Unveiling the Mass,
Queens University
June 2009

The masses of galaxy halos

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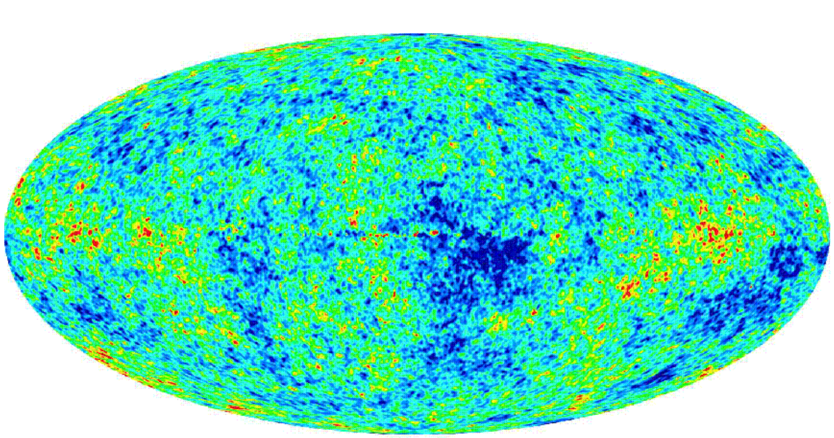
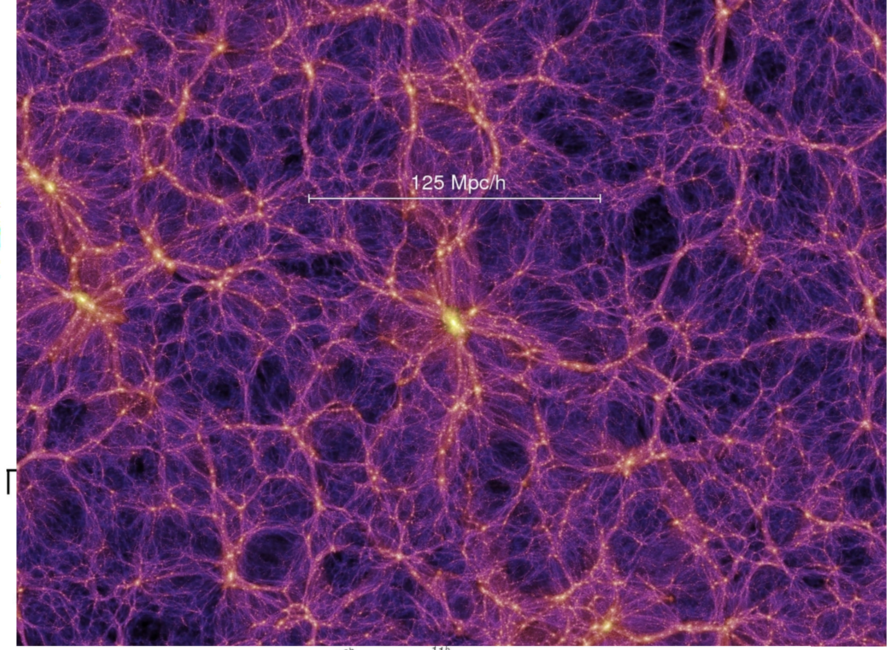
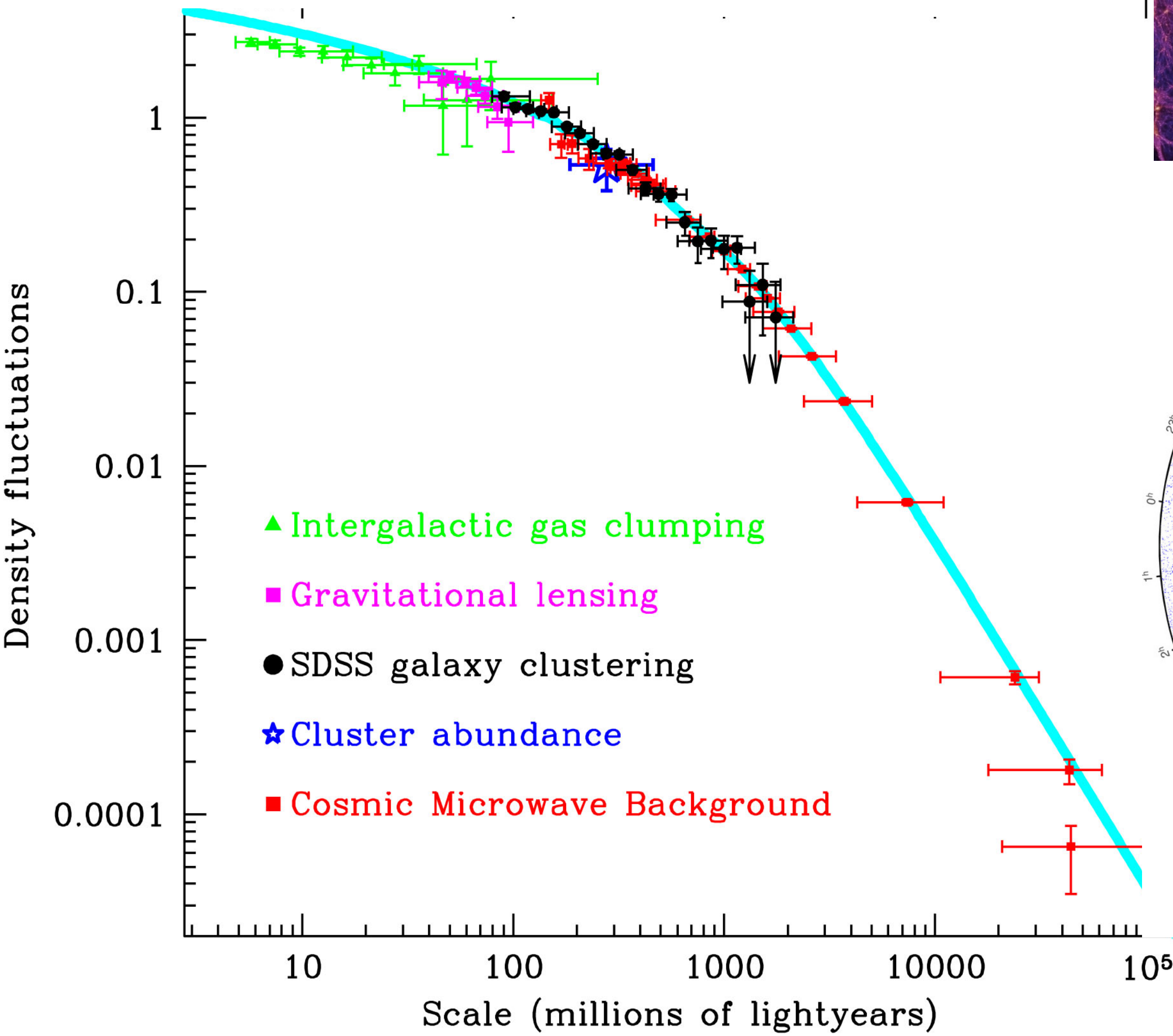
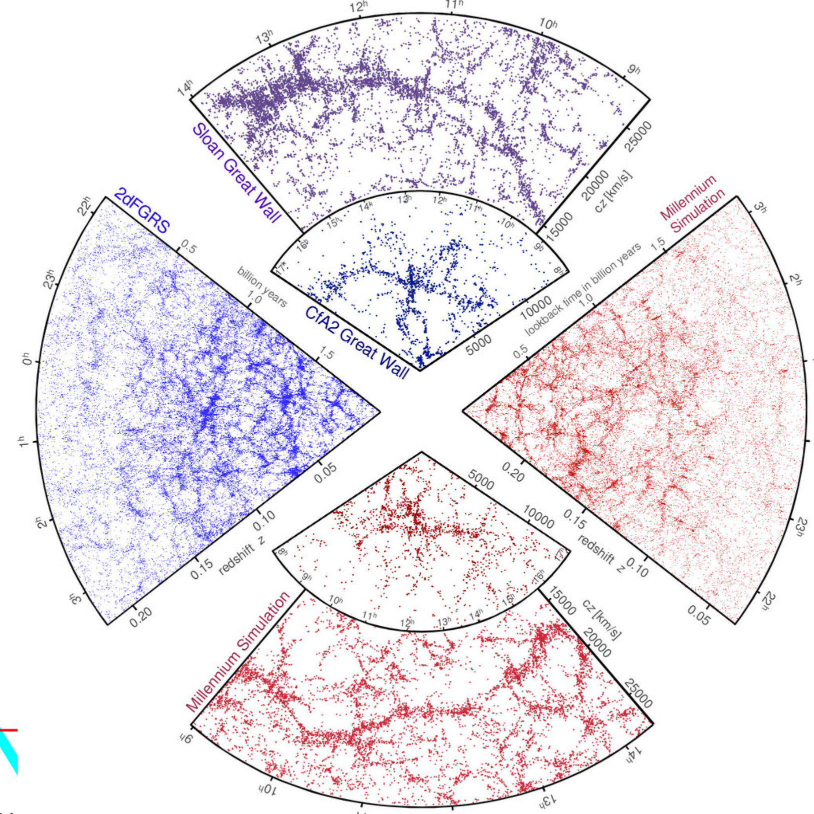



125 Mpc/h

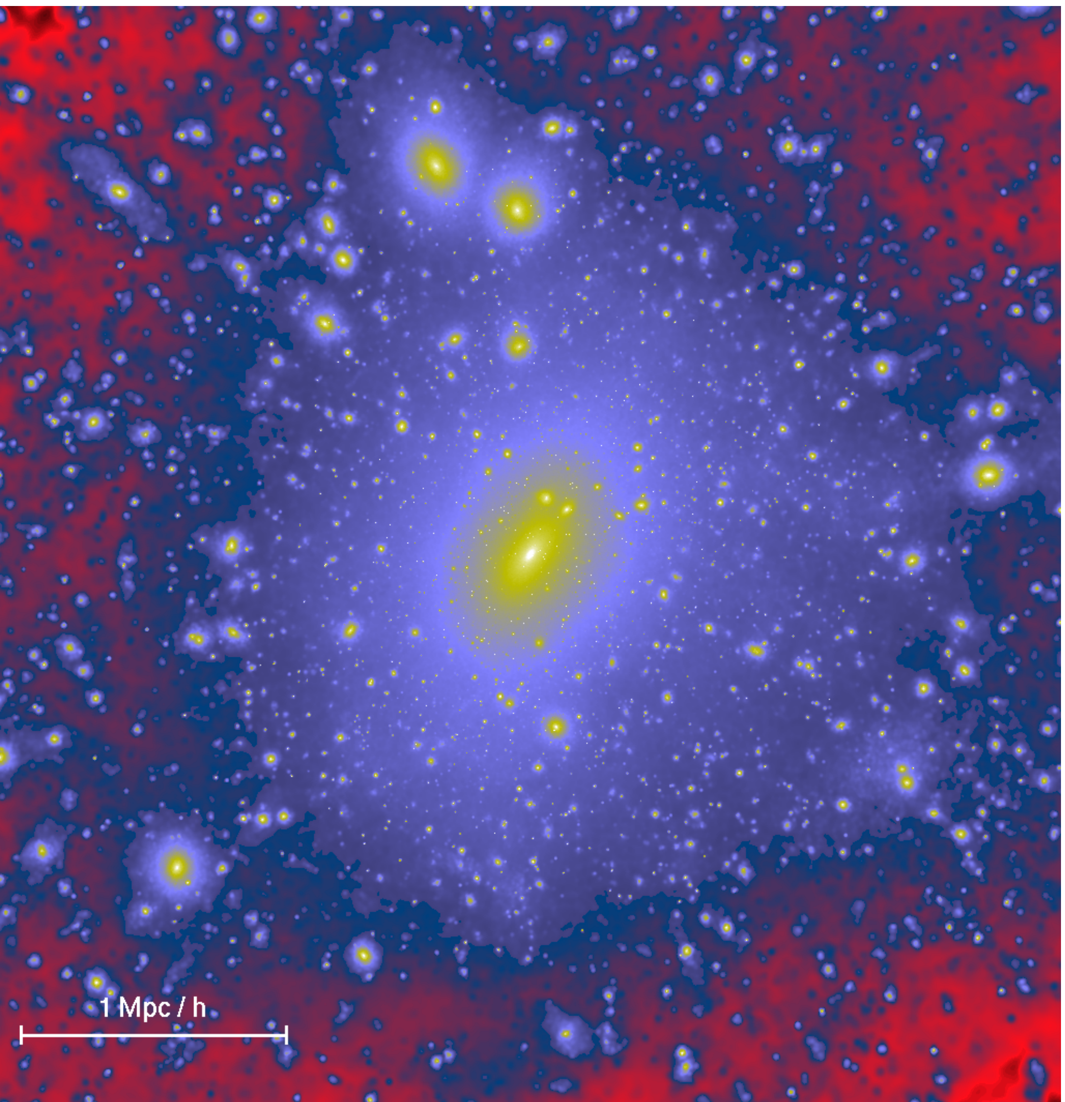

Density fluctuations
1
0.1
0.01
0.001
0.0001
10
100
1000
10000
10⁵
Scale (millions of lightyears)
Intergalactic gas clumping
Gravitational lensing
SDSS galaxy clustering
Cluster abundance
Cosmic Microwave Background

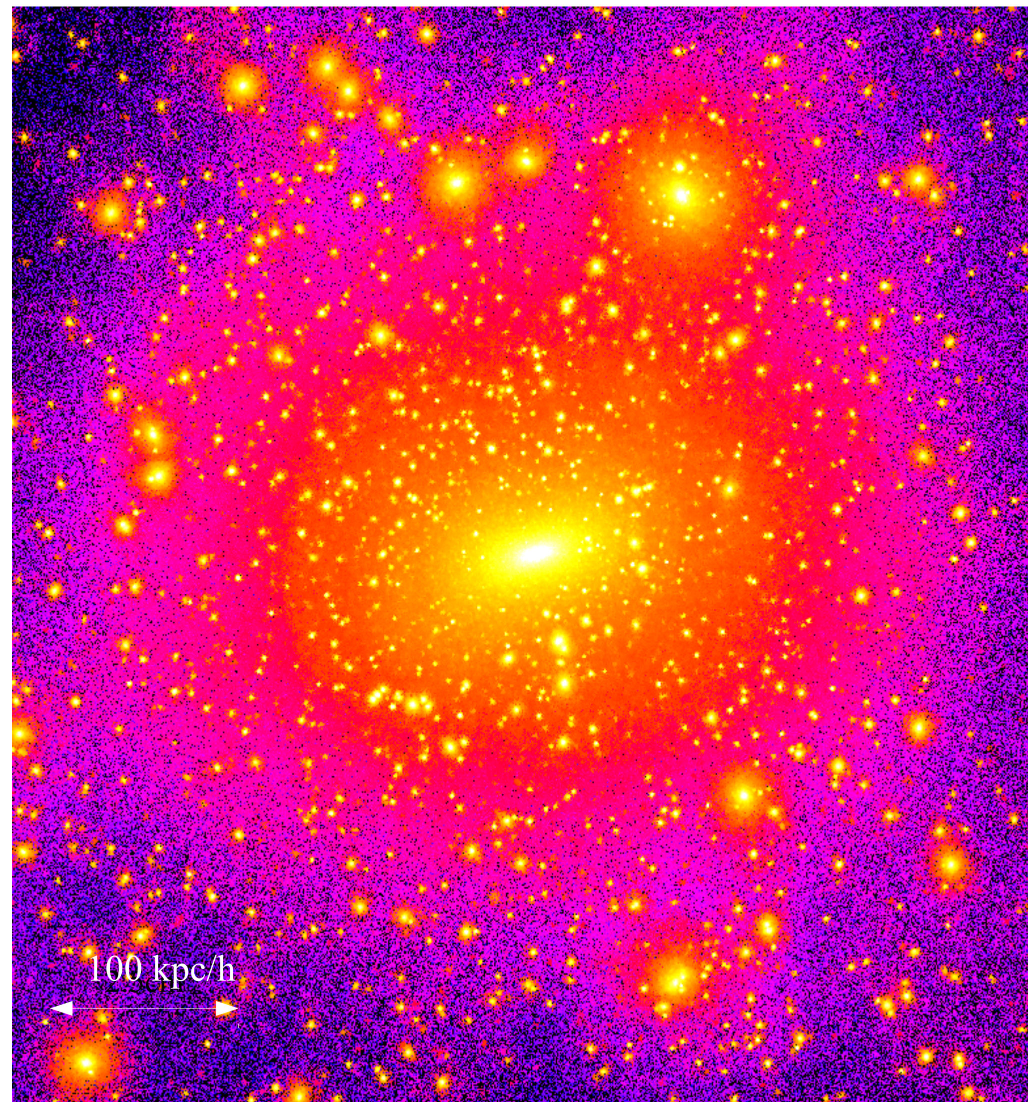

Sloan Great Wall
CfA2 Great Wall
2dFGRS
Millennium Simulation
Millennium Simulation
cz [km/s]
redshift z
billion years
lookback time in billion years

