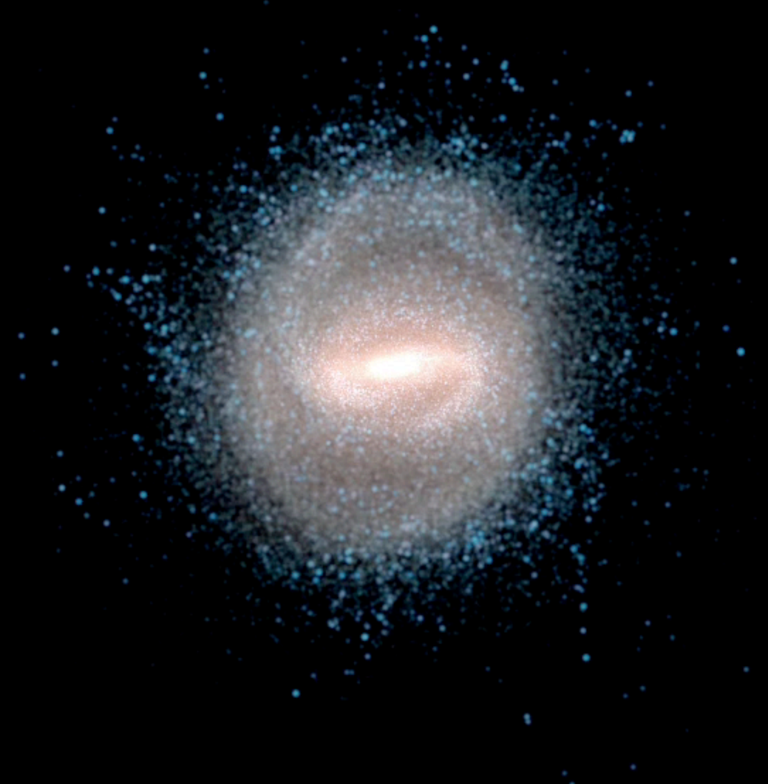
THE BAR CONNECTION:
HOW THE MILKY WAY BAR SHAPES THE BULGE AND DISC

FRANCESCA FRAGKOUDI

(Fran-gōō-dee)

MPA



In collaboration with:

P. Di Matteo, S. White, D. Katz, M. Haywood, A. Gomez, W. Trick, F. Combes,
M. Schultheis, A. Hallé, S. Khoperskov, R. Pakmor, R. Grand, V. Springel

OUTLINE

- Introduction
- The bulge-bar connection in the Milky Way
- The disc-bar connection in the Milky Way
- Summary and thoughts for future

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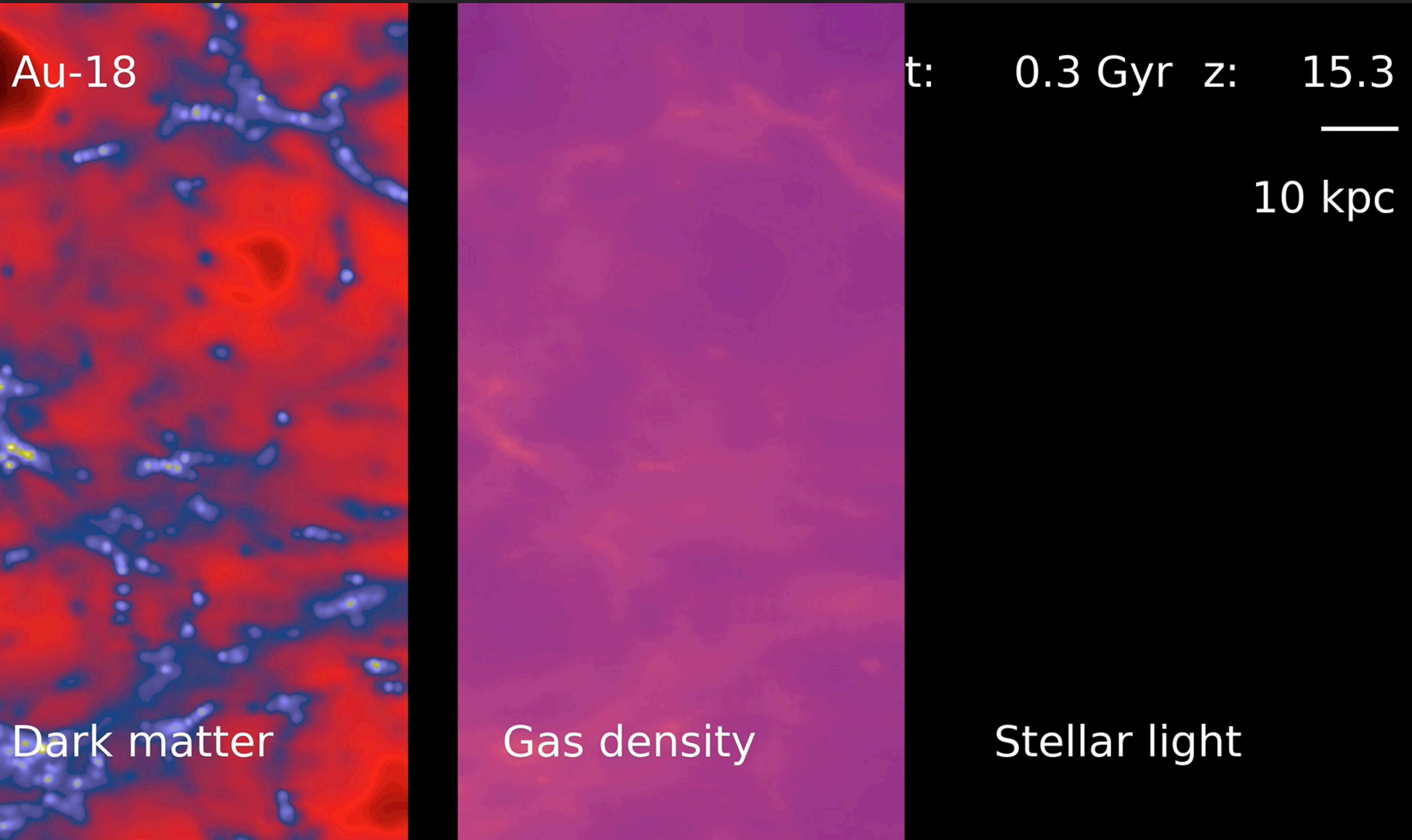
FORMING BARRED SPIRAL GALAXIES

Movie Credit: R. Pakmor (Auriga Simulations)



BARRED GALAXIES

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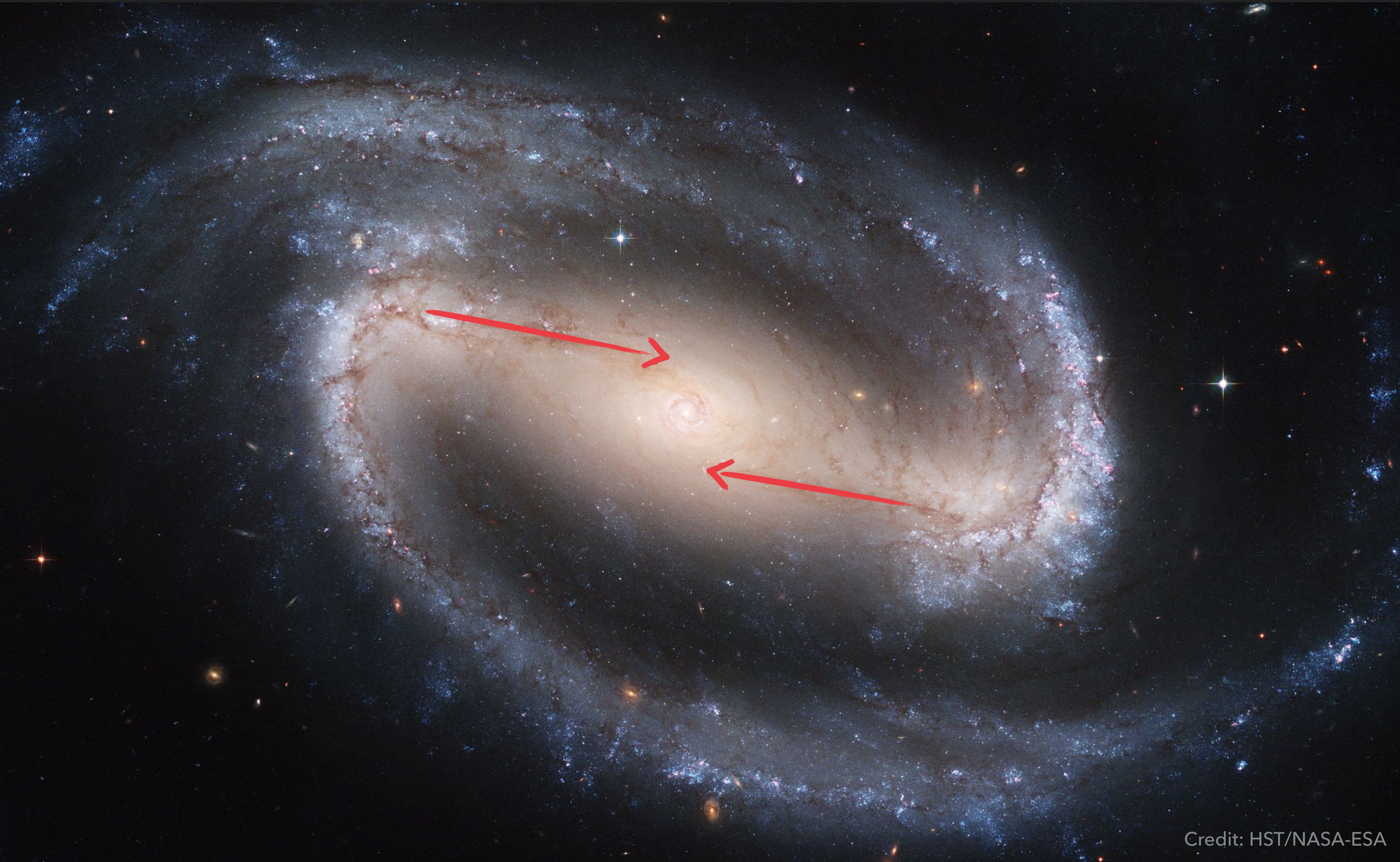

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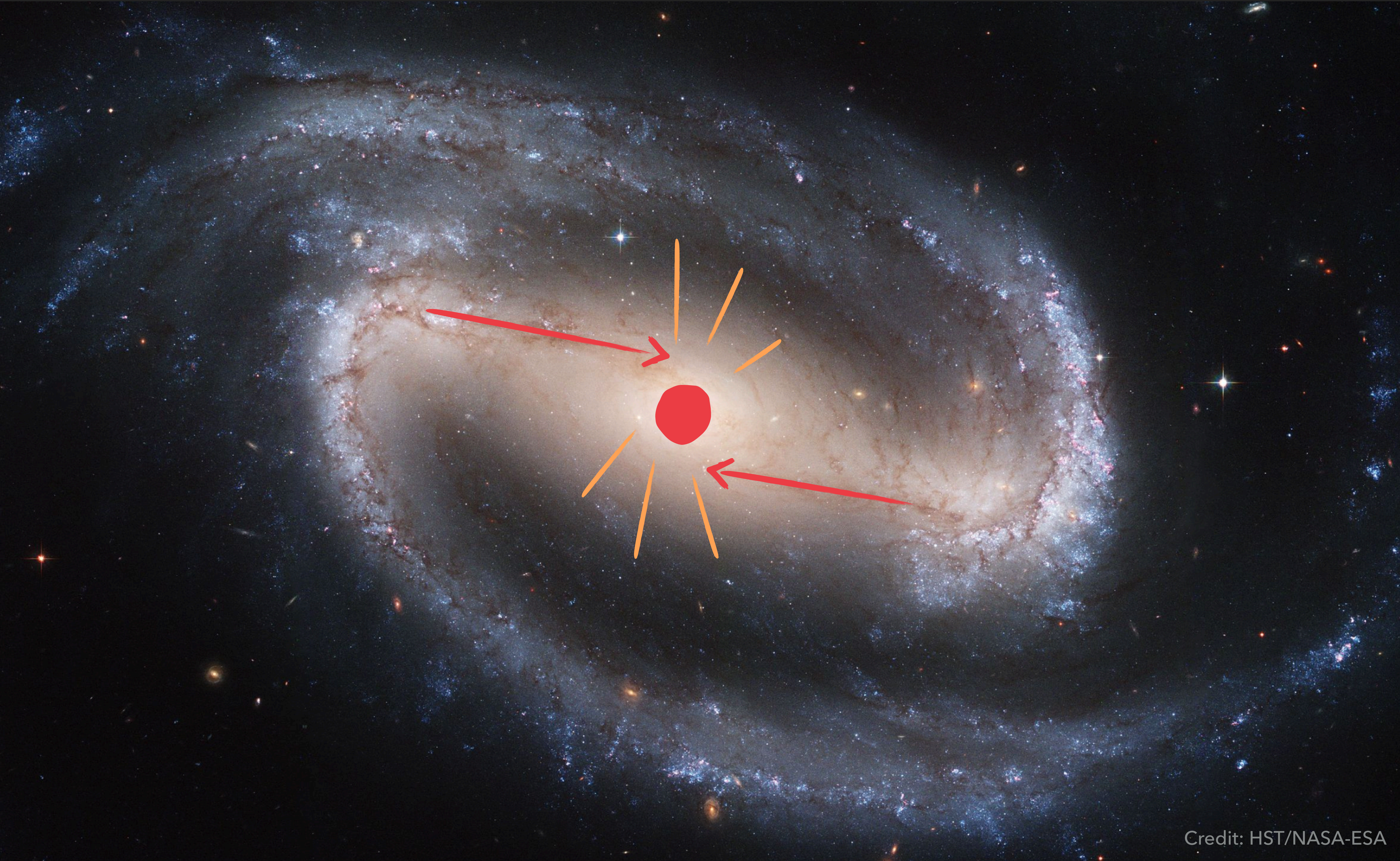
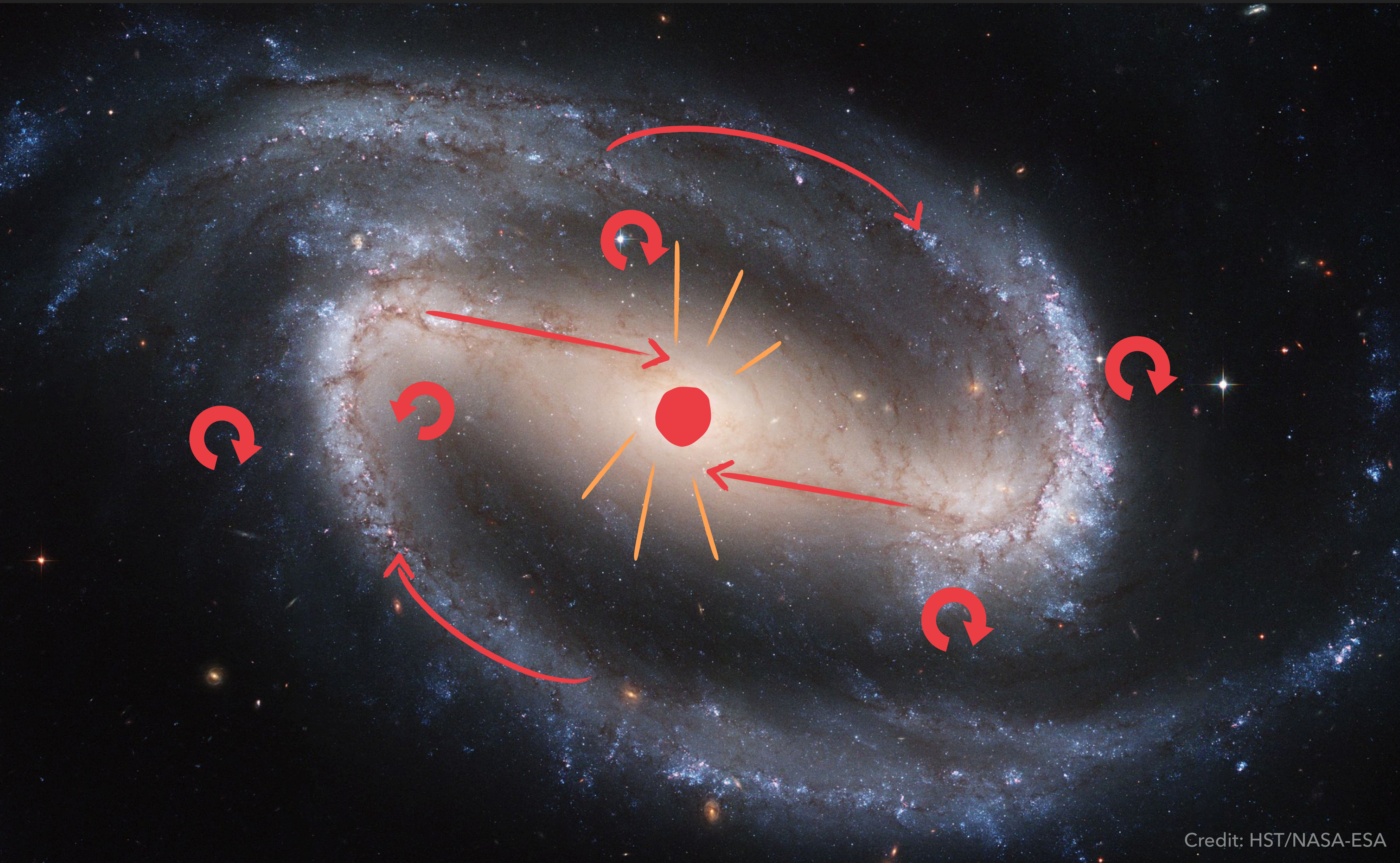

Credit: HST/NASA-ESA

BARRED GALAXIES



Credit: HST/NASA-ESA

BARRED GALAXIES

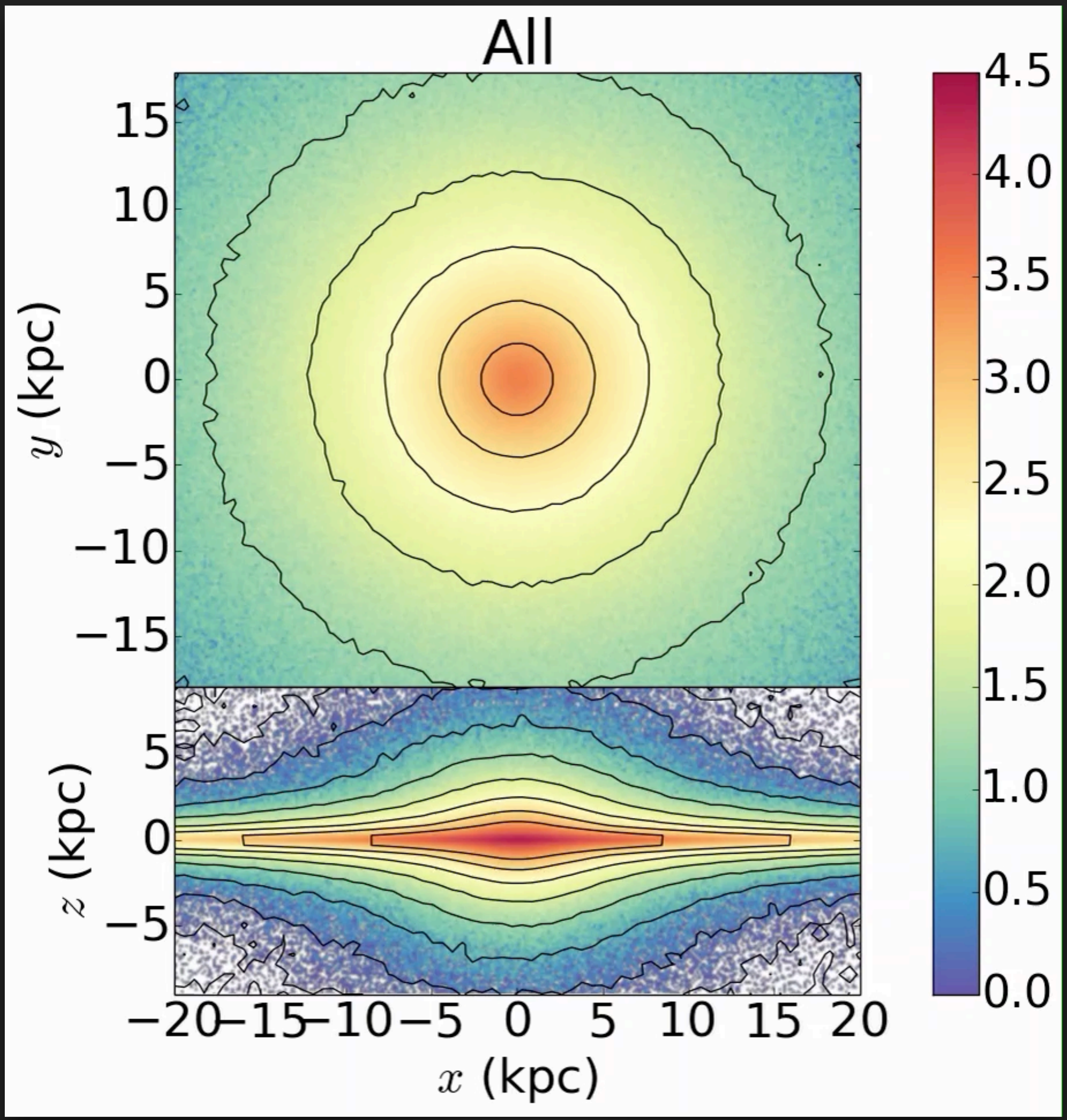
Credit: HST/NASA-ESA

BARRED GALAXIES

2/3 of disc galaxies in the local Universe have bars (e.g. Aguerri et al. 2009, Gadotti 2009)

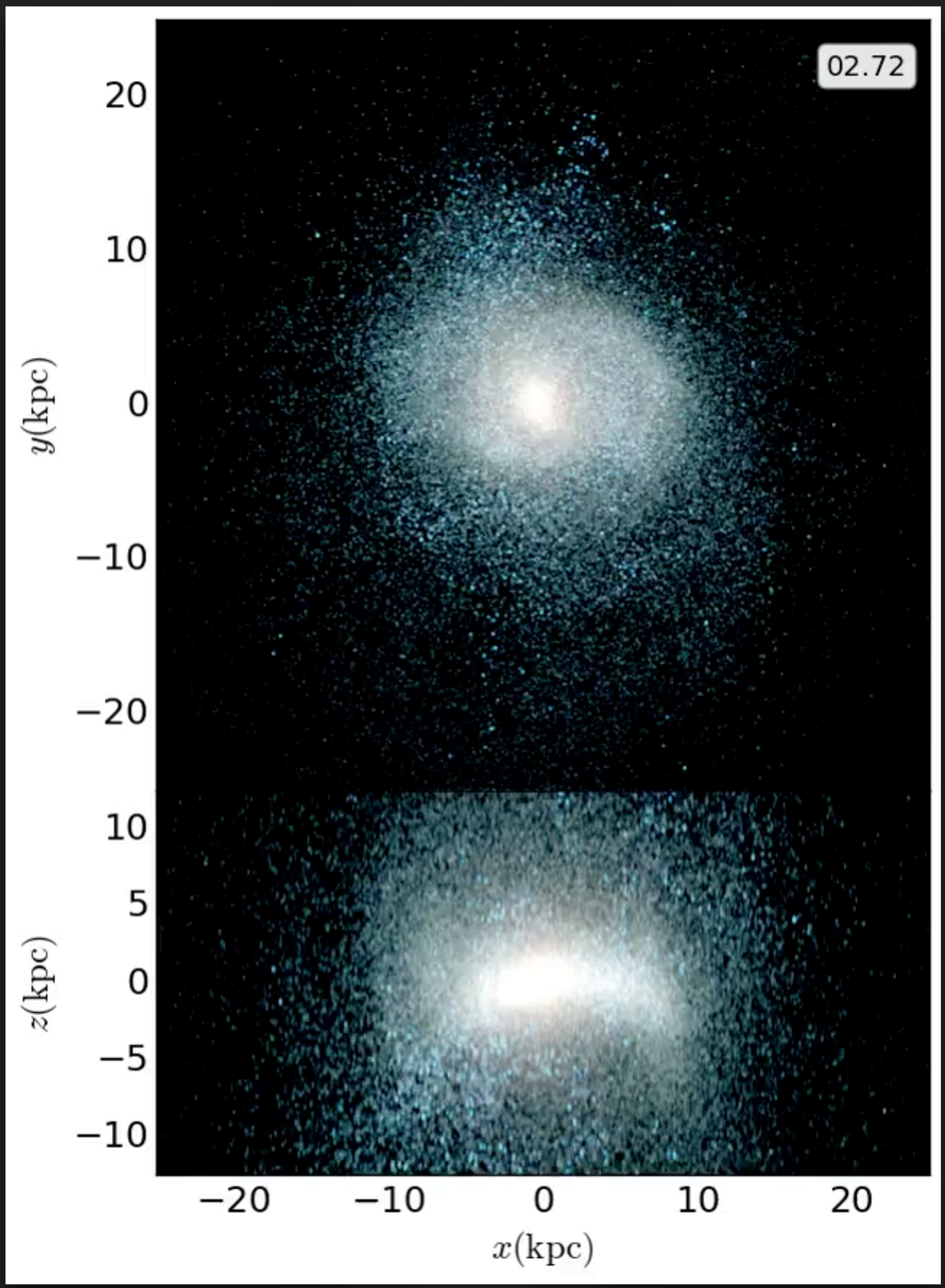
BAR FORMATION

Isolated/Idealised Model



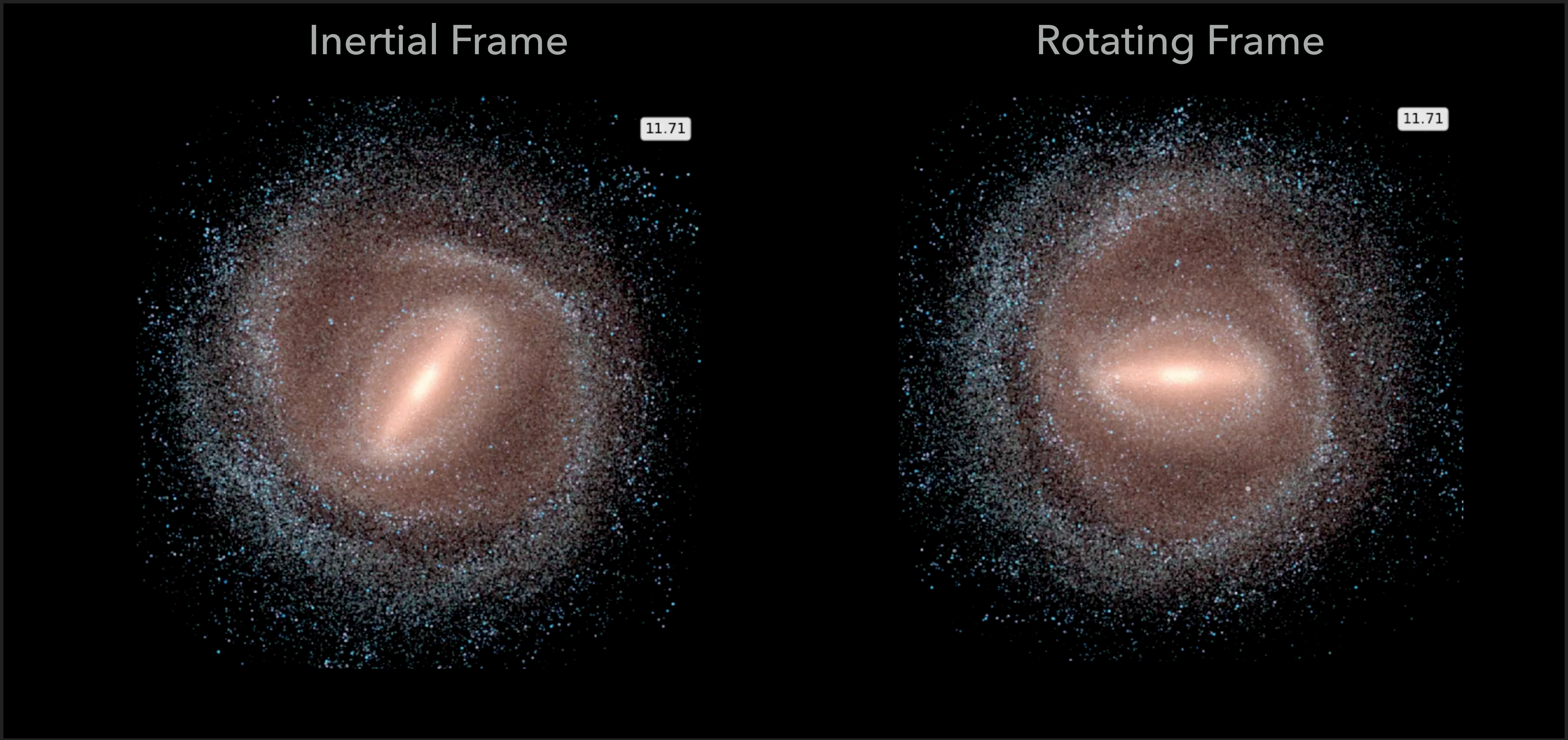
Fragkoudi et al. (2017c)

Cosmological Model (Grand+17)



Fragkoudi et al. in prep.

BAR FORMATION: ORBITS IN BARS

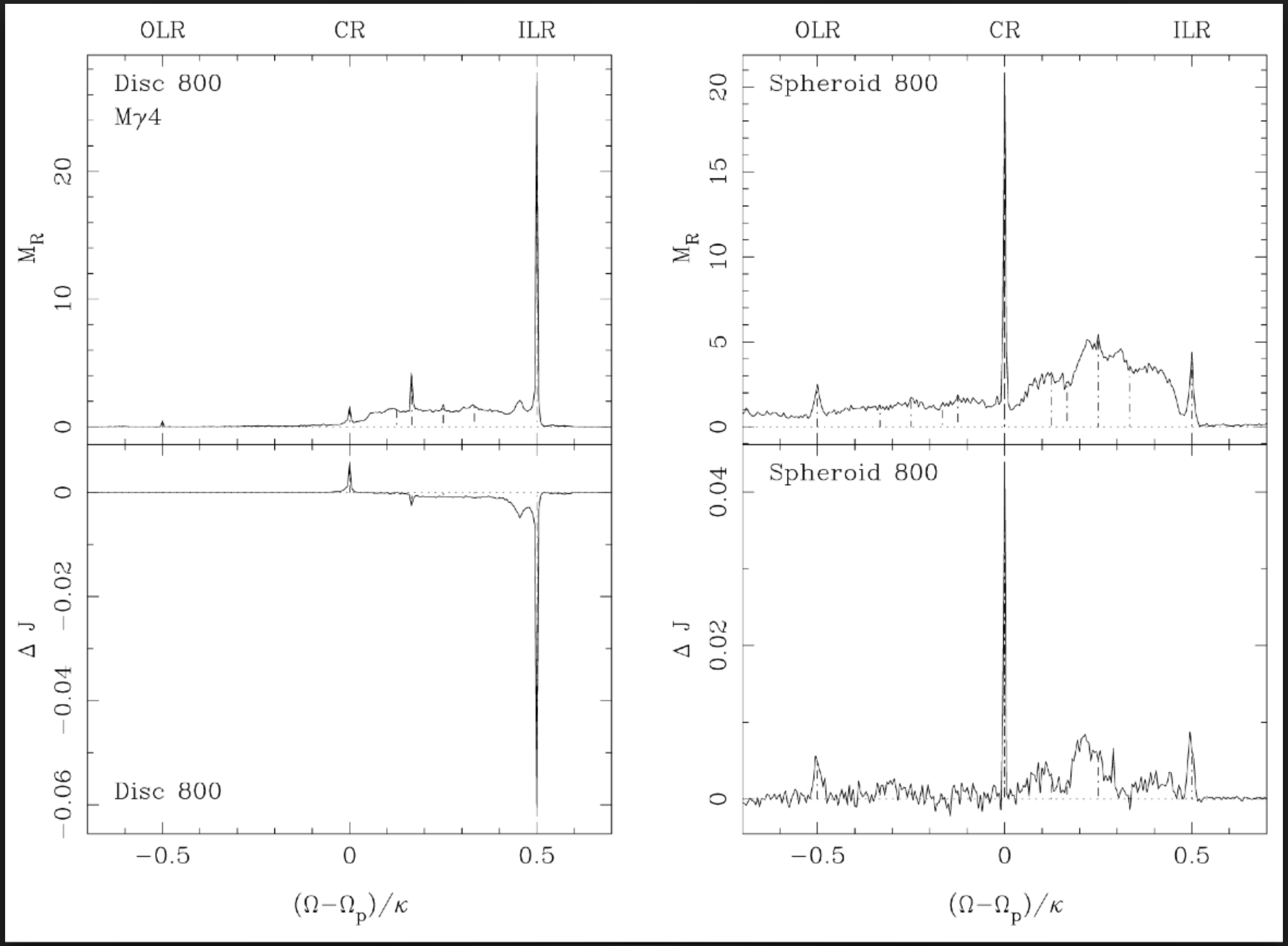


Bars trap stars at resonances:
main ones are co-rotation, inner and outer Lindblad Resonance

$$l\kappa + m(\Omega - \Omega_{\rm p}) = 0$$

Movie: F. Fragkoudi

BAR FORMATION: ANGULAR MOMENTUM EXCHANGE



Athanassoula (2003)

Bars facilitate angular momentum exchange between the inner and outer disc and halo: brings galaxy into lower energy configuration

