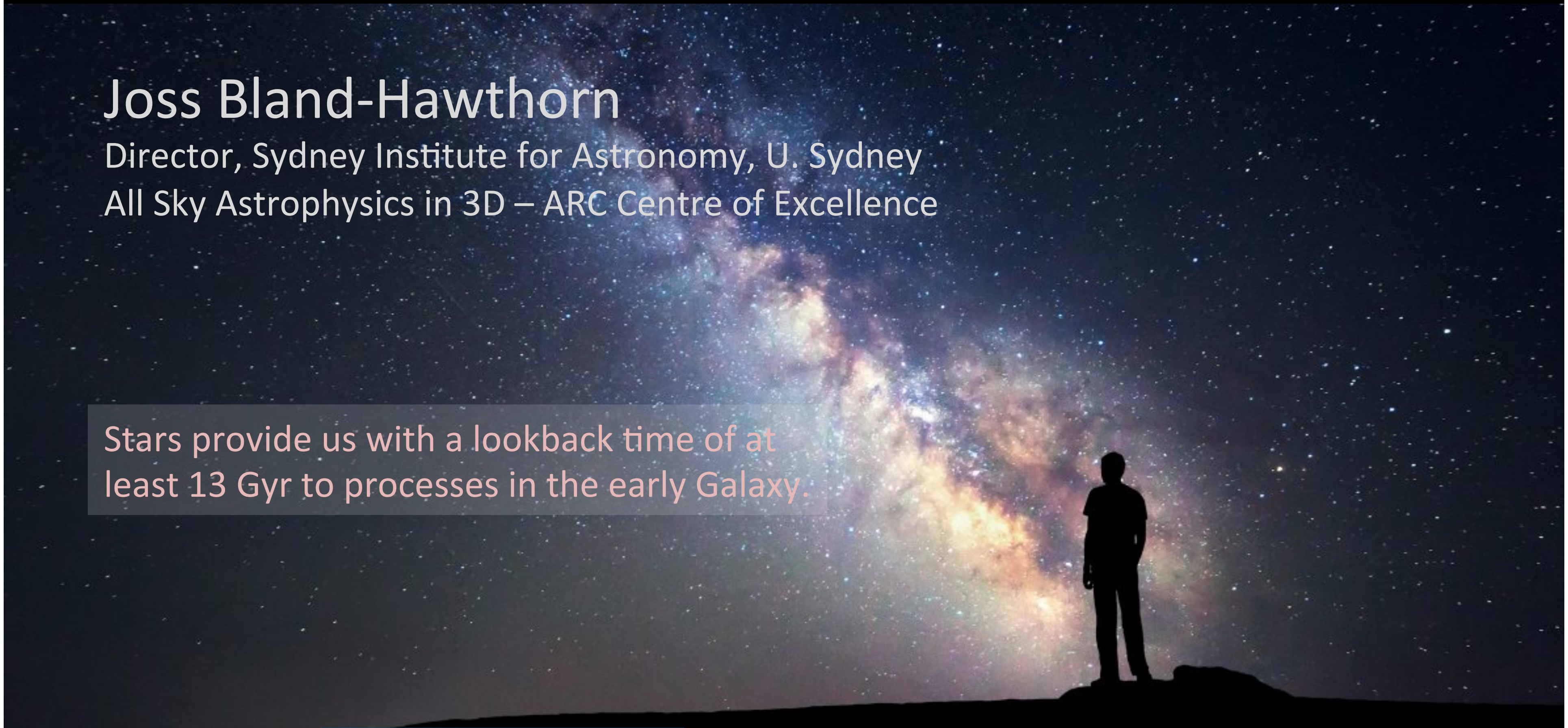
A Galaxy in crisis – complex disk dynamics in action, age, abundance space



Joss Bland-Hawthorn

Director, Sydney Institute for Astronomy, U. Sydney

All Sky Astrophysics in 3D – ARC Centre of Excellence

Stars provide us with a lookback time of at least 13 Gyr to processes in the early Galaxy.

THE UNIVERSITY OF SYDNEY

ASTRO 3D

Australian Astronomical Optics (AAO)

Near-field cosmology

The distance scale across the Galaxy is the underpinning of the Universal distance ladder, e.g. distances to star clusters, Galactic Centre.

Three recent breakthroughs:

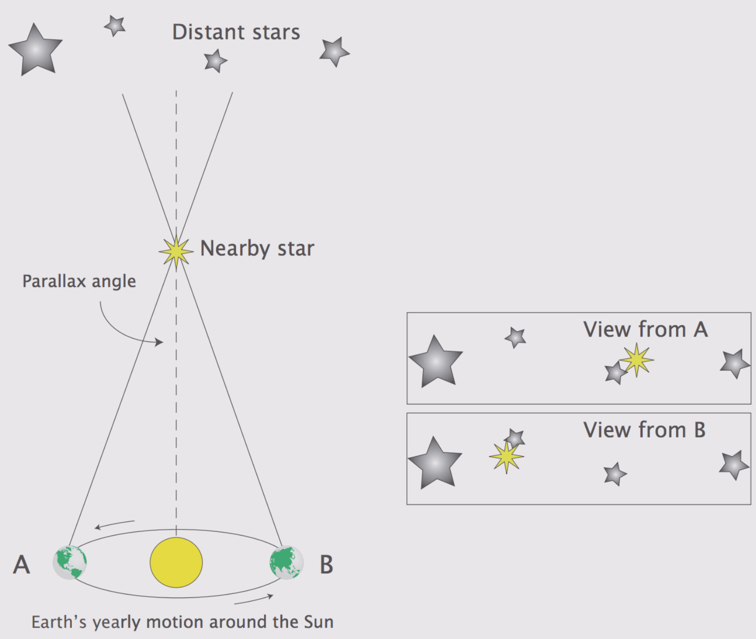
Radio phase-referenced astrometry (e.g. VLBA)
Localised

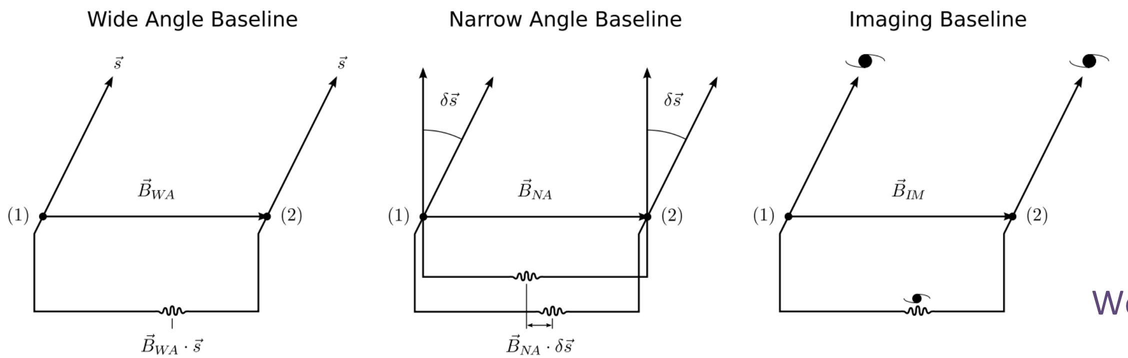
IR narrow-angle astrometry (e.g. Gravity)
Localised

Optical wide-angle astrometry (e.g. Gaia)
All-sky reference frame

Astrometry is built into the distance scale, i.e.

PARSEC = **Par**allax of One **Sec**ond of Arc

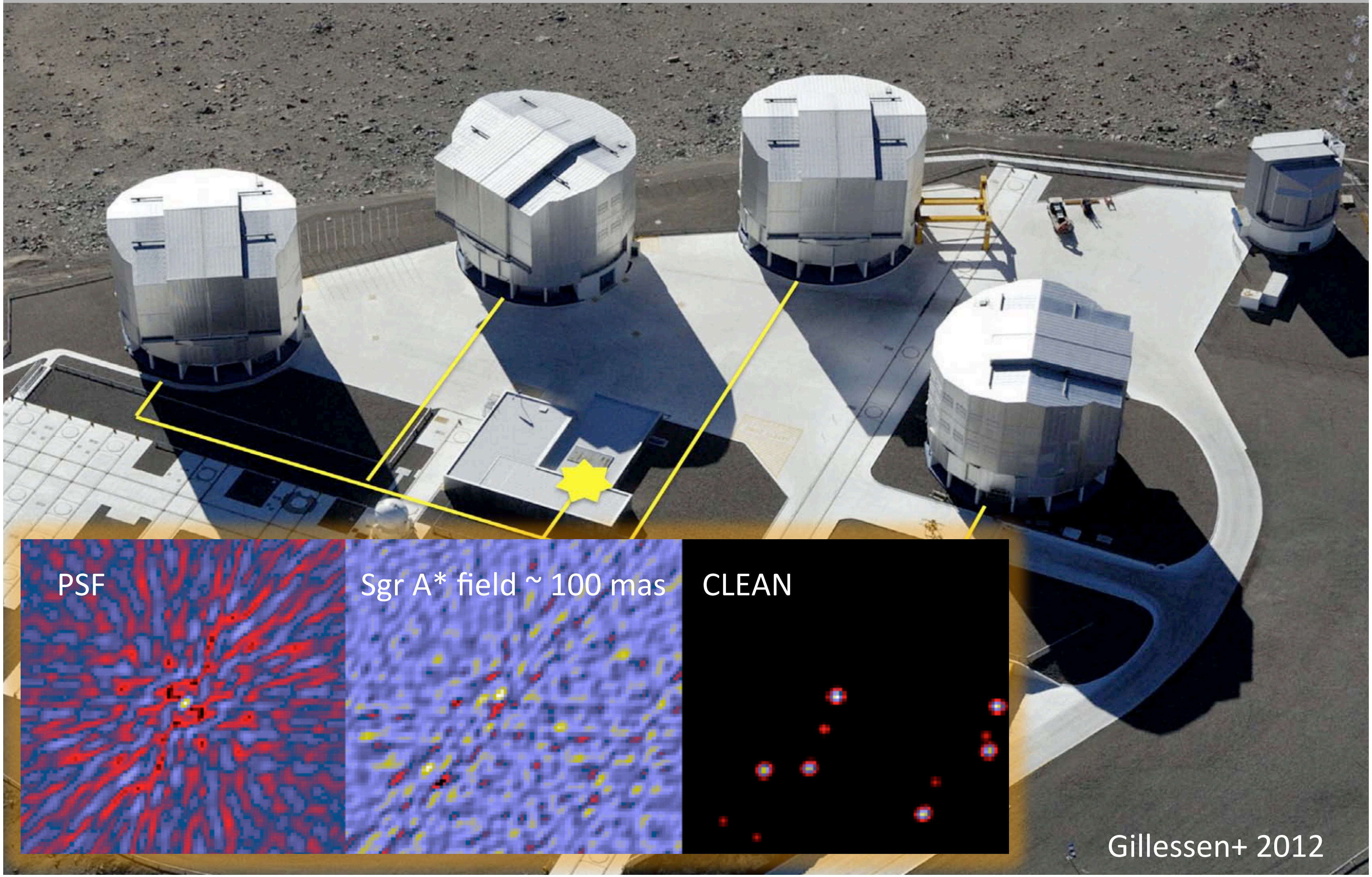




Woillez & Lacour 2013

Gravity: narrow-angle, phase-reference µ-arcsec astrometry

(builds on remarkable history: SUSI @ Sydney, CHARA, AMBER/MIDI/VINCI @ VLTi)



Fundamental constants of near-field cosmology tied to Sgr A*

	ESO Gravity (GRAVITY collab. 2018)	JBH & Gerhard (ARAA 2016)
Galactic Centre distance, $R_\odot$ (kpc)	8.125 +/- 0.03	8.2 +/- 0.1
Black hole mass, $M_\bullet$ (10^6 $M_\odot$)	4.10 +/- 0.03	4.2 +/- 0.2
Sun's circular velocity ($\Theta_\odot$) around Galactic Centre (km/s) ✪	245.7 +/- 1.3	248 +/- 3

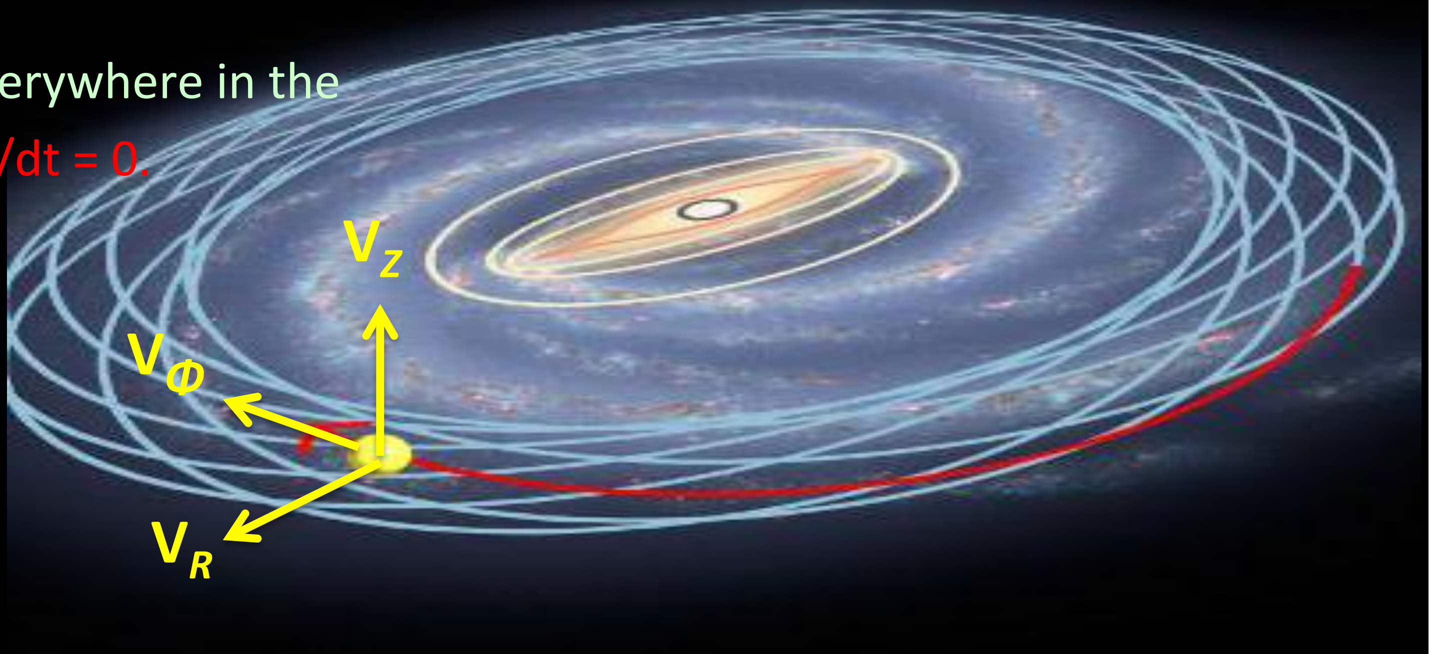
✪ uses Reid's proper motion for Sgr A* from radio phase-referenced astrometry

Near-field cosmology: understand the Galaxy's current state before we can hope to unravel the past.

In a time-independent, axisymmetric potential **Φ**, orbits are regular, i.e. discrete frequencies that are integer combinations of 3 fundamental frequencies → orbit invariants → integrals of motion – J_R J_Φ J_Z – a triplet for each star.

Now find **DF** $f(J_i)$ everywhere in the Galaxy, such that $df/dt = 0$.

Jeans' theorem.

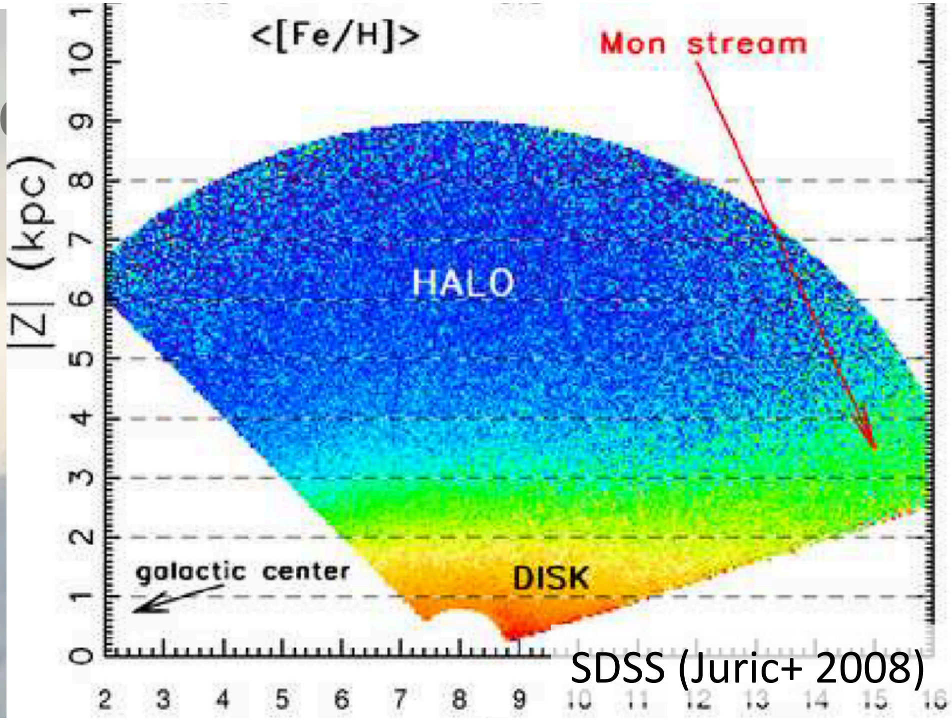


The search for a **(Φ, ρ)** pairing associated with the **DF** is a profoundly difficult challenge to engage us for decades. The task assumes the Galaxy is in dynamical equilibrium, but is it ? If it is not, we can study the system's response to perturbations – this is not weather.