The dark matter structure of ΛCDM halos

A rich galaxy cluster halo
Springel et al 2001

A 'Milky Way' halo
Power et al 2002





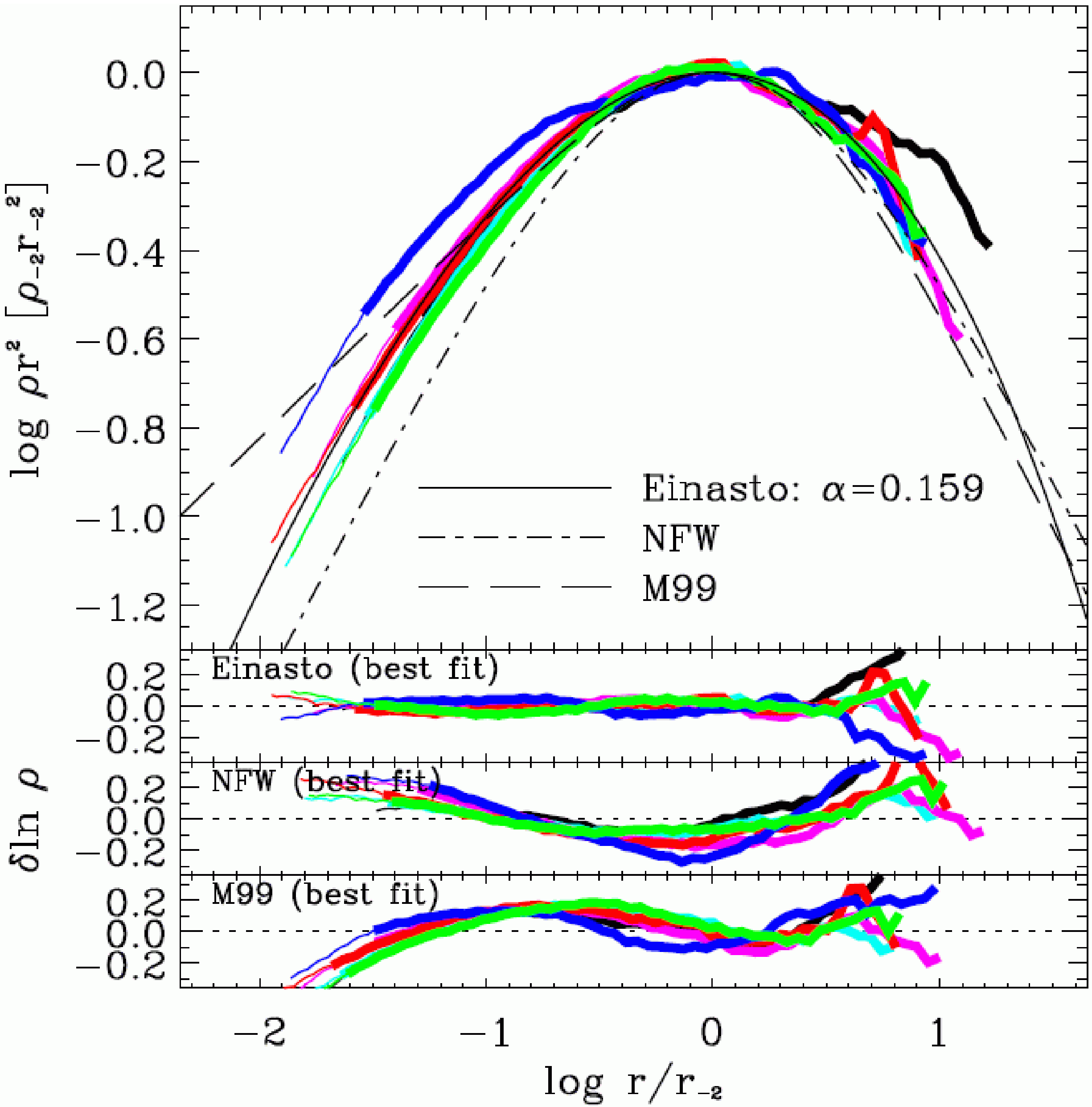
ΛCDM galaxy halos (without galaxies!)

- Halos extend to ~10 times the 'visible' radius of galaxies and contain ~10 times the mass in the visible regions
- Halos are not spherical but approximate triaxial ellipsoids
  -- more prolate than oblate
  -- axial ratios greater than two are common
- "Cuspy" density profiles with outwardly increasing slopes
  -- $d\ ln\ \varrho\ /\ d\ ln\ r = \gamma$ with $\gamma < -2.5$ at large r
  $\gamma > -1.0$ at small r
- Substantial numbers of self-bound subhalos contain ~10% of the halo's mass, are concentrated at large r and have $d N / d M \sim M^{-1.9}$

→ Most substructure mass is in most massive subhalos

Density profiles for ΛCDM galaxy halos

Navarro et al 2009

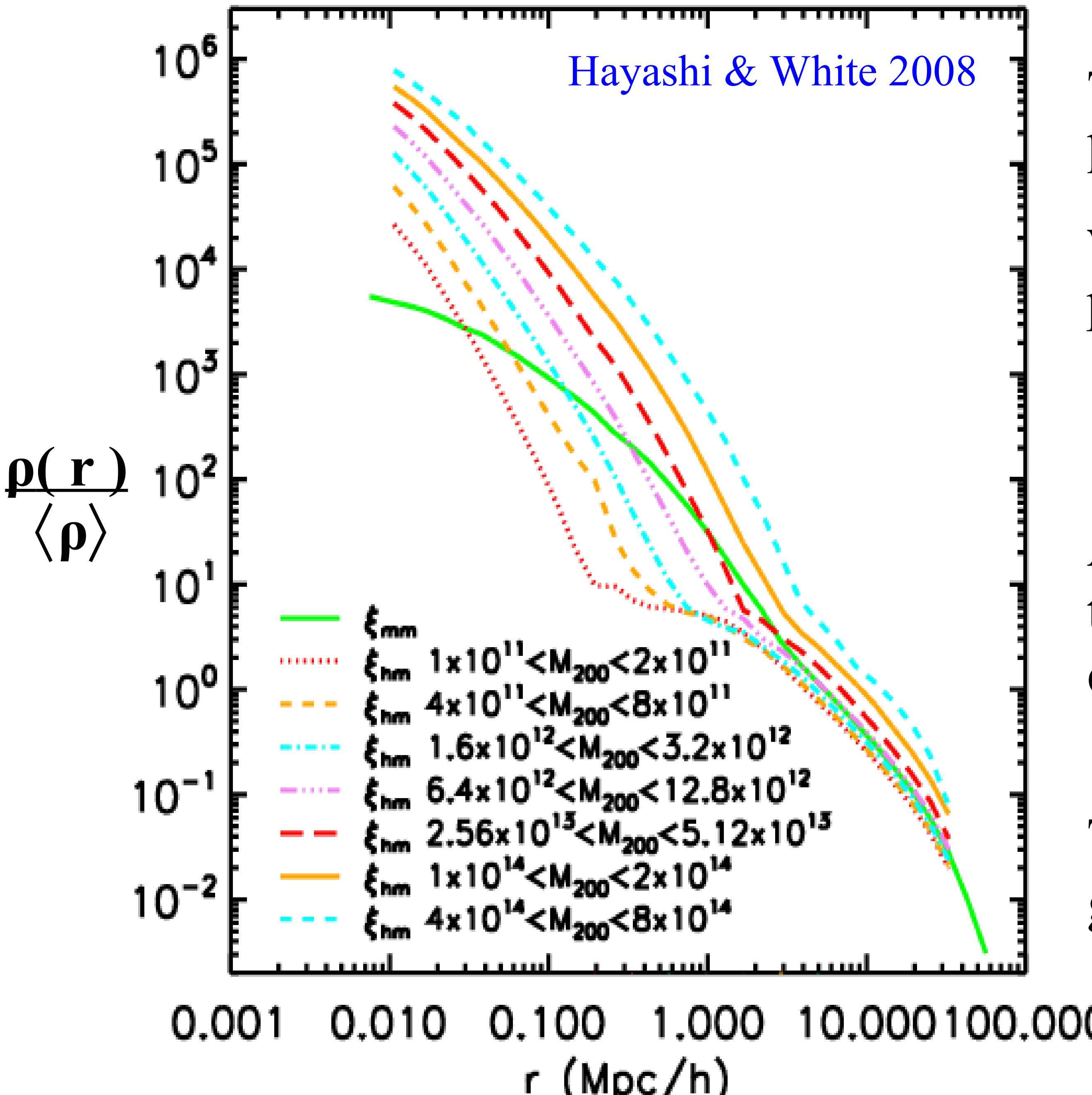


- Six MW-like halos at very high resolution from the Aquarius project
- Density profiles differ from halo to halo
- Two-parameter functions can fit 150pc < r < 75kpc to an *rms* accuracy of
  - ~10% (Moore 1999)
  - ~6% (NFW)
  - ~2.5% (Einasto, α = 0.15)

Conclusions about ΛCDM galaxy halos

- Most are triaxial/prolate
- Most are NFW to 5%, and Einasto to 2.5% in the relevant regions
- Baryon effects exceed the scatter/noise in the visible regions
  - --inner regions become denser and more nearly axisymmetric
  - --dependent on details of galaxy assembly
  - --effects of bars?
- Substructure "noise" is large beyond 50 to 100 kpc
  - --stack data to study mean profiles at larger radii?

Stacked mean halo density profiles to large radius

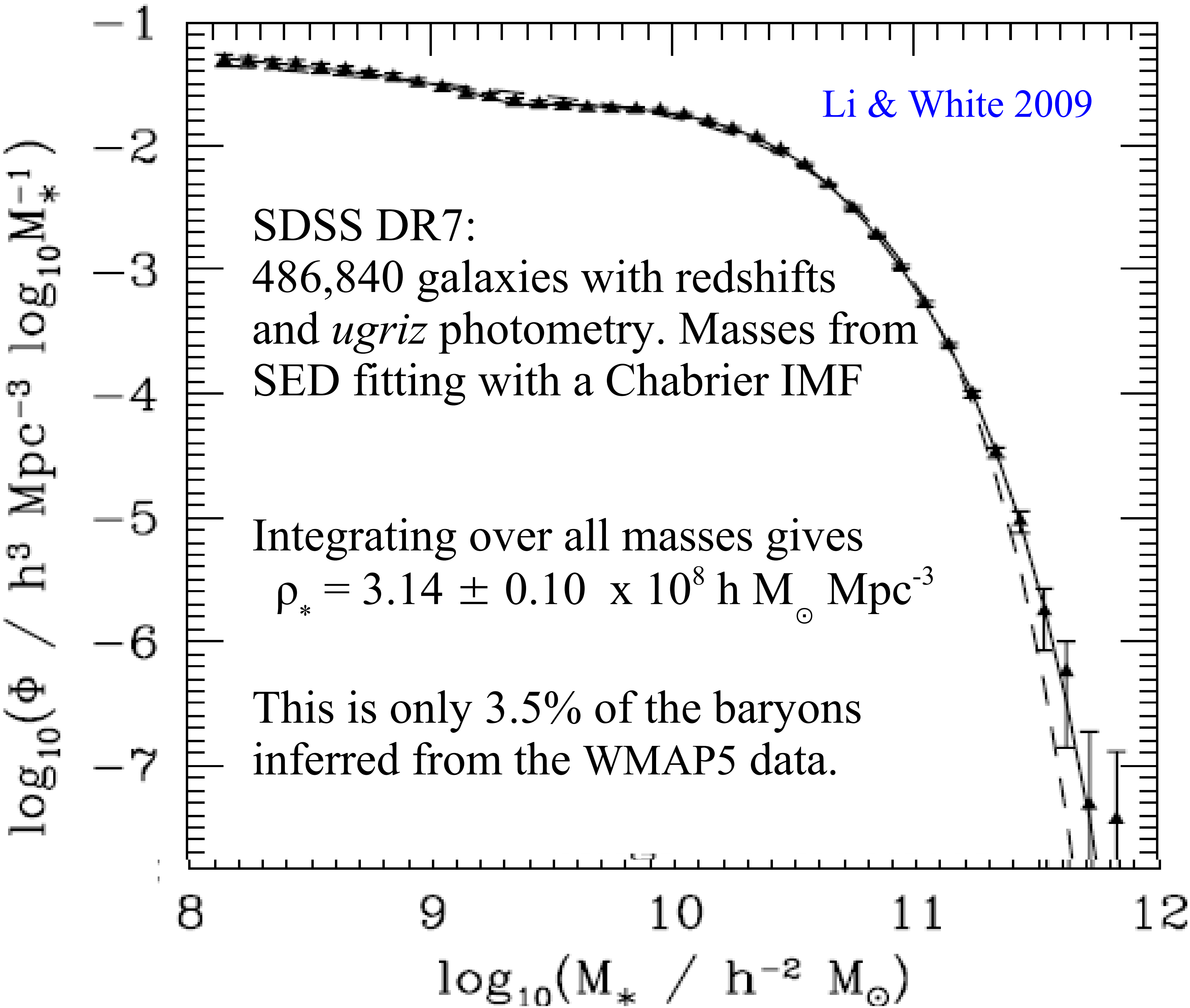


The mean profile of many halos of similar M_{200} is well fit by an Einasto profile out to