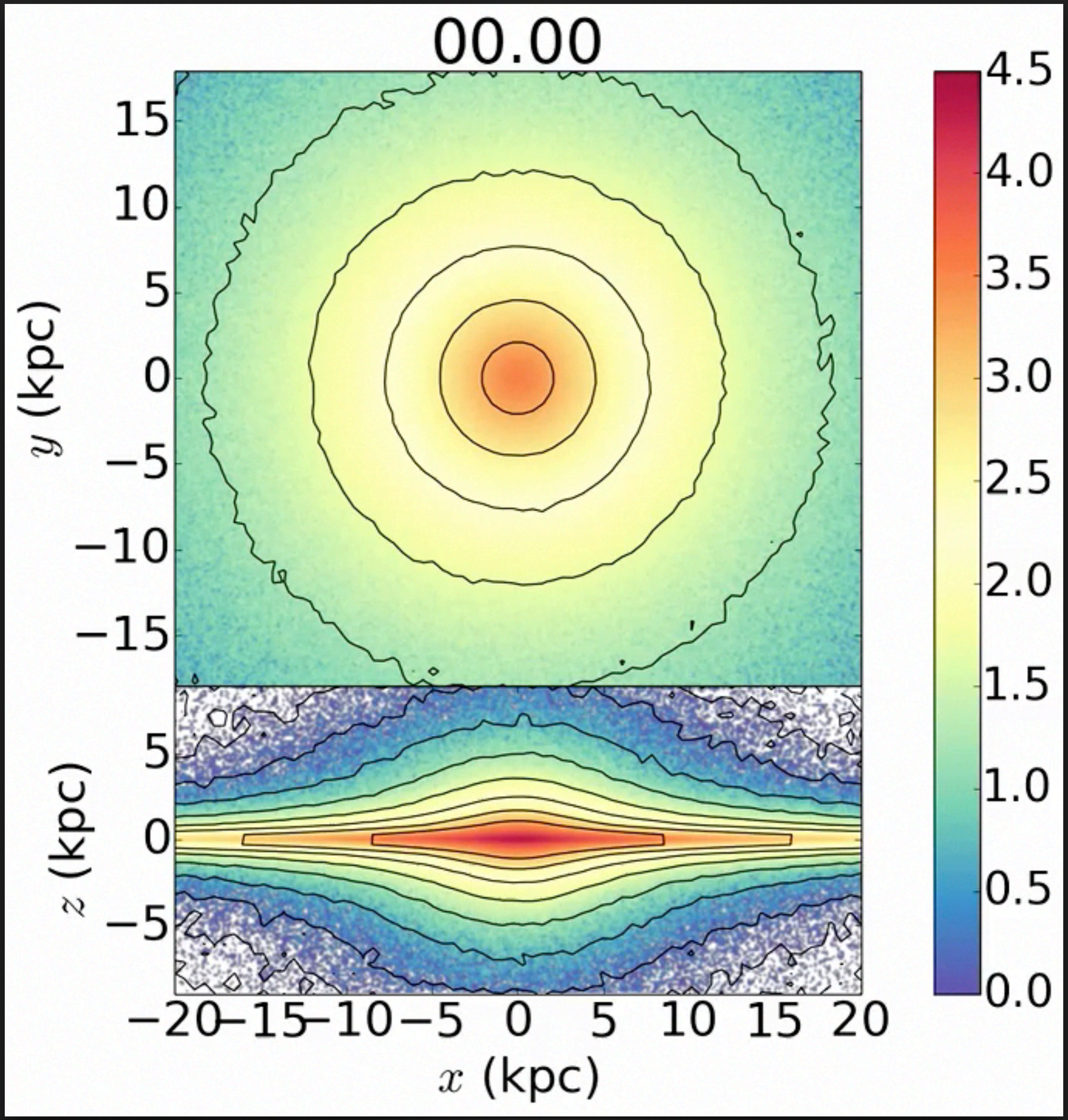
BOXY/PEANUT BULGES

Numerical studies have shown that boxy/peanut bulges are the bar seen edge-on (Combes & Sanders 1981, Raha et al. 1991, Martinez-Valpuesta et al. 2006)

Fraction of edge-on disc galaxies with boxy/peanuts is comparable to the fraction of barred galaxies (Lutticke et al. 2000)

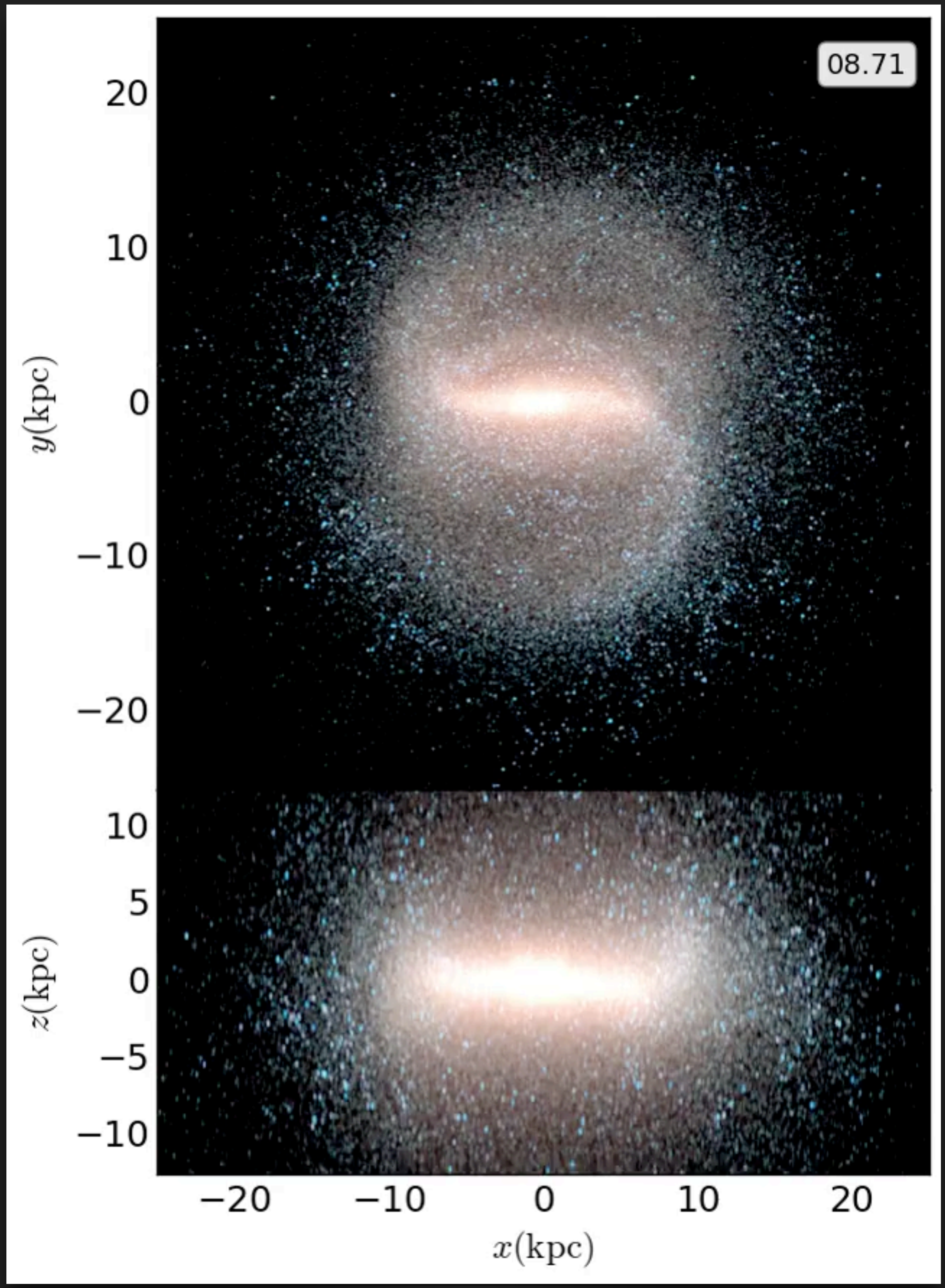
BOXY/PEANUT BULGE FORMATION

Isolated/Idealised Model



Fragkoudi et al. (2017c)

Cosmological Model (Auriga)



Fragkoudi et al. in prep.

OUTLINE

- Introduction
- The bulge-bar connection in the Milky Way
  - The Milky Way as a pure disc galaxy: Clues from morphology, kinematics and chemistry
- The disc-bar connection in the Milky Way
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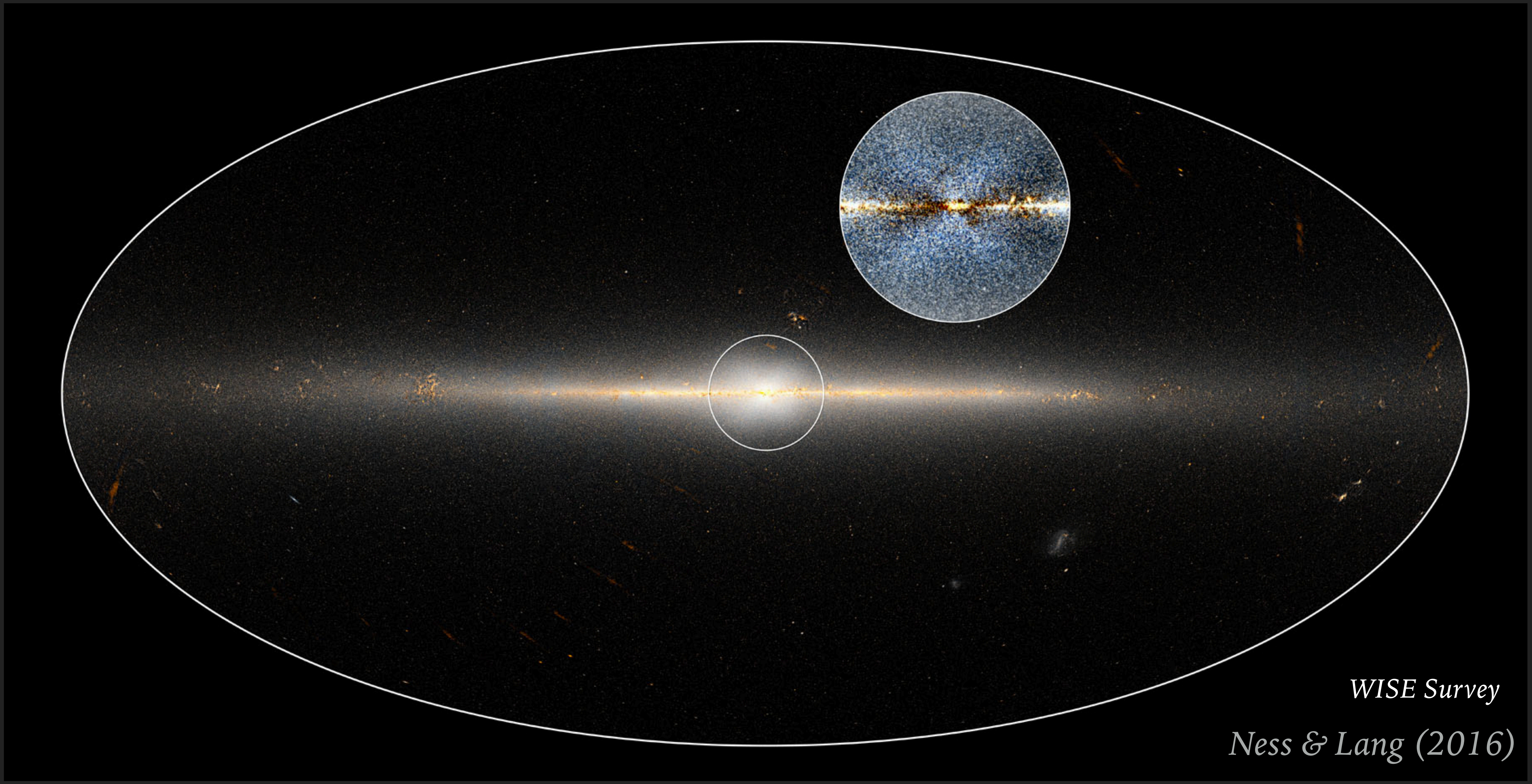
WHAT DO WE KNOW ABOUT THE MILKY WAY BULGE?

- **Morphology**: X/boxy/peanut-shape (e.g. Weiland+94, Dwek+95, McWilliam+10) - forms due to bar buckling/vertical resonances (e.g. Combes+81)



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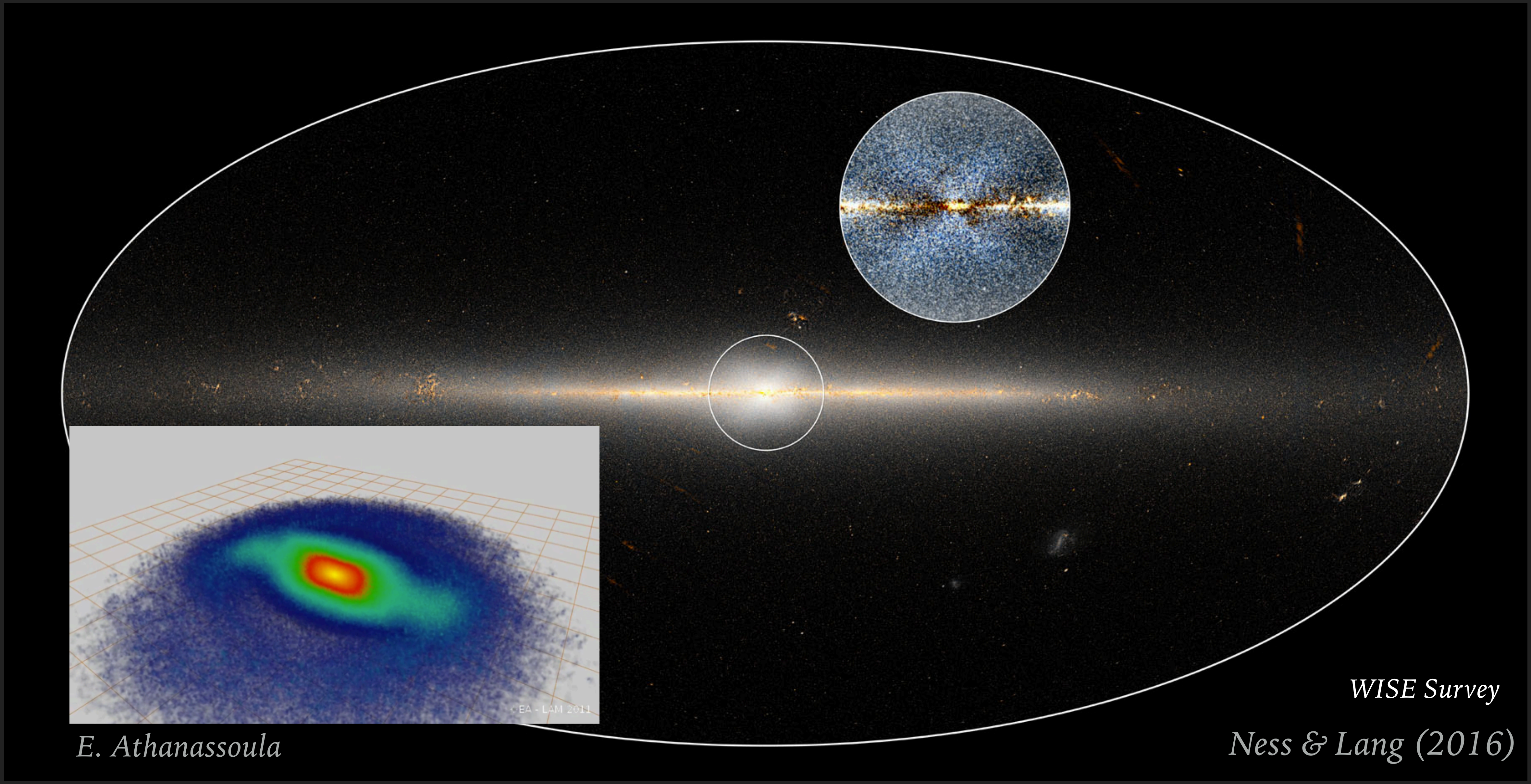

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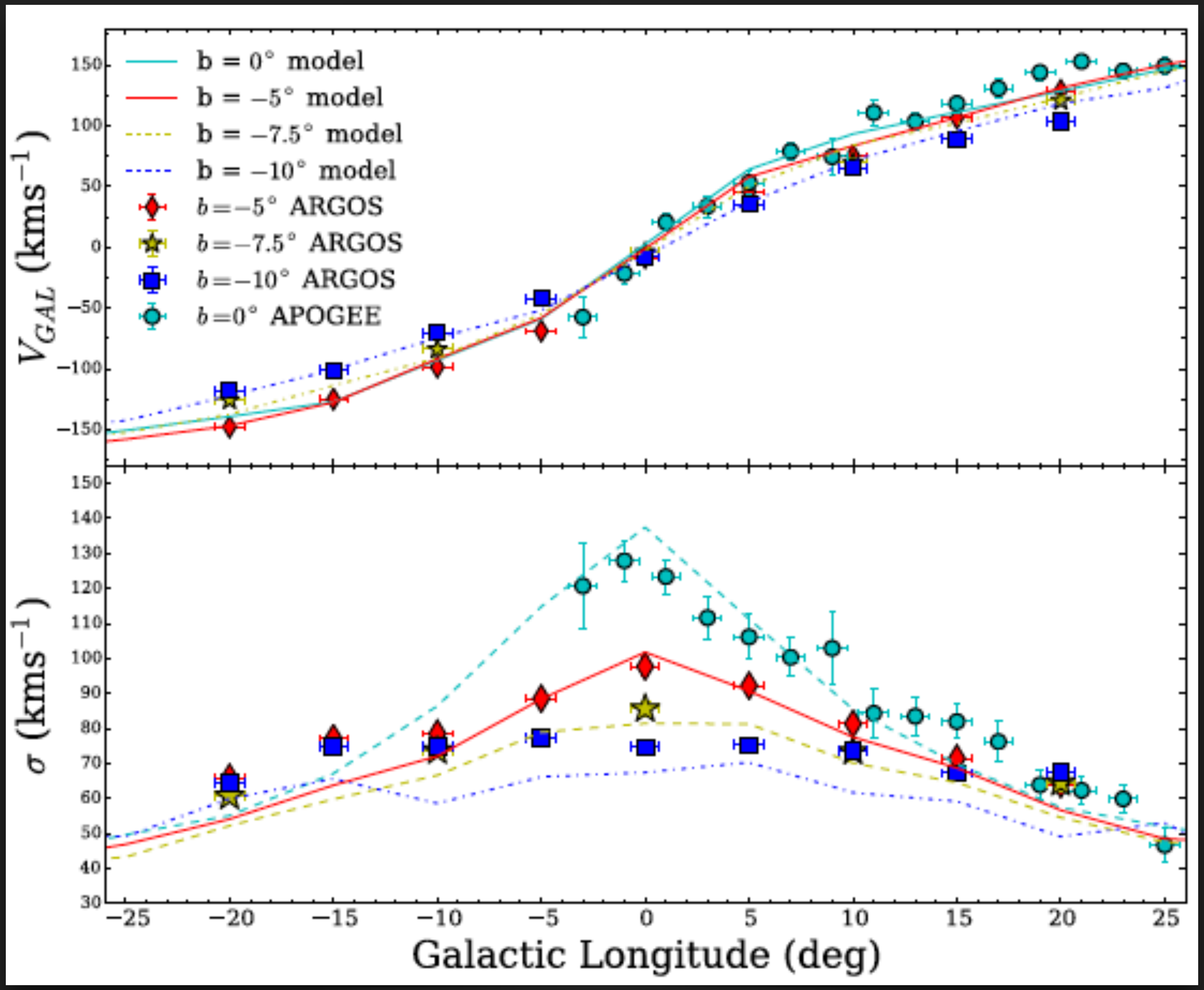

Ness+16

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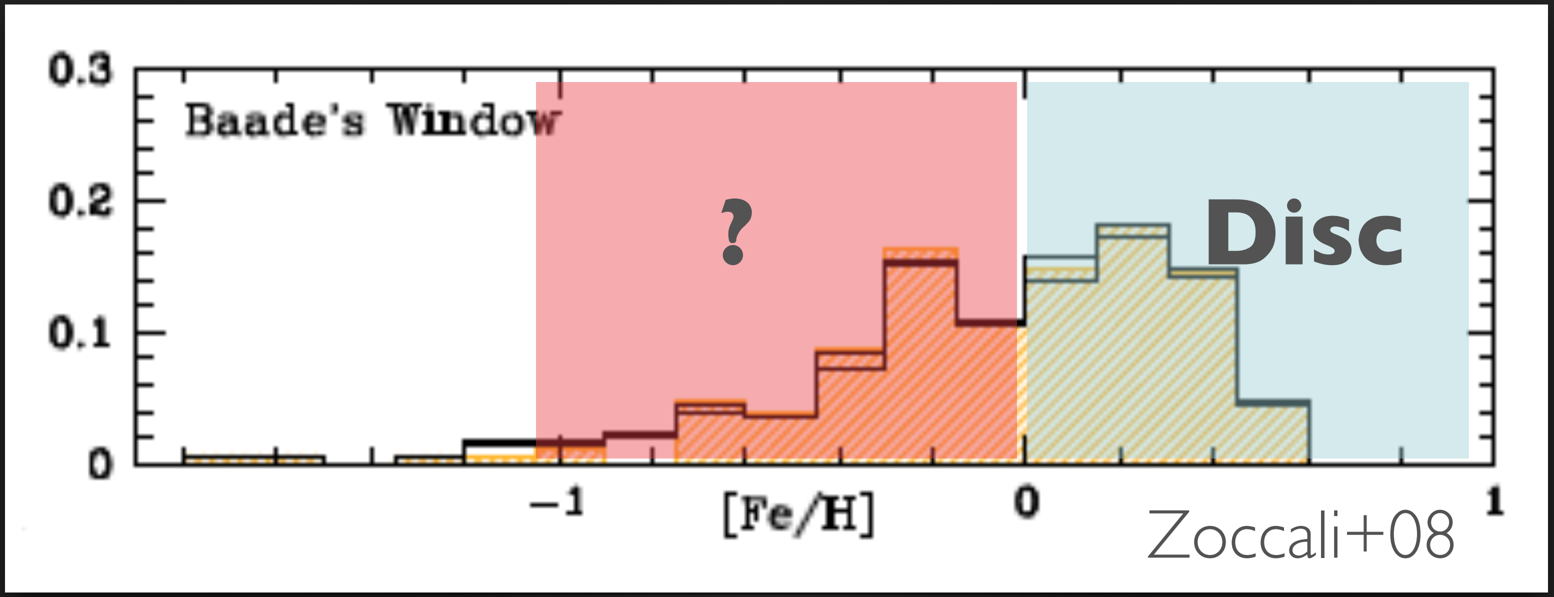
- **Chemistry**: broad metallicity distribution function (e.g. McWilliam+94, Zoccali+08, Hill+11, Ness+13, Rojas-Arriagada+14,17) – Coexistence of multiple stellar pops.



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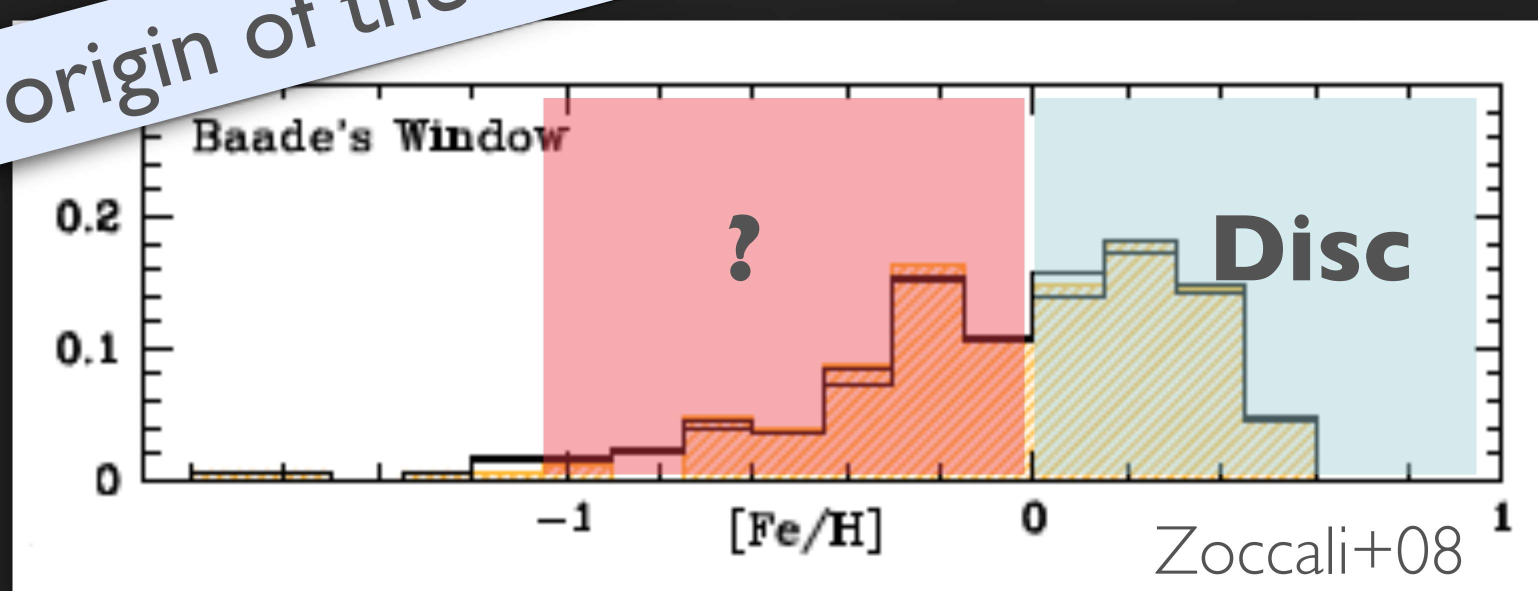
What is the origin of the metal-poor populations in the bulge?



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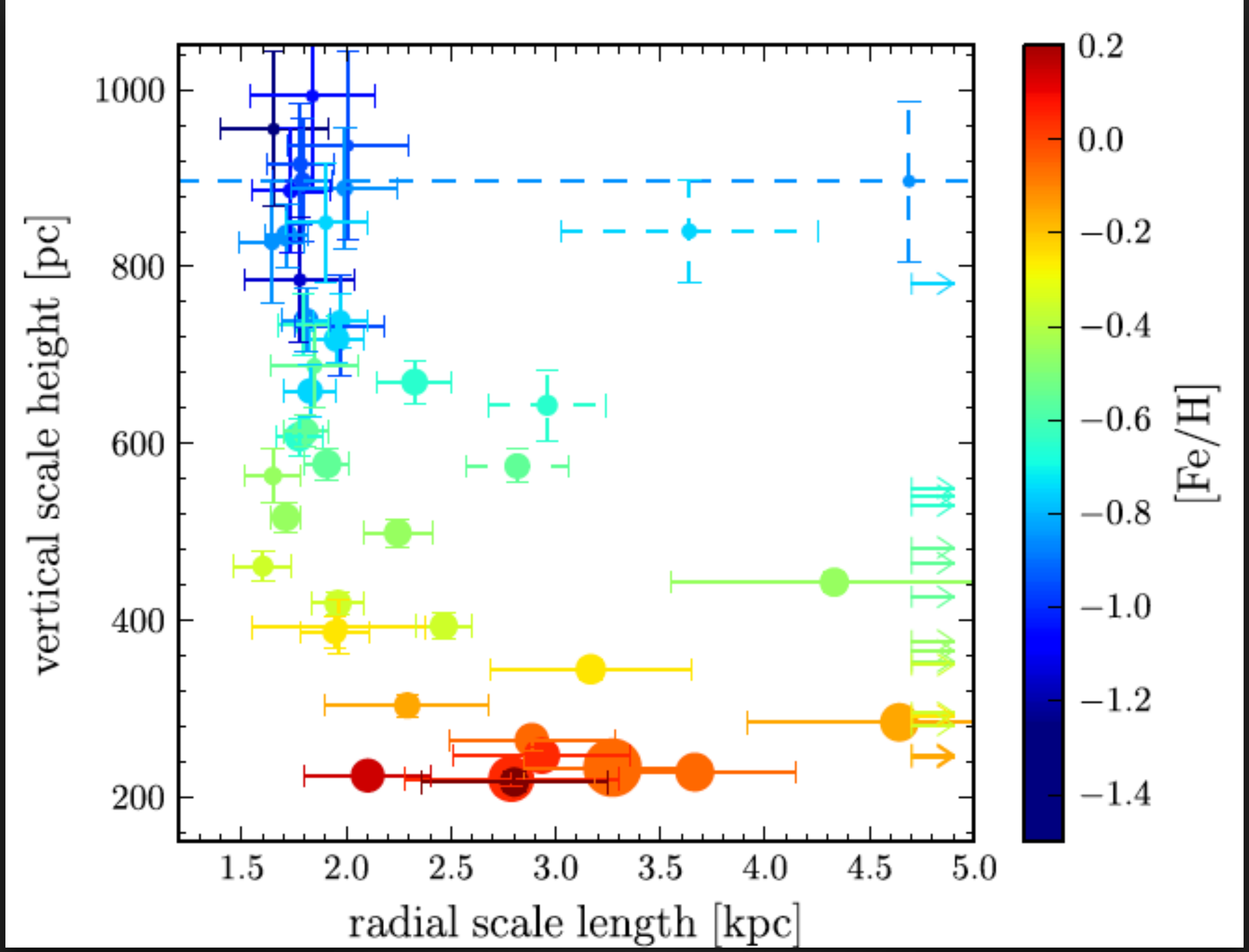
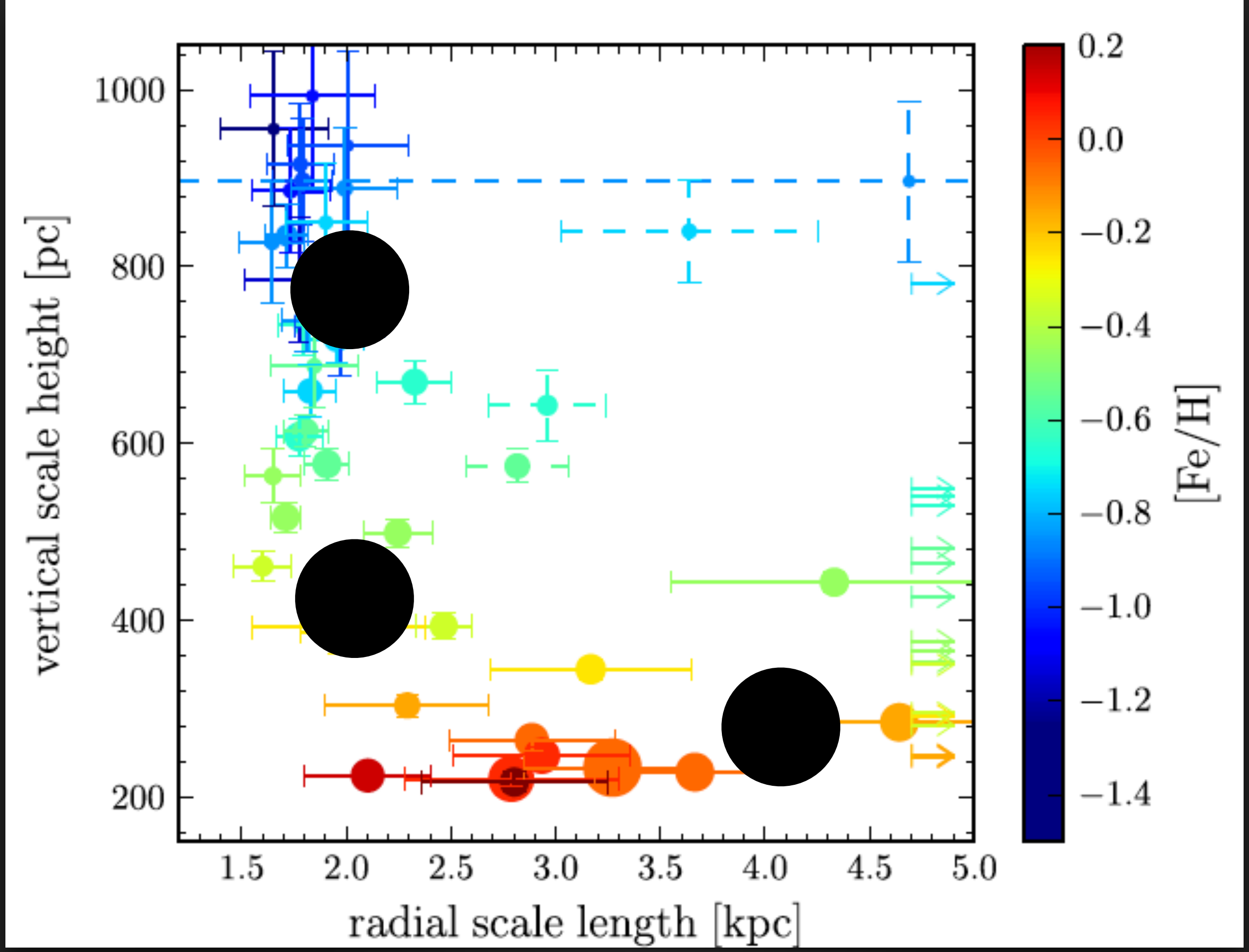
Dispersion dominated spheroid (classical bulge) VS Hot/Thick disc

HOW WE CONSTRUCT PURE DISC MODEL



Bovy+12c

HOW WE CONSTRUCT PURE DISC MODEL



Bovy+12c

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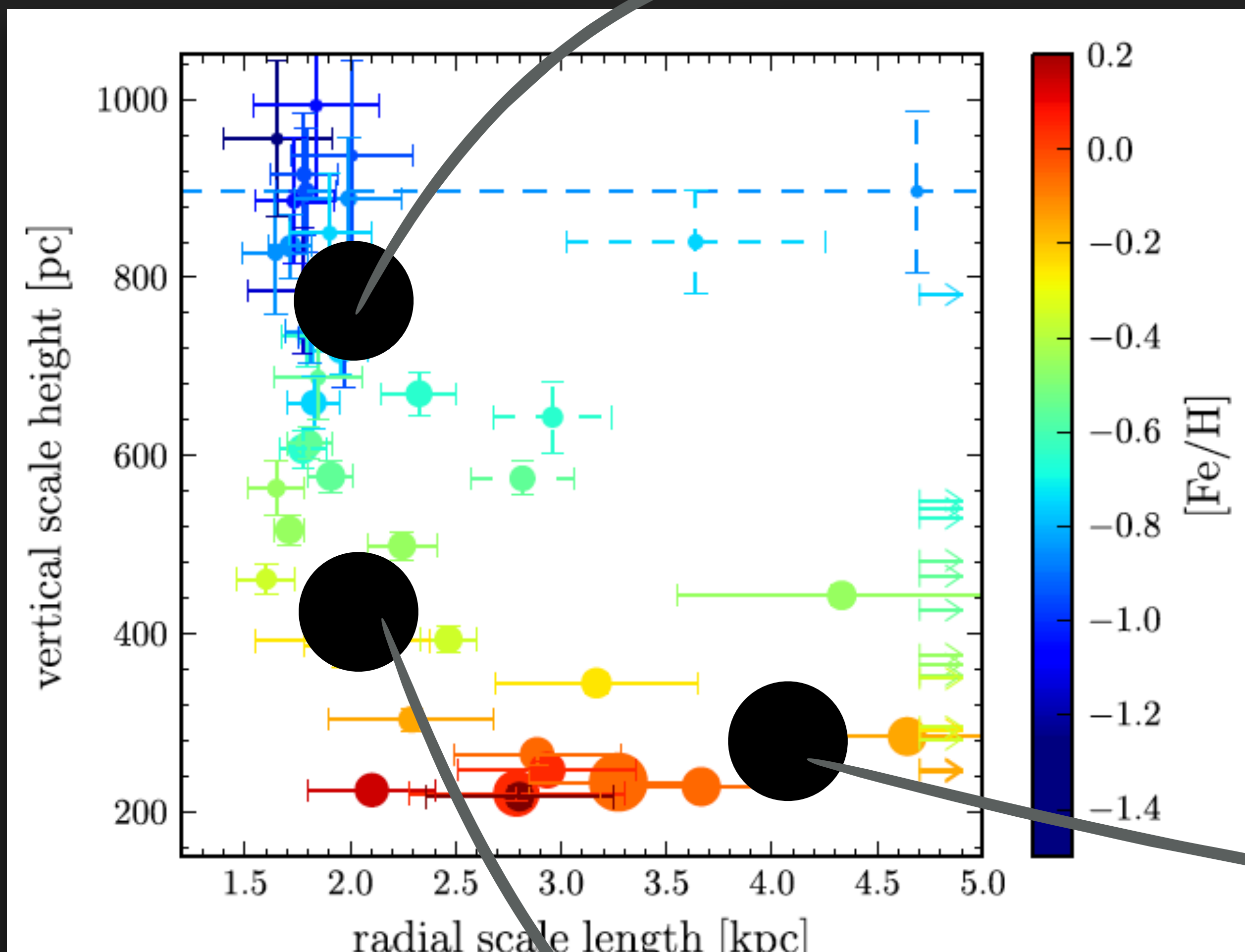
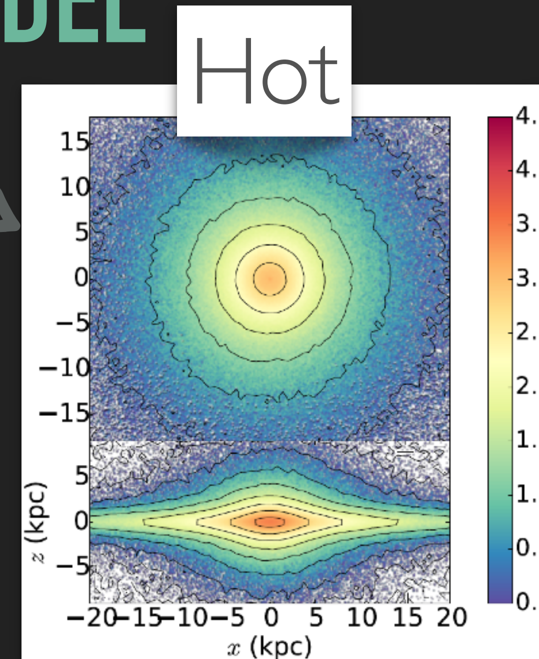
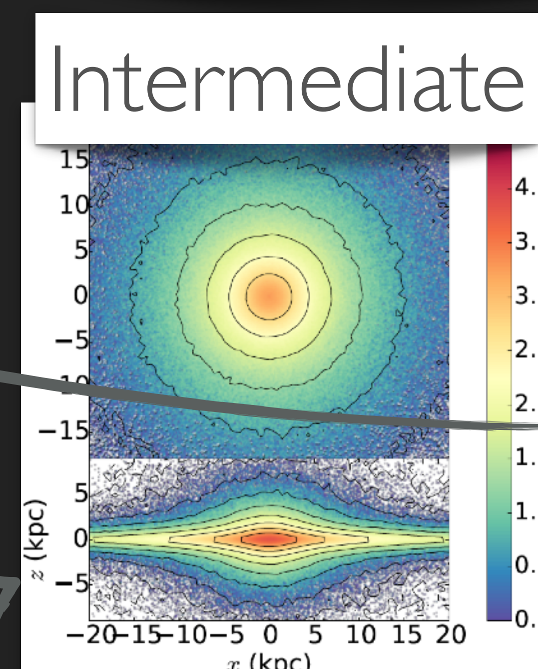
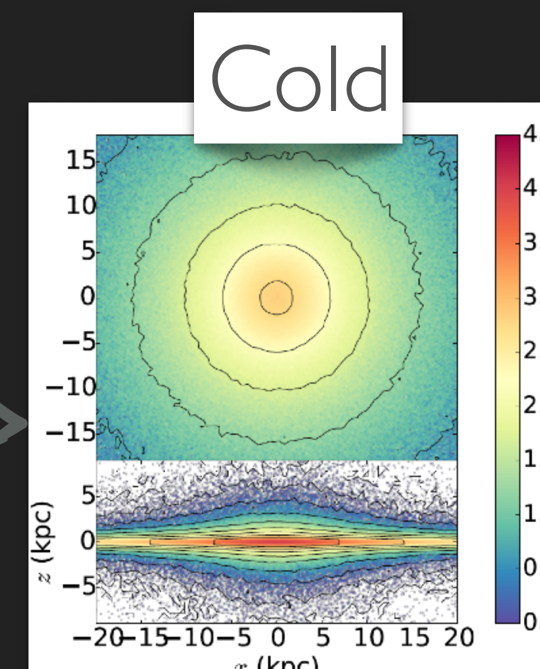


