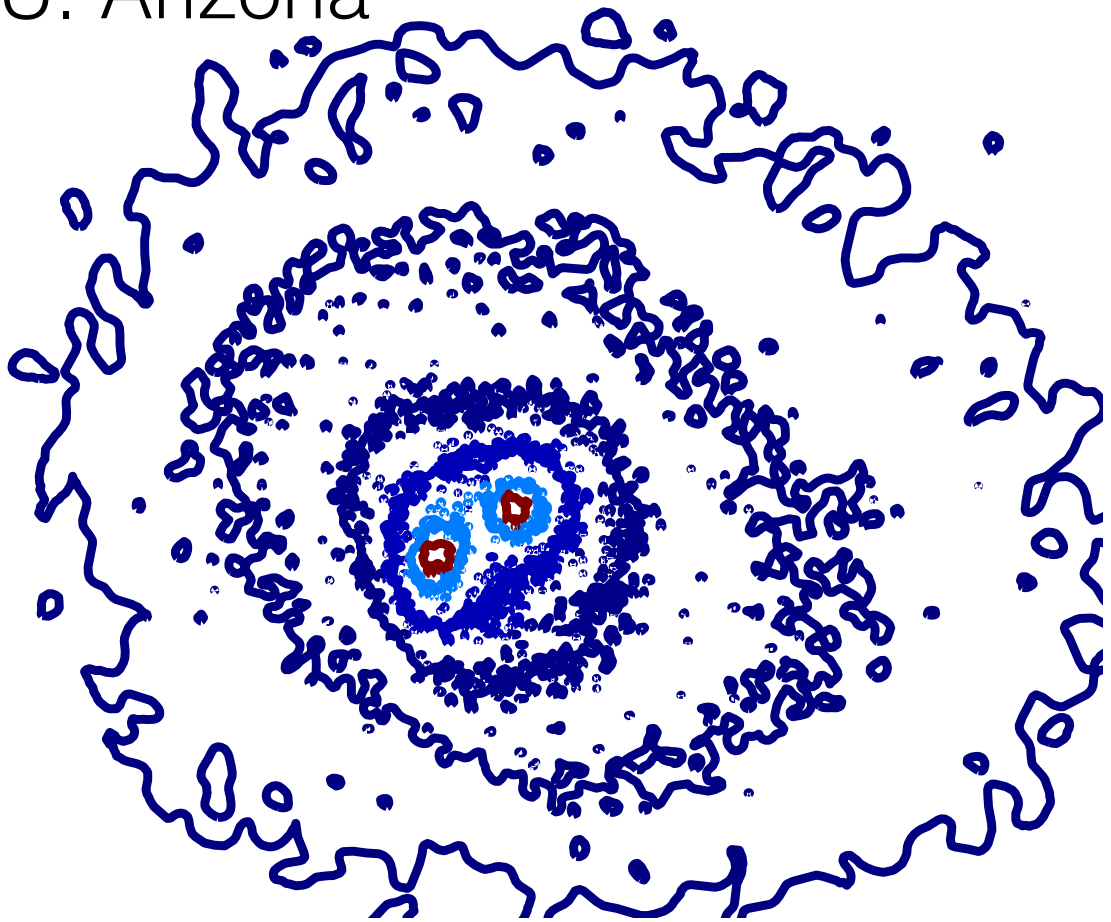
Satellite galaxies as probes and modifiers of the Host Dark Matter Halo

Gurtina Besla

U. Arizona

Ekta Patel
Nicolas Garavito
Kaisey Mandel
Tony Sohn

Nitya Kallivayalil
Chervin Laporte
Facundo Gomez
Roeland van der Marel
Jay Anderson



HSTPROMO

The HST Proper Motion Collaboration

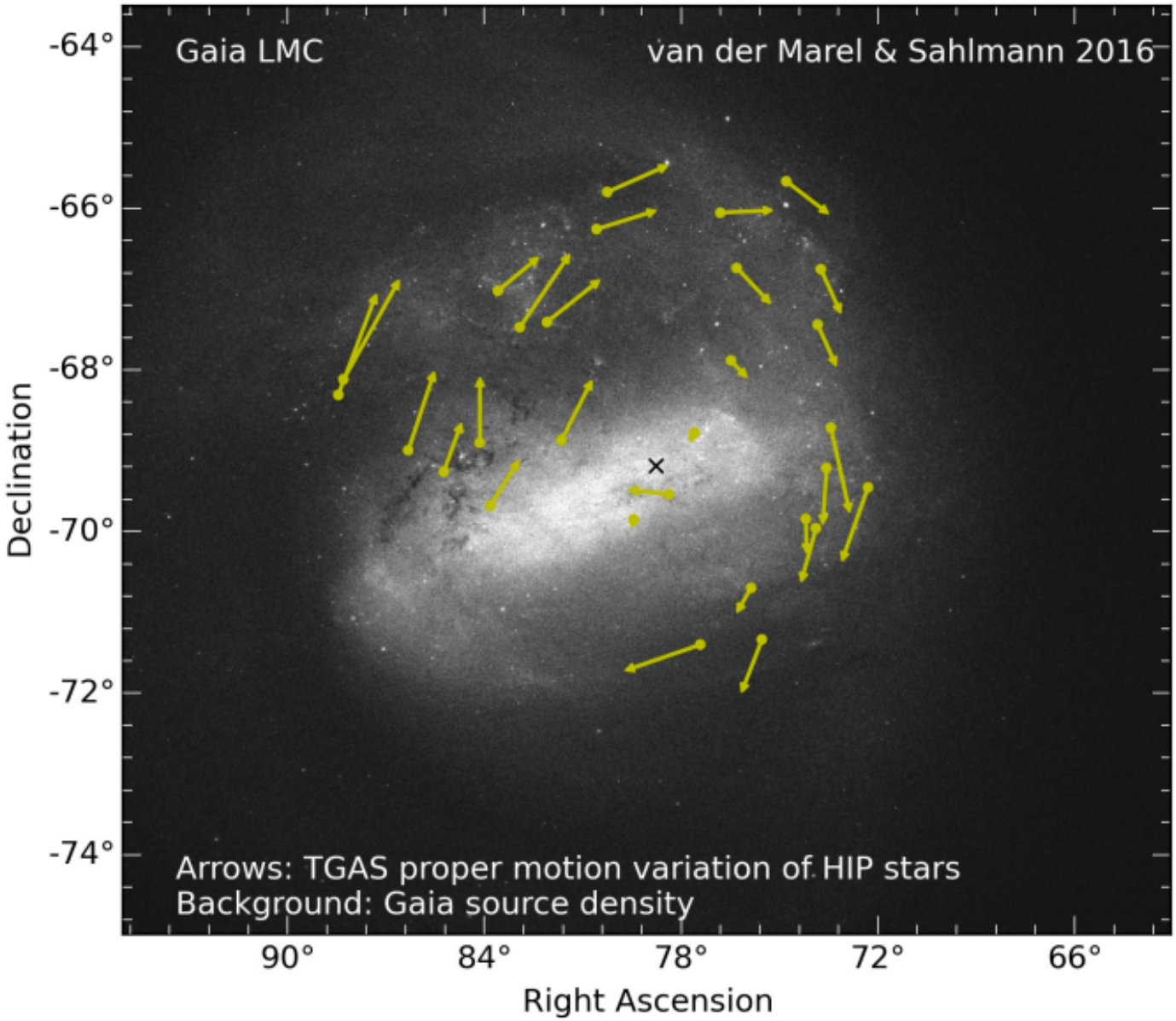
(http://www.stsci.edu/~marel/hstpromo.html)

