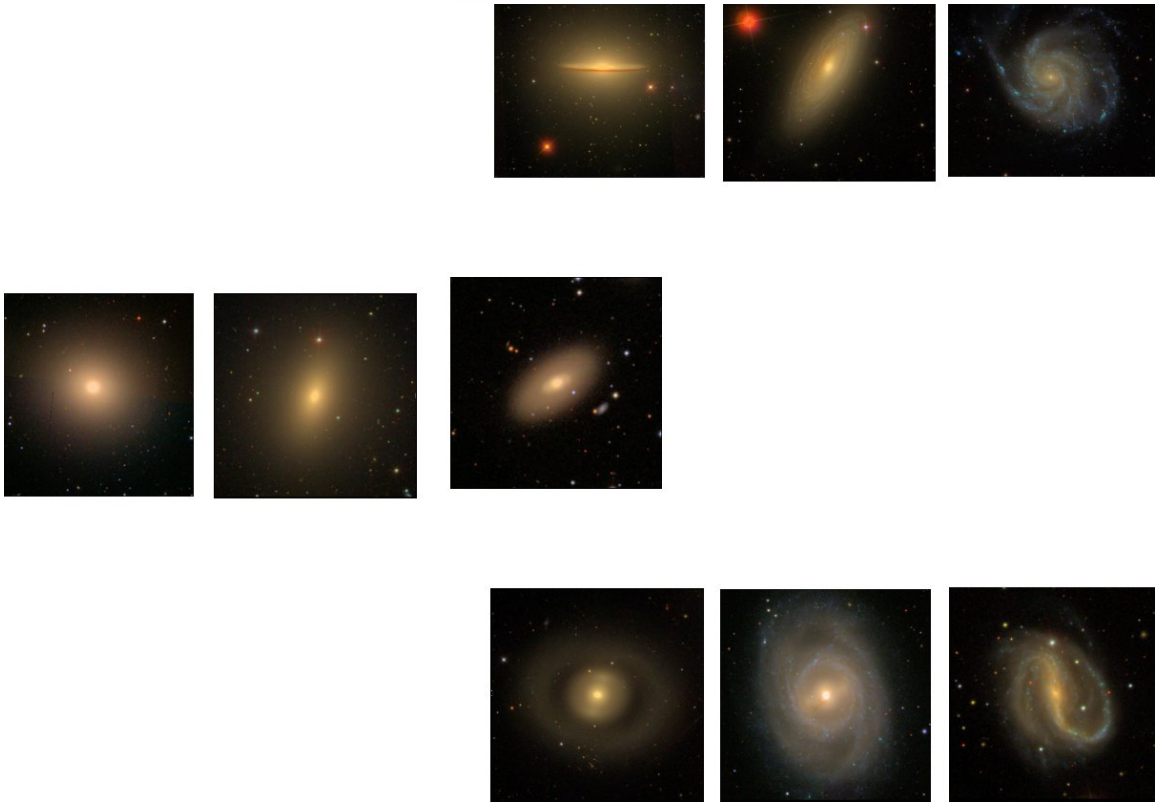
Scheme

- Introduction to the Spiral Arms
  - The case of the Milky Way

- Spiral Arms as traced by Radial Actions
  - Observations (Palicio+23a)
  - Simulations (Palicio+25)

- Conclusions

The morphology of galaxies



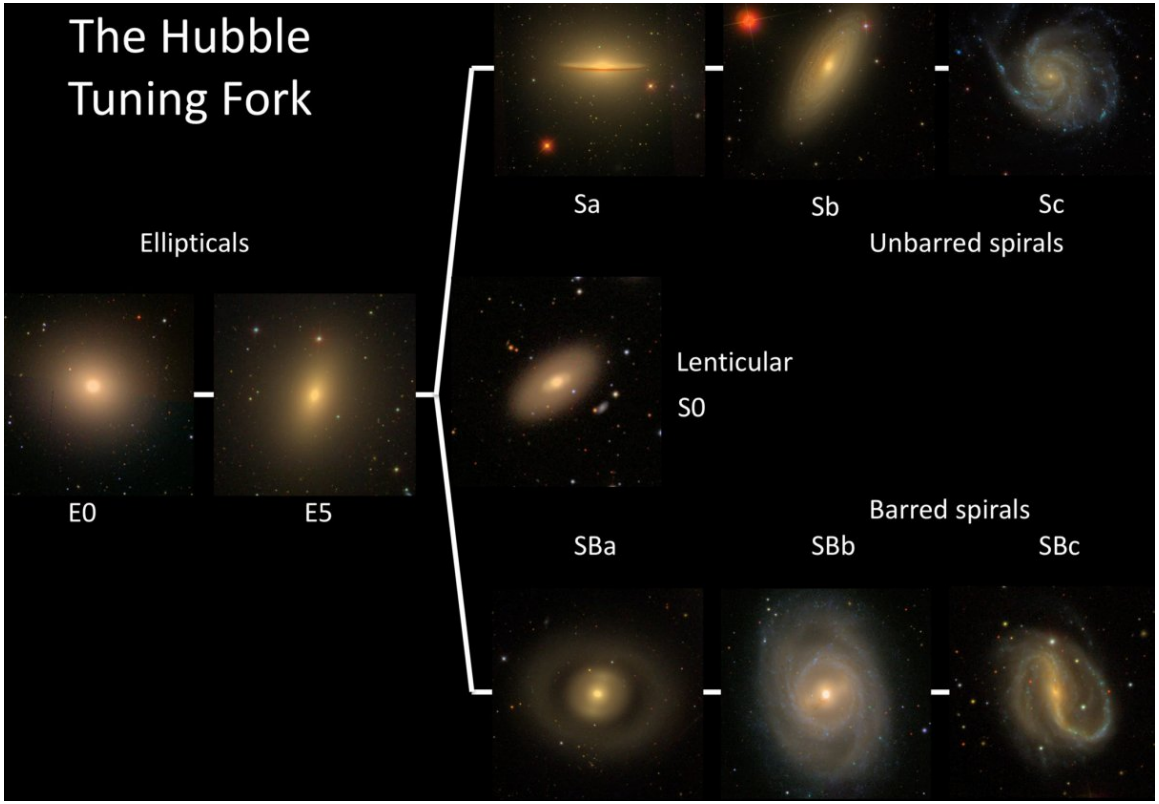
Galaxies are **not** all the same.

Variety of colors, sizes, luminosities, ages...

~2/3 of galaxies in the local universe show any **spiral feature** (e.g., Masters et al. 2019)

Credit of the images: SDSS (York et al. 2000)

The morphology of galaxies



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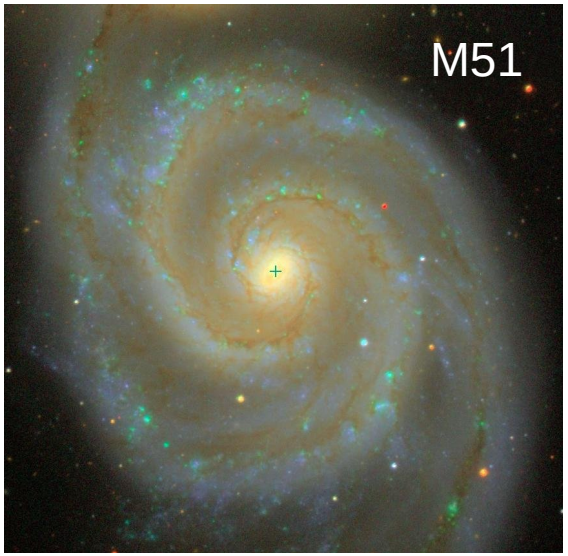
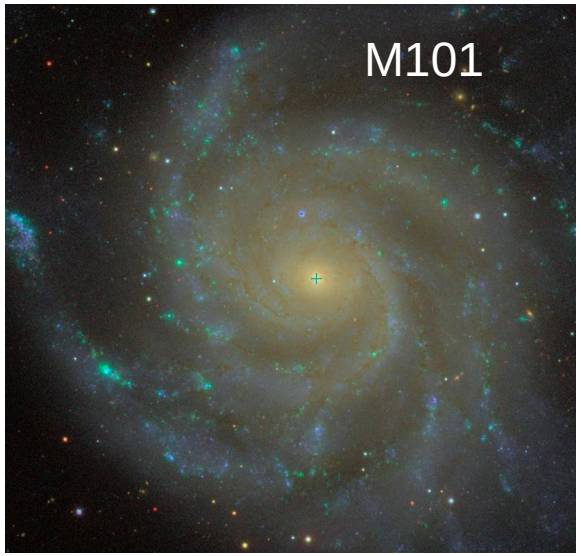
The morphology of the spiral arms

Grand design



- Length: ~galactic size
- Continuous.
- Symmetric.
- Long-lived.

Intermediate/Multi armed



- Length: ~fraction of the galaxy.
- Branches & bifurcations.
- Short-lived

Flocculent

- Length: short.
- Patchy segments.
- Short-lived

Classification from **Elmegreen 1981**

Credit of the pictures: SDSS. Extracted from SIMBDAD

The case of the Milky Way

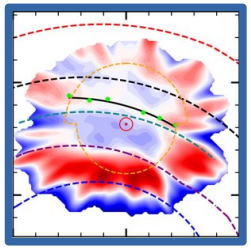
Artistic image of the Milky Way. Credit: NASA/JPL-Caltech/ESO/R. Hurt

What type of spiral arms has the Milky Way?

Real picture remains uncertain.

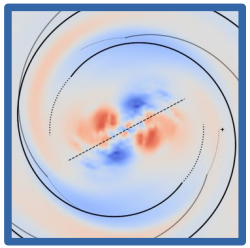
No face-on perspective ⟹ indirect methods for tracing spiral arms

Stellar density



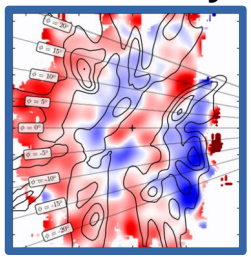
Lin+22

Kinematics



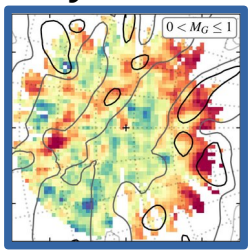
Khalil+25

Chemistry



Barbillon+25

Dynamics



Widmark & Aneesh 24

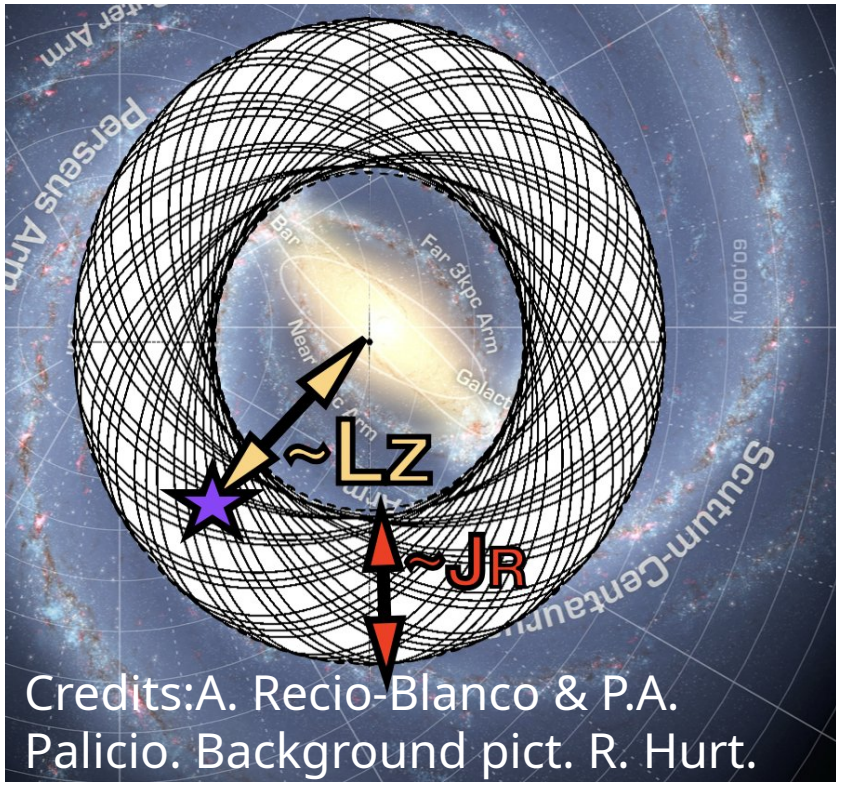
Theoretical background

- **Actions (J)** are special "**momentum**" variables that simplify the so-called **Hamilton's Equations**.

- Hamilton's equations: alternative to the equations of motion. Describe the time evolution of the system.

- The **angular momentum** L_z in axisymmetric potentials is an action variable (L_Z):

$$H(R, z, \phi, p_R, p_Z, L_Z)$$

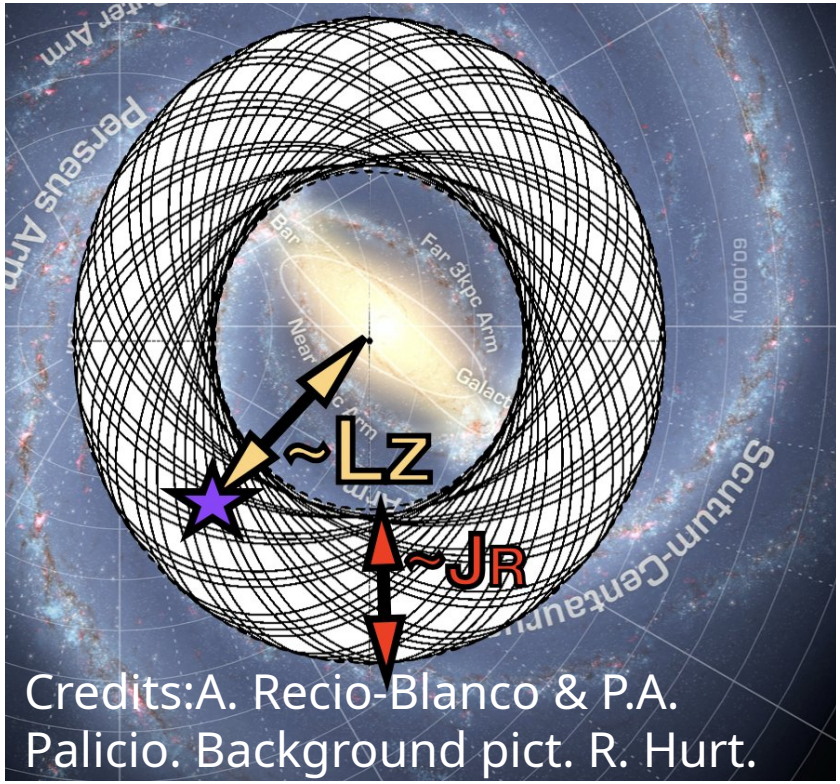


Theoretical background

- The other non-trivial actions are J_R and J_Z.
  - **J_R** tunes the amplitude of the epicycles.
  - **J_Z** controls the vertical displacement.
  - **L_Z** determines the guiding radii.

