Establishing the relationship between galaxies and dark matter halos

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The Cold Dark Matter Paradigm

- **The spacetime: the standard cosmology**
  $\Omega_{\rm m}$, Ω_Λ, h
- **Matter content: the universe is dominated by cold dark matter**
  $\Omega_{\rm CDM}$, $\Omega_{\rm baryon}$, etc
- **Initial conditions: density perturbations from inflation ($P_i(k) = Ak^n$)**
  A(or σ_8) and n

$\Omega_m \approx 0.25$, $\Omega_\Lambda \approx 0.75$, $h \approx 0.7$, $\sigma_8 \approx 0.75$, $\Omega_b h^2 \approx 0.022$, $n \approx 0.95$.

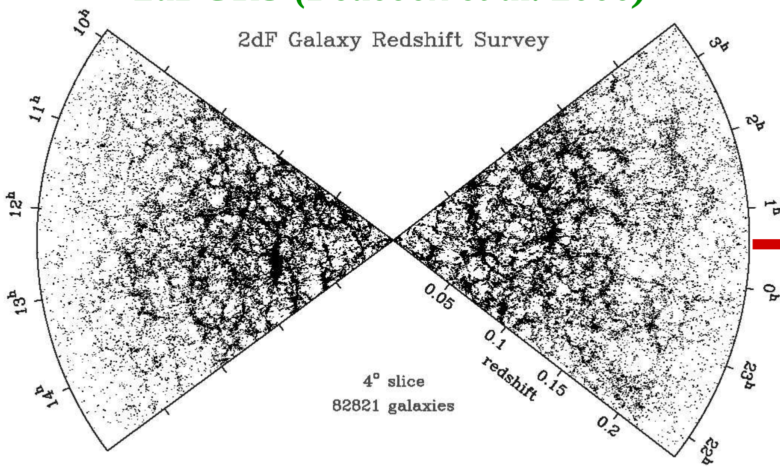
- Density perturbations in dark matter collapse into quasi-static clumps (dark matter halos)
- Dark matter halos are well-defined objects: $\overline{\rho}_{\rm halo} \sim 350\overline{\rho}_{\rm U}$
- Galaxies are assumed to form in dark matter halos

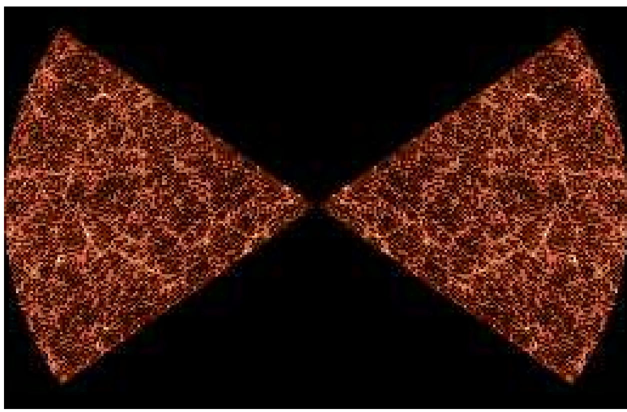
Properties of CDM halos: well understood

- Mass function: $n(M)\mathrm{d}M$
- Spatial clustering: halo bias $b(M)$
- Internal structure: density profile, shape, substructure angular momentum, etc

Connecting galaxies and dark halos: two ways

2dFGRS (Peacock et al. 2000)





CDM simulation (Virgo consortium)

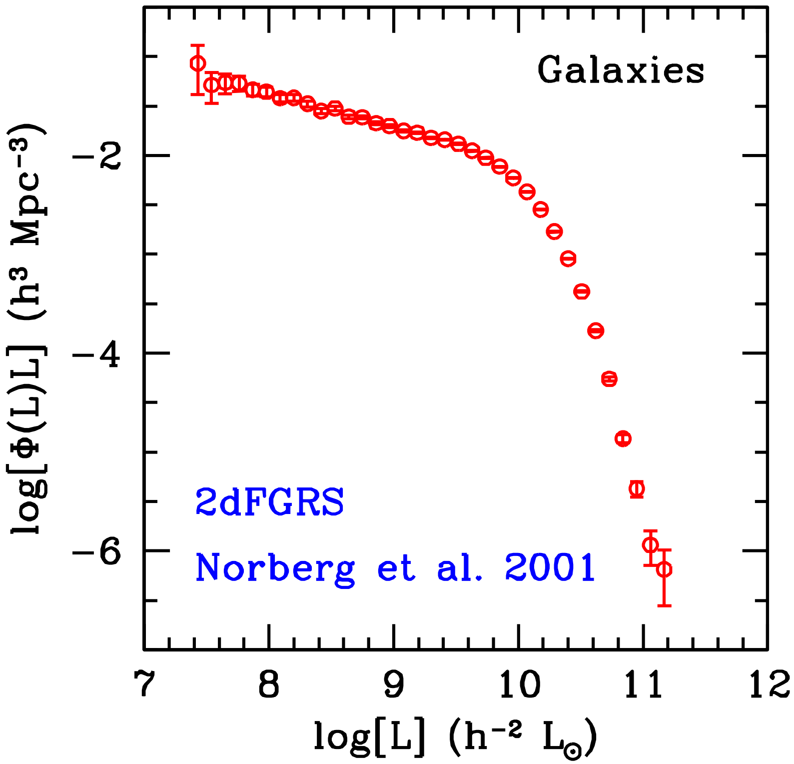
HON

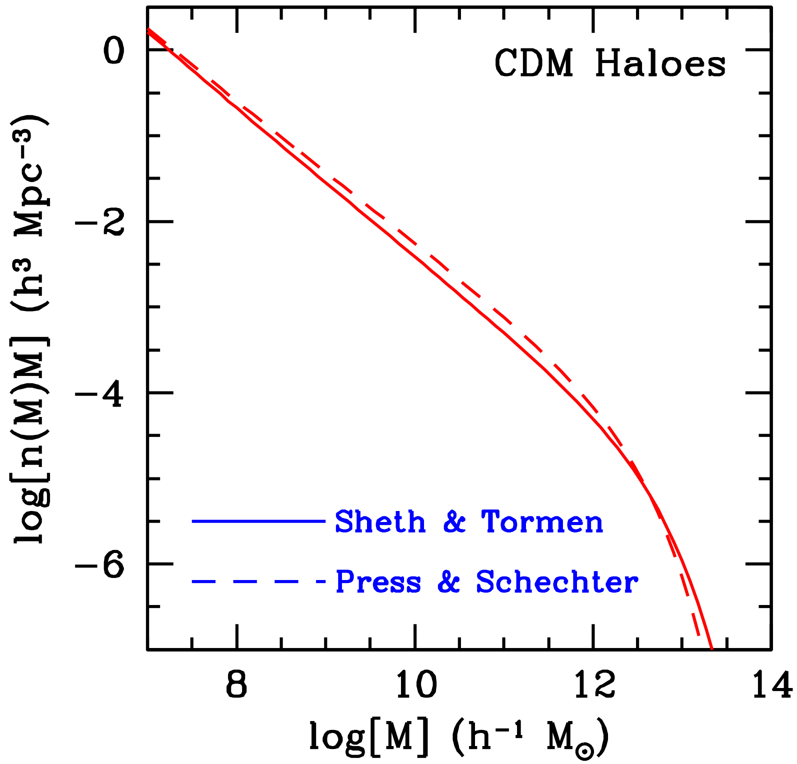
P(N|M)

1. Halo Occupation Distribution: $P(N|M)$,
   the probability that a halo of mass M contains N galaxies (of given properties)
2. Galaxies in groups and clusters

HOD: Lighting-Up the Dark Matter

$\Phi(L)\mathrm{d}L =$ comoving number density of galaxies with luminosities in the range L, $L + \mathrm{d}L$.





We use the Conditional Luminosity Function to link the distributions of galaxies and CDM halos

$\Phi(L|M)\mathrm{d}L =$ average number of galaxies with luminosities in the range L, $L + \mathrm{d}L$ that 'live' in halos of mass M.

The Conditional Luminosity Function

Yang, Mo, van den Bosch (2003)

The luminosity function:

$$\Phi(L) = \int_0^\infty \Phi(L|M)\, n(M)\, \mathrm{d}M$$

The average luminosity in a halo of mass M:

$$\langle L \rangle(M) = \int_0^\infty \Phi(L|M)\, L\, \mathrm{d}L$$

The average number of galaxies in a halo of mass M with $L > L_1$:

$$N_M(L > L_1) = \int_{L_1}^\infty \Phi(L|M)\, \mathrm{d}L$$

Clustering properties of galaxies as function of luminosity:

$$\xi_{\rm gg}(r|L) = b^2(L)\, \xi_{\rm dm}(r)$$

$$\bar{b}(L) = \frac{1}{\Phi(L)} \int_0^\infty \Phi(L|M)\, b(M)\, n(M)\, \mathrm{d}M$$

REMINDER: $n(M), b(M), \xi_{\rm dm}(r)$ are well-understood halo properties

The conditional LF is the ideal statistical ‘tool’ to link the distributions of dark matter halos and galaxies.