- Characteristic velocity accuracy necessary
  ~10 km/s at 70 kpc (Milky Way halo/satellite dynamics)
- Corresponding PM accuracy
  ~ 30 μas / yr

(~ speed of human hair growth
at distance of the Moon)

With HST we can measure a change of 0.006 ACS/WFC pixels over a 10 yr baseline

Confirmation of LMC PMs With Gaia




esa
Years from now: 1,494,750
gaia
Gaia
DPAC

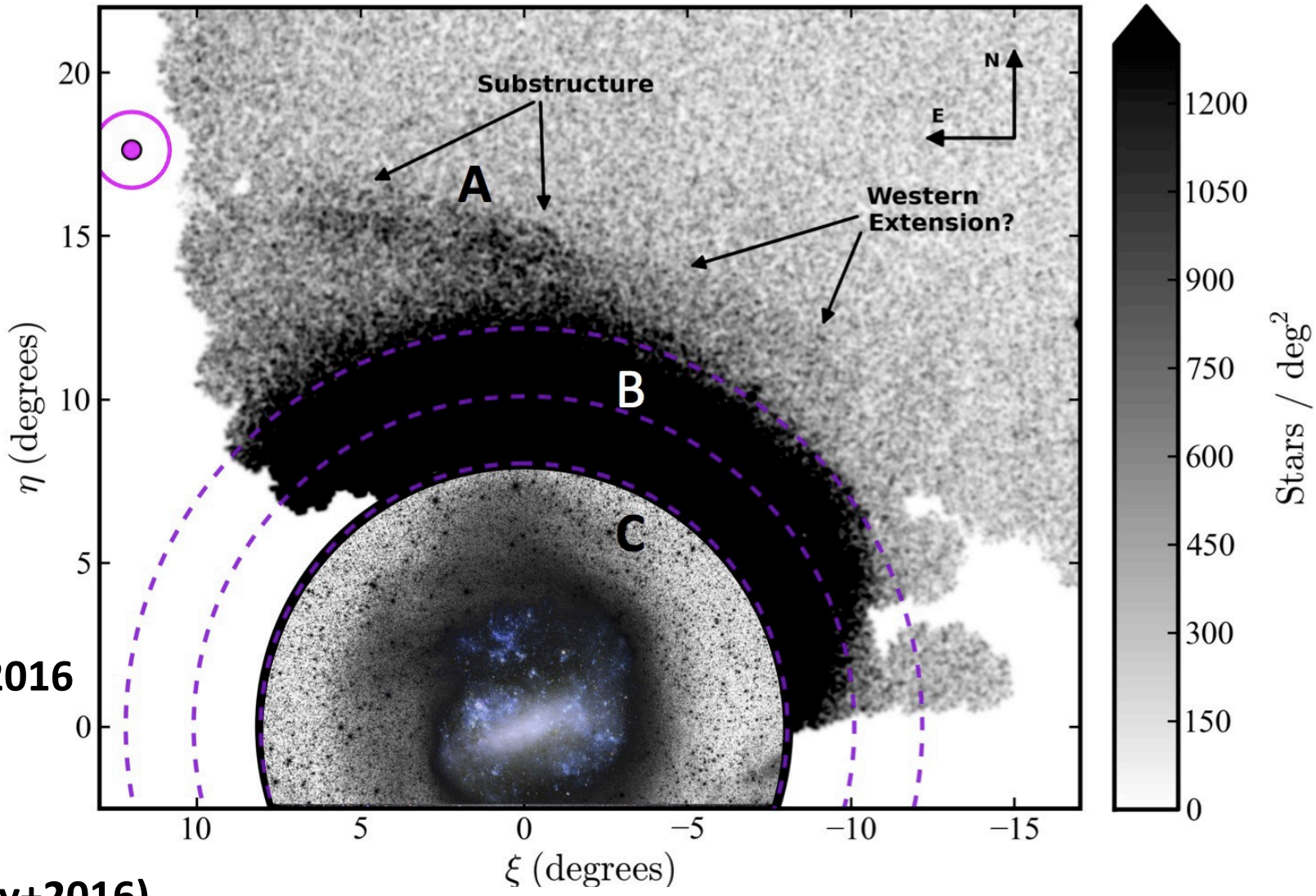
The LMC as a Massive Satellite

- Rotation Curve (8.9 kpc) Lower limit:

  $M_{tot} > \sim 1.7 \times 10^{10} M_{\odot}$ (van der Marel & Kallivayalil 2014)

- Baryon Fraction
  - Typical Disk/Dark Matter Fraction ~3-5%
  - LMC $M_{*} = 2.7 \times 10^{9} M_{\odot}$ → DM ~ 0.5 -1 x $10^{11} M_{\odot}$
- Abundance Matching (similar argument)
  - $M_{200} \sim 1.5 \times 10^{11} M_{\odot}$ Moster+ 2013

The LMC Radius > 18.5 kpc

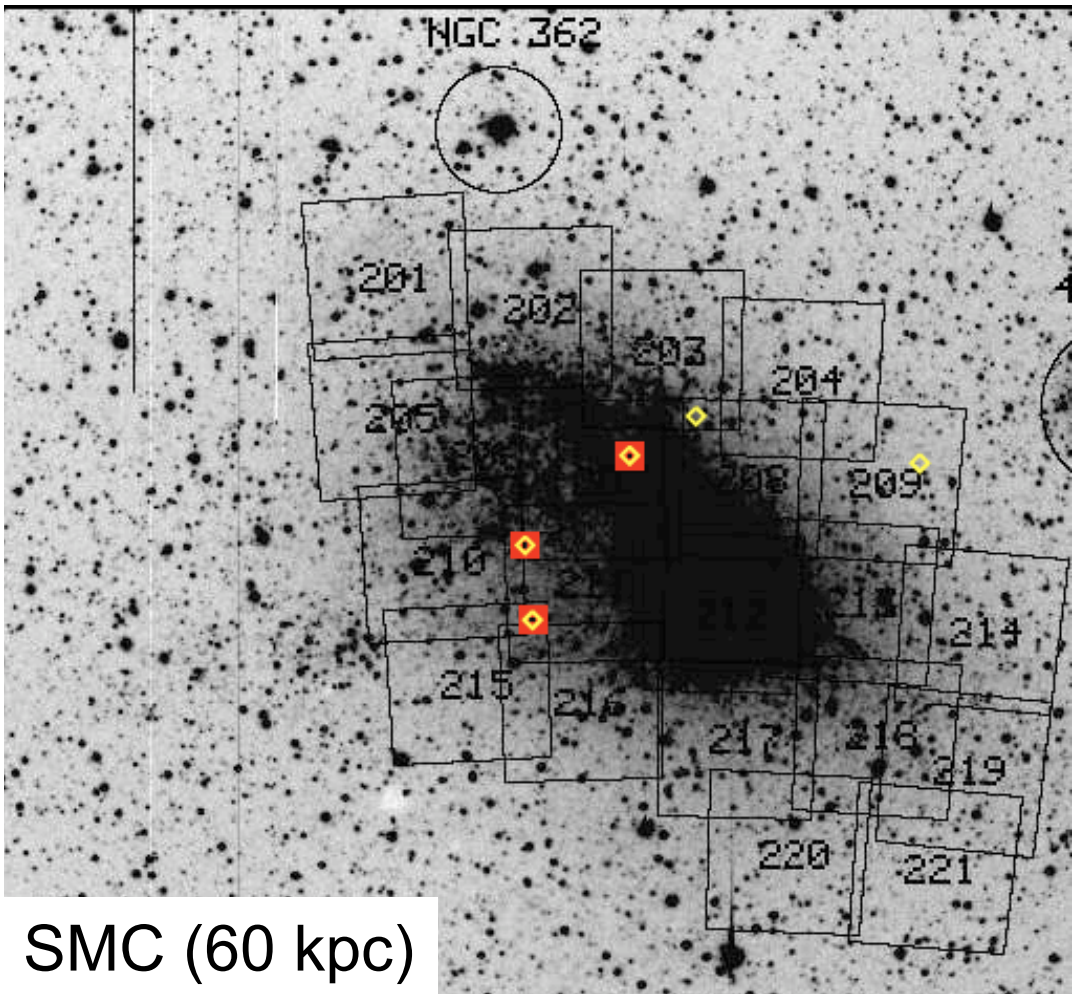


Inner: Besla+2016

Outer: DES (Mackey+2016)

See also: Balbinot et al. 2015; Saha et al. 2010

Motion of the SMC Relative to the LMC



SMC (60 kpc)

(Kalllivayalil, van der Marel, Besla + 2013)