Bovy+12c



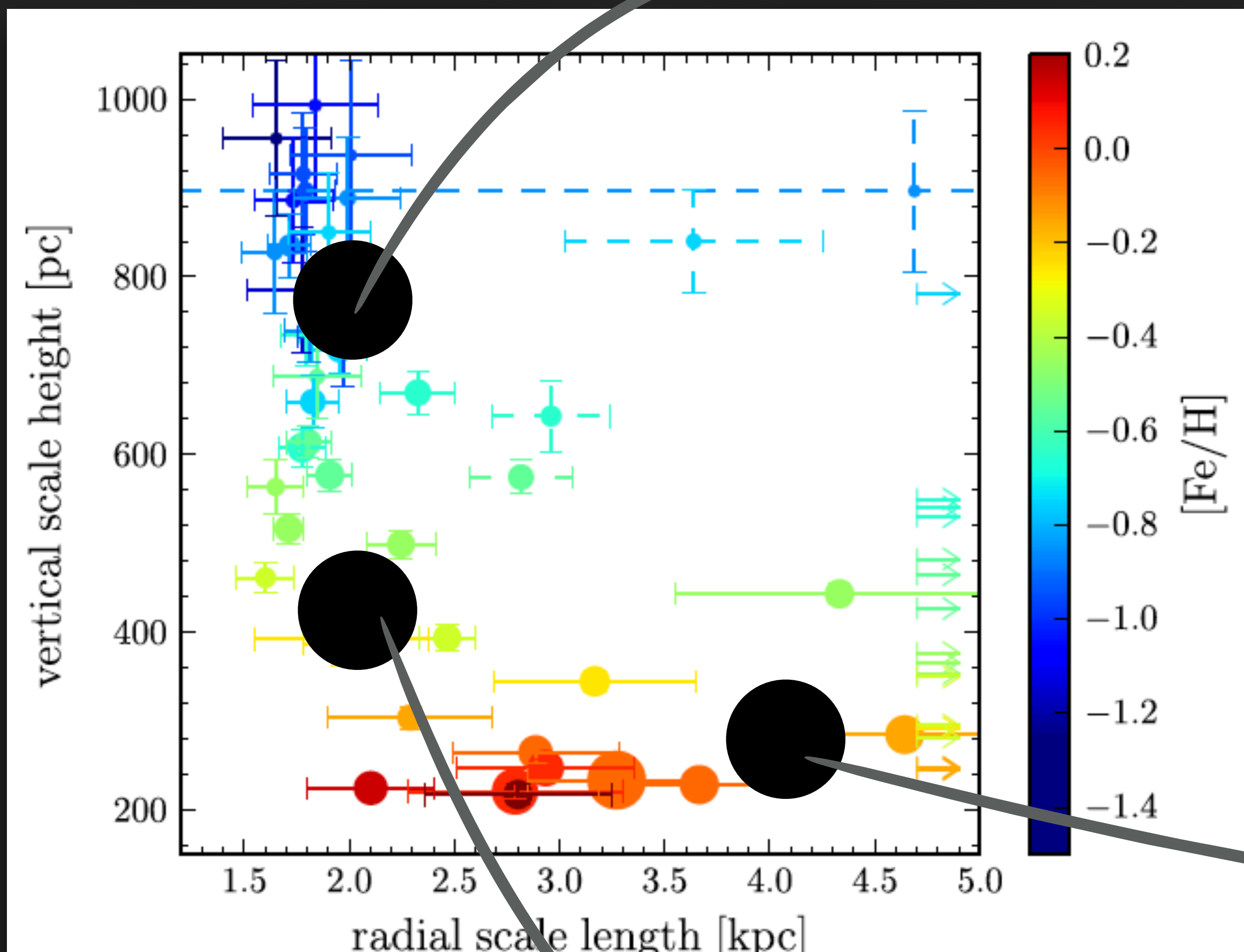
10M disc particles
5M DM halo
ε = 50pc





- Run controlled N-body experiment
- Set masses, scale lengths, scale heights & kinematics of discs to represent discretised version of the Milky Way disc (metal-poor 50%, metal-rich 50%)
- Assign metallicities and α-abundances to the discs corresponding to properties of MW disc stellar populations

HOW WE CONSTRUCT PURE DISC MODEL



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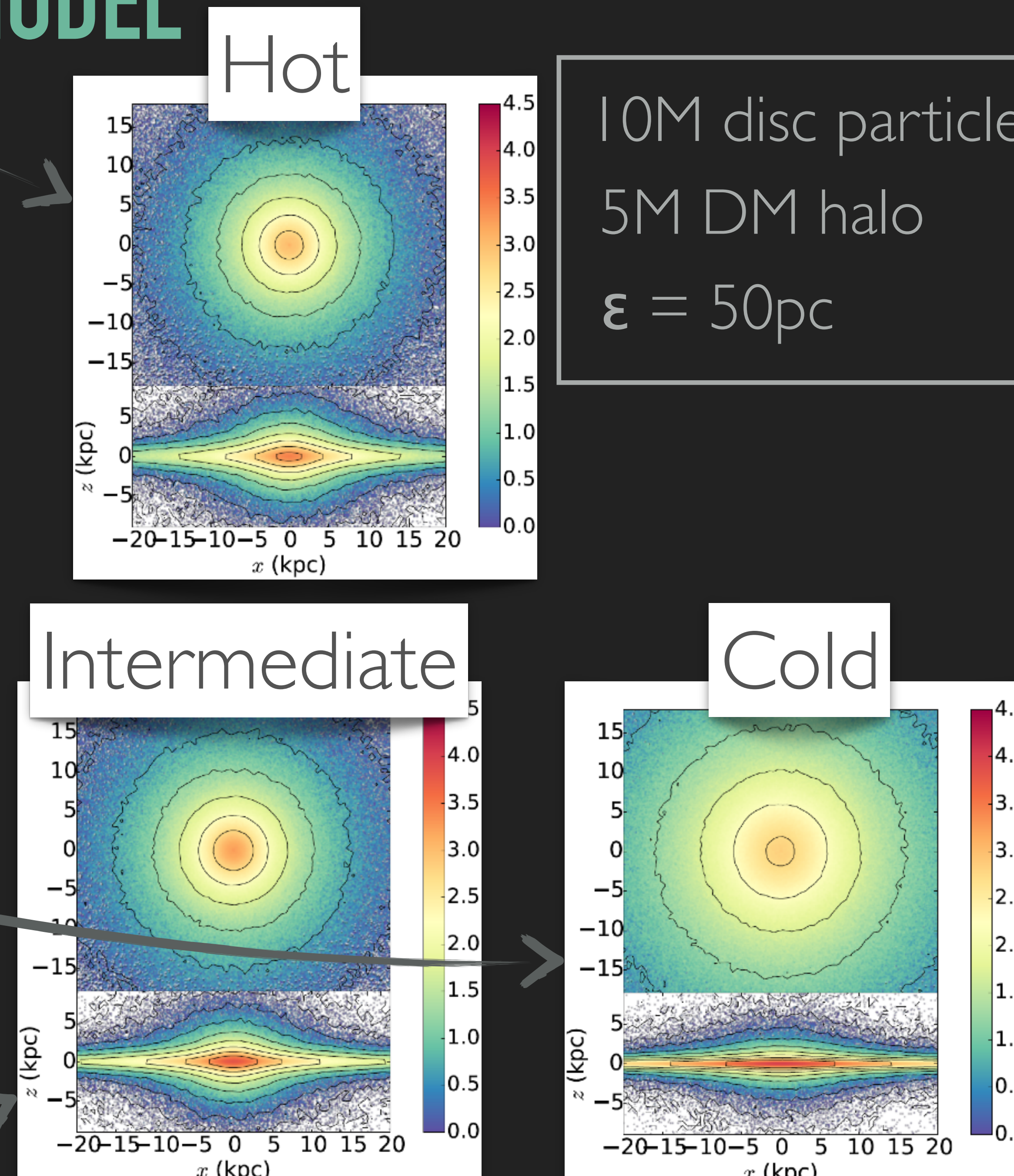


10M disc particles

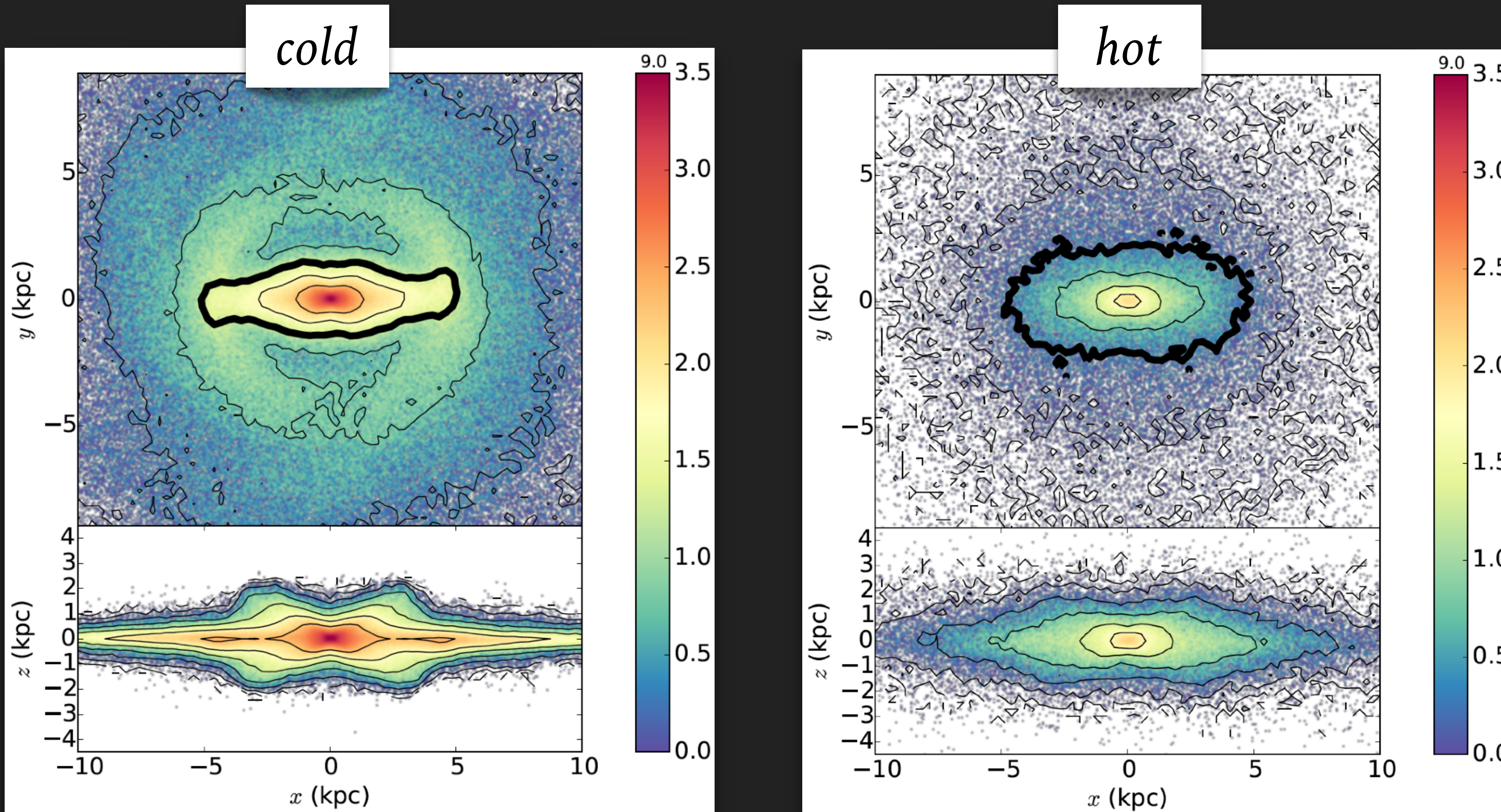
5M DM halo

ε = 50pc

Evolves secularly in isolation - forms bar & b/p bulge

MORPHOLOGY

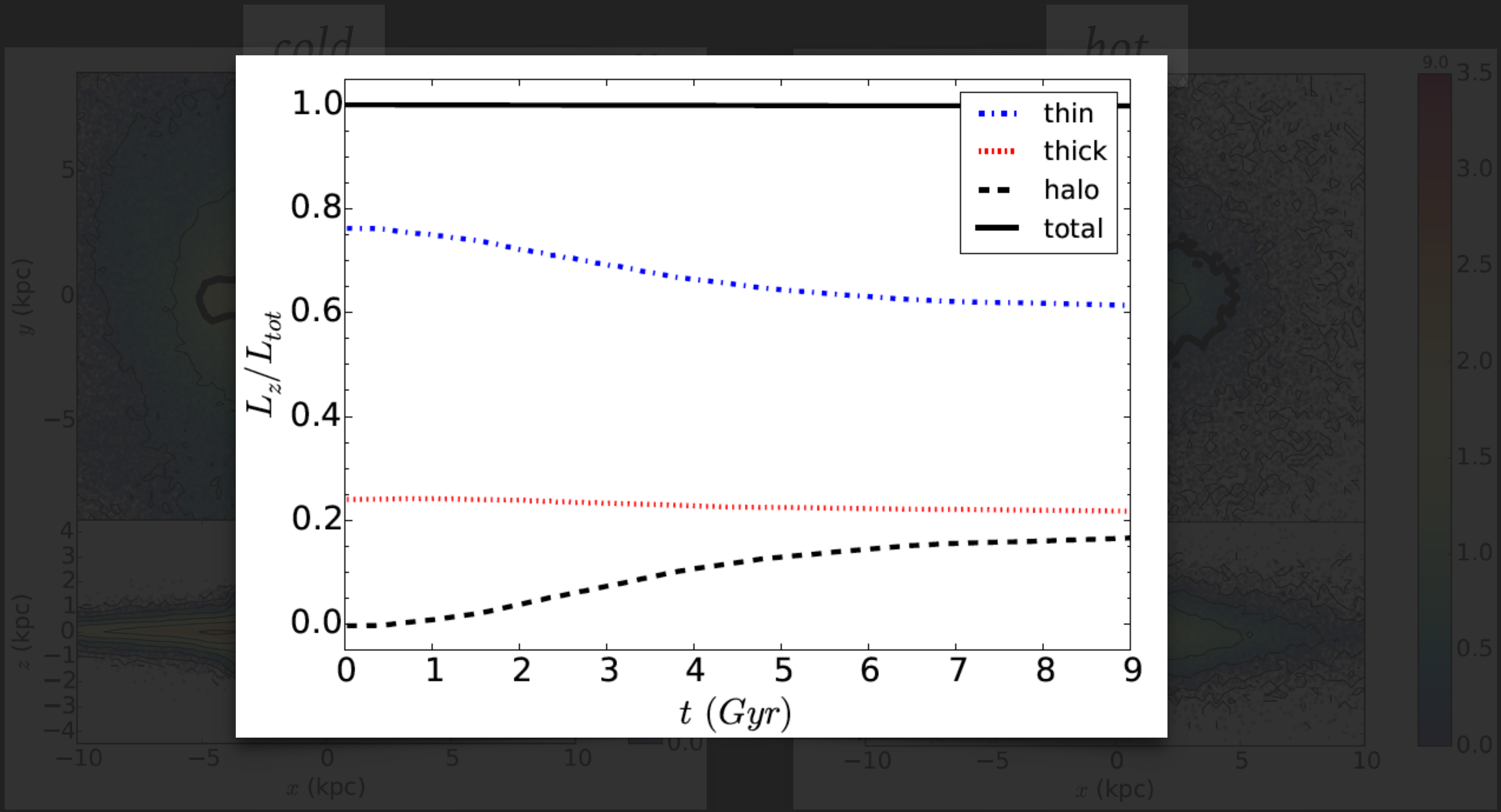
MORPHOLOGY



Cold population has a more barred and peanut-like morphology, compared to the hot component

Fragkoudi+17b, A&A, 606, A47

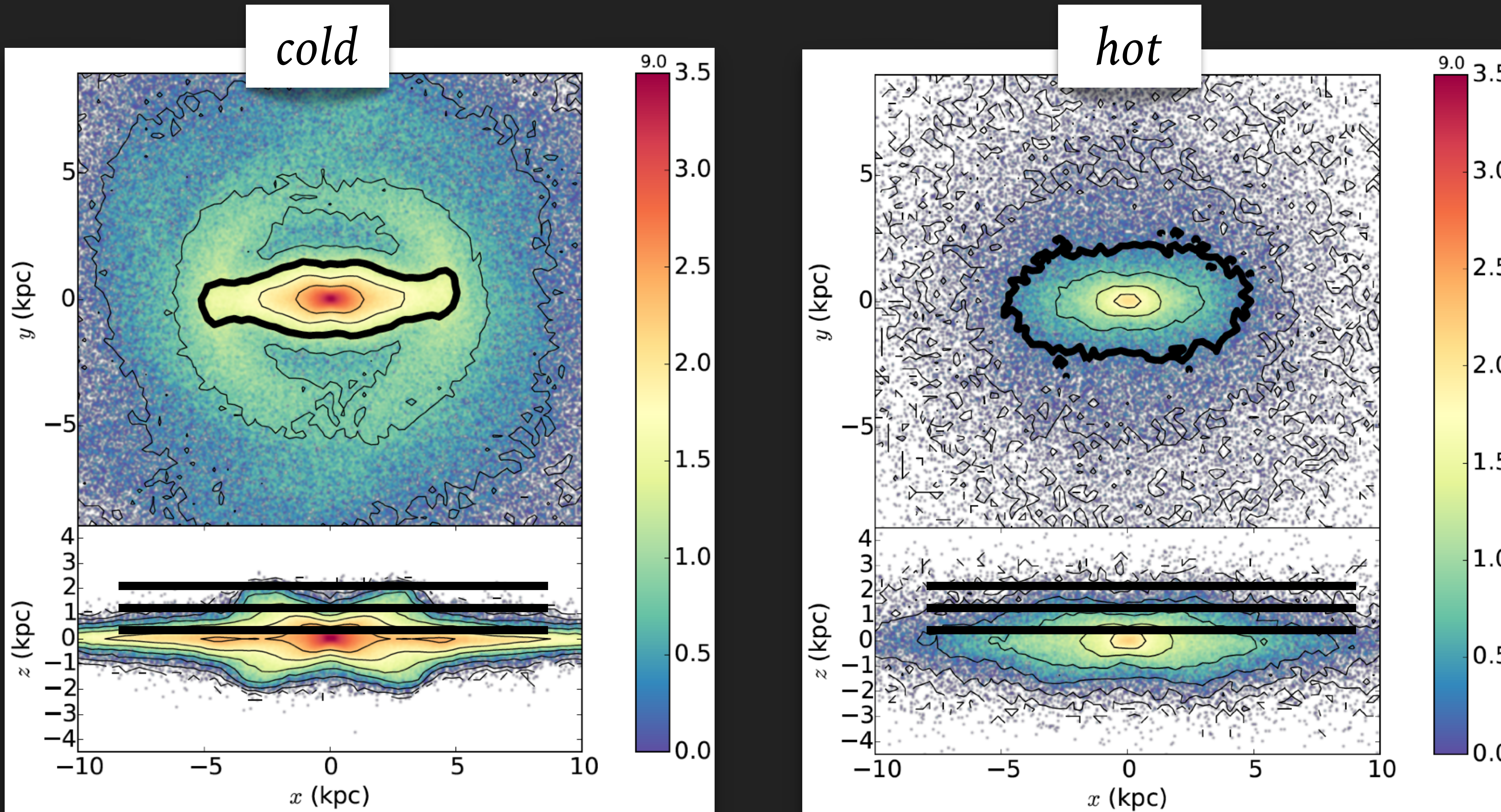
MORPHOLOGY



Cold/thin disc loses more angular momentum than hot/thick disc

Fragkoudi+17b, A&A, 606, A47

MORPHOLOGY



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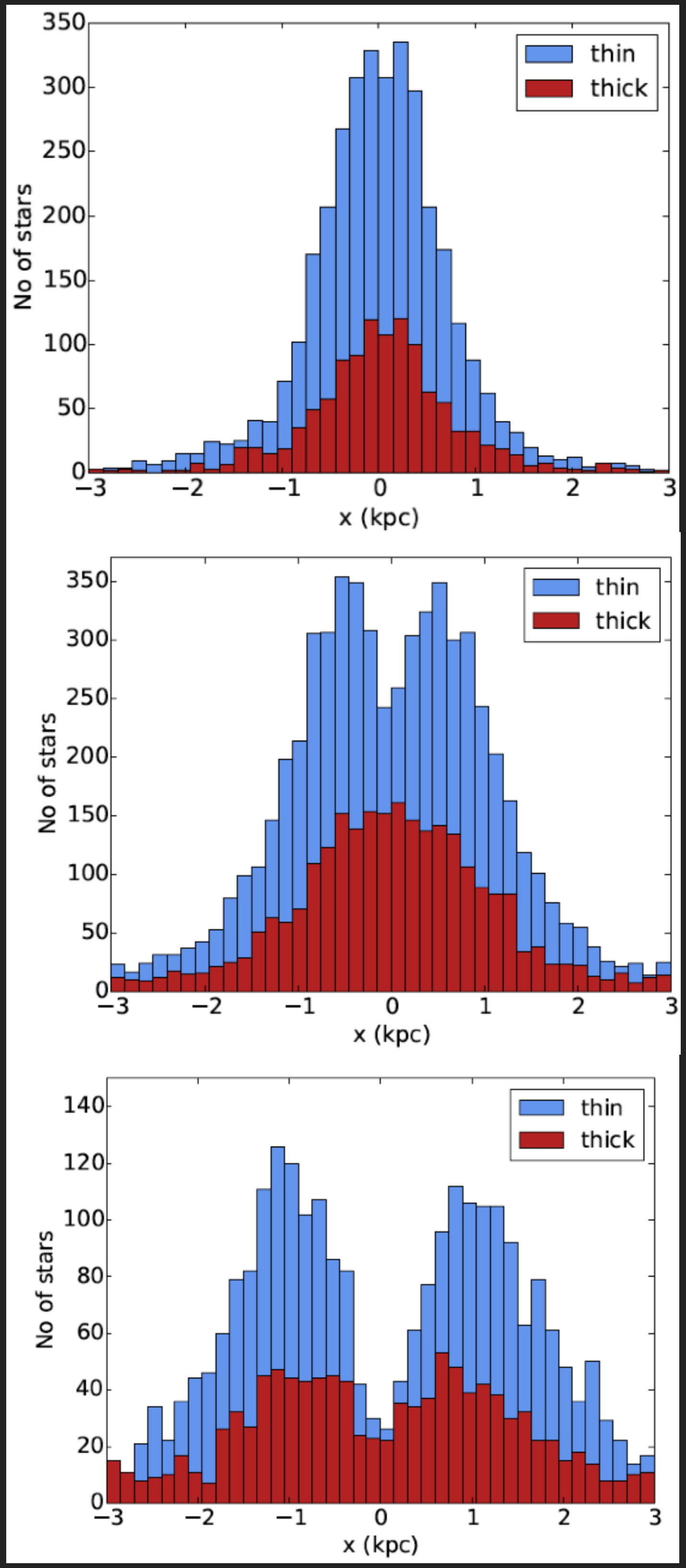