The Model

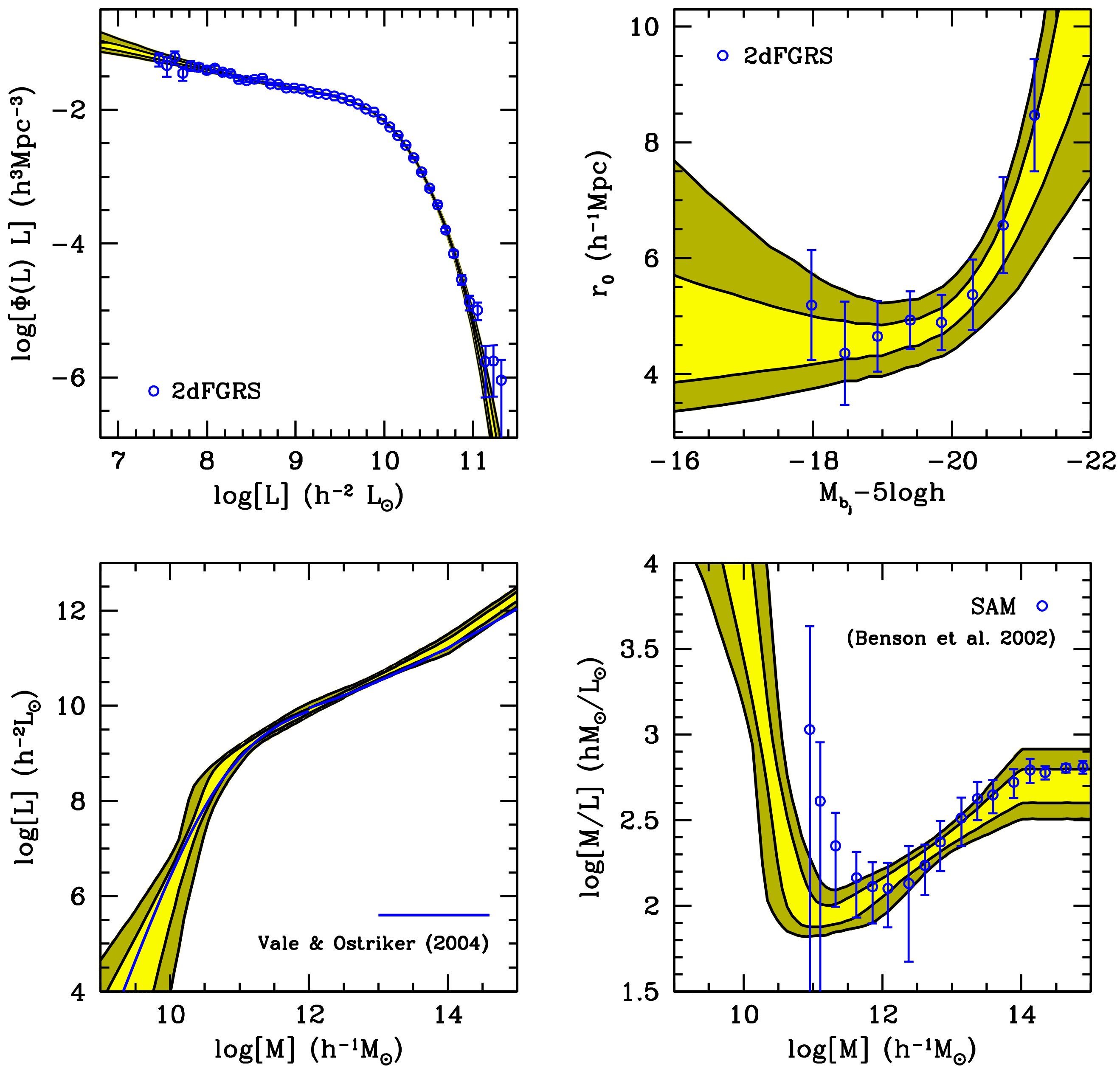
We assume that the CLF also has the Schechter form:

$$\Phi(L|M)\mathrm{d}L = \frac{\tilde{\Phi}^*}{\tilde{L}^*}\left(\frac{L}{\tilde{L}^*}\right)^{\tilde{\alpha}} \exp(-L/\tilde{L}^*)\,\mathrm{d}L$$

Here $\tilde{\Phi}^*$, $\tilde{L}^*$ and $\tilde{\alpha}$ all depend on M.

- **Parameterize $\tilde{\Phi}^*$, $\tilde{L}^*$ and $\tilde{\alpha}$. In total our model has 8 free parameters**
- **Construct Monte-Carlo Markov Chain to sample posterior distribution of free parameters.**

The Relation between Light and Mass

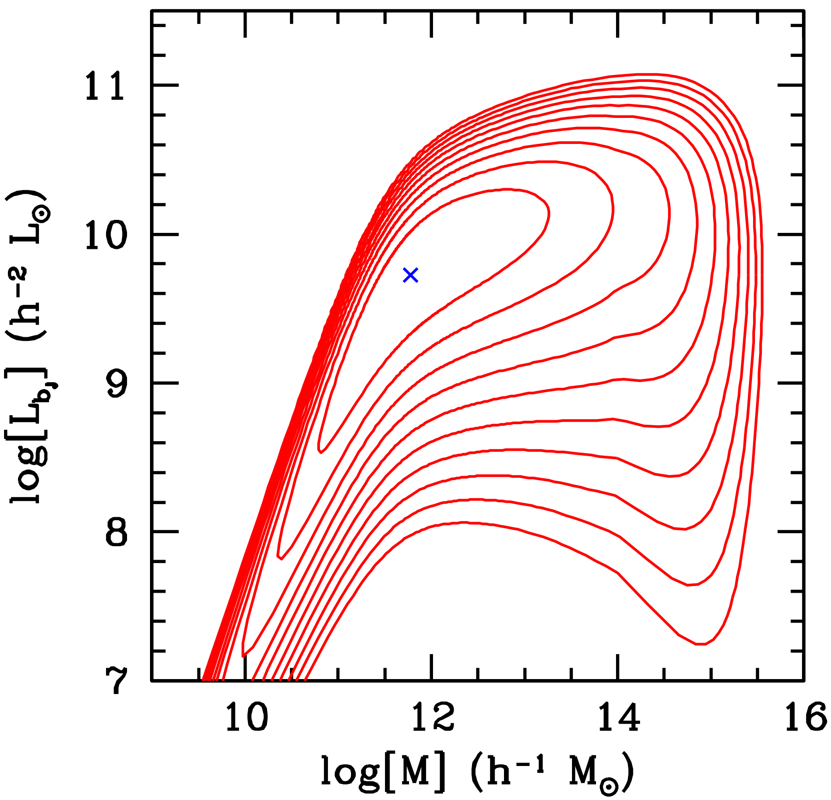


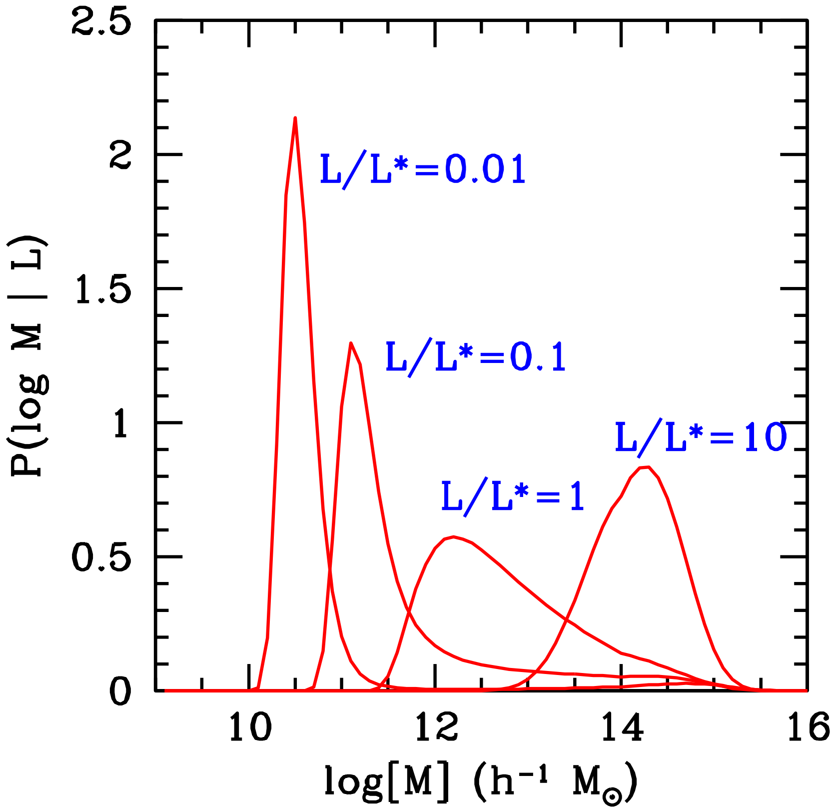
vdB, Yang, Mo & Norberg, 2004 (astro-ph/0406246)

Light distribution in the Universe

$$P(L,M)\,\mathrm{d}L\,\mathrm{d}M = \frac{1}{\bar{\rho}_L}\,n(M)\,\Phi(L|M)\,L\,\mathrm{d}L\,\mathrm{d}M$$

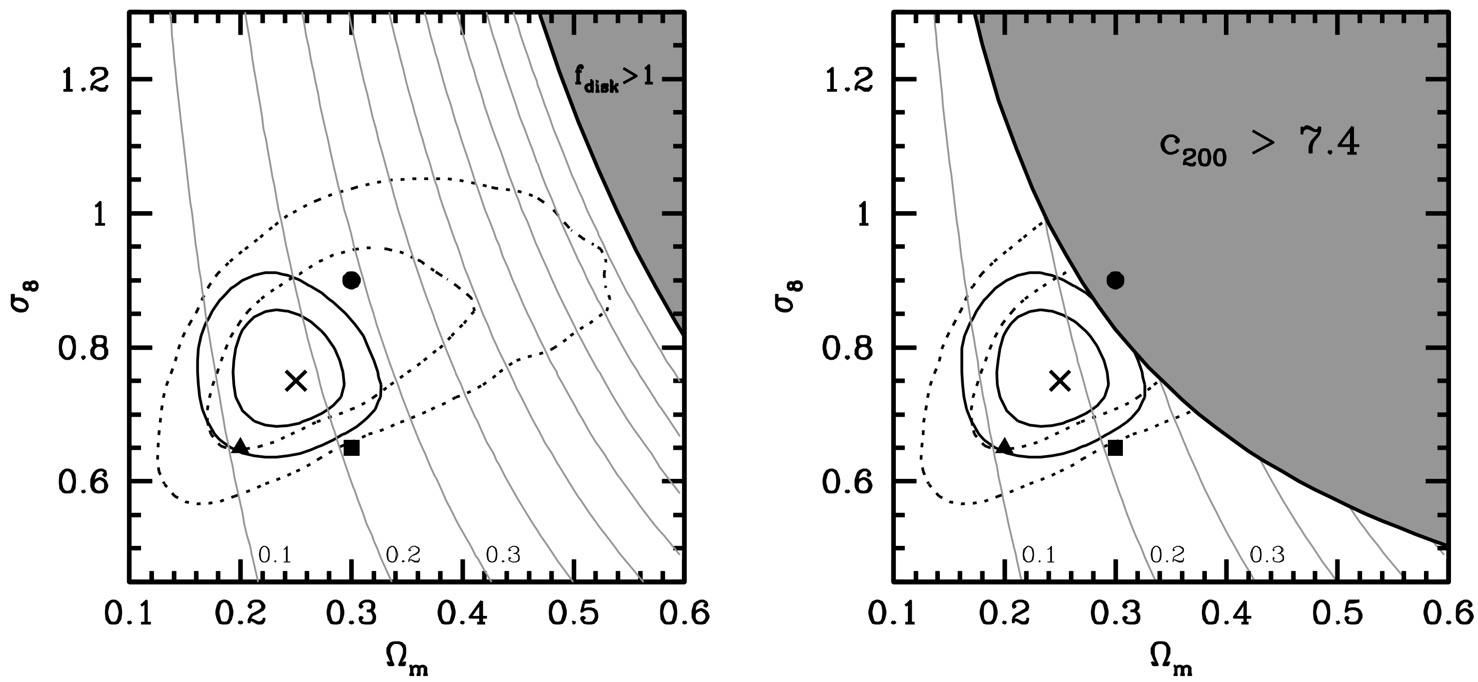
$$P(M|L)\mathrm{d}M = \frac{\Phi(L|M)\,n(M)\,\mathrm{d}M}{\Phi(L)}$$





50% of light is produced in halos $M \lesssim 2\times10^{12}h^{-1}\,\mathrm{M}_\odot$.

