Probing Dark Matter Halos with Satellite Kinematics & Weak Lensing

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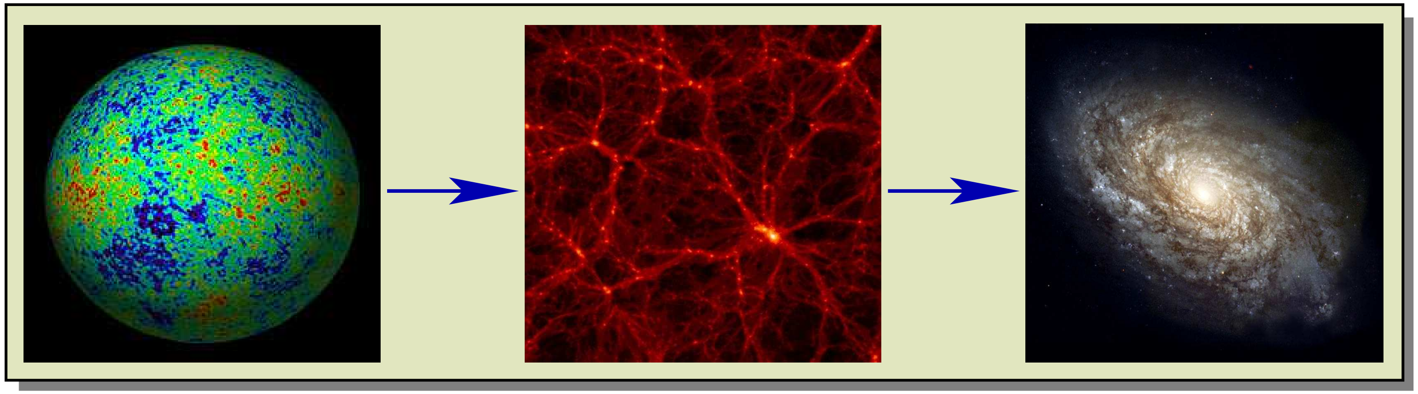
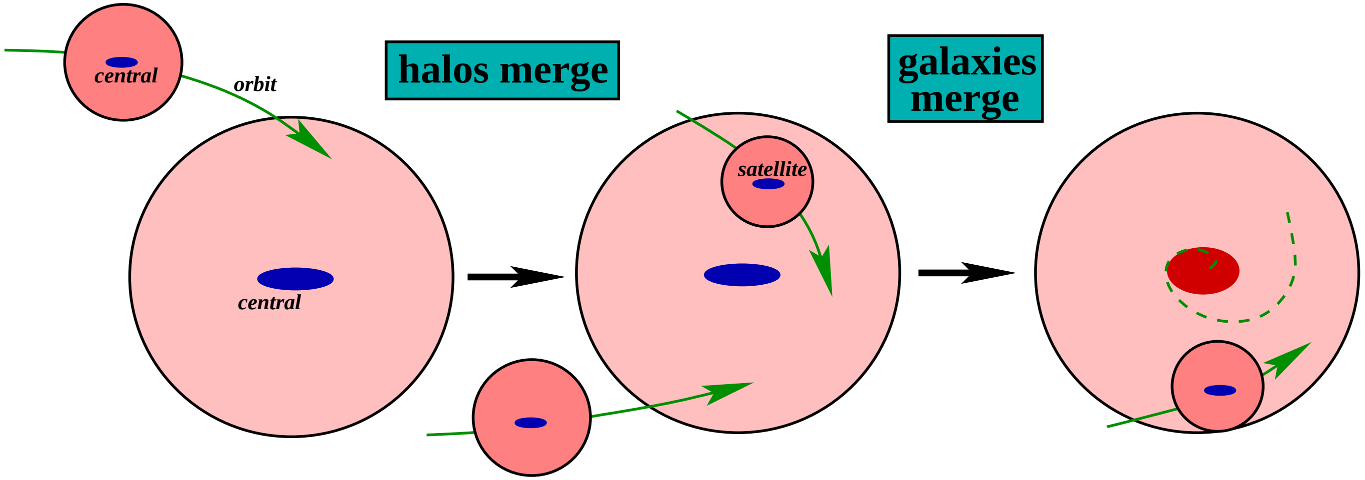
Galaxy Formation in a Nutshell



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



Twin Perspectives

Theory	**Observations**
Given the mass of a DM halo, what is the luminosity of the central galaxy?	**Given the luminosity of a central galaxy, what is the mass of its DM halo?**
$\langle L\rangle(M)$	$\langle M\rangle(L)$
First moment of $P(L\|M)$	**First moment of** $P(M\|L)$

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$$P(L|M)\, n(M) = P(M|L)\, \Phi(L)$$

$n(M) =$ Halo mass function

$\Phi(L) =$ Galaxy Luminosity Function

Twin Perspectives

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Ab Initio Modeling

- semi-analytical models
- numerical simulations

Observational Data

- rotation curves & X-ray data
- satellite kinematics
- gravitational lensing
- clustering

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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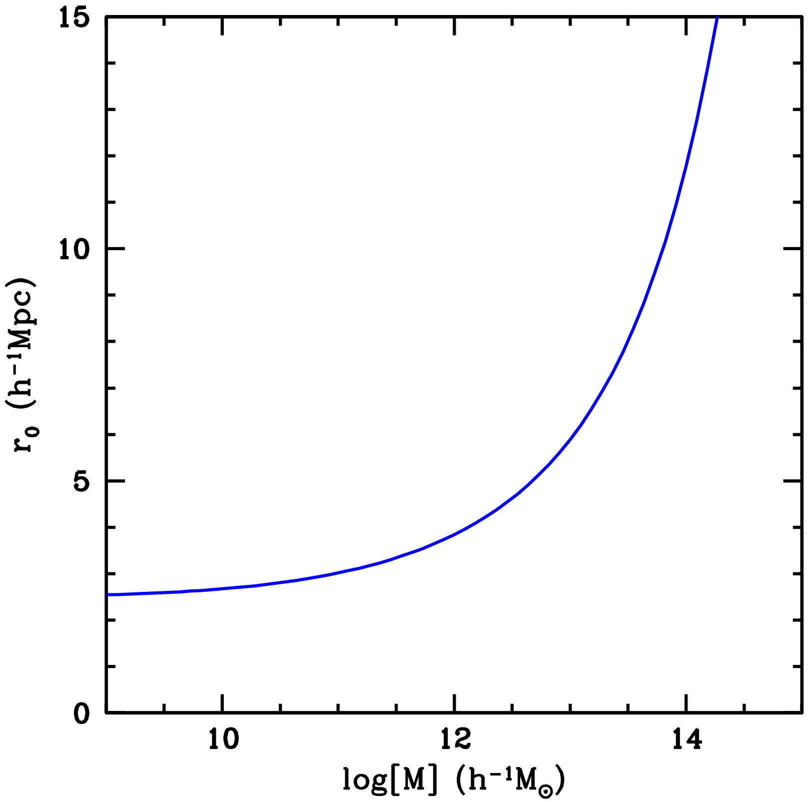

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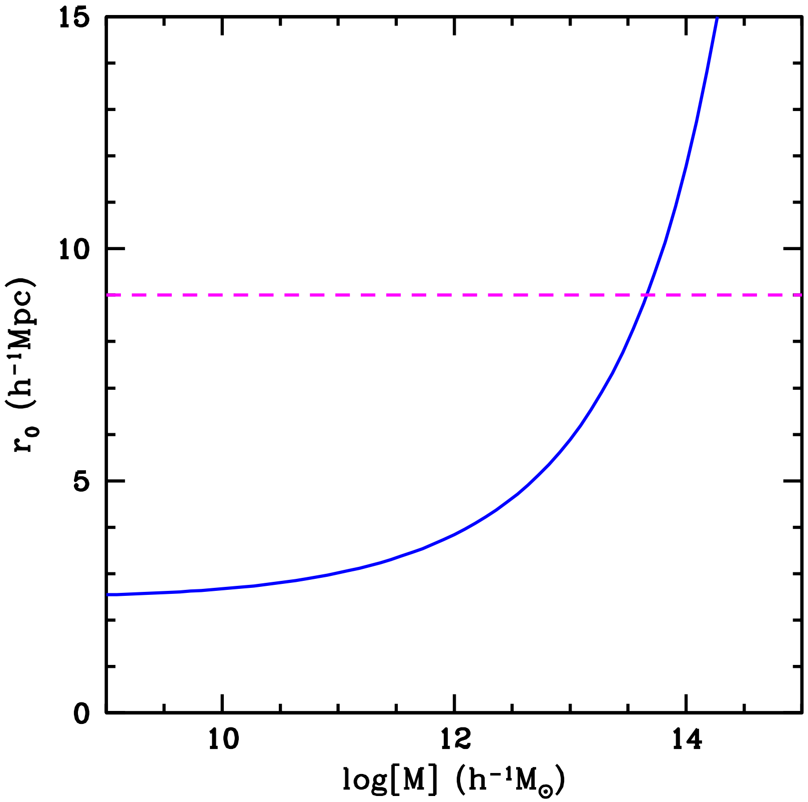

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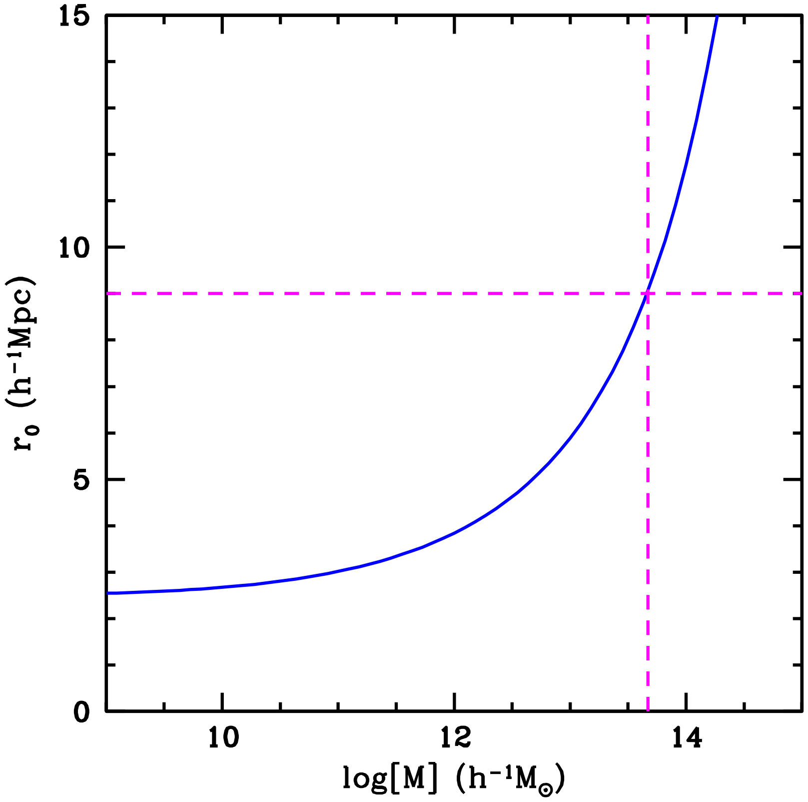

