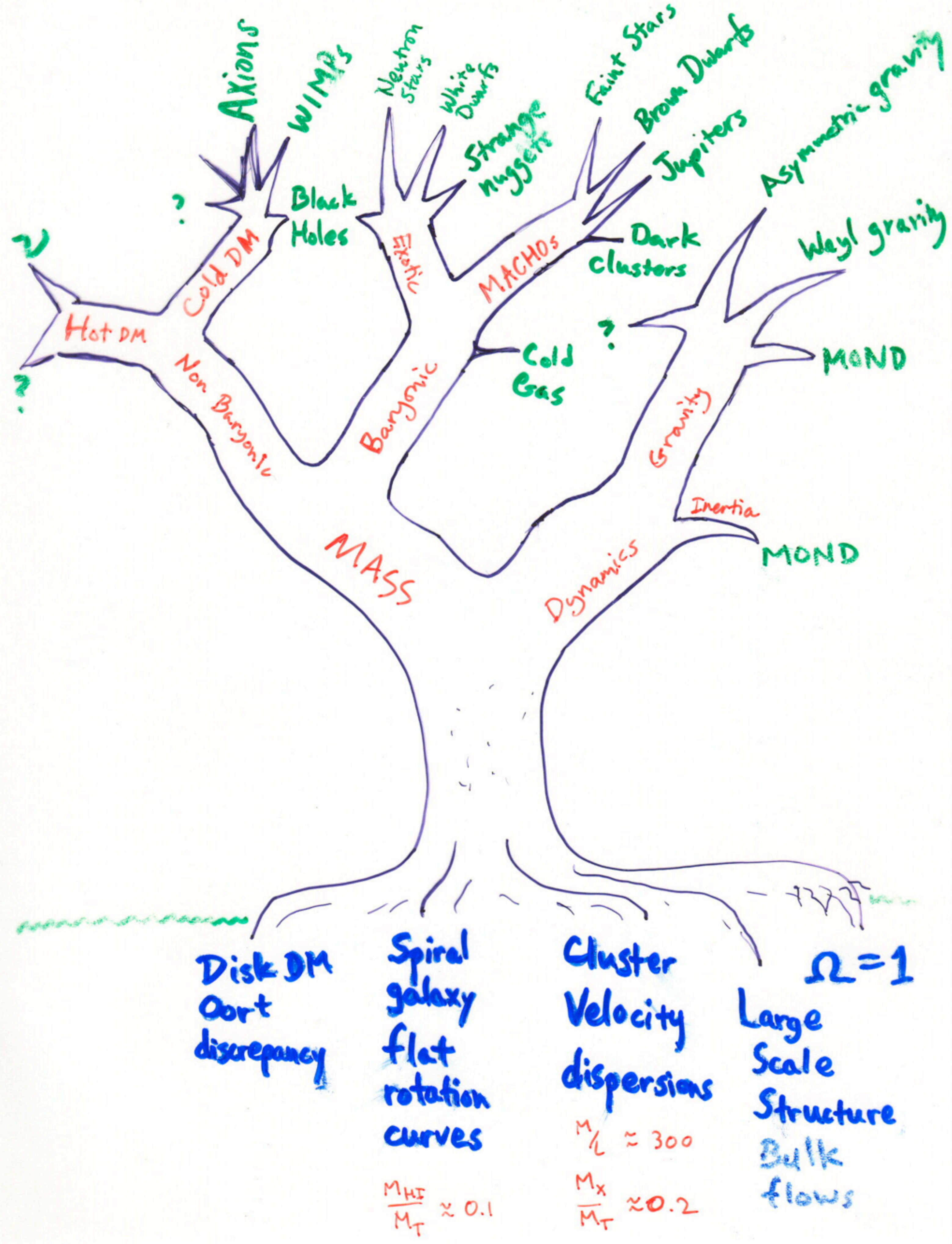
Dark Matter

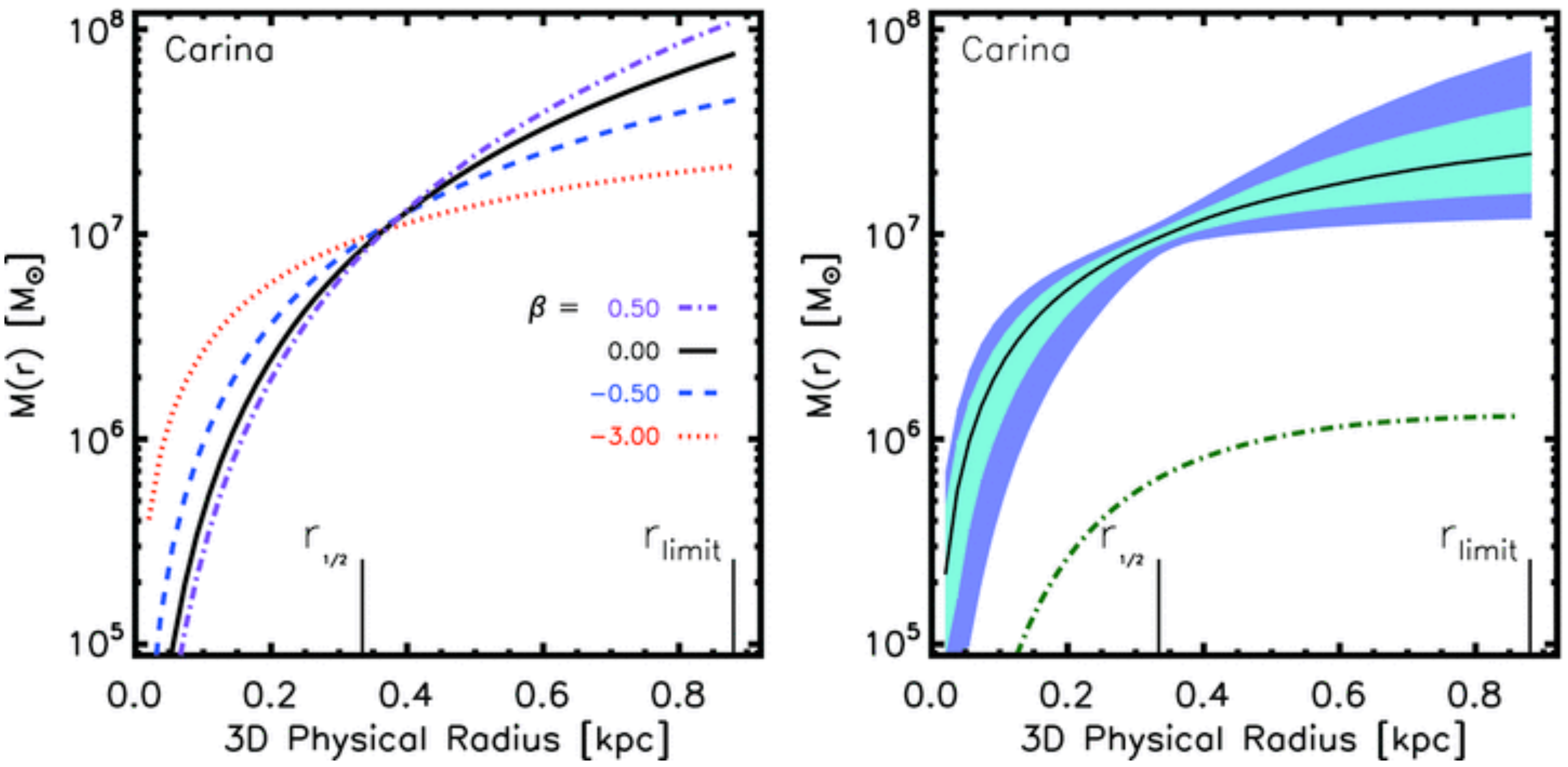
ASTR 333/433

TODAY

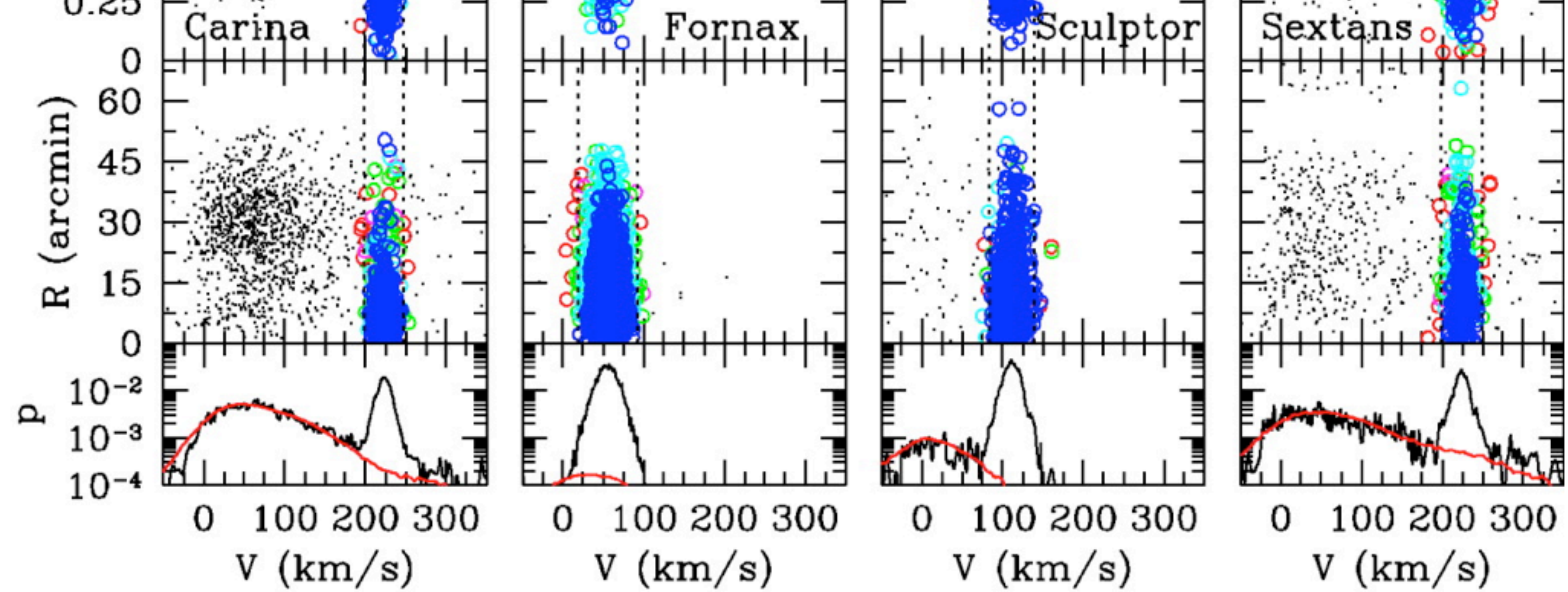
Cusp-Core in dSphs
Too Big To Fail
Planes of Satellites
Kitchen-Sink Models

