

INFALLING TOGETHER: FAINT AND DARK COMPANIONS OF DWARF GALAXIES

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VIRGO

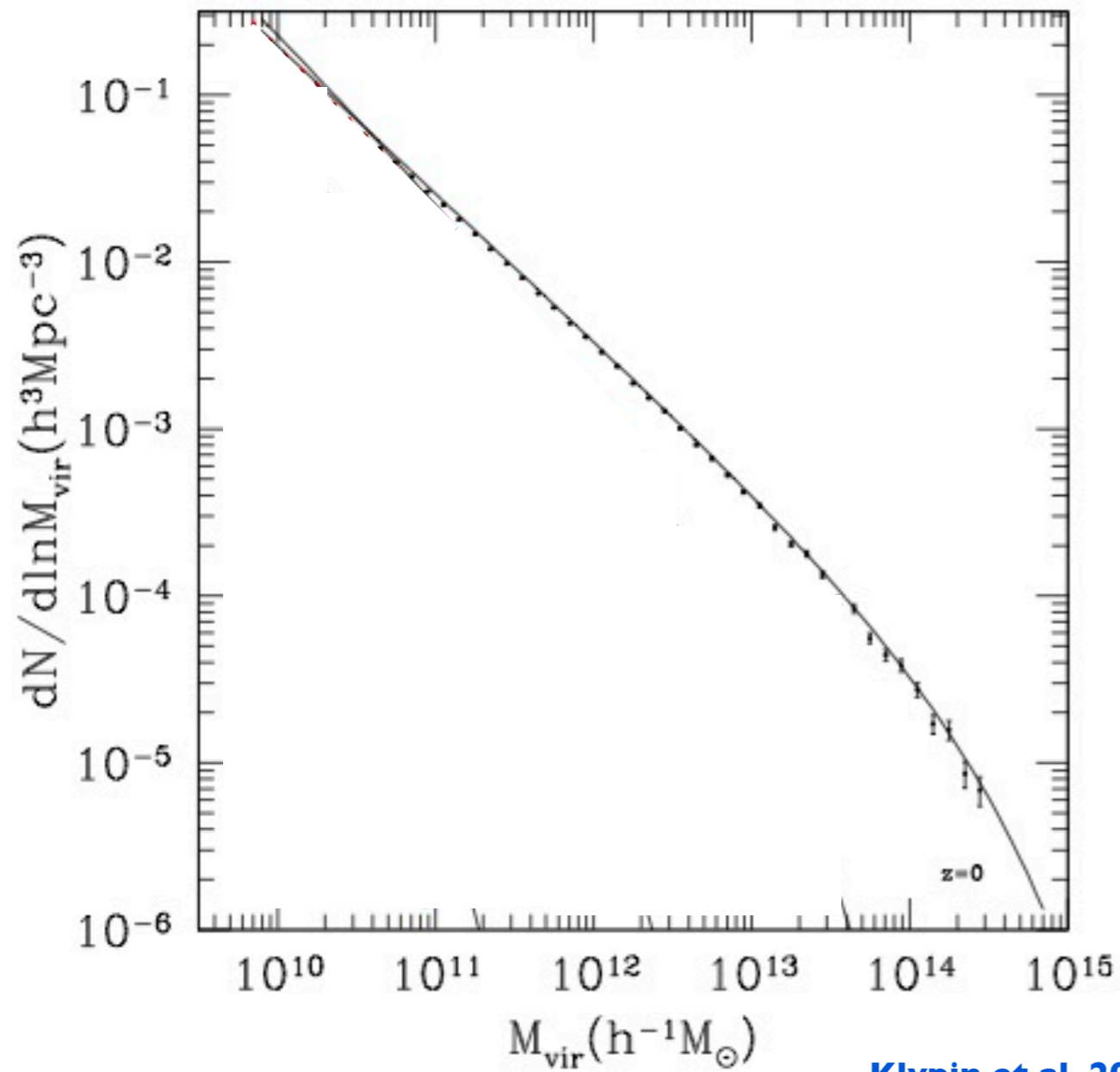
Collaborators:

Julio Navarro, Simon White, Carlos Frenk, Amina Helmi,
Ismael Ferrero, Mario Abadi



Abundance of Structures in the Universe

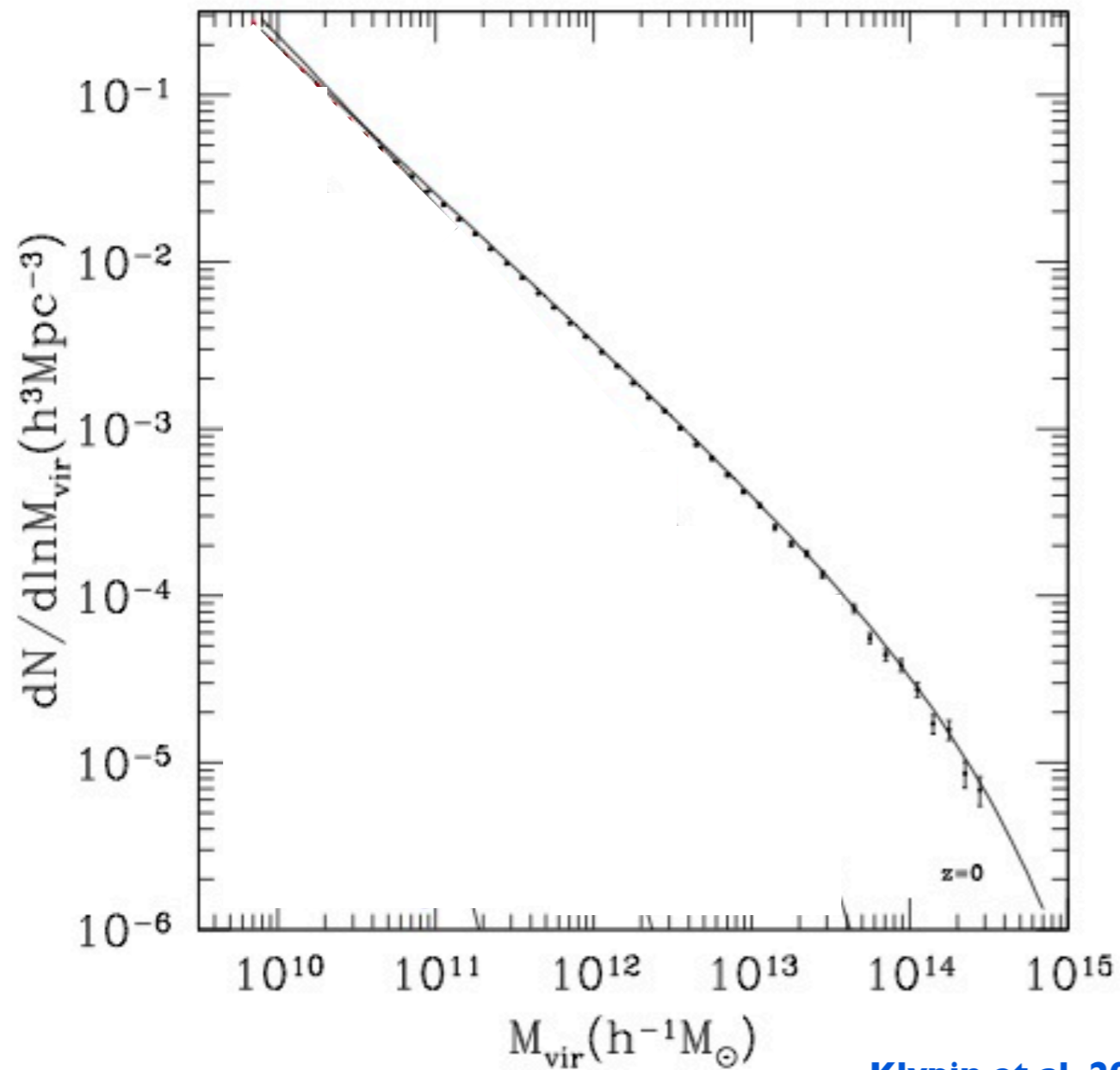
Halo Mass Function



Klypin et al. 2011

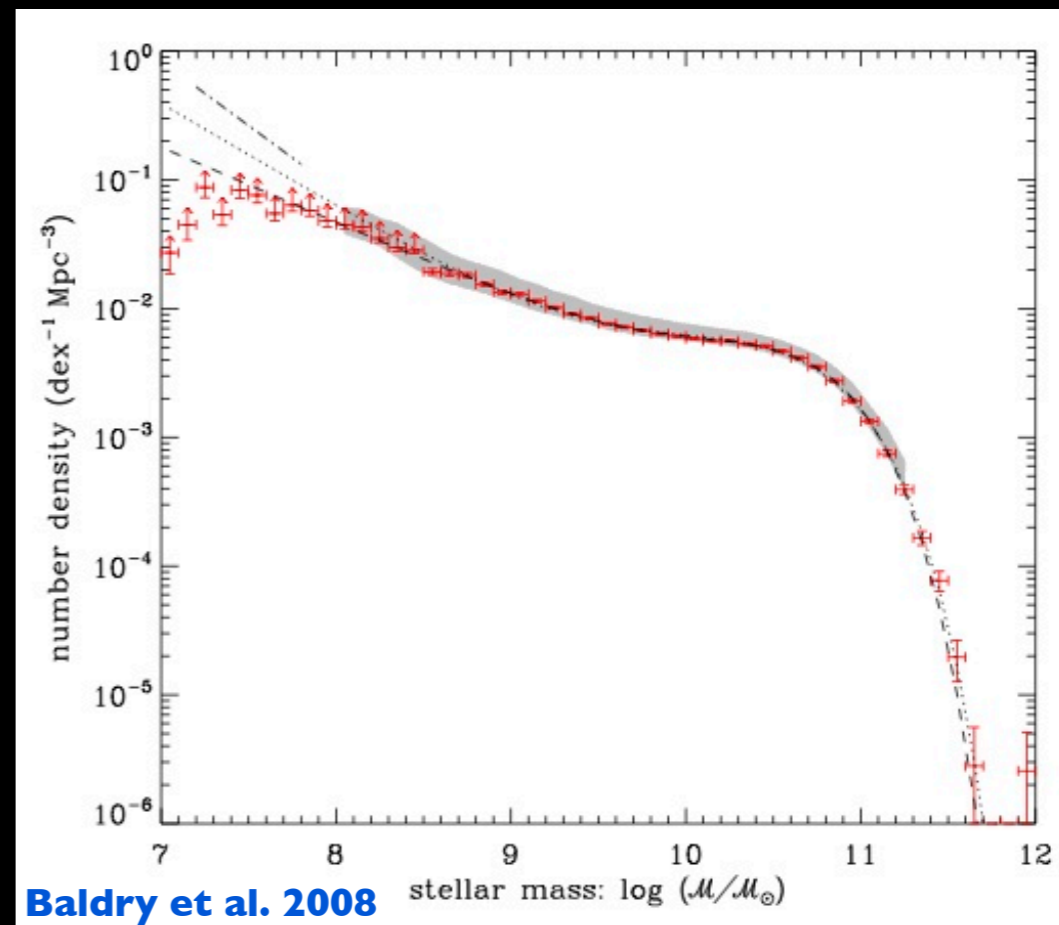
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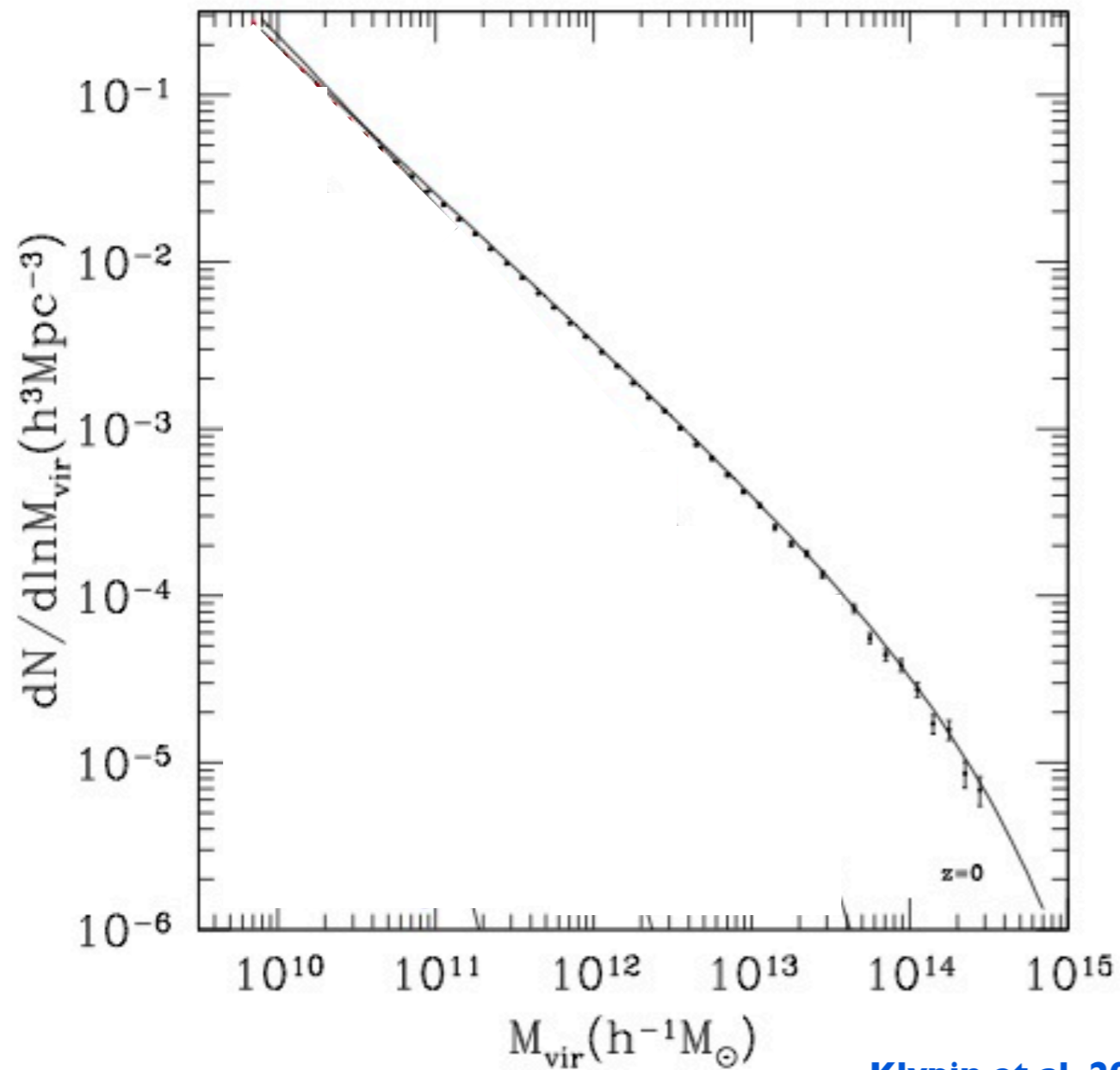
Galaxy Luminosity Function



Baldry et al. 2008

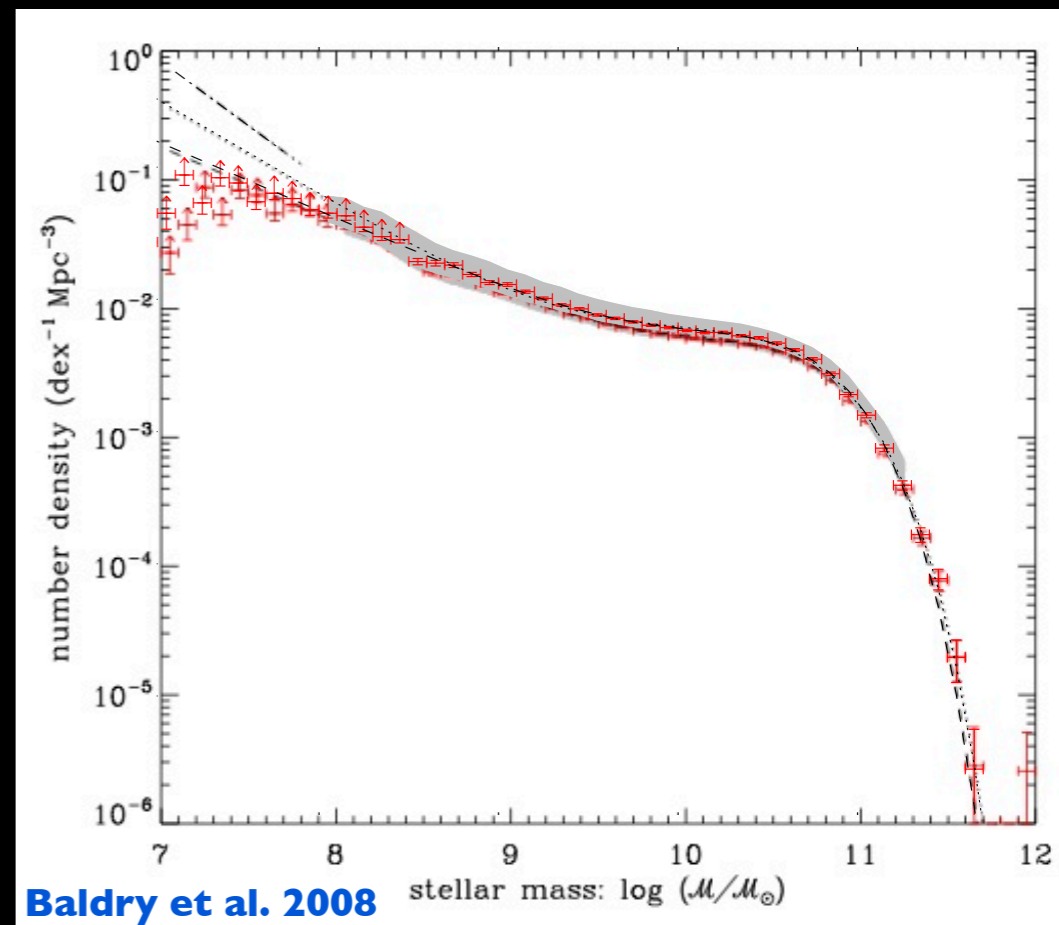
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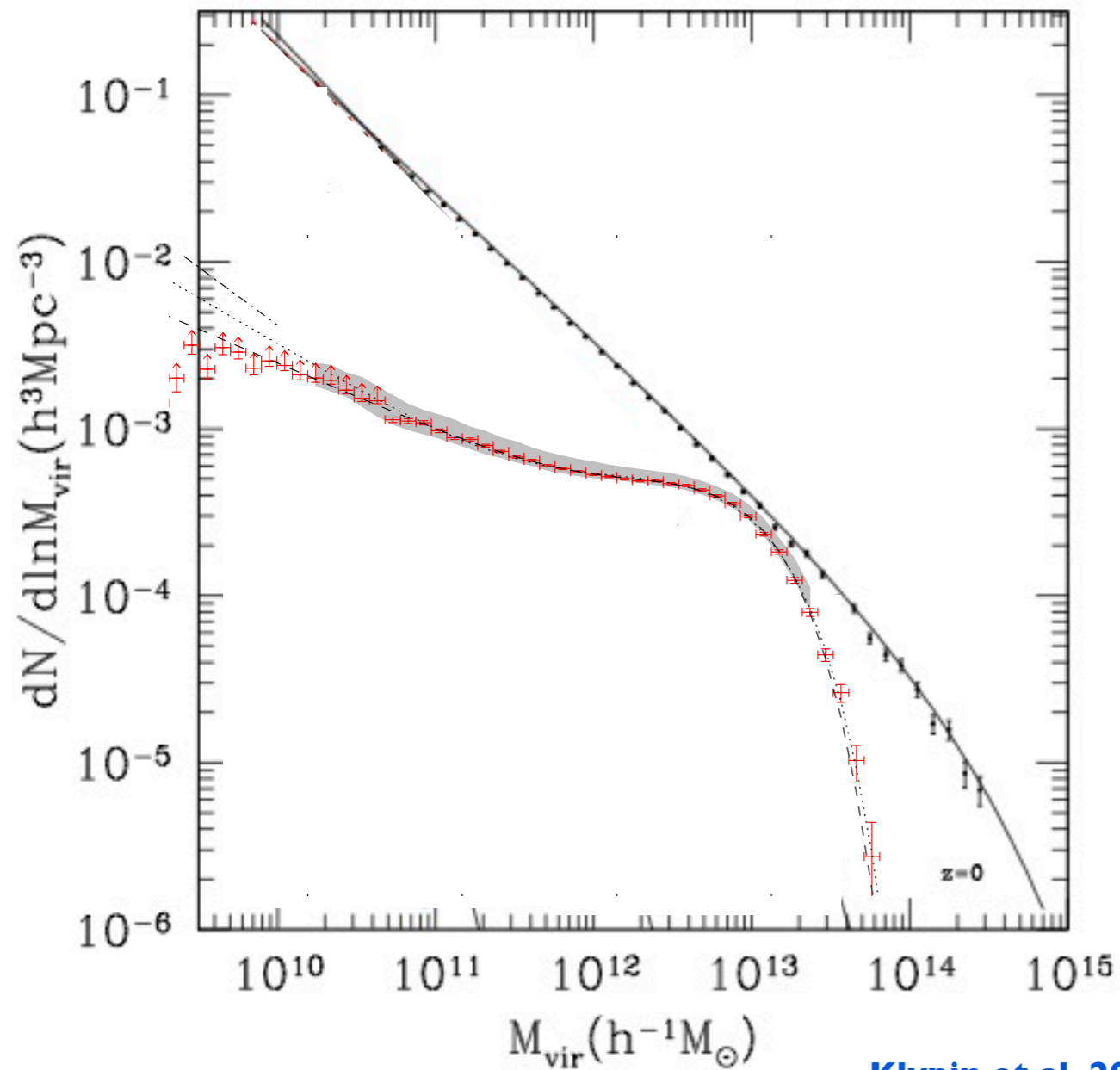
Galaxy Luminosity Function