$V_{SMC} = 217 +/- 26$ km/s

$V_{SMC-LMC} =$
128 +/- 32 km/s

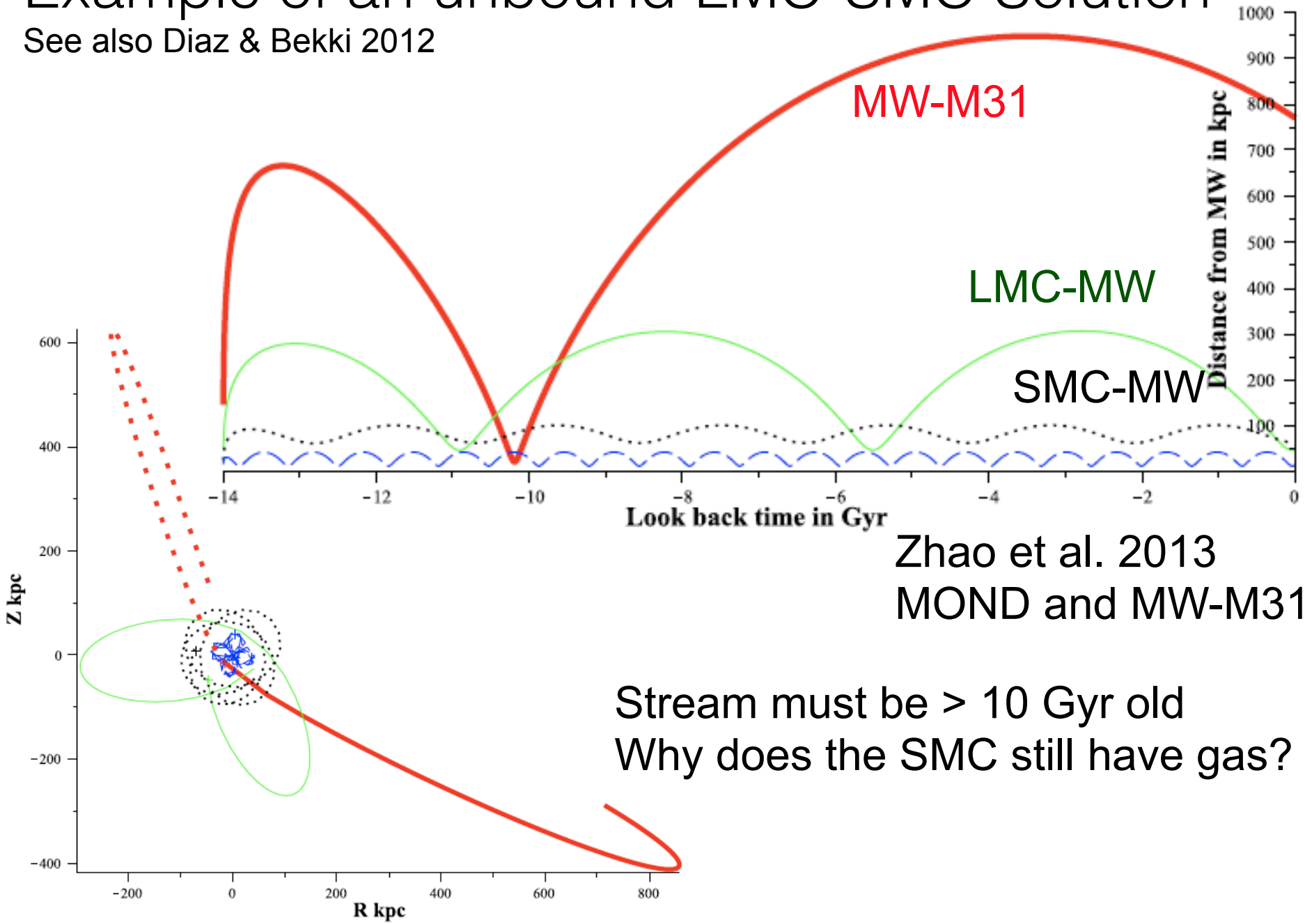
Ground Based PMs agree,
See Vieira+2008

$M_{LMC}(23\ kpc) > 5 \times 10^{10}\ M_{\odot}$
for
$V_{esc}\ (23\ kpc) > 128$ km/s

(but also have to contend with the MW's tidal field)

