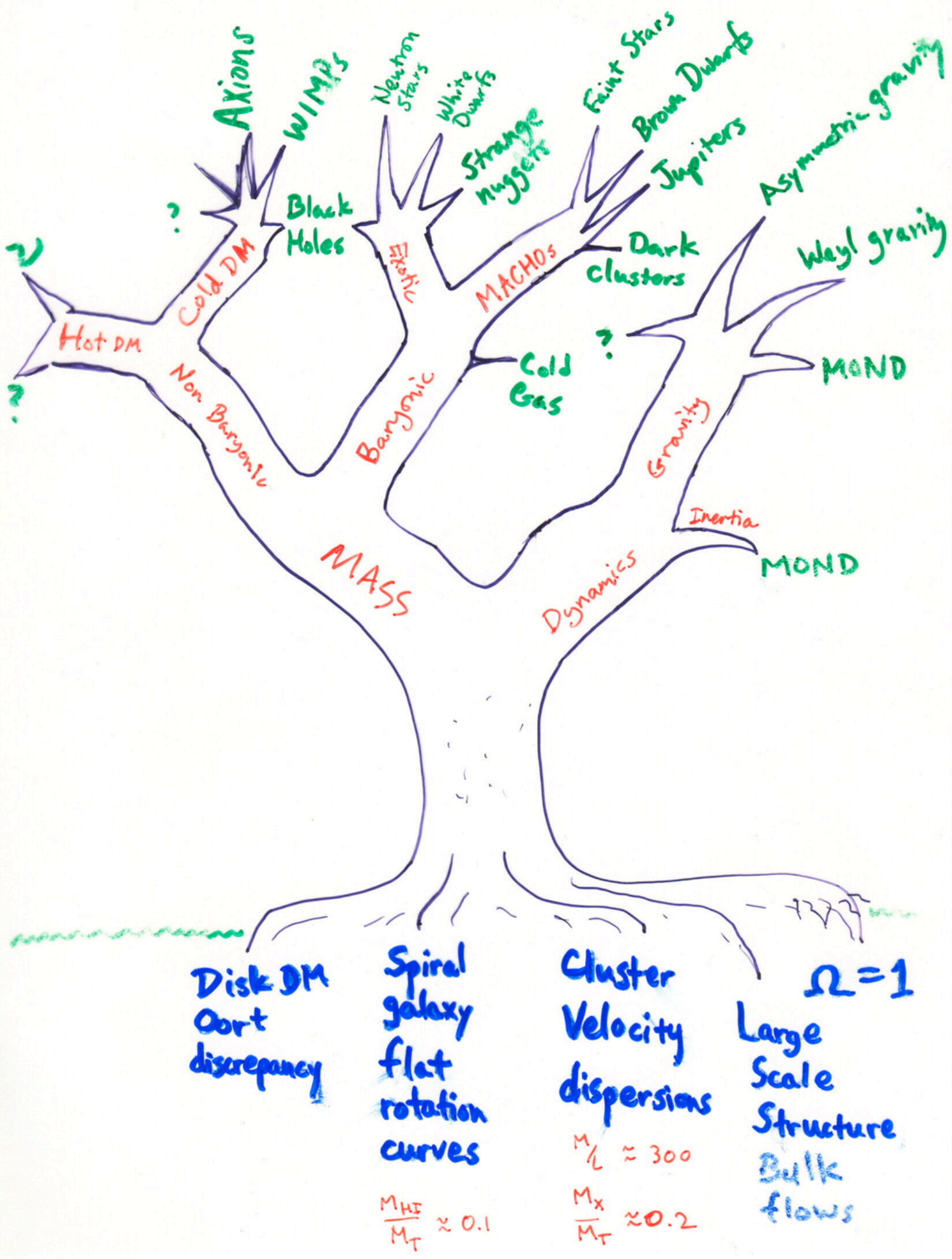
DARK MATTER

ASTR 333/433

TODAY

BIG TROUBLE AT SMALL SCALES
CUSP/CORE
MISSING SATELLITES
TOO BIG TO FAIL
SATELLITE PLANES



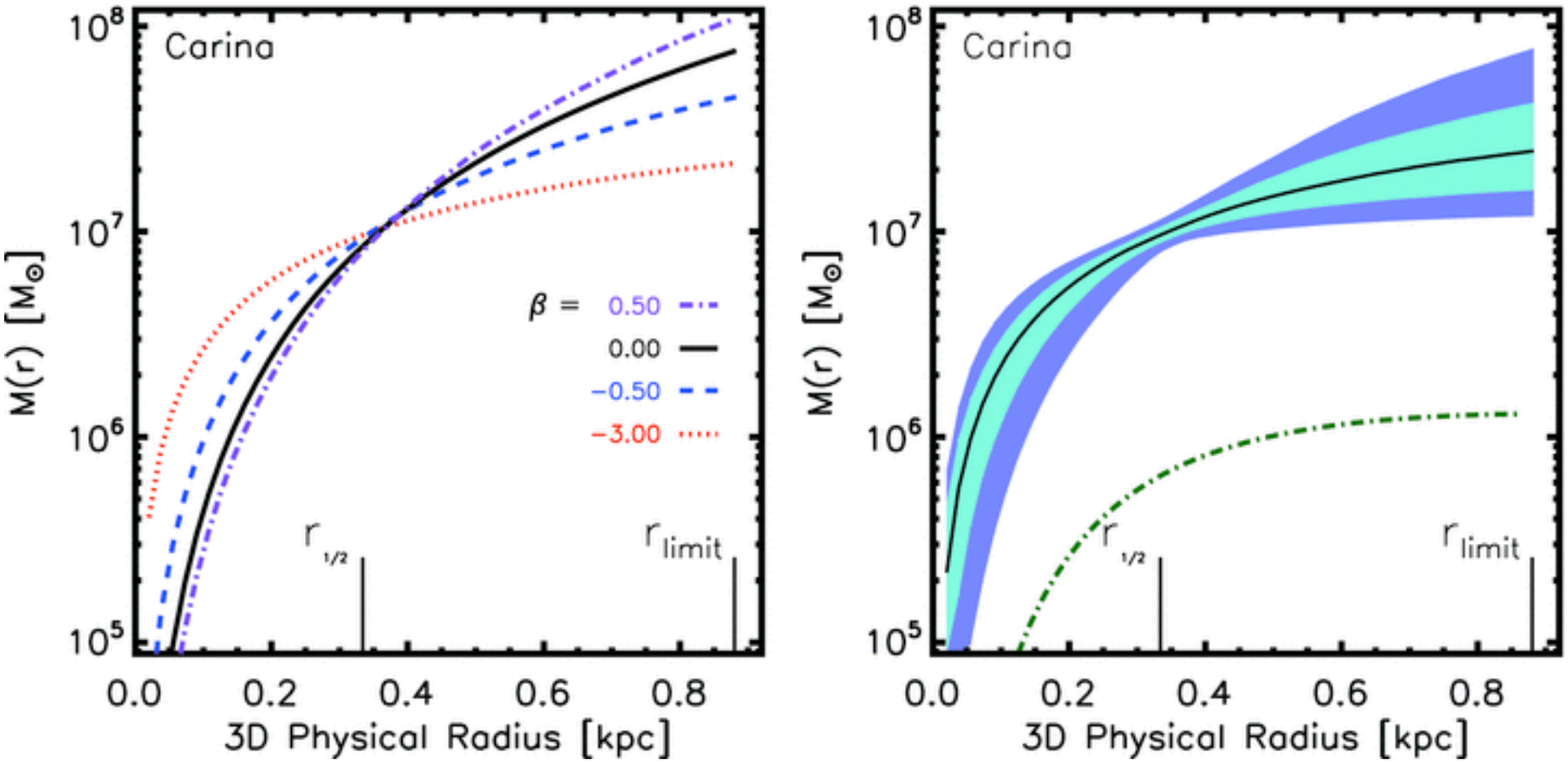
Dwarf satellite galaxies are problematic for CDM in several ways:

- Missing Satellites
  - should be thousands rather than dozens
- Cusp/core problem
  - dark matter halos lack central cusps
- Too Big To Fail
  - dearth of intermediate mass satellites
- Satellite Planes
  - satellites tend to reside in narrow, co-orbiting planes

Cusp/Core Problem

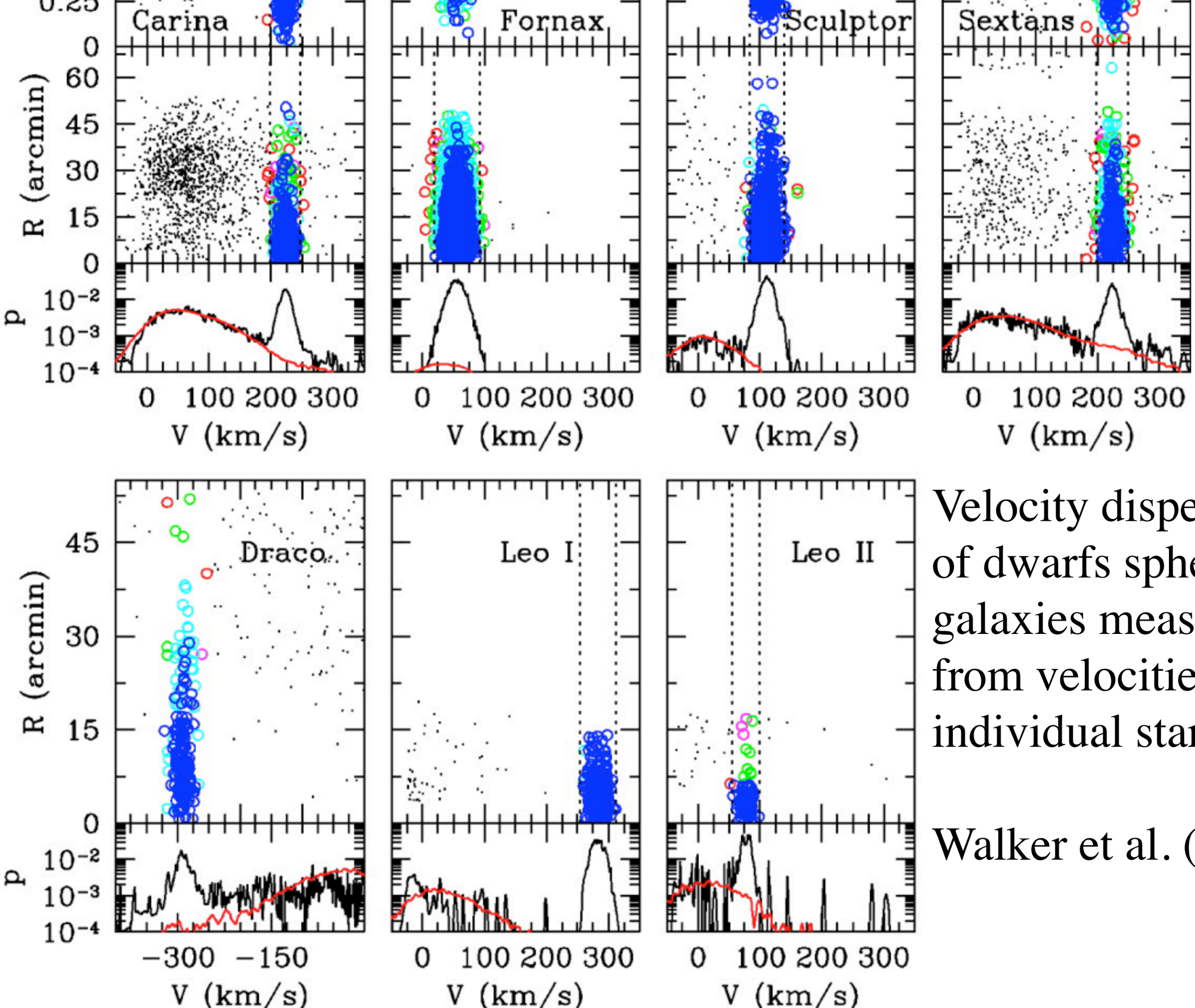
in Local Group dwarf spheroidals

Wolf et al. (2010)



