A panoramic photograph of the Galactic bar from long-period variables

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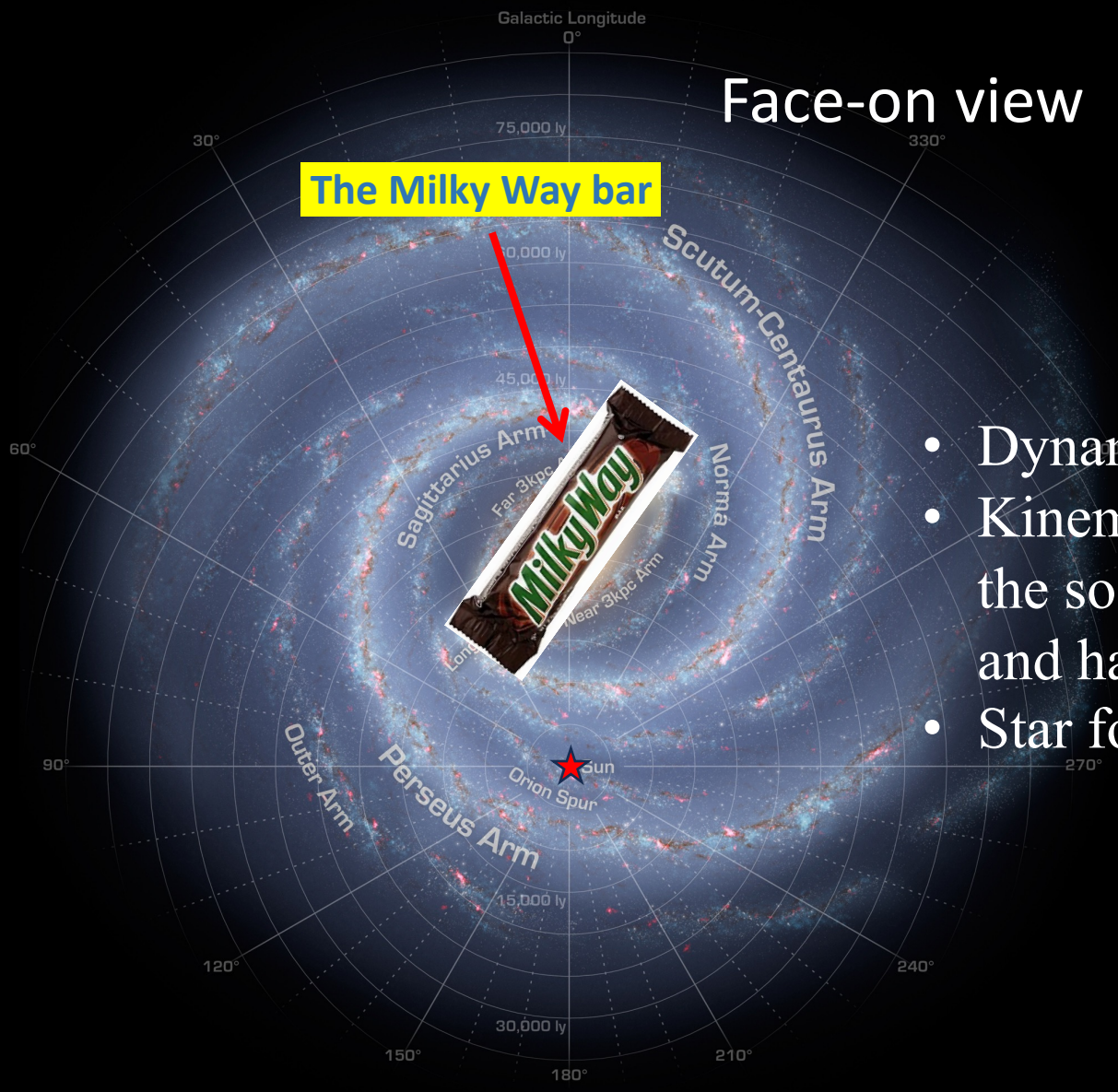
ioa

1) Zhang et al. 2024, MNRAS, 533, 3395–3414, arxiv: 2406.06678

2) Zhang et al. 2024, submitted, arxiv:2408.16815

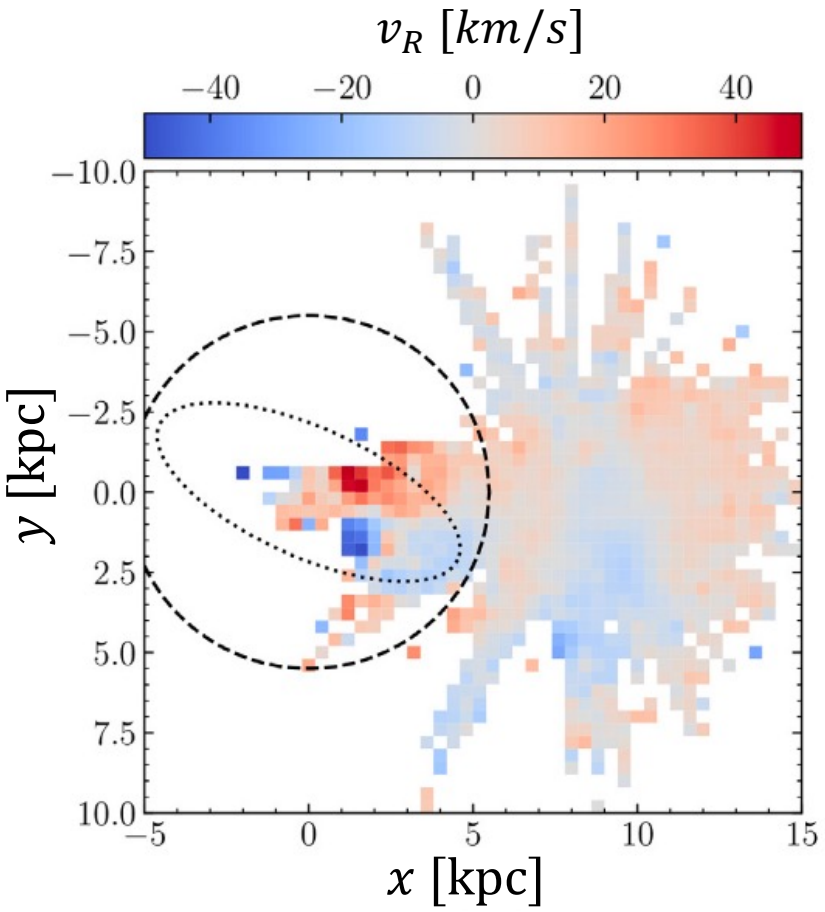
Structures at the inner Galaxy



- Dynamics at the inner Galaxy
- Kinematic and equilibrium in the solar neighbourhood, disc, and halo
- Star formation history

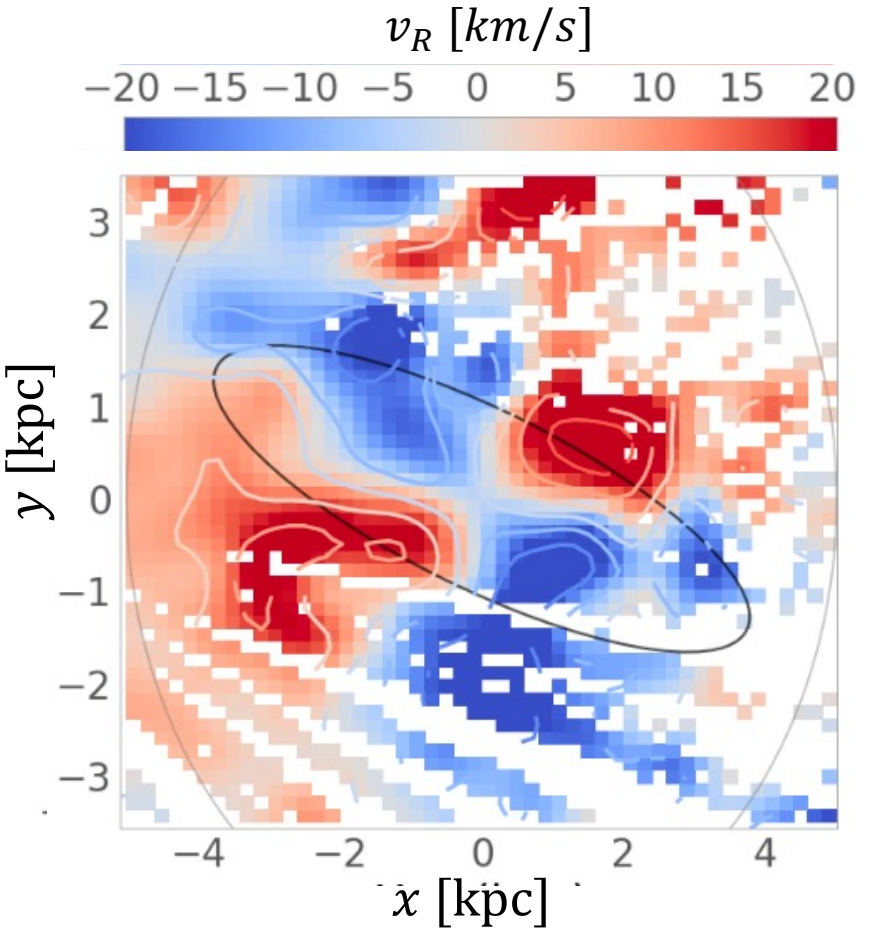
Previous “photographs” of the Galactic bar:

Bovy+19, Queiroz+21 using spectroscopic distances



Bovy+19: APOGEE-AstroNN distances

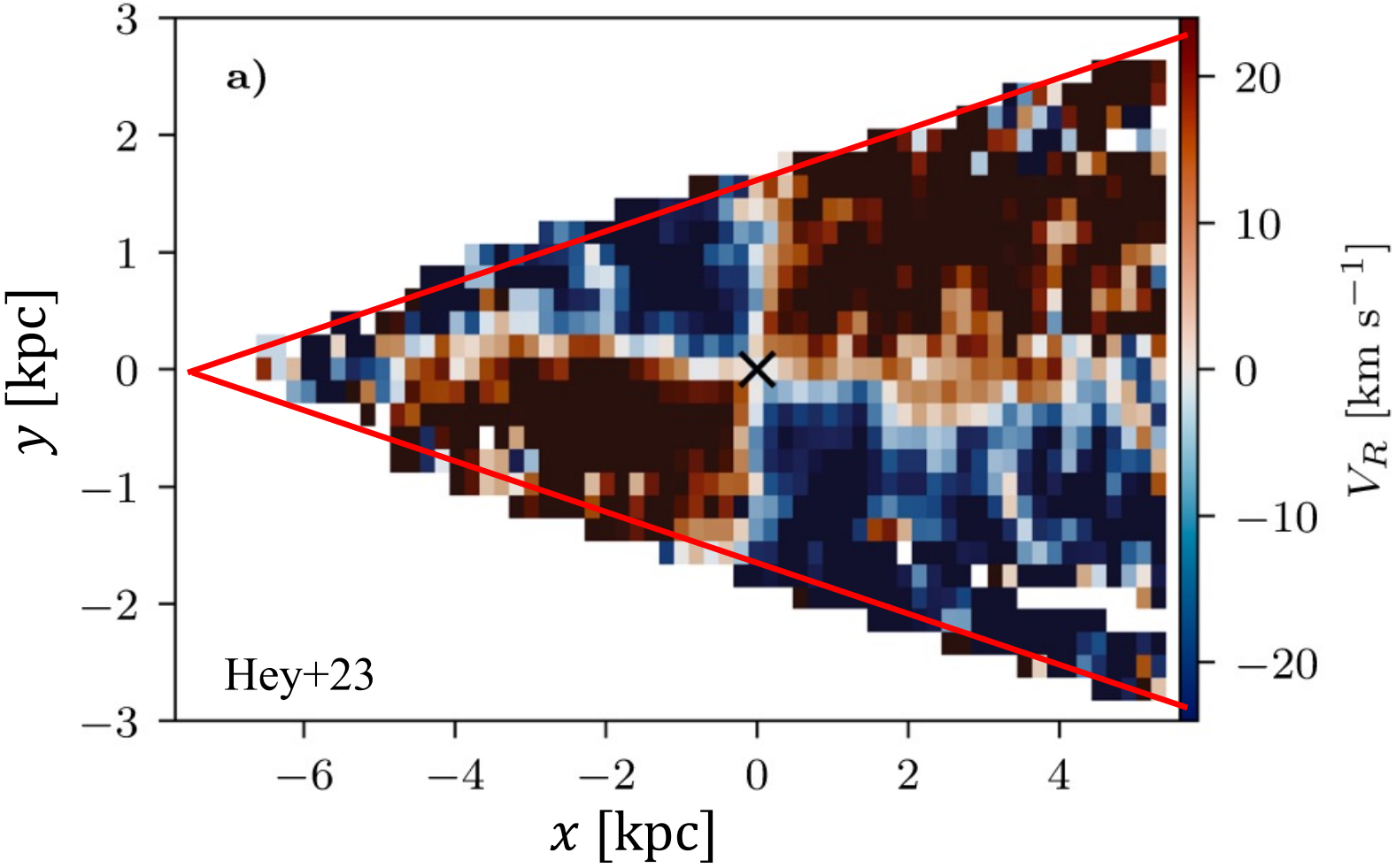
Also see Leung+23 for an updated version



Queiroz+21 : APOGEE-StarHorse distances

Previous “photographs” of the Galactic bar:

Hey+23 using semi-regular variables in the OGLE survey

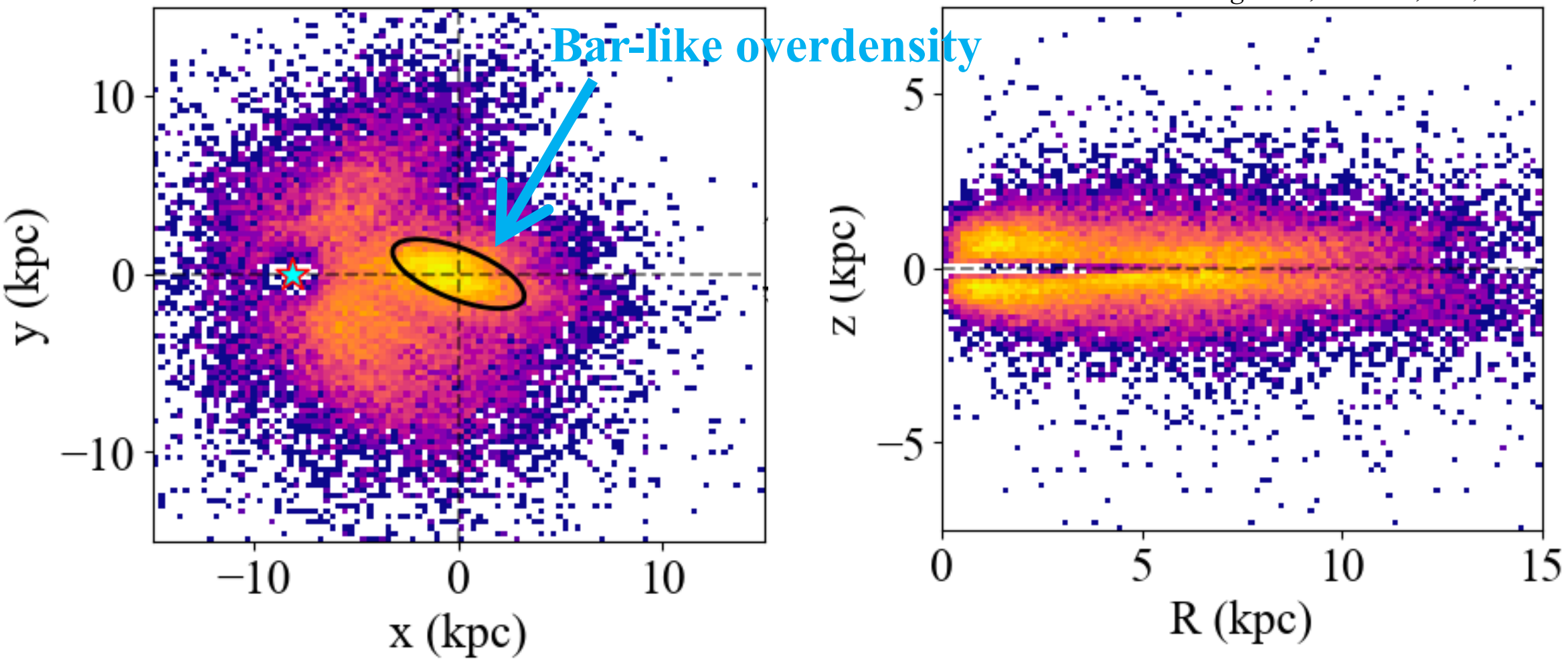


Low-amplitude, Long-period variable (LA-LPV)

- It is also called OGLE Small Amplitude Red Giants (OSARG)
- Long-period: $P \sim 10 - 100\ day$ (SRV and Mira usually have period ≥ 100 days)
- Smaller amplitude: $\Delta G \sim ? - 0.2\ mag$ (SRV and Mira usually have $\Delta G \geq 0.15\ mag$)
- LA-LPV has compact period-luminosity relation resulting in a luminosity distance assignement with uncertainty of $10 - 15\%$ (similar uncertainty to Mira and RRL)
- Better than Mira: LA-LPV has well measured line-of-sight velocity in Gaia DR3 already due to its smaller pulsation amplitude

Spatial distribution of LA-LPV in this sample

Zhang et al., MNRAS, 533, 3395–3414



~34000 stars with full 6D phase space measurements & ~20000 are in the inner 5 kpc

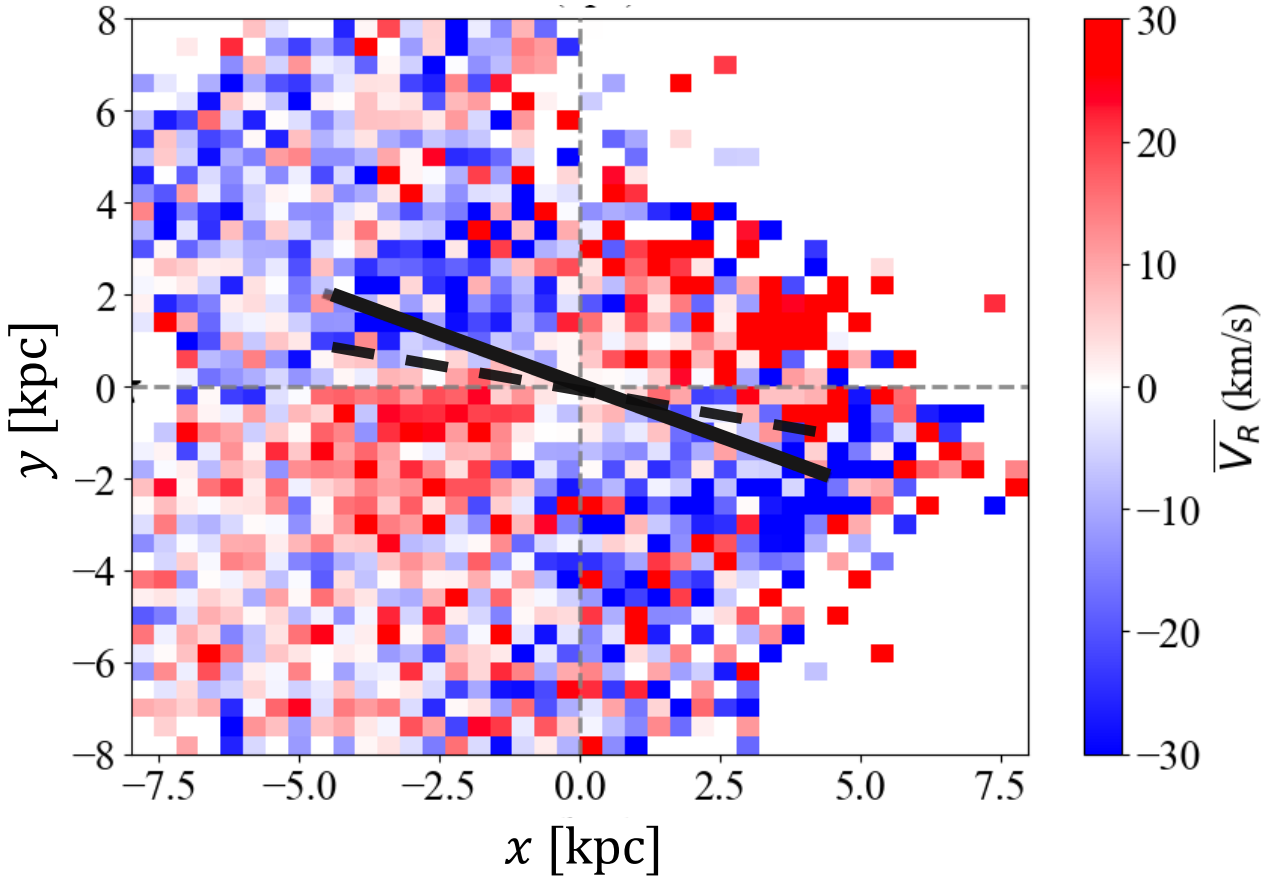
Kinematics of the LA-LPV sample

Bar signature: Quadrupole v_R pattern

- Quadrupole pattern seen due to the streaming motion of the bar (Bovy+ 19)

- Sign-switching line biased towards the Sun-GC (Galactic centre) line due to the distance uncertainty

  (see Hey+23; Vislosky+24; Liao+24)



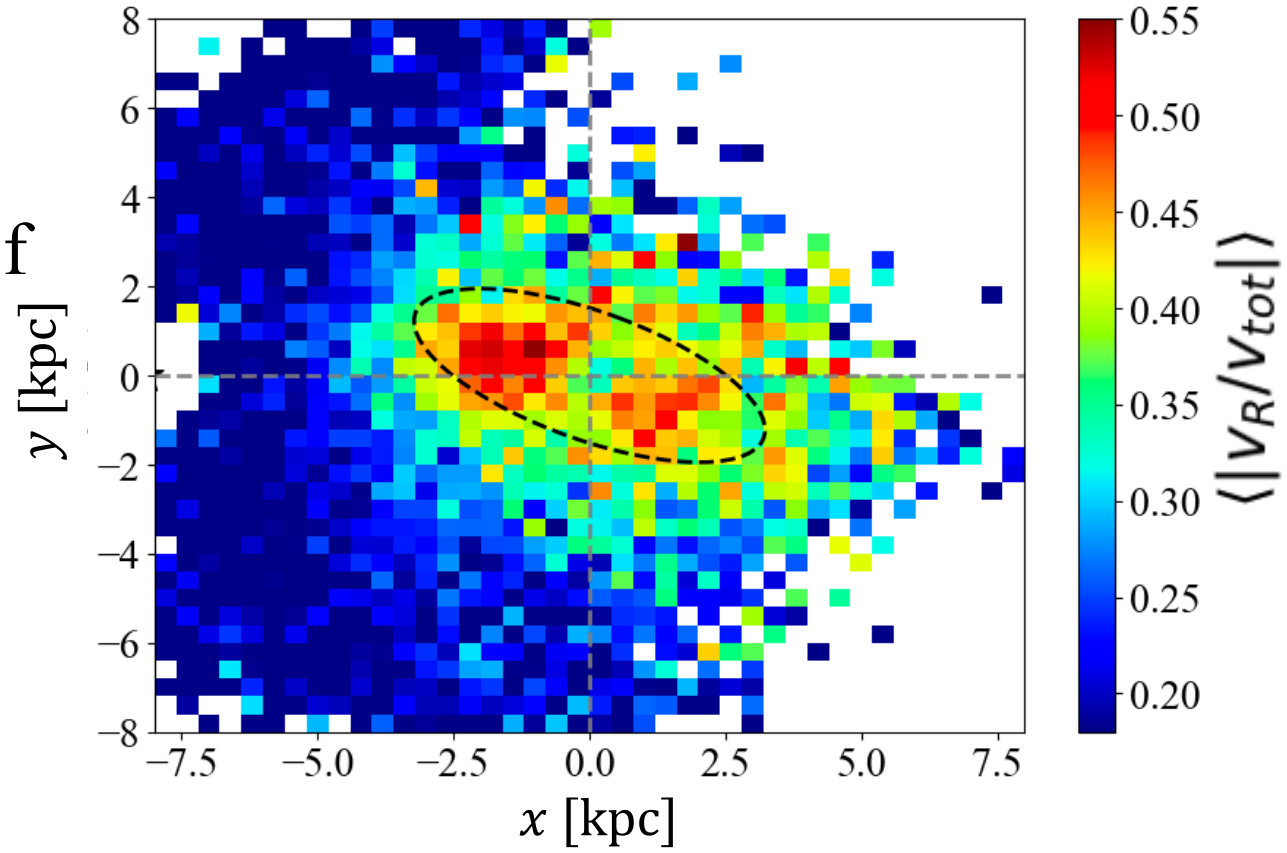
Kinematics of the LA-LPV sample

$$\left\langle \left| \frac{v_R}{v_{\rm tot}} \right| \right\rangle = \frac{1}{N} \sum_j^N \frac{|v_{R,j}|}{v_{{\rm tot},j}},$$

