Effects of a large Galactic bar in local phase-space

Giacomo Monari

Leibniz-Institut für Astrophysik Potsdam (AIP)

Stars without borders - 15/6/19

Outline

G. Monari, B. Famaey, A. Siebert, C. Wegg and O. Gerhard, 2019, A&A, 626, A41

or

arXiv:1812.04151

- Action/angle/DF models simple and scan parameter space fast → constrain potentials/DFs efficiently and using information of single stars.
- degeneracy between possible models of non-axisymmetries? → help from models of the Galactic centre
- **This talk: Galactic centre model → predictions for the solar neighnbourhood → test them**

Angle/Action variables and Jeans Theorem

Angle/action variables:

- $(\boldsymbol{x}, \boldsymbol{v}) \xrightarrow{\text{can. transf.}} (\boldsymbol{\theta}, \boldsymbol{J})$, $\boldsymbol{J} = const$, $\boldsymbol{\theta} = \boldsymbol{\theta}_0 + \boldsymbol{\Omega} t$
- natural phase-space coordinates for regular orbits in (quasi)-integrable systems
- phase-space canonical coordinates such that $H = H(\boldsymbol{J})$

Jeans Theorem:

- $\boldsymbol{J}$ integrals of motion $\rightarrow f(\boldsymbol{J})$ solution of the CBE
- at equilibrium $f_0(\boldsymbol{J})$ (OK for *axisymmetric* models of MW)

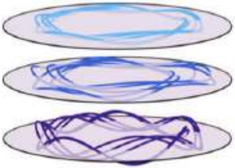


Figure: Orbits with different J_R and J_z (Fouvry et al. 2016).

- Far from resonances: Linearization of the CBE (see **Monari, Famaey & Siebert 2016, MNRAS, 457, 2569)**
- **Near resonances: perturbation/pendulum theory**

Linearized CBE approach

Linearization (action/angle, **Monari, Famaey & Siebert 2016). Assume:**

- $\Phi = \Phi_0 + \Phi_1$, $|\nabla\Phi_1| \ll |\nabla\Phi_0|$,
- $f = f_0 + f_1$, **and** $f_0(\boldsymbol{J})$,

$$\frac{\mathrm{d}f_1}{\mathrm{d}t} = \frac{\partial f_0}{\partial \boldsymbol{J}} \cdot \frac{\partial \Phi_1}{\partial \boldsymbol{\theta}}, \tag{1}$$

$$\Phi_1(\boldsymbol{J}, \boldsymbol{\theta}, t) = \mathrm{Re}\left\{ g(t) \sum_{\boldsymbol{n}} c_{\boldsymbol{n}}(\boldsymbol{J}) \mathrm{e}^{\mathrm{i}(\boldsymbol{n}\cdot\boldsymbol{\theta} - m\Omega_\mathrm{p} t)} \right\}, \tag{2}$$

$$f_1(\boldsymbol{J}, \boldsymbol{\theta}, t) = \mathrm{Re}\left\{ \frac{\partial f_0}{\partial \boldsymbol{J}}(\boldsymbol{J}) \cdot \sum_{\boldsymbol{n}} \boldsymbol{n} c_{\boldsymbol{n}}(\boldsymbol{J}) \frac{\mathrm{e}^{\mathrm{i}(\boldsymbol{n}\cdot\boldsymbol{\theta} - m\Omega_\mathrm{p} t)}}{\boldsymbol{n}\cdot\boldsymbol{\omega} - m\Omega_\mathrm{p}} \right\}. \tag{3}$$