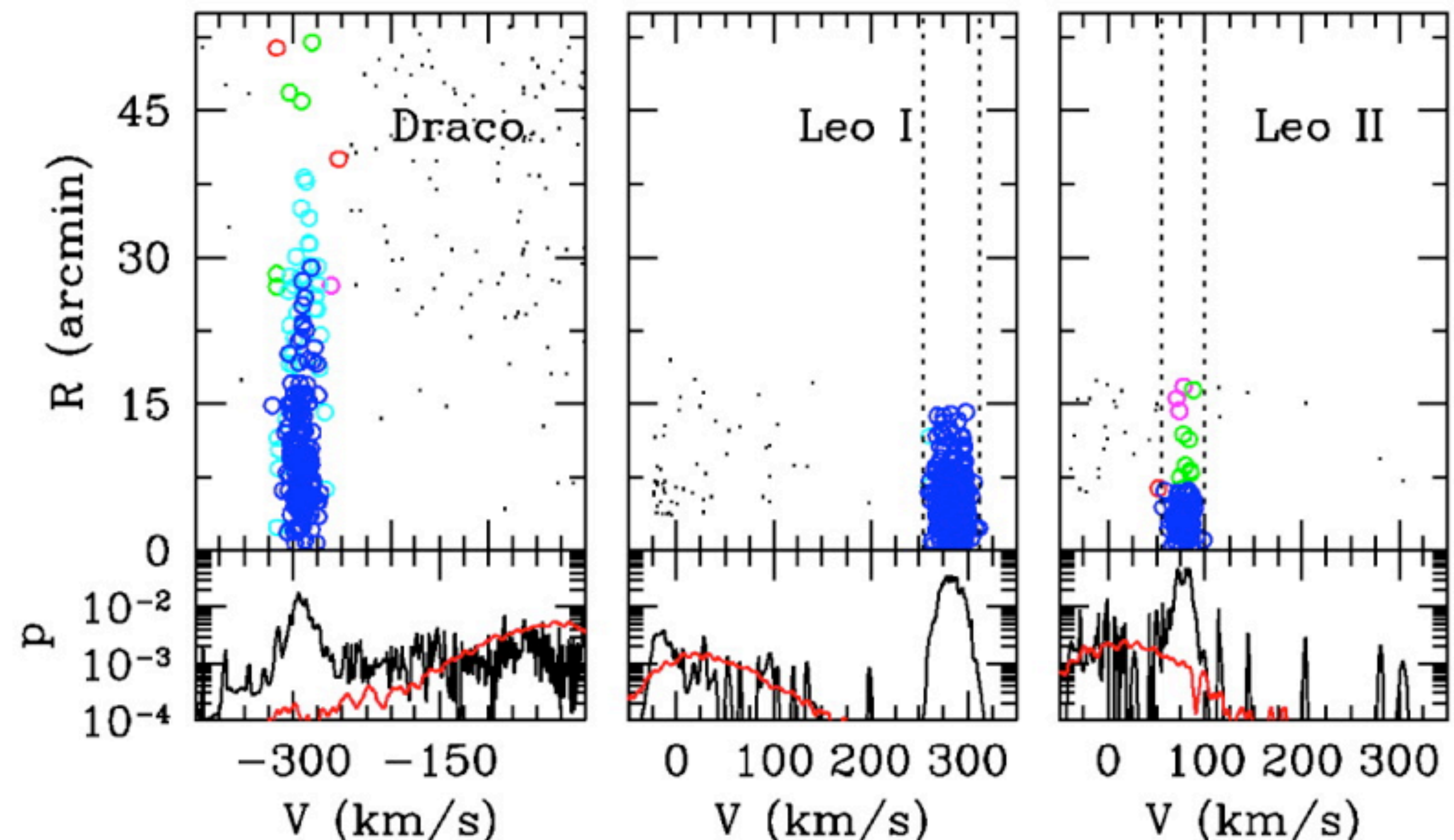


Wolf et al. (2010)



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



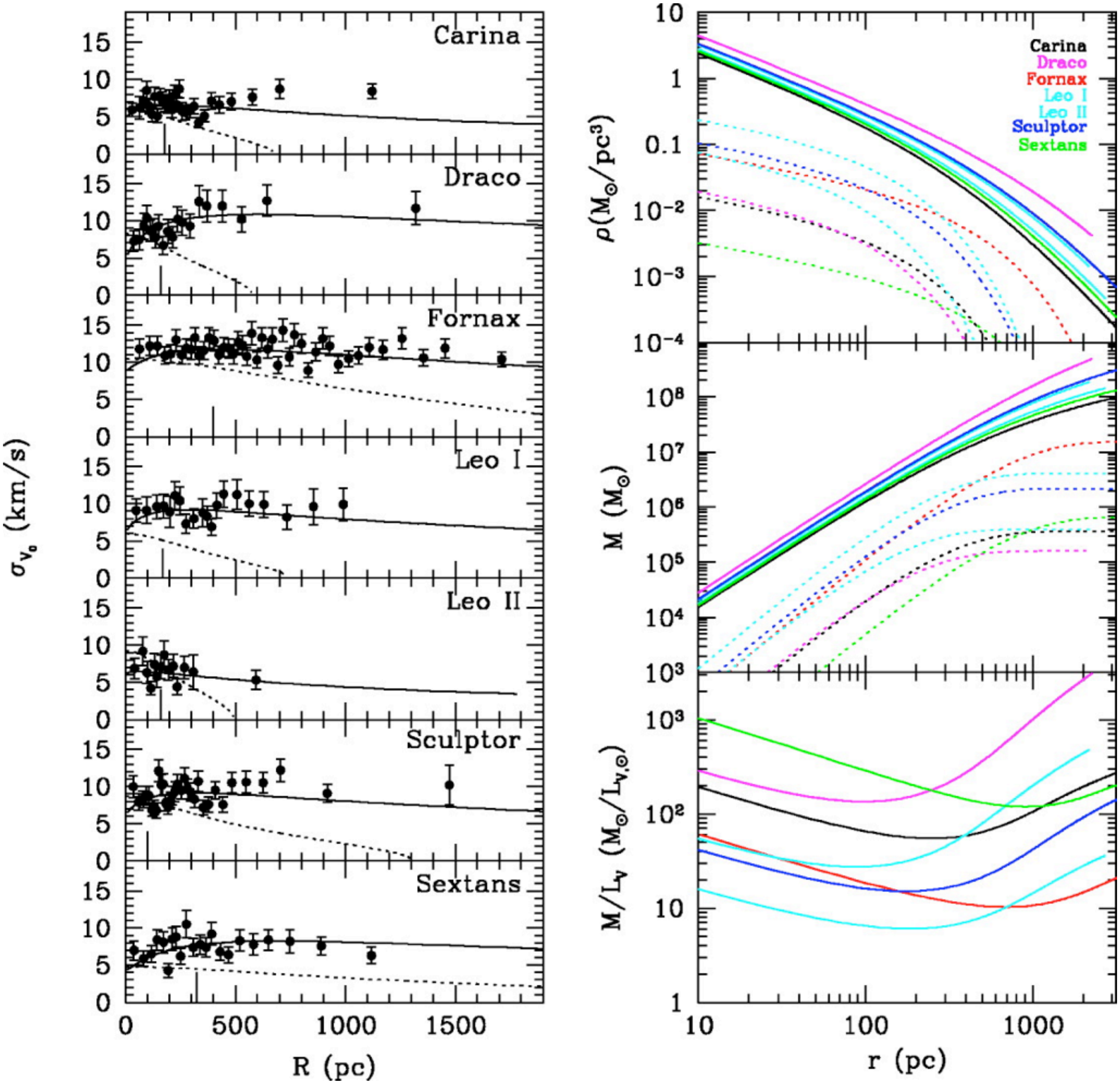


Velocity dispersions of dwarfs spheroidal galaxies measured from velocities of individual stars.

Walker et al. (2007)

Velocity dispersion profiles of dwarfs spheroidal galaxies approximately flat.

Walker et al. (2007)



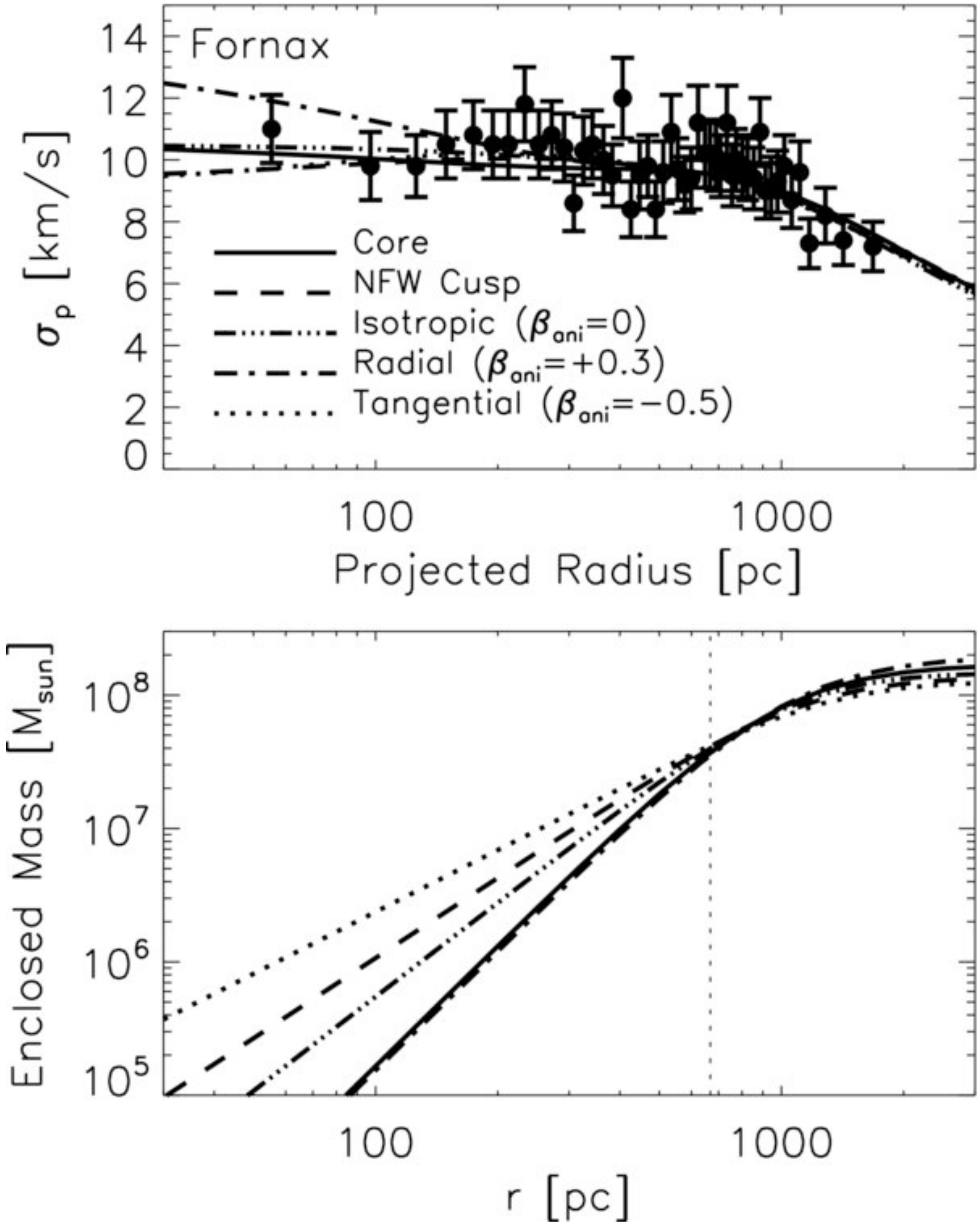
Walker & Penarrubia (2011) find that dSph galaxies suffer the same cusp-core problem as found in rotating low surface brightness galaxies

