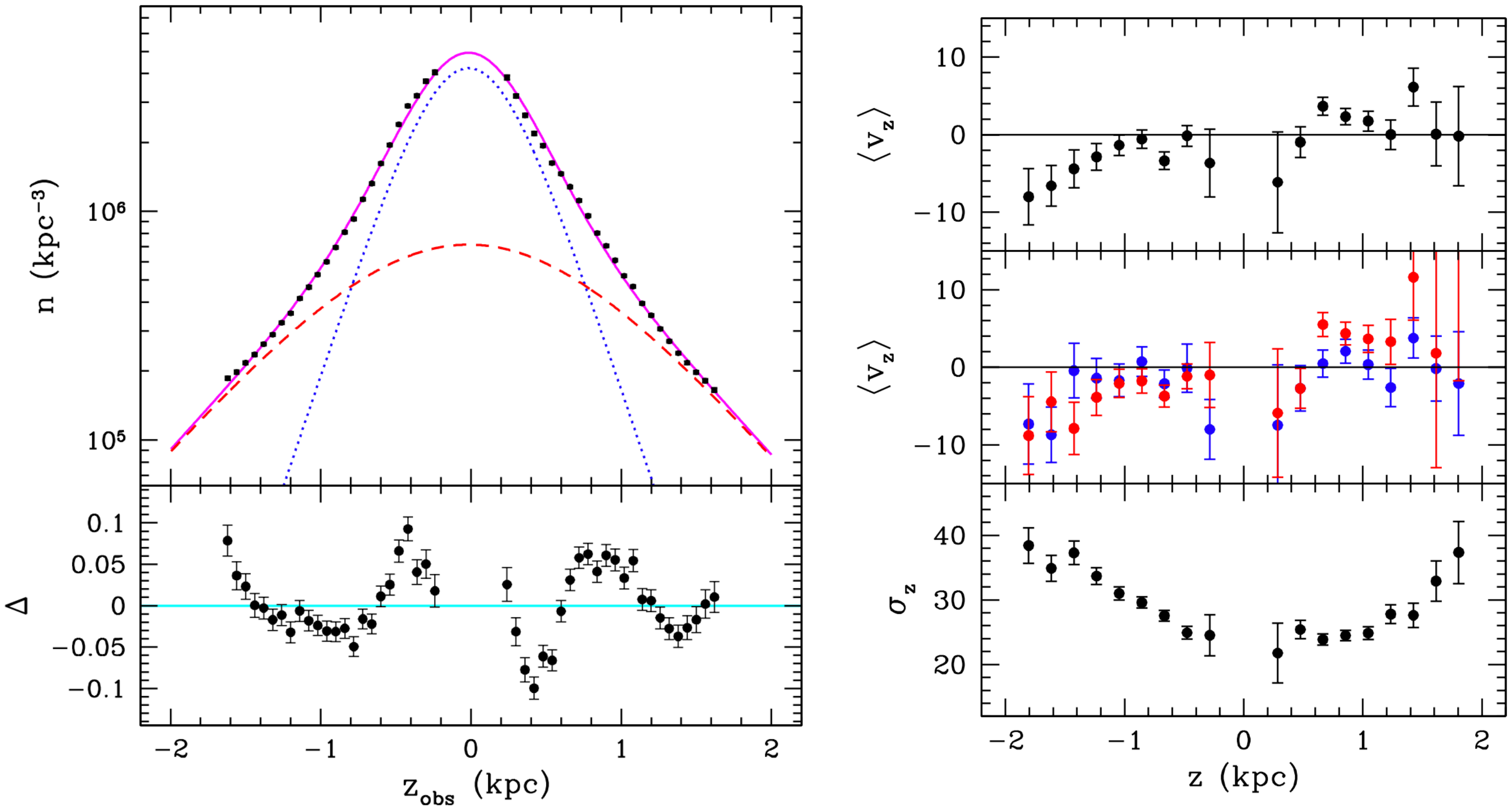
Outline

1. **INTRODUCTION**

2. **KINEMATICS OF THE GALACTIC DISK**

3. **NON-EQUILIBRIUM SIGNATURES OF THE MERGING HISTORY OF THE GALAXY**
   1. Pre-Gaia observations: vertical density and velocity asymmetries, corrugations, bending and breathing modes
   2. Gaia data: spirals in the Z-Vz plane
   3. The origin of the phase spiral:
      1. phase-mixing
      2. Modelling of the spirals, Miyamoto-Nagai potential, realistic vertical frequencies
      3. Timing the perturbation event
      4. Sagittarius dwarf: prime suspect, N-body modelling, impulse approximation
      5. Alternative interpretations: bar’s buckling, bending waves
   4. Other discovered past events
   5. Conclusions & Future perspectives

Pre-Gaia observations: vertical density and velocity asymmetries, corrugations, bending and breathing modes

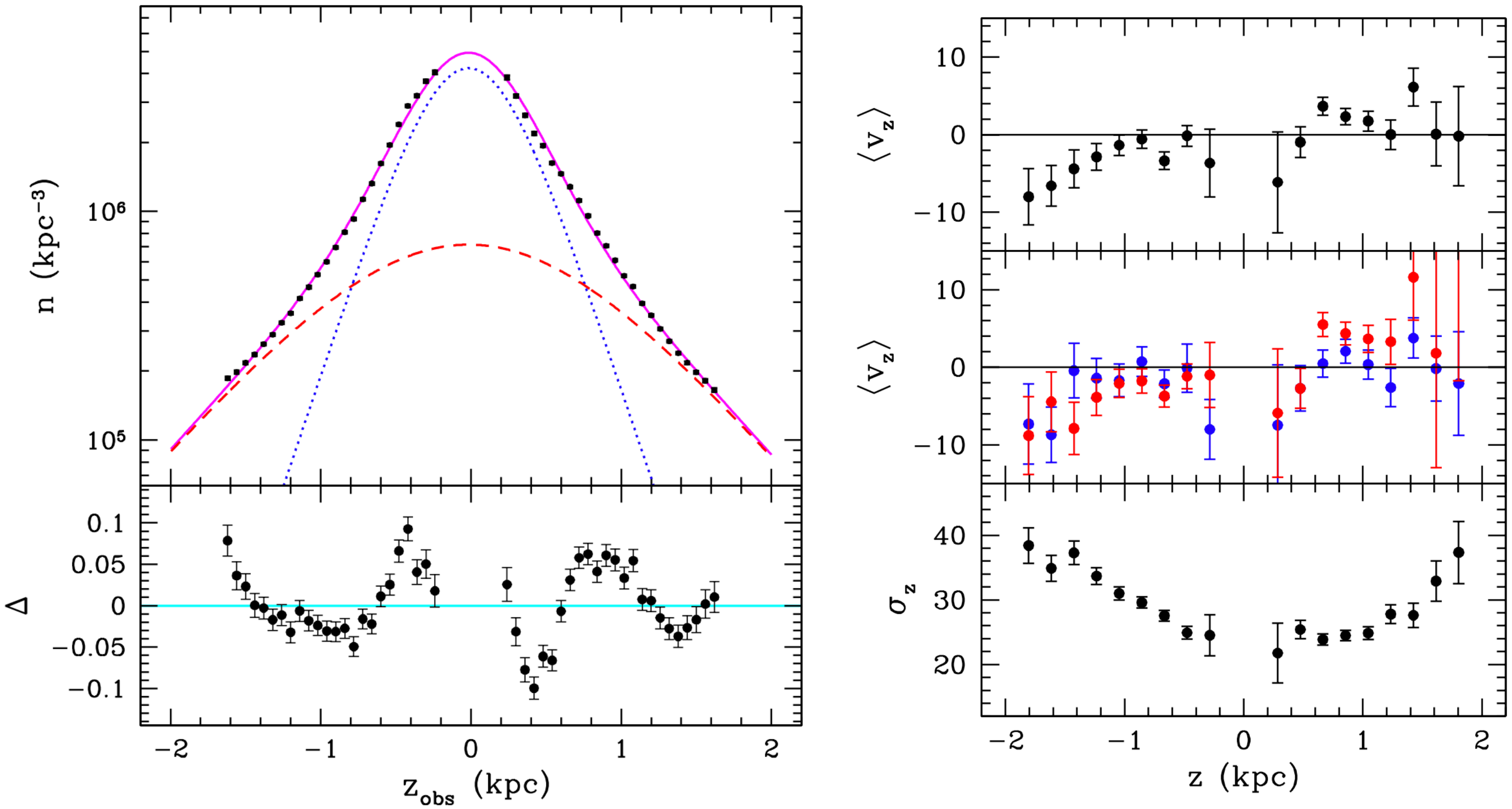


Widrow et al. 2012

SDSS

asymmetry in the vertical number density & velocity

Pre-Gaia observations: vertical density and velocity asymmetries, corrugations, bending and breathing modes



SDSS

asymmetry in the vertical number density & velocity

Widrow et al. 2012

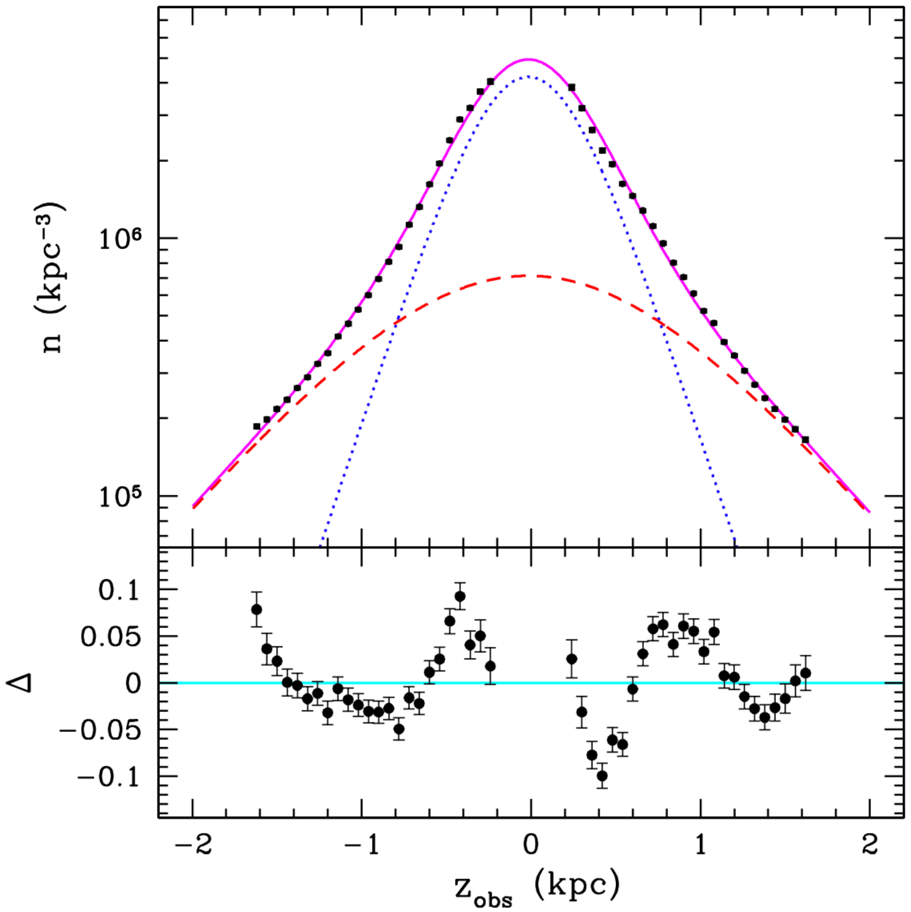
Bending mode: vertical movement of the midplane

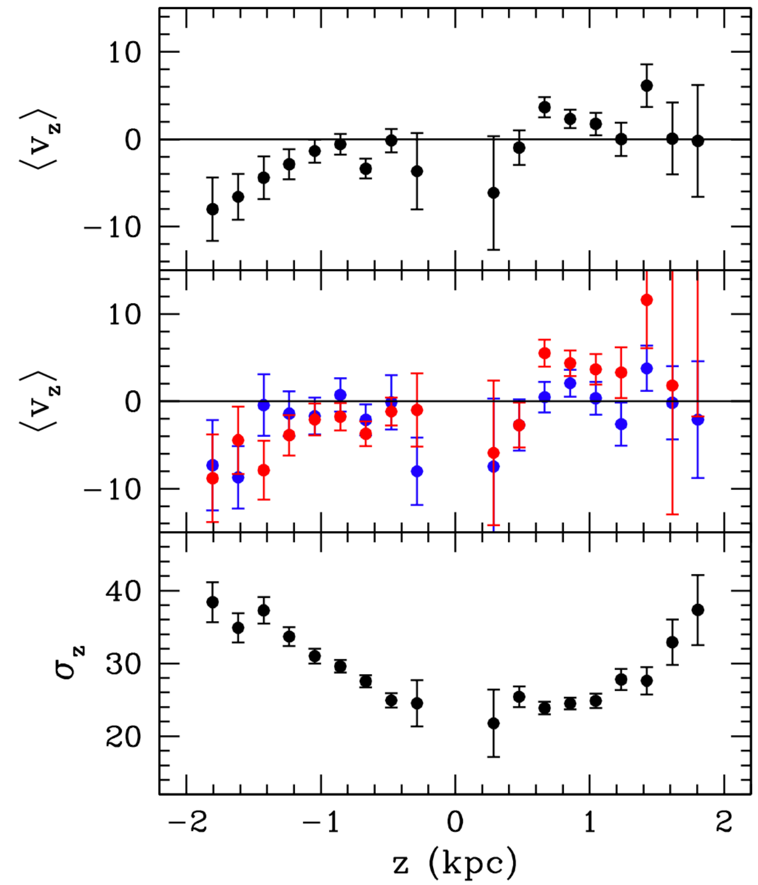
$$\Delta V_z(\text{bending}) = \frac{1}{2}\left(V_{z,north} + V_{z,south}\right)$$

Breathing mode: compression and rarefaction of the vertical scale

$$\Delta V_z(\text{breathing}) = V_{z,north} - V_{z,south}$$

Pre-Gaia observations: vertical density and velocity asymmetries, corrugations, bending and breathing modes





Widrow et al. 2012

SDSS

asymmetry in the vertical number density & velocity

- **Galaxy not in equilibrium?**
- **Gravitational impact of satellites ?**

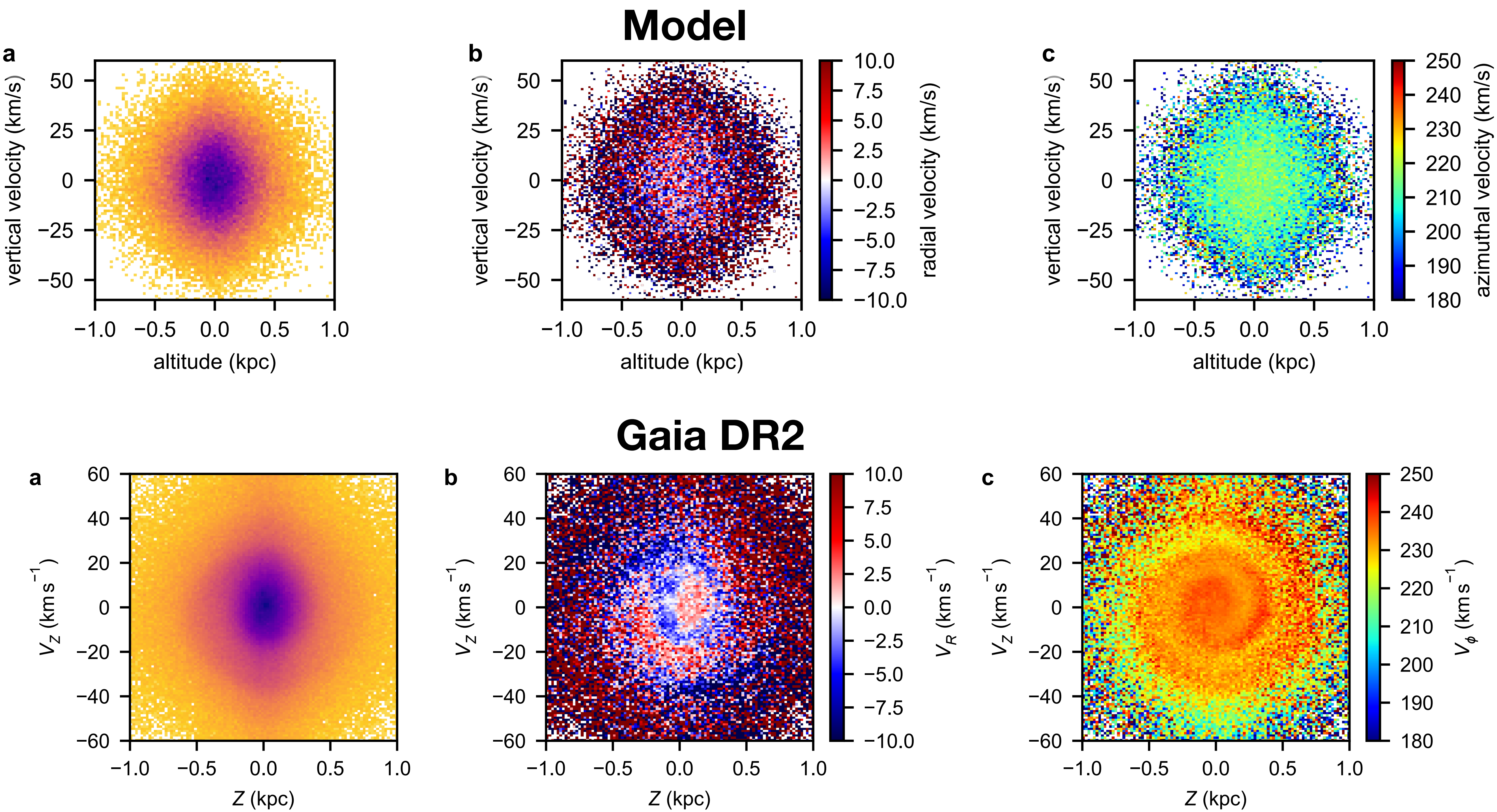
Bending mode: vertical movement of the midplane

$$\Delta V_z(\text{bending}) = \frac{1}{2}\left(V_{z,north} + V_{z,south}\right)$$

Breathing mode: compression and rarefaction of the vertical scale

$$\Delta V_z(\text{breathing}) = V_{z,north} - V_{z,south}$$

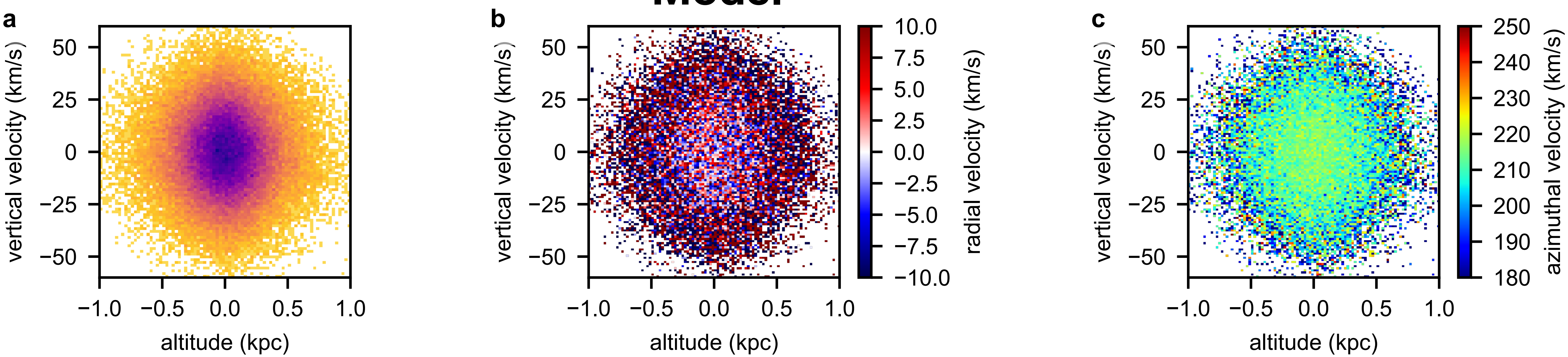
Observations



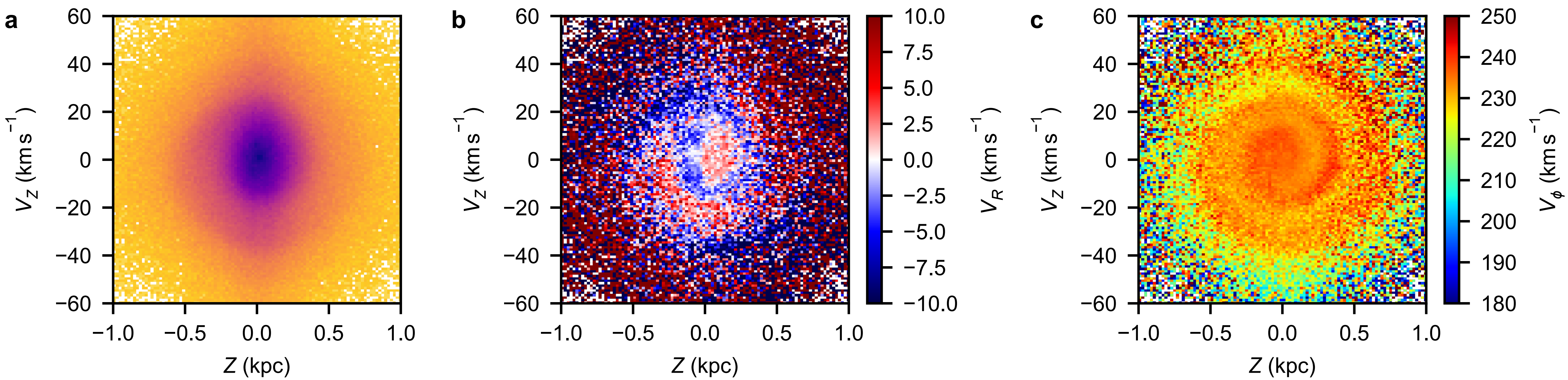
Antoja et al. 2018

Observations

Model



Gaia DR2

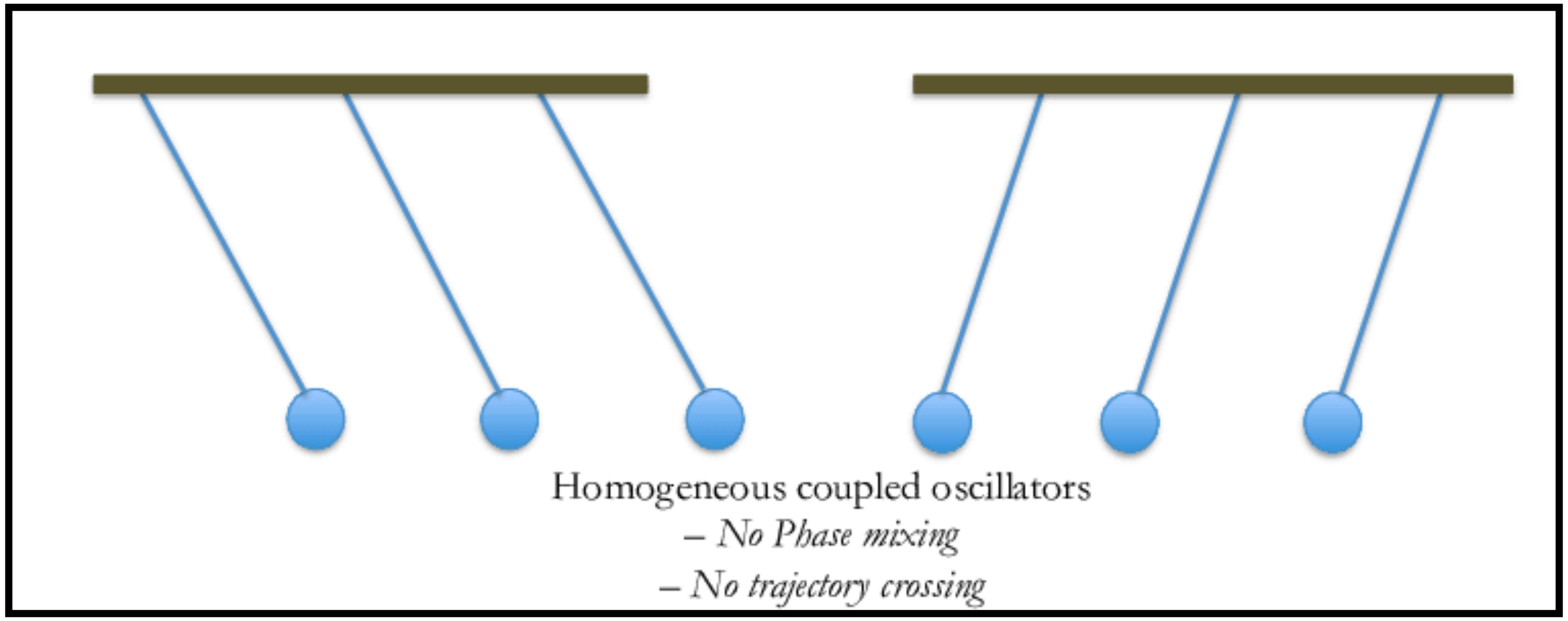


Antoja et al. 2018

Phase-mixing !!

