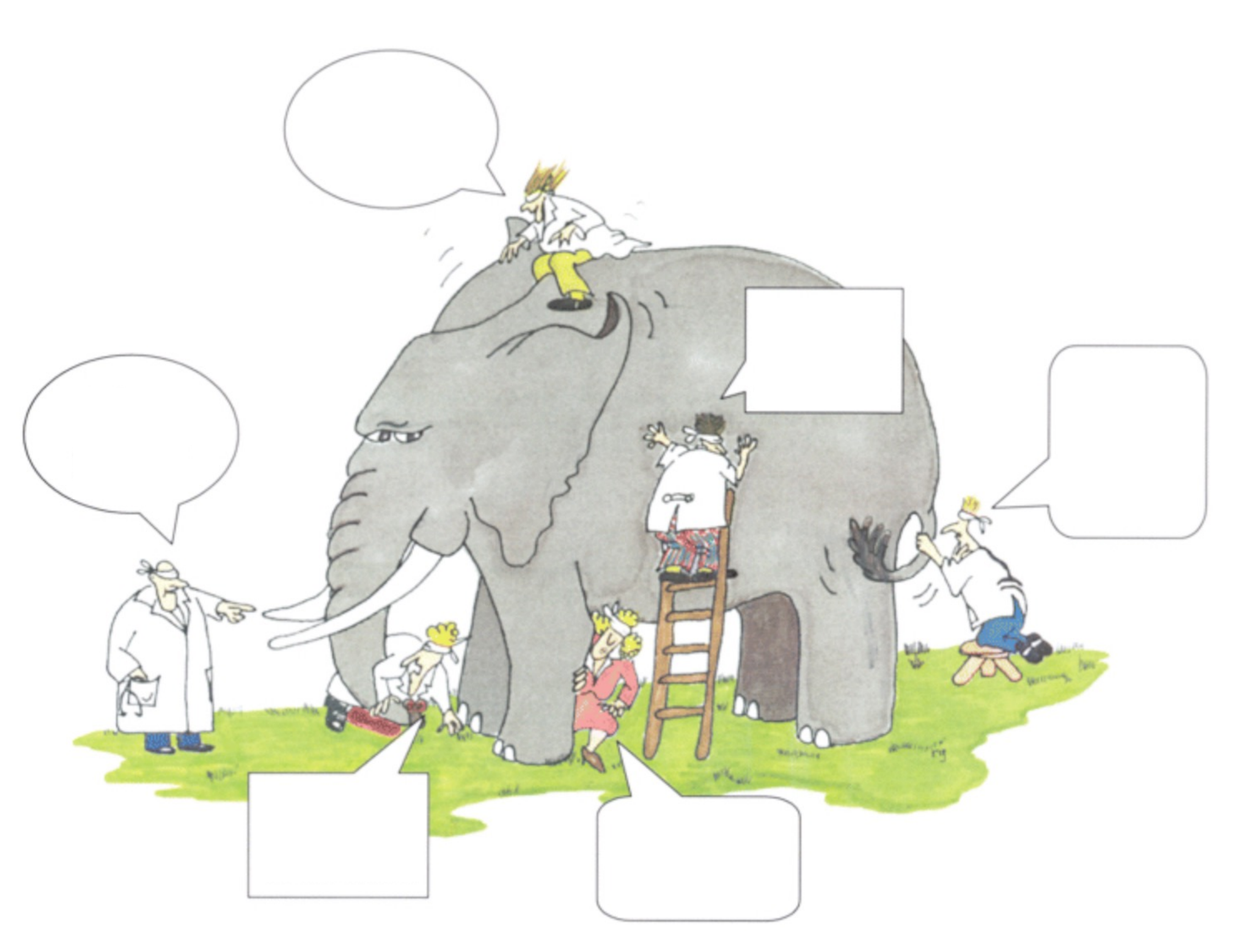
Agreeing on the elephant

Milky Way dynamics in the Gaia era

Paul McMillan
(Lund Observatory, Division of Astrophysics)
(Collabs: Simon Alinder, Thomas Bensby, Viktor Hrannar Jönsson, Jonathan Petersson, Thor Teppar-Garcia, Joss Bland-Hawthorne, Teresa Antoja and the Gaia EDR3 anicentre paper team, Gaia DPAC)

@McMillan_Astro
@LundObservatory

Galactic dynamics in the Gaia era (an artist's impression)



Picture credit: Unknown

Why the confusion?

Milky Way is a fairly average Galaxy…

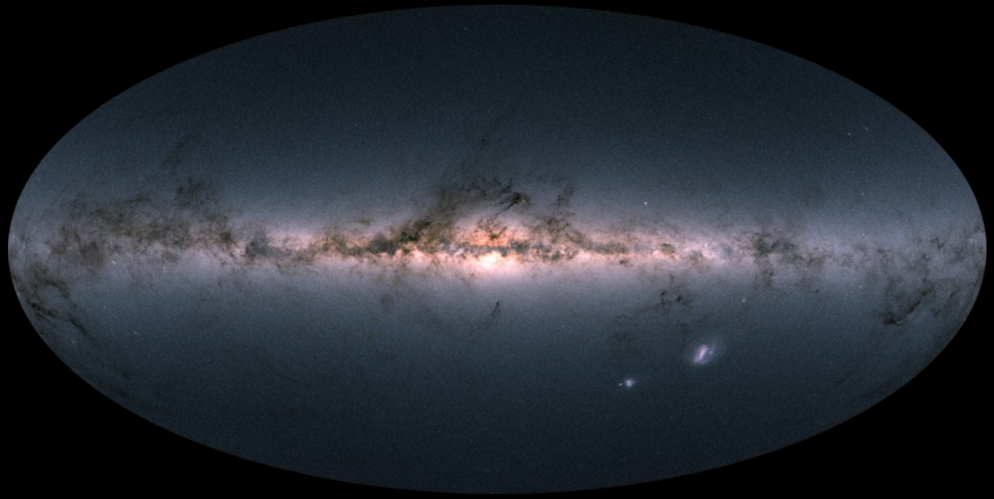
… but the way we view it is unique

<u>BIG advantages:</u>

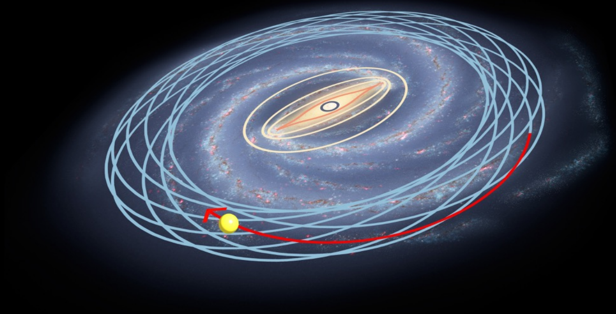
6D phase-space data, detailed chemical abundances on star-by-star basis.

<u>Important disadvantage:</u>

We can’t see it from the outside!



ESA/Gaia/DPAC

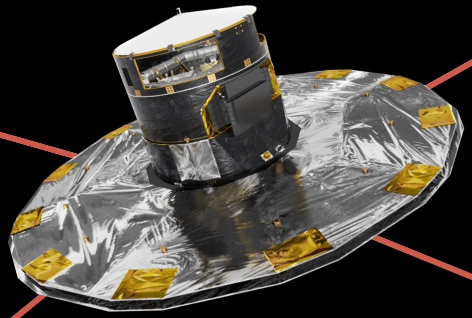


Adapted from NASA/JPL/Hurt image

Gaia DR3 contains:

Astrometry & photometry
1.5 billion
brightness, colour, parallax & proper motion

Line-of-sight velocity
33 million

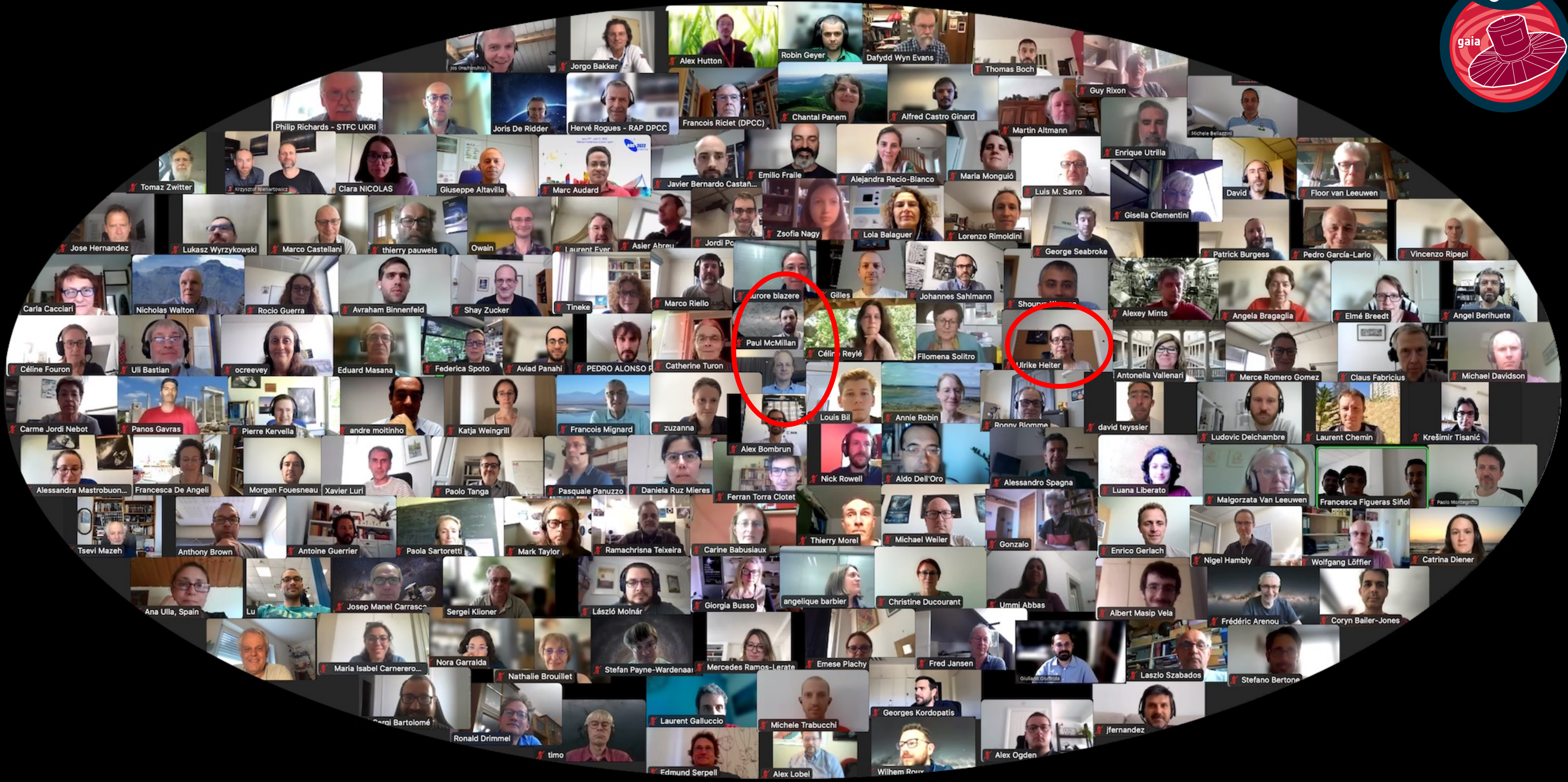


Low resolution spectroscopy

470 million
astrophysical parameters (AP)

'High' resolution spectroscopy

5.6 million AP



esa gaia

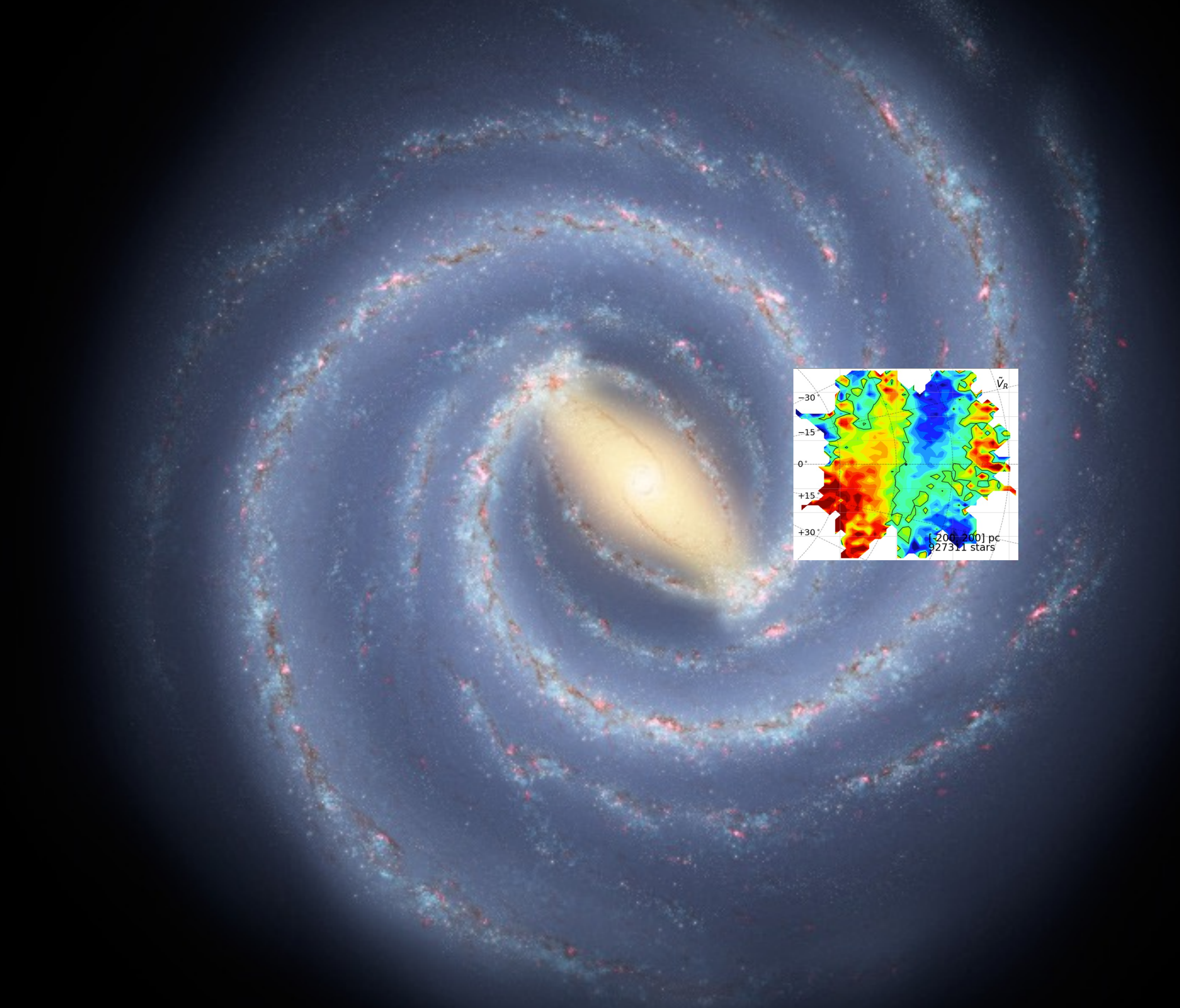
Gaia DPAC

The disturbed Milky Way

The Milky Way is not a simple smooth object

We know it has spiral arms & a bar

Gaia has measured associated velocity disturbance (Gaia Collaboration: Katz et al 2018)



