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THE LONG GALACTIC BAR

NON-AXISYMMETRIES IN GALAXIES

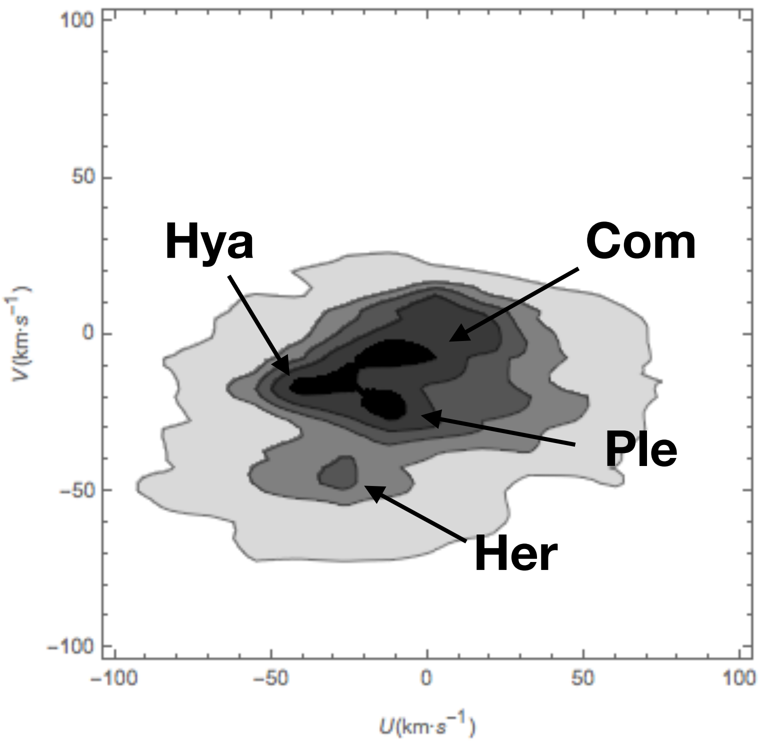
They are important because:

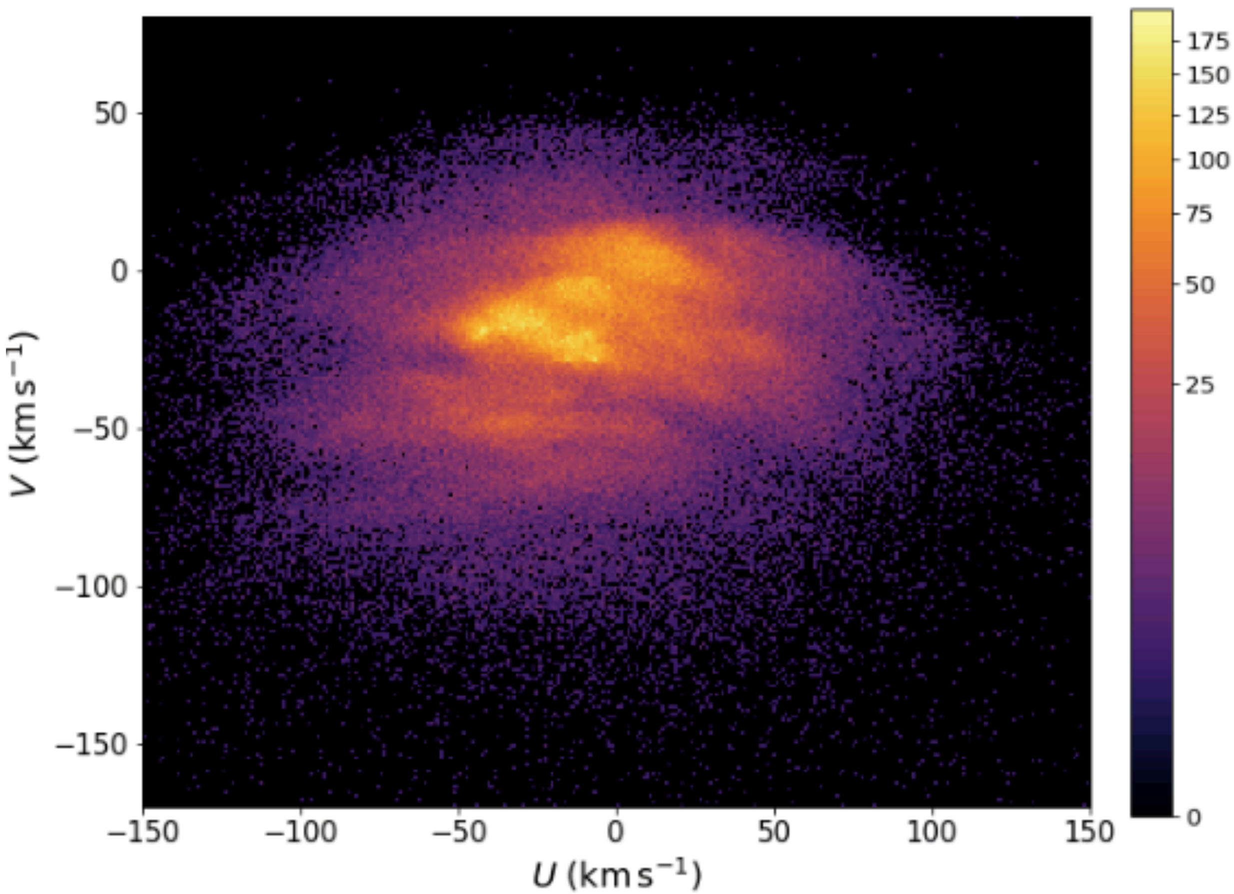
- They are there (see Gaia DR2)
- Ignore them $\longrightarrow$ bias dynamical model (e.g. bending waves and $\rho_{DM,}$ see Banik et al. 2017, Haines et al. 2019)
- They are an opportunity: halo/disc degeneracy $\rightarrow$ $X \propto (m\Sigma)^{-1}$ (Julian & Toomre 1966, stronger amplification for larger *m* at low Σ)
- They drive secular evolution of galaxies, e.g. radial migration (Sellwood & Binney 2002)

THE MILKY WAY IS NOT AXISYMMETRIC (KINEMATICS)

Gaia collab., Katz et al. (2018)

Monari with RAVE + TGAS (2017)

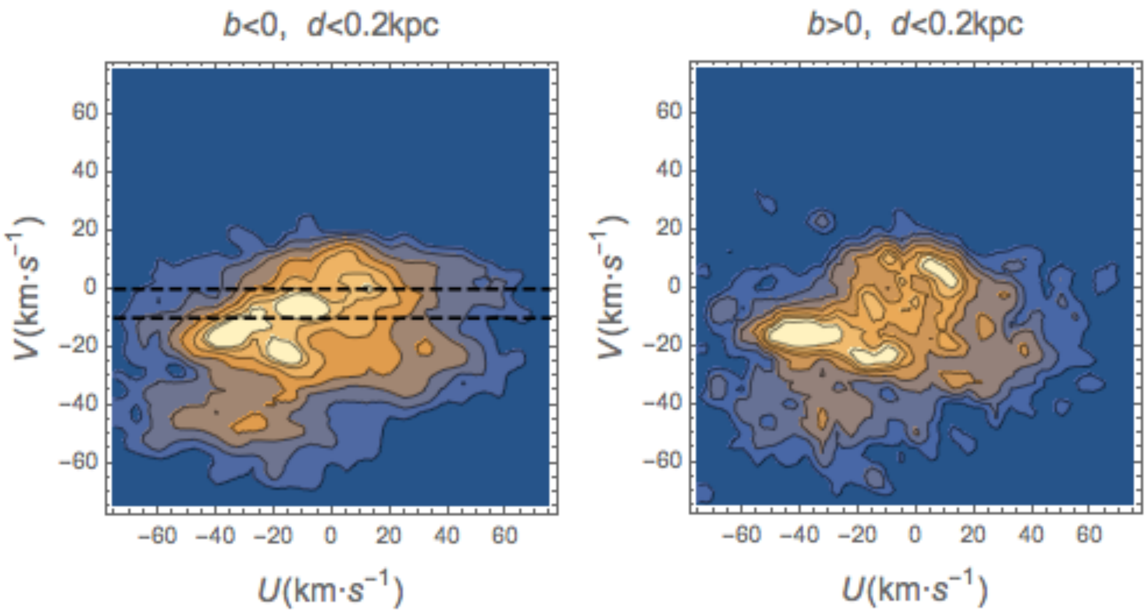




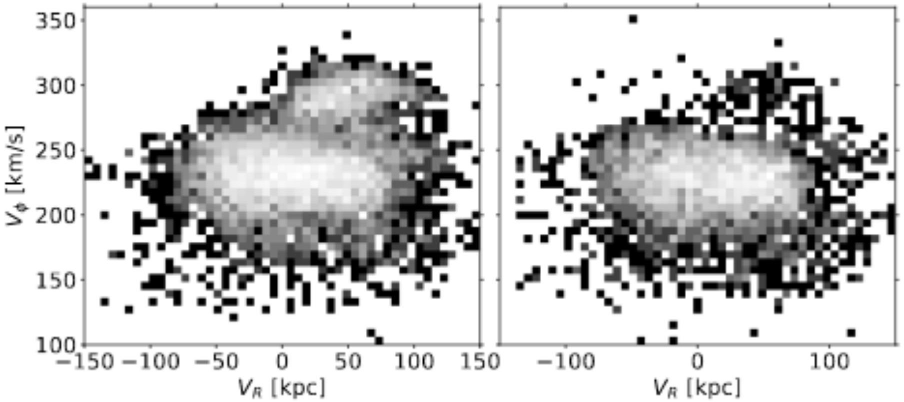
THE MILKY WAY IS NOT AXISYMMETRIC (KINEMATICS)

Quillen et al. (2018, GALAH) discovered North-South asymmetry of moving groups

Monari et al. (2018, RAVE and Gaia DR2)

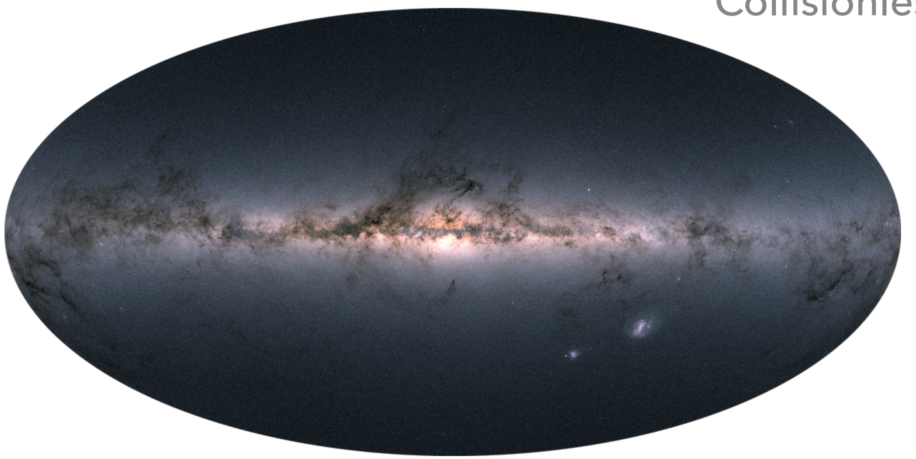


Laporte et al. (2018, simulations)