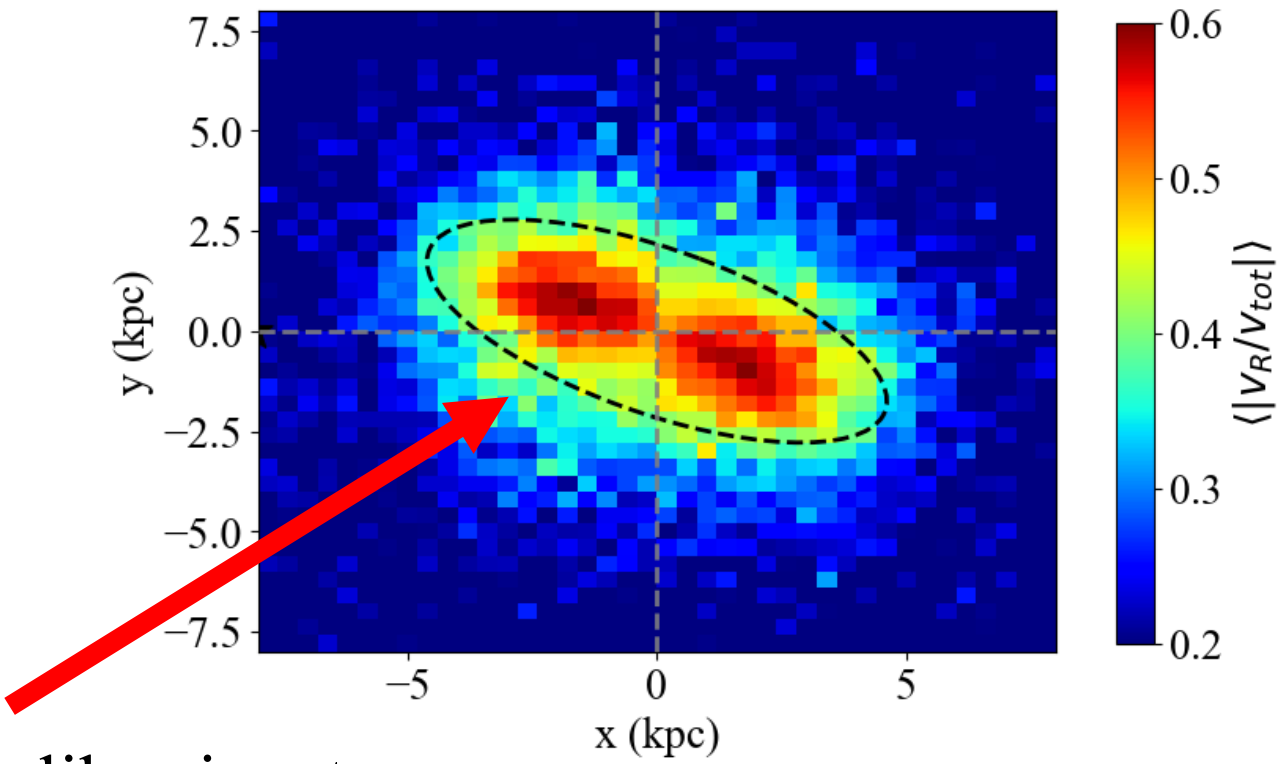
- High value is expected in the bar region due to the orbital structures of bar-supporting stars

- Less biased by the distance uncertainty as $\langle |v_R|/v_{tot} \rangle$ is a dimensionless quantity

Bar signature: $\langle |v_R|/v_{tot} \rangle$ *map*

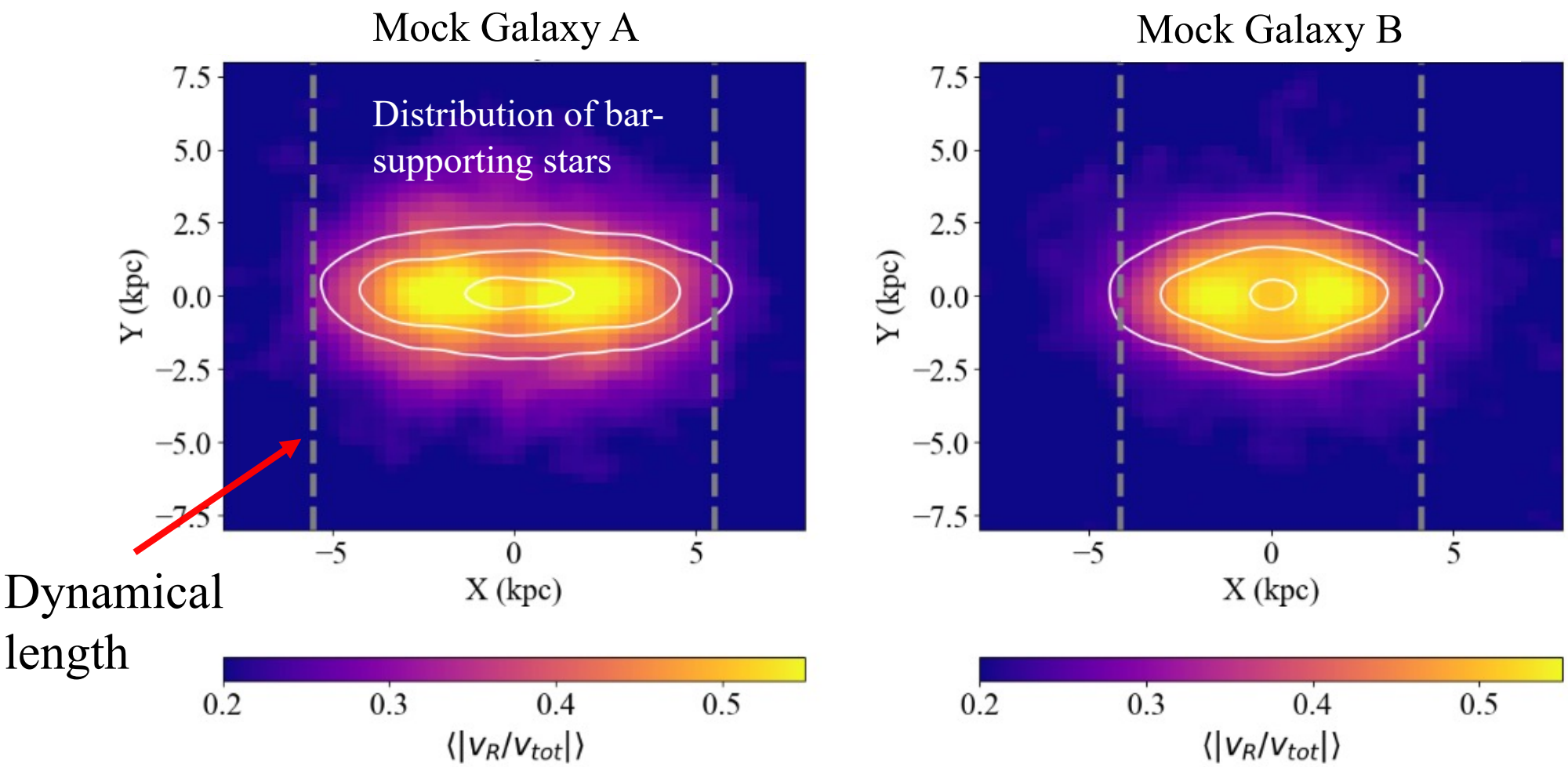


$|v_R/v_{tot}|$ map in a N-body simulated Galaxy



A bi-symmetric bar-like signature

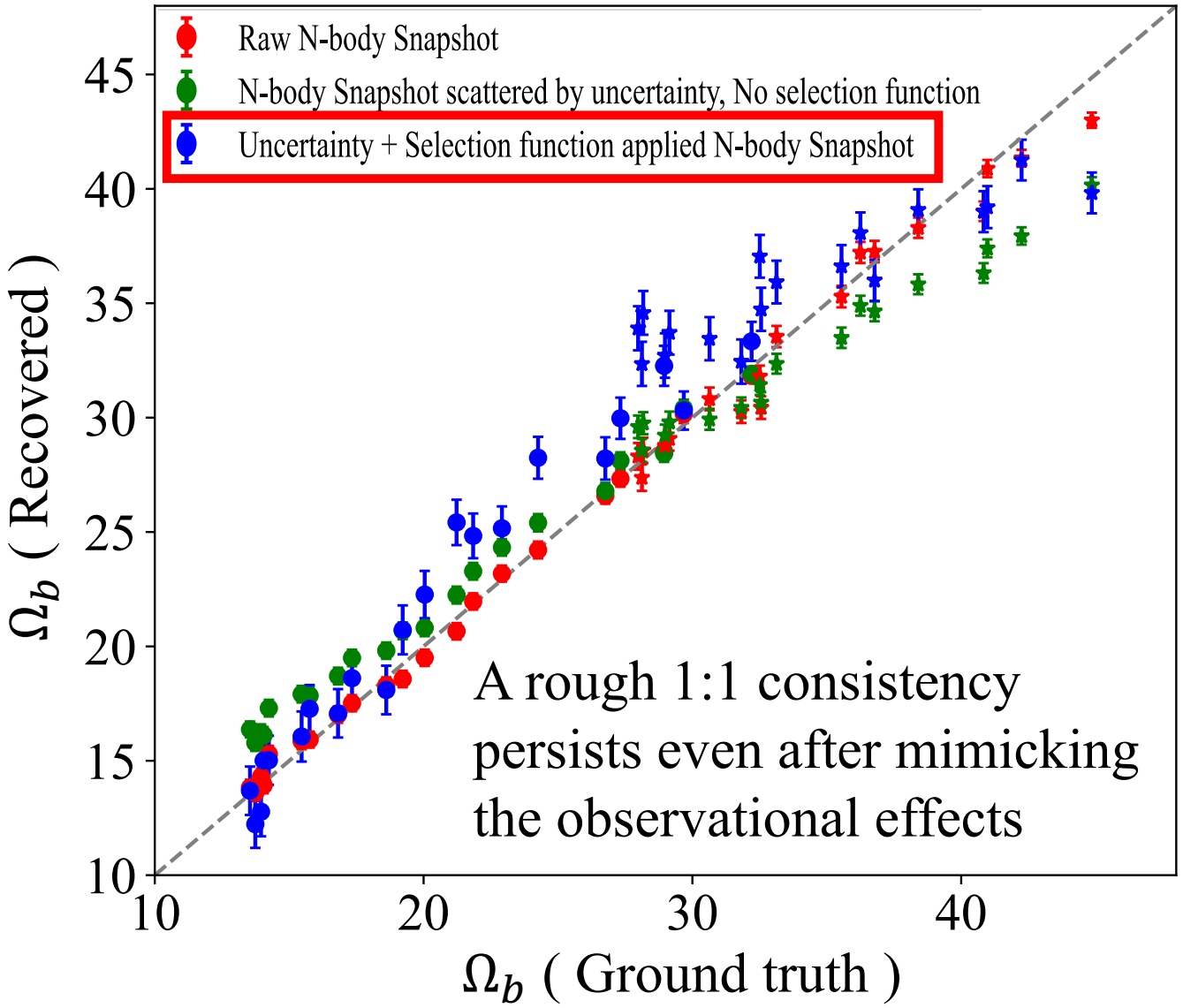
$|v_R/v_{tot}|$ map as a tracer of the bar-supporting stars



- Bar-supporting stars distributed similarly to the signal in the $|v_R/v_{tot}|$ map
- Can be used as an estimator of the dynamical length of the MW bar → 4.0 kpc

Also see Petersen+24 for a similar method that is applicable for extragalactic observations

Estimation of the pattern speed using Dehnen+23's method



Designed for simulation;
Introducing distance uncertainty and selection function typically lead to bias

Apply to the LA-LPV sample

$\boldsymbol{\Omega_b \sim 34.1 \pm 2.4\ km\ s^{-1} kpc^{-1}}$

for the Milky Way bar

Consistent to other observations using different methods (see Dillamore+23,24; Clarke&Gerhard 22, etc.)

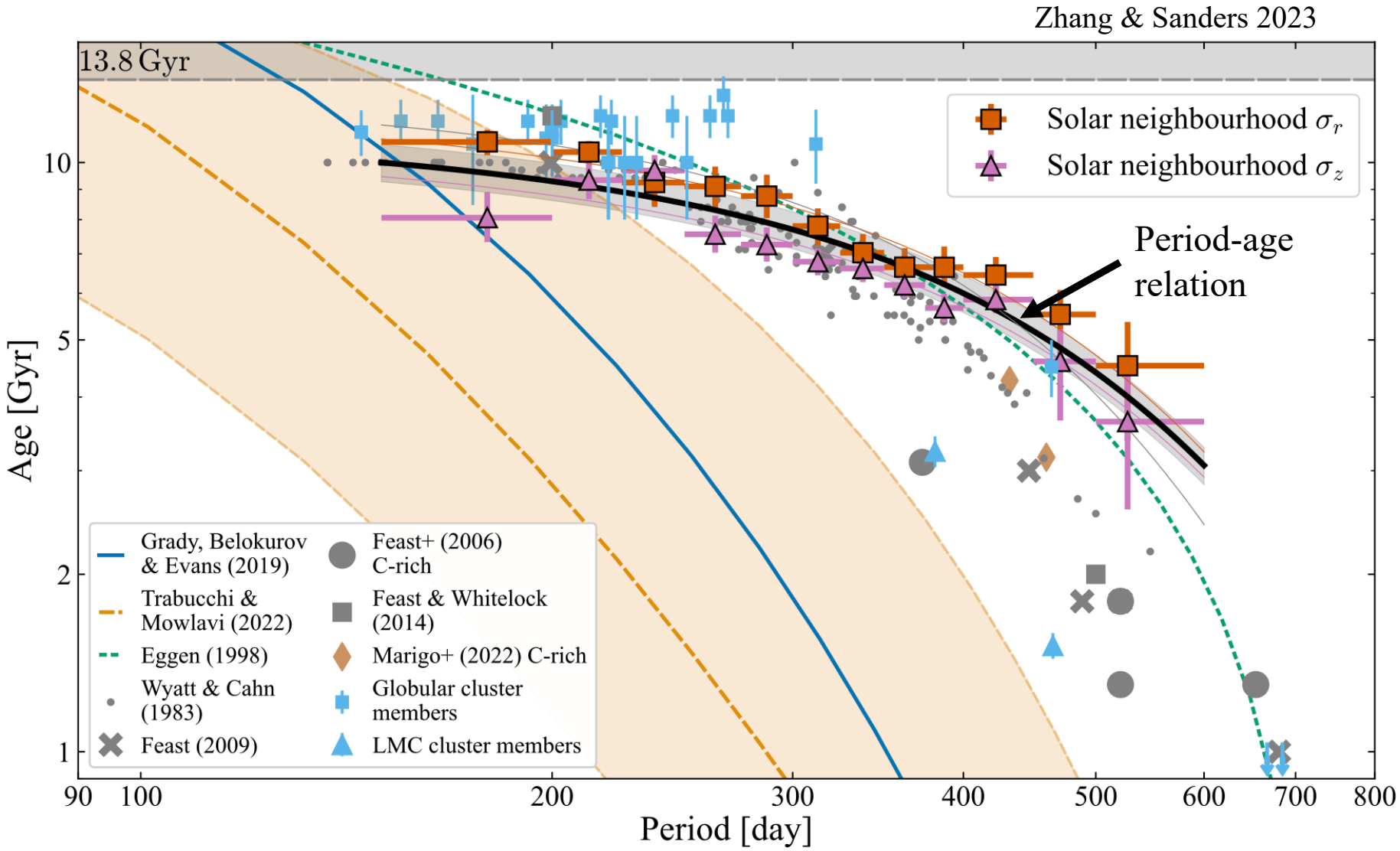
Timing the Galactic disc formation through bar chrono-kinematics

2) Zhang et al. 2024, submitted, arxiv:2408.16815

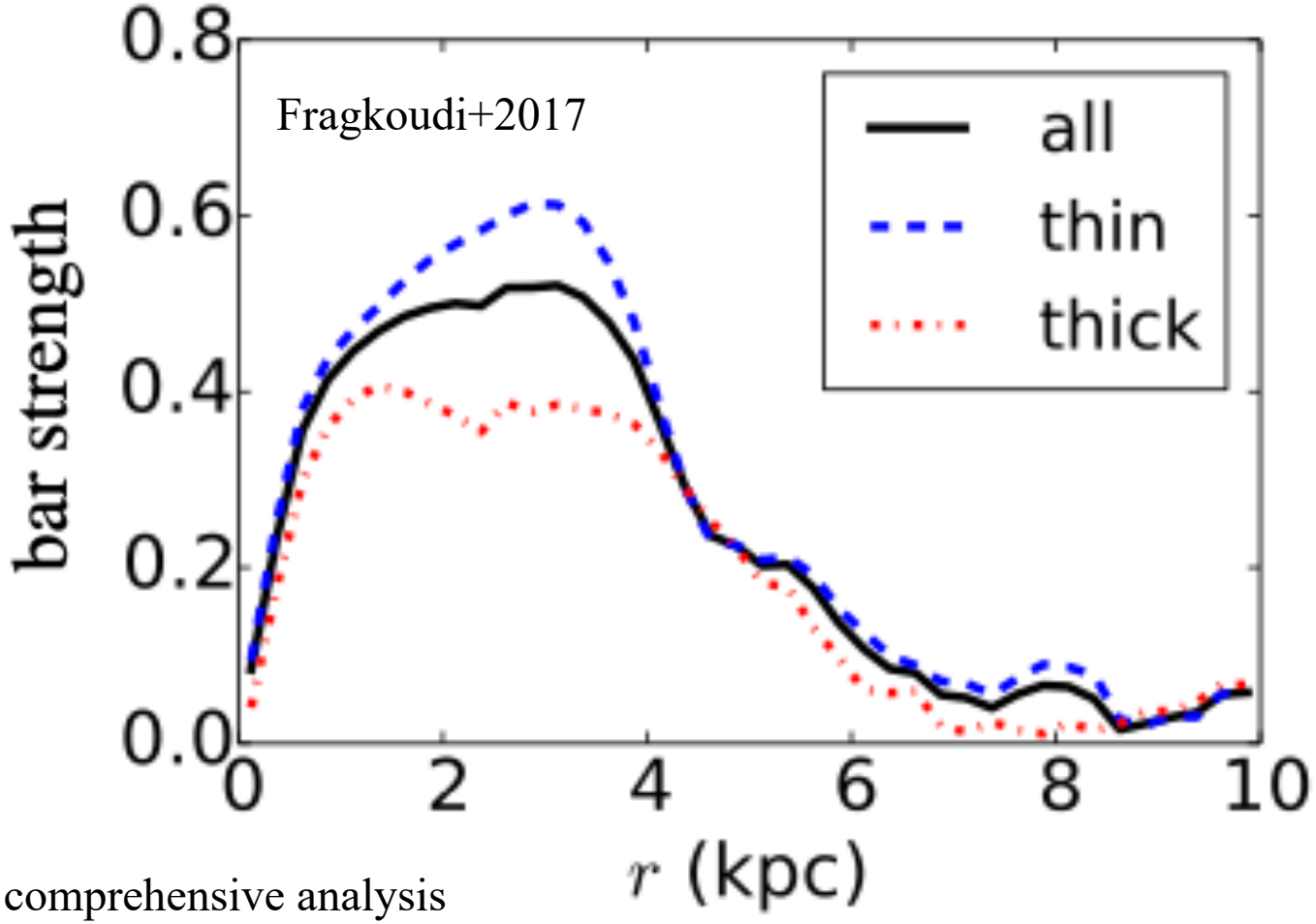
Deciphering the Milky Way disc formation time encrypted in the chrono-kinematics of the bar

Hanyuan Zhang[1]★, Vasily Belokurov[1], N. Wyn Evans[1], Zhao-Yu Li[2,3], Jason L. Sanders[4] and Anke Ardern-Arentsen[1]

Ingredient 1: Period-age relation of Mira variables



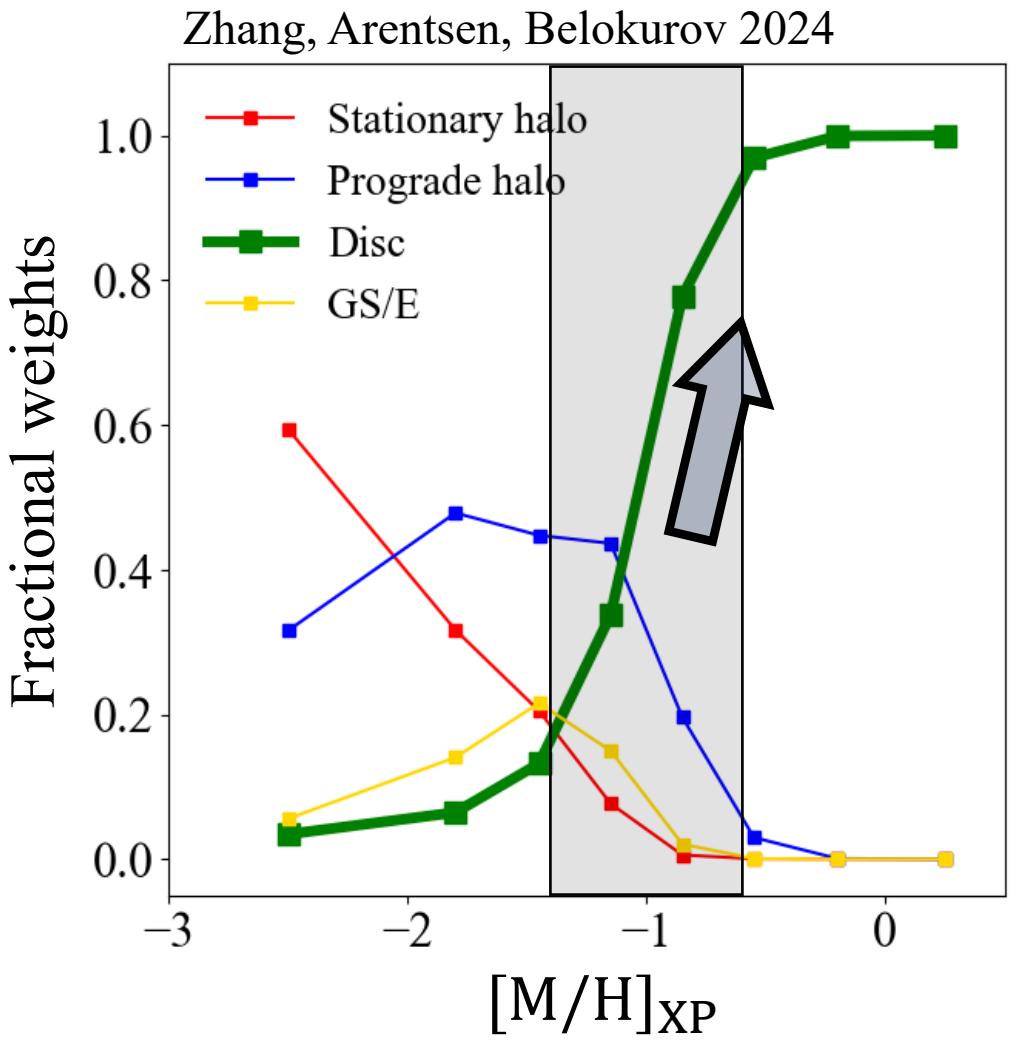
Ingredient 2: Kinematically cold stars response more actively to the bar

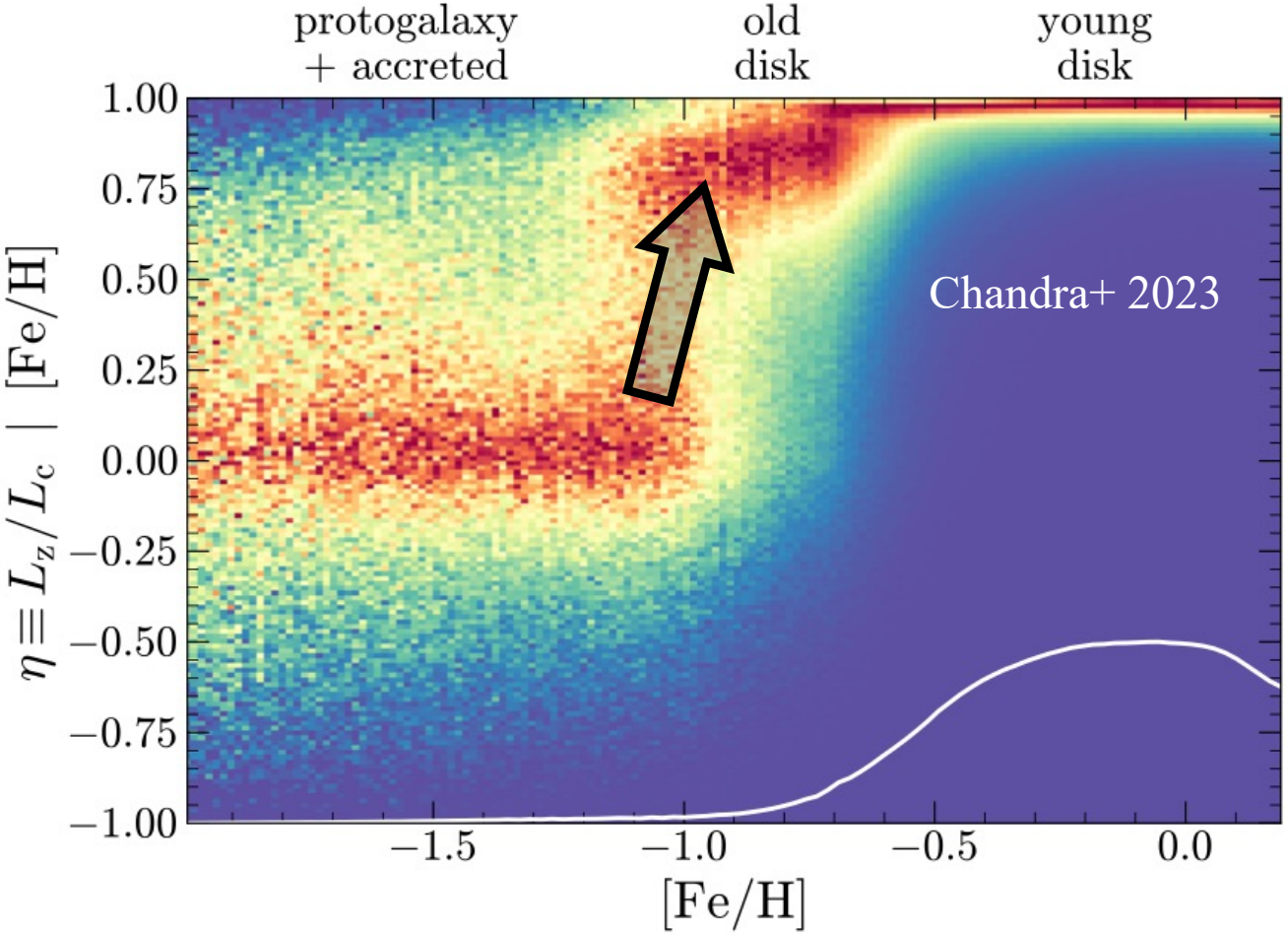


See Debattista+17 for a more comprehensive analysis

See also Di Matteo+15 & 19 and Ness+13 for a more evidence on bar constituents and inner Galactic kinematics with different metallicities