cold

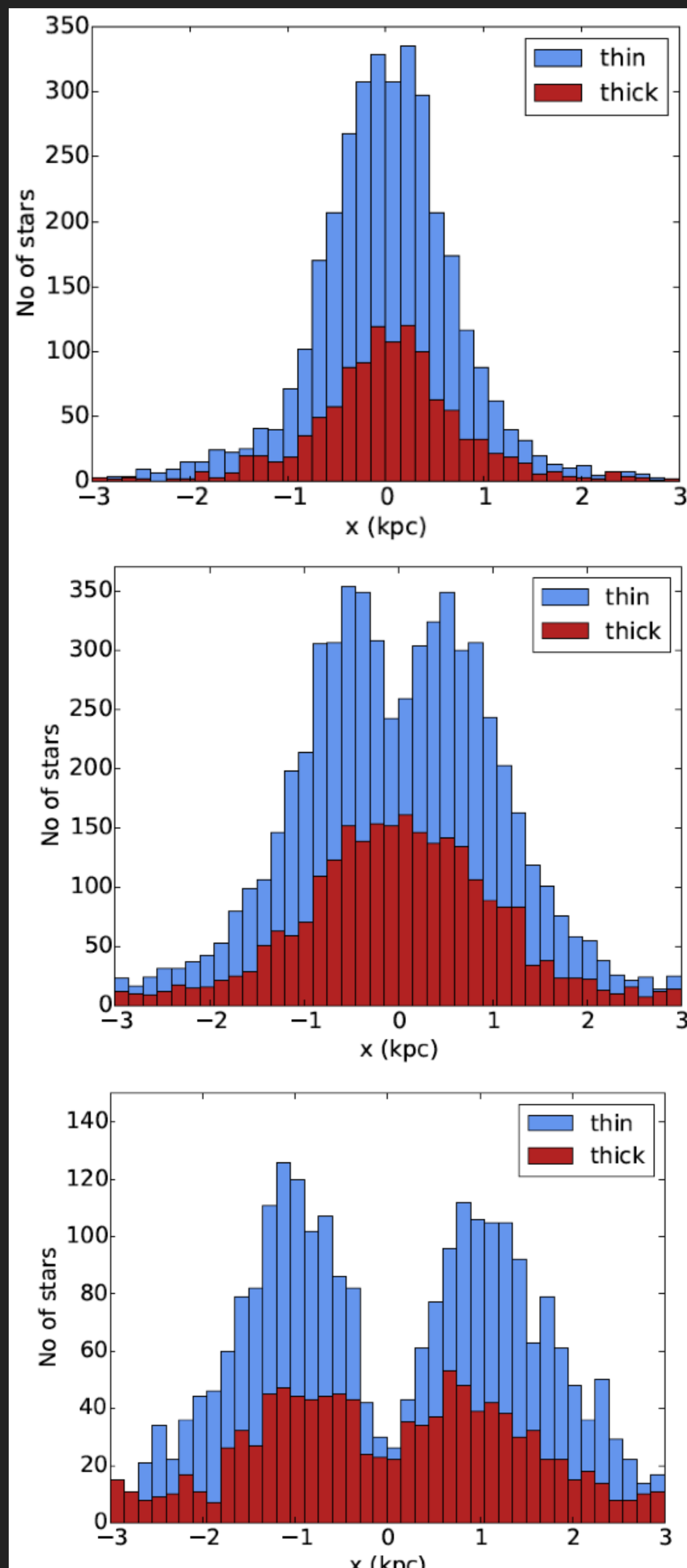
hot

close to plane

far from plane

Fragkoudi+17b, A&A, 606, A47

MORPHOLOGY

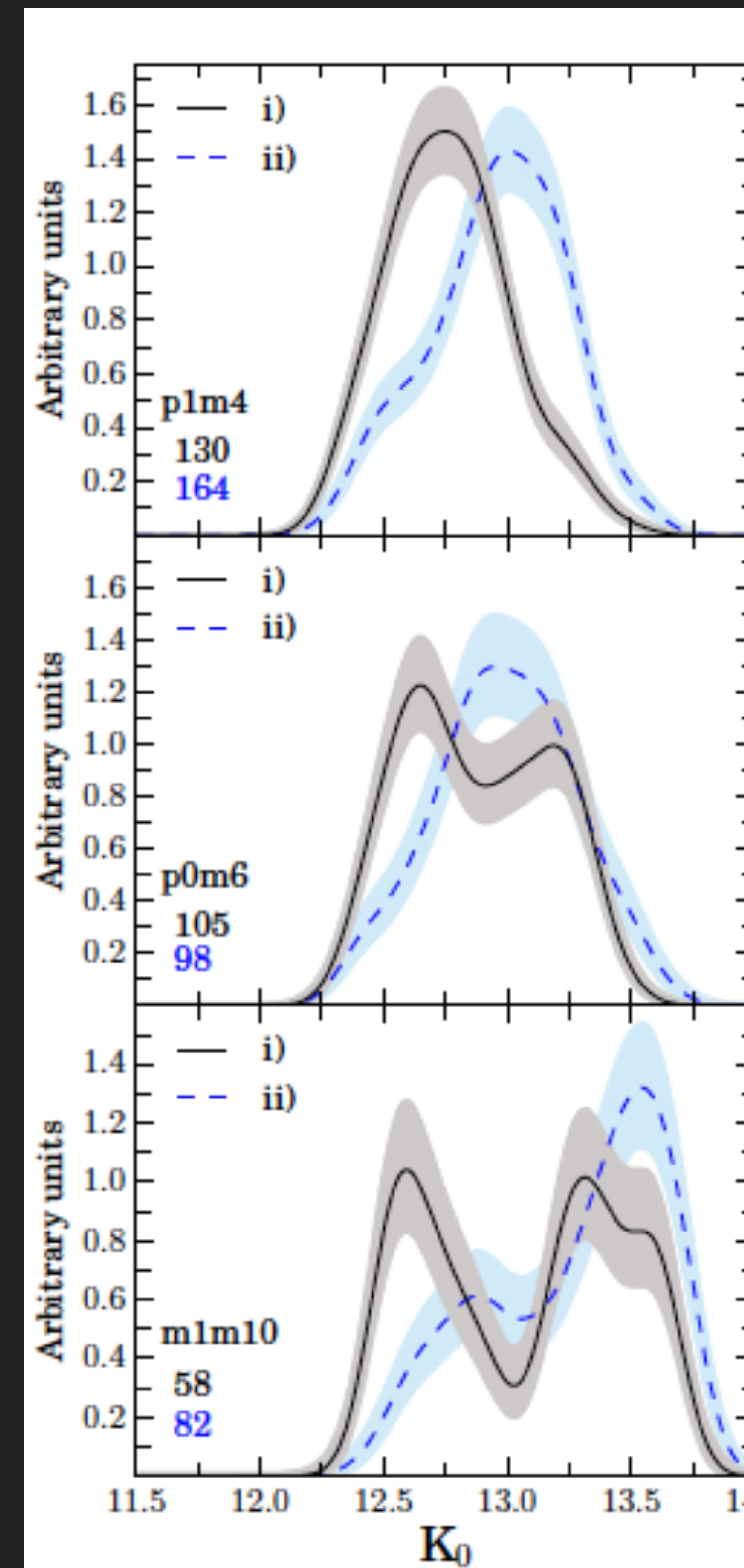


cold

hot

close to plane

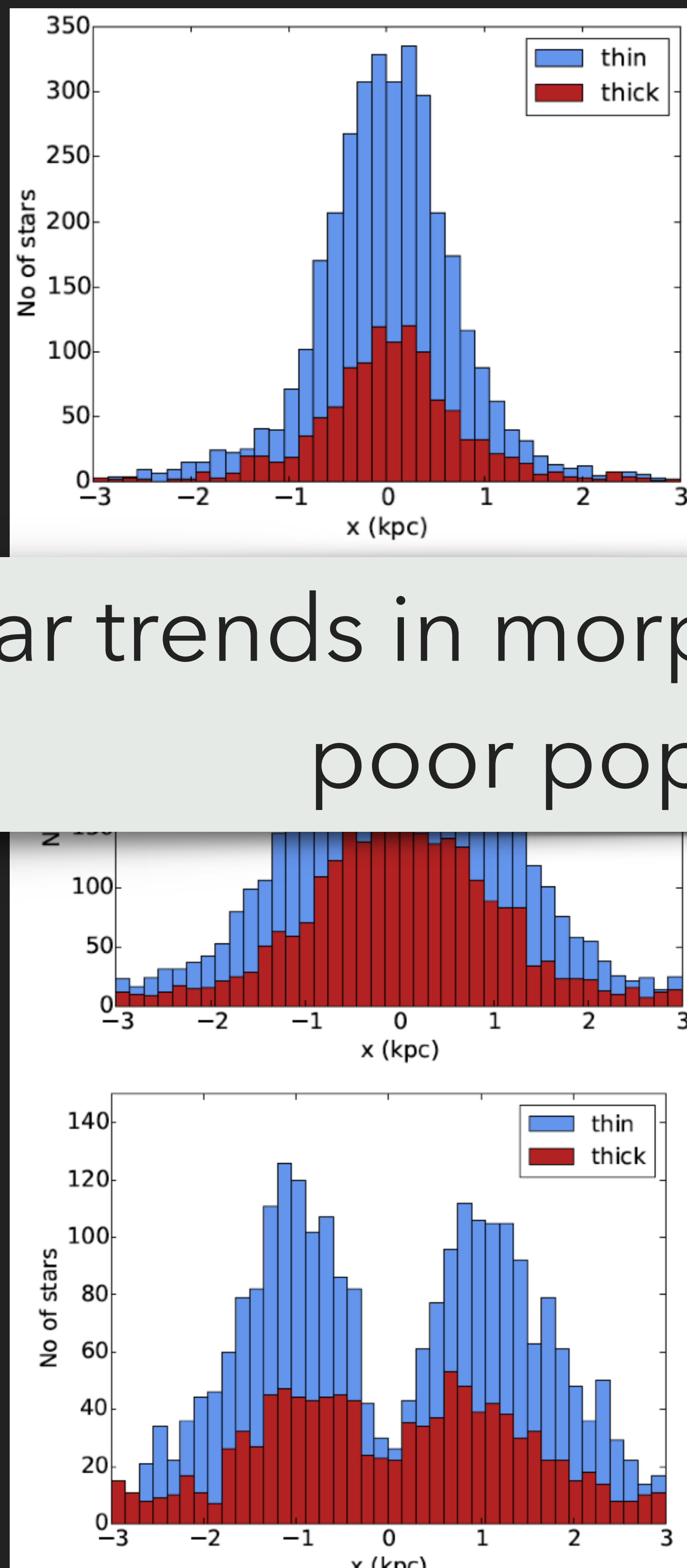
far from plane



Fragkoudi+17b, A&A, 606, A47

Rojas-Arriagada+14

MORPHOLOGY



cold

hot

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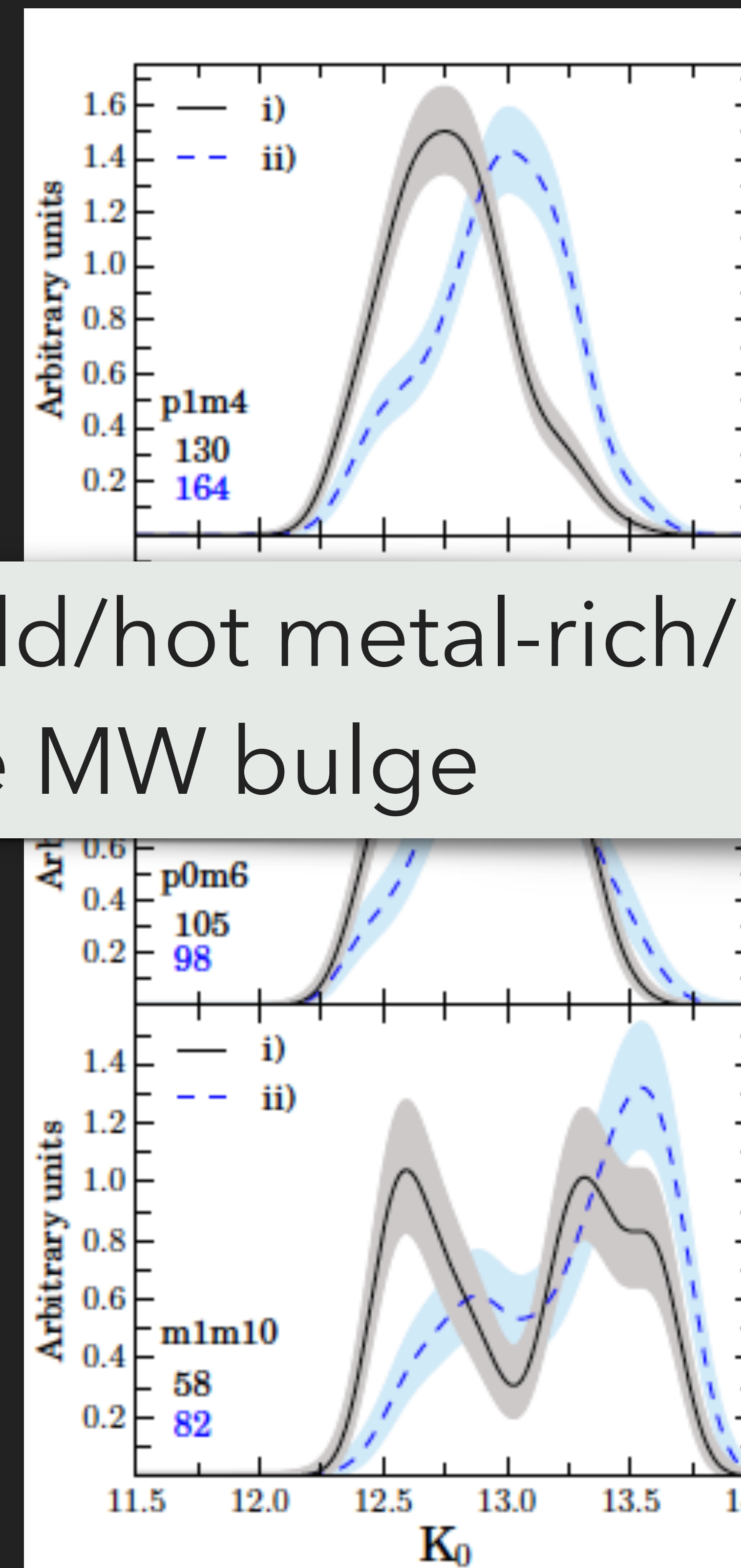
far from plane



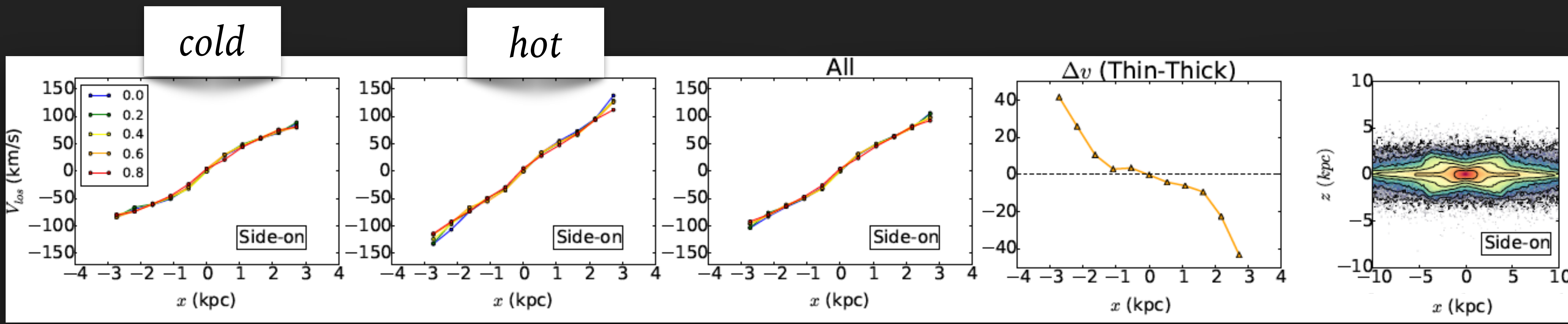
Similar trends in morphology for cold/hot metal-rich/metal-poor populations in the MW bulge

Fragkoudi+17b, A&A, 606, A47

Rojas-Arriagada+14

KINEMATICS

KINEMATICS



Fragkoudi+17b, A&A, 606, A47

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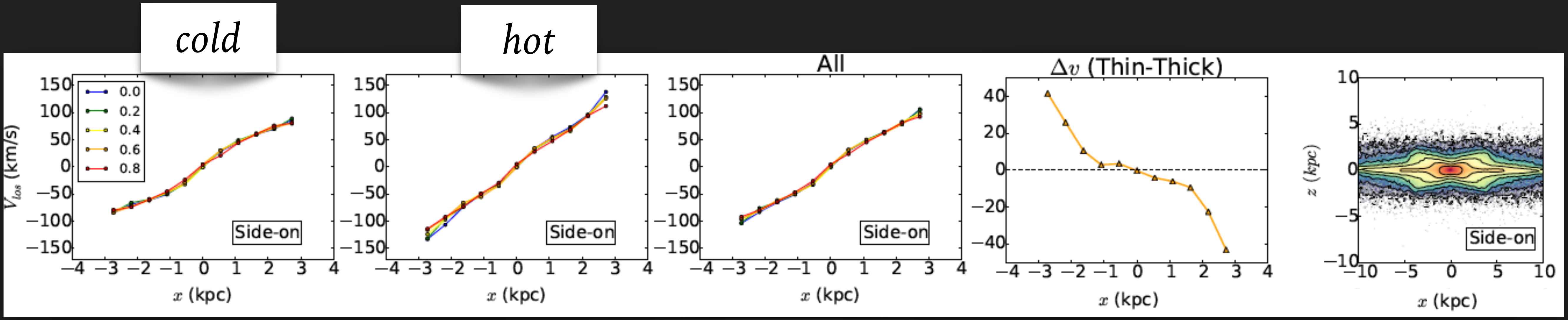
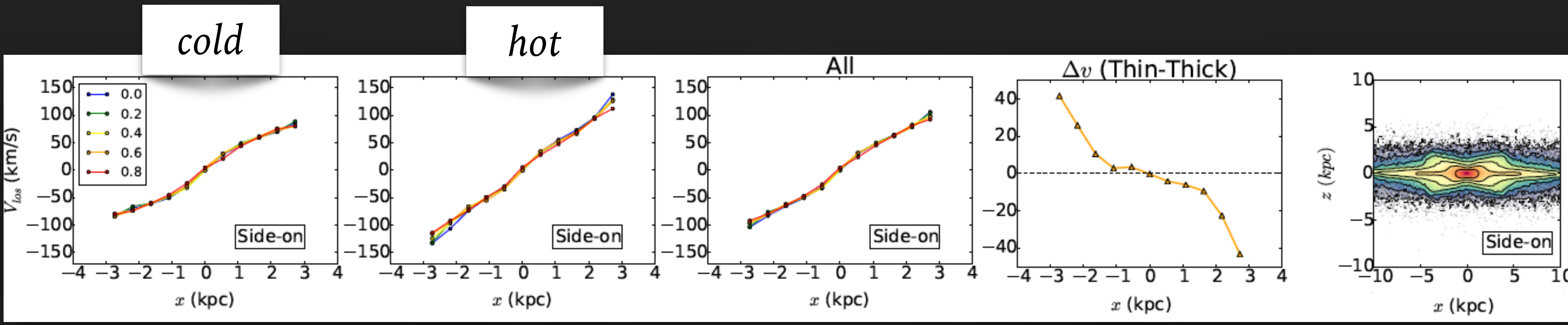


Hot/thick disc has higher los velocity than thin disc in the b/p bulge region

Fragkoudi+17b, A&A, 606, A47

KINEMATICS



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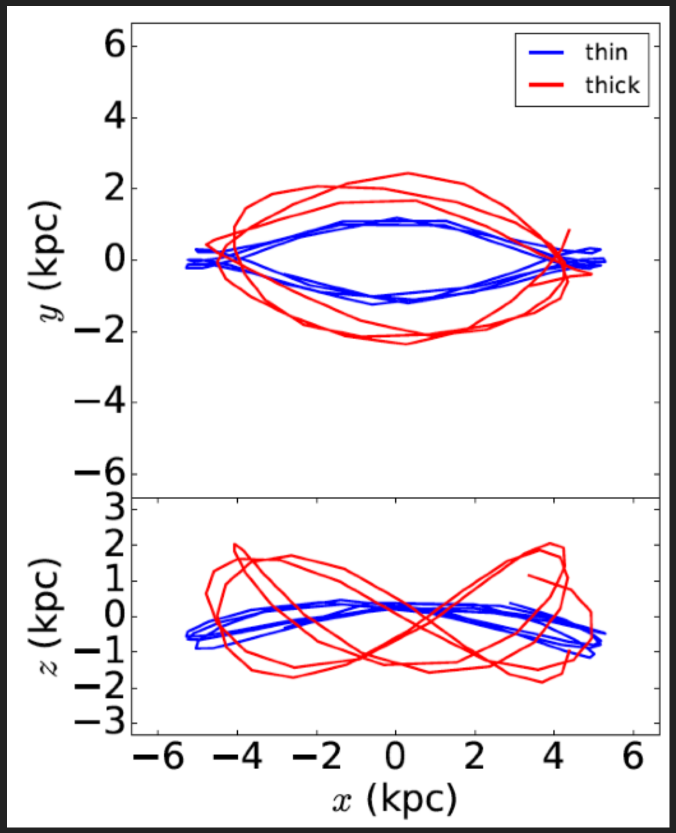
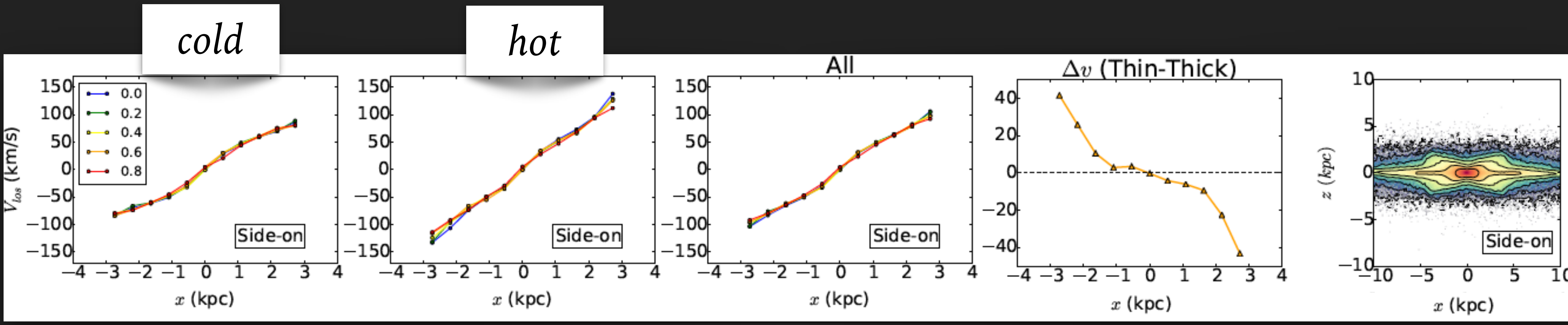


Hotter (thick disc) population has rounder orbits and therefore higher los velocities

Fragkoudi+17b, A&A, 606, A47

KINEMATICS



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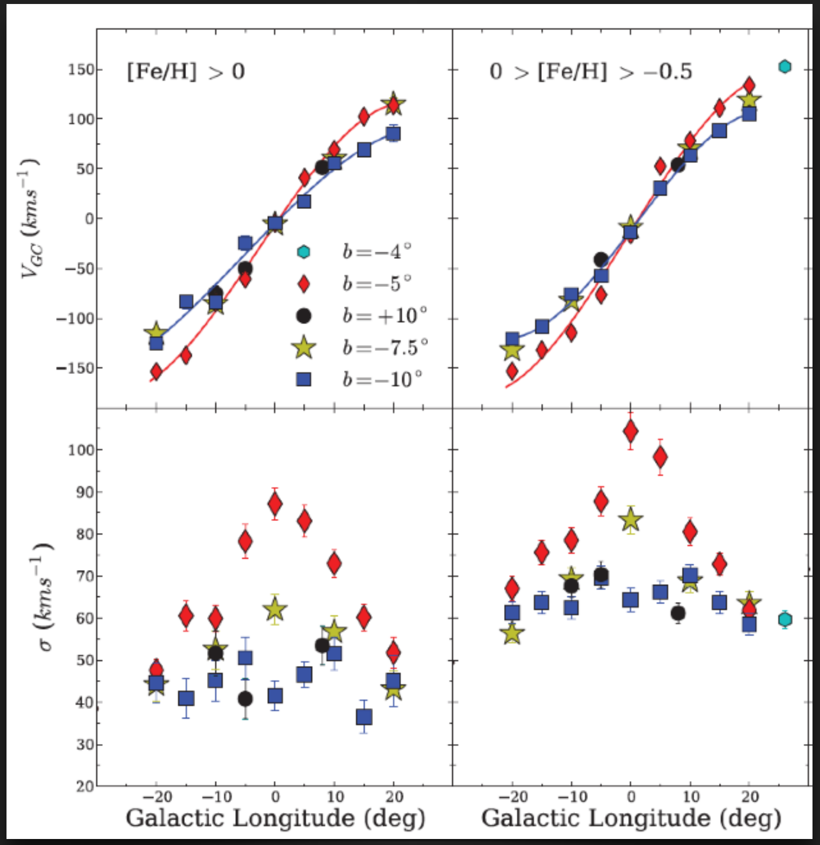
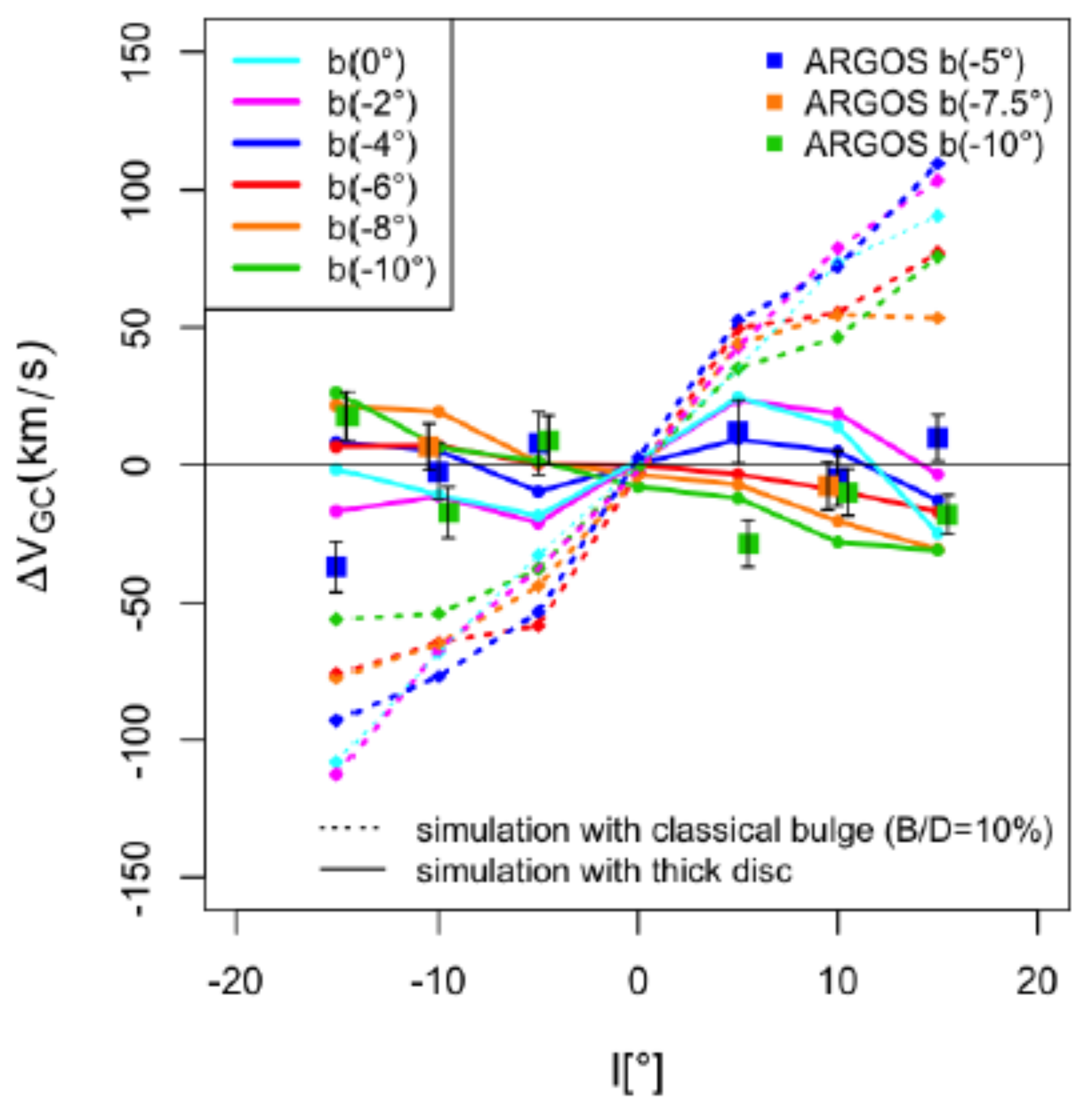
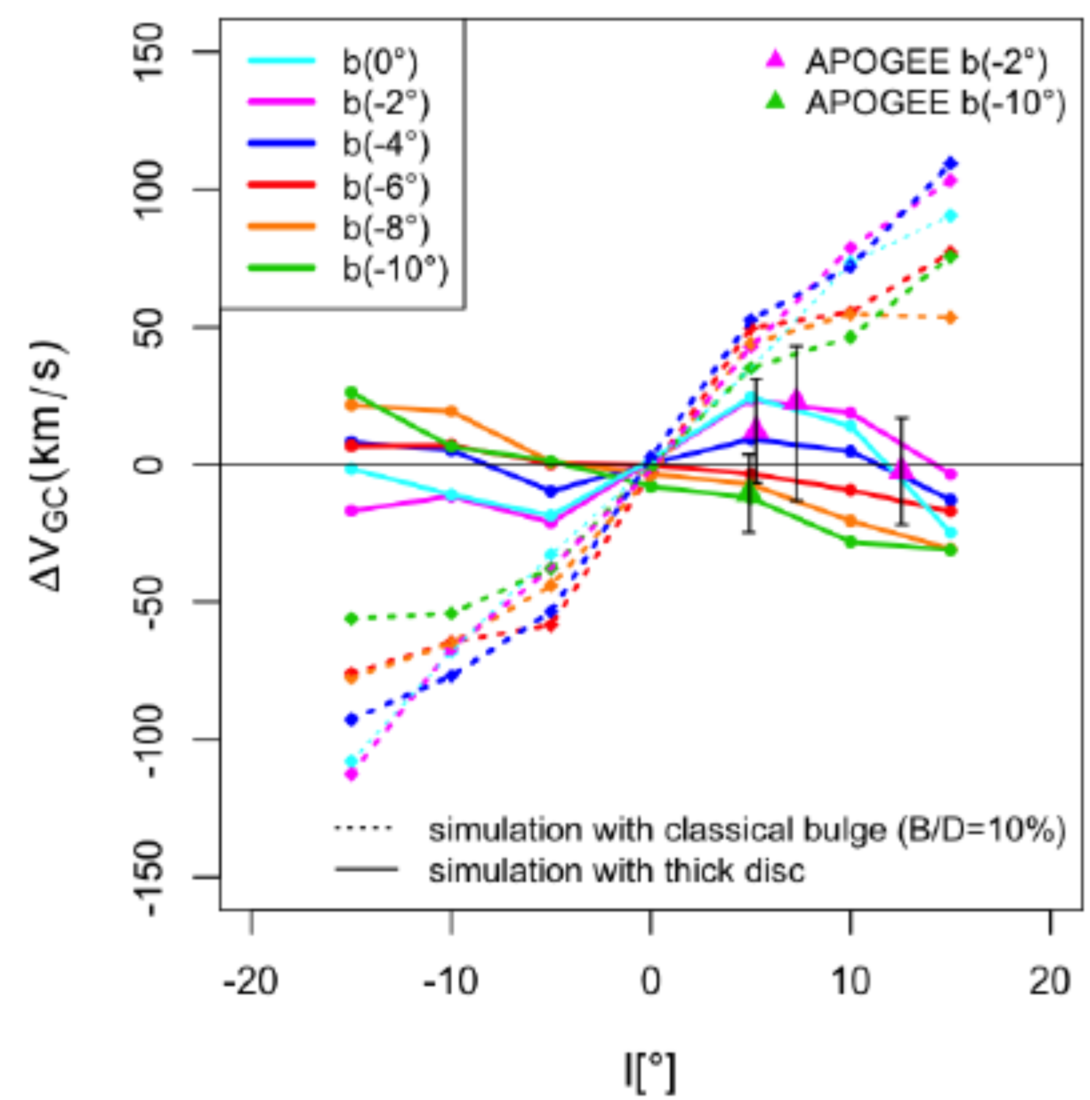


Stellar populations in the MW bulge show similar trends for cold and hot populations

Fragkoudi+17b, A&A, 606, A47

KINEMATICS

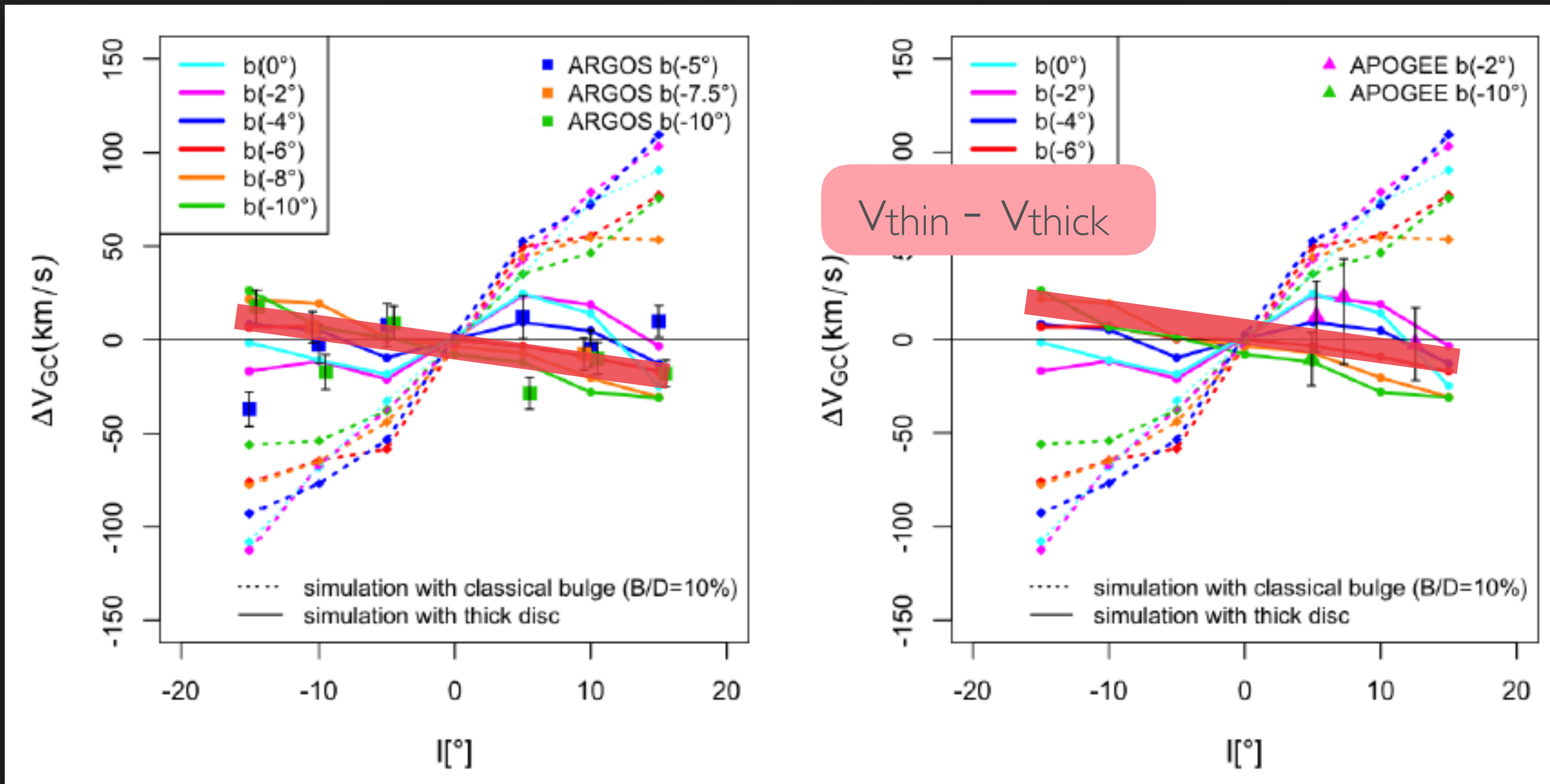




Δv: difference in velocity between metal-rich and metal-poor populations

Gómez, Di Matteo, Schultheis, FF+18

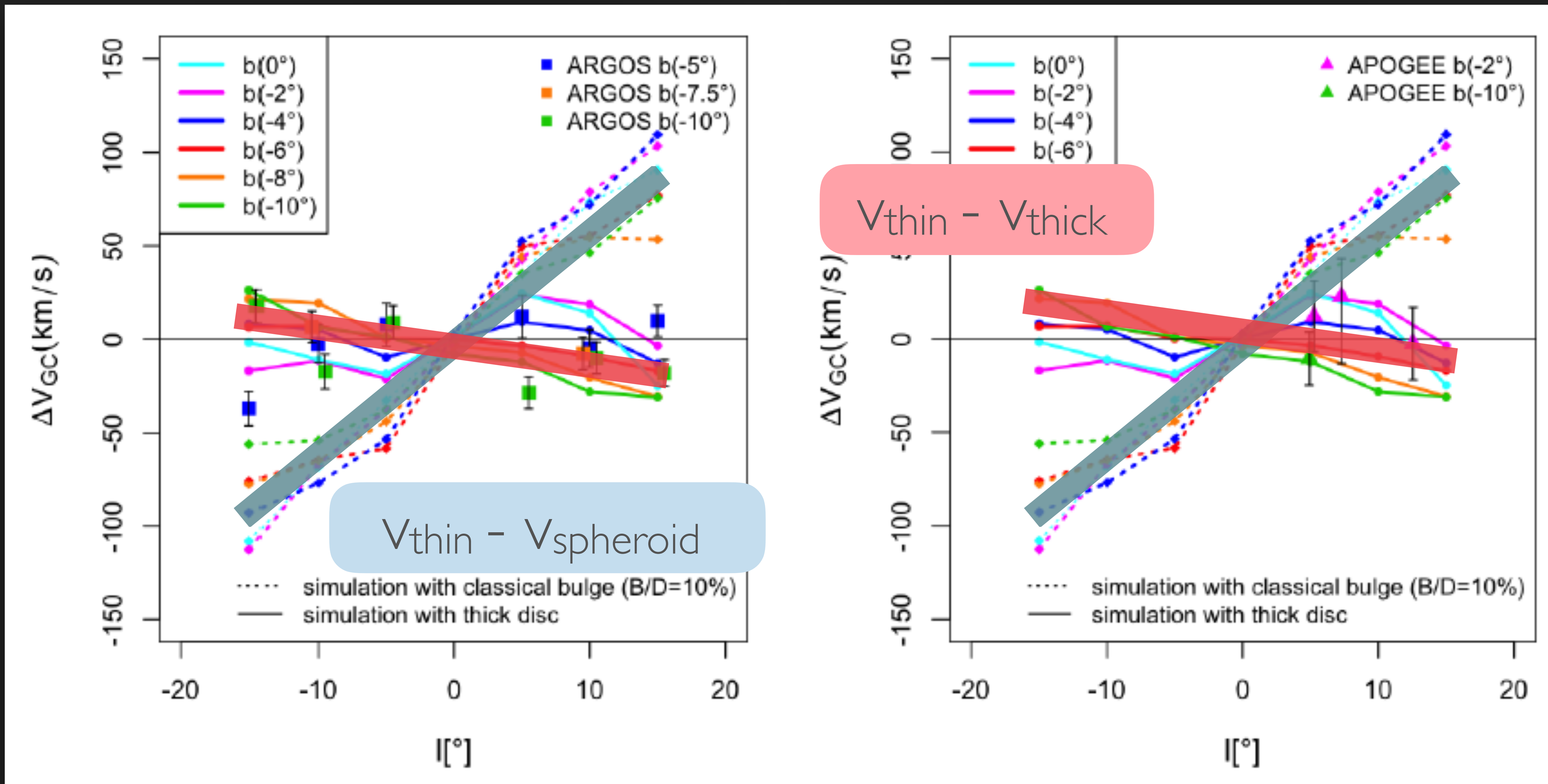
KINEMATICS



Solid : thin+thick disc

Gómez, Di Matteo, Schultheis, FF+18

KINEMATICS

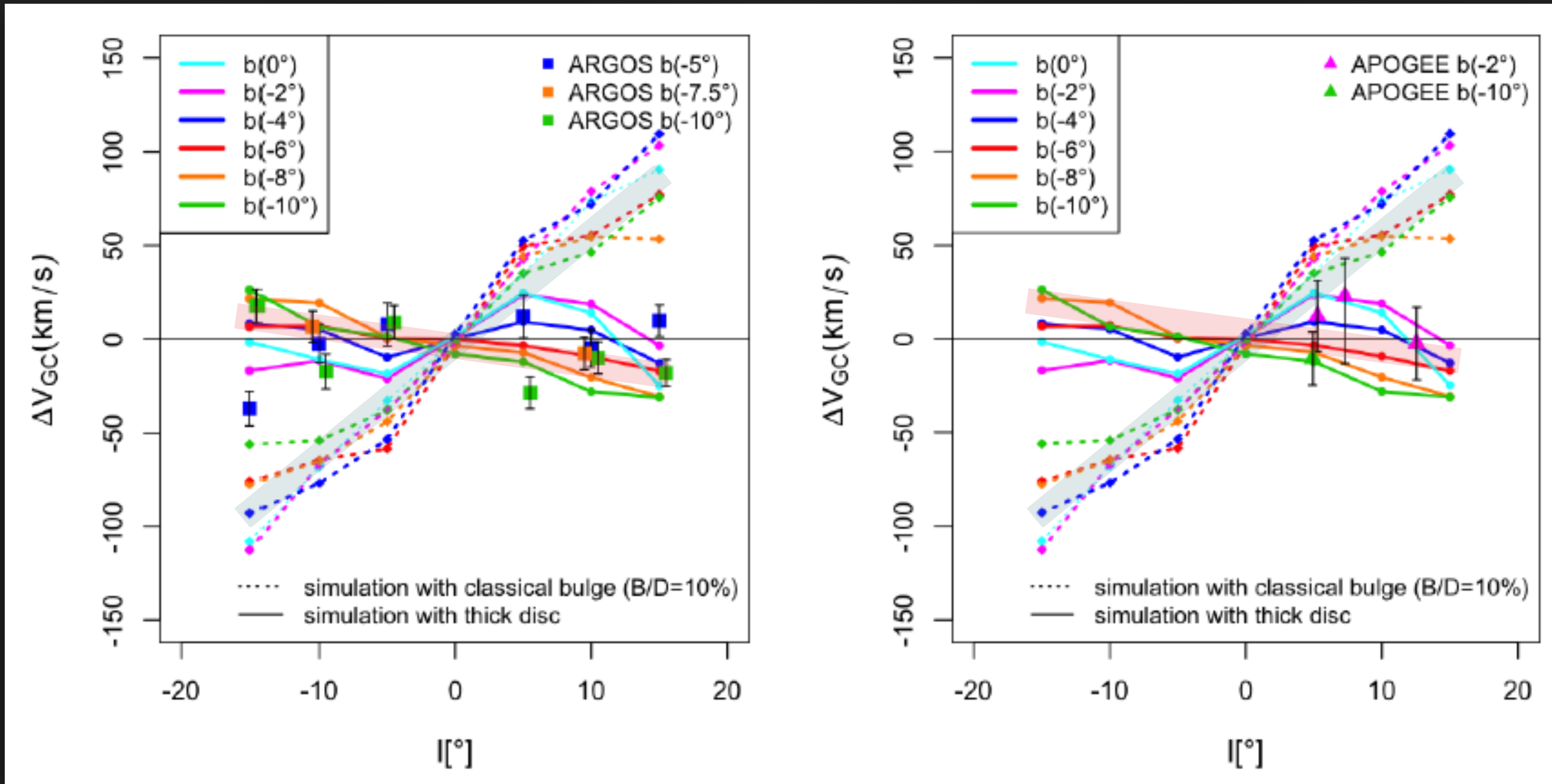


Solid : thin+thick disc

Dashed : thin disc+classical bulge

Gómez, Di Matteo, Schultheis, FF+18

KINEMATICS



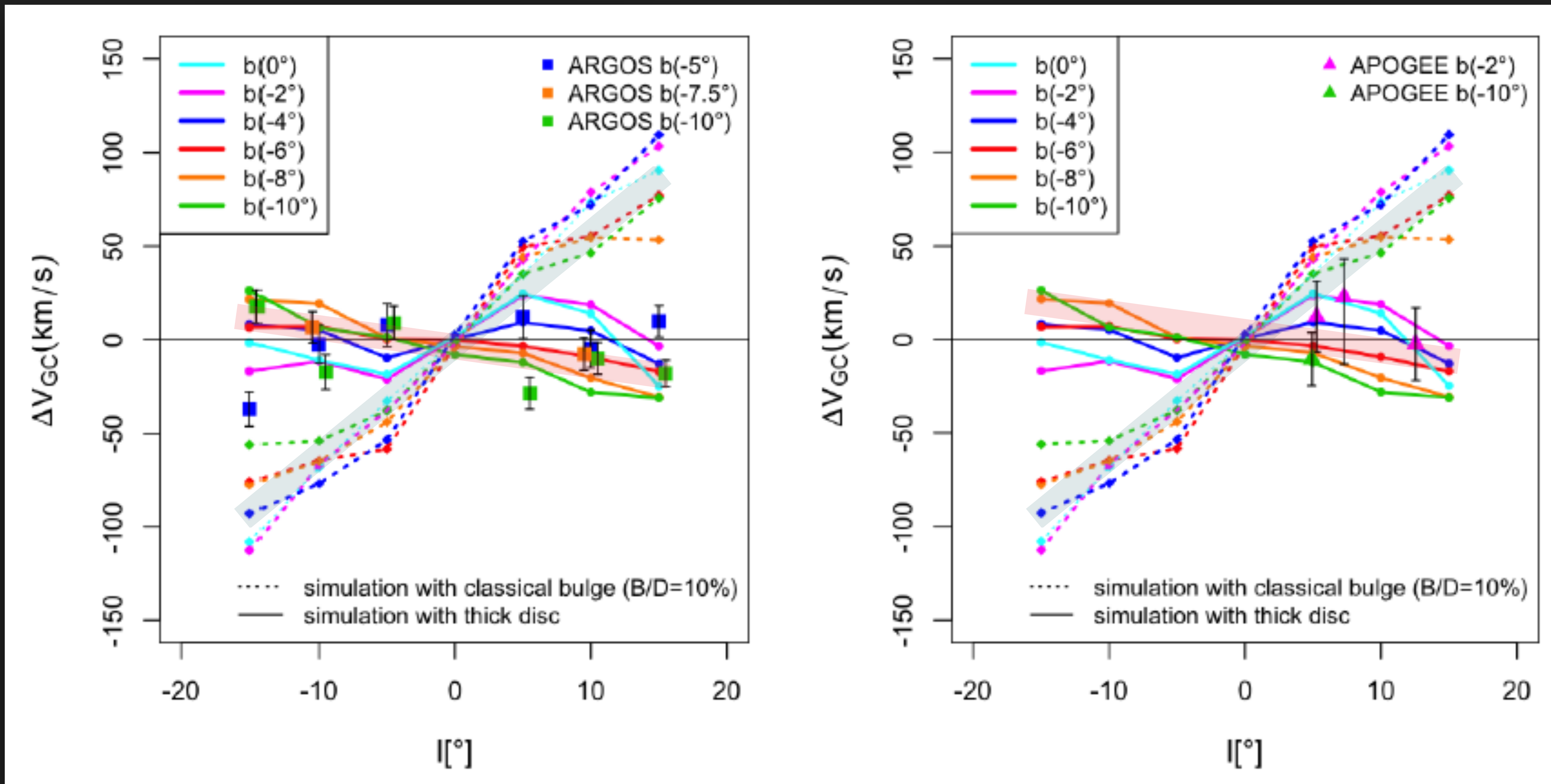
Solid : thin+thick disc

Dashed : thin disc+classical bulge

Data : ARGOS & APOGEE

Gómez, Di Matteo, Schultheis, FF+18

KINEMATICS



Good fit to data with thick disc model
(dispersion dominated spheroidal component is incompatible)

