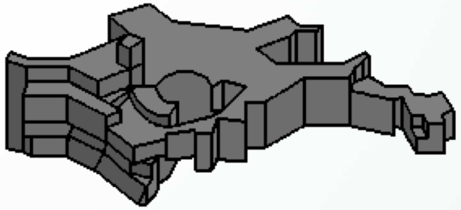
„Stars without Borders: A Galaxy in Crisis“
Ljubljana, 14. June 2019

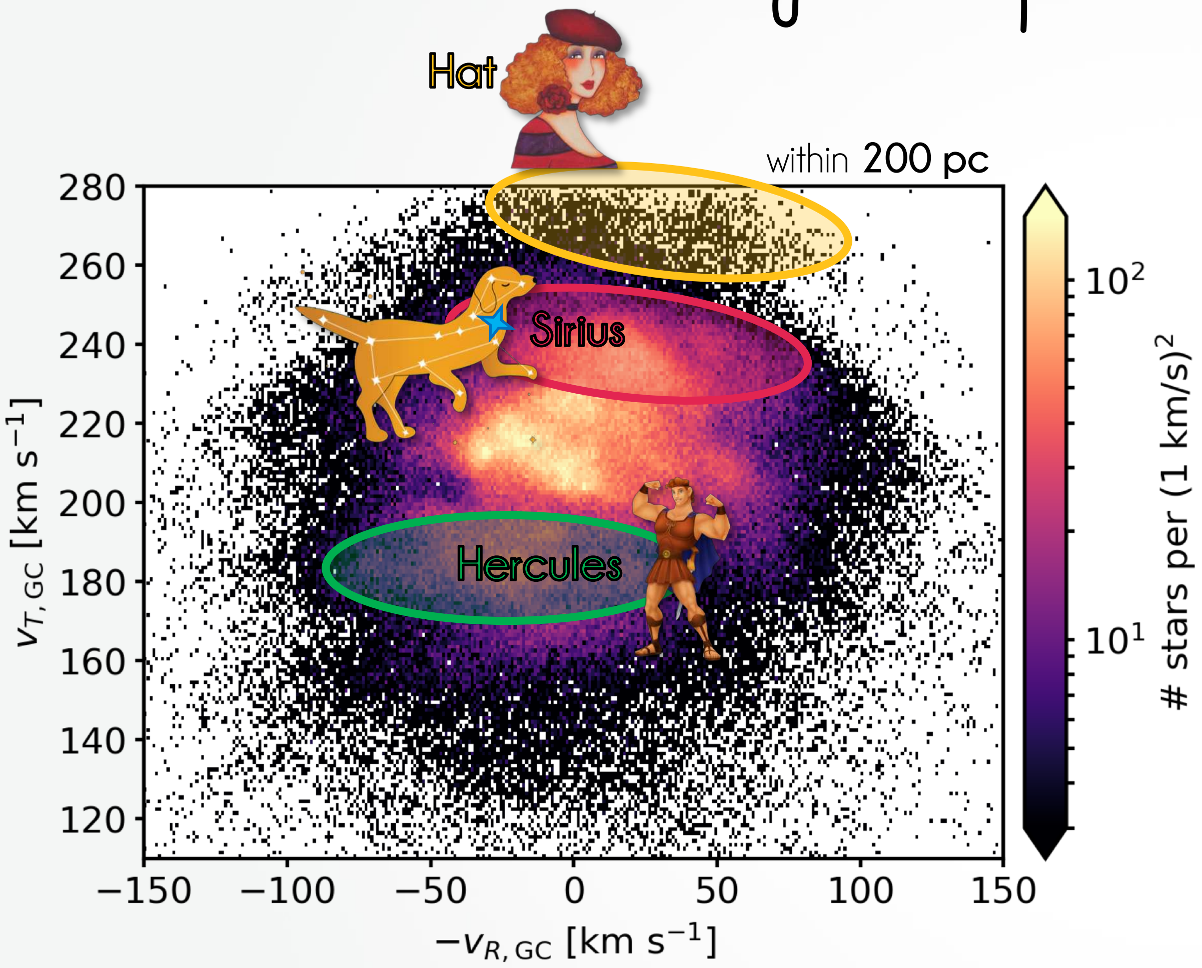
The Galactic Disk and Bar Resonances in Action Space

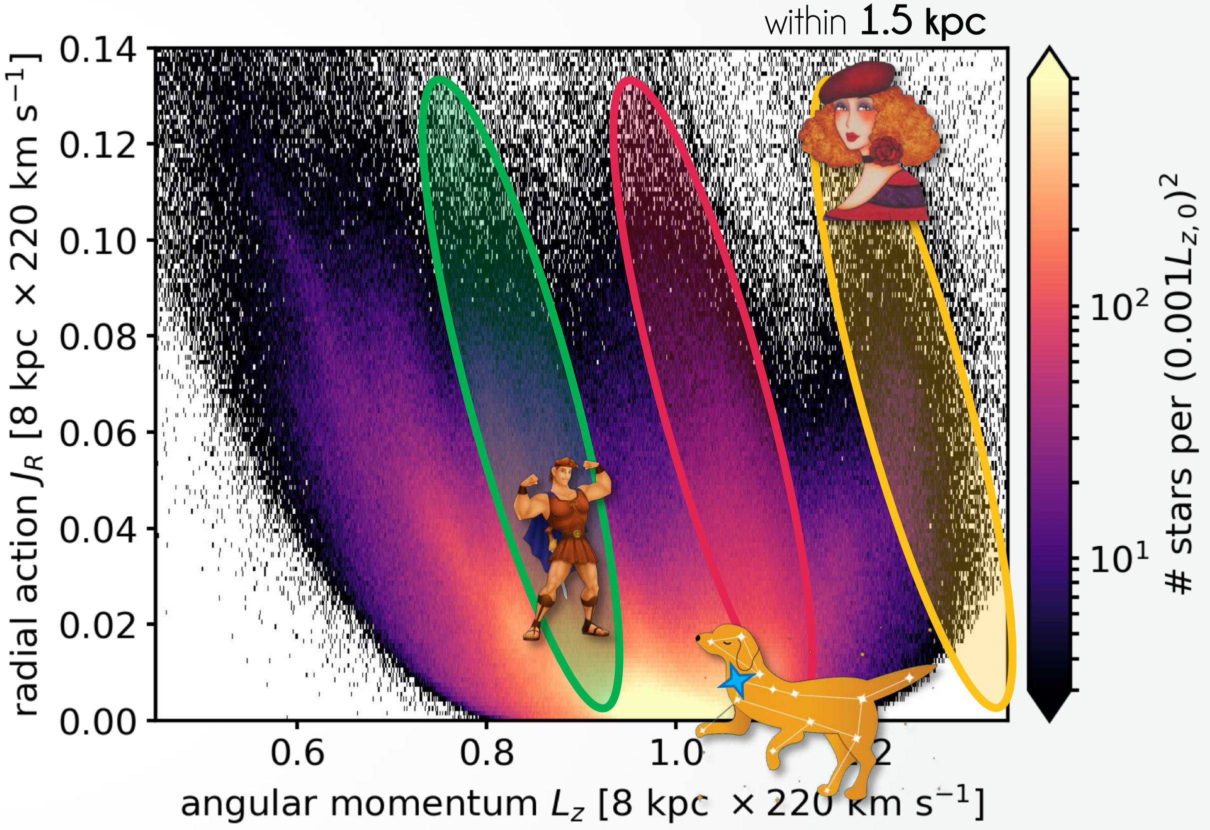
Wilma Trick (MPA, Garching/Munich)



Francesca Fragkoudi (MPA Garching), Jason Hunt (Uni Toronto),
Johanna Coronado (MPIA Heidelberg), Ted Mackereth (Uni Birmingham),
Simon White (MPA Garching), Hans-Walter Rix (MPIA Heidelberg)

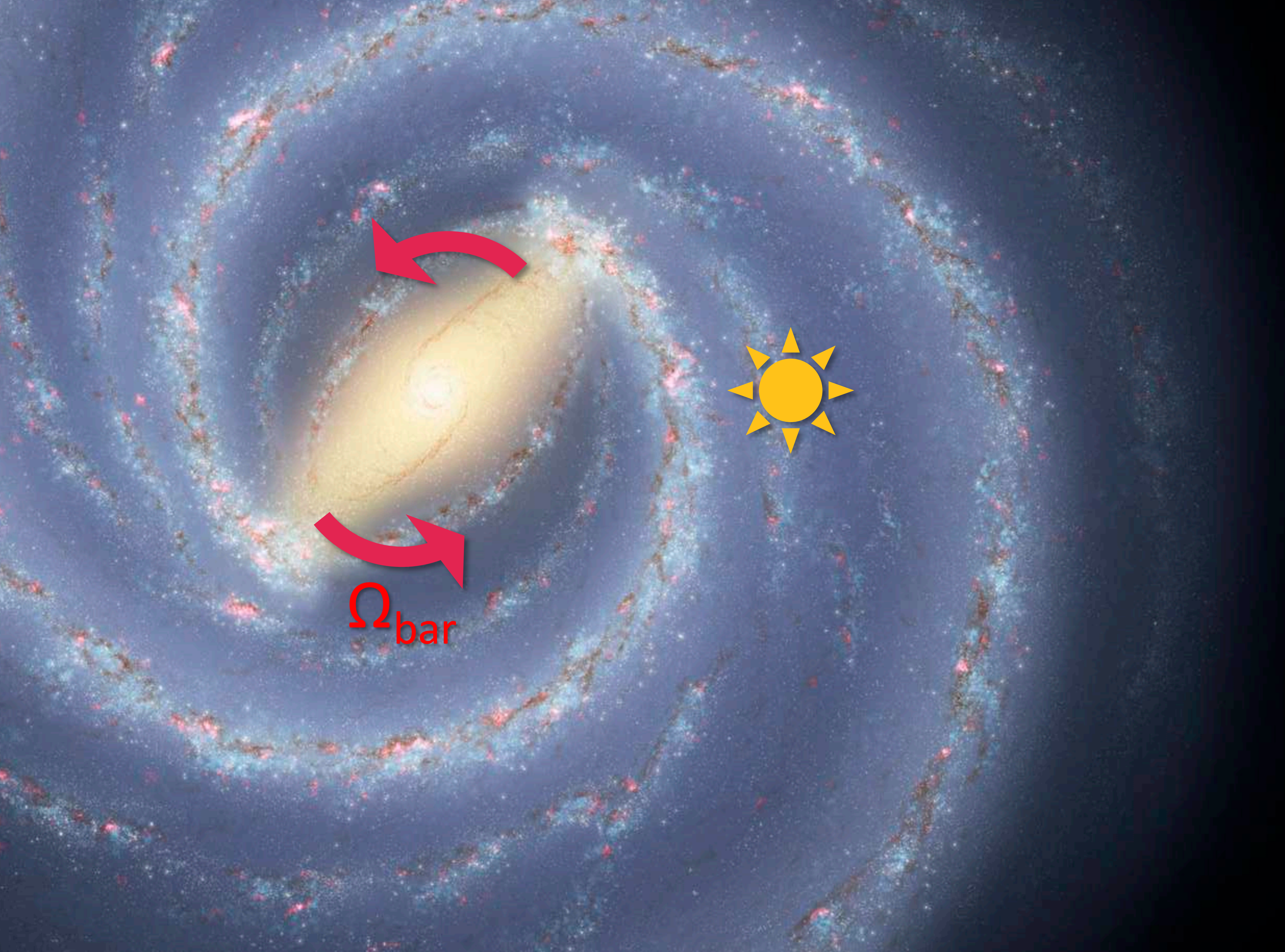
The Moving Groups in Velocities AND Actions



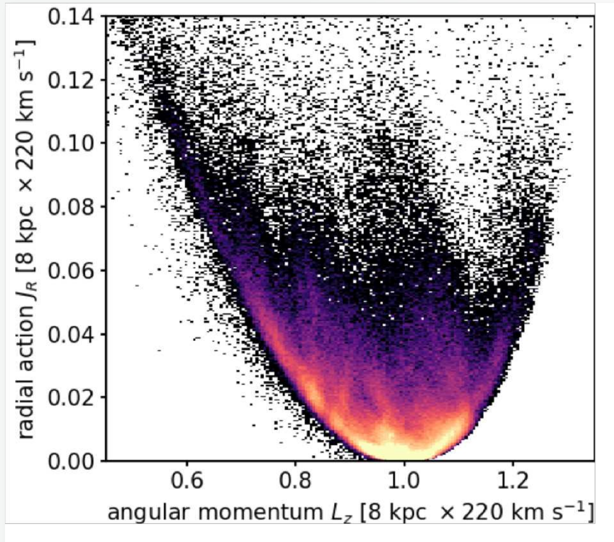


Gaia Collaboration: Katz et al. (2018)

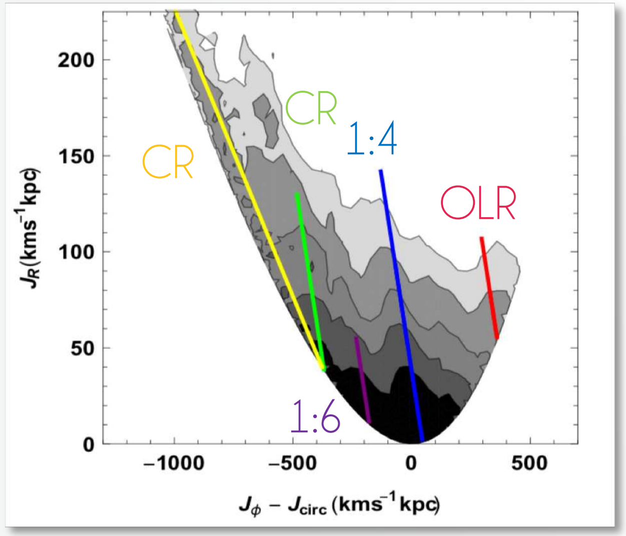
Trick, Coronado, & Rix (2019)


Ω_{bar}

Resonance models can be tuned to look like the Gaia data

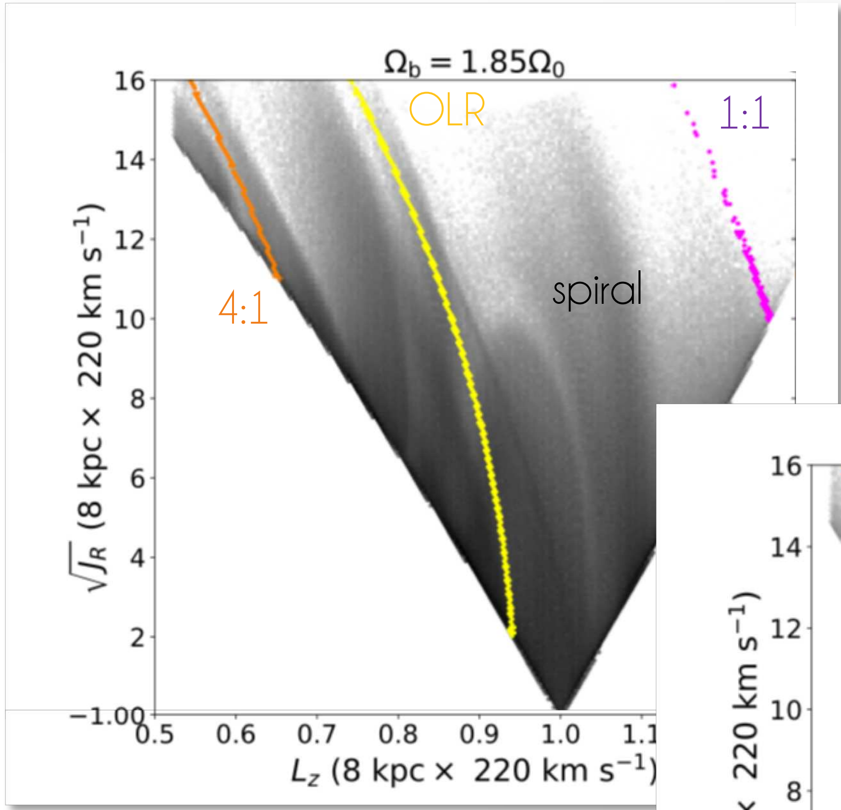


Gaia DR2 RVS
d < 200 pc



Long slow bar
with substructure

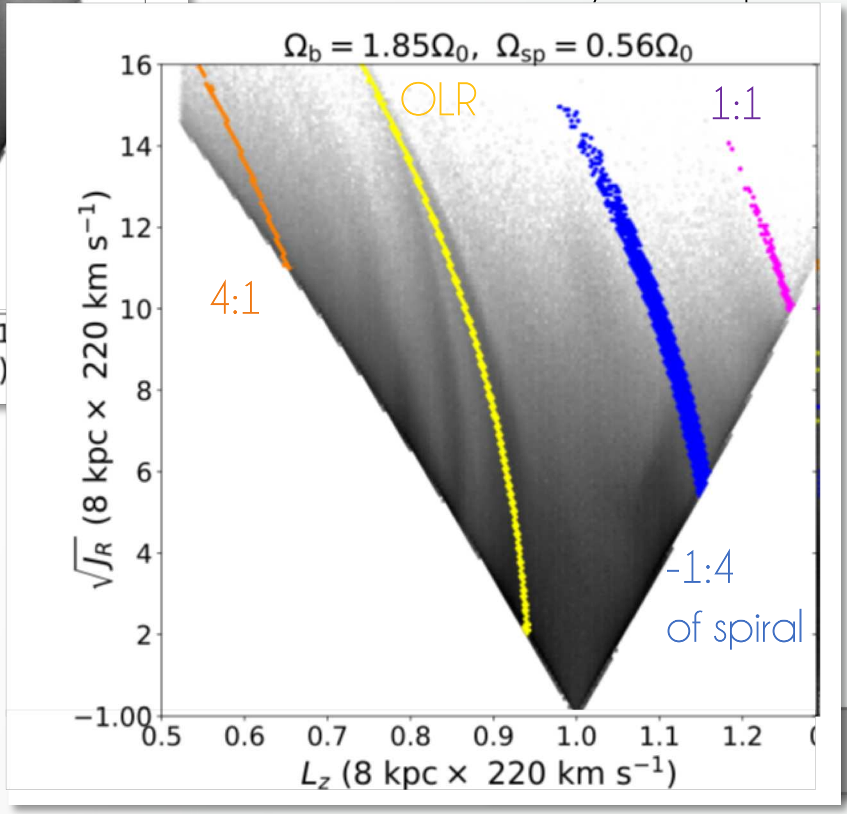
Monari+19, Ω_{bar}= 1.3 Ω_0 (Pérez-Villegas+17)
Bar Fourier components: m=2,3,4,6



