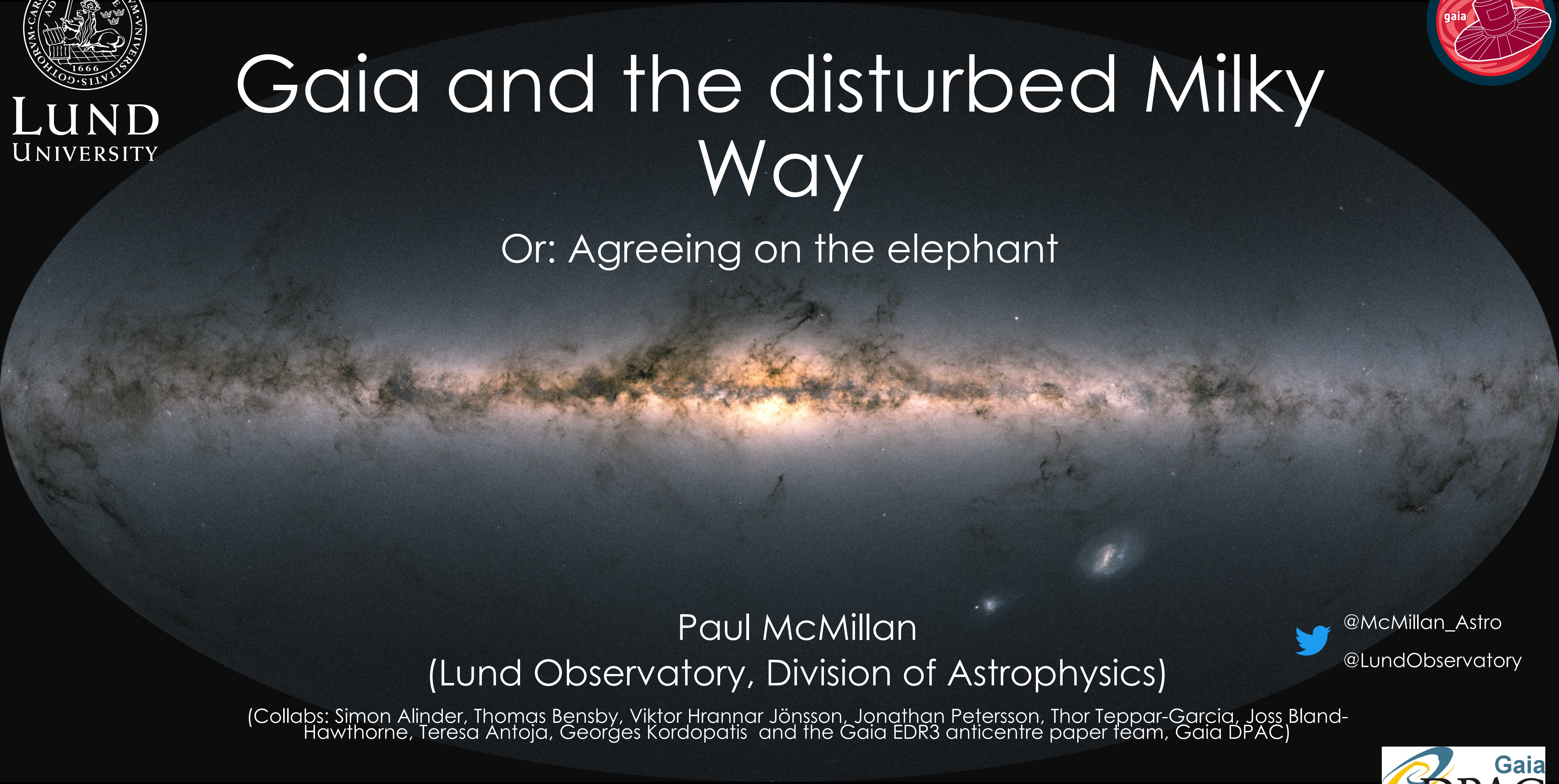


Gaia and the disturbed Milky Way

Or: Agreeing on the elephant

Paul McMillan
(Lund Observatory, Division of Astrophysics)

@McMillan_Astro
@LundObservatory

(Collabs: Simon Alinder, Thomas Bensby, Viktor Hrannar Jönsson, Jonathan Petersson, Thor Teppar-Garcia, Joss Bland-Hawthorne, Teresa Antoja, Georges Kordopatis and the Gaia EDR3 anticentre paper team, Gaia DPAC)

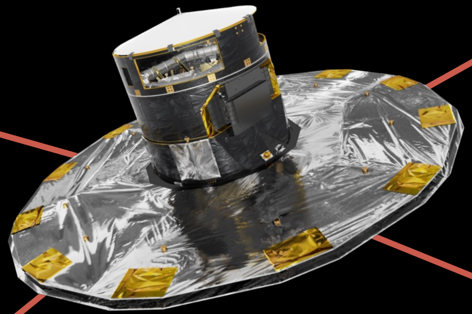

esa
gaia


IEEC
Gaia
DPAC
SanDiego

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)

Higher resolution spectroscopy

5.6 million AP

Why do we go to all this effort?

Milky Way is a fairly average Galaxy…

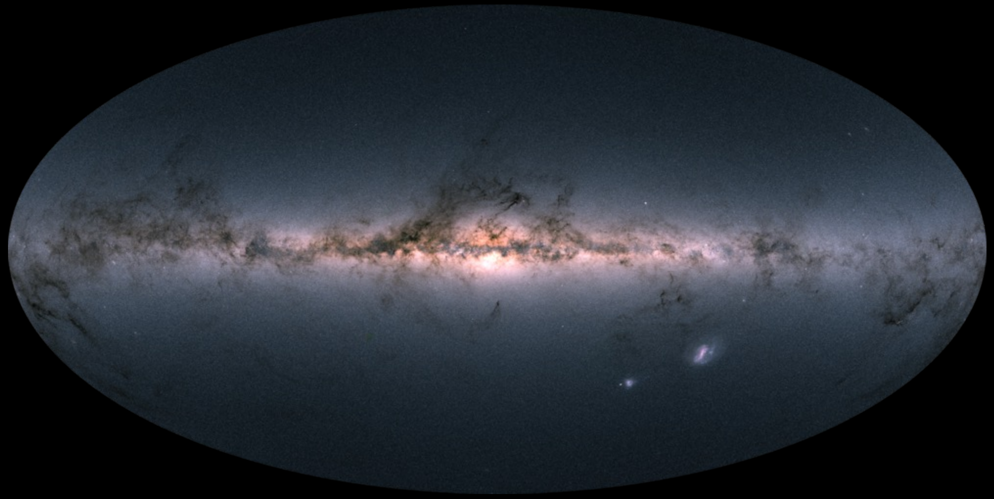
… but the way we view it is unique

<u>BIG advantages:</u>

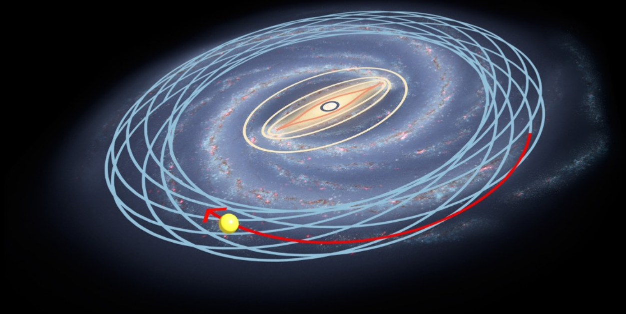
6D phase-space data, detailed chemical abundances on star-by-star basis.

<u>Important disadvantage:</u>

We can't see it from the outside!



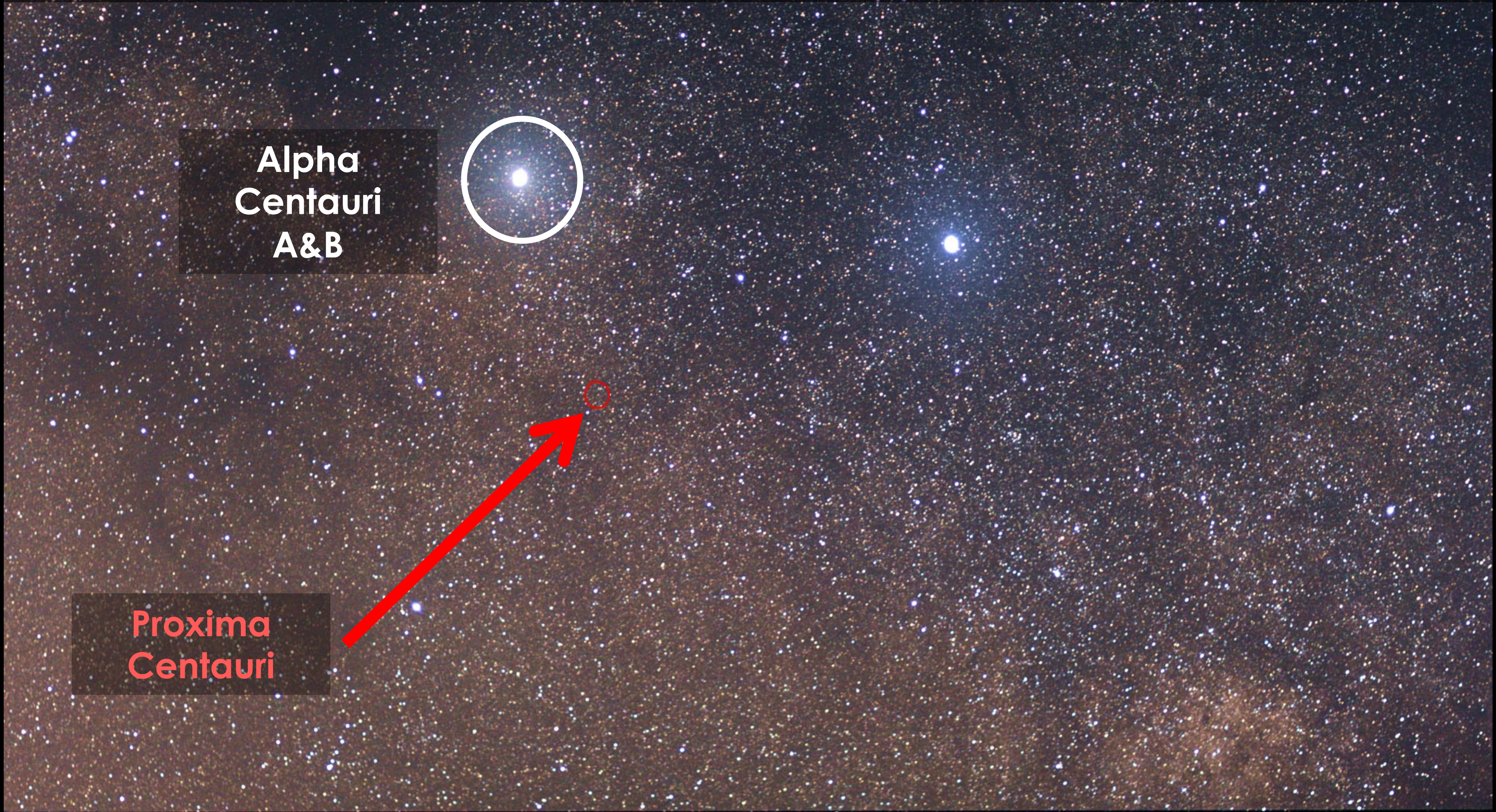
ESA/Gaia/DPAC



Adapted from NASA/JPL/Hurt image

The three closest stars to the Sun

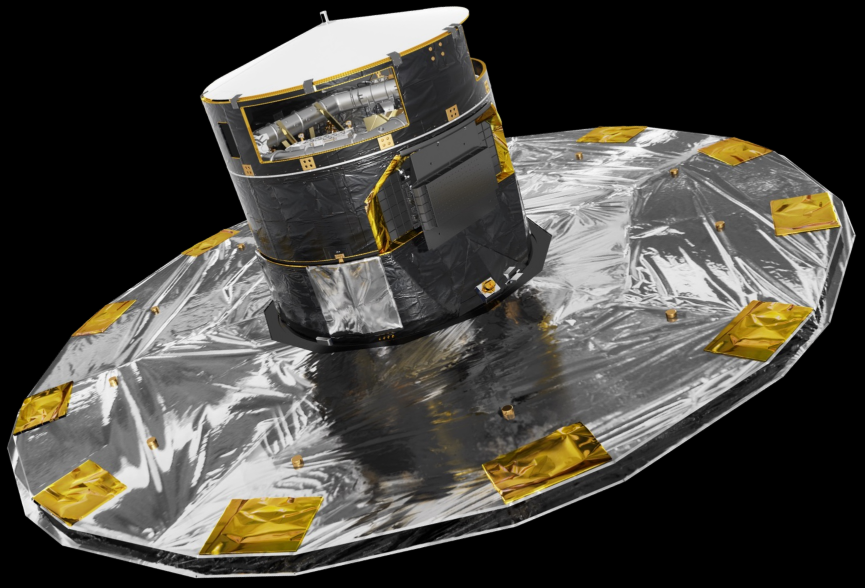
The three closest stars to the Sun

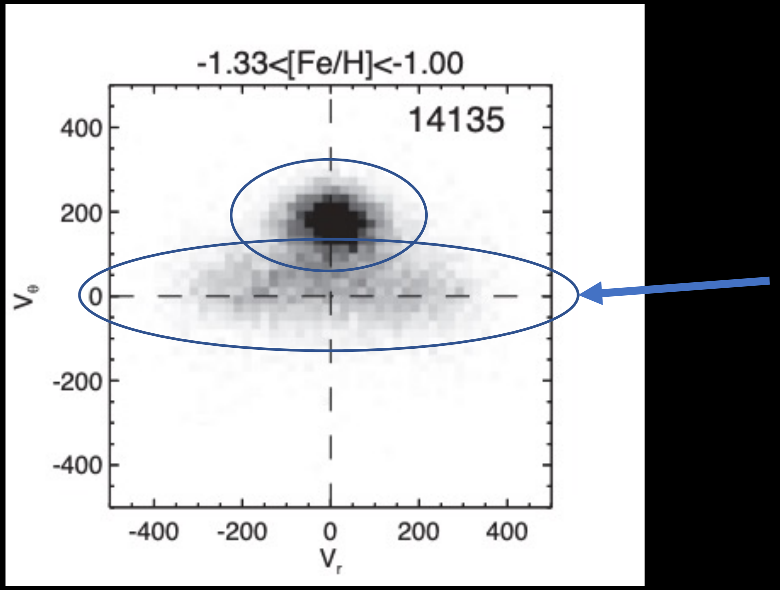


Gaia has been <u>unbelievably</u> influential

Over 10,000 unique citations to data release/mission papers.

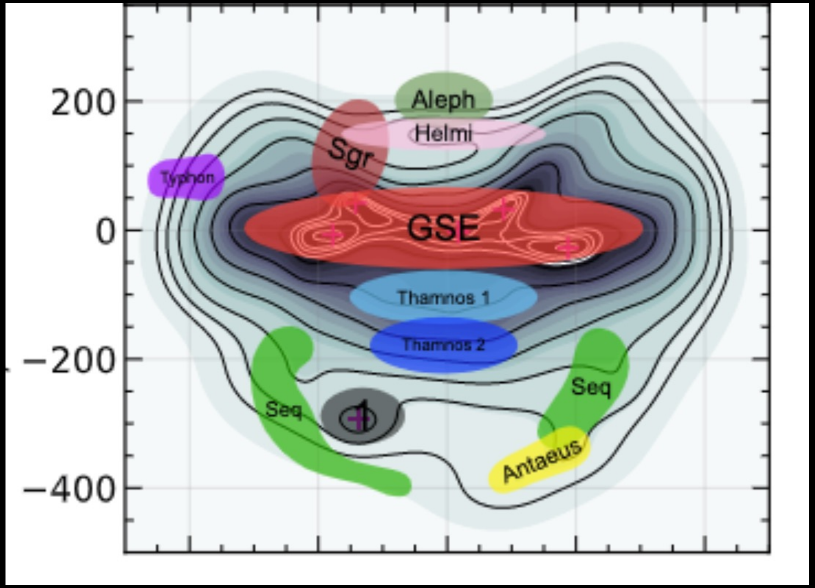
Incredible scientific output (on which I will just scratch the surface)



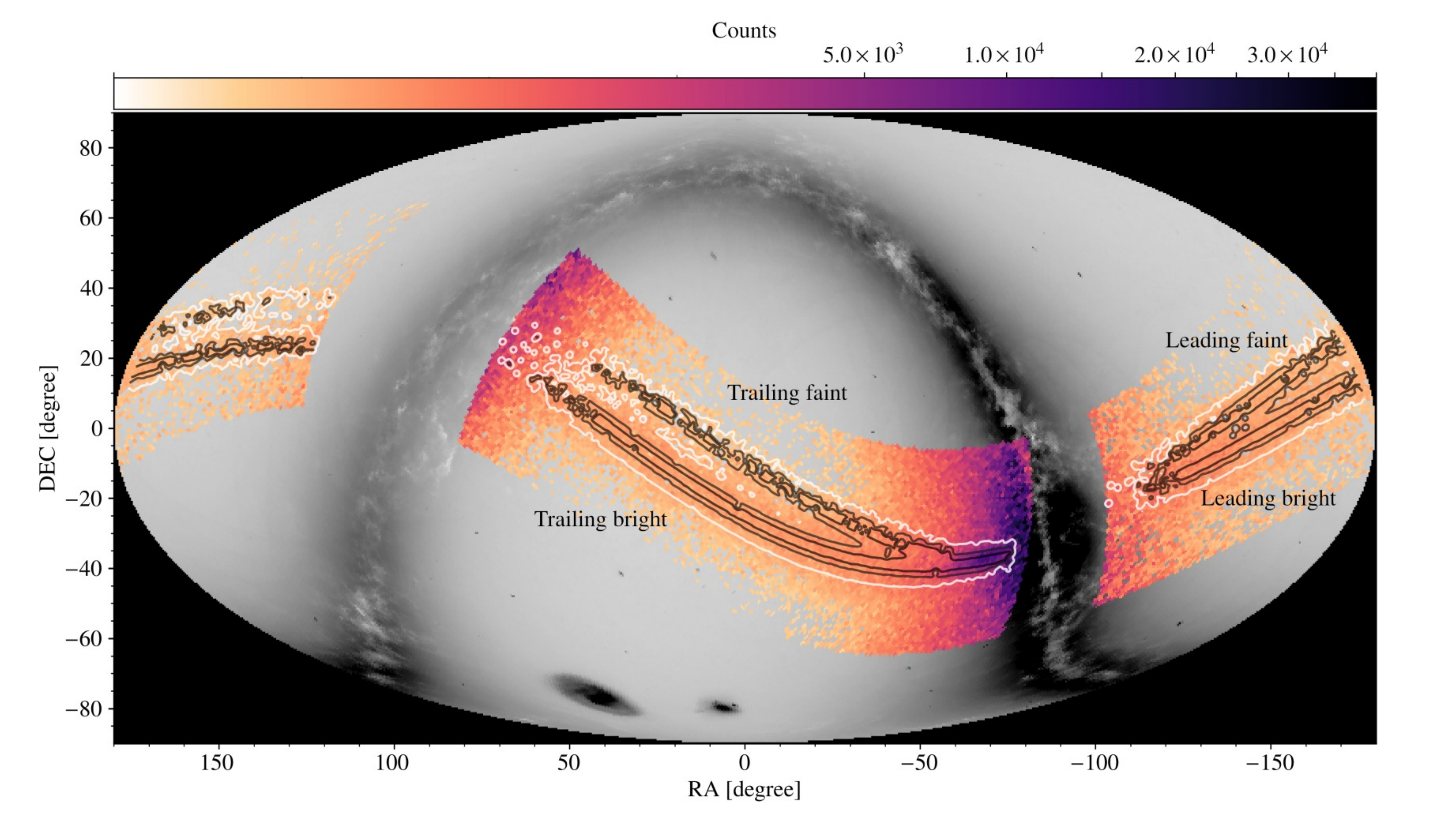


The 'Gaia sausage'

Belokurov et al (2018)

