Great Planes of Dwarfs:
A challenge for cosmology?

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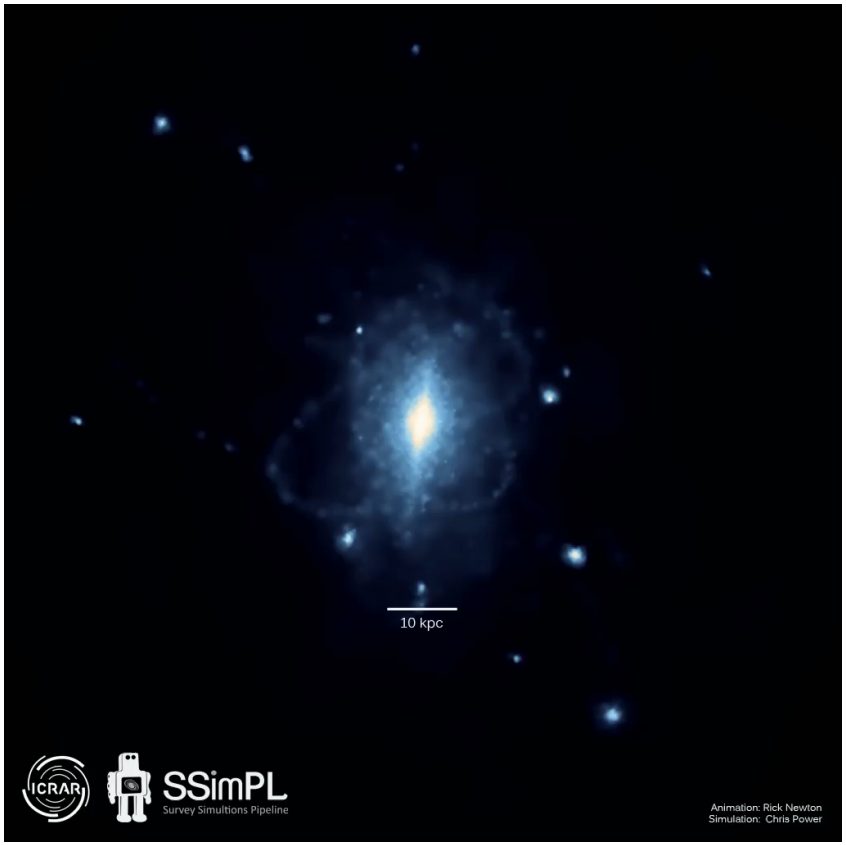
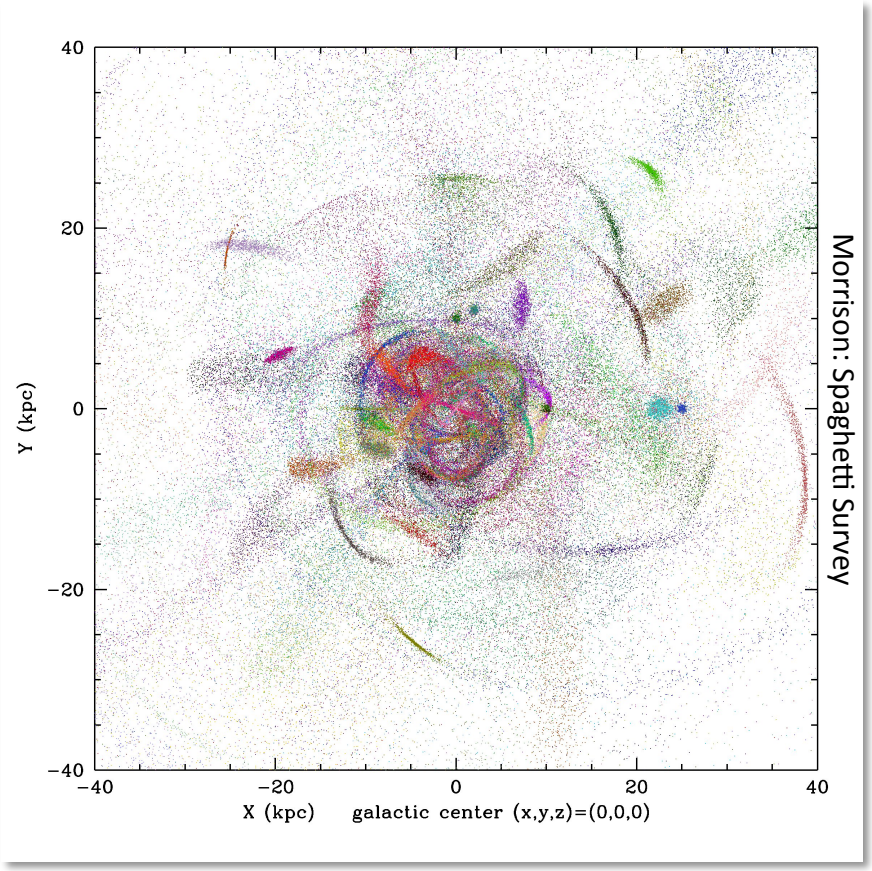
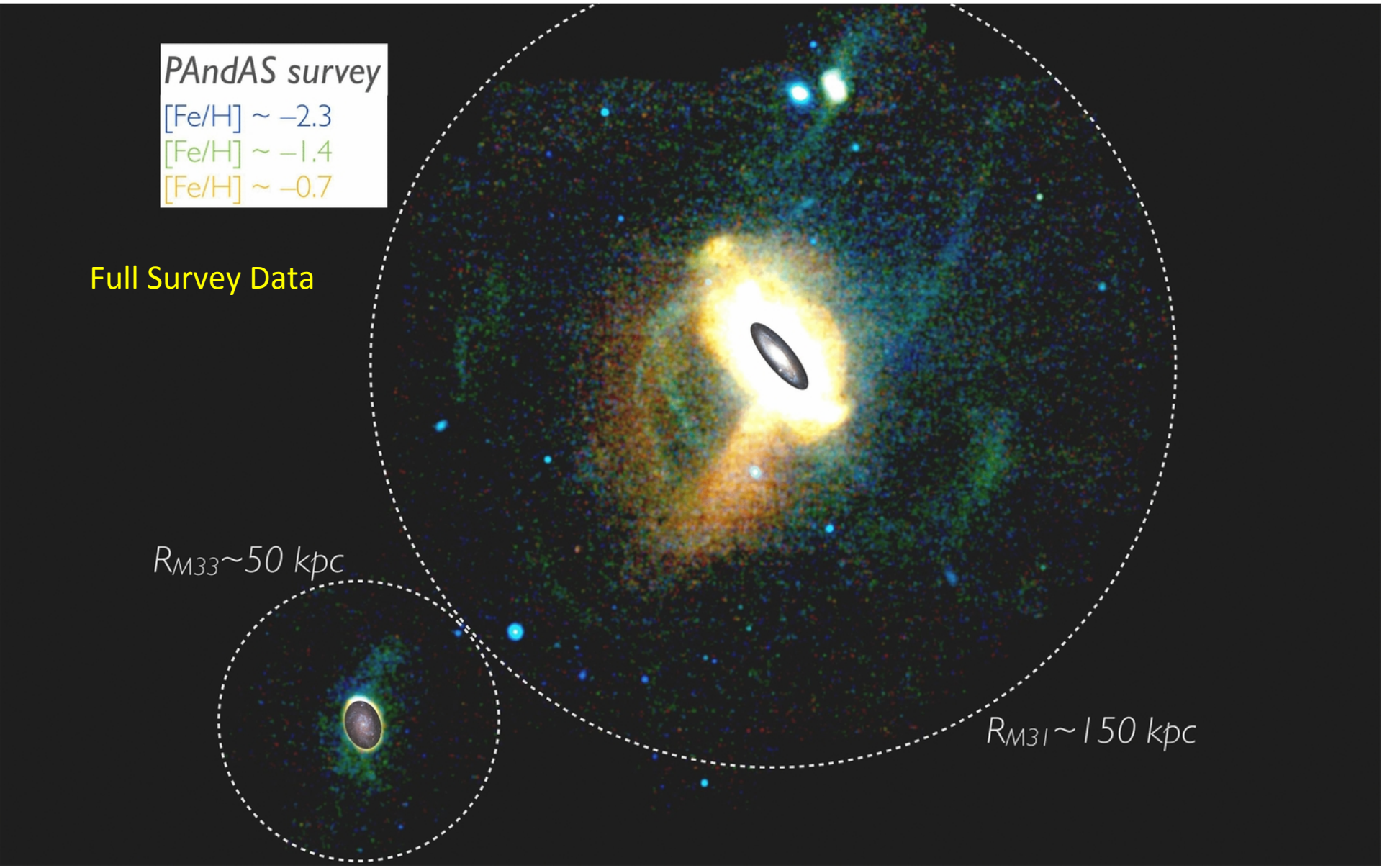
Cosmological Predictions