Moments of the linearized DF - spiral arms

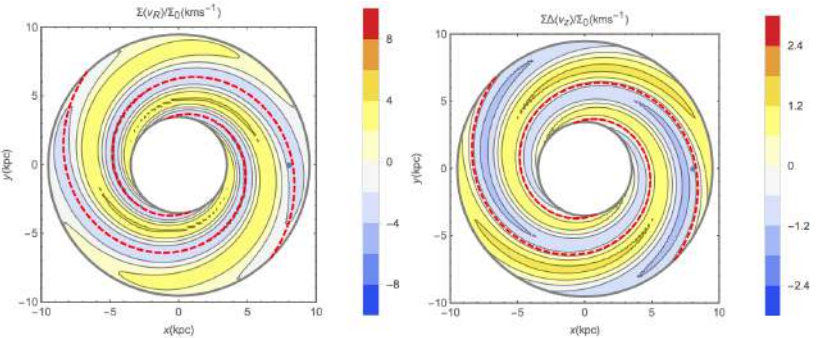


Figure: Momenta in the Galactic plane for the case of spiral arms. Left: $\langle v_R \rangle$. Right: $\Delta\langle v_z \rangle$.

Moments of the linearized DF - spiral arms

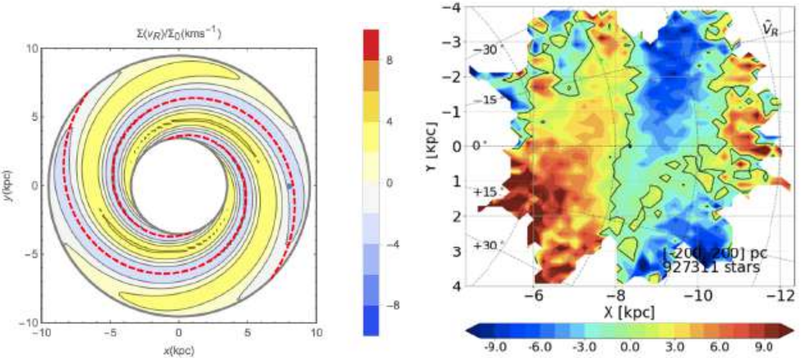


Figure: Momenta in the Galactic plane for the case of spiral arms. Left: $\langle v_R \rangle$. Right: Katz et al. (2018).

Resonances

- Resonances when $l\omega_R + m(\omega_\phi - \Omega_\mathrm{p}) = 0$
- $l = 0$ for CR; $l = 1$ OLR; $l = -1$ ILR
- Linear theory diverges

Dynamics near a resonance

Near $l\omega_R + m(\omega_\phi - \Omega_{\rm p}) = 0$ (**Monari, Famaey, Fouvry, Binney 2017**):

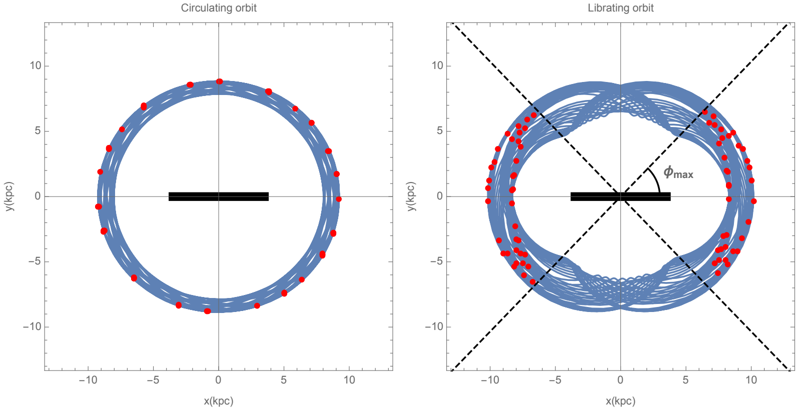
- $(J_R, J_\phi, \theta_R, \theta_\phi) \to (J_{\rm s}, J_{\rm f}, \theta_{\rm s}, \theta_{\rm f})$
- $\theta_{\rm s} = l\theta_R + m(\theta_\phi - \Omega_{\rm b} t), \quad \theta_{\rm f} = \theta_R,$
- $J_{\rm s} = J_\phi / m, \quad J_{\rm f} = J_R - lJ_{\rm s},$
- $\theta_{\rm s}$ **'slow'** because near resonance $\Omega_{\rm s} \equiv \dot{\theta}_{\rm s} \approx 0,$
- $\Omega_{\rm s}(J_{\rm s,res}, J_{\rm f}) = 0$ (axisymmetric potential).