Simple pendulum

For small swings the pendulum approximates a harmonic oscillator, and its motion as a function of time, *t*, is approximately simple harmonic motion



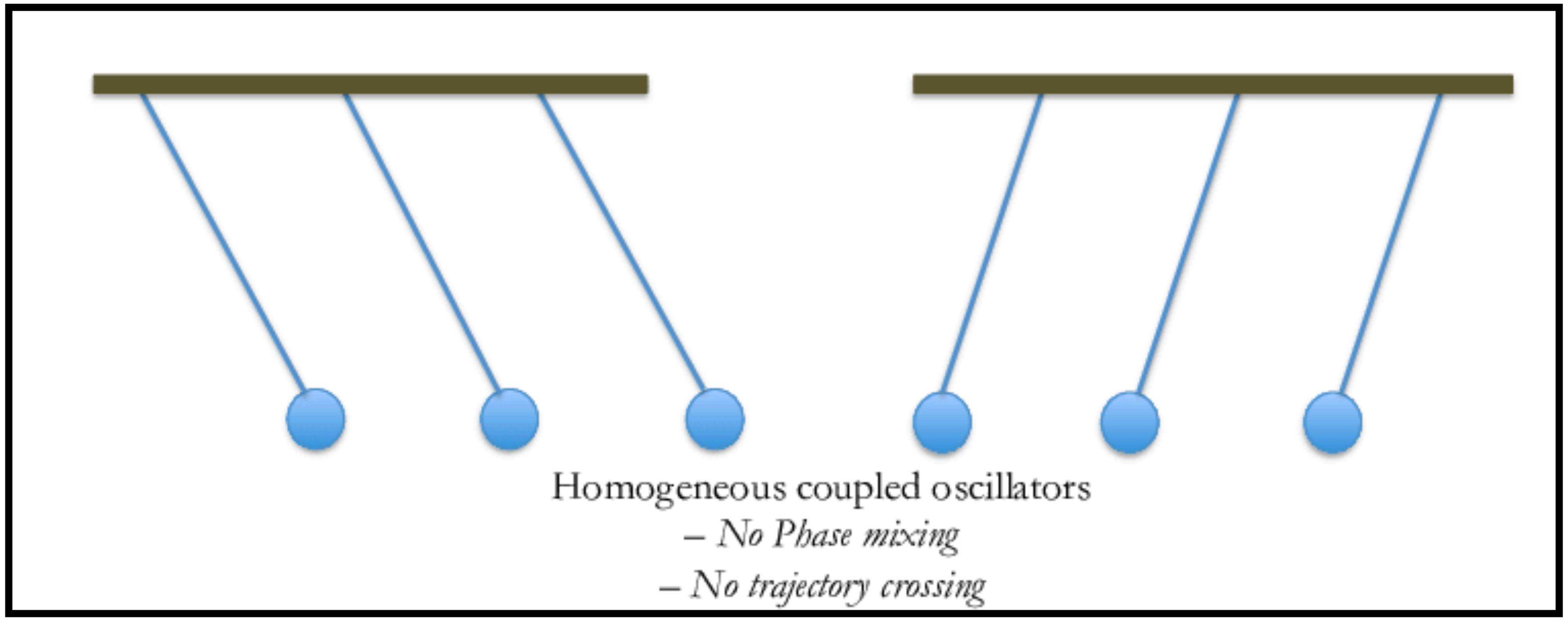
$$T \approx 2\pi\sqrt{\frac{L}{g}}$$

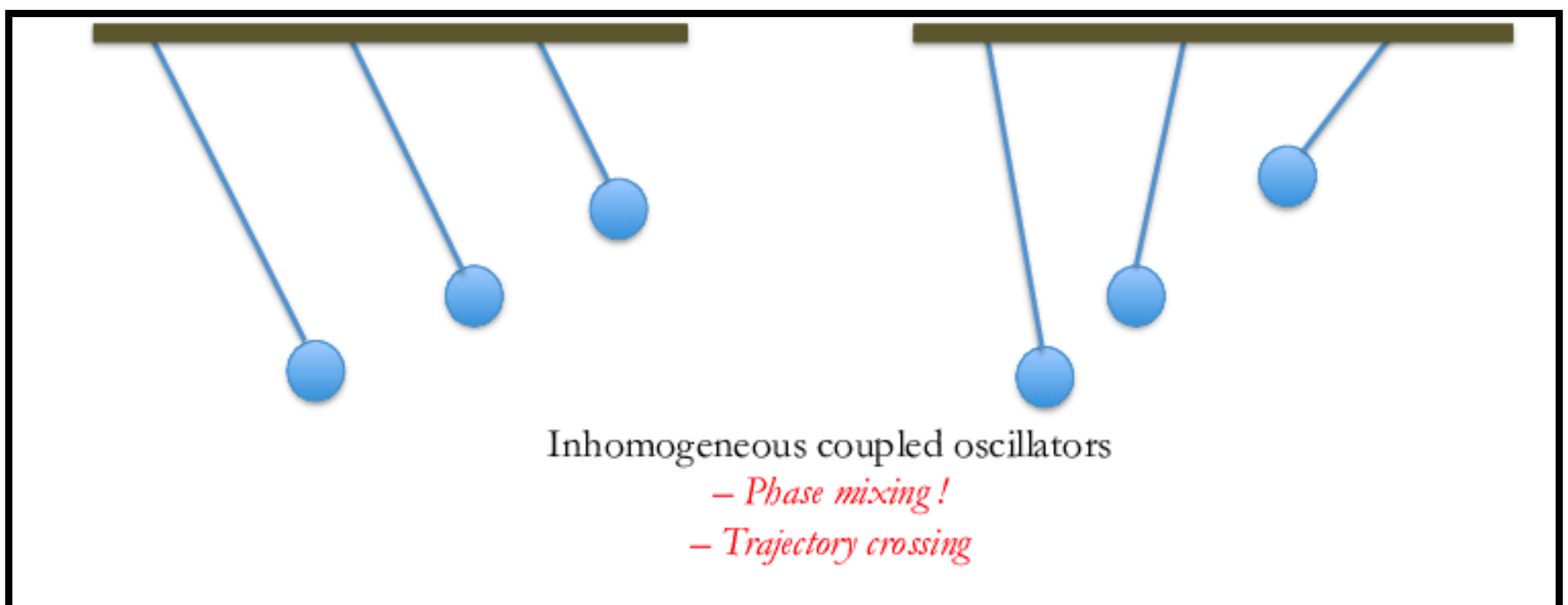
$$\theta_0 << 1\, rad$$

ResearchGate

Phase mixing

For small swings the pendulum approximates a harmonic oscillator, and its motion as a function of time, *t*, is approximately simple harmonic motion





$$T \approx 2\pi\sqrt{\frac{L}{g}}$$

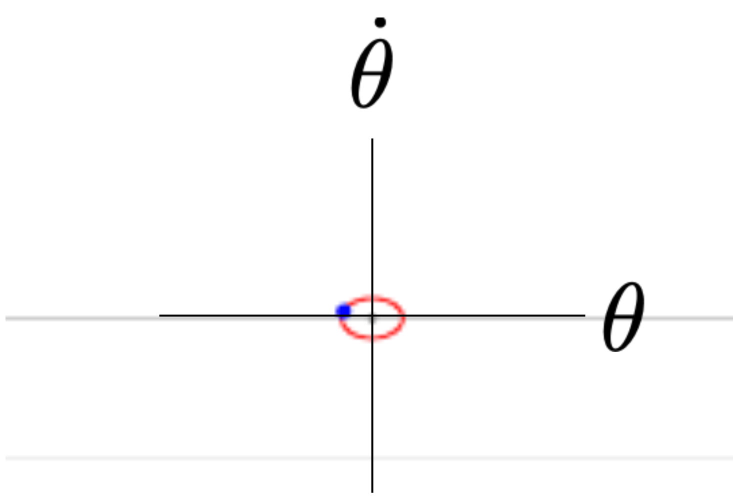
$$\theta_0 << 1\, rad$$

ResearchGate

Frequencies of pendulum with SMALL swings

For small swings the pendulum approximates a harmonic oscillator, and its motion as a function of time, t, is approximately simple harmonic motion

$$\theta(t) = \theta_0 \cos\left(\sqrt{\frac{g}{L}}\,t\right) \quad \theta_0 << 1\, rad$$



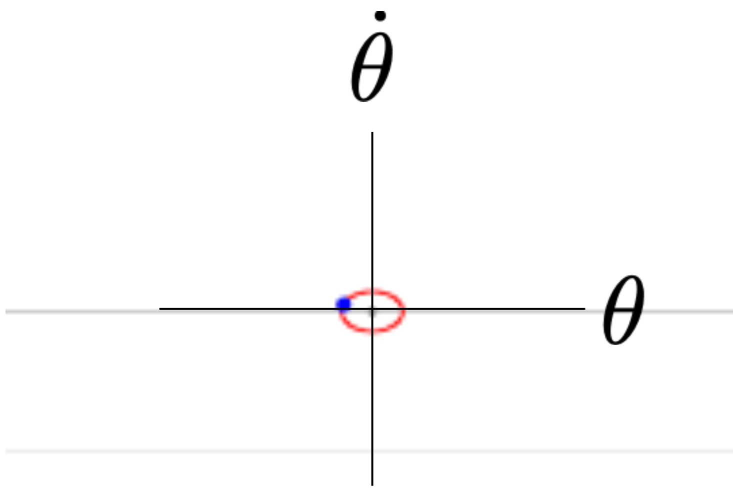
Initial angle at 30°

https://en.wikipedia.org/wiki/Pendulum

Frequencies of pendulum with SMALL swings

For small swings the pendulum approximates a harmonic oscillator, and its motion as a function of time, *t*, is approximately simple harmonic motion

$$\theta(t) = \theta_0 \cos\left(\sqrt{\frac{g}{L}}\,t\right) \quad \theta_0 << 1\,rad$$



Initial angle at 30°

https://en.wikipedia.org/wiki/Pendulum

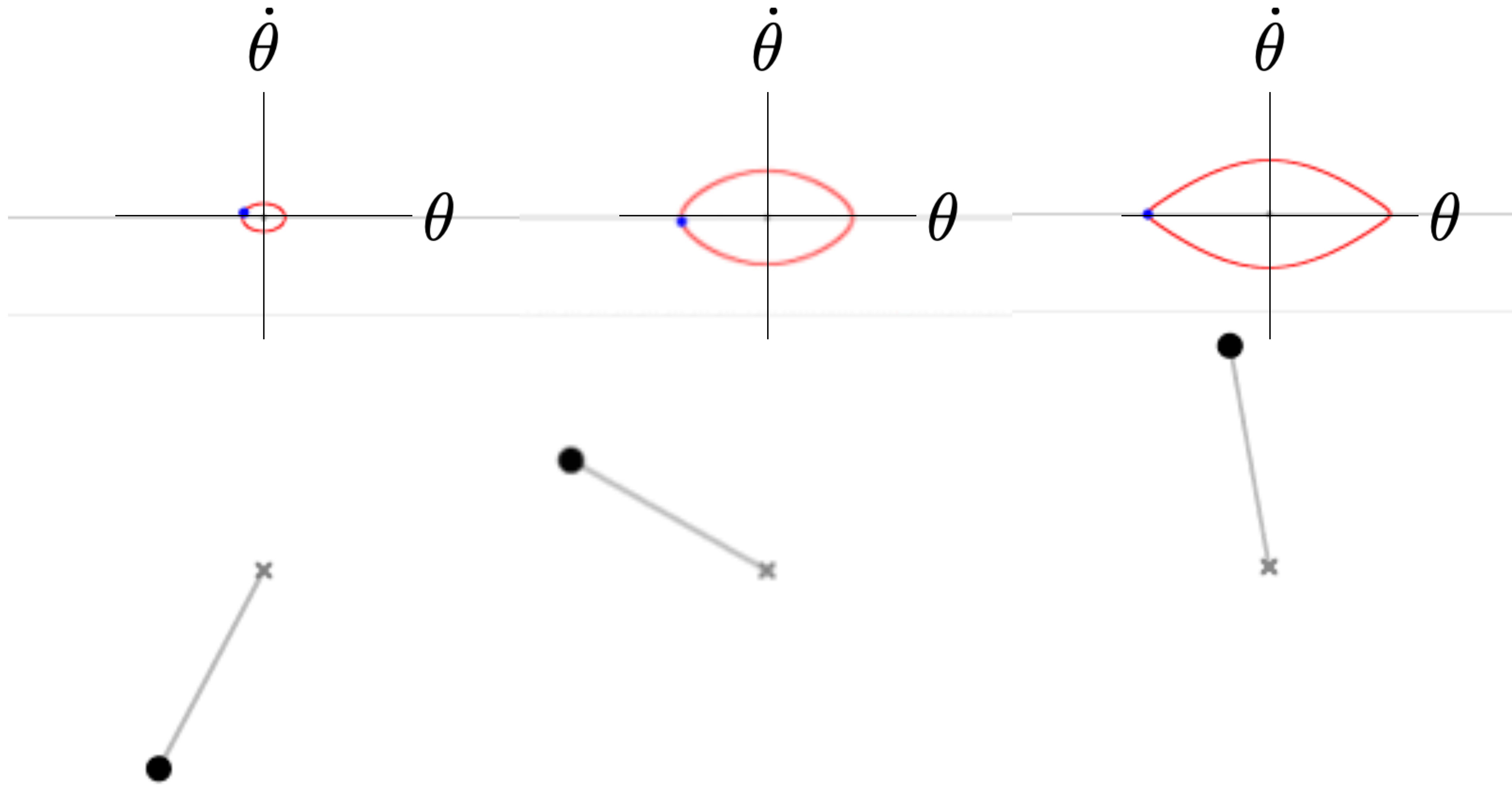
Frequencies of pendulum with LARGE swings

$$\cancel{\theta(t) = \theta_0 \cos\left(\sqrt{\frac{g}{L}}t\right) \quad \theta_0 << 1 rad}$$

The period of a pendulum gets longer as the amplitude θ_0 (width of swing) increases

$$T \approx 2\pi\sqrt{\frac{L}{g}}\left(1 + \frac{1}{16}\theta_0^2 + \frac{11}{3072}\theta_0^4 + ...\right)$$

Animation of pendulum starting at 30°, 120° and 170°



Initial angle at 30° | Initial angle at 120° | Initial angle at 170°

https://en.wikipedia.org/wiki/Pendulum

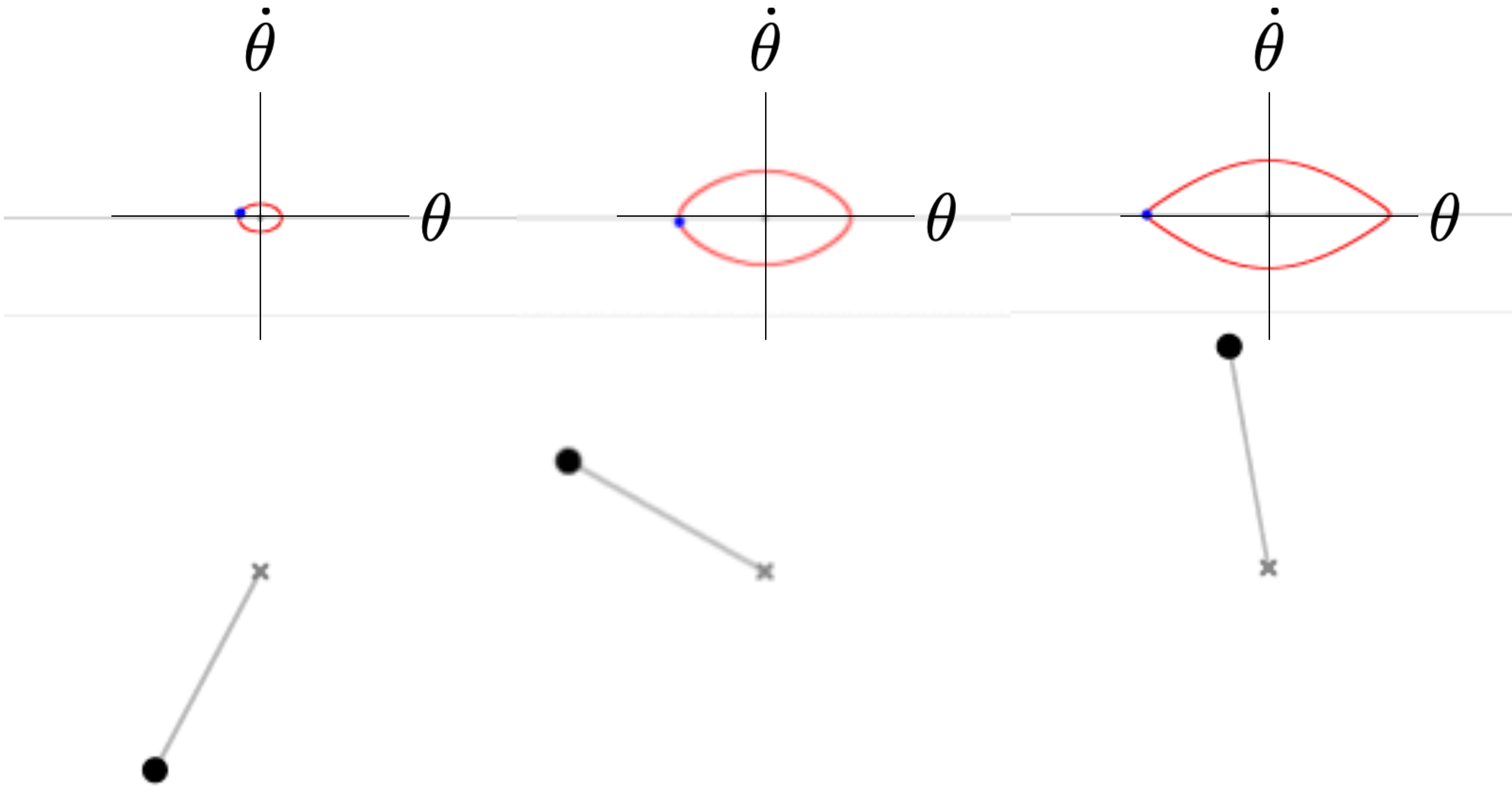
Frequencies of pendulum with LARGE swings

$$\cancel{\theta(t) = \theta_0 \cos(\sqrt{\frac{g}{L}}t) \quad \theta_0 << 1 rad}$$

The period of a pendulum gets longer as the amplitude θ_0 (width of swing) increases

$$T \approx 2\pi\sqrt{\frac{L}{g}}(1 + \frac{1}{16}\theta_0^2 + \frac{11}{3072}\theta_0^4 + ...)$$

Animation of pendulum starting at 30°, 120° and 170°



Initial angle at 30°　　Initial angle at 120°　　Initial angle at 170°

https://en.wikipedia.org/wiki/Pendulum

Miyamoto-Nagai potential

I need to make nicer plots with galpy

Epicyclic vertical motion is not a good approximation
Lets examine a more realistic model

$$\Phi_M(R,z) = -\frac{GM}{\sqrt{R^2 + (a + \sqrt{z^2 + b^2})^2}}$$

For Milky Way:

$a = 6.5$ kpc, $b = 0.26$

74 Chapter 2:

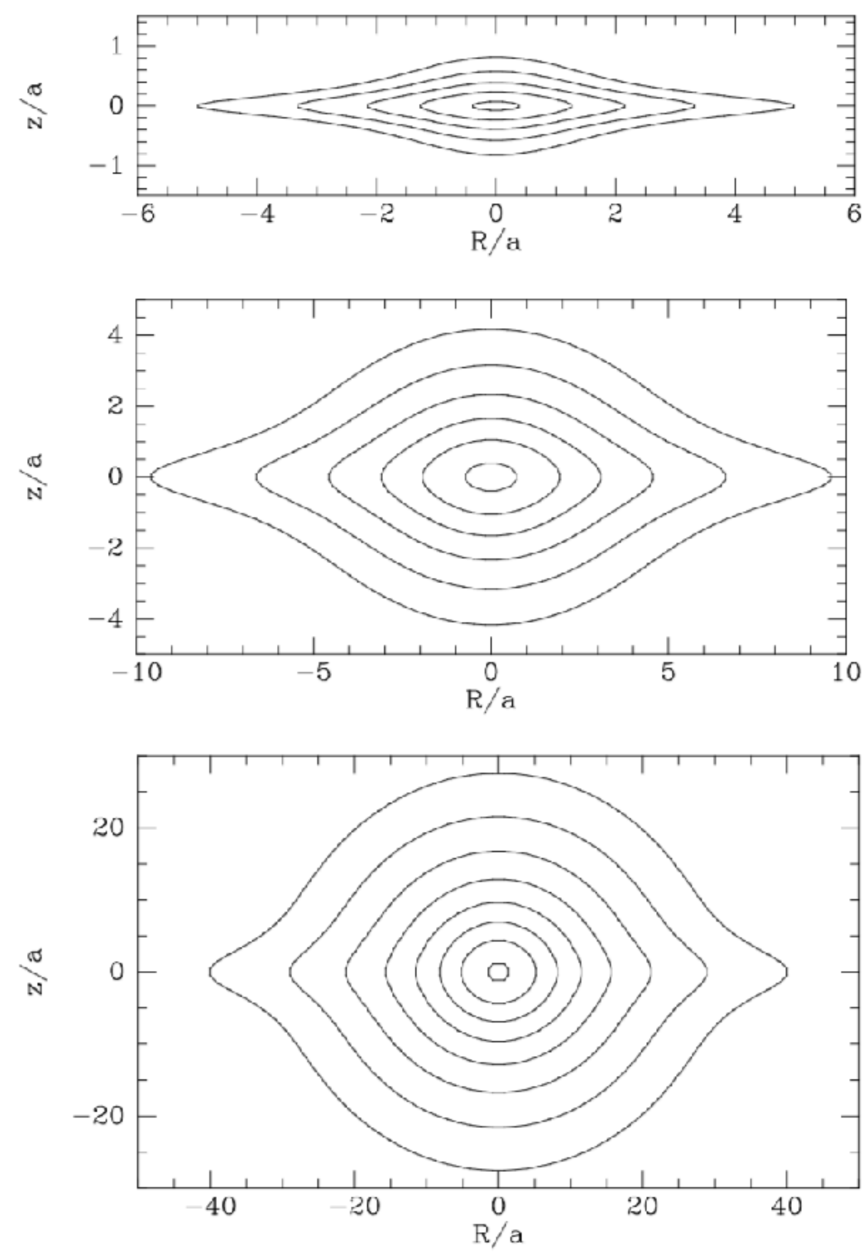


Figure 2.7 Contours of equal density in the (R, z) plane for the Miyamoto–Nagai density distribution (2.69b) when: $b/a = 0.2$ (top); $b/a = 1$ (middle); $b/a = 5$ (bottom). There are two contours per decade, and the highest contour levels are $0.3M/a^3$ (top), $0.03M/a^3$ (middle), and $0.001M/a^3$ (bottom).

