Galactic dynamics with Gaia

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Gaia DR2 in numbers

- 1.69×10^9 with positions and G magnitudes down to G=20.7, essentially complete from 12<G<17

- 1.38×10^9 with GBP and GRP photometry

- 1.33×10^9 with positions, parallaxes and proper motions

- 7.2×10^6 with radial velocities down to G=13

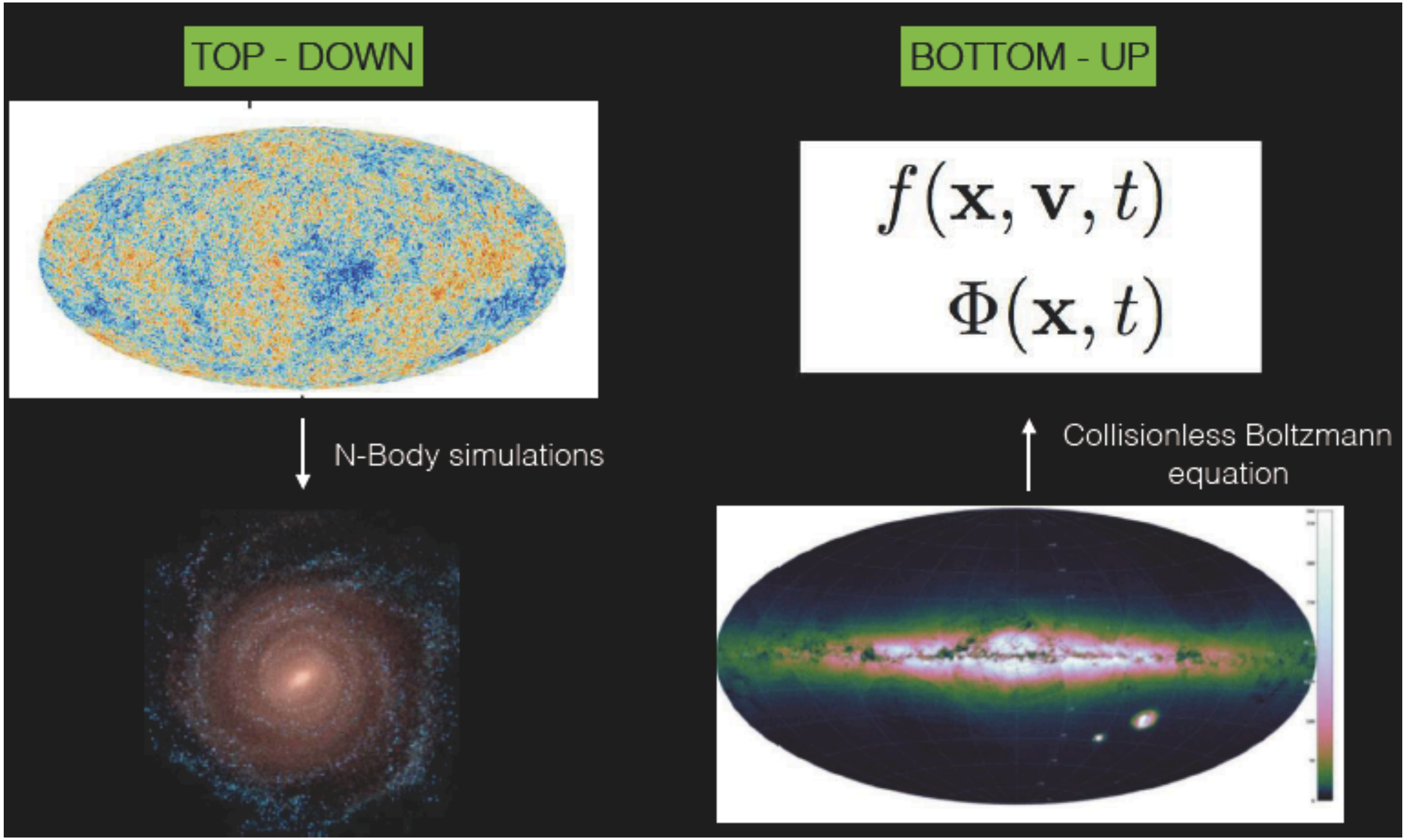
- Various published Bayesian estimates of the distances for stars with relative precision on the parallax larger than 10% to 20%

Gaia-era Milky Way questions

- Decipher the structure of the Galaxy, and of each of its components (stellar pops, gas, satellite population), including its **dark matter** distribution, *e.g.*:
  - **total mass,**
  - **core vs. cusp,**
  - **phase-space distribution**

- Is it consistent with ΛCDM, with specific DM alternatives (warm DM, self-interacting DM…), with modified gravity (MOND)?

MW dynamical models



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

Actions and angles

$$J_k \equiv \oint p_k \, dq_k$$ => $H_0 = H_0(\mathbf{J})$ (renormalize by $1/2\pi$)

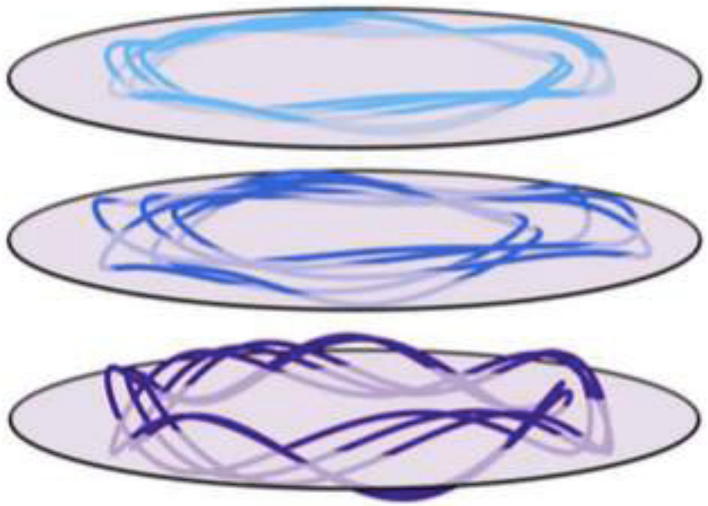
$$\dot{\theta} = \frac{\partial H_0}{\partial J} = \omega(J)$$

-For thin disk: epicyclic approximation:

$$J_\phi = \frac{1}{2\pi} \int_0^{2\pi} \mathrm{d}\phi L_z = L_z \,,$$

$$J_z \simeq \frac{1}{\pi} \int_{z_{\min}}^{z_{\max}} \mathrm{d}z \sqrt{2[E_z - \Phi_{0,z}]} = \frac{E_z}{\nu},$$

$$J_R \simeq \frac{1}{\pi} \int_{R_{\min}}^{R_{\max}} \mathrm{d}R \sqrt{2(E_R - \Phi_{0,R})} = \frac{E_R}{\kappa}$$



Fouvry et al.

Parametric distribution functions

- The « quasi-isothermal » DF for disk populations, which become « Shu-Schwarzschild » for the epicyclic approximation:

$$f_0(J_R, J_\phi, J_z) = \frac{\Omega(R_g(J_\phi))}{(2\pi)^{3/2} 2\kappa(R_g(J_\phi))} \underbrace{\frac{\tilde{\Sigma}(R_g(J_\phi))}{\tilde{\sigma}_r^2(R_g(J_\phi))\tilde{\sigma}_z^2(R_g(J_\phi)) z_0}}_{\text{radial distribution in } R_g(J_\phi)} \times \underbrace{e^{-\frac{J_R \kappa}{\tilde{\sigma}_r^2} - \frac{J_z \nu}{\tilde{\sigma}_z^2}}}_{\text{velocity ellipsoid}}$$

velocity ellipsoid together with the velocity disp.dependence in previous factor

- There are also DFs appropriate for NFW halos and cored DM halos (see e.g. Posti et al. 2015 , Cole & Binney 2017)

Vertical equilibrium

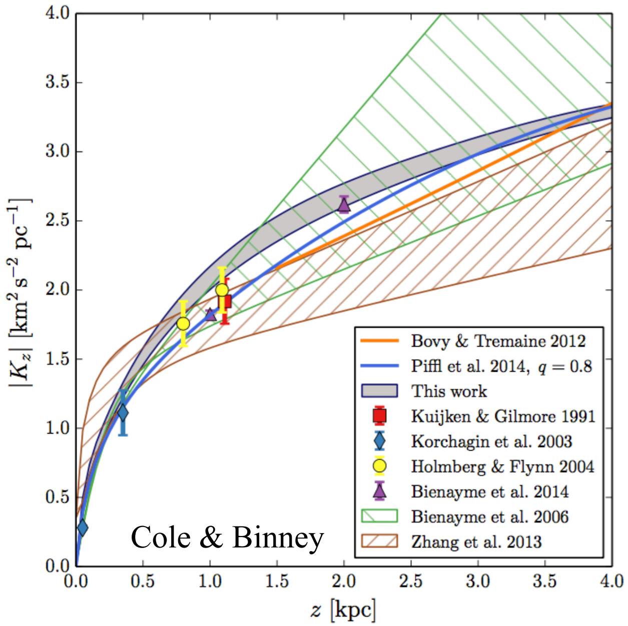
$$-4\pi G\Sigma(Z) = \int_{-Z}^{Z} \frac{1}{R}\frac{\partial}{\partial R}(RF_R)dz + 2\cdot[F_z(Z) - F_z(0)],$$

Poisson eq.

