The Galaxy–Dark Matter Connection

constraining cosmology & galaxy formation

Frank C. van den Bosch (MPIA)

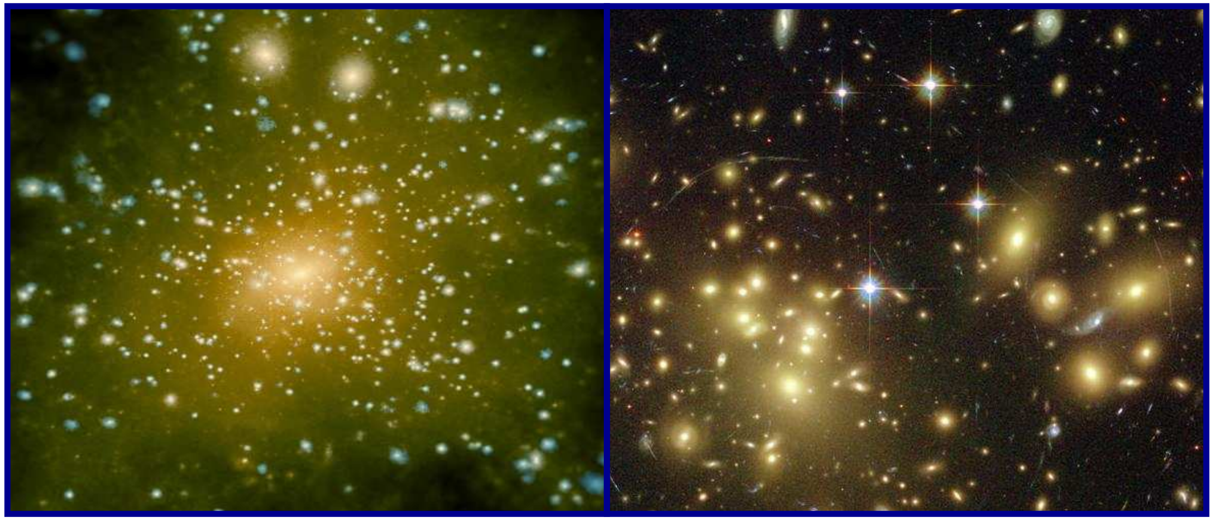
Collaborators: Houjun Mo (UMass), Xiaohu Yang (SHAO)

Marcello Cacciato, Surhud More (MPIA)

Outline, Motivation & Techniques

Why study the Galaxy-Dark Matter Connection?

- To constrain the physics of **Galaxy Formation**
- To constrain **Cosmological Parameters**



Two Methods to Constrain Galaxy-Dark Matter Connection

- Large Scale Structure
- Galaxy-Galaxy Lensing

New Cosmological Constraints

- Precision cosmology using **non-linear** structure

The Conditional Luminosity Function

In order to parameterize the Halo Occupation Statistics we introduce the Conditional Luminosity Function (CLF), $\Phi(L|M)$, which is the direct link between the halo mass function $n(M)$ and the galaxy luminosity function $\Phi(L)$:

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

The CLF contains a wealth of information, such as:

- **The average relation between light and mass:**

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

- **The occupation numbers of galaxies:**

$$\langle N\rangle(M) = \int_{L_{\rm min}}^\infty \Phi(L|M)\, \mathrm{d}L$$

We have constrained CLF using four different, independent techniques

Galaxy Group Catalogues **Large Scale Structure**

Satellite Kinematics **Galaxy-Galaxy Lensing**

The CLF Model

Motivated by results obtained from galaxy group catalogue, we split CLF in central and satellite components

$$\Phi(L|M)\mathrm{d}L = \Phi_{\rm c}(L|M)\mathrm{d}L + \Phi_{\rm s}(L|M)\mathrm{d}L$$

- **For centrals we adopt a log-normal distribution**

$$\Phi_{\rm c}(L|M)\mathrm{d}L = \frac{1}{\sqrt{2\pi}\,\sigma_{\rm c}} \exp\left[-\left(\frac{\ln(L/L_{\rm c})}{\sqrt{2}\sigma_{\rm c}}\right)^2\right] \frac{\mathrm{d}L}{L}$$

- **For satellites we adopt a modified Schechter function**

$$\Phi_{\rm s}(L|M)\mathrm{d}L = \frac{\Phi_{\rm s}}{L_{\rm s}} \left(\frac{L}{L_{\rm s}}\right)^{\alpha_{\rm s}} \exp[-(L/L_{\rm s})^2]\,\mathrm{d}L$$

Note that $L_{\rm c}$, $L_{\rm s}$, $\sigma_{\rm c}$, $\phi_{\rm s}$ and $\alpha_{\rm s}$ all depend on halo mass M

Free parameters are constrained by fitting data

Use Monte-Carlo Markov Chain to sample the posterior distribution of free parameters, and to put confidence levels on derived quantities

Occupation Statistics from Clustering

- **Galaxies occupy dark matter halos.**
- **CDM: more massive halos are more strongly clustered.**
- **Clustering strength of given population of galaxies indicates the characteristic halo mass**

Clustering strength measured by correlation length r_0

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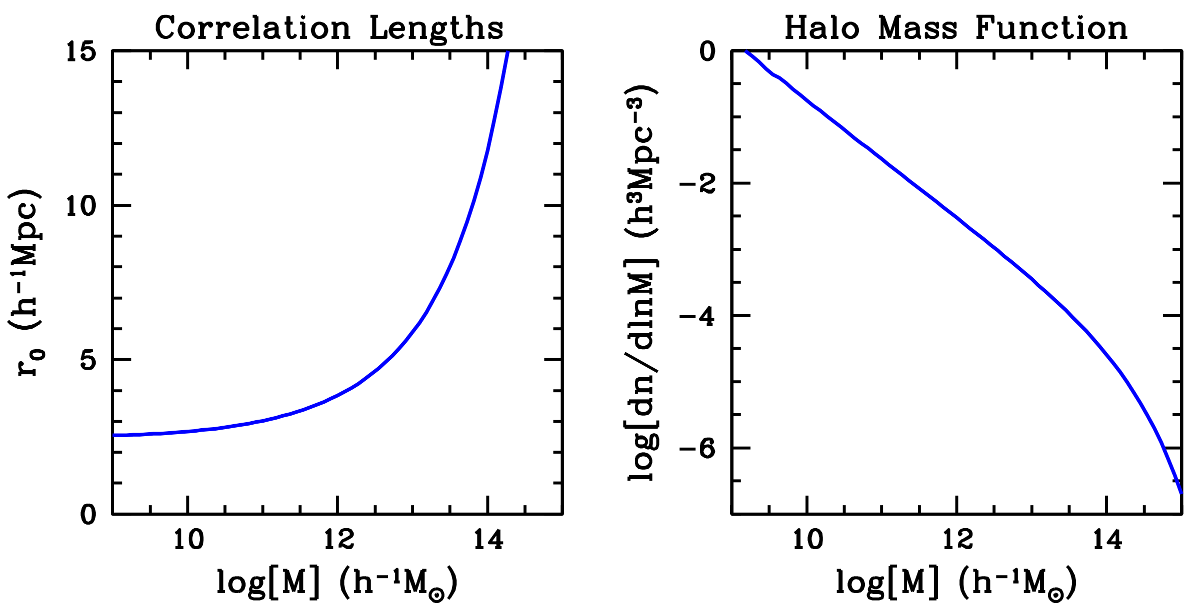

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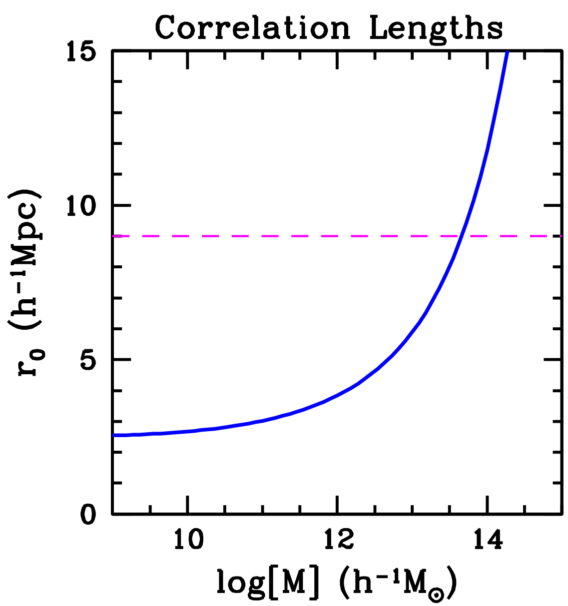

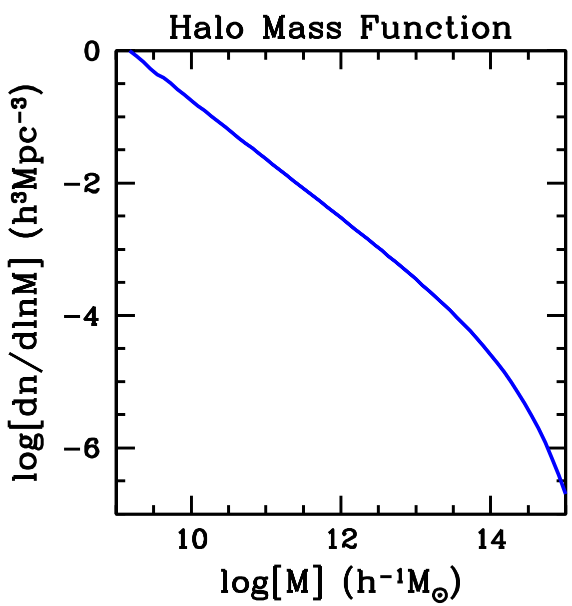

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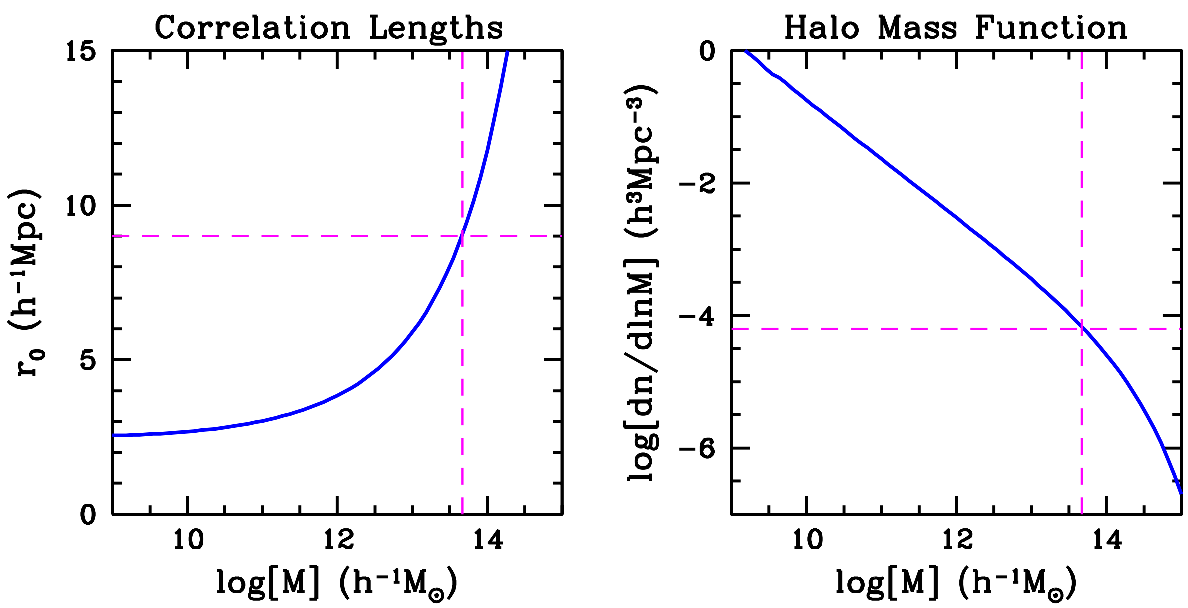