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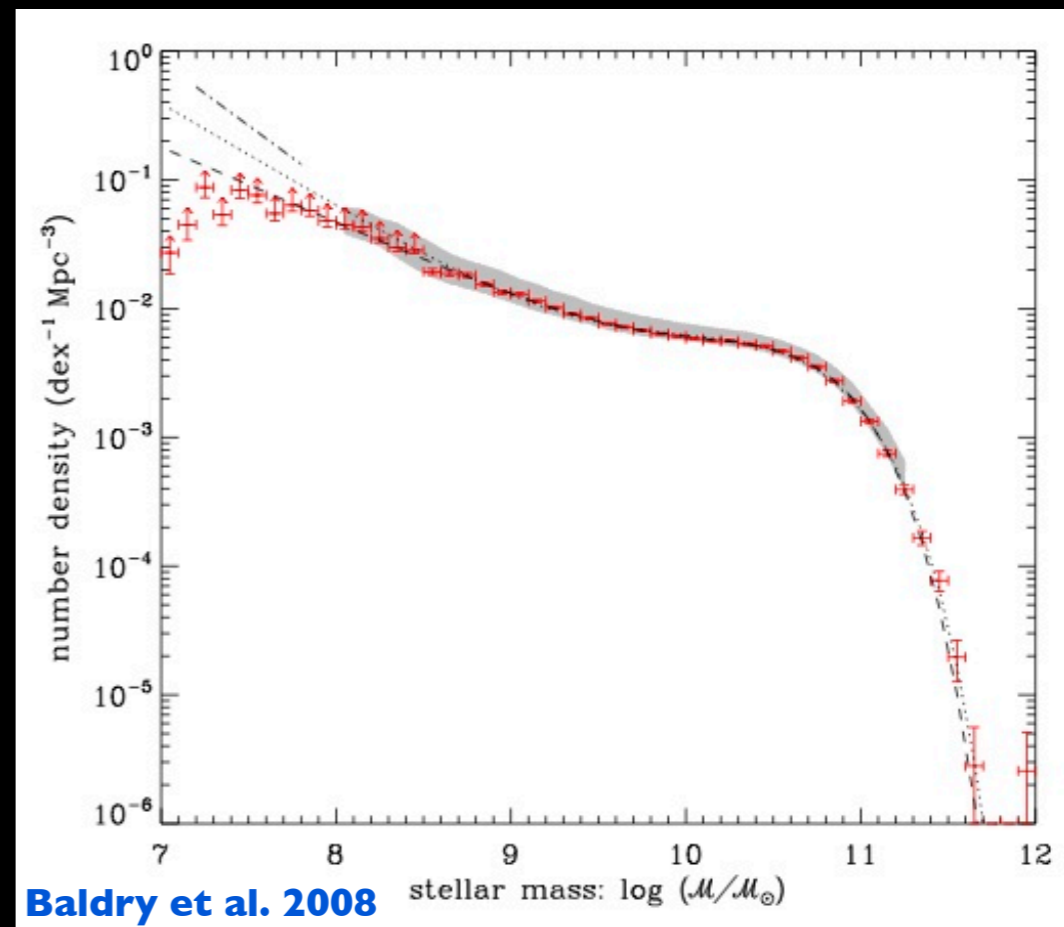
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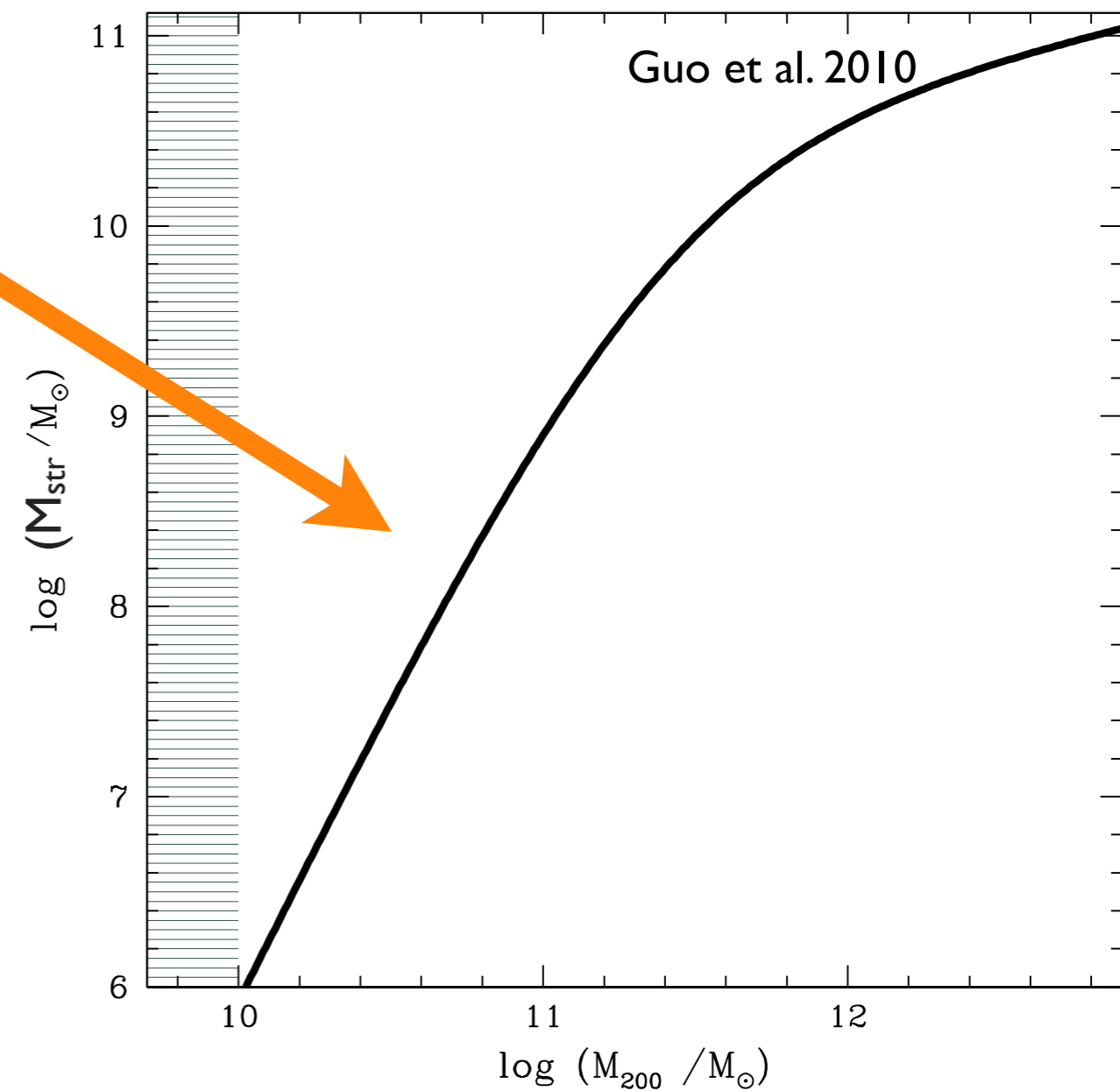
Galaxy Luminosity Function



Baldry et al. 2008

The $M_{\text{halo}} - M_{\text{star}}$ relation

Galaxy formation increasingly inefficient toward low mass end



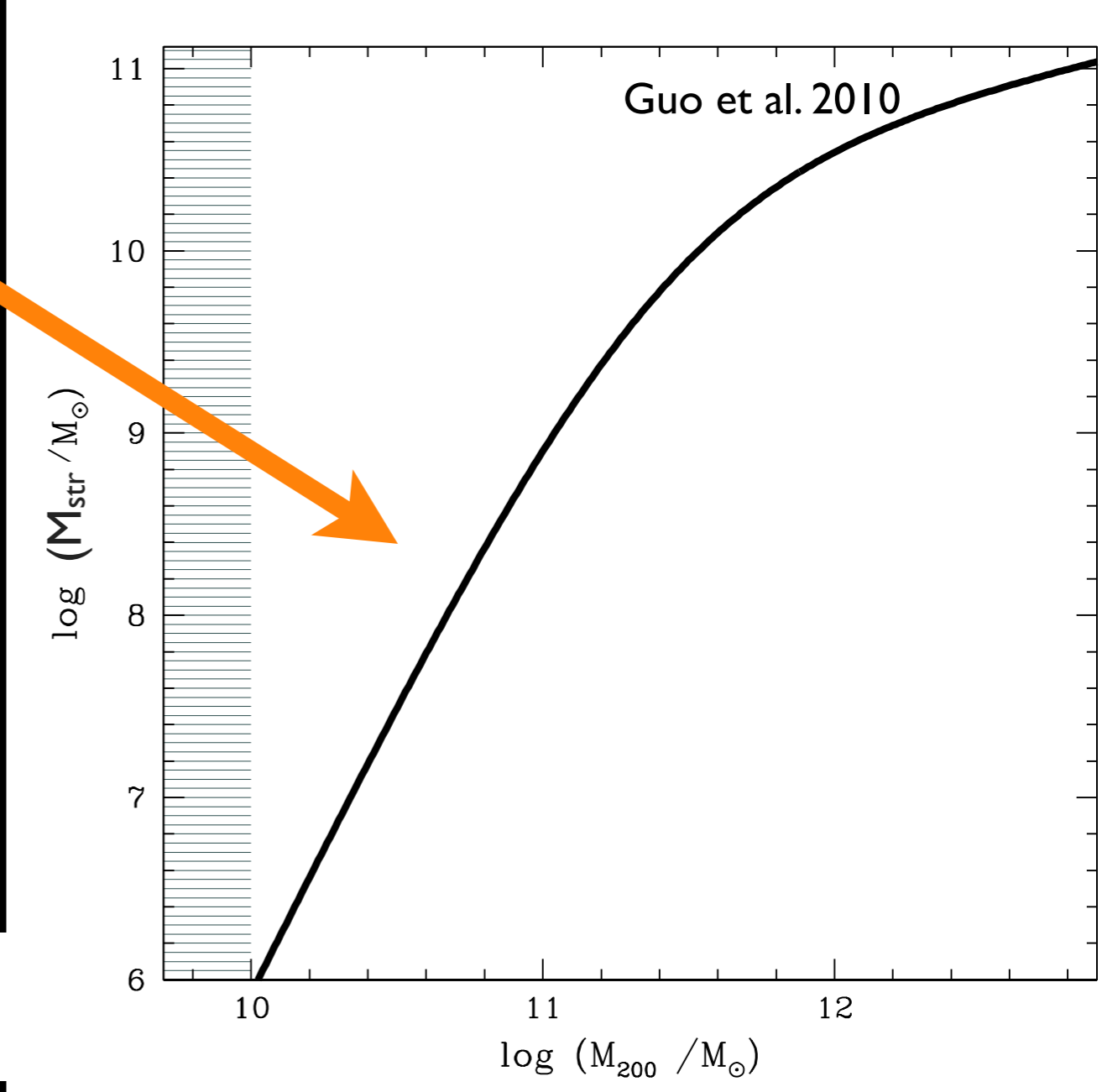
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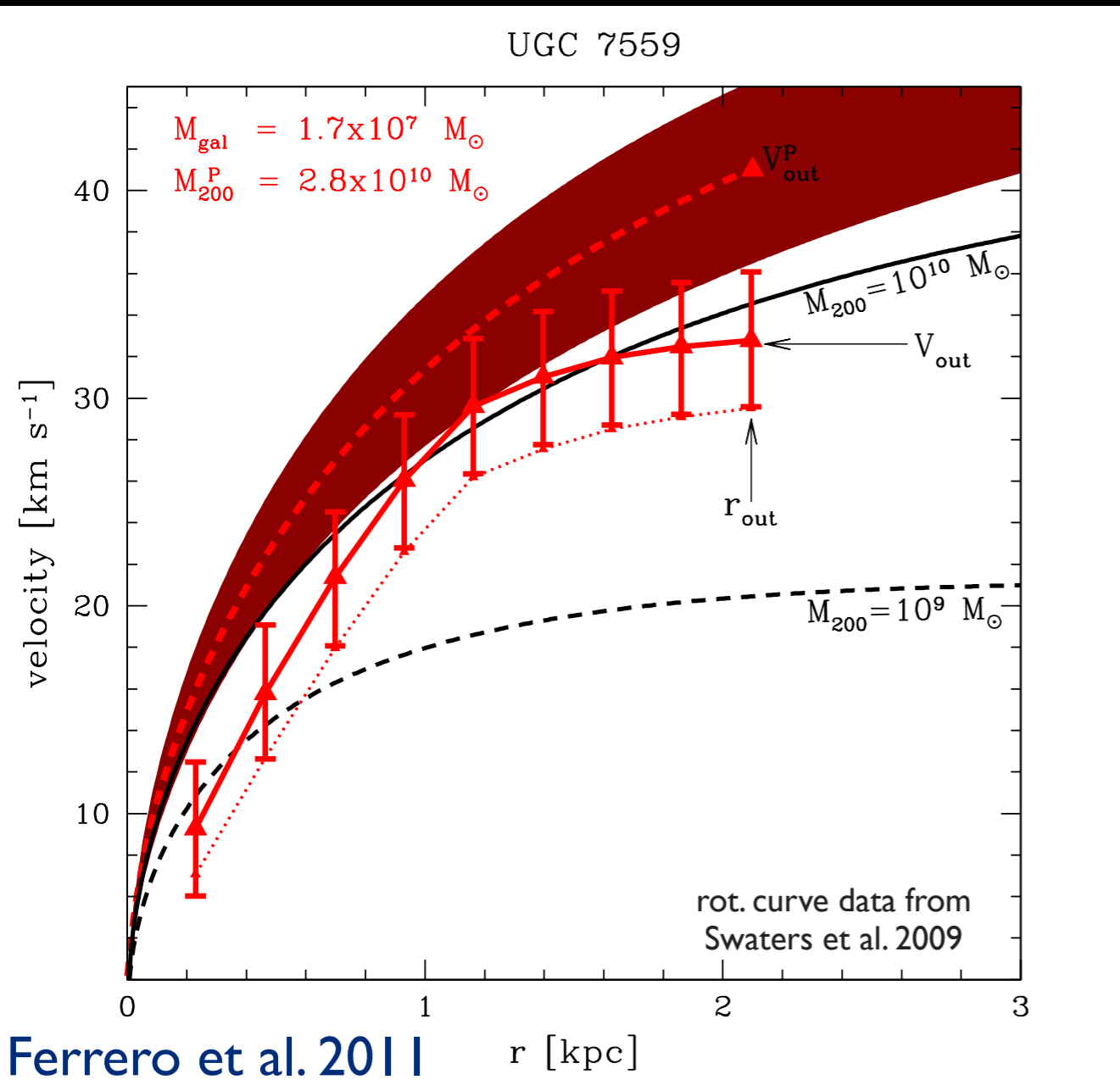
Dwarf's kinematics

Milky Way dSphs
(Boylan-Kolchin 2011a,b)