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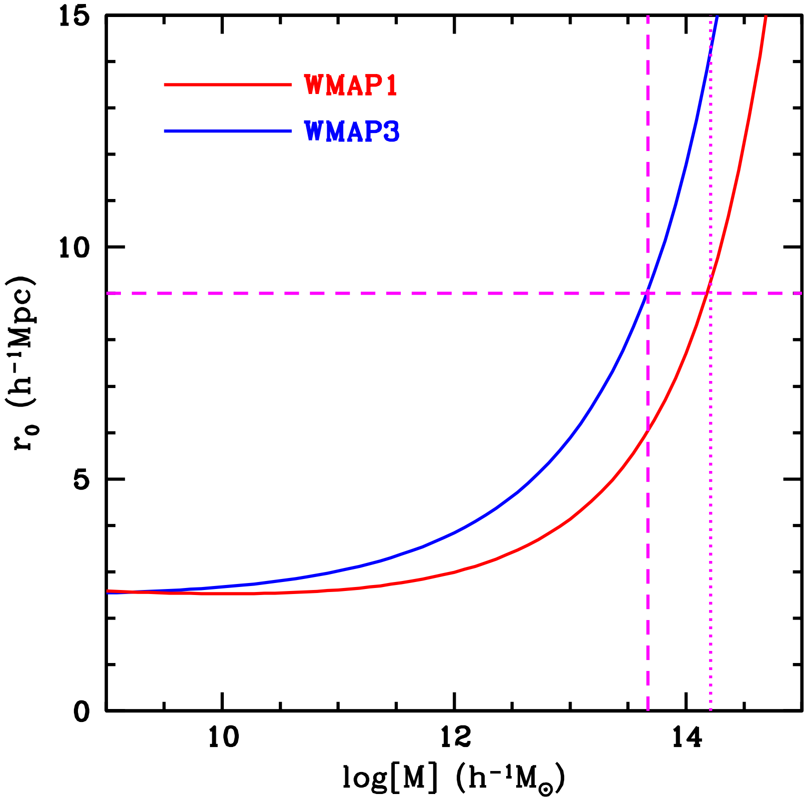


WMAP1

$\Omega_m = 0.30$

$\Omega_\Lambda = 0.70$

$\sigma_8 = 0.90$

WMAP3

$\Omega_m = 0.24$

$\Omega_\Lambda = 0.76$

$\sigma_8 = 0.74$

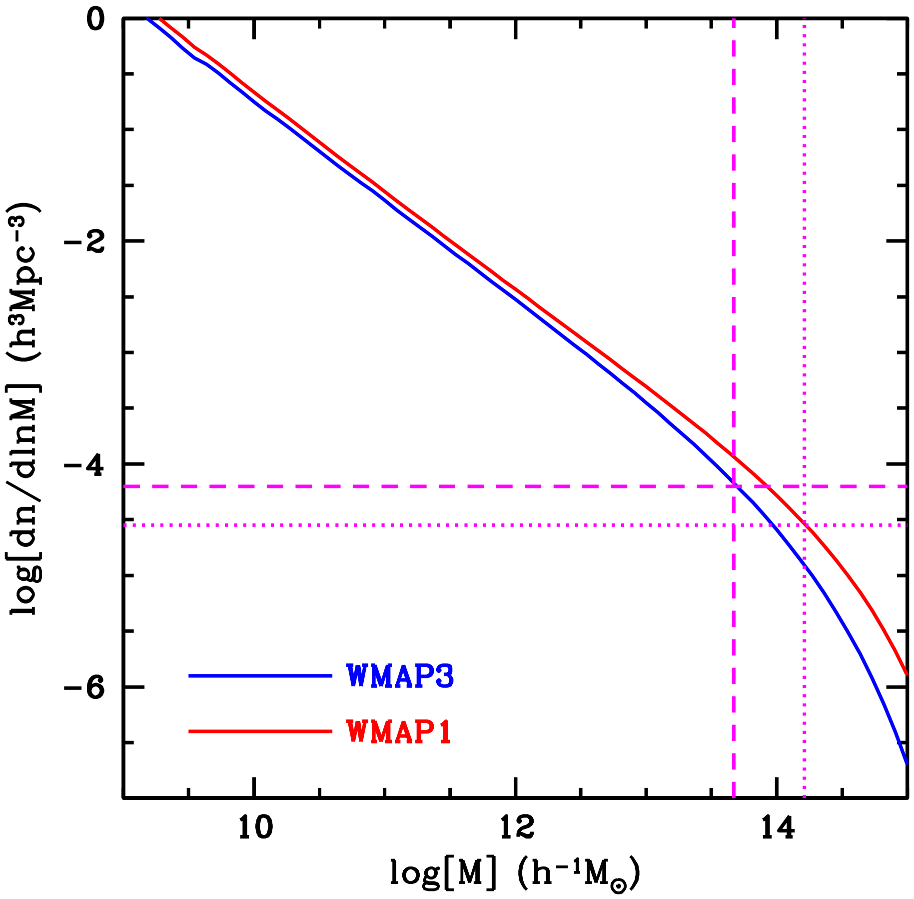
Halo Mass Functions and Occupation Numbers

Using the halo mass inferred from clustering strength

the corresponding number density from the halo mass function,

and the observed number density of the galaxies,

one obtains the average occupation numbers



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 $\Phi(L)$:

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

The CLF contains a wealth of information, such as:

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

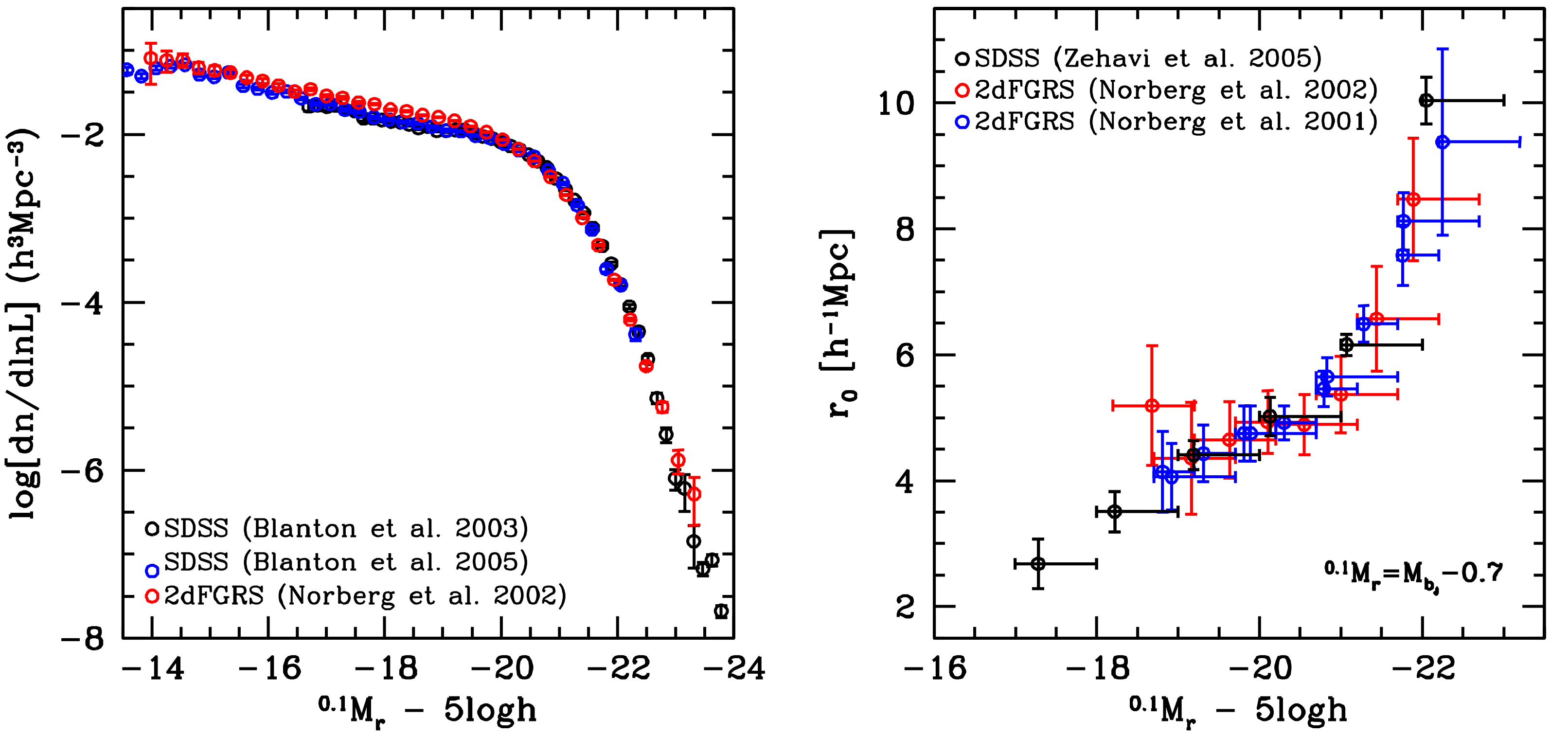
$$\boxed{\langle L\rangle(M) = \int_0^\infty \Phi(L|M)\, L\, \mathrm{d}L}$$

- **The occupation numbers of galaxies:**

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

We constrain the CLF using the luminosity function, $\Phi(L)$, and the correlation lengths as function of luminosity, $r_0(L)$, from SDSS