Averaging along fast $\theta_{\rm f}$ and **expanding** $J_{\rm s}$ around $J_{\rm s,res}$, near resonances we obtained the averaged pendulum Hamiltonian

$$H \approx \frac{1}{2} G (J_{\rm s} - J_{\rm s,res})^2 - F \cos(\theta_{\rm s} + g). \quad (4)$$

Pendulum - circulating and librating orbits

- $E_{\mathrm{p}} = H/G$,
- $\omega_0^2 = FG$,
- $k = [1/2(1 + E_{\mathrm{p}}/\omega_0^2)]^{1/2}$



(a) $k > 1$ (circulating) (b) $k < 1$ (librating)

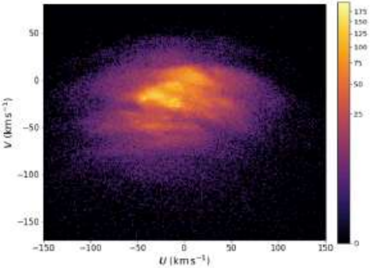
DF in the trapping zone

Pendulum Hailtonian has its own action/angle variables $(J_{\rm p}, \theta_{\rm p})$ and $J_{\rm s}(J_{\rm p}, \theta_{\rm p})$.

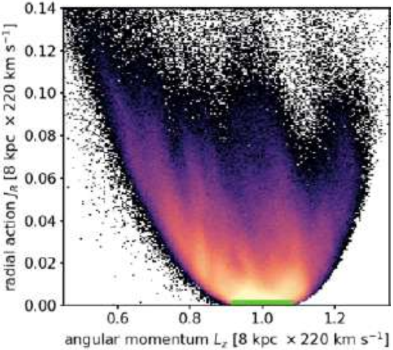
For $k < 1$, trapping zone, librating/trapped orbits (see Binney 2016; Monari et al. 2017; Binney 2018)

$$f_{\rm tr}(J_{\rm f}, J_{\rm p}) = \overline{f_0} \equiv \frac{1}{2\pi}\int_0^{2\pi} f_0(J_{\rm f}, J_{\rm s}(J_{\rm p}, \theta_{\rm p})), \quad (5)$$

i.e. phase-mixing over $\theta_{\rm p}$.



(a) Gaia collab., Katz et al. (2018)



(b) Trick et al. (2019)

Figure: Velocity and action distribution in the solar neighbourhood.

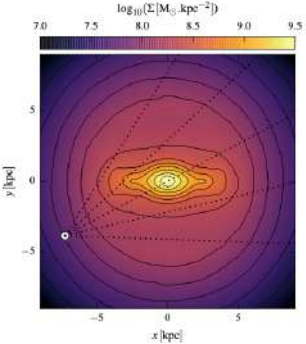
Gaia DR2

Velocity and action space ridges due to

- Bar,
- Spiral arms, including past transient ones (Sellwood et al. 2019, Hunt et al. 2019),
- Ongoing phase-mixing (Minchev et al. 2009, Antoja et al. 2018 and all the works on the phase-space spiral),
- ...

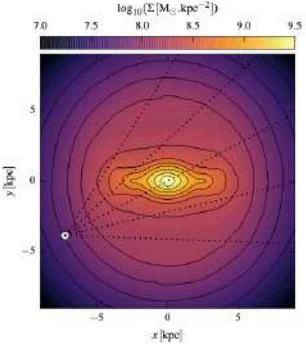
Q: what does the bar alone do to local stellar kinematics? A: a lot.

Where is the MW bar corotation?



- Millions of RC stars: VVV + 2MASS + UKIDDS + GLIMPSE
- Long flat ($h < 50$ pc) extension of the bar out to $R > 5$ kpc
- Fit to BRAVA + ARGOS kinematics
  $\rightarrow \Omega_{\rm p} = 39$ kms^{-1}kpc$\sim 1.33\Omega_0$ (**Portail et al. 2017**, confirmed Clarke et al. 2019; Sanders et al. 2019)
- **Corotation at** ~ 6 **kpc and OLR beyond 11 kpc**

Where is the MW bar corotation?