$$M(r) = \frac{r\sigma_r^2}{G}(\gamma_* + \gamma_\sigma - 2\beta)$$

β is the anisotropy parameter

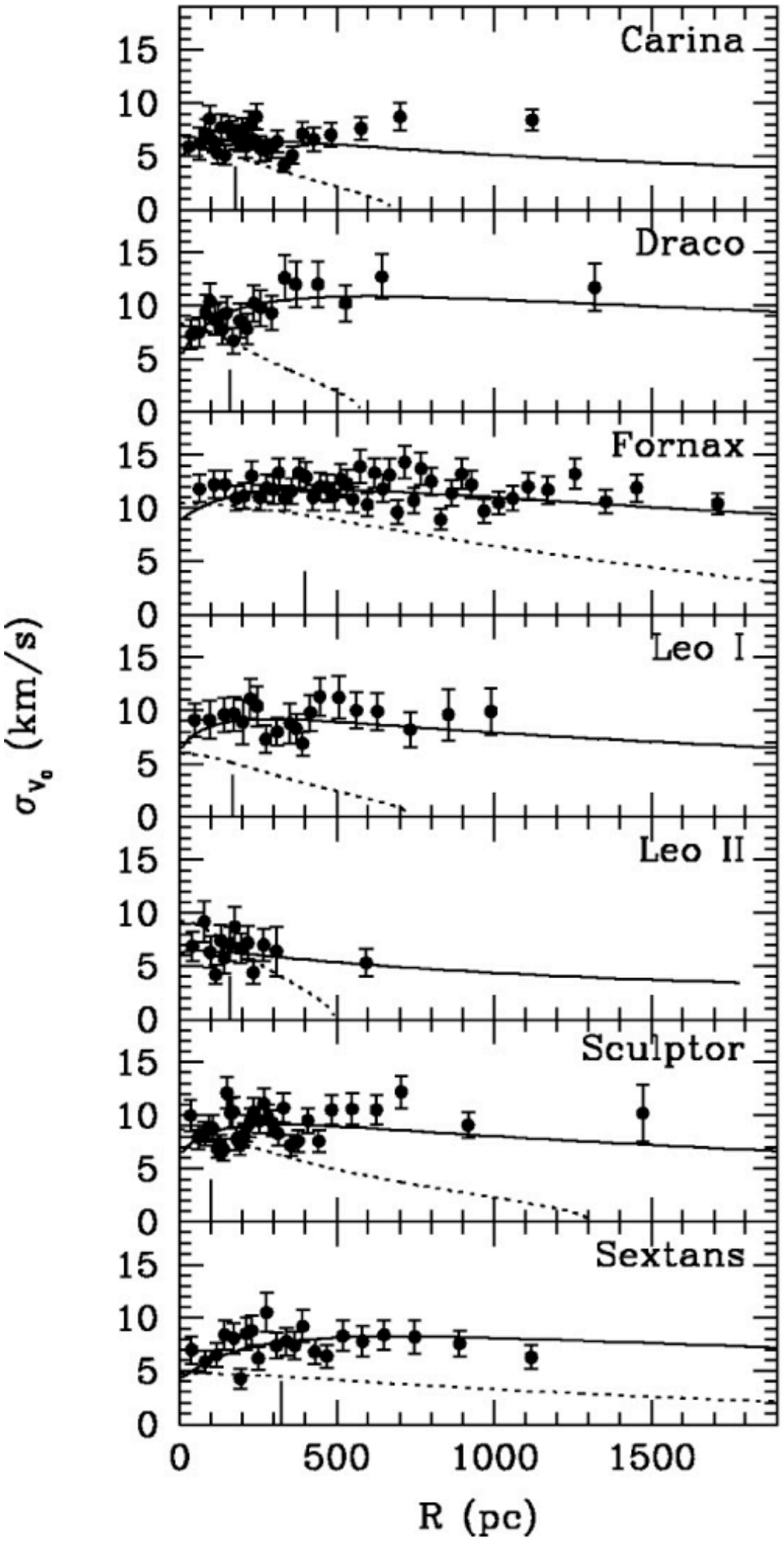


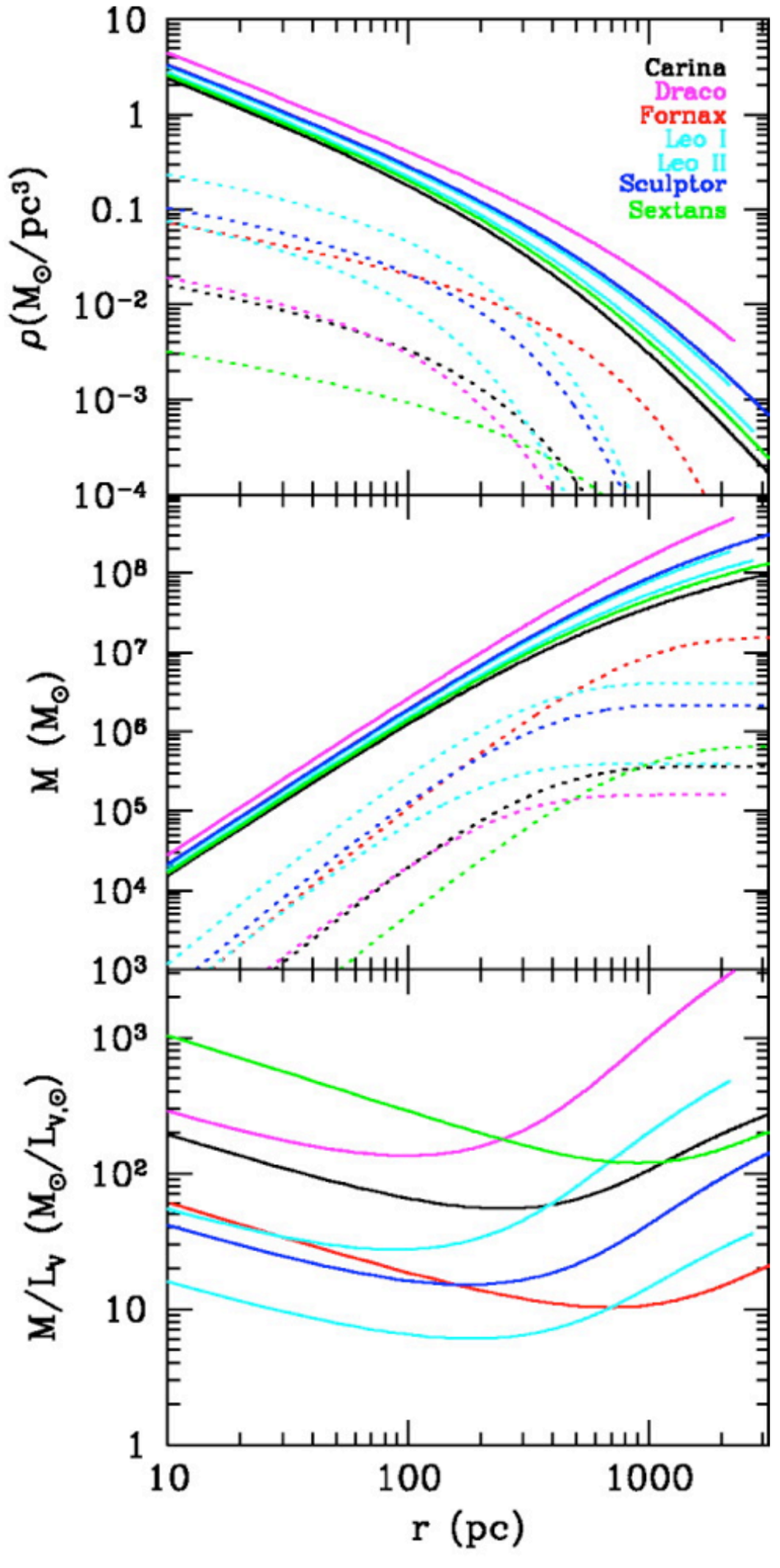
Velocity dispersions of dwarfs spheroidal galaxies measured from velocities of individual stars.

Walker et al. (2007)

Velocity dispersion profiles of dwarfs spheroidal galaxies approximately flat.