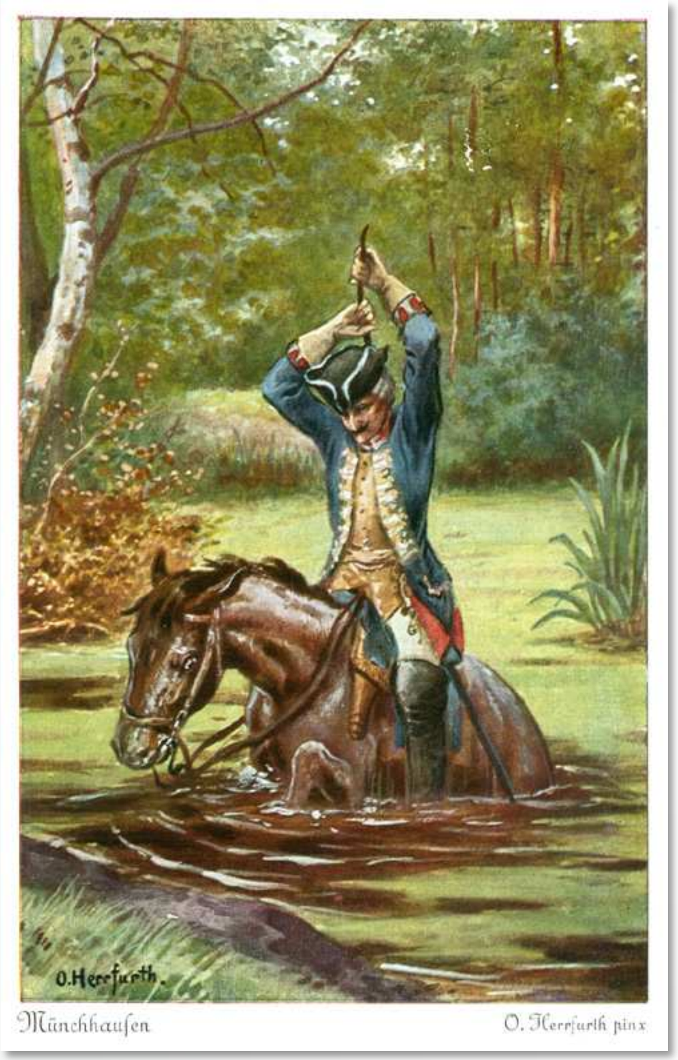
Short fast bar
with transient winding spiral

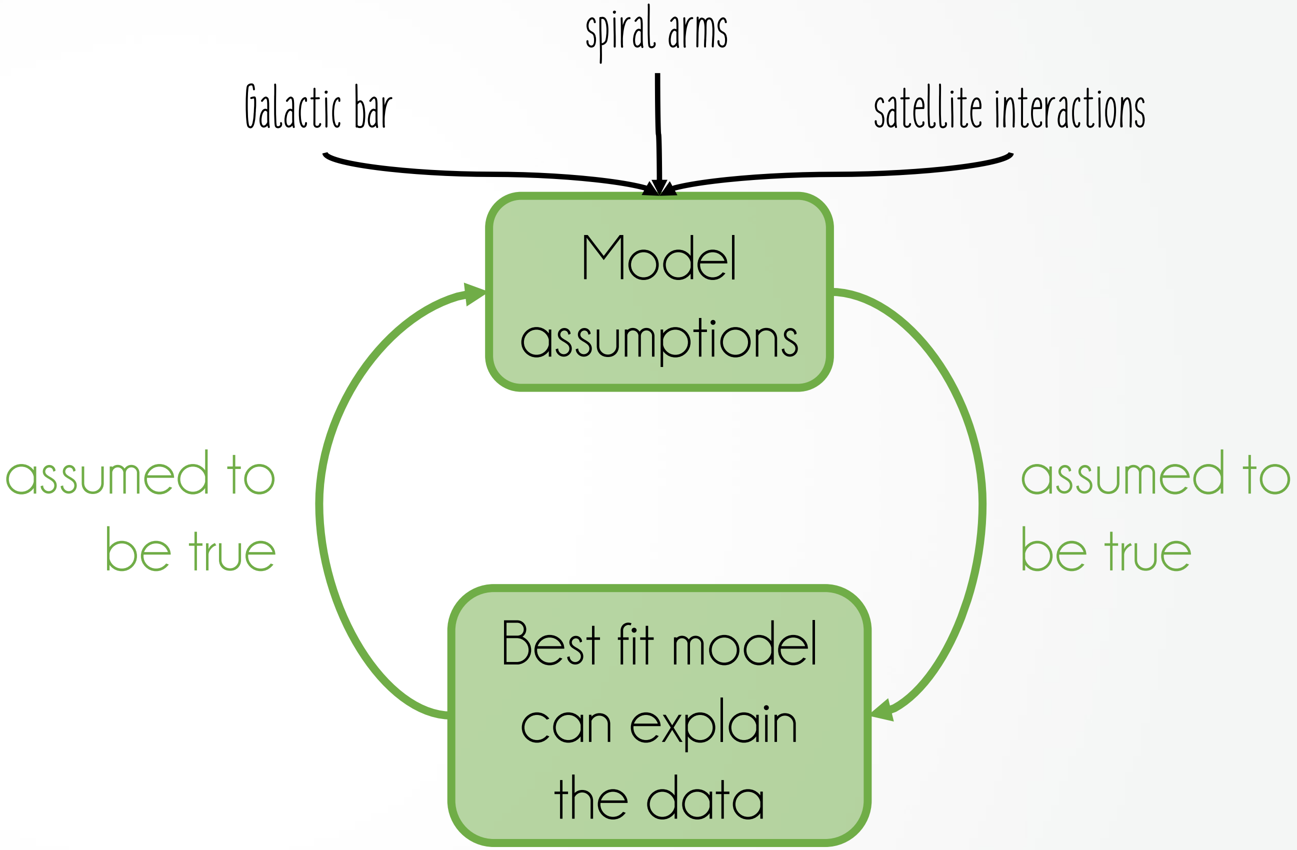
Hunt+19, Ω_{bar} = 1.85 Ω_0
(Dehnen+00, Antoja+14)

Short fast bar
with density wave spiral



The Munchhausen Trilemma

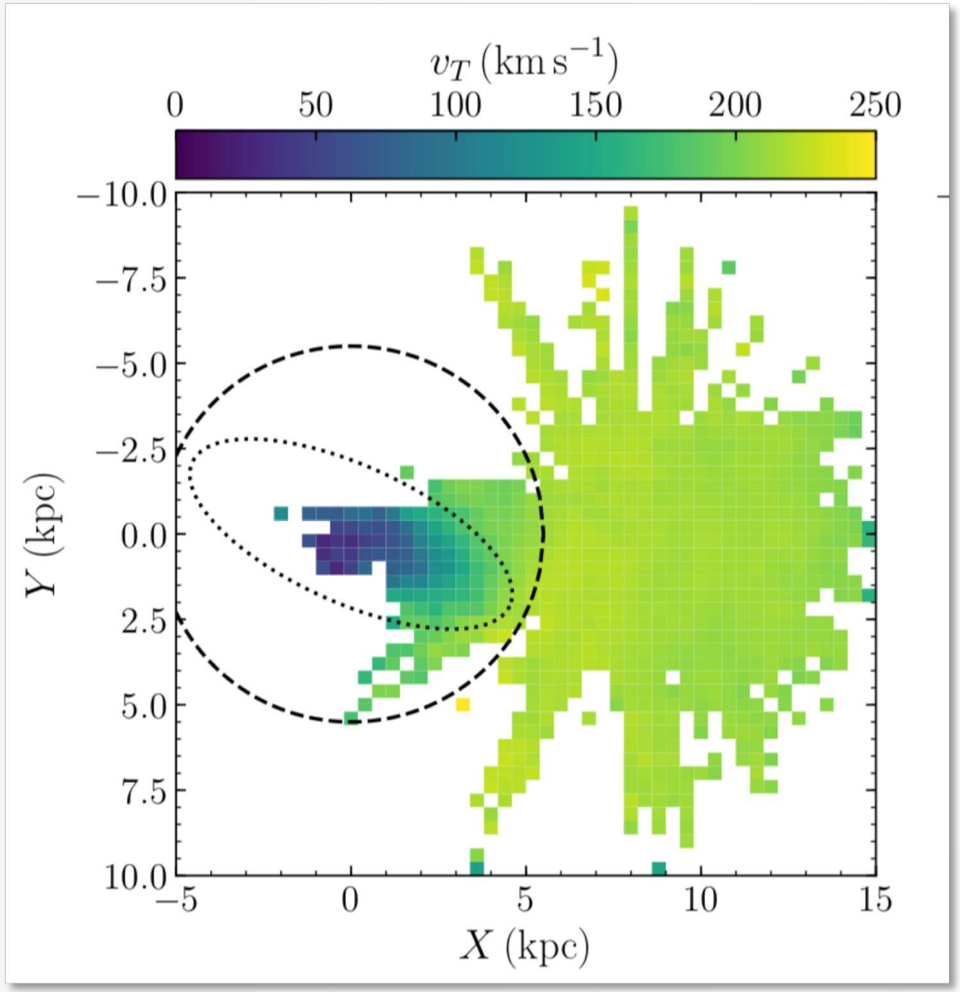




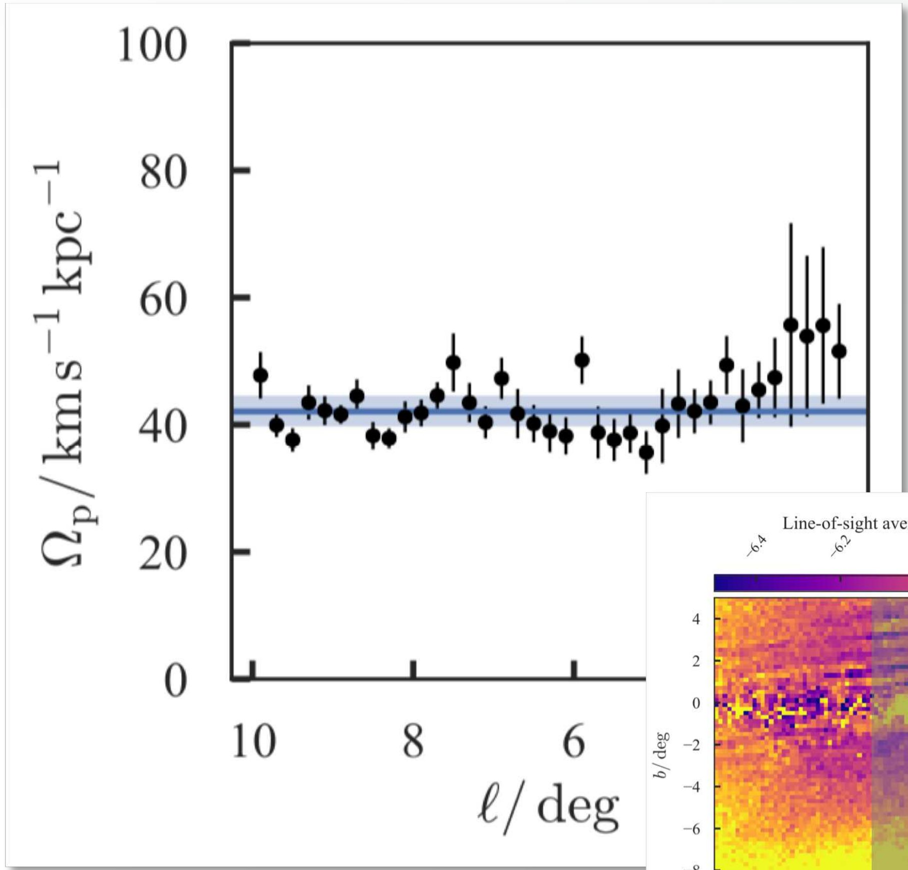
The bar pattern speed measured in/towards the Galactic center

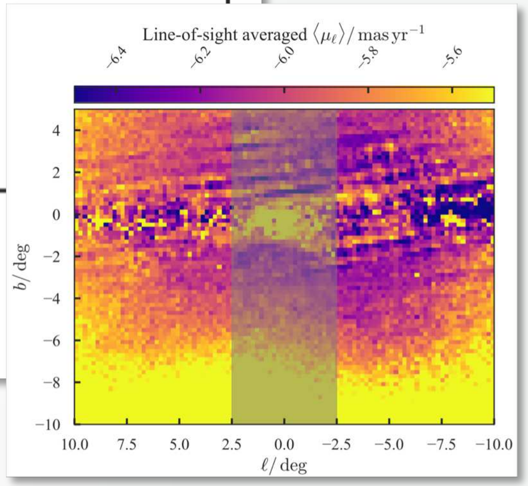
Intermediate bar:

$\Omega_{bar} = 41 \pm 3$ km/s/kpc ~ $1.5 \pm 0.1\ \Omega_0$



Bovy et al. (2019)





Sanders et al. (2019)

The (L_z, J_R) plane of Galactic in-plane motions

1. Substructure in Gaia DR2 RVS

Describe the data properties.
(e.g. Gaia Collaboration+18, Antoja+18, Trick+19a)

2. Signature across the bar's Outer Lindblad Resonance (OLR)

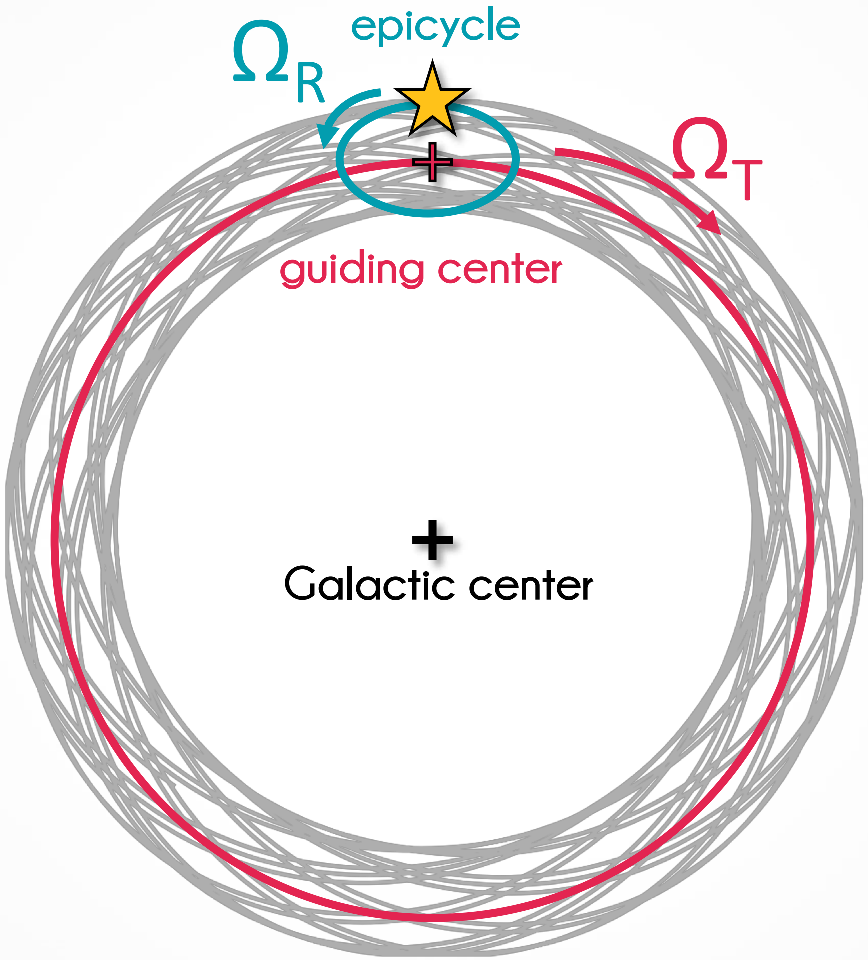
Gain intuition about bar resonances in action space.
(e.g. Trick+19b, Hunt+19, Fragkoudi+19, Monari+19, Binney 18)

3. OLR candidates from Gaia DR2 RVS AND bar pattern speed

Start by identifying 1 (!) bar resonance directly from the action data.
(attempted by Trick+19b and others)

Identify all other features....
(no-one so far)

Disk Orbits in the Epicycle Approximation

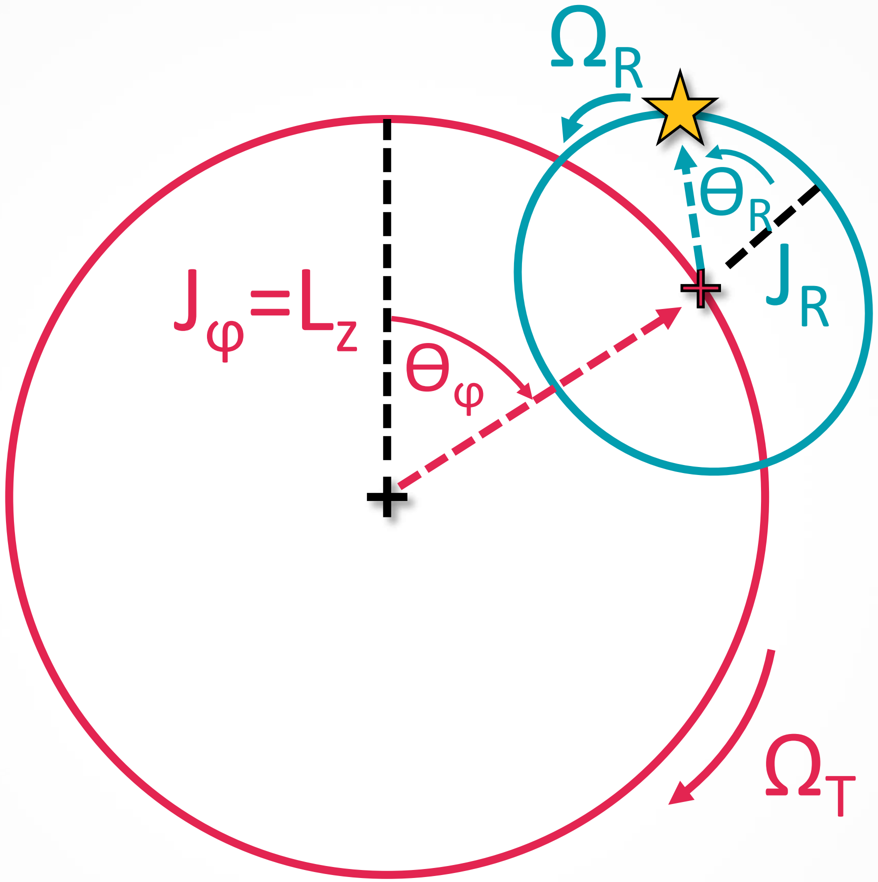


Action-Angle Coordinates (explained with Epicycles)

size of circle
→ actions J
→ „label“ one orbit

position on circle
→ angles $\theta = \Omega \cdot t$

fundamental
frequencies Ω



(x,v)
observed by Gaia

↓

axisymmetric MW
grav. potential model

MWPotential2014
(Bovy 2015)

