THE MASS OF M31

Wyn Evans

Institute of Astronomy, Cambridge

Jin An, Vasily Belokurov, Alis Deason & Laura Watkins

HISTORY

Most modern authors assume that M31 is the most massive member of the Local Group.

Most authors prior to 1985 assumed that the Milky Way galaxy was the most massive member of the Local Group (e.g., Lynden-Bell & Lin 1982).

In 1985, IAU Commission 33 adopted 220 km/s as the local circular velocity of the Milky Way (instead of 250 km/s).

EVIDENCE

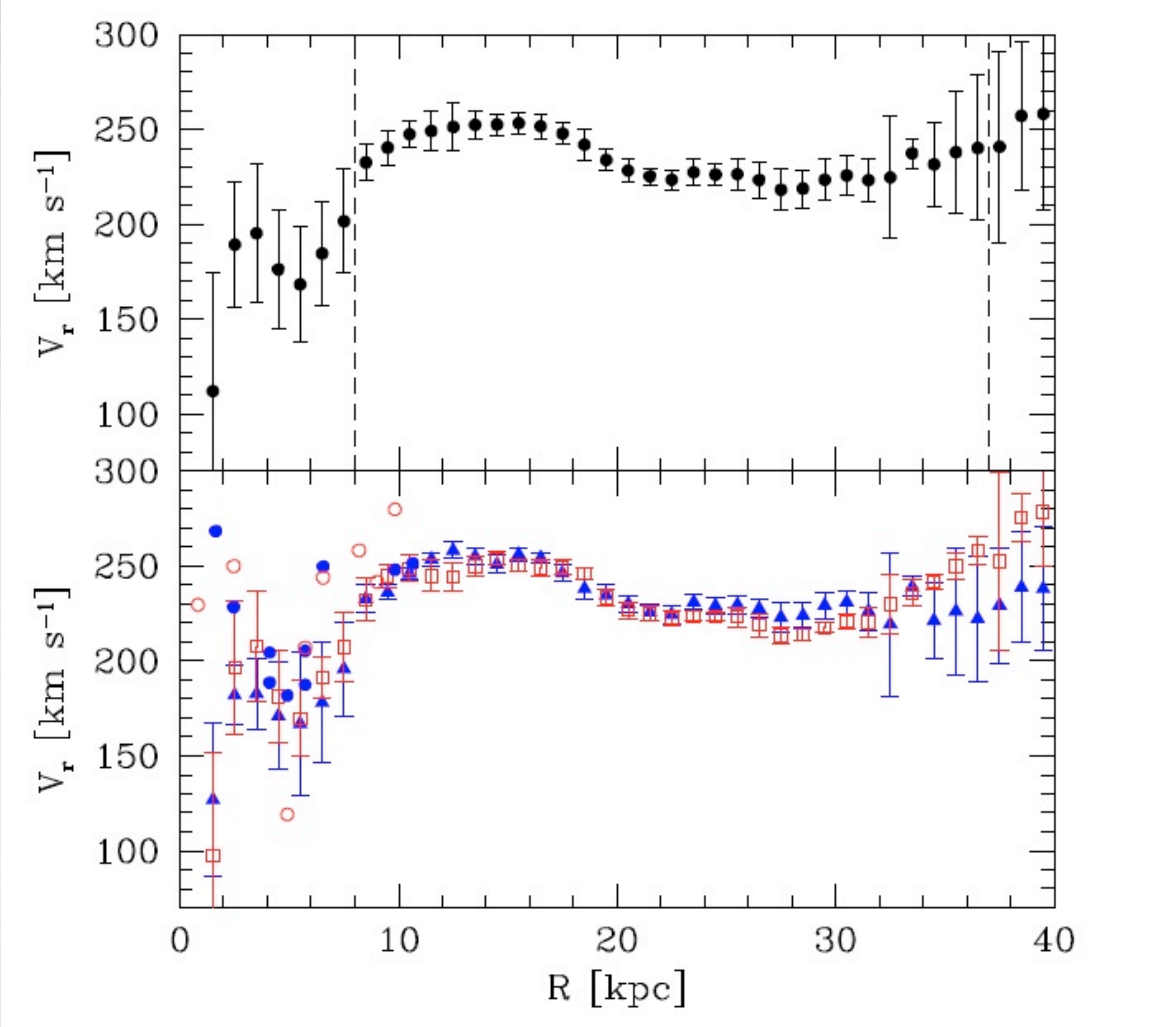
- The M31 rotation curve extends out to ~ 40 kpc and provides indirect evidence on the matter distribution. It can be decomposed into bulge, disk and halo contributions, though this procedure is inflicted by well-known degeneracies.
- The satellites of M31 extend out to ~ 300 kpc. They probe further, but they have their own limitations (selection effects, rogue satellites).

THE M31 ROTATION CURVE

M31 has a complex merging history, extended stellar streams. Accretion events produce morphological and dynamical signatures in the disc, (ring-like features, flares, filaments).

The disk of M31 warps from 25 kpc outwards. This causes the outer disc to be at higher inclination and lower position angle than the inner disc.

Corbelli et al. (2010) used an elegant tilted ring model to model the HI data from 8 to 37 kpc.



Corbelli et al 2010

THE M31 ROTATION CURVE

Beyond 27 kpc, the northern and southern halves do not give consistent rotation curves. This is due to the highly perturbed orbits in the outermost regions, especially for the southern half which is close to M31.

