Galactic dynamics: news, challenges, impact of Gaia

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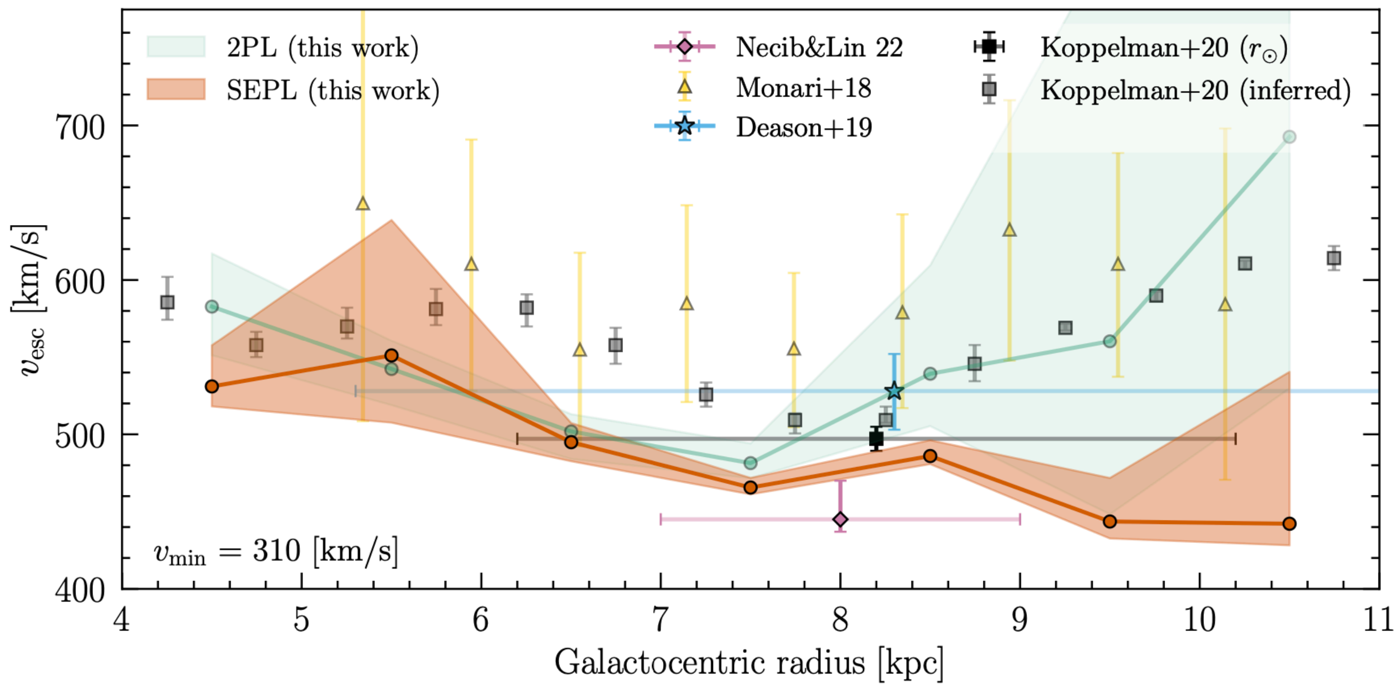
The MW mass debates

Monari et al. (2018) : 3x10³ counter-rotating stars from Gaia DR2, fit tail of velocity distribution with a power-law => **escape speed curve**
=> $M_{200} = 1.28 \times 10^{12}\ M_{sun}$ (7.8×10^{11} at 1 sigma)

Roche et al. (2024) : 1.2x10⁴ stars with speed > 300 km/s from Gaia DR3, with "stretched exponential power law", lower escape speed
=> $M_{200} = 7 \times 10^{11}\ M_{sun}$ (4.5×10^{11} at 1 sigma)



The MW mass debates

Monari et al. (2018) : 3 x 10^3 counter-rotating stars from Gaia DR2, fit tail of velocity distribution with a power-law => **escape speed curve**
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Roche et al. (2024) : 1.2 x 10^4 stars with speed > 300 km/s from Gaia DR3, with "stretched exponential power law", lower escape speed
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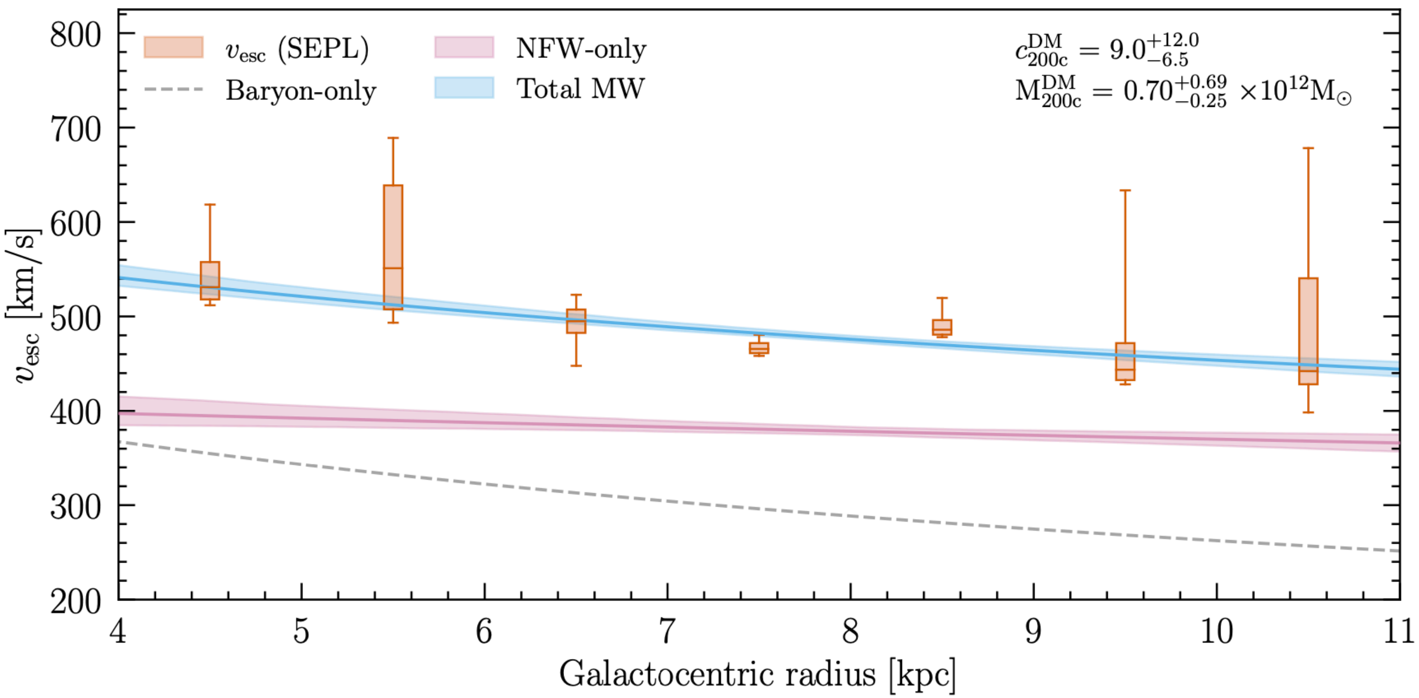


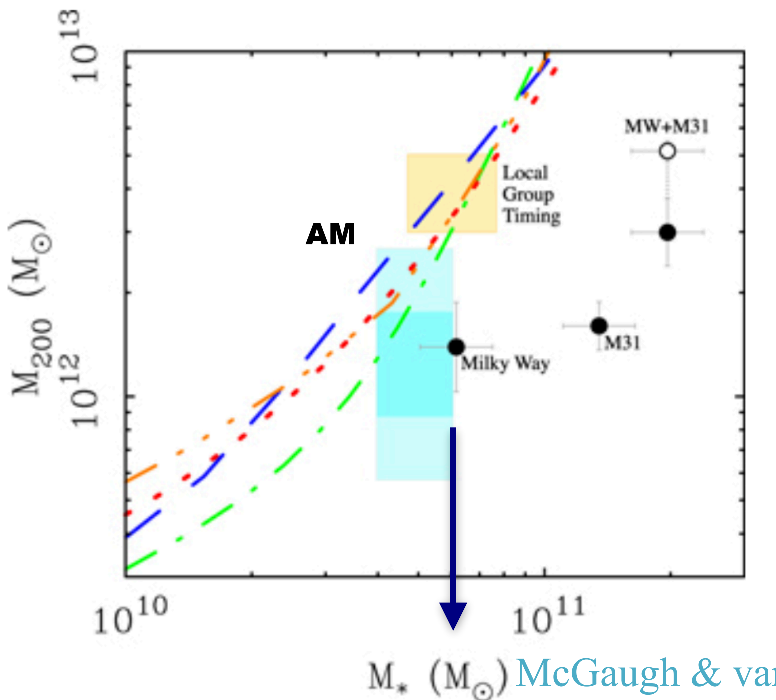
The MW mass debates

What about the MW **rotation curve/circular velocity curve** ?