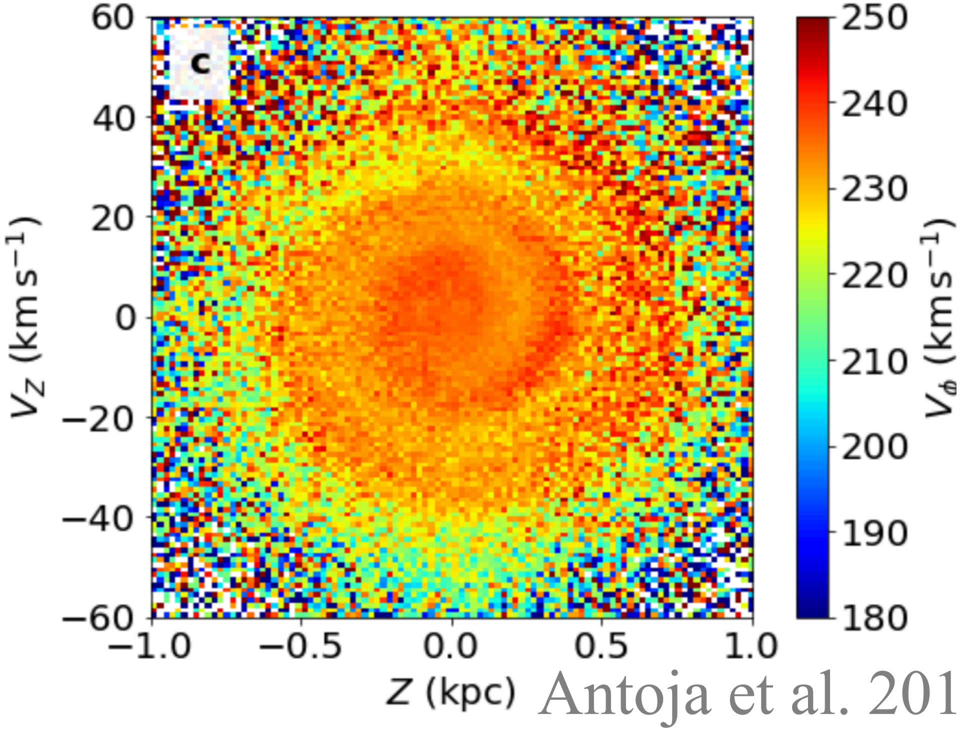
$$F_R = -\frac{\partial\phi}{\partial R} = \frac{1}{\rho}\frac{\partial(\rho\overline{U^2})}{\partial R} + \frac{1}{\rho}\frac{\partial(\rho\overline{UW})}{\partial Z} + \frac{\overline{U^2} - \overline{V^2}}{R} + \frac{1}{\rho}\frac{\partial(\rho\overline{U})}{\partial t},$$

$$F_Z = -\frac{\partial\phi}{\partial Z} = \frac{1}{\rho}\left[\frac{\partial(\rho\overline{W^2})}{\partial Z} + \frac{\rho\overline{UW}}{R} + \frac{\partial(\rho\overline{UW})}{\partial R} + \frac{\partial(\rho\overline{W})}{\partial t}\right],$$

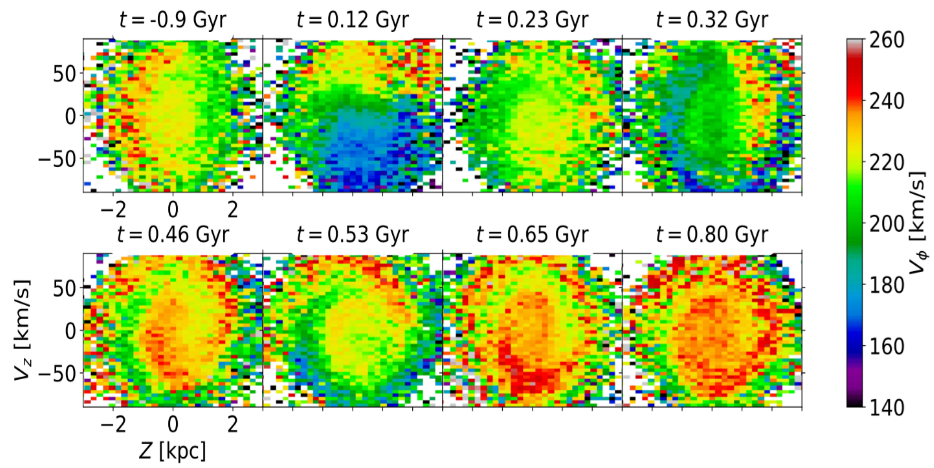
Jeans eqs.



But the disk is vertically perturbed



Antoja et al. 2018

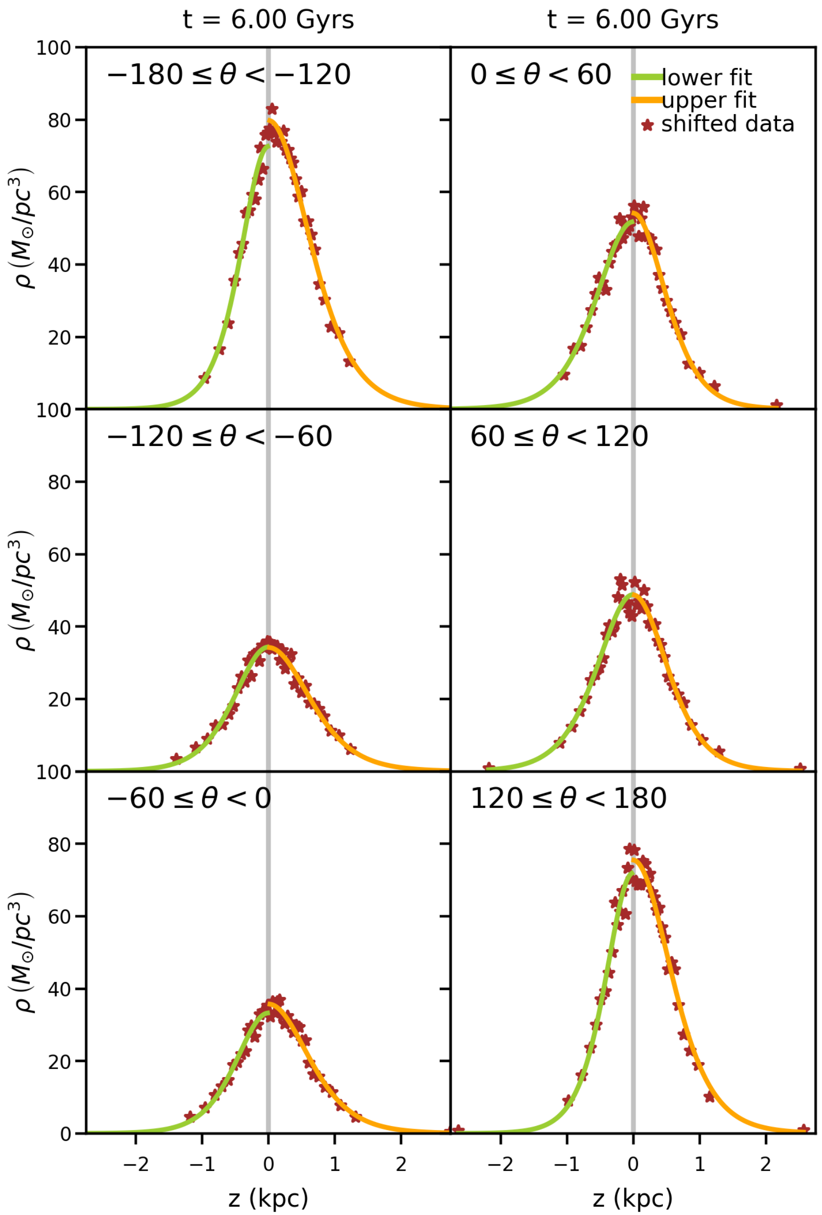


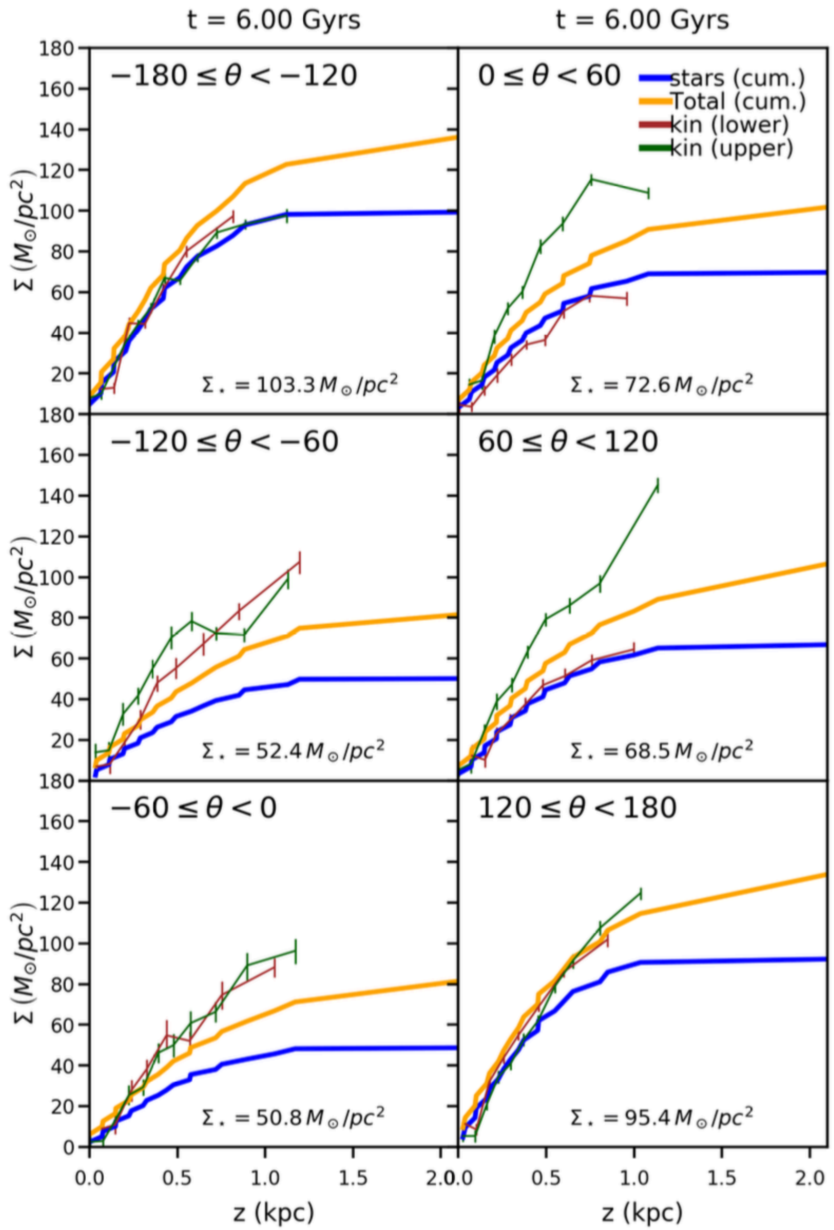
Laporte et al. 2018

(last pericentric passage of Sgr dwarf at t=0)