- Millions of RC stars: VVV + 2MASS + UKIDDS + GLIMPSE
- Long flat ($h < 50$ pc) extension of the bar out to $R > 5$ kpc
- M2M fit to BRAVA + ARGOS kinematics
  $\rightarrow \Omega_{\rm p} = 39$ kms^{-1}kpc$\sim 1.33\Omega_0$ (**Portail et al. 2017**, confirmed Clarke et al. 2019; Sanders et al. 2019)
- **Implications for dark matter profile: 2 kpc size core.**

Portail et al. (2017) bar model

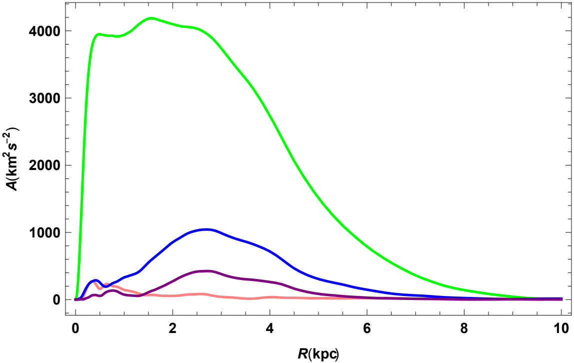


Figure: Fourier amplitudes for the Portail et al. (2017) bar

Resonant zones

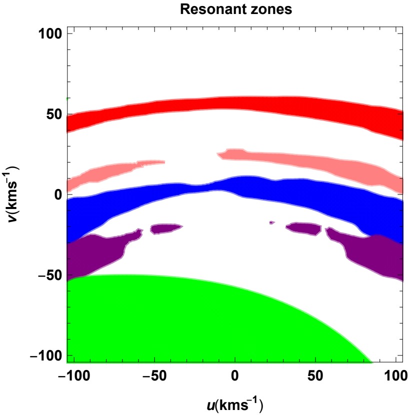
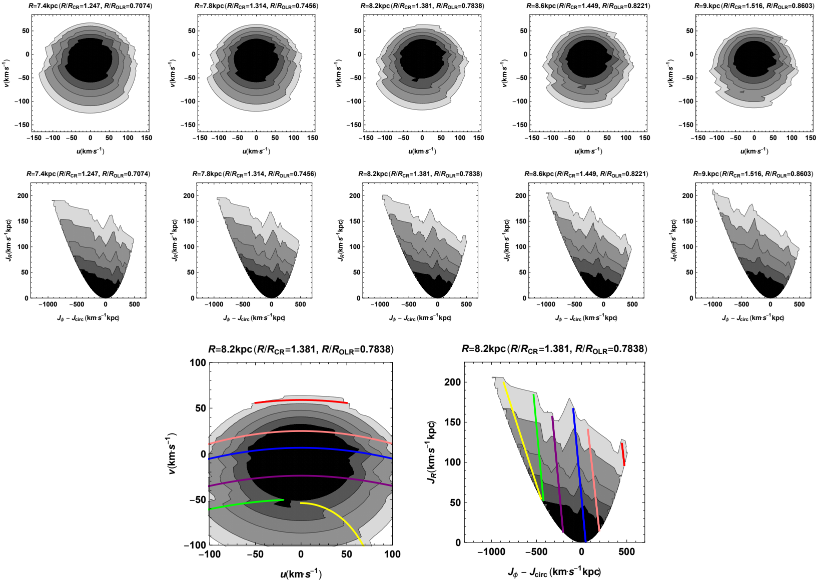
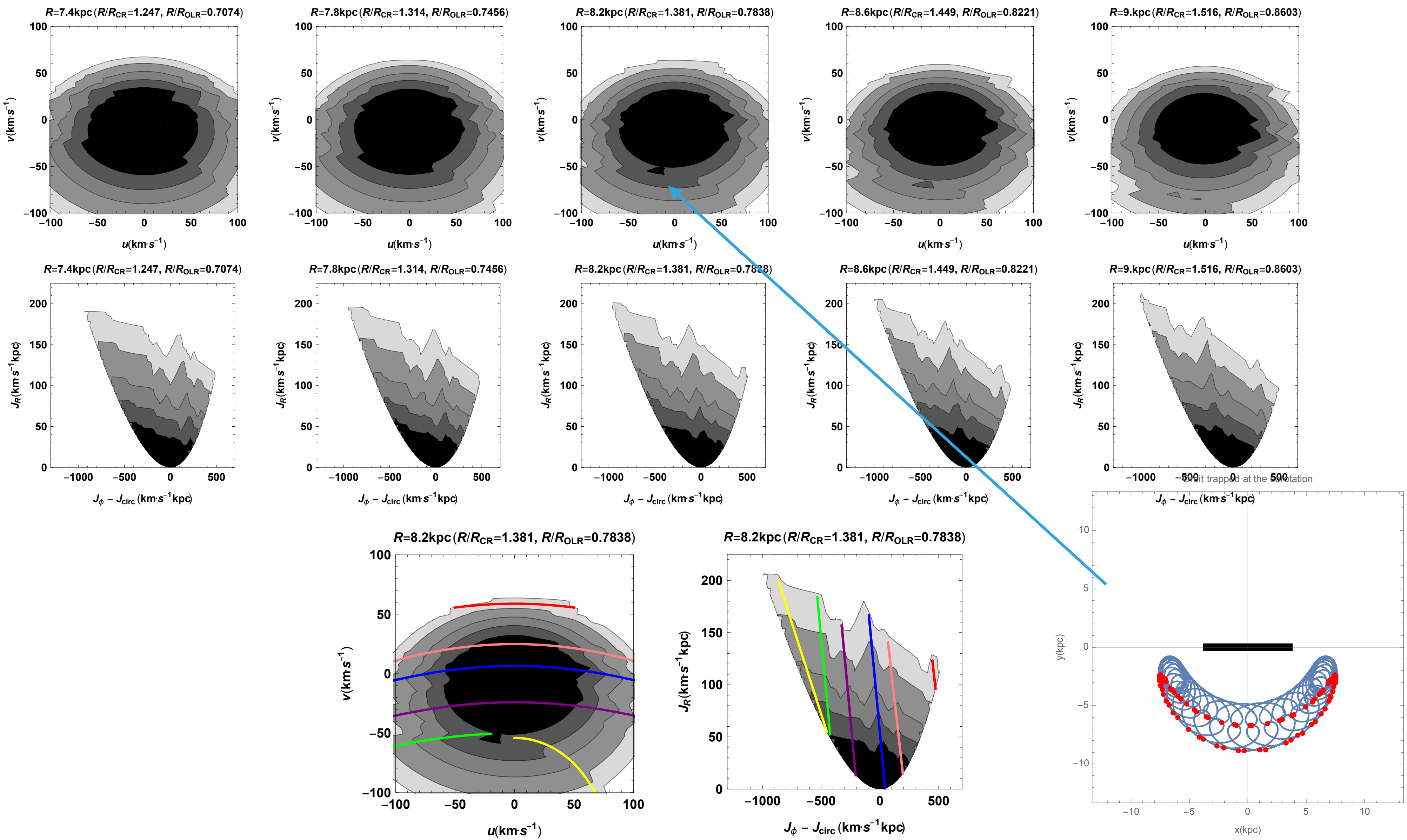


Figure: Resonant zones in local velocity space ($R_0 = 8.2$ kpc, $\phi = -28^\circ$).

