„In the Balance: Stasis and Disequilibrium in the Milky Way“
KITP, Santa Barbara, 1. April 2018

The Galactic Disc & Bar in Action-Angle Space as seen by Gaia DR2

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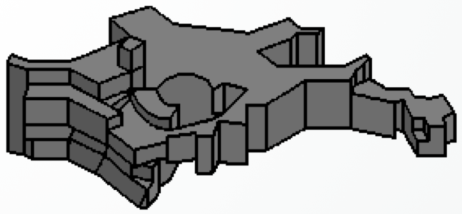
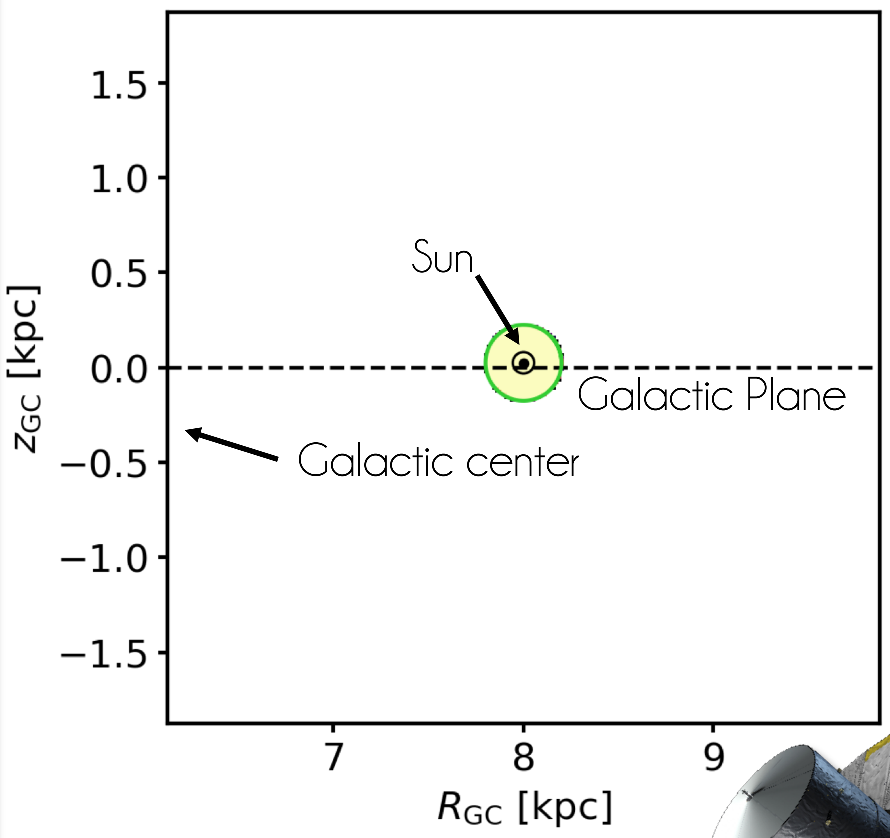
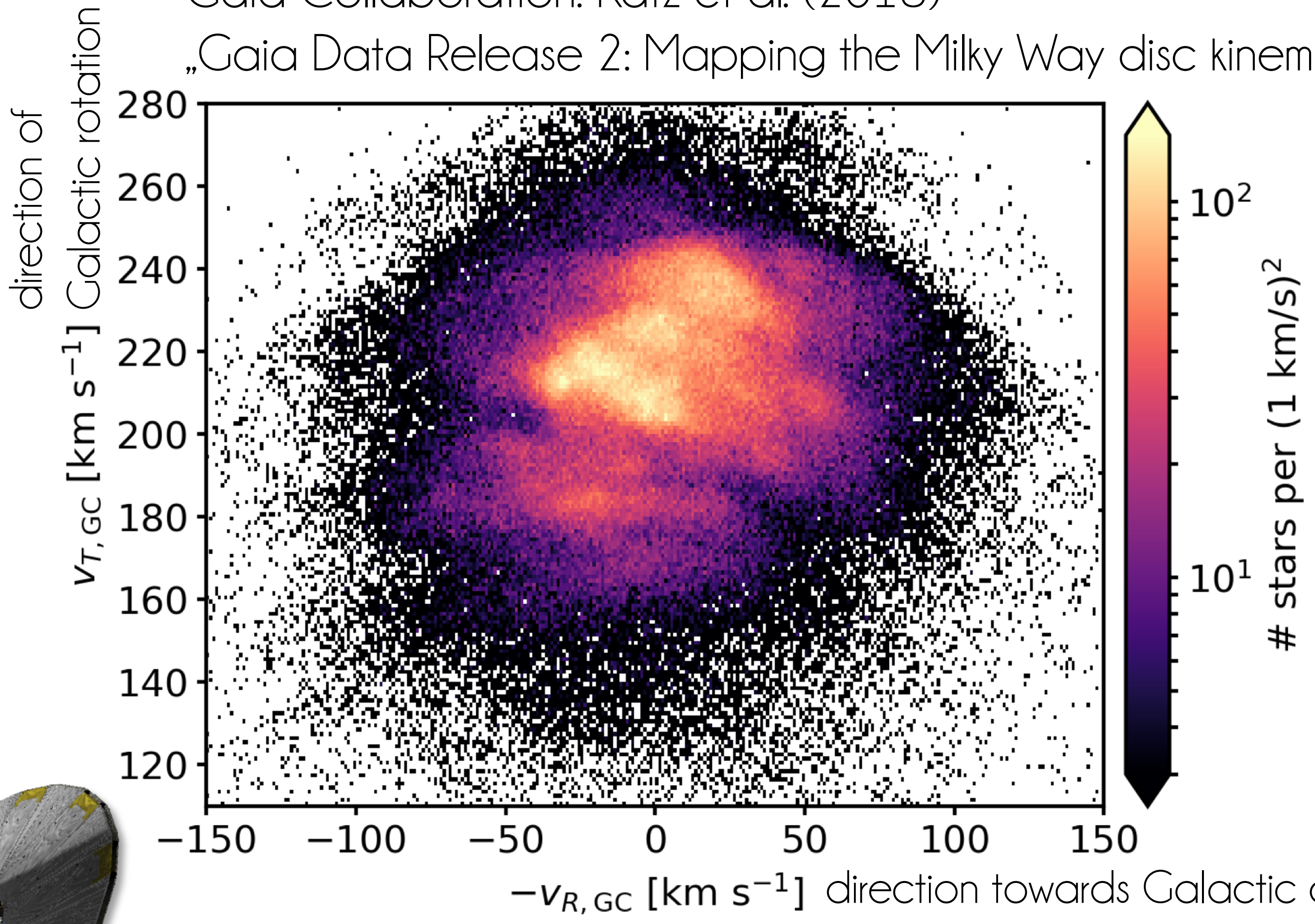
Jason Hunt (Uni Toronto), Ted Mackereth (Uni Birmingham),
Hans-Walter Rix (MPIA Heidelberg), Jerry Sellwood (Uni Arizona),
Simon White (MPA Garching), Jo Bovy (Uni Toronto)

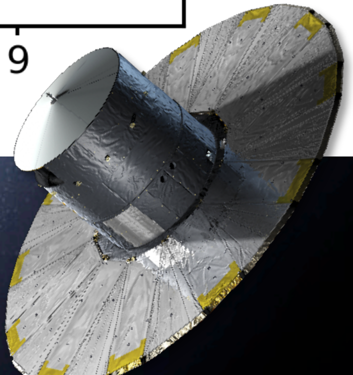


The In-Plane Motions of the Solar Neighbourhood: Gaia DR2



Gaia Collaboration: Katz et al. (2018)
„Gaia Data Release 2: Mapping the Milky Way disc kinematics"





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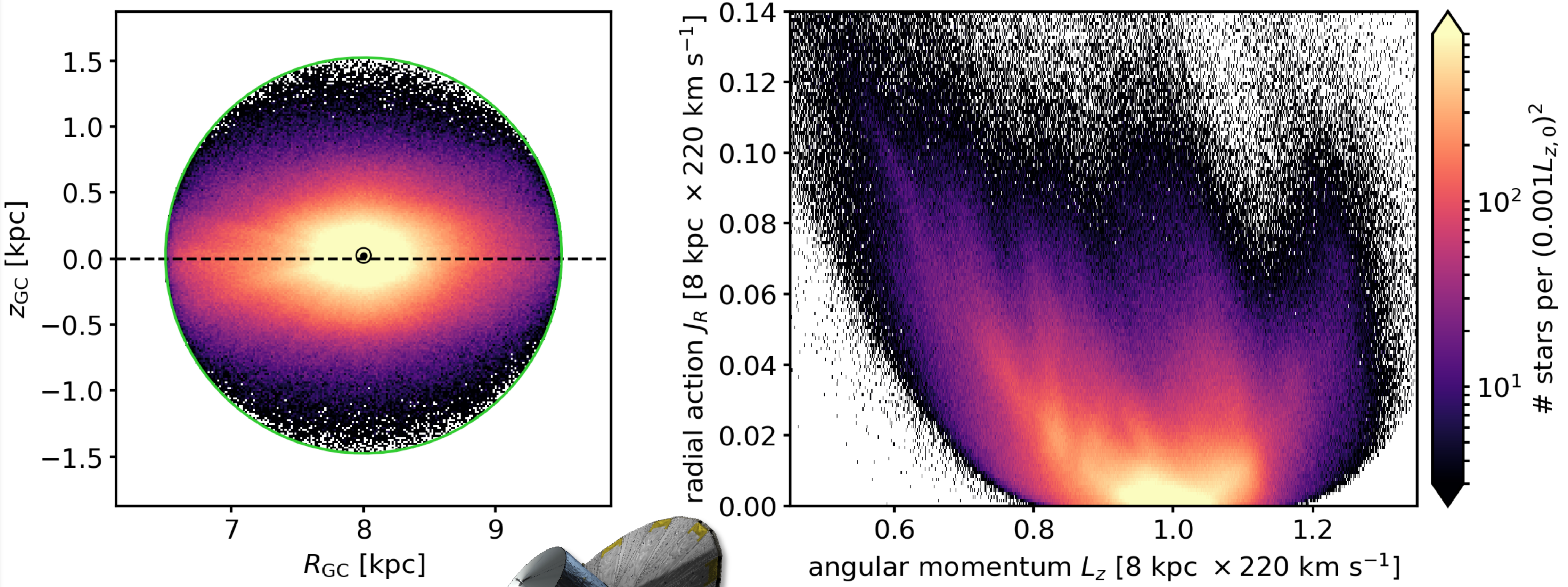
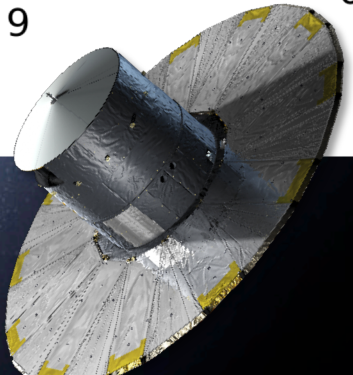
The In-Plane Motions out to 1.5 kpc: Gaia DR2 in Action Space

see Trick, Coronado, & Rix (2019)





Stars in the **Gaia DR2 / RVS sample** within **1.5 kpc**, most stars have `parallax_over_error` > 20
→ 5% distance error

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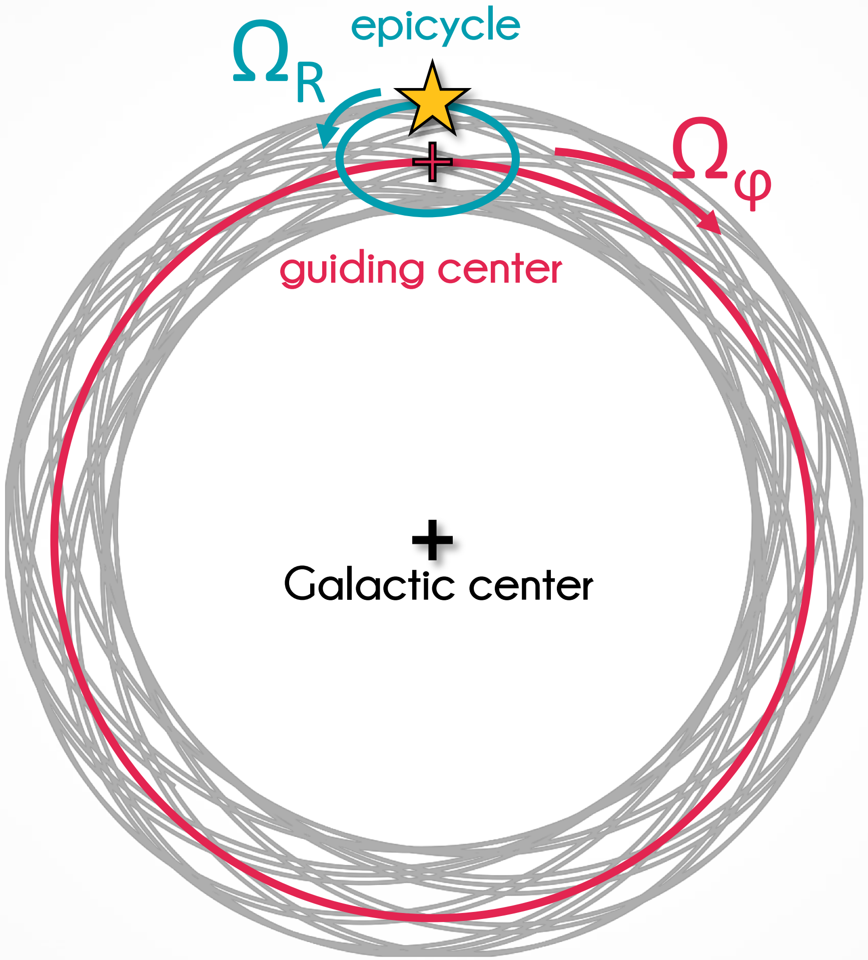
Disk Orbits in the Epicycle Approximation

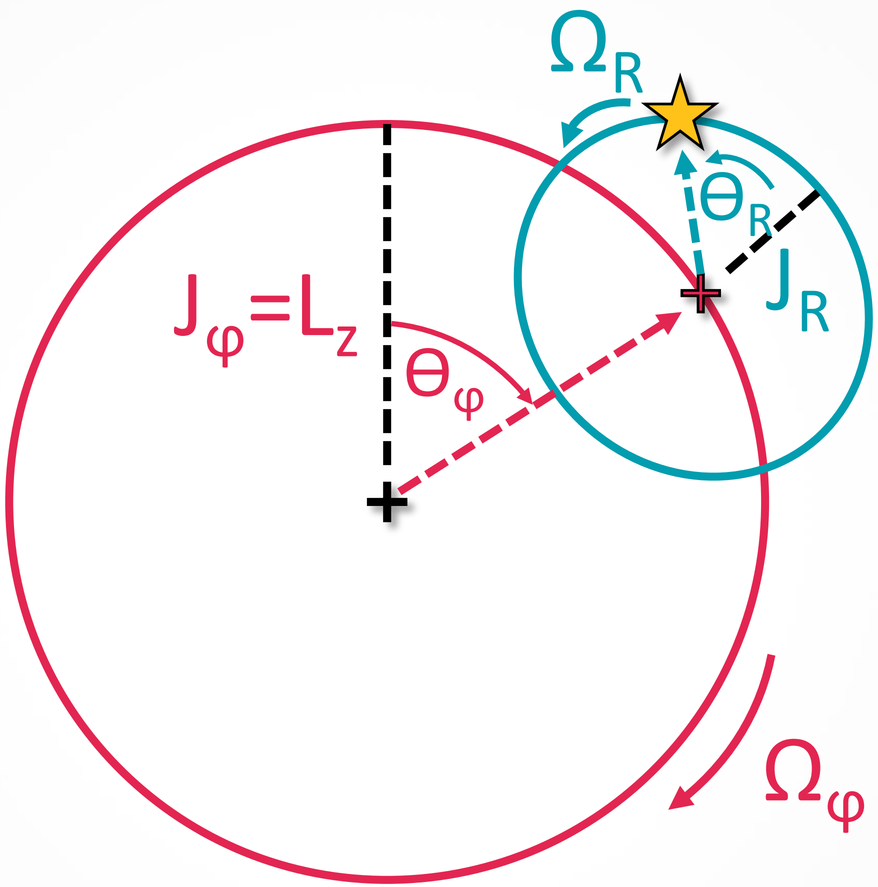


Action-Angle Coordinates (explained with Epicycles)

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

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

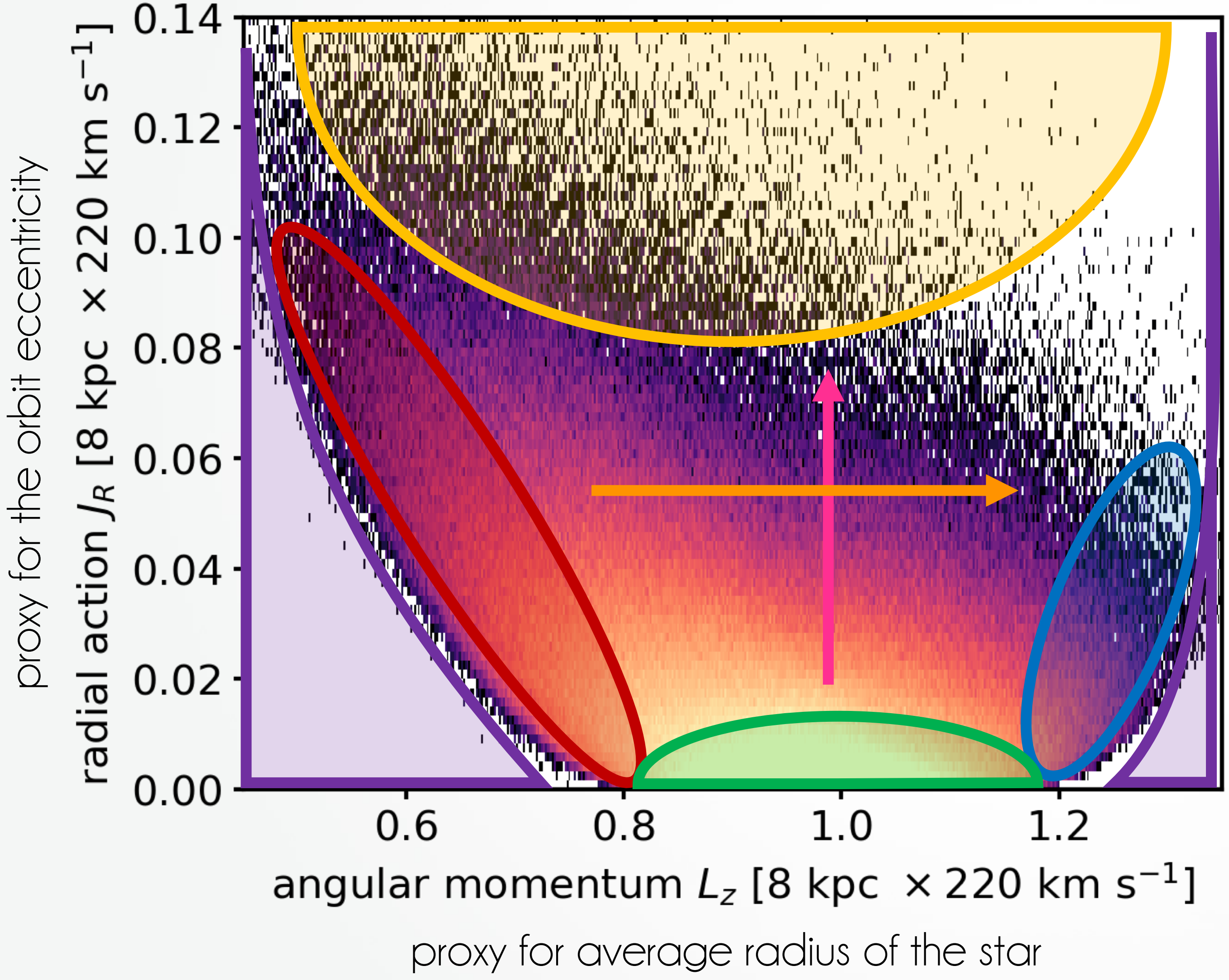
fundamental
frequencies Ω



(x,v)
observed by Gaia
↓
axisymmetric MW
grav. potential model

MWPotential2014
(Bovy 2015)
+
estimation algorithm:
Stäckel Fudge (Binney 2012)
↓
axisym. actions,
angles & frequencies

Understanding Action Space



Interpretation:

Stars on...

