Galactic highlights from 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

Model of the Galaxy and of each of its components (stellar populations, gas, dark matter) through DF-potential pair

Collsionless Boltzmann Equation for the stellar and DM DF:

$$df/dt = 0 \Leftrightarrow \frac{\partial f}{\partial t} + [f, H] = \frac{\partial f}{\partial t} + \mathbf{v} \cdot \frac{\partial f}{\partial \mathbf{x}} - \frac{\partial \Phi}{\partial \mathbf{x}} \cdot \frac{\partial f}{\partial \mathbf{v}} = 0,$$

Moments of *f* (integrate over velocity space) give configuration space averaged observables such as vel. disp. profiles

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

Vertical equilibrium

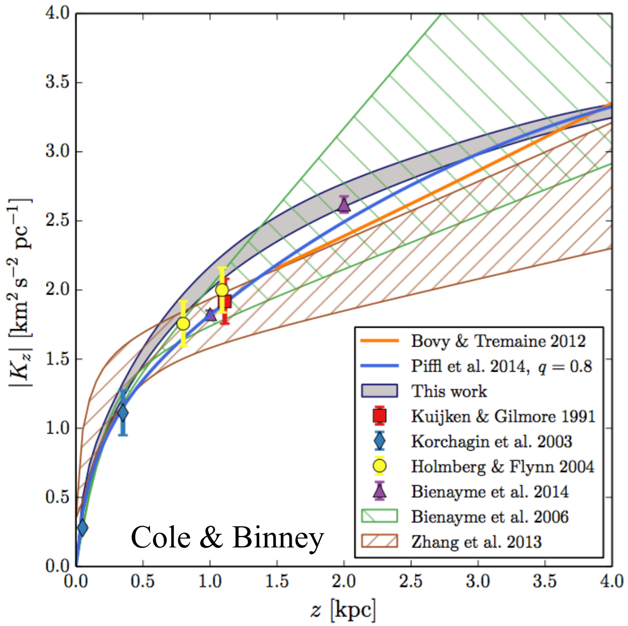
$$-4\pi G\Sigma(Z) = \int_{-Z}^{Z} \frac{1}{R}\frac{\partial}{\partial R}(RF_R)dz + 2\cdot[F_z(Z) - F_z(0)],$$

Poisson eq.

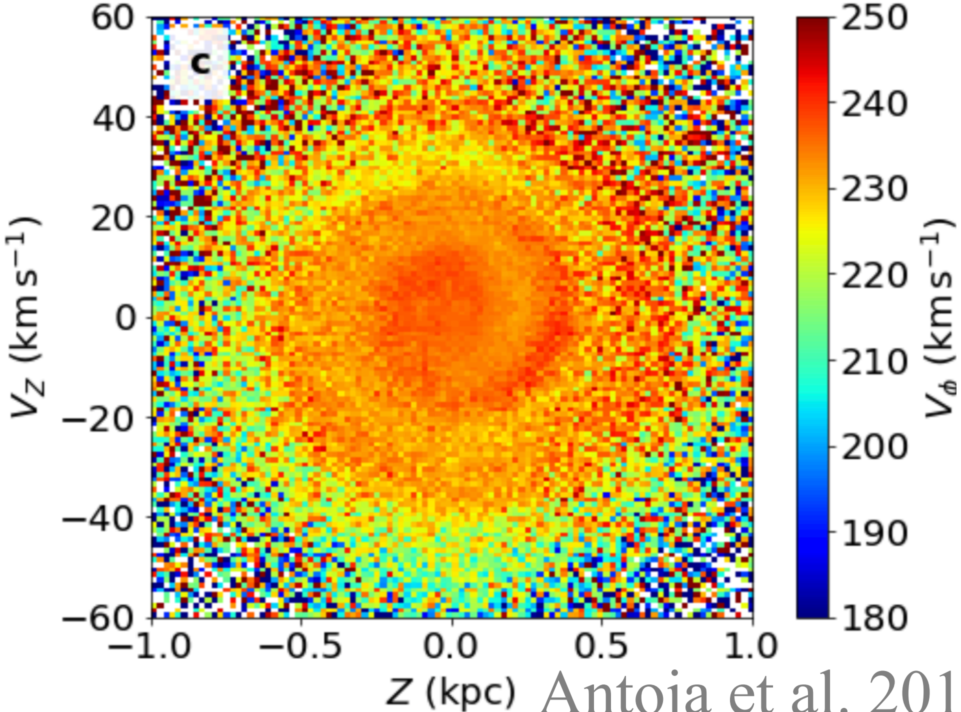
$$F_R = -\frac{\partial\phi}{\partial R} = \frac{1}{\rho}\frac{\partial(\rho\overline{U^2})}{\partial R} + \frac{1}{\rho}\frac{\partial(\rho\overline{UW})}{\partial Z} + \frac{\overline{U^2}-\overline{V^2}}{R} + \frac{1}{\rho}\frac{\partial(\rho\overline{U})}{\partial t},$$

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

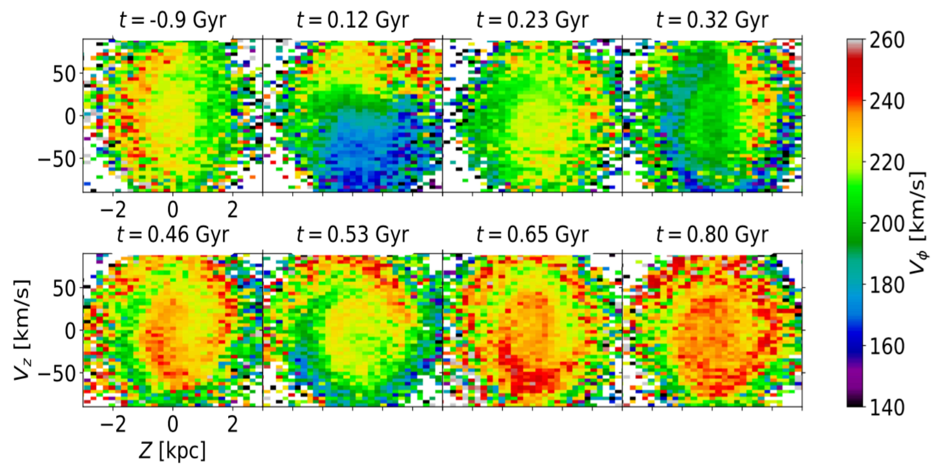
Jeans eqs.