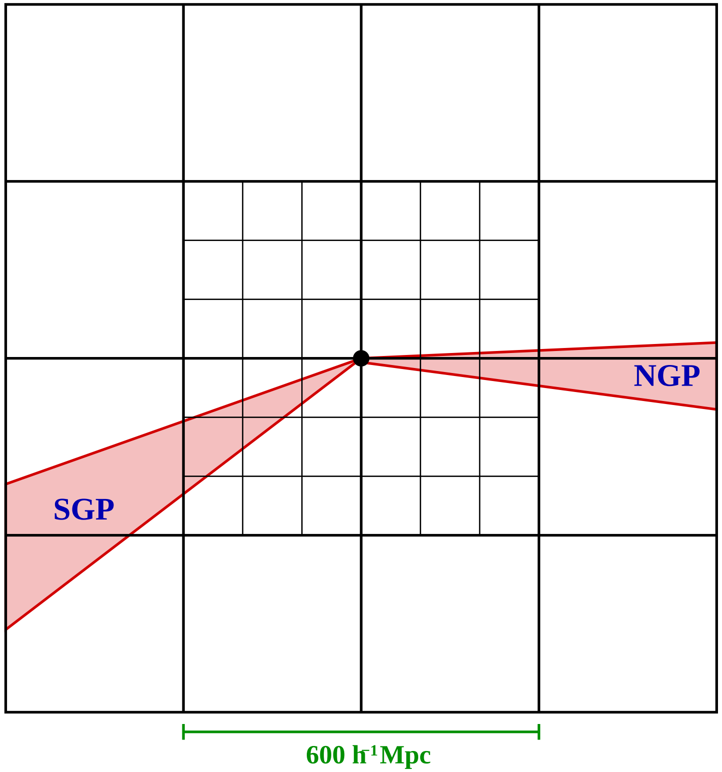
Constraints on Ω_m and σ_8



vdB, Mo & Yang 2003, MNRAS, 345, 923

Constructing mock catalogs

- **Run numerical simulations: ΛCDM concordance cosmology; $L_{\rm box} = 100h^{-1}$ Mpc and $L_{\rm box} = 300h^{-1}$ Mpc with 512^3 CDM particles each.**
- **Identify dark matter halos (FOF algorithm, $b = 0.2$).**
- **Populate halos with galaxies using CLF.**
- **Stack boxes to create virtual universe and mimick observations (magnitude limit, completeness, geometry)**



Large Scale Structure

Correlation function in redshift-space:

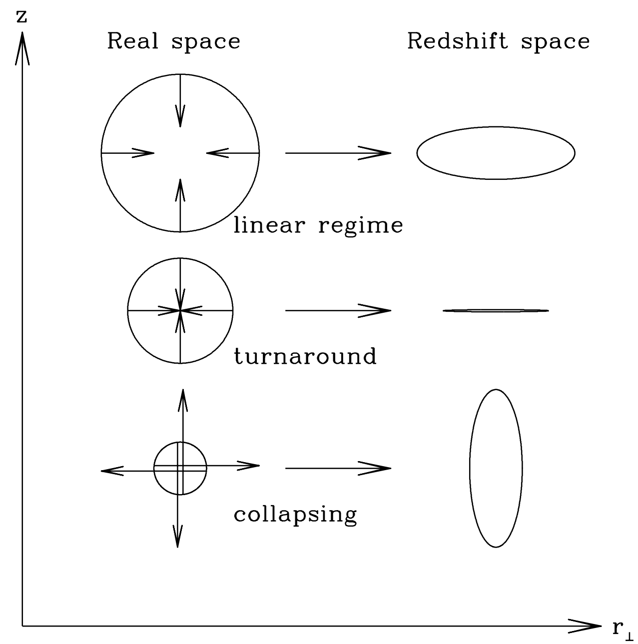
$$\xi(r_p, \pi) = \frac{GG(r_p, \pi)}{RR(r_p, \pi)} - 1\,,$$

where r_p and π the pair separations perpendicular and parallel to the line-of-sight.

redshift space CF: $\xi(s)$ **with** $s = \sqrt{r_p^2 + \pi^2}$.

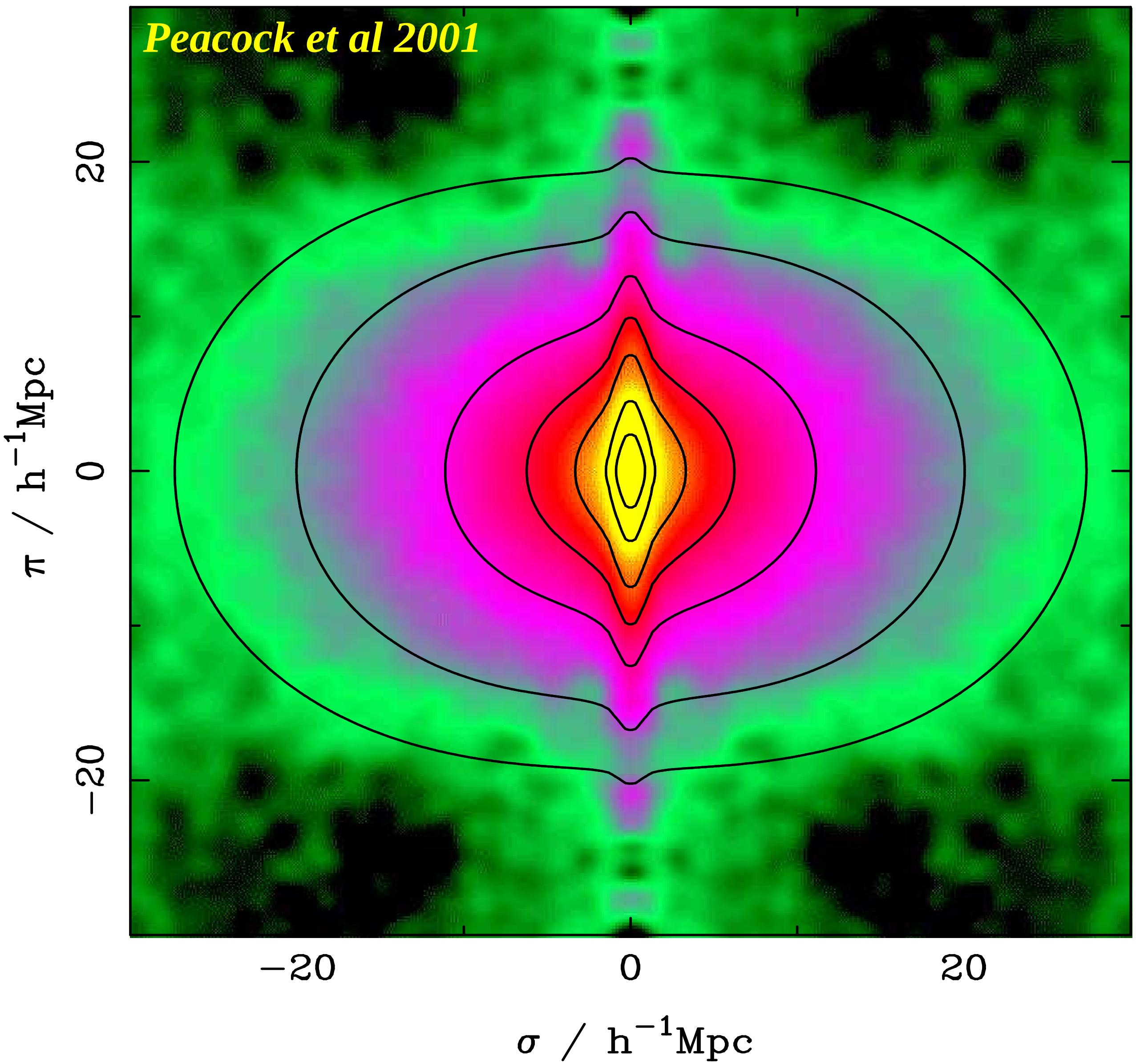
projected CF: $w_p(r_p) = \int\limits_{-\infty}^{\infty} \xi(r_p, \pi)\mathrm{d}\pi = 2\int\limits_{r_p}^{\infty} \xi(r)\, \frac{r\,\mathrm{d}r}{\sqrt{r^2 - r_p^2}}$

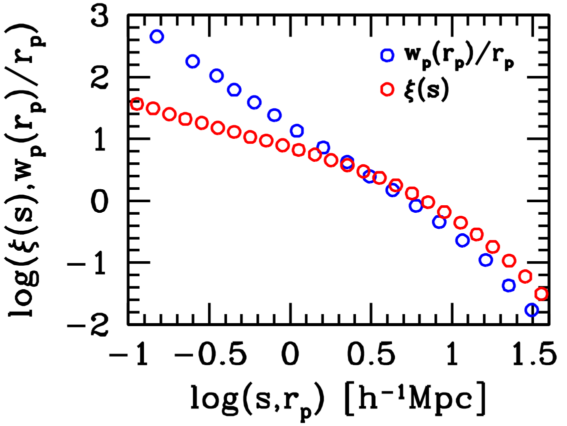
Peculiar velocities cause anisotropy of $\xi(r_p, \pi)$ and differences between $\xi(s)$ and $\xi(r)$. Anisotropy of $\xi(r_p, \pi)$ is quantified by quadrupole-to-monopole ratio denoted by $q(s)$.

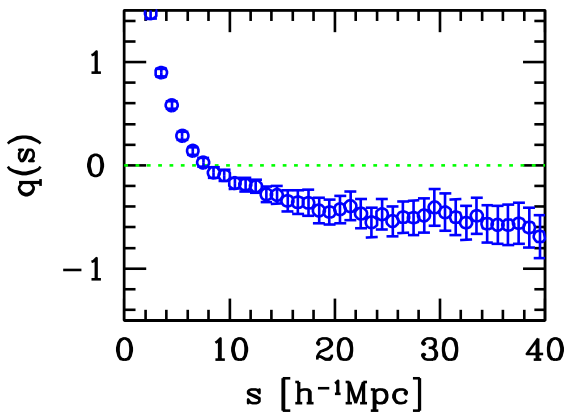


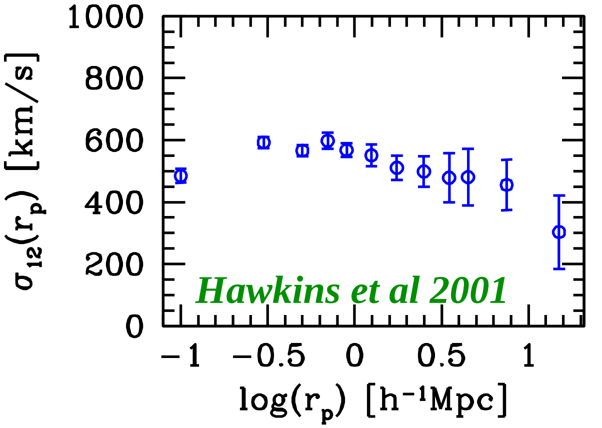
- **Large Scales:** Infall ("Kaiser Effect"); boosts $\xi(s)$ w.r.t. $\xi(r)$. $q(s)$ is a measure of $\beta \equiv \sigma_8 \Omega_m^{0.6}$
- **Small Scales:** Virialized motion ("Finger-of-God"); suppresses $\xi(s)$ w.r.t. $\xi(r)$. $q(s)$ isa measure for the pairwise velocity dispersions (PVDs) denoted by σ_{12}.

