19th September 2016,
Institut d'Astrophysique de Paris

The response of the Milky Way disc to the Large Magellanic Cloud and Sagittarius dSph

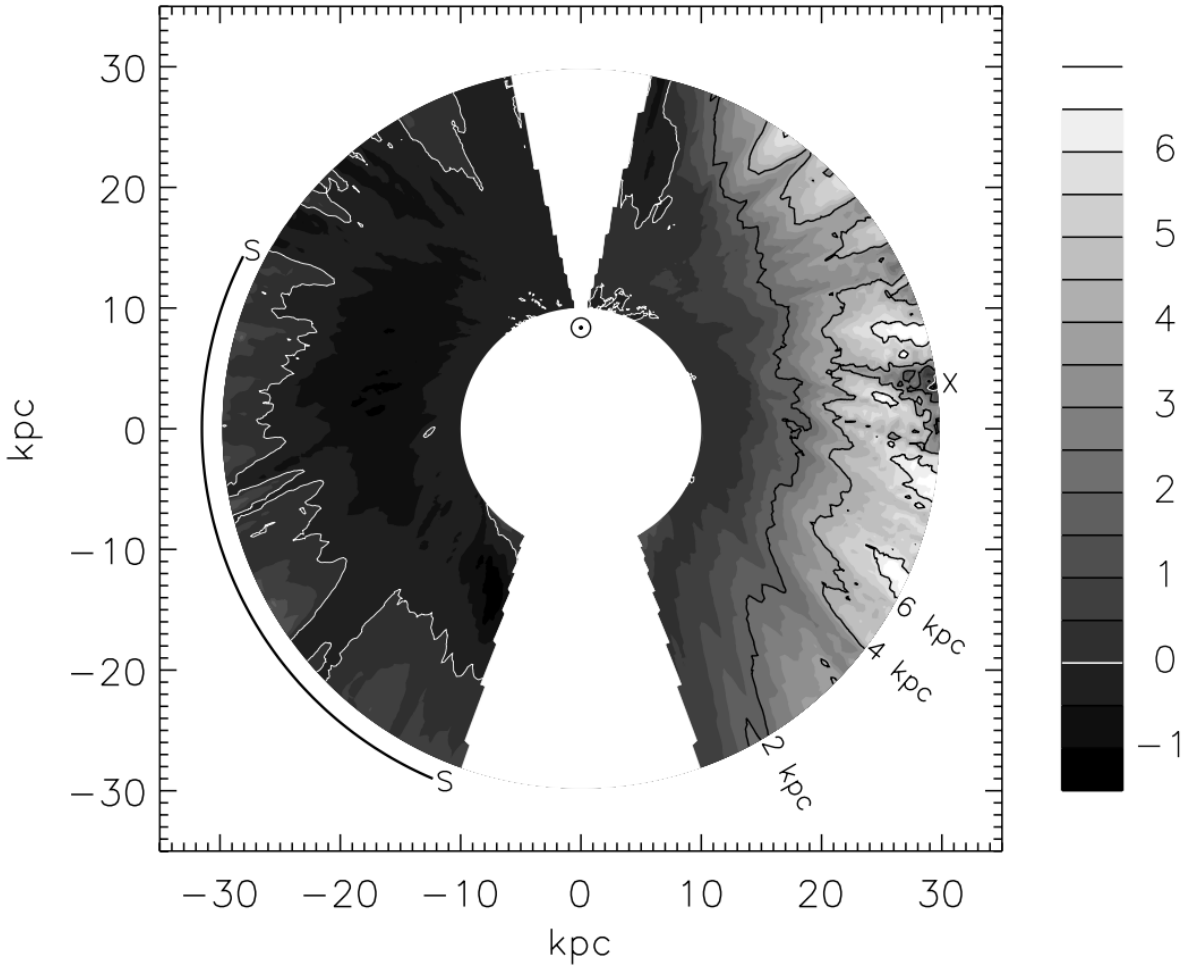
Chervin F. P. Laporte
Simons Fellow, Columbia University

arXiv:1608.04743,

with F. Gomez (MPA), G. Besla (Arizona), K. Johnston (Columbia), N. Garavito-Camargo (Arizona)

photo credit: Denis Erkal (IoA)

Vertical structure of the disc: **the HI view**



Levine, Blitz, Heiles 2006

see also Kalberla07,09

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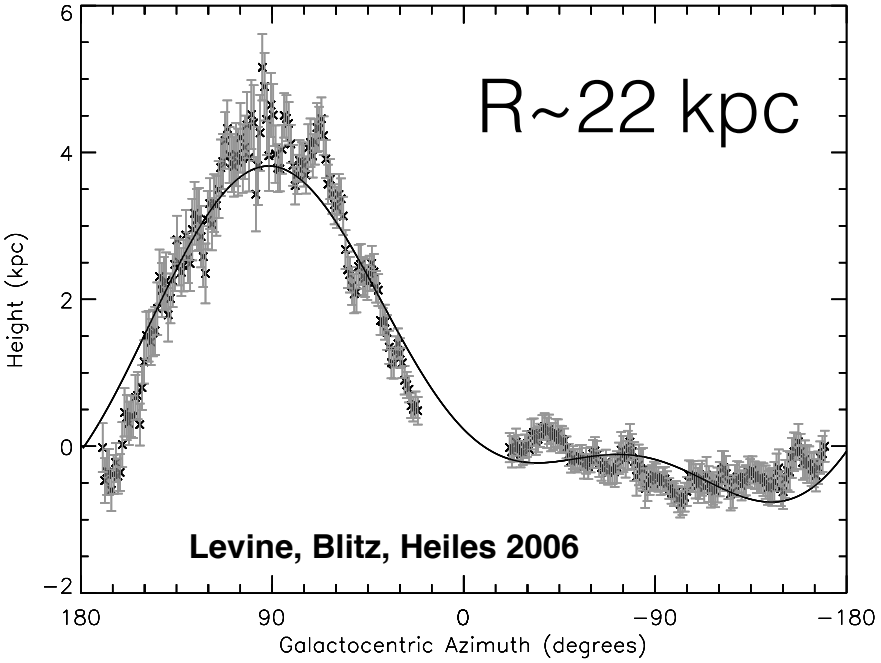
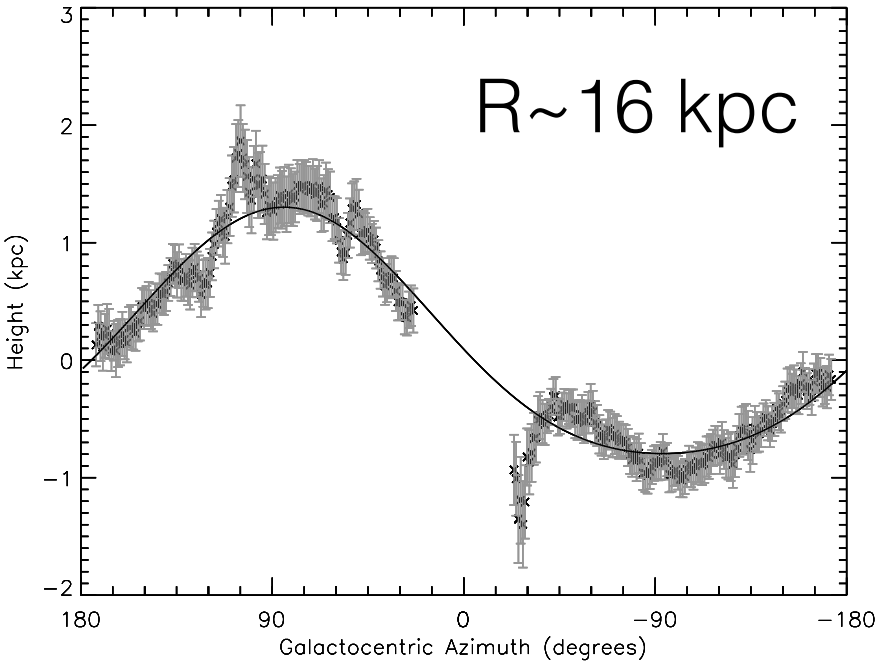
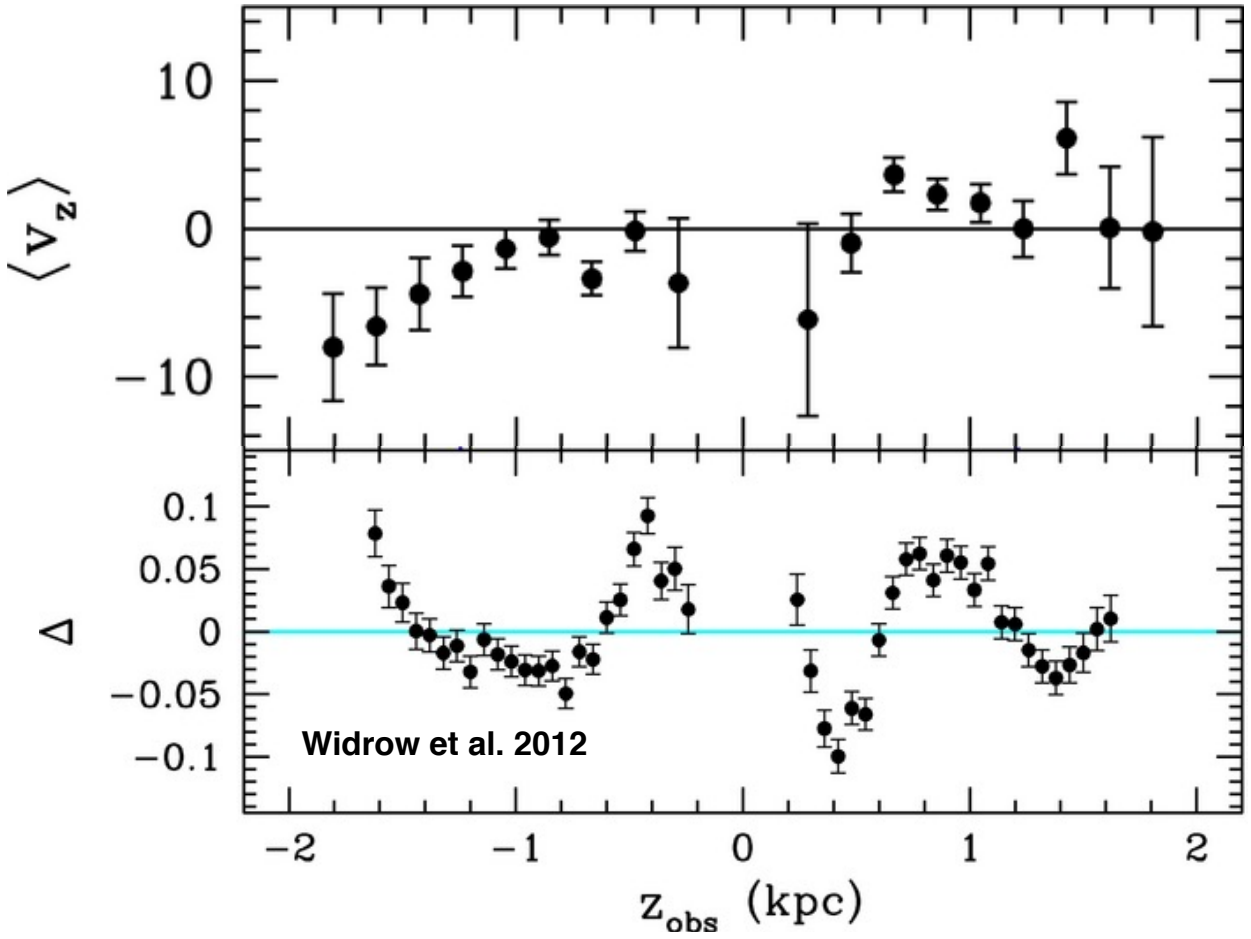




HI warp Z(R) structure: characterised by the linear combination of 3 Fourier modes (m=0,1,2)

Vertical structure of the disc: **the stars view**



Solar neighbourhood

North-South asymmetry
velocity space, number density
counts

see also William13, Carlin13 (for similar results for vz)

Vertical structure of the disc: **the stars view**

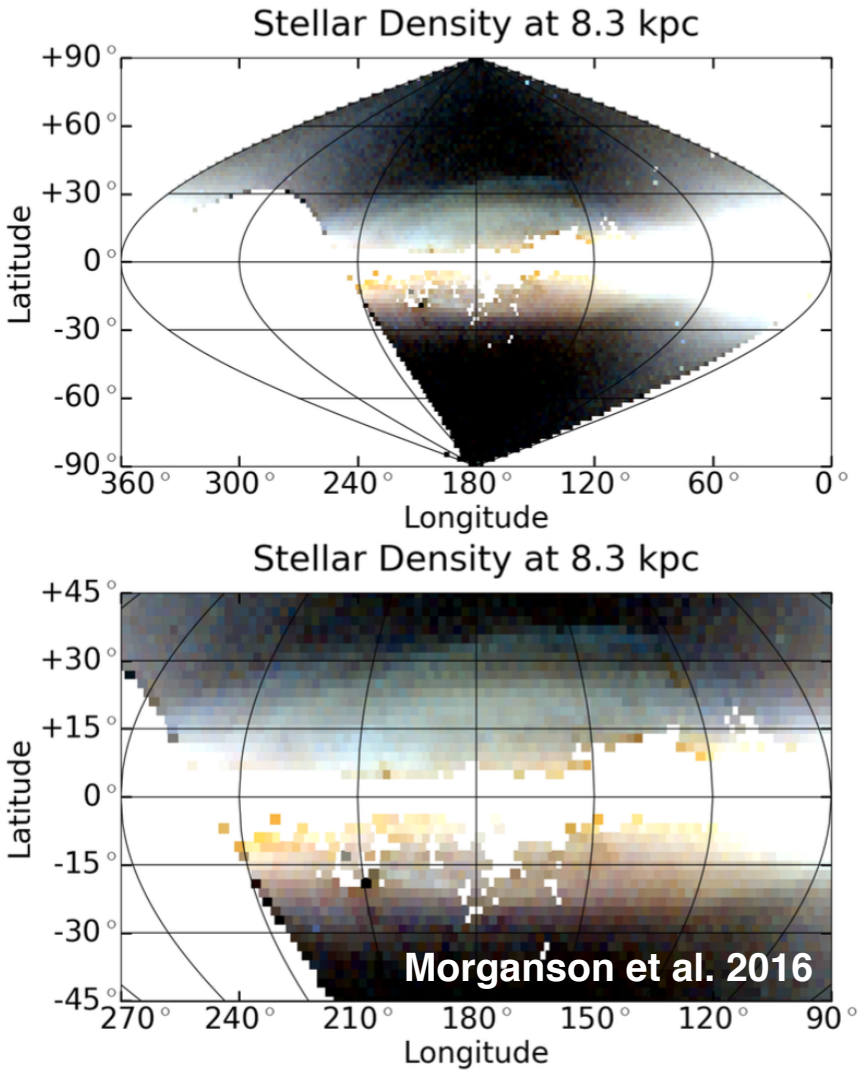
GASS/Monoceros Ring

Originally detected as an overdensity of stars in SDSS footprint, also imaged in 2MASS and PANSTARRS (here)

structure extends:
$120^\circ < l < 240^\circ$, $-30^\circ < b < +40^\circ$

Hd~6kpc in South
Hd~9kpc in North

Newberg et al. 2002, Ibata et al. 2003, Rocha-Pinto et al. 2003, Slater et al. 2014, Morganson et al. 2016



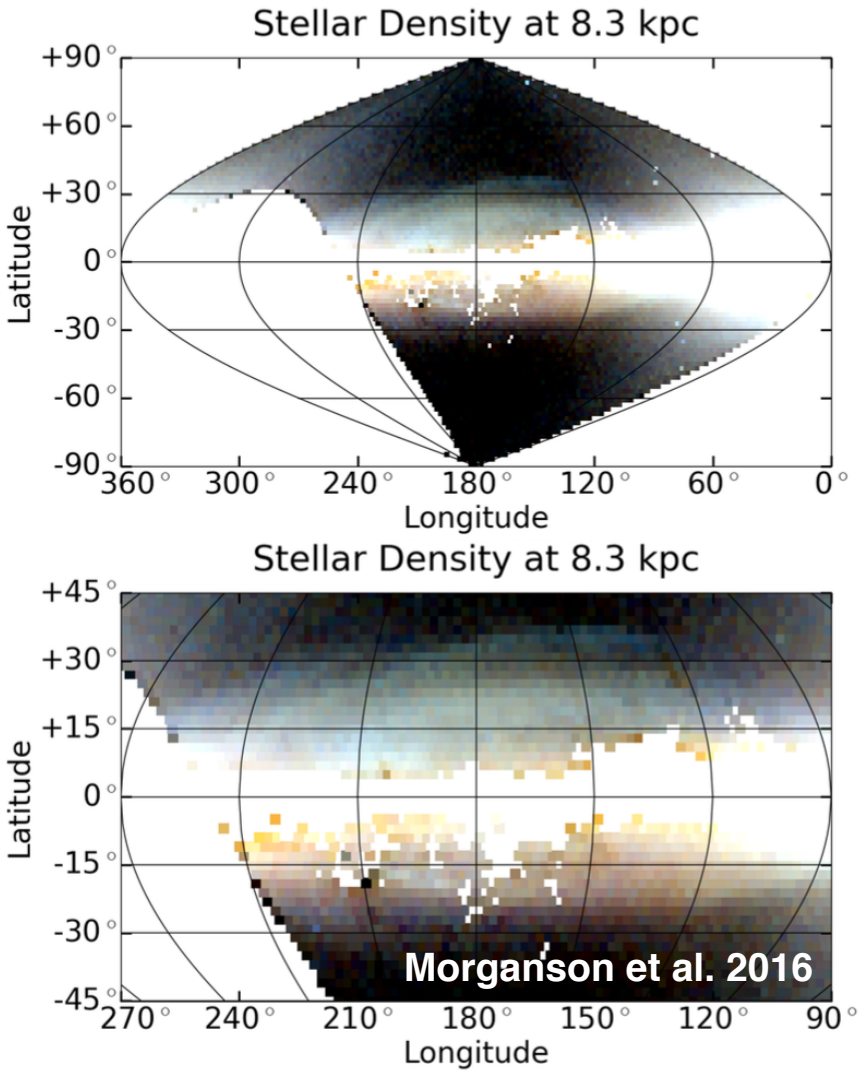
Vertical structure of the disc: **the stars view**