But the disk is vertically perturbed



Antoja et al. 2018

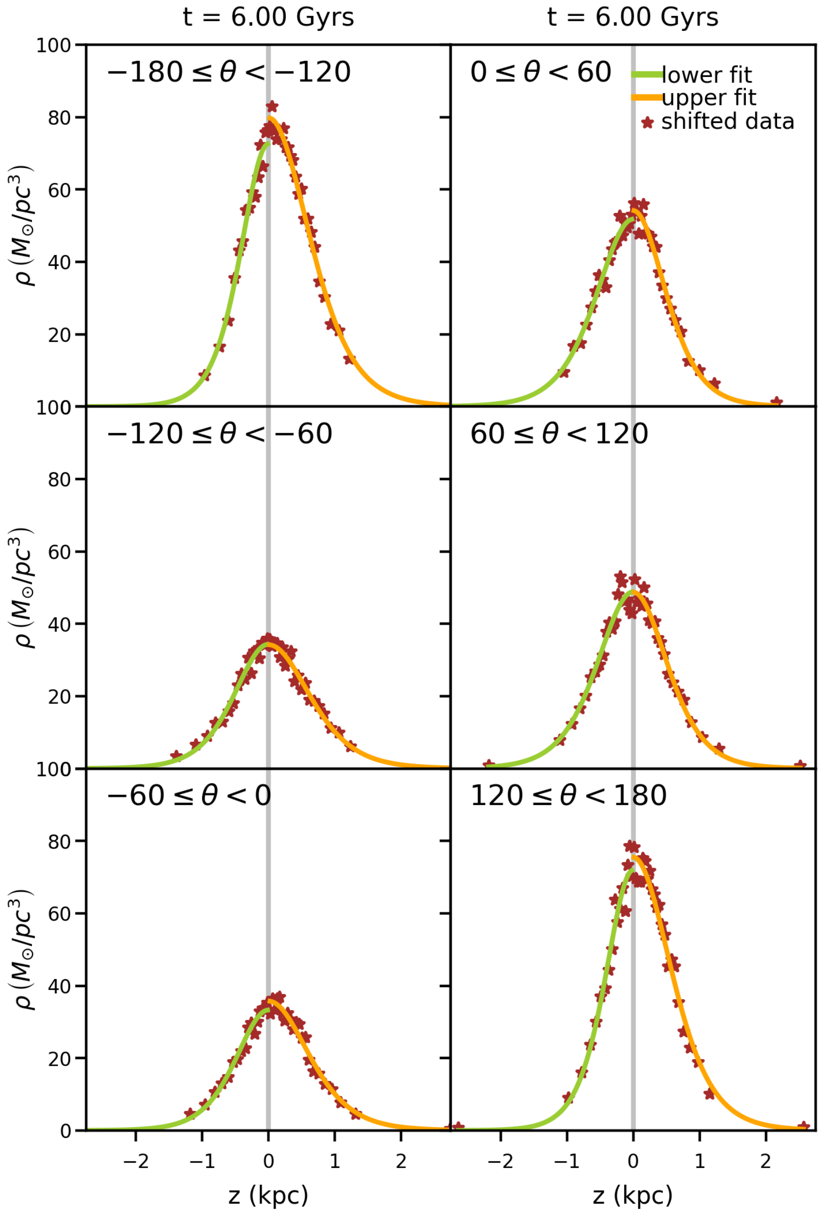


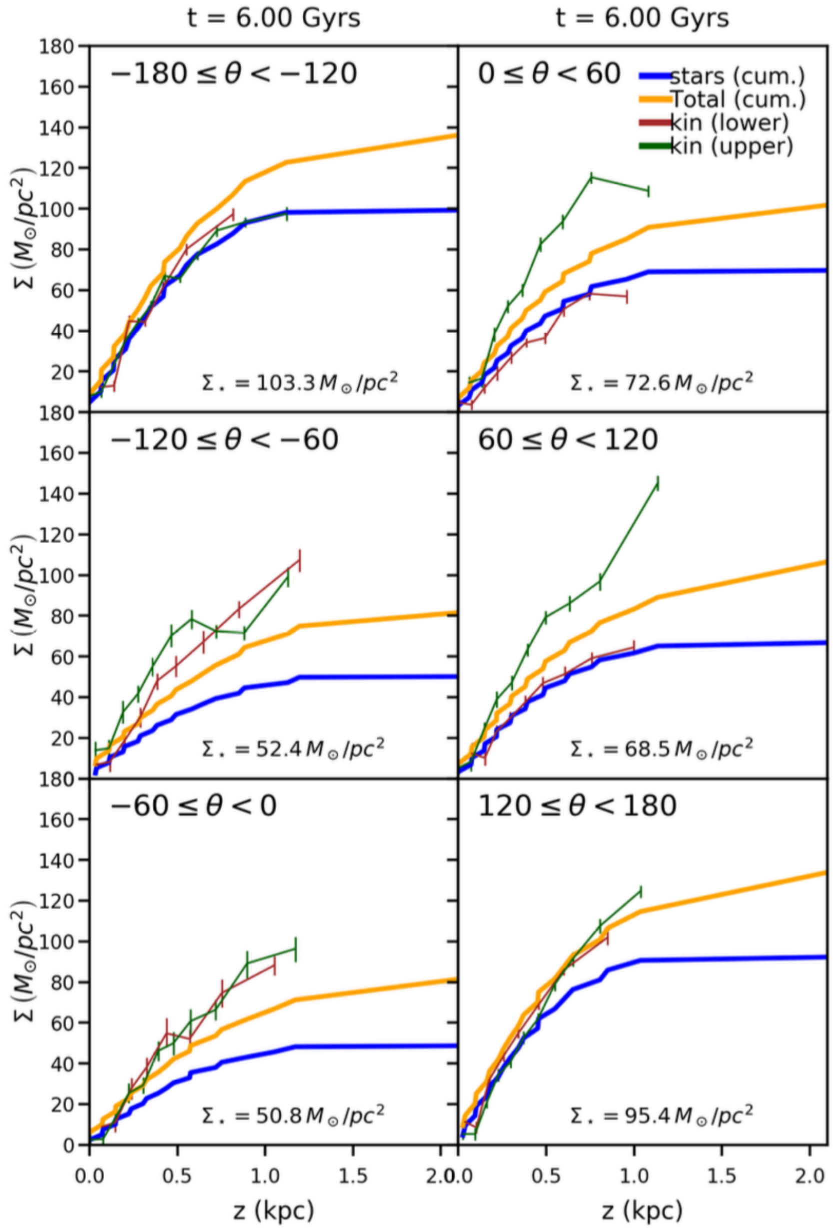
Laporte et al. 2018
(last pericentric passage of Sgr dwarf at t=0)

See Chervin Laporte's talk

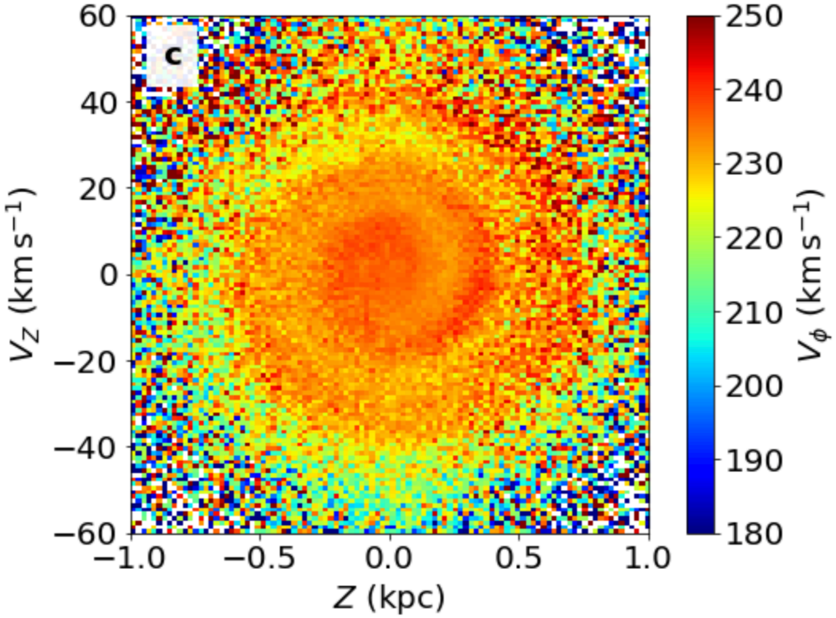
⇒ Can traditional Jeans modelling be applied?

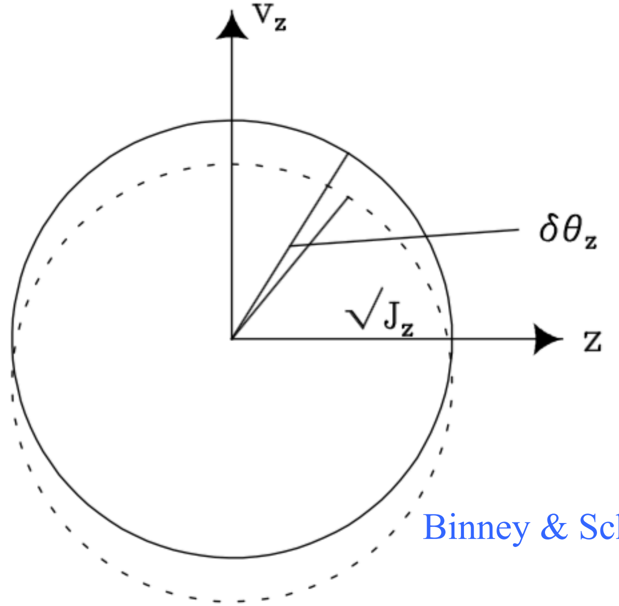
Haines, D'Onghia, Famaey, Laporte, Hernquist 2019





Use this as a feature & not a bug

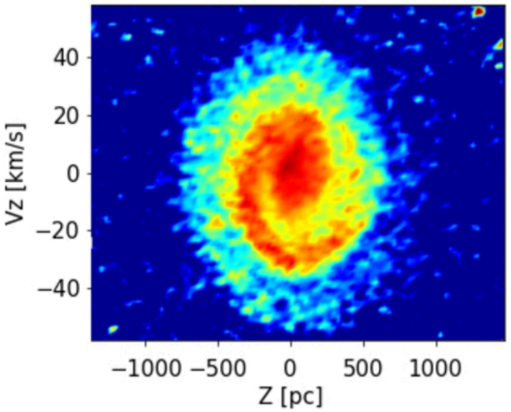




Binney & Schönrich 2018

$f(J_z) \rightarrow f(\theta_z, J_z)$ 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?



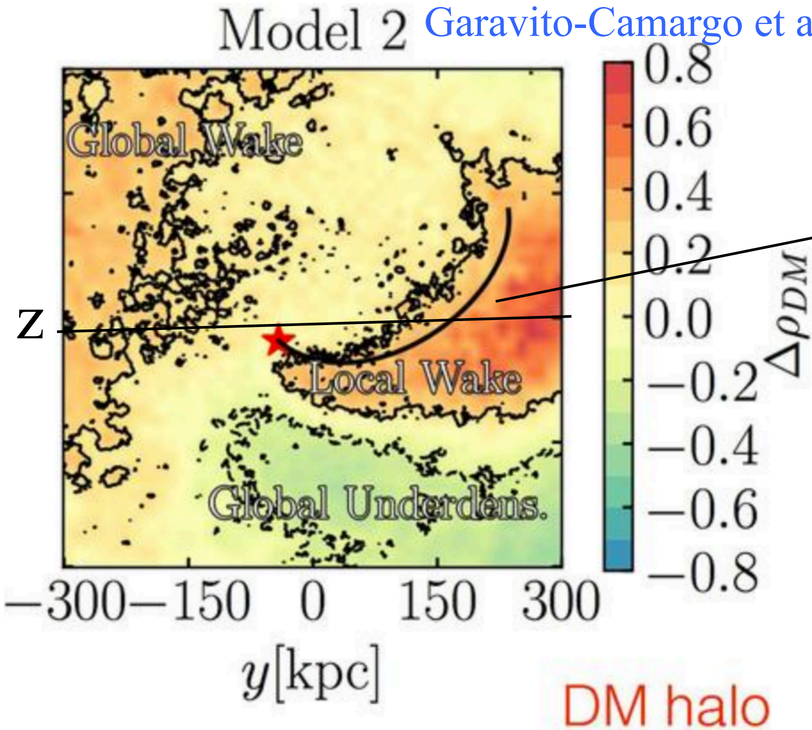
Khoperskov et al. 2019

Phase-spiral >Gyr after bar buckling phase

Response of the DM halo?