... near-circular orbits with R ∈ $R_\odot$ ± 1.5 kpc

... rare, highly eccentric orbits

Population effects:

- radially decreasing stellar density
- radial velocity dispersion

Selection effects:

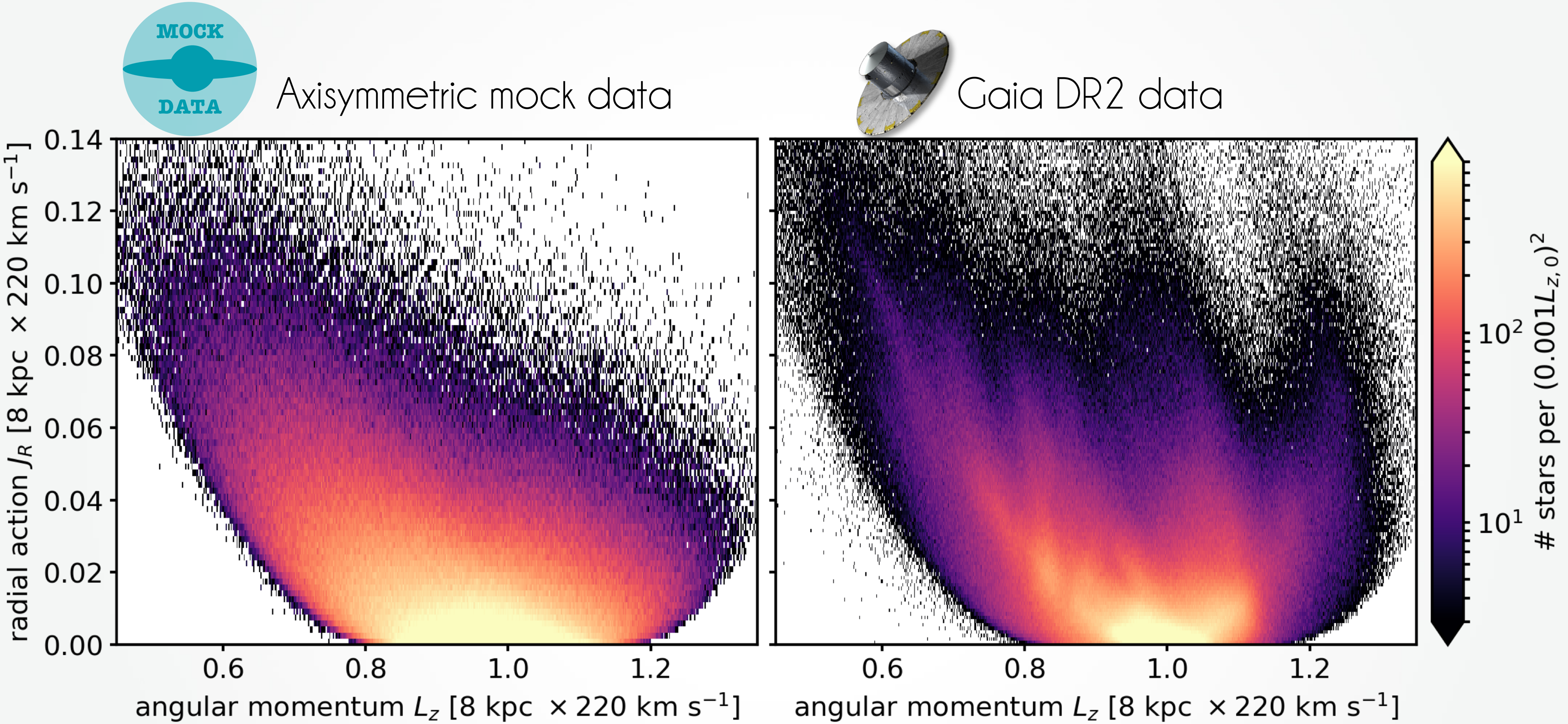
Stars...

... close to pericenter

... close to apocenter

... on orbits that do not reach into the survey volume (exist, but are not observed)

The In-Plane Motions out to 1.5 kpc: Gaia DR2 in Action Space



see Trick, Coronado, & Rix (2019)

Mock data model:

- MWPotential2014 (Bovy 2015)
- quasi-isothermal distribution function for the stellar disk (Binney & McMillan 2011)
- spherical survey volume around the Sun, r=1.5kpc (Trick et al. 2016)

The Way Forward

Gaia DR2 🤯

The Goal with Gaia:

axisymmetric **action-based dynamical modeling** of the MW disk

→ grav. **potential** (e.g. dark matter)
→ chemo-orbital distr. of disk stars
→ as baseline for perturbation theory

Understanding action sub-structure:

1) **Data:** Properties of the substructure

2) **Theory:** signatures of underlying mechanisms – e.g. **resonances**

3) **Qualitative: „labelling"** the features by perturber (bar, spiral arm, satellite fly-by)

4) **Quantitative:** dynamical **modeling** using informed guess & improved models

Resonances in...
...velocity space:
e.g. Binney & Lacey 88; De Simone 04; Quillen+ 03,05; Antoja+ 2011; Fux+ 01; Monari et al. 17, Fragkoudi,...,Trick,+ 19
...axisym. action space:
e.g. Sellwood & Binney 02; Sellwood 10; McMillan 11; Fouvry+ 15a,b; Sellwood, Trick,+ 19

Axisym. actions & DFs:
Binney 12; Binney & McMillan 11; Sanders & Binney 15

RoadMapping modeling:
my PhD thesis, Trick+ 16,17; Bovy & Rix 13;
Similar approach: Piffl+ 15

action-based modeling incl. perturbations:
Monari+ 16,17,19; Binney 18

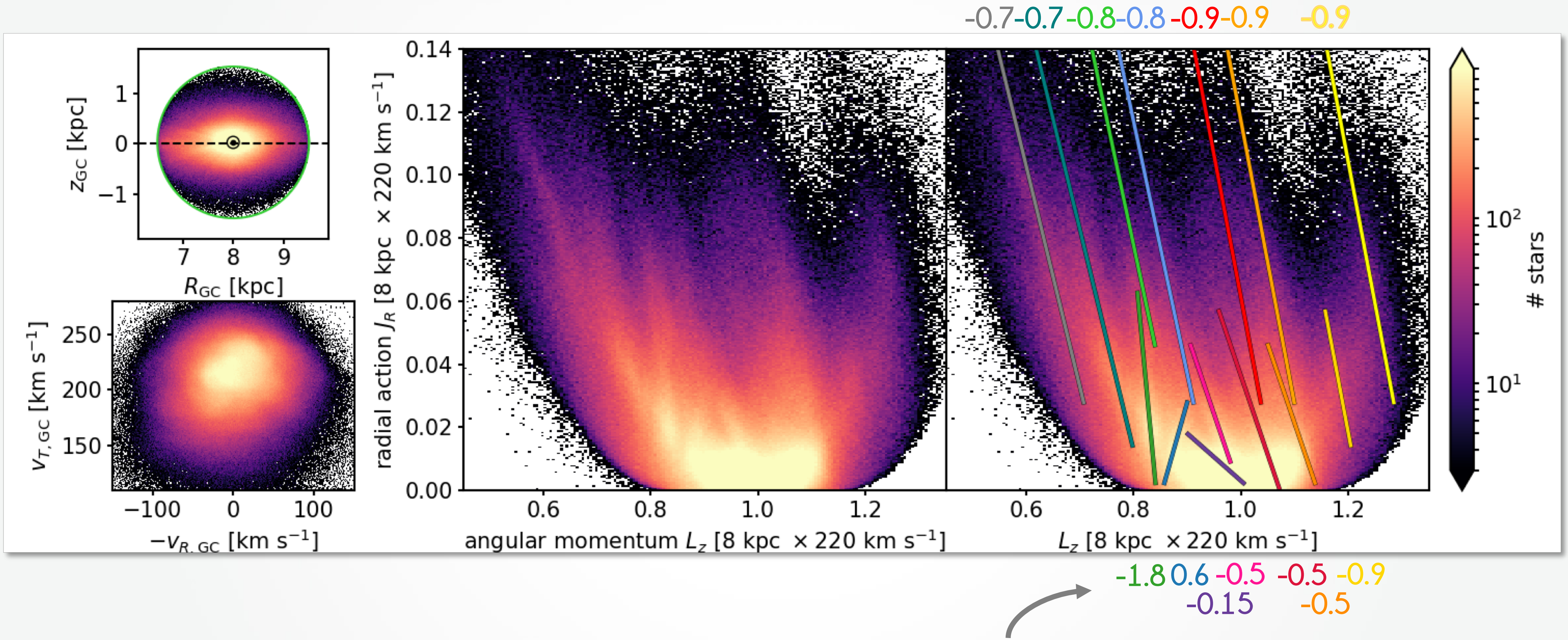
of velocity space with Hipparcos or Gaia DR1:
e.g. Dehnen 00; Minchev+ 10; Antoja+ 15; Monari+ 17

...simpler middle ground using **axisymmetric actions**, angles & frequencies...?

Part 2:
The extended Orbit Sub-Structure of the Galactic Disk as seen by Gaia DR2

Trick, Coronado, & Rix (2019)

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

The Solar Neighbourhood: moving groups

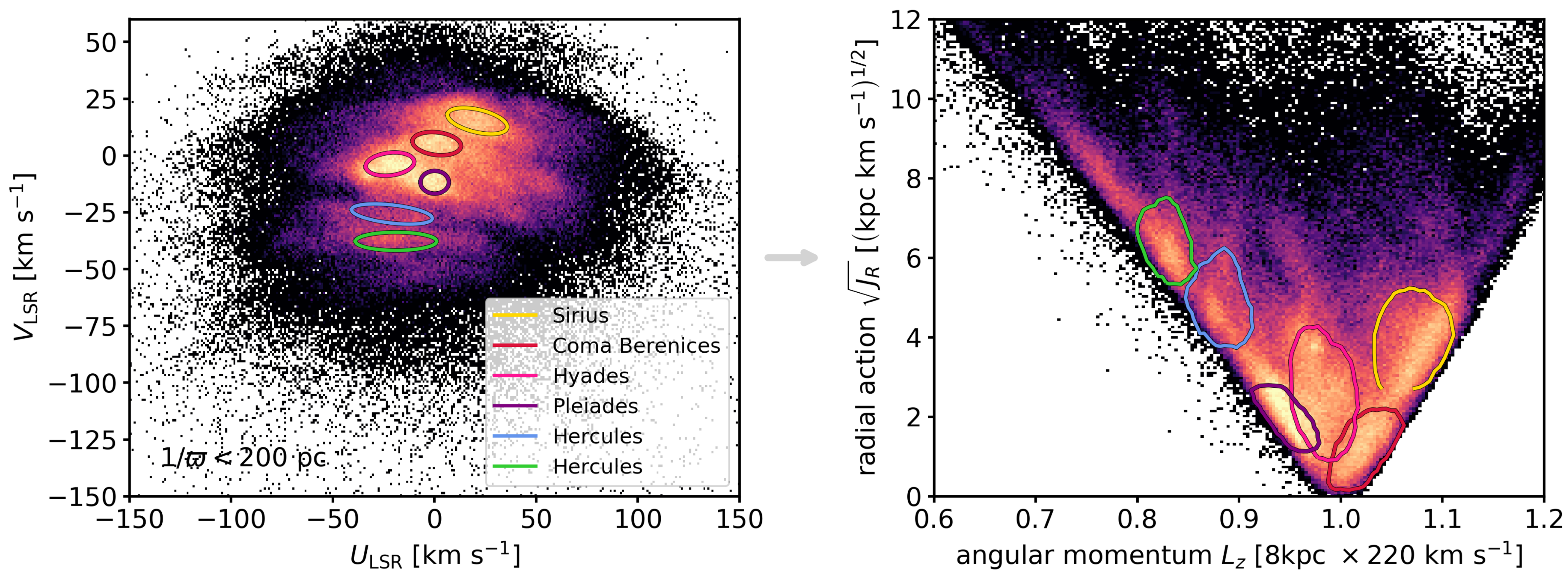


figure from Trick, Coronado & Rix (2019)

The Solar Neighbourhood: moving groups & Arches

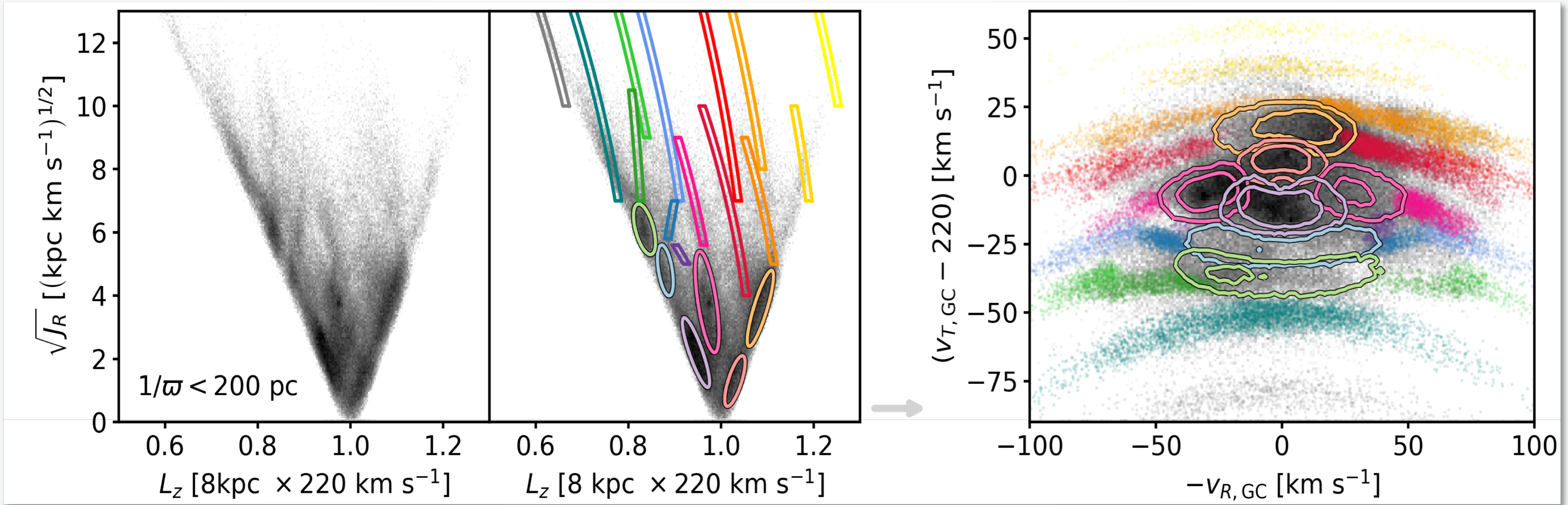


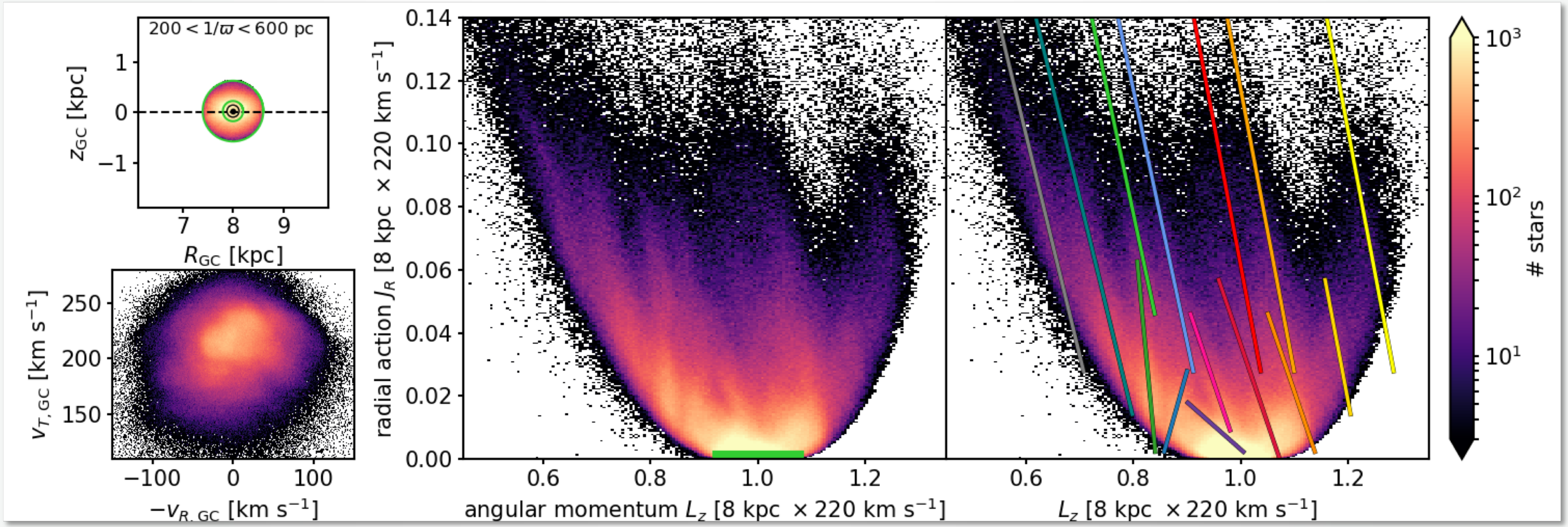
figure from Trick, Coronado & Rix (2019)

In the Solar neighbourhood, the lines in action space correspond to the **arches in velocity space** discovered by Gaia Collaboration: Katz et al. (2018) and Kawata et al. (2018).

BUT: More nicely visible in action space. 😊

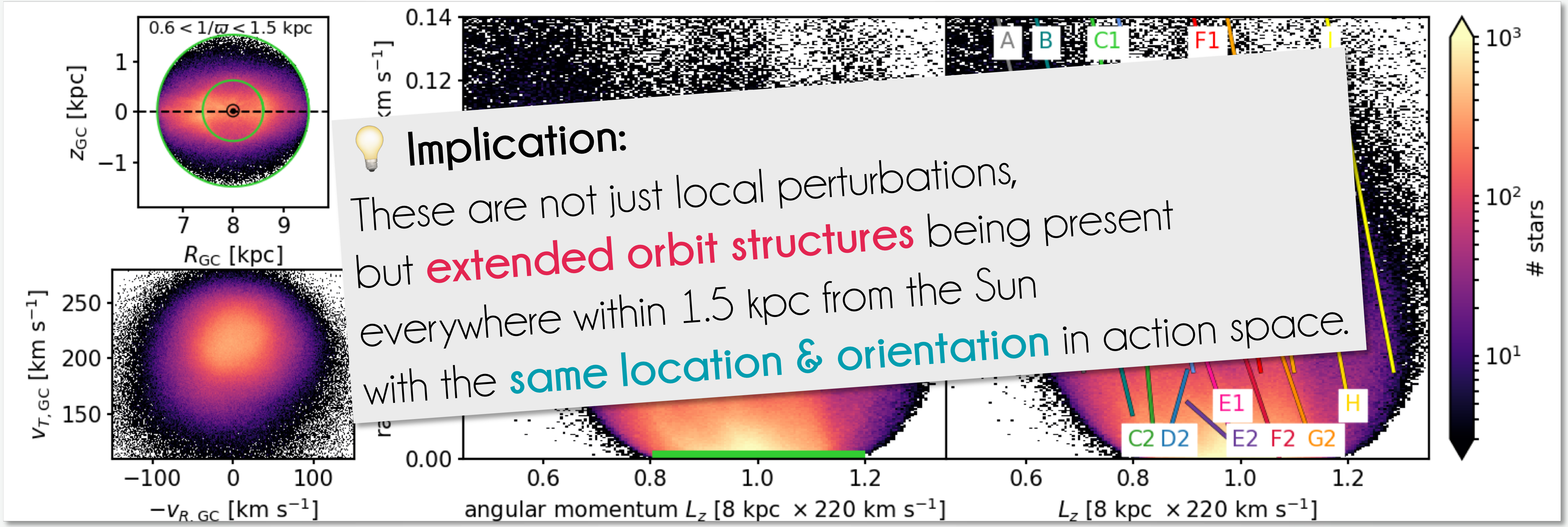
NOTE: Asymmetric numbers of stars in positive and negative radial velocity

Outside of the Solar neighbourhood: the extended orbit structure



Trick, Coronado, & Rix (2019)

Outside of the Solar Neighbourhood: the extended orbit structure



💡 **Implication:**

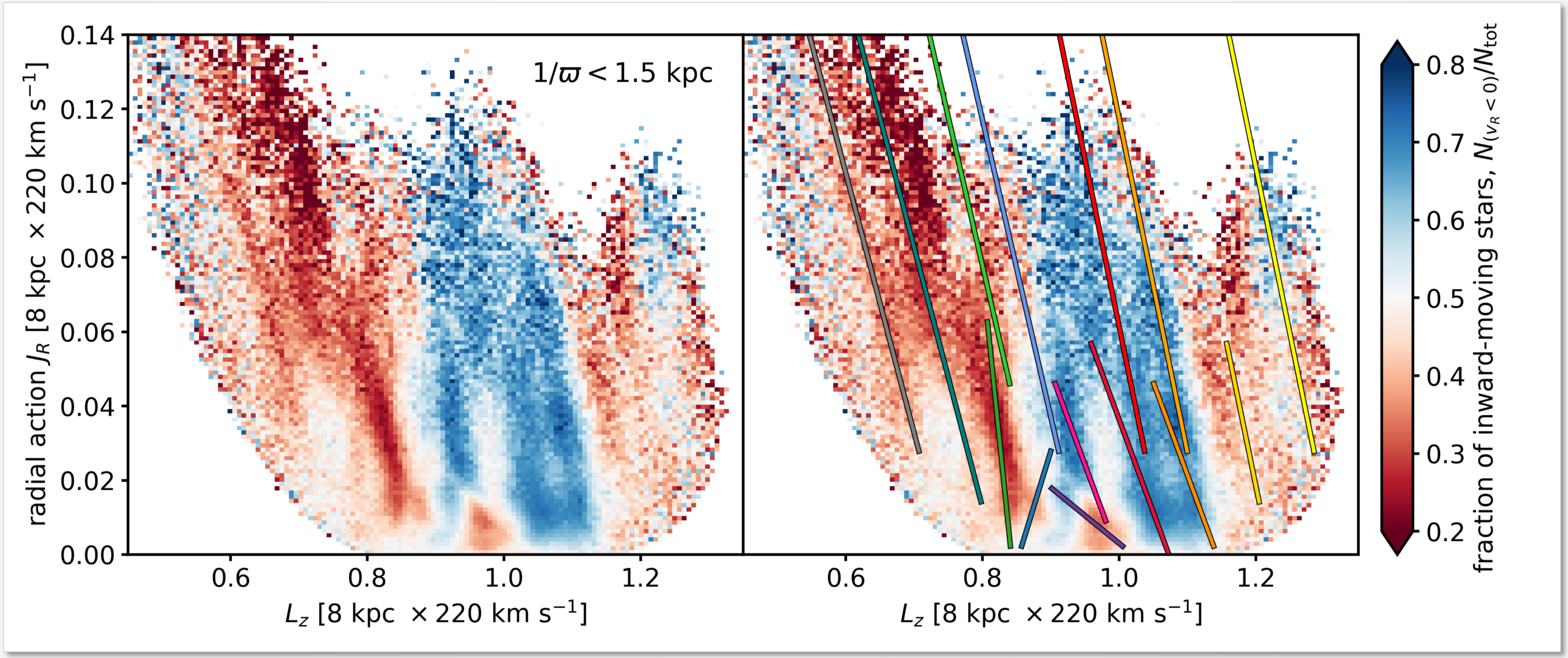
These are not just local perturbations, but **extended orbit structures** being present everywhere within 1.5 kpc from the Sun with the **same location & orientation** in action space.