Stormclouds on the horiz

Non-equilibrium structures:

Hercules Stream (Dehnen 1998)
Monoceros Ring (Newberg+ 2002)
Hercules Thick Disk Cloud (Parker+ 2003)
TriAndromeda Ring (Rocha-Pinto+ 2004)
Virgo Overdensity (Newberg+ 2007)
Hercules-Aquila Cloud (Belokurov+ 2007)

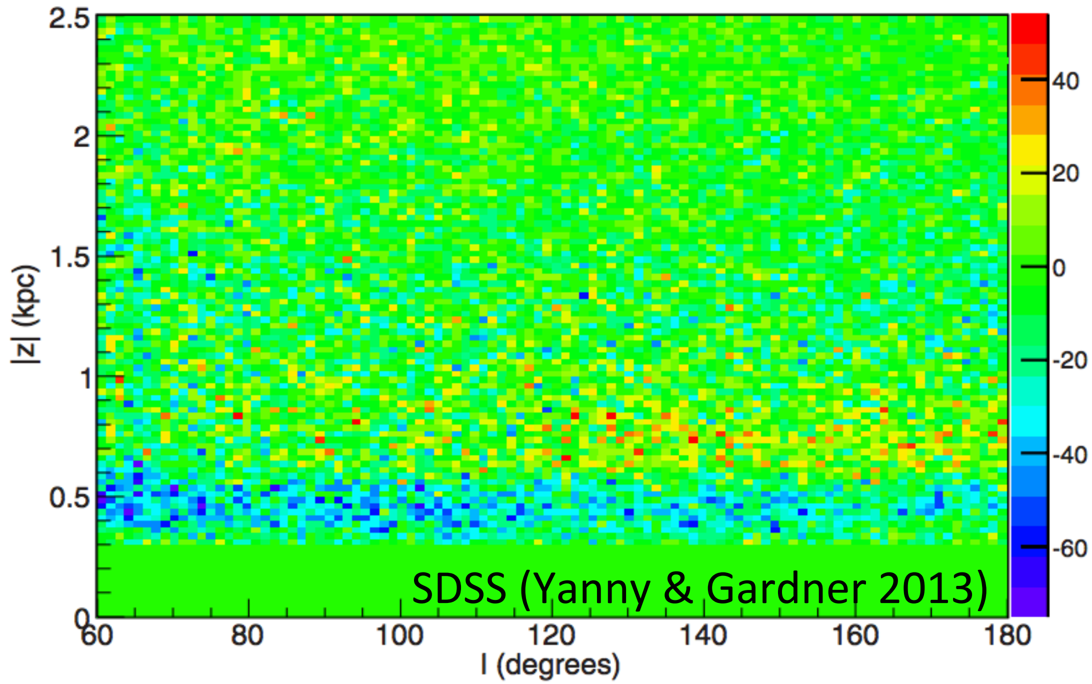


Non-equilibrium kinematics:

SDSS (Widrow+ 2012)
RAVE (Williams+ 2013)
LAMOST (Carlin+ 2013)

North-south star counts:

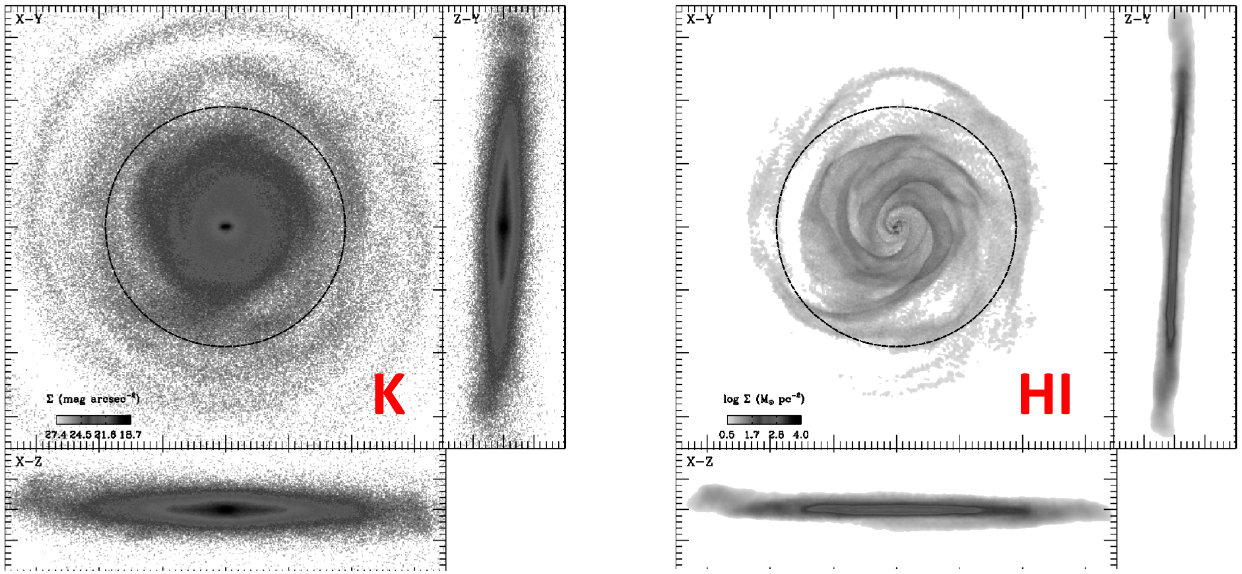
SDSS (Yanny & Gardner 2013)
PanSTARRS1 (Slater+ 2014)
SDSS (Xu+ 2015)



Simulators found perturber-induced outer rings easy to form

Younger+ 2008
Kazantzidis+ 2008

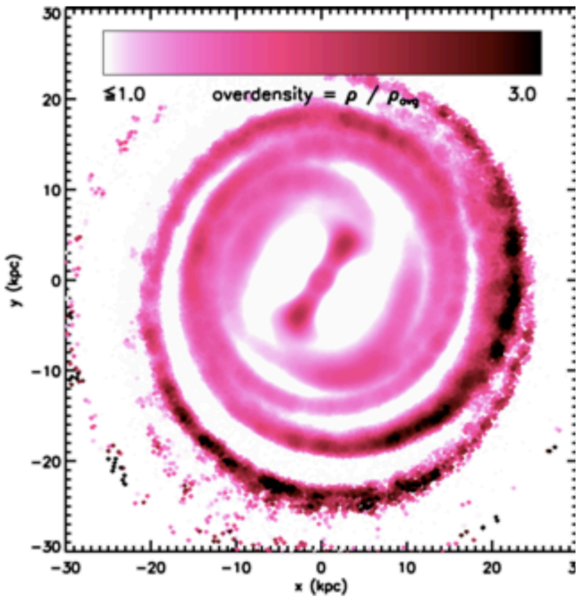
Recall C. Laporte's talk

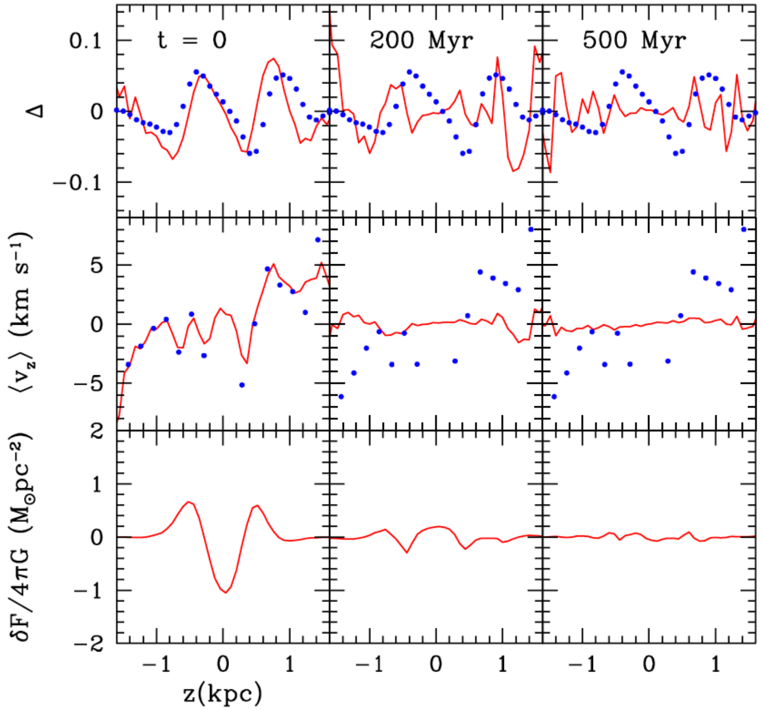


Later simulators noticed inner corrugations & waves, ΔΣ vs. ΔV_z

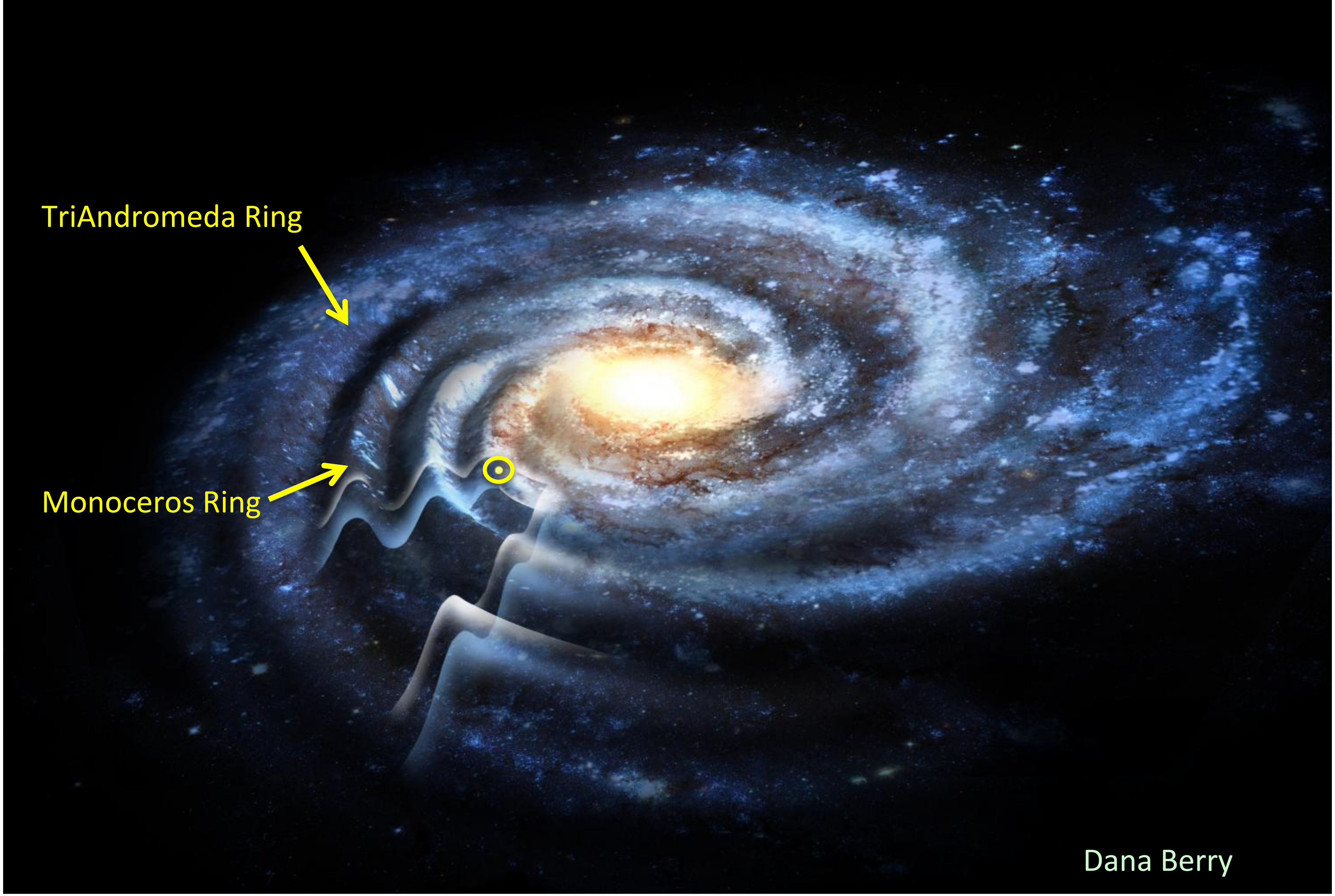
Purcell+ 2011
Widrow+ 2012
Gomez+ 2013, 2018
D'Onghia+ 2016
Laporte+ 2018
Chequers+ 2018
Bennett & Bovy 2018

Masset & Tagger 1997





Giant waves propagating across the disc



Galactoseismology

Widrow+ 2012

Chequers & Widrow 2017

Can we interpret time-dependent modal behaviour?

ΔZ

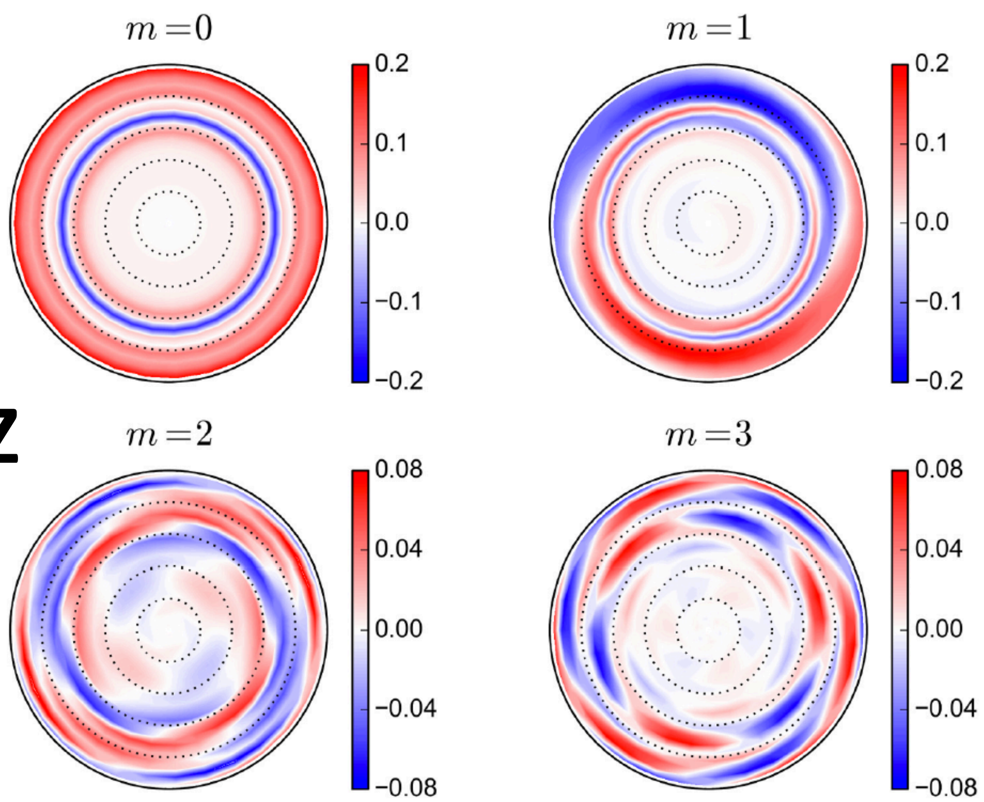


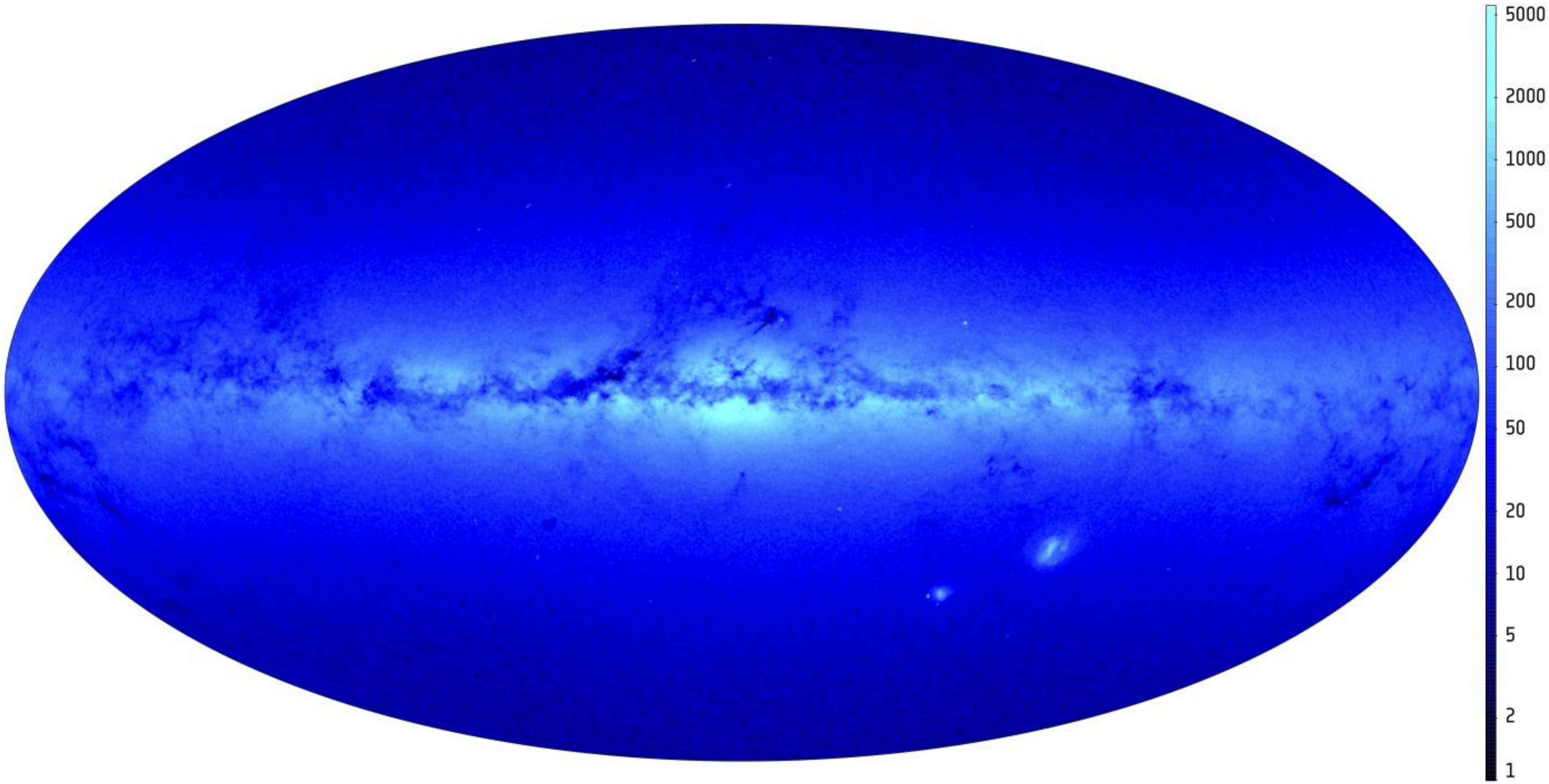
Figure 4. Fourier mode decomposition of $Z(R, \phi, t \sim 4\,\mathrm{Gyr})$ for $m = 0$, 1, 2, and 3, as indicated, for Model 1. Dotted concentric circles indicate increments of 5 kpc in radius. The rotation of the disc is counter-clockwise. The colour scale is in units of kpc, and differs between the upper and lower panels in order to highlight the extremal values for each m. The factor of 1/2 for the zeroth order term in the Fourier Series is reflected in the $m = 0$ panel. From the figure it is clear that the (leading) $m = 1$ term is the