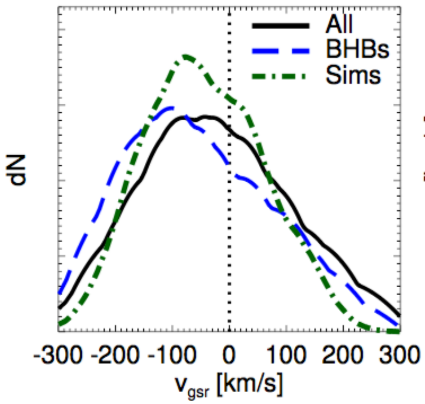
- LMC, Sagittarius dwarf and their own DM halo can exchange energy and angular momentum with the MW DM halo: **our best shot at proving the existence of DM !**

Garavito-Camargo et al. 2019

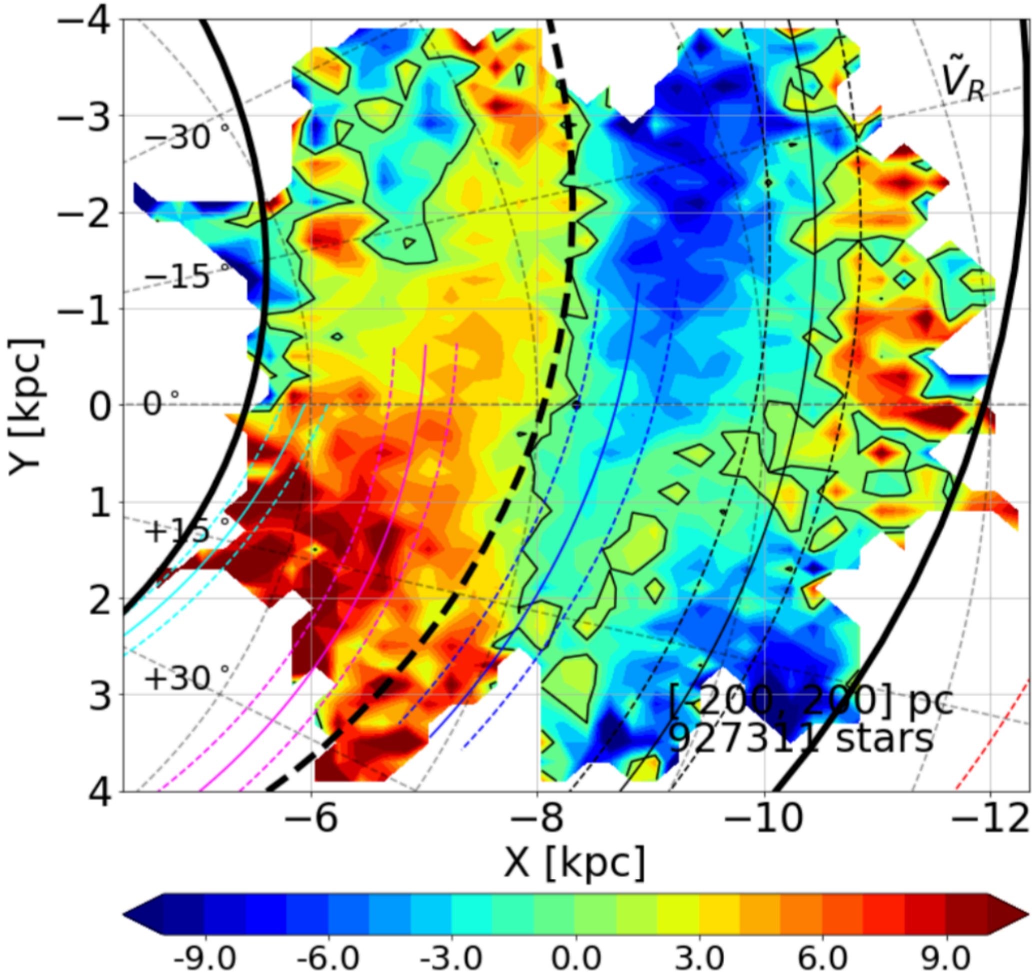


Pisces plume detected with Gaia DR2 and PS1 RRLyrae ?
(Belokurov et al. 2019)

+Effect of the global wake on the Sgr stream?



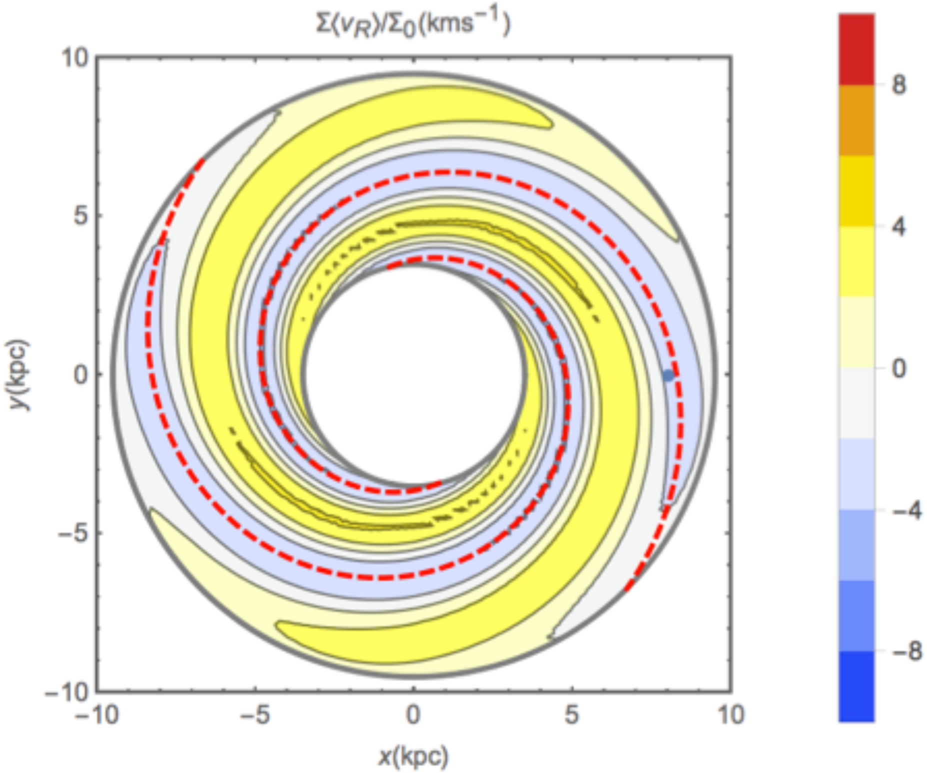
Back to the Galactic plane



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

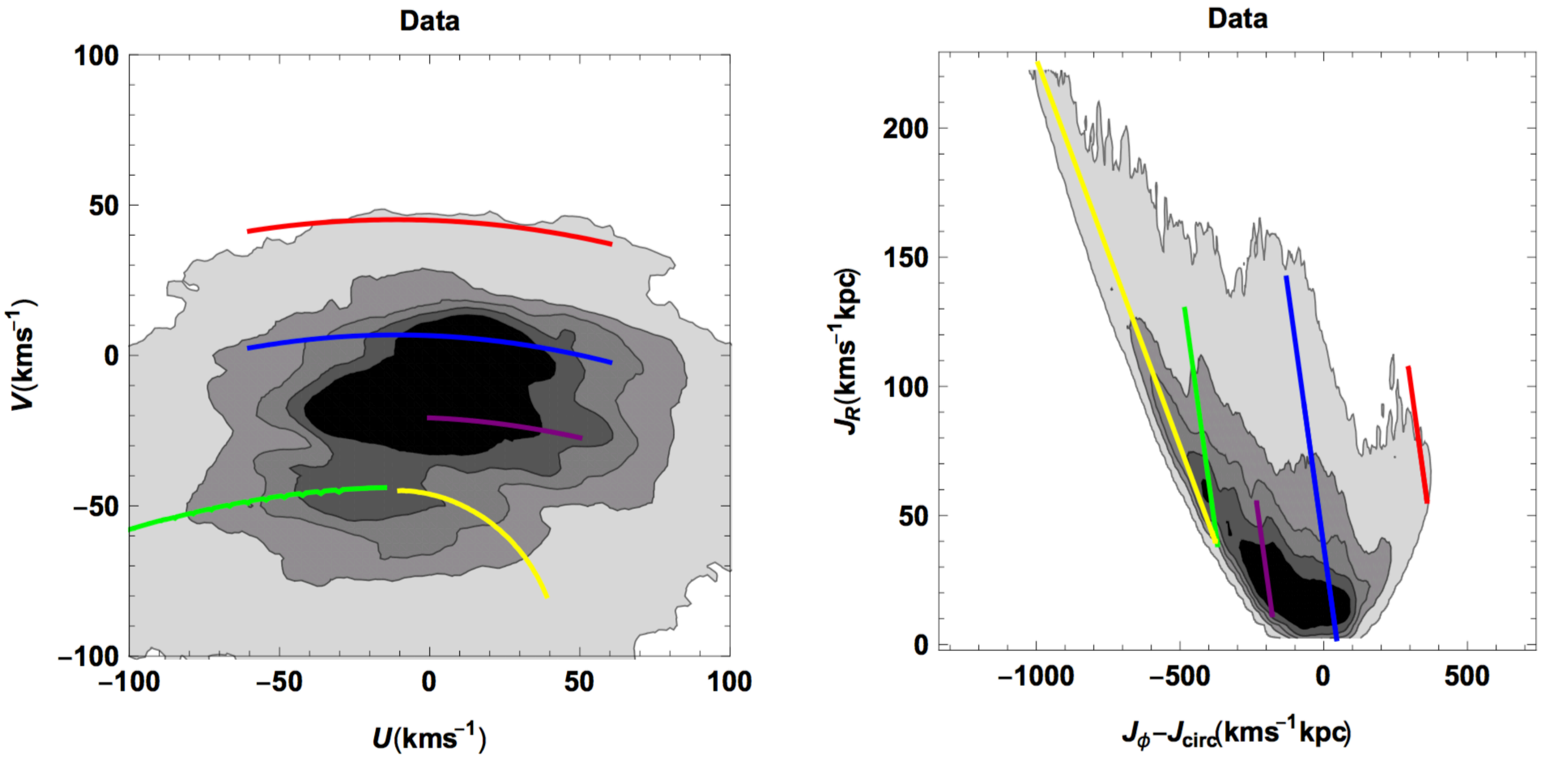
At resonances where new action-angle variables can be defined **(see Giacomo's talk!)**

