gaia

Perturbed distribution functions for models of the Milky Way disk

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Jeans theorem

- Natural phase-space coordinates for regular orbits in (quasi)-integrable systems: **actions J and angles θ**
= phase-space canonical coordinates such that H=H(**J**)

=> at equilibrium f_0 (**J**) solution of CBE

Linearized CBE approach

- Start from:

$$\Phi_1(\boldsymbol{J},\boldsymbol{\theta},t) = \mathrm{Re}\left\{\mathcal{G}(t)\sum_{\boldsymbol{n}} c_{\boldsymbol{n}}(\boldsymbol{J})\mathrm{e}^{\mathrm{i}\boldsymbol{n}\cdot\boldsymbol{\theta}}\right\} \quad \text{and} \quad \frac{\mathrm{d}f_1}{\mathrm{d}t} = \frac{\partial f_0}{\partial \mathbf{J}}\cdot\frac{\partial \Phi_1}{\partial \boldsymbol{\theta}}$$

$$\downarrow$$

$$\mathcal{G}(t) = g(t)h(t)$$, $h(t)=\exp(i\omega_p t)=\exp(-im\Omega_p t)$

- Then perturbed DF is:

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

Assumption: we are currently in plateau of max amplitude

(Monari, Famaey & Siebert 2016)

Resonances Monari, Famaey, Fouvry & Binney (2017)

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

- Resonance when $l\kappa + m(\Omega_\phi - \Omega_\mathrm{b}) = 0,$
- (l,m)=(0,2): CR; (l,m)=(1,2): OLR
- **FOR EACH RESONANCE:** canonical transformation to disentangle slow and fast motion & average over fast motion :

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

- Averaged Hamiltonian (Jacobi integral)

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

- For each J_f, define J_{sres} such that $\Omega_\mathrm{s}(J_\mathrm{f}, J_\mathrm{s,res}) = 0.$
- Expand around J_{sres} up to 2^{nd} order
  => **Hamiltonian of a pendulum of angle θ_s and momentum J_s** $(=J_\phi / m)$

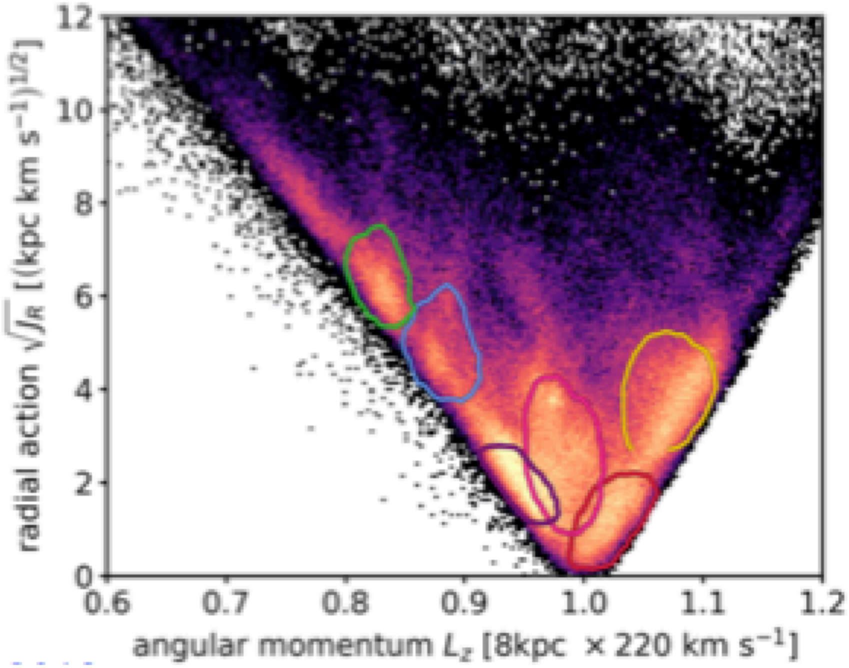
=> angle-action variables for pendulum (J_p, θ_p)

- In the trapping zone, phase-mix over θ_p :

$$f_{tr}(J_f, J_p) = \langle f_0(J_f, J_p, \theta_p) \rangle_{\theta p}$$

Gaia DR2

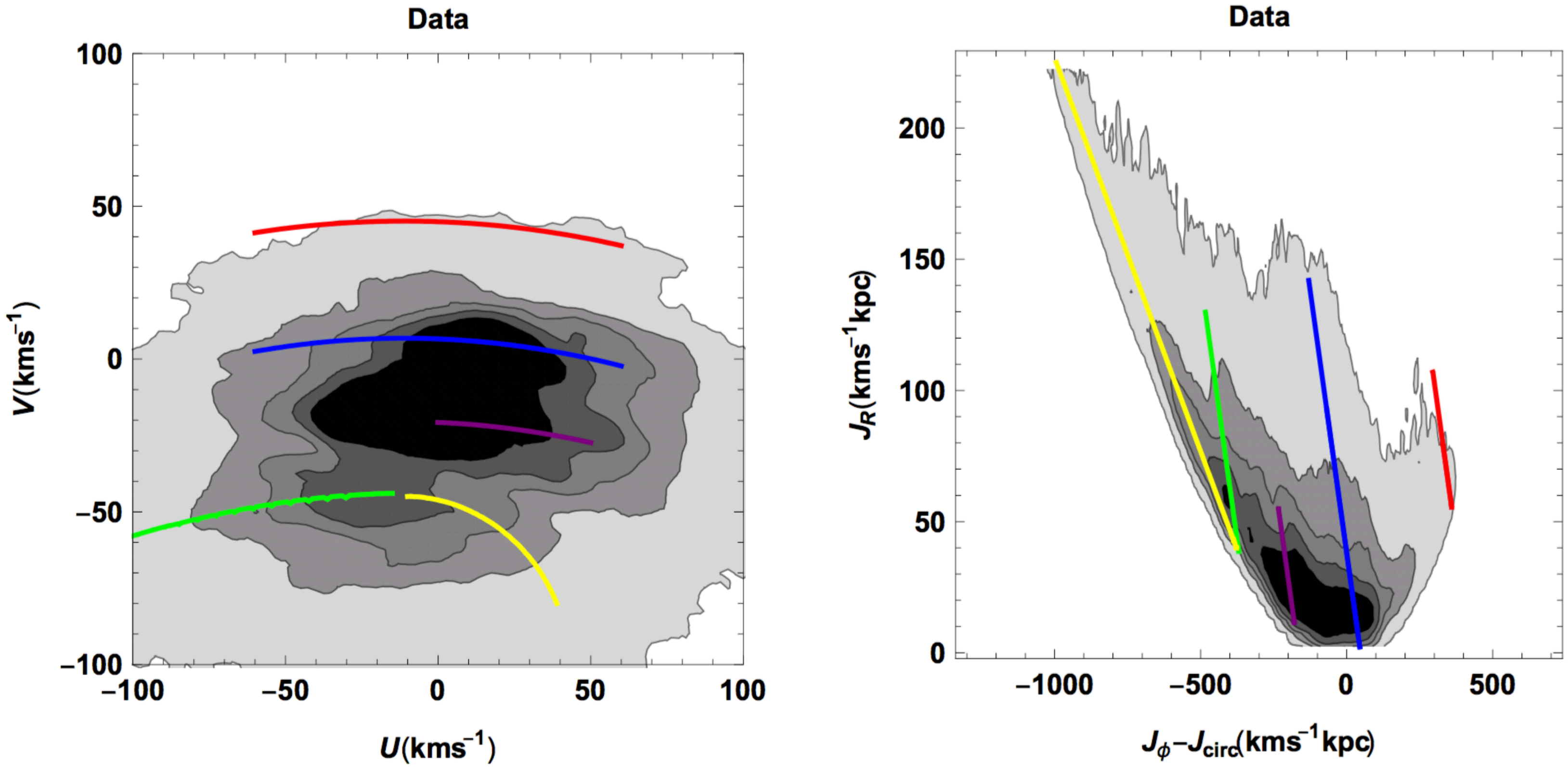
- 7.2×10^6 stars with radial velocities down to G=13
- Various published Bayesian estimates of the distances for stars with relative precision on the parallax larger than 10% to 20%



