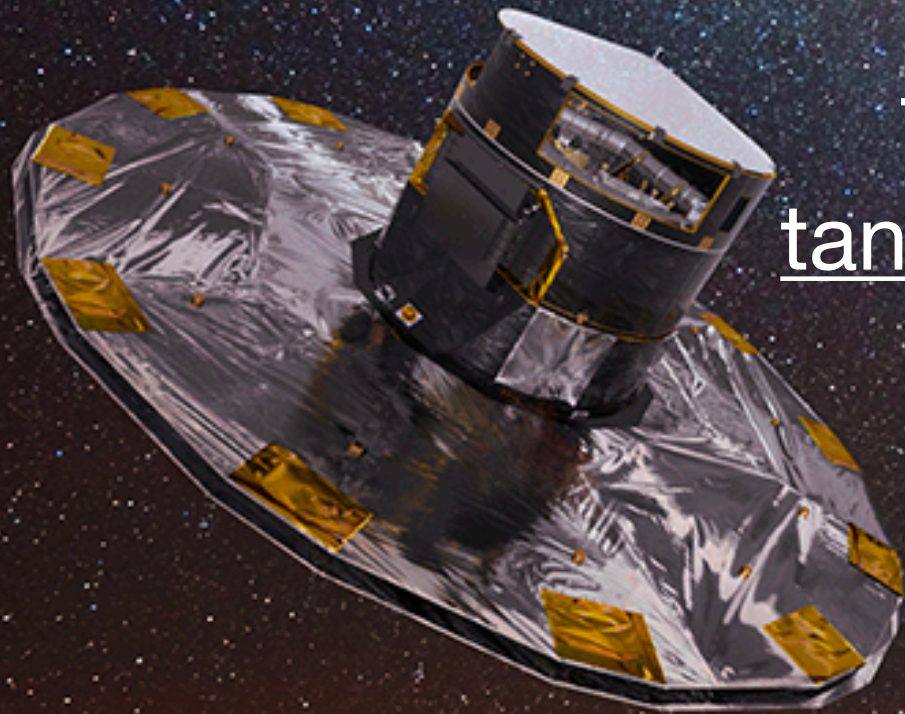


Late accretion history of the Milky Way encoded in the disc phase space

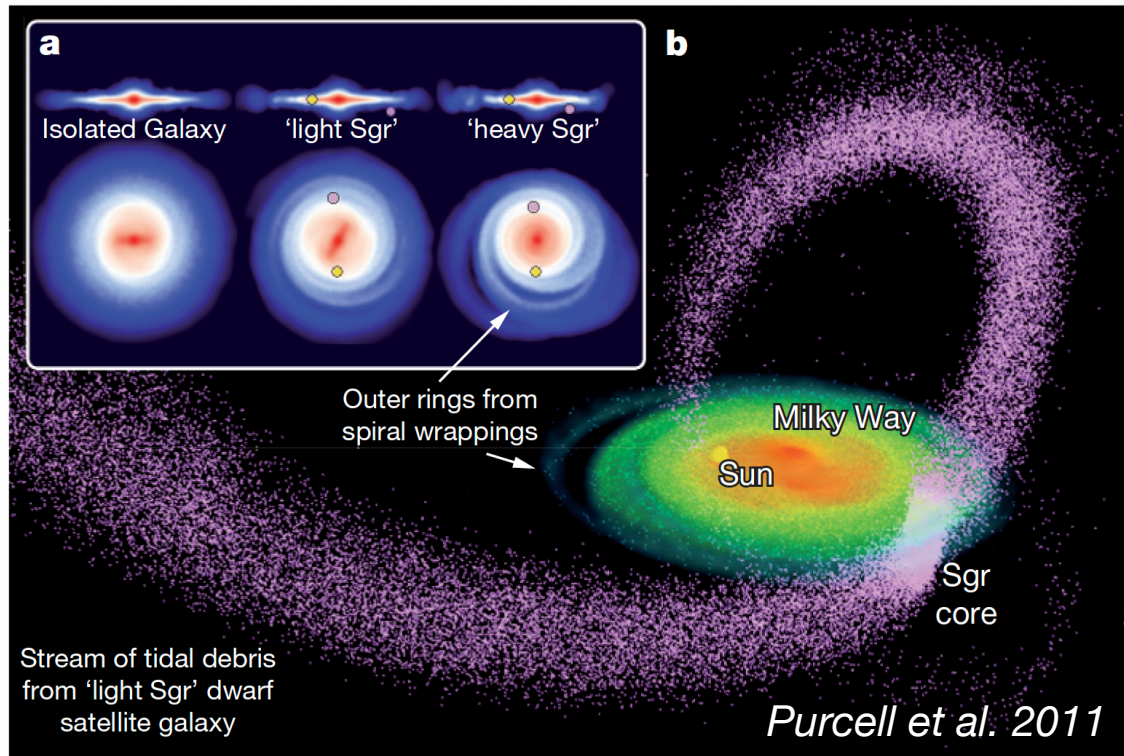


Teresa Antoja
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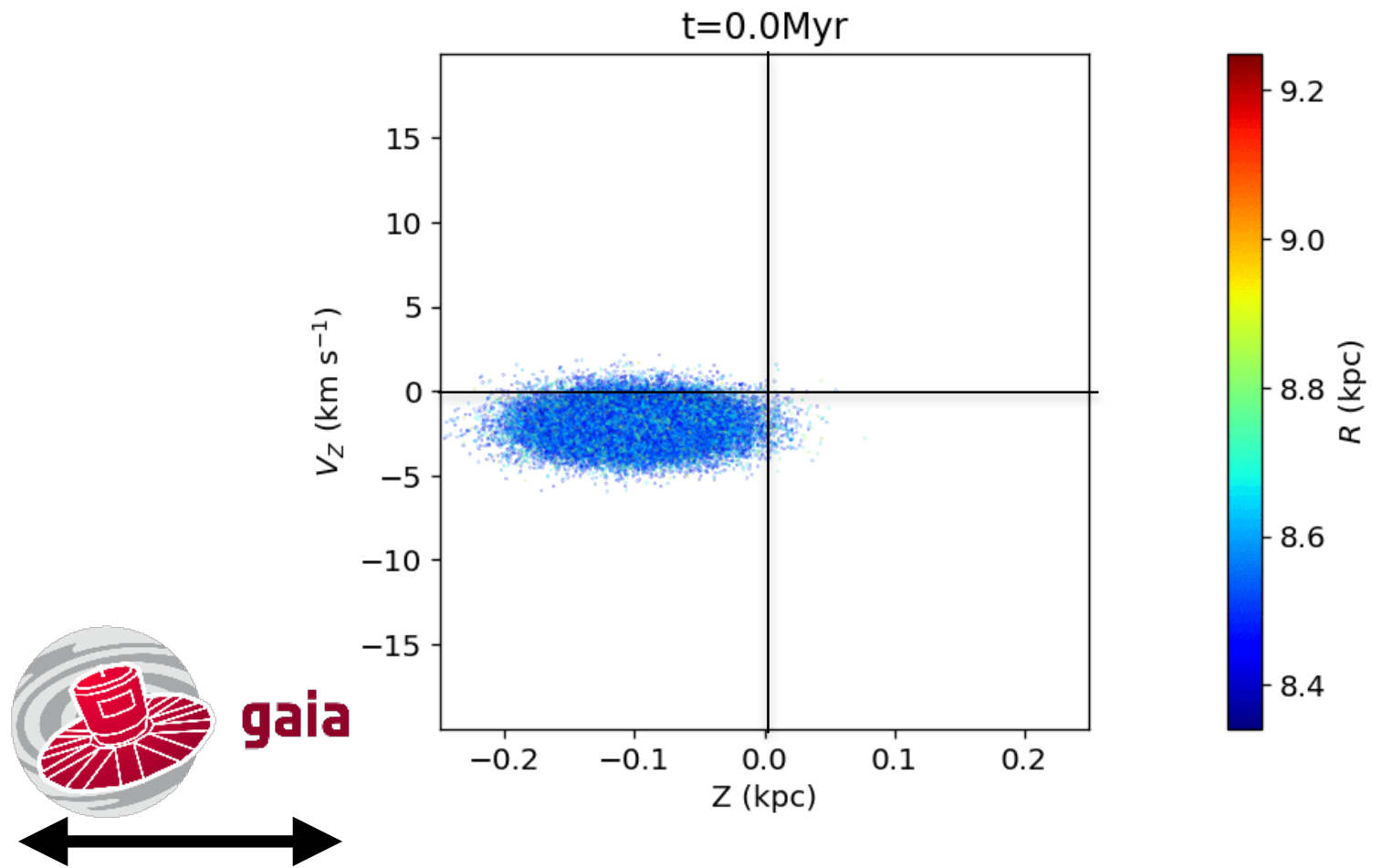
The Milky Way Assembly tale
Bologna
May 2024