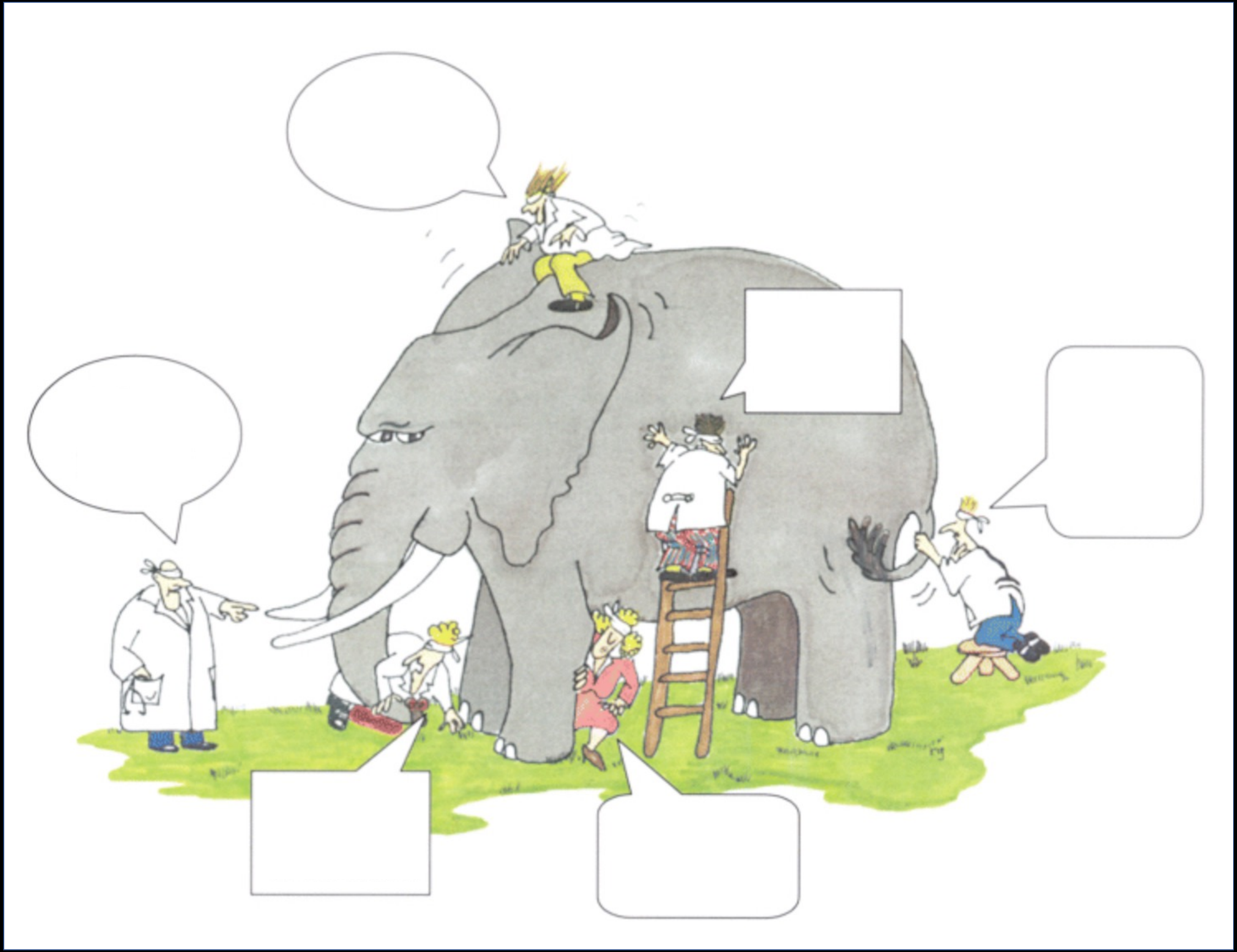


Mikkola, McMillan & Hobbs (2023)



New clarity about streams and disrupted dwarfs (e.g., Ramos et al 2022)

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



The disturbed Milky Way

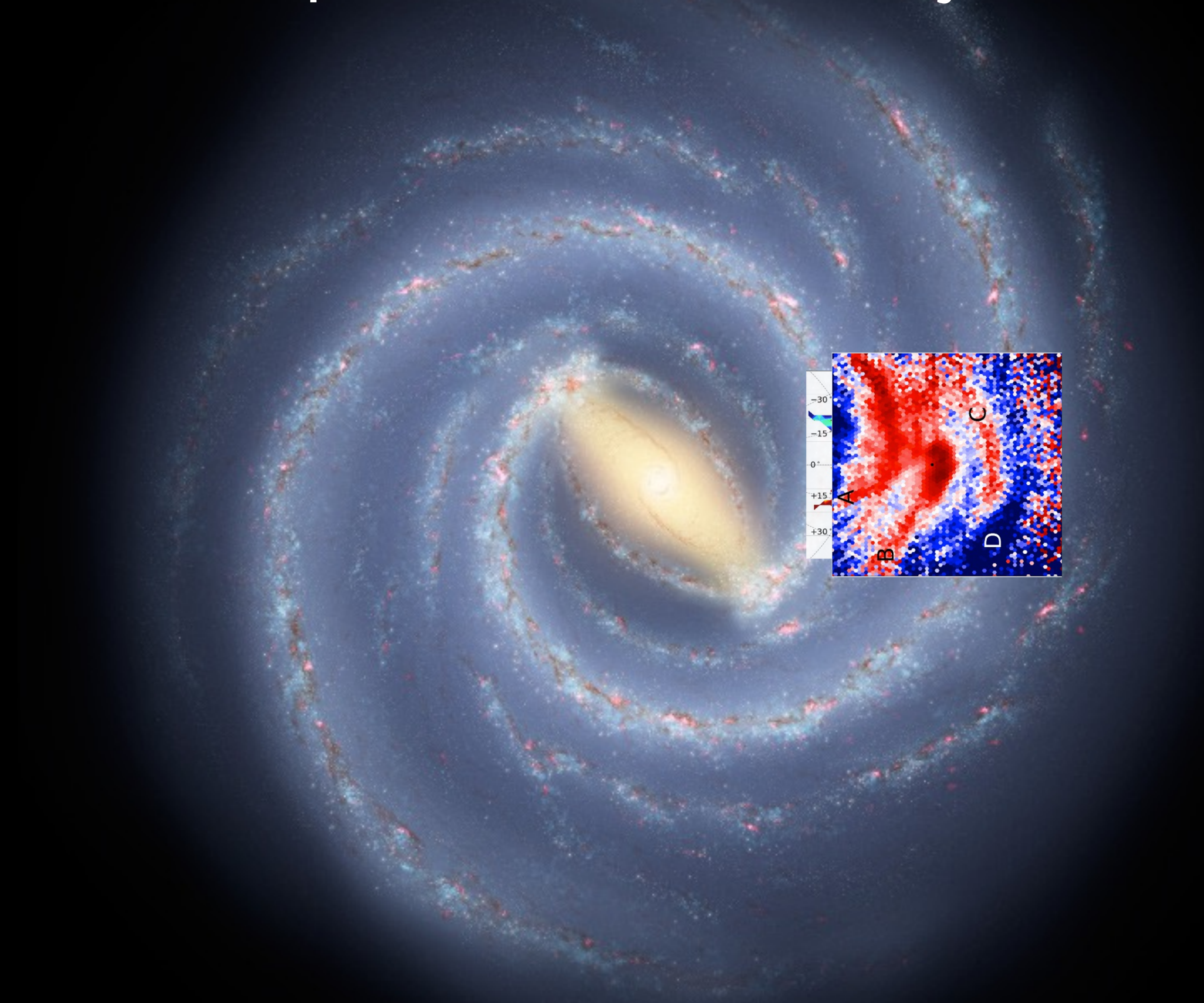
The Milky Way is not a simple smooth object

We know it has spiral arms & a bar

Gaia has measured associated velocity disturbance

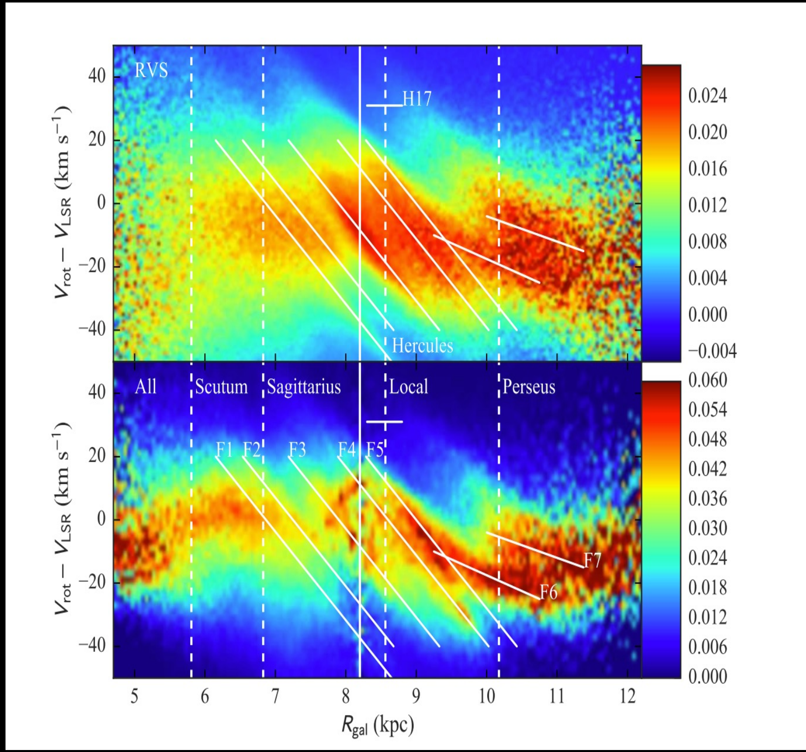
(Gaia Collaboration: Katz et al 2018)

(Palicio et al. 2023)

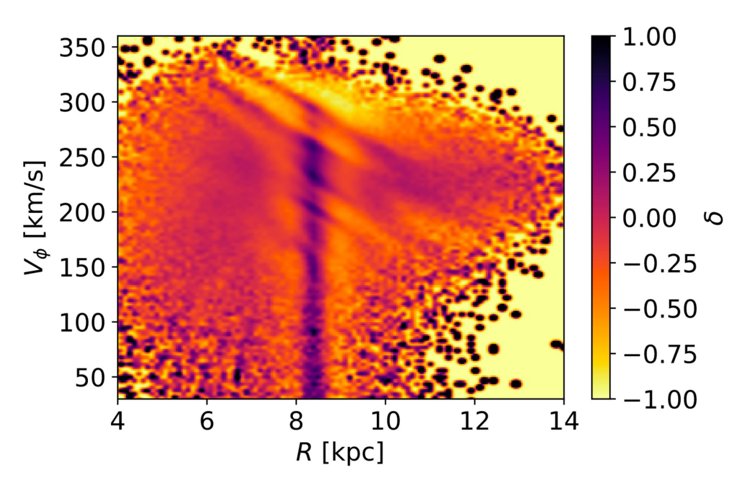


This is not a photo!
Credit: NASA/JPL-Caltech/R. Hurt

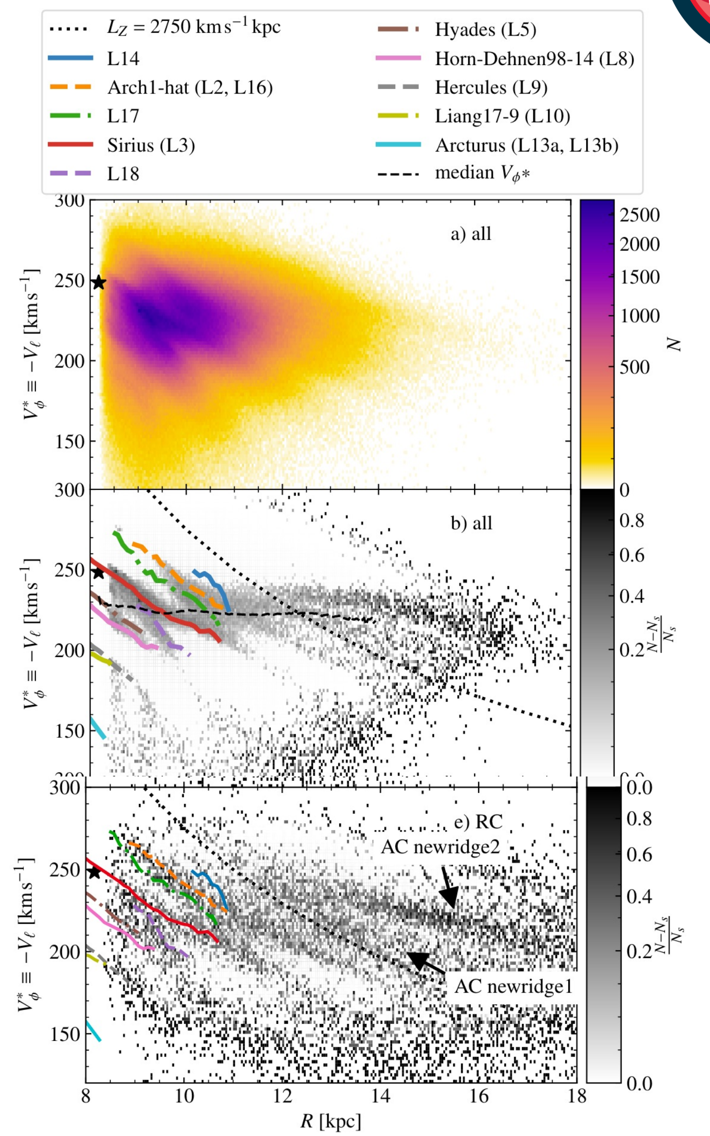
Velocity ridges



Kawata et al (2018)

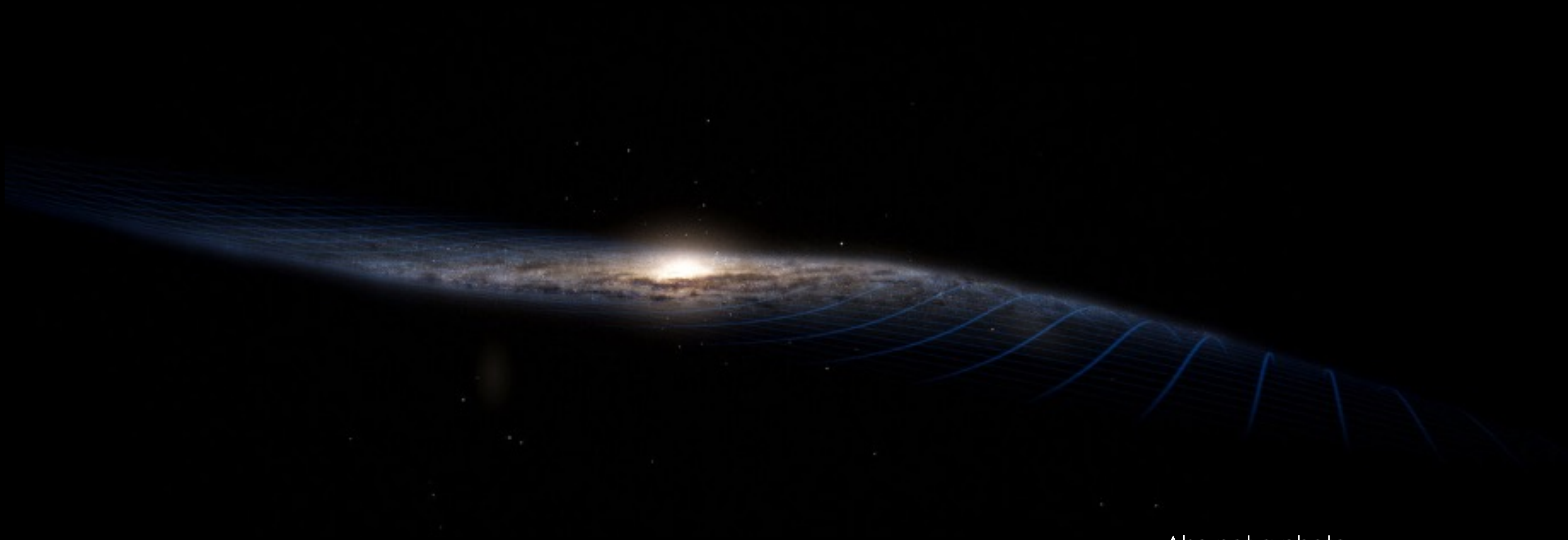


Laporte et al (2019)



Gaia Collaboration: Antoja et al (2021)