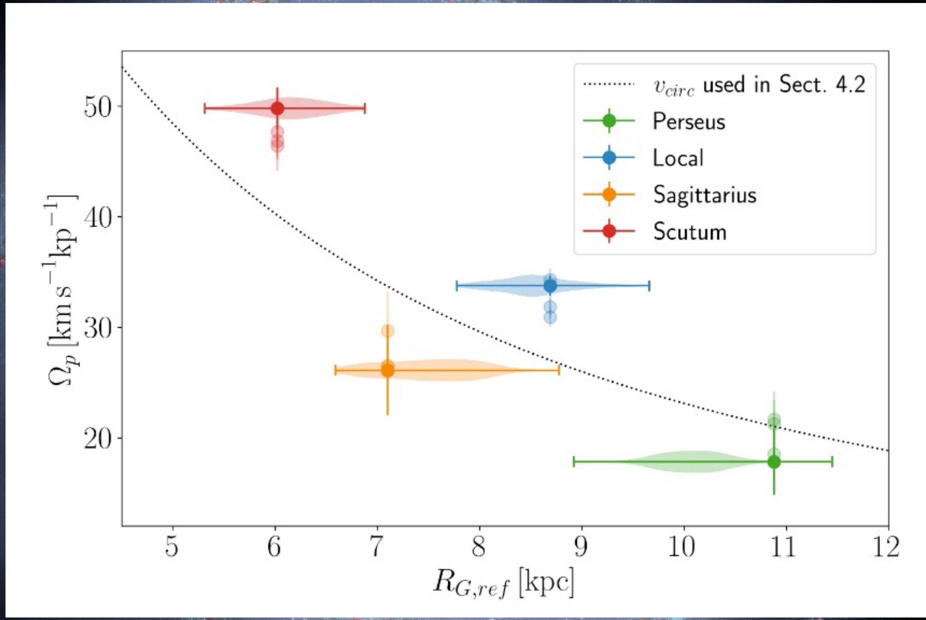
This is not a photo!
Credit: NASA/JPL-Caltech/R. Hurt

Spirals

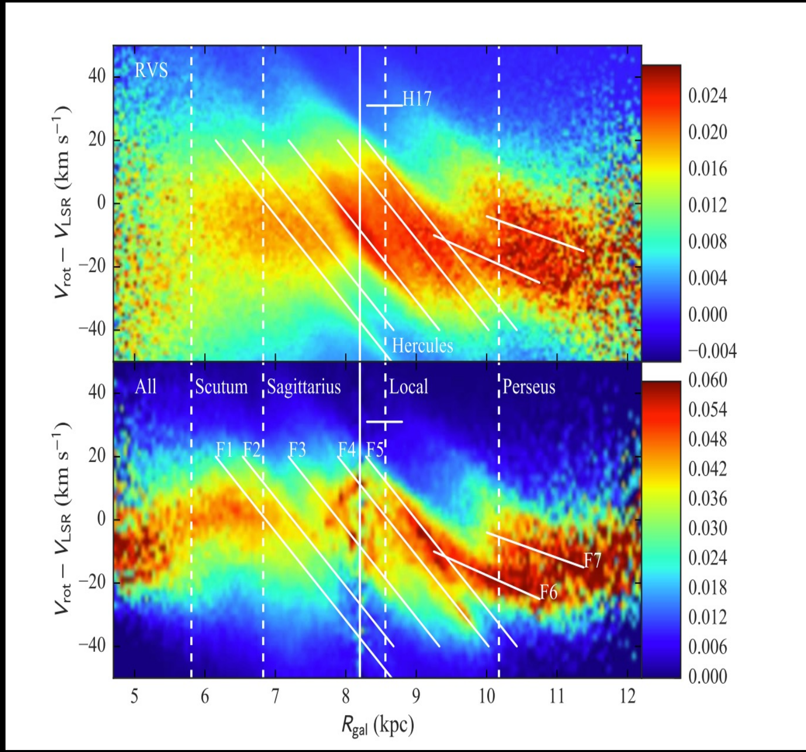
How many arms?

4 in masers
(BeSSeL Reid et al 2019)
2 in the IR
(GLIMPSE: Churchwell et al 2009)

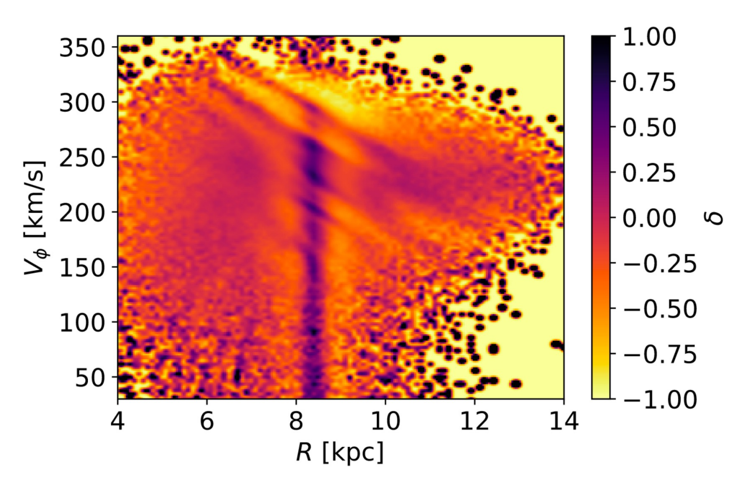
Individual pattern speeds
Castro-Ginard et al (2021)
found pattern speeds for
the (4) arms



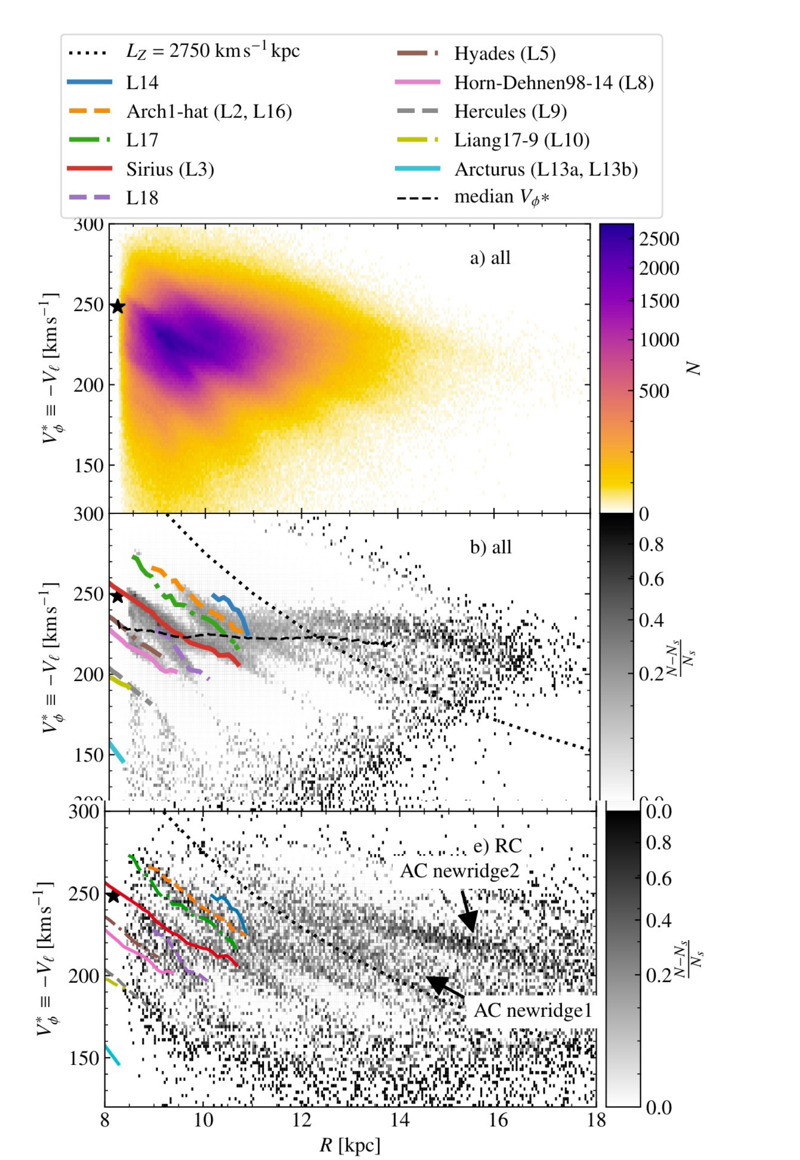
Velocity ridges



Kawata et al (2018)



Laporte et al (2019)

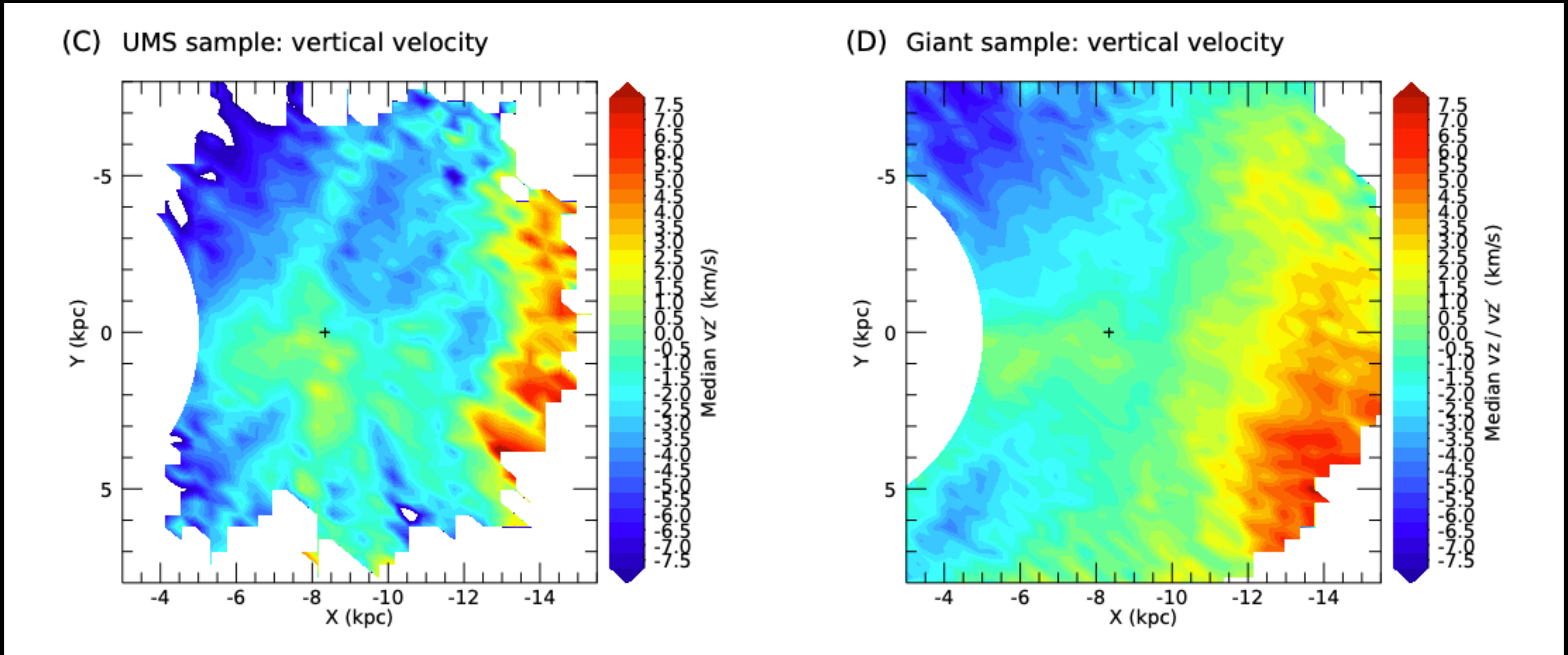


Gaia Collaboration: Antoja et al (2021)

And a warp

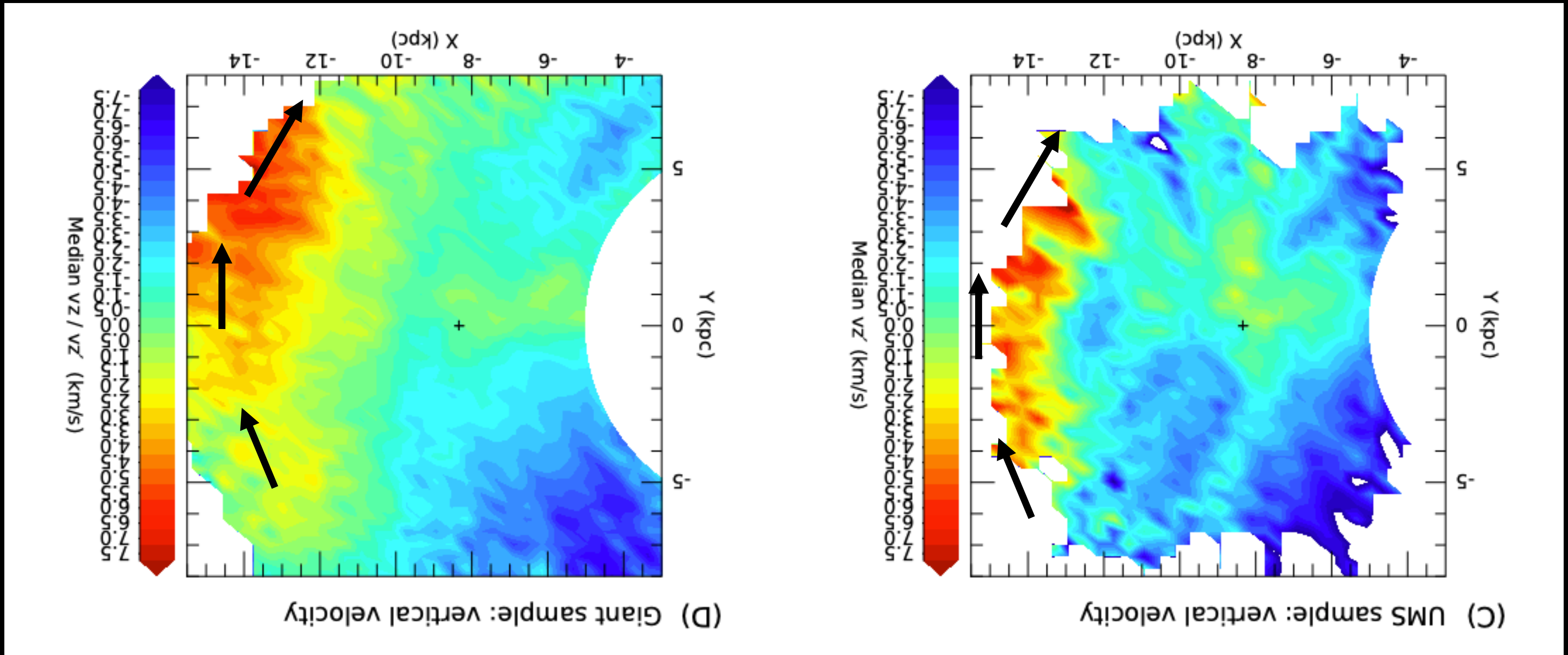
Also not a photo
Credit: Stefan Payne-Wardenaar

And a warp



Poggio et al 2018

And a warp



Poggio et al 2018

Looking a bit further with Gaia DR3

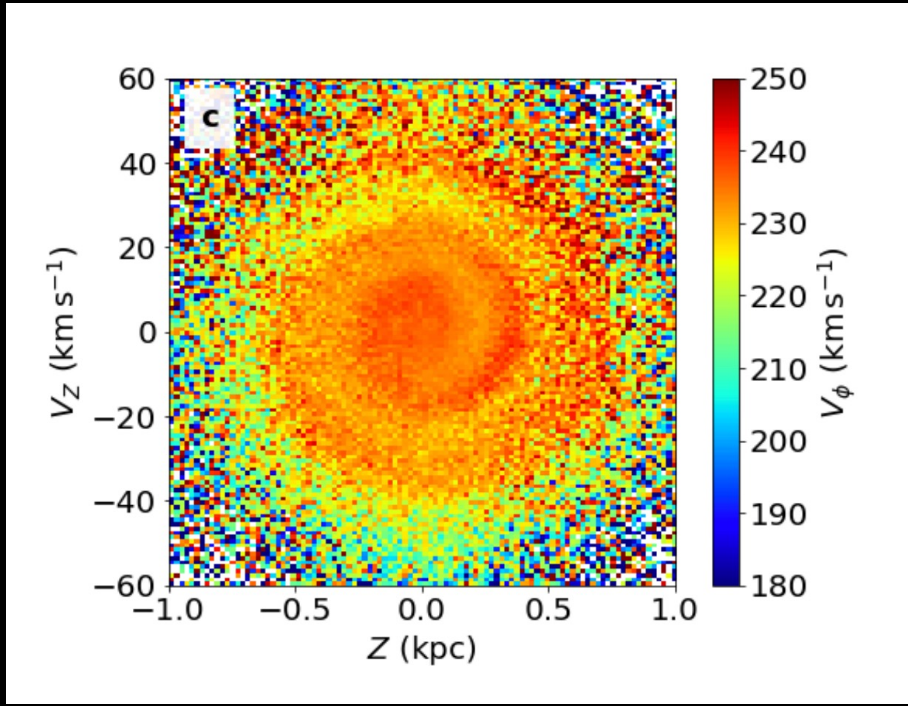
Note that the velocity goes upwards, then downwards

This is the warp precession catching up with the stars!