Example of an unbound LMC-SMC Solution

See also Diaz & Bekki 2012



Zhao et al. 2013
MOND and MW-M31

Stream must be > 10 Gyr old
Why does the SMC still have gas?

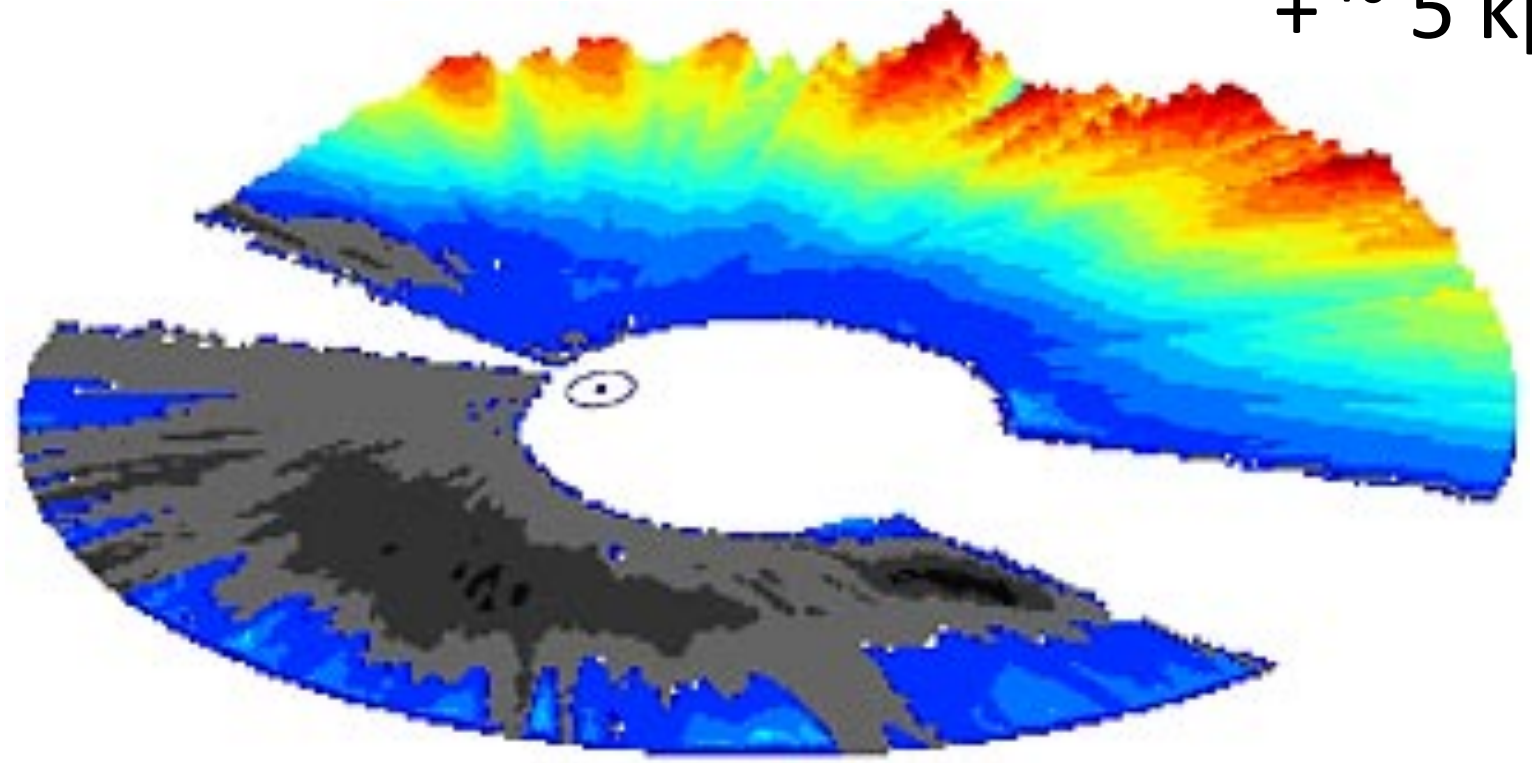
What is the Impact of a Massive LMC on the MW?