Trick, Coronado, & Rix (2019)

The moving groups are the local, selection function affected manifestation of this extended orbit structure.

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)

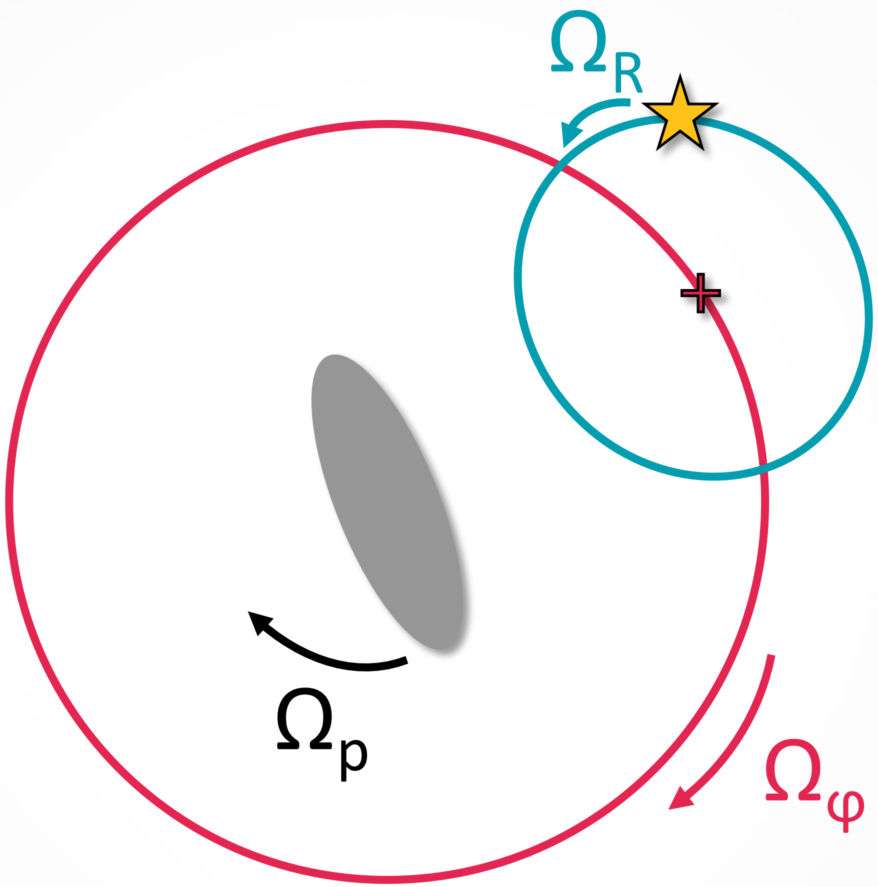
Part 3:

What do „Axisymmetric Actions" tell us about the Galactic Bar?

🚧 Paper to be submitted soon... ⚒️

Resonances in a Non-Axisymmetric Galaxy

$$m \cdot (\Omega_p - \Omega_\varphi) - l \cdot \Omega_R = 0$$



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)

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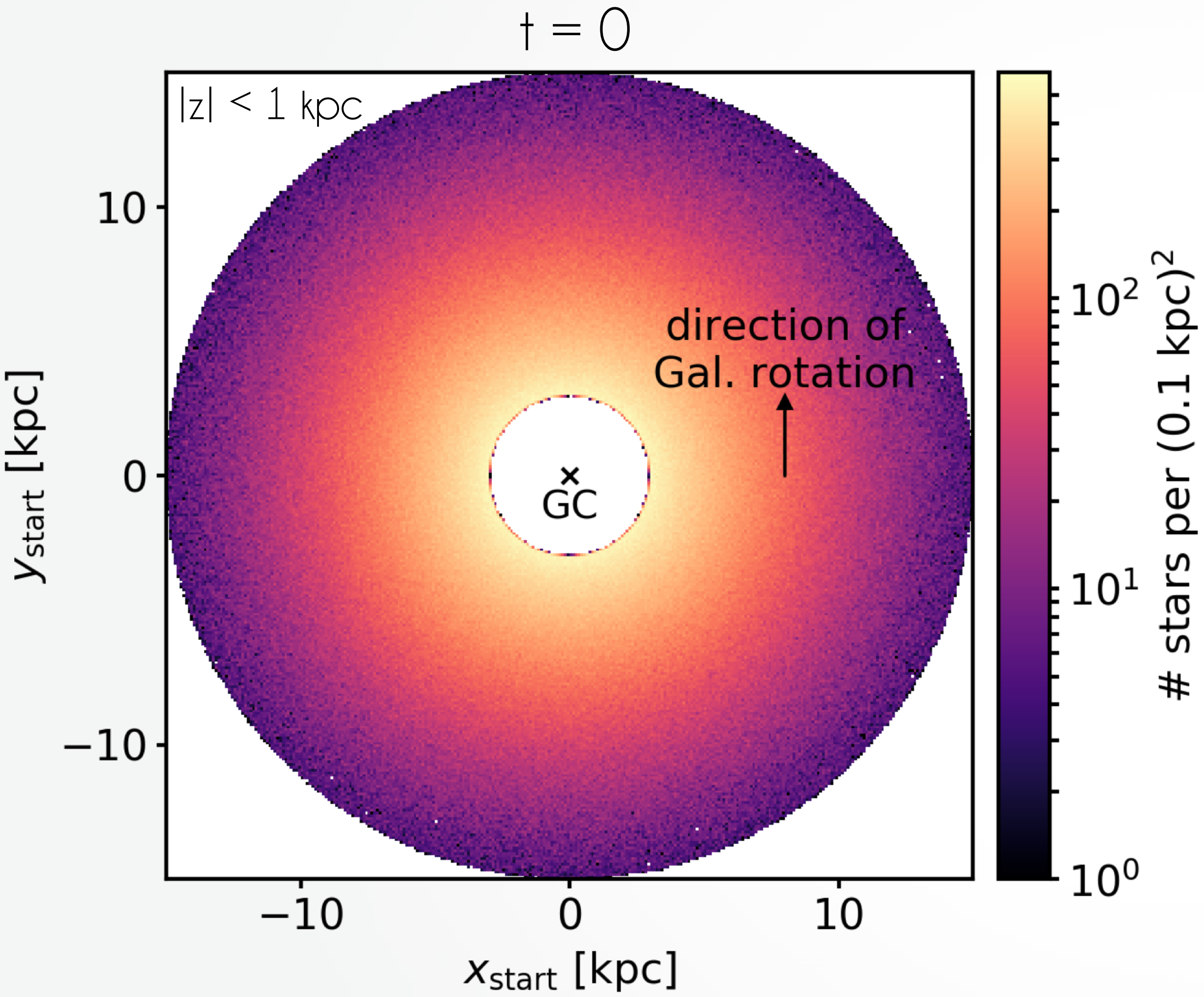
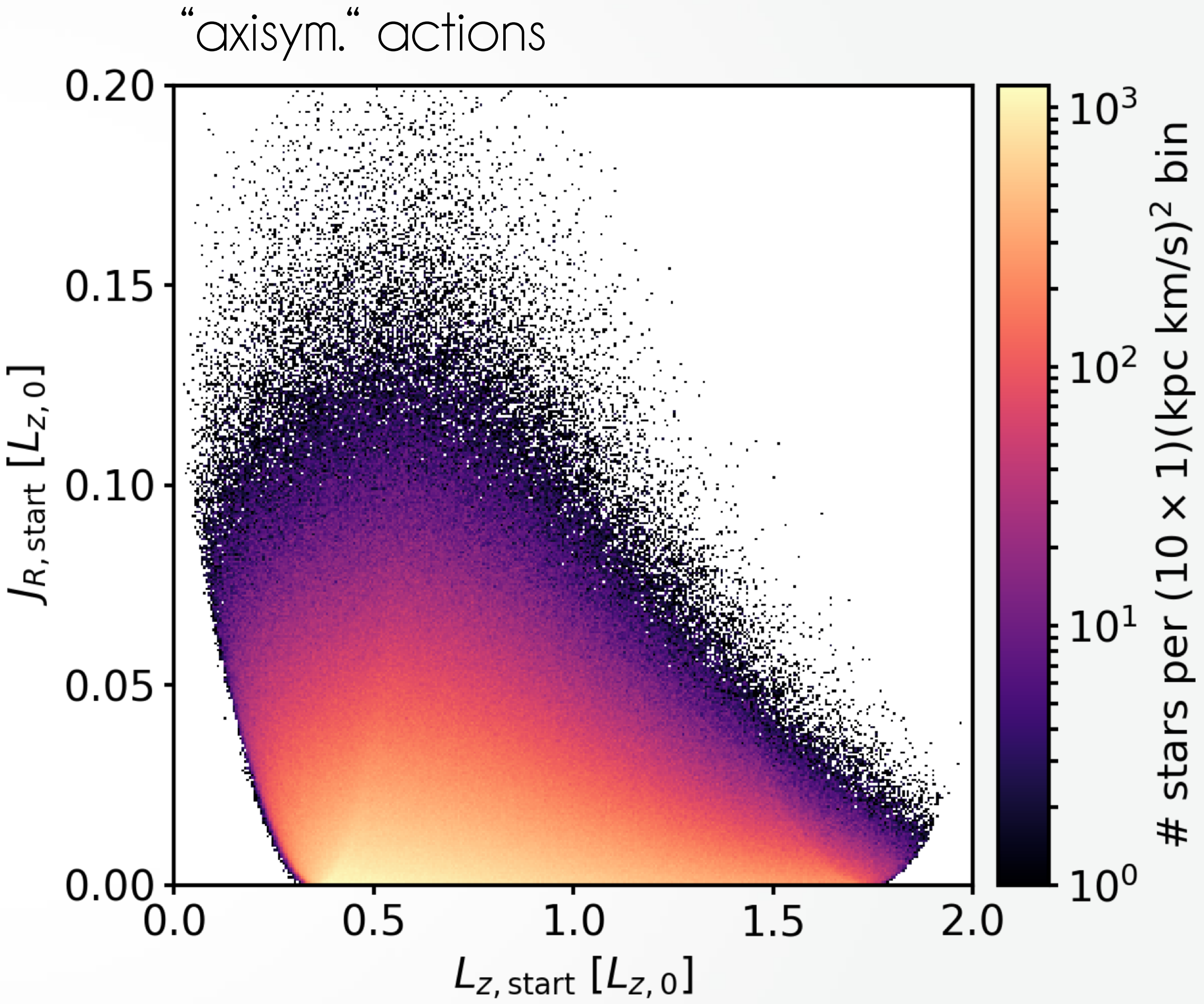
Create Mock Data Stars in MW Potential

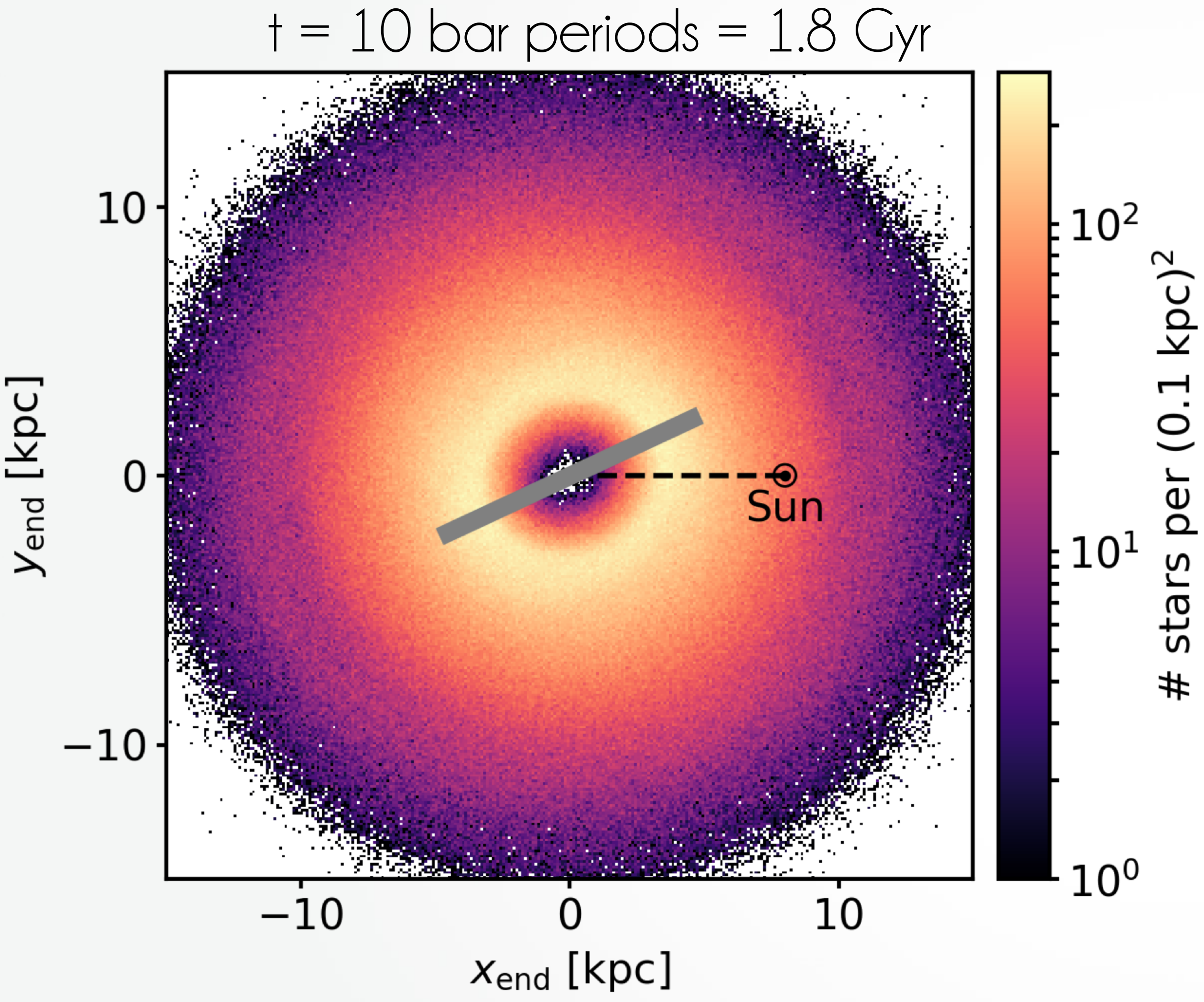


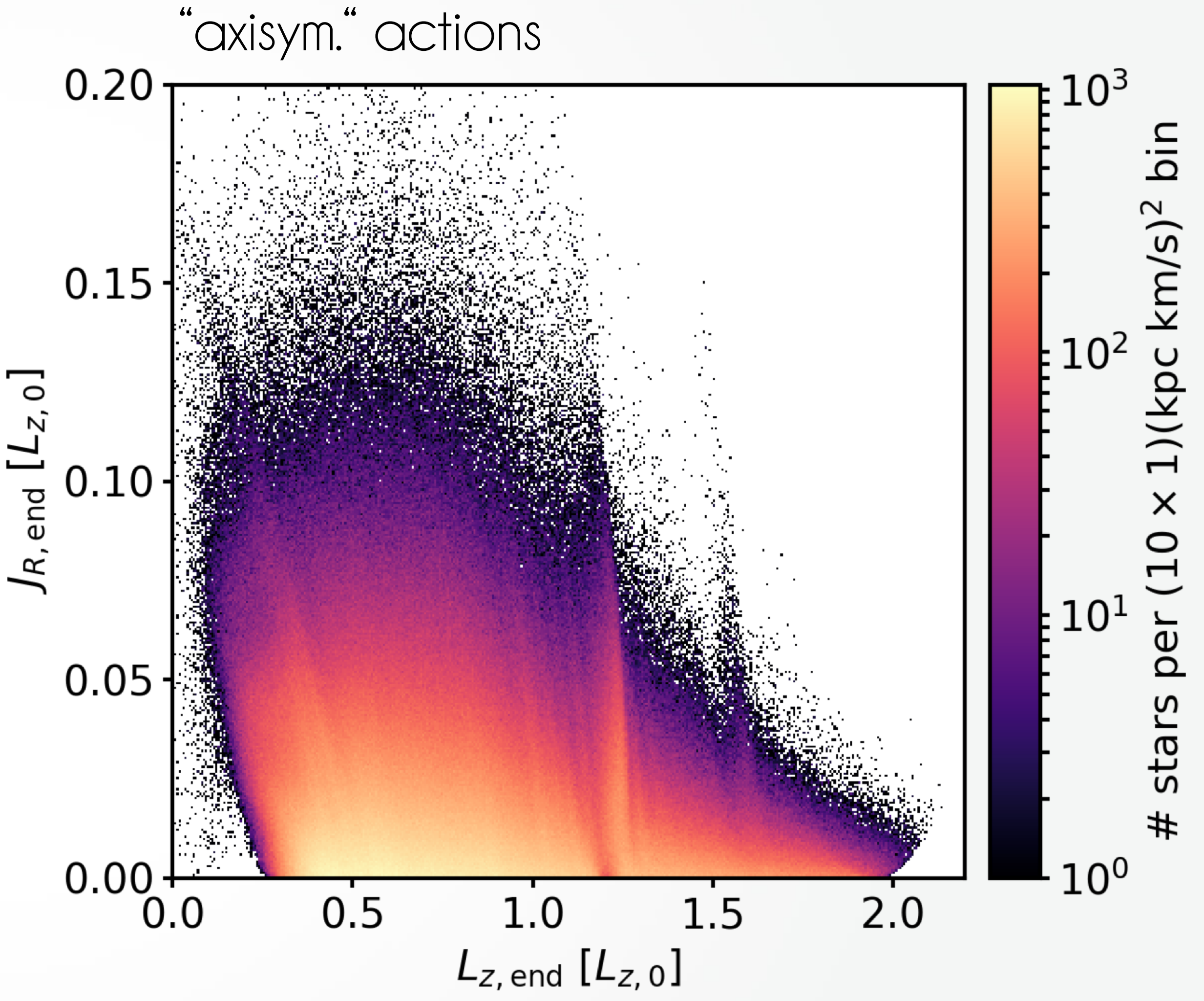


axisymmetric MWPotential2014 (Bovy 2014)

quasi-isothermal distribution function (Binney & McMillan 2011)