Walker et al. (2007)





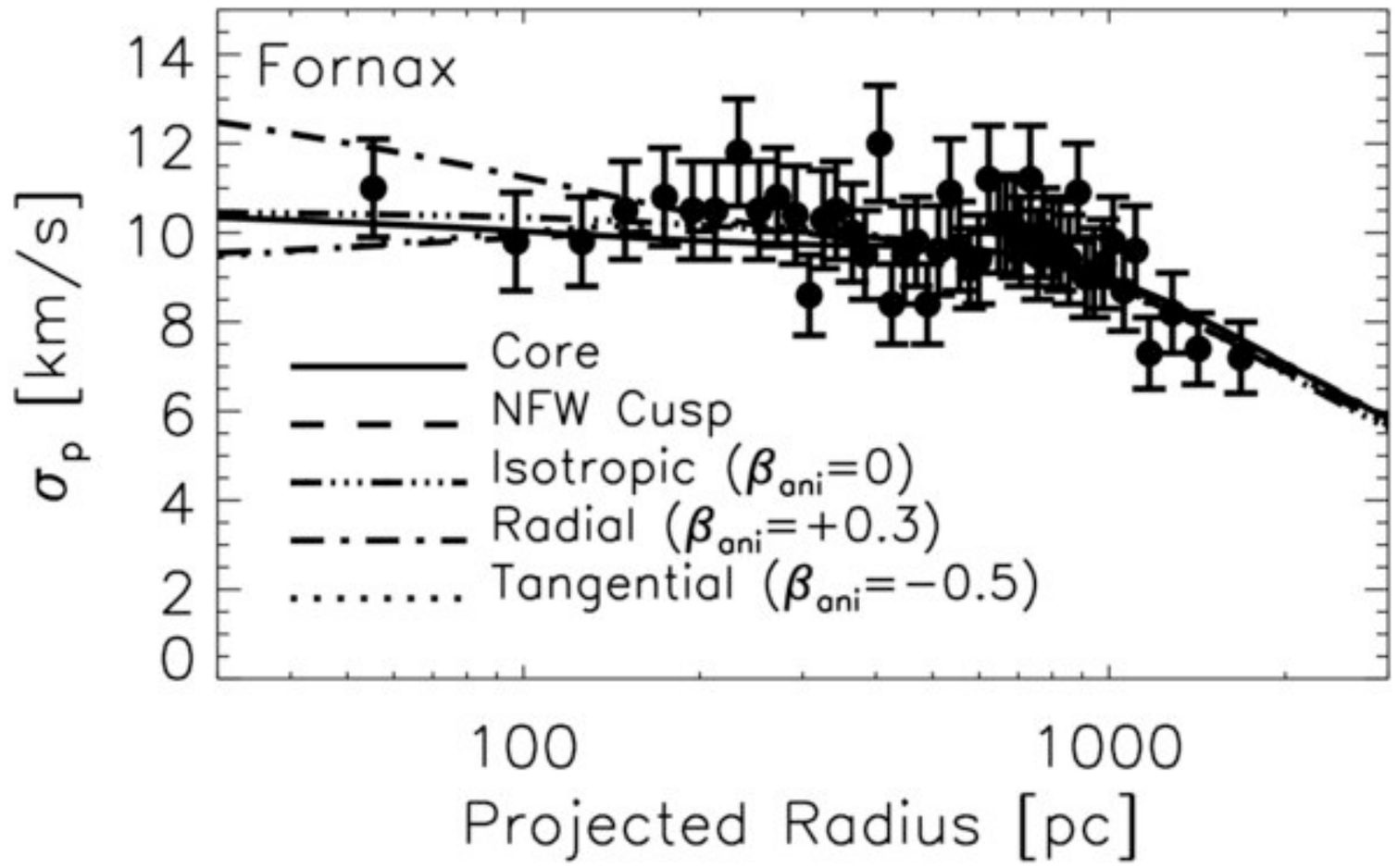
Walker & Penarrubia (2011) find that dSph galaxies suffer the same cusp-core problem as found in rotating low surface brightness galaxies

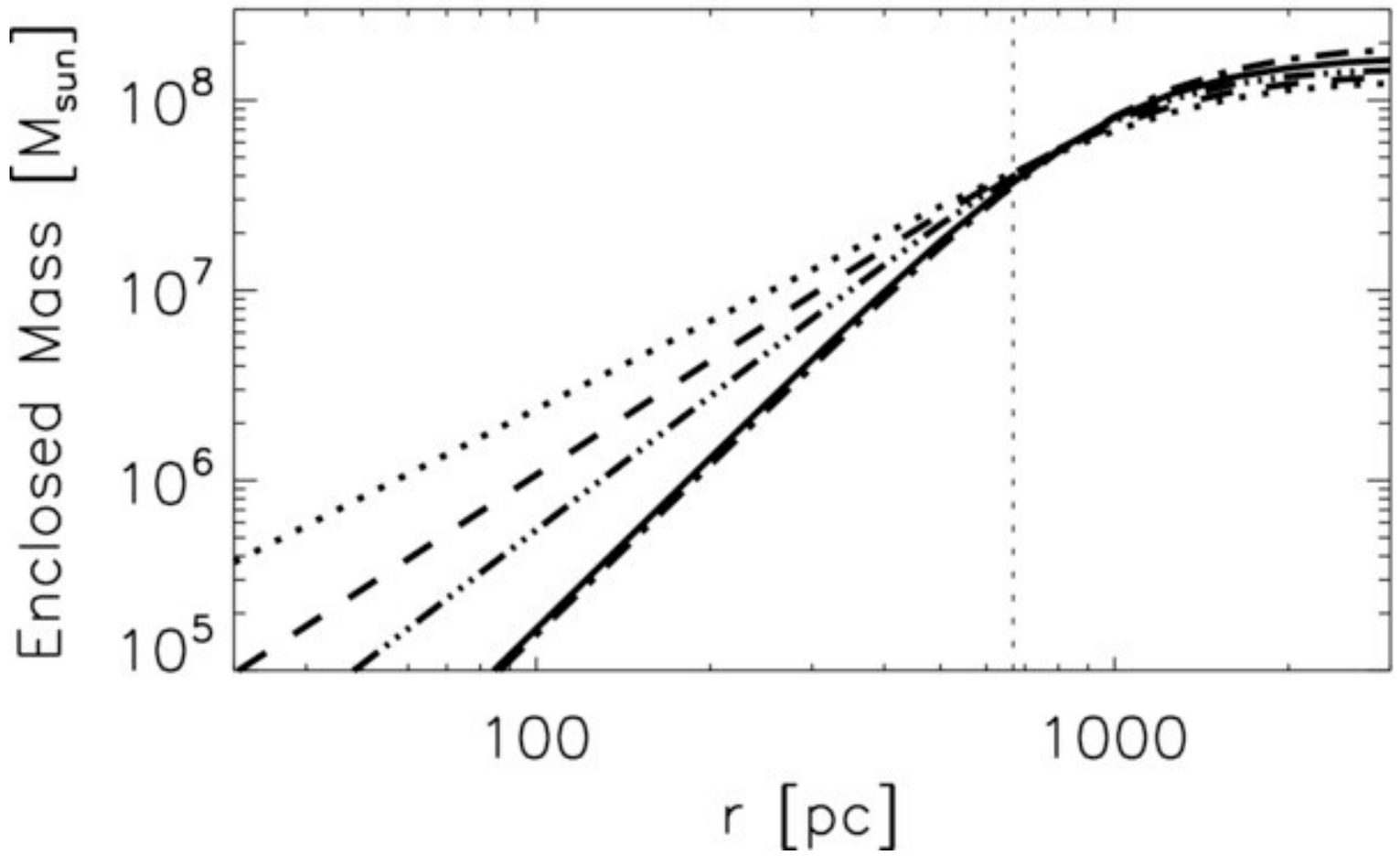
$$\rho \sim r^{-\gamma}$$

$\gamma = 0.39$ Fornax

$\gamma = 0.05$ Sculptor

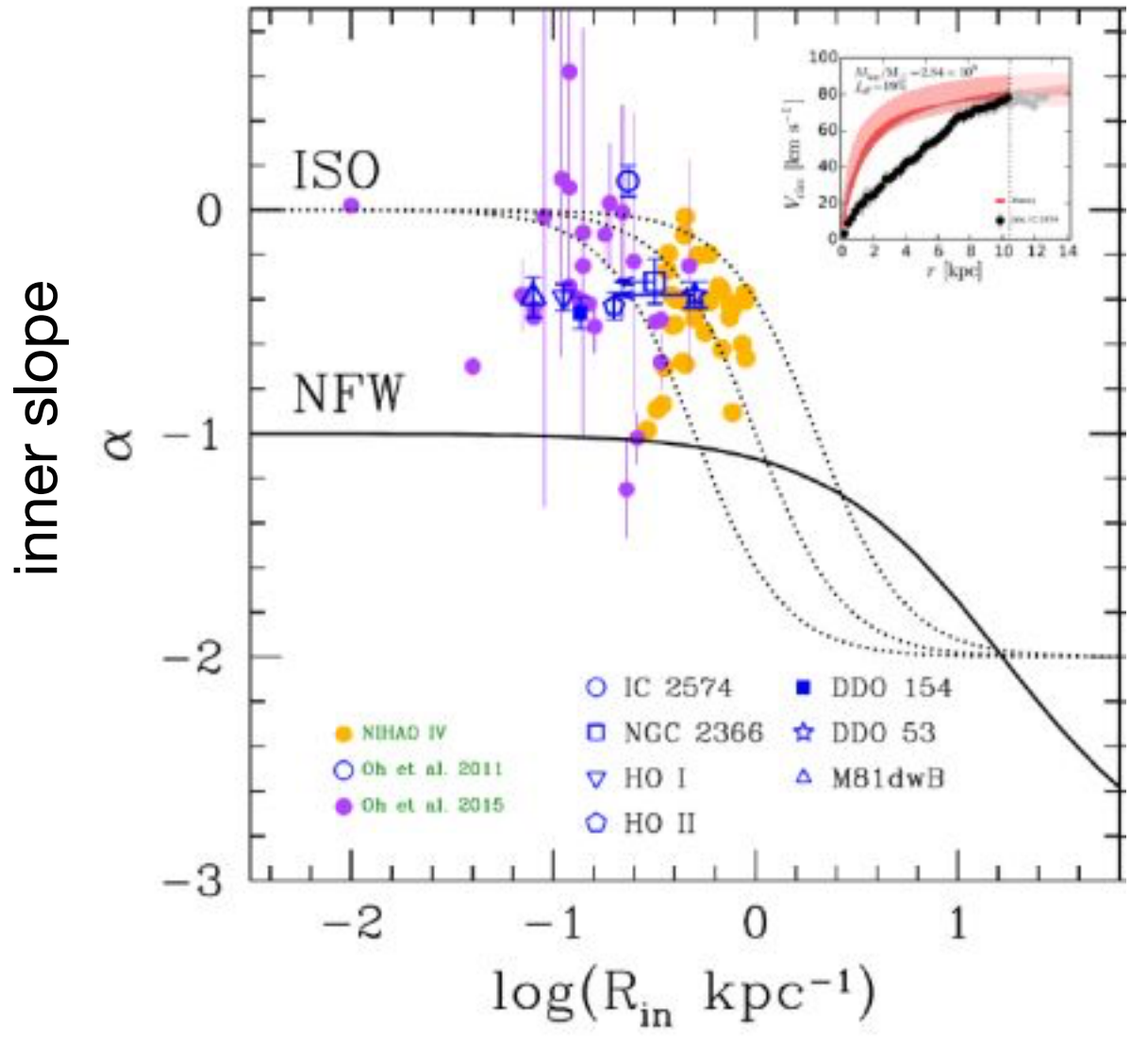
$$\left[\begin{array}{ll} \gamma = 1 & \text{cusp} \\ \gamma = 0 & \text{core} \end{array} \right]$$





The cusp-core problem
in rotating low surface
brightness galaxies -
not just a problem in satellites

Bosma (2017)
https://ned.ipac.caltech.edu/level5/March17/Bosma/Bosma_contents.html