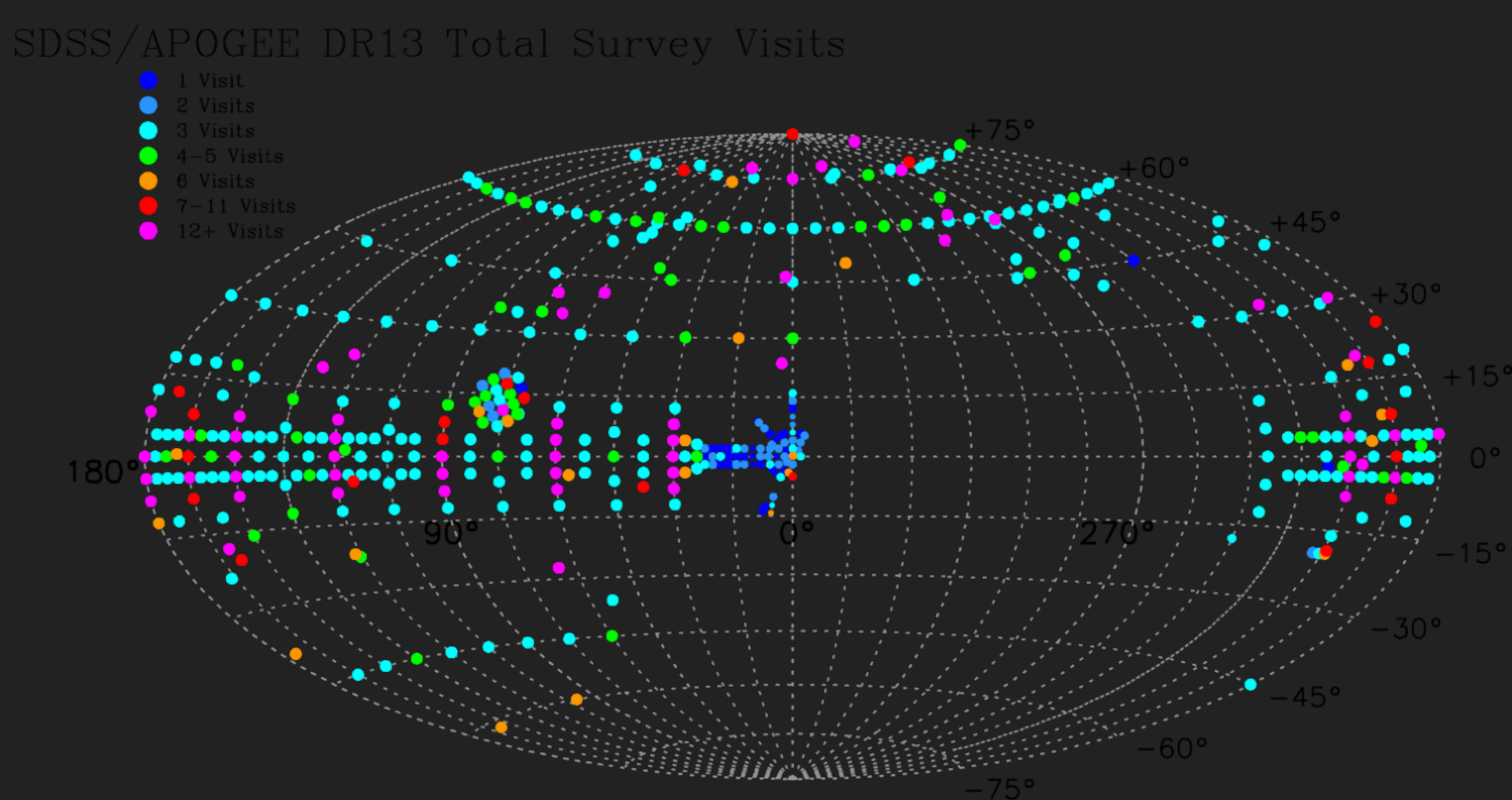
Gómez, Di Matteo, Schultheis, FF+18

CHEMISTRY

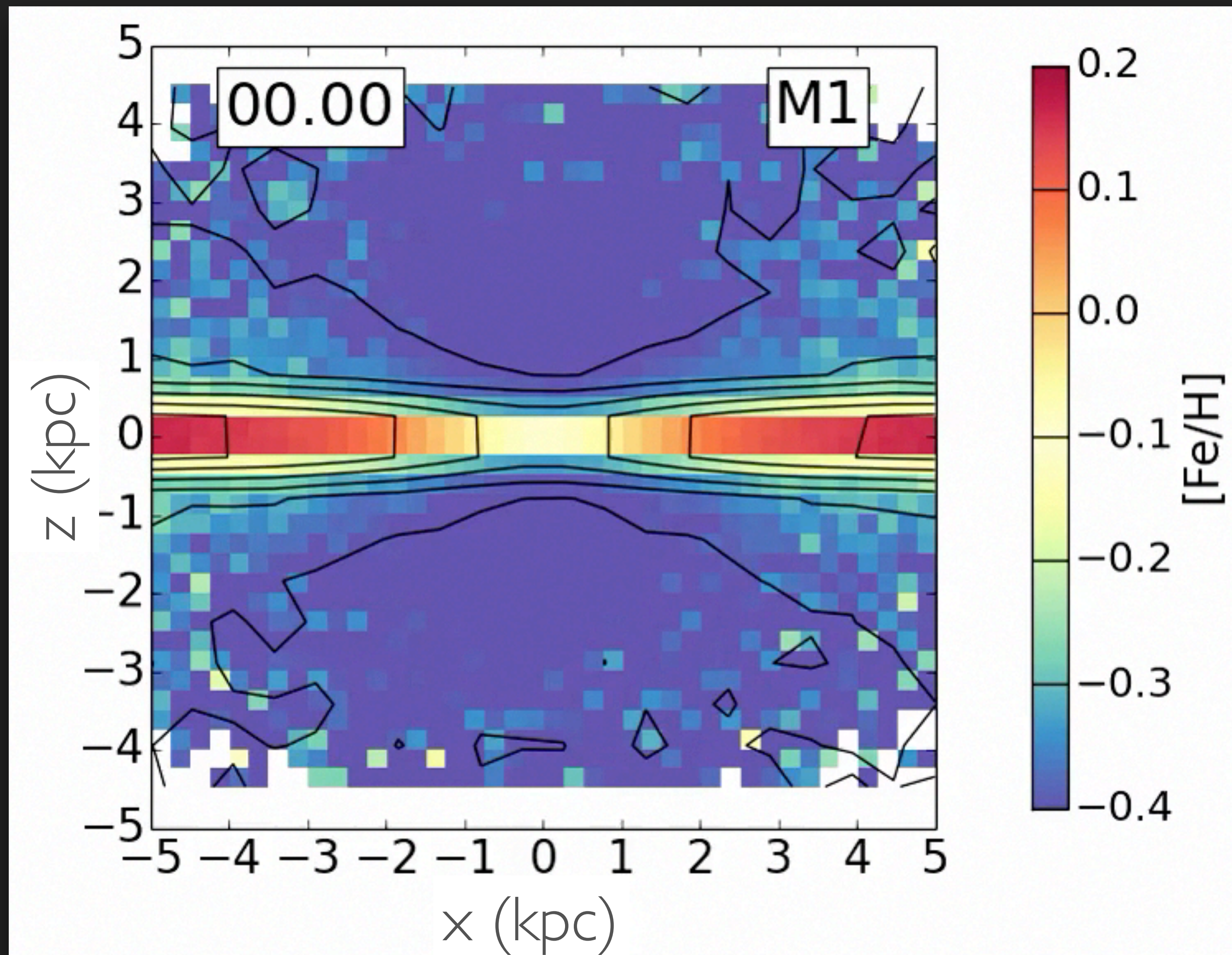
CHEMISTRY

APOGEE Survey:

- Near infrared high resolution spectroscopic survey, part of SDSS III (Majewski+17)
- Covers regions also close to the plane of the MW, including inner disc and bulge
- We use data release 13 (SDSS+16)



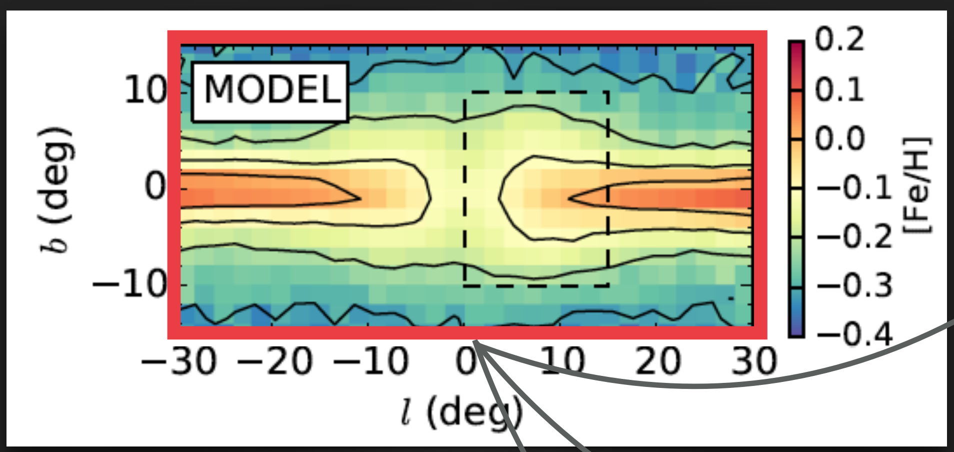
CHEMISTRY

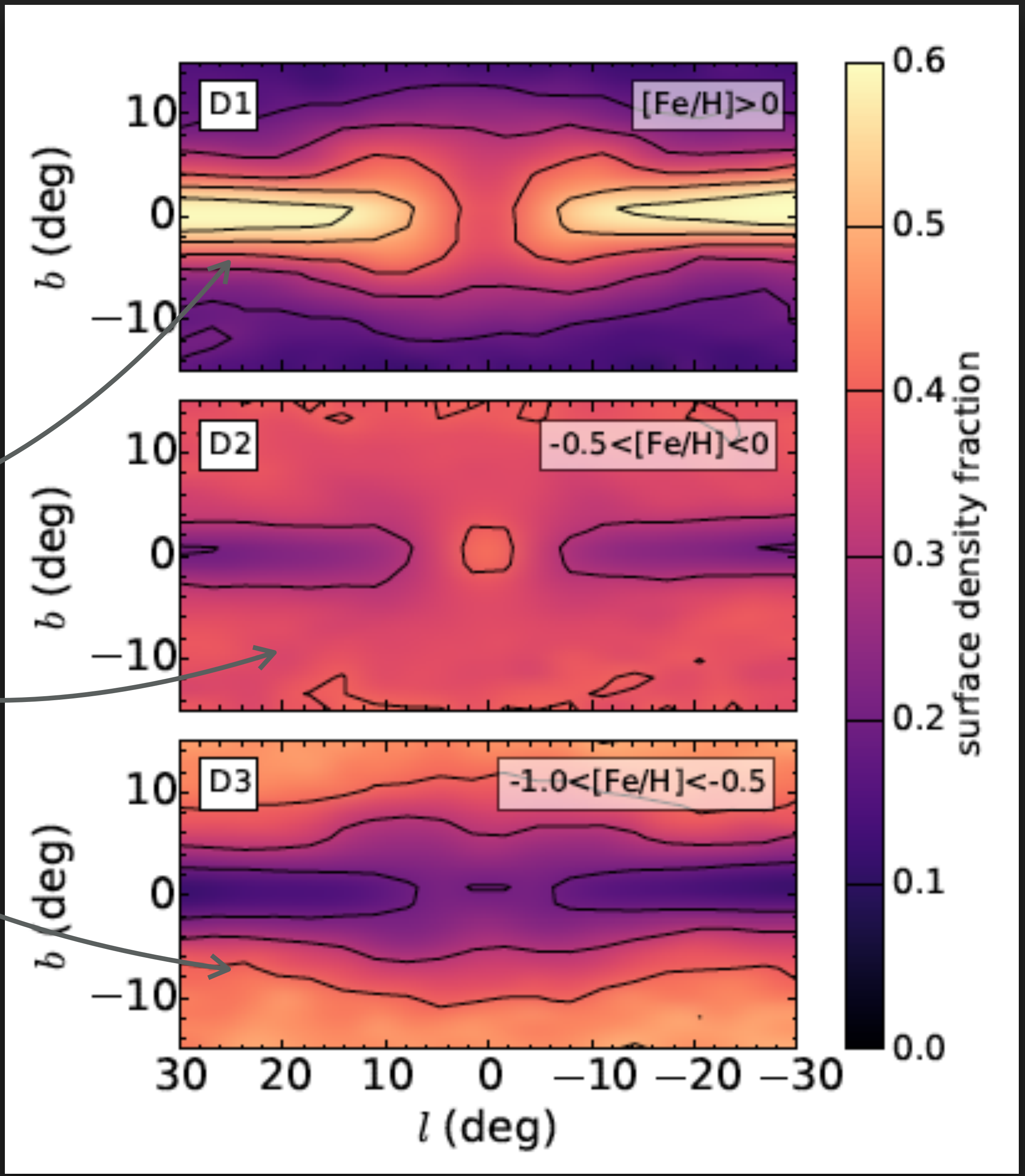


Vertical metallicity gradient is present initially and persists after formation of bar and b/p
(see also Bekki+11, Di Matteo+14)

Fragkoudi+17c, A&A, 607, L4

CHEMISTRY



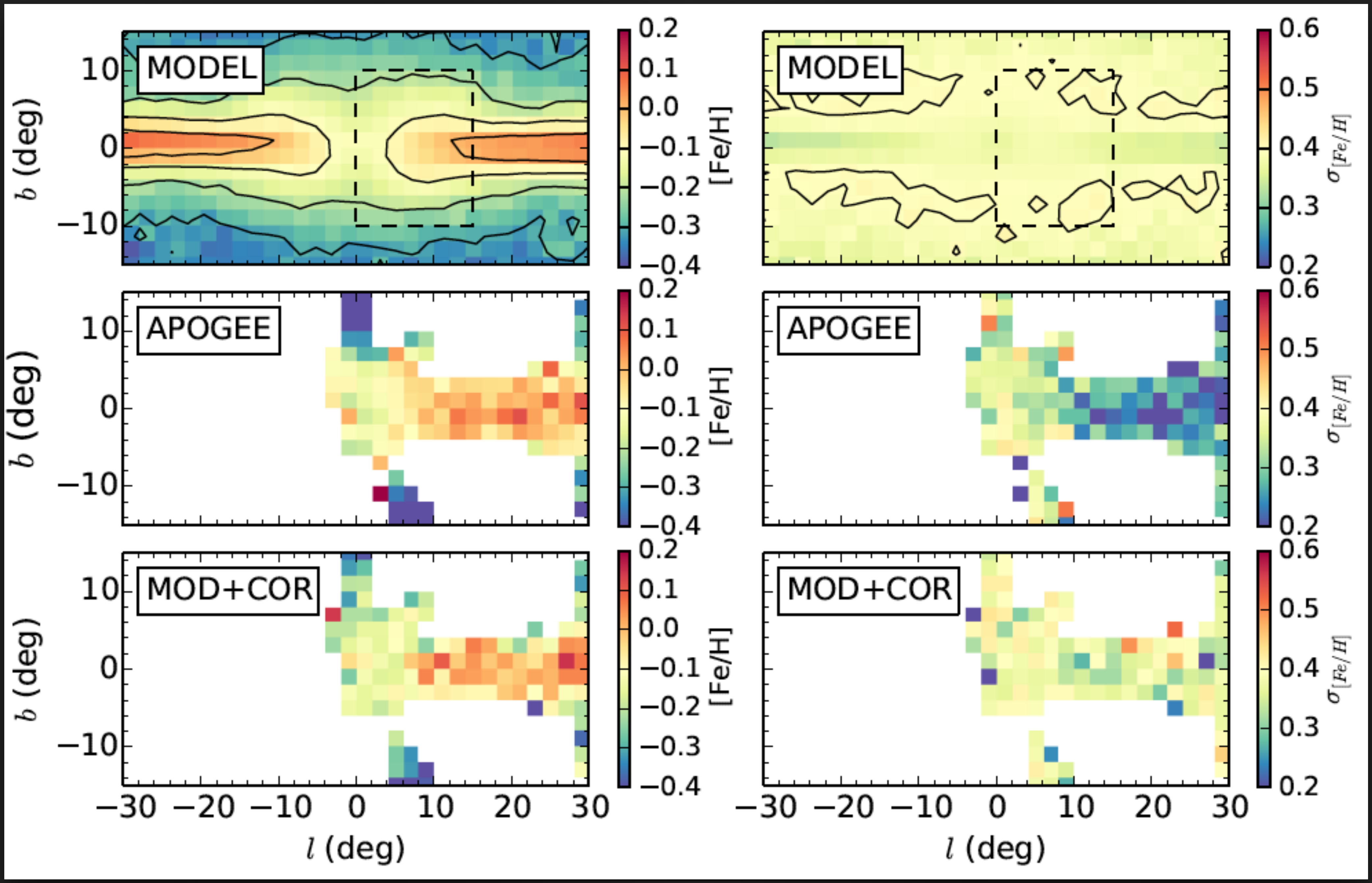


In composite disc model the thin metal-rich disc dominates close to the plane and metal-poor thick disc dominates far from plane

Fragkoudi+17c, A&A, 607, L4

Fragkoudi+18, A&A 616, 180

CHEMISTRY

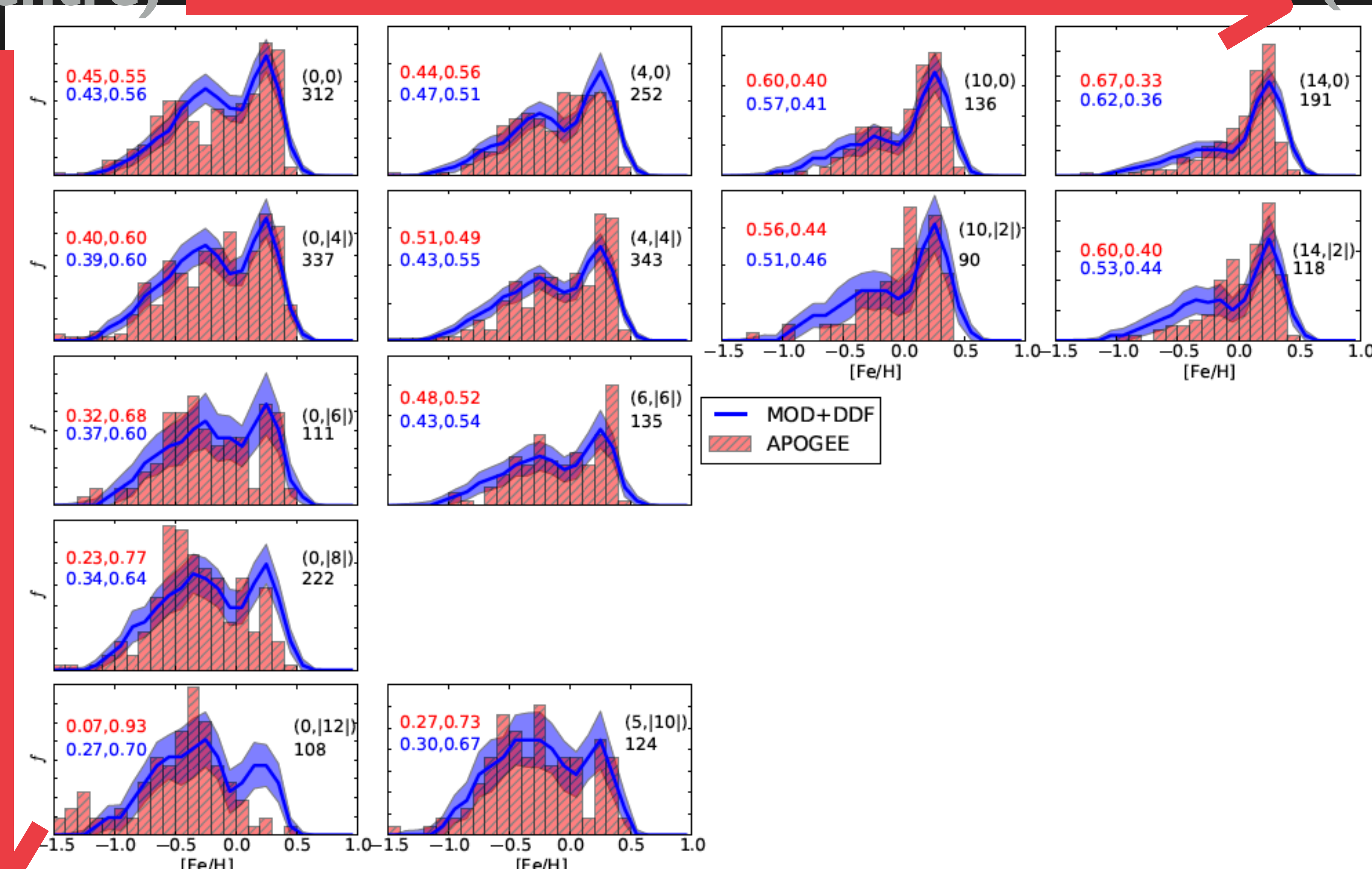


This difference in fractional contribution leads to a vertical and longitudinal metallicity gradient in the bulge/inner disc

Fragkoudi+18, A&A 616, 180

CHEMISTRY

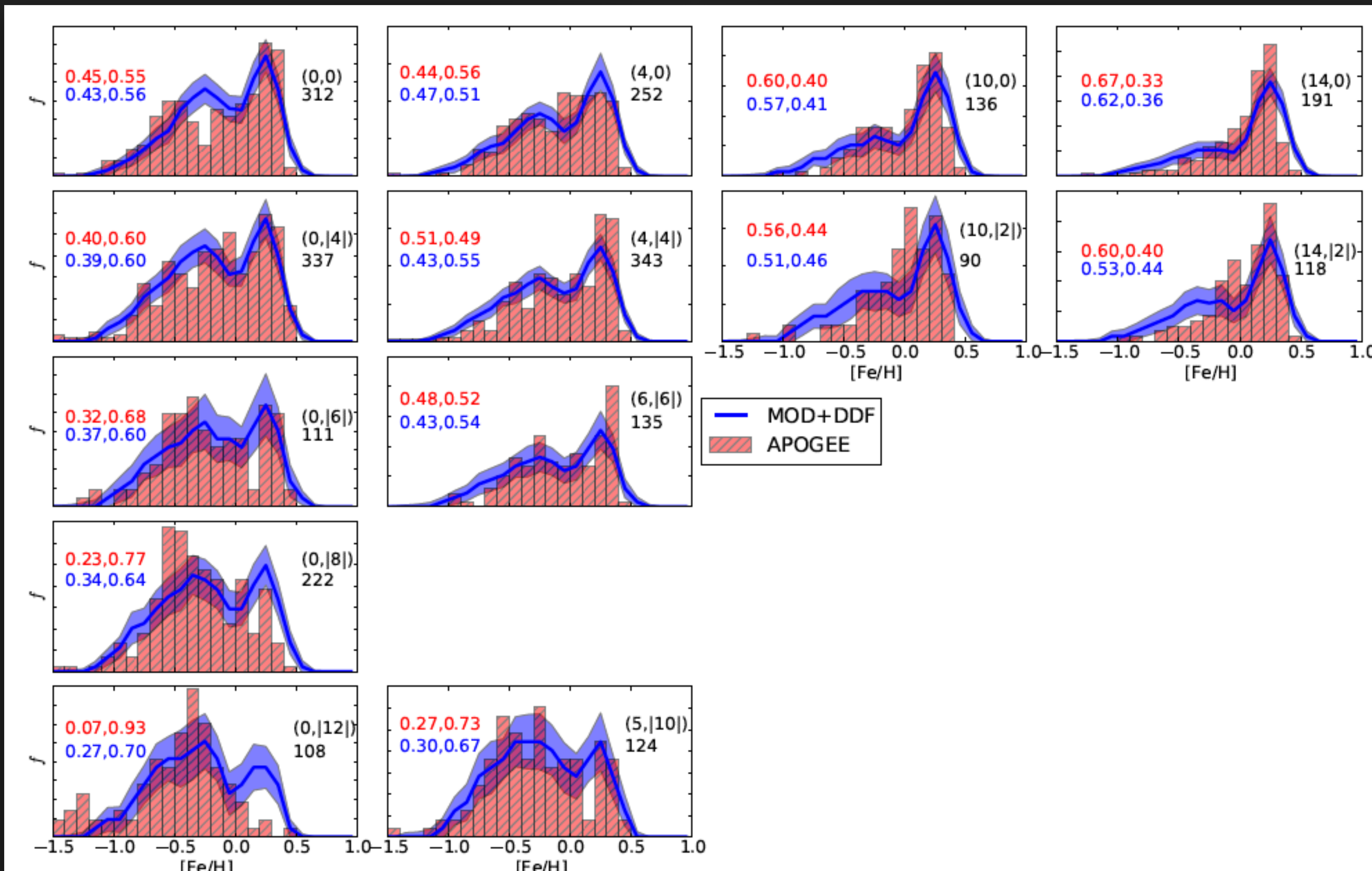
(centre)
(disc)



(below plane)

Fragkoudi+18, A&A 616, 180

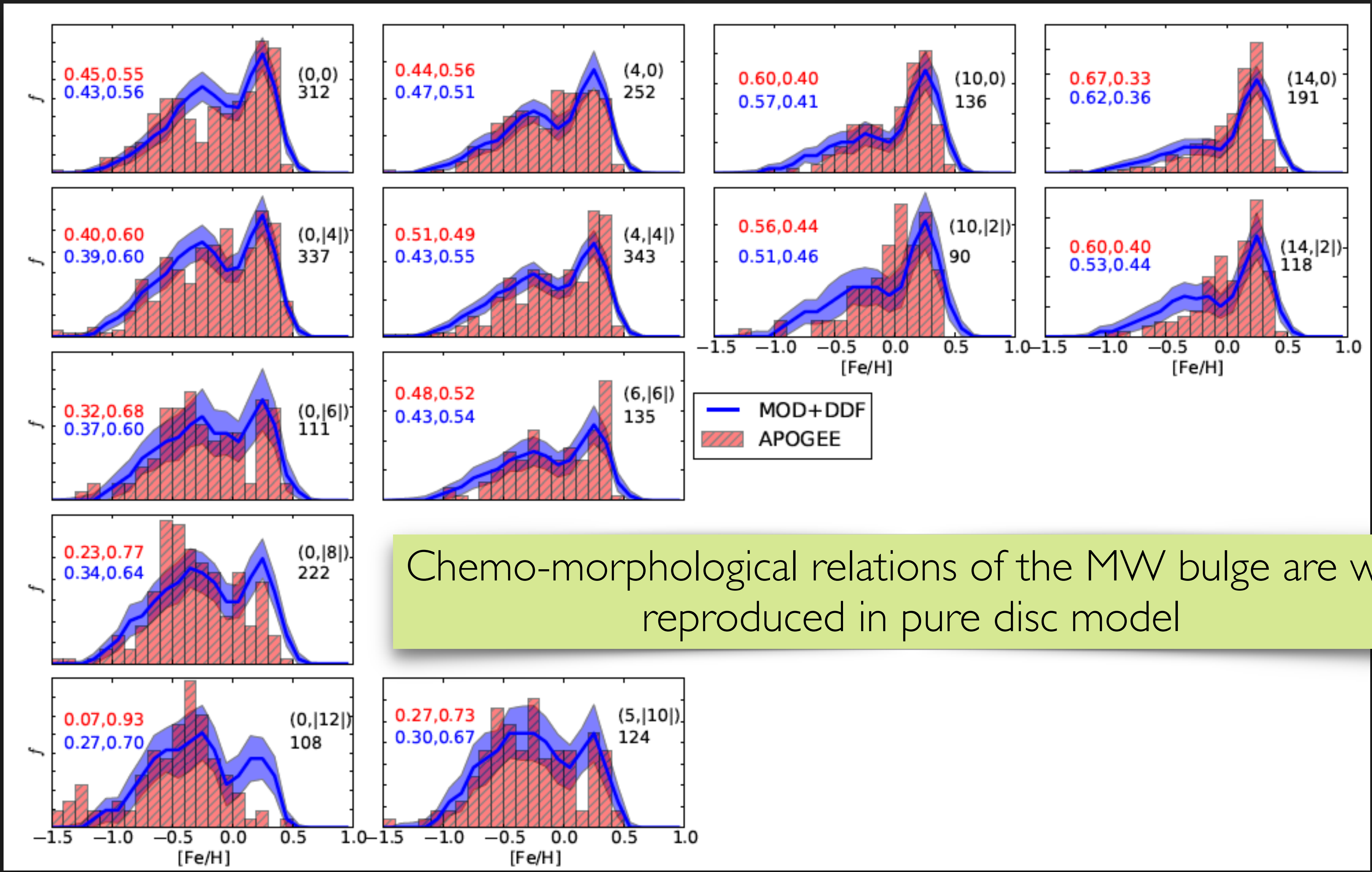
CHEMISTRY



MDF of model reproduces bulge MDF from APOGEE data

Fragkoudi+18, A&A 616, 180

CHEMISTRY



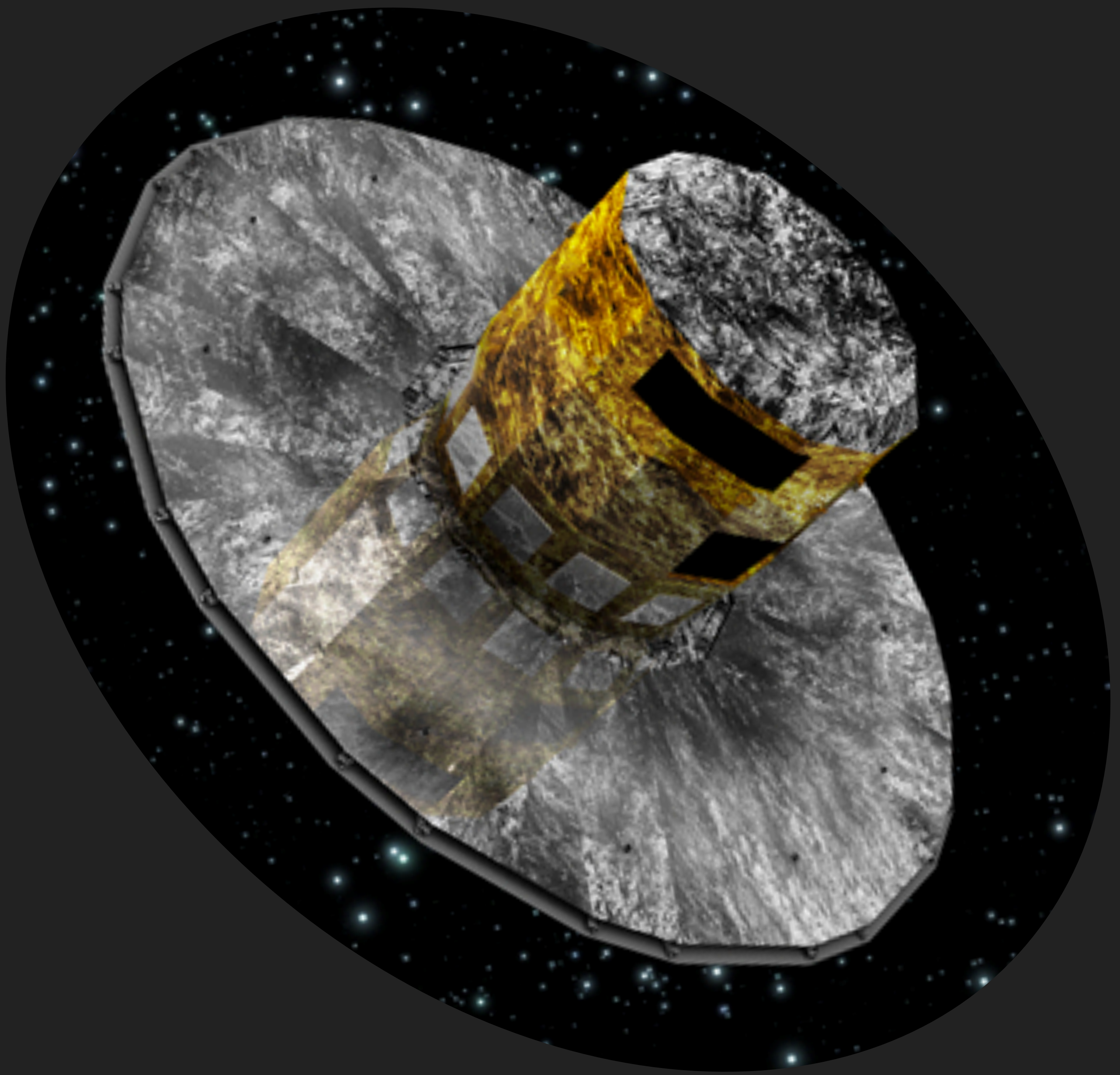
Chemo-morphological relations of the MW bulge are well reproduced in pure disc model