BT08

Approximating Myiamoto-Nagai model

For small Z (A<<b=0.26 kpc), we can approximate:

$$\Phi(Z) \propto -\alpha_0 + \frac{1}{2}\alpha_1 Z^2 - \frac{1}{4}\alpha_2 Z^4$$

Anharmonic potential

α **'s depend on**

$a\,b\,R$

$$\nu(A,R) = \alpha_1(R)^{1/2}\left(1 - \frac{3\alpha_2(R)A^2}{8\alpha_1(R)}\right)$$

Approximation of movement as simple harmonic motion with different frequencies:

$$Z = A\cos\left(\nu(A,R)t + \phi_0\right)$$
$$V_Z = -A\nu(A,R)\sin\left(\nu(A,R)t + \phi_0\right)$$

Vertical frequencies in a realistic Galaxy disk

$$T \approx 2\pi\sqrt{\frac{L}{g}}\left(1 + \frac{1}{16}\theta_0^2 + \frac{11}{3072}\theta_0^4 + ...\right)$$

Vertical frequencies in a realistic Galaxy disk

$$T \approx 2\pi\sqrt{\frac{L}{g}}\left(1 + \frac{1}{16}\theta_0^2 + \frac{11}{3072}\theta_0^4 + ...\right)$$

$$T = f(R, A_Z)$$

Vertical frequencies in a realistic Galaxy disk

$$T \approx 2\pi\sqrt{\frac{L}{g}}\left(1 + \frac{1}{16}\theta_0^2 + \frac{11}{3072}\theta_0^4 + \ldots\right)$$

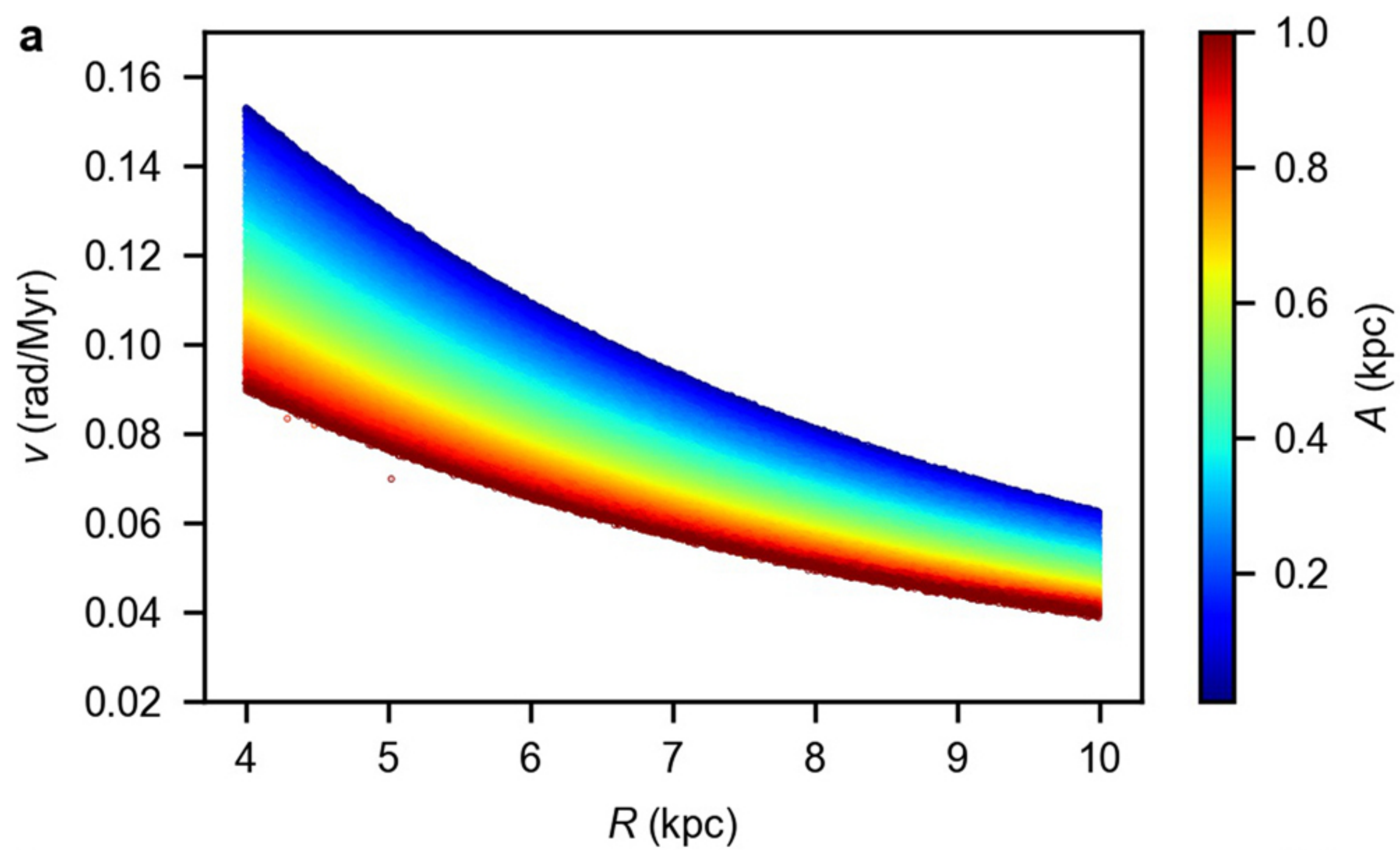
$$T = f(R, A_Z)$$

$$T = \frac{2\pi}{\nu}$$

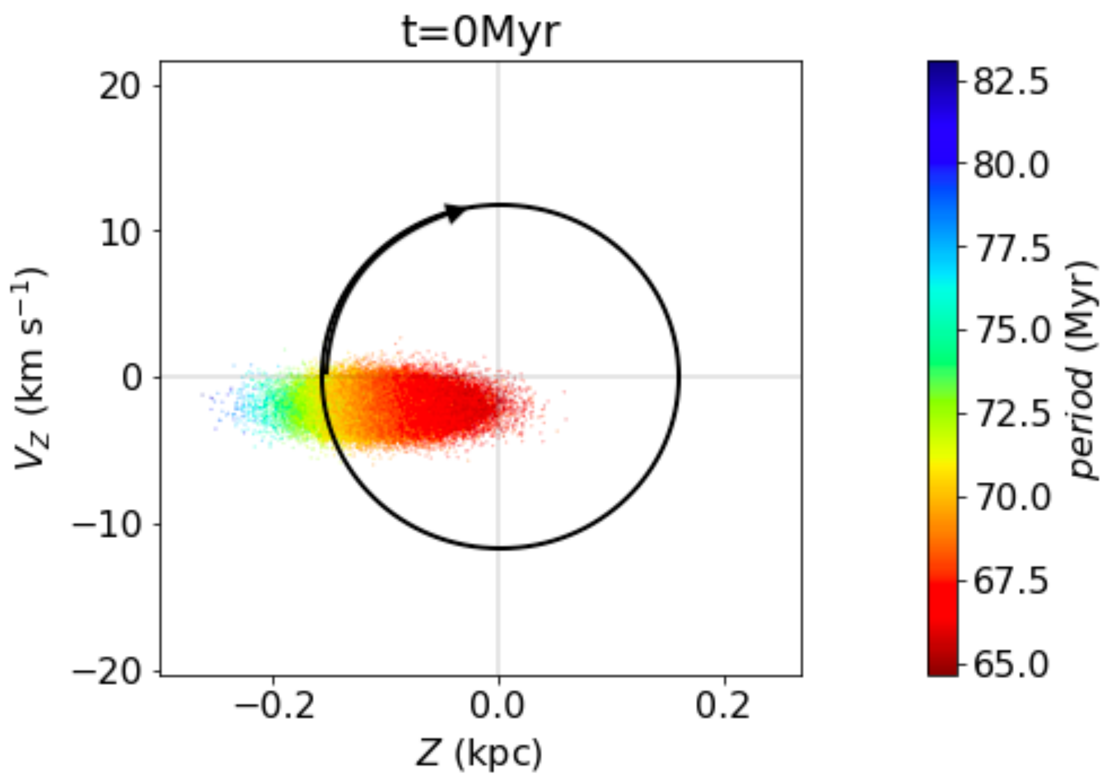
40 Myr

300 Myr

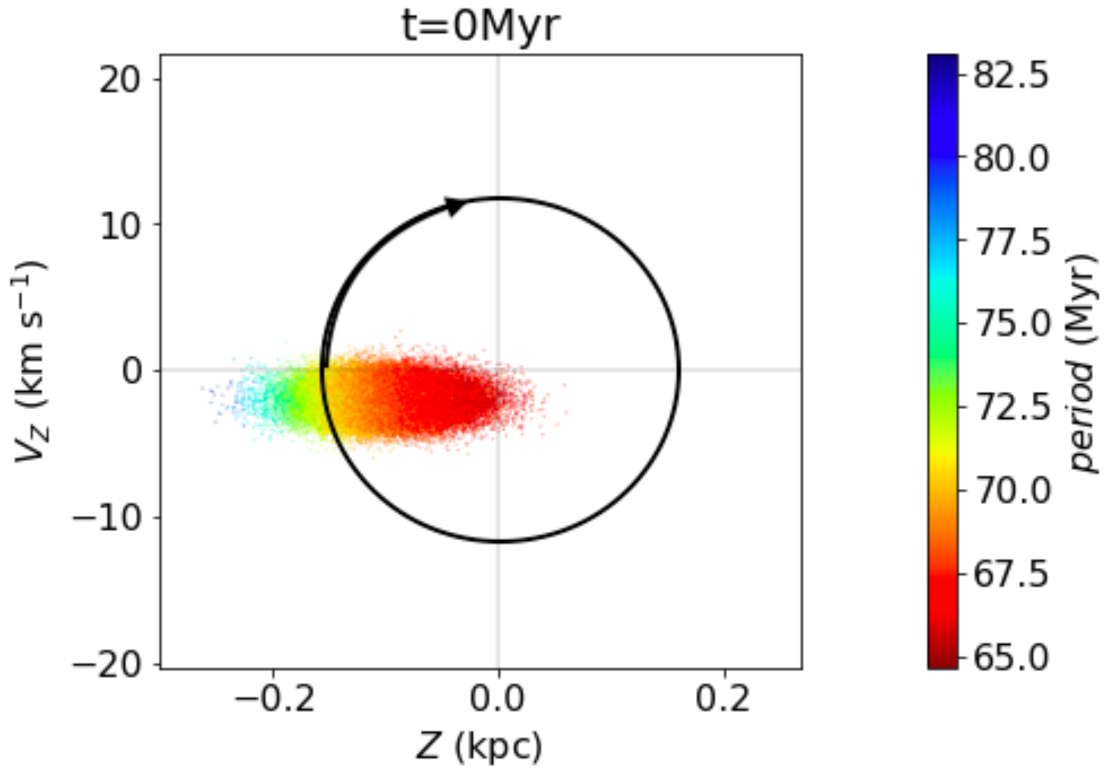
Vertical frequencies for updated Allen & Santillan model