GASS/Monoceros Ring

FORMATION scenarios:

1) Disc material kicked out to high-latitude by satellite encounter (Kazantzidis09,Purcell11,Gomez13,Price-Whelan15)

2) Remnant stream of in-plane accreted dwarf (Penarrubia05)



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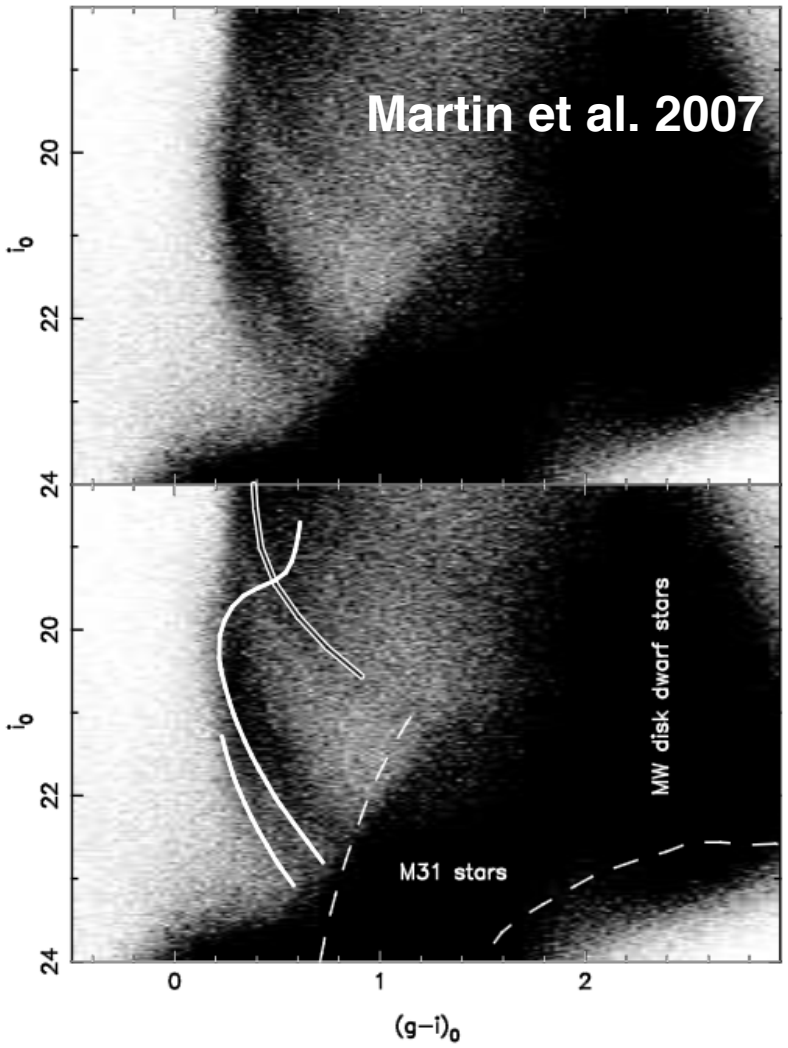
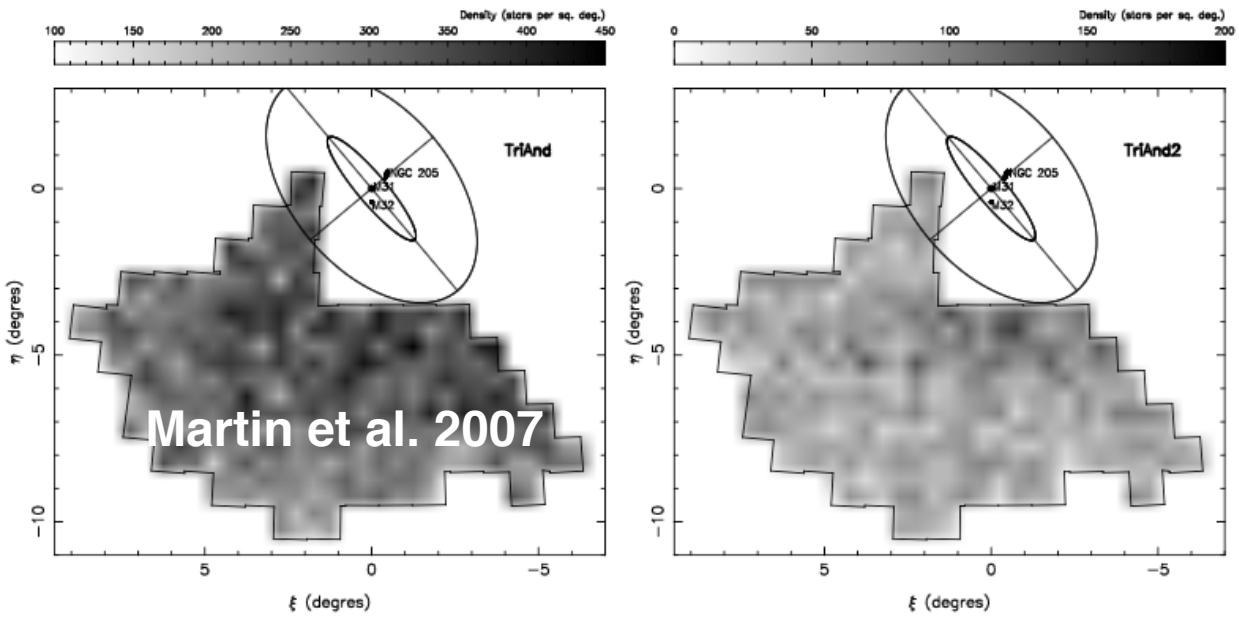


TriAnd I & II Clouds

R~30 kpc, Z~-10 kpc

(see also Sheffield14, Xu15, Price-Whelan15)

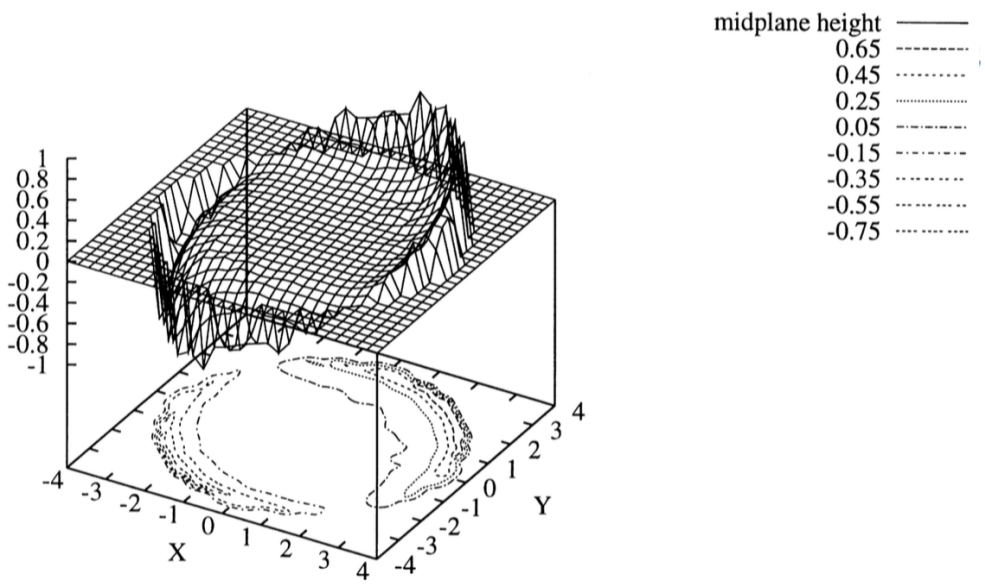


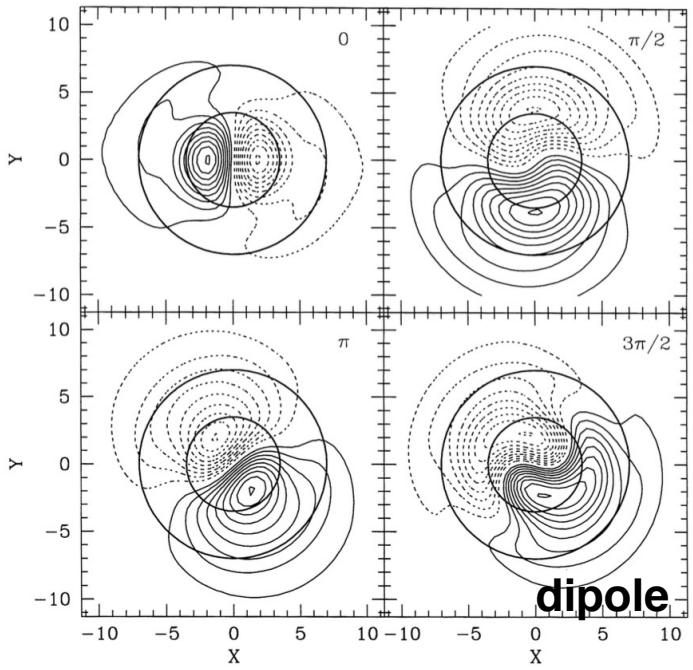
Satellite-halo interactions: tidal interaction and DM halo wakes

Dynamics of an interacting luminous disc, dark halo and satellite companion

Martin D. Weinberg*† **1998**
Department of Physics and Astronomy, Universi

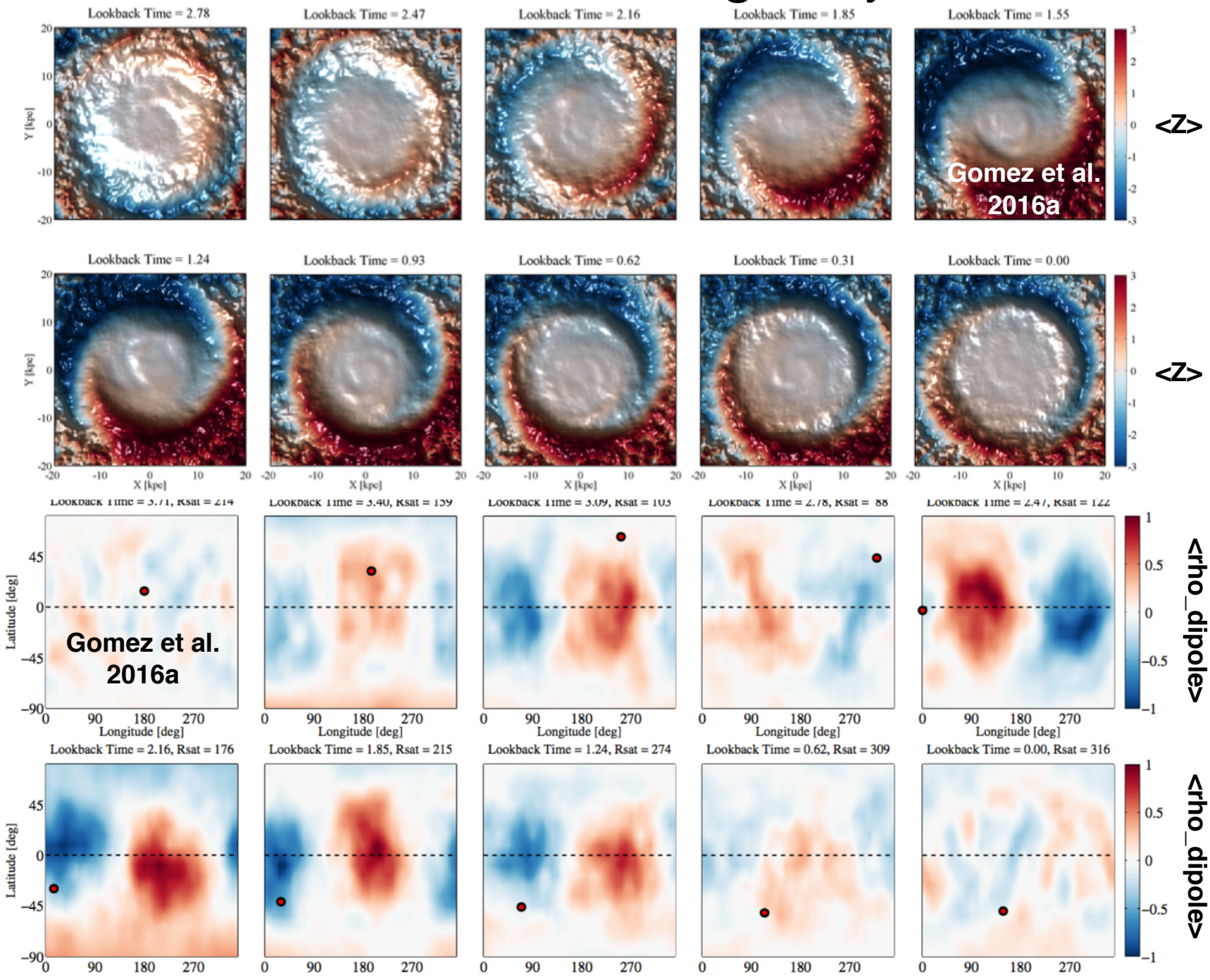
DM halo wake excited by perturbing satellite



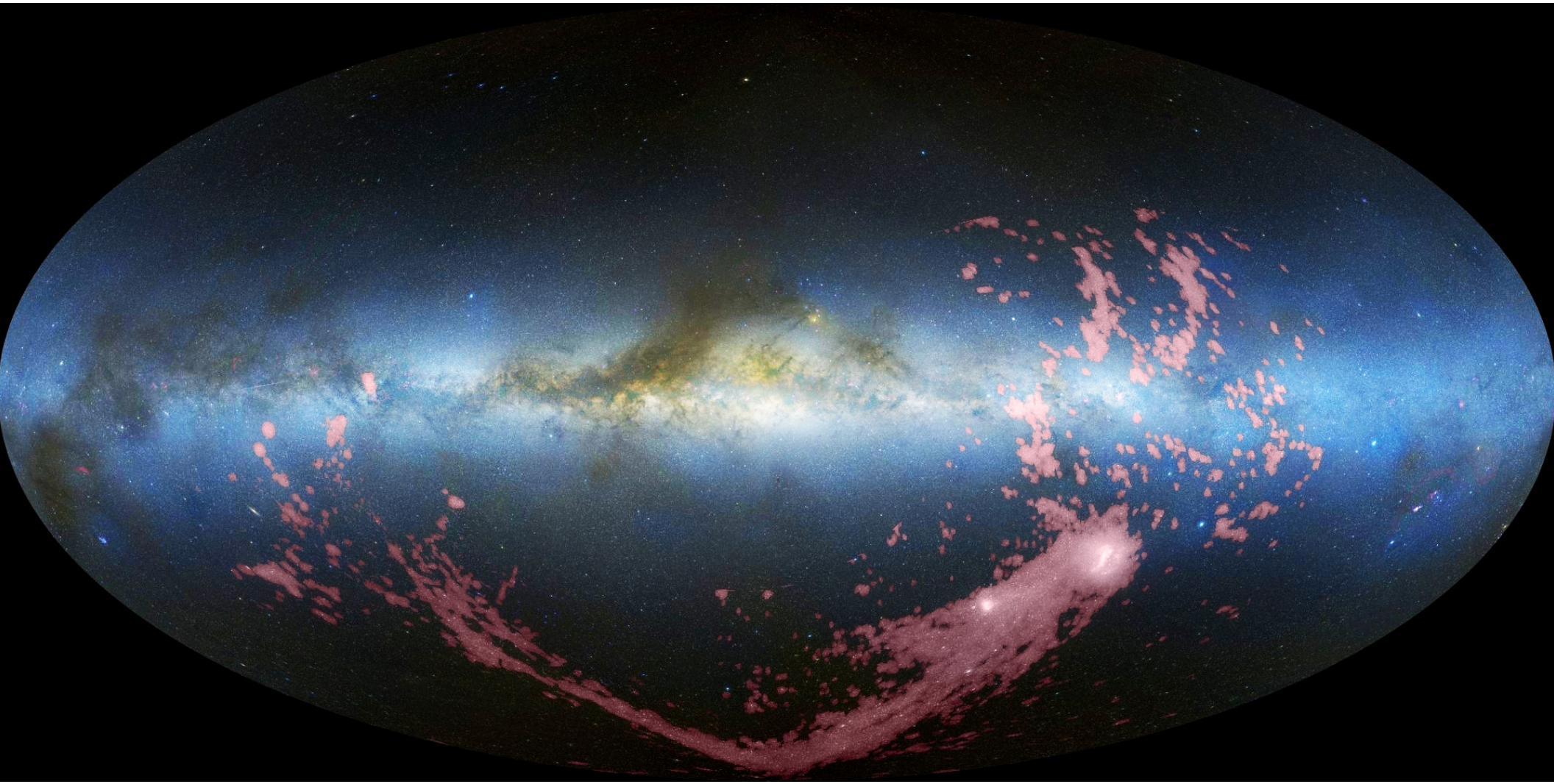


See also Weinberg 89, Vesperini & Weinberg 00, Weinberg&Blitz06

Fly-bys in cosmological hydrodynamical N-body simulations of MW-mass galaxy formation