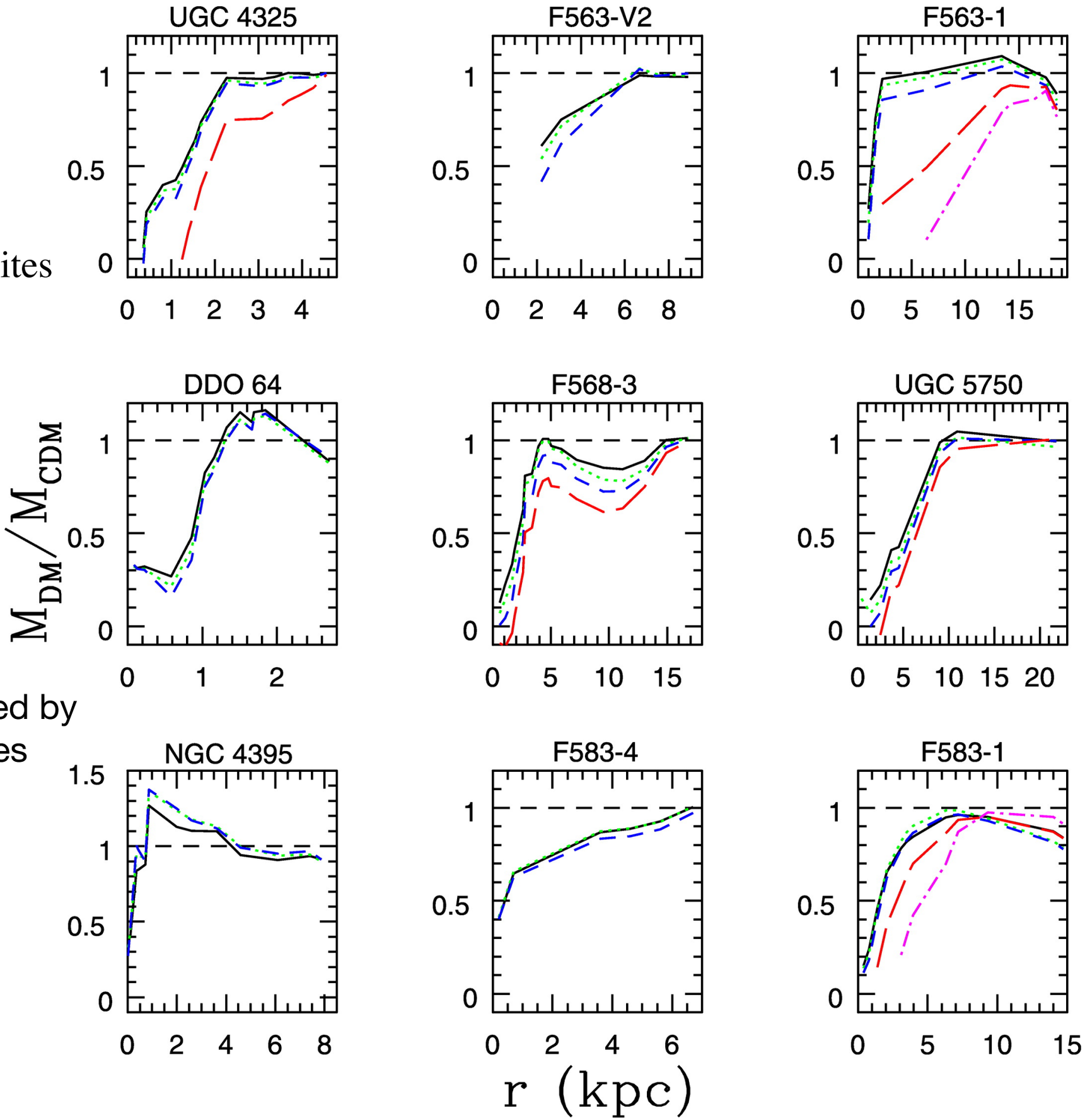


Inner slope α in
$\rho \propto r^{\alpha}$ as $r \to 0$.

innermost measured radius

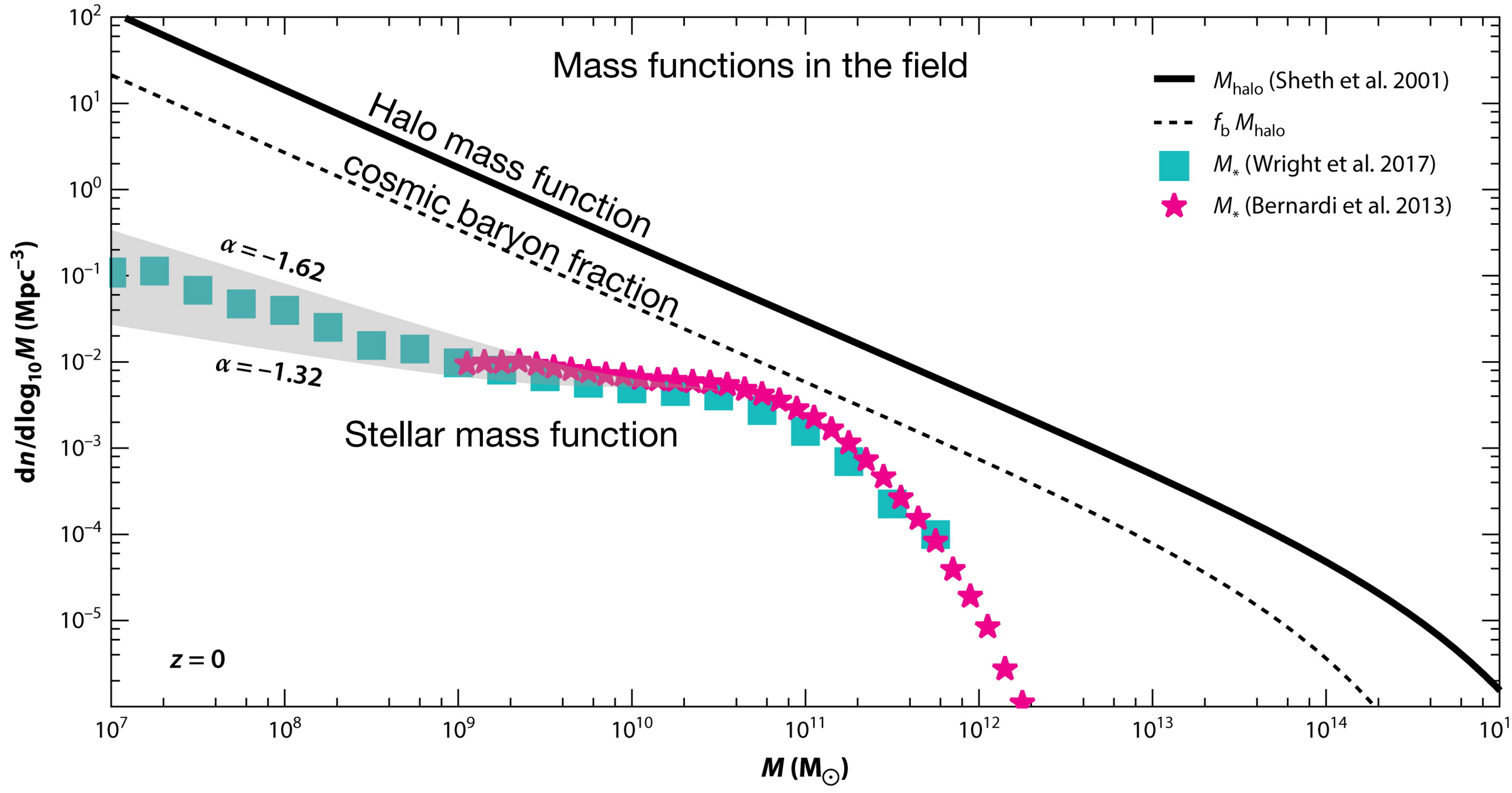
The cusp-core problem
in rotating low surface
brightness galaxies -
not just a problem in satellites

central mass over-predicted by
a factor of ~2 in most cases



Missing Satellites

Same problem as with the field luminosity function:
Too few faint things. Can extend to much lower mass locally.



Bullock JS, Boylan-Kolchin M. 2017.
Annu. Rev. Astron. Astrophys. 55:343–87

$$f_* = \frac{M_*}{M_{200}} \quad \text{varies with M}*$$

Missing Satellites

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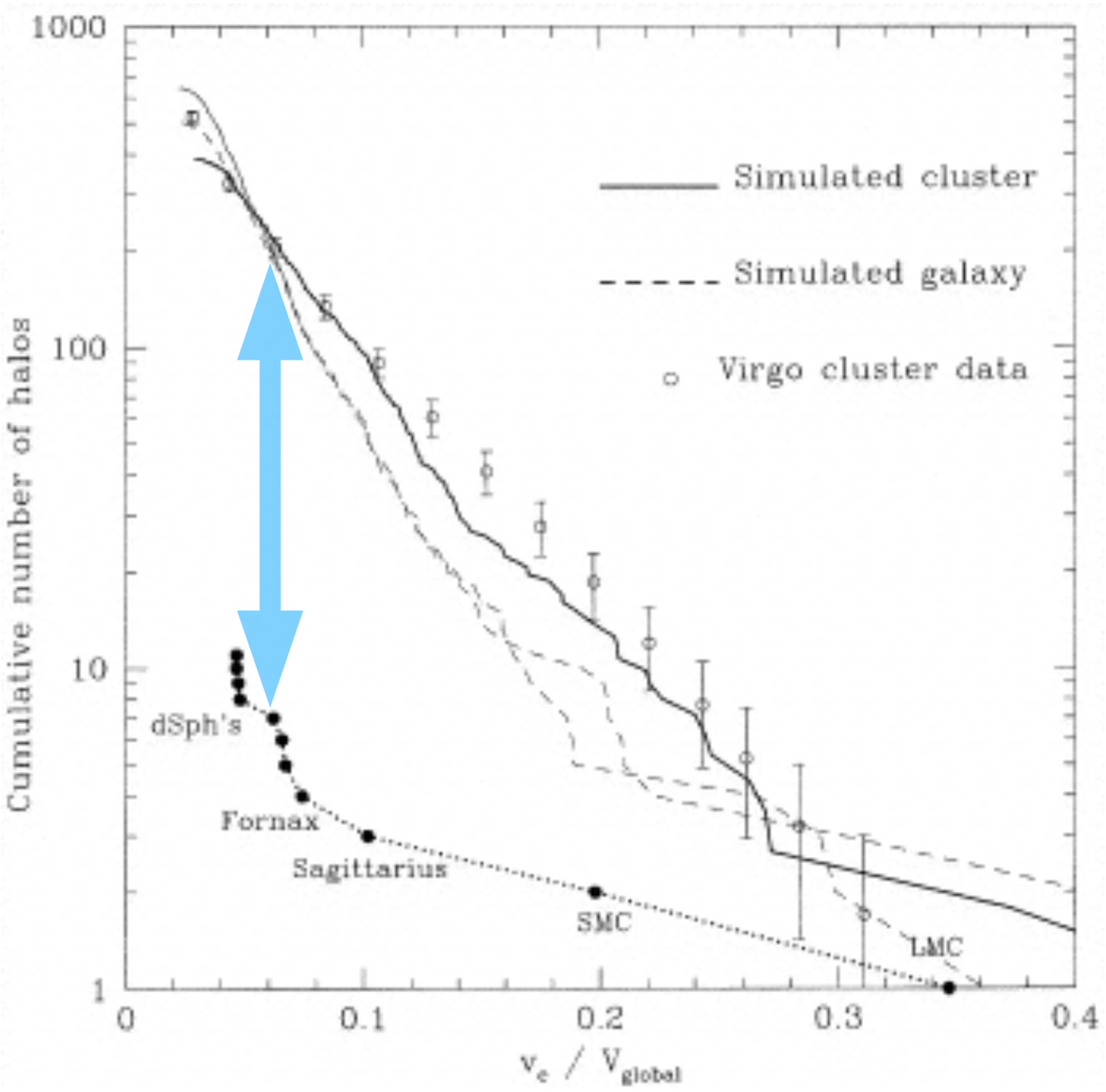
Too few faint things. Can extend to much lower mass locally.

e.g., Moore et al. (1999); Klypin et al. (1999)



N

V_c/V_{parent}

CDM is scale free

The Local Group

does not look like a simulated dark matter halo

≠

The Local Group is typical - see the same thing elsewhere

NGC 6946

one degree

see all the dwarf galaxies?