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

$\gamma = 0.39$ Fornax

$\gamma = 0.05$ Sculptor

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

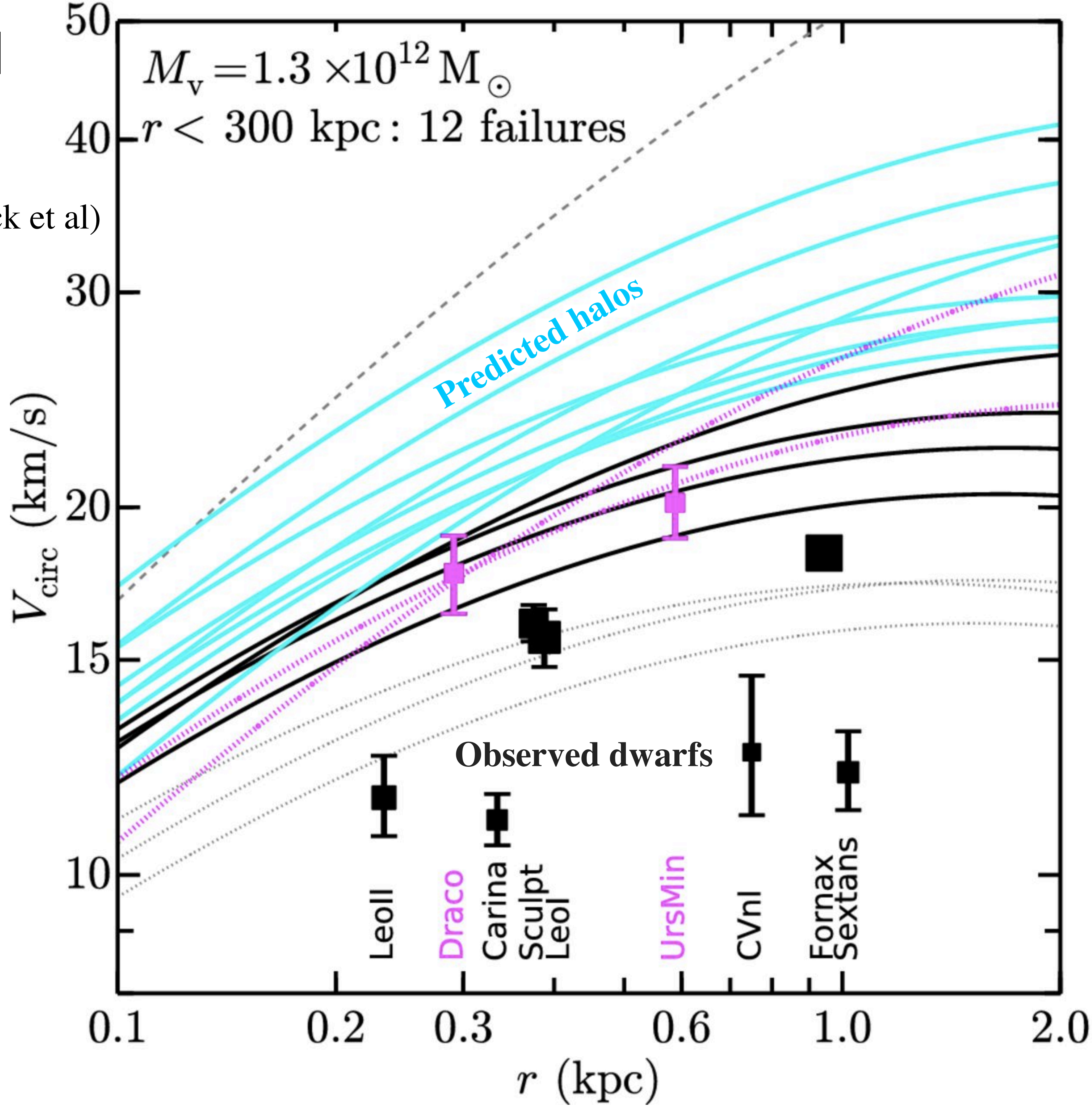


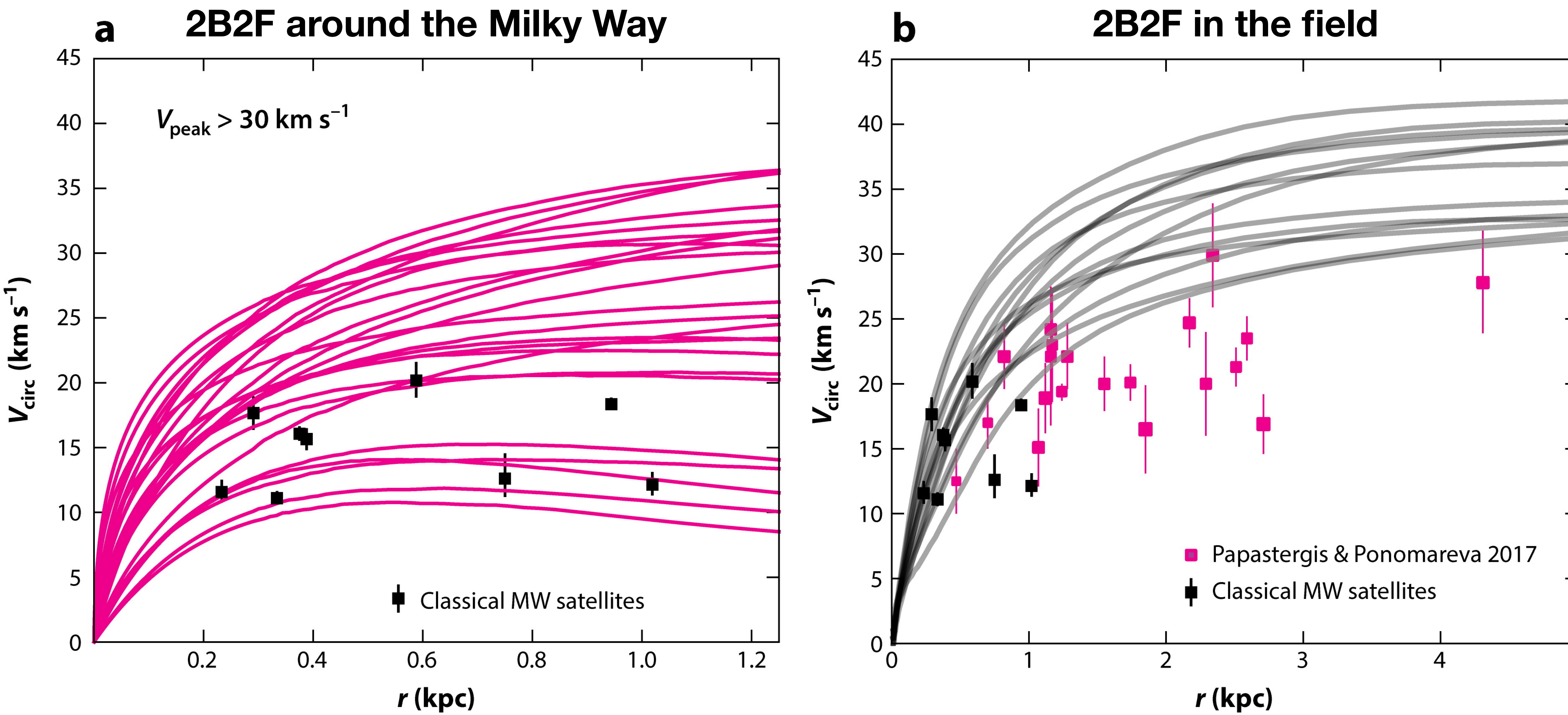
Too Big to Fail?

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?