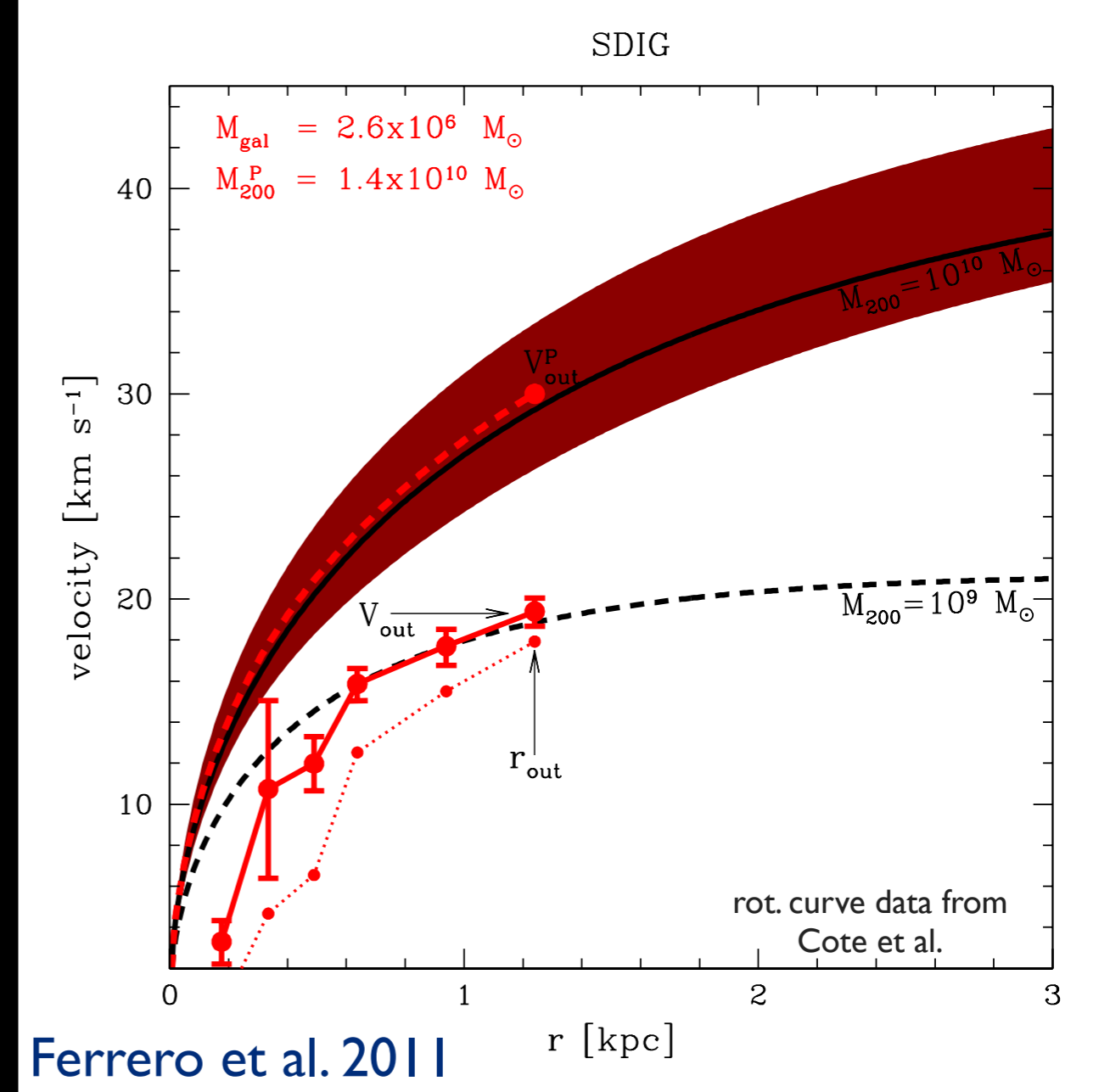
Isolated dwarfs HI
rotation curves



The dark matter halo of isolated dwarf galaxies

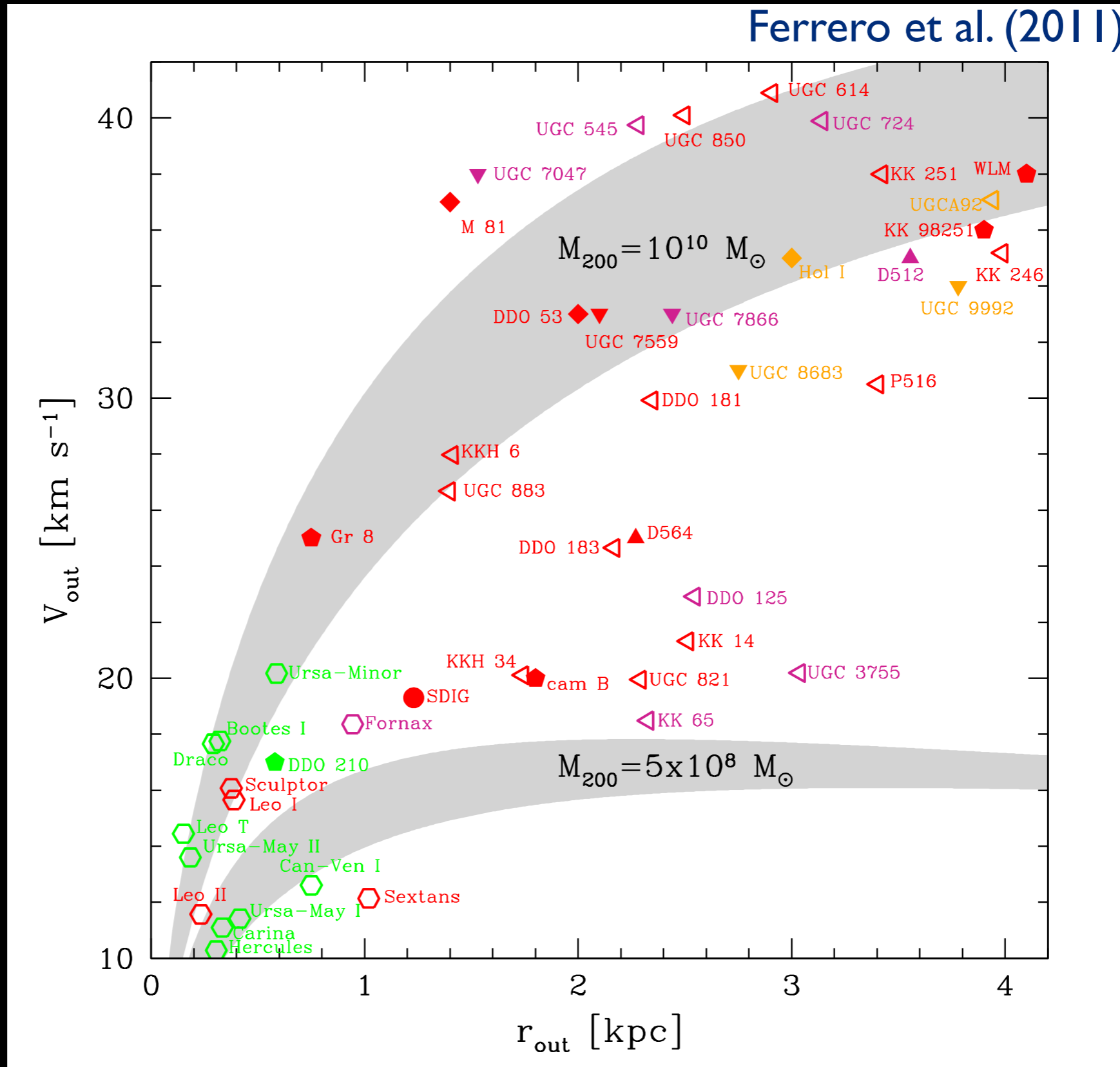


Consistent
with $\sim 10^{10}$ minimum halo mass



Inconsistent
with $\sim 10^{10}$ minimum halo mass

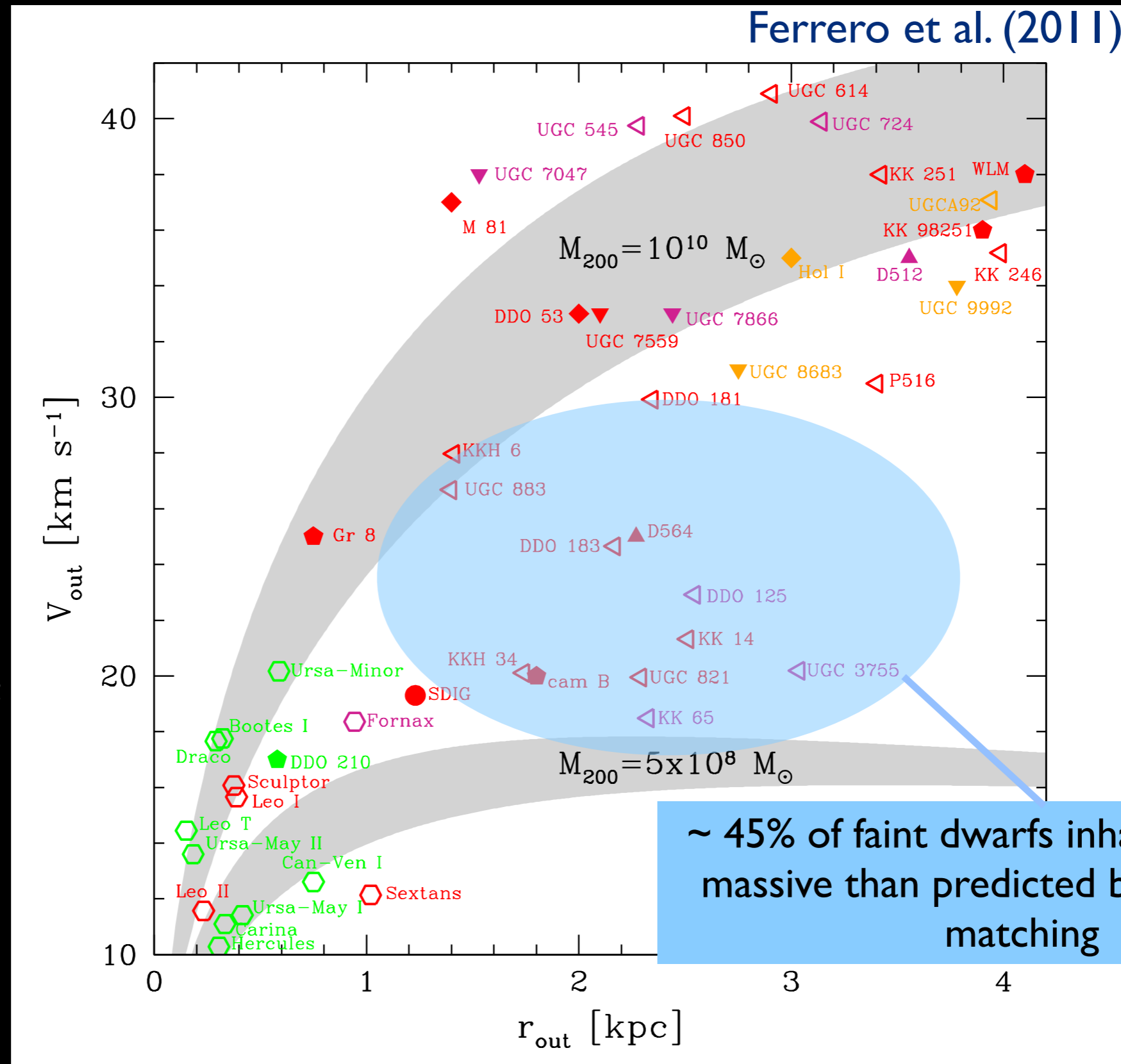
The dark matter halo of isolated dwarf galaxies



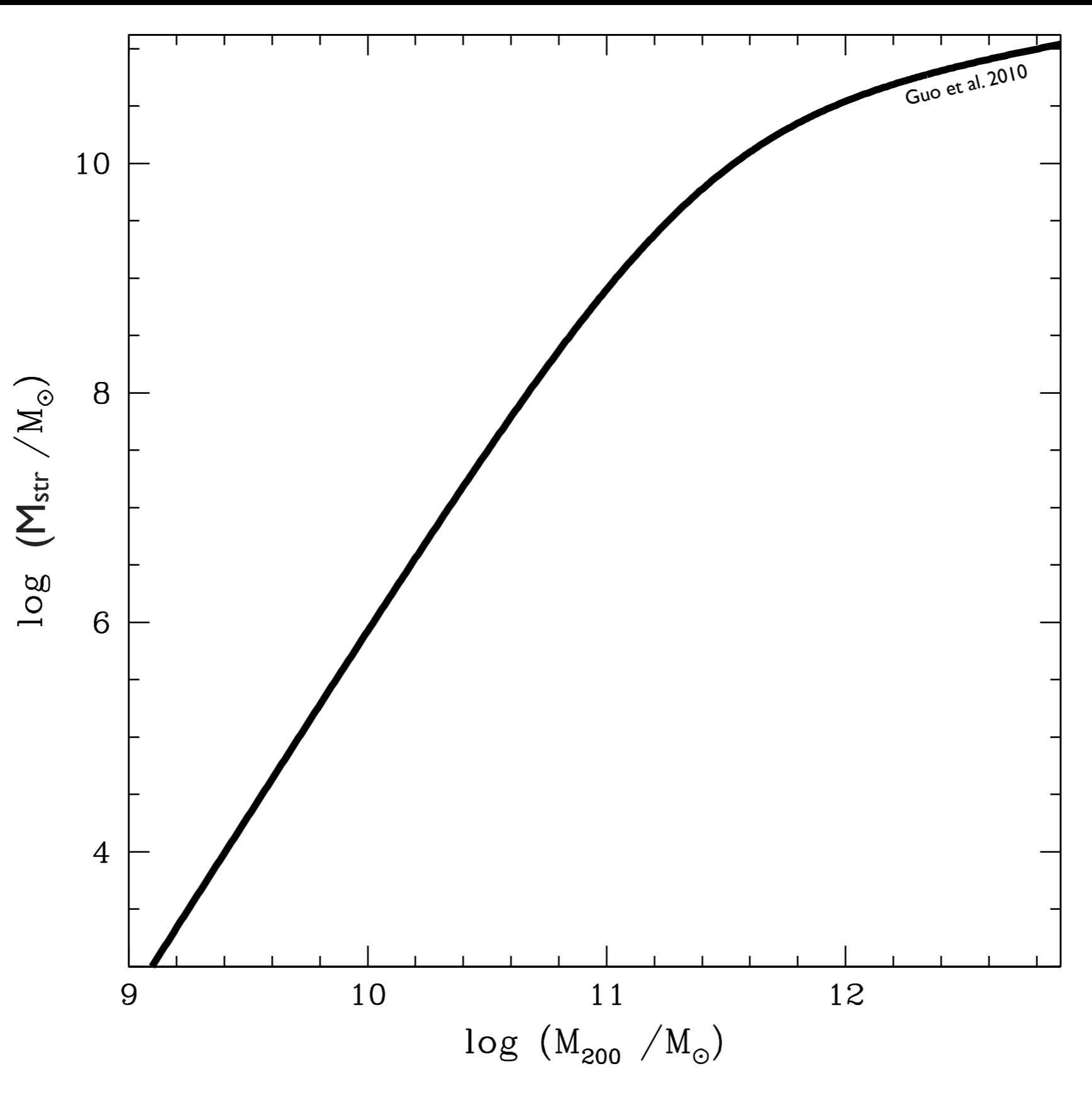
Data compilation from:

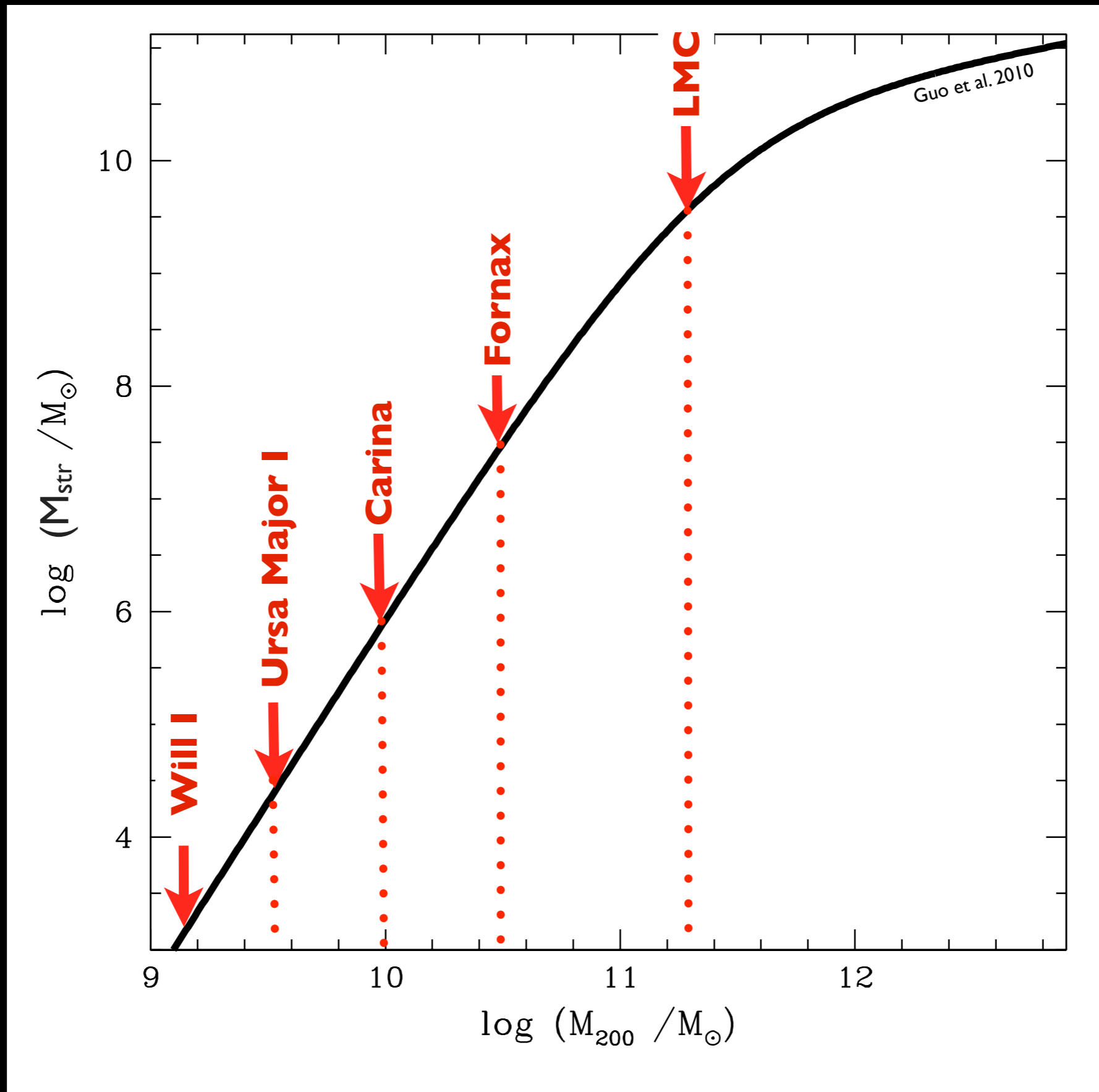
Swaters 1999,
 Cote 2000,
 McGaugh 2005,
 Begum 2008 (FIGGS),
 Stark 2009,
 Trachternach 2009,
 Oh 2011 (THINGS)