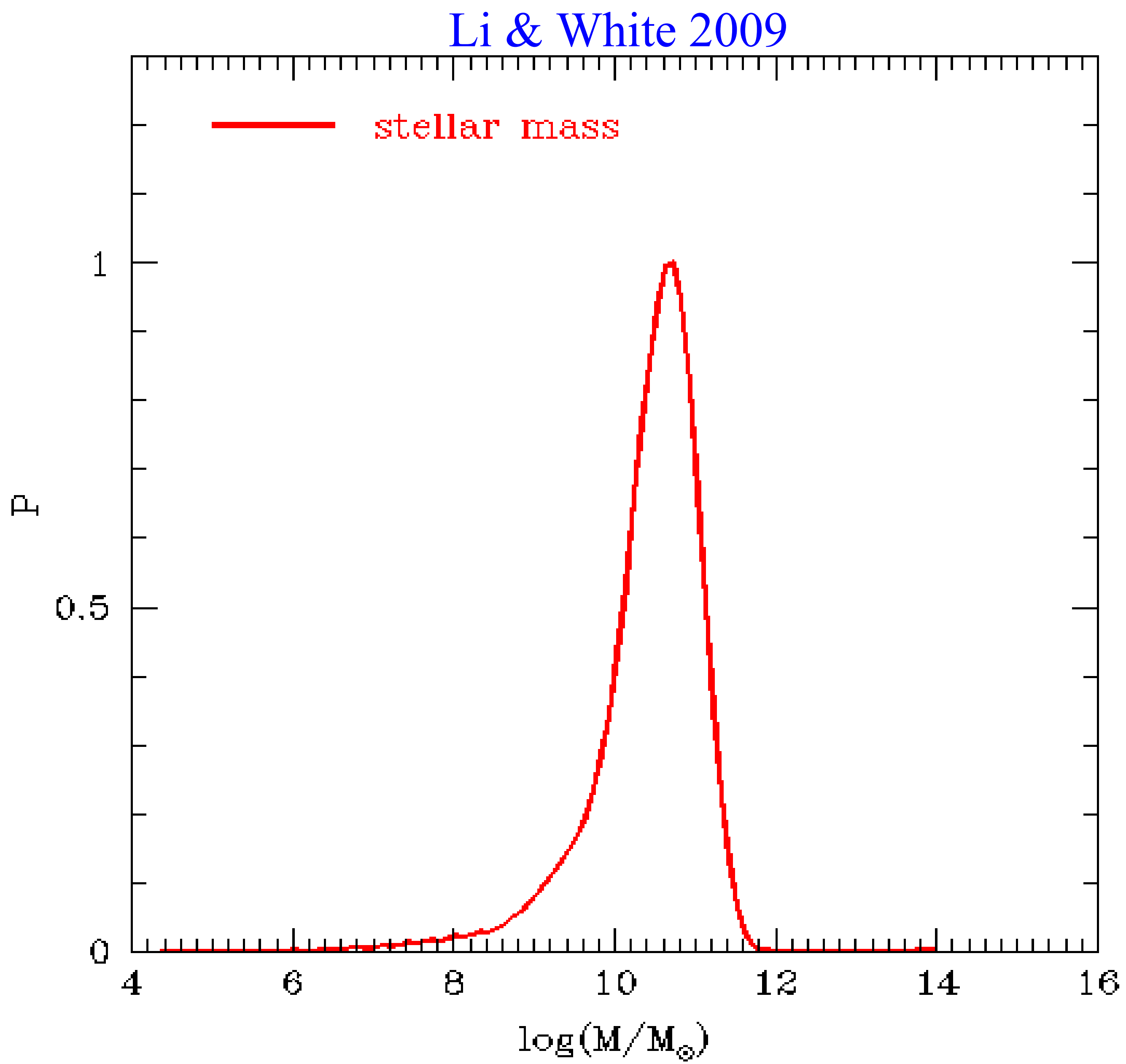
$$\rho(r) \sim 10\,\langle\rho\rangle$$

At larger radii it parallels the *linear* mass auto-correlation function

This also holds for *central* galaxies of similar L

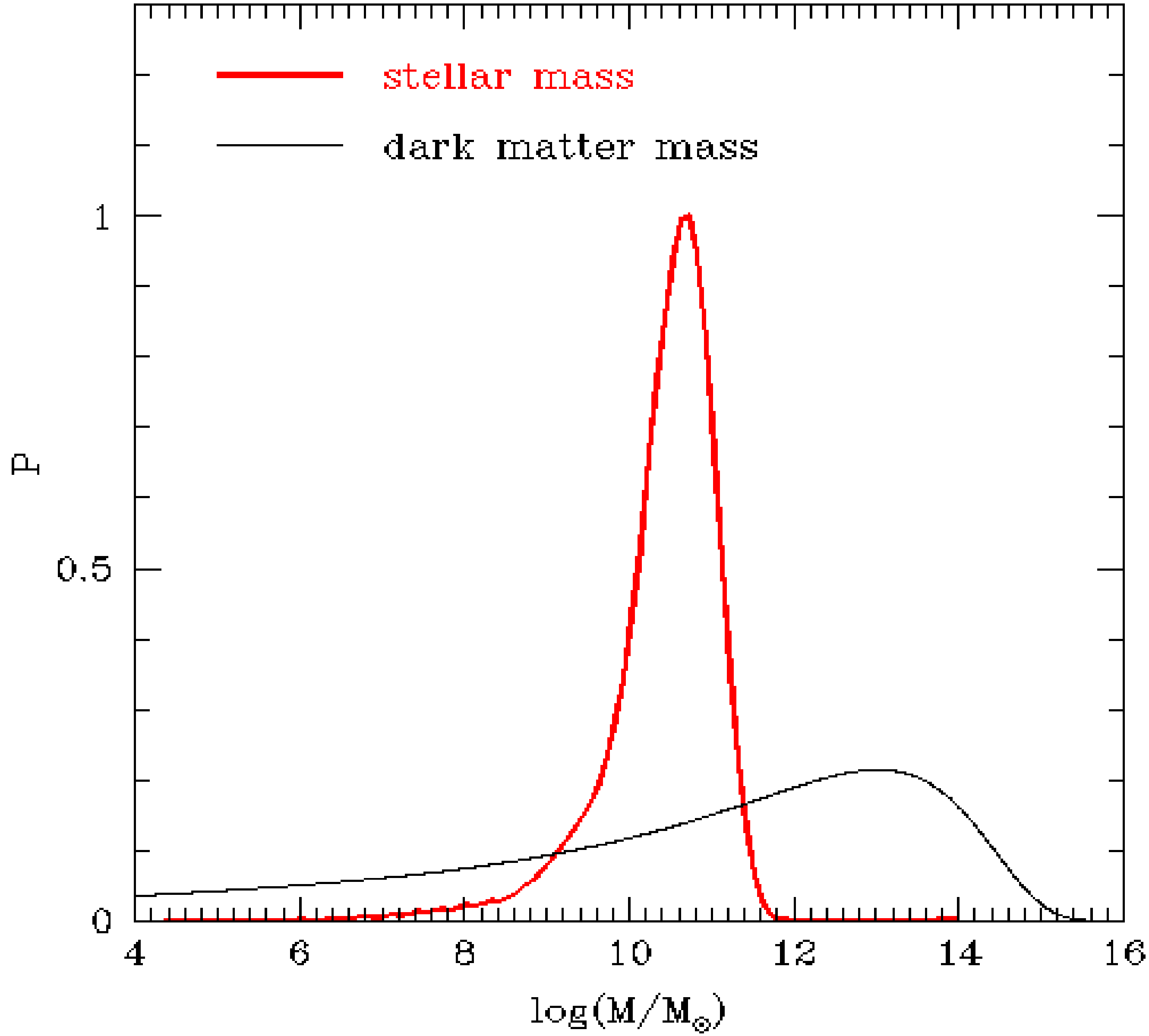

Li & White 2009
SDSS DR7:
486,840 galaxies with redshifts
and ugriz photometry. Masses from
SED fitting with a Chabrier IMF
Integrating over all masses gives
ρ* = 3.14 ± 0.10 x 10^8 h M⊙ Mpc^-3
This is only 3.5% of the baryons
inferred from the WMAP5 data.
log10(Φ / h^3 Mpc^-3 log10M*^-1)
log10(M* / h^-2 M⊙)
−1
−2
−3
−4
−5
−6
−7
8
9
10
11
12

Most stars are in galaxies with similar stellar mass to the Milky Way



Most stars are in galaxies with similar stellar mass to the Milky Way
Dark matter (and baryons) are *much* more broadly distributed across halo mass in the WMAP5 cosmology

Li & White 2009



A counting argument relating halo and galaxy masses

The SDSS/DR7 data give a precise measurement of the abundance of galaxies as a function of stellar mass threshold, $n(> M_*)$

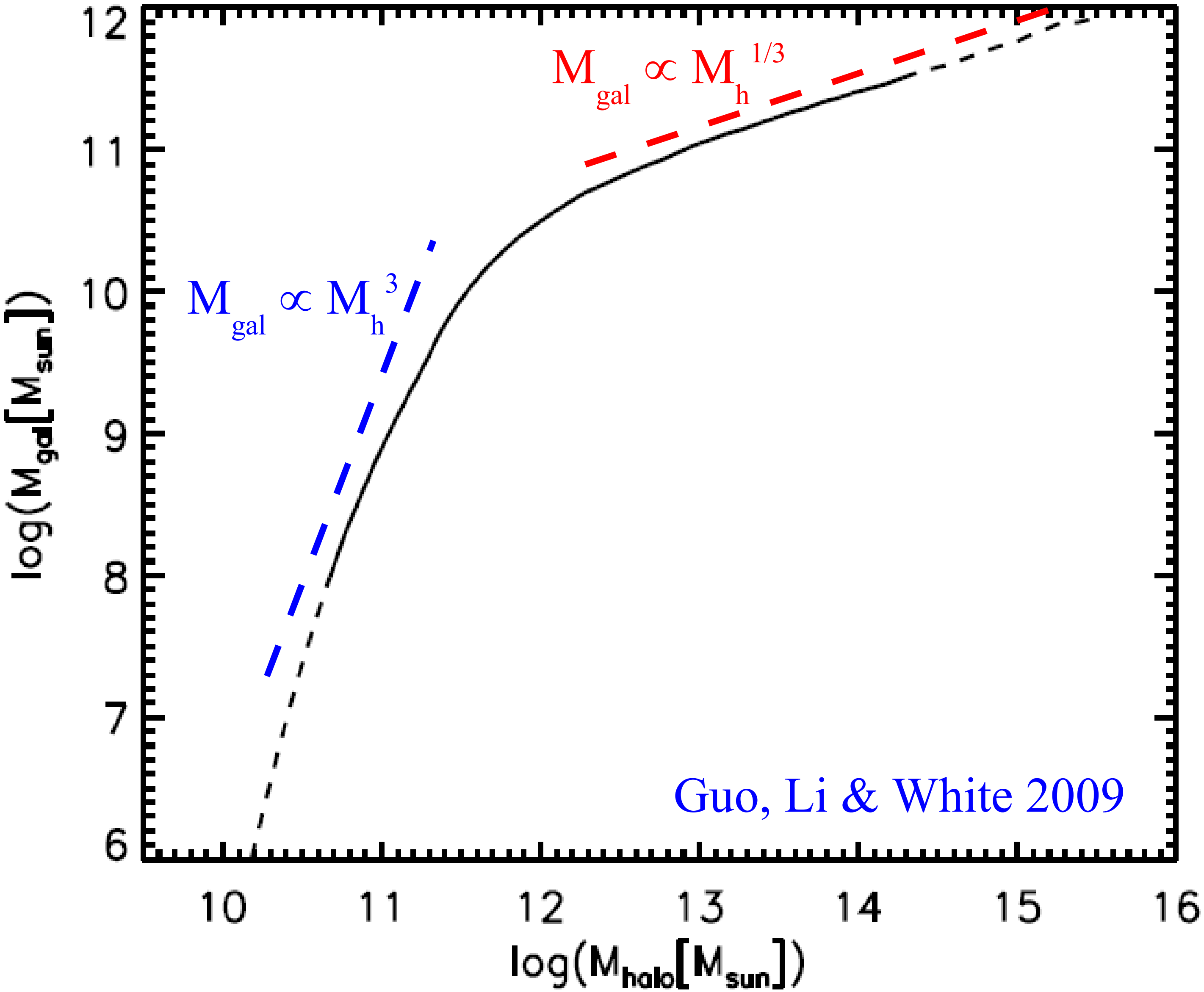
The Millennium and MS-II simulations allow all halos/subhalos massive enough to host z=0 galaxies to be identified

Define $M_{h,max}$ as the maximum mass *ever* attained by a halo/subhalo

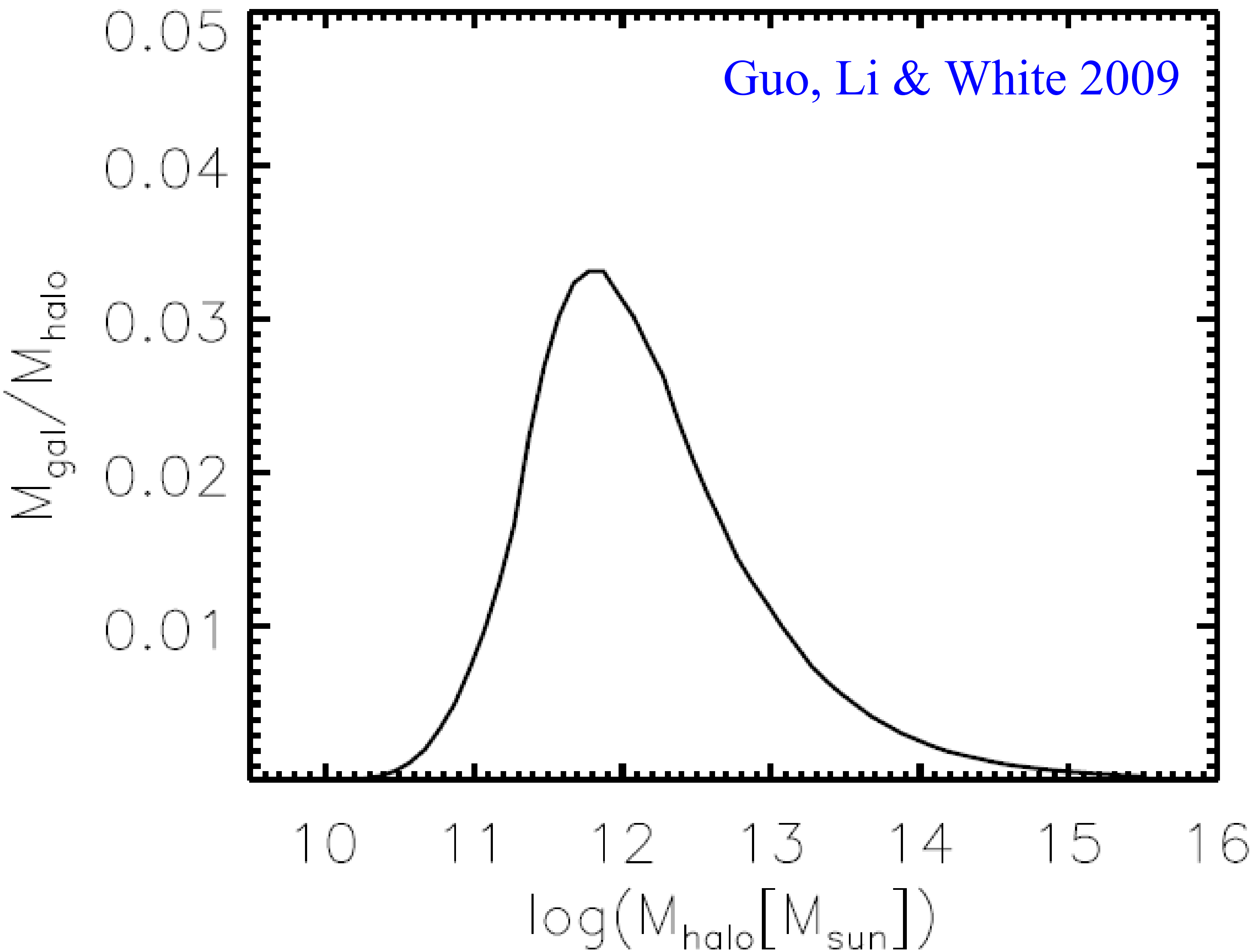
The simulations then give the halo/subhalo abundance, $n(> M_{h,max})$

Ansatz: Assume the stellar mass of a galaxy to be a monotonically increasing function of the maximum mass ever attained by its halo