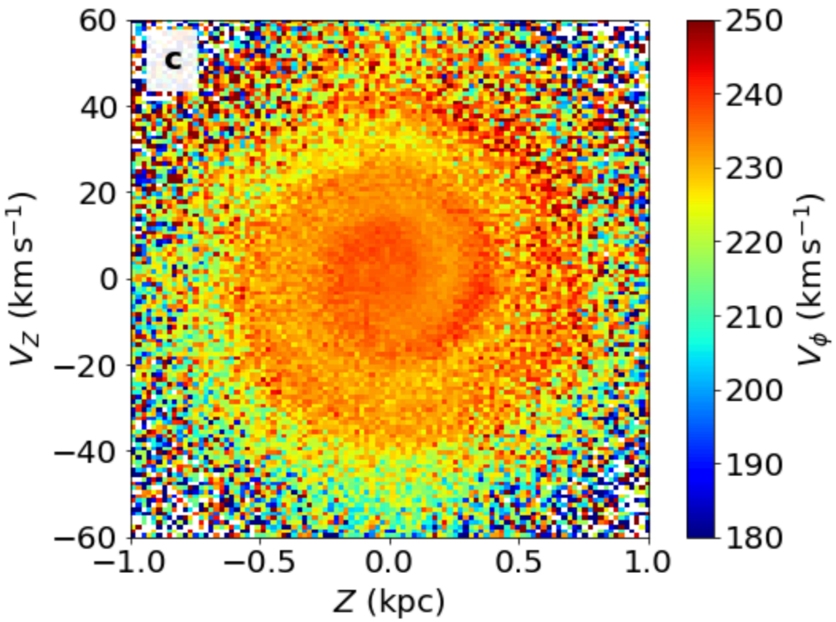
⇒ Can traditional Jeans modelling be applied?

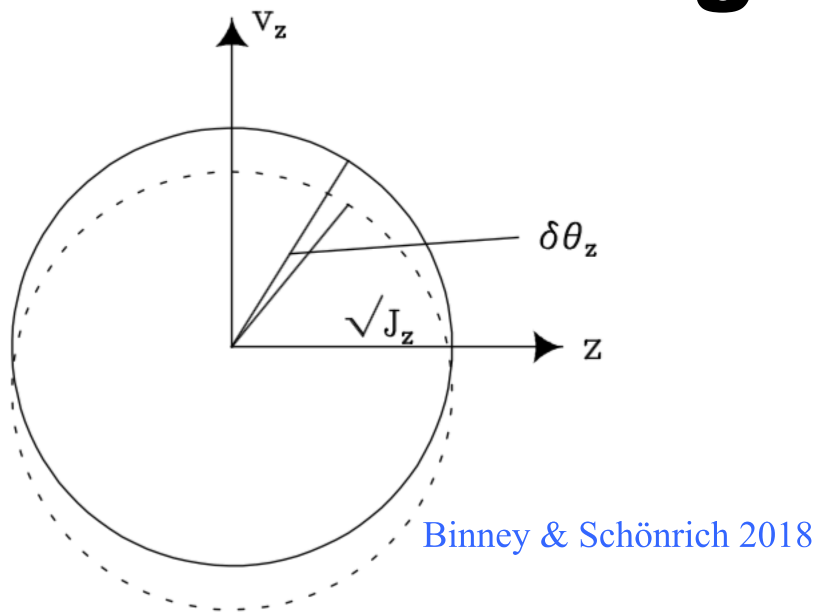
Haines, D'Onghia, Famaey, Laporte, Hernquist 2019





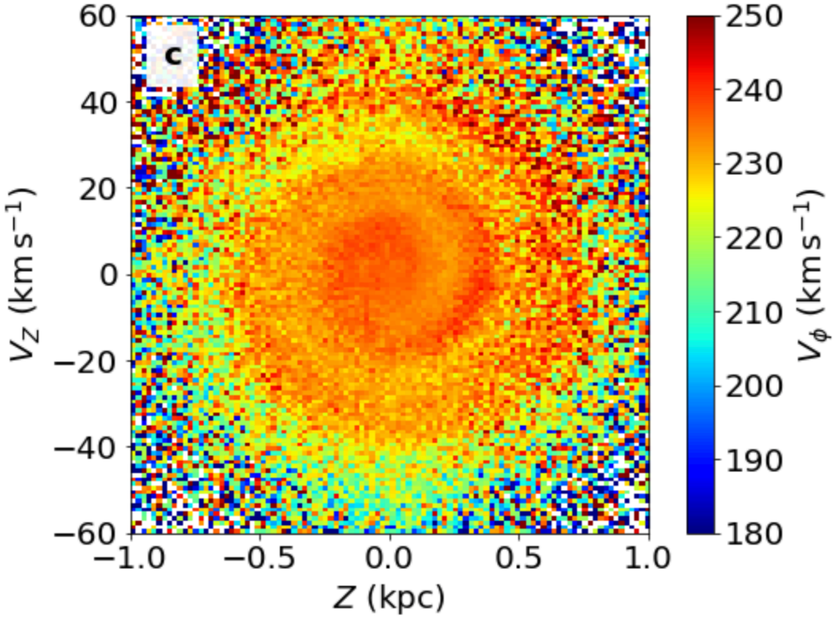
Use this as a feature & not a bug

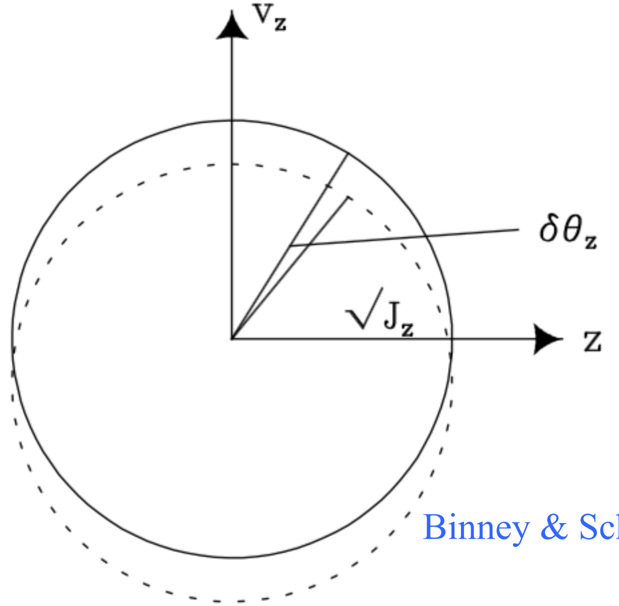




$f(J_z) \rightarrow f(\theta_z, J_z)$ with concentration around $\theta_z = \pi$, then stars oscillate with their own ω_z depending on (J_ϕ, J_R)

Use this as a feature & not a bug

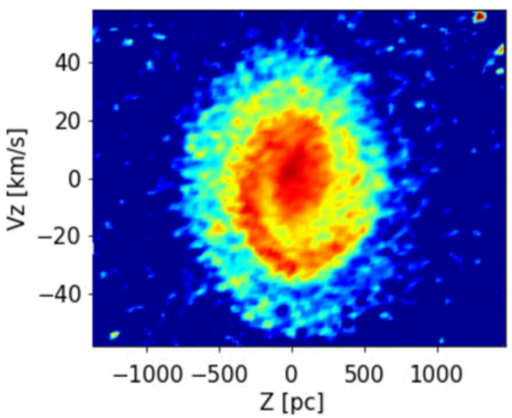




Binney & Schönrich 2018

$f(J_z) \rightarrow f(\theta_z, J_z)$ with concentration around $\theta_z=\pi$, then stars oscillate with their own ω_z depending on (J_ϕ, J_R) **… and H**

Collective response of the disk?