cf. M51; Salo & Laurikainen 2000

cf. MW; Quillen+ 2011

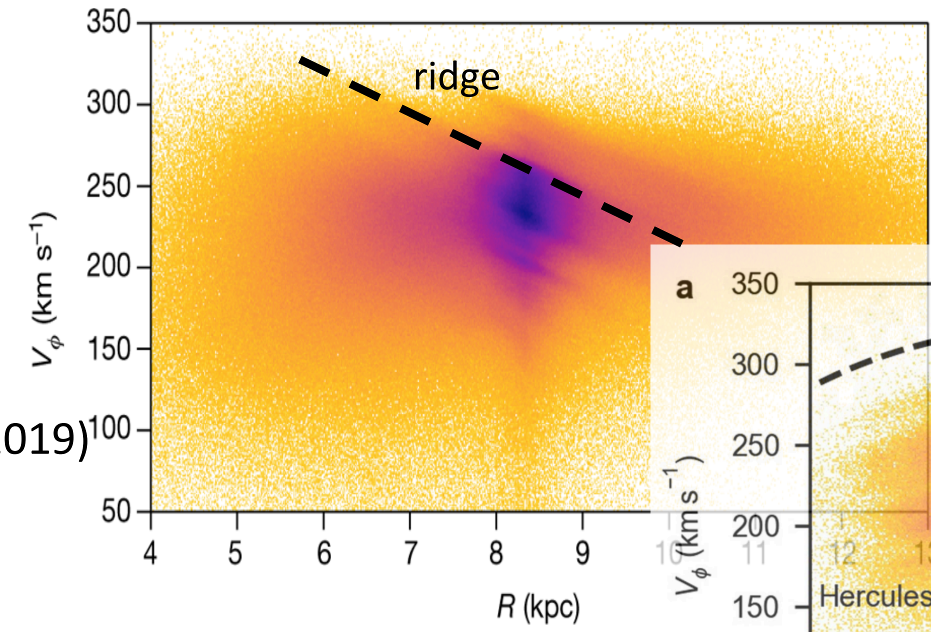
cf. M31; Dierickx+ 2014

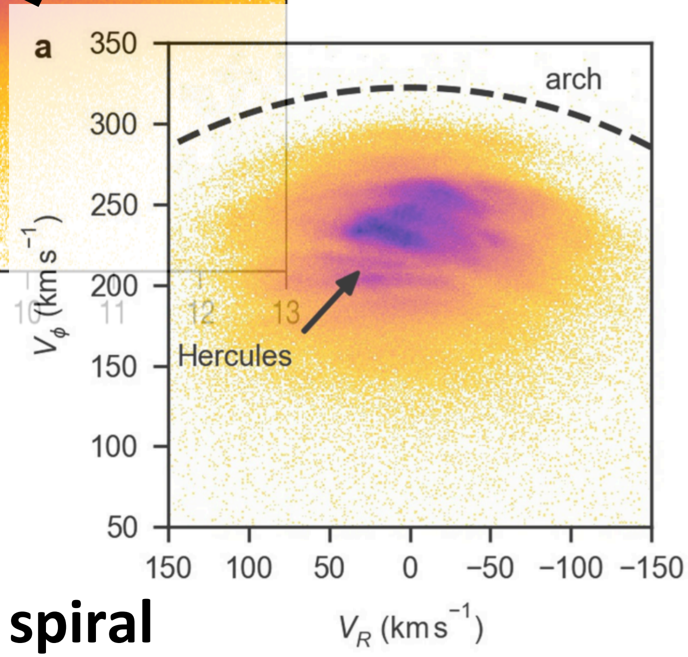
ESA *Gaia* era

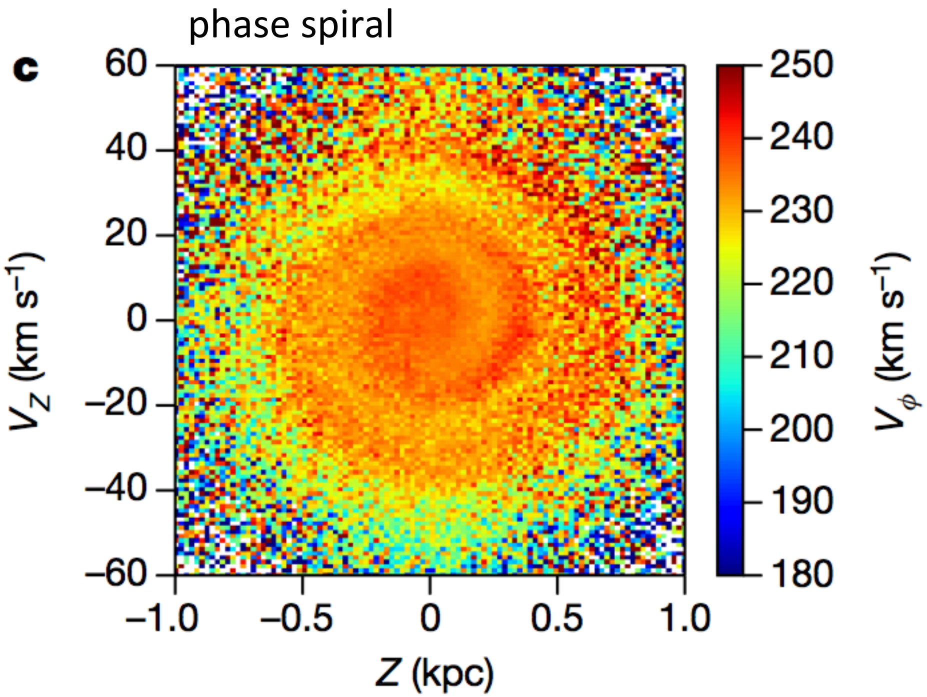

5000
2000
1000
500
200
100
50
20
10
5
2
1
number of sources/pixel

Arches & ridges

Antoja et al (2018)
Fragkoudi et al (2019)
Hunt et al (2019)
Kawata et al (2018)
Khanna et al (2019)
Martinez-Medina et al (2019)
Quillen et al (2018)
Ramos et al (2018)







Phase spiral

Antoja et al (2018)
Binney & Schönrich (2018)
Bland-Hawthorn et al (2019)
Darling & Widrow (2019)
Khoperskov et al (2019)
Laporte et al (2019)
Michtchenko et al (2019)
Tian et al (2019) Wang et al (2019)

GALAH survey @ AAT, Siding Spring

Eight year mission to measure up to **30** elements and velocities in a **million** stars across the Galaxy.

400 optical fibres positioned robotically

Major surveys, past, present, future:

2MASS, SDSS, APASS, PanStarrs, LSST...
RAVE, Gaia-ESO, APOGEE, LAMOST…
Kepler, K2, TESS, PLATO…
Hipparcos, Gaia...

GALAH team

50% ASTRO-3D

Strong overseas:
Germany, NZ, USA, Sweden, Italy, UK, Slovenia, France

2018 GALAH DR2:
24 published papers

GALAH design:
Sharma

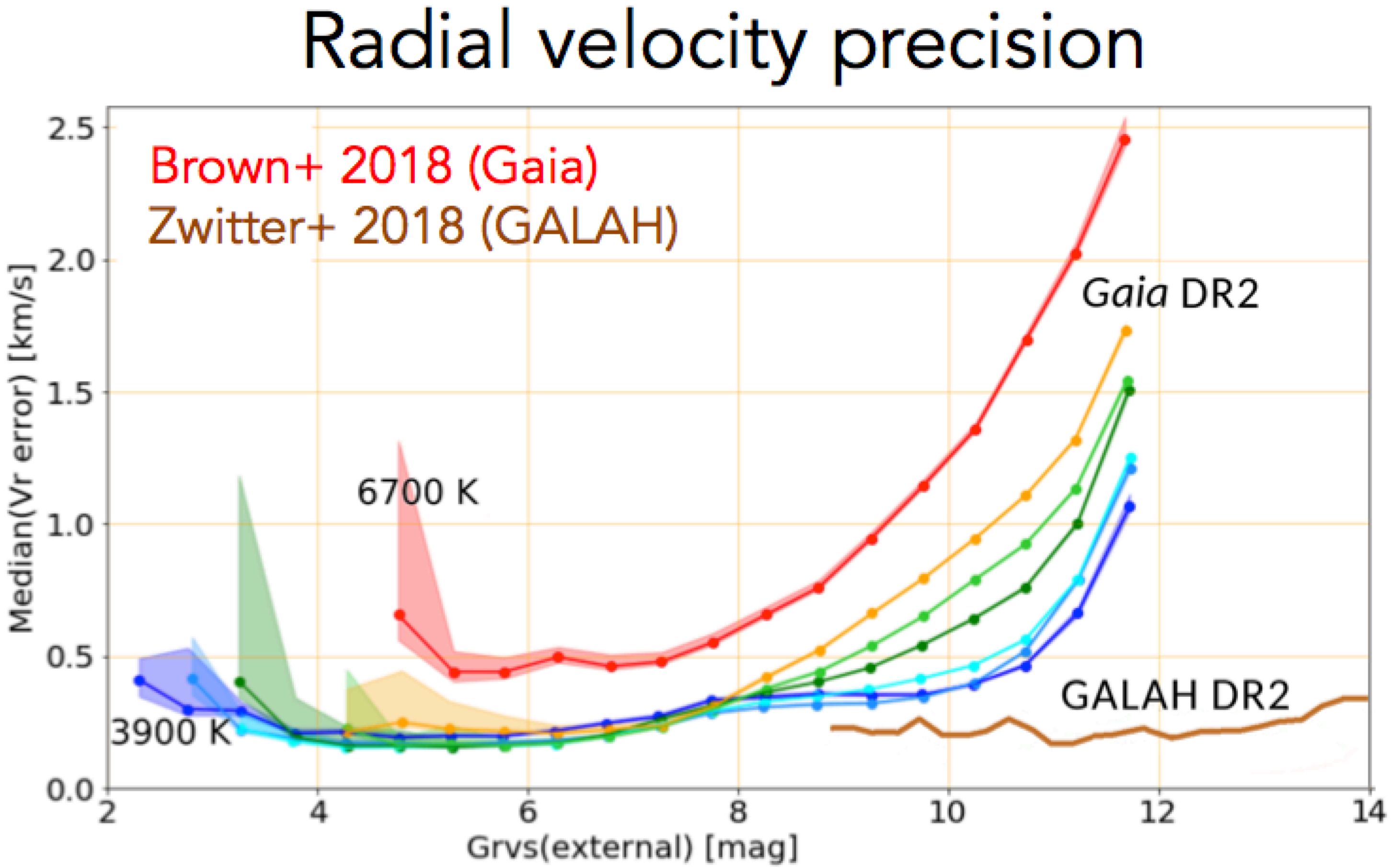
GALAH ops:
De Silva, Martell

GALAH pipeline:
Kos, Zwitter

GALAH abundance:
Buder, Lind, Asplund

Kepler, K2, TESS:
Sharma, Stello

GALAH DR2 Release (Buder+ 2018; 12 papers)

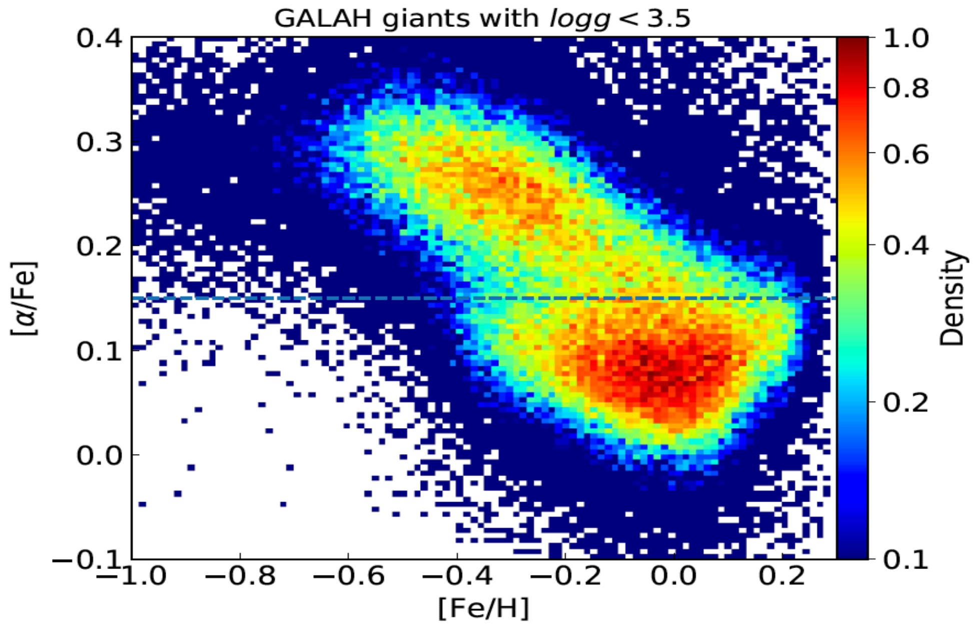


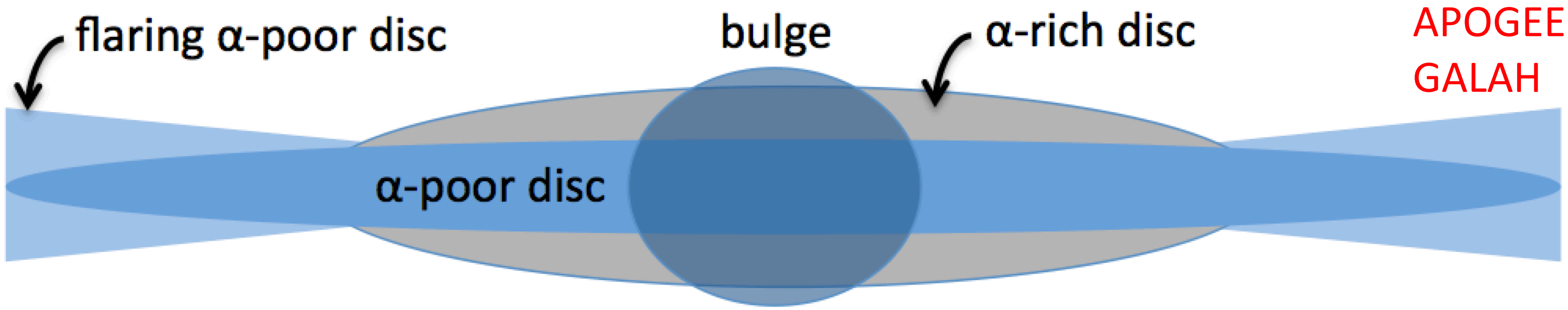
Stellar chemistry (Z) – the most fundamental invariant for any star – "chemical tagging"

❖ stellar mass is approx. invariant for most stars but seismics not easy

❖ stellar age, location, motion are <u>not</u> invariant

❖ it is <u>not</u> obvious that real J_i are invariant on Galactic timescales, e.g. $J_\phi = L_z$ during stellar migration





Bensby+ 2011
APOGEE
GALAH

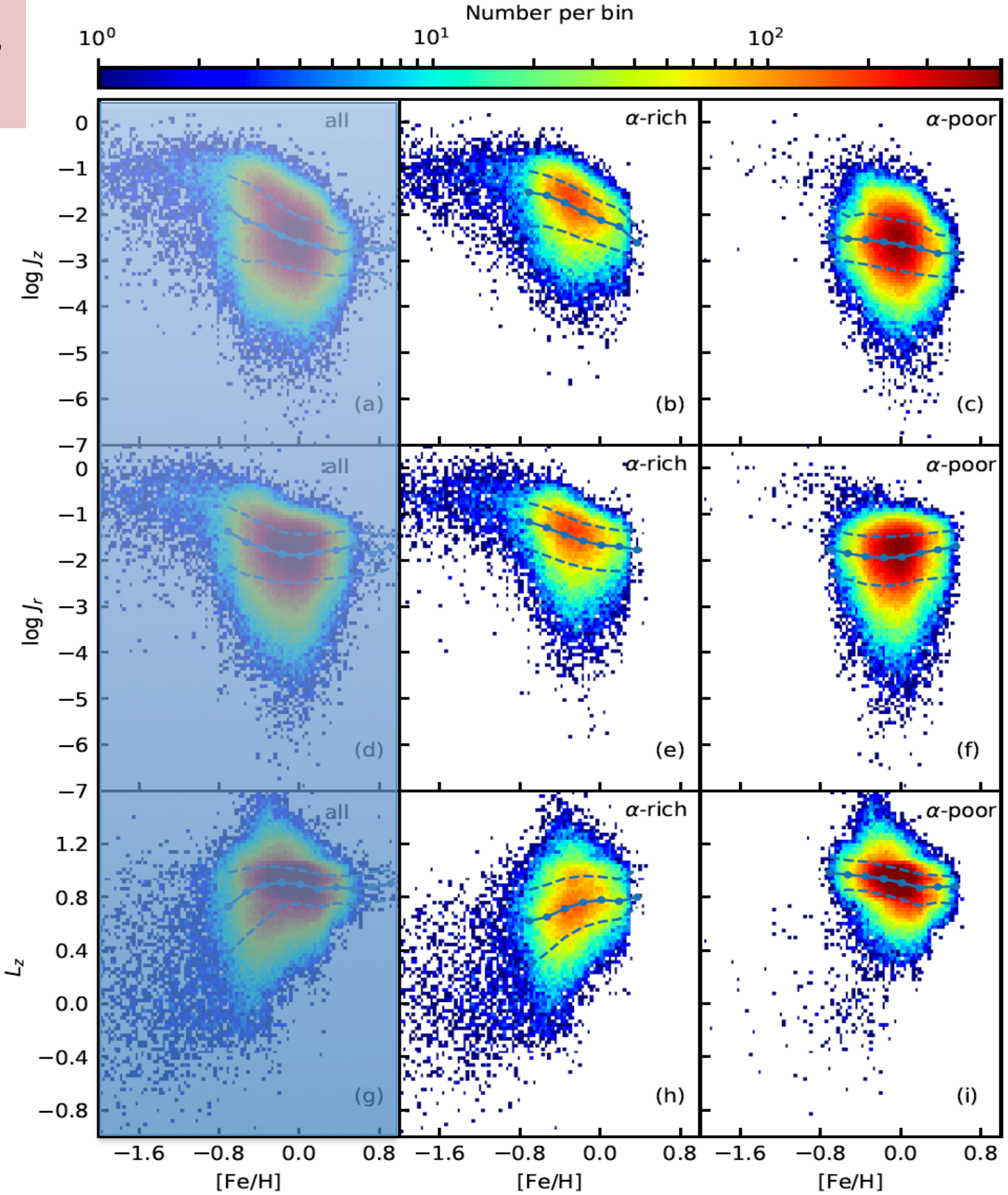
The GALAH survey and Gaia DR2: dissecting the stellar disc's phase space by age, action, chemistry

GALAH radial velocities
Gaia proper motions

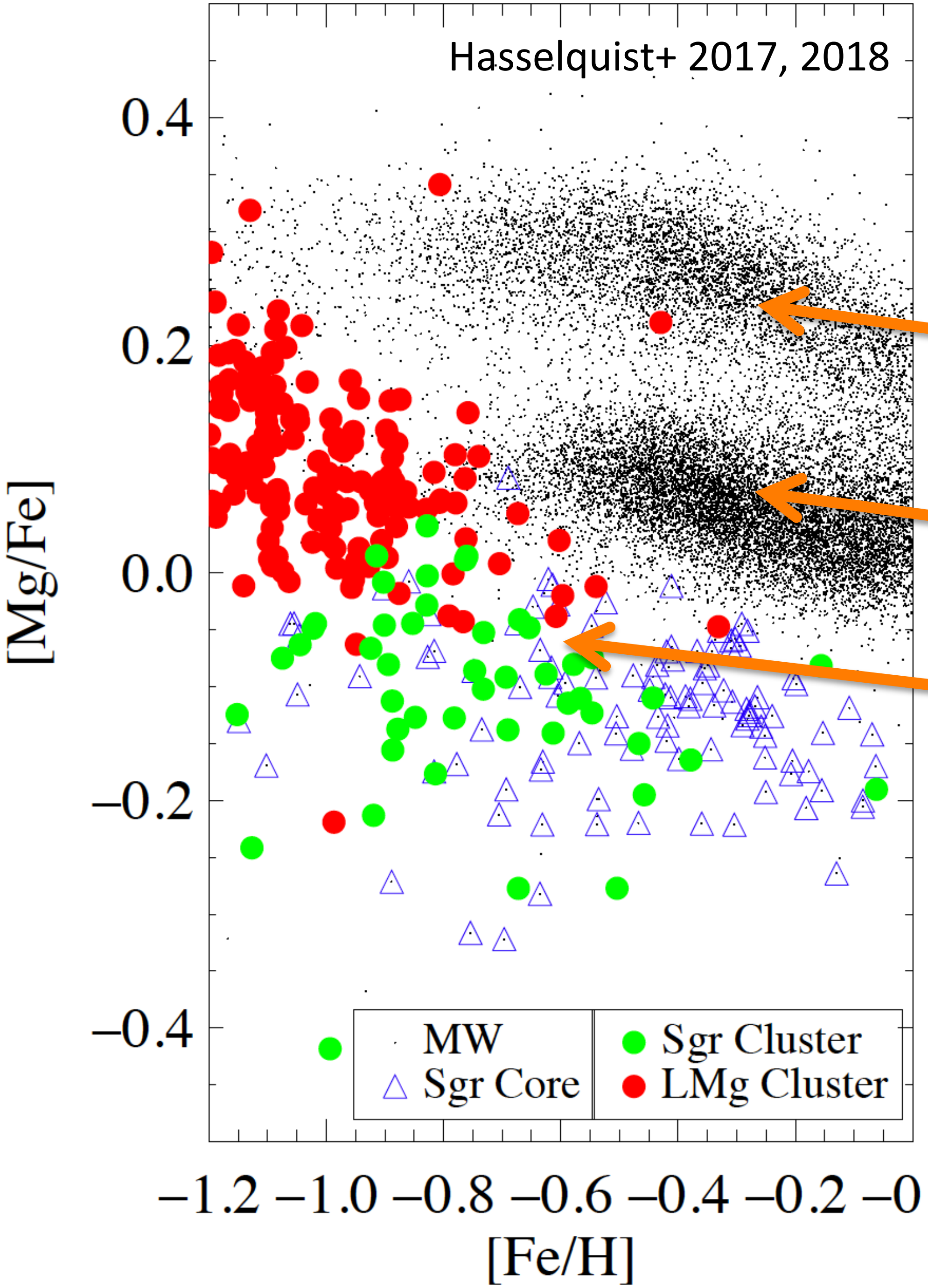
J_Z

J_R

$L_z = J_\Phi$



Mean trends and 1σ envelopes shown. *Bland-Hawthorn et al 2019*



Towards better nomenclature

As a community, we should consider better nomenclature for the α-components. (JBH et al 2019)