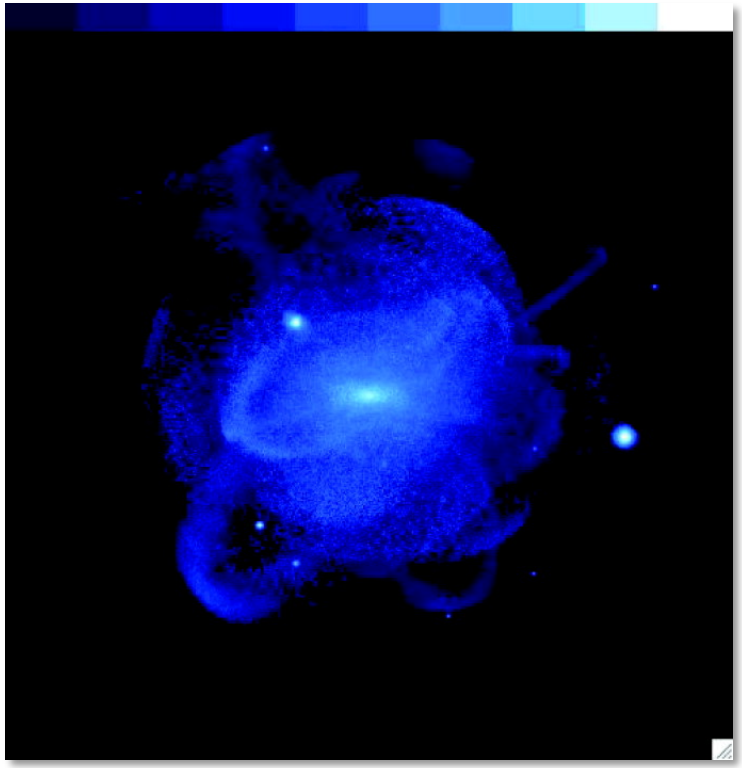




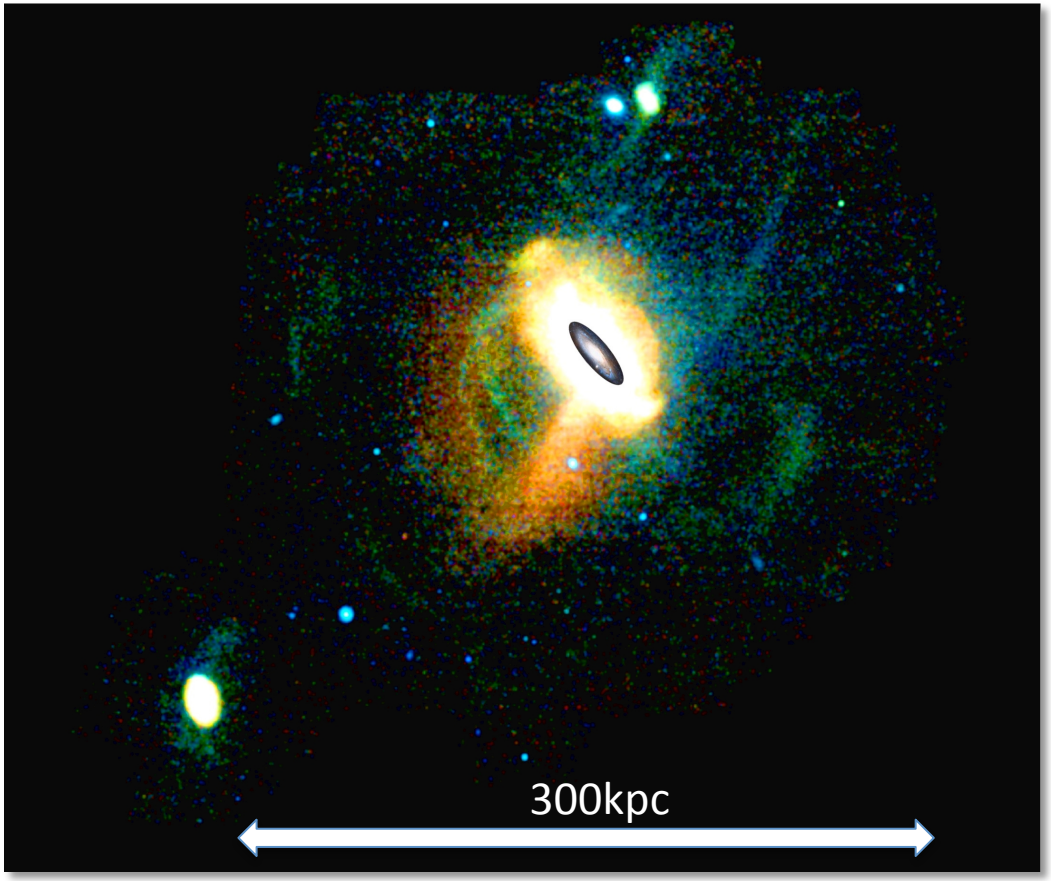
- Should be surrounded by extensive debris.
- This is very faint (~31 mags/□”) and below detection in integrated light.
- Need to use CCDs to identify individual stars: resolved stellar populations.


PAndAS survey
[Fe/H] ~ –2.3
[Fe/H] ~ –1.4
[Fe/H] ~ –0.7
Full Survey Data
RM33~50 kpc
RM31~150 kpc

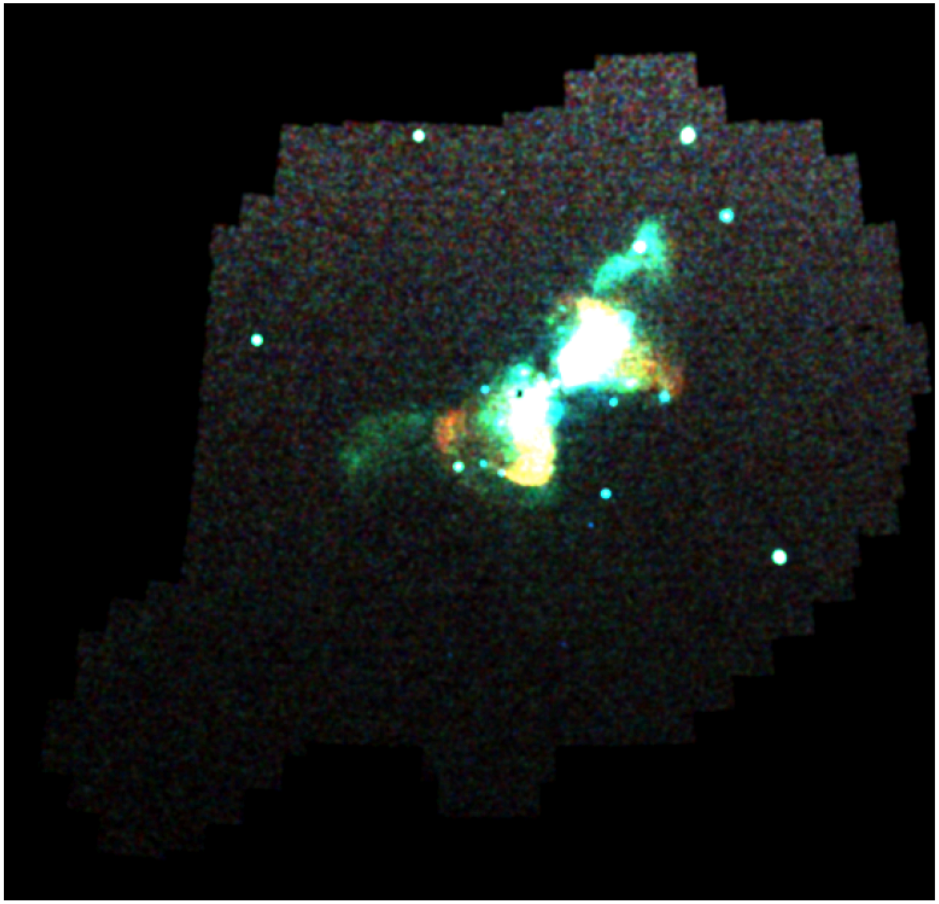
Comparing to Simulations

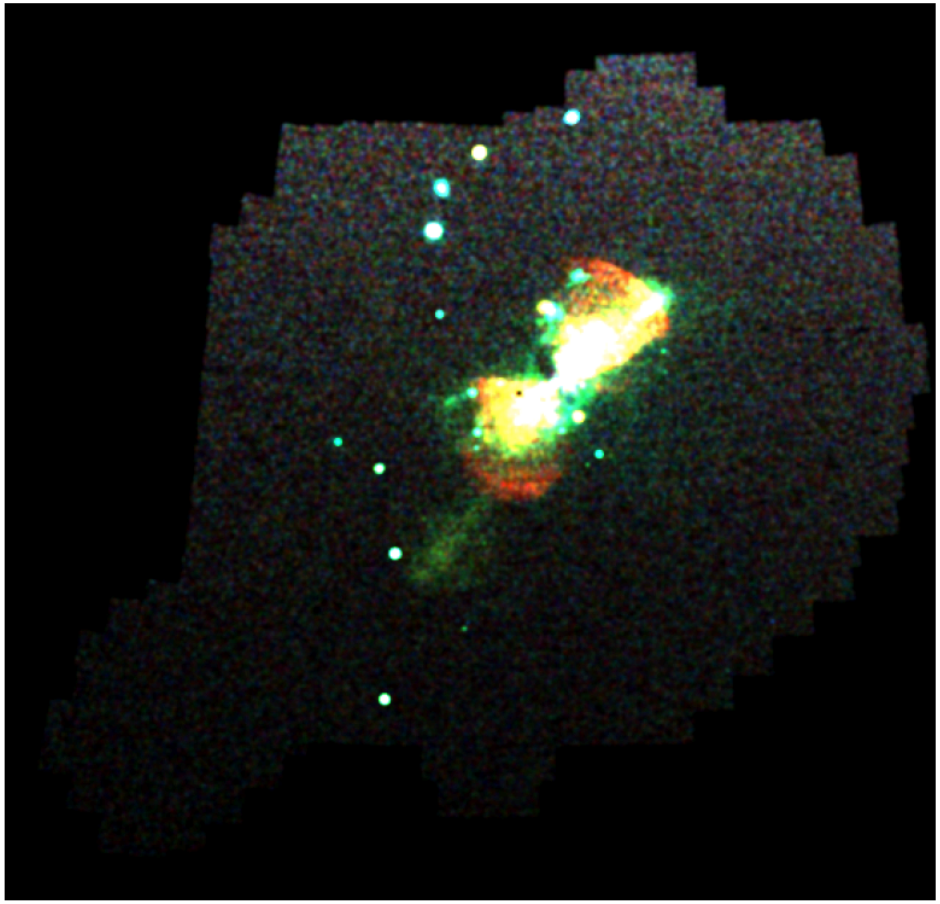


Bullock & Johnston (2005)