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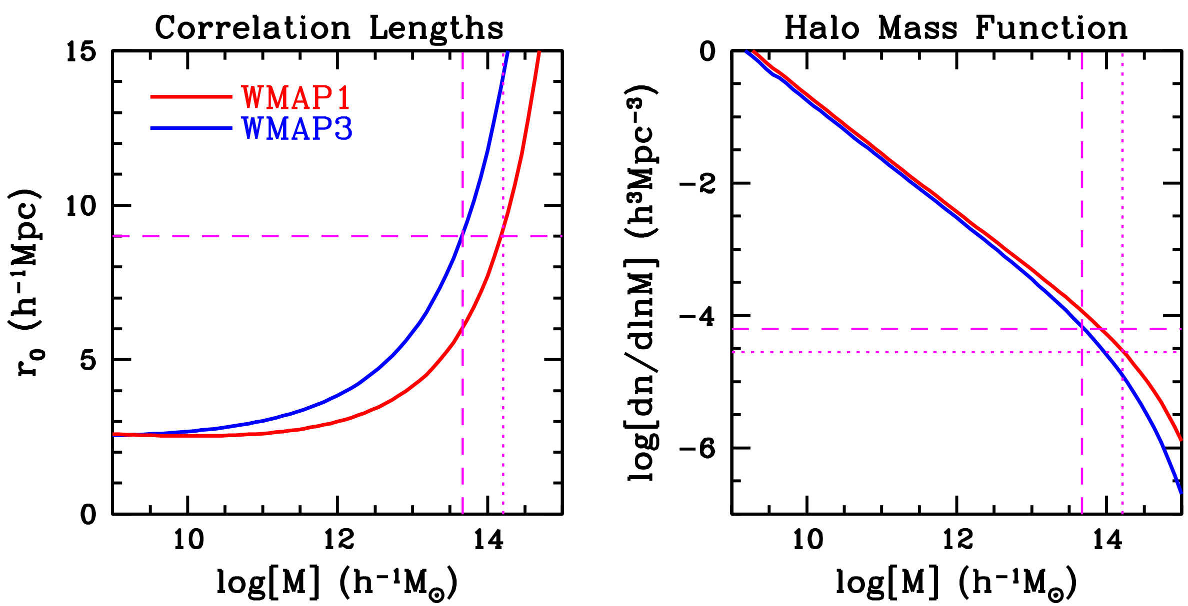
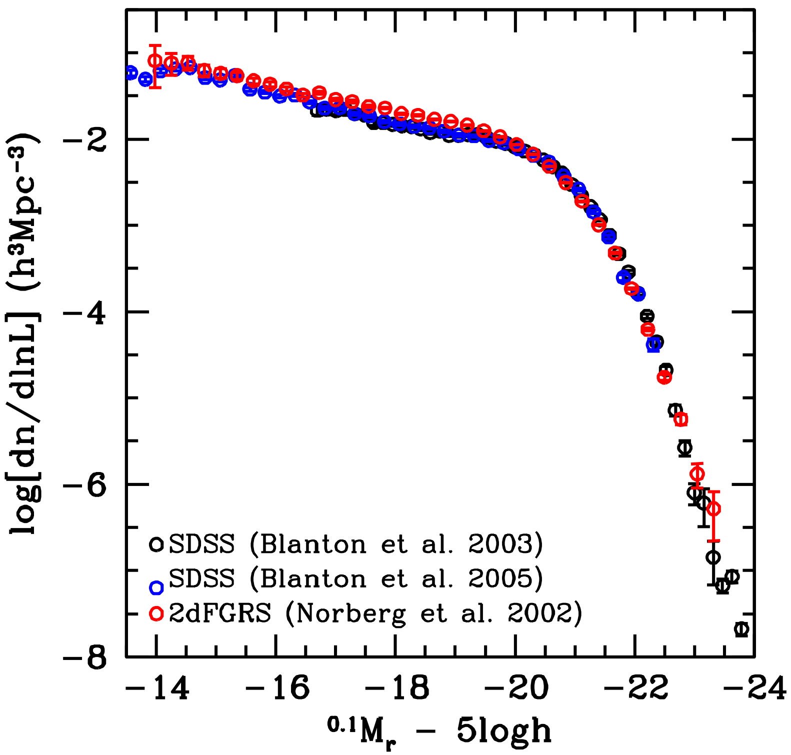


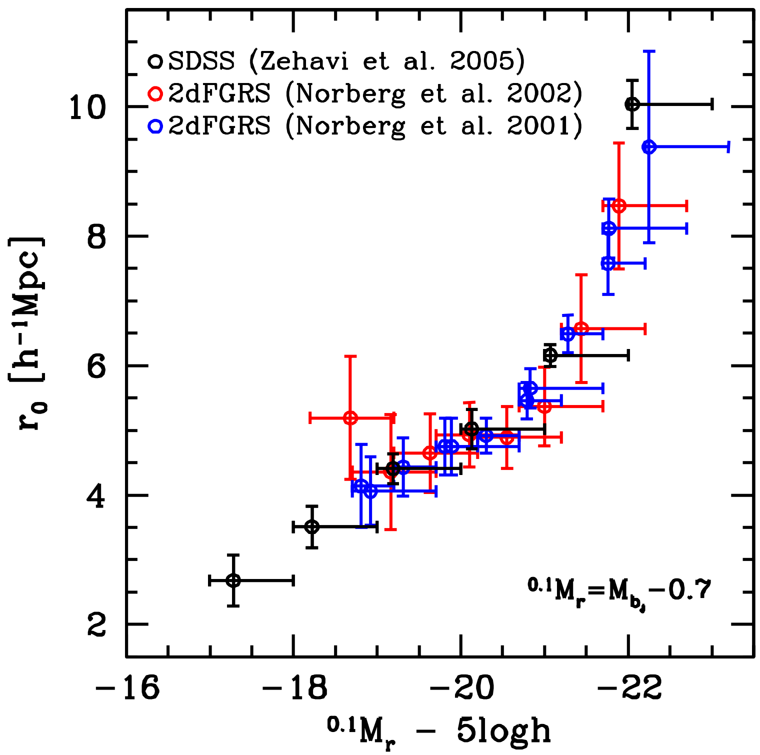
WMAP1
$\Omega_m = 0.30$
$\Omega_\Lambda = 0.70$
$\sigma_8 = 0.90$

WMAP3
$\Omega_m = 0.24$
$\Omega_\Lambda = 0.76$
$\sigma_8 = 0.74$

CAUTION: Results depend on cosmological parameters

Luminosity & Correlation Functions





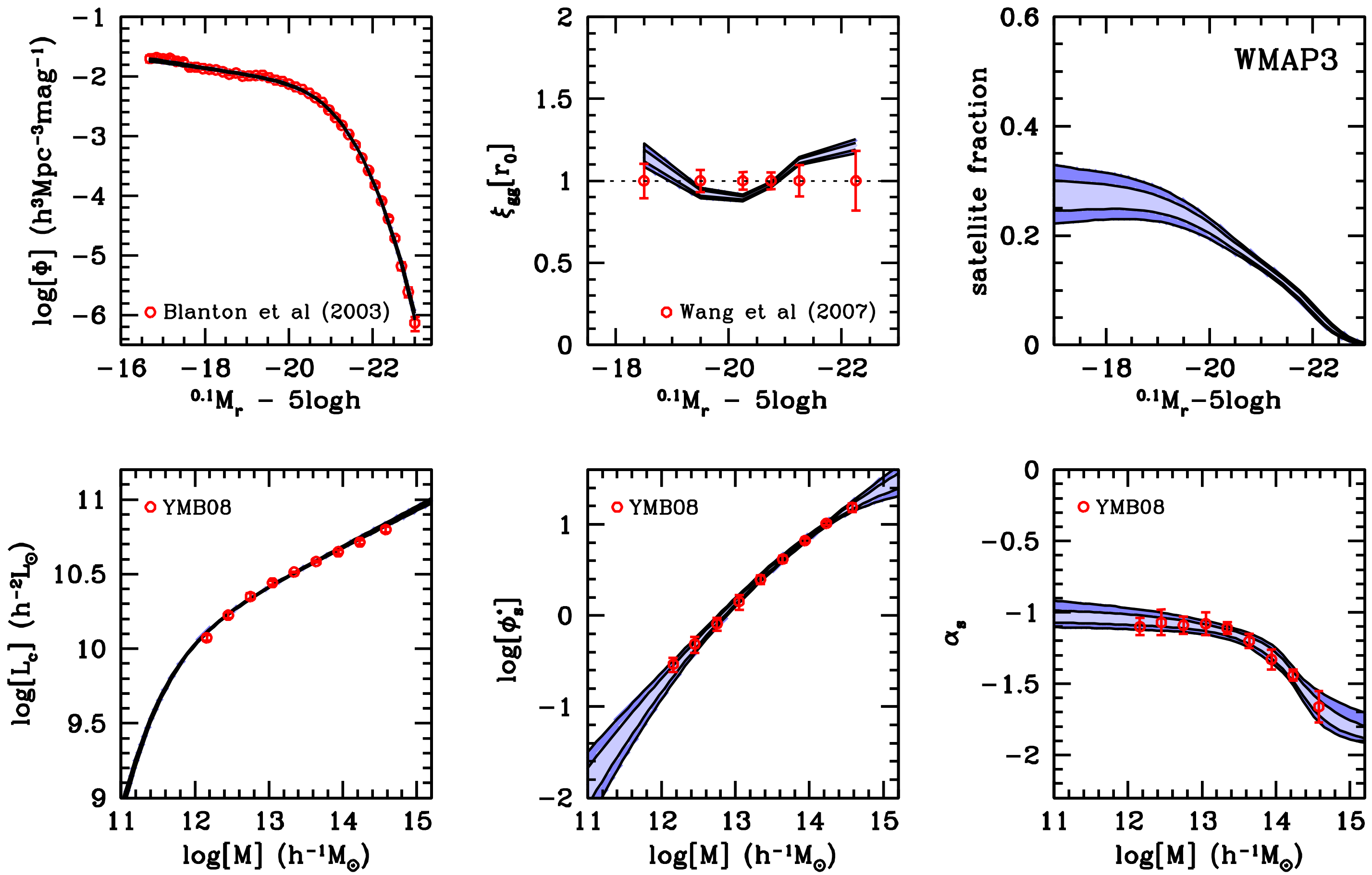
- **DATA:** More luminous galaxies are more strongly clustered.
- **ΛCDM:** More massive haloes are more strongly clustered.