Trick et al. 2019

3×10^5 stars within 200 pc

Gaia DR2



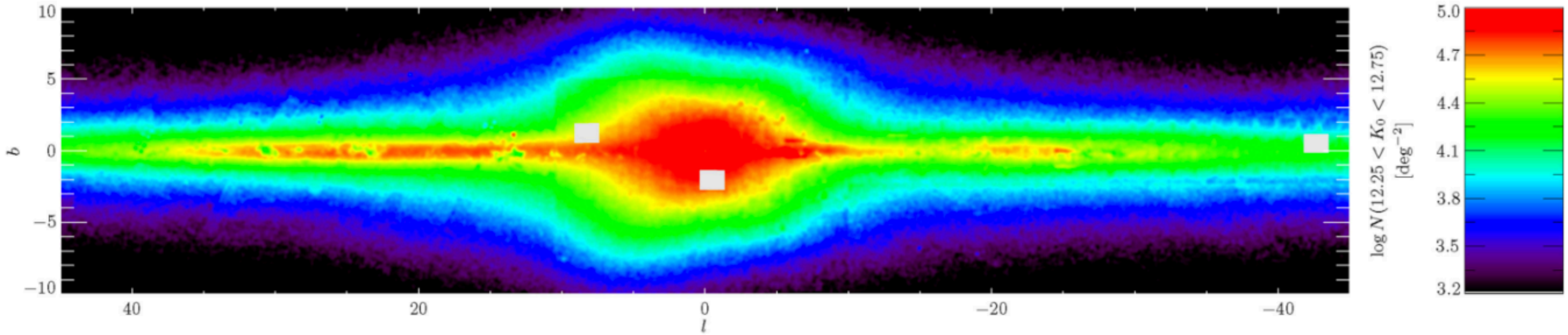
$3x10^5$ stars within 200 pc

(actions in epicyclic approximation)

Gaia DR2

- Velocity and action space ridges due to
  - The bar
  - Spiral arms, including past transient ones (Sellwood et al. 2019)
  - Ongoing phase-mixing (Antoja et al. 2018)
  - …
- Q: What does the bar alone do by itself to local stellar kinematics?
- A: More than I had thouht

Where is the MW bar corotation?



Wegg C., Gerhard O., Portail M., 2015, MNRAS, 450, 4050

- Millions of RC stars from VVV survey + 2MASS+ UKIDDS + GLIMPSE
- => long flat (h_z<50 pc) extension of the bar out to >5 kpc from the center (l>30°)
- Fit to BRAVA kinematics (central 10° in long.)
  +ARGOS (28000 stars -30°<l<30° and -10°<b<-5°)

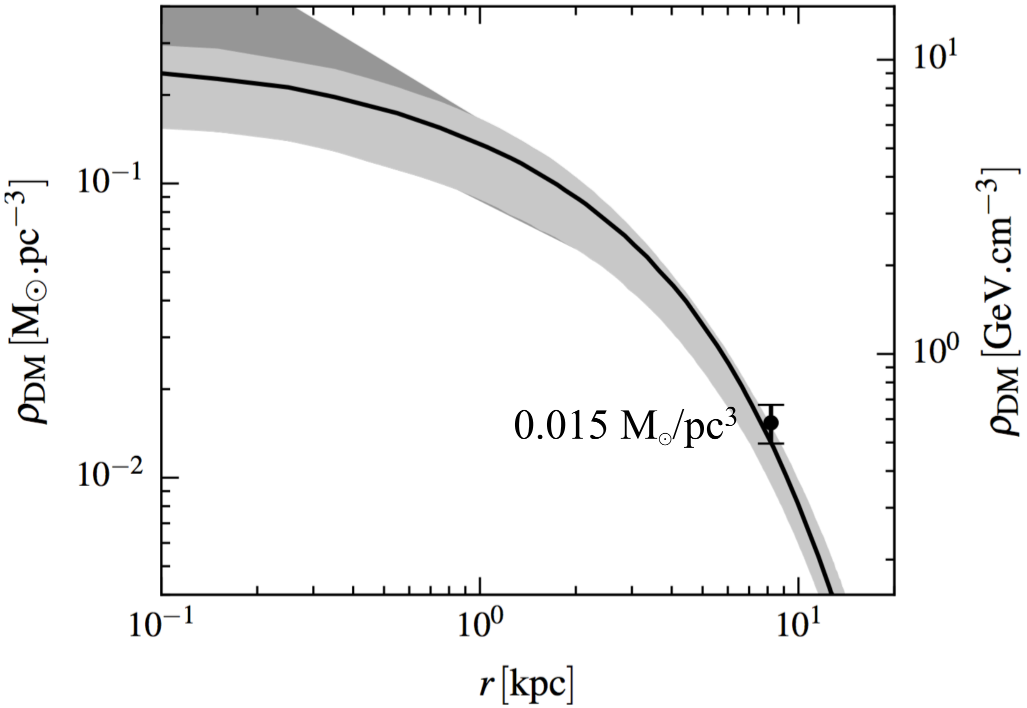
⇒ **Ω_b = 39 km/s/kpc ~ 1.33 Ω_0** (Portail et al. 2017)

⇒ Corotation at 6 kpc and OLR beyond 11 kpc !?