⇒ Combination of multiple patterns: bar+spirals

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

Nature of spiral arms? (see -- perhaps -- James' talk)

Back to the solar neighbourhood

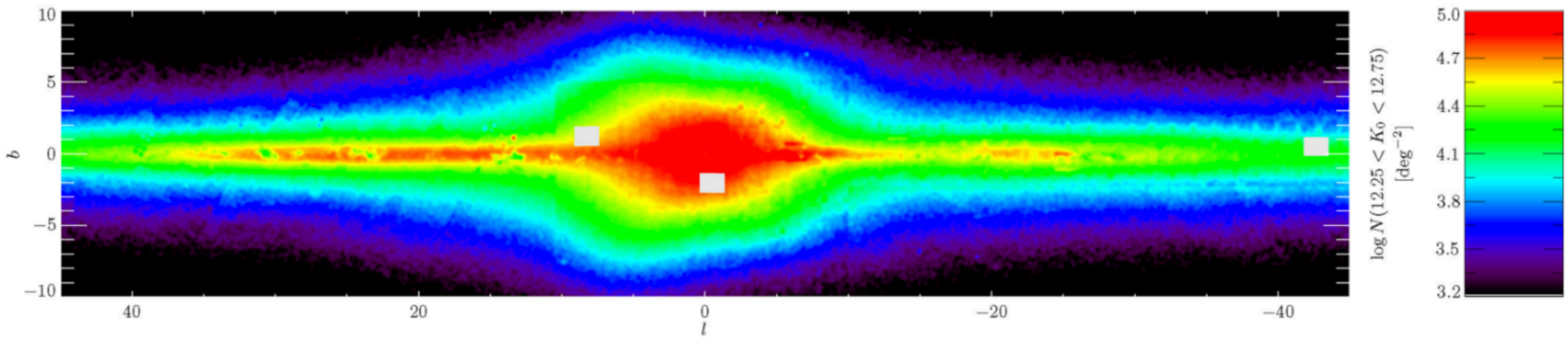


Monari et al. 2019

⇒Multiple ridges highly suggestive of multiple patterns

But… what can the bar **alone** do?

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

1.75x10[8] PMs (!!!) at
-10°<l<10°, -10°<b<5°
in the VVV Infrared
Astrometric Catalogue
(VIRAC), calibrated on
Gaia DR2 (Clarke et al. 2019)

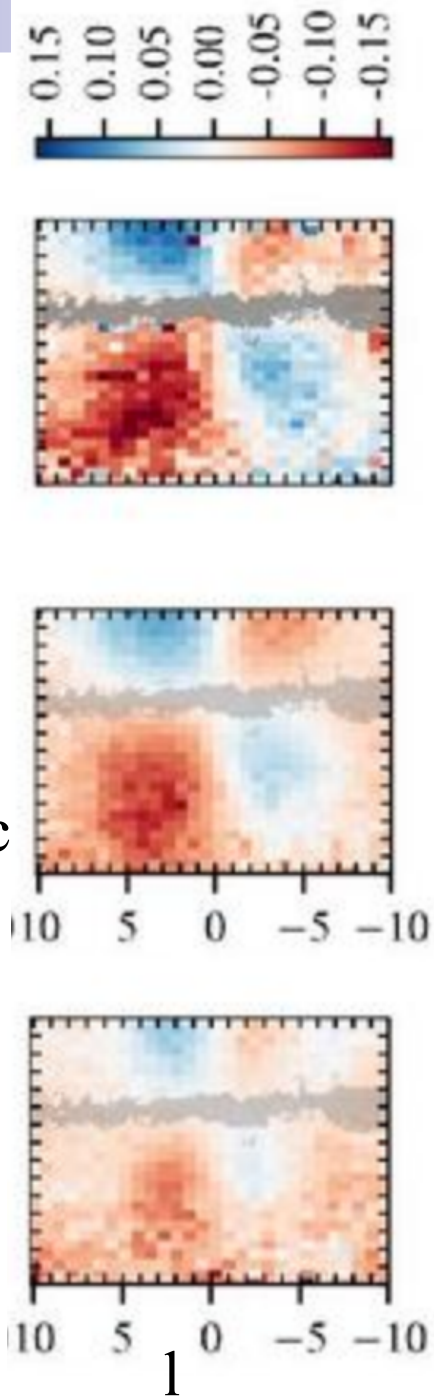
See also Sanders et al. (2019)

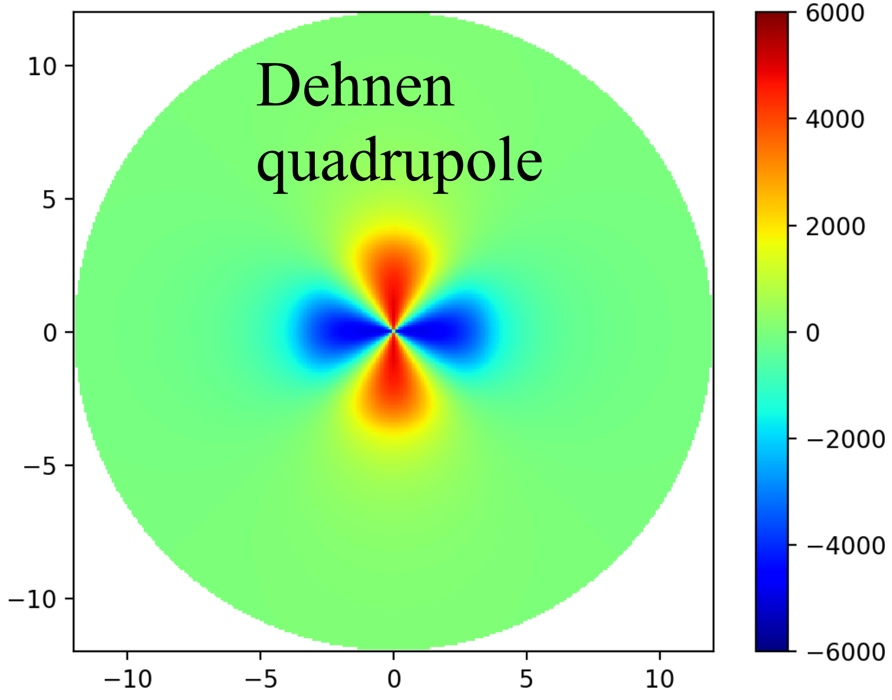
$\frac{\sigma_{lb}^2}{\sigma_l \sigma_b}$, obs.