Plot redacted

Hrannar Jönsson (Master's project)

Recent discoveries with Gaia data

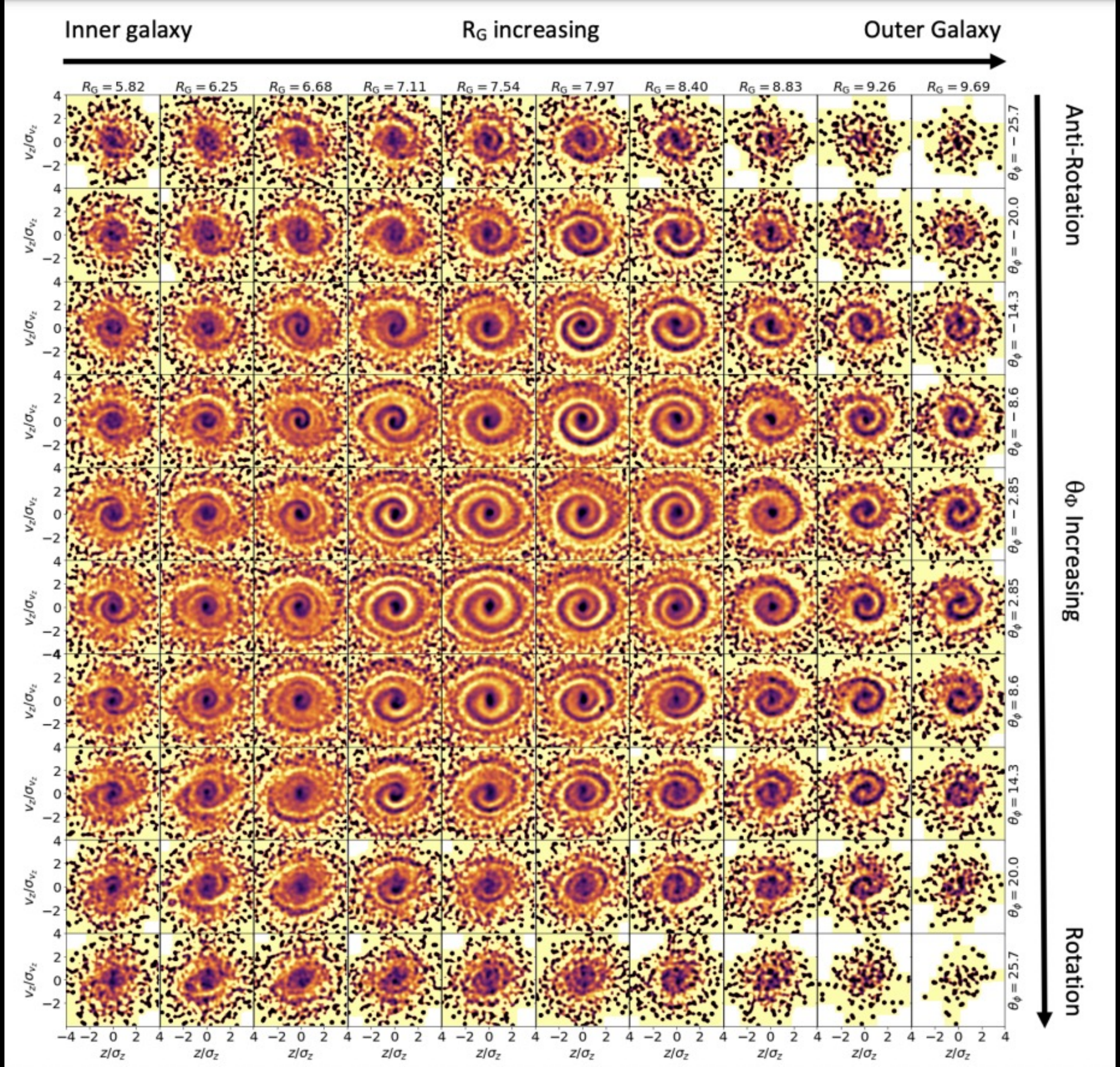


R~8kpc

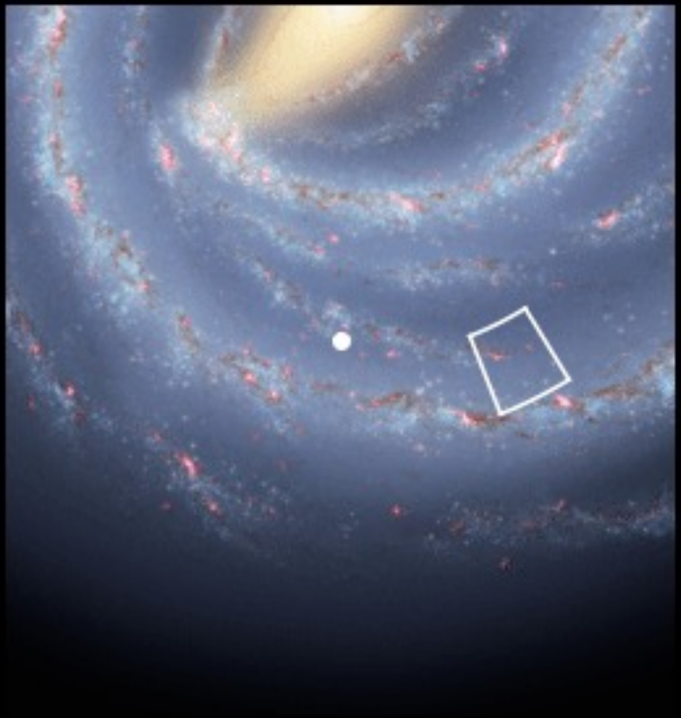
Phase spiral
(Antoja et al 2018, and others)

In a paper submitted to the arXiv within 3 hours of Gaia DR3 last year

(Hunt et al 2022)



If you look carefully, you can even see it rotate when you look around the Galaxy



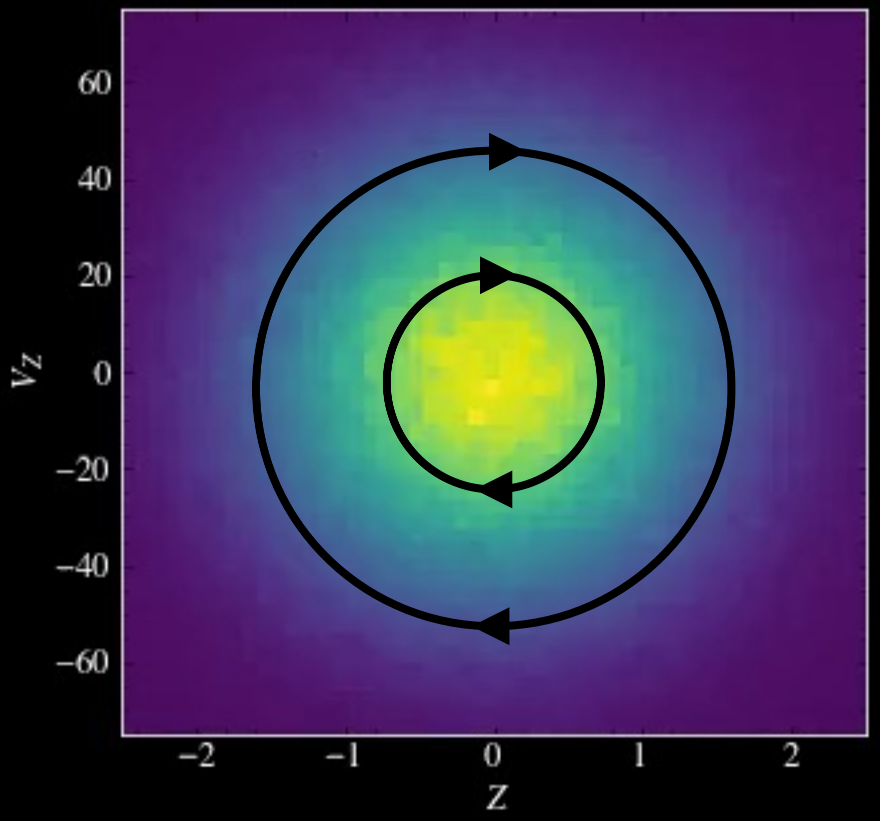
Animation redacted

Alinder, McMillan & Bensby (in prep)

A simple model:

Stars go round the centre of the z-vz diagram with a period that is shortest for a small excursion

If this gets disturbed, it winds up into a spiral

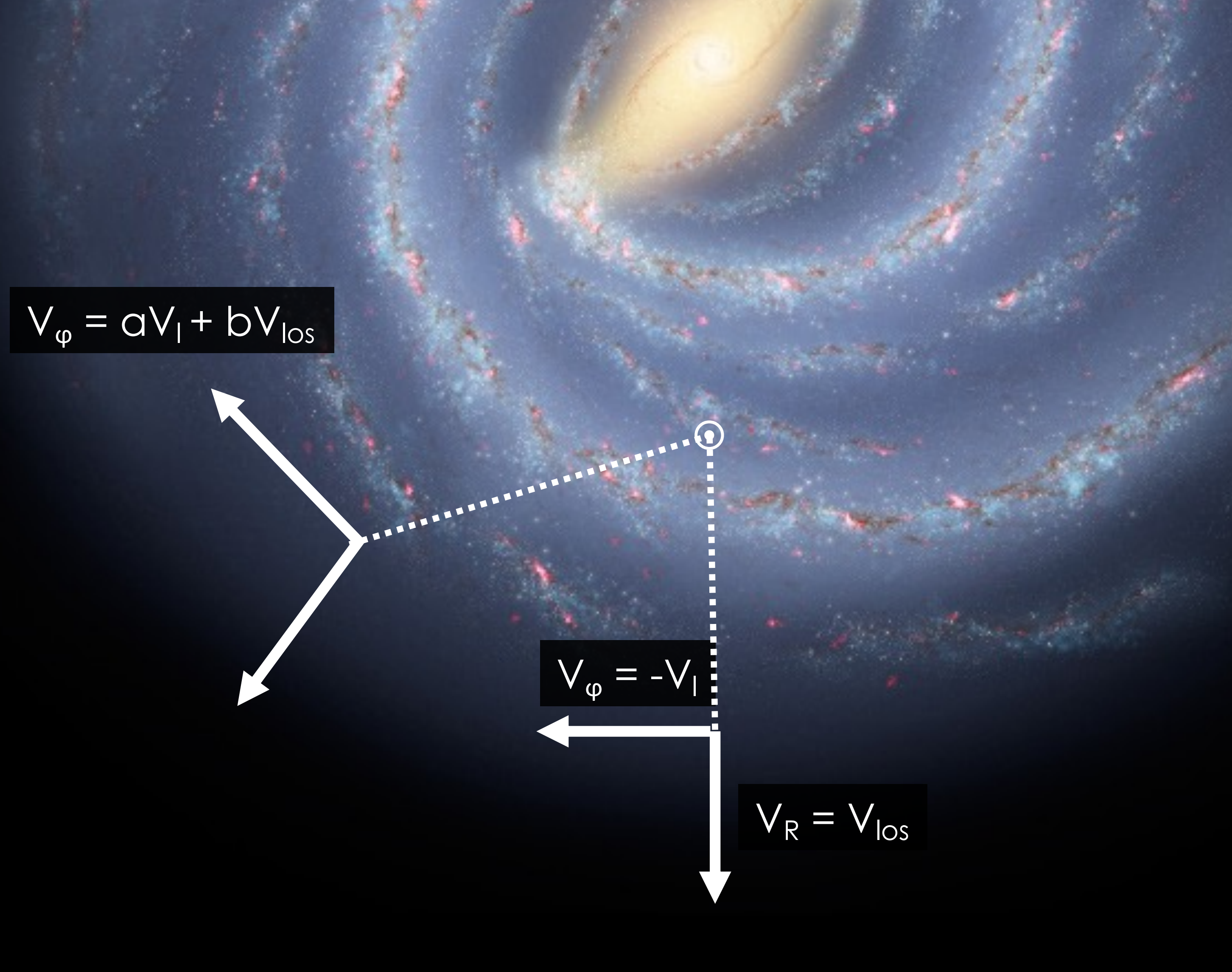


The Galactic anticentre

(l≈180°, b≈0°) i.e. looking directly away from the Galactic centre

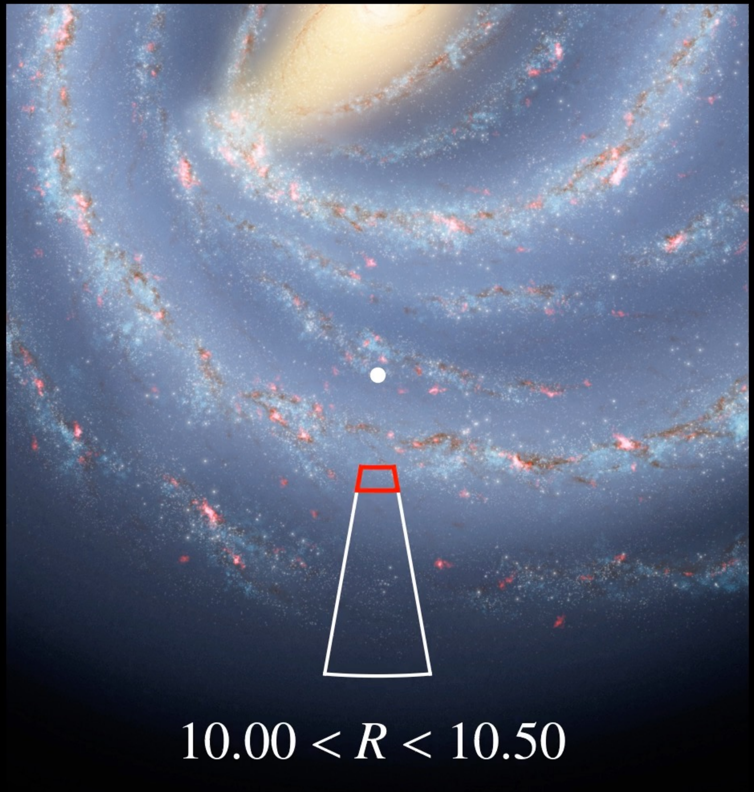
In this direction, V_z and V_φ are in (roughly) proper motion directions