This pattern speed, first uncovered by Weiner & Sellwood (1999) is confirmed by inner Galaxy PM’s based on VVV and Gaia DR2 (Clarke et al. 2019, Sanders et al. 2019)

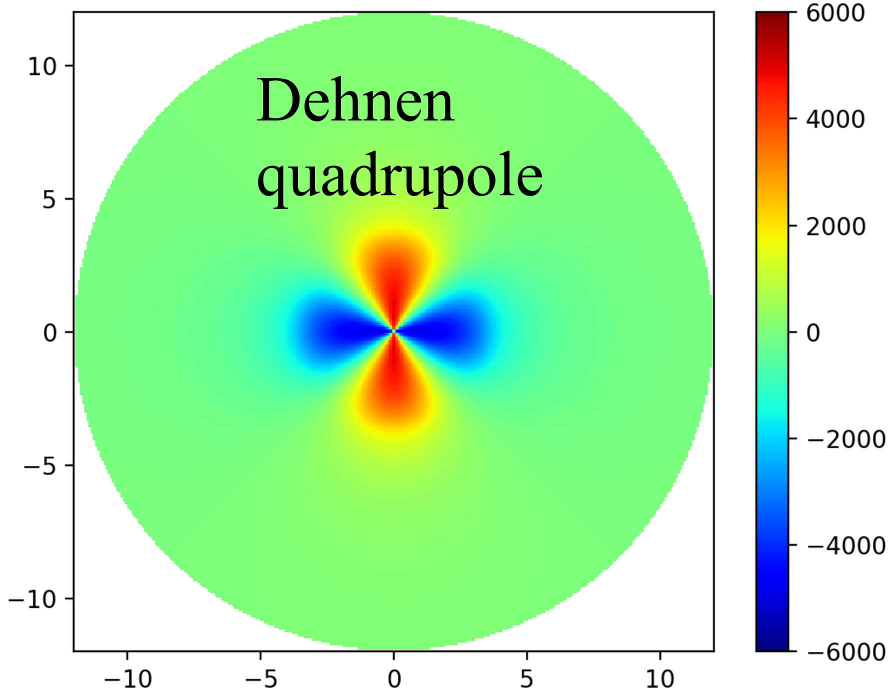
A DM core in the MW?

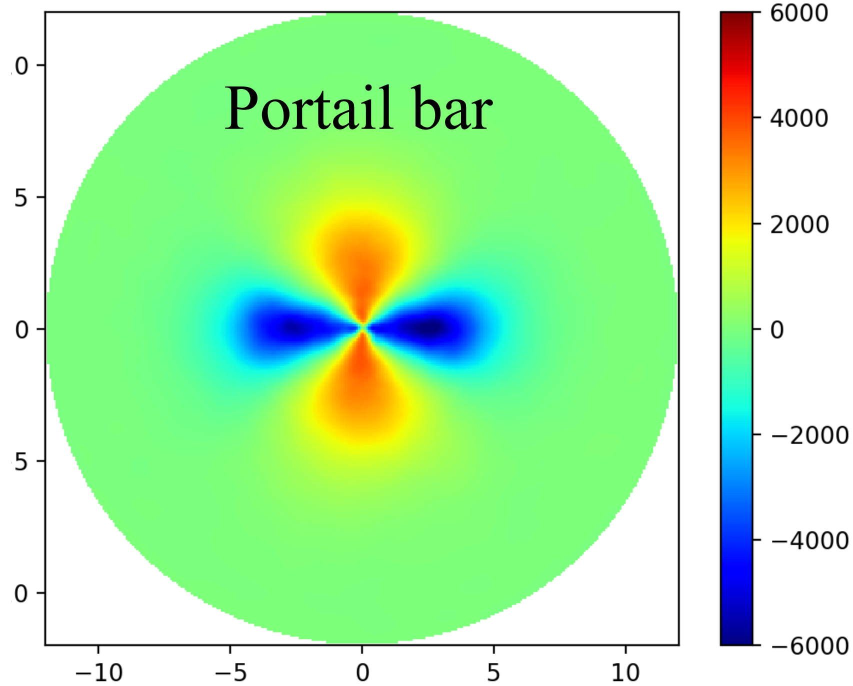
- Bulge mass (2.2 kpc, 1.4 kpc, 1.2 kpc): 1.85×10^{10} $M_\odot$
  - Stellar mass: 1.32×10^{10} $M_\odot$
  - Additional nuclear disk: 2×10^{9} $M_\odot$
  - Dark matter mass: 3.2×10^{9} $M_\odot$

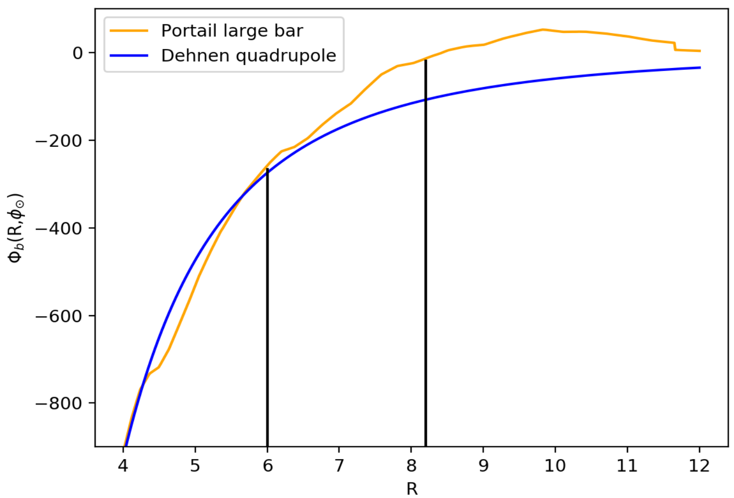


Portail et al. (2017)