The peak value of the M31 rotation curve is ~ 255 km/s.

If we accept recent revisions upward of the local circular speed to ~250 km/s (Reid et al. 2009), then the Milky Way and M31 are comparably massive.

THE M31 DISC & BULGE

The disk is modeled as exponential with a scale-length between 4.5 and 6.1 kpc. The bulge is modeled as Sersic with index n=4, or n=1.6 & effective radius 2.0 or 0.7 kpc. The halo is modeled as NFW.

The best-fitting model implies a stellar disk and bulge mass of $\sim 1.3 \times 10^{10}\ M_\odot$, stellar mass-to-light ratio of 4.2 & disk scale-length 4.5 kpc. Adding the cold gas mass (neutral and molecular hydrogen plus helium) of $\sim 7.7 \times 10^{9}\ M_\odot$ gives a total baryonic mass of $\sim 1.4 \times 10^{10}\ M_\odot$ (Corbelli et al. 2010).

THE M31 DARK HALO

The dark halo mass is ~ $1.2 \times 10^{12} M_{\odot}$ together with a concentration of c ~12. The baryonic fraction is 0.12, similar to the cosmic inferred value of 0.14 (Corbelli et al 2010).

Similar algorithms have been employed by others.

Seigar et al. (2008) used a Spitzer 3.6 μm image, a mass-to-light ratio based on B-R colour, together with the rotation curve. They obtain a dark halo mass of ~ $8.2 \times 10^{11} M_{\odot}$ and a concentration c ~ 20.

THE M31 SATELLITES

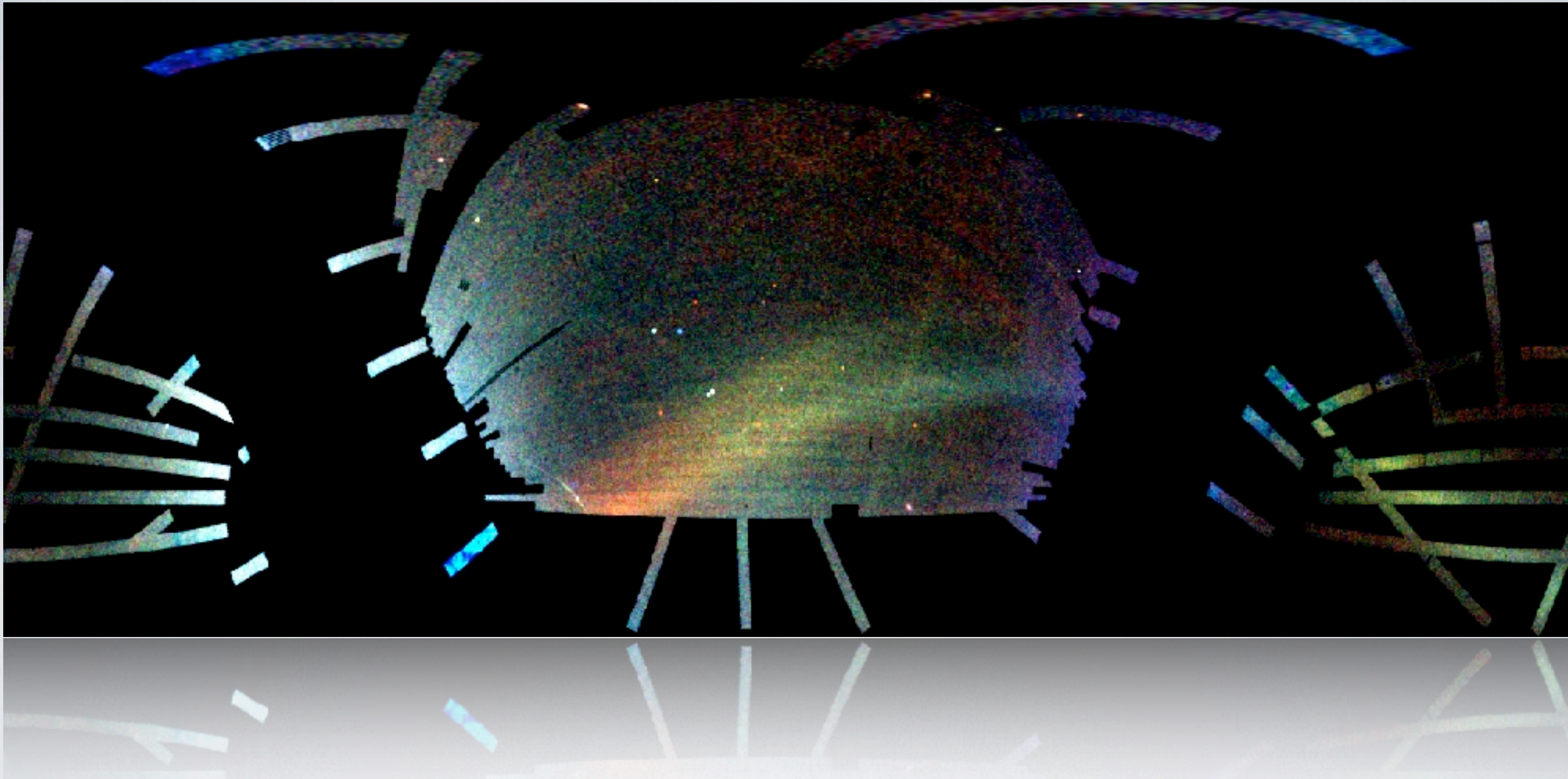
The only denizens of the far halo of M31 with velocities and positions are the satellite galaxies.