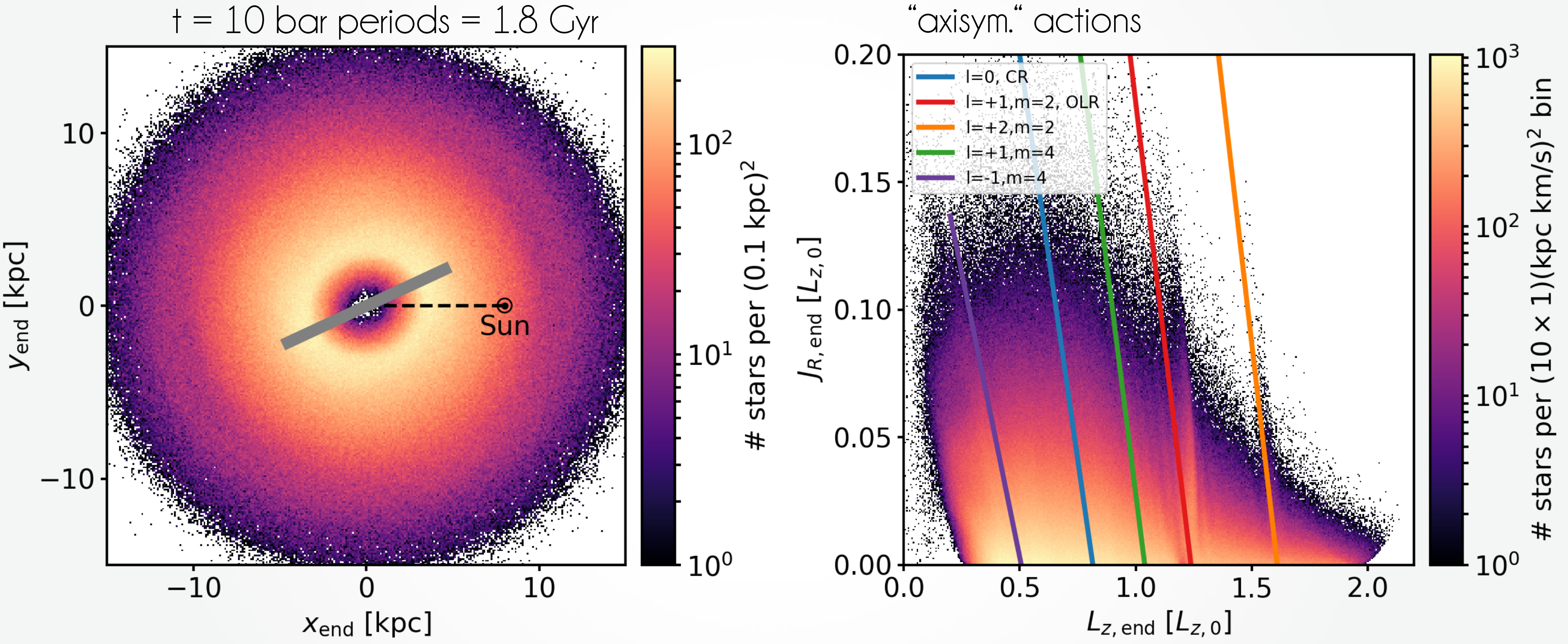
Integrate Mock Stars in Bar Potential





MW pot + „Dehnen" bar,
pattern speed: **Ω_p = 35 km/s/kpc**

Resonance Lines based on Axisym. Frequencies



Resonance condition: $m \cdot (\Omega_p - \Omega_\varphi) - l \cdot \Omega_R = 0$

pattern speed: Ω_p = 35 km/s/kpc

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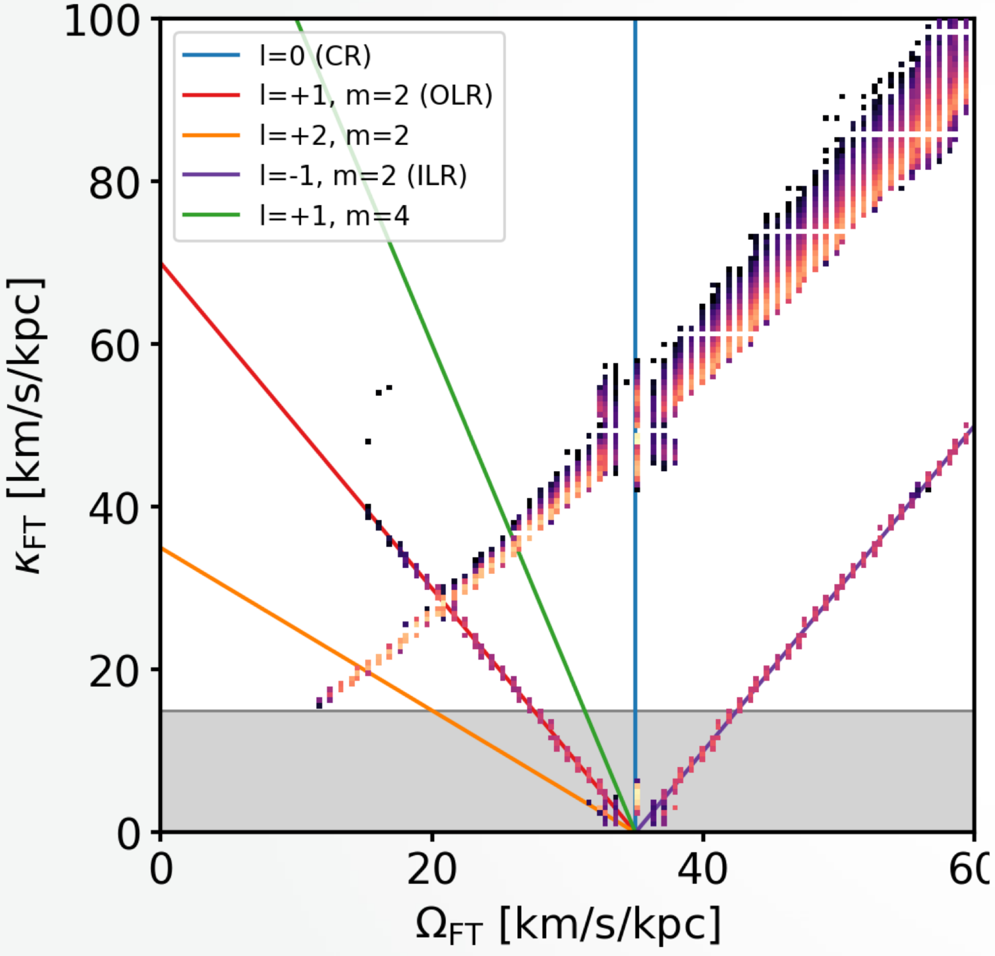
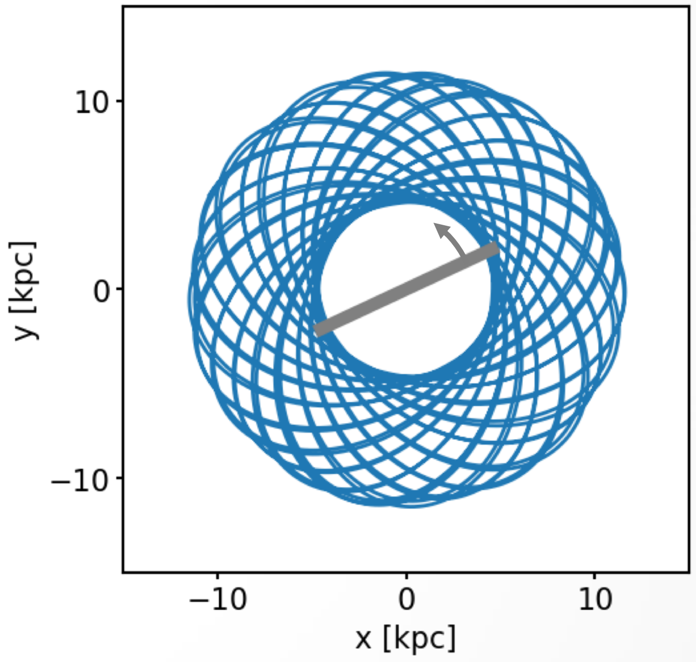
Selecting Stars in Resonance with the Bar





Fourier transform spatial coord. to get „real" fundamental frequencies:

R(t)

→ epicycle κ_{FT}

cos(ϕ)(t)

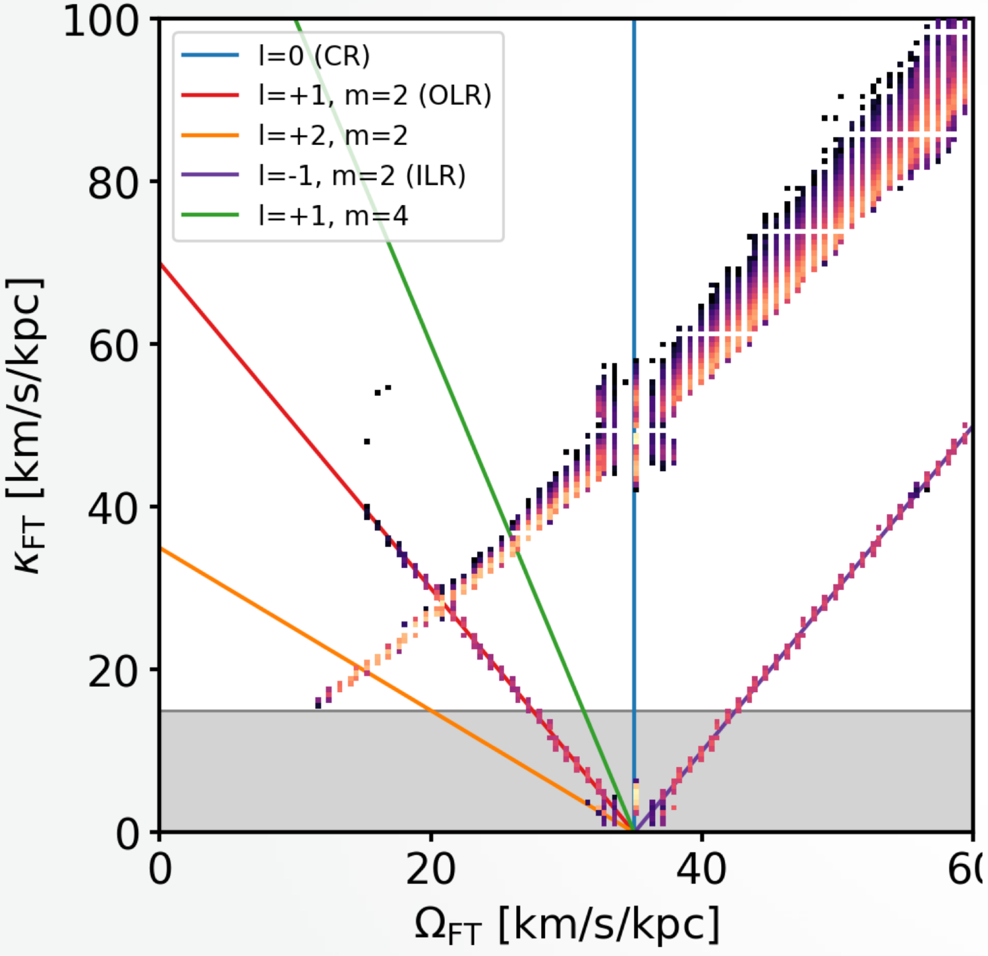
→ circular Ω_{FT}

$$m \cdot (\Omega_p - \Omega_{FT}) - l \cdot \kappa_{FT} \sim 0$$

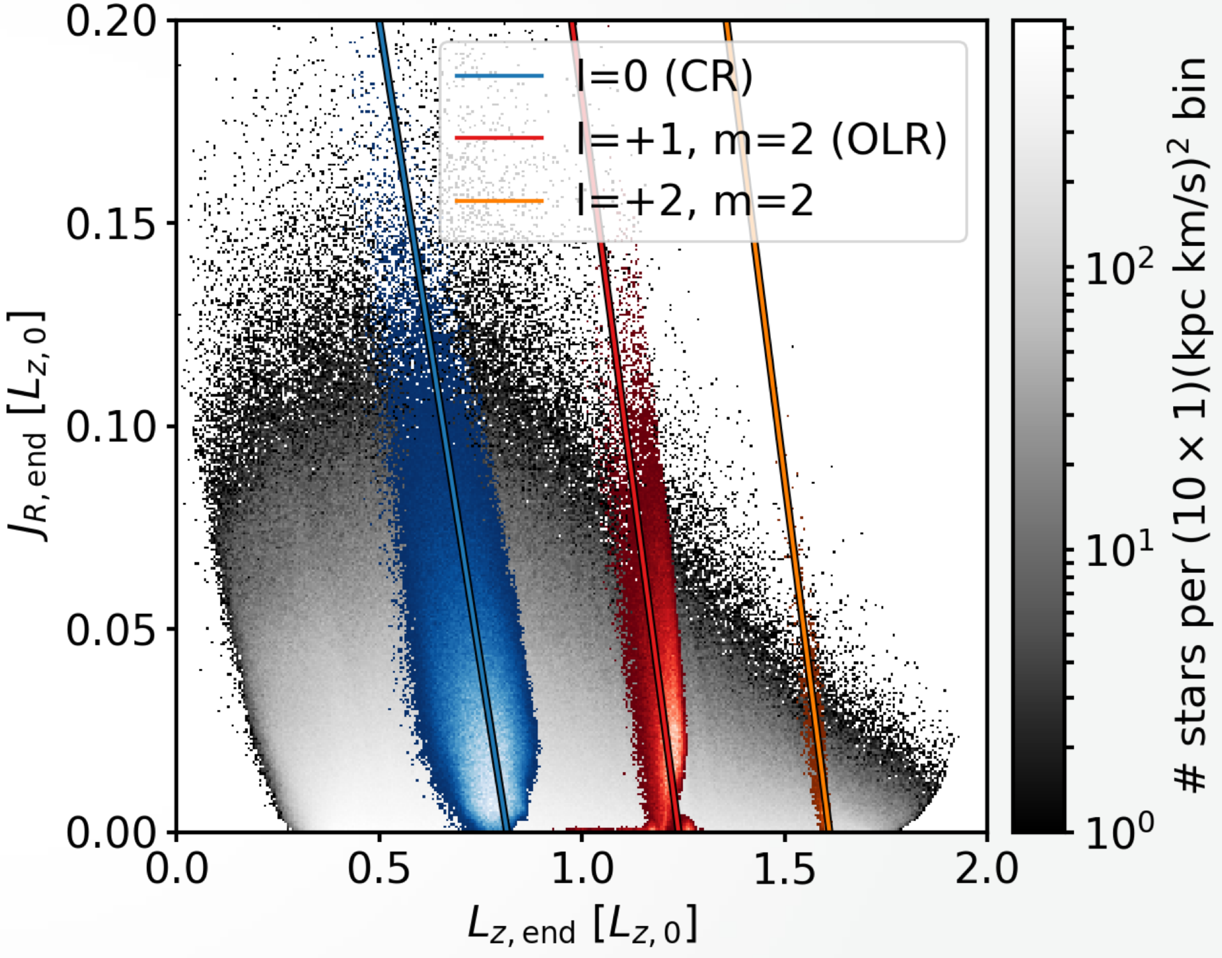
see also Fragkoudi et al (2019)

Location of „truly" resonant Stars

Bar resonances & axisym. Actions



… versus the axisymmetric resonance lines



$$m \cdot (\Omega_p - \Omega_{FT}) - l \cdot \kappa_{FT} \sim 0$$

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Effect of Resonances on "Axisymmetric Actions"

„Scattering" (i.e. lasting changes)
in axisym. action space

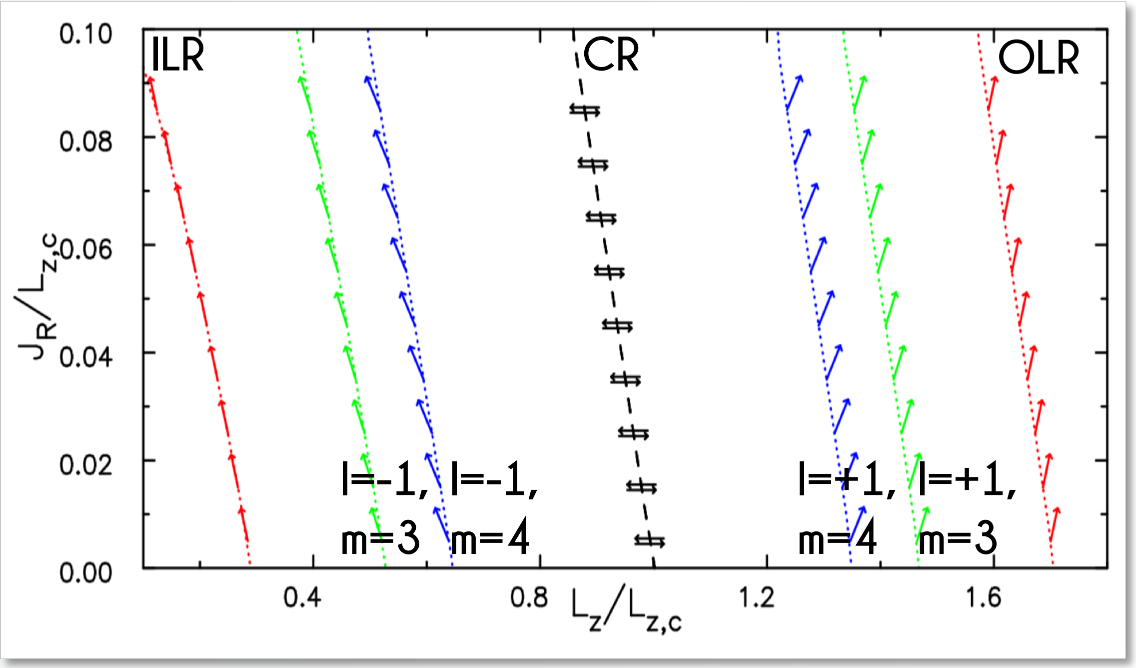
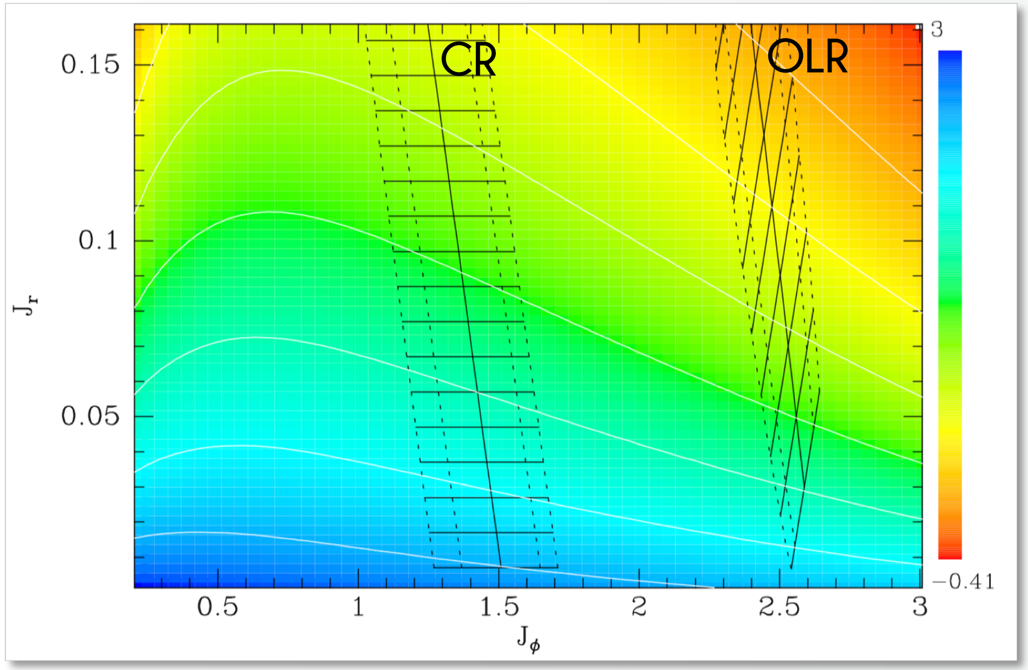


figure taken from Sellwood, Trick et al. (2019),
see also Sellwood & Binney (2002), Lynden-Bell & Kalnajs (1972)

from conservation of Jacobi energy:

$E_J = E - \Omega_p \times L_z = \text{const.} \rightarrow \Delta J_R = l/m \, \Delta L_z$