Ingredient 3: Rapid disc formation of the Milky Way





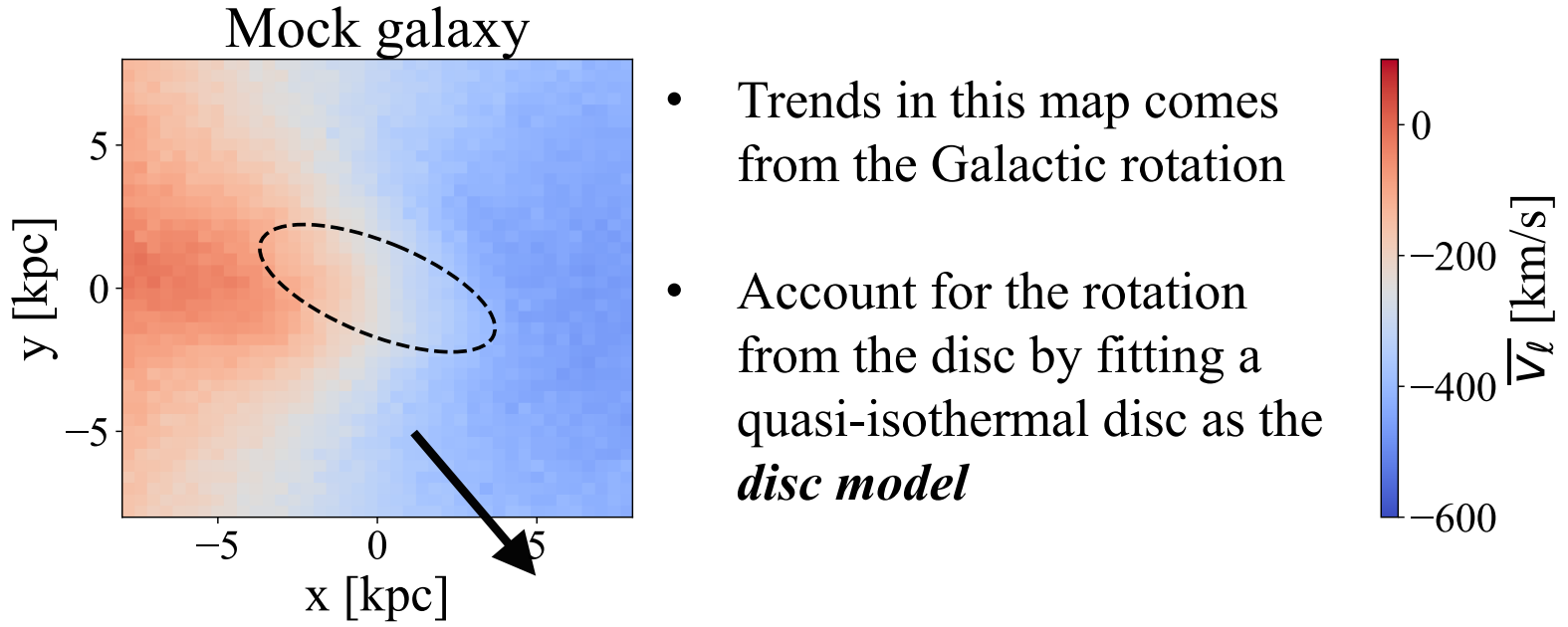
See also Belokurov & Kravtsov 22 & 24 for more observation evidence and Dillamore+ 2024 for simulation

Δv_l map as a tracer of bar signatures: N-body galaxy

Velocity in the Galactic longitude direction

i.e. $v_l = 4.74\,\mu_l \times d$

Although v_l is the velocity in a heliocentric coordinate, it still embed the information on the *Galactic rotation* as it is an in-plane velocity

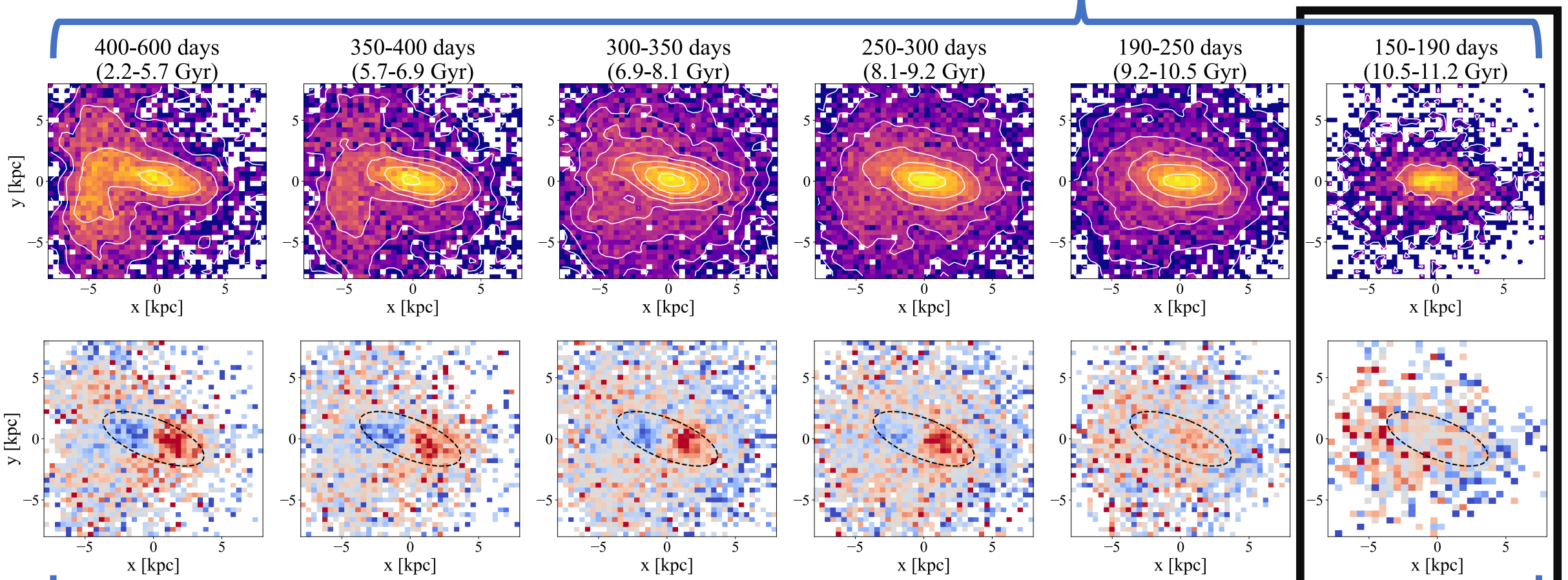


- Trends in this map comes from the Galactic rotation
- Account for the rotation from the disc by fitting a quasi-isothermal disc as the ***disc model***

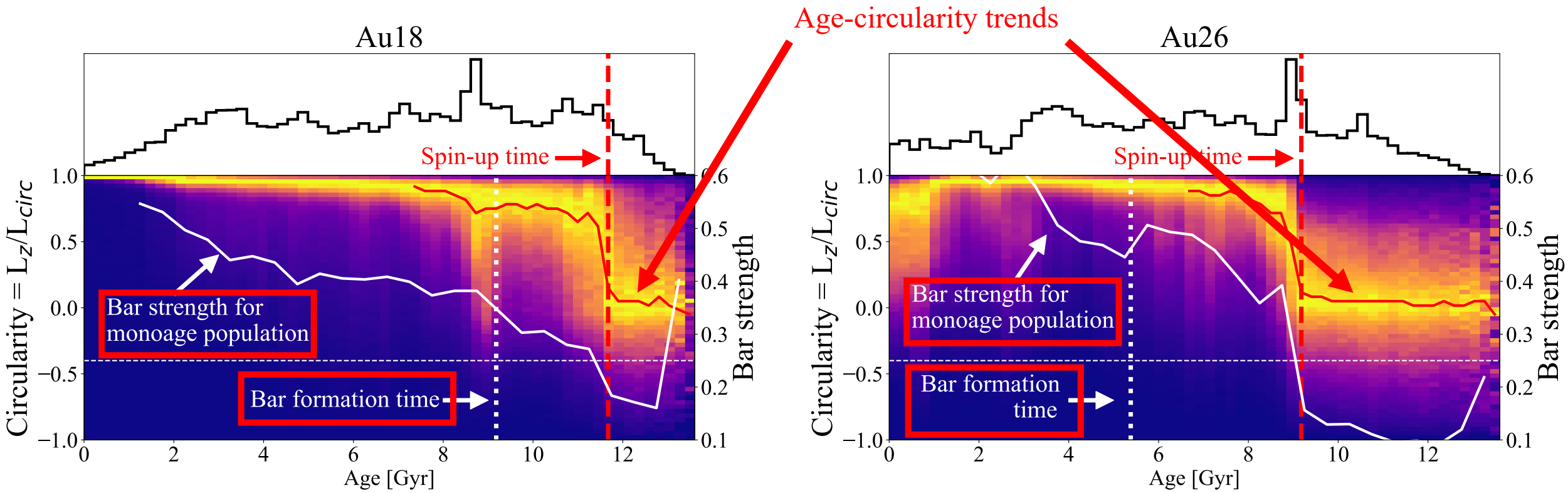
Dipole-like signature caused by the bar

Bar chrono-kinematic from Mira variables

See also Grady+20, Semczuk+22 for age-morphology trends



Auriga cosmological simulations: Spin-up in Au18 & Au26 and its relation to bar strength



Bar signature appears for population born right after the disc formation because:

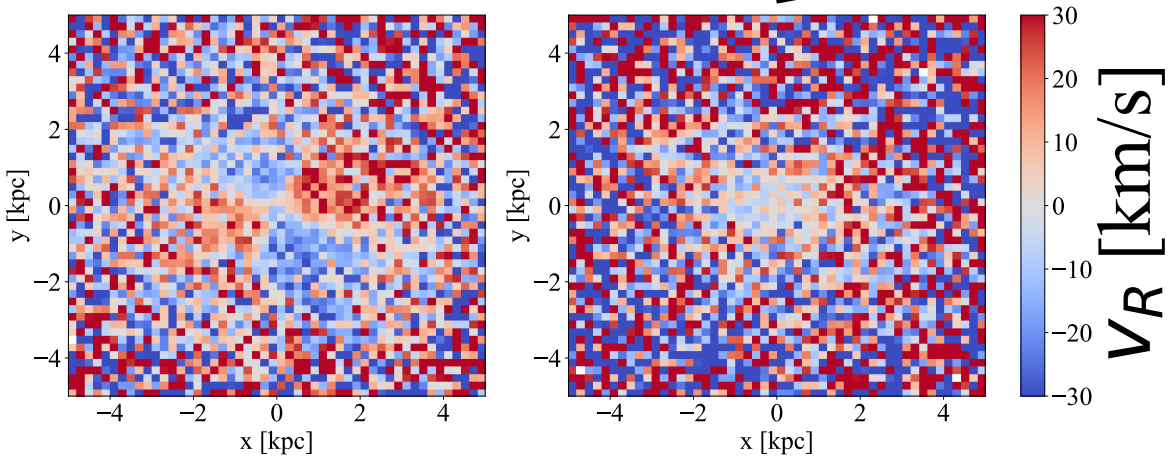
- the disc formation was rapidly so that disc population quickly dominate over the halo stars
- the disc population born after the spin-up (but before bar formation) are captured by the bar and show bar signatures at the present-day

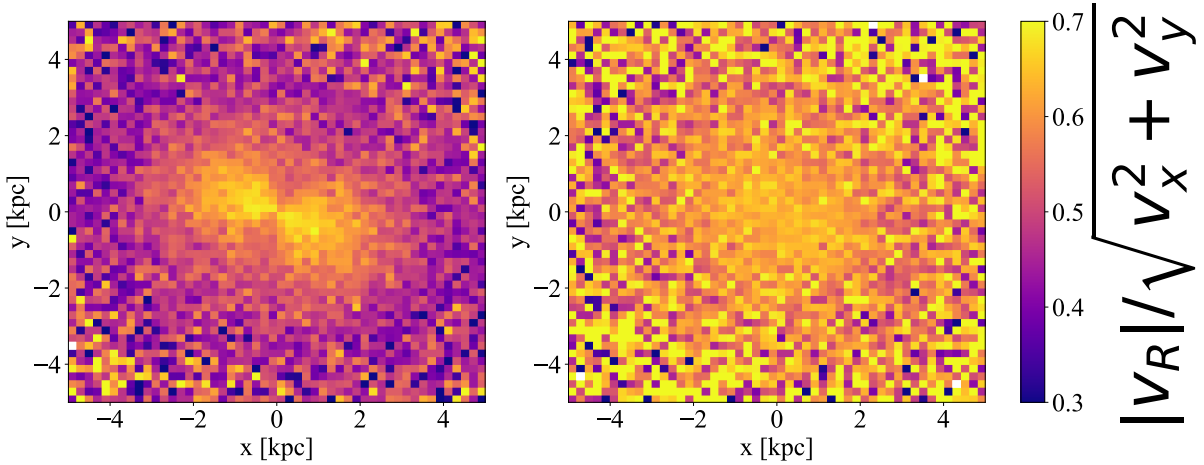
Population born within
1Gyr ***after*** the spin-up

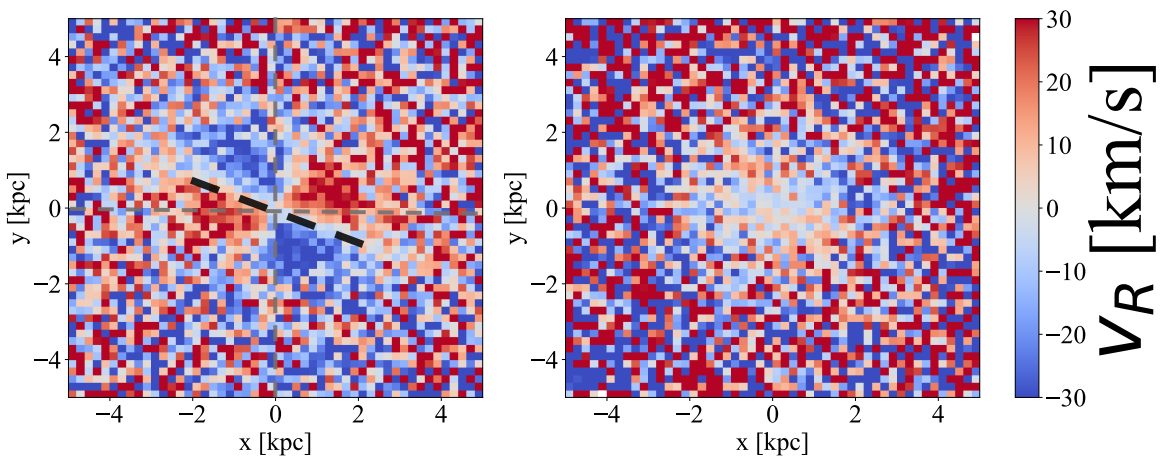
Population born within
1Gyr ***before*** the spin-up

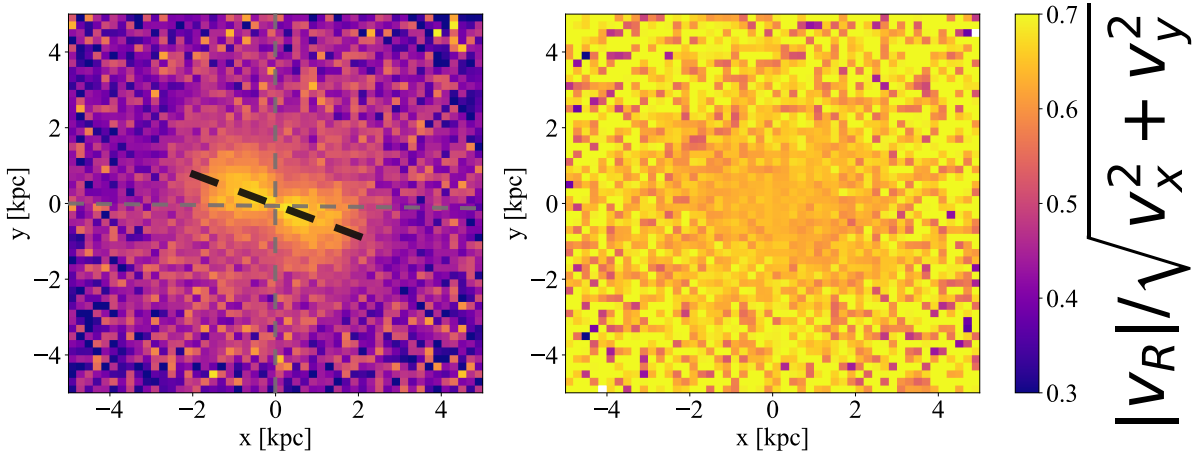
Au18

Au26

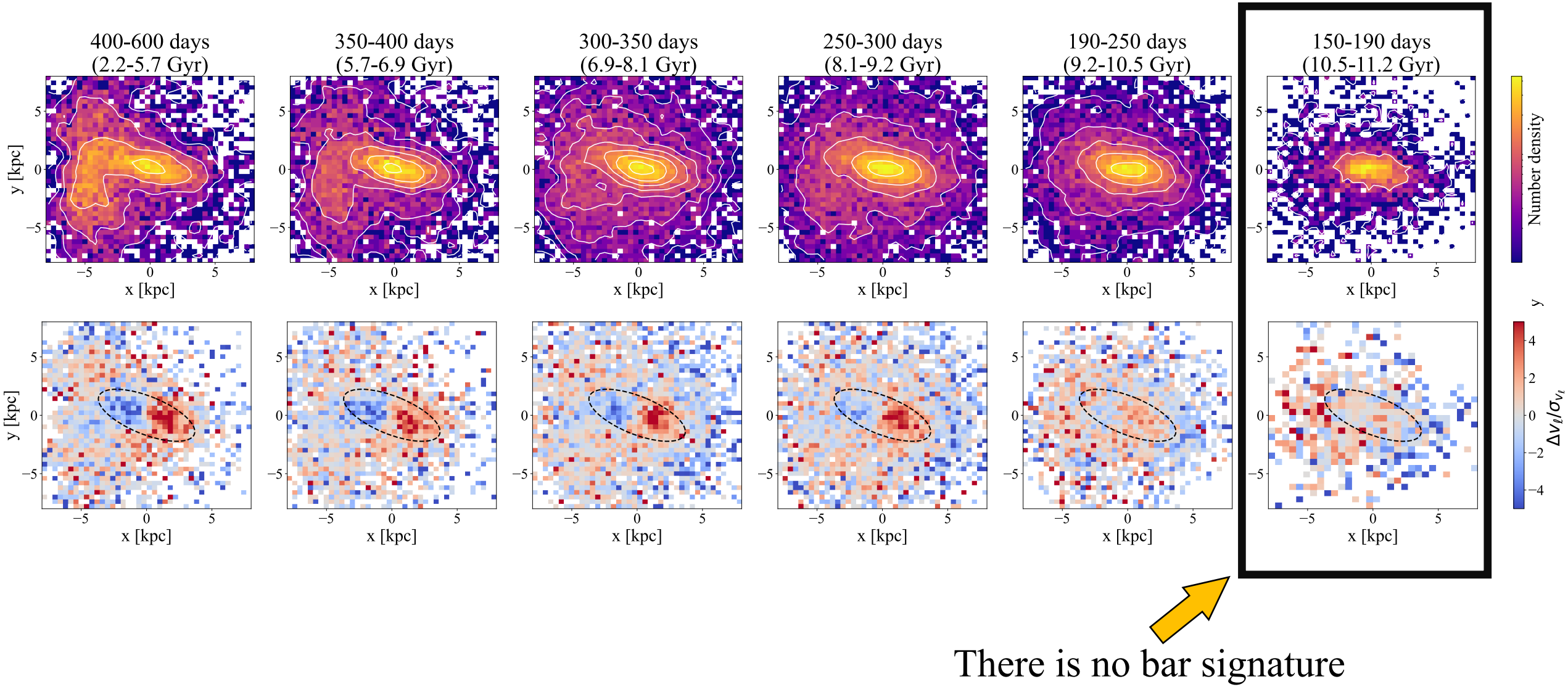








Bar chrono-kinematic from Mira variables



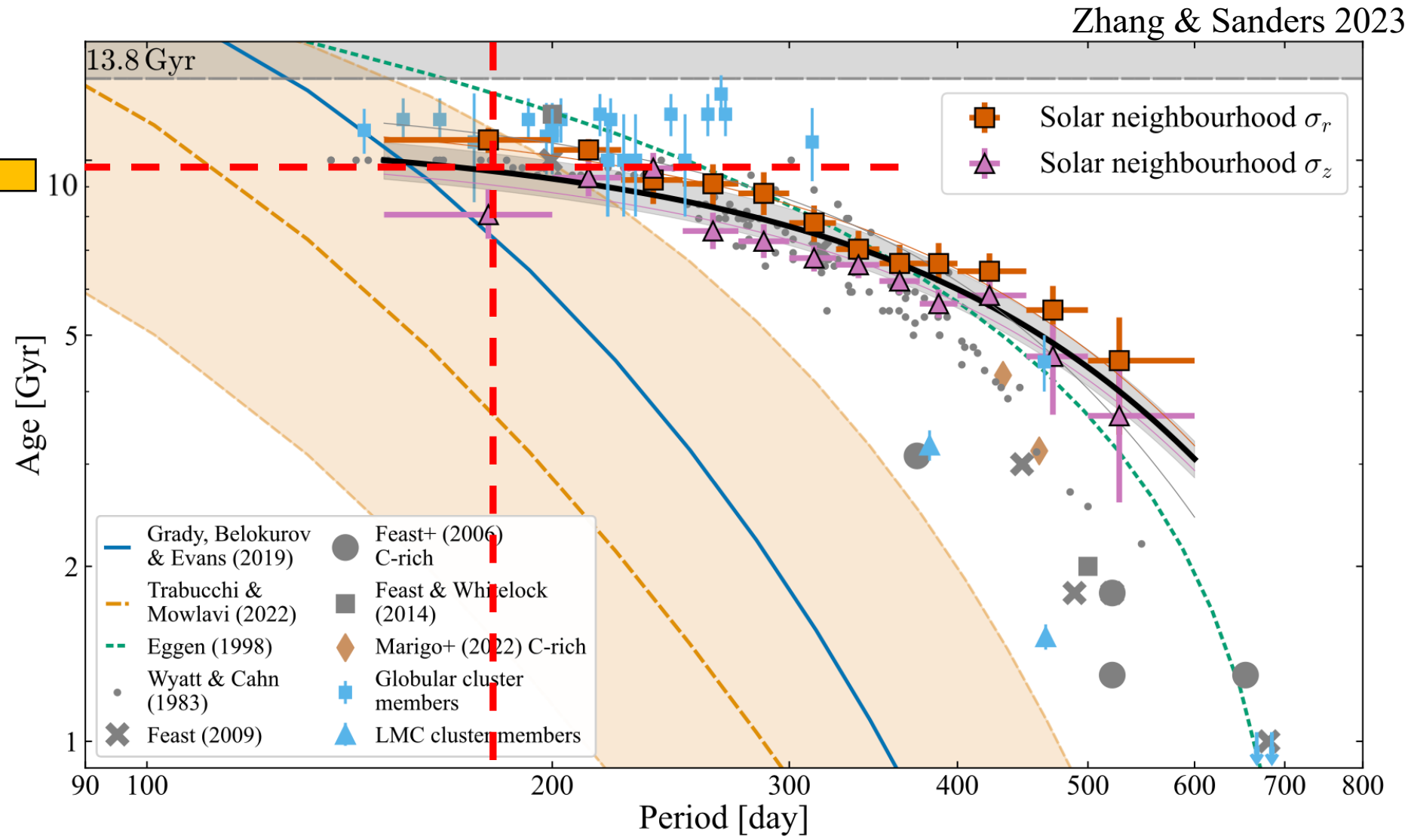
There is no bar signature

Constrain on the Galactic spin-up time

Mira with period around 190 days

10.5 $\pm$ 1.2 Gyr

A disc younger than 12 Gyr



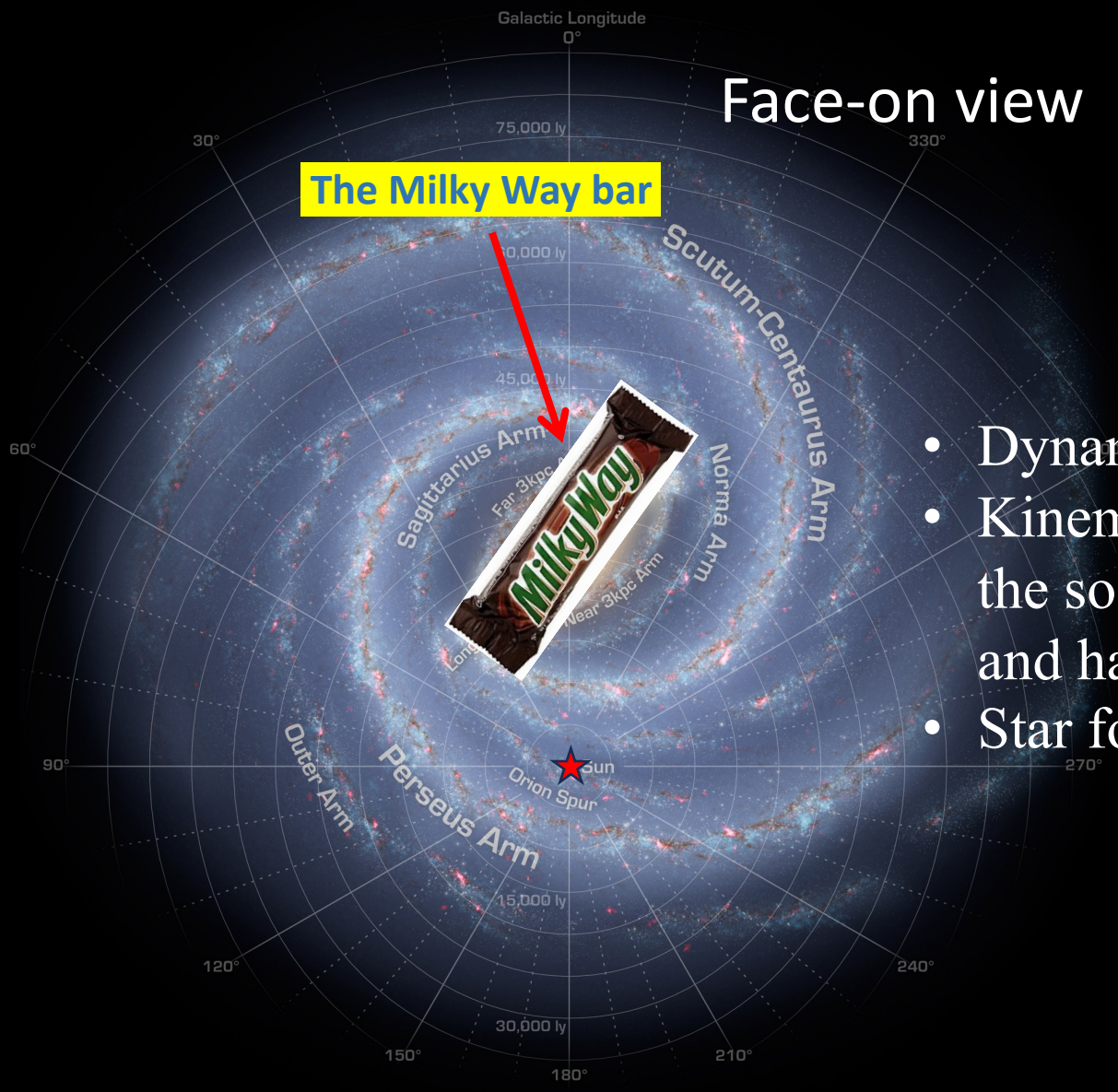
Summary:

arxiv:2406.06678

- With LA-LPV:
  - Kinematic maps (v_R and $|v_R/v_{tot}|$ map) of the inner Galaxy with minimal spatial selection function and large coverage – LA-LPV is a good kinematic tracer to map the inner Galaxy
  - $|v_R/v_{tot}|$ map can trace the bar-supporting stars and hence can be used to estimate the dynamical length of the Milky Way bar: $R_b \sim 4.0$ kpc
  - We calculate the pattern speed of the Galactic bar $\Omega_b \sim 34.1 \pm 2.4$ km s^{-1}kpc^{-1} using the pattern speed estimator developed in Dehnen+23
- With Mira:
  - We demonstrate the correlation between the disc chrono-kinematics and bar chrono-kinematics using Auriga simulations, and proposed to use that to measure the disc formation time
  - We trace the chrono-kinematic signature of the inner Galaxy and find no bar signature for Mira with period shorter than 190 days (Age$\sim 10.5 \pm 1.2$ Gyr)
  - Therefore, we can constrain the Milky Way's disc to be younger than $\sim$12 Gyr