DYNAMICAL MODELS OF THE MILKY WAY

- Orbits of stars and of the dark matter
- Mass distribution of the Galaxy
- Gravitational field of the Galaxy



Collisionless Boltzmann Eq. (CBE)

$$\boxed{\begin{array}{c} f(\mathbf{x}, \mathbf{v}, t) \\ \Phi(\mathbf{x}, t) \end{array}}$$

DYNAMICAL MODELS OF THE MILKY WAY

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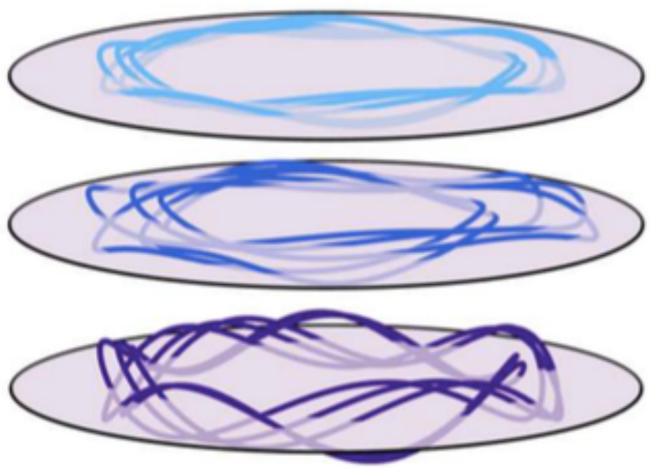
Collisionless Boltzmann Eq. (CBE)

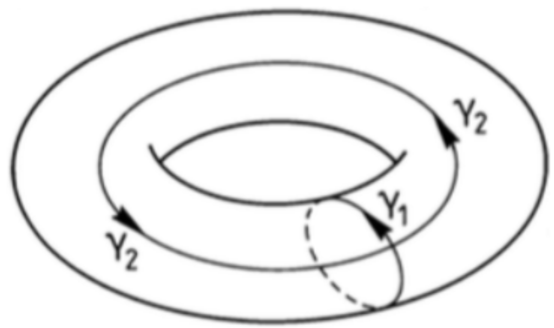
$$\frac{\mathrm{df}}{\mathrm{dt}} = \frac{\partial f}{\partial t} + \frac{\partial f}{\partial \mathbf{w}} \cdot \dot{\mathbf{w}} = 0$$

AXISYMMETRIC MODELS OF THE MILKY WAY

- Angles-actions: $(\boldsymbol{x},\boldsymbol{v}) \xrightarrow{\text{canonical transf.}} (\boldsymbol{\theta},\boldsymbol{J})$, $\boldsymbol{J} = \text{const}$, $\boldsymbol{\theta} = \boldsymbol{\theta}_0 + \boldsymbol{\Omega} t$
- Jeans theorem: $\boldsymbol{J}$ int. of motion → $f(\boldsymbol{J})$ solution of the CBE
- $f(\boldsymbol{J})$ contains info about Φ through $\boldsymbol{J}$ and generates self consistently Φ



Fouvry et al. (2016)



Binney & Tremaine (2008)

DYNAMICAL MODELS OF THE MILKY WAY

- Orbits of stars and of the dark matter
- Mass distribution of the Galaxy
- Gravitational field of the Galaxy

Collisionless Boltzmann Eq. (CBE)

$$\frac{\partial f}{\partial t} + \frac{\partial f}{\partial \theta} \cdot \mathbf{\Omega} = 0$$

TREATING NON-AXISYMMETRIES

- **Far from resonances**: solution of linearized perturbed CBE in 3D3V (Monari et al. 2016, MNRAS, 457, 2569)
- Assume $\Phi = \Phi_0 + \Phi_1$ and look for f_1, where for $f = f_0 + f_1$
- $(\boldsymbol{x},\boldsymbol{v}) \longrightarrow (\boldsymbol{\theta},\boldsymbol{J})$ in Φ_0

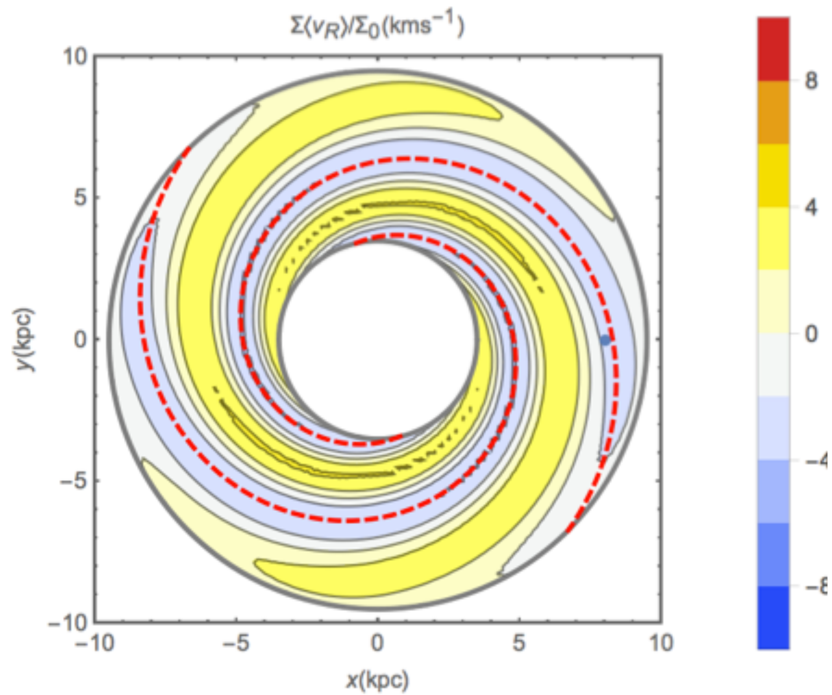
$$\frac{\mathrm{d}f_1}{\mathrm{d}t} = \frac{\partial f_0}{\partial \mathbf{J}} \cdot \frac{\partial \Phi_1}{\partial \boldsymbol{\theta}}$$

$$f_1(\boldsymbol{J},\boldsymbol{\theta},t) = \mathrm{Re}\left\{ \frac{\partial f_0}{\partial \boldsymbol{J}}(\boldsymbol{J}) \cdot \sum_{\boldsymbol{n}} \boldsymbol{n} c_{\boldsymbol{n}}(\boldsymbol{J}) \frac{h(t)\mathrm{e}^{\mathrm{i}\boldsymbol{n}\cdot\boldsymbol{\theta}}}{\boldsymbol{n}\cdot\boldsymbol{\omega} + \omega_p} \right\}$$

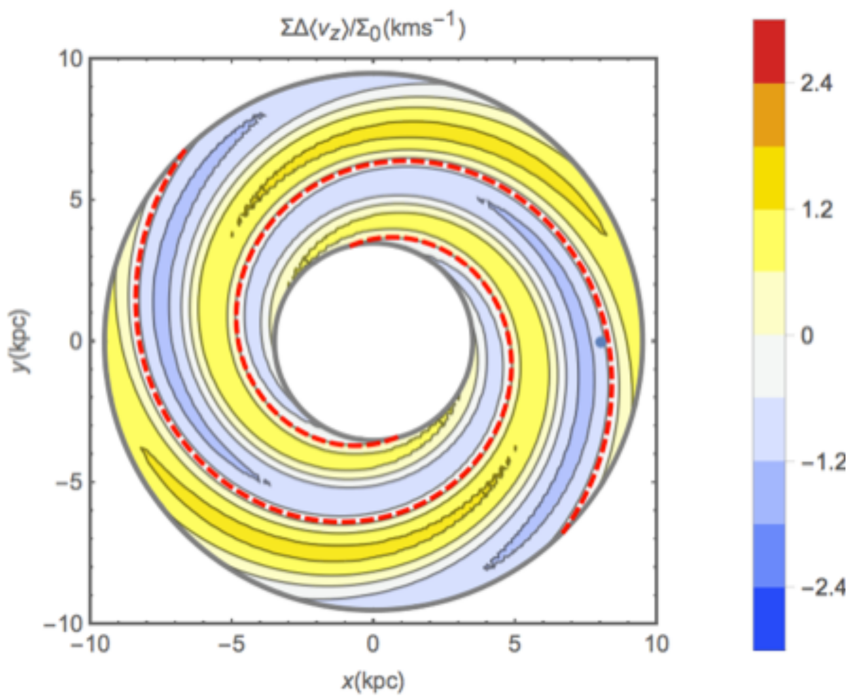
TREATING NON-AXISYMMETRIES

- **Far from resonances**: solution of linearized perturbed CBE in 3D3V (Monari et al. 2016, MNRAS, 457, 2569)

Radial velocity gradient



Breathing modes



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=0 at the resonances

TREATING NON-AXISYMMETRIES

- **Near resonaces**: fast and slow AA (Monari, Famaey, Fouvry, Binney, MNRAS, 471, 4314)
- $\boldsymbol{\theta} = (\theta_R, \theta_\phi)$, $\boldsymbol{J} = (J_R, J_\phi)$, $\mathrm{d}\theta_R/\mathrm{d}t = \omega_R$, $\mathrm{d}\theta_\phi/\mathrm{d}t = \omega_\phi$
- $(\theta_R, \theta_\phi, J_R, J_\phi) \longrightarrow (\theta_\mathrm{f}, \theta_\mathrm{s}, J_\mathrm{f}, J_\mathrm{s})$

$$l\omega_R(J_R, J_\phi) + m\left[\omega_\phi(J_R, J_\phi) - \Omega_\mathrm{b}\right] = 0$$

$$\begin{aligned} \theta_\mathrm{s} &= l\theta_R + m\left(\theta_\phi - \Omega_\mathrm{b} t\right), & J_\phi &= mJ_\mathrm{s}, \\ \theta_\mathrm{f} &= \theta_R, & J_R &= lJ_\mathrm{s} + J_\mathrm{f}, \end{aligned}$$

TREATING NON-AXISYMMETRIES

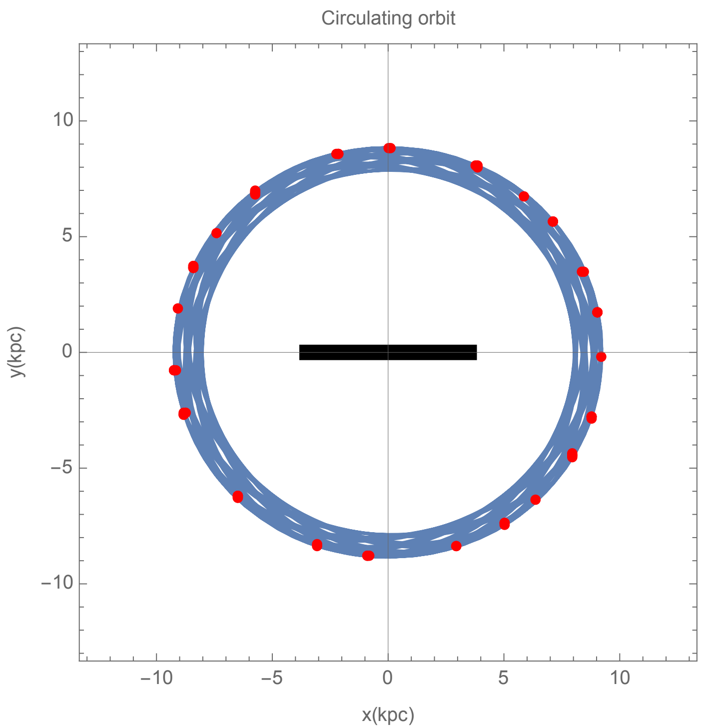
- **Near resonaces**: fast and slow AA (Monari, Famaey, Fouvry, Binney, MNRAS, 471, 4314, see also Binney 2018)
- $\boldsymbol{\theta} = (\theta_R, \theta_\phi)$, $\boldsymbol{J} = (J_R, J_\phi)$, $\mathrm{d}\theta_R/\mathrm{d}t = \omega_R$, $\mathrm{d}\theta_\phi/\mathrm{d}t = \omega_\phi$
- $(\theta_R, \theta_\phi, J_R, J_\phi) \longrightarrow (\theta_\mathrm{f}, \theta_\mathrm{s}, J_\mathrm{f}, J_\mathrm{s})$