Within the plane : $v_c^2 \simeq \langle v_\phi^2 \rangle + \langle v_R^2 \rangle (R - h_R)/h_R - R\partial \langle V_R^2 \rangle / \partial R$

Eilers et al. (2019) => M = 7.25 ± 0.26 x 10^{11} M_{sun}

BUT Jiao et al. (2023) => M = $2.06^{+0.24}_{-0.13}$ x 10^{11} M_{sun}



McGaugh & van Dokkum (2021)

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- Note that tracers are taken up to 3 kpc heights

- Even correcting for tilt of the velocity ellipsoid as a function of z doesn't guarantee that one probes the actual circular velocity at z=0

- The disk is perturbed

The MW mass debates

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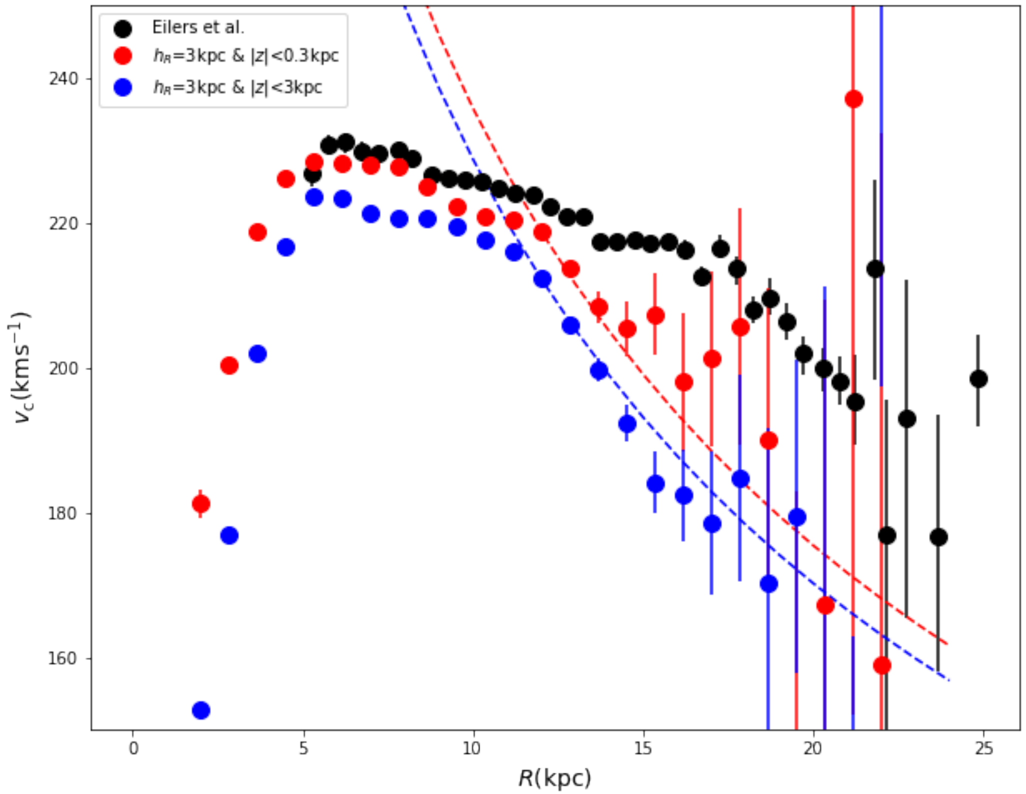
As an exercise (Monari et al. in prep.), let's take the (5×10^6 stars) Gaia RVS RGB sample (with Bailer-Jones distances) and check the influence of the height selection



The MW mass debates

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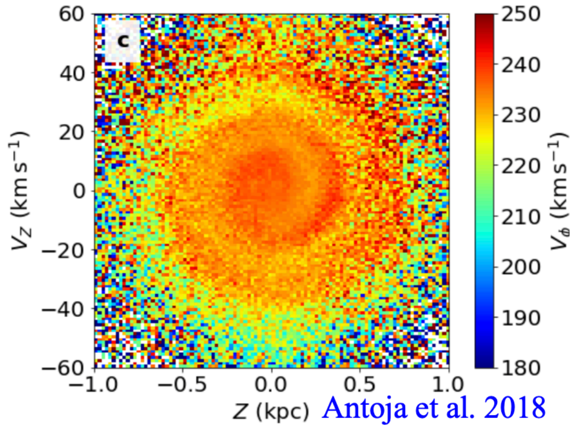
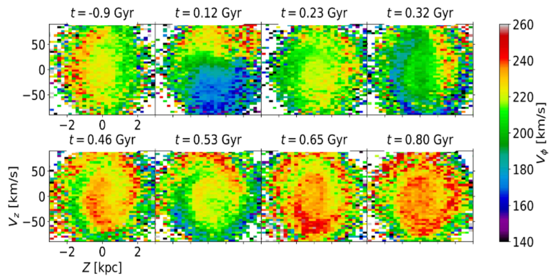
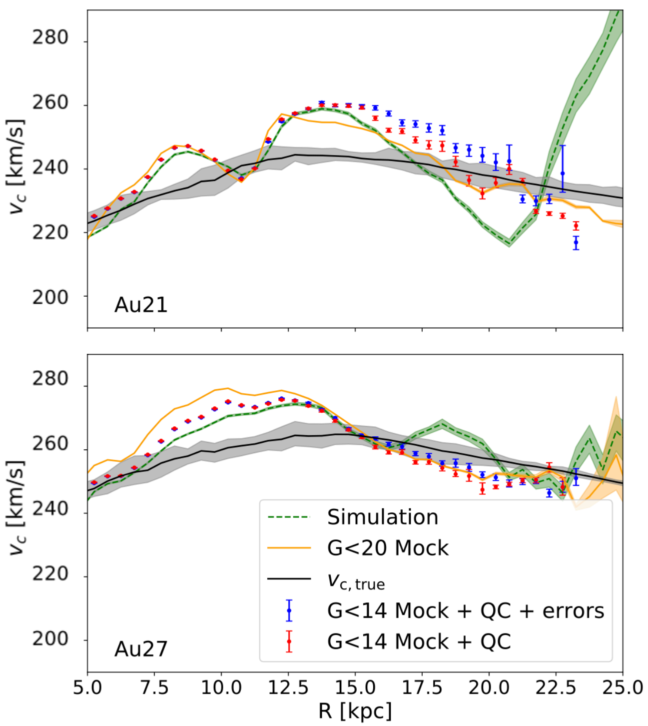
The outer disk is perturbed