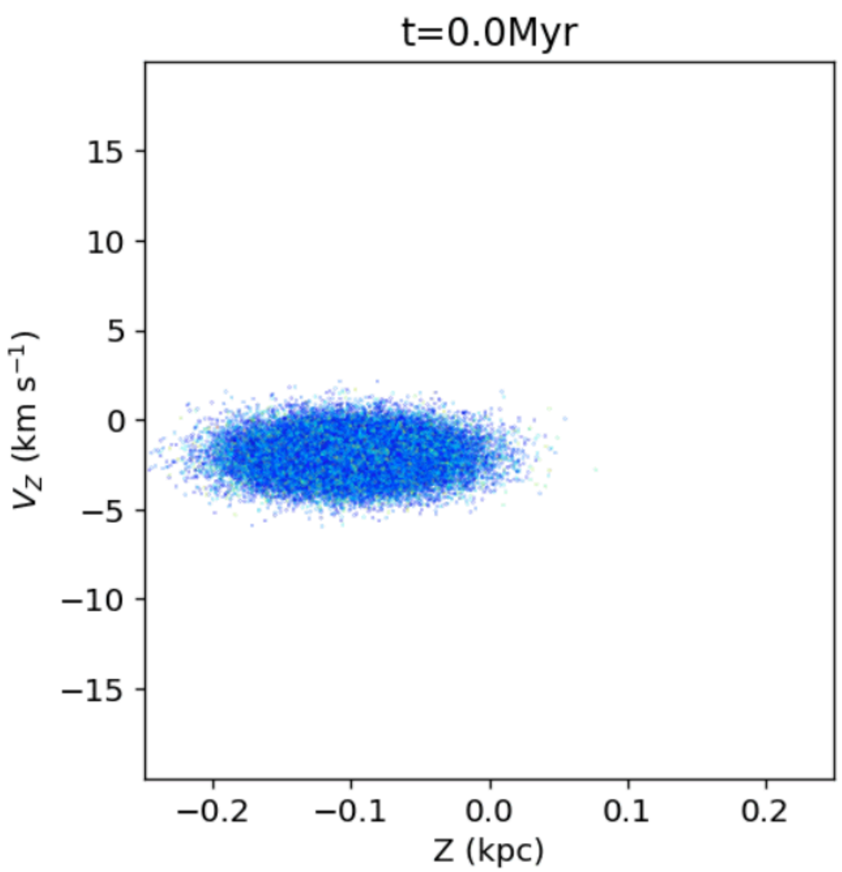


Toy model of the phase space spiral

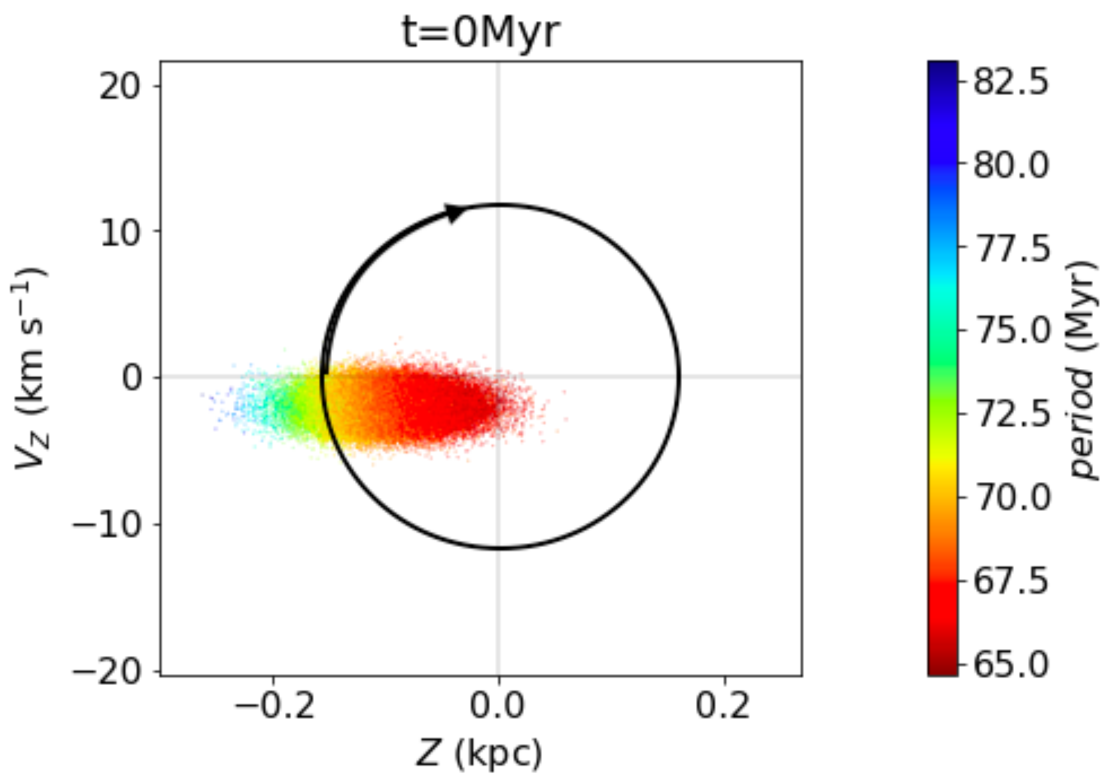


Toy model of the phase space spiral

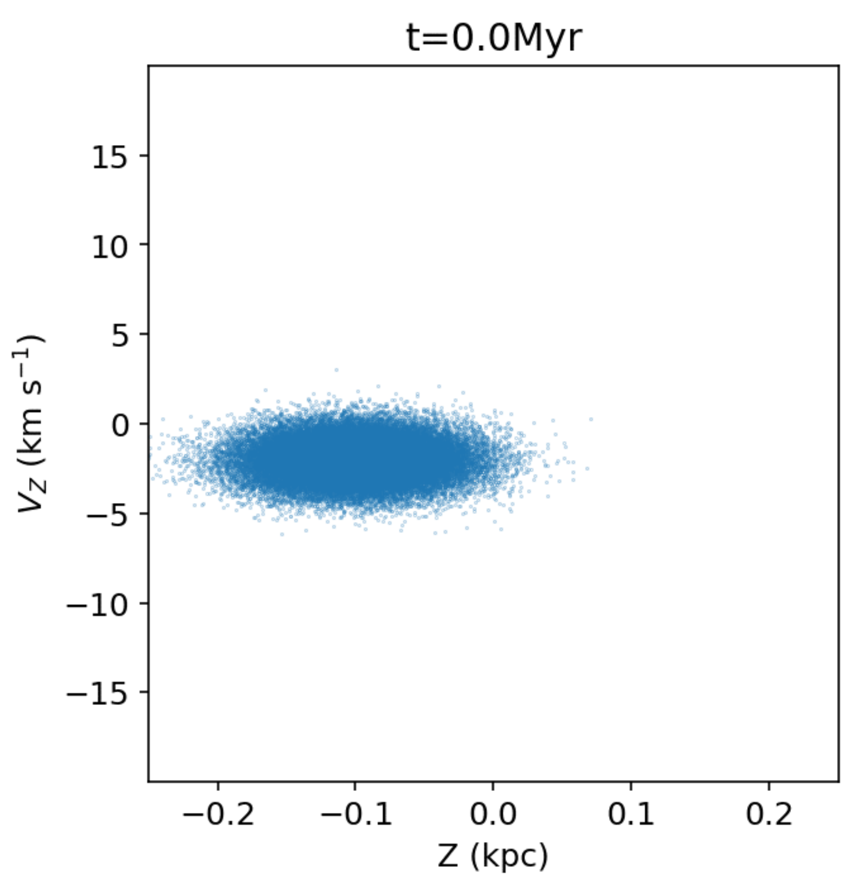




Toy model of the phase space spiral

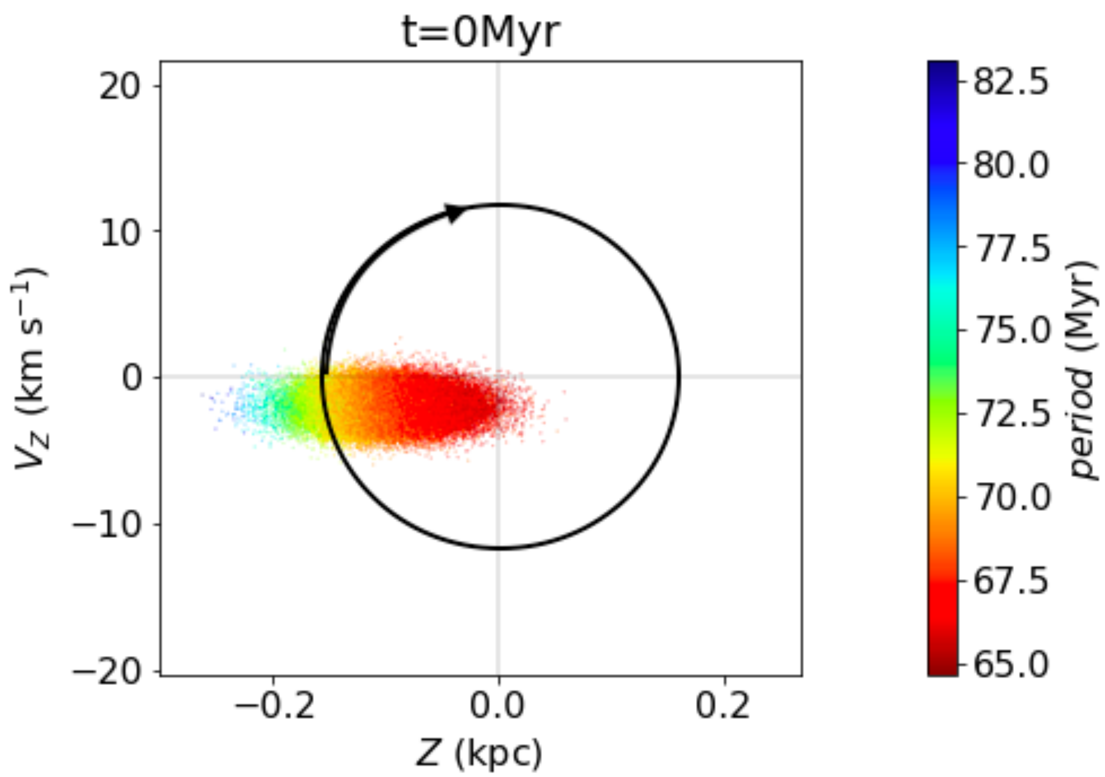


Fixed R



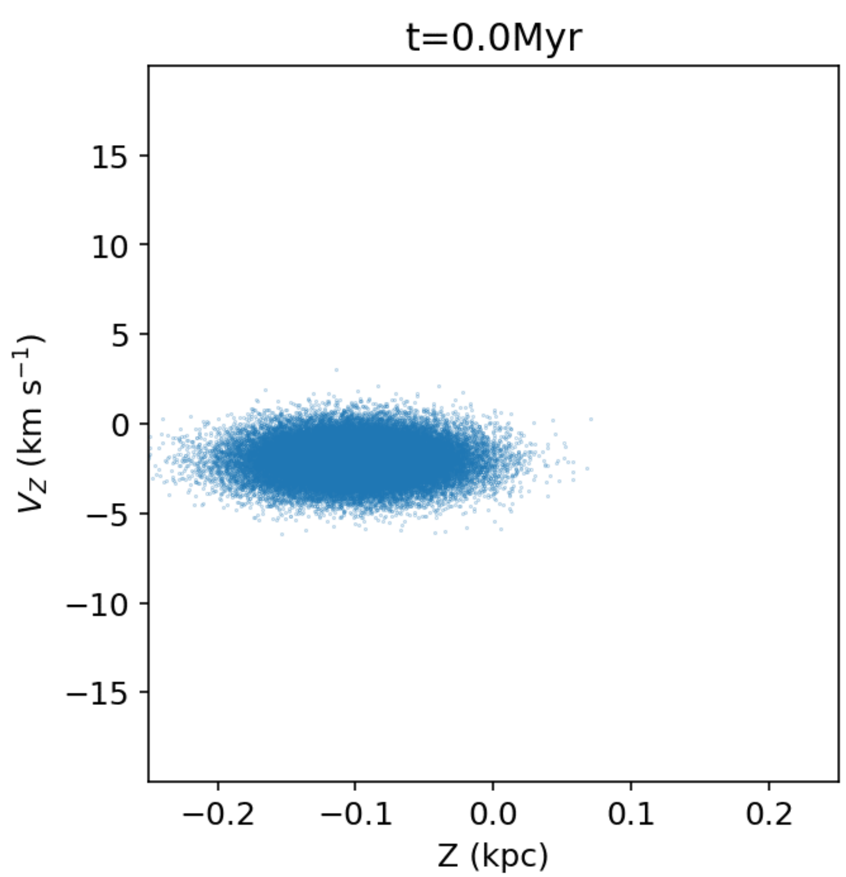
$$T = f(A_Z)$$

Toy model of the phase space spiral

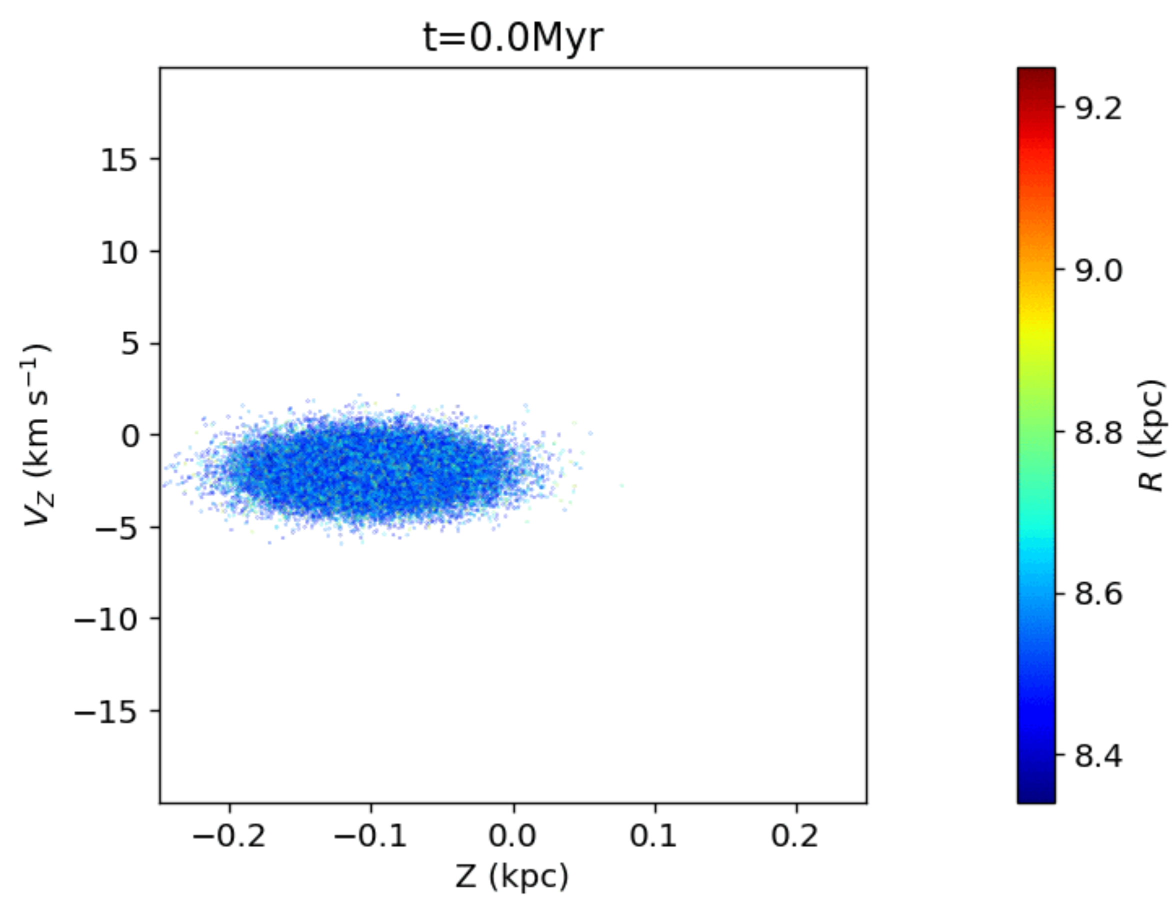


More realistic: include orbits that come from other radii due to their radial oscillations

Fixed R



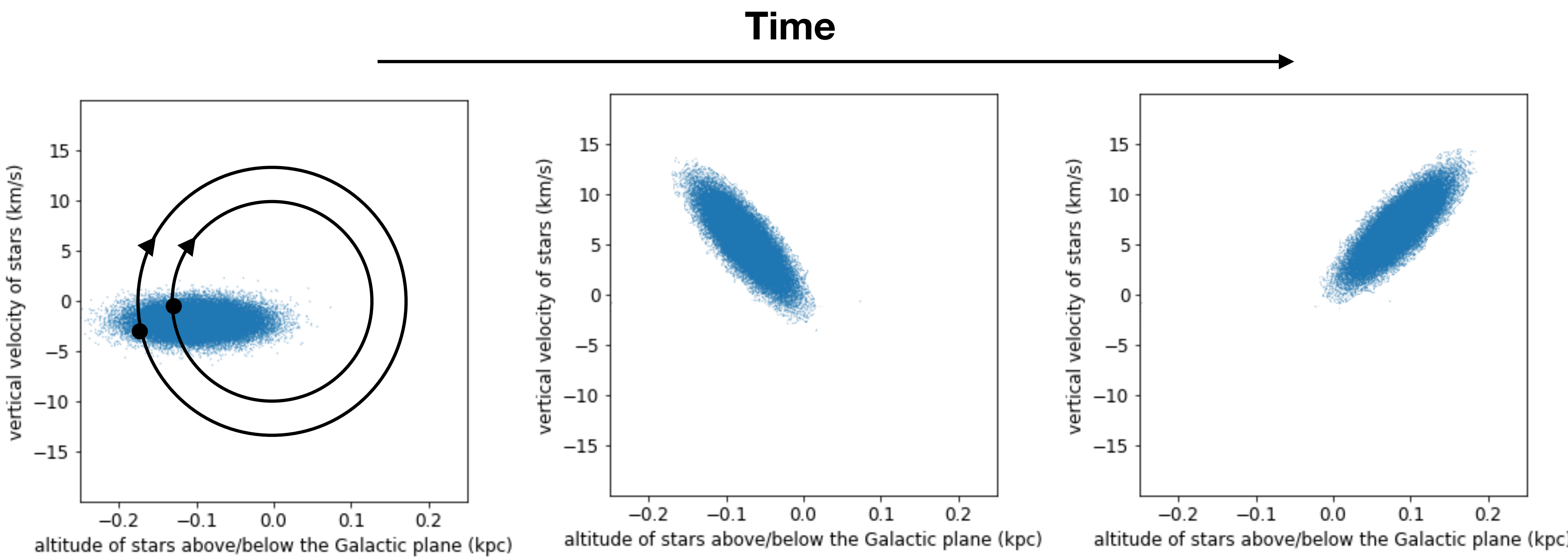
$$T = f(A_Z)$$



$$T = f(R, A_Z)$$

Modelling

The spirals in the Gaia data are phase mixing signatures



Simple epicyclic approximation doesn't work to explain the phase mixing: we need different frequencies playing a role

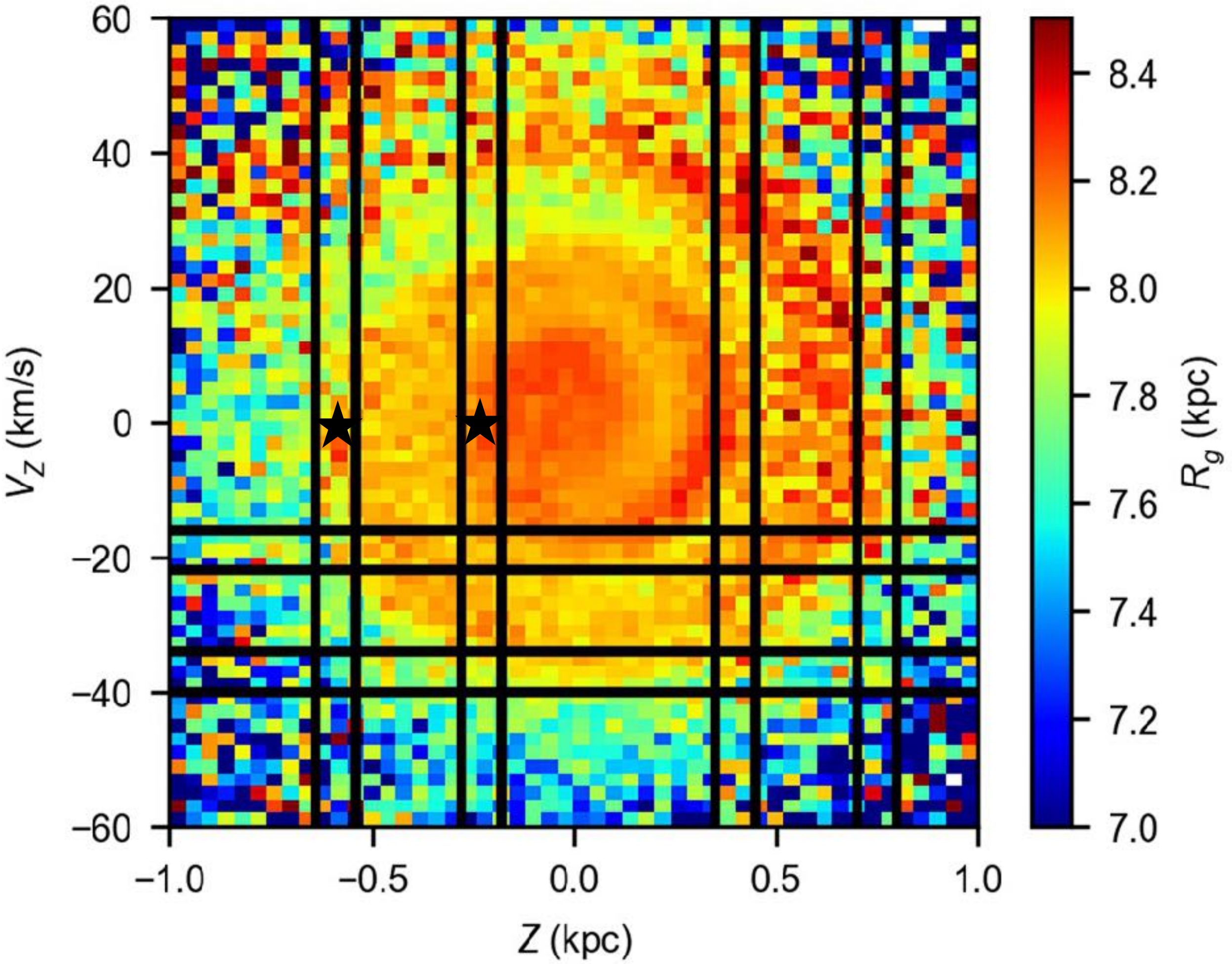
Can we unwind the spiral to determine WHEN all this mess started?

Timing the event

Guiding radius approximation

$$R_g V_c = V_\phi R_\odot \longrightarrow R_g = \frac{V_\phi R_\odot}{V_c}$$

$$t = \frac{2\pi}{\nu_2 - \nu_1}$$

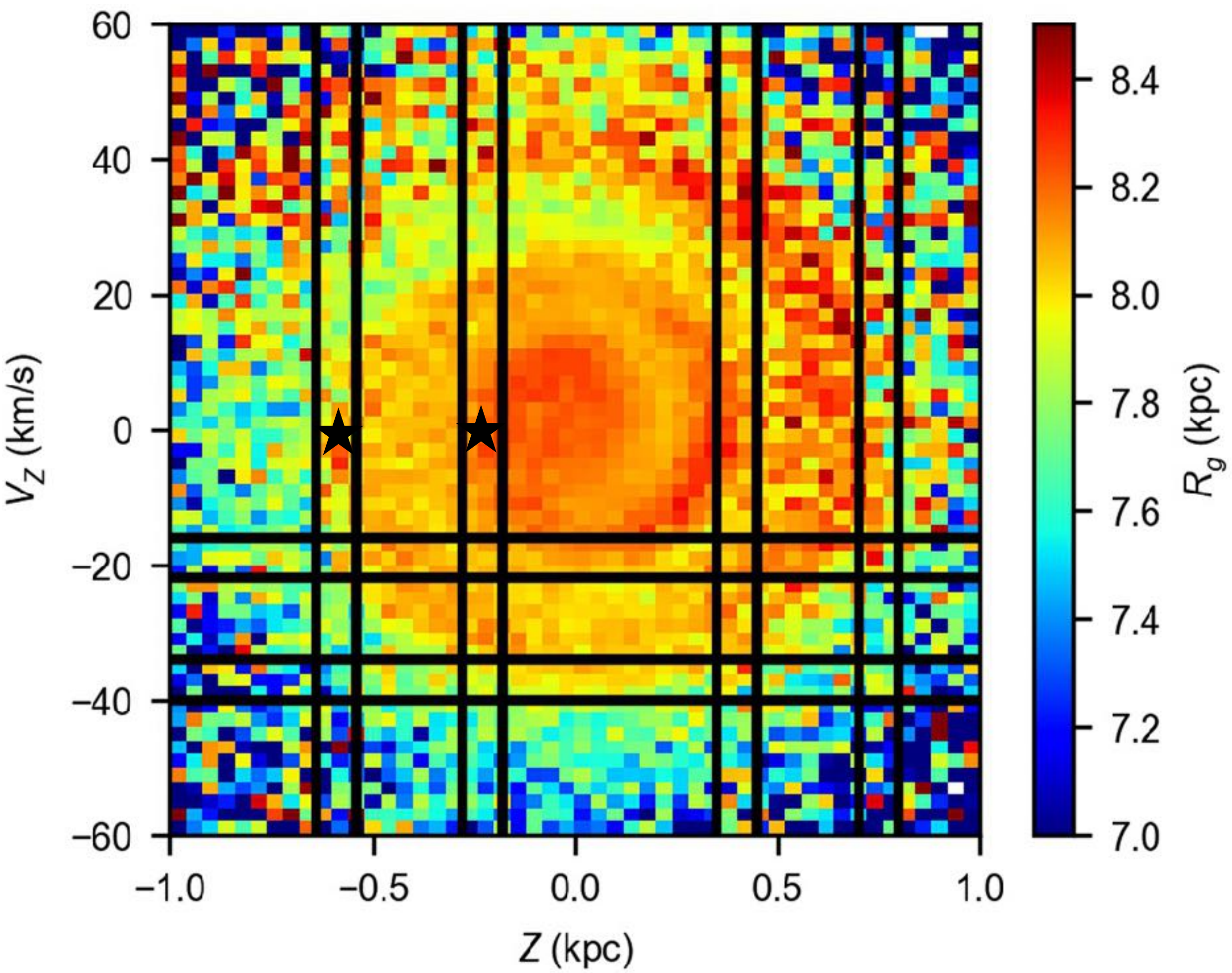


Timing the event

Guiding radius approximation

$$R_g V_c = V_\phi R_\odot \longrightarrow R_g = \frac{V_\phi R_\odot}{V_c}$$

$$t = \frac{2\pi}{\nu_2 - \nu_1}$$



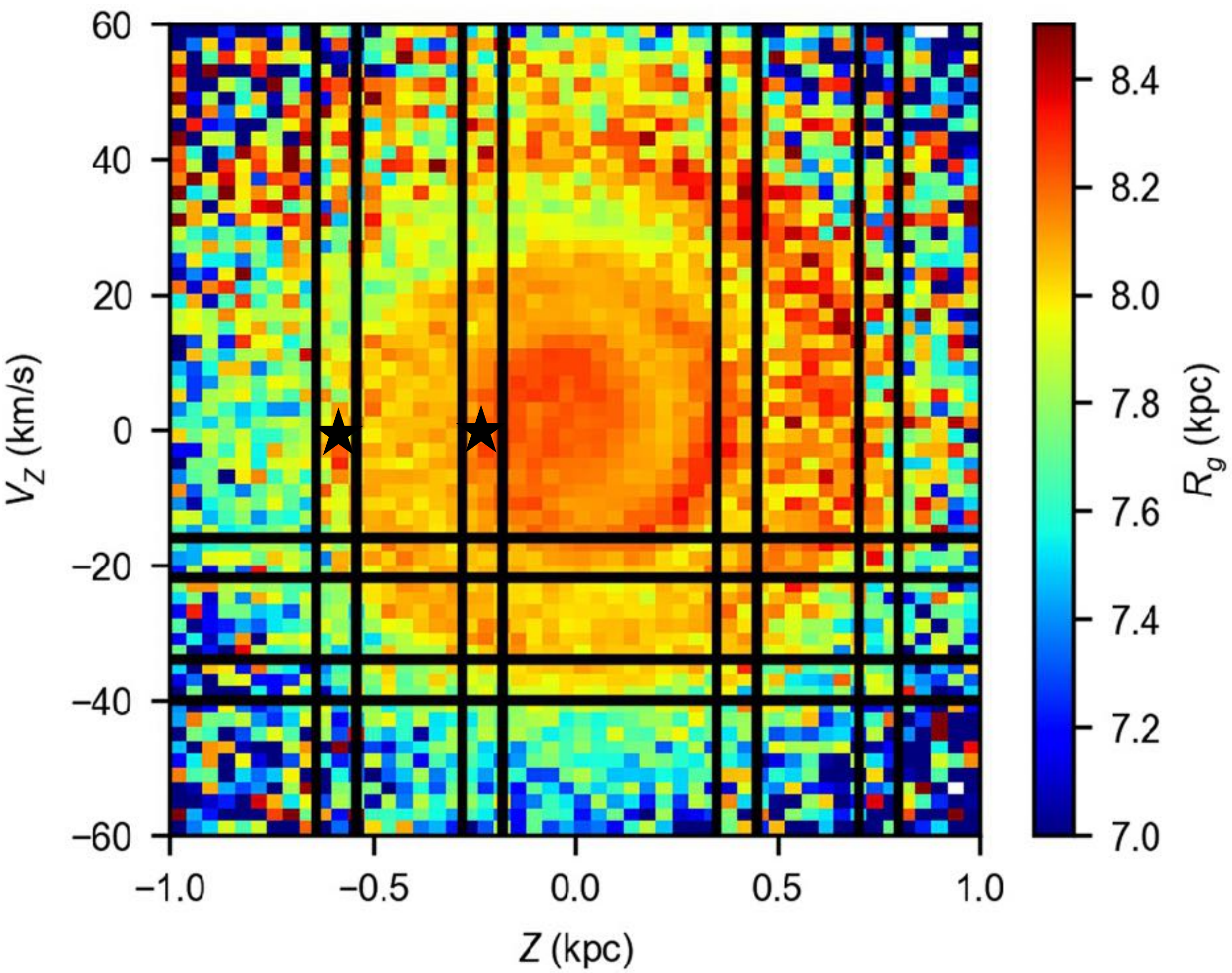
Z (kpc)		ν (rad/Myr)	Time (Myr)
-0.59	± 5	$0.058^{+0.002}_{0.002}$	461^{+183}_{-105}
-0.23	± 5	$0.072^{+0.002}_{0.002}$	
0.40	± 5	$0.065^{+0.003}_{0.003}$	566^{+290}_{-140}
0.75	± 5	$0.054^{+0.001}_{0.001}$	

Timing the event

Guiding radius approximation

$$R_g V_c = V_\phi R_\odot \longrightarrow R_g = \frac{V_\phi R_\odot}{V_c}$$

$$t = \frac{2\pi}{\nu_2 - \nu_1}$$



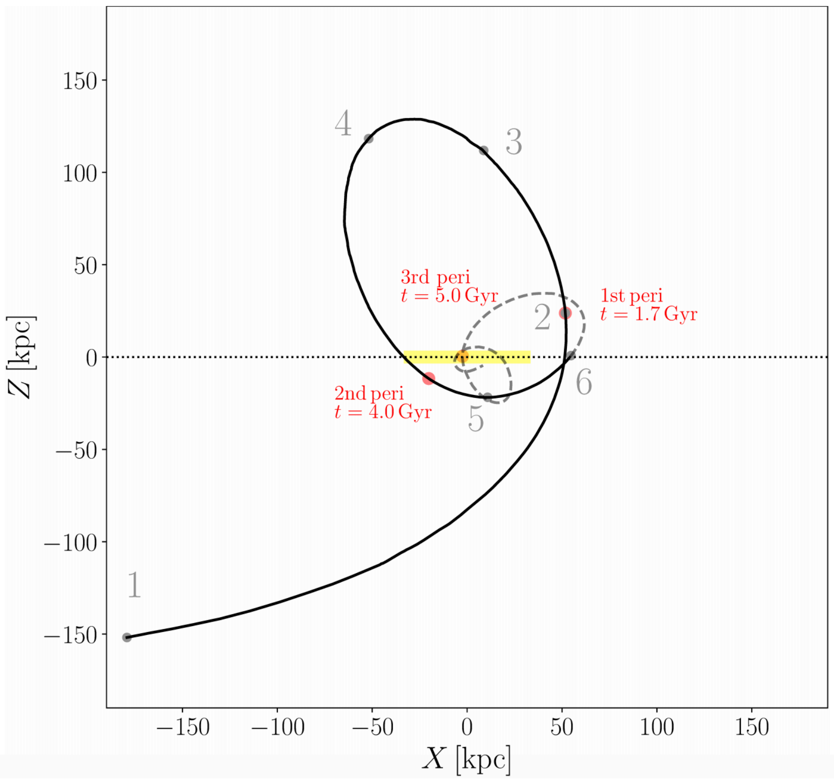
Z (kpc)		ν (rad/Myr)	Time (Myr)
-0.59	± 5	$0.058^{+0.002}_{0.002}$	461^{+183}_{-105}
-0.23	± 5	$0.072^{+0.002}_{0.002}$	
0.40	± 5	$0.065^{+0.003}_{0.003}$	566^{+290}_{-140}
0.75	± 5	$0.054^{+0.001}_{0.001}$	

Something occurred 300-900 Myr ago

???

