Warps and waves in fully cosmological models of galactic disks

Facundo A. Gómez (MPA)

Collaborators

S. White (MPA)

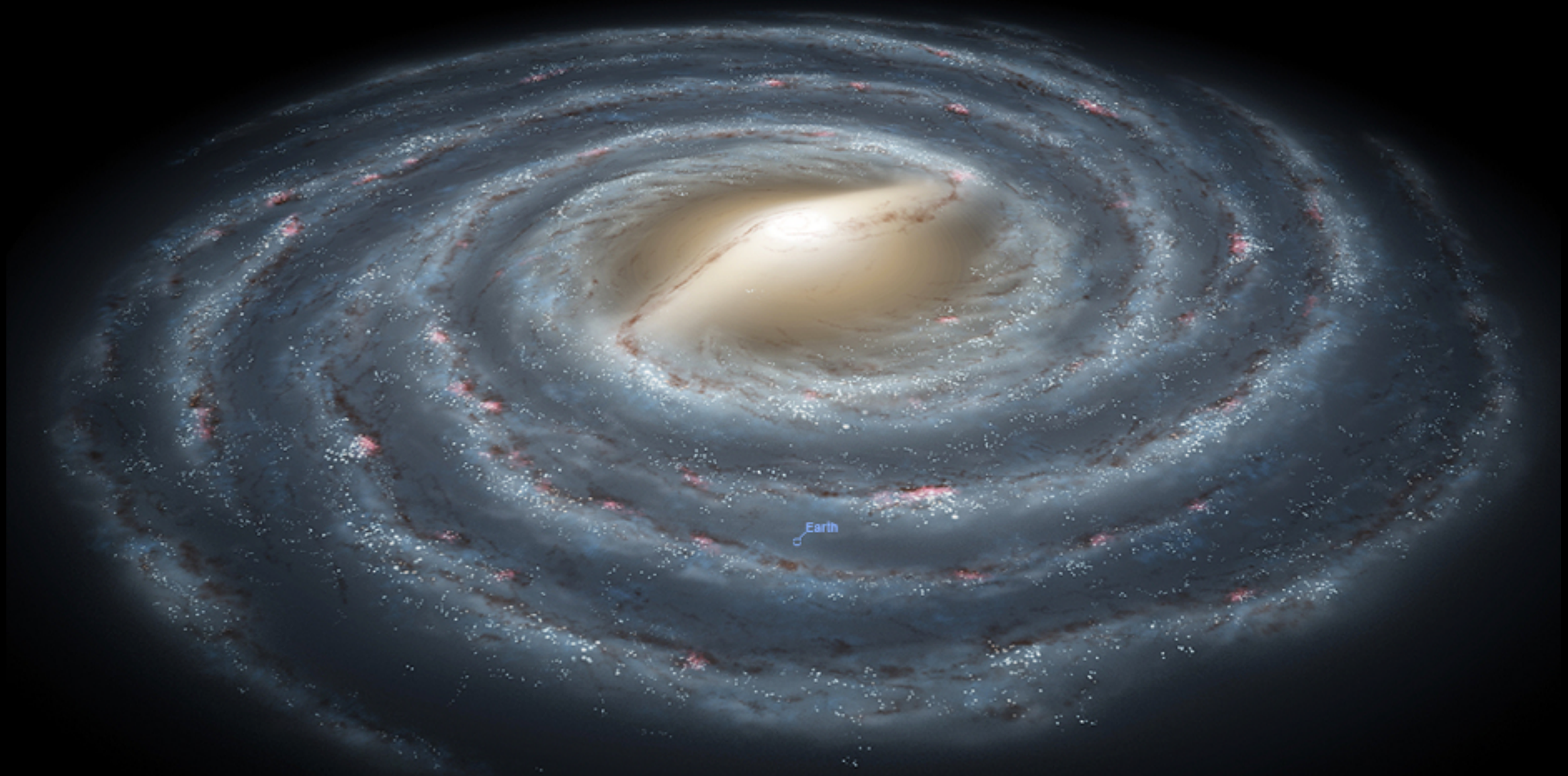
R. Grand (HITS)

F. Marinacci (MIT)

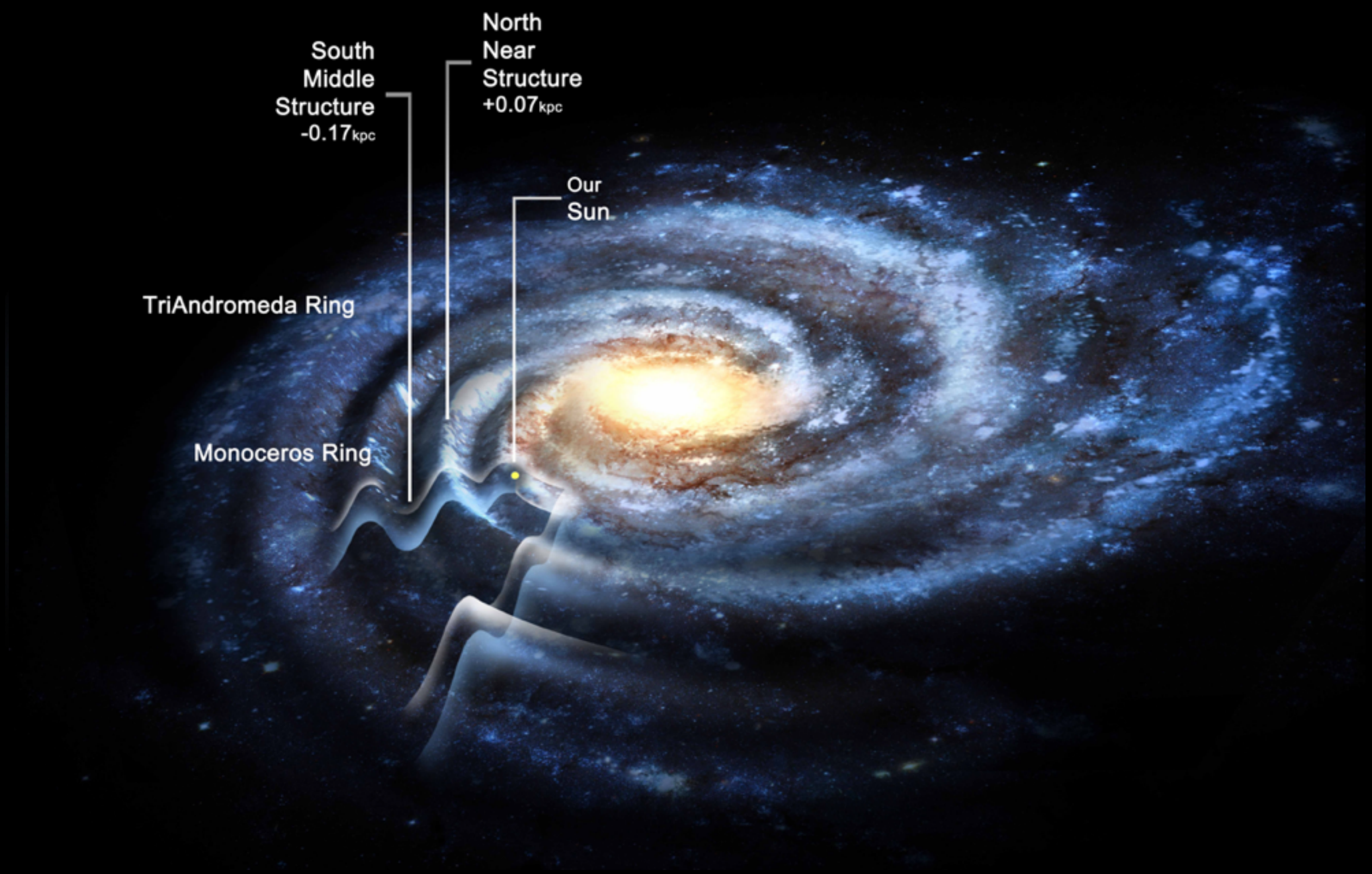
R. Pakmor (HITS)

V. Springel (HITS)

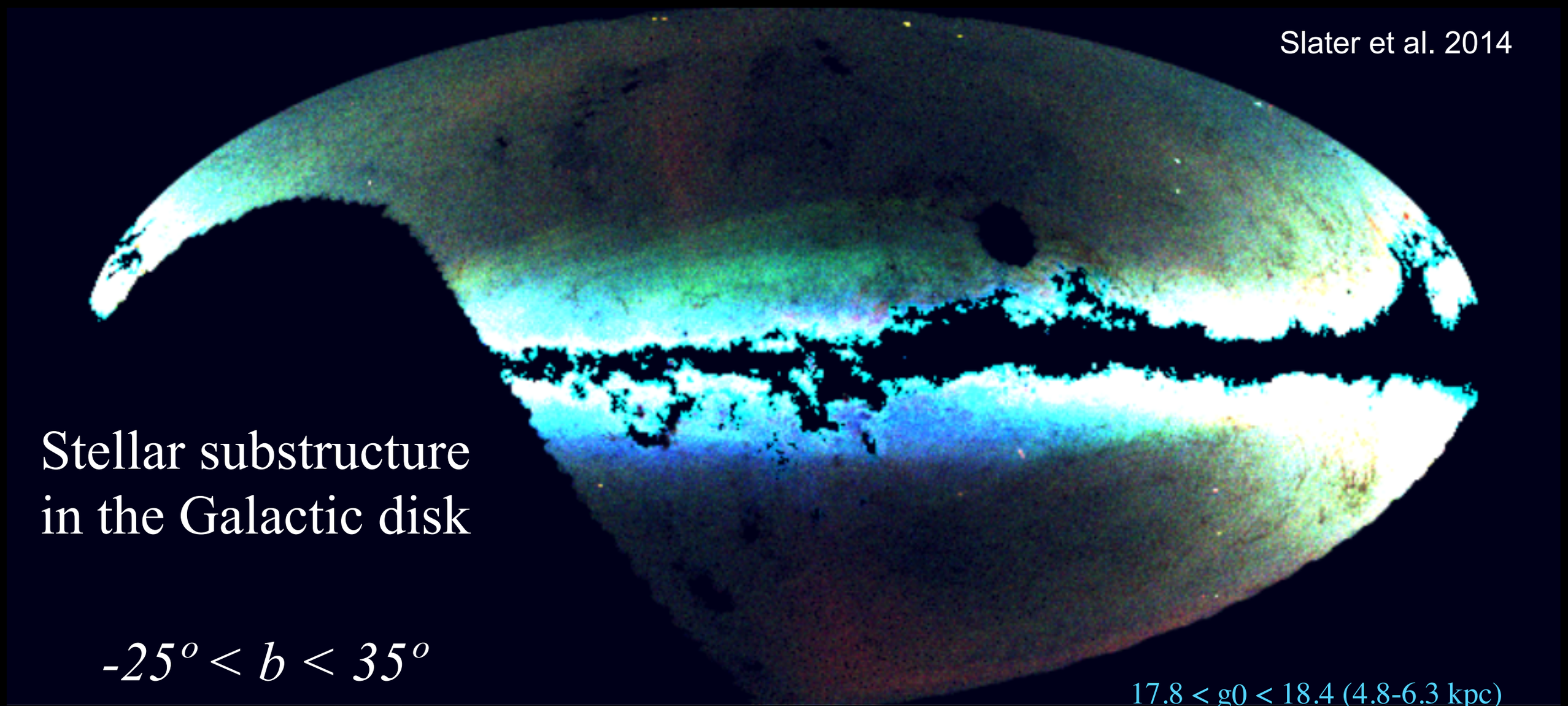
The vertical structure of the Milky Way disk



The vertical structure of the Milky Way disk



Monoceros Ring as seen by Pan-STARRS



Stellar substructure in the Galactic disk

$-25^o < b < 35^o$
over 130° in l

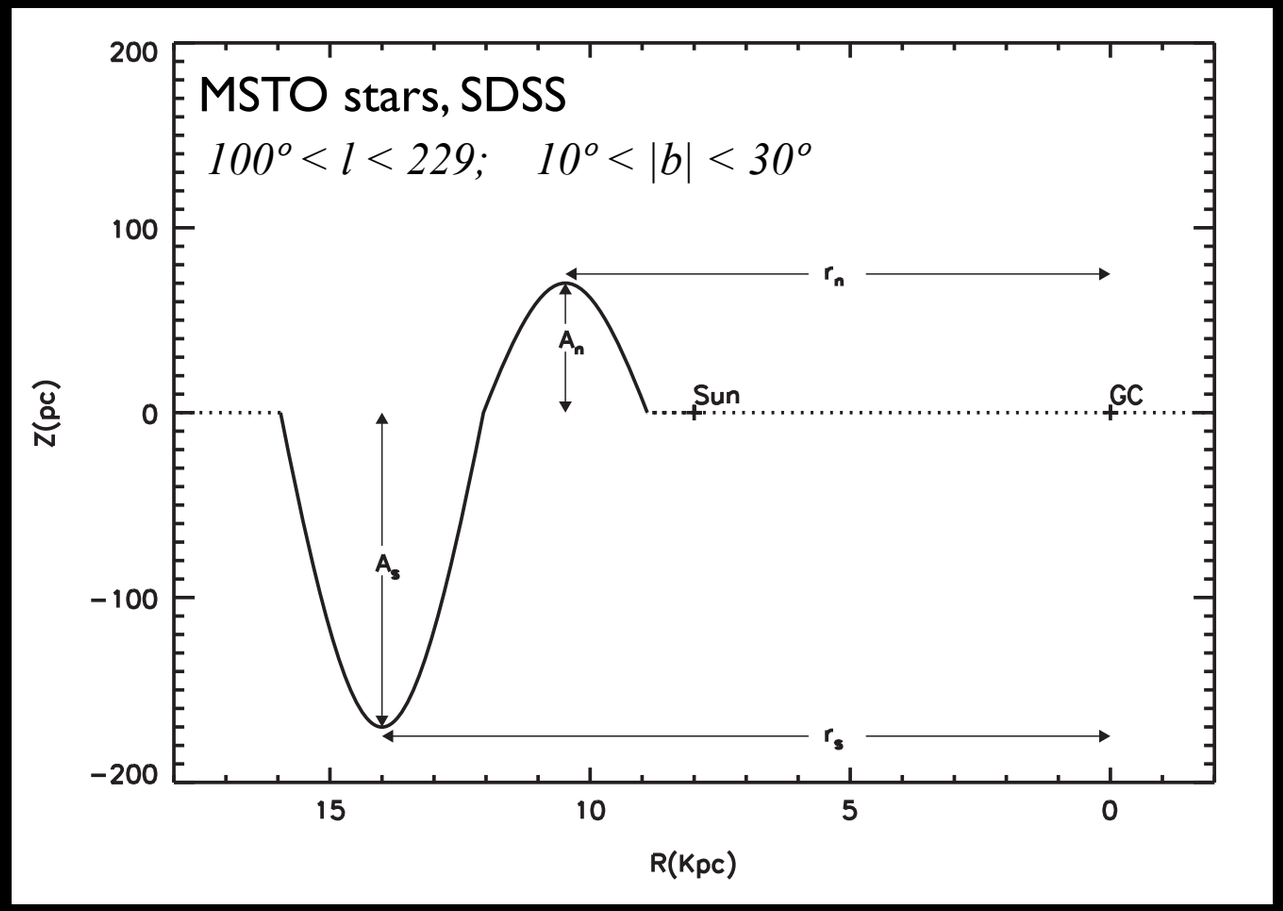
17.8 < g0 < 18.4 (4.8-6.3 kpc)

18.8 < g0 < 19.6 (7.6 - 11.0 kpc)

20.2 < g0 < 20.6 (14.4 - 17.4 kpc)