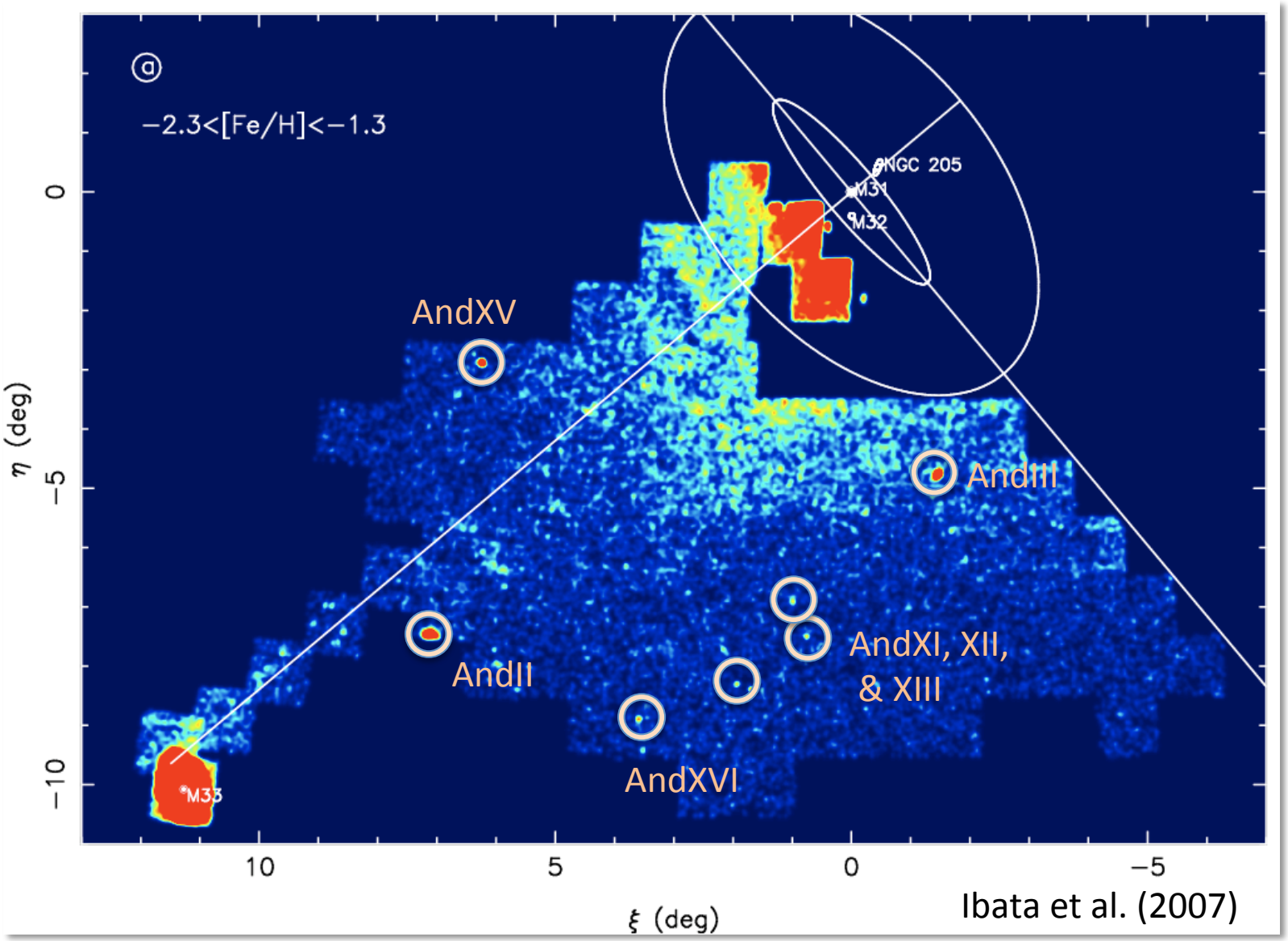
Comparing to Simulations





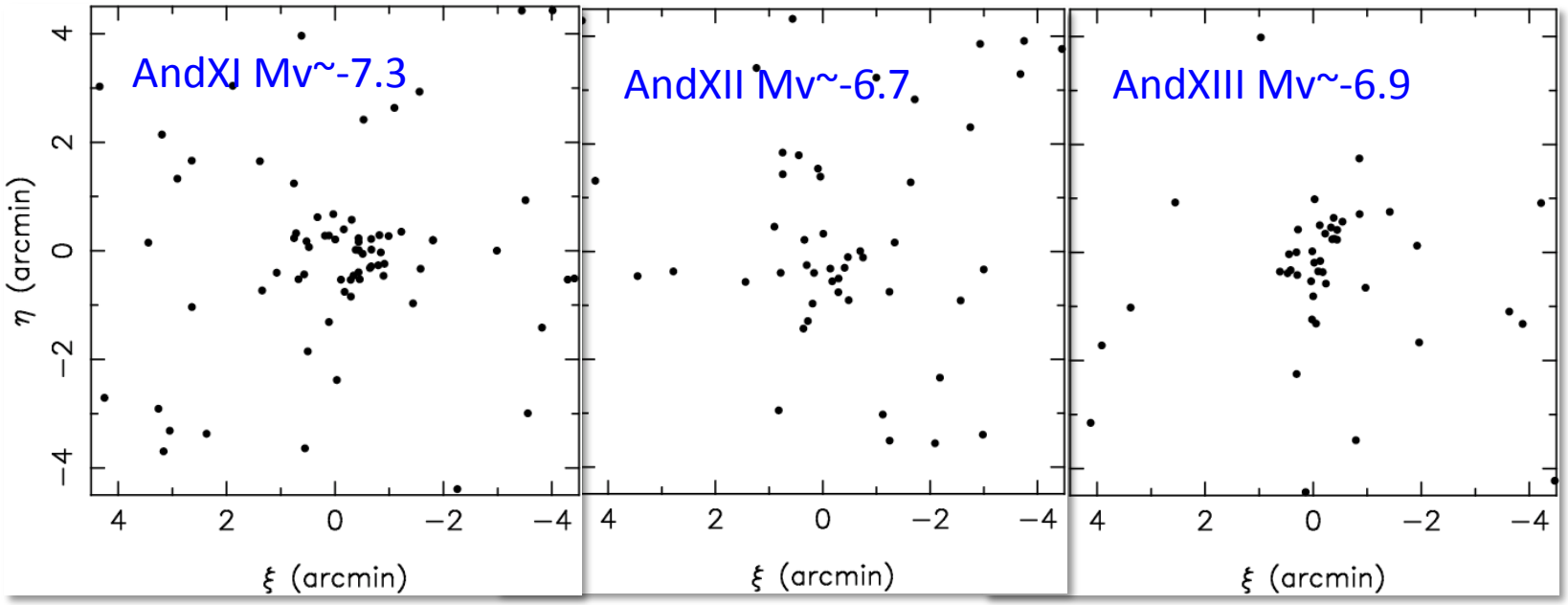
Thomas et al. & The Aquarius Simulation (2014)

New Dwarf Galaxies

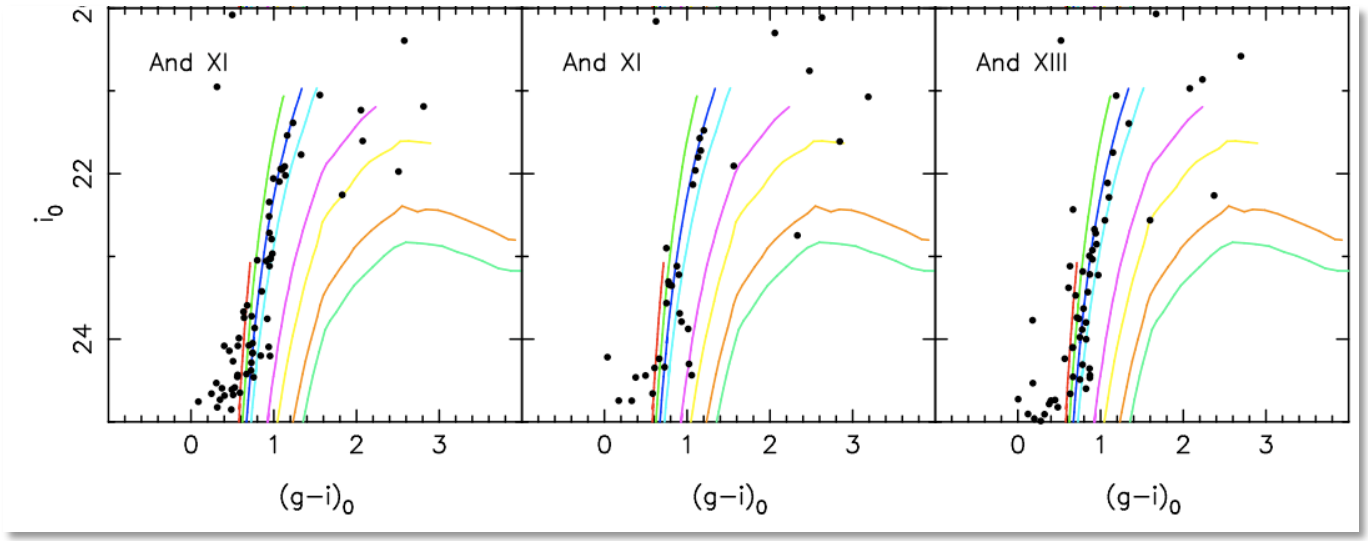


Ibata et al. (2007)

New Dwarf Galaxies



Martin et al (2006)

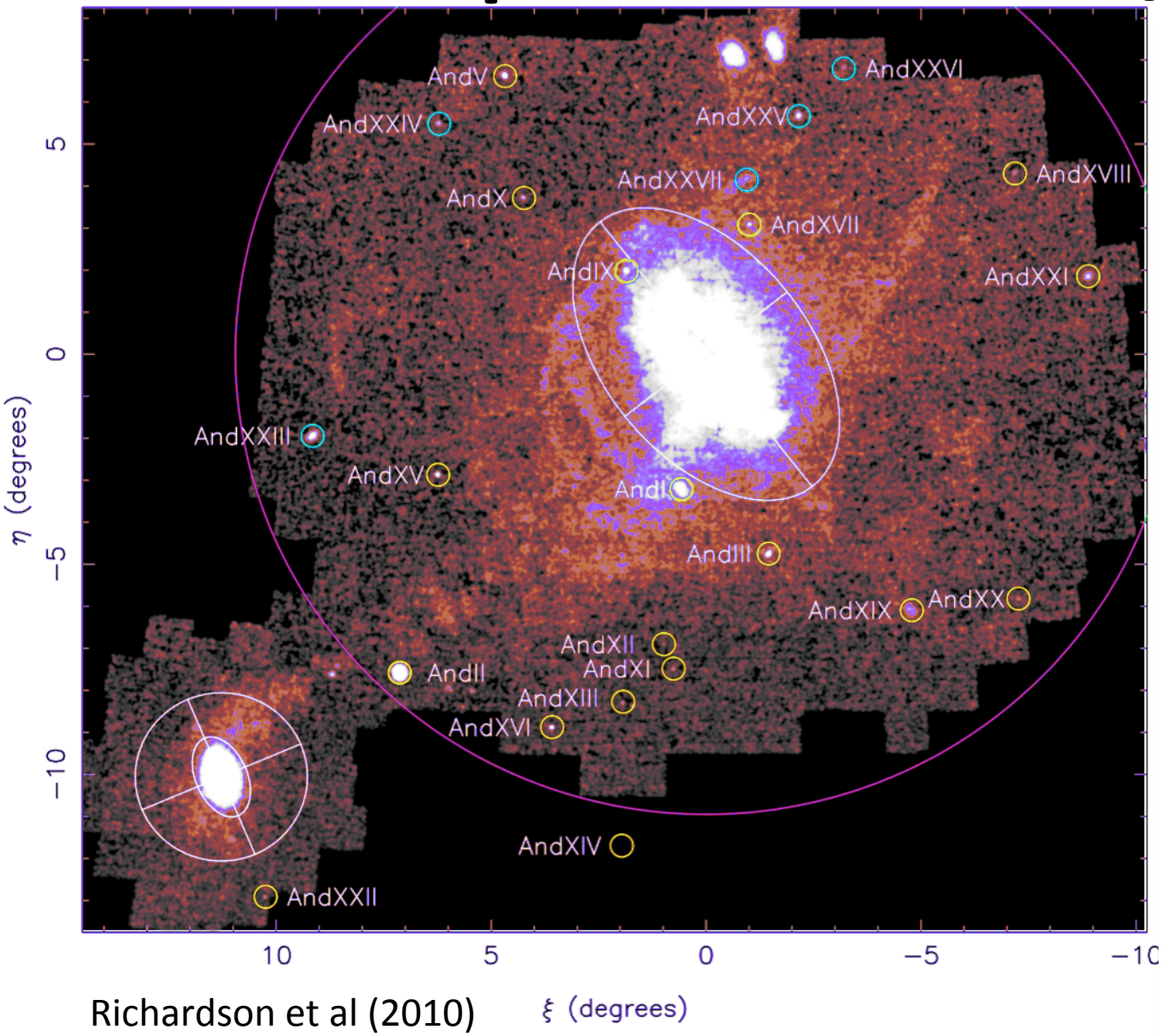


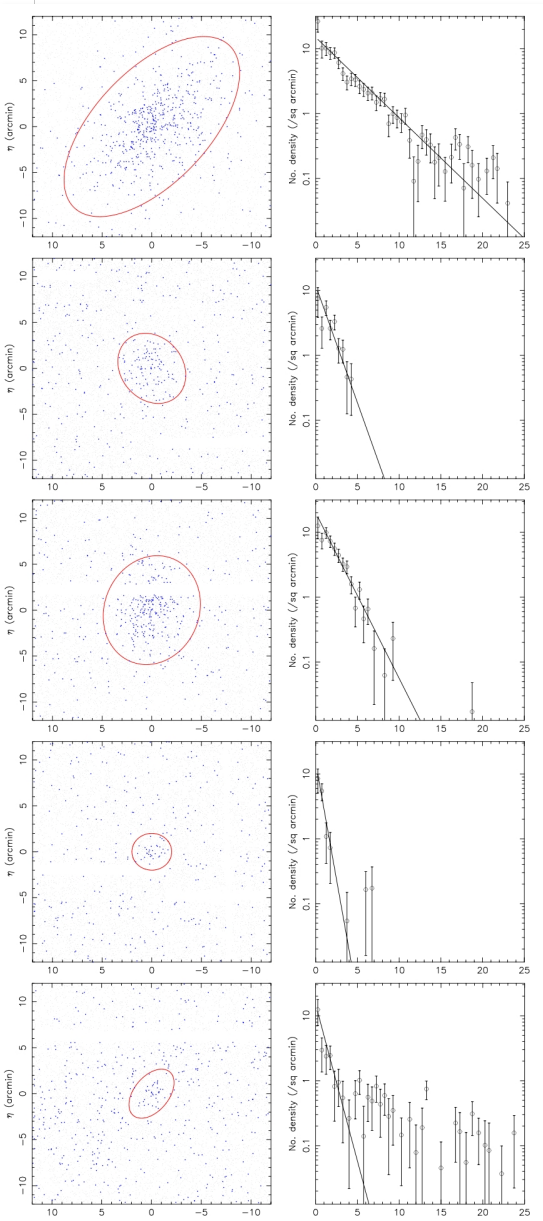
And XI: Vr=-430 km/s
And XII: Vr=-560 km/s
And XIII: Vr=-200 km/s

And XII may not be bound to M31 (first pass or ejected).