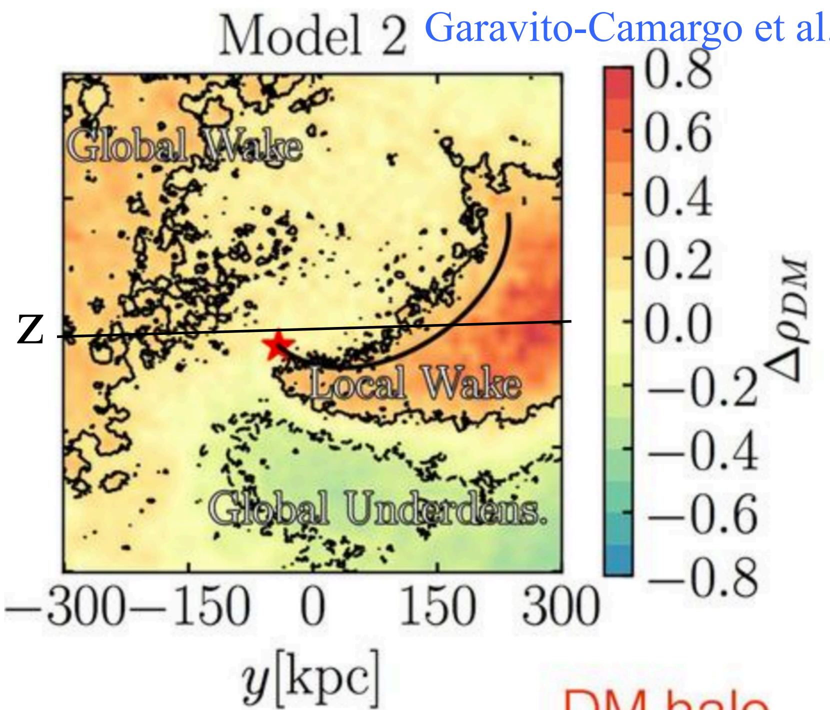
Khoperskov et al. 2019

Phase-spiral >Gyr after bar buckling phase

Response of the DM halo?

- LMC, Sagittarius dwarf and their own DM halo can exchange energy and angular momentum with the MW DM halo: **our best shot at proving the existence of DM !**

Garavito-Camargo et al. 2019



DM halo

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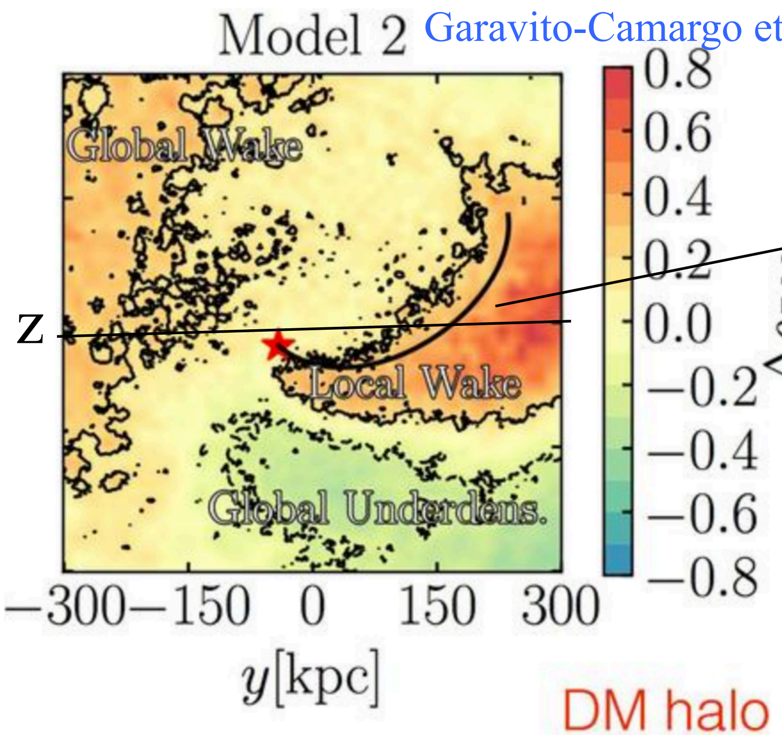
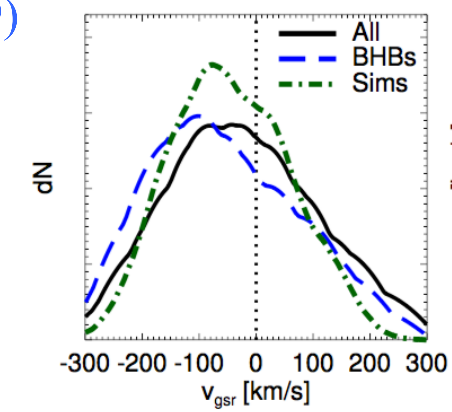


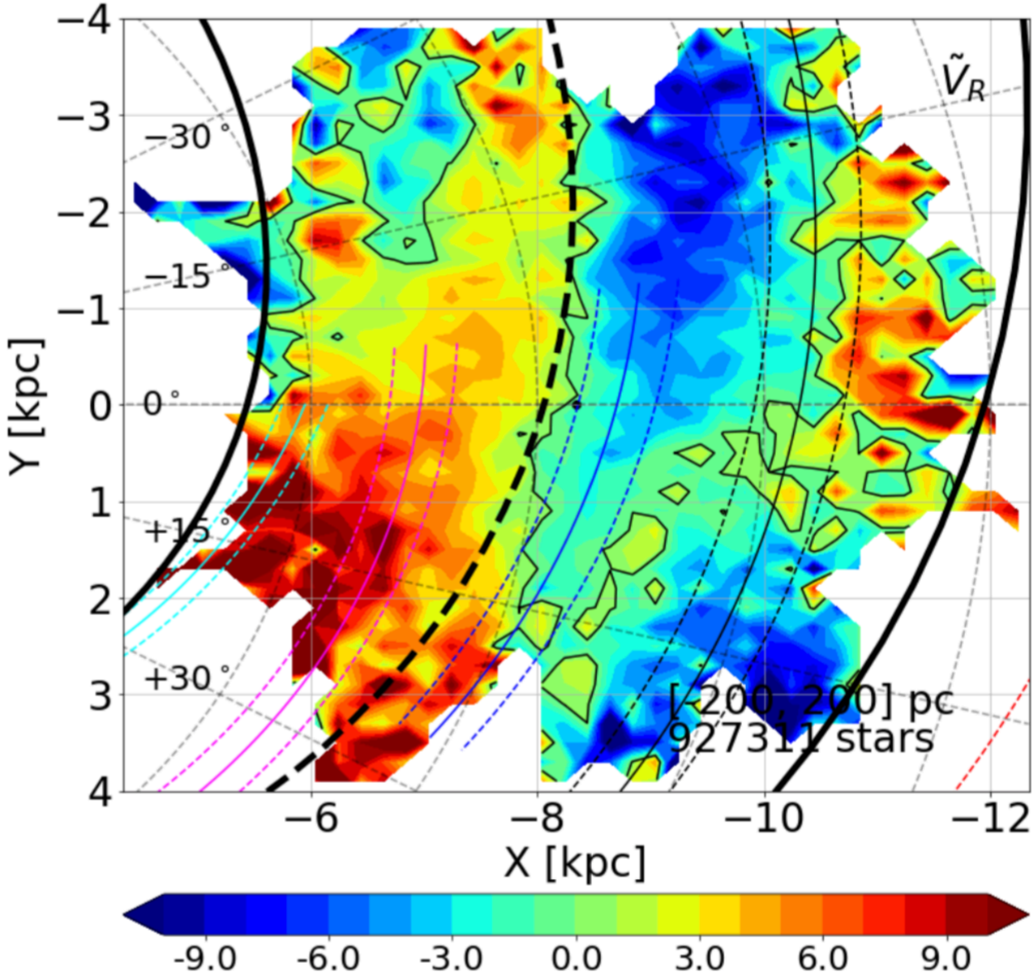
Pisces plume detected with Gaia DR2 and PS1 RRLyrae ?

(Belokurov et al. 2019)

+Effect of the global wake on the Sgr stream?