- Actions are **ideal orbit tags**: **unchanged** after slow perturbations of the potential (*adiabatic invariants*).

- **Problem**: Not all the potentials have analytic expression for the actions, but there are alternative methods (Sanders & Binney, 2016).



Motivation

If stars are formed in spiral arms, and actions preserve information of the birthplace (under certain conditions), then **actions must provide information of the spiral arms.**

Computation of Actions. The MW Model.

- Actions require positions and velocities:
  Gaia eDR3 & DR3: 33 M full-kinematic sources (table at CDS of Palicio+23a)

- Actions computed assuming:
  - **Stäckel-fudge** (Sanders & Binney+16).
  - **Axisymmetric potential** of McMillan +17 (rescaled in R_0, V_0)

- Error estimation: 25 random realisations of input Gaia data.

- Quality and selection criteria:
  - 15% error in proper motions
  - 20% error in distances (Bailer-Jones et al. 2021)
  - 5 km/s error in line-of-sight velocities
  - Only disc stars (Z_{max}<500 pc)

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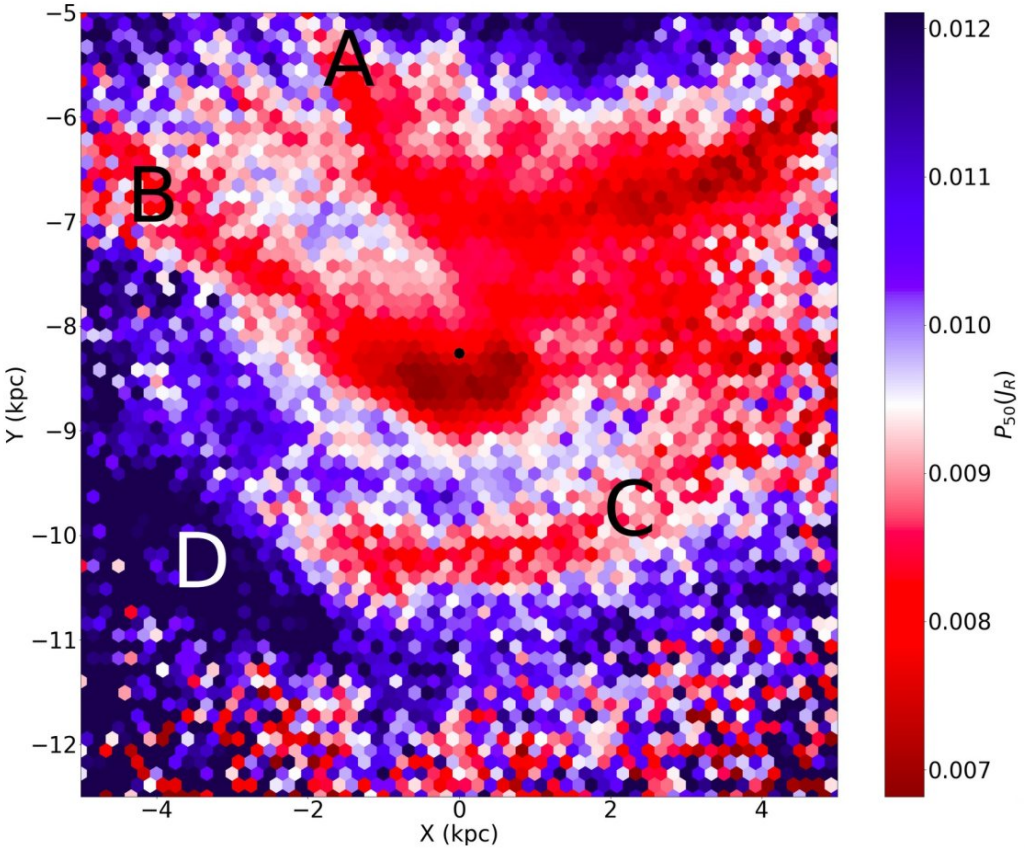
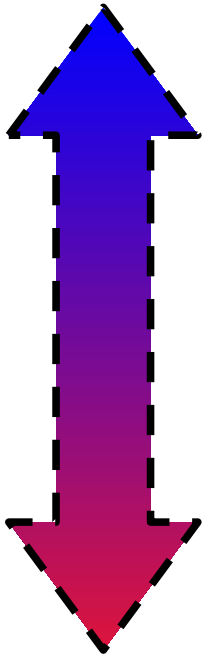
Map of Median(J_R)

- Sun at (0,-8.249) kpc
- GC at (0,0)
- MW rotation is clockwise
- |Zmax|<0.5 kpc



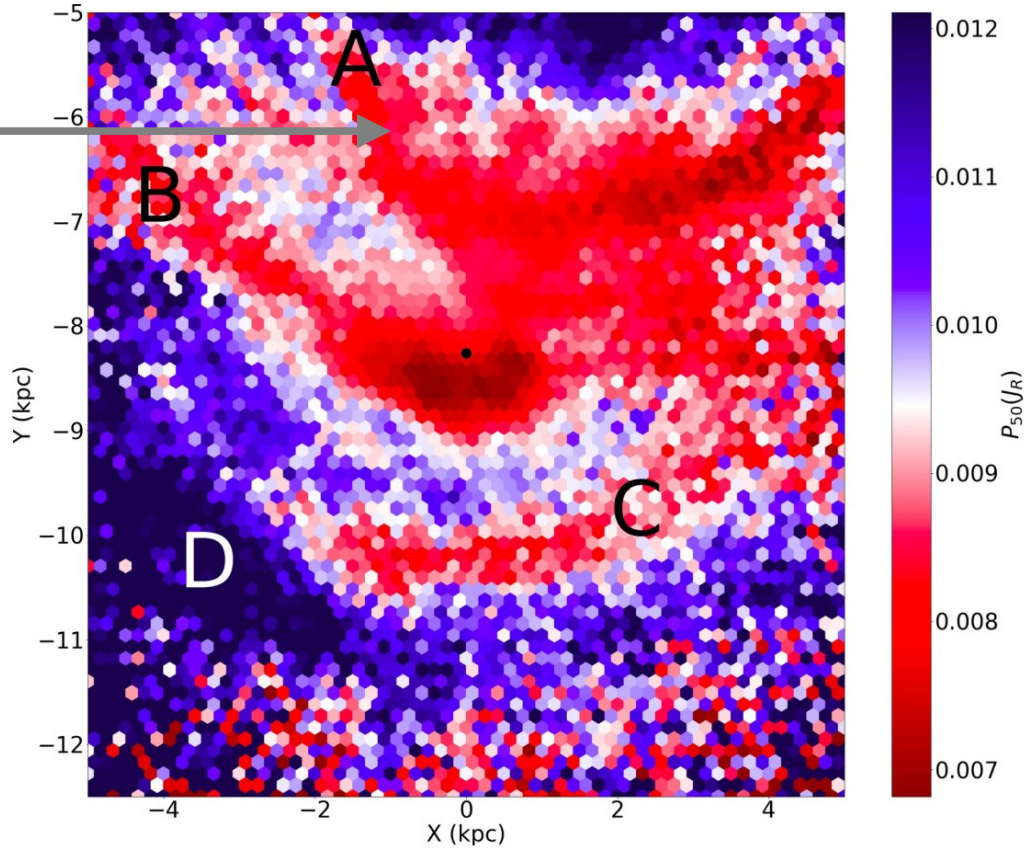
More eccentric



More circular

Map of Median(J_R): Structure A

From 6 kpc to 7 kpc
(variable pitch angle)



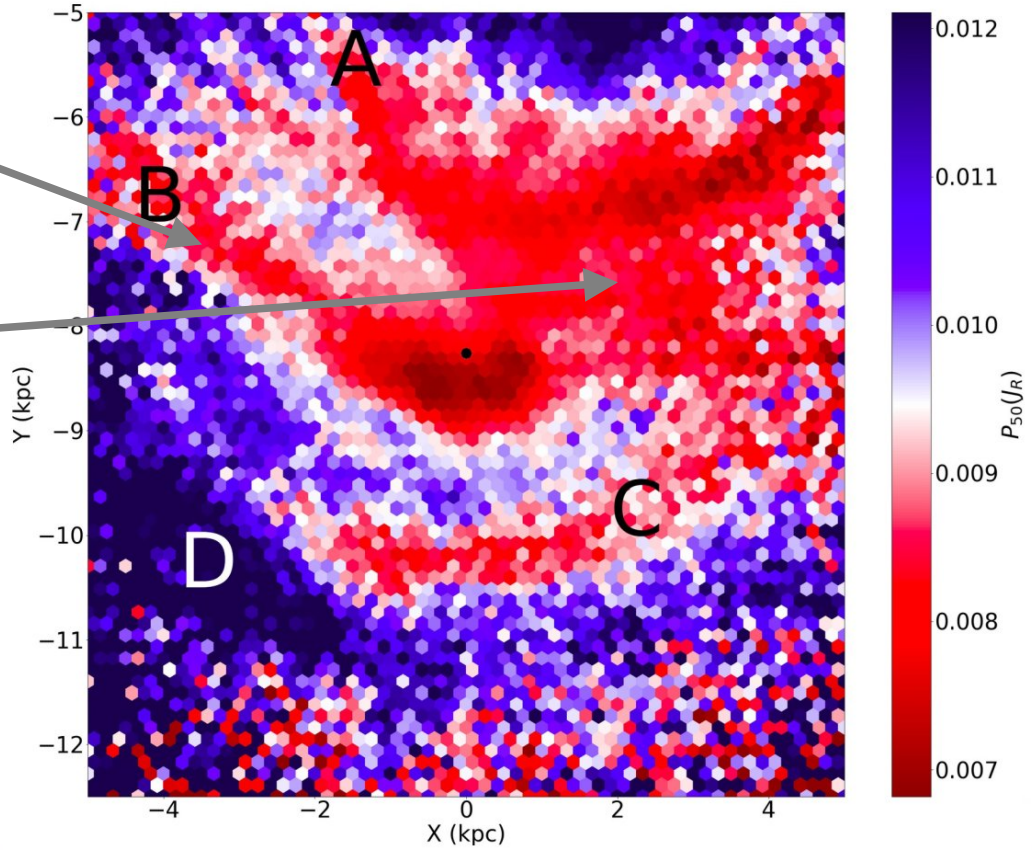
More eccentric

More circular

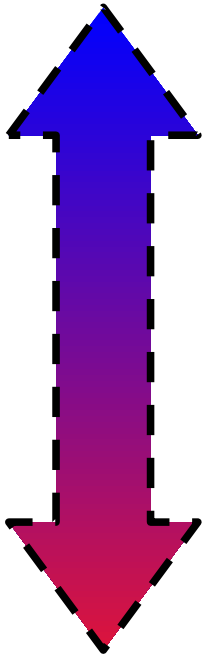
Map of Median(J_R): Structure B

Clearer defined in the leftmost part

Big low JR area



More eccentric



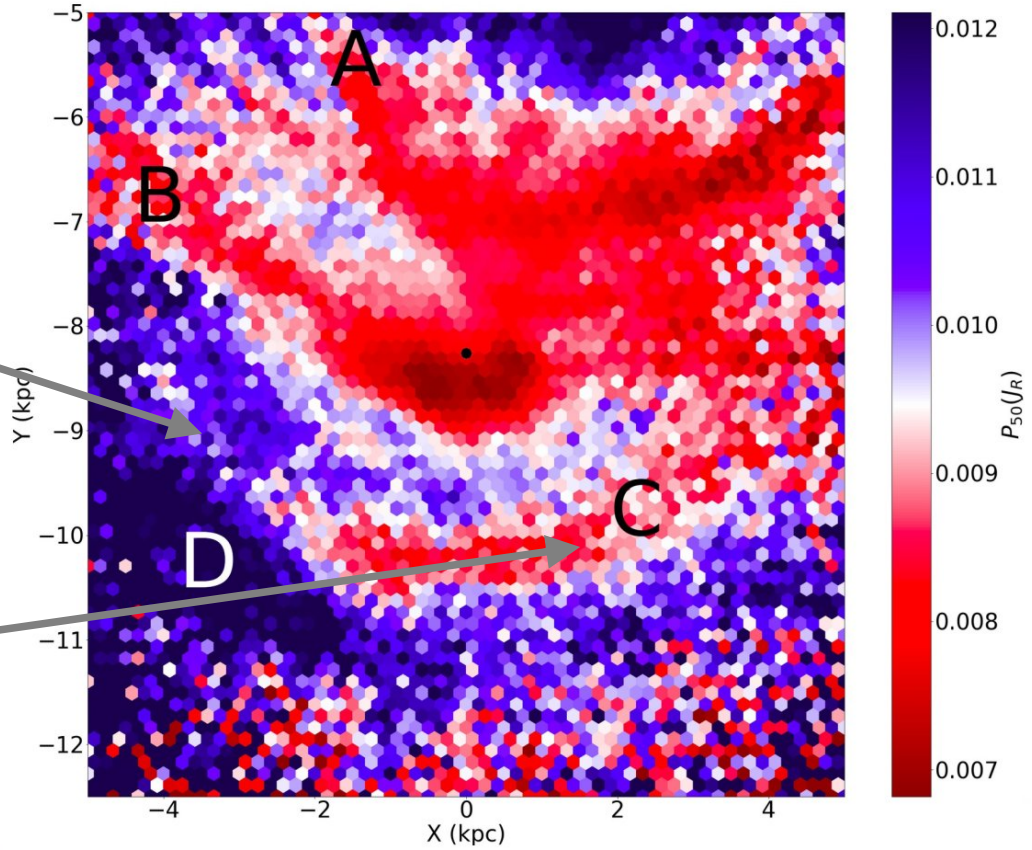
More circular

Map of Median(J_R): Structure C

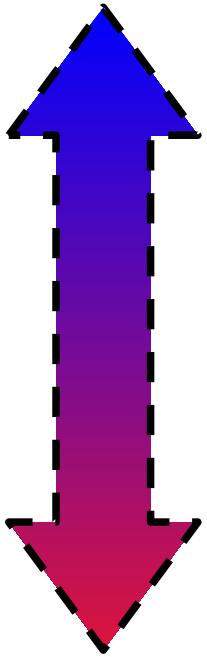
Observed in higher percentiles (>50) compared to A&B

Tail?