The suspects



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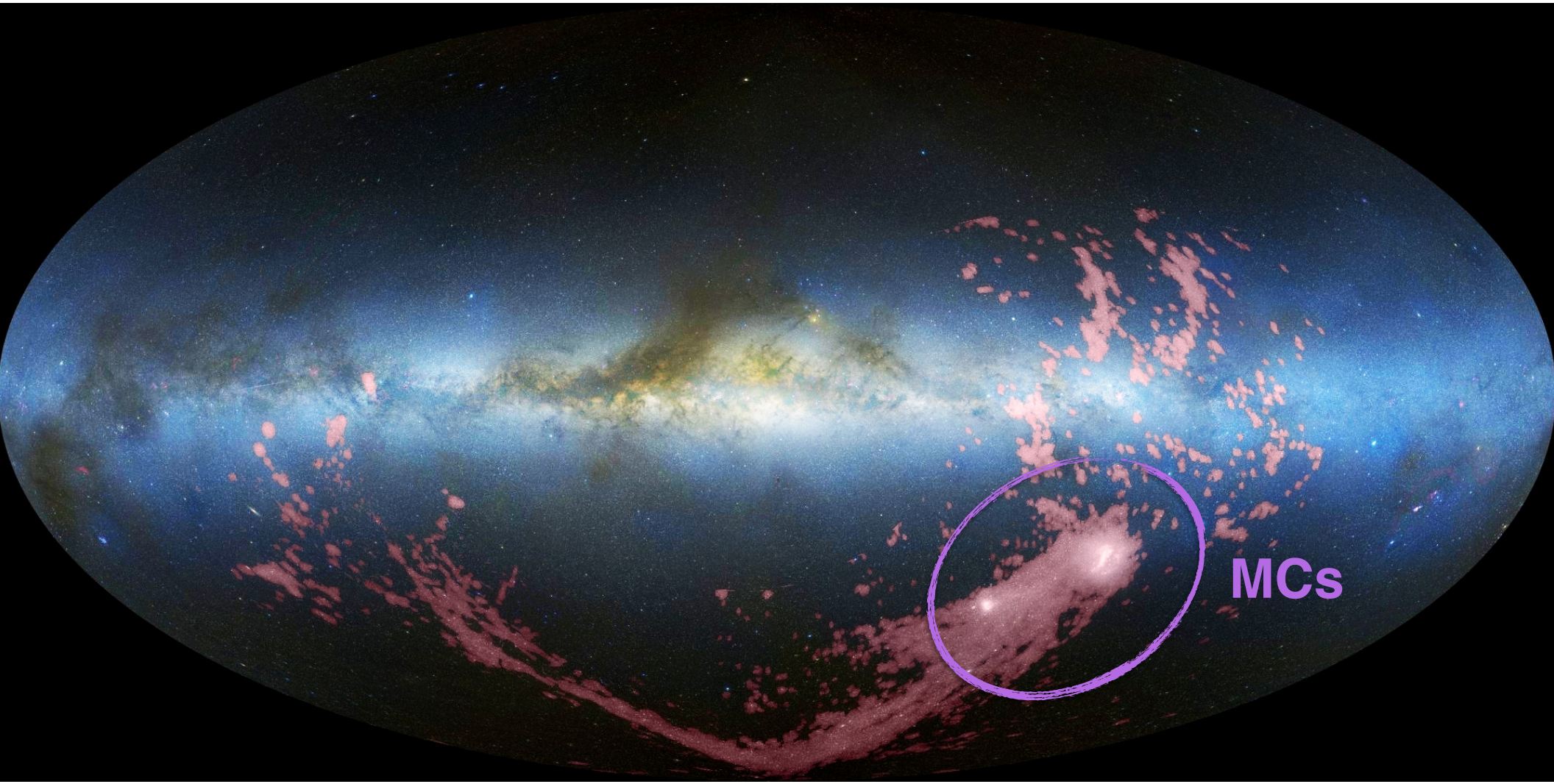

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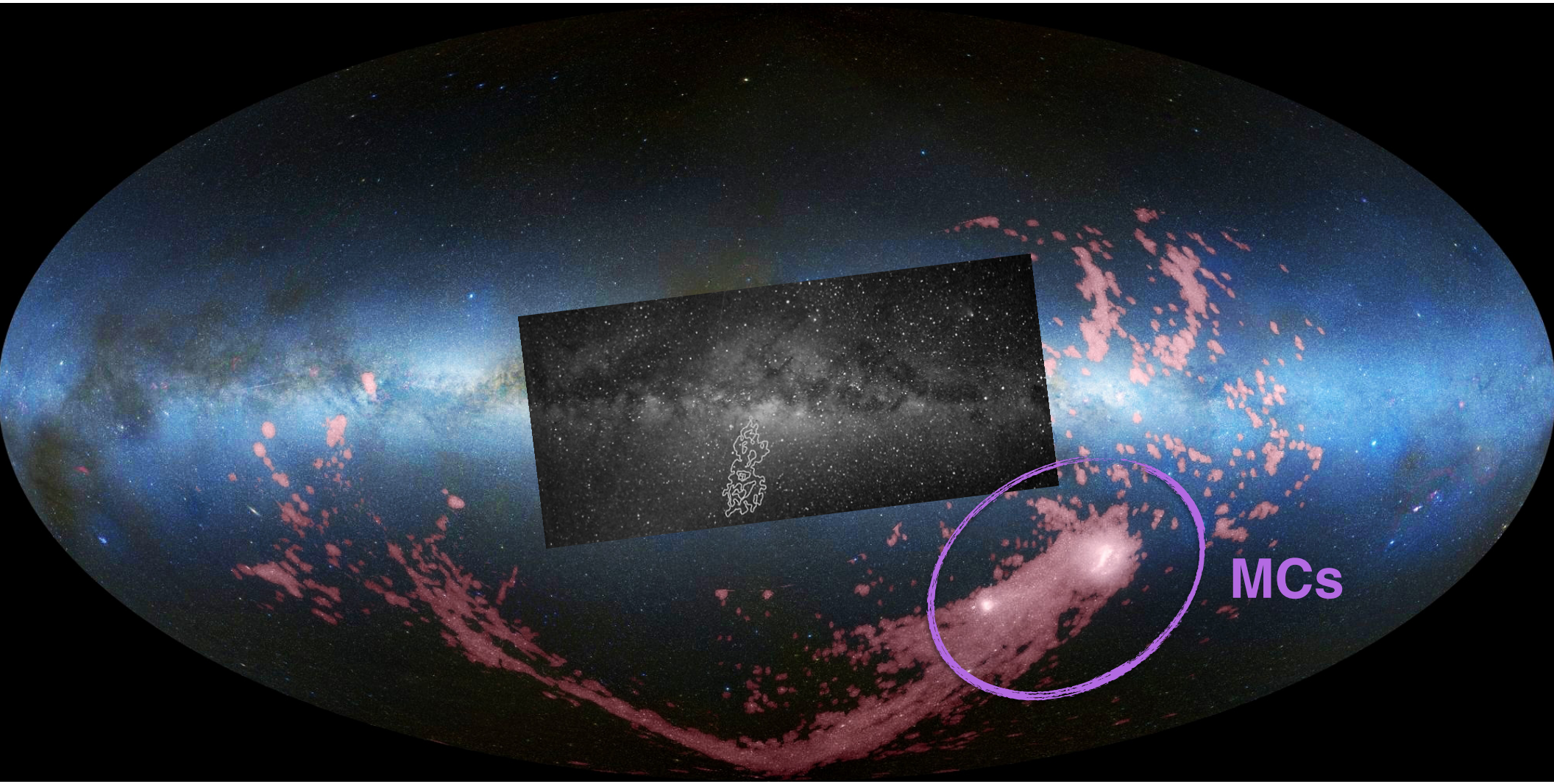

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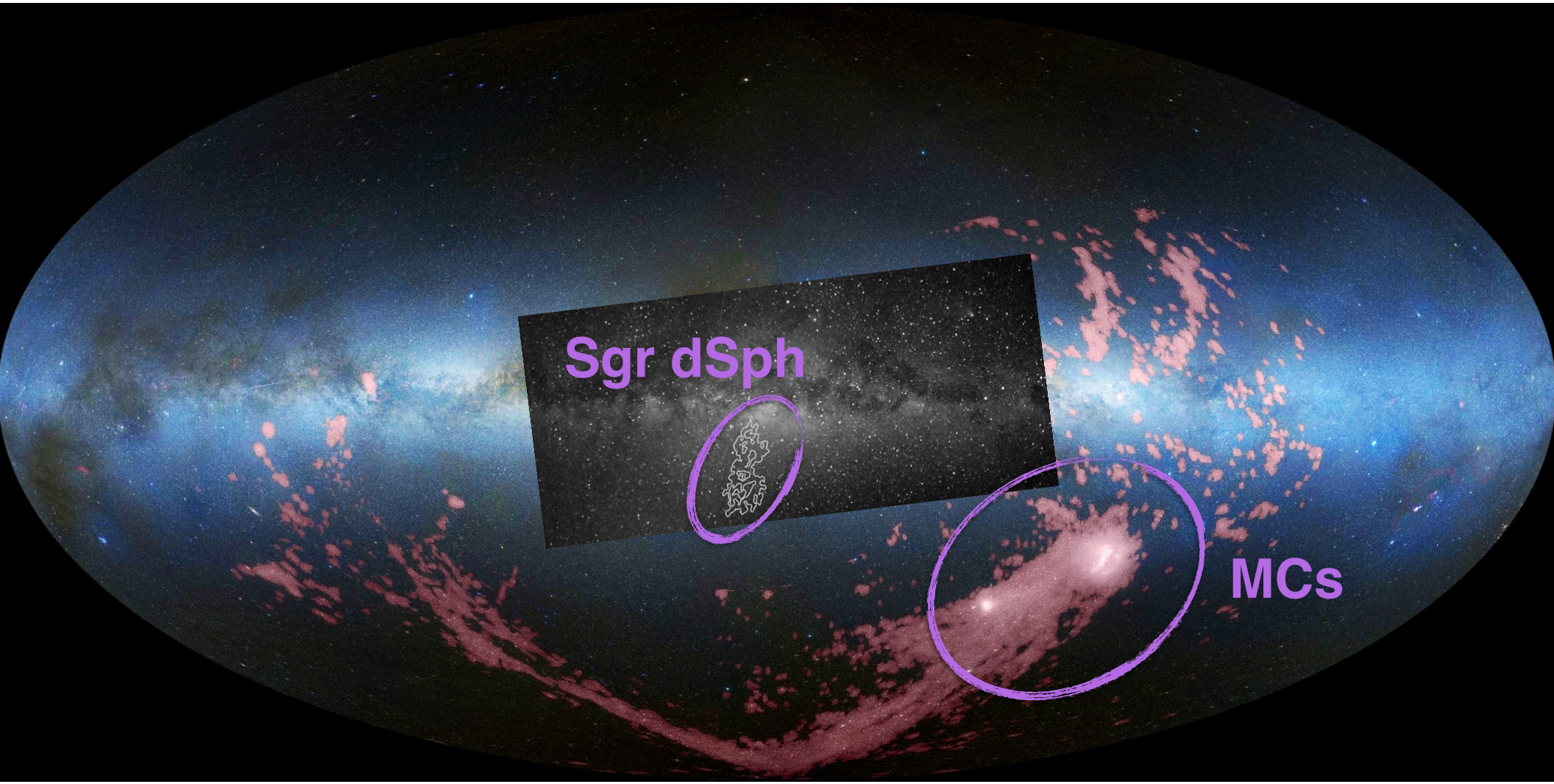