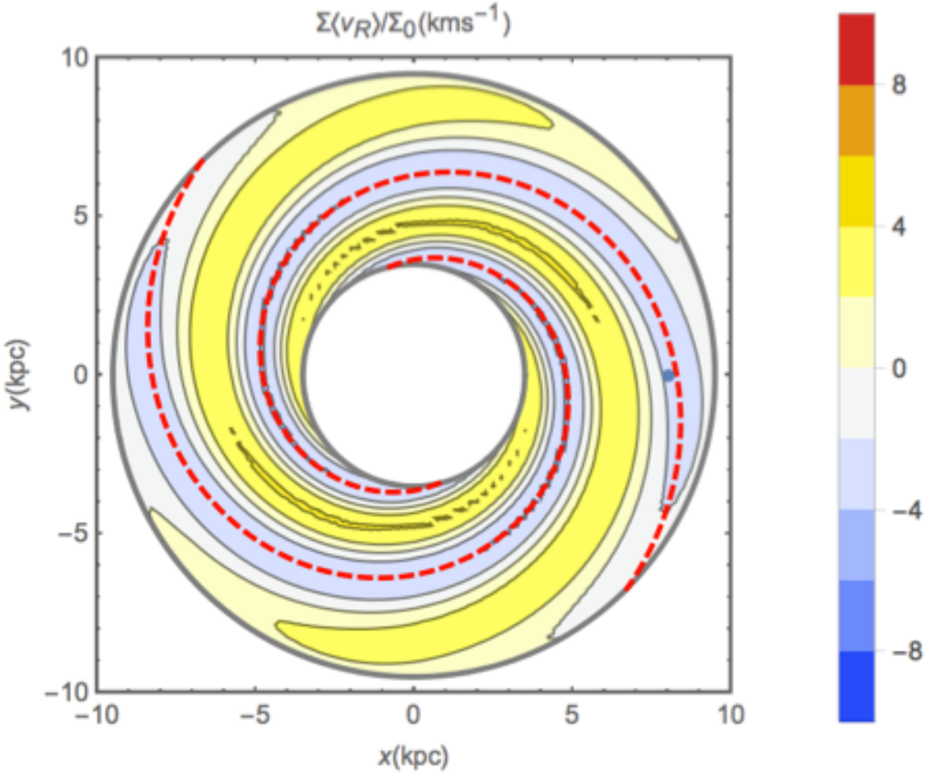
Back to the Galactic plane



Gaia collab, Katz et al. 2018

Perturbing the CBE

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



Monari et al. 2016

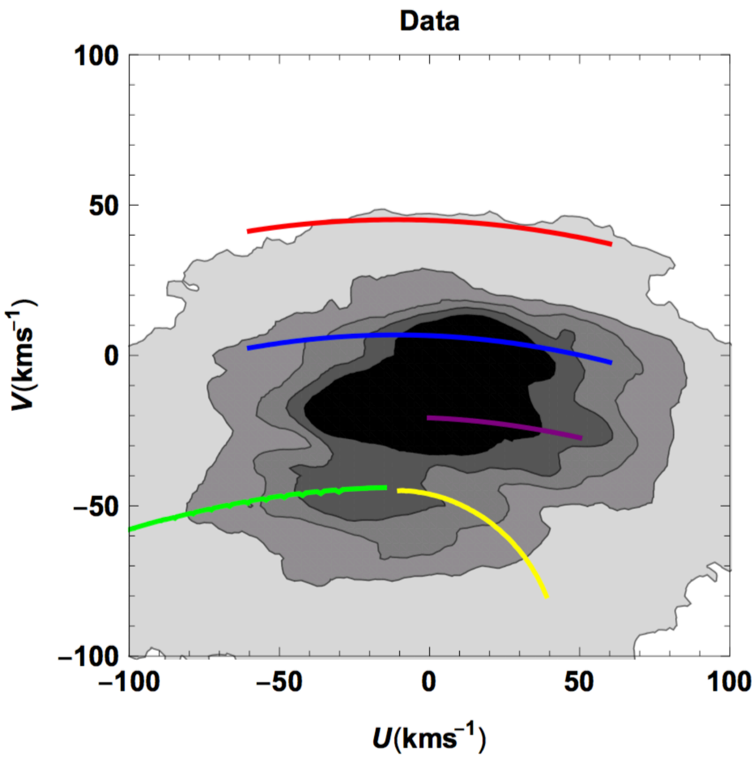
More complicated at resonances where new action-angle variables can be defined

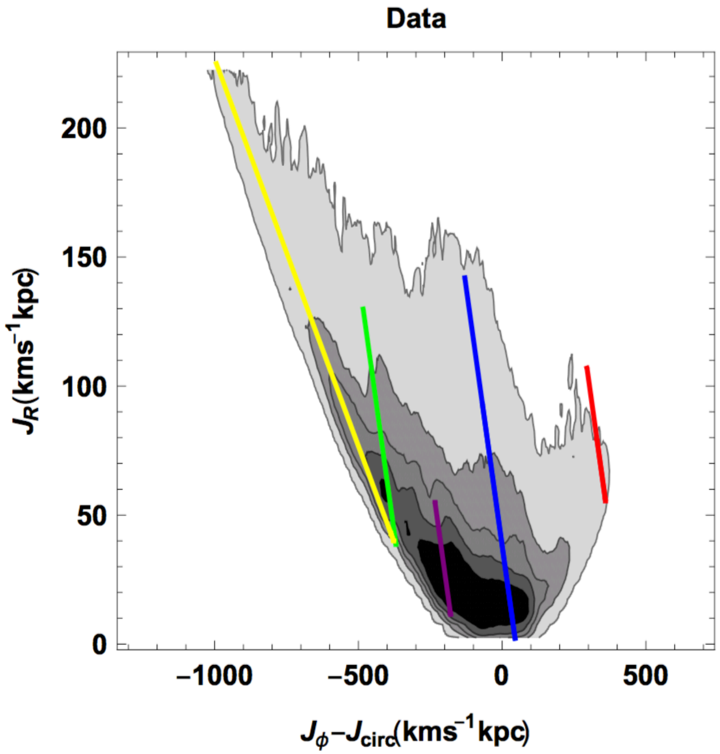
⇒ Combination of multiple patterns: bar+spirals

Slow (~30-40 km/s/kpc) or fast (>50 km/s/kpc) bar?

Nature of spiral arms?

Back to the solar neighbourhood





Monari et al. 2019 (3x10^5 stars within 200 pc)

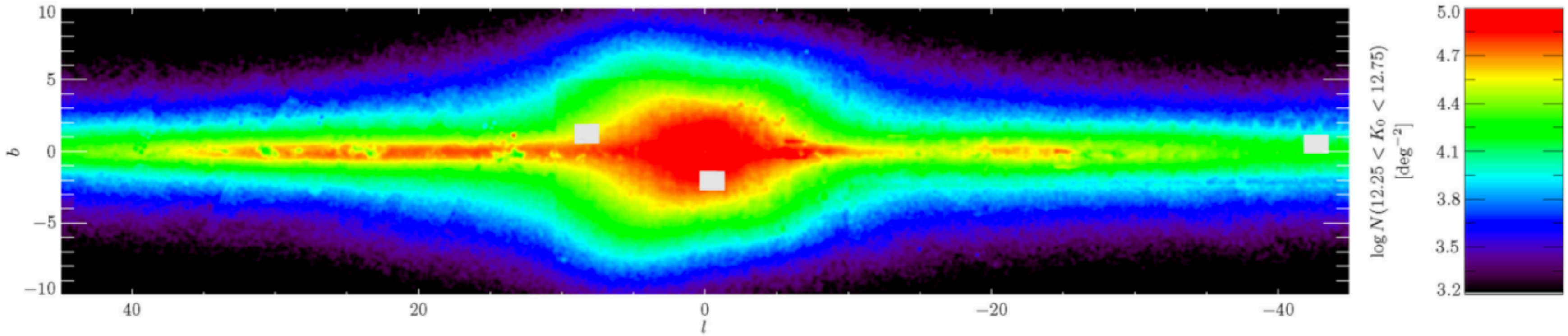
⇒Multiple ridges highly suggestive of multiple patterns

But… what can the bar **alone** do?

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 thought !

The Garching MW bar model



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 (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 10 kpc !

Post-Gaia DR2

1.75×10^8 PMs (!!!) at $-10° < l < 10°$, $-10° < b < 5°$ in the VVV Infrared Astrometric Catalogue (VIRAC), calibrated on Gaia DR2 (Clarke et al. 2019)