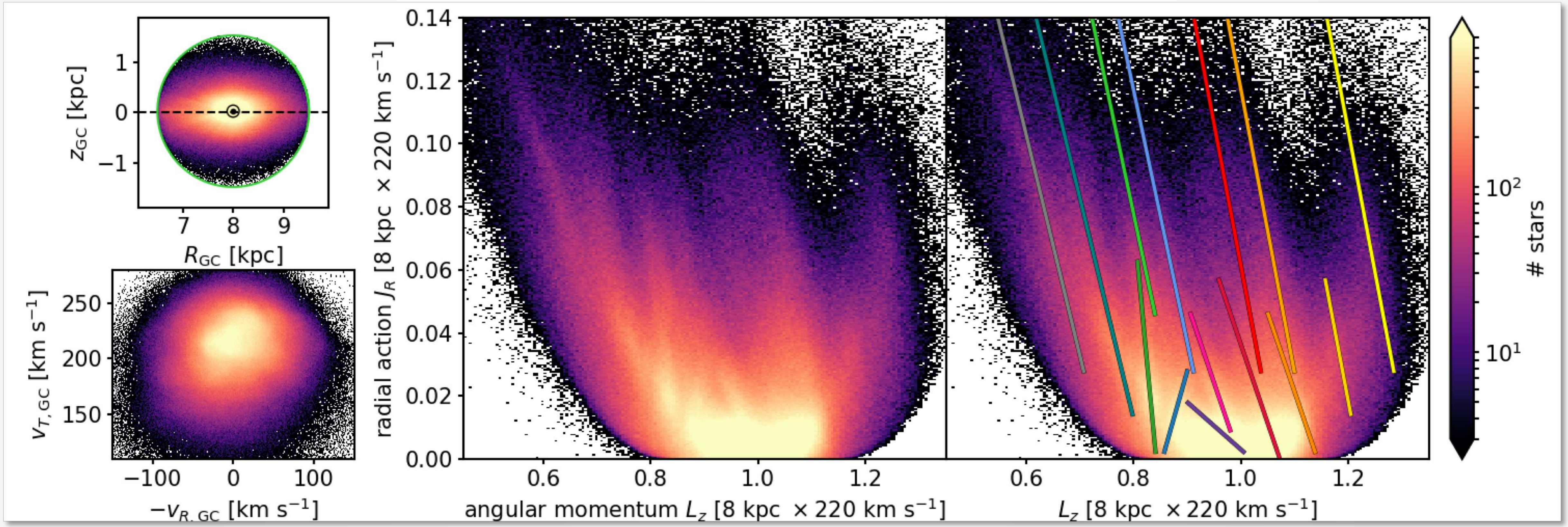
+

estimation algorithm:
Stäckel Fudge (Binney 2012)

↓

axisym. actions,
angles & frequencies

Outside of the Solar Neighbourhood: The Extended Orbit Structure

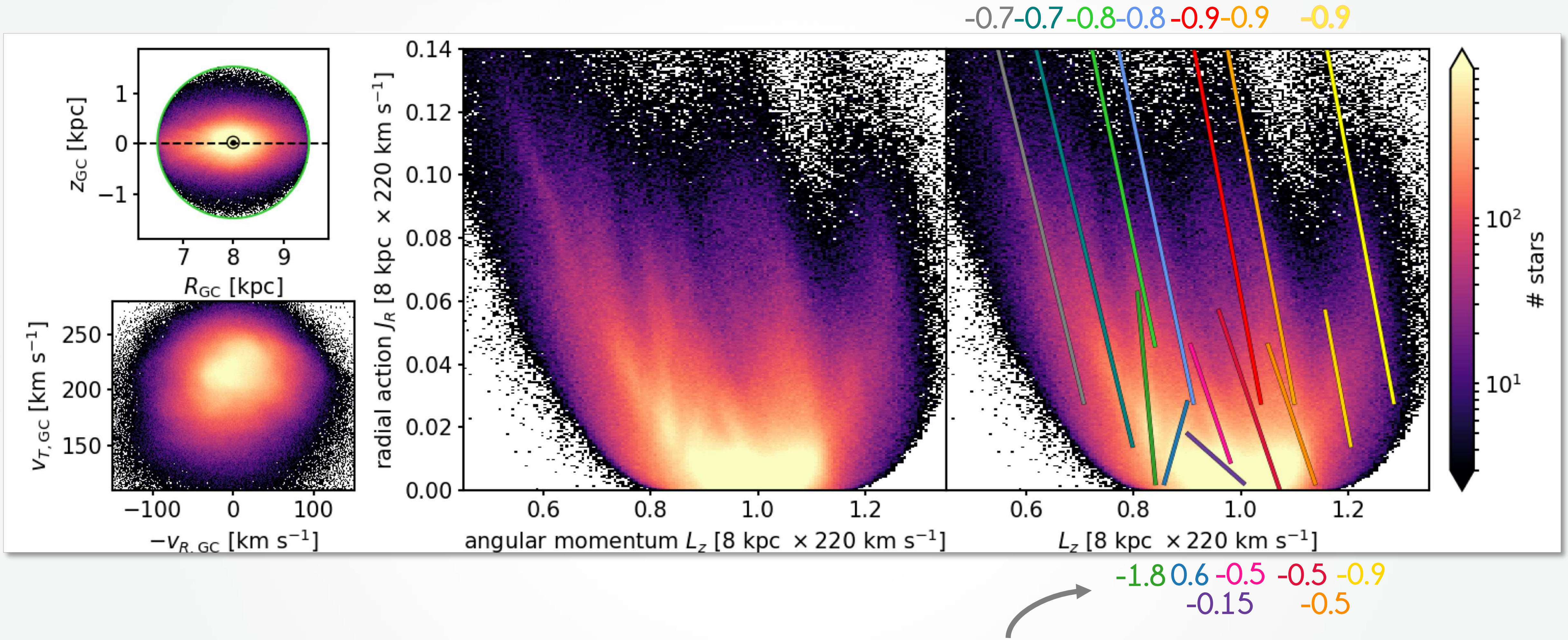


Trick, Coronado, & Rix (2019)

The kinematic substructure exists everywhere (out to at least ~1.5 kpc) in the Galactic disk
The Solar neighbourhood moving groups are just the local, selection-affected manifestation of **this extended orbit structure**.

Wilma Trick (MPA)

Outside of the Solar Neighbourhood: The Extended Orbit Structure



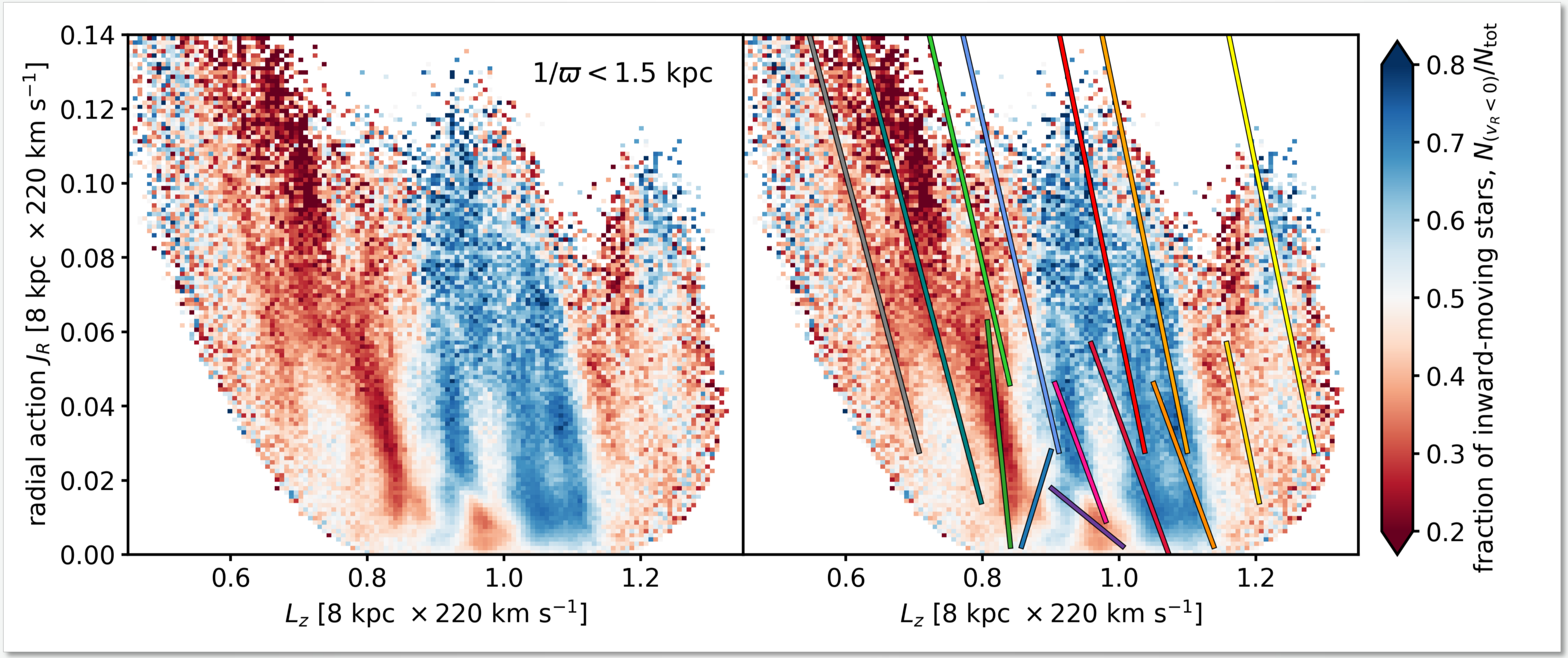
Trick, Coronado, & Rix (2019)

high J_R:
1) overdensities along linear lines
2) parallel pairs

low J_R:
1) different slopes
2) one with positive slope

Properties of the Extended Orbit Structure

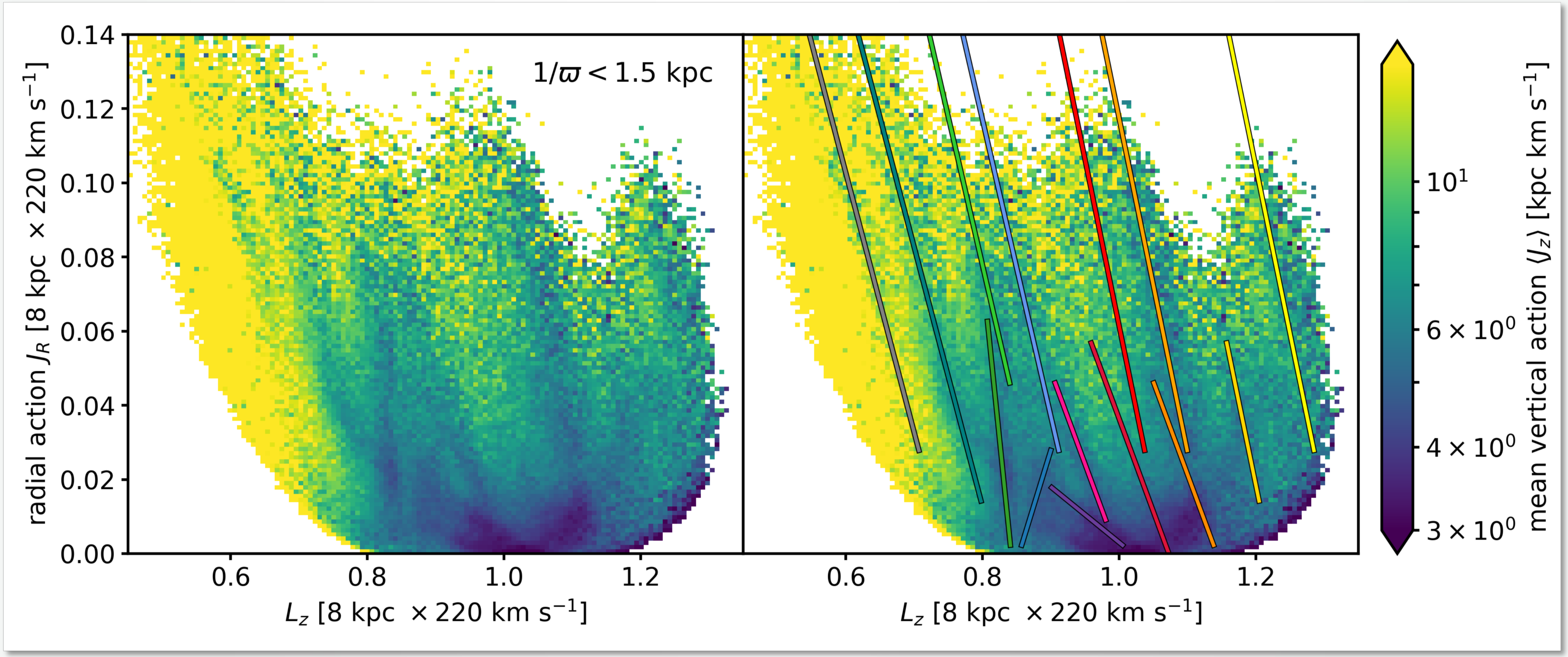
1) stars are not phase-mixed along orbits ➜ large-scale analogue to asymmetry in (v_R, v_T) plot
2) strongest asymmetries related to action-space overdensities



Trick, Coronado, & Rix (2019)

Properties of the Extended Orbit Structure

more pronounced at low vertical actions (i.e. in in-plane orbits)



Trick, Coronado, & Rix (2019)

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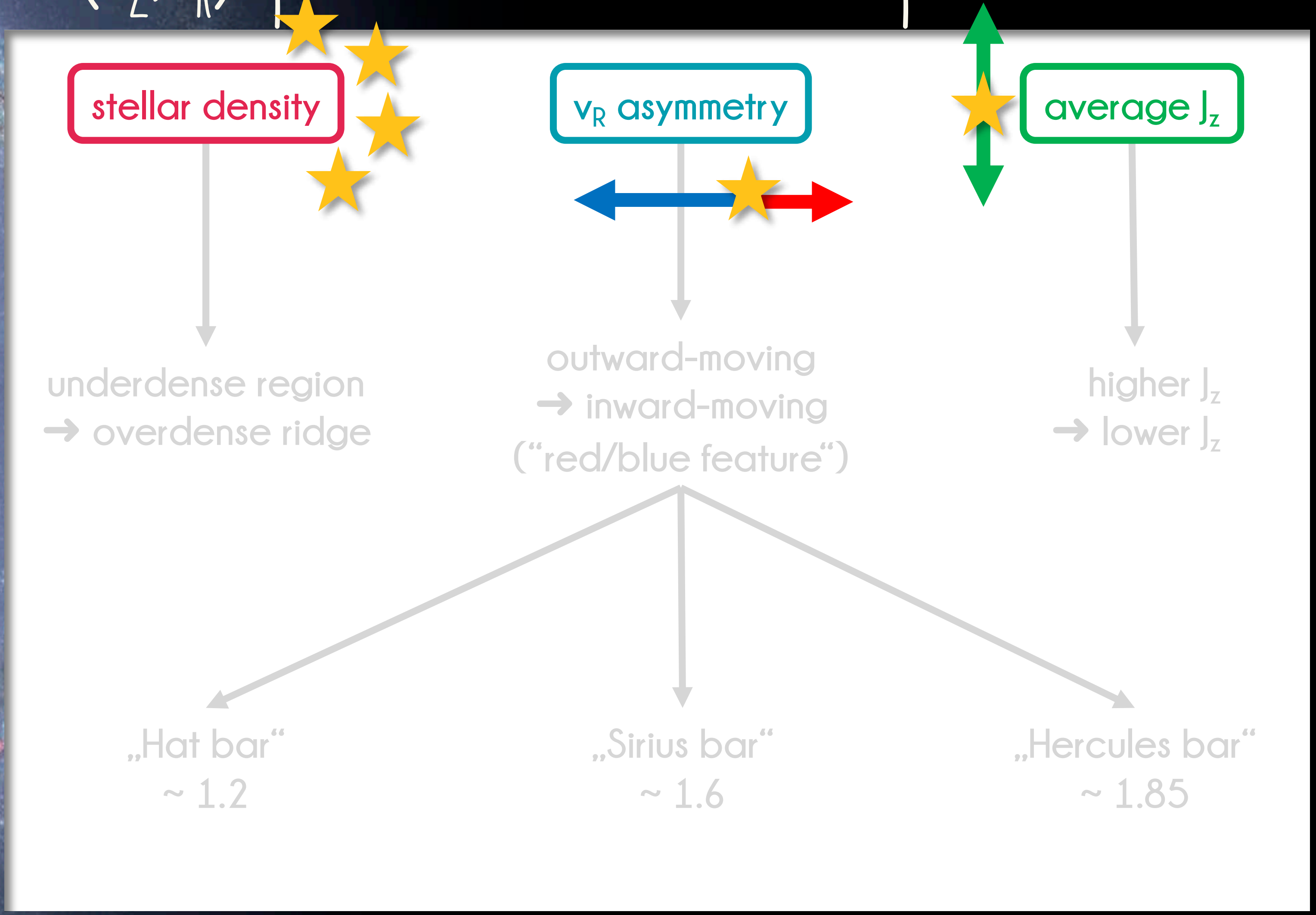
1. Substructure in Gaia DR2 RVS in:

2. Signature across the bar's Outer Lindblad Resonance (OLR) line:

3. OLR candidates from Gaia DR2 RVS
AND bar pattern speed
$\Omega_{bar}/\Omega_0 \pm 0.1$



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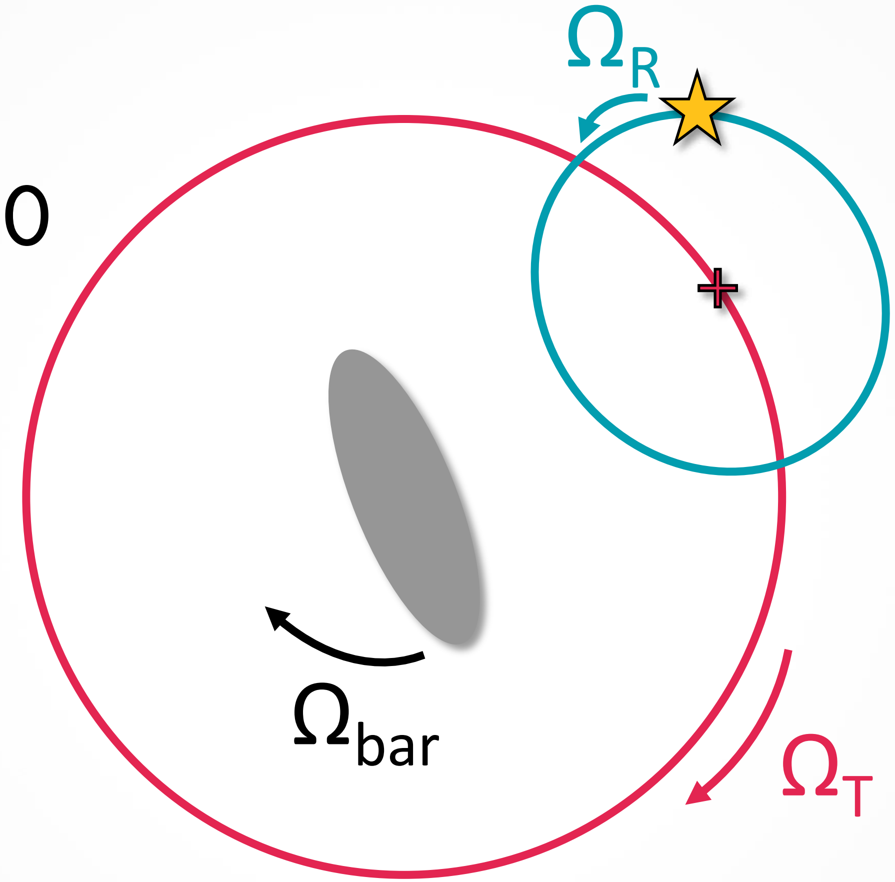
Resonances in a Non-Axisymmetric Galaxy

$$m \cdot (\Omega_{bar} - \Omega_T) - l \cdot \Omega_R = 0$$



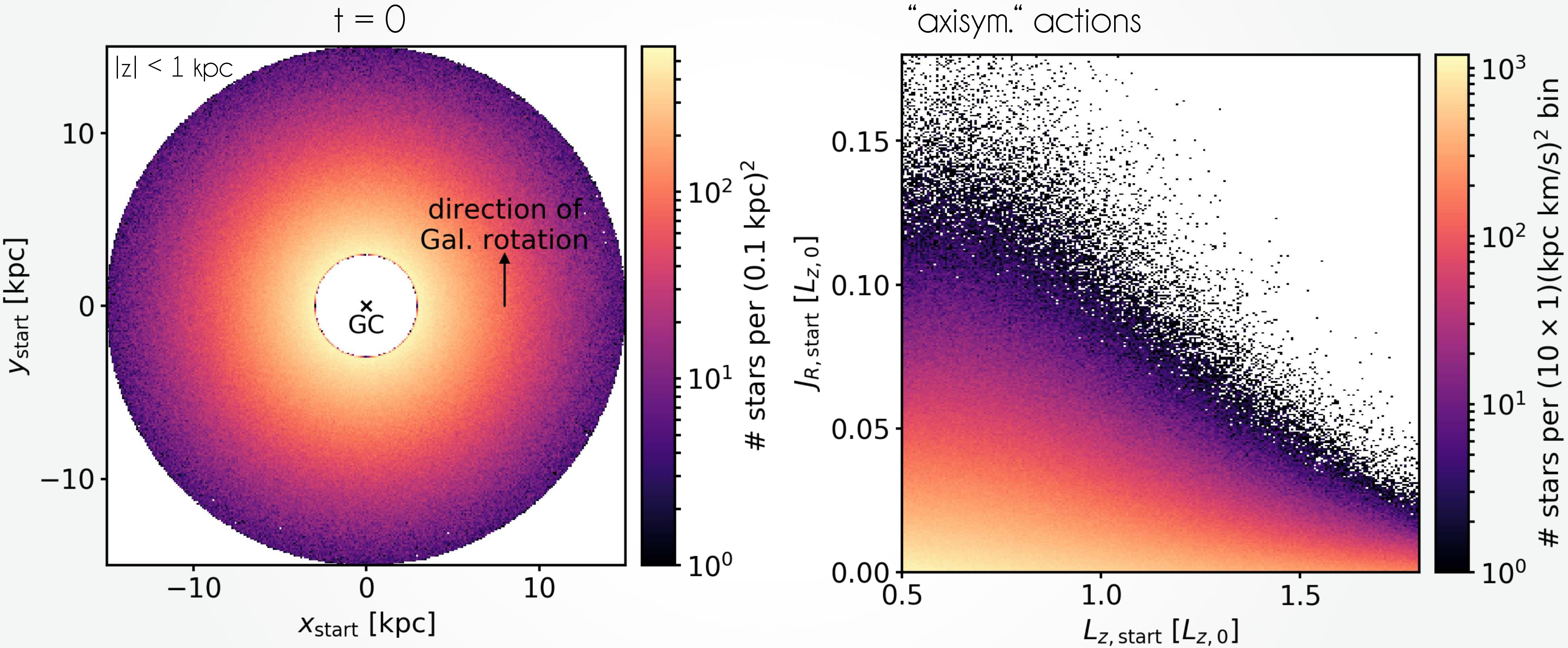
m-fold symmetric perturbation
e.g. m = 2 is strong for bar

l = 0: Co-rotation resonance (CR)
l = +1: Outer Lindblad resonance (OLR)
l = -1: Inner Lindblad resonance (ILR)

Wilma Trick (MPA)

Create Mock Data Stars in MW Potential

Trick, Fragkoudi, Hunt et al.
(arXiv:1906.04786)



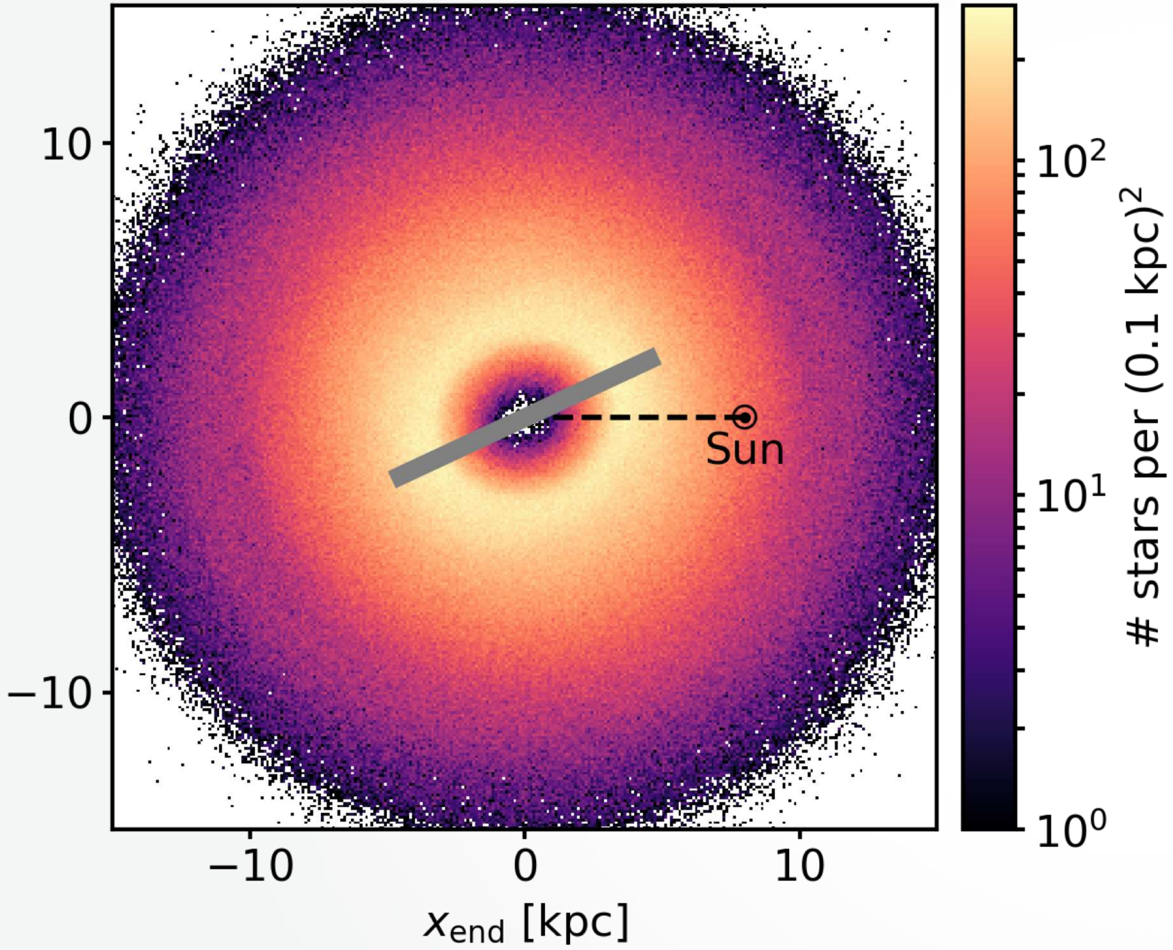
axisymmetric MWPotential2014 (Bovy 2014)

quasi-isothermal distribution function (Binney & McMillan 2011)

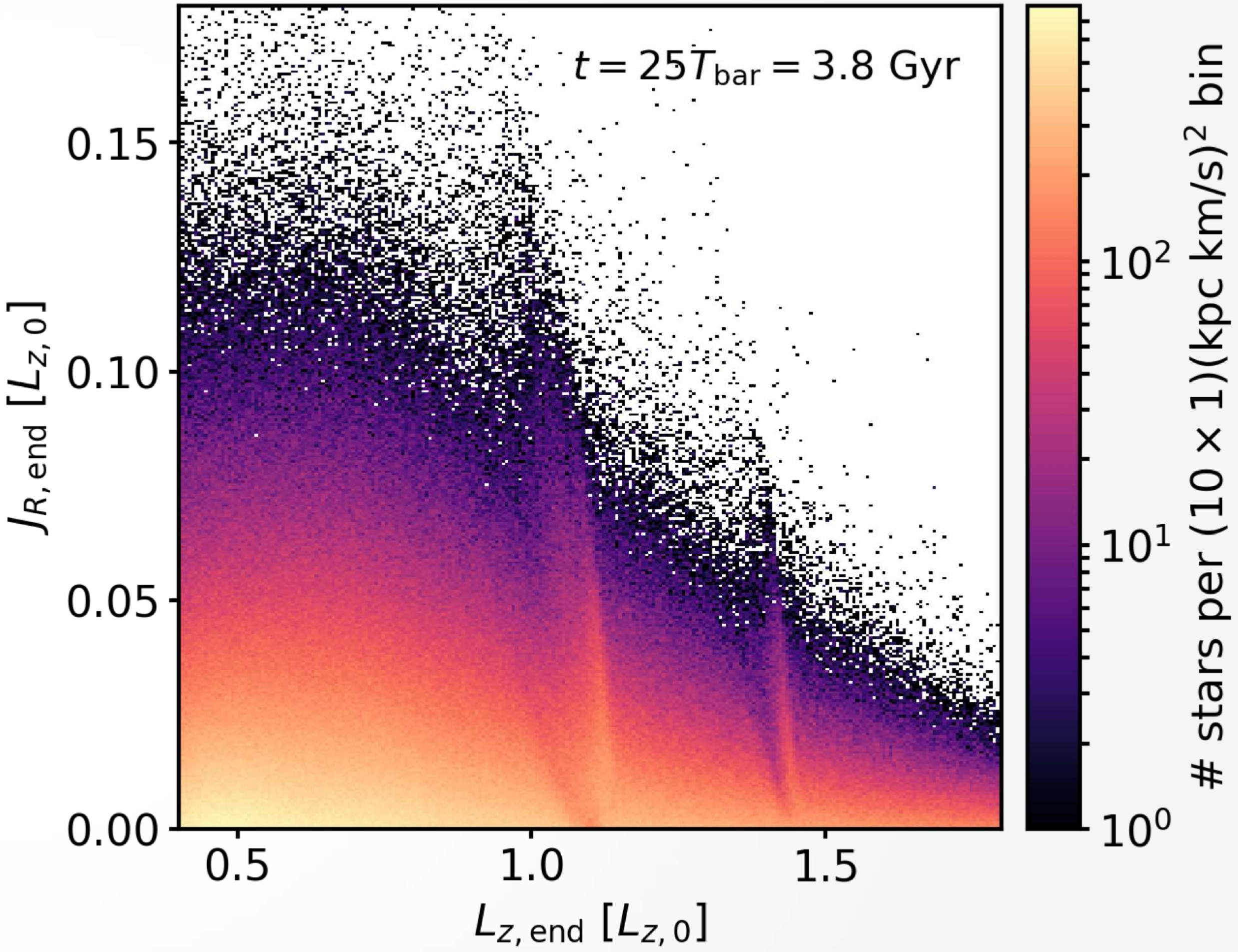
Integrate Mock Stars in Bar Potential

Trick, Fragkoudi, Hunt et al. (arXiv:1906.04786)

t = 25 bar periods = 3.8 Gyr



"axisym." actions



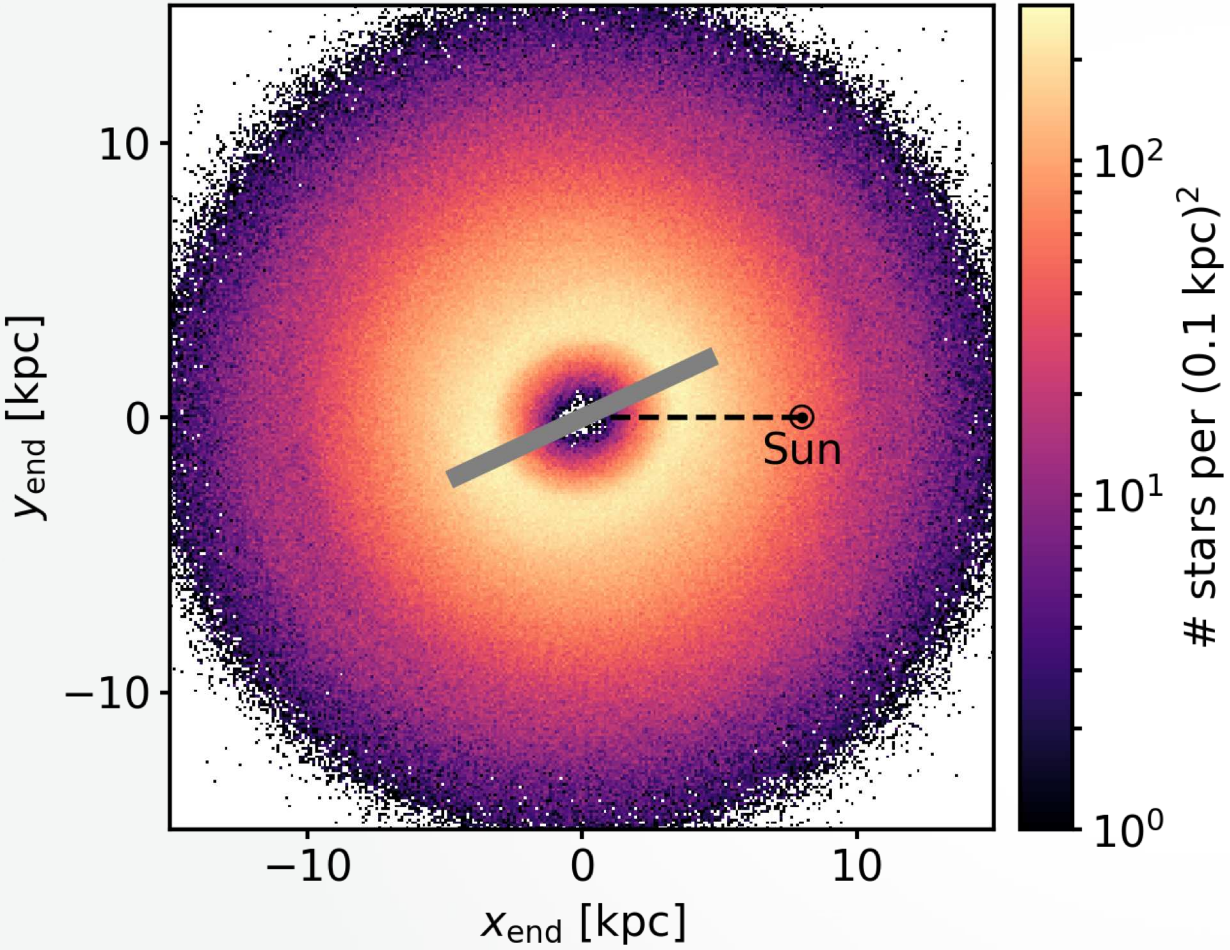
MW pot + „Dehnen" bar,
pattern speed: **Ω_{bar} = 40 km/s/kpc**

Trick, Fragkoudi, Hunt et al.
(arXiv:1906.04786)

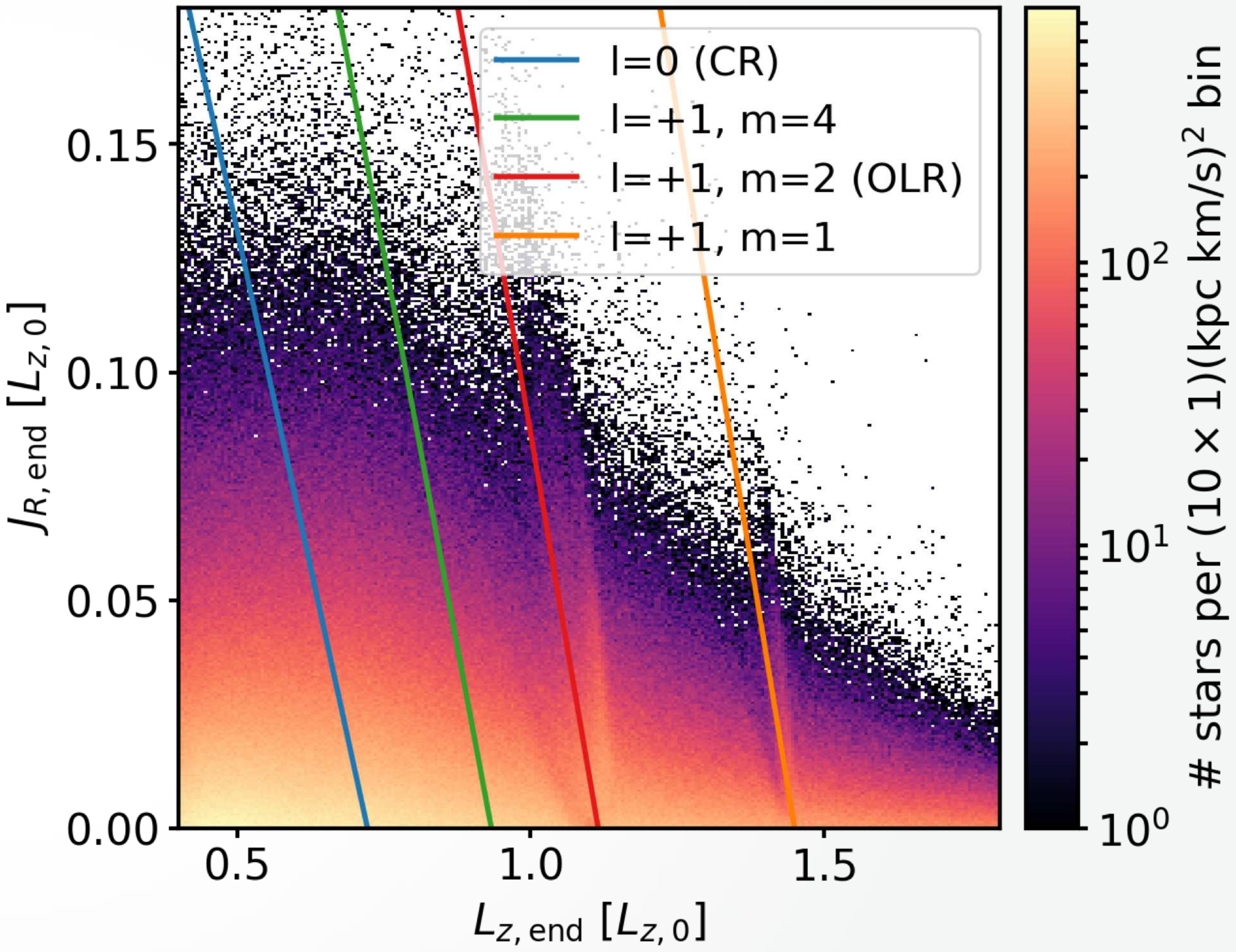
Resonance signatures in actions

Resonance Lines based on Axisym. Frequencies

t = 25 bar periods = 3.8 Gyr



"axisym." actions



Resonance condition: $\mathbf{m \cdot (\Omega_{bar} - \Omega_T) - l \cdot \Omega_R = 0}$