„Oscillation" around resonance lines
in axisym. action space



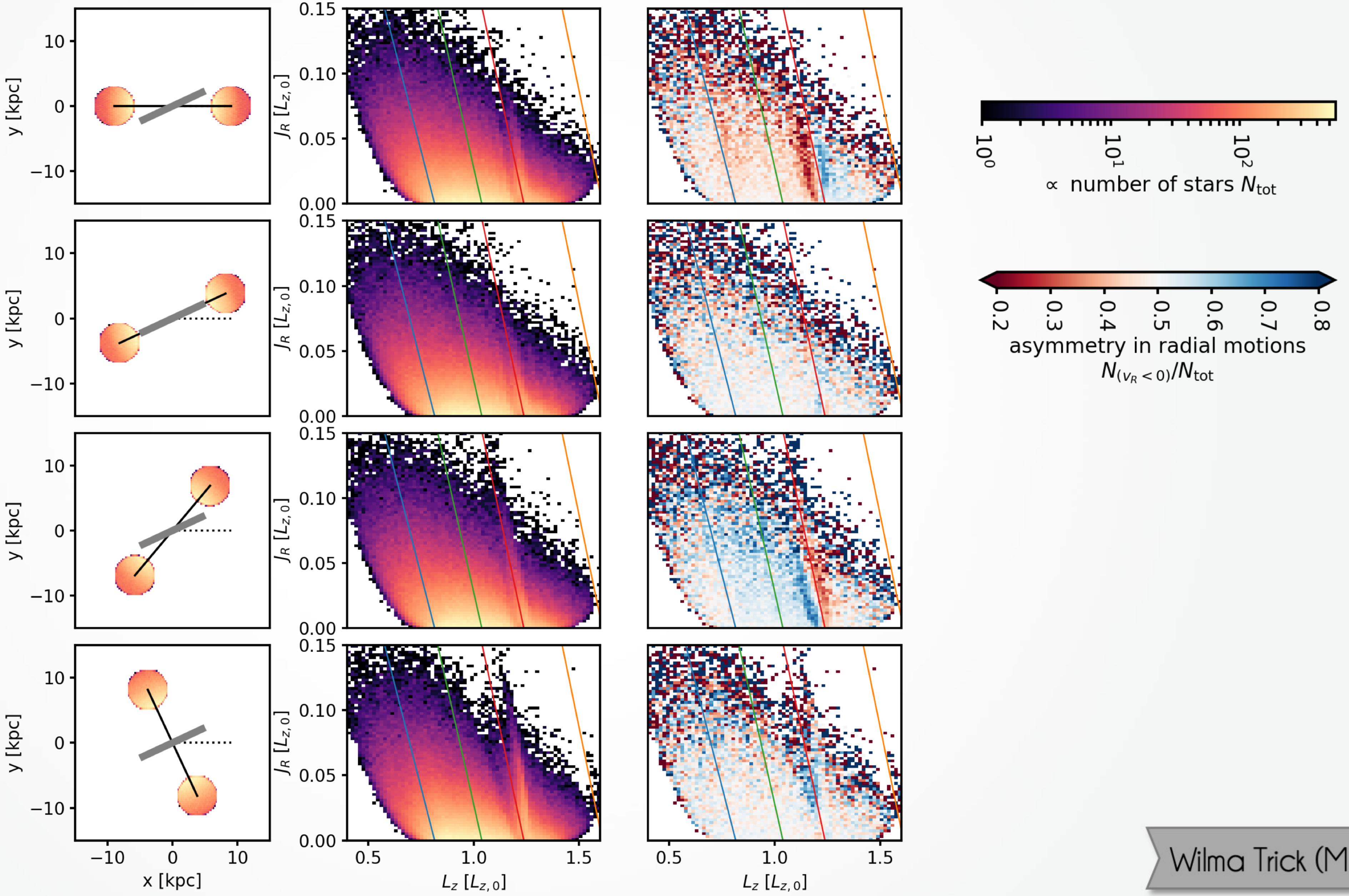
Binney (2018)

from perturbing axisymmetirc orbital tori
(actions & angles) in a bar potential

Location of Solar Volume With Respect to the Bar

Orbit integration time:
10 bar periods
= 1.8 Gyr

MOCK DATA



– CR
– OLR
– l=+2,m=2
– l=+1,m=4

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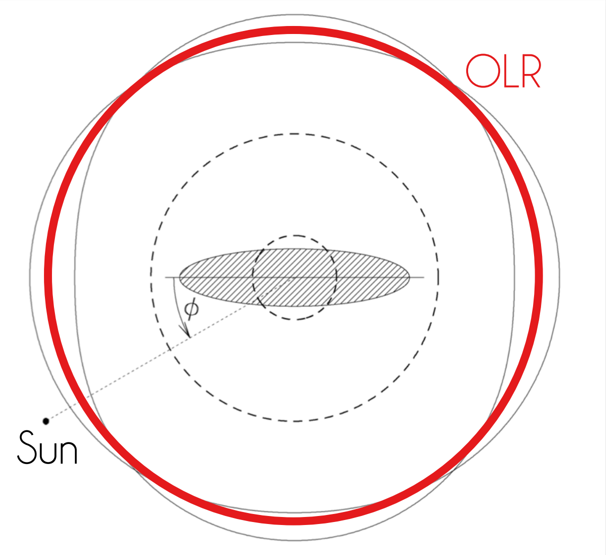
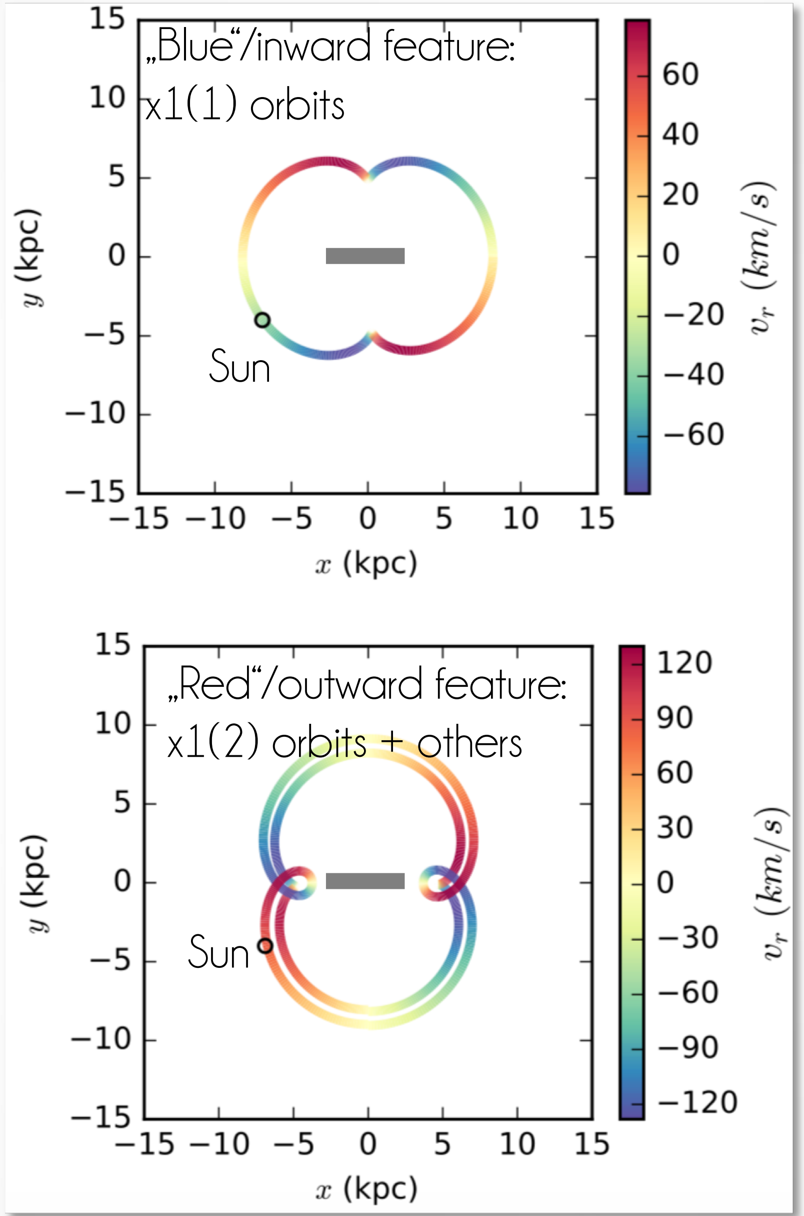
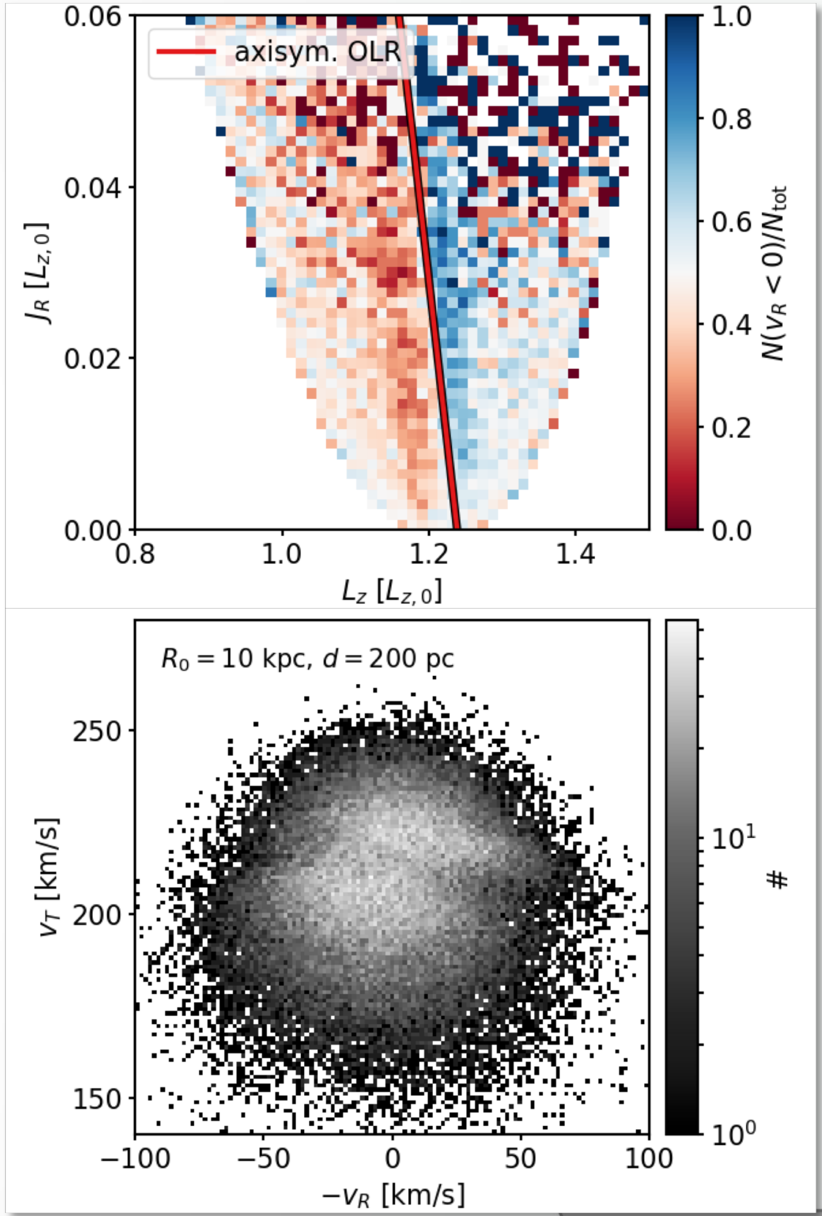
The outward-inward (red-blue) Signature of the OLR



Dehnen (2000)



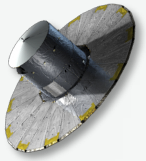
Fragkoudi,...,Trick,... et al. (2019)

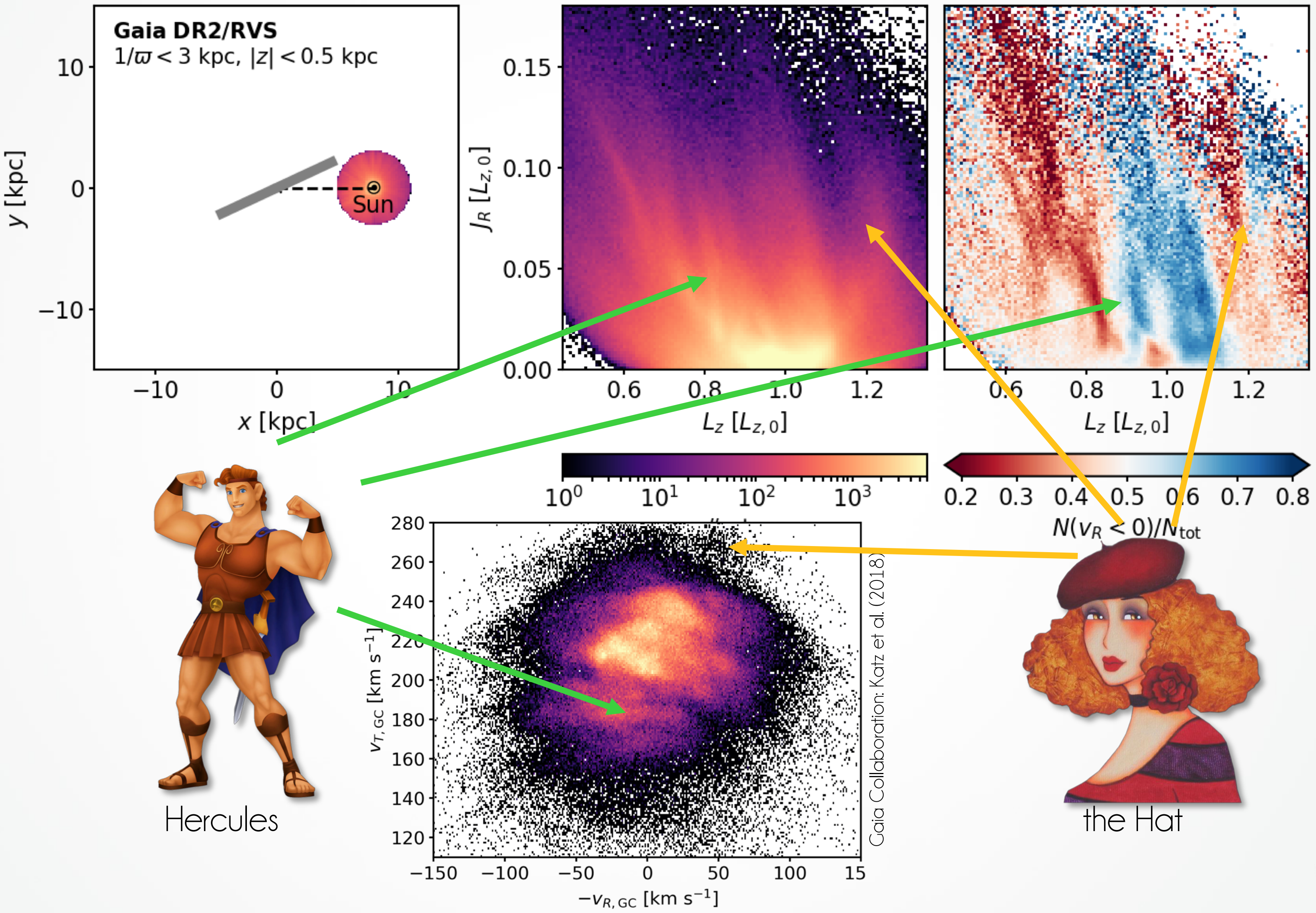


Trick et al. (in prep.)

Orbits flip their orientation at the axisym. OLR line.

Comparing Gaia DR2 to the Model





Bar resonances & axisym. Actions

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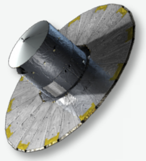
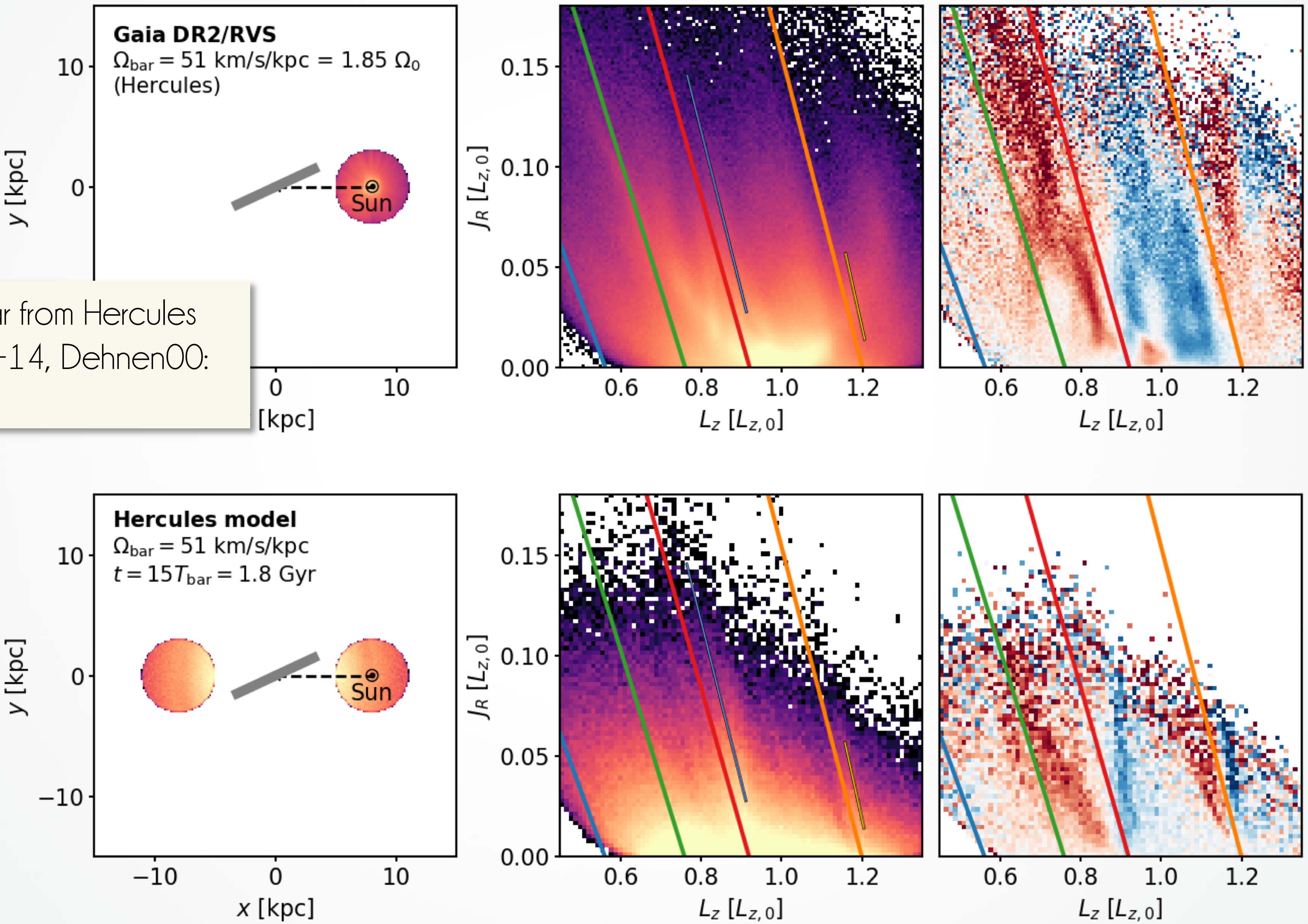
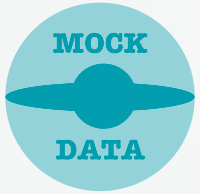
Assuming Bar OLR is Near Hercules

Bar resonances & axisym. Actions





very close to fast bar from Hercules modeling by Antoja+14, Dehnen00:
$\Omega_p \sim 1.8\ \Omega_0$



- CR
- OLR
- l=+2,m=2
- l=+1,m=4

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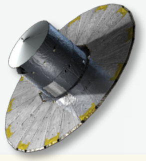
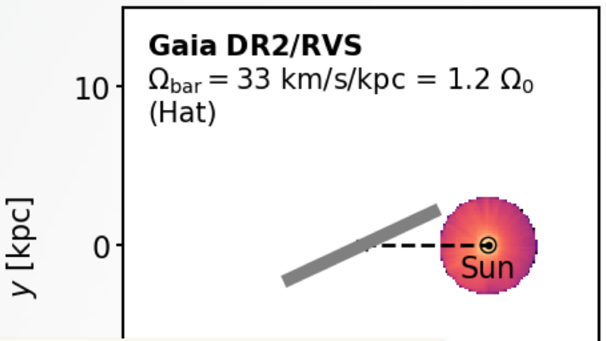
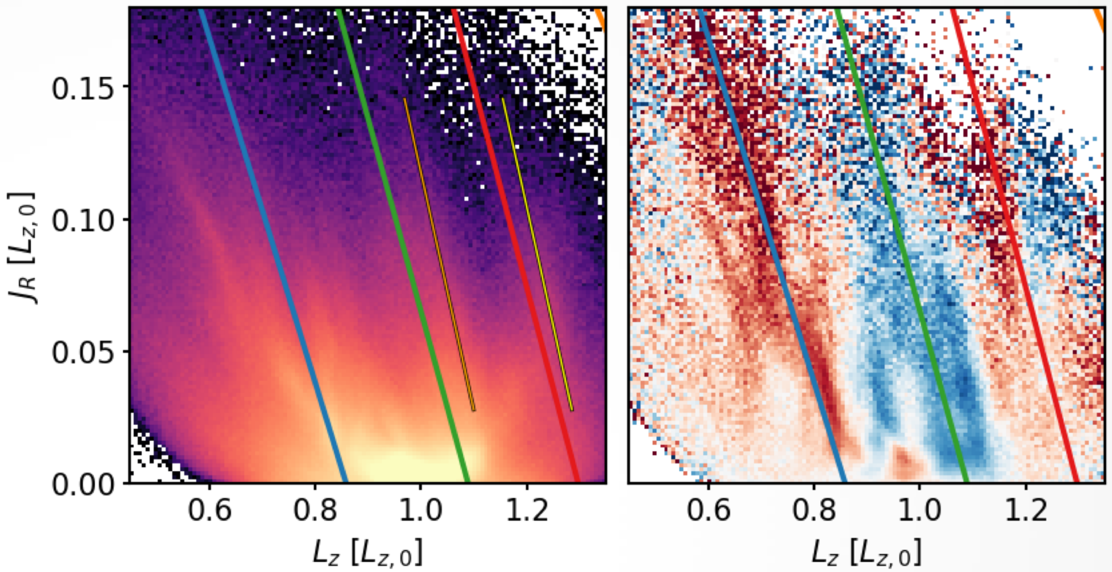
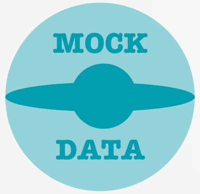
Assuming Bar OLR is Near the Hat