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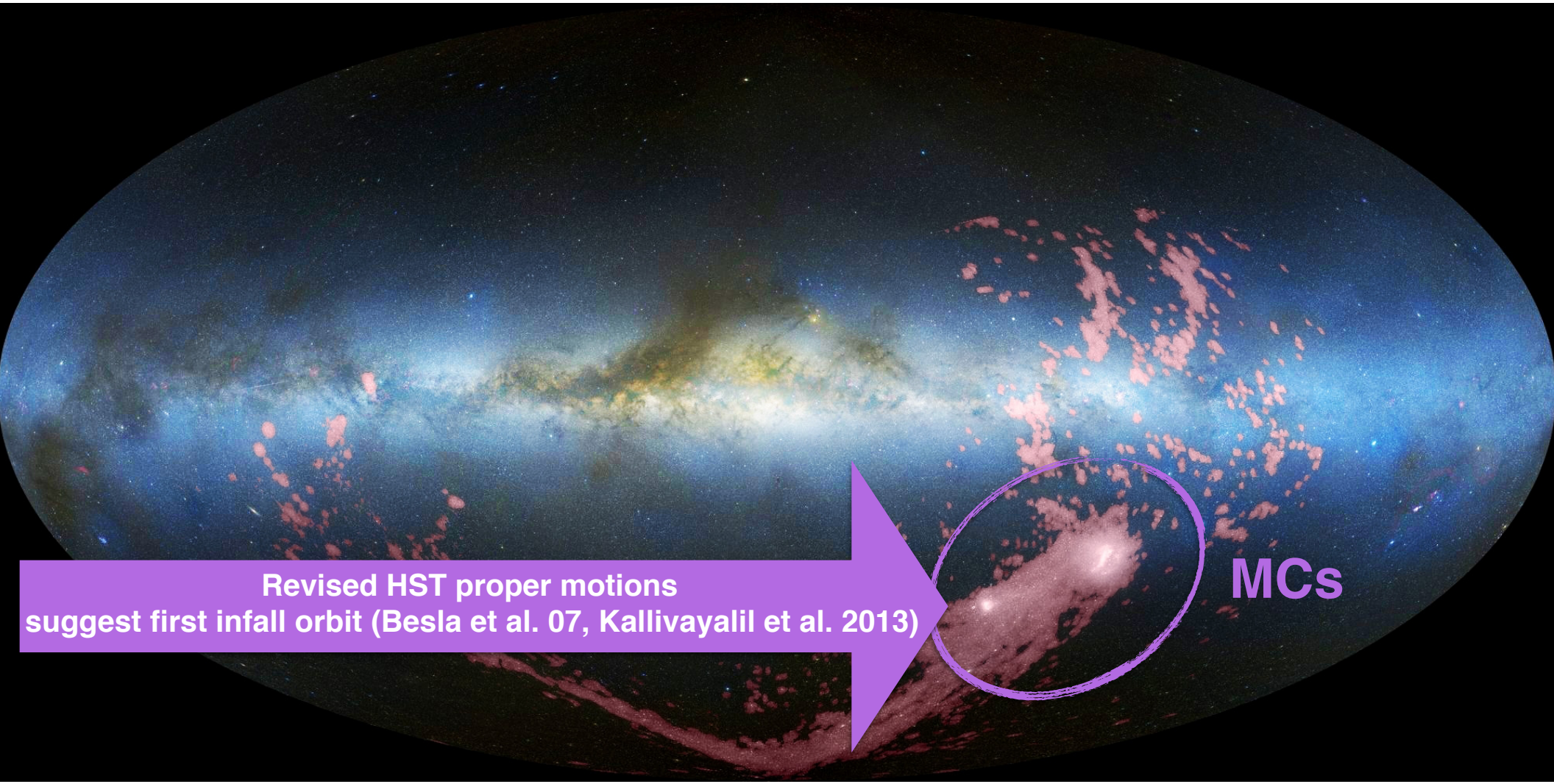
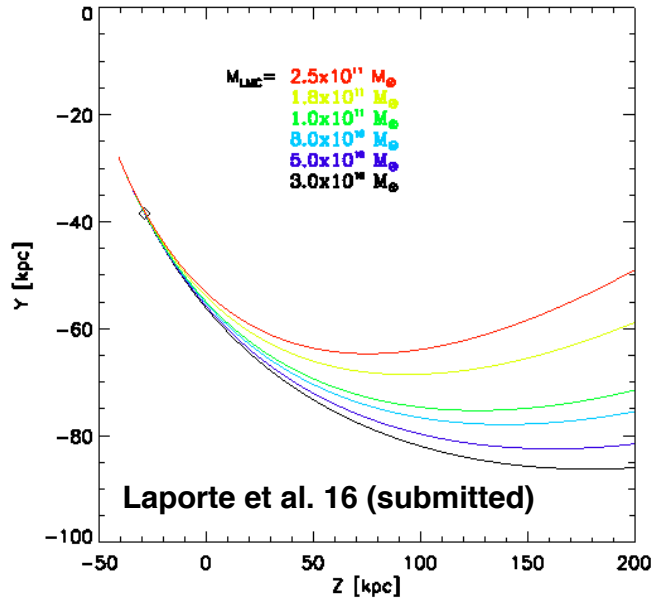
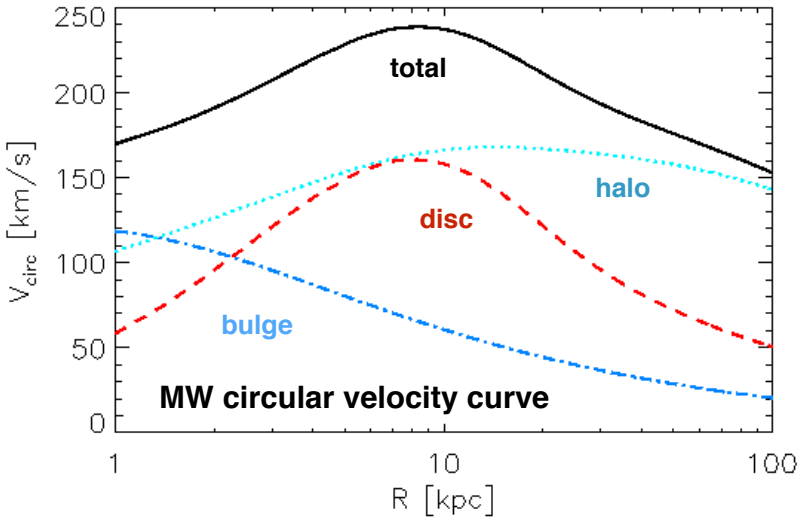
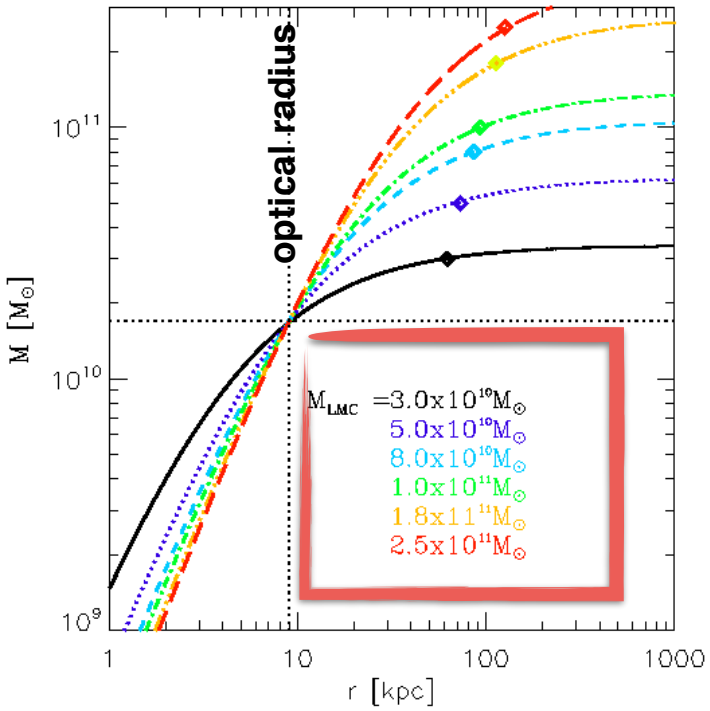


Six LMC models on a first infall







Components		units
DM halo		$N_{part} = 20,000,000$
Virial mass	1×10^{12}	$M_\odot$
Scale radius	28	kpc
Concentration	10	
Stellar disc		$N_{part} = 6,000,000$
Mass	6.5×10^{10}	$M_\odot$
Scale length	3.5	kpc
Scale height	0.53	kpc
Bulge		$N_{part} = 1,000,000$
Mass	1×10^{10}	$M_\odot$
Scale radius	0.7	kpc
Gas disc		$N_{part} = 1,000,000$
Mass	8.7×10^{9}	$M_\odot$
Scale length	3.5	kpc

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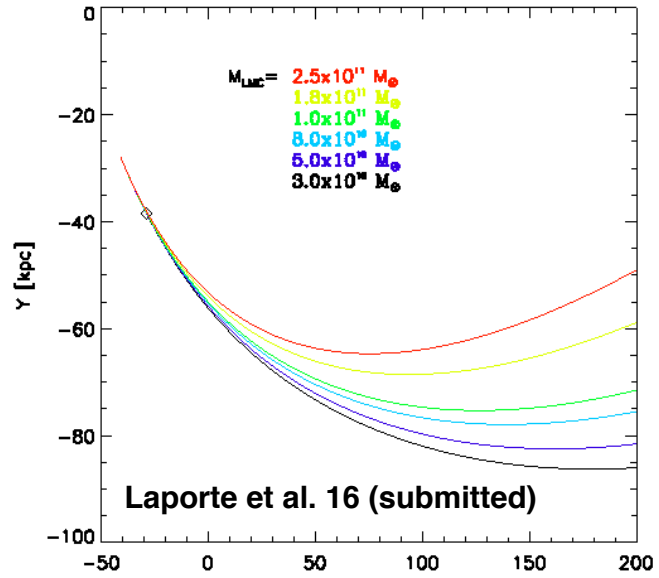

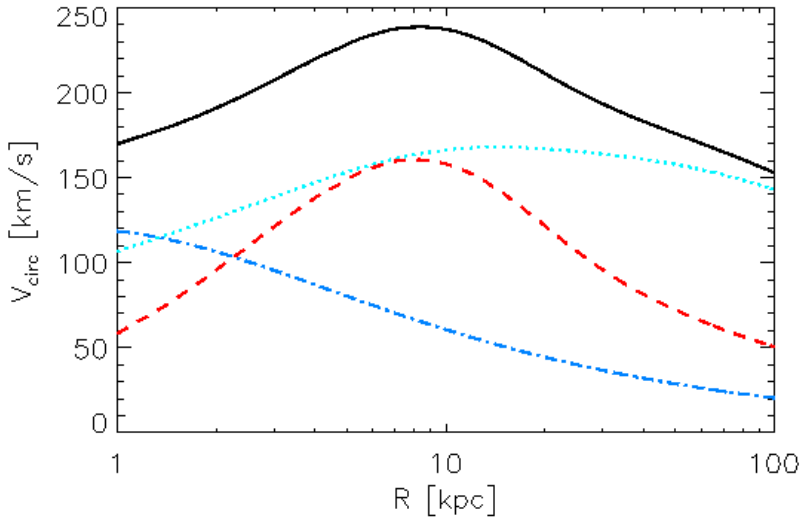

#	Δx	Δy	Δz	Δv_x	Δv_y	Δv_z	ΔD	Δv
1	-0.1	4.0	0.3	-11.0	-12.5	34.3	-3.5	34.7
2	-0.4	3.8	2.0	2.5	6.9	40.9	-4.3	24.5
3	-0.6	3.1	2.3	3.2	5.6	42.9	-3.8	26.8
4	-0.2	3.5	1.8	-1.8	7.7	42.8	-3.9	26.1
5	-1.6	-0.6	5.8	-4.2	-16.5	50.4	-2.4	47.8
6	-1.1	0.0	3.9	3.9	-32.9	46.9	-2.0	55.0

Table 3. Differences $\Delta = X_{sim} - X_{data}$ in position, velocity, position and speed between the model realisations and LMC data from (Kallivayalil et al. 2013). The adopted phase-space location of the LMC is taken to be $X_{data} = (-1.06, -41.0, -27.0, -57.4, -225.5, 220)$. The final distance and speeds for the various LMC models are within 2σ from those determined observationally - $\sigma_v = 24$km/s (Kallivayalil et al. 2013) and $\sigma_D = 2.5$ kpc (Freedman et al. 2001) - except for the last model which slightly exceeds 2σ.

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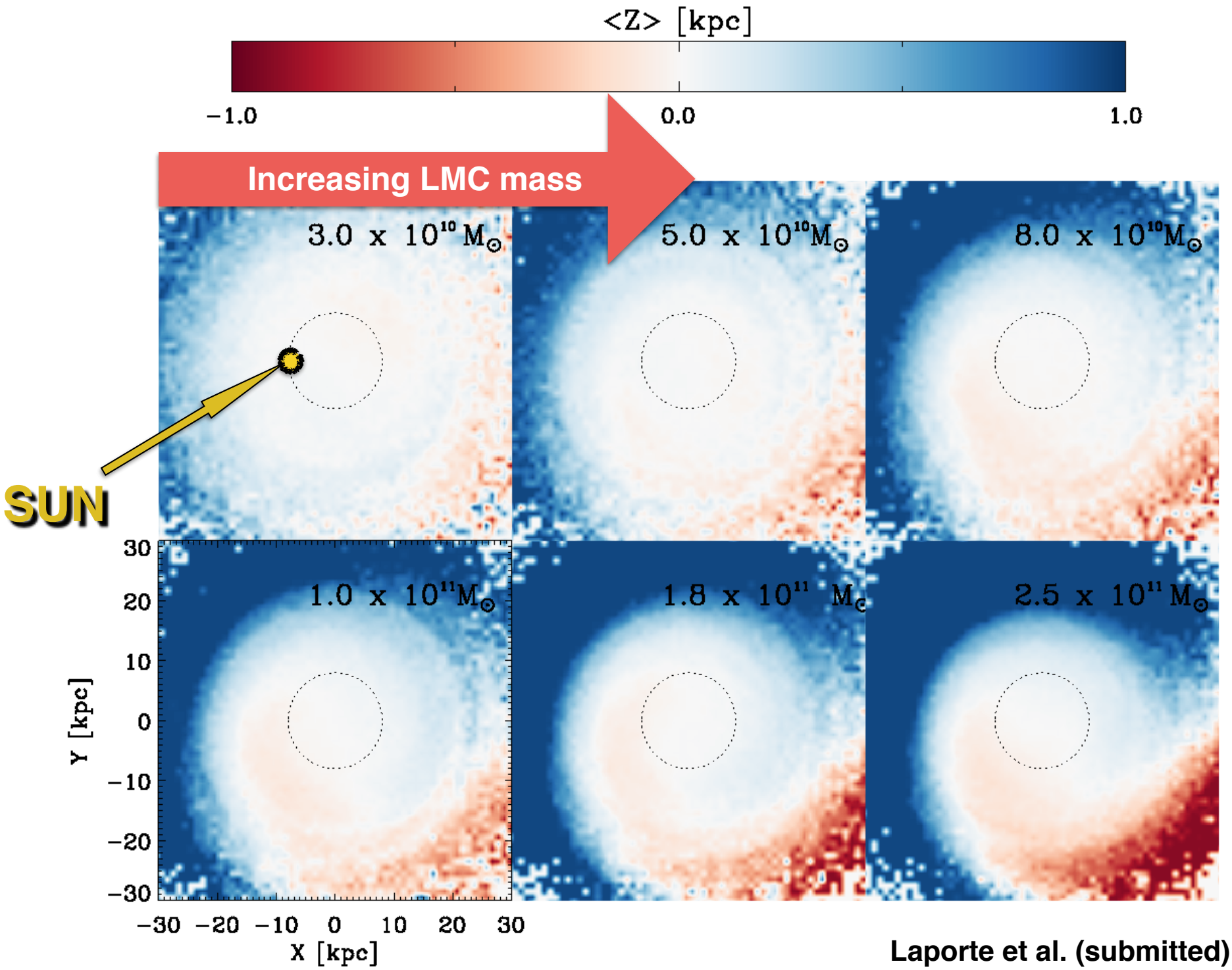


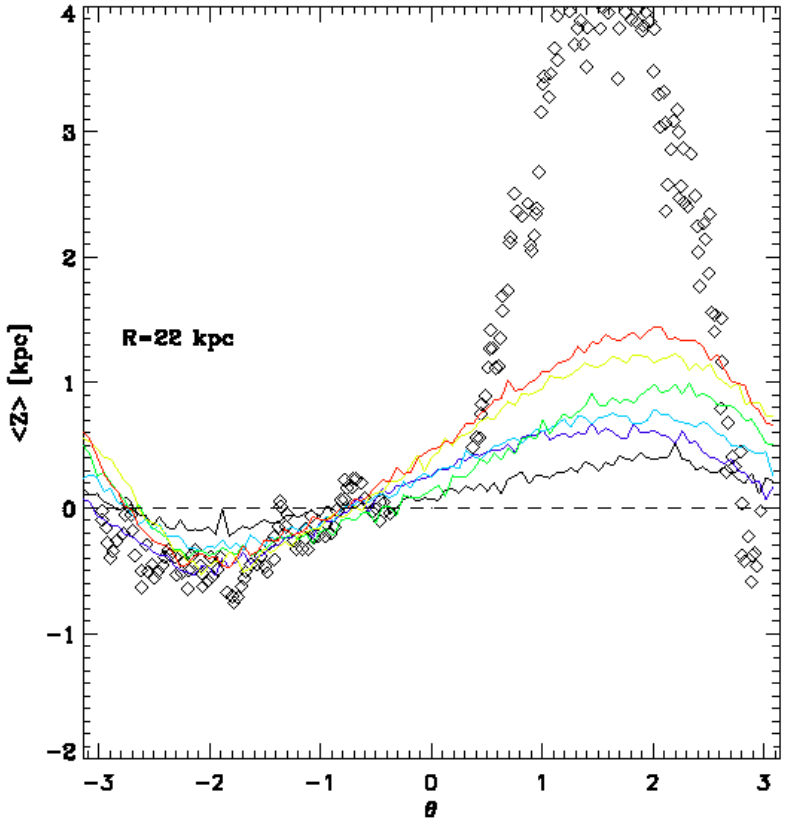
Laporte et al. (submitted)

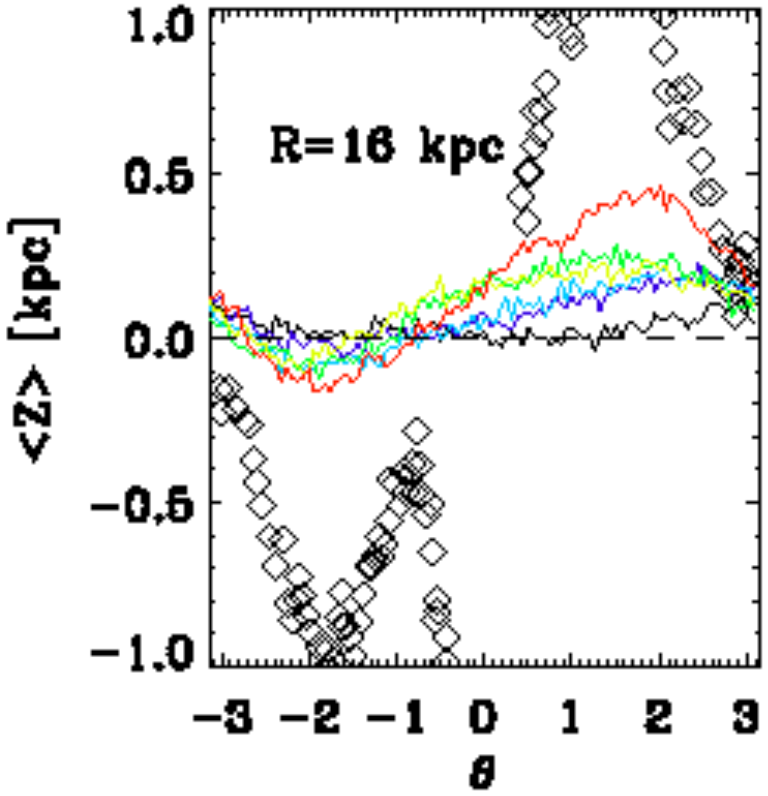
Lines of Node

Asymmetrical warp shape

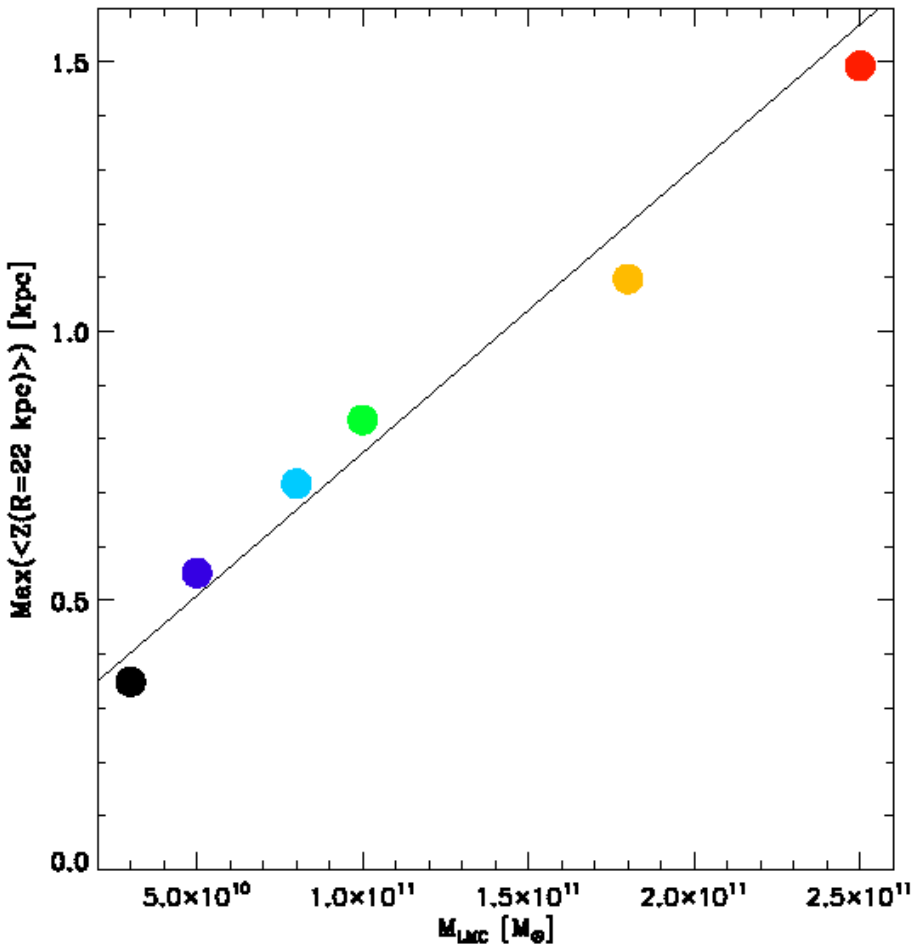
Z(R) is characterised by 3 Fourier terms