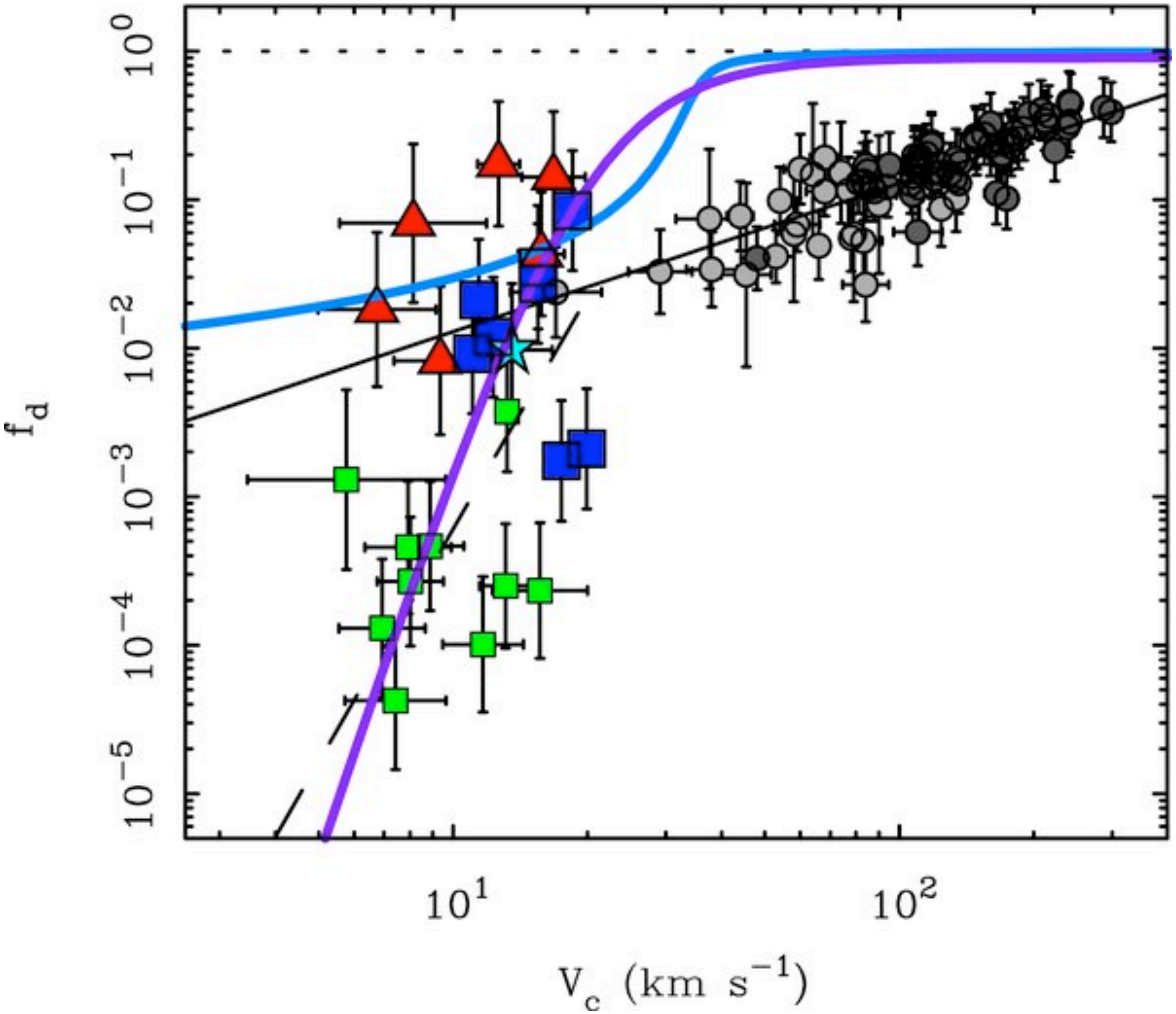




Bullock JS, Boylan-Kolchin M. 2017.
Annu. Rev. Astron. Astrophys. 55:343–87

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.

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

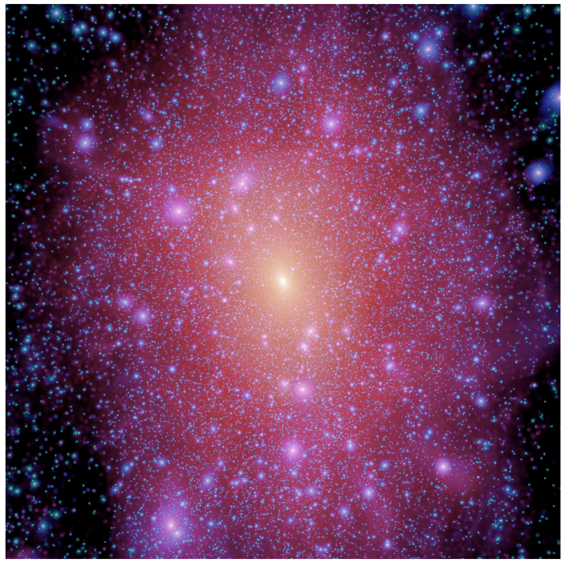


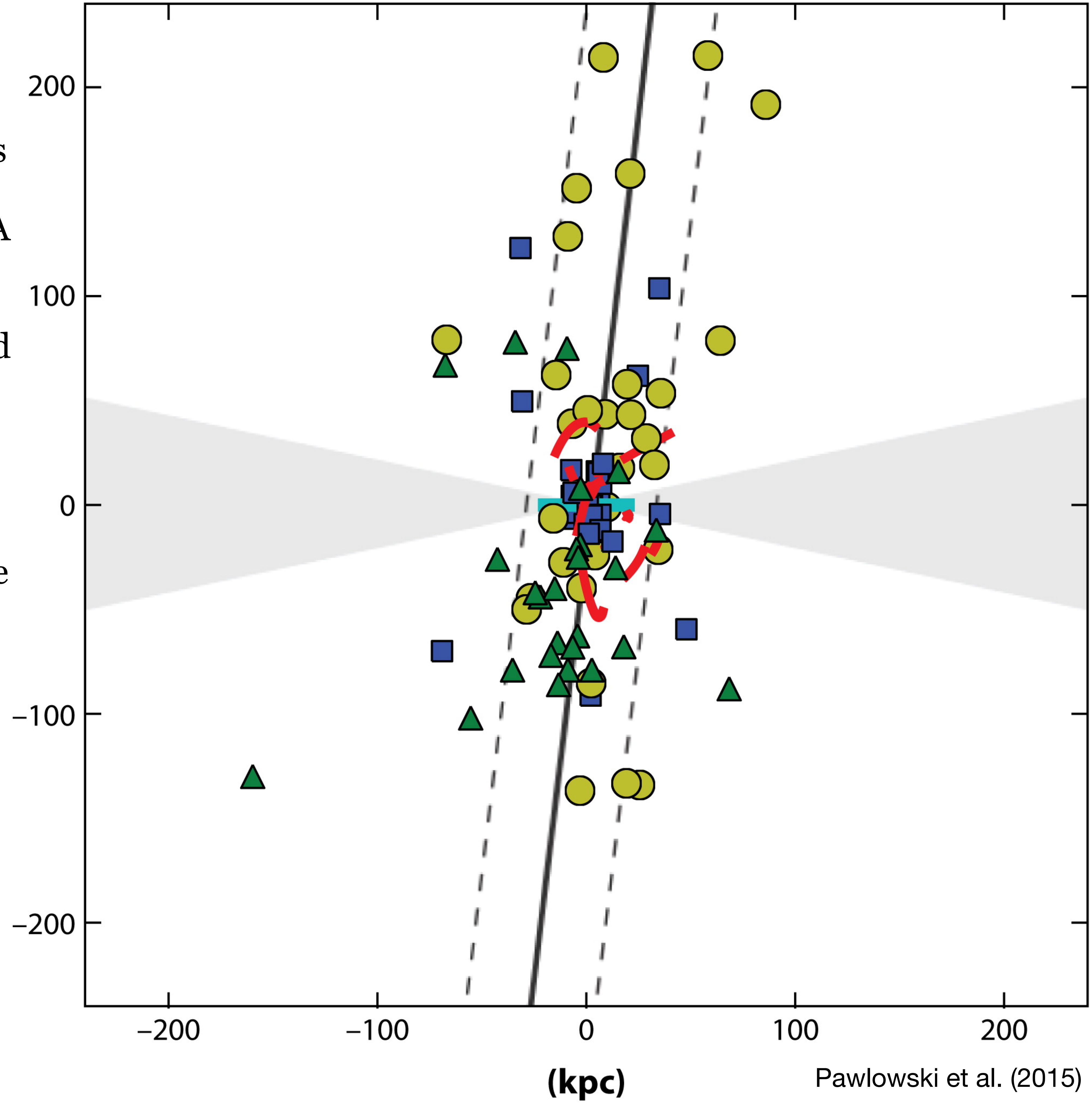
e.g., Reionization models illustrated here are good for explaining the smallest galaxies, but not ~40 km/s halos, which are too big to fail.

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.

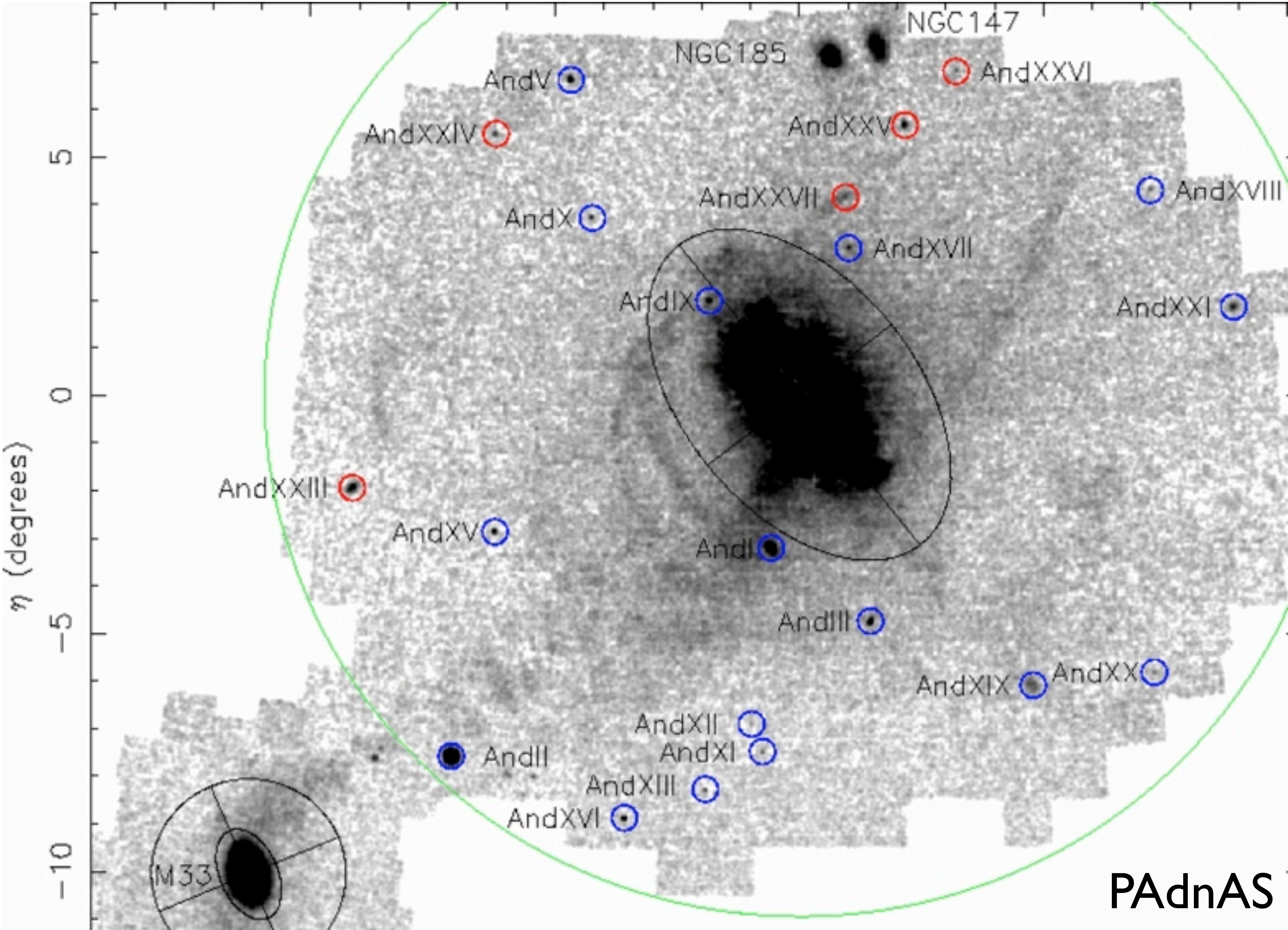
In DM simulations, the sub-halos thought to host dwarf satellites have highly radial orbits that are randomly oriented.