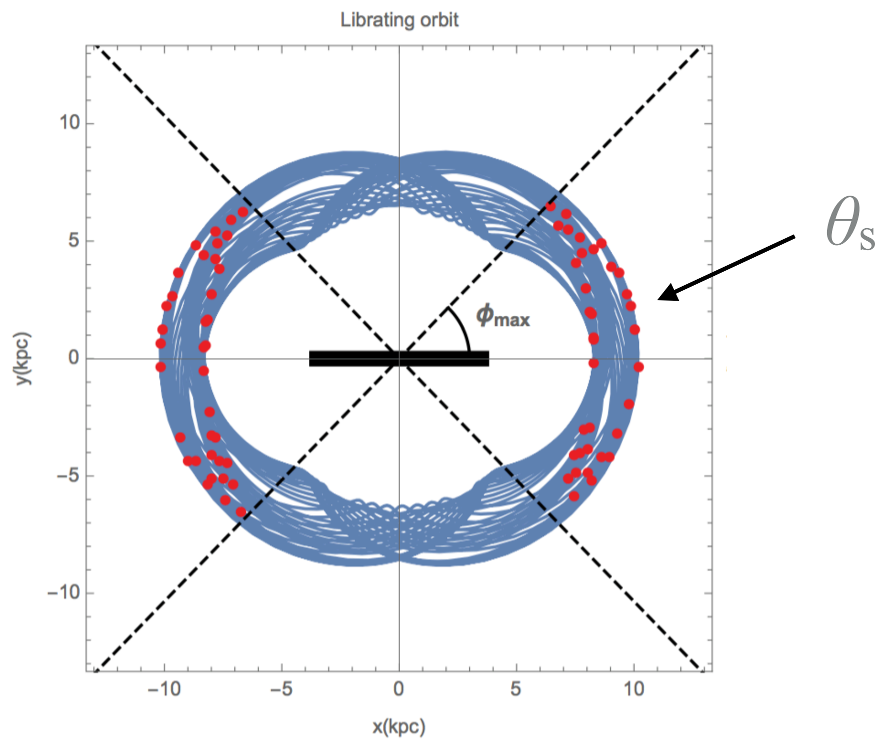
Arnold's averaging principle

$$\overline{H} = H_0(J_\mathrm{f}, J_\mathrm{s}) - m\Omega_\mathrm{b} J_\mathrm{s} + \mathrm{Re}\left\{c_{lm}(J_\mathrm{f}, J_\mathrm{s})\mathrm{e}^{\mathrm{i}\theta_\mathrm{s}}\right\}$$

TREATING NON-AXISYMMETRIES

- **Near resonances**: treatment with the perturbation theory / 'pendulum' dynamics in action/angle (Monari, Famaey, Fouvry, Binney, MNRAS, 471, 4314)



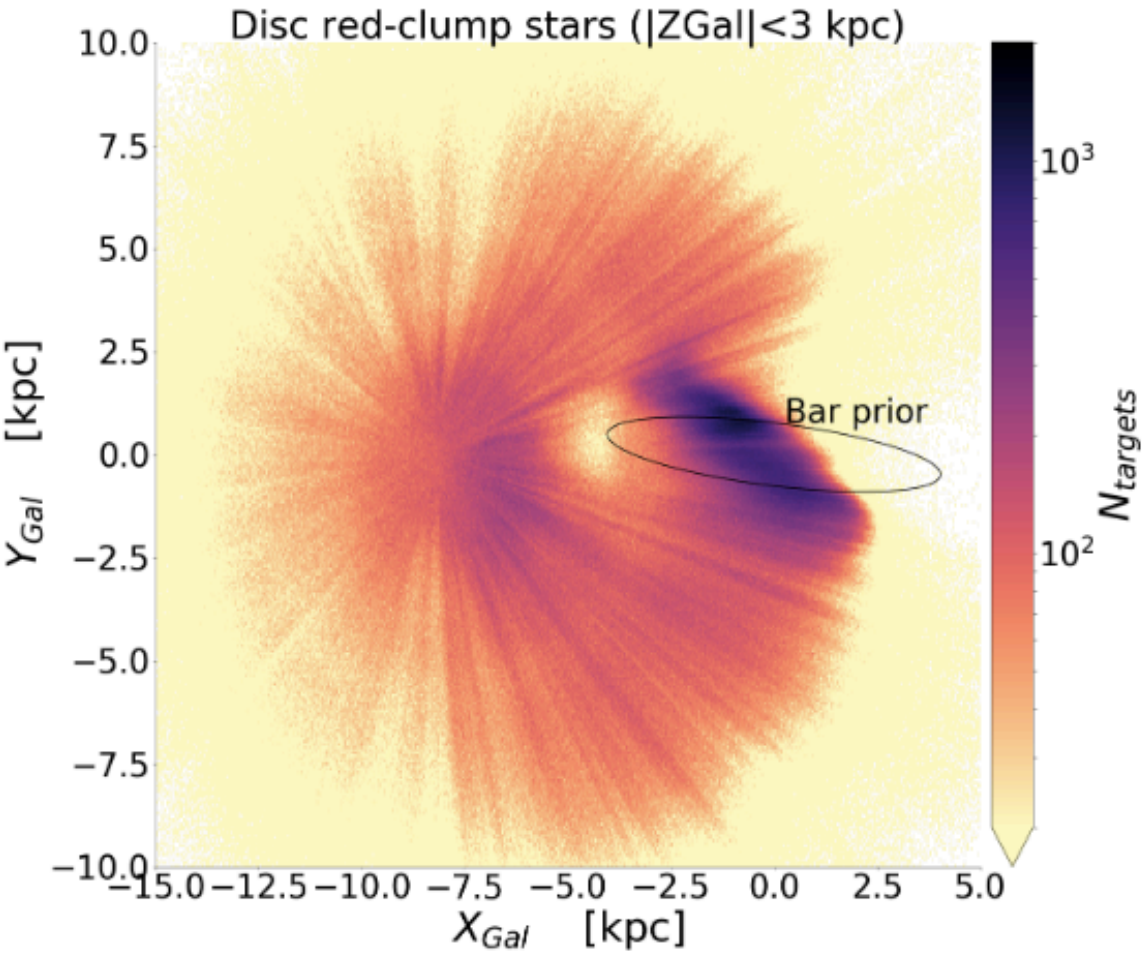


TREATING NON-AXISYMMETRIES

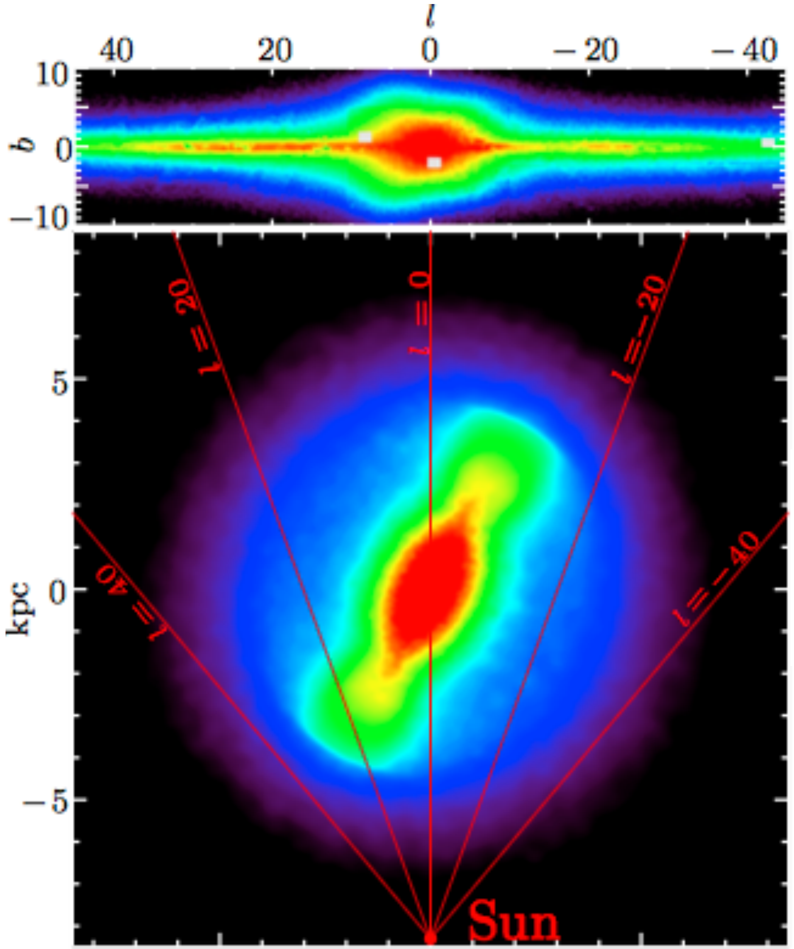
- **Near resonaces**: fast and slow AA (Monari, Famaey, Fouvry, Binney, MNRAS, 471, 4314)
- $\theta_{\rm s}(\theta_{\rm p},J_{\rm p}),\;\; J_{\rm s}(\theta_{\rm p},J_{\rm p})$
- $f_0(J_{\rm f},J_{\rm s})$
- $f = \langle f_0(J_{\rm f},J_{\rm s}(\theta_{\rm p},J_{\rm p}))\rangle$ in the resonant trapping region
- $f = f_0(J_{\rm f},\langle J_{\rm s}(\theta_{\rm p},J_{\rm p})\rangle)$ outside resonant region

THE MILKY WAY IS NOT AXISYMMETRIC (BAR)

Anders et al. 2019, StarHorse distances



THE MILKY WAY IS NOT AXISYMMETRIC (BAR)



Wegg et al. (2015)

UKIDS RGC, 2MASS, VVV, GLIMPSE

end; (v) constructing parametric models for the red clump magnitude distributions, we find a bar half-length of 5.0 ± 0.2 kpc for the two-component bar, and 4.6 ± 0.3 kpc for the thin bar component alone. We conclude that the Milky Way contains a central box/peanut bulge which is the vertical extension of a longer, flatter bar, similar as seen in both external galaxies and *N*-body models.