The far halo of the Milky Way galaxy can be probed both with the satellite galaxies and with halo stars. Samples of distant A-type stars, with measured velocities -- particularly blue horizontal branch stars -- are becoming available at large distances from the Galactic Centre and provide an alternative dataset to the satellite galaxies.

MASS ESTIMATORS

Simple estimators are often used to compute the mass of a dark halo from the positions and velocities of the satellite galaxies. They make simplifying assumptions, such as spherical symmetry of the dark halo, or constant velocity anisotropy.

There are numerous effects – triaxiality of the halo, continuing infall to the present day, variation of anisotropy with radius – that are not accounted for in the mass estimators.



THE FIELD OF STREAMS

Belokurov, Zucker, Evans et al 2006

CALIBRATION

To have any confidence in the results, any mass estimator will need to be calibrated against simulations.

The Galaxies-Intergalactic Medium Interaction Calculation (GIMIC, Crain et al. 2009) consists of a set of hydrodynamical re-simulations of five spherical region (~ $20h^{-1}$ Mpc in radius) extracted from the Millennium Simulation.

Includes (i) a prescription for star formation, (ii) radiative gas cooling, (ii) SN feedback.

THE GIMIC SIMULATIONS

Haloes and satellites are extracted with a FoF algorithm. The main galaxy is the most massive halo in a FoF system. The other self-bound substructures are classified as satellite galaxies. Resolution of dark matter and gas particles is ~ 10^7 $M_\odot$.

Deason et al (2011) extracted a sample of haloes corresponding to late-type galaxies together with their satellite populations (431 haloes, 4864 satellites). Mass range of satellites is 10^8 to 10^{10} $M_\odot$.

MASS ESTIMATORS

Tracer mass estimators take the general form:

$$M = C \sum_i v^2_{los,i} R_i^{\alpha}$$

where $v_{los,i}$ and R_i are the line of sight velocity and projected position of the i-th satellite, and C is a constant. When $\alpha = 1$ fo, this is the projected mass estimator (PME) of Bahcall & Tremaine (1981) derived for a Keplerian potential.

Watkins, Evans & An (2011) showed that $\alpha \approx 0.5$ is a good choice for NFW haloes ($\psi \sim r^{-0.5}$) .