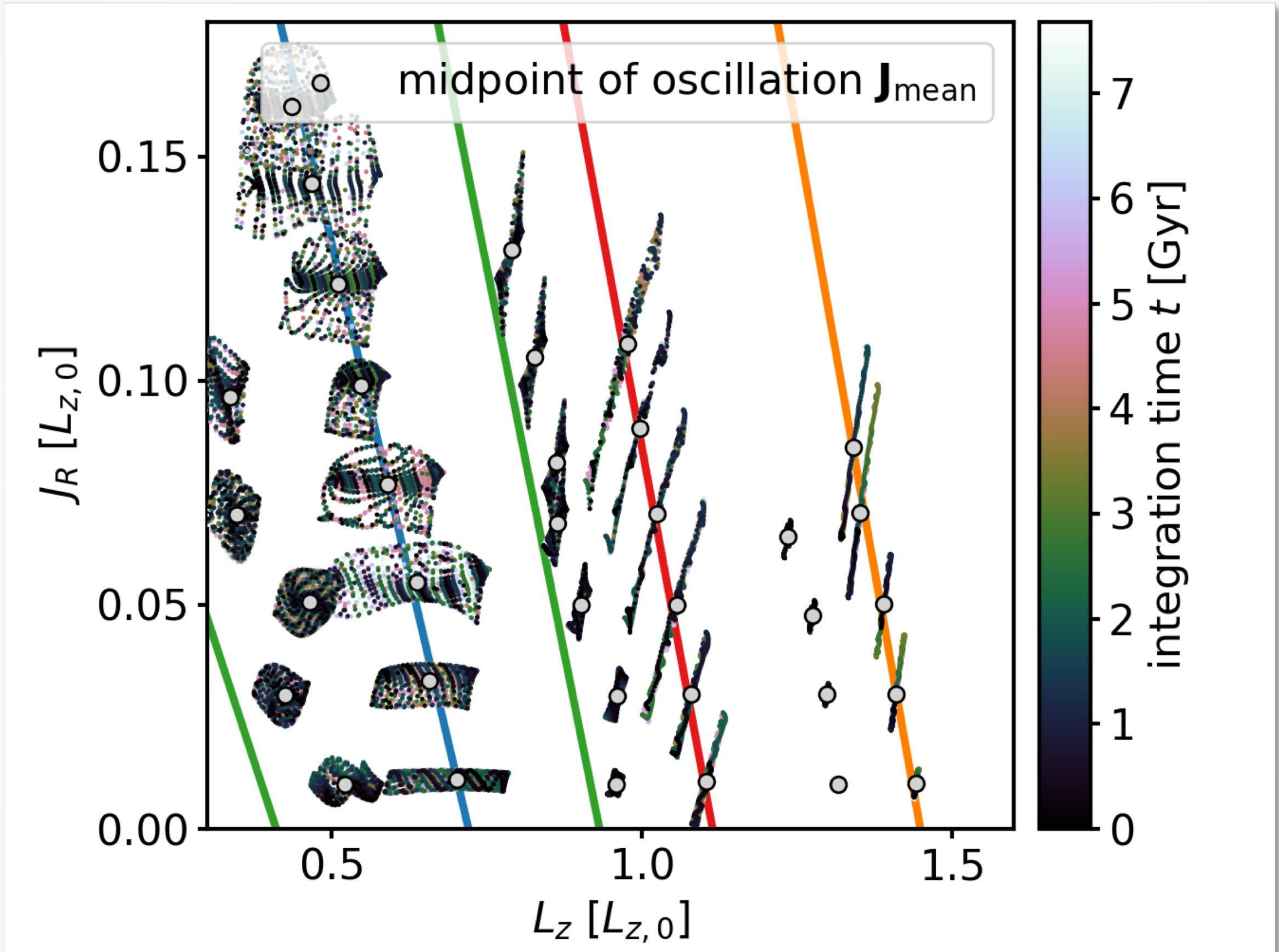
pattern speed: $\mathbf{\Omega_{bar} = 40}$ **km/s/kpc**

„Axisymmetric Actions" of Orbits in a Barred Potential

Resonance signatures in actions

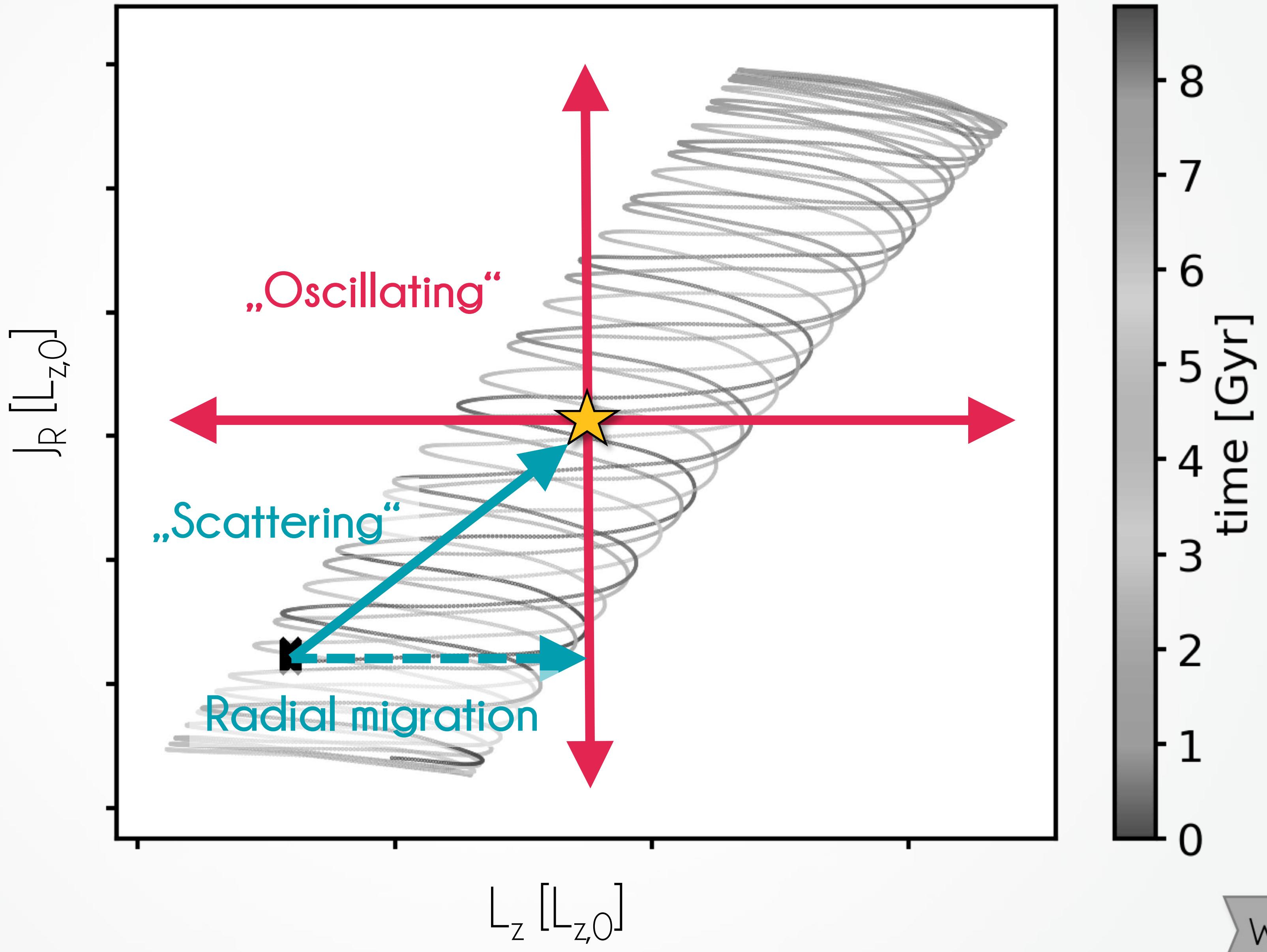
Trick, Fragkoudi, Hunt et al.
(arXiv:1906.04786)

see also Binney (2018)



– CR
– OLR
– 1:1
– 1:4

„Axisymmetric Actions" of an Orbit in a Barred Potential



✗: orbit in axisym. potential $(L_z, J_R)_{axi}$

☆: mid-point around which the bar-affected orbit oscillates $(L_z, J_R)_{mean}$

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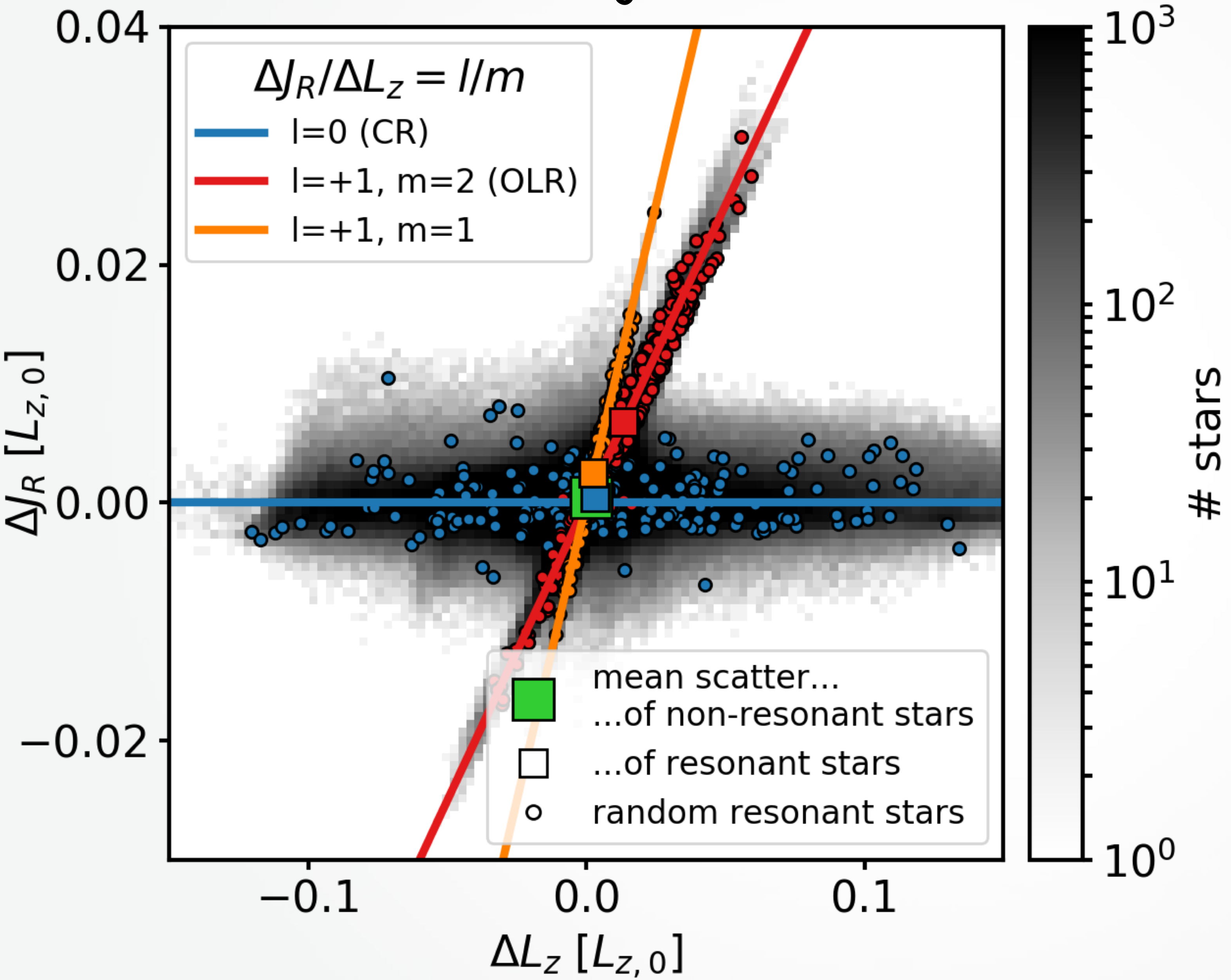
Scattering of Orbits at the Resonance

Trick, Fragkoudi, Hunt et al. (arXiv:1906.04786)



Jacobi energy:
$E_J = E - \Omega_{bar} L_z = \text{const.}$
Sellwood & Binney (2002)

at CR: $\Delta J_R \sim 0$
→ no preferred scattering direction in L_z
→ mixed

at OLR: $\Delta J_R \propto \Delta L_z$
→ circular orbits can only become more eccentric
→ $\Delta L_z > 0$
→ underdensity & ridge

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$\Omega_{bar}/\Omega_0 \pm 0.1$

stellar density

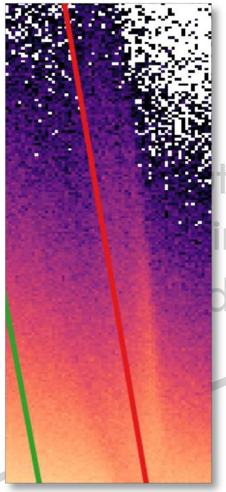
underdense region
→ overdense ridge

v_R asymmetry

tward-moving
inward-moving
d/blue feature")

average J_z

higher Jz
→ lower Jz



„Hat bar"
~ 1.2

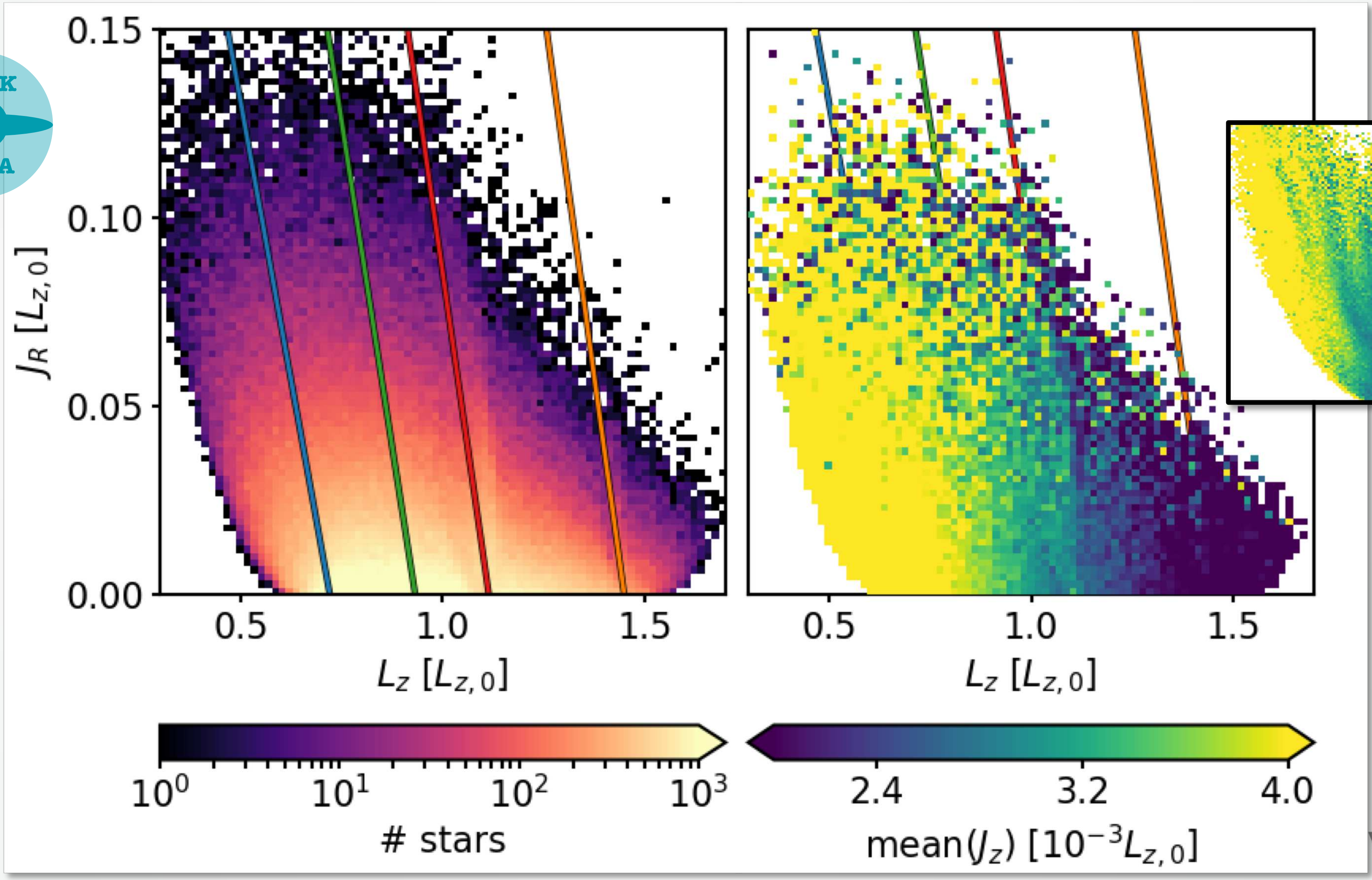
„Sirius bar"
~ 1.6

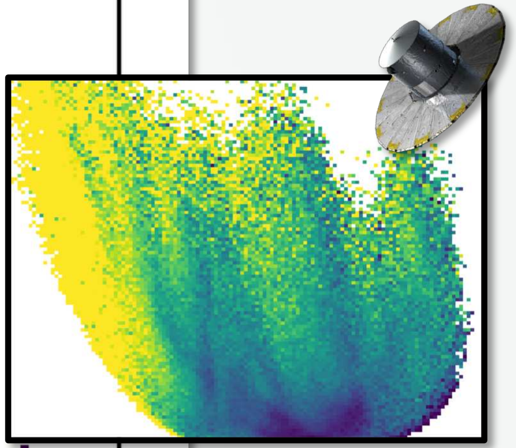
„Hercules bar"
~ 1.85

A ridge with Jz gradient at the OLR

Trick, Fragkoudi, Hunt et al.
(arXiv:1906.04786)

MOCK DATA



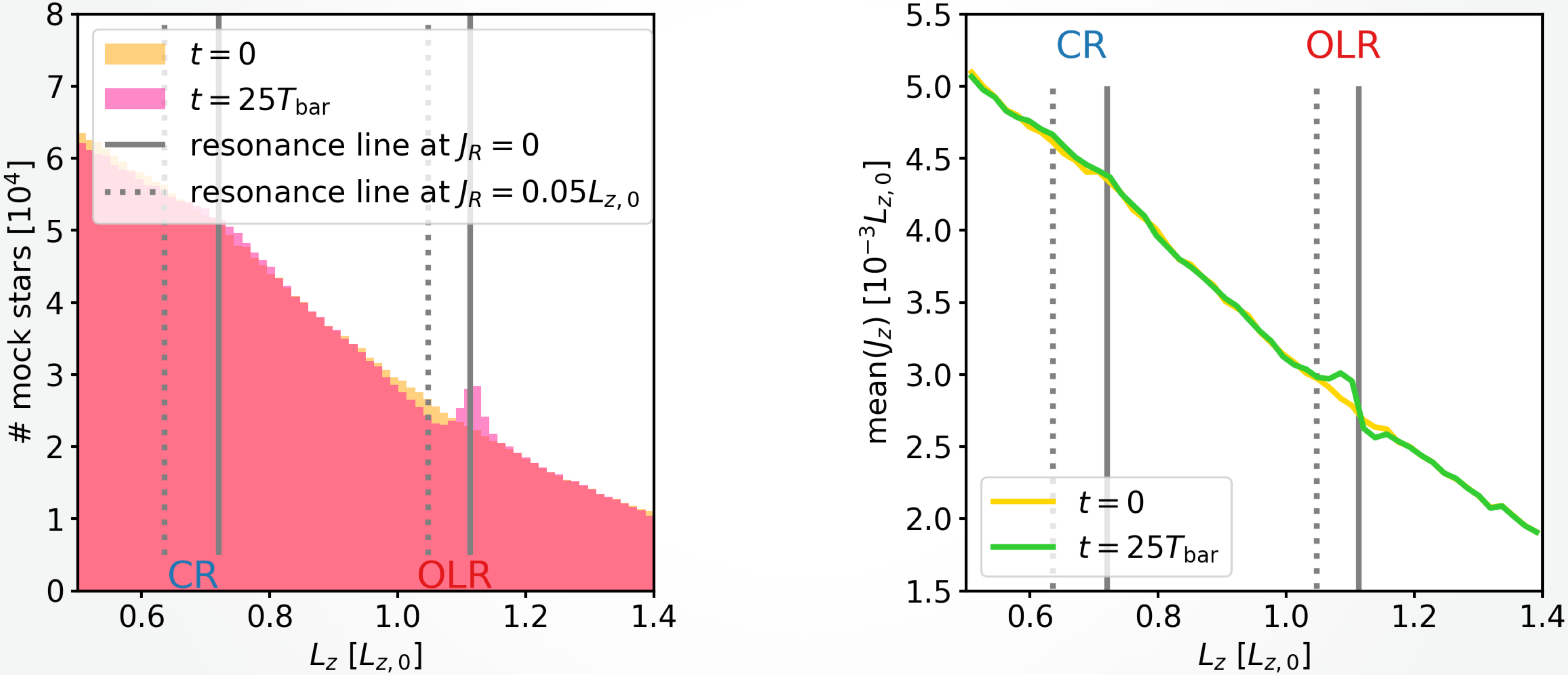


- just as in the data!