Vertical waves - Global behavior

Xu, Newberg, et al. 2015

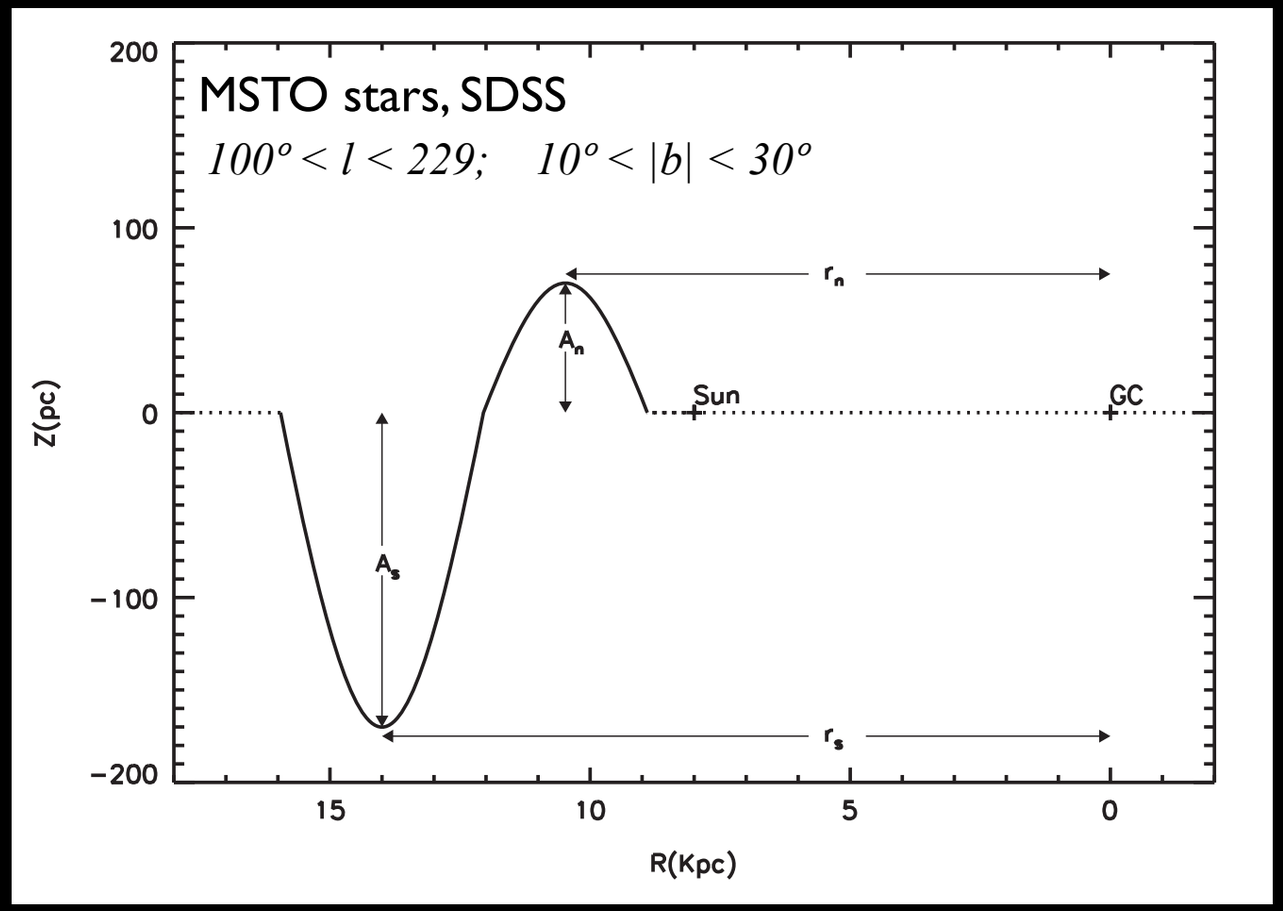


oscillating asymmetry in the main-sequence star counts

Xu, Newberg, et al. 2015

Vertical waves - Global behavior

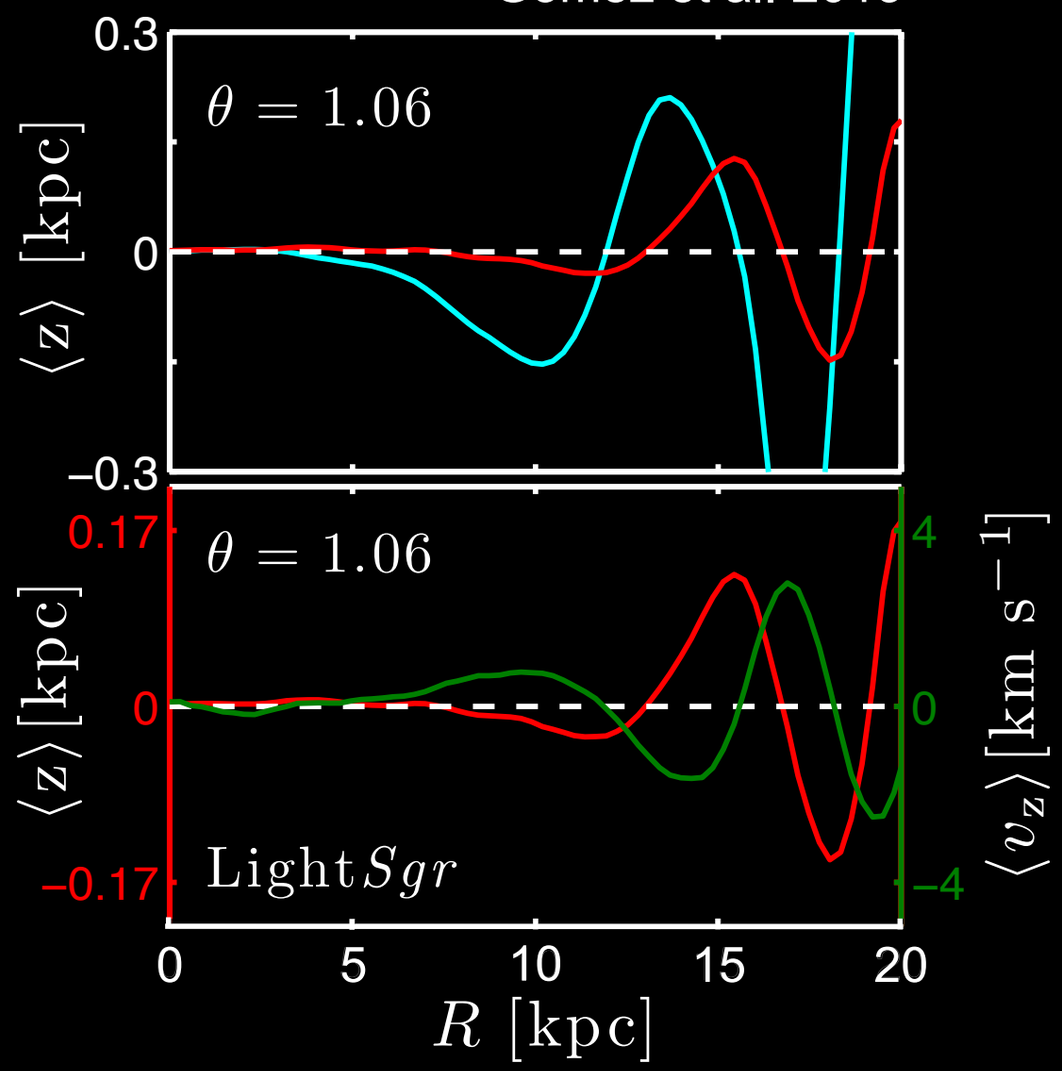
Xu, Newberg, et al. 2015



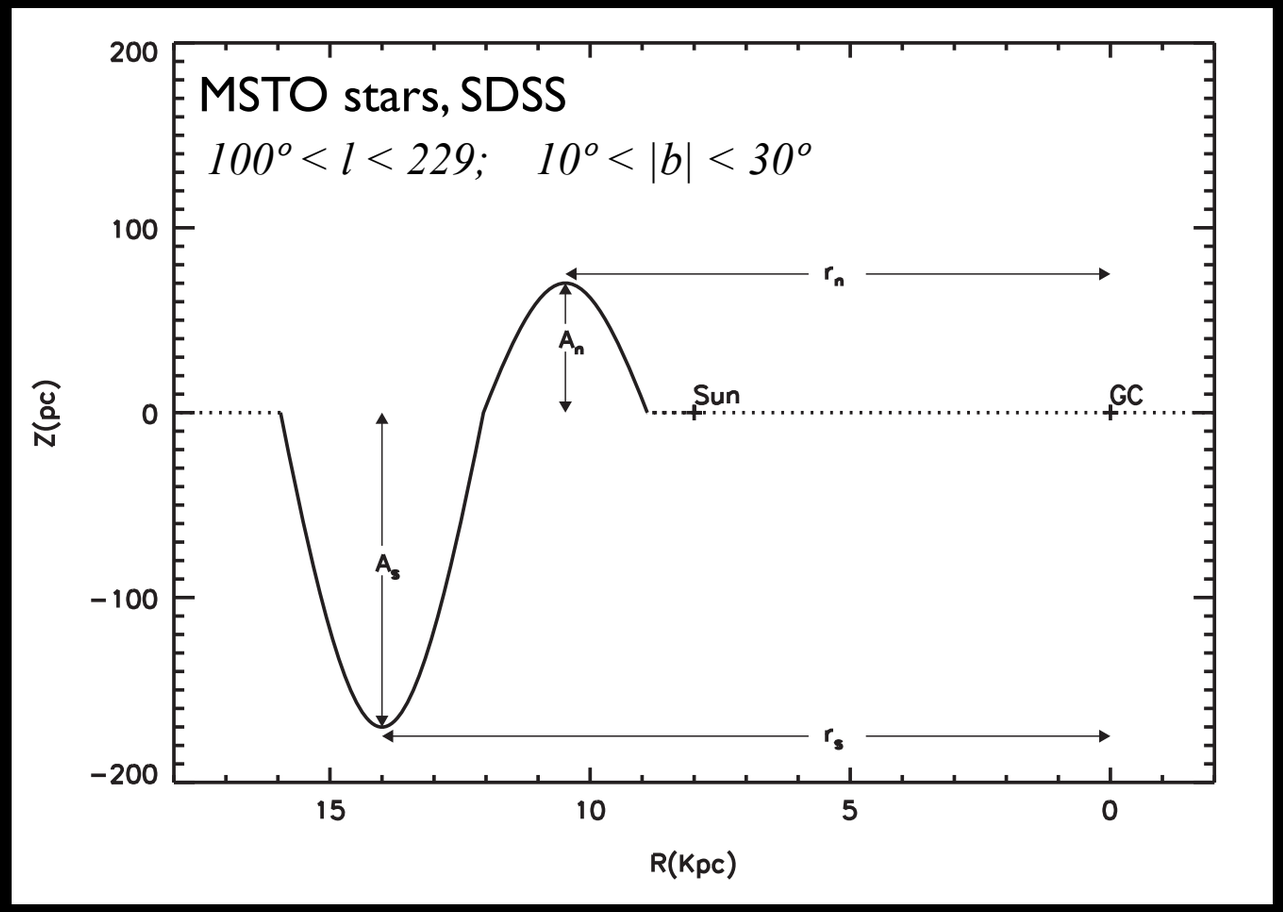
oscillating asymmetry in the main-sequence star counts

Vertical waves - Global behavior

Gómez et al. 2013



Xu, Newberg, et al. 2015



oscillating asymmetry in the main-sequence star counts

Oscillatory behavior!

But idealized simulations...

Can we observe these perturbations in fully cosmological hydrodynamical simulations? Auriga simulations: Aq-C4

Marinacci, Pakmor and Springel 2013

Run	$R_{\rm vir}$ (kpc)	$M_{\rm tot}$ ($10^{10}{\rm M}_\odot$)	$M_{\rm gas}$ ($10^{10}{\rm M}_\odot$)	$M_\star$ ($10^{10}{\rm M}_\odot$)	$M_{\rm dm}$ ($10^{10}{\rm M}_\odot$)	$N_{\rm cells}$	$N_\star$	$N_{\rm dm}$	$m_{\rm gas}$ ($10^5{\rm M}_\odot$)	$m_{\rm dm}$ ($10^5{\rm M}_\odot$)	$f_{\rm b}$
Aq-C-5	234.5	159.74	7.09	7.00	145.64	163726	273124	674547	4.11	21.59	0.51
Aq-C-6	235.5	161.82	9.86	5.95	146.00	28702	26803	84525	32.90	172.73	0.57
Aq-C-4	234.4	159.48	8.39	5.31	145.71	1526514	1637981	5399079	0.51	2.70	0.49

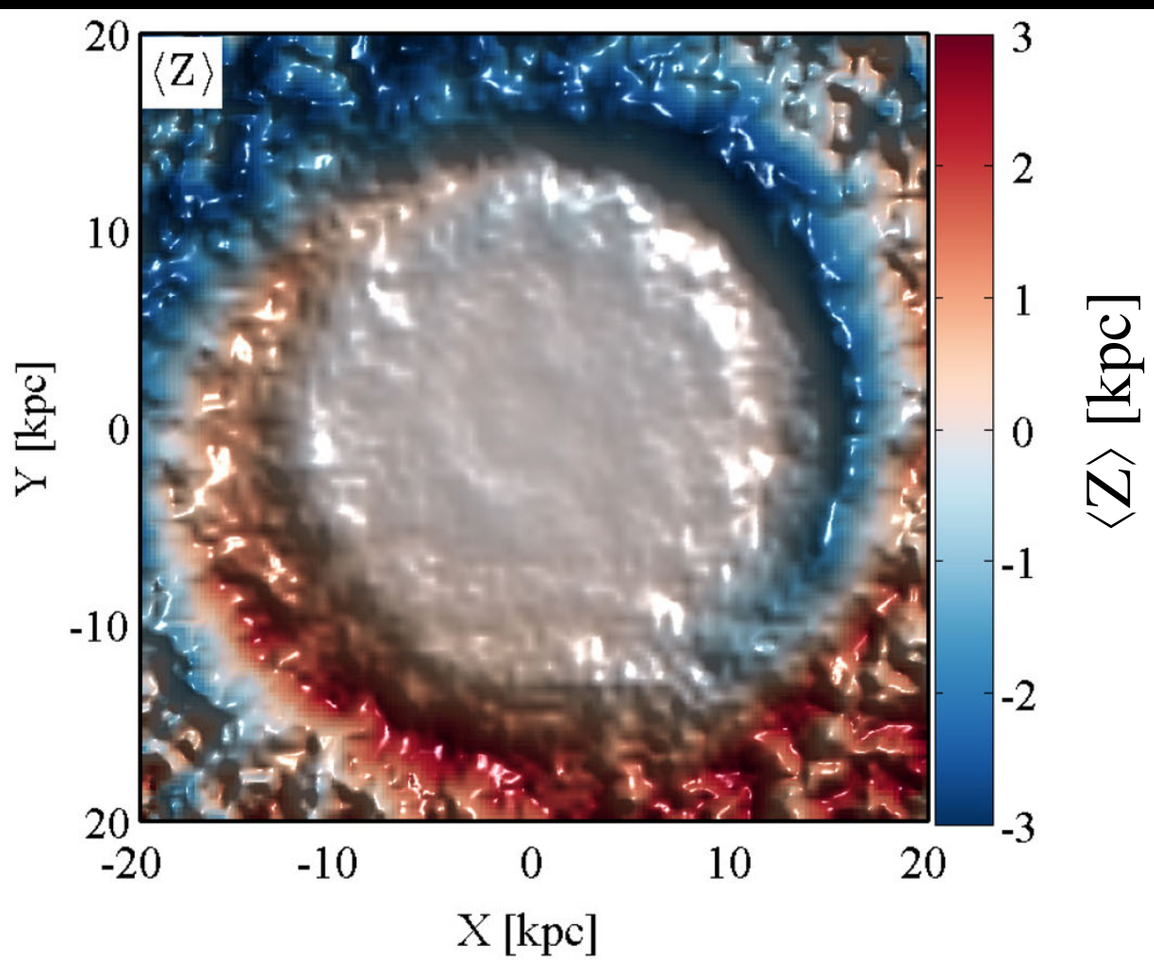
Can we observe these perturbations in fully cosmological hydrodynamical simulations? Auriga simulations: Aq-C4