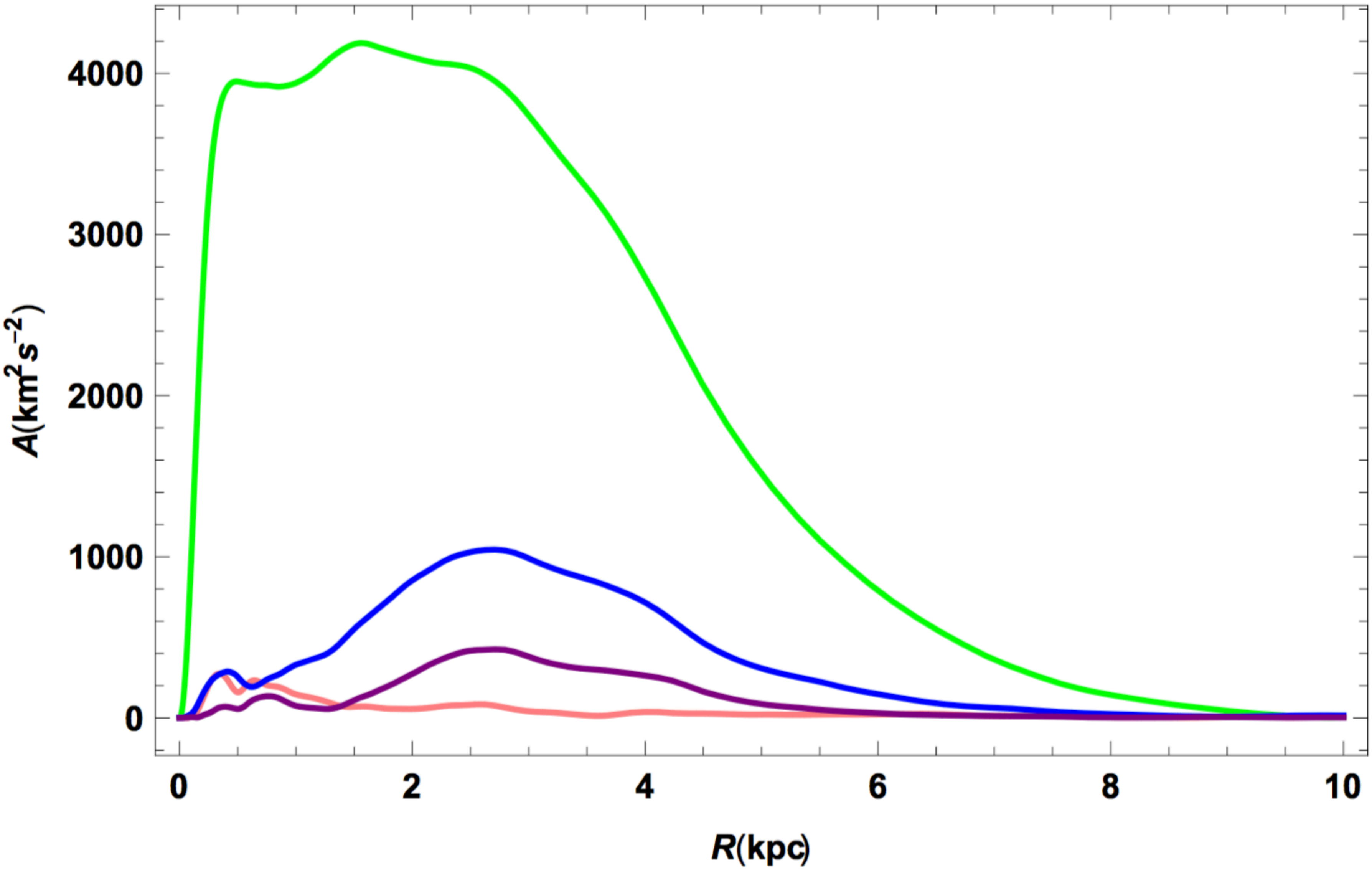
Sharp falloff to keep the RC constant between 6 kpc and 8 kpc => cored profile at the center





