Kinematic substructure in the Galactic disc

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(-> Flatiron research fellow from September)

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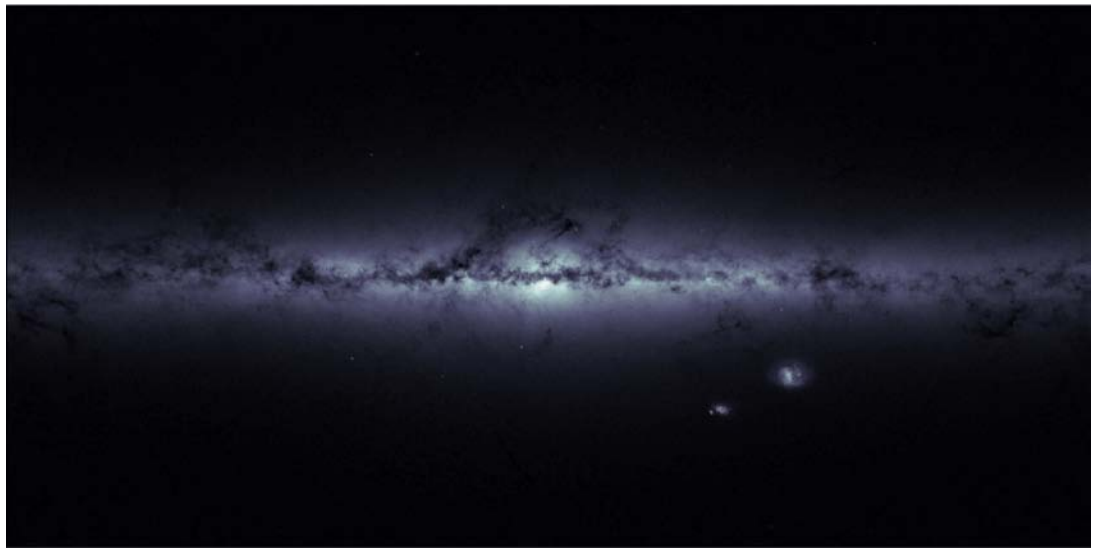
The Goals

- Milky Way Structure & Dynamics unknown;
  - R_0=8.35 ± 0.35 kpc
  - M_d=6.43 ± 0.63 x 10^{10} $M_\odot$
  - $R_{d,thin}$=2.6 ± 0.52 kpc
  - $R_{d,thick}$=3.6 ± 0.72 kpc
  - $V_{rot,\odot}$=239 ± 5 km s^{-1}
- Hard to know global picture due to position and extinction.
- We still argue over the bar & spiral arms…

e.g. from McMillan (2011)



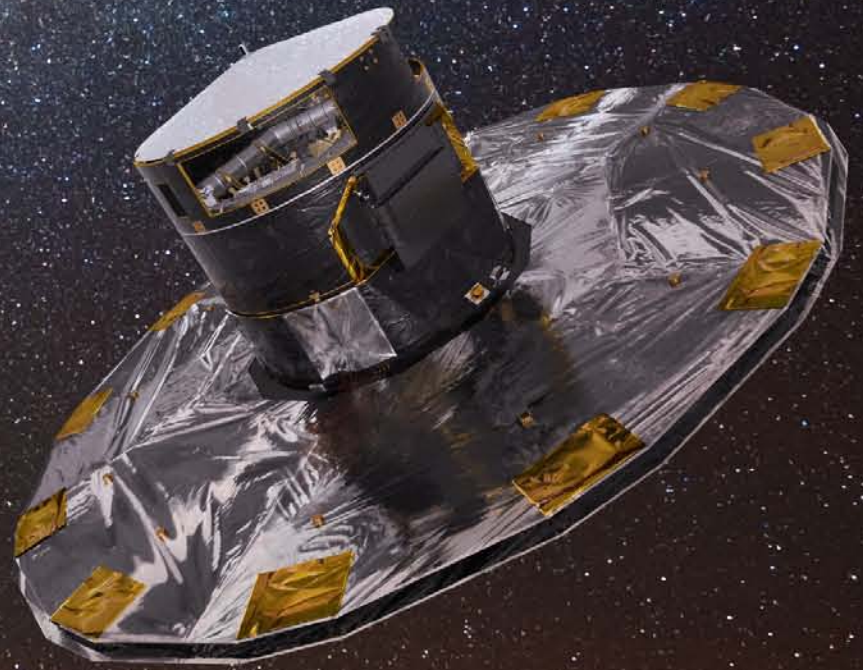
Credit: Gaia!

Thus we need good surveys and good models!

Gaia: Mapping one billion stars in the Milky Way

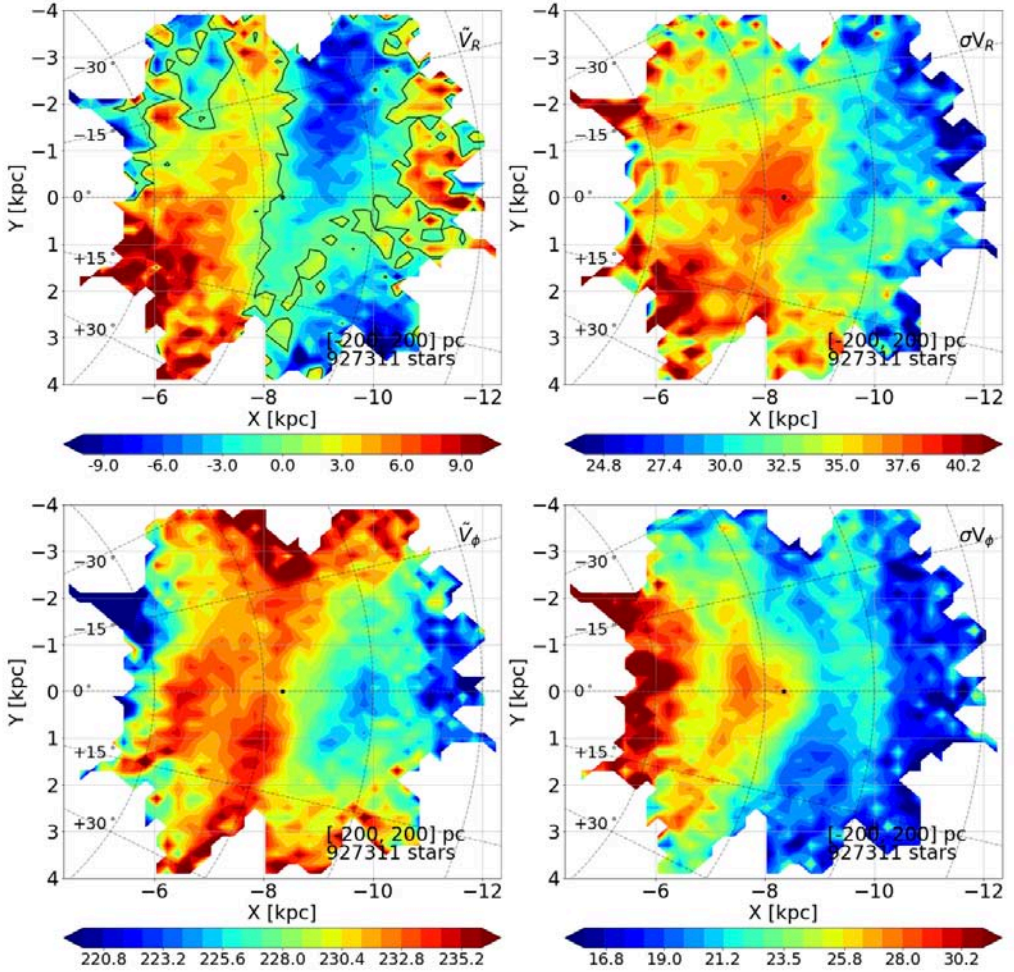
Gaia (Launched 19th December 2013)
ESA corner-stone mission
Has observed a lot more than one billion…

- Positions and velocities for the whole sky, for G<20
- Also: ground based surveys, e.g. APOGEE, RAVE, GALAH etc.



So what's (somewhat) new in the disc?

- 3D velocities for ~7x10^6 stars, over around 2 kpc.
- Can trace disc kinematics further and more accurately than ever before.
- E.g. V_R and V_T maps ->



Gaia Collaboration et al., 2018, A&A, 616, A11

Striking spiral patterns in Z-V_z

- Spiral features in the Z-V_z distribution, especially when colored by V_{rot}

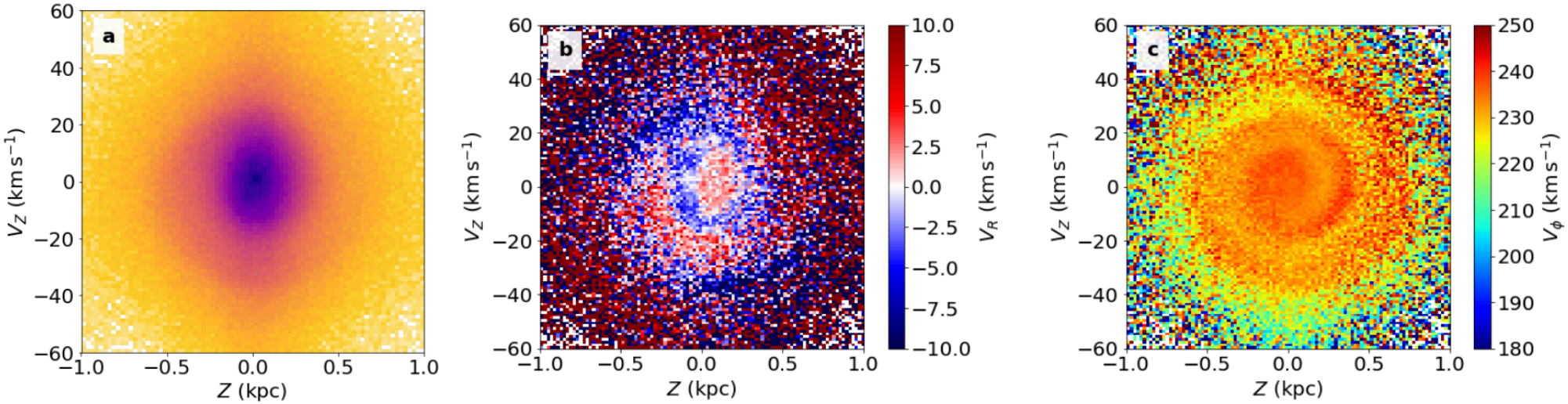


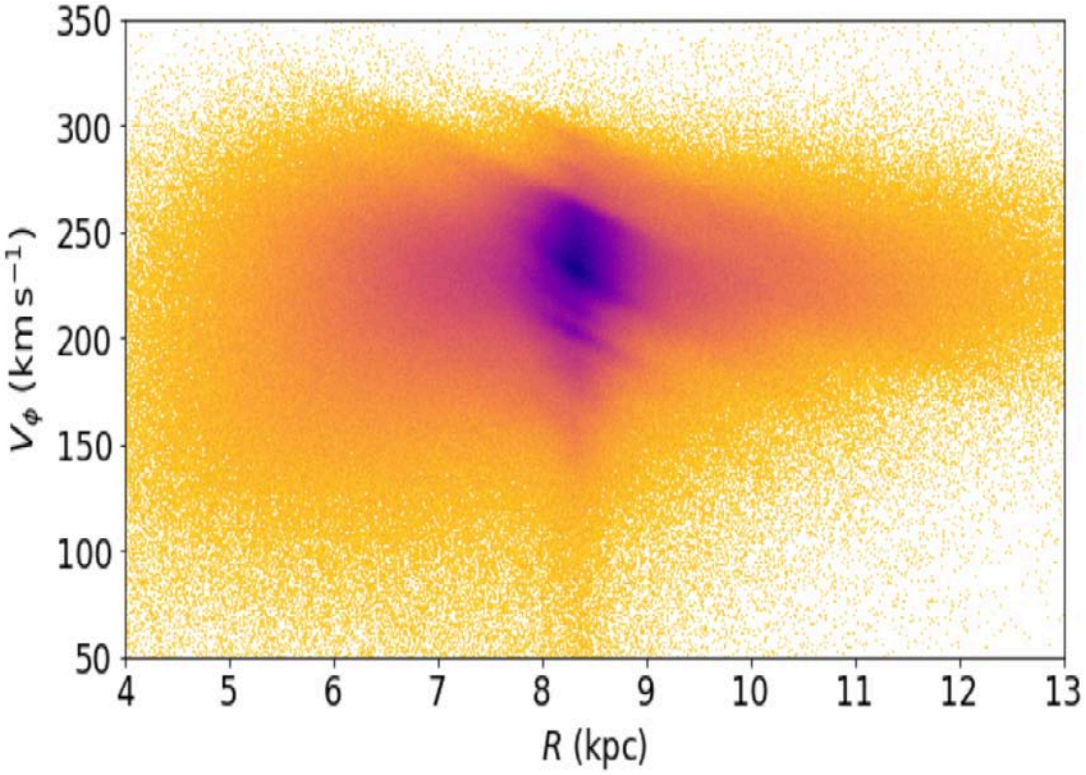
Figure 2. Distribution of stars in the vertical position-velocity plane Z-V_Z for stars selected as in Fig. 1. a) Two-dimensional histogram in bins of $\Delta Z = 0.01$ kpc and $\Delta V_Z = 0.1\,\mathrm{km\,s^{-1}}$; b) Z-V_Z plane coloured as a function of median V_R in bins of $\Delta Z = 0.02$ kpc and $\Delta V_Z = 1\,\mathrm{km\,s^{-1}}$; c) Same as b) but for V_ϕ.

Antoja et al., 2018, Nature, 561, 360

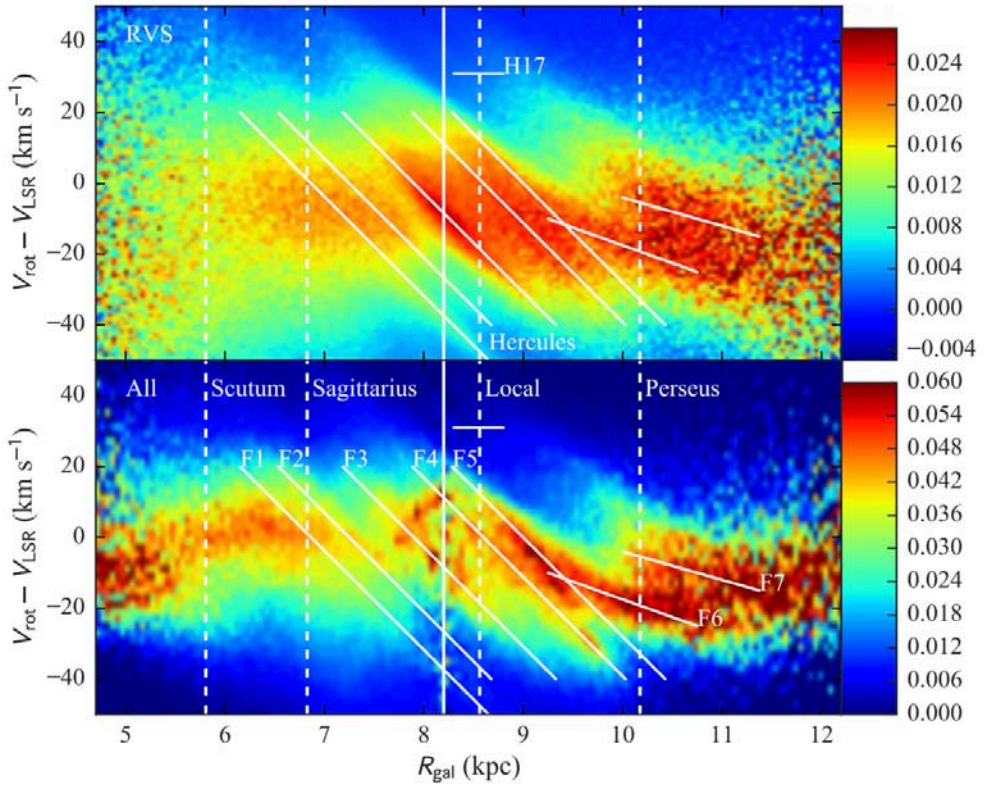
Also, the ridges in R vs V_{rot}

- Submitted on the same day after DR2:

Antoja et al., 2018, Nature, 561, 360



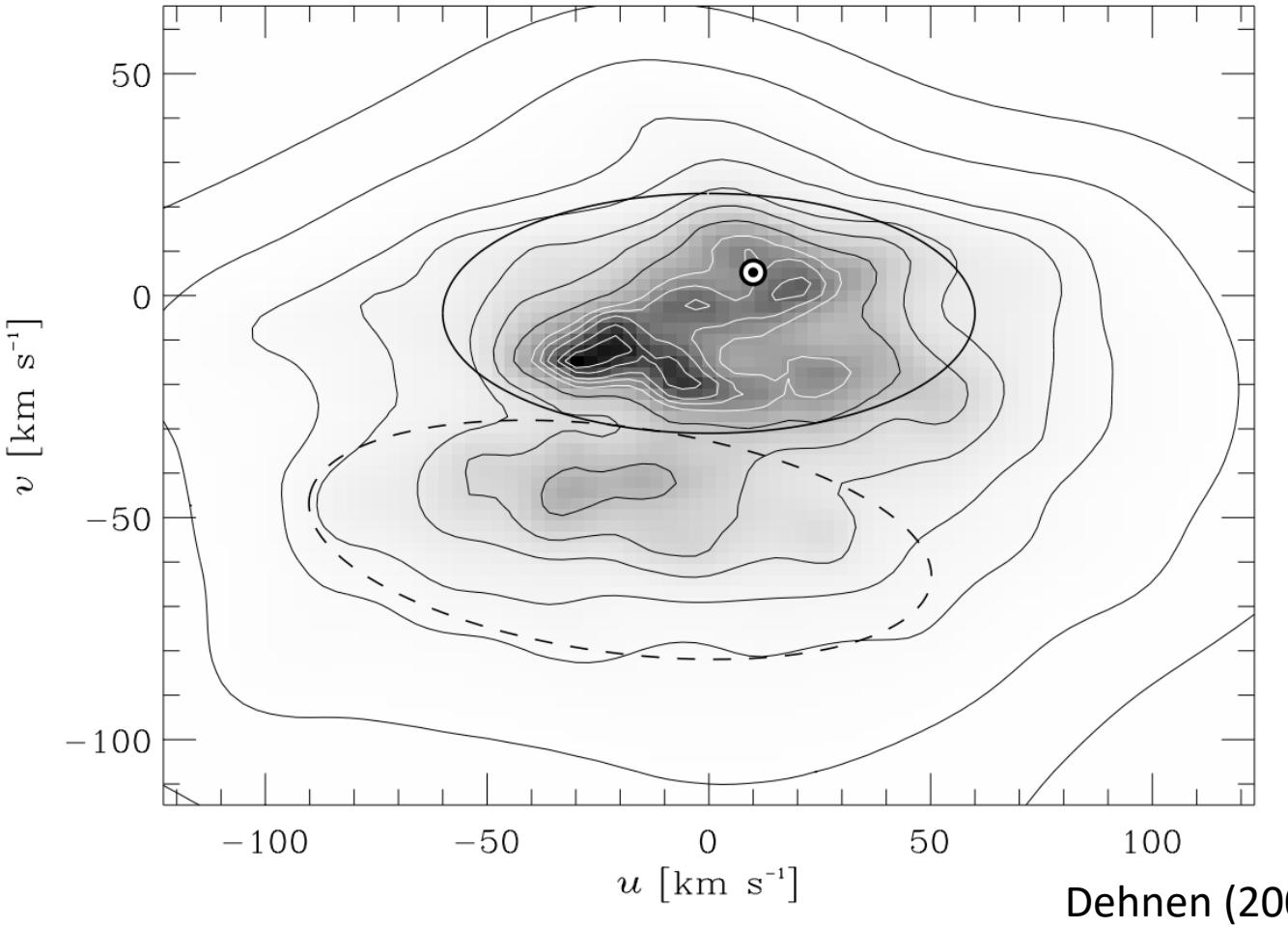
Kawata et al., 2018, MNRAS, 479, 108



Stellar velocities in the Solar neighborhood

- Data from Hipparcos allowed us to visualise the 3D motion of nearby stars.
- V in direction of rotation
- U in direction of centre

- Rich substructure, including moving groups.



Dehnen (2000)

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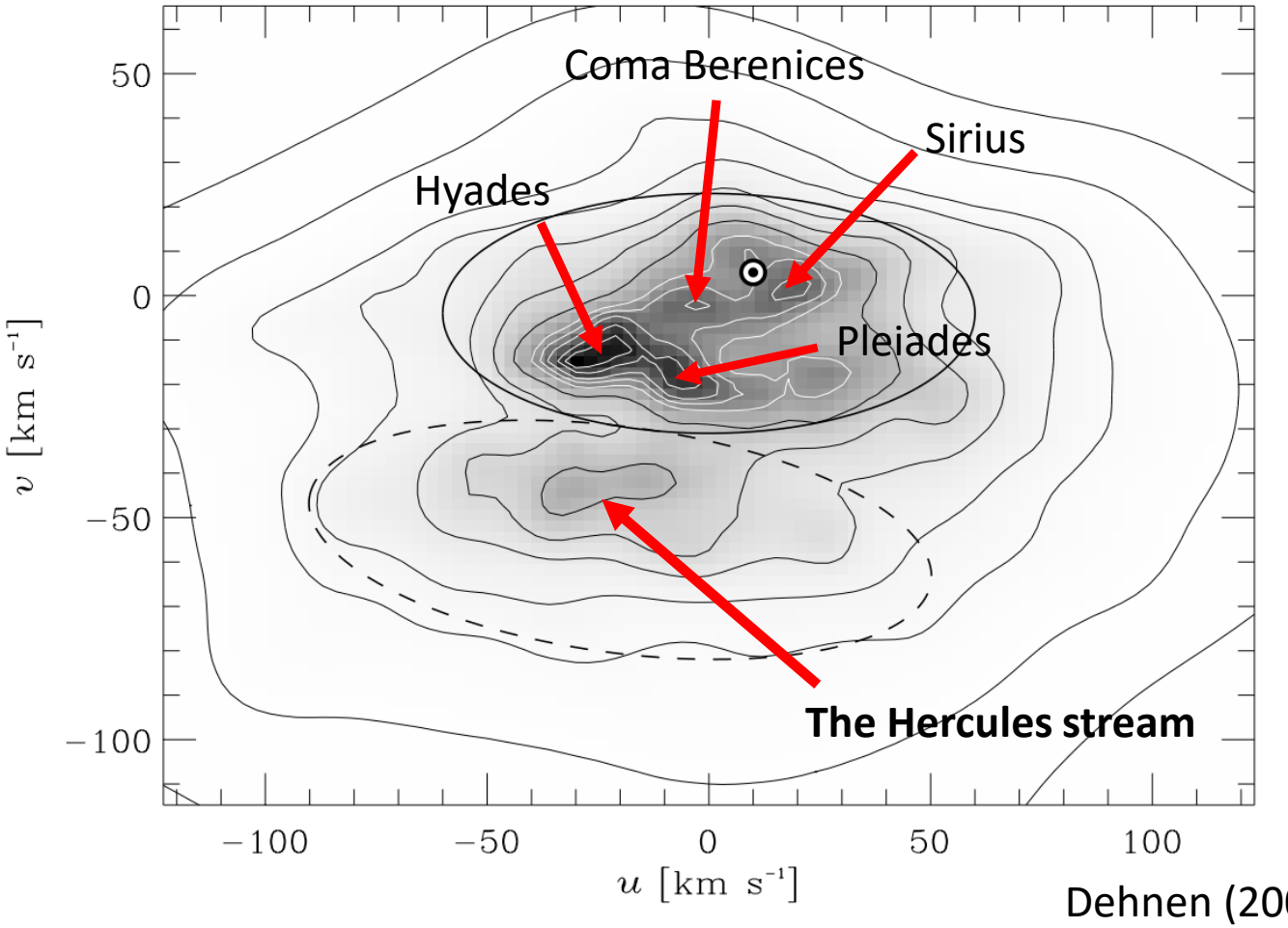
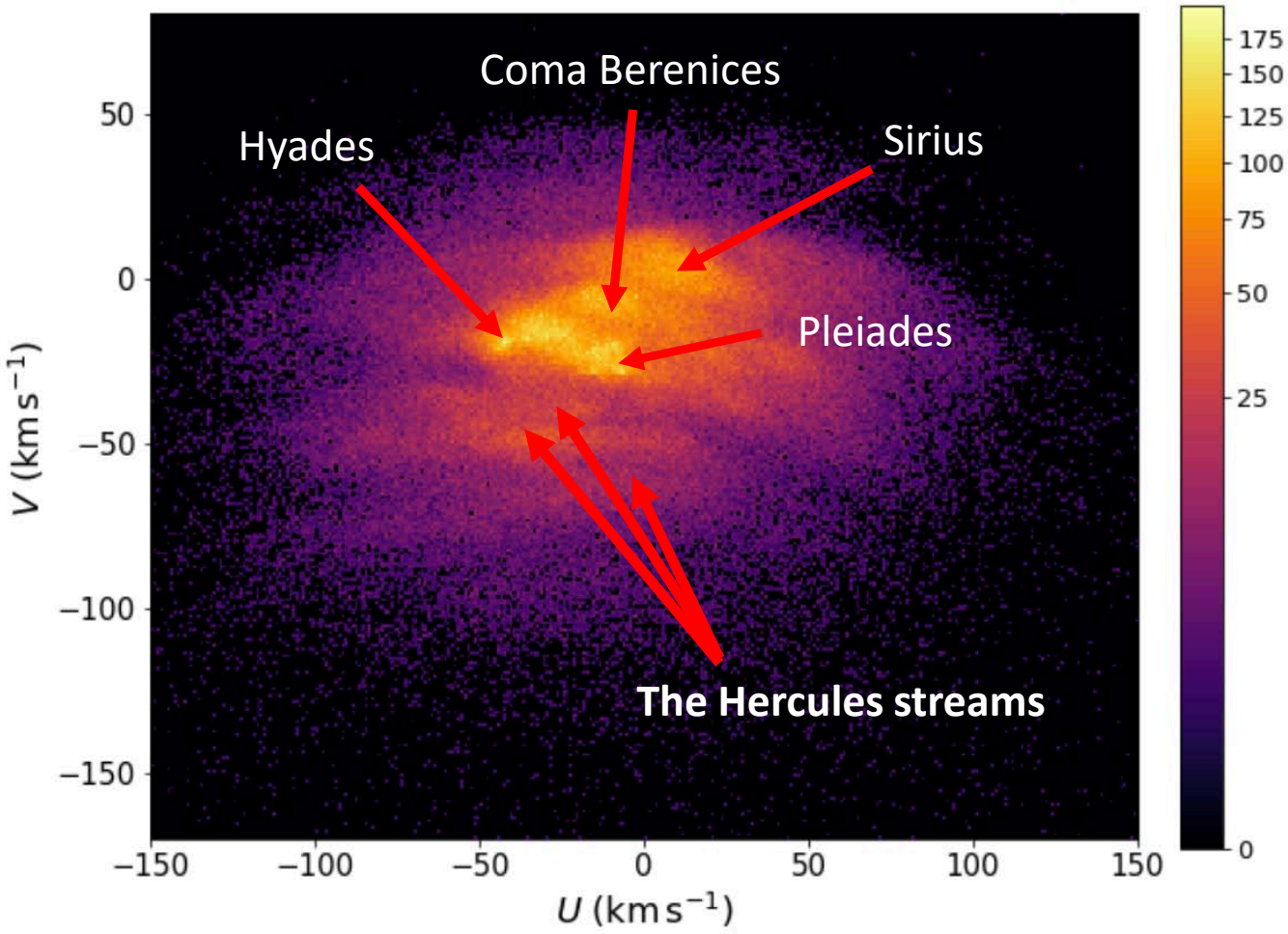


Dehnen (2000)

Stellar velocities in the Solar neighborhood

- Gaia DR2 allows a refinement of the picture.
- Multiple components in the Hercules stream



Gaia Collaboration et al (2018)

A bit of background: What causes Hercules?