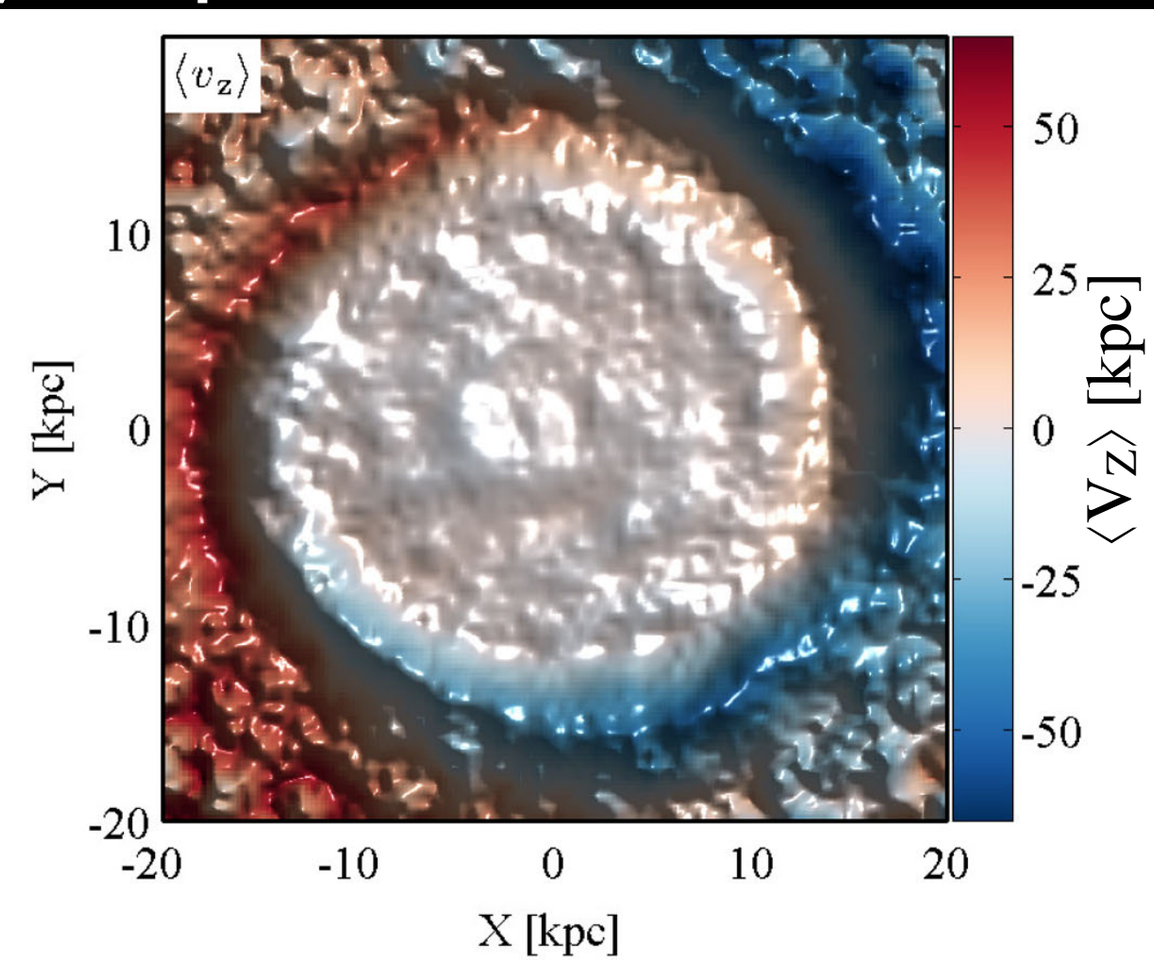
Marinacci, Pakmor and Springel 2013

Run	$R_{\rm vir}$ (kpc)	$M_{\rm tot}$ ($10^{10}{\rm M}_\odot$)	$M_{\rm gas}$ ($10^{10}{\rm M}_\odot$)	$M_\star$ ($10^{10}{\rm M}_\odot$)	$M_{\rm dm}$ ($10^{10}{\rm M}_\odot$)	$N_{\rm cells}$	$N_\star$	$N_{\rm dm}$	$m_{\rm gas}$ ($10^5{\rm M}_\odot$)	$m_{\rm dm}$ ($10^5{\rm M}_\odot$)	$f_{\rm b}$
Aq-C-5	234.5	159.74	7.09	7.00	145.64	163726	273124	674547	4.11	21.59	0.51
Aq-C-6	235.5	161.82	9.86	5.95	146.00	28702	26803	84525	32.90	172.73	0.57
Aq-C-4	234.4	159.48	8.39	5.31	145.71	1526514	1637981	5399079	0.51	2.70	0.49

Present-day maps

Gomez el al. 2016a

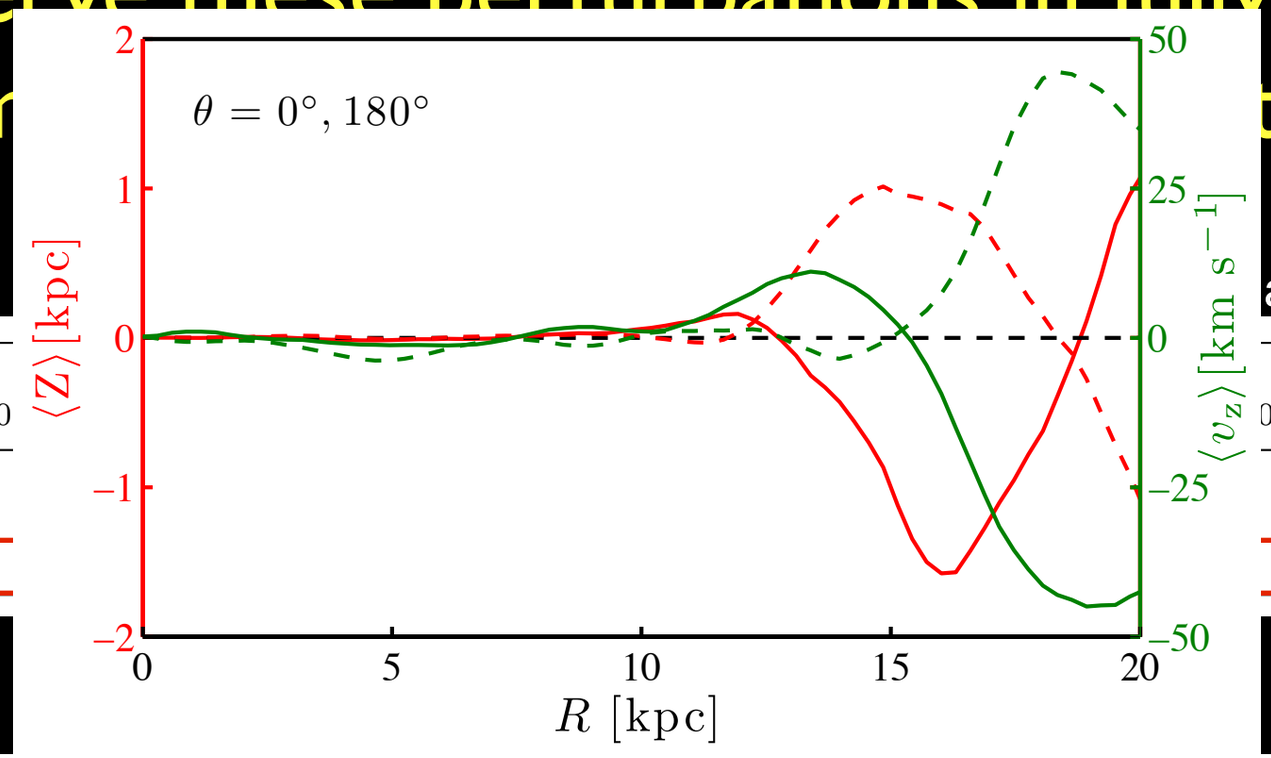




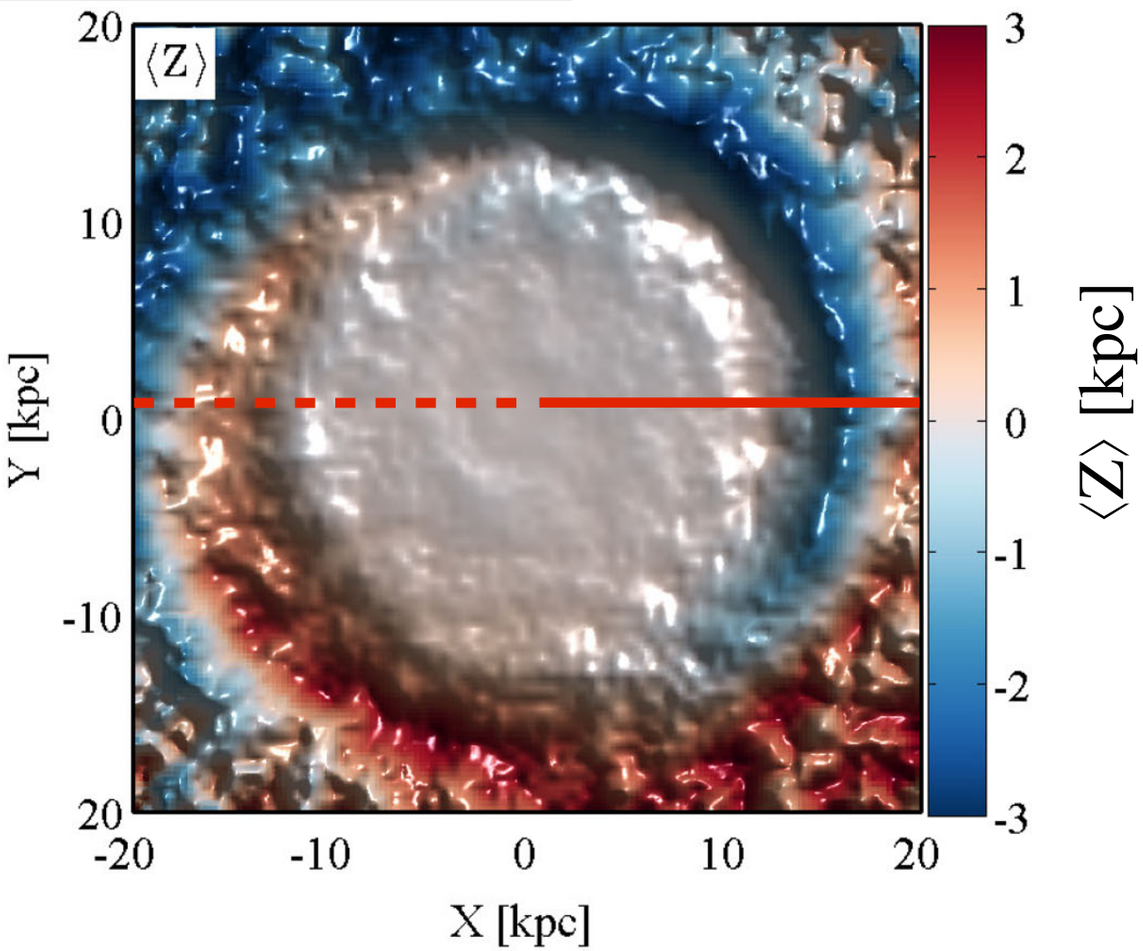
Can we observe these perturbations in fully cosmological hydrodynam tions: Aq-C4

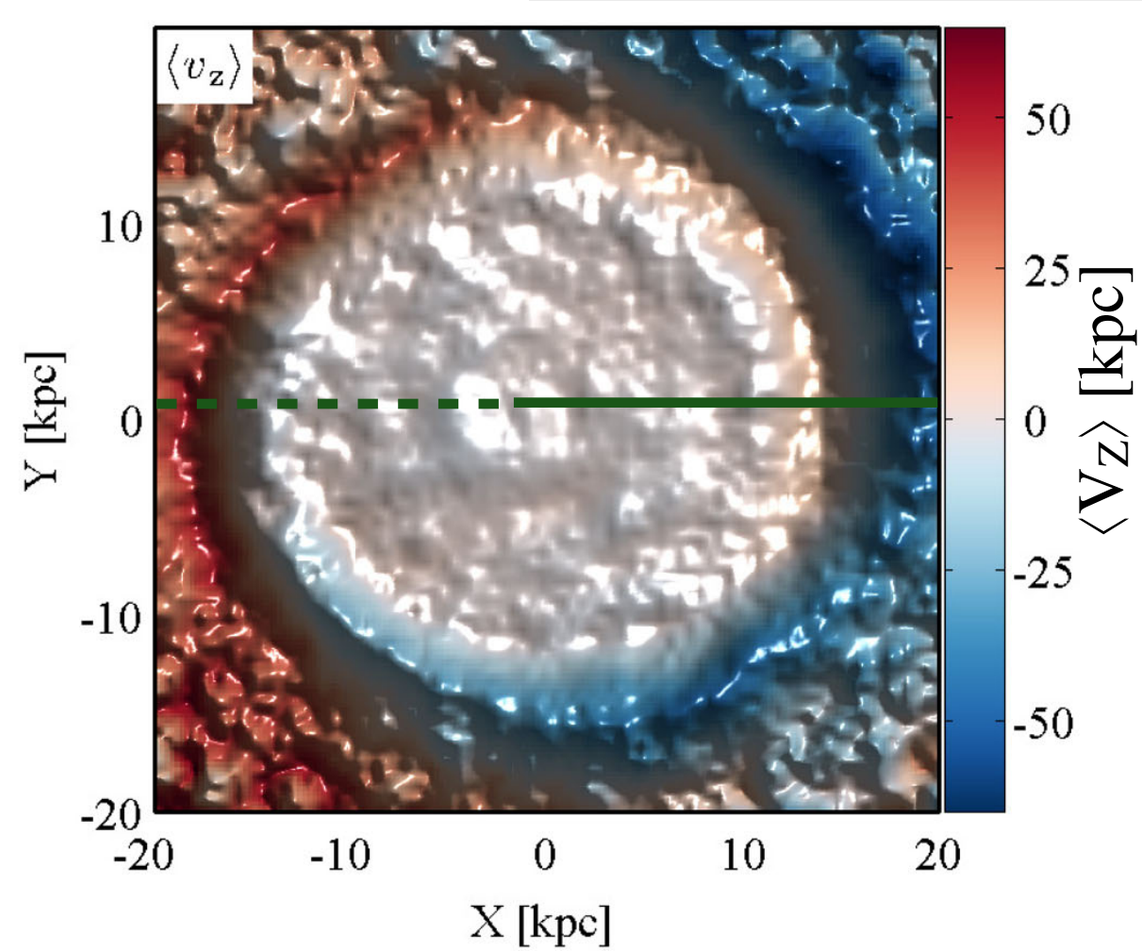
and Springel 2013

Run	R_{vir} (kpc)	(10	m_{gas} $(10^5 M_\odot)$	m_{dm} $(10^5 M_\odot)$	f_b
Aq-C-5	234.5		4.11	21.59	0.51
Aq-C-6	235.5		32.90	172.73	0.57
Aq-C-4	234.4		0.51	2.70	0.49