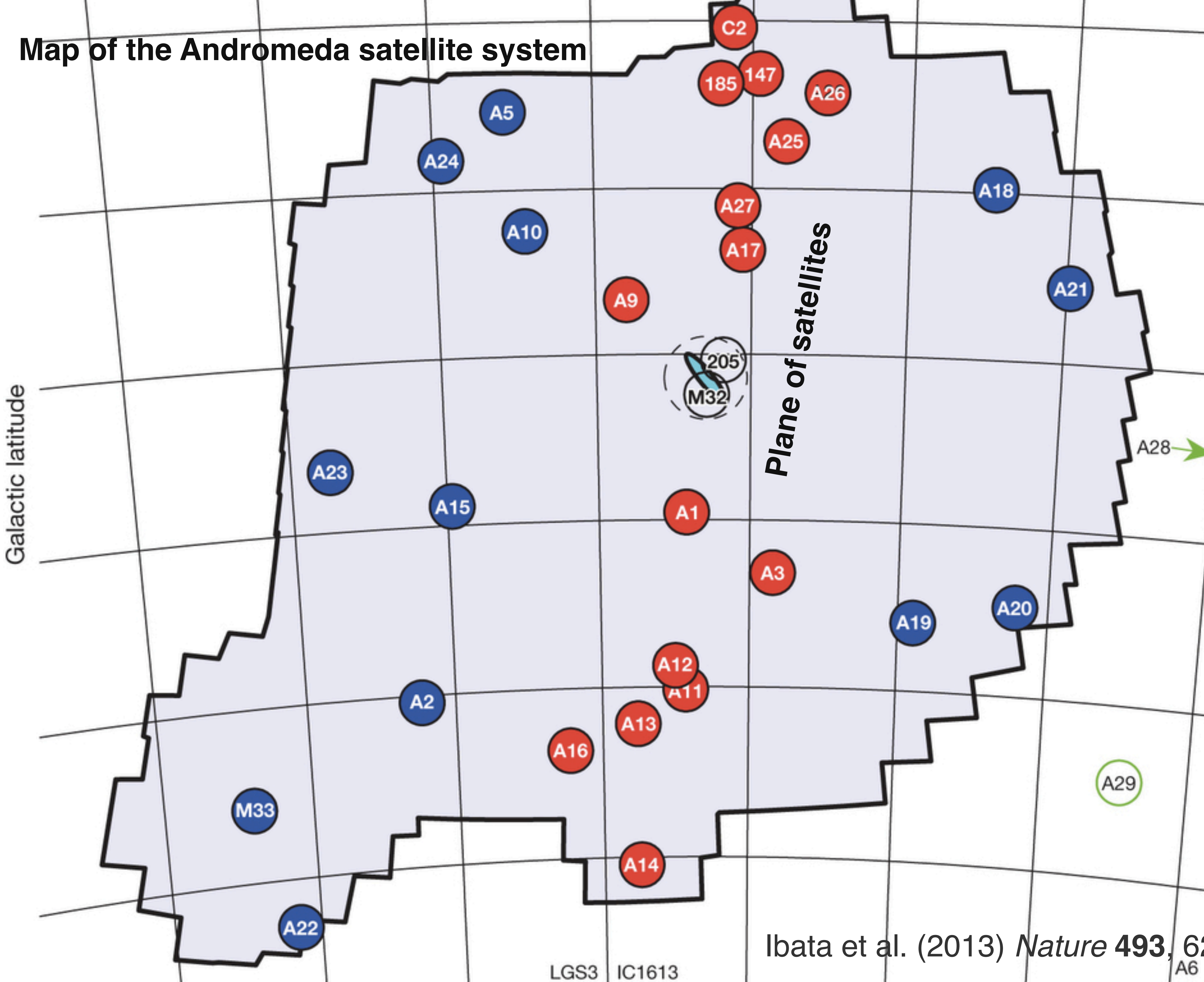
Pawlowski et al. (2015)

The dwarf satellites of Andromeda



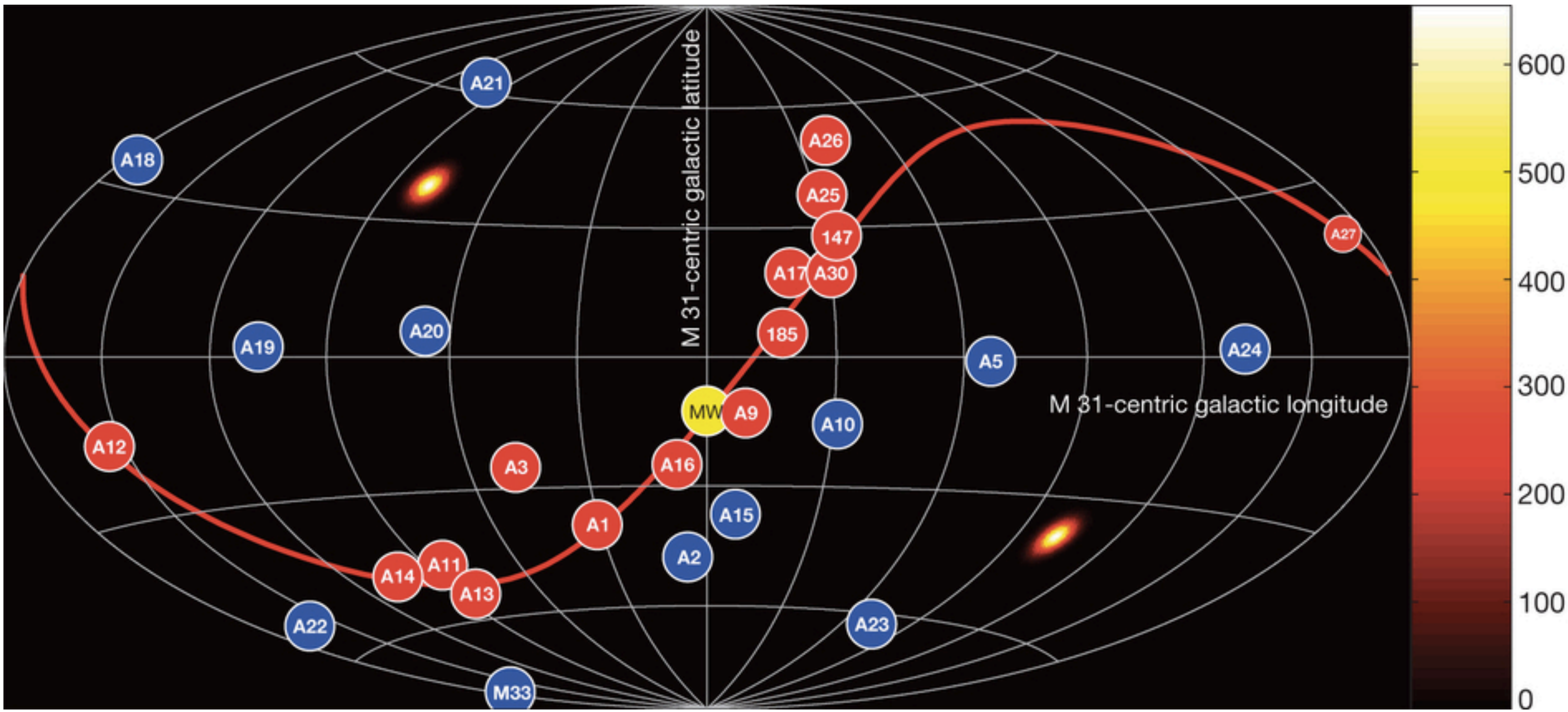
PAdnAS

Map of the Andromeda satellite system



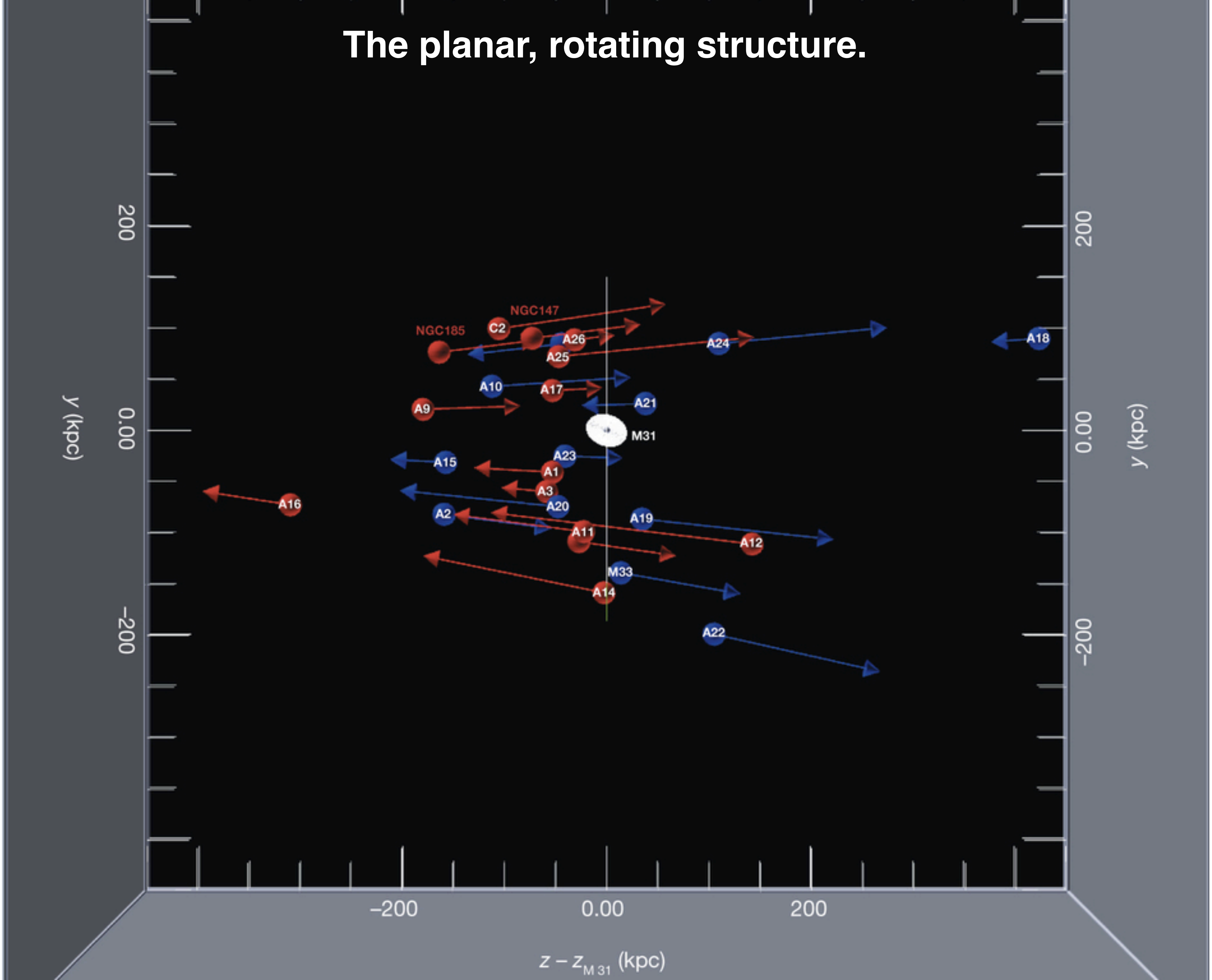
Ibata et al. (2013) *Nature* **493**, 62