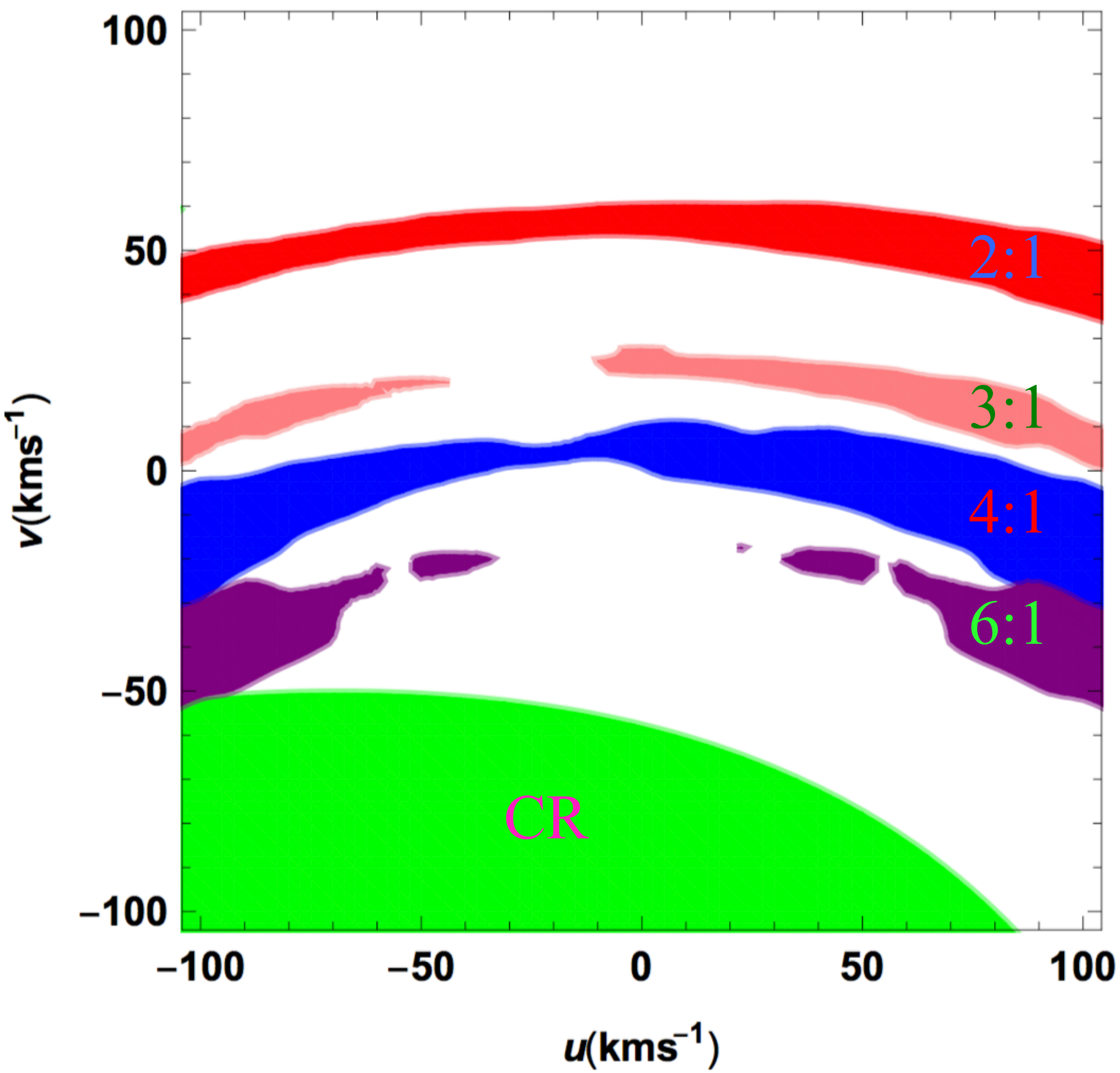


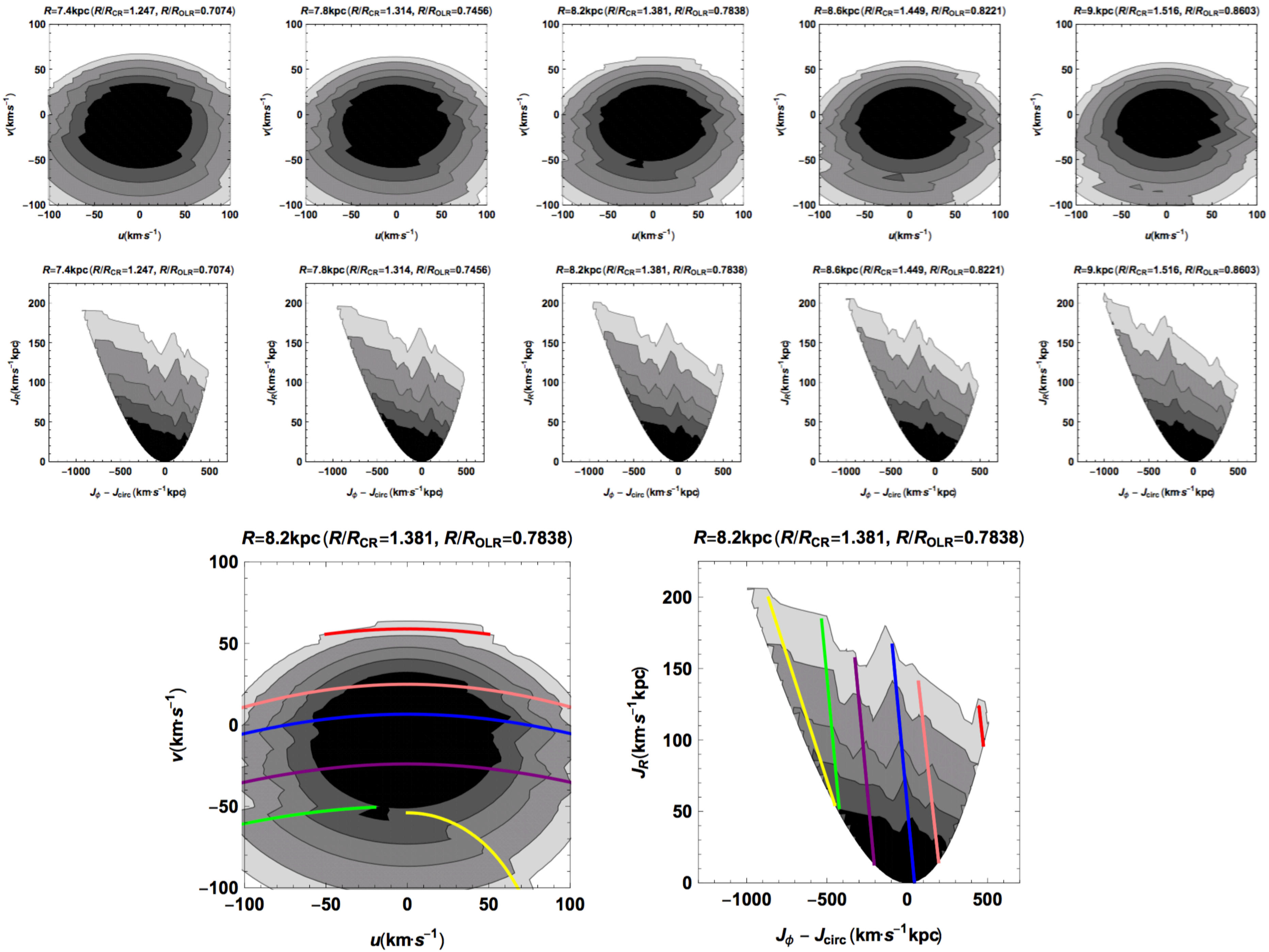
Study the m=2, m=3, m=4 and m=6 modes in **Monari et al. 2019** arXiv:1812.04151 (revised version)