Fragkoudi+18, A&A 616, 180

OUTLINE

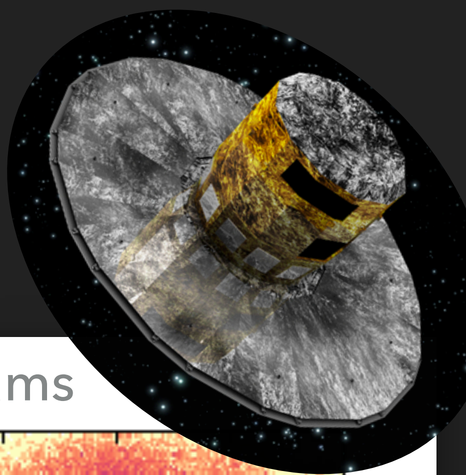
- Introduction
- The bulge-bar connection in the Milky Way
- The disc-bar connection in the Milky Way
  The phase-space substructures in Gaia DR2 & their relation to bar-induced orbital structure
- Summary and thoughts for the future

USING GAIA TO TRACE THE MOVEMENT OF (MILLIONS OF) STARS

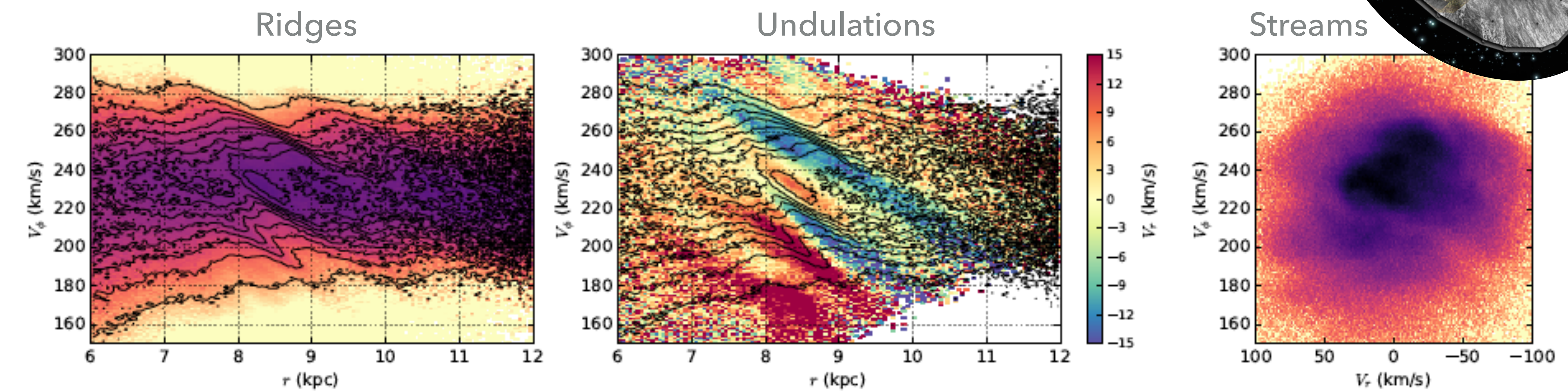


Gaia DR2: Full 6D phase-space information (parallaxes, proper motions & radial velocities) for a few million stars (Gaia Collaboration et al. 2018)

LINKING PHASE-SPACE TOPOGRAPHY TO UNDERLYING ORBITAL STRUCTURE



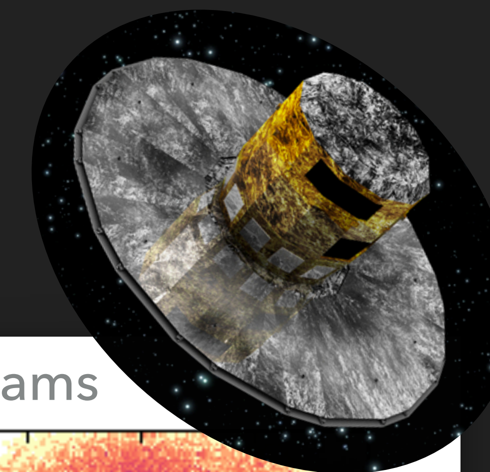
Phase-space of the disc in Gaia DR2



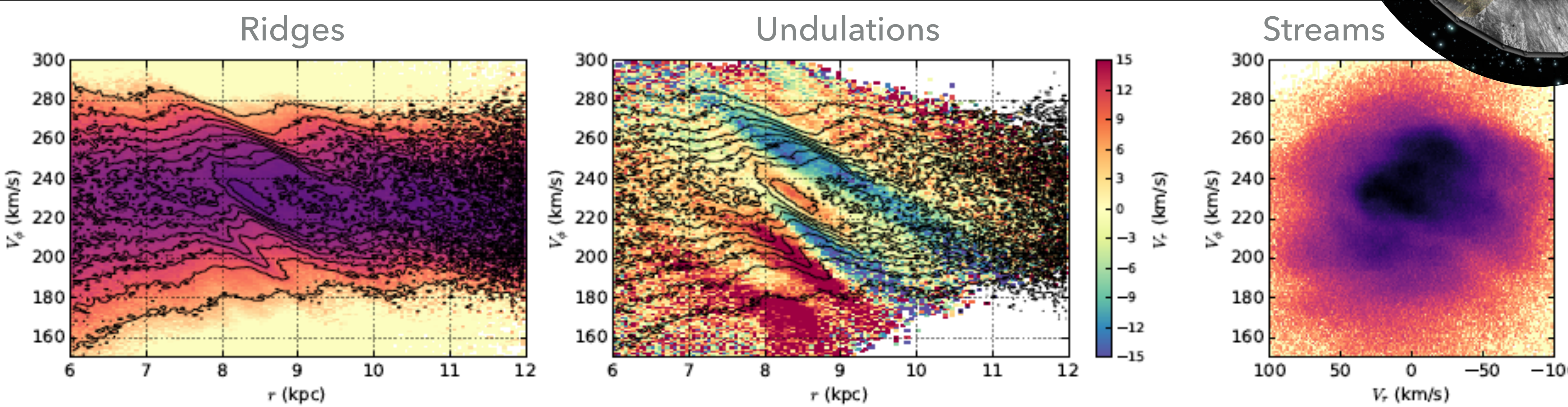
Fragkoudi et al. (submitted)

(see Kawata et al. 2018, Antoja et al. 2018, Ramos et al. 2018)

LINKING PHASE-SPACE TOPOGRAPHY TO UNDERLYING ORBITAL STRUCTURE



Phase-space of the disc in Gaia DR2

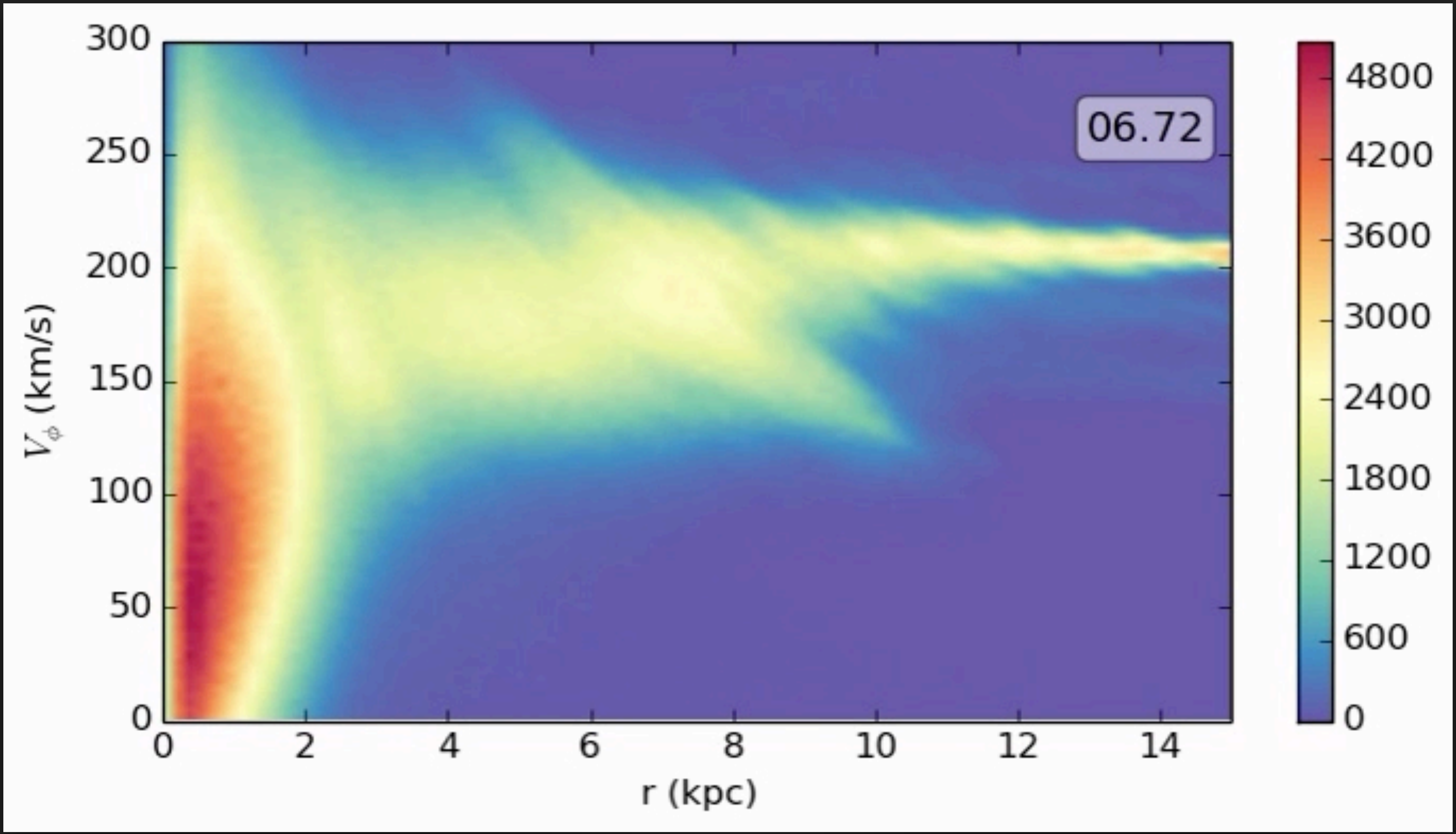


Fragkoudi et al. (submitted)

(see Kawata et al. 2018, Antoja et al. 2018, Ramos et al. 2018)

To understand the origin of the phase-space topography in the Milky Way disc we explore the phase-space substructures in our self-consistent N-body simulation and the underlying orbital structure which gives rise to it

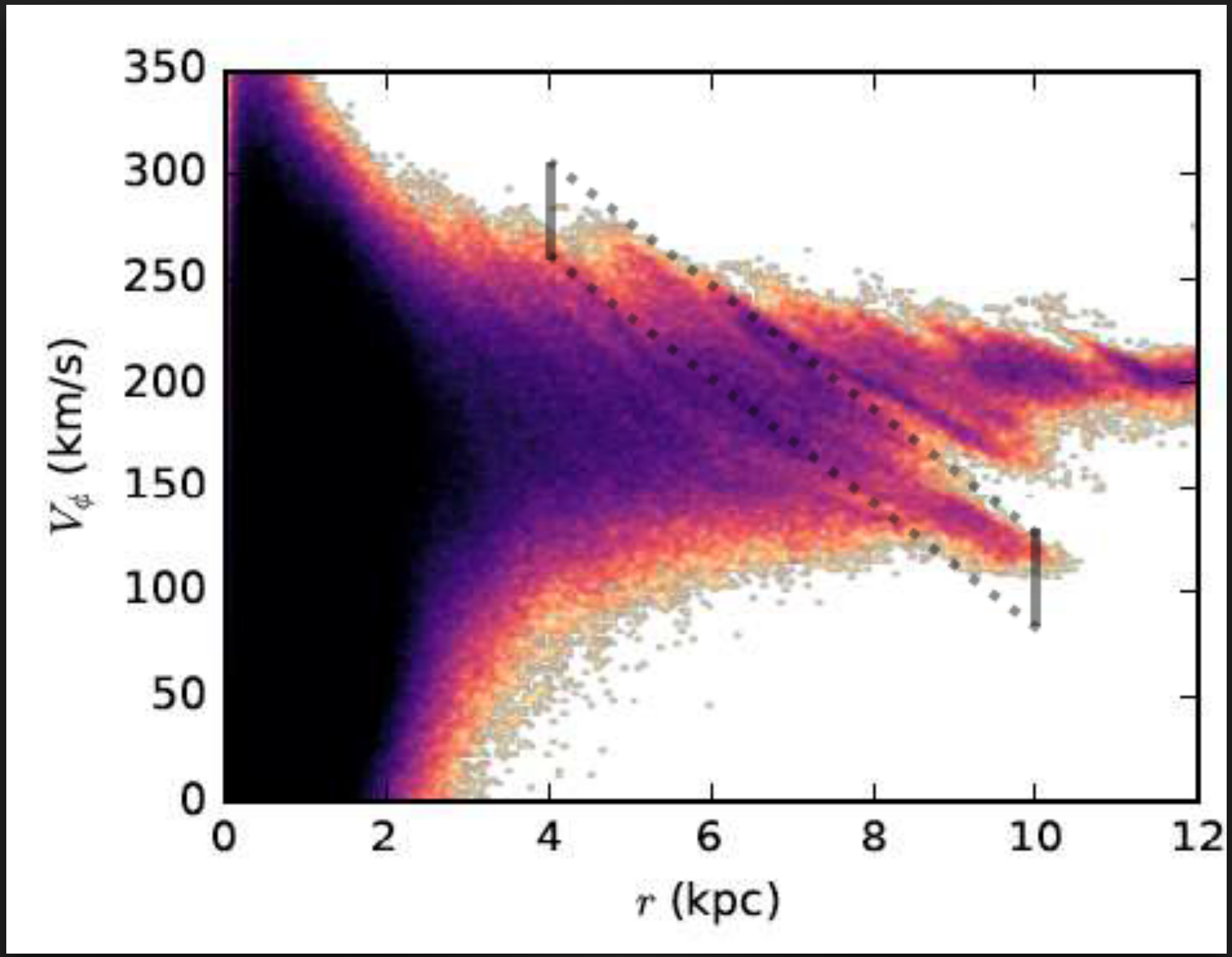
LINKING PHASE-SPACE TOPOGRAPHY TO UNDERLYING ORBITAL STRUCTURE



Fragkoudi et al. (submitted)

LINKING PHASE-SPACE TOPOGRAPHY TO UNDERLYING ORBITAL STRUCTURE

Ridge-like structures are formed due to non-axisymmetries



Fragkoudi et al. (submitted)

LINKING PHASE-SPACE TOPOGRAPHY TO UNDERLYING ORBITAL STRUCTURE

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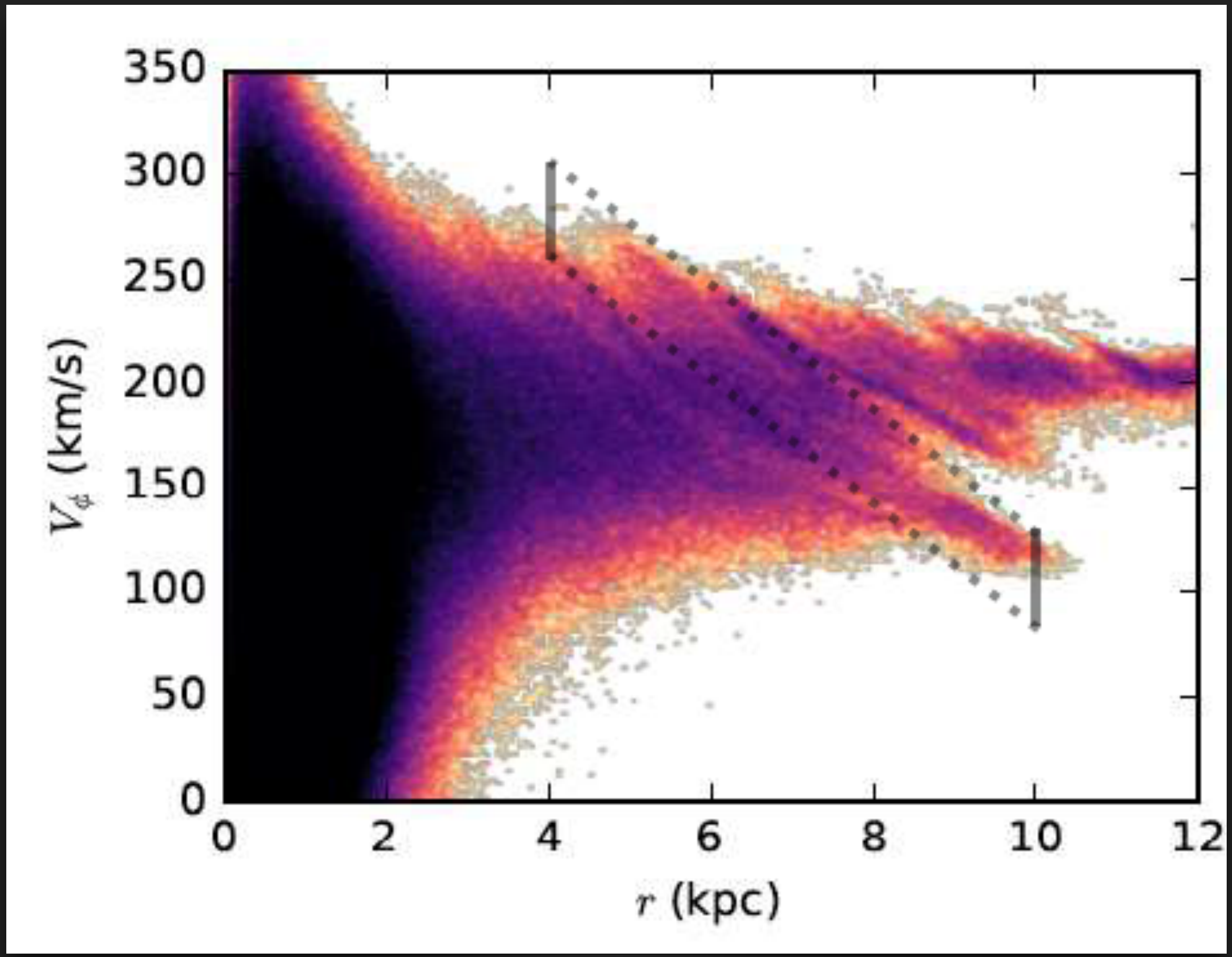
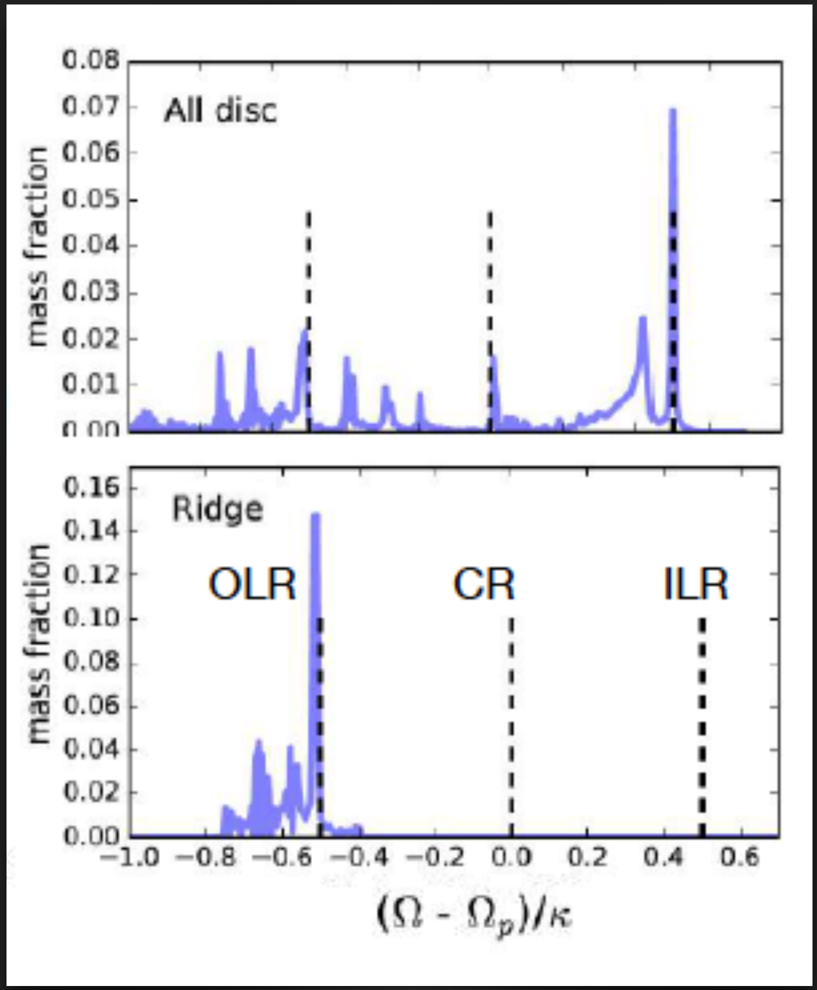


Spectral analysis of orbits



Fragkoudi et al. (submitted)

LINKING PHASE-SPACE TOPOGRAPHY TO UNDERLYING ORBITAL STRUCTURE

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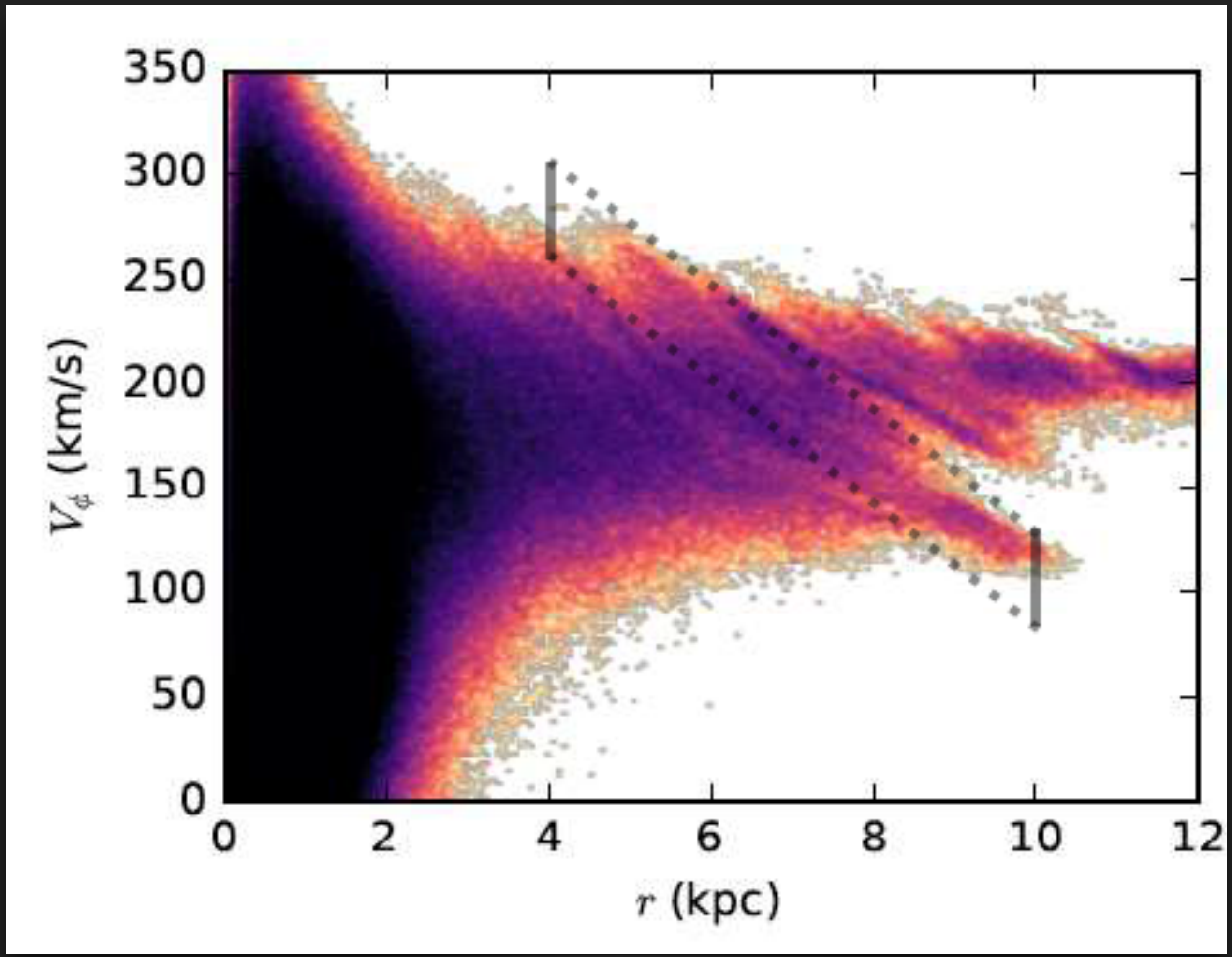

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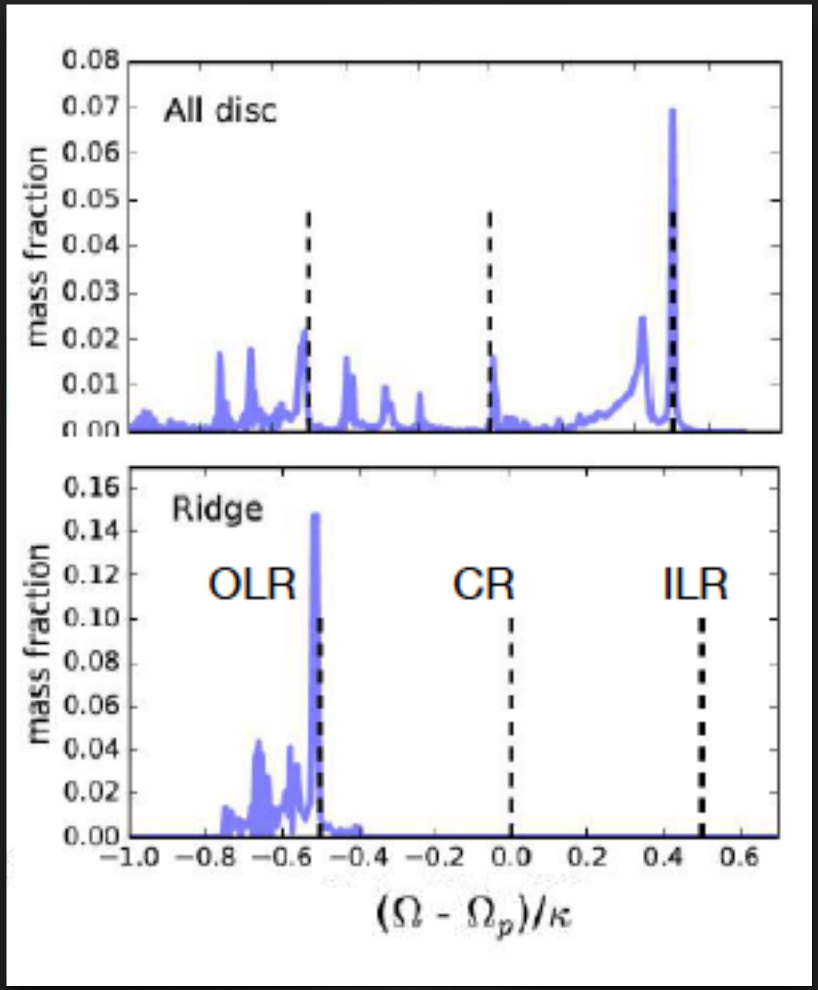
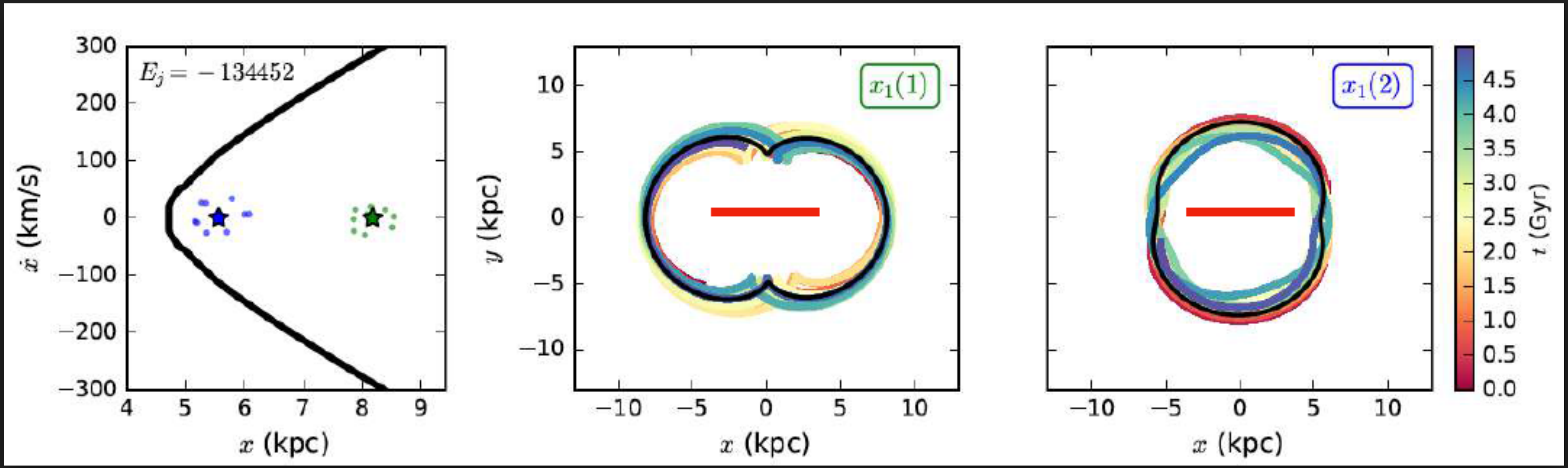


Longest ridge in V_φ - r plane associated to bar OLR orbits

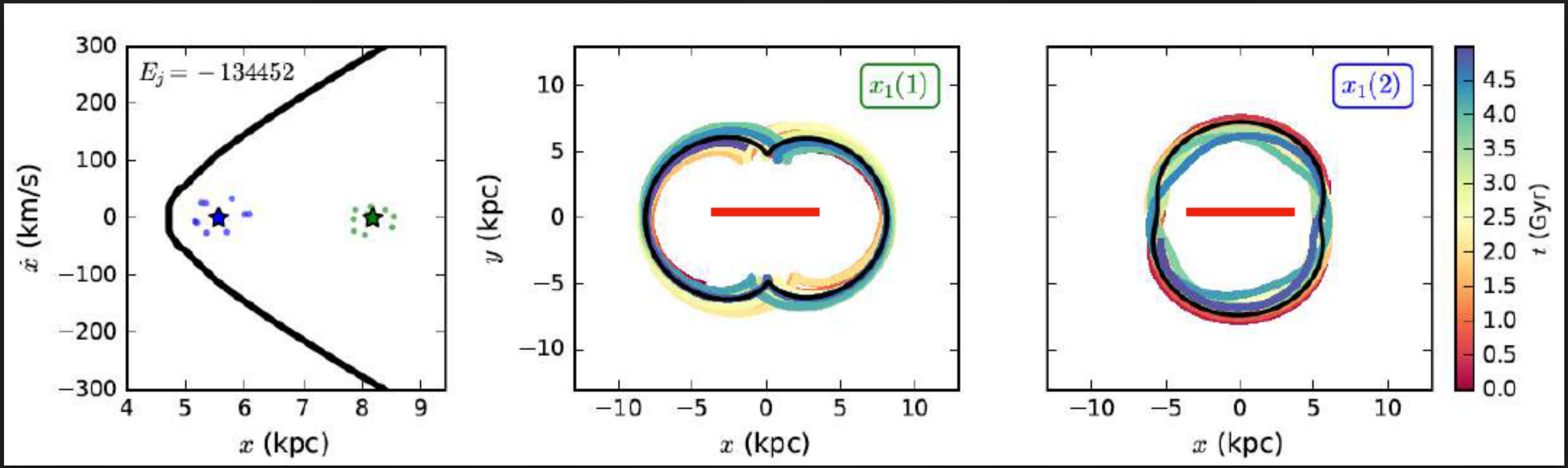
Fragkoudi et al. (submitted)

CLOSED PERIODIC AND TRAPPED LIBRATING ORBITS



At bar OLR have two main families of stable closed periodic orbits: x1(1) (aligned) and x1(2) (anti-aligned)