α_+ Formerly α-rich

α_o Formerly α-poor

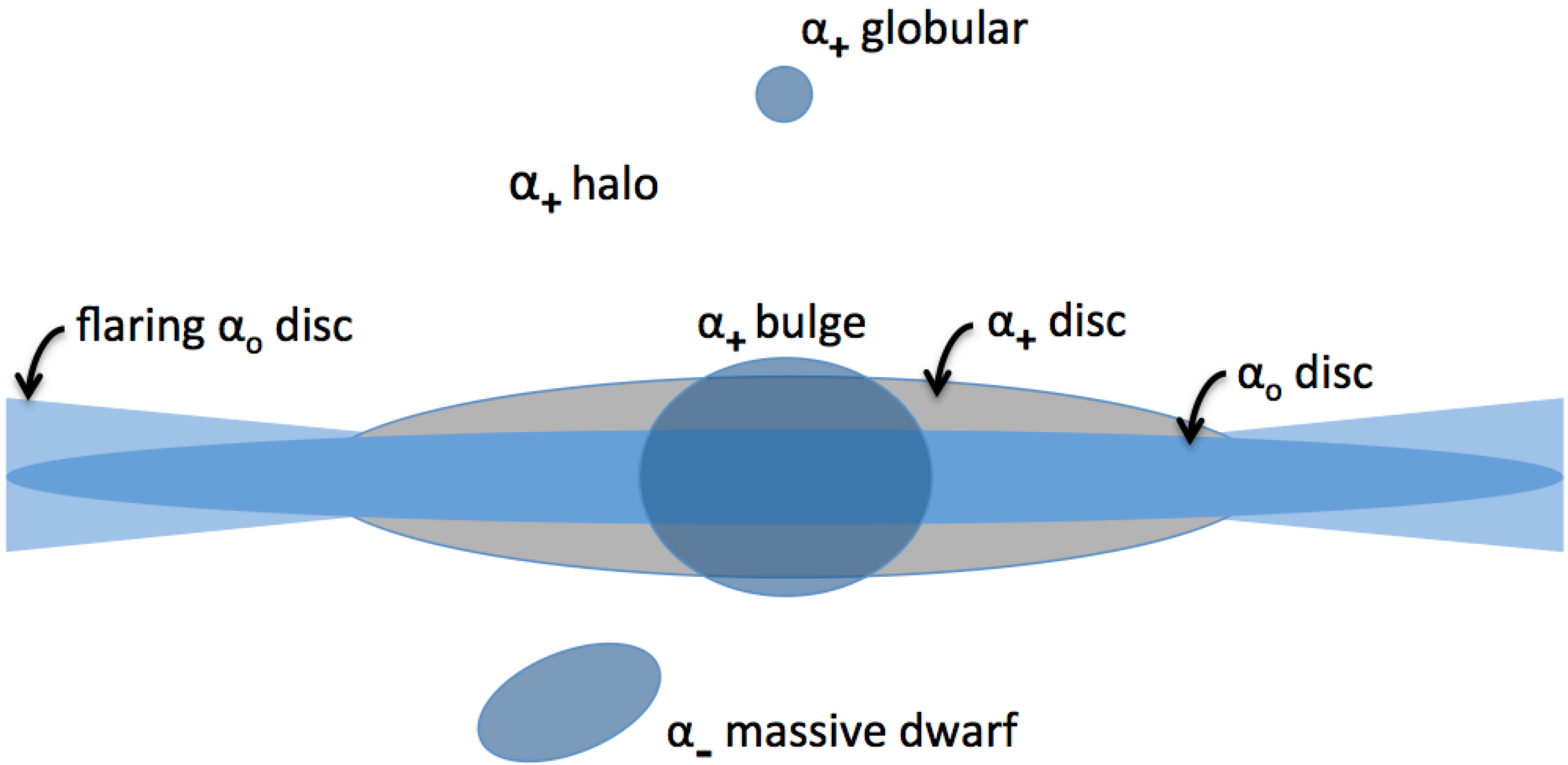
α_- Formerly unlabelled

There are three sequences in the α/Fe-Fe/H chemical plane. The middle sequence carries most of the Galactic stellar mass, but the upper sequence is substantial (~30%).

The lower sequence is from accreted massive dwarfs. We recognize that some low mass dwarfs have strange tracks in this space (e.g. Tostoy 2009 ARAA).

We need to avoid using thick vs. thin disk, alpha-rich vs. alpha-poor disk (eventually).

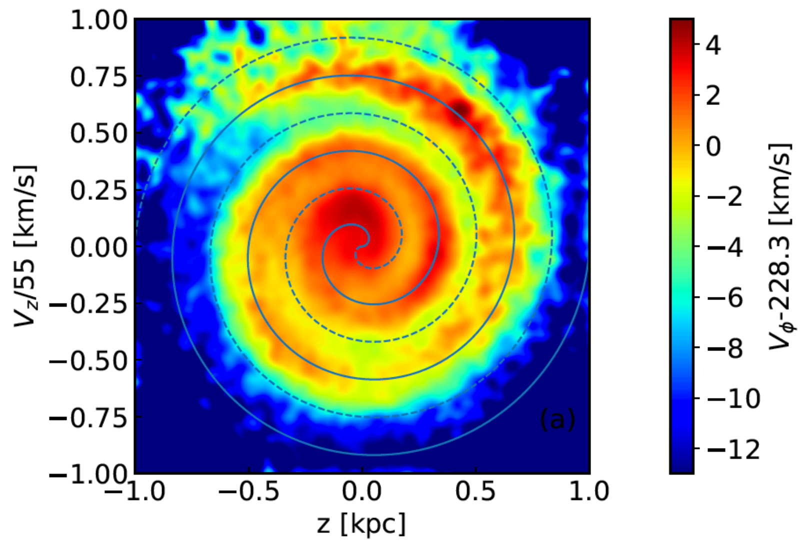
(JBH et al 2019)

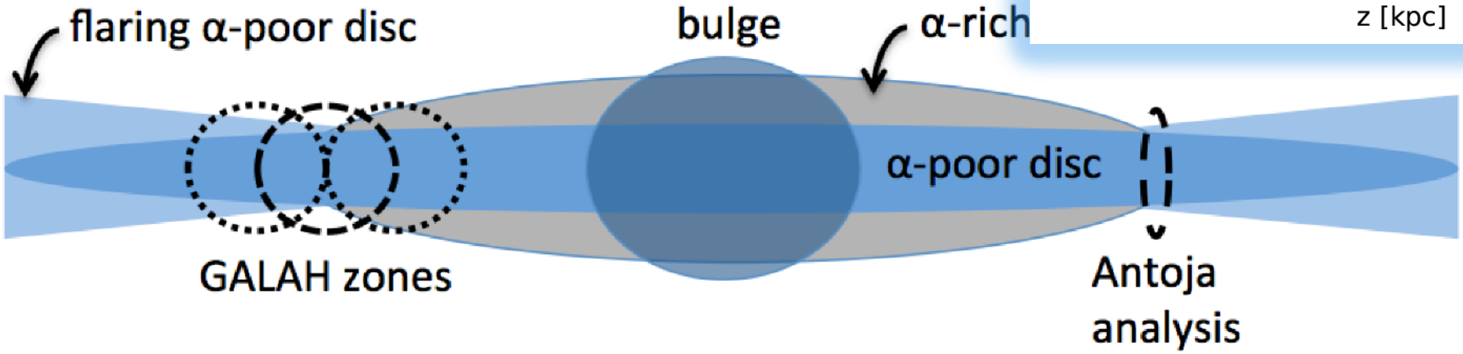


The GALAH survey and *Gaia* DR2: dissecting the stellar disc's phase space by age, action, chemistry and location

Joss Bland-Hawthorn[1,2,3★], Sanjib Sharma[1,2], Thor Tepper-Garcia[1], James Binney[4], Ken C. Freeman[5], Michael R. Hayden[1,2], Janez Kos[1], Gayandhi M. De Silva[1,6], Geraint F. Lewis[1], Martin Asplund[2,5], Sven Buder[7,8], Andrew R. Casey[9,10], Valentina D'Orazi[11], Ly Duong[5], Prajwal R. Kafle[12], Jane Lin[5], Karin Lind[13], Sarah L. Martell[14], Melissa K. Ness[15,16], Jeffrey D. Simpson[13], Daniel B. Zucker[6], Tomaž Zwitter[17] and the GALAH team
(Affiliations listed after the references)

Notice how Antoja's z-V_z "phase spiral" appears circular – the scaling is arbitrary





- The language of **phase space** was laid down in the 19th Century.

- It speaks of phase point, phase line, phase integral, phase vector, phase trajectory, phase velocity, phase plane, phase diagram, phase portrait, and so on. There are published examples where the word **space** is inserted, e.g. **phase-space mixing**, but it less common.

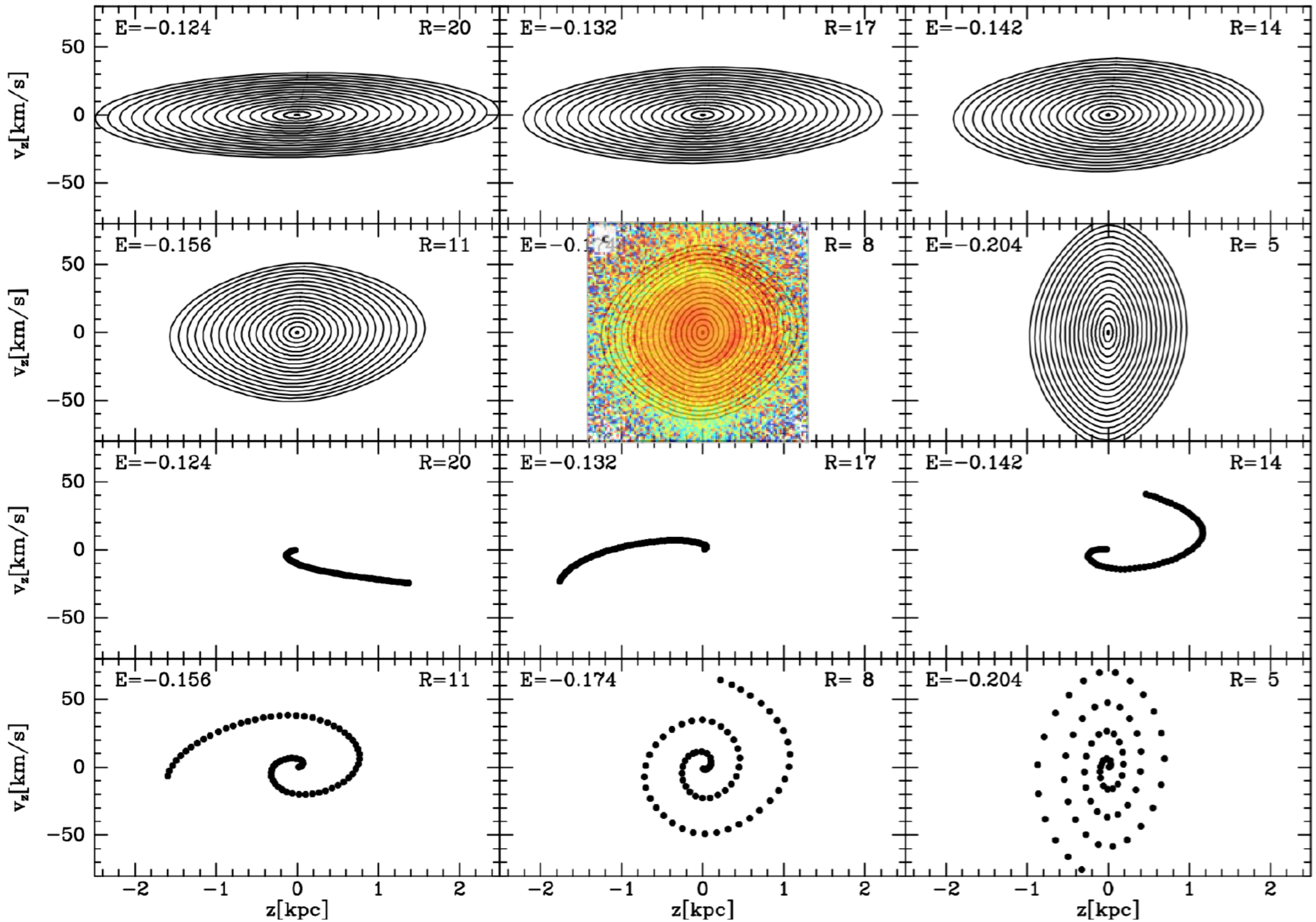
- Consistent with this language, Lynden-Bell, like many that followed (e.g. BT08), spoke of **phase mixing** and **phase wrapping** (1960s).

- In an attempt to be consistent, we adopted **phase spiral** instead of **phase-space spiral** for the Gaia discovery.

- This allows you to construct sentences like “the coherent phase spiral demonstrates phase mixing in action space.”

The GALAH survey and Gaia DR2: dissecting the stellar disc's phase space by age, action, chemistry

Bland-Hawthorn et al 2019 E = circular orbit at *R*; $2\pi J_z$ = const. for outer contour



*Interpreting the "**phase spiral**" depends critically on local disc properties. For a useful **dynamical clock**, the vertical structure (prior to perturbation) must be established. (AGAMA+Piffl2014)*

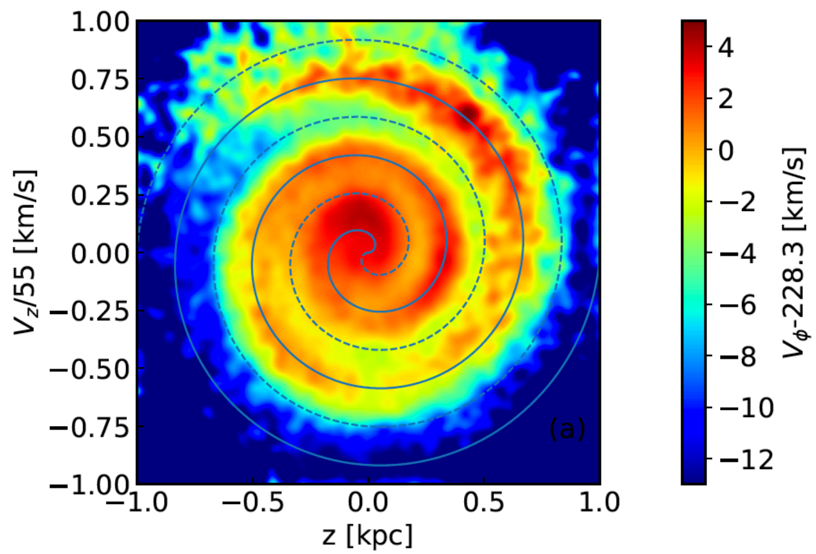
Gaia+GALAH DR2 movie
(colour coded in $\boldsymbol{L_z}$ as a function of ***R***)

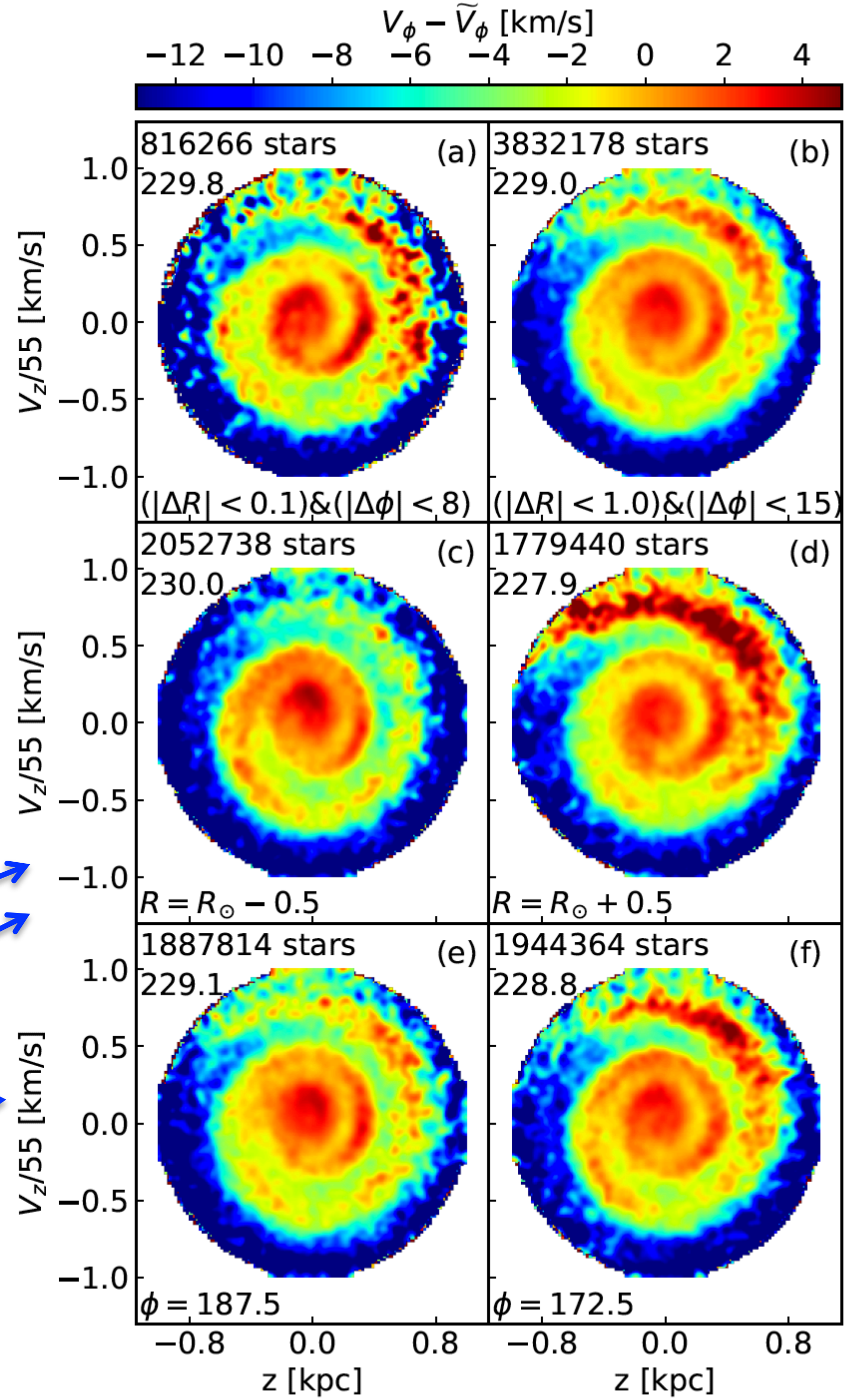
by Sanjib Sharma

Similar dependence in ***R*** was recently presented by Wang et al (2019) for **Gaia+LAMOST**

Slicing by location

6 *Bland-Hawthorn et al.*





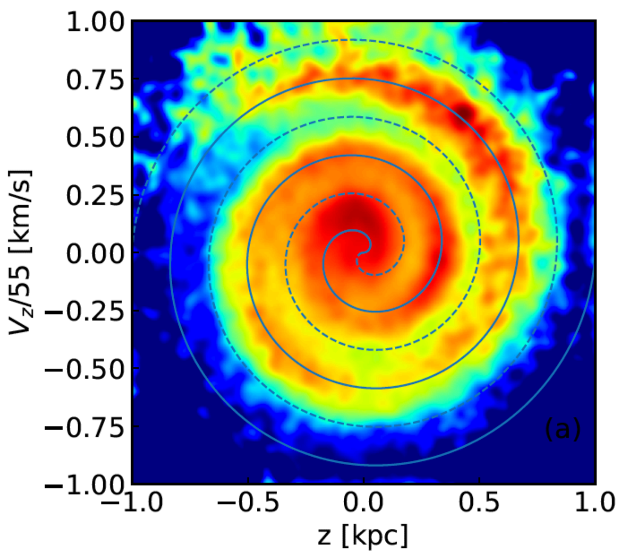
Note varying aspect ratio and phase with *R*.