– CR
– OLR
– 1:1
– 1:4

A ridge with Jz gradient at the OLR

Trick, Fragkoudi, Hunt et al.
(arXiv:1906.04786)

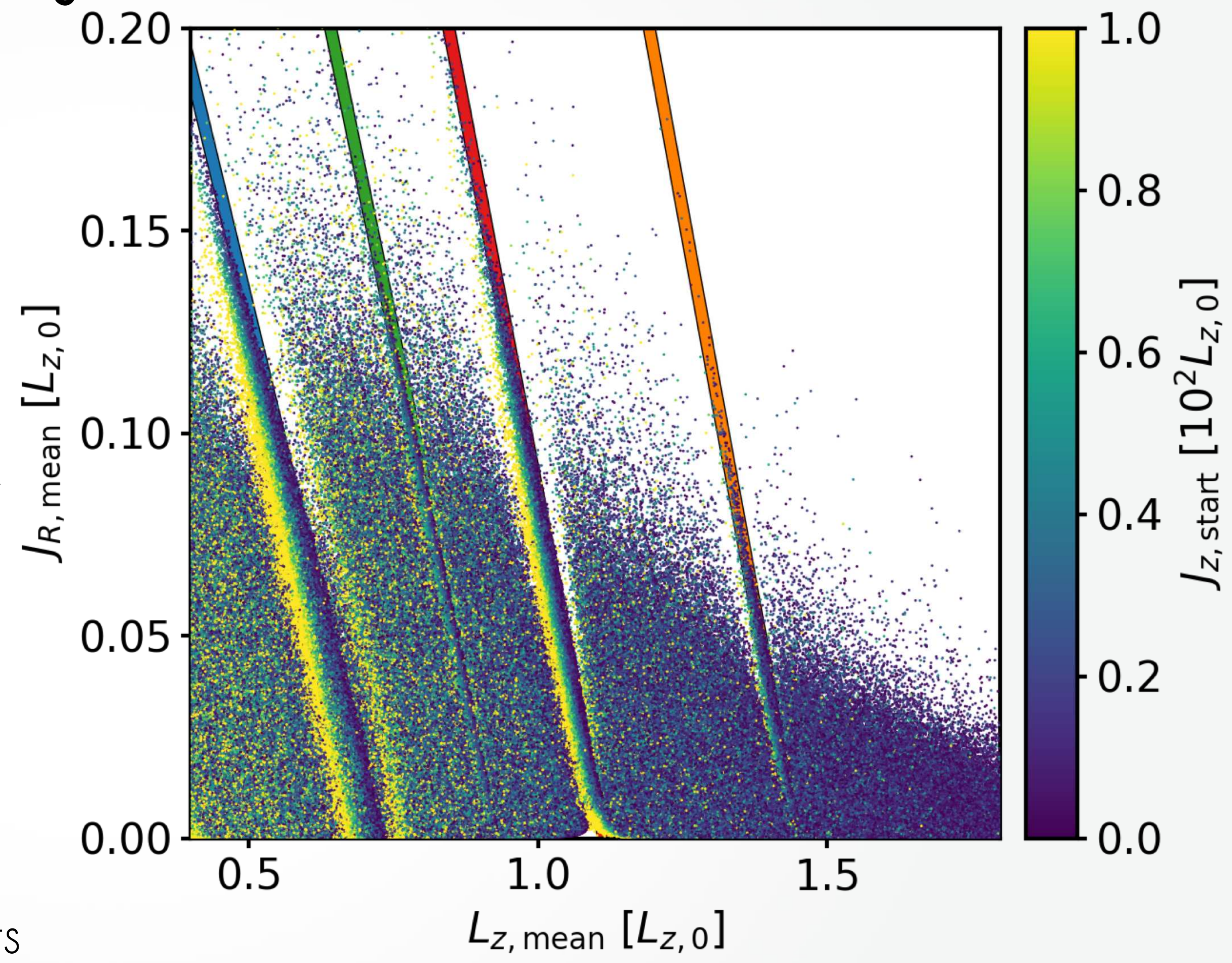


… but the in-plane resonance does not affect the vertical motion of a star!

A ridge with J_z gradient at the OLR

Trick, Fragkoudi, Hunt et al.
(arXiv:1906.04786)

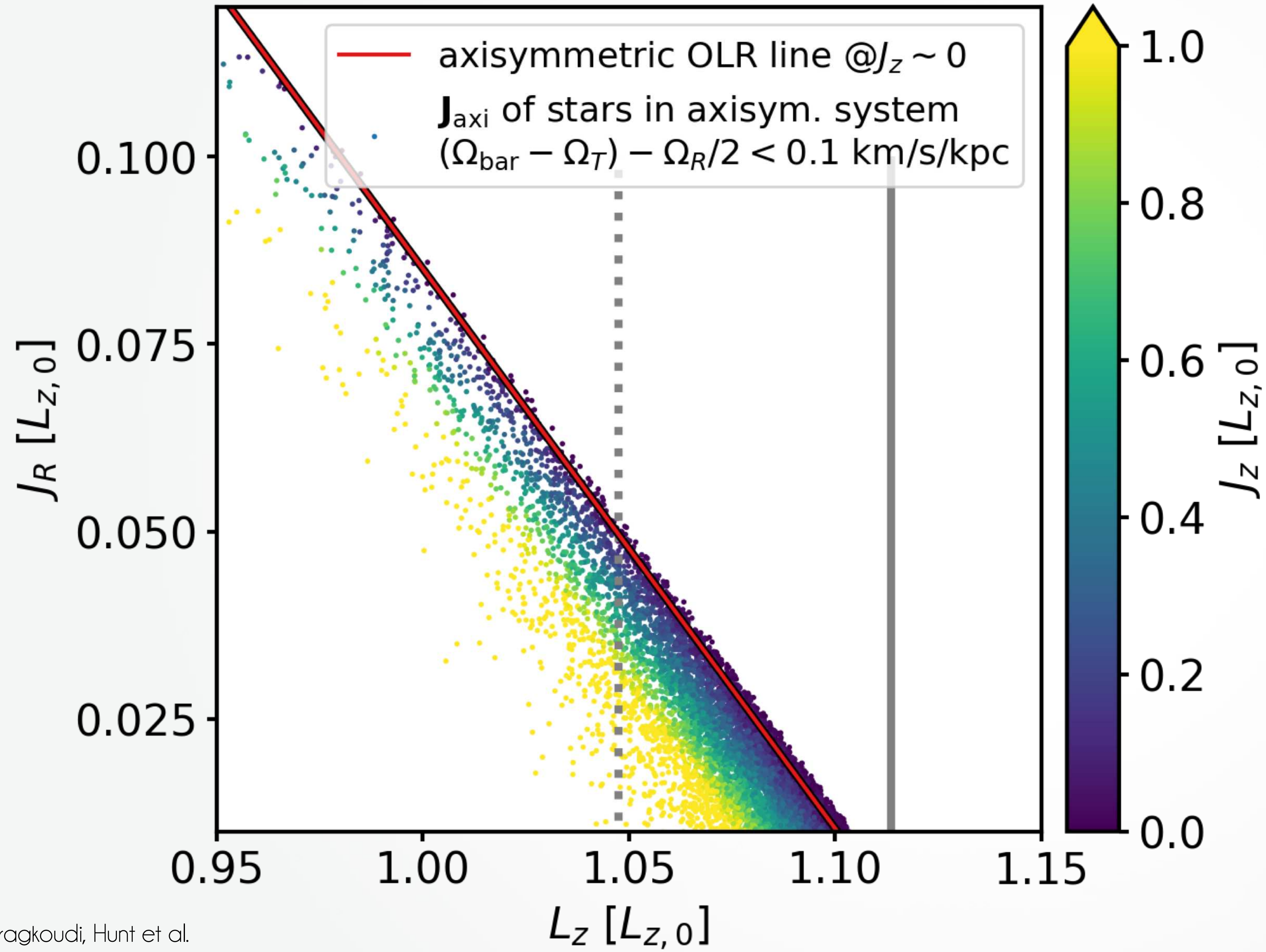
The resonance sorts the stars according to J_z.



Oscillation midpoints of the bar-affected orbtis in axisym. action space.

– CR
– OLR
– 1:1
– 1:4

Axisym. Potential: Resonance condition depends on Jz

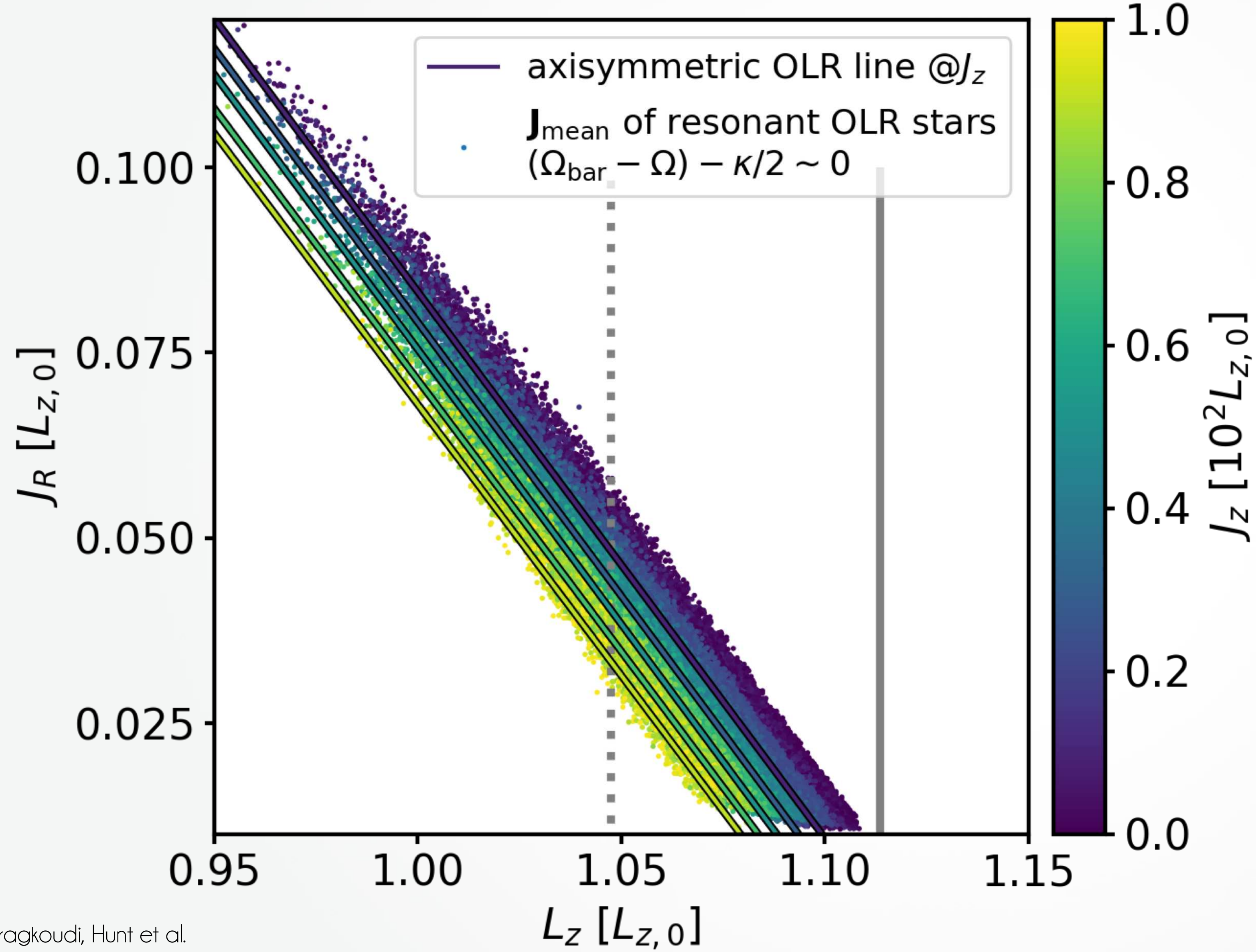


Fundamental orbital frequencies Ω_T and Ω_R **depend also on J_z** (b/c of the potential at $\langle |z| \rangle_t$)

⇒ anti-correlations between J_R, L_z, and J_z for resonance line

Trick, Fragkoudi, Hunt et al. (arXiv:1906.04786)

Barred Pot: Stars oscillate around axisym. resonance line for the same Jz



OLR:

- Scattering preferentially towards larger Lz (→ ridge),
- weaker oscillation than at CR

→ J_z ordering remains visible

Trick, Fragkoudi, Hunt et al. (arXiv:1906.04786)

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$\Omega_{bar} / \Omega_0 \pm 0.1$

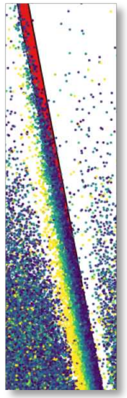
stellar density → underdense region → overdense ridge

v_R asymmetry → outward-moving → inward-moving ("red/blue feature")