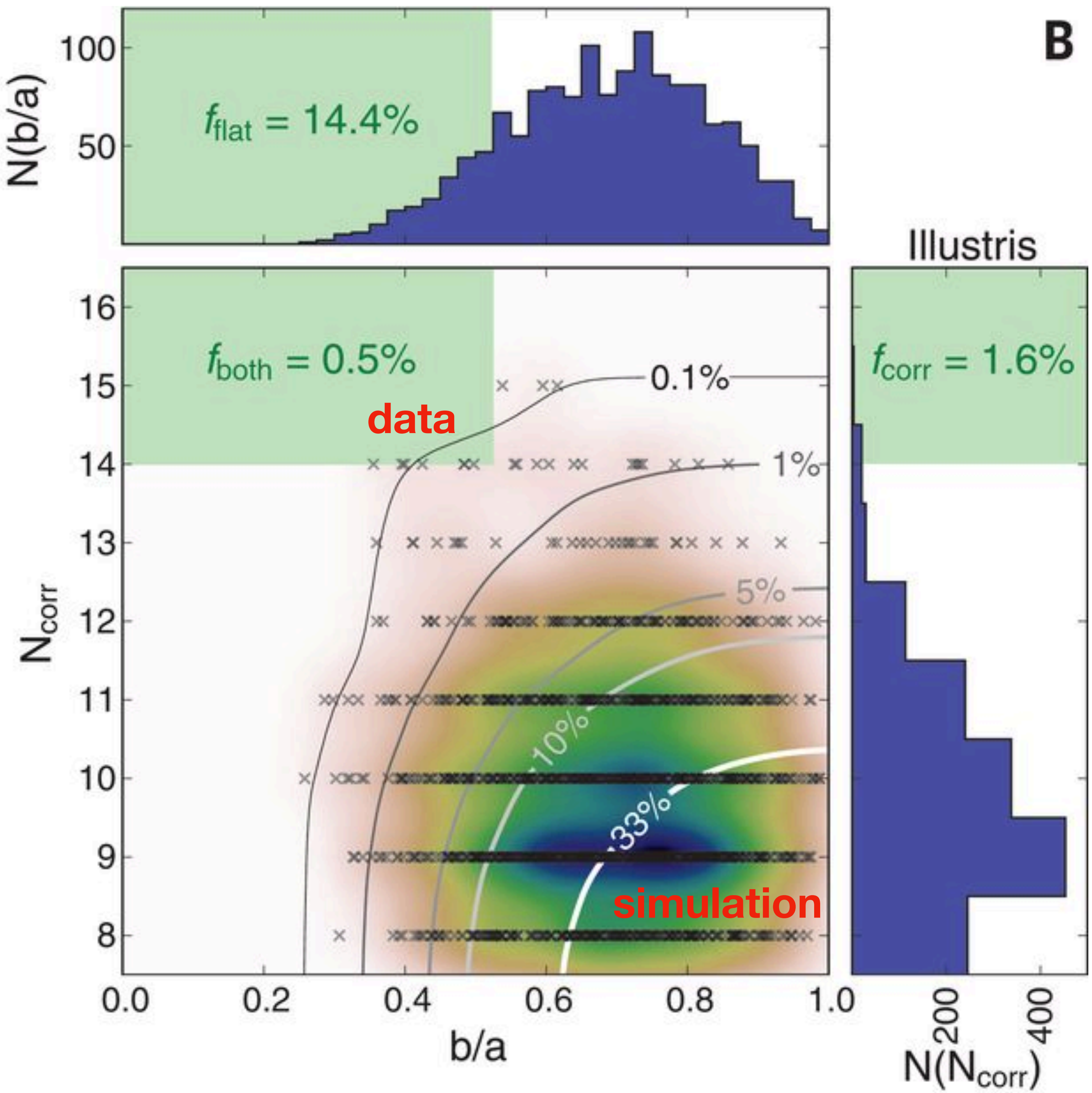
Satellite galaxy positions as viewed from Andromeda



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)

Dwarf satellite galaxies are problematic for CDM in several ways:

- there should be thousands of them rather than dozens
  (missing satellite problem)

- they have shallow dark matter halo profiles
  (cusp/core problem)

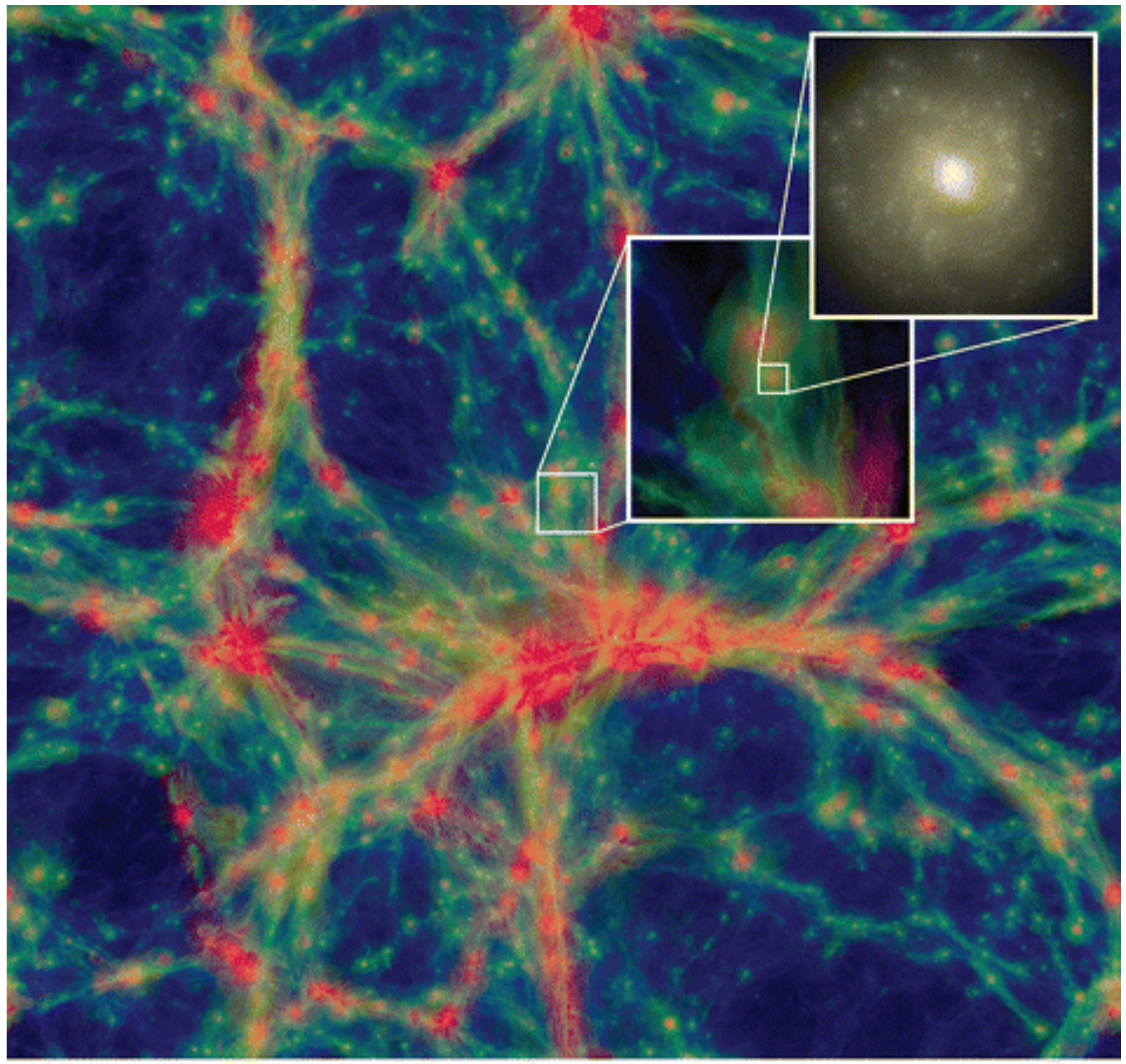
- Too Big to Fail
  (related to cusp/core problem)

- they tend to reside in co-orbiting planes
  (do not exhibit the expected isotropy in phase space)
  the phase space distribution could hardly be *more* different -
  observed thin planes in ordered rotation vs.
  predicted isotropic distribution of objects on predominantly radial orbits