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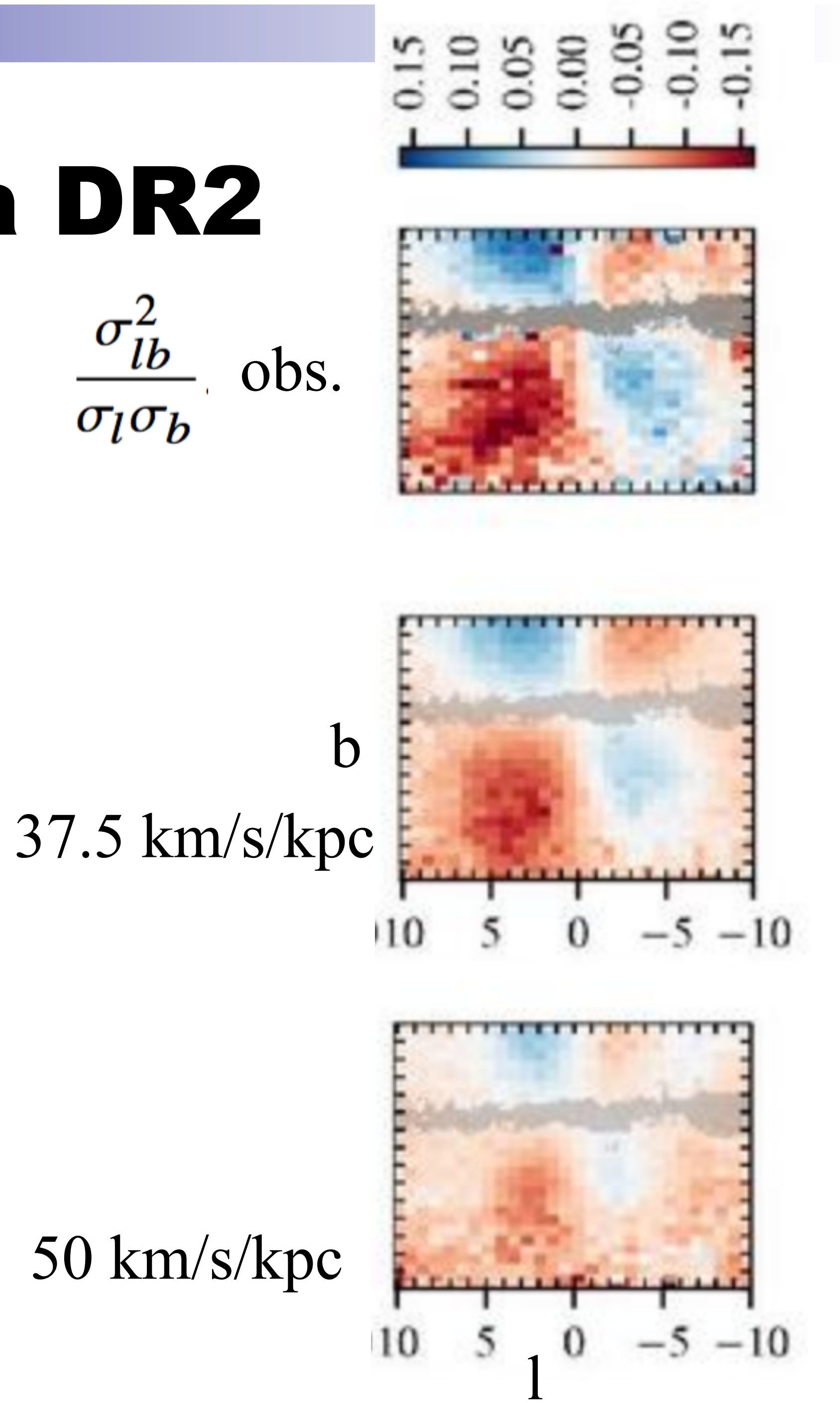
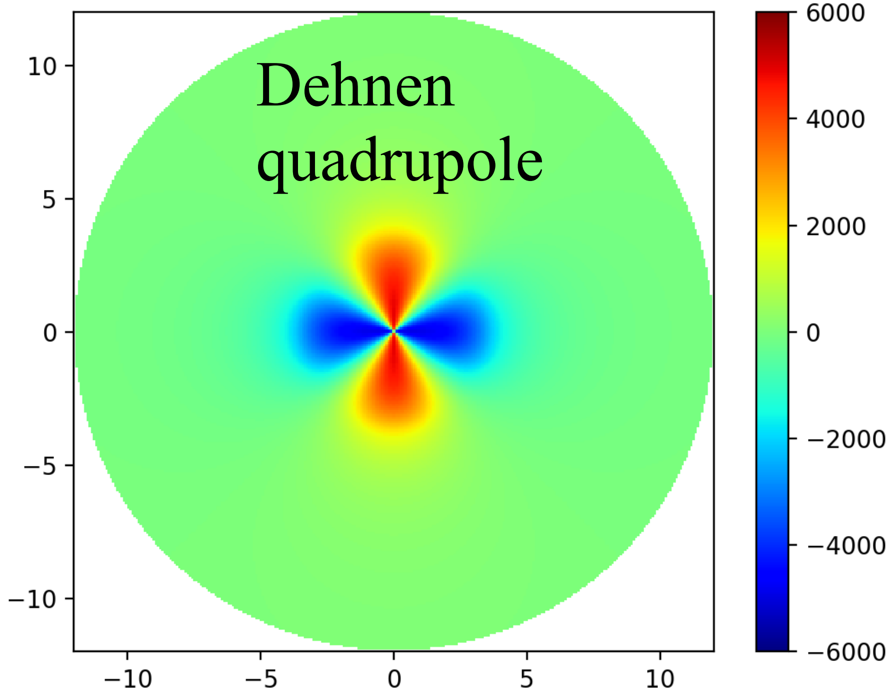
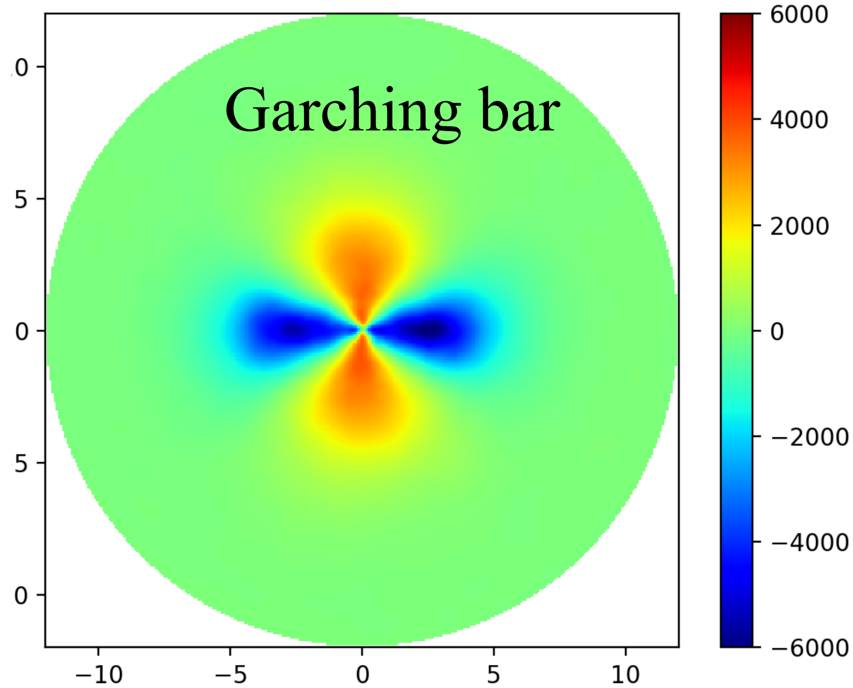
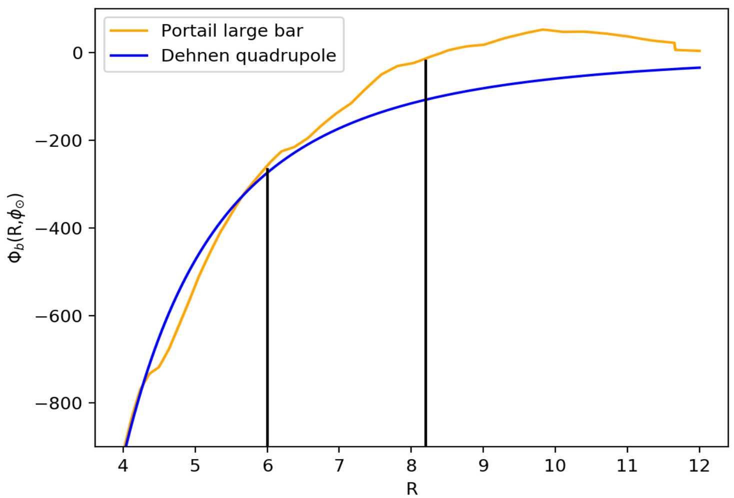


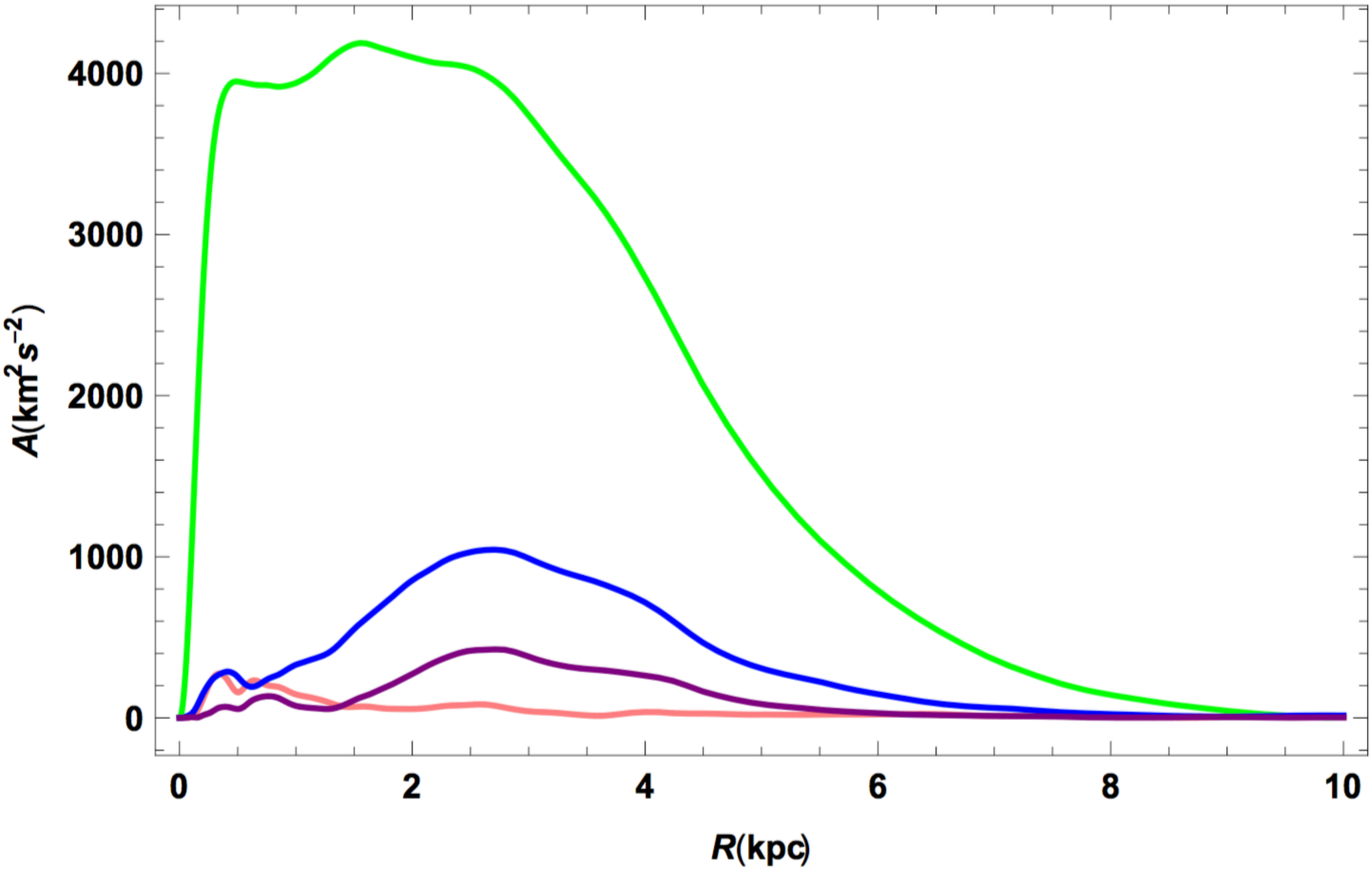
See also Sanders et al. (2019)