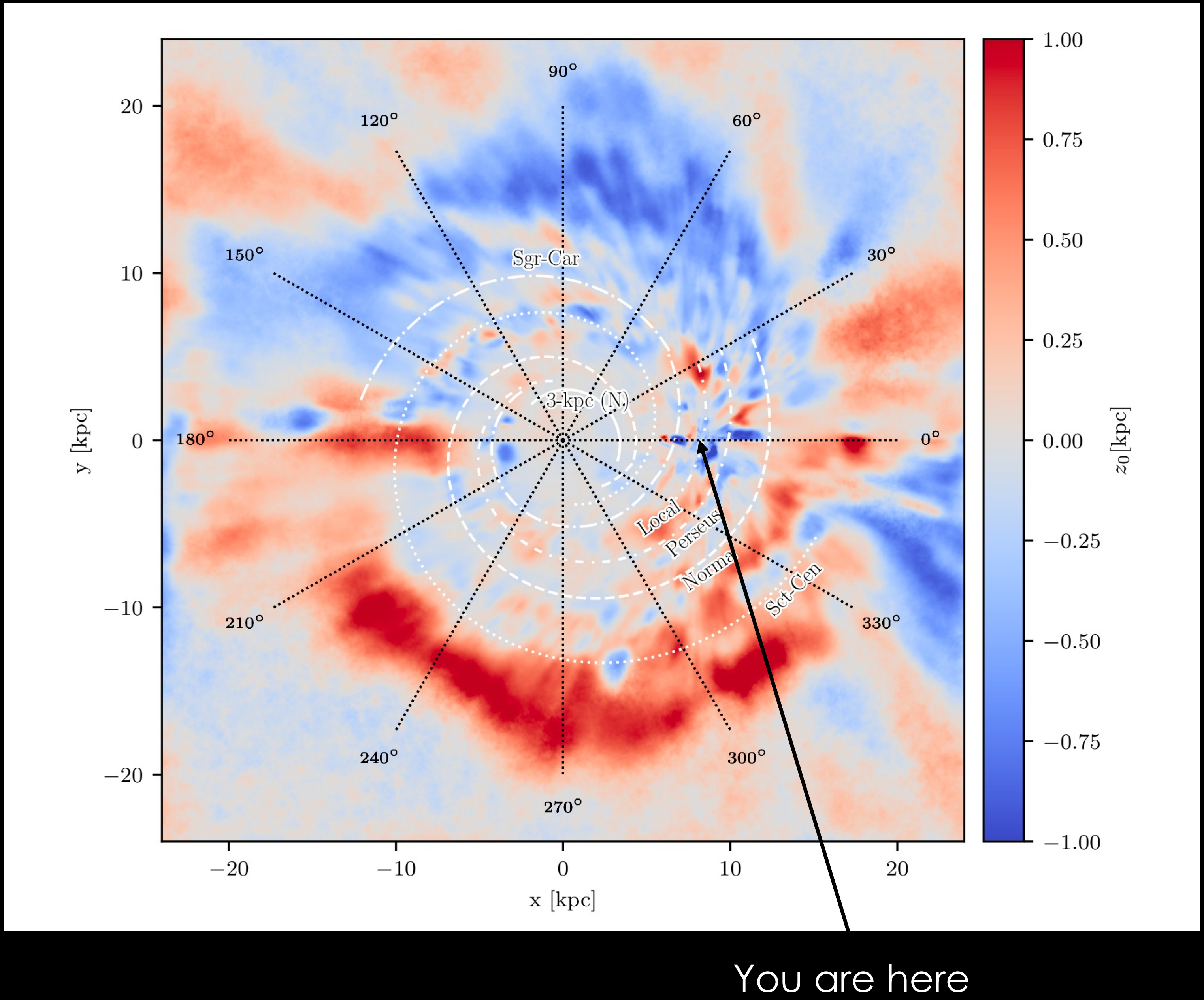
And a warp



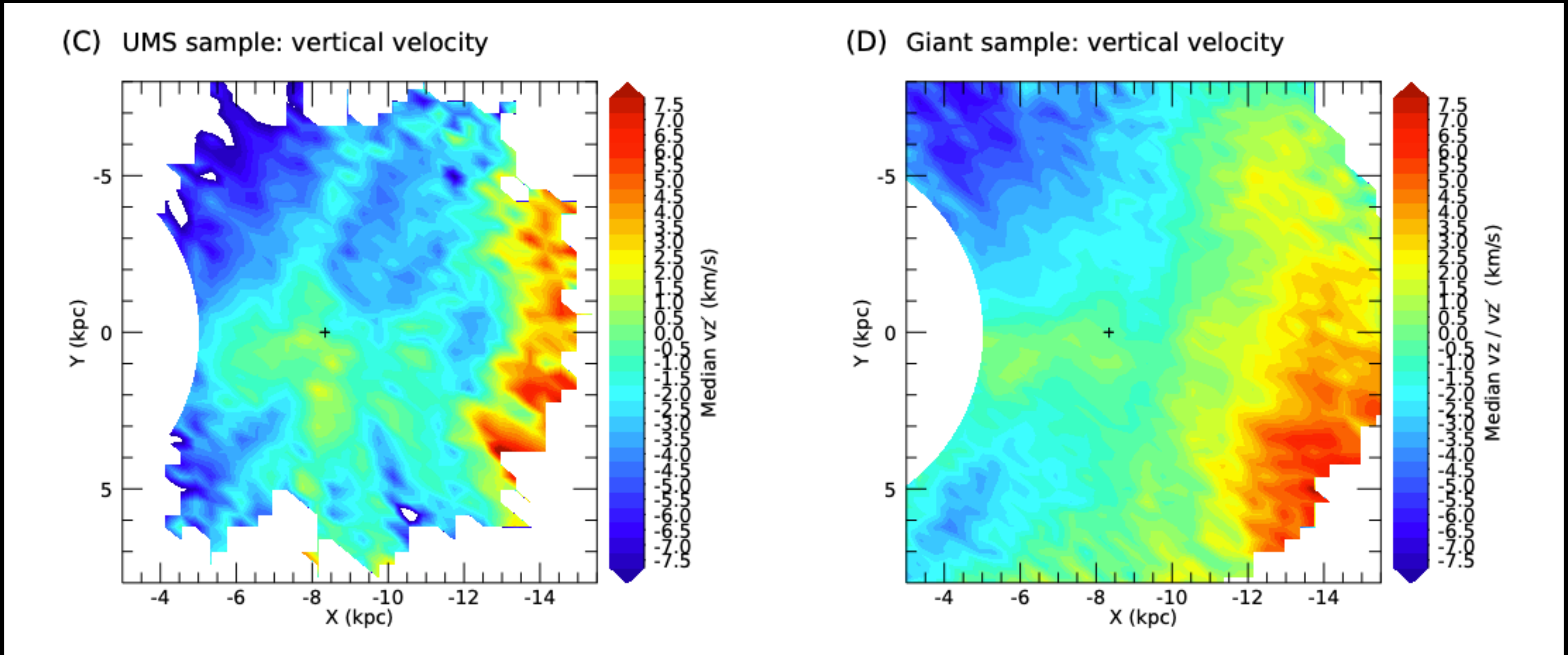
Also not a photo
Credit: Stefan Payne-Wardenaar

Clearly seen in the distribution of HI gas

(Mertsch & Phan 2022)

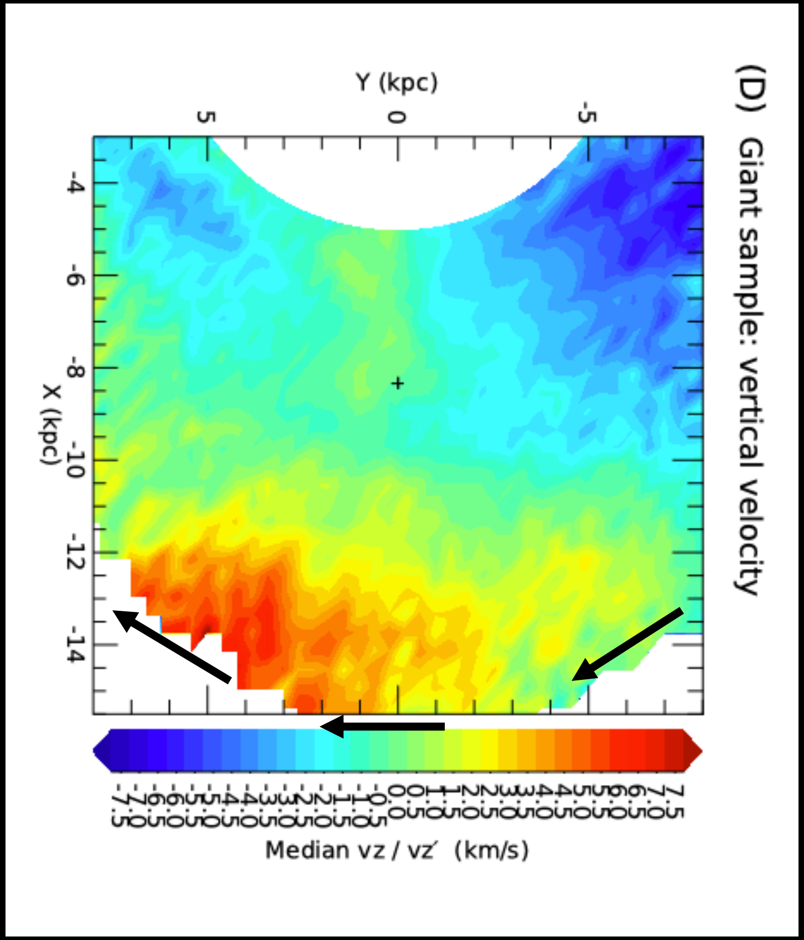


And a warp



Poggio et al 2018

And a warp

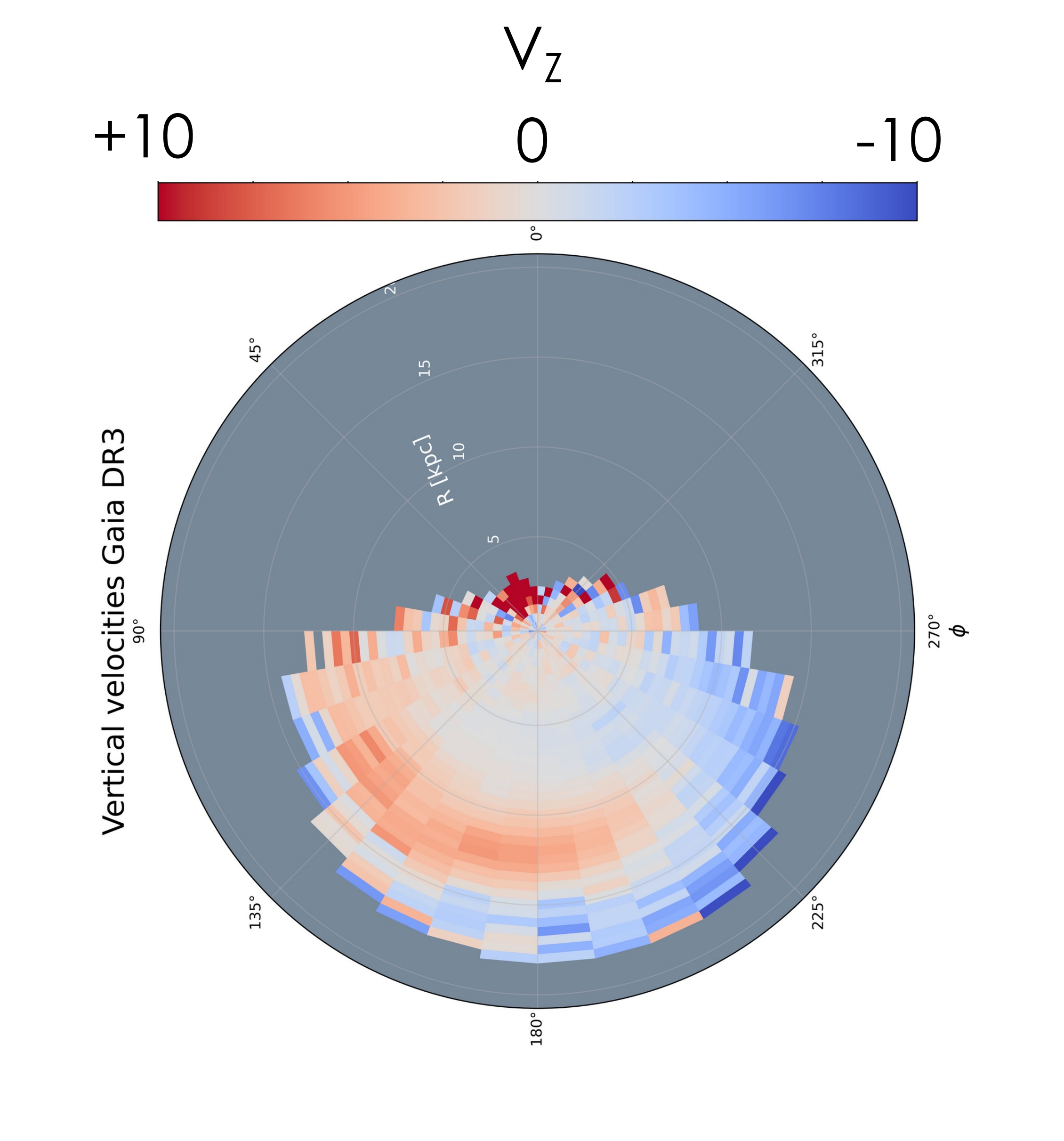


Poggio et al 2018

Looking a bit further with Gaia DR3

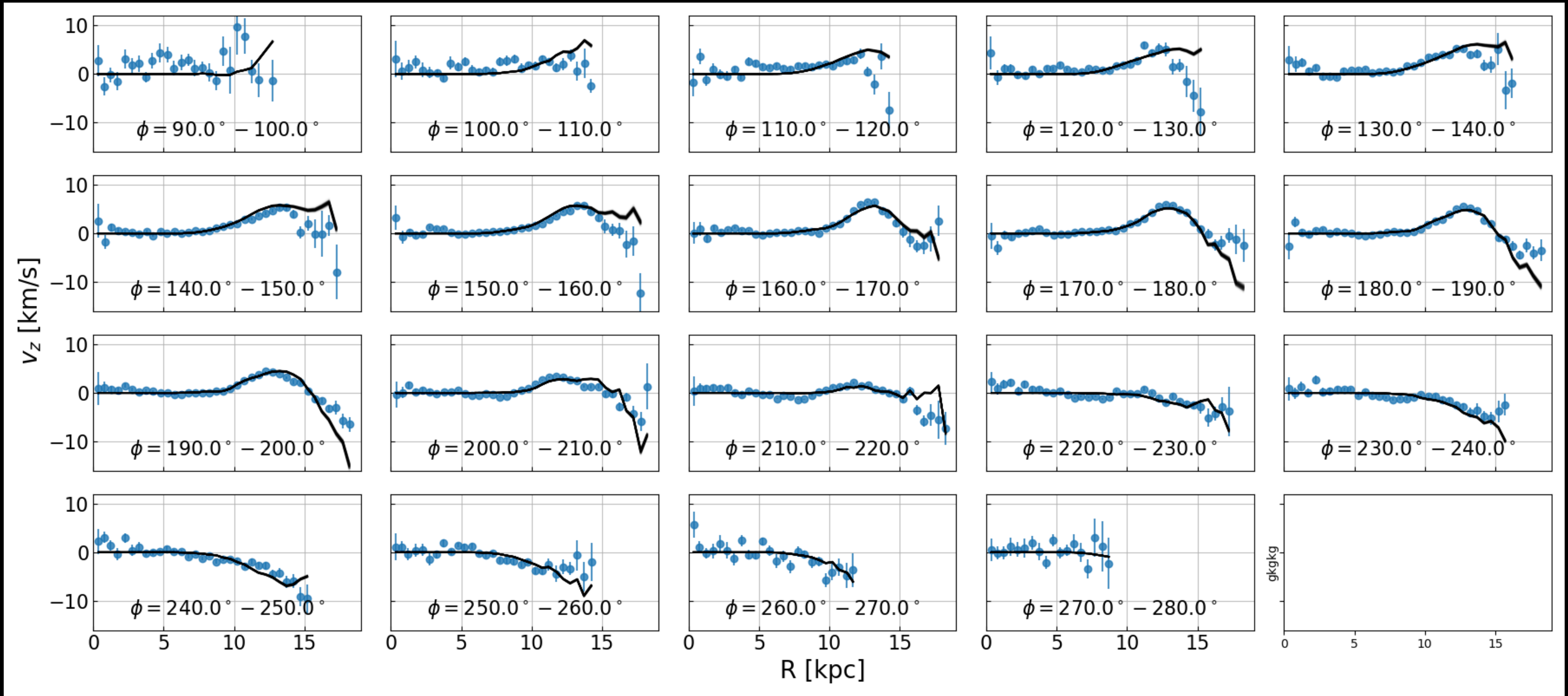
Note that the velocity goes upwards, then downwards

This is the warp precession catching up with the stars!



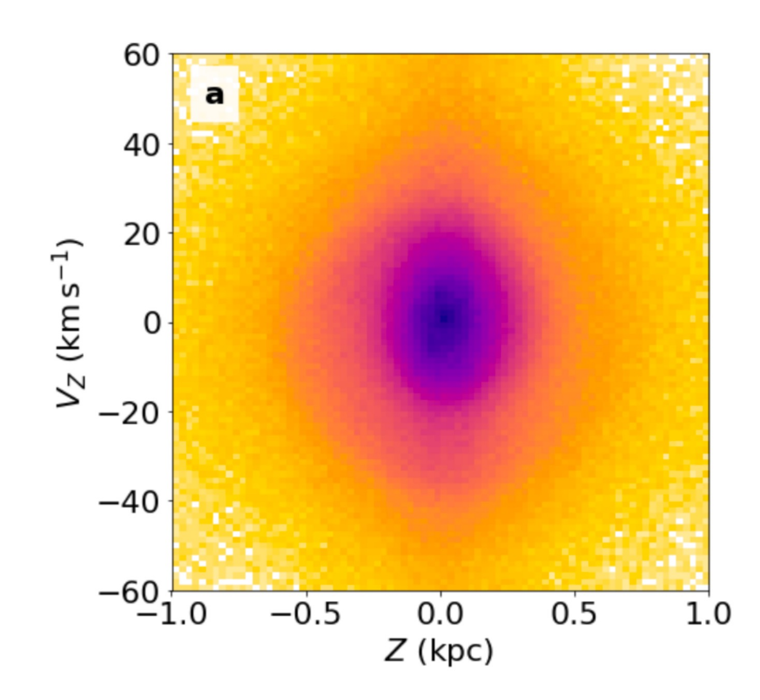
Hrannar Jónsson (Master's project – in progress)

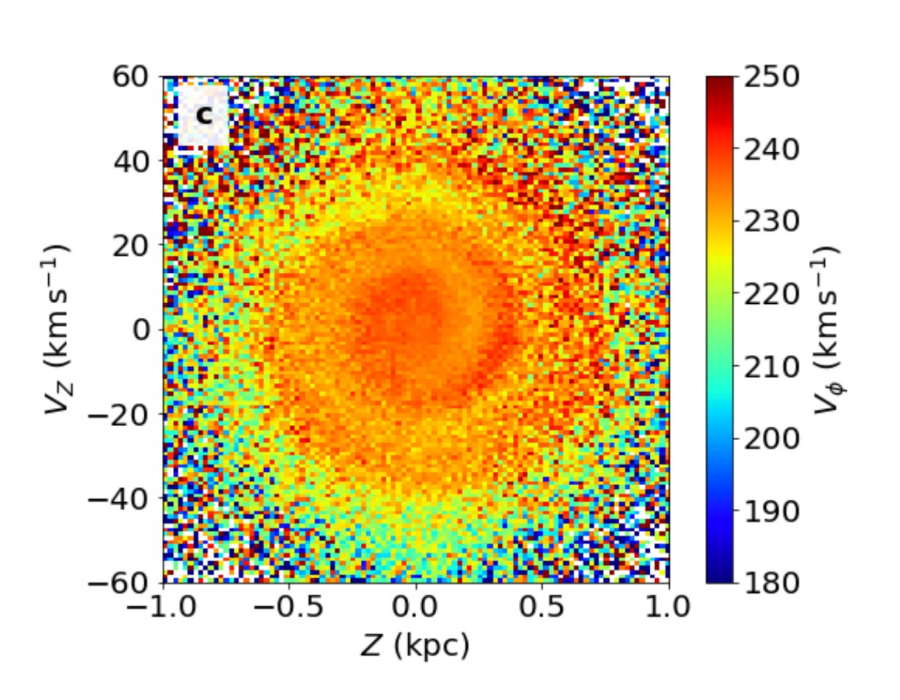
We can fit a warp model to this data with some success
Precession ~10 km/s/kpc



Hrannar Jónsson (Master's project – in progress)

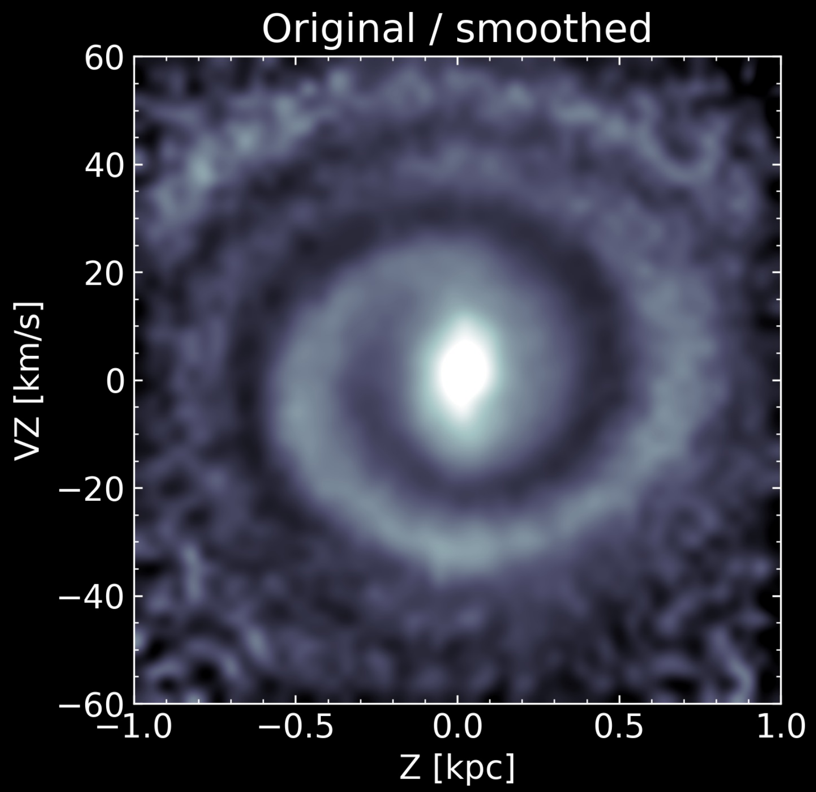
There's even something going on in the Solar neighbourhood