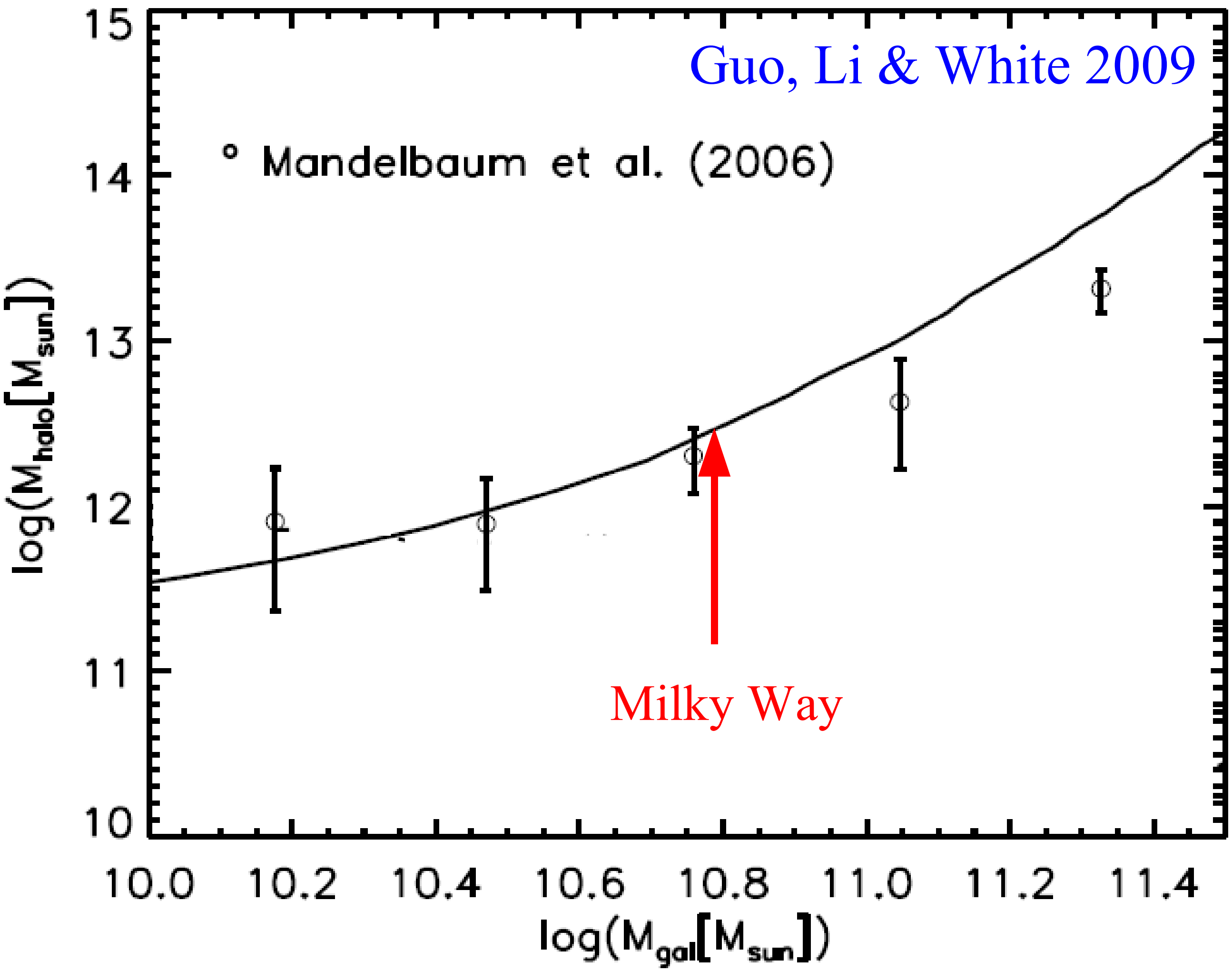
We can then derive $M_*(M_{h,max})$ by setting $n(> M_*) = n(> M_{h,max})$



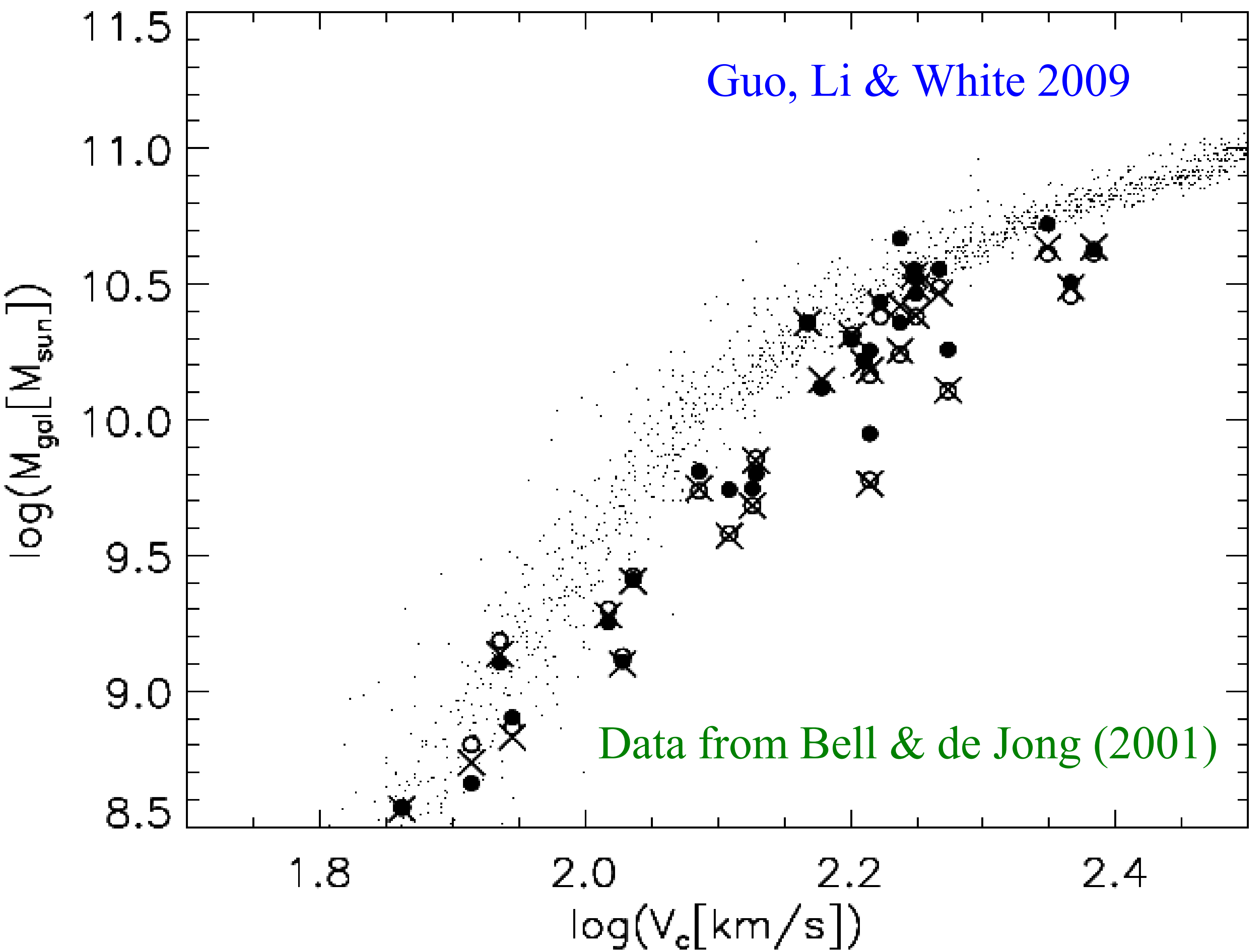
- The stellar mass of the central galaxy increases rapidly with halo mass at small halo mass, but slowly at large halo mass
- The characteristic halo mass at the bend is $5 \times 10^{11}\ M_{\odot}$



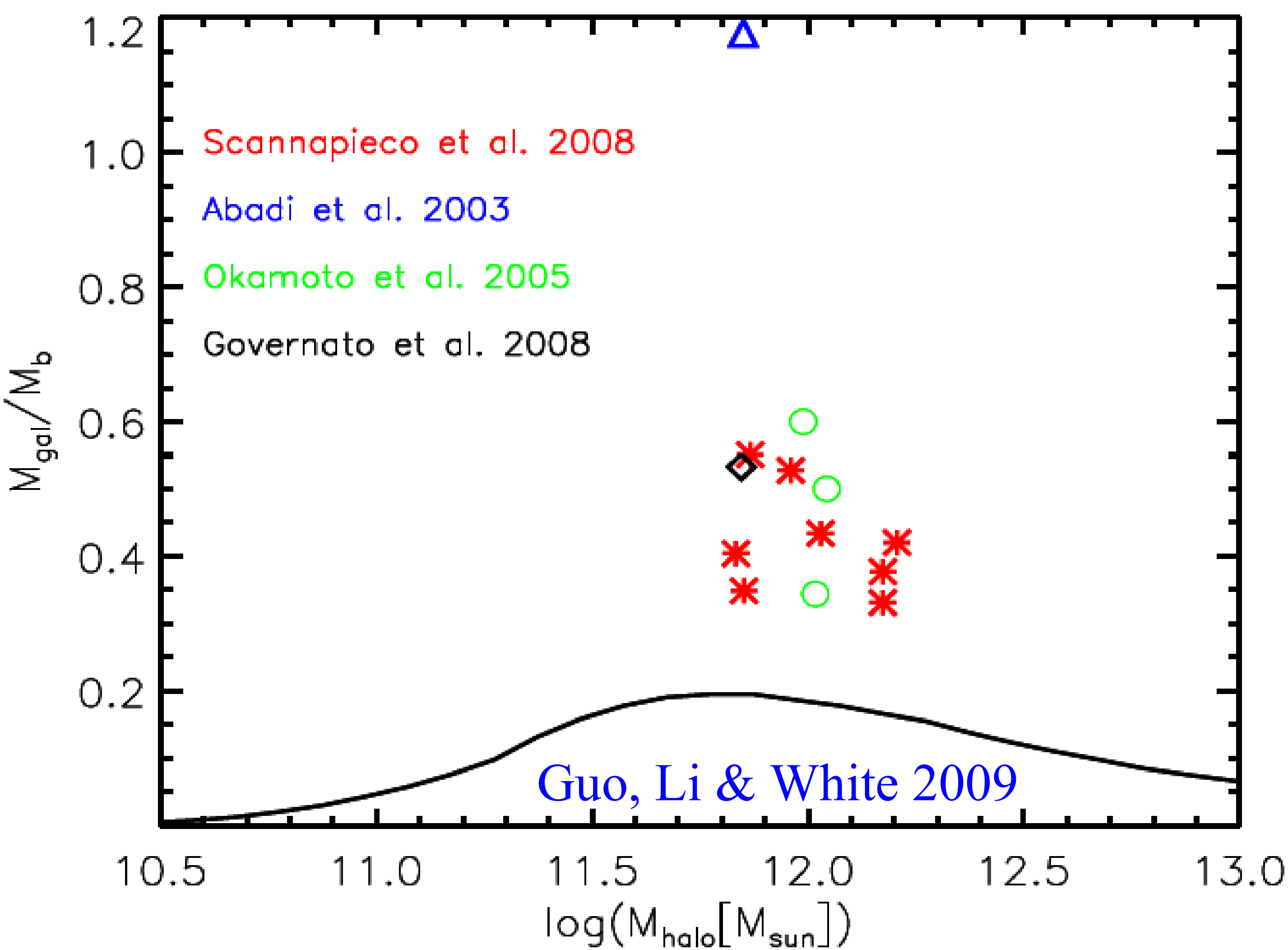
- The maximum halo mass fraction in central galaxy stars is 3.5%
- This is attained for halos similar in mass to the Milky Way's halo
- The fraction drops very rapidly to higher and lower masses



- The (maximum) halo masses inferred as a function of stellar mass agree well with those inferred from galaxy-galaxy lensing
- For $M_* = 6 \times 10^{10}\ M_\odot$ the Milky Way should have $M_h = 2 \times 10^{12}\ M_\odot$
- For $M_h = 1.0 \times 10^{12}\ M_\odot$ it should have $M_* = 3.5 \times 10^{10}\ M_\odot$

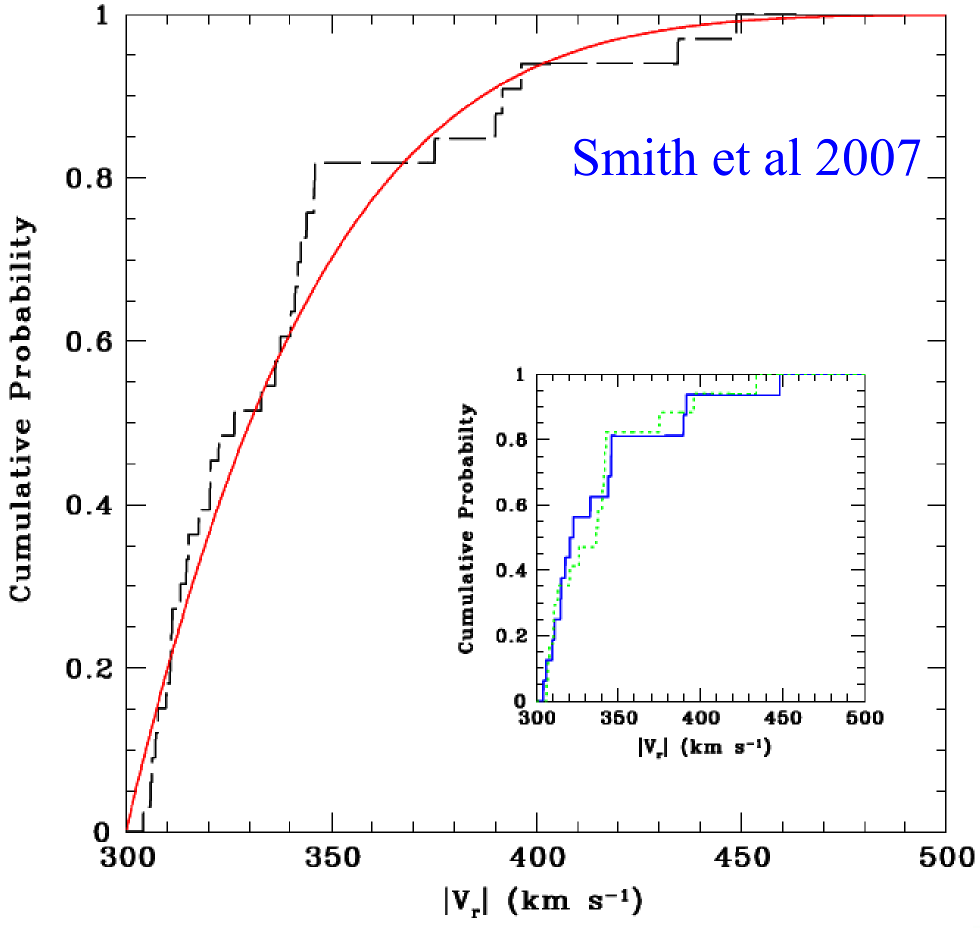


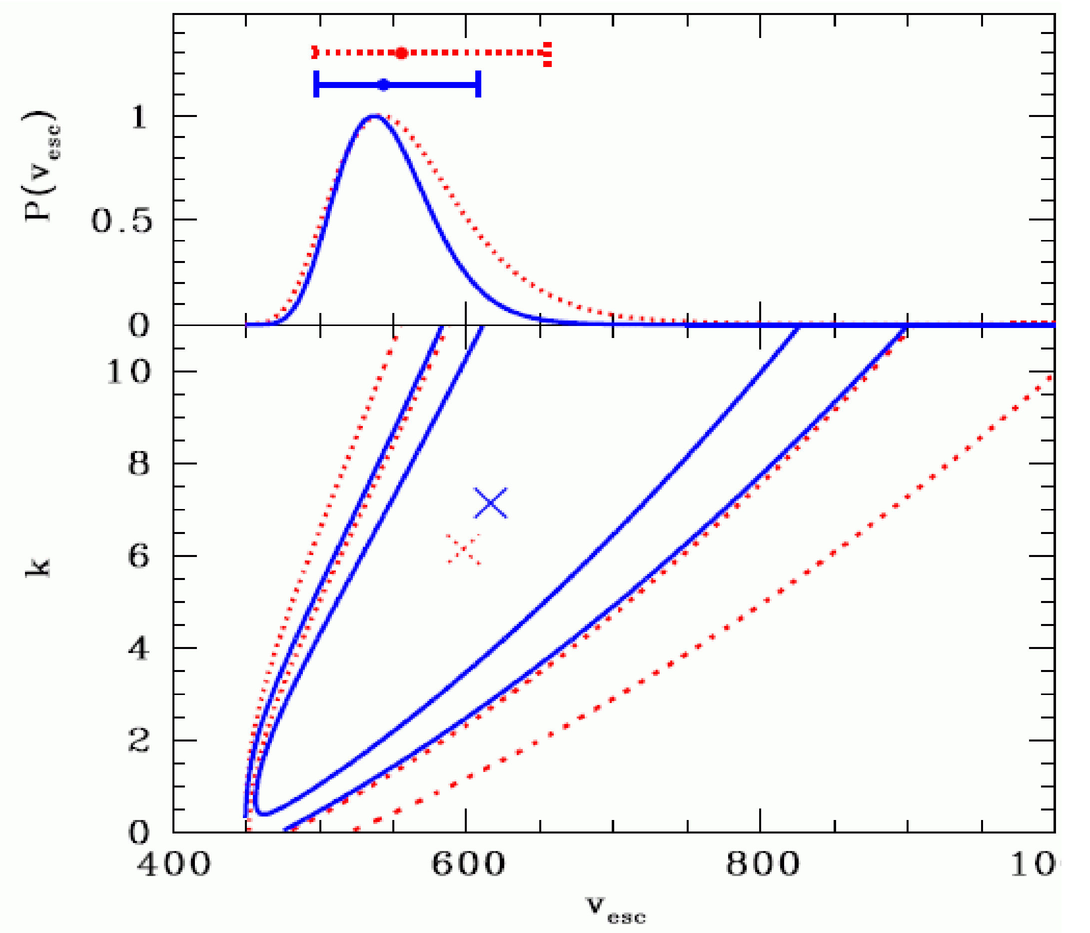
- The inferred relation between stellar mass and halo maximum circular velocity is consistent with the M_* “Tully-Fisher” relation