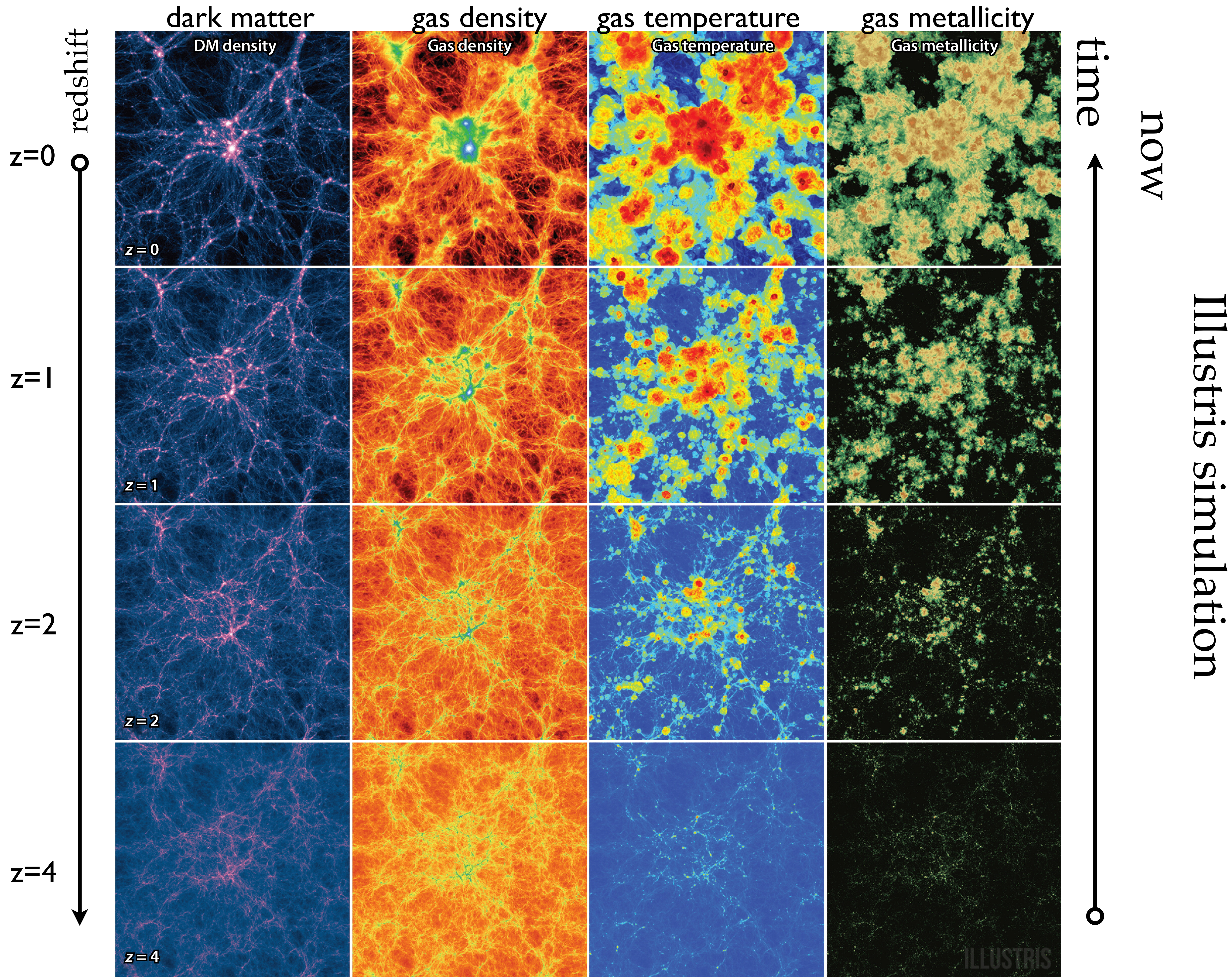
Too Big to Fail is basically a restatement of the cusp-core problem, convolved with the missing satellite problem, which itself is a rephrasing of the luminosity function problem (flat rather than steep faint end slope).