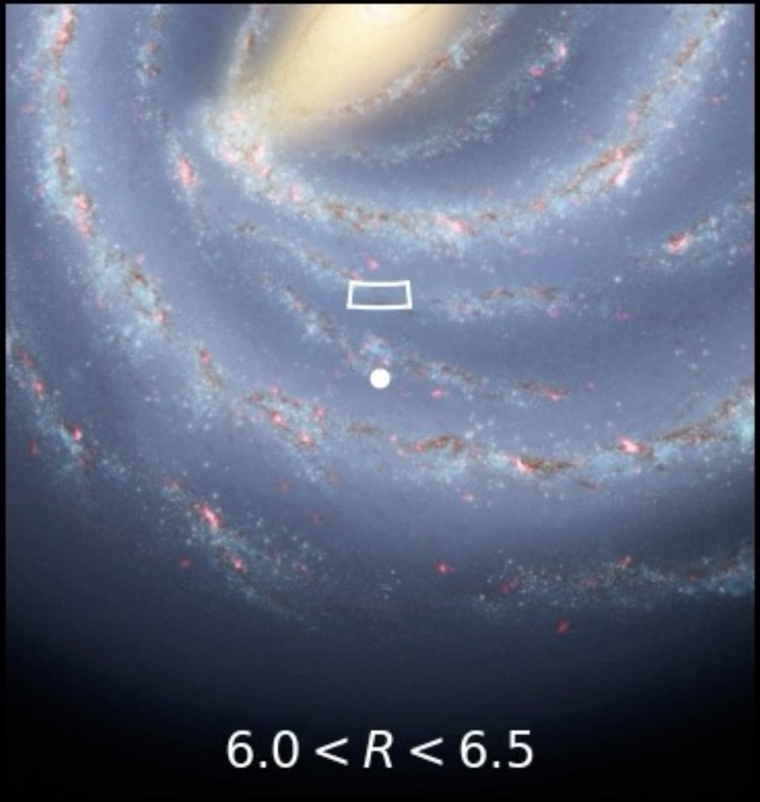
R~8kpc

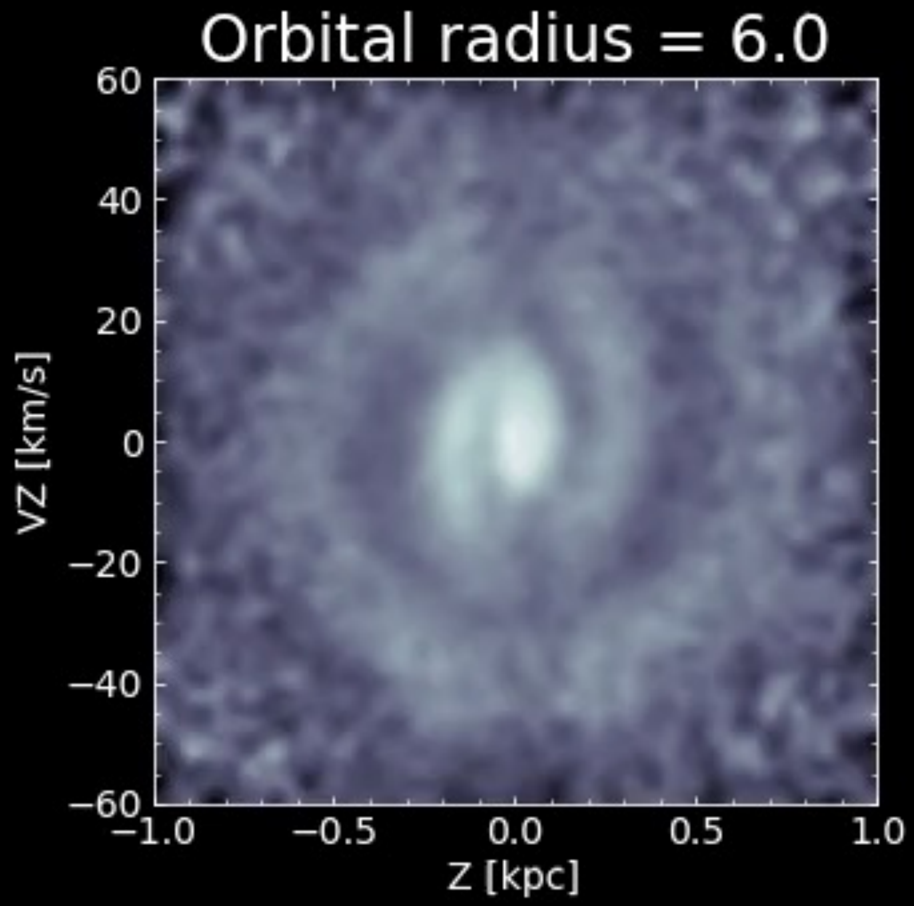
Phase-space snail, Phase-spiral, …
(Antoja et al 2018, and others)



Kanelbulle

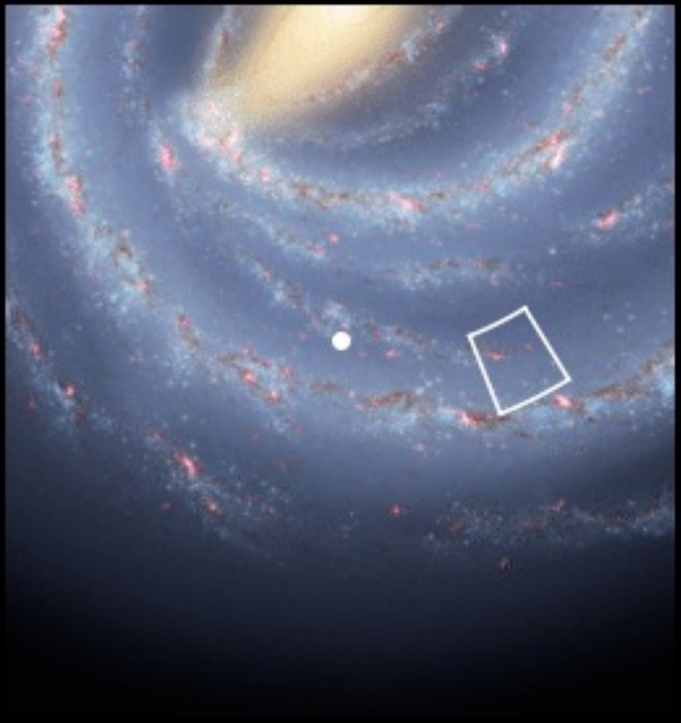
Kanelbulle changes in shape and character as I look outwards in the disc

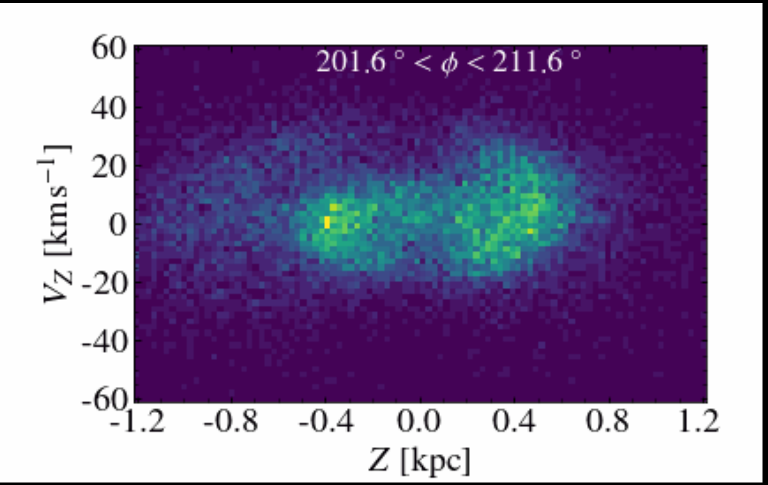




[Orbital radius = L_z/236 km/s]

Looking carefully, you can even see the kanelbulle rotate when you look around the Galaxy





Alinder, McMillan & Bensby (submitted, arXiv:2303.18040)

How do we make kanelbullar?

Ingredienser

ca 40 bullar eller 4 längder

- 150 g smör eller margarin, rumsvarmt (eller 1½ dl flytande)
- 5 dl mjölk
- 50 g (1 pkt) jäst för söta degar
- 1 dl strösocker eller vit baksirap
- ½ tsk salt
- eventuellt 2 tsk stött kardemumma
- 800 g (ca 1,4 l) Kungsörnen Vetemjöl av fint kärnvete

Kanelfyllning:

- 150 g rumsvarmt smör eller margarin
- 1 dl strösocker
- 2 msk kanel

Kanelbullar - grundrecept

Vårt klassiska recept på Vetebullar/Kanelbullar/Vetebröd, samma recept som återfinns på våra vetemjöls-förpackningar! Receptet ger 40 småbullar eller 4 längder. Förutom den klassiska fyllningen med kanel finner du nedan tips på nya alternativ - testa Choklad- och hasselnötsfyllning, mandelmassa- och apelsinfyllning, eller Nutellafyllning och tyck till nedan om vilken som är din favorit!

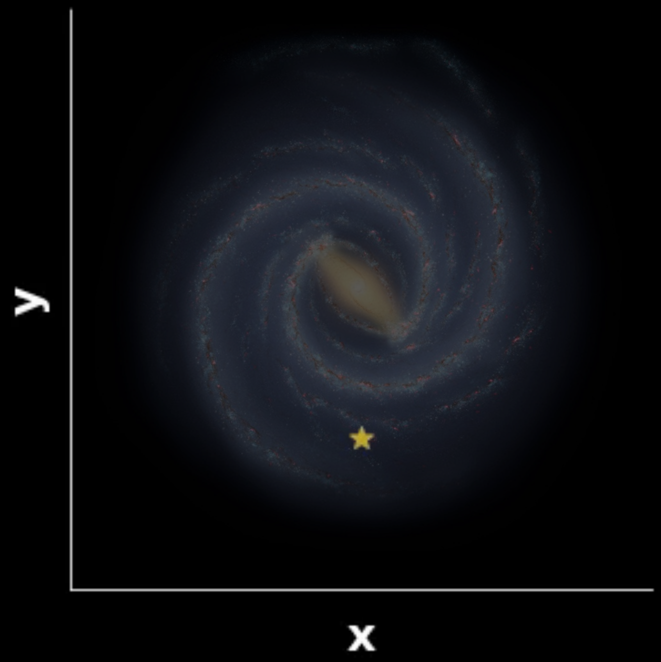
Så här tillagar du receptet (ca 120 minuter):

1. Värm mjölken till 37°C (fingervarmt).
2. Smula ner jästen i en degskål på 3-4 l. Häll över mjölken och rör om. Tillsätt matfettet i bitar, socker eller sirap, salt och eventuell kardemumma.
3. Mät upp mjölet. Häll det luftigt direkt ur påsen i ett litermått. Skaka inte måttet. Tillsätt mjölet men spar ½ dl till utbakningen.
4. Arbeta degen kraftigt, cirka 5 minuter med maskin eller 10 minuter för hand, tills den känns smidig.
5. Låt degen jäsa övertäckt med bakduk cirka 30 minuter.
6. Arbeta ner degen med maskin eller knåda den lätt på mjölat bakbord. Dela degen i 4 delar. Kavla ut varje del till en avlång kaka.
7. Rör ihop ingredienserna till valfri fyllning och bred ett tunt lager på kakan. Rulla ihop till en rulle. Fler utbakningsförslag, se längre ner.
8. Låt bröden svalna på galler under bakduk.

Lantmän

Bullar: Skär rullen i 10 delar och lägg dem med snittytan upp i pappersformar eller på plåtar täckta med bakplåtspapper. Låt jäsa under bakduk cirka 40 minuter. Värm ugnen till 225-250°C. Pensla med ägg och grädda sedan bullarna mitt i ugnen, 5-10 minuter.

View from above



View from the side

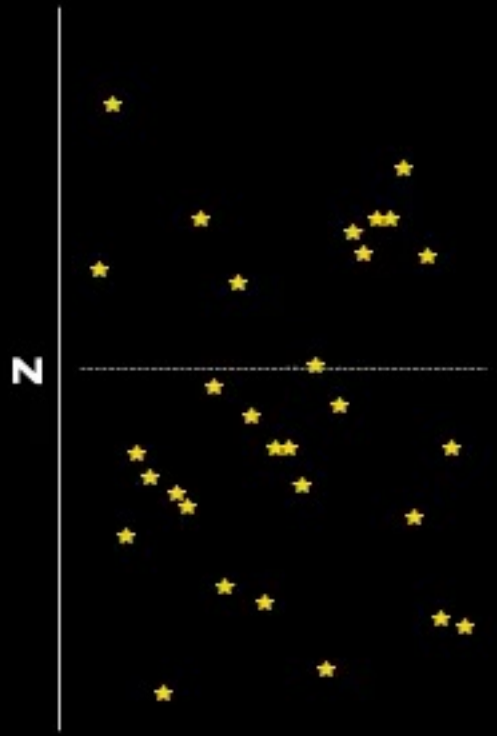
Orbiting stars also oscillate above and below the plane

To a good* approximation for stars at the same radius, we can isolate this and ignore other movement

* good enough for now, anyway

Stars oscillate around z = 0

Frequency decreases as oscillation gets bigger

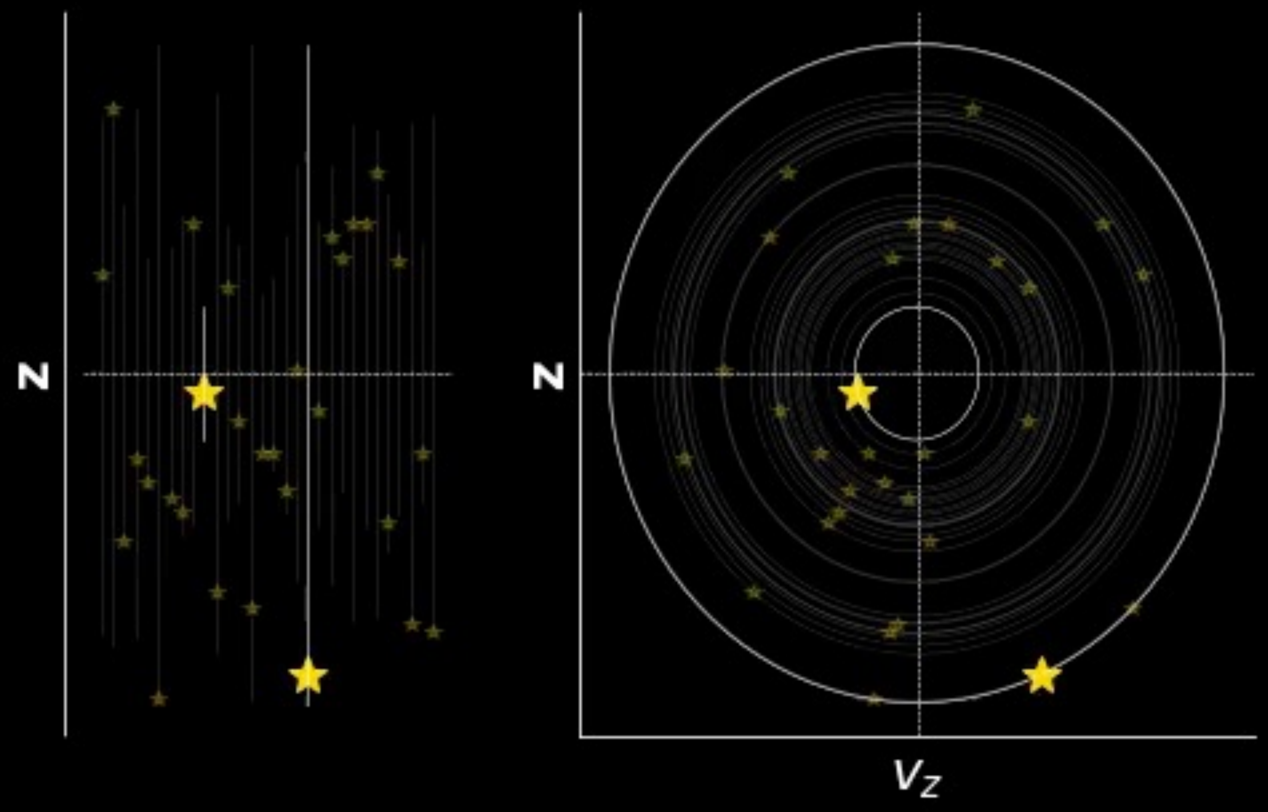


N.B. offset on x-axis completely arbitrary

Stars oscillate around z = 0

Frequency decreases as oscillation gets bigger

(isolating two stars so you can see this clearly)

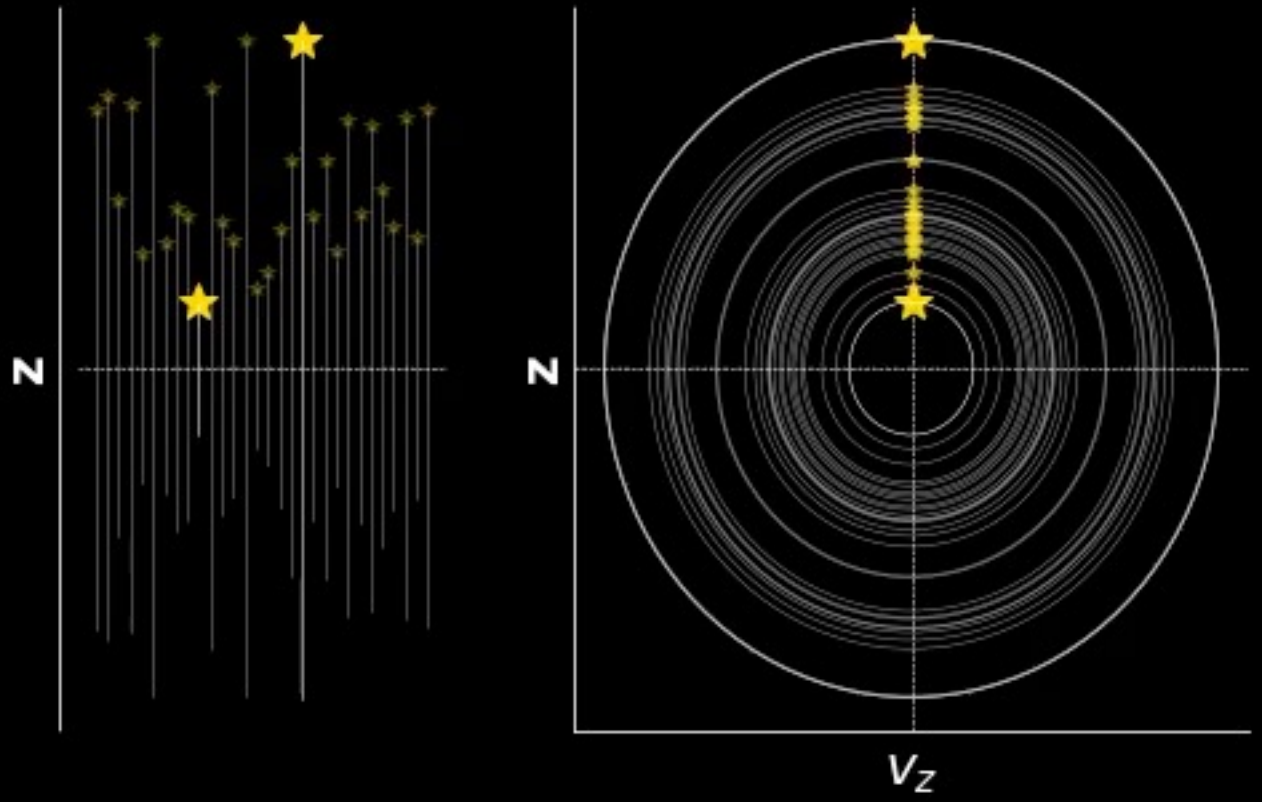


Stars oscillate around z = 0

Frequency decreases as oscillation gets bigger

In the z-v_z plane, each star follows an ellipse/circle*

*roughly.