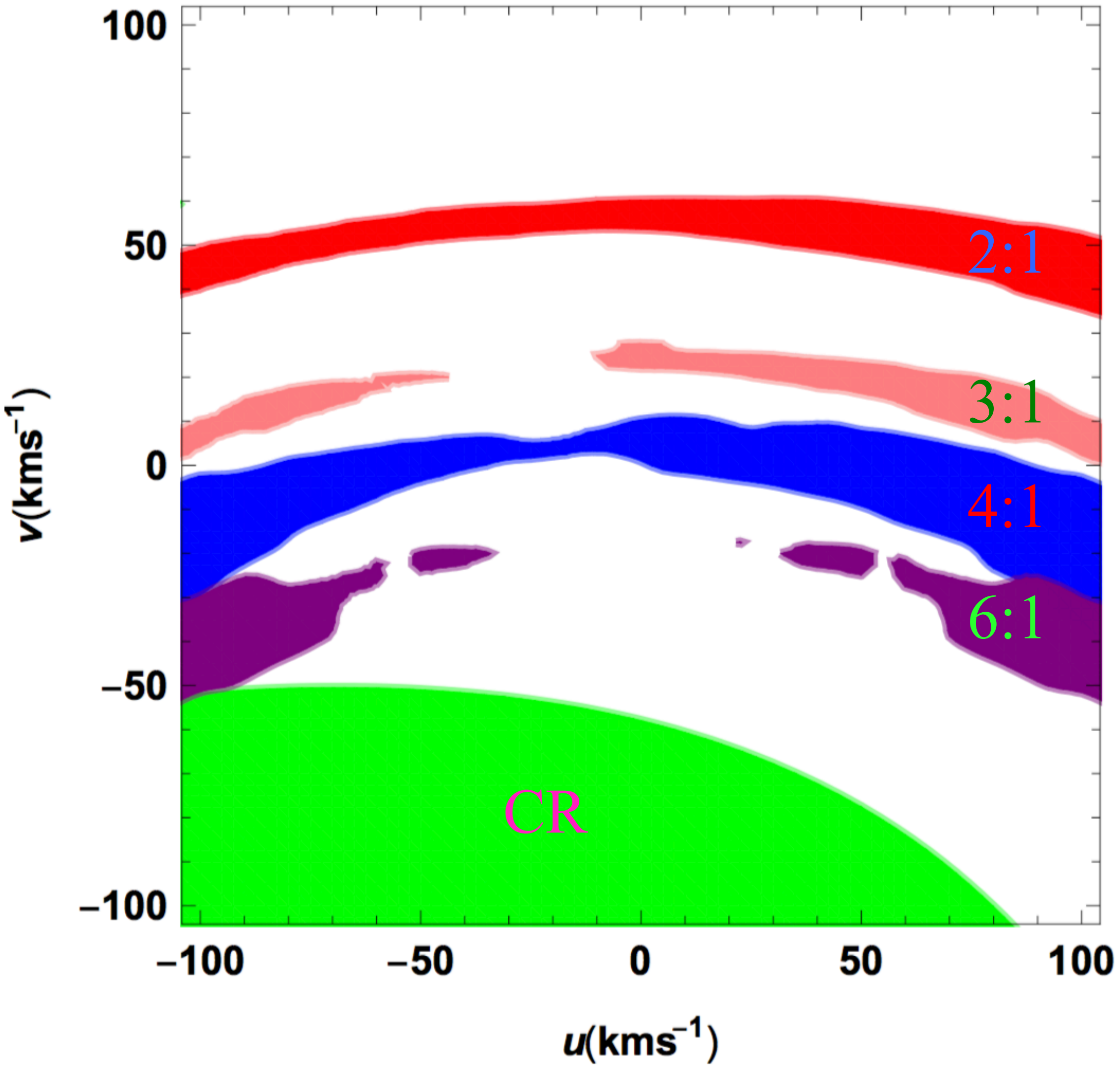


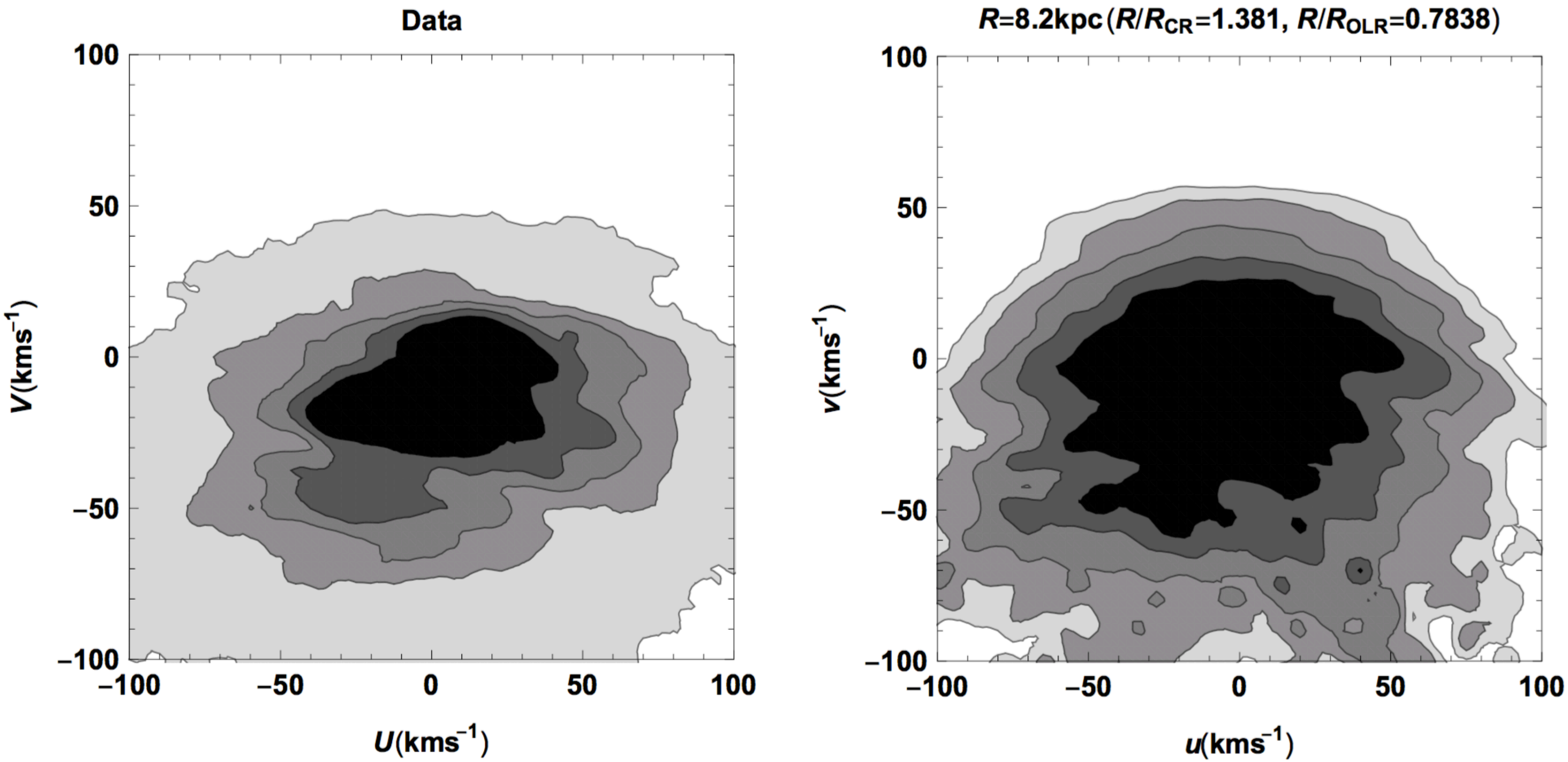
Study the m=2, 3, 4 and 6 modes in Monari et al. 2019 arXiv:1812.04151



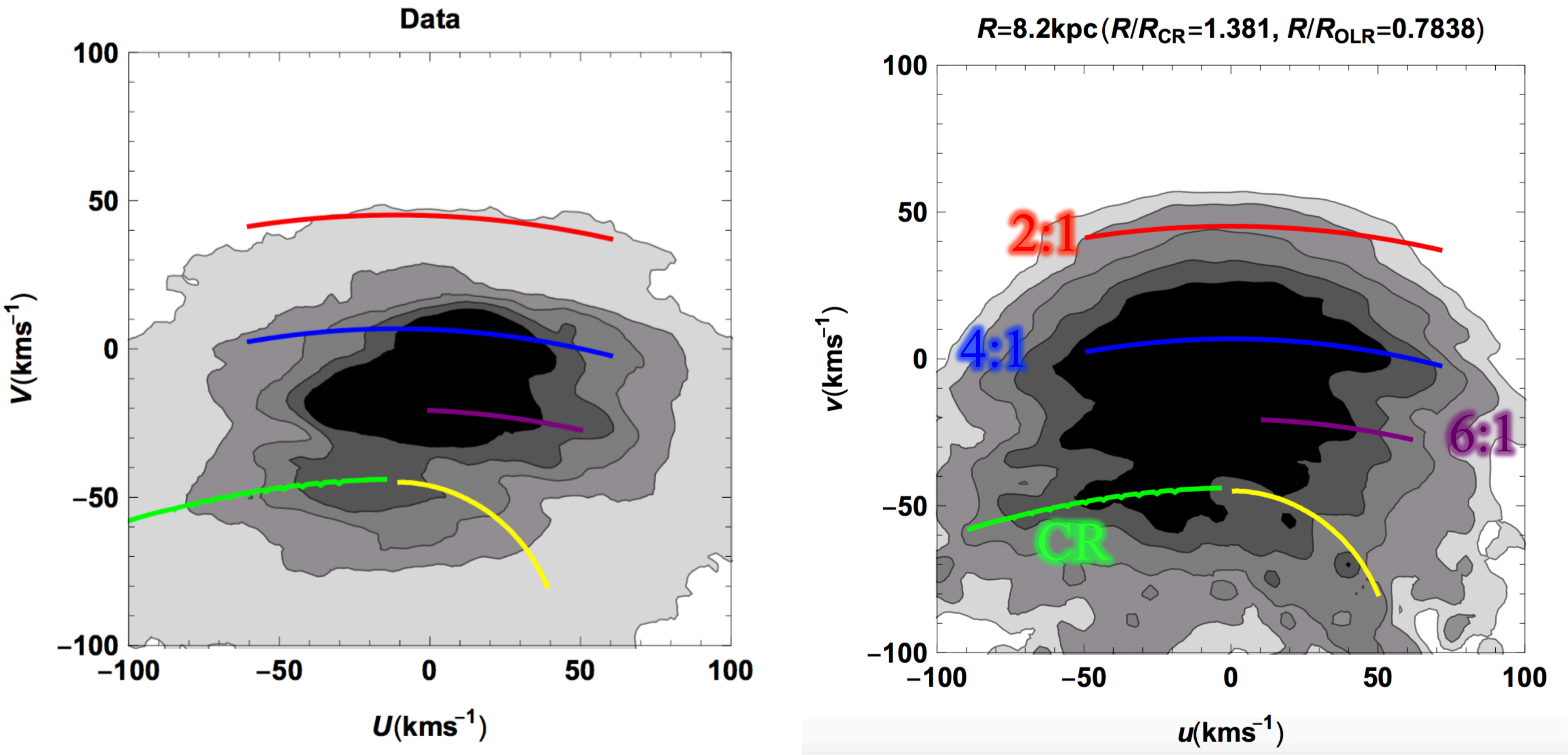
4000
3000
2000
1000
0
$A(\mathrm{km}^2\mathrm{s}^{-2})$
0
2
4
6
8
10
R(kpc)