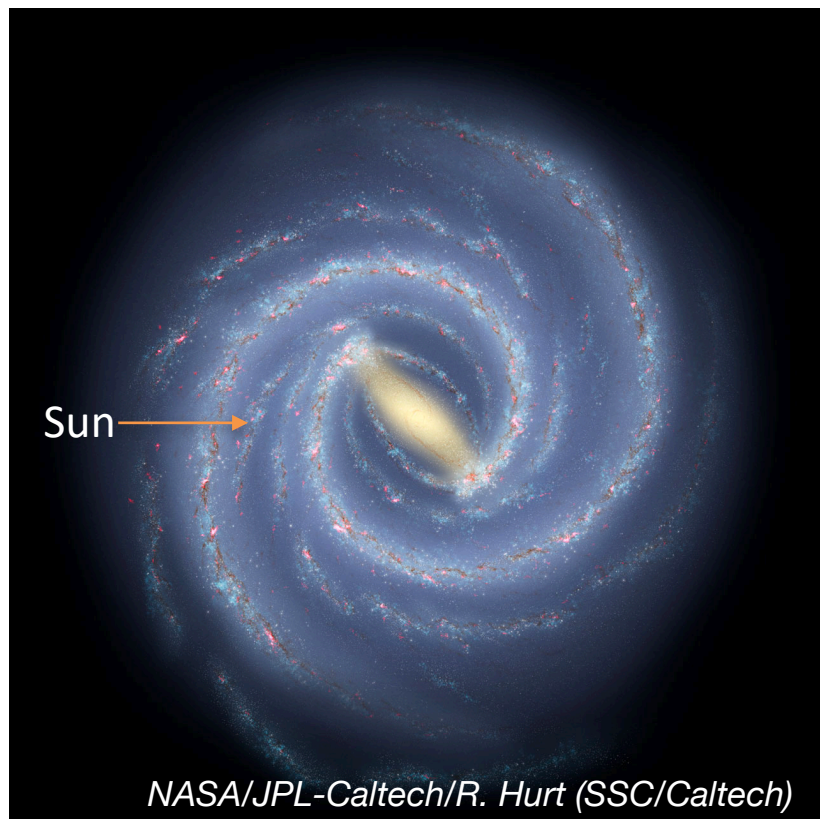
EXTERNAL: Sagittarius, LMC



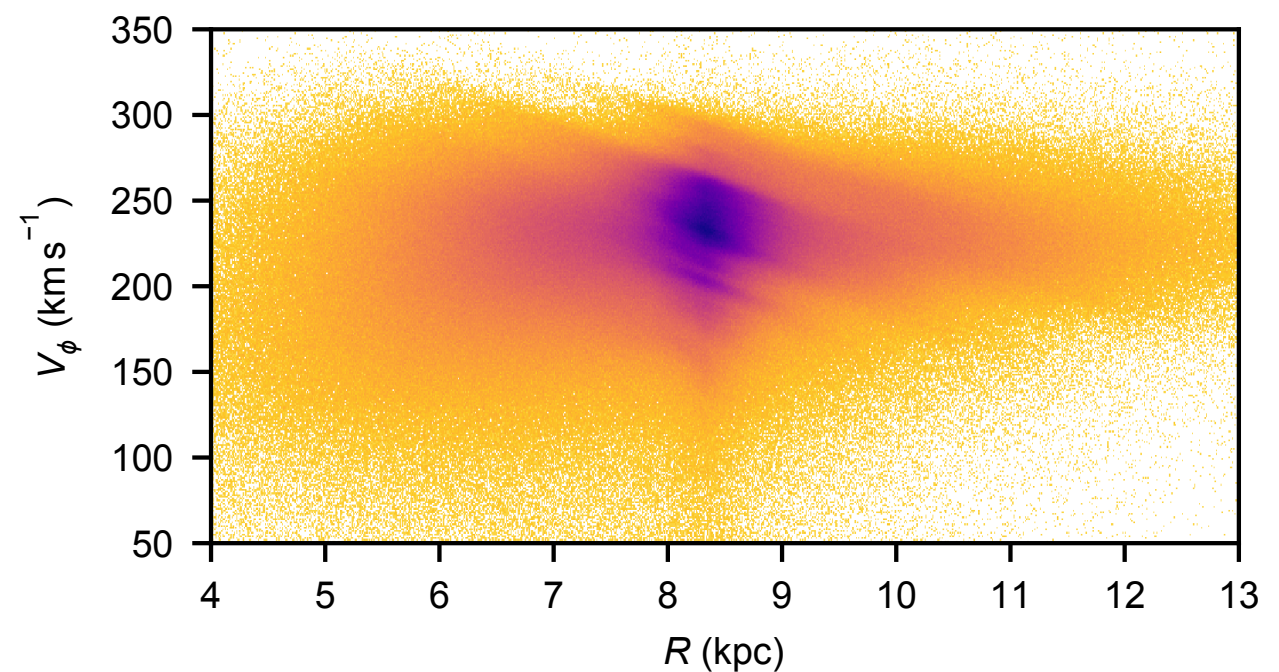
PHASE SPIRAL



INTERNAL: bar, spiral arms



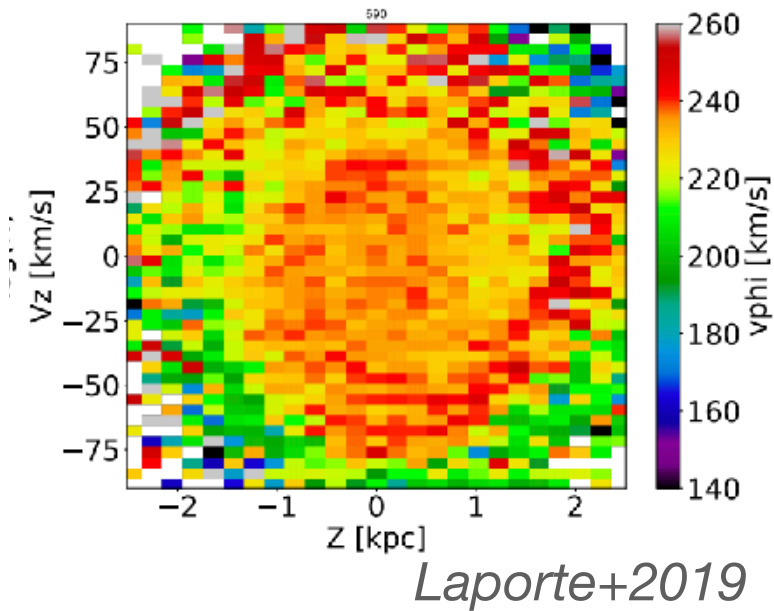
MOVING GROUPS / RIDGES



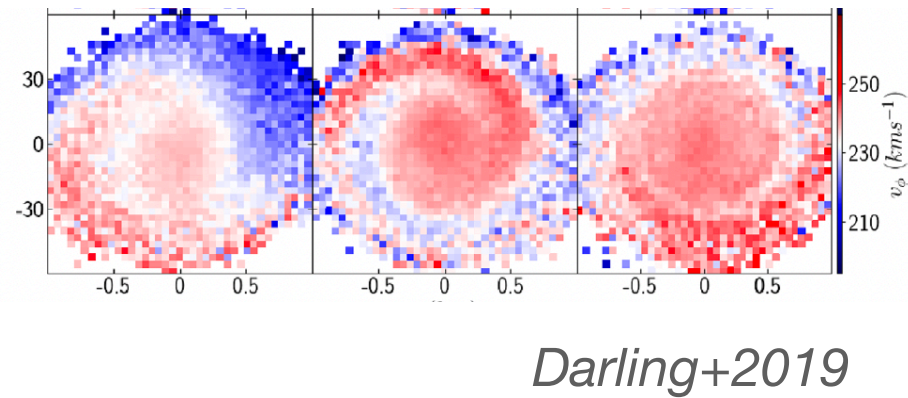
Antoja+2018

Origin of the phase spiral

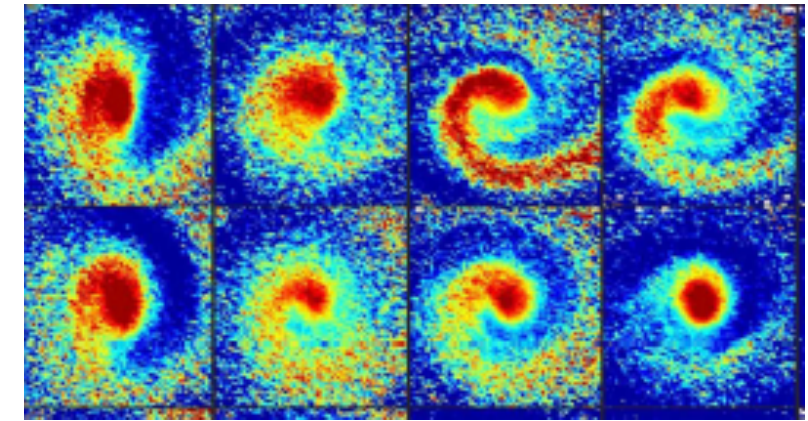