(Chapman et al. 2007, Collins et al. 2010)

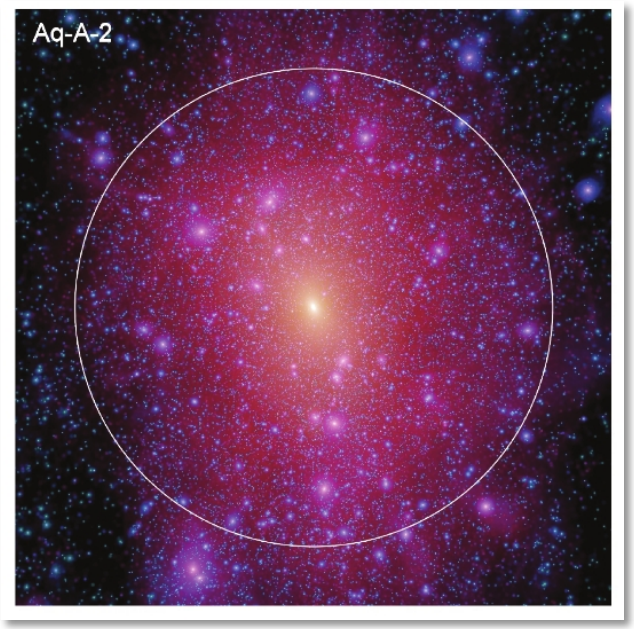
Dwarf Population in M31/M33





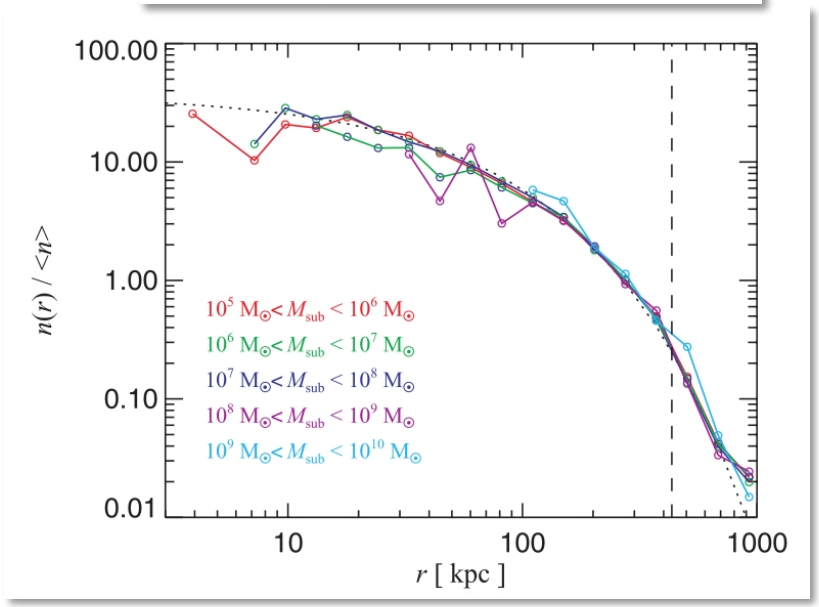
Richardson et al (2010)

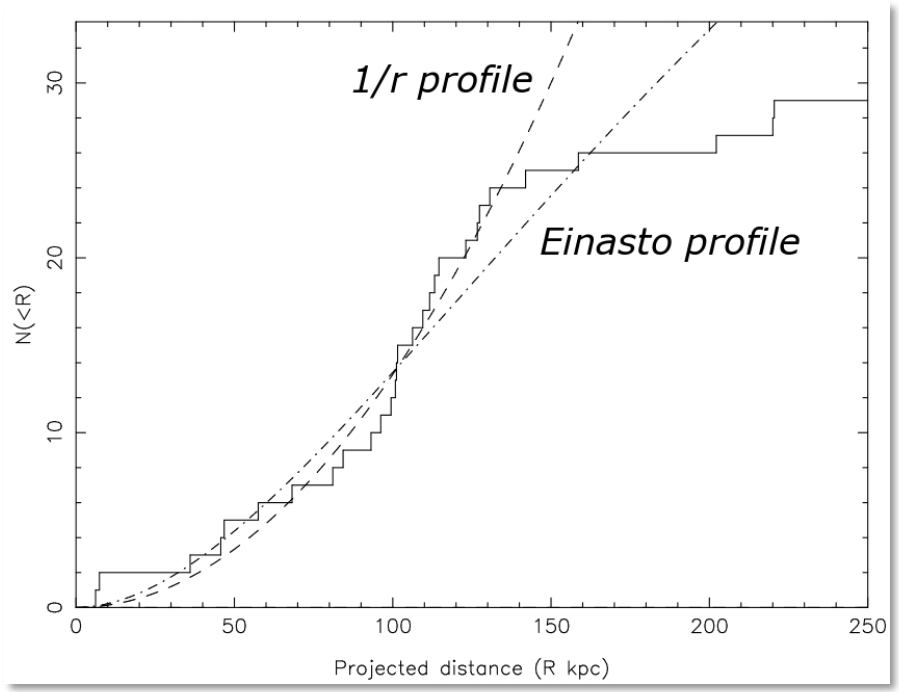
Dwarf Distribution



With the imaging data, we can directly confront theoretical ideas.

Already, is the spatial distribution of dwarf is at odds with expectations?

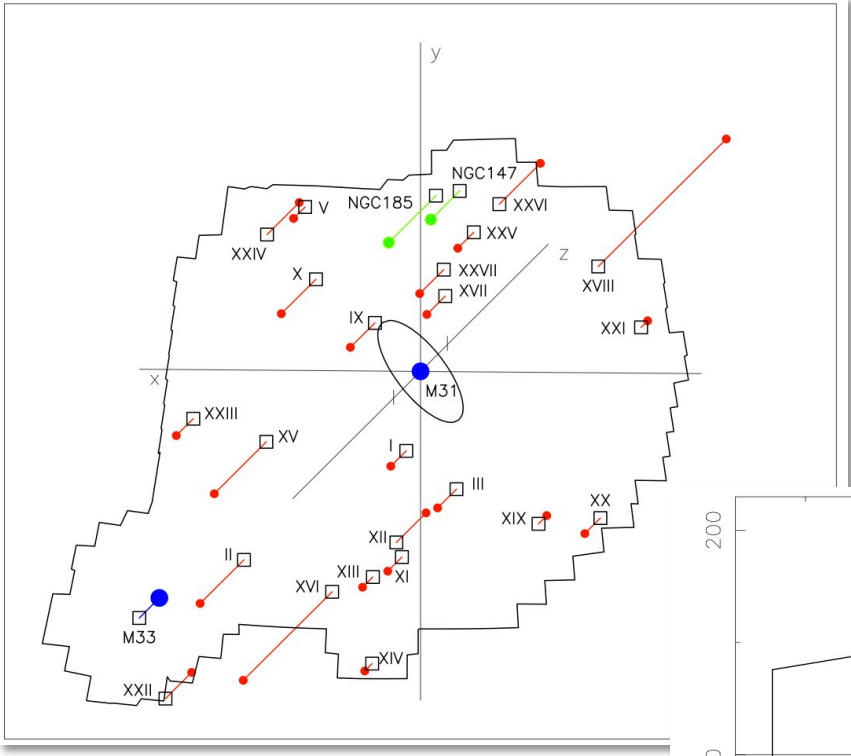




Richardson et al (2010)

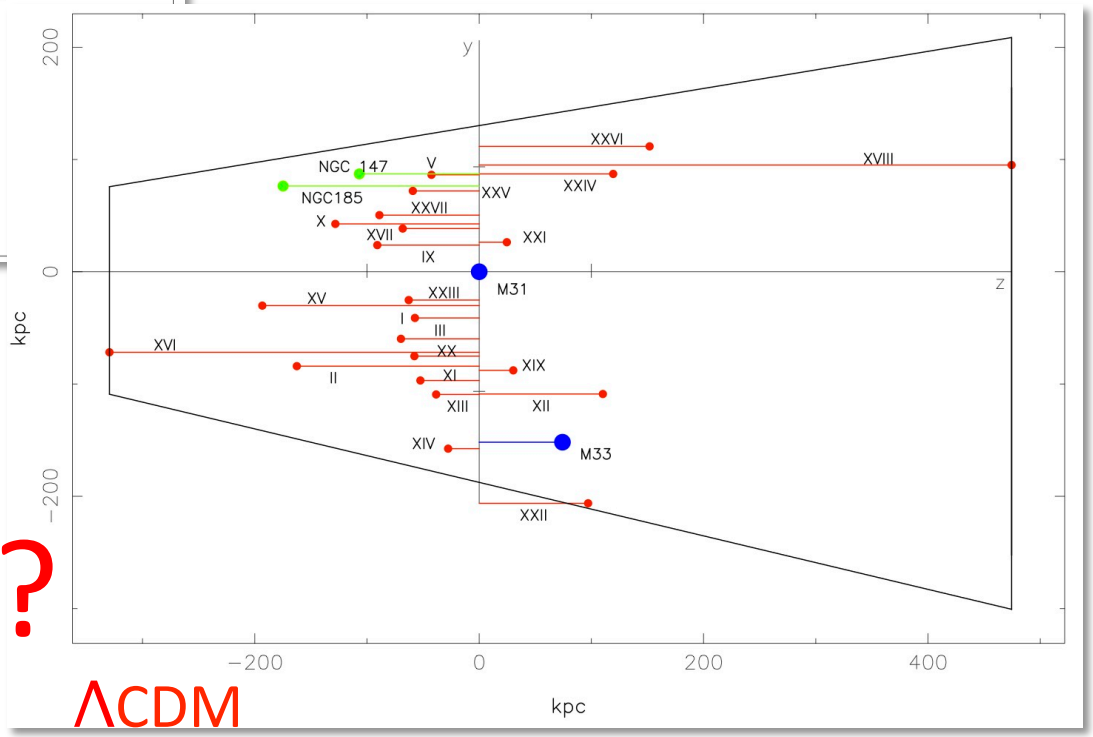
Distances: Results

Conn et al. (2012)



Taking into account the various uncertainties (the calibration of the RGB Tip etc), we get distances with an accuracy of a few 10s of kpc.

Clearly there is a strong asymmetry in the dwarf population towards the MW.