- Disruption of clusters?
  - Unlikely, as Hercules is comprised of stars spanning a range of metallicities and ages.
- Disruption of infalling dwarf galaxies?
  - Again, here you would expect Hercules to consist of low metallicity stars. Also unlikely to reproduce disc like kinematics.
- Interaction with large scale galactic structure such as the bar and spiral arms?
  - The remaining explanation. Is there a dynamical process that can reproduce Hercules?

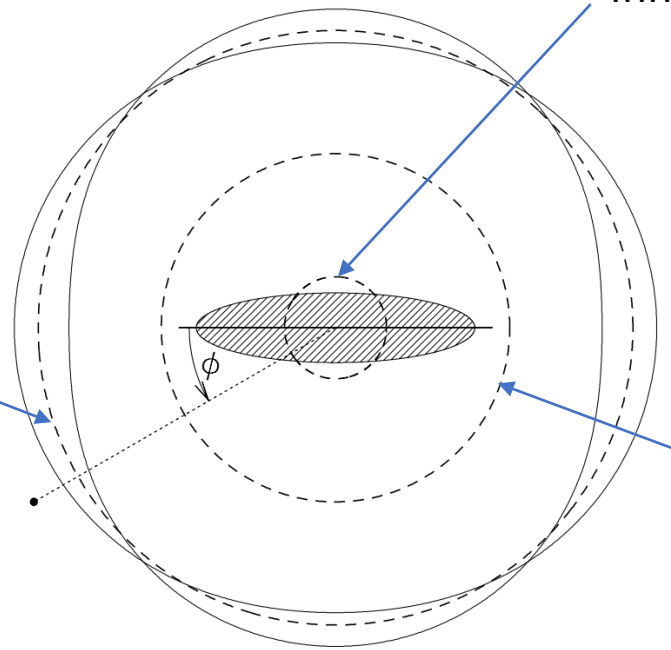
The Bar, and it's resonances

Inner Lindblad resonance (ILR)

$\Omega_p=\Omega_{rot}-\Omega_R/2$

Outer Lindblad resonance (OLR)

$\Omega_p=\Omega_{rot}+\Omega_R/2$



Corotation (CR)

$\Omega_p=\Omega_{rot}$

FIG. 1.—Closed orbits (*solid curves*) just inside and outside the OLR of a rotating central bar (*hatched ellipse*). The circles (*dashed curves*) depict the positions of the ILR, CR, and OLR (from inside out) for circular orbits. Note the change of the orbits' orientation at the OLR, resulting in the crossing of closed orbits at four azimuths. A possible position of the Sun is shown as filled circle. The bar angle ϕ is indicated for the case of a clockwise-rotating bar.

Dehnen (2000)

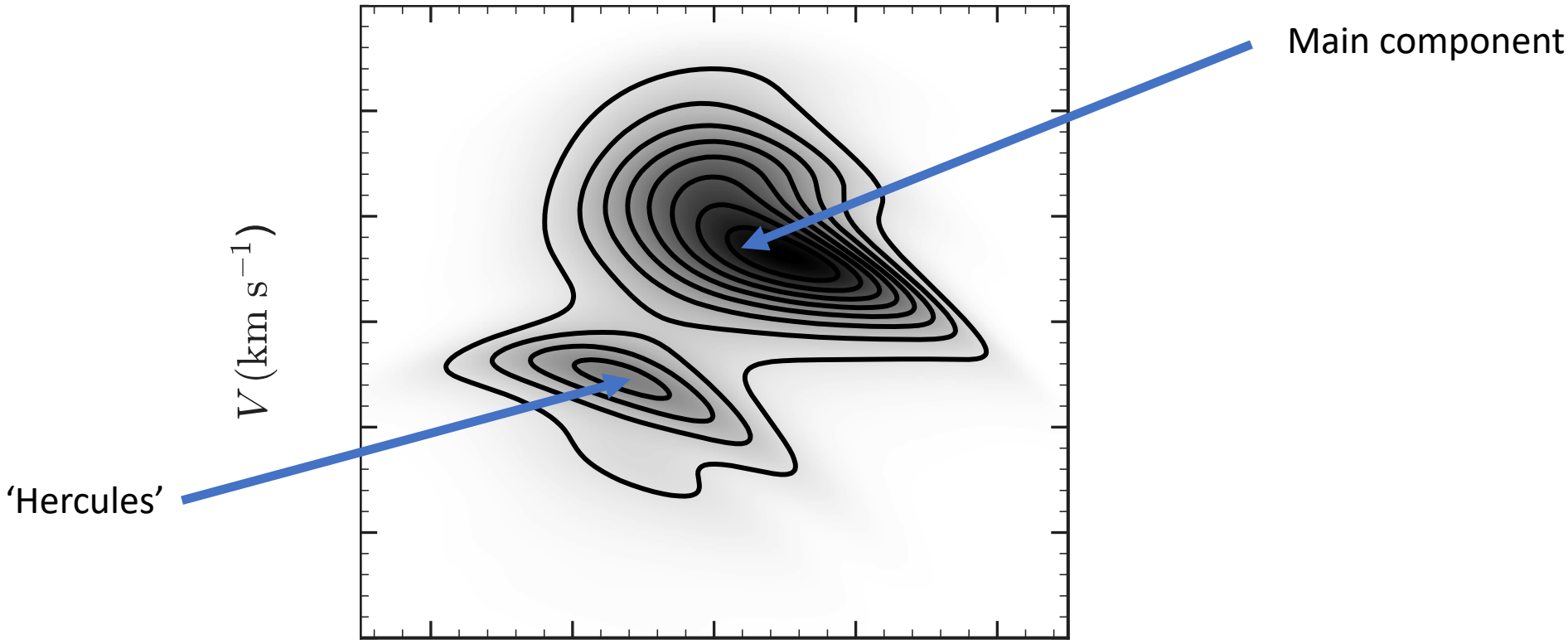
Higher order resonaces, e.g.

4:1 ILR $\Omega_p = \Omega_{rot} - \Omega_R/4$

4:1 OLR $\Omega_p = \Omega_{rot} + \Omega_R/4$

UV plane, with a short fast bar (OLR model)

Dehnen (2000)



(Created with galpy, bovy 2015)

The long slow bar – Hercules from CR

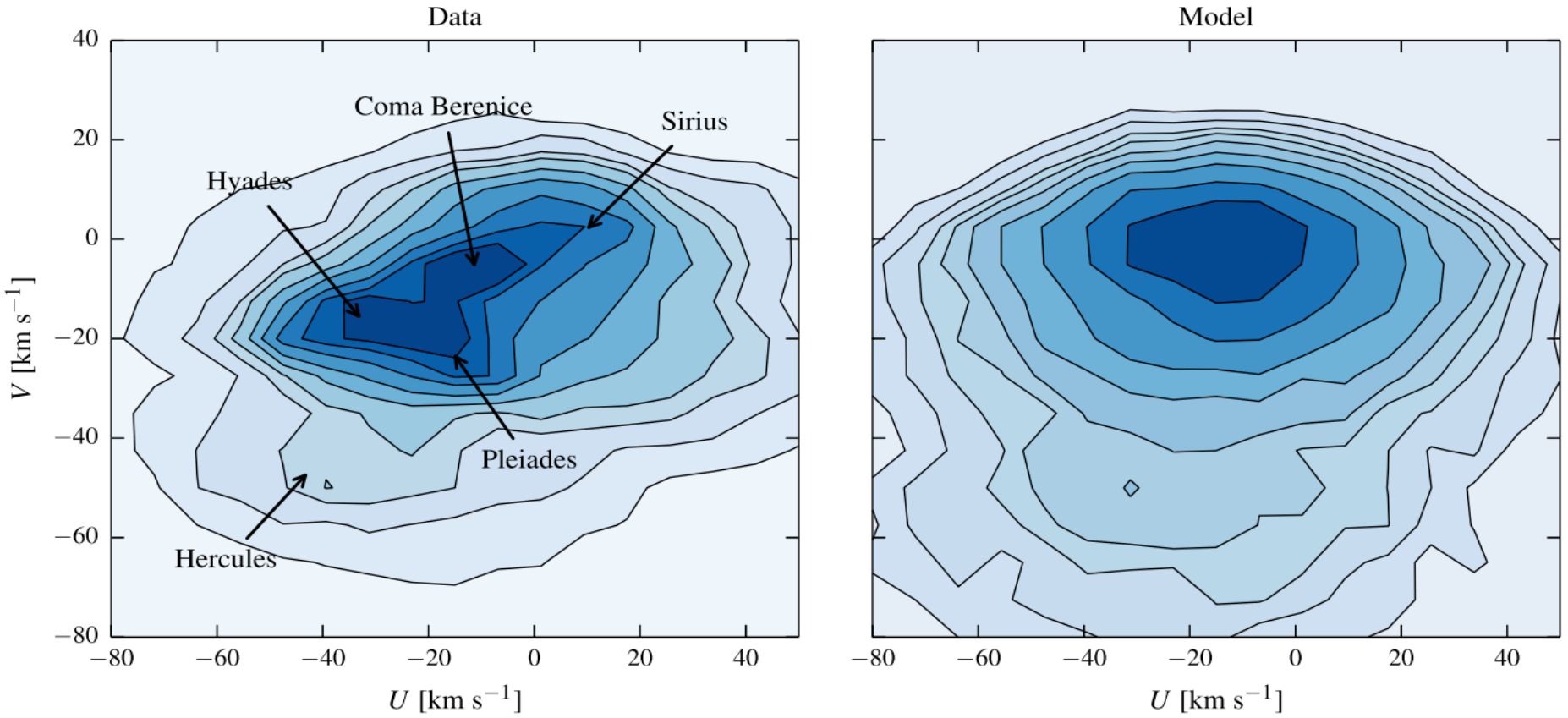


Figure 2. Velocity distribution in the SNd U–V-plane (relative to the Sun) for the data catalog (left) and the cross-matched model (right) within 300 pc from the Sun. The LSR is put at $U = -11.1$ km s^{-1}, $V = -12.24$ km s^{-1}. The contours contain, from inside outward, 10%, 20%, 30%, 40%, 50%, 60%, 80%, 90% of the stars (left) or model particles (right).

Pérez-Villegas et al. (2017)

Slightly faster long bar – Hercules from 4:1 OLR

- Contours overlaid on TGASxRAVE data, cut for error and distance.
- Can produce a bimodality in the area of Hercules from the 4:1 OLR -> $\Omega_p = \Omega_{rot} + \Omega_R/4$
- But has this 'hat' feature that is not as strong in the data.

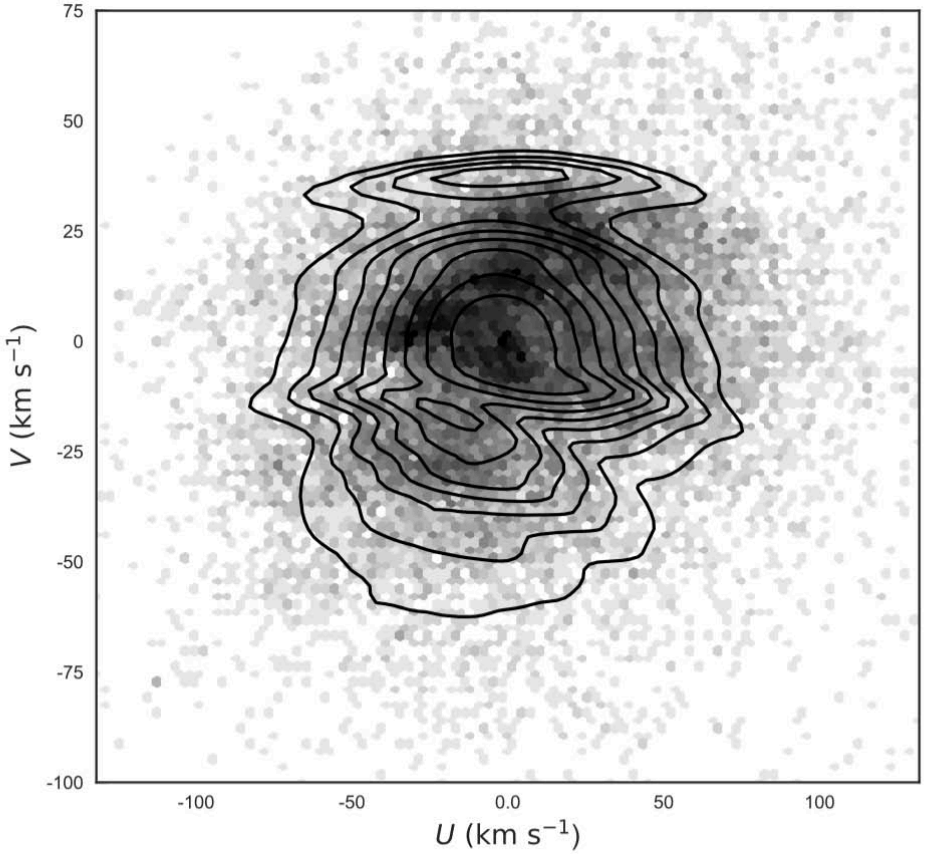
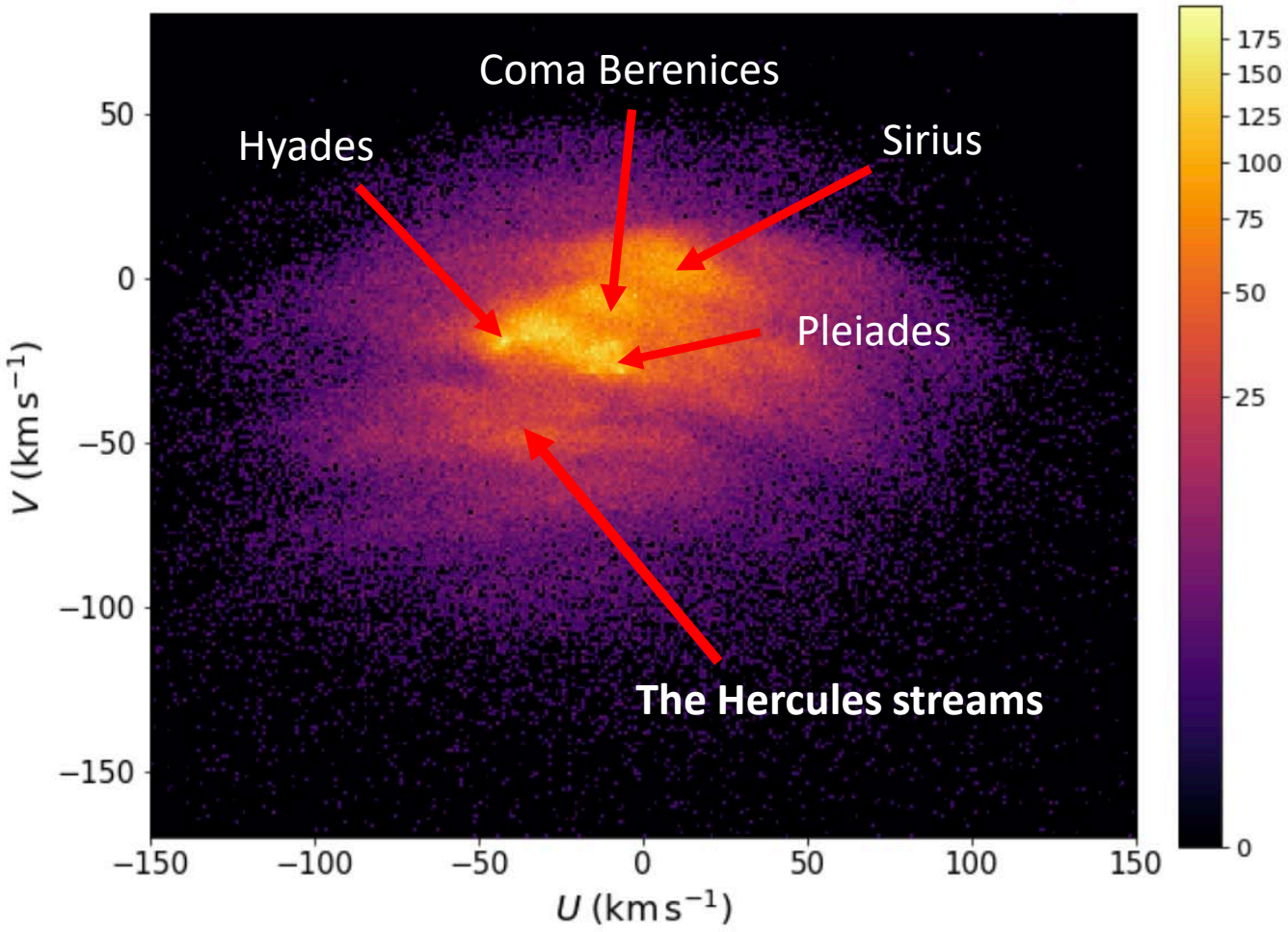


Figure 8. UV plane for the long slow bar model with $\Omega_b = 1.425 \times \Omega_0$, $\alpha_{m=2} = 0.01$ and $\alpha_{m=4} = -0.0005$ (contours) overlaid on the TGAS-RAVE UV plane (hexbin). Hunt & Bovy (2018)

But there's something missing here

- Any of the bar only models, regardless of length or pattern speed do not reproduce the other moving groups.

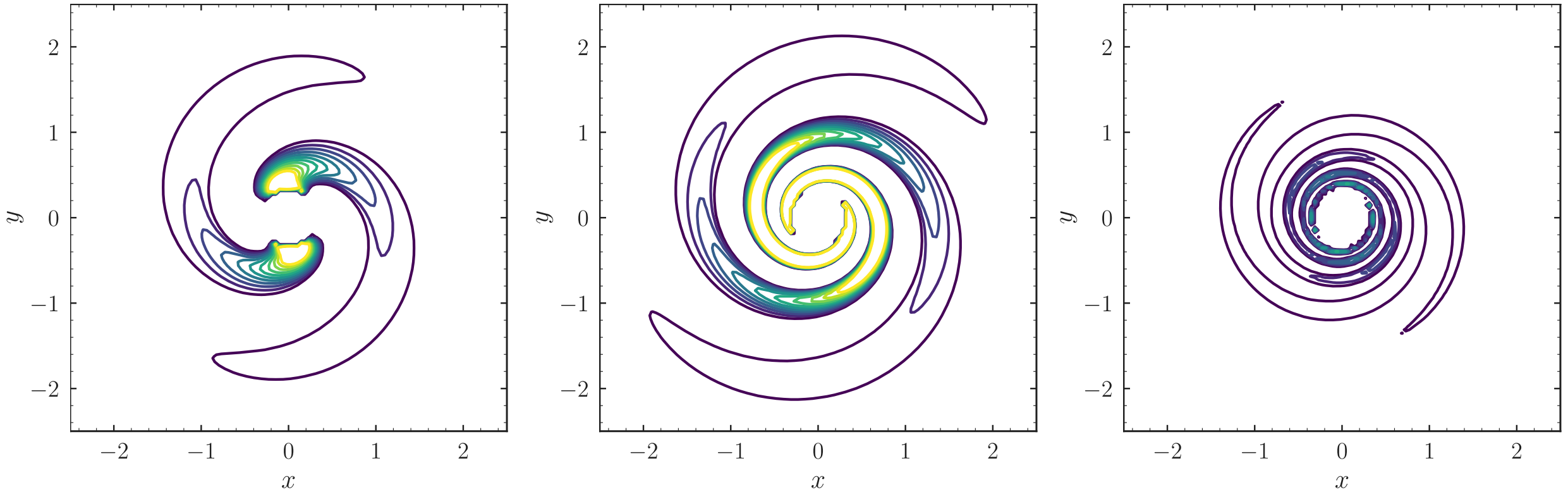
- We need to add spiral structure.



Gaia Collaboration et al (2018)

Transient winding spirals

- We wind the classic density wave potential up such that it rotates with the stars at all radii, and weight its amplitude with a gaussian.

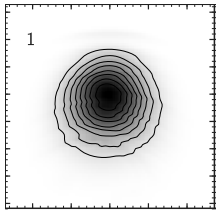


Hunt et al. (2018b)

<- Longer ago

More recently ->

One occurrence

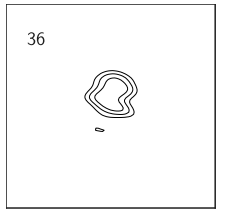


- The effect of a single winding N=2 spiral on the local kinematics is varied

- Wide range of features from arms with different lifetimes and formation times.

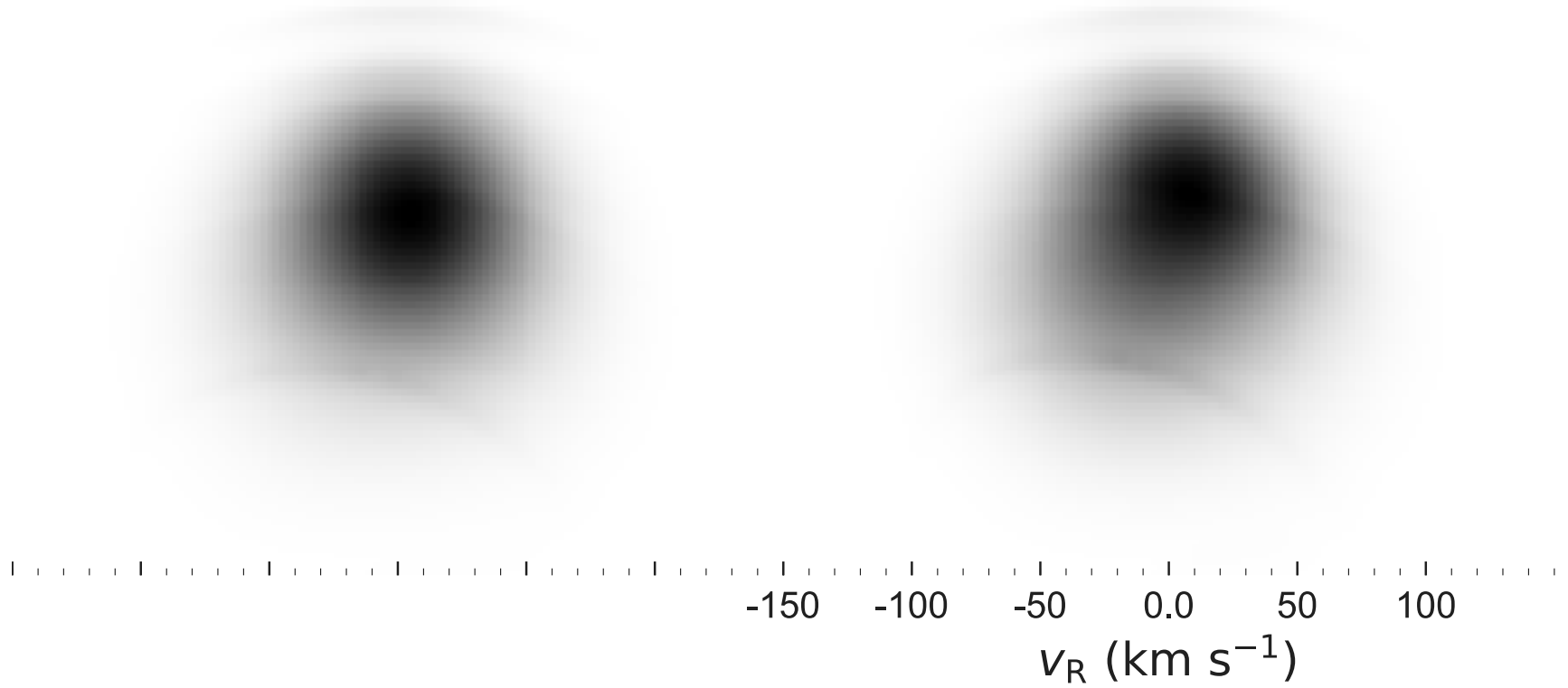
<- Shorter lived

Longer lived ->



Hunt et al. (2018b)

This is phase wrapping, not resonances



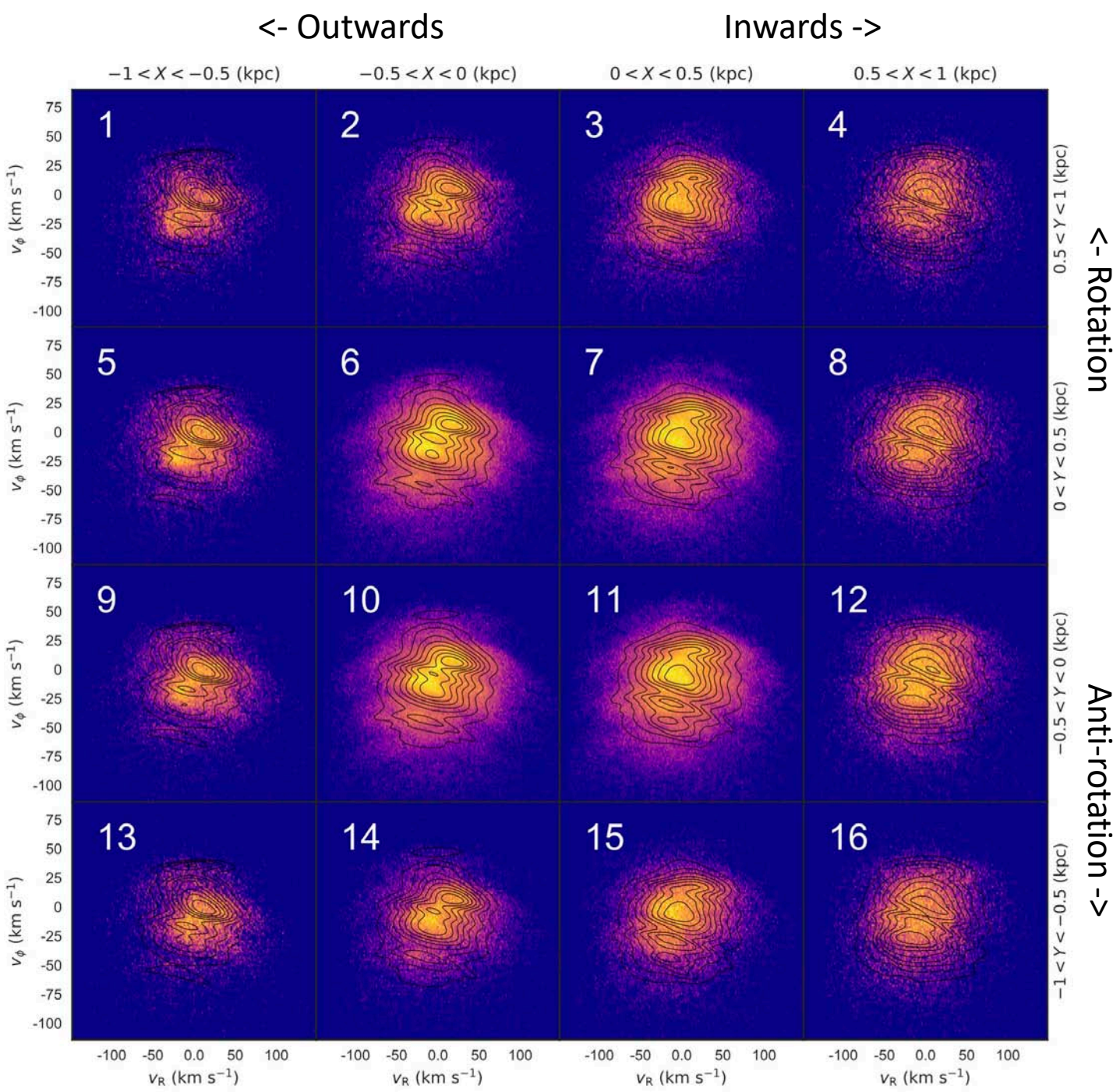
Hunt et al. (2018b)