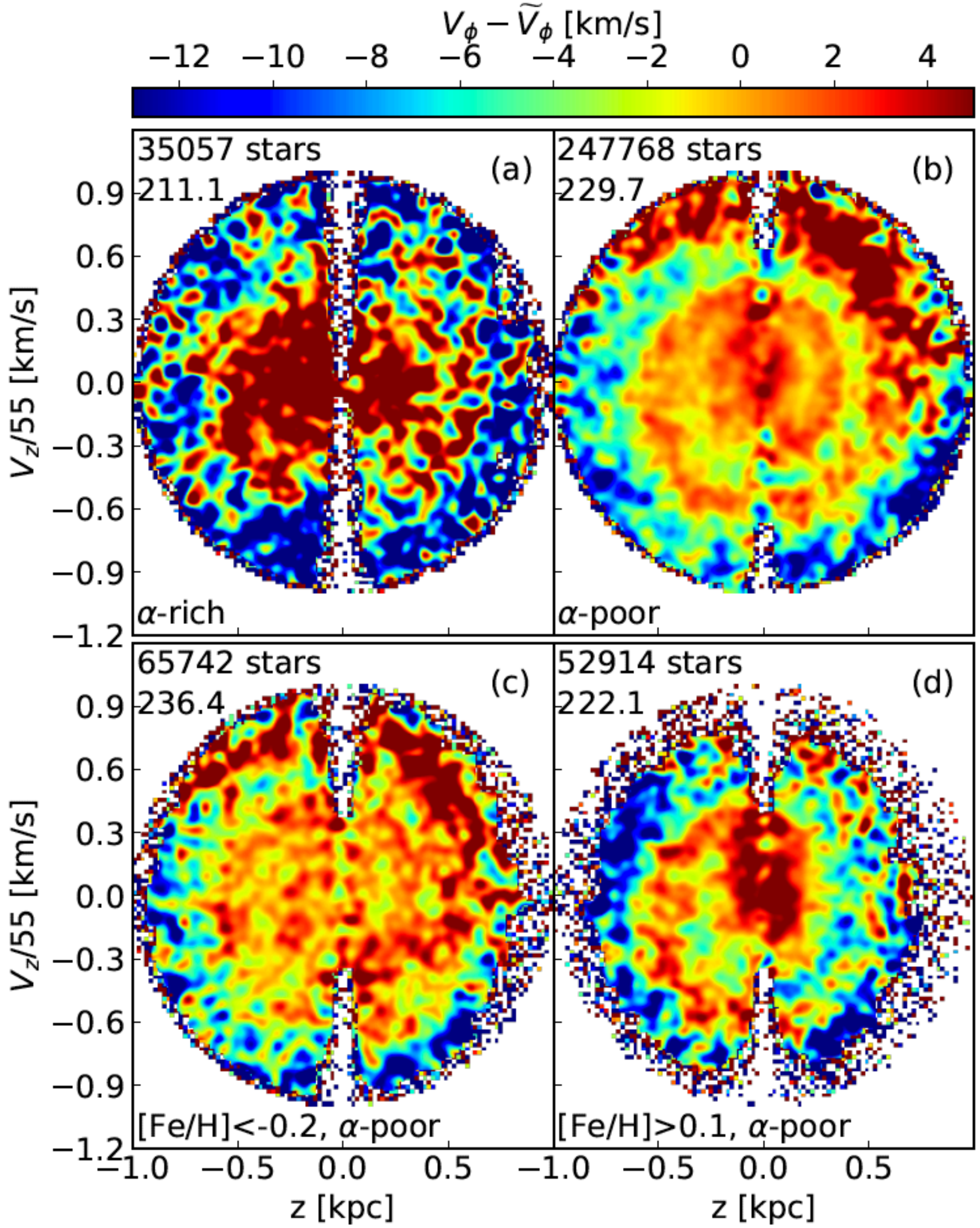
Note asymmetry in *R* and *φ*.

This is a disc-wide phenomenon.

Slicing by chemistry

6 *Bland-Hawthorn et al.*





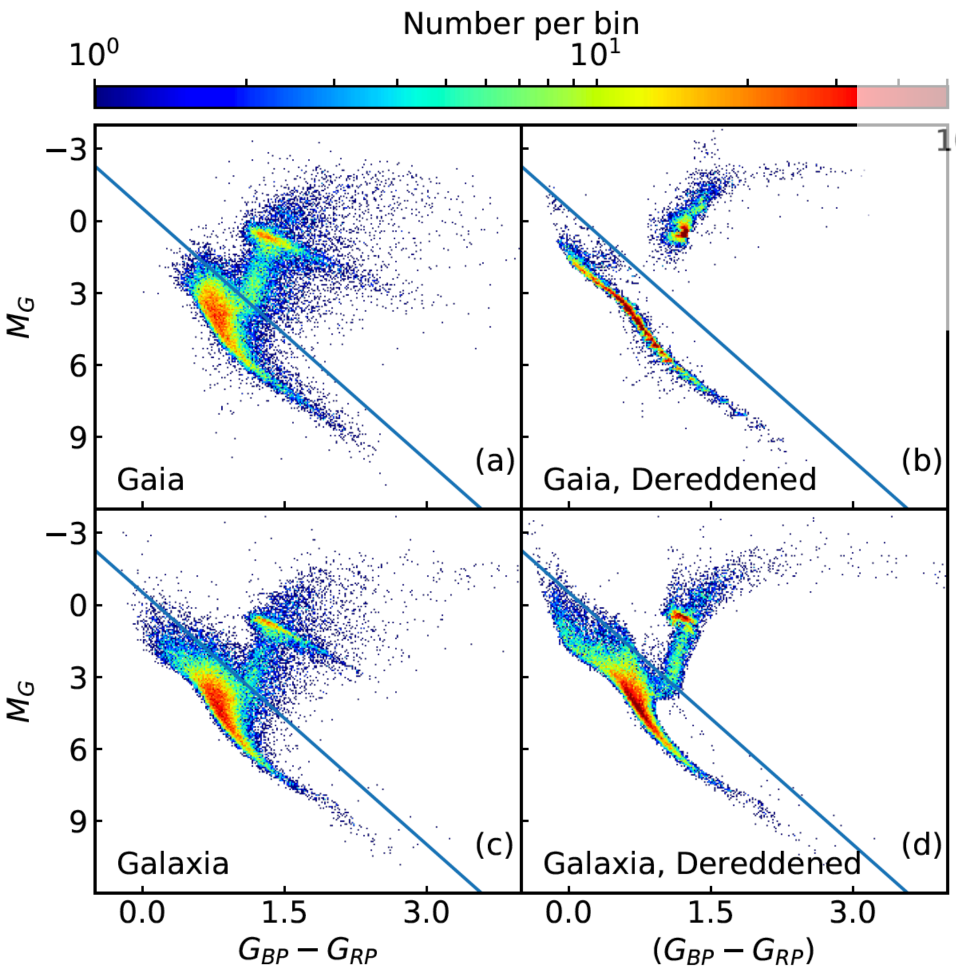
The perturbation reflects the overall metallicity gradient in *R* and *z*. Is it blurring a pre-existing gradient ?

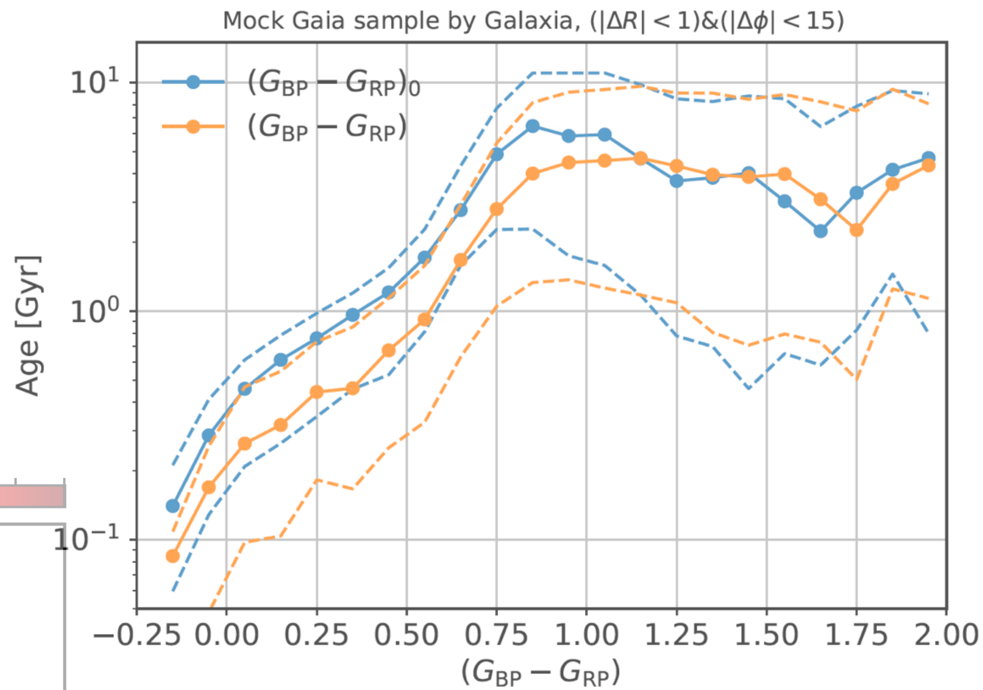
The perturbation favours the α-poor disc even when we match star counts.

ASTRO 3D

Colour-age relation from *Galaxia* calibration

(Sharma et al 2011)





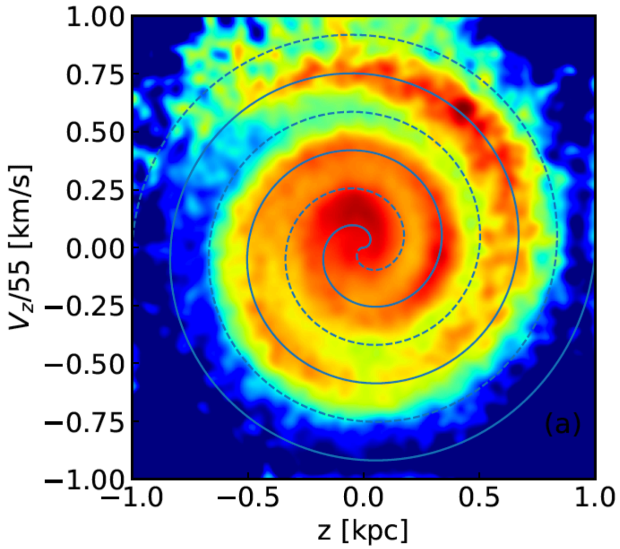
Gaia dereddened data are a biassed set, so should not be used for colour-age analysis.

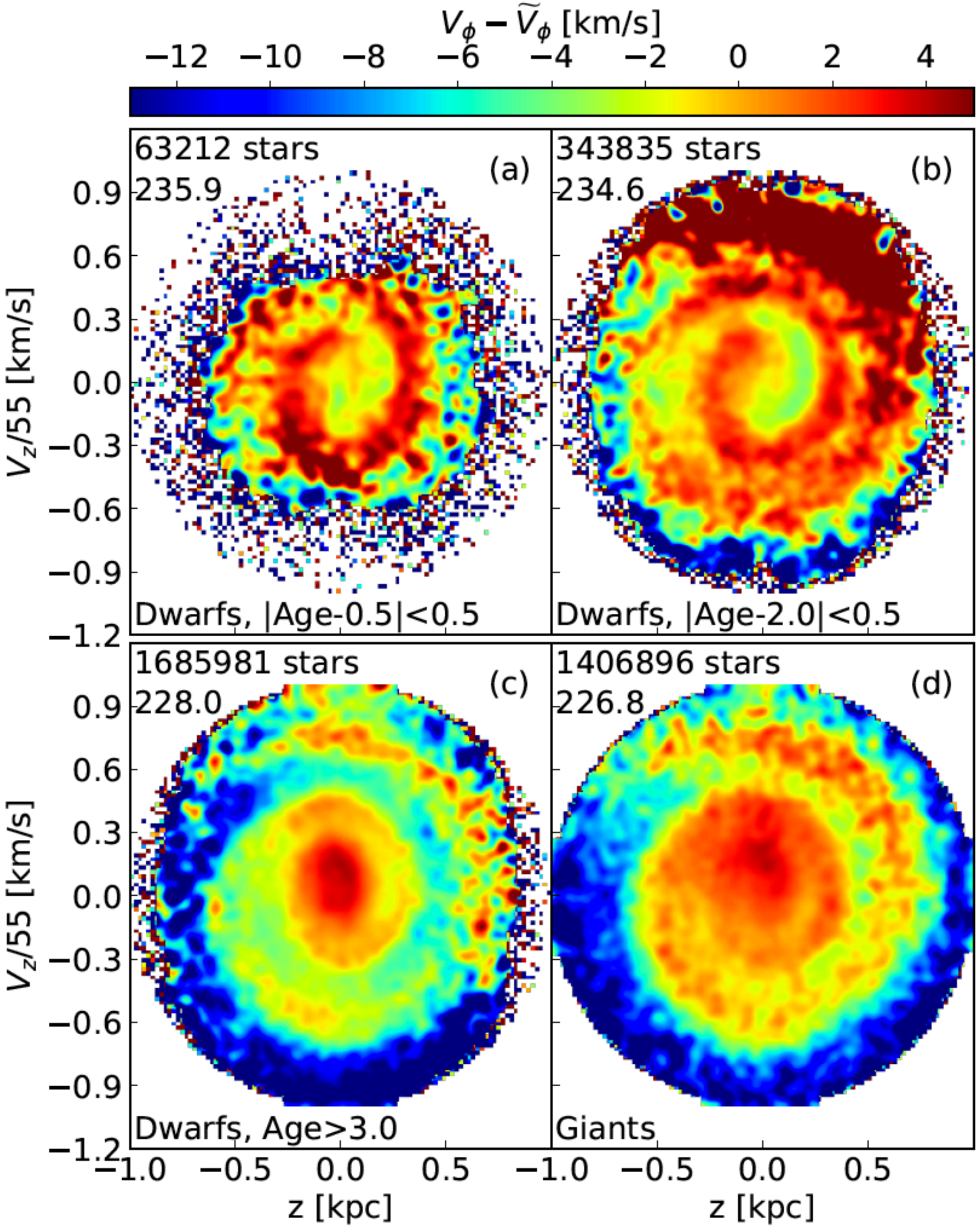
But uncorrect and corrected data tell the same story, clear trend until 3.5 Gyr.

Mean trends and 1σ envelopes shown.

Slicing by ages

6 *Bland-Hawthorn et al.*



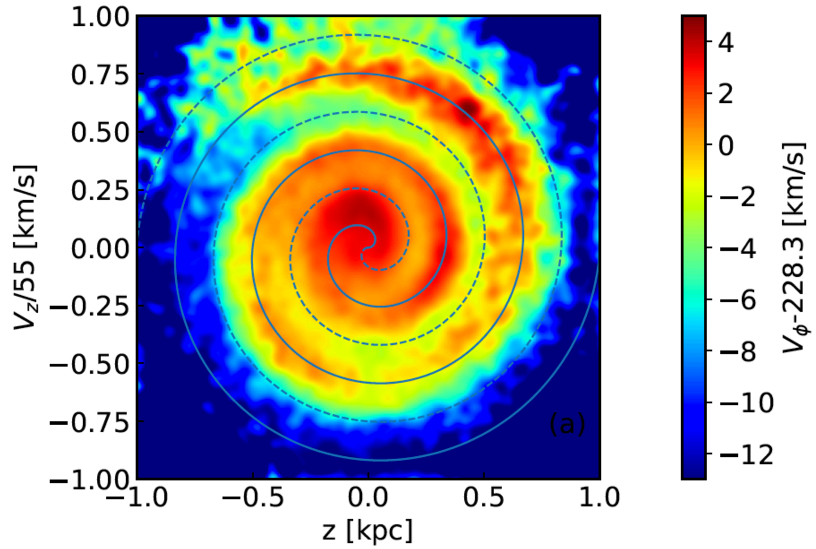


Younger dwarfs (< 2.5 Gyr) show the clearest "phase spiral" all the way to the origin.

The "outer spiral" is from older stars.