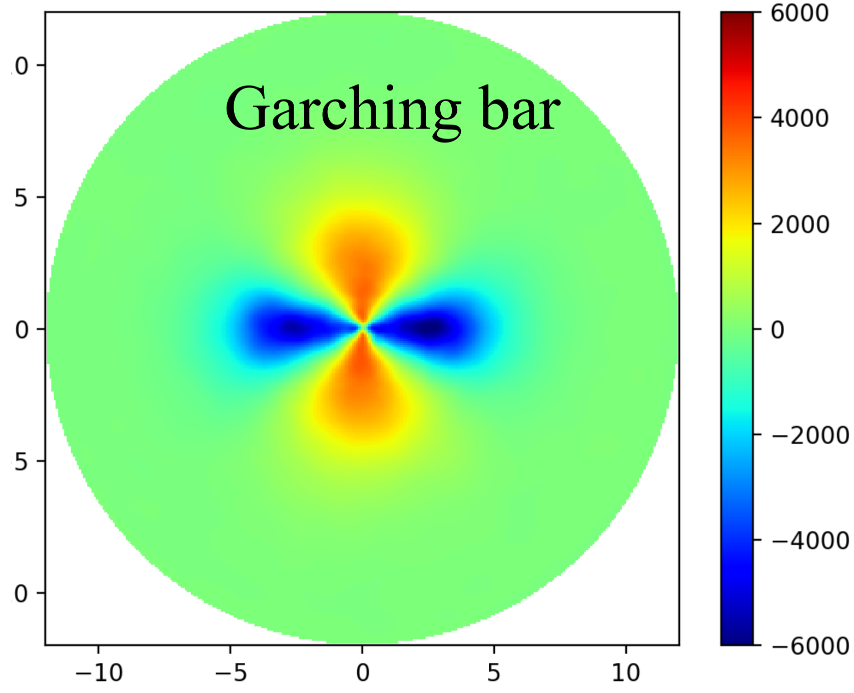
37.5 km/s/kpc

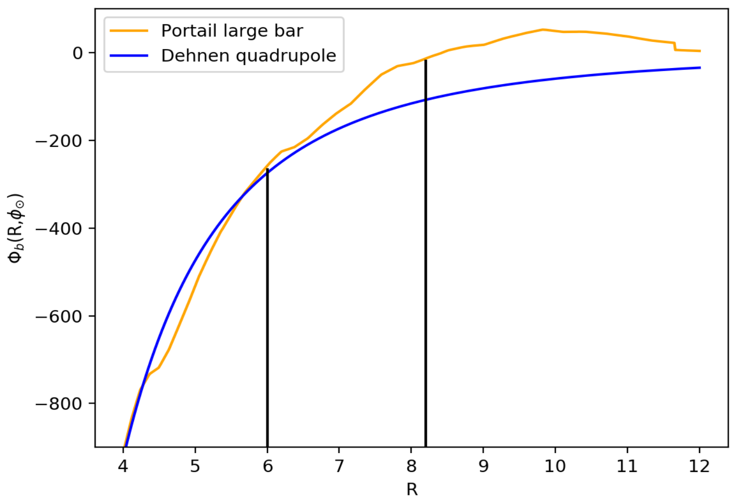
b

50 km/s/kpc

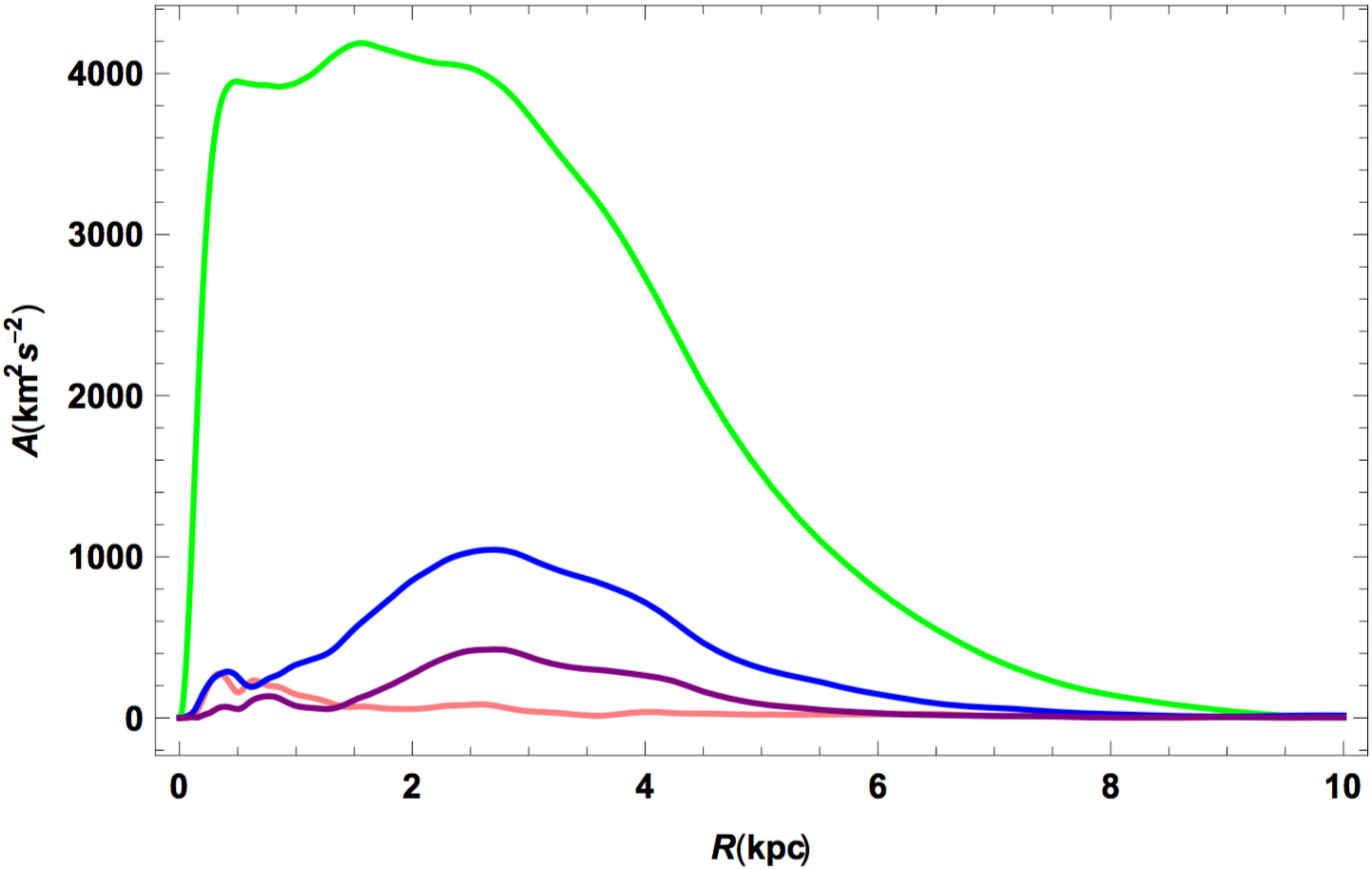






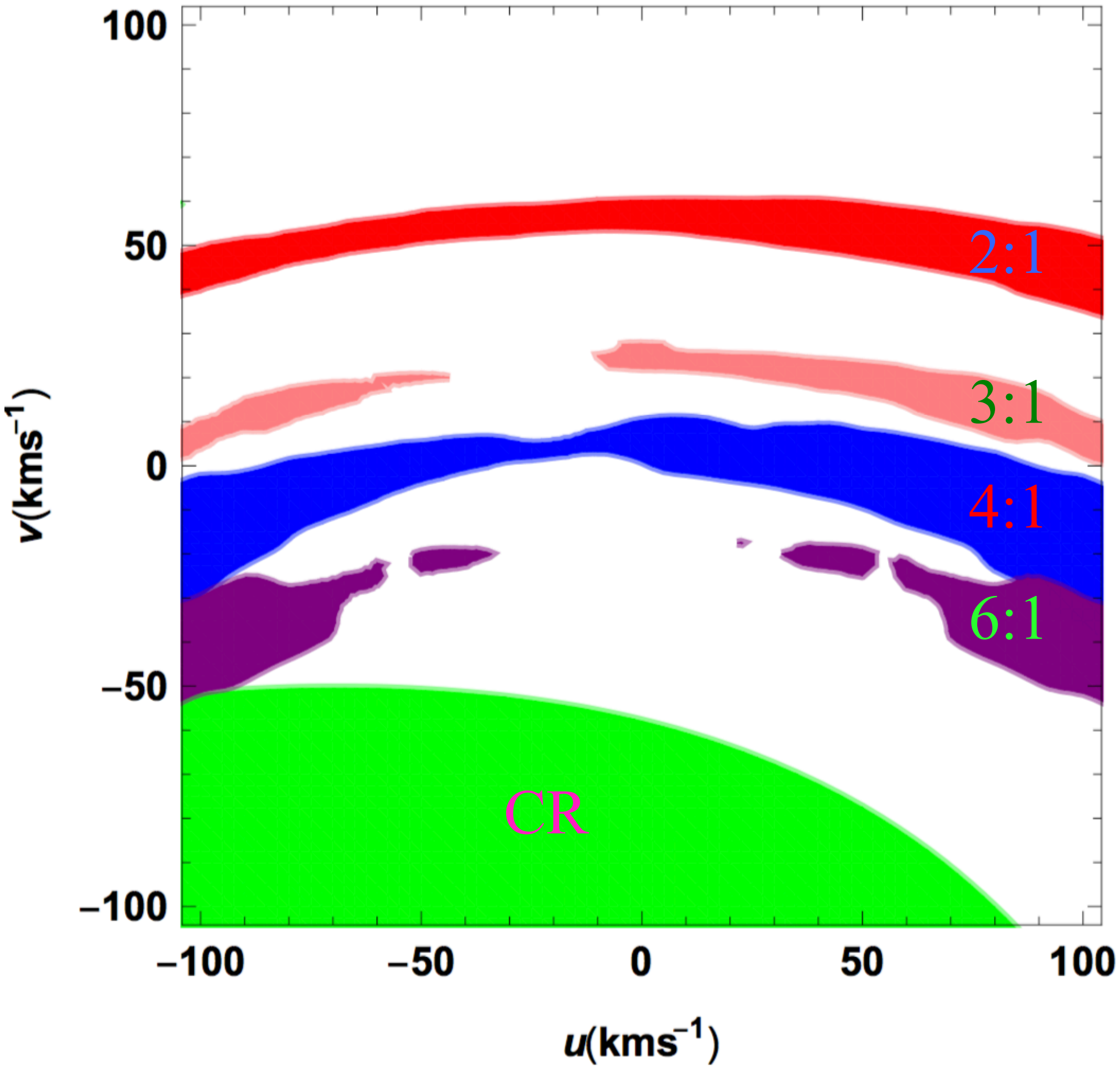


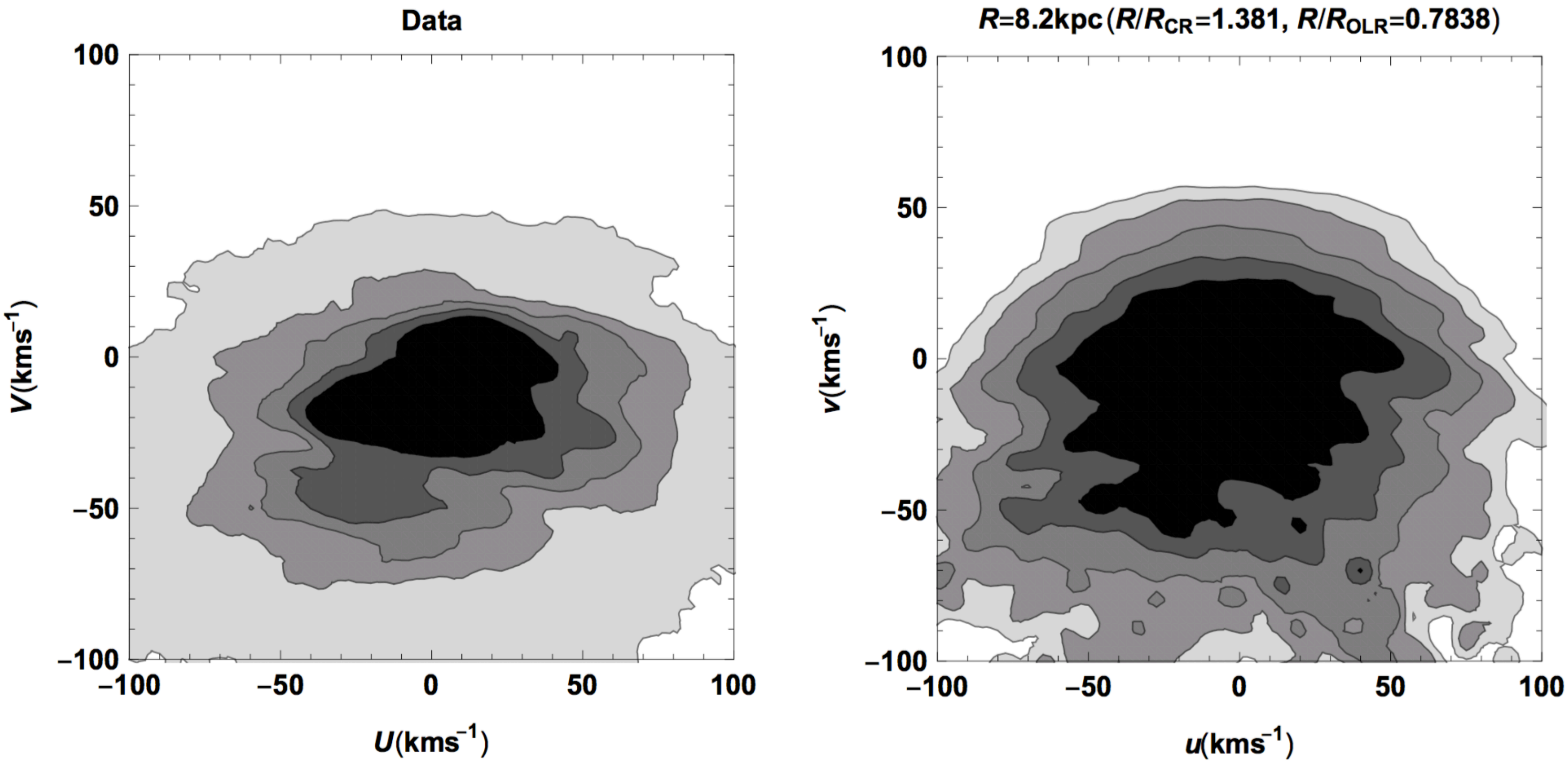
Study the m=2, 3, 4 and 6 modes in Monari et al. 2019 arXiv:1812.04151