Luminosity & Correlation Functions

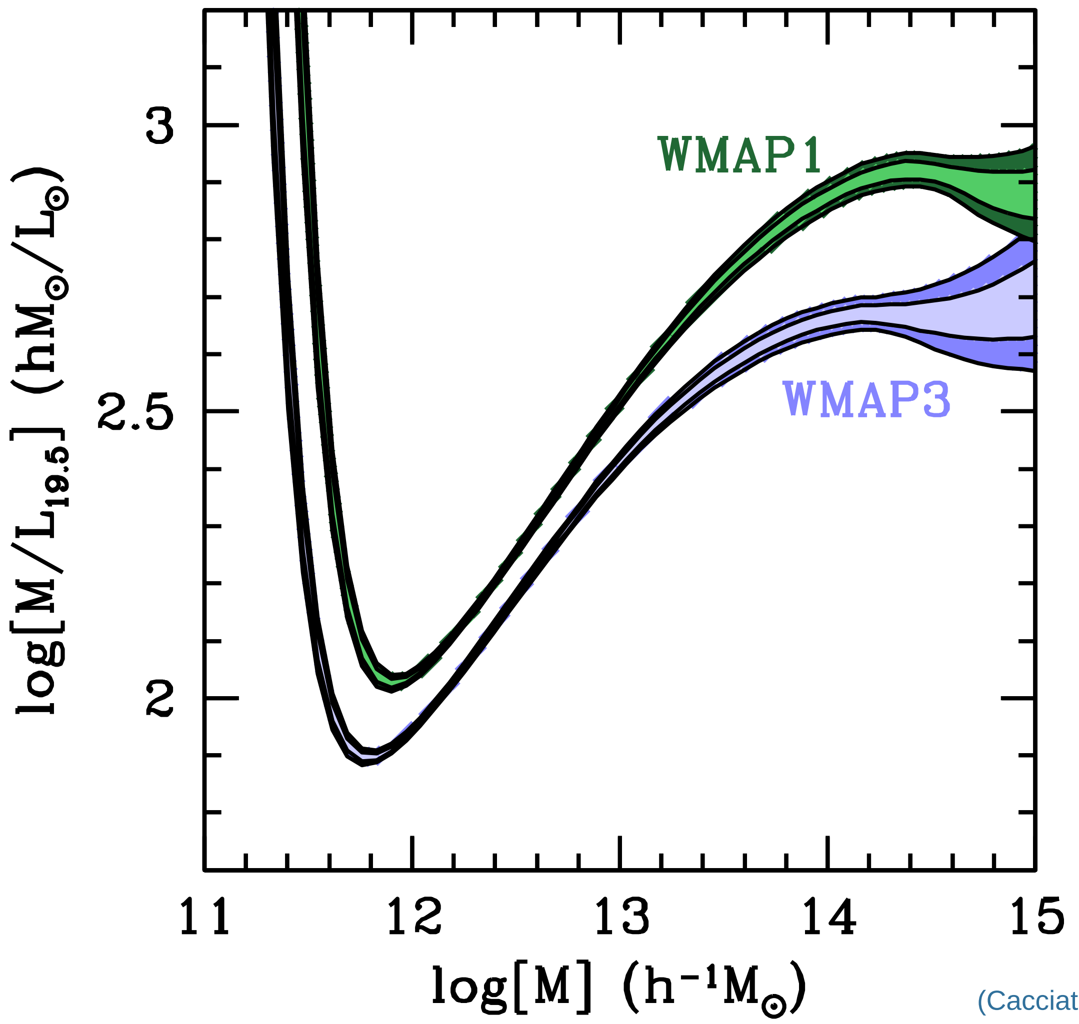


- **DATA:** More luminous galaxies are more strongly clustered.
- **ΛCDM:** More massive haloes are more strongly clustered.

More luminous galaxies reside in more massive haloes

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

Results



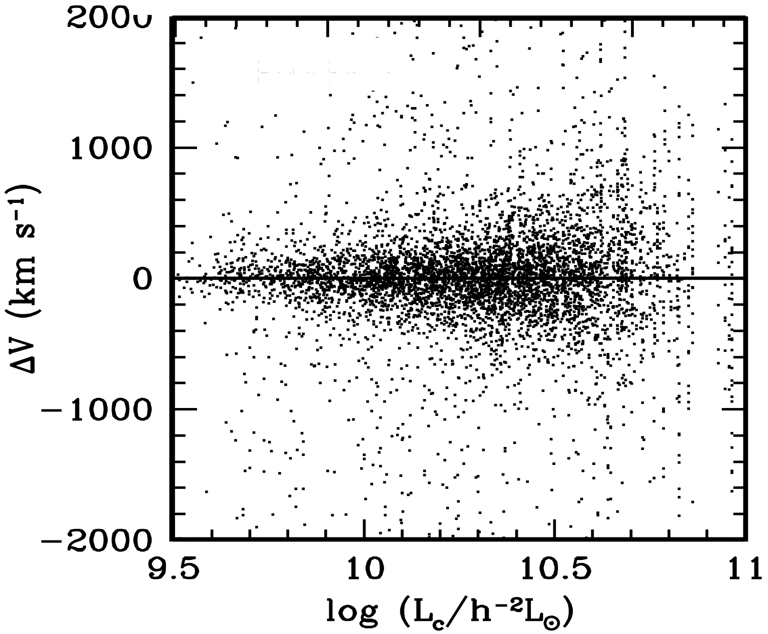
(Cacciato, vdB et al. 2008)

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

Satellite Kinematics: Methodology

Select **centrals** and their **satellites** from a redshift survey

Using redshifts, determine $\Delta V = V_{\rm sat} - V_{\rm cen}$ as function of L_c



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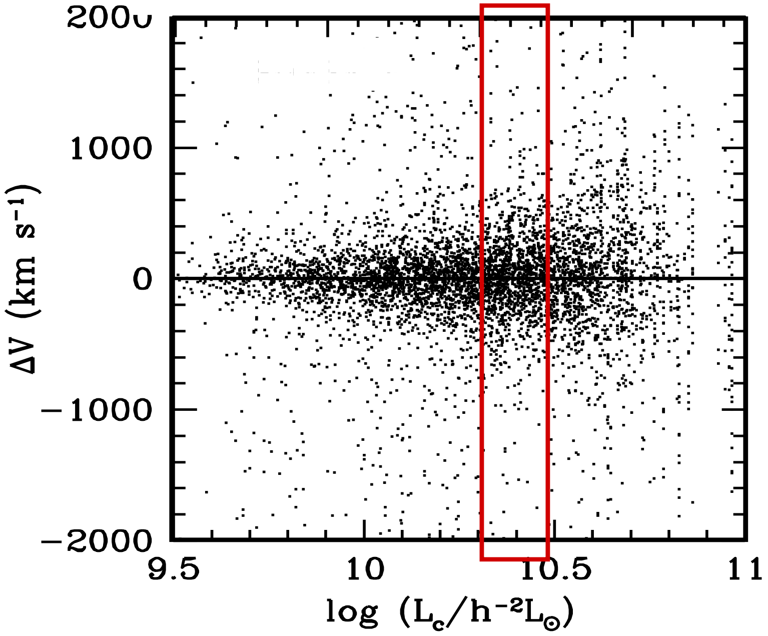

Satellite Kinematics: Methodology

Introduction

Clustering

Conditional Luminosity Function

Satellite Kinematics
- Satellite Kinematics: Methodology
- Satellite Kinematics: Mass Estimates
- Satellite Weighting or Host Weighting?
- Satellite Kinematics in the SDSS
- Modeling Methodology & Results
- Implications for Galaxy Formation Stochasticity
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Extra Material

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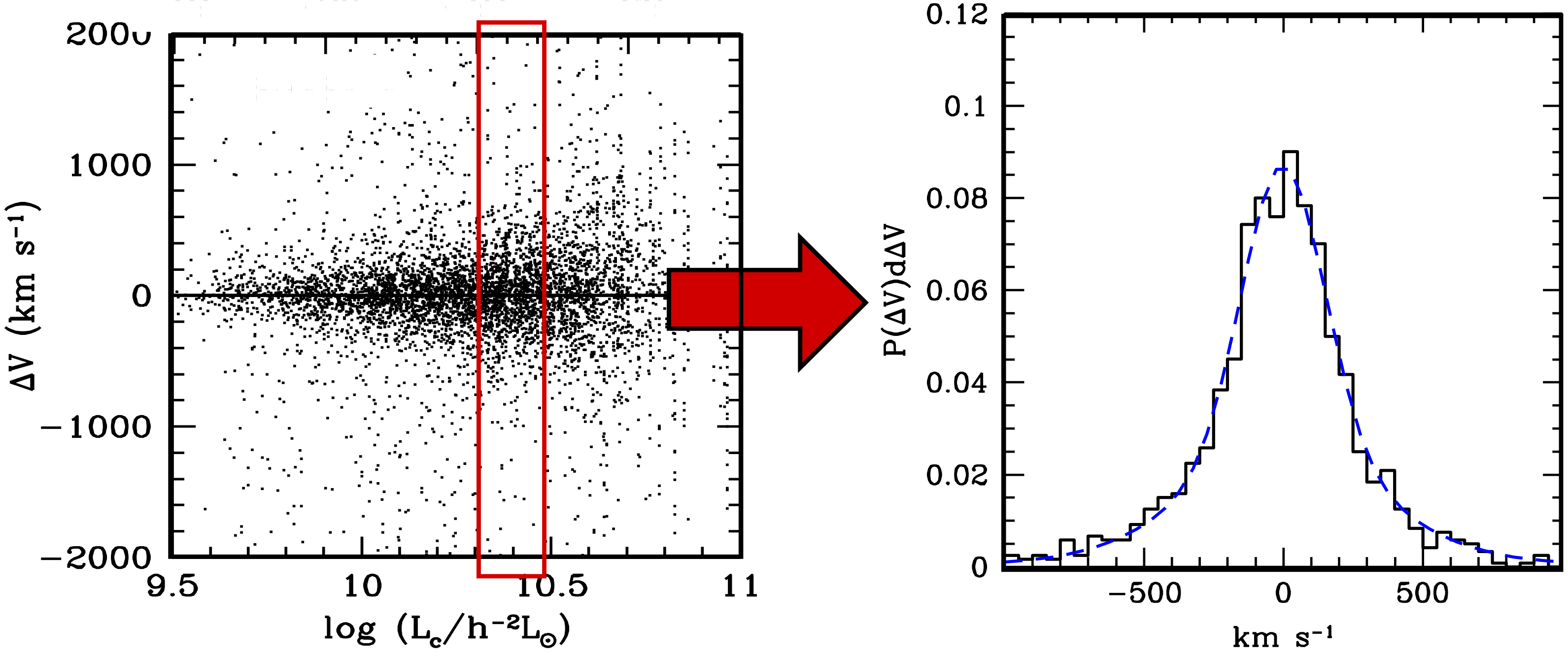