For a series of three recurrent arms

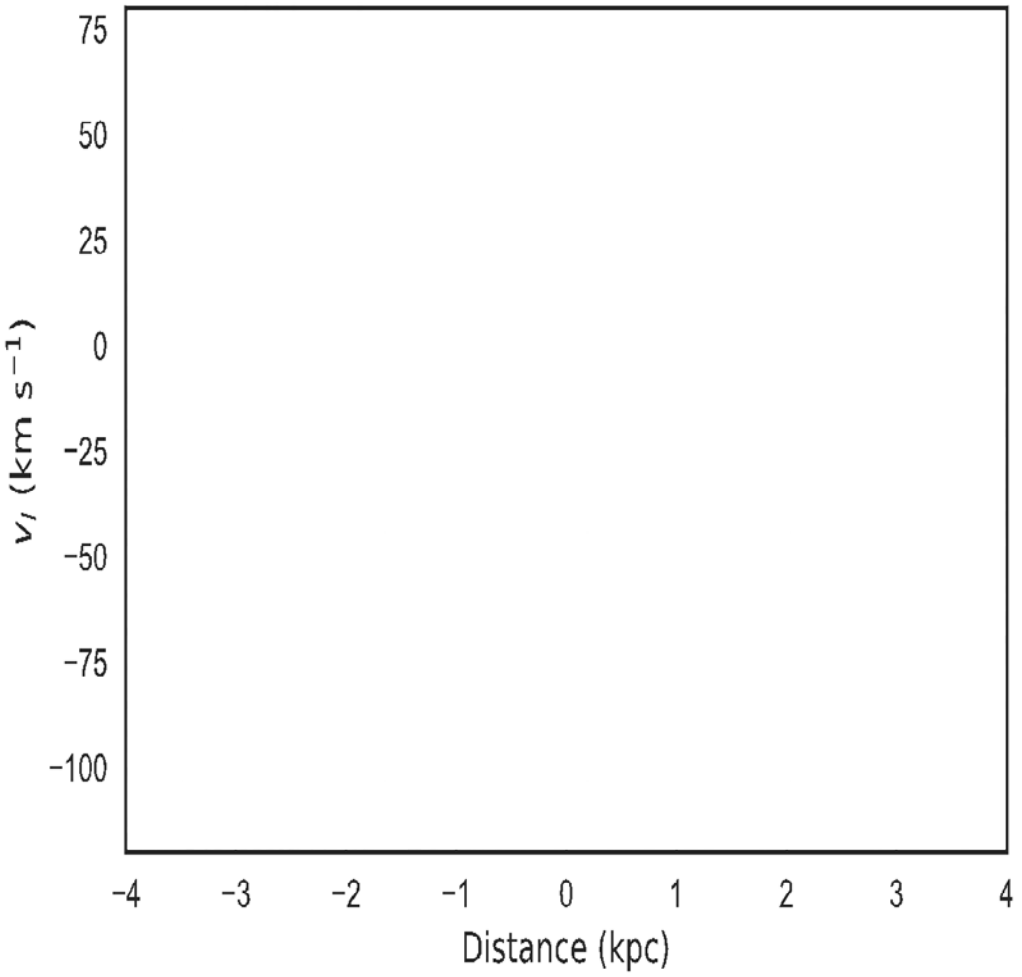
Hunt et al. (2018b)

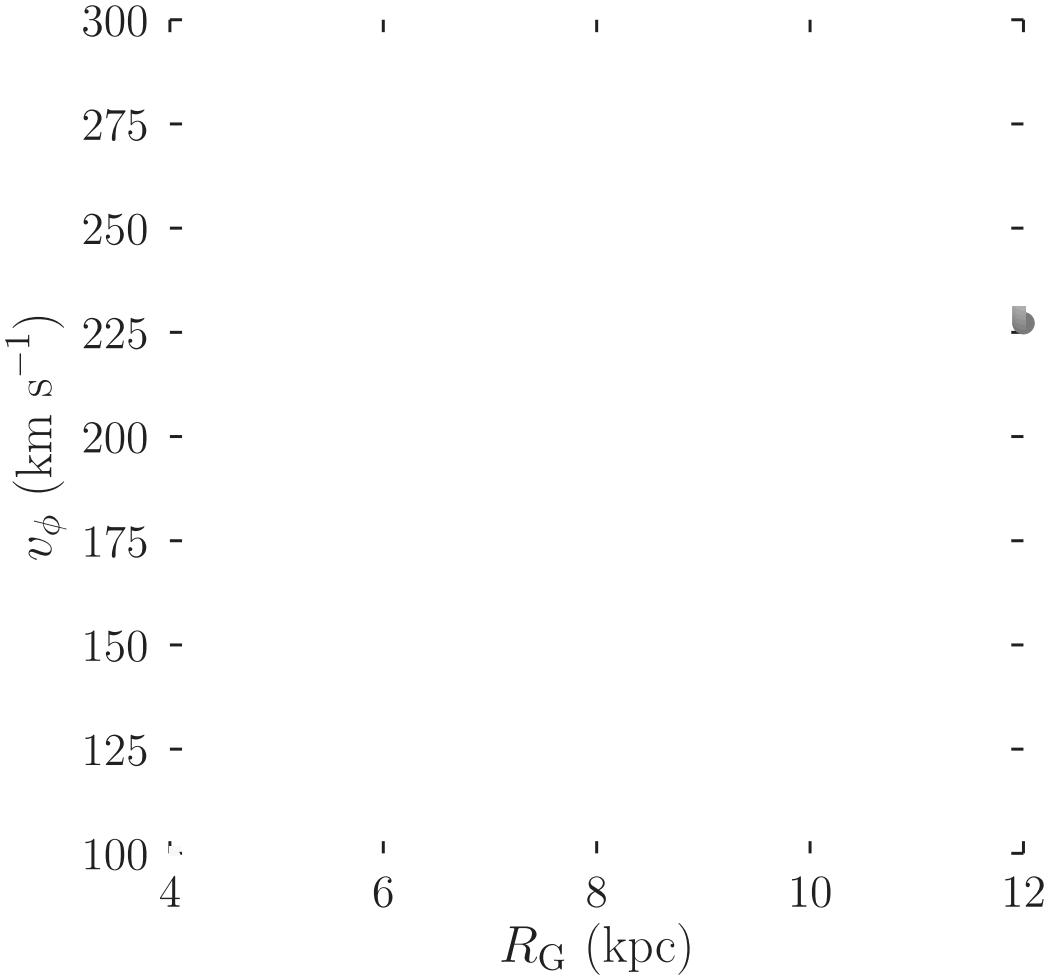
Tracing further from the SNd

- Double Hercules appears towards the Galactic centre.
- Three main moving groups within the main mode.
- Not expected to be perfect!



Reproduces the ridge structure (qualitatively)

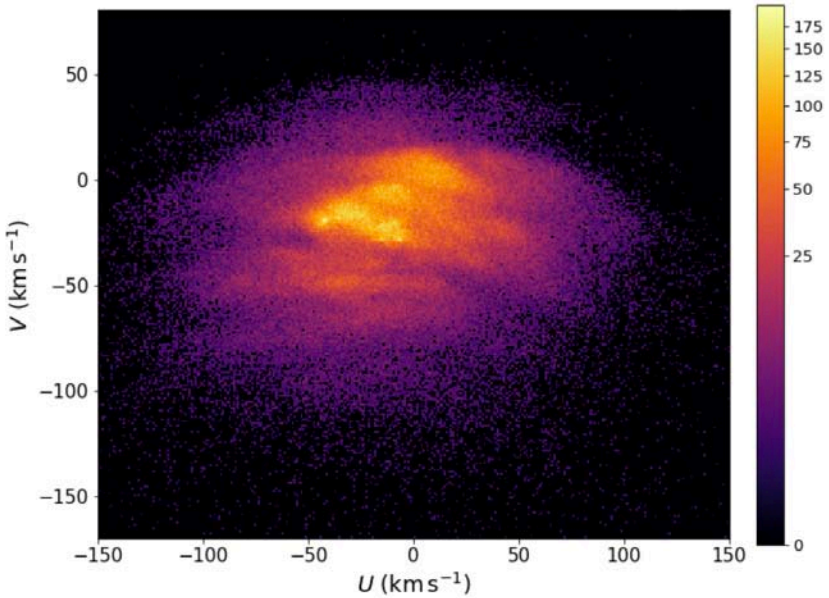




Hunt et al. (2018b)

We can also look in action angle coordinates

- E.g. done in Trick et. al 2018, Sellwood et al. 2018.

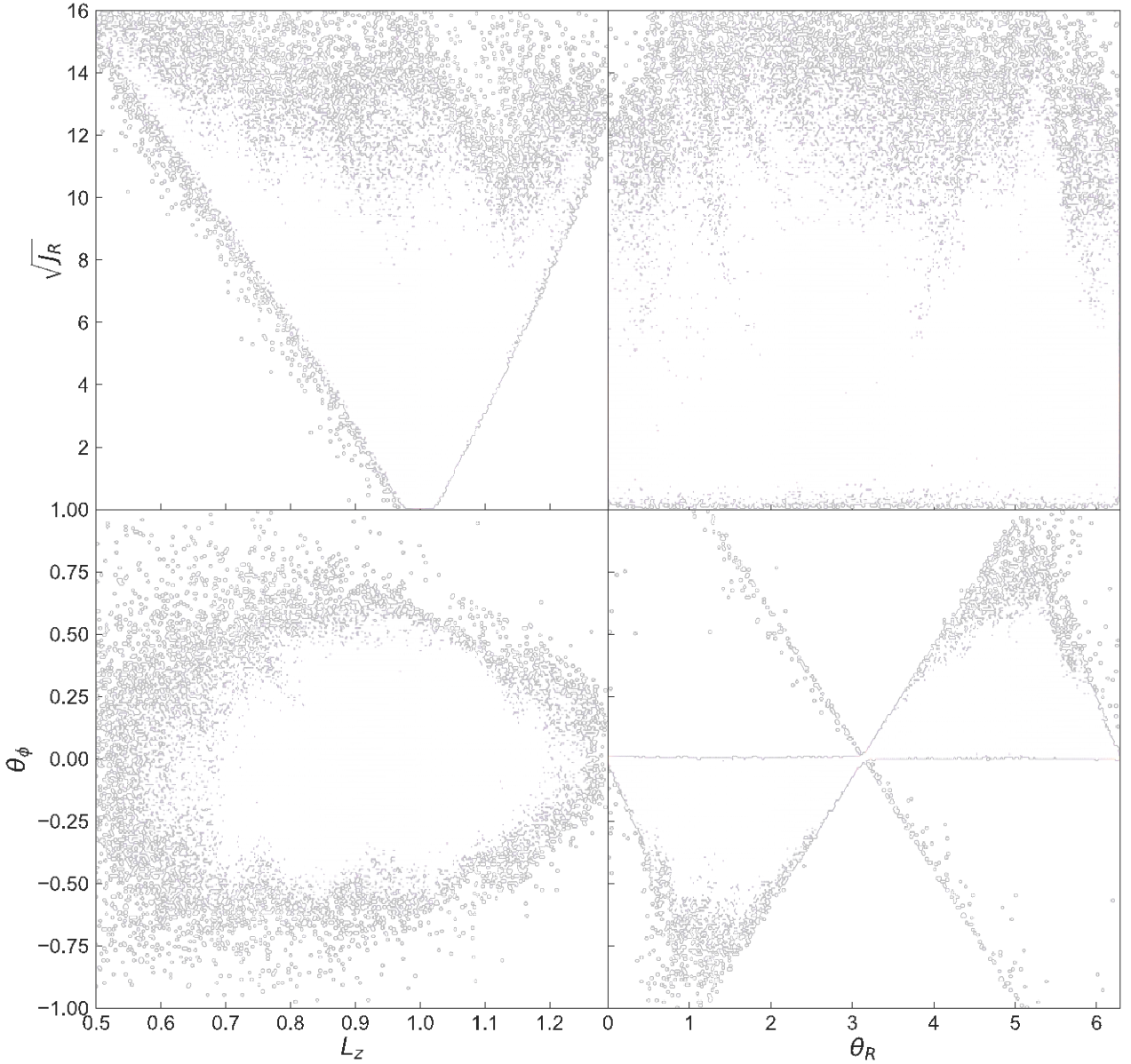


Angular momentum

Radial angle

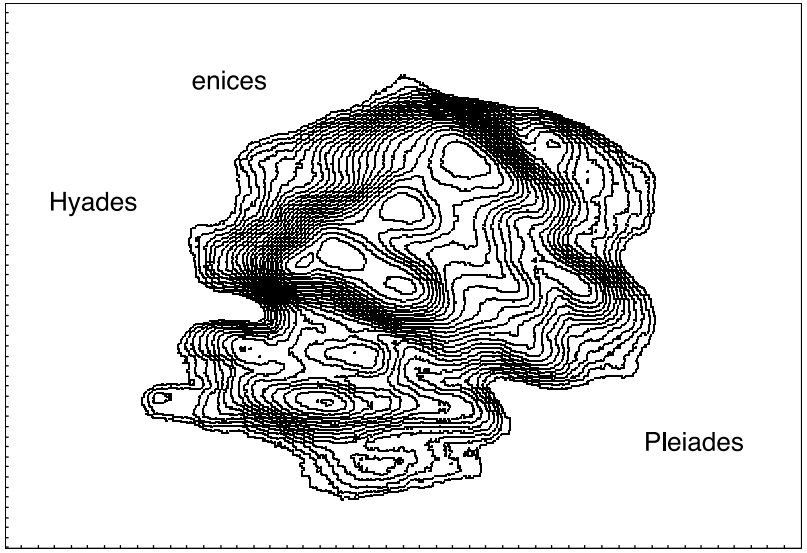
Radial eccentricity

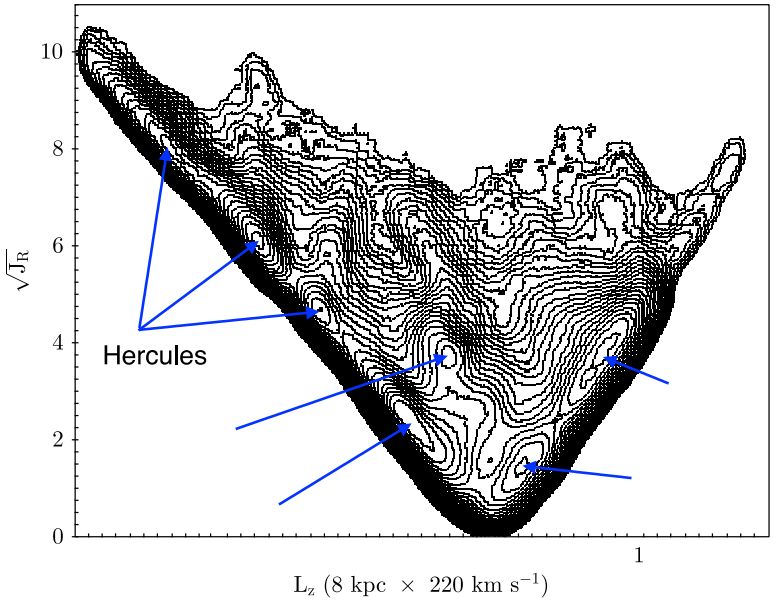
Azimuthal angle

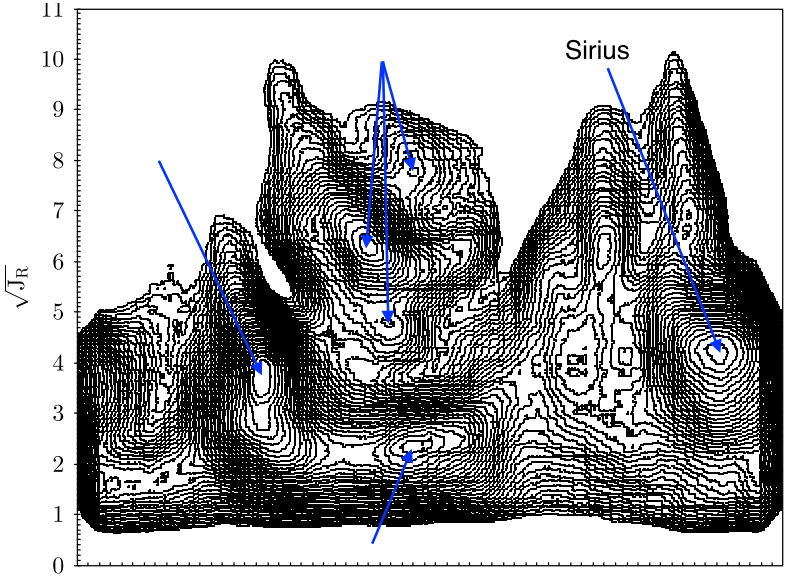


The moving groups in Action-Angle space

- The moving groups are (unsurprisingly) clearly visible in actions and angles.