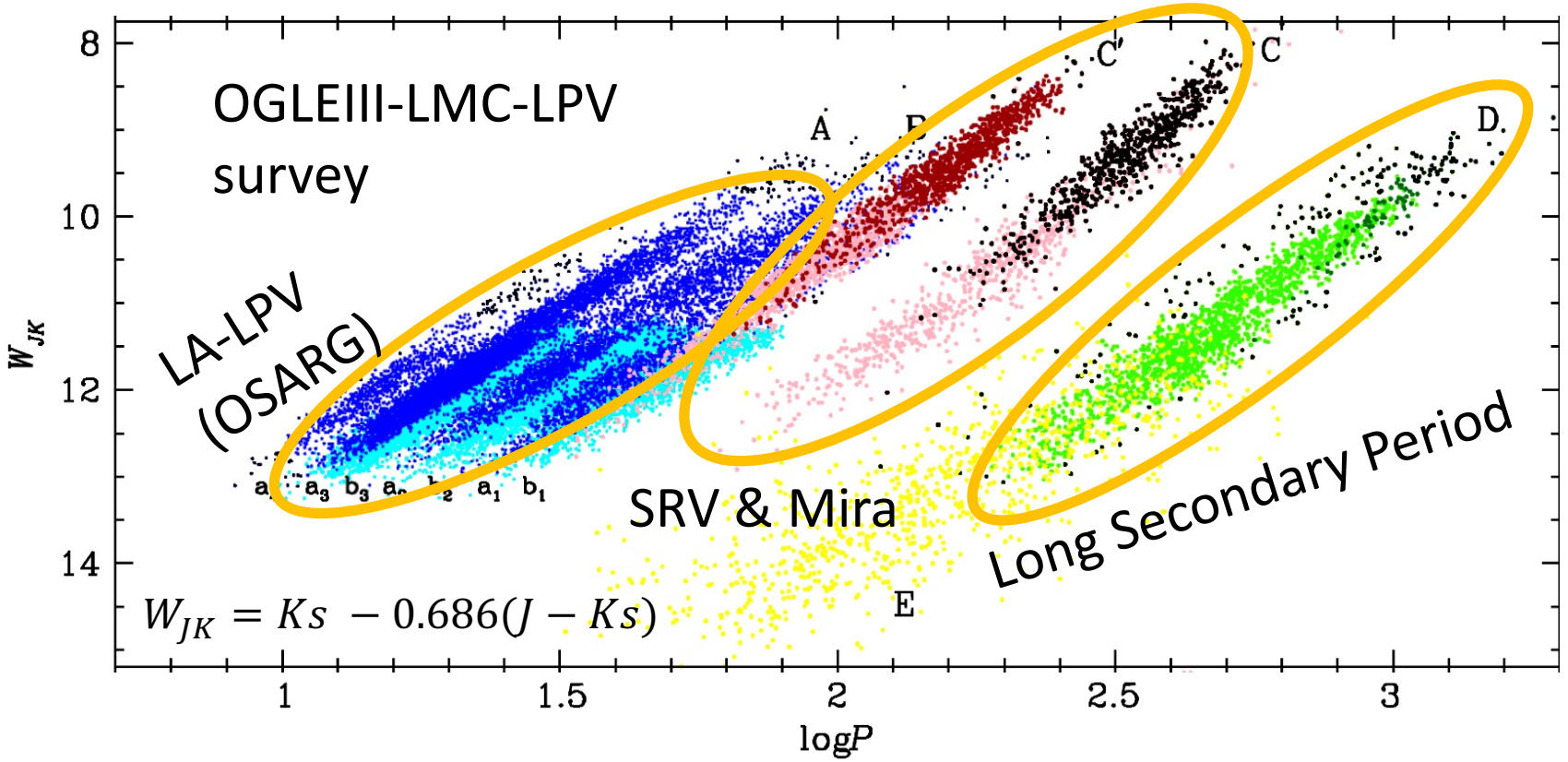
arxiv:2408.16815

Structures at the inner Galaxy

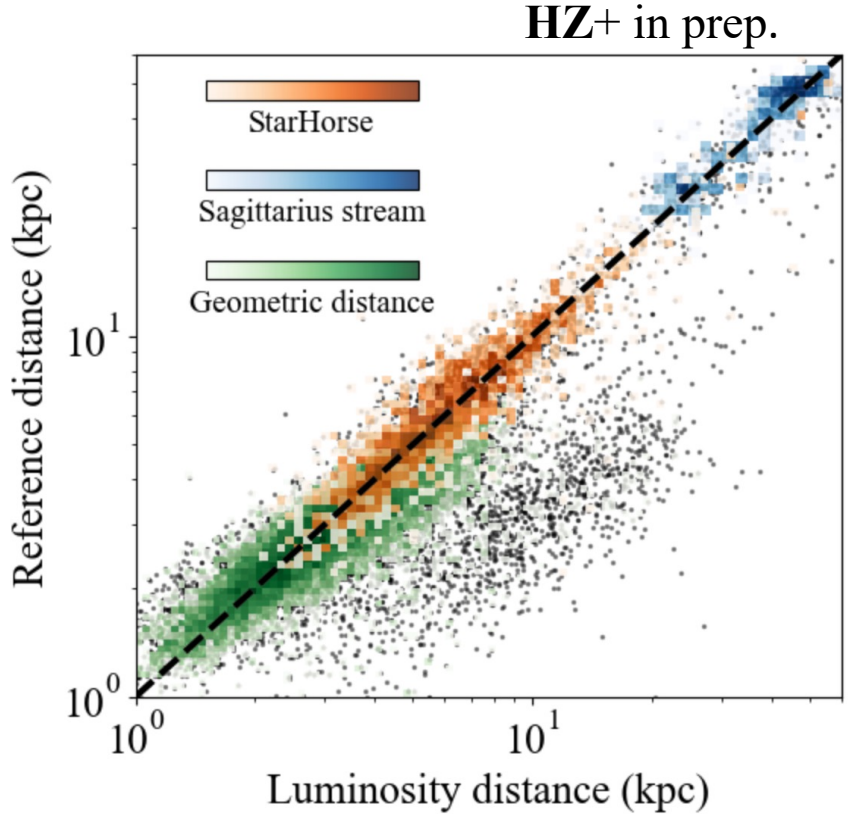


- Dynamics at the inner Galaxy
- Kinematic and equilibrium in the solar neighbourhood, disc, and halo
- Star formation history

LA-LPV as distance indicators



Soszynski+07

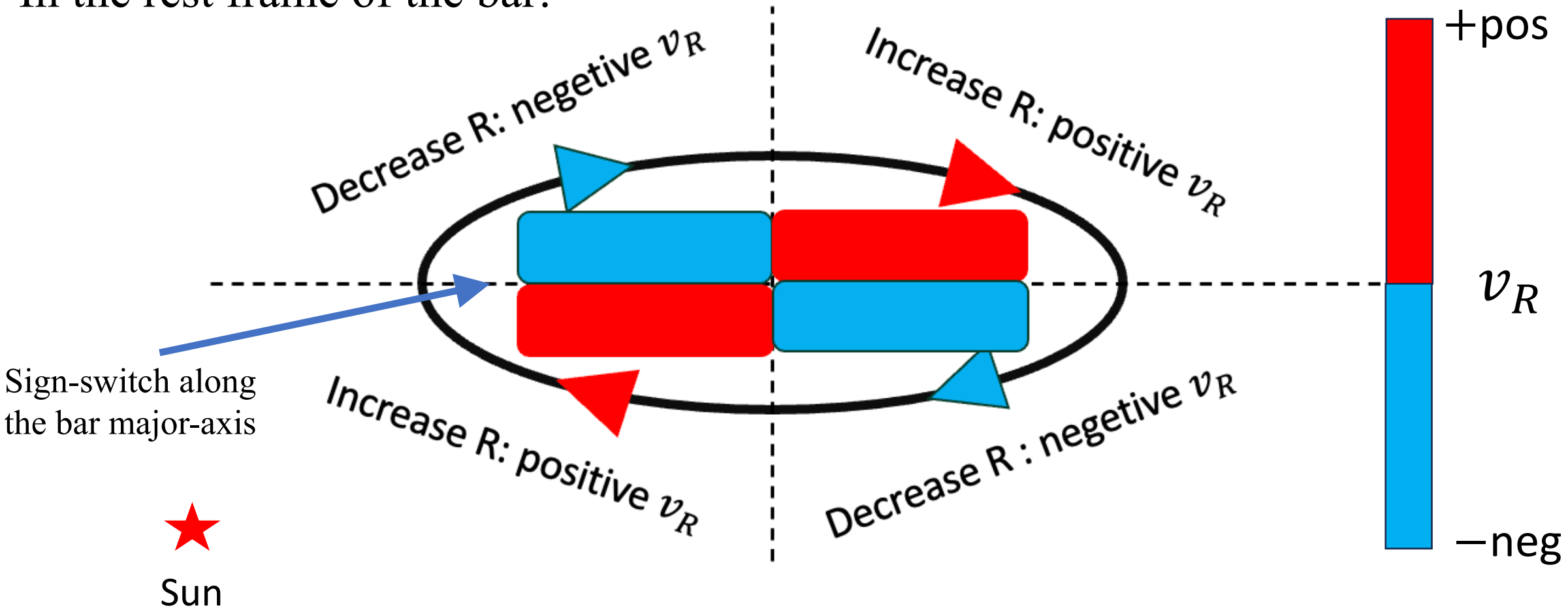


$\sigma_d \sim 10 - 15\%$

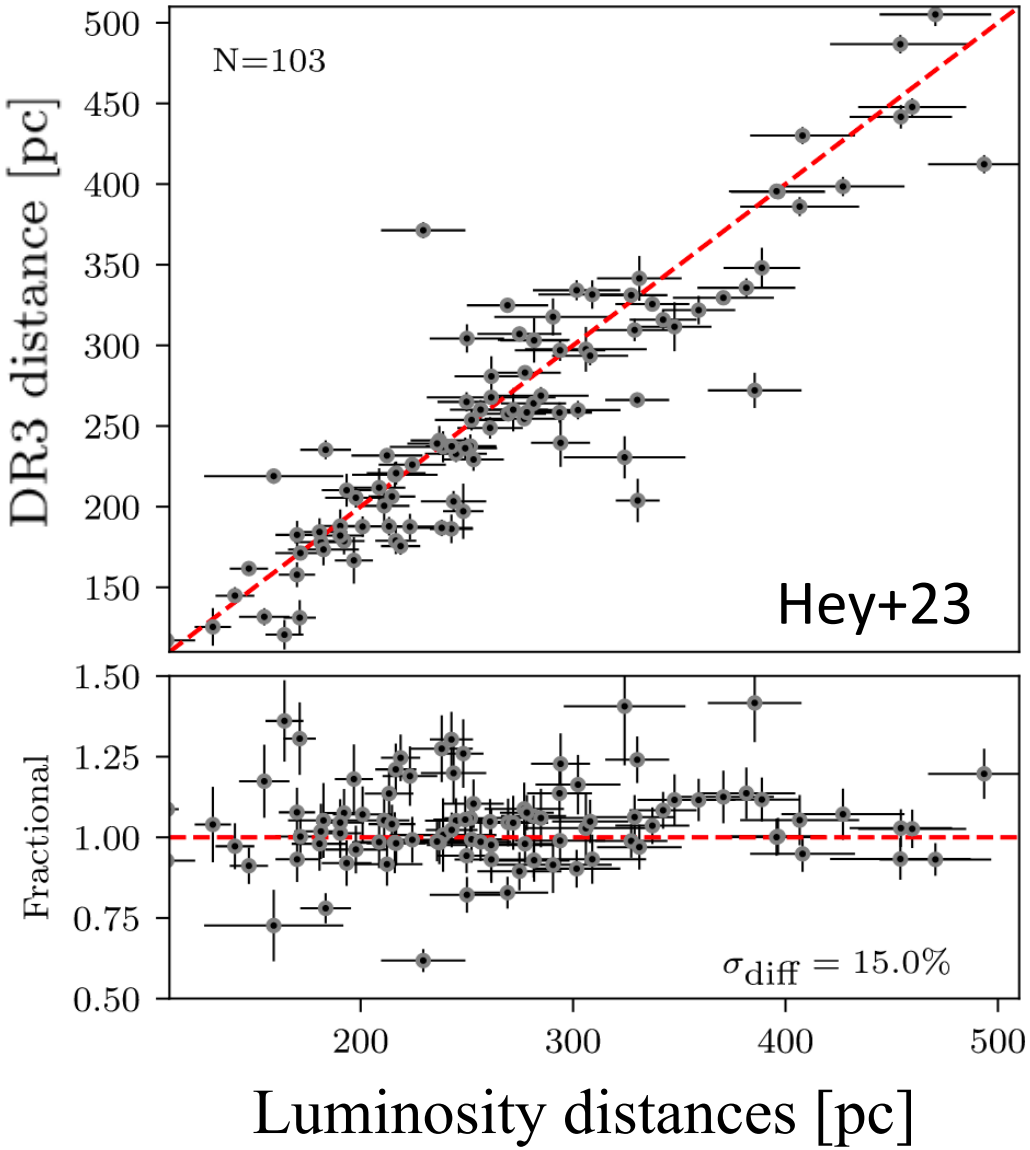
Kinematic signature of the bar:

Quadrupole pattern in v_R

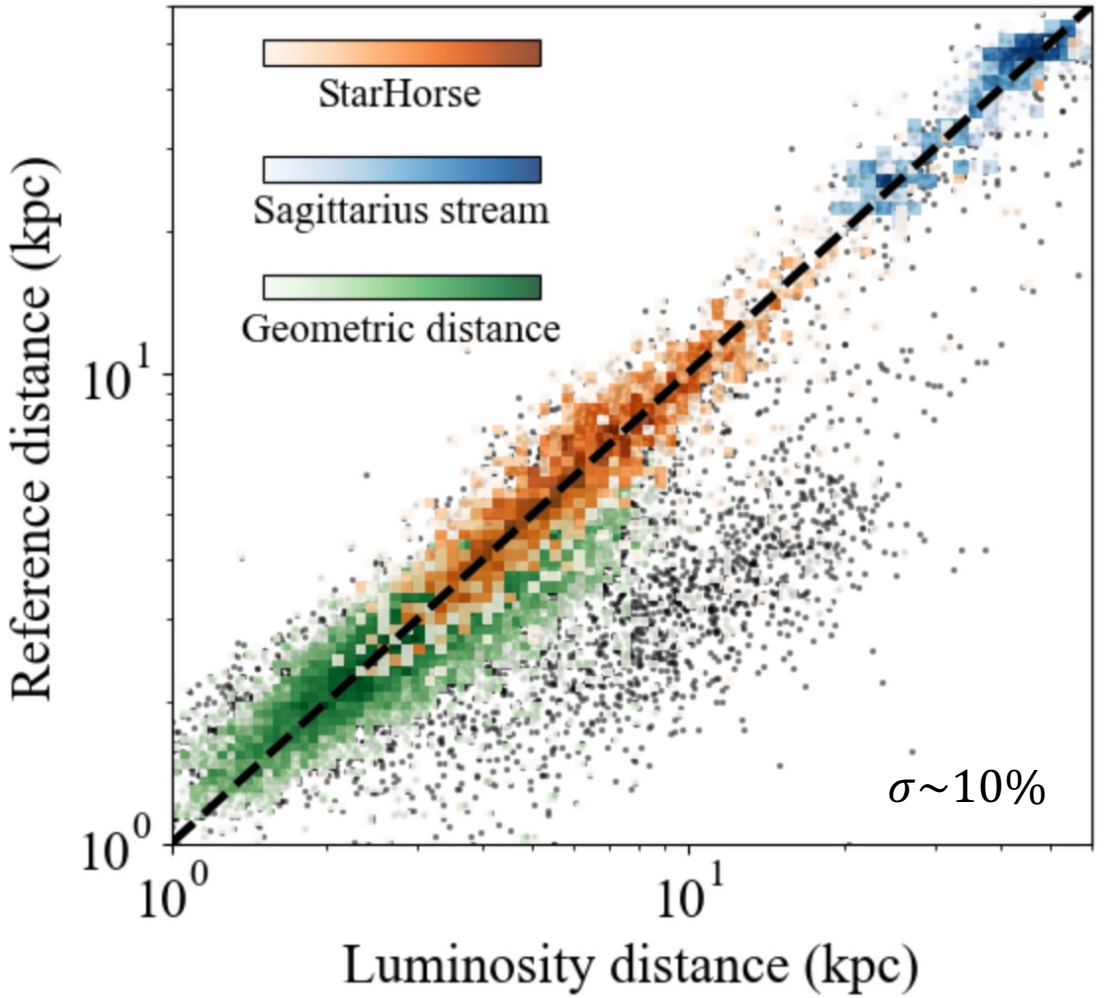
In the rest frame of the bar:



The accuracy and precision of the luminosity distances

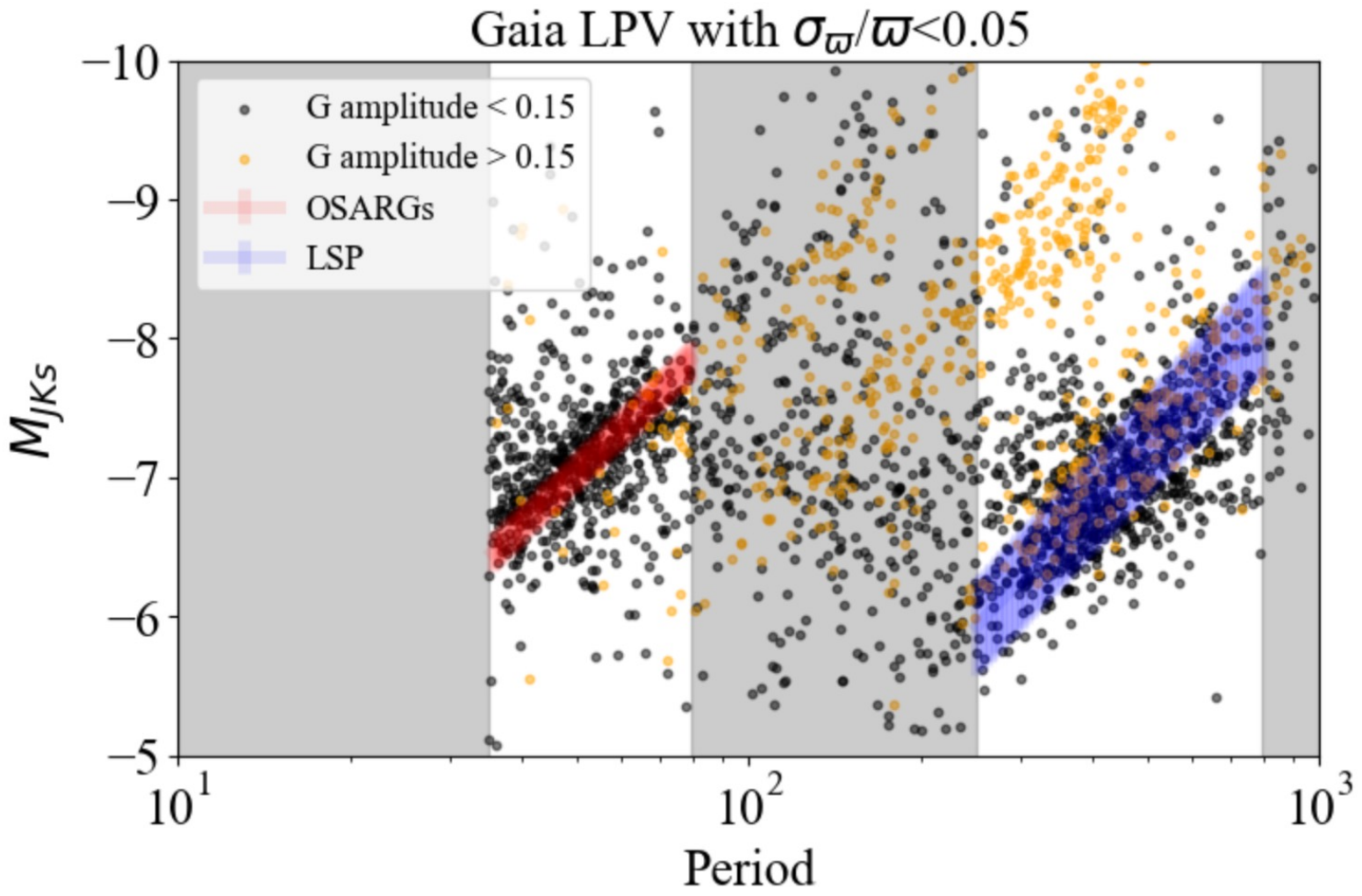


Zhang et.al in prep.