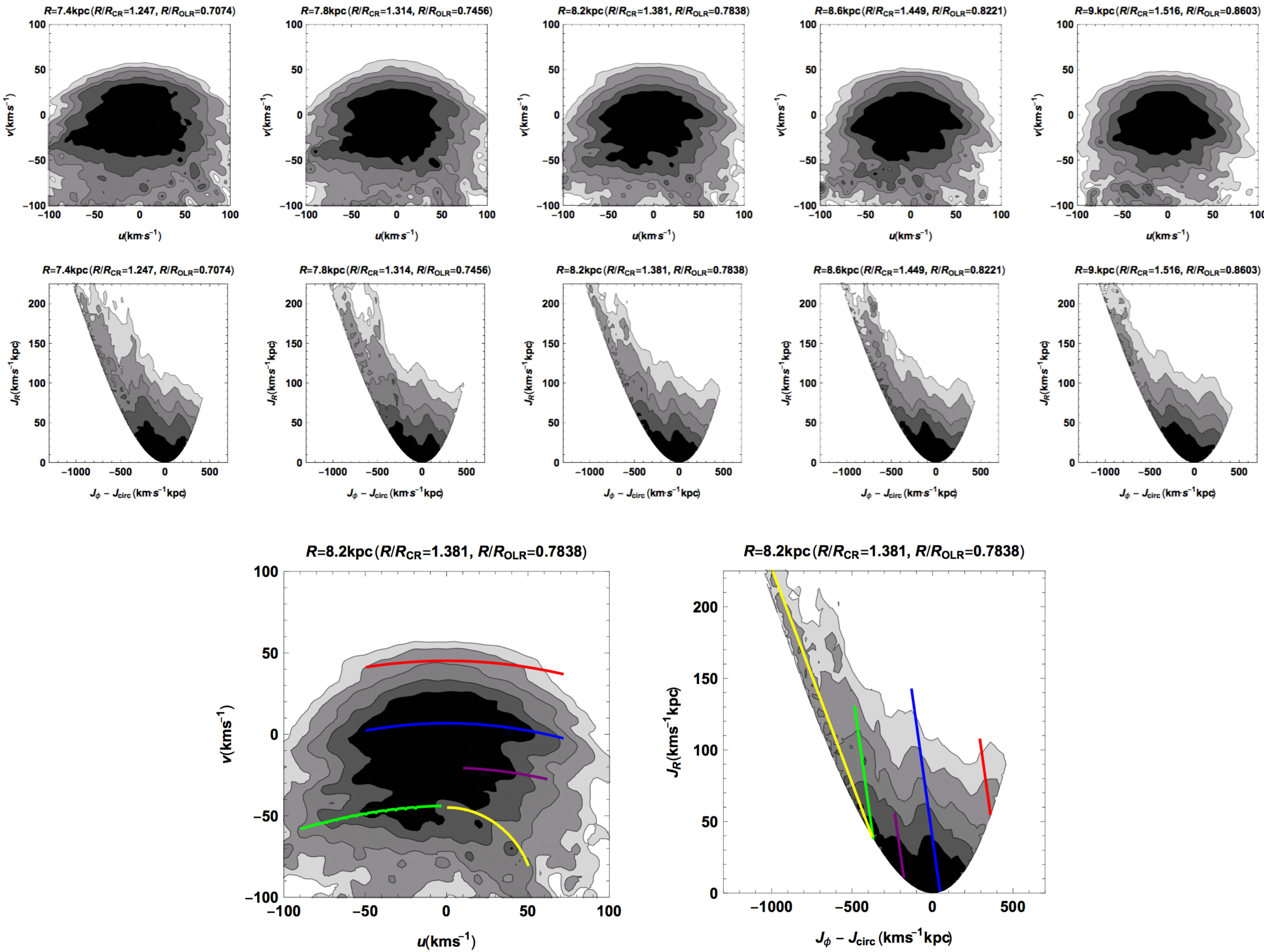
4000
3000
2000
1000
0
A(km²s⁻²)
0
2
4
6
8
10
R(kpc)

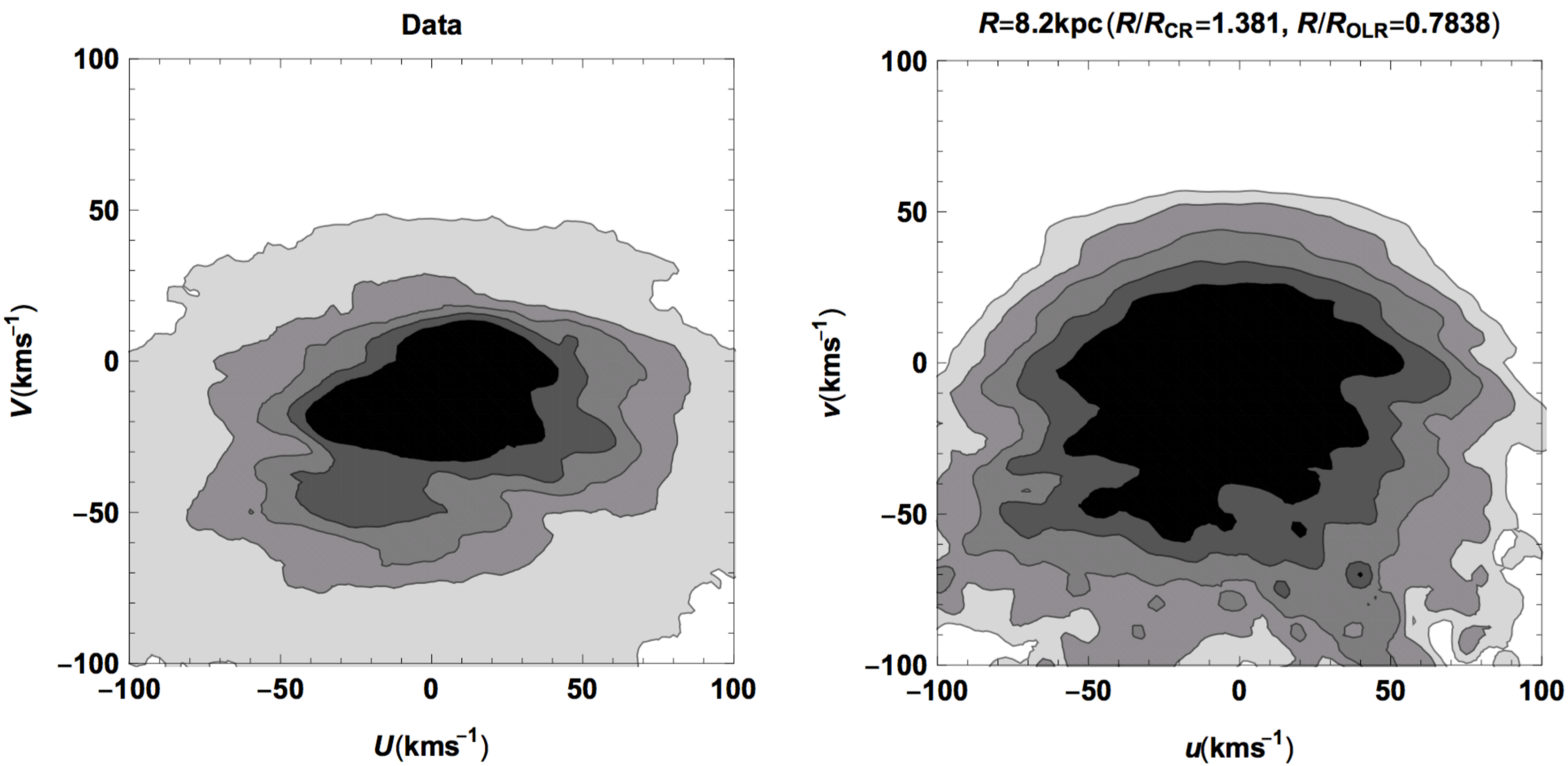
The resonant zones in local velocity space