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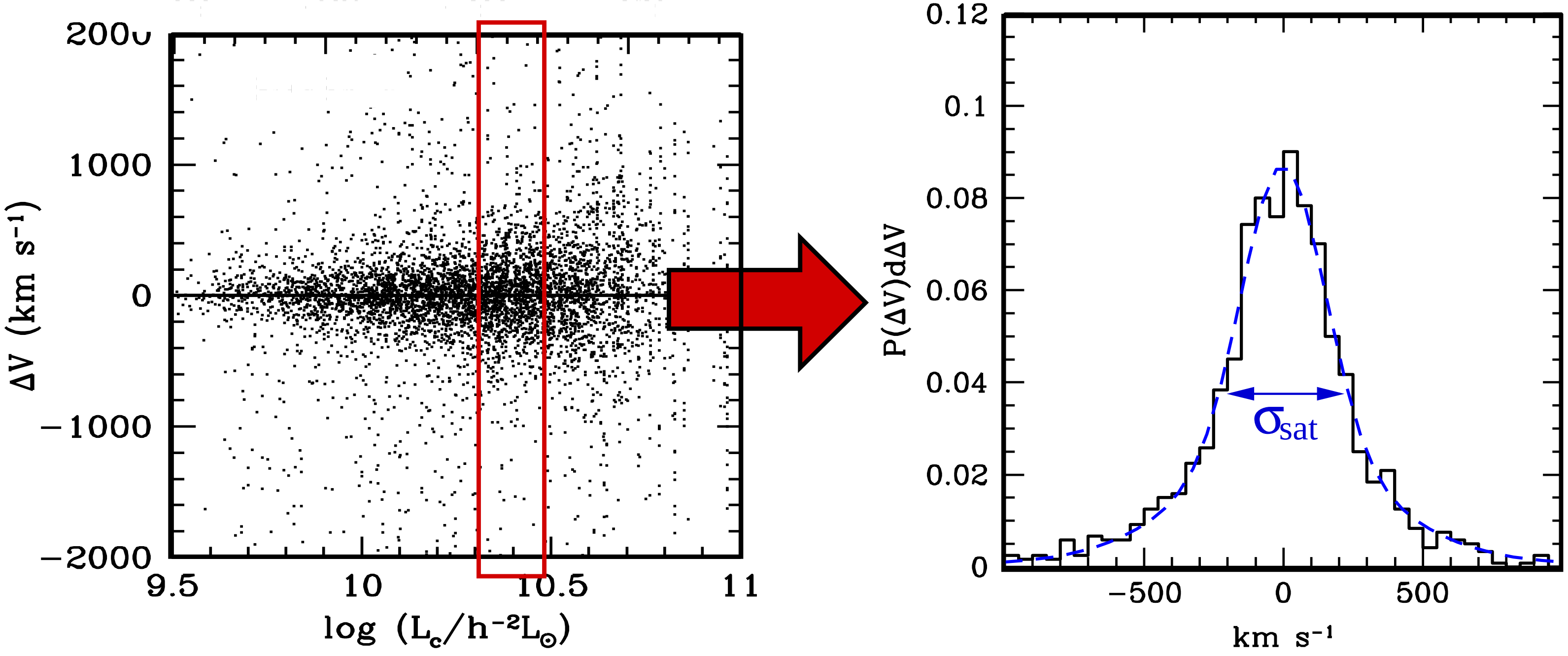

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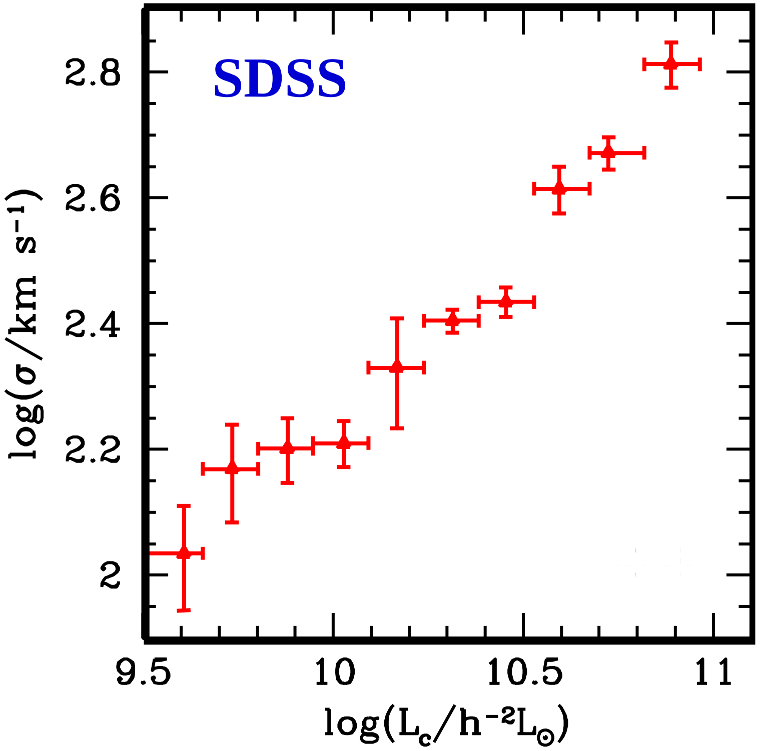

(More, vdB et al. 2008)

Brighter centrals reside in more massive haloes.

Satellite Kinematics: Mass Estimates

Using **virial equilibrium** and **spherical collapse model**:

$$\sigma^2 \propto \frac{GM}{R} \qquad M \propto R^3 \qquad \sigma \propto M^{1/3}$$

Satellite Kinematics: Mass Estimates

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On average only ~ 2 satellites per central → **stacking**

Unless $P(M|L_c)$ is a Dirac delta function, stacking means combining halos of different masses

Consequently, one has to distinguish two different weighting schemes:

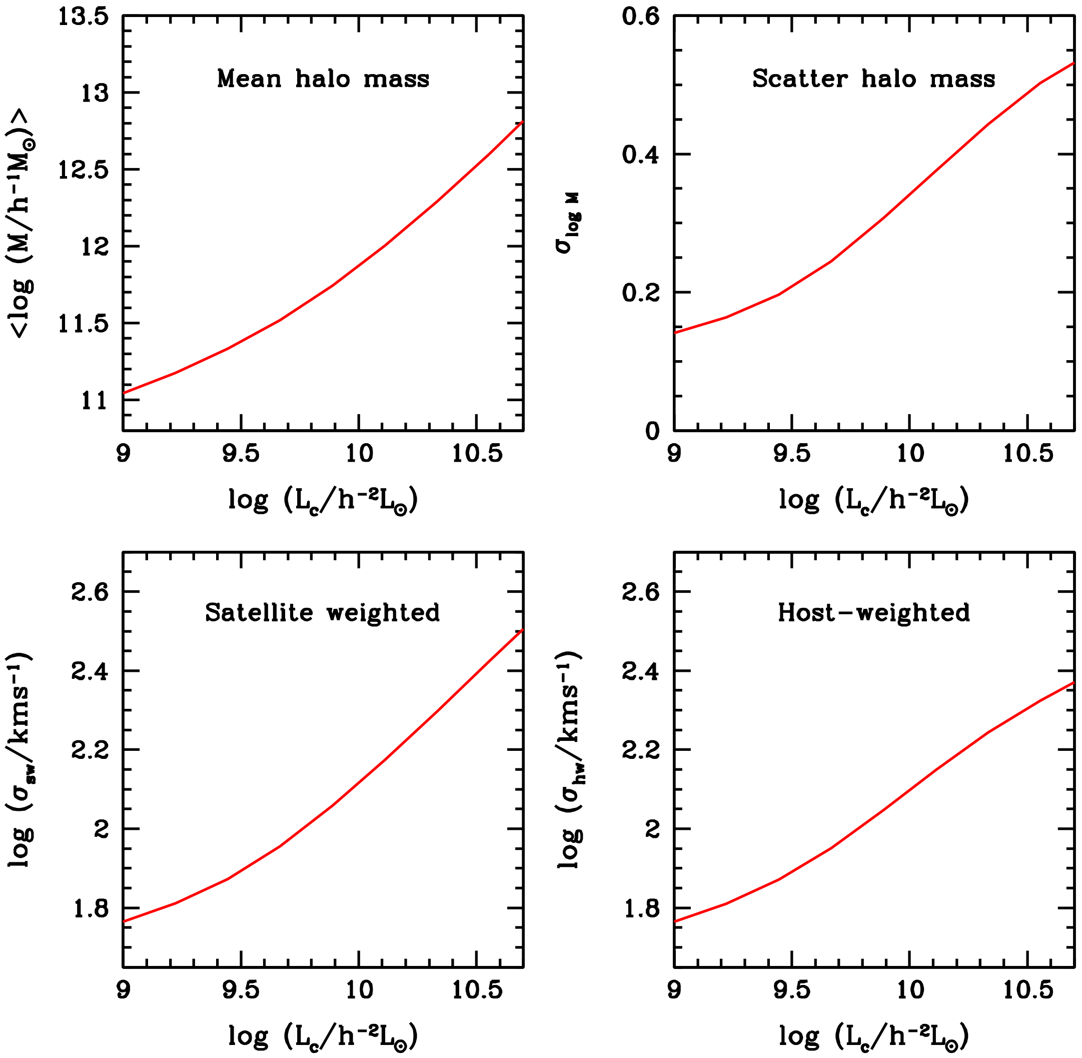
Satellite Weighting: each satellite receives weight of one

$$\boxed{\sigma^2_{\rm sw} = \frac{\int P(M|L_c)\,\langle N_{\rm sat}\rangle_M\,\sigma^2_{\rm sat}(M)\,{\rm d}M}{\int P(M|L_c)\,\langle N_{\rm sat}\rangle_M\,{\rm d}M}}$$

Host Weighting: each host receives weight of one

$$\boxed{\sigma^2_{\rm hw} = \frac{\int P(M|L_c)\,\sigma^2_{\rm sat}(M)\,{\rm d}M}{\int P(M|L_c)\,{\rm d}M}}$$

Satellite Weighting or Host Weighting?