1) Sagittarius



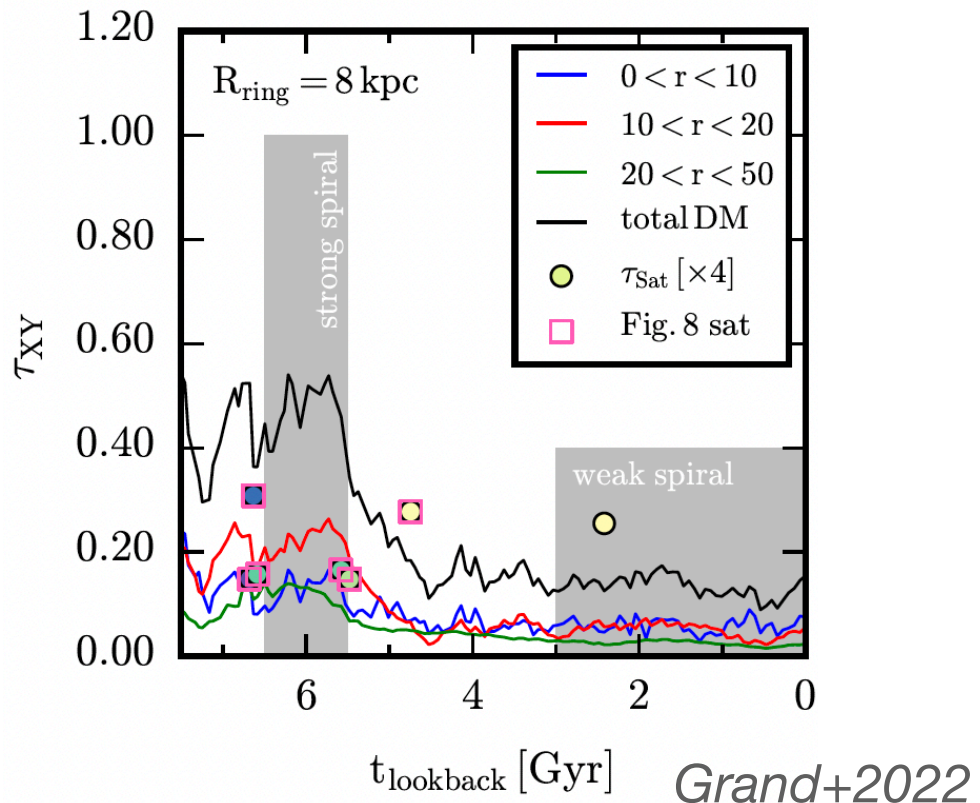
2) Multiple (dark) satellites



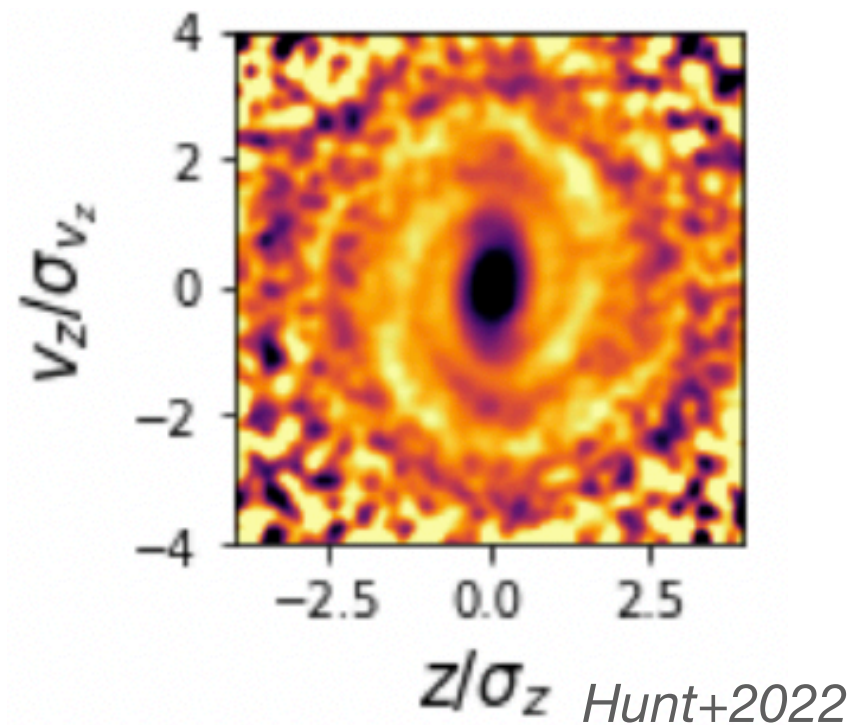
3) Bar buckling



4) Dark matter wake

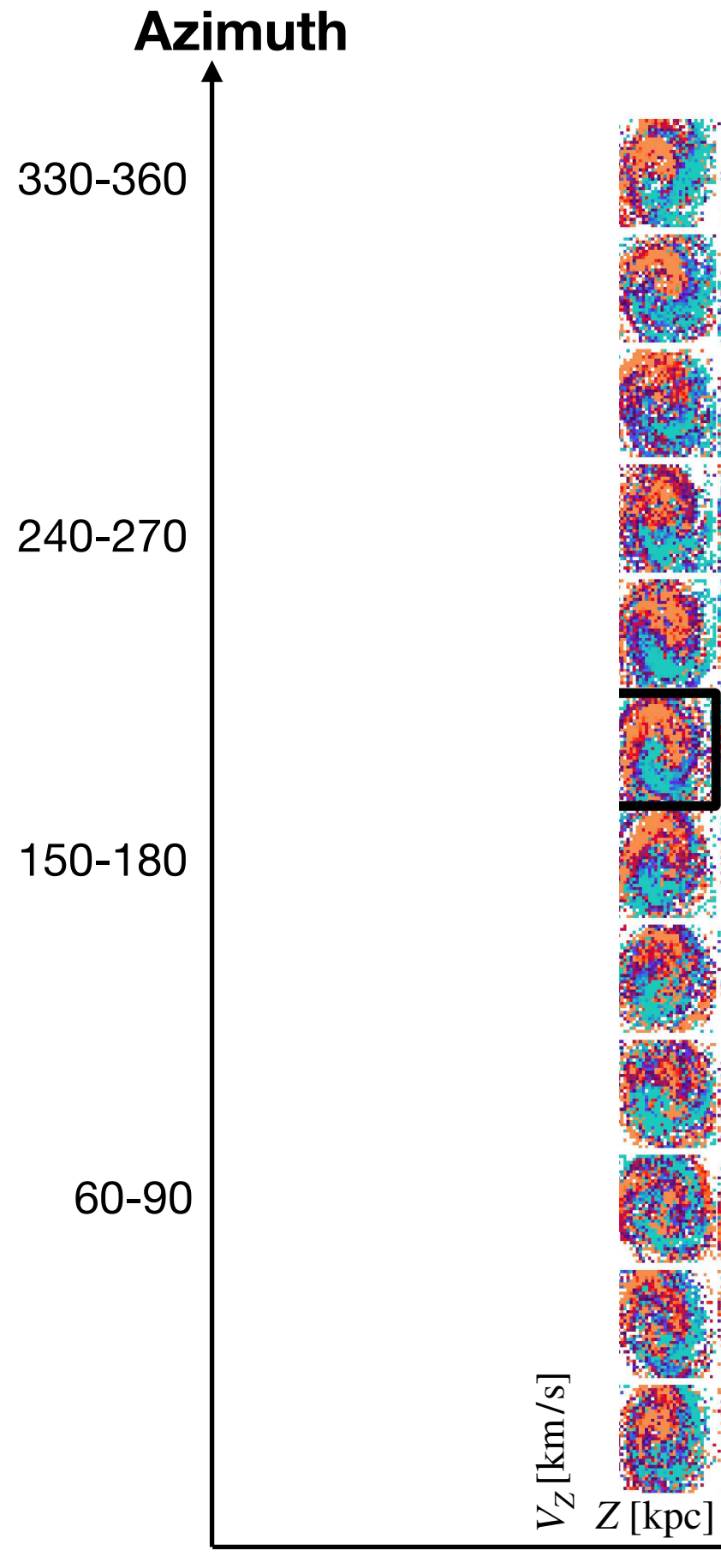


5) Breathing modes of bar/spiral arms



See also: *Chequers+2018*, *Tremaine+2023*, *Bland-Hawthorn+2021*, *Binney+2018*, *Hunt+2021*