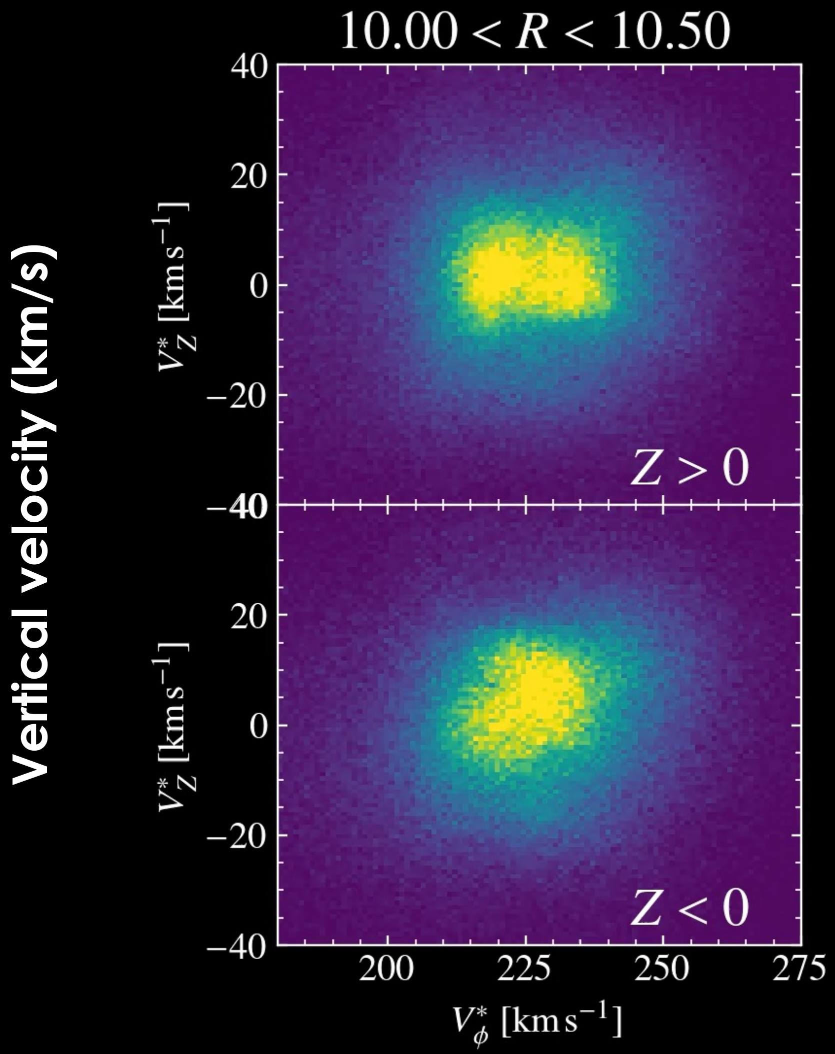
We use a large fraction of Gaia stars, not just the <1% with radial velocities



Gaia Collaboration: Antoja, McMillan et al. (2021)

The Galactic anticentre





Rotation velocity around the Galactic centre (km/s)

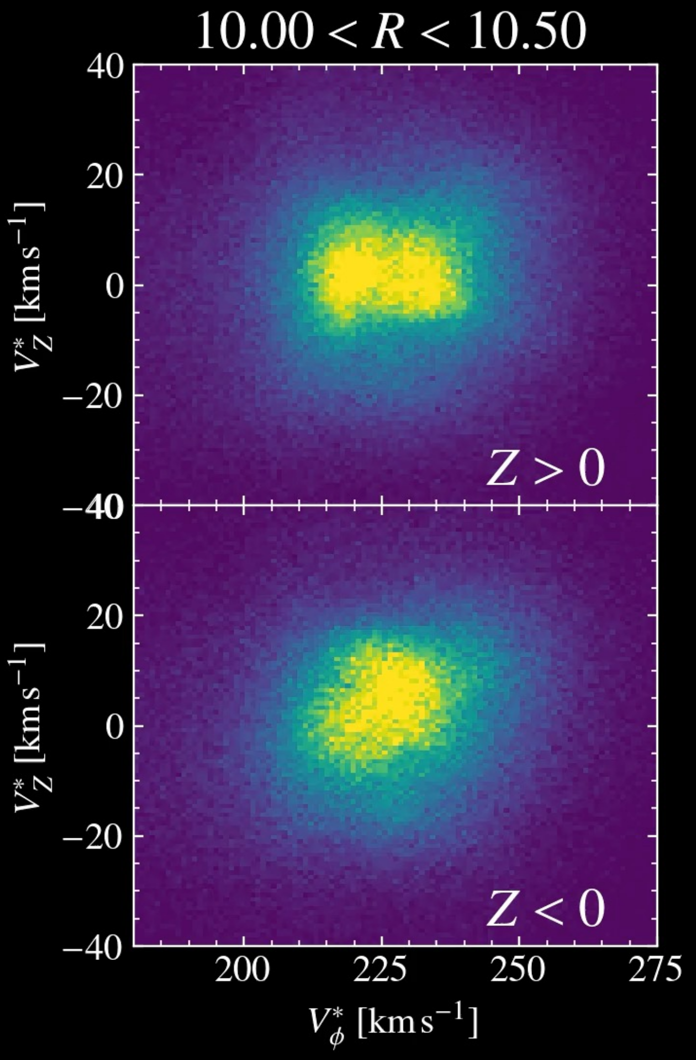
The Galactic anticentre

Clear bimodal structure

Above plane, dominated by stars moving downwards, rotating slower

Below plane, dominated by stars moving upwards and rotating faster

Vertical velocity (km/s)

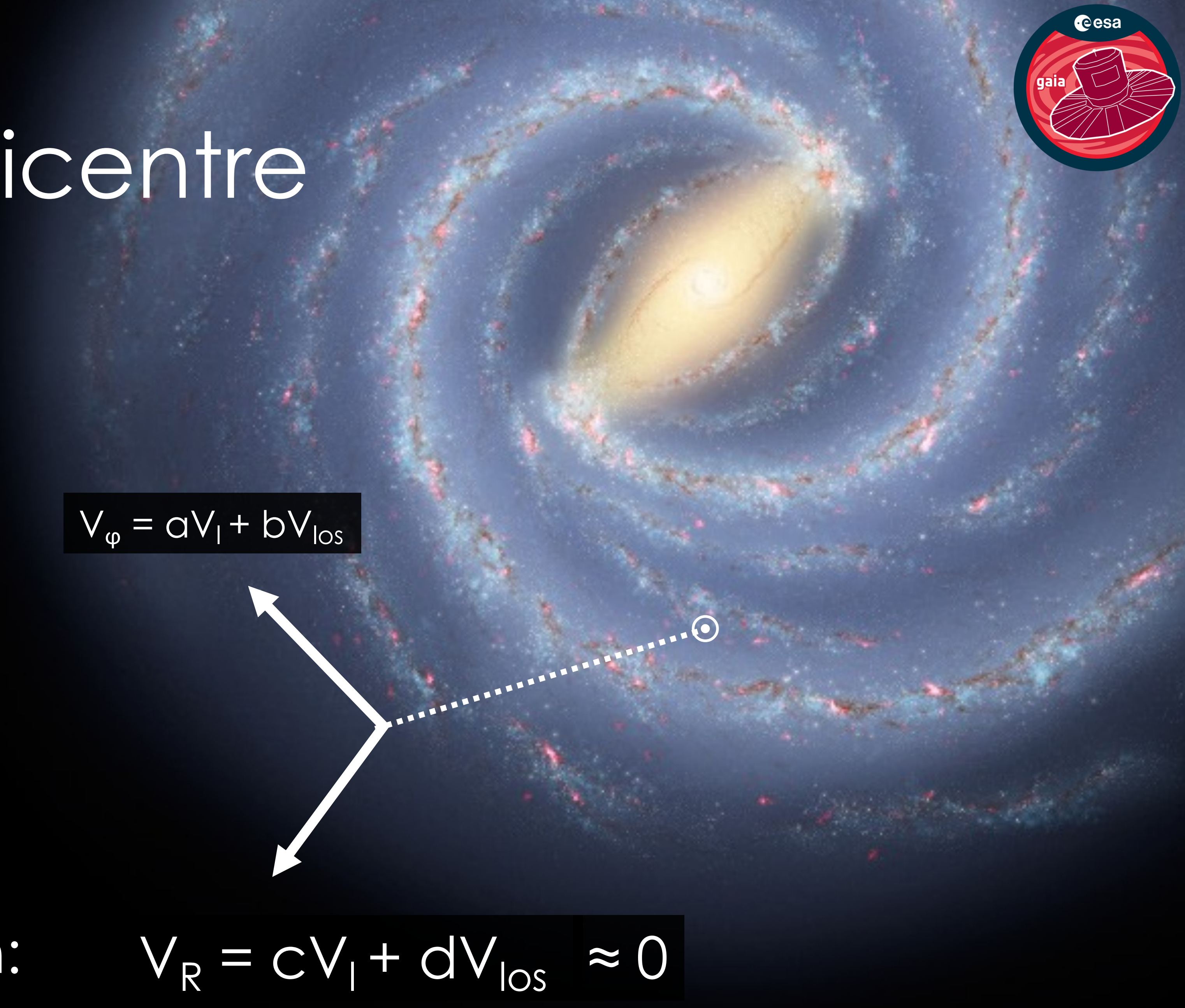


Rotation velocity around the Galactic centre (km/s)

Away from anticentre

Either

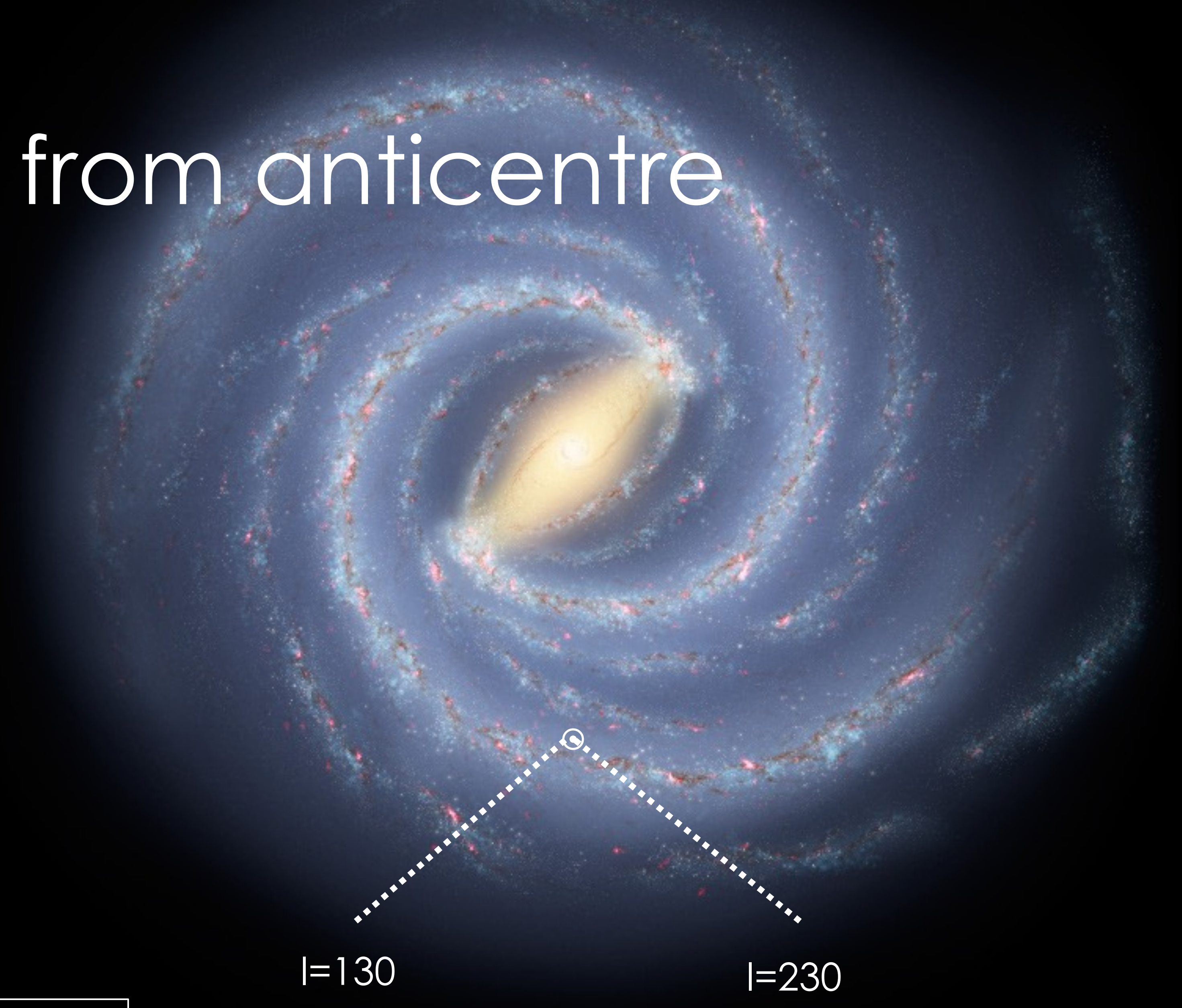
1) Restrict analysis to stars with measured radial velocities



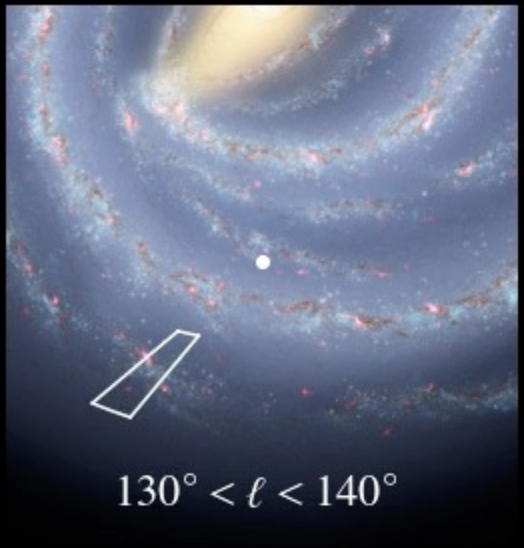
$V_\varphi = aV_l + bV_{los}$

2) Make an approximation: $V_R = cV_l + dV_{los} \approx 0$

Away from anticentre



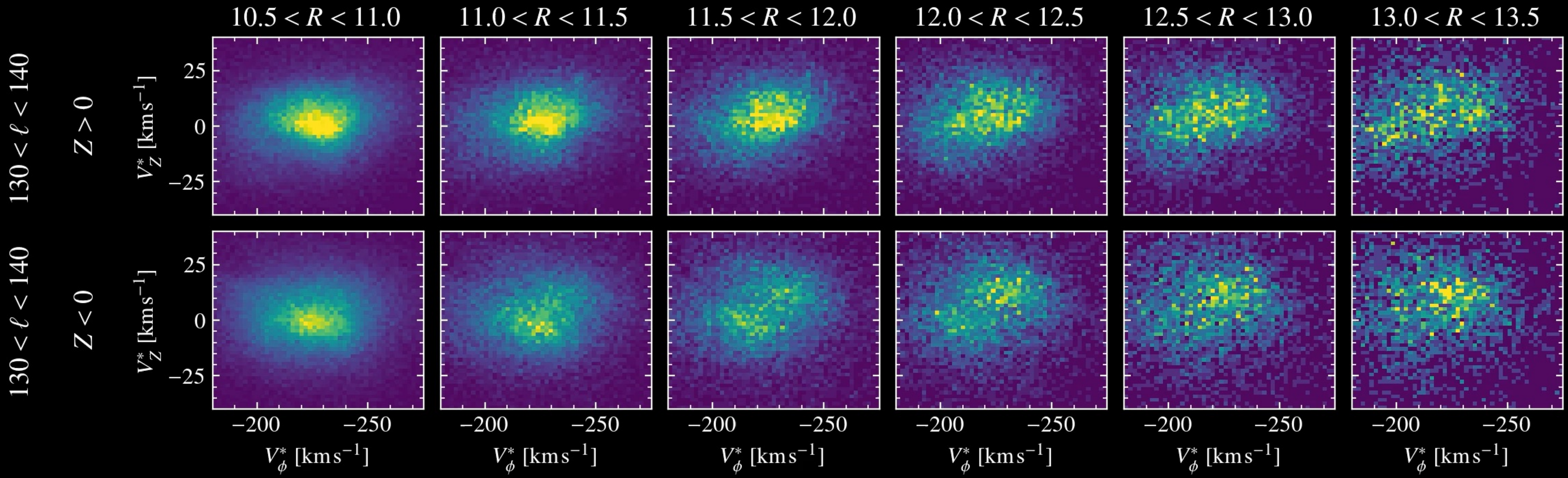
McMillan et al (2022)