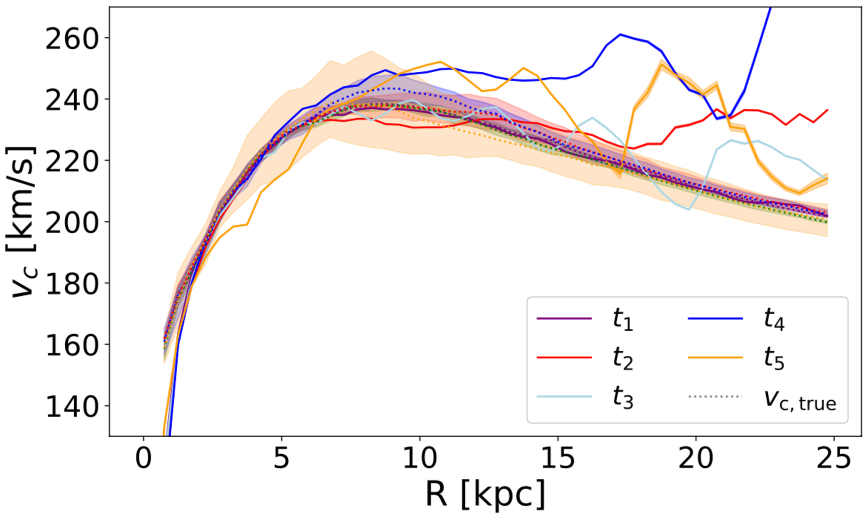


Antoja et al. 2018



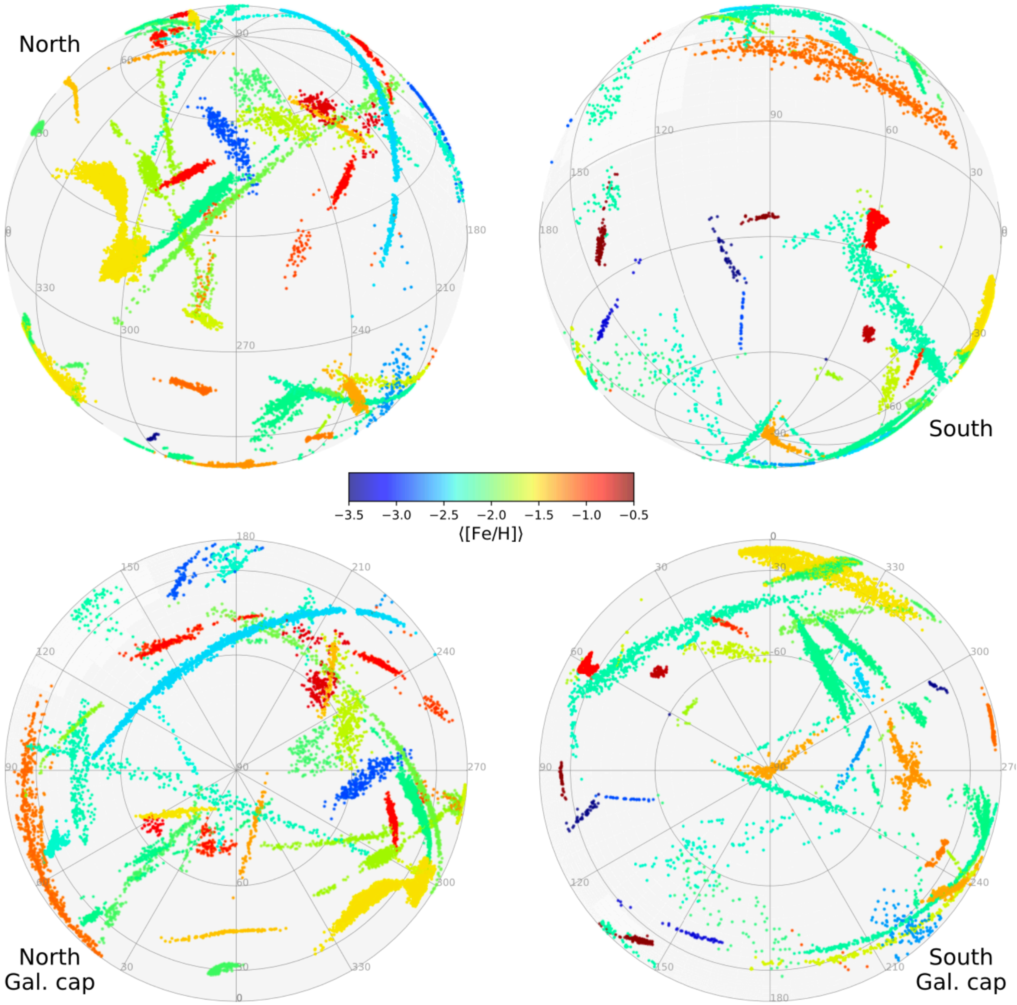
Laporte et al. 2018
(last pericentric passage of
Sgr dwarf at t=0)





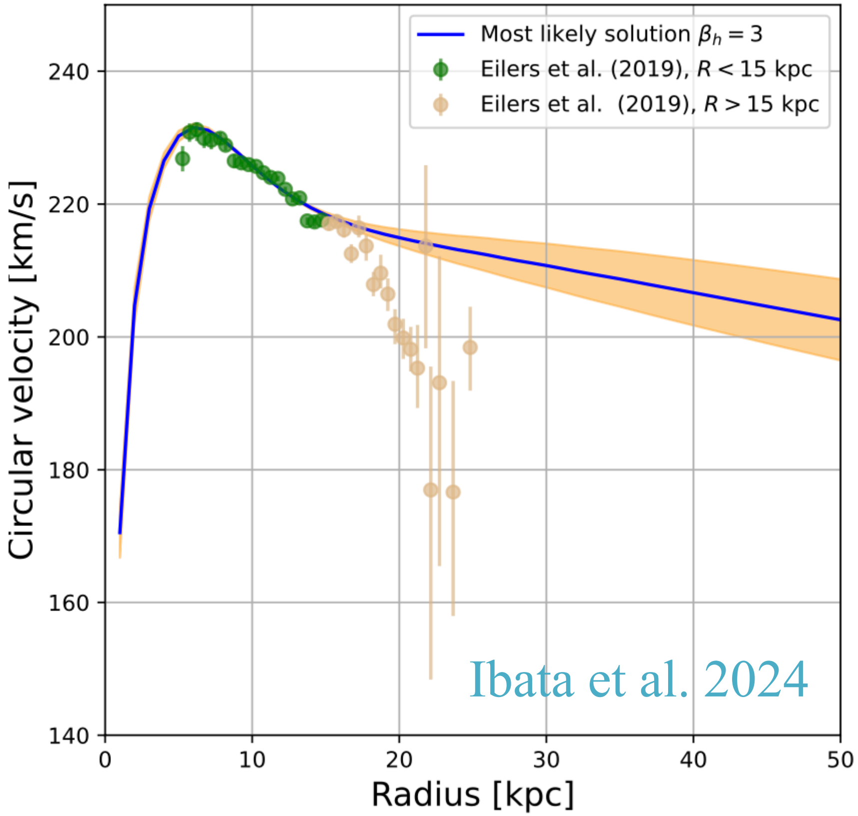
Koop et al. (2024)

Stellar streams



87 thin streams in Gaia DR3 (Ibata et al. 2024)

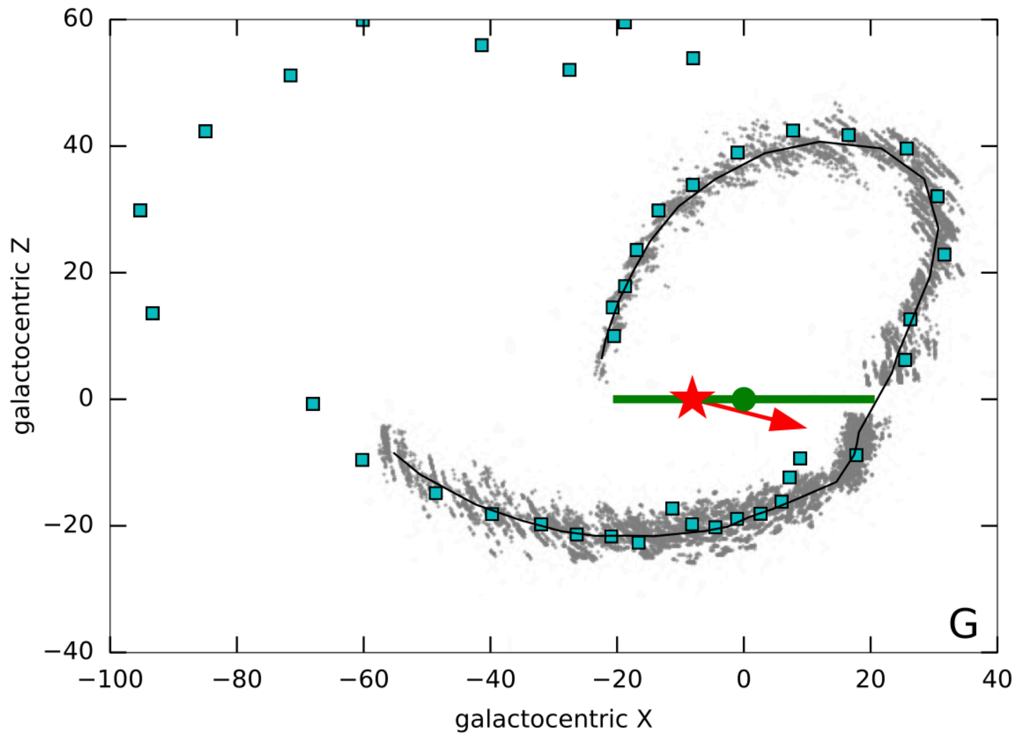
Stellar streams



Conservative sample of 29 thin streams in Gaia DR3 for the fit of the orbit corrected from test-particle sim

=> $M = 1.09^{+0.19}_{-0.14} \times 10^{12} M_{sun}$

The Sagittarius stream

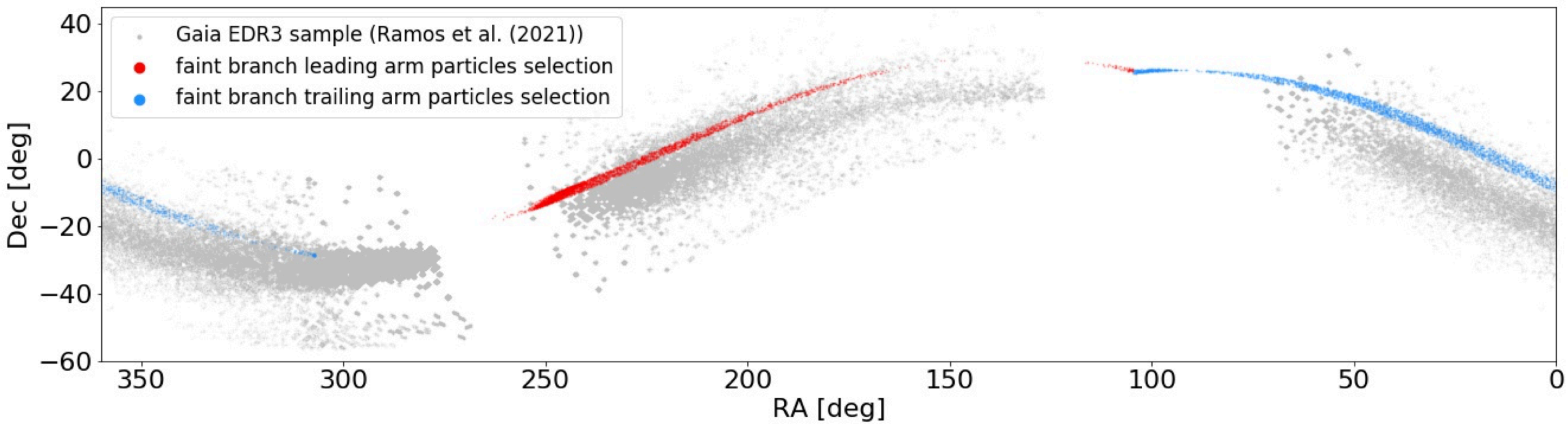


Velocities in the leading arm can be explained by a massive LMC (Vasiliev et al. 2021)