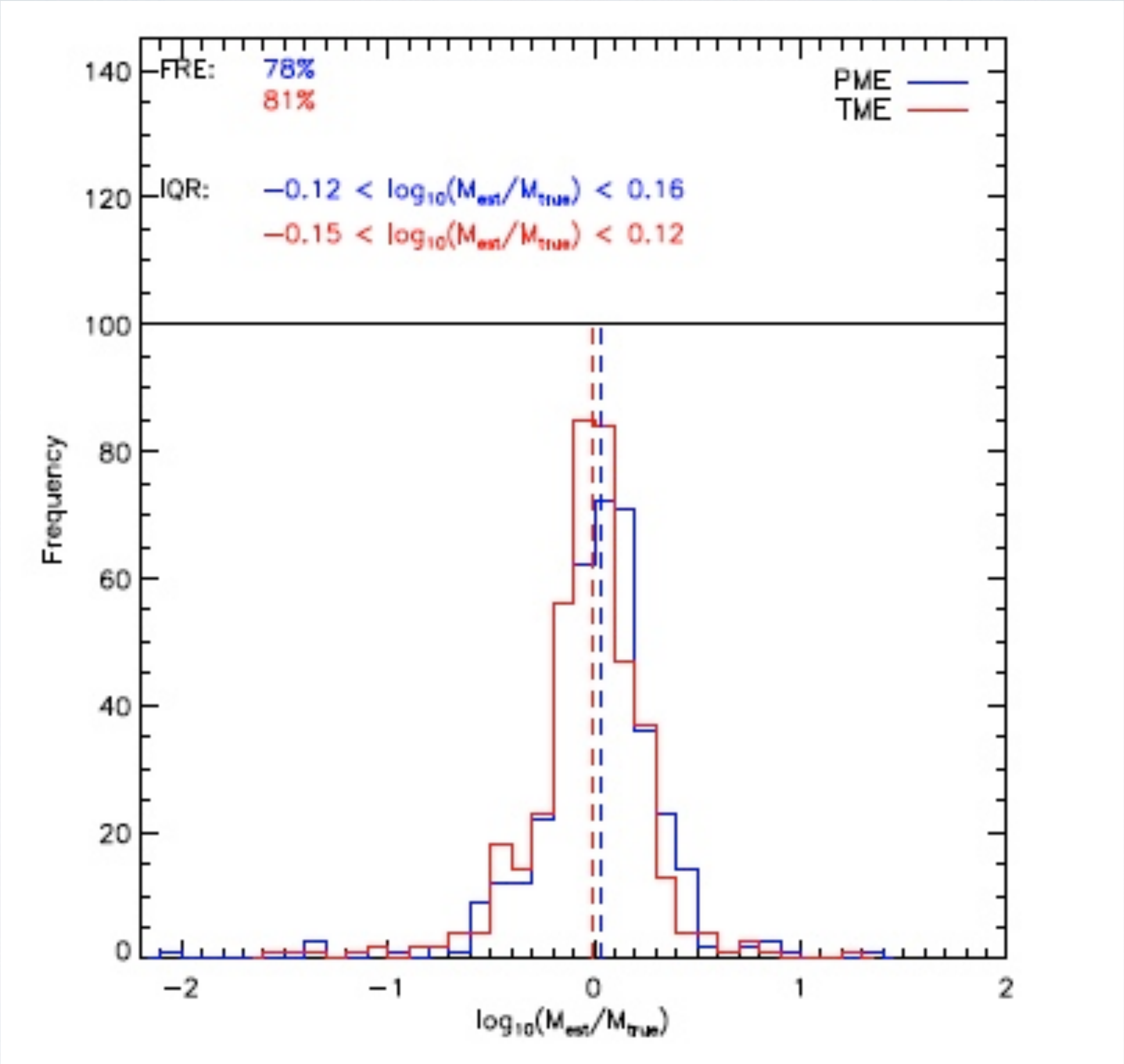
MASS ESTIMATORS

For any gravitational potential, there is an optimum mass estimator of form

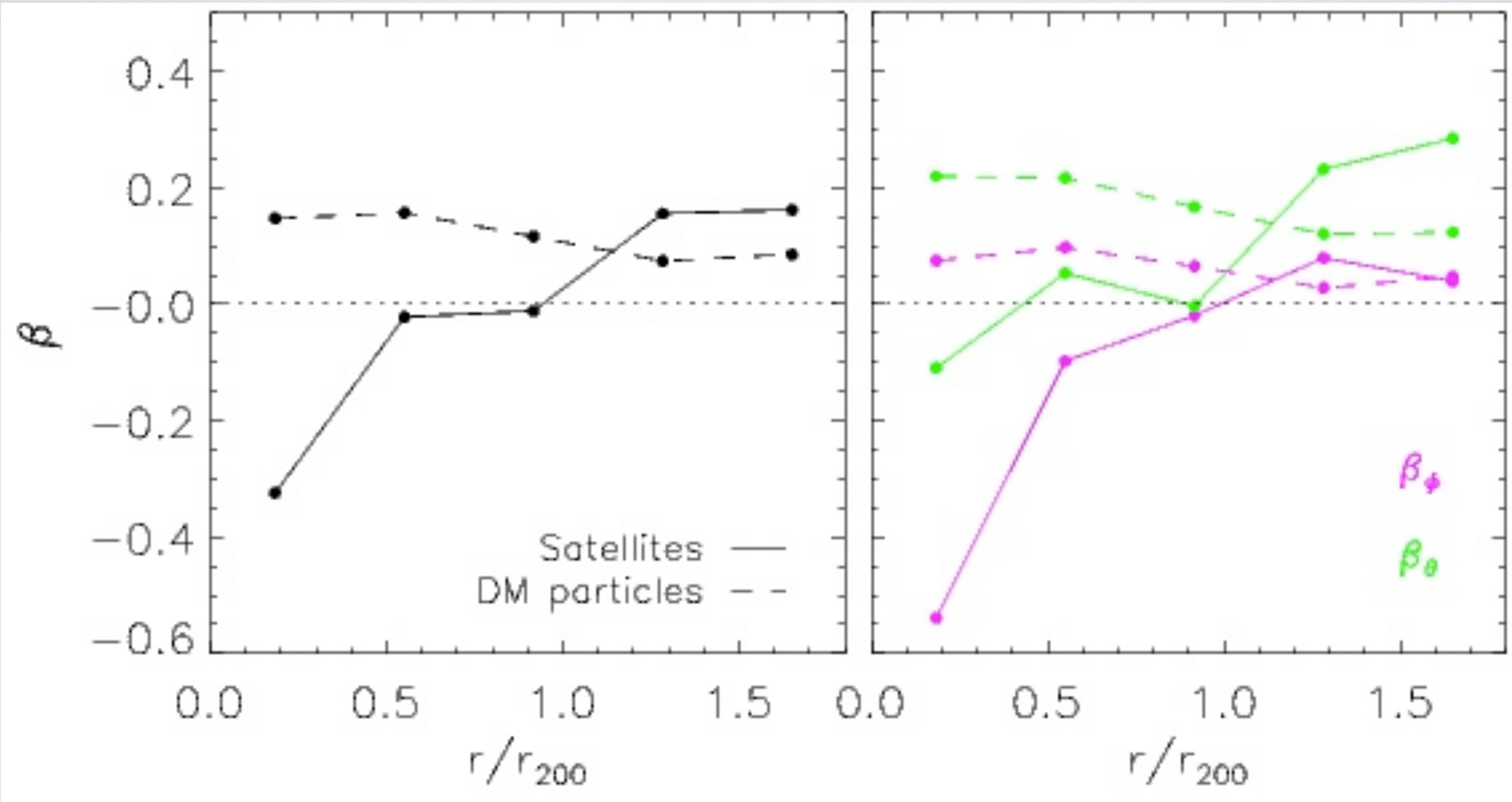
$$M = C \sum v^2_{los,i} R_i w(R_i)$$

where $w(R_i)$ is a weight-function.

An & Evans (2011) show how to construct the weight-function given the potential and provide forms for some of the commonly used halo models (NFW). For most practical purposes, the TME with $\alpha \approx 0.5$ suffices.