Clearer in the rightmost area



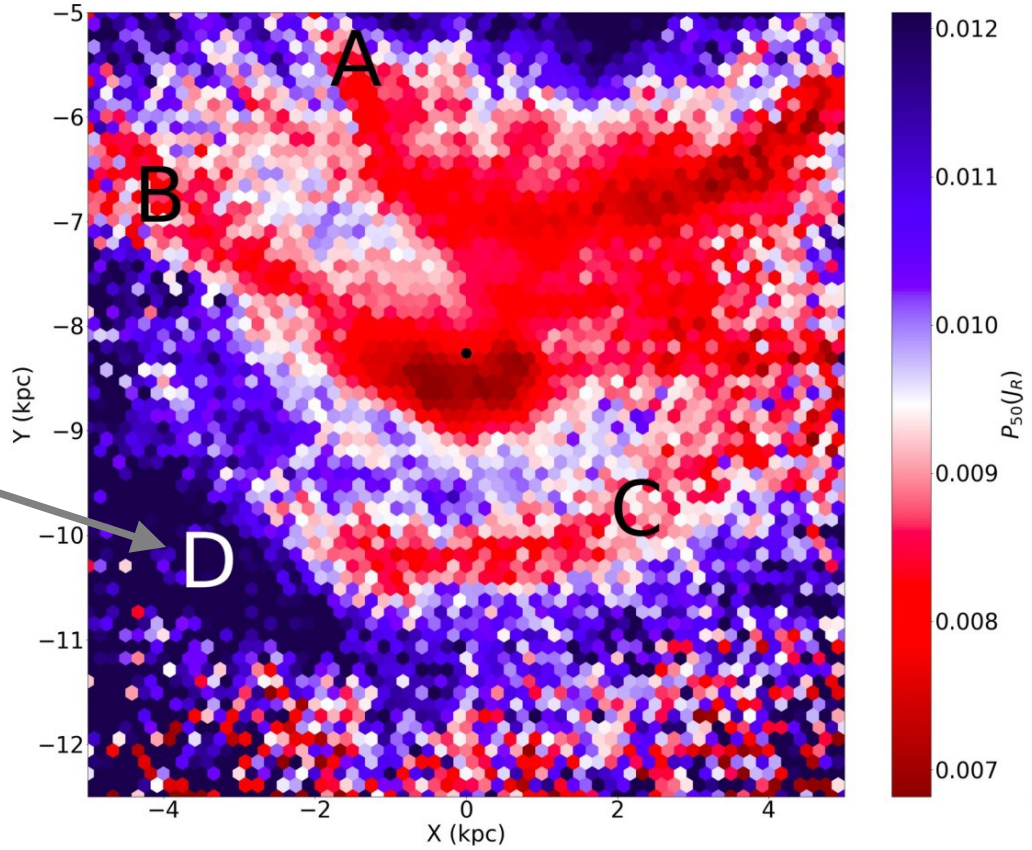
More eccentric



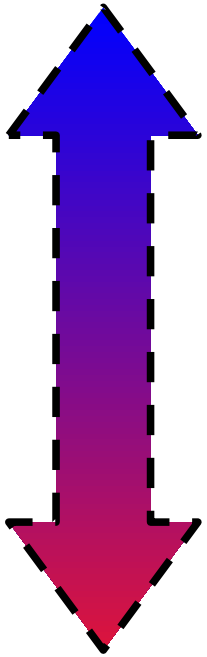
More circular

Map of Median(J_R): Structure D

Constant radii
of 10.5 kpc
(1kpc width)



More eccentric

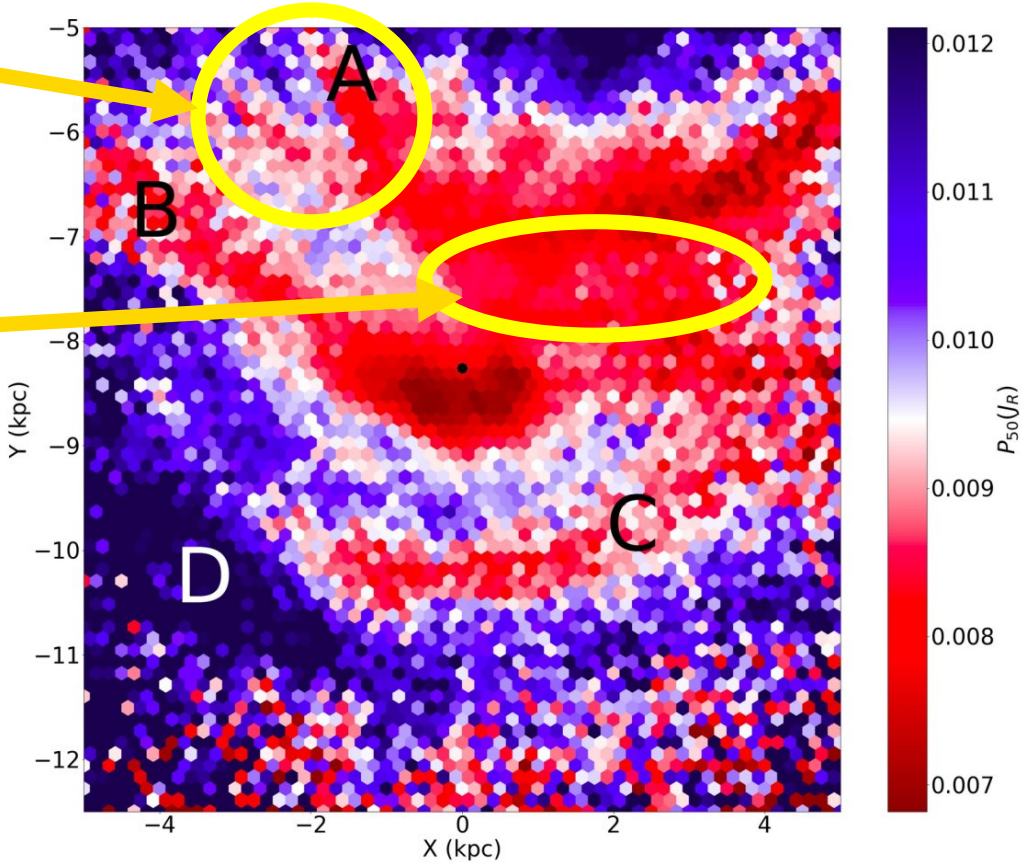


More circular

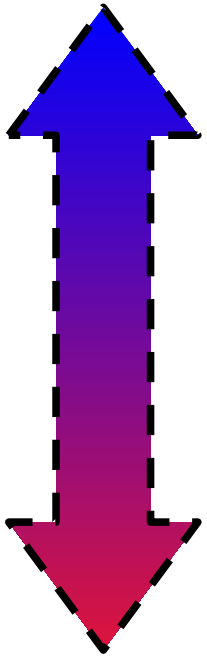
Map of Median(J_R): minor features

Bifurcation

Minor low J_R area



More eccentric



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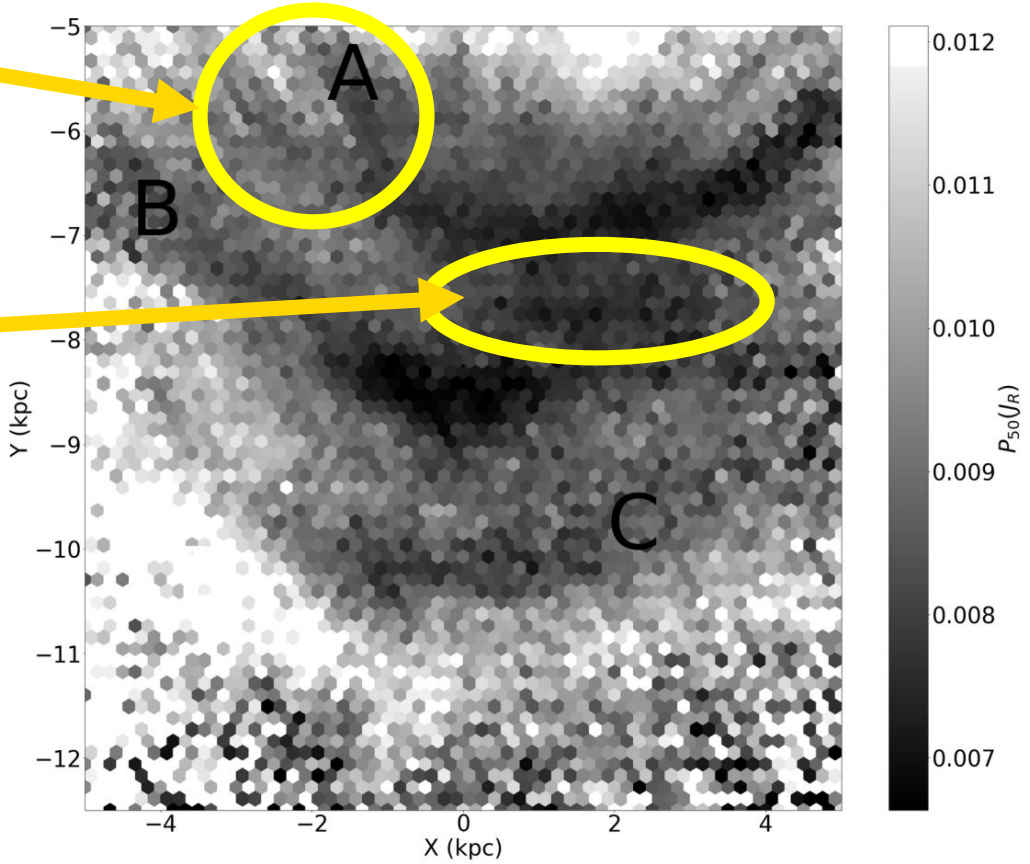

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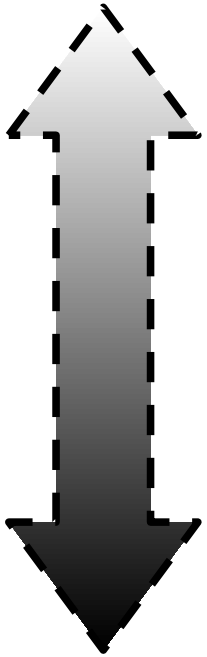
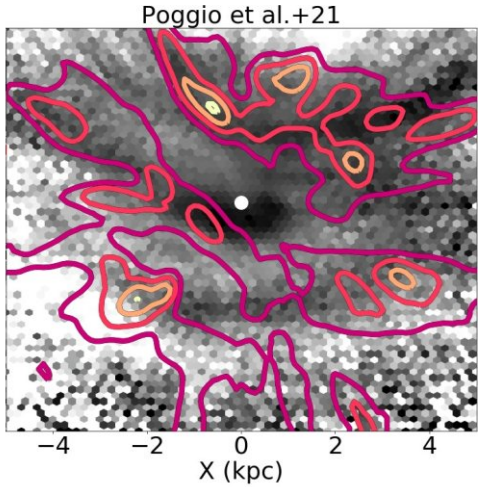