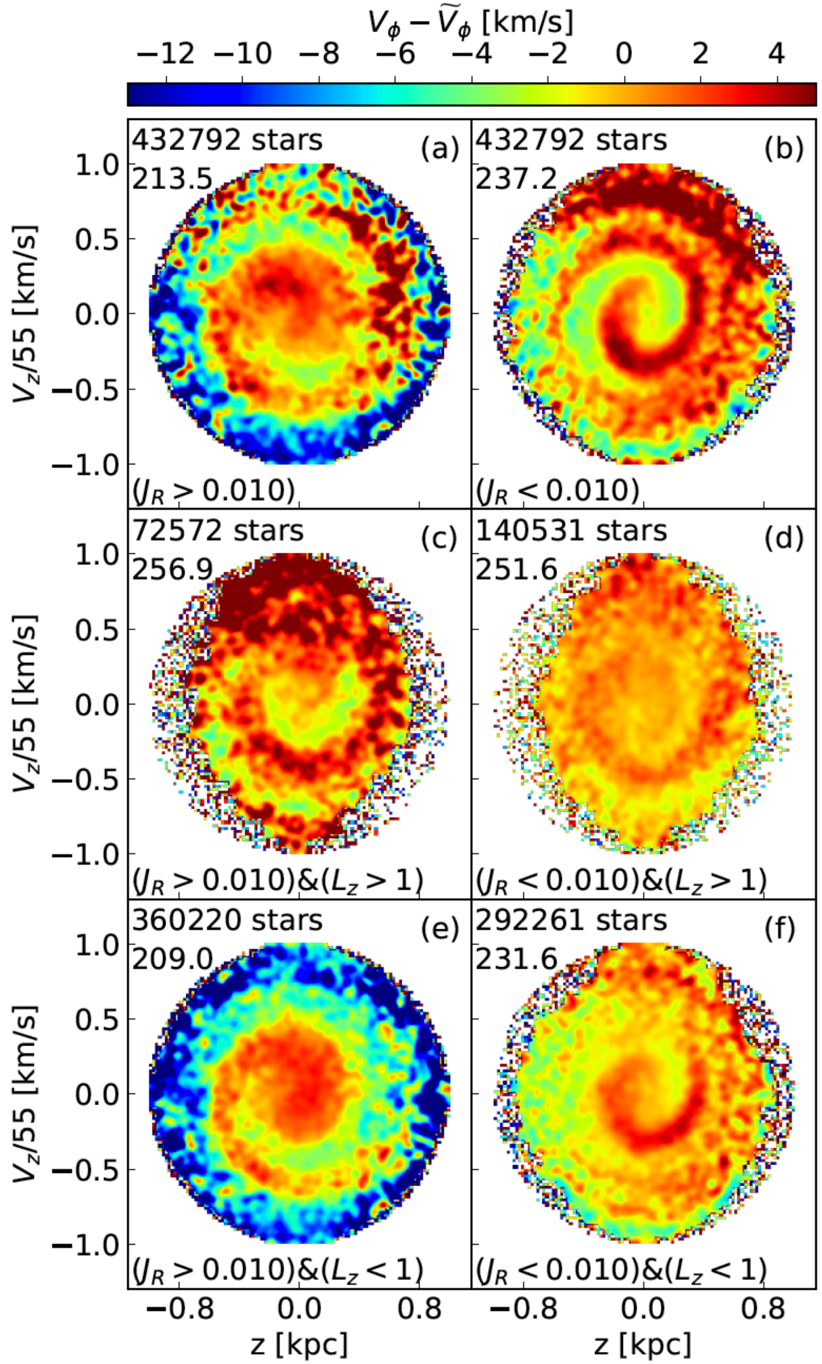
Slicing by actions

6 *Bland-Hawthorn et al.*



Younger dwarfs (< 2.5 Gyr) show the clearest "phase spiral" all the way to the origin. These are on circular orbits.

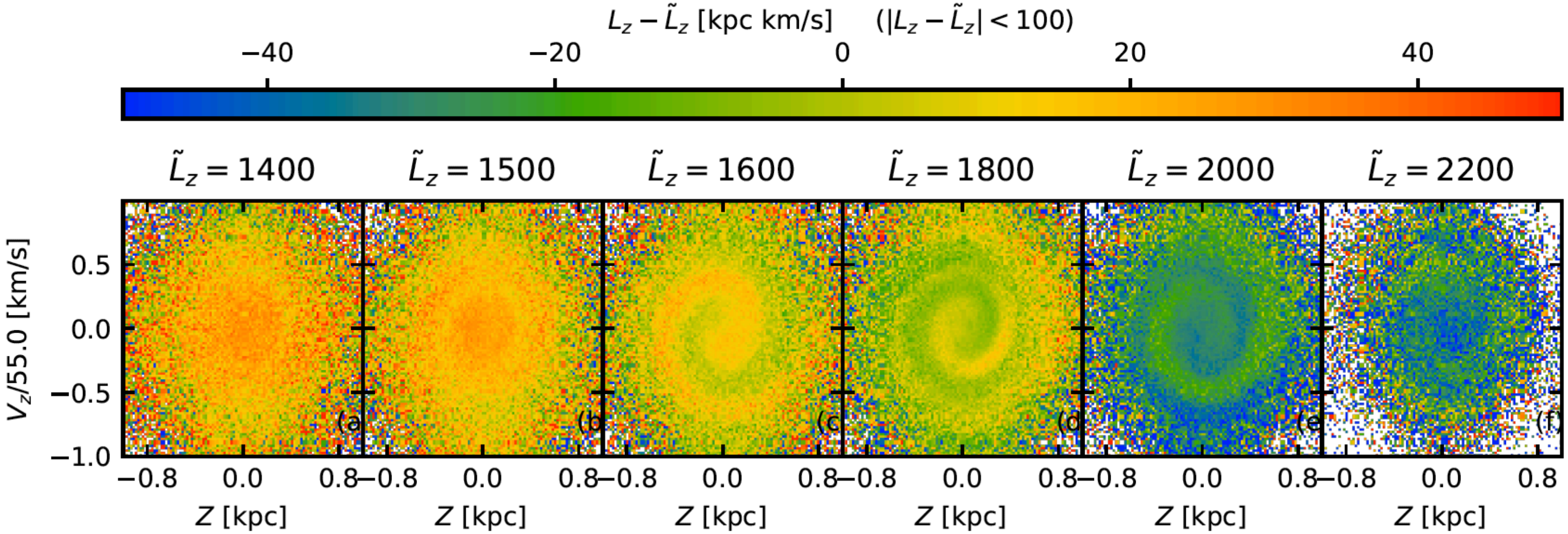
The "outer spiral" is from older stars on more elliptic orbits that appear less relaxed, hence "inner spiral" and "outer spiral" less clear.



ASTRO 3D

Gaia+GALAH DR2 movie
(colour coded in L_z as a function of L_z)
by Sanjib Sharma

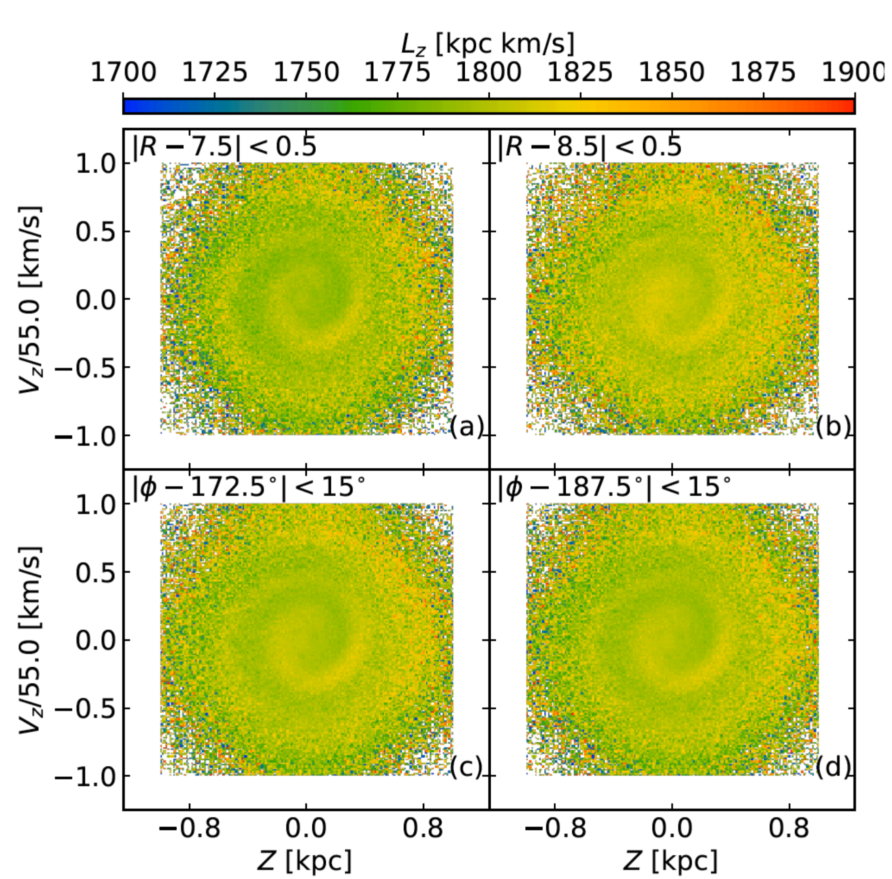
Summary at bottom discussed in Khanna et al (2019): *smoothest regional variations in phase spiral are seen in L_z*



The GALAH survey and *Gaia DR2*: Linking ridges, arches and vertical waves in the kinematics of the Milky Way

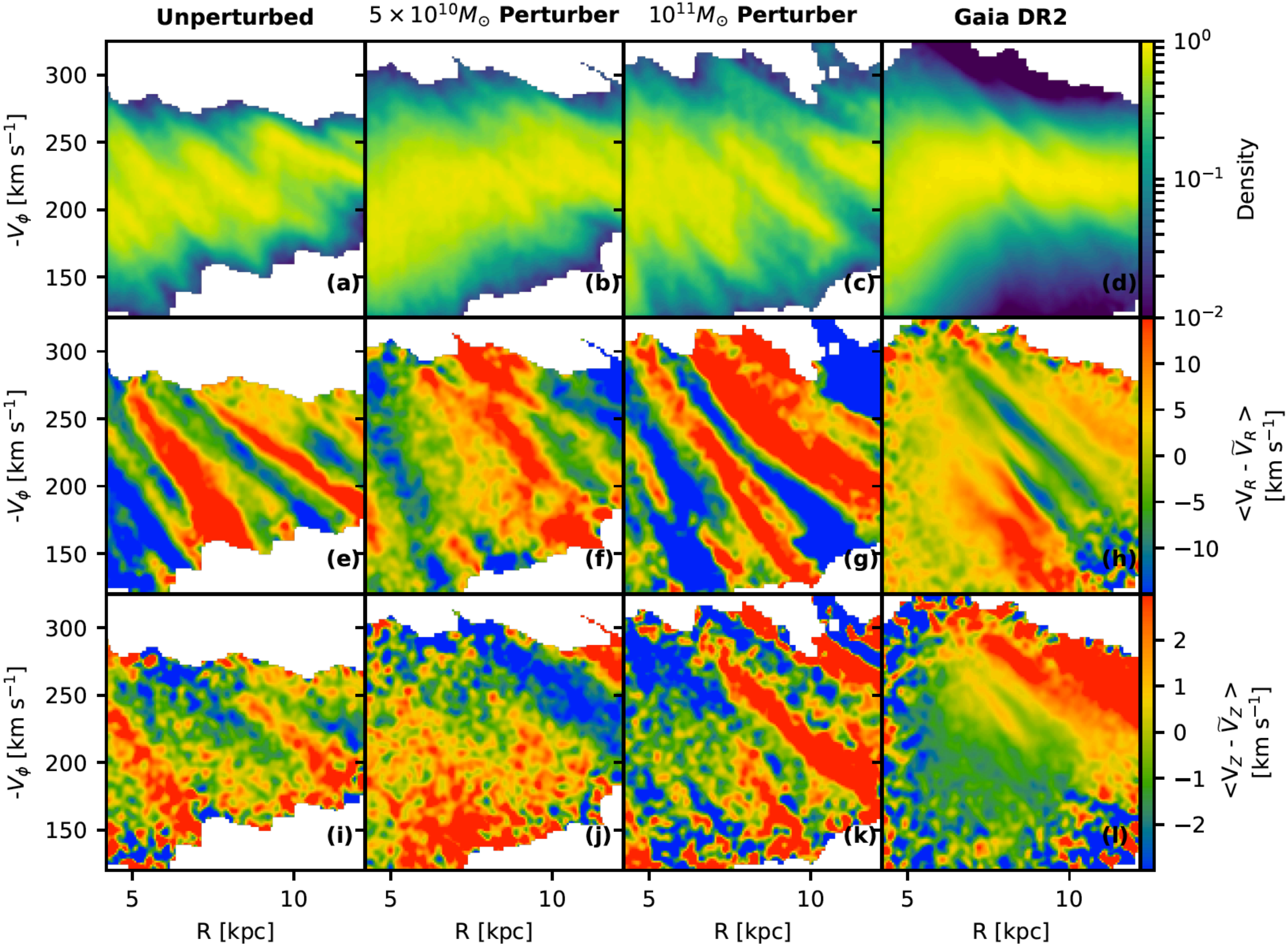
Shourya Khanna[1,2]★, Sanjib Sharma[1,2], Thor Tepper-Garcia[1,2], Joss Bland-Hawthorn[1,2,3], Michael Hayden[1,2], Martin Asplund[6,2], Sven Buder[7], Boquan Chen[1,2], Gayandhi M. De Silva[5,1], Ken C. Freeman[6], Janez Kos[4,1], Geraint F. Lewis[1], Jane Lin[6], Sarah L. Martell[8,2], Jeffrey D. Simpson[13], Dennis Stello[8], Yuan-Sen Ting[9,10,11], Daniel B. Zucker[5], Tomaž Zwitter[4]

[1] *Sydney Institute for Astronomy, School of Physics, A28, The University of Sydney, NSW, 2006, Aust*
[2] *ARC Centre of Excellence for All Sky Astrophysics in Three Dimensions (ASTRO-3D)*
[3] *Miller Professor, Miller Institute, UC Berkeley, Berkeley CA 94720*
[4] *Faculty of mathematics and physics, University of Ljubljana, Jadranska 19, 1000 Ljubljana, Slover*
[5] *Department of Physics and Astronomy, Macquarie University, Sydney, NSW 2109, Australia*
[6] *Research School of Astronomy & Astrophysics, Australian National University, ACT 2611, Australi*
[7] *Max Planck Institute for Astronomy (MPIA), Koenigstuhl 17, D-69117 Heidelberg*
[8] *School of Physics, University of New South Wales, NSW 2052, Australia*
[9] *Institute for Advanced Study, Princeton, NJ 08540, USA*
[10] *Department of Astrophysical Sciences, Princeton University, Princeton, NJ 08544, USA*
[11] *Observatories of the Carnegie Institution of Washington, 813 Santa Barbara Street, Pasadena, CA*



Smoothest regional variations in phase spiral are seen in L_z moving in radius and azimuth

Recall how highly structured the phase spiral appears using Vφ or V_R coding



Unperturbed
$5\times10^{10}M_{\odot}$ Perturber
$10^{11}M_{\odot}$ Perturber
Gaia DR2
$-V_{\phi}$ [km s^{-1}]
R [kpc]
Density
$<V_R - \widetilde{V}_R>$ [km s^{-1}]
$<V_Z - \widetilde{V}_Z>$ [km s^{-1}]
(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
(i)
(j)
(k)
(l)

The Sagittarius dwarf galaxy: Where did all the gas go?

Thor Tepper-García[★,1] and Joss Bland-Hawthorn[1,2,3]
[1]*Sydney Institute for Astronomy, School of Physics, University of Sydney, NSW 2006, Australia*
[2]*Centre of Excellence for All Sky Astrophysics in Three Dimensions (ASTRO-3D), Australia*
[3]*Miller Professor, Miller Institute, University of California Berkeley, Berkeley, CA 94720, USA*

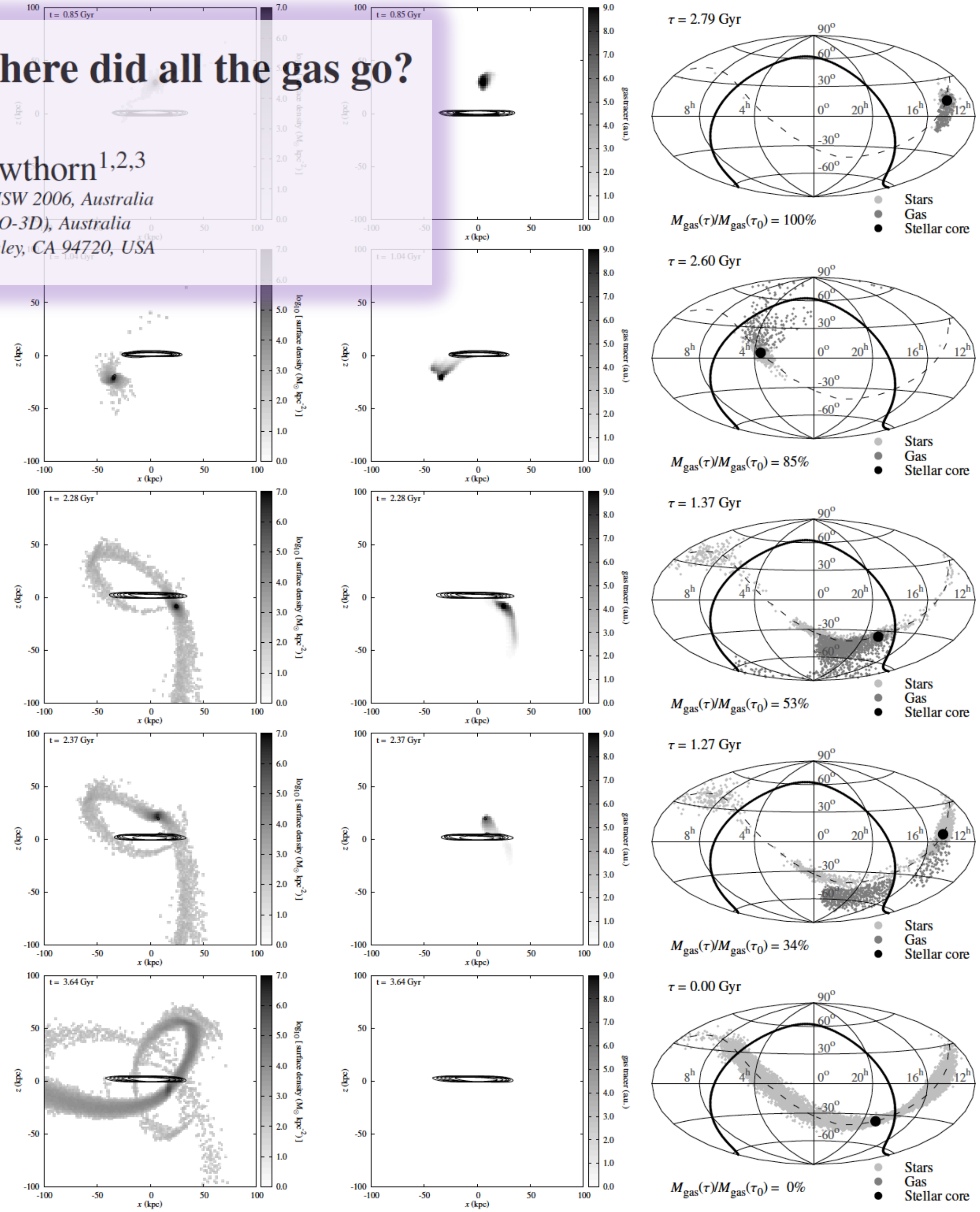
Static MW potential with N-body model for Sgr:
Johnston et al. (1995, 1999, 2005) Velázquez & White (1995) Ibata et al. (1997) Ibata & Lewis (1998) Helmi & White (2001) Helmi (2004a,b) Law et al. (2005) Fellhauer et al. (2006) Law & Majewski (2010) Niederste-Ostholt et al. (2012)

Full N-body models:
Edelsohn & Elmegreen (1997) Gómez-Flechoso et al. (1999) Jiang & Binney (2000) Peñarrubia et al. (2010,2011) Lokas et al. (2010) Myers et al. (2010) Purcell et al. (2011) Gibbons et al. (2014, 2017) Gómez et al. (2012,2013) Dierckx & Loeb (2017a,b) Laporte et al. (2018)