More luminous galaxies reside in more massive haloes

REMINDER: Correlation length r_0 defined by $\xi(r_0) = 1$

Introduction
Conditional Luminosity Function
Large Scale Structure
● Occupation Statistics from Clustering
● Luminosity & Correlation Functions
● Results
● Cosmology Dependence
Galaxy-Galaxy Lensing
Conclusions
Extra Material

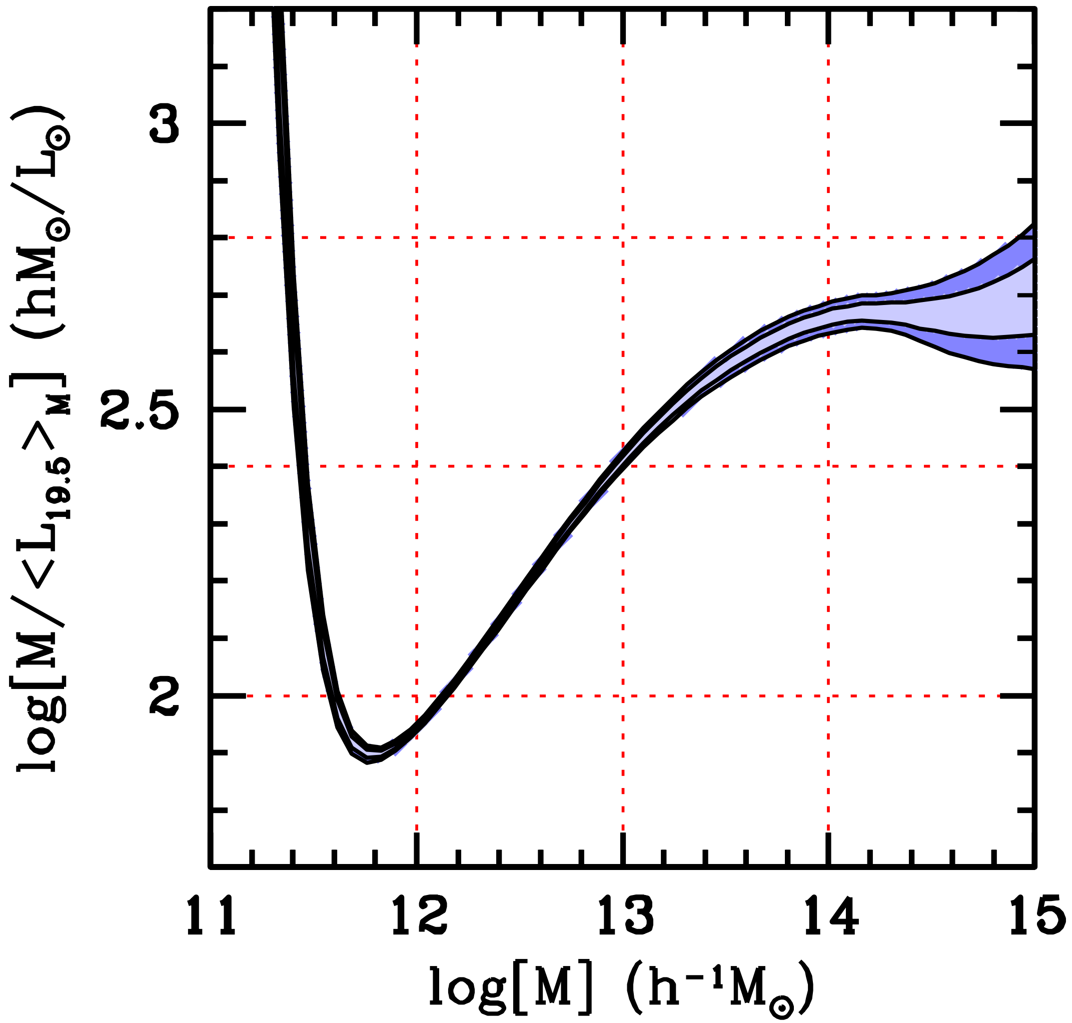
Results



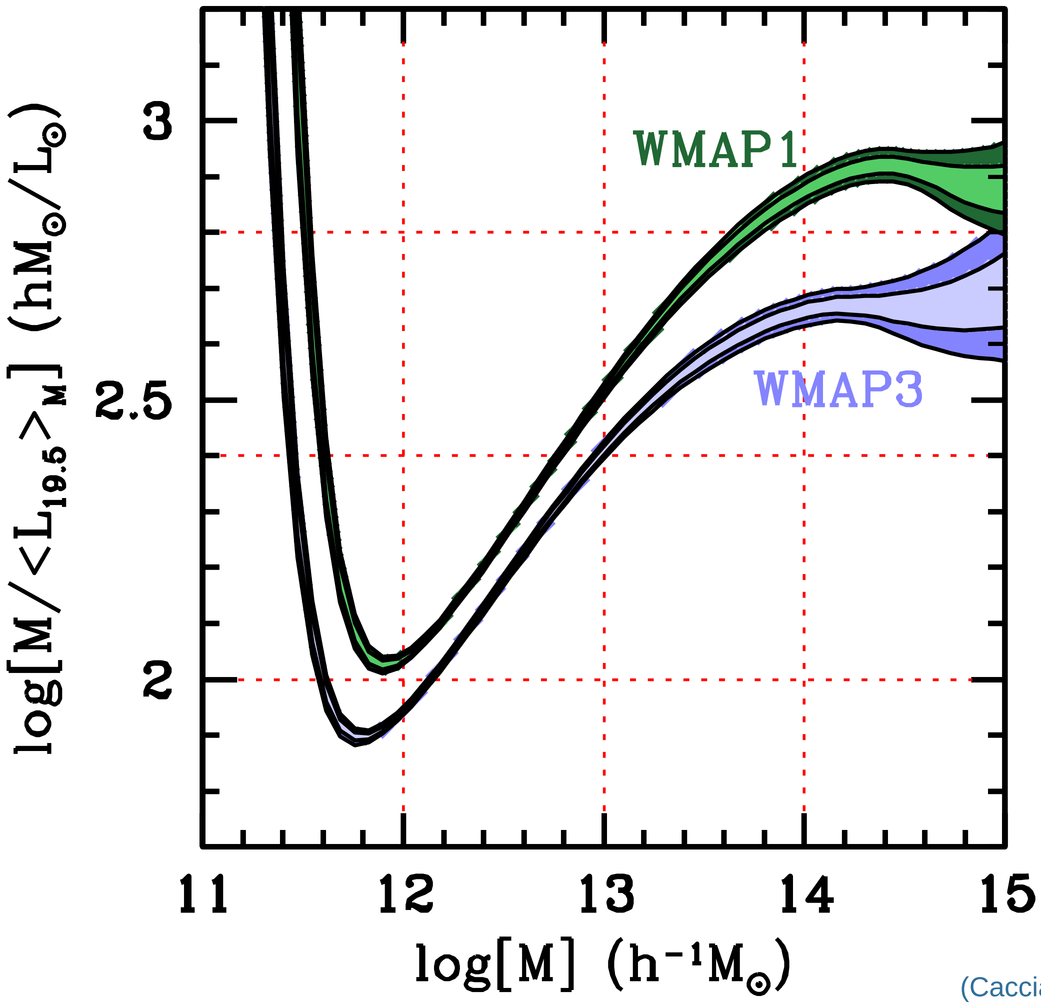
(Cacciato, vdB et al. 2008)

Model fits data extremely well with $\chi^2_{\rm red} \sim 1$
Same model in excellent agreement with results from SDSS galaxy group catalogue of Yang et al. (2008)

Cosmology Dependence



Cosmology Dependence

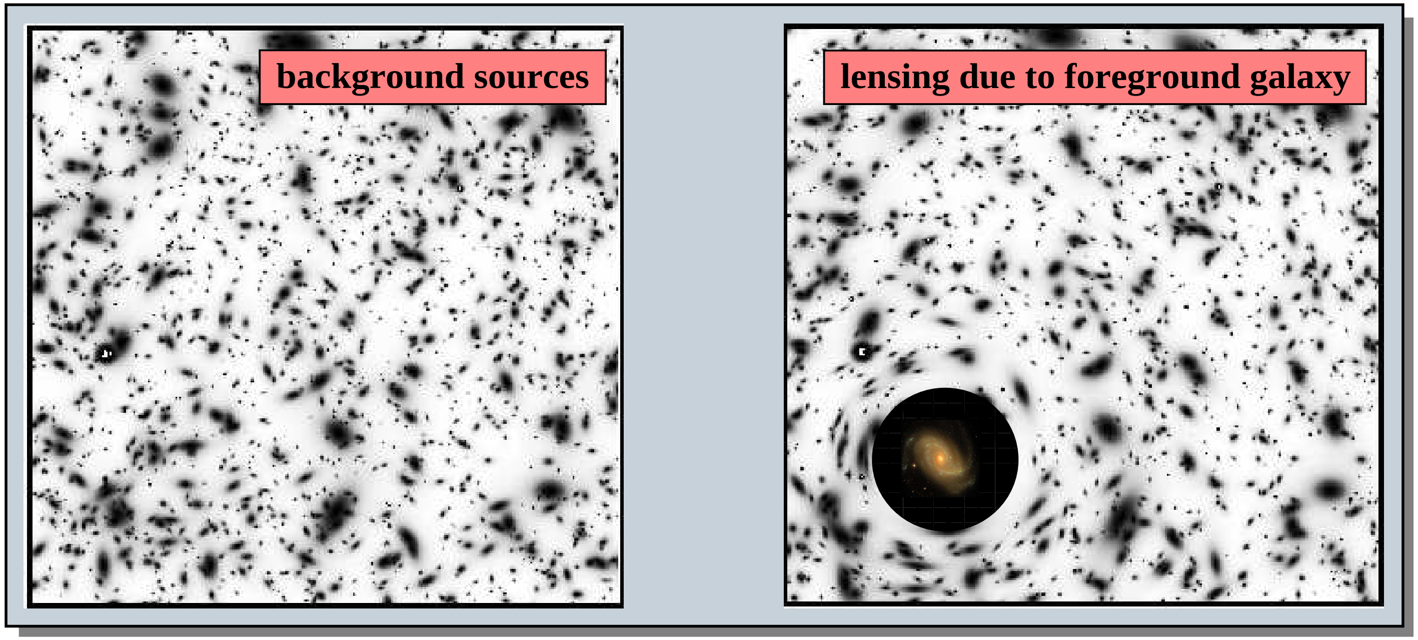


(Cacciato, vdB et al. 2008)

Mass-to-Light ratios tightly constrained, but with strong dependence on cosmology

Galaxy-Galaxy Lensing

The mass associated with galaxies lenses background galaxies



Lensing causes correlated ellipticities, the **tangential shear**, γ_t, which is related to the **excess surface density**, $\Delta\Sigma$, according to