More circular

Structures in J_R

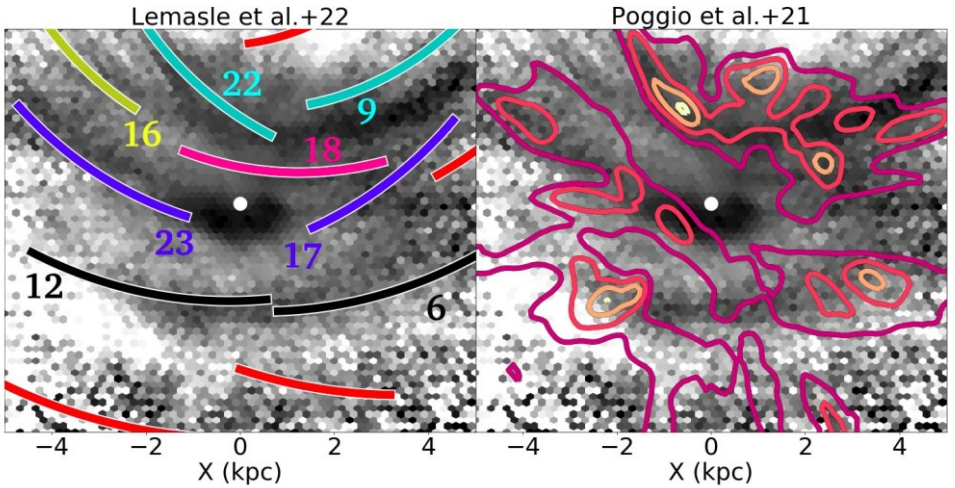
Upper Main Sequence



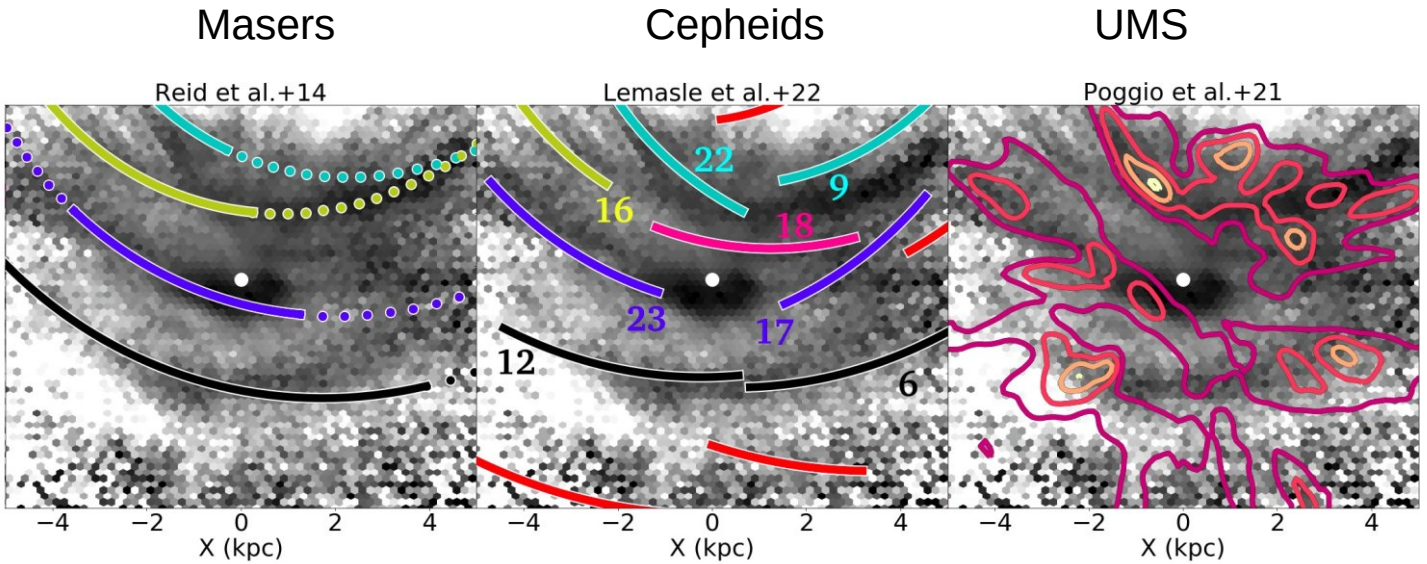
Structures in J_R

Cepheids

Upper Main Sequence



Structures in J_R



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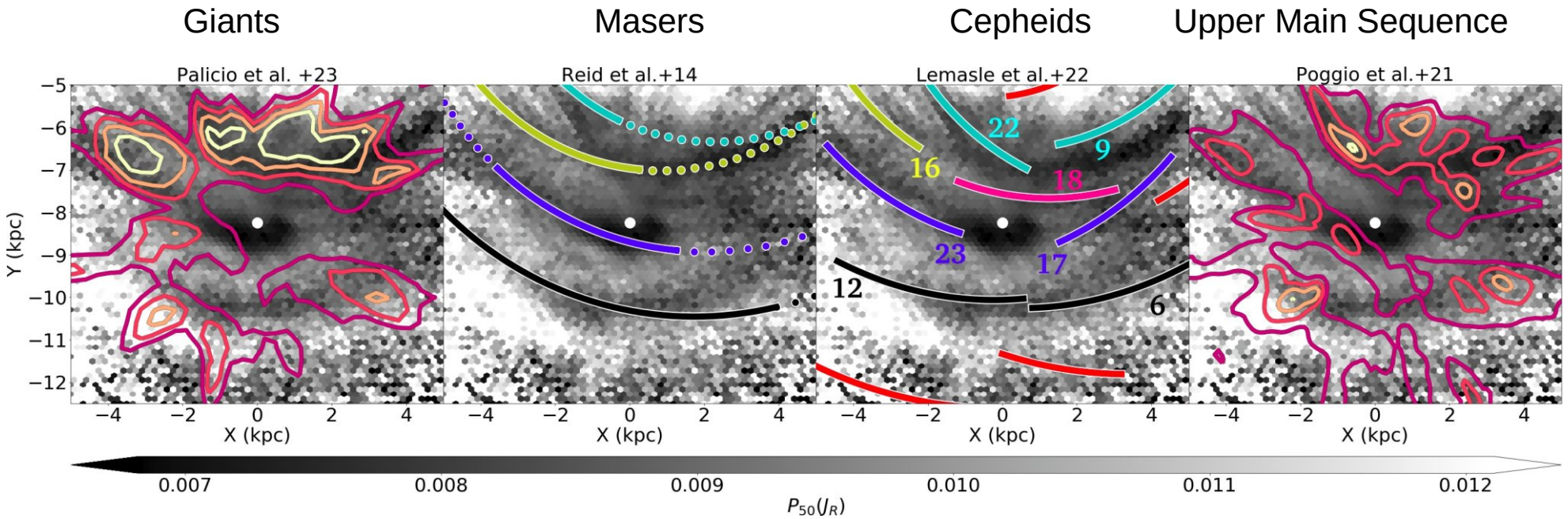

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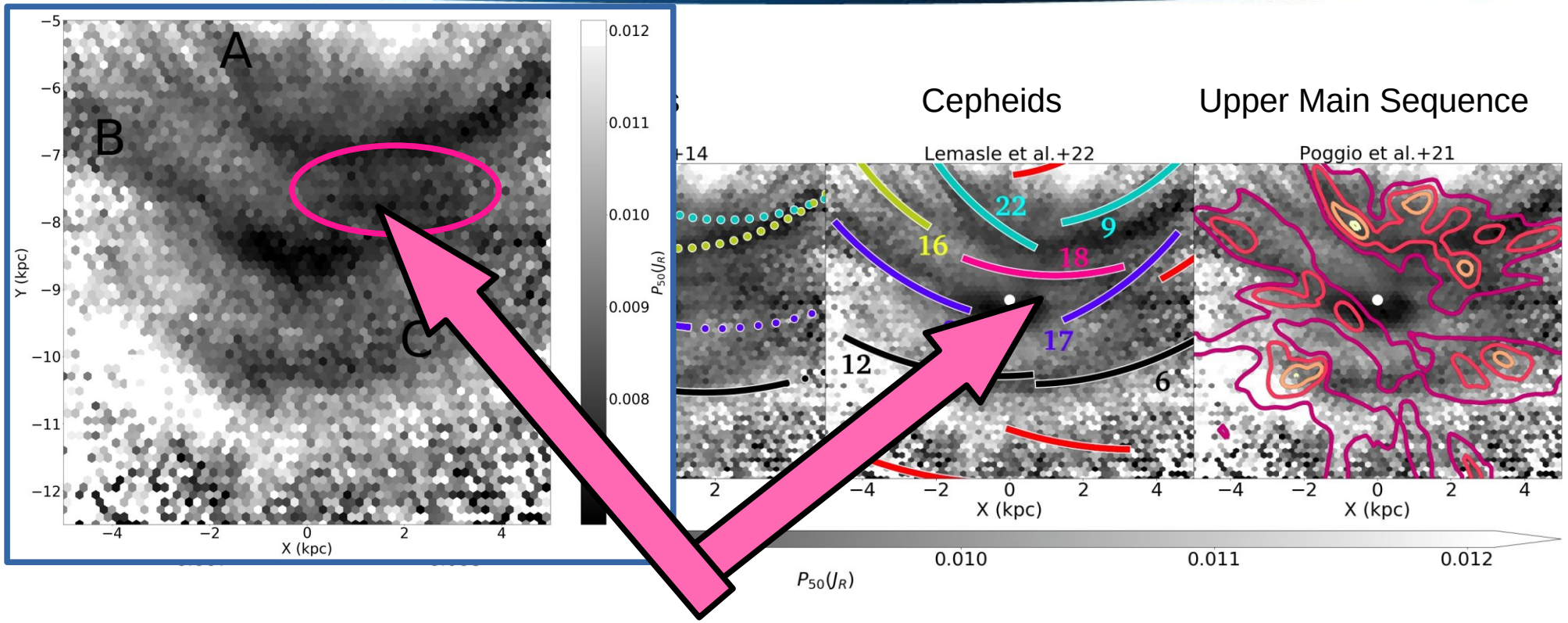
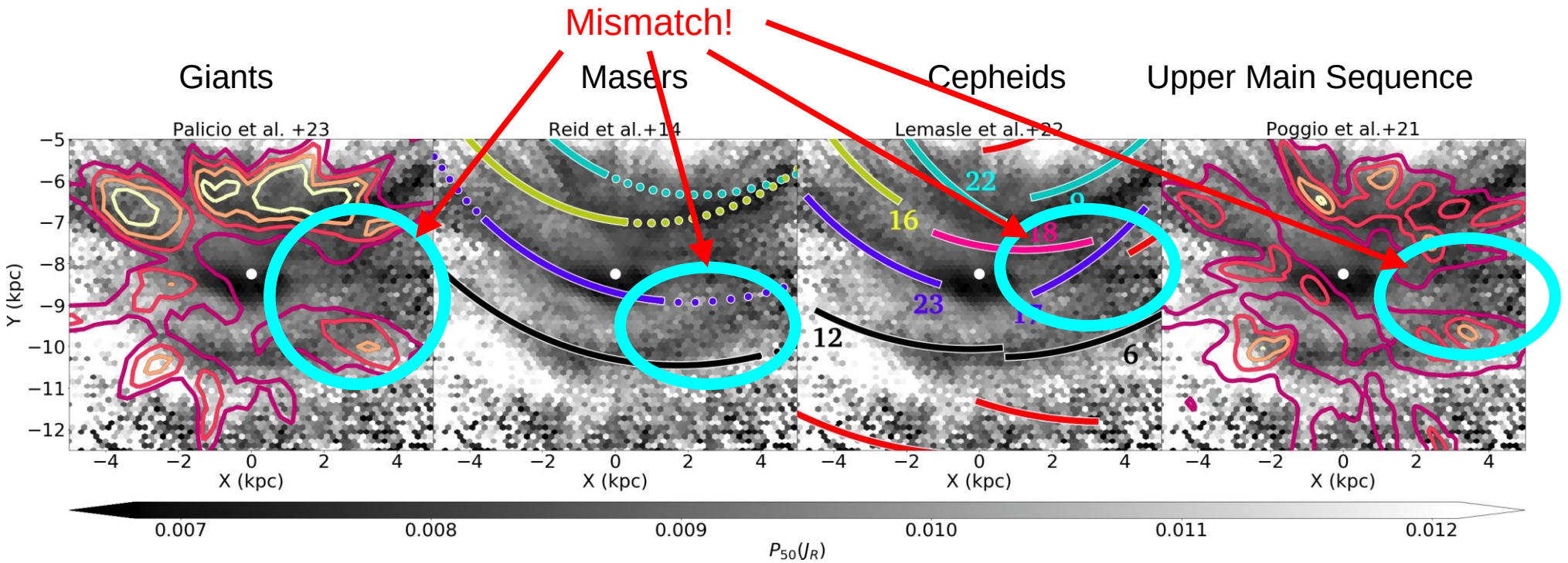


Segment 18: No clear spiral arm assignation in Lemasle+22…
but it is in our very low J_R region.

Structures in J_R

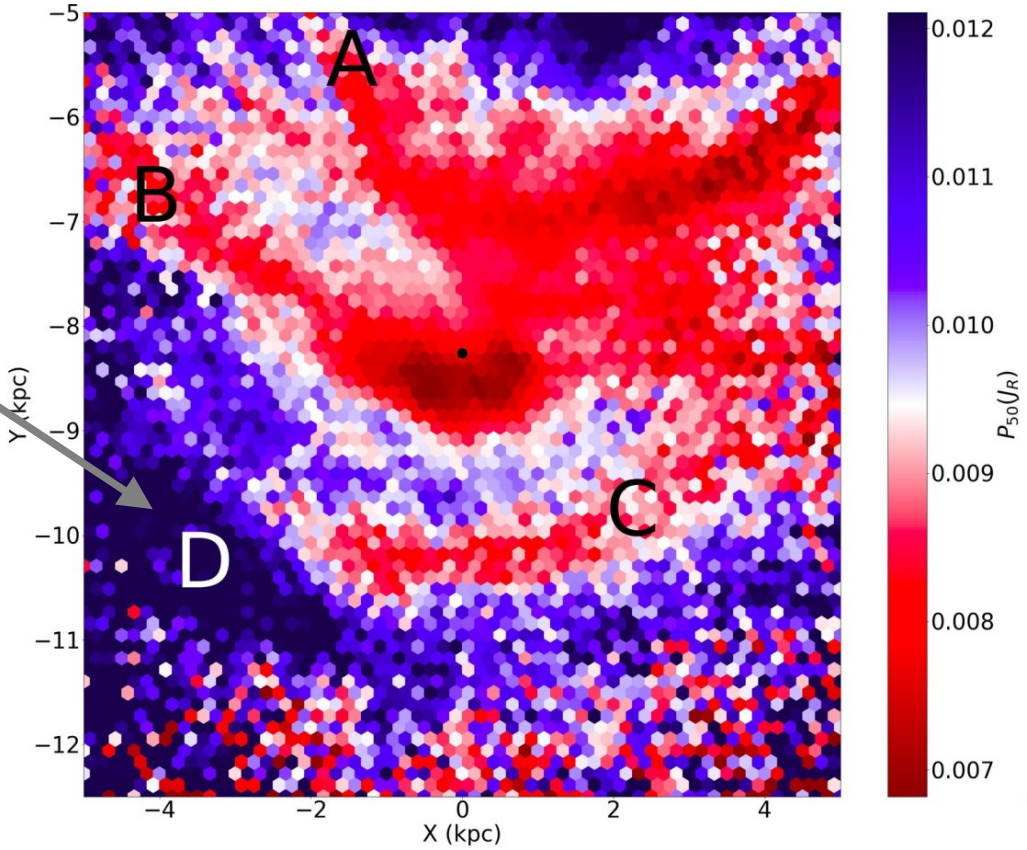


The structure D

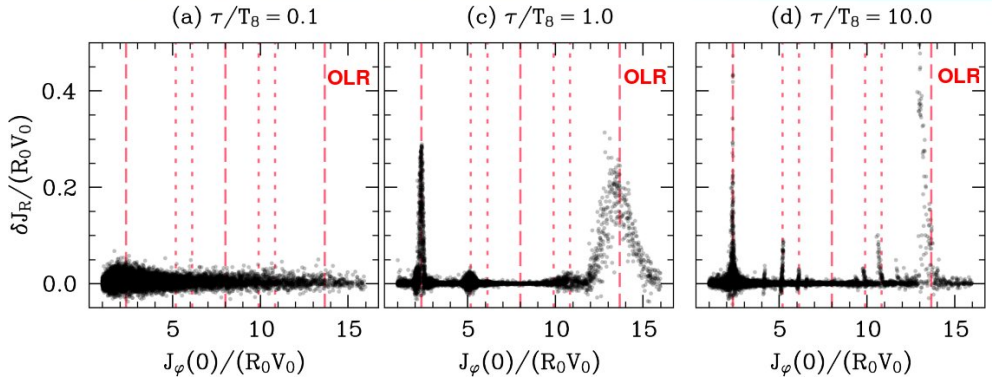
Signature of the outer Lindblad resonance (OLR)?