→ „Hat bar" ~ 1.2

→ „Sirius bar" ~ 1.6

→ „Hercules bar" ~ 1.85

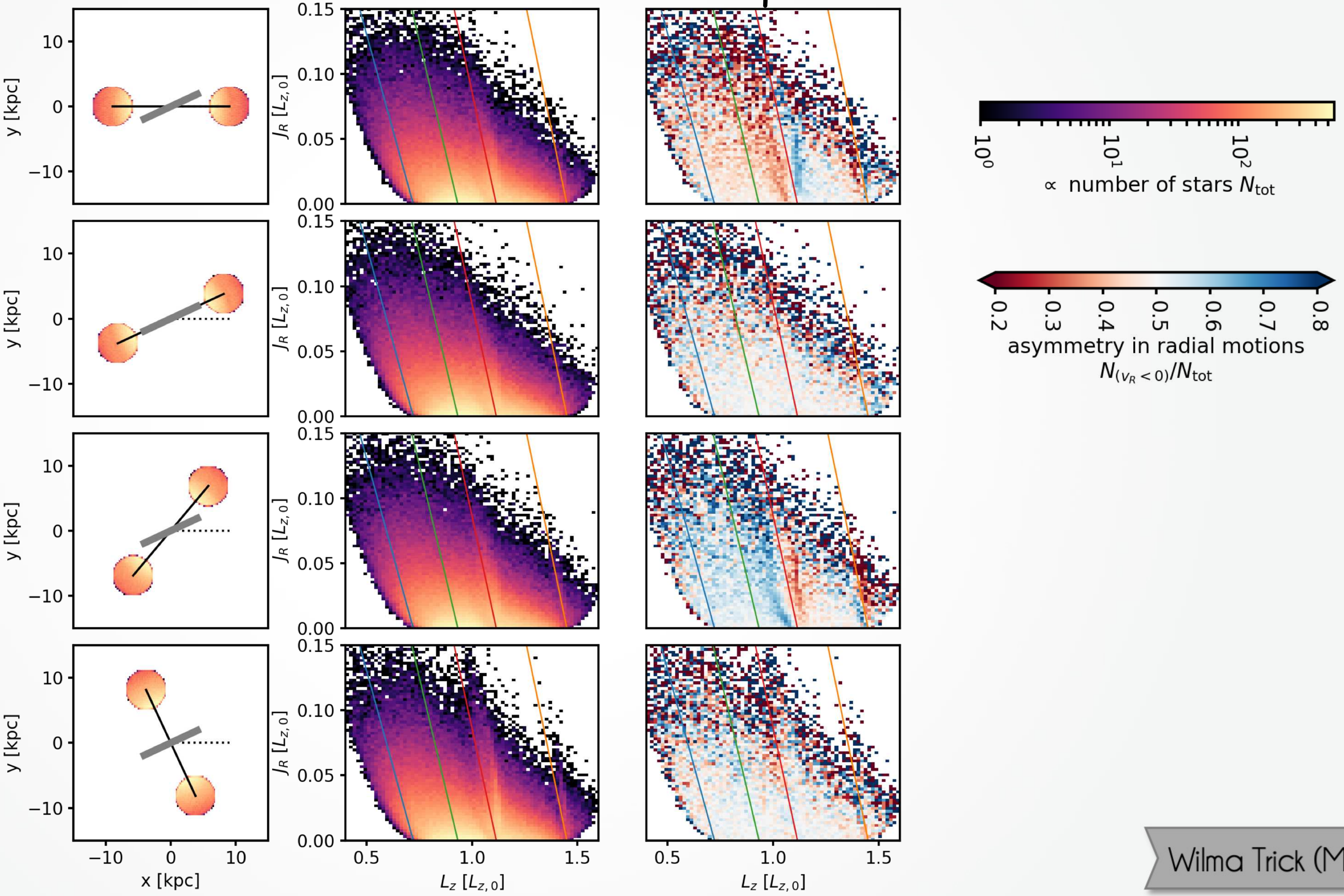


average J_z → higher Jz → lower Jz

Location of Solar Volume With Respect to the Bar

Orbit integration time:
25 bar periods
= 3.8 Gyr

MOCK DATA



– CR
– OLR
– 1:1
– 1:4

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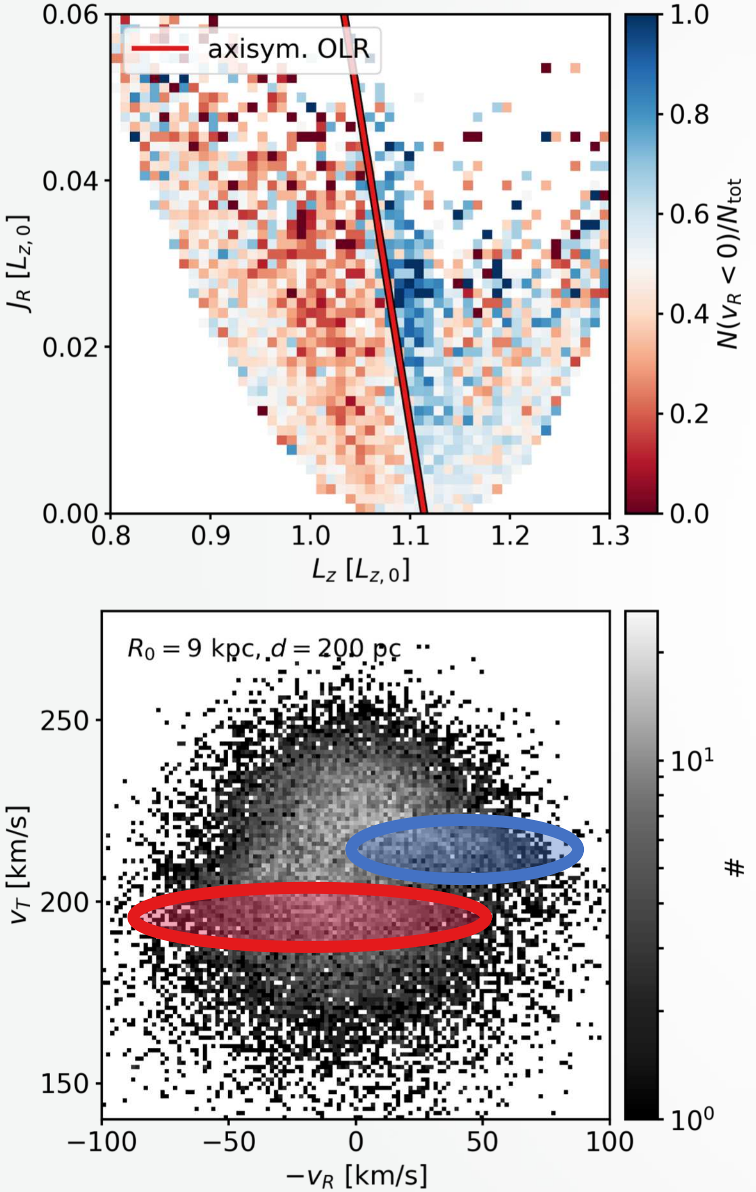
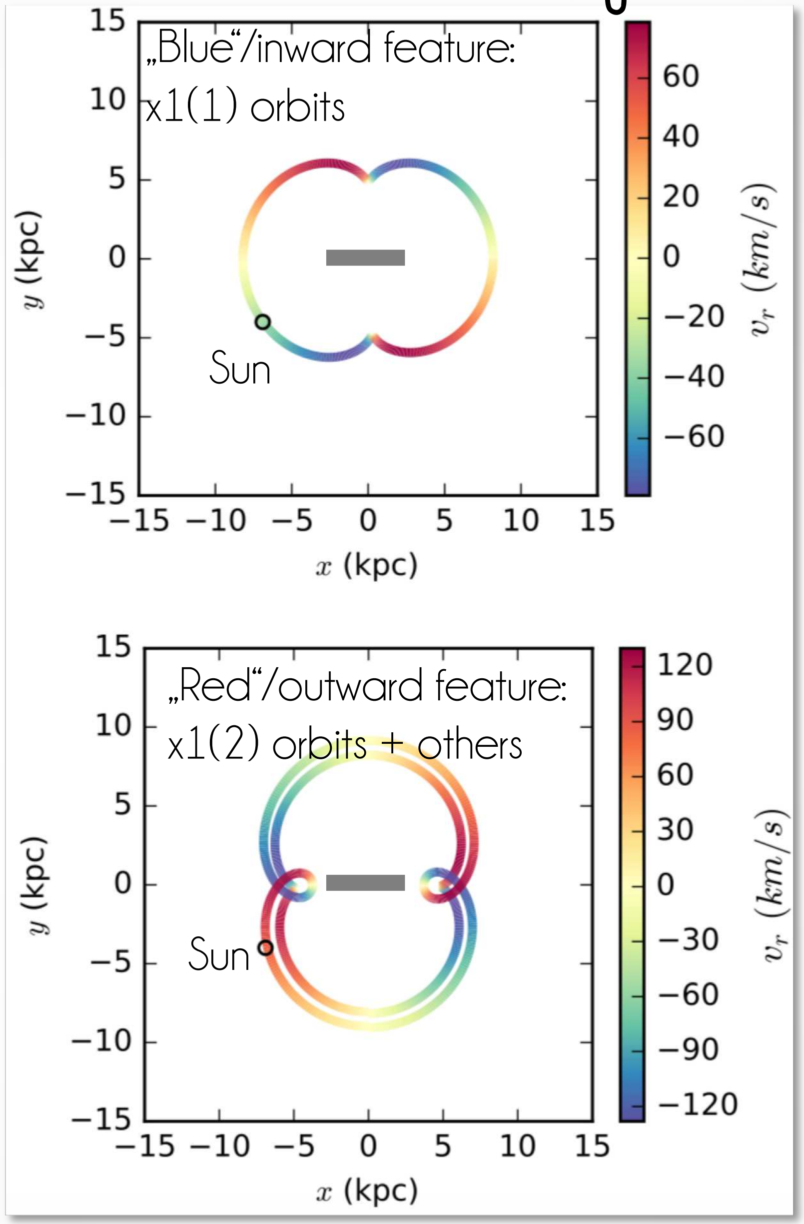
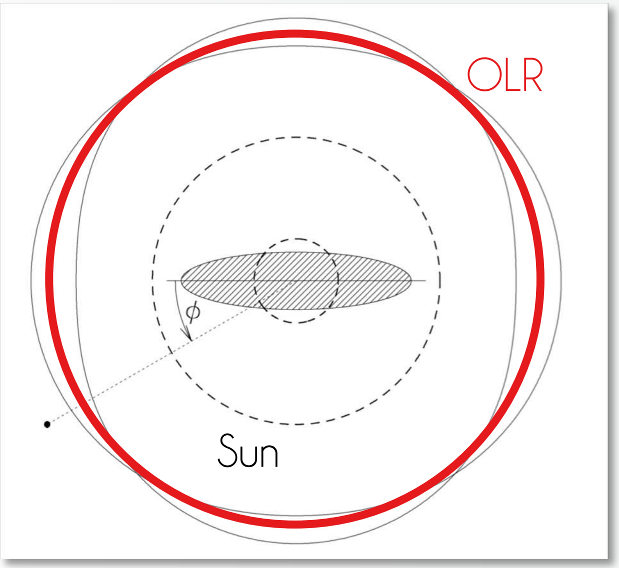
The outward-inward (red-blue) Signature of the OLR



Trick, Fragkoudi, Hunt et al. (2019)



Fragkoudi, Katz, Trick et al. (2019)



Dehnen (2000)

Orbits flip their orientation at the axisym. OLR line.

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stellar density
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v_R asymmetry
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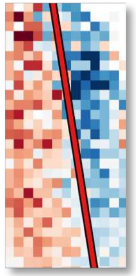

average J_z
higher Jz
→ lower Jz

„Hat bar"
~ 1.2

„Sirius bar"
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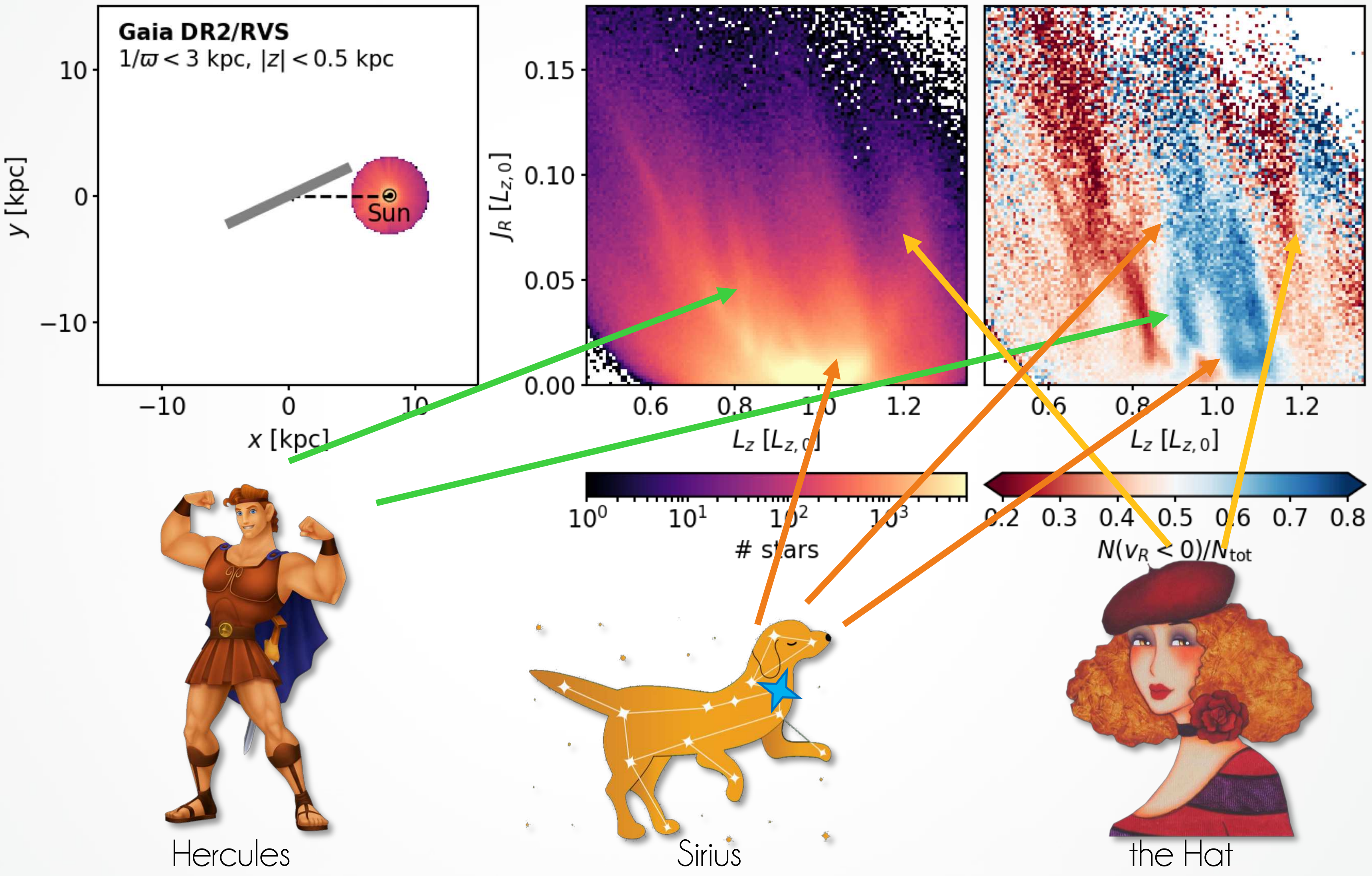
~ 1.85

Comparing Gaia DR2 to the Model

Trick, Fragkoudi, Hunt et al.
(arXiv:1906.04786)



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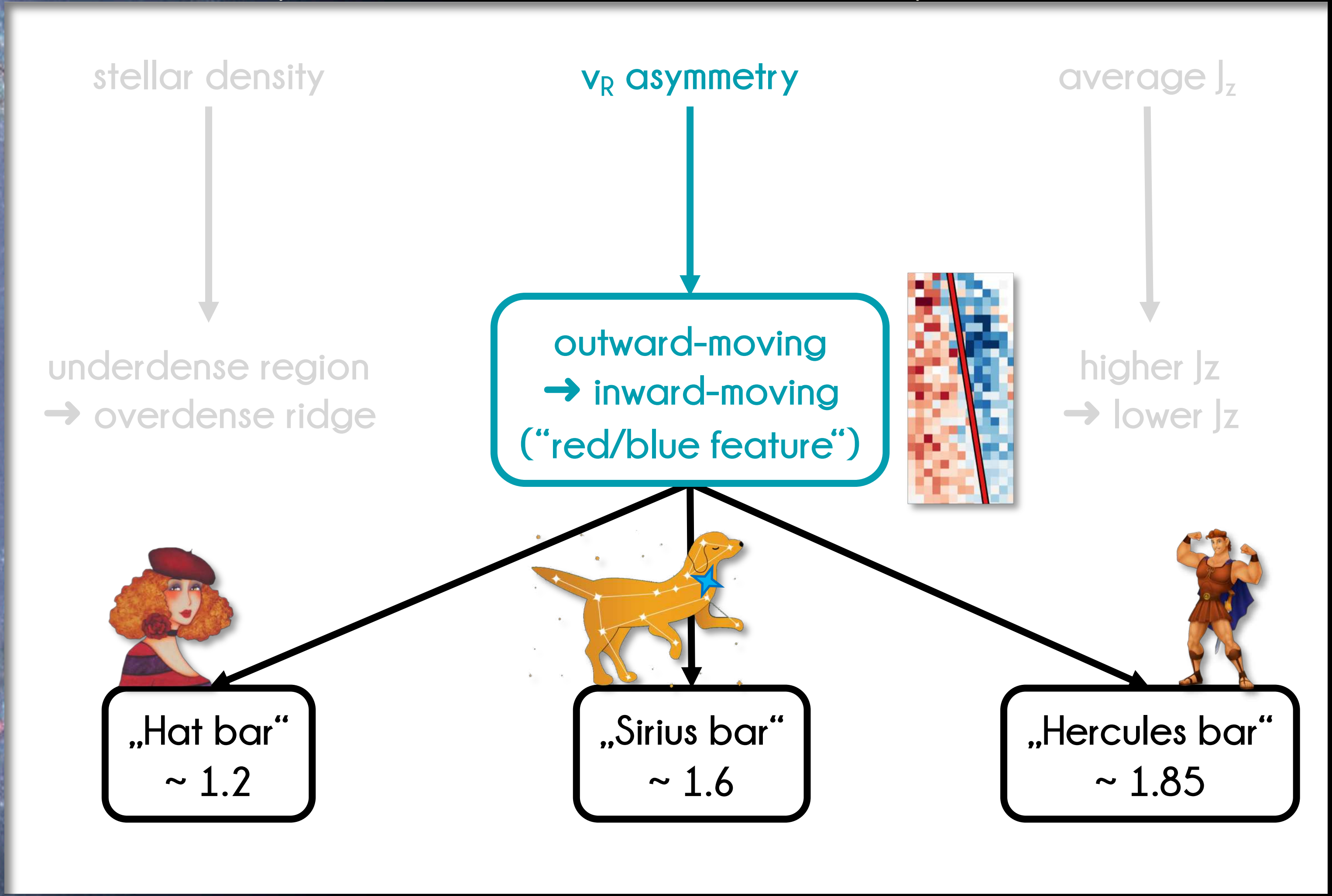
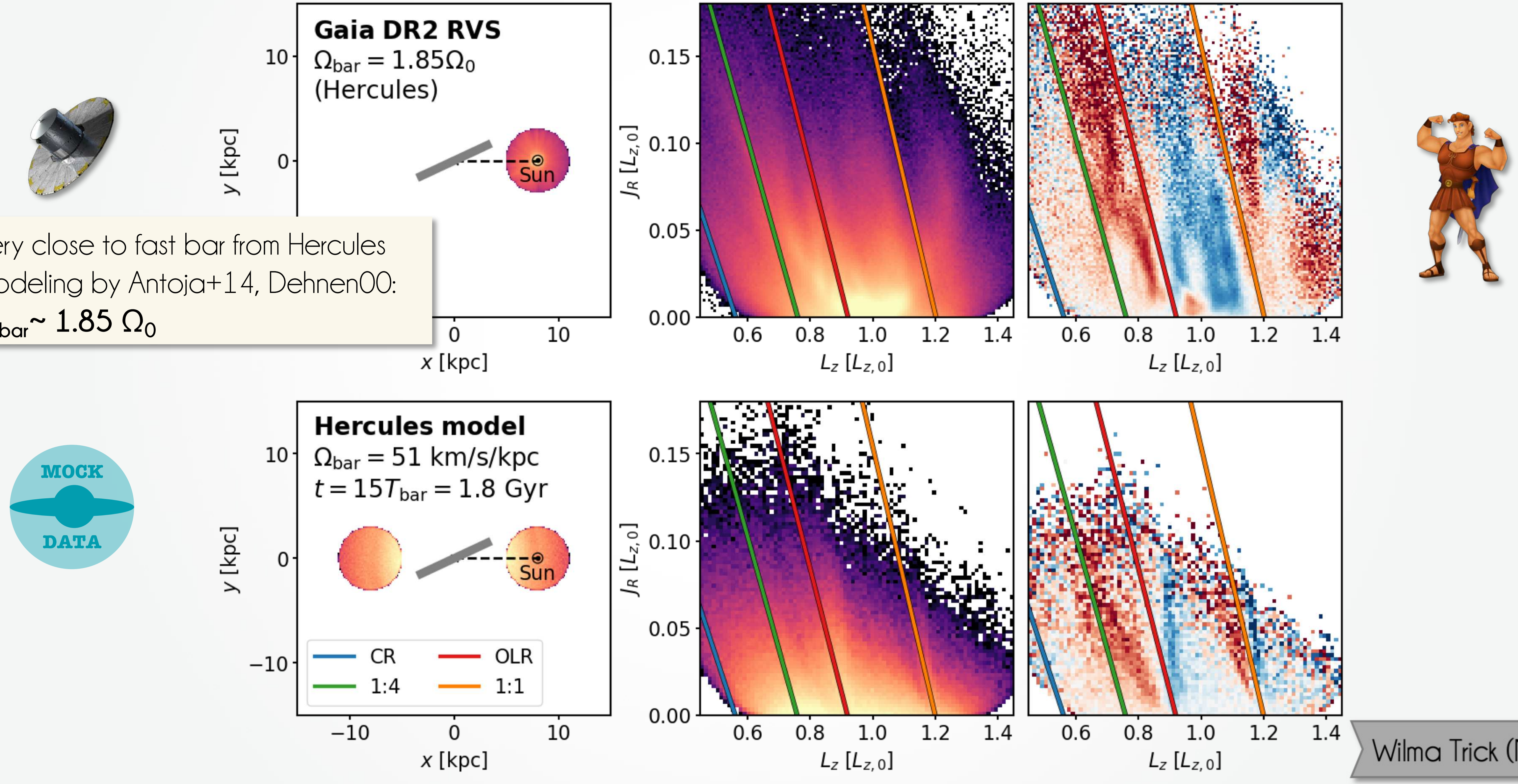