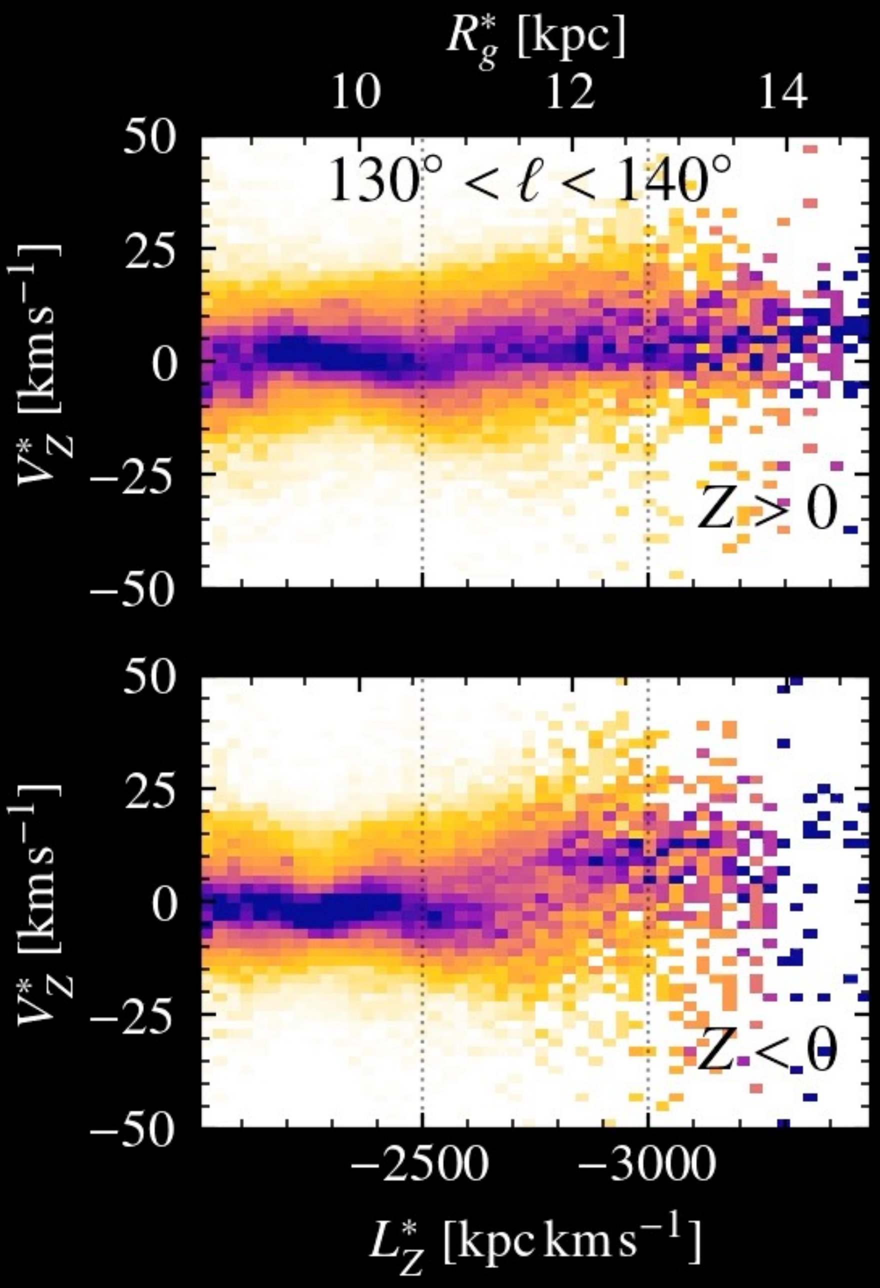


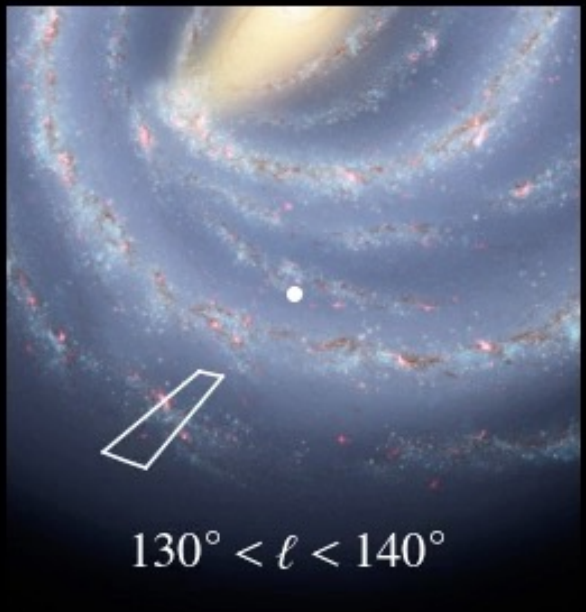
Star velocities across the outer galaxy are:

Bimodal

Different above and below plane

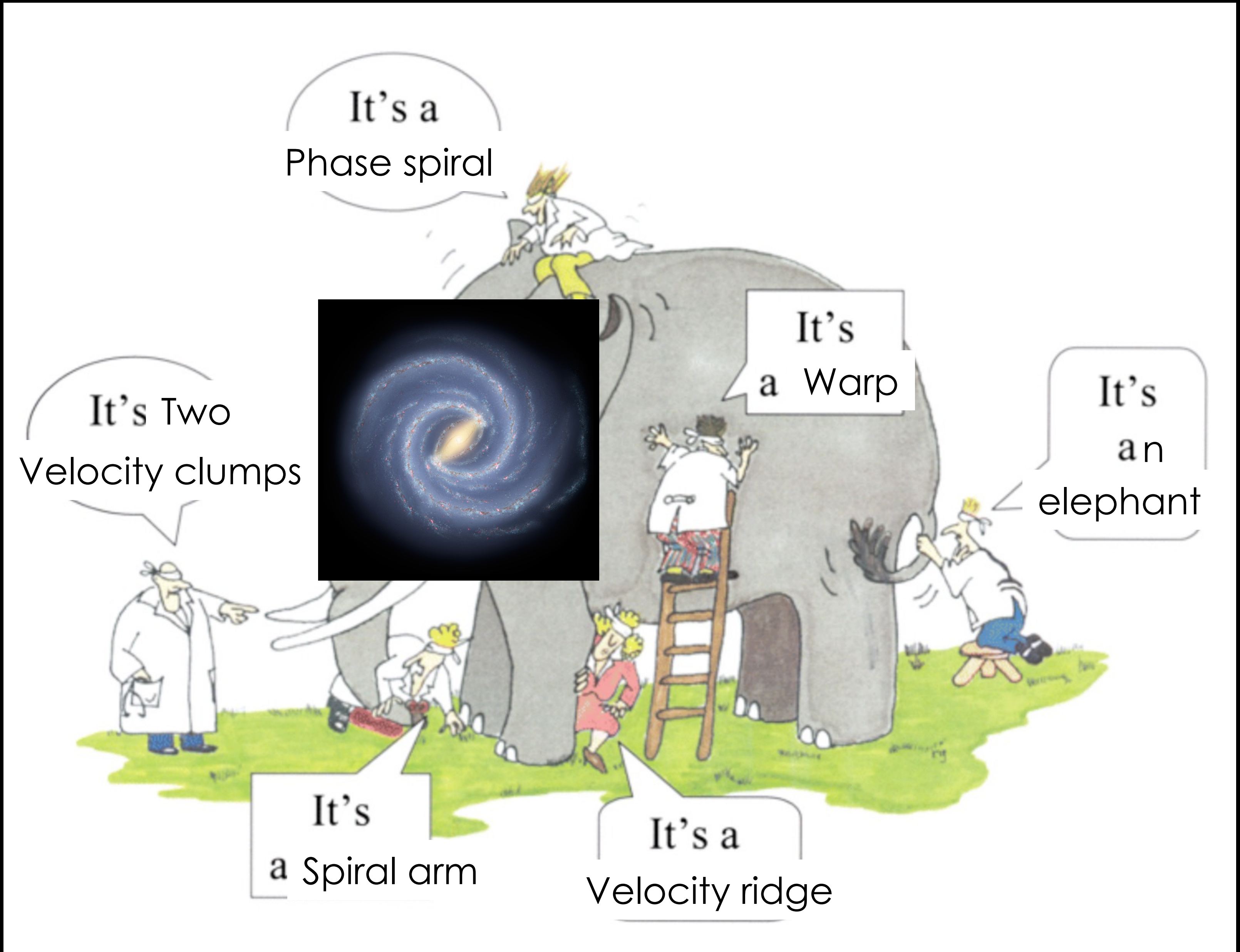






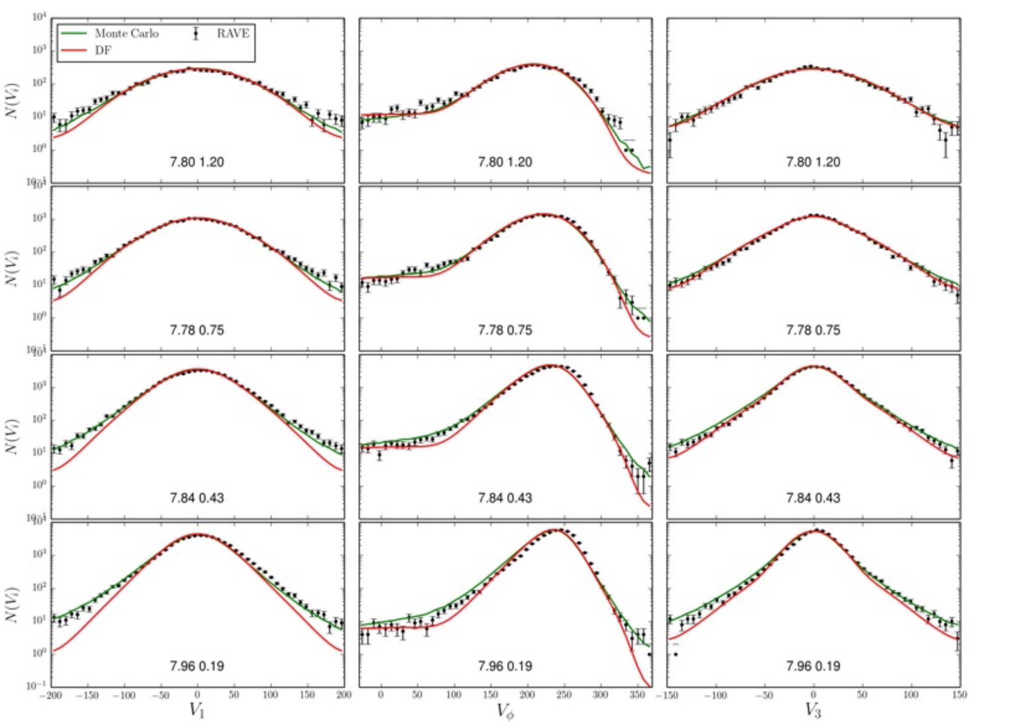
Nicely shown in angular momentum

Galactic dynamics in the Gaia era (an artist's impression)

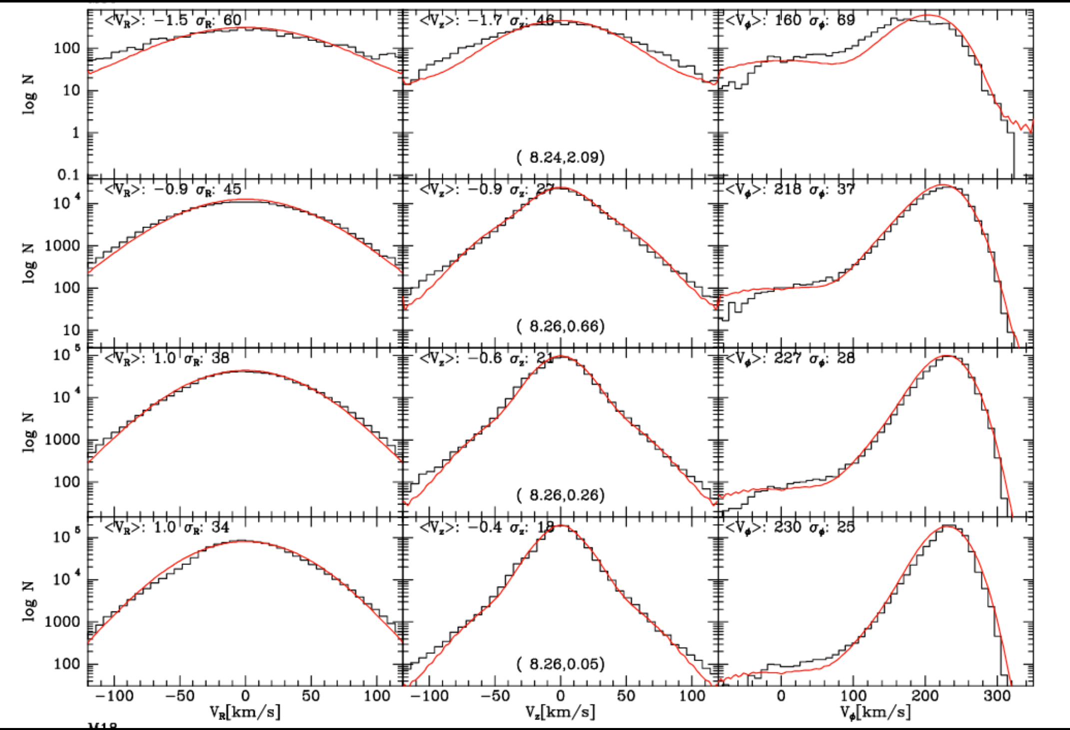


So, what can theorists do about this?

We were prepared to analyse the data under the approximation that the galaxy was in equilibrium



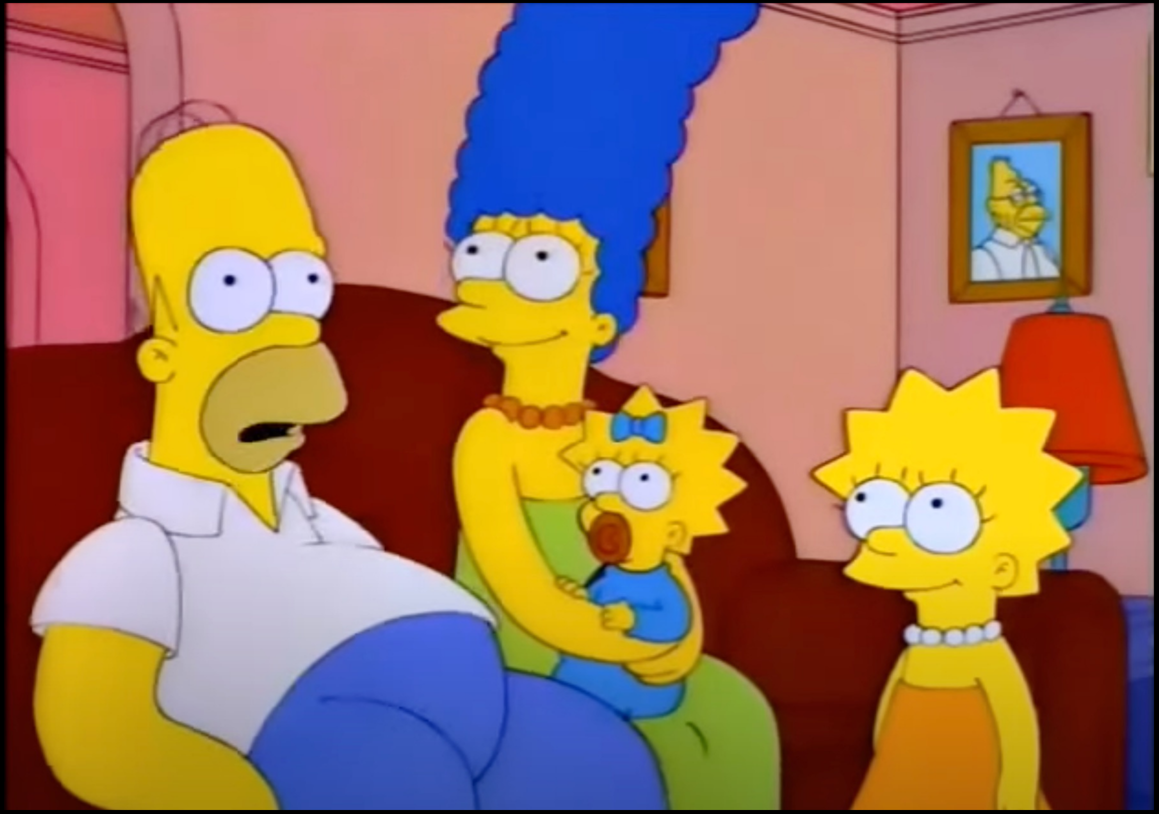
Piffl et al (2014)



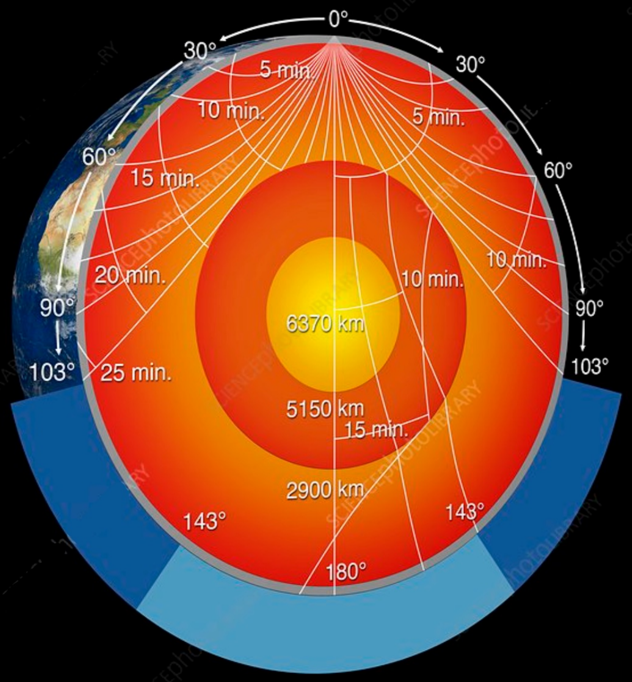
Binney & Vasiliev (2022)

Fitting equilibrium models to velocity histograms

Crisis ∈ Opportunity?