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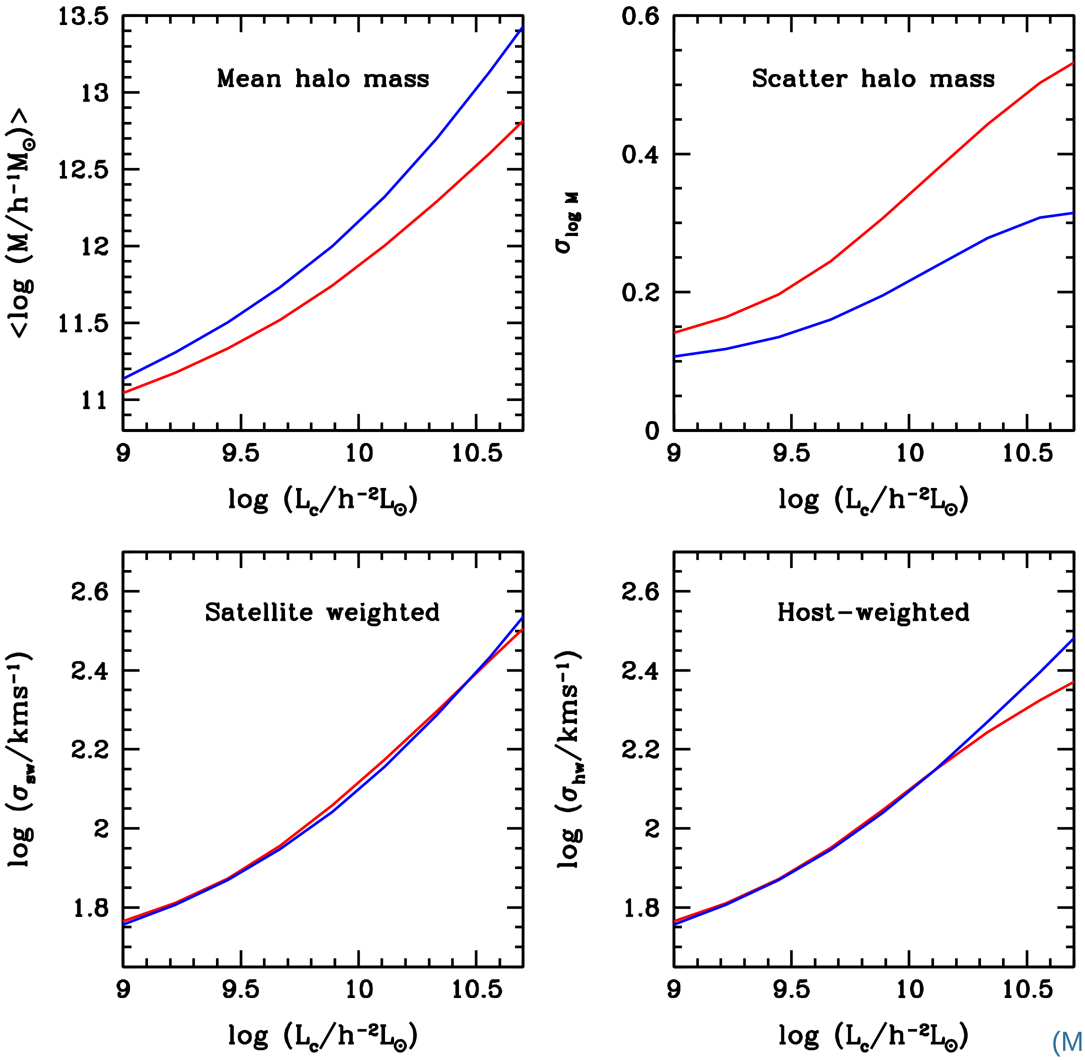

(More, vdB et al. 2008)

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

Satellite Kinematics in the SDSS

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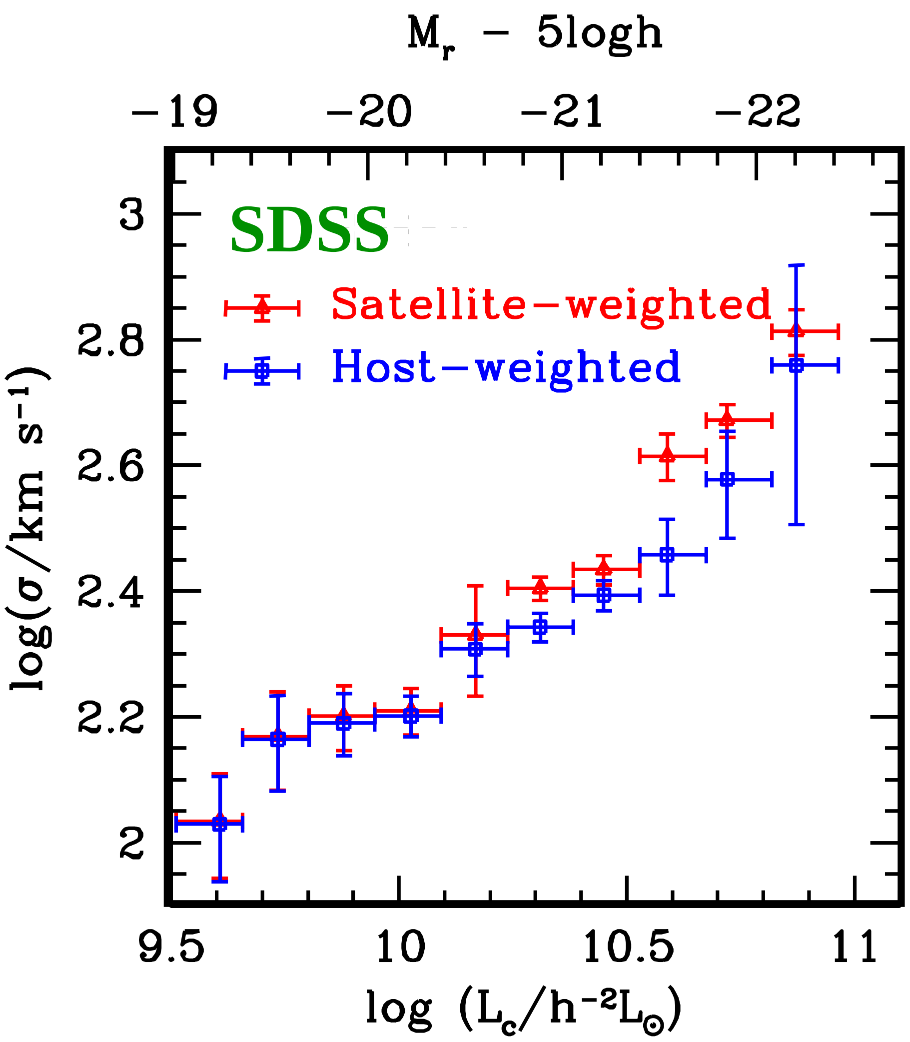

Based on SDSS volume-limited sample with 3863 centrals & 6101 satellites

Note that $\sigma_{\mathrm{sw}} \neq \sigma_{\mathrm{hw}} \Rightarrow$ non-zero scatter in $P(M|L_c)$

Modeling Methodology & Results

Recall:

$$\sigma^2_{\rm sw} = \frac{\int P(M|L_{\rm c})\,\langle N_{\rm sat}\rangle_M\,\sigma^2_{\rm sat}(M)\,{\rm d}M}{\int P(M|L_{\rm c})\,\langle N_{\rm sat}\rangle_M\,{\rm d}M}$$

$$\sigma^2_{\rm hw} = \frac{\int P(M|L_{\rm c})\,\sigma^2_{\rm sat}(M)\,{\rm d}M}{\int P(M|L_{\rm c})\,{\rm d}M}$$

- Jeans equations yield $\sigma^2_{\rm sat}(M)$ for NFW halos
- Use parametric model for $P(M|L_{\rm c})$ and $\langle N_{\rm sat}\rangle_M$
- Constrain model parameters by fitting the observed $\sigma_{\rm sw}(L_{\rm c})$ and $\sigma_{\rm hw}(L_{\rm c})$

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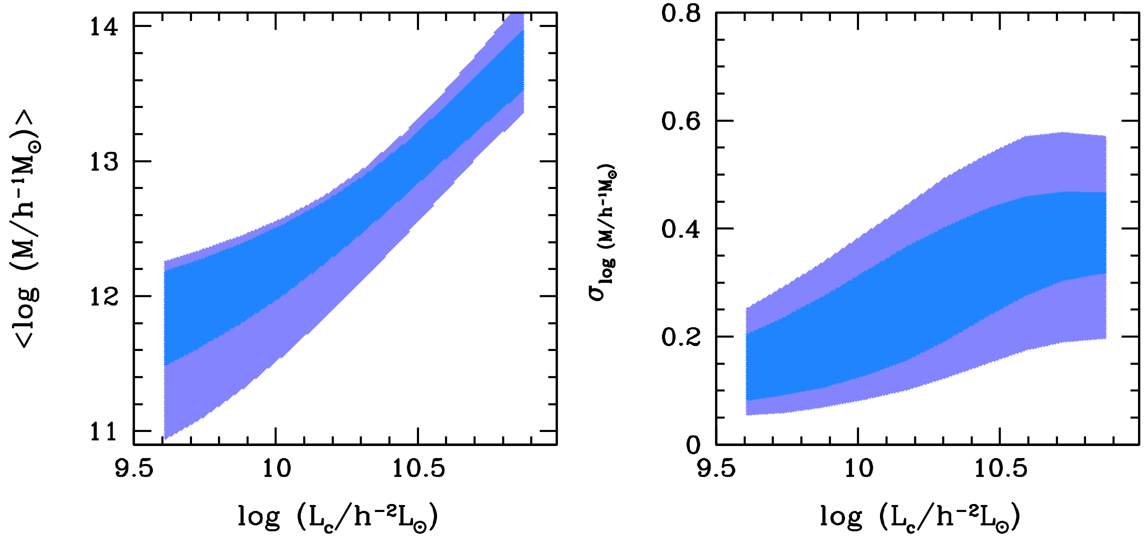