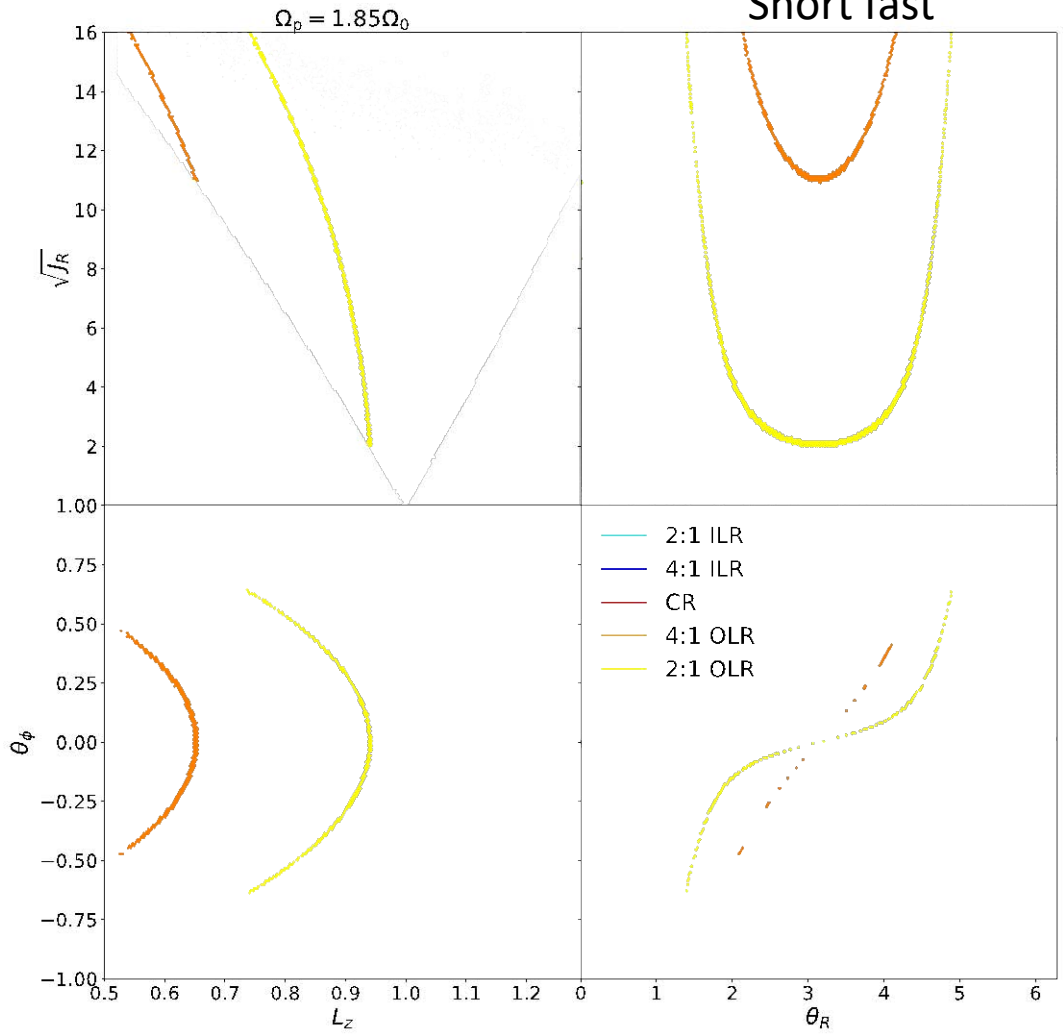




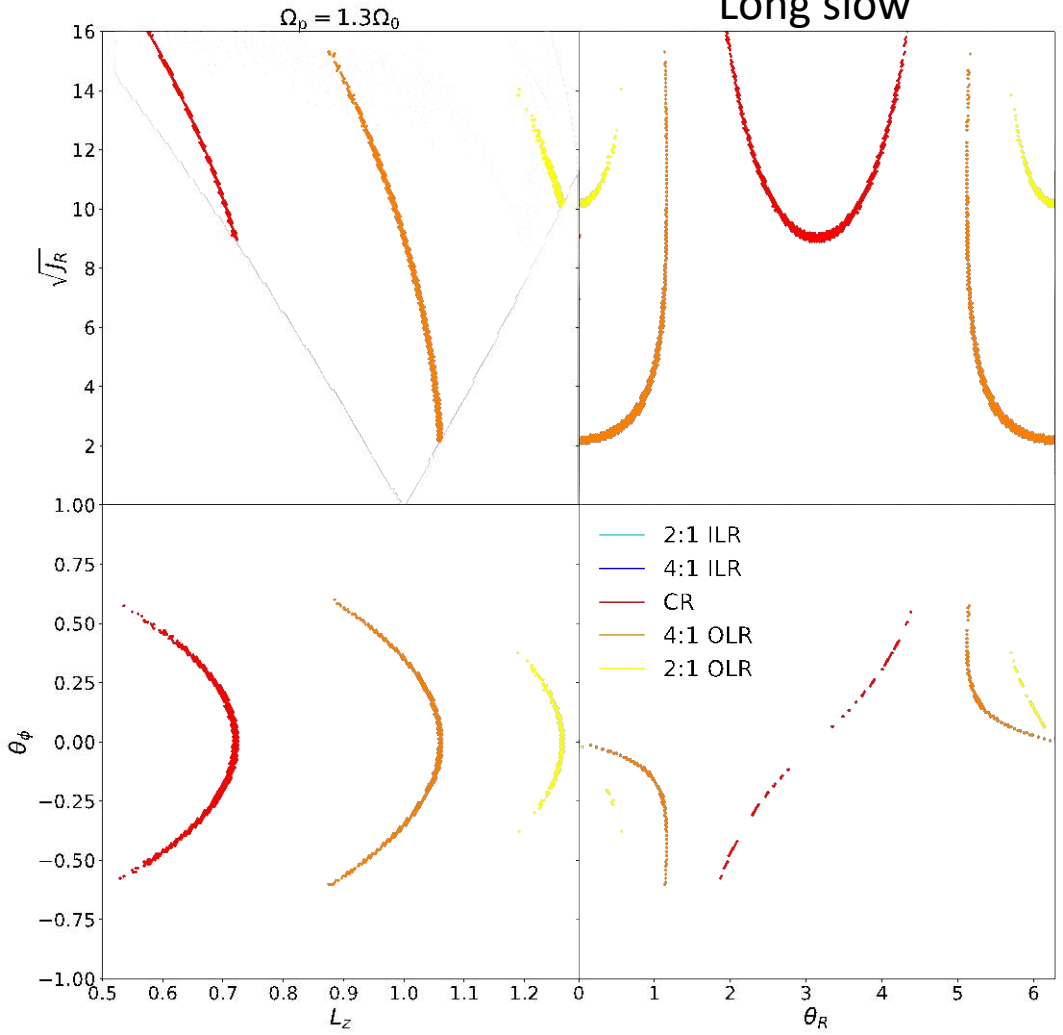


The bar models in Action-Angle

Short fast

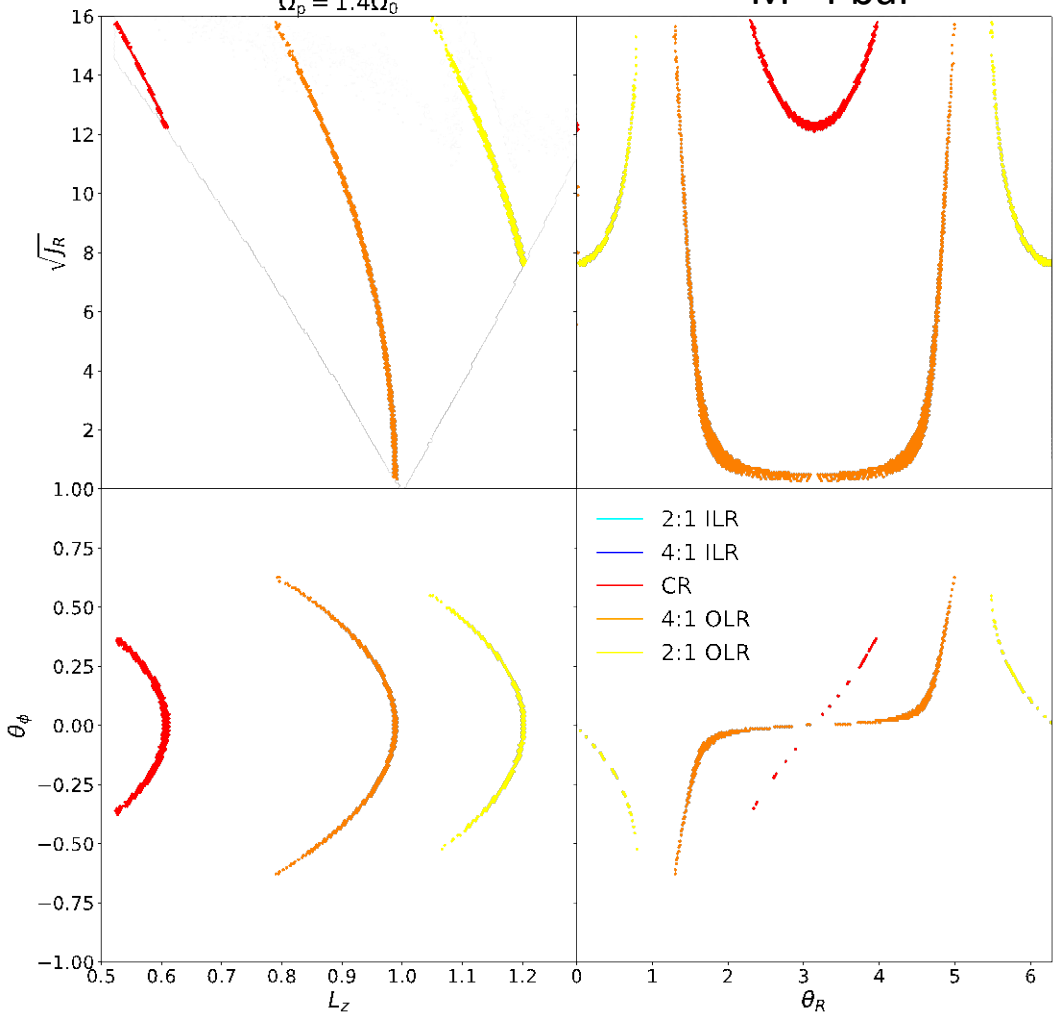


Long slow

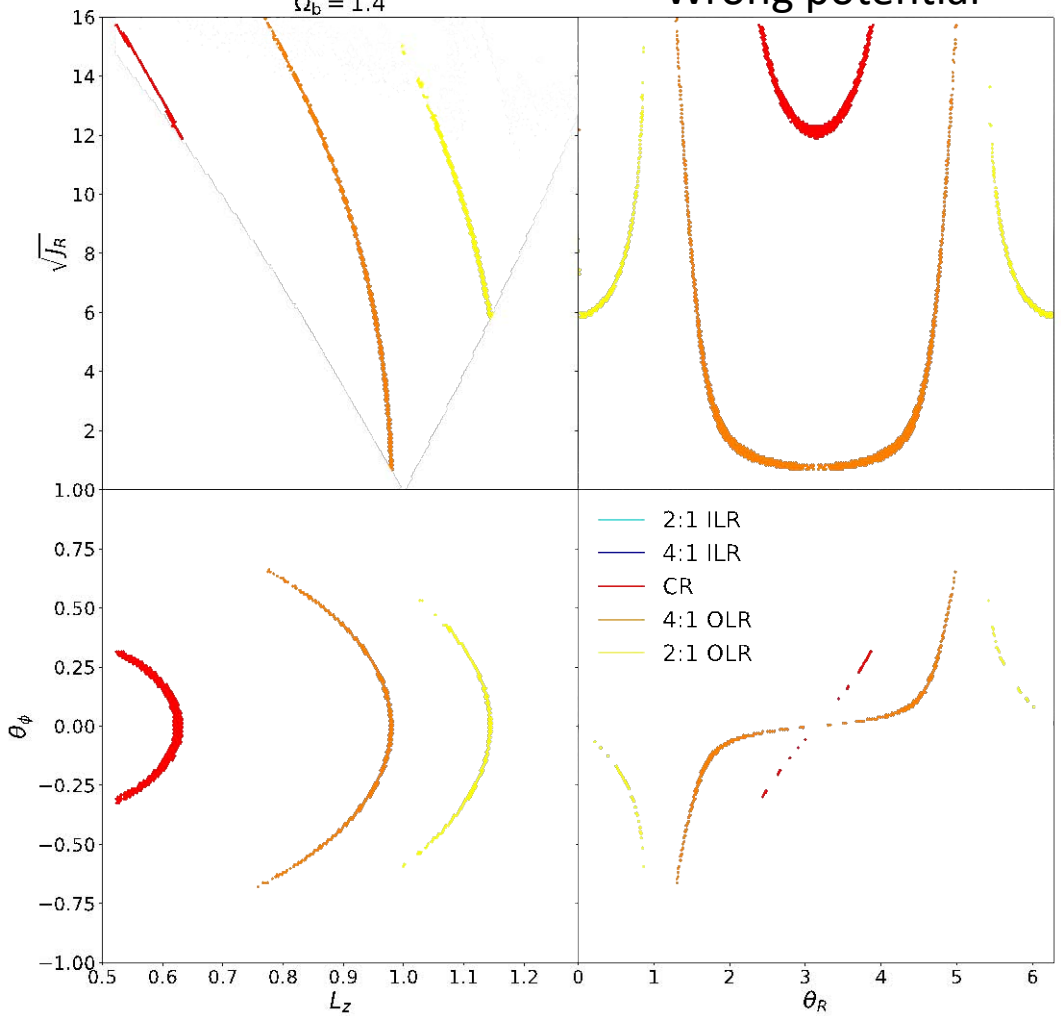


The frequencies are dependent on the potential

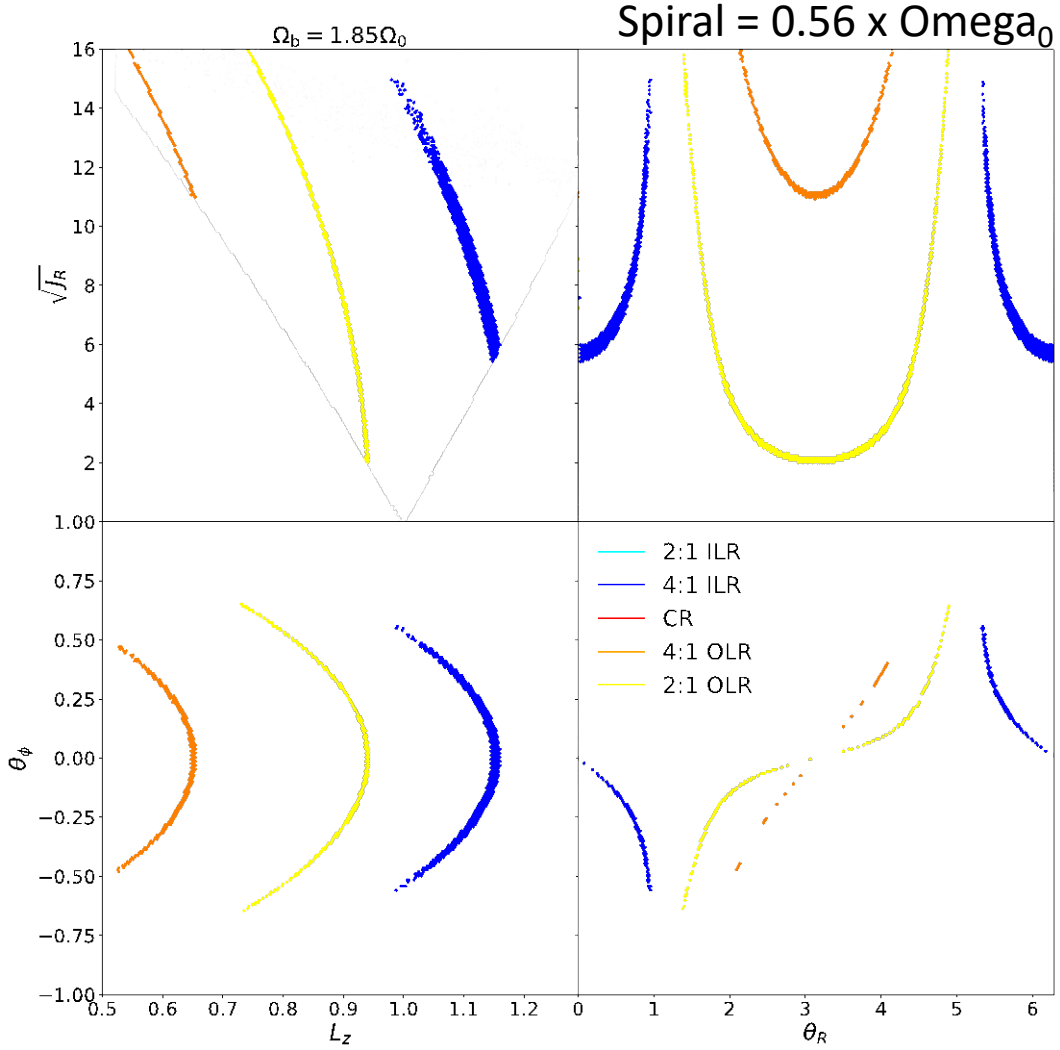
M=4 bar

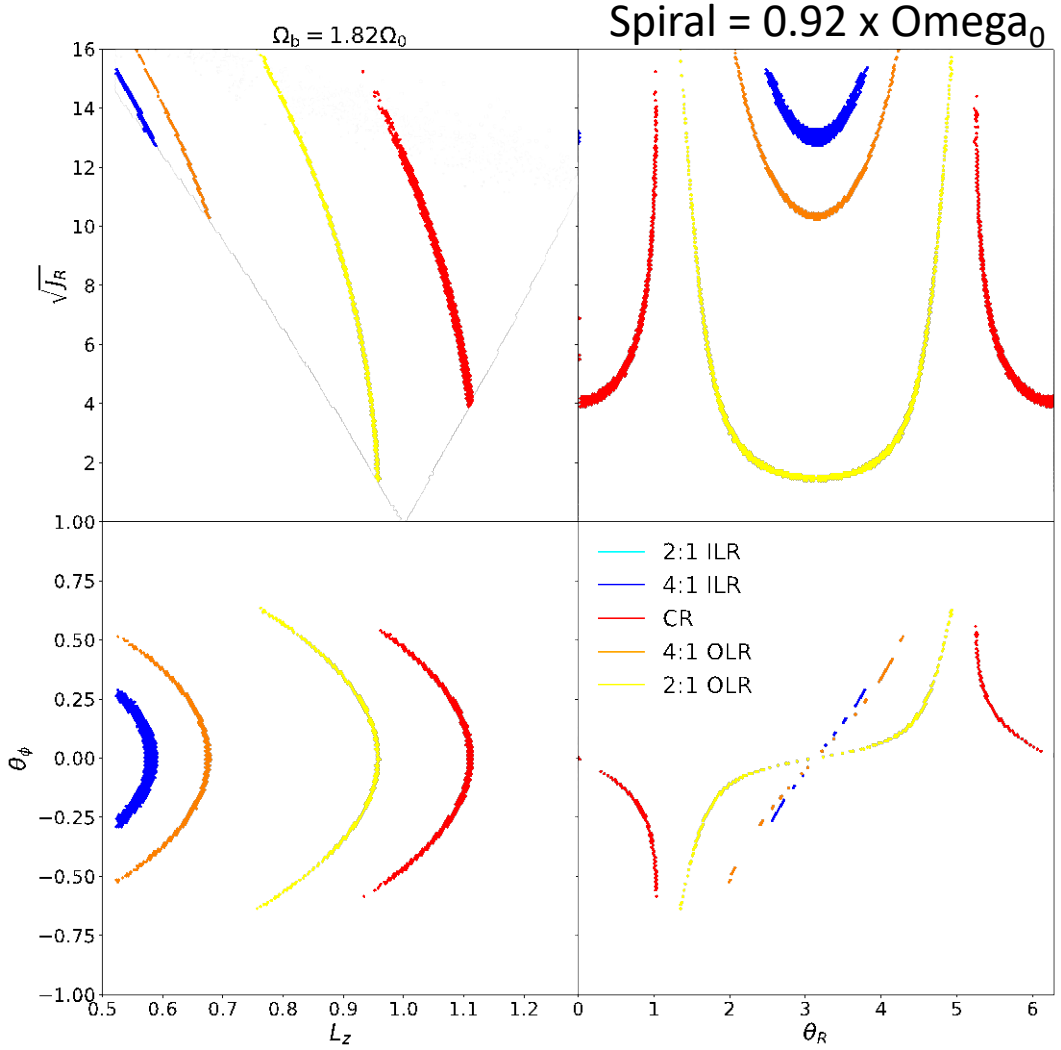


Wrong potential

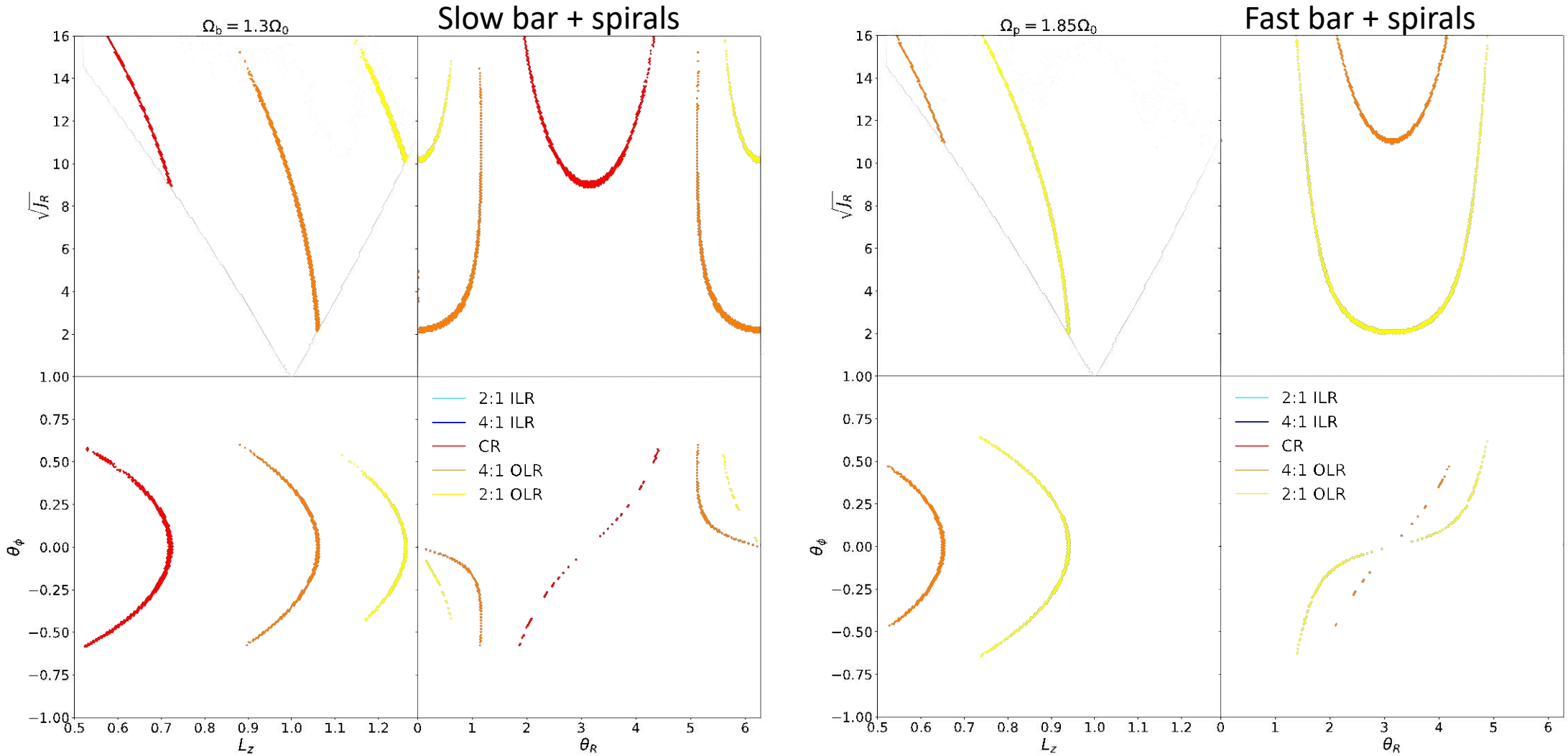


Combination with spirals (density waves)

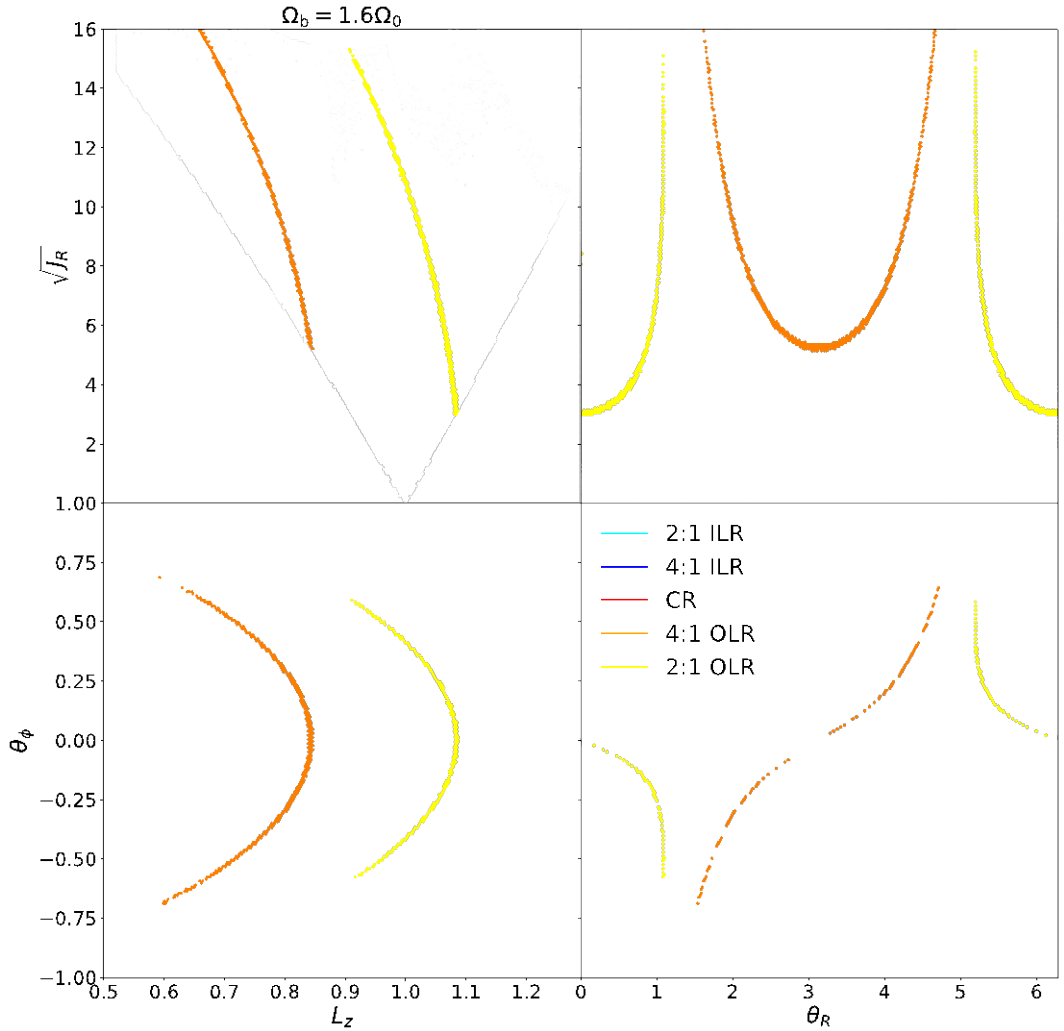


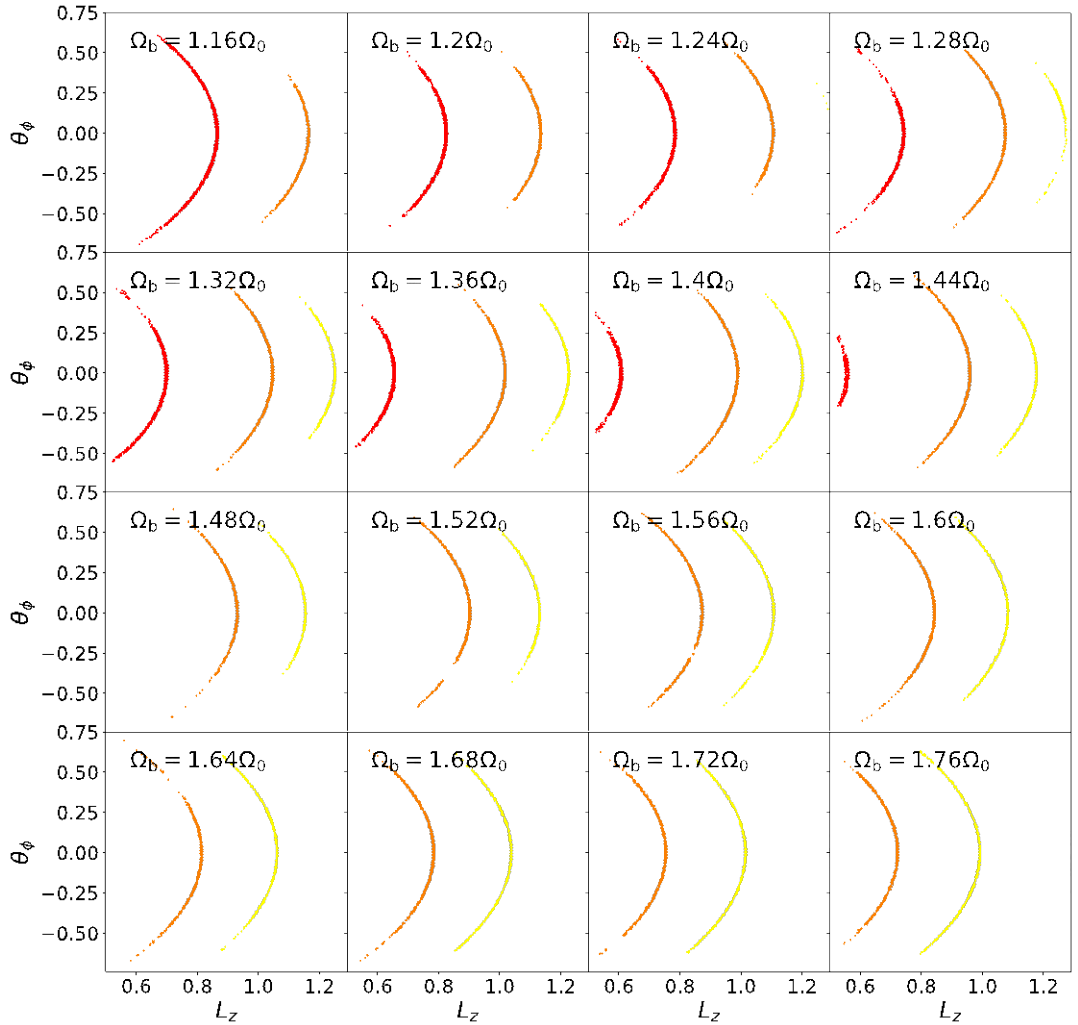


Combination with spirals (transient winding)



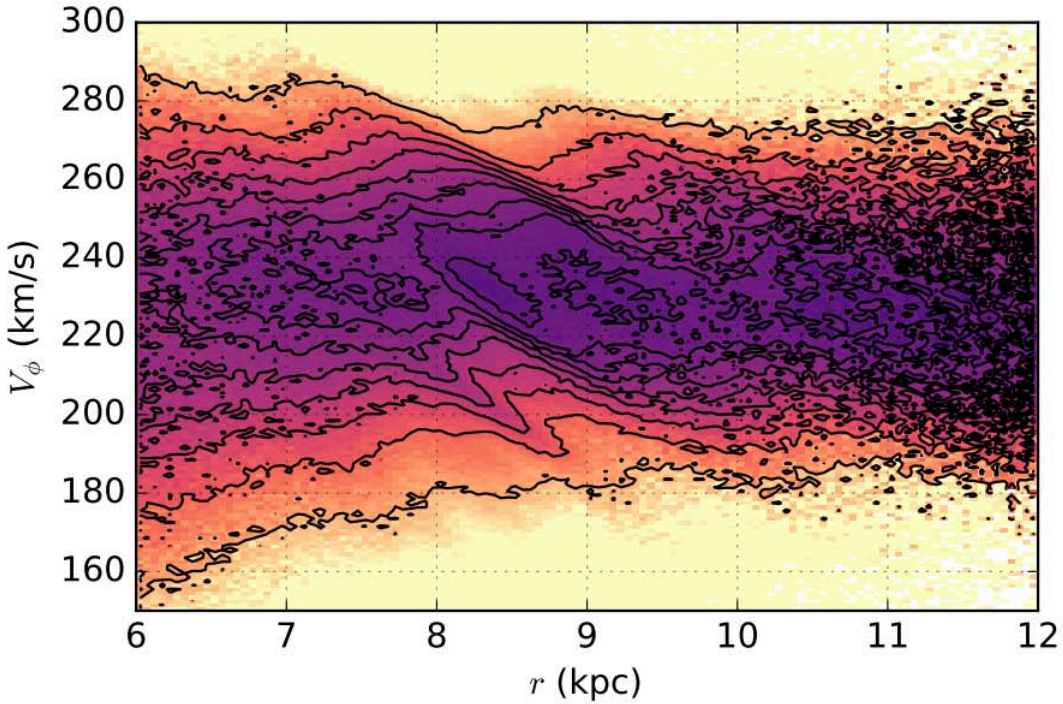
Also other pattern speeds fit well

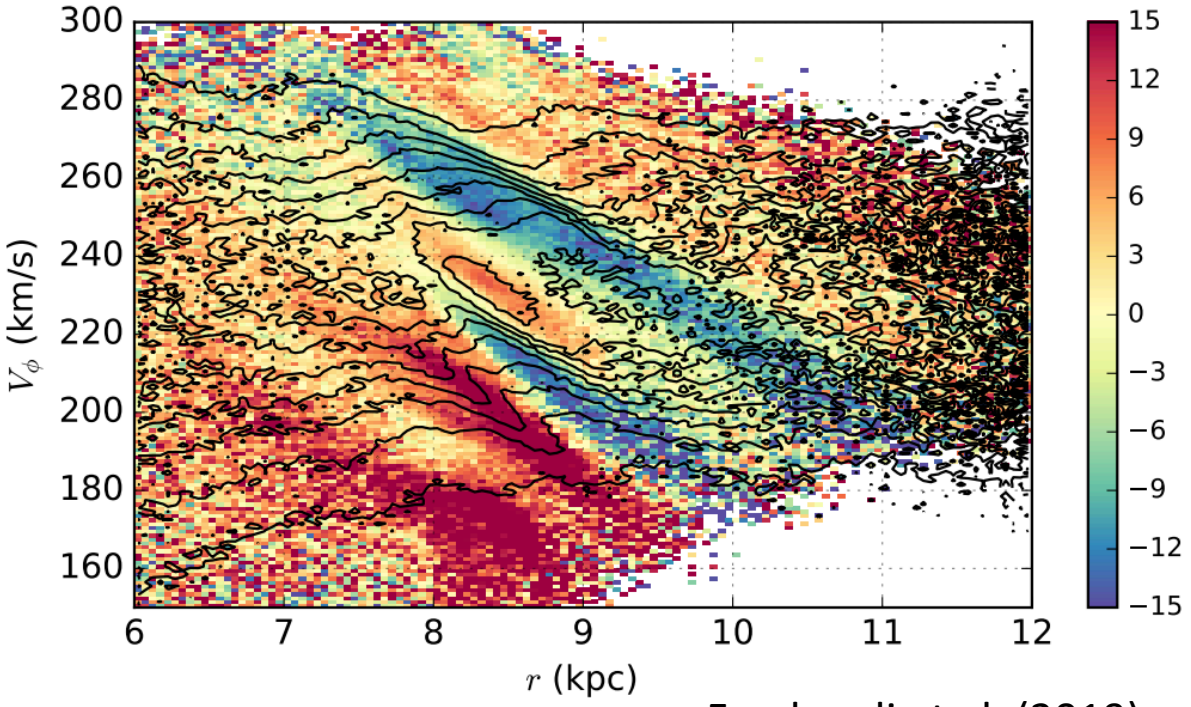




And back to the R-v_{phi} ridges

- The ridges are also distinct in v_R (e.g. as shown in Fragkoudi et al. 2019)