Is it observable?

The HI Disk of the MW is Warped

Can we use the properties of the MW disk to constrain the total mass of the LMC?

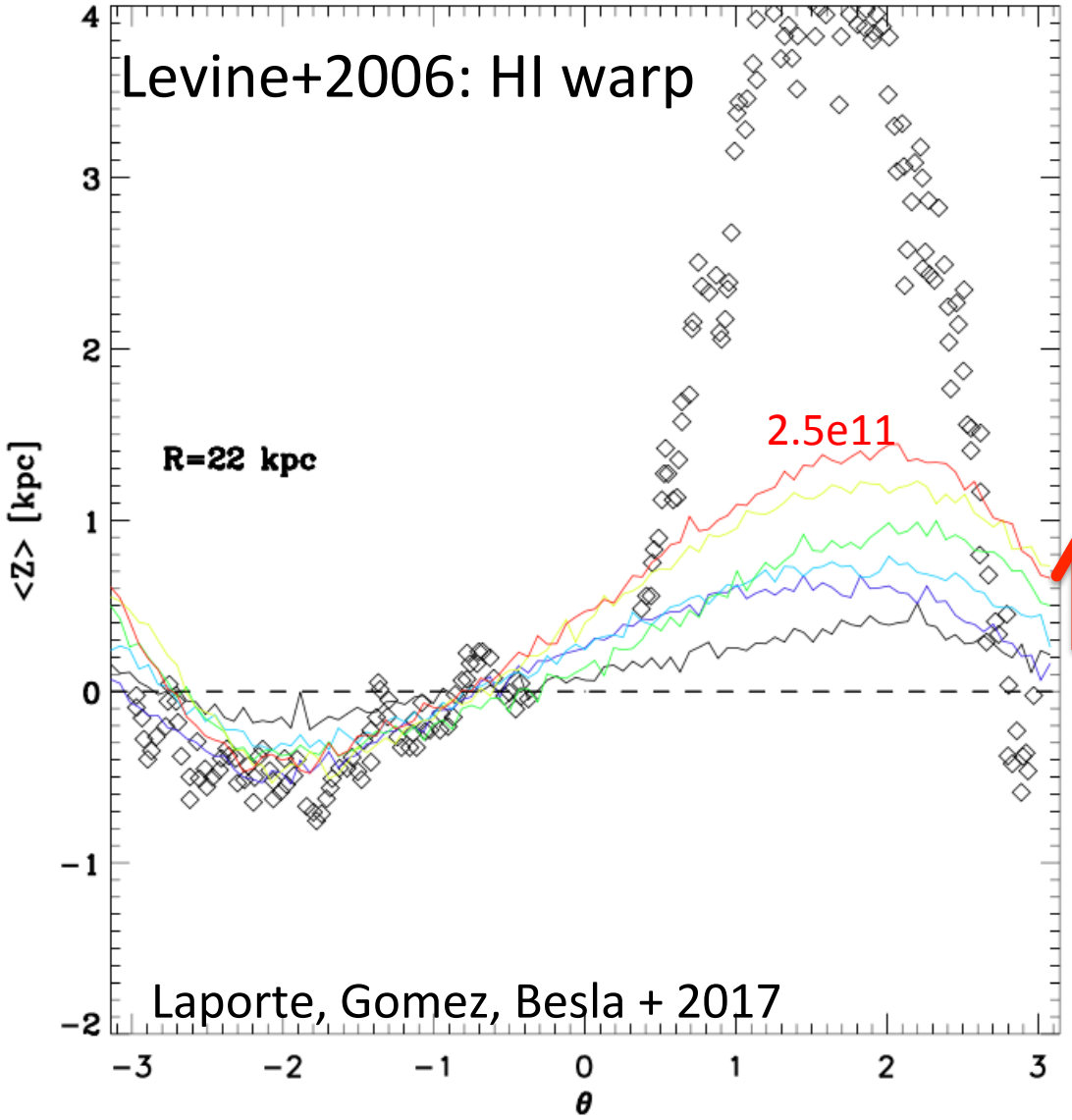
+ ~ 5 kpc



- ~1-2 kpc

Kalberla+2009
Levine+2006

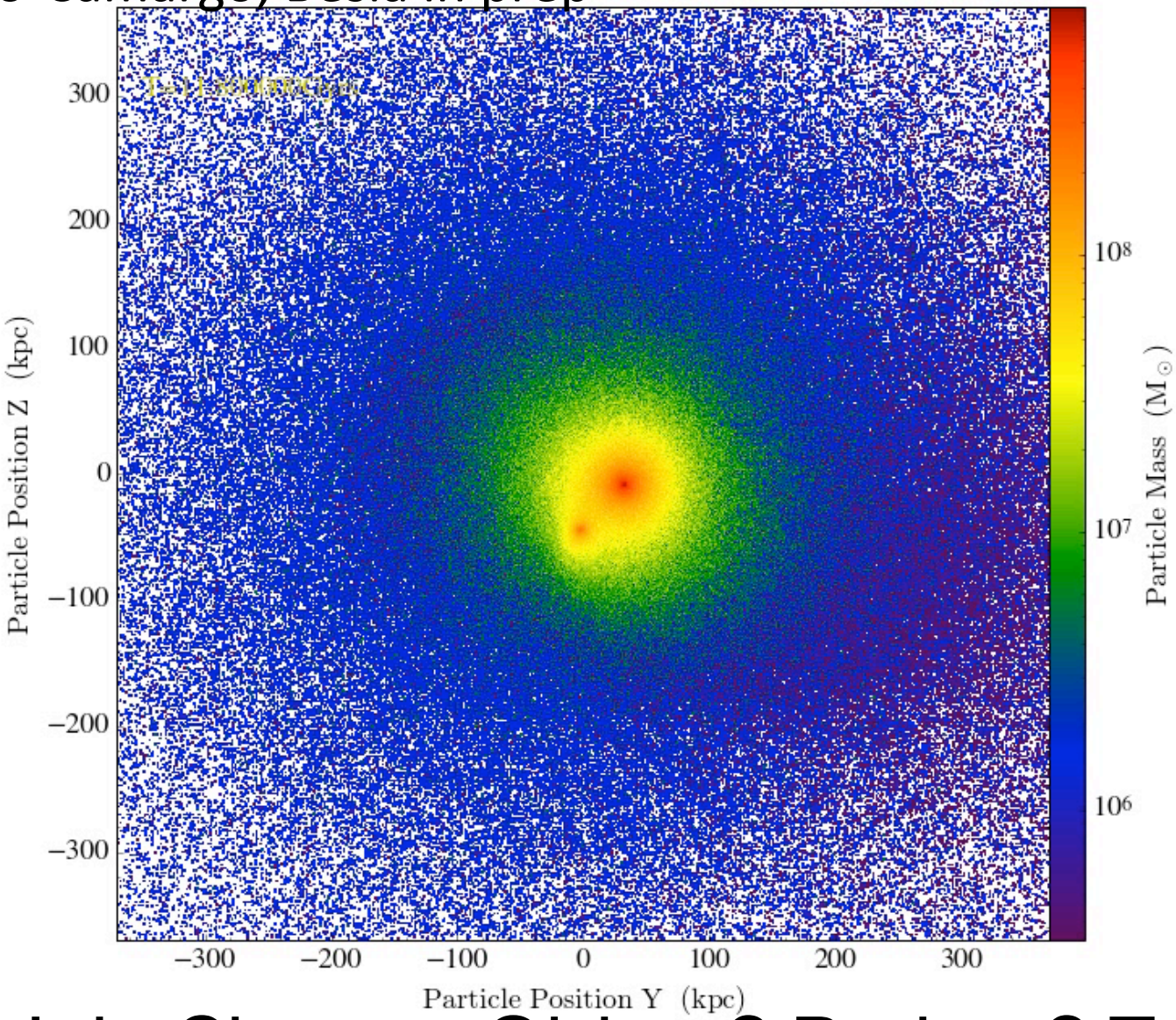
The LMC Can Warp the MW Disk, but might need help: Sagittarius?