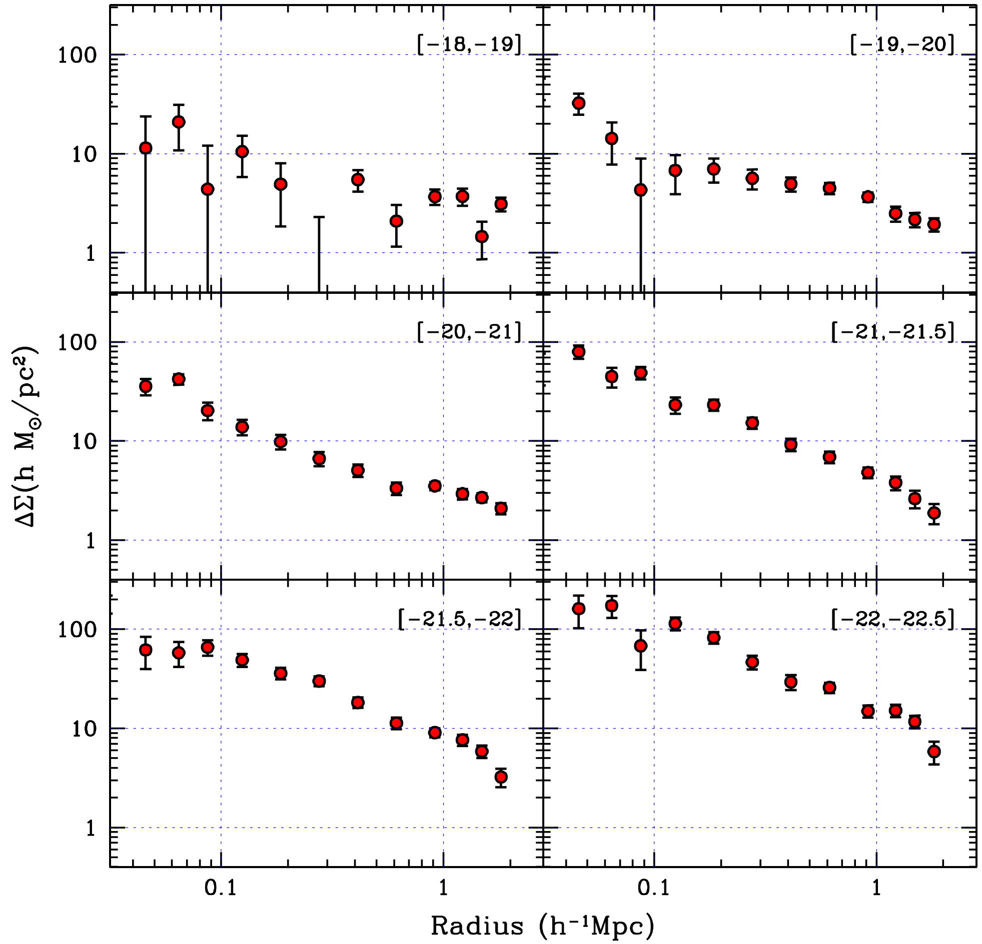
$$\gamma_{\rm t}(R)\Sigma_{\rm crit} = \Delta\Sigma(R) = \bar{\Sigma}(< R) - \Sigma(R)$$

$\Sigma(R)$ is line-of-sight projection of **galaxy-matter cross correlation**:

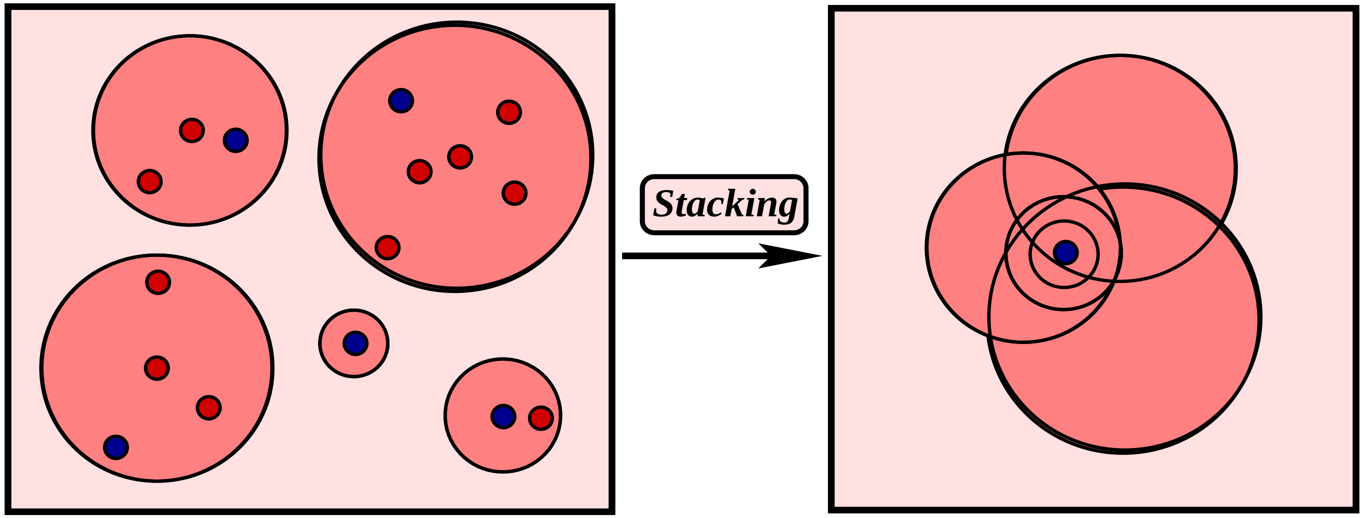
$$\Sigma(R) = \bar{\rho} \int_0^{D_S} \left[1 + \xi_{\rm g,dm}(r)\right] d\chi$$

The Measurements

- Number of background sources per lens is limited.
- Measuring γ_t with sufficient S/N requires stacking of many lenses
- $\Delta\Sigma(R|L_1, L_2)$ has been measured using the SDSS by Mandelbaum et al. (2005) for different bins in lens luminosity



How to interpret the signal?



Because of stacking the lensing signal is difficult to interpret

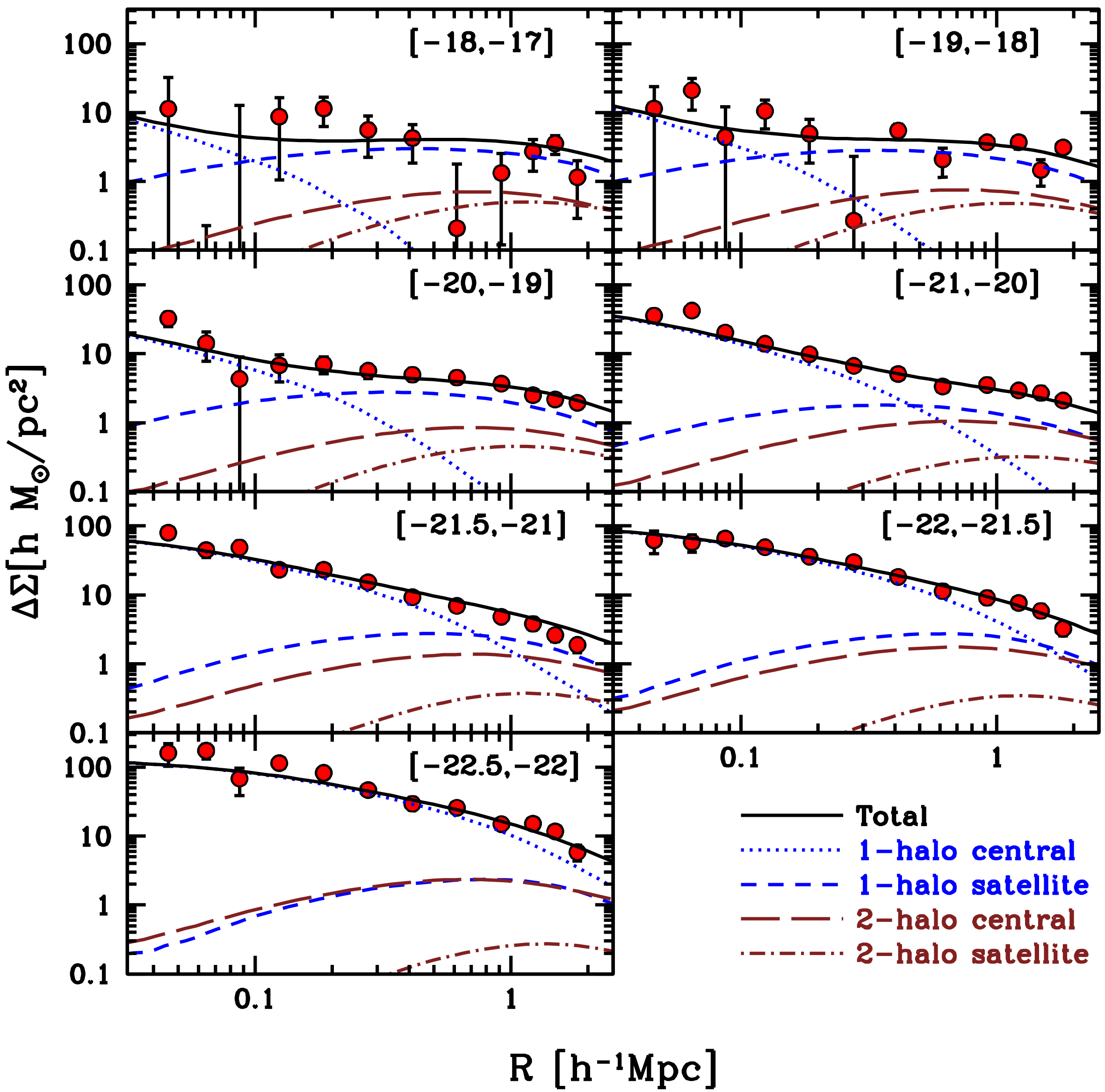
In order to model the data, what is required is:

$P_{\rm cen}(M|L)$ $P_{\rm sat}(M|L)$ $f_{\rm sat}(L)$

These can all be computed from the CLF

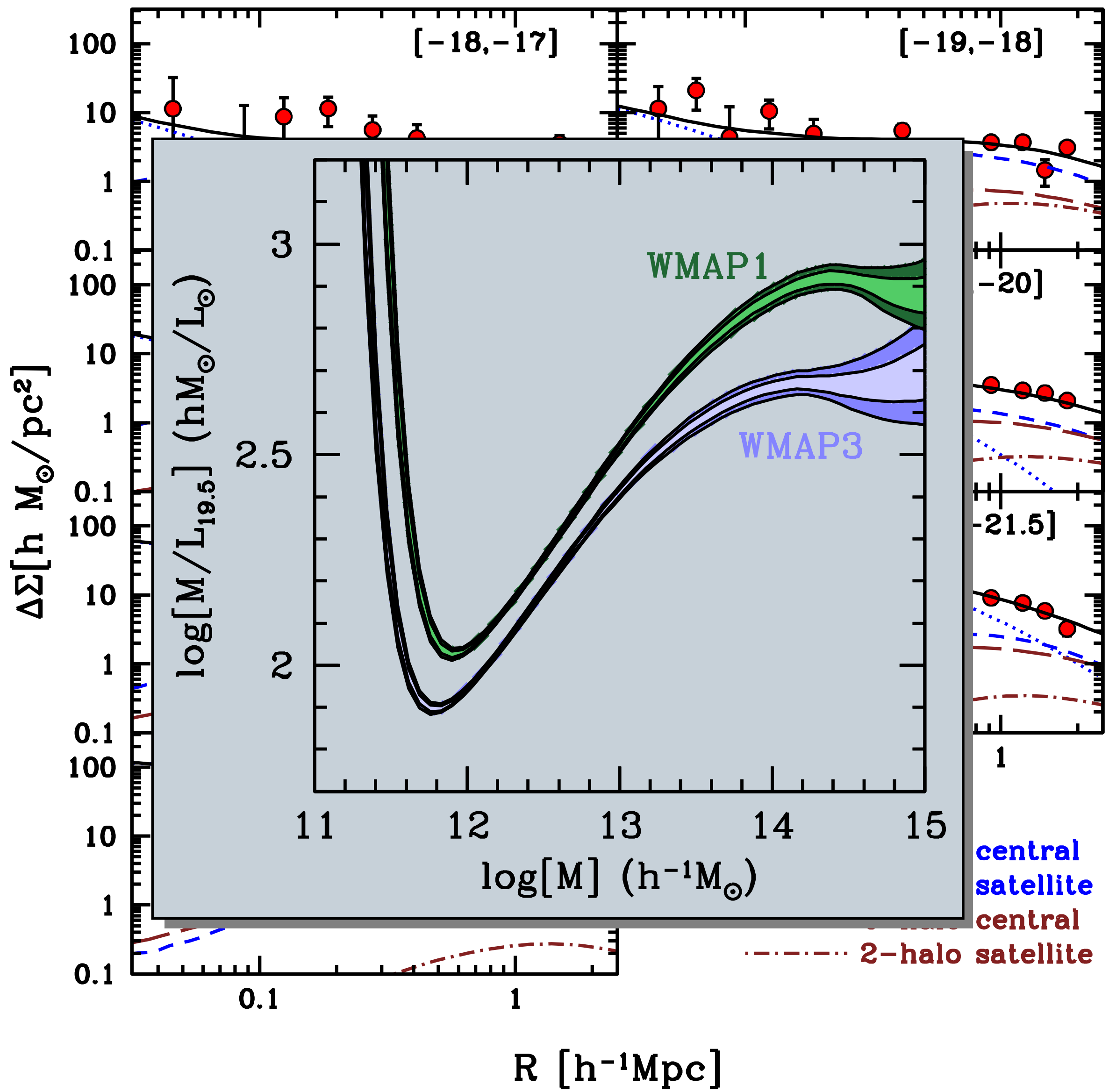
Using $\Phi(L|M)$ constrained from clustering data, we can predict the lensing signal $\Delta\Sigma(R|L_1, L_2)$

Comparison with CLF Predictions



NOTE: This is not a fit, but a prediction based on CLF

Comparison with CLF Predictions



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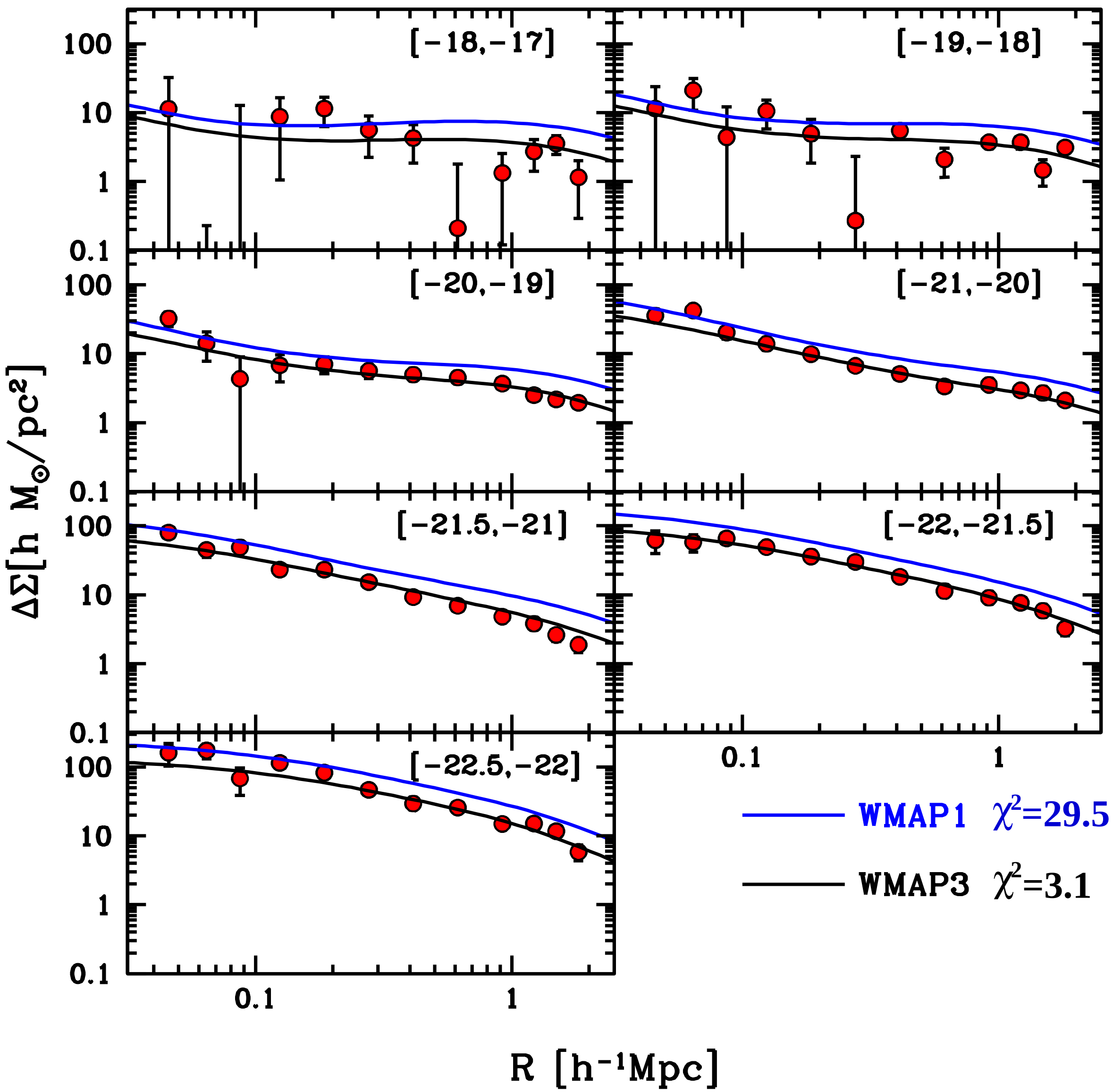
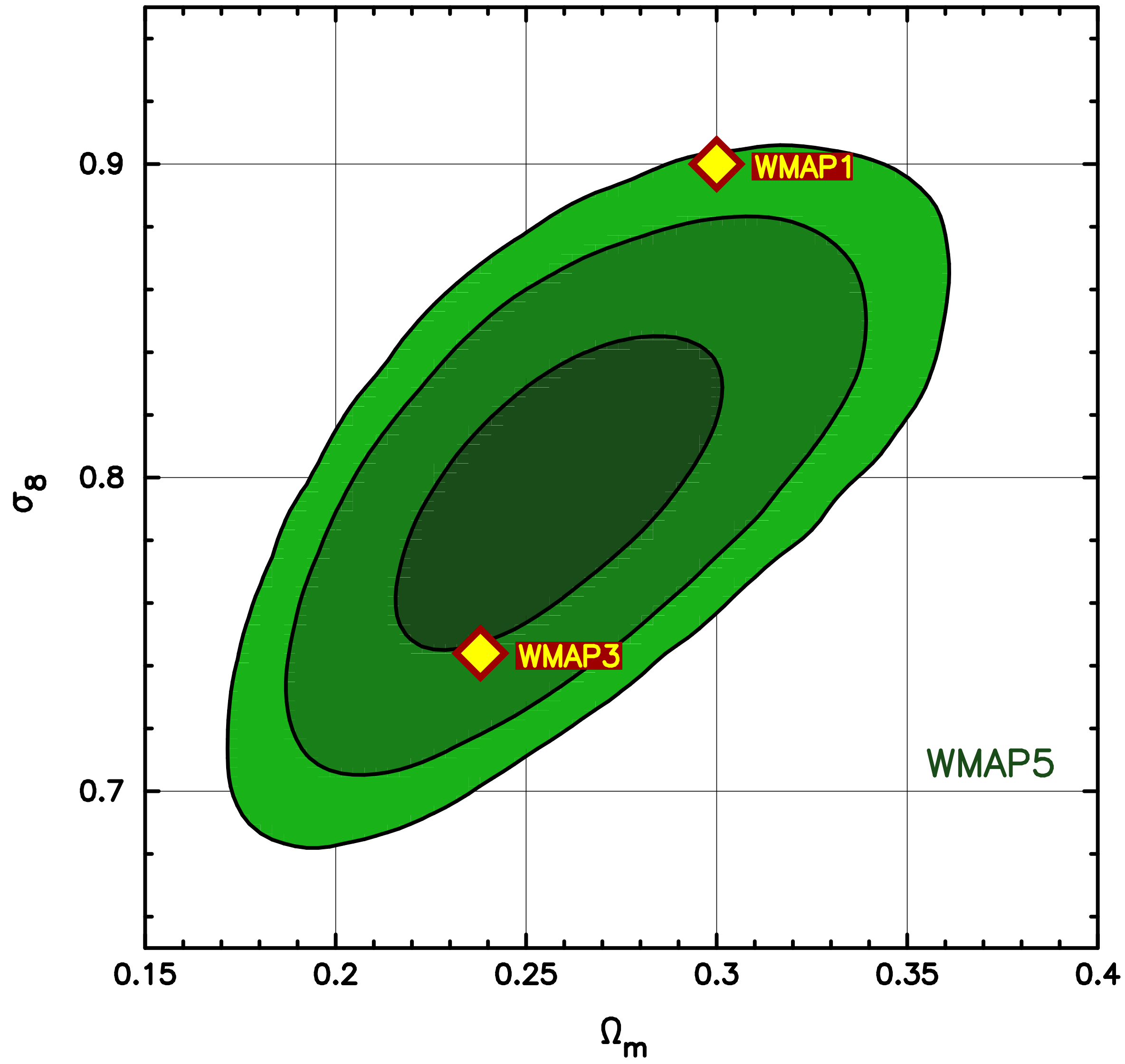
WMAP3 vs. WMAP1