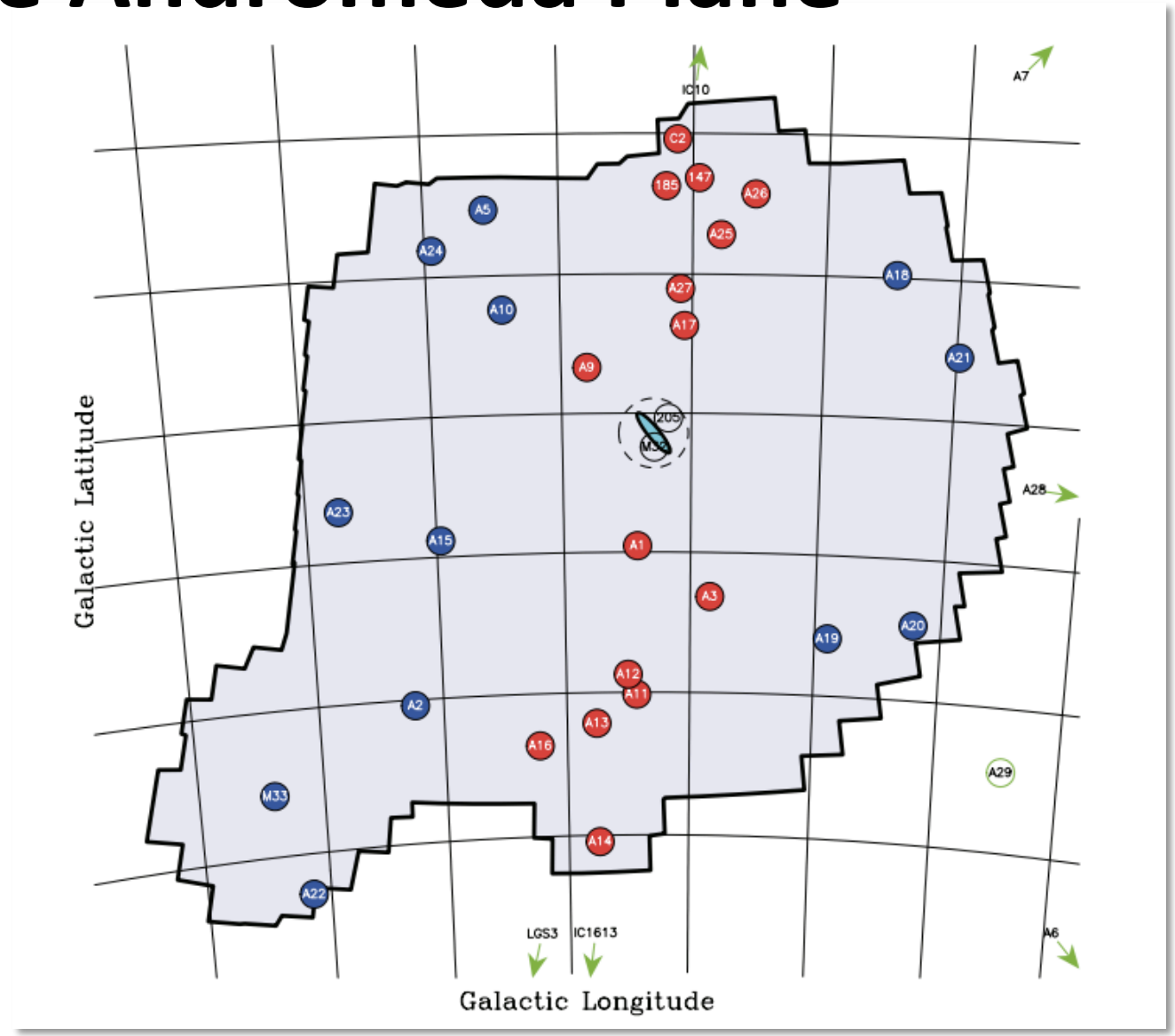


?

ΛCDM

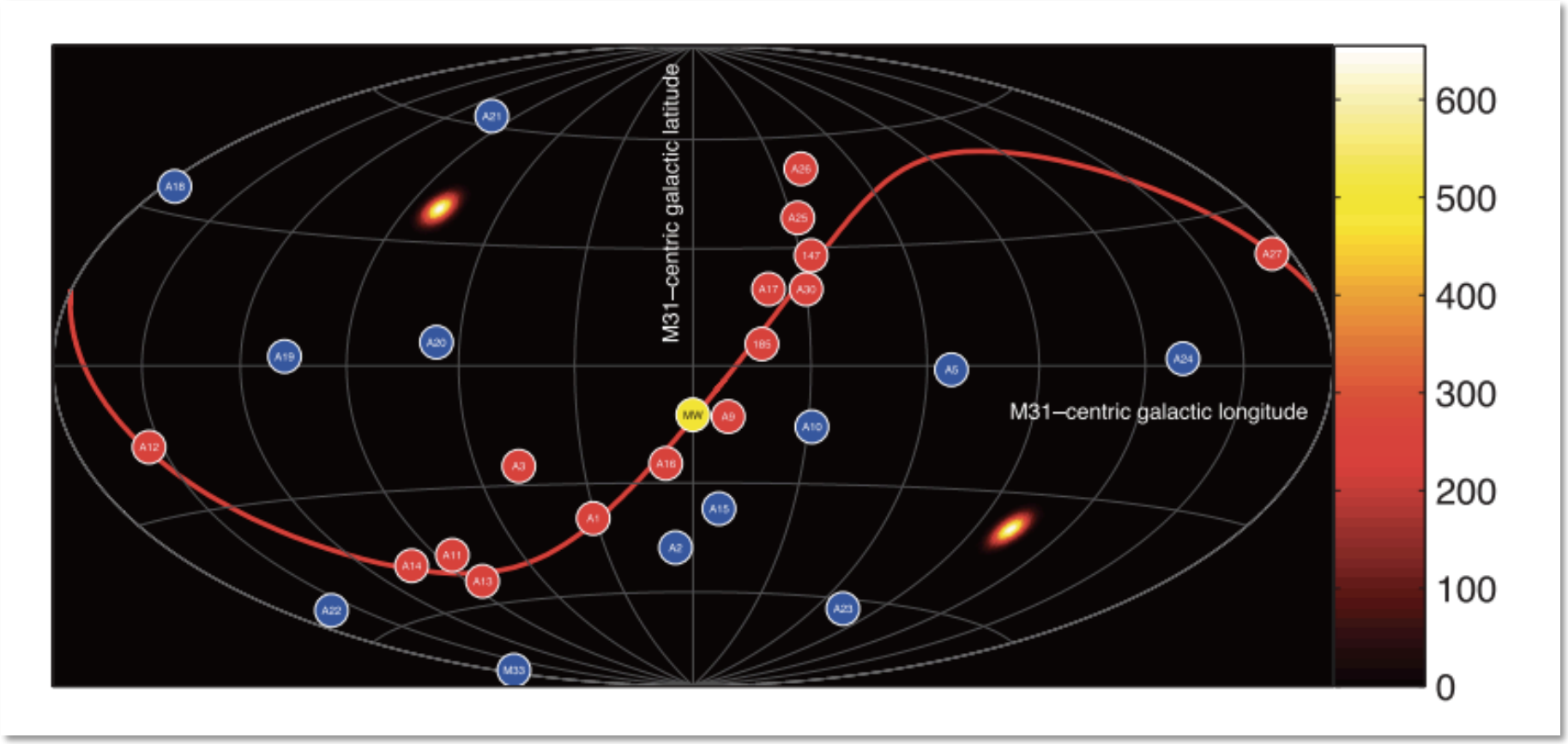
The Andromeda Plane

Ibata et al. (2013)



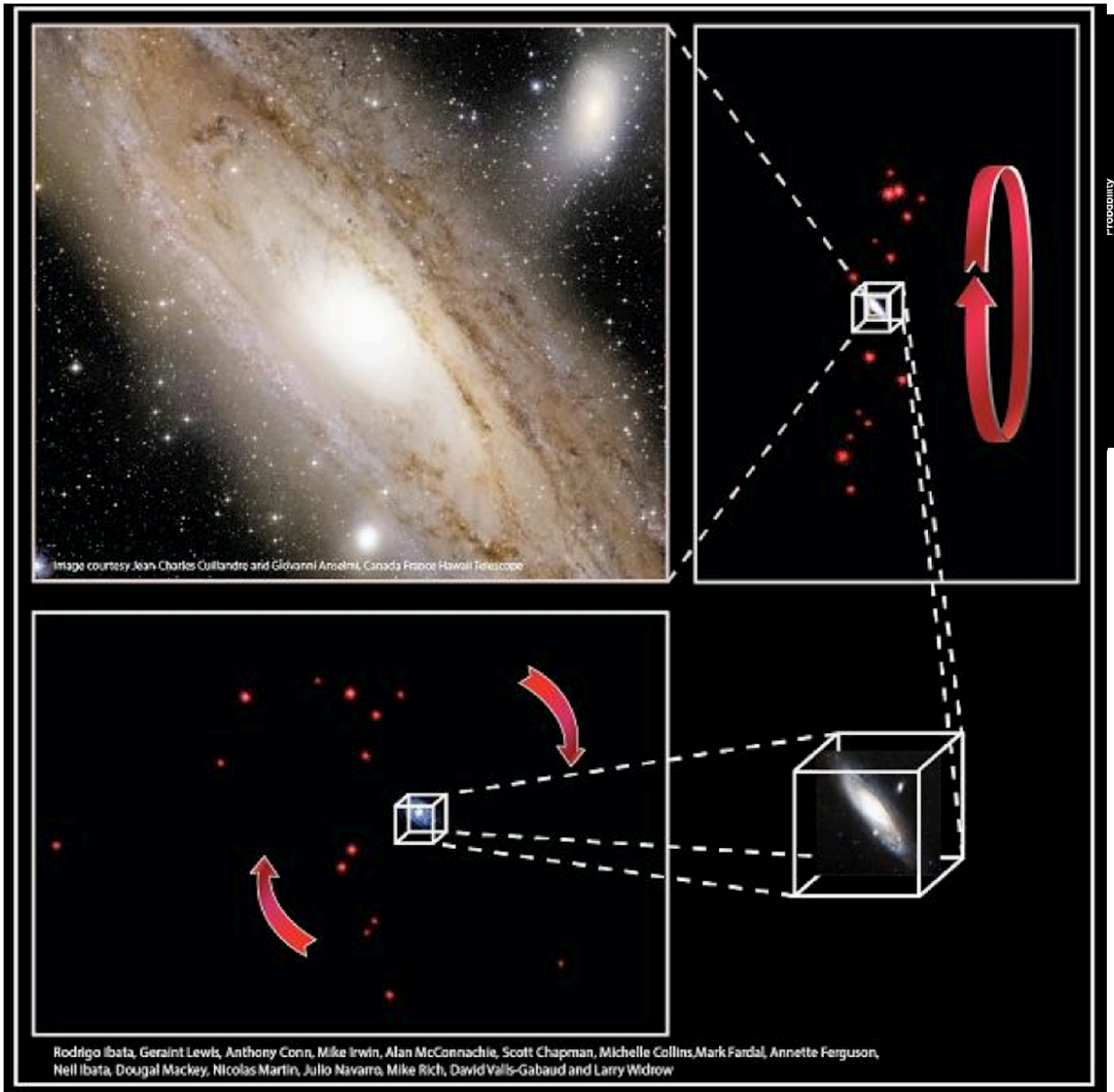
The result: a significant plane of ~½ of the entire population.