Large Scale Structure: The 2dFGRS

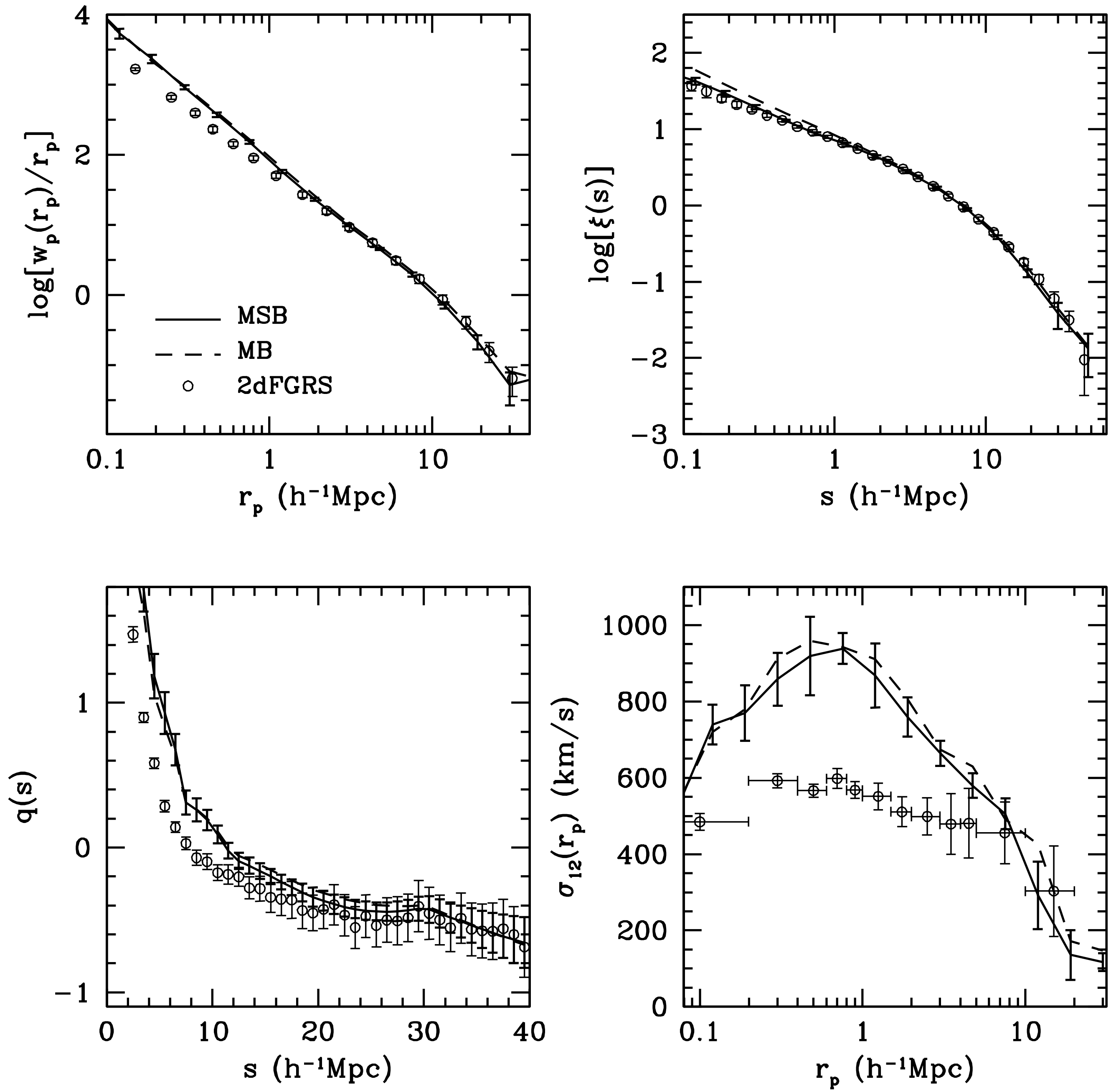






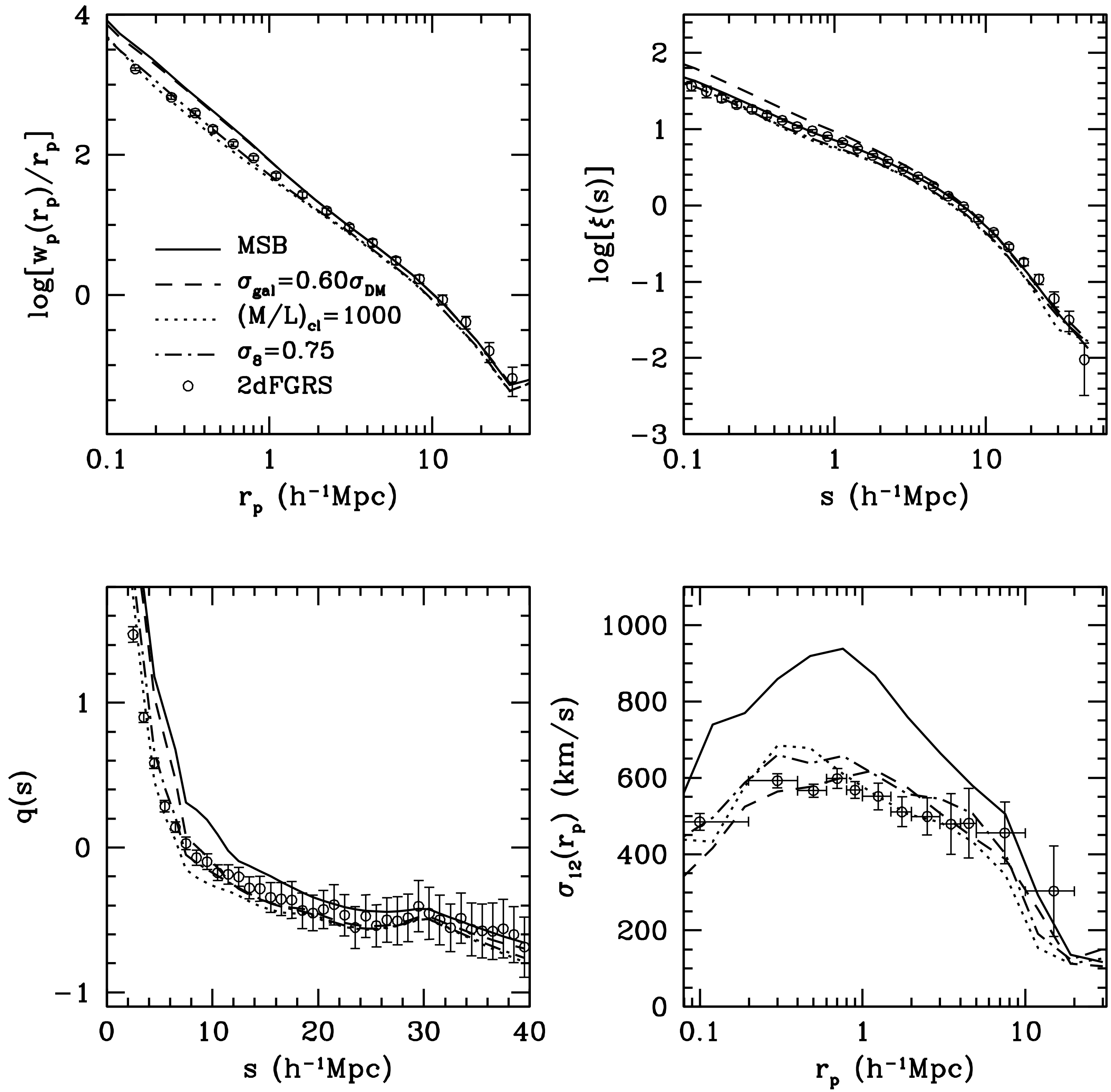


Mock versus 2dFGRS: round 1



Yang, Mo, Jing, vdB & Chu, 2004, MNRAS, 350, 1153

Mock versus 2dFGRS: round 2



Yang, Mo, Jing, vdB & Chu, 2004, MNRAS, 350, 1153

Galaxy Groups: a halo-based group finder

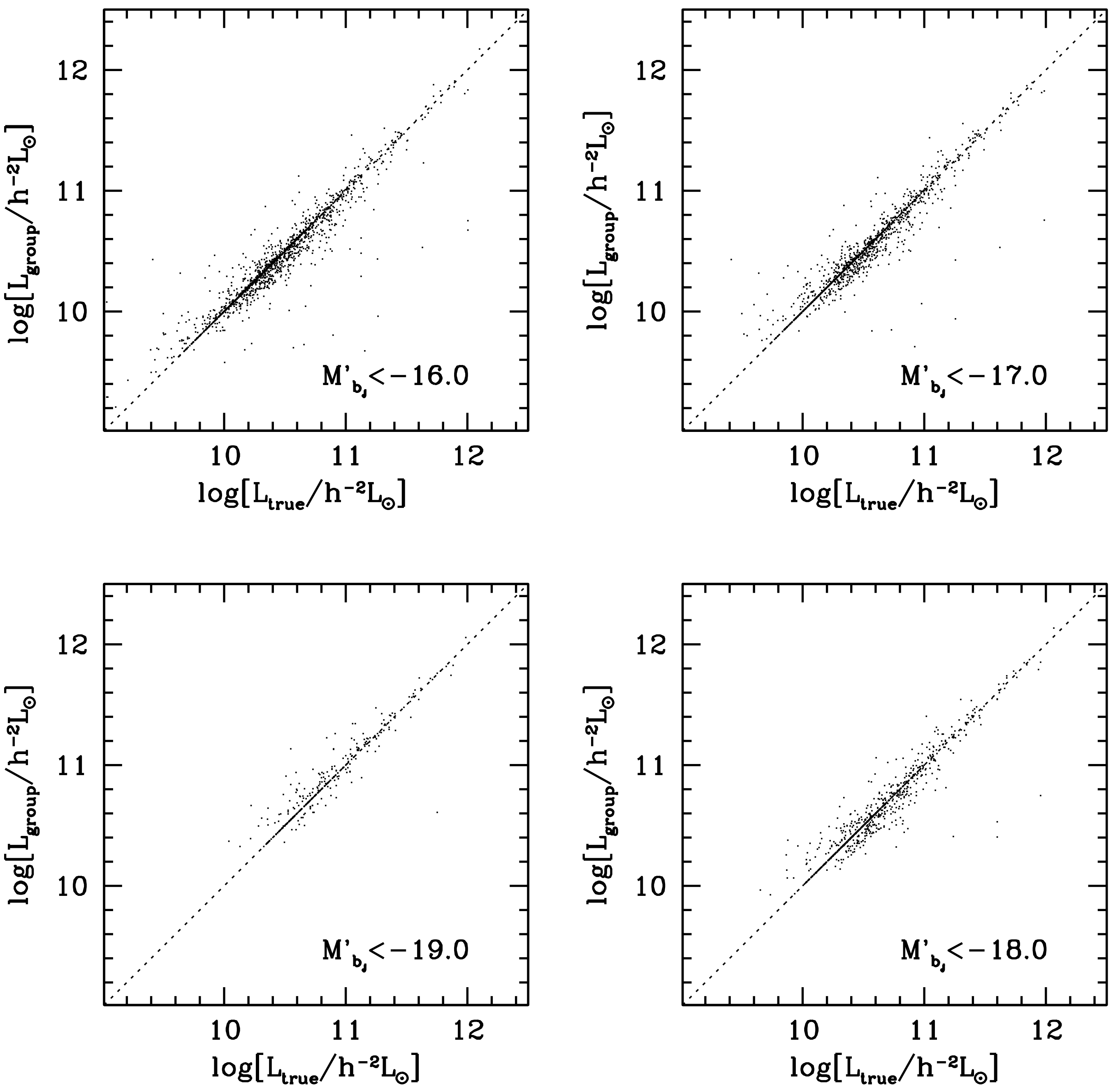
Goal: to group observed galaxies according to common halos