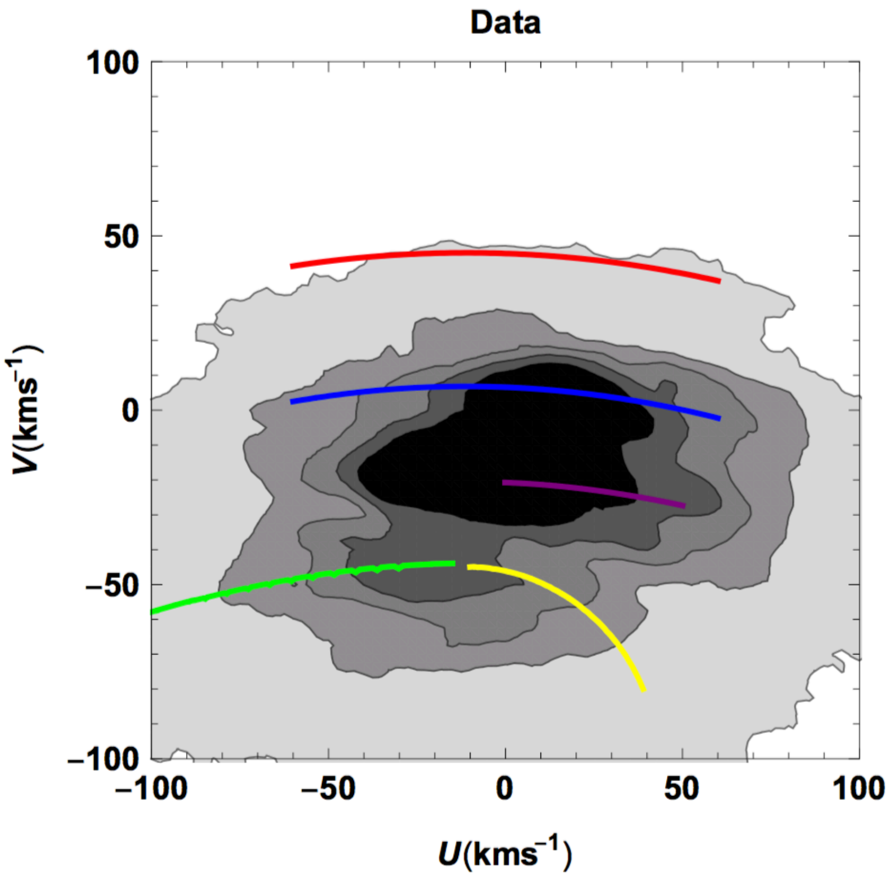


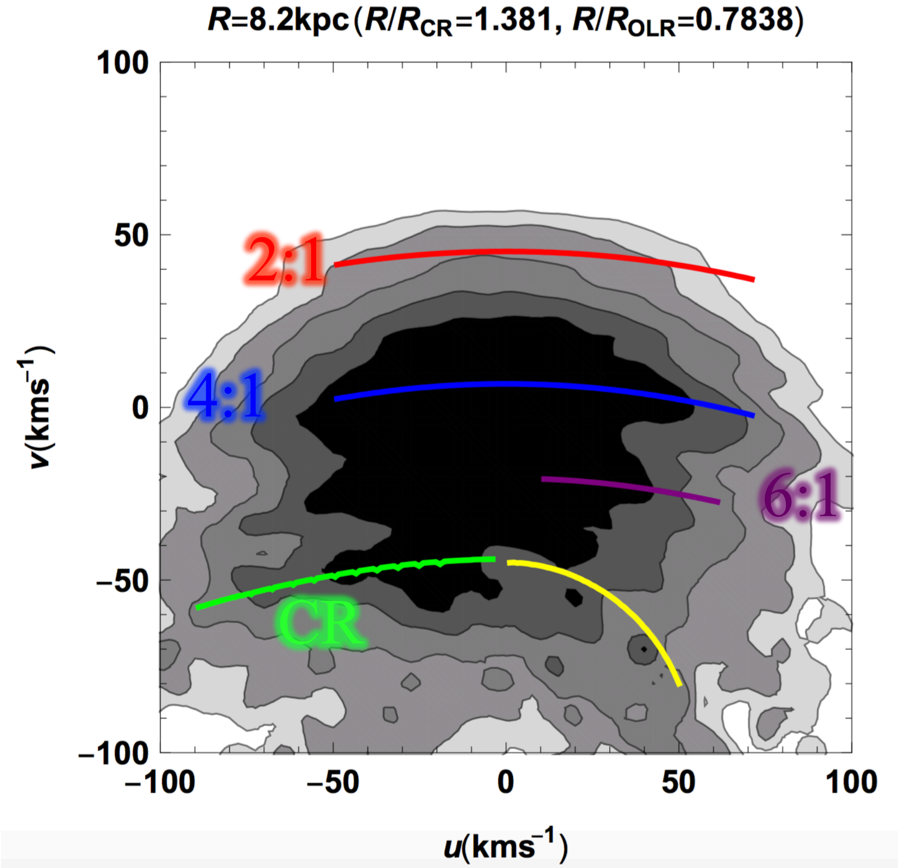
4000
3000
2000
1000
0
$A(\mathrm{km}^2\mathrm{s}^{-2})$
0
2
4
6
8
10
R(kpc)

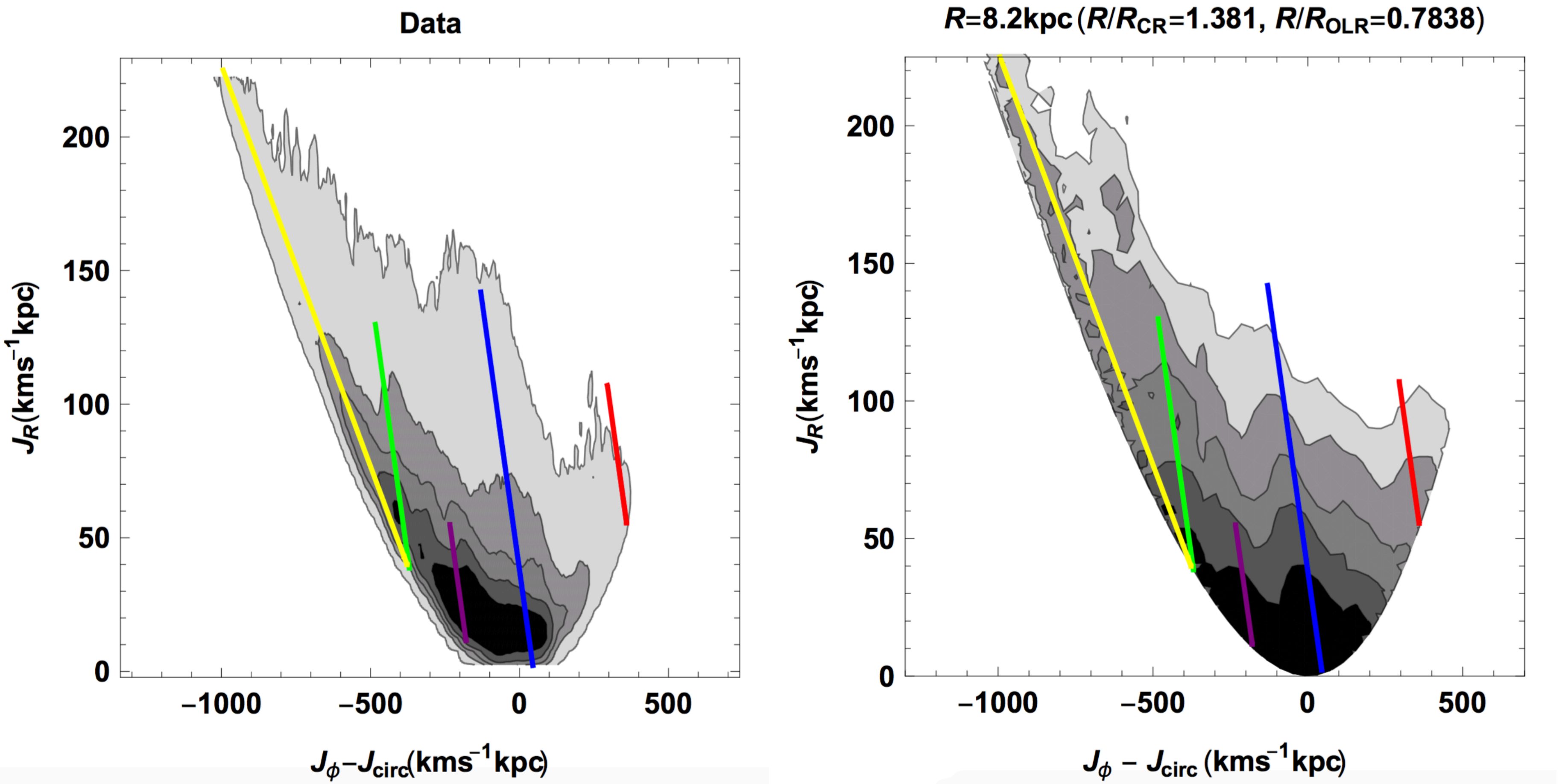
The resonant zones in local velocity space