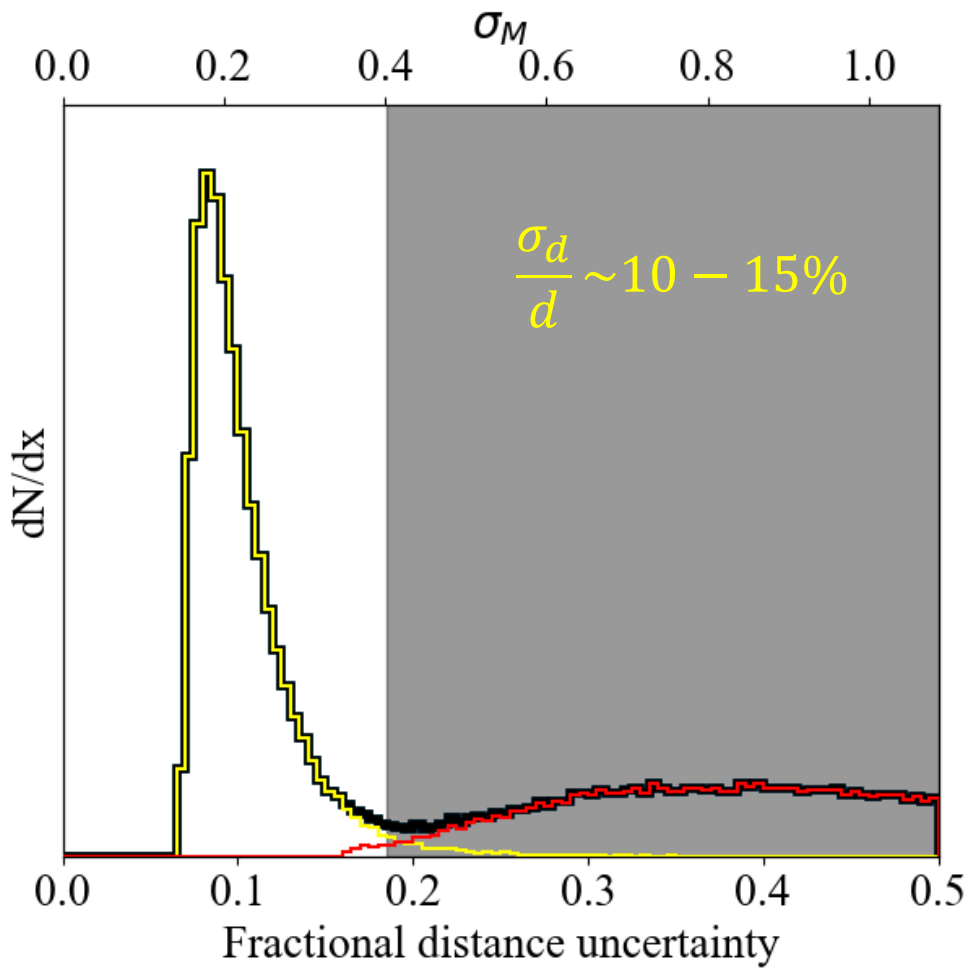


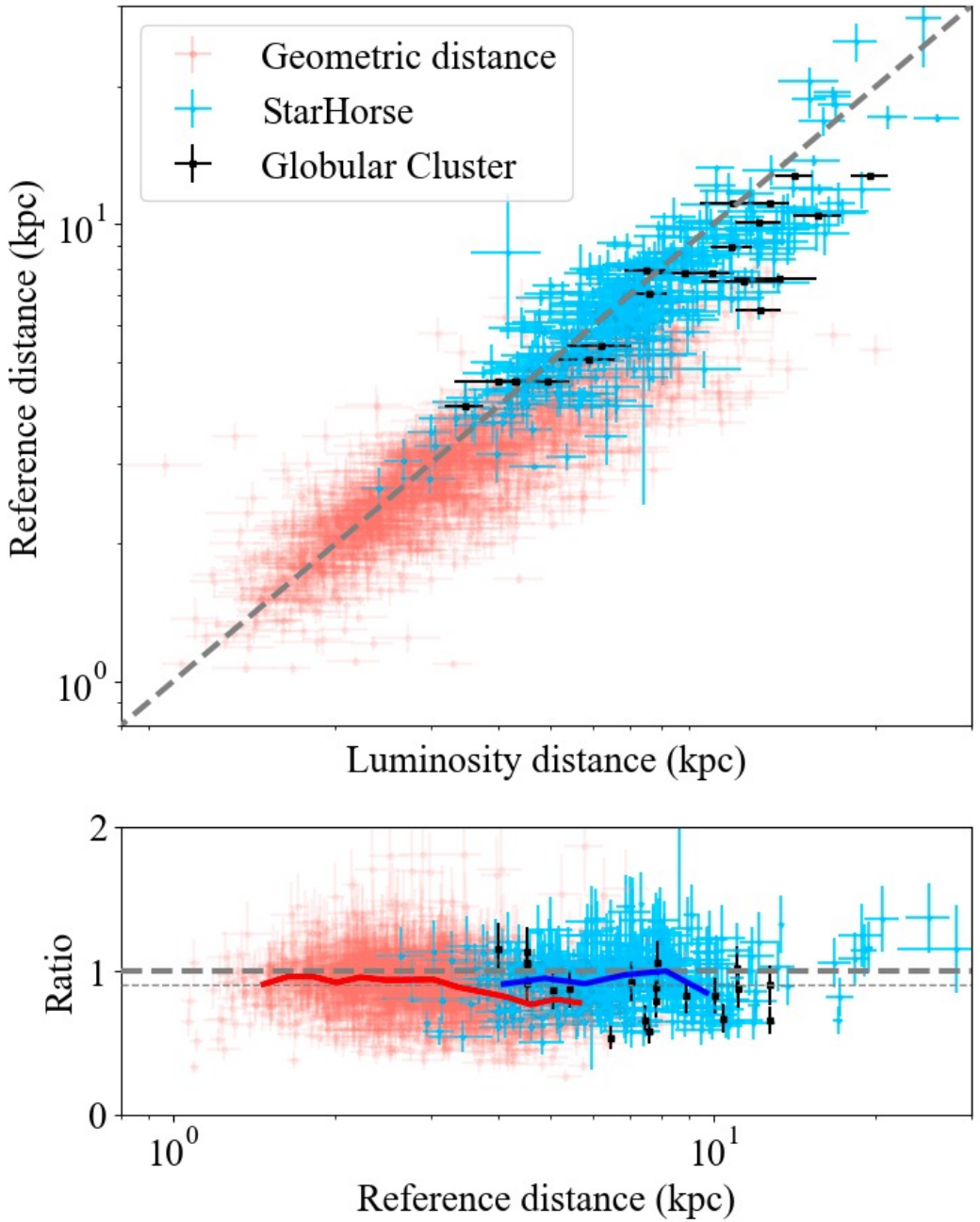
Period-Luminosity plane in Gaia LPV catalogue

- Only one characteristic period can be extracted from the *Gaia* light curve
- Using the light curve amplitude to distinguish LA-LPV from SRV and Miras

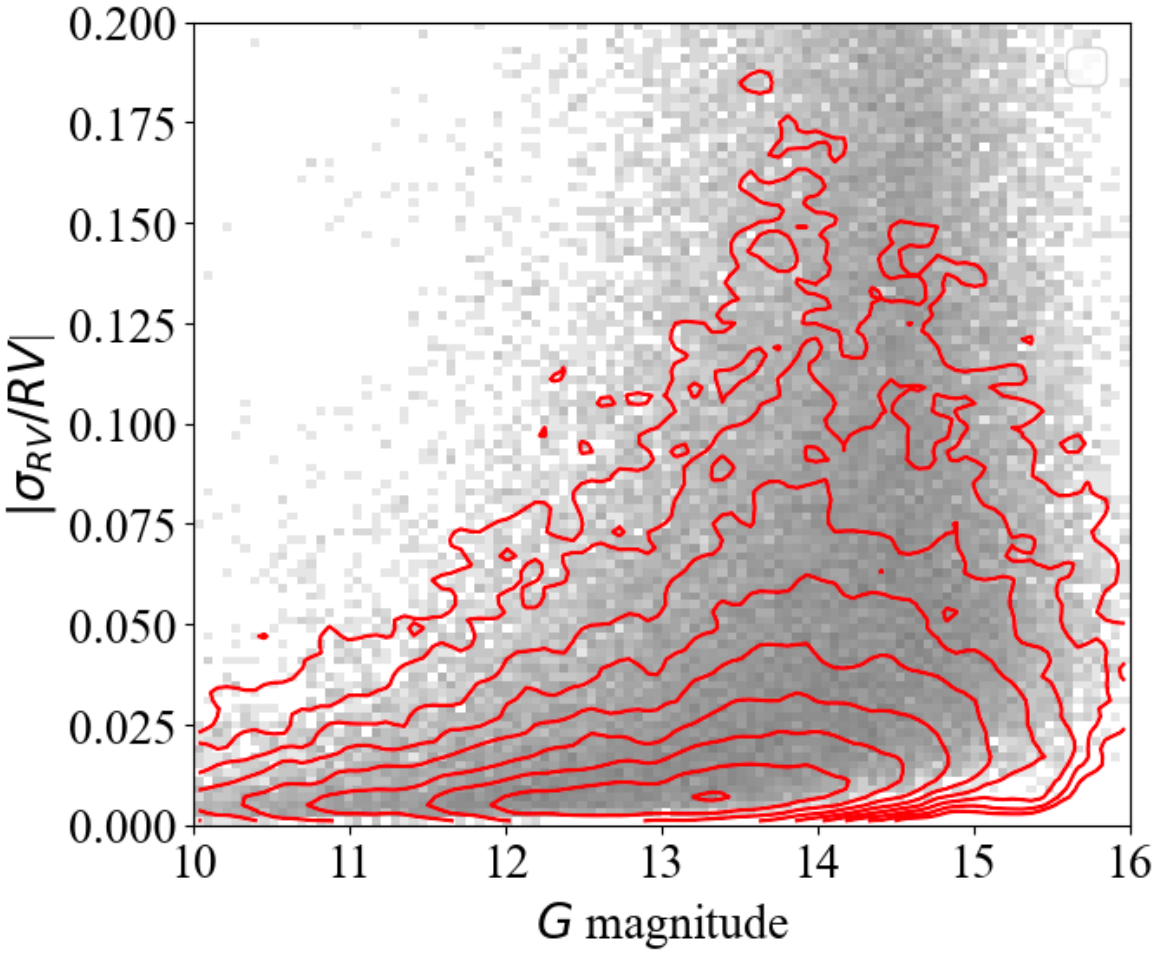


Validation of luminosity distances





Is the line-of-sight velocity bad due to the variability? – NO

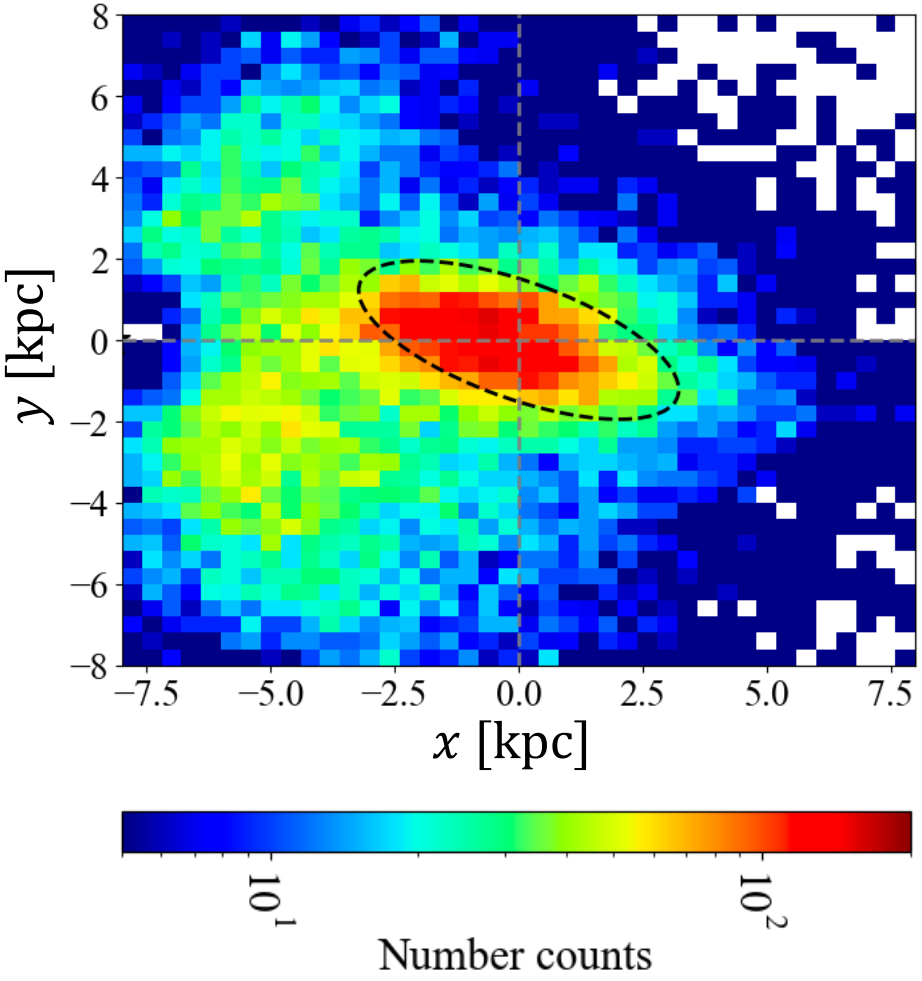


- Black 2D histogram in the background: Randomly selected Gaia DR3 stars
- Red contour in the foreground: LA-LPVs in this sample

The identical distribution in this plane verified the reliability of the Gaia line-of-sight velocity measurement for these LA-LPVs

Why the spatial selection function is minor

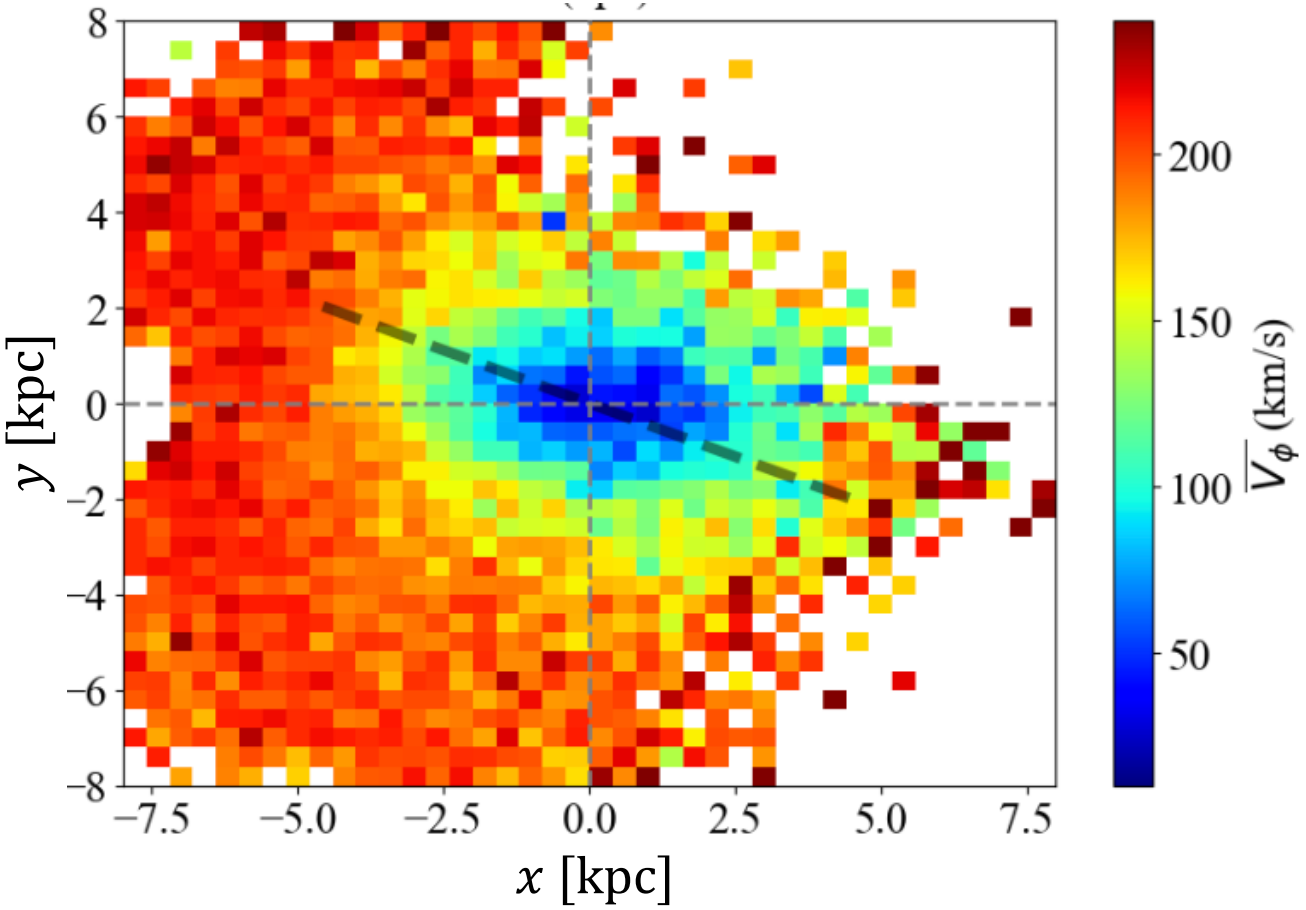
- Gaia full-sky coverage avoid sharp cutoff around the edge of footprints (unlike OGLE and APOGEE)
- Mostly photometric selections avoid stronge selection function in magnitude
- The amplitude and period selections restrict the brightness of the star to $-7 < M_{JK} < -8$, which cancel out the magnitude selection function to the first order



Kinematics of the LA-LPV sample

Sanity check: Mean azimuthal velocity map

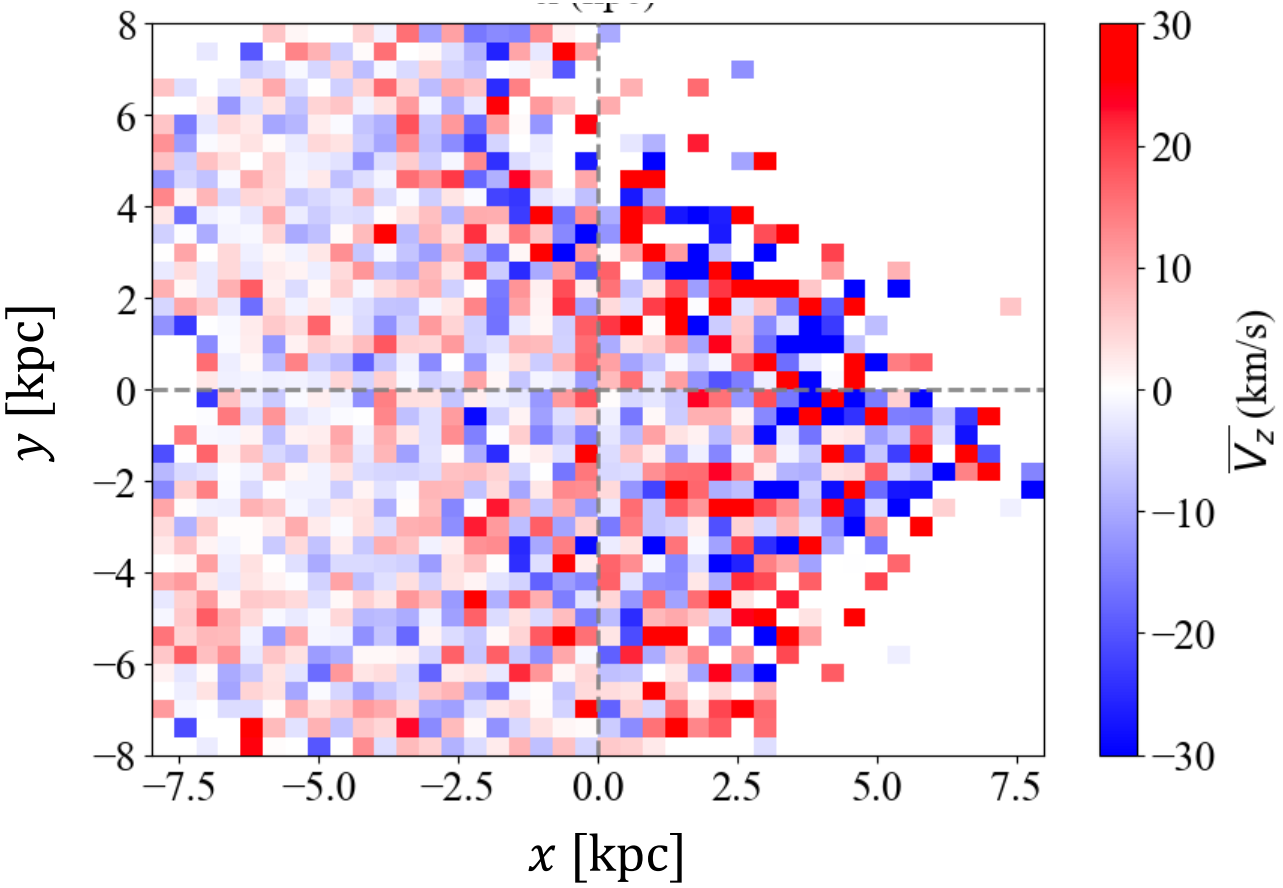
- Constant rotation curve at large radii (around the solar vicinity)
- Rotation drops to almost zero at the very inner centre (see Leung+23)



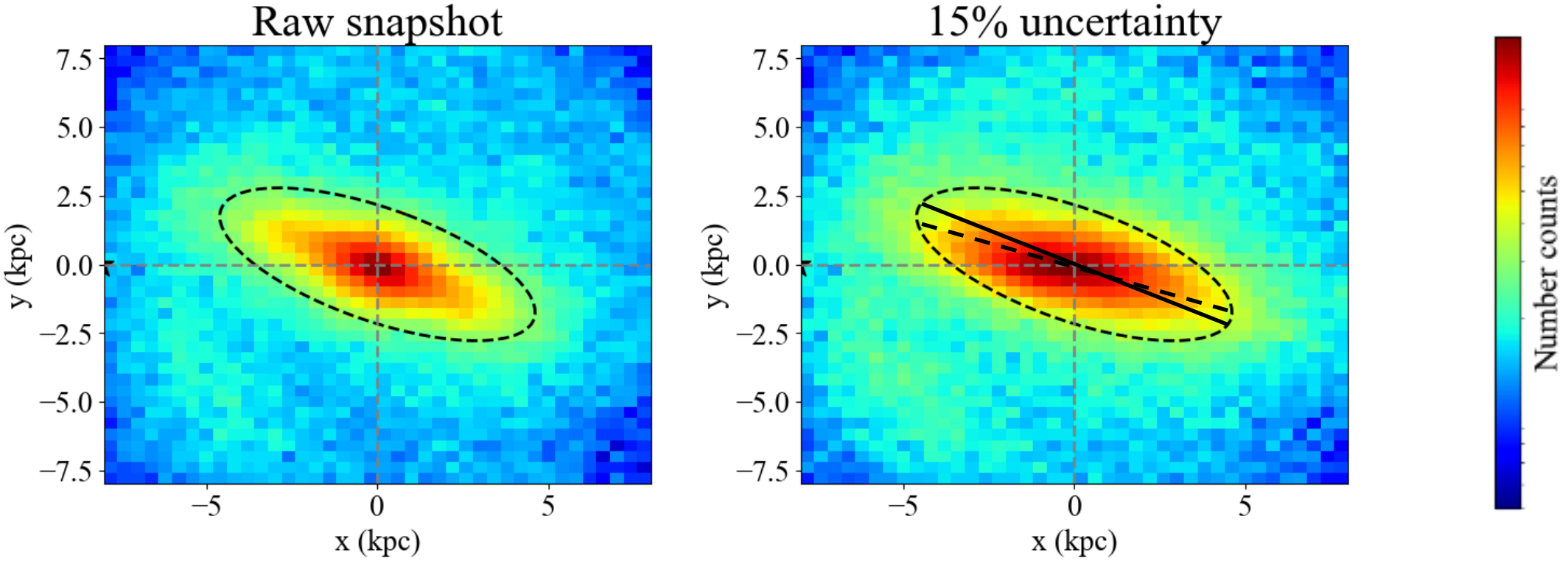
Kinematics of the LA-LPV sample

- No obvious signal is seen, which means the inner Galactic is vertically dynamically quiet

Mean v_z map

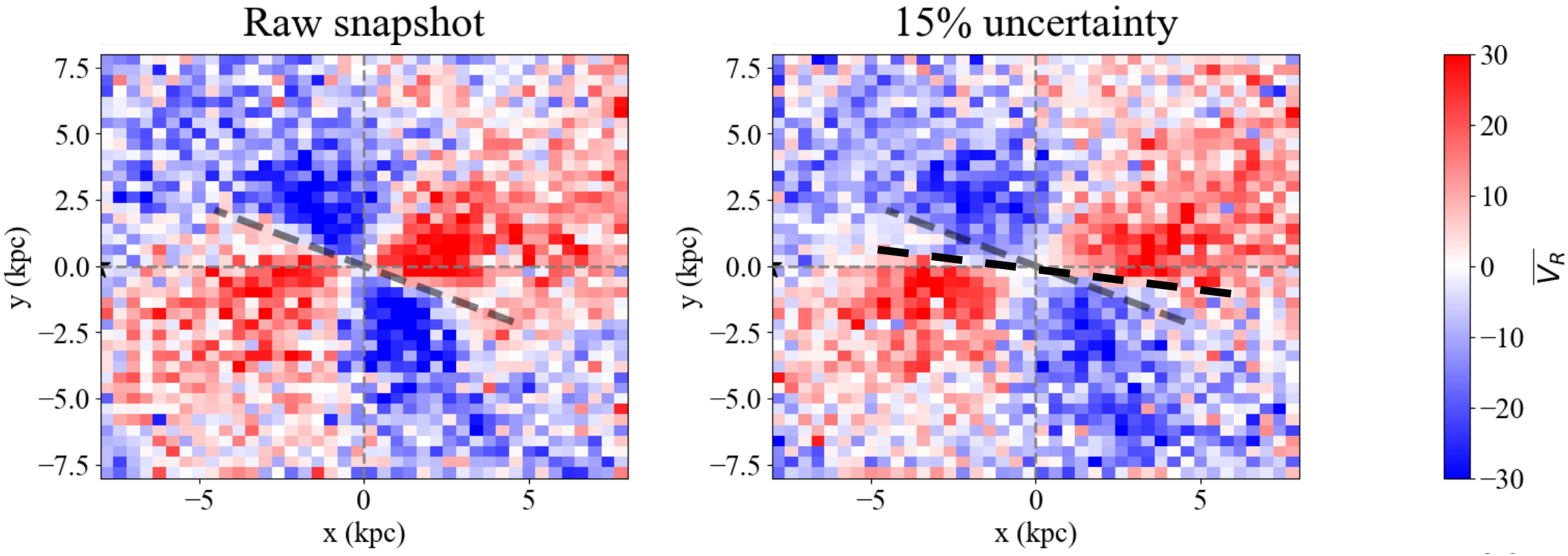


Effects of the heliocentric distance uncertainty



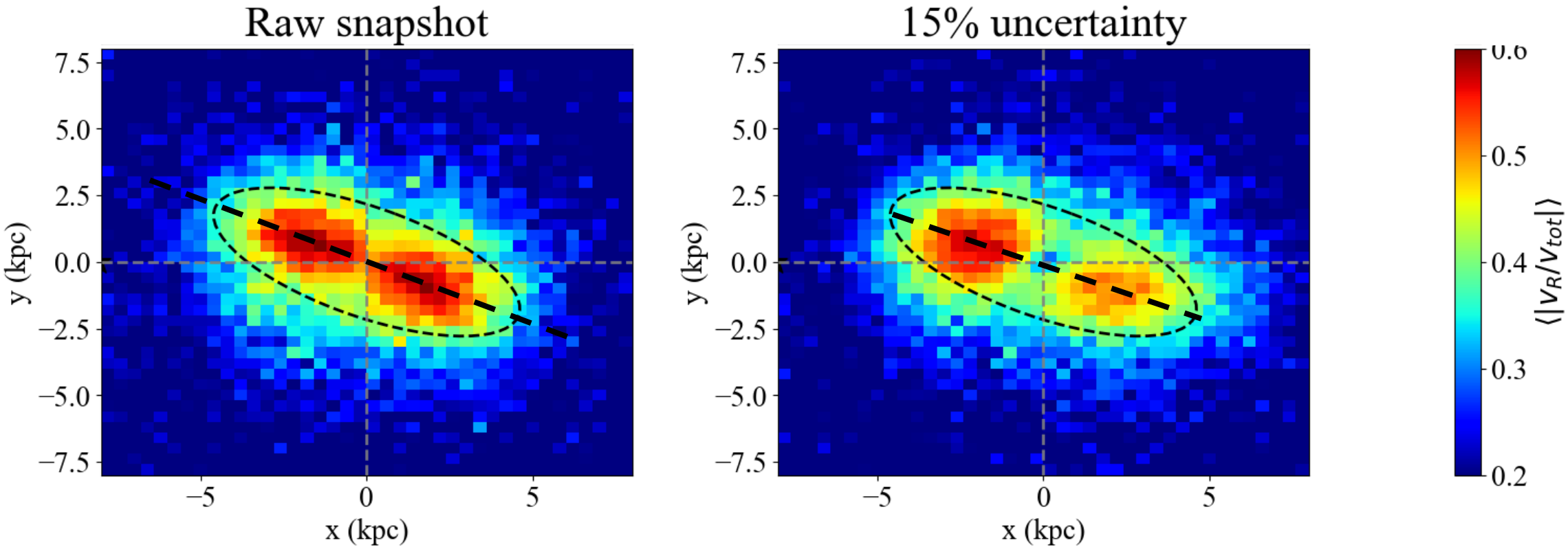
- Distance uncertainty smears each star along the line-of-sight direction bending the major-axis of the bar from its truth to the Sun-GC line

Effects of the heliocentric distance uncertainty



- The $\langle v_R \rangle$ map is even more biased, which demonstrates that the distance uncertainty in the Galactic bar region propagated in a non-Gaussian manner!