- **Assume M/L as function of halo mass**
- **Select candidate groups using FOF**
- **Compute group luminosity & estimate halo mass from assumed M/L**
- **Use corresponding virial quantities, i.e. size and velocity dispersion, to assign group membership**
- **Iterate until group membership convergence**

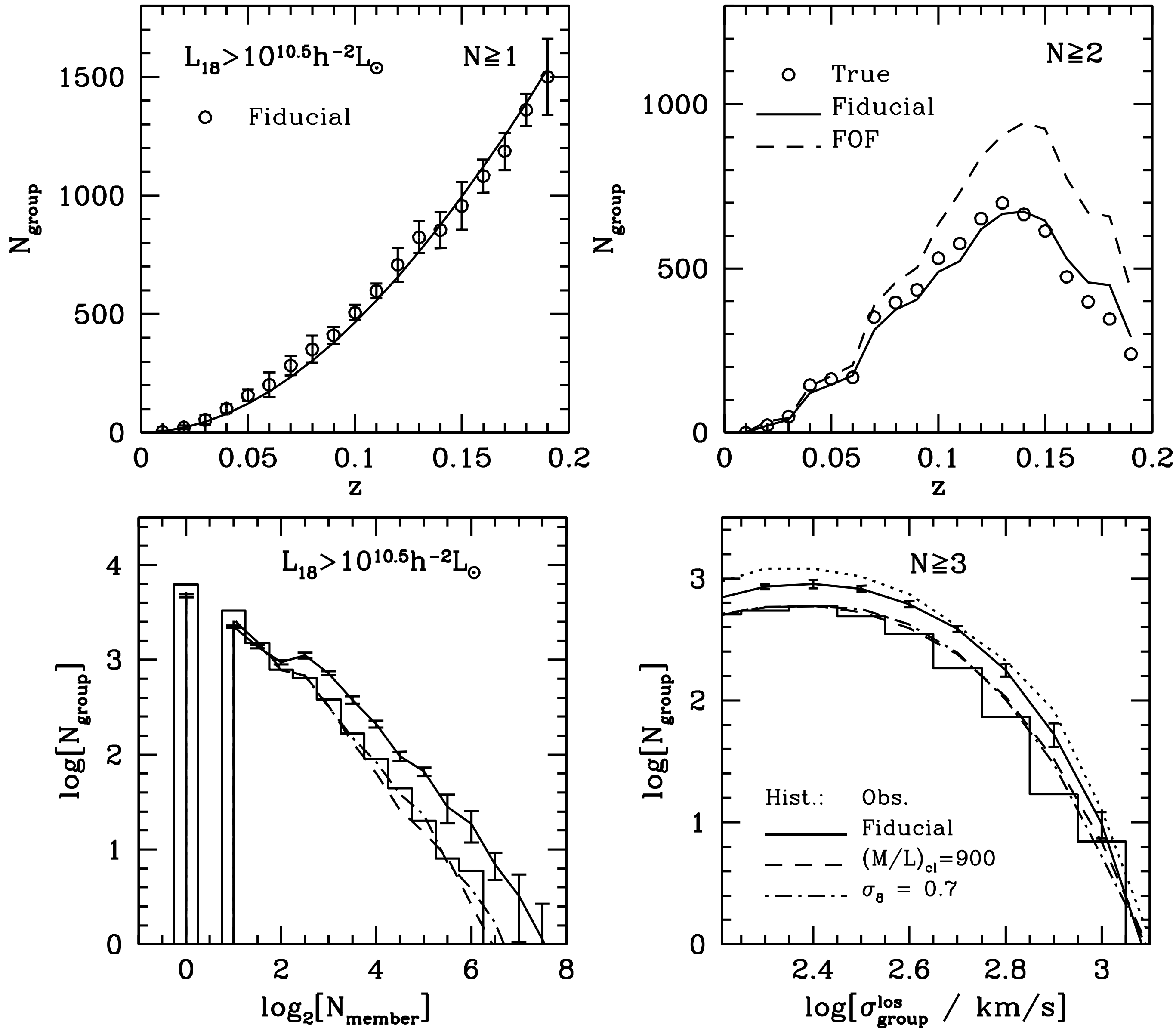
*** Group catalogue insensitive to initial, assumed M/L**
*** Significantly fewer interlopers than with pure FOF selection**
*** Galaxy groups are associated with individual dark matter halos**

Yang, Mo, vdB, Jing 2004 (astro-ph/0405234)