The 68 and 95 percent confidence levels from MCMC

Modeling Methodology & Results

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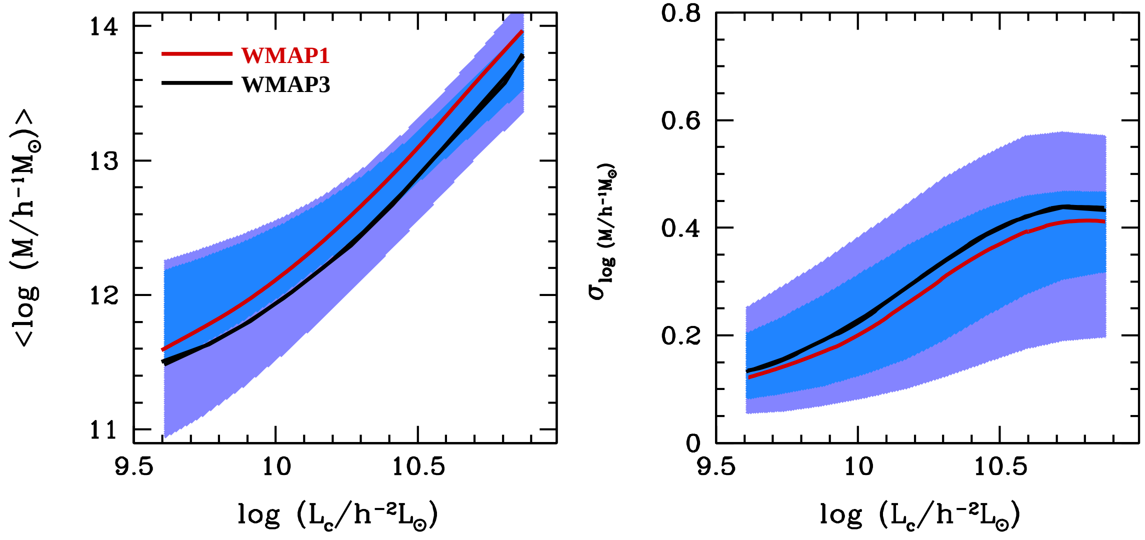

Good agreement with CLF clustering results

Modeling Methodology & Results

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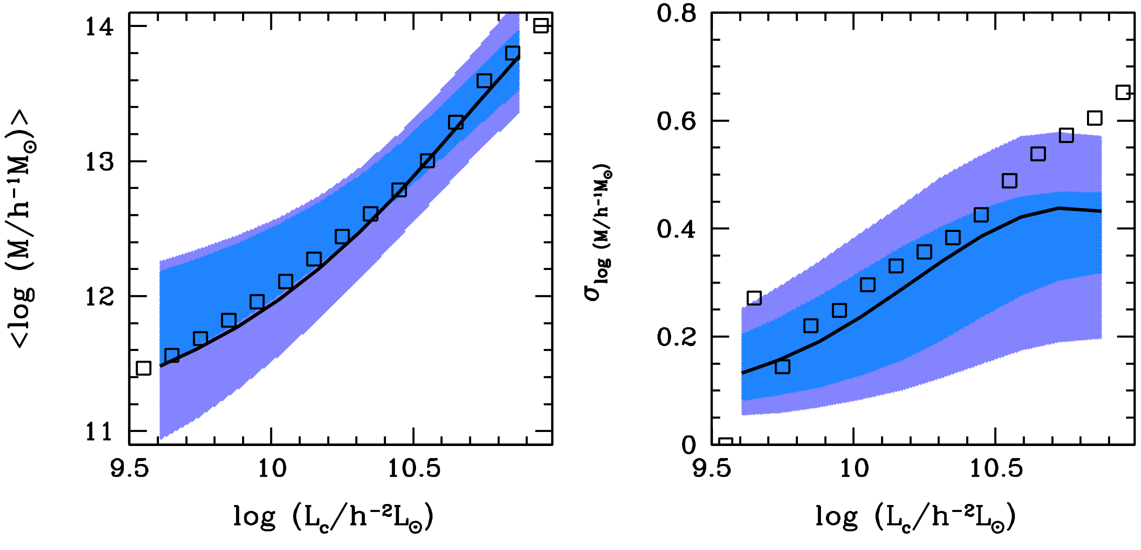
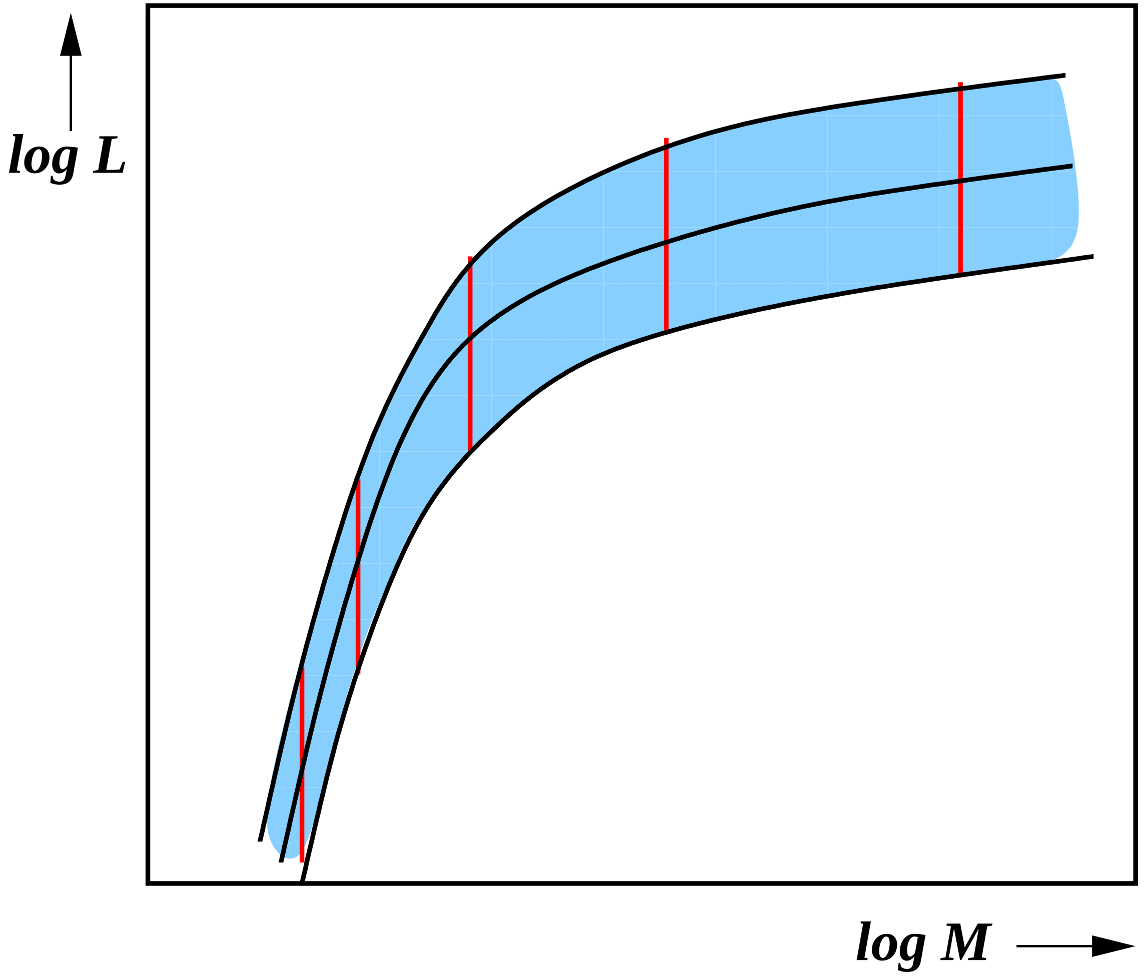


and with the SAM predictions of Croton et al. (2006)

Implications for Galaxy Formation Stochasticity



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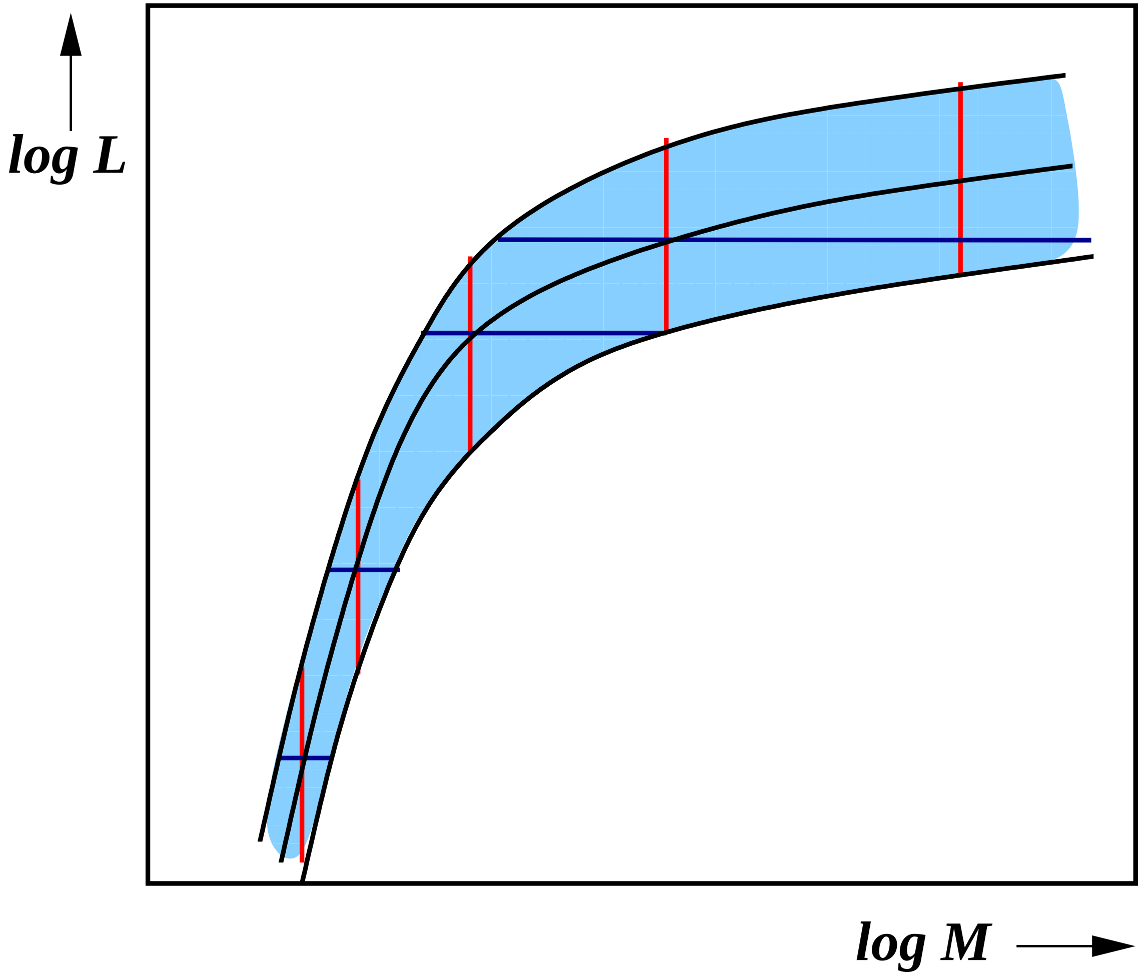