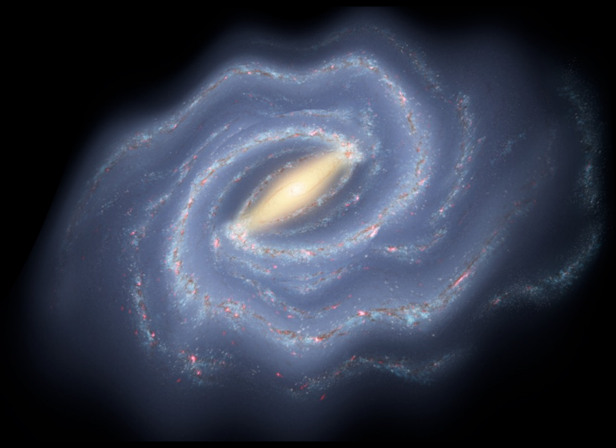


Seismology



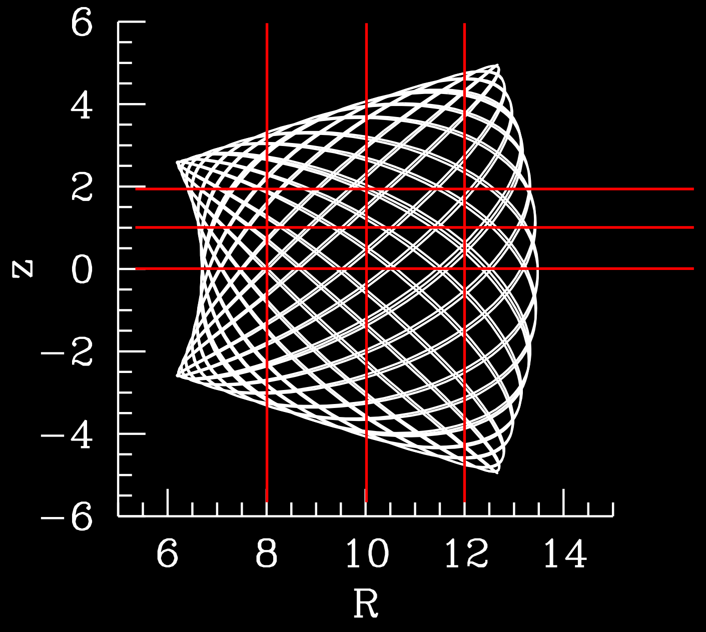
Asteroseismology

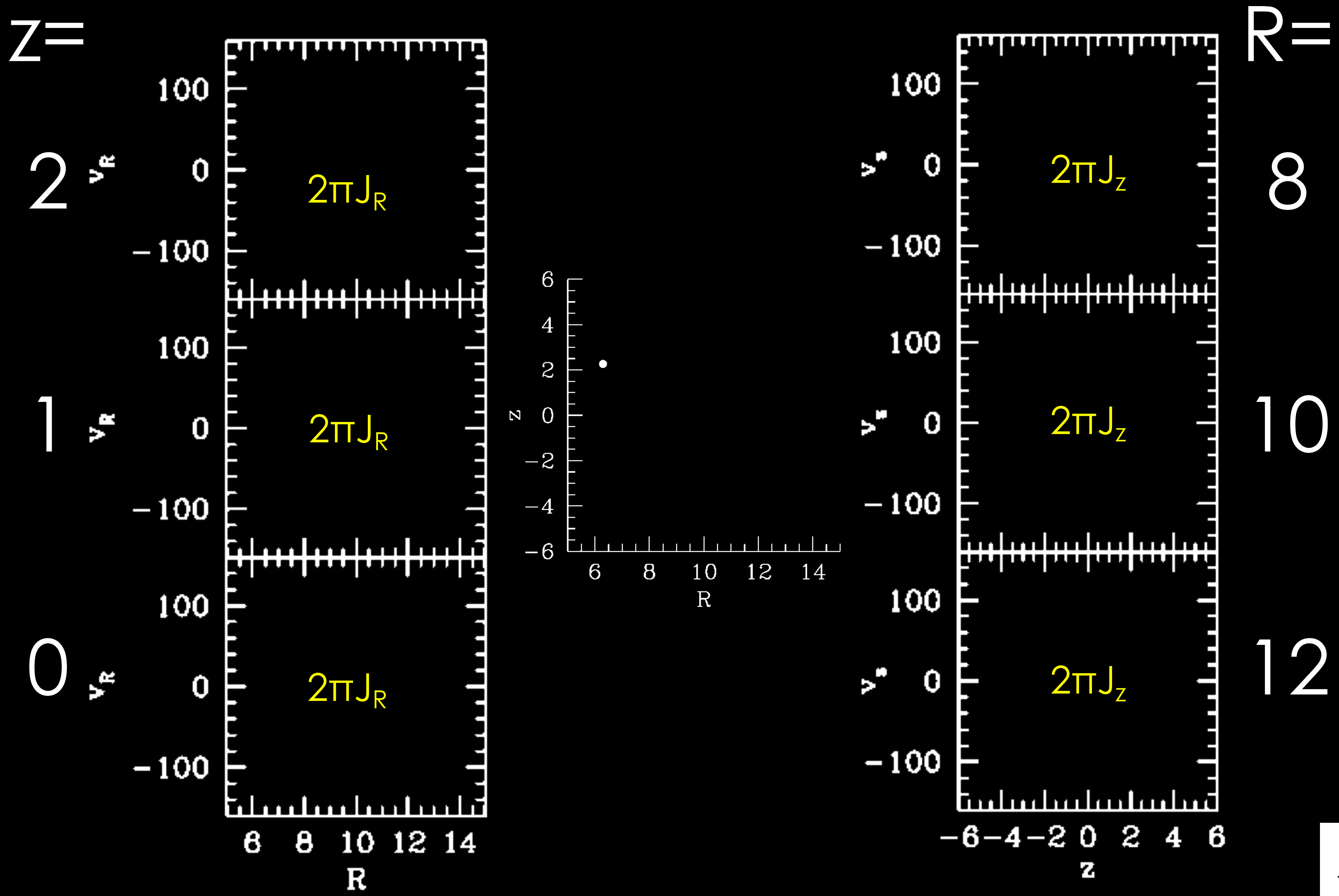
Galactoseismology?



We need a way to describe orbits: Orbital actions (J)

Action-angle variables are incredibly useful for dynamics, and have become part of the standard toolkit for Galactic studies





$$\frac{1}{2\pi}\oint_{\gamma_i} \mathbf{p}\cdot \mathrm{d}\mathbf{q}$$

Useful properties of actions

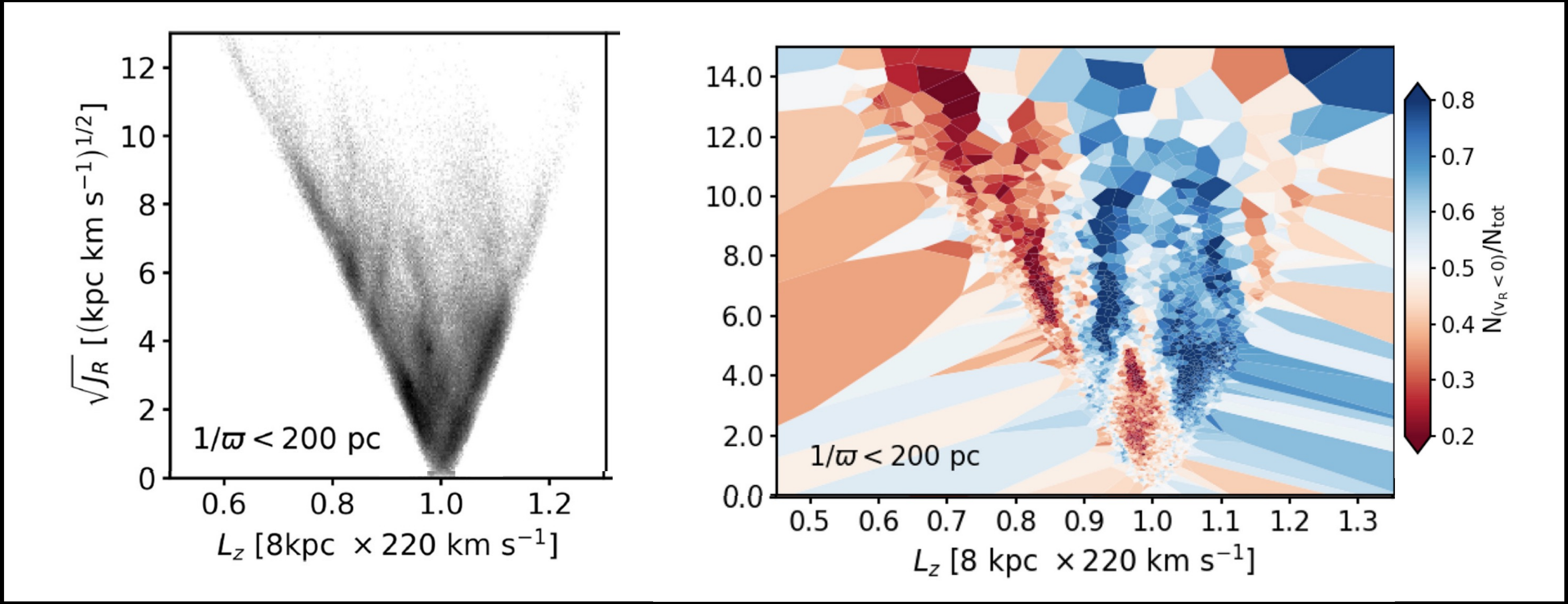
1. Conserved on orbits, even under adiabatic changes in potential

2. Come with angle coordinates which are convenient way of describing orbital phase

3. Physical processes which affect Galactic discs are conveniently described in these coordinates.

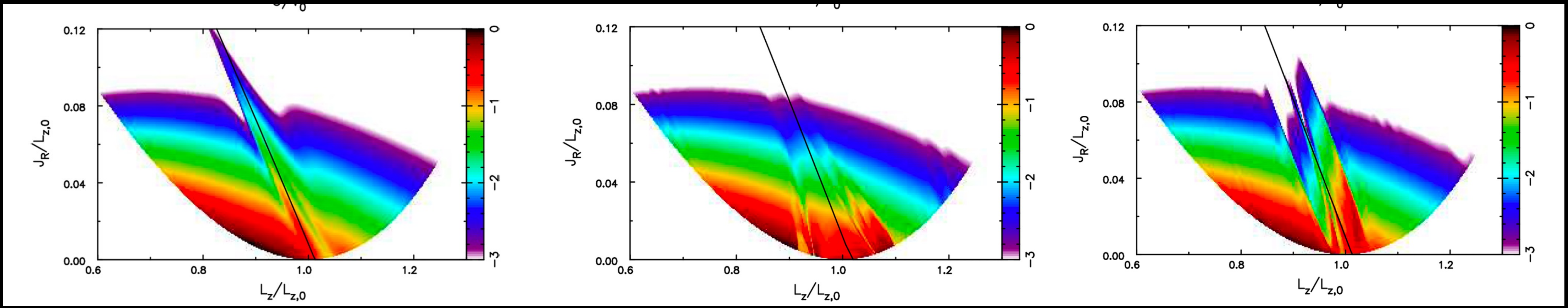
Internal disturbances

The Milky Way has a bar, and spiral arms



Stars dragged into overdensities with preferred sign of v_R by resonances
Trick et al (2019)

Models of different spirals



Inner Lindblad Resonance

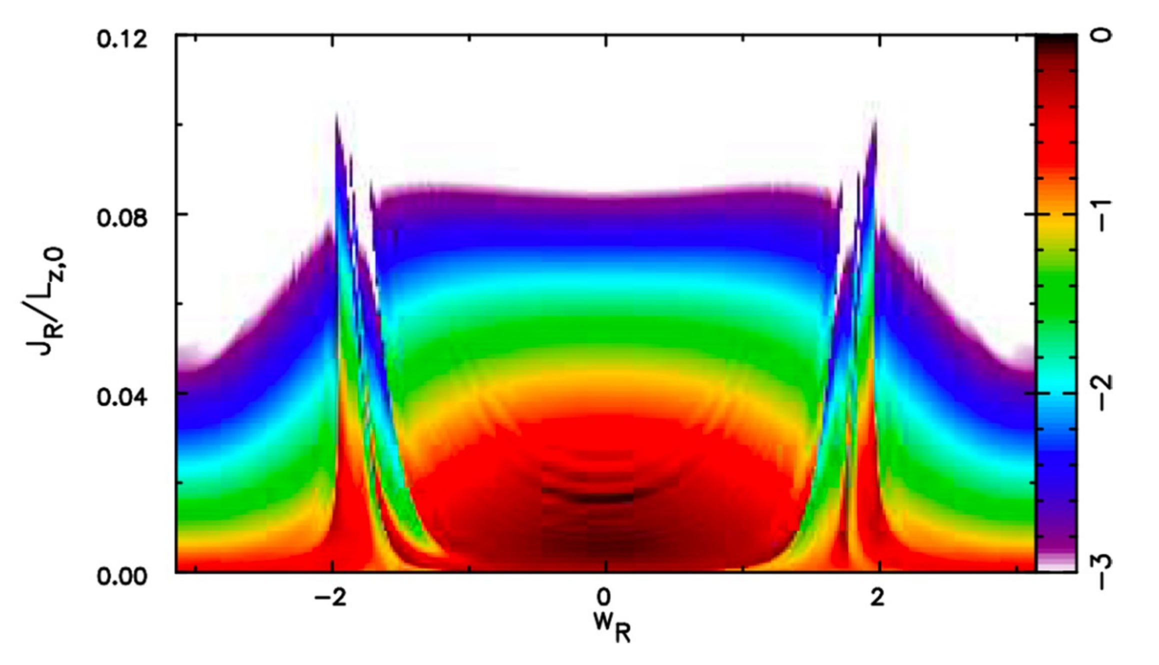
Corotation Resonance

Outer Lindblad Resonance

Transient mode (fixed pattern speed)