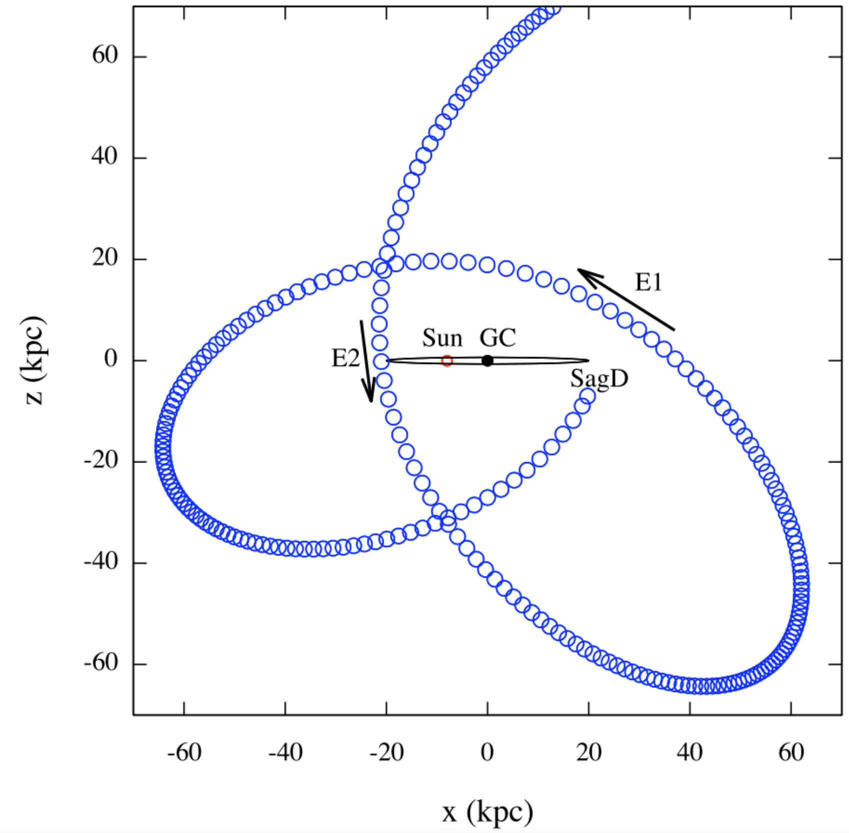
Sagittarius orbit

Laporte et al. 2019



de la Vega et al 2015

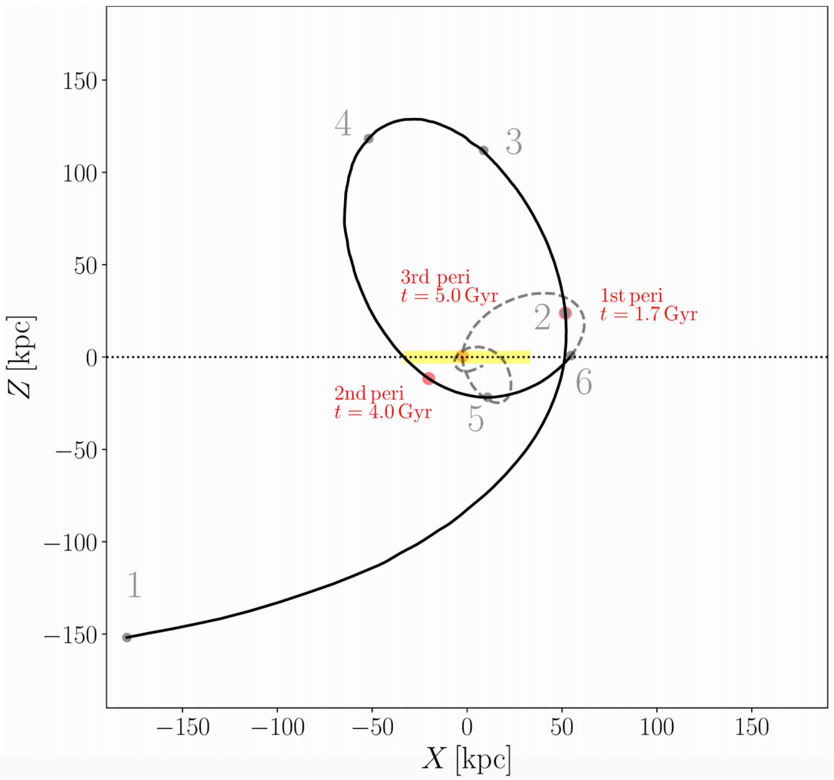
E model by Chakrabarti et al. 2014



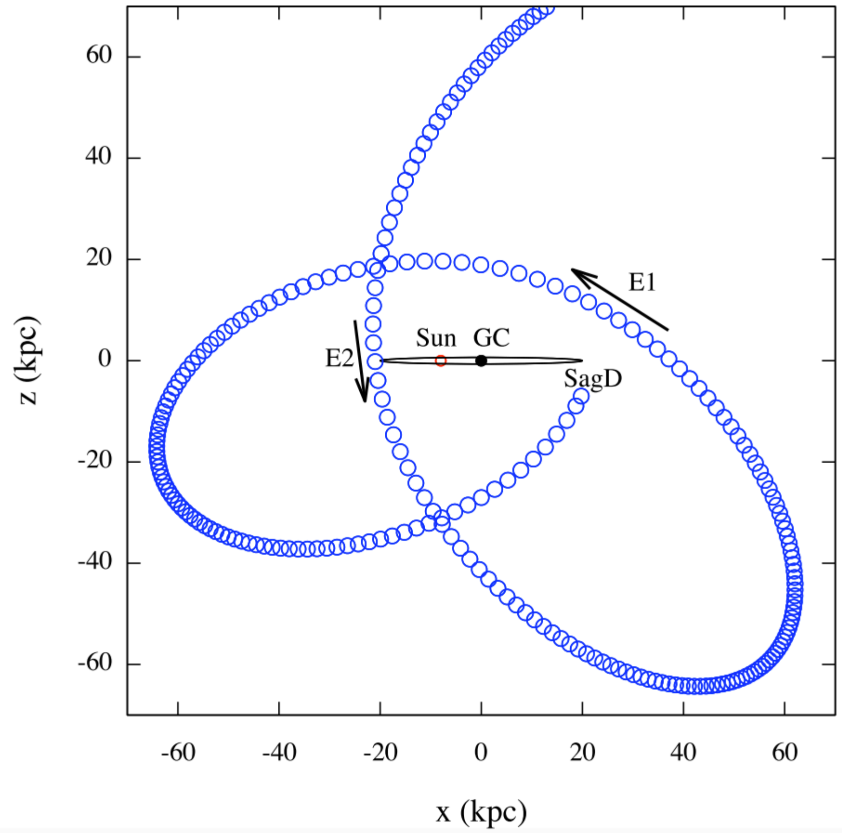
Chakrabarti et al. 2014	~1000 Myr
Laporte et al. 2018	200-1000 Myr
Law & Majewski 2010	~800 Myr

Sagittarius orbit

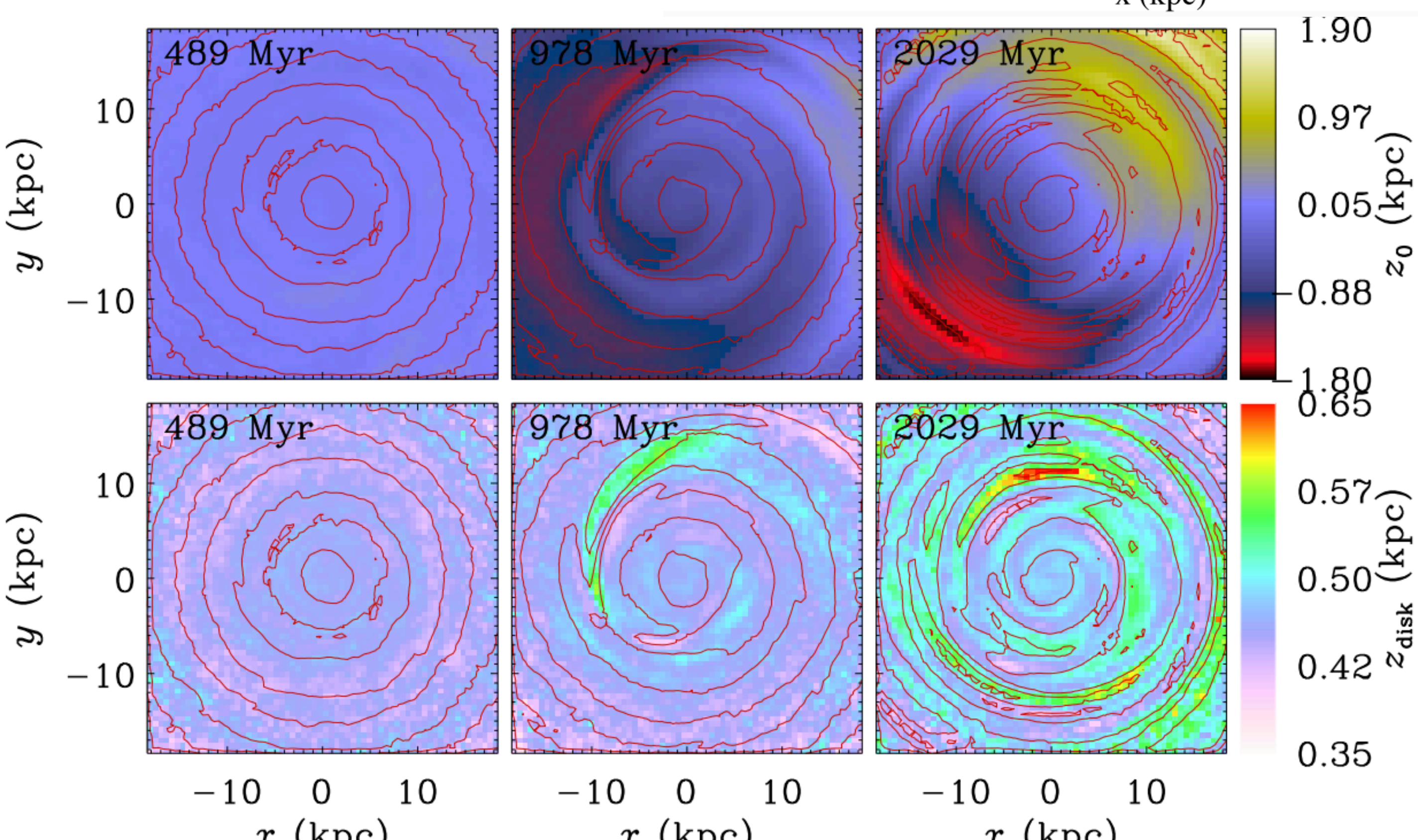
Laporte et al. 2019



de la Vega et al 2015
E model by Chakrabarti et al. 2014



Chakrabarti et al. 2014	~1000 Myr
Laporte et al. 2018	200-1000 Myr
Law & Majewski 2010	~800 Myr

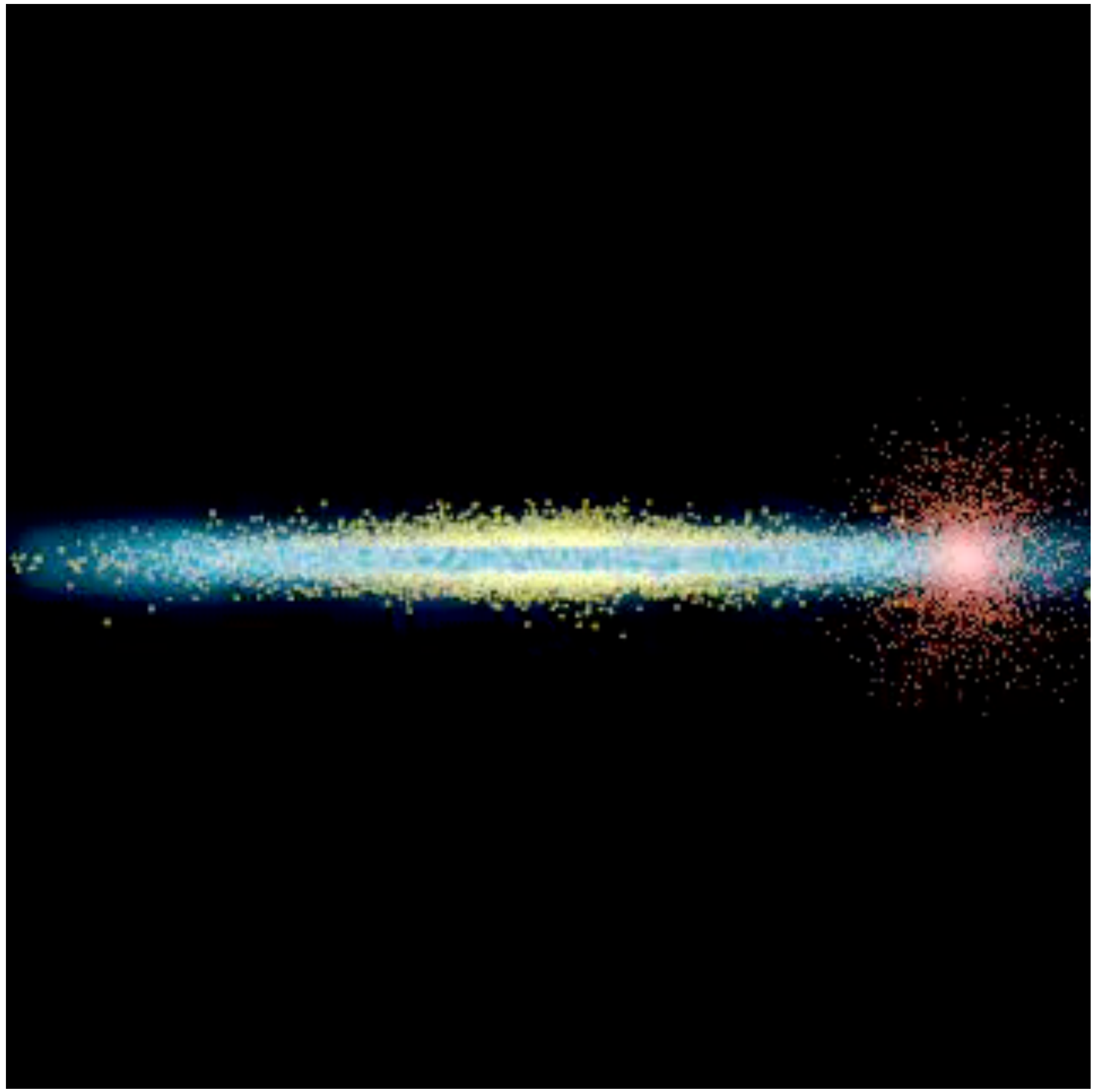


Mean z

Thickness

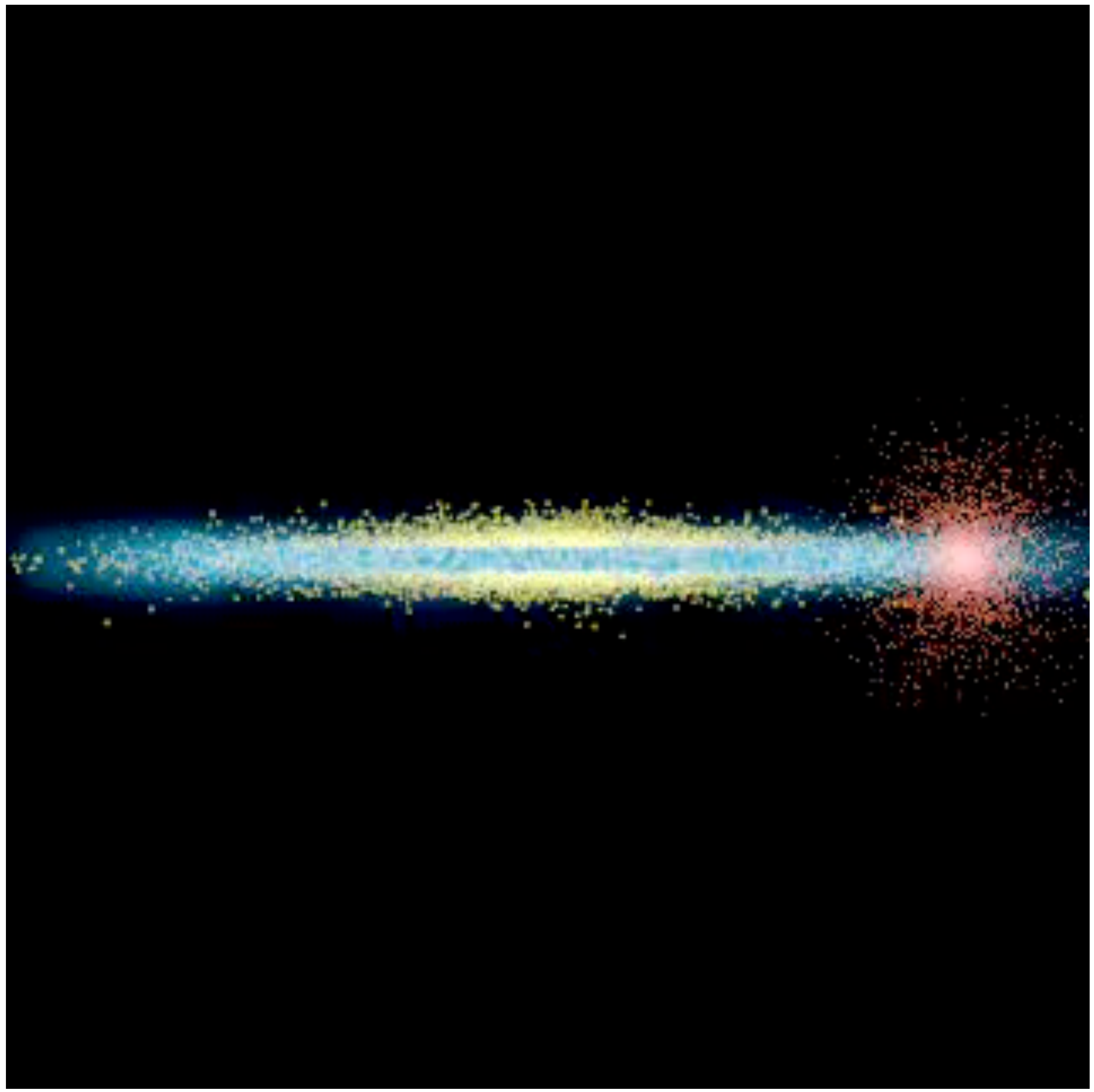
D'Onghia et al. 2016

N-body model of a Galactic collision



Chris Mihos and Sean Maxwell (Case Western Research University)

N-body model of a Galactic collision



Chris Mihos and Sean Maxwell
(Case Western Research
University)

Sagittarius effects

Footprints of the Sagittarius dwarf galaxy in the Gaia data set
Chervin F. P. Laporte et la. 2018
https://arxiv.org/pdf/1808.00451.pdf

- N-body simulation of interaction of a Sagittarius-like dSph with the Milky Way
- Sgr excites coupled oscillations in the vertical and radial directions
- Able to reproduce qualitatively many of the recently uncovered features in the 6D Gaia data
- Too large amplitude of the features
- We need more detailed modelling

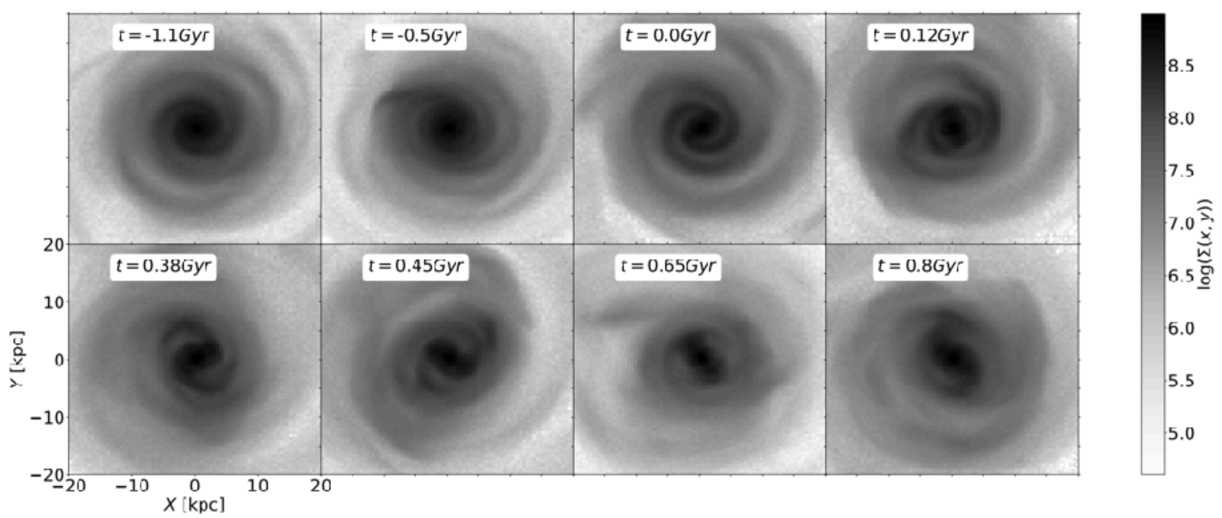


Figure 1. Surface density evolution of the Galactic disc during the last stage of the Sgr impact on the disc. The last two pericentric passages of Sgr occur at $t \sim -0.5$ Gyr and $t \sim 0.0$ Gyr which seed the formation of a strong bi-symmetric spiral as well as fast bar with pattern speed $\Omega = \omega/m \sim 65$ km/s/kpc. Sgr's present-day position in the L2 model is reached at $t \sim 0.38$Gyr but due to the uncertainty in the orbital period of Sgr (Niederste-Ostholt et al. 2012; Dierickx & Loeb 2017; Laporte et al. 2018b), we follow the response of the disc for another $\Delta \sim 0.5$ Gyr window.

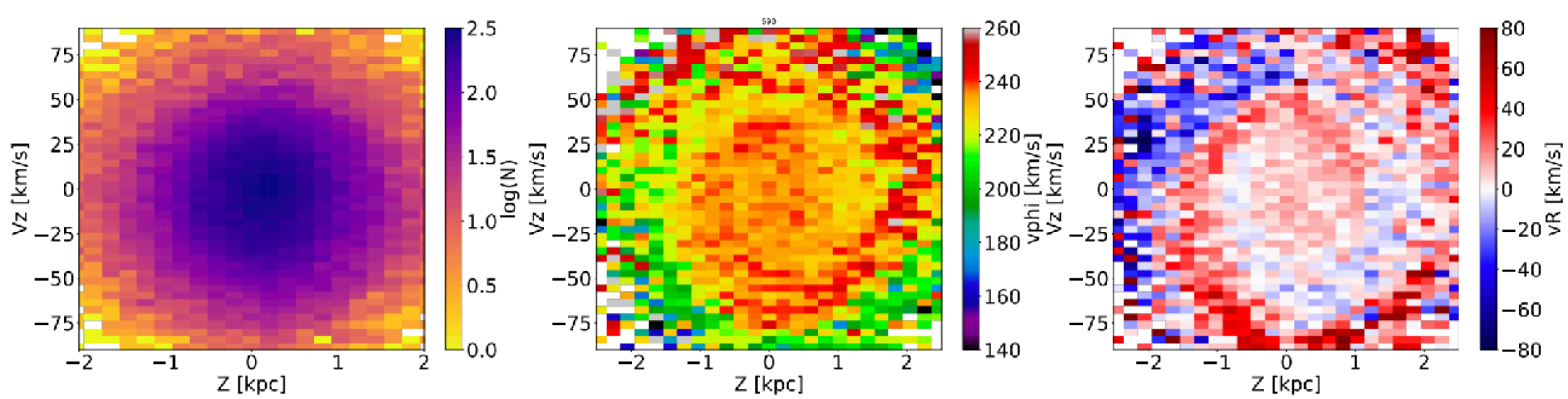


Figure 3. Phase-space spiral in a solar neighbourhood-like region in the disc following after the impact with Sgr at $t = 0.8$ Gyr. *Left:* $\rho(Z, V_Z)$ map. *Middle:* $V_\phi(Z, V_Z)$ snail pattern showing ~ 2 wraps . *Right:* $V_R(Z, V_Z)$ map showing two consecutive wraps. These maps are in qualitative agreement with those observed in the real data. These are first such maps reproduced by an N-body simulation of the Sgr dwarf impacting the disc. Disagreements on the quantitive side lie in the amplitude of the spiral pattern which is larger by a factor of ≈ 2.