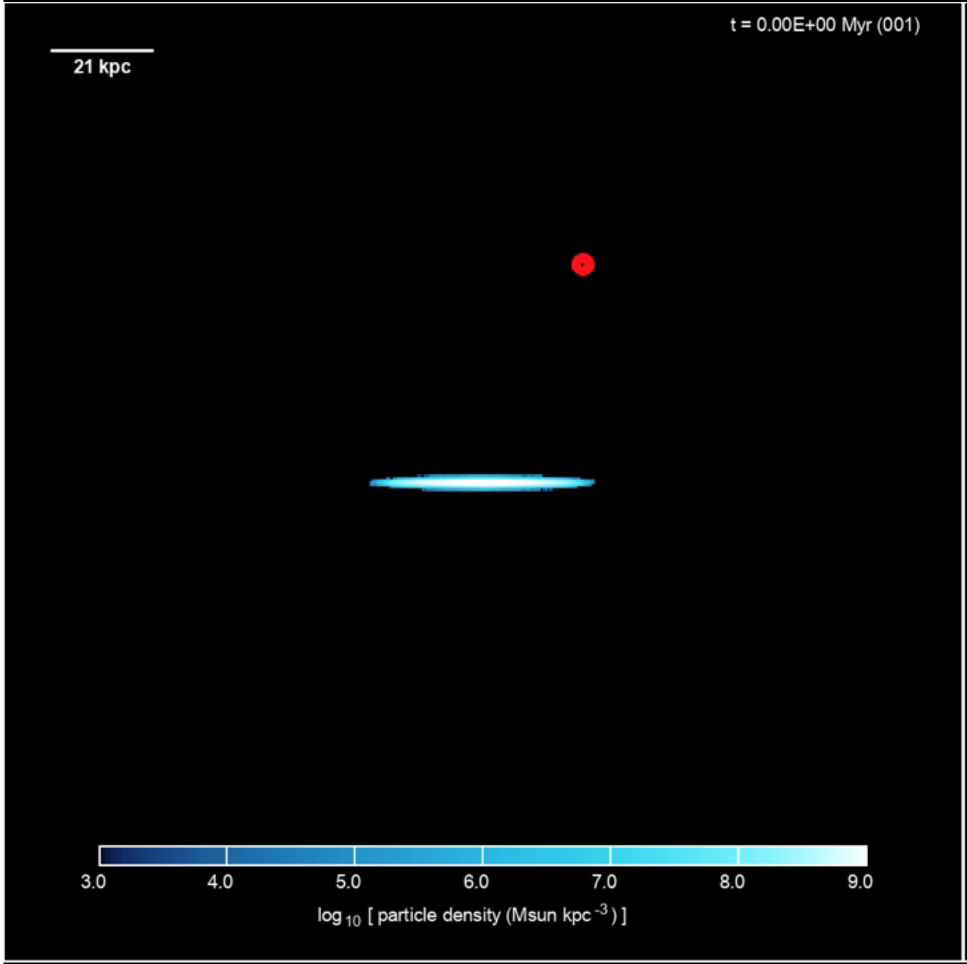
Full N-body + hydrodynamic models:
Tepper-García & Bland-Hawthorn (2018)

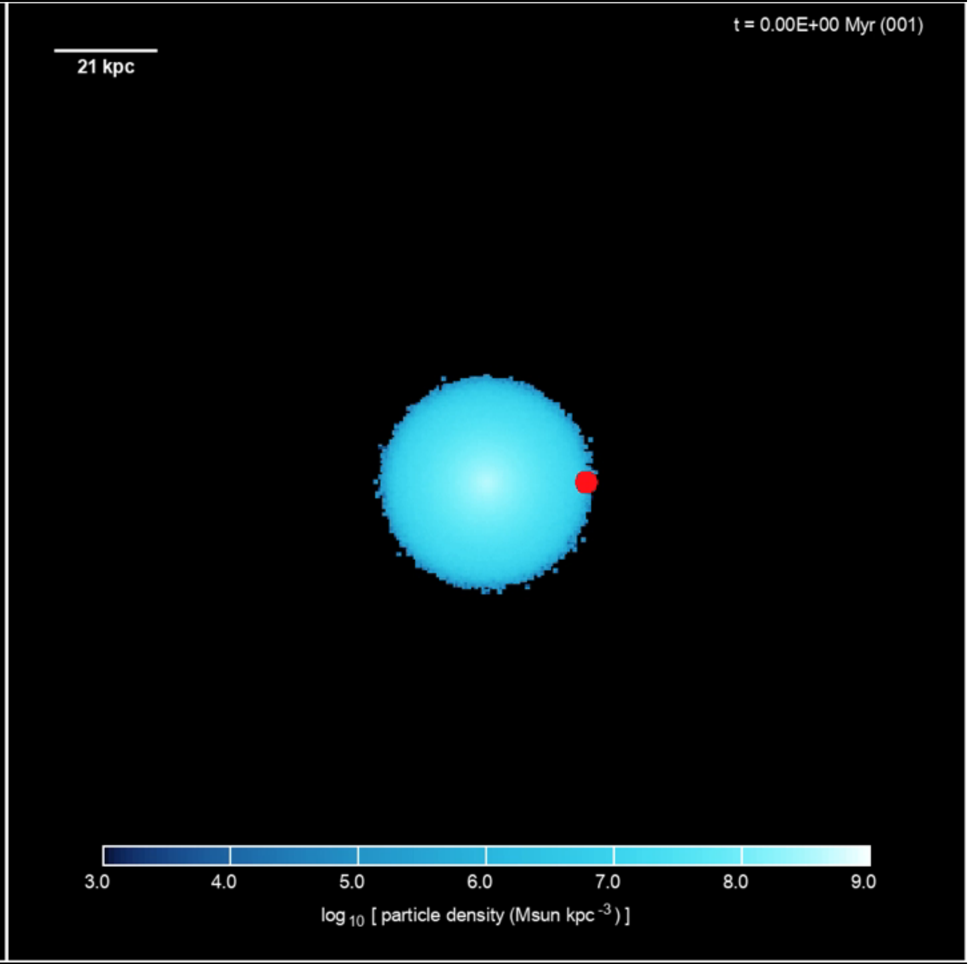
Since 2005, models have converged on the “trefoil” orbit.

Gas is important for orbit transit timings and it is **demanded** by the extended SFH in Sgr with cut-off ~1 Gyr ago.



High mass impactor, hyperbolic single transit (stripped to 5 x 10^{10} $M_{\odot}$)





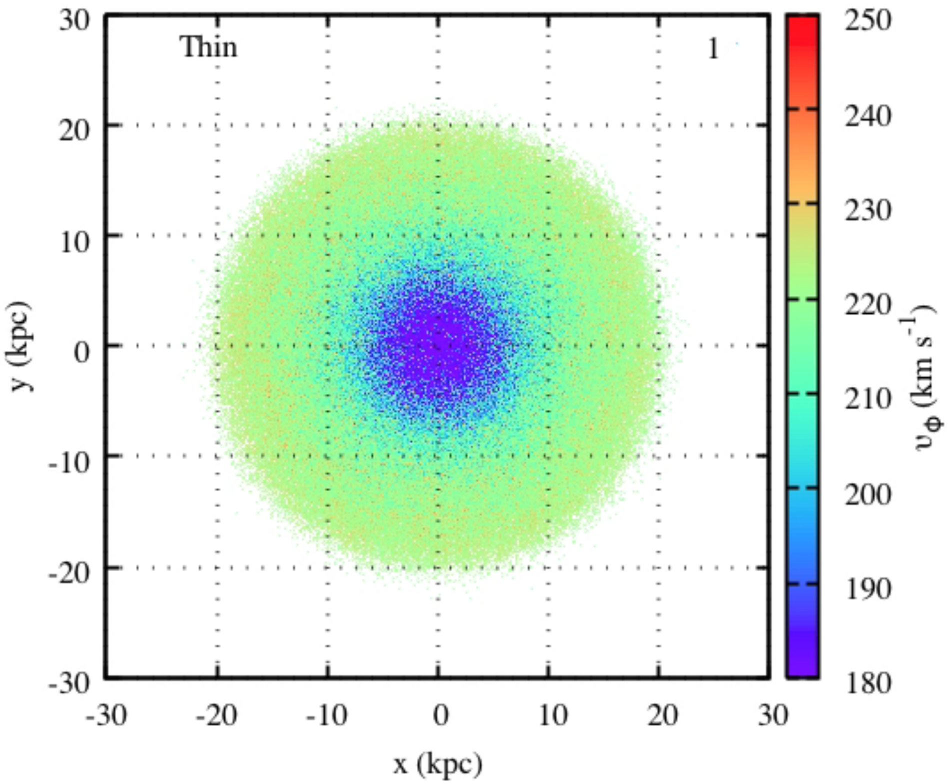
Σ (x,z)

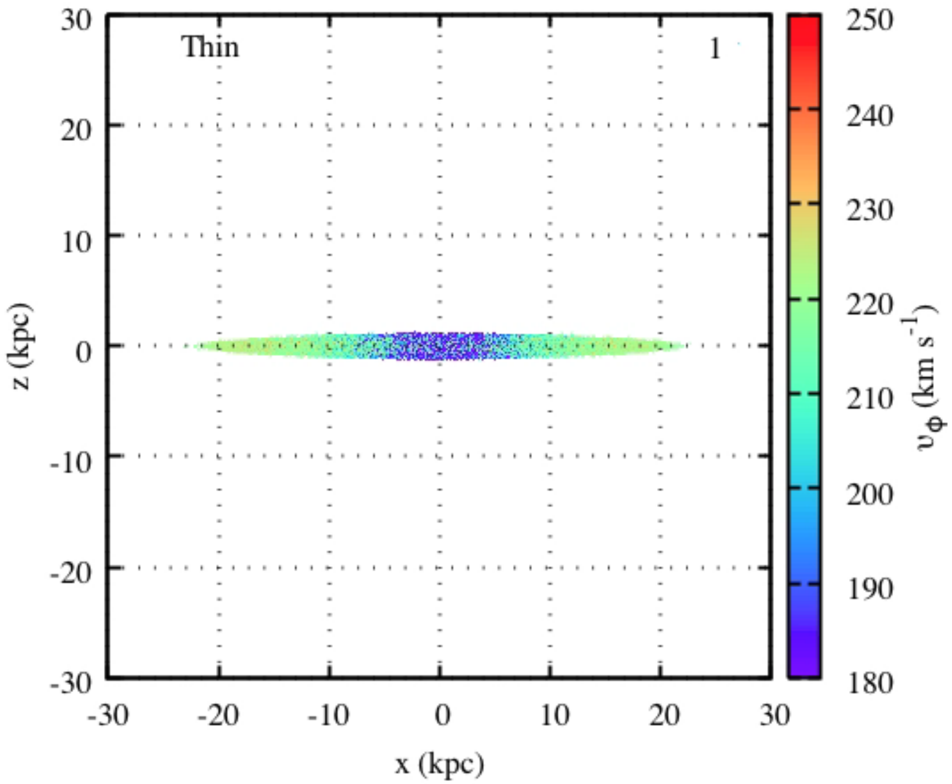
Σ (x,y)

High mass impactor, hyperbolic single transit $V_{\varphi}(x, y)$

Ack: T. Tepper-Garcia

Timestep is
10 Myr



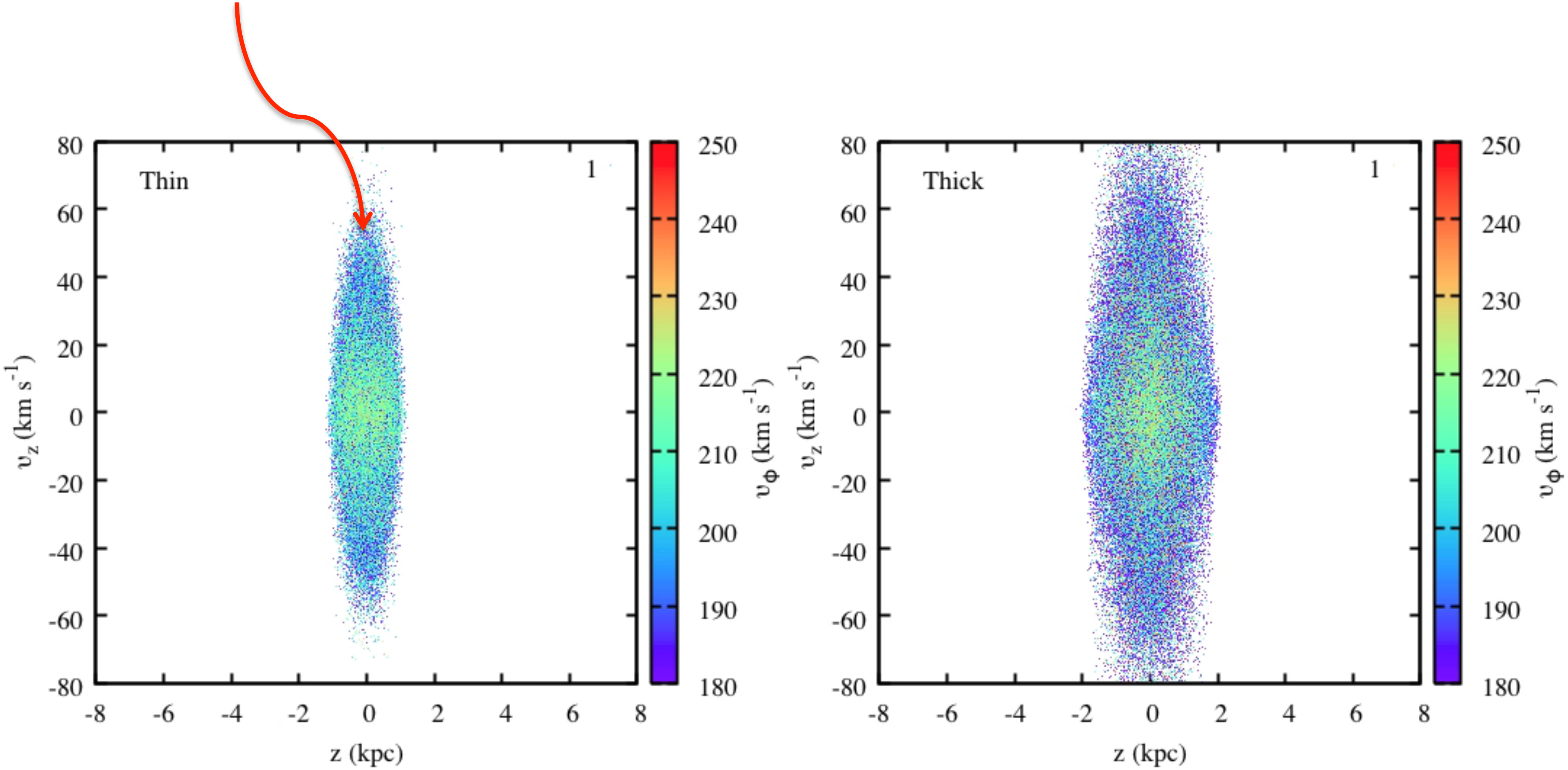


Outer warp, corrugations, ripples are apparent everywhere **after** Sgr has transited

High mass impactor, hyperbolic single transit $V_{\varphi}(z, V_z)$

Ack: T. Tepper-Garcia

Inner disc mostly removed



Corrugations all have phase space counterparts, specifically “phase spirals”

Low mass impactor, hyperbolic single transit

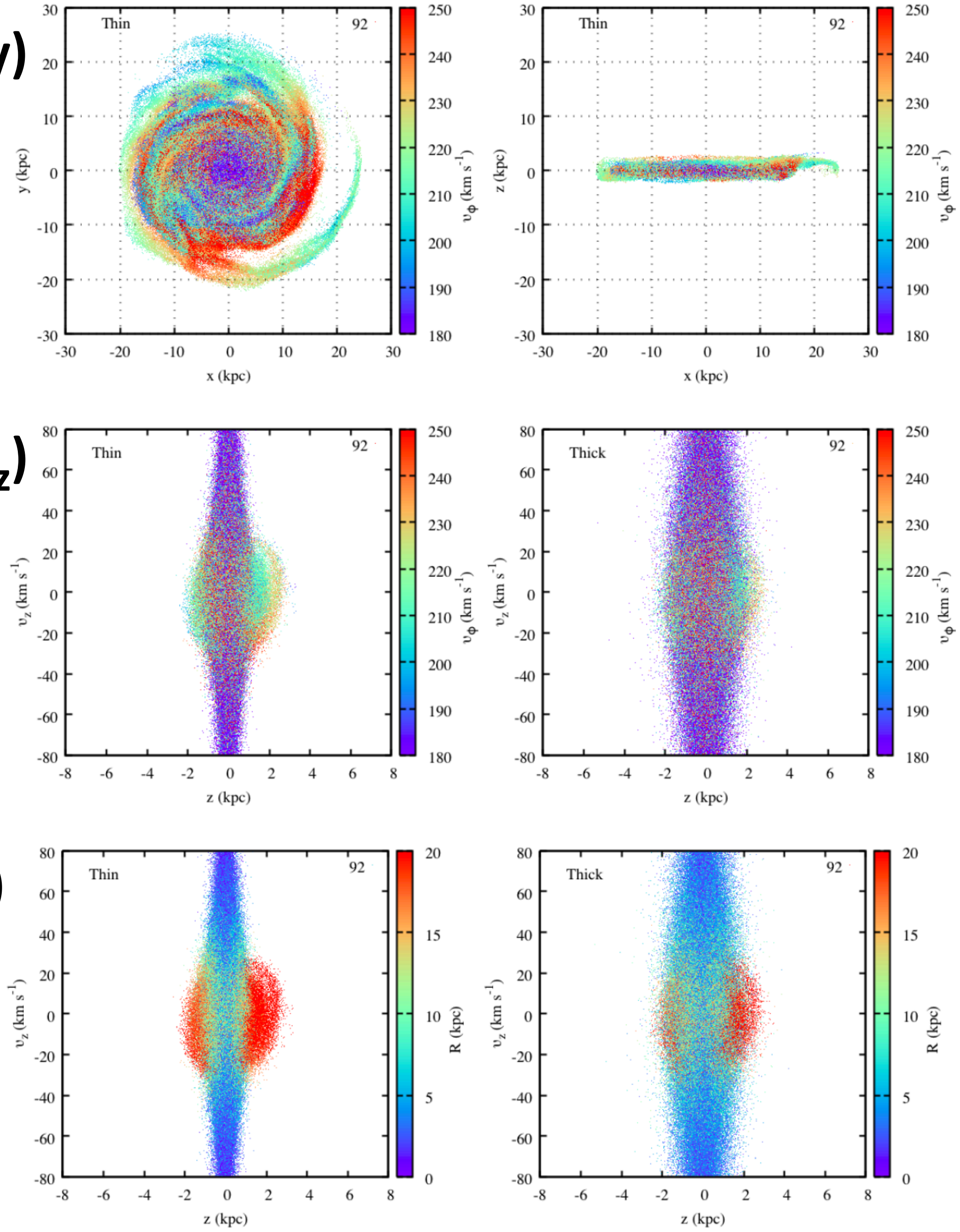
(stripped to 1 x 10^{10} $M_{\odot}$)

Lower amplitude structure seen over parts of the disc

Σ (x, y)

V_{φ} (z, V_z)