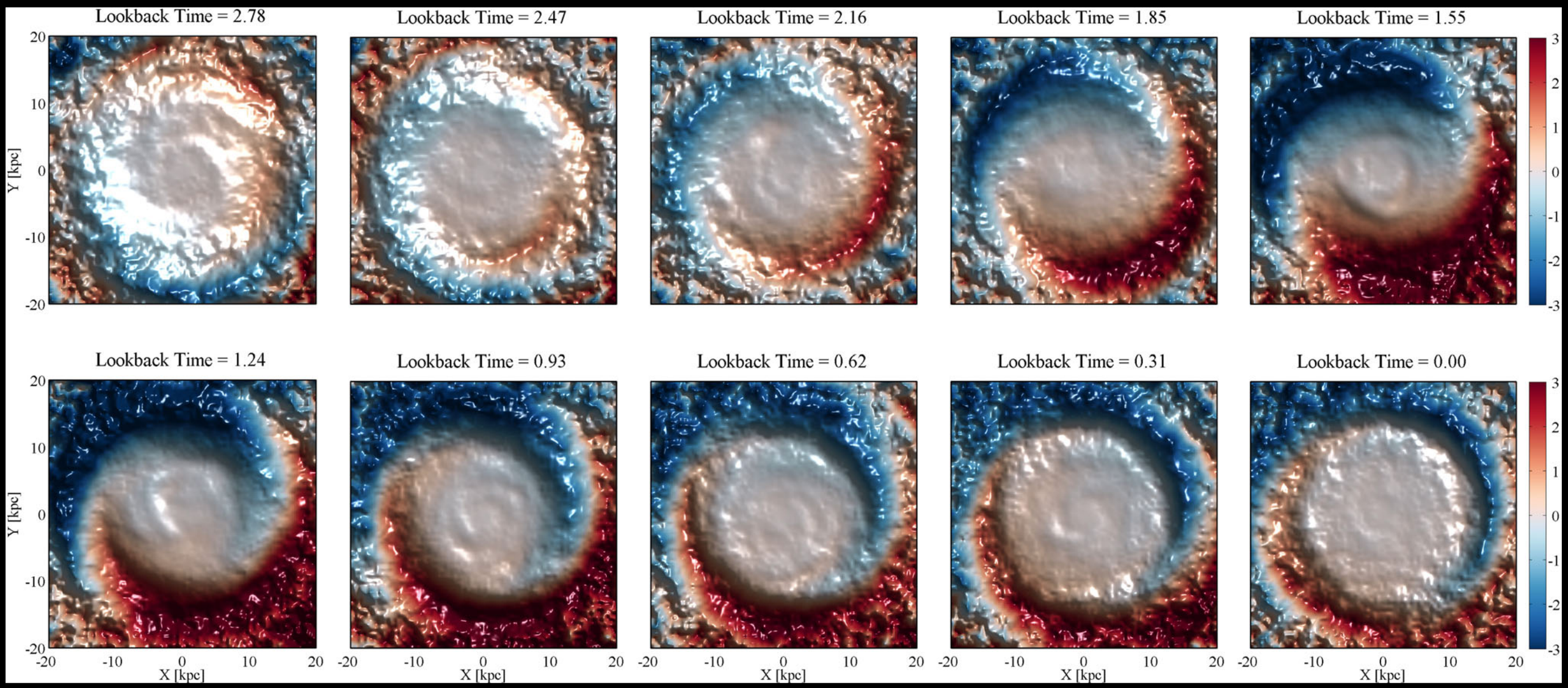
Gomez el al. 2016a





(pre) Auriga simulation: Aq-C4

Time evolution of vertical perturbation



Gómez et al. 2016a

$\langle Z \rangle$ maps in kpc

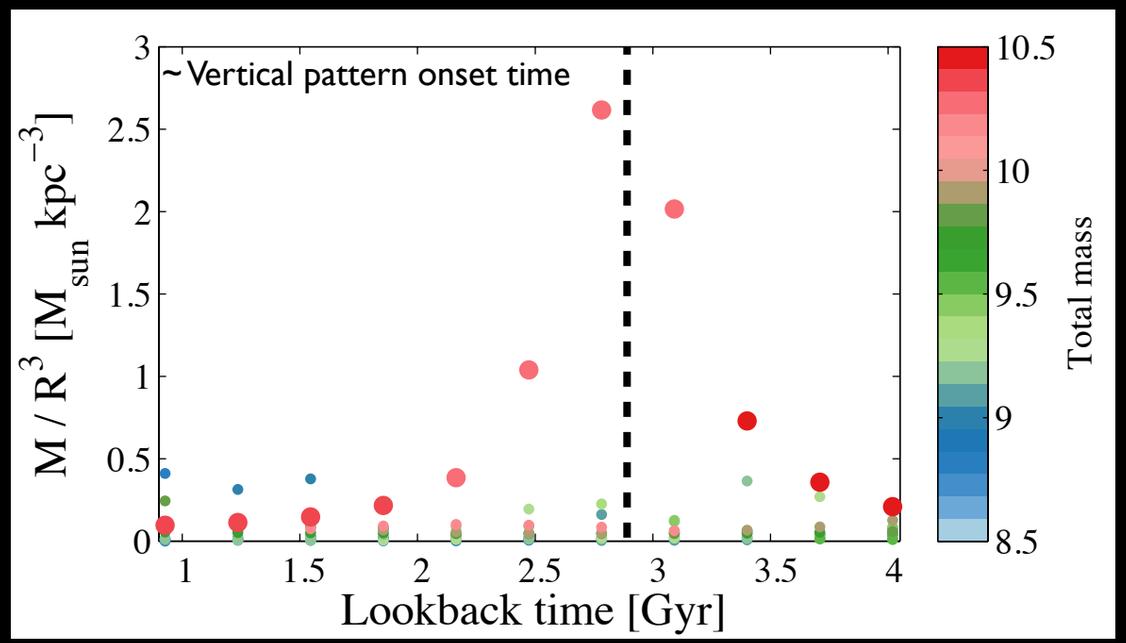
What excited this pattern?

What about the perturber?

Most plausible perturber:

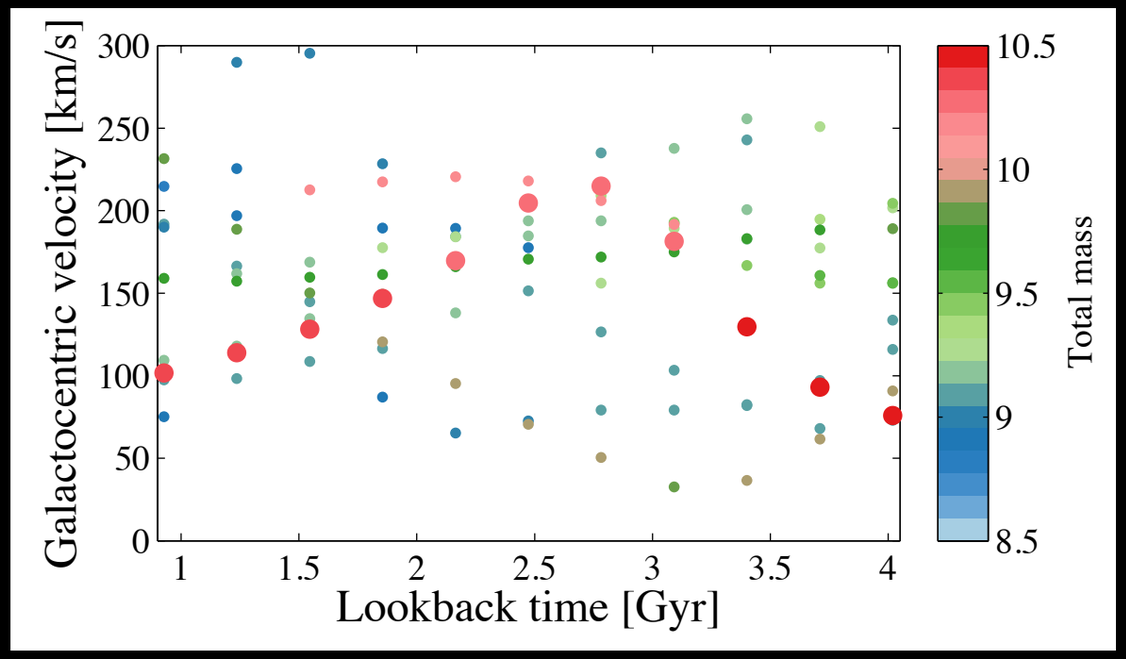
Msat ~ 4e10 (at Rvir)
Time of pericenter passage:
~ 2.7 Gyr ago

Top 20 "massive" satellites (at every snapshot)

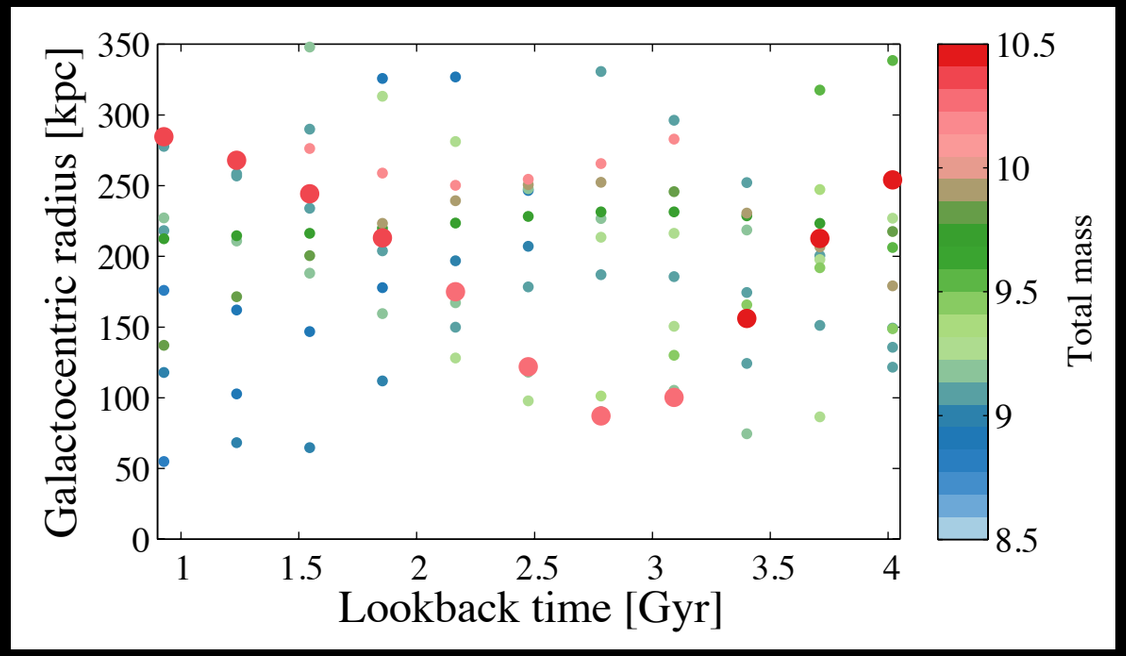


Gómez et al. 2016a

Velocity at pericenter ~ 215 km/s



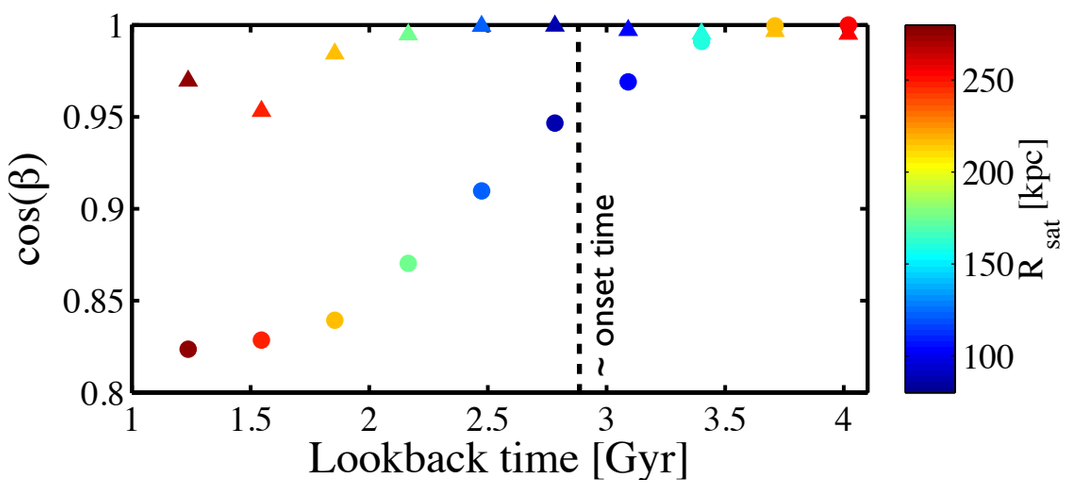
Pericenter ~ 80 kpc



Where is the torque coming from?

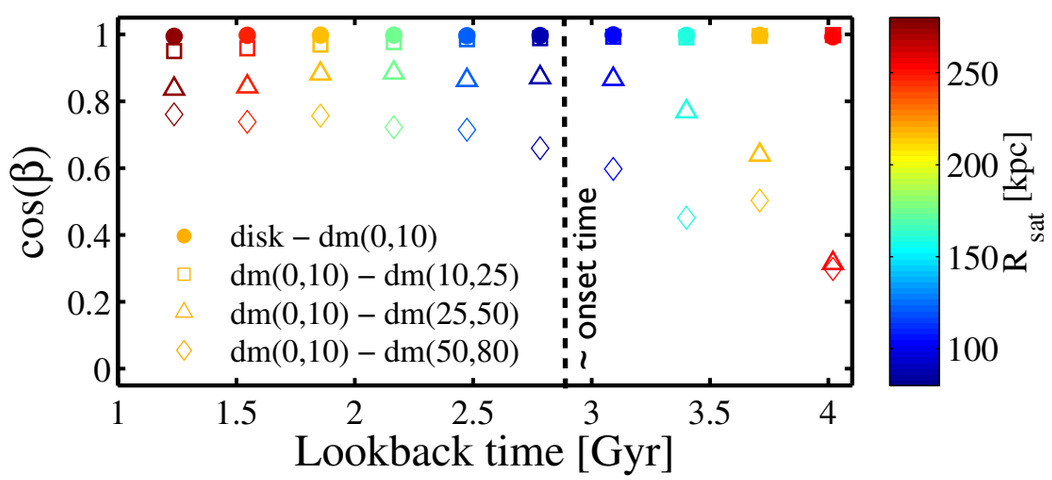
Cold gas vs stellar disk misalignment?

Scannapieco et al. 2009



Stellar disk - DM halo misalignment?

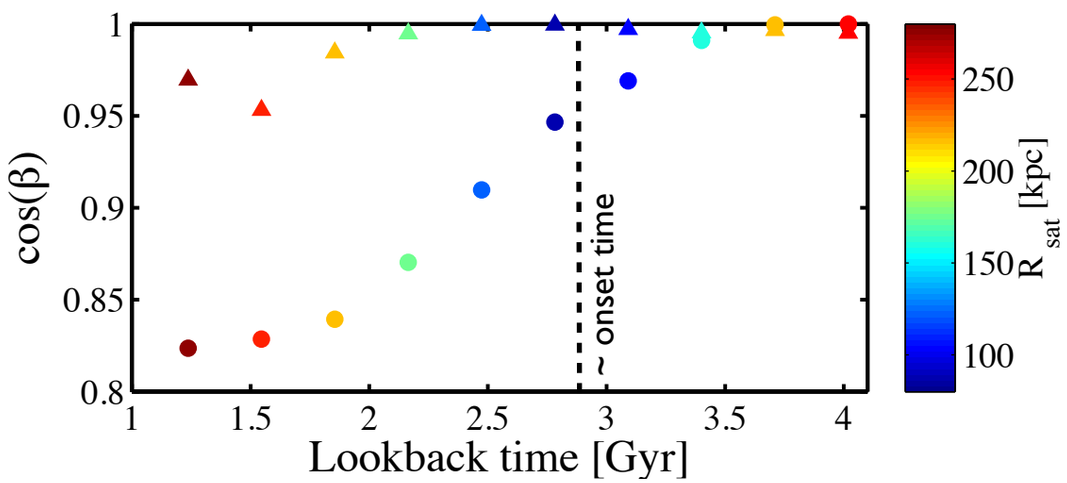
e.g. Shen & Sellwood 2006



Where is the torque coming from?

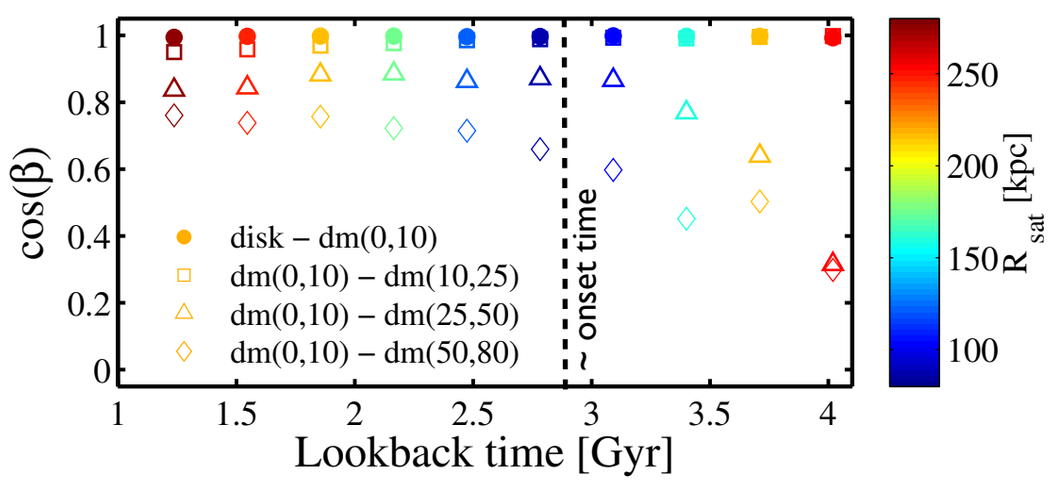
Cold gas vs stellar disk misalignment?