Sellwood et al (2019)

In all cases ~symmetric about V_R=0 (θ_R=0)



θ_R

Transient mode (fixed pattern speed)

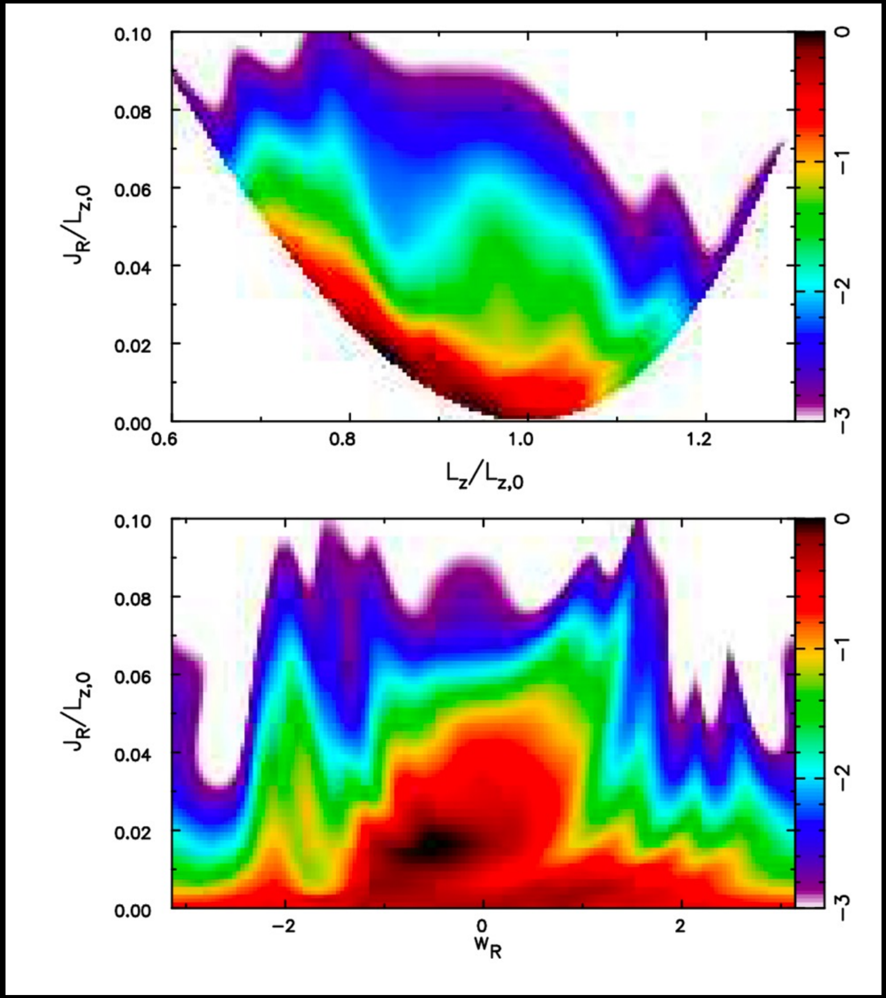
Sellwood et al (2019)

Swing amplified material arm

Not symmetrical in θ_R

Broad disturbances in action distribution.

Sellwood et al (2019)

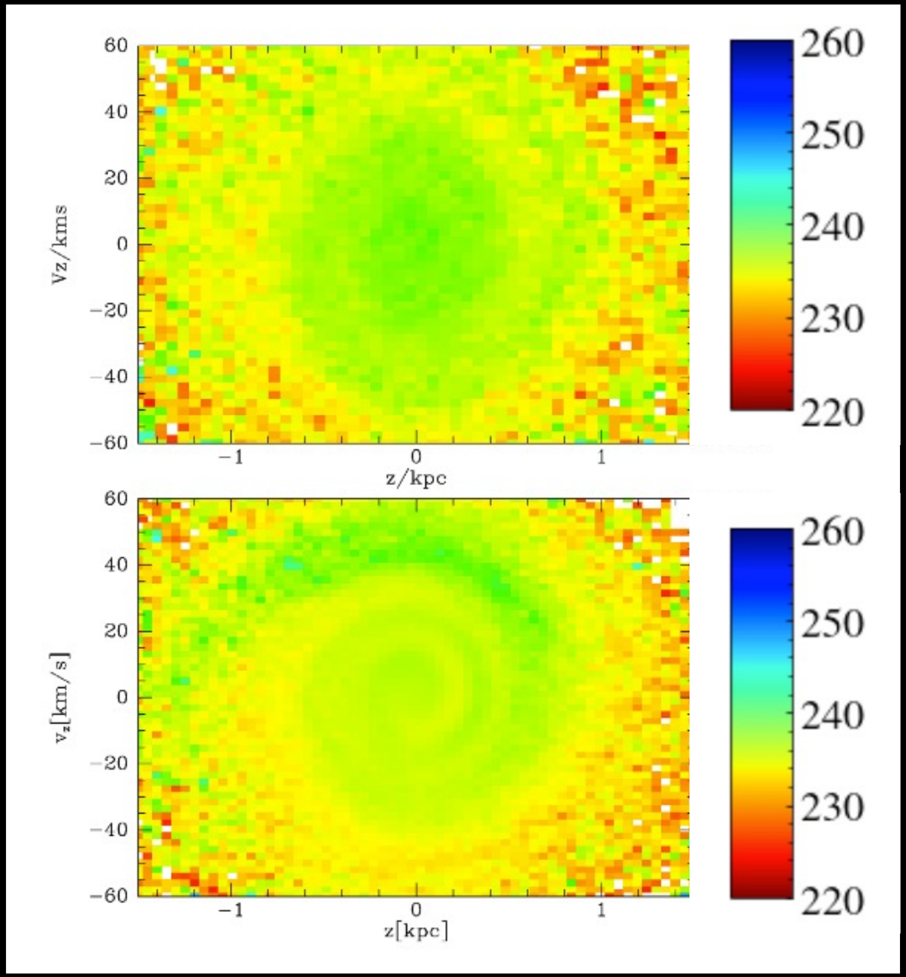


External disturbances

Action-angle model of Sagittarius' impact

400 Myr after impulse (model)

Gaia data



Binney & Schönrich (2018)
Requires $2{\times}10^{10}\ M_\odot$ Sgr

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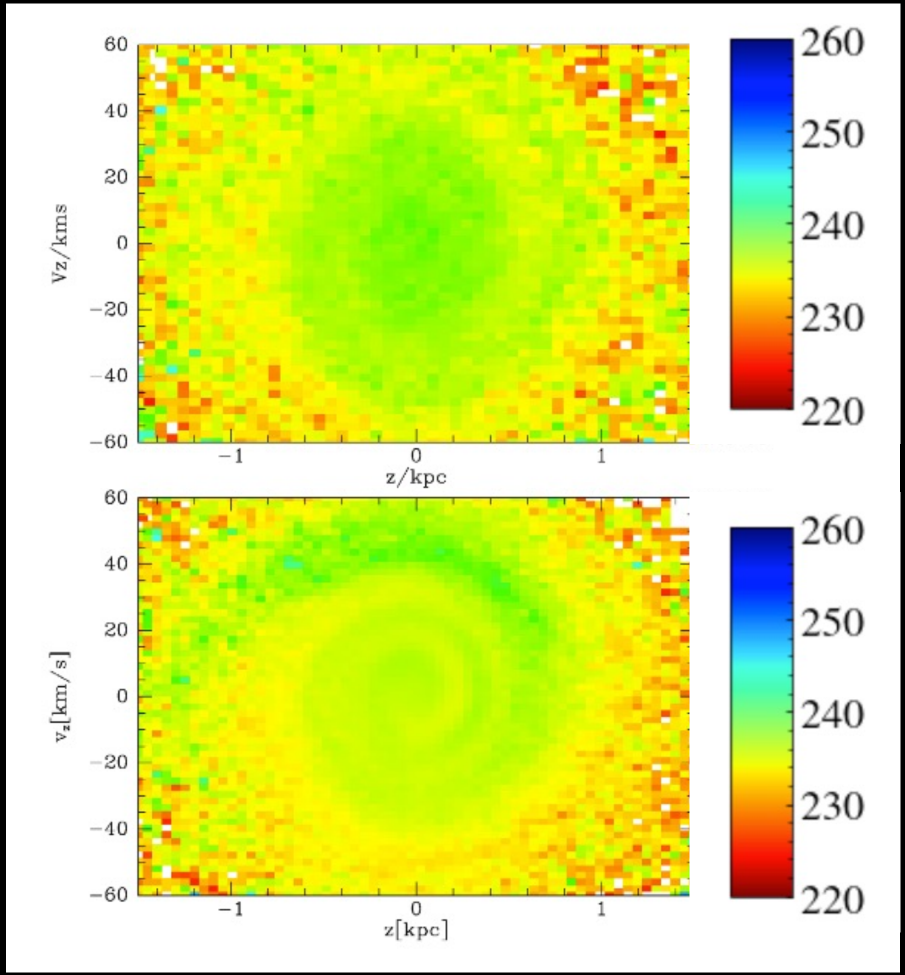

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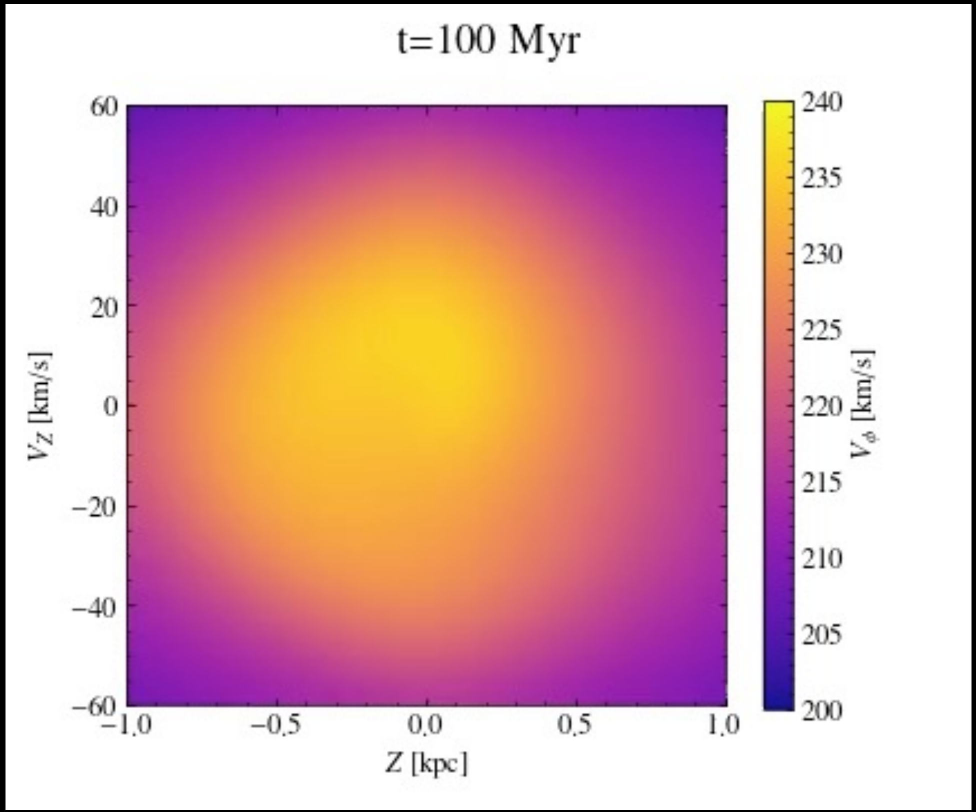
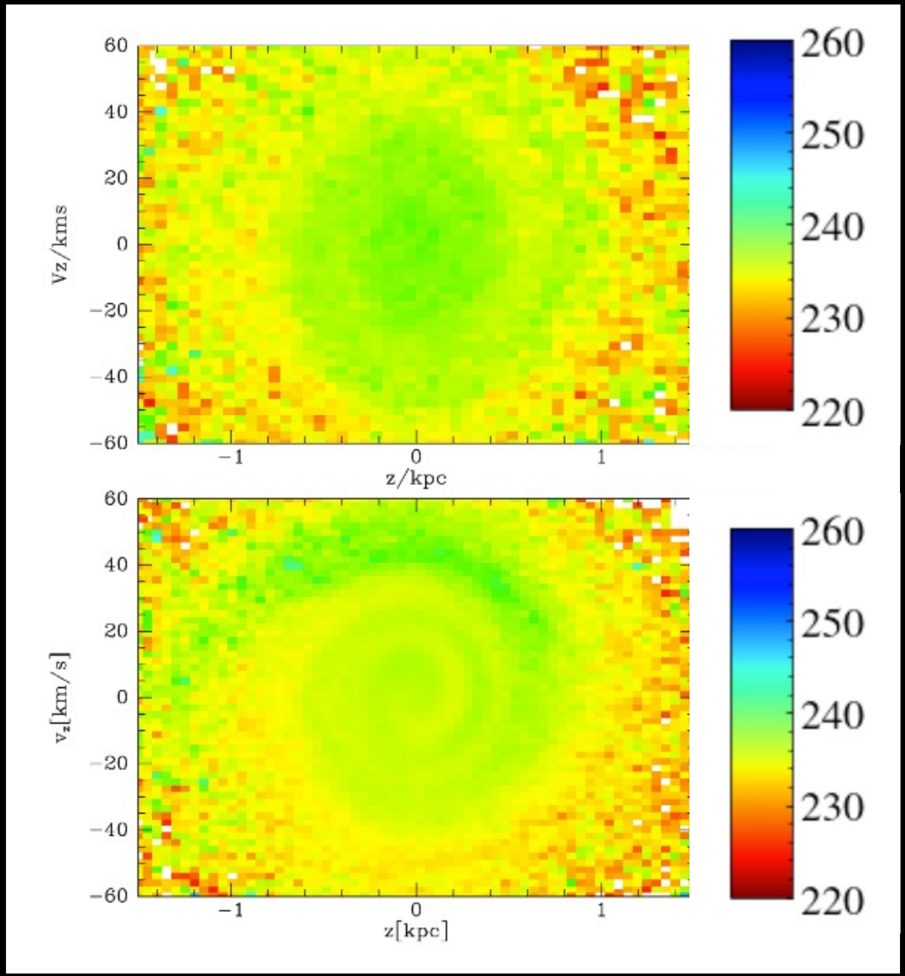