The resonant zones in local velocity space

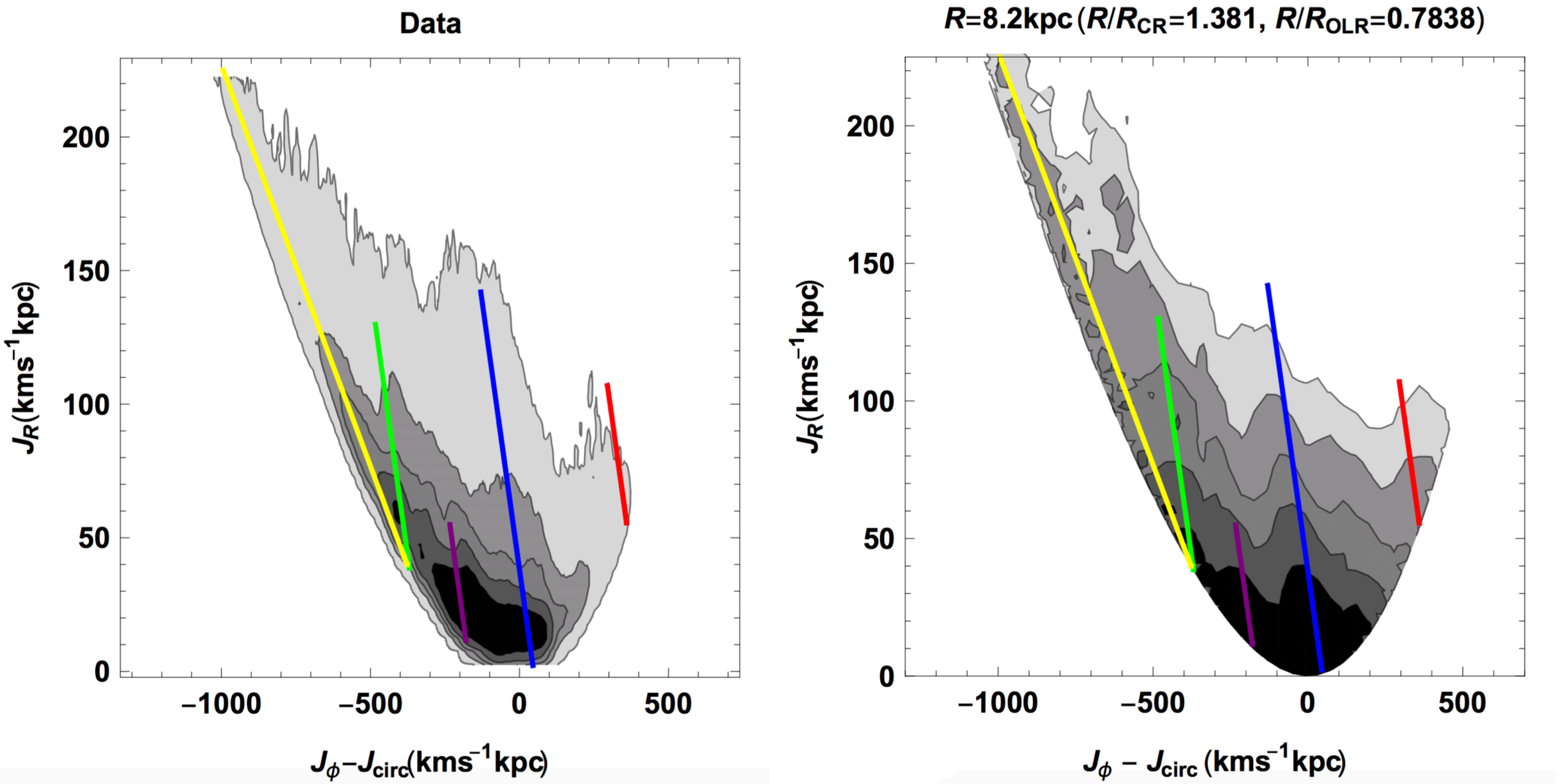




Data
R=8.2kpc (R/R_CR=1.381, R/R_OLR=0.7838)
100
50
0
−50
−100
−100
−50
0
50
100
V(kms^-1)
U(kms^-1)
v(kms^-1)
u(kms^-1)



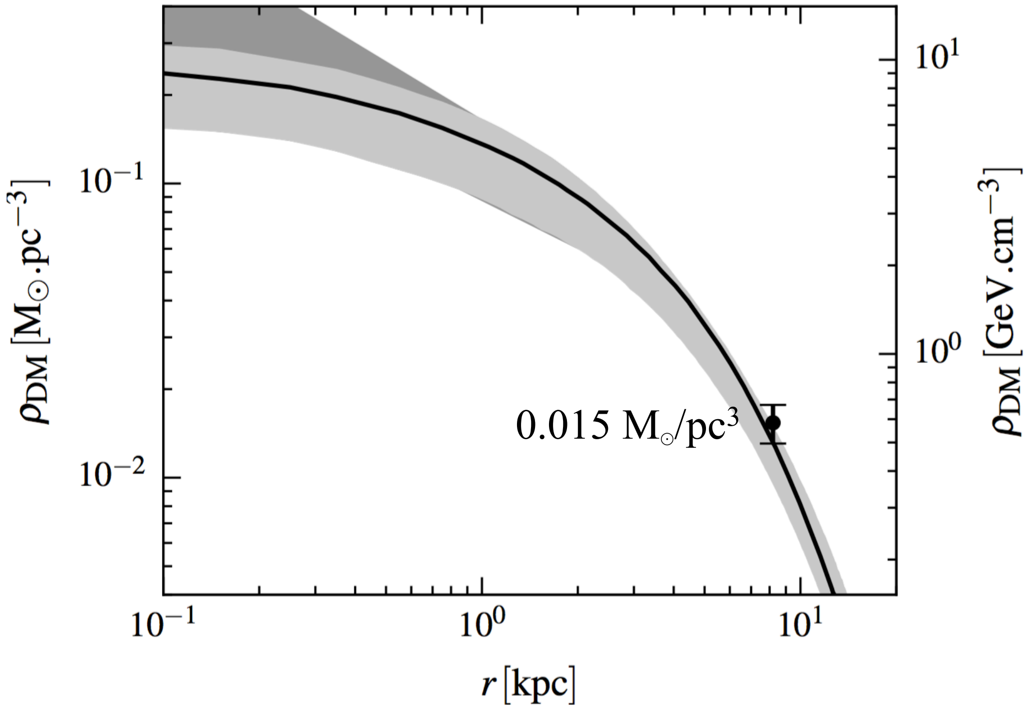
Data
V(kms^-1)
U(kms^-1)
R=8.2kpc (R/R_CR=1.381, R/R_OLR=0.7838)
v(kms^-1)
u(kms^-1)
2:1
4:1
6:1
CR



Data
R=8.2kpc (R/RCR=1.381, R/ROLR=0.7838)
JR(kms-1kpc)
Jϕ−Jcirc(kms-1kpc)
200
150
100
50
0
−1000
−500
0
500

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 DM profile at the center**

What's next?

- Next data releases will improve even more the observational situation (e.g., RVS data for $3.5x10^7$ stars down to G~15)

- FROM US **(DYNAMICISTS):** improvements needed: on the **MODELLING** side (vertical perturbations with collective effects, bar and spiral arms formation, chemo-dynamical modelling…), also related to constraining the **DM PHASE-SPACE DISTRIBUTION**, and testing alternatives

- At the horizon 2020: **WEAVE** as spectroscopic counterpart to Gaia. High-res survey (R~20000) will allow chemical labelling to G~16 for ~$1.2x10^6$ stars

  \+ Low-res surveys (disk and HighLat) for ~$2.75x10^6$ stars (R~5000) deep in the disk and halo down to G~20