Scannapieco et al. 2009

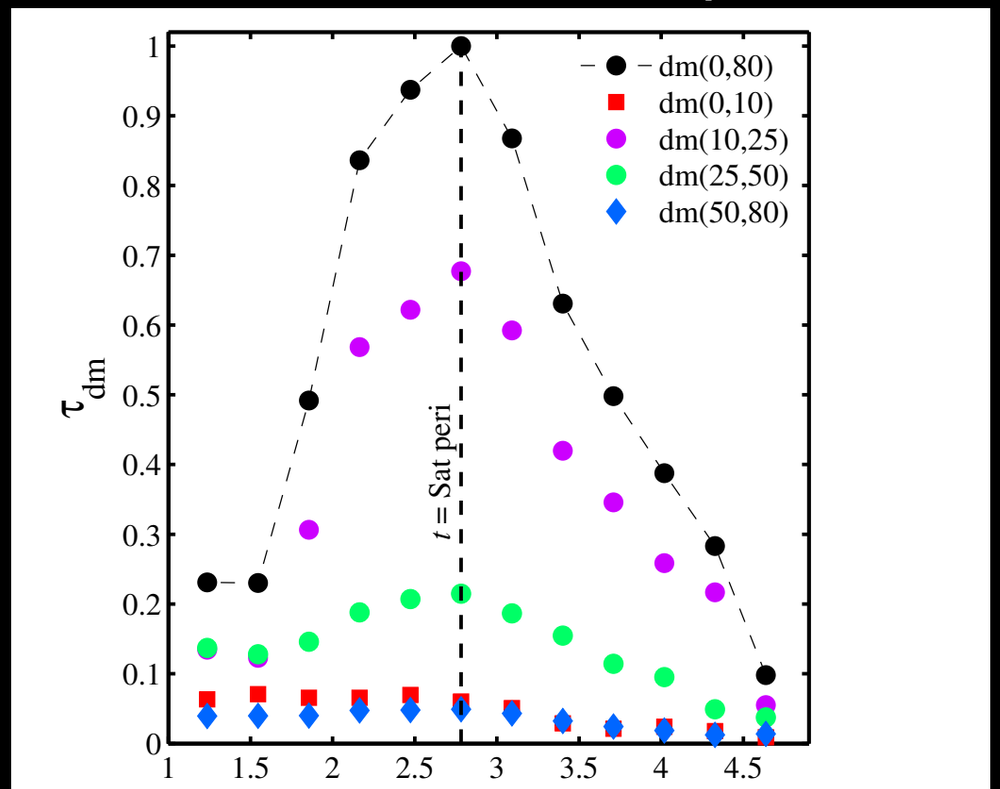


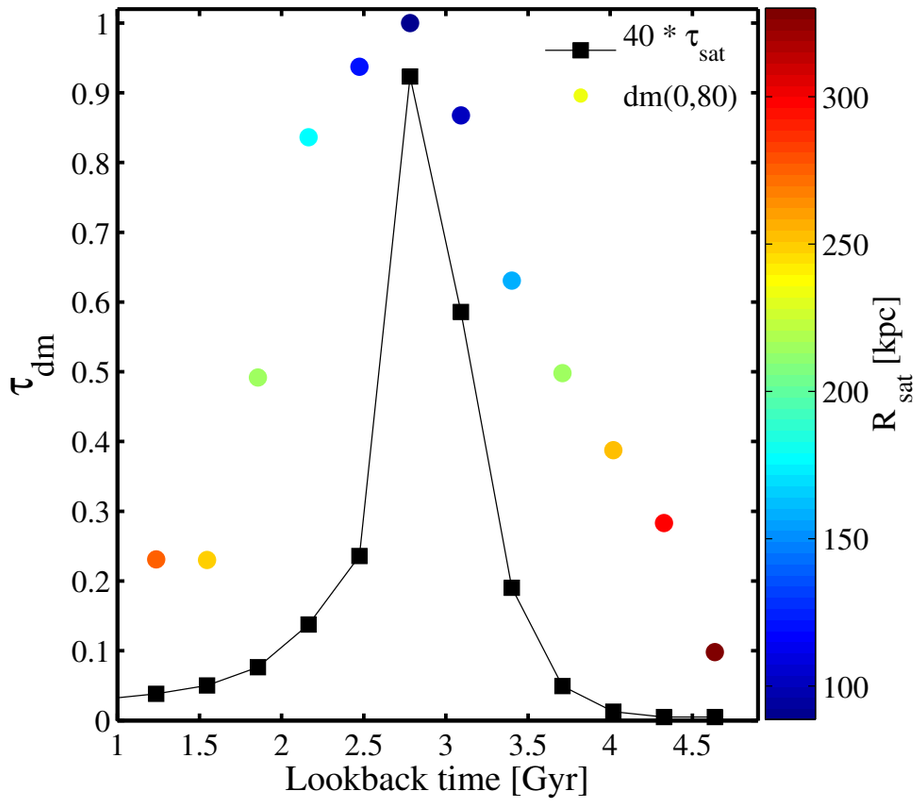
Stellar disk - DM halo misalignment?

e.g. Shen & Sellwood 2006



Ring of stellar disk particles within 14 < R < 15 kpc



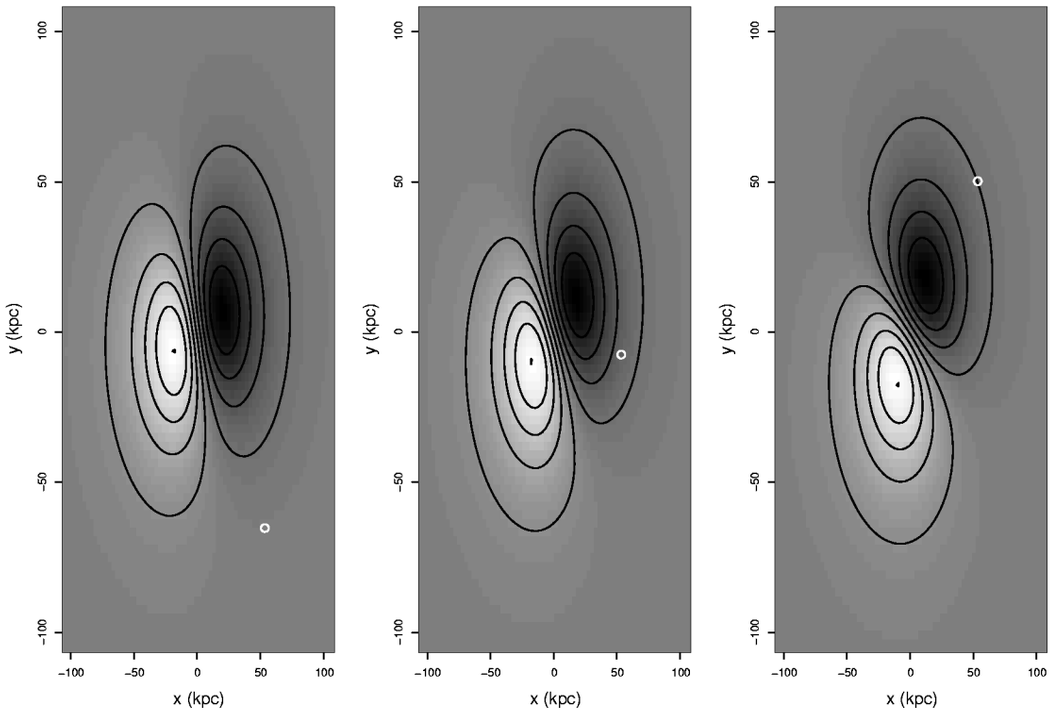


Perturbations of DM halos during fly-by encounter

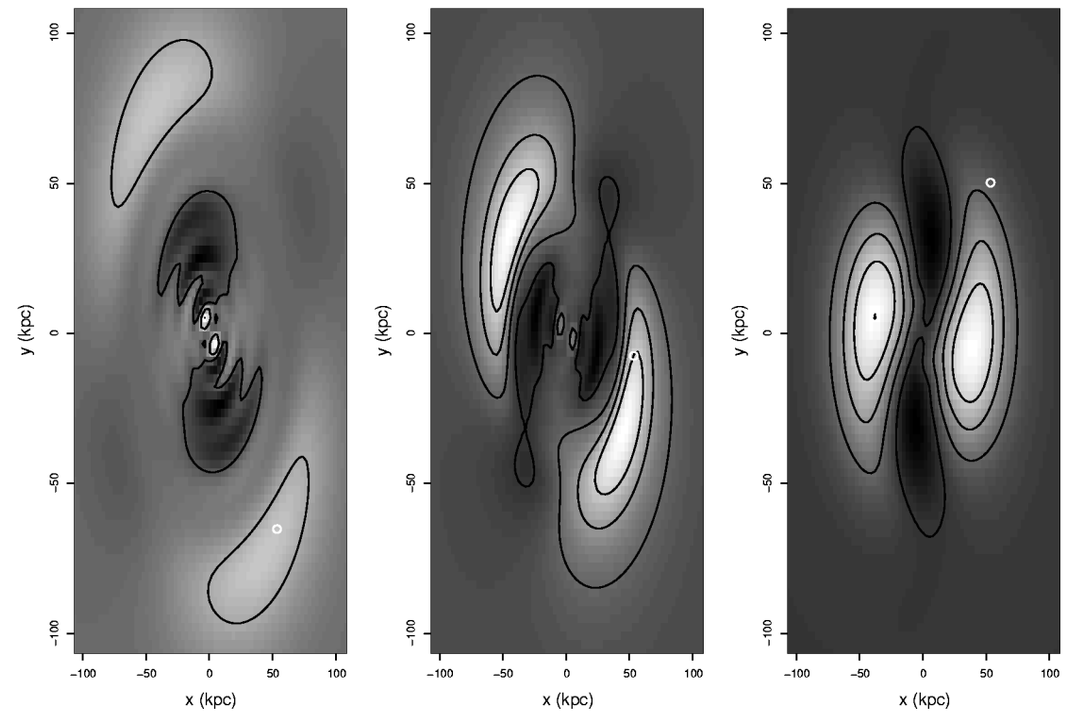
Pericenter ~ 53 kpc (= $R_{halfmass}$ Host); Vsat = 200 km/s; Msat = 0.1 Mhost; Mhost = 6e11 Msun

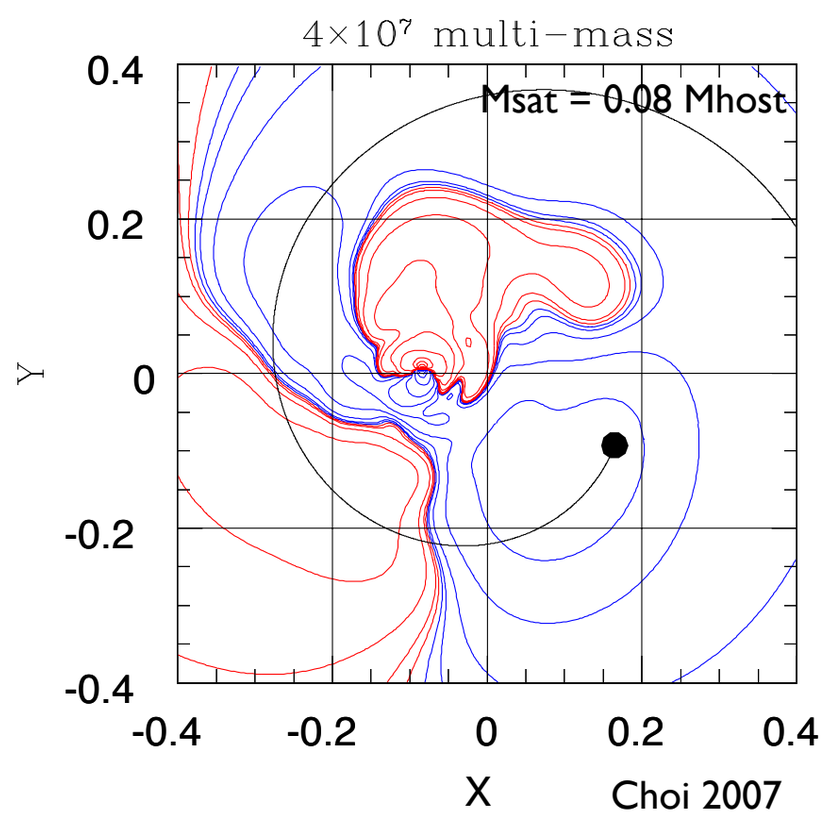
$l = 1$

Vesperini & Weinberg 2000

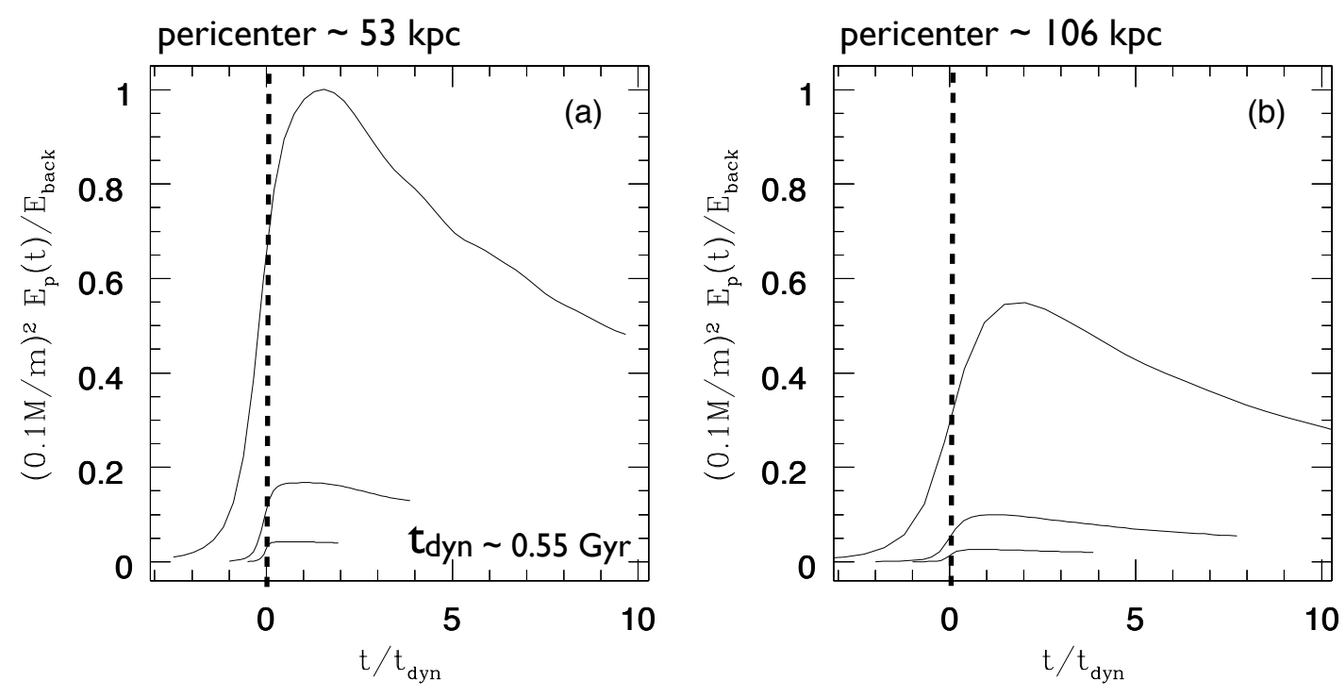


$l = 2$





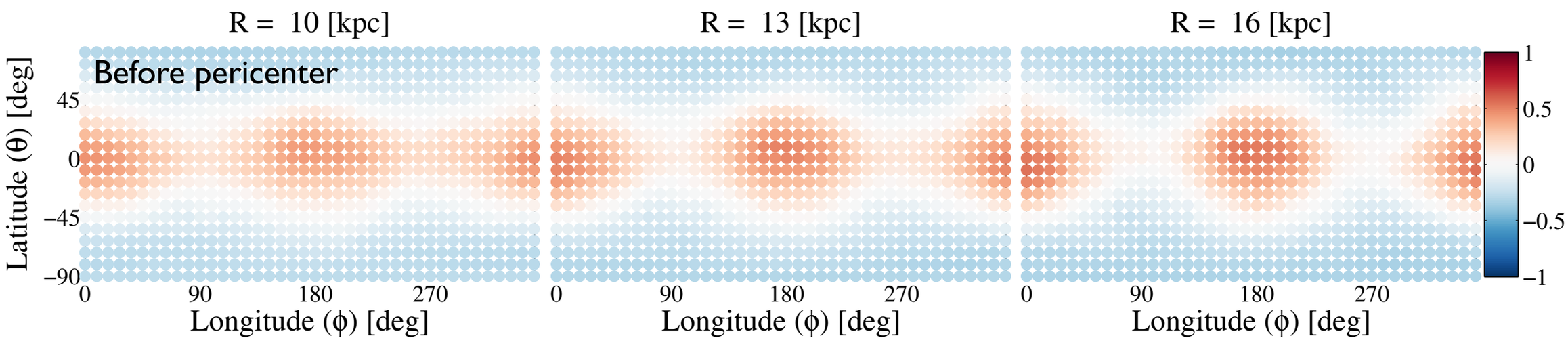
Choi 2007



Peaks after pericenter

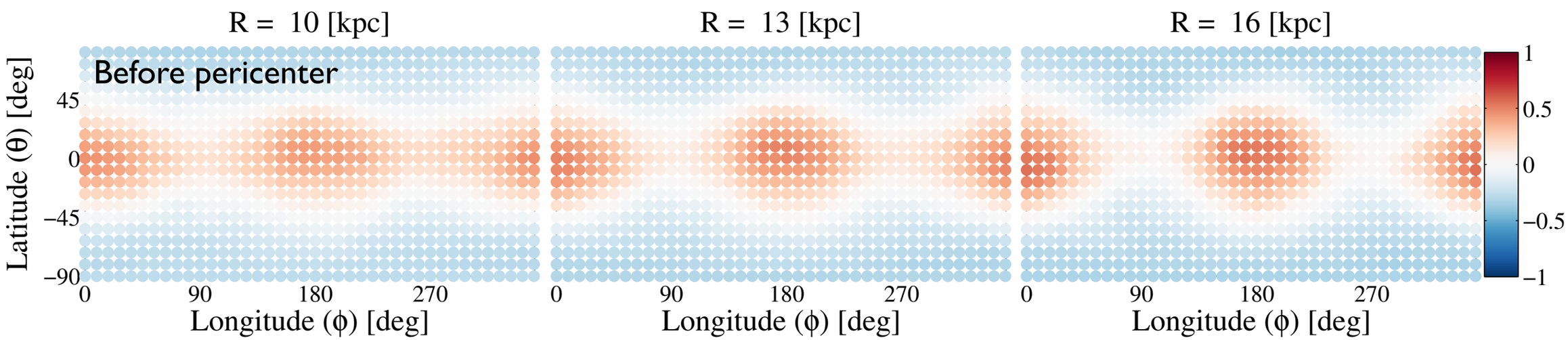
Perturbations of DM halos during fly-by encounter

$$\rho_{\rm cont} = \frac{\rho_{\rm loc} - \langle\rho\rangle_{\rm sph}}{\langle\rho\rangle_{\rm sph}} \longrightarrow \frac{\rho_{\rm cont} - \rho_{\rm cont}^{180^\circ}}{2}$$