KK98-250

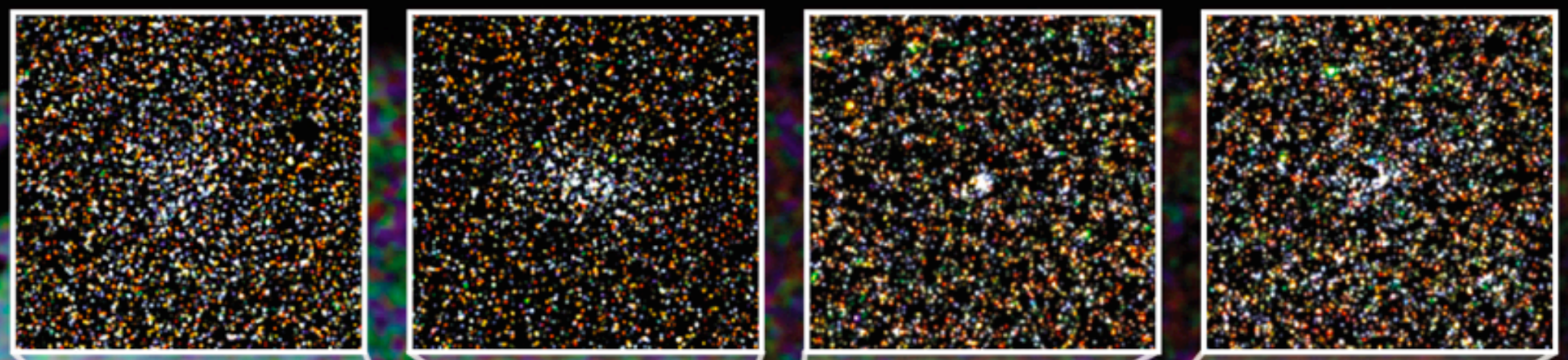
KK98-251

~ 70 kpc

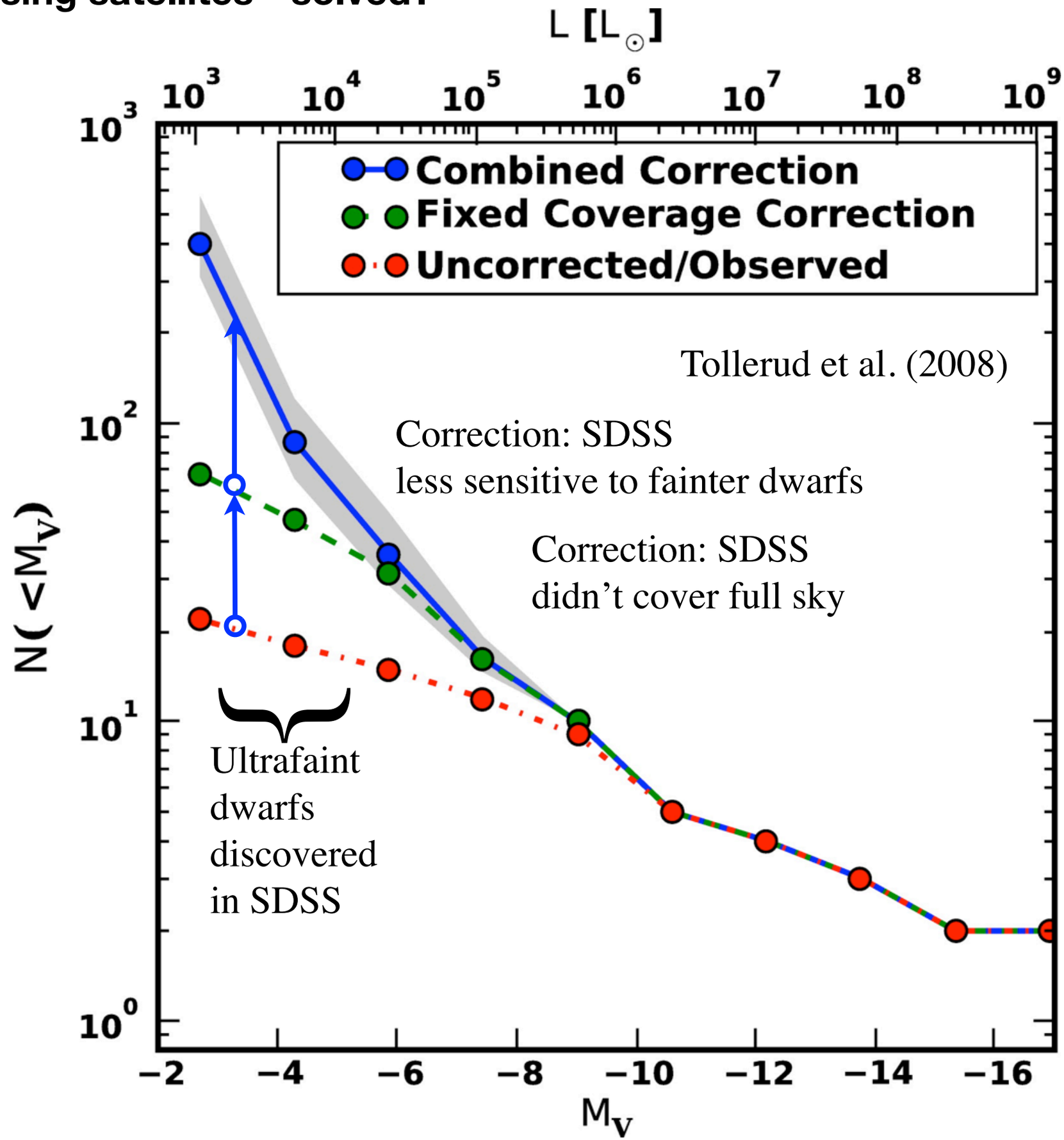
NGC 6946

Gets better with recent discoveries, but is it enough?

Ultrafaint dwarf satellite galaxies discovered by SDSS

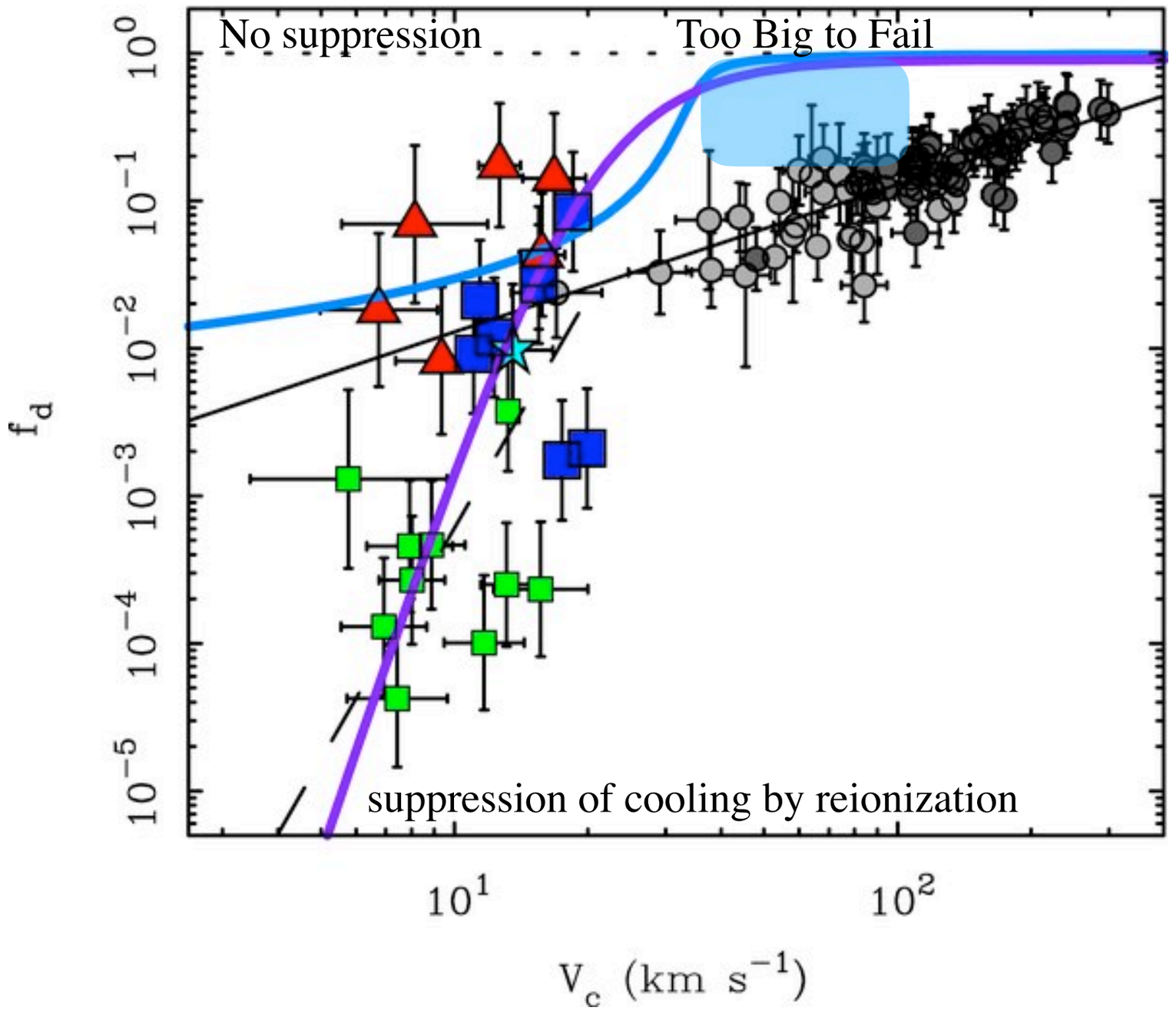


Milky Way Missing satellites - solved?