- Galaxy formation efficiency is: $\varepsilon = M_* / (\Omega_b M_{h,max} / \Omega_m)$
- This *maximises* at about 20%
- It is much lower than in all current galaxy formation simulations
- In the Milky Way about $2 \times 10^{11} M_\odot$ of baryons are "missing"

Milky Way mass from local escape velocity





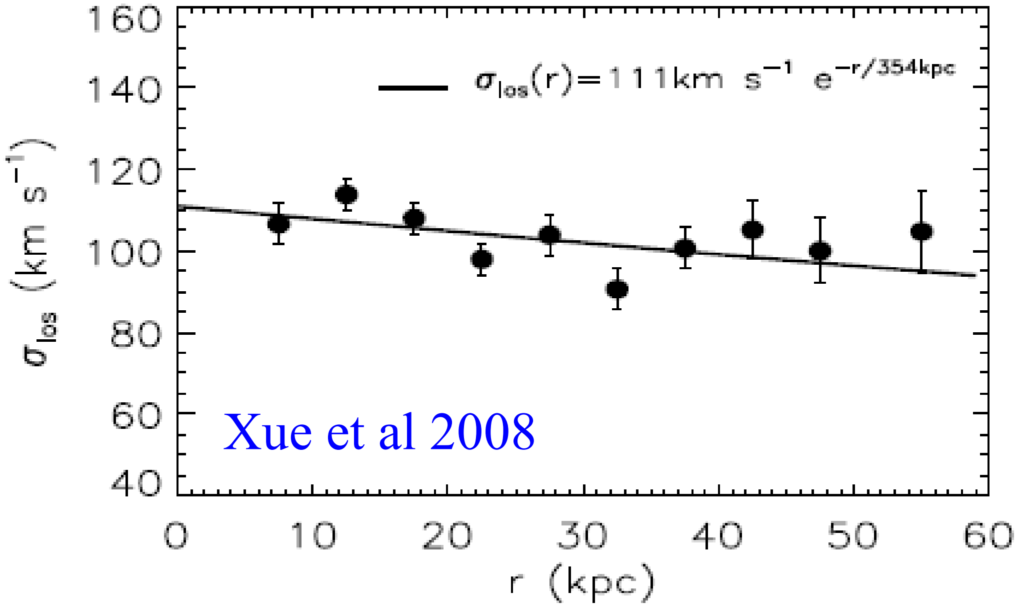
- Estimate based on 16 RAVE+ 17 archival stars with V > 300 km/s

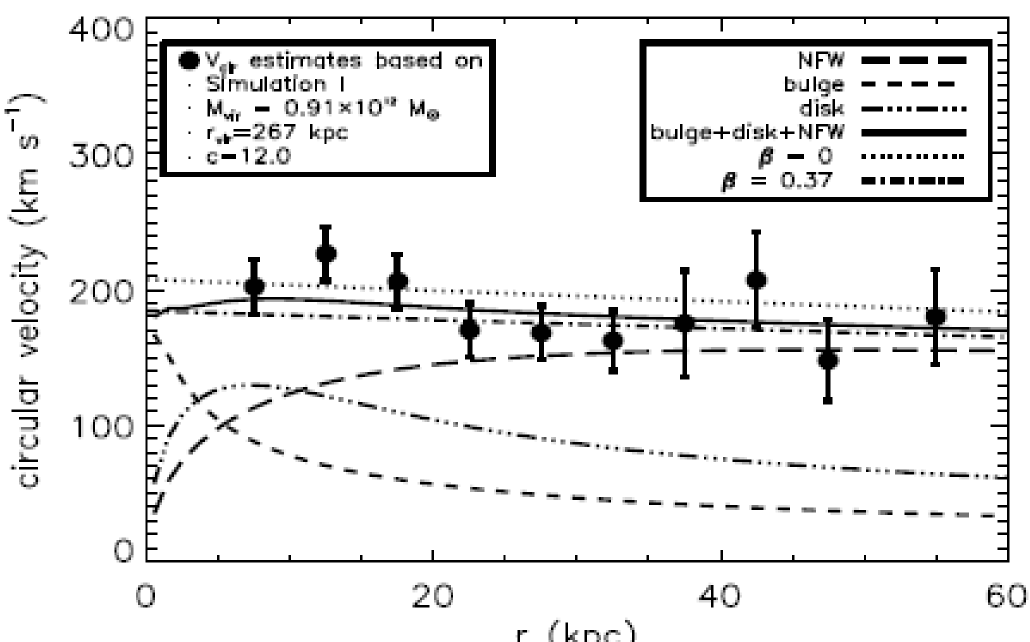
$498 \text{ km/s} < V_{ESC} < 608 \text{ km/s}$ (90% confidence)

→ $9 \times 10^{11} M_{\odot} < M_{NFW} < 2.5 \times 10^{12} M_{\odot}$

- Sensitive to assumptions about shape and cut-off of high-velocity tail

Milky Way mass from distant tracer velocities

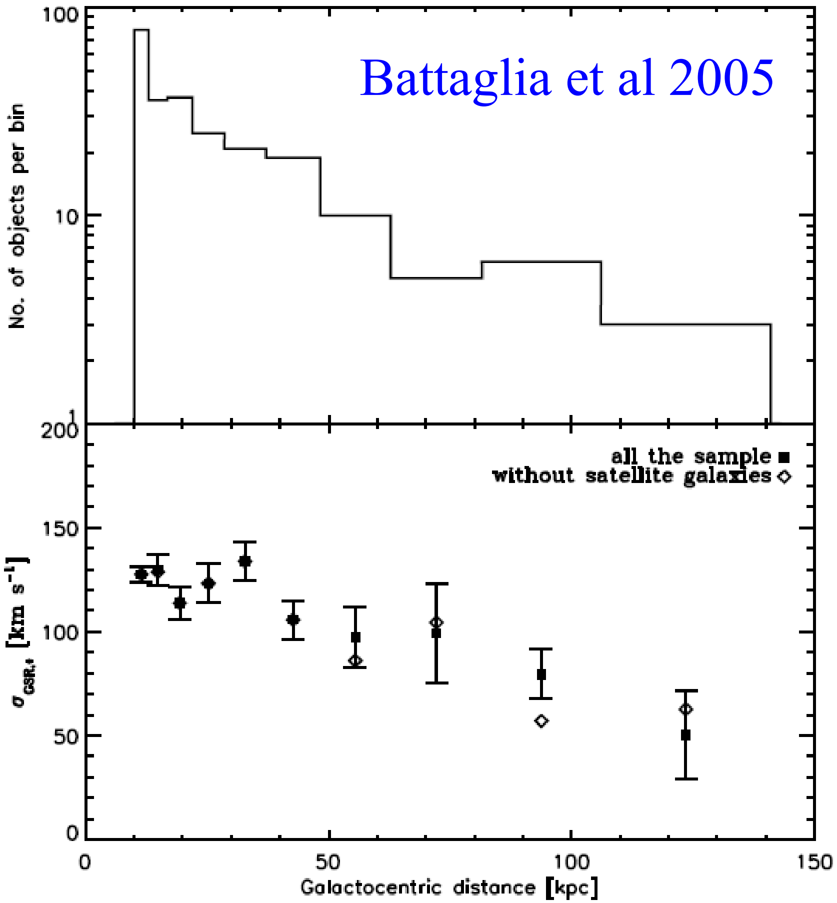


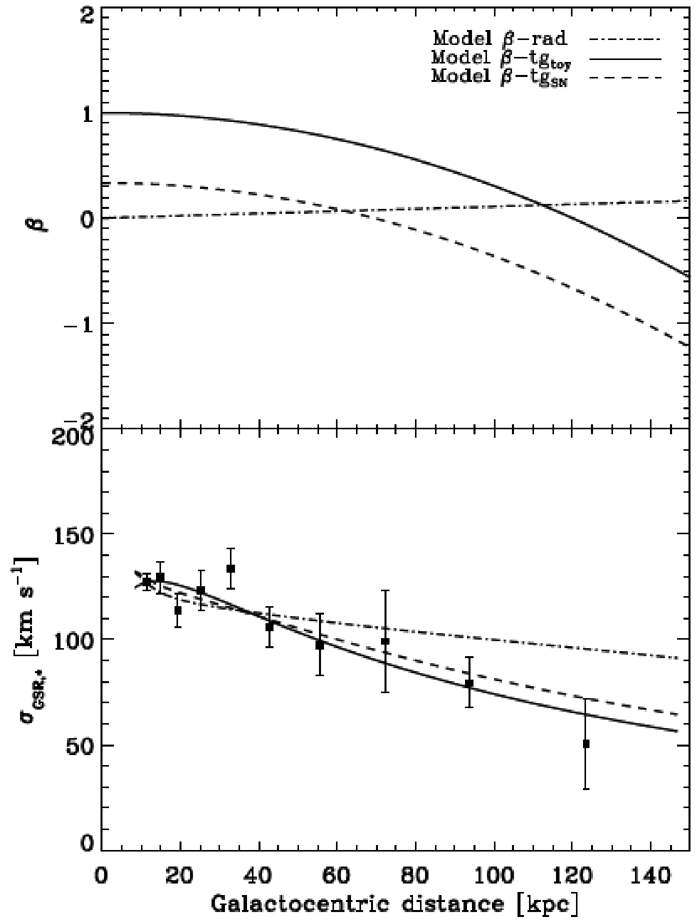


- Dispersions based on 2401 BHB stars from SDSS with |z| > 4 kpc
- Fit to CDM simulations of galaxy formation, adjusted using Jeans equations for differences in halo tracer profile and in V_{circ}
- Good fits to NFW+disk for halo masses (at 68% confidence)

  $8 \times 10^{11} M_\odot < M_{NFW} < 1.6 \times 10^{12} M_\odot$

Milky Way mass from distant tracer velocities

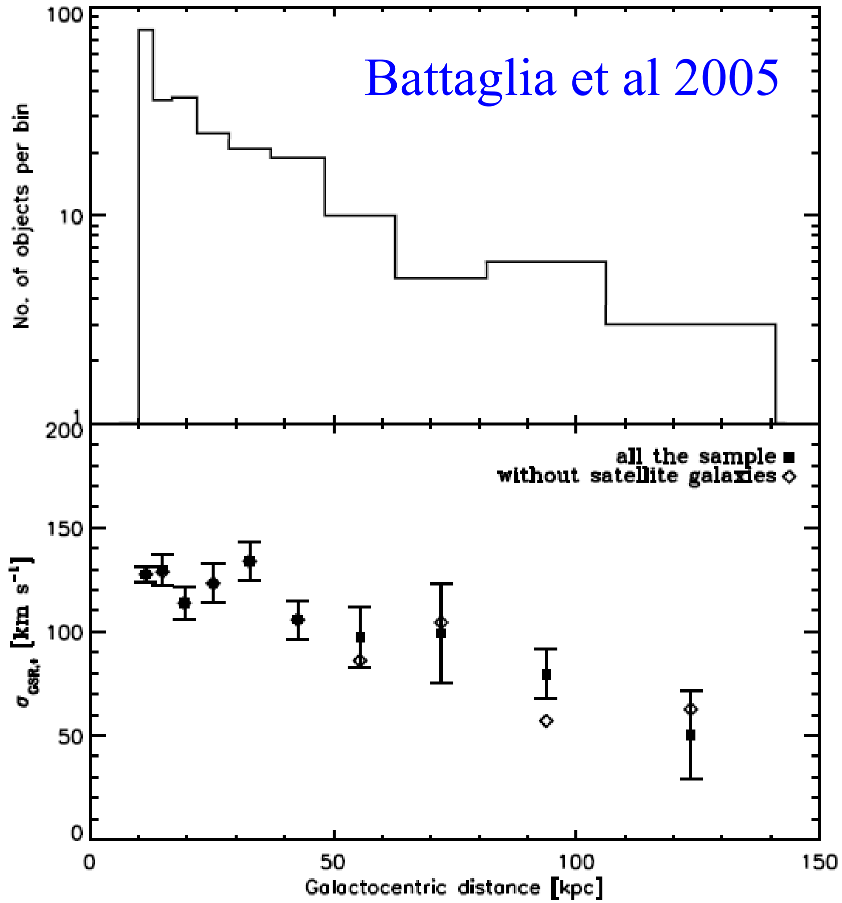


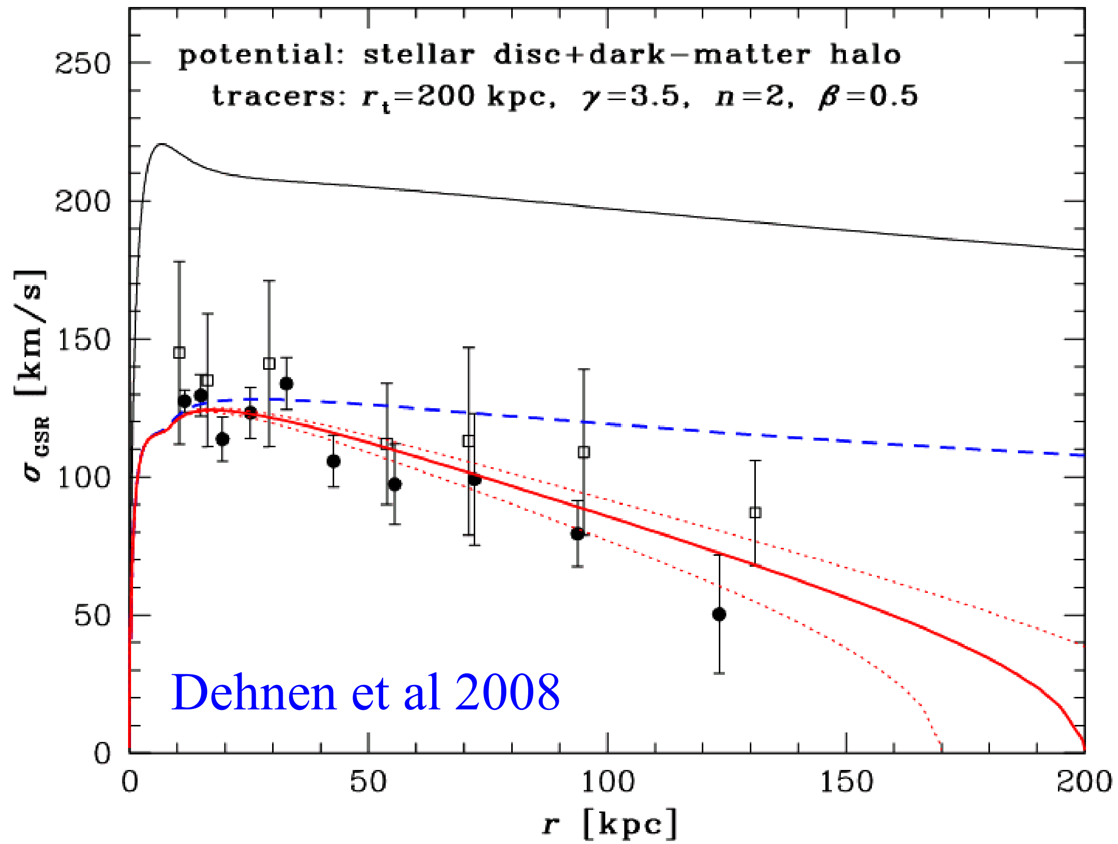


- Velocity dispersion from 240 halos stars + glob.clusters + satellites
- Jeans equations <u>assuming</u> $\rho \propto r^{-3.5}$
- Tangentially biased velocities at large *r* needed to match fall in σ

$6 \times 10^{11} M_\odot < M_{NFW} < 2.0 \times 10^{12} M_\odot$ (at 68% confidence)