=> $M = 9.0 \pm 1.3 \times 10^{11}\ M_{sun}$

$M_{LMC} = 1.3 \pm 0.3 \times 10^{11}\ M_{sun}$

The Sagittarius stream

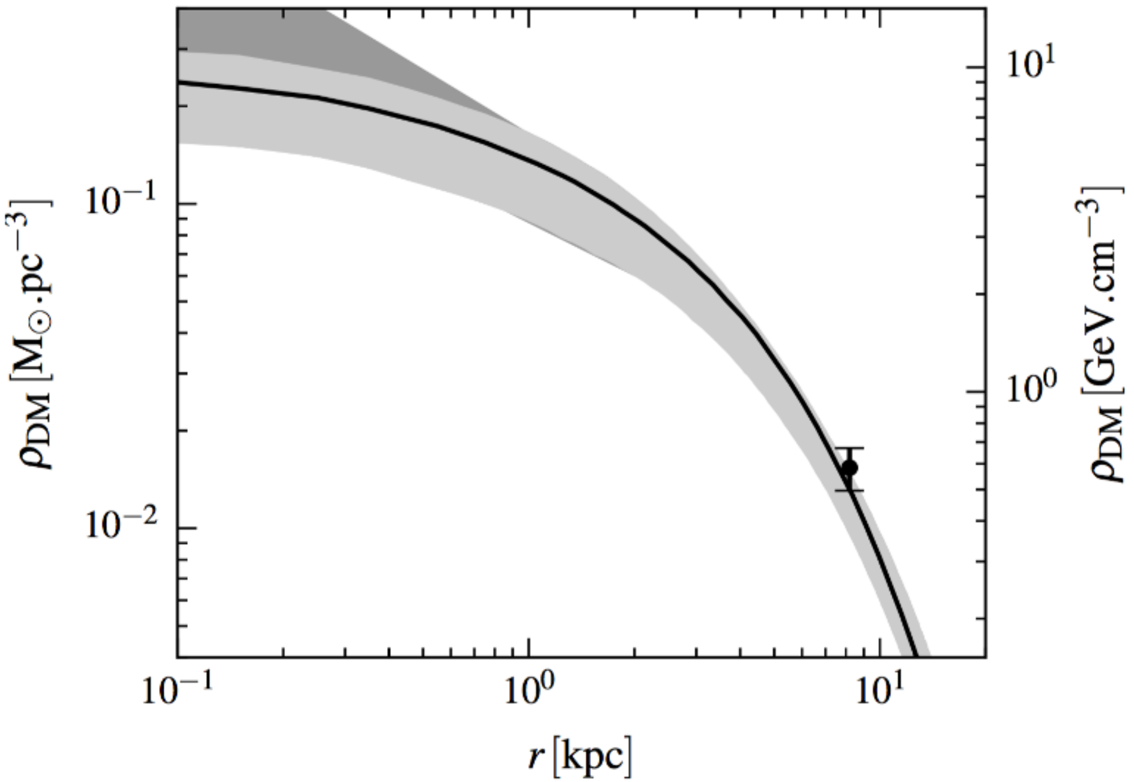


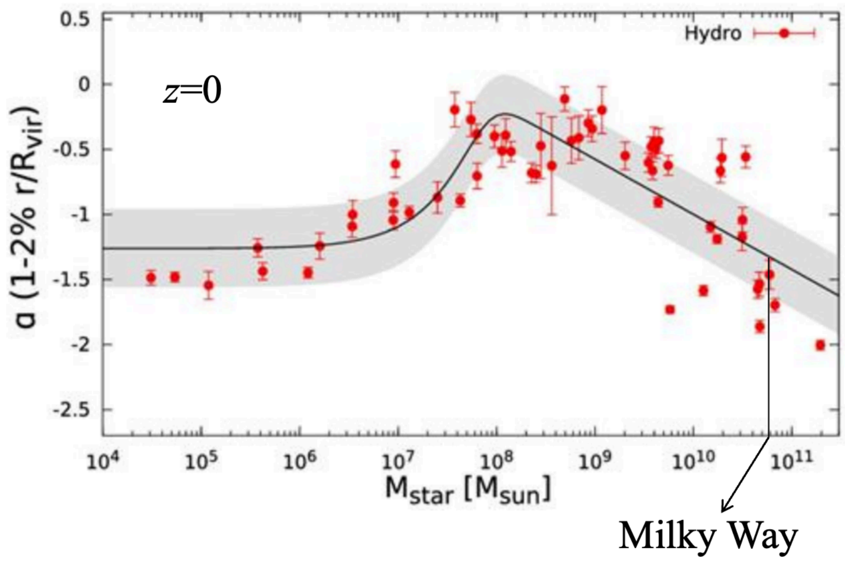
The bifurcation, originally understood as precession of the stream with successive wraps, imposes a very nearly spherical potential which doesn't work under the current best-fit potential:

tracing back particles => faint branch = originally disky distribution at t = -3 Gyr
(nearly perpendicular to both the MW disk and Sgr orbital plane)
(Oria et al. 2022)

Core or cusp ?

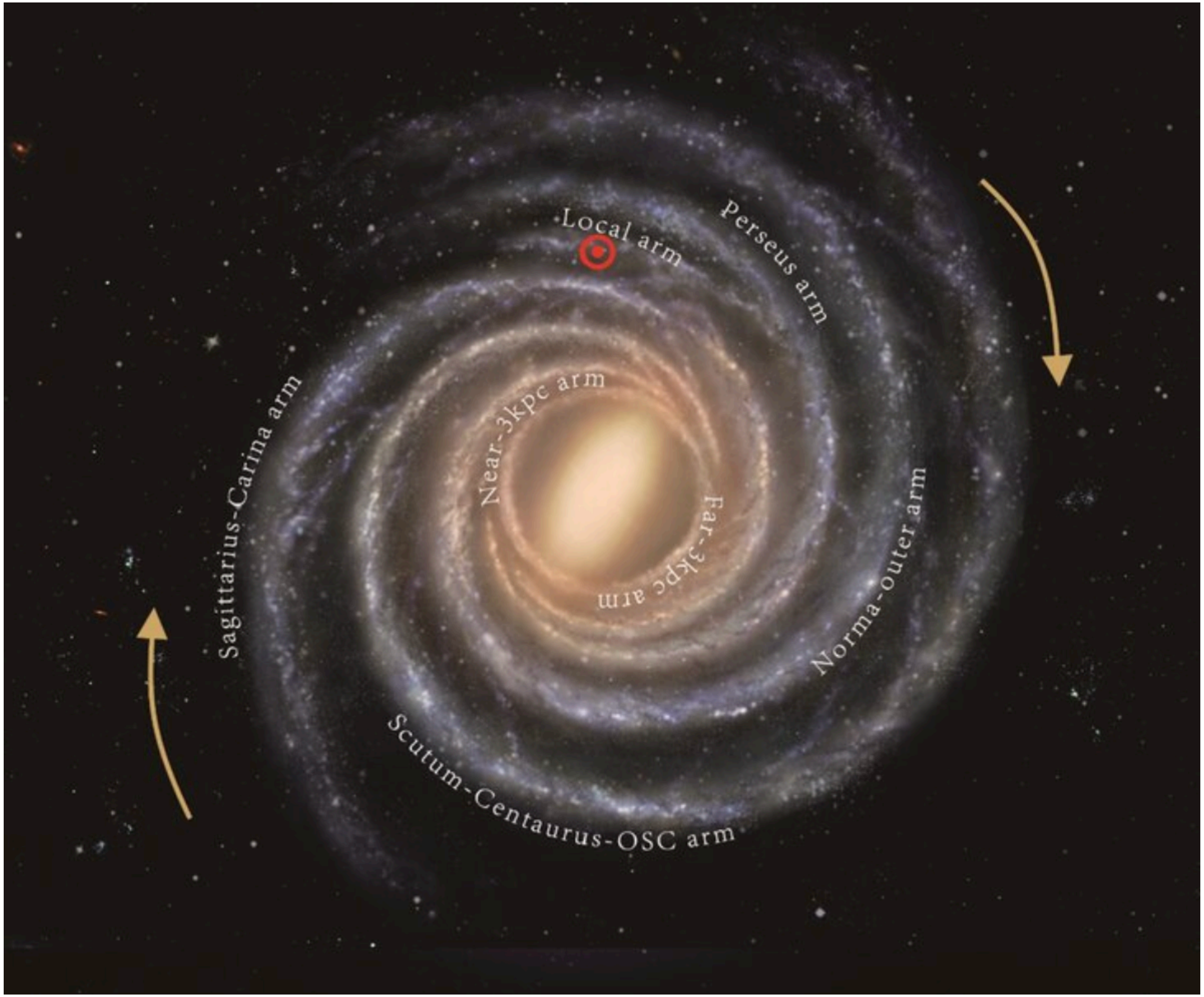
Constraints from inner rotation curve, z-structure of stellar disc, optical depths to microlensing of bulge stars + kinematics all point to a **core**, both in self-consistent axisymmetric (Cole & Binney 2017, Binney & Vasiliev 2023) and non-axisymmetric (Portail et al. 2017) models (combination of bar model and RC constraint between R=6 and R=8 kpc)





CORE

The bar and spiral arms



- The two most prominent non-axisymmetric features of the MW disk
- Play a leading role in terms of the secular evolution of the disk
- Structure and dynamics still poorly known/debated