Discrepancy with amplitude (0.5-0.7kpc, 2-3 kpc)





LMC models on a first infall



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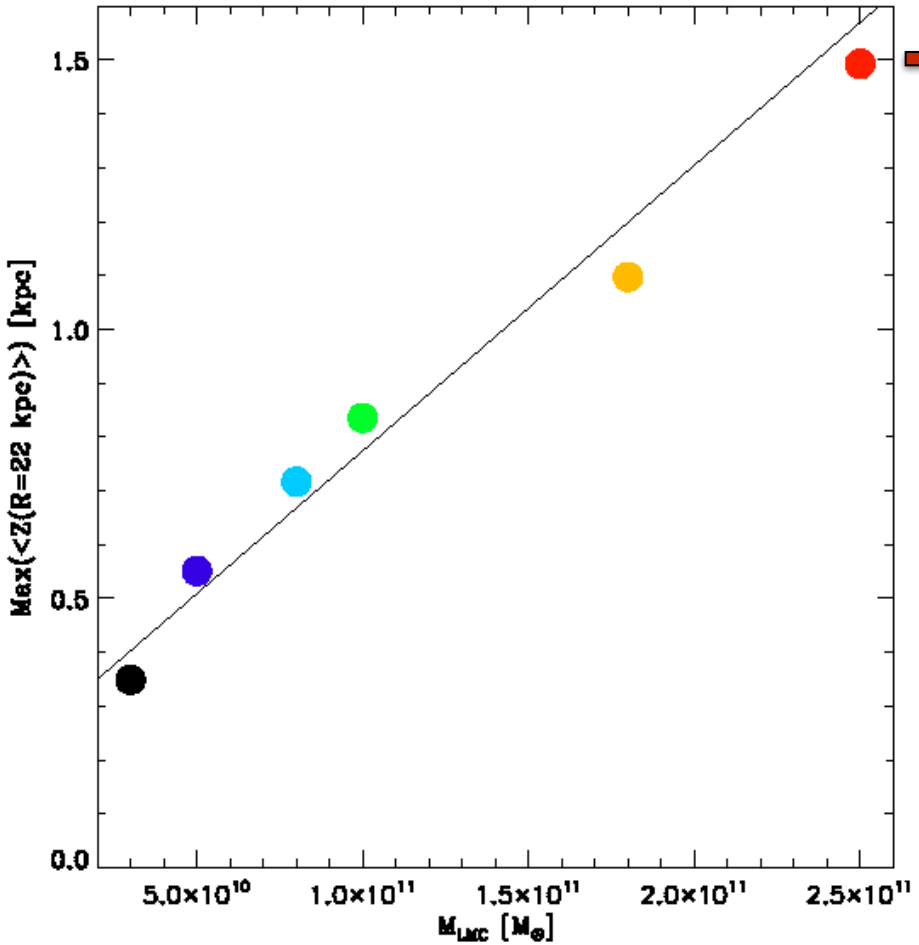

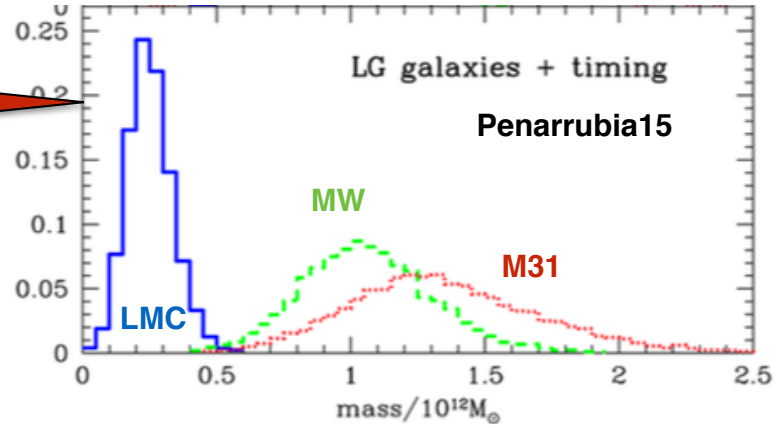

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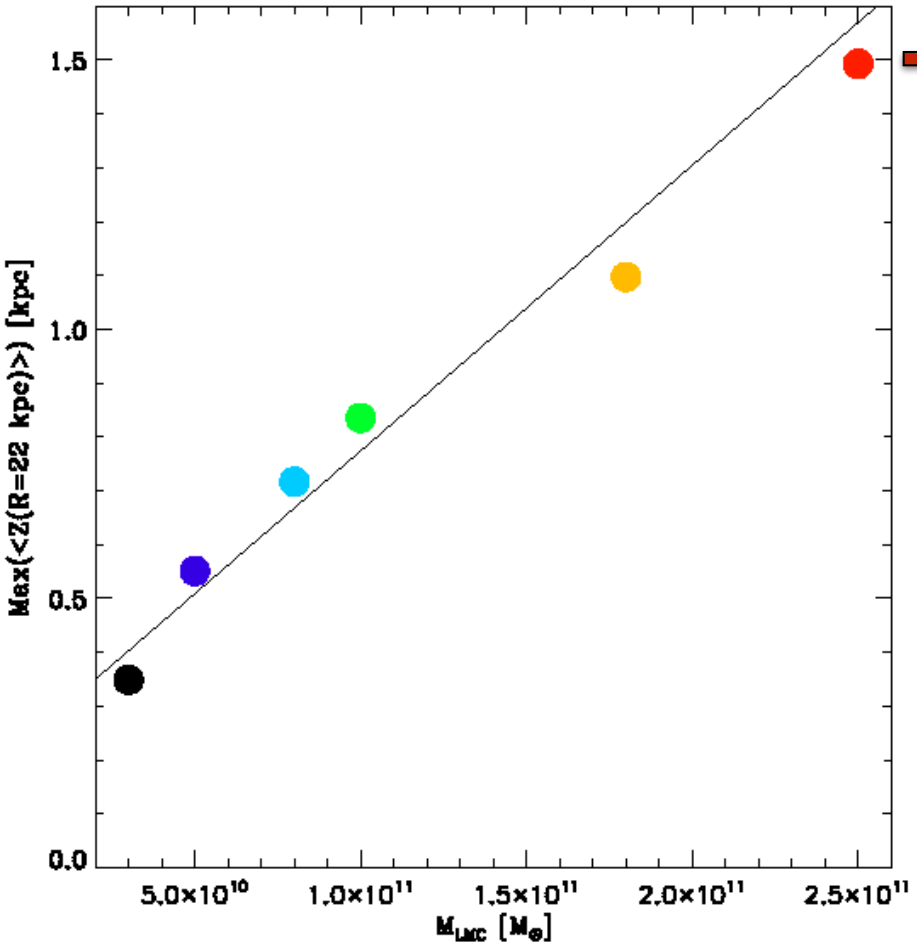

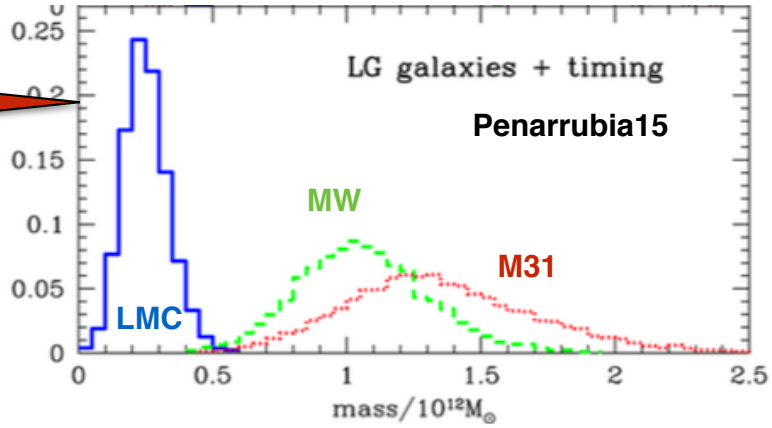

More massive LMC?
e.g. 3.5e11Msun -> Zmax~2 kpc

SMC? difference in stellar mass by 10 can still imply difference in halo mass by factor 2-3 (see Moster et al. 2013, also Behroozi13)

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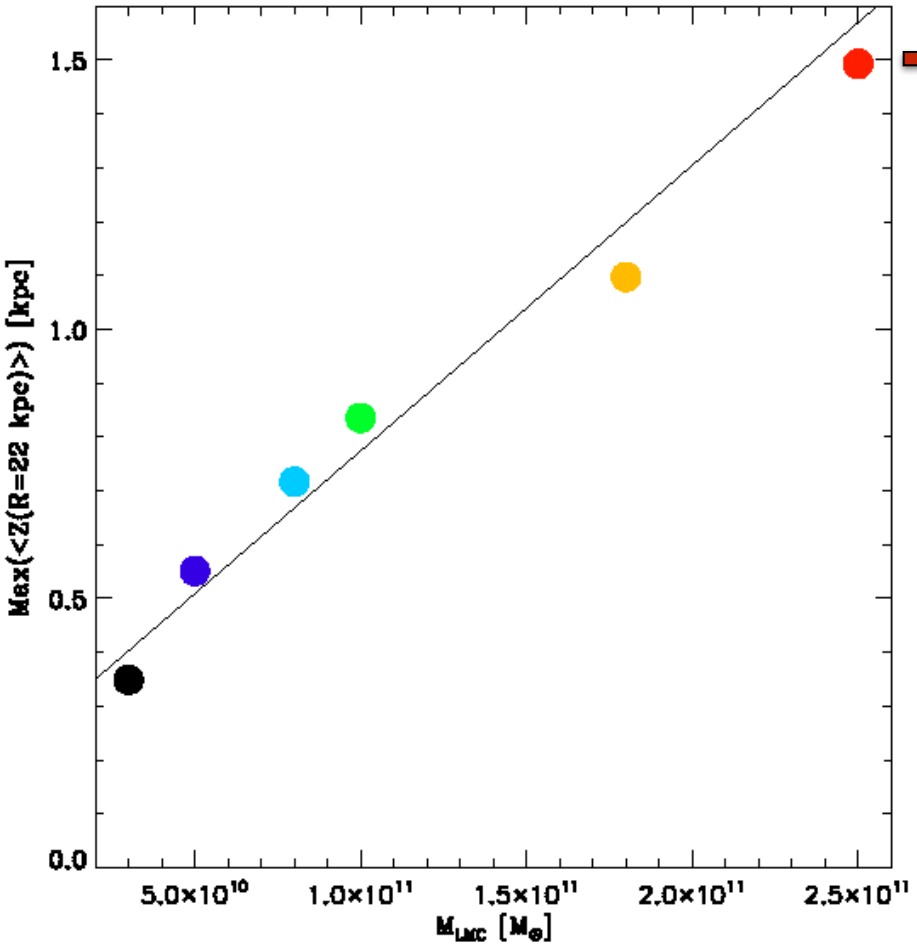

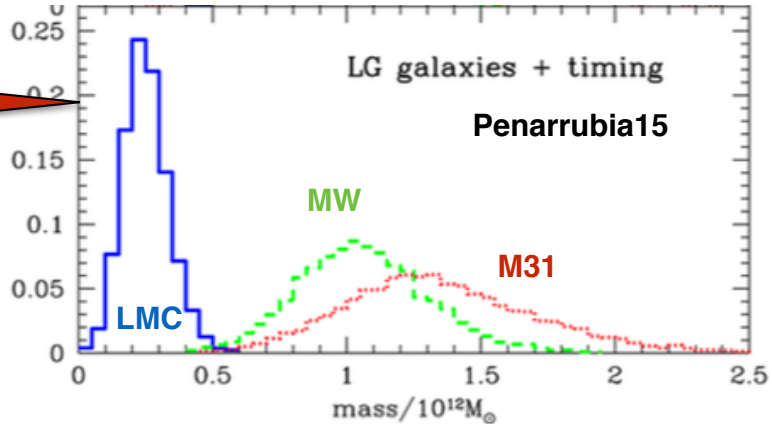

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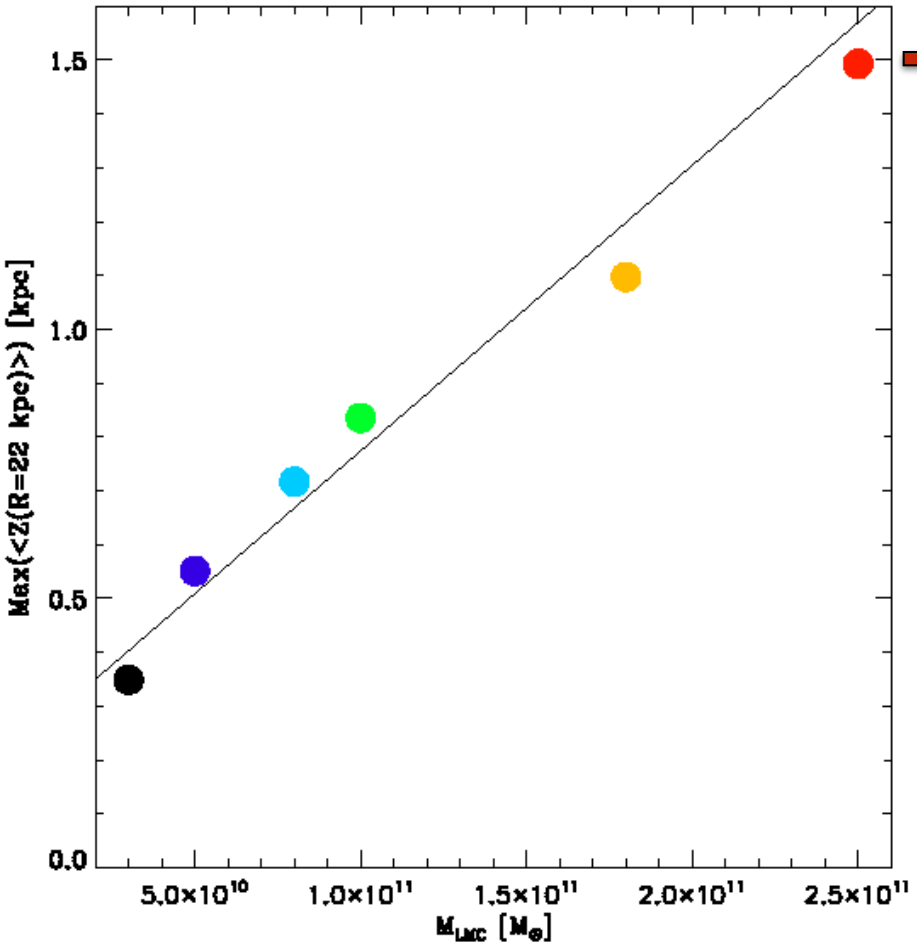