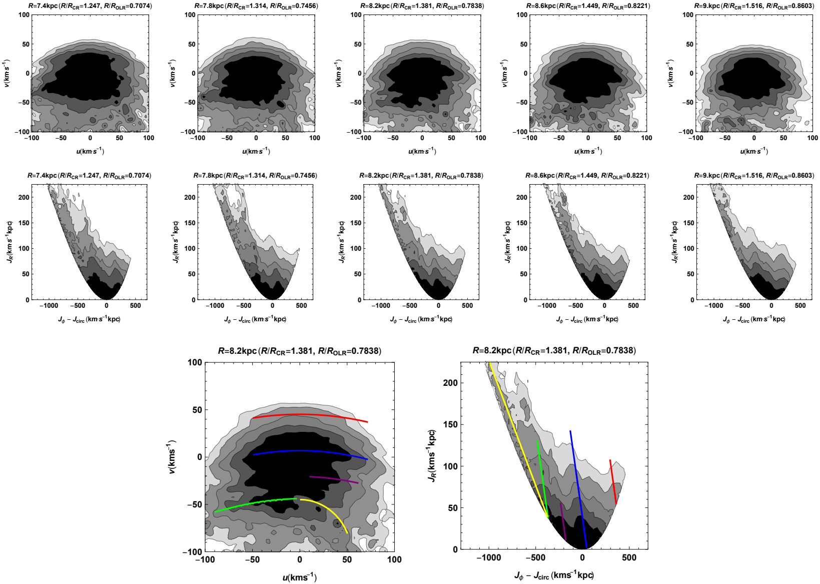
DF under the bar's influence (analytical)



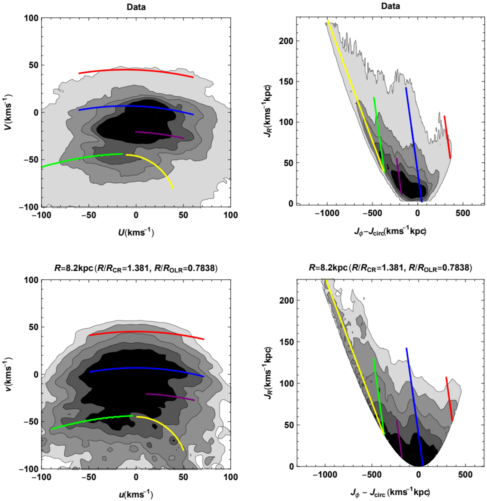
DF (ANALYTICAL)



DF under the bar’s influence (backwards integrationsl)



Data and model



$V_\odot = 0$?

R vs. v_ϕ ridges

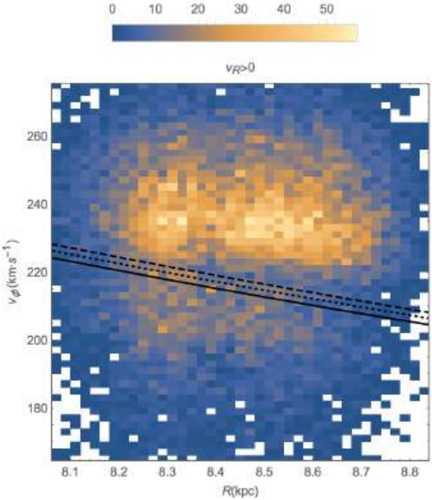


Figure: Monari et al. (2017), TGAS + LAMOST, Gaia Image of the Week

R vs. v_ϕ ridges

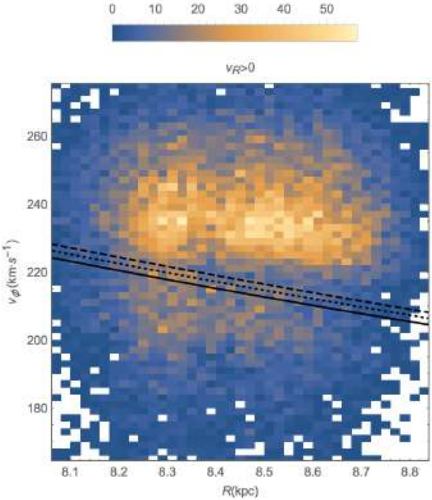


Figure: Monari et al. (2017), TGAS + LAMOST, Gaia Image of the Week. With Gaia DR2 Kawata et al. (2018), Antoja et al. (2018), Laporte et al. (2019), Fragkoudi et al. (2019).