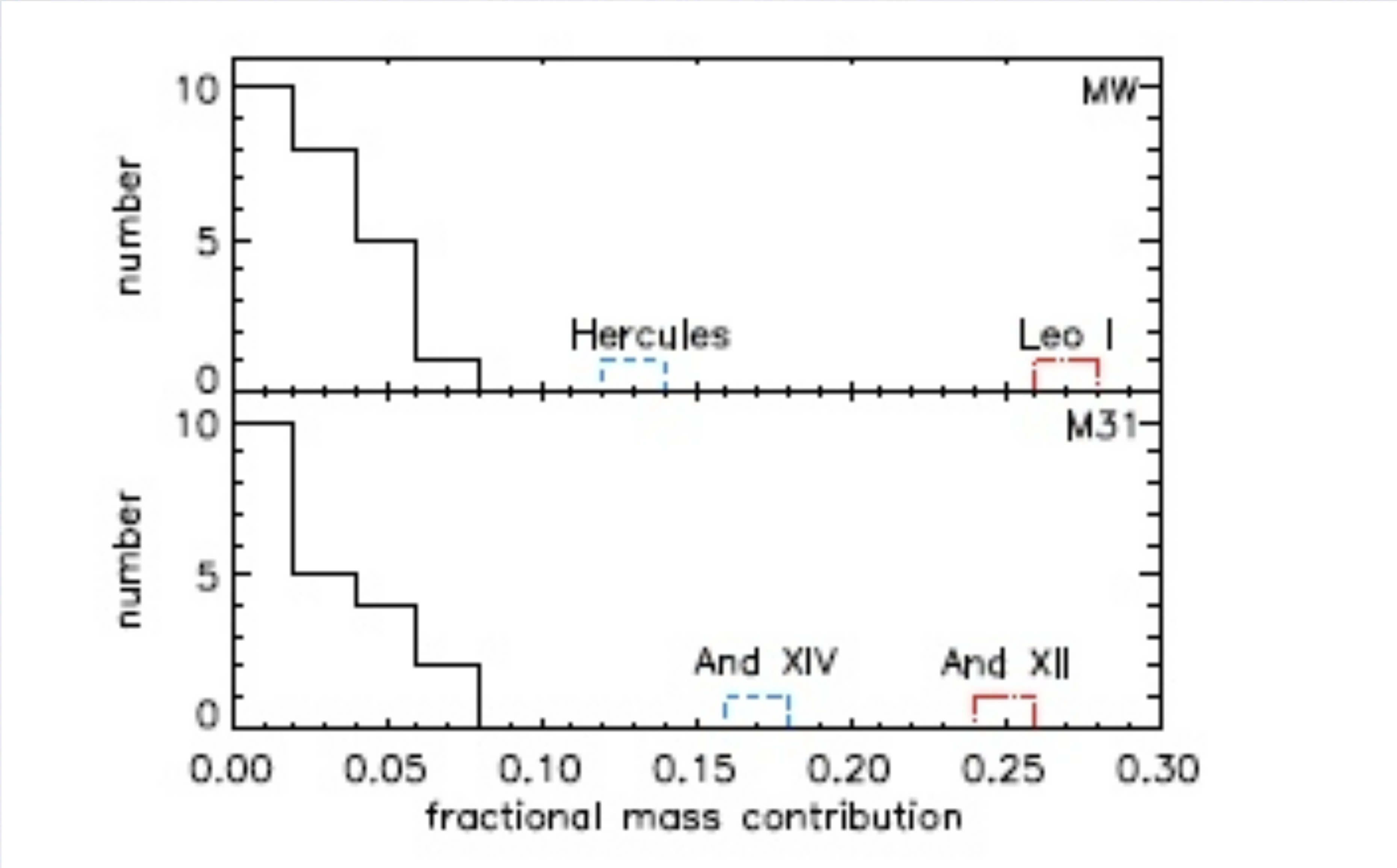


Deason et al 2011

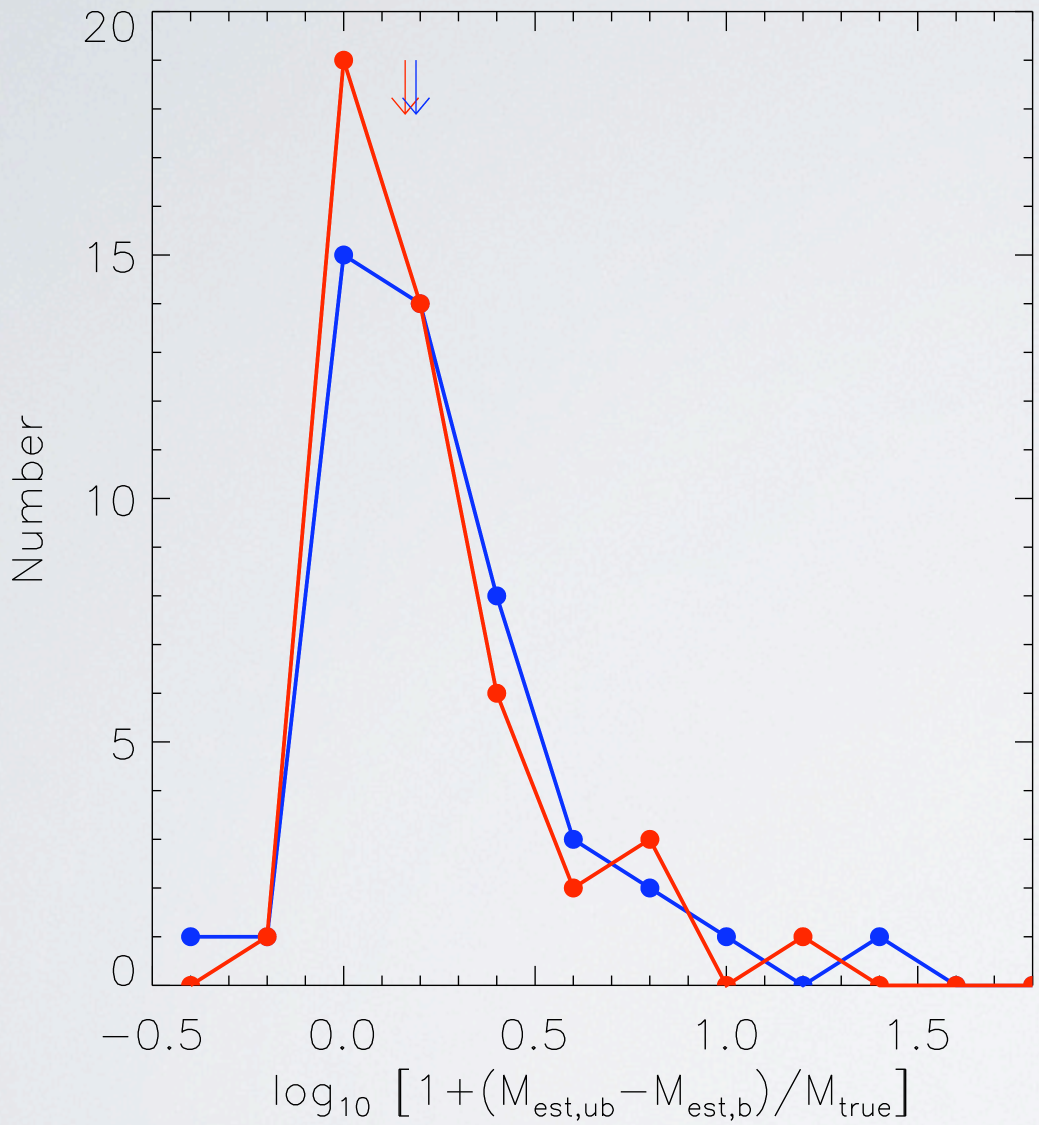


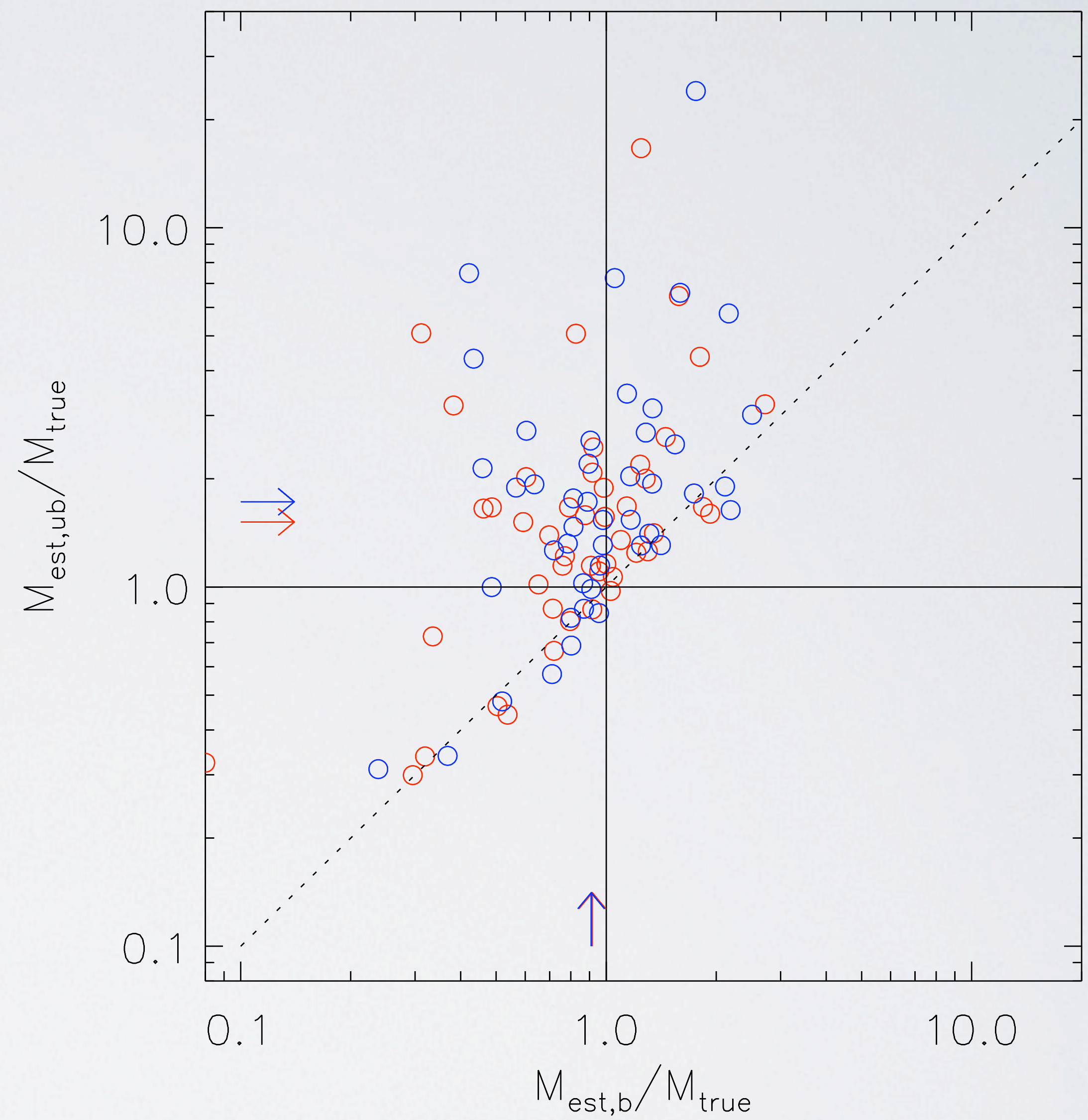
Deason et al 2011

UNBOUND SATELLITES ?



Watkins, Evans, An 2010





Deason et al 2011

CALIBRATION

The mass estimators provide good results especially considering