Stars oscillate around z = 0

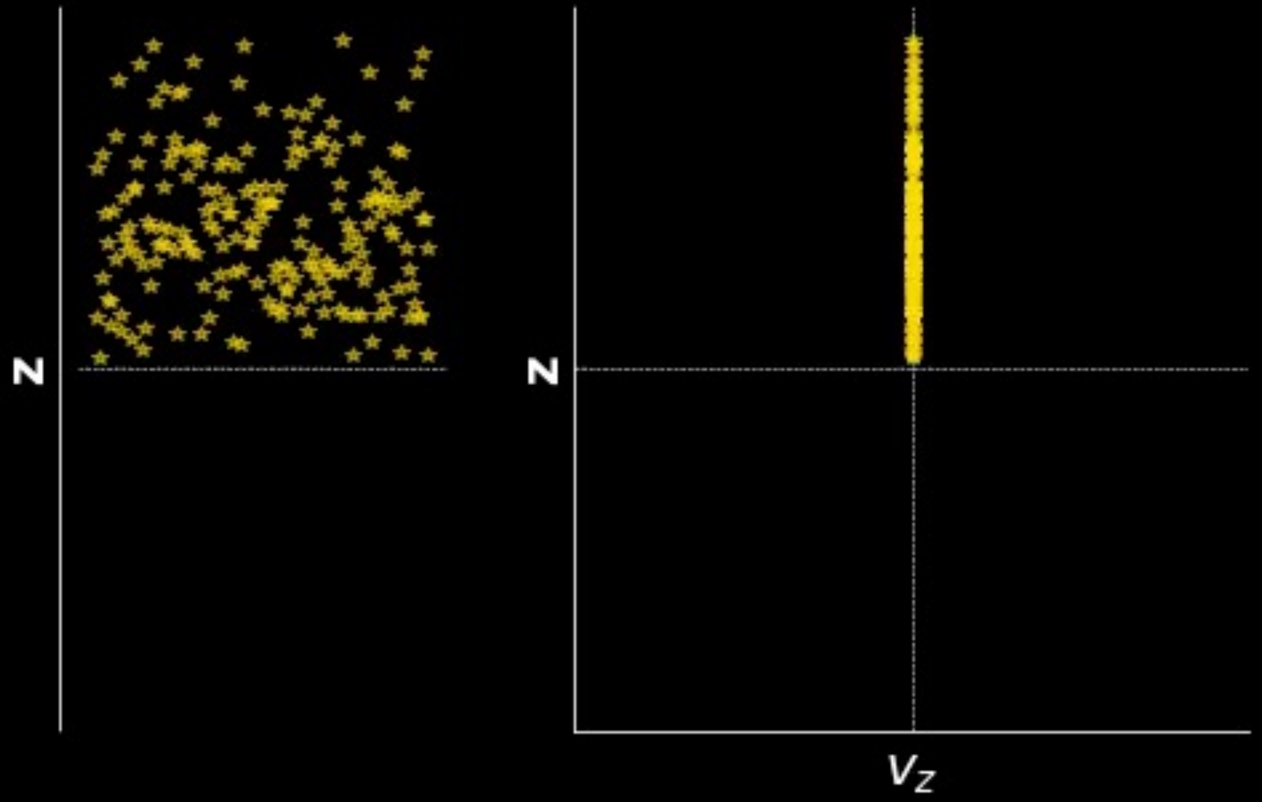
Frequency decreases as oscillation gets bigger

In the z-v_z plane, each star follows an ellipse/circle*

If we start all orbits at their maximum z, decreasing frequency → kanelbulle

frequency → spiral

*roughly.



Stars oscillate around z = 0

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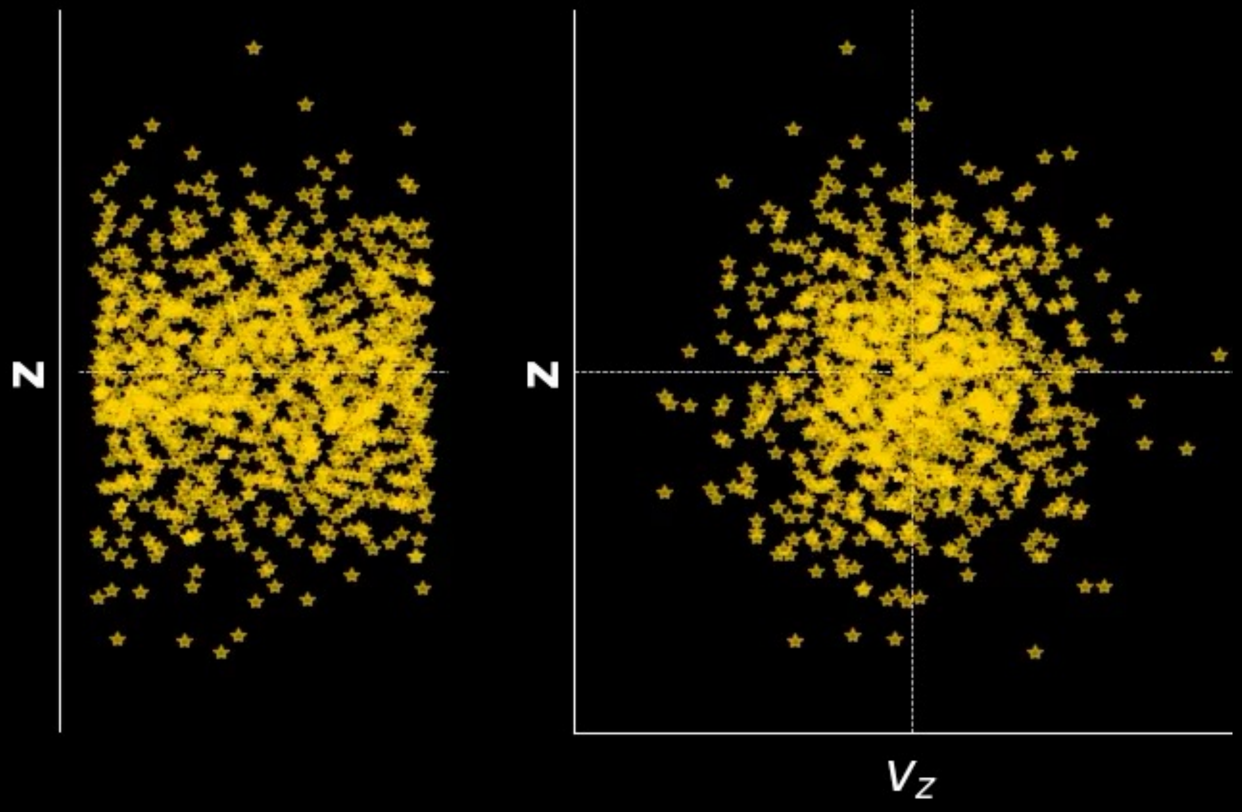
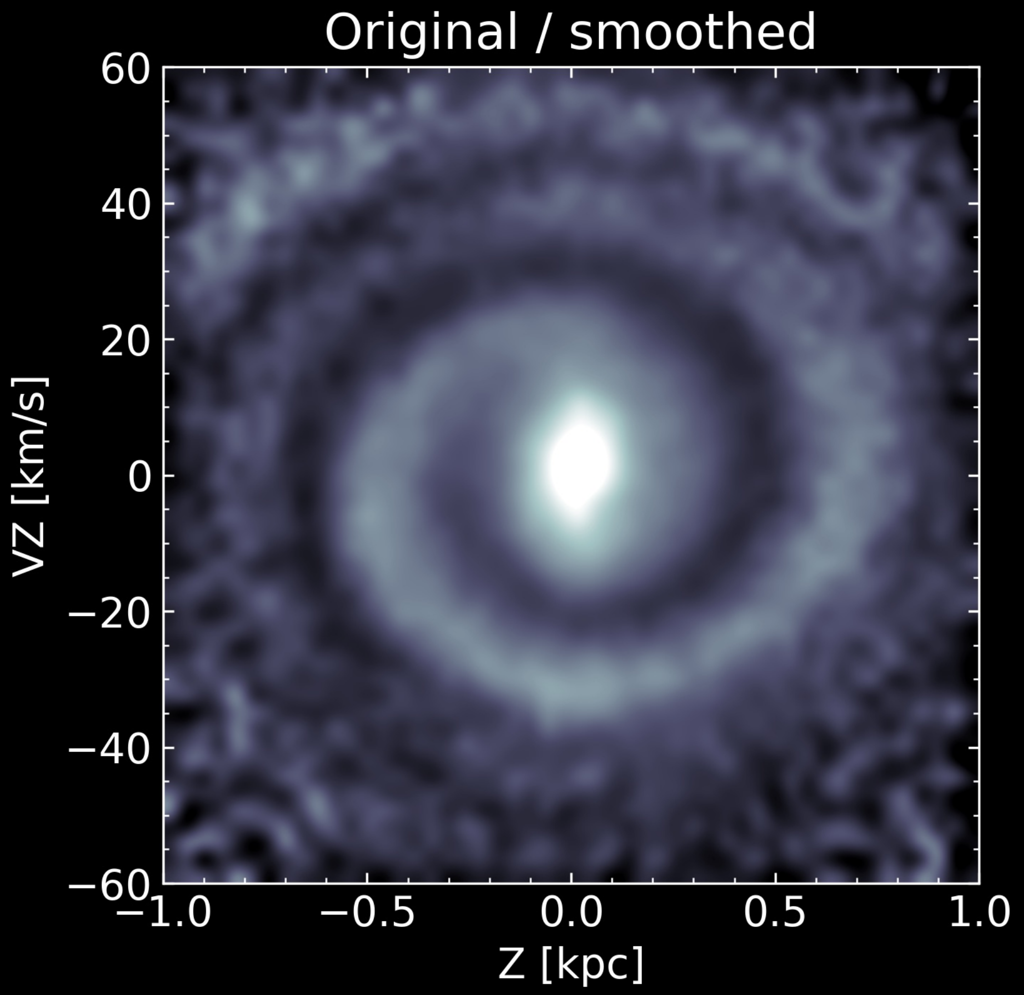
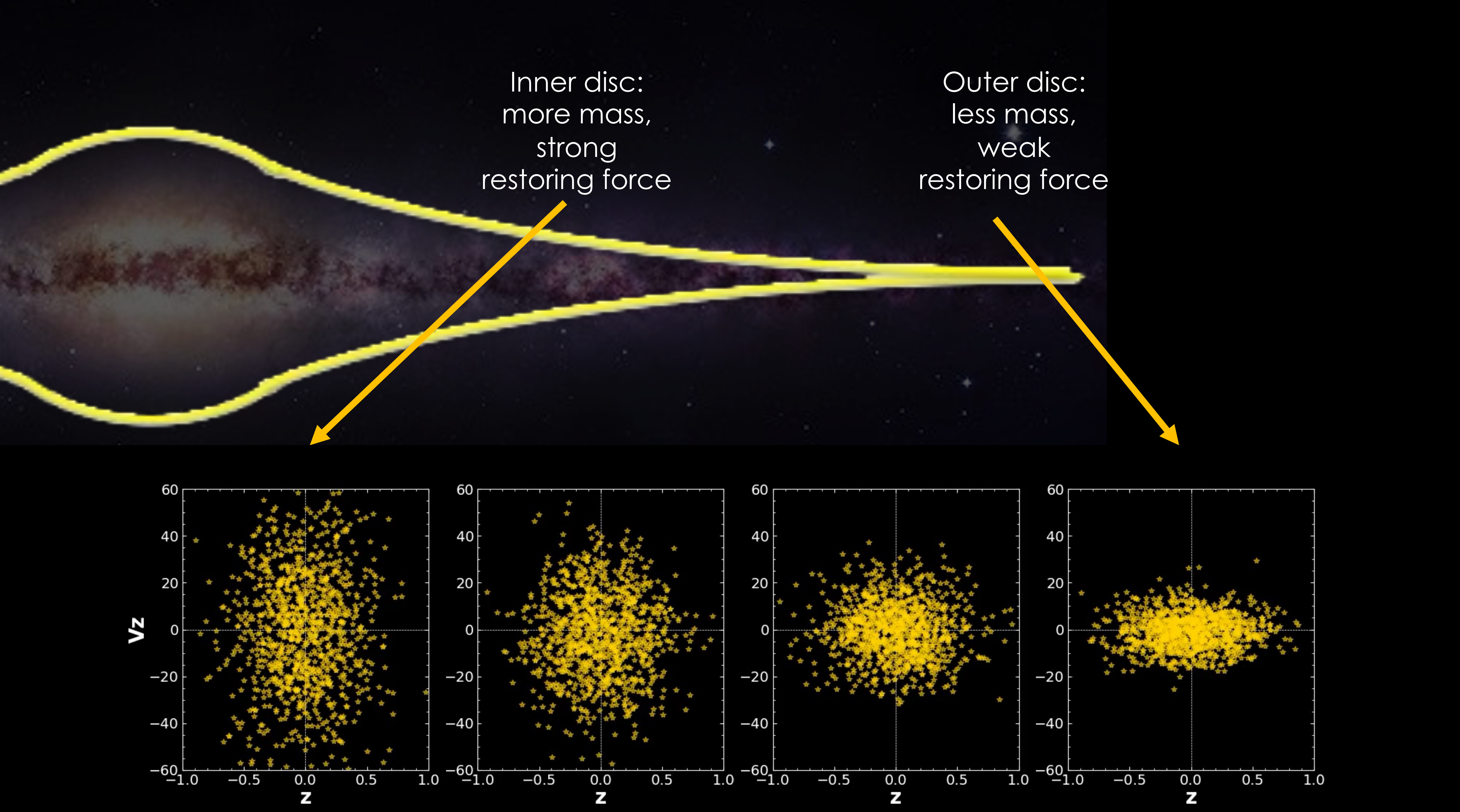
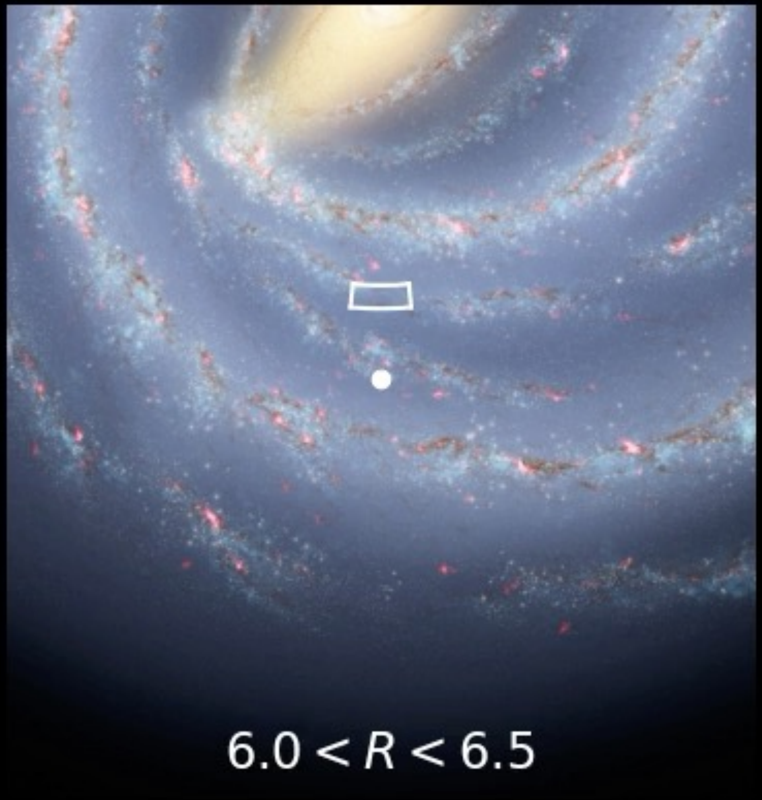
*roughly.

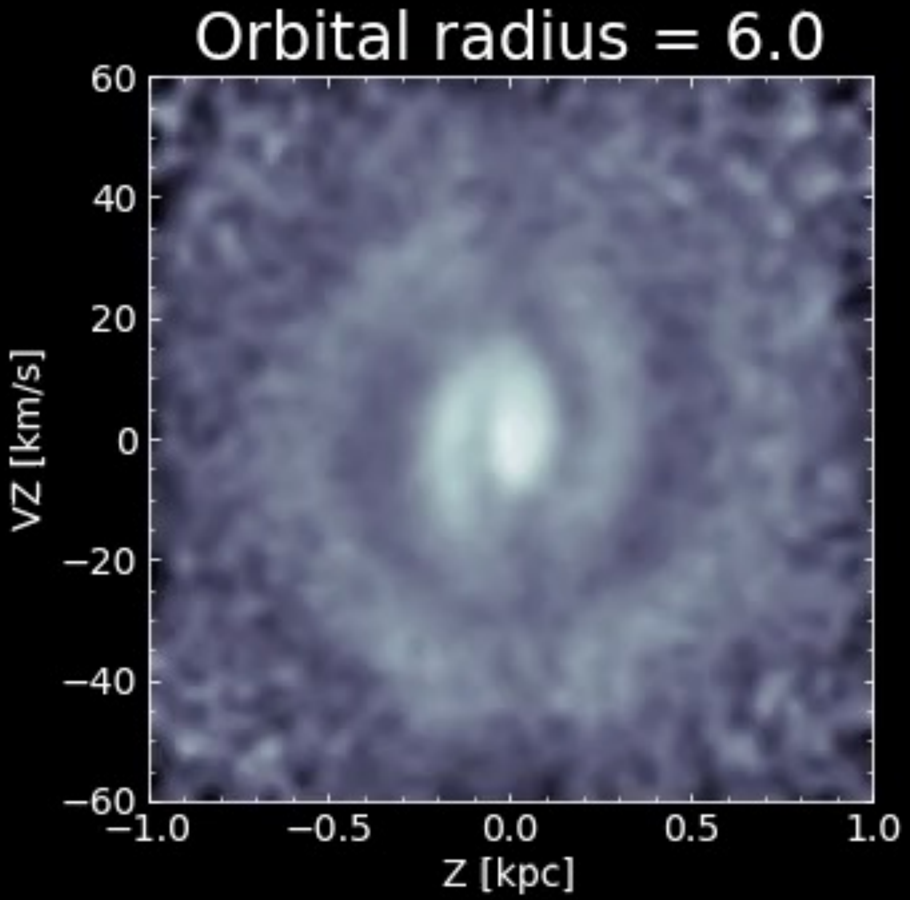

Z
Z
V_Z

Original / smoothed
60
40
20
0
−20
−40
−60
VZ [km/s]
−1.0
−0.5
0.0
0.5
1.0
Z [kpc]



Inner disc:
more mass,
strong
restoring force
Outer disc:
less mass,
weak
restoring force
Vz
z
z
z
z

Which explains (some of) what we see here





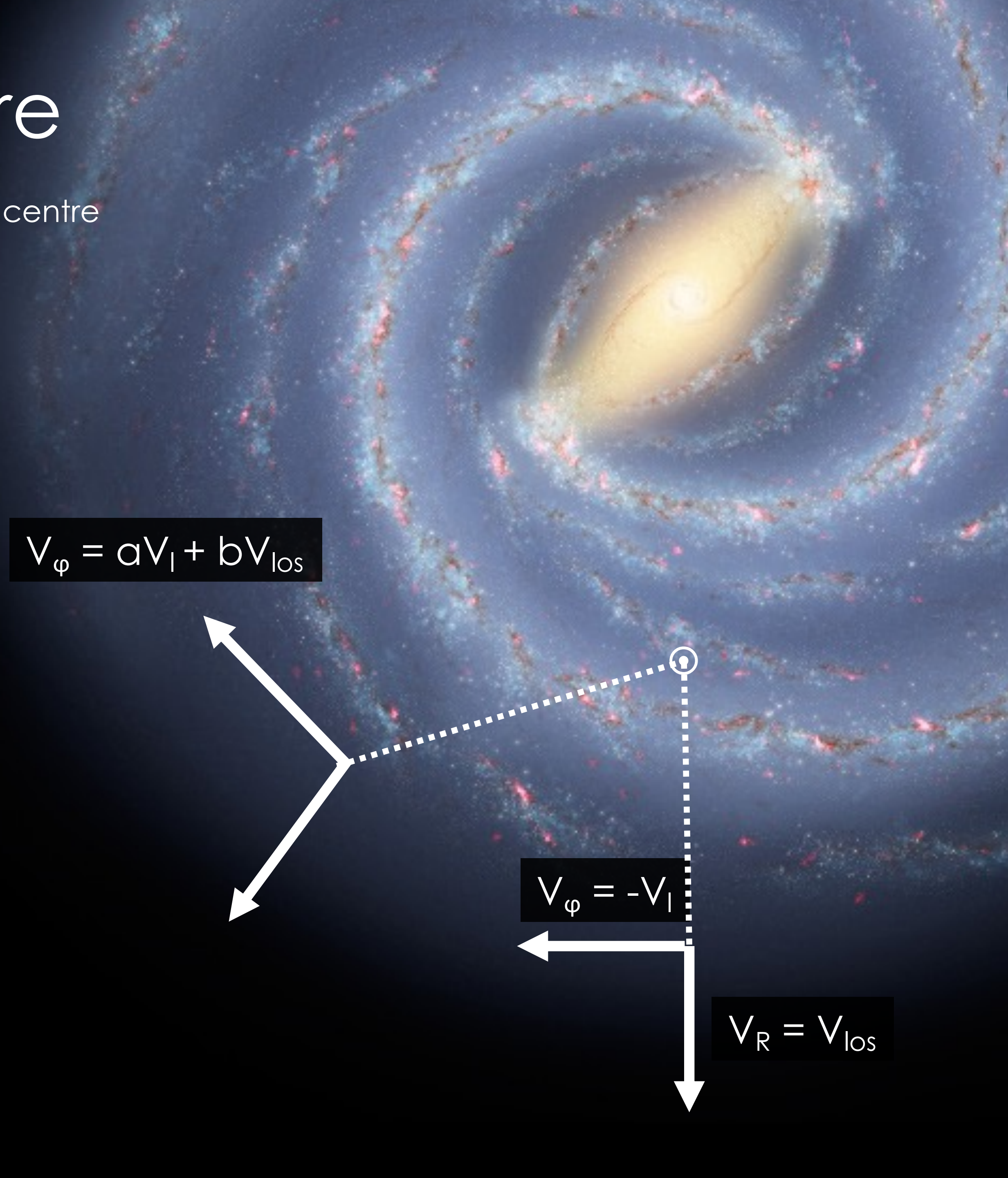
What else can we see in the outer disc?