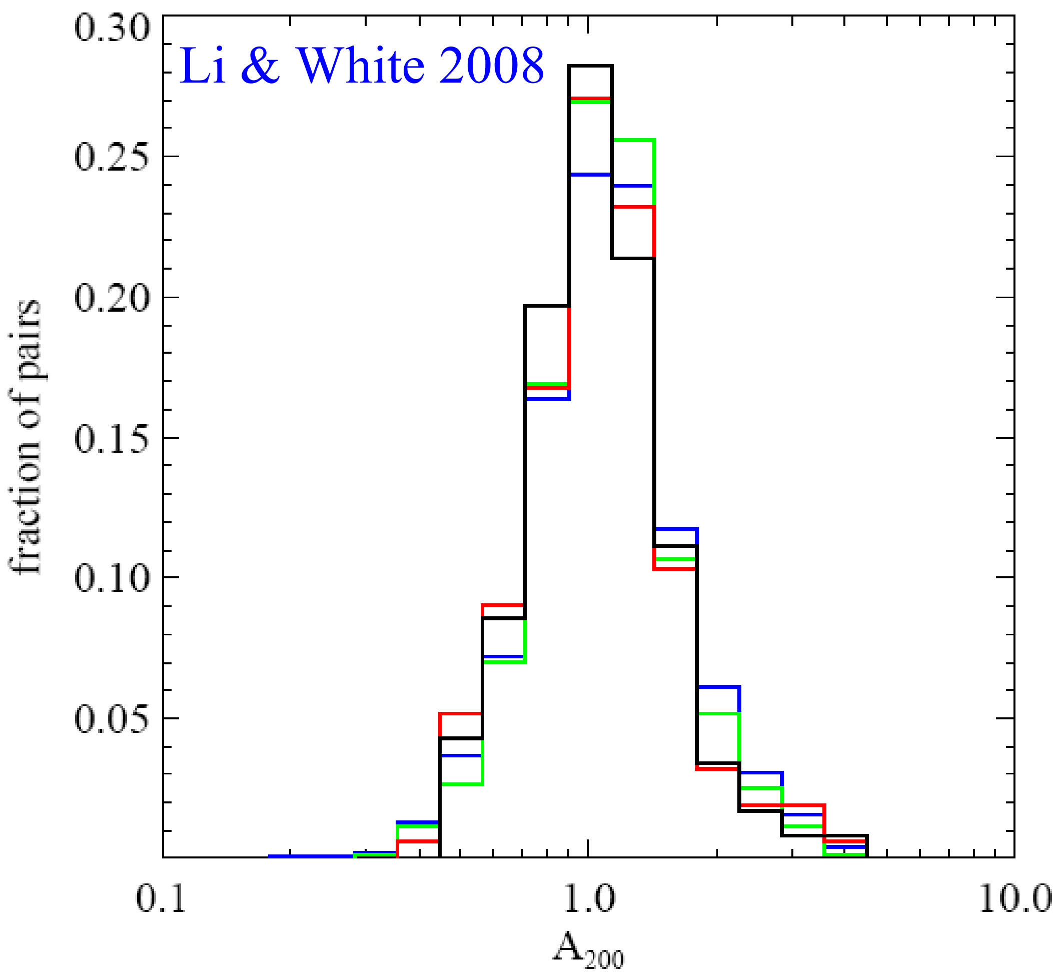
Milky Way mass from distant tracer velocities





- Velocity dispersion from 240 halos stars + glob.clusters + satellites
- Jeans equations <u>assuming</u> a cut-off in tracer density at $r \sim 200$ kc
- Radially anisotropic models now fit and there is *no* strong constraint on M_{NFW} from the data

Timing Argument masses in the Local Group



$M_{\text{Timing Argument}} / (M_{200}(MW) + M_{200}(M31))$ for ~ 10^3 Local Group analogues in the Millennium Simulation

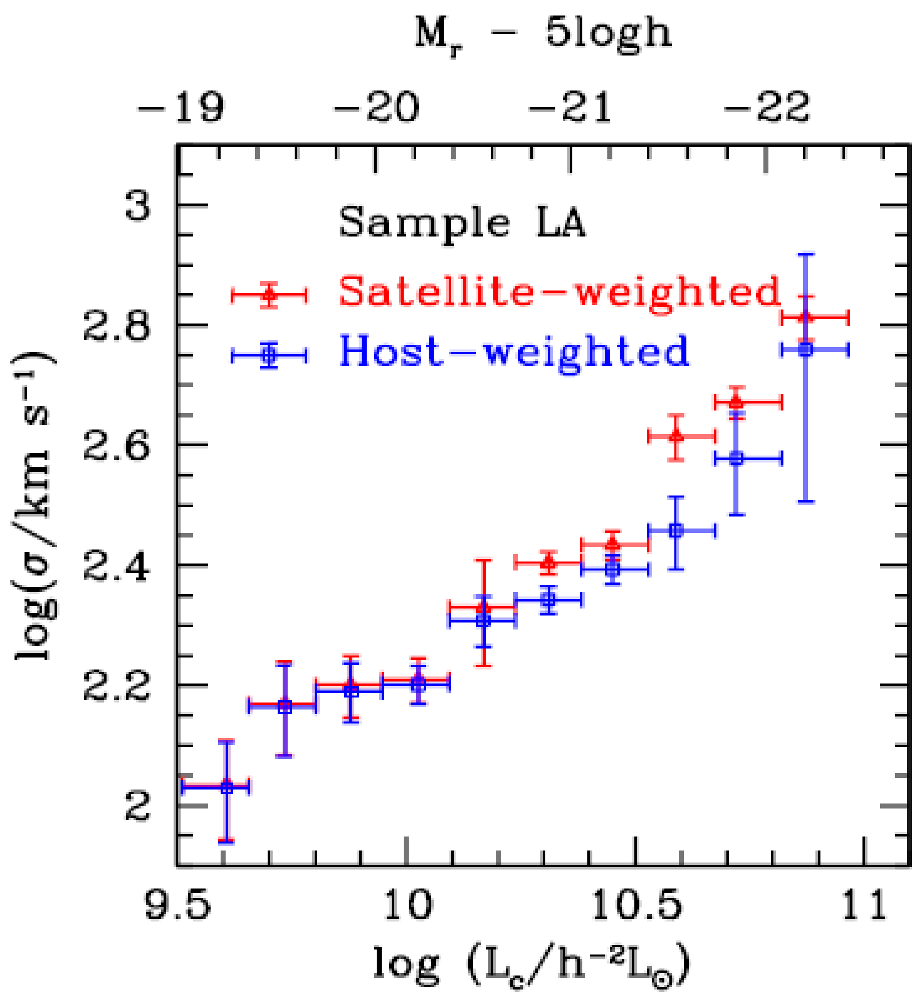
The Kahn & Woltjer timing argument estimates the mass of the Local Group from the age of the Universe and the separation and relative radial velocity of the MW and M31

Calibrating using the Millennium Simulation gives (at 90% conf.) $1.9 \times 10^{12} M_\odot < M_{LG} < 1.0 \times 10^{13} M_\odot$

A similar argument using Leo I gives $M_{MW} \sim 2.4 \times 10^{12} M_\odot$ with $M_{MW} > 8 \times 10^{11} M_\odot$ at 95% conf.

Galaxy halo masses from (stacked) satellite dynamics

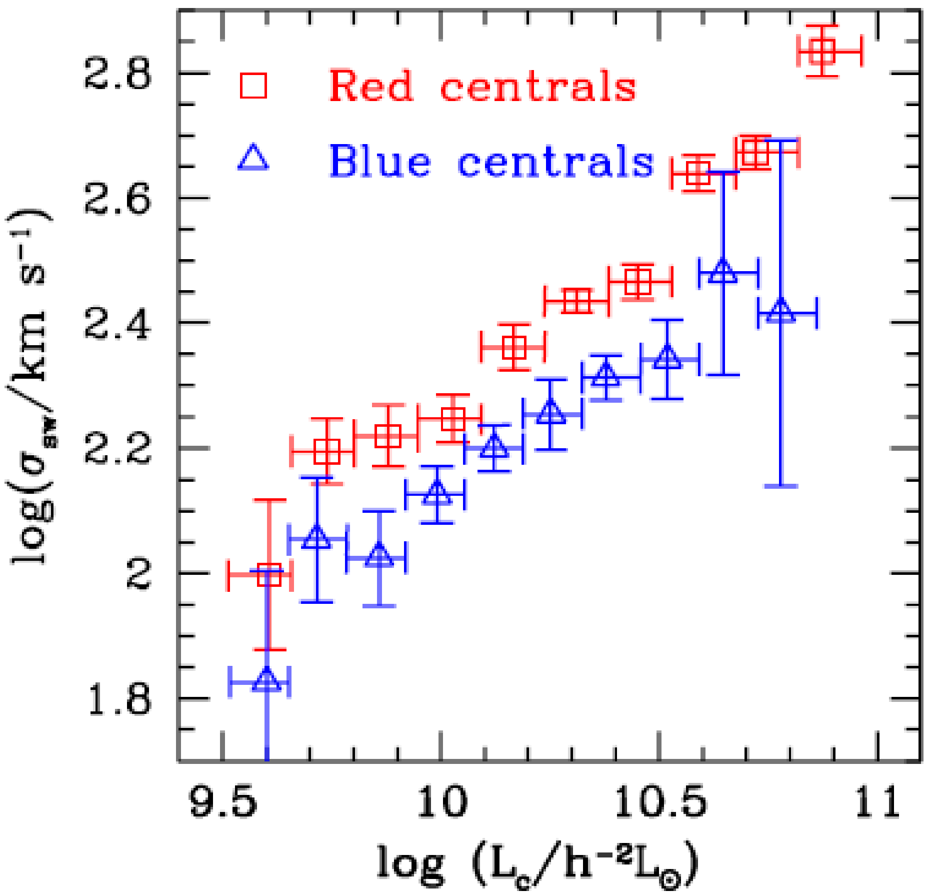
Surhud More, PhD thesis



Complete SDSS set of 6101 *central* galaxies. 3863 have ≥ 1 satellite
Velocity dispersions estimated within 0.375 x nominal "virial" radius
Clear trend of increasing dispersion with increasing central luminosity

Galaxy halo masses from (stacked) satellite dynamics

Surhud More, PhD thesis

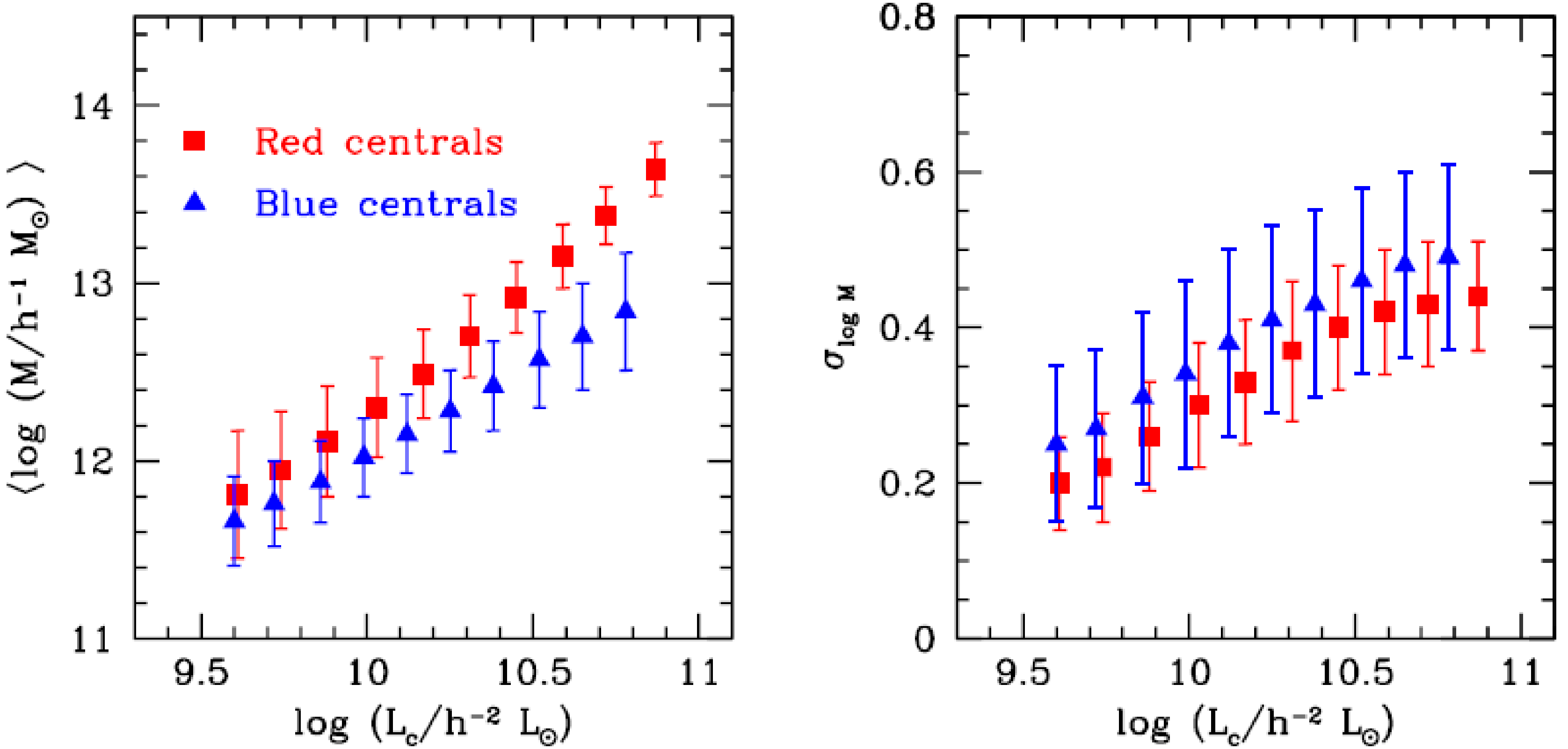


Complete SDSS set of 6101 *central* galaxies. 3863 have ≥ 1 satellite, of which 2503 are red and 1221 are blue

Velocity dispersions are higher for red centrals than for blue at given L

Galaxy halo masses from (stacked) satellite dynamics

Surhud More. PhD thesis

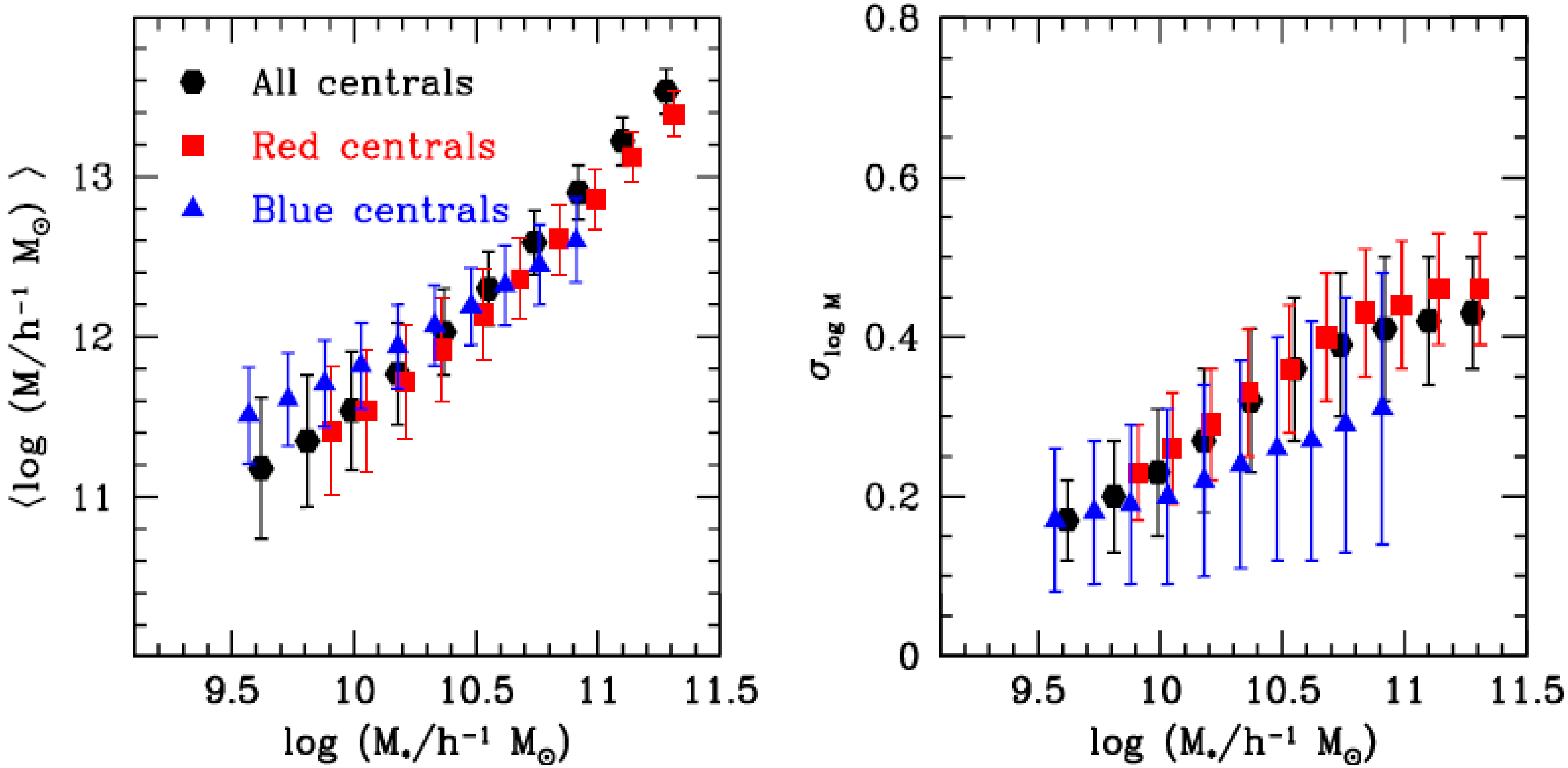


Assume: (i) NFW halos with standard concentration mass relation
(ii) satellite radial distribution less concentrated than mass (fit to obs.)
(iii) scatter in satellite number at given mass (from HOD fit to obs.)
(iv) isotropic distribution of satellite velocities