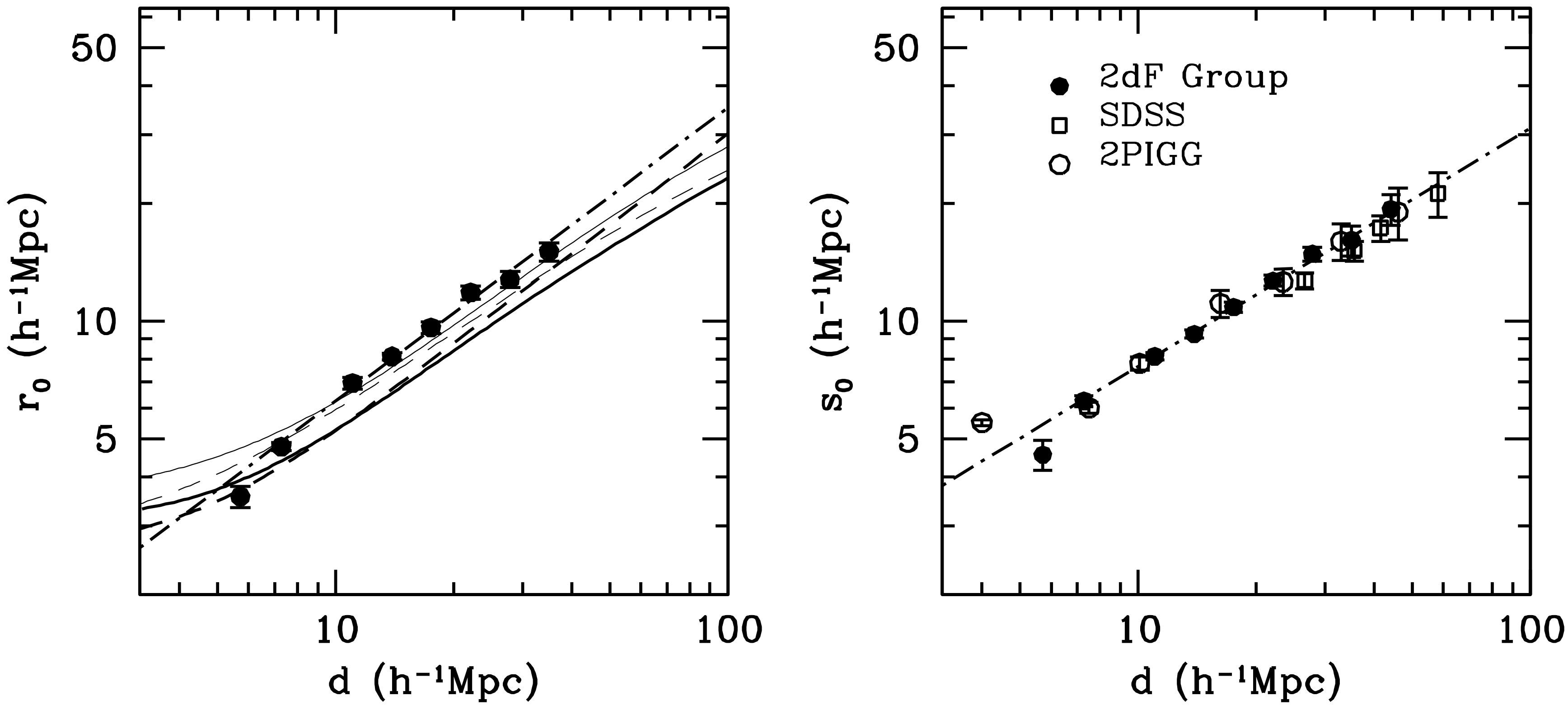
Tests with mock catalogs



Tests with mock catalogs



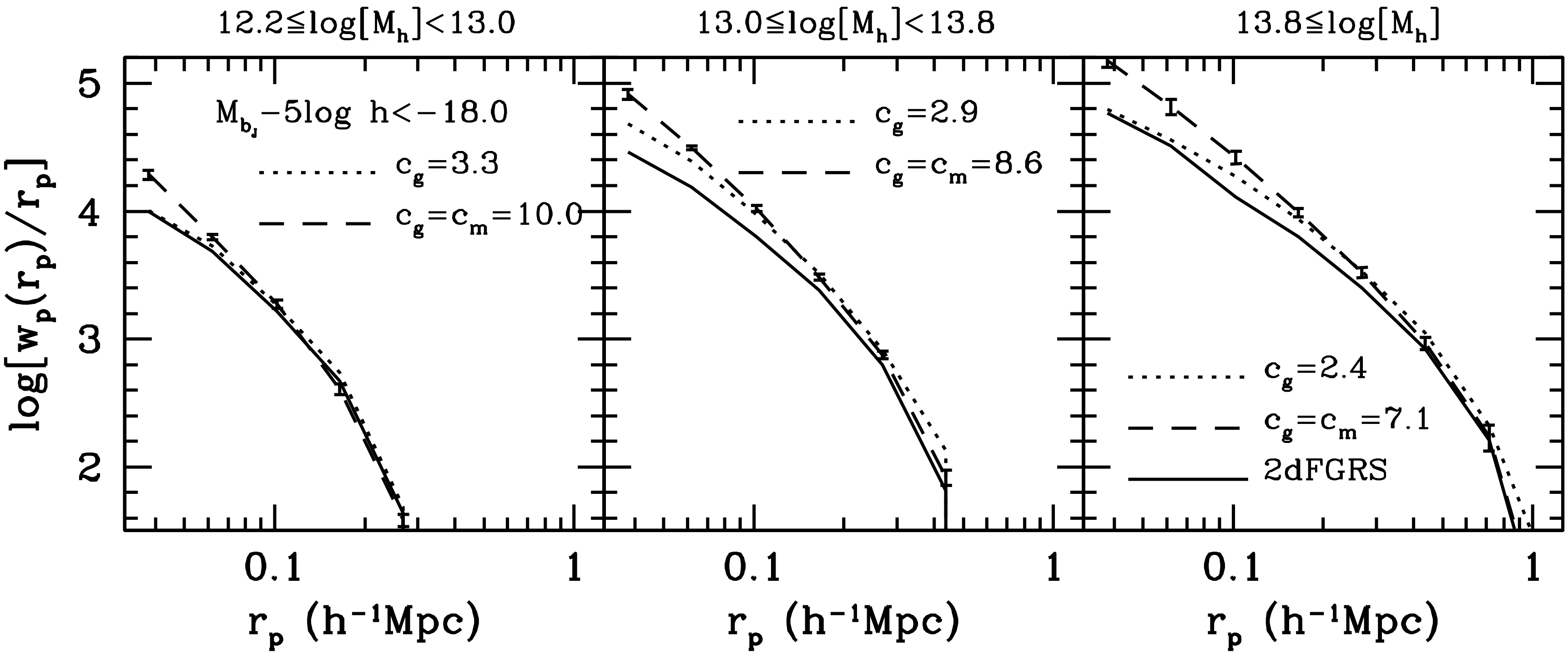
Probing Clustering of Dark Matter Halos



Yang, Mo, vdB & Jing 2004 (astro-ph/0406593)

Group correlation matches well halo correlation.

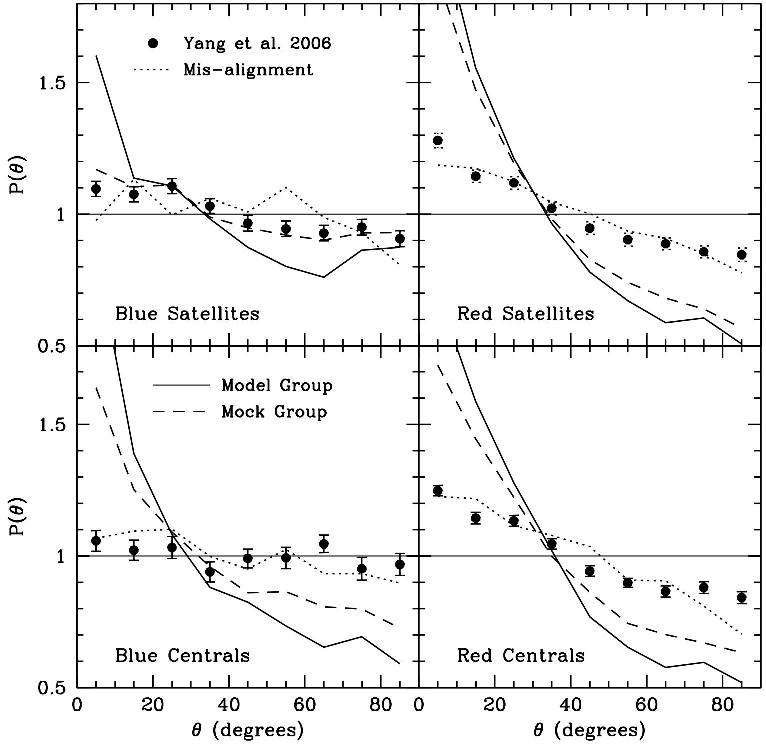
Galaxy distribution in groups

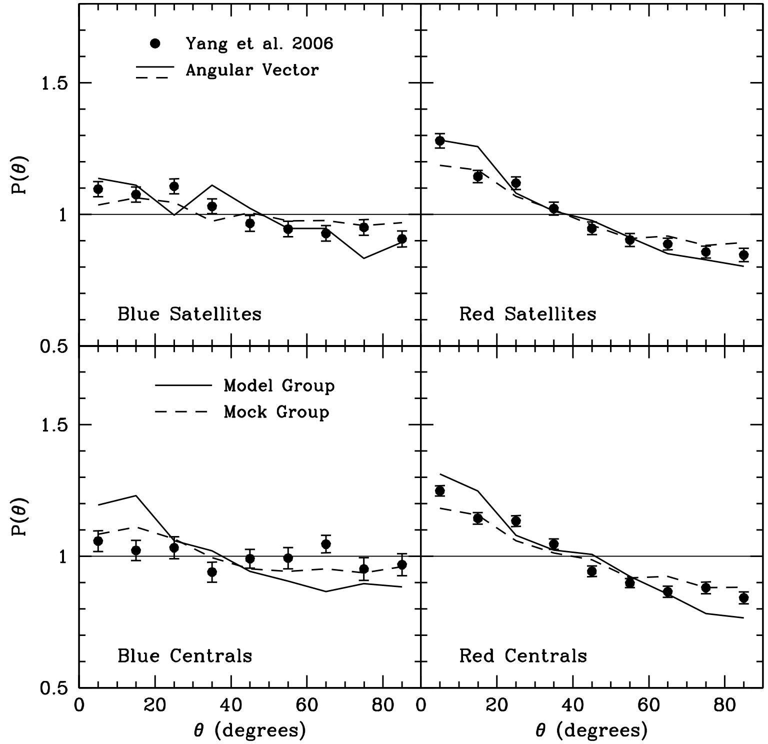


Yang, et al. 2005

Galaxy distribution is much less concentrated than dark matter.

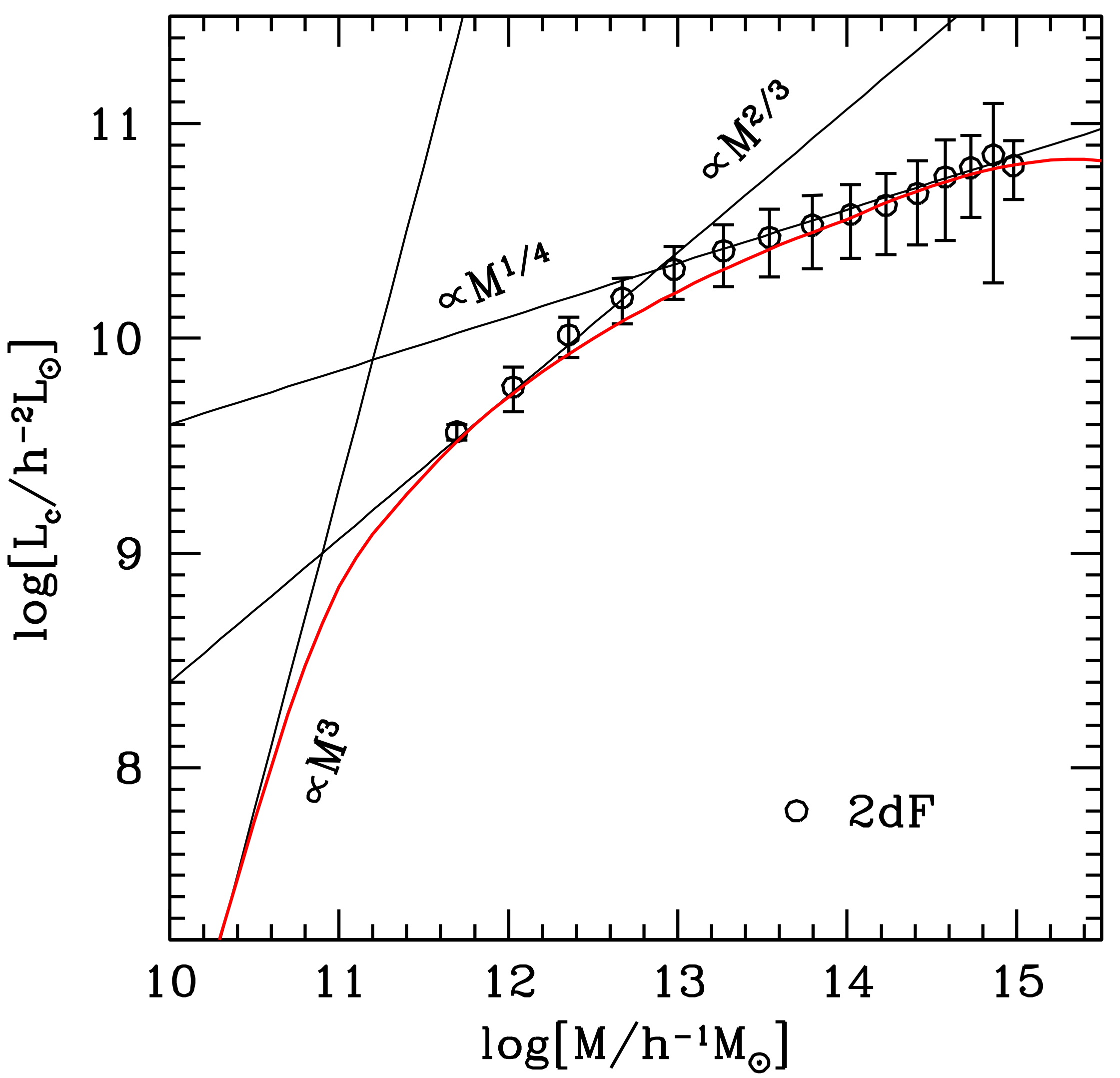
Galaxy Alignment





Orientation of blue centrals follows halo spin.