Data
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)
v(kms⁻¹)
u(kms⁻¹)


Data
100
50
0
−50
−100
−100
−50
0
50
100
V(kms⁻¹)
U(kms⁻¹)

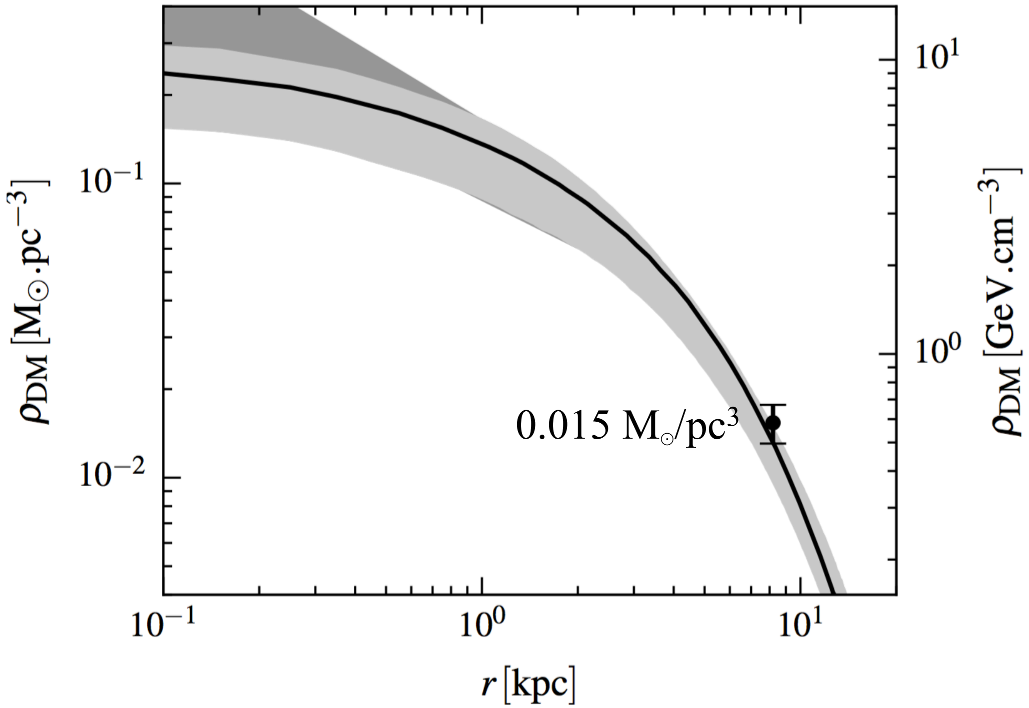

R=8.2kpc (R/R_CR=1.381, R/R_OLR=0.7838)
2:1
4:1
6:1
CR
100
50
0
−50
−100
−100
−50
0
50
100
v(kms⁻¹)
u(kms⁻¹)



Data
R=8.2kpc (R/R_{CR}=1.381, R/R_{OLR}=0.7838)
J_R(kms^{-1}kpc)
$J_\phi - J_{circ}$(kms^{-1}kpc)
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): $1.85 \times 10^{10}\ M_\odot$
  - Stellar mass: $1.32 \times 10^{10}\ M_\odot$
  - Additional nuclear disk: $2 \times 10^{9}\ M_\odot$
  - Dark matter mass: $3.2 \times 10^{9}\ M_\odot$



Portail et al. (2017)

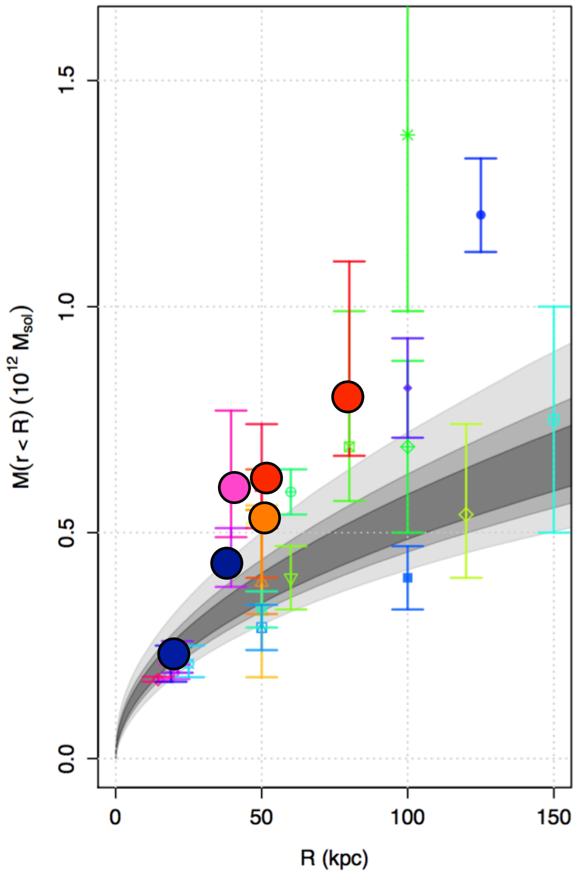
Sharp falloff to keep the RC constant between 6 kpc and 8 kpc
=> **cored DM profile at the center**

Back to the (stellar) halo

Globular clusters :

Vasiliev (2018): catalog of 150 GCs with PMs out to ~130 kpc

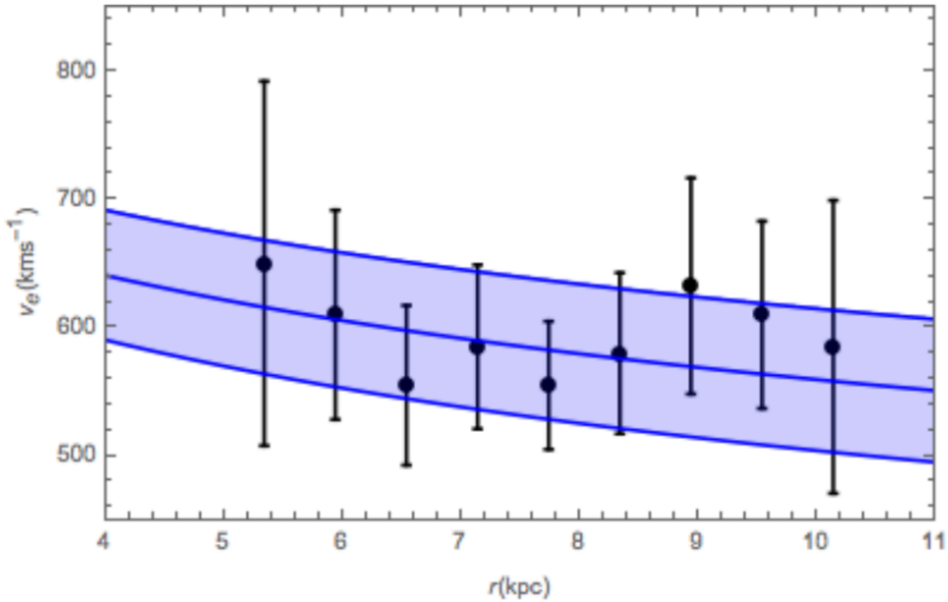
Various attempts to use GCs as dynamical tracers by constructing equilibrium DFs or Jeans mass estimators:
Watkins et al, Posti et al, Vasiliev (all 2018)
Sohn et al. (HST), Eadie & Juric (2018),…
Virial masses ranging from **0.7 to 1.6 x 10^{12} $M_{\odot}$**



Various different results… Not clear where the differences come from
The GC system does not extend very far and the result for M_{vir} is quite sensitive to large distances

A massive Milky Way?