The dark matter halo of isolated dwarf galaxies



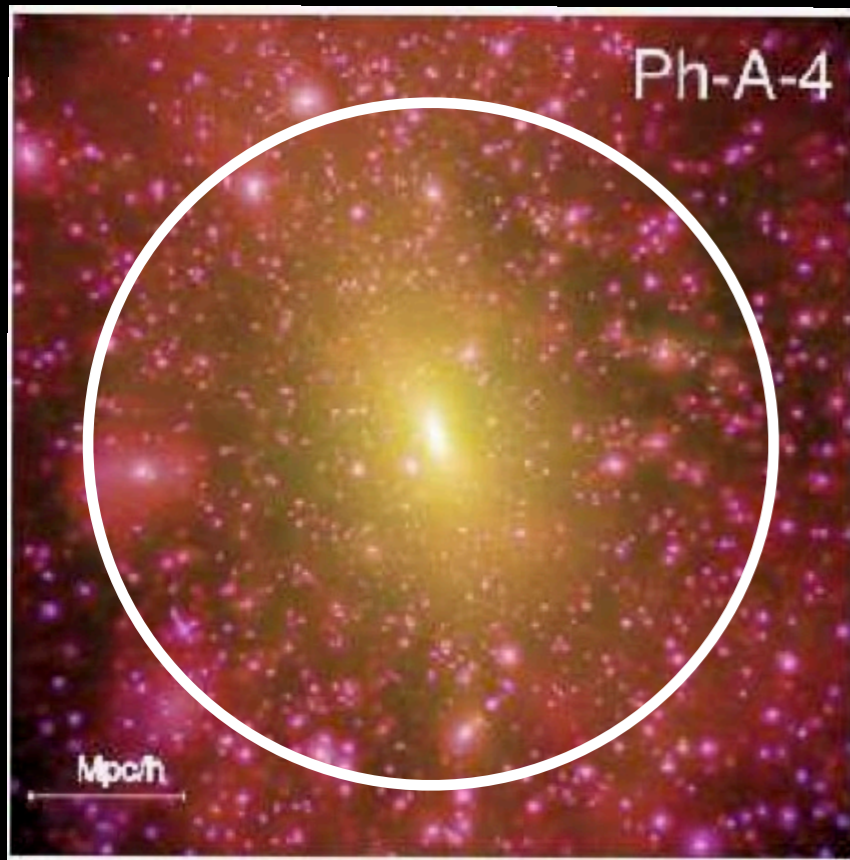
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The Substructure of Dark Matter Haloes

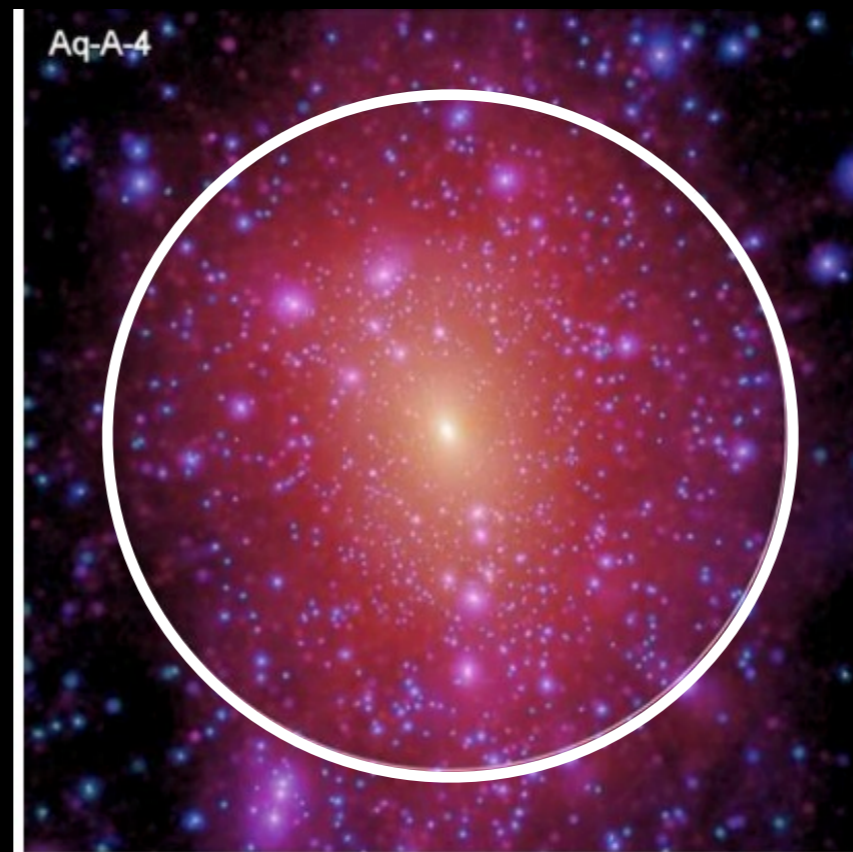
The Phoenix Project
Gao et al. 2012



Cluster Halo

$$M_{\text{vir}} \sim 6.5 \times 10^{14} M_{\text{sun}}$$

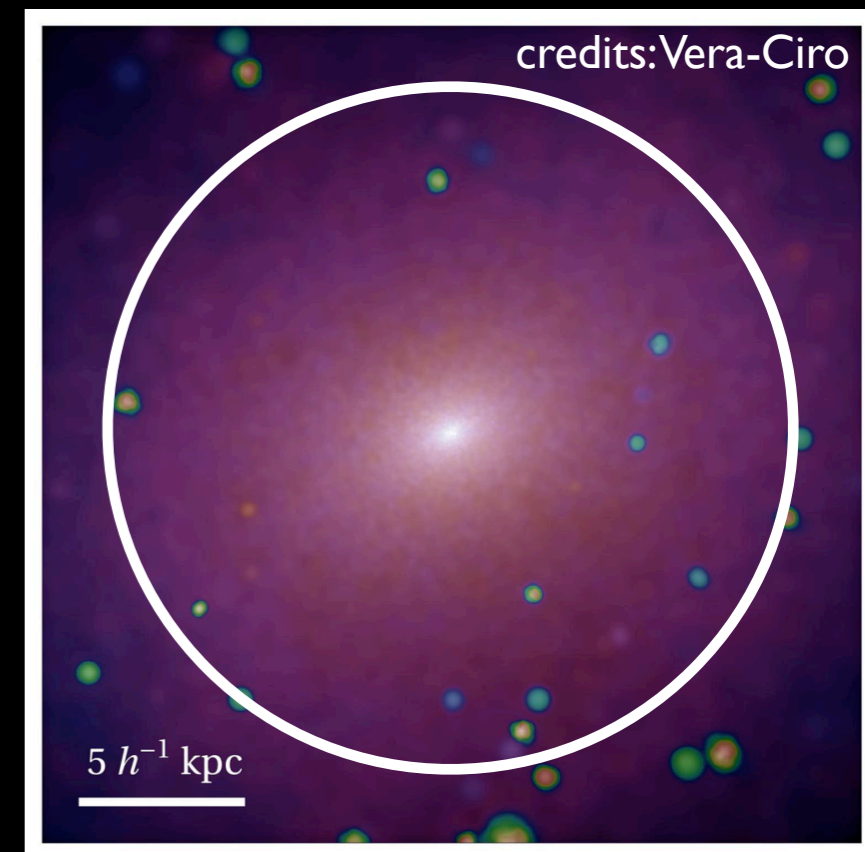
The Aquarius Project
Springel et al. 2008



Galaxy Halo

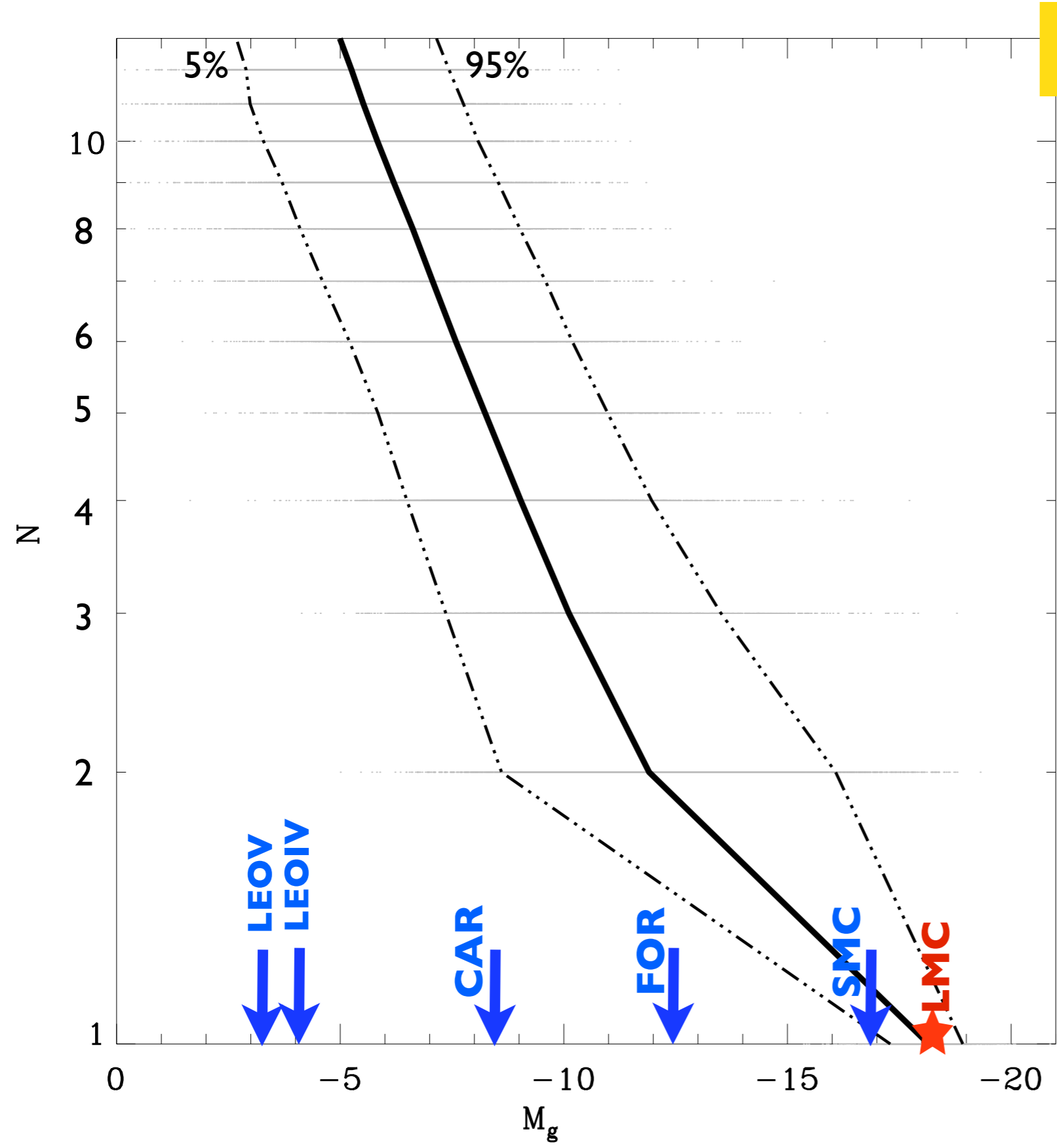
$$M_{\text{vir}} \sim 1.3 \times 10^{12} M_{\text{sun}}$$

The Aquarius Project (subhalo)



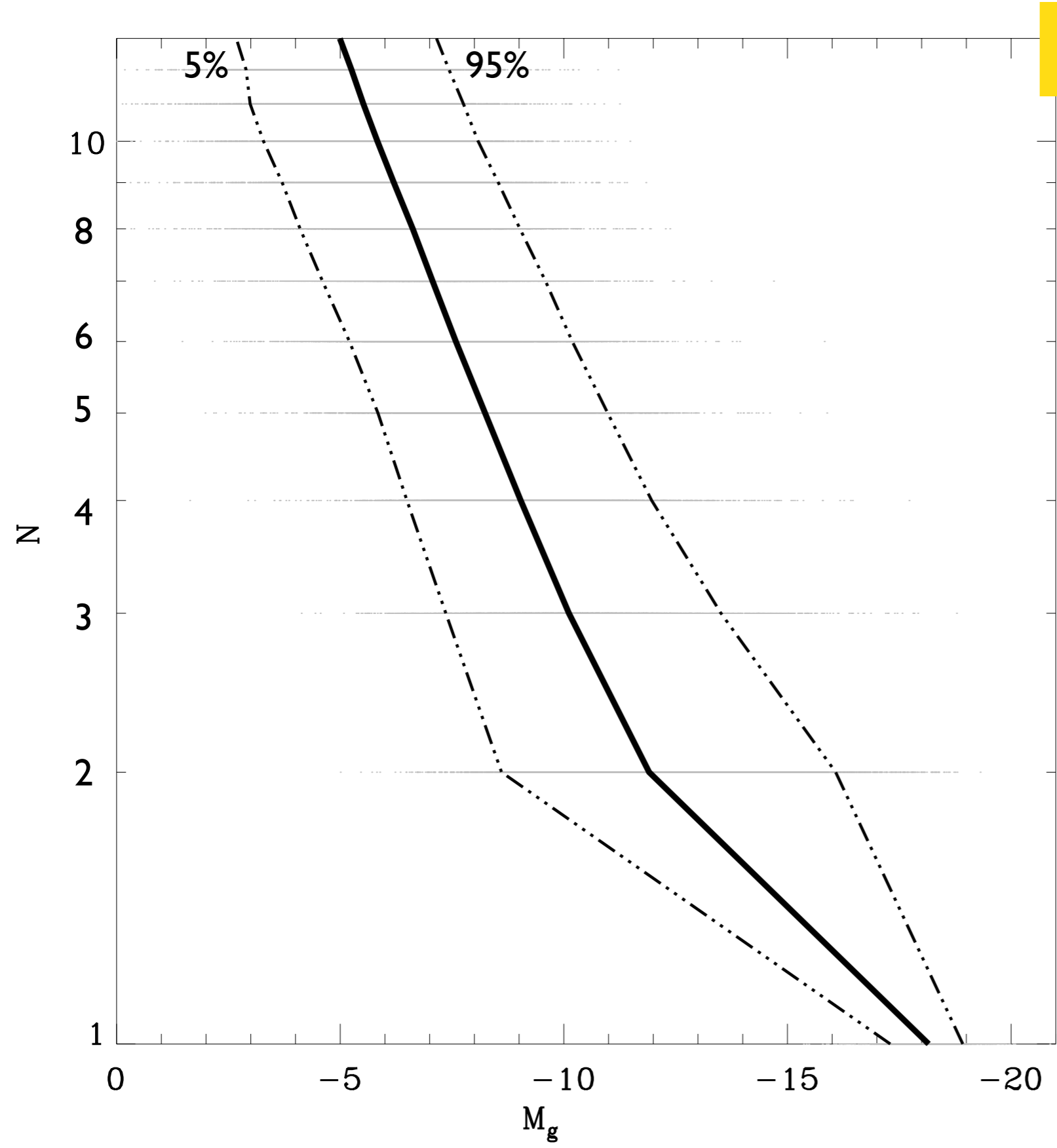
Dwarf Halo

$$M_{\text{vir}} \sim 1 \times 10^9 M_{\text{sun}}$$



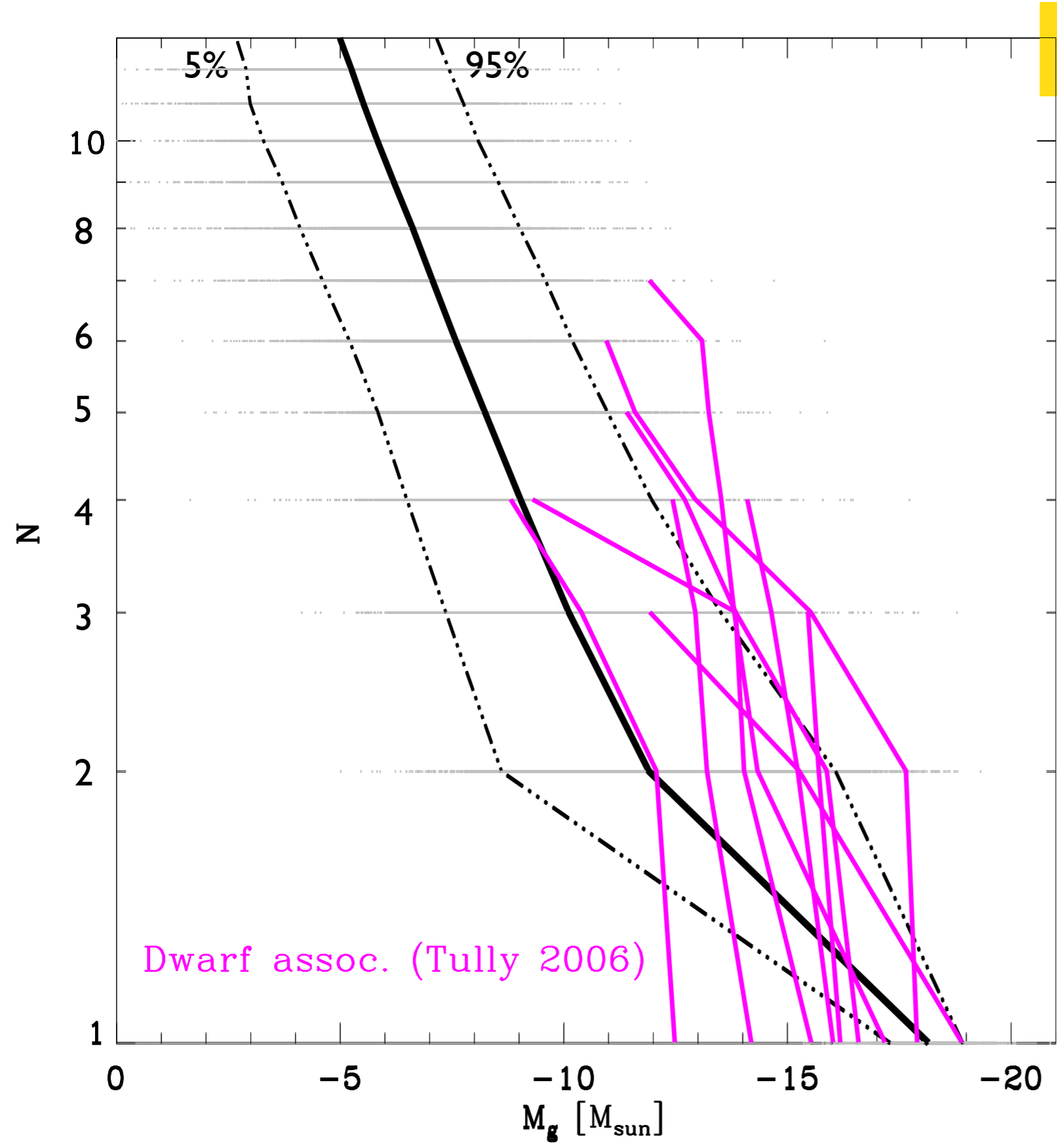
Cumulative luminosity function of $\sim 10^{11} M_{\text{sun}}$ isolated halos in Millennium II + SAM

Because halo structure is self-similar, faint galaxies are surrounded by (even fainter!) companions; in a manner reminiscent of dwarf satellites orbiting MW/M31