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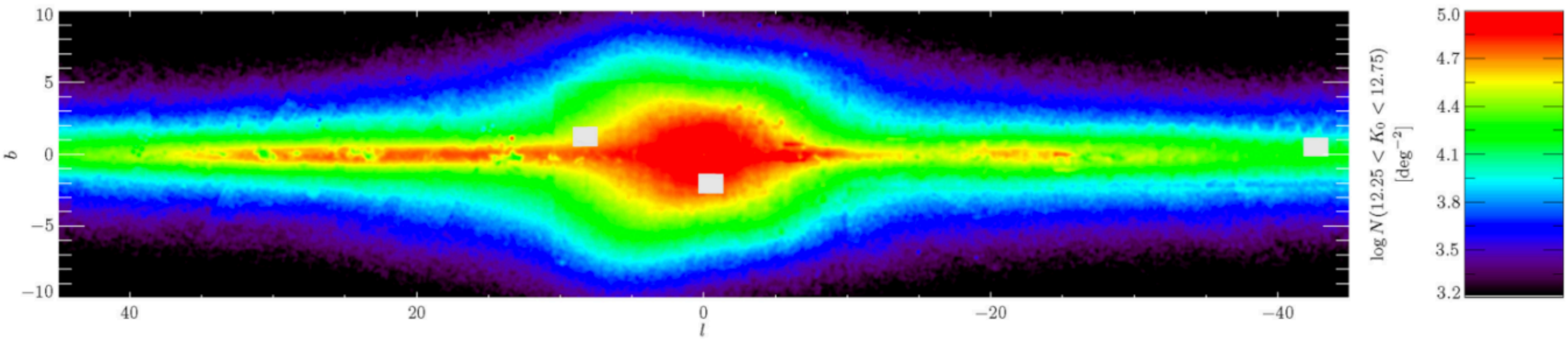
Bar: first hints from gas kinematics (de Vaucouleurs 1964; Peters 1975), confirmed in NIR observations (e.g., COBE; Binney et al. 1997)

Early estimates of the pattern speed as high as **60 km/s/kpc**

Discovery of a possible long bar extending beyond 5 kpc using RCG star counts (Wegg et al. 2015) + simulations of bulge kinematics (BRAVA, ARGOS + VIRAC proper motions) => much lower pattern speed

Some recent estimates from APOGEE-Gaia (Horta et al. 2024) as low as **24 km/s/kpc**…



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

VIRAC PMs

1.75 x 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)

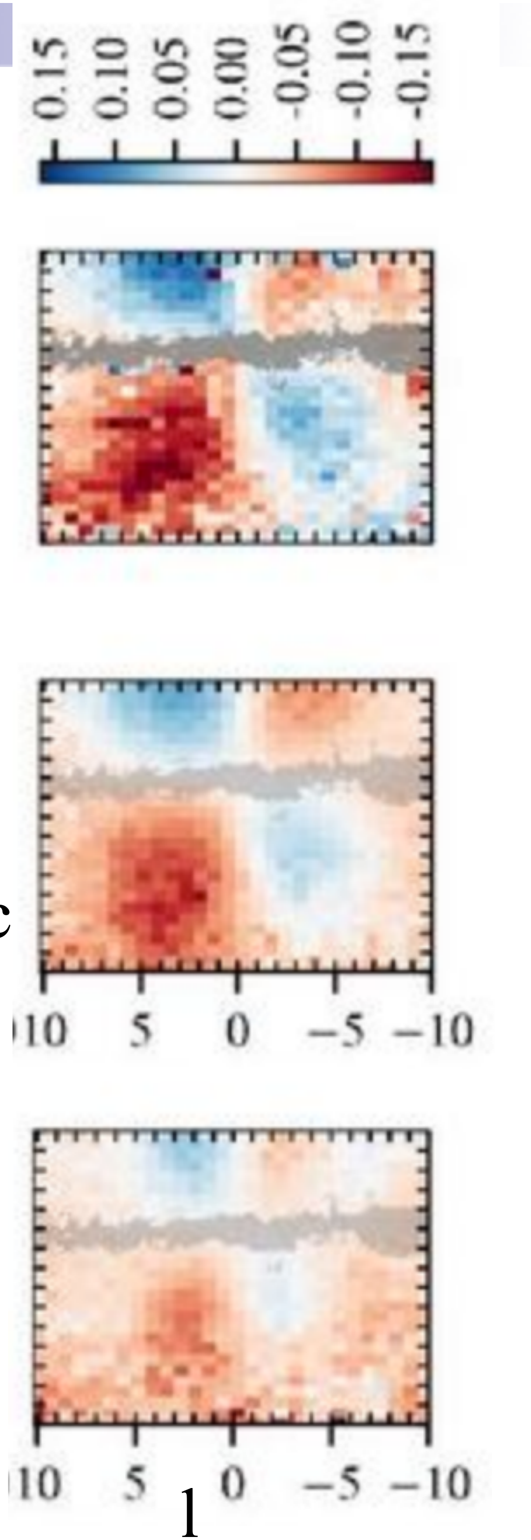
See also Sanders et al. (2019)
+ e.g. Monari et al. (2019)
+ Binney (2020) for local kinematics

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

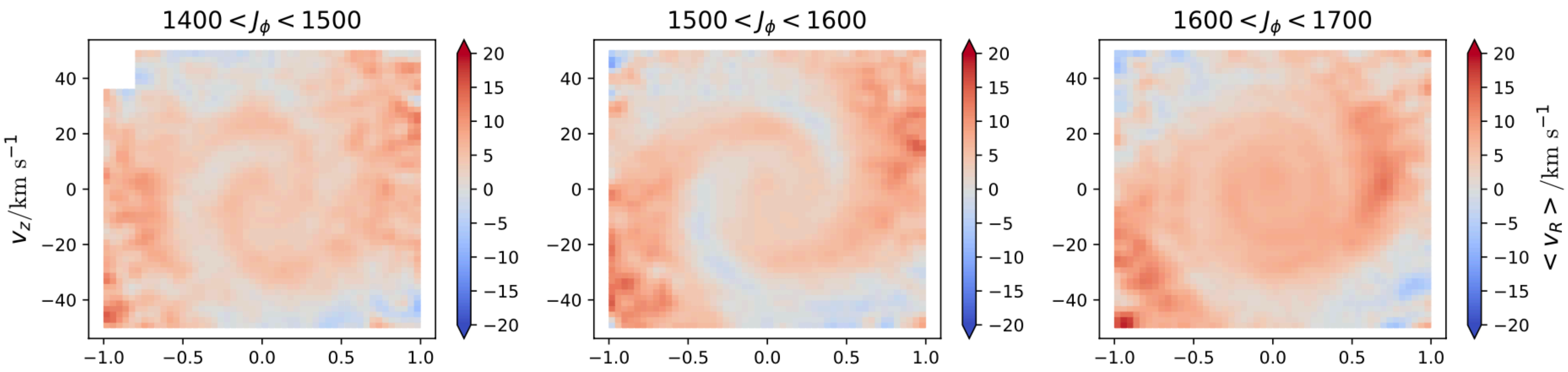
b

37.5 km/s/kpc

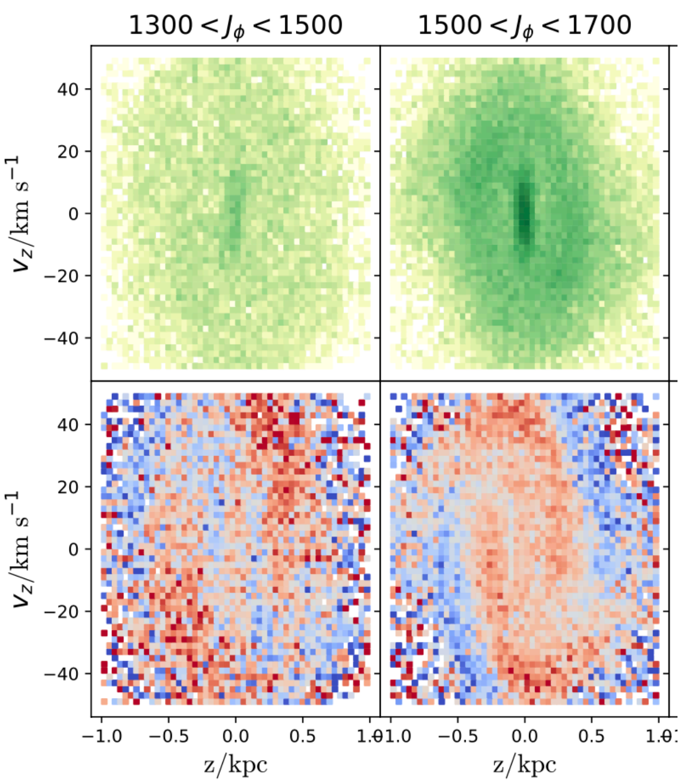
50 km/s/kpc



A decelerating bar?



Li et al. (2023) Gaia DR3 RVS
Two-armed phase spiral!