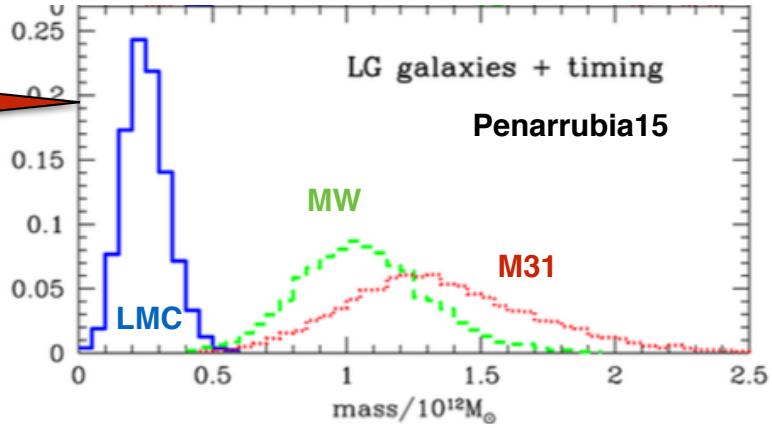

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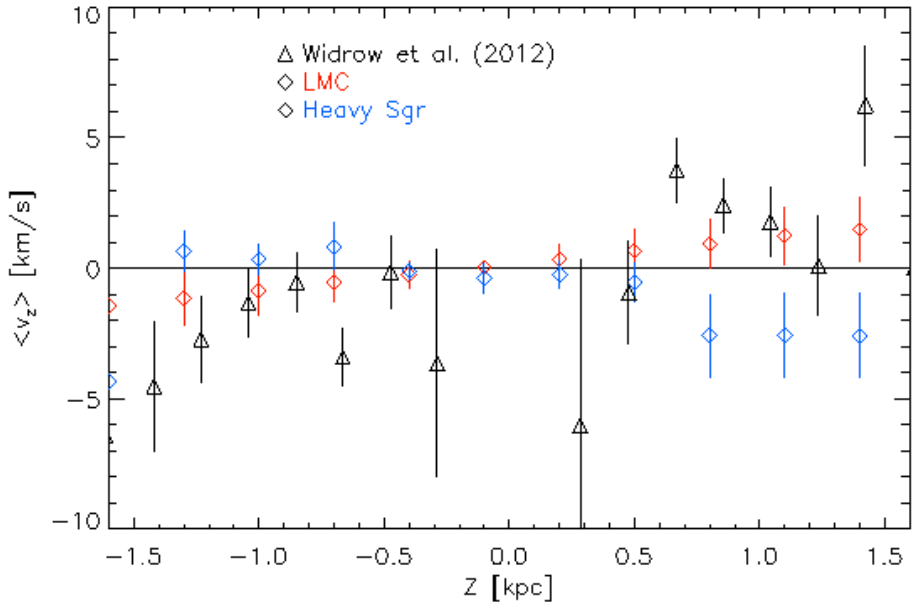
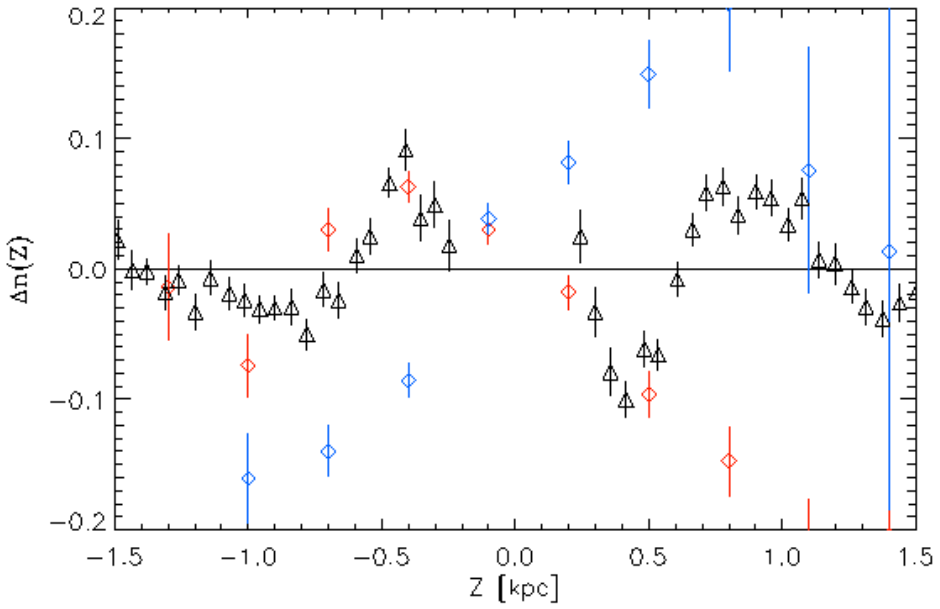
Systematics? OR recent misaligned infall?

Are solar neighbourhood constraints satisfied?

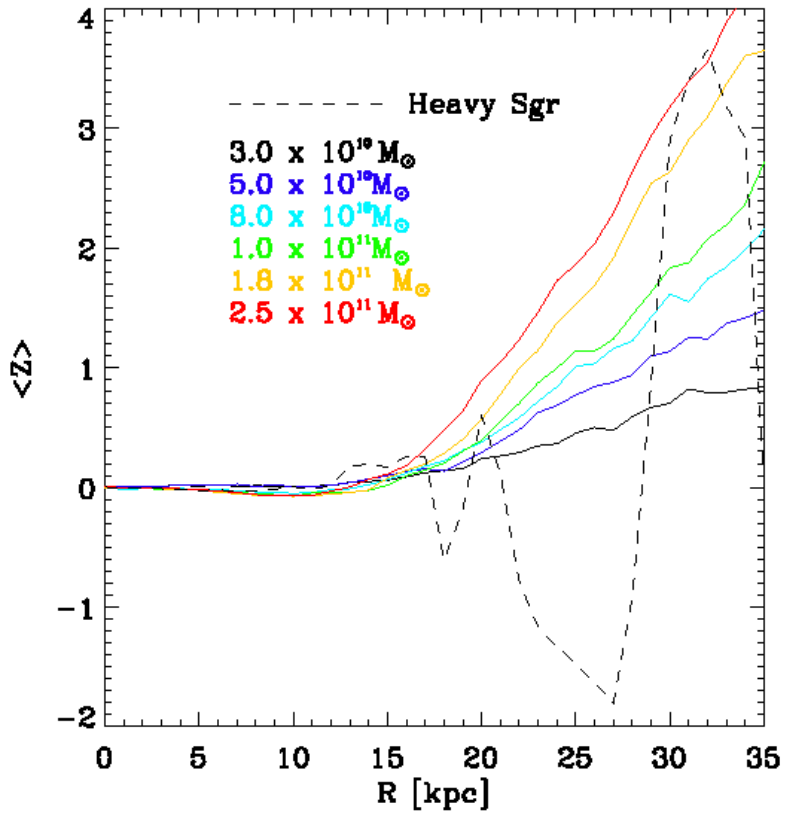
LMC mass of 2.5e11 Msun does not affect dramatically SN constraints

Larger masses still viable



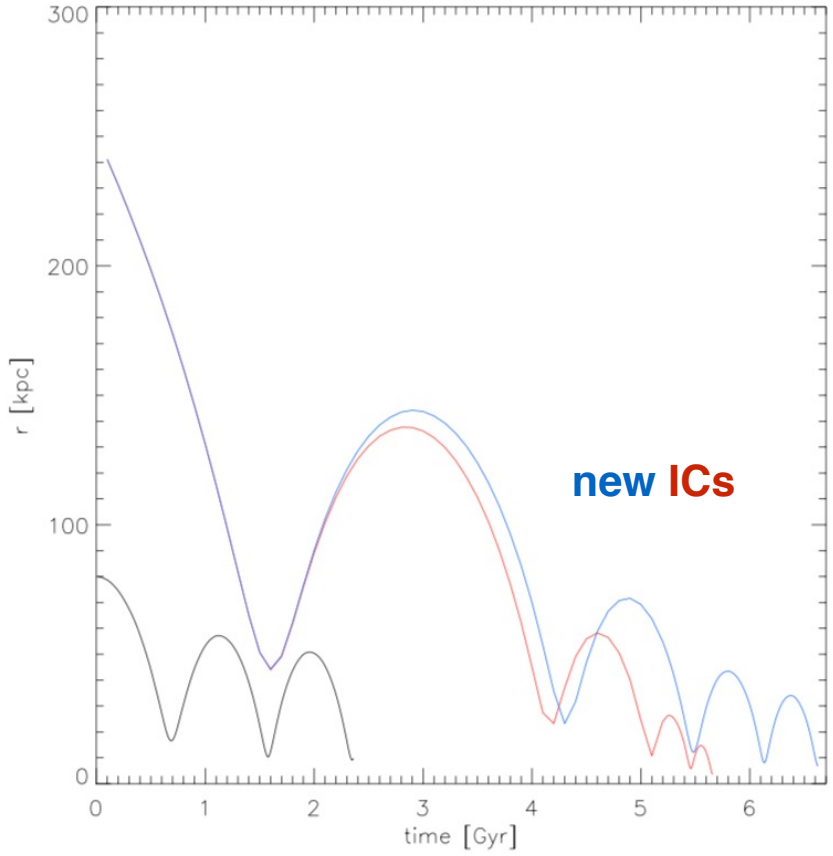


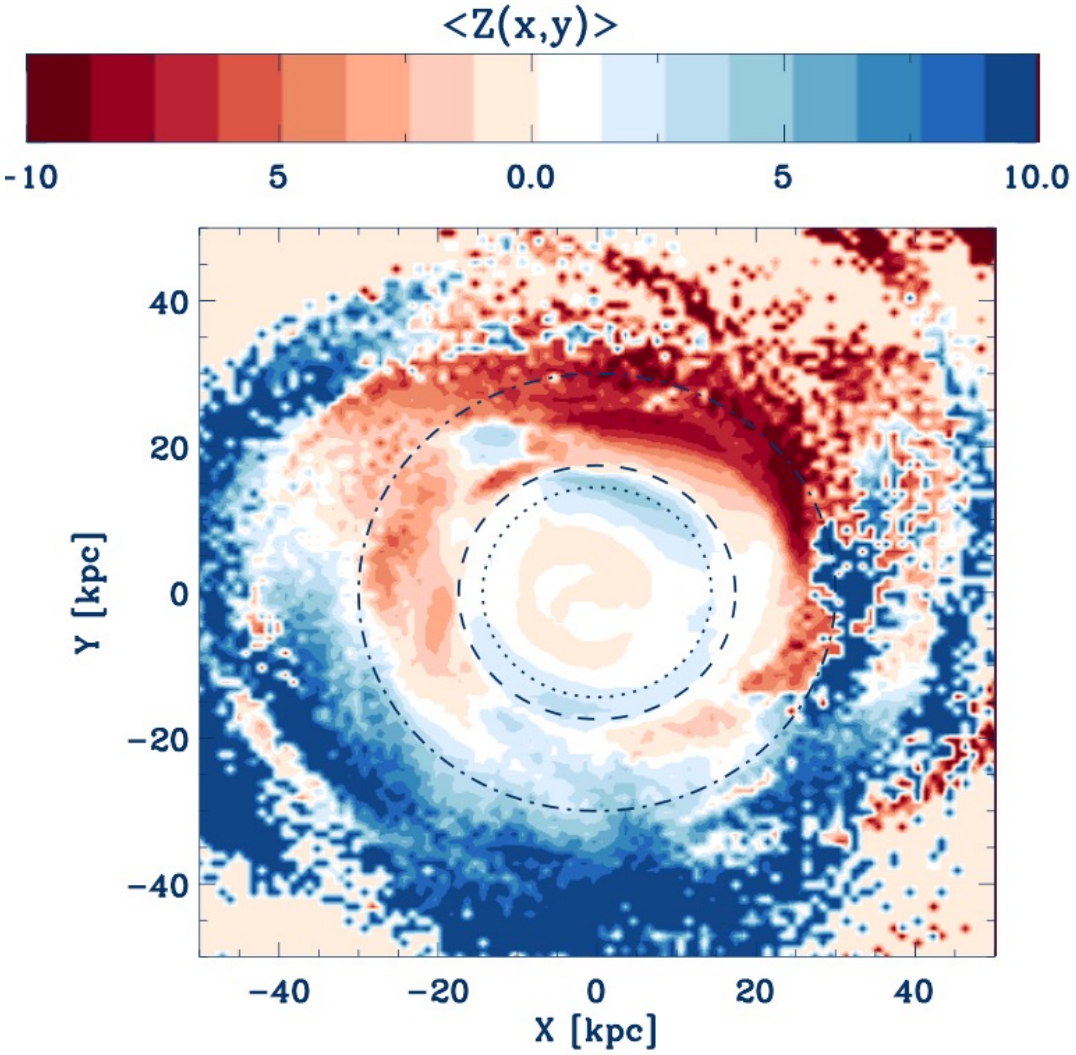
Comparison with a massive (10^11Msun Sgr dSph model)



Revised Sgr Models

orbit taking into account virial radius infall





Laporte, Gomez, Besla, Johnston, Garavito-Camargo **(in prep.)**

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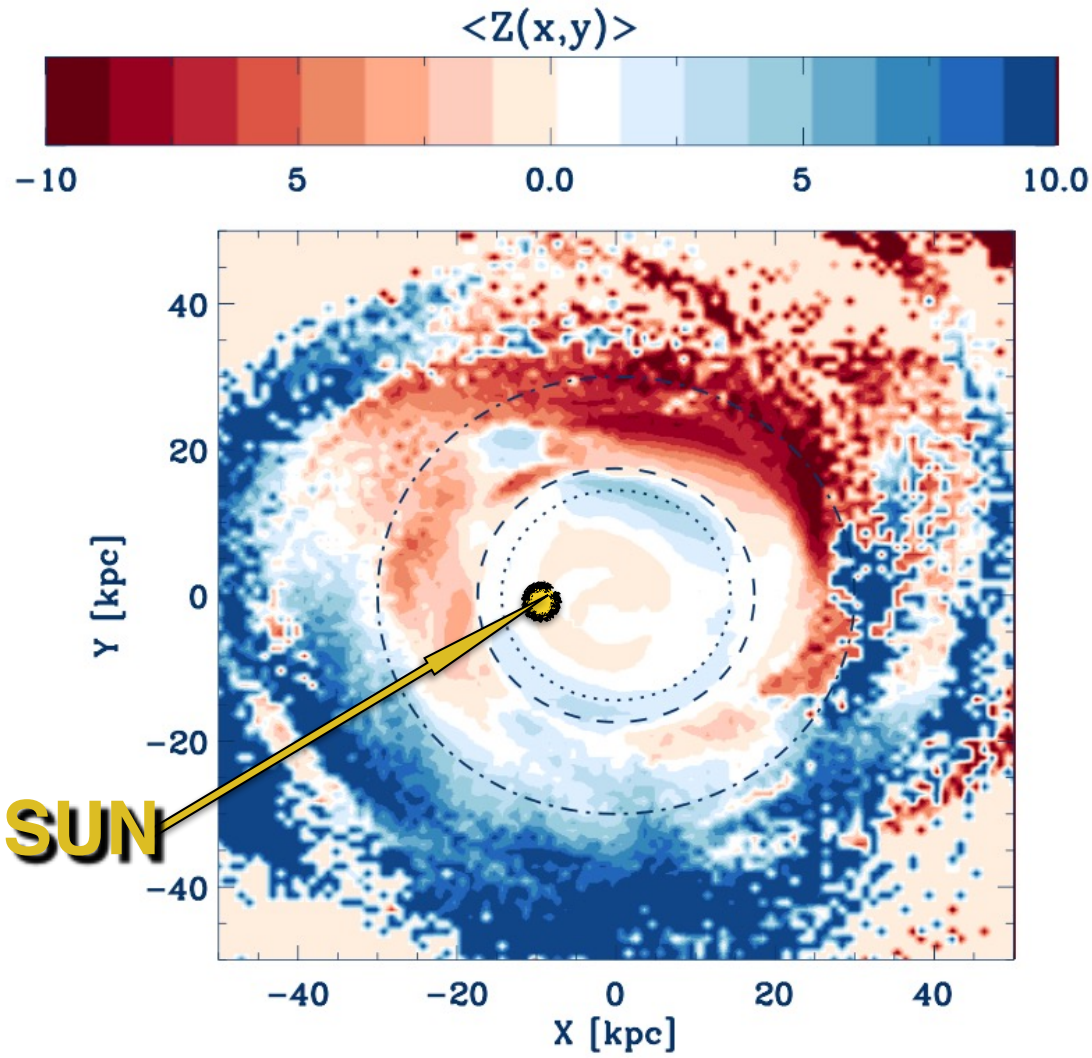