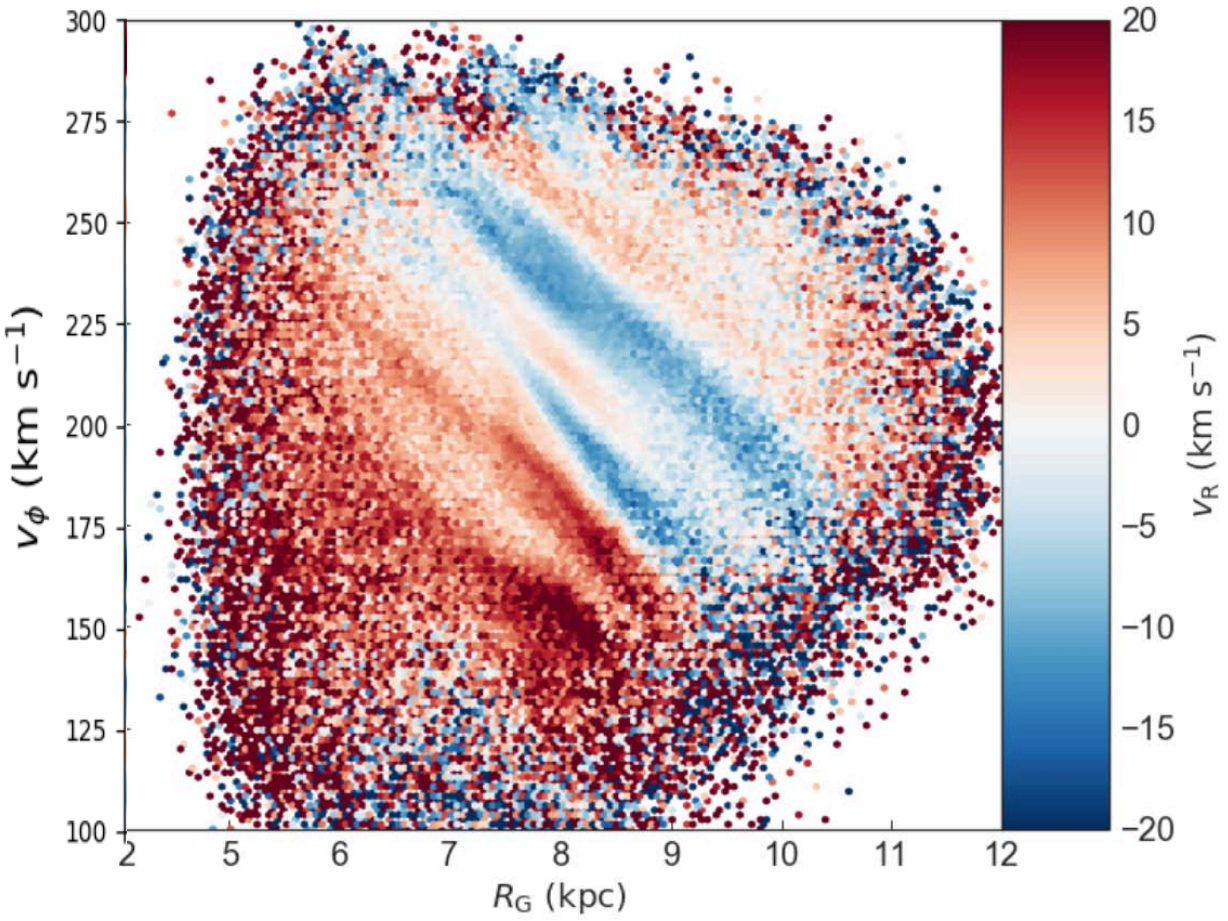


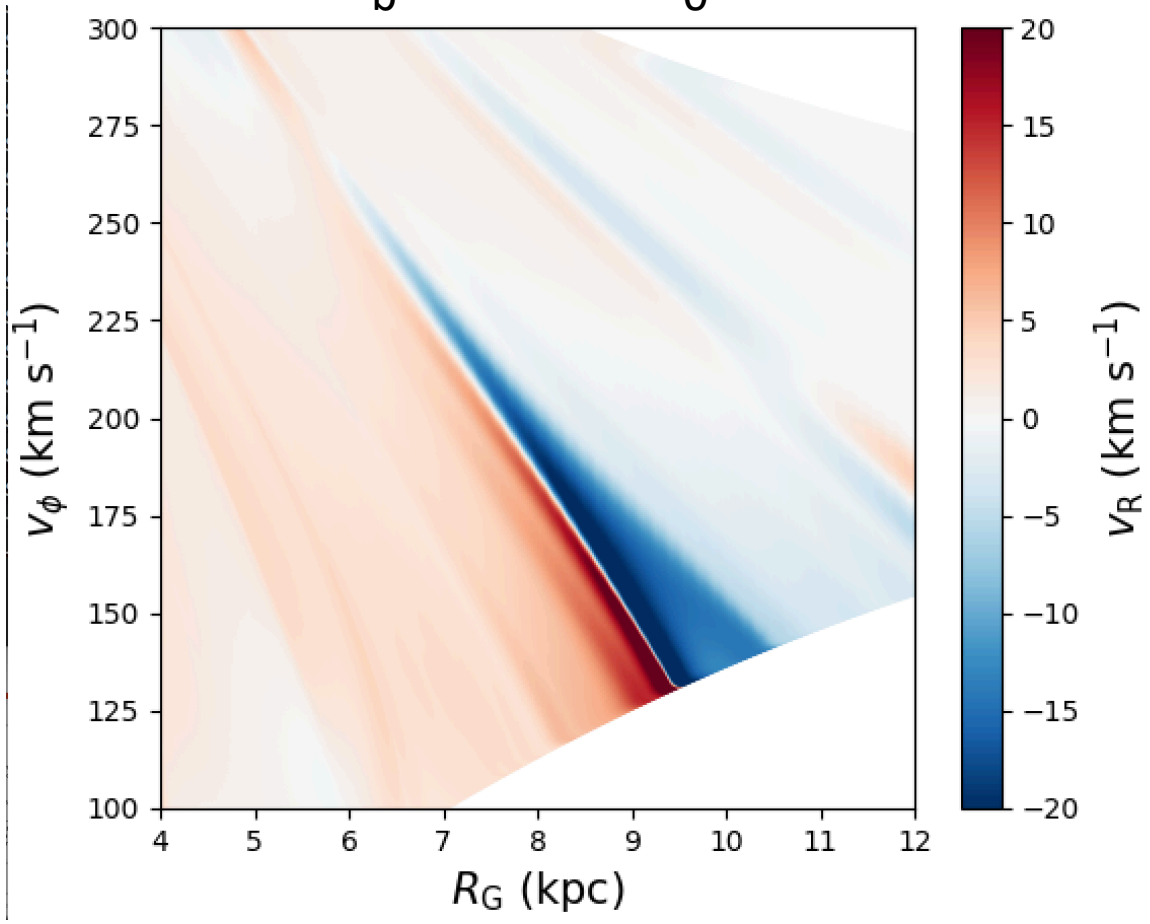


Fragkoudi et al. (2019)

So let's go through these again: short fast bar

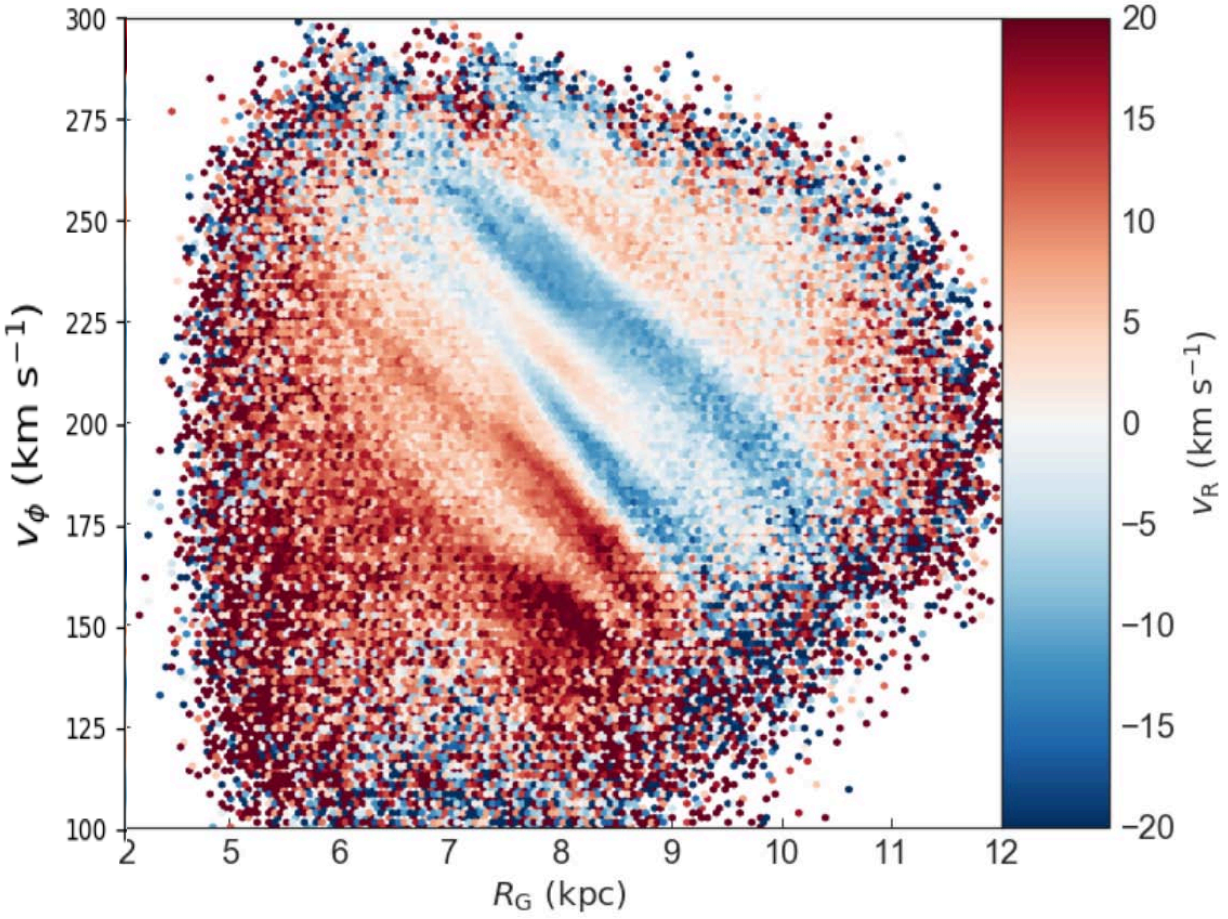
Ω_b=1.85 x Ω_0



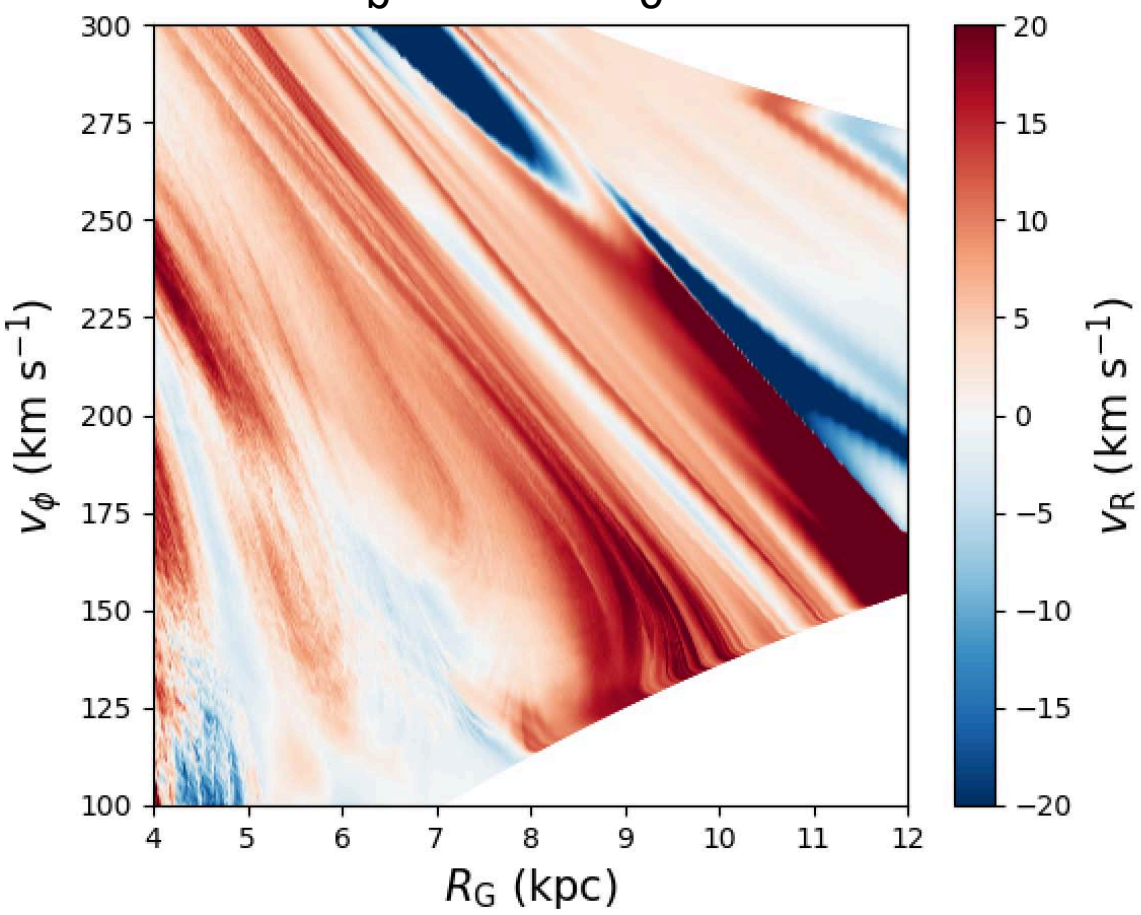


OLR makes a clear red-blue feature (as discussed in Wilma Trick's talk yesterday)

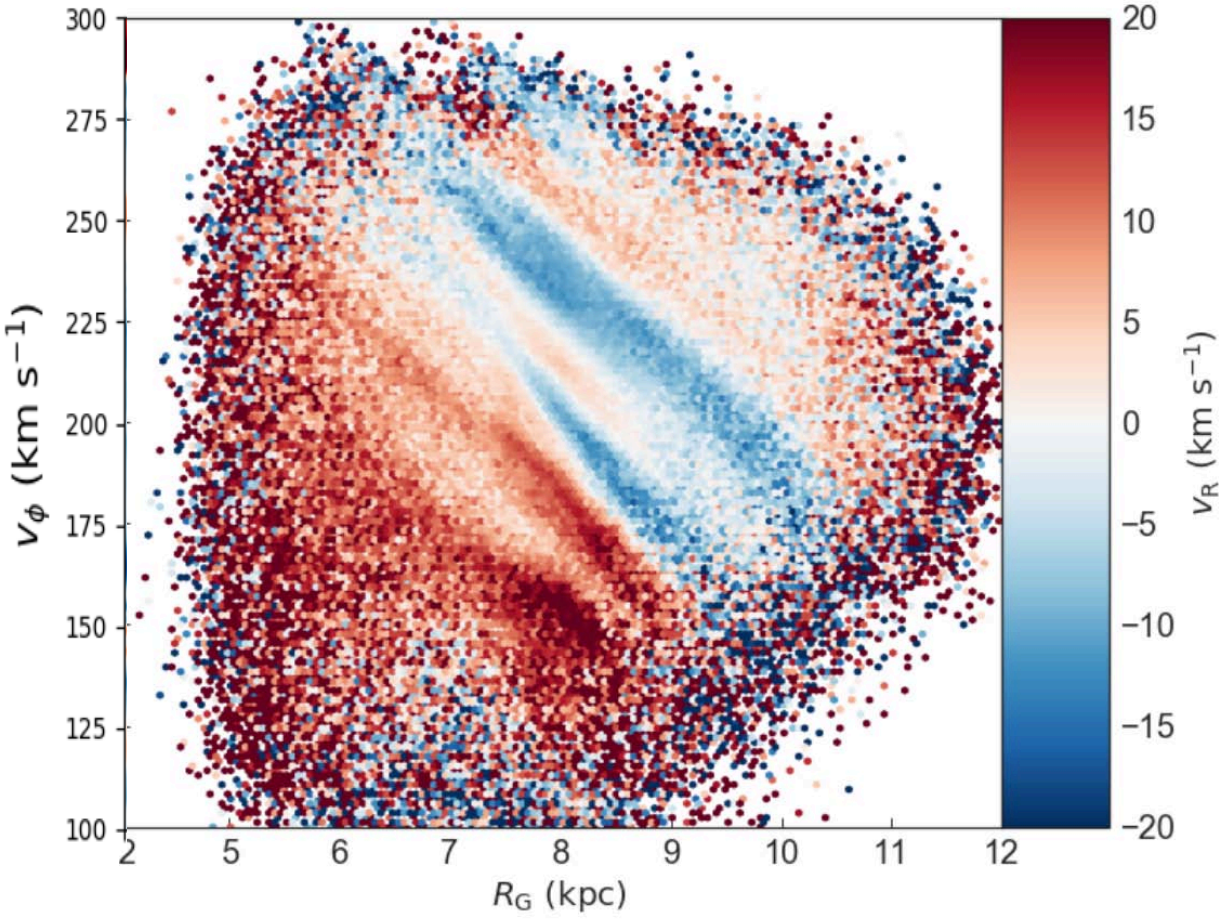
So let's go through these again: long slow bar



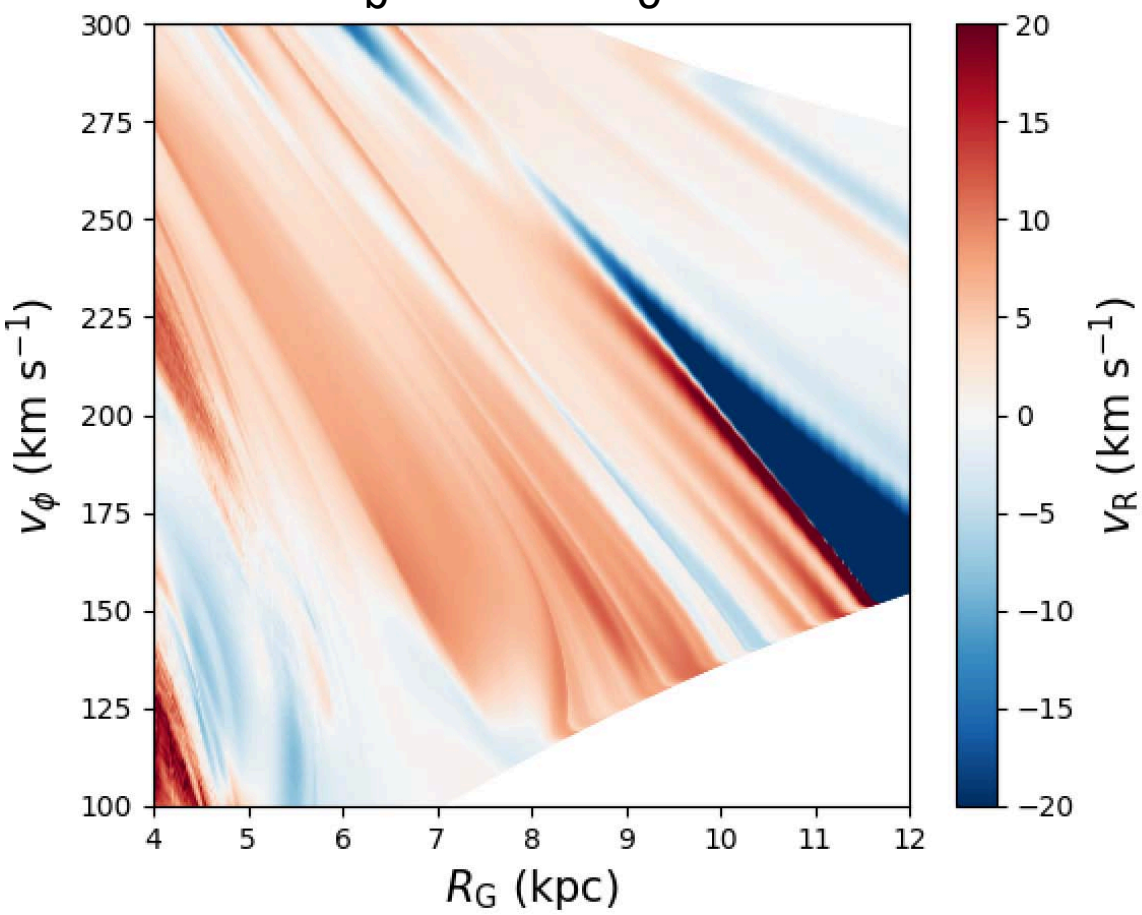
Ω_b=1.3 x Ω_0



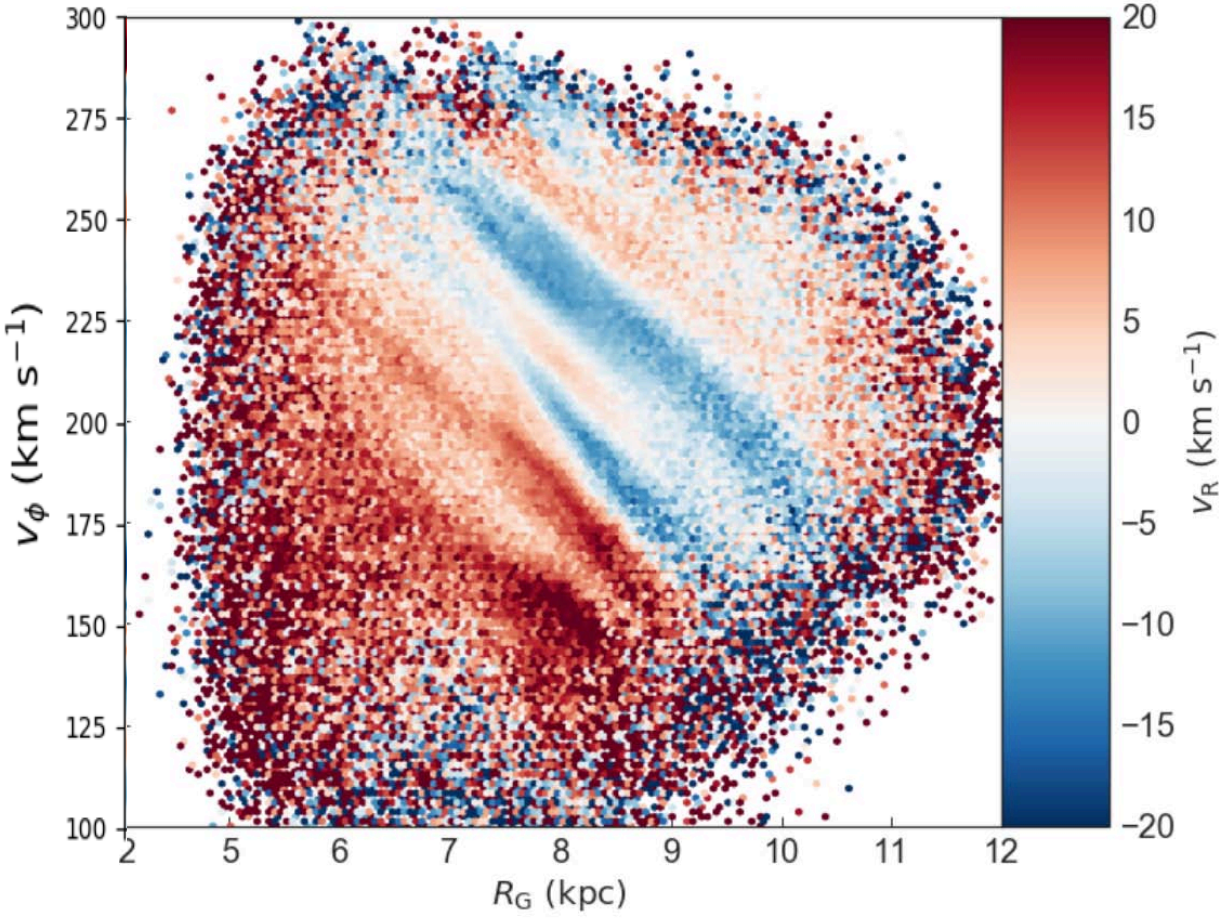
So let's go through these again: 1.4 bar