Bar effects

“The echo of the bar buckling: phase-space spirals in Gaia DR2”
Khoperskov et al 2018

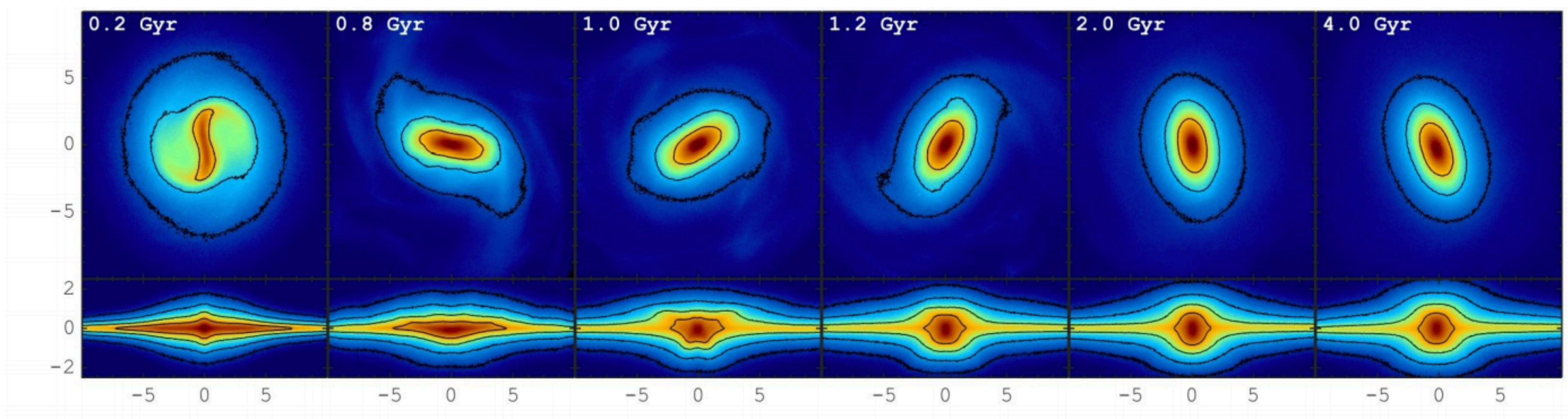


Fig. 1. Face on and edge on projected density evolution of the galactic disk. Buckling phase of the bar is depicted in second and third frames. Note that beyond the bar radius the disk density distribution stays axisymmetric during the entire simulation.

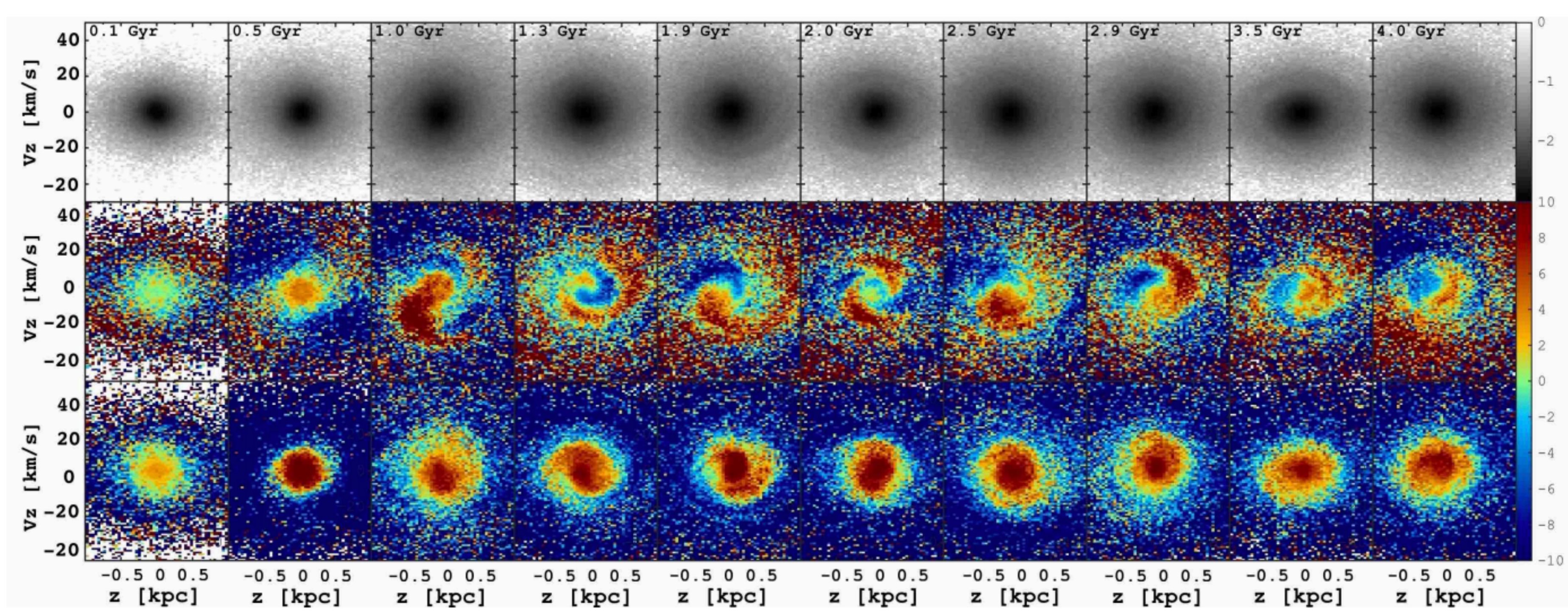


Fig. 3. Evolution of phase-space spiral in $z - v_z$ plane for a solar neighbourhood-like region in the disk, at $R = 8$ kpc. At all times (except the first frame) the bar is rotated by 30 degrees relative to the direction on the galactic center. *Top row:* stellar density distribution $\log(\rho(z, v_z)/\max(\rho(z, v_z)))$, *middle row:* the mean radial velocity, and *bottom row:* the mean residual azimuthal velocity $v_\varphi(z, v_z) - \langle v_\varphi(z, v_z)\rangle$.

- N-body simulation of an isolated Milky Way-type galaxy
- Phase-space spirals develop from vertical oscillations driven by the buckling of the stellar bar
- Bending waves appear and are supported for a long time via disk self-gravity
- Phase-space spirals may have been caused by perturbations originated several Gyrs ago

Vertical bending waves

"Bending Waves in the Milky Way's disc from halo substructure"
Matthew H. Chequers et al. 2018

N-body simulations with smooth dark matter halo + population of subhaloes
Bending waves are excited in the thin disc, superposition of waves and vertical resonances
The Gaia data features might be due to long-lived waves of a dynamically active disc

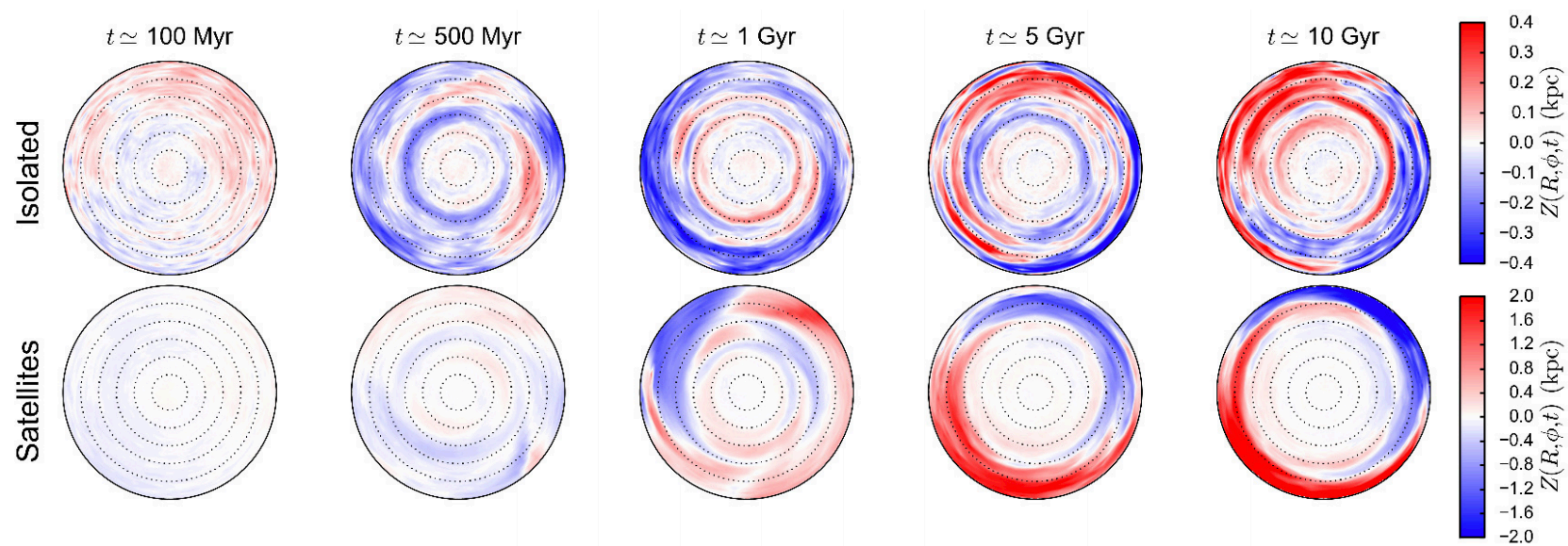


Figure 9. Face-on maps of mean vertical displacement $Z(R, \phi, t)$ for the isolated (top row) and satellite (bottom row) simulations at the same five epochs in Fig. 8. Dotted concentric circles indicate increments of 5 kpc in radius. The rotation of the discs is counter-clockwise.

Implications of the phase spiral

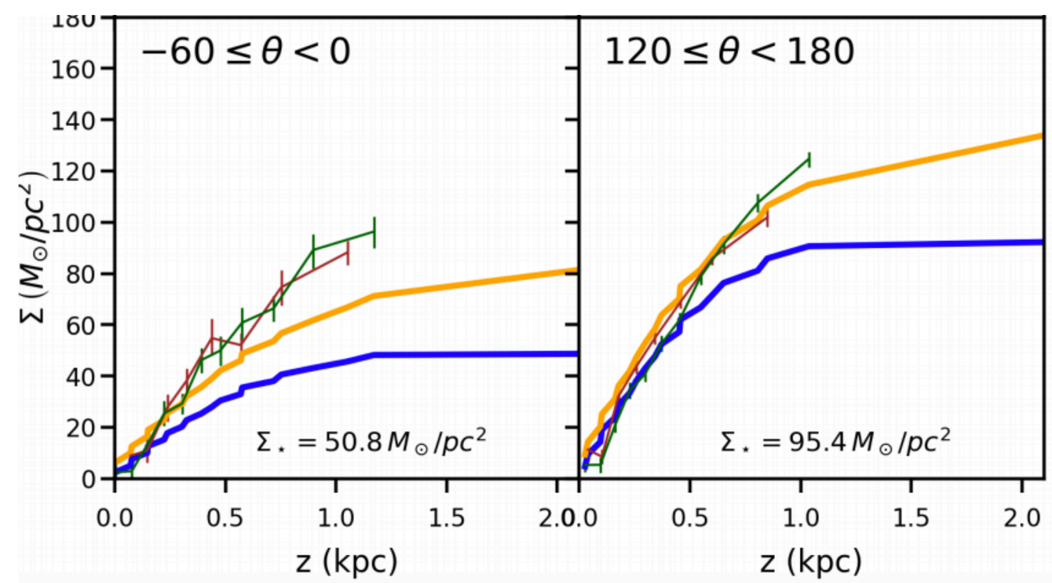
Disk is very sensitive to perturbations, strongly changes with time

Modelling the disk as axisymmetric and time-independent is incorrect

Constraints on the characteristics of Sagittarius (or other perturber) and its orbit

Constraints on the Galaxy potential

SIMULATIONS



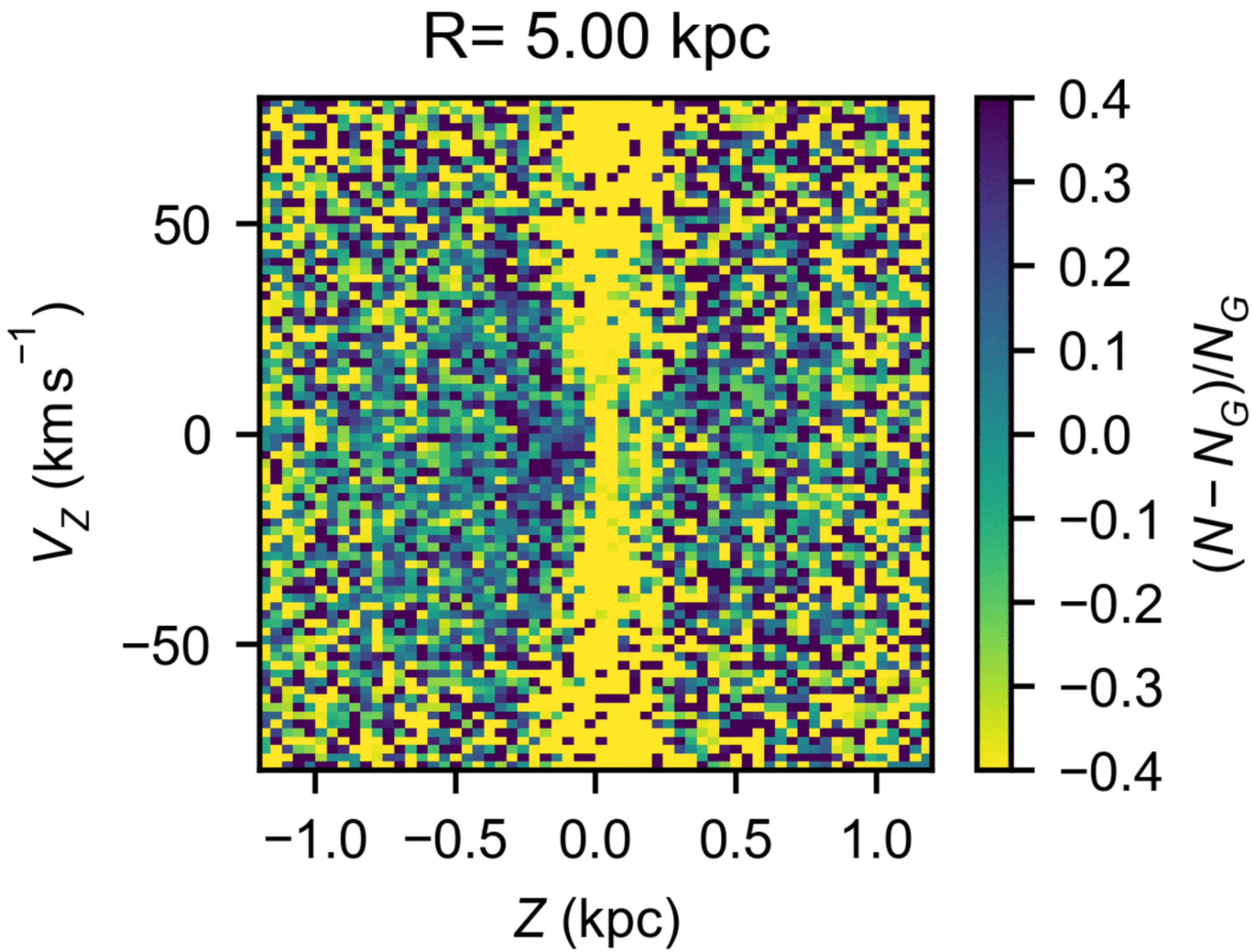
Haines et al. 2019

Jeans modelling could over-predict local dark matter content

Including disequilibria terms?

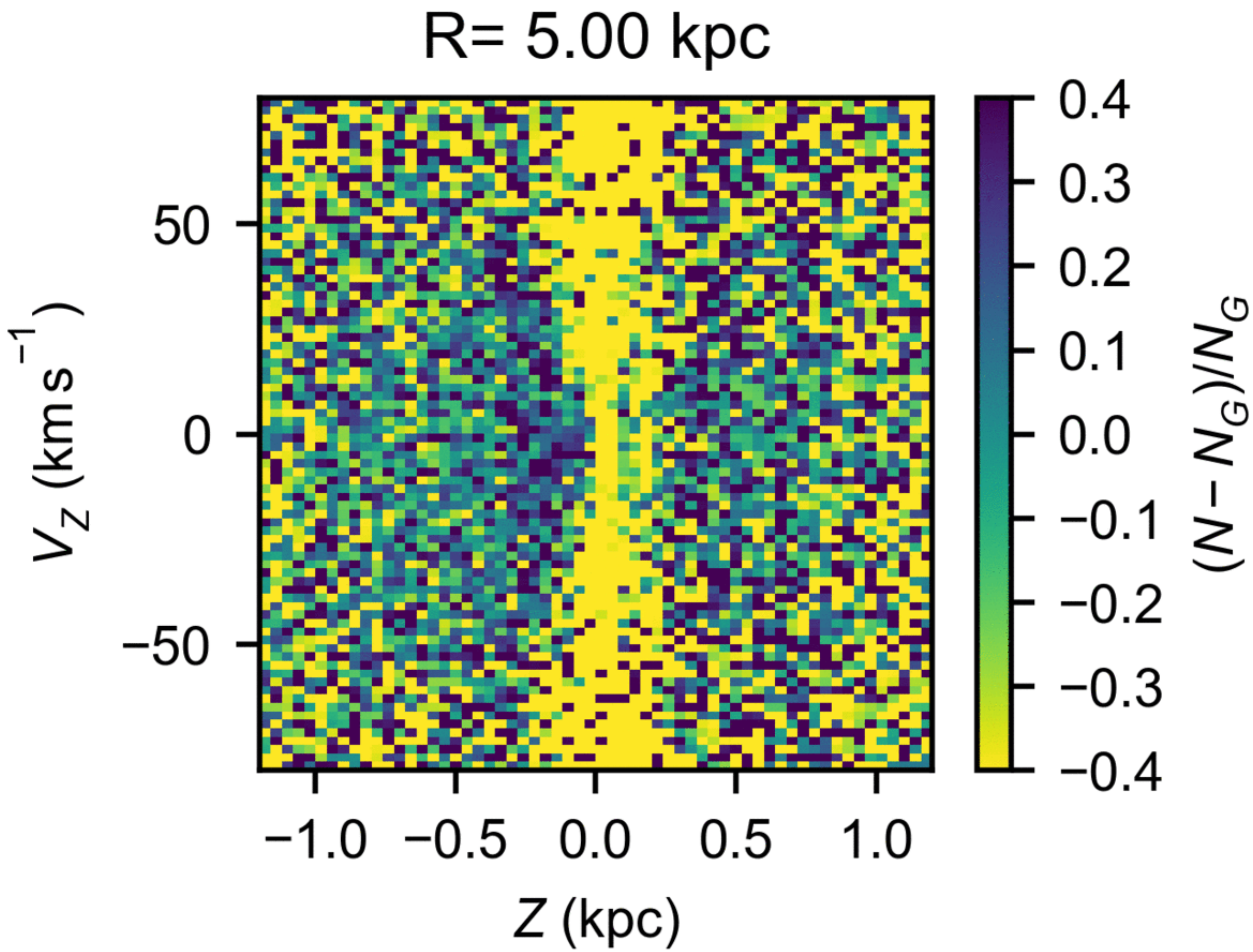
Gaia spiral with R

Gaia spiral with R



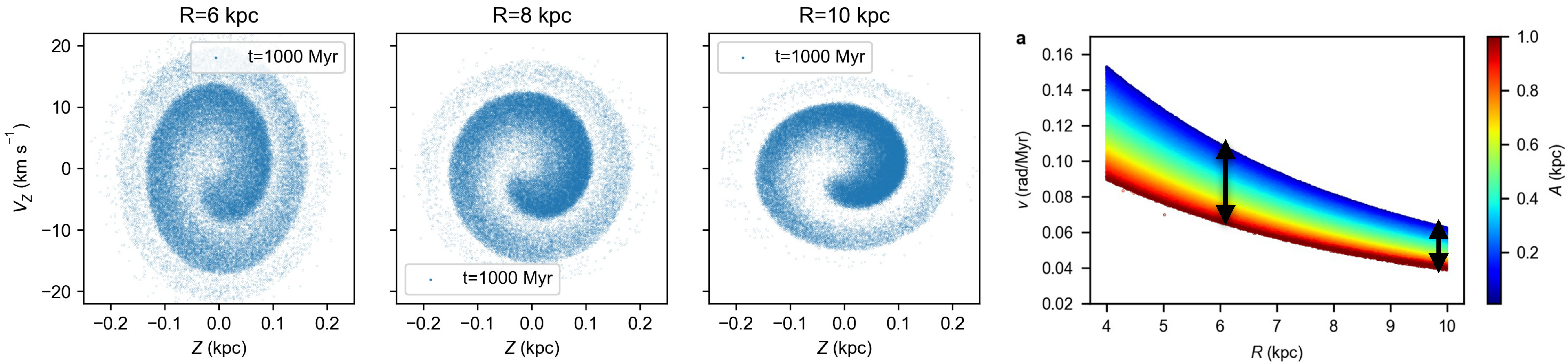
Gaia spiral with R

Phase spiral becomes flattened with R



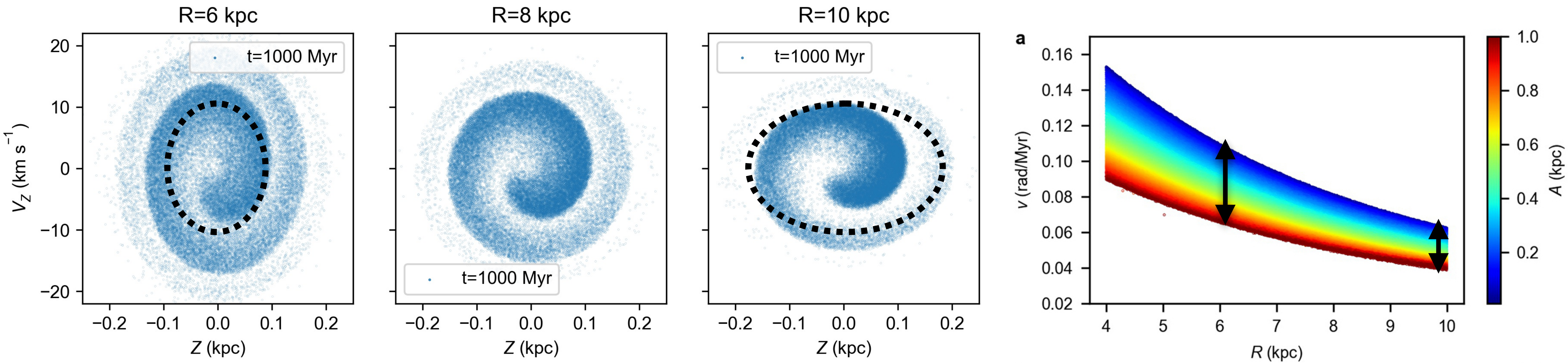
Shape of the spiral for different positions & potentials

Different Galactocentric radius



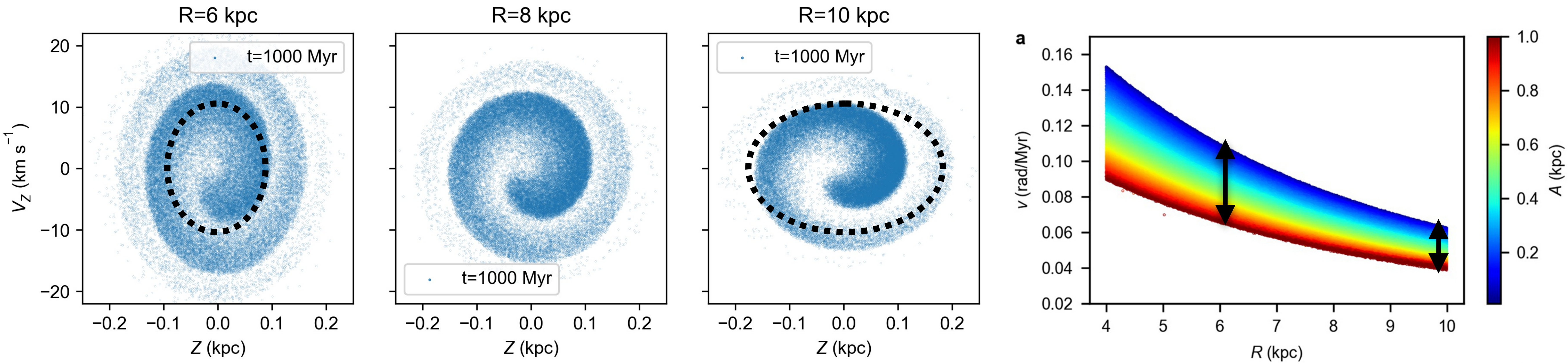
Shape of the spiral for different positions & potentials