R vs. v_ϕ ridges

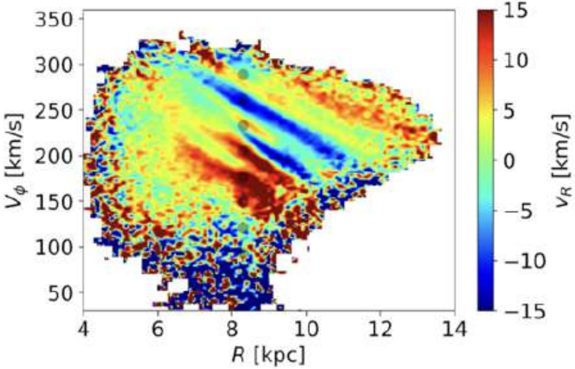
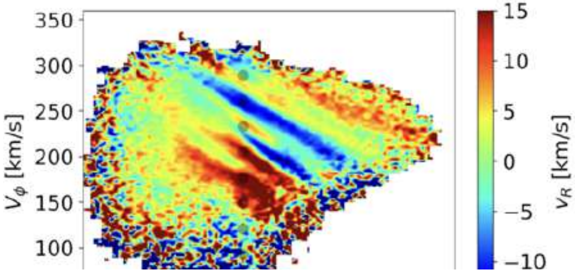


Figure: Laporte et al. (2019)

R vs. v_ϕ ridges



Do not demand from us the formula unfolding worlds before you,
rather a few crooked syllables - and dry like a twig.
That alone today we can tell you,
who we are not, what we do not want.

Eugenio Montale, from "Ossi di Seppia", 1923

R vs. v_ϕ ridges

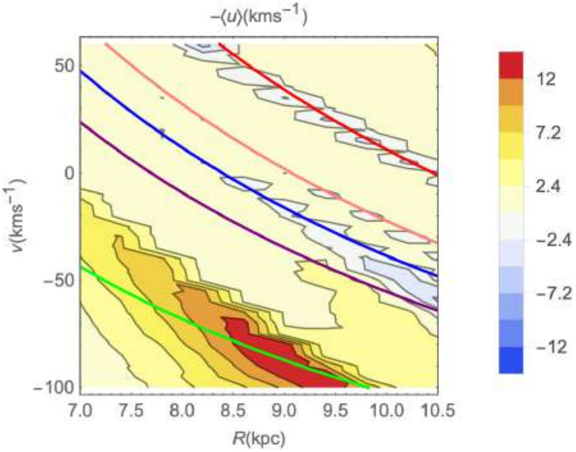
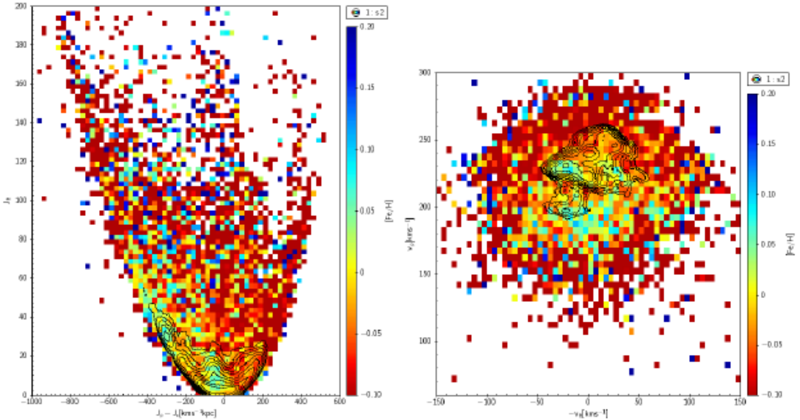


Figure: Monari et al. (2019)