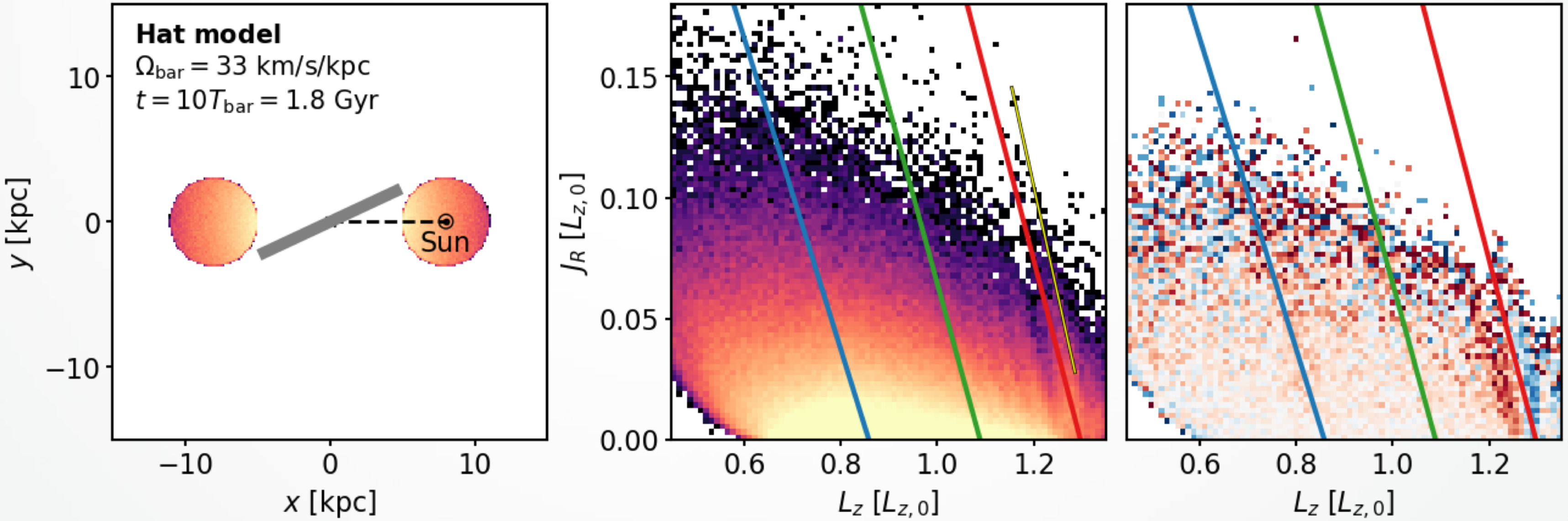






slightly lower than the slow bar $\Omega_p \sim 1.3\ \Omega_0$
as found by Sanders+19 & Clarke+19
from kinematics in the Gal. center
(similar labeling of action space in Monari+18)





- CR
- OLR
- l=+2,m=2
- l=+1,m=4

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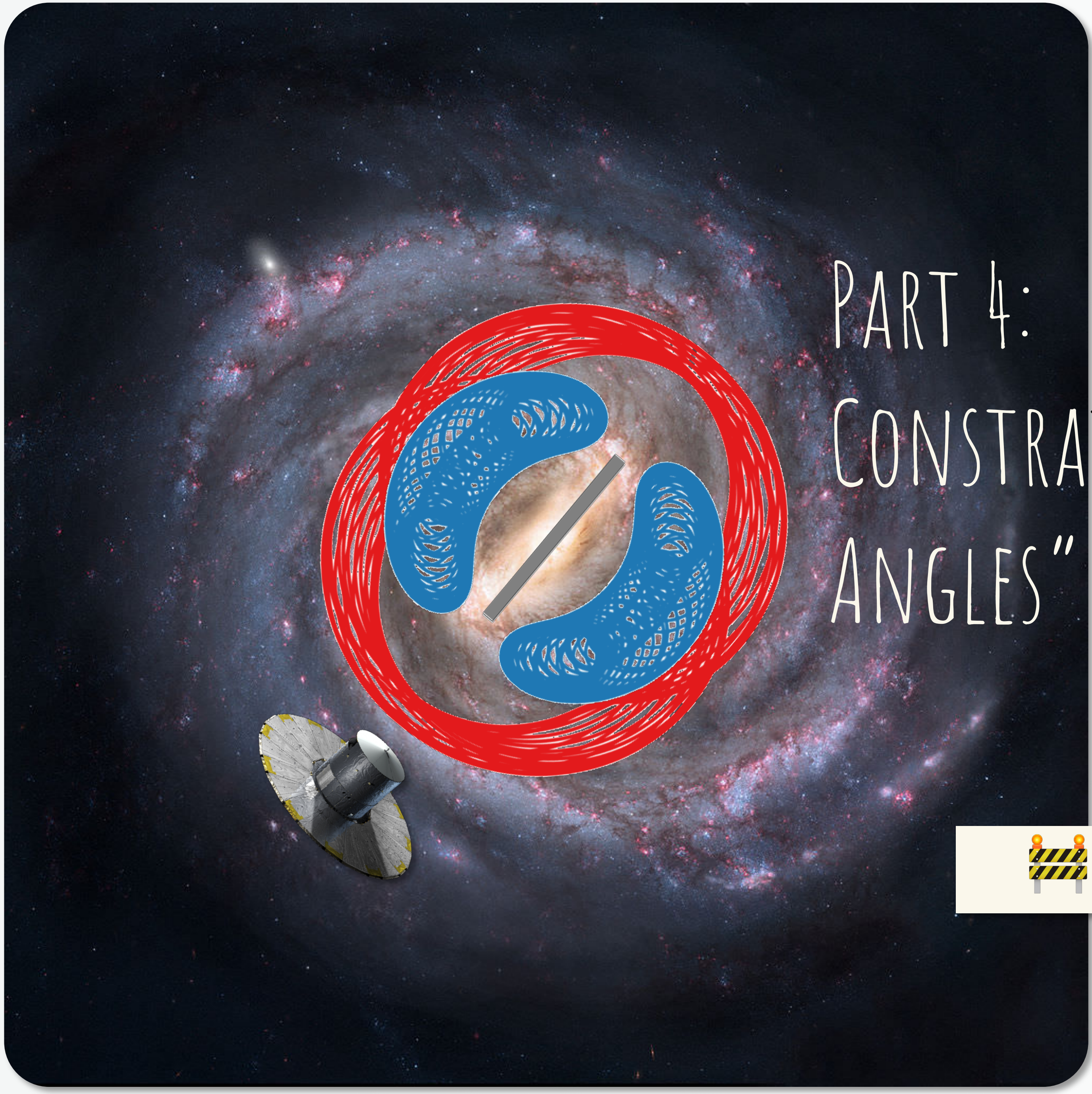


Part 4: Constraints from the „Axisym. Angles" on the Galactic Bar

🚧 Work in progress... ⚒️

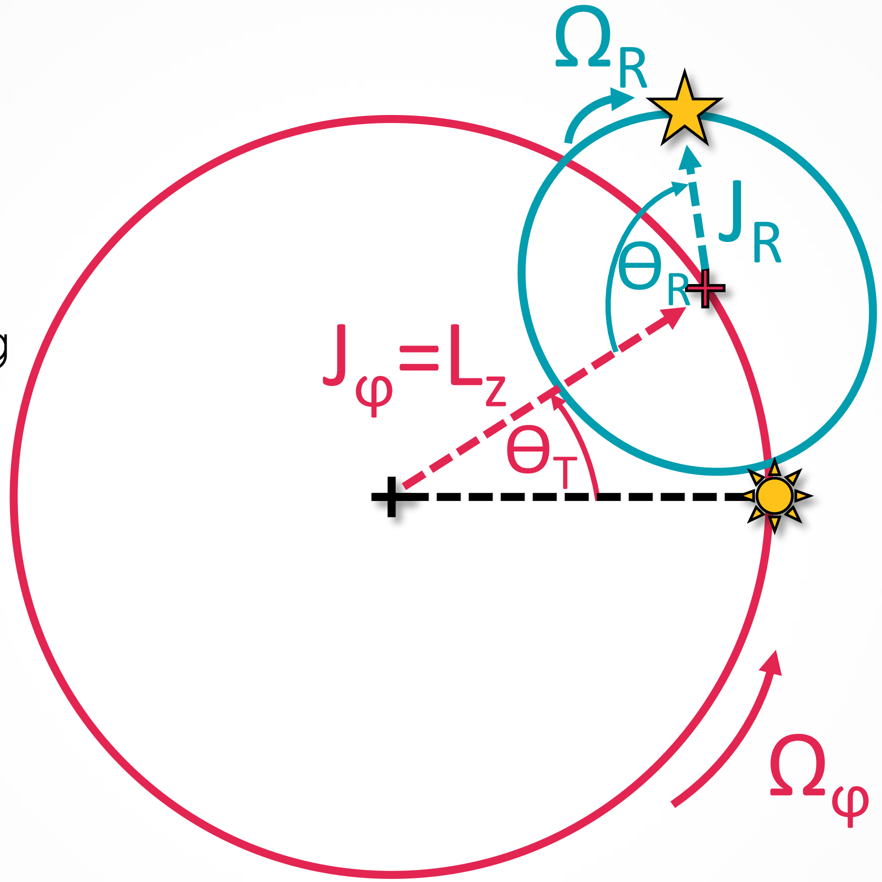
Angle Coordinates (explained with Epicycles)

$\theta_R = 0$: pericenter

$\theta_R > 0$: outward moving

$\theta_R = \pm\pi$: apocenter

$\theta_R < 0$: inward moving



$\theta_T = 0$: azimuth of the Sun

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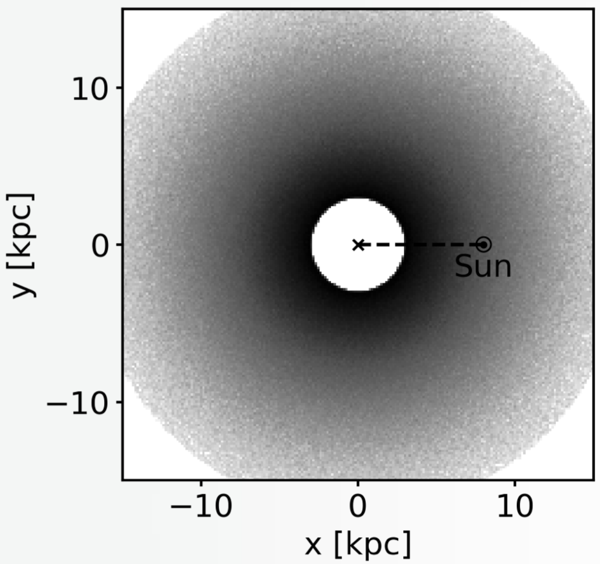
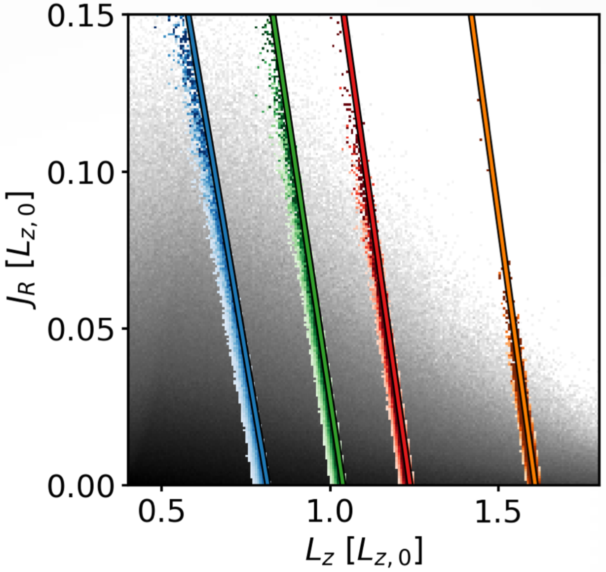
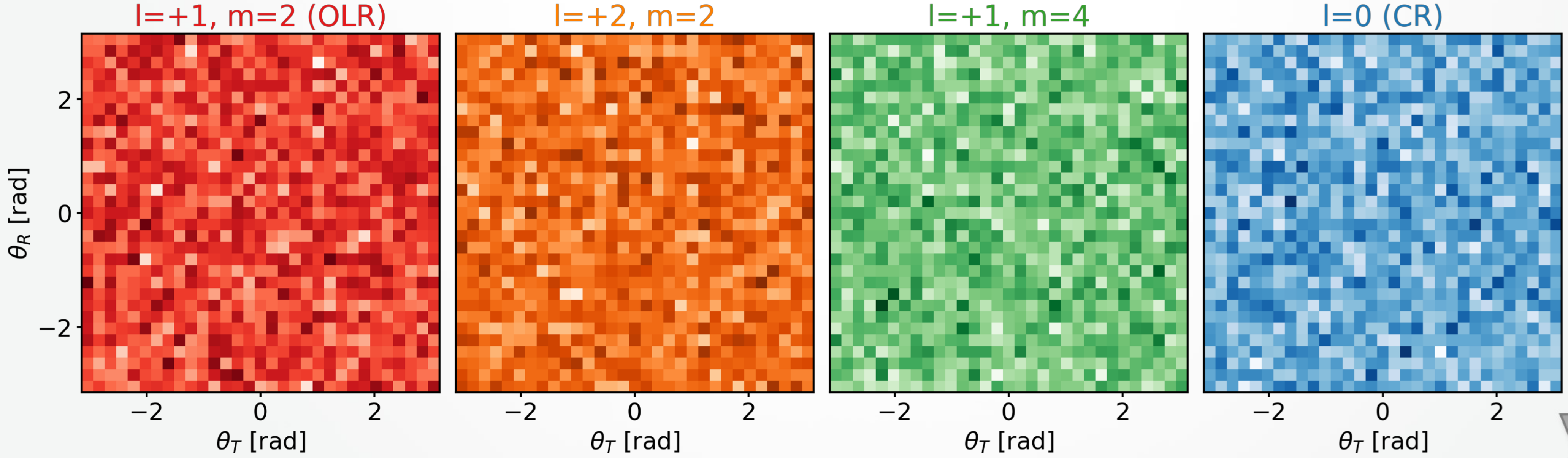
Angle Space of Axisymmetric Mock Data





- Time: **before the bar**
- Stars: **along resonance lines**



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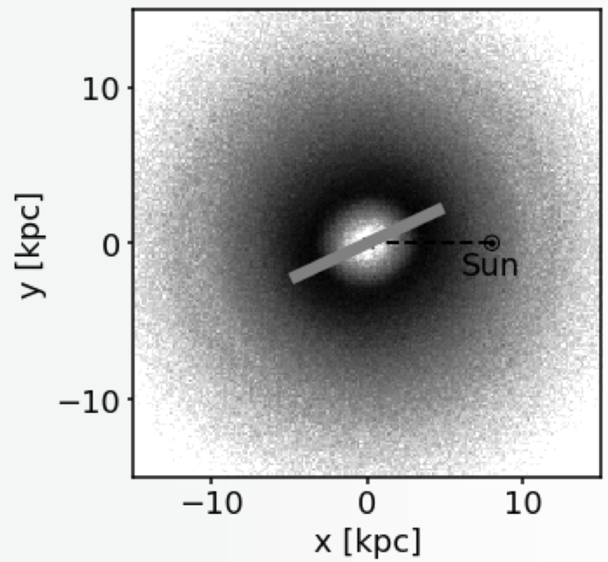
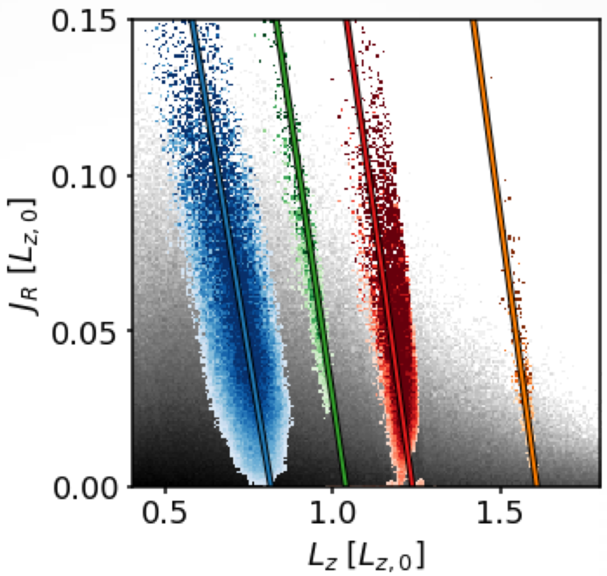
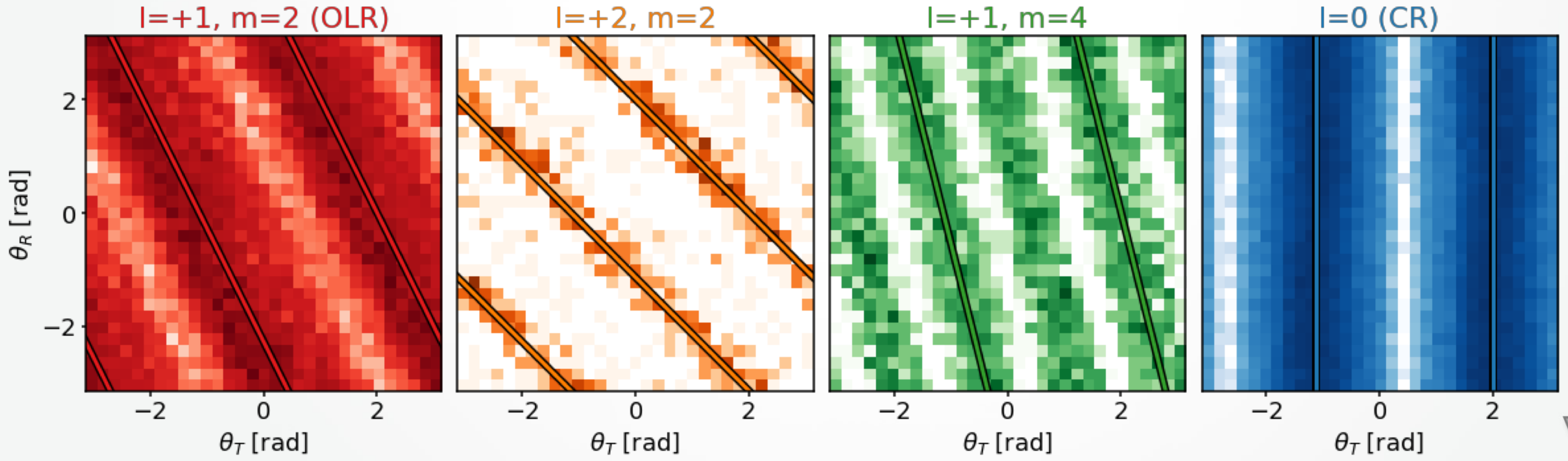
Angle Space for Stars Integrated in Bar Potential

- Time: "today"
- Stars: "real" resonant stars



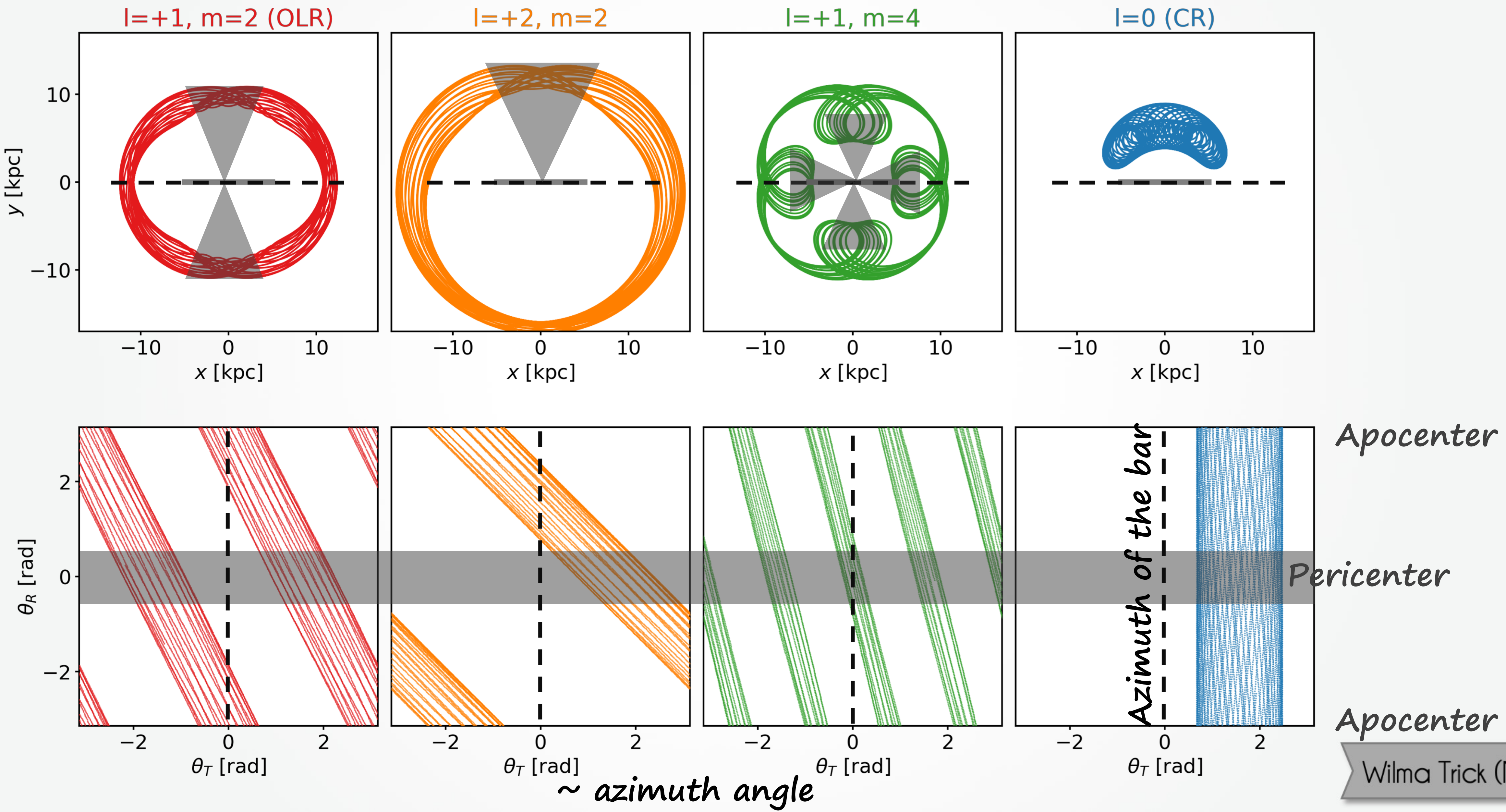


angle distribution follows predicted slope: **-m/l**
--> use to decide which resonance!?