Different Galactocentric radius

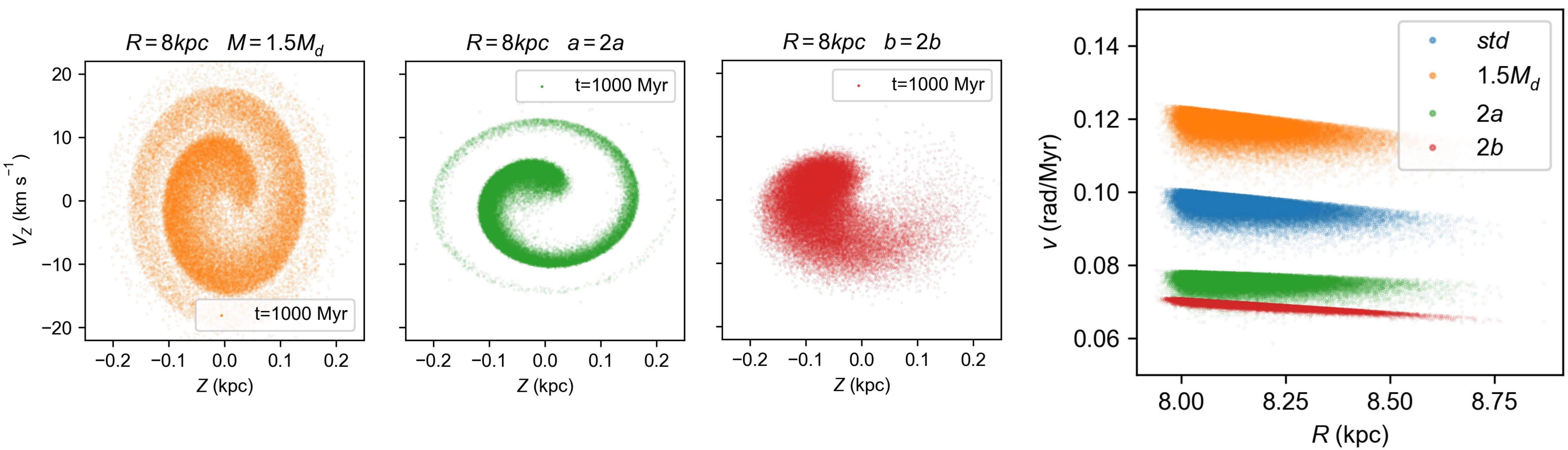


Shape of the spiral for different positions & potentials

Different Galactocentric radius

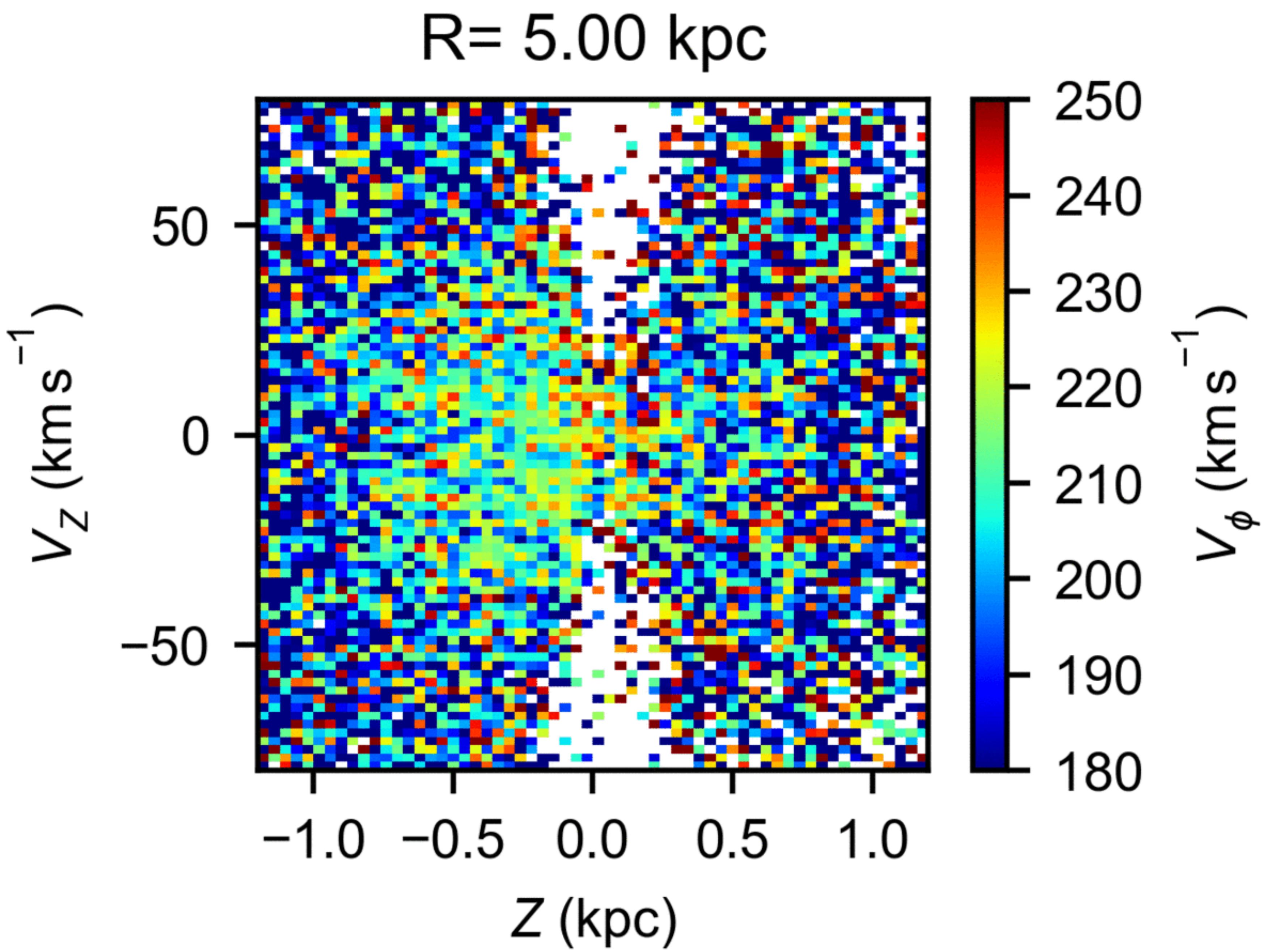


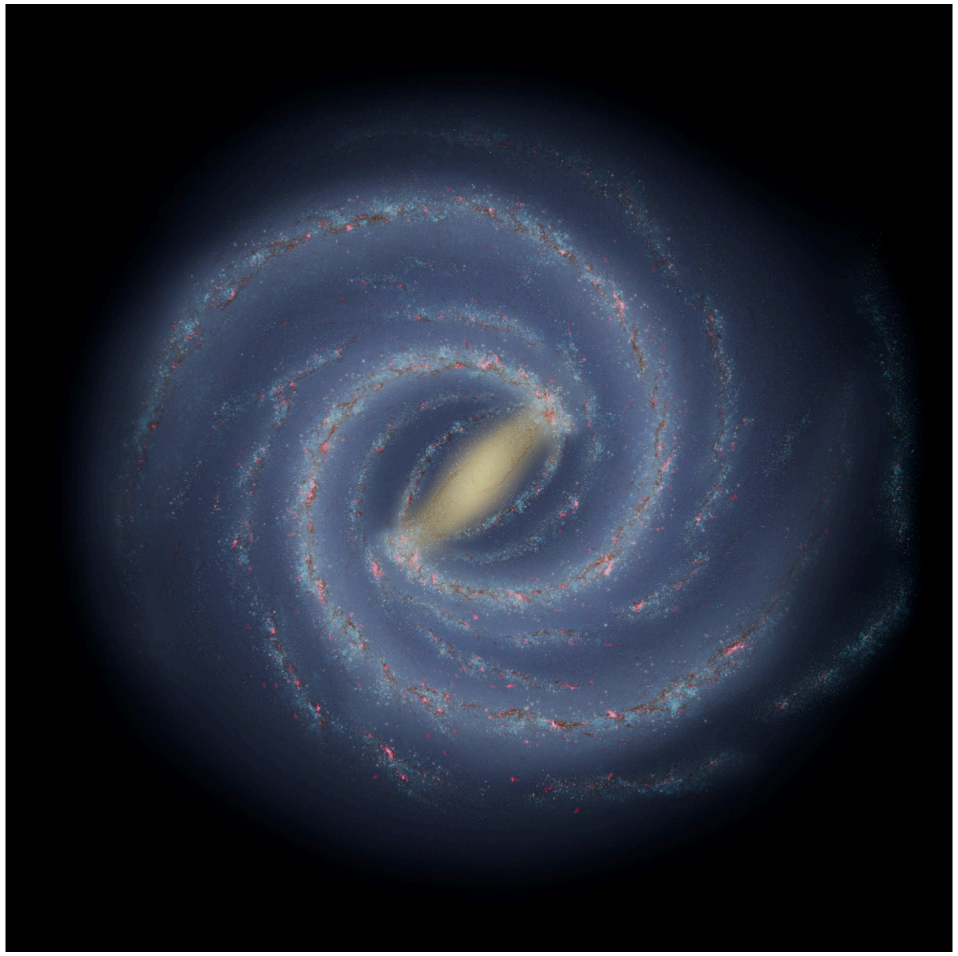
Different Miyamoto-Nagai potential parameters



Gaia spiral with R

Gaia spiral with R





NASA/JPL-Caltech/R. Hurt (SSC/Caltech)

Conclusions & future perspectives

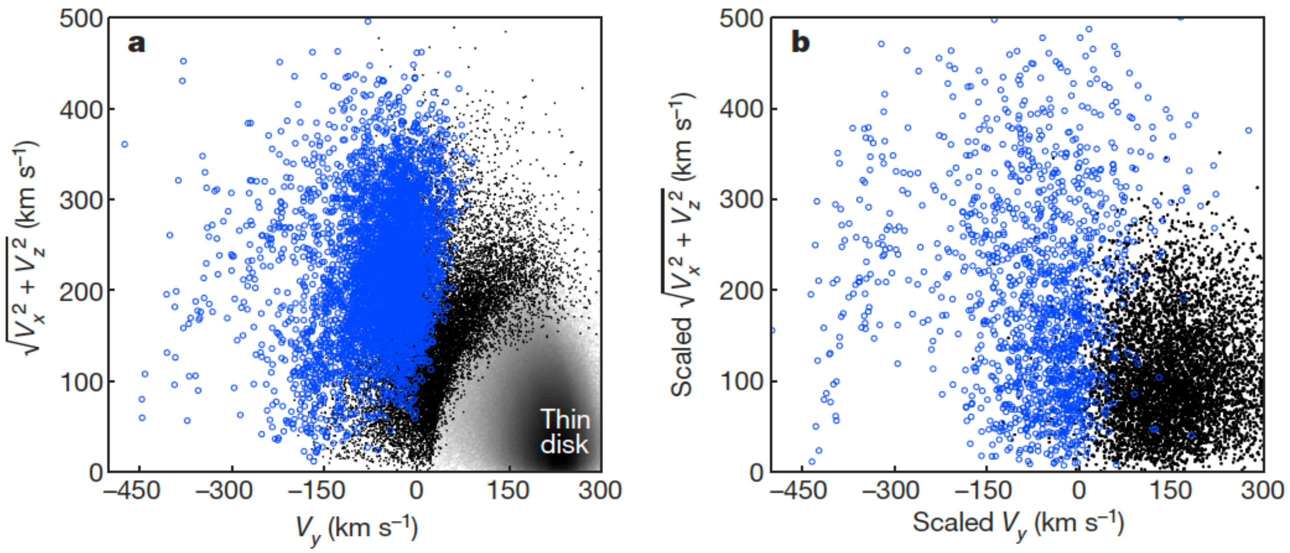
Disk dynamics

- A disk that is highly perturbed
- Debate on how much the evolution of the disk is ruled by internal non-axisymmetries (bar and spiral arms) of by external perturbations
- Towards a definitive theory of spiral structure?
- A disk that is highly out of equilibrium, challenge to classic dynamical modelling
- Self-gravitating bending waves? Signatures of previous impacts? More phase spirals?

Gaia-Enceladus

A disrupted massive galaxy swallowed by the Milky Way

Data from local stars　　Simulation 5:1 merger



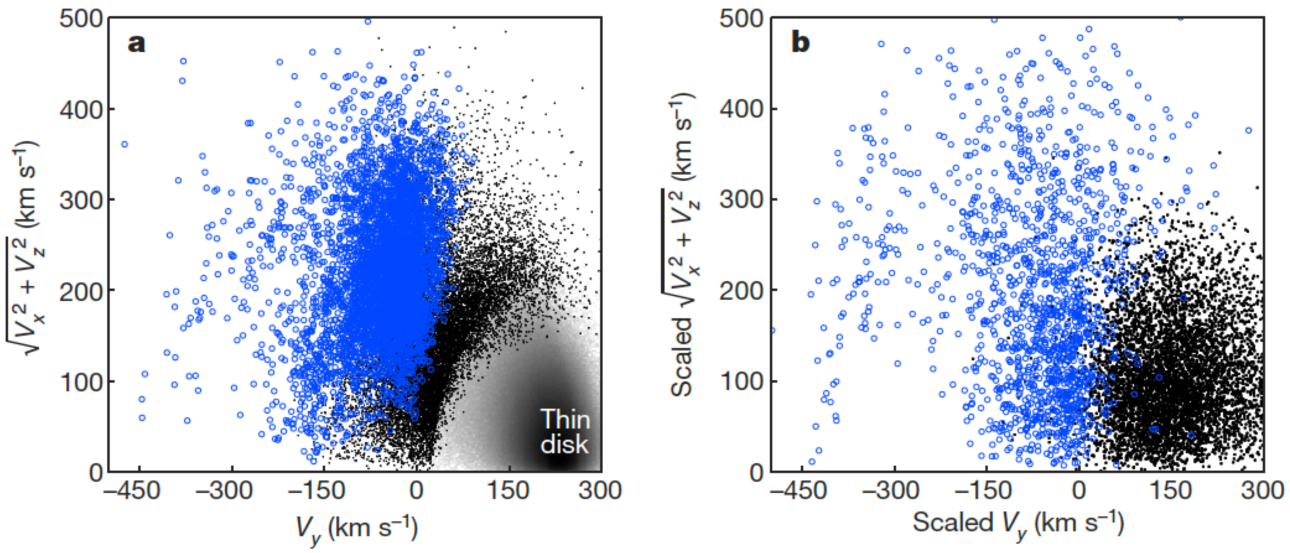
Helmi et al. 2018, Koppleman et al. 2018

See also Belokurov et al 2018, Myeong et al 2018, Gaia colab. Babusiaux et al. 2018, Iorio et al. 2019

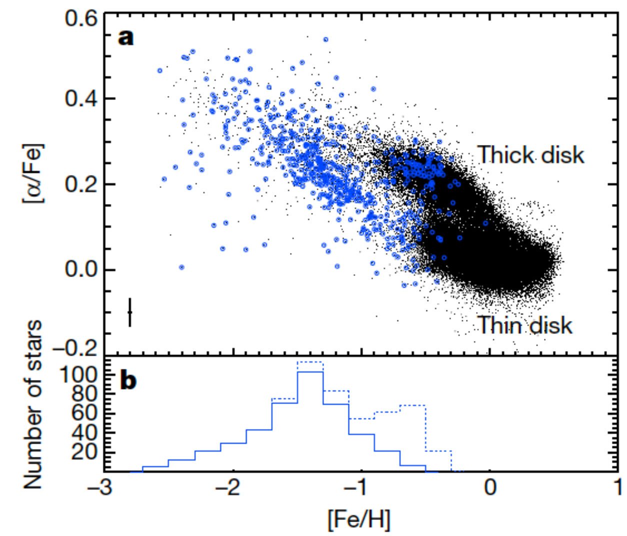
Gaia-Enceladus

A disrupted massive galaxy swallowed by the Milky Way

Data from local stars | Simulation 5:1 merger

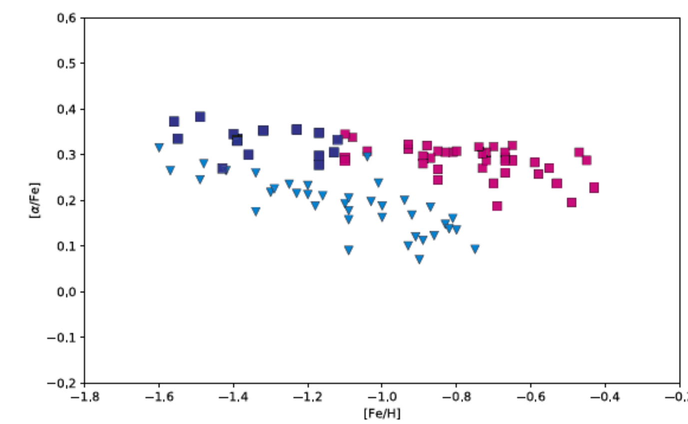


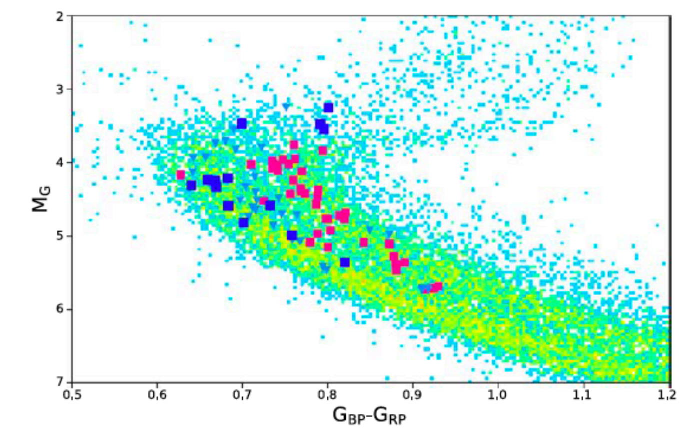
Gaia DR2+APOGEE



Helmi et al. 2018

Gaia DR2+Nissen & Schuster 2010





Helmi et al. 2018, Koppleman et al. 2018

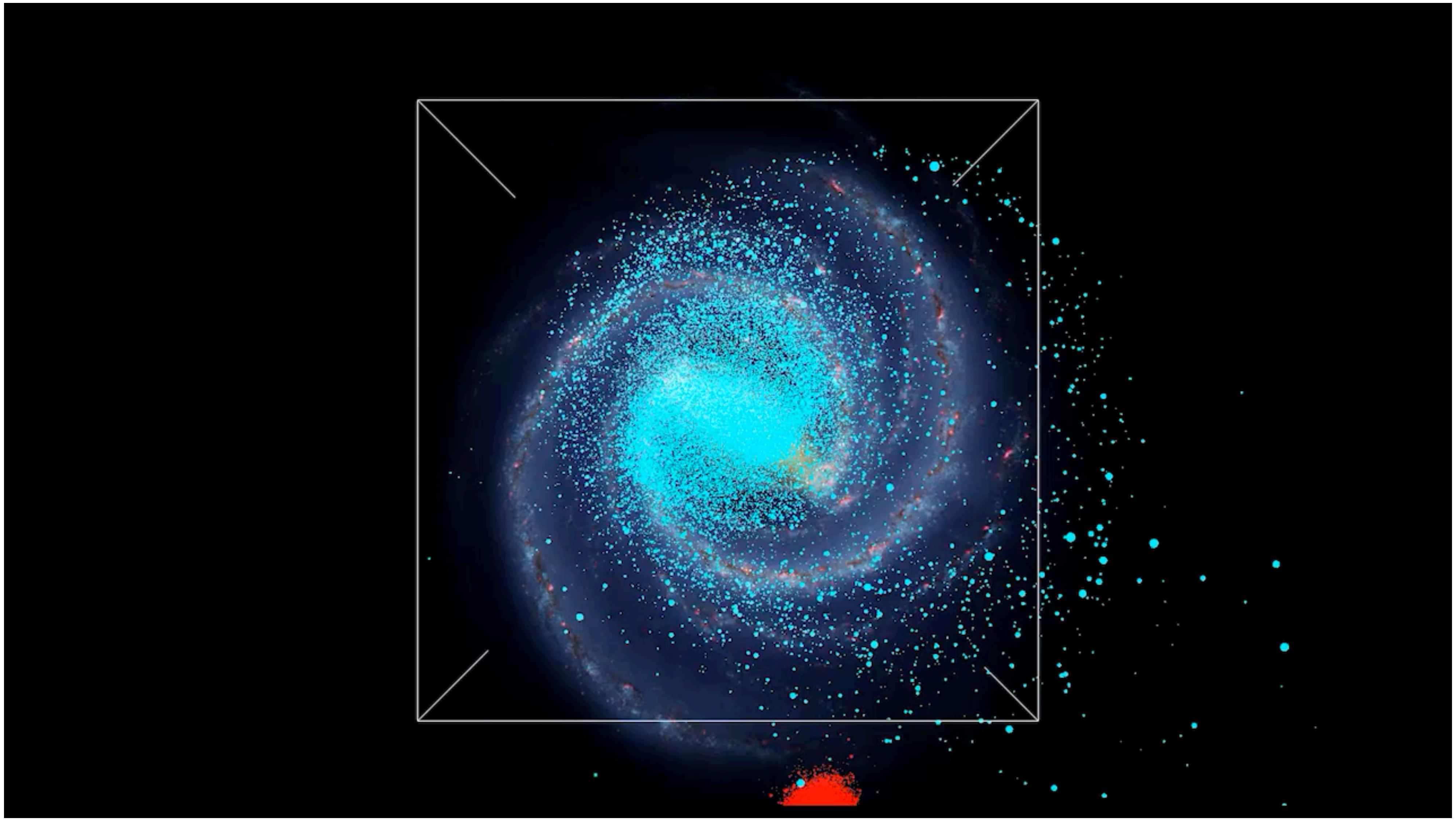
Haywood et al 2018

Chemo-dynamical evindence indicates:

- External origin
- Total mass 10^{11} $M_\odot$ (comparable to SMC today) 4:1 merger
- Merged about 10 Gyr
  —> ORIGIN OF THE THICK DISK
- It could represent 50% of stars in MW halo, expected from simulations
  —> HALO MOSTLY ACCRETED. IS THERE EVEN AN IN-SITU HALO?