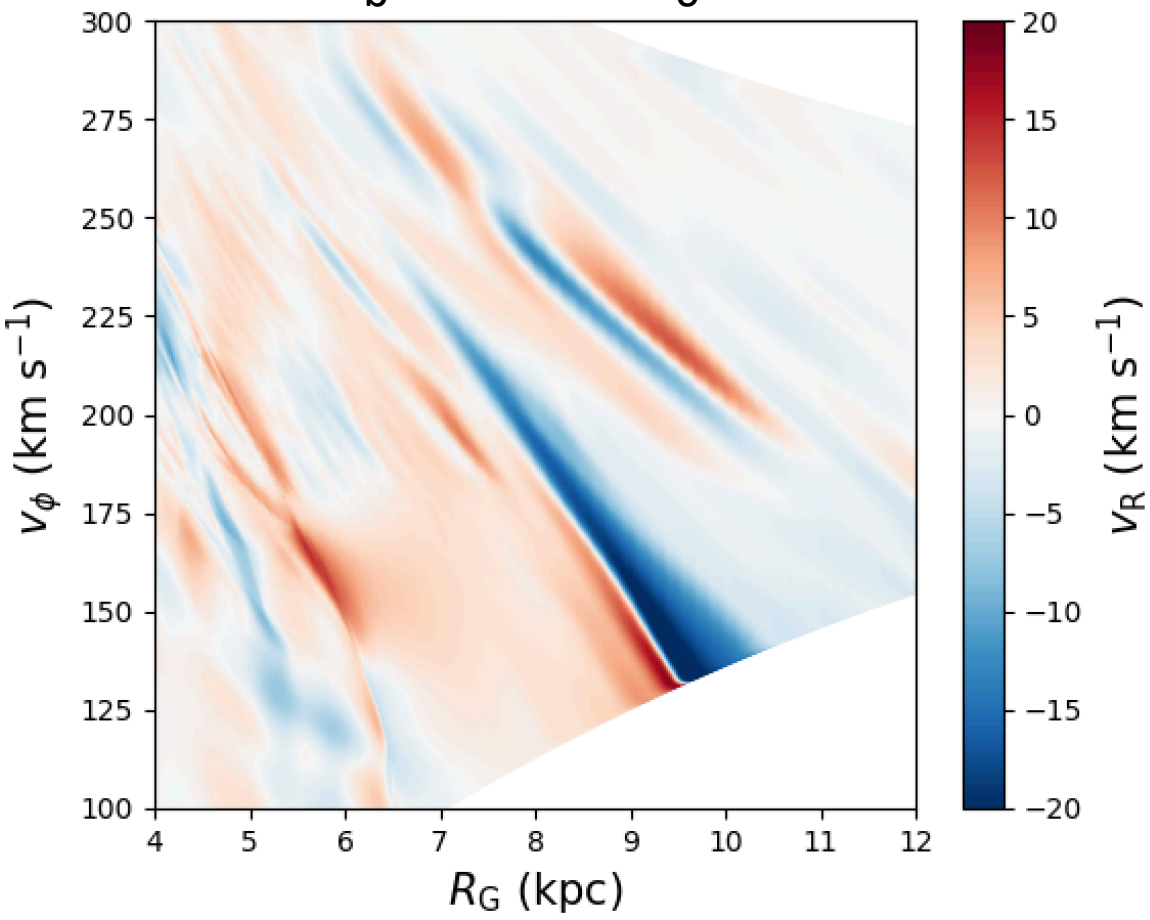
Ω_b=1.4 x Ω_0



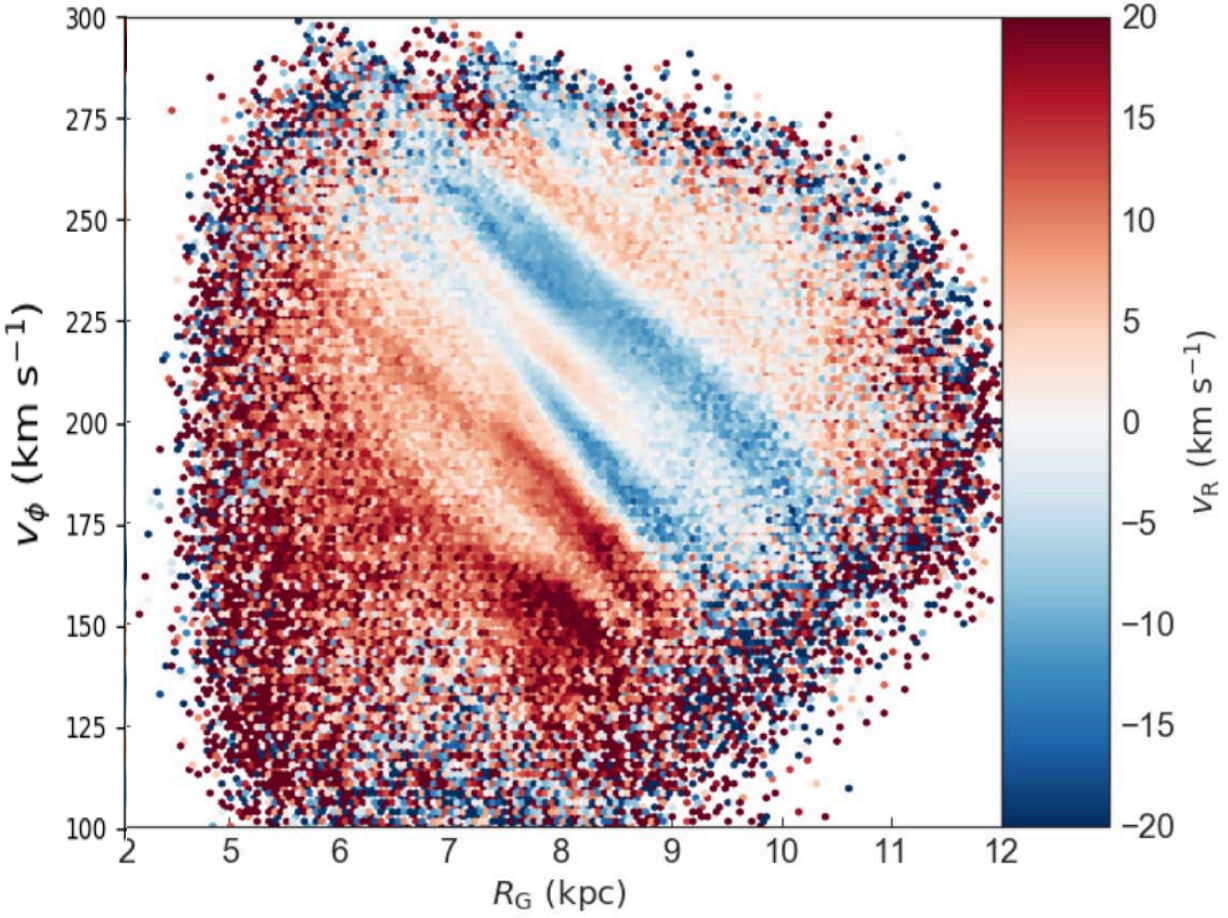
So let's go through these again: $\Omega_{sp}=0.56x\Omega_0$



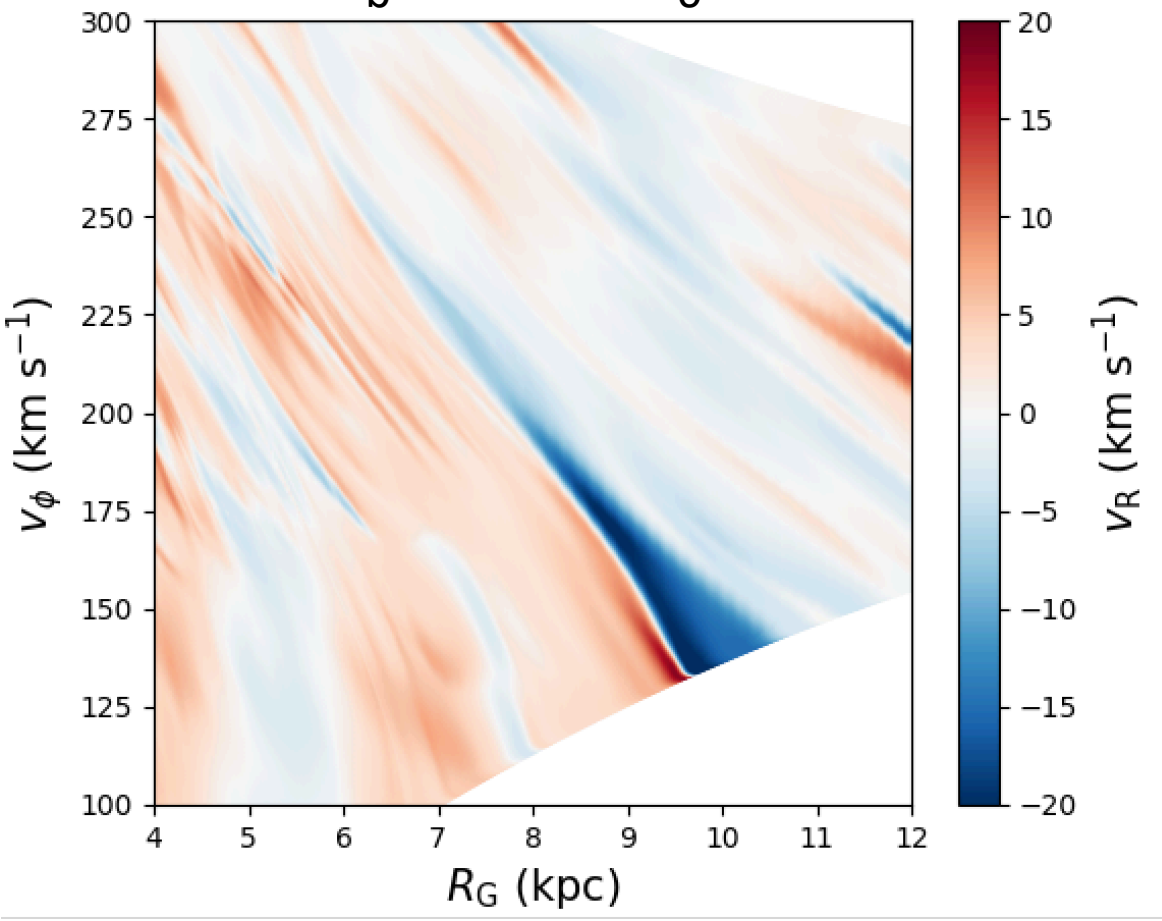
$\Omega_b=1.85 \times \Omega_0$



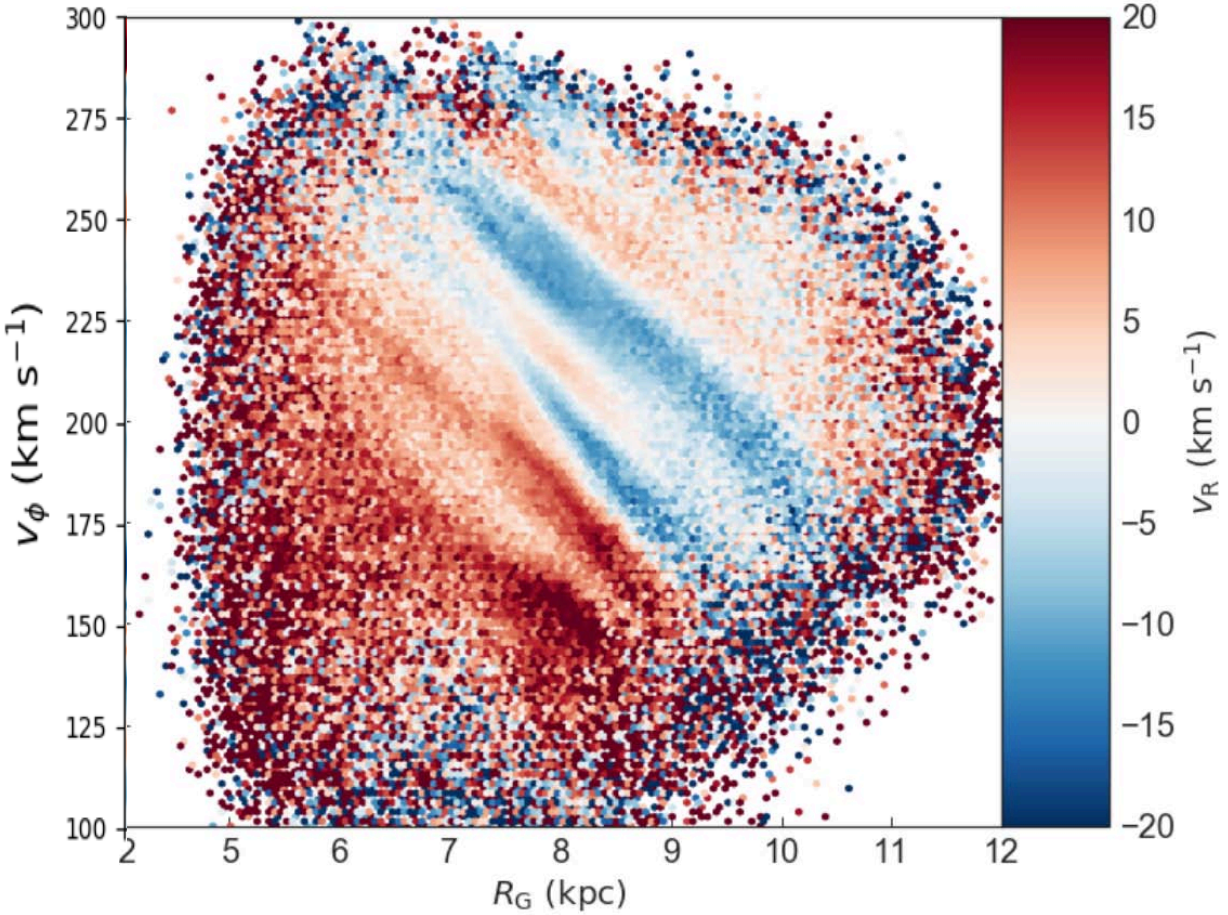
So let's go through these again: $\Omega_{sp}=0.91x\Omega_0$



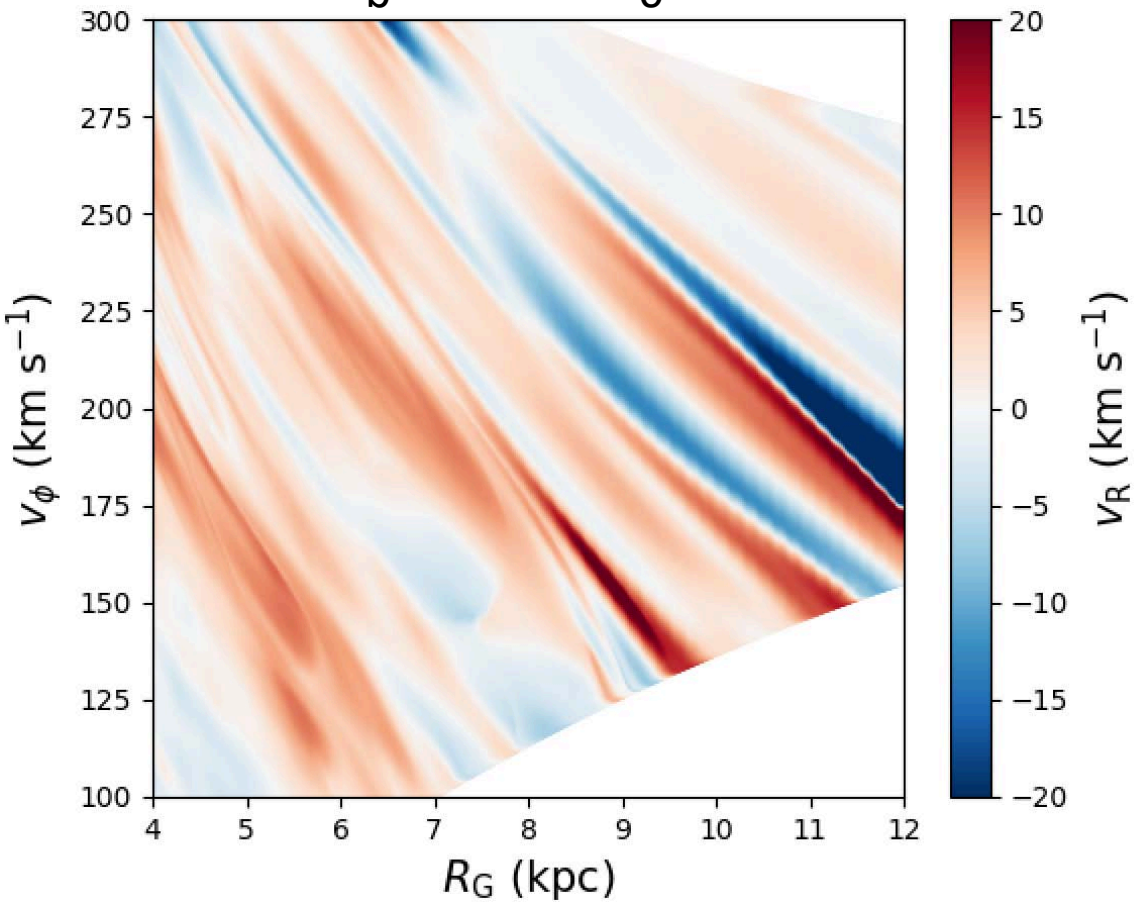
$\Omega_b=1.85 \times \Omega_0$



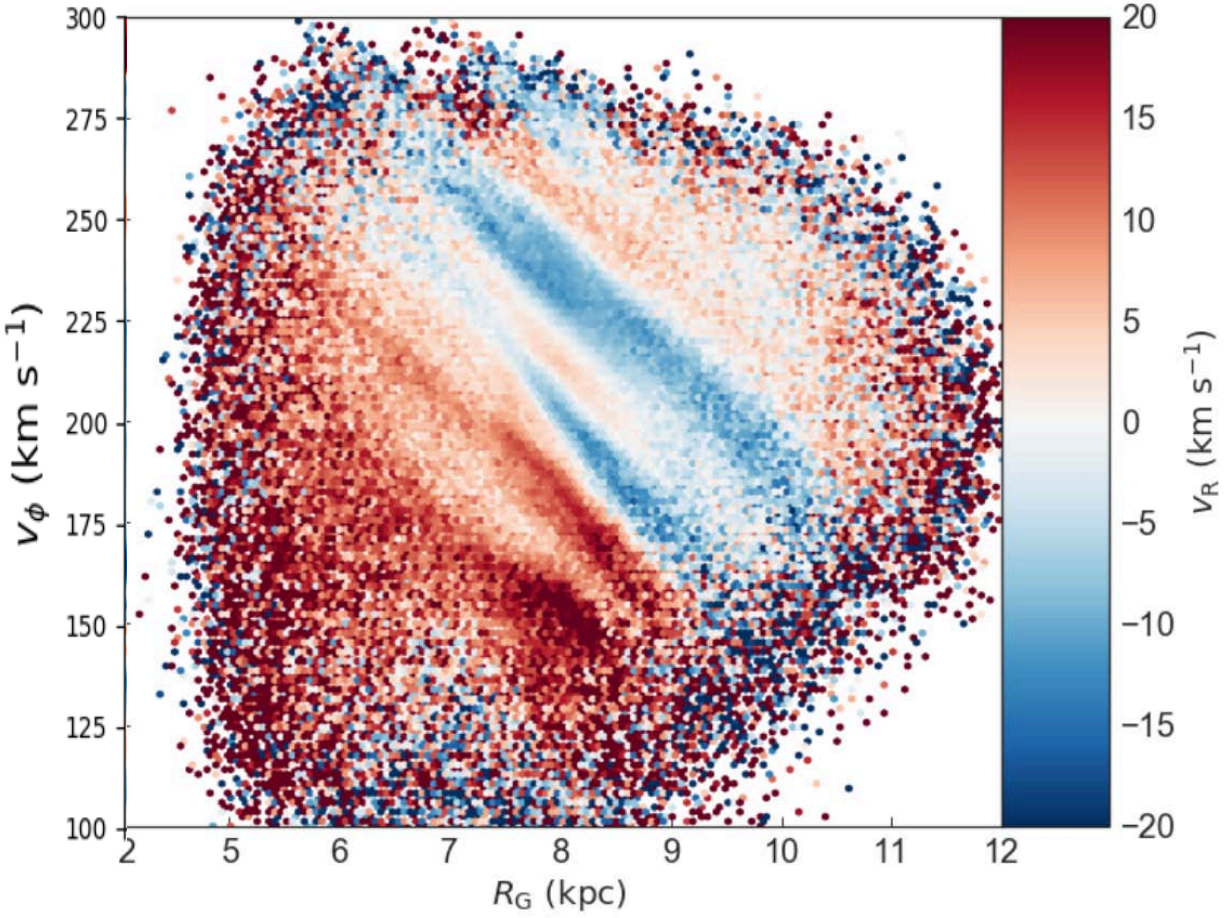
So let's go through these again: Transient + long slow