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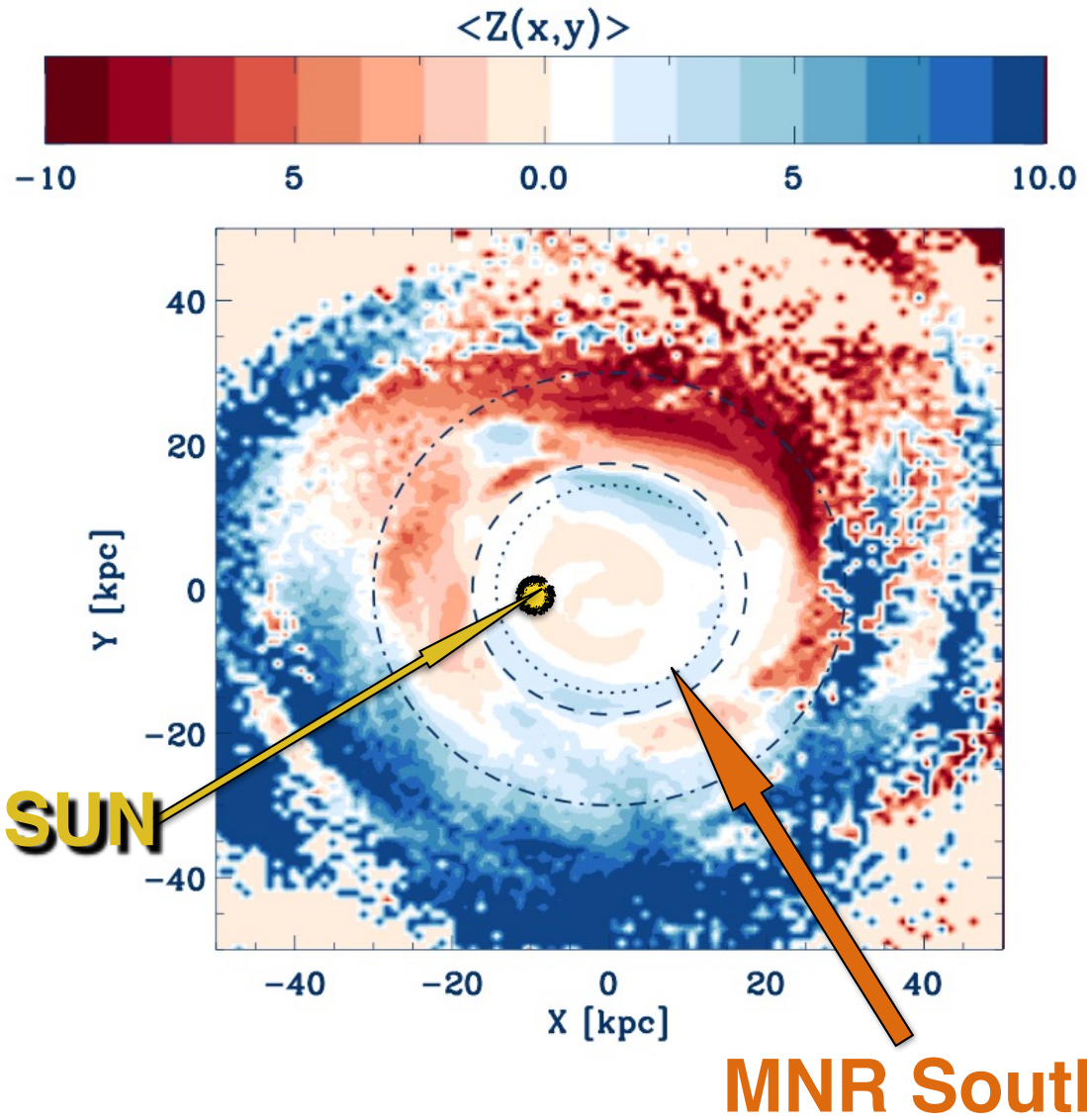

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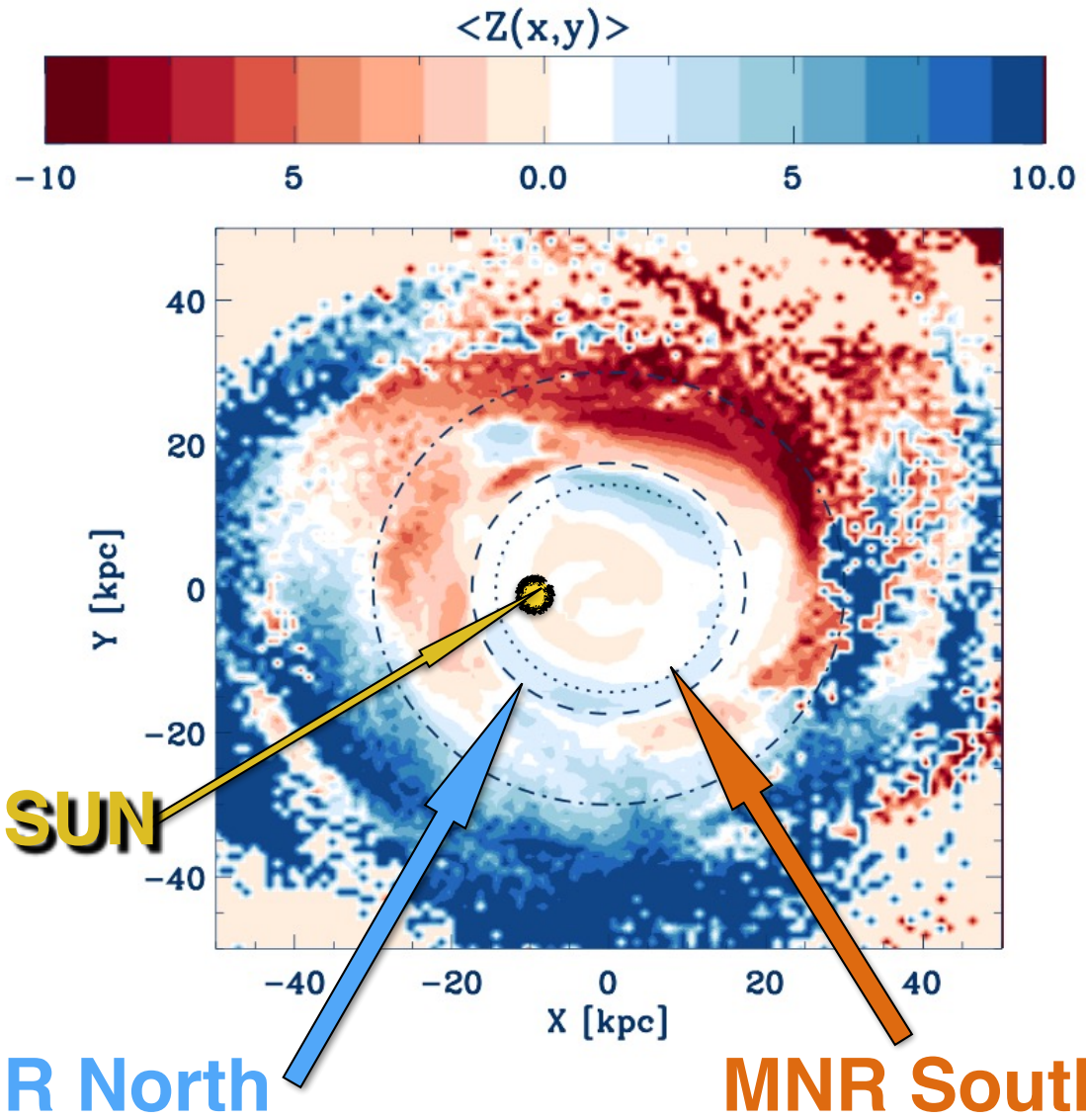

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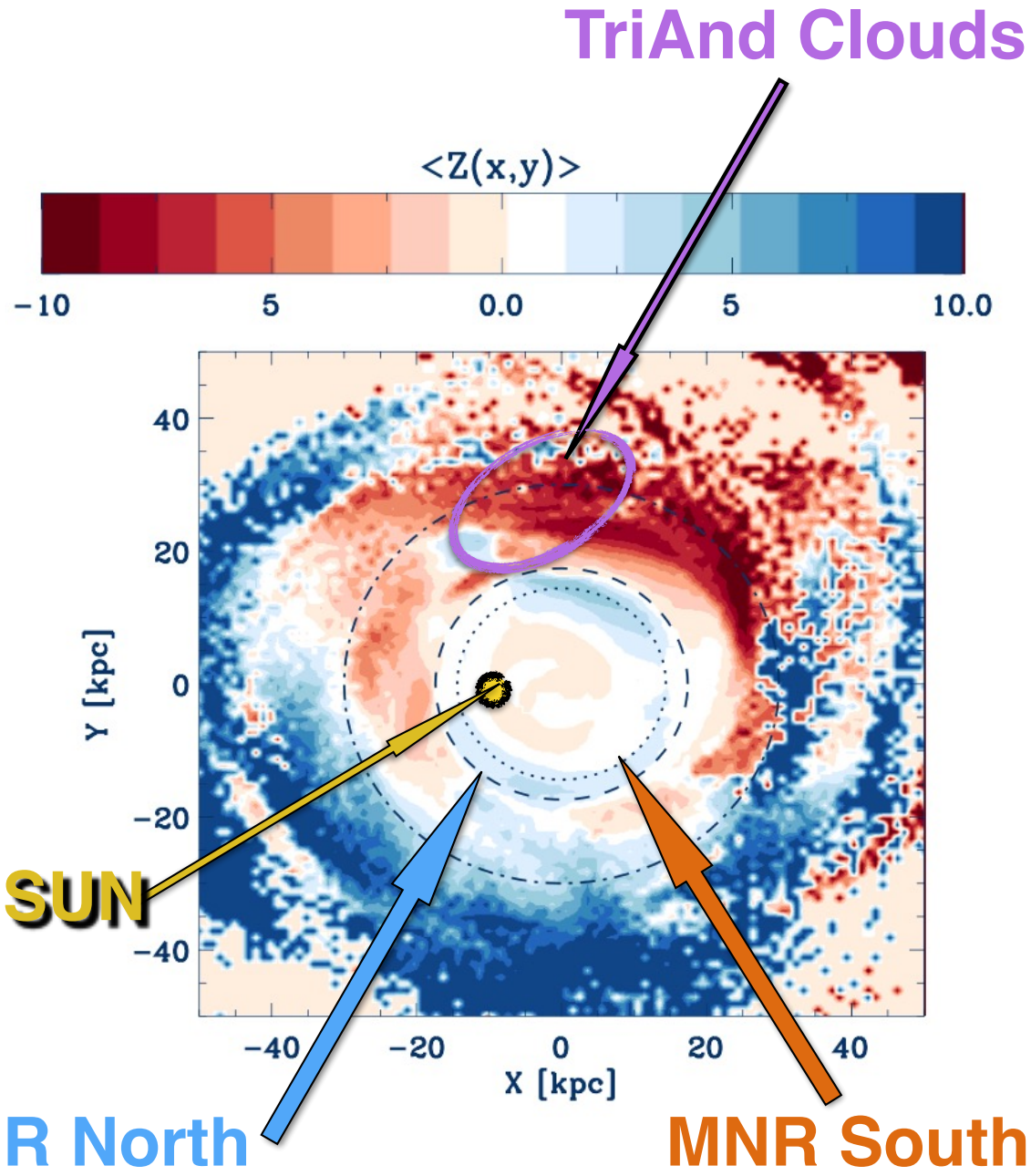

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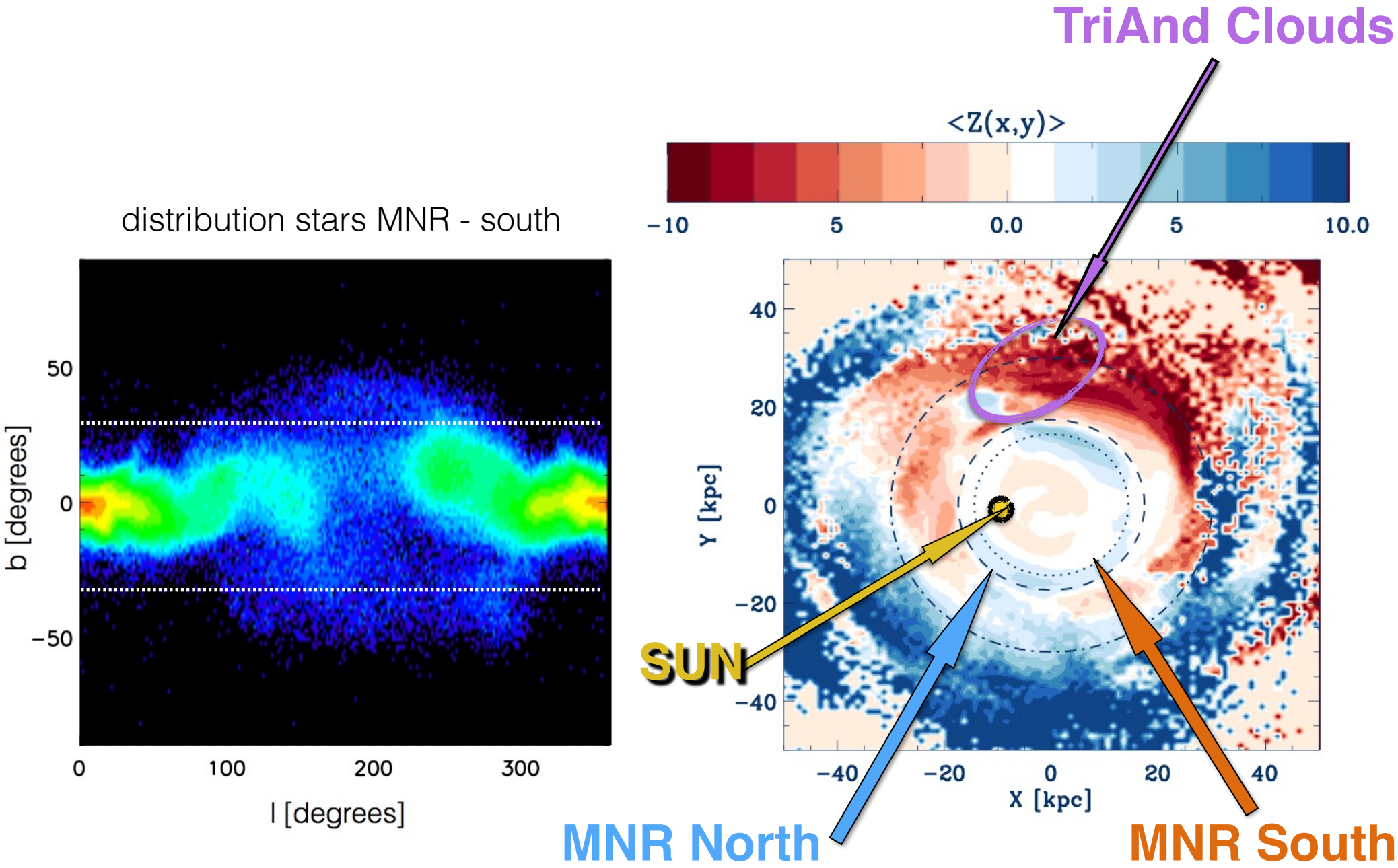