<= decelerating bar toy-model (no Sgr)

Also claimed by Chiba & Schönrich (2021) but possible degeneracy with spiral arms to be explored

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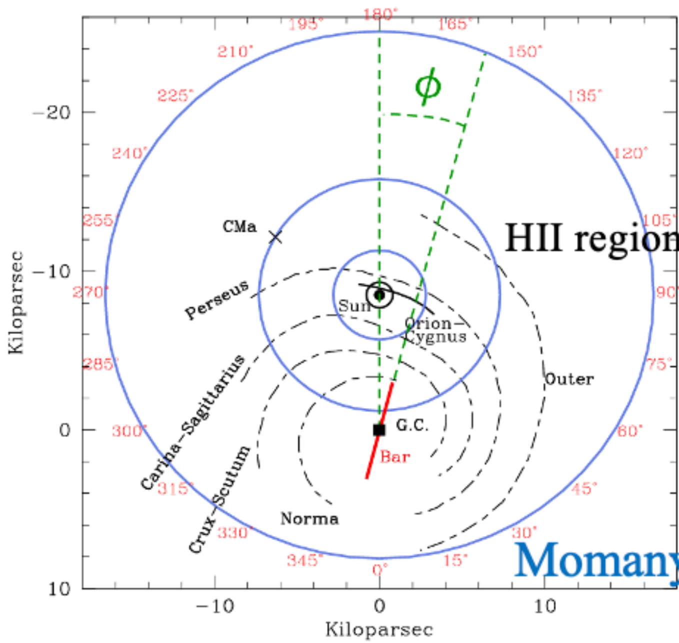
Spiral arms: first hints from HII regions (Morgan et al. 1952), confirmed from multiple tracers since then (young stars, OB associations, GMCs, HI kinematics, but also with NIR to mid-IR tracers), pointing to **different structure, number of arms, amplitudes**, etc. depending on tracers



HII regions spirals

Momany et al. (2006)

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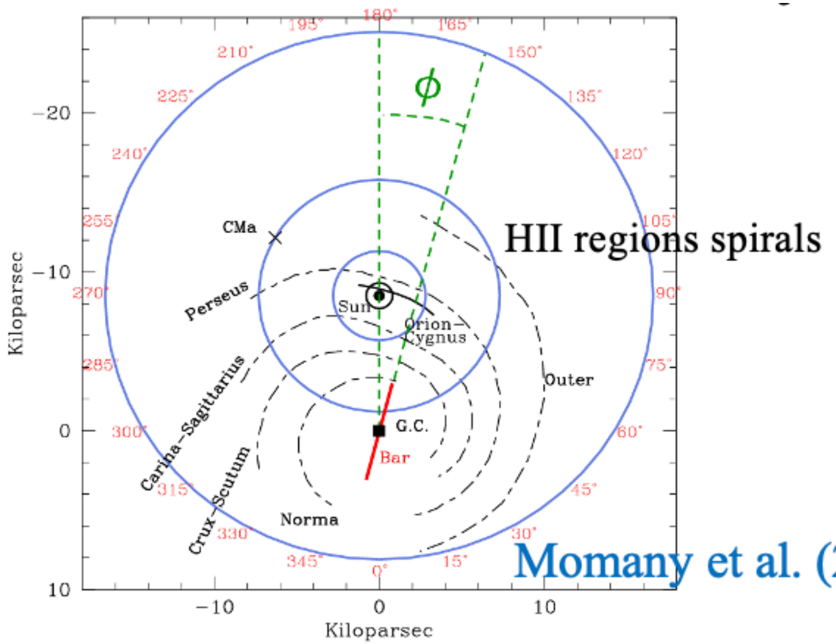
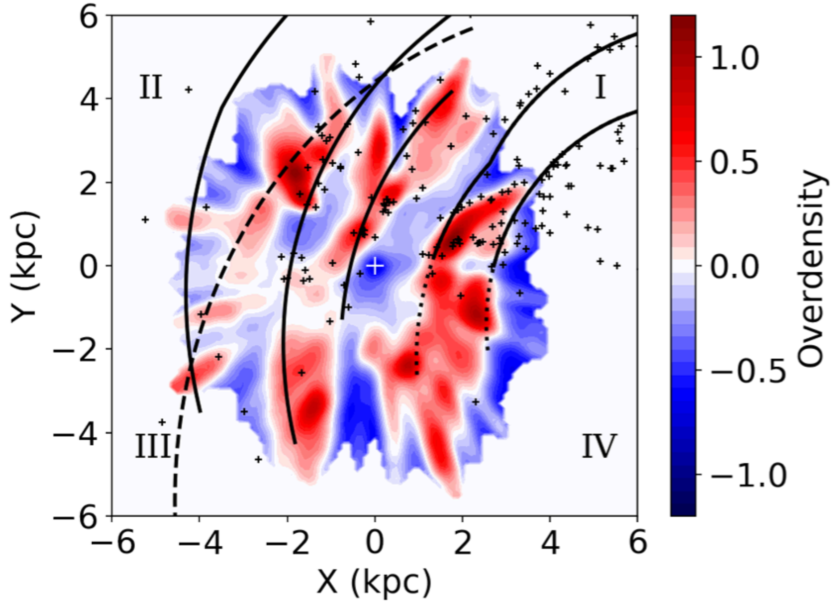


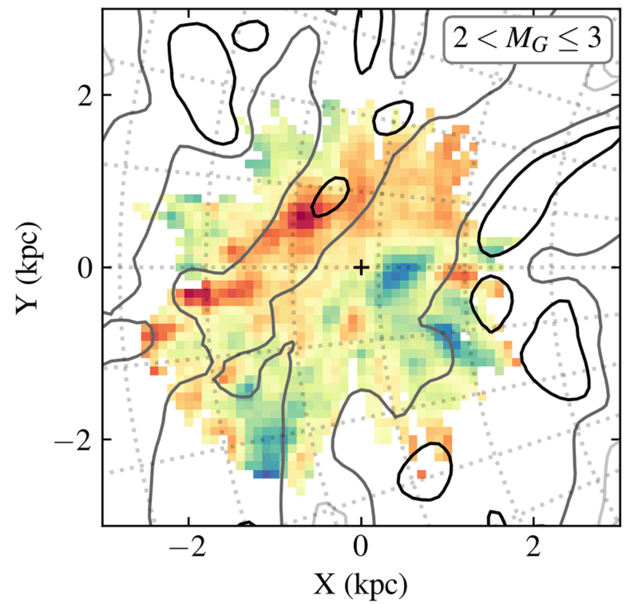
Momany et al. (2006)

Pattern speed(s) even less clear : Amaral & Lépine (1997) m=2 + m=4 with **20 km/s/kpc**
Siebert et al. (2012) m=2 spiral fit to RAVE data with pattern speed of **18.6 km/s/kpc**
Castro-Ginard et al. (2021) integrate backward OCs to their birthplace and find decreasing pattern speeds with radius from **50 km/s/kpc** (Scutum) to **17 km/s/kpc** (Perseus)

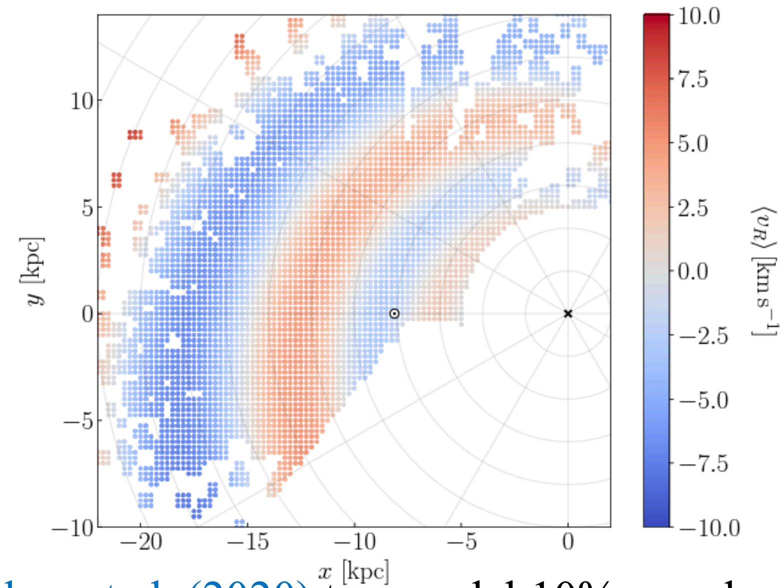
Non-axisymmetries with Gaia

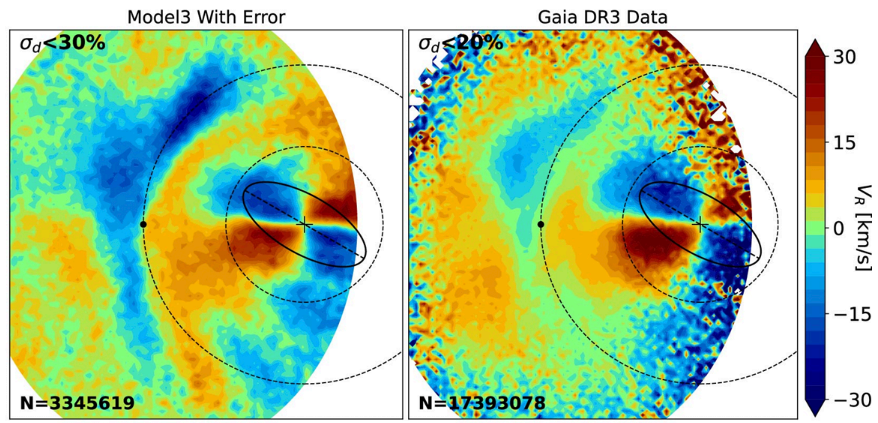


Young upper main-sequence stars (Poggio et al. 2021)