Effects of the heliocentric distance uncertainty



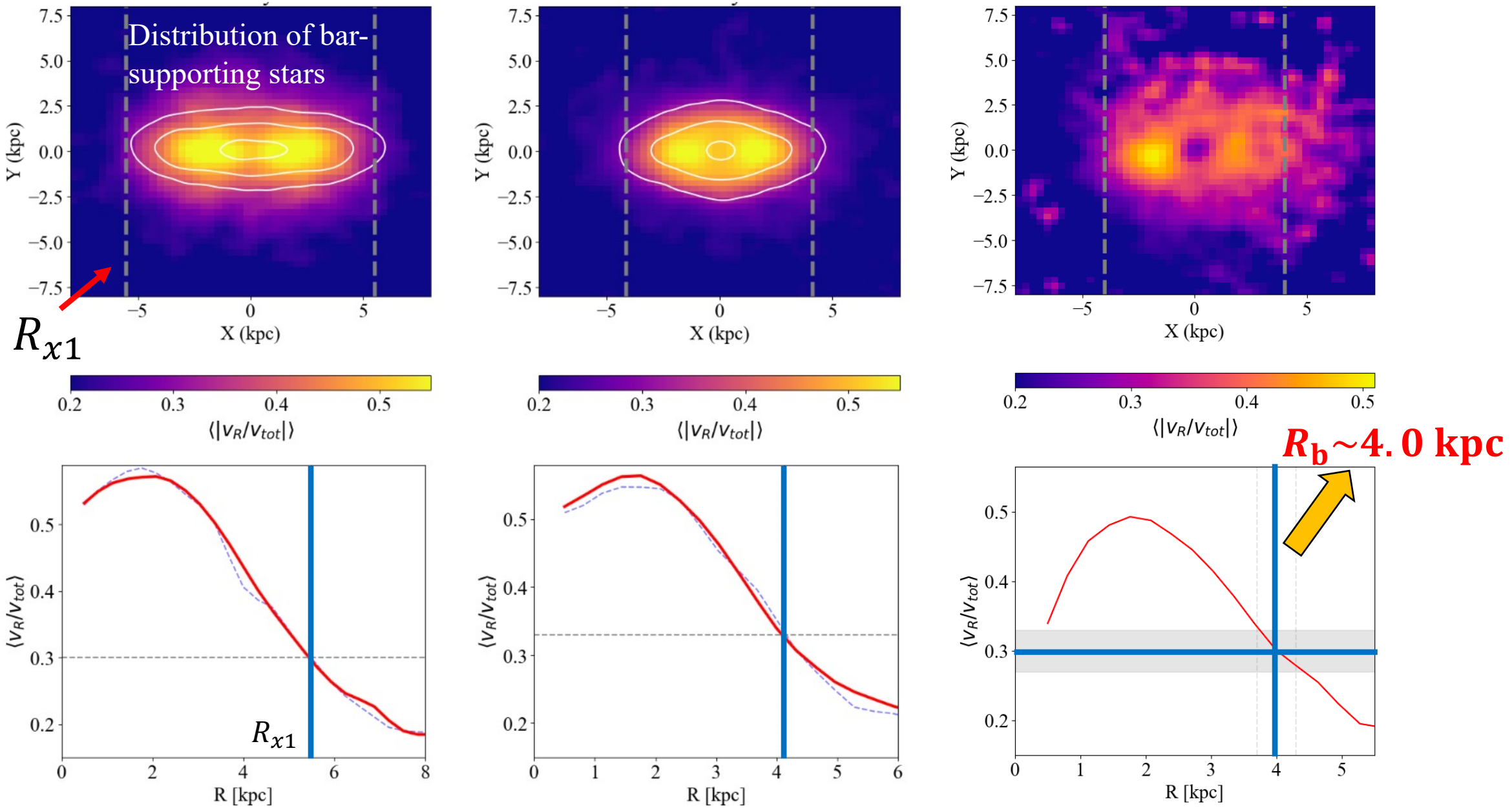
- The $\langle |v_R|/v_{tot} \rangle$ maps are much less affected by the distance uncertainty comparing to the $\langle v_R \rangle$ map because it is dimensionless

Kinematically estimate the dynamical length of the bar

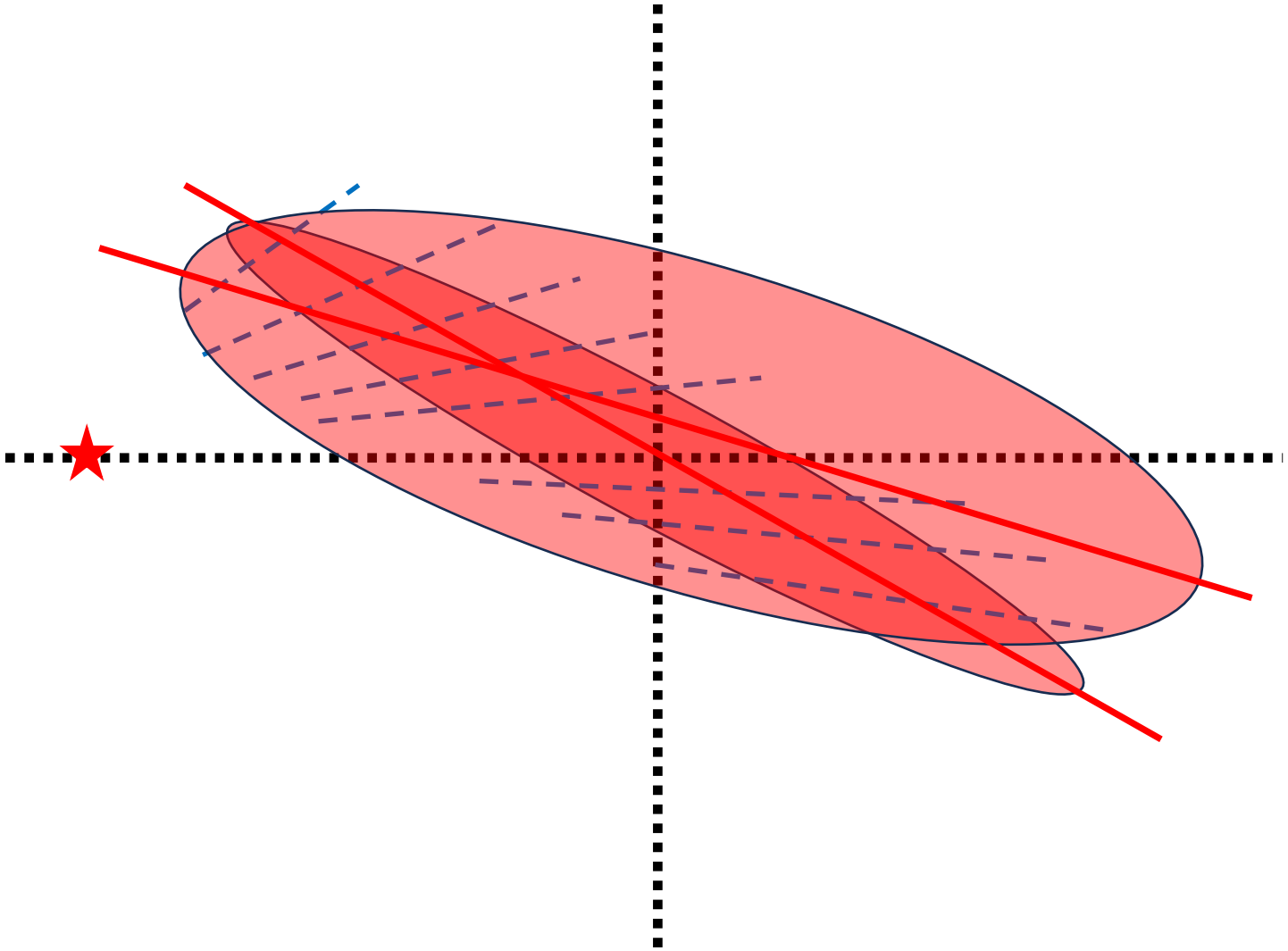
Mock Galaxy A

Mock Galaxy B

LA-LPV sample



Bias due to the distance uncertainty



Estimation of the pattern speed

- Dehnen+23 developed a method to extract pattern speed from simulations using the continuity equation

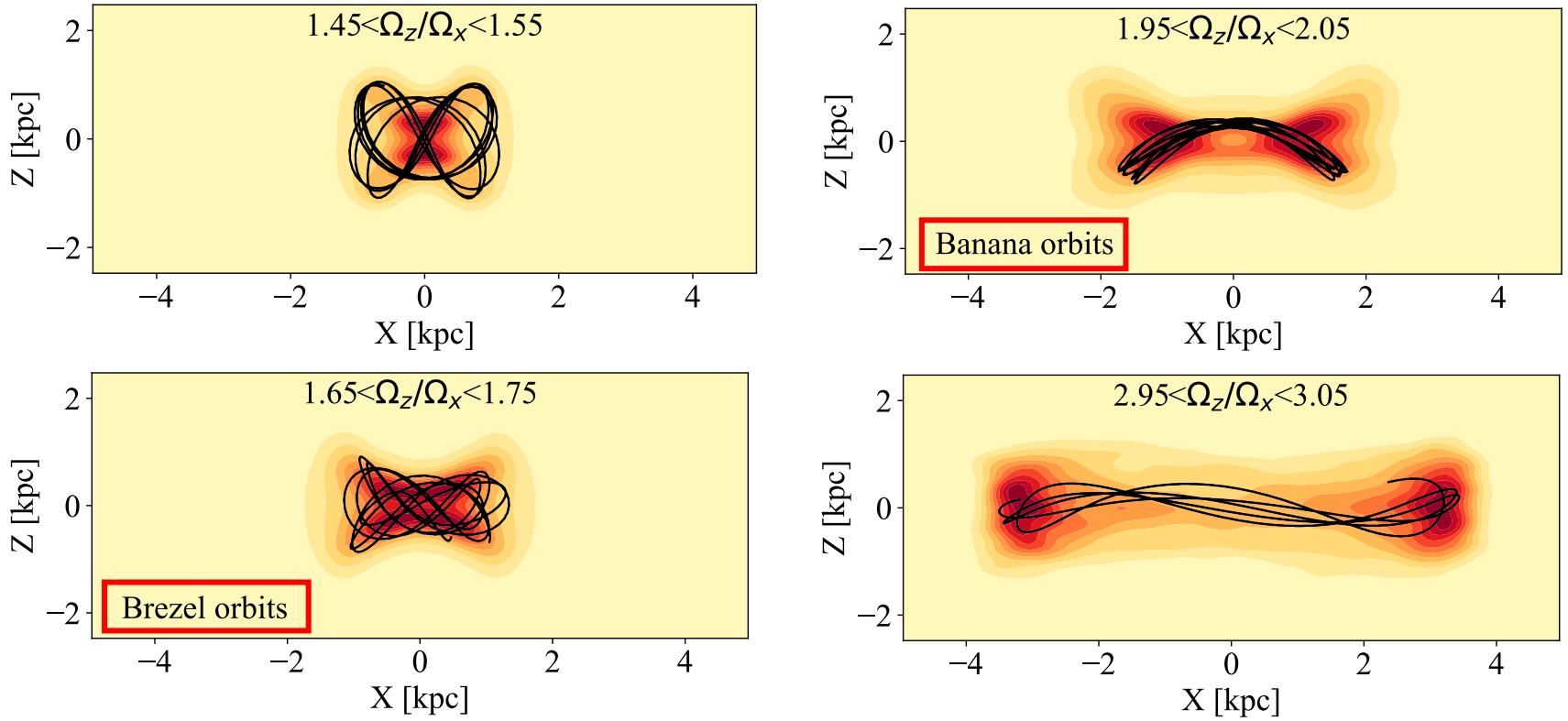
$$\partial\rho/\partial t + \nabla\cdot(\rho\bar{\boldsymbol{v}}) = 0 \longrightarrow \Omega = \frac{\int \mathrm{d}^3\boldsymbol{x}\,\rho\left[W\bar{\dot{\varphi}} + \frac{\mathrm{i}}{m}\bar{v}_R(\partial W/\partial R)\right]\mathrm{e}^{-\mathrm{i}m\varphi}}{\int \mathrm{d}^3\boldsymbol{x}\,\rho\,W\,\mathrm{e}^{-\mathrm{i}m\varphi}}.$$

- Can't directly apply to any observation because:
  - The continuity equation can't handle uncertainties
  - This formulation also can't accept the azimuthal selection function

- We can test how much these two observational caveats would influence the pattern speed calculation using the N-body simulation snapshots

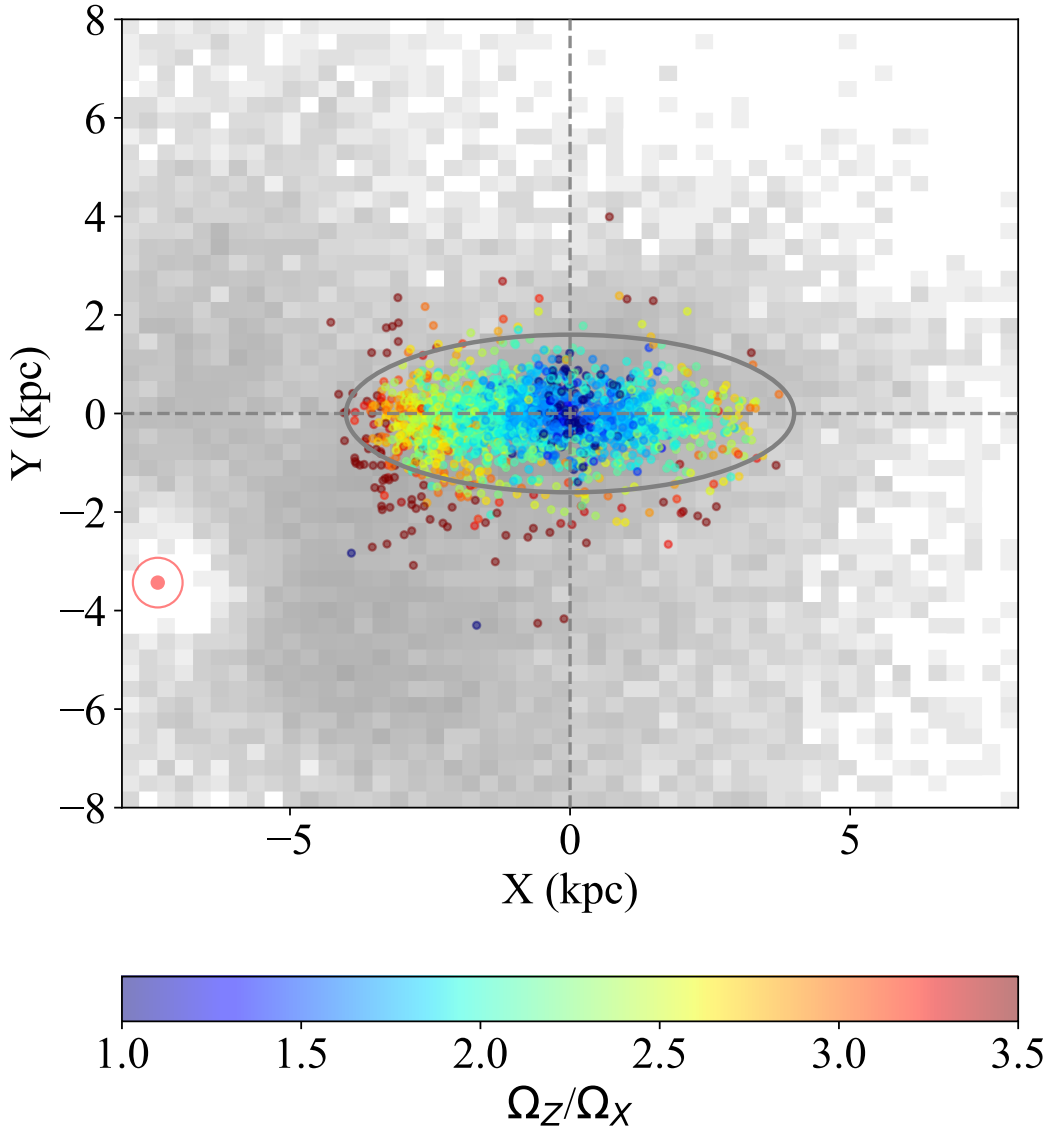
Play more with the dynamics!

- Assume the Galactic potential from the M2M model in Portail+17 (Sormani+22) is correct
- Select bar stars with $1.8 < \Omega_R/\Omega_X < 2.2$
- Shed light on the vertical structure of the bar using the Ω_Z/Ω_X value



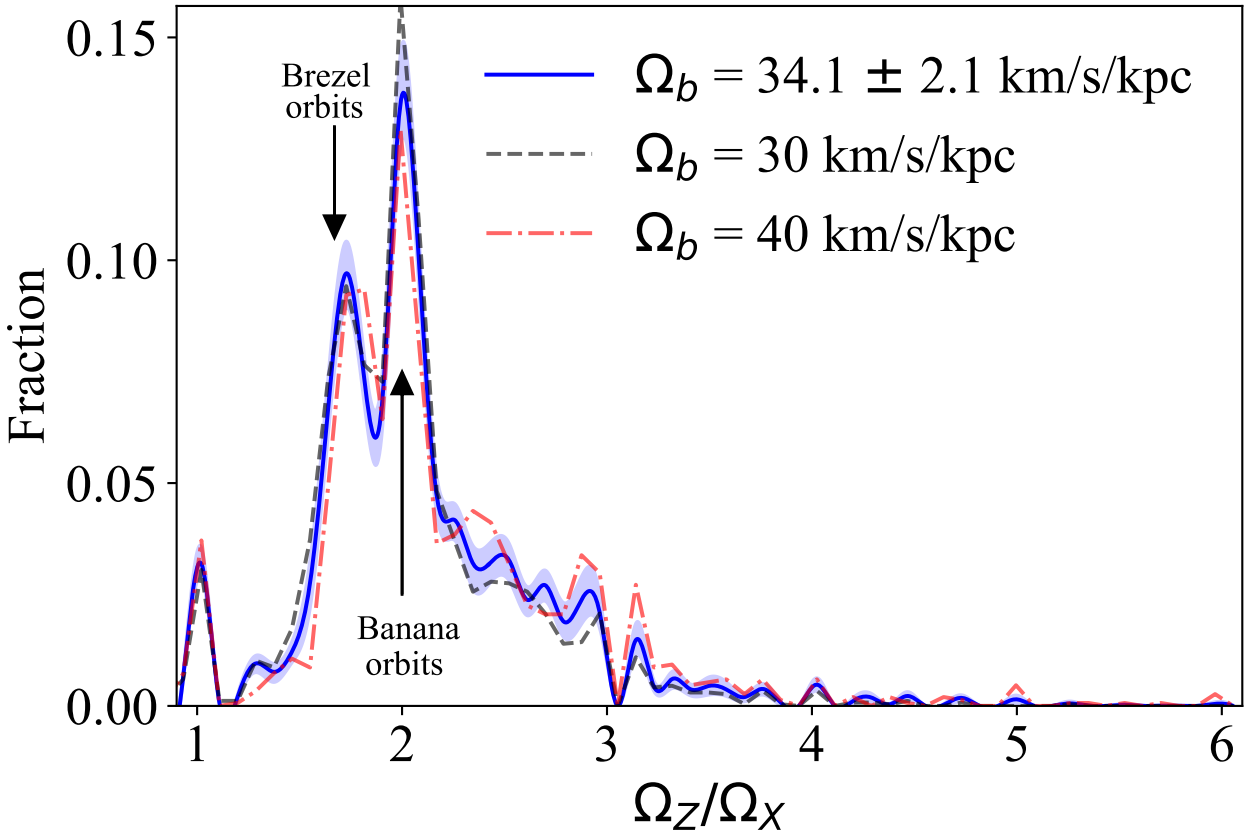
In-plane distribution of bar stars

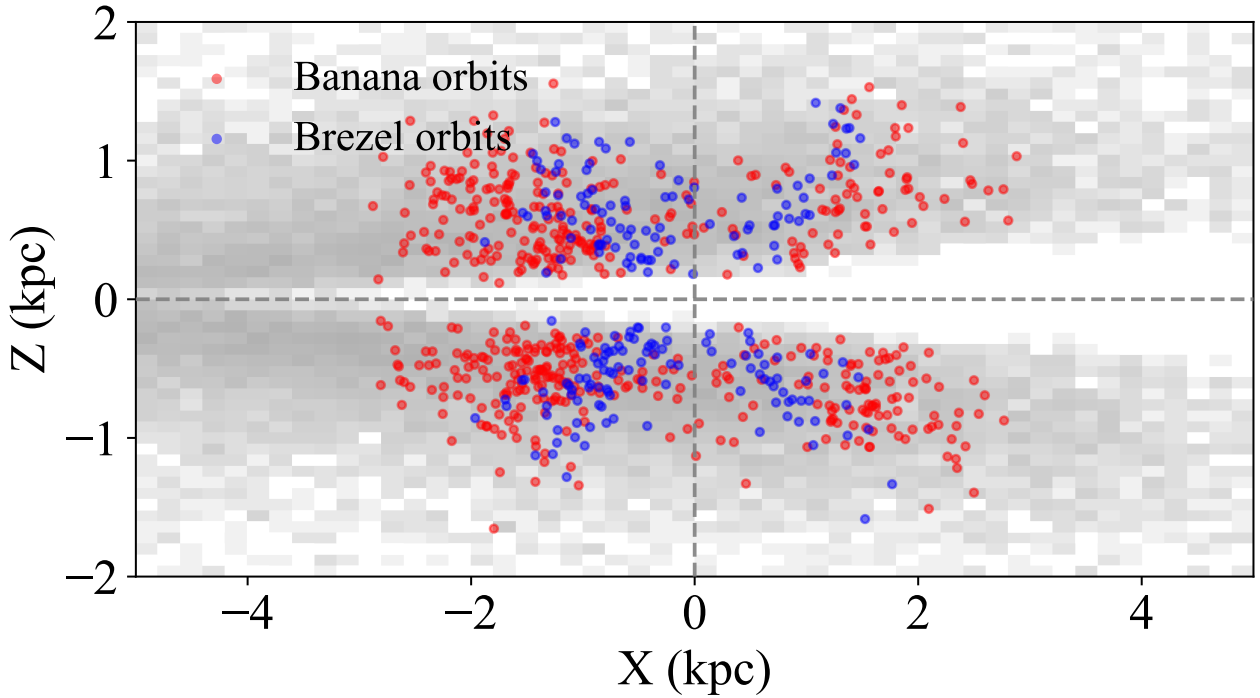
- Stars with greater Ω_Z/Ω_X value span **larger** radius and reside **farther** from the Galactic centre



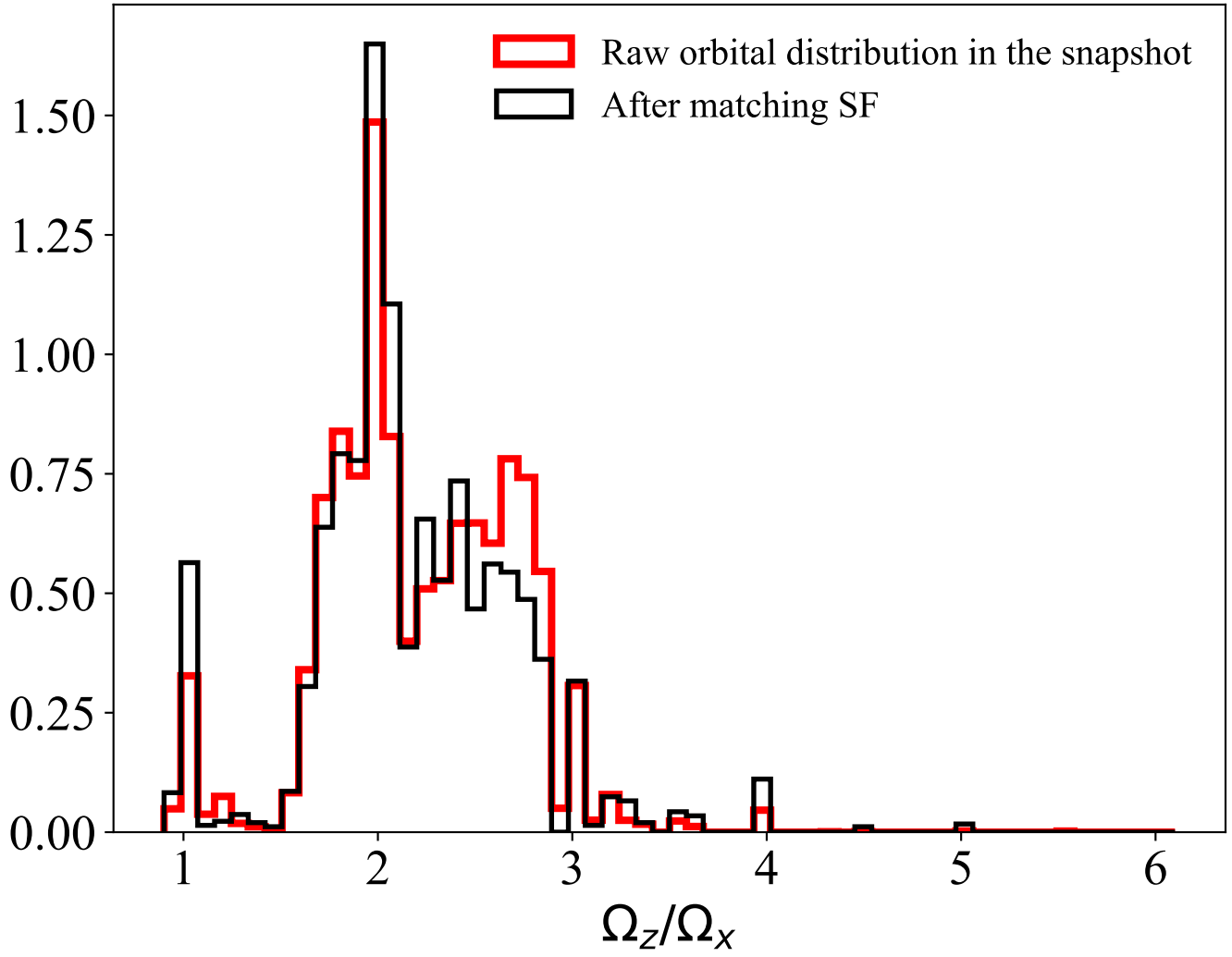
What contribute the Galactic X-shaped stucture

Banana or Brezel ?