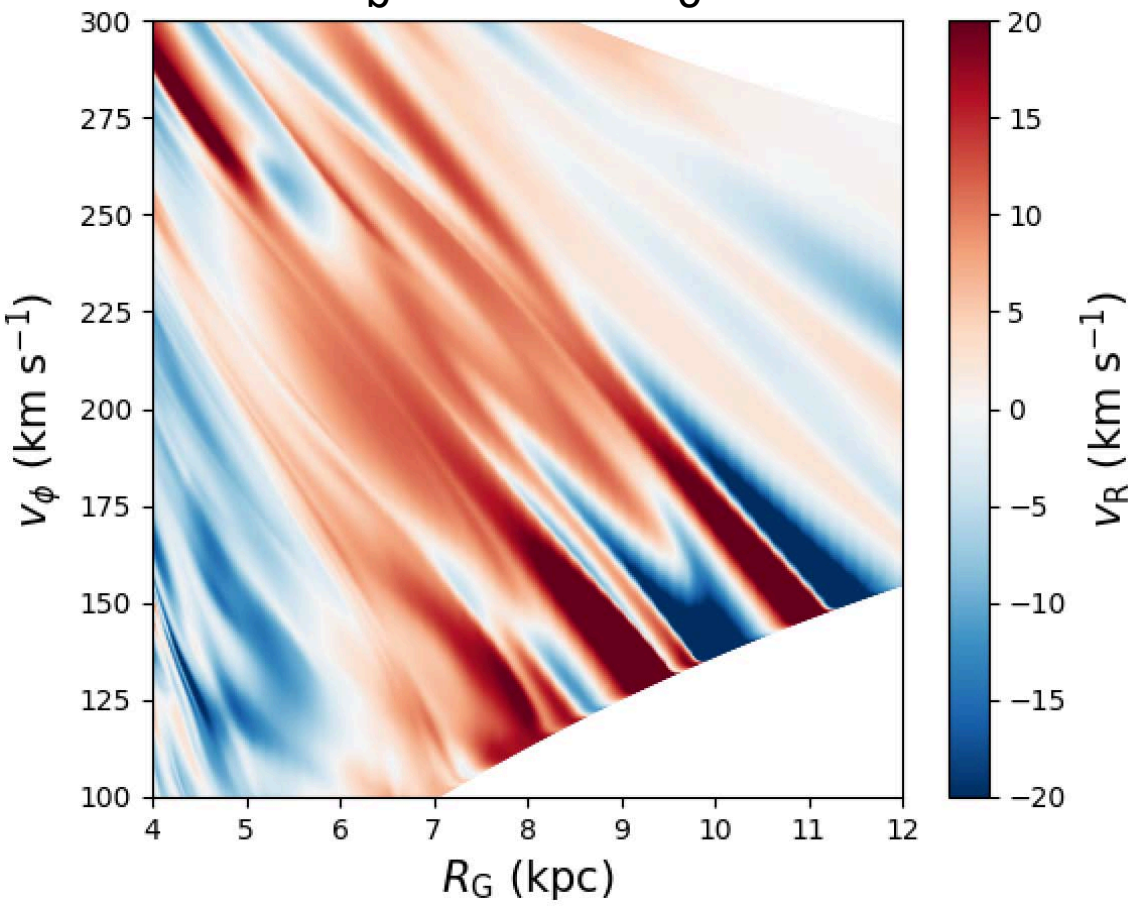
Ω_b=1.3 x Ω_0



So let's go through these again: Transient + short fast

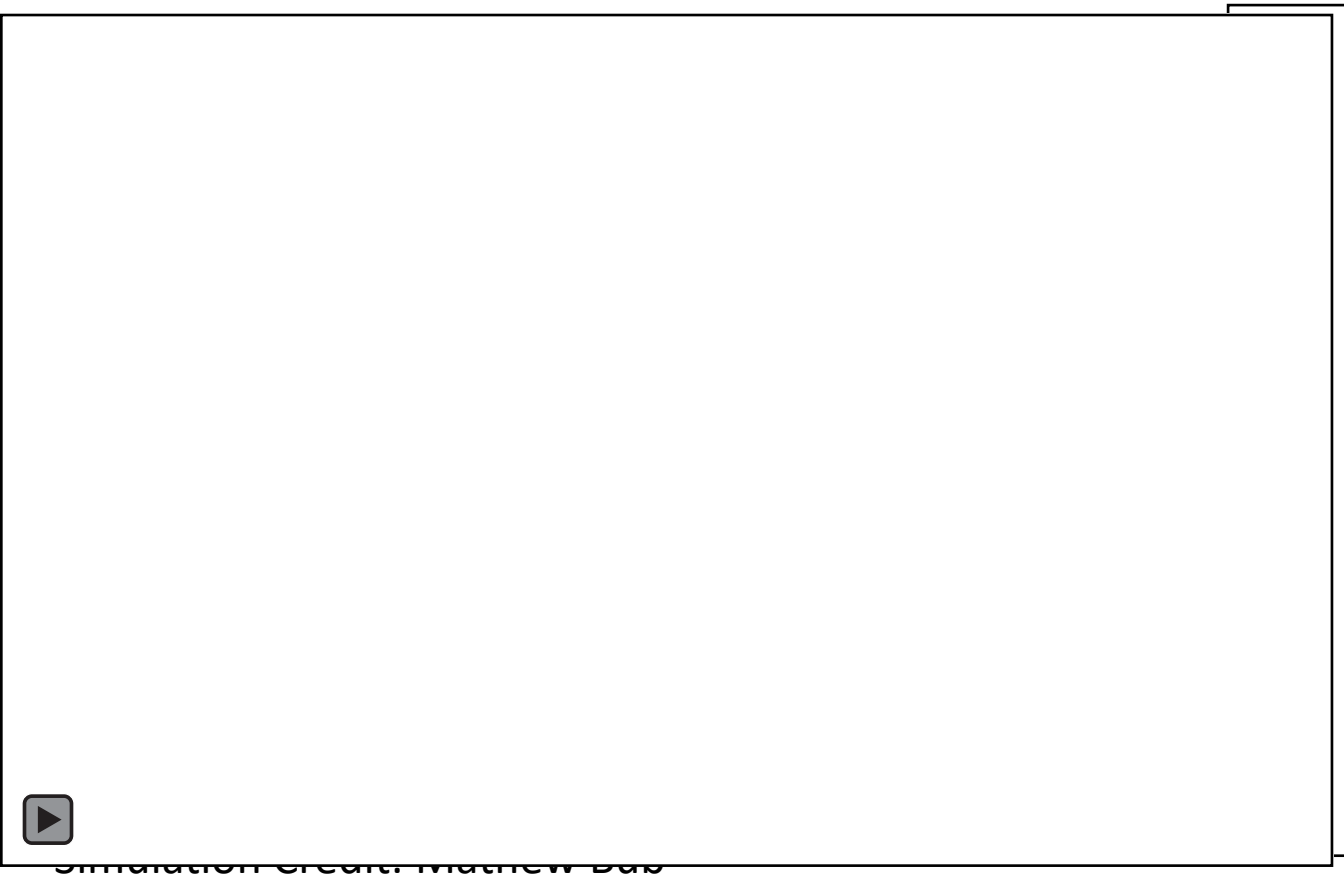


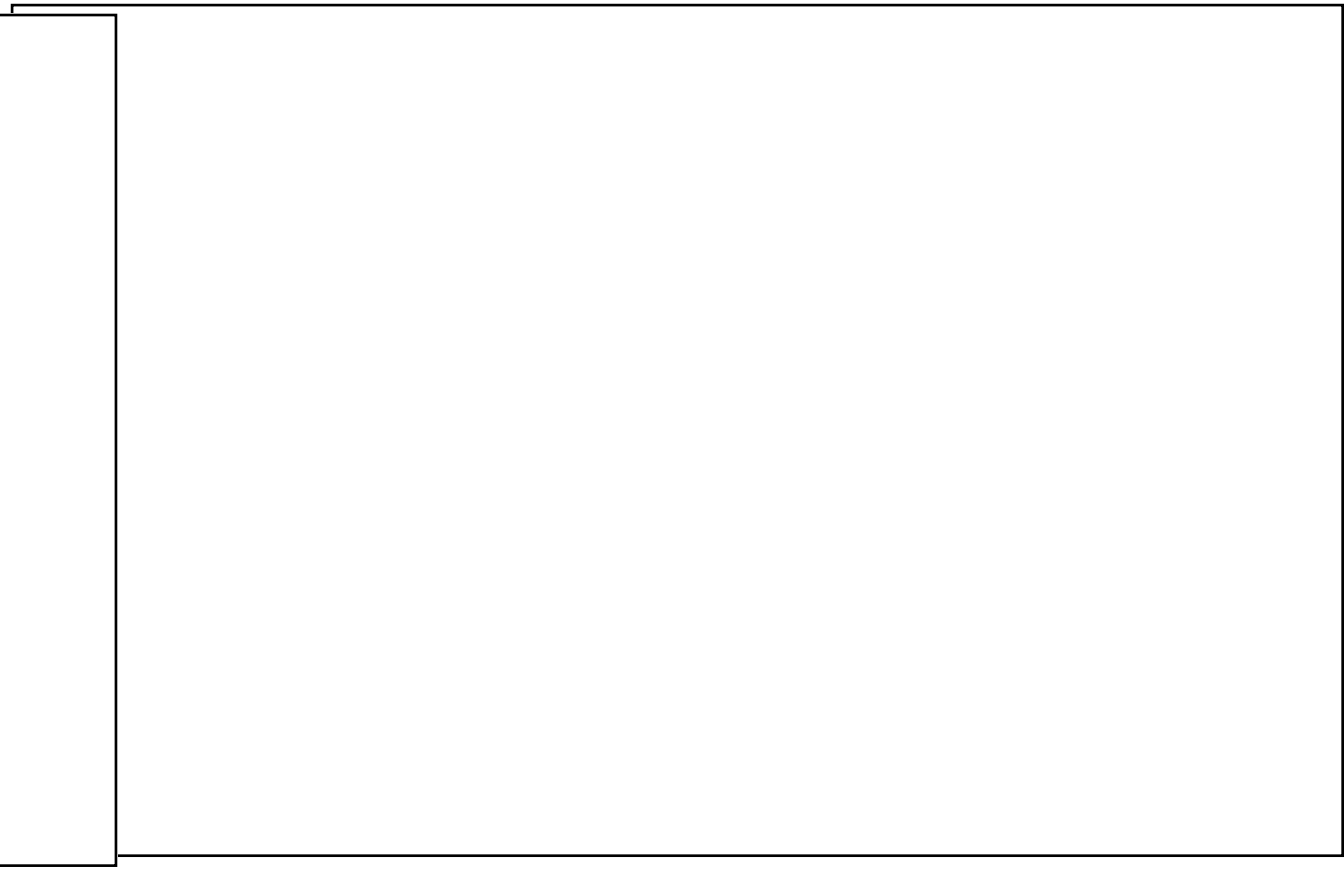
Ω_b=1.85 x Ω_0



But these are transient, so time dependent

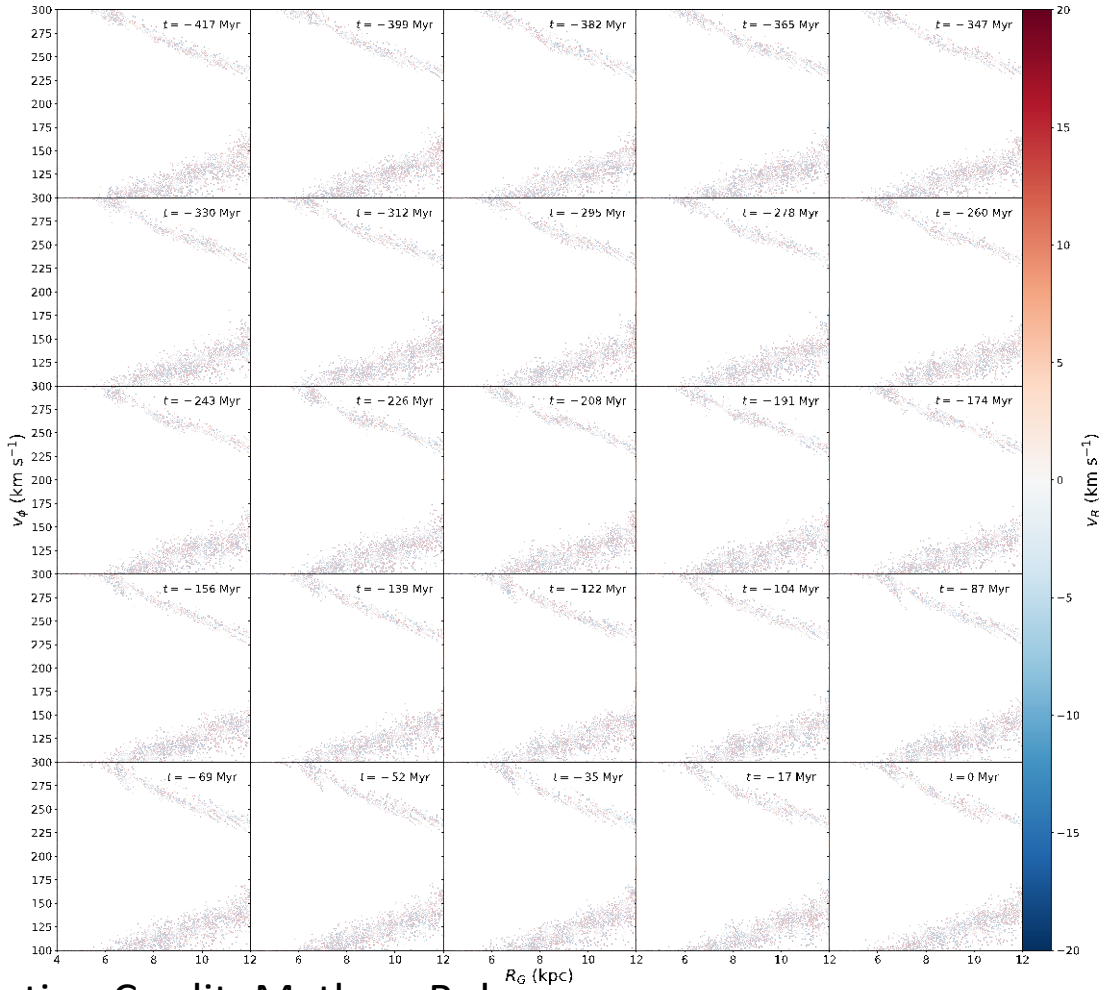
- Fixed bar angle, long slow bar on the left, short fast bar on the right
- Weaker spirals on the left, stronger on the right (by design, not from bar)

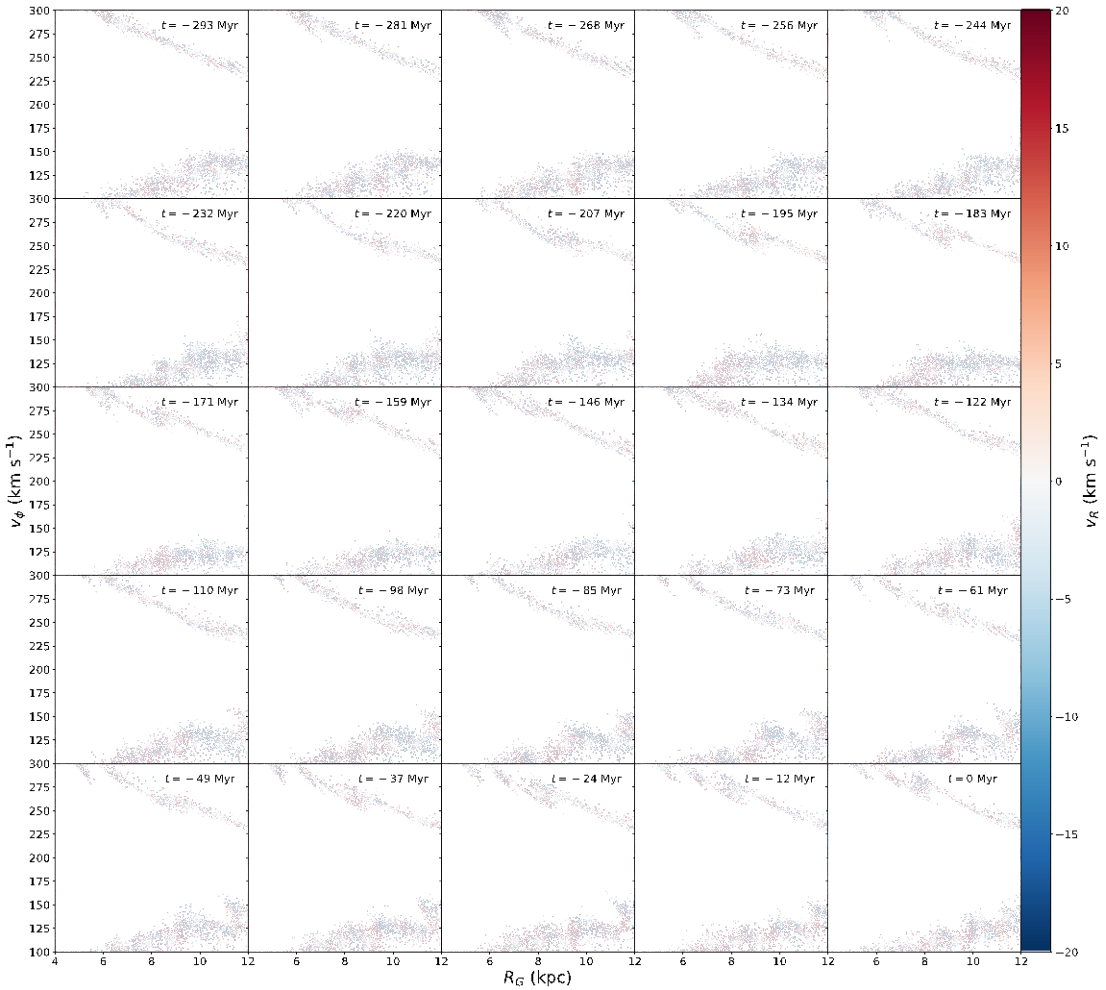




Simulation Credit: Mathew Bub

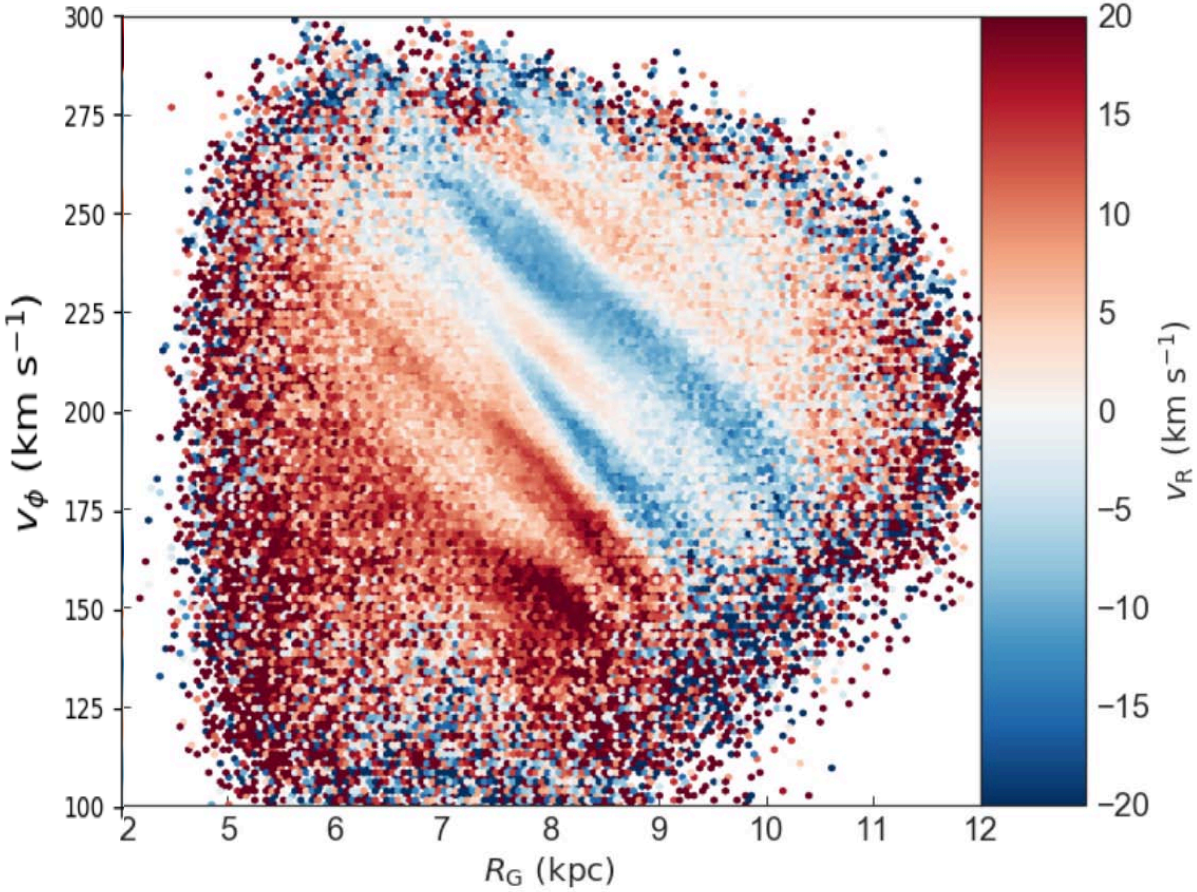
OLR always clear with weak arms, not when strong



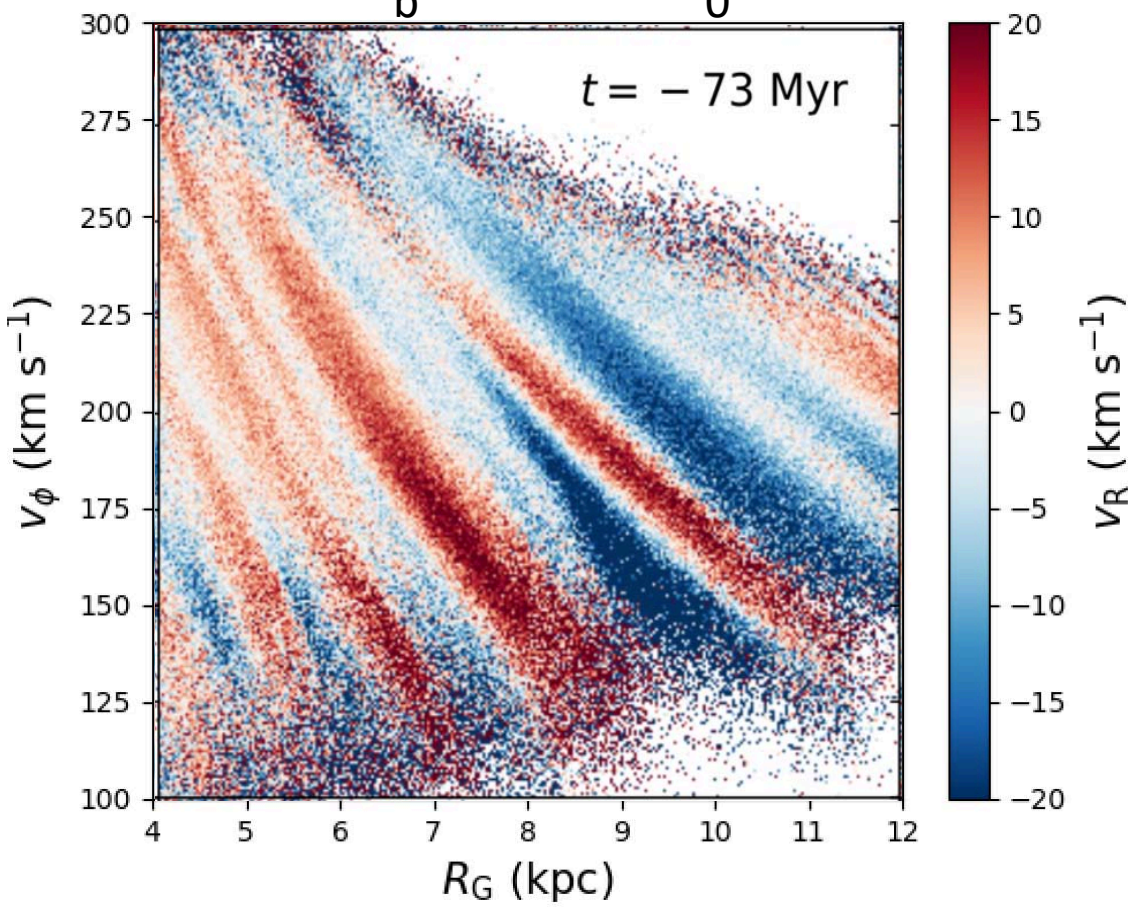


Simulation Credit: Mathew Bub

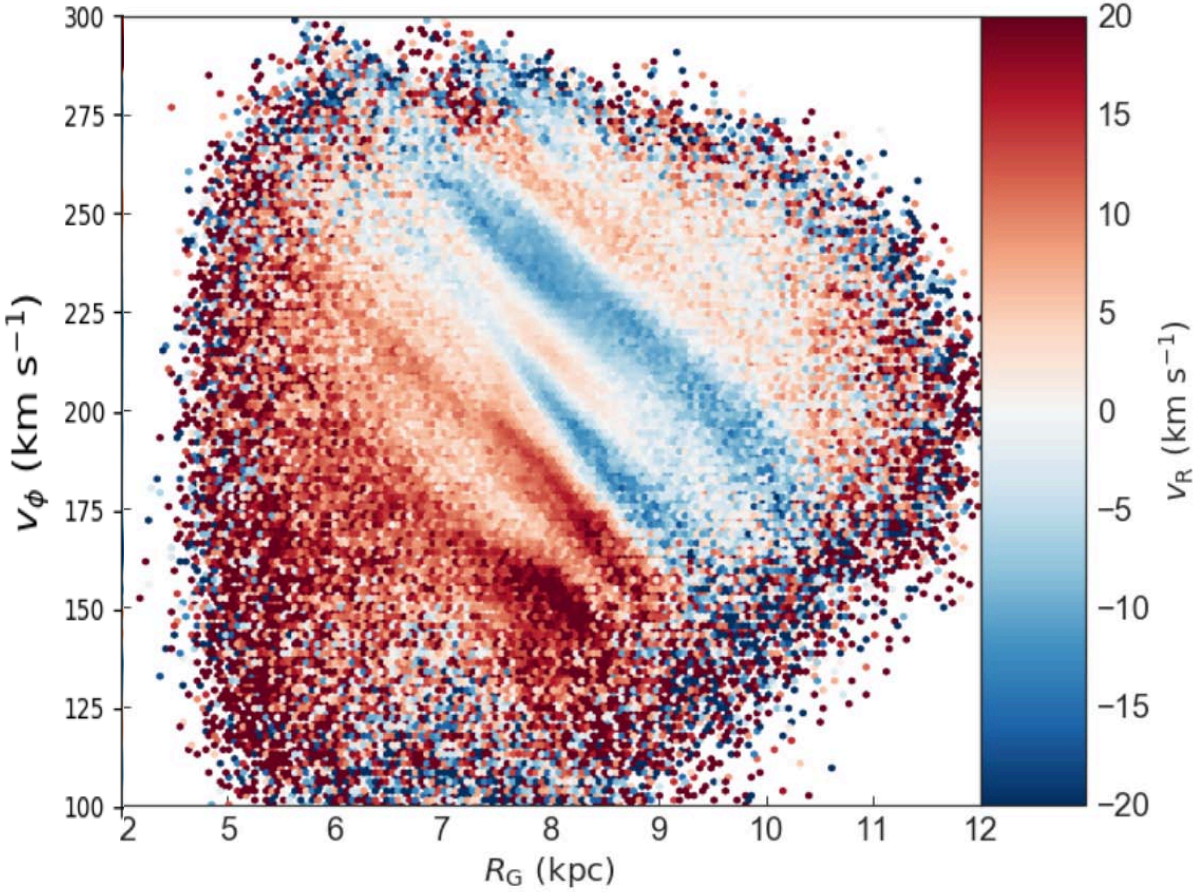
Reasonable agreement at certain time-steps



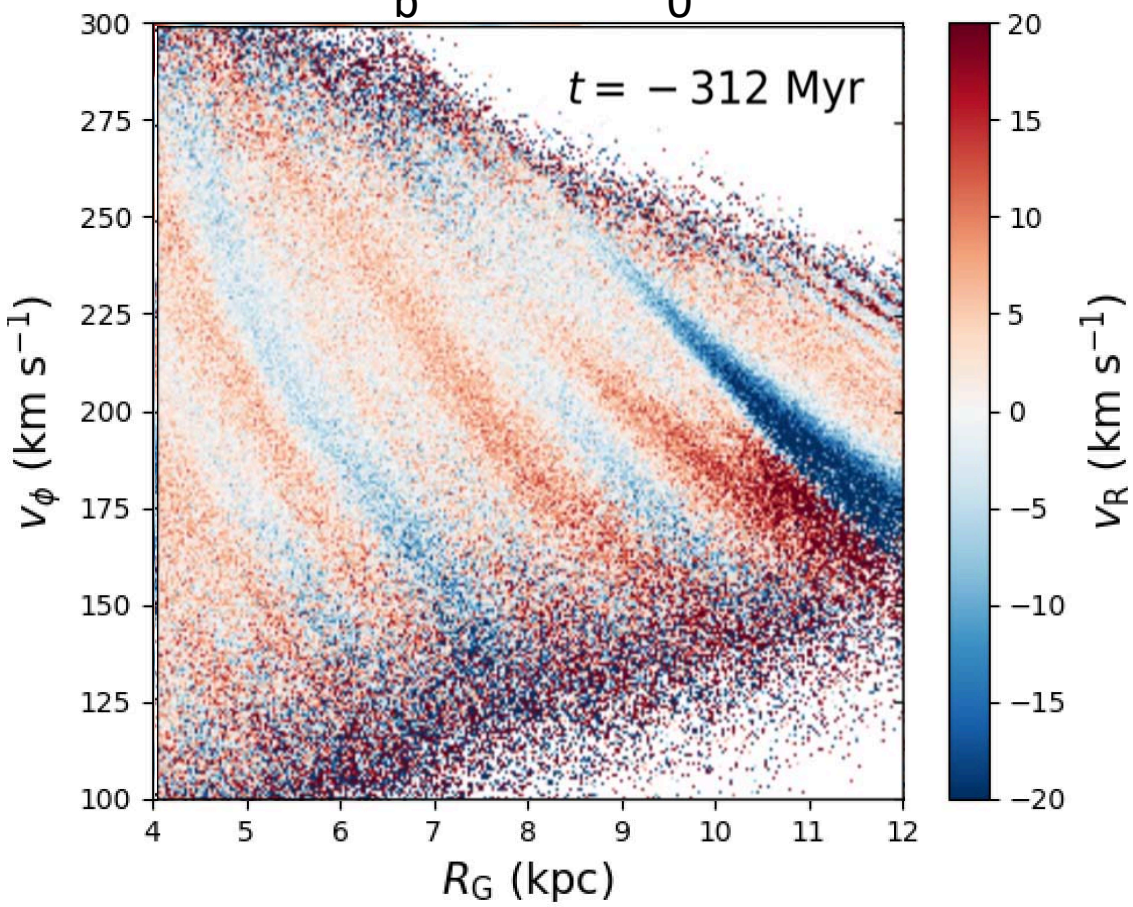
Ω_b=1.85 x Ω_0



A combination of resonance and wrapping?



Ω_b=1.3 x Ω_0



So, is it hopeless?

- Regardless of your favored bar model, it's apparent that spiral structure has a significant effect, and is currently poorly constrained (e.g. What type of spiral? N=?).

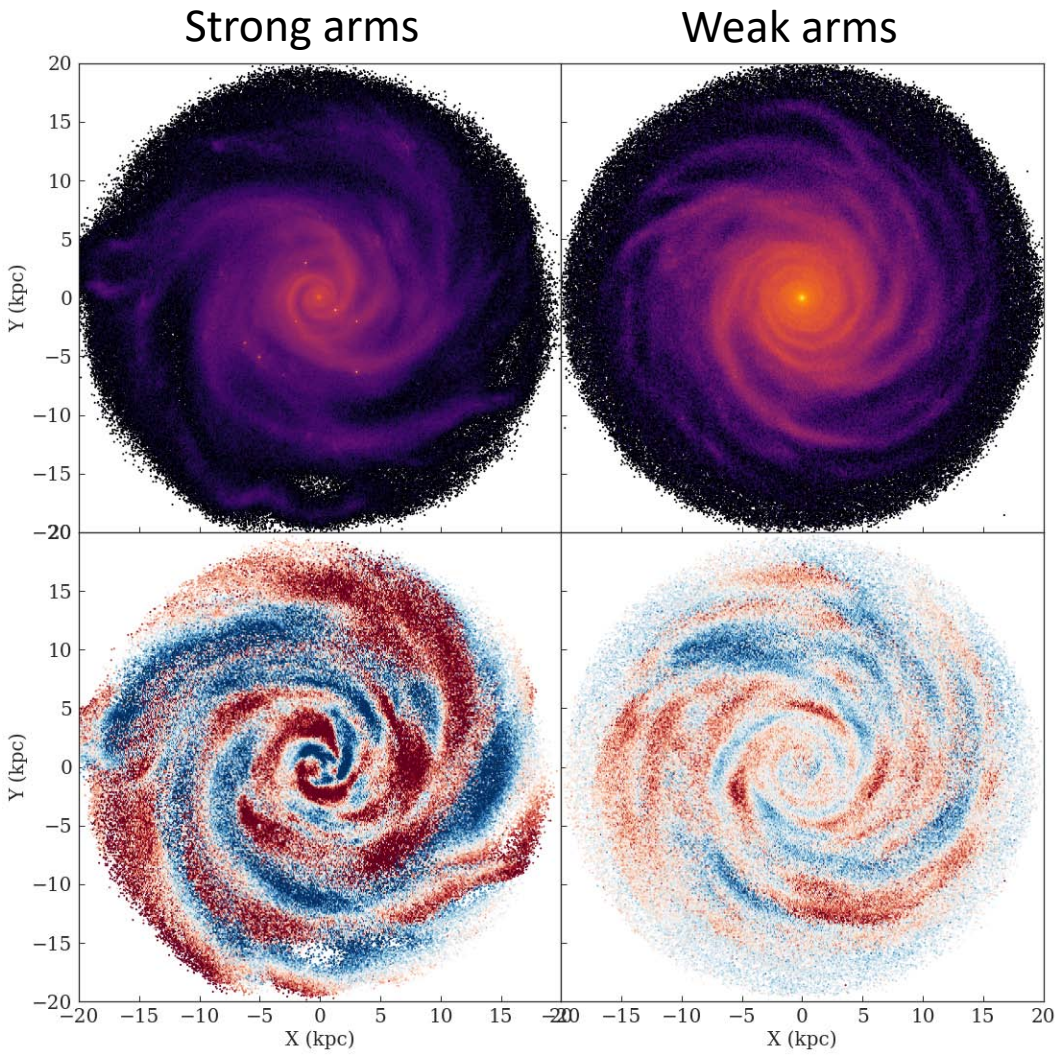
- Winding arms naturally lead to ridges/ripples in the kinematics.
  - Doesn't mean there's no Sagittarius, just that not every ridge comes from there.