Kitchen sink cosmological models

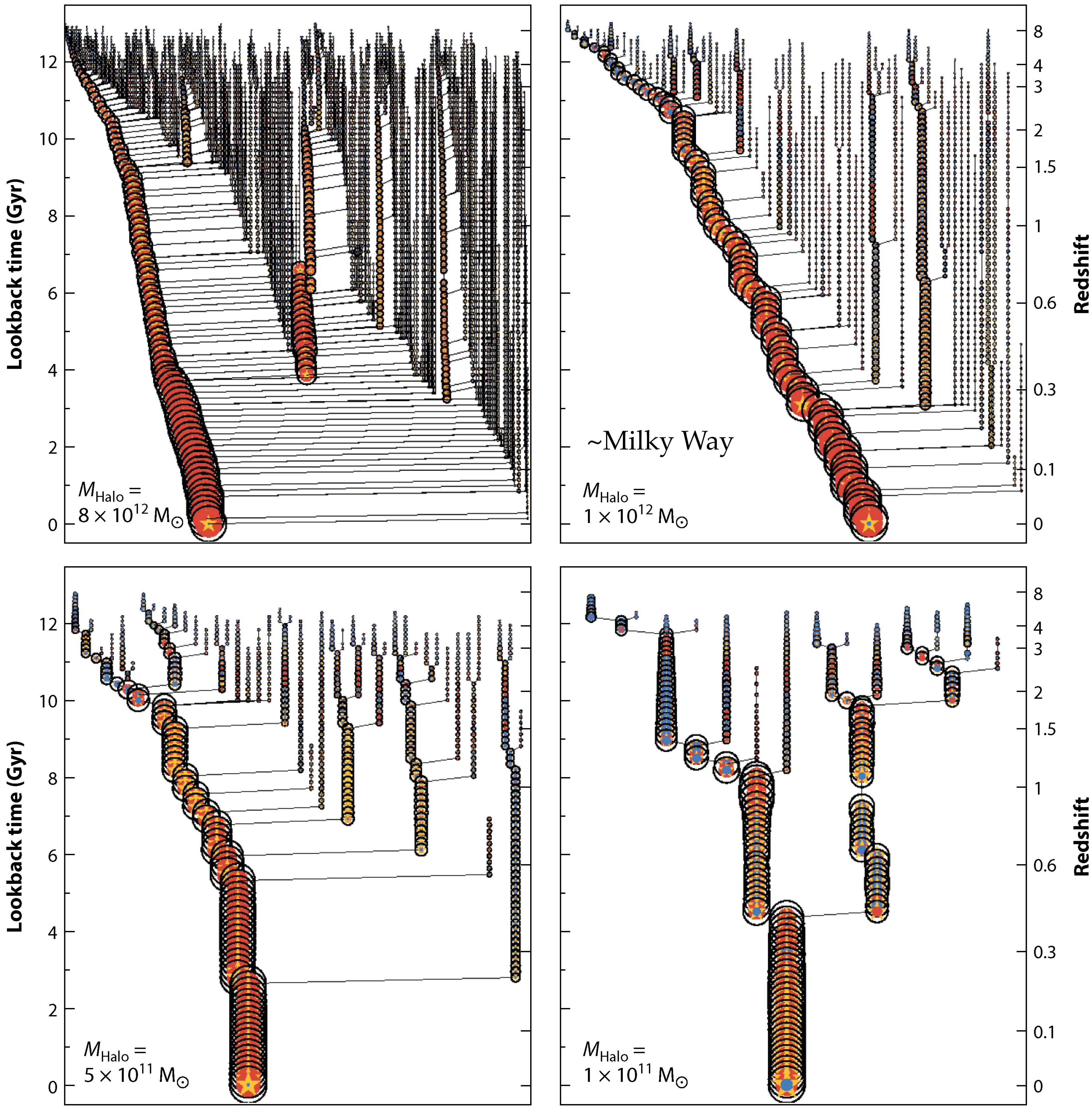
Somerville & Dave 2015 ARA&A, 53, 51

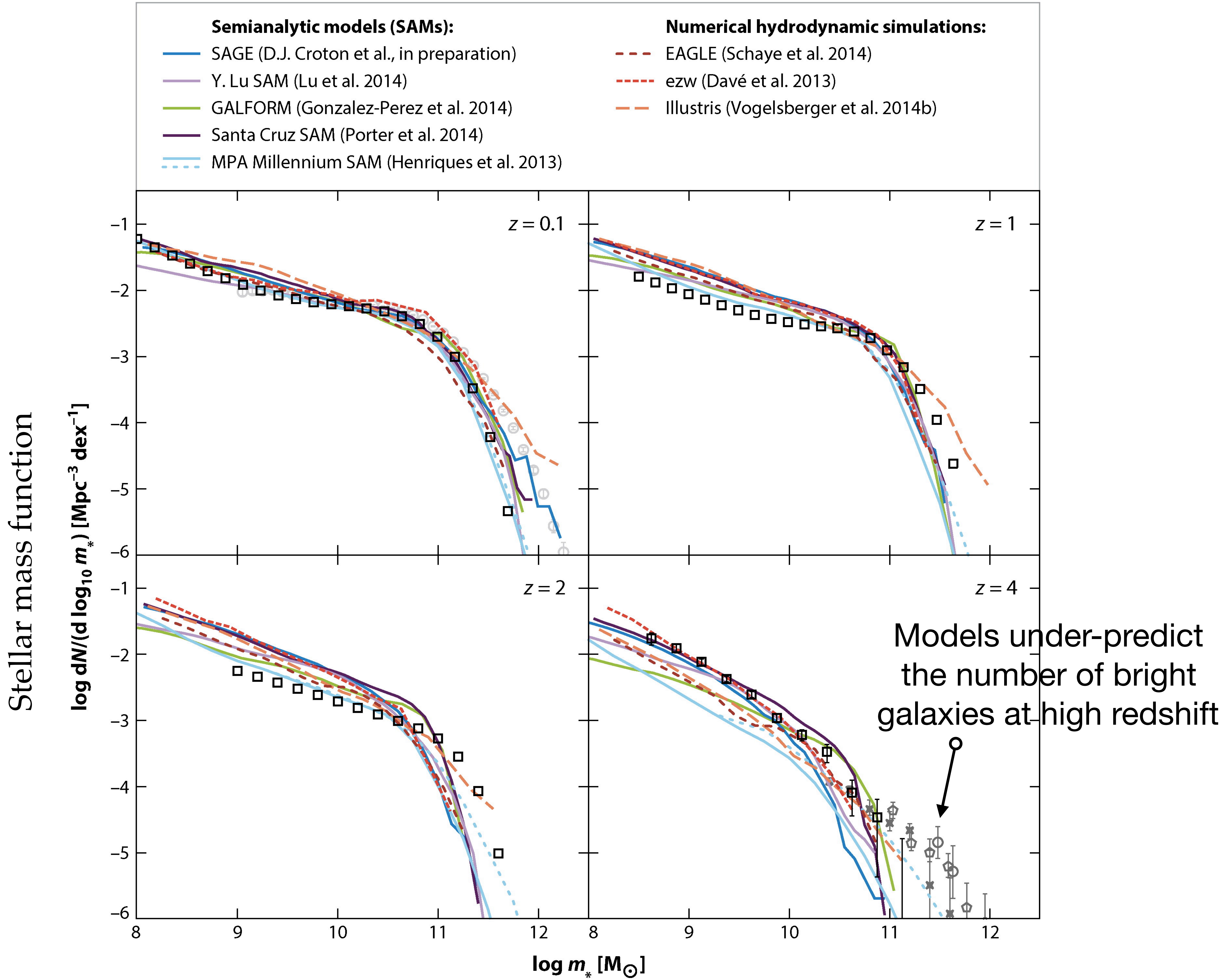


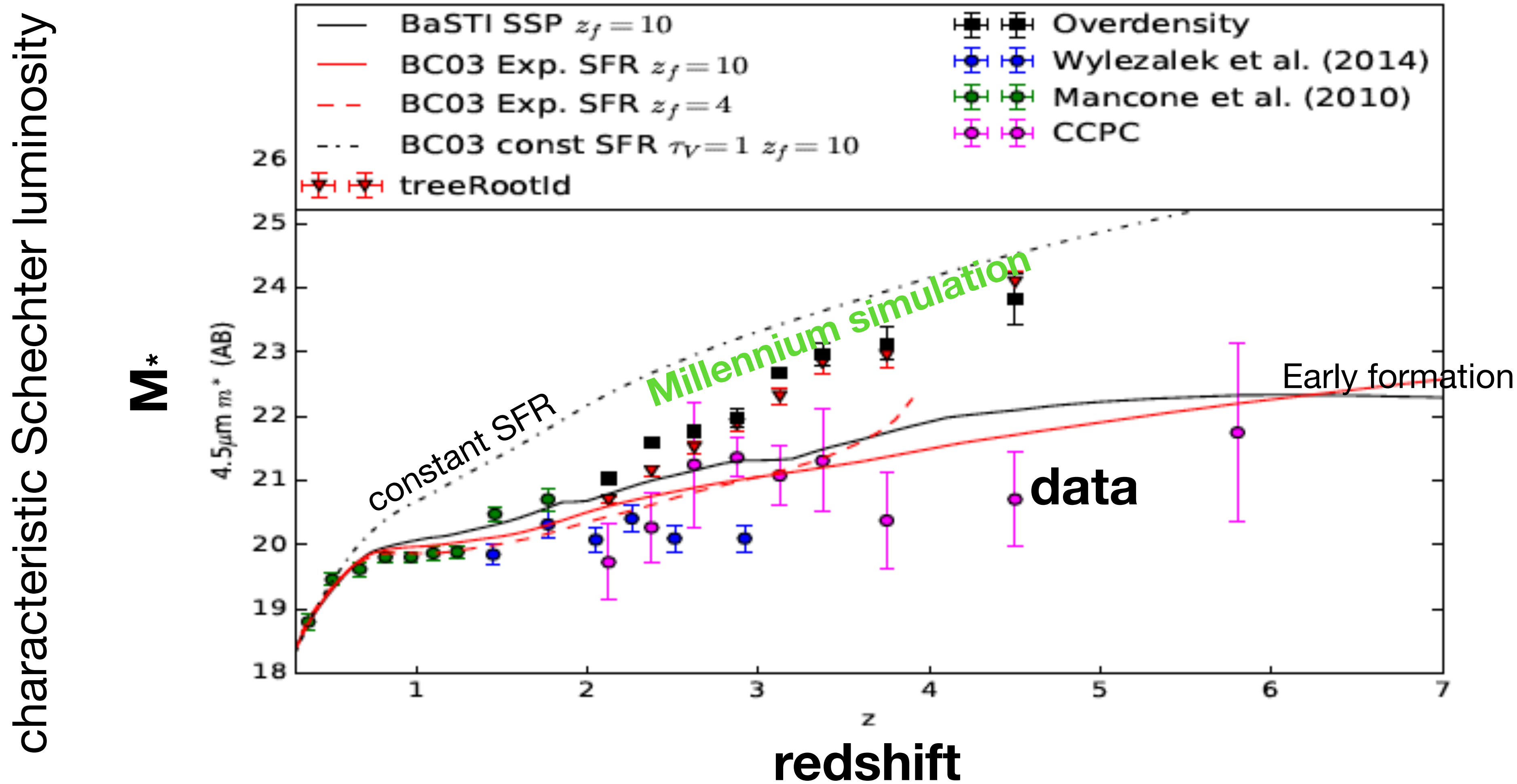
Somerville RS, Davé R. 2015.
Annu. Rev. Astron. Astrophys. 53:51–113


dark matter
gas density
gas temperature
gas metallicity
DM density
Gas density
Gas temperature
Gas metallicity
redshift
z=0
z=1
z=2
z=4
z = 0
z = 1
z = 2
z = 4
time
now
Illustris simulation
ILLUSTRIS

Halo assembly by mass

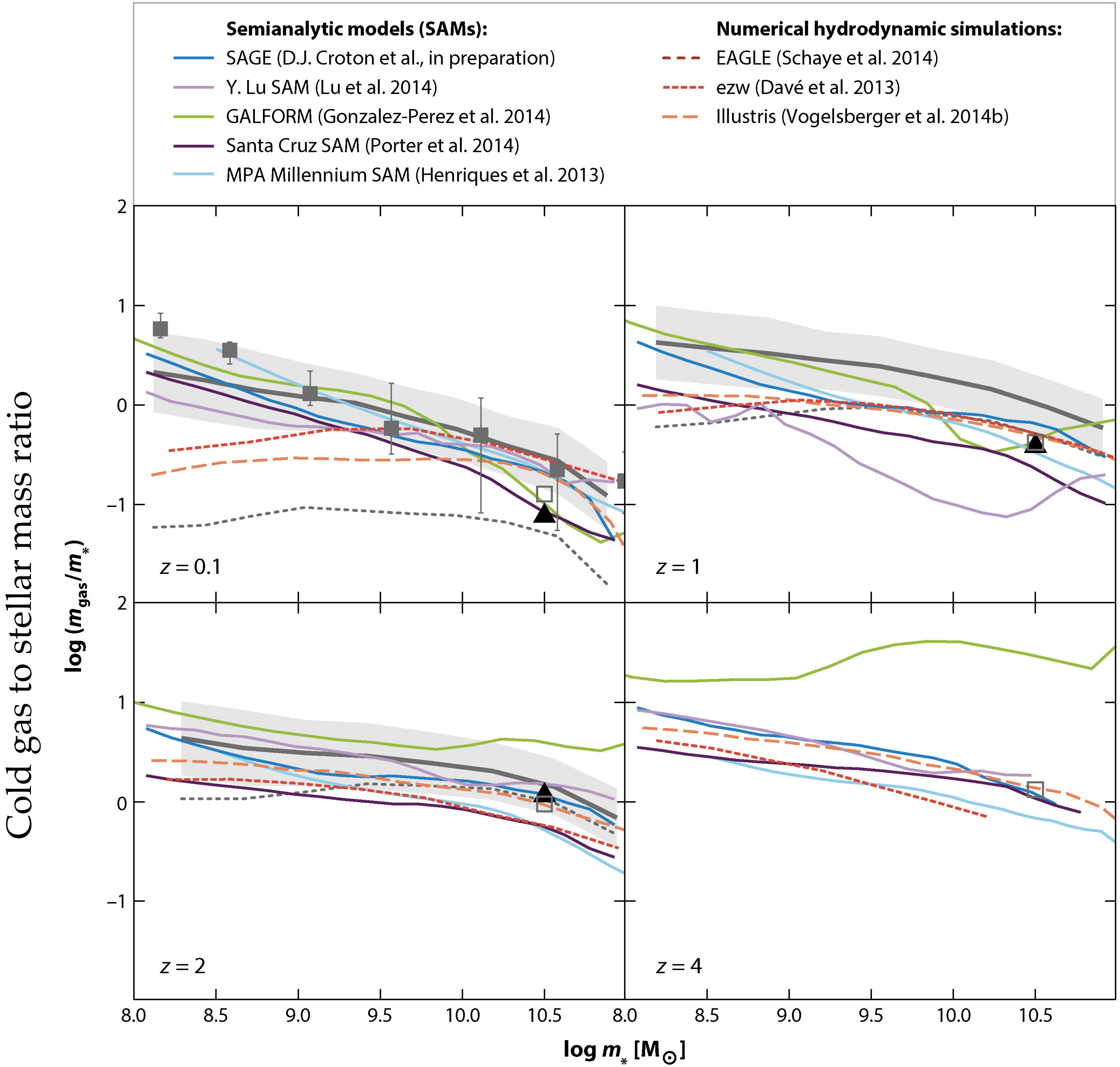



Semianalytic models (SAMs):
SAGE (D.J. Croton et al., in preparation)
Y. Lu SAM (Lu et al. 2014)
GALFORM (Gonzalez-Perez et al. 2014)
Santa Cruz SAM (Porter et al. 2014)
MPA Millennium SAM (Henriques et al. 2013)
Numerical hydrodynamic simulations:
EAGLE (Schaye et al. 2014)
ezw (Davé et al. 2013)
Illustris (Vogelsberger et al. 2014b)
z = 0.1
z = 1
z = 2
z = 4
Stellar mass function
log dN/(d log10 m*) [Mpc−3 dex−1]
log m* [M⊙]
Models under-predict the number of bright galaxies at high redshift



Franck (2017 PhD CWRU)

Figure 5.5: The evolution of the characteristic [4.5] magnitude of galaxies and their simulated counterparts as a function of redshift. Red triangles represent simulated protocluster galaxies as identified within the Millennium simulation by their *treeRootId*. Overdense galaxies (black squares) are identified in the Henriques et al. (2015) lightcones using the CCPC algorithm, and then fitted to a Schechter function to estimate $m^*(z)$ values at 4.5μm, as seen in Table 5.2. As a comparison, $m^*(z)$ for the CCPC are plotted as magenta points, along with galaxies in clusters and protoclusters at lower redshifts from the literature (Mancone et al., 2010; Wylezalek et al., 2014). Galaxy stellar population models constructed using EzGal are plotted as comparisons, but we are not assuming that these protoclusters and clusters are a progenitor-descendant matched sample. The mock data has a $m^*(z)$ trend that looks more similar to a constant star formation model (dust extinction of $\tau_V = 1$) shown by a dash-dot red line (Bruzual & Charlot, 2003) up to $z \sim 2$, where it might merge into a passive evolution model born at high redshift ($z_f > 7$). The simulations predict a large stellar mass assembly between $2 < z < 6.6$, while these data seem best fit by a massive, old population of galaxies.



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MPA Millennium SAM (Henriques et al. 2013)
Numerical hydrodynamic simulations:
EAGLE (Schaye et al. 2014)
ezw (Davé et al. 2013)
Illustris (Vogelsberger et al. 2014b)
Cold gas to stellar mass ratio
log (m_gas/m_*)
z = 0.1
z = 1
z = 2
z = 4
log m_* [M_⊙]