***R* (z, V_z)**

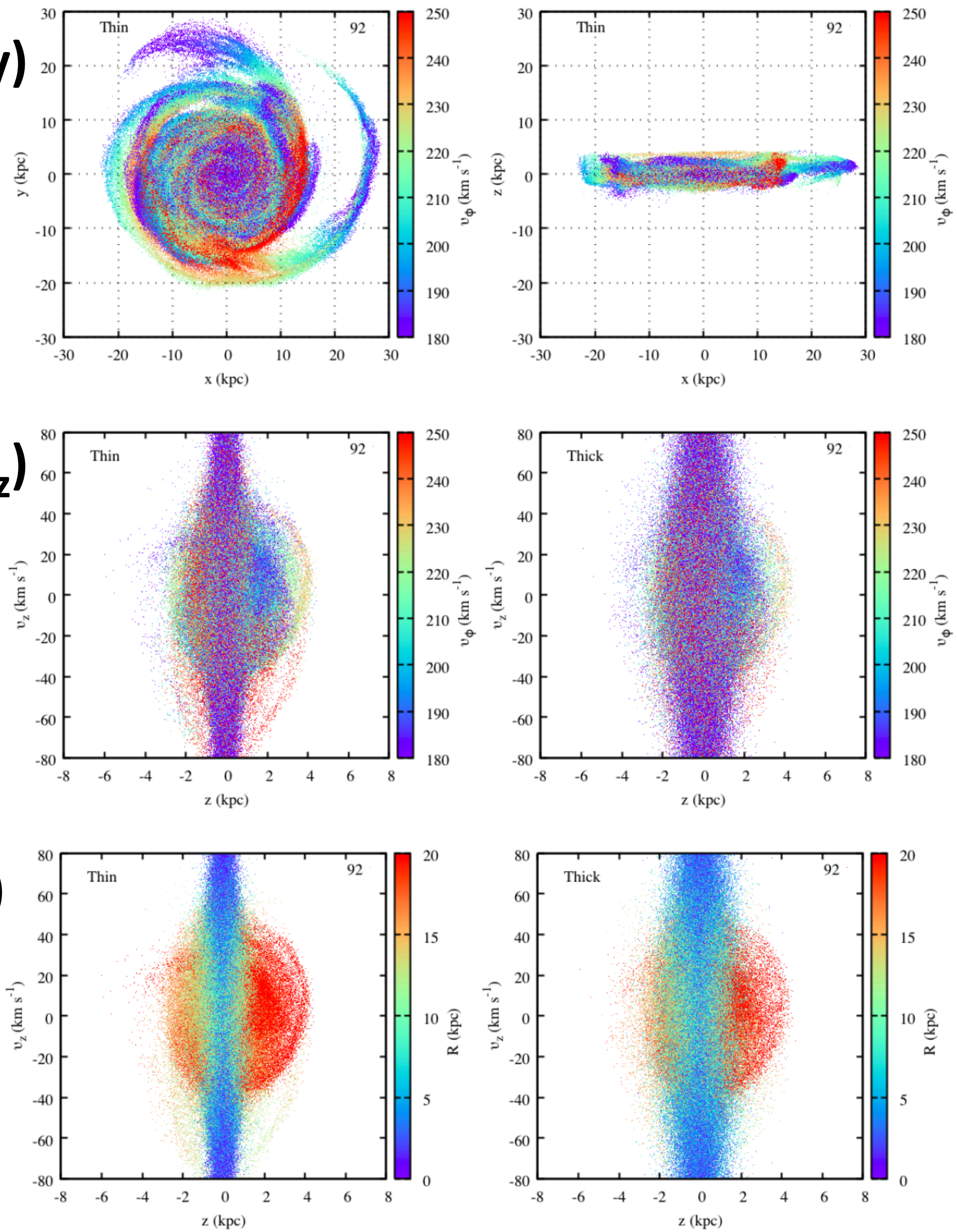


High mass impactor, hyperbolic single transit

Σ (x, y)

V_{φ} (z, V_z)

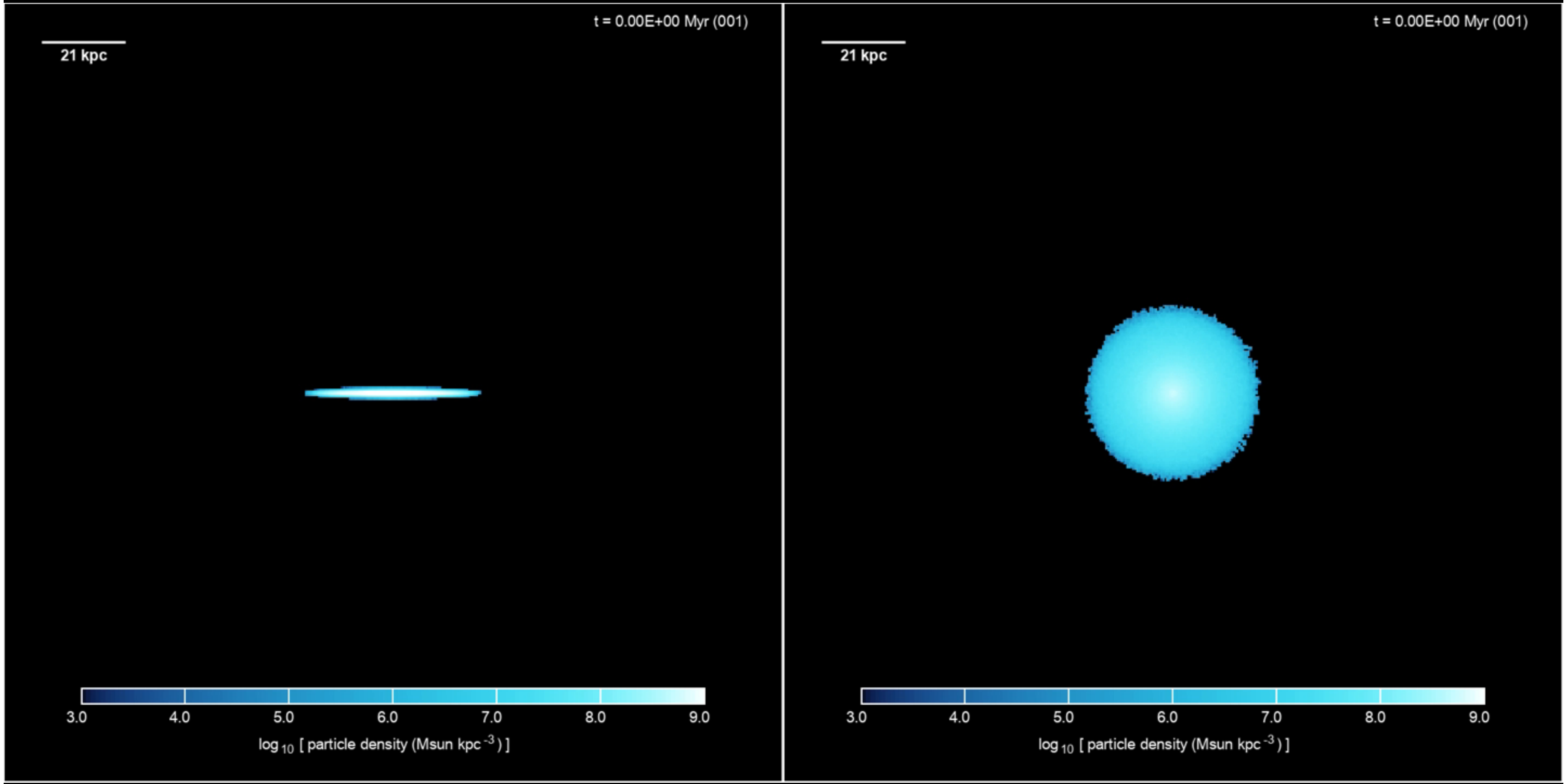
R **(z, V_z)**



Higher amplitude structure over entire disc, which can survive for > 2 Gyr.

Note "phase spiral" evolution predicted by Binney plot.

High mass impactor, realistic Sgr orbit ("trefoil")



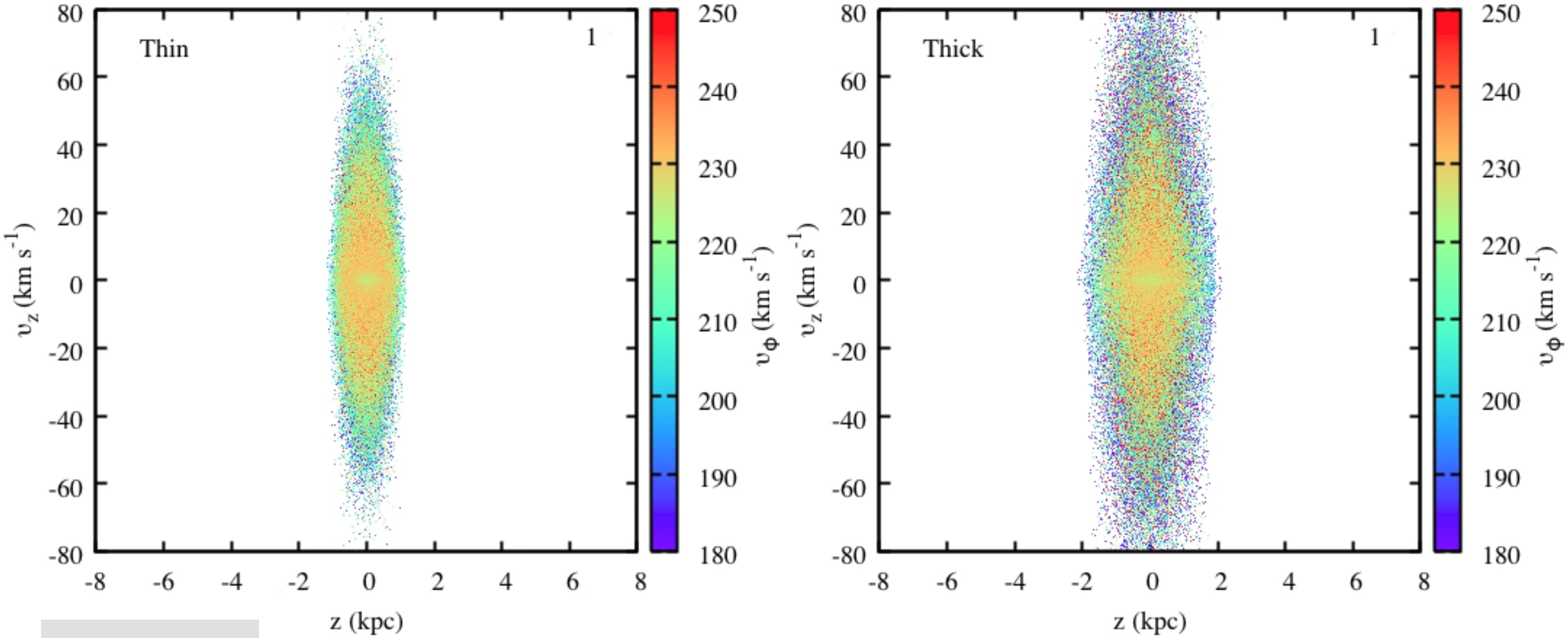
$\Sigma\ (x,z)$ $\Sigma\ (x,y)$

FIRST IMPACT

900 Myr

NEXT IMPACT

1.8 Gyr



Time steps are 10 Myr

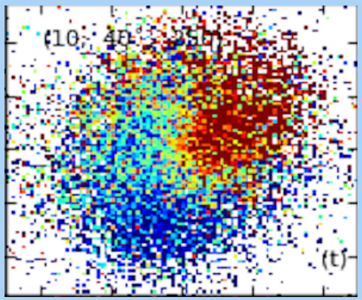
ASTRO 3D

SUMMARY

z-V_z amplitude at R = 8 kpc consistent with initial ~5 x 10^{10} $M_\odot$ stripped down to ~3 x 10^{10} $M_\odot$ at most recent transit ~ 450 Myr ago.

It **cannot** be much older due to decoherence caused by crossing.

Gaia volume

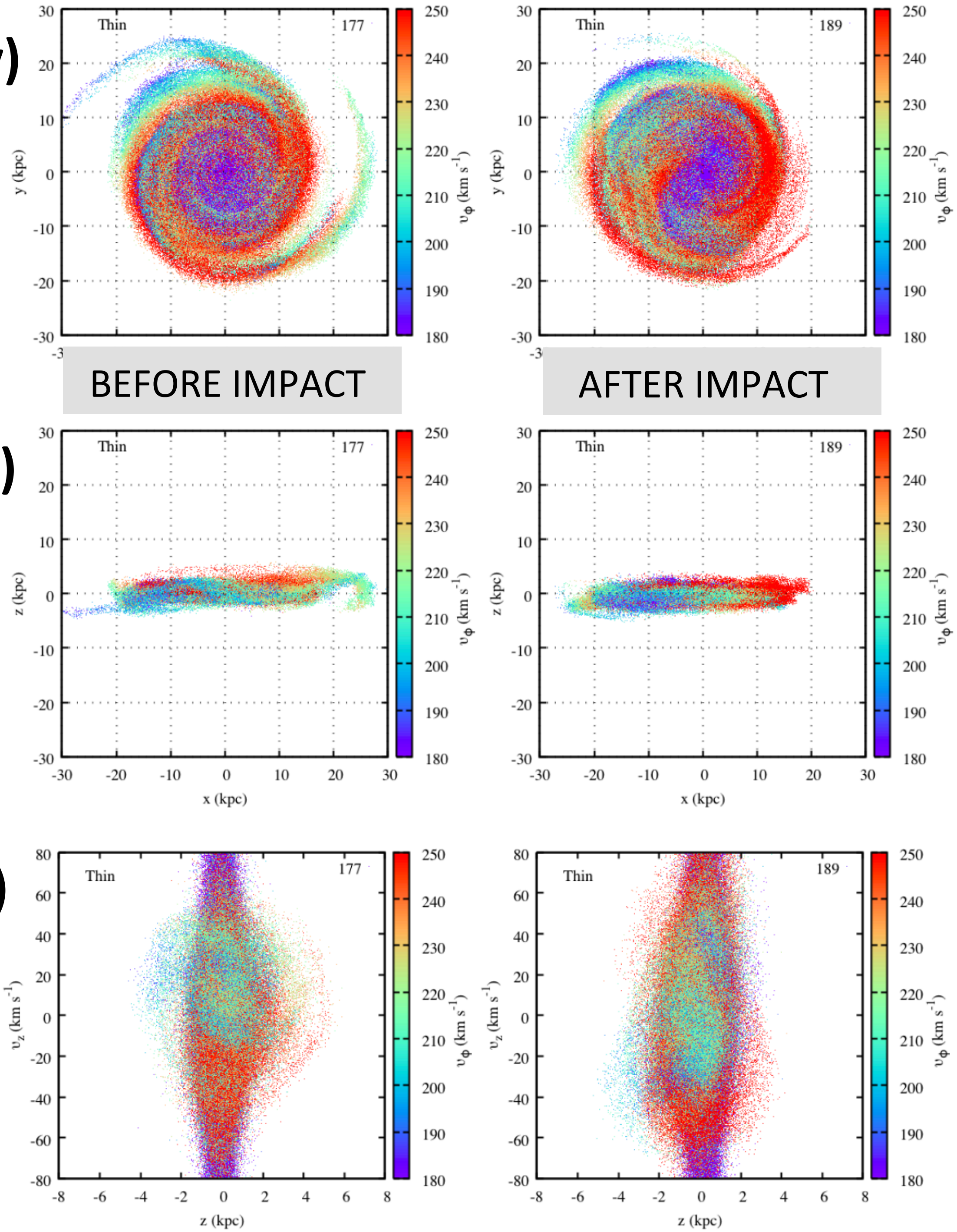


Impact of **forced oscillation** is fixed “phase spiral” pattern and disc heating.

Σ (x, y)

Σ (x, z)

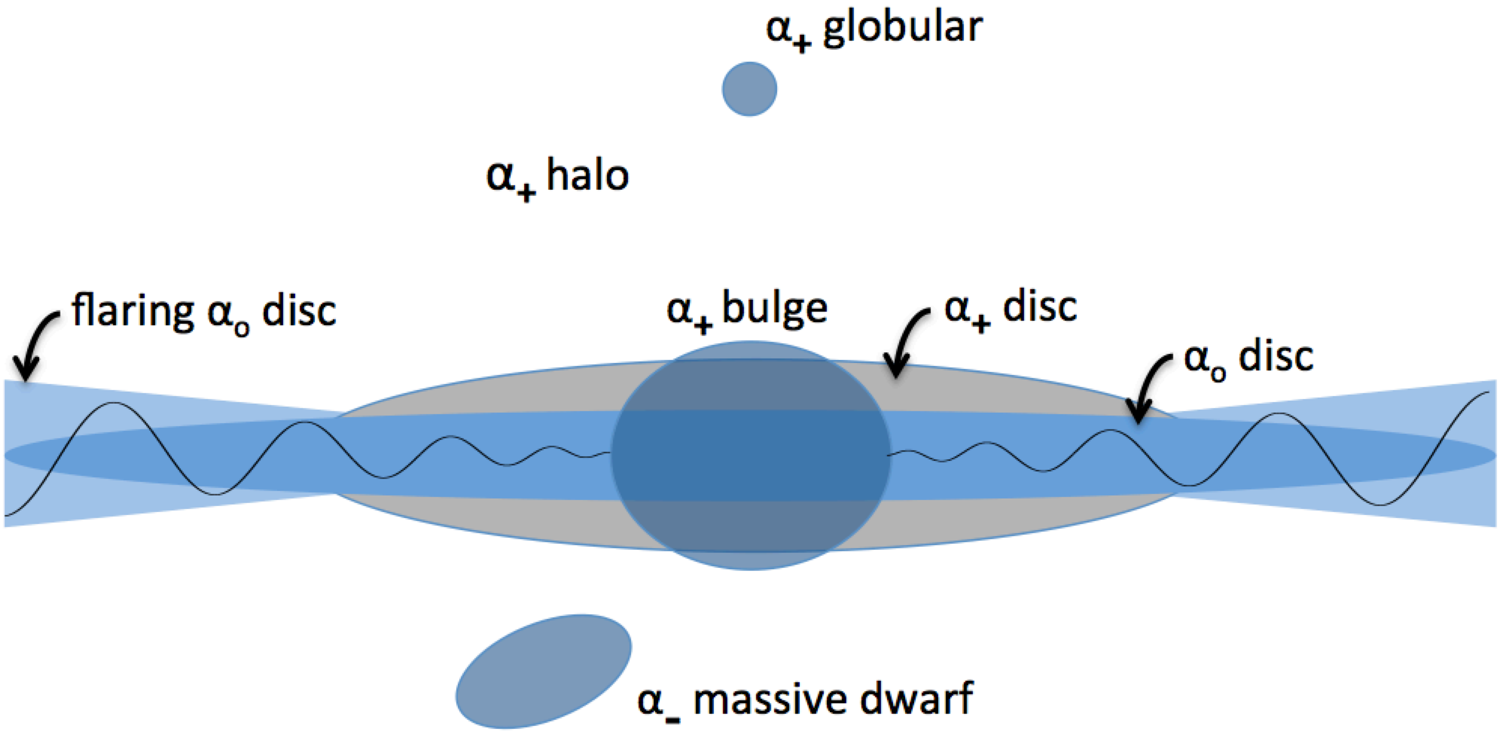
V_φ (z, V_z)



SUMMARY

Phase spiral mostly confined to the $\boldsymbol{\alpha_o}$ disk. It cannot be older than the time since the last crossing ~400-500 Myr ago.

There is no clear evidence that the **phase spiral** or **arches & ridges** know about each other. The impact wipes out both phenomena.



Looking forward

- *Gaia* shows us a different future for Galactic studies and how little we know – the Galaxy is not an **equilibrium figure**. Unravelling the past is now more challenging.
- What is the impact of **galactoseismology** on prior structure? What does it mean to derive parametrized relations today? We need to revisit what we thought we knew.
- How does **galactoseismology** work with **secular evolution** (e.g. migration) and more generally with the **bar** and **spiral arms**?
- When and how did it all start? How much information is lost, how much survives? The **dynamical clock** requires a deeper understanding of how the disc responds.
- Future Galaxy models will need to be far more sophisticated using all **baryon phases** along with the **dark matter**.
- The search for the "true" **DF** (and **Φ, ρ** pair) continues… 2019 ff promise to be golden years for Galactic studies.
- Near future? – **nano-arcsecond astrometry** (proposed by C. Boehm for ESA Theia satellite) may be technically feasible and would provide an astonishing probe to **unwinding** and **forward-evolving** the Galaxy, on the nature of dark matter, inter alia.

- Never got to talk about V_R, V_Phi coupling and how we see ellipsoid tilt directly for the first time (JBH+2019)