the idealized assumptions under which they are derived. The IQR shows that the uncertainty in the mass estimate is ~30%.

In simulations, ~ 3% of "satellites" are unbound. They're not common, but their inclusion in mass estimators can cause large deviations from the true mass. The median difference is ~ 50% of the true mass when unbound satellites are included/excluded.

MASS OF M31

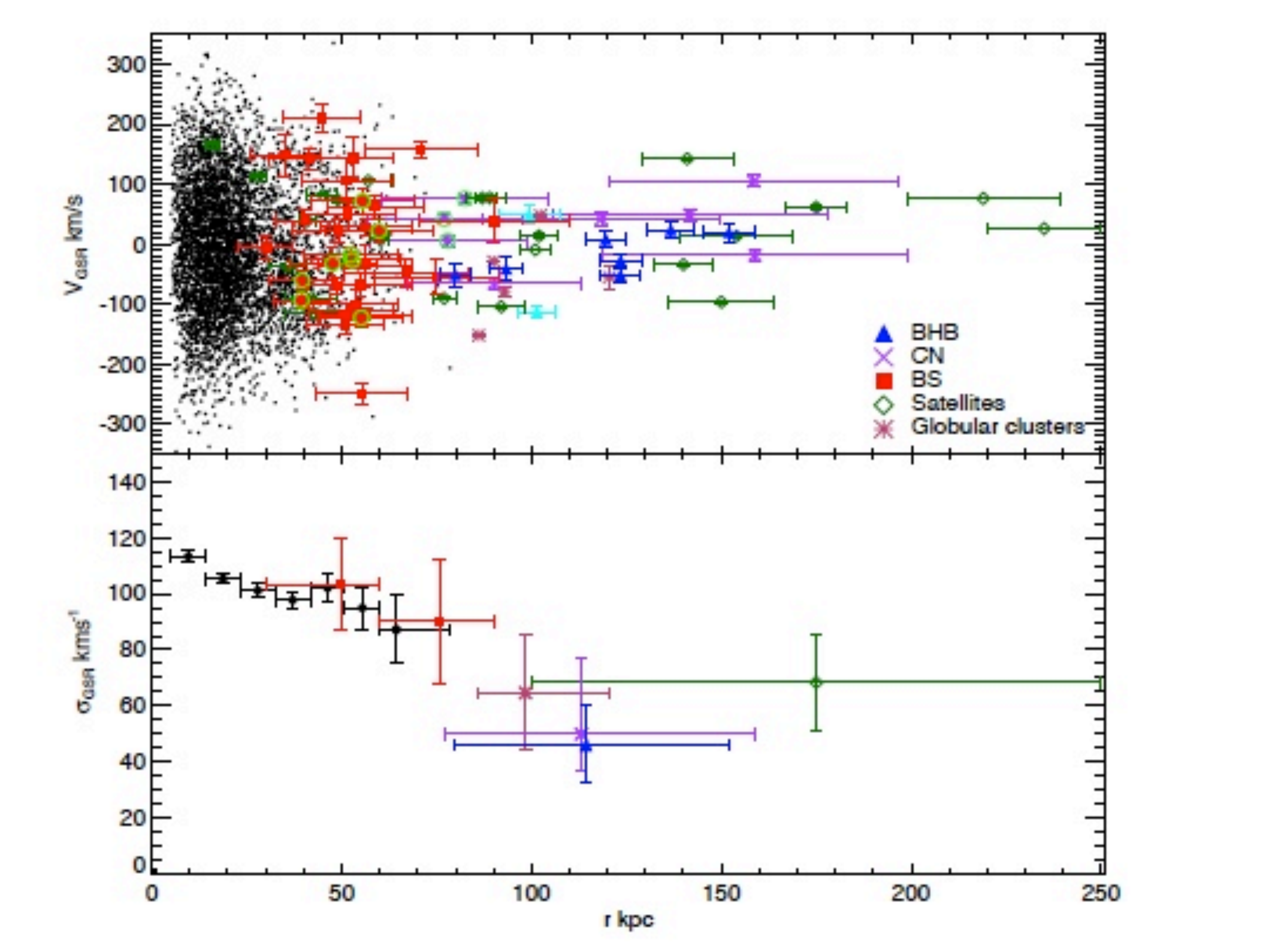
- The mass of M31 within 300 kpc could possibly be as low as 0.9 +/- 0.2 $\times 10^{12}$ $M_{\odot}$. This would be the case if both And XII and And XIV are not gravitationally bound.