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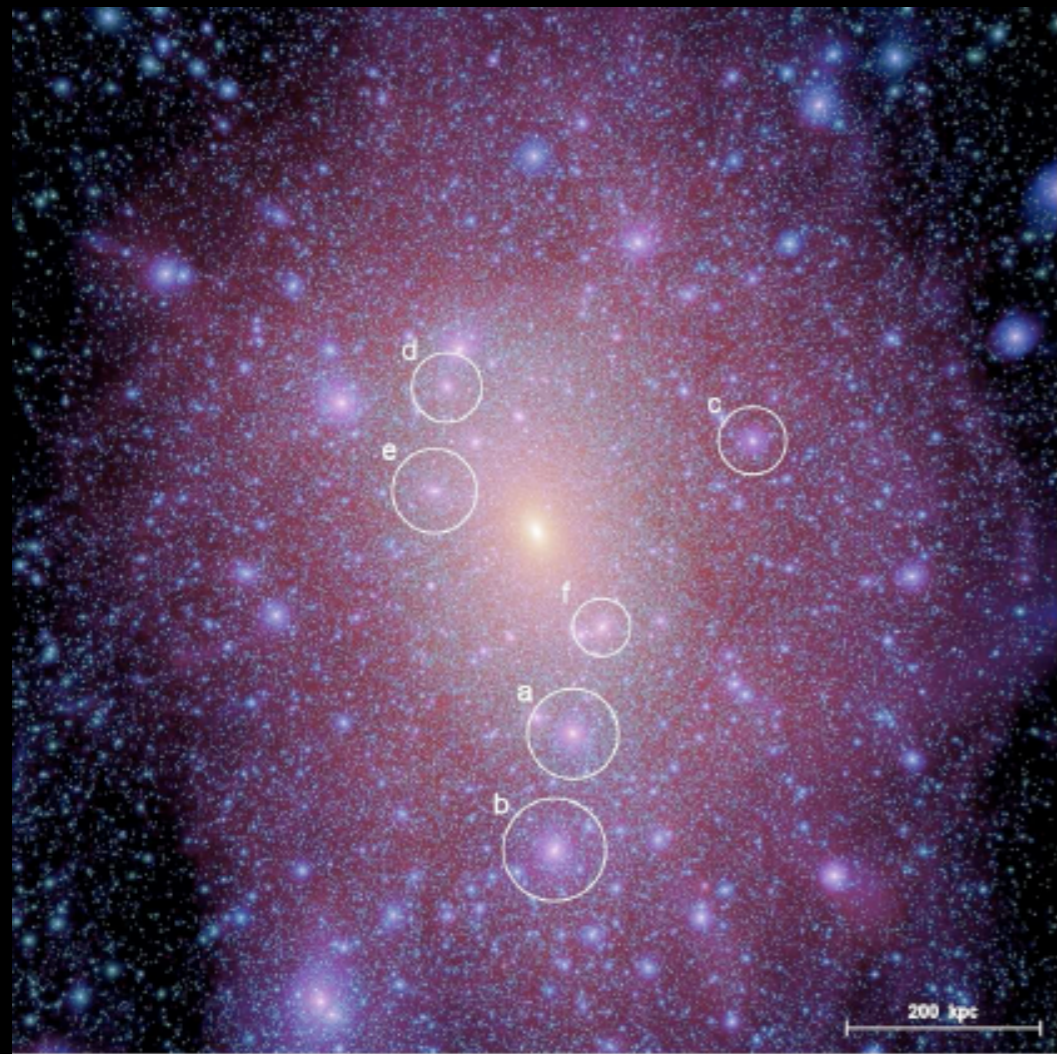


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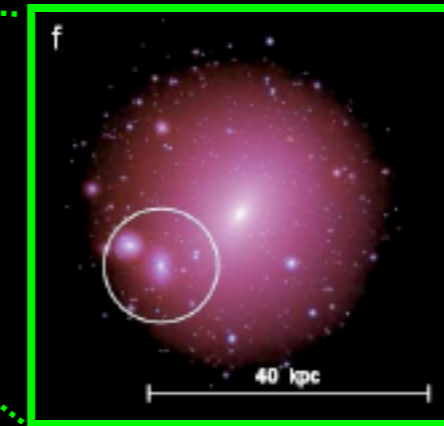
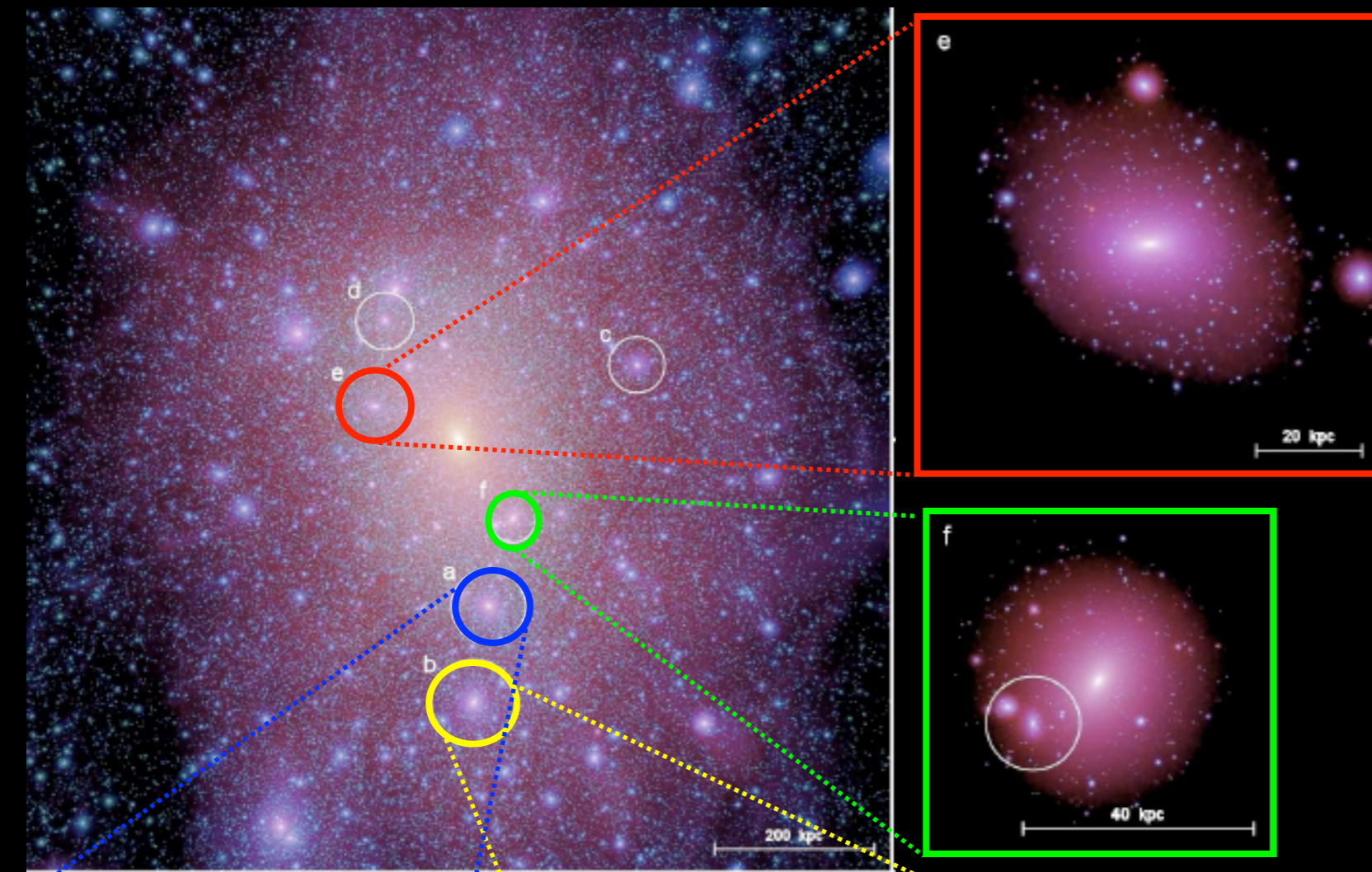
The CDM hierarchy as revealed by the Aquarius Simulations

Springel et al. 2008a,b

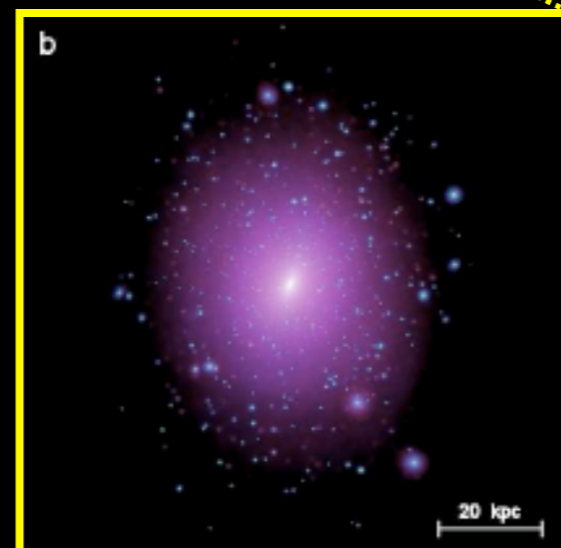
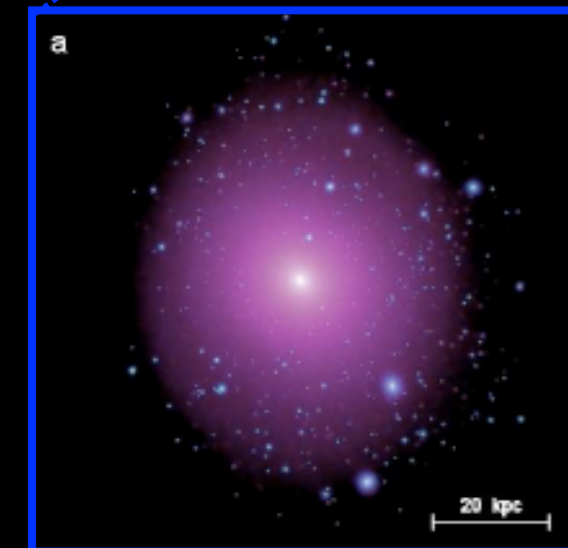


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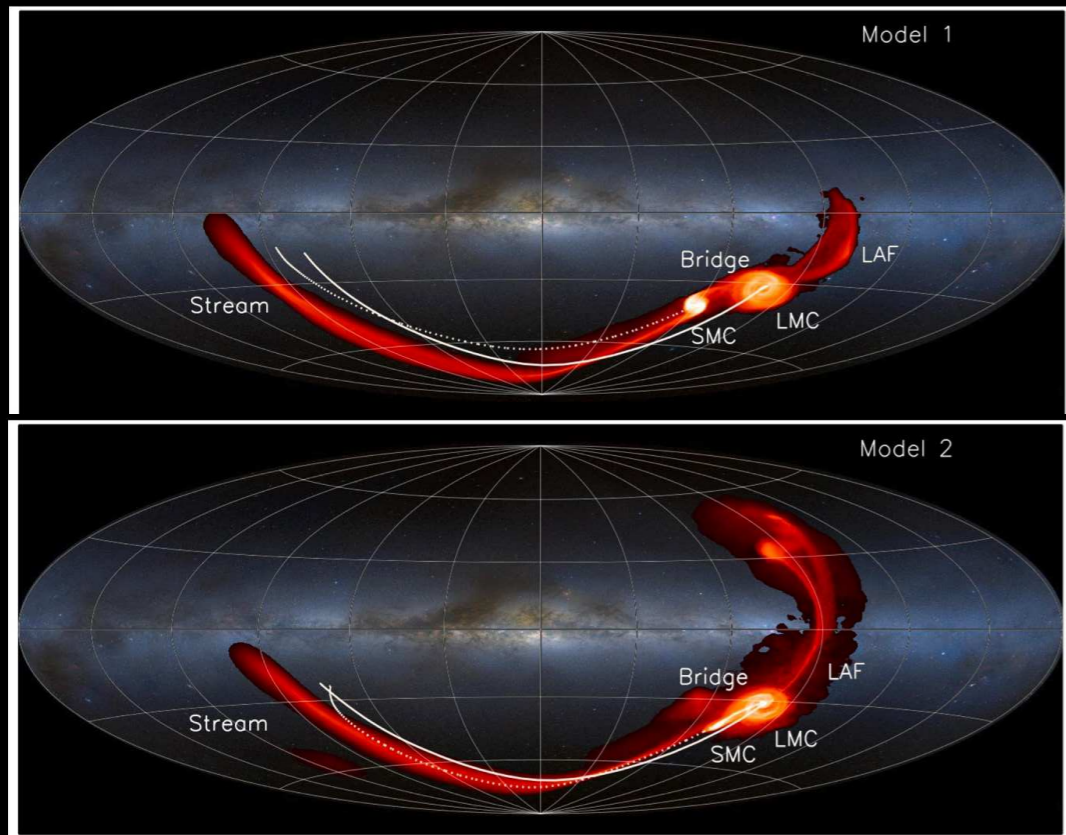
Nested structure of substructure



Satellites infall as part of larger groups of subhalos

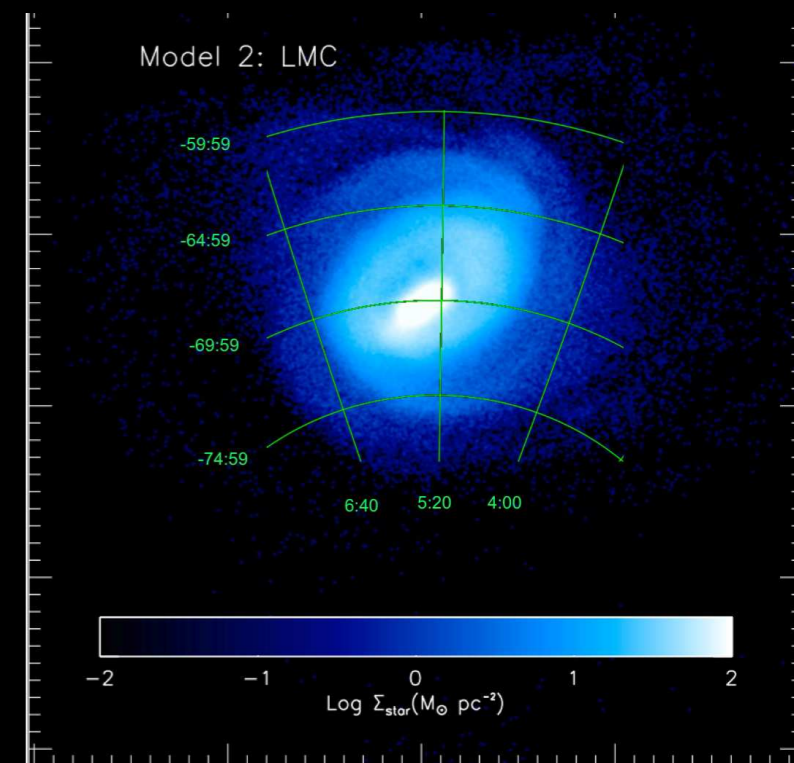
Are there more examples in the Milky Way?

Besla et al. 2012



LMC-SMC interactions before infall as the origin of the Magellanic Stream

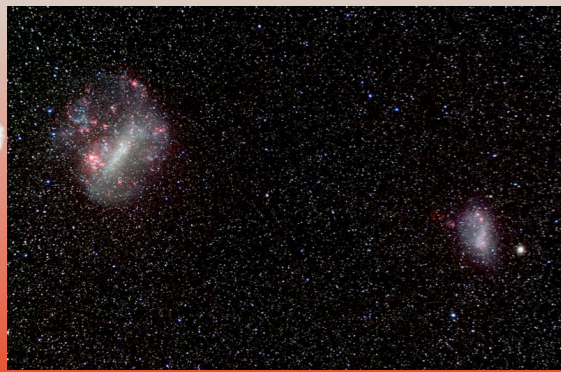
Recent close interaction with the SMC might explain several morphological features of the LMC, such as off-centered/tilted stellar bar.



Common among “Magellanic Irregulars” ?

Infall of satellites in groups: are there more examples in the Milky Way?

LMC-SMC

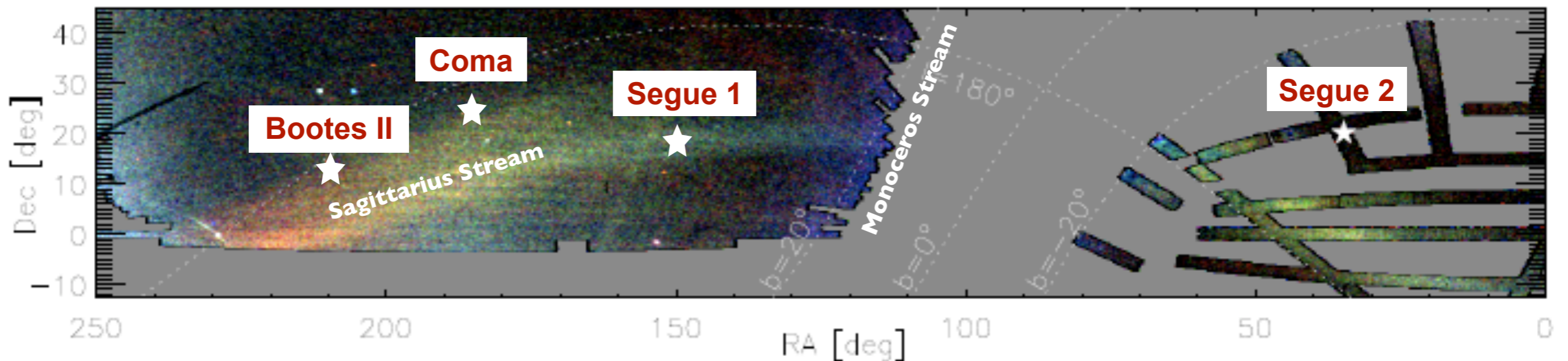


LeoIV - LeoV

-- suggested by their similar position, distance and velocities --

(Belokurov et al. 2008)

Boo II, Seg I, Seg II and Coma as companions of Sagittarius Dwarf (Belokurov et al. 2009)



Looking for the former companions of the LMC

- Because...
- Orbit
 - Most Luminous

Aquarius Simulation

(Springel et al. 2008)

We have selected LMC-candidates

- * Close pericenter passage ($r_{\text{LMC}} \sim 50$ kpc)
- * Velocities as close as possible to the LMC measurements
- * Relatively massive satellite ($M_{\text{sat}}/M_{\text{host}} > 0.01$)