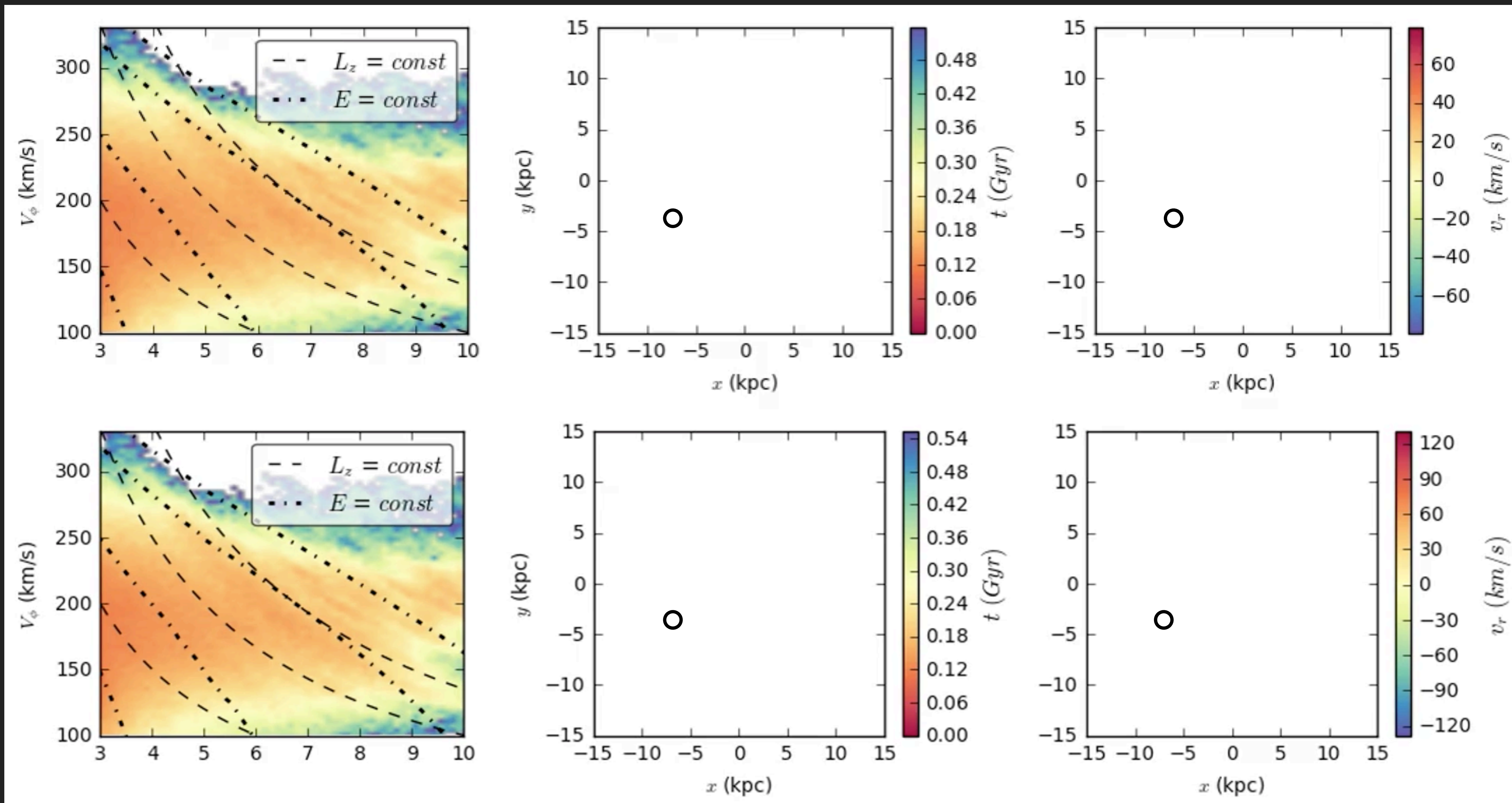
CLOSED PERIODIC AND TRAPPED LIBRATING ORBITS



At bar OLR have two main families of stable closed periodic orbits: x1(1) (aligned) and x1(2) (anti-aligned)

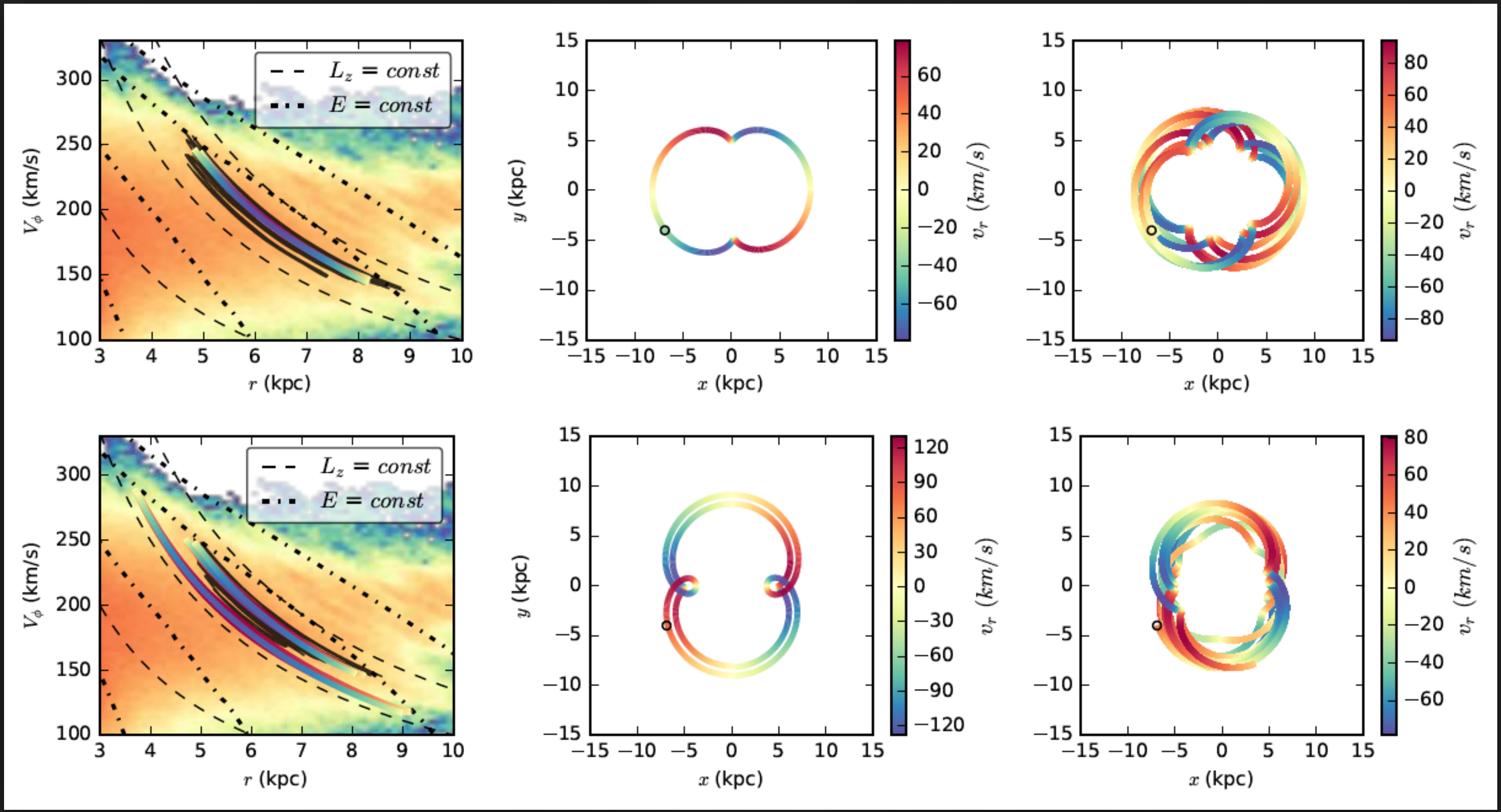
Stable closed periodic orbits trap around them librating orbits. Trapped orbits can have different libration amplitudes (distance from closed periodic orbit in phase-space)

LINKING PHASE-SPACE TOPOGRAPHY TO UNDERLYING ORBITAL STRUCTURE



Fragkoudi et al. (submitted)

LINKING PHASE-SPACE TOPOGRAPHY TO UNDERLYING ORBITAL STRUCTURE

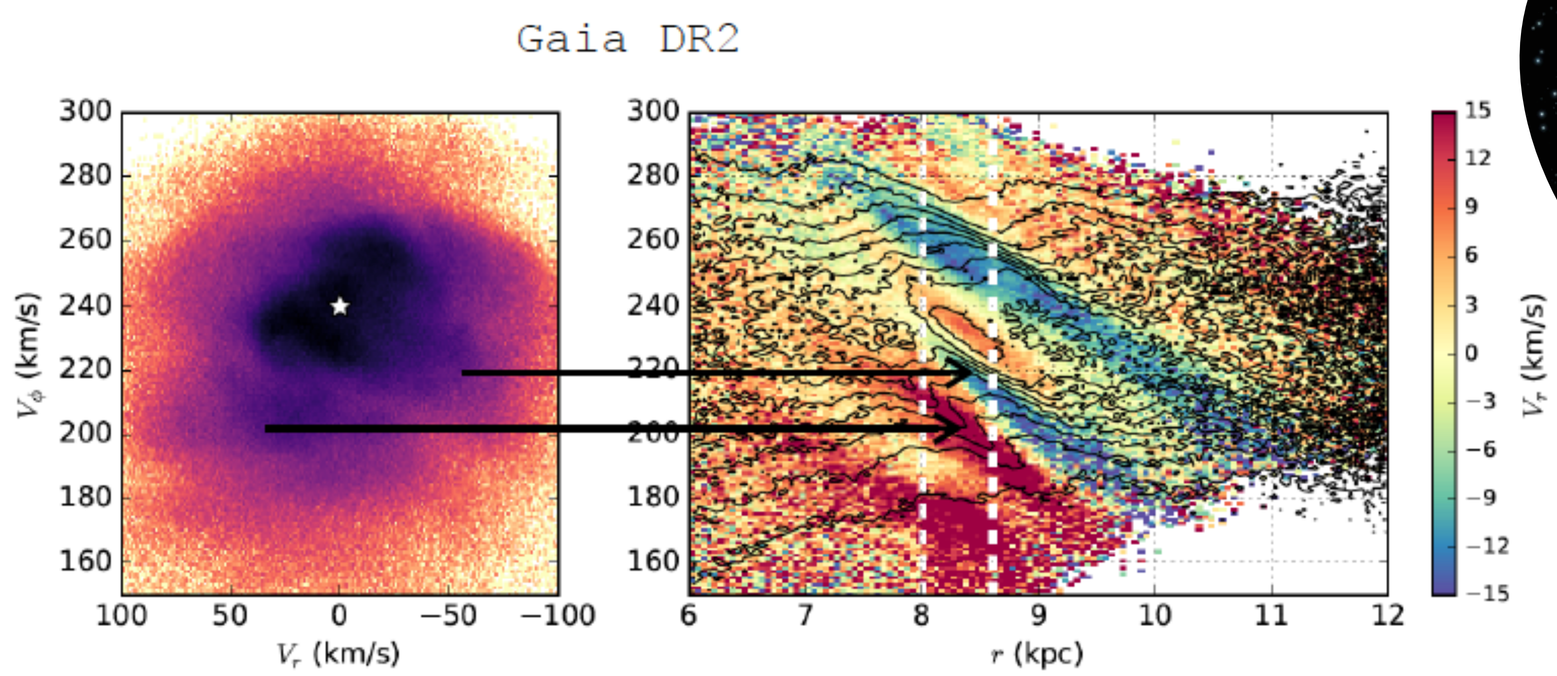


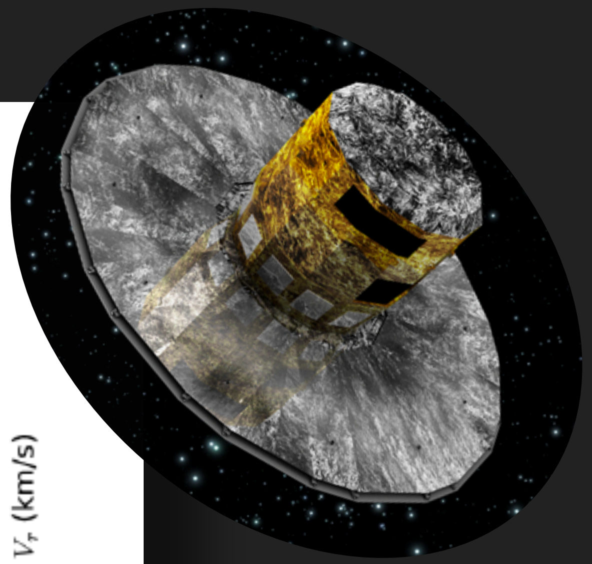
Small excursions in angular momentum and energy for OLR orbits

Ridges follow lines of constant energy and constant angular momentum

Fragkoudi et al. (submitted)

LINKING PHASE-SPACE TOPOGRAPHY TO UNDERLYING ORBITAL STRUCTURE

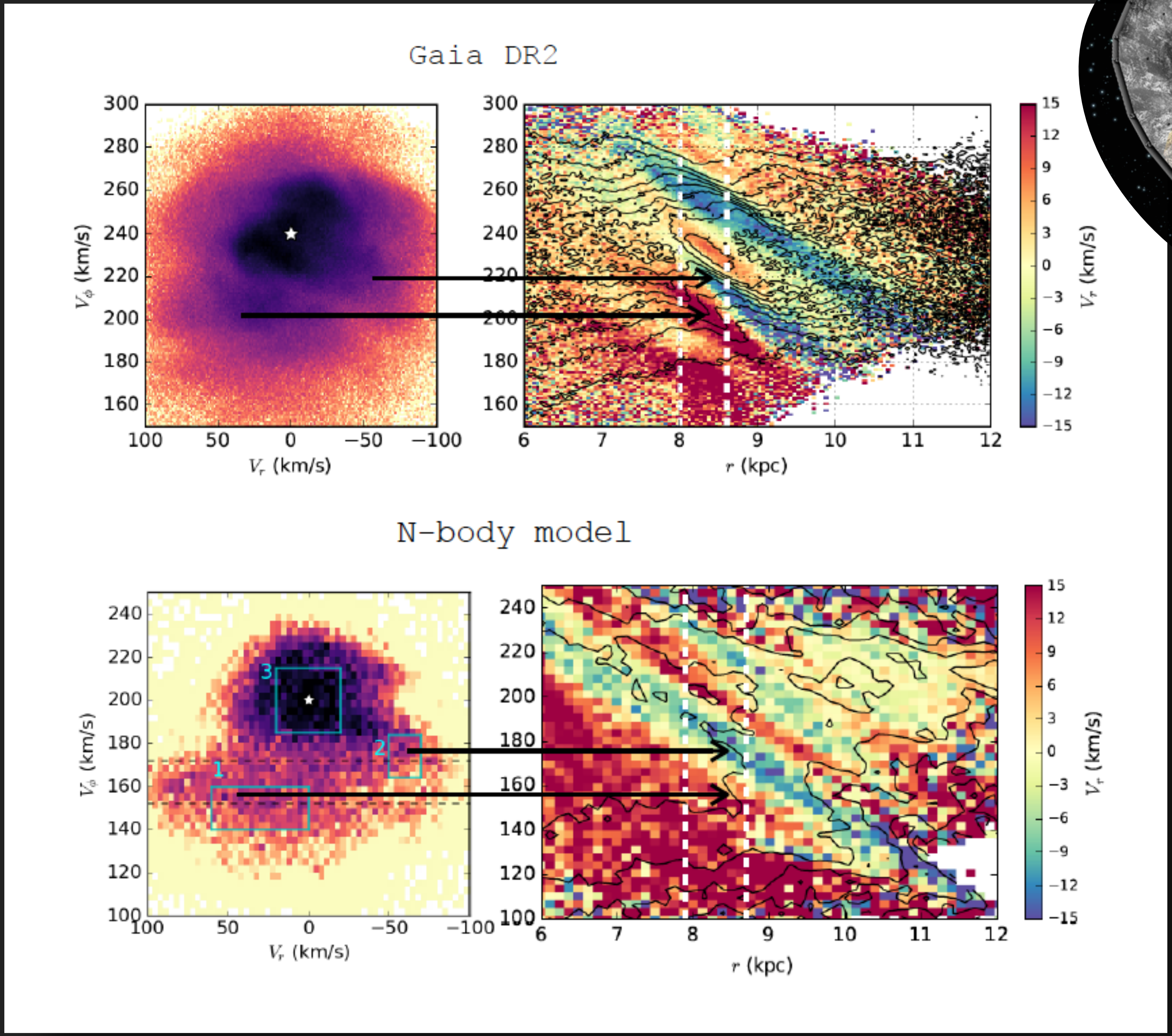


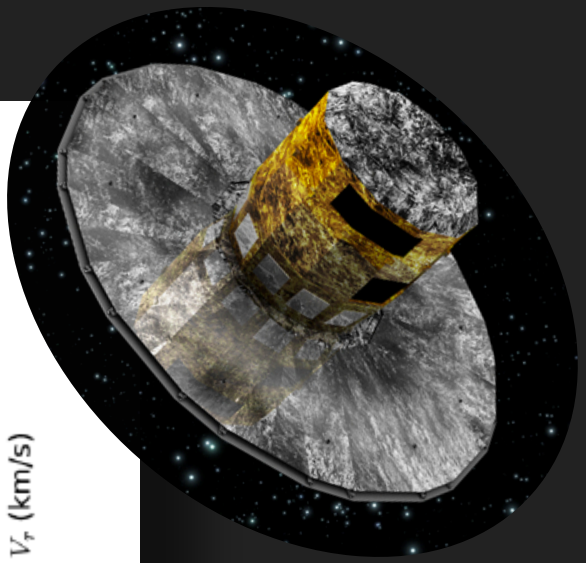


Correlation between ridges and Vr undulations

Fragkoudi et al. (submitted)

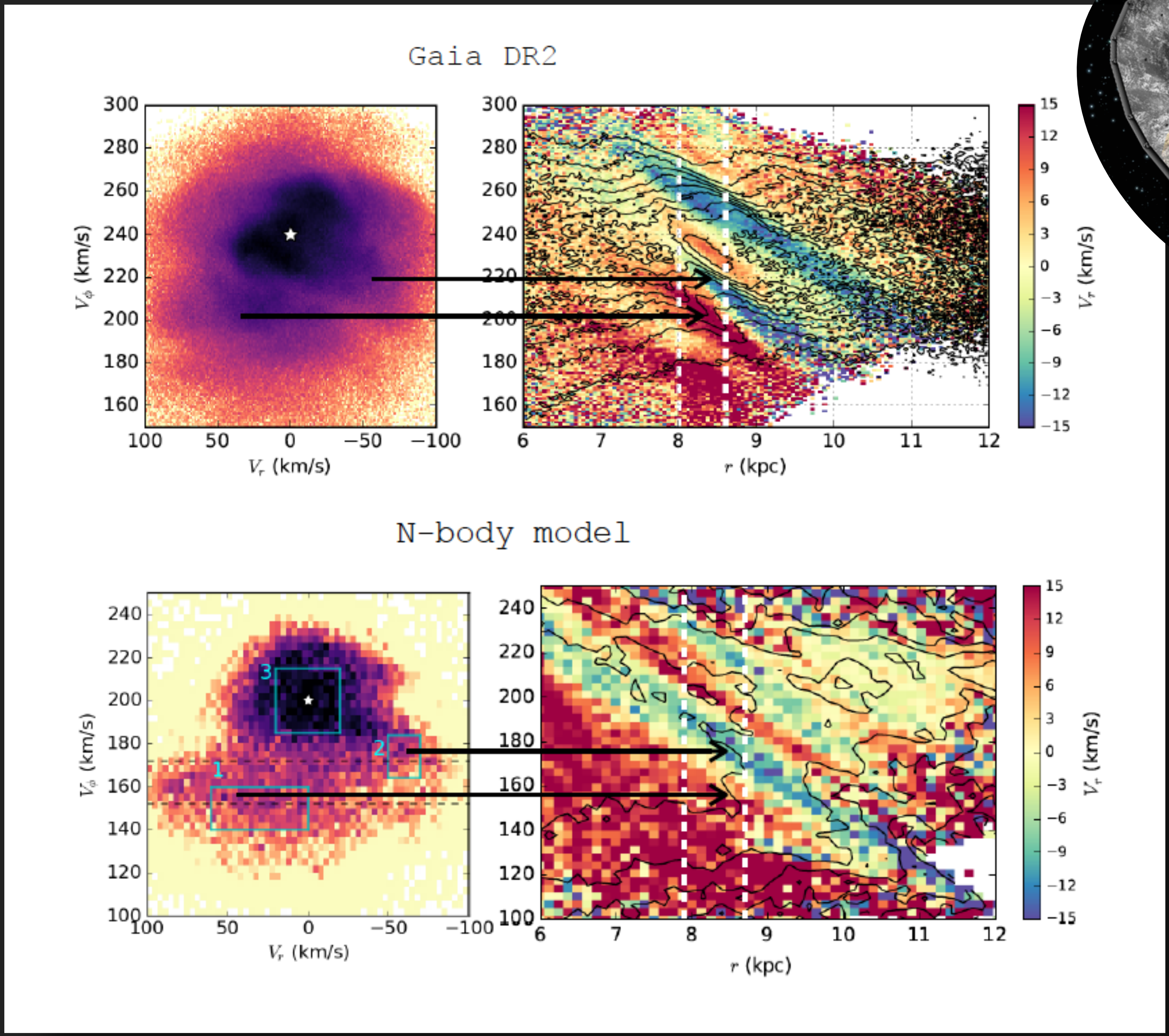
LINKING PHASE-SPACE TOPOGRAPHY TO UNDERLYING ORBITAL STRUCTURE

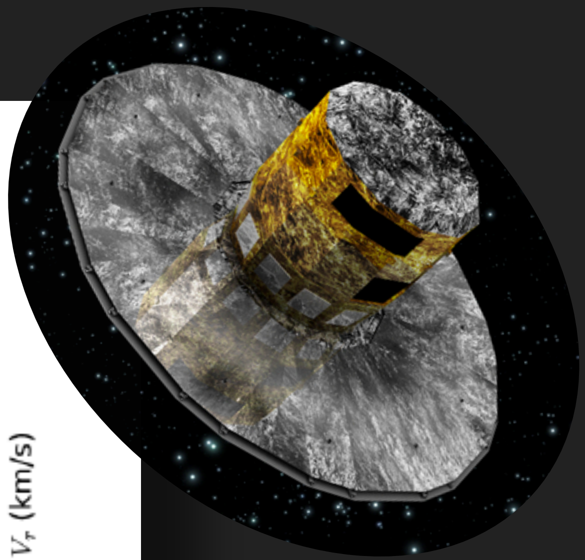




Fragkoudi et al. (submitted)

LINKING PHASE-SPACE TOPOGRAPHY TO UNDERLYING ORBITAL STRUCTURE





Fragkoudi et al. (submitted)

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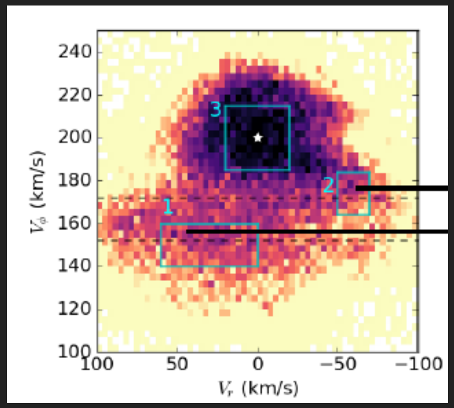
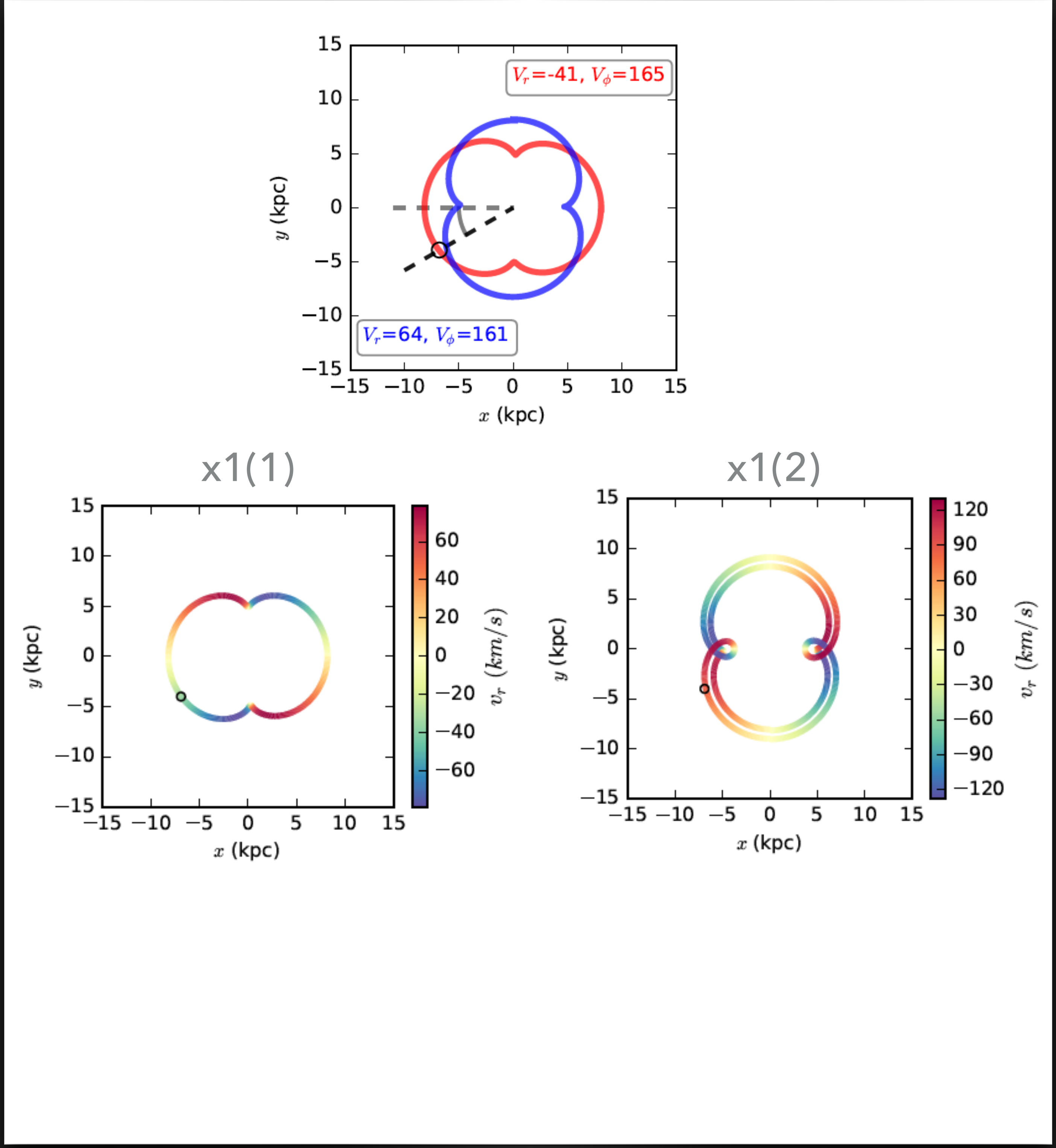
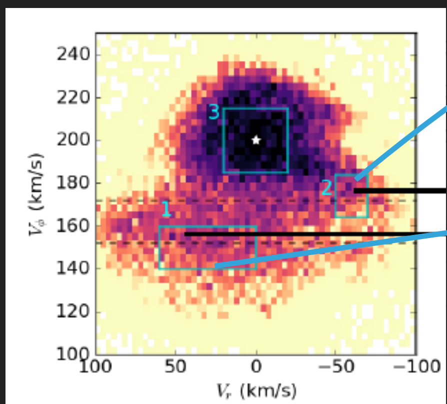


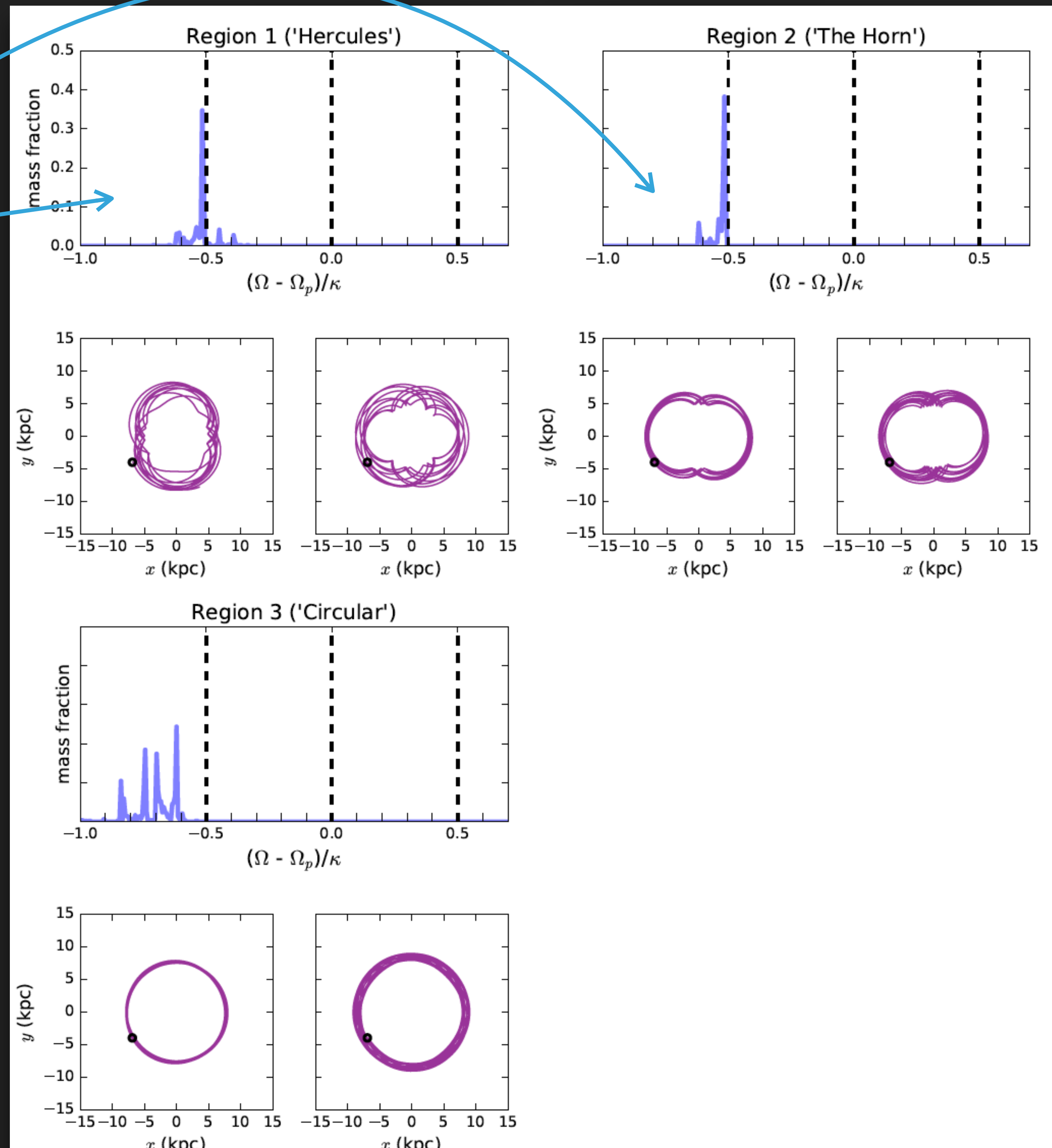


Dehnen (2000) associated Hercules stream to x1(2) orbits at the OLR (outwards moving)

LINKING PHASE-SPACE TOPOGRAPHY TO UNDERLYING ORBITAL STRUCTURE

Fragkoudi et al. (submitted)

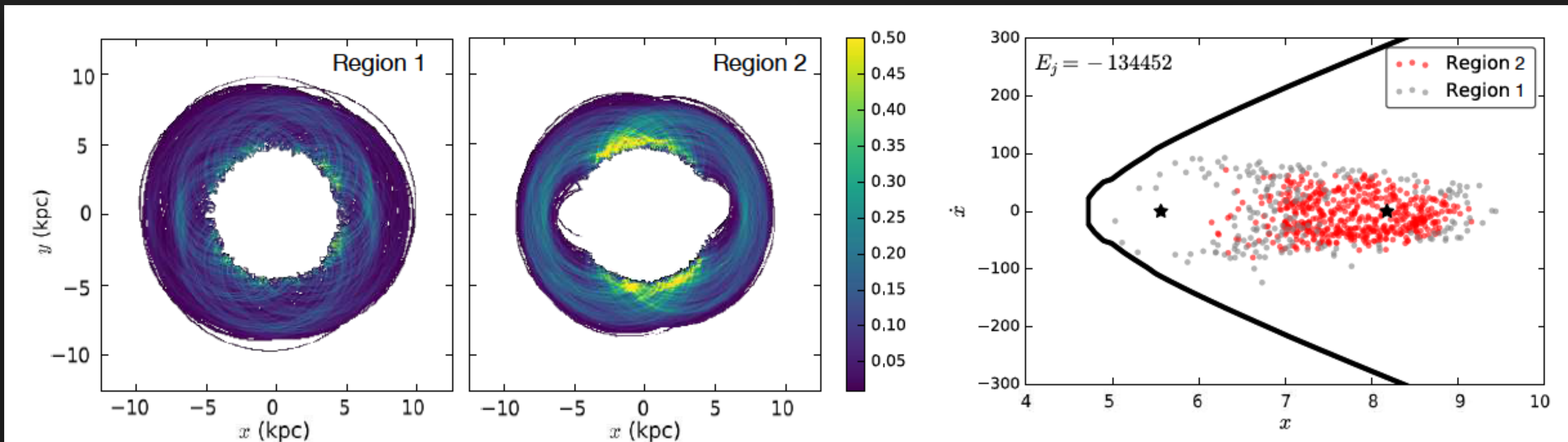




Hercules made from x1(2) type orbits but also highly librating x1(1) orbits.