Effect of increasing the mass of the LMC

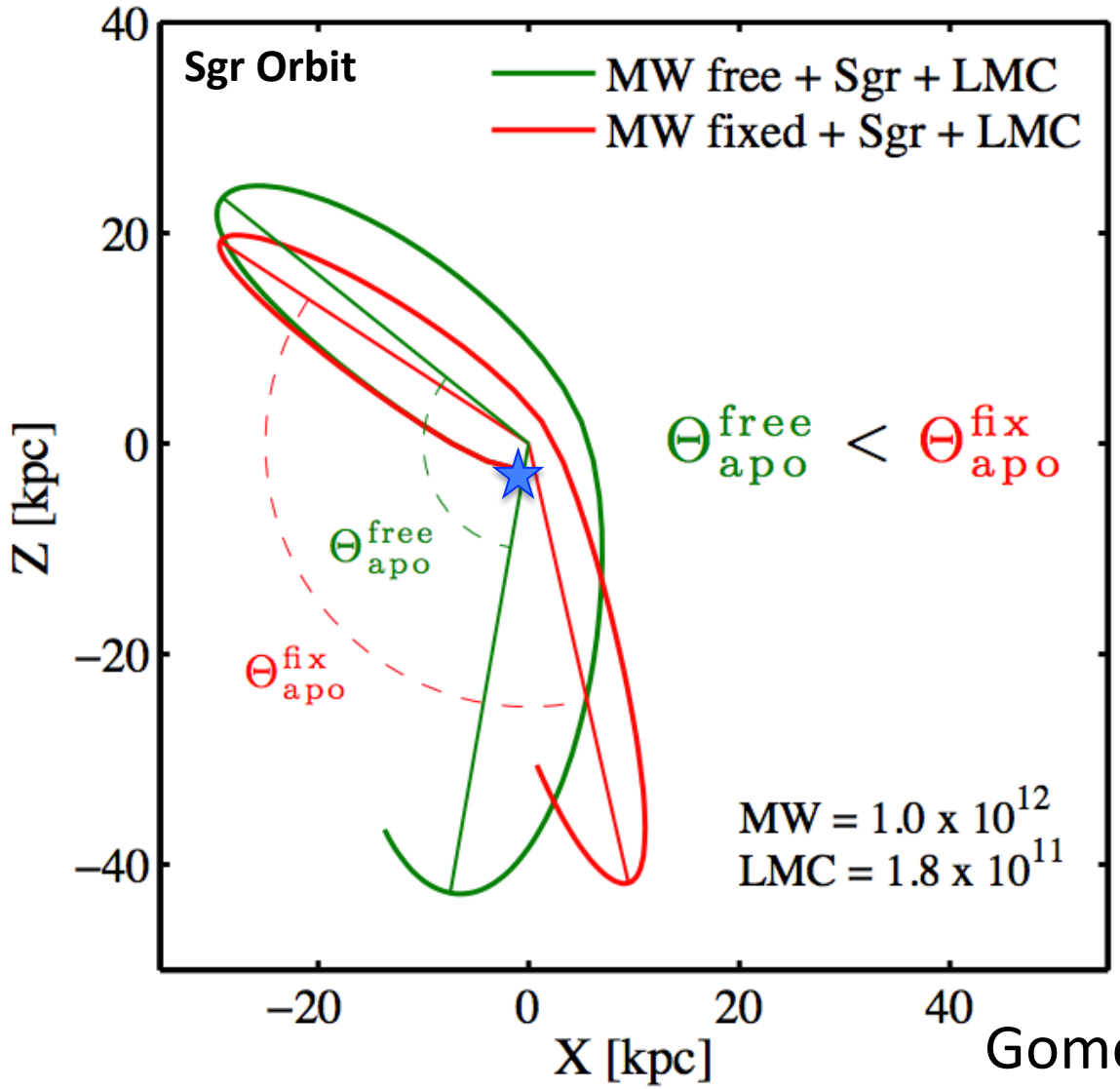
Impact of a Massive LMC on the DM Halo of the MW

Garavito-Camargo, Besla in prep



MW Halo Shape: Oblate? Prolate? Triaxial?

Ignoring the LMC will force artificial adjustments in the MW gravitational potential



Gomez, Besla + 2015

Anisotropy Parameter (Beta) of the MW's Halo

Changes in different octants of the halo – even in regions where the LMC hasn't yet reached.

With Gaia we may be able to search for the response of the DM halo of the MW owing to the motion of the LMC !

Garavito-Camargo, Besla in prep

(See also Loebman+2017)

Satellites with 6-D Phase Space Information:

Statistically Constraining the Host Mass in a Cosmological Framework

Satellite Kinematics & MW Mass

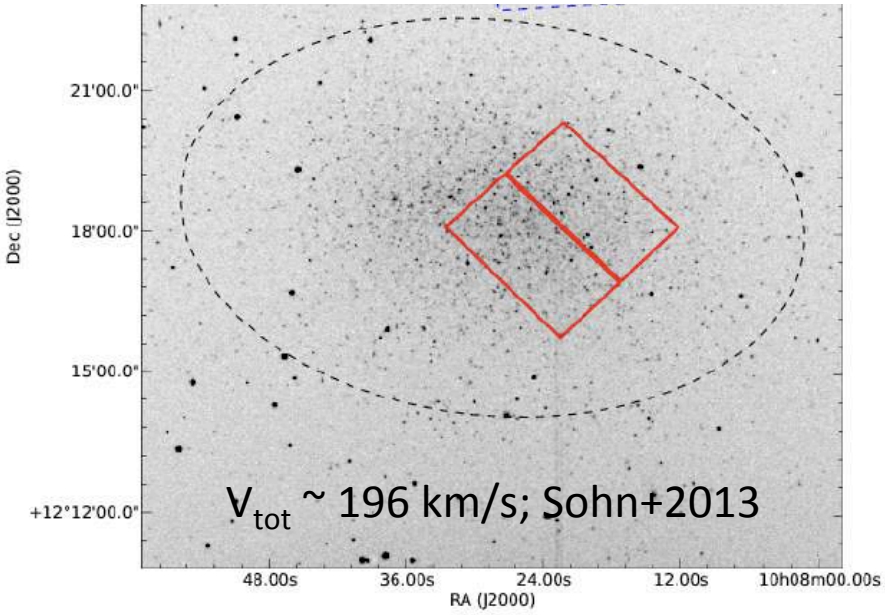
- Mass constraints using radial velocities of satellites:
  - Kochanek 1996: 3.2-5.5 (4.0-6.4) x 10^{11} $M_\odot$ (<50 kpc)
  - Sakamoto et al. 2003: 1.1-2.2 (1.5-3) x 10^{12} $M_\odot$ (< Rvir)

  Leo I plays an outsized role owing to high radial velocity (168 km/s) and large distance (260 kpc): inclusion of Leo I as a bound satellite increases MW halo mass by 25-30%

A lower bound to the MW Mass:

To keep Leo I bound to the MW $M_{vir} > 10^{12}$ $M_\odot$ (Sohn+2013)