Sellwood & Binney (2002):

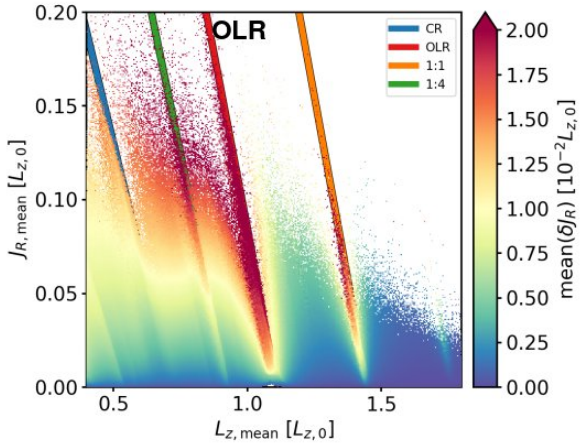
$$\Delta J_R = \frac{\Omega_{\rm bar} - \Omega_\phi}{\Omega_R}\Delta L_z = \frac{l}{m}\Delta L_z$$



The structure D: J_R at OLR



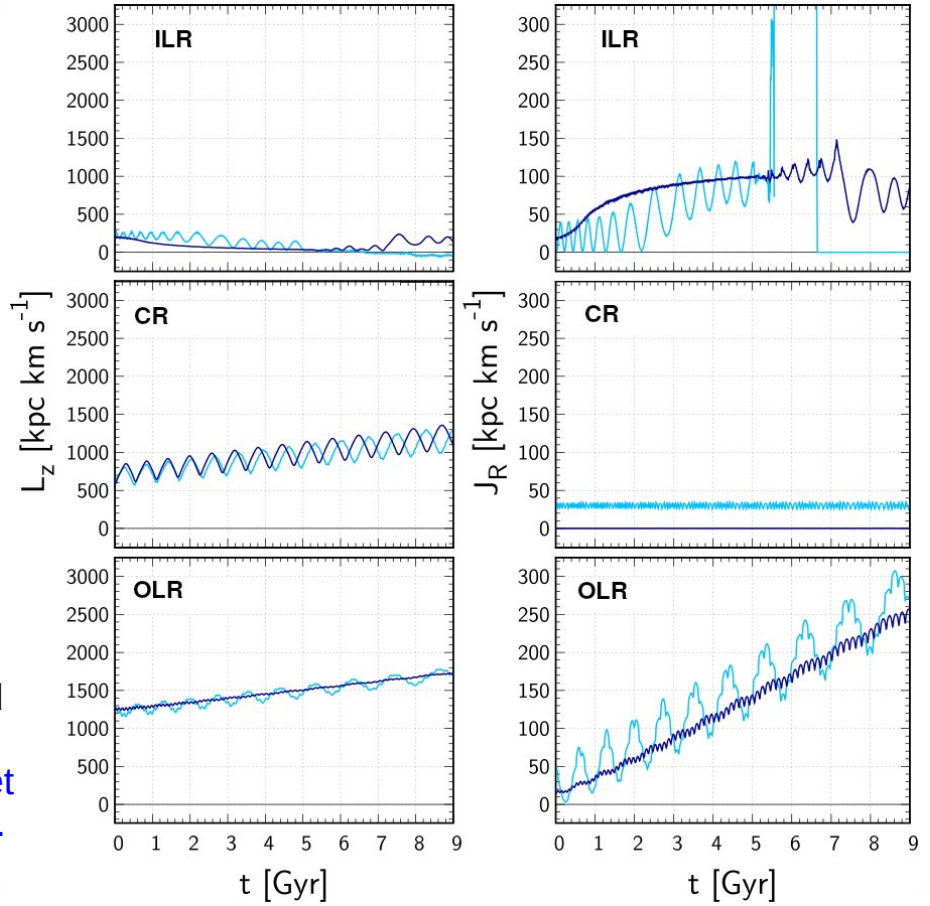
Hamilton et al. (2024)



(a) Amplitude of oscillation in the action plane in J_R-direction.

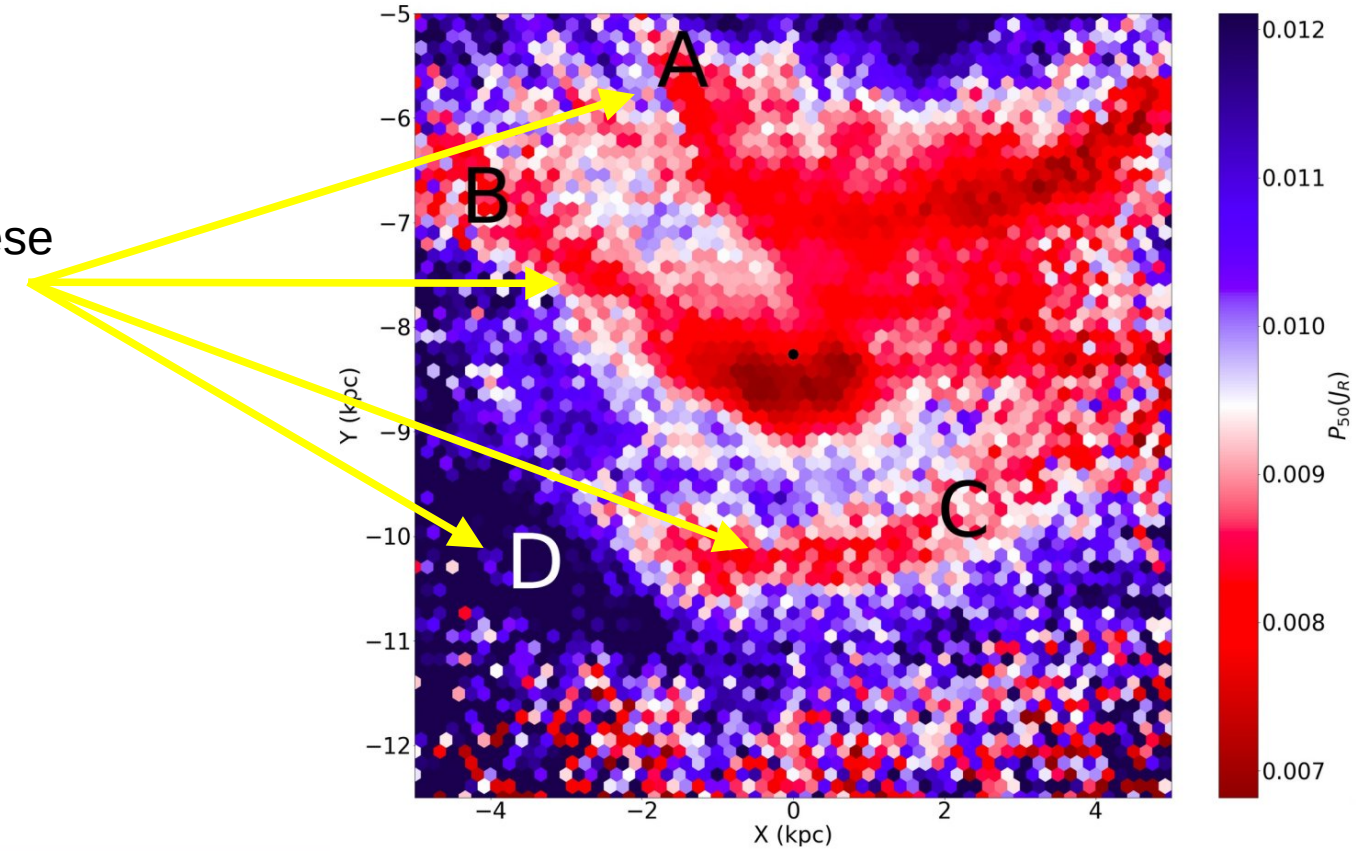
Trick et al. 2021

Adapted from Chibba et al. 2021.



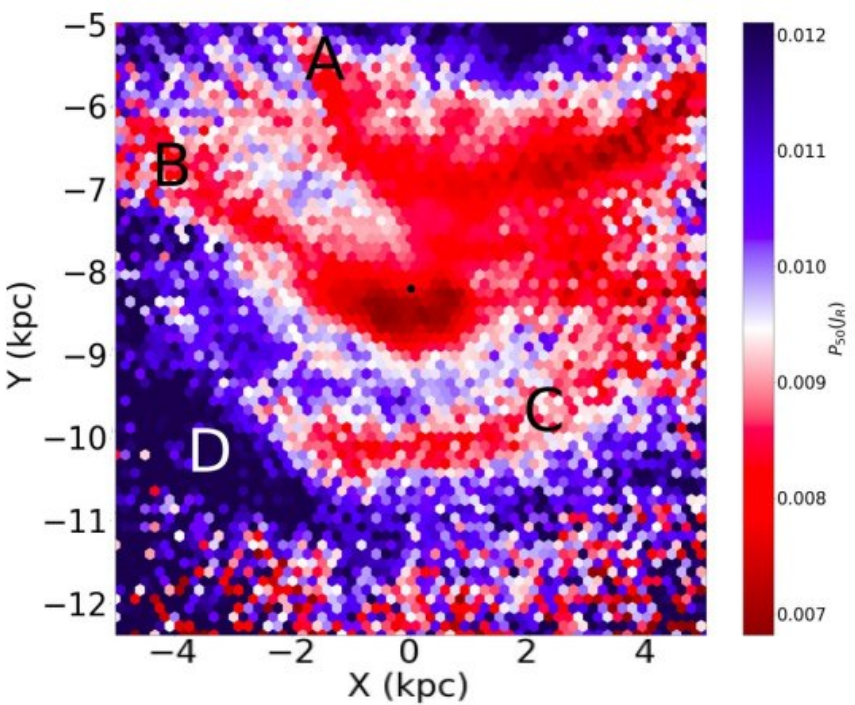
Alternative explanations

Can we explain these features without invoking the spiral arms?