The Galactic anticentre

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

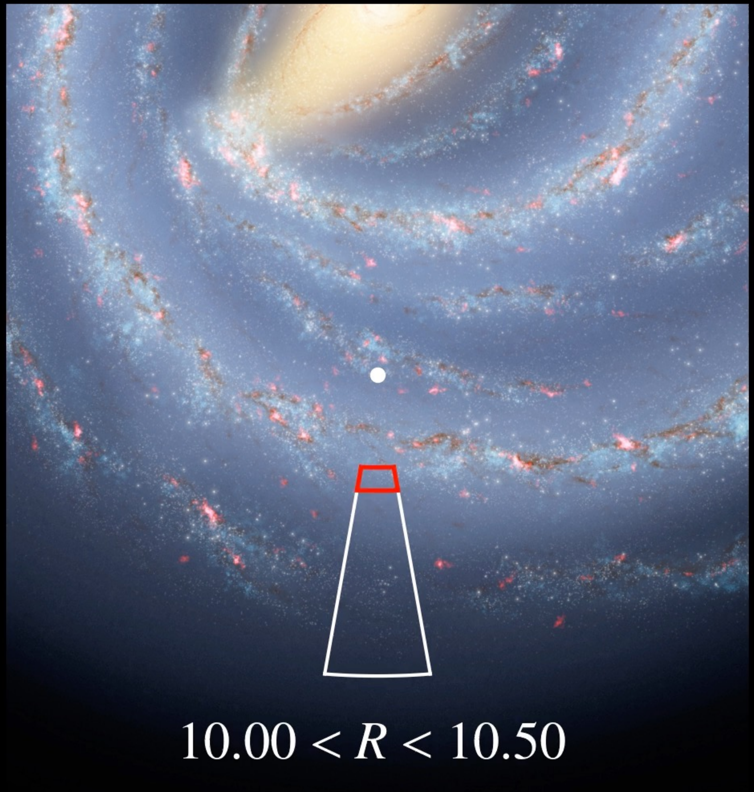
In this direction, V_z and V_φ are in (roughly) proper motion directions

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

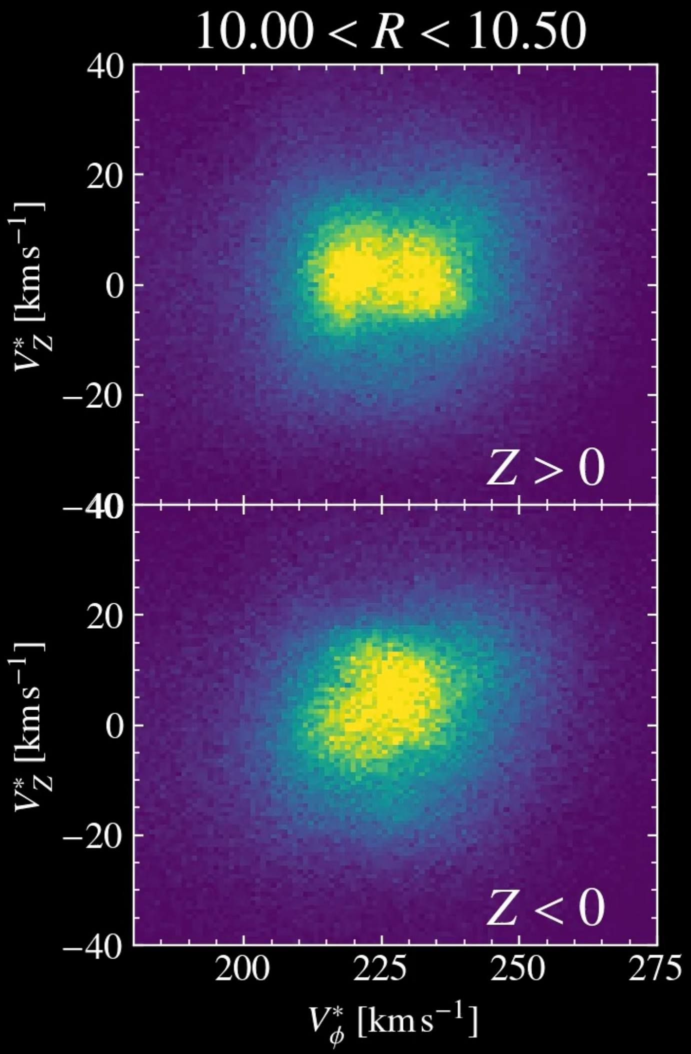


Gaia Collaboration: Antoja, McMillan et al. (2021)

The Galactic anticentre



Vertical velocity (km/s)



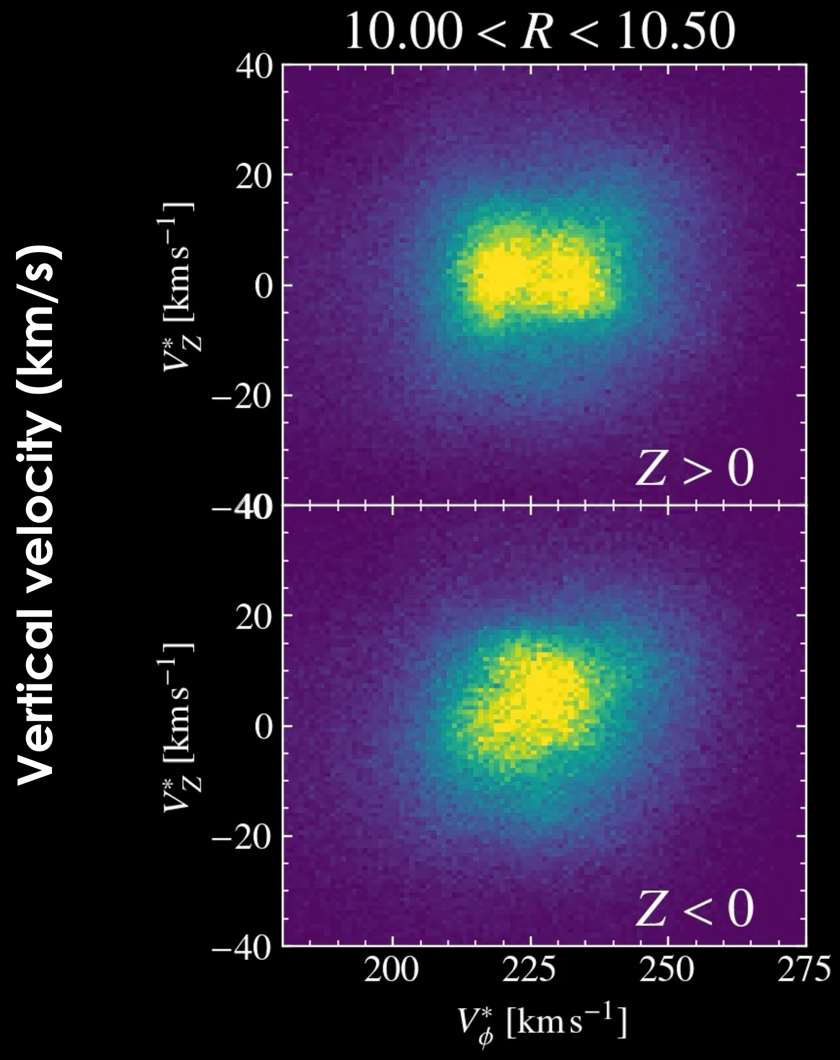
Rotation velocity around the Galactic centre (km/s)

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

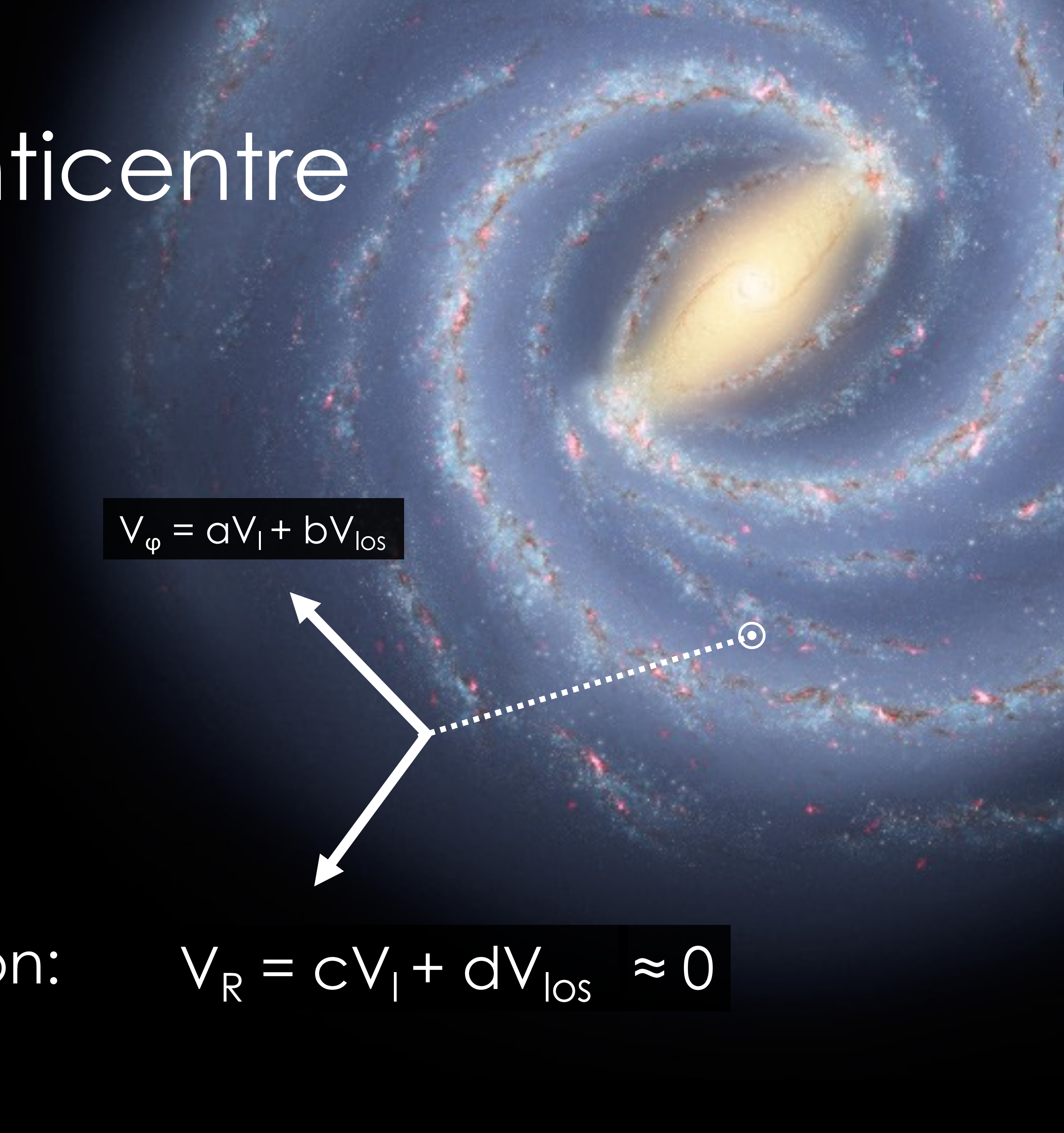


Rotation velocity around the Galactic centre (km/s)

Away from anticentre

Either

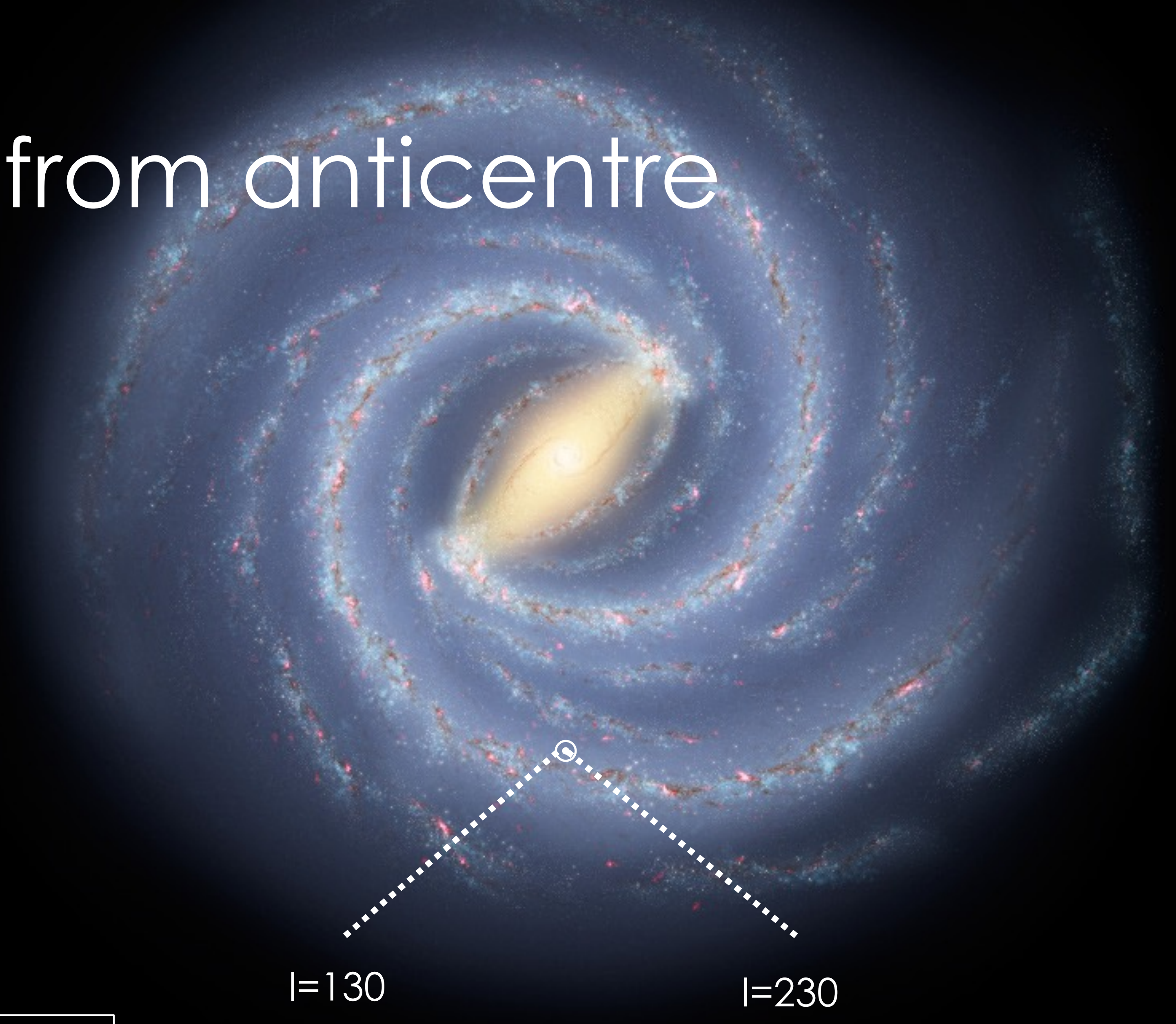
1) Restrict analysis to stars with measured radial velocities



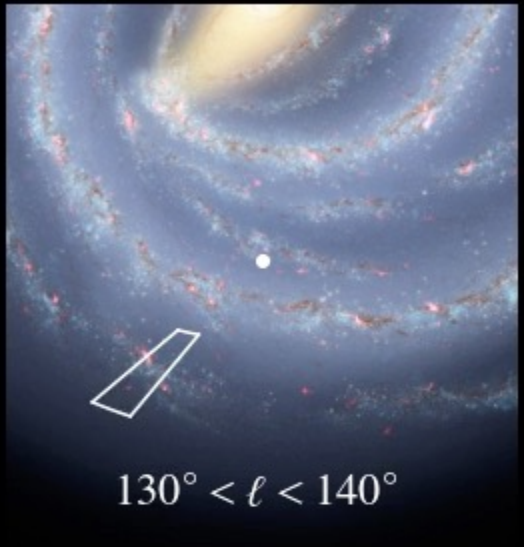
$V_\varphi = aV_l + bV_{los}$

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

Away from anticentre



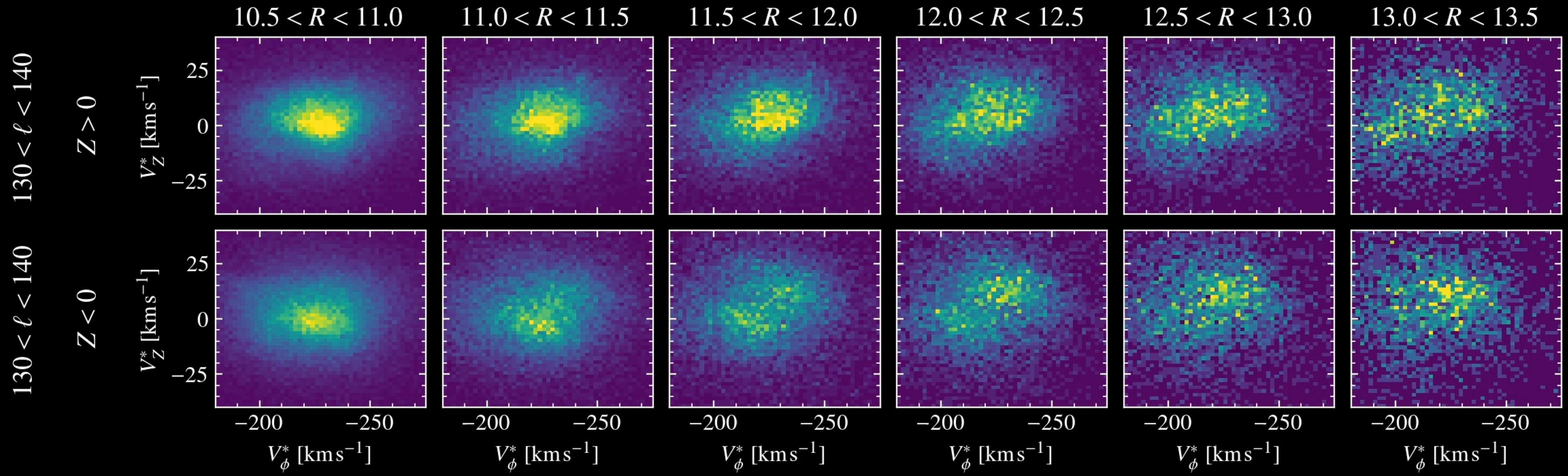
McMillan et al (2022)