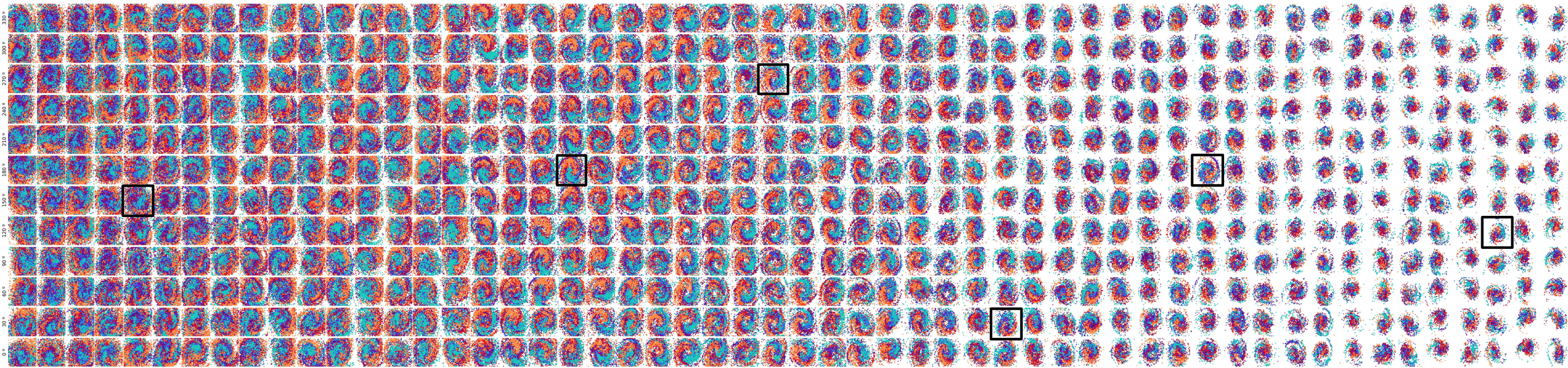
Phase Spiral in Cosmological Simulations



García-Conde et al. 2022

GARROTXA simulation
(Roca-Fàbrega+2016)

Phase Spiral in Cosmological Simulations



6 Gyr

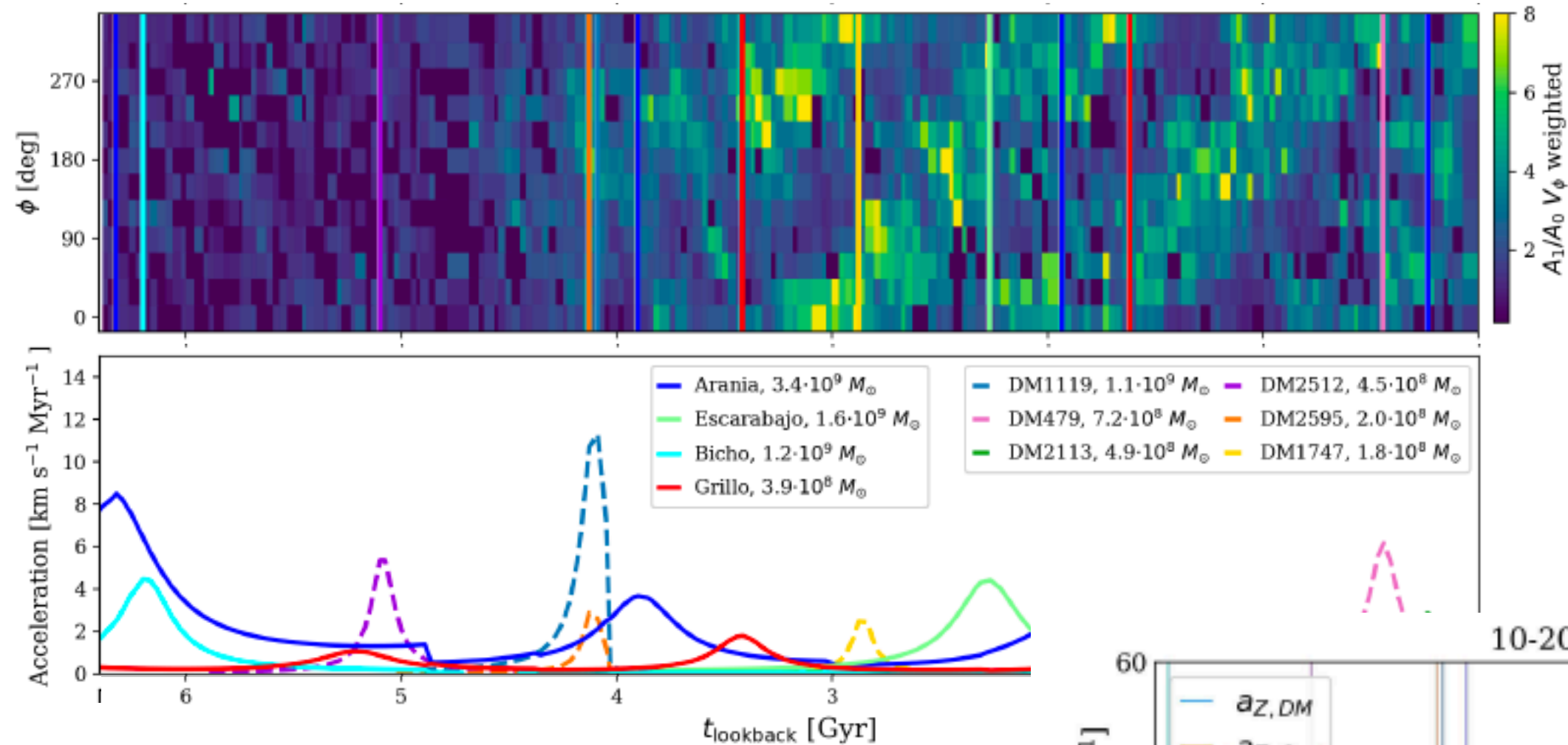


Time

13 Gyr

García-Conde et al. 2022

Phase spiral in cosmological simulations



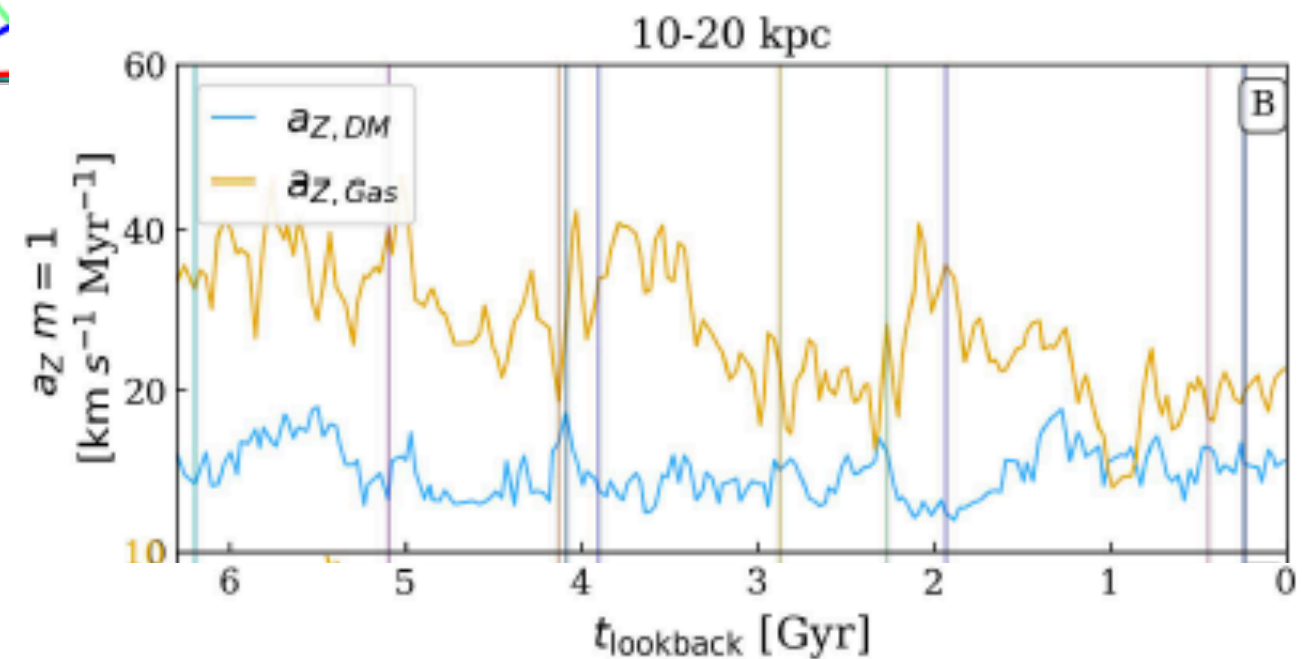
García-Conde et al. 2024

Satellites too light (4 satellites $10^9 M_\odot$, some dark)?

- Collective effects?
- Cold disk due to gas and star formation?