Too Big to Fail?

Many models can be invoked to suppress galaxy formation in small dark matter halos; is harder to prevent in mid-size halos.

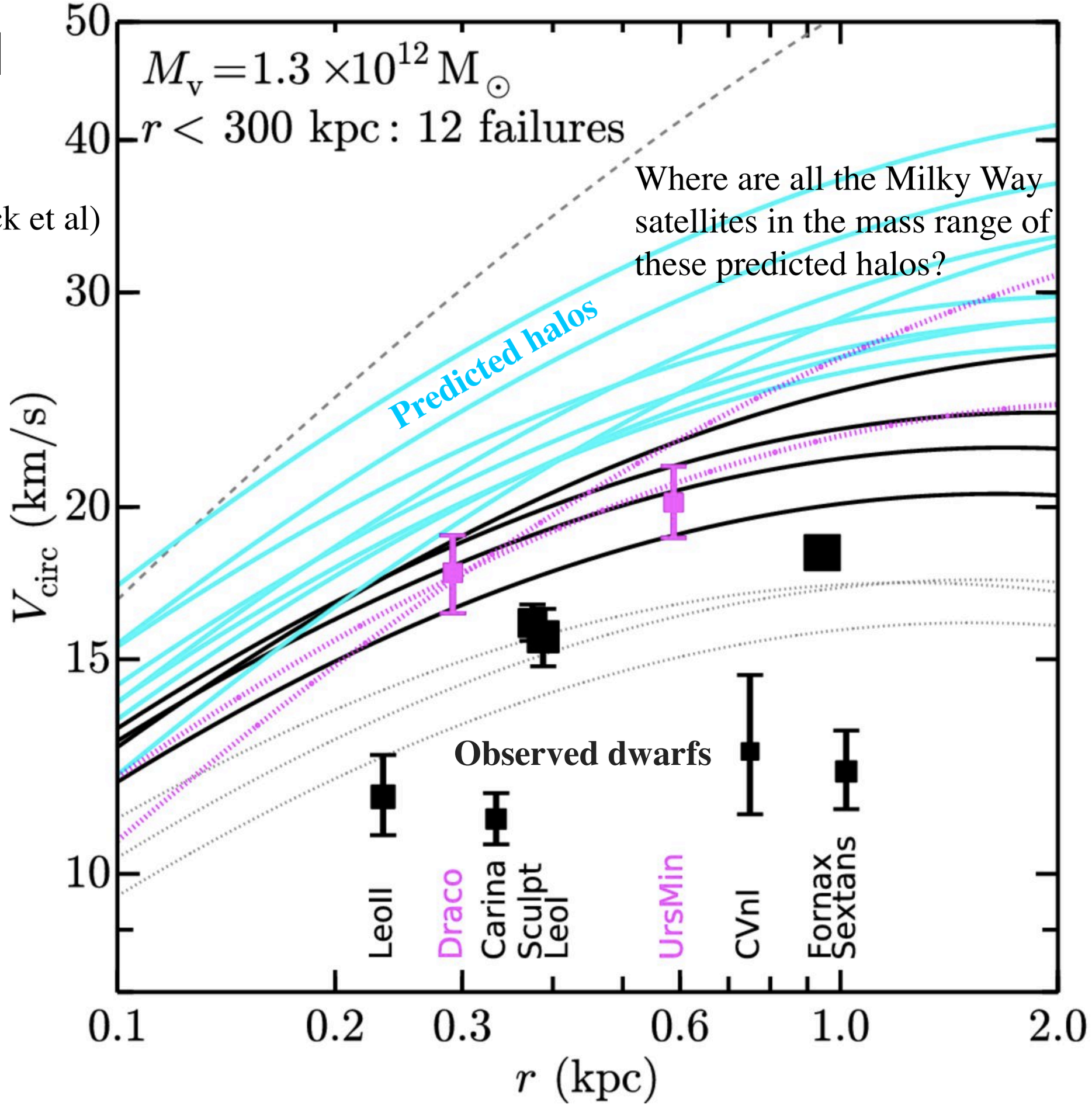


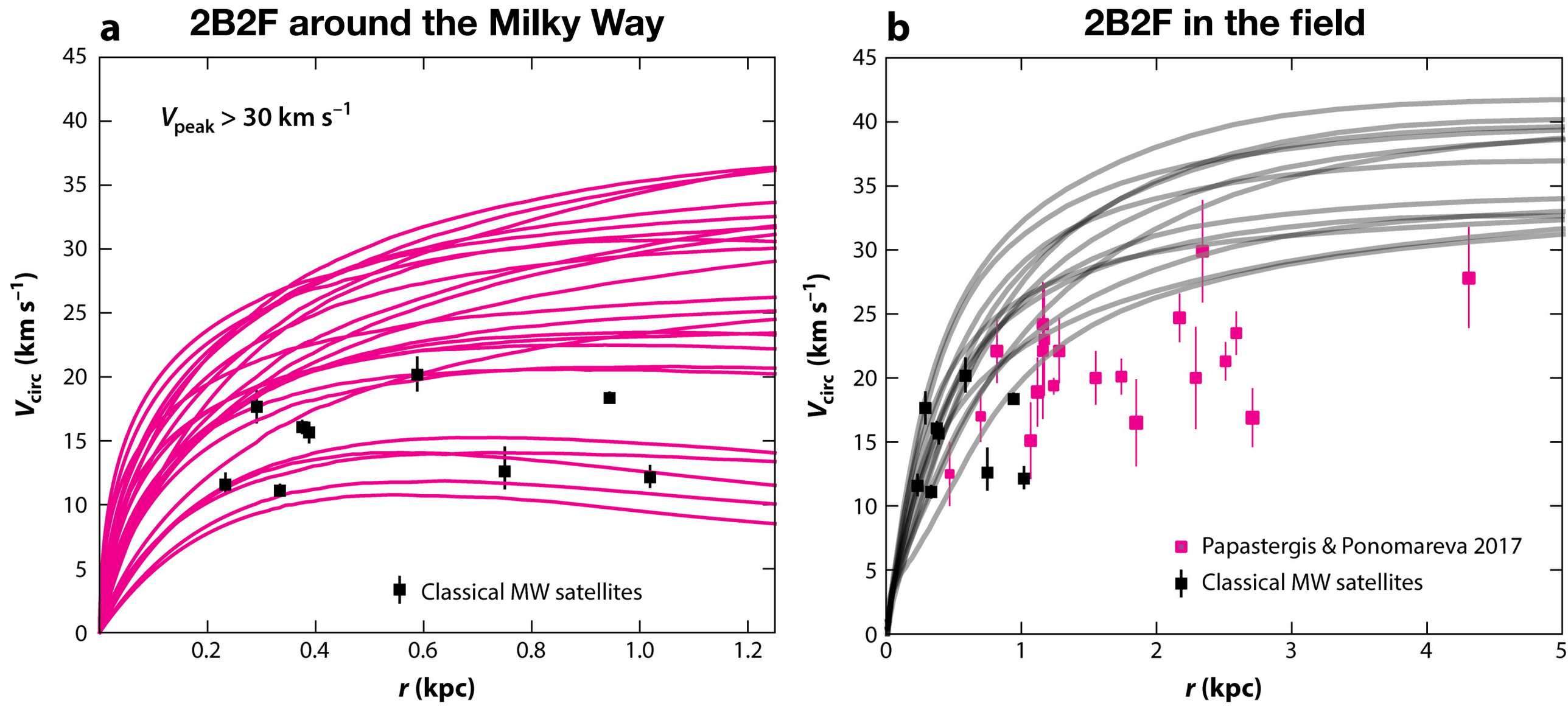
e.g., Reionization models illustrated here are good for explaining the smallest galaxies, but not ~40 km/s halos, which are too big to fail.

Too Big To Fail

(Bovill & Ricotti;
Boylan-Kochlin & Bullock et al)

LCDM models predict many sub-halos that are denser & more massive than the observed dwarf satellites. If the little sub-halos managed to make dwarfs, why didn't these bigger ones?





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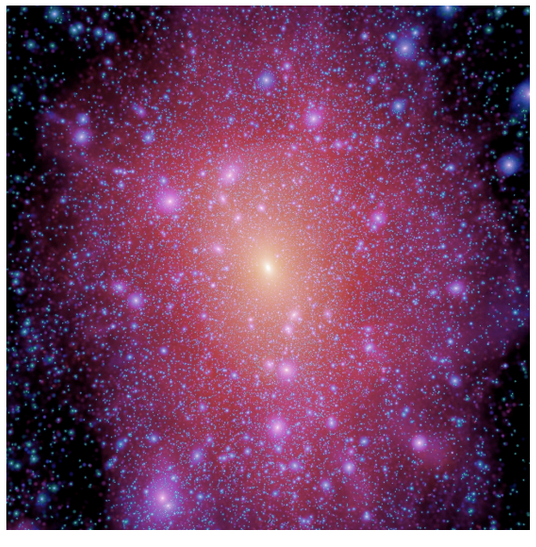
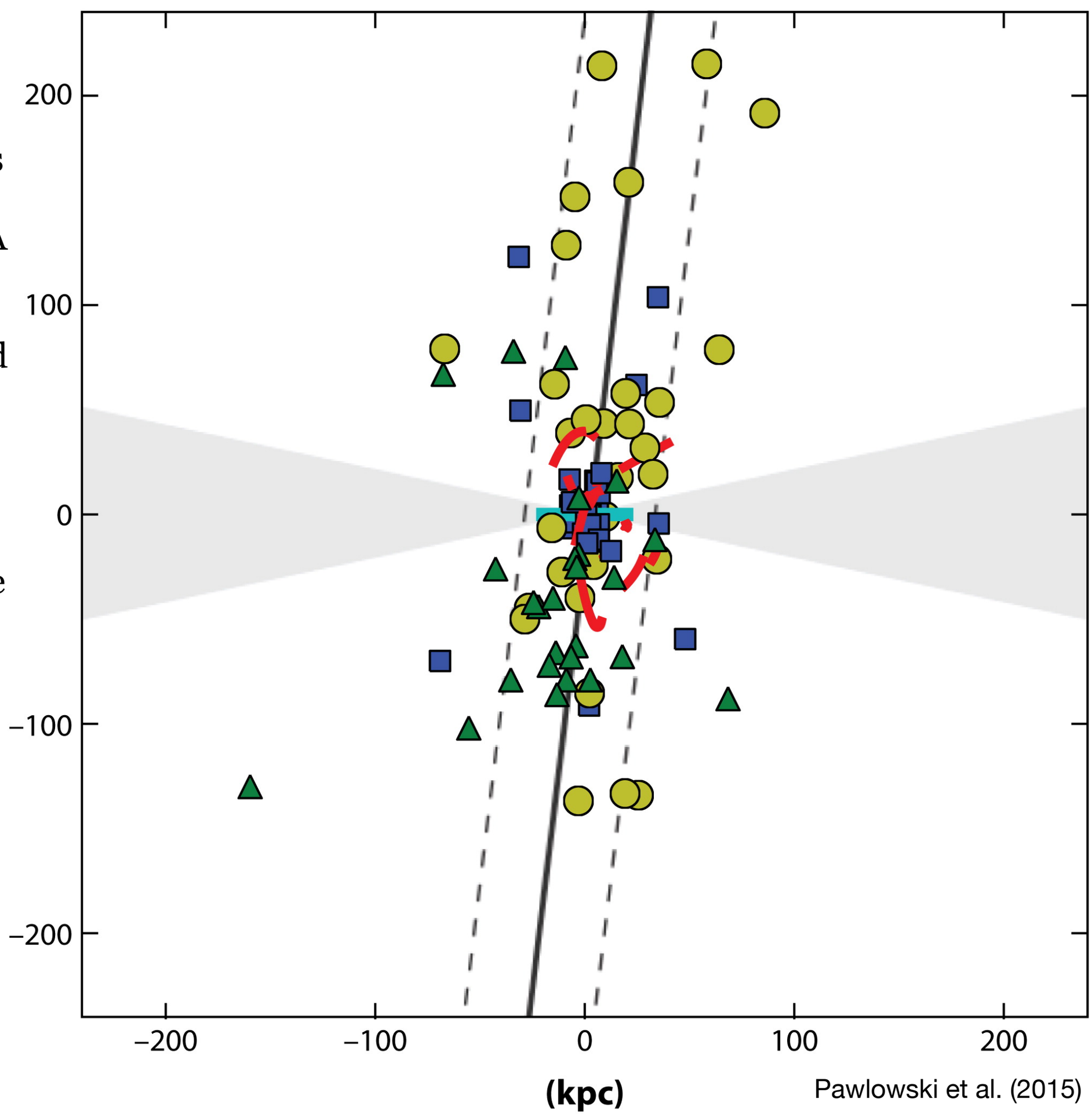
Too Big to Fail happens in the field, too. It can't be a process specific to satellites. Sort of combines the missing satellite and cusp-core problems.