Aquarius Simulation

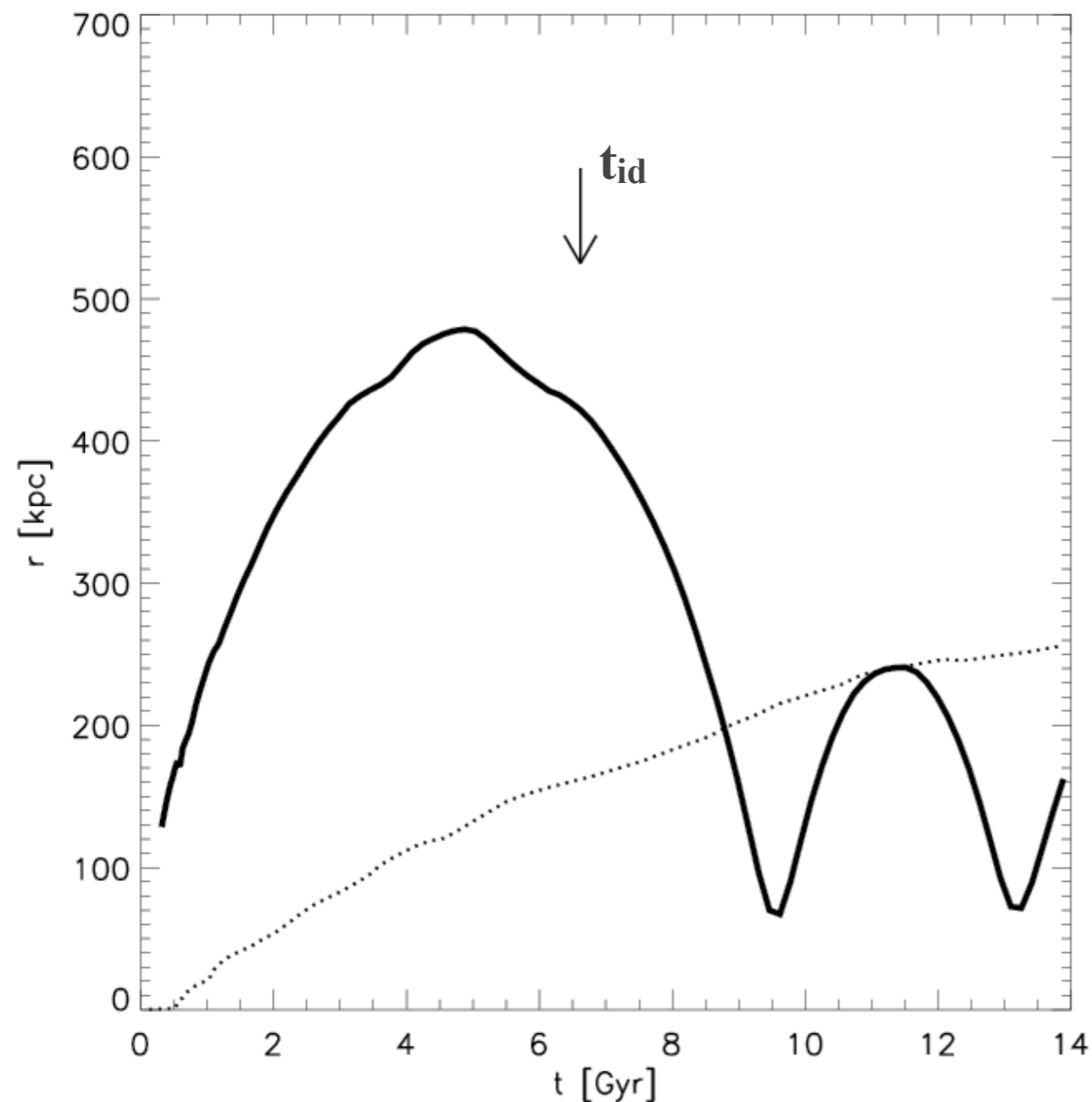
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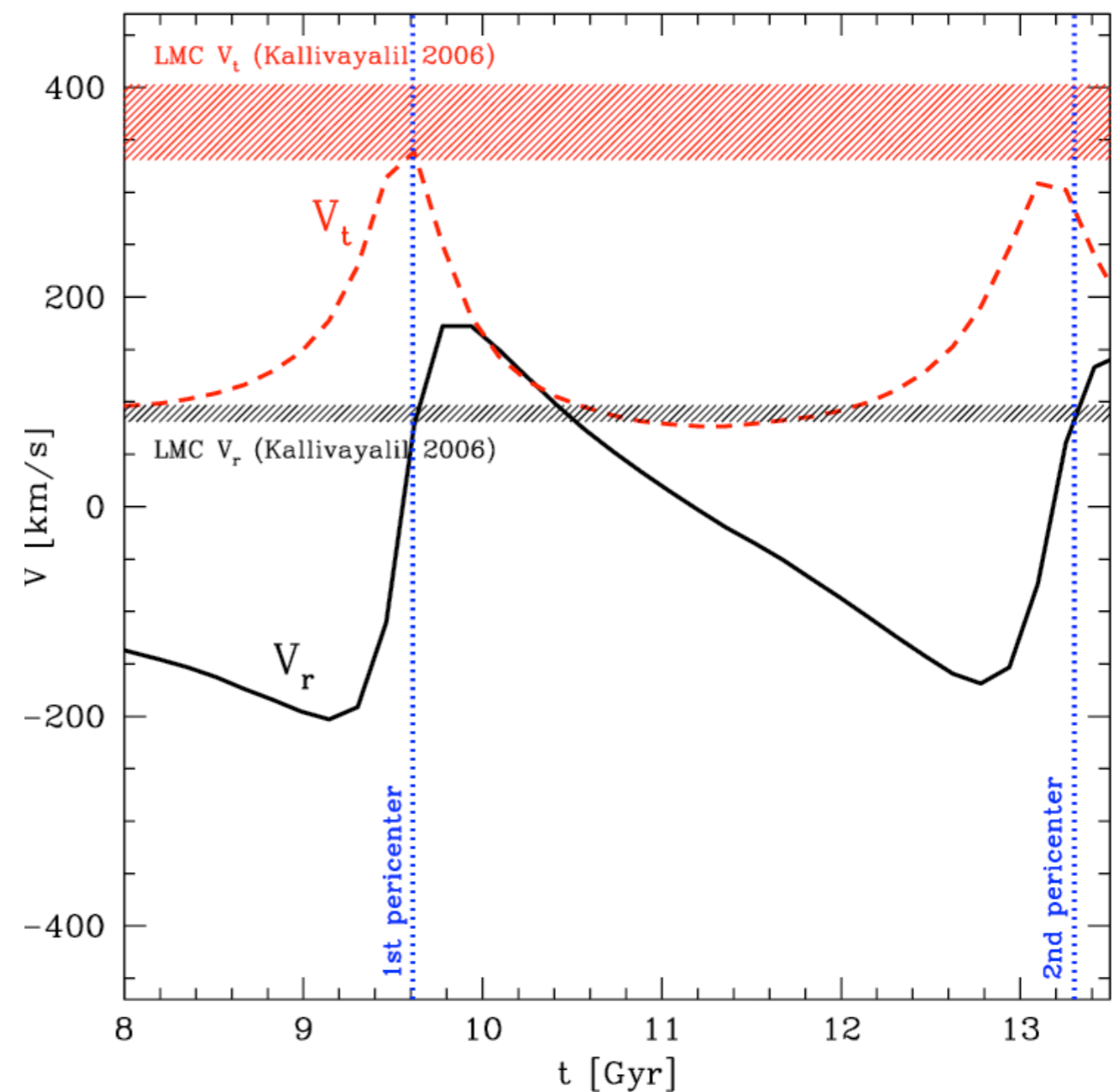
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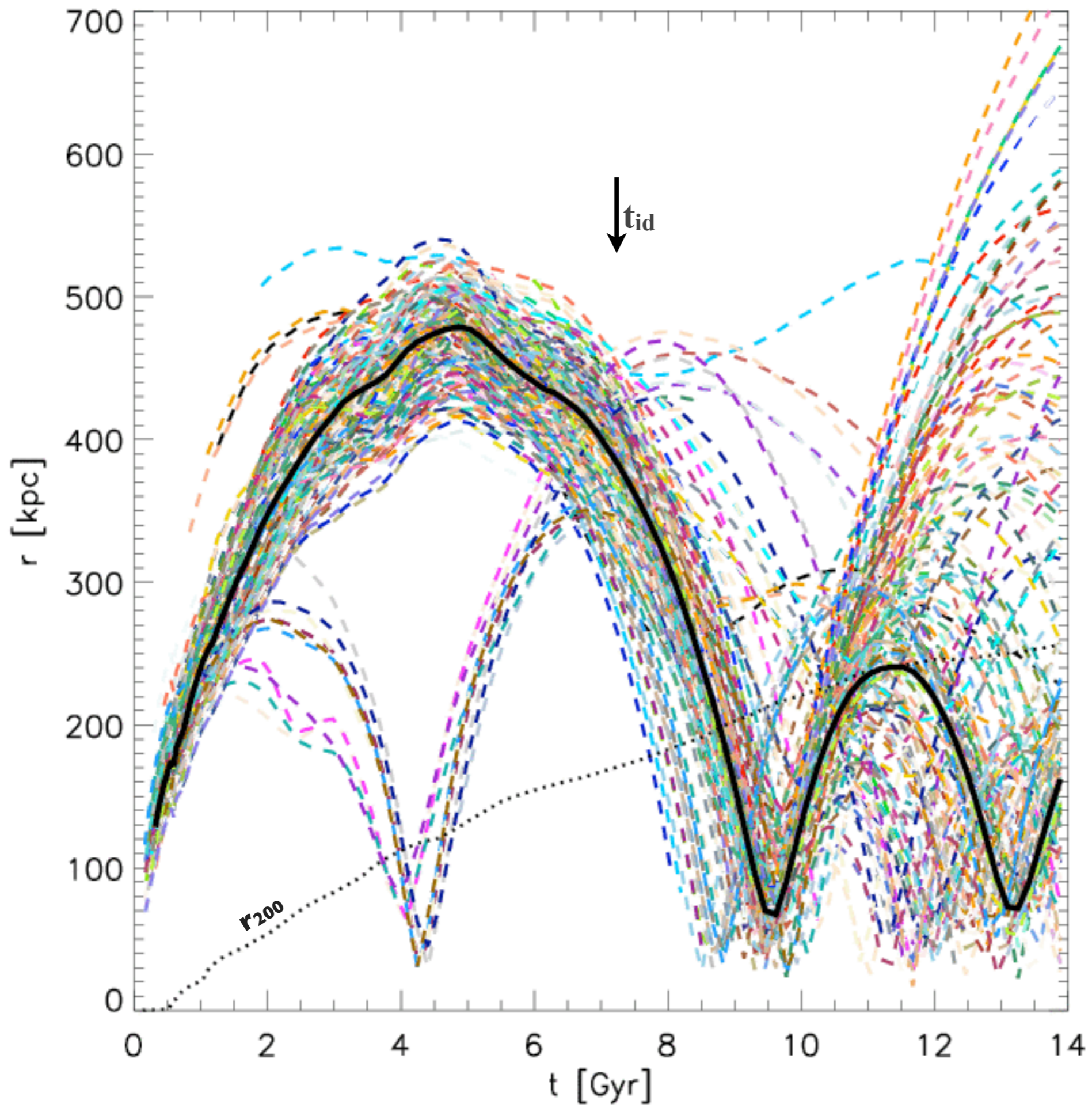
Our best LMC dynamical analog