Simple (self-gravity-free) model of Sagittarius' impact

400 Myr
after
impulse
(model)

Gaia
data



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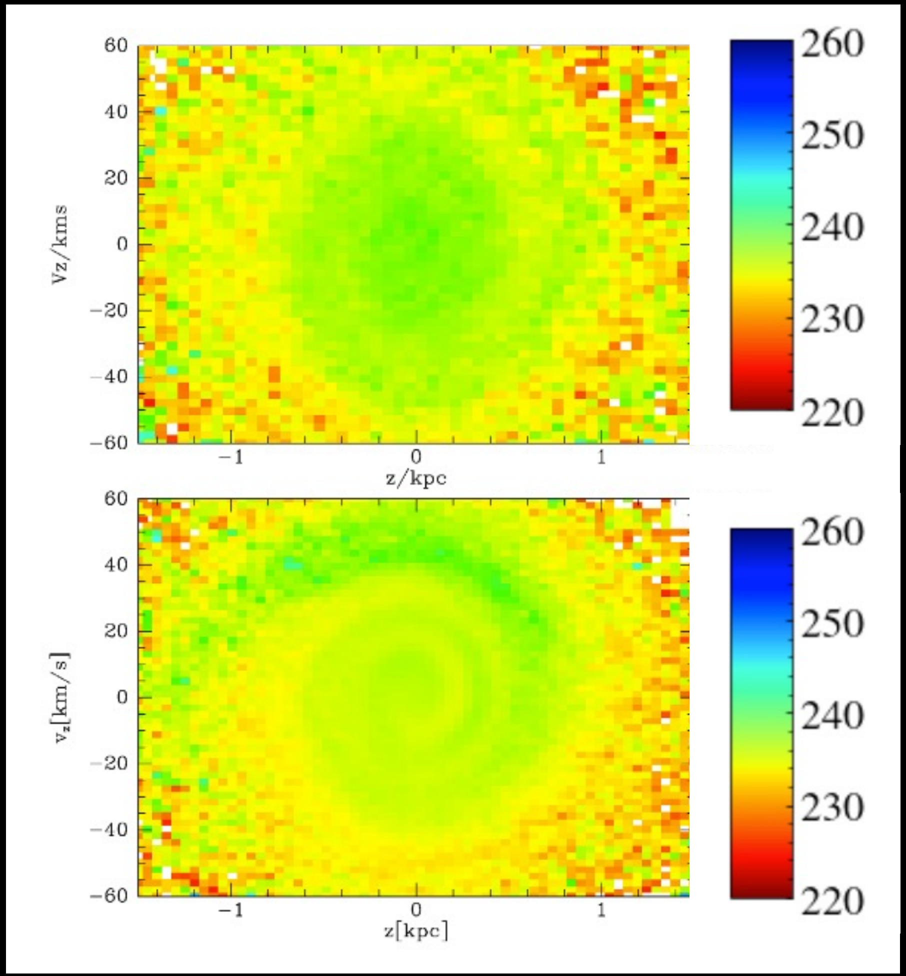

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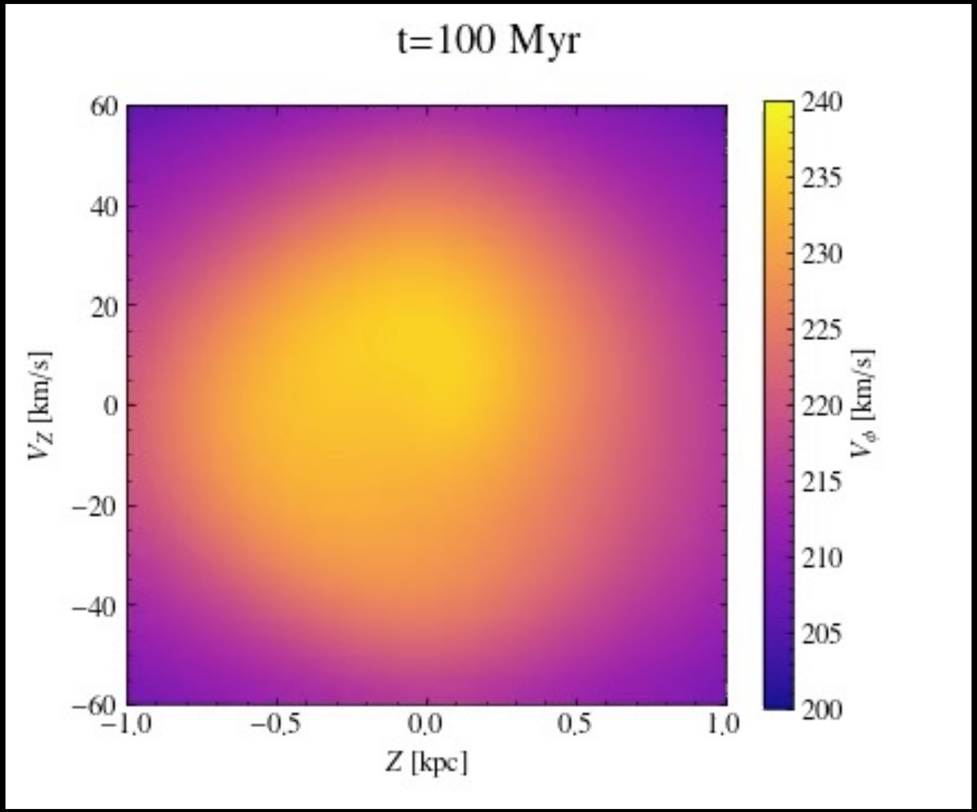
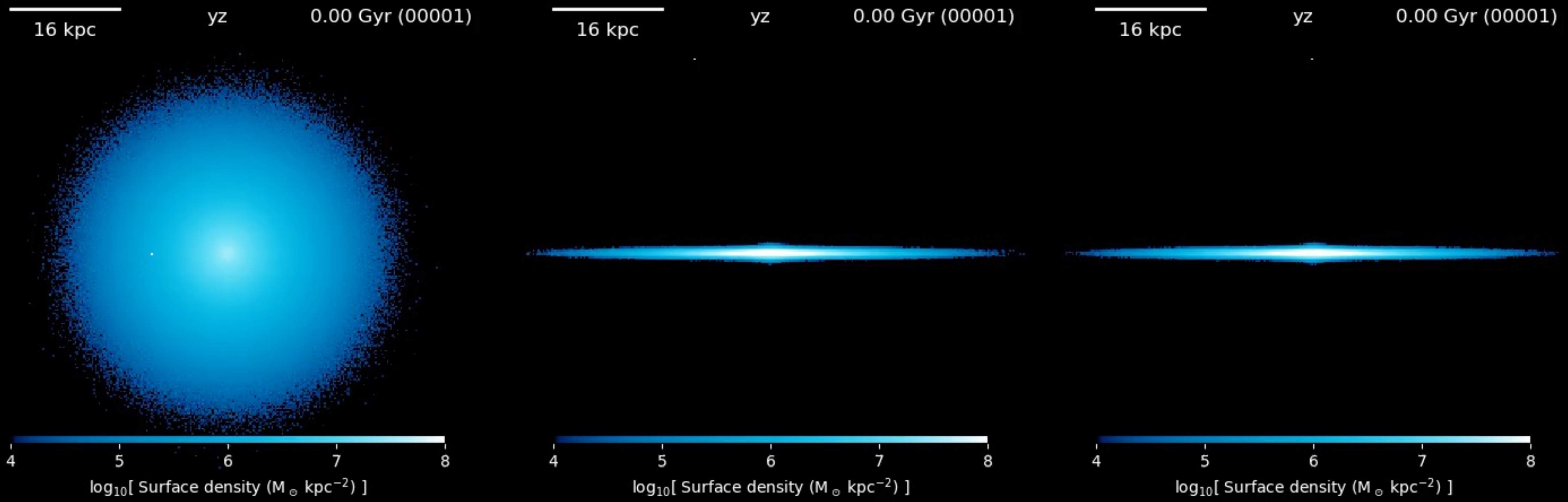


Bland-Hawthorn & Tepper-Garcia (2021)

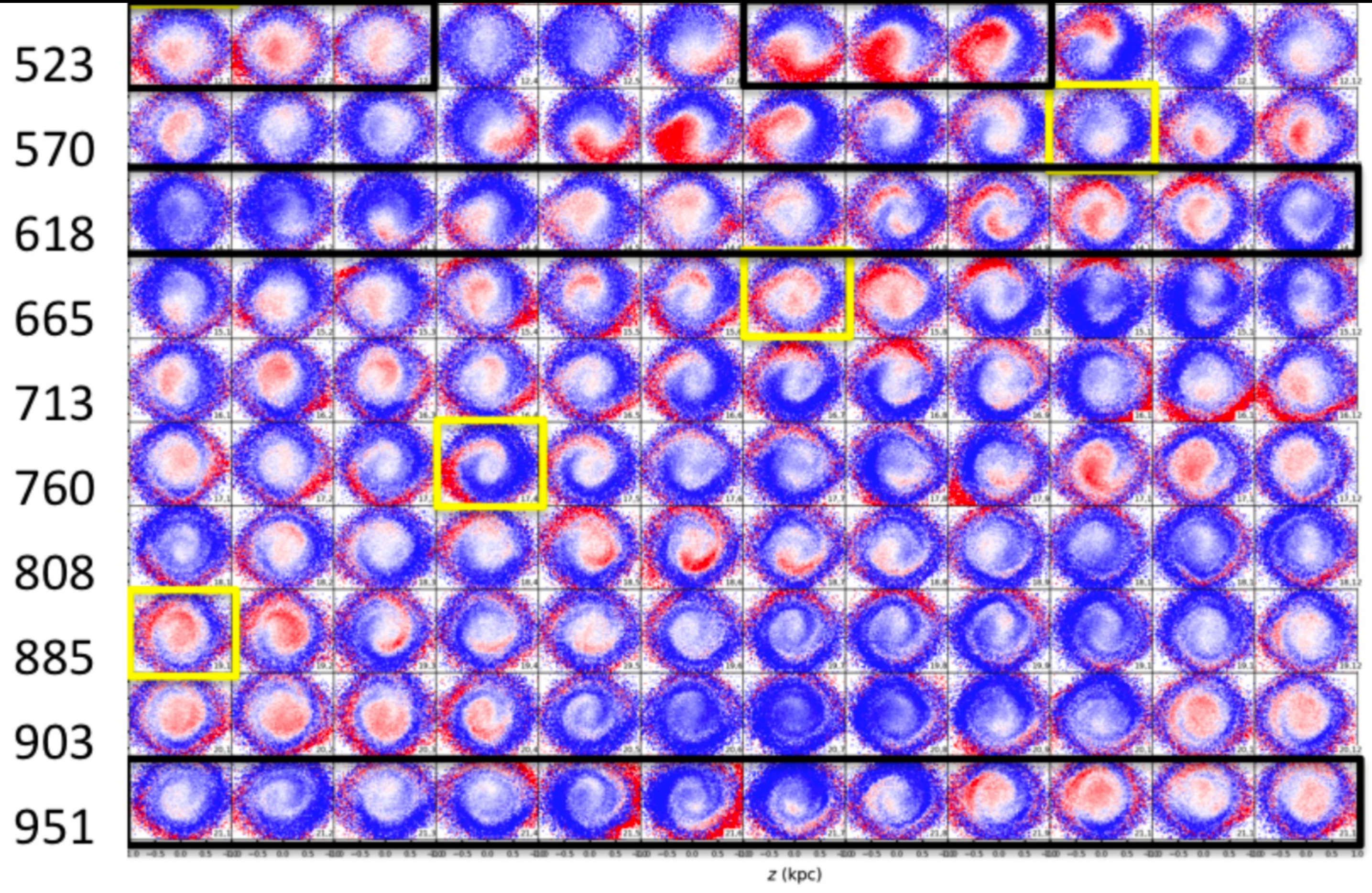


Simplified simulation of impact

Set up to be a self gravitating ~equivalent to the Binney & Schönrich calculations.

Phase-spiral forms later and is less wound

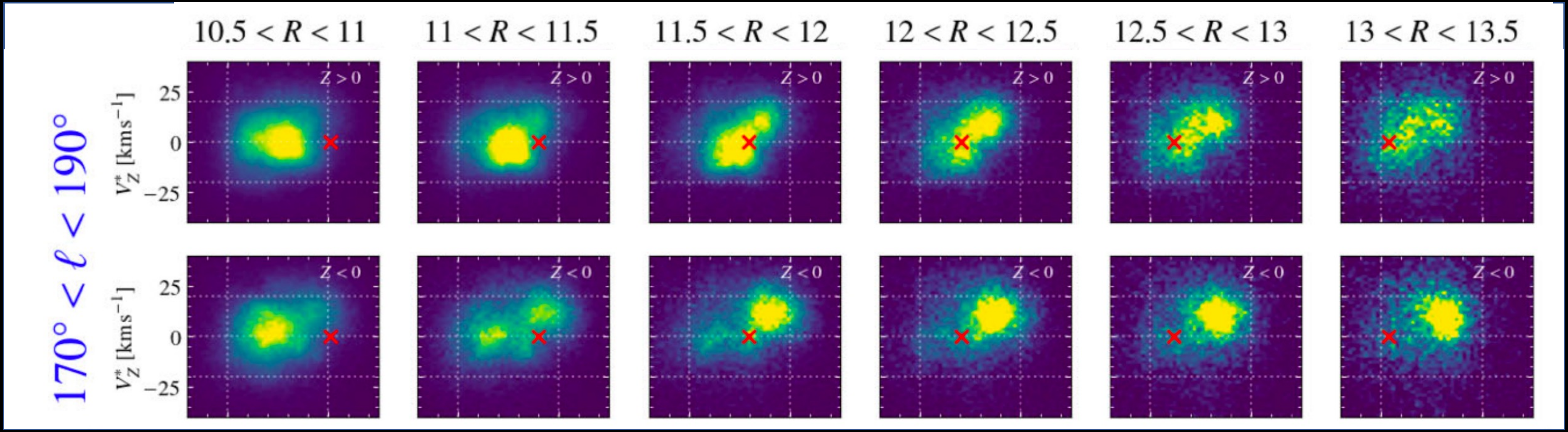
Time in Myr →



← Different angles around galaxy →

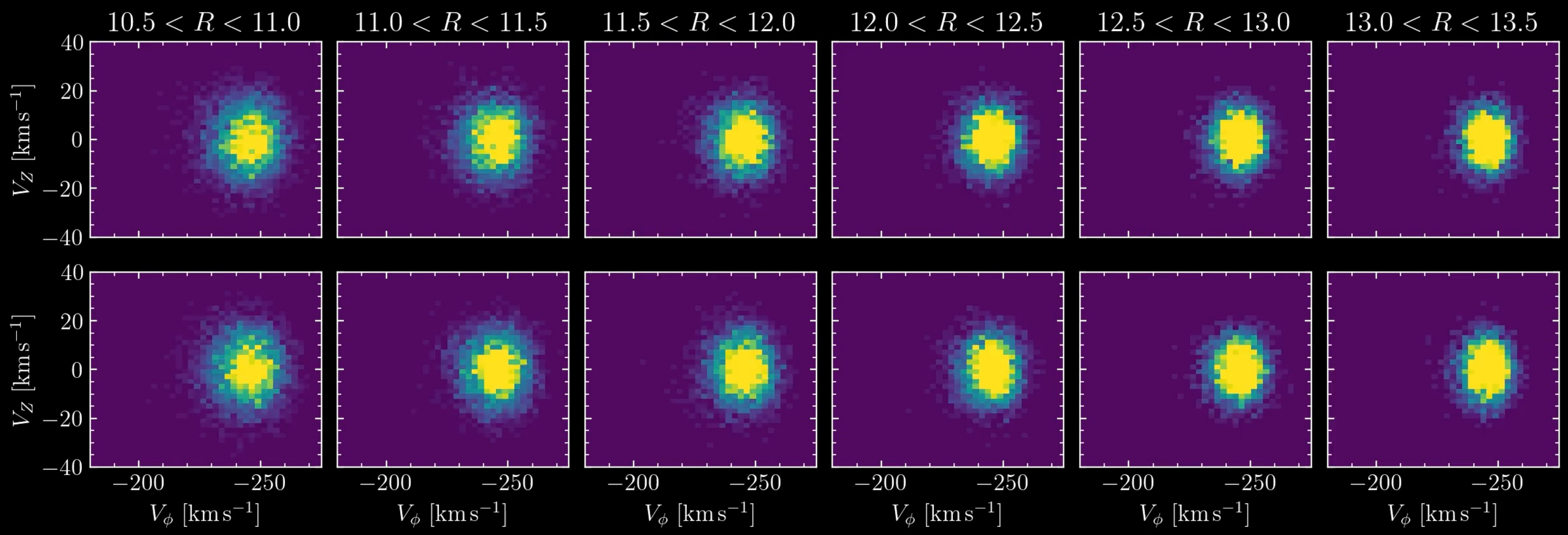
See also Laporte et al 2019, Hunt et al 2021, Gandhi et al 2022

Reminder of what we see in the Milky Way



Simulations of ‘Sgr dwarf’

0.00 Gyr



Summary

The outer disc is shaking, probably because of a recent flyby of the Sgr dwarf

Reproducing all the parts of the elephant (or: all we see in the Milky Way) will allow us to learn its structure & history through "Galactic seismology"

This probably isn't going to be as easy as I'd hope

1.5 billion >> 33 million. We must not be afraid to work without all components of velocity