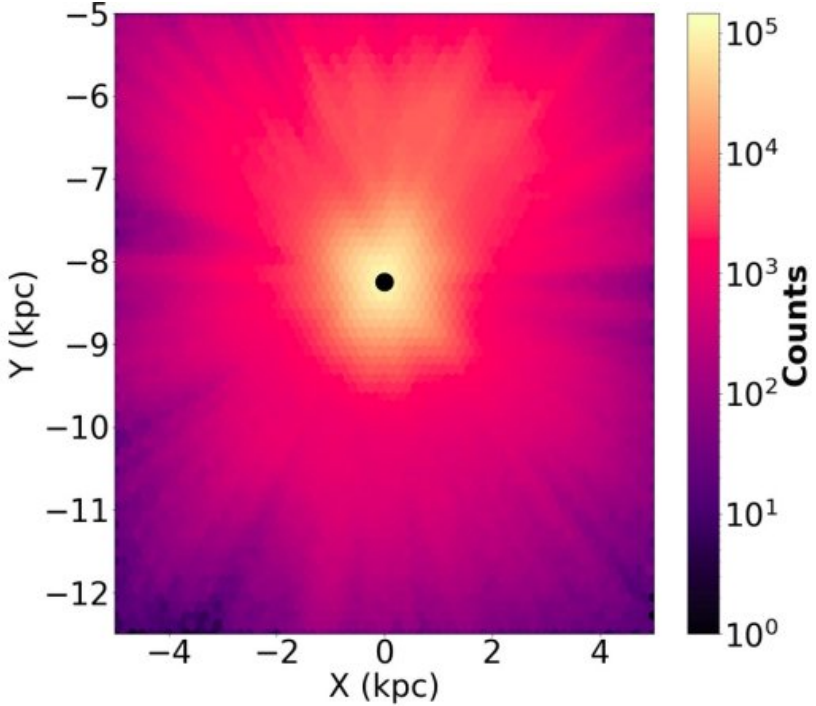
Alternative explanations

Median J_R



Arc-shaped structures

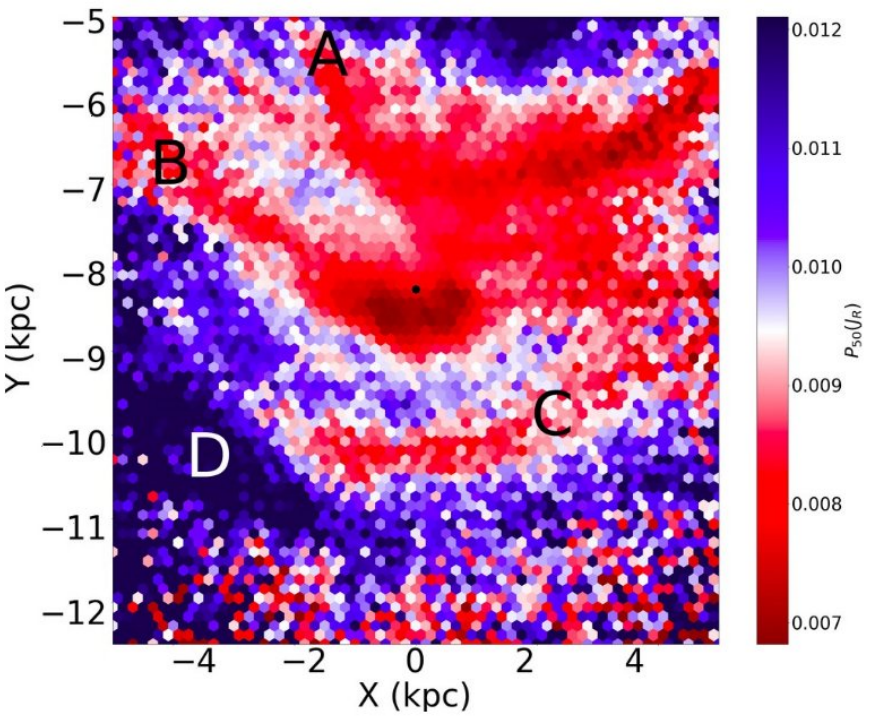
Density



- Max. in the Solar Neighborhood
- Decreases with heliocentric distance

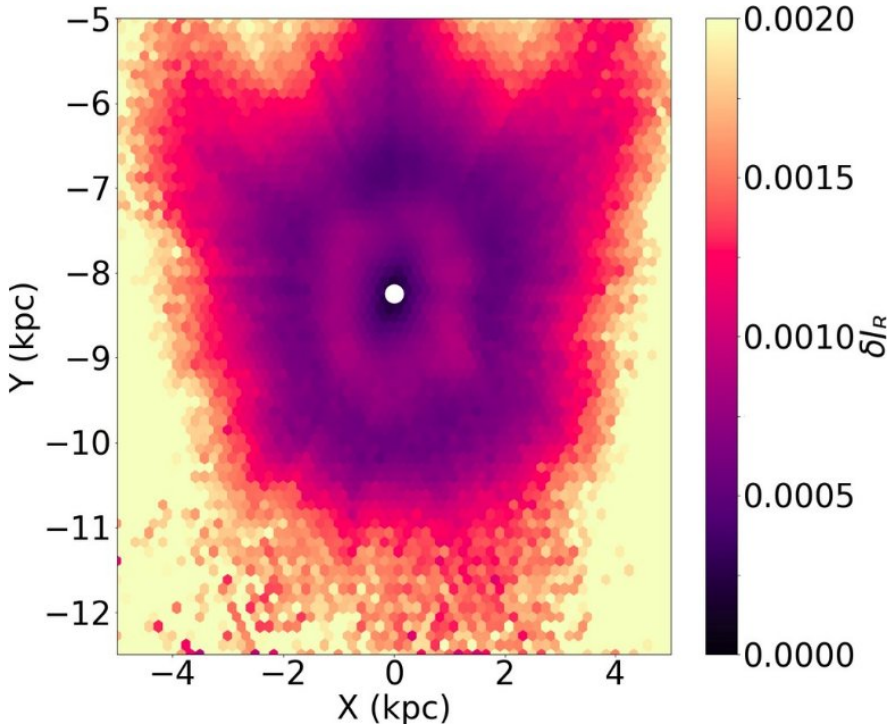
Alternative explanations

Median J_R



Arc-shaped structures

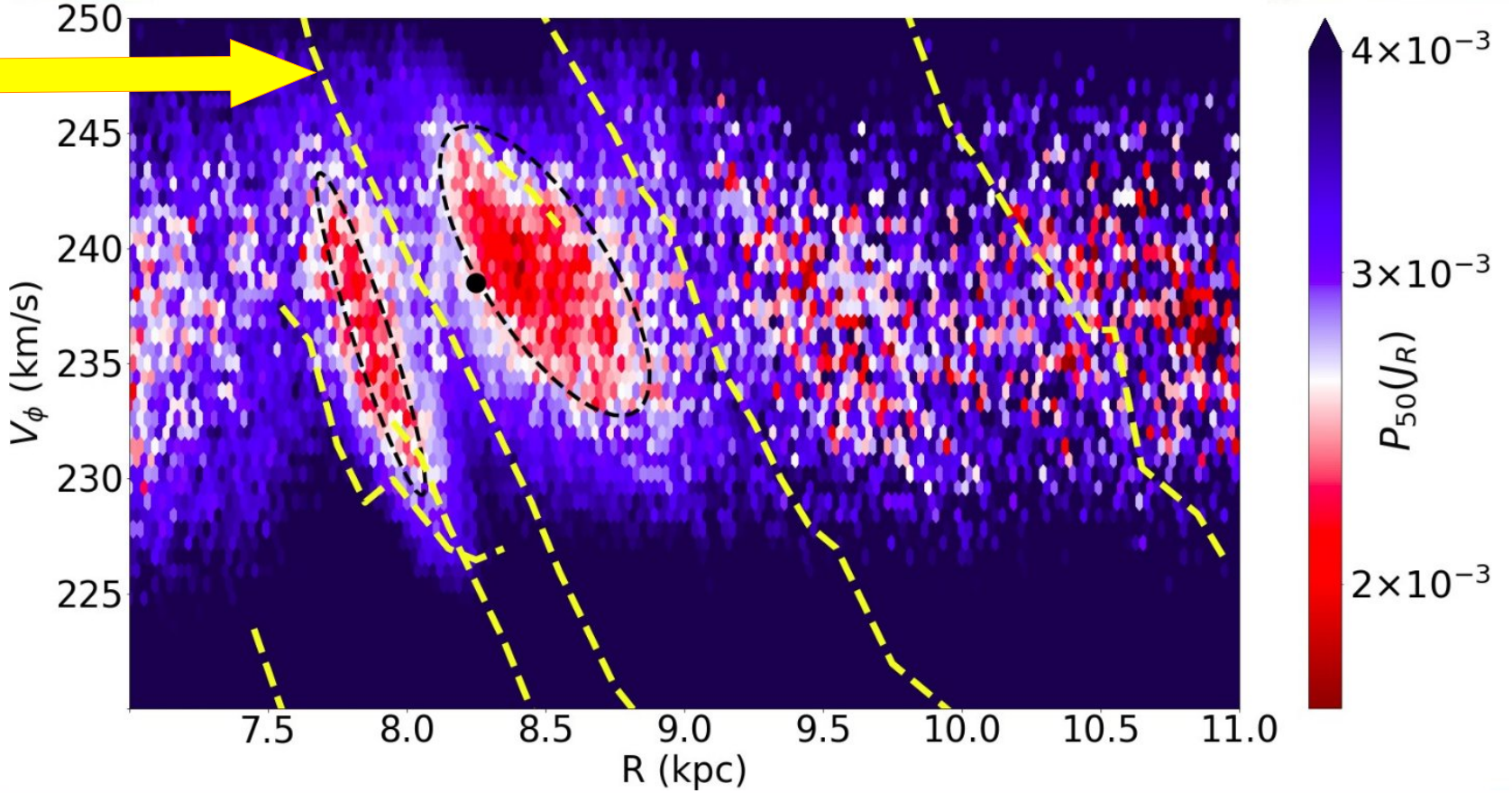
Error in J_R



Ring, but not arcs. Gaia's selection function.

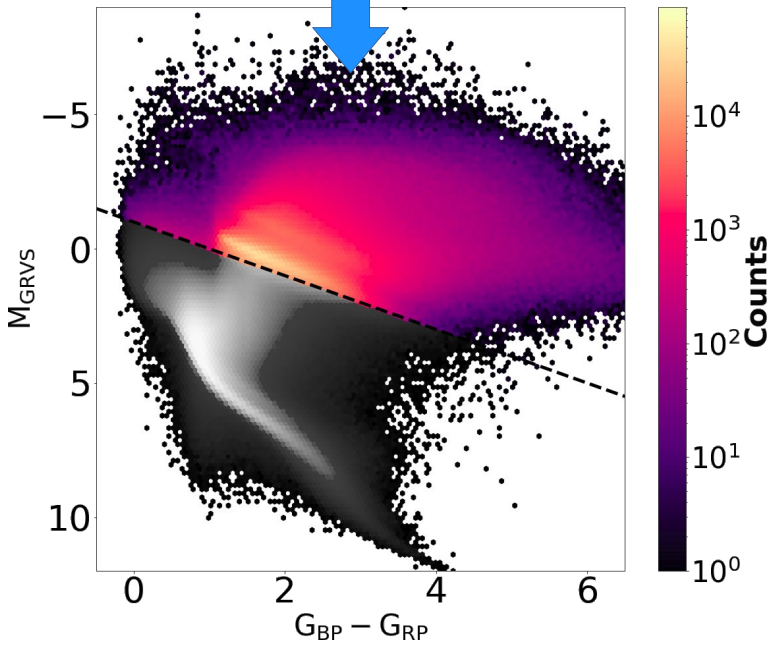
Moving groups?

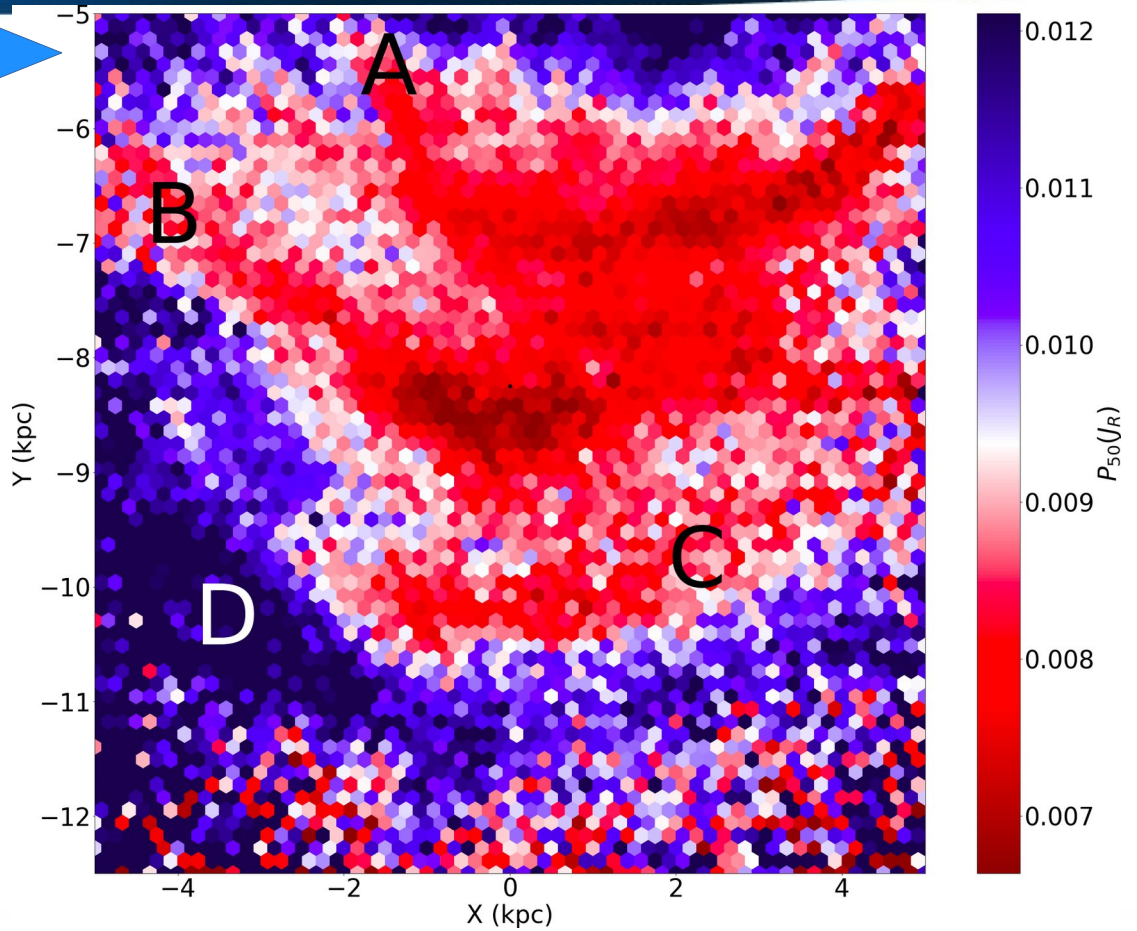
Ridges of Ramos et al. (2018)



Giant vs dwarfs

Only giants

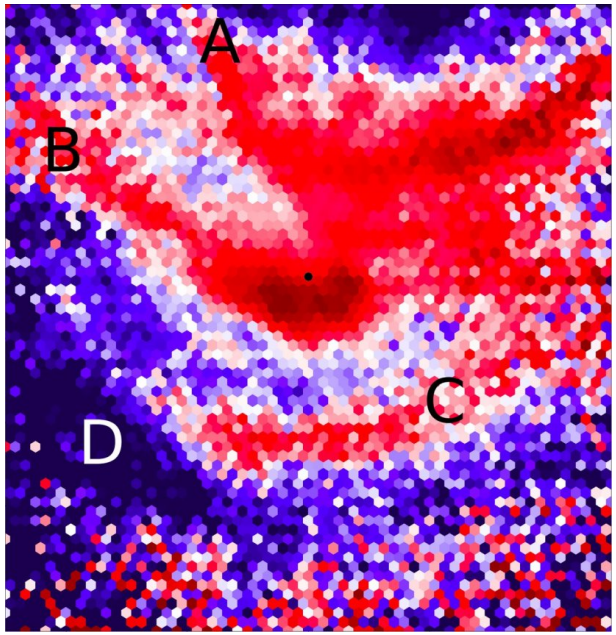




Quick summary of the observations

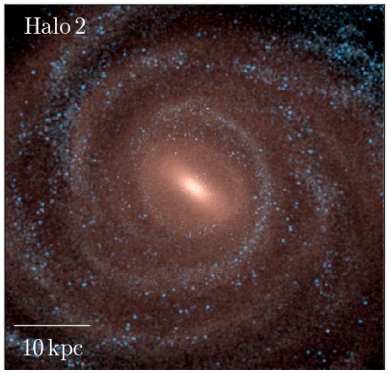
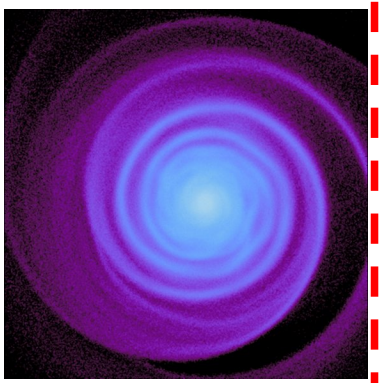
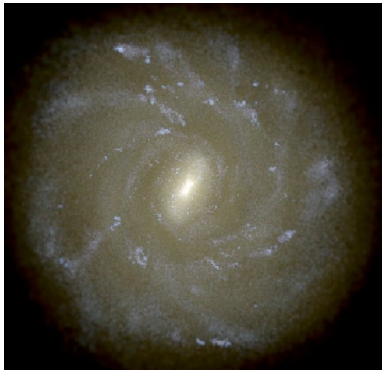
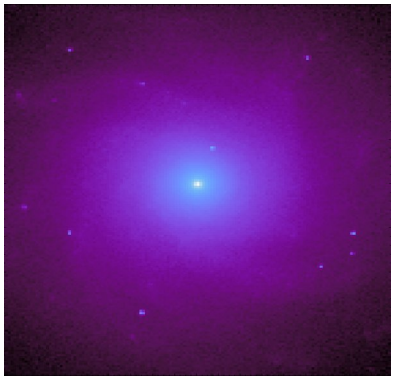
- **Arc-shape structures in the distribution of J_R** on the Galactic disc:
  - Likely associated to the **spiral arms** (though discrepancies).
  - Unlikely due to Gaia Selection Function, input errors or moving groups.
  - Also supported by **old, giant stars.**

- **Numerical simulations needed (Palicio et al., 2025)**



Simulations

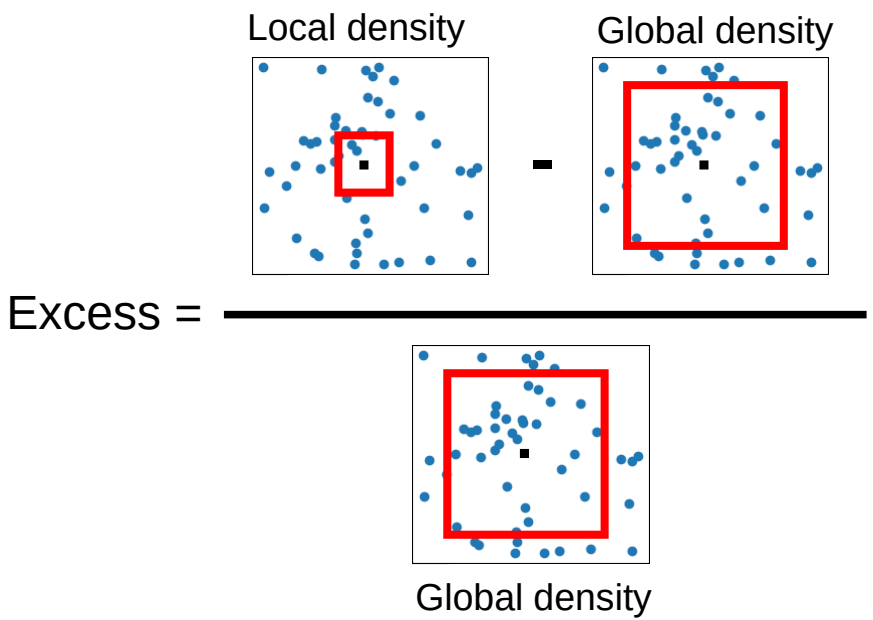
- 23 Simulated **Milky Way-like galaxies** from 5 independent groups