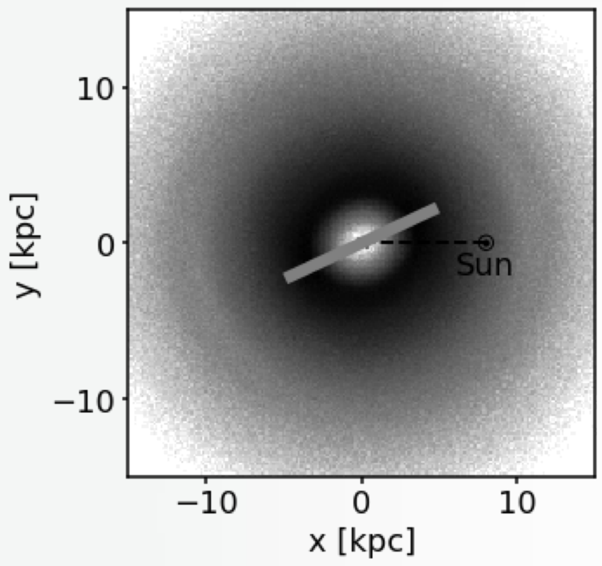
see also
Sellwood (2010)

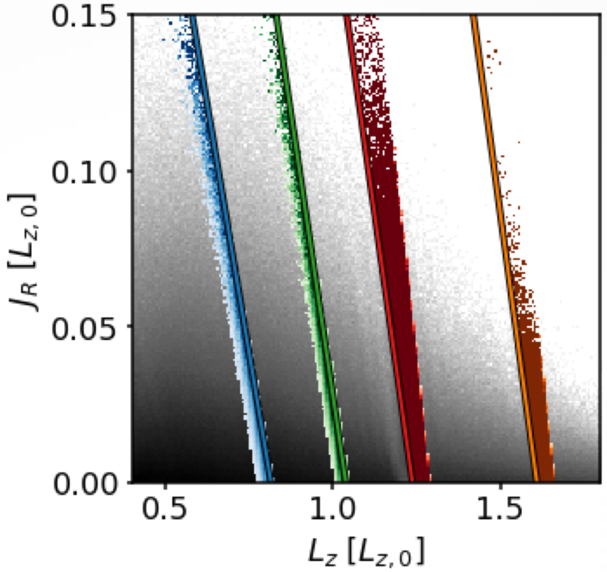
Resonant Orbits in Angle Space



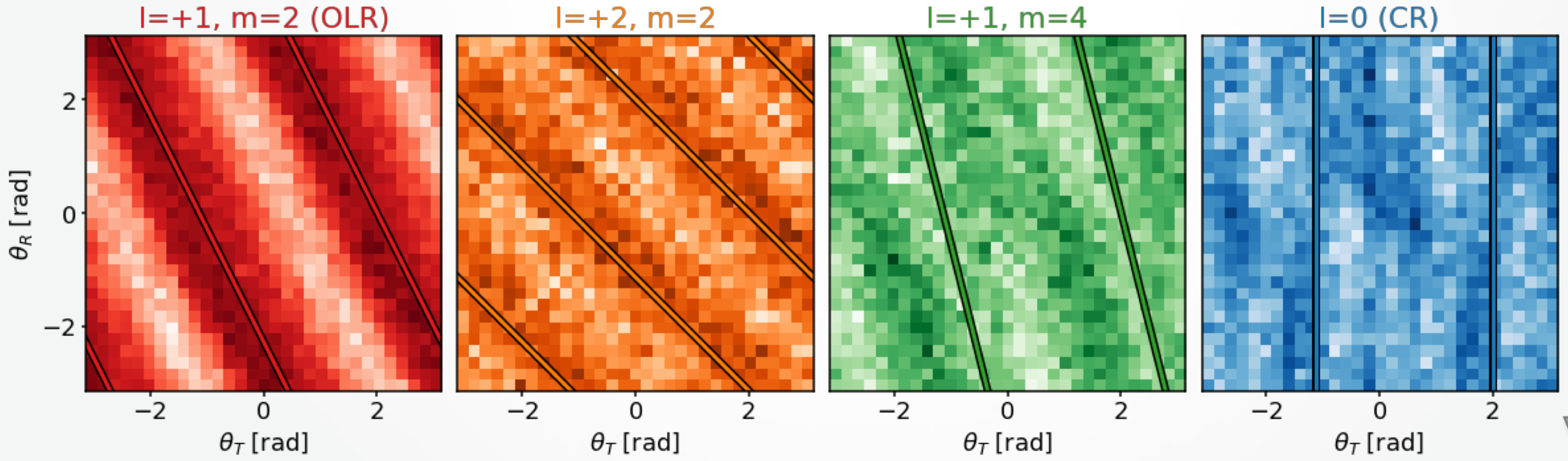
Wilma Trick (MPA)

Angle Space for Stars selected at the Resonances

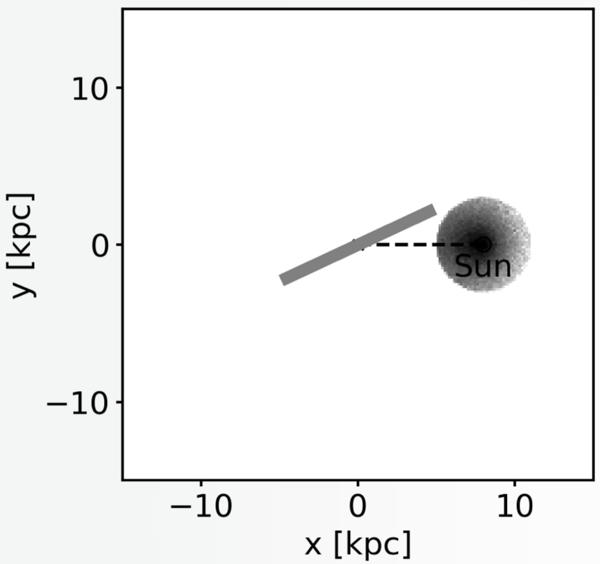


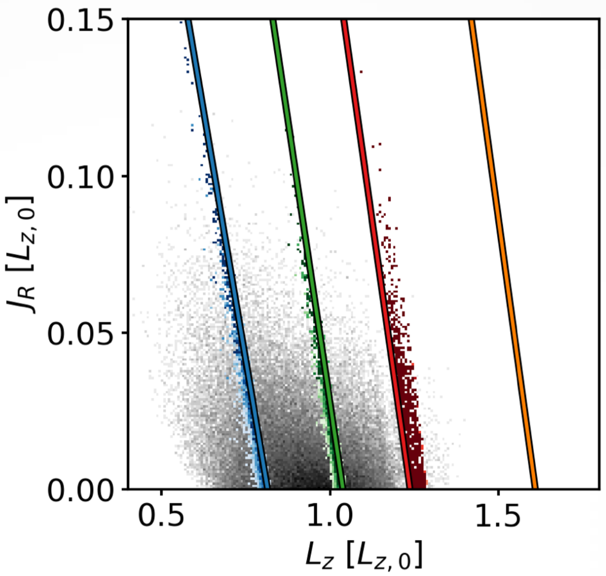


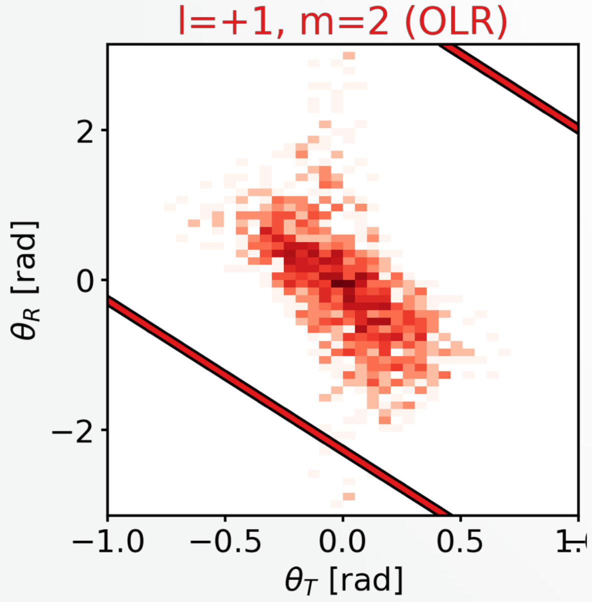
- Time: "today"
- Stars: **selected by hand in action space → hoping to capture resonant stars**



Angle Space & Selection Effects



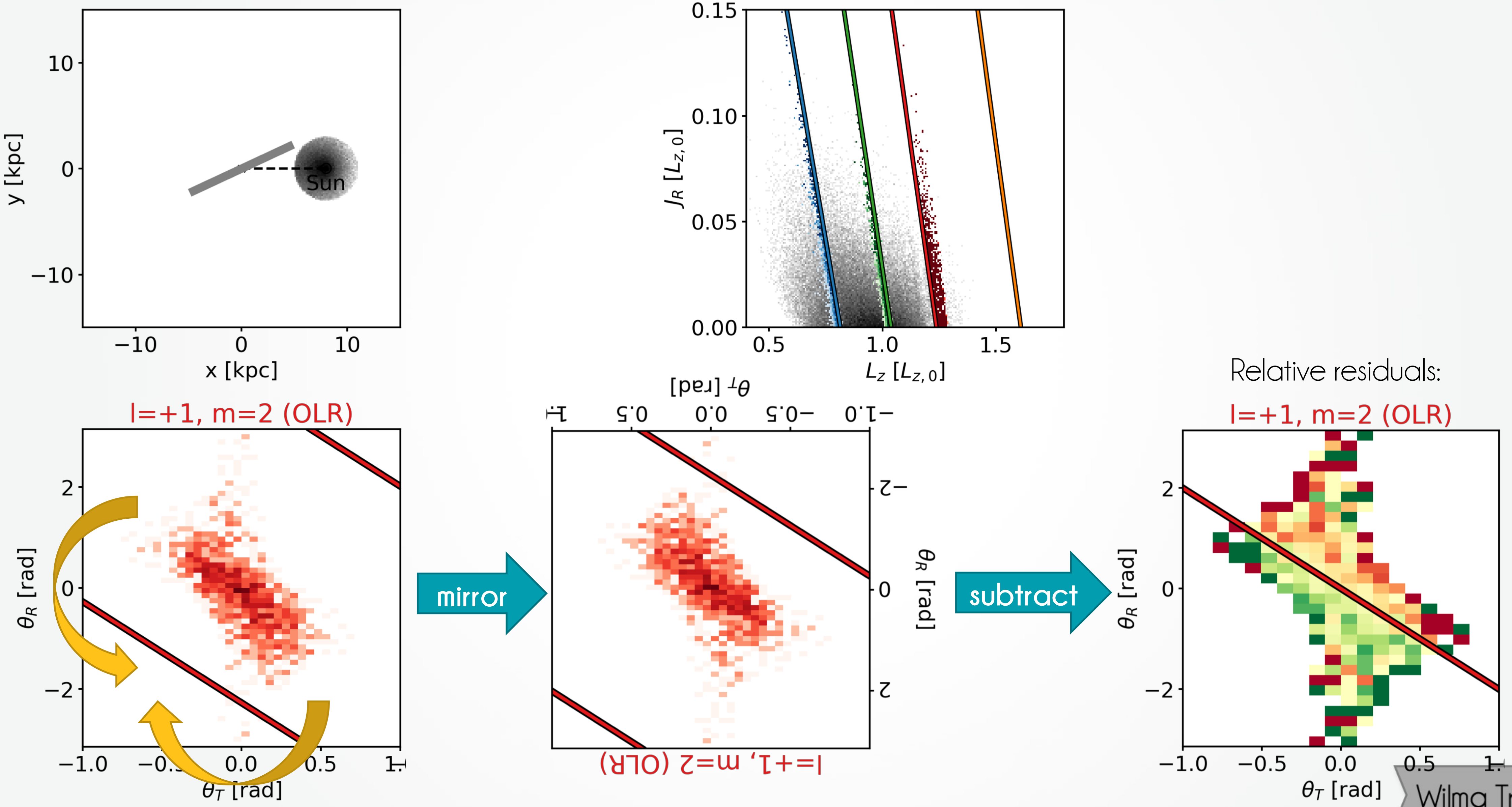




- Time: **"today"**
- Stars: **picked by hand in action space**
- Selection: **3 kpc sphere + exponential decrease of completeness with distance from Sun**

see also McMillan (2013)

Idea: How to deal with the Selection Effects



Bar esonances & axisym. Angles

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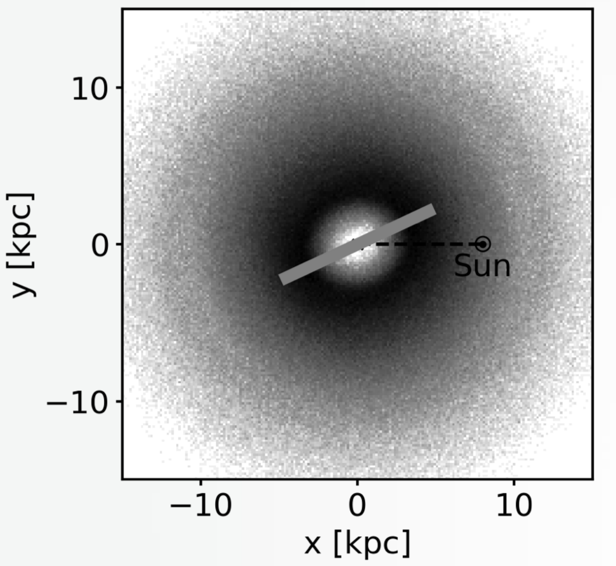
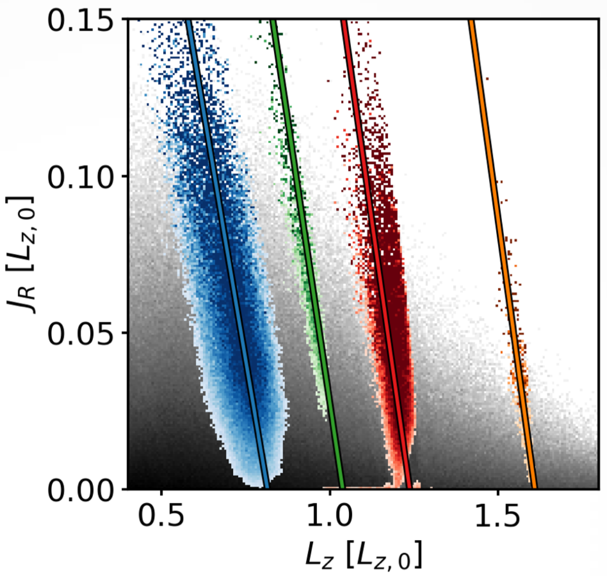
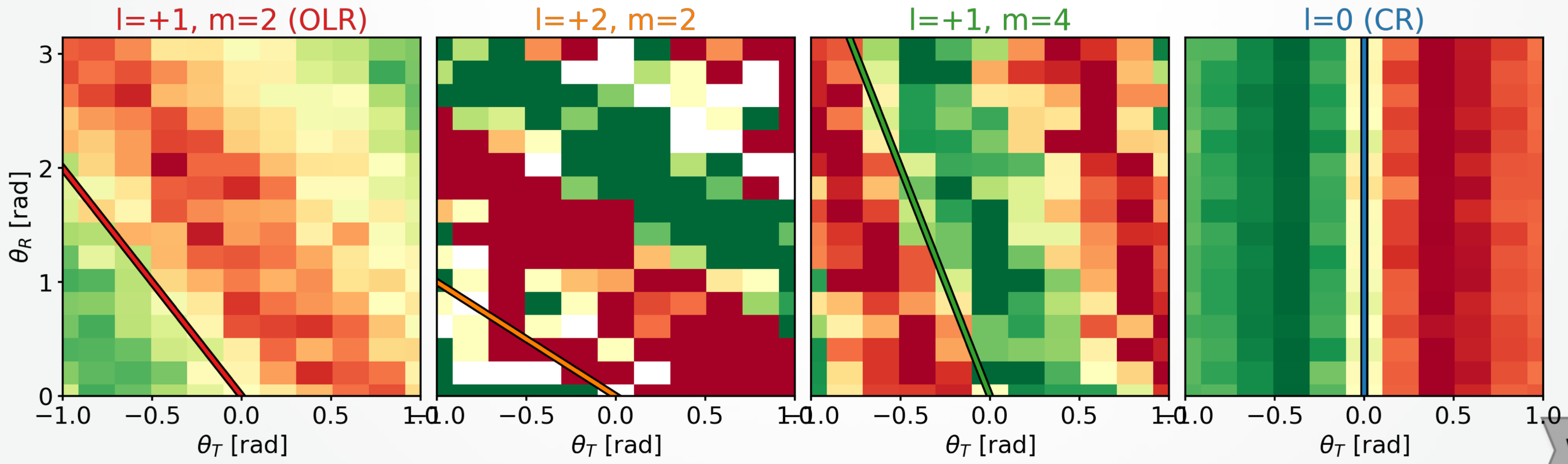
Idea: How to deal with the Selection Effects