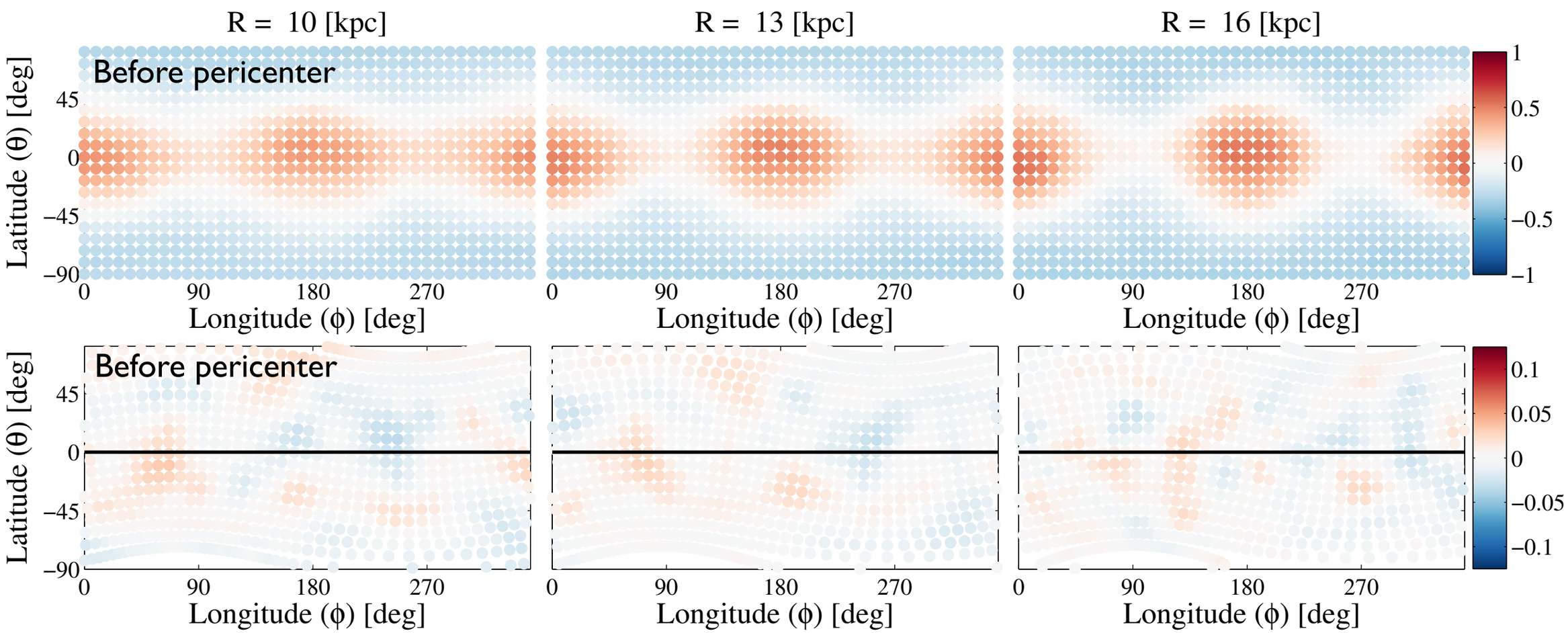
Perturbations of DM halos during fly-by encounter

$$\rho_{\rm cont} = \frac{\rho_{\rm loc} - \langle\rho\rangle_{\rm sph}}{\langle\rho\rangle_{\rm sph}} \longrightarrow \frac{\rho_{\rm cont} - \rho_{\rm cont}^{180^\circ}}{2}$$



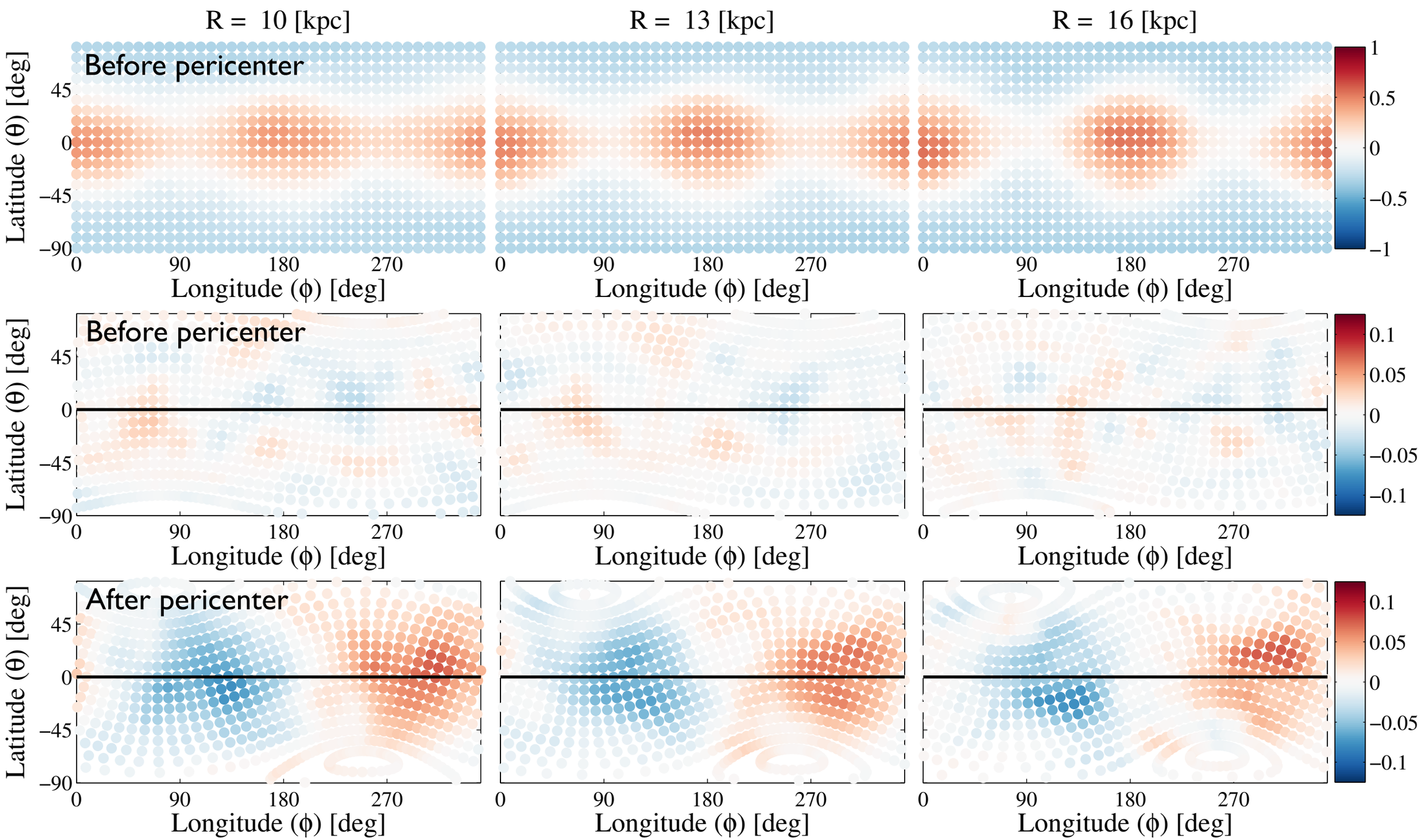
Perturbations of DM halos during fly-by encounter

$$\rho_{\rm cont} = \frac{\rho_{\rm loc} - \langle\rho\rangle_{\rm sph}}{\langle\rho\rangle_{\rm sph}} \longrightarrow \frac{\rho_{\rm cont} - \rho_{\rm cont}^{180^\circ}}{2}$$



Perturbations of DM halos during fly-by encounter

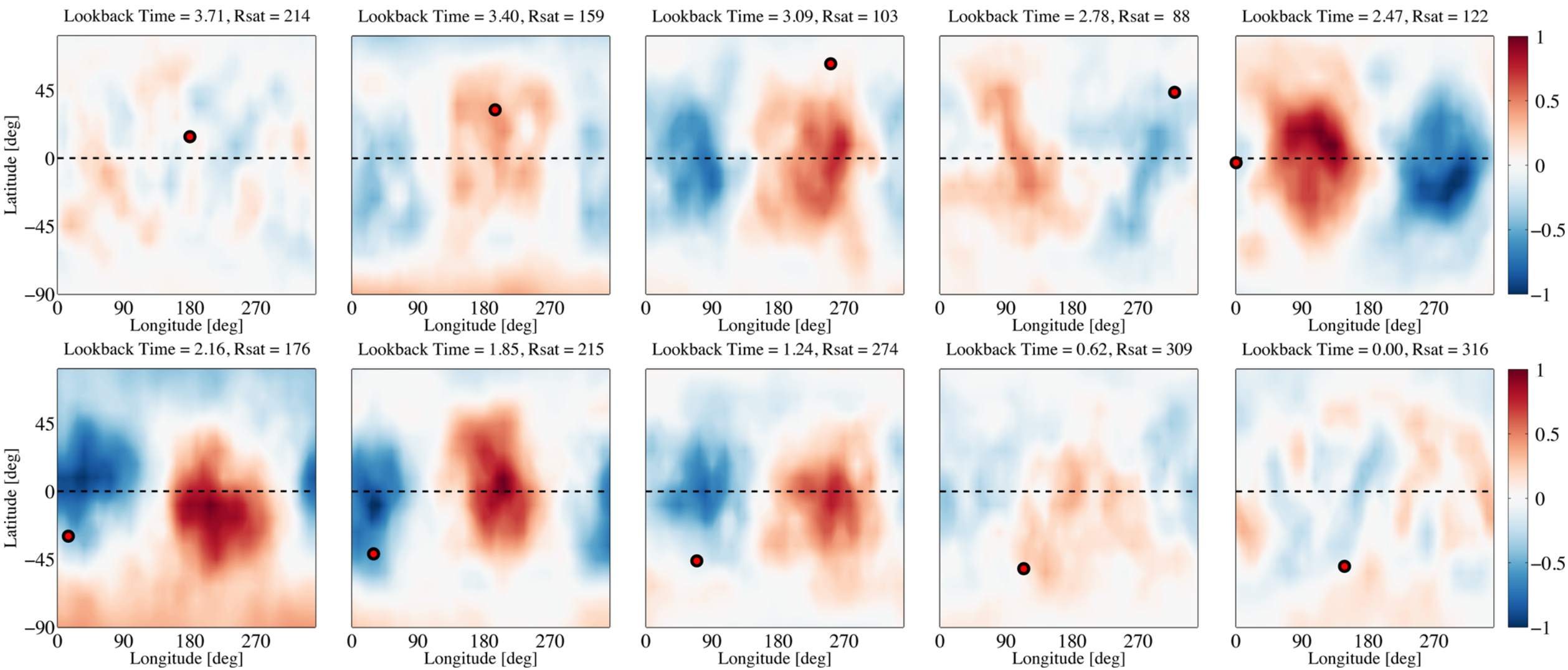
$$\rho_{\rm cont} = \frac{\rho_{\rm loc} - \langle\rho\rangle_{\rm sph}}{\langle\rho\rangle_{\rm sph}} \longrightarrow \frac{\rho_{\rm cont} - \rho_{\rm cont}^{180^\circ}}{2}$$



Perturbations of DM halos during fly-by encounter

(see also Gao & White 2006)

Stack of all distance slices at a given time



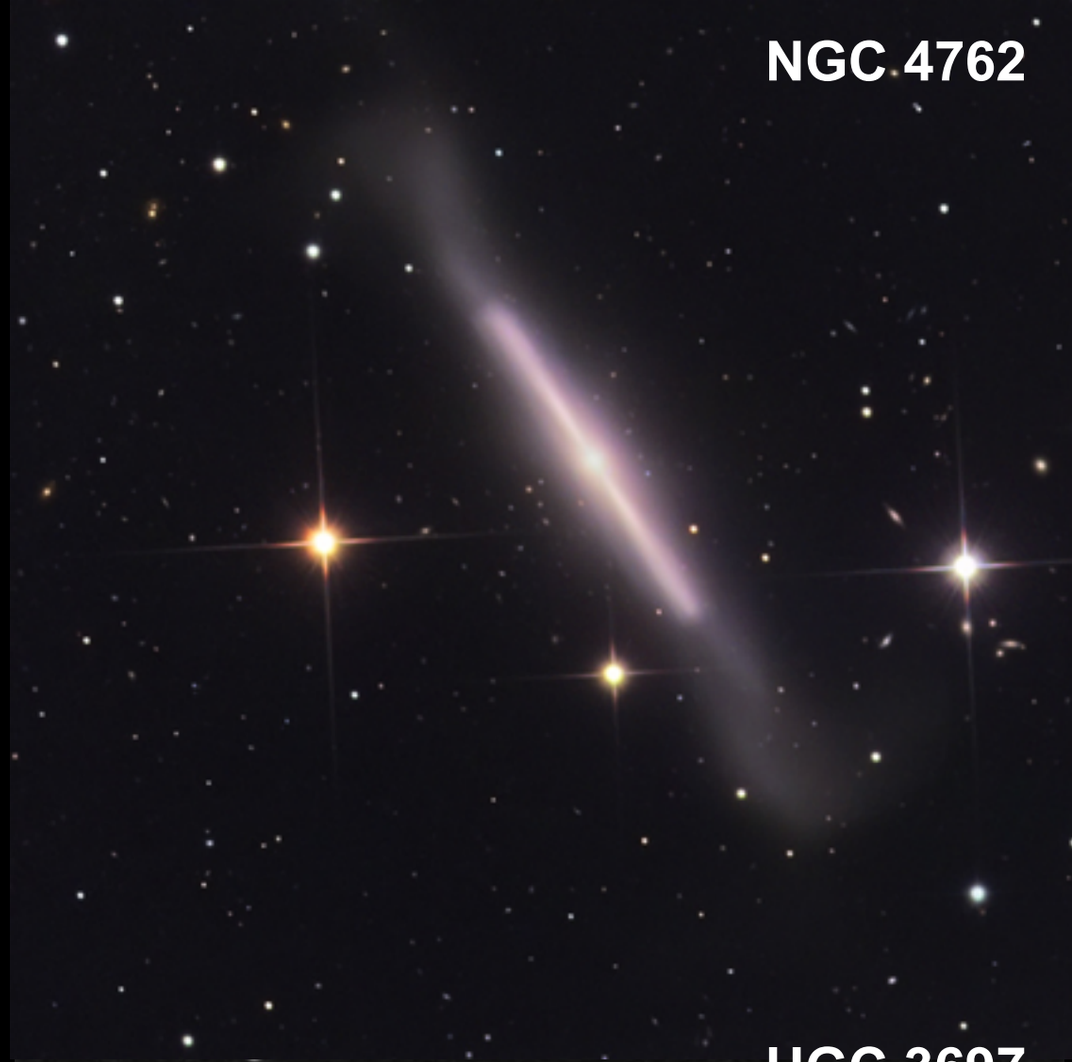
Dipolar response of the DM density field