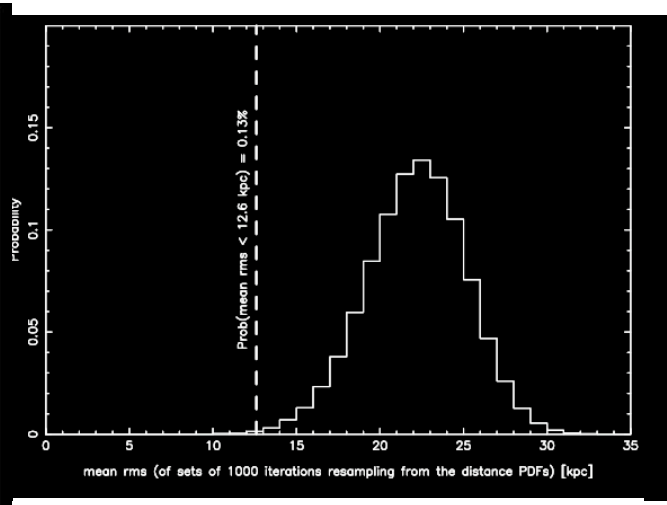
The View from Andromeda



Ibata et al. (2013) The plane is extremely thin, ~14kpc, and 400kpc in extent.

Just how likely?





With just the positions, the alignment is quite unlikely.

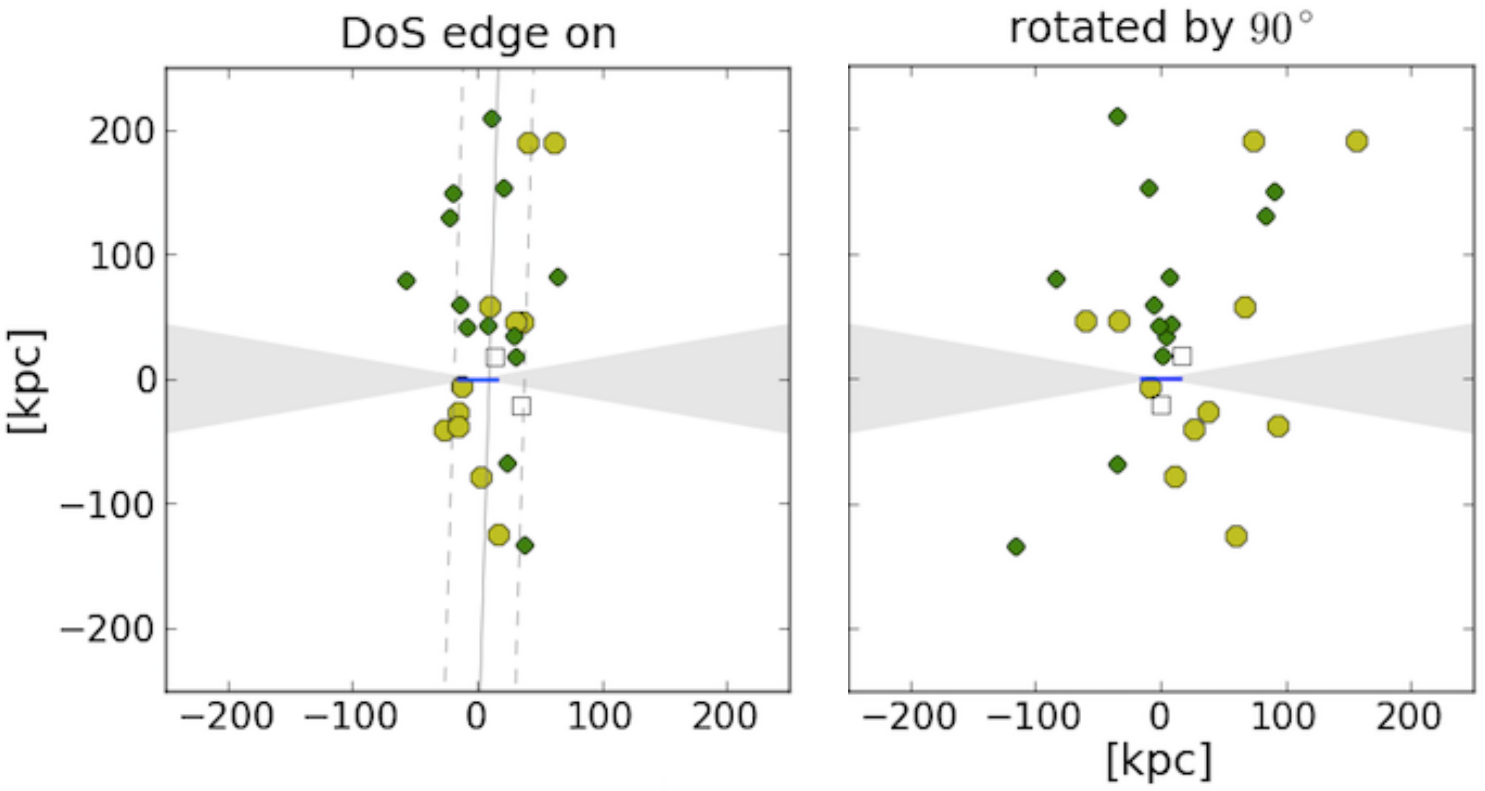
However, once we consider the velocities, we find that the dwarfs appear to be co-rotating.

This is 99.998% significant!

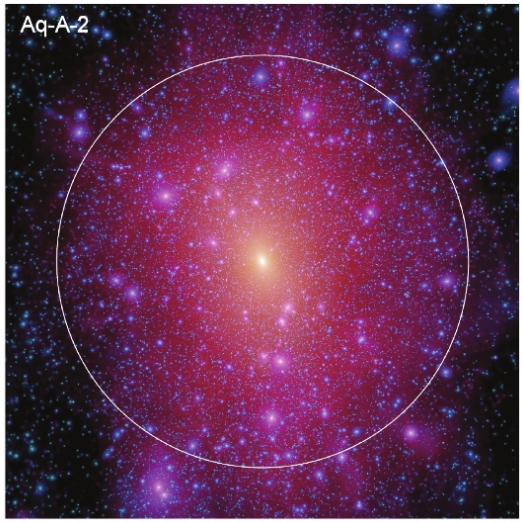
(Ibata et al. 2013)

VPOS in the Milky Way

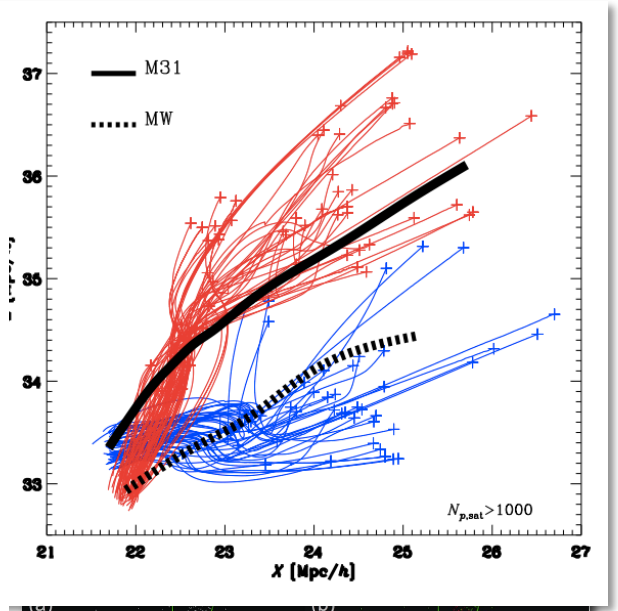
Kroupa, Metz et al



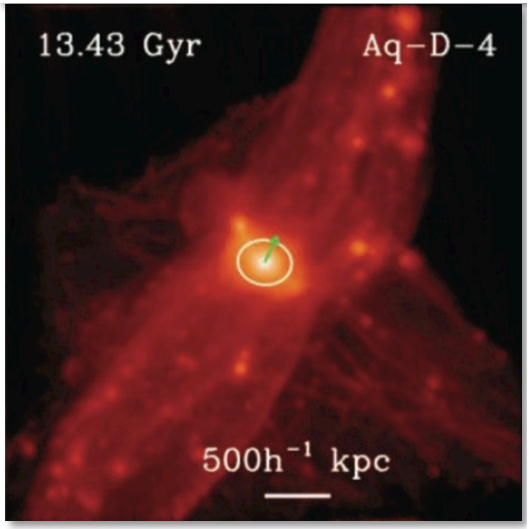
Solutions: ΛCDM or not?



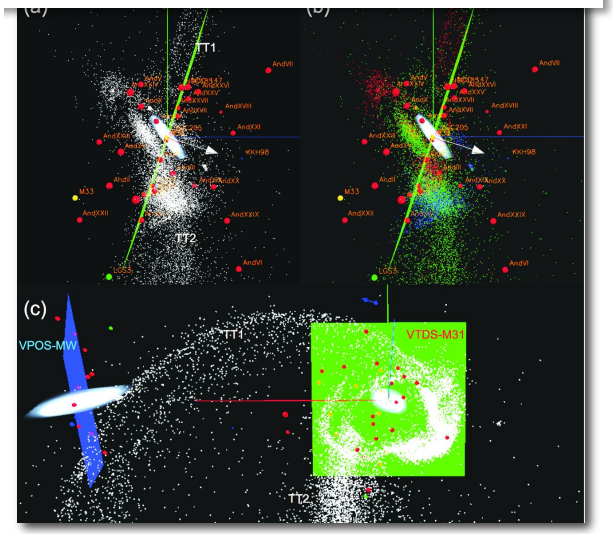
Gas Physics?



Funky Orbits?



Filament Feeding?



MOND?

Something Else?

But what if the Milky Way or the Local Group are somehow special?

Doesn't that mean they tell us little about the Universe?

Cosmologist

Are satellite alignments common?
(around isolated giant galaxies)

The Milky Way and M31 appear to have satellite alignments

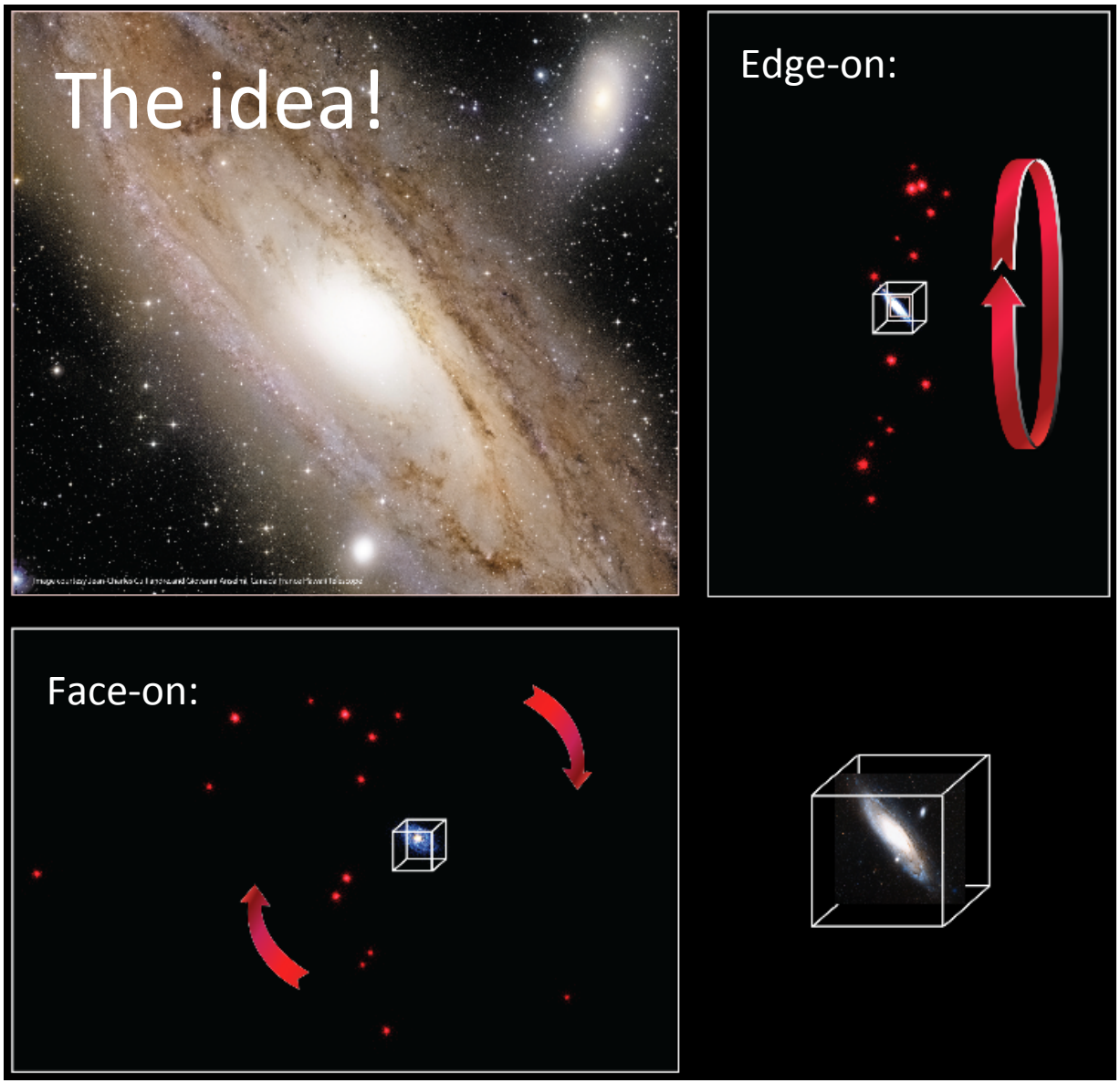
- containing a significant fraction (but certainly not all) of the population
- thin, planar configurations
- in M31, apparently co-rotating