Galaxy Properties versus Dark Halos

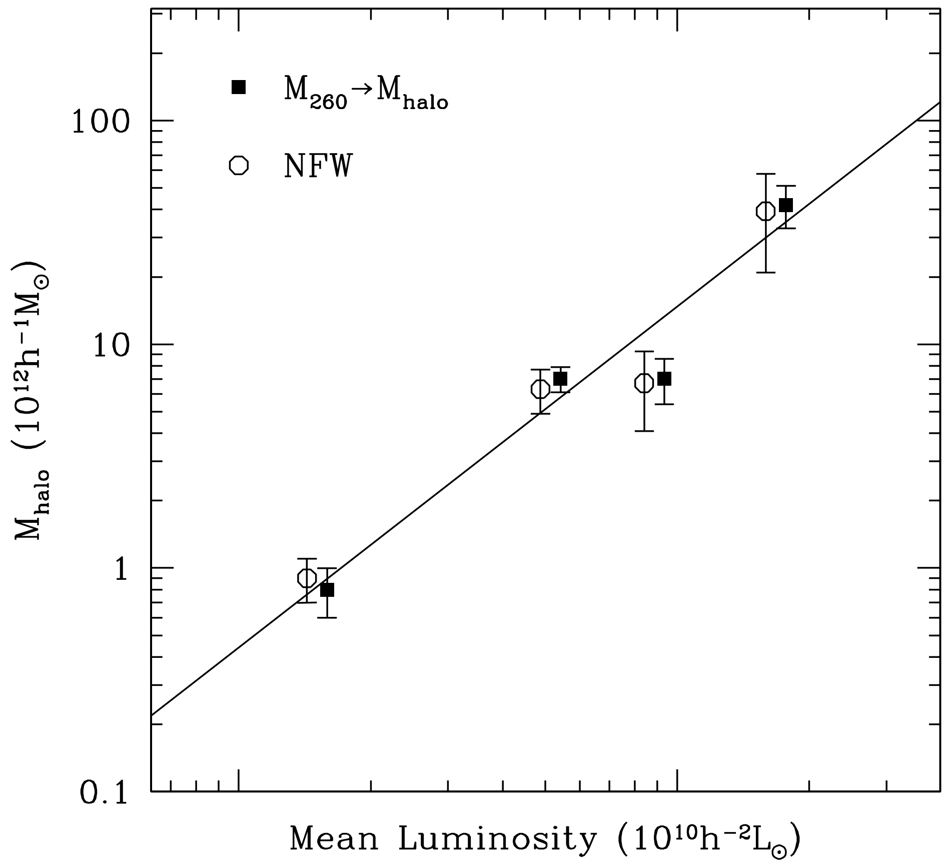


Two characteristic mass scales:

$M_h \sim 10^{11} h^{-1}$ $M_\odot$ (feedback mass scale?)

$M_h \sim 10^{13} h^{-1}$ $M_\odot$ (cooling mass scale?)

Comparison with lensing results



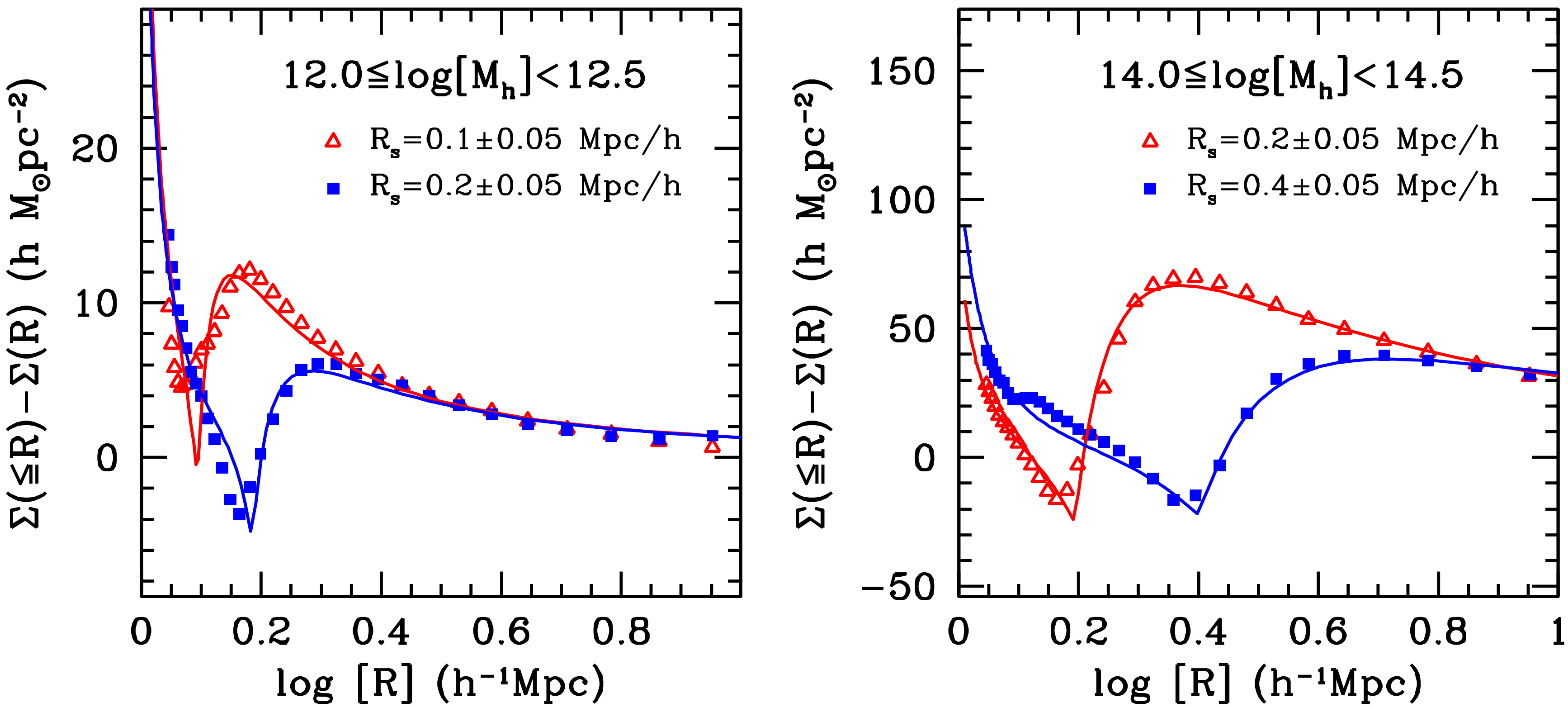
Yang, et al. (2003)

$M_{\rm halo} \sim 2.0 \times 10^{12} (L/L_\star)^{1.5} h^{-1} {\rm M}_\odot$

$M_{\rm halo}/L \sim 100h$ for isolated L_*- galaxies

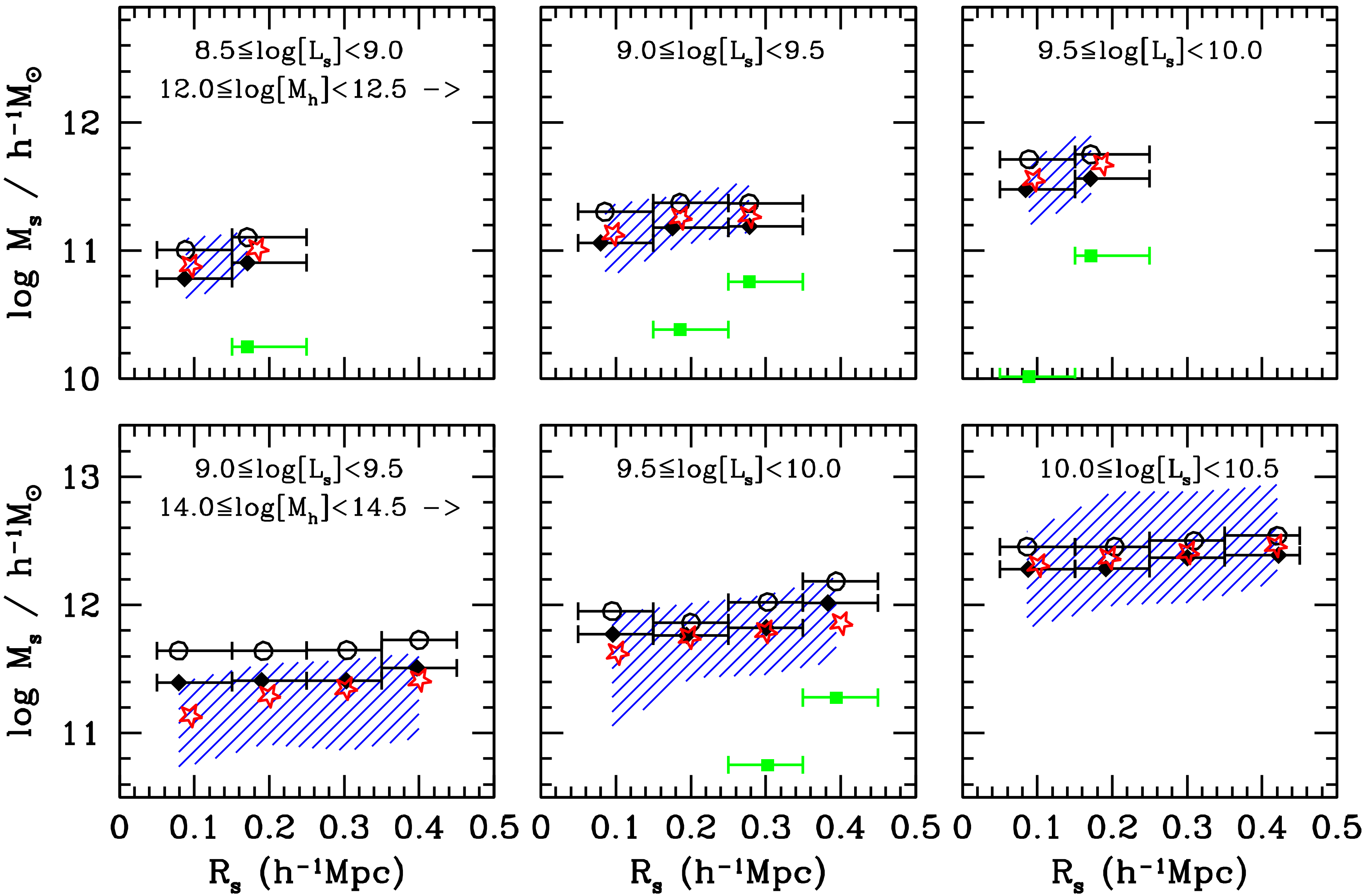
Subhalos with lensing

Assign each satellite galaxy with a halo according to its luminosity; halo truncation depends on halo-centric distance.