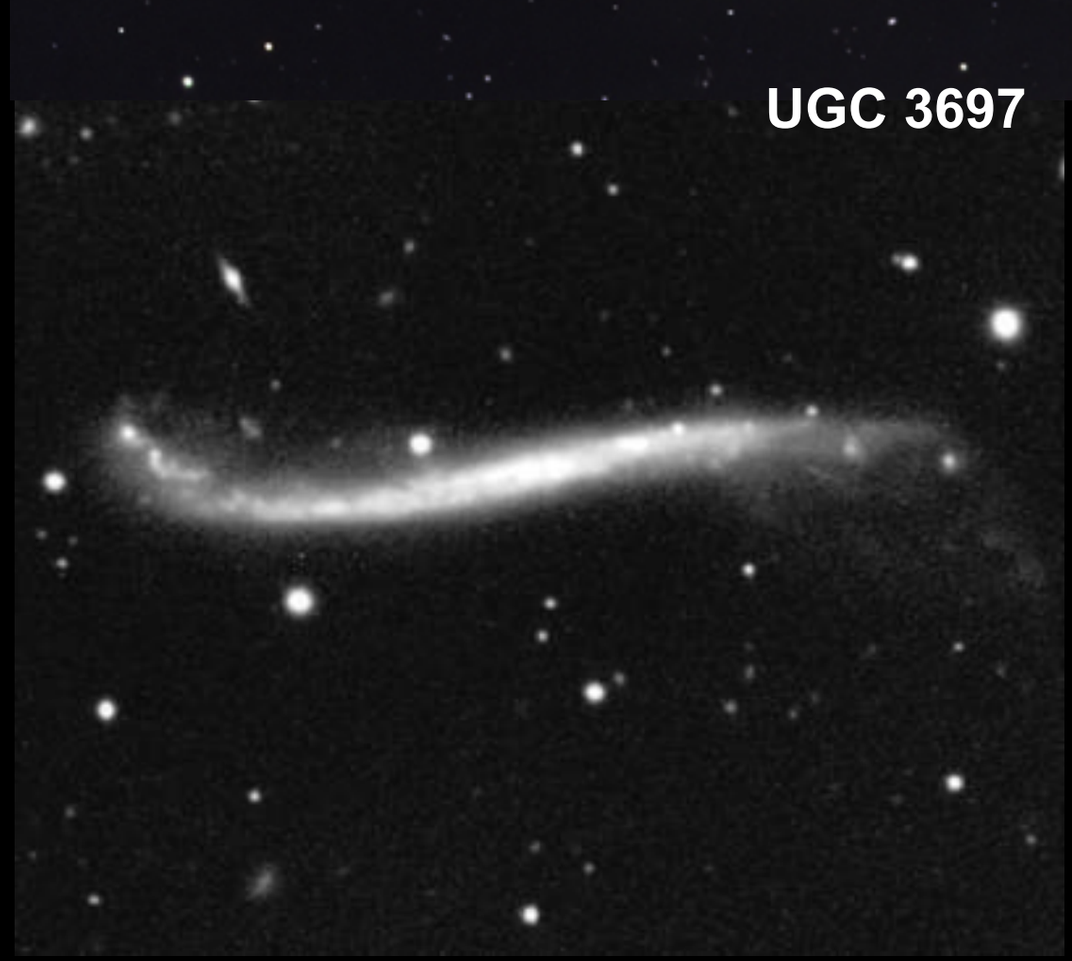
Optical warps - Very common feature

Ann & Park 2006:
Morphology of 325 edge-on spirals from SDSS

73% — warped disks:
51% — S-shaped warps
22% — U-shaped warps

How often wave-like oscillating asymmetries arise in a cosmological context?