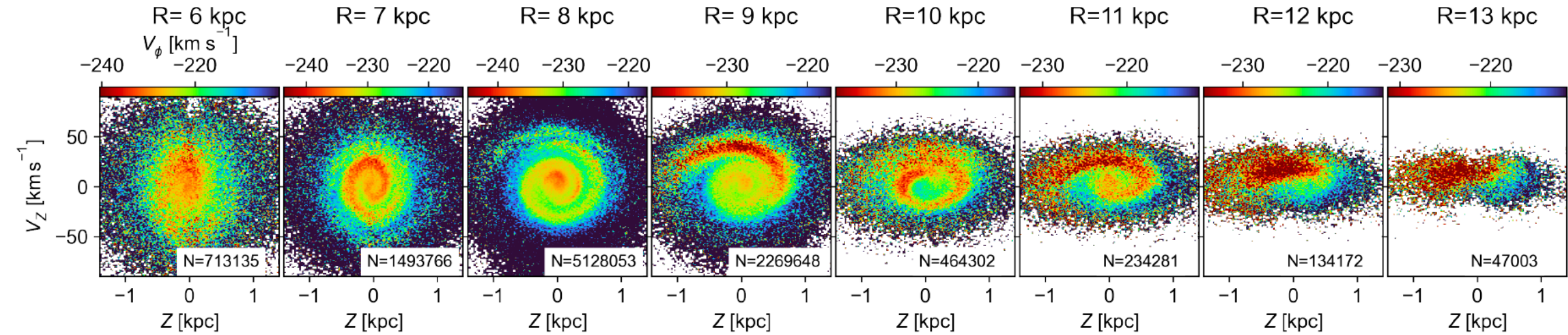
Also non negligible forces from:

- anisotropic gas infall / misalignment gaseous disc
- misalignment with the dark matter halo/bulge



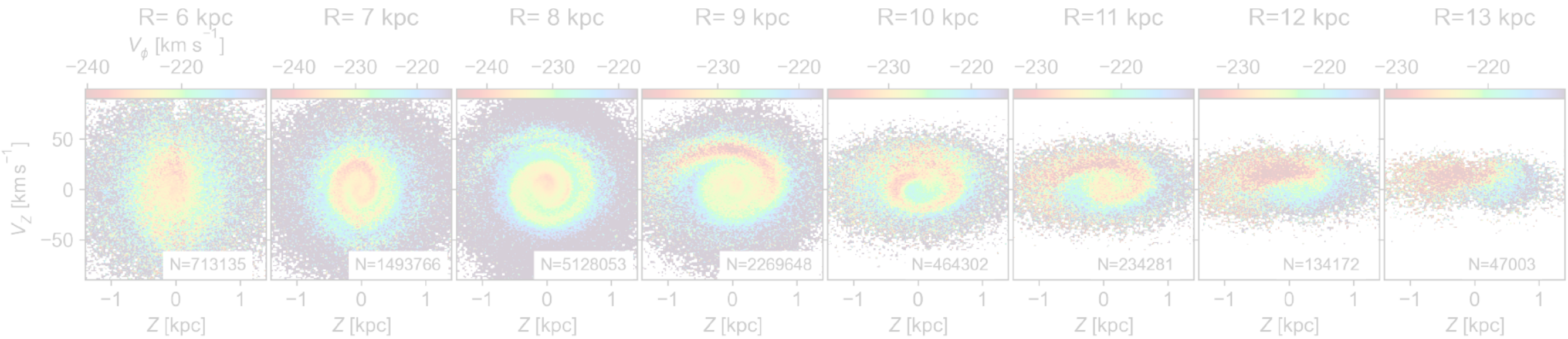
Phase spiral in DR3

See also *Frankel+2023*,
Hunt+2022, *Darragh-Ford+2023*



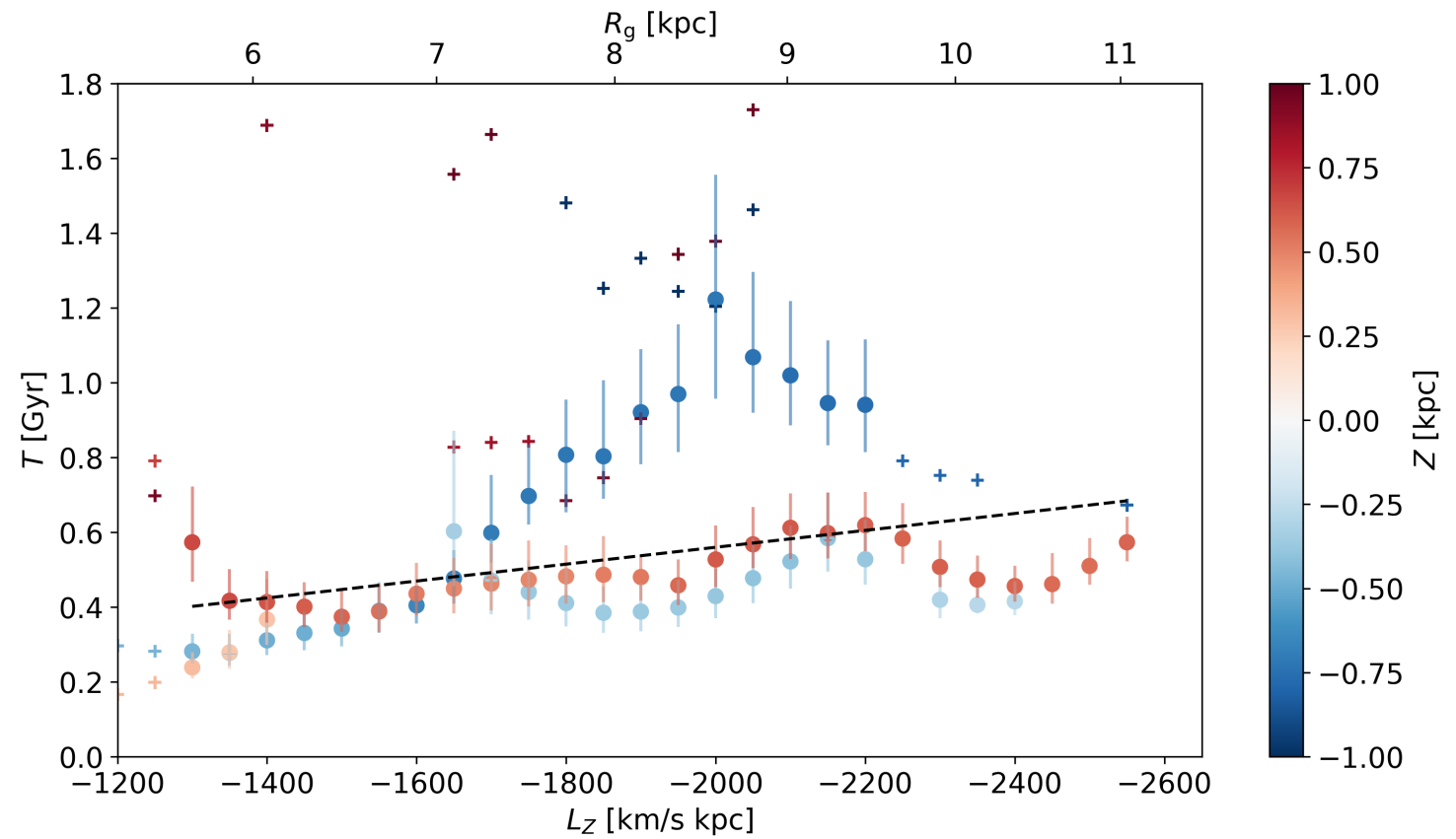
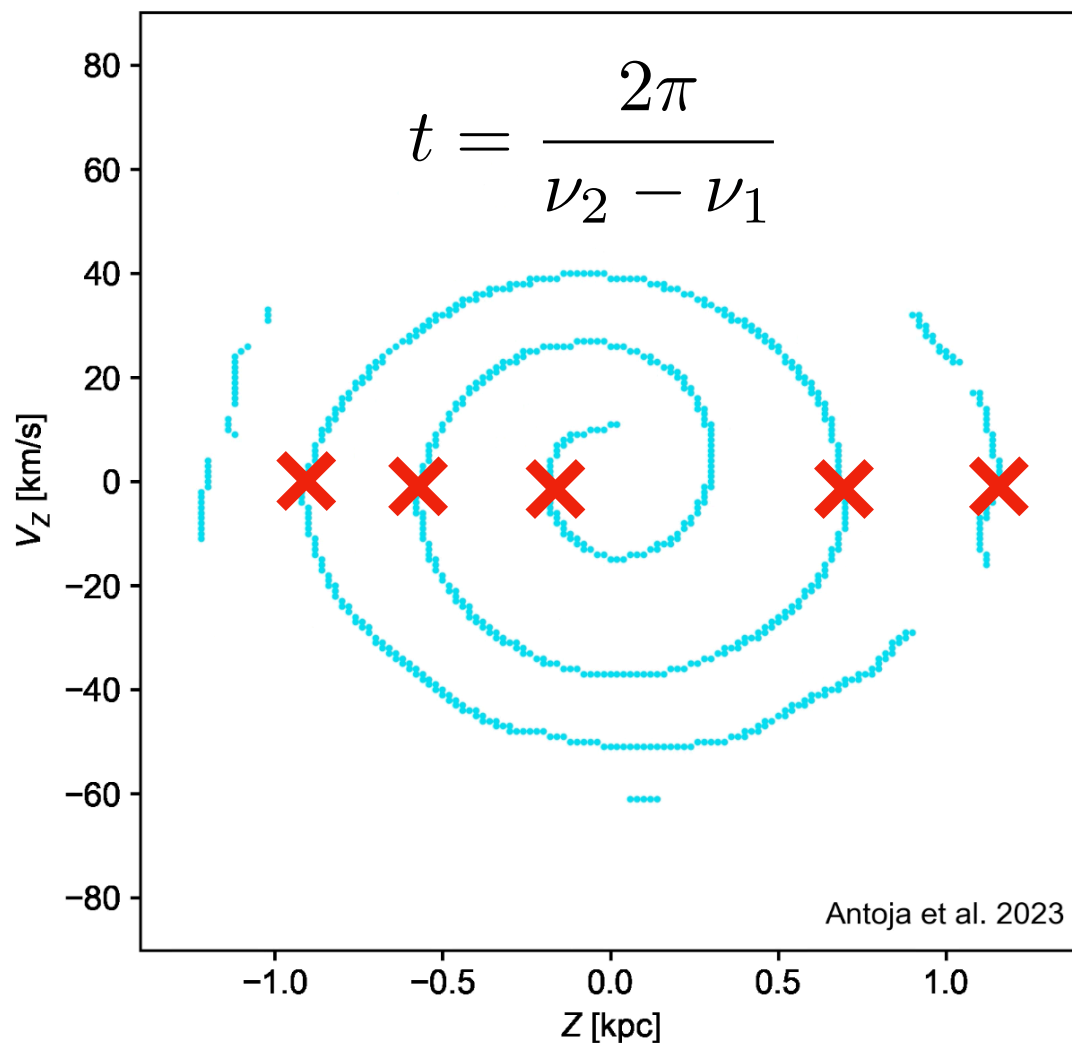
Antoja+2023