Larger L galaxies have halos with larger mean virial mass and more scatter

Galaxy halo masses from (stacked) satellite dynamics

Surhud More. PhD thesis

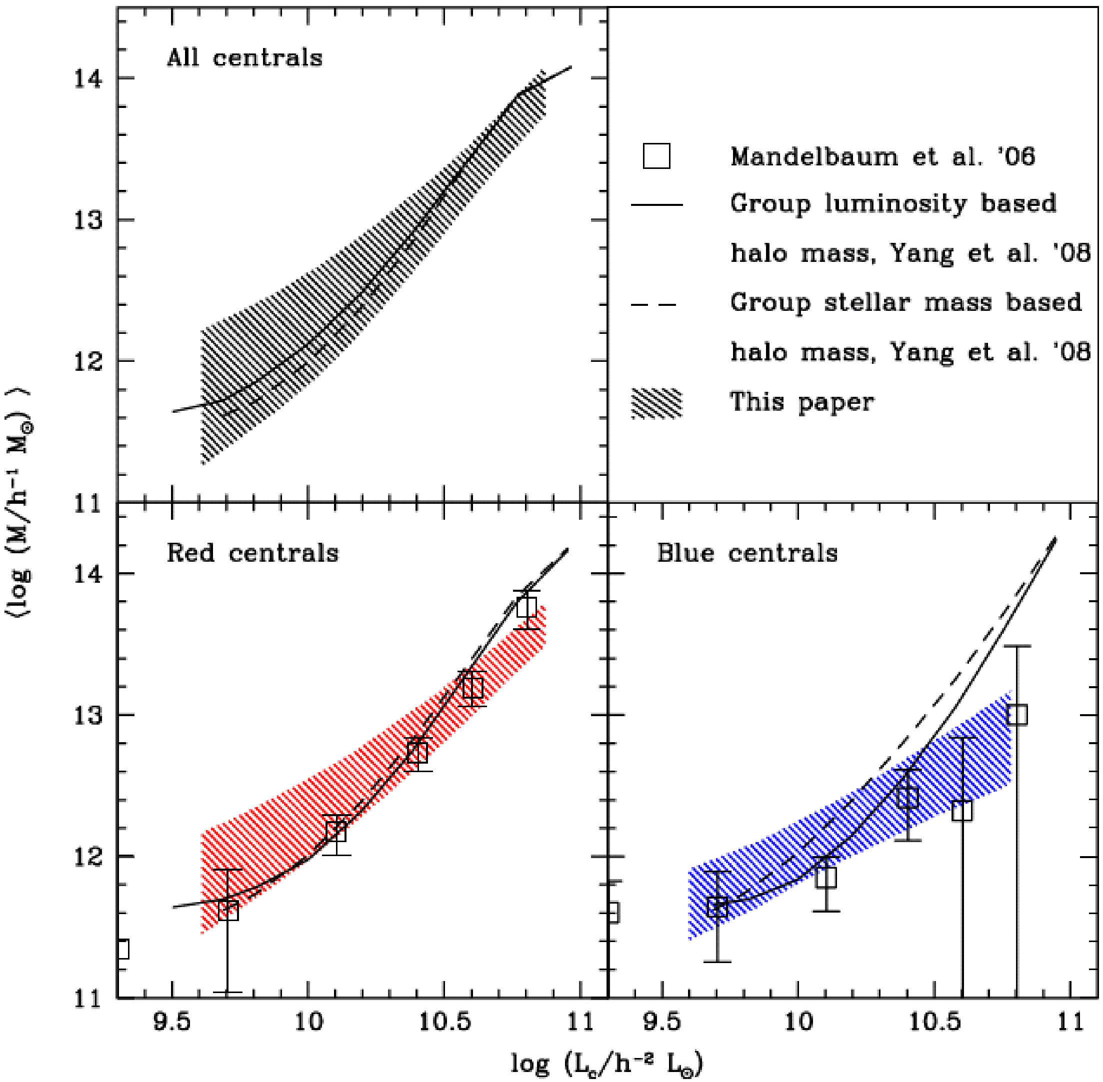


Assume: (i) NFW halos with standard concentration mass relation
(ii) satellite radial distribution less concentrated than mass (fit to obs.)
(iii) scatter in satellite number at given mass (from HOD fit to obs.)
(iv) isotropic distribution of satellite velocities

At given M_* blue and red central galaxies have *similar* mass halos

Galaxy halo masses from (stacked) satellite dynamics

Surhud More, PhD thesis

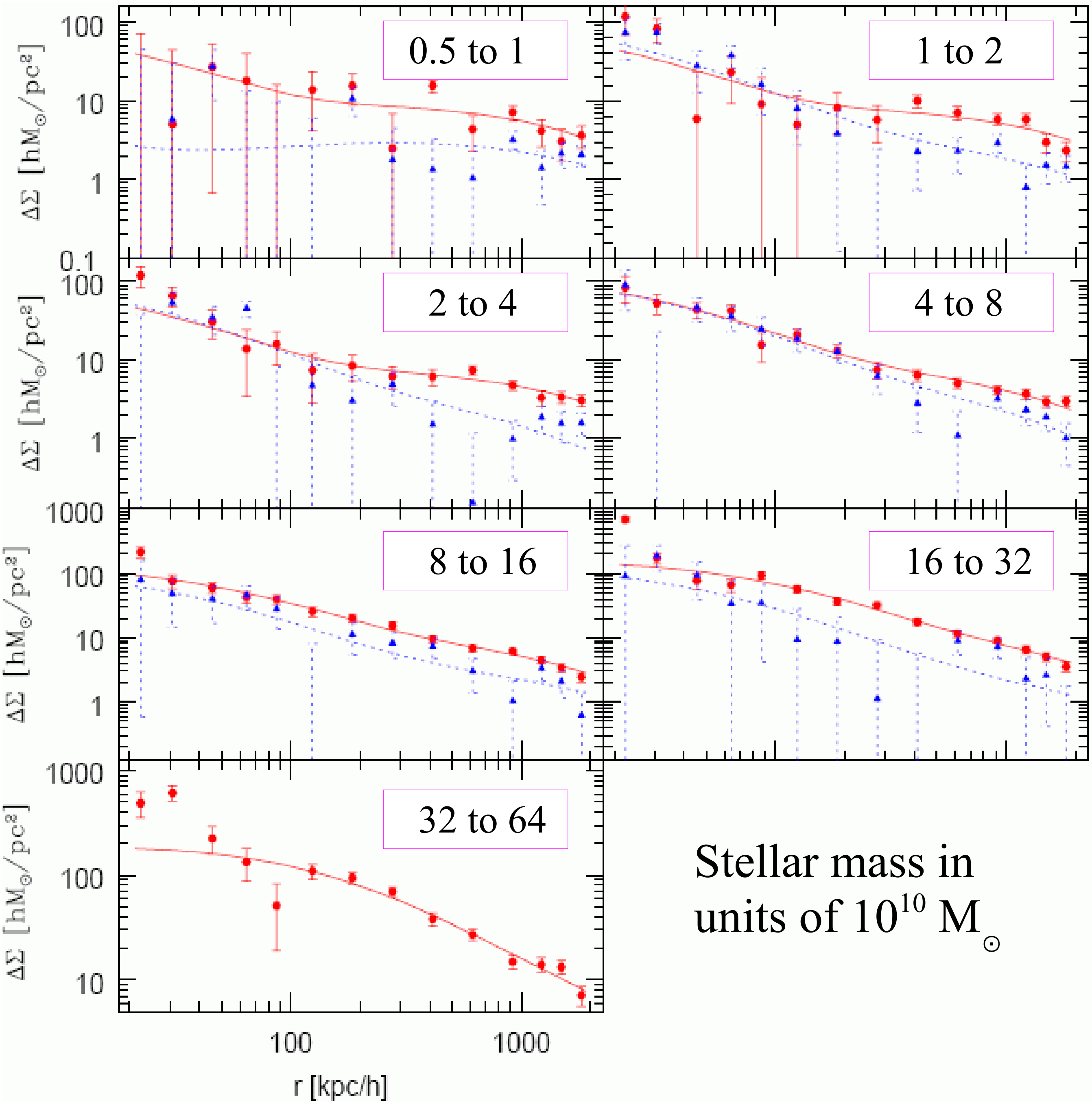


Satellite dynamics estimates of halo masses agree well

(i) with those from counting arguments

(ii) with lensing estimates

Galaxy halo masses from (stacked) weak lensing

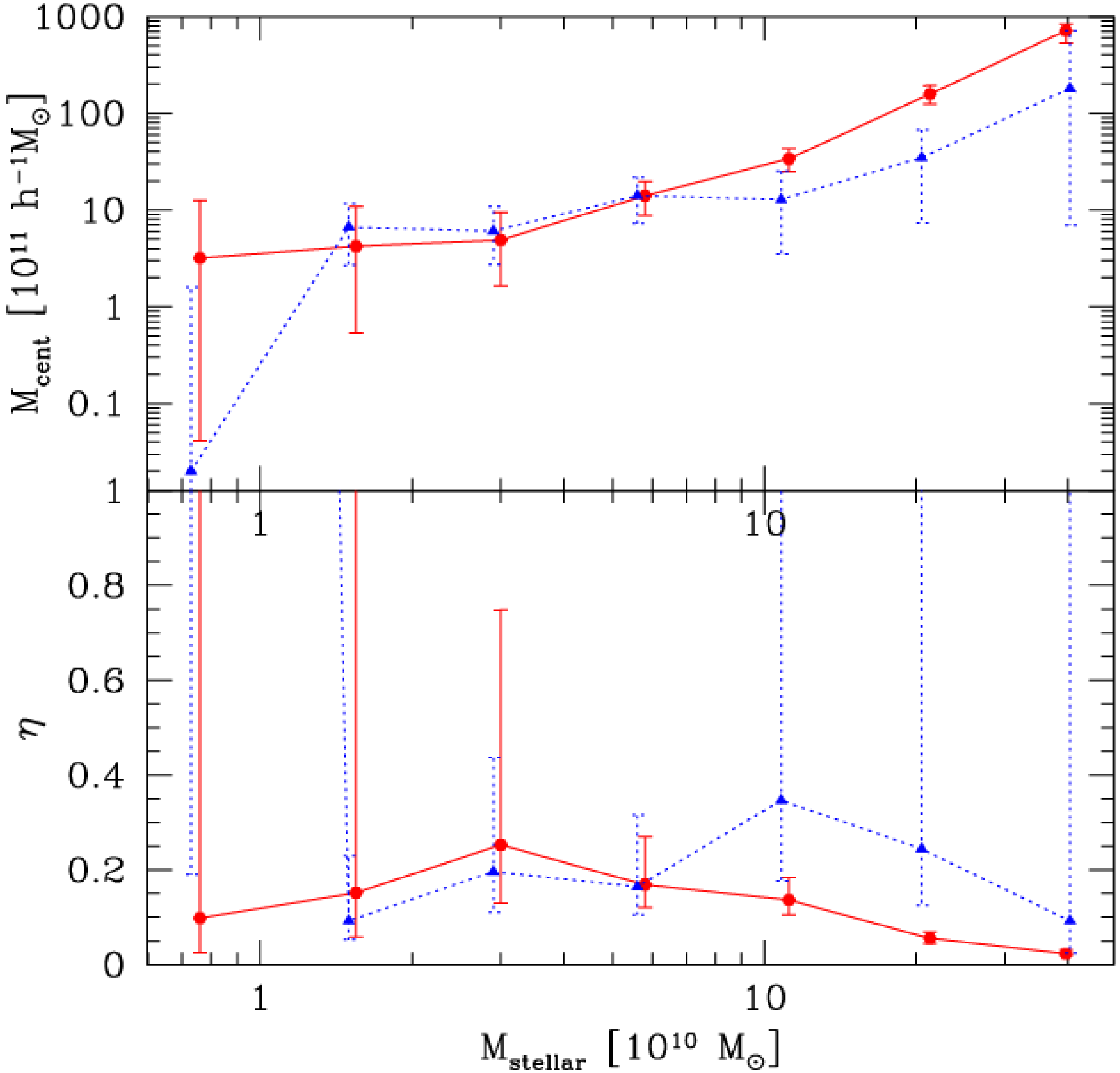


Stellar mass in units of 10^{10} $M_\odot$

Mandelbaum et al 2006

- Halos detected for all stellar mass ranges
- Larger stellar mass → larger halo mass
- Red galaxies have more massive halos
- Substantial contribution from satellite galaxies