WHERE IS THE MW BAR COROTATION

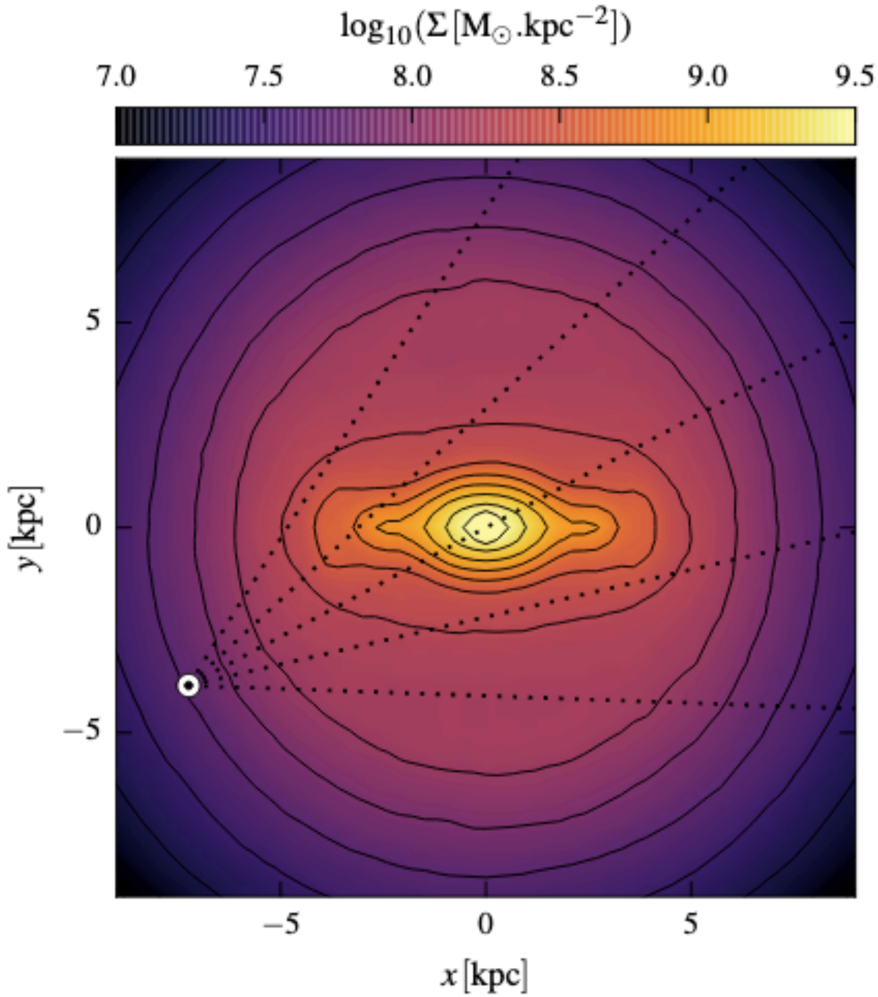
- Millions of RC stars from surveys VVV + 2MASS + UKIDDS + GLIMPSE
- Long flat extension of the bar (h_z < 50 pc) out to > 5 kpc from the centre (l > 30°)
- Fit to BRAVA kinematics (cental 10° in l) + ARGOS (28000 stars, -30° < l < 30° and -10° < b < -5°)
- $\Omega_b = 39$ kms^{-1}kpc^{-1}
- Corotation at 6 kpc and OLR beyond 11 kpc.

Pattern speed confirmed by inner Galaxy PMs based on VVV & Gaia DR2 (Clarke et al. 2019, Sanders et al. 2019)

PORTAIL ET AL. (2017) GALACTIC MODEL

- Fit internal kinematics MW
- 'Slow' bar rotating at 39 km/s/kpc
- Corotation ~ 6 kpc
- Force different than a quadrupole bar
- Complex bar, formed by several Fourier modes: we use m=2 and m=4

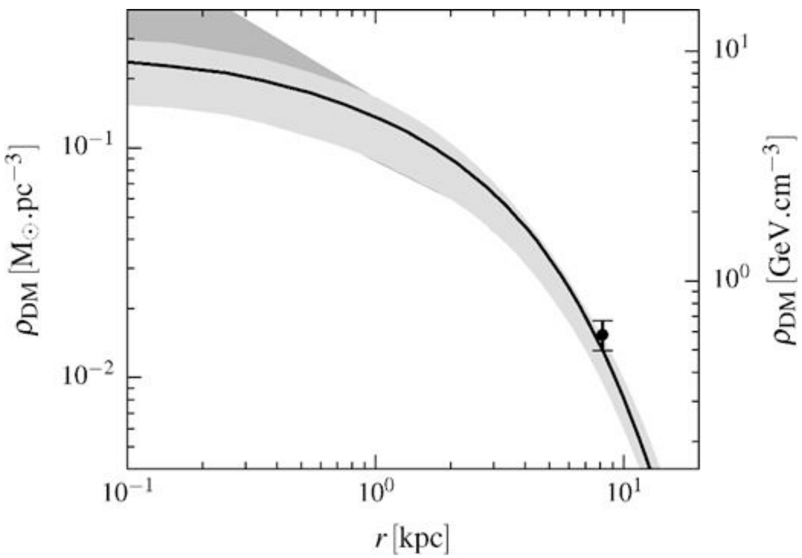
PORTAIL ET AL. (2017) GALACTIC MODEL



A DARK MATTER CORE IN THE MW

- Bulge mass (2.2 kpc, 1.4 kpc, 1.2 kpc): $1.85 \times 10^{10}\ M_\odot$
  1. Stellar mass: $1.32 \times 10^{10}\ M_\odot$
  2. Additional nuclear disc: $2 \times 10^{9}\ M_\odot$
  3. Dark matter mass: $3.2 \times 10^{9}\ M_\odot$falloff to keep the RC constant between

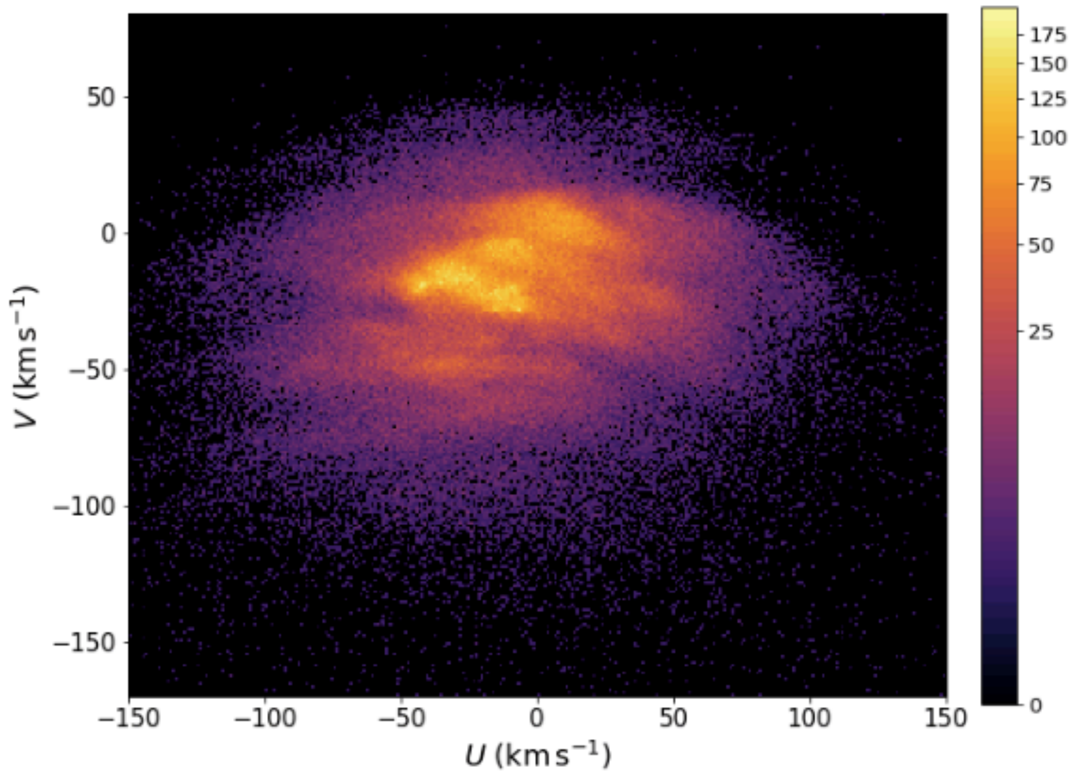
Portail et al. 2017



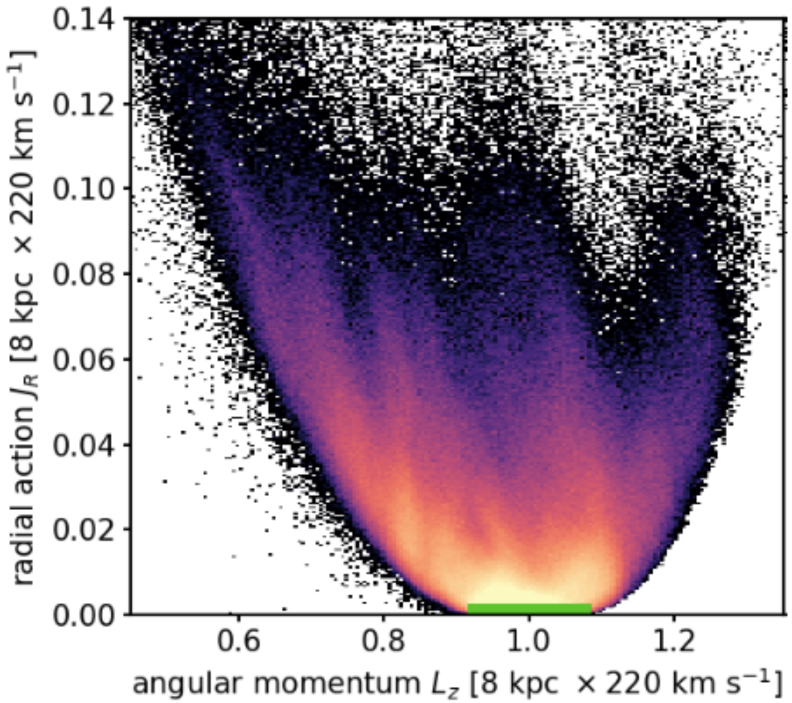
Sharp falloff (keep the RC constant between 6 kpc and 8 kpc) → cored profile at centre (see also Cole & Binney 2017).

THE MILKY WAY IS NOT AXISYMMETRIC (KINEMATICS)

Gaia collab., Katz et al. (2018)



Trick et al. (2019)



GAIA DR2

- Velocity and action space ridges due to:
  1. Bar,
  2. Spiral arms, including past transient ones (Sellwood et al. 2019, Hunt et al. 2019),
  3. Ongoing phase-mixing (Antoja et al. 2018),
  4. …
- Q: what does the bar alone do to local stellar kinematics?
- A: a lot.