`The horn' made from x1(1) orbits with small libration amplitudes

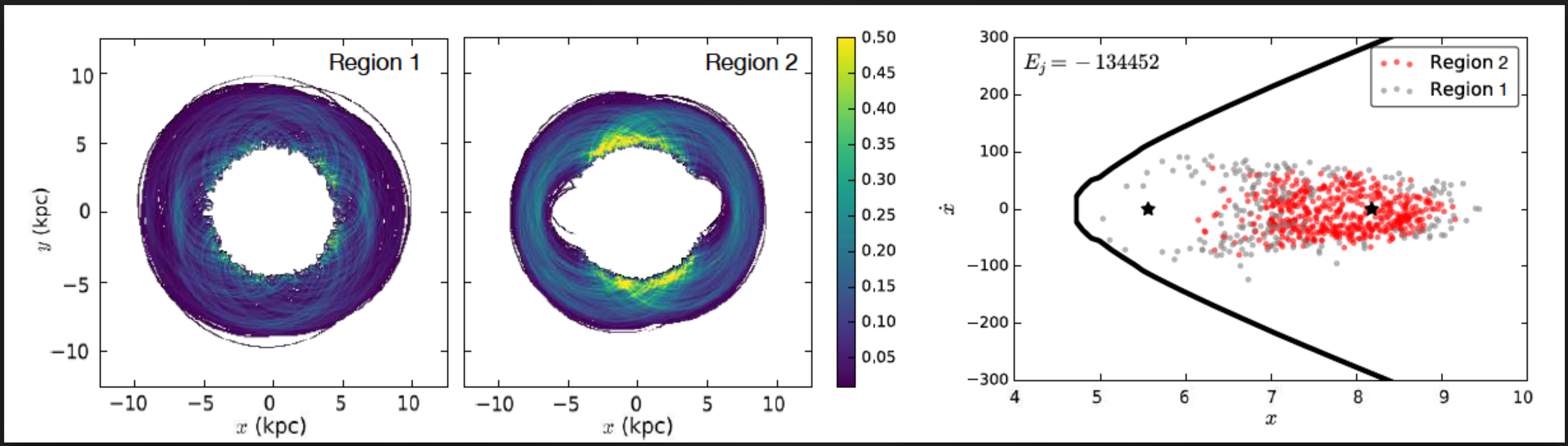
LINKING PHASE-SPACE TOPOGRAPHY TO UNDERLYING ORBITAL STRUCTURE

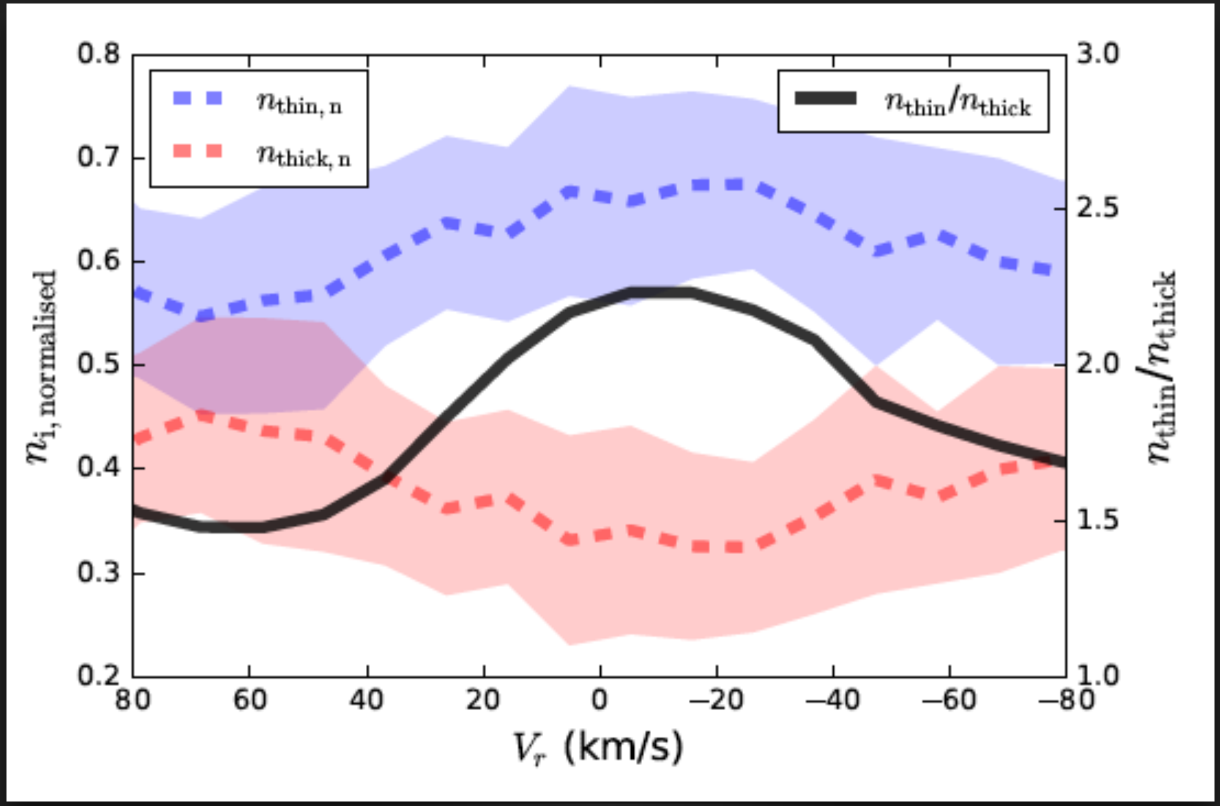


Orbits in Hercules and `the horn' have different libration amplitudes.

Fragkoudi et al. (submitted)

LINKING PHASE-SPACE TOPOGRAPHY TO UNDERLYING ORBITAL STRUCTURE



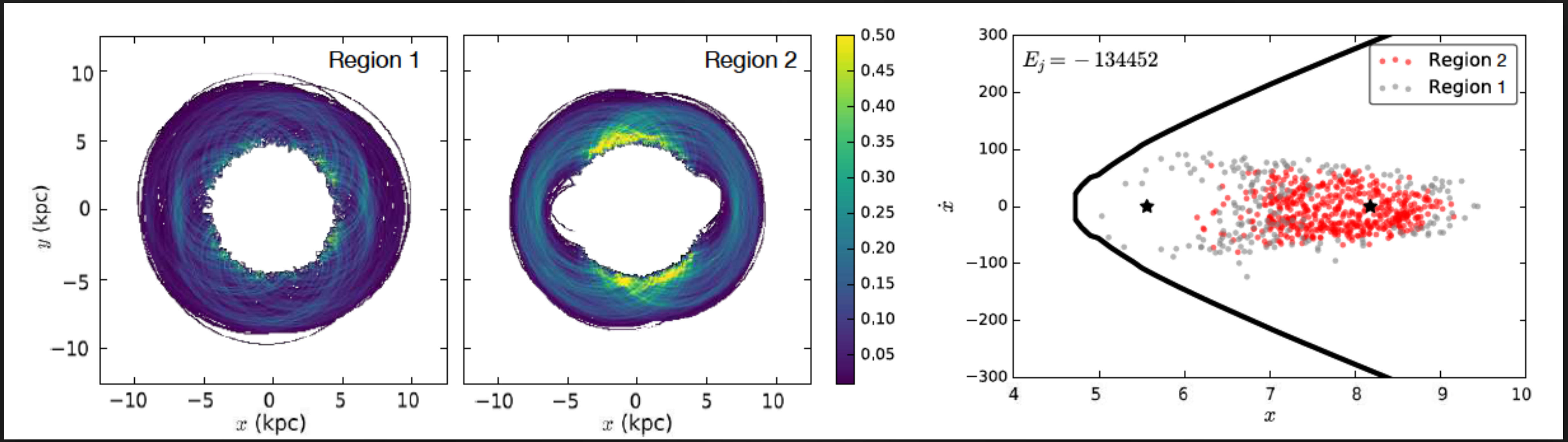


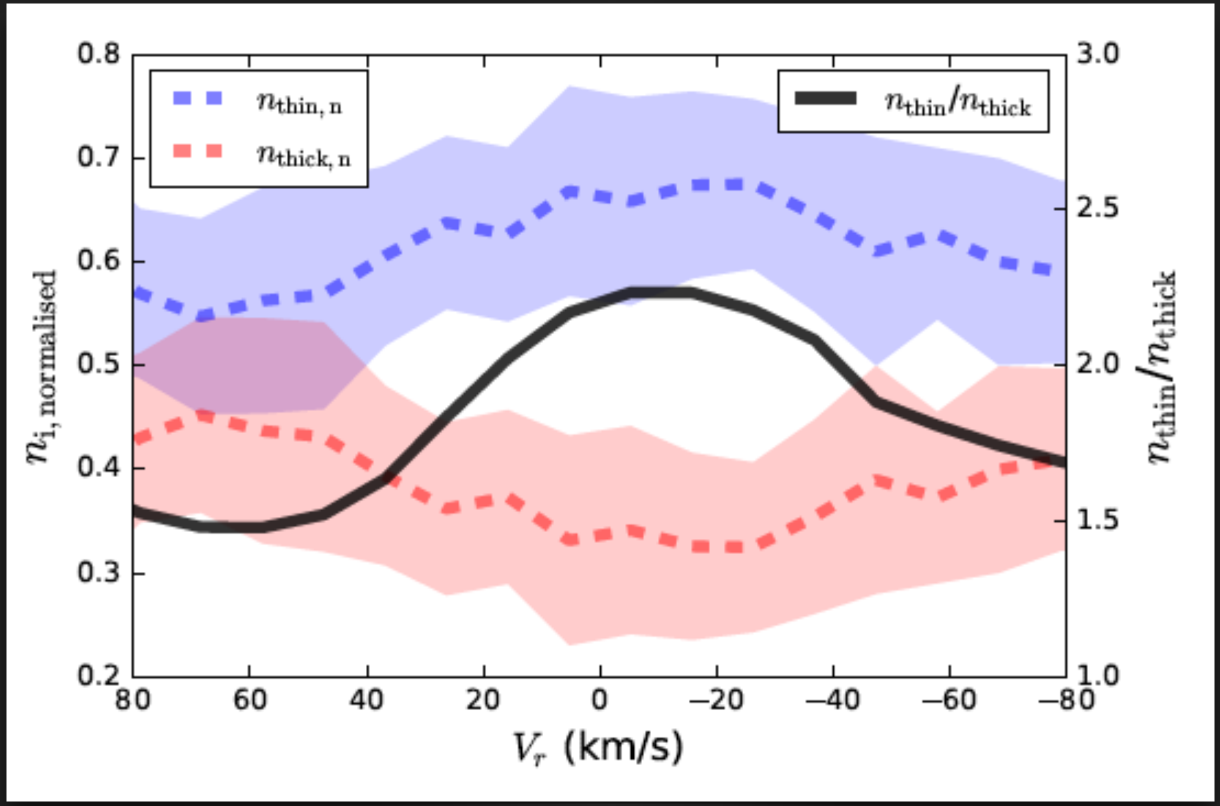
Orbits in Hercules and `the horn' have different libration amplitudes.

This could lead to difference in ratio of thin to thick disc stars in these regions

Fragkoudi et al. (submitted)

LINKING PHASE-SPACE TOPOGRAPHY TO UNDERLYING ORBITAL STRUCTURE





Orbits in Hercules and `the horn' have different libration amplitudes.

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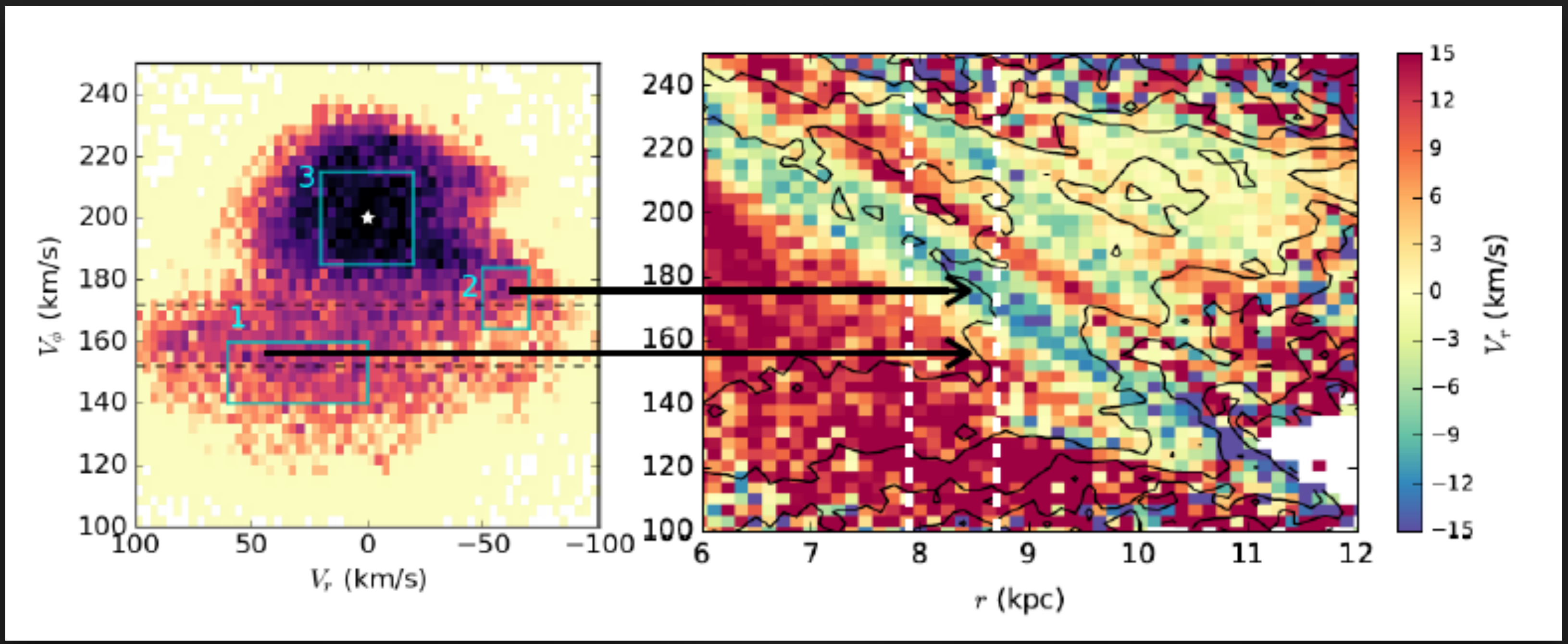
Can have implications on metallicity distribution in Vφ - Vr plane

Fragkoudi et al. (submitted)

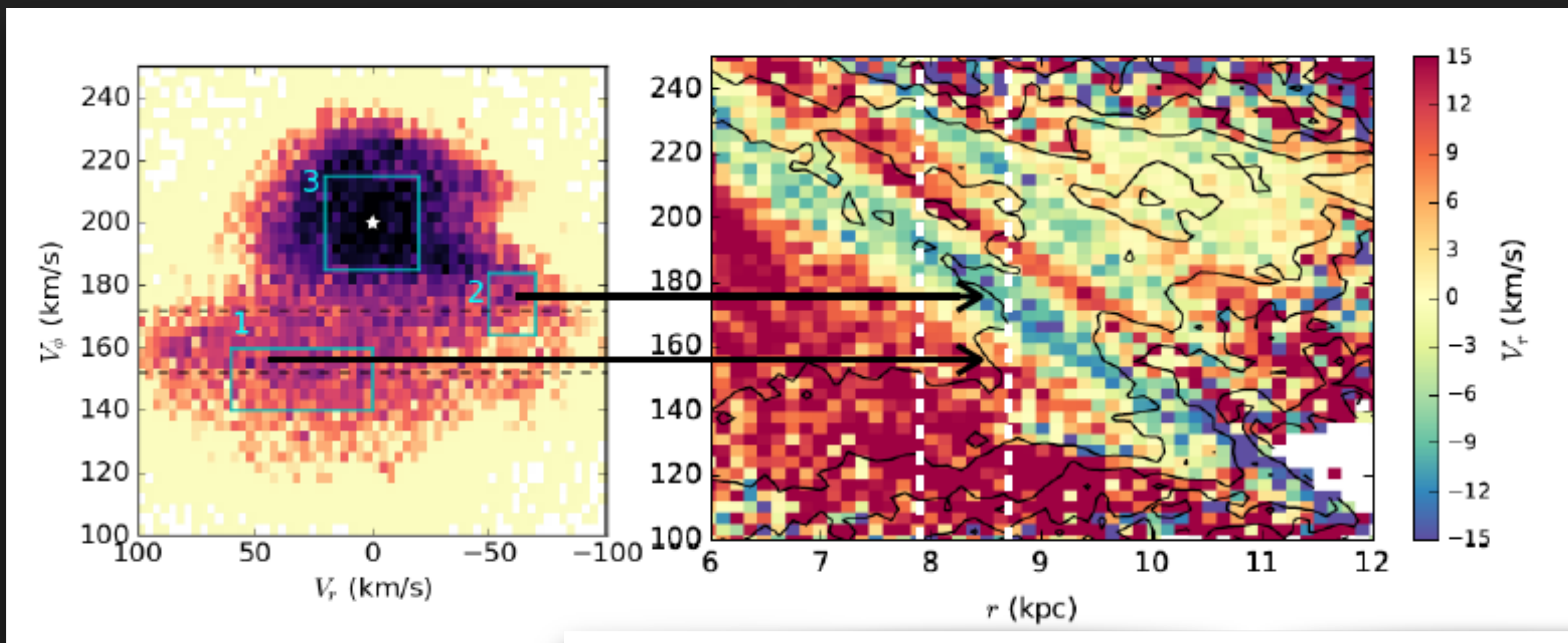
LINKING PHASE-SPACE TOPOGRAPHY TO UNDERLYING ORBITAL STRUCTURE



Short/fast bar (e.g. Dehnen 2000)

Fragkoudi et al. (submitted)

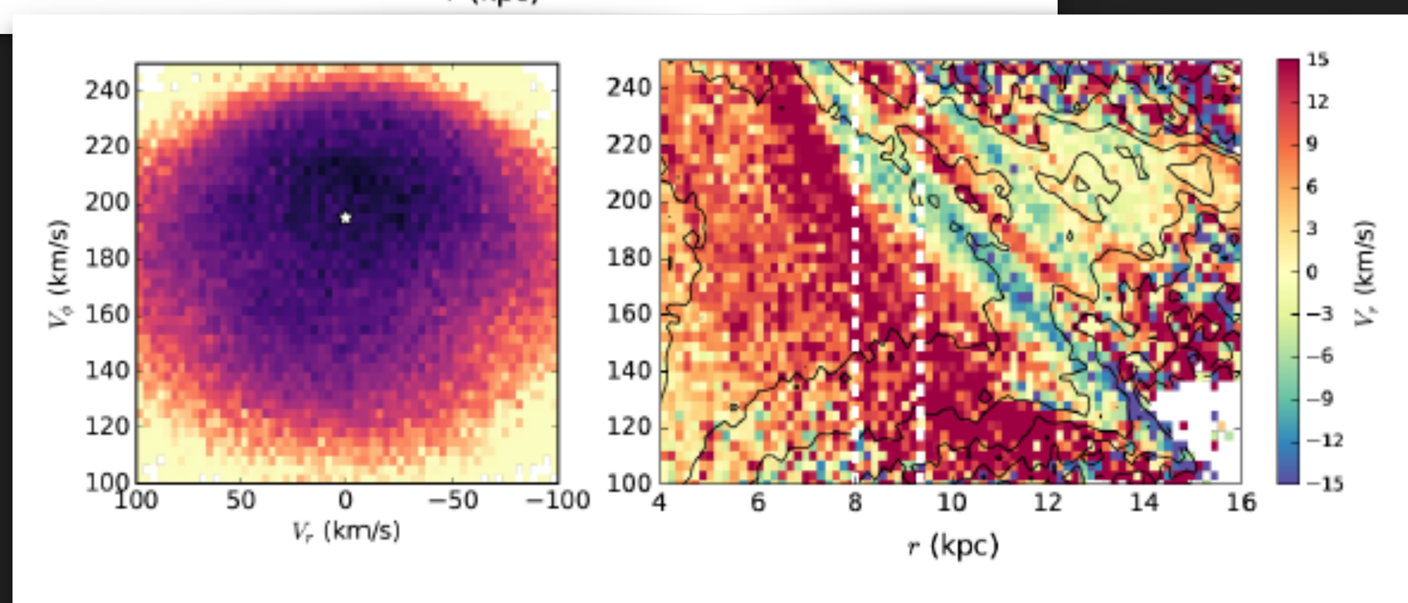
LINKING PHASE-SPACE TOPOGRAPHY TO UNDERLYING ORBITAL STRUCTURE

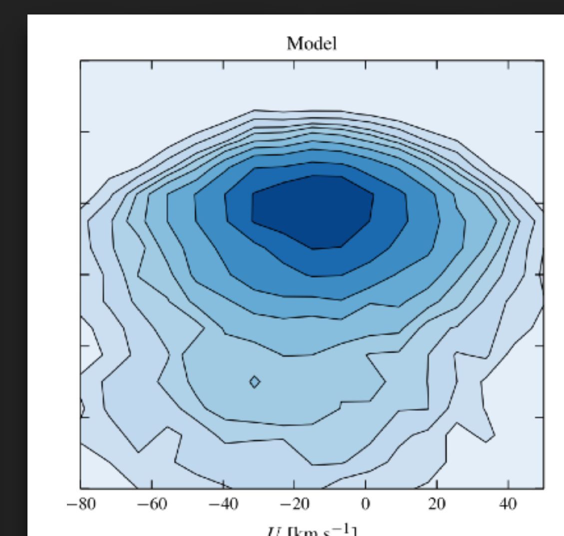


Short/fast bar (e.g. Dehnen 2000)

vs

Long/slow bar (e.g. Wegg+2015, Portail+2017, Perez-Villegas+2017)

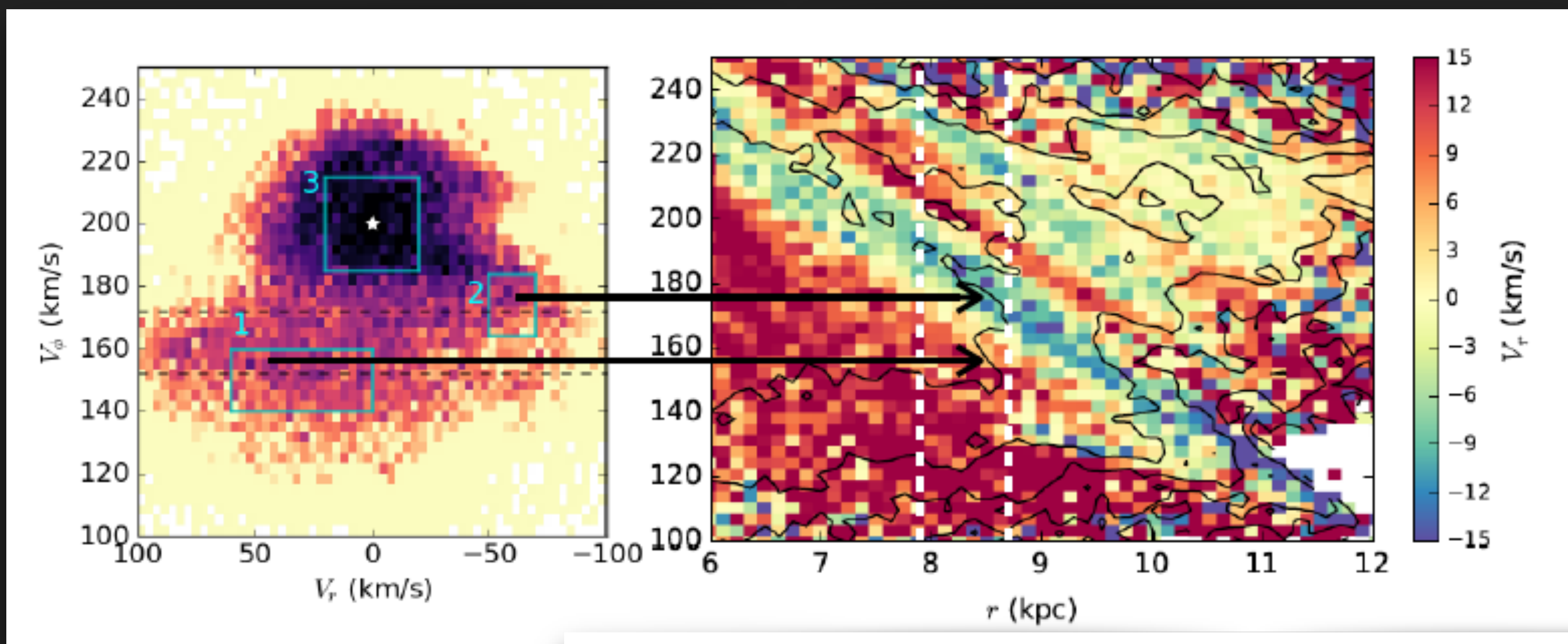




Perez-Villegas et al. (2017)

Fragkoudi et al. (submitted)

LINKING PHASE-SPACE TOPOGRAPHY TO UNDERLYING ORBITAL STRUCTURE



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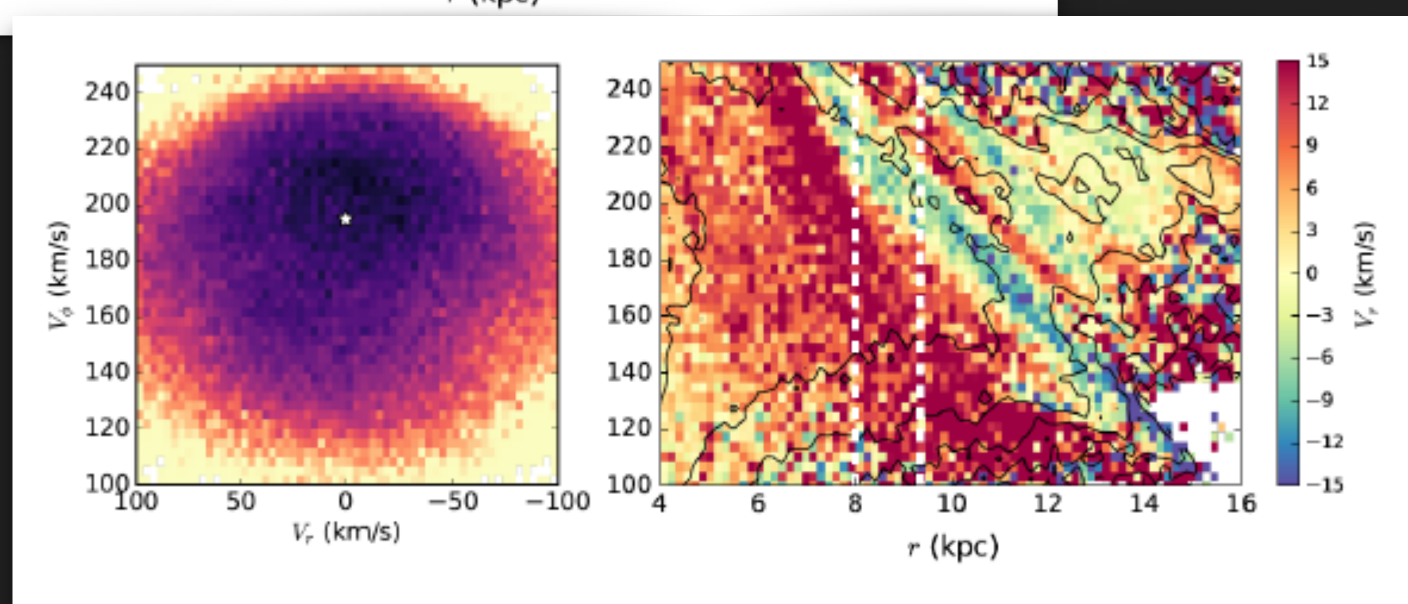
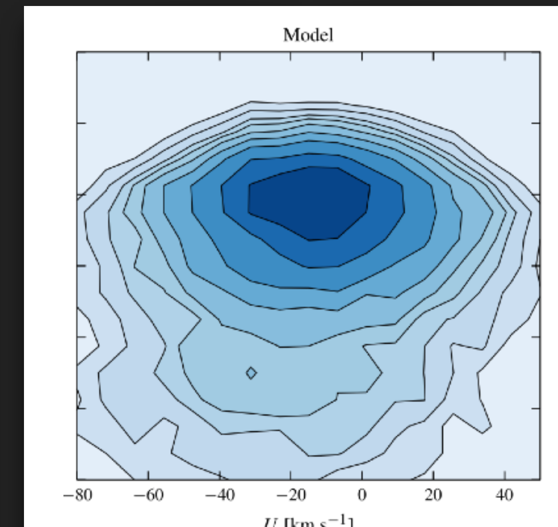




Perez-Villegas et al. (2017)

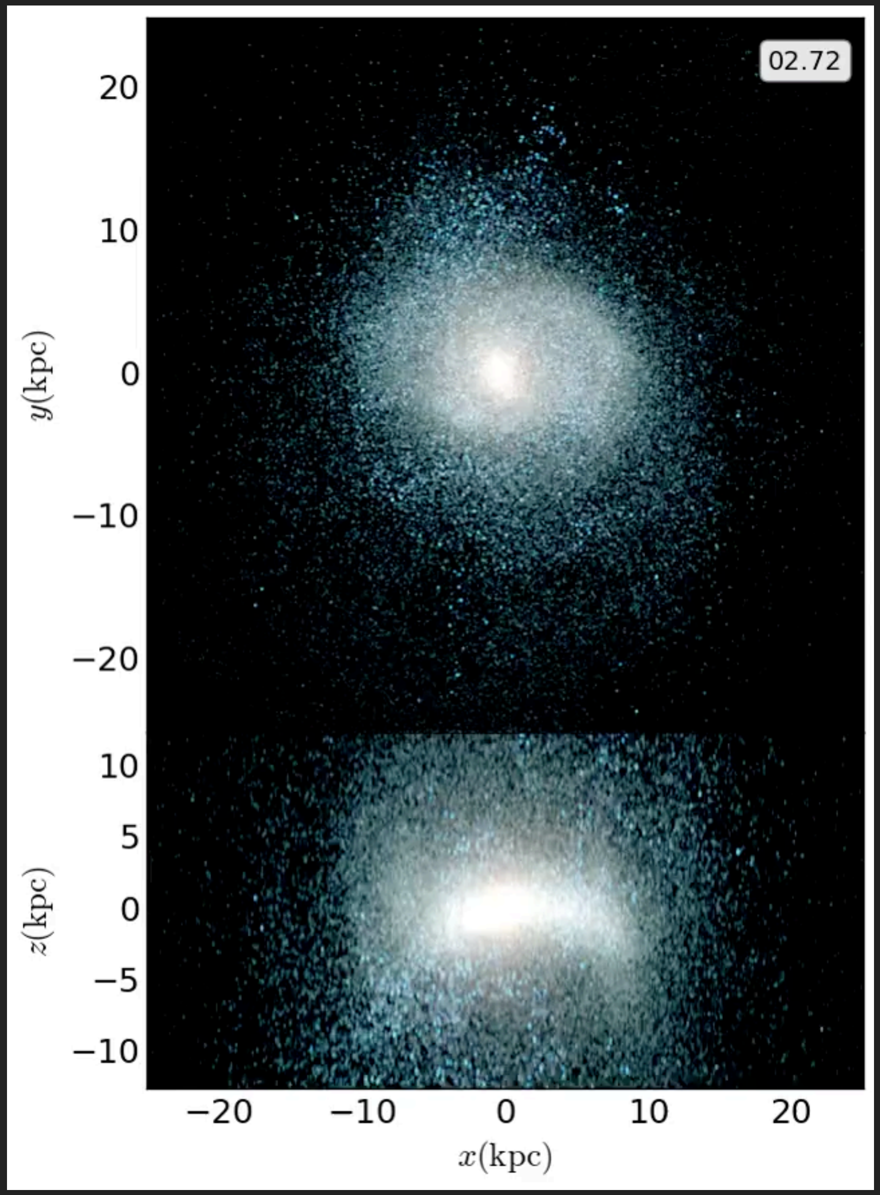
Model in which Sun is outside bar corotation i.e., slow/long bar scenario, does not reproduce Hercules/Horn asymmetry - would need some other mechanism to produce it (e.g. spirals or m=4, e.g. Hunt et al. 2018, Hunt & Bovy 2018)

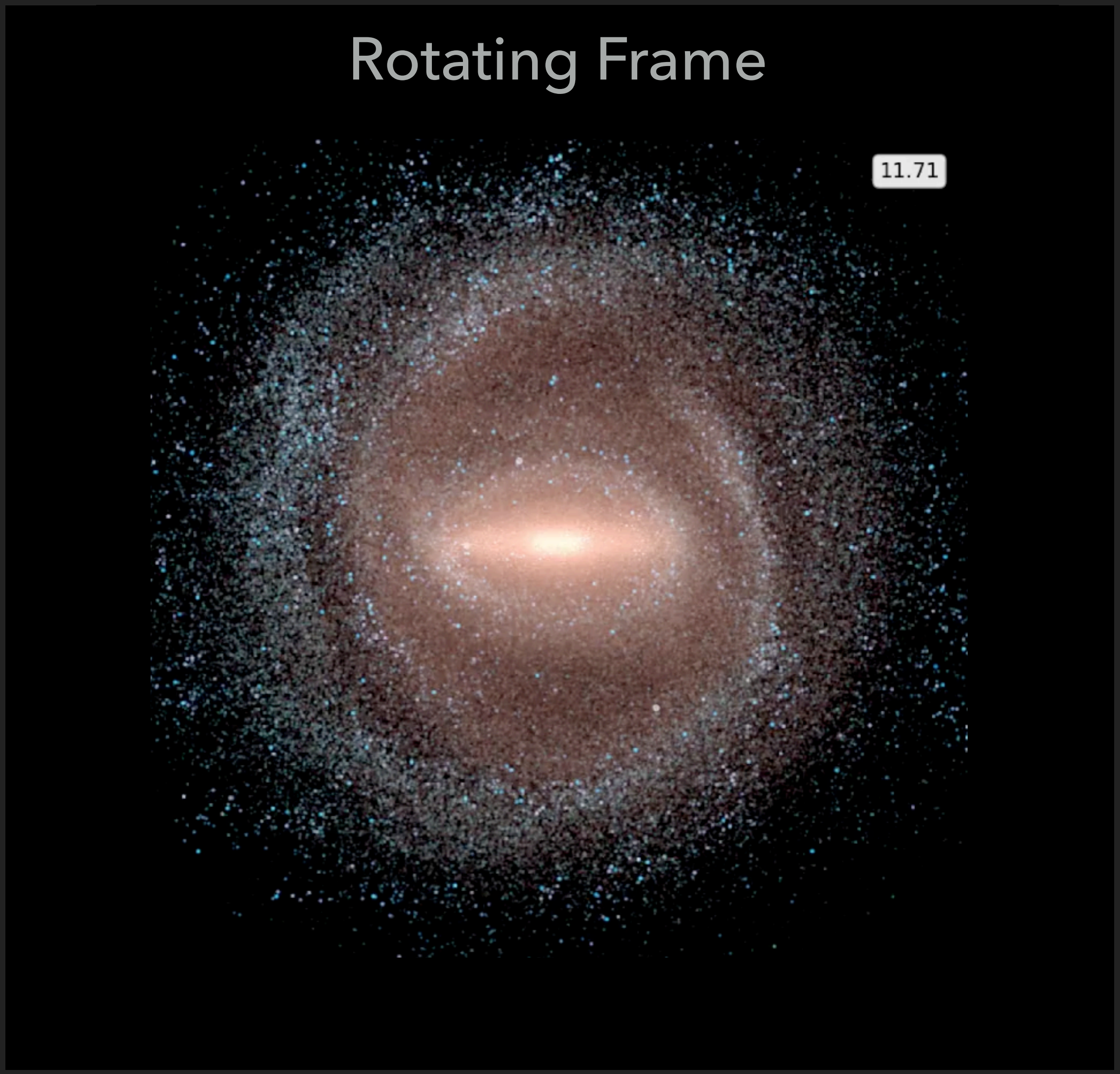
Fragkoudi et al. (submitted)

OUTLINE

- Introduction
- The bulge-bar connection in the Milky Way
- The disc-bar connection in the Milky Way
- Summary and thoughts for future

GALAXY DYNAMICS IN THE COSMOLOGICAL CONTEXT





Study secular processes (bar formation, peanut formation, orbital resonances in the disc) in full cosmological context

Fragkoudi et al. in prep.

SUMMARY

- Milky Way bulge is compatible with a pure thin+thick disc (in situ) origin (morphology, kinematics, chemistry)
  - Hotter, metal-poor populations have weaker peanut and bar morphology (rounder)
  - Hotter, metal-poor populations can have slightly higher los velocities at edge of peanut
  - Can reproduce bulge abundances maps and MDF in different fields with thin+thick disc model

Fragkoudi+17b, A&A, 606, A47

Gómez, Di Matteo, Schultheis, FF+18

Fragkoudi+17c, A&A, 607, L4

Fragkoudi+18, A&A, 616, 180

- Gaia DR2 revealed complex in-plane phase-space substructures. Bar-induced resonances give rise to ridges and undulations in phase-space
  - The longest ridge in V_φ-r plane is due to bar OLR
  - Undulations in V_r are caused by bar OLR (x1(1) and x1(2) orbits) - produce Hercules and `the horn'
  - Difference in libration amplitudes of orbits in Hercules and the horn can lead to different thin/thick disc ratio and therefore metallicity distribution in V_φ-V_r plane
  - Slow/long bar model cannot produce Hercules/Horn asymmetry - would need some other mechanism (spirals? m=4?)

Fragkoudi+19 (arXiv:1901.07568)

Merci - ευχαριστώ

- Galaxy dynamics (bar/peanut formation) in the full cosmological context

Fragkoudi+in prep.