See also Belokurov et al 2018, Myeong et al 2018, Gaia colab. Babusiaux et al. 2018, Iorio et al. 2019

Gaia-Enceladus

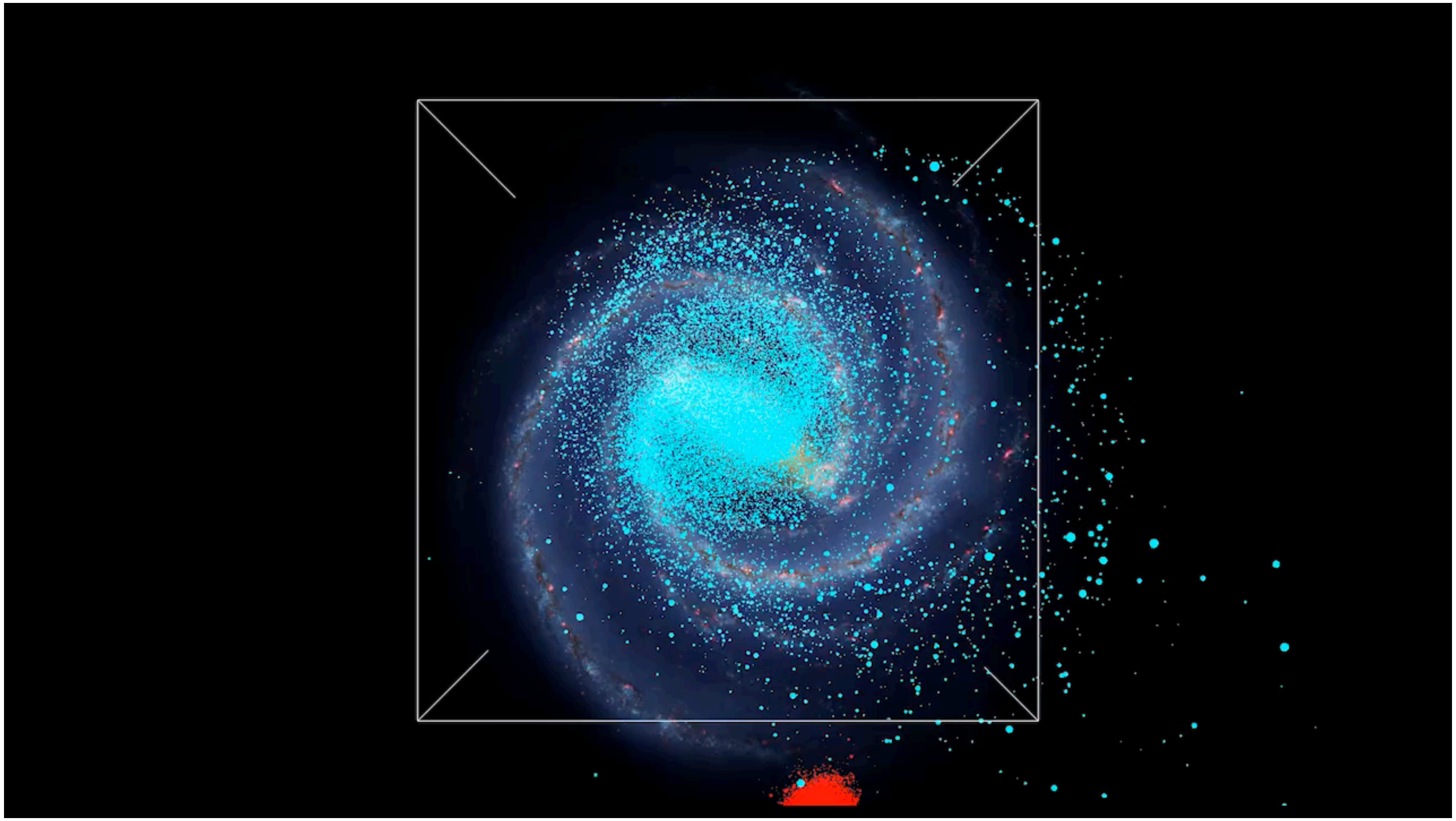


Simulation 5:1 merger

Koppelman, Villalobos & Helmi

Movie in: http://sci.esa.int/gaia/60892-galactic-ghosts-gaia-uncovers-major-event-in-the-formation-of-the-milky-way/

Gaia-Enceladus

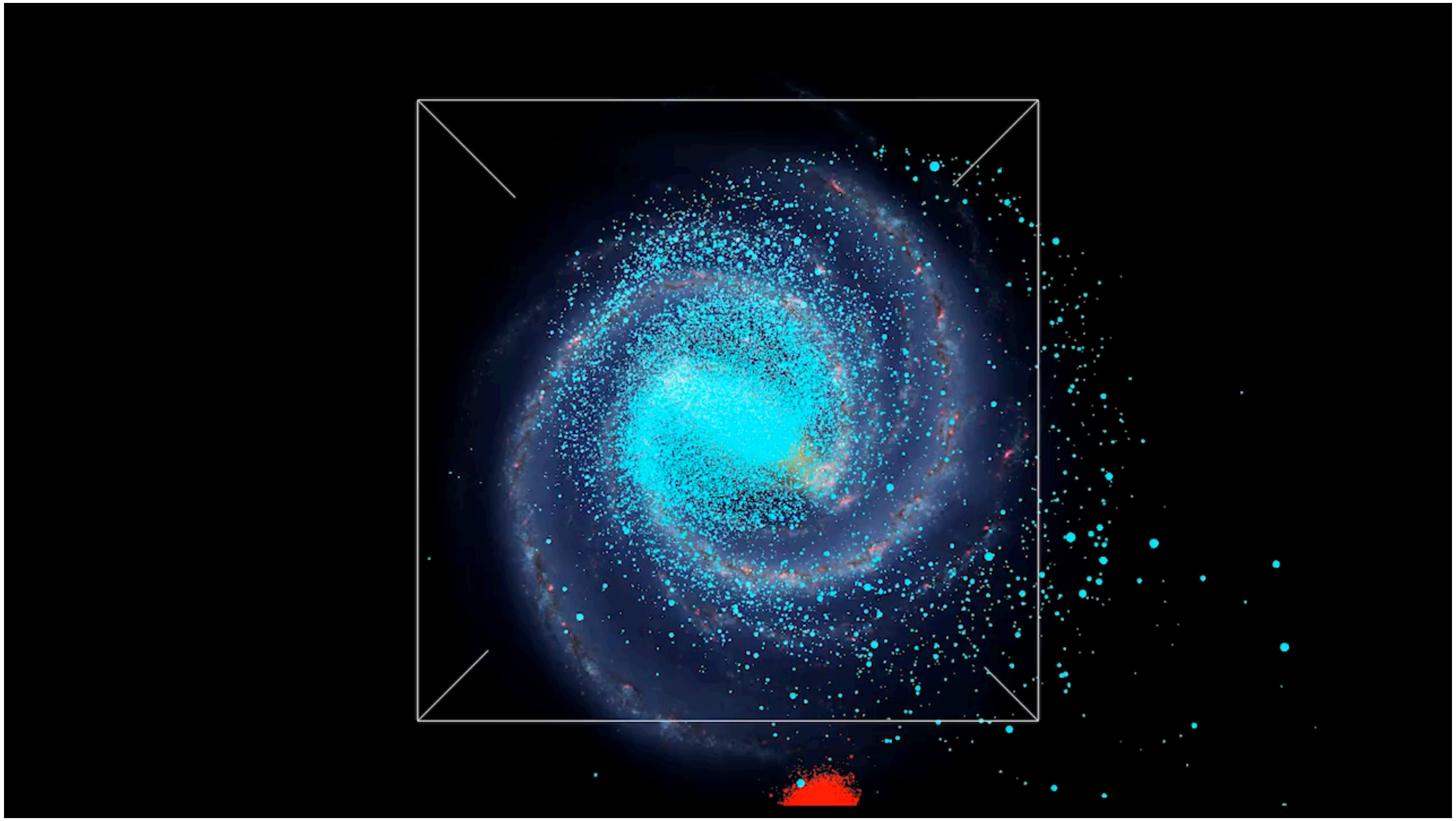


Simulation 5:1 merger

Koppelman, Villalobos & Helmi

Movie in: http://sci.esa.int/gaia/60892-galactic-ghosts-gaia-uncovers-major-event-in-the-formation-of-the-milky-way/

Gaia-Enceladus



Simulation 5:1 merger

Koppelman, Villalobos & Helmi

Movie in: http://sci.esa.int/gaia/60892-galactic-ghosts-gaia-uncovers-major-event-in-the-formation-of-the-milky-way/

Implications for dark matter searches? Data is not well described by standard halo model

Necib et al. 2019, Evans et al. 2019

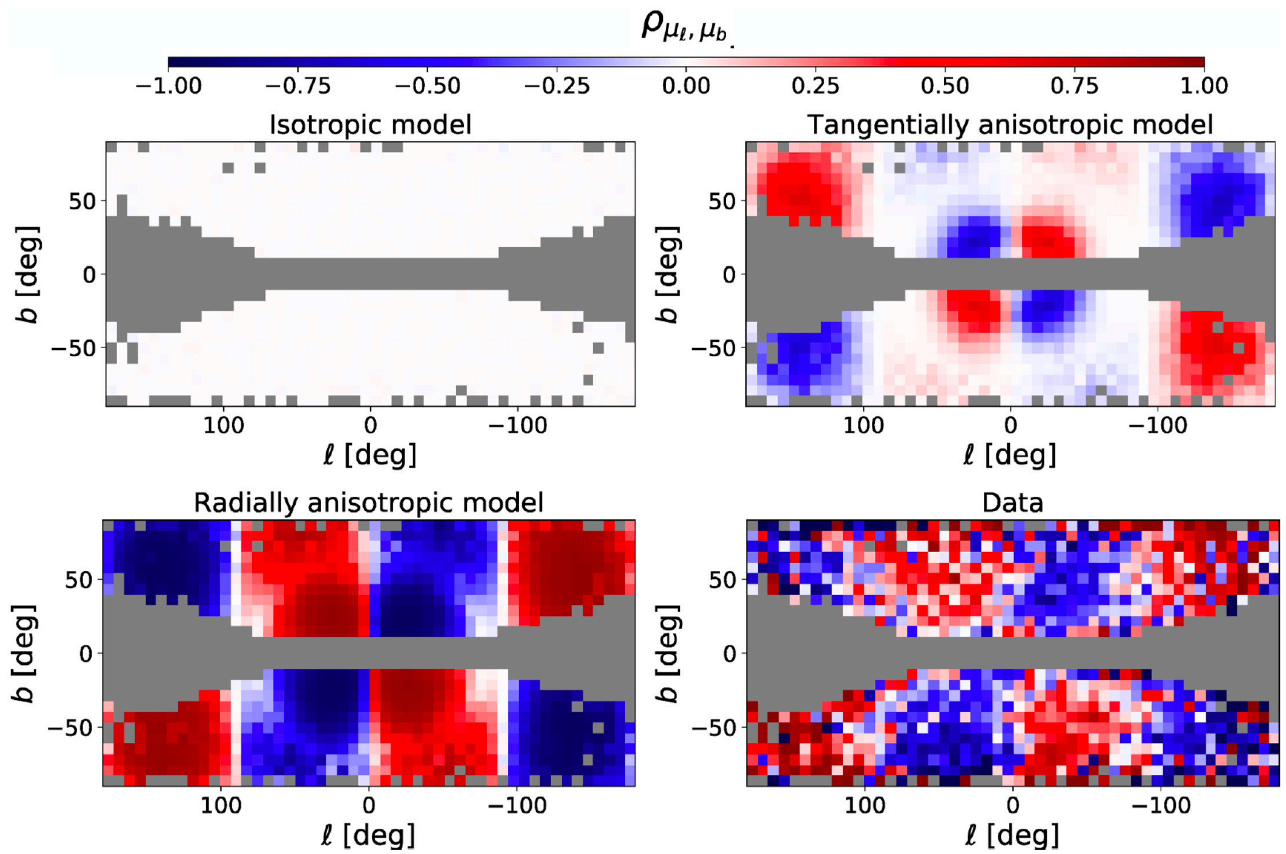
Gaia-Enceladus or Gaia sausage

Also in the outer parts of the halo

Gaia-Enceladus or Gaia sausage

Also in the outer parts of the halo

~93 000 RR Lyrae



Iorio et al. 2018

high-eccentricity orbits suggesting low-angular momentum collision (head-on)

Other dead galaxies and their globular clusters

Each accreted galaxy came with its own retinue of globular clusters

Now identified through orbital properties with Gaia

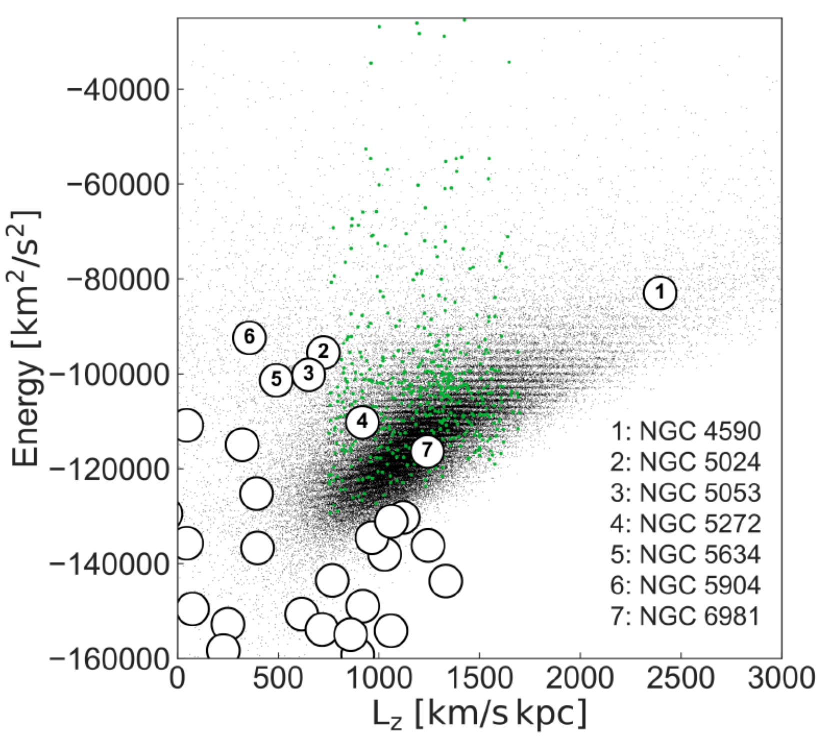
Helmi et al. 2018, Myeong et al. 2018, Koppelman et al. 2018

Progenitor of the Helmi streams

10^8 $M_\odot$

accreted 5-8 Gyr ago

10-15 % of halo



Koppelman et al. 2019

Other dead galaxies and their globular clusters

Each accreted galaxy came with its own retinue of globular clusters

Now identified through orbital properties with Gaia

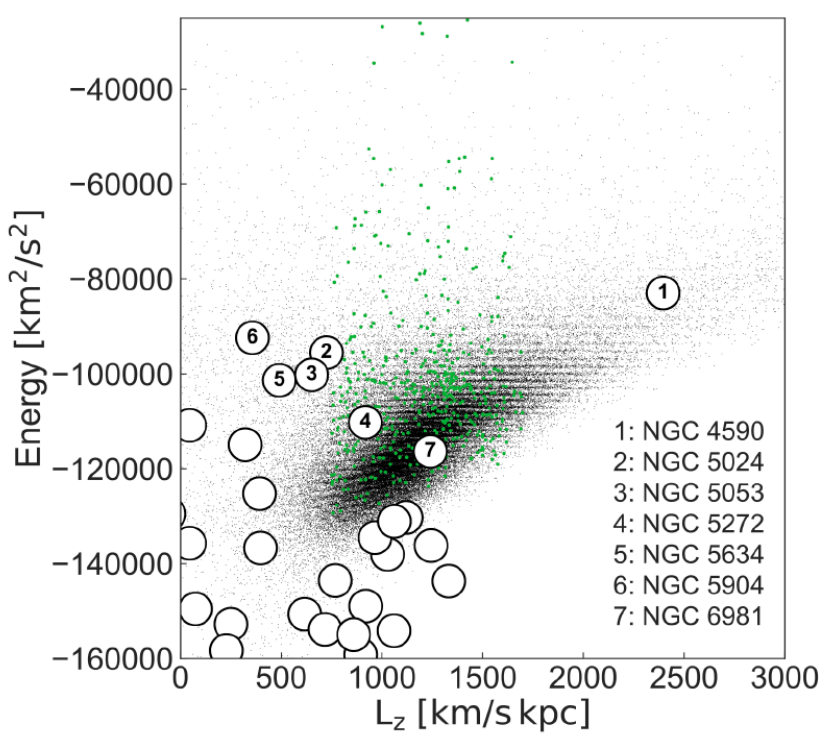
Helmi et al. 2018, Myeong et al. 2018, Koppelman et al. 2018

Progenitor of the Helmi streams

10^8 M⊙

accreted 5-8 Gyr ago

10-15 % of halo

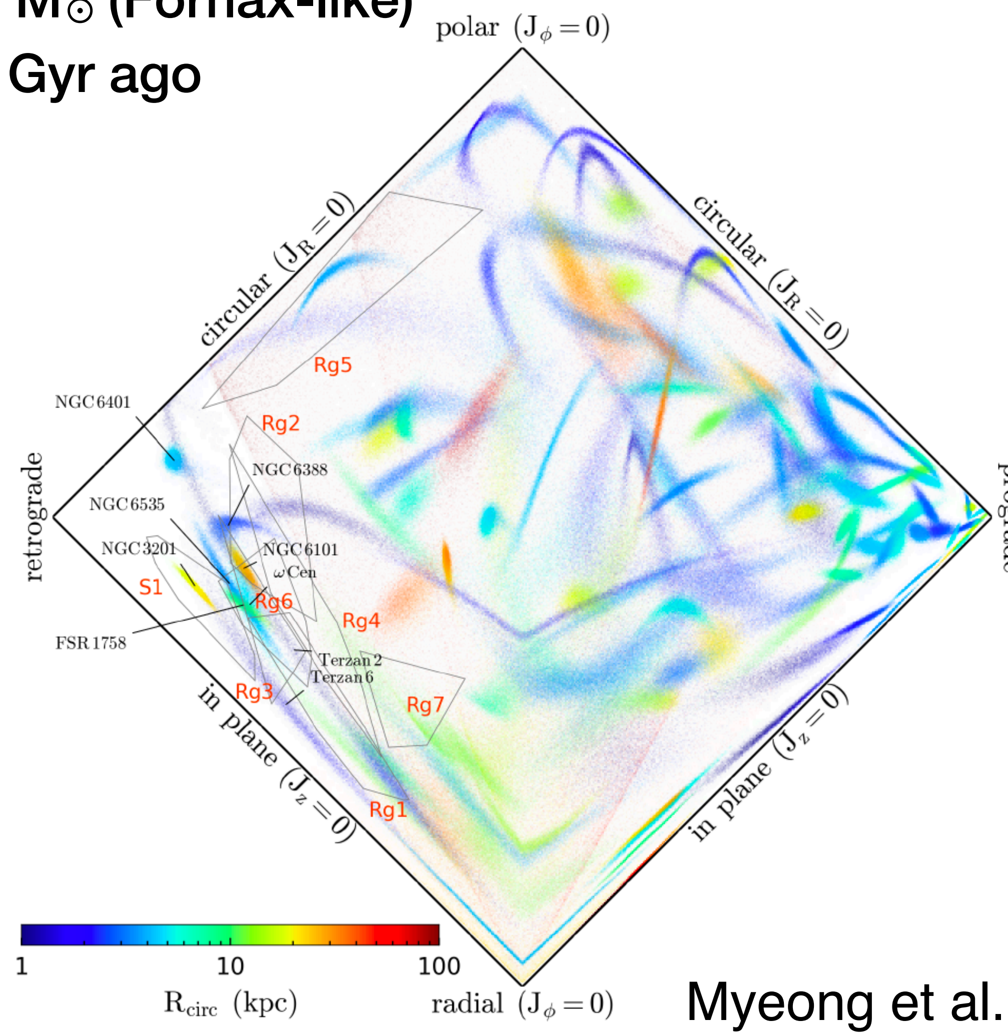


Koppelman et al. 2019

Sequoia

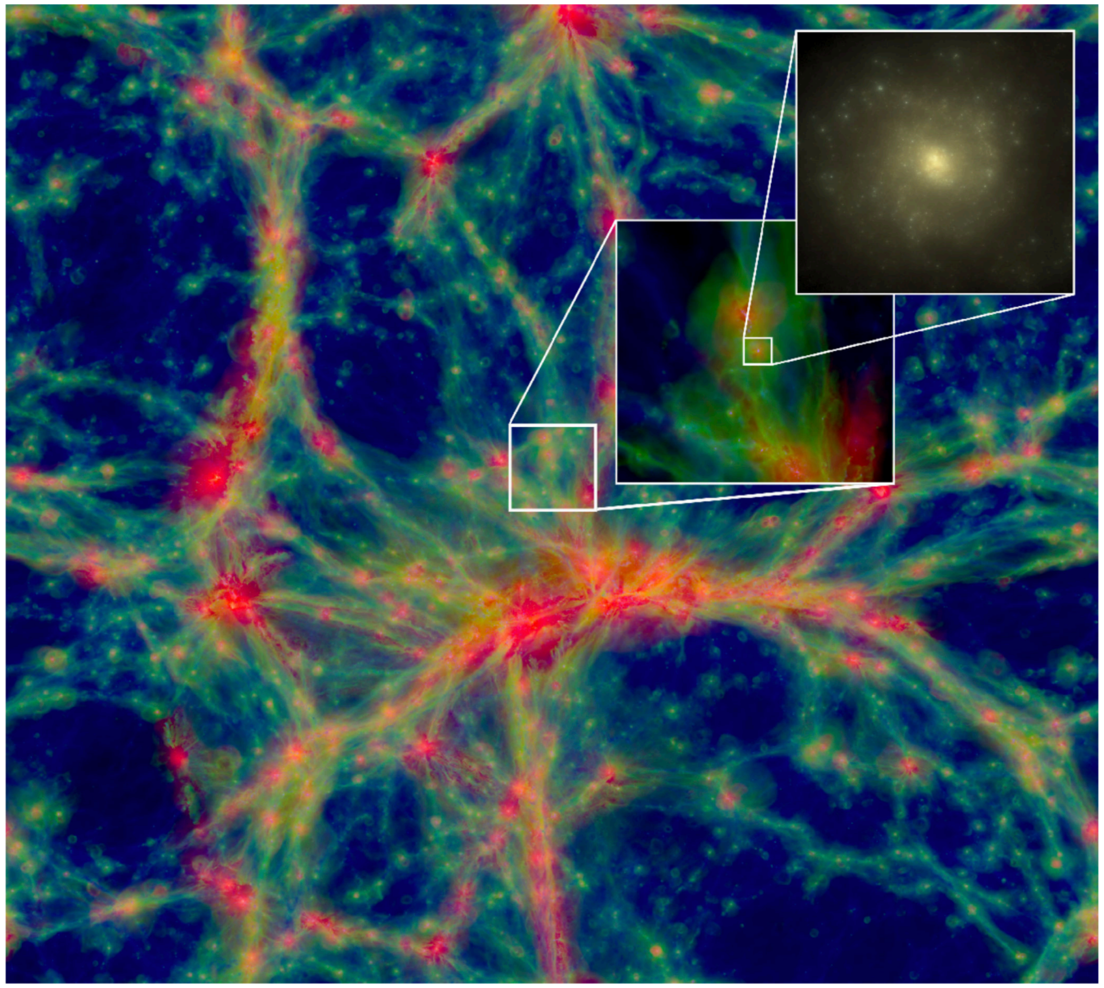
10^{10} M⊙ (Fornax-like)

~10 Gyr ago



Myeong et al. 2019

- At least 5 GCs in a common accretion event
- ωCen progenitor?
- Enceladus and Sequoia associated in the past and accreted at same time?



Schaye et al. 2015

Formation history of the Milky Way

- Redefinition of stellar halo (and thick/old disk, see Haywood et al. 2018 , Di Matteo et al. 2019, Gallart et al. 2019)
- Deciphering the particular events that formed the Milky Way halo
- How these events gave shape to the Galaxy, e.g. creating thick disk, inducing strong disequilibria in thin disk

Anyone interested in solving the so many open questions?