The signatures of the resonances of a large Galactic bar in local velocity space

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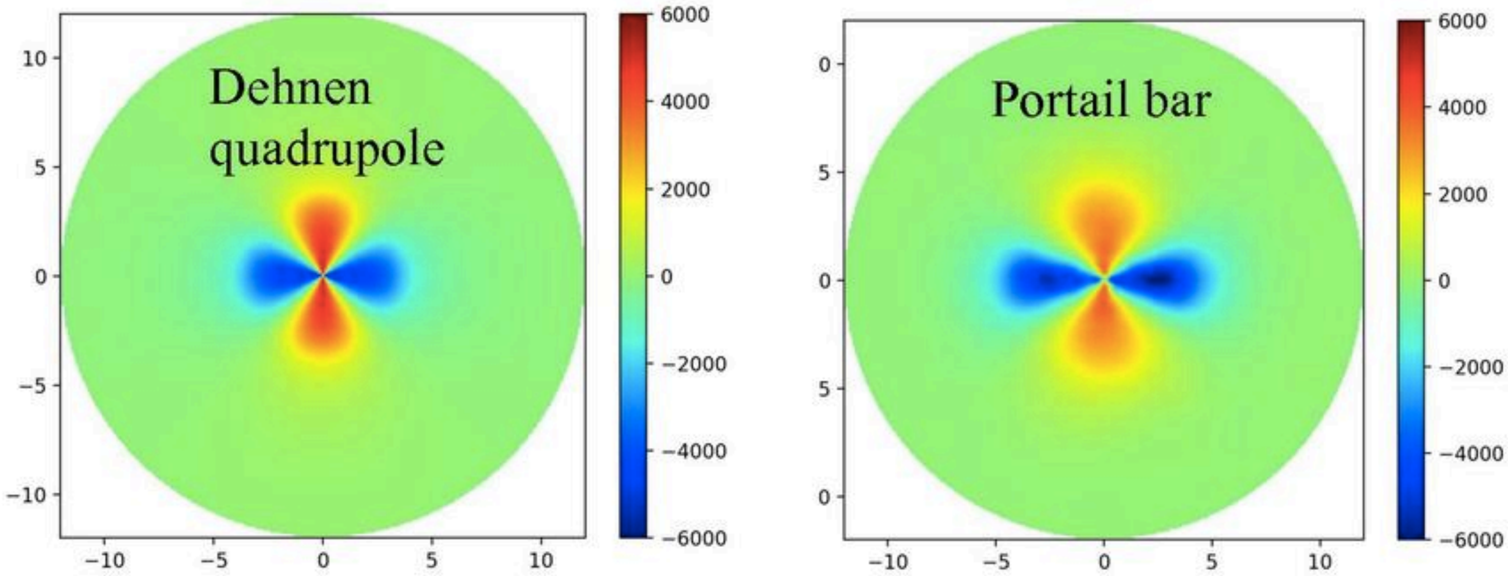
Received xxxx; accepted xxxx

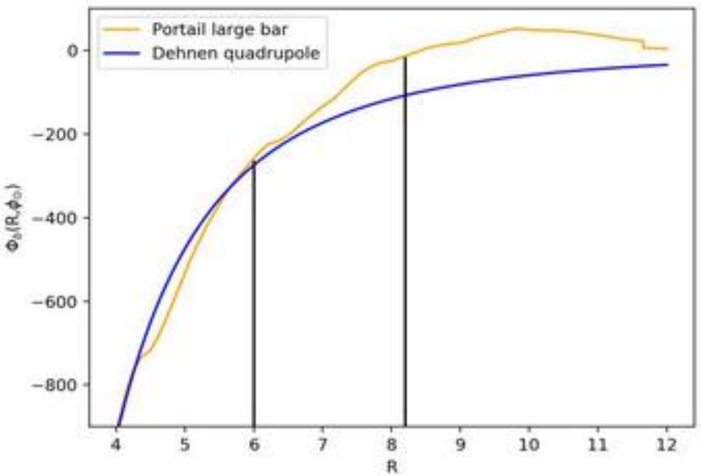
ABSTRACT

The second data release of the Gaia mission has revealed a very rich structure in local velocity space. In terms of in-plane motions, this rich structure is also seen as multiple ridges in the actions of the axisymmetric background potential of the Galaxy. These ridges are probably related to a combination of effects from ongoing phase-mixing and resonances from the spiral arms and the bar. We have recently developed a method to capture the behaviour of the stellar phase-space distribution function at a resonance, by re-expressing it in terms of a new set of canonical actions and angles variables valid in the resonant region. Here, by properly treating the distribution function at resonances, and by using a realistic model for a slowly rotating large Galactic bar with pattern speed $\Omega_b = 39$ km s^{-1} kpc^{-1}, we show that no less than six ridges in local action space can be related to resonances with the bar. Two of these at low angular momentum correspond to the corotation resonance, and can be associated to the Hercules moving group in local velocity space. Another one at high angular momentum corresponds to the outer Lindblad resonance, and can tentatively be associated to the velocity structure seen as an arch at high azimuthal velocities in Gaia data. The other ridges are associated to the 3:1, 4:1 and 6:1 resonances. The latter can be associated to the so-called 'horn' of the local velocity distribution. While it is clear that effects from spiral arms and incomplete phase-mixing related to external perturbations also play a role in shaping the complex kinematics revealed by Gaia data, the present work demonstrates that, contrary to common misconceptions, the bar alone can create multiple prominent ridges in velocity and action space.

Key words. Galaxy: kinematics and dynamics – Galaxy: disc – Galaxy: solar neighborhood – Galaxy: structure – Galaxy: evolution

PORTAIL ET AL. (2017) GALACTIC MODEL

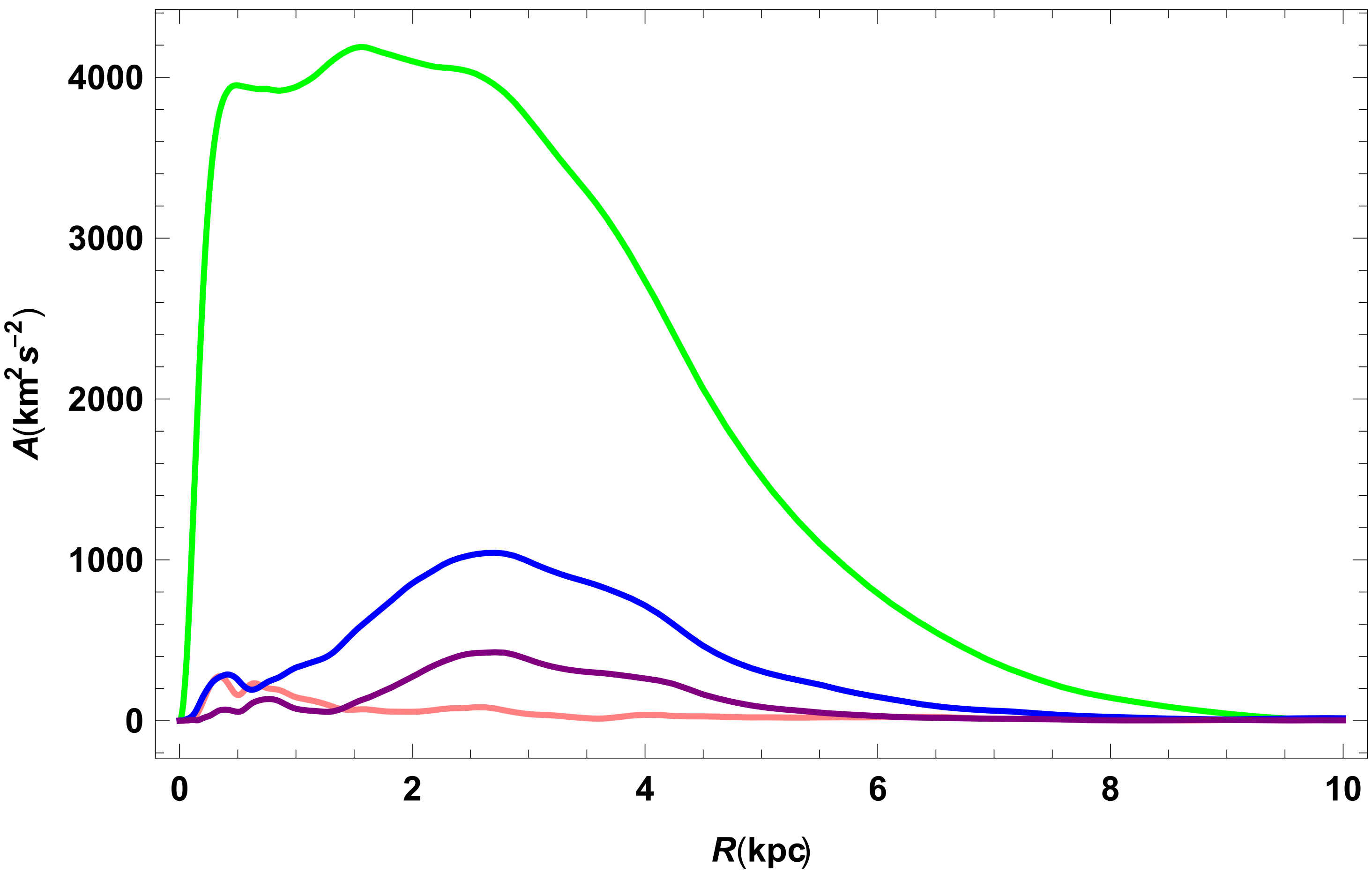




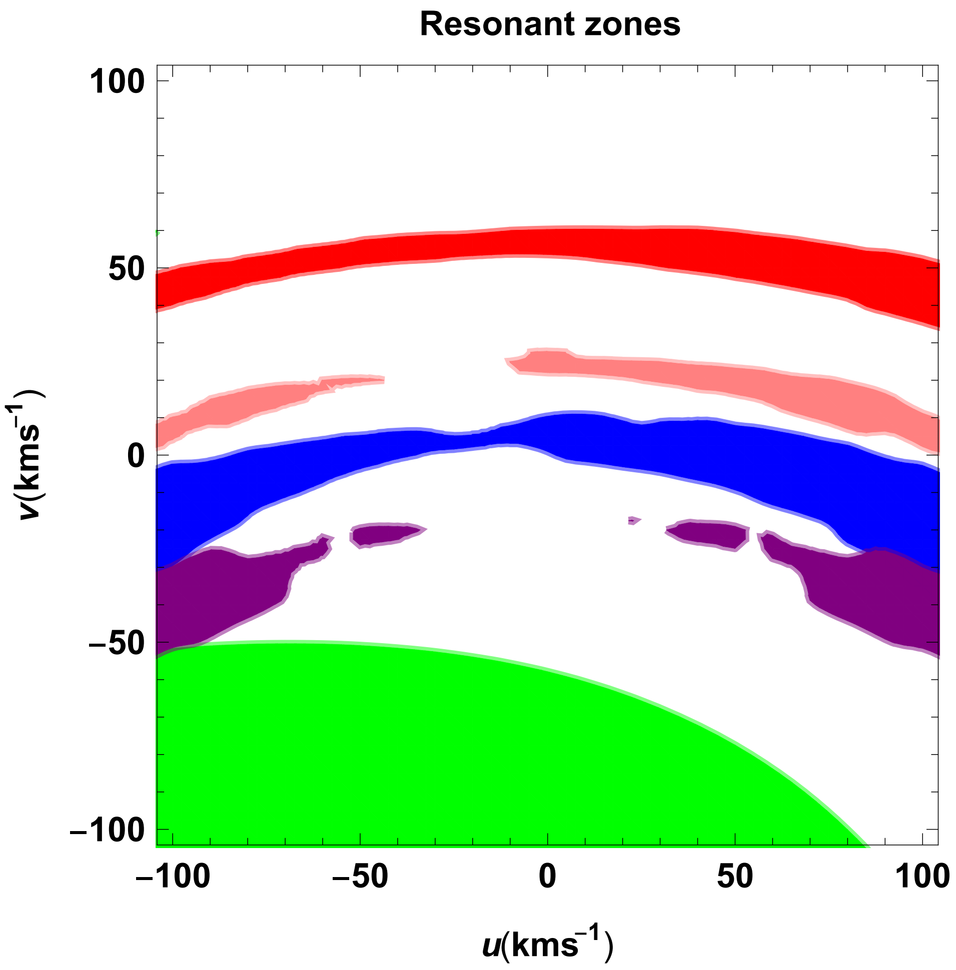
Study the m=2, 3, 4, 6 modes

in Monari et al. (2019)