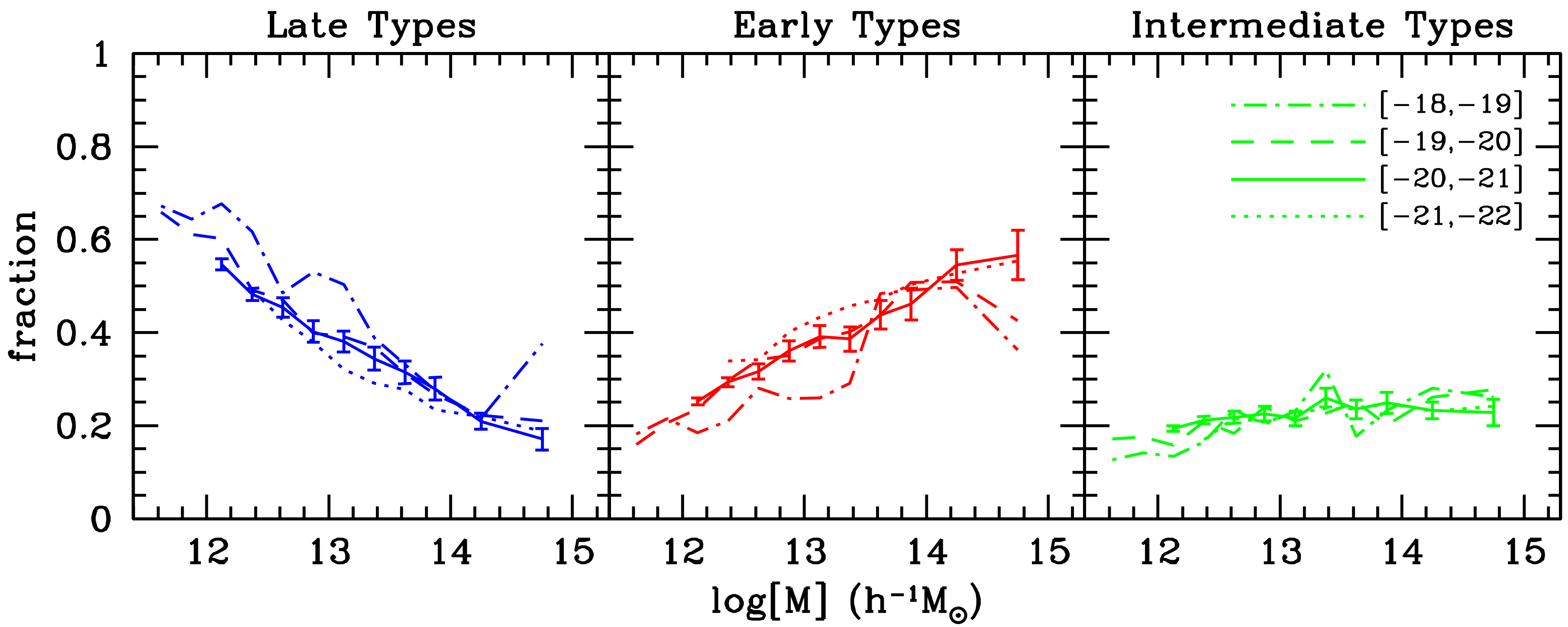
Yang, et al. (2006)

Subhalos with lensing



Galaxy populations in dark halos

Halo mass dependence:



The fractions of early and late type galaxies depend strongly on halo mass.

At fixed halo mass, there is virtually no luminosity dependence.

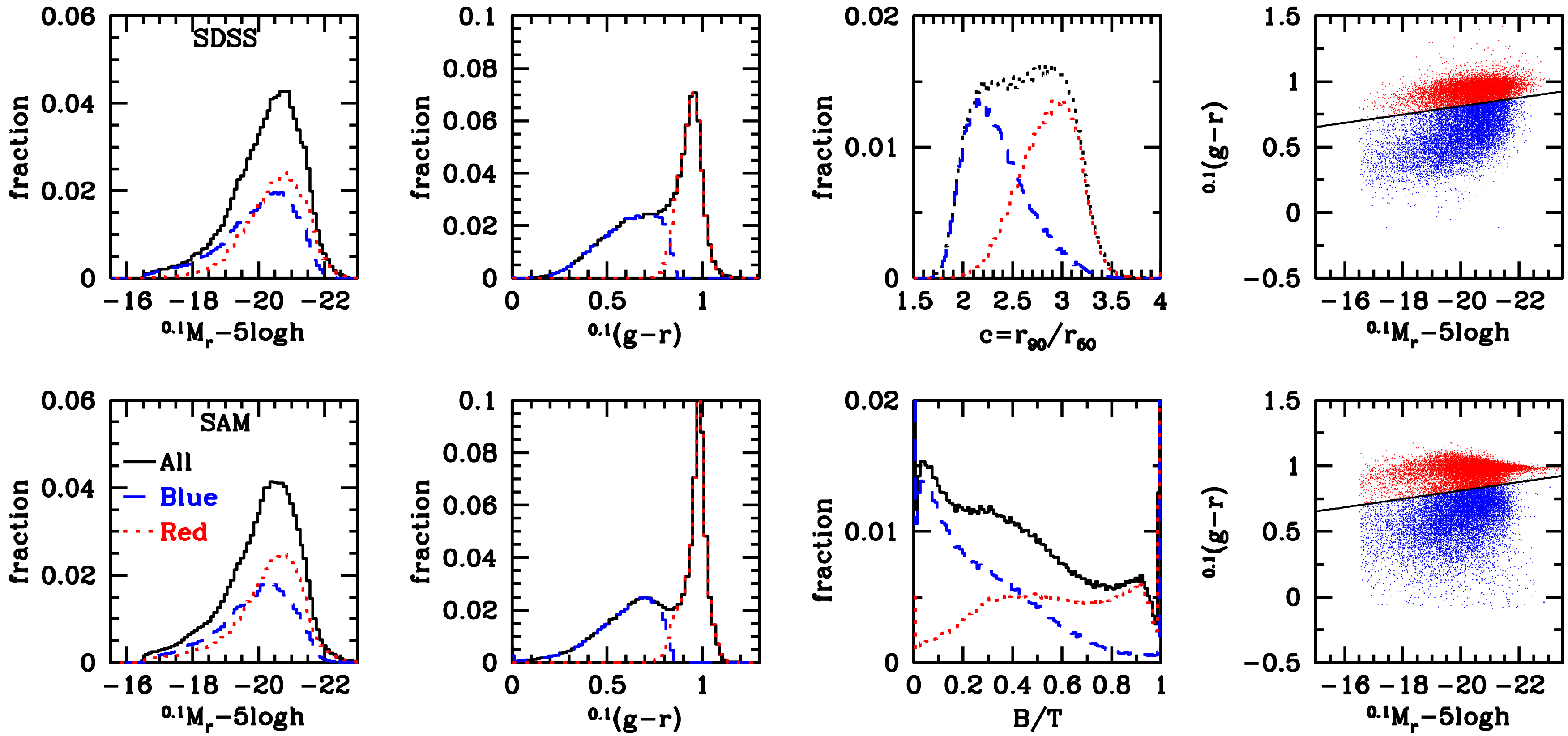
The mass dependence is smooth: there is no characteristic mass scale

The intermediate type fraction is independent of luminosity and mass.

(Weinmann, vdB, Yang & Mo, 2006)

Comparison with Semi-Analytical Model

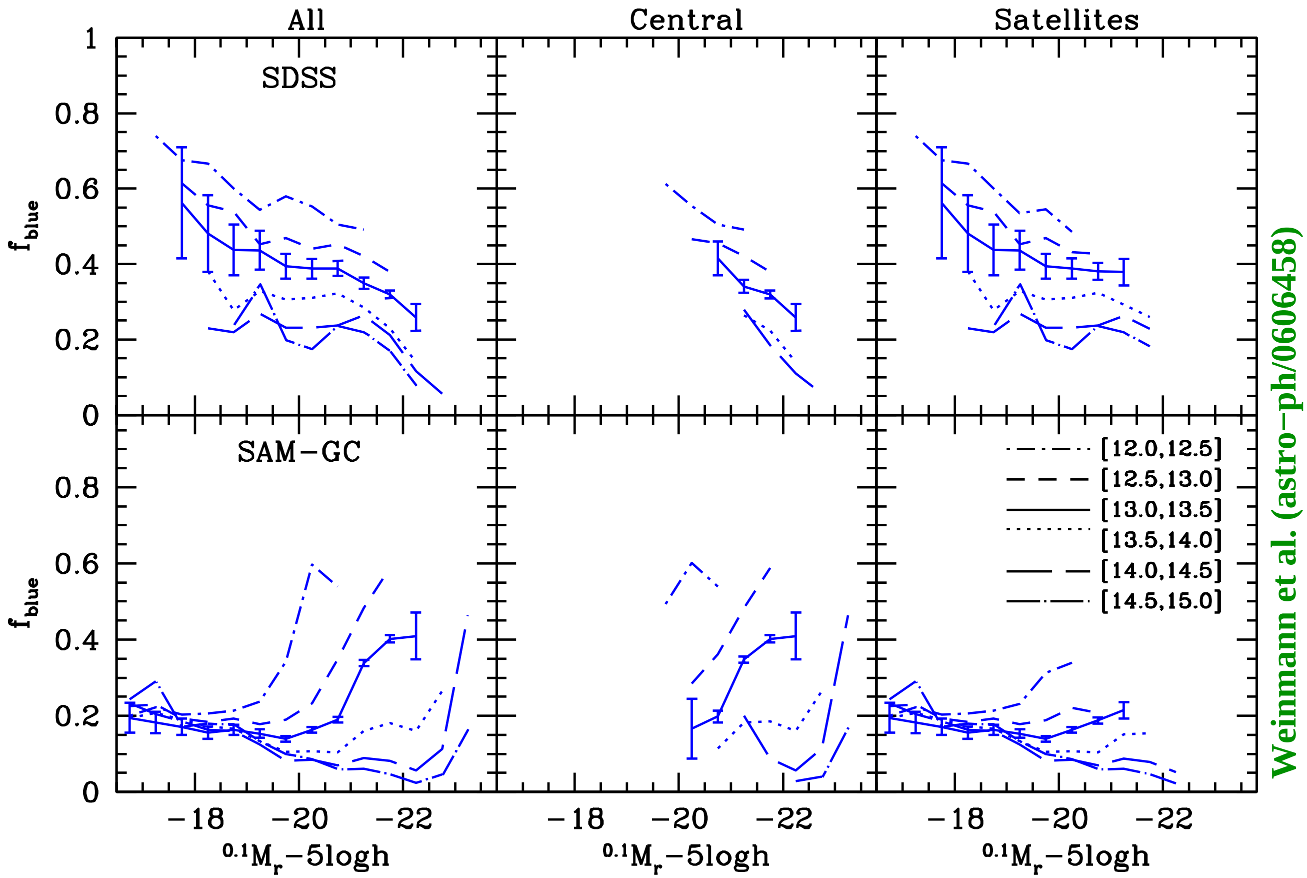
Comparison of Group Occupation Statistics with Semi-Analytical Model of Croton et al. 2006. Includes 'radio-mode' AGN feedback.



- **SAM matches global statistics of SDSS**
- **Luminosity function, bimodal color distribution, and overall blue fraction**
- **But what about statistics as function of halo mass?**

Constraining Star Formation Truncation

To allow for fair comparison, we run our Group Finder over SAM.



Satellites: red fraction too large: ▷ **strangulation too efficient as modelled**

Centrals: $f_{\rm blue}(L|M)$ **wrong:** ▷ **AGN feedback has problem**

$f_{\rm blue}(L,M)$ **useful to constrain SF truncation mechanism**

Conclusions

- **The conditional luminosity function (CLF) model is a powerful tool to establish the galaxy-dark matter connection**
- **The halo occupations obtained from the CLF model are in good agreement with those obtained directly from galaxy groups**
- **Study of how different galaxies occupy different halos can provide vital clues about galaxy formation.**