Bar resonances & axisym. Angles







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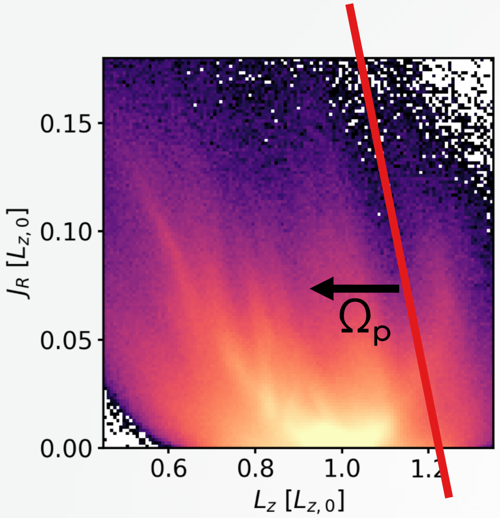
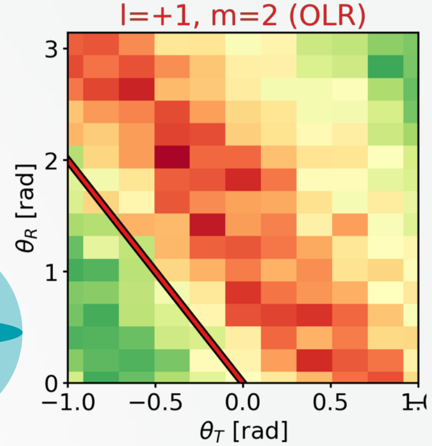
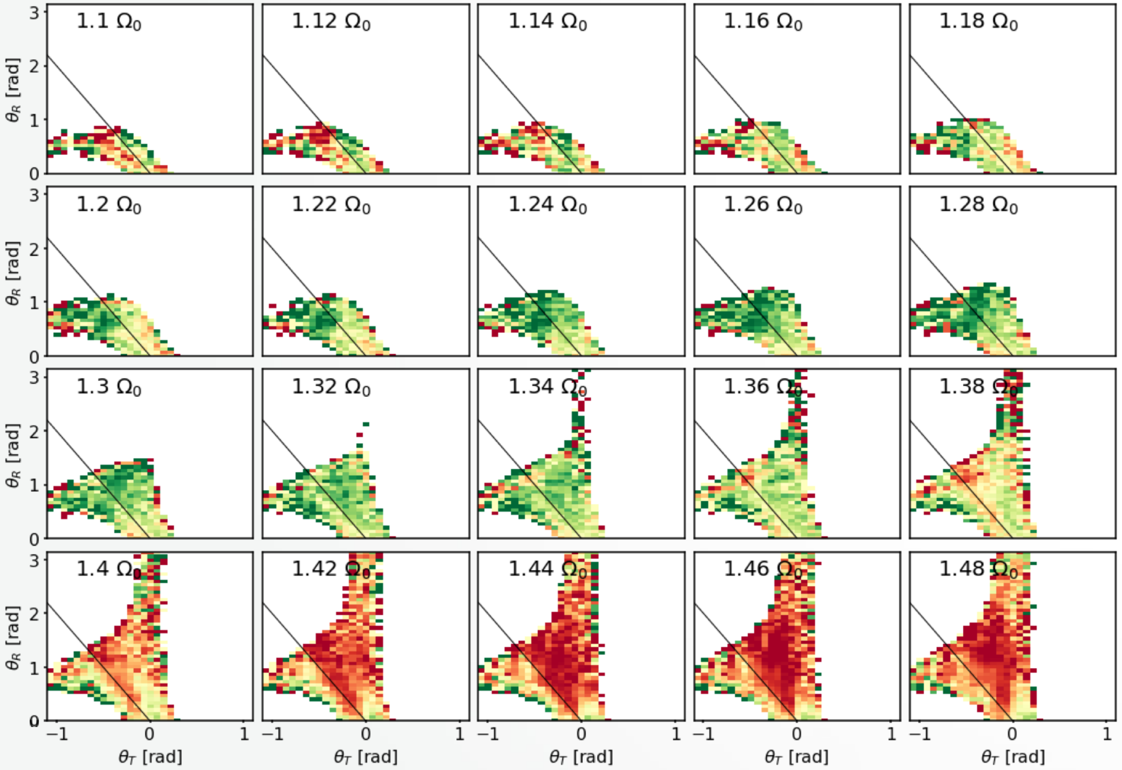
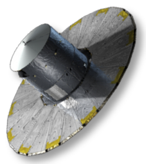
Angle Space at the OLR assuming a Pattern Speed

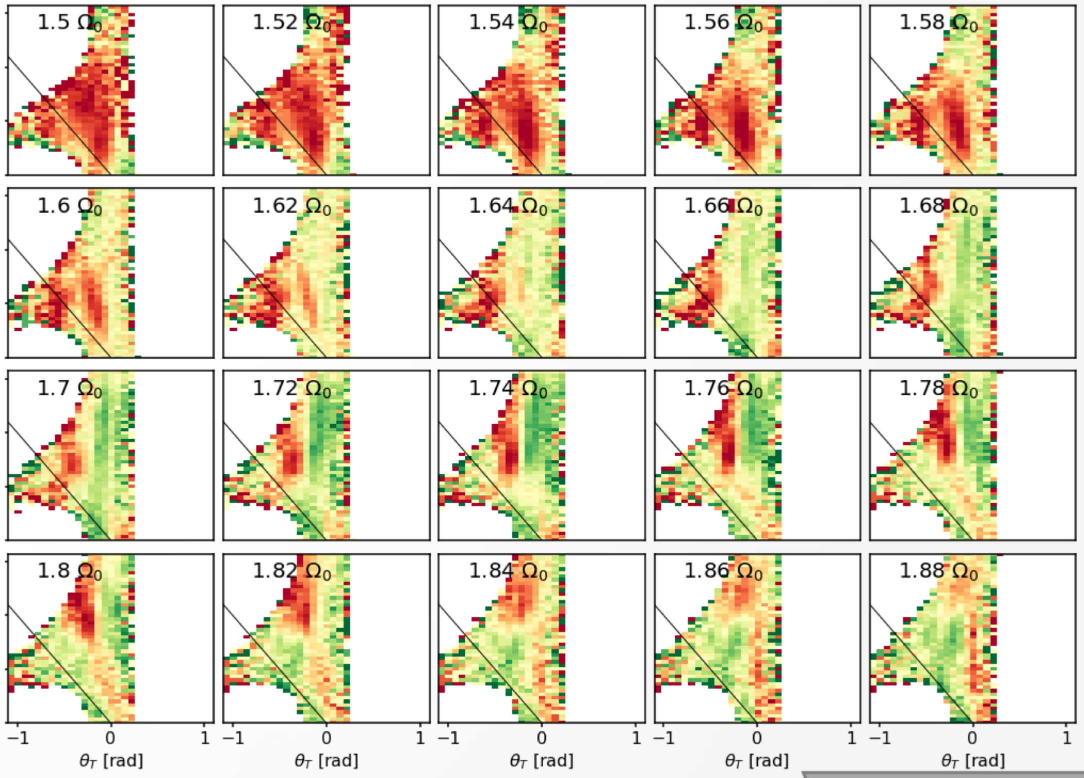


MOCK DATA



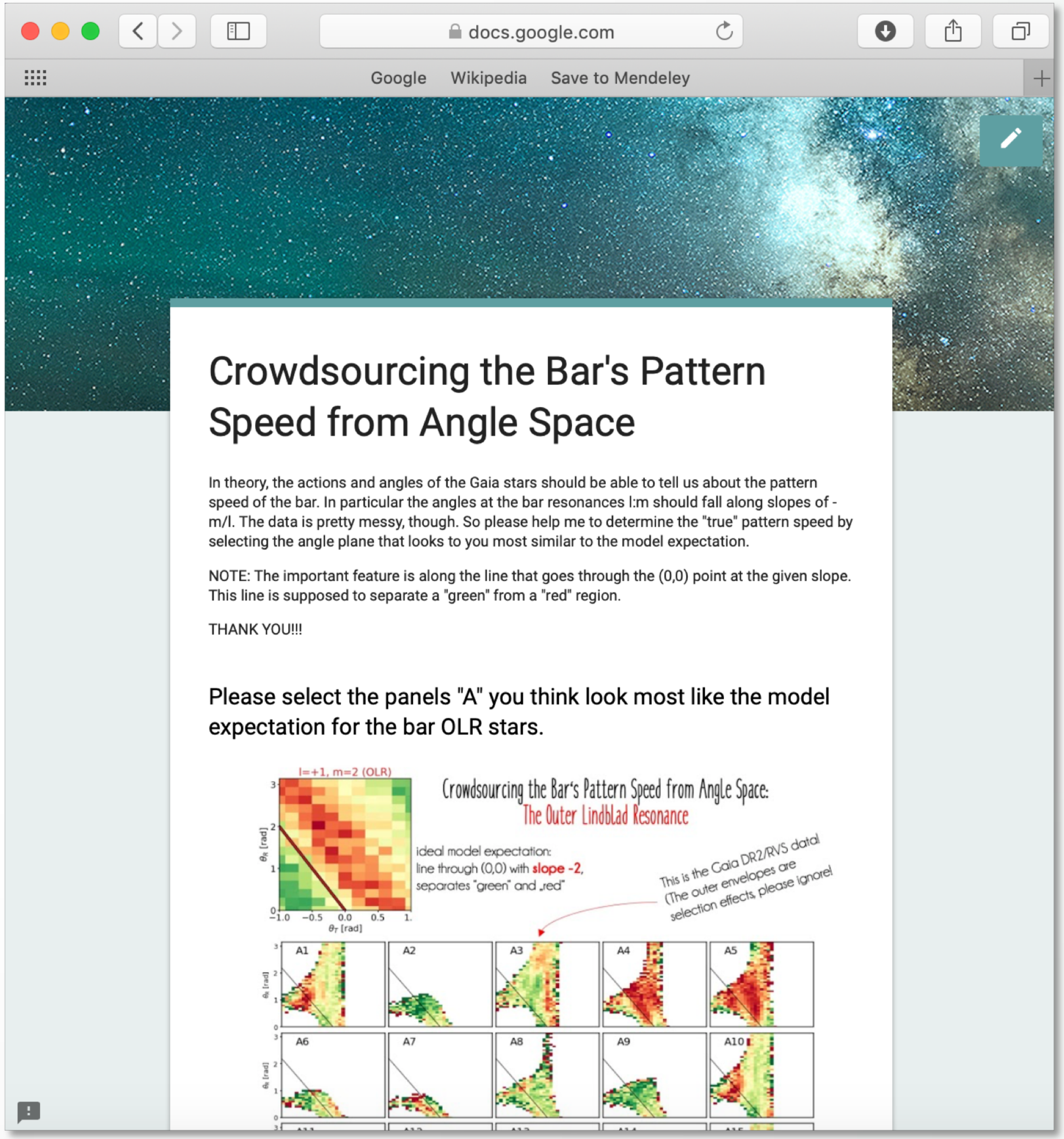






Crowdsourcing the Bar's Pattern Speed from the Axisymmetric Angles

https://goo.gl/n2omwv



Crowdsourcing the Bar's Pattern Speed from Angle Space

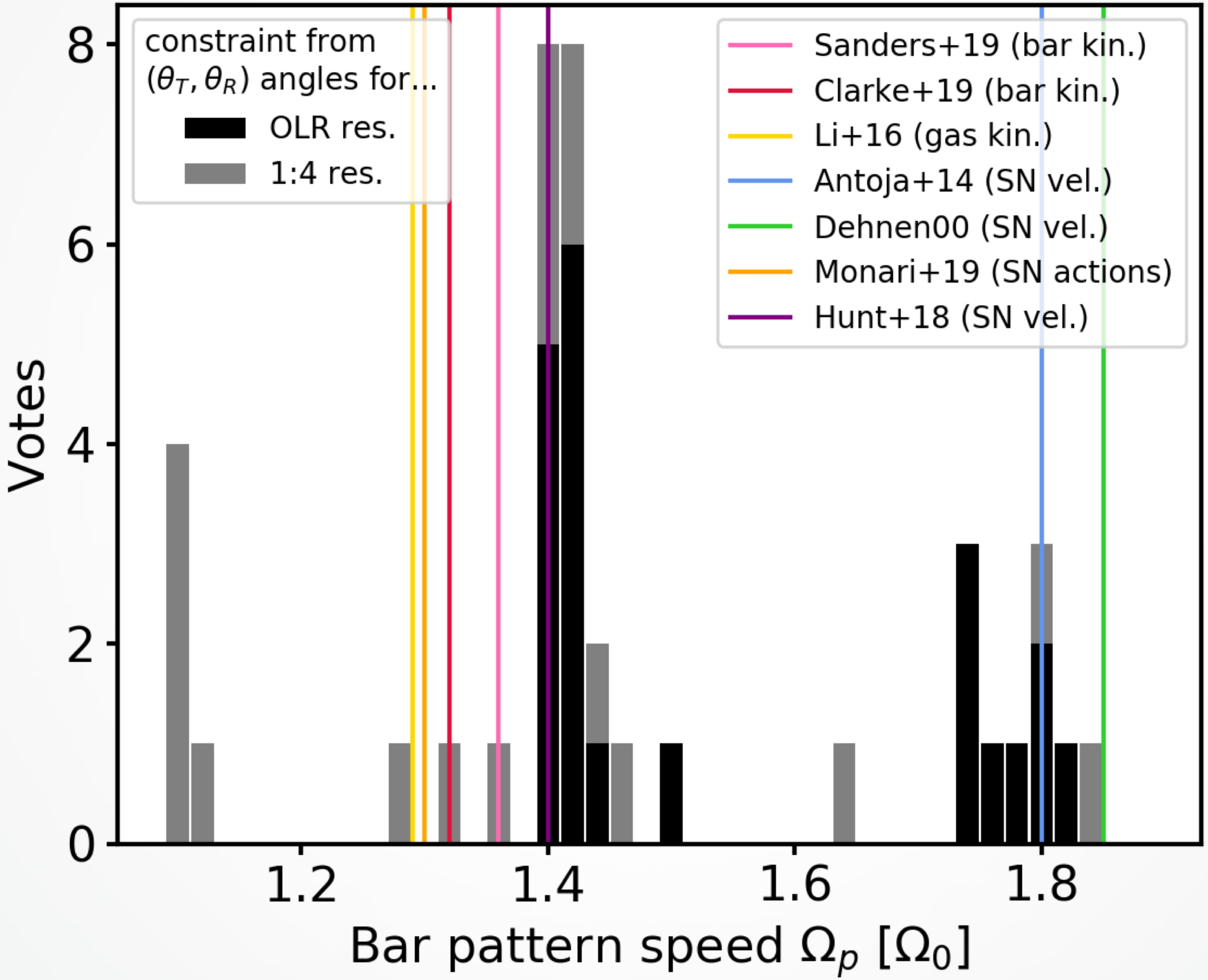
In theory, the actions and angles of the Gaia stars should be able to tell us about the pattern speed of the bar. In particular the angles at the bar resonances l:m should fall along slopes of -m/l. The data is pretty messy, though. So please help me to determine the "true" pattern speed by selecting the angle plane that looks to you most similar to the model expectation.

NOTE: The important feature is along the line that goes through the (0,0) point at the given slope. This line is supposed to separate a "green" from a "red" region.

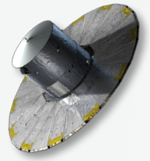
THANK YOU!!!

Please select the panels "A" you think look most like the model expectation for the bar OLR stars.

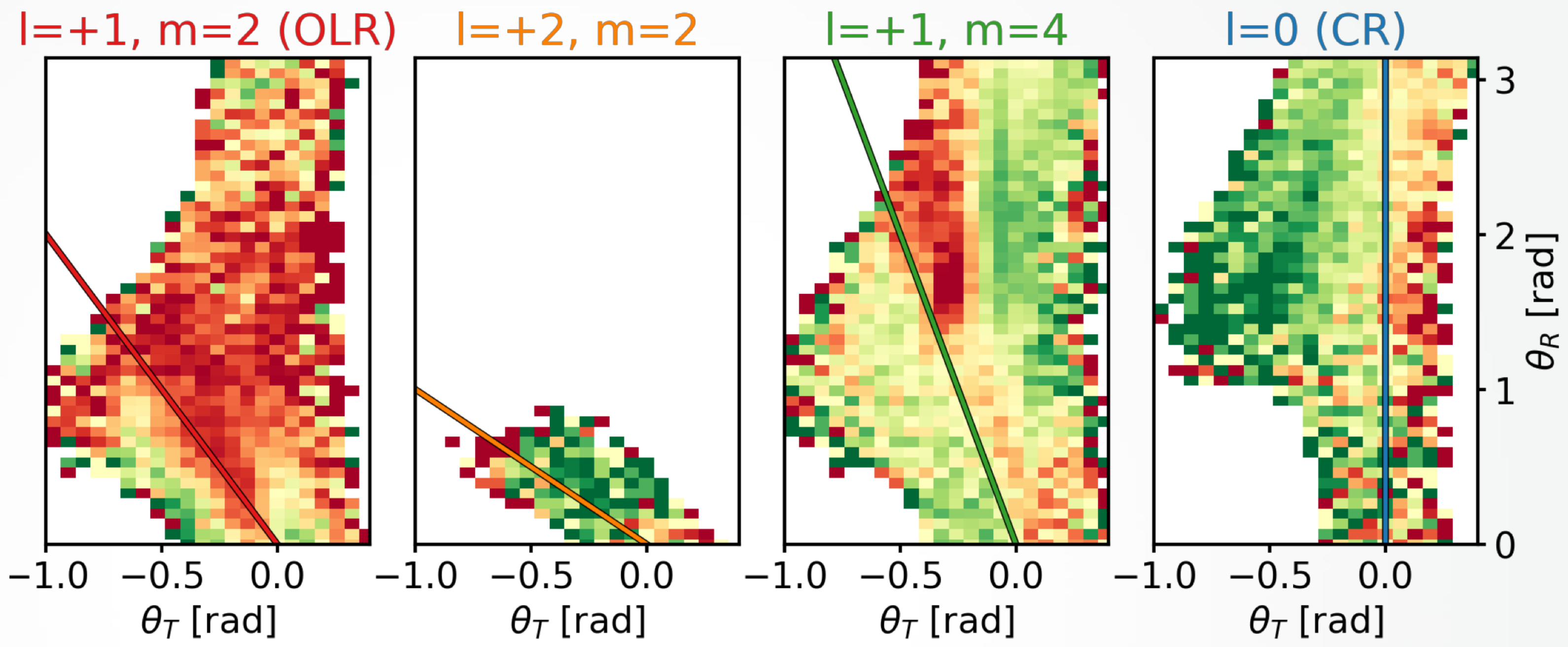
Crowdsourcing the Bar's Pattern Speed from the axisymmetric Angles

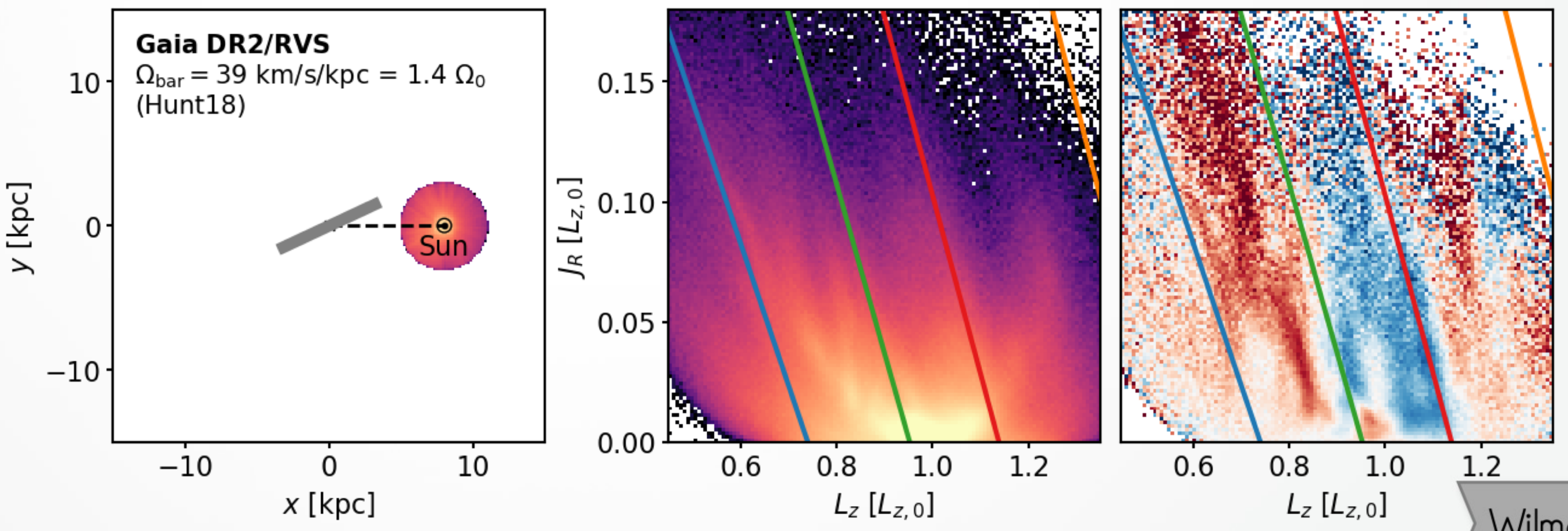


Crowdsourcing the Bar's Pattern Speed from the axisymmetric Angles



very close to model by Hunt+18
(Hercules caused by 1:4 bar res.):
$\Omega_p \sim 1.4\ \Omega_0$





– CR
– OLR
– l=+2,m=2
– l=+1,m=4

Wilma Trick (MPA)

Summary: The Bar in Gaia DR2's Action-Angles

- The space of axisymmetric actions (L_z,J_R) of Gaia DR2 reveals...
  ... a system of **orbit sub-structure that extends out to 1.5 kpc** from the Sun
  ... asymmetric radial motions

  Trick, Coronado, & Rix (2019)

- The space of axisymmetric angles (Θ_T, Θ_R) in Gaia DR2 **surprisingly prefers the bar model by Hunt** et al. (2018). *Trick et al. (in preparation)*

- The **OLR** of the bar is expected to cause an „outward-inward" feature in action space.

  Fragkoudi, [...],Trick et al. (2019)

  Simple comparison to the **Gaia DR2 data proposes two bar models close to the existing** fast (e.g. Antoja et al. 2014) and slow (e.g. Portail et al. 2015) bar models.

  Trick, Fragkoudi, Hunt, Sellwood, Mackereth, White et al. (to be submitted)

- I am optimistic that **dynamical modeling with axisymmetric actions / angles / frequencies** can and will be still super interesting after Gaia DR2. 😊👍