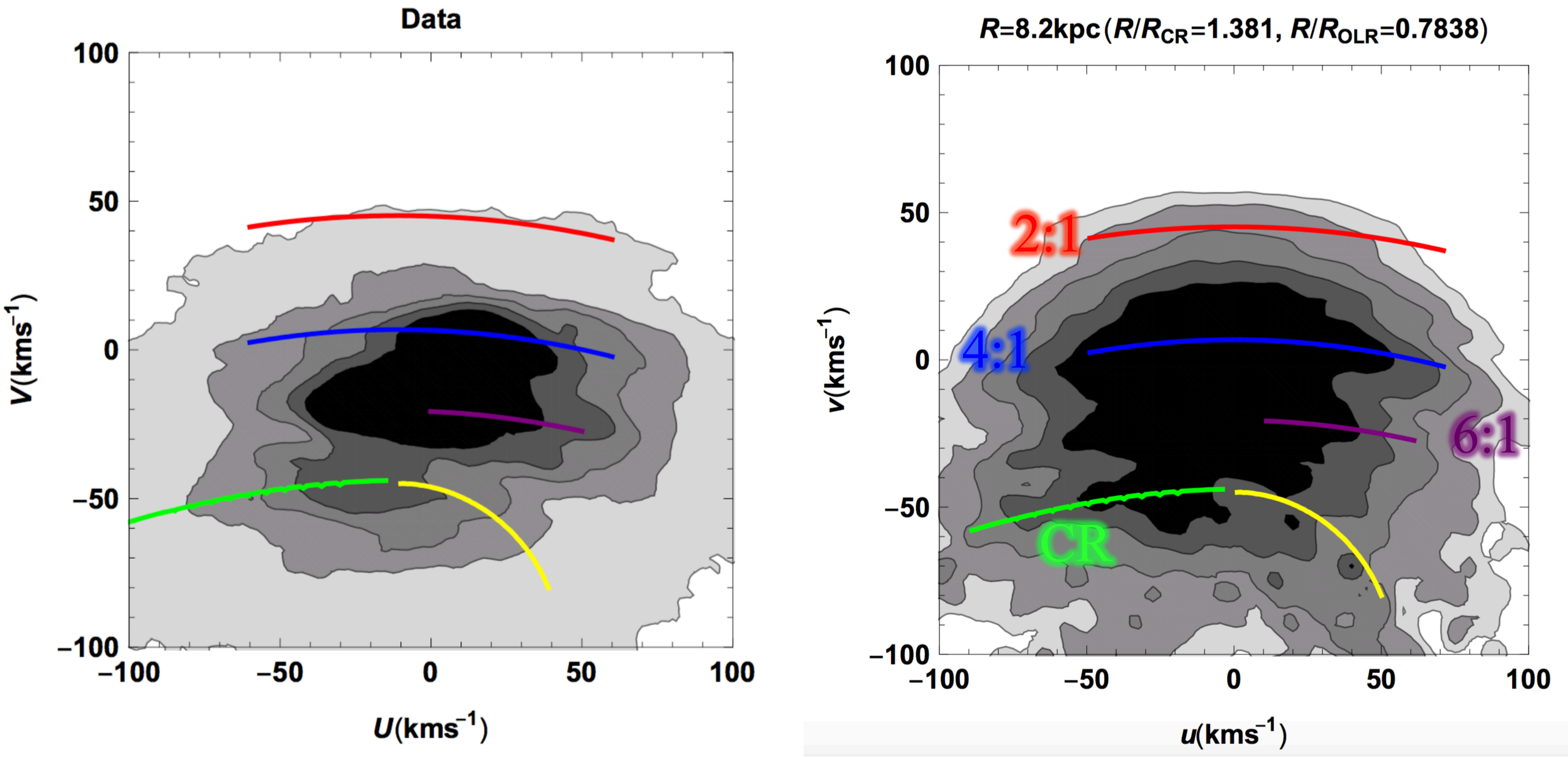




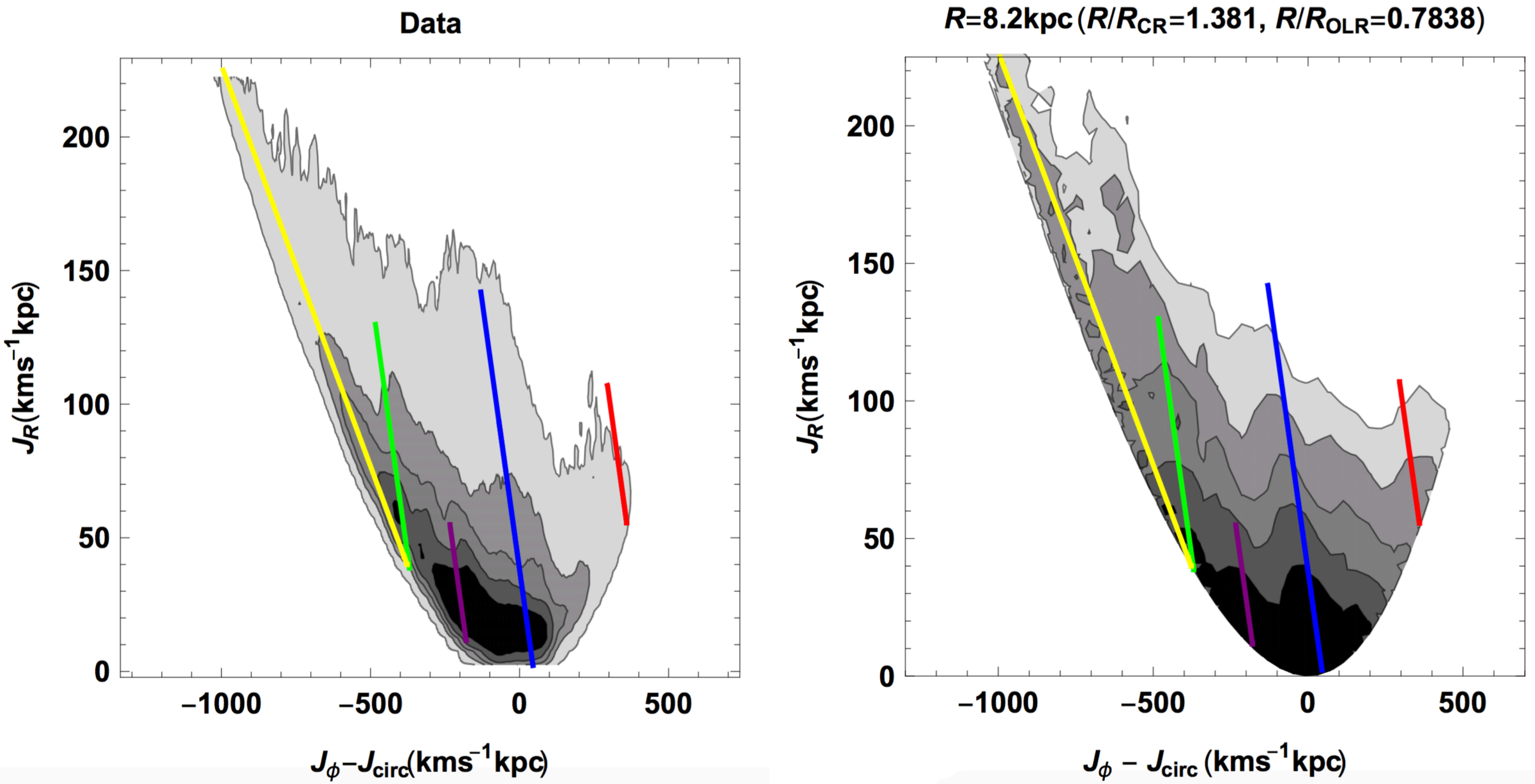
R=7.4kpc (R/R_CR=1.247, R/R_OLR=0.7074)
R=7.8kpc (R/R_CR=1.314, R/R_OLR=0.7456)
R=8.2kpc (R/R_CR=1.381, R/R_OLR=0.7838)
R=8.6kpc (R/R_CR=1.449, R/R_OLR=0.8221)
R=9.kpc (R/R_CR=1.516, R/R_OLR=0.8603)
u(km·s⁻¹)
v(km·s⁻¹)
J_R(km·s⁻¹kpc)
J_φ − J_circ (km·s⁻¹kpc)


R=7.4kpc (R/RCR=1.247, R/ROLR=0.7074)
R=7.8kpc (R/RCR=1.314, R/ROLR=0.7456)
R=8.2kpc (R/RCR=1.381, R/ROLR=0.7838)
R=8.6kpc (R/RCR=1.449, R/ROLR=0.8221)
R=9.kpc (R/RCR=1.516, R/ROLR=0.8603)
v(km·s−1)
u(km·s−1)
JR(km·s−1kpc)
Jϕ − Jcirc (km·s−1kpc)
v(kms−1)