Planes of satellites

Dwarf satellite galaxies of the Milky Way, Andromeda, and Cen A are observed to be orbiting on quasi-circular orbits confined to narrow planes.

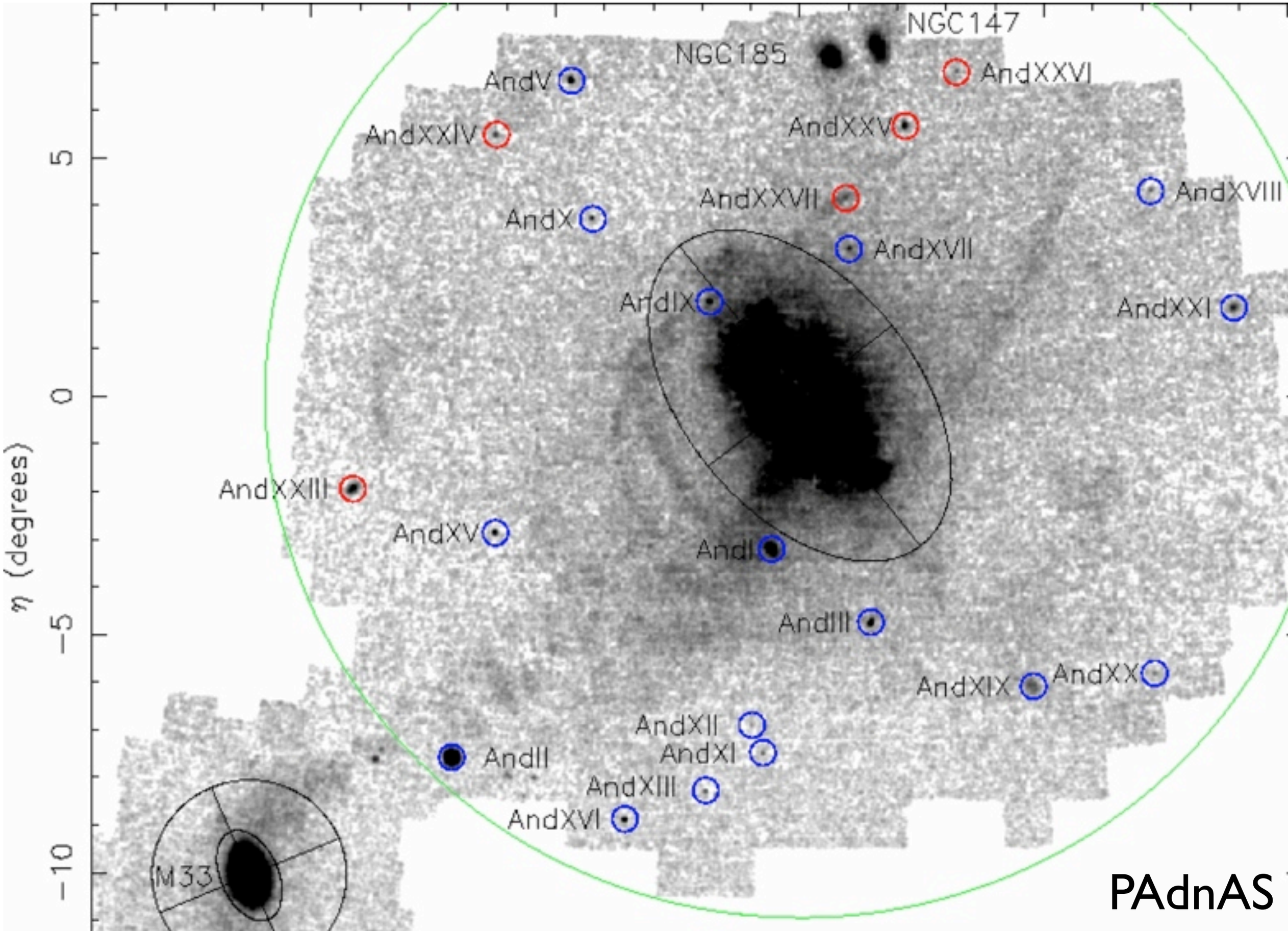
In DM simulations, the sub-halos thought to host dwarf satellites have highly radial orbits that are randomly oriented.





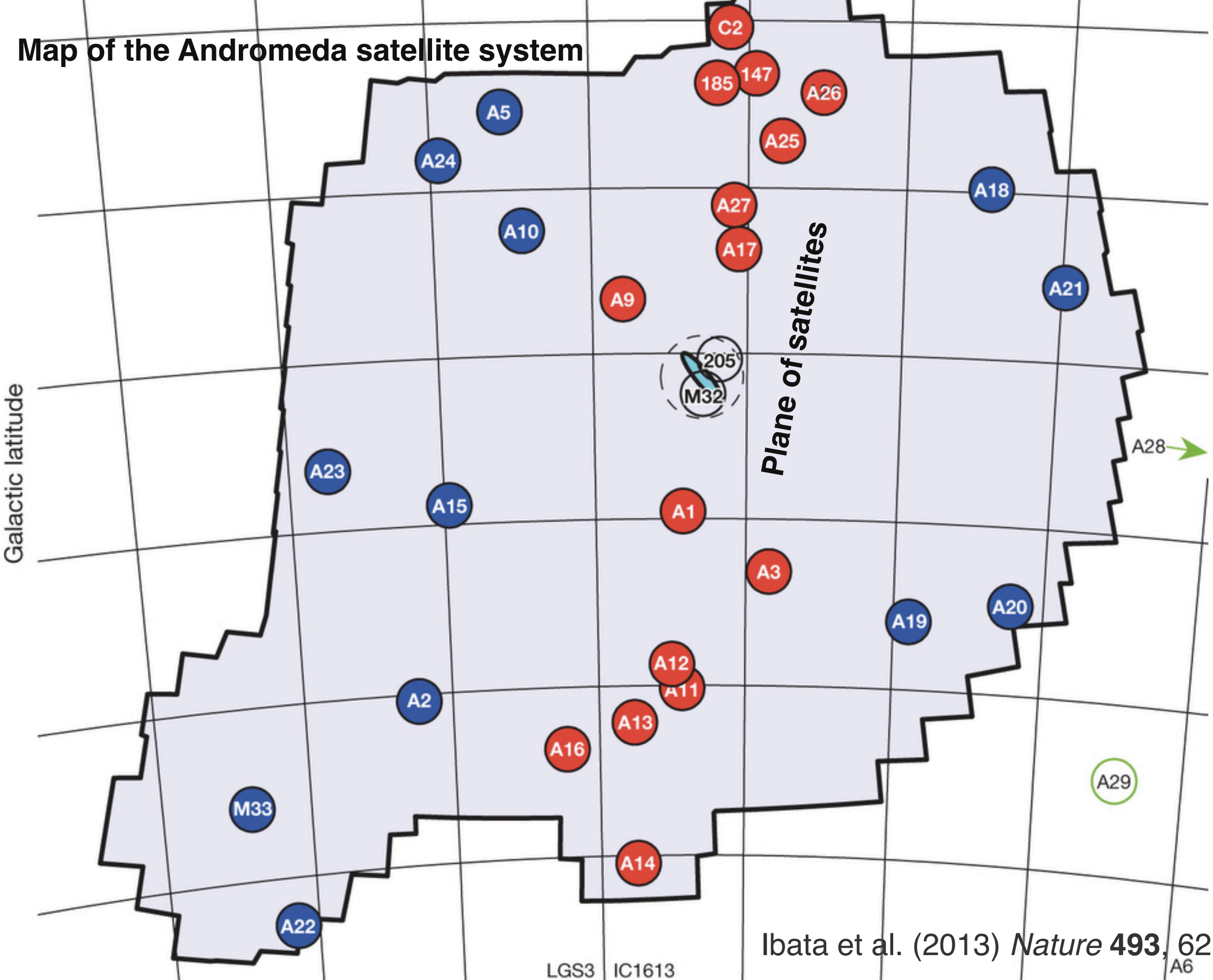
Pawlowski et al. (2015)