Phase spiral in DR3



Antoja+2023

$L_Z = -1840 \text{ km/s kpc}$ ($R_g = 7.7 \text{ kpc}$)

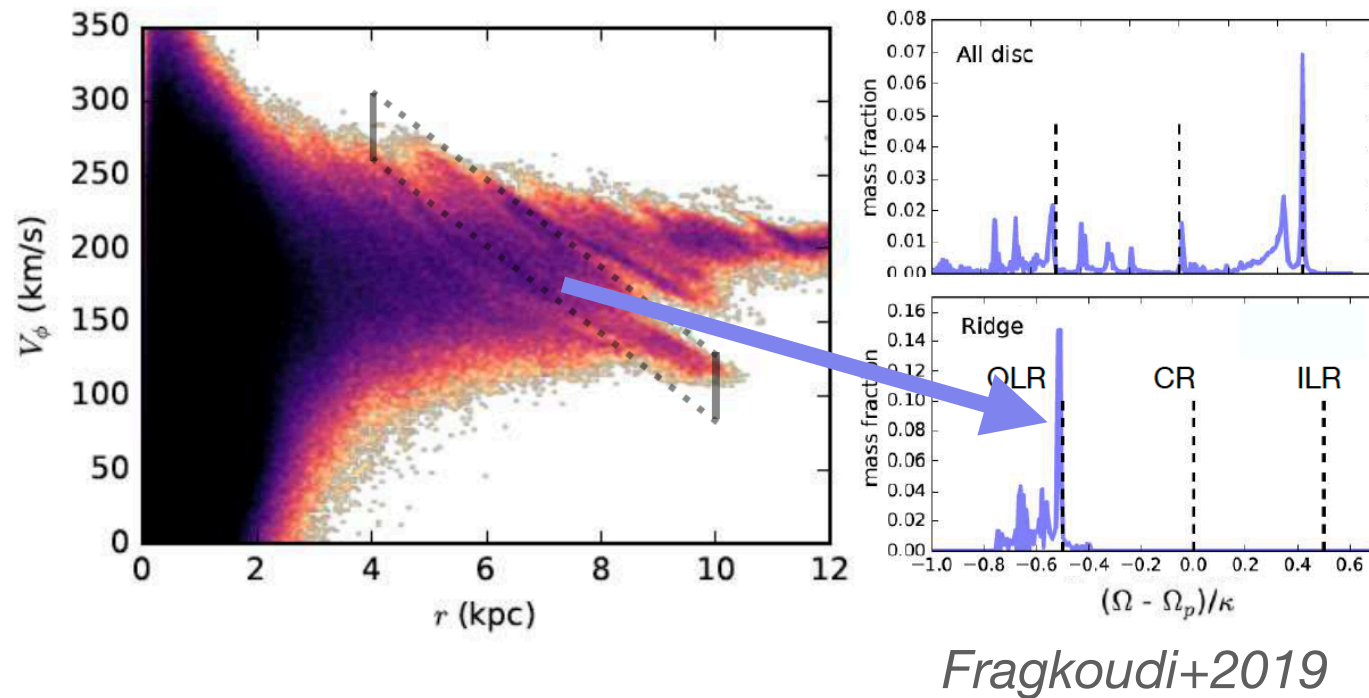


PHASE MIXING:
[0.3–0.9] Gyr

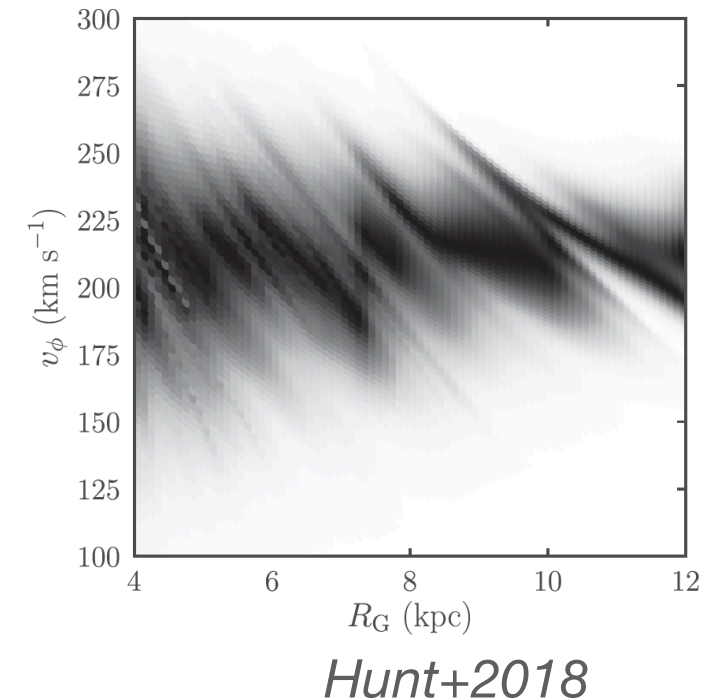
*See also Frankel+2023,
Hunt+2022, Darragh-Ford+2023*