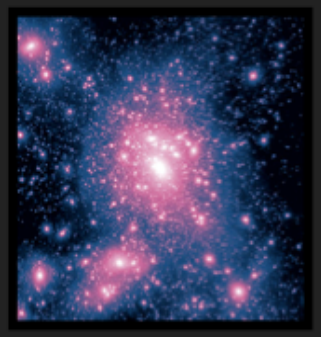
This is consistent with expectations from cosmological simulations (Boylan-Kolchin+2013)



THE BAYESIAN METHOD USING COSMO. SIMS.:

A DIRECT CONNECTION BETWEEN OBSERVATIONS AND THEORY

PRIOR Broad selection of simulated halos with satellite subhalos (host halo mass is free parameter)



Illustris Collaboration
(Vogelsberger+14, Nelson+15)

DATA Satellite's observed | j | derived from 6D phase space (or R and V_{tot})

$j = r \times v$
(specific angular momentum)

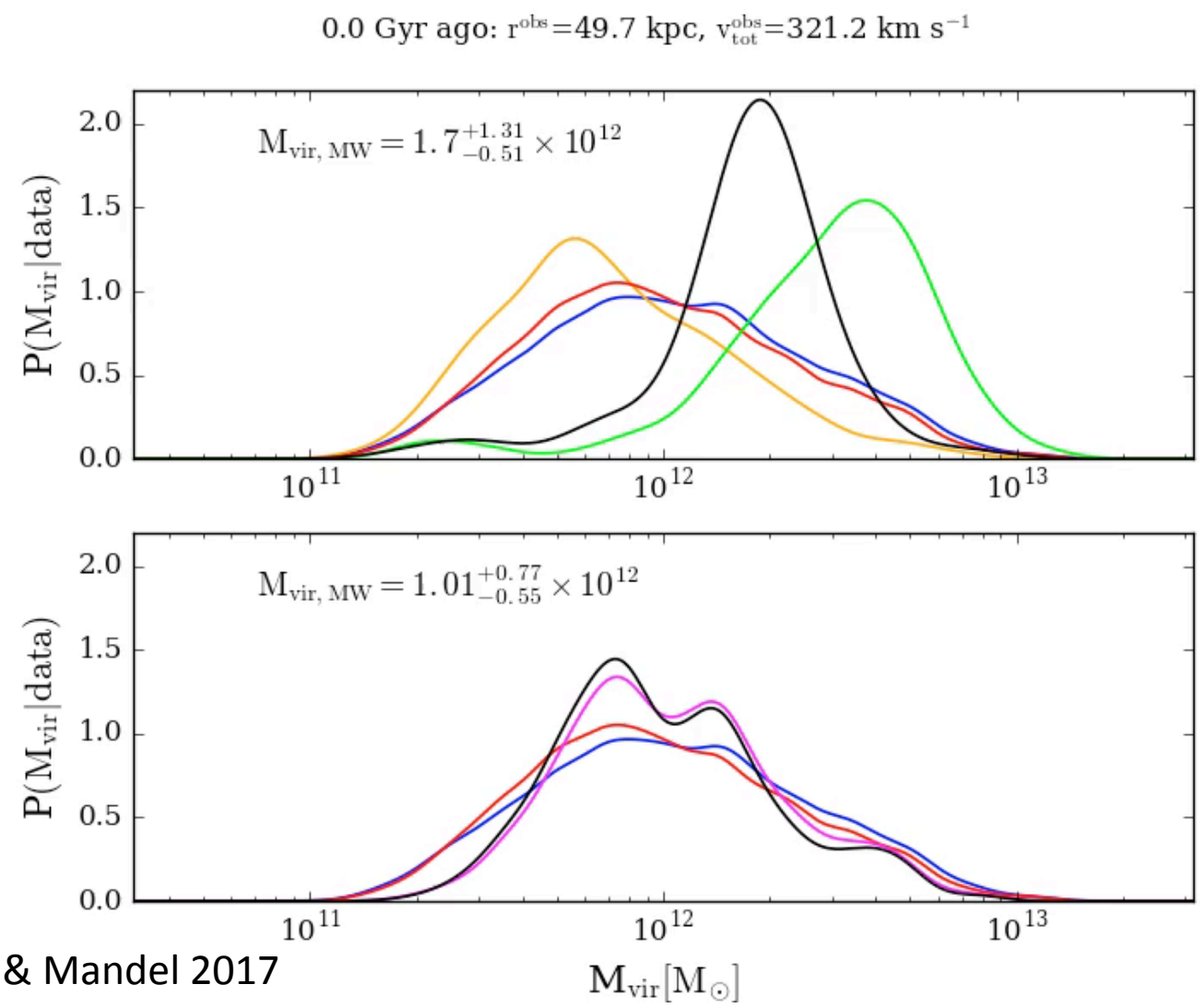
LIKELIHOOD Product of Gaussian distributions built around observed satellite properties (data: | j |, v_{max}) R and V_{tot}

POSTERIOR Calculate likelihoods for prior sample using the data to derive a posterior probability distribution

$$P(\theta \mid \text{Data}) = \frac{P(\theta)\ P(\text{Data} \mid \theta)}{P(\text{Data})}$$

Patel, Besla & Mandel 2017

R_{gal} & V_{tot} vs. j
Instantaneous properties depend on orbital phase; j stays constant



Patel, Besla & Mandel 2017

conclusions

- Evidence that the LMC is massive (~10^{11} $M_\odot$) is mounting. The LMC needs to be a massive satellite to hold on to the SMC.
- A massive LMC can:
  - Induce warps in the MW disk (not enough???)
  - Change the shape of the MW Halo, inducing perturbations in the motions of satellites and stars
- Using 6-D information for multiple satellites can improve MW (and M31) mass estimates
  - The Specific Orbital Angular Momentum (j) of satellites is a powerful constraint on halo mass
  - High and Low j satellites are the key constraints on the mass of the MW, rather than high/low speed satellites