Escape speed :



Assuming that v_e allows to reach $3xR_{340}$, as well as the mass-concentration relation of ΛCDM, one gets: $\mathbf{M_{200} = 1.55(-0.51, +0.64) \times 10^{12} M_\odot}$

Use 2850 counter-rotating stars at d<5kpc and ε_d/d<10% (StarHorse bayesian distance estimates)

Fit the tail of the velocity distribution to ~100 Monte Carlo realizations at Galactocentric radii 5 kpc< R<10.5 kpc

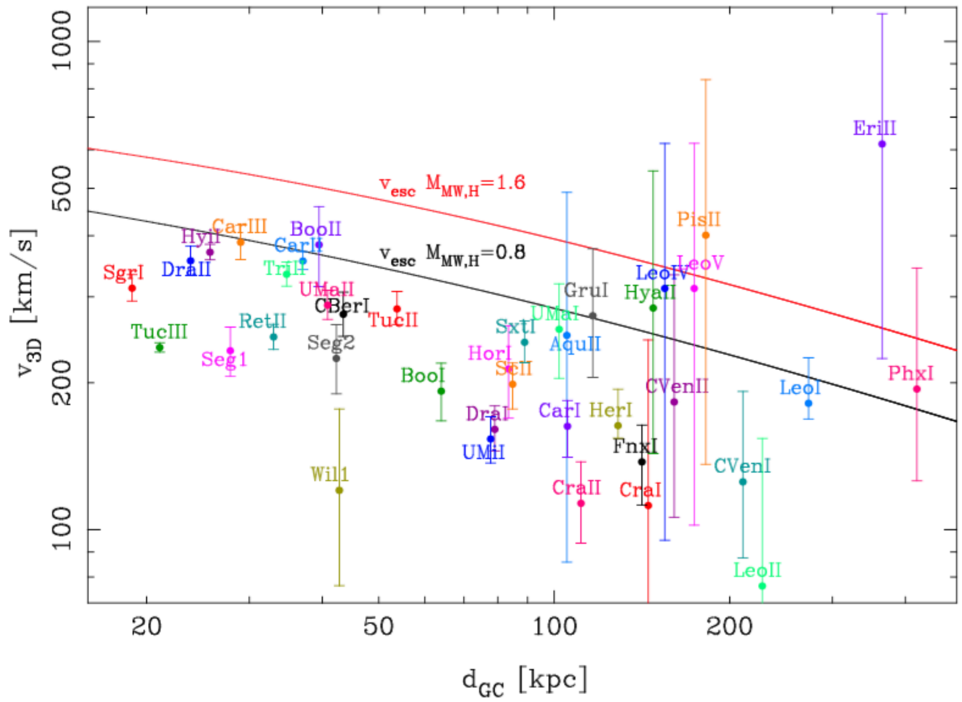
$$f(v|v_e, k) = \begin{cases} (k+1)(v_e - v)^k/(v_e - v_{cut}), & v \leq v_e \\ 0, & v > v_e \end{cases}$$

=> v_e ($R_\odot$) = 580±63 km/s

Monari et al. (2018)

Dwarf spheroidals

Dwarf galaxies :



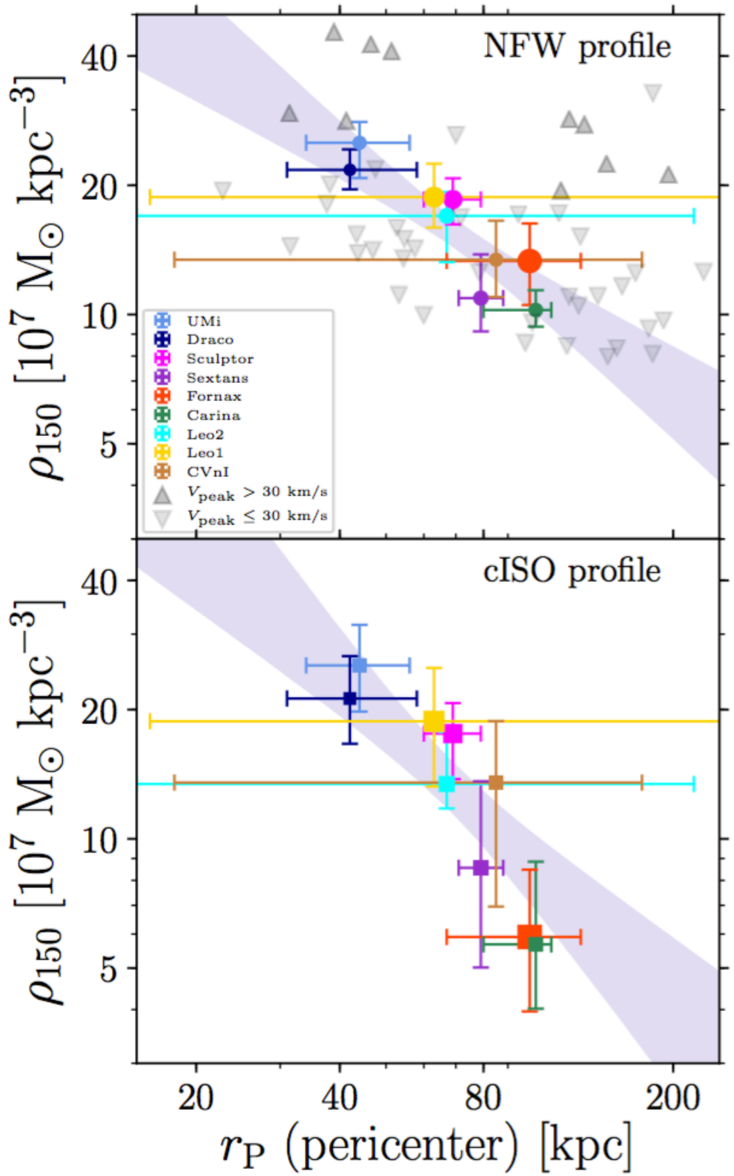
Systemic velocities of dwarfs from stars that also have spectroscopic measurements

Out of 39 dwarfs, 17 do align with the « plane of satellites » (11 co-orbiting, 6 counter-orbiting), 10 more might align

Velocity distribution also favours a high Milky virial mass ~**1.6 x 10^{12} M$_\odot$**

Fritz et al. (2018)

A provocative result on dSphs



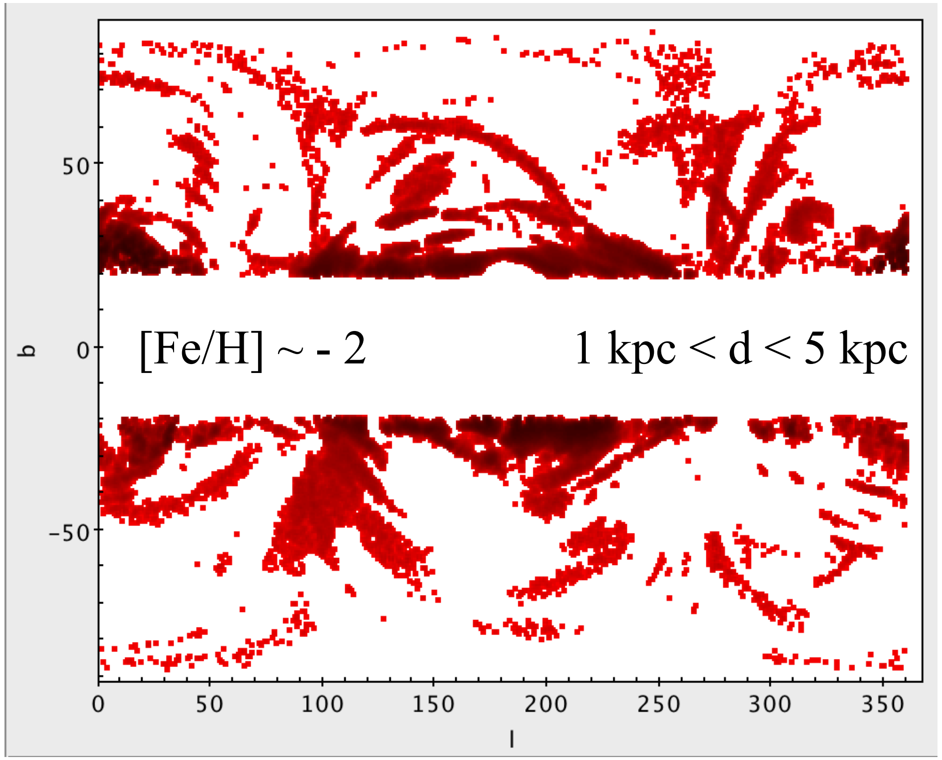
Anticorrelation of central DM density and pericenter of classical dSphs?

(Kaplinghat et al. 2019)

Note: in SIDM, tidal stripping of the outer DM particles enhances core-collapse…

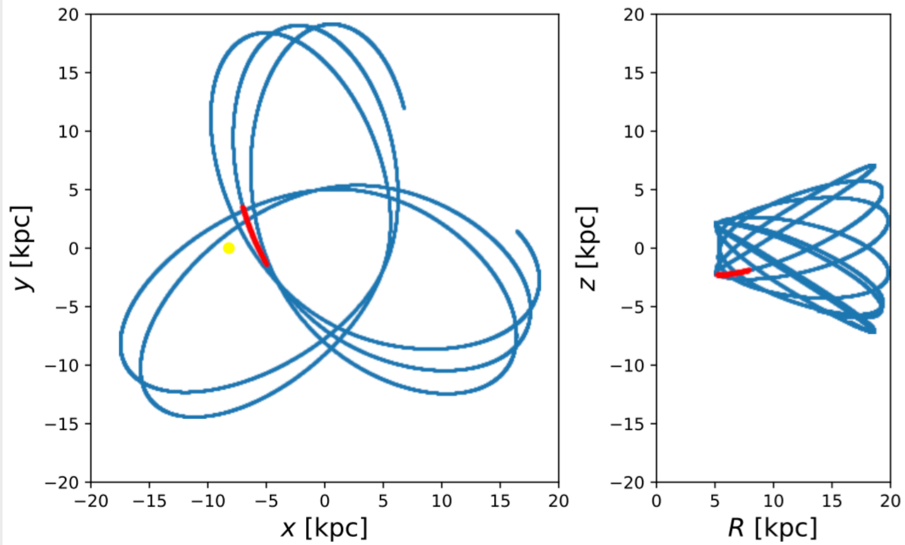
Also many new stellar streams!

Streams (Ibata et al.):



>>10 new confirmed streams

Integrate streams orbits by exploring all distances and radial velocities until stream candidate found (STREAMFINDER)



Phlegethon: a faint nearby(3.8 kpc) disk-like retrograde stream (~2580 $M_\odot$) Ibata et al (2018)

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:** 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