Widmark & Naik (2024) Jeans modelling detects Local arm with 20% overdensity



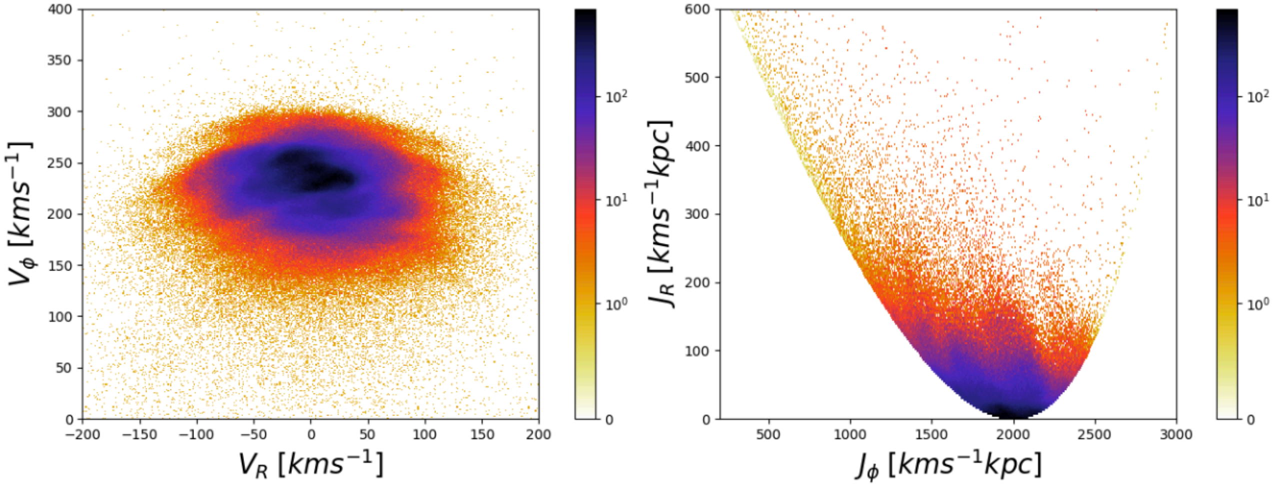


Vislosky et al. (2024) compare directly to a simulation

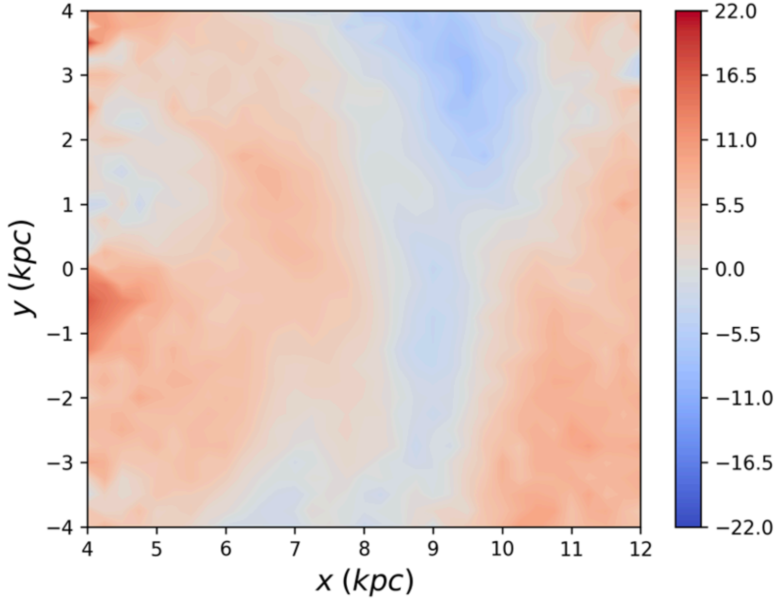
Eilers et al. (2020) toy-model:10% overdensity for Local arm, fixing 12 km/s/kpc

Non-axisymmetries with Gaia

Given the exquisite quality of Gaia data, can we fit it a bit more in detail?



~10^6 stars within 200 pc



~1.3 x 10^7 stars from Gaia DR3 RVS and StarHorse distances

General idea: start from an equilibrium $f_0(\mathbf{J})$ (à-la-Binney & Vasiliev) model and perturb it

Backward integration

The analytical treatment of multiple perturbers is limited to very small regions of phase space (maximally trapped orbits + no resonance overlap)

=> backward integrations: conservation of the DF in infinitesimal phase-space patches following the Hamiltonian flow, which allows us to compute the current DF by integrating orbits backward in time to an axisymmetric equilibrium state, $f_0(\mathbf{J})$

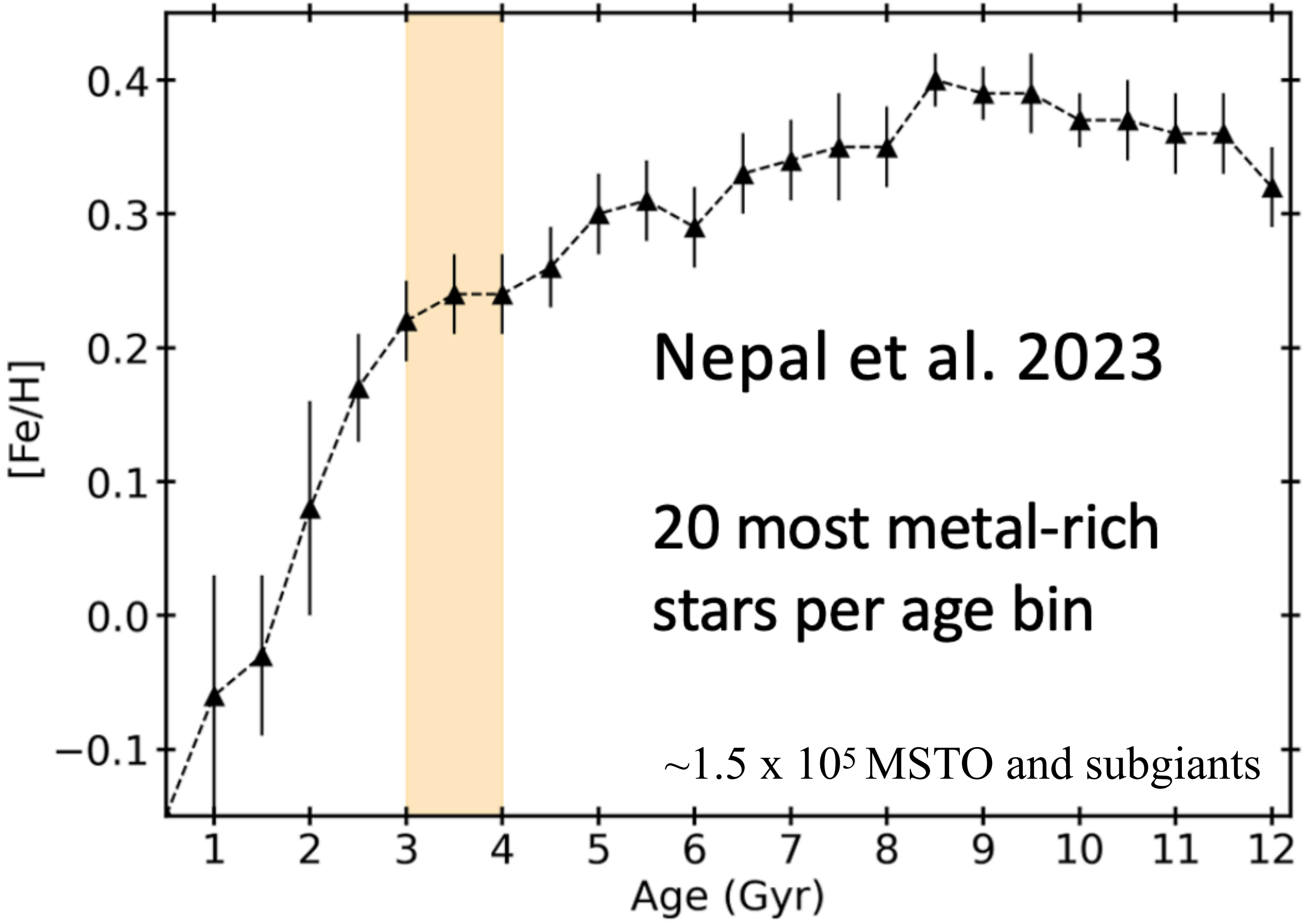
$$f_{\mathrm{T}}(p_1, t_1) = f_{\mathrm{T}}[p(t_0), t_0]$$

Vauterin & Dejonghe (1997)