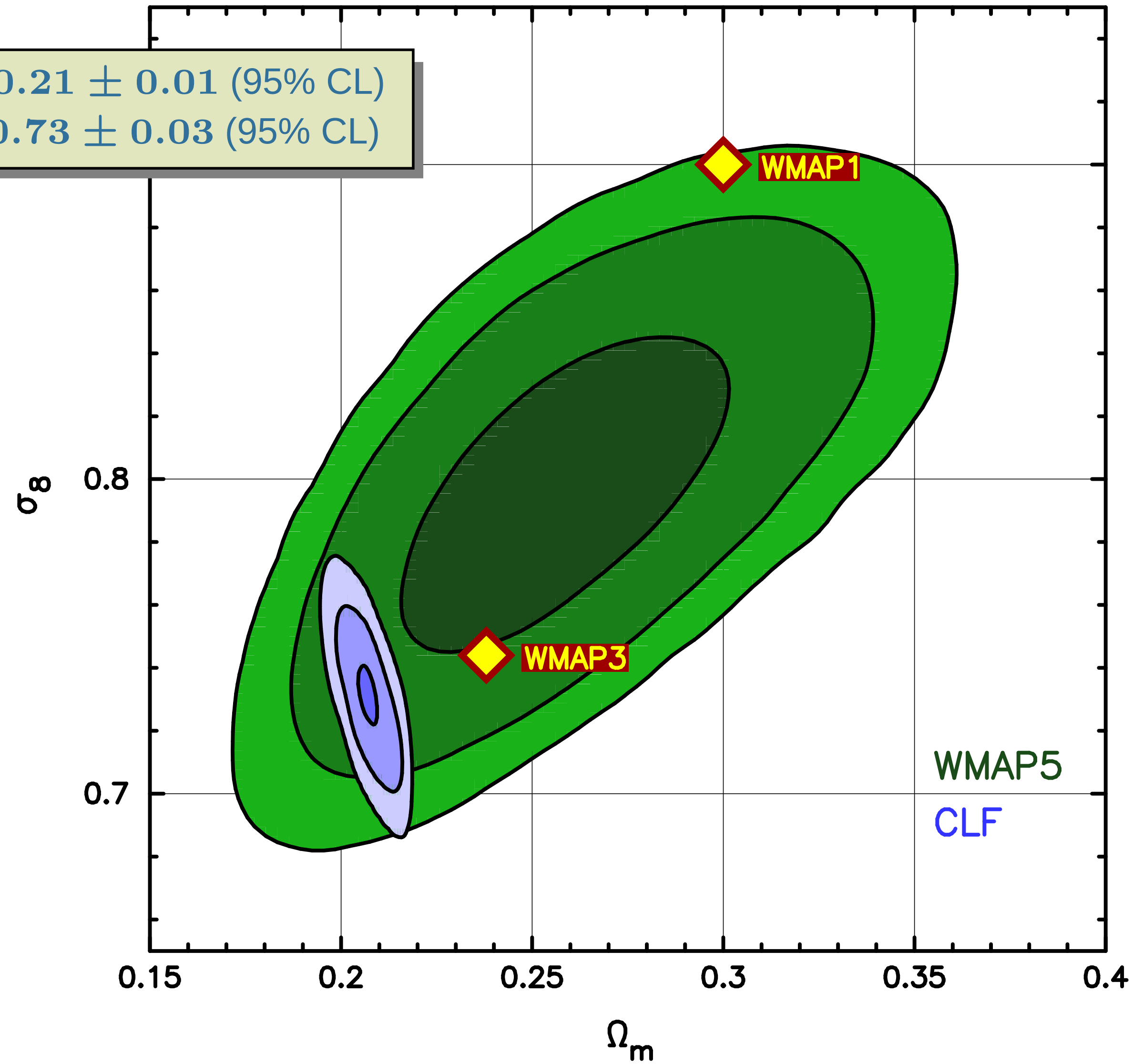
WMAP3 cosmology clearly preferred over WMAP1 cosmology

Cosmological Constraints



Cosmological Constraints

$$\Omega_m = 0.21 \pm 0.01 \text{ (95\% CL)}$$
$$\sigma_8 = 0.73 \pm 0.03 \text{ (95\% CL)}$$



Precision Cosmology using non-linear structure!!

Conclusions

For a given cosmology, luminosity dependence of clustering yields tight constraints on CLF, and thus on galaxy formation

Combining clustering and galaxy-galaxy lensing we obtain tight constraints on cosmological parameters, which are in excellent agreement with CMB constraints

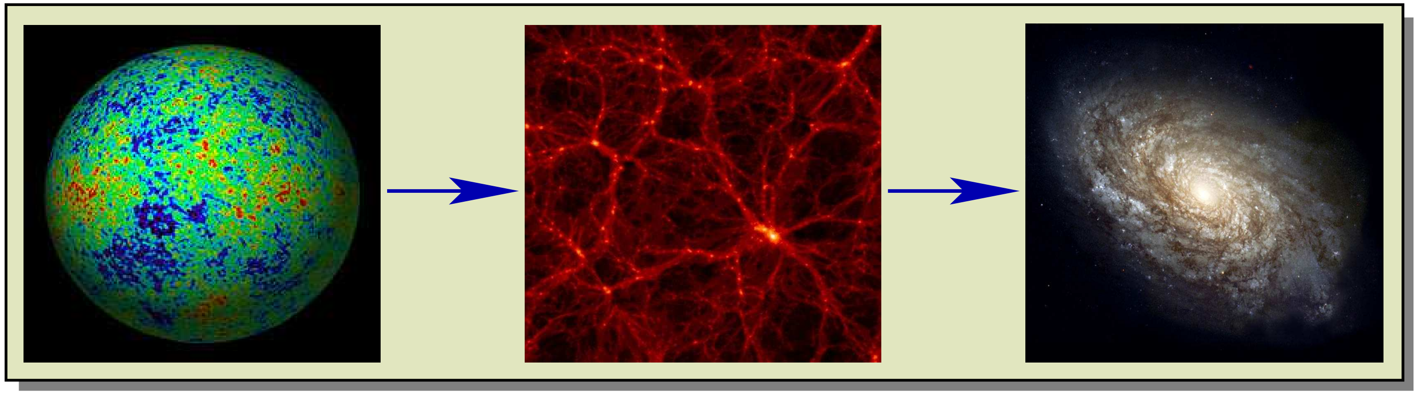
Current (preliminary) results suggest

$$\Omega_m = 0.21 \pm 0.01 \text{ (95\% CL)}$$
$$\sigma_8 = 0.73 \pm 0.03 \text{ (95\% CL)}$$

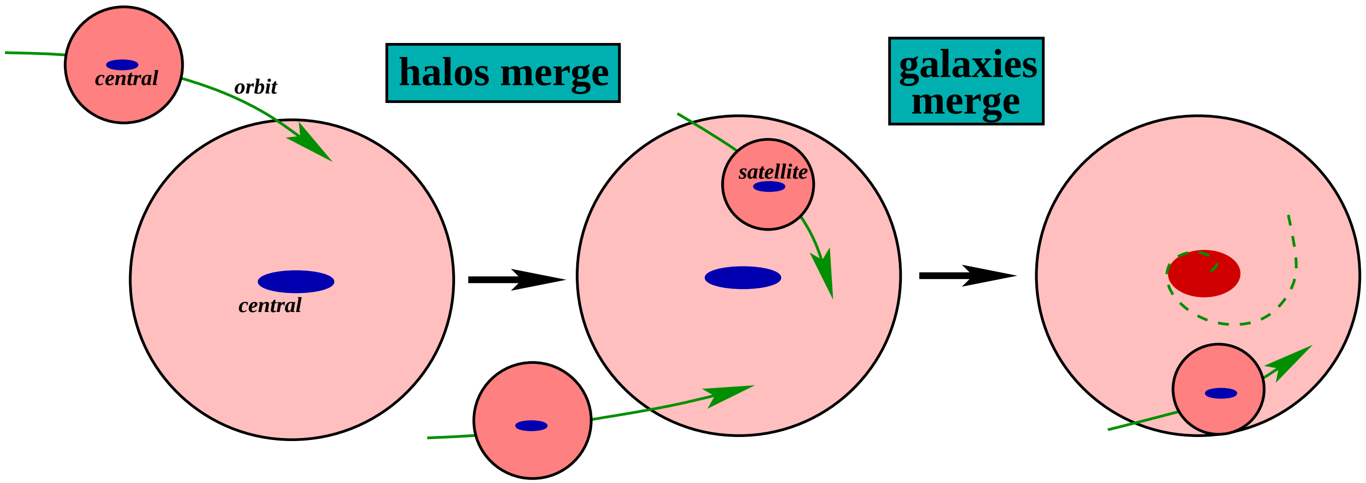
This technique is competative with and complementary to BAO, cosmic shear, SNIa and Lyα forest

If anything, our results indicate that our model for structure formation is accurate on non-linear scales

Galaxy Formation in a Nutshell



- Perturbations grow due to gravitational instability and collapse to produce (virialized) dark matter halos
- Baryons cool, accumulate at center, and form stars $\Rightarrow$ galaxy
- Dark matter halos merge, causing hierarchical growth
- Halo mergers create satellite galaxies that orbit halo



Satellite Weighting or Host Weighting?

Introduction

Conditional Luminosity Function

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Galaxy-Galaxy Lensing

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Extra Material

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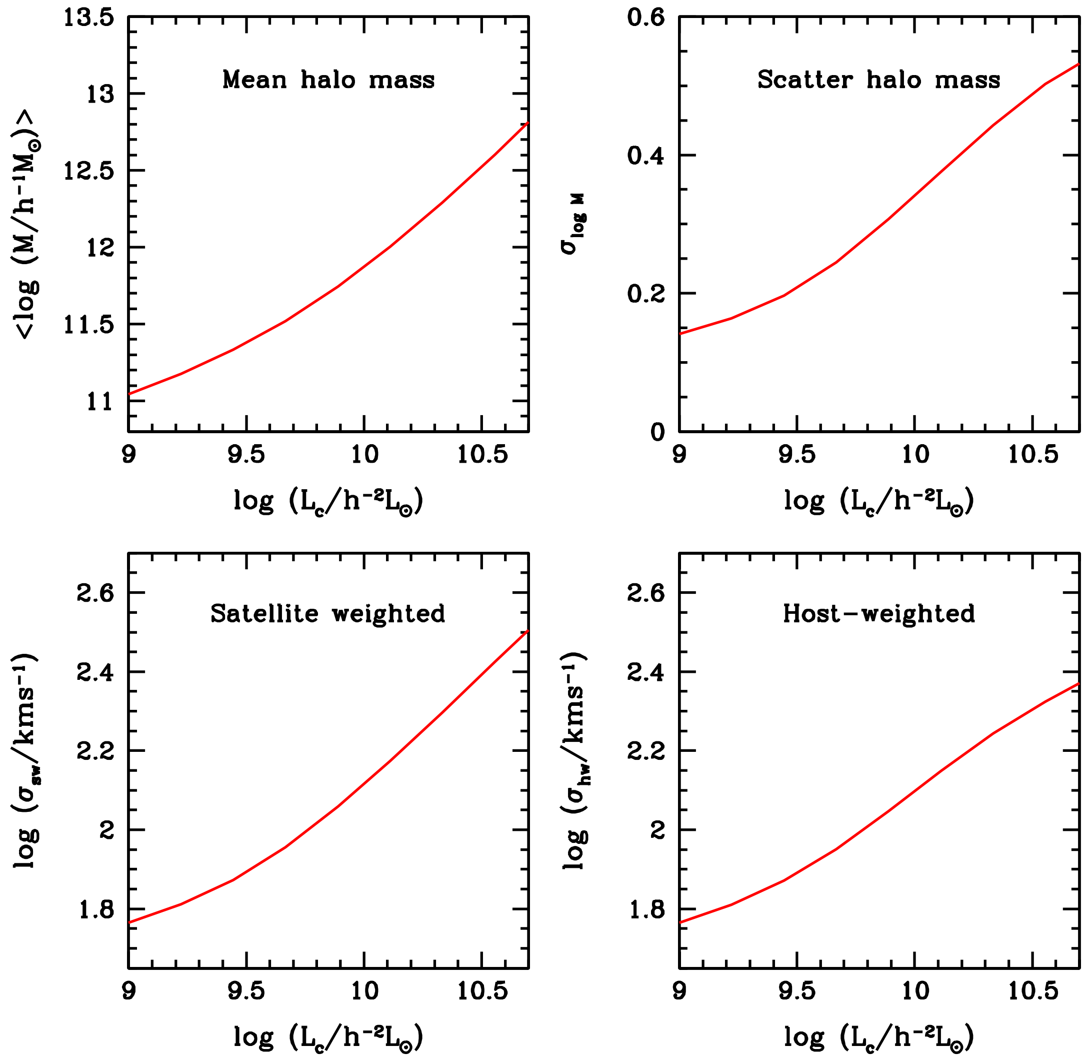
- Satellite Weighting or Host Weighting?
- Implications for Galaxy Formation Stochasticity
- Comparison with other Constraints
- Halo Occupation Numbers