Could these be found in HST surveys?

- 6 orbits of ACS at 10Mpc: area=PAndAS/700, RGB tip at I=25.7, distance error=180kpc

Could these be found in surveys such as the SDSS?

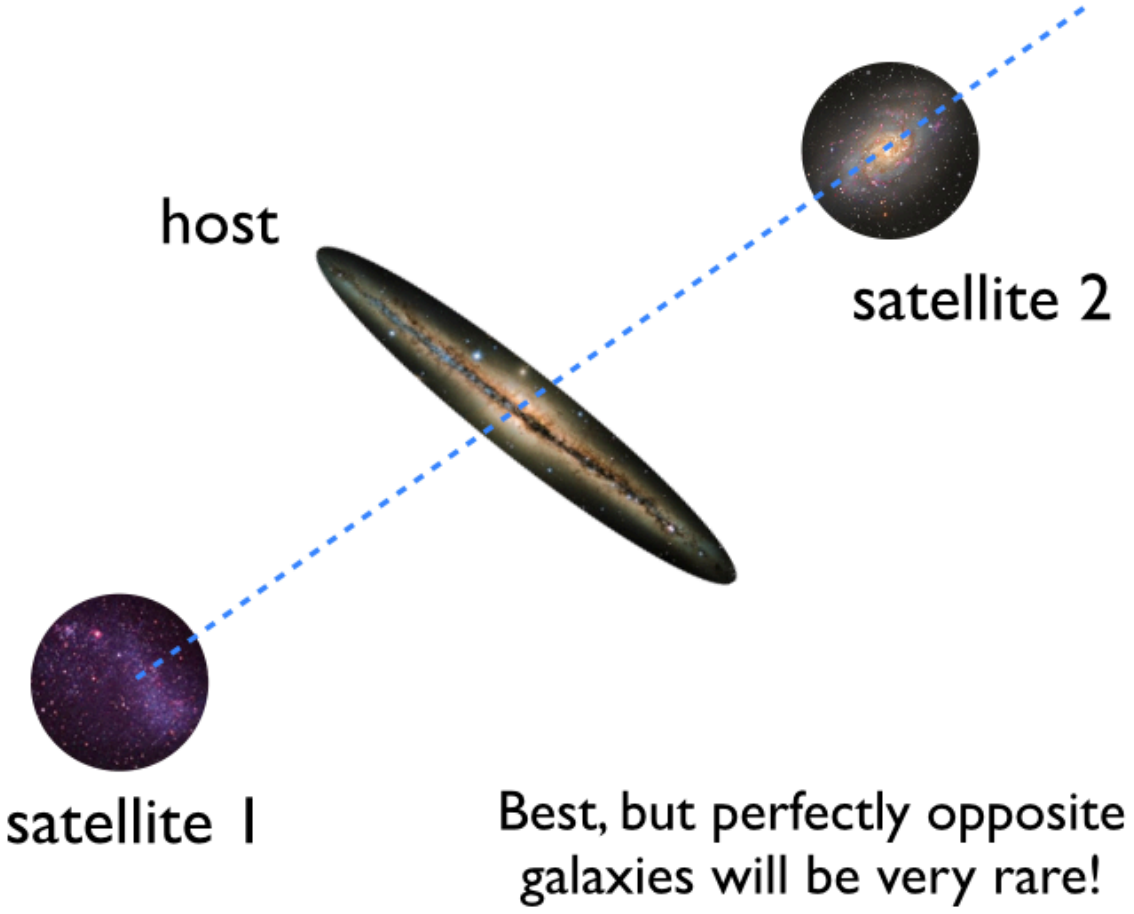
- hosts with one satellite? - lots, but hopeless!
- hosts with 2 satellites? (projected positions alone) - need ~10^6 systems
- hosts with 3 satellites? (projected positions alone) - very few in SDSS
- hosts with 2 satellites? (projected positions and velocities) - **hmmm...**



Effect will be most pronounced for edge-on configurations

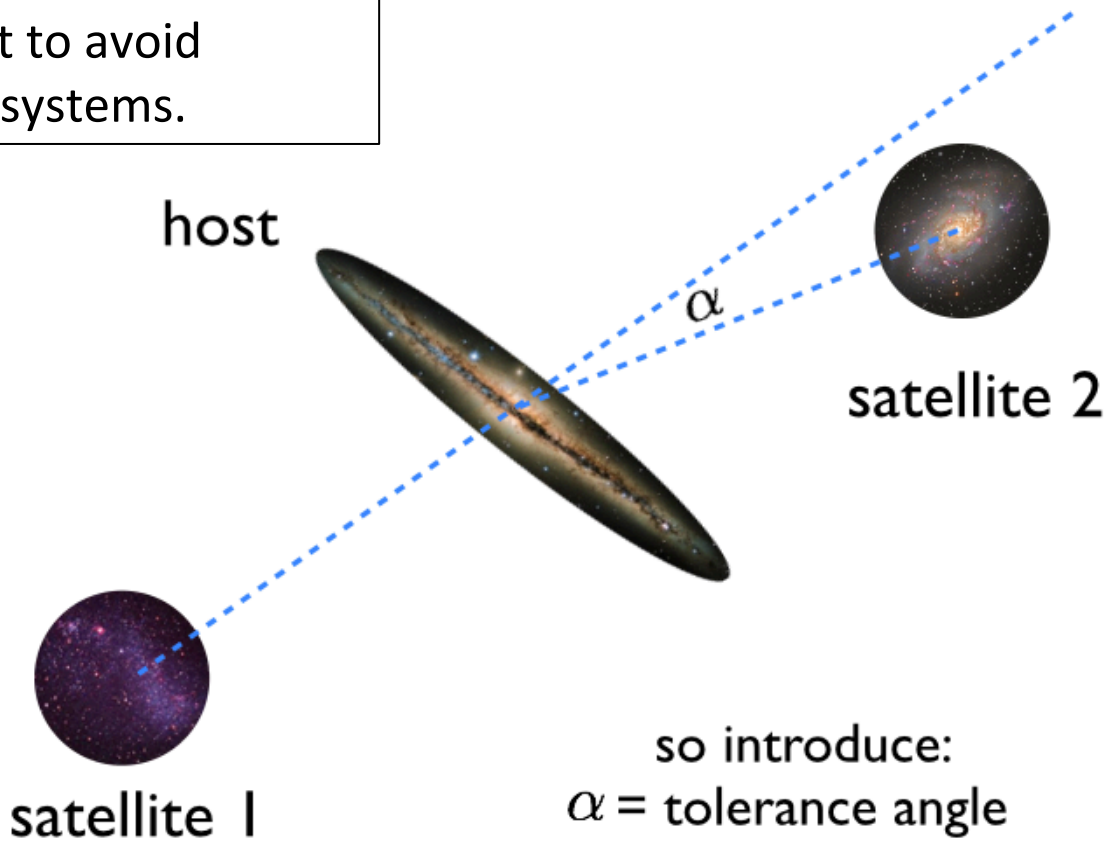
Satellites on opposite sides of their host will have anti-correlated velocities

To select edge-on alignments



To select edge-on alignments

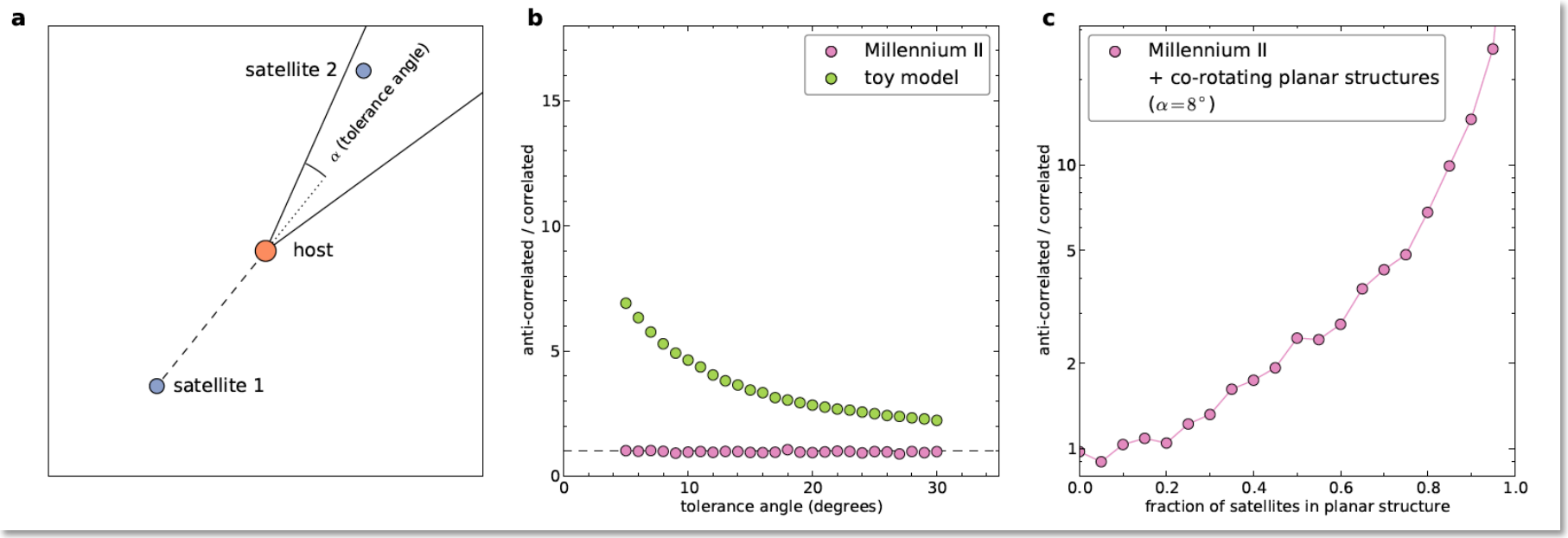
We reject satellites on the same side of their host to avoid selecting binary systems.