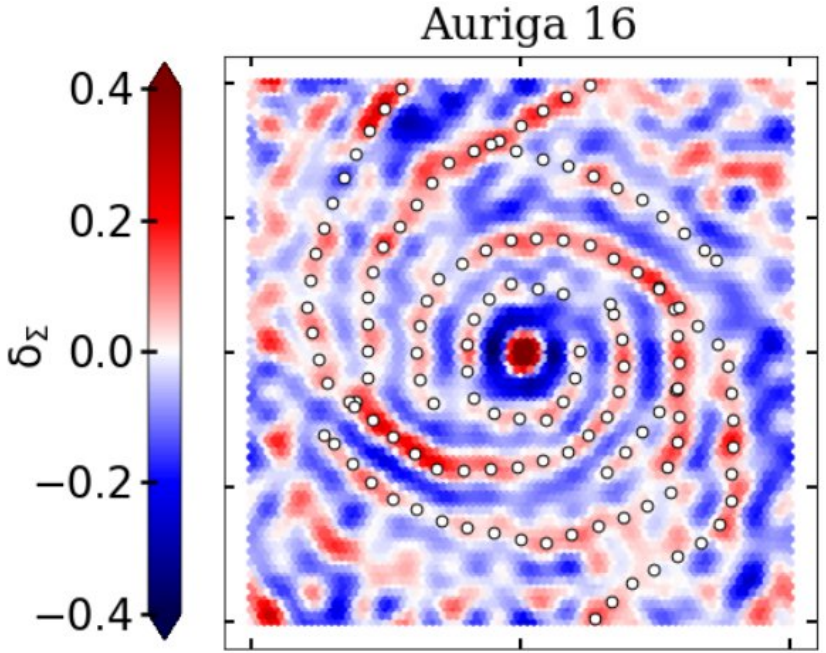
Auriga	Illustris TNG-50	NEXUS	NIHAO-UHD	NewHorizon
				
Grand et al. 2017, 2024	Pillepich et al. 2024	Tepper-García et al. 2024	Buck et al. 2020	Dubois et al. 2021
7 galaxies	10 galaxies	4 galaxies	1 galaxy	1 galaxy

Not discussed today

Methodology: Spiral Arm identification

- We use the **Kernel Density Estimator** (KDE) technique to **enhance the spiral arms** overdensity (Poggio+21).

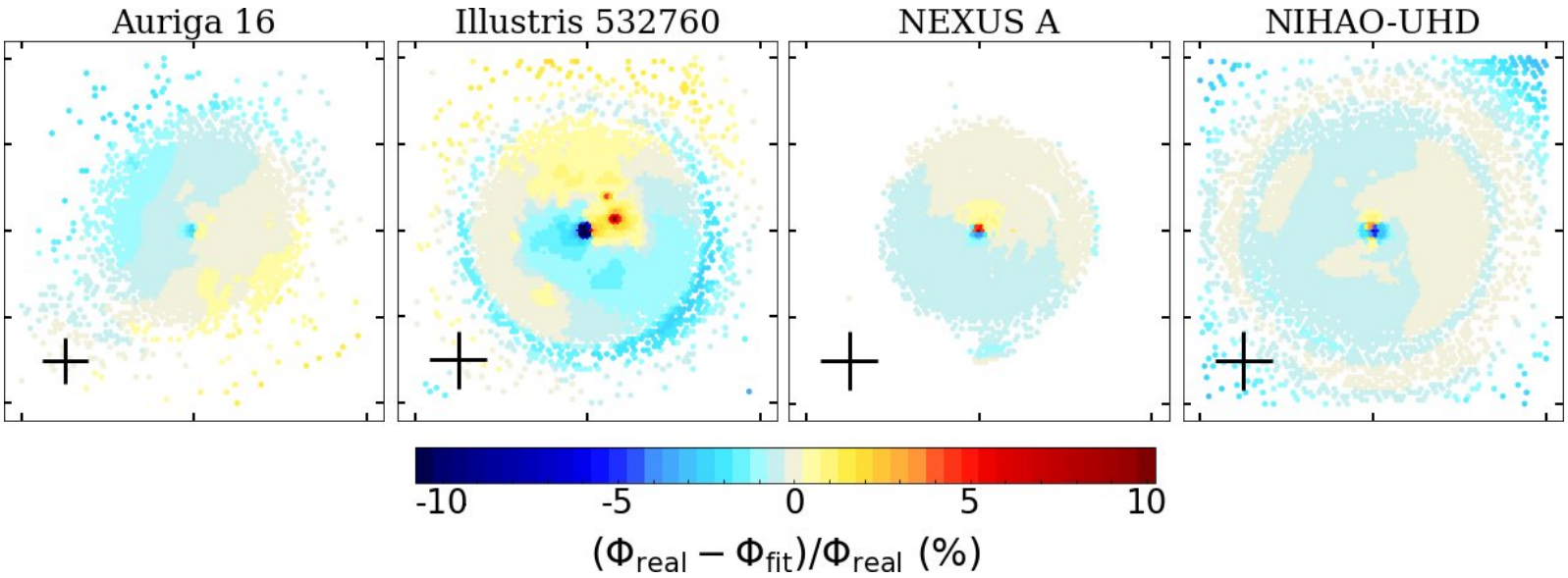




Methodology: Potential fit & Actions

We fit the potential by a series of polynomials

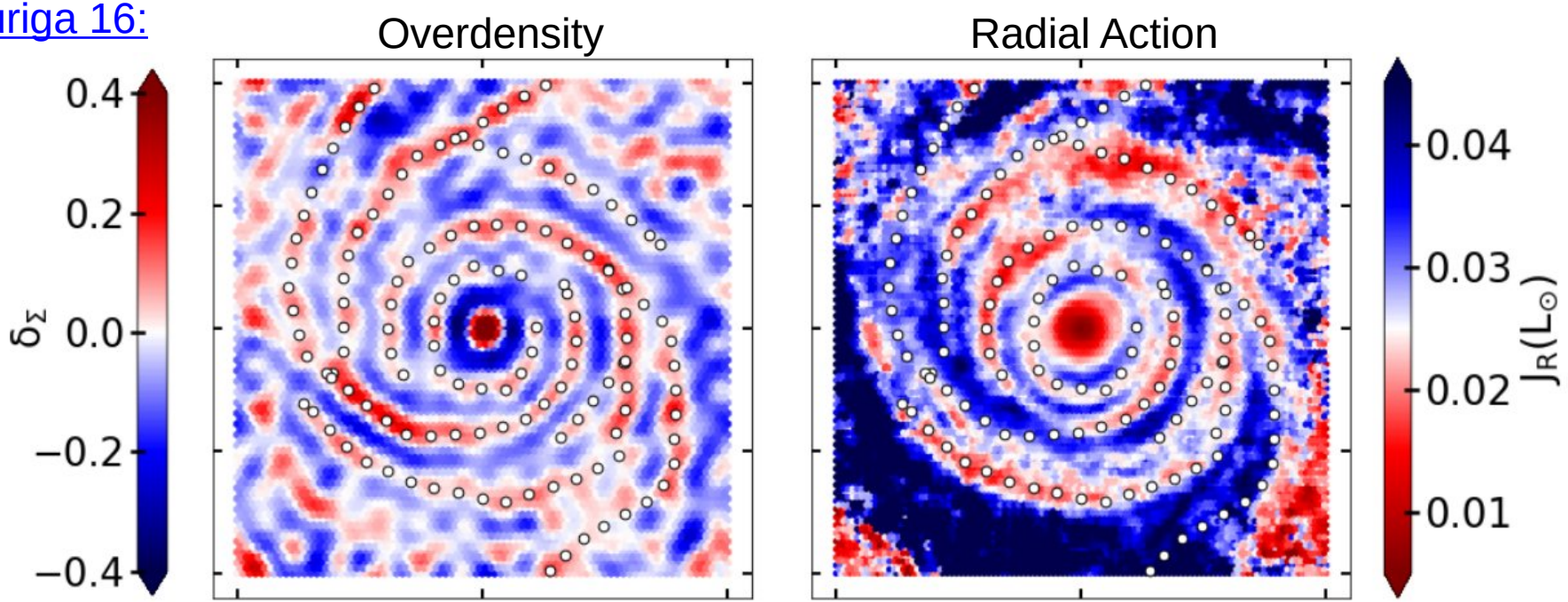
$$\Phi(r,\theta) = -\sum_{n=0}^{N}\sum_{\substack{\ell=0 \\ even}}^{L} A_{n,\ell}\sqrt{2\ell+1}\frac{(ar)^{\ell}}{(a+r)^{2\ell+1}}C_n^{(2\ell+3/2)}(\xi)P_{\ell,0}(\cos\theta)$$



Results: Radial Actions of Spiral Arms

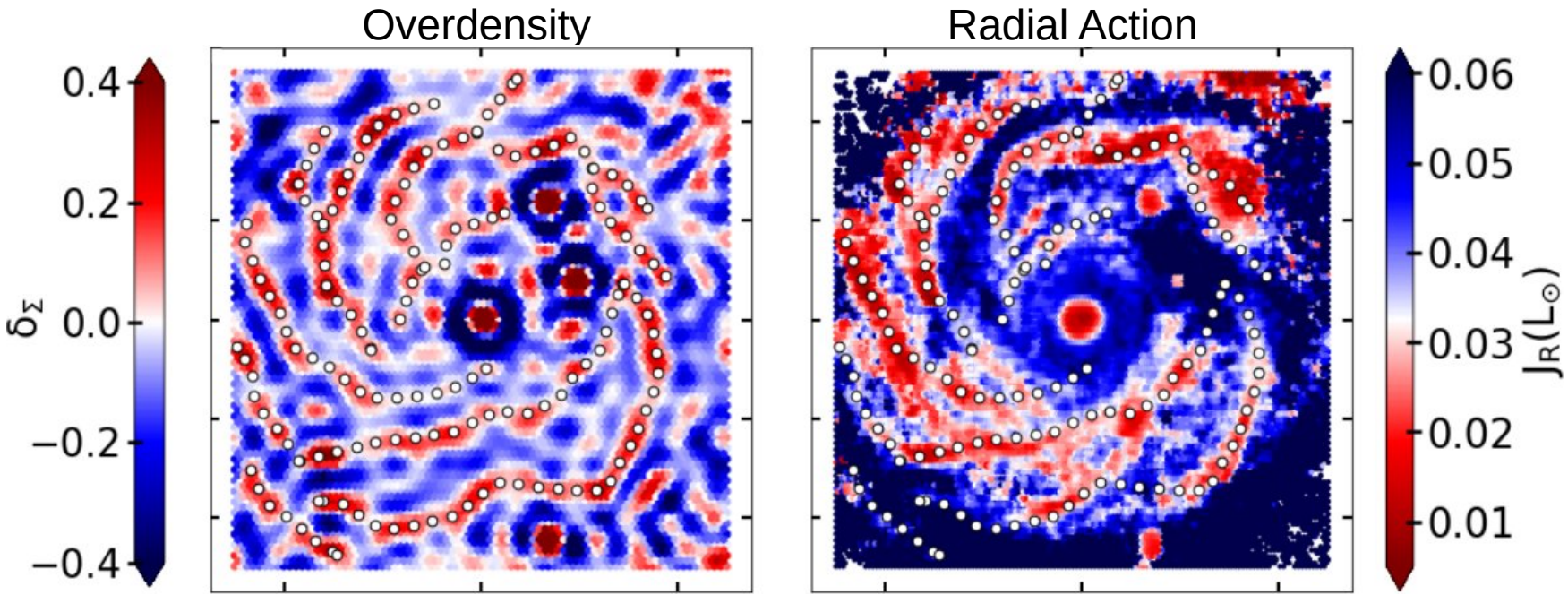
With the potential fit, we computed the **radial actions (J_R)** under the same **Staeckel approximation** used with the Gaia DR3 data, and mapped them.

Auriga 16:



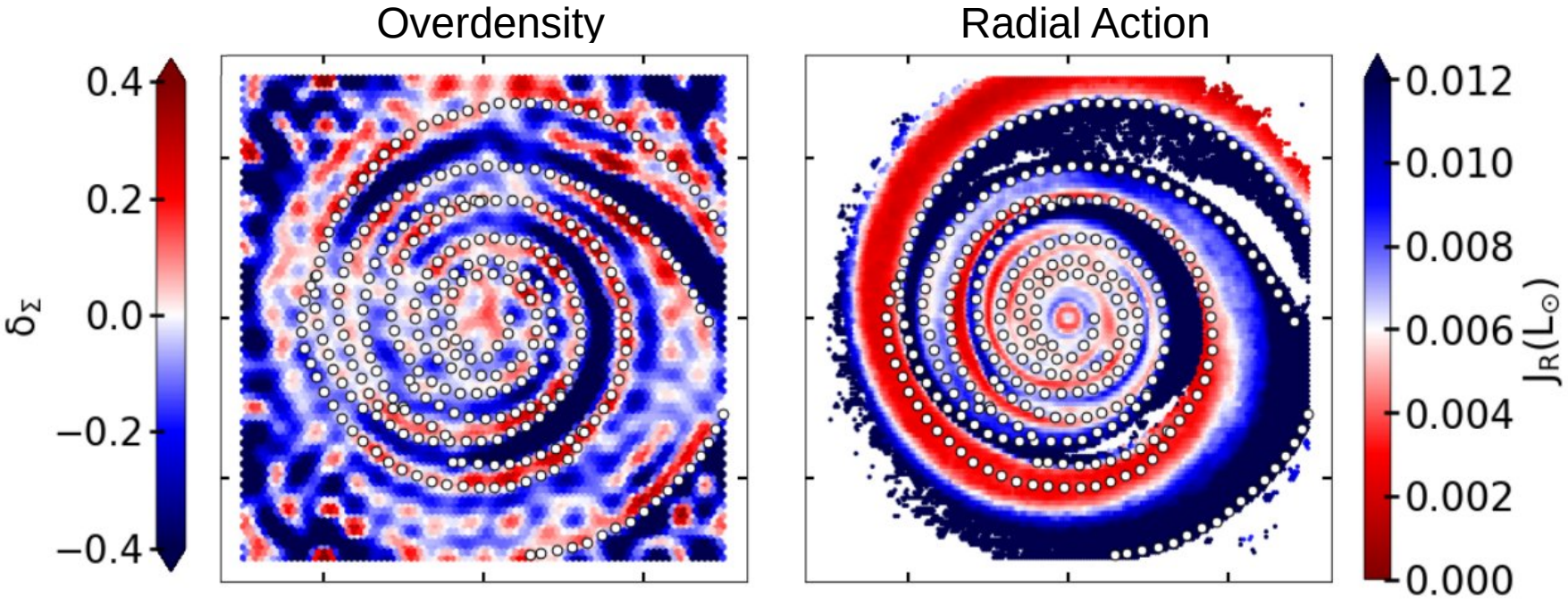
Results: Radial Actions of Spiral Arms

Illustris 532760:

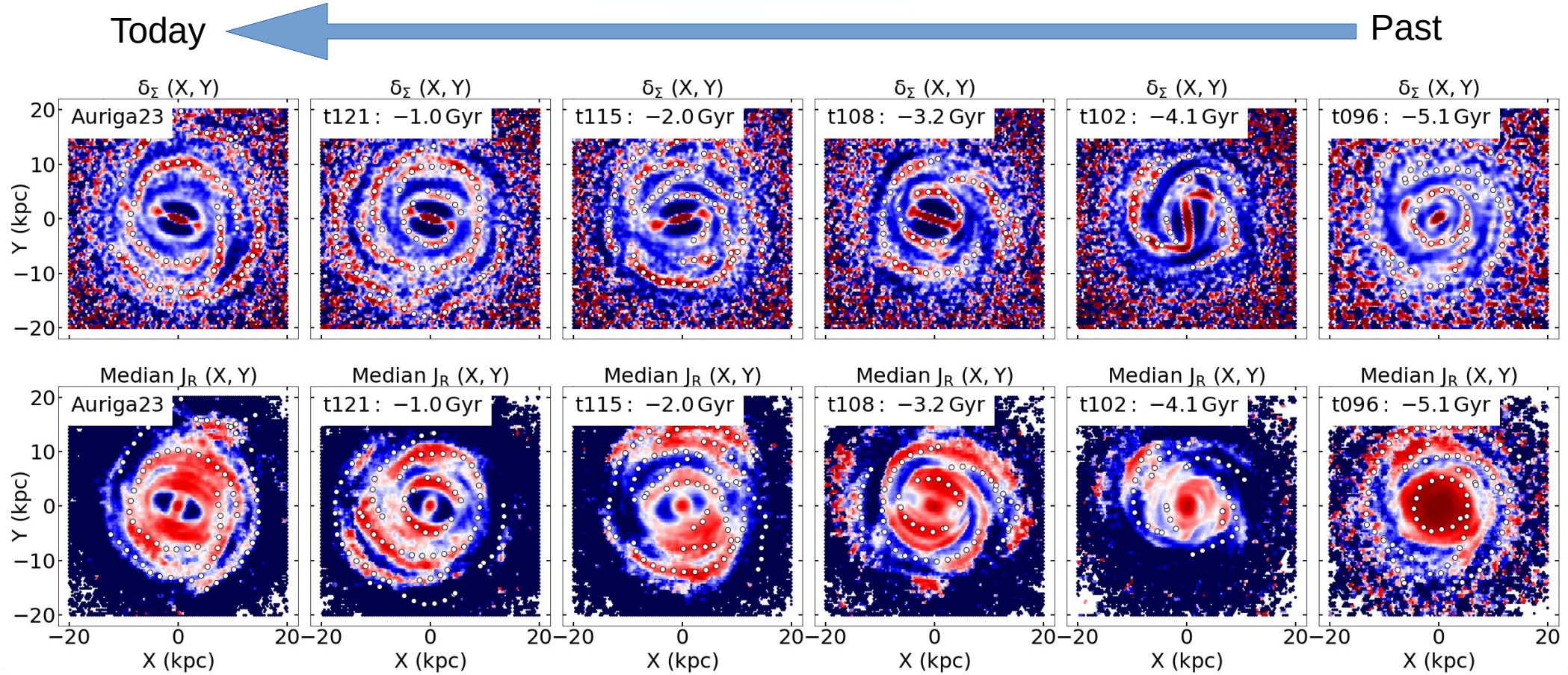


Results: Radial Actions of Spiral Arms

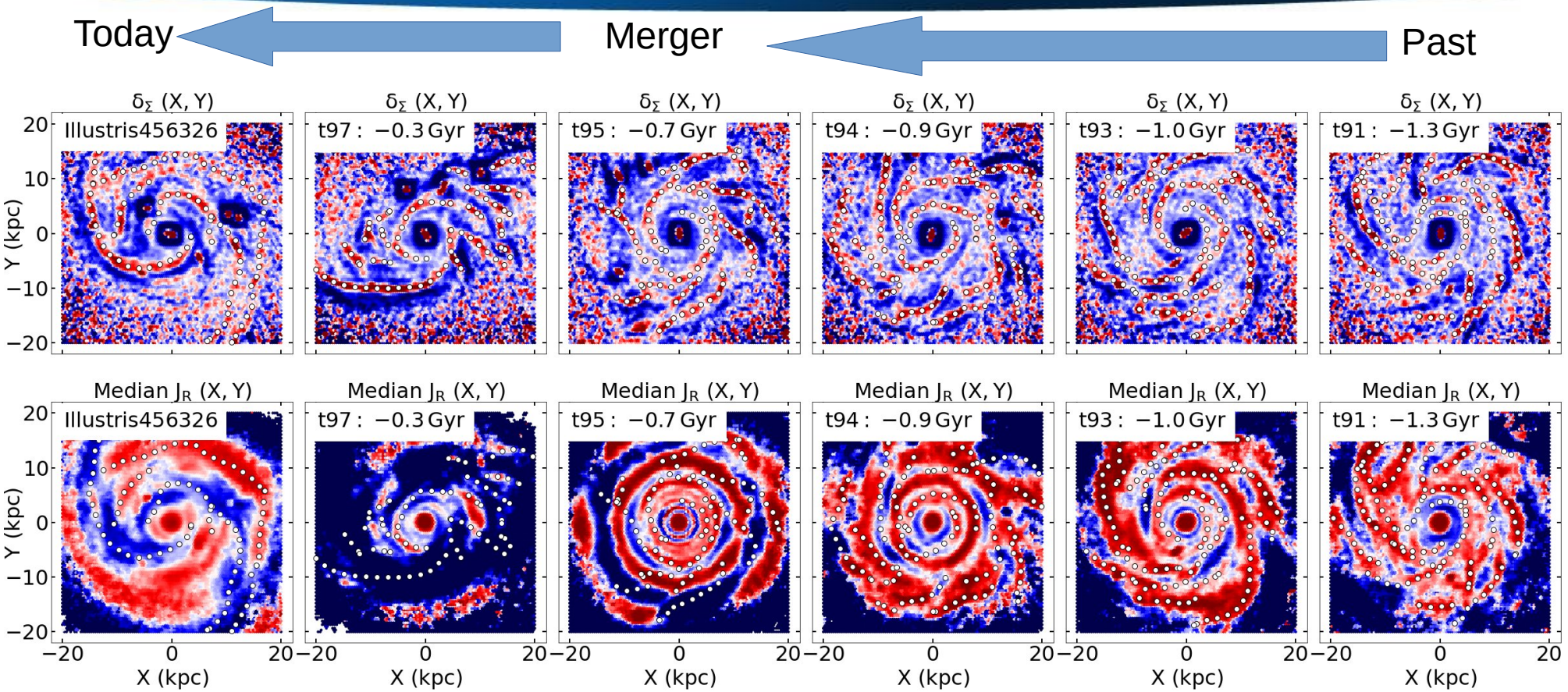
NEXUS: Still Winding up spiral



Results: Barred galaxy (Auriga 23)



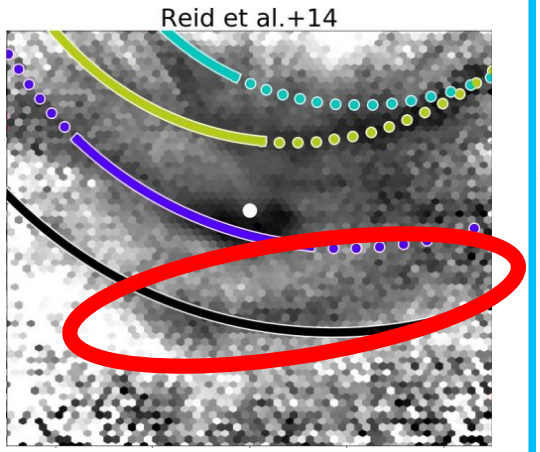
Results: Mergers (Illustris 456326)



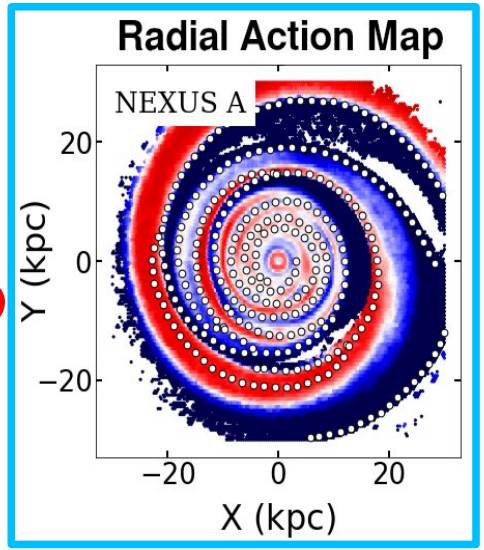
Perseus Arm mismatch

Can one of these scenarios explain the mismatch between JR and the Perseus spiral arm?

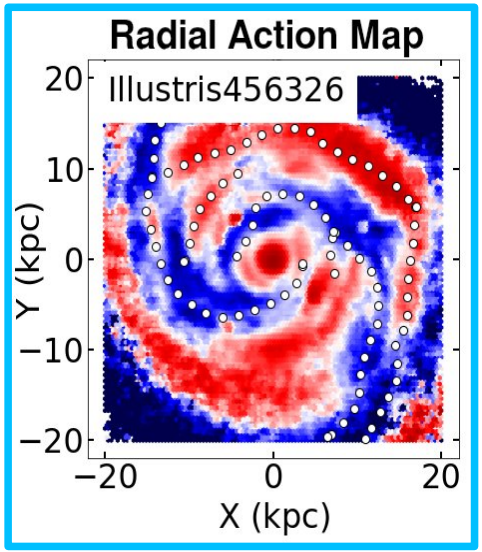
Observations



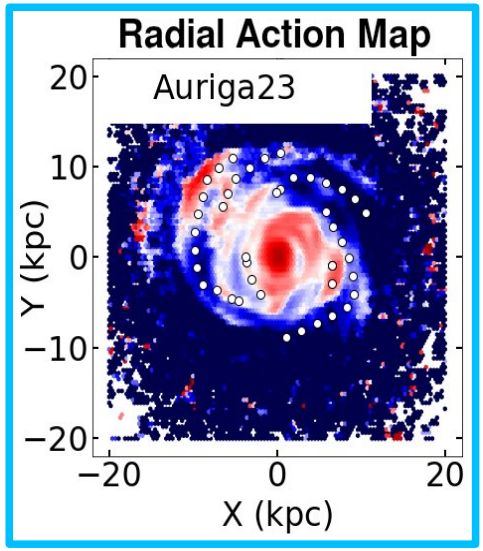
Winding-up spirals



Mergers

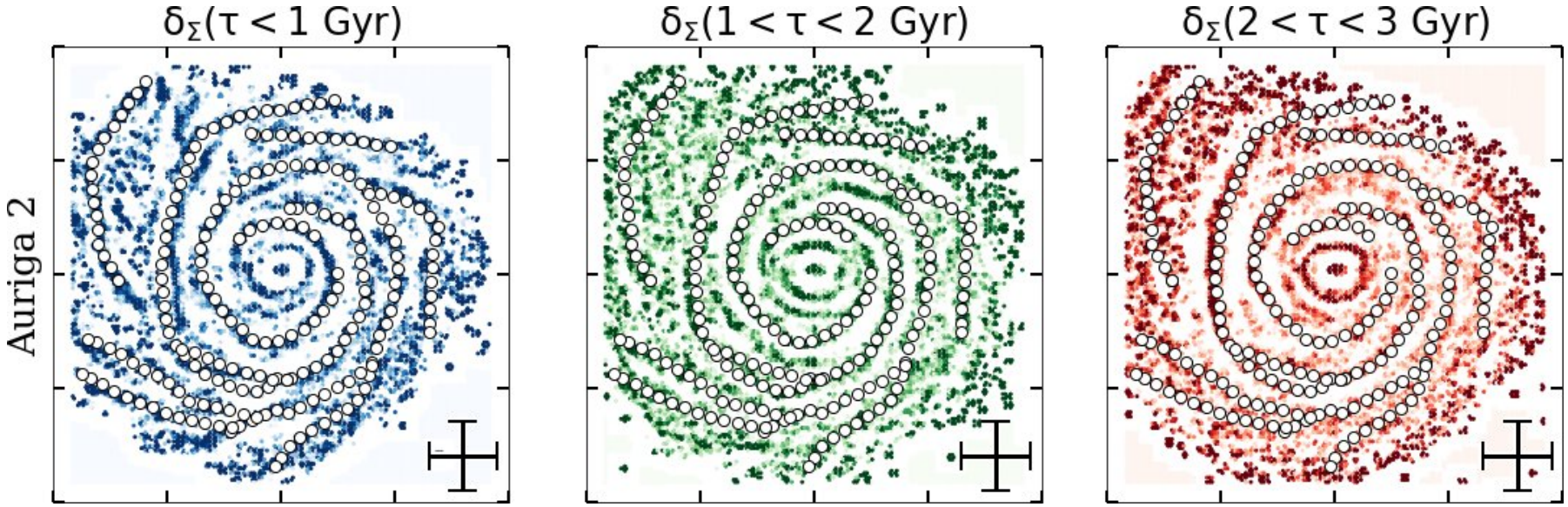


Strong bars



Results: Old populations in Spiral Arms

- Populations up to 3 Gyr can trace the spiral arms.



Conclusions

- The statistics of **the radial actions reveal arc-shape structures** in the Galactic disc (**Palicio et al. 2023a**).
- The **spiral arms** account for most of these structures, but there are some discrepancies that must be addressed: the spiral structure of the Milky Way might be different depending on the considered stellar population.
- The arc-structure reported is supported by the **old, giant stars without a dominant contribution of the moving groups**. This contrast with the usual young tracers for the spiral arms.
- **Numerical simulations** confirm observed spiral arms-J_R relation **Palicio et al. (2025).**
- **Discrepancy in the Perseus arm:** three possible explanations (winding up spiral, bar effect, merger/interaction). Further studies with ages required.