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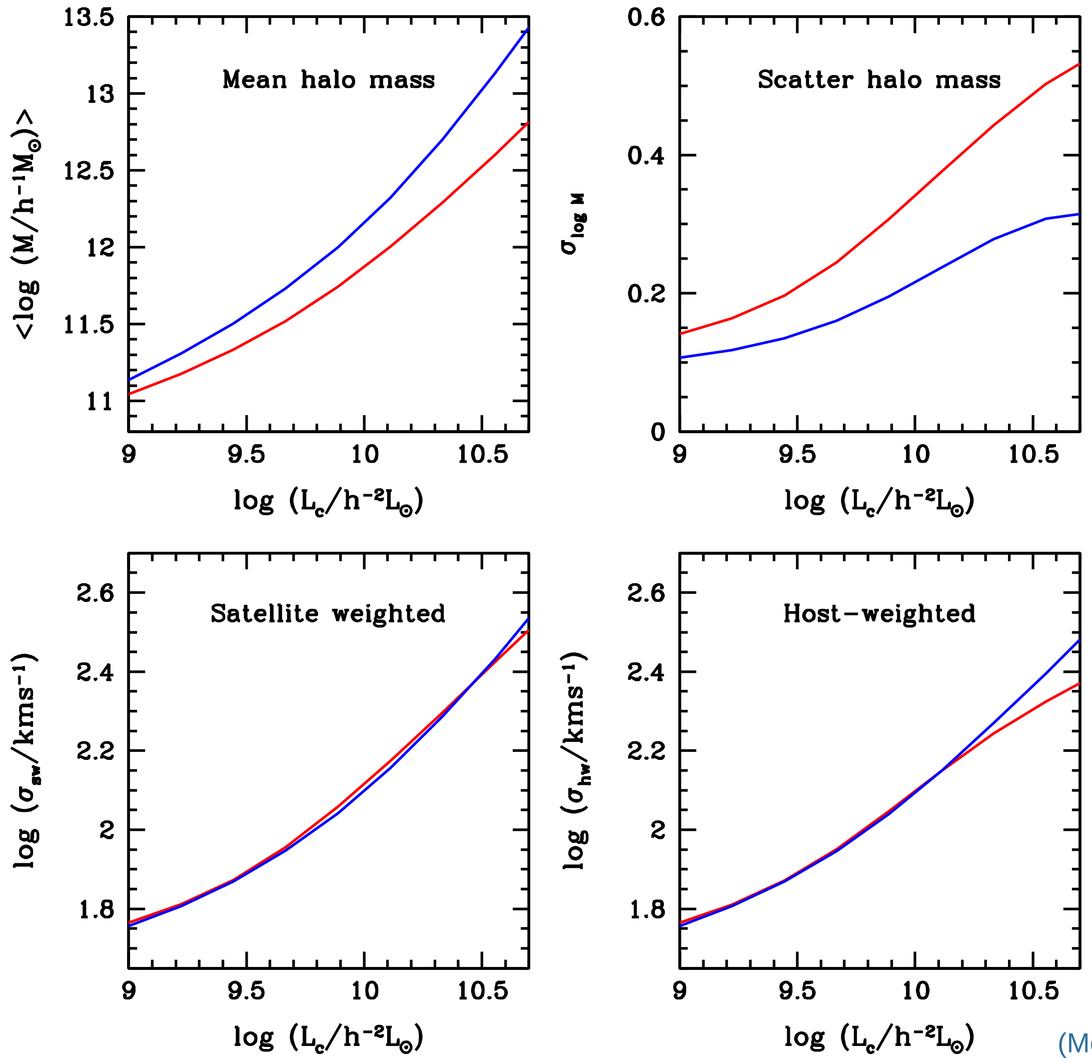
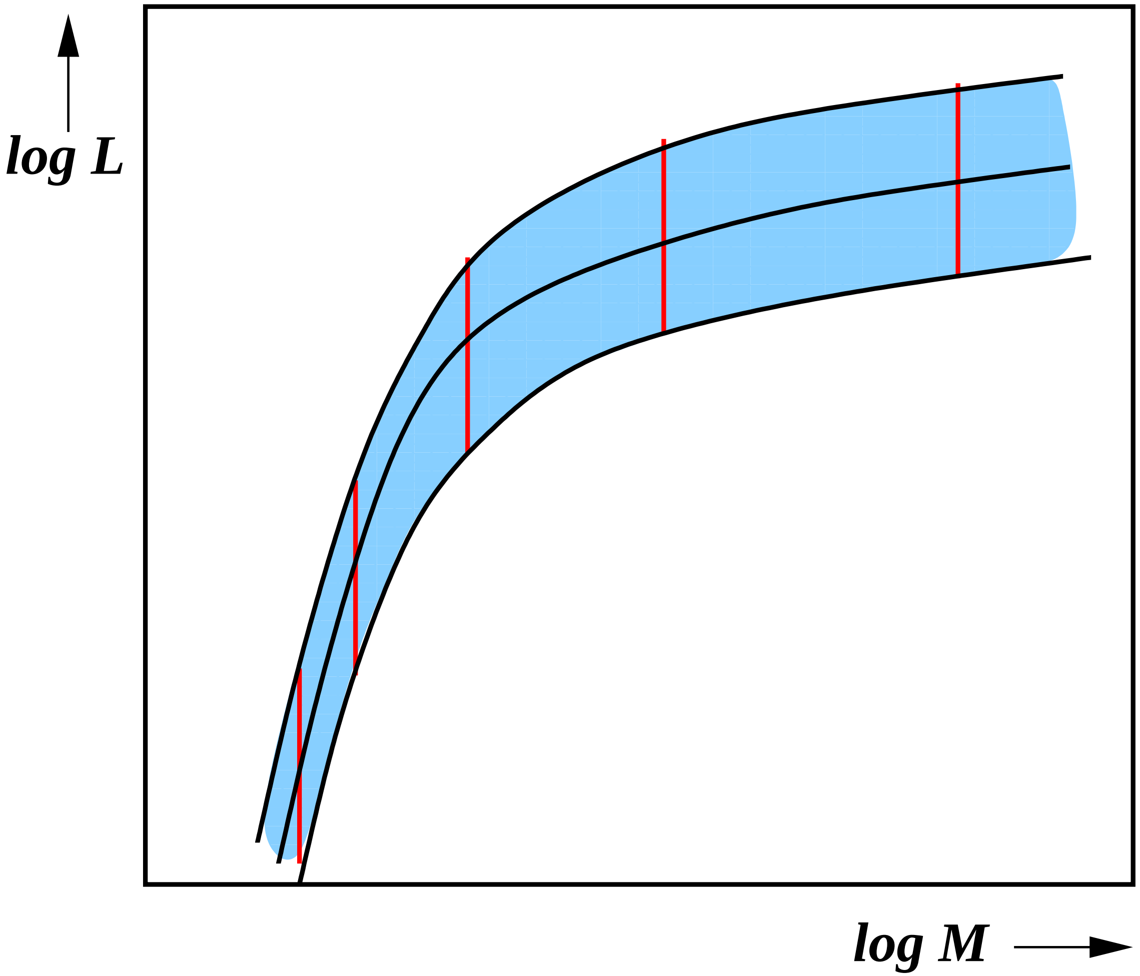


(More, vdB et al. 2008)

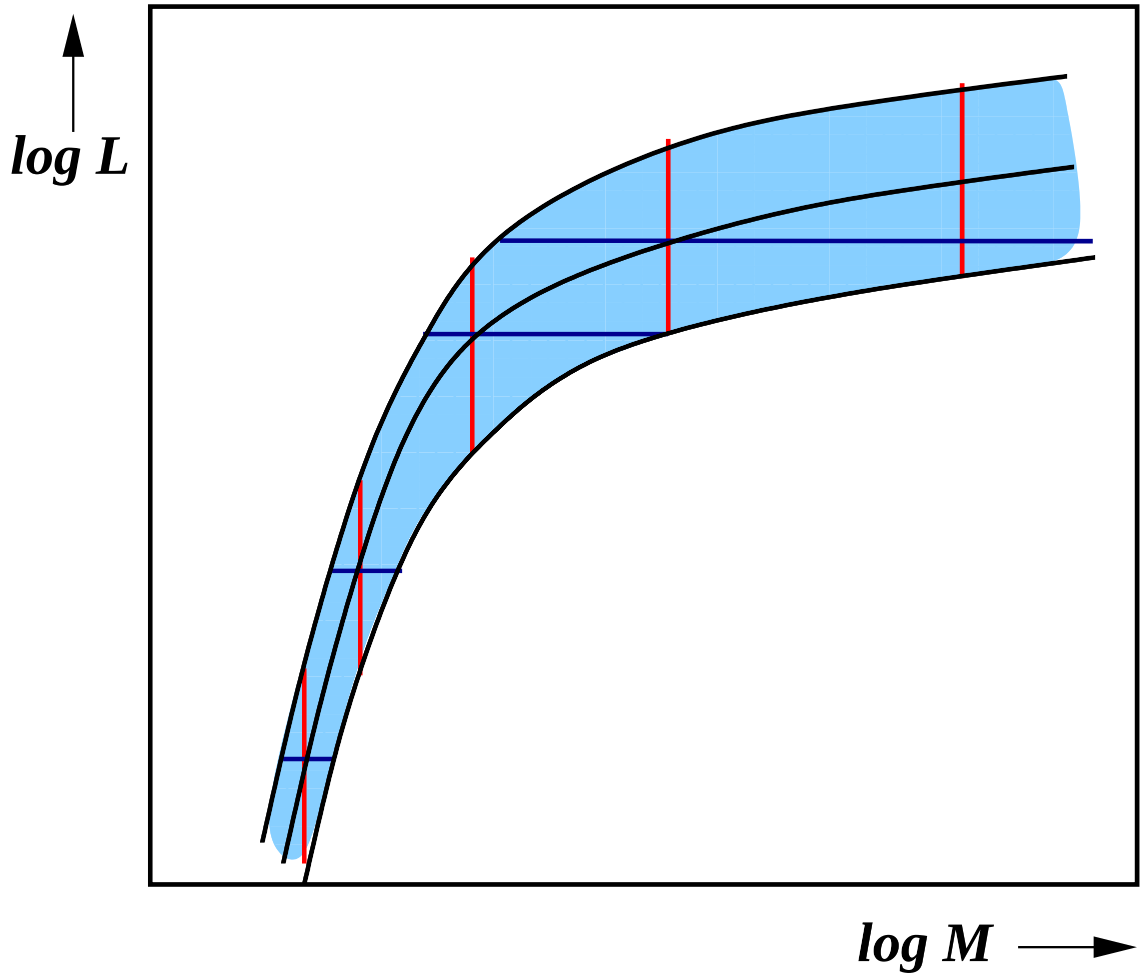
The combination of $\sigma_{\rm sw}$ and $\sigma_{\rm sw}$ allows one to determine mean and scatter of $P(M|L_{\rm c})$