- The scatter in $P(L_{\rm cen}|M)$ is independent of M
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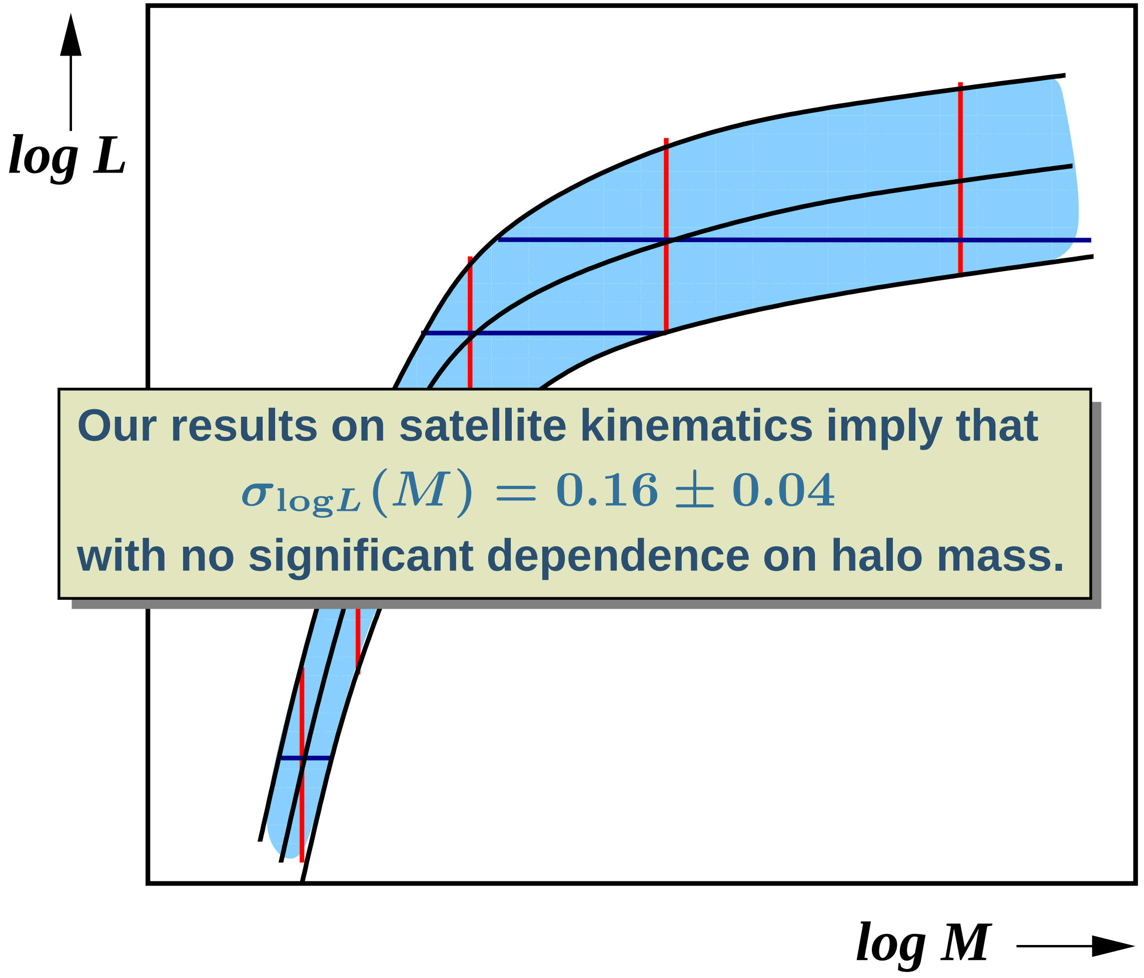
Implications for Galaxy Formation Stochasticity



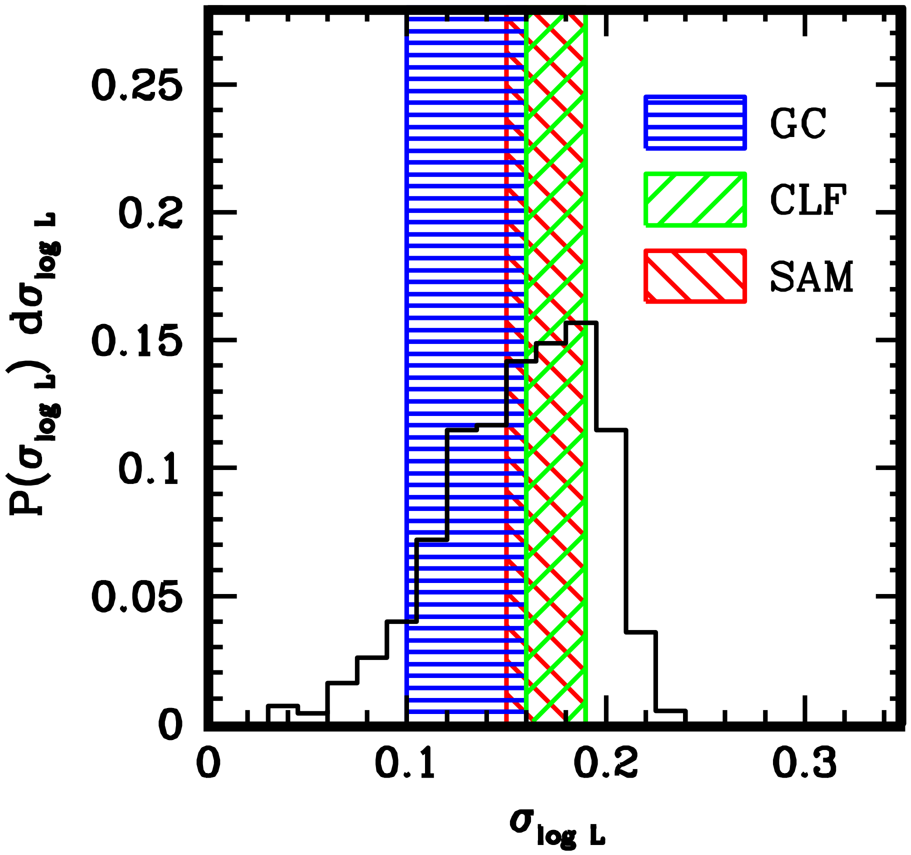
Our results on satellite kinematics imply that