Wilma Trick (MPA)

Assuming Bar OLR is Near Hercules

Trick, Fragkoudi, Hunt et al.
(arXiv:1906.04786)

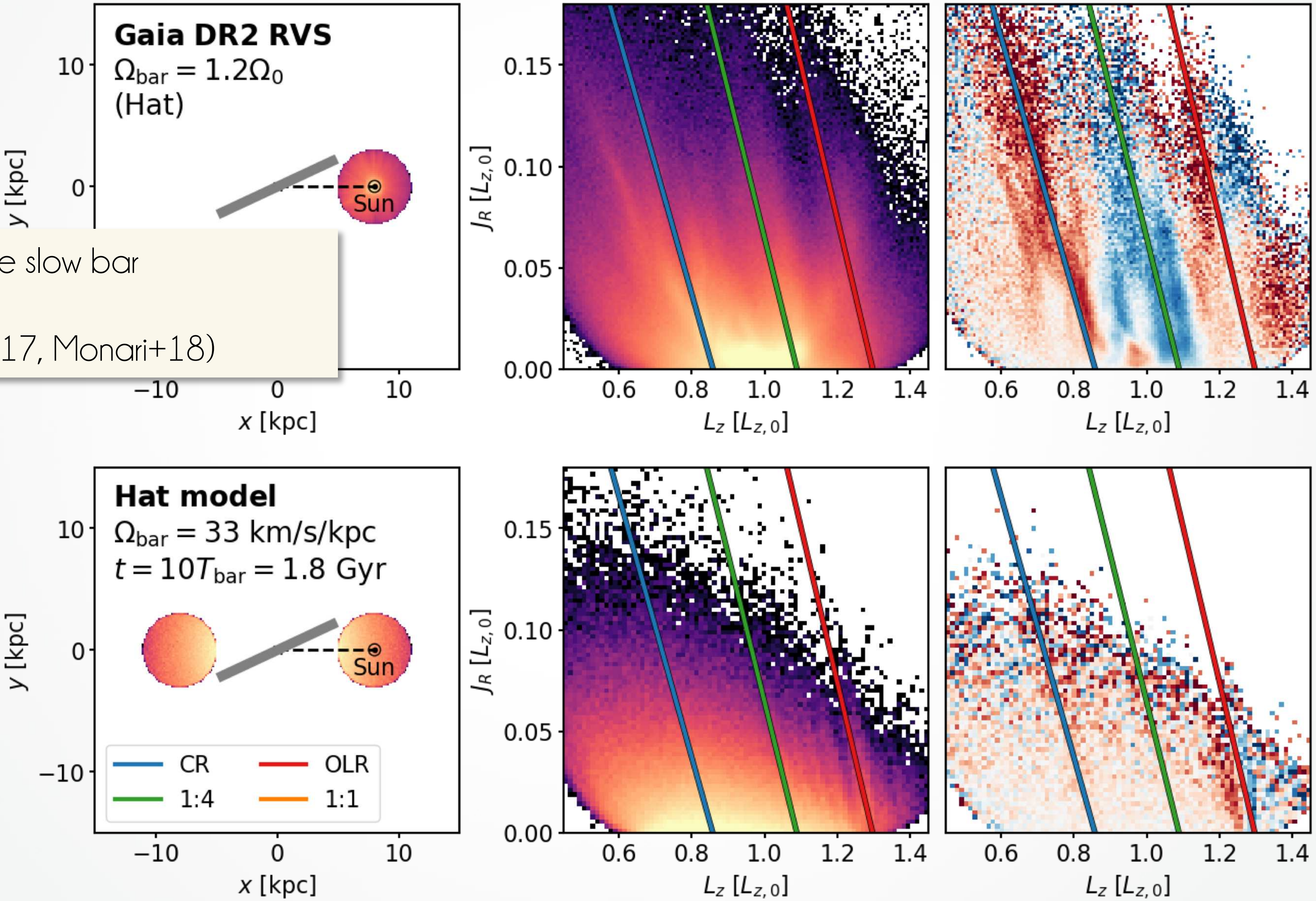
Identifying the OLR in Gaia data



very close to fast bar from Hercules modeling by Antoja+14, Dehnen00: $\Omega_{bar} \sim 1.85\ \Omega_0$

Trick, Fragkoudi, Hunt et al.
(arXiv:1906.04786)

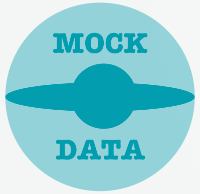
Assuming Bar OLR is Near the Hat



slightly lower than the slow bar

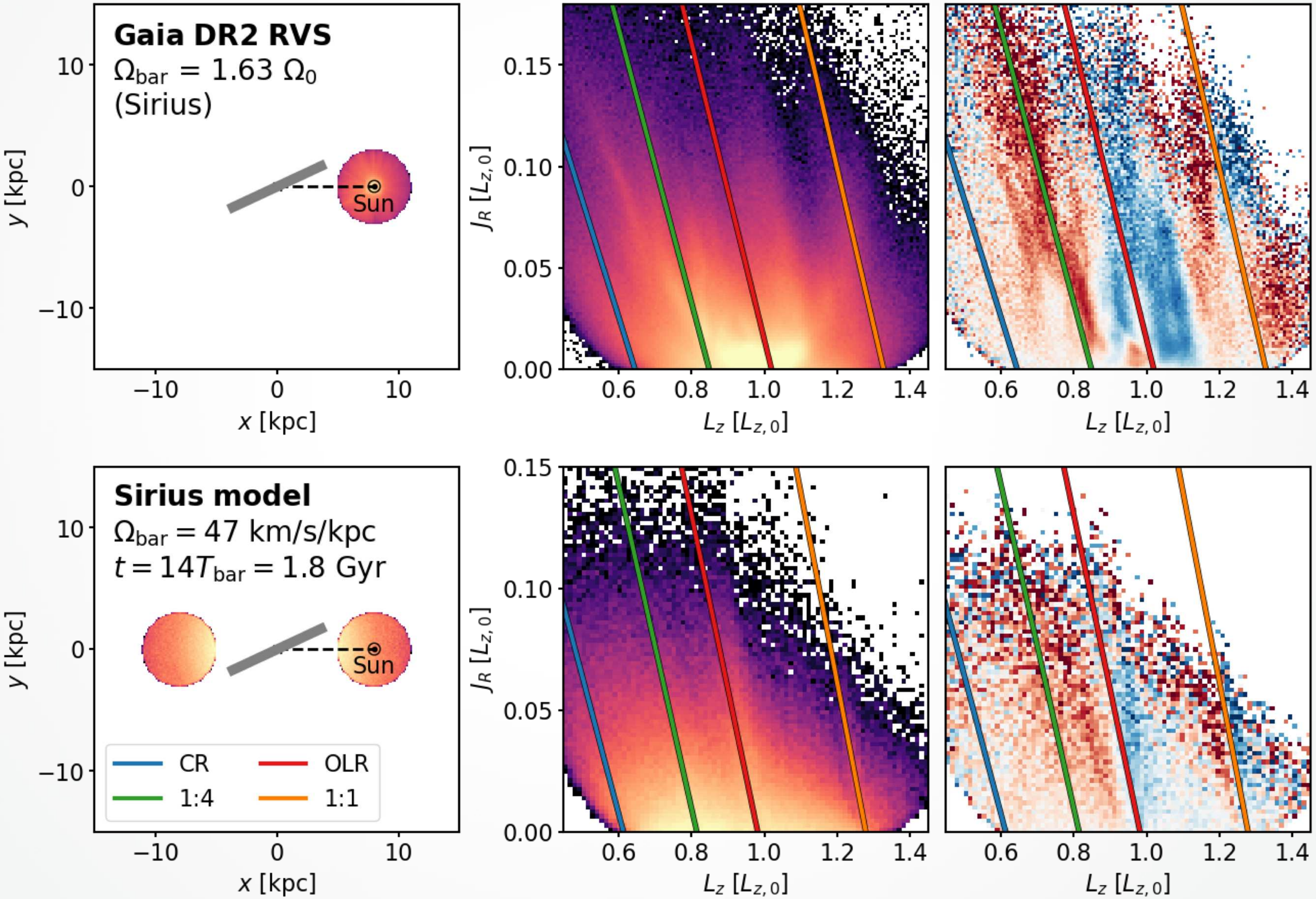
$\Omega_{\rm bar} \sim 1.3\ \Omega_0$

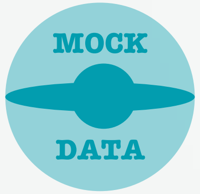
(e.g. Perez-Villegas+17, Monari+18)



Assuming Bar OLR is Near Sirius

Trick, Fragkoudi, Hunt et al.
(arXiv:1906.04786)



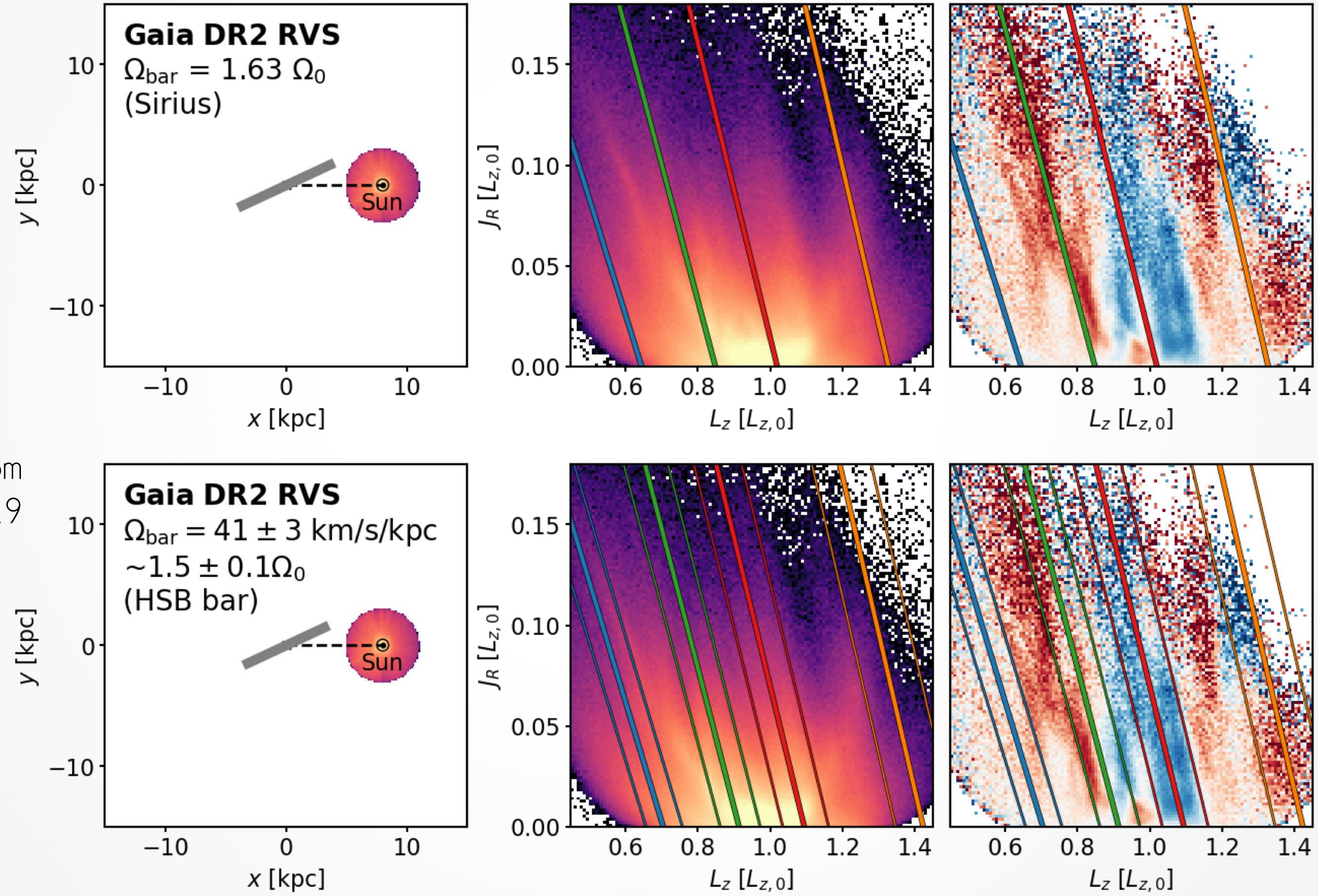


The Sirius Bar vs. The Intermediate Bar

Trick, Fragkoudi, Hunt et al.
(arXiv:1906.04786)

Pattern speed from
Sanders+19, Bovy+19

- CR
- OLR
- 1:1
- 1:4



Hercules stream:
1:4 resonance of
bar with m=4
component
(Hunt & Bovy 18)

The (L_z, J_R) plane of Galactic in-plane motions

1. Substructure in Gaia DR2 RVS in:

Trick et al. 2019a

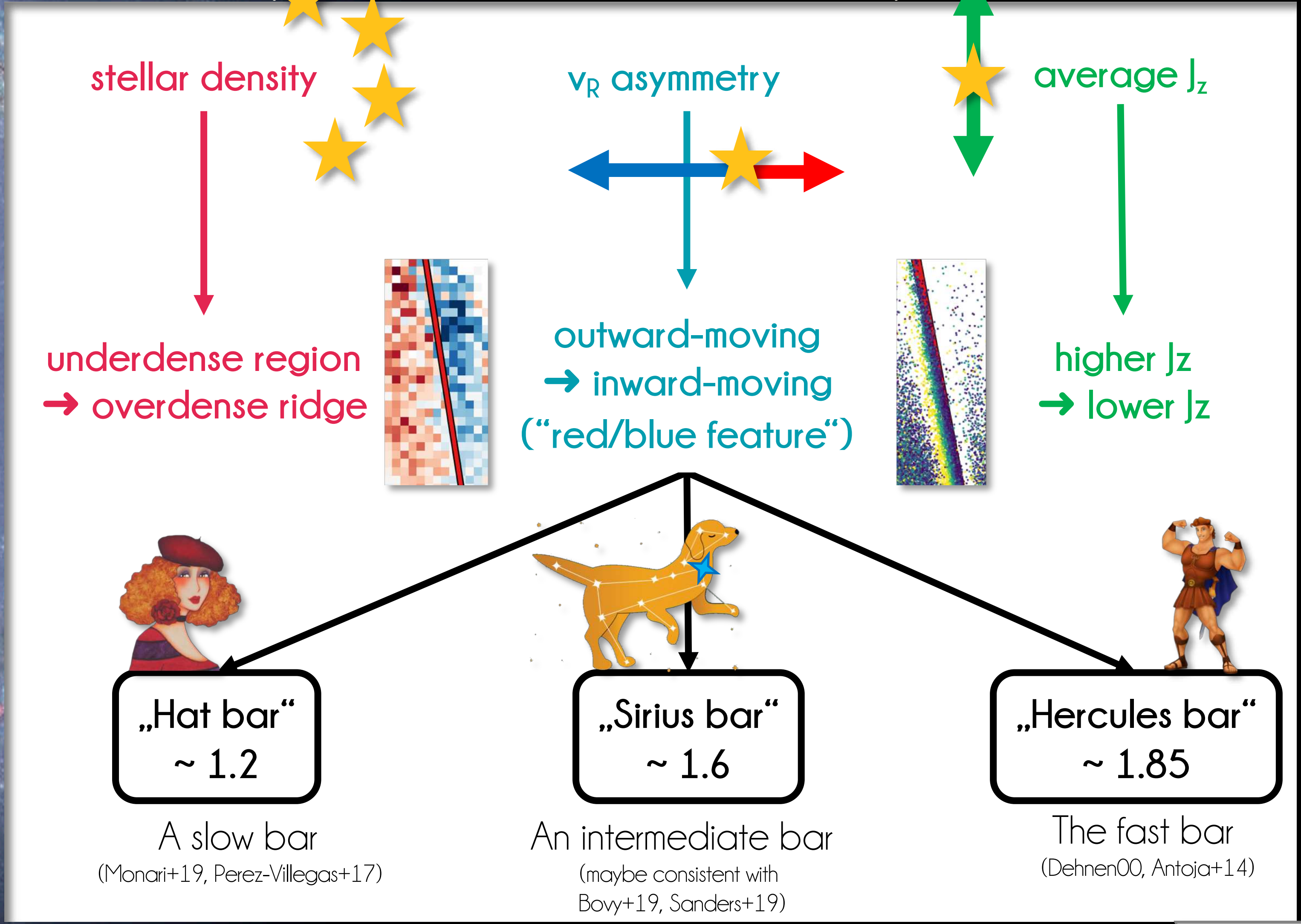
2. Signature across the bar's Outer Lindblad Resonance (OLR) line:

Trick et al. 2019b

3. OLR candidates from Gaia DR2 RVS AND bar pattern speed

$\Omega_{bar} / \Omega_0 \pm 0.1$

Trick et al. 2019b



Astrophysics > Astrophysics of Galaxies

Identifying resonances of the Galactic bar in Gaia DR2: Clues from action space

Wilma H. Trick, Francesca Fragkoudi, Jason A. S. Hunt, J. Ted Mackereth, Simon D. M. White

(Submitted on 11 Jun 2019)

Action space synthesizes the orbital information of stars and is well-suited to analyse the rich amount of kinematic disk substructure in the Gaia DR2 radial velocity sample (RVS). In this work, we revisit one of the strongest perturbers in the Milky Way (MW) disk: the m=2 bar. We investigate how its resonances affect the actions of individual test particle stars, i.e., (JR,Lz,Jz) estimated in an axisymmetric MW potential. We confirm that the stars' behaviour is well approximated by scattering and oscillation along a slope Delta JR / Delta Lz = l/m centered on the l:m resonance lines. The Outer Lindblad Resonance (OLR, l=+1,m=2) creates signatures in the stellar action space that can be used to identify the Galactic bar's OLR in the Gaia DR2 RVS data: (a) The JR dependence of the oscillation causes an overdensity ridge (underdensity region) at Lz larger (smaller) than the resonance line in the (Lz,JR) plane. (b) For the first time, we demonstrate that the OLR is expected to cause a gradient in average Jz with Lz across the resonance. (c) We show that the change of predominantly outward to inward motions at the OLR occurs along the resonance line in action space. The latter signature allows us to identify three candidates for the bar's OLR – and therefore its pattern speed Omega_bar – in the Gaia data within 3 kpc from the Sun: 1.85 Omega0, 1.2 Omega0, and 1.6 Omega0 (with ~0.1 Omega0 uncertainty). This demonstrates that (i) the local Gaia action data is consistent with both the short-fast and long-slow bar models in the literature, and that (ii) axisymmetrically estimated actions are a powerful diagnostic even in non-axisymmetric systems.

Comments: 20 pages, 13 figures, 1 table; submitted to MNRAS

Subjects: **Astrophysics of Galaxies (astro-ph.GA)**

Cite as: arXiv:1906.04786 **[astro-ph.GA]**