Yassin's talk

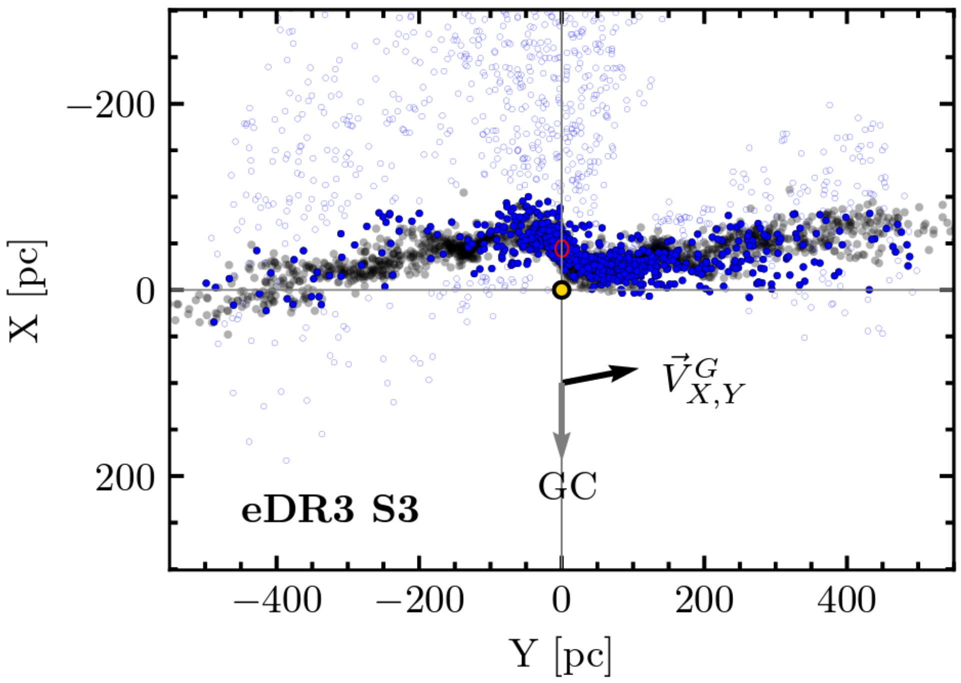
Age of the (end of growth of) the bar ?

A slowing-down bar would imply a relatively old bar. But what happened in the last 3 Gyr ?



Disk tidal streams: a new probe

With Gaia, tidal tails of open clusters in the disk have started being discovered (combination of exquisite Gaia data and detailed N-body simulations)



Jerabkova et al. (2021)

The bar exerts torques on orbits

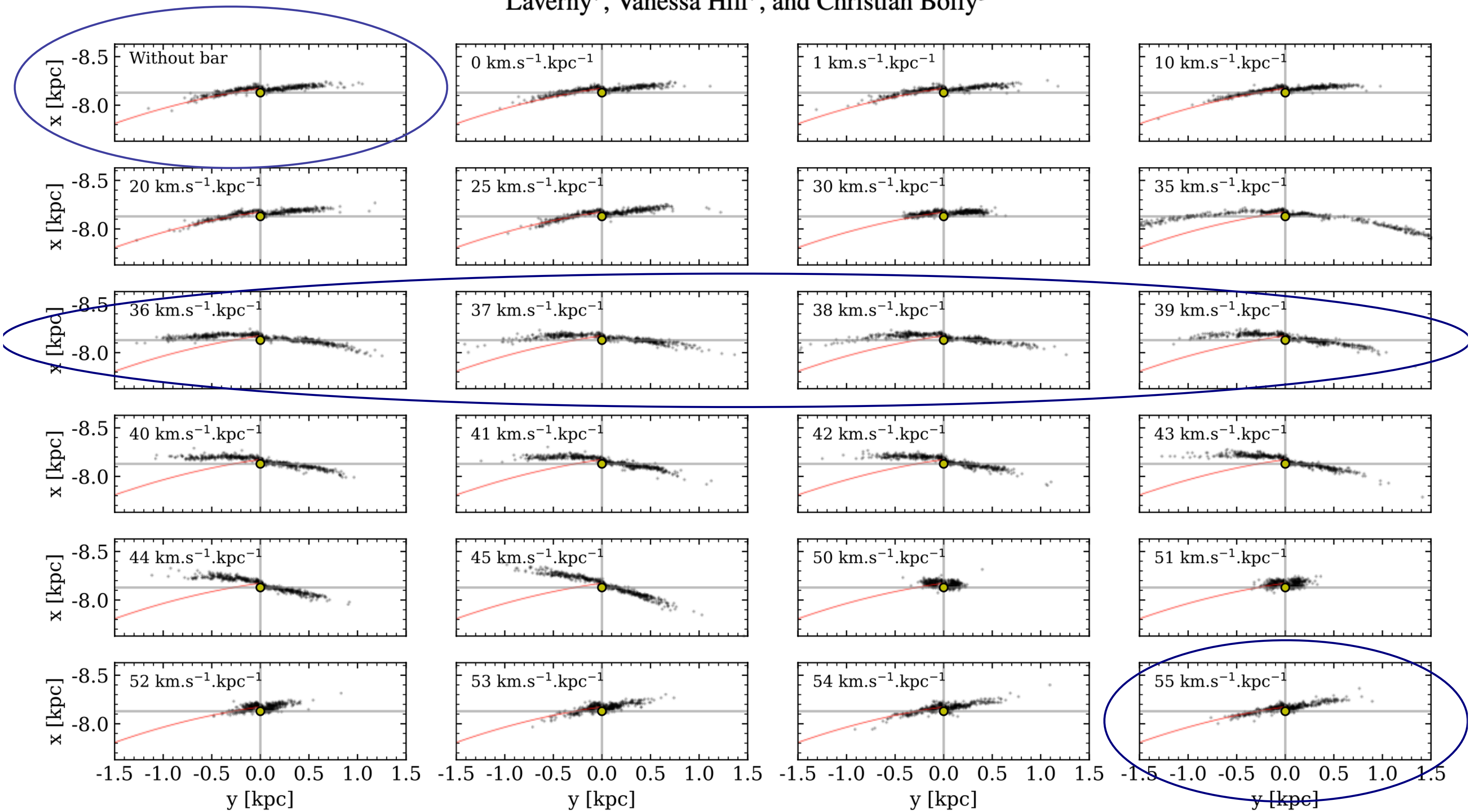
- $L_z = J_\phi$ conserved in axisymmetric potentials but not in a barred one
- Oscillation especially important at resonances (remember that J_ϕ then oscillates as a pendulum)
- Because of conservation of Jacobi integral $E_J = E - \Omega_b J_\phi$, variations of J_ϕ also imply variations of energy

⇒ ***« shepherding » of streams*** (Hattori et al. 2016) : depending on the phase of the orbit, the amount of angular momentum and energy variations is different

⇒ differential changes imply different orientations (through differential angular momentum changes) and spread (through differential energy changes) of the streams

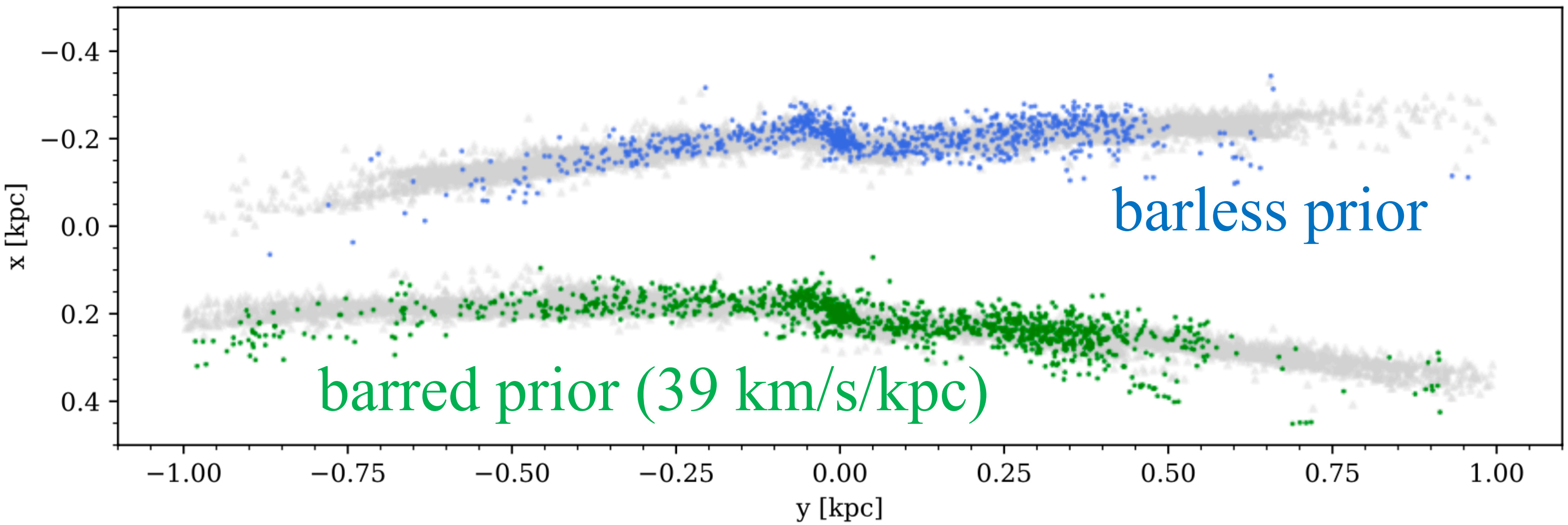
Shepherding the Hyades stream

Guillaume F. Thomas[1,2], Benoit Famaey[3], Giacomo Monari[3], Chervin F. P. Laporte[4,5,6], Rodrigo Ibata[3], Patrick de Laverny[7], Vanessa Hill[7], and Christian Boily[3]



Shepherding the Hyades stream

Bayesian membership selection from photometric filtering + kinematics



- Both selections well populated => stars from the disc having similar photometry/dynamical properties as Hyades > number of stars from stream itself

- Needs to add spirals

- Needs HR chemical labelling ! (Li at $5000\ K < T_{eff} < 6500\ K$)