Origin of the ridges/moving groups

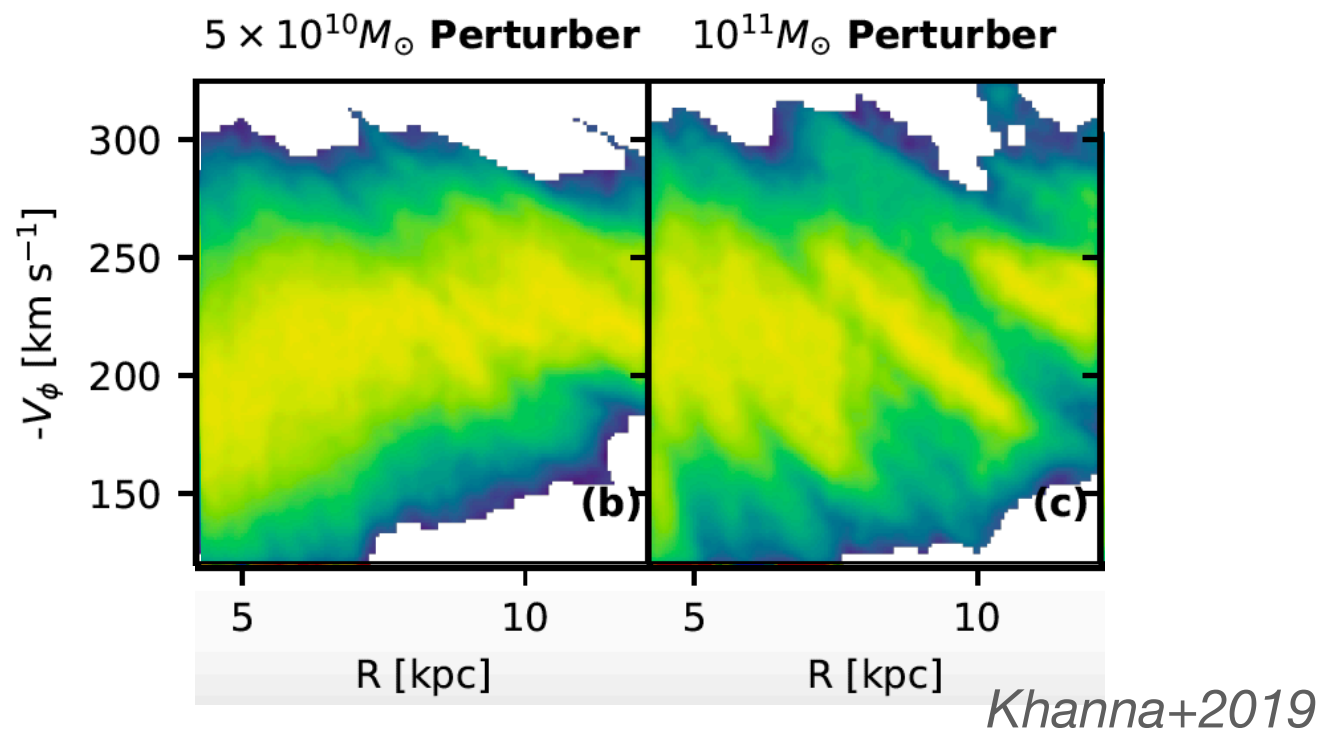
1) Resonances of the bar/spirals



2) Phase mixing of transient spiral structure

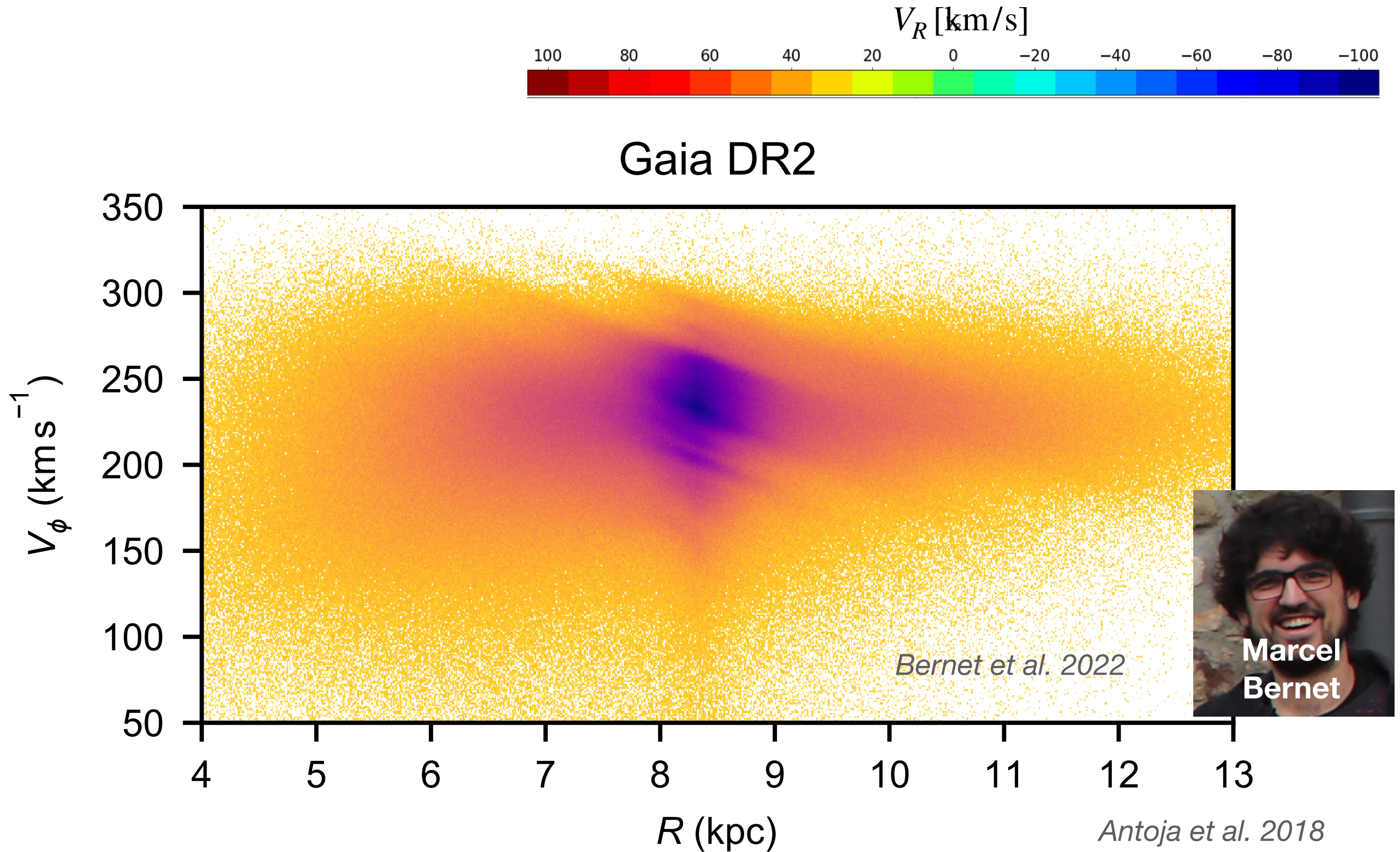


3) Sagittarius / external satellites

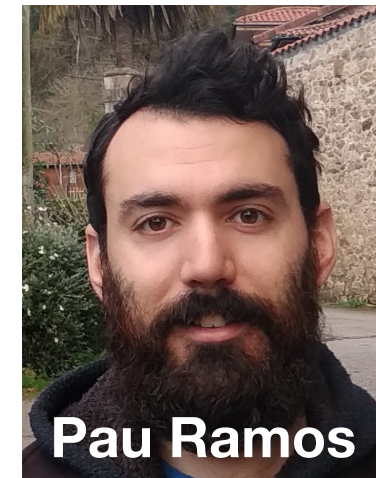
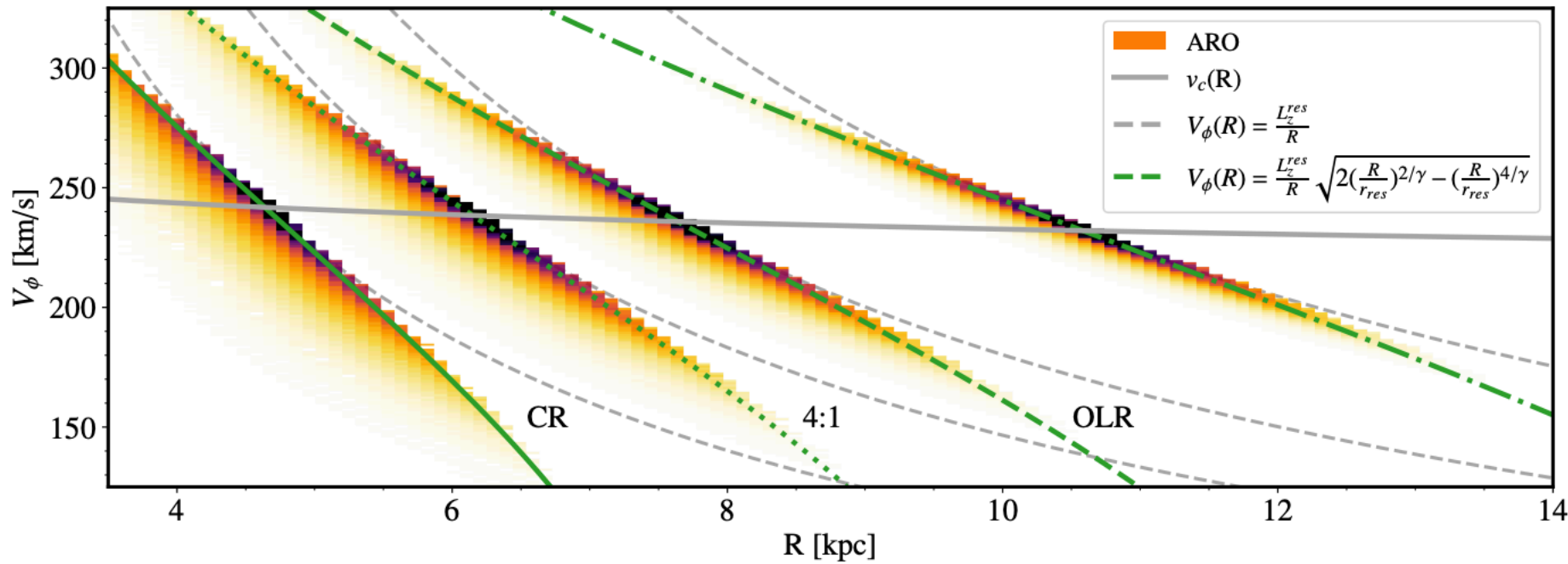


See also: Gaia Collaboration, Antoja+2021, Chiba+2021, Hunt+2019, Martinez-Medina+2019, Kawata+2021, Wang+2020, Laporte+2020, Lian+2019, Khanna+2019, Trick+2029, Kawata+2018, Ramos+2018