Let's test this!!

Simple statistic: count number of satellite pairs with **anti-correlated** velocities vs. **correlated** velocities.

Let's take a look with Millennium & toy models?



And for real?

NYU Value Added Galaxy Catalog (SDSS DR7, update to Blanton et al. 2005)

- 2.5 million sources, gives estimates of absolute mag (and stellar mass)

Select M31 and Milky Way-like hosts

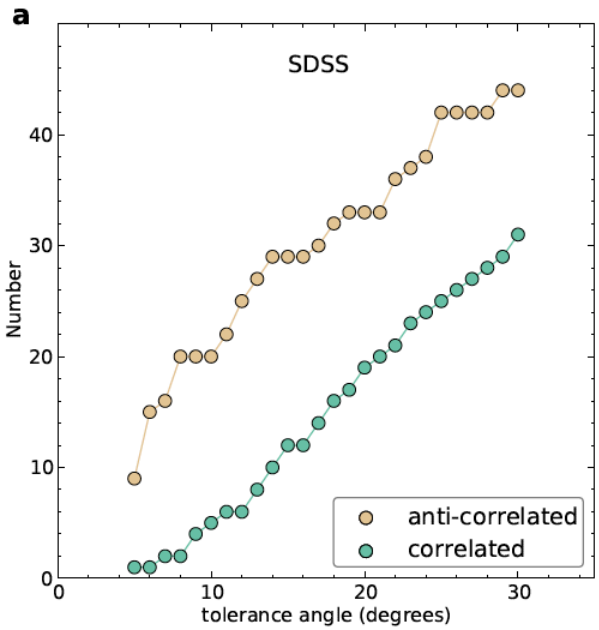
- $-23 < Mr < -20$
- Isolated: No brighter neighbour within 0.5 Mpc, and 1500 km/s
- $z < 0.05$ (very few satellite pairs beyond this redshift)
- sample contains: 24772 hosts

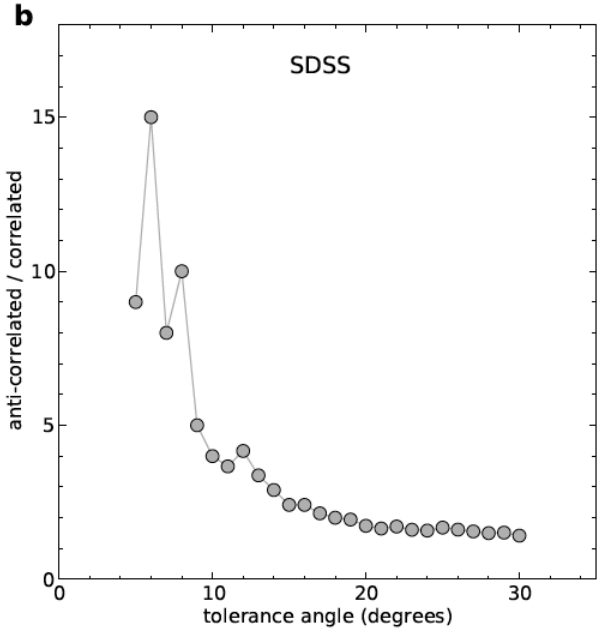
Satellites

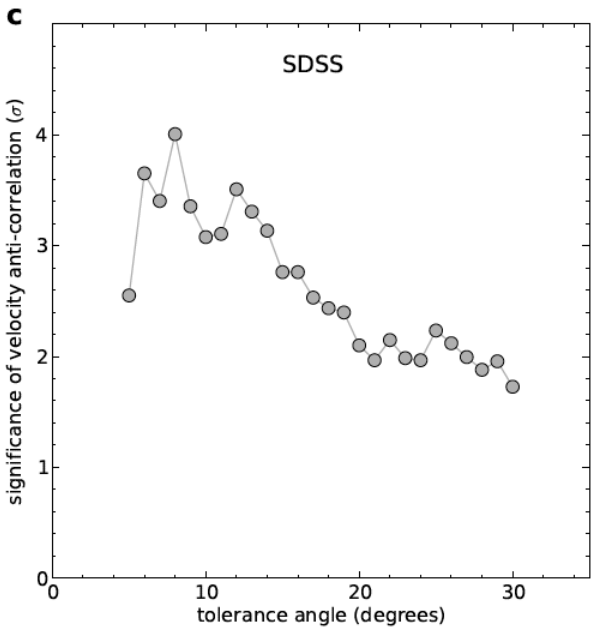
- at least 1 mag fainter than host, but brighter than $Mr = -16$
- distance from host: $20 < R < 150$ kpc (like PAndAS) , and within 300 exp(-(R/300kpc)0.8) km/s
- max velocity error: 25 km/s (typical error 15 km/s)
- velocity direction wrt host resolved: $|v - vhost| > error(|v - vhost|)$
- final sample: 380 **pairs** of satellites

And for real?

Running the same simple statistic!







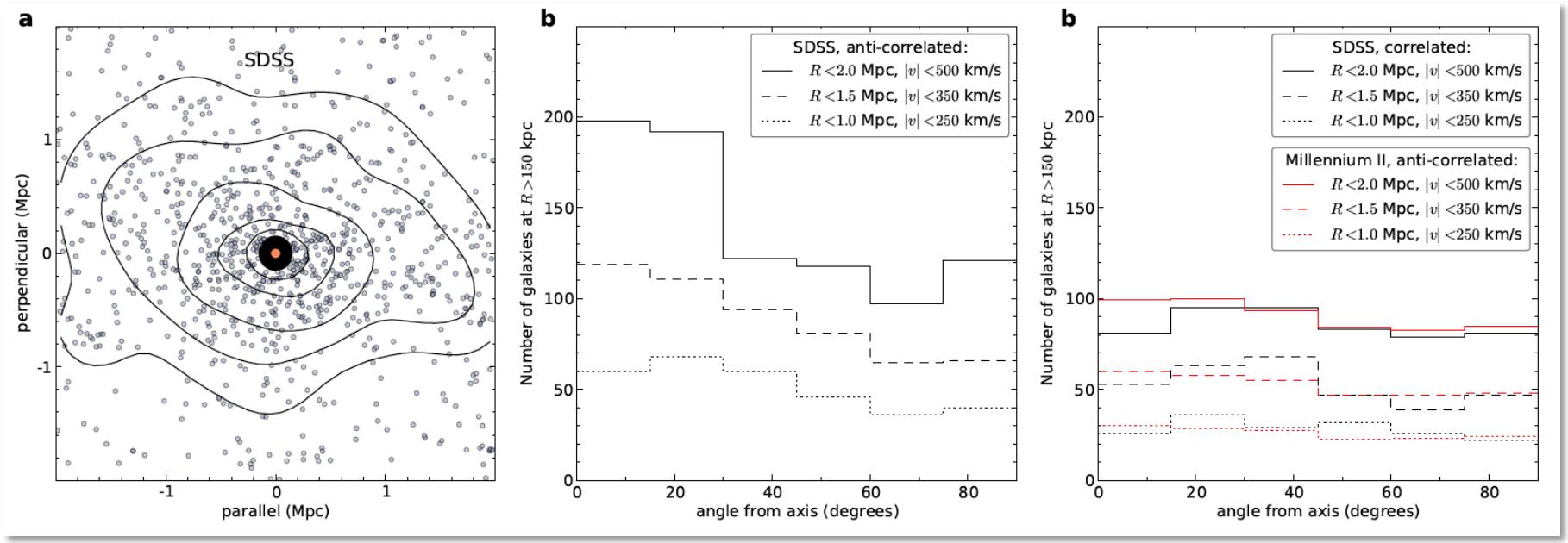
Clear signal of anti-correlated velocities; coherent orbits?

Ibata et al. (2014; Nature)

Large scale correlations!

What if there were correlated dwarf orbits everywhere?

And are they correlated with Large Scale Structure?



Yes!

Ibata et al. (2014; Nature)

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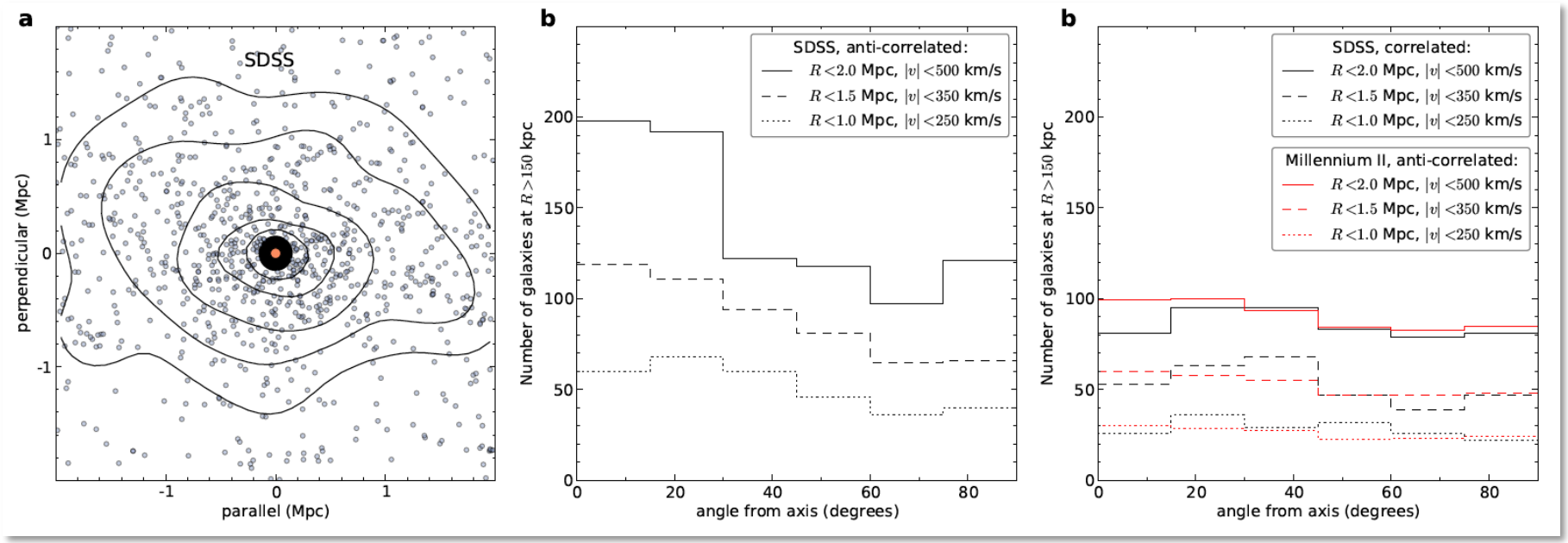

Ibata et al. (2014; Nature)

Yes! What does it mean?

Ummmm ????????

Cosmologist

Conclusions

- **PAndAS:** We now have the most comprehensive view of a galaxy halo out to 150kpc (as well as to 50kpc in M33)

- **Substructure:** We see extensive substructure, consisting of streams and clumps. We are currently comparing this to simulations.

- **Dwarf Population:** We've uncovered a large populations of dwarf galaxies, but still not as many as expected from cosmological predictions (modulo gas physics).

- **Great Plane:** A subsample of the dwarfs sit on a highly significant plane, 400kpc in extent but only 14kpc wide, which appears to have coherent rotation. A similar structure is seen in the Milky Way – Coincidence?

A Challenge for Cosmology?


The End