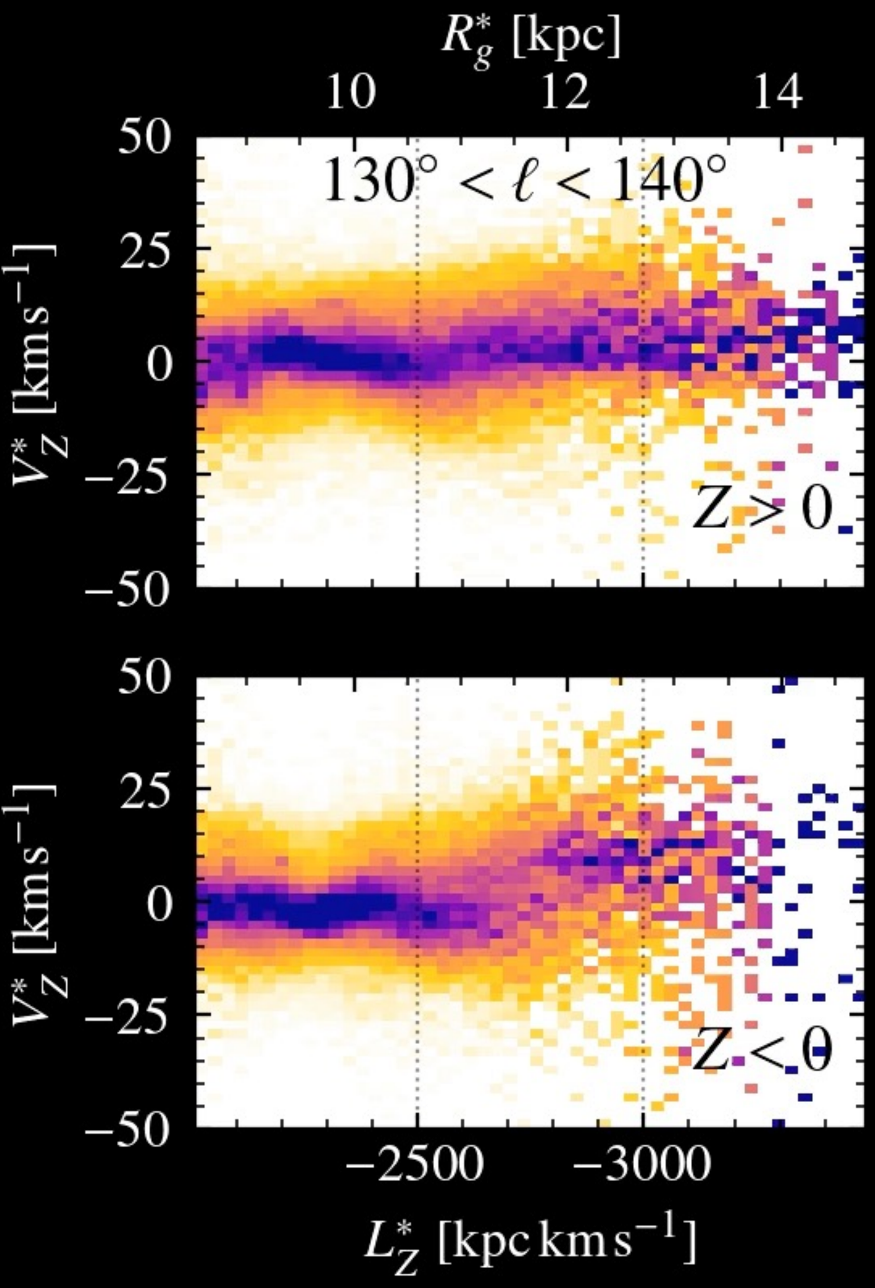


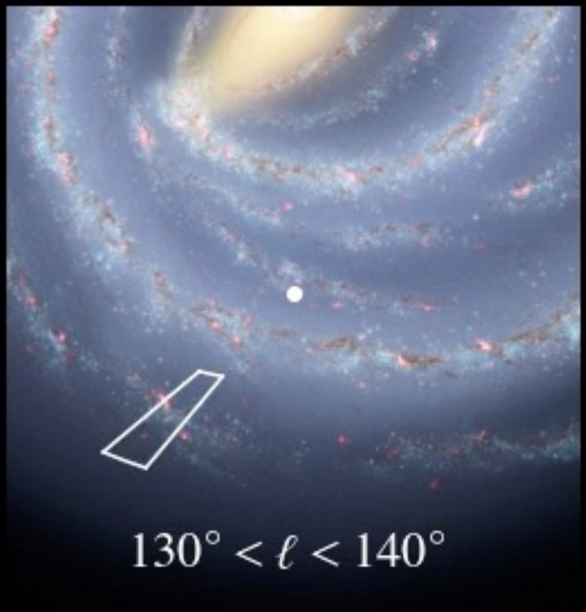
Star velocities across the outer galaxy are:

Bimodal

Different above and below plane

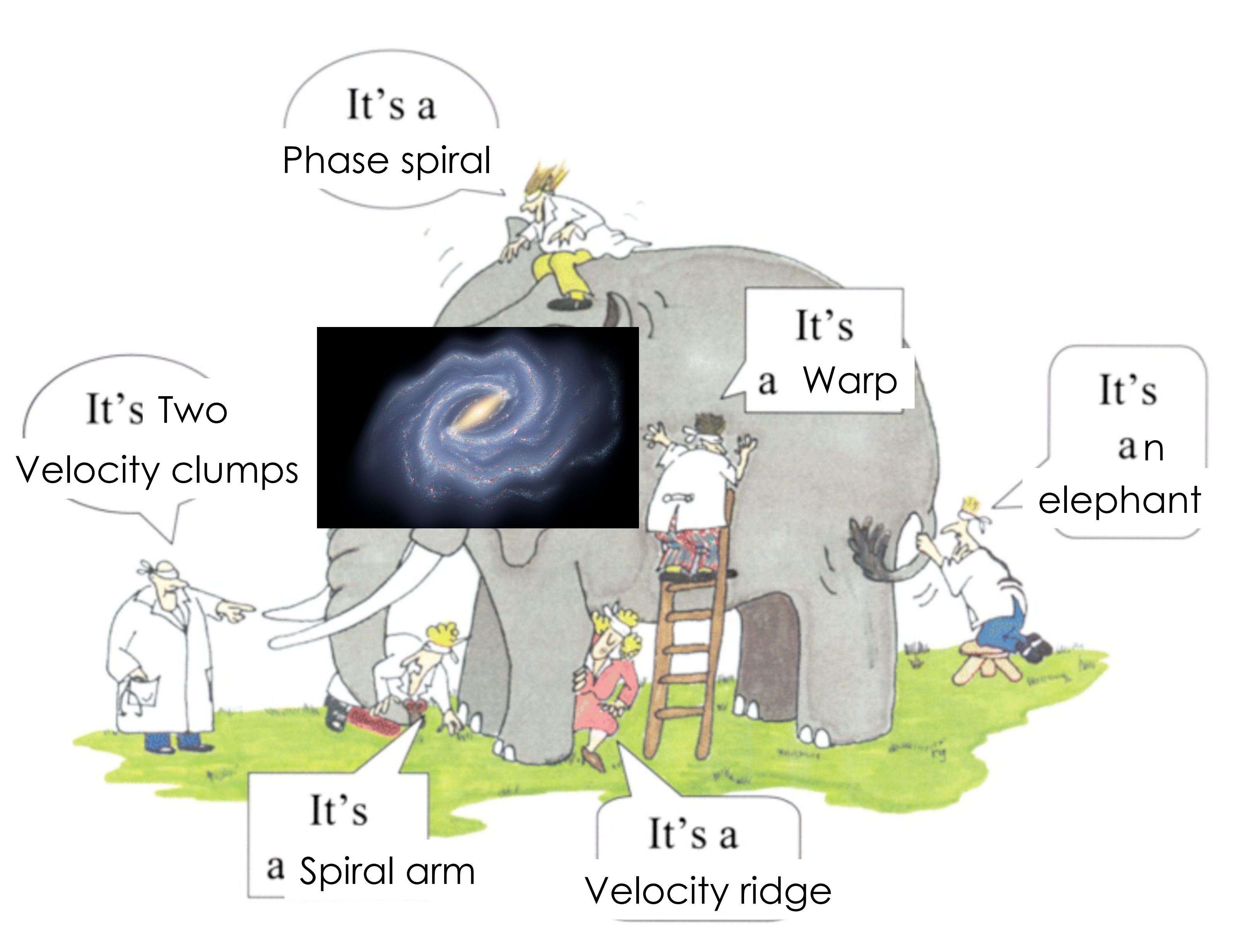






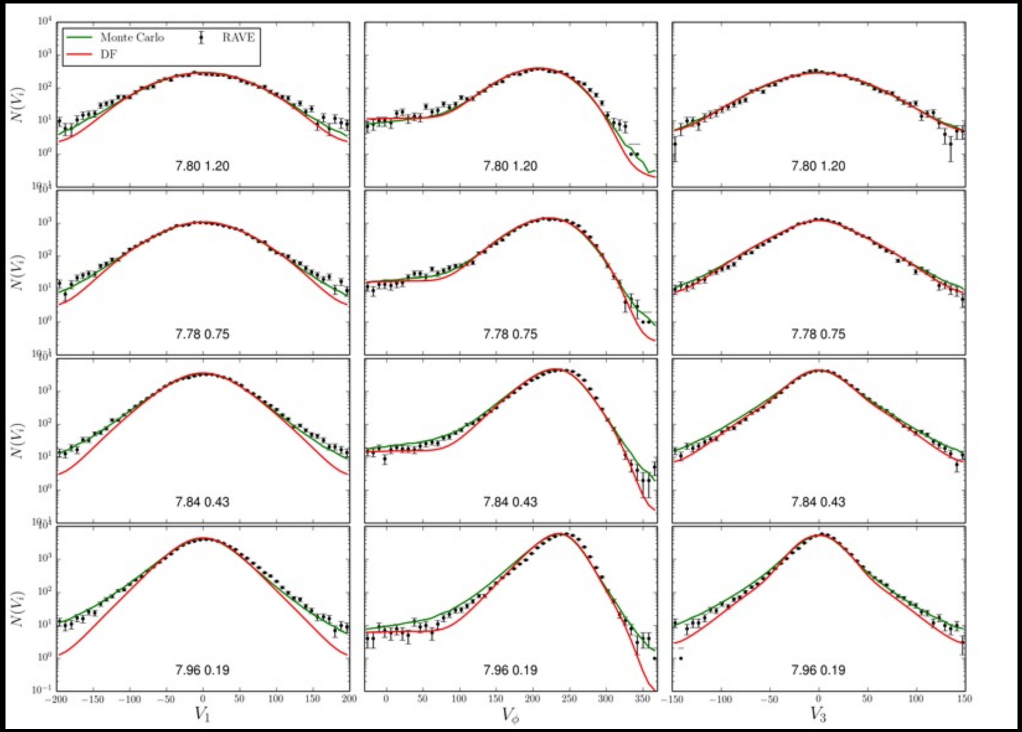
Nicely shown in angular momentum

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

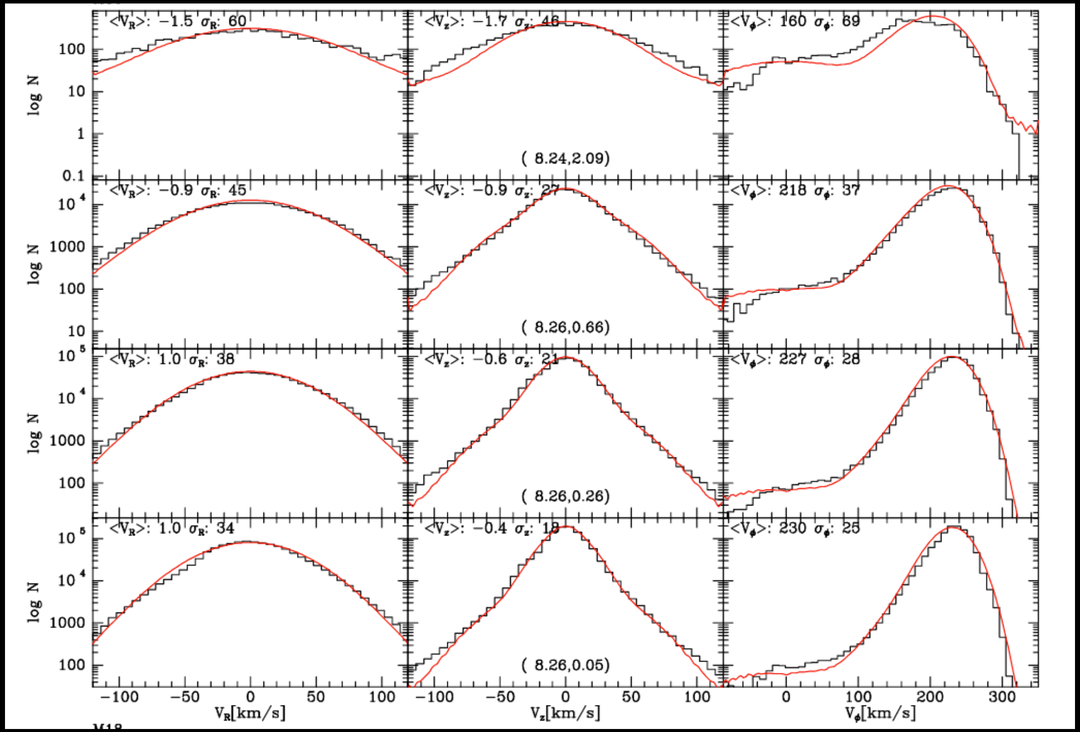


So, what can theorists do about this?

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



Piffl et al (2014)

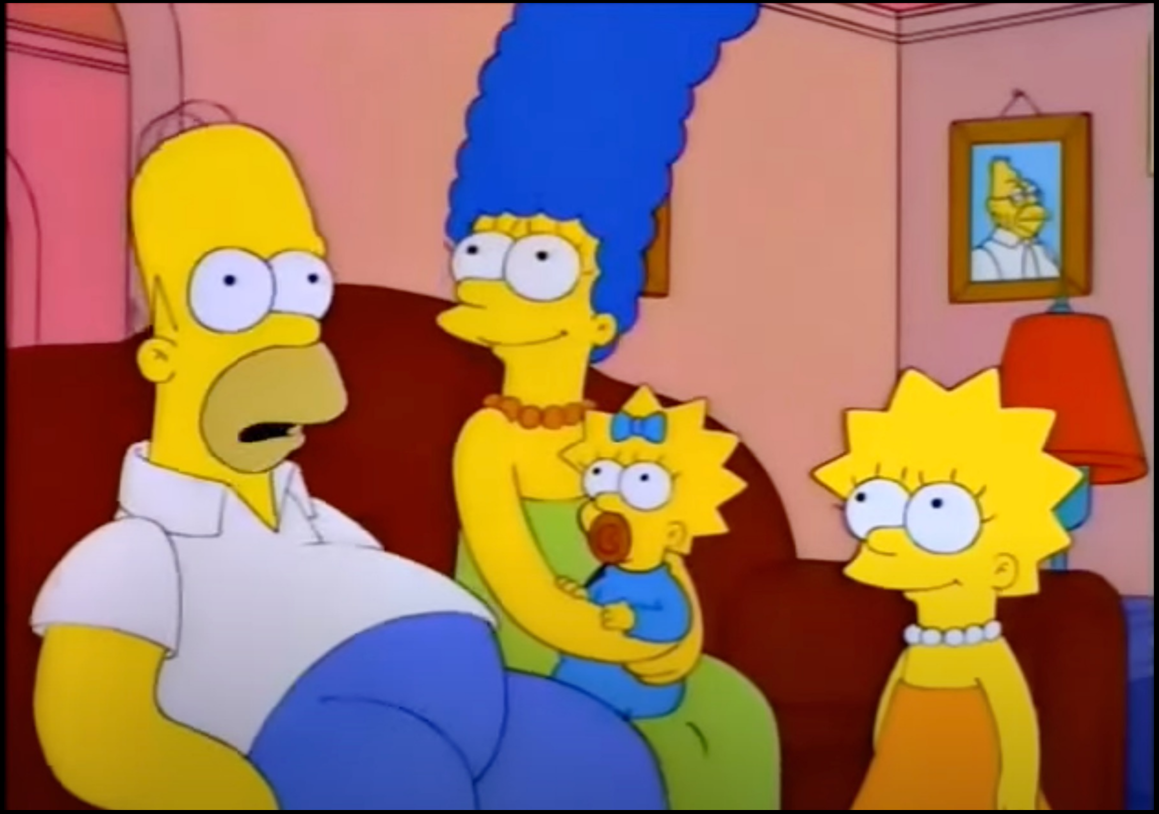


Binney & Vasiliev (2022)

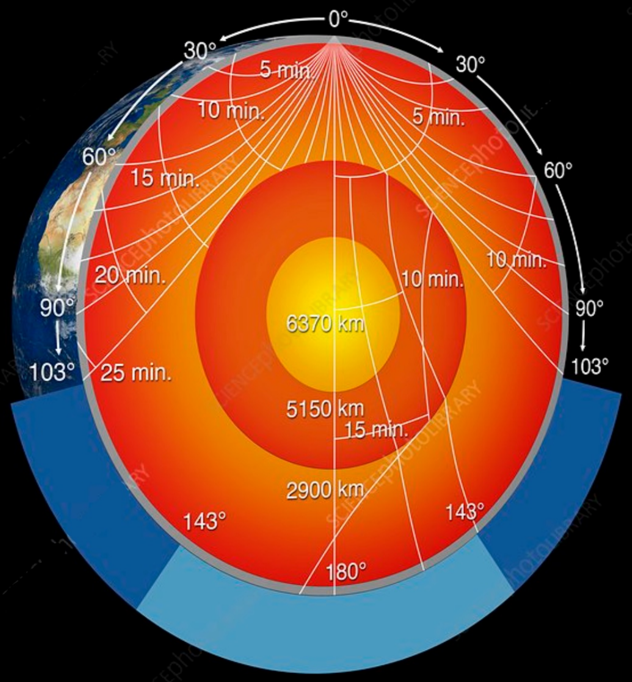
Fitting equilibrium models to velocity histograms

Crisis ∈ Opportunity?

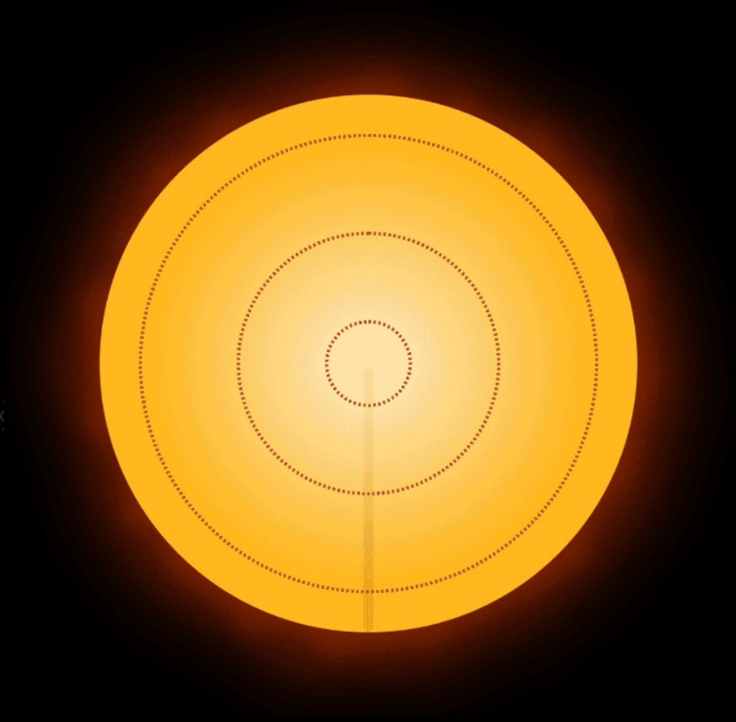
Crisis!



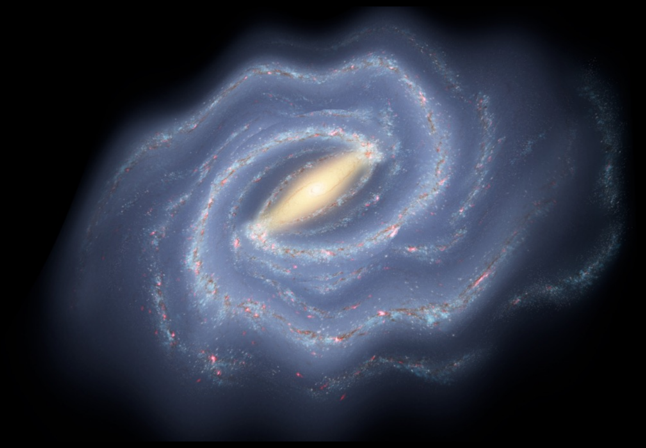
Seismology



Asteroseismology



Galactoseismology?