From ridges to manifolds

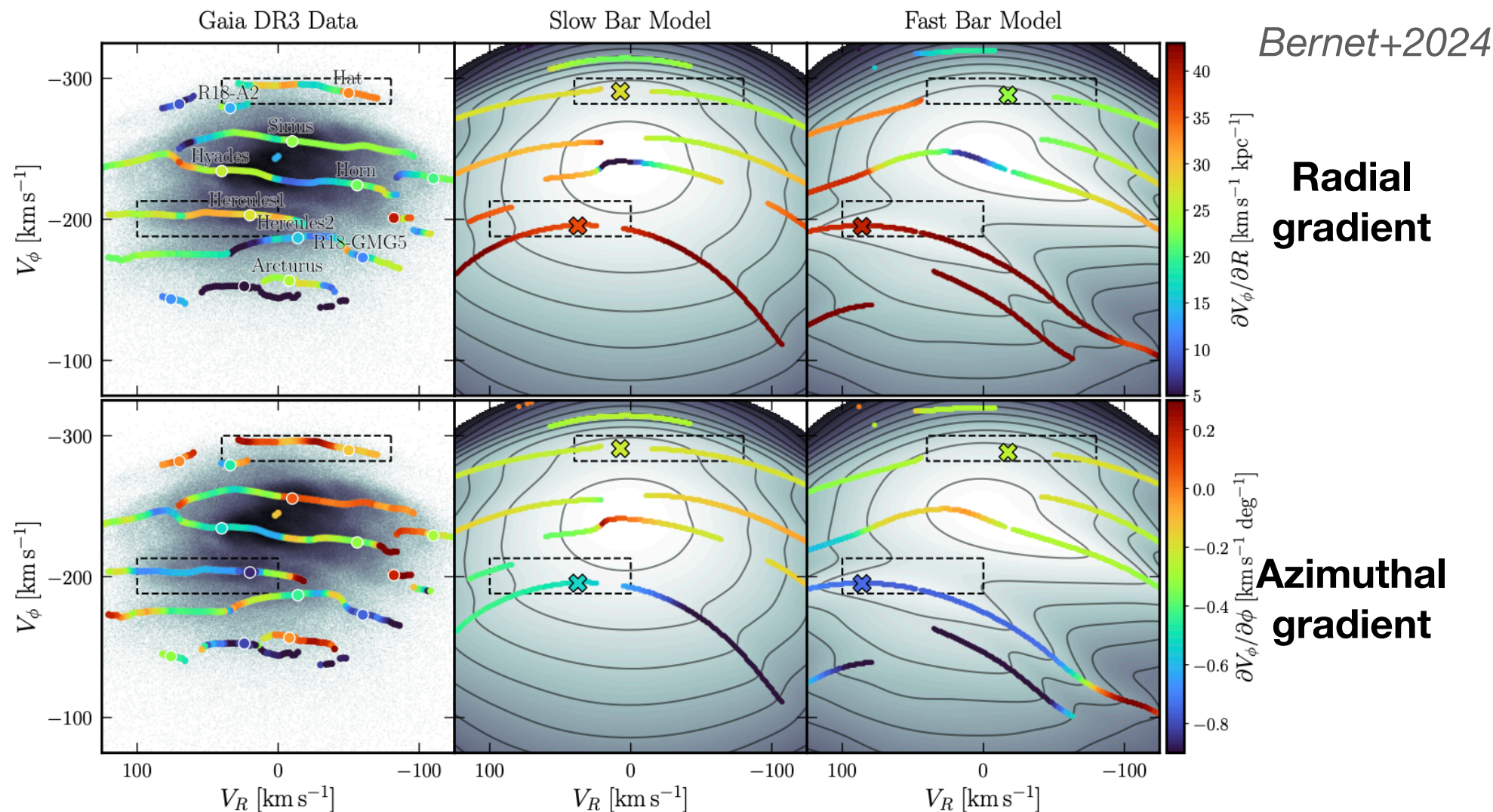


Bar effects: slope of the ridges



Pau Ramos

Ramos+2024, *subm.*



Bernet+2024



Marcel Bernet

Radial gradient

- Hercules:

- azimuthal gradient $\partial V_\phi / \partial \phi$ fits slow & fast bar models

- radial gradient $\partial V_\phi / \partial R <$ simple models

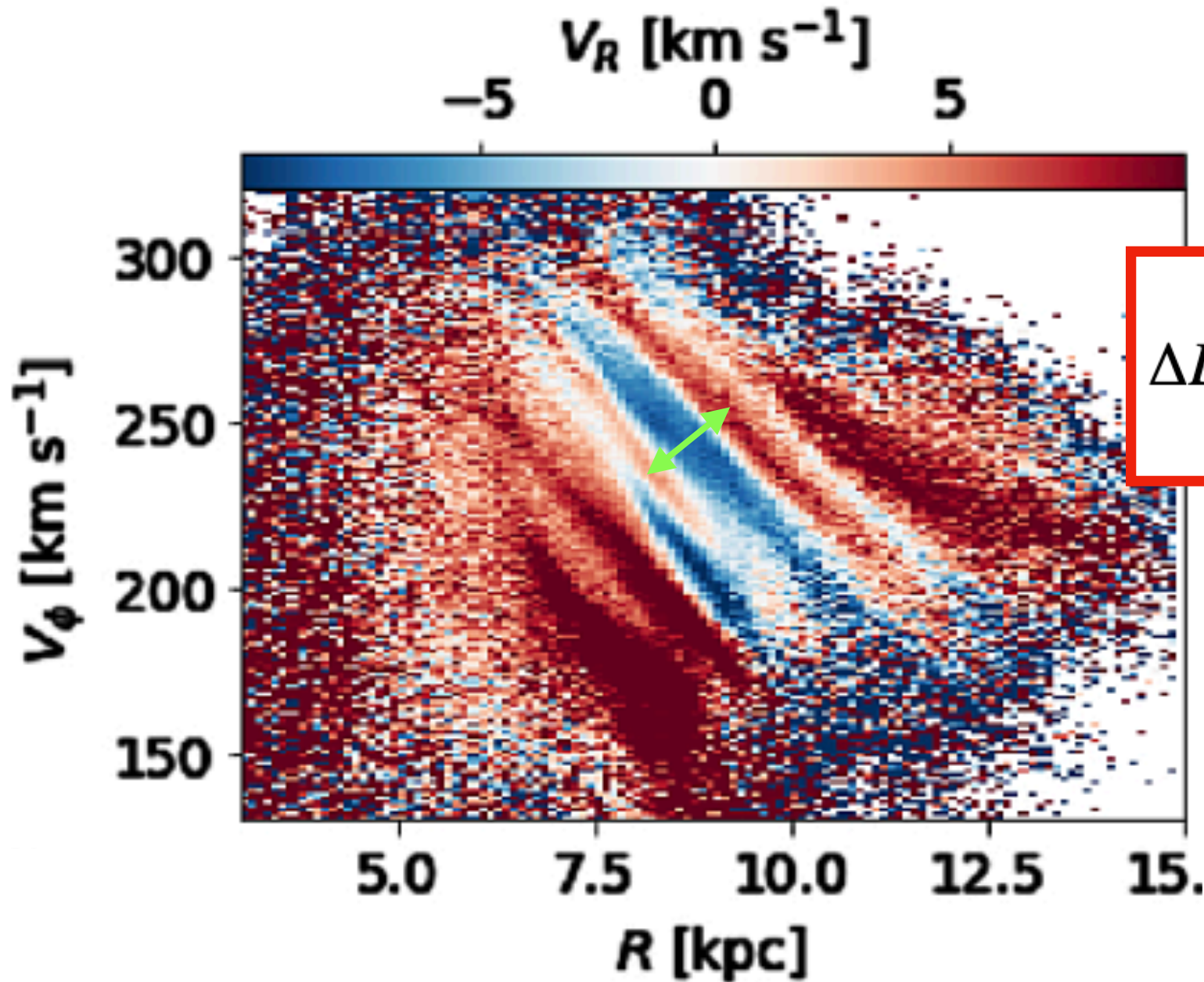
Azimuthal gradient

- Different bar potential, spiral arms, slowing bar, complex circular velocity curve, external perturbations ?

Spiral wraps from a tidal interaction in the MW ?

Gaia DR3 RVS data

Antoja+2022



$$\Delta L_Z^{\frac{n-1}{n+1}} = \left(\frac{V_c}{R_0^n} \right)^{\frac{-2}{1+n}} \frac{1}{1 - \frac{1}{2} \sqrt{2(n+1)}} \frac{\pi}{t}$$

**Times from two
frequencies:
<0.6 Gyr
[0.8–2.1] Gyr**

See also Minchev+2019, Friske+2019, Chiba & Schoenrich 2021

Summary

- 3 new possibilities for origin of phase spiral:
 - dark satellites
 - halo-disc misalignment
 - misaligned gas accretion
- Gaia DR3 phase spiral: secondary branch, estimated impact time 0.3-0.90 Gyr
- Need to incorporate more complex physics to study of phase spiral: self-gravity, response times, etc
- Analytical approximations to ridges created by bar
- Simple bar models present radial variations of ridges that do not match data
- Analytical approximations to ridges created by tidal interactions; derived impact times: <0.6 Gyr & 0.8–2.1 Gyr