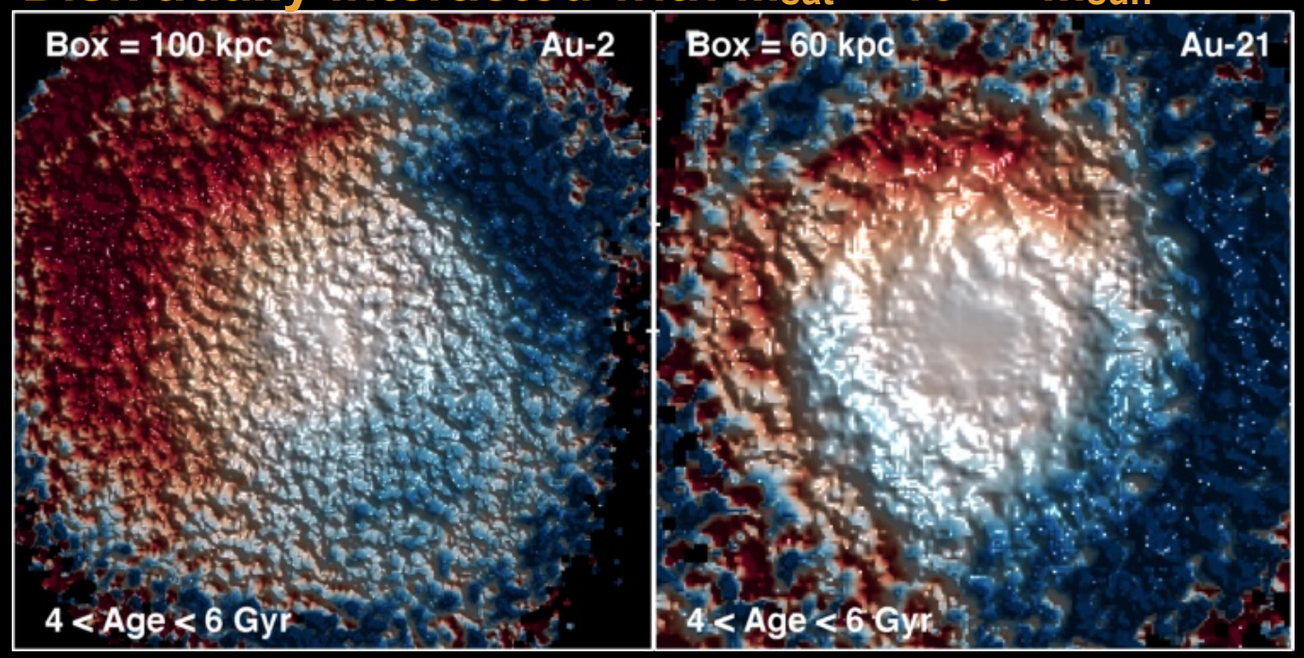
The Auriga suite

Surface brightness maps, μ_V

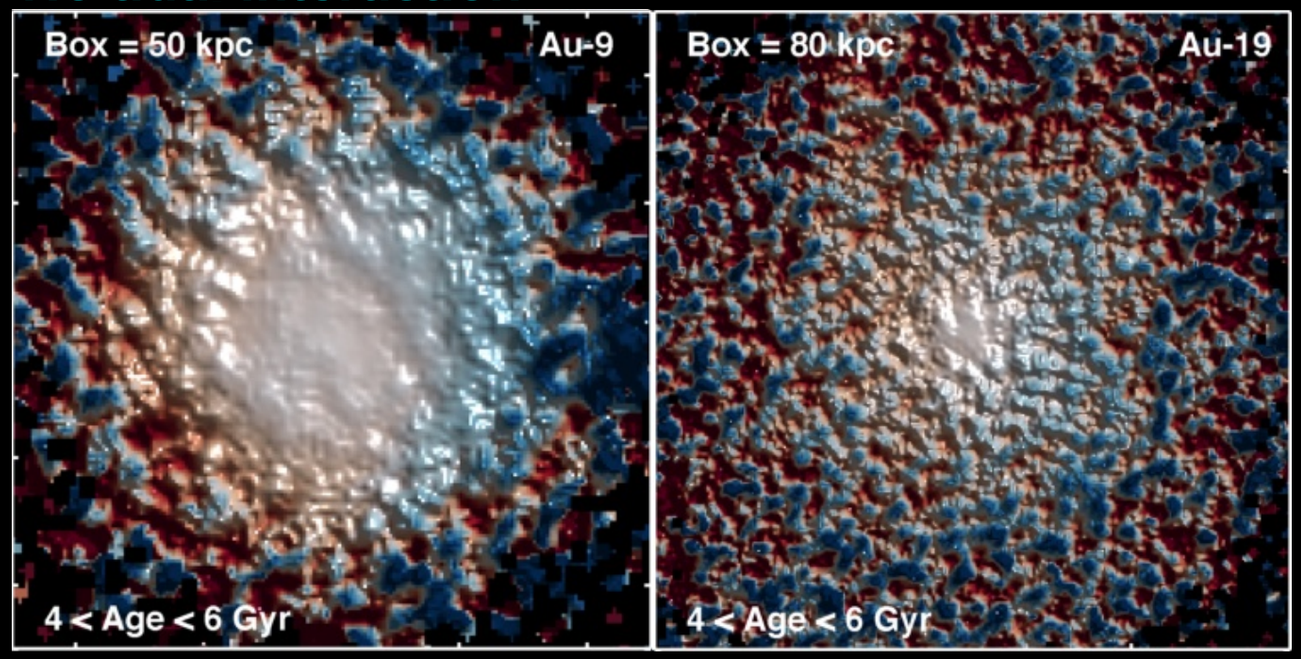
Gómez et al. 2016b

Tidal interaction vs. Misaligned cold gas accretion

Disk tidally interacted with $M_{sat} > 10^{10.5} M_{sun}$



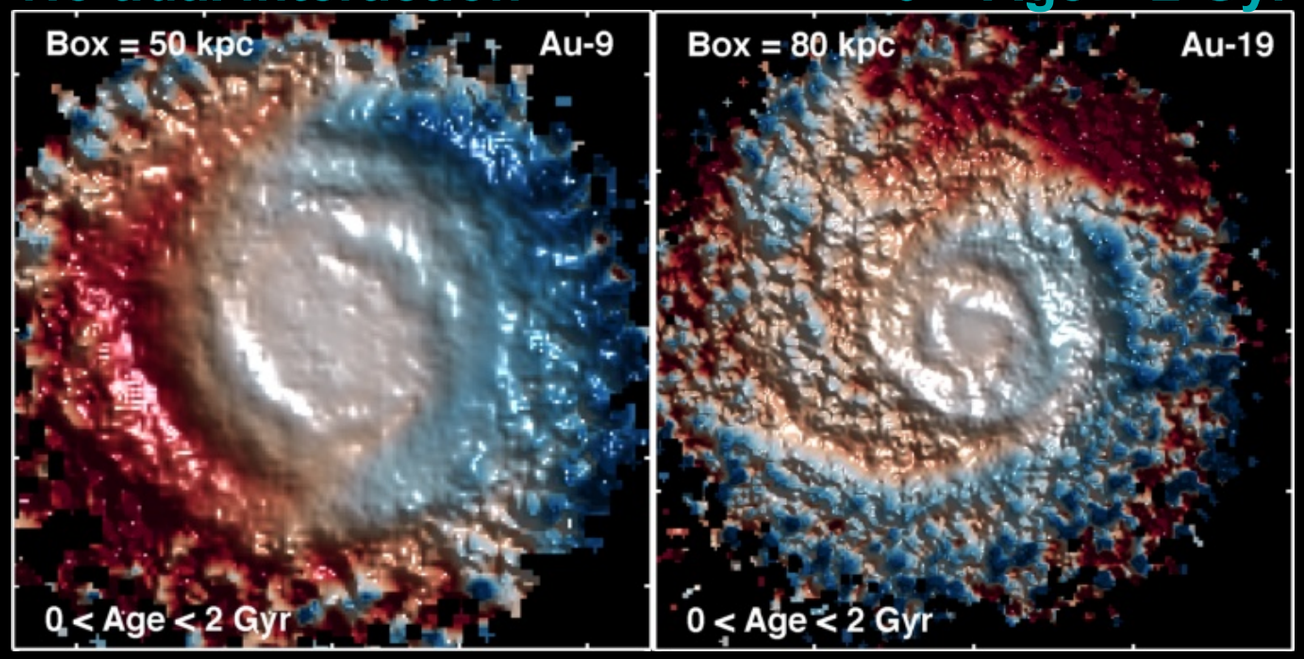
No tidal interaction



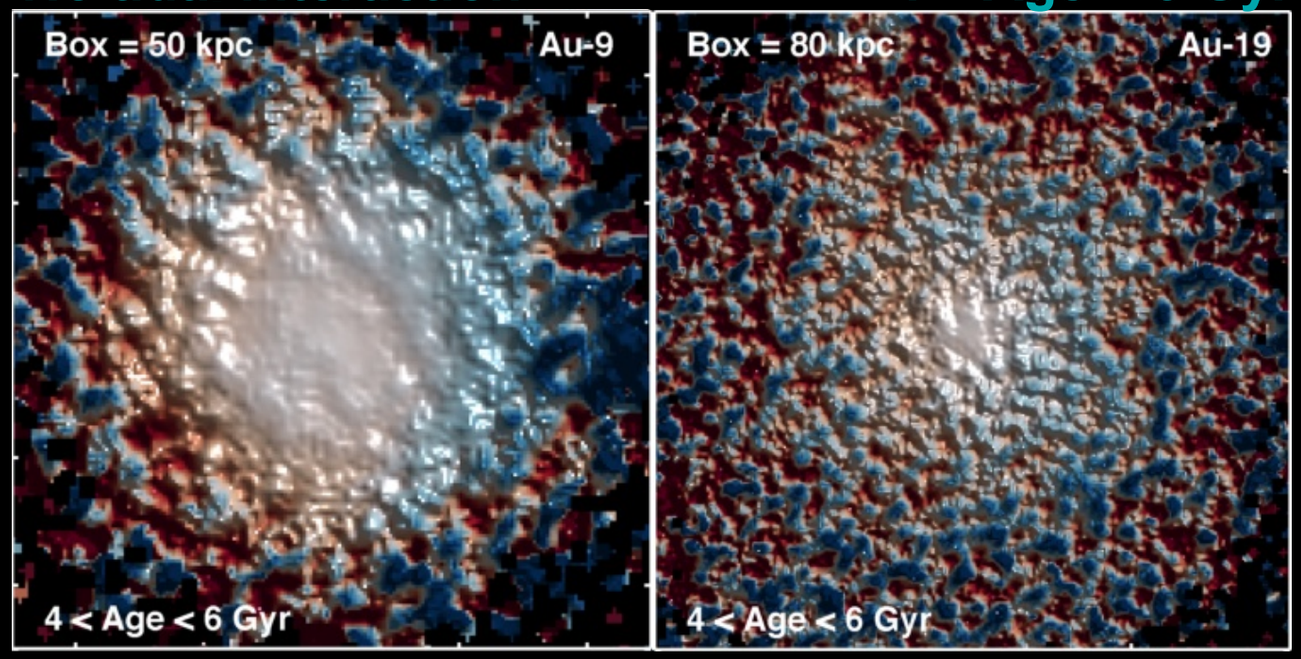
Gómez et al. 2016b

Tidal interaction vs. Misaligned cold gas accretion

No tidal interaction **0 < Age < 2 Gyr**



No tidal interaction **4 < Age < 6 Gyr**

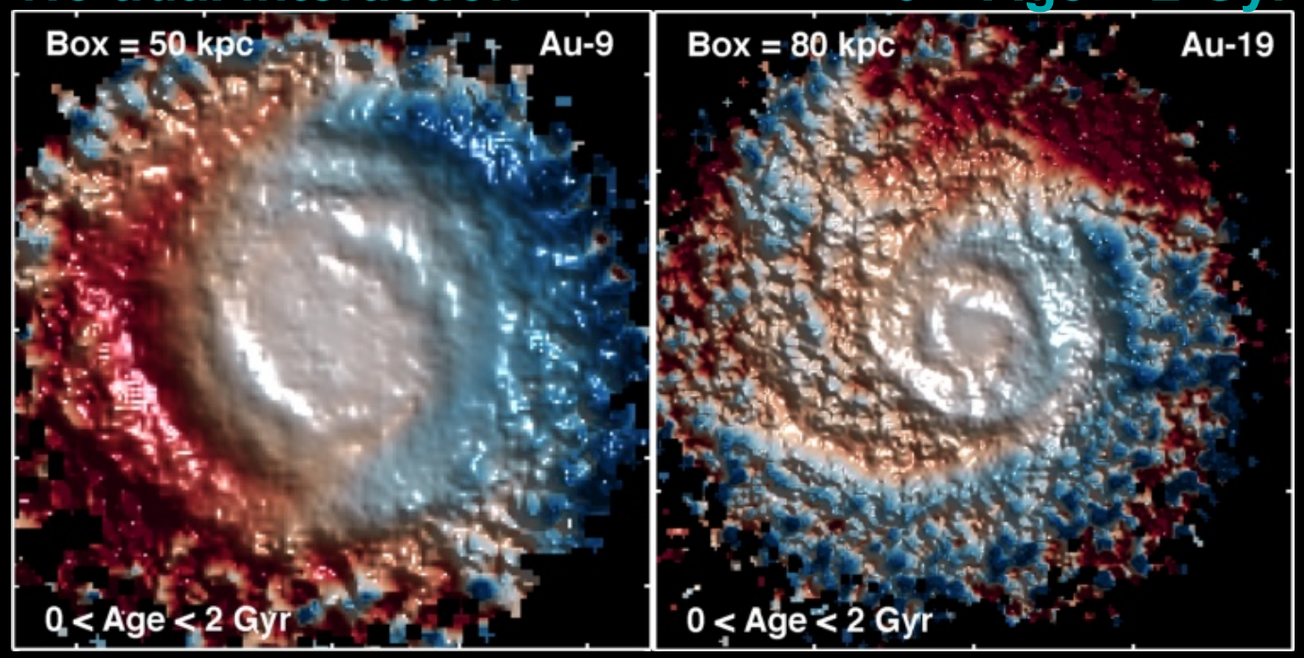


Gómez et al. 2016b

Tidal interaction vs. Misaligned cold gas accretion

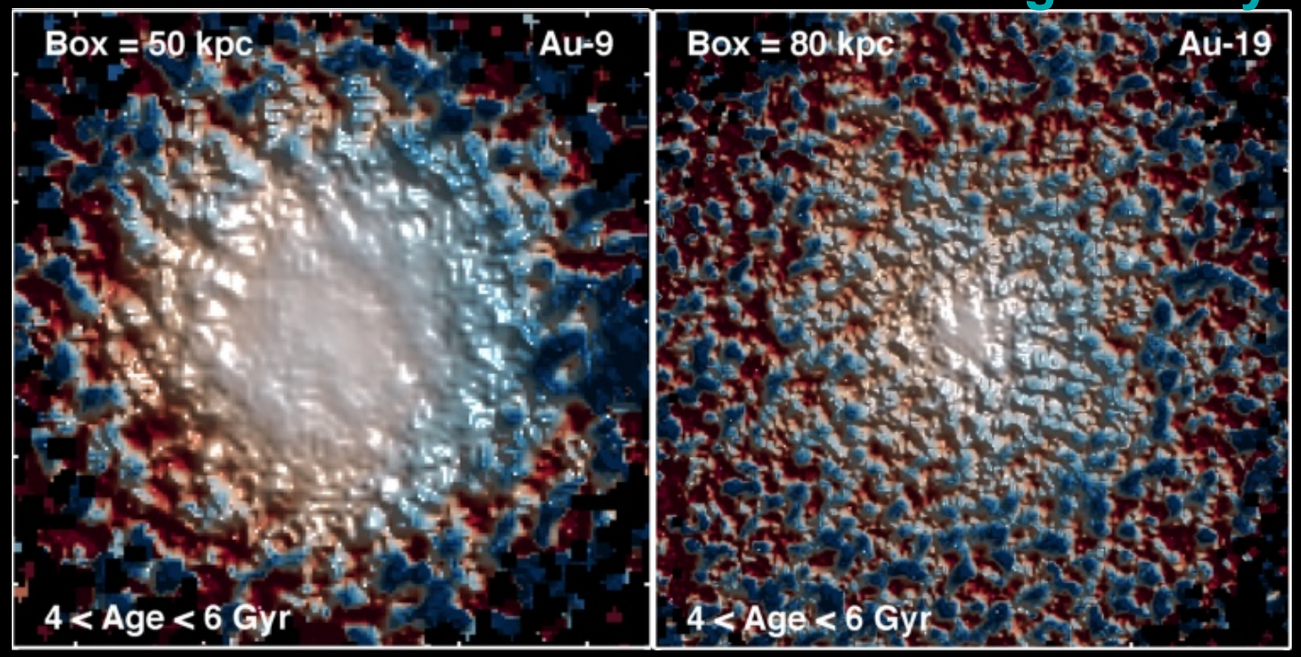
No tidal interaction

0 < Age < 2 Gyr



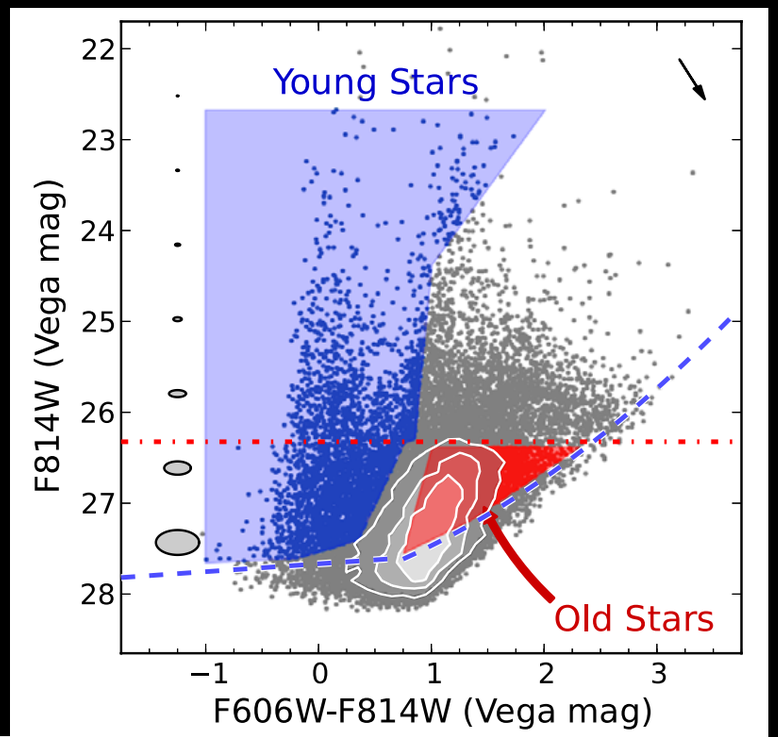
No tidal interaction

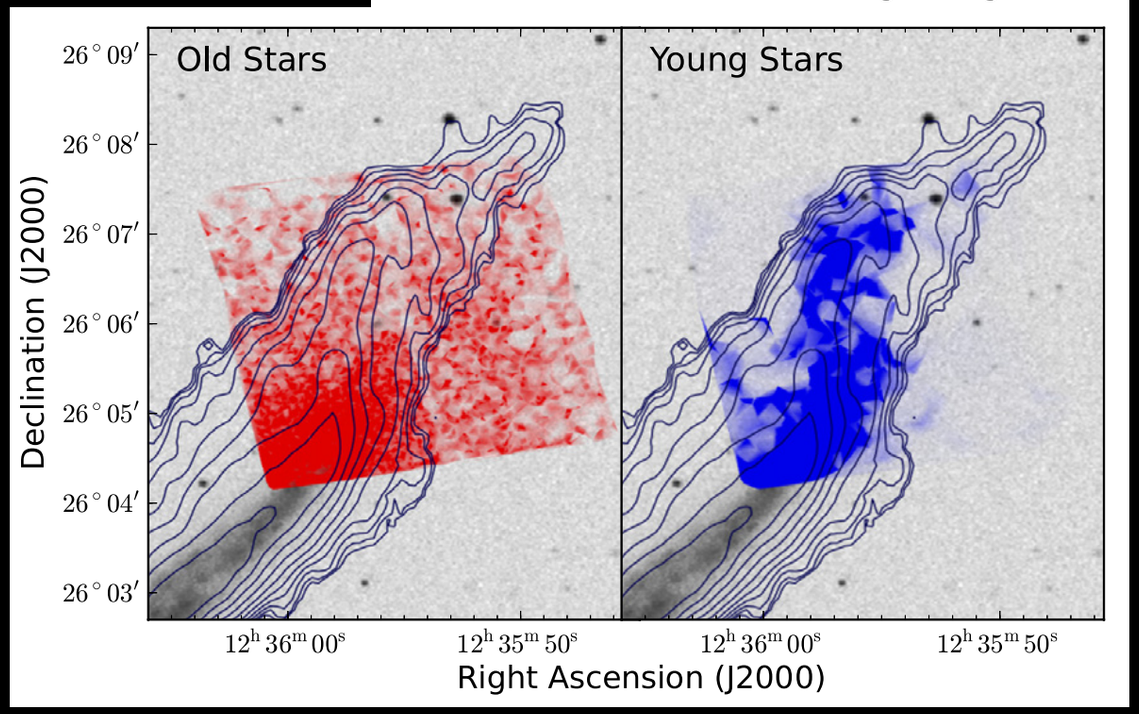
4 < Age < 6 Gyr



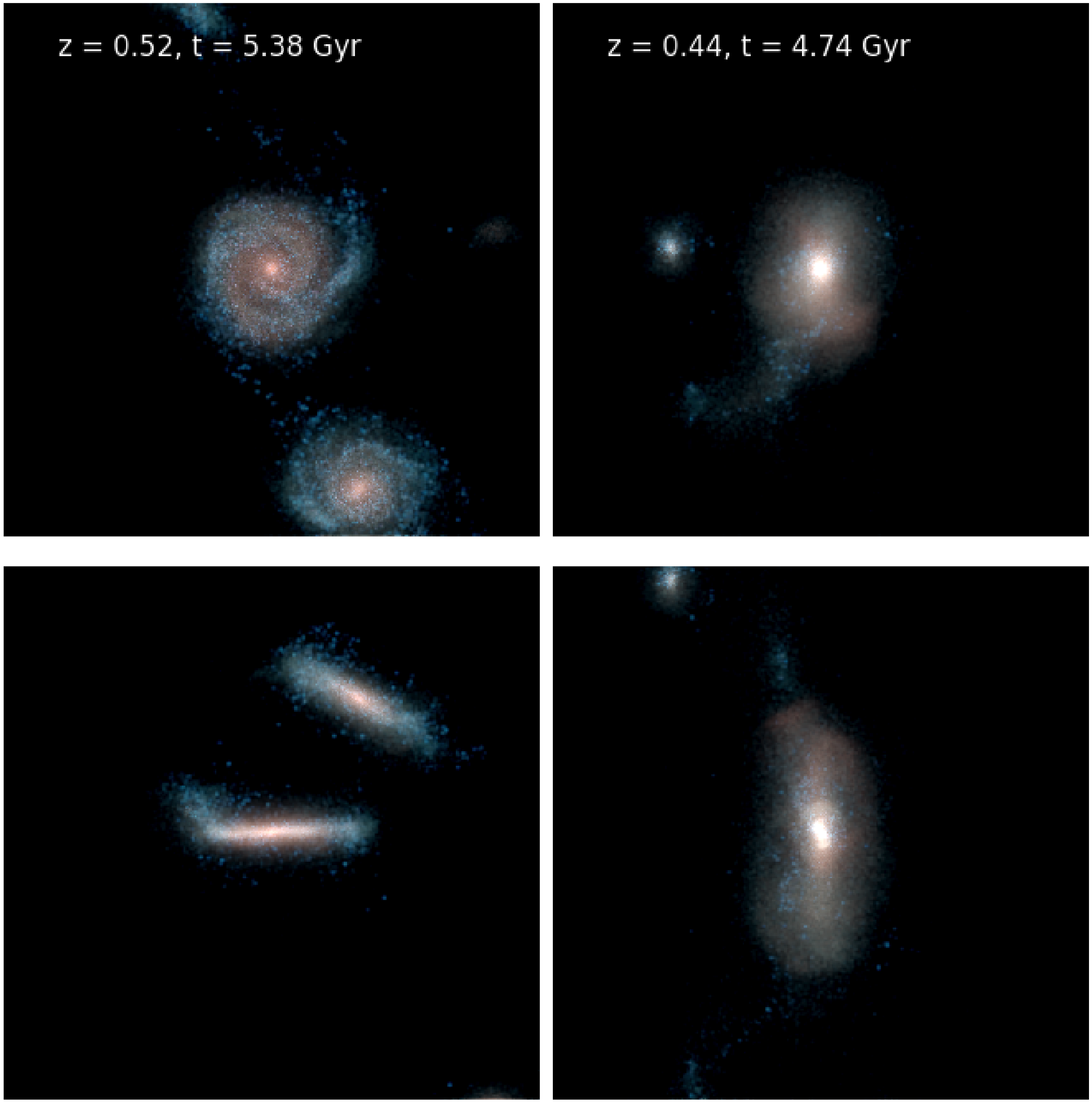
Gómez et al. 2016b

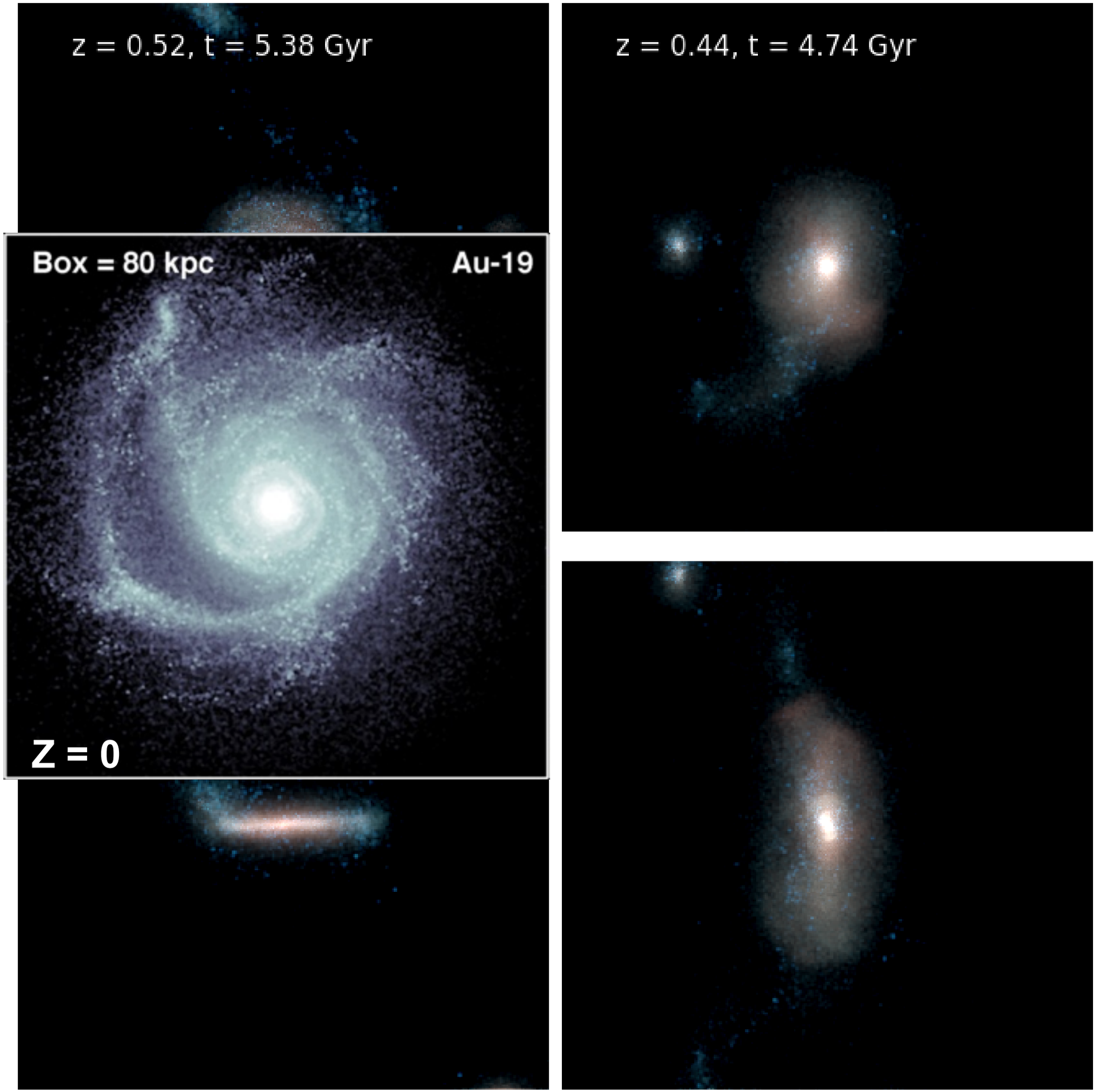
NGC 4565 — HST ACS





Radburn-Smith et al. 2014


z = 0.52, t = 5.38 Gyr
z = 0.44, t = 4.74 Gyr


z = 0.52, t = 5.38 Gyr
z = 0.44, t = 4.74 Gyr
Box = 80 kpc
Au-19
Z = 0

Summary and future

- Minor mergers can induce substructure on the Galactic disk, both in the radial and vertical directions
- Substructure induced in the DM halo density: can also perturb the galactic disk
- 70% of our galactic disk present strong vertical patterns,
- 30% present wave-like patterns. Not uncommon
- Perturbations in these disks arise from a variety of different mechanism

Thanks!