PORTAIL ET AL. (2017) GALACTIC MODEL (FOURIER MODES)

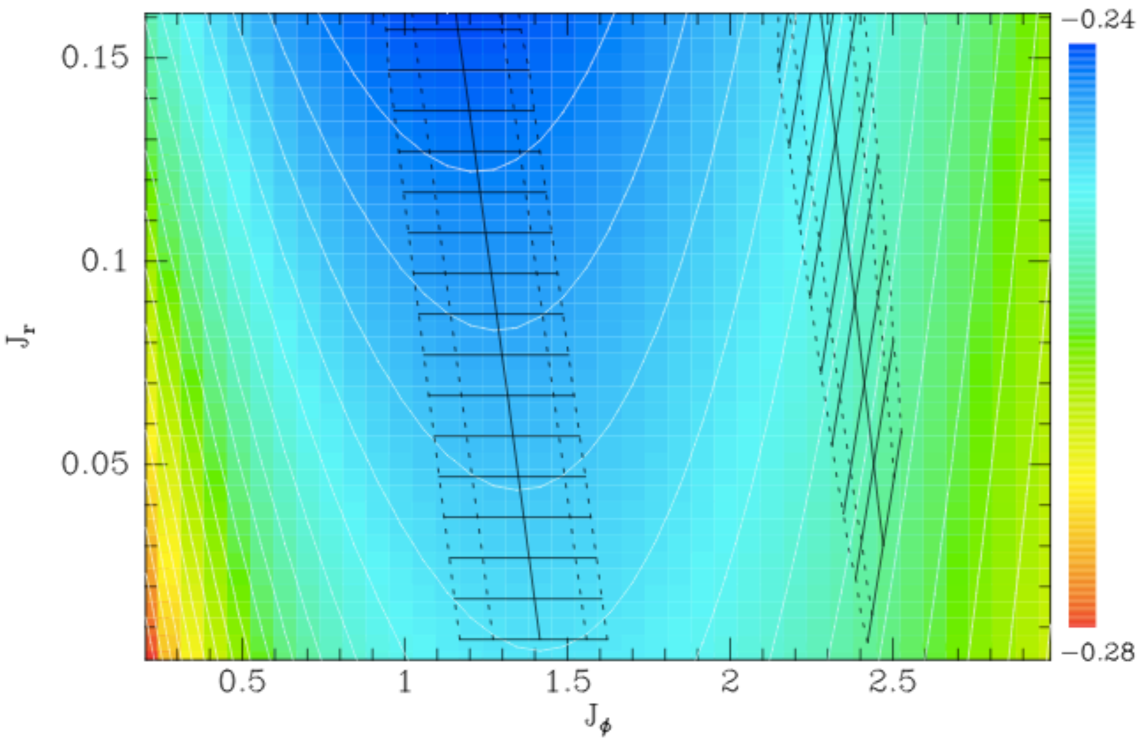


THE RESONANT ZONES IN LOCAL VELOCITY SPACE

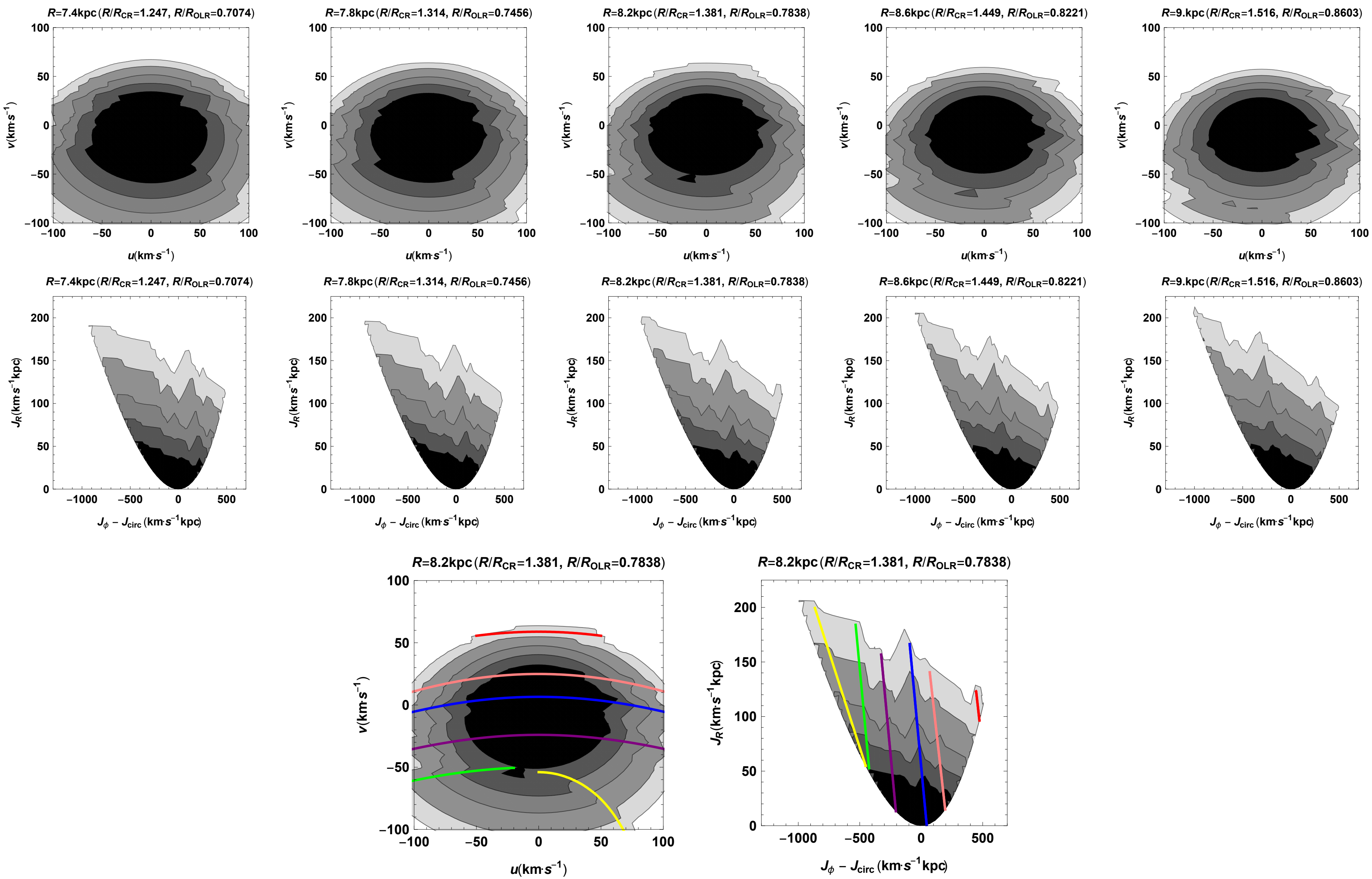


THE RESONANT ZONES IN ACTION SPACE

Binney (2018)



DF (ANALYTICAL)