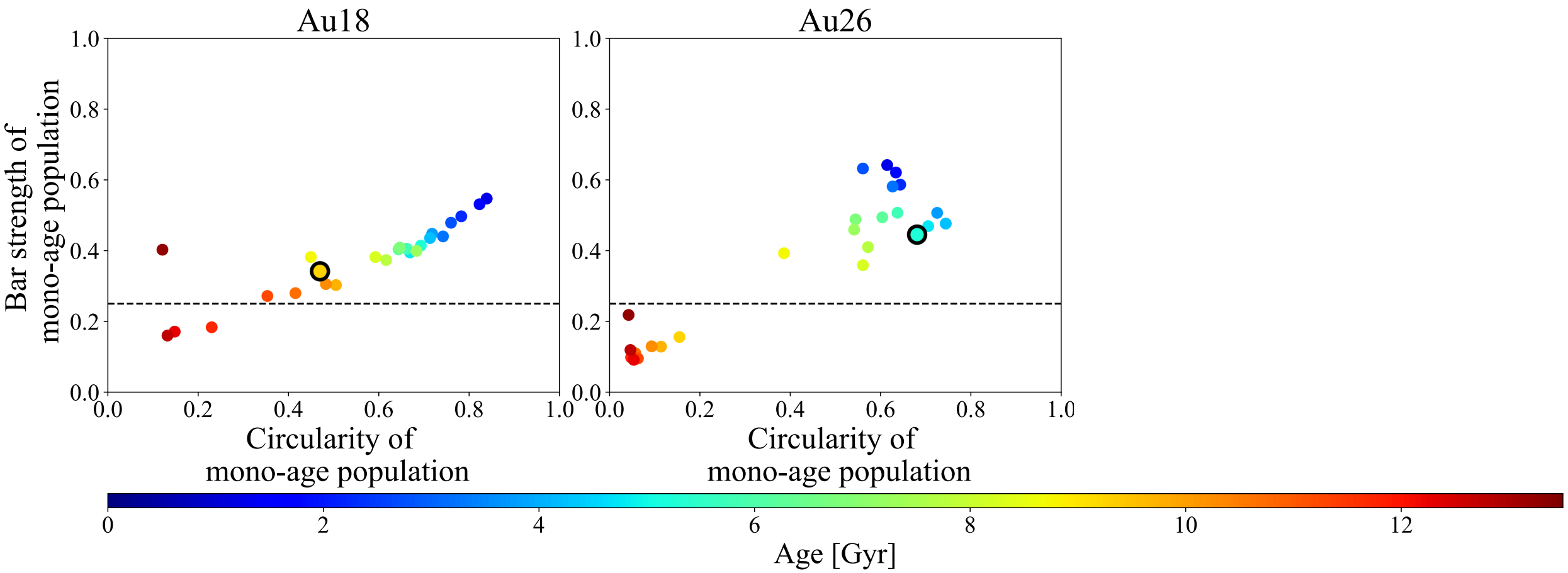




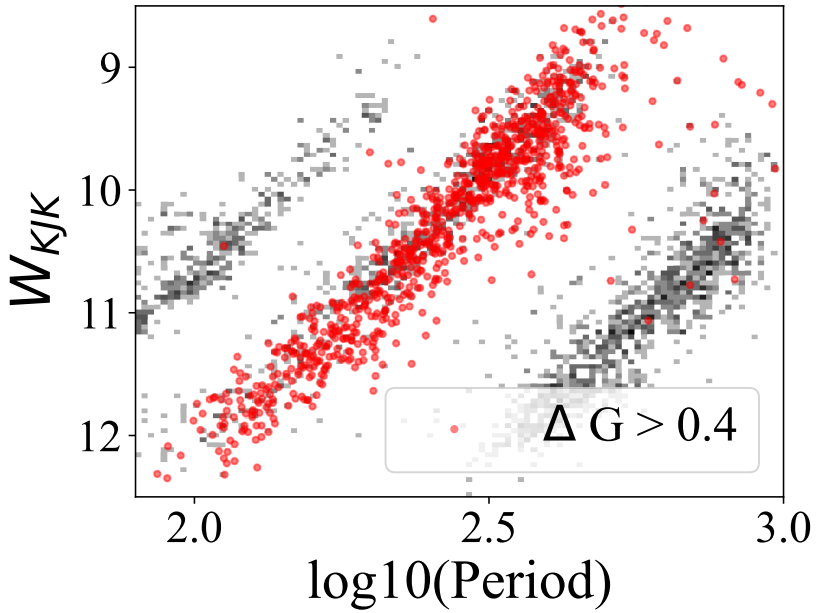
Selection function effect on bar orbital family distribution

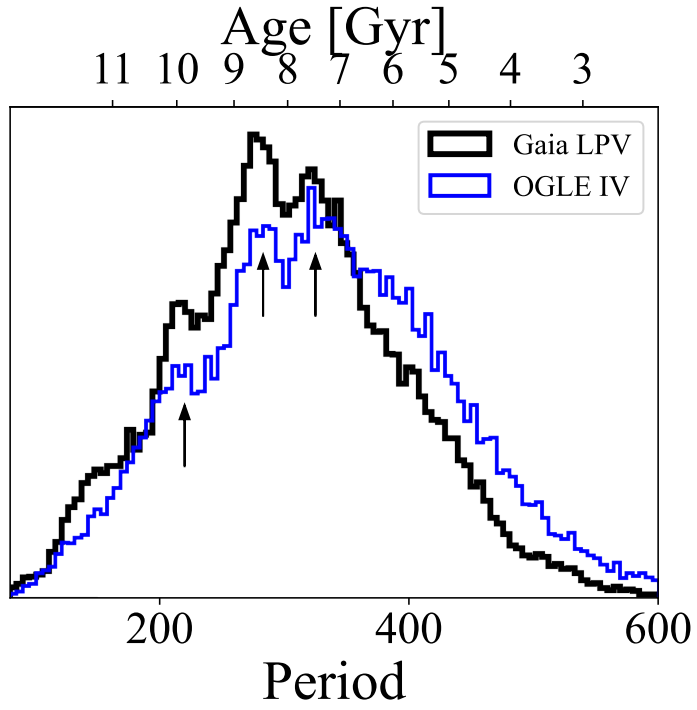


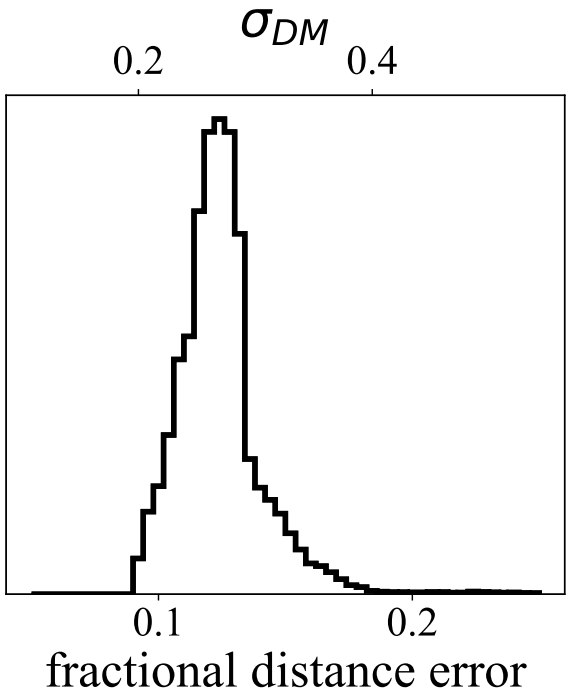
Correlation between kinematics and bar strength

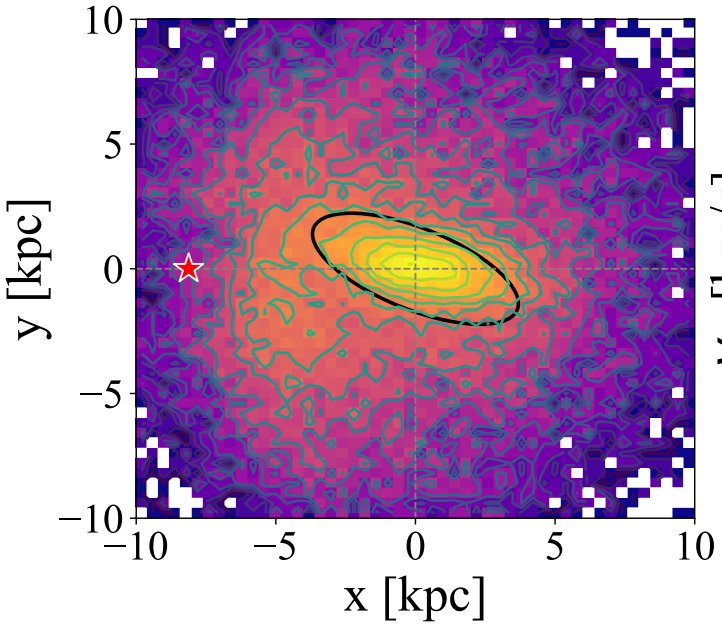


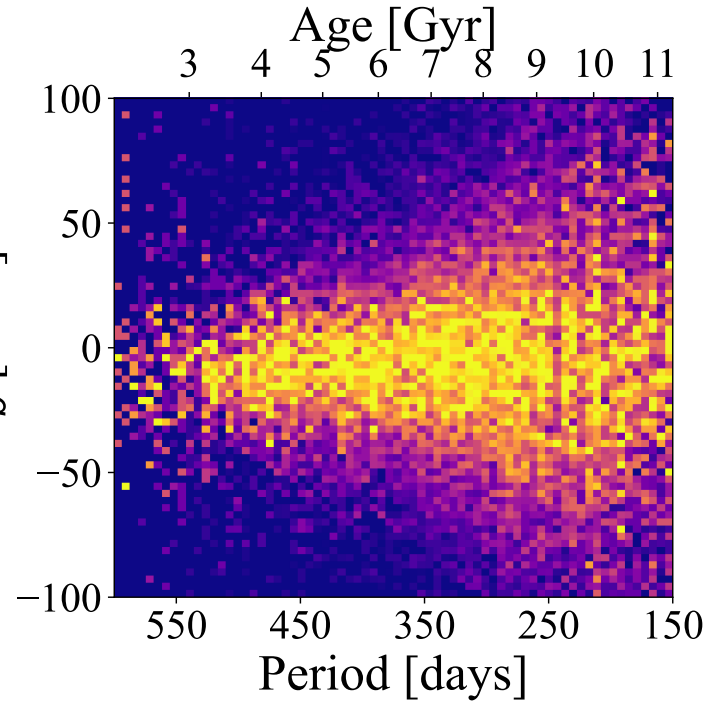
Mira sample property



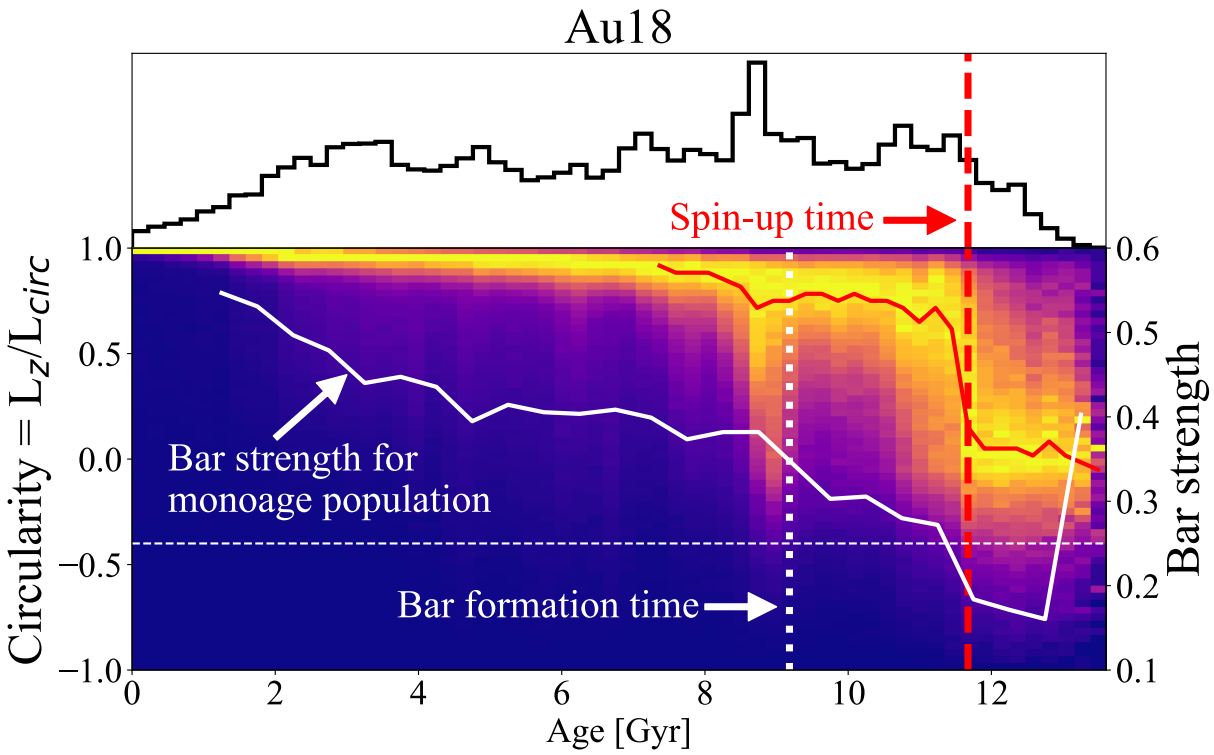


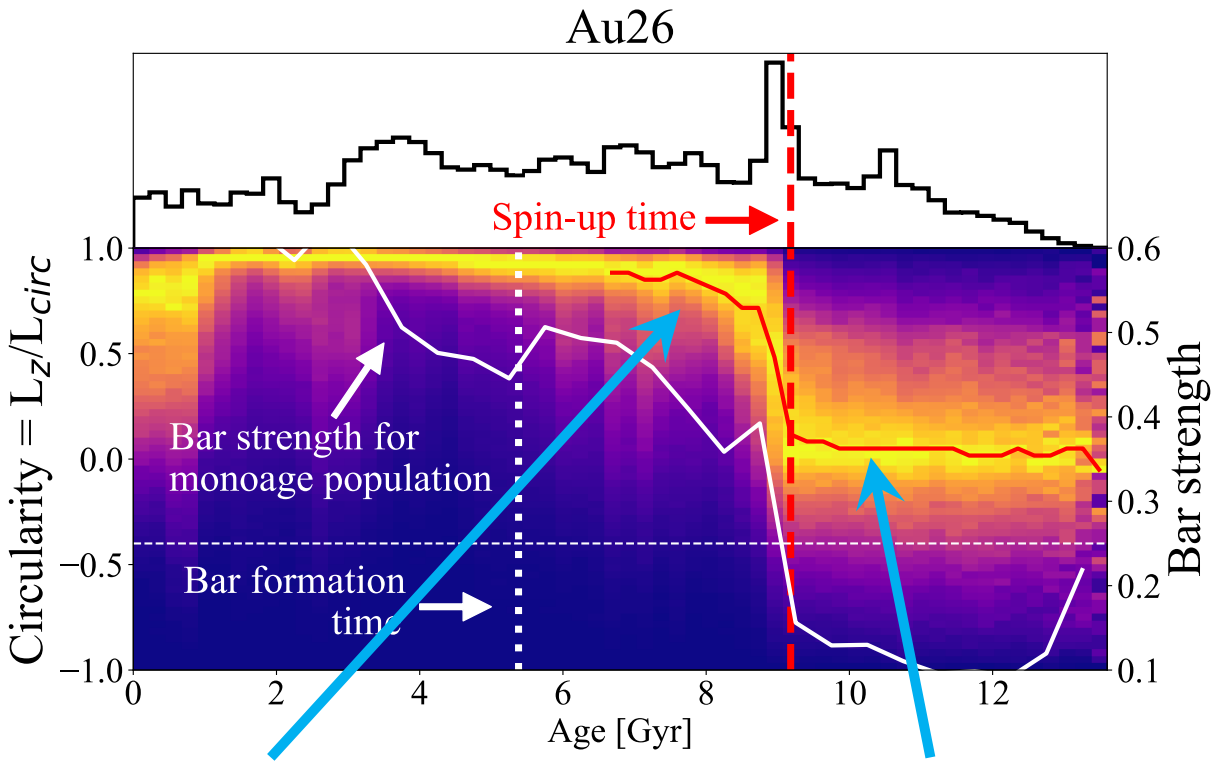






Auriga cosmological simulations: Spin-up in Au18 & Au26

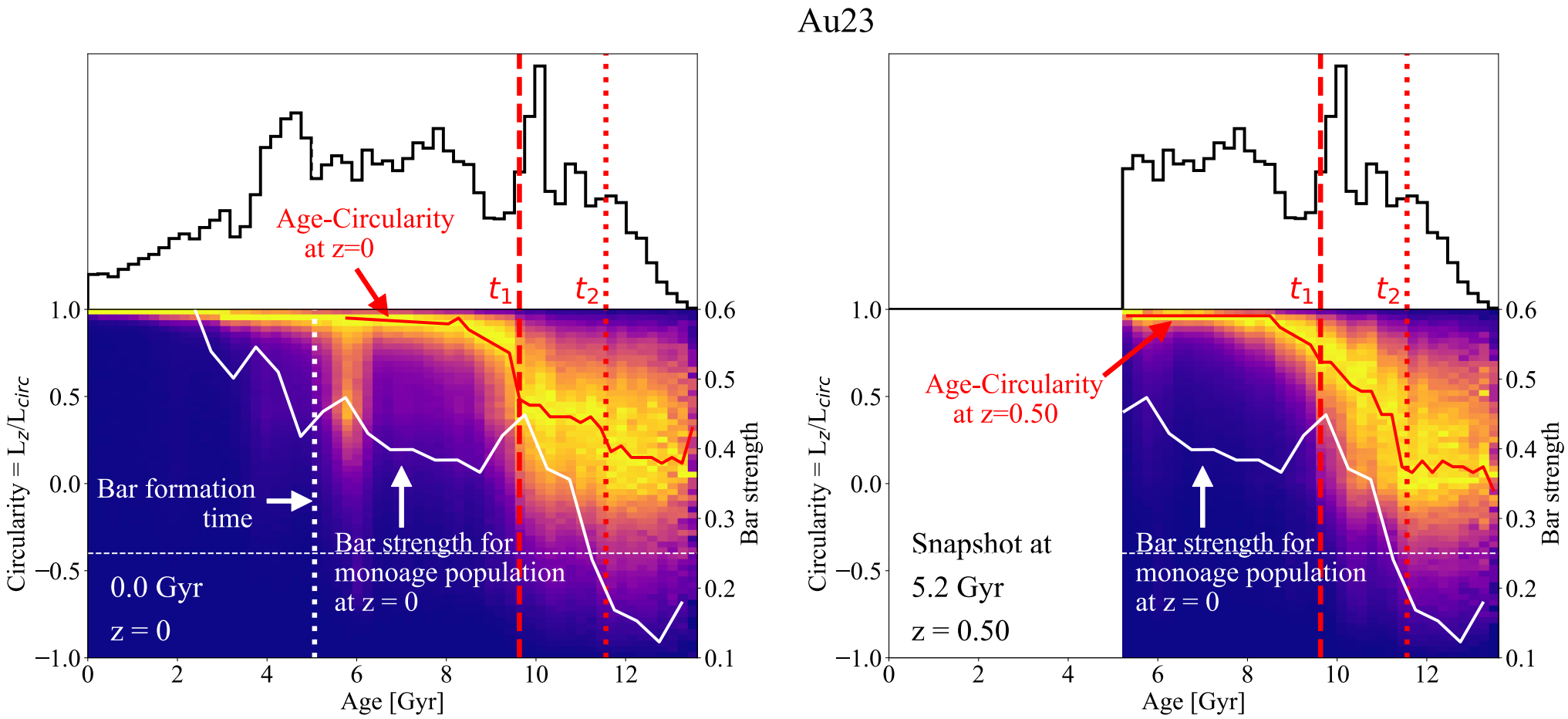


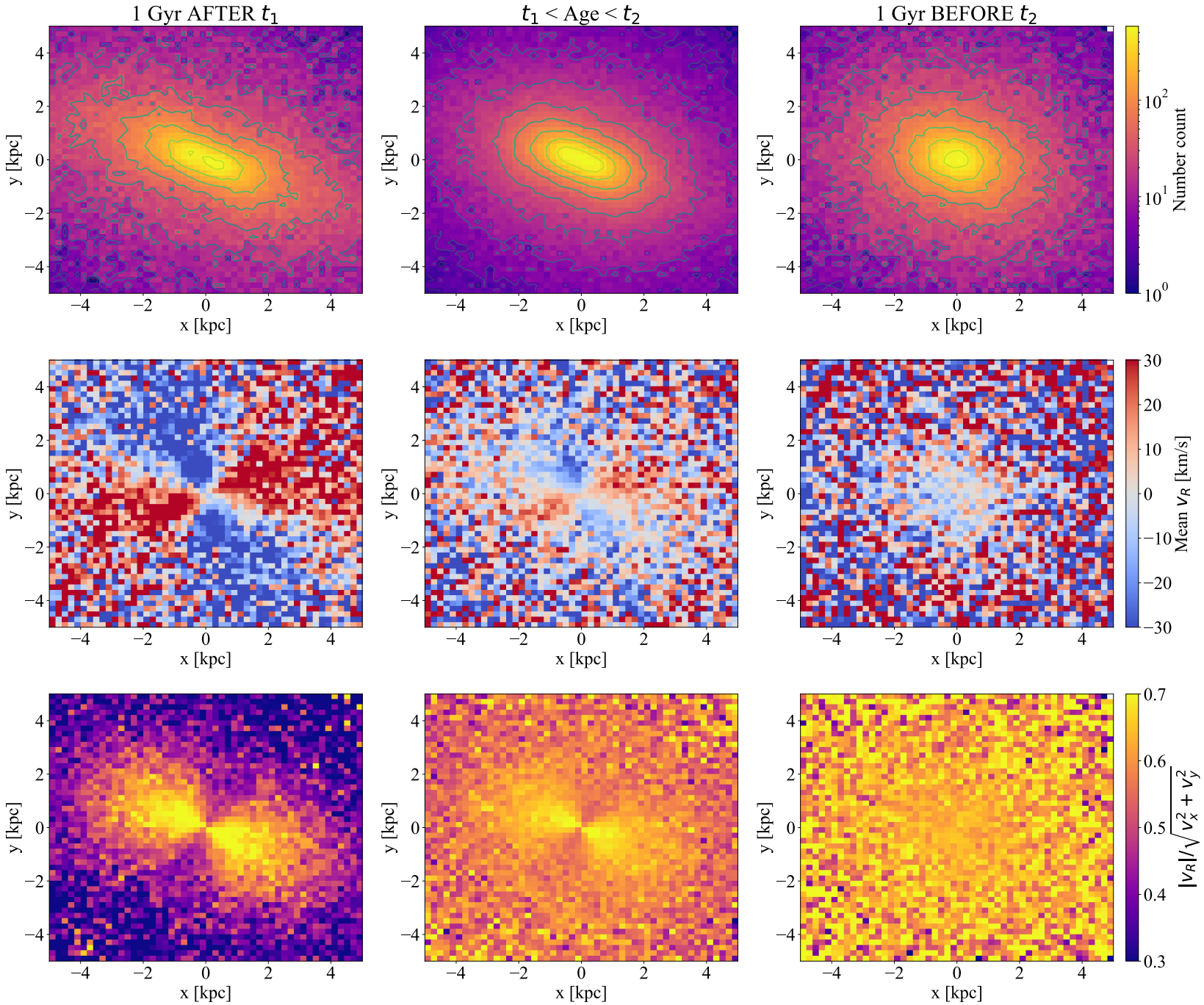


Population with disc-like kinematics; efficiently captured by the bar and show bar signature