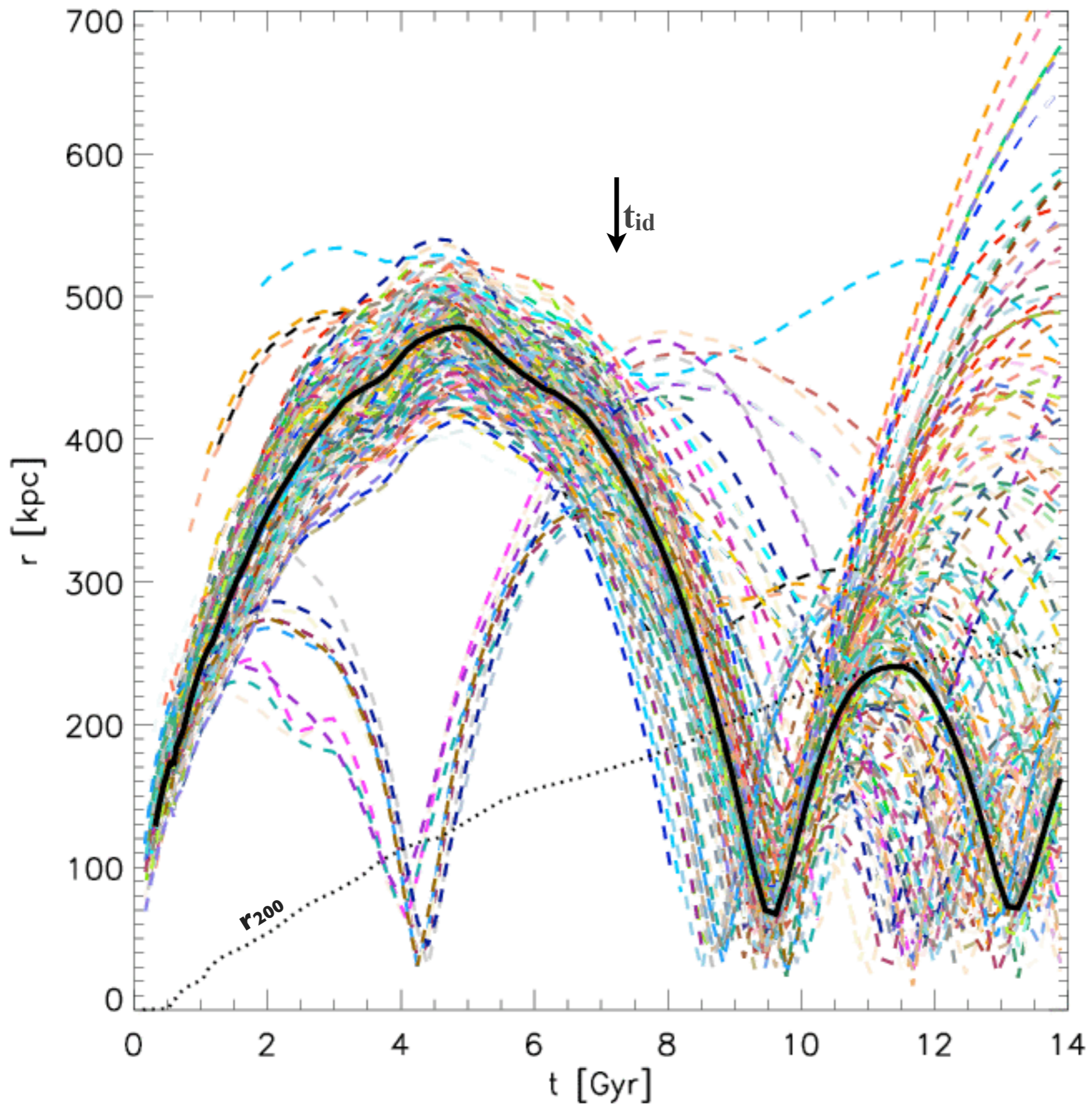
Positions



Velocities





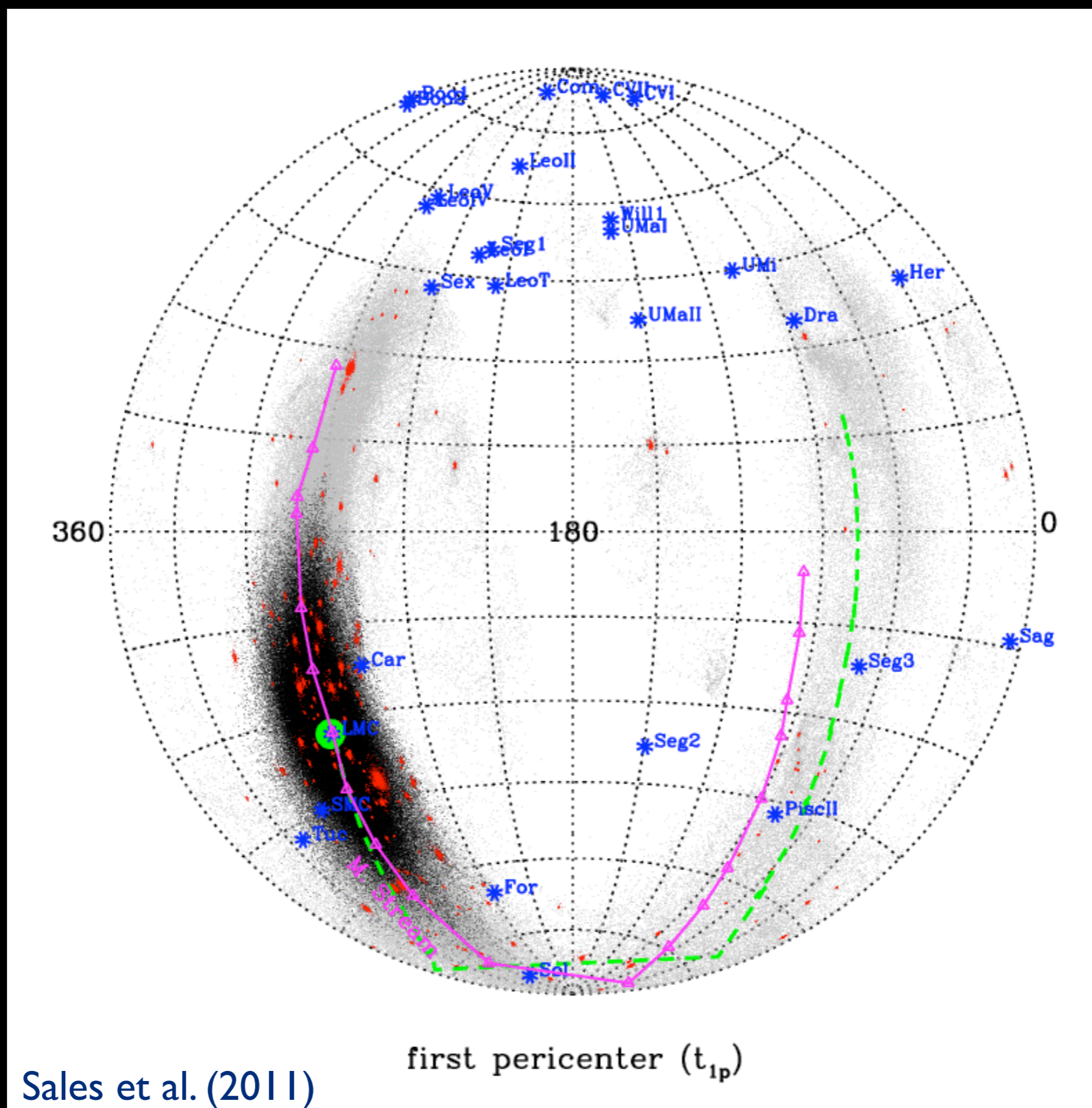


**Complexity of
group's orbits**

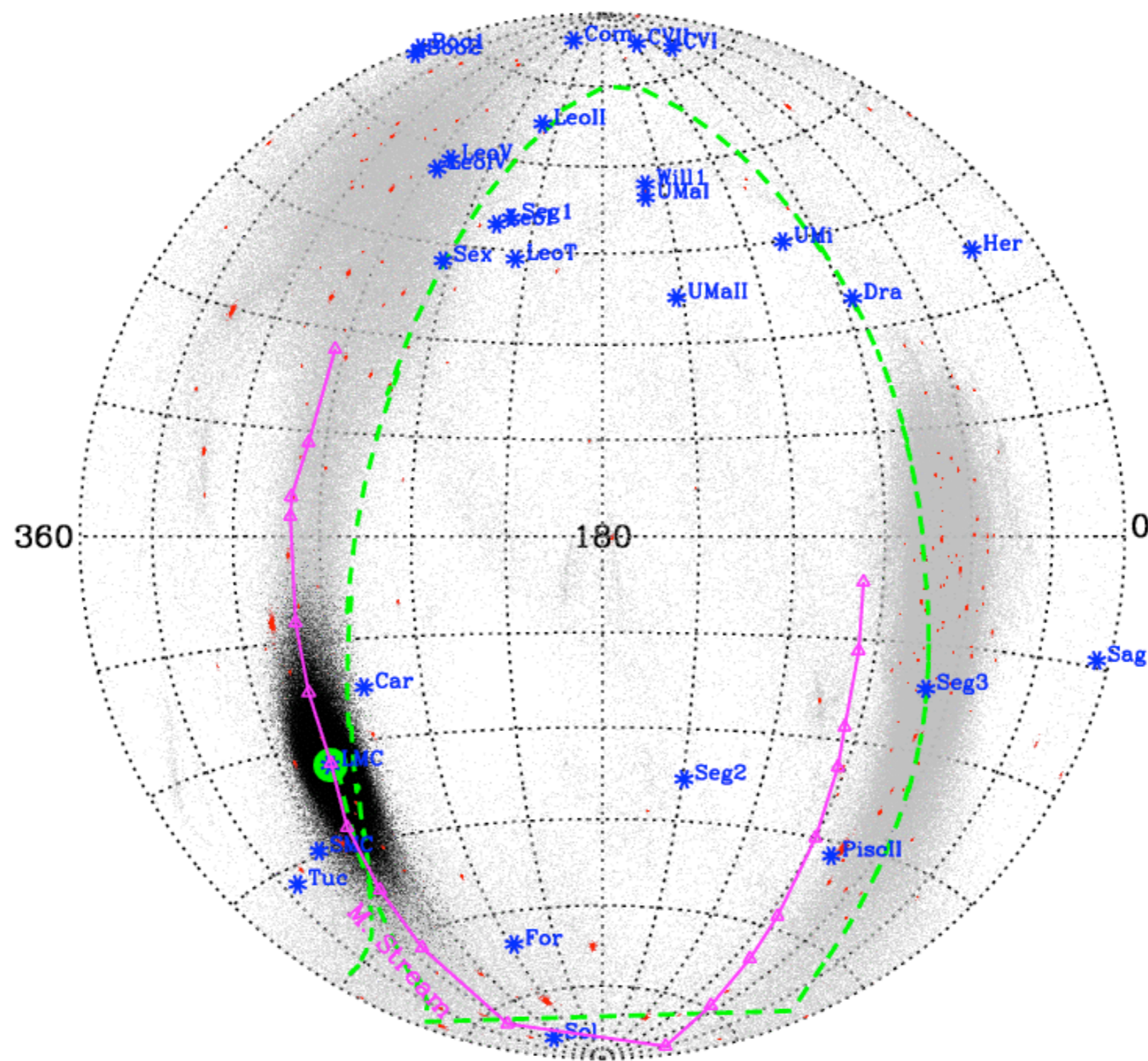
**Initial infall from
~450 kpc**

**Main satellite
remains bound to
the central
potential**

Distribution of LMC companions on the sky



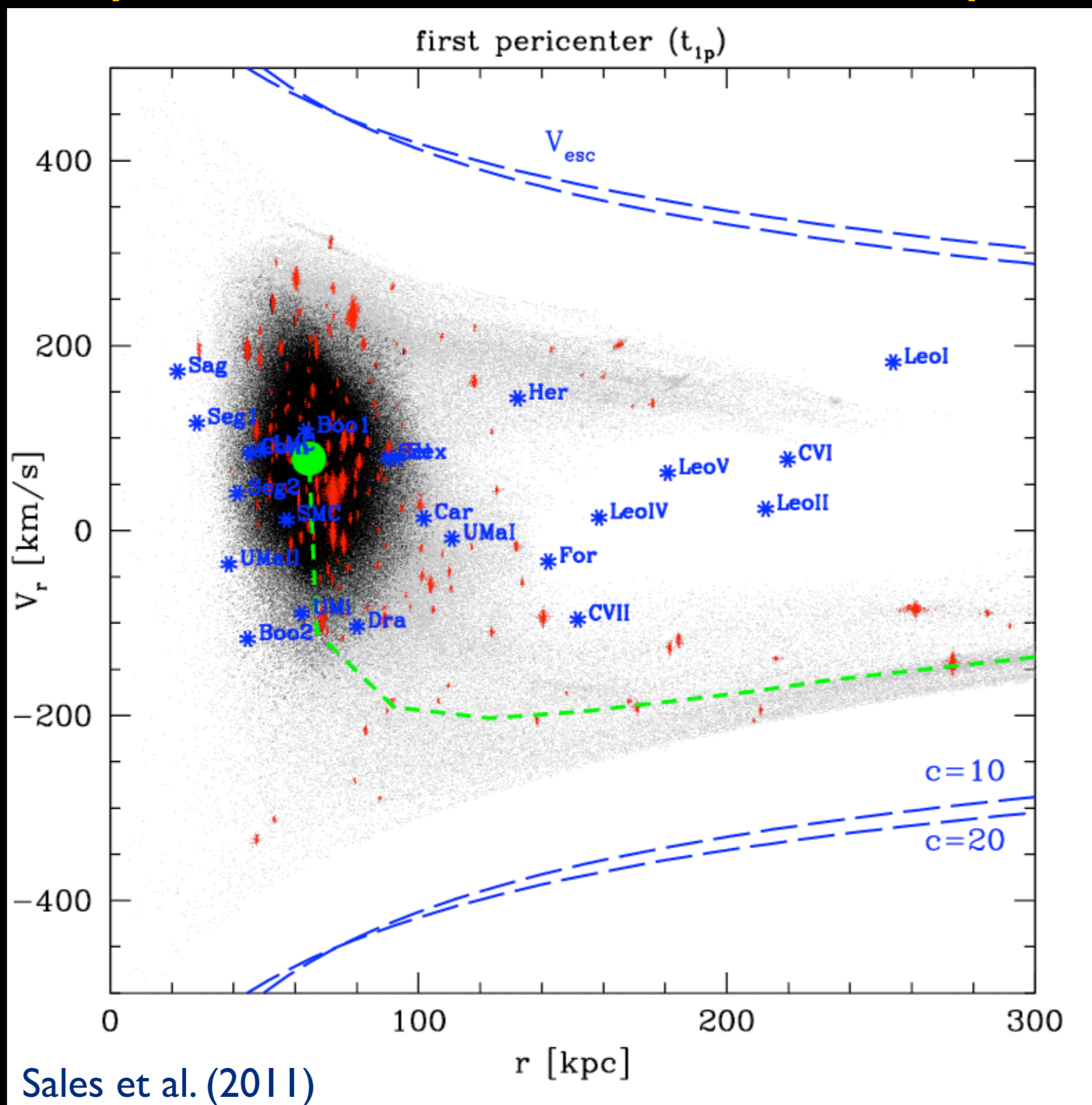
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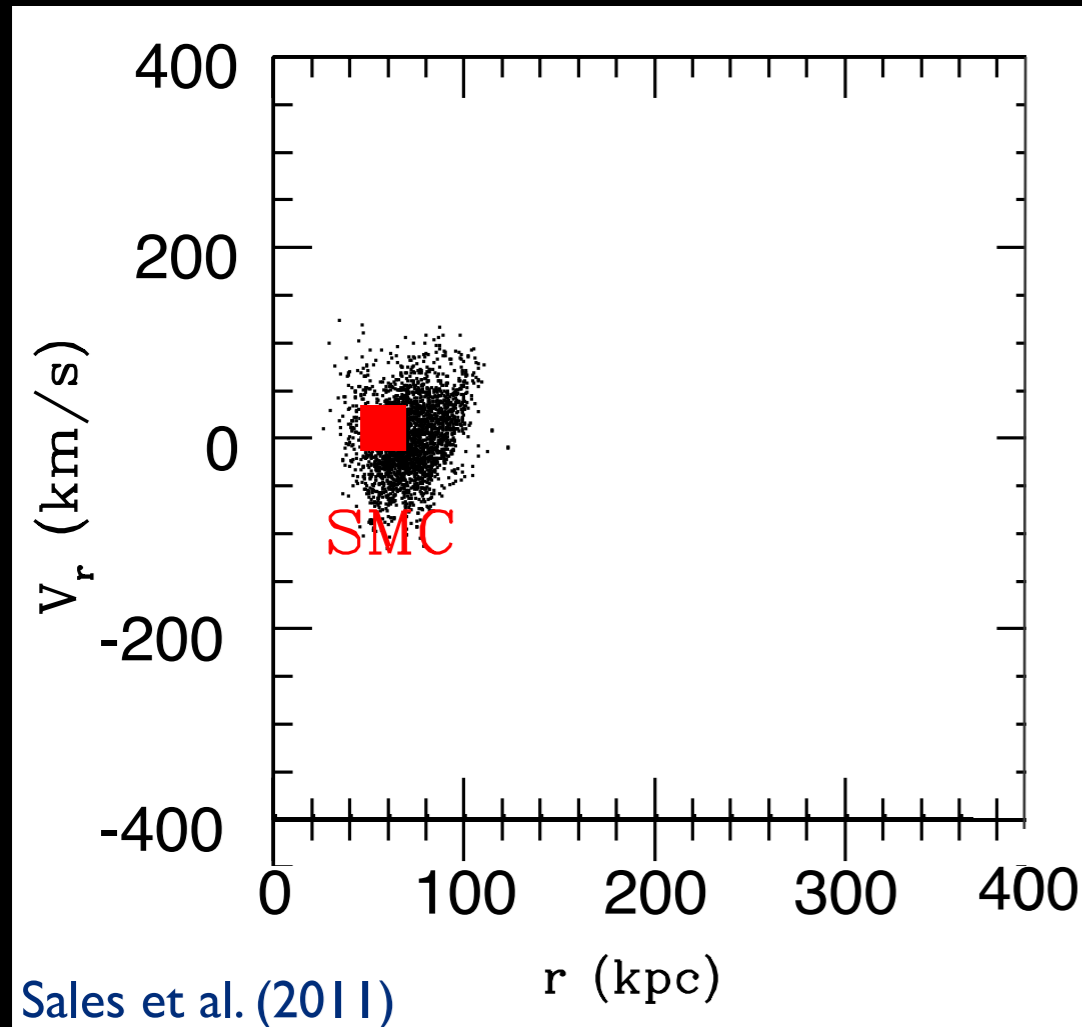
Sales et al. (2011)

second pericenter (t_{2p})

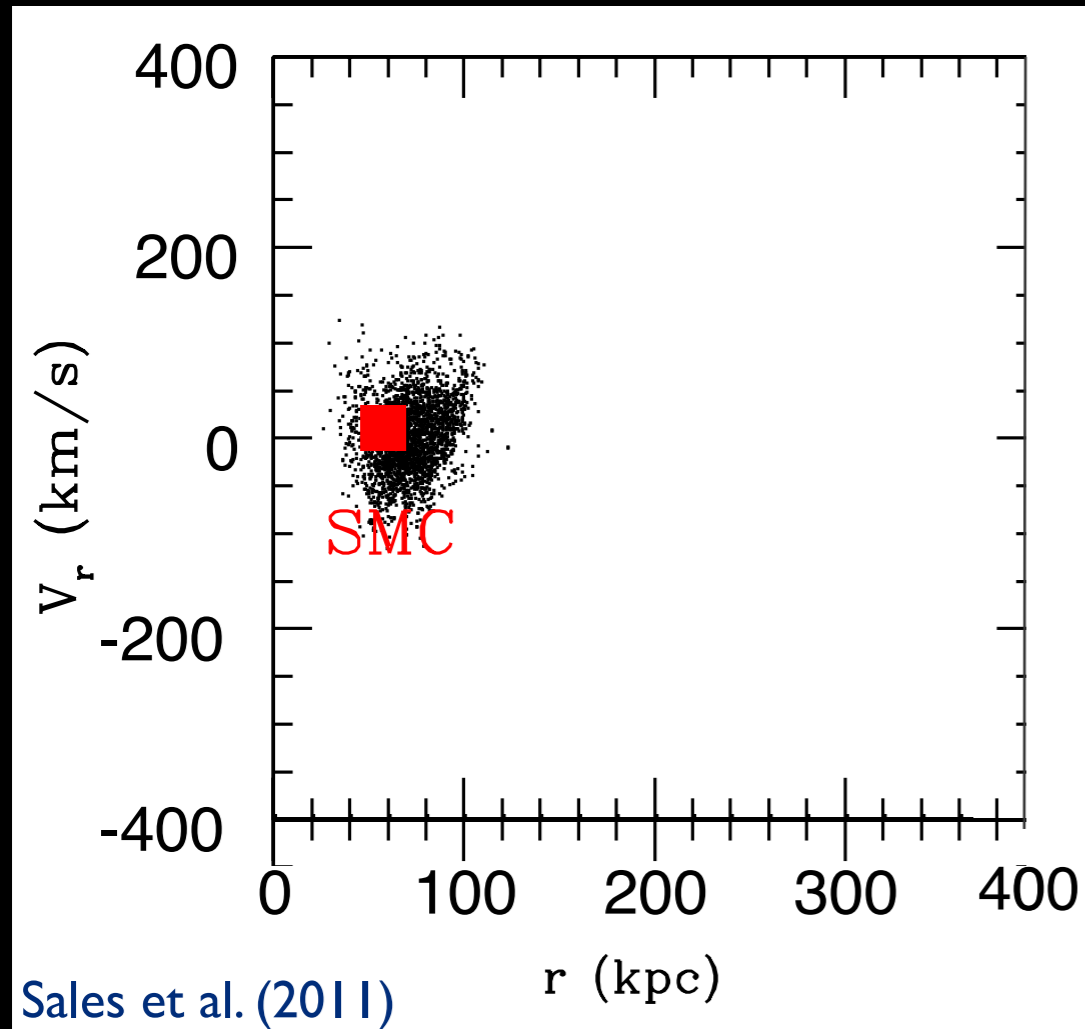
Phase-space distribution of LMC companions



Dwarfs consistent with the LMC group debris

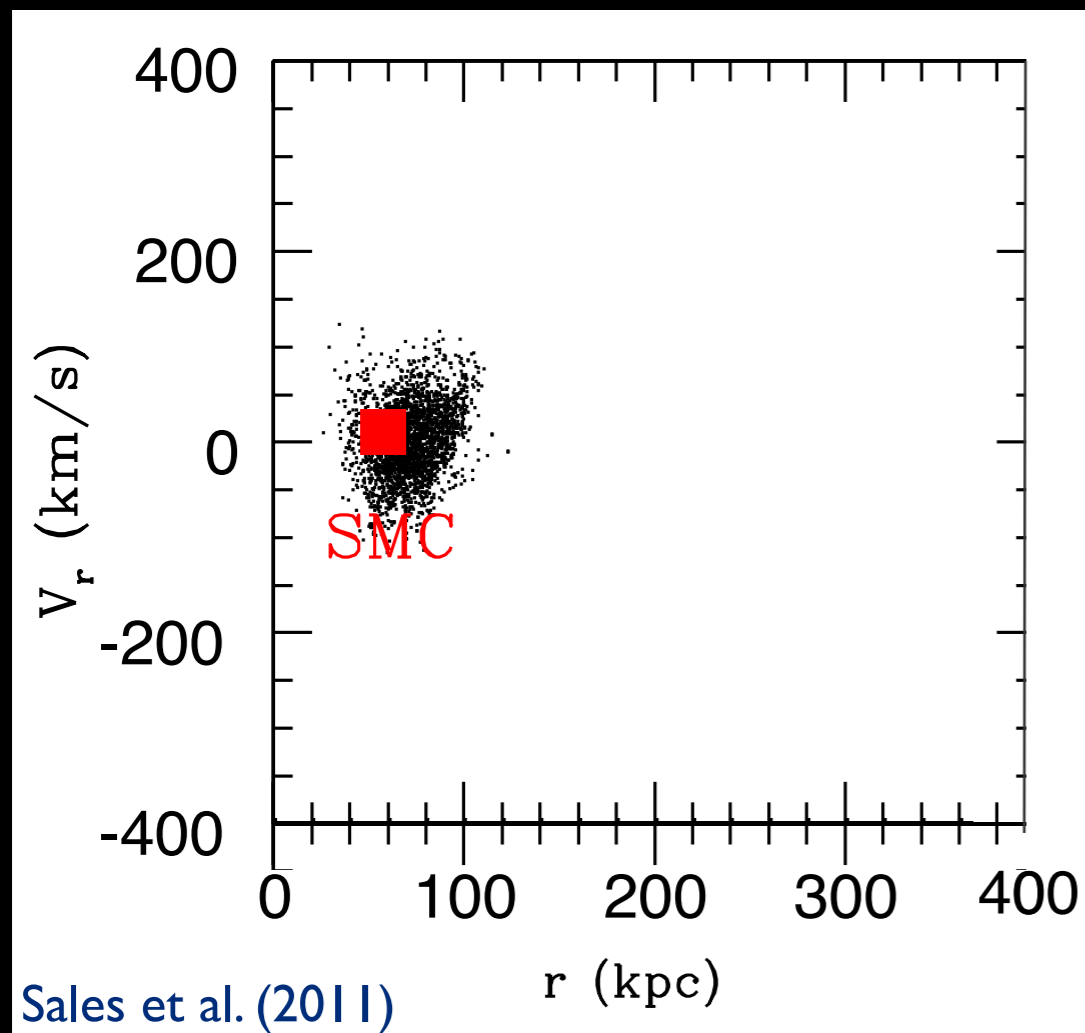


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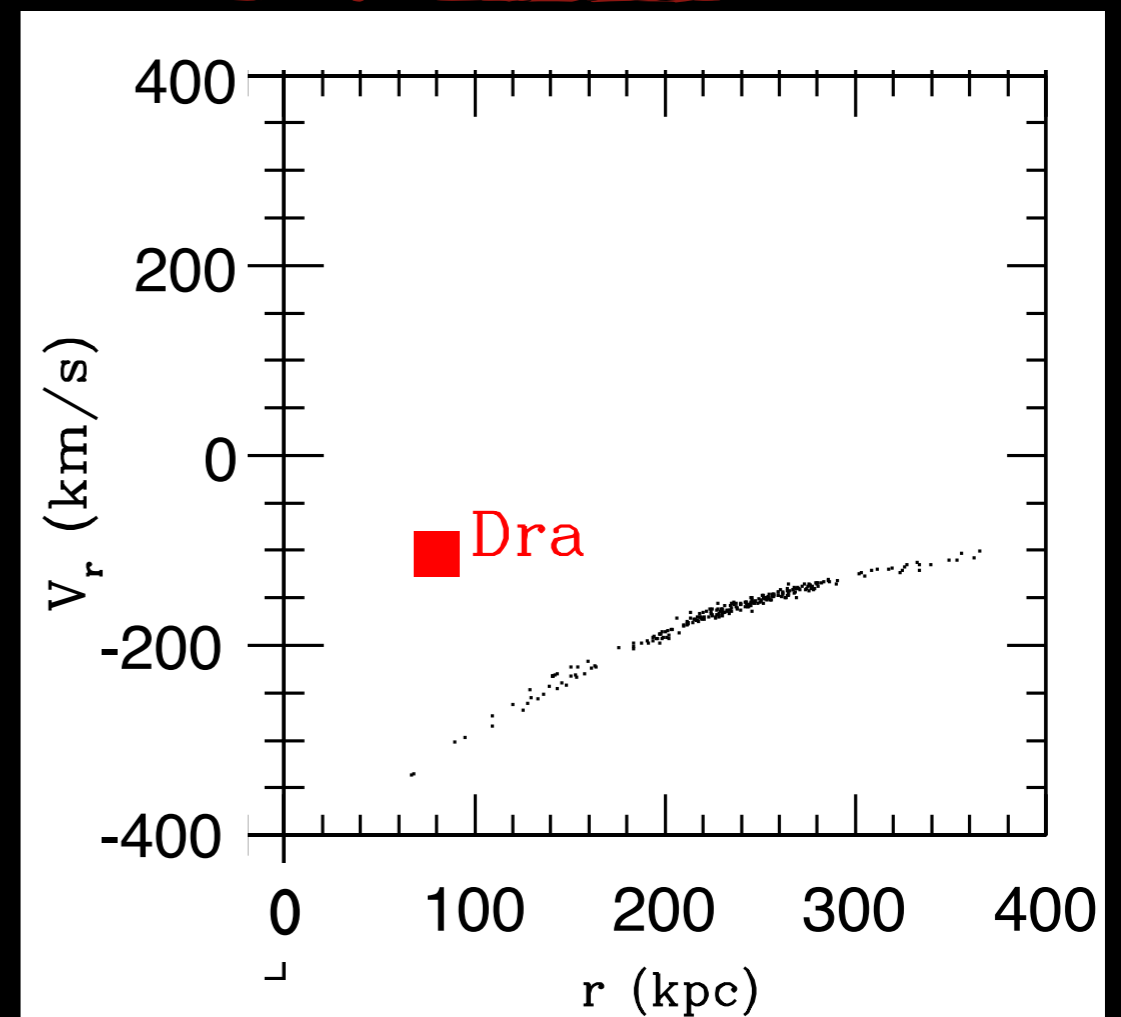