The dwarf satellites of Andromeda



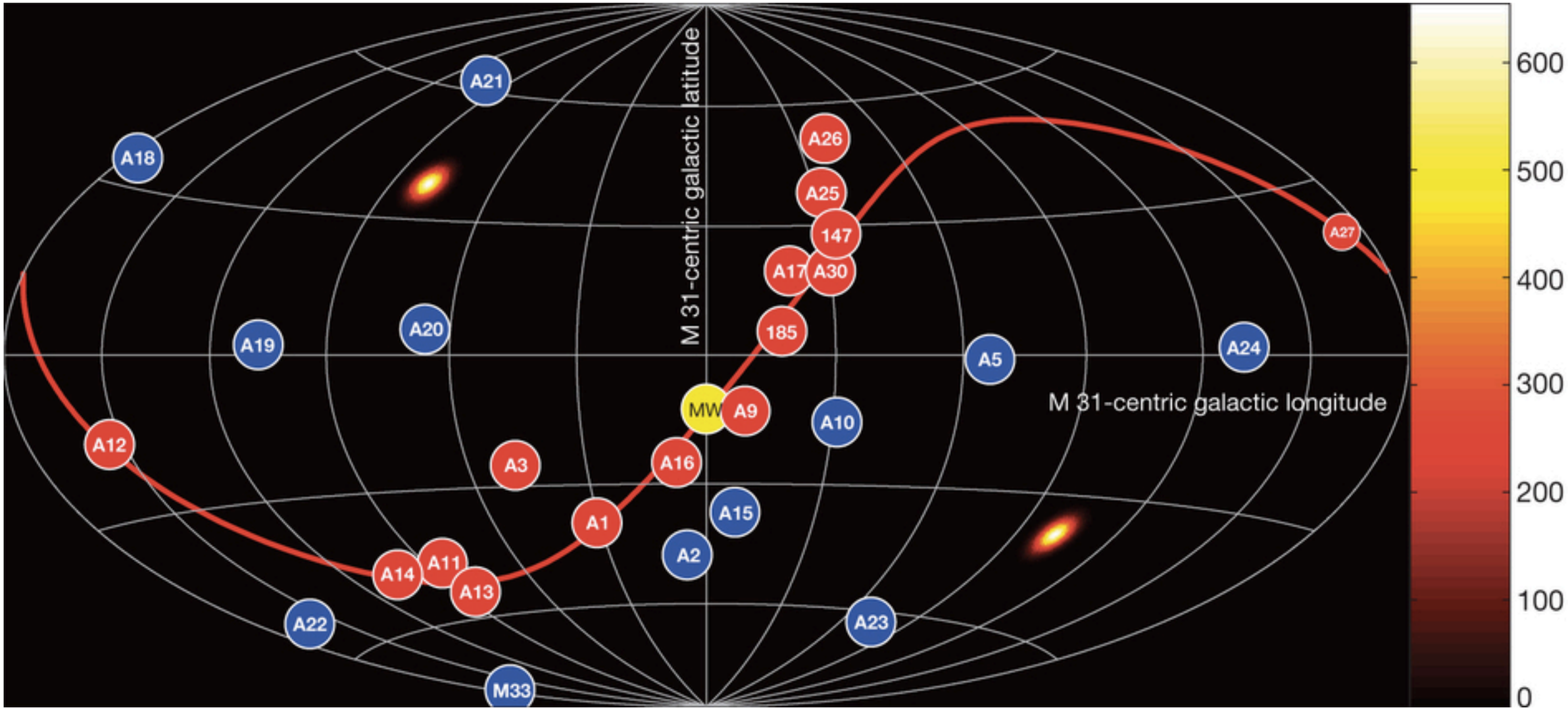
PAdnAS

Map of the Andromeda satellite system



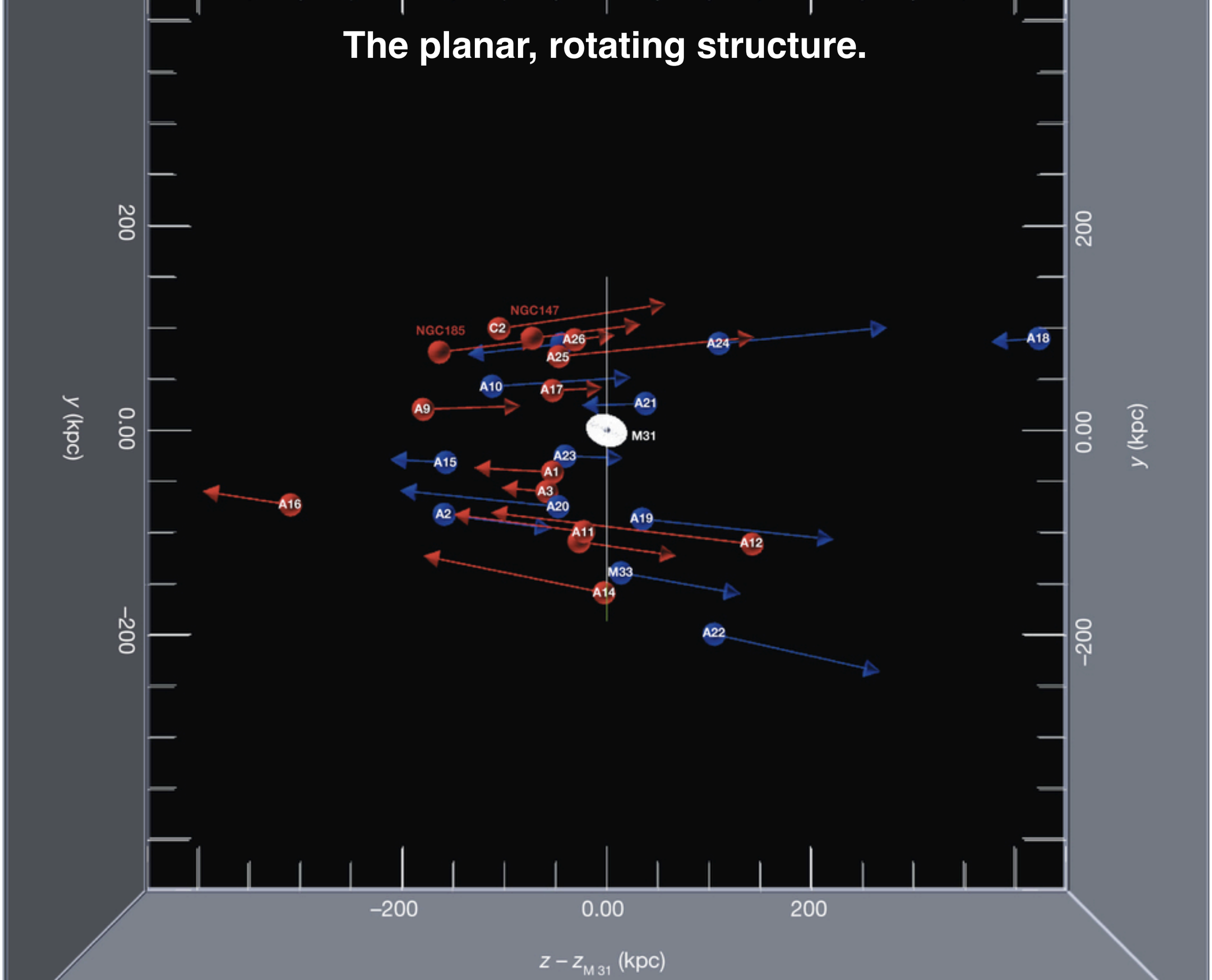
Ibata et al. (2013) *Nature* **493**, 62

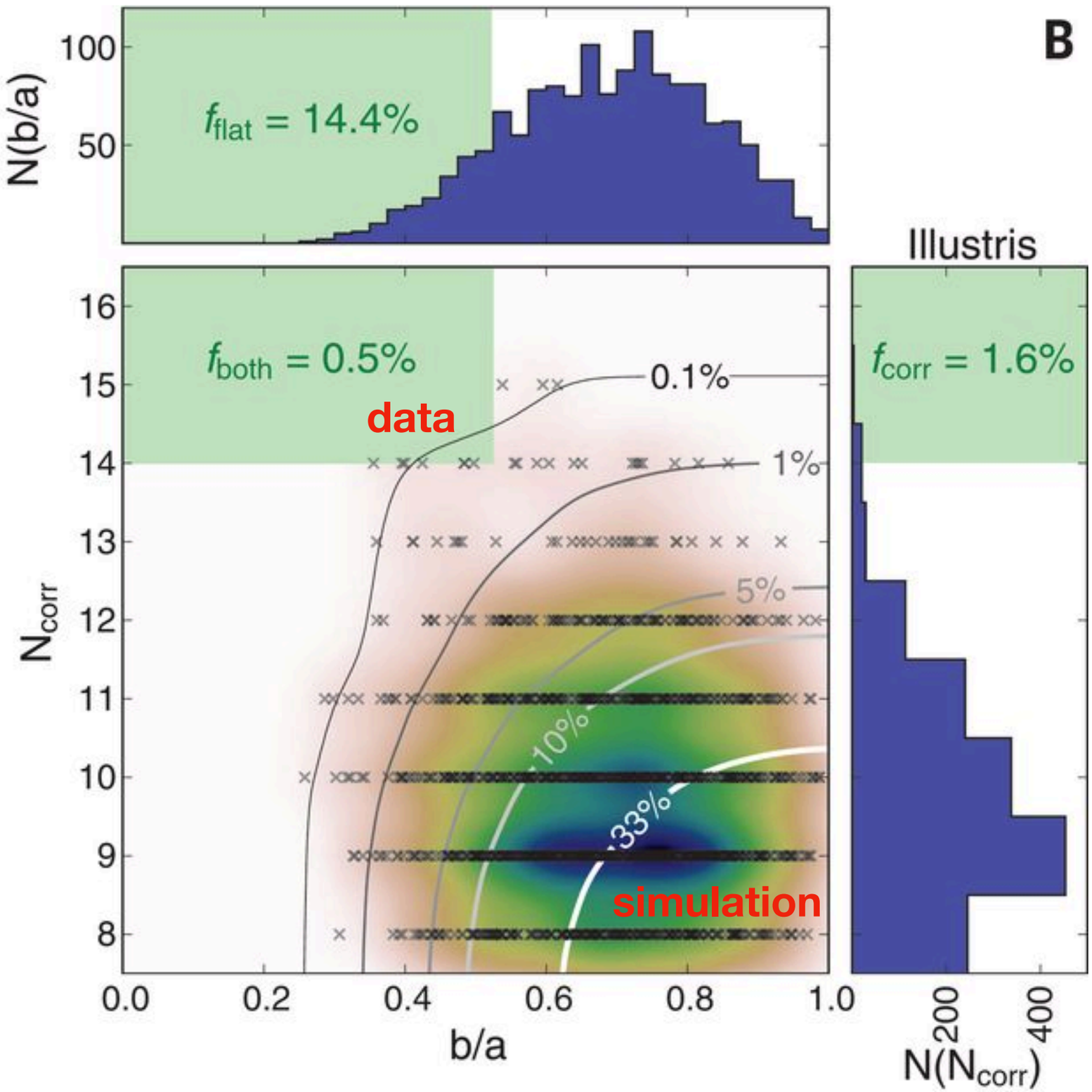
Satellite galaxy positions as viewed from Andromeda



Ibata et al. (2013) *Nature* **493**, 62

The planar, rotating structure.





The chance of the satellite plane of Cen A being both as flattened and as kinematically correlated as observed is < 1% in simulations

(Müller et al. 2018 *Science*, **359**, 534)

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