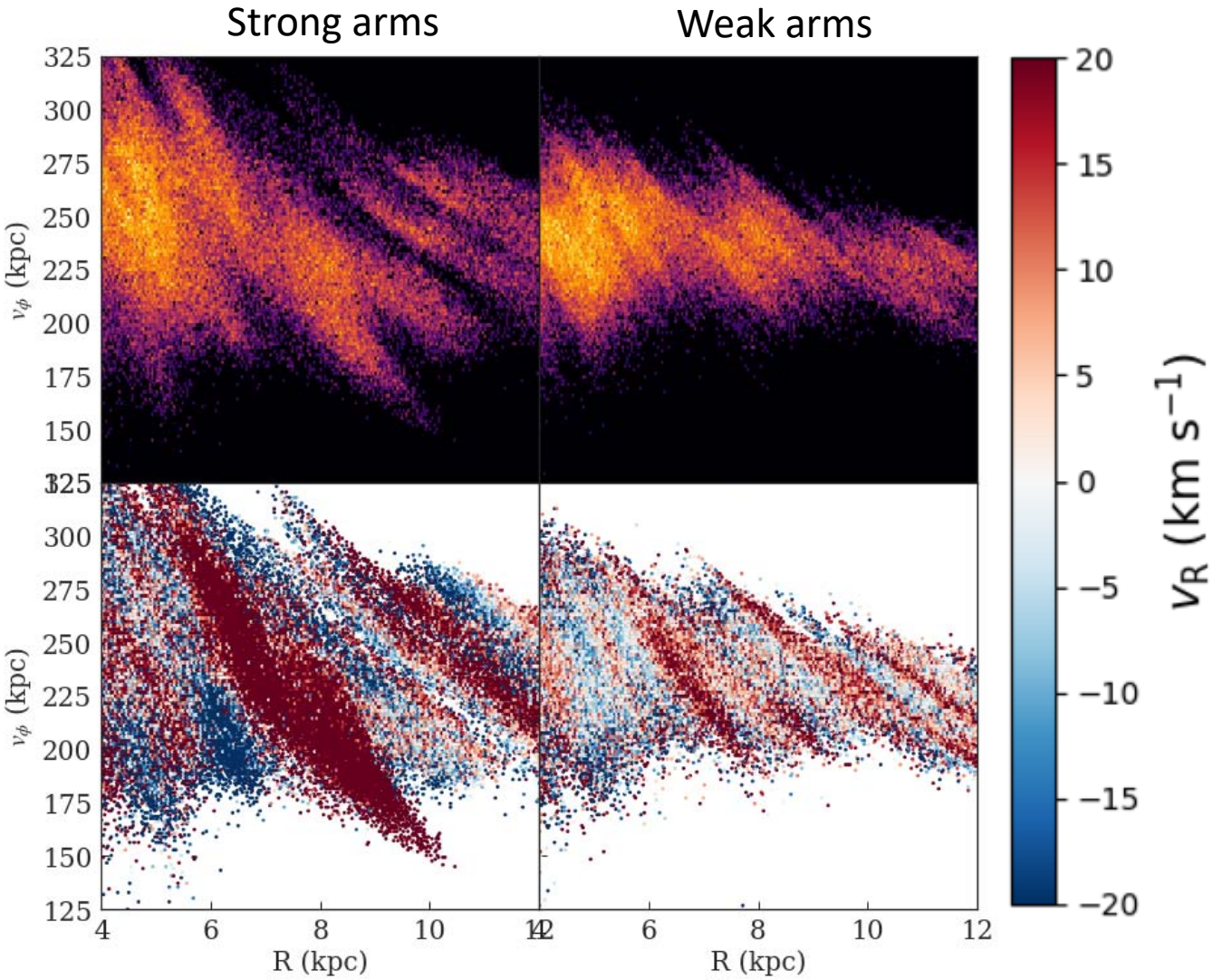
- Many things can now reproduce Hercules and the other moving groups. It's most likely a mix of effects, and disentangling them is not trivial! E.g. While bars and spirals make comparatively clear signals by themselves, the coupling leads to non-trivial outcomes.

The way forward

- Direct measurement of the bar extent / pattern speed (e.g. Ortwin's talk).
- Relative strength of the bar and the spiral structure: E.g. a strong bar with weaker arms should still stand out in kinematic space.
- The V_R asymmetry in the data doesn't look quite as strong as in the 'strong arm' case. The OLR is distinctive, and DR3 may resolve it.
- Mapping further across the disc. Resonances and phase wrapping will vary differently as we probe further from the Solar neighbourhood.

Are test particle models representative?

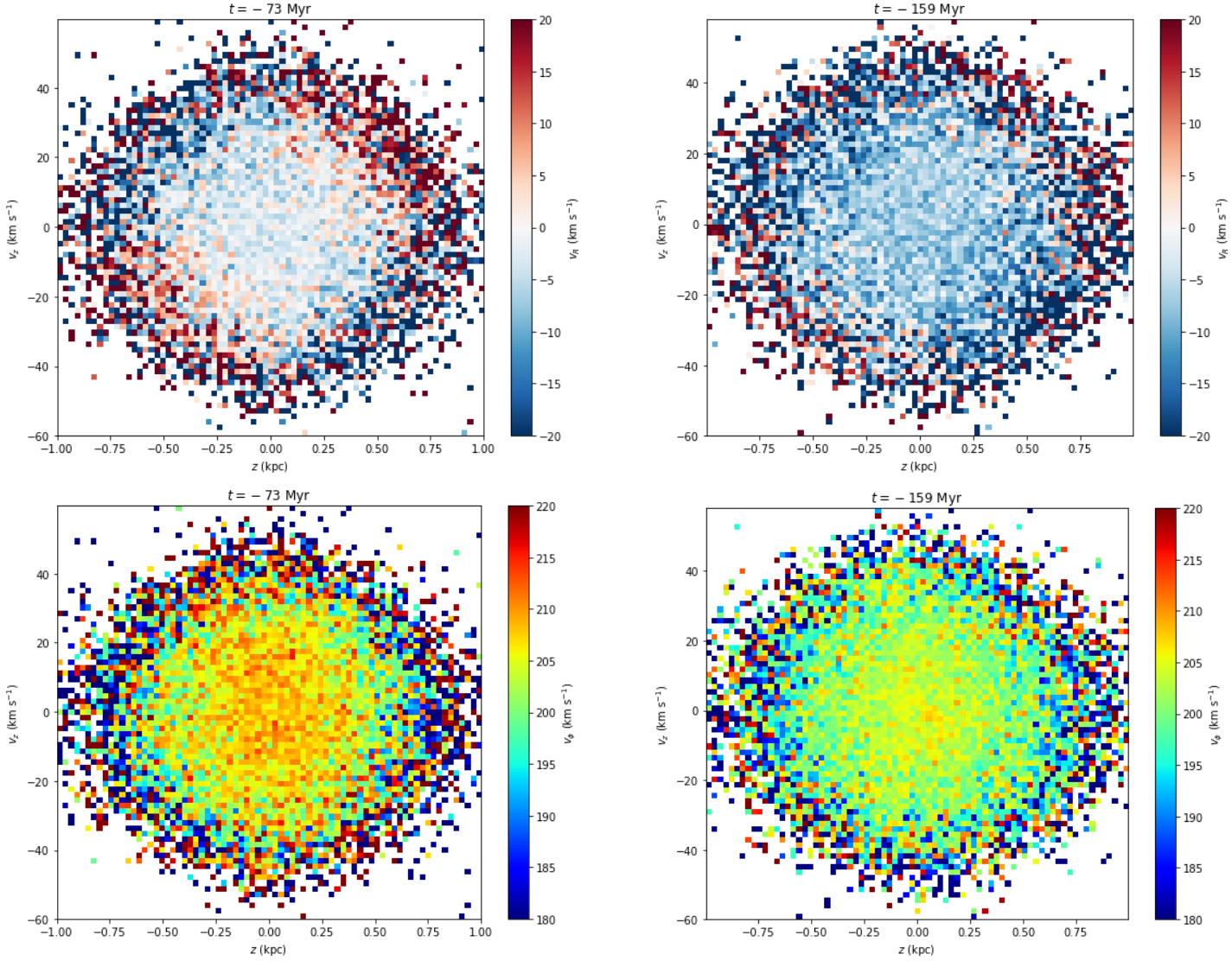




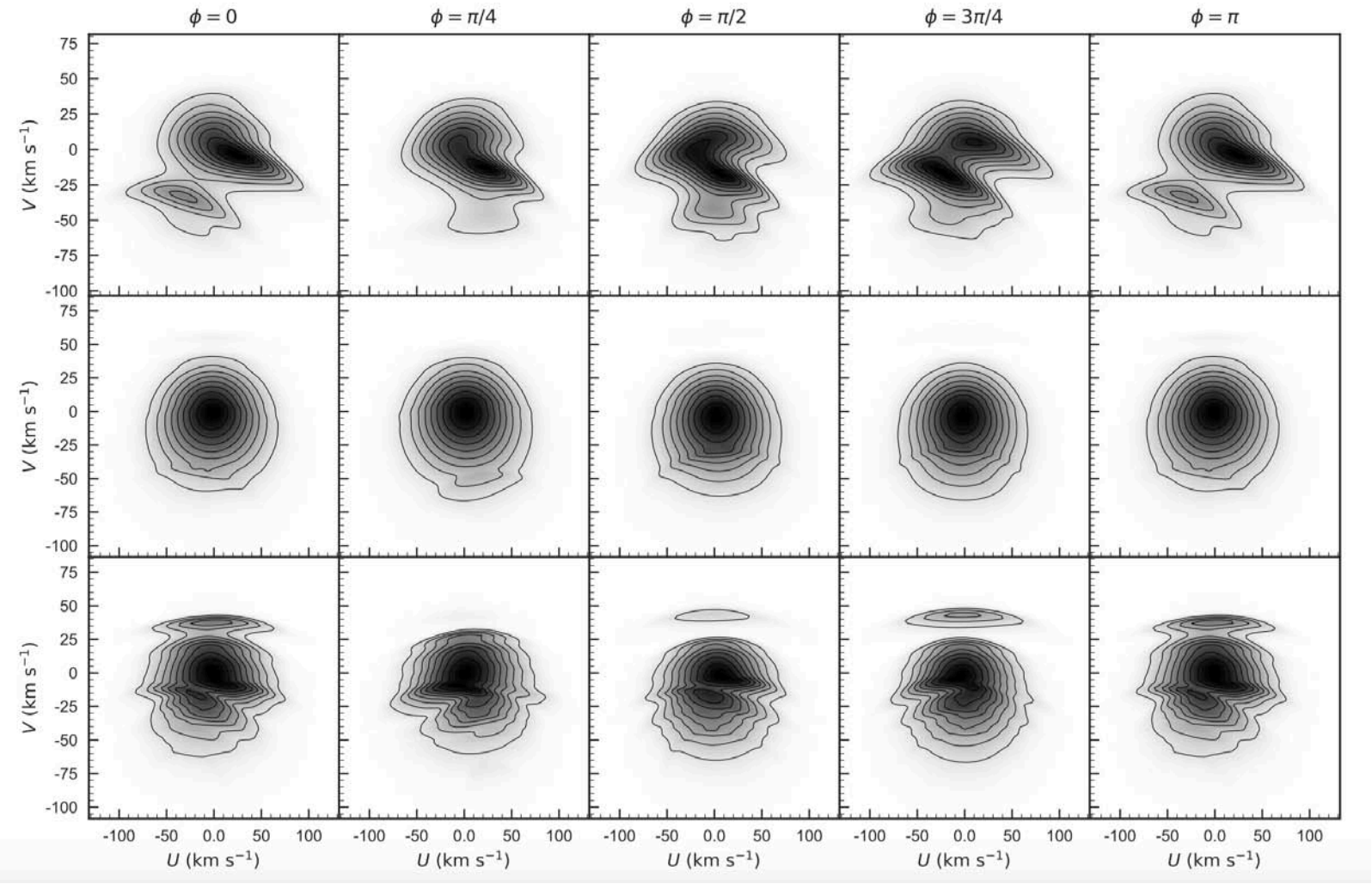
Simulations from Alex Pettitt (live N-body, with gas)

Do transient spirals make phase space spirals?

Nope!

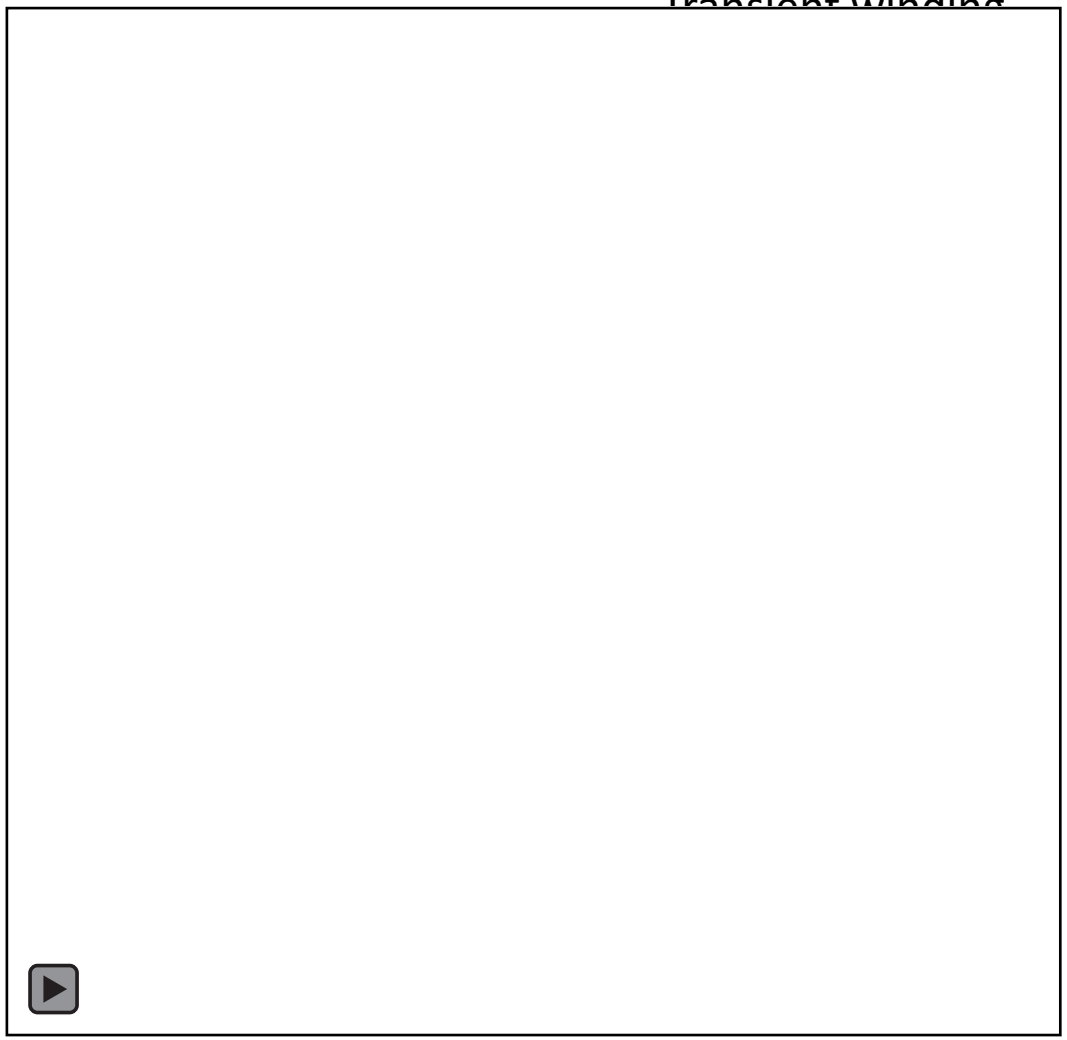


Further across the disc?

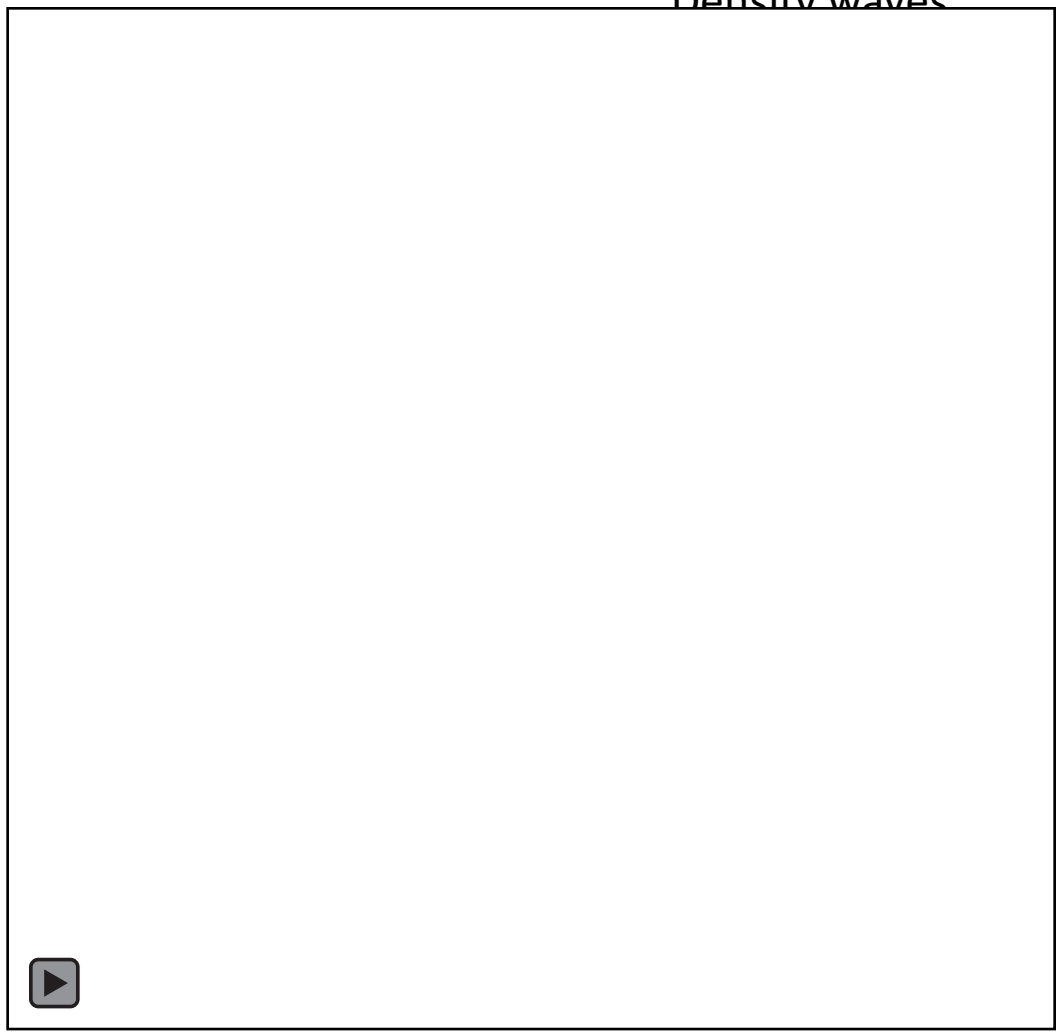


For the full range…

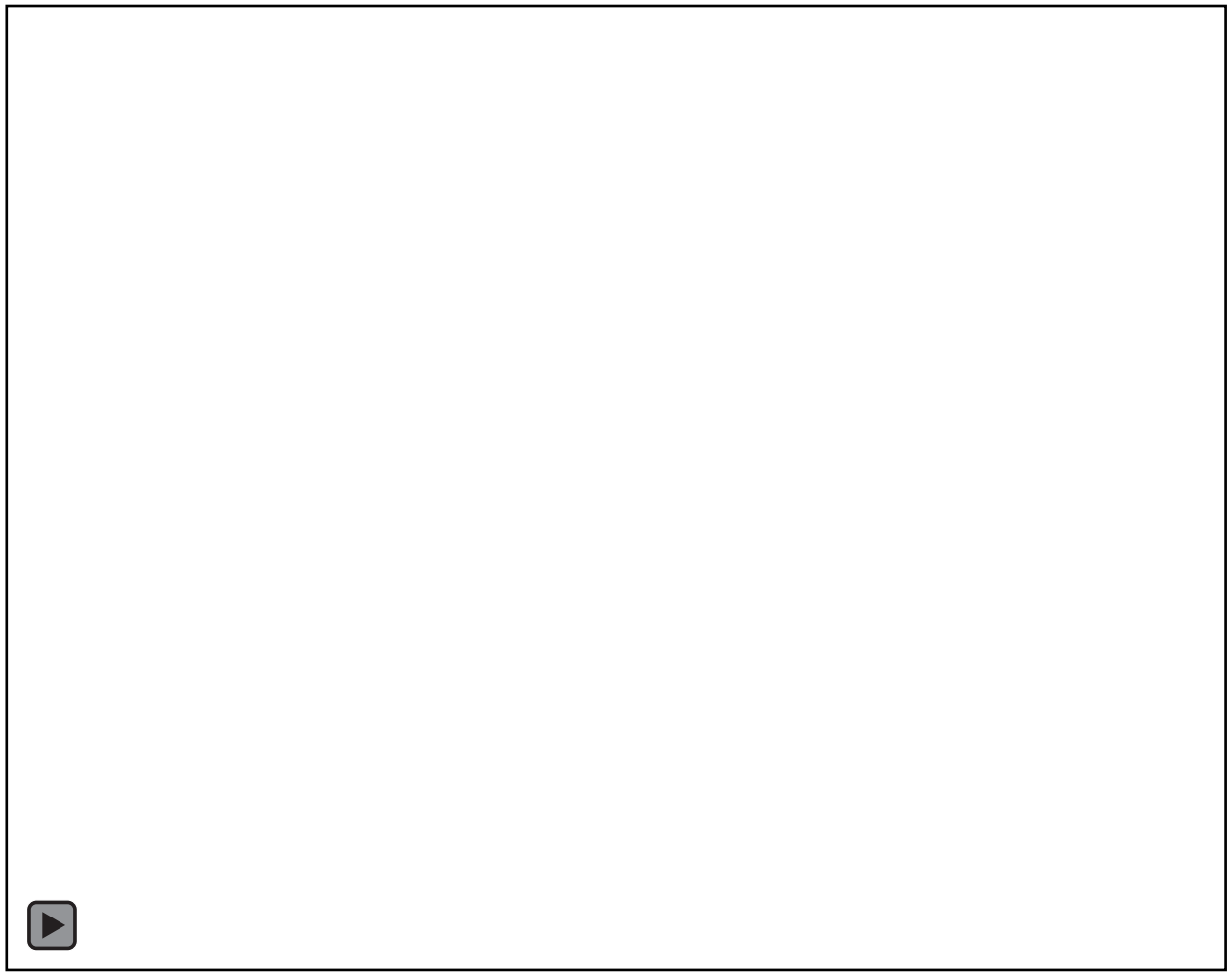
Transient winding

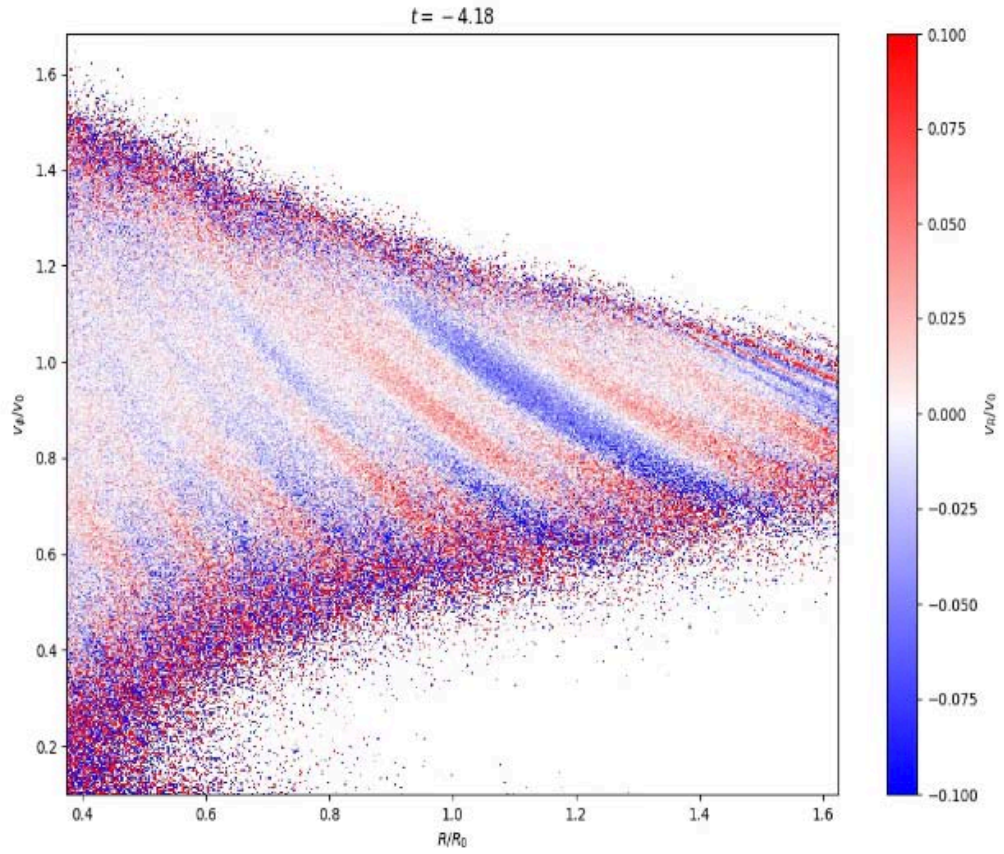


Density waves



Without any bar at all?





Simulation Credit: Mathew Bub

Resonance criteria:

- 2:1 ILR = $\Omega_p - \Omega_{rot} + \Omega_R/2 = 0$
- 4:1 ILR = $\Omega_p - \Omega_{rot} + \Omega_R/4 = 0$

- CR = $\Omega_p - \Omega_{rot} = 0$

- 4:1 OLR = $\Omega_p - \Omega_{rot} - \Omega_R/4 = 0$
- 2:1 OLR = $\Omega_p - \Omega_{rot} - \Omega_R/2 = 0$

What about for a fixed pattern speed?

- 2:1 ILR = $\Omega_p - \Omega_{rot} + \Omega_R/2 = 0$
- 4:1 ILR = $\Omega_p - \Omega_{rot} + \Omega_R/4 = 0$

- CR = $\Omega_p - \Omega_{rot} = 0$

- 4:1 OLR = $\Omega_p - \Omega_{rot} - \Omega_R/4 = 0$
- 2:1 OLR = $\Omega_p - \Omega_{rot} - \Omega_R/2 = 0$