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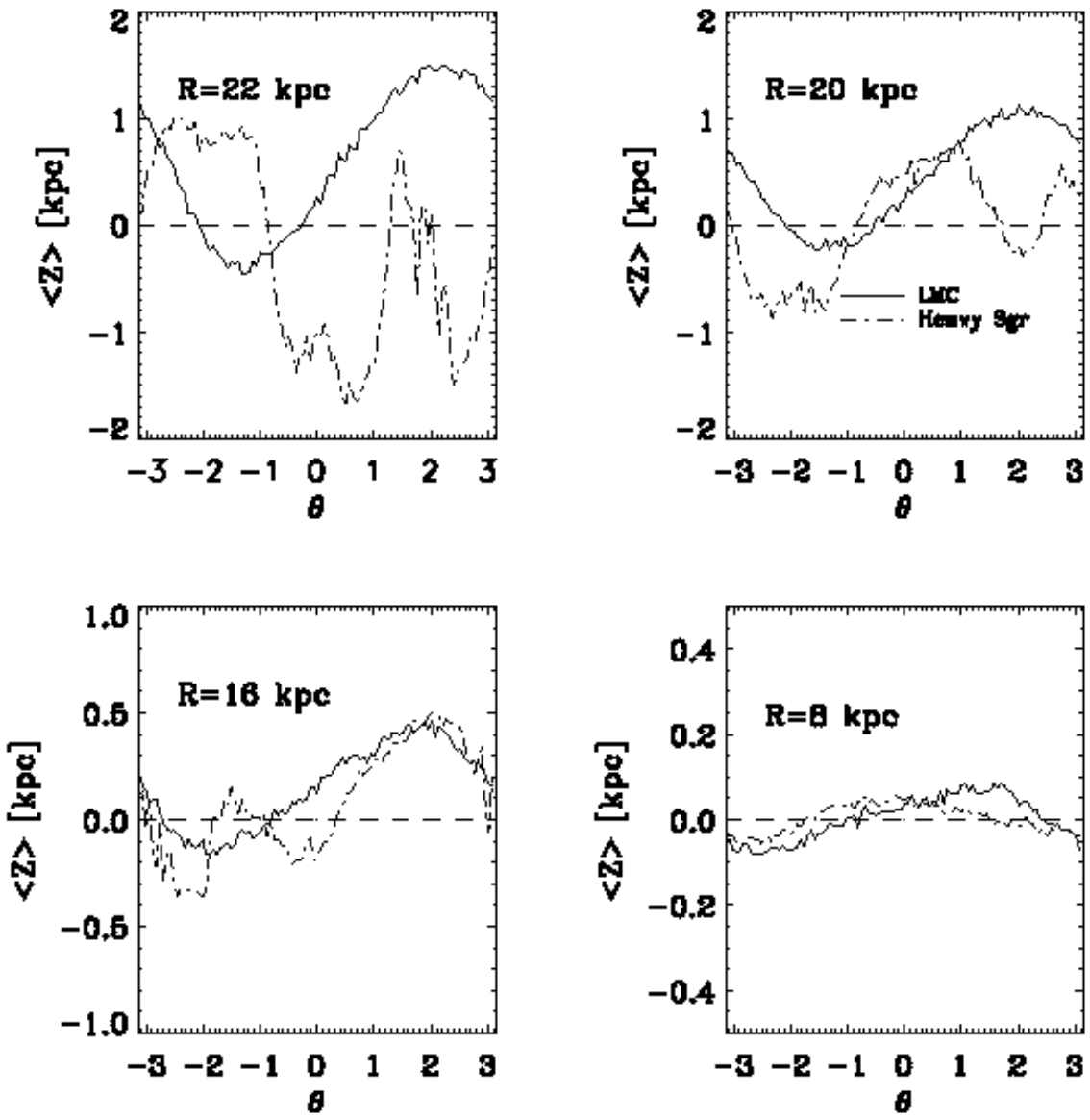
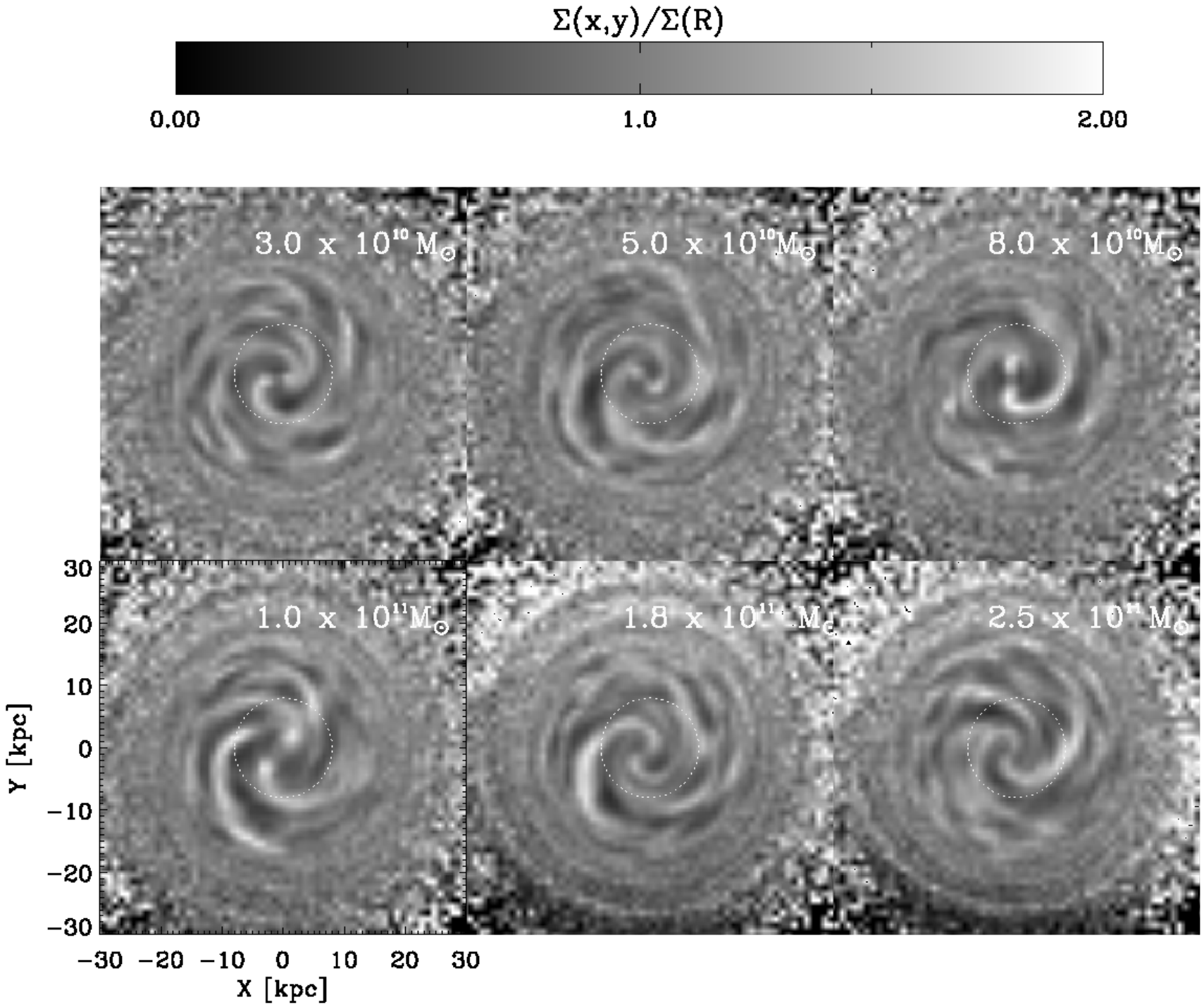
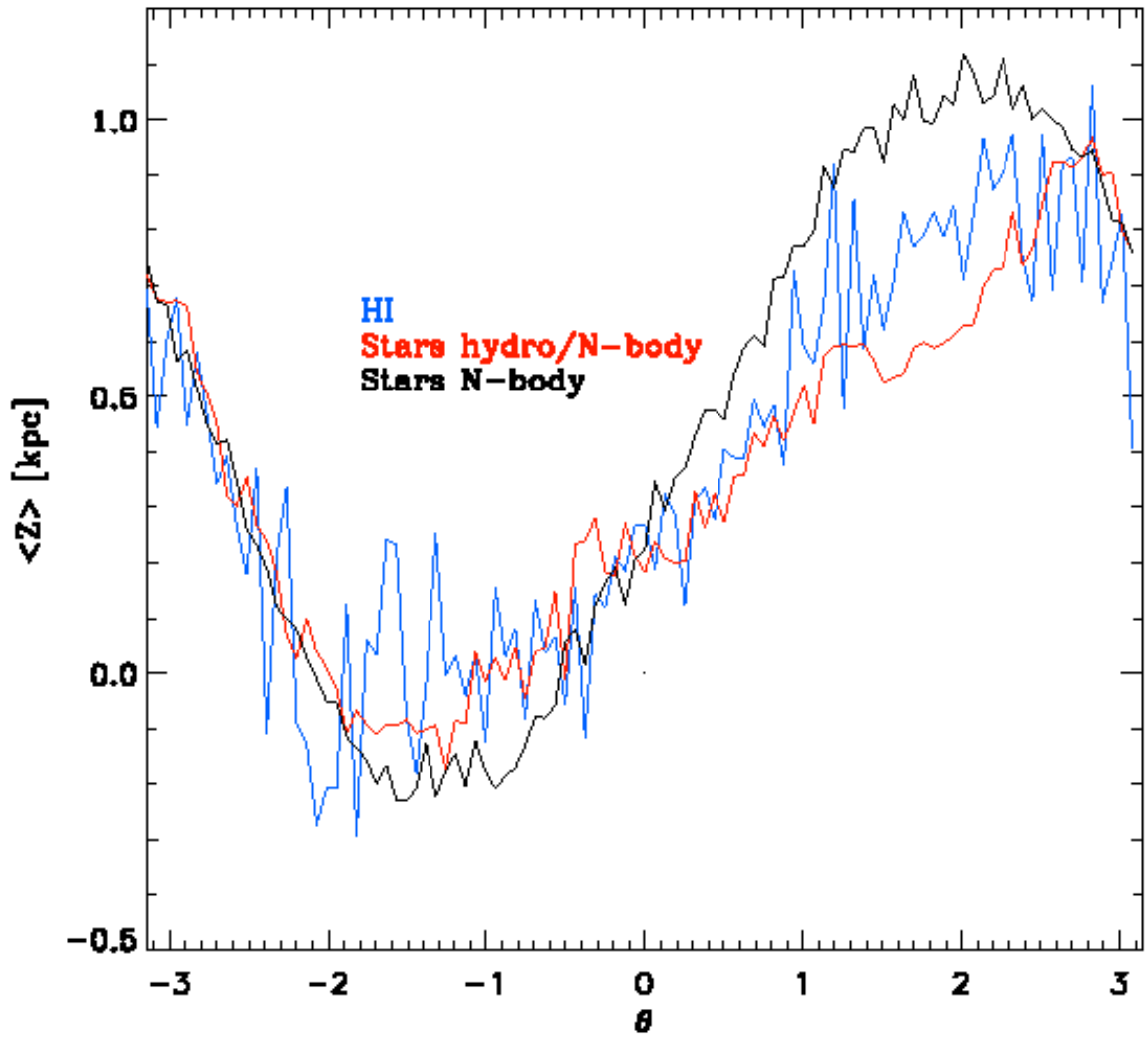
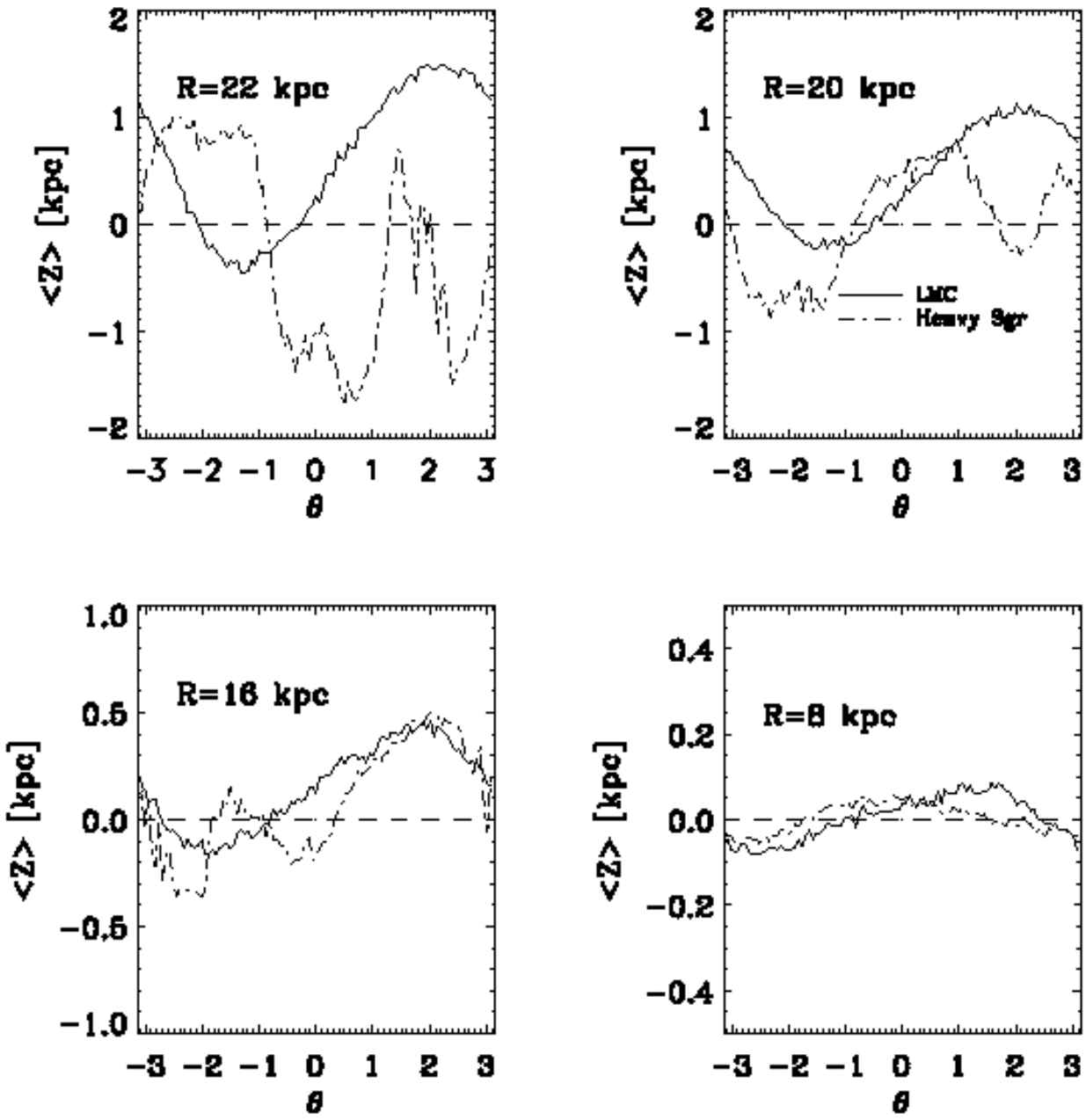
- Large scale asymmetries seen in outer disc can **quantitatively** be attributed to satellite accretion. Heavy Sgr model (~1e11Msun) consistently reproduces location of MR (north and south), TriAnd Clouds (Z~-10 kpc and R~30kpc) - (models being further explored)
- Structure of HI and stars in disc point out **MW is most likely currently being shaped by the combination of the MCs and Sgr**.

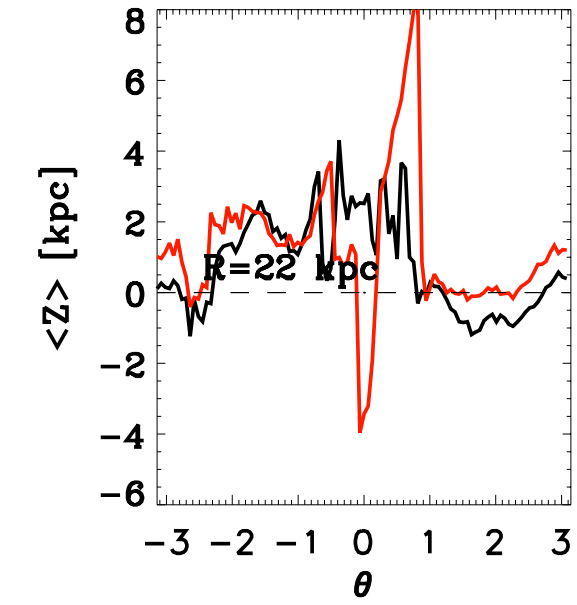
Comparison with a massive (10^11Msun Sgr dSph model)

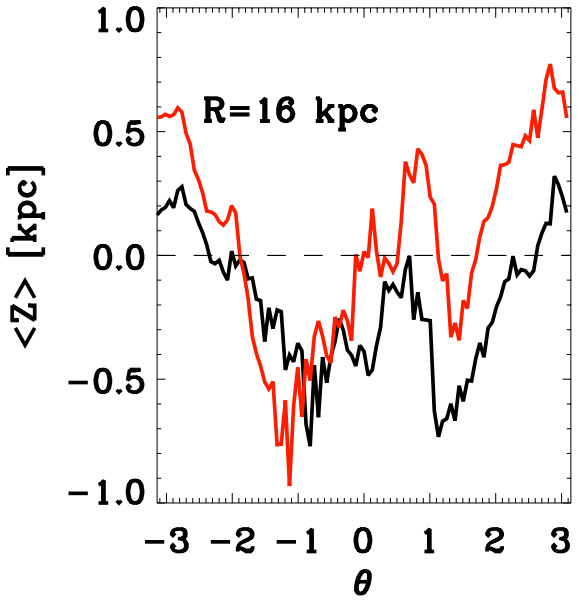



Σ(x,y)/Σ(R)
0.00
1.0
2.00
3.0 x 10^10 M⊙
5.0 x 10^10 M⊙
8.0 x 10^10 M⊙
1.0 x 10^11 M⊙
1.8 x 10^11 M⊙
2.5 x 10^11 M⊙
Y [kpc]
X [kpc]
30
20
10
0
−10
−20
−30
−30 −20 −10 0 10 20 30


HI
Stars hydro/N-body
Stars N-body
<z> [kpc]
θ
1.0
0.5
0.0
−0.5
−3
−2
−1
0
1
2
3


R=22 kpc
R=20 kpc
R=16 kpc
R=8 kpc
<Z> [kpc]
θ
LMC
Heavy Sgr


8
6
4
2
0
−2
−4
−6
<Z> [kpc]
R=22 kpc
−3 −2 −1 0 1 2 3
θ


1.0
0.5
0.0
−0.5
−1.0
<Z> [kpc]
R=16 kpc
−3 −2 −1 0 1 2 3
θ