- The mass of M31 within 300 kpc could plausibly be as high as large as 1.6 +/- 0.4 $\times$ 10^{12} $M_{\odot}$ (whole sample of satellite galaxies, tangential anisotropy).

MASS OF M31

- Assuming isotropy, the positions and velocities of the satellite galaxies imply that the mass within 300 kpc is $1.4 \pm 0.4 \times 10^{12}\ M_\odot$ (Watkins et al 2010).
- This may be compared with the earlier estimate from the rotation curve of $\sim 1.2 \times 10^{12}\ M_\odot$ (Corbelli et al 2010).
- Should you be convinced ?

A CAUTIONARY TALE



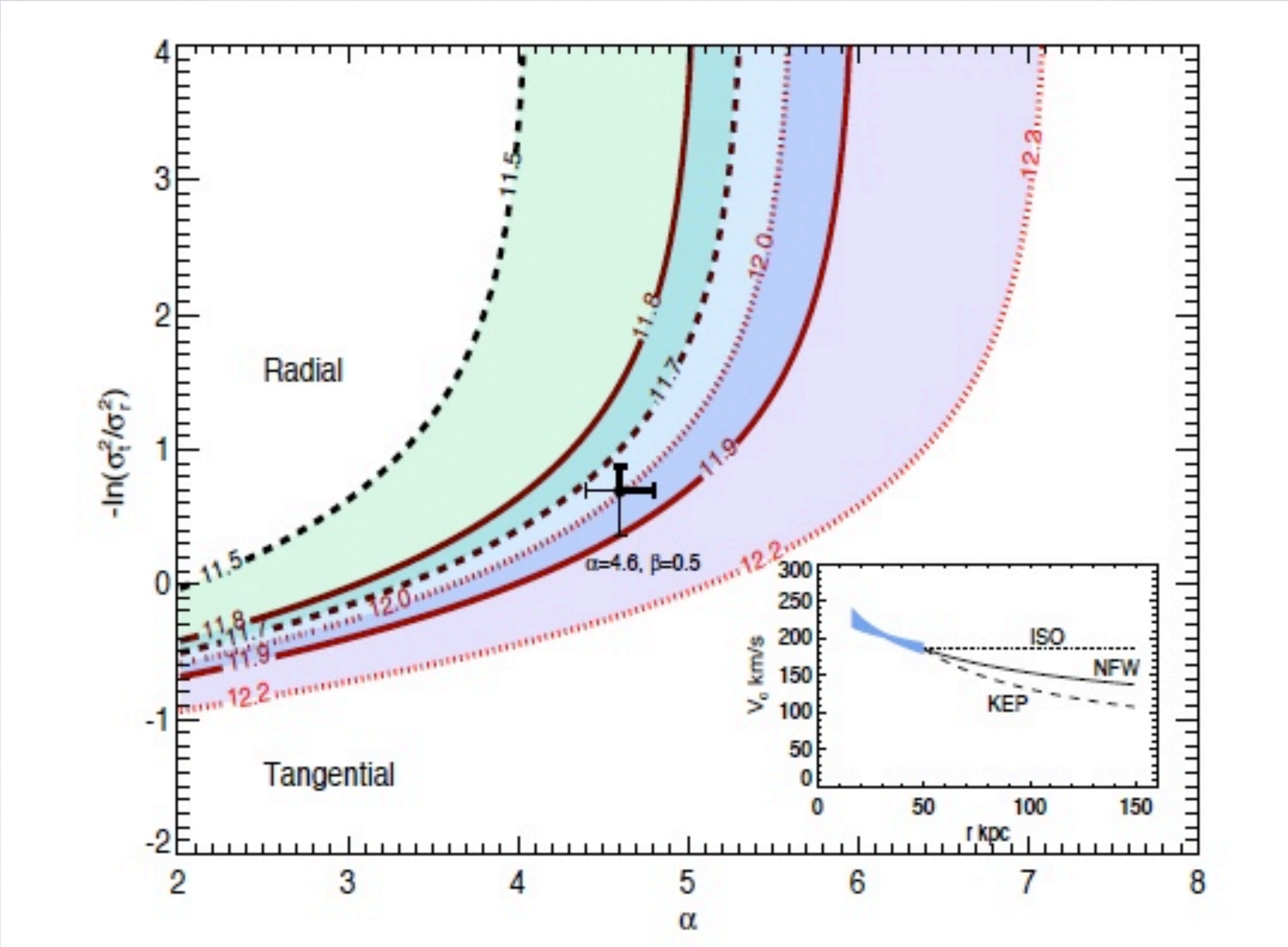
Deason et al 2012

THE MILKY WAY DARK HALO

The sample of satellite galaxies (including Leo I) yield dark halo masses ~ $2.0 \times 10^{12} M_{\odot}$.

The velocity dispersion of the distant BHB and CN stars is surprisingly low with $\sigma \sim 50-60$ km/s.

The implications for the total mass of our Galaxy depends on the density profile & velocity anisotropy of the tracer population. However, discounting a stellar population with a tangential velocity bias and/or a rapid tracer density fall-of, the total mass within 150 kpc is $(5-10) \times 10^{11} M_{\odot}$.



Deason et al 2012