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

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 $L_{\rm cen}$**

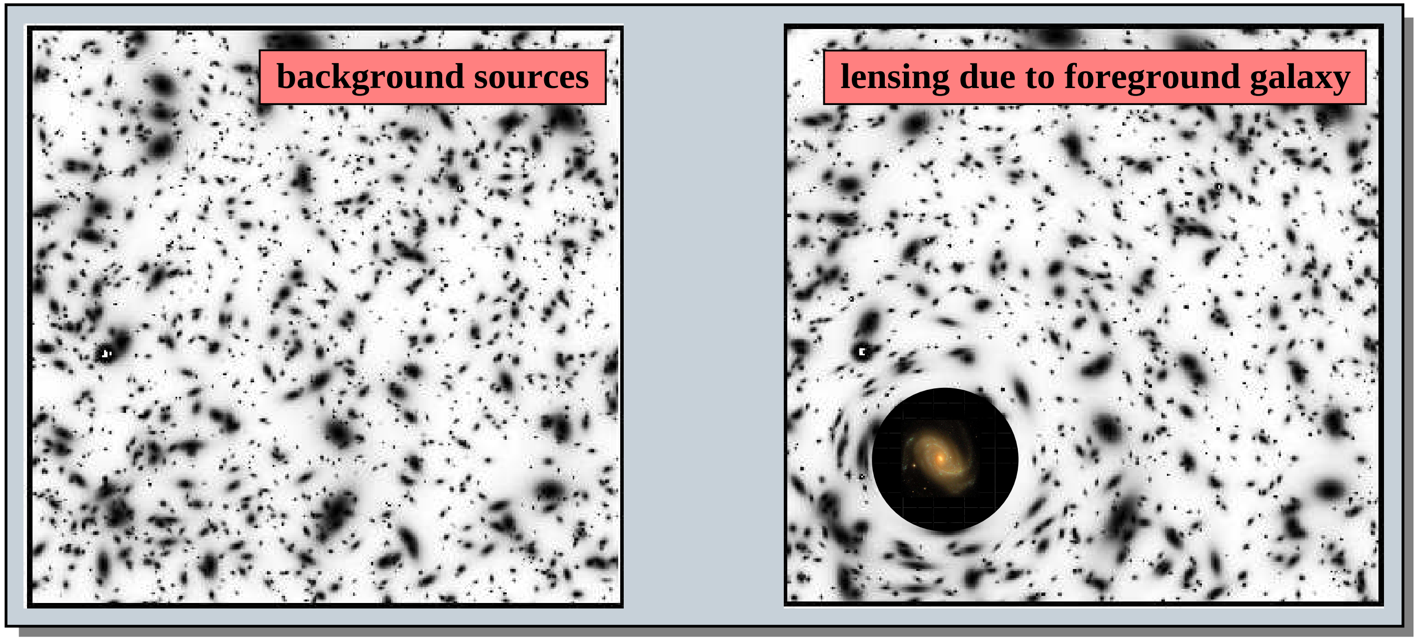
Comparison with other Constraints



- **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)**

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

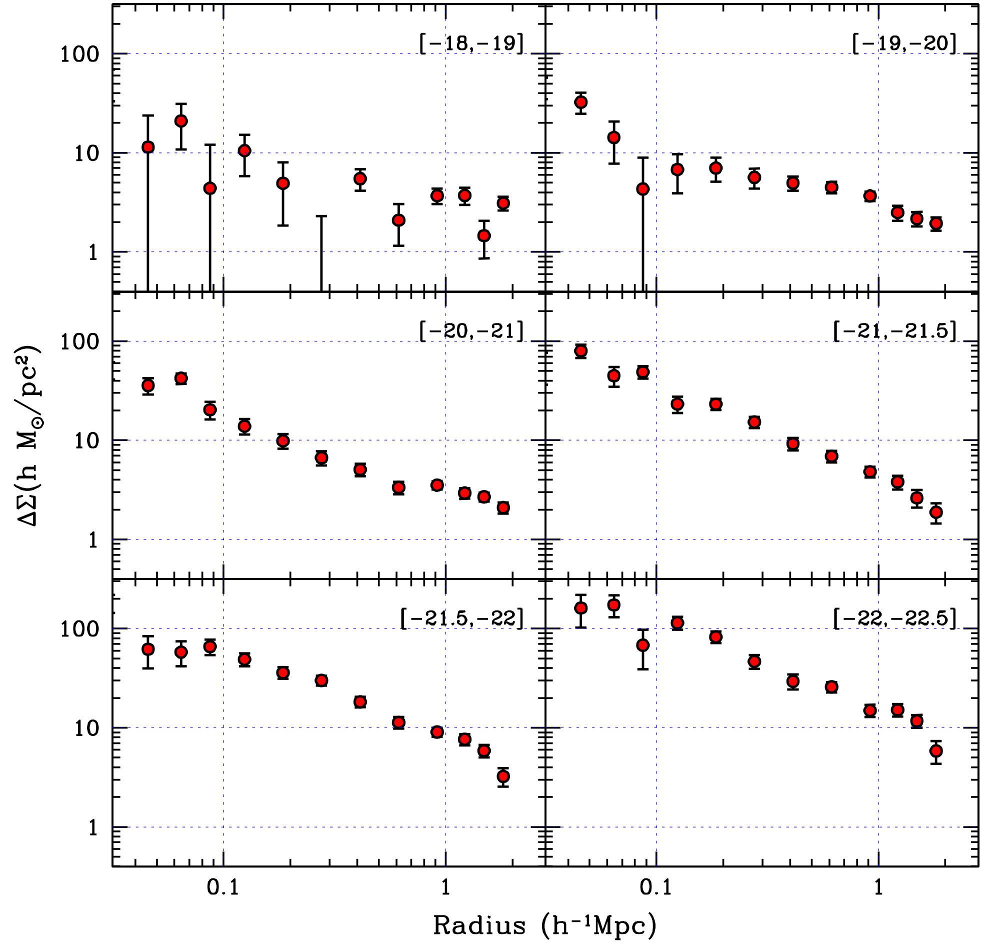
$$\boxed{\gamma_t(R)\Sigma_{\rm crit} = \Delta\Sigma(R) = \bar{\Sigma}(< R) - \Sigma(R)}$$

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

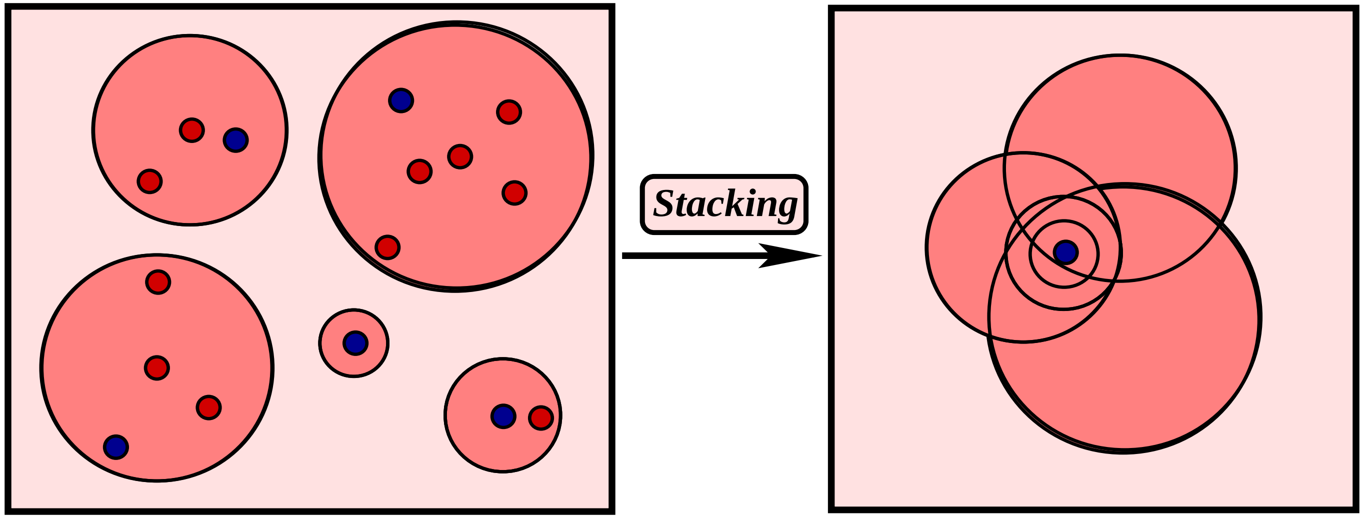
$$\boxed{\Sigma(R) = \bar{\rho} \int_0^{D_S} [1 + \xi_{\rm g,dm}(r)] \, d\chi}$$

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?



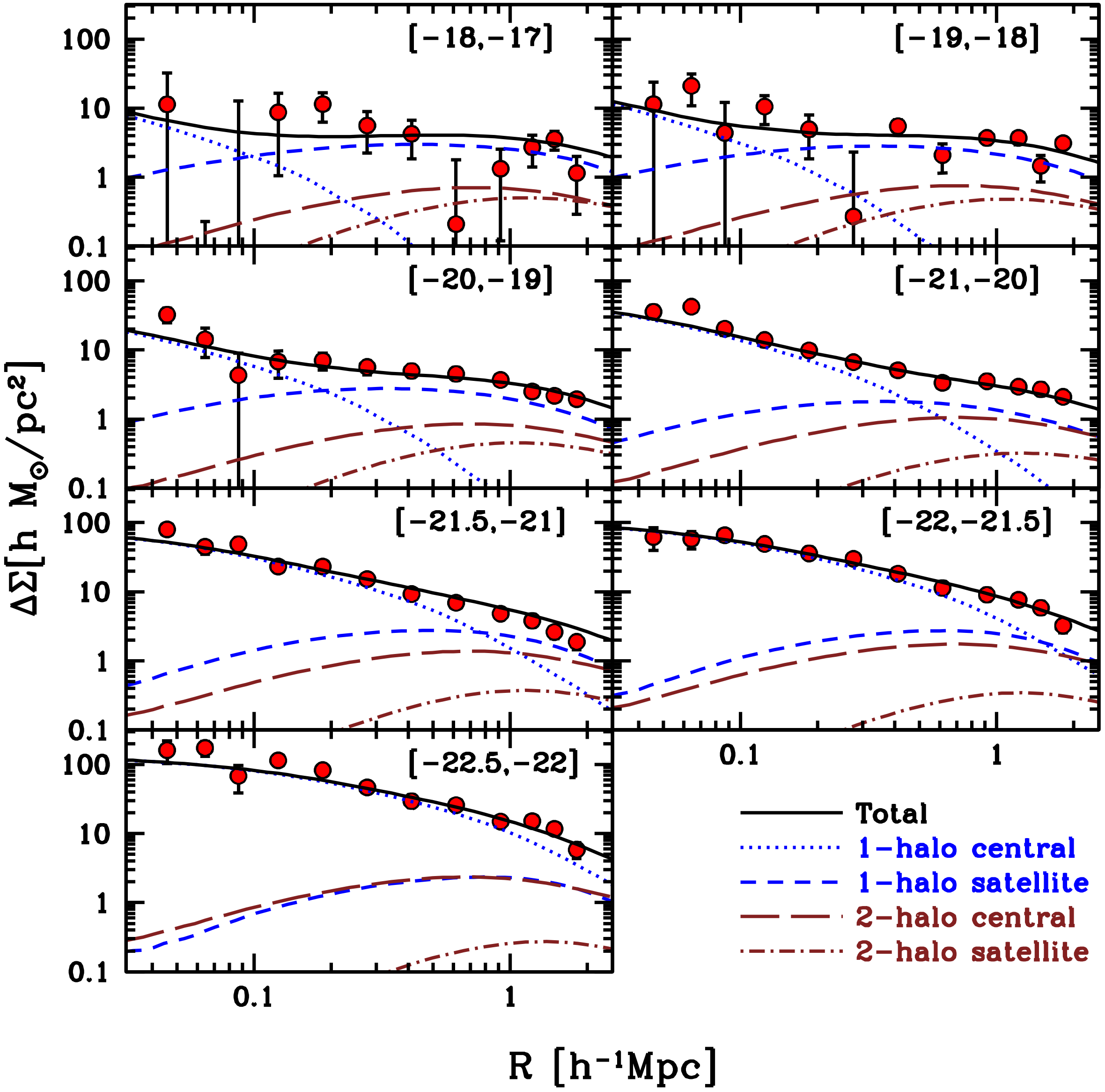
Because of stacking the lensing signal is difficult to interpret

$$\Delta\Sigma(R|L) = [1 - f_{\rm sat}(L)]\Delta\Sigma_{\rm cen}(R|L) + f_{\rm sat}(L)\Delta\Sigma_{\rm sat}(R|L)$$
$$\Delta\Sigma_{\rm cen}(R|L) = \int P_{\rm cen}(M|L)\ \Delta\Sigma_{\rm cen}(R|M){\rm d}M$$
$$\Delta\Sigma_{\rm sat}(R|L) = \int P_{\rm sat}(M|L)\ \Delta\Sigma_{\rm sat}(R|M){\rm d}M$$

$P_{\rm cen}(M|L)$ **and** $P_{\rm sat}(M|L)$ **can be computed from** $\Phi_{\rm cen}(L|M)$ **and** $\Phi_{\rm sat}(L|M)$ **and so can** $f_{\rm sat}(L)$

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

Introduction

Clustering

Conditional Luminosity Function

Satellite Kinematics

Galaxy-Galaxy Lensing
- Galaxy-Galaxy Lensing
- The Measurements
- How to interpret the signal?
- Comparison with CLF Predictions
- Cosmological Constraints

Conclusions

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