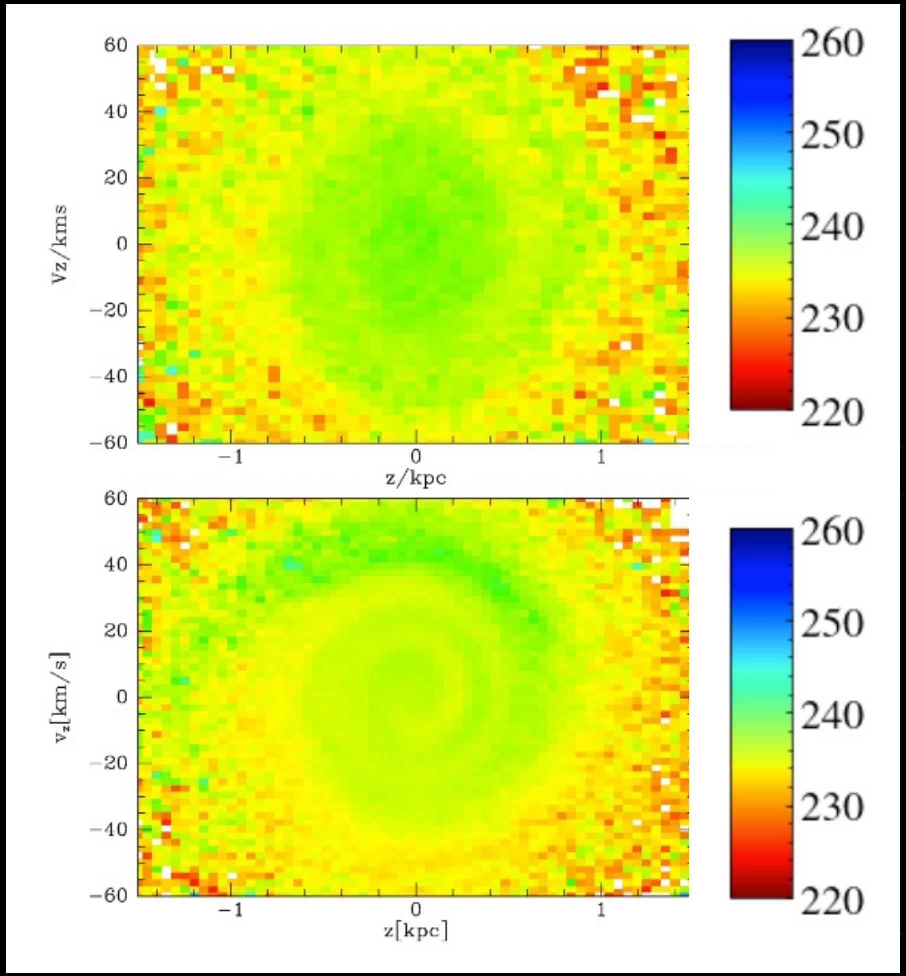


Simple (self-gravity-free) model of Sagittarius' impact

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

400 Myr after impulse (model)

Gaia data



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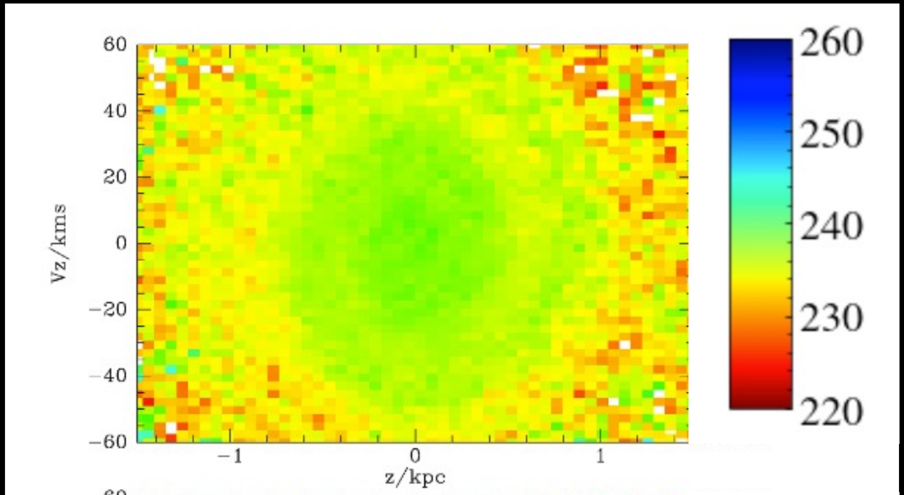

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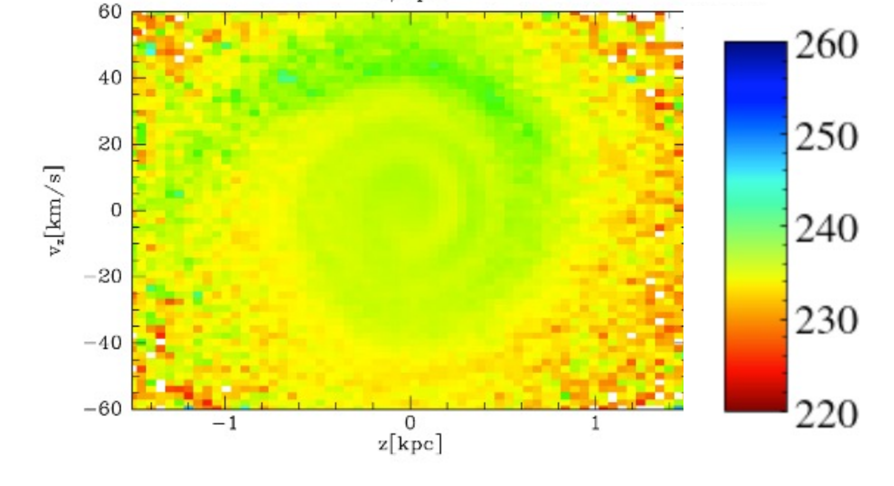

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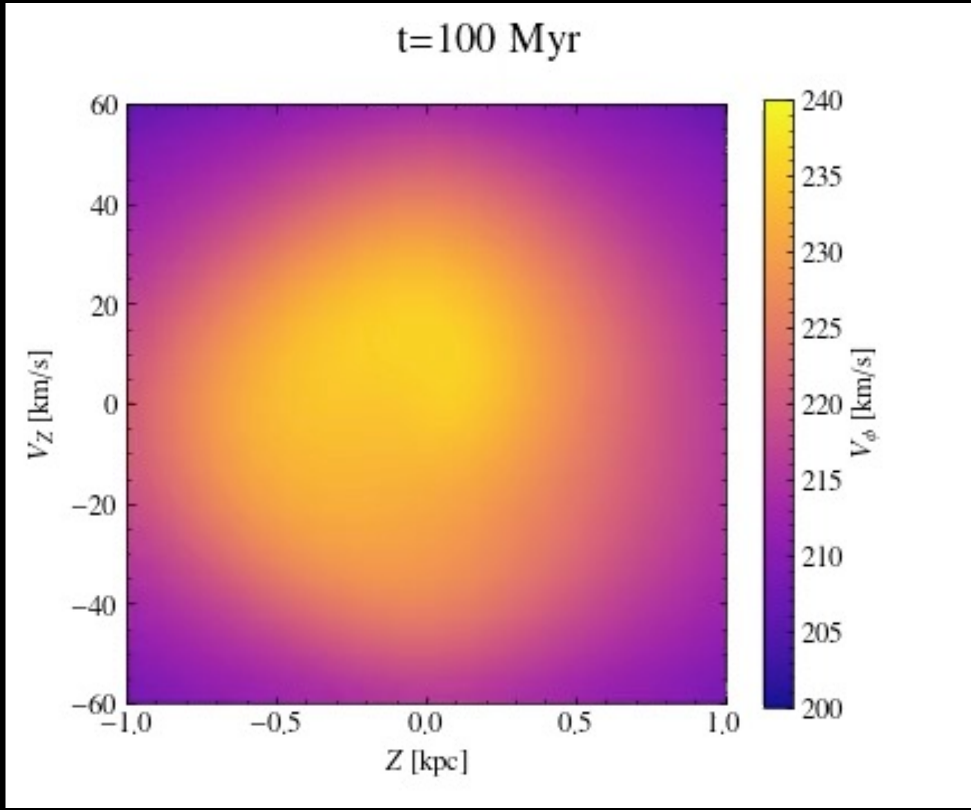
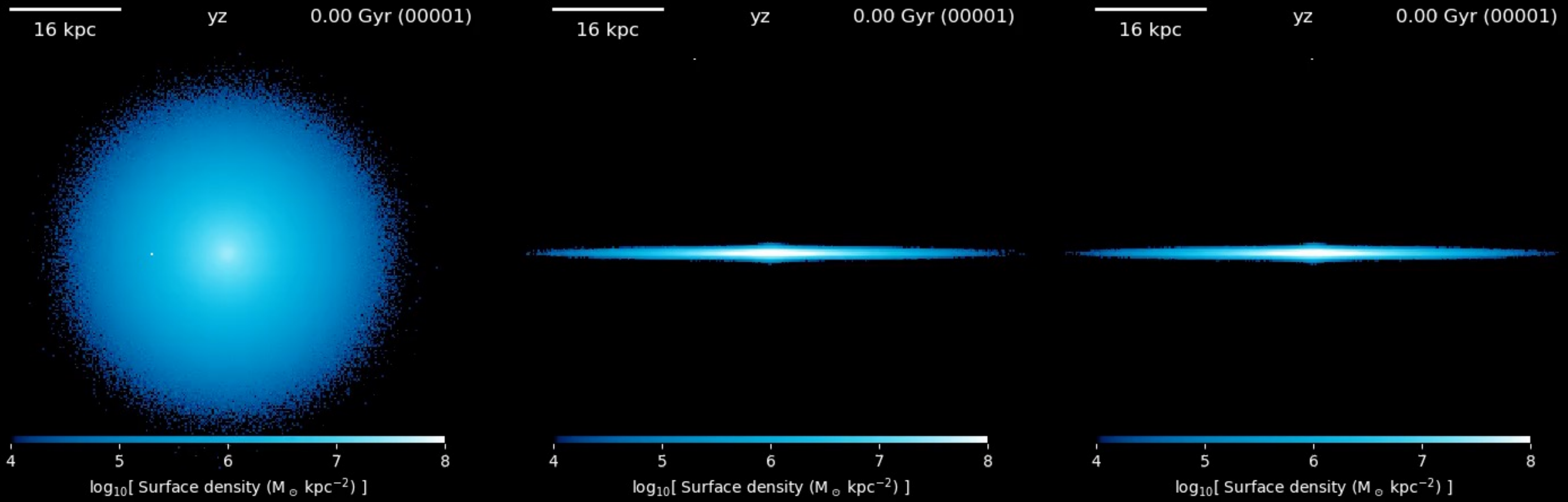


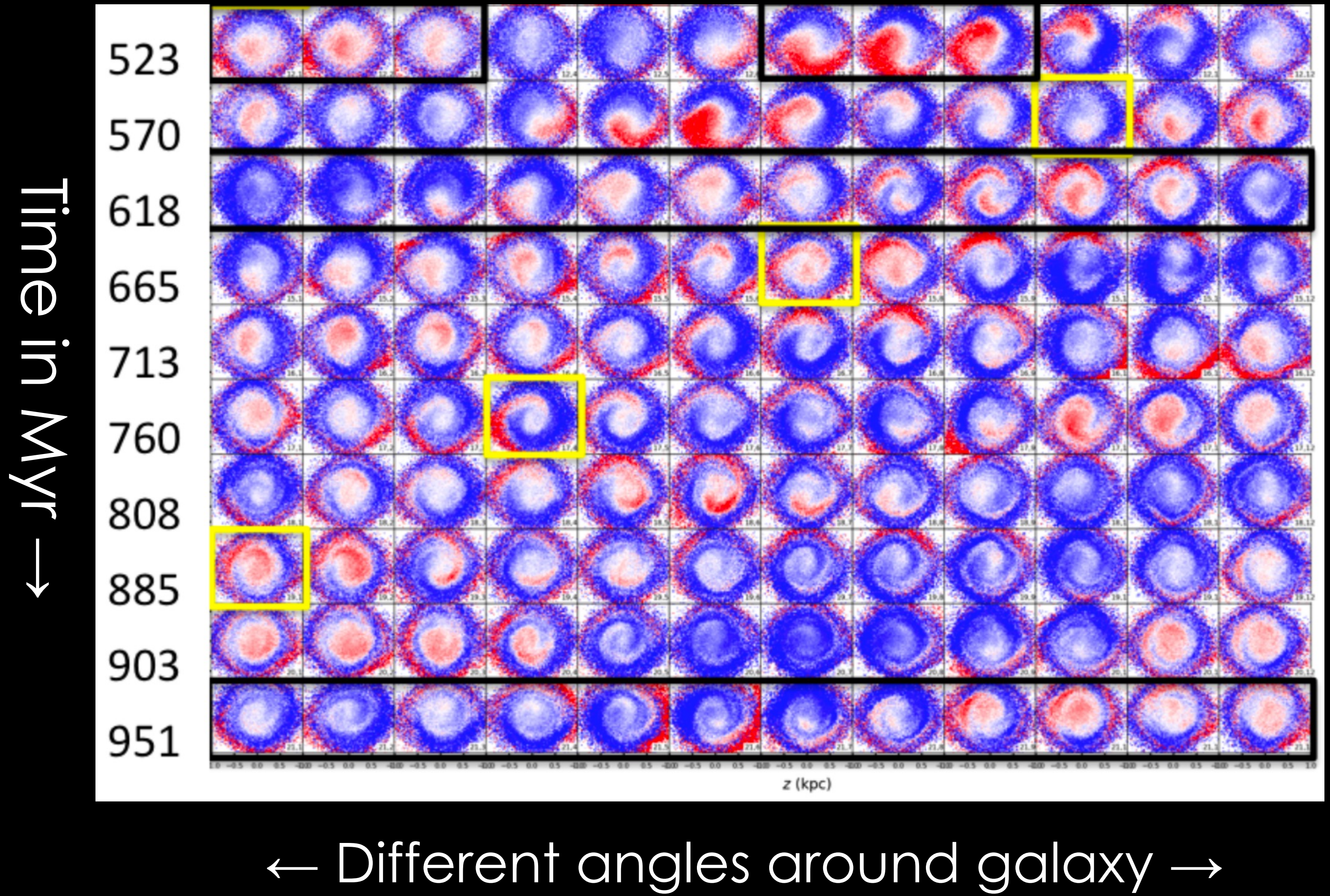
Bland-Hawthorn & Tepper-Garcia (2021)



Simplified simulation of impact

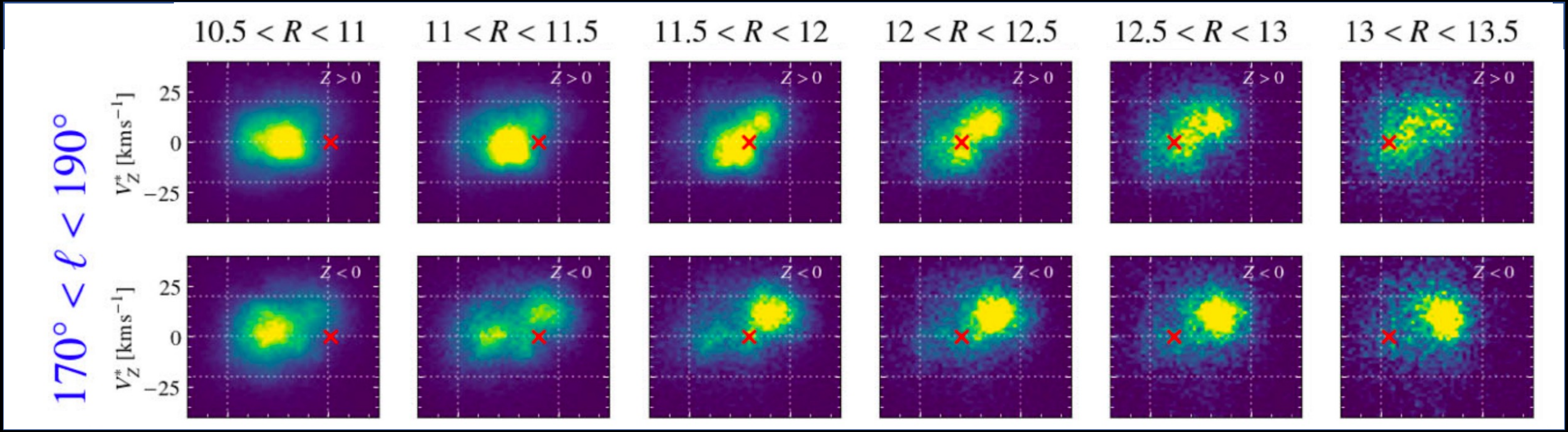
Set up to be a self gravitating ~equivalent to the Binney & Schönrich calculations.

Phase-spiral forms later and is less wound



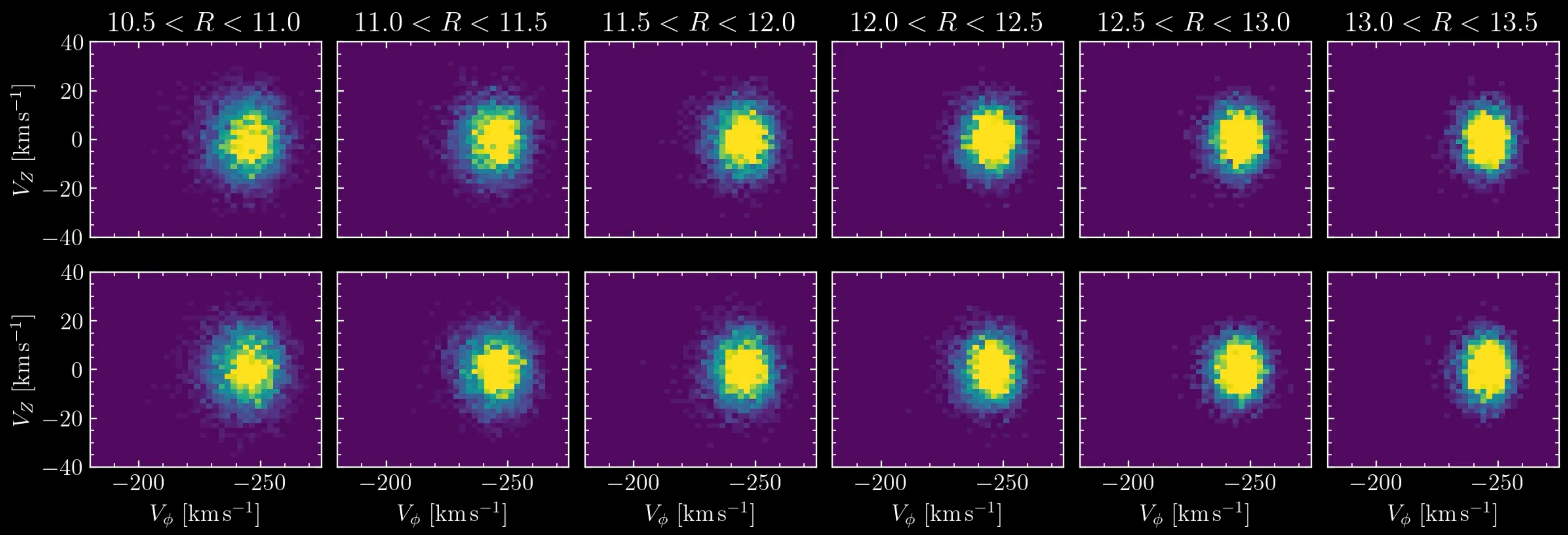
See also Laporte et al 2019, Hunt et al 2021, Gandhi et al 2022

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