Galaxy halo masses from (stacked) weak lensing

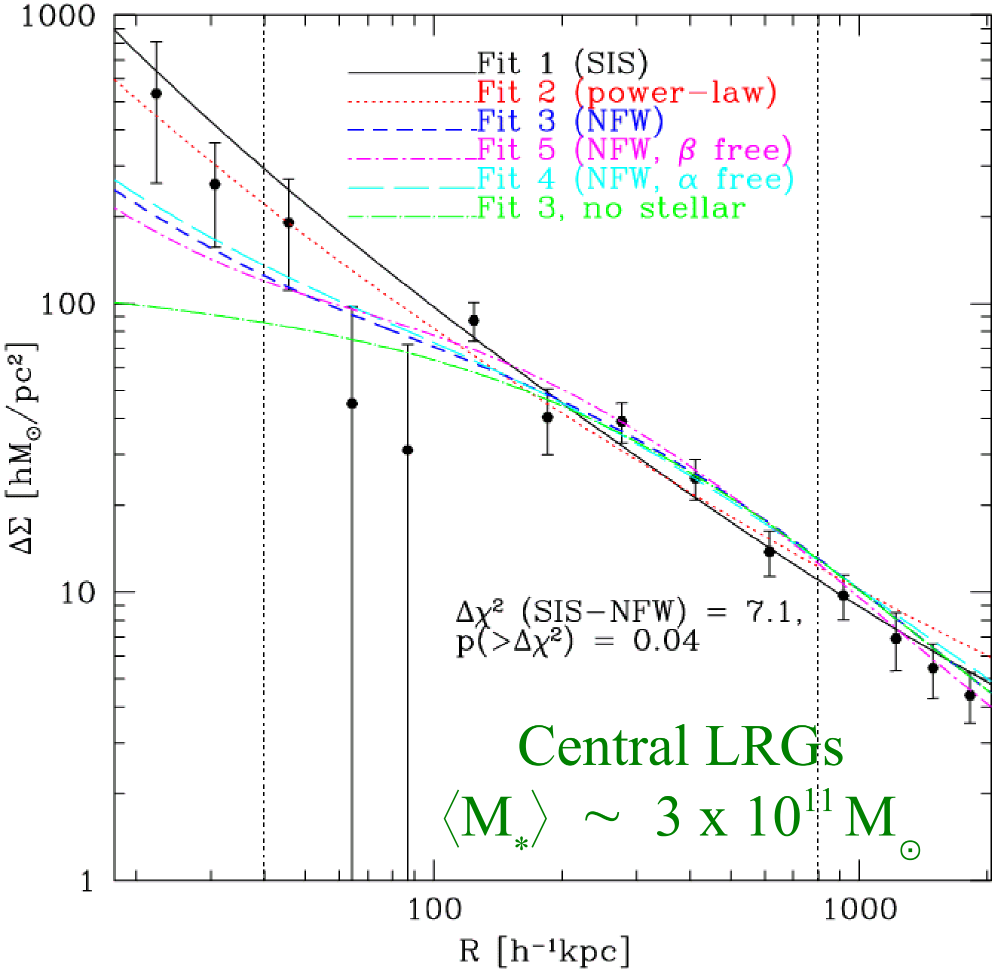


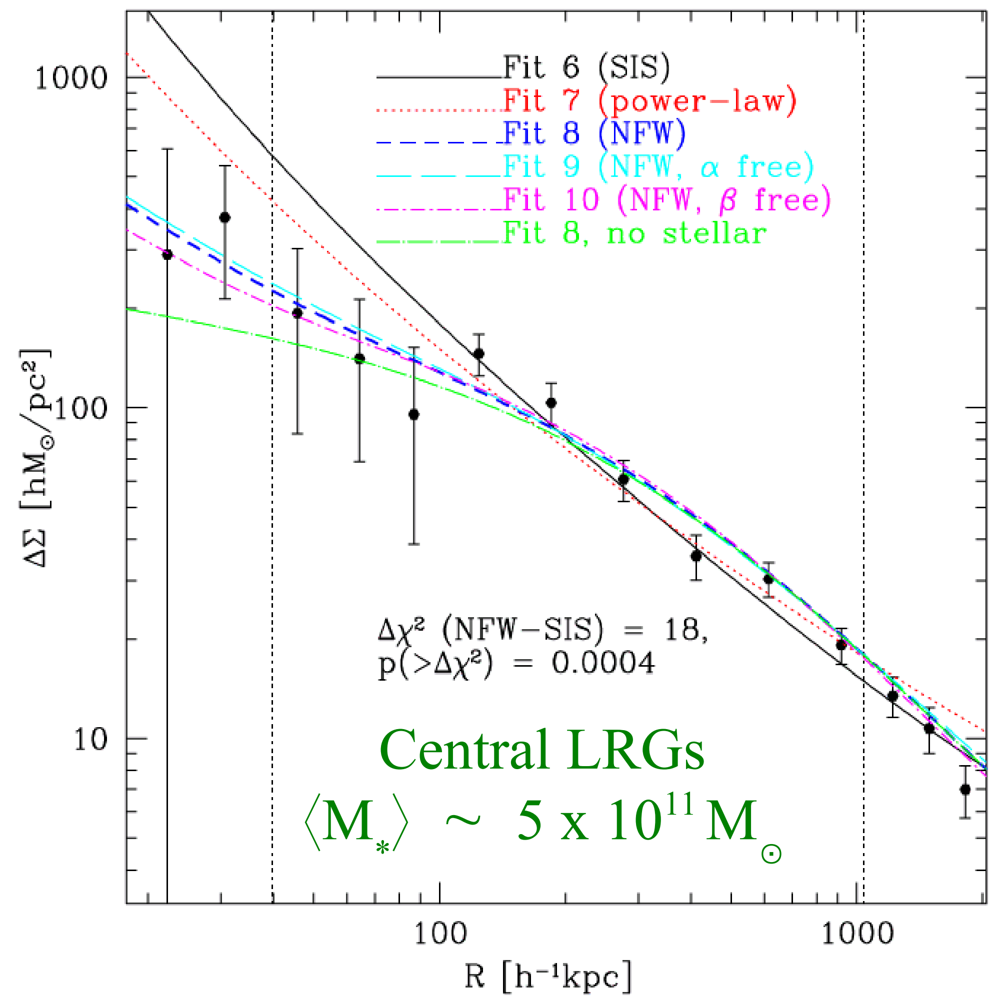
Mandelbaum et al 2006

- Halo masses for *central* galaxies and satellite fractions (from HODs)
- Satellite fractions small, esp. for red galaxies
- At low stellar mass, red and blue centrals have halos of similar mass
- At high stellar mass, red centrals have more massive halos

Galaxy halo masses from (stacked) weak lensing

Mandelbaum et al 2006

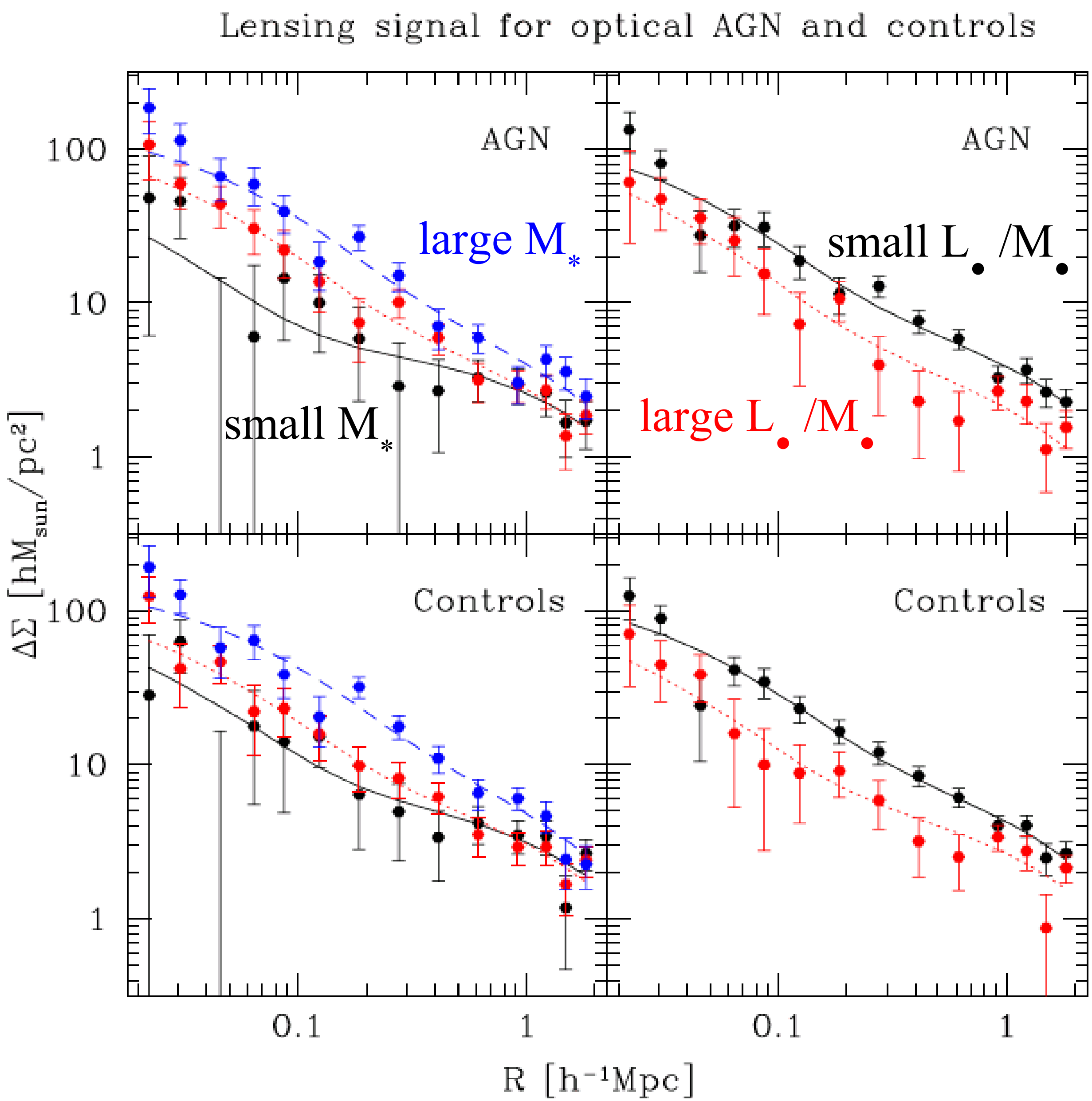




For massive centrals both the NFW profile and the stellar mass are seen

Galaxy halo masses from (stacked) weak lensing

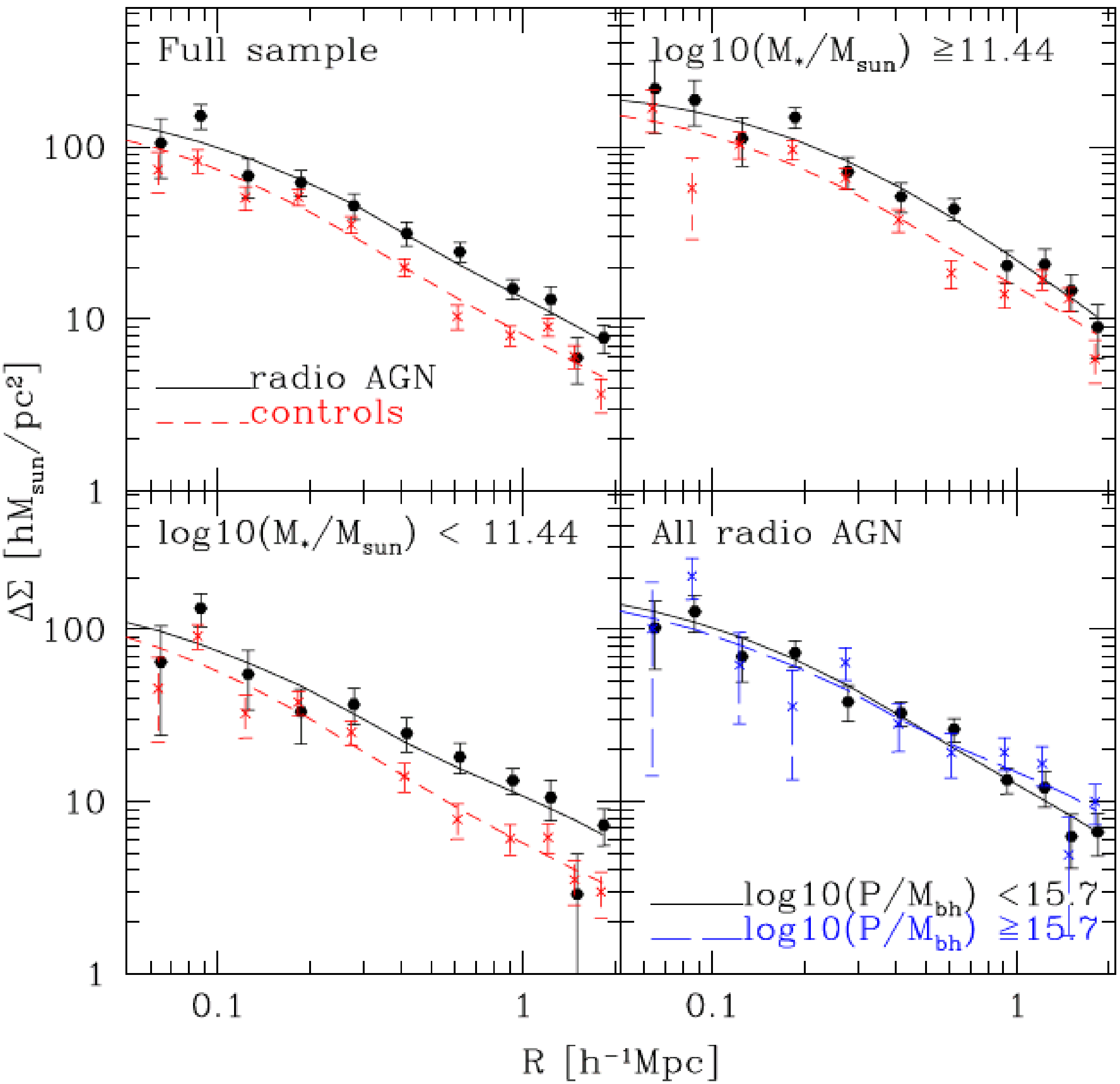
Mandelbaum et al 2009



Optically luminous AGN have similar mass halos to inactive galaxies of similar stellar mass and population

Galaxy halo masses from (stacked) weak lensing

Mandelbaum et al 2009



<u>Radio</u> luminous AGN have *more* massive halos than inactive galaxies of similar stellar mass and population

Halo mass increases with stellar mass but *not* with radio power for radio galaxies

Galaxy halo masses from X-ray imaging+spectroscopy

- For central ellipticals of groups and clusters there is now good agreement with lensing analyses in most cases

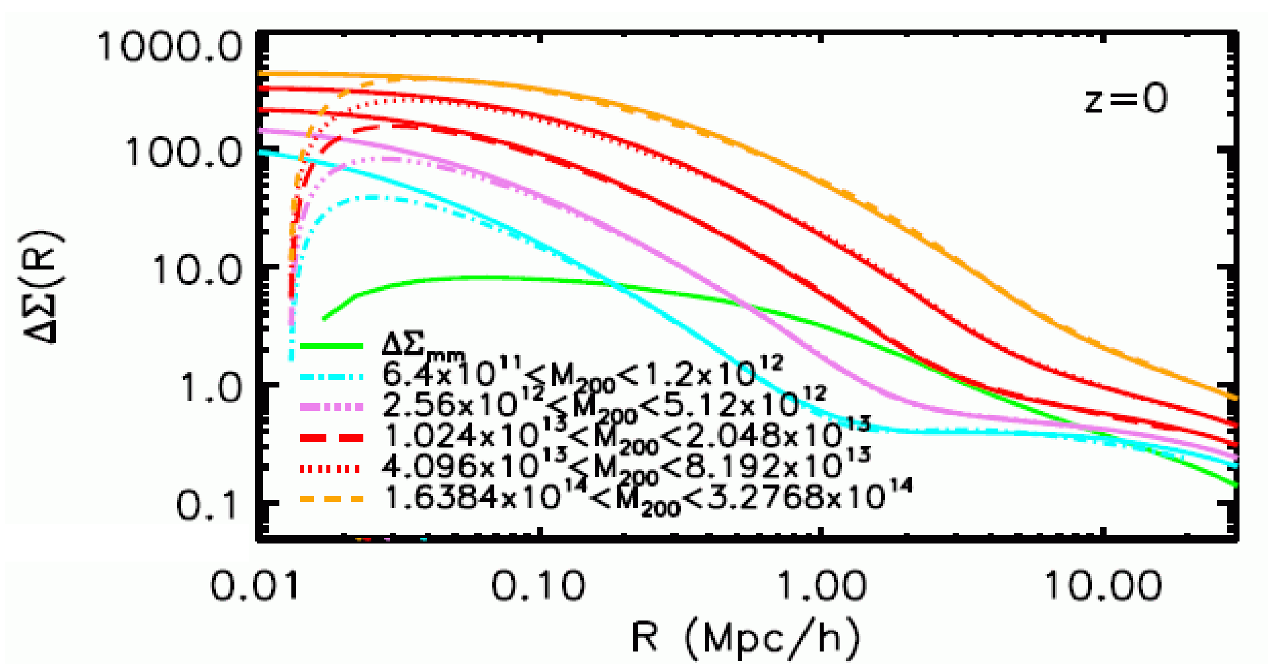
  -- halo shapes?

- For central spirals there is still no confirmed detection of an extended hot halo

  --where are the missing baryons? (75% of the total!)

The next steps?

- Find the missing baryons
- Detect halo shapes by aligning central galaxies
- Detect the 1-halo/2-halo transition



Hayashi & White 2008