Summary

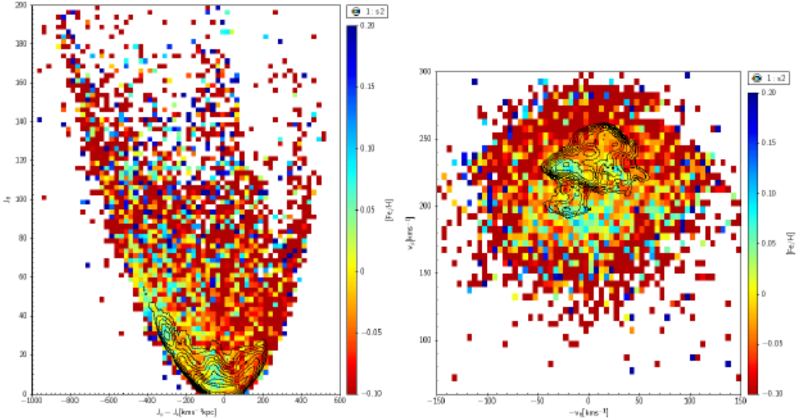
- 2D analytical formalism available for bar and spiral arms
- Slow bar (CR $R \sim 6$ kpc) adjusted for MW centre reproduces **alone** many features in local velocity/action space
- Non-axisymmetric model to use to study further perturbations
- Next steps: better action/angles, add spiral arms and vertical direction

Work in progress: actions and metallicities



- some ridges in action/angle space have peculiar metallicities (but see Antoja et al. 2017)
- secular evolution of the disc carves ridges in phase-space (e.g. Fouvry et al. 2015), divide $f(\boldsymbol{J}, \boldsymbol{\theta}, \tau, [\mathrm{Fe/H}])$

Work in progress: actions and metallicities



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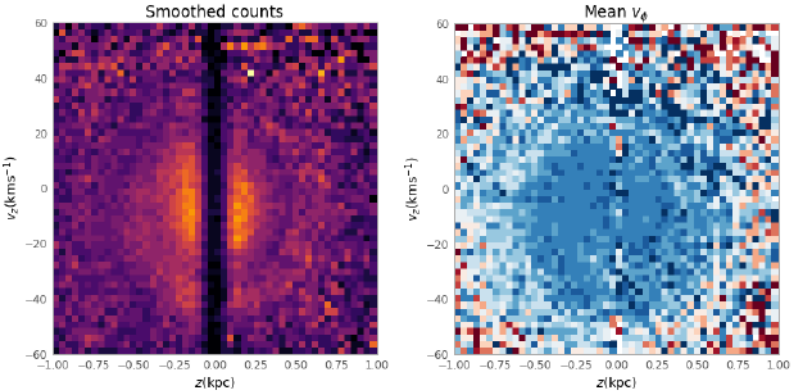
Work in progress: phase-space spiral



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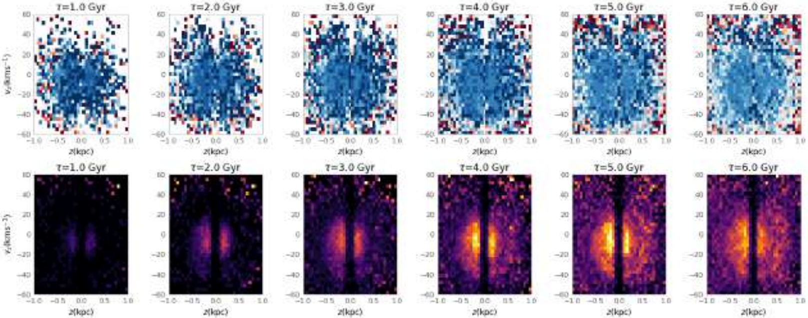

Figure: (z, v_z) space

Work in progress: phase-space spiral

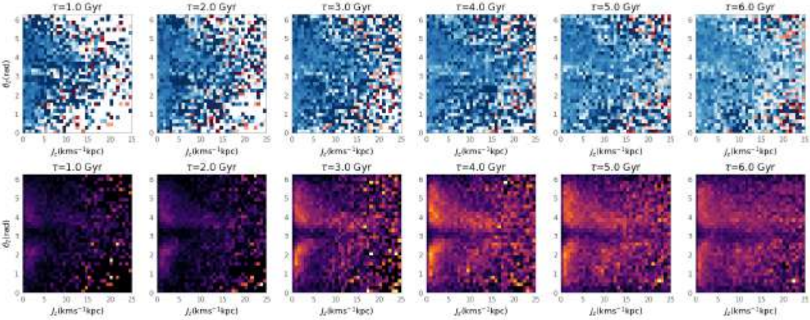

Figure: (J_z, θ_z) space