✓ **consistent**

Dwarfs consistent with the LMC group debris

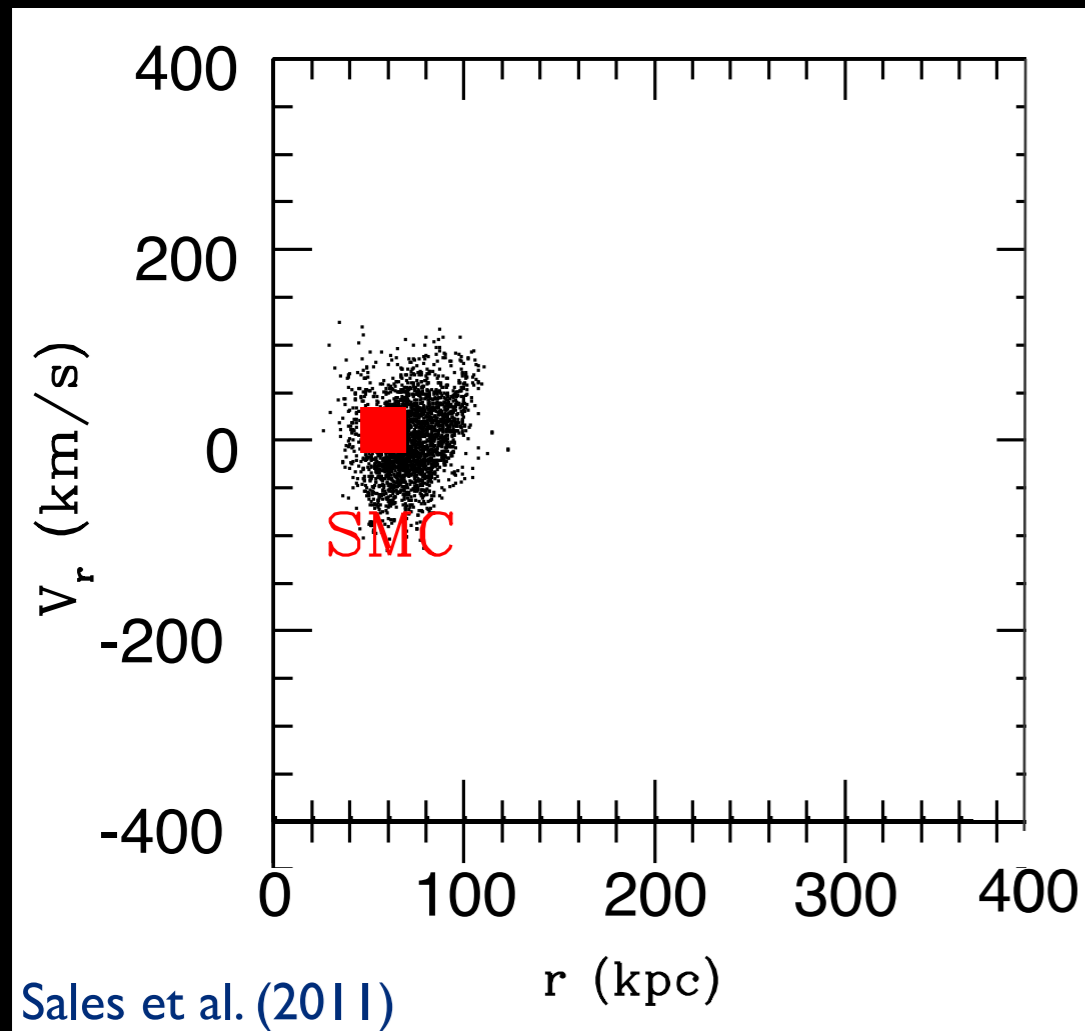


✓ **consistent**

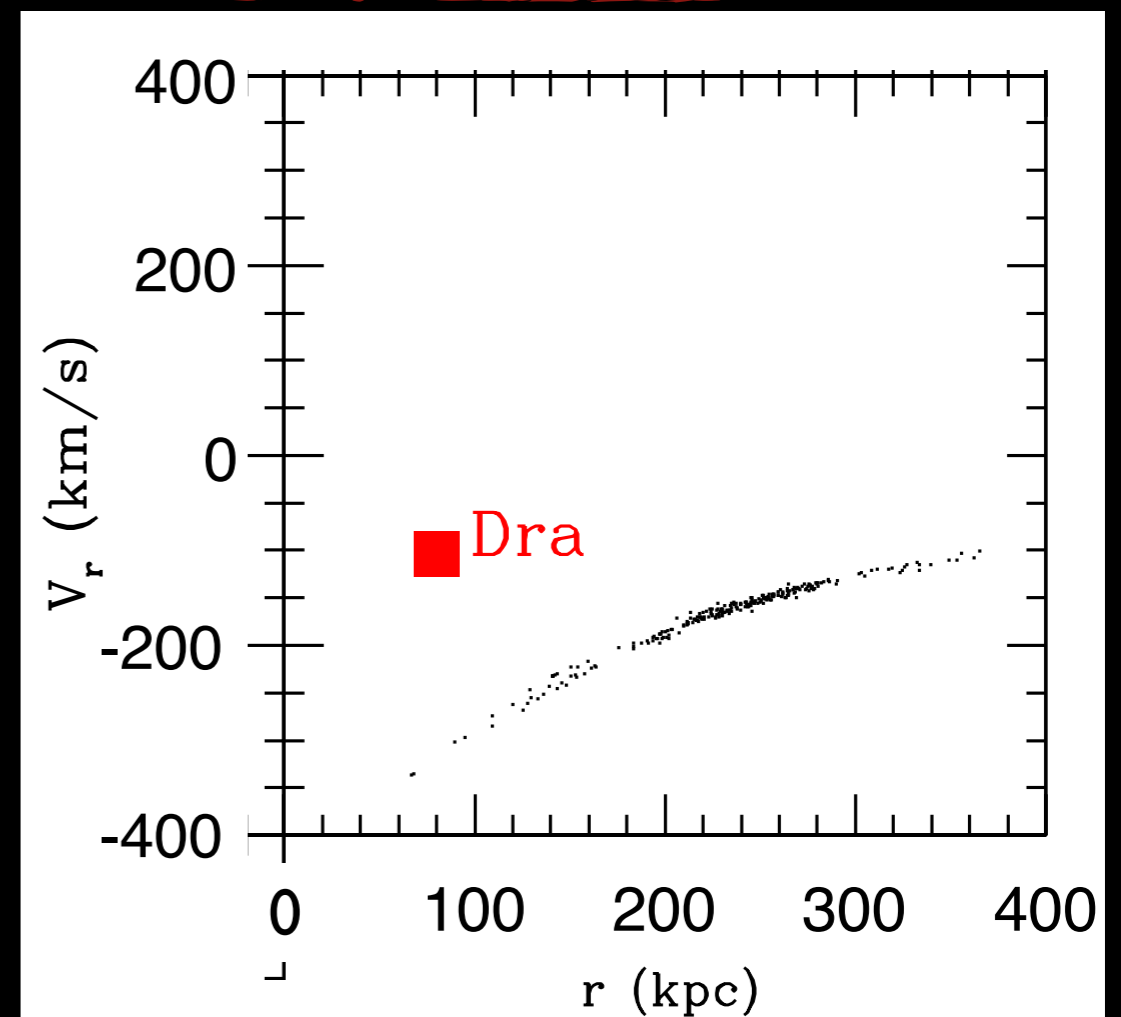


— **inconsistent**

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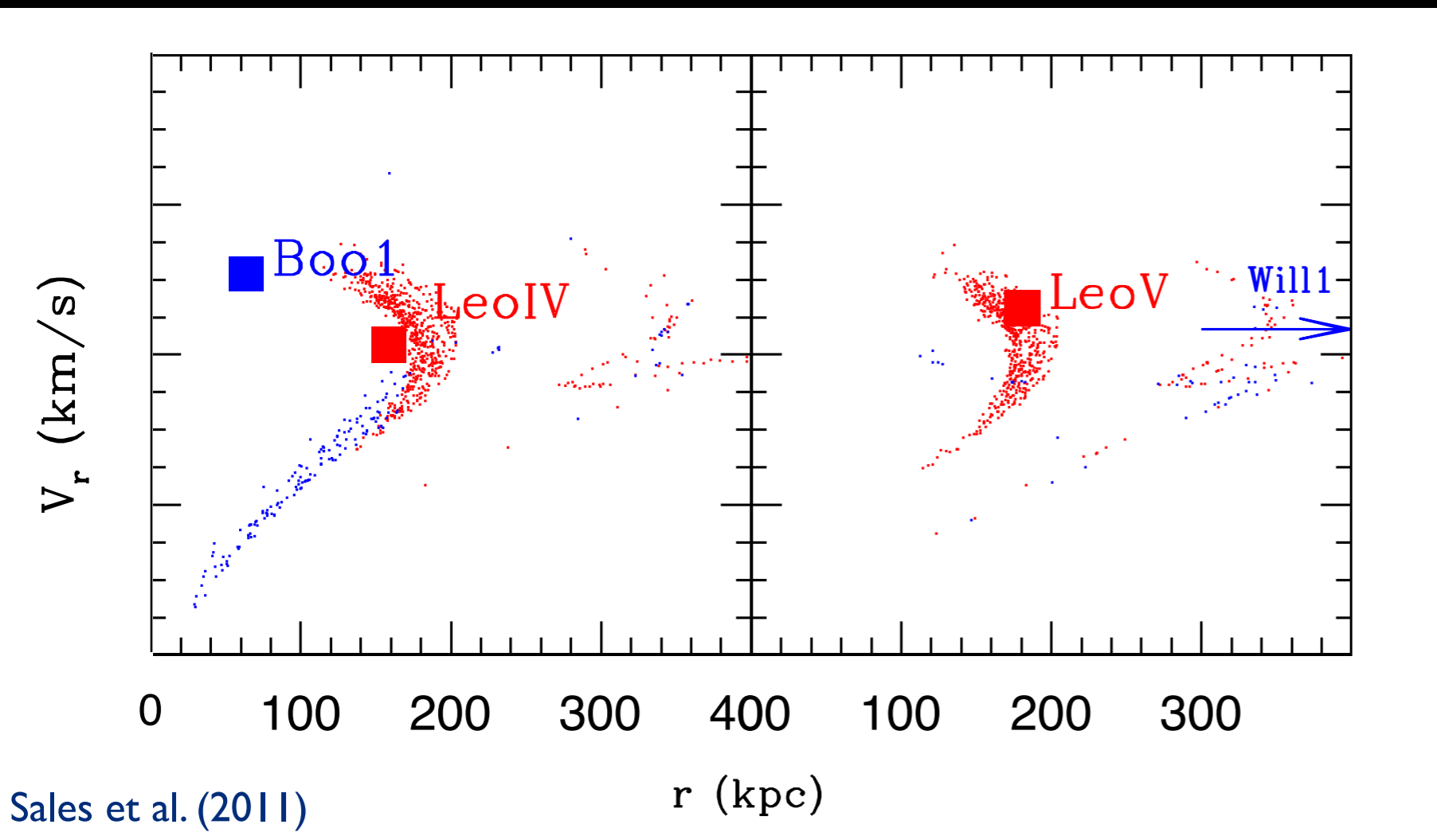


✓ **consistent**



— **inconsistent**

At first pericenter, only Carina & Fornax have reasonable chances of being associated to the Clouds

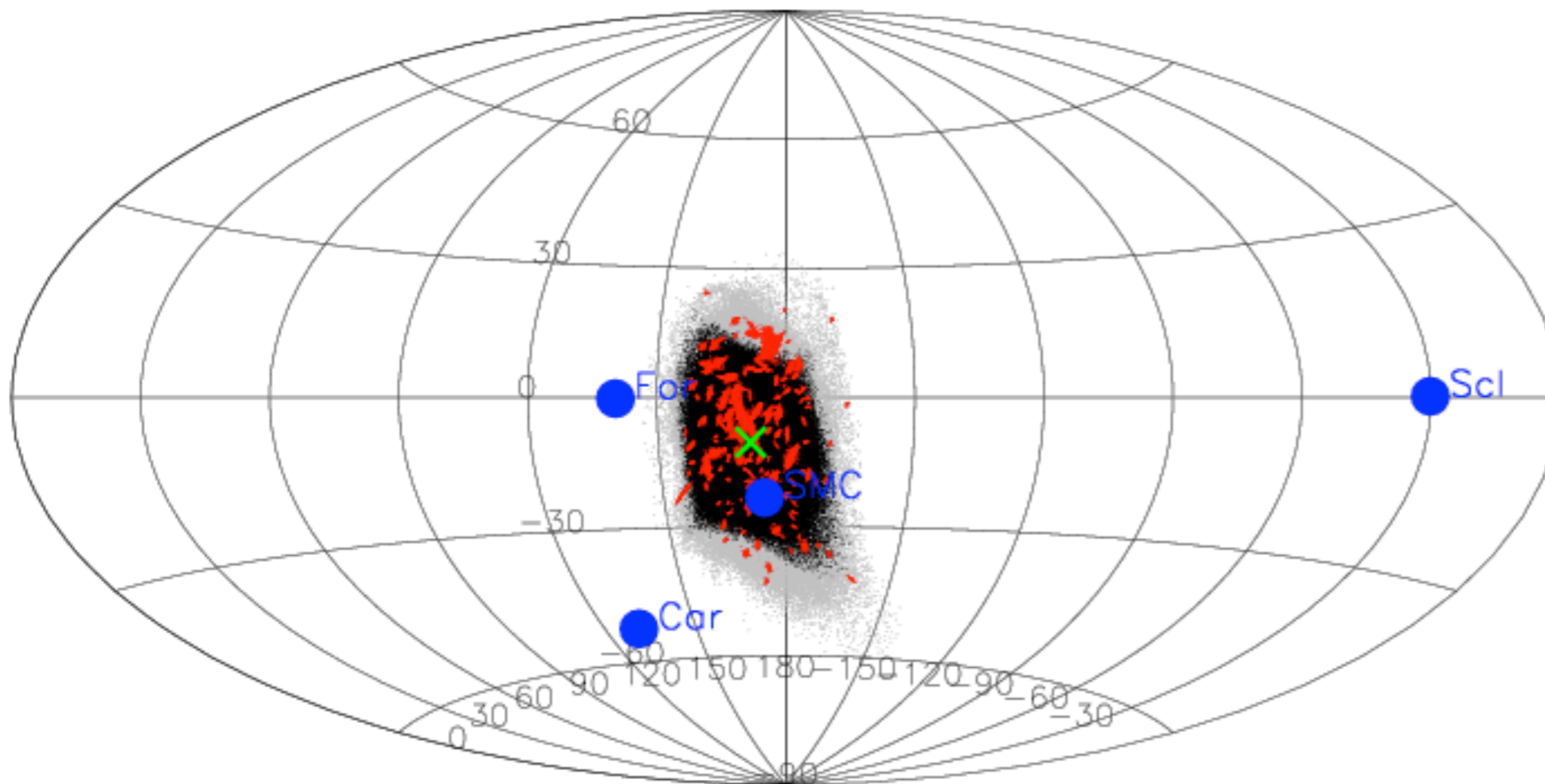


- ✓ Leo IV, Leo V
consistent
- Boo I, Will I
inconsistent

At the second pericenter, a more extended footprint of the LMC group on the sky allows few extra companions, such as CVI, CVII, Leo II, IV, V

Orbital angular momentum

Sales et al. (2011)



First pericenter

The direction of angular momentum of a dwarf might be the cleanest test of association to the Clouds

New/better proper motions can provide more definitive answers

Conclusions

- * Approximately half of the faint isolated dwarfs with measured rotation curves seem to live in halos of lower masses than predicted by the $M_{\text{halo}}-M_{\text{str}}$ relation within ΛCDM .
- * The predicted halo mass for the LMC allows it to infall onto the MW along with several dark and luminous companions.
- * The kinematics of the Clouds can be reconciled with a first or second pericenter passage.
- * Carina and Fornax are consistent with a previous association to the Clouds. If the LMC is on its second approach to the MW, few ultra faint dwarfs qualify as possible companions, such as CVI, CVII, Leo II, LeoIV and LeoV.
- * The surroundings of the Clouds may prove a fertile hunting ground for faint, previously unnoticed MW satellites.