Population with halo-like kinematics; response less to the bar and no bar signature

Au23


Au23
Age-Circularity
at z=0
t_1
t_2
Bar formation
time
Bar strength for
monoage population
at z = 0
0.0 Gyr
z = 0
Circularity = L_z/L_{circ}
Bar strength
Age [Gyr]
Age-Circularity
at z=0.50
Snapshot at
5.2 Gyr
z = 0.50

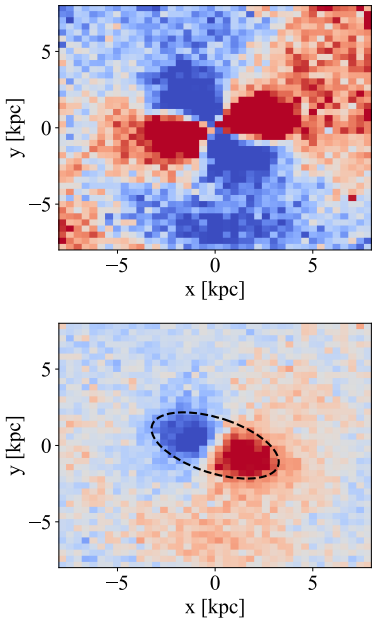

1 Gyr AFTER t_1
t_1 < Age < t_2
1 Gyr BEFORE t_2
y [kpc]
x [kpc]
Number count
Mean v_R [km/s]
$|v_R|/\sqrt{v_x^2 + v_y^2}$

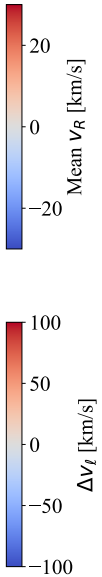
Use v_l map to track the chrono-kinematics of inner Galaxy: Au18 as an example

After the spin-up

Before the spin-up

1 < Age [Gyr] < 3





Use v_l map to track the chrono-kinematics of inner Galaxy: Au18 as an example

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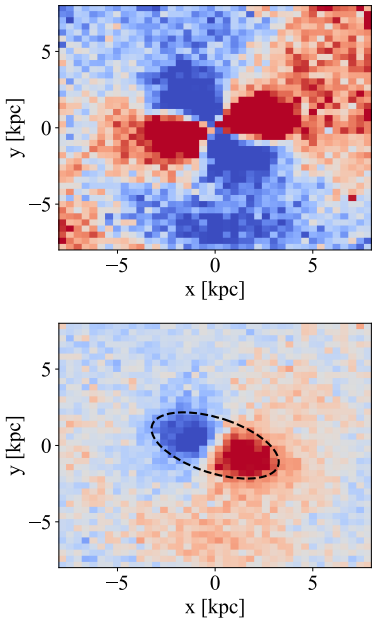
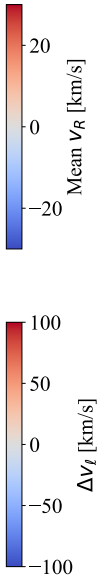
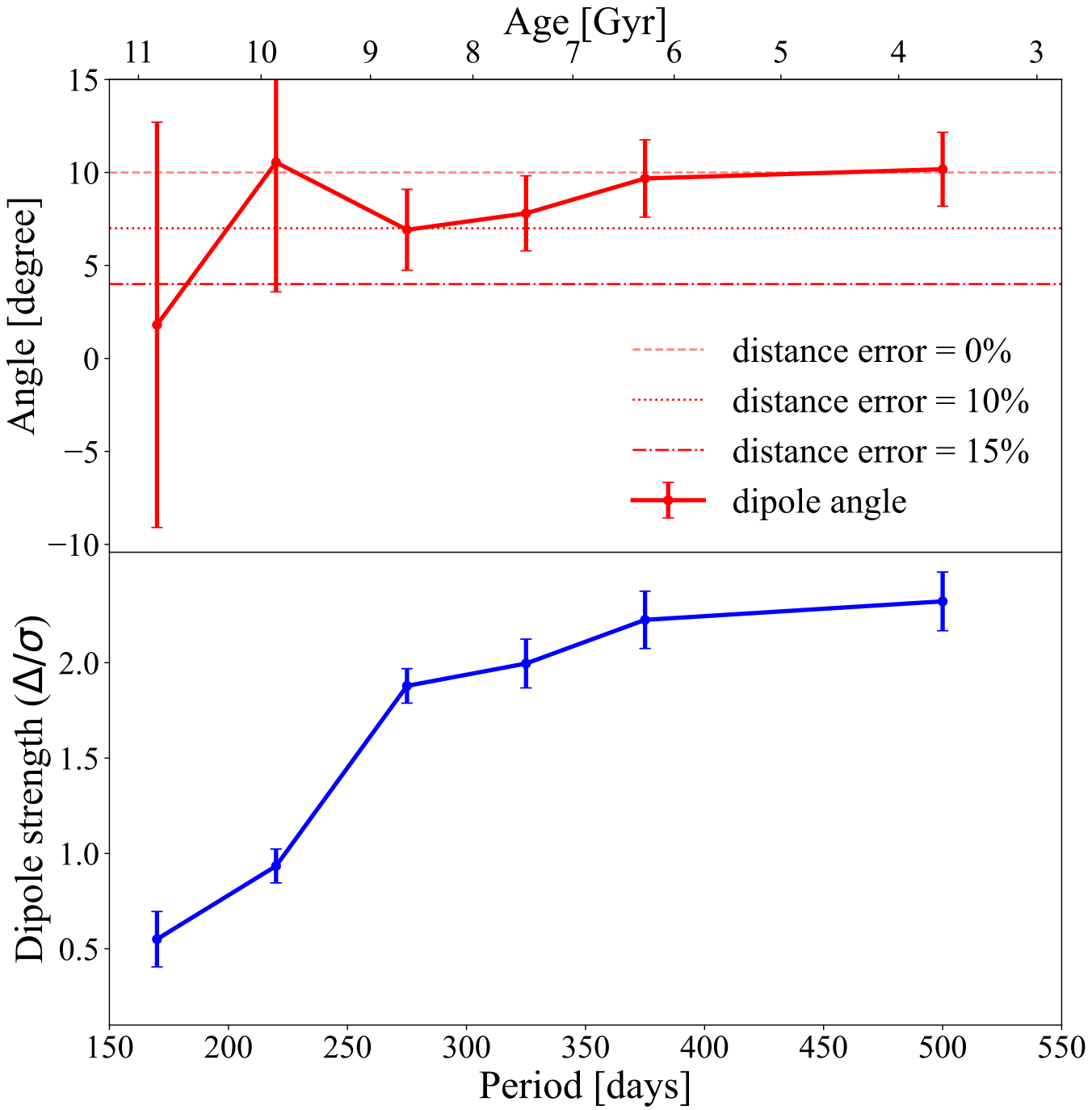
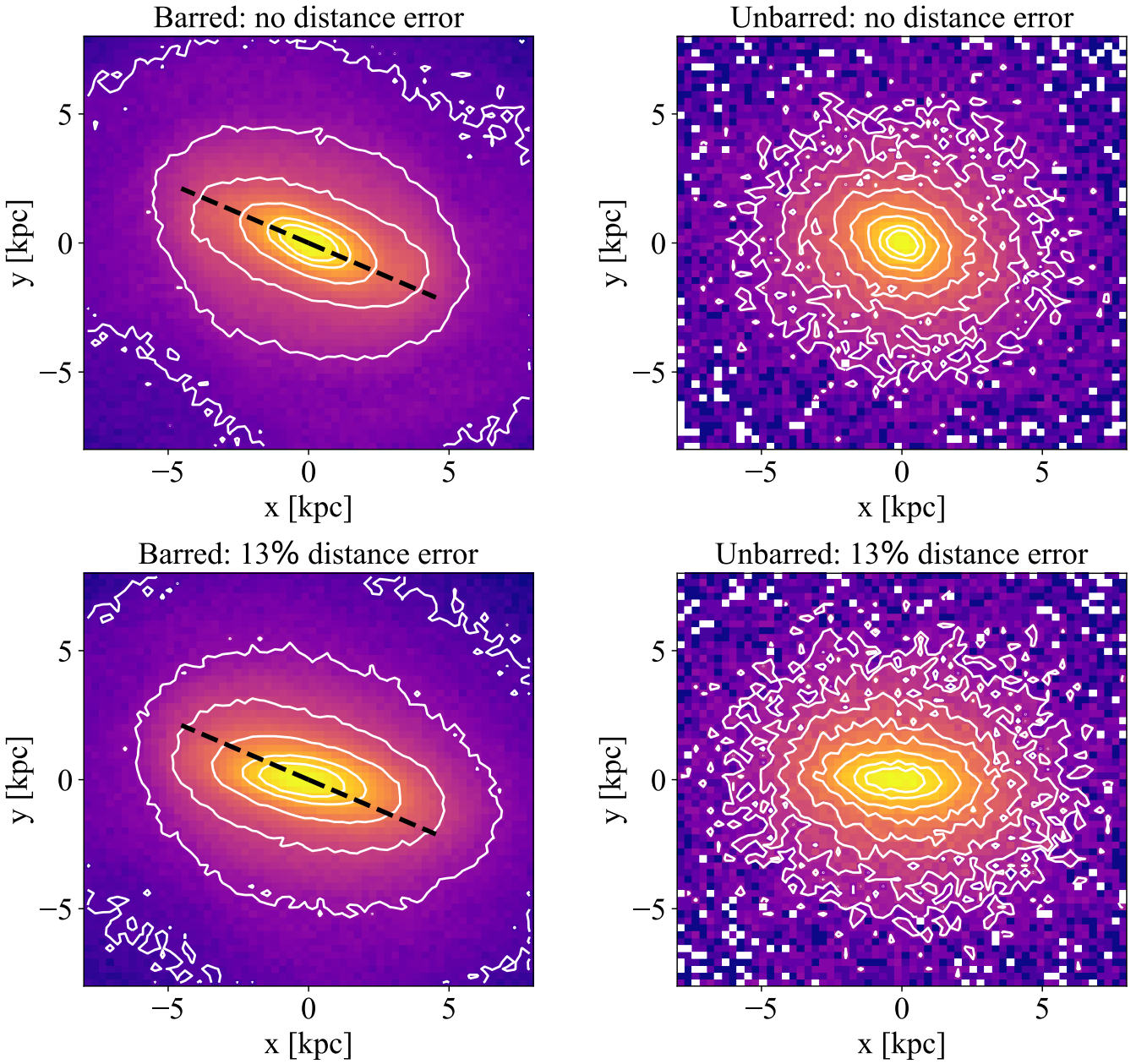




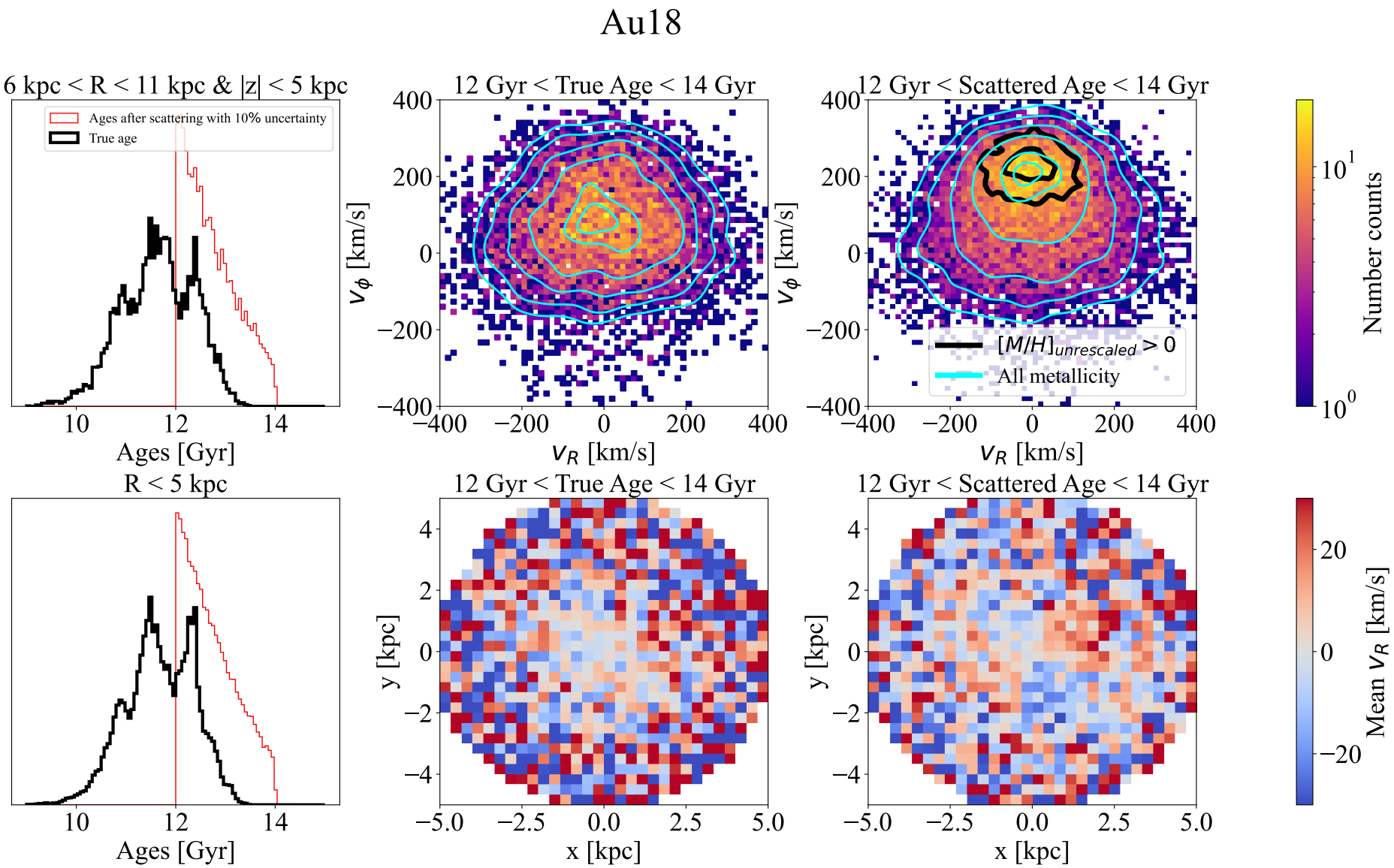
Quantify bar-driven dipole signature in Δv_l map



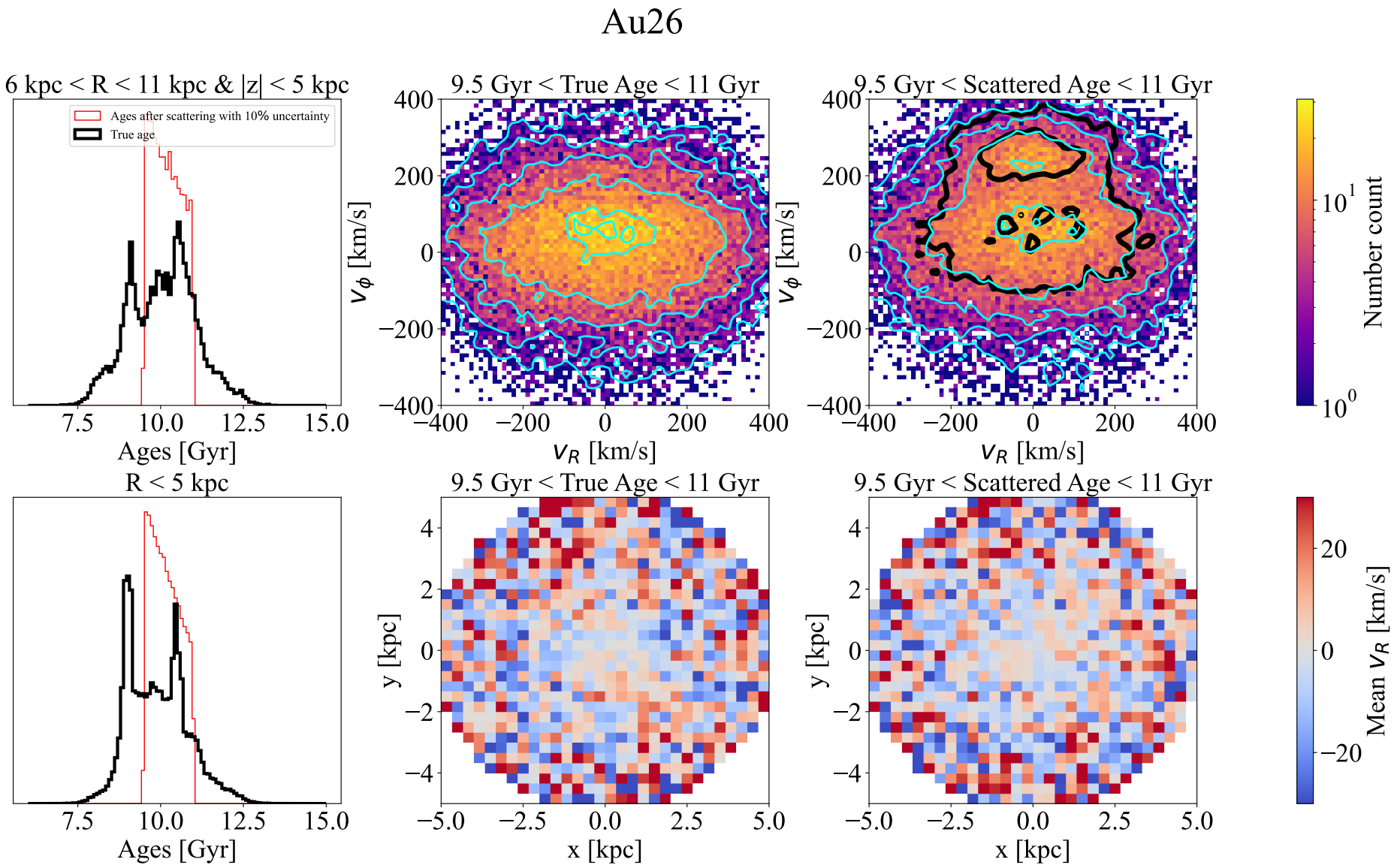
Effect of the distance uncertainty

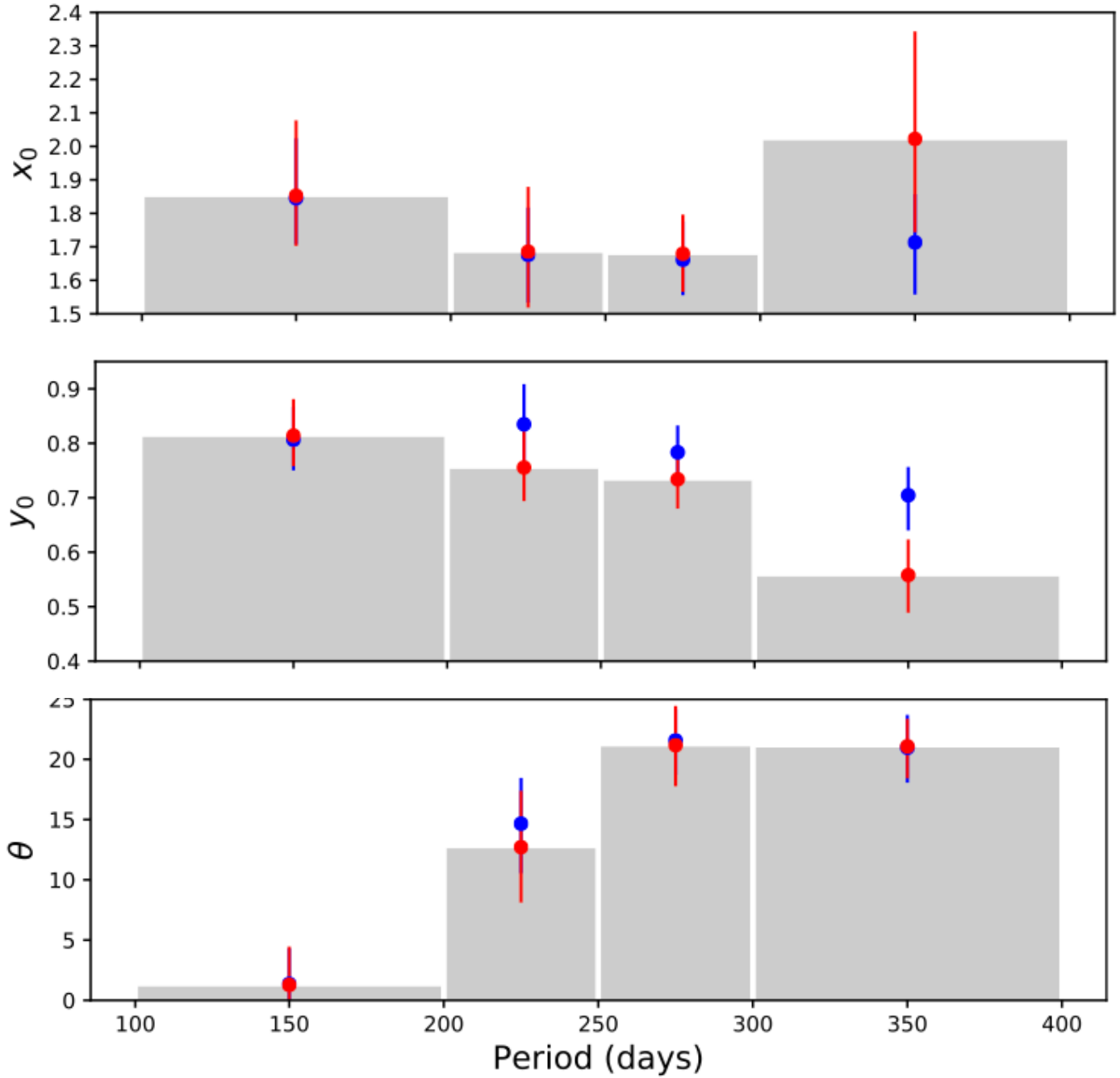


Effect of age uncertainty

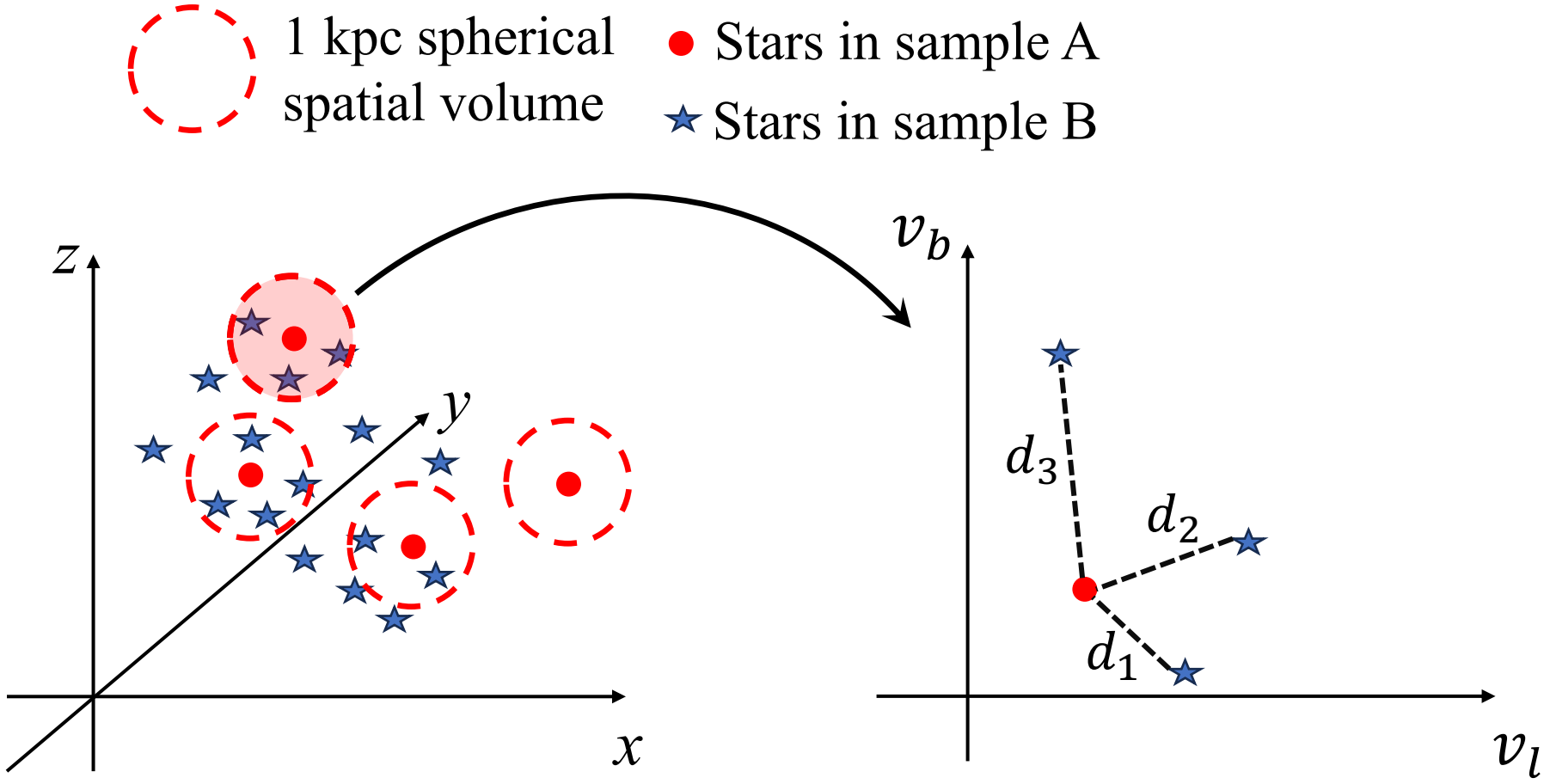


Effect of age uncertainty





Grady+ 2020


1 kpc spherical
spatial volume
Stars in sample A
Stars in sample B
z
y
x
v_b
v_l
d_3
d_2
d_1