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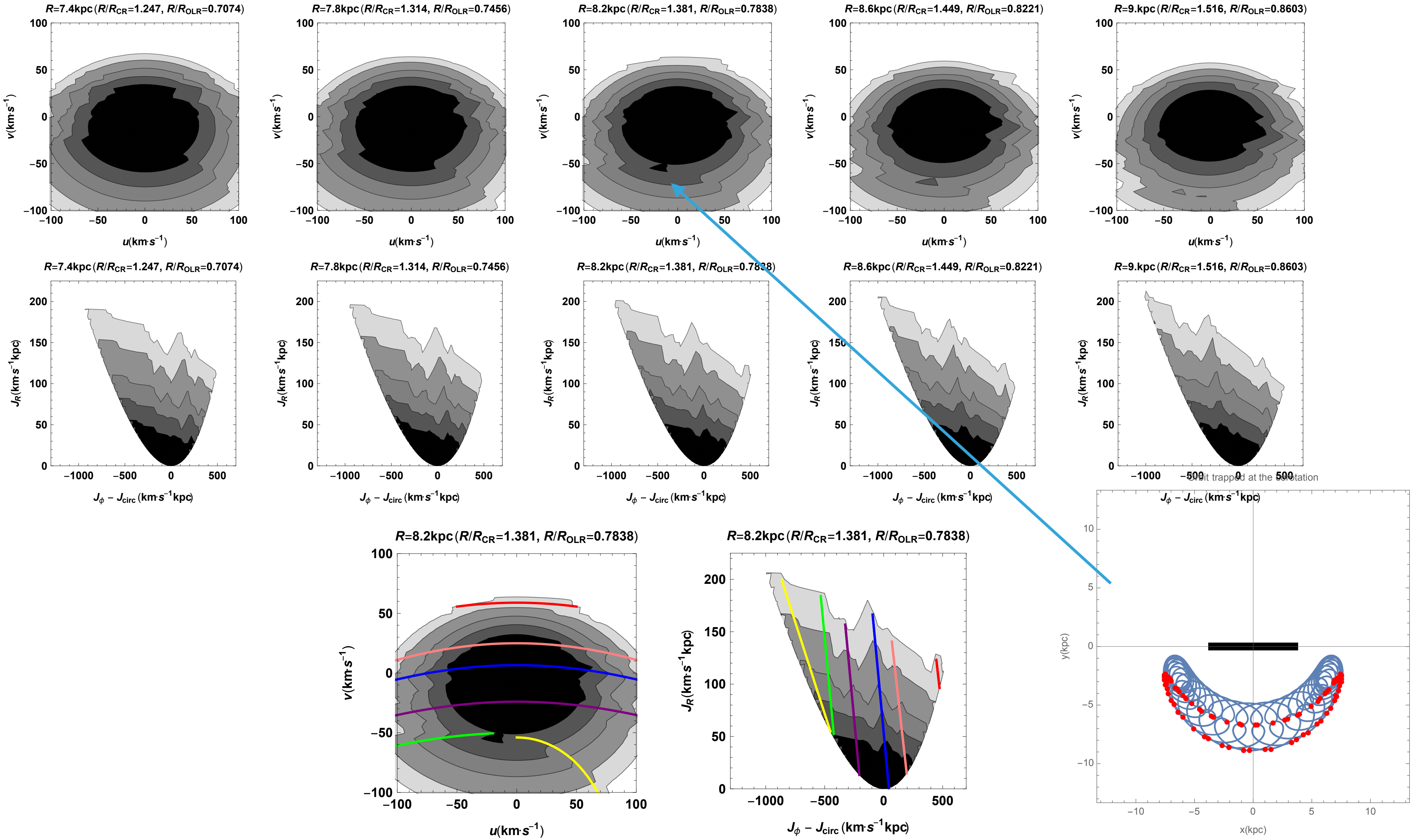
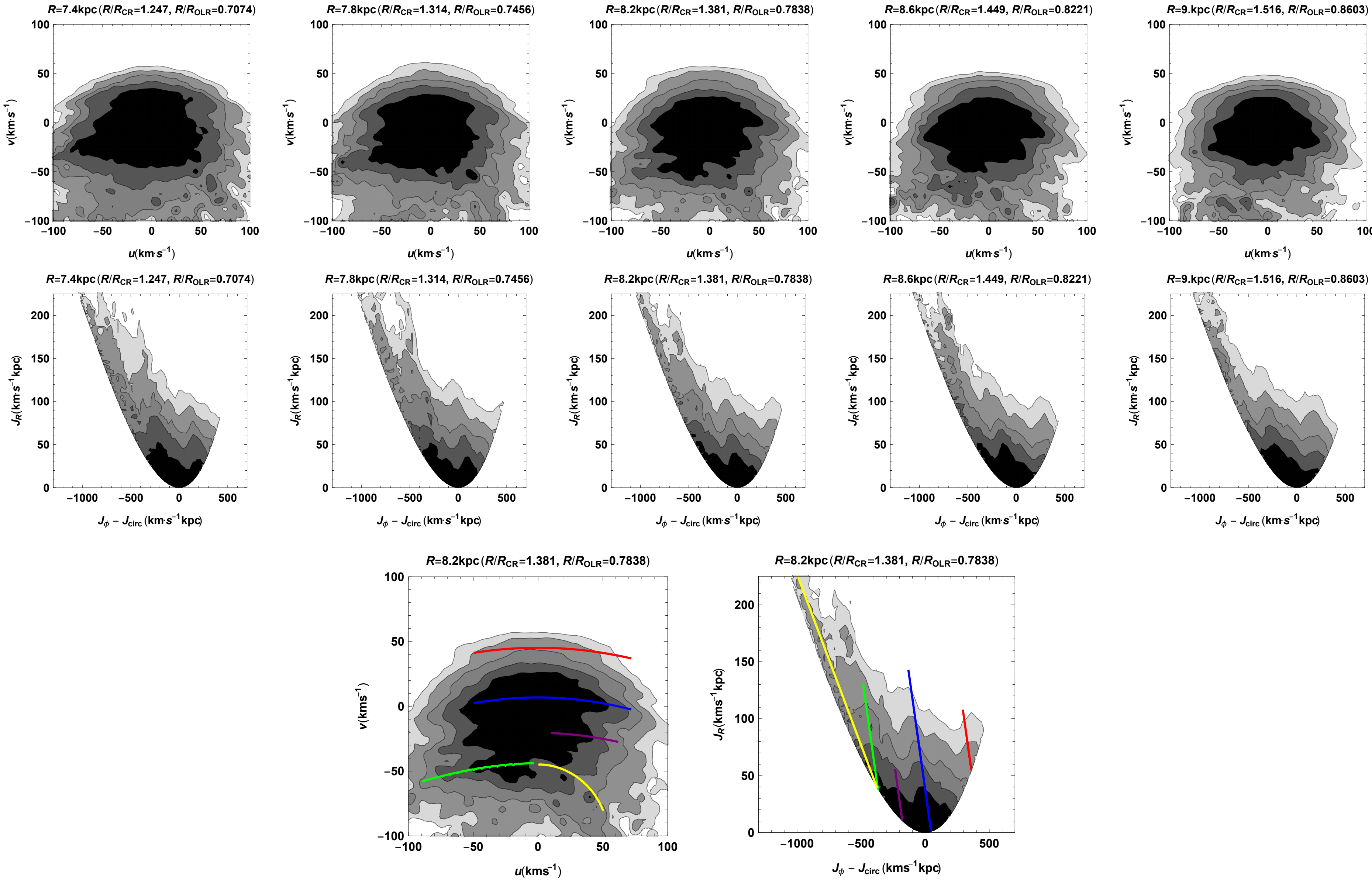
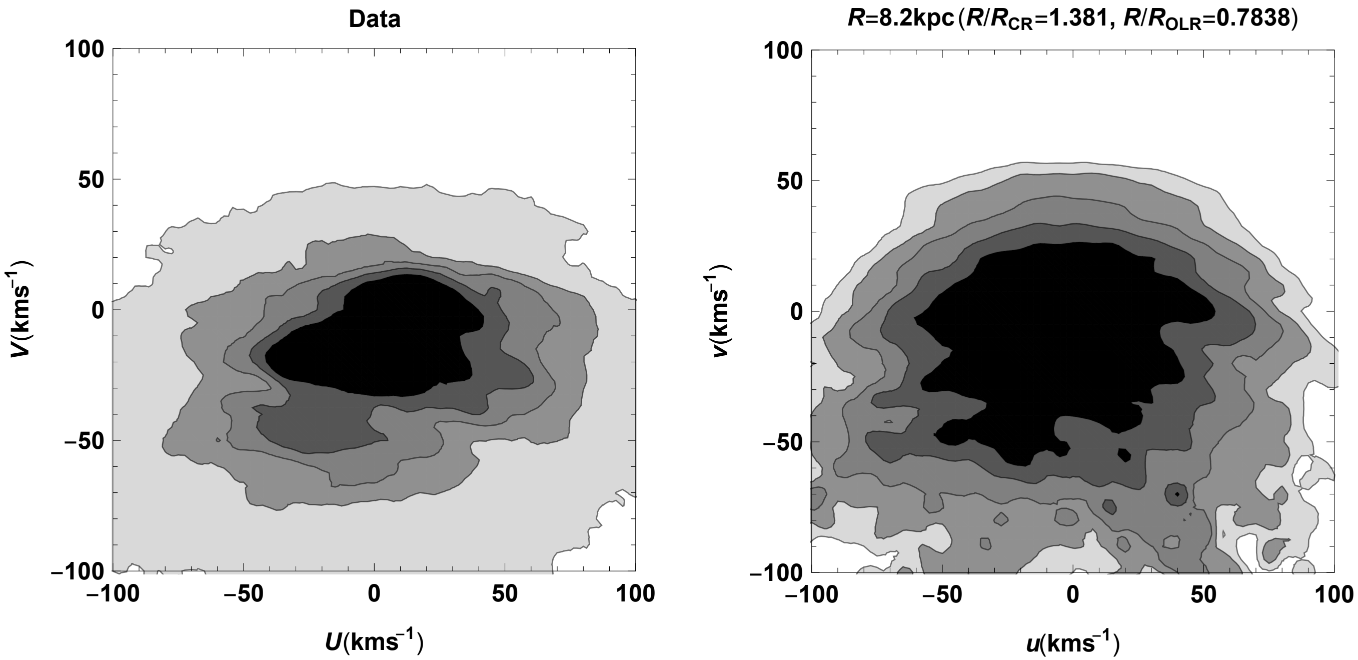


DF (BACKWARD INTEGRATIONS)



COMPARISON WITH THE DATA



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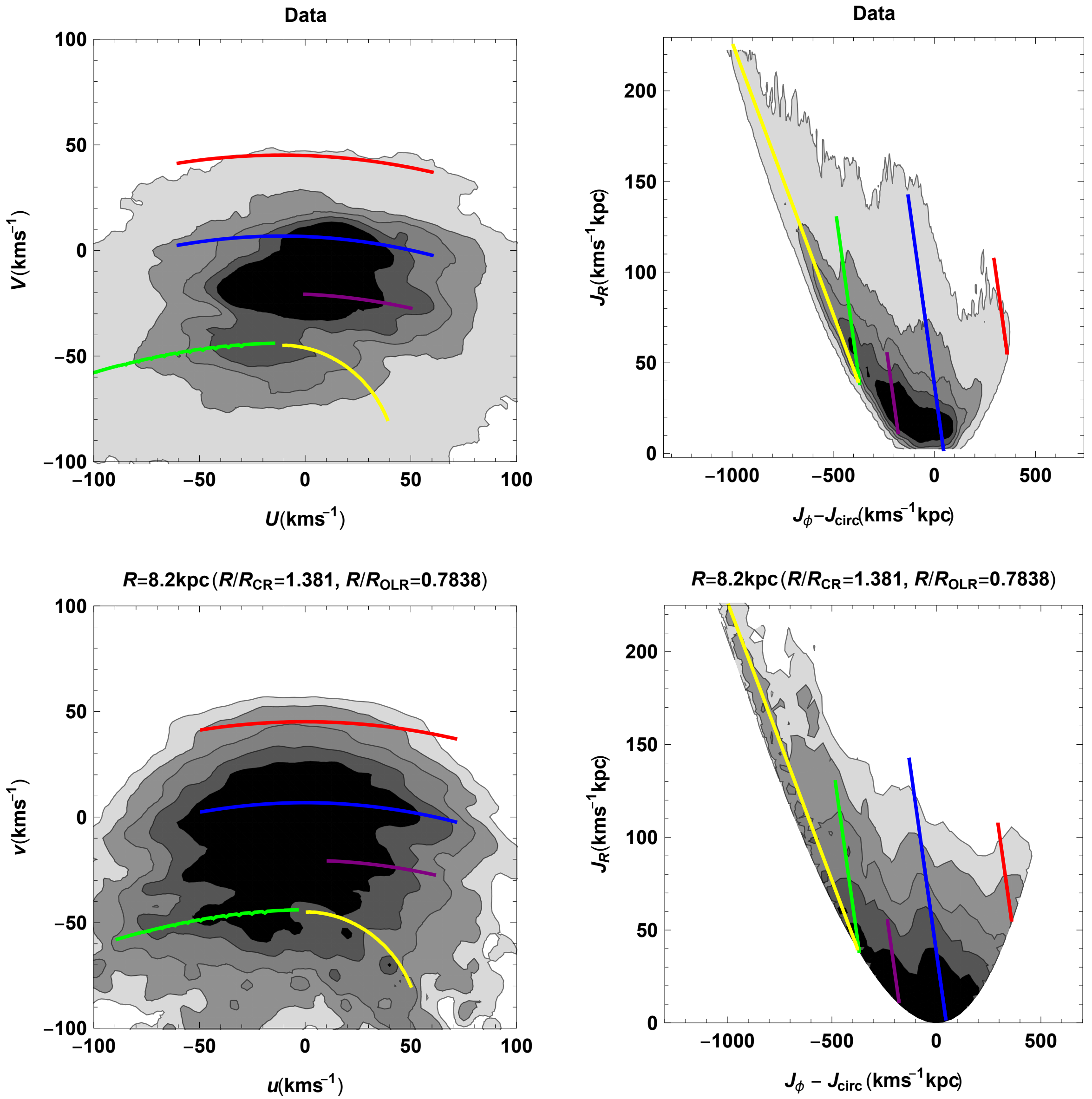

But $V_{\odot}$=0 ?