Implications for Galaxy Formation Stochasticity



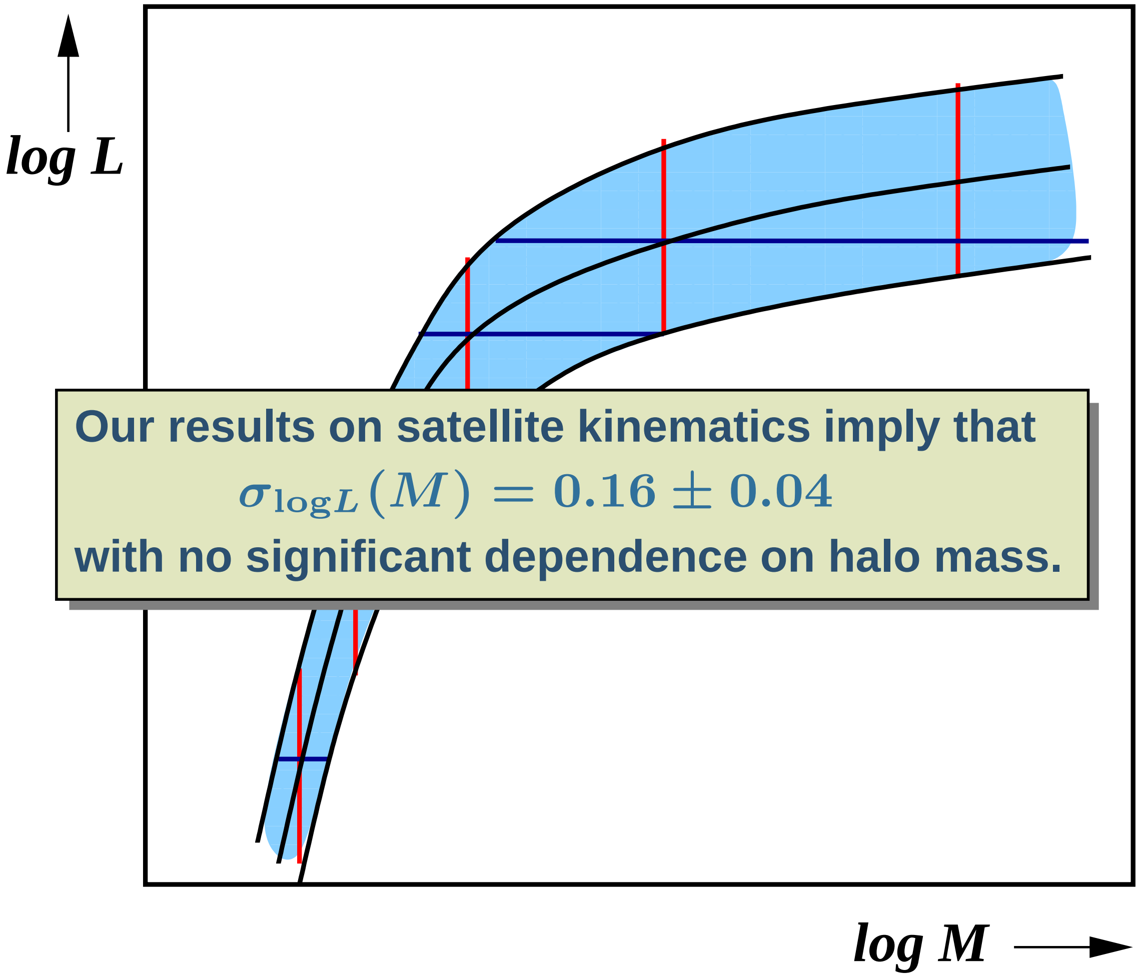
- **The scatter in $P(L_{\rm cen}|M)$ is independent of M**

Implications for Galaxy Formation Stochasticity



- **The scatter in $P(L_{\rm cen}|M)$ is independent of M**
- **The scatter in $P(M|L_{\rm cen})$ increases strongly with $L_{\rm cen}$**

Implications for Galaxy Formation Stochasticity



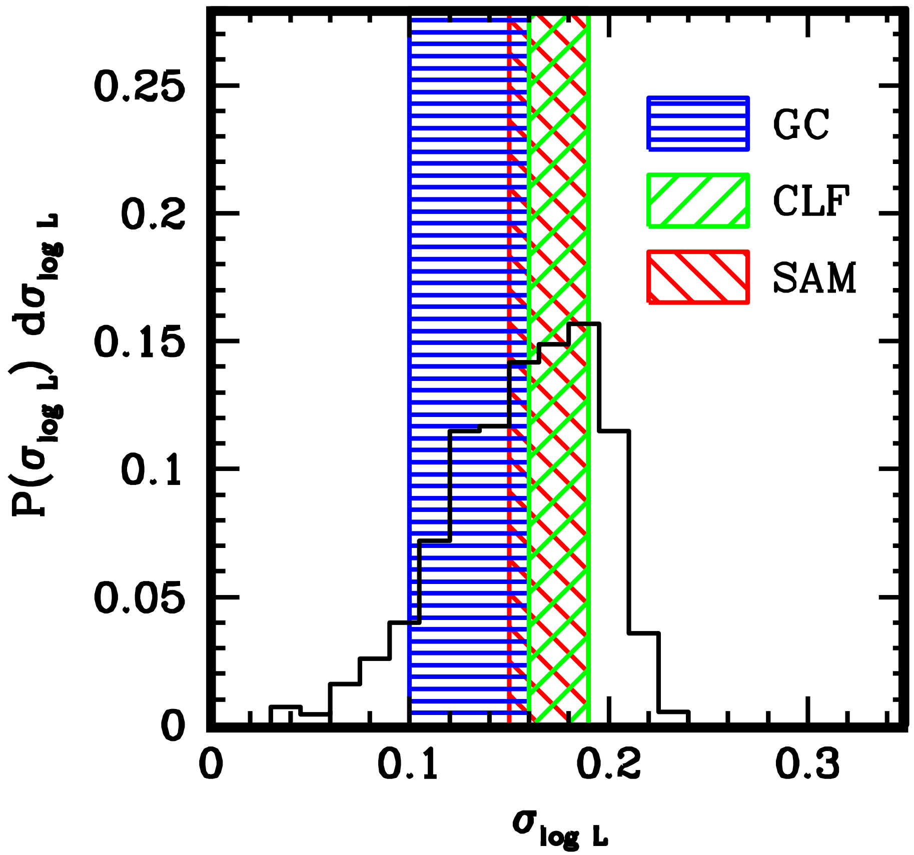
Our results on satellite kinematics imply that

$$\sigma_{\log L}(M) = 0.16 \pm 0.04$$

with no significant dependence on halo mass.

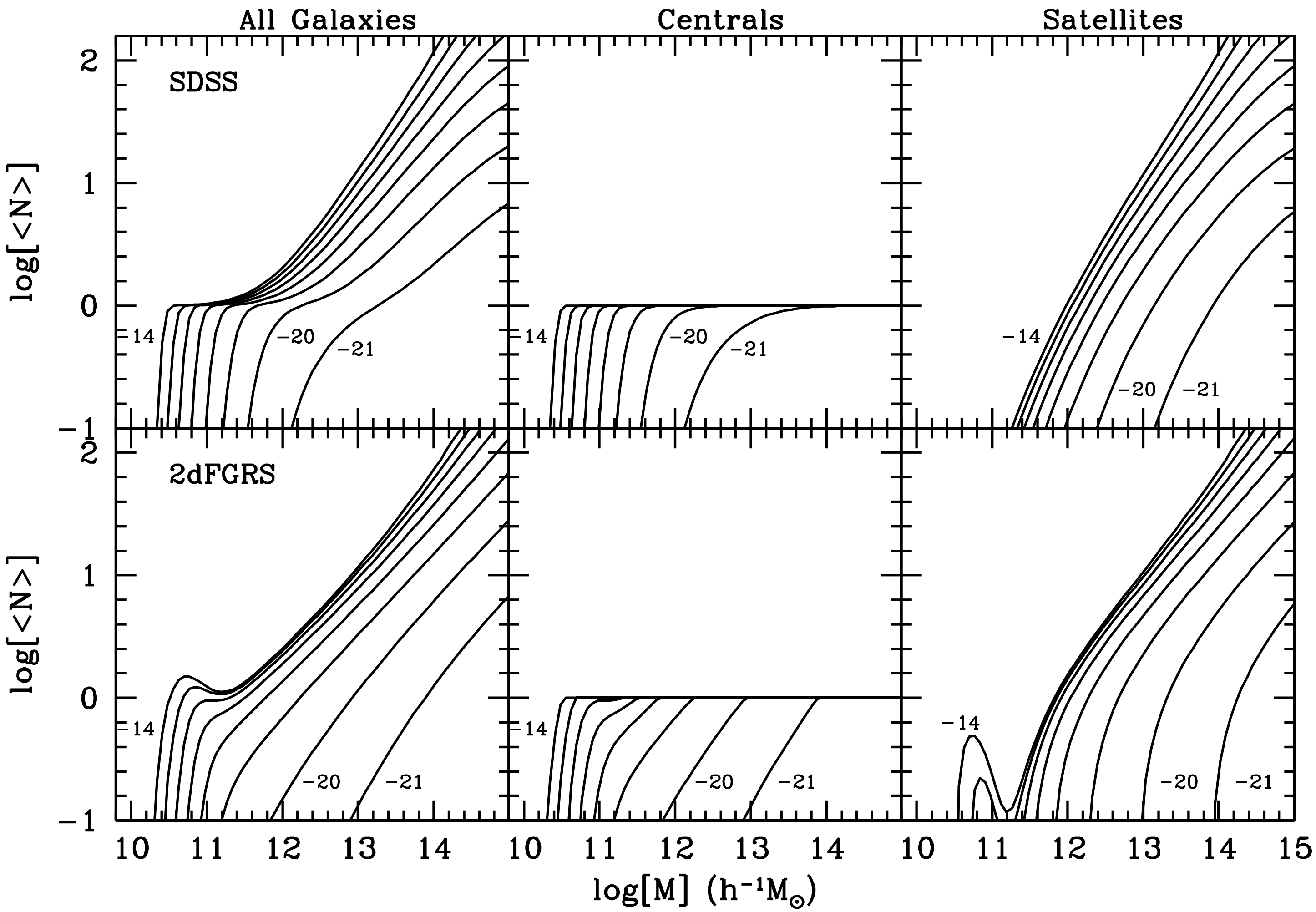
- **The scatter in $P(L_{\rm cen}|M)$ is independent of M**
- **The scatter in $P(M|L_{\rm cen})$ increases strongly with $L_{\rm cen}$**

Comparison with other Constraints



- Probability Distribution from Satellite Kinematics
- Constraints from Galaxy Group Catalogue (Yang et al. 2008)
- Constraints from Clustering Analysis (Cooray 2006)
- Predictions from Semi Analytical Model (Croton et al. 2006)

Halo Occupation Numbers



- Unlike **2dFGRS**, the **SDSS** reveals clear shoulders at $\langle N \rangle_M = 1$
- Most likely this is an ‘artefact’ of the functional form of the **CLF**