u(kms−1)
JR(kms−1kpc)
Jϕ − Jcirc (kms−1kpc)

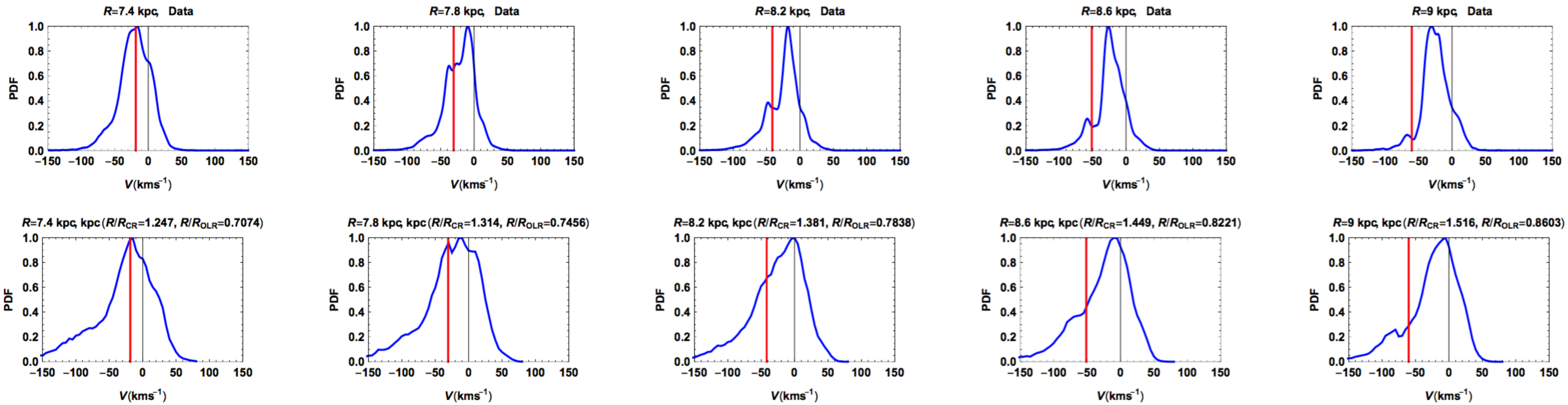

Data
100
50
0
−50
−100
V(kms−1)
−100
−50
0
50
100
U(kms−1)
R=8.2kpc (R/R_CR=1.381, R/R_OLR=0.7838)
100
50
0
−50
−100
v(kms−1)
−100
−50
0
50
100
u(kms−1)



Data
100
50
0
−50
−100
−100
−50
0
50
100
V(kms^{-1})
U(kms^{-1})
R=8.2kpc (R/R$_{CR}$=1.381, R/R$_{OLR}$=0.7838)
2:1
4:1
6:1
CR
v(kms^{-1})
u(kms^{-1})



But $V_{\odot} = 0$ km/s ??



Also, slightly declining RC allows to get a more realistic $V_\odot$ = 8 km/s

Conclusion and next steps

- 2D analytic 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