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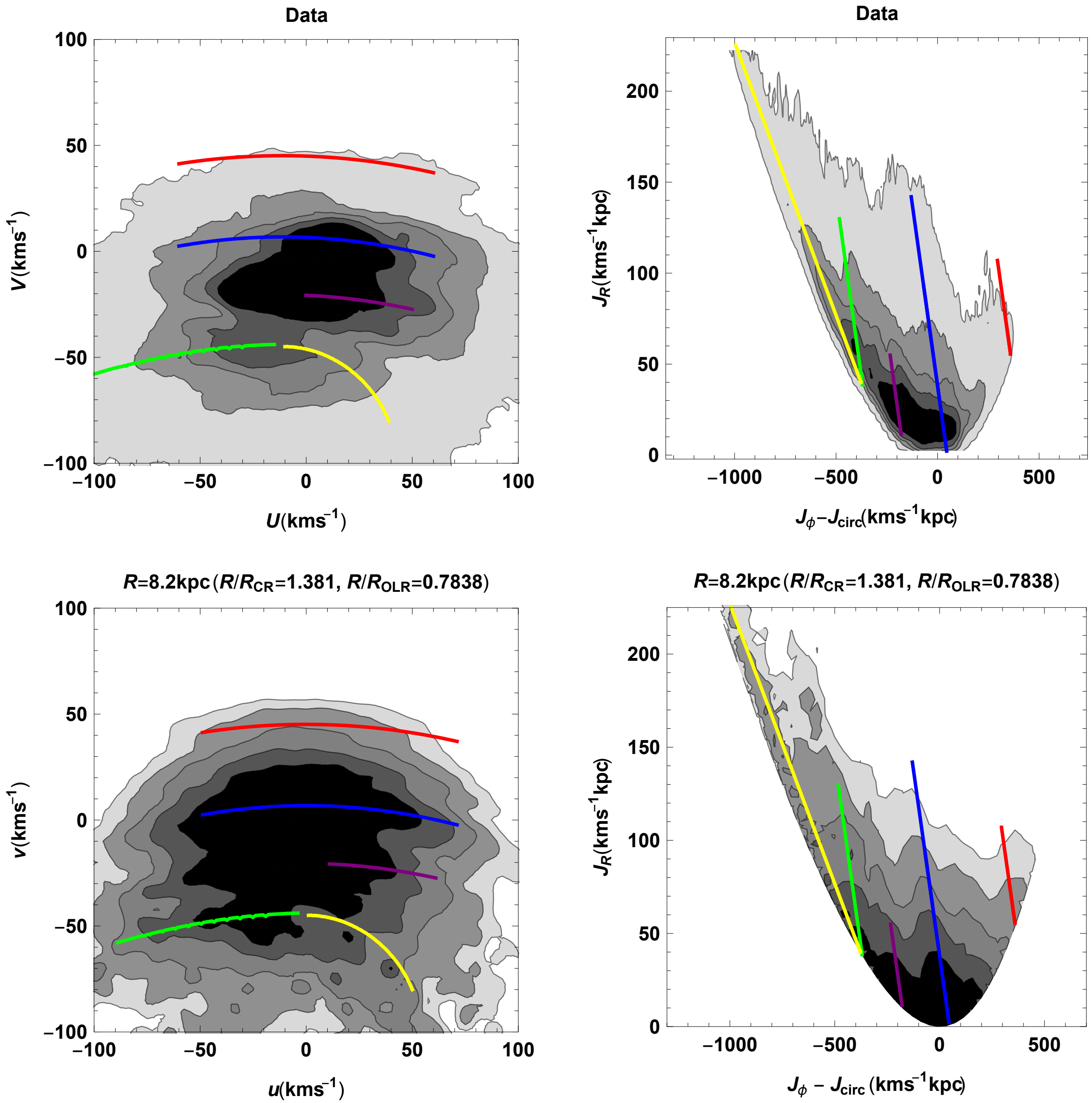
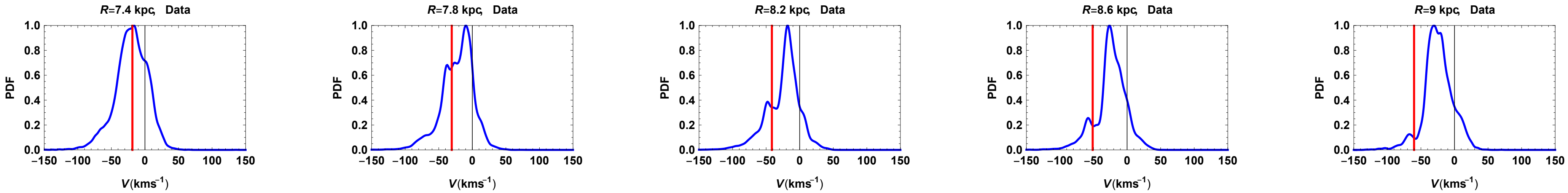


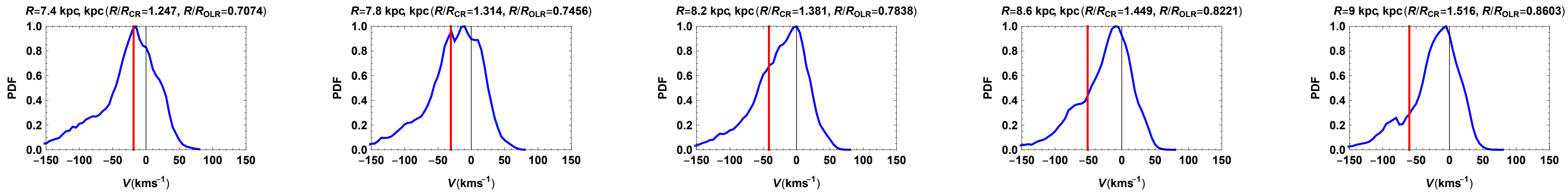
But $V_\odot$=0 ?

COMPARISON WITH THE DATA

Data



Model (backwards)

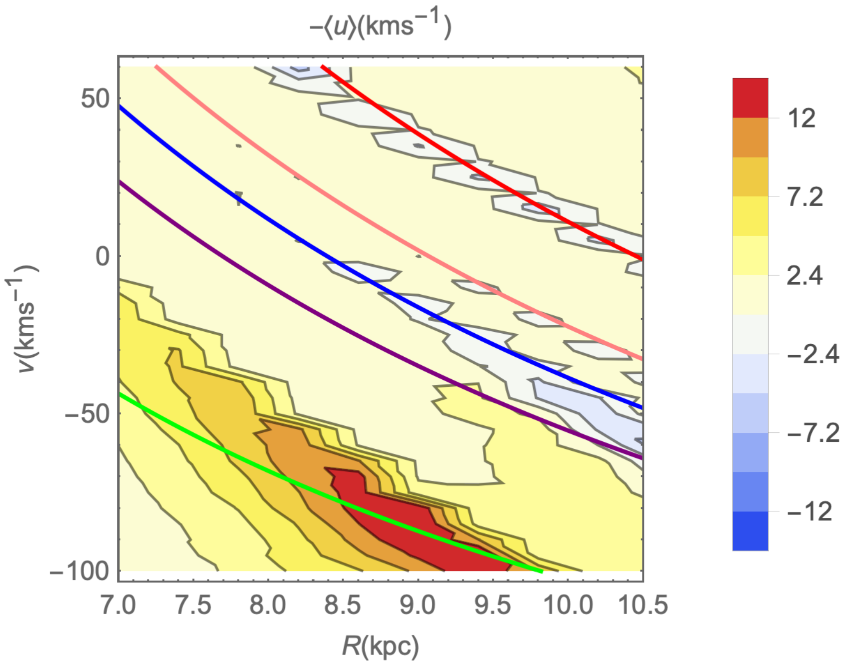


Also slightly declining RC allows to

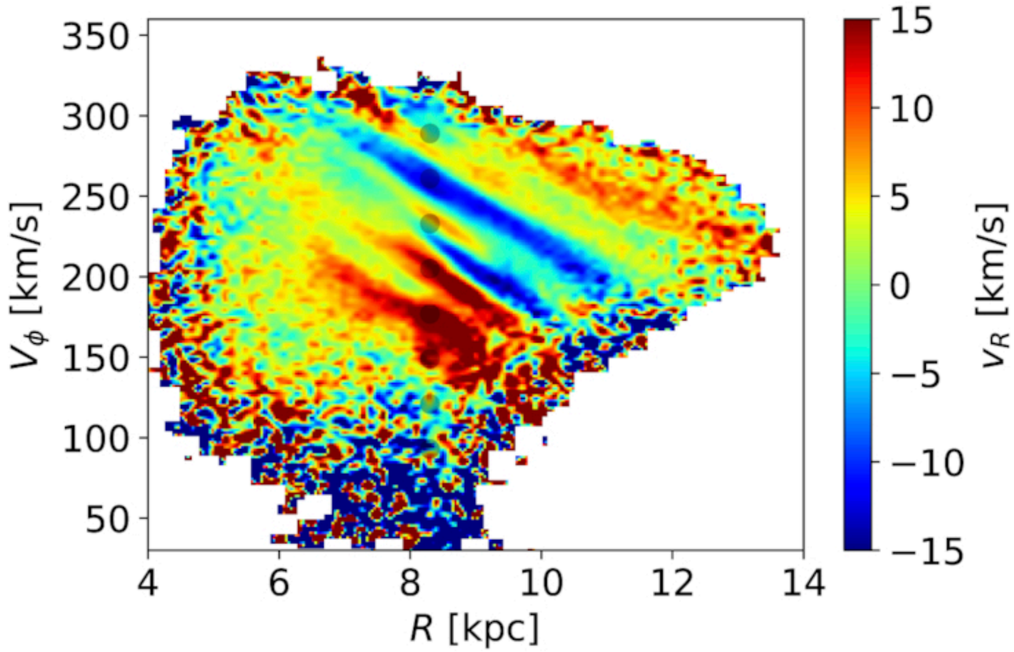
get a more realistic But $V_\odot = 8$ kms^{-1}

RIDGES IN (R,V_ϕ)

Model (analytical)



Data (Laporte et al. 2019)

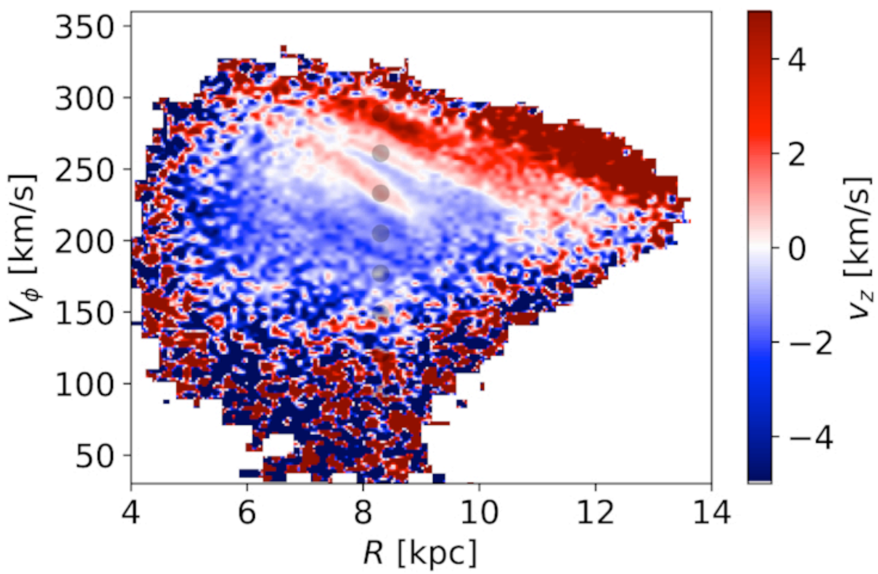


CONCLUSION

- 2D analytical formalism available for bar and spirals.
- Slow bar with CR at 6 kpc adjusted to fit the bulge kinematics qualitatively reproduces **alone** a surprisingly large amount of features in local action-space and velocity-space.

Next steps:

- Use better actions (AGAMA, Vasiliev 2019).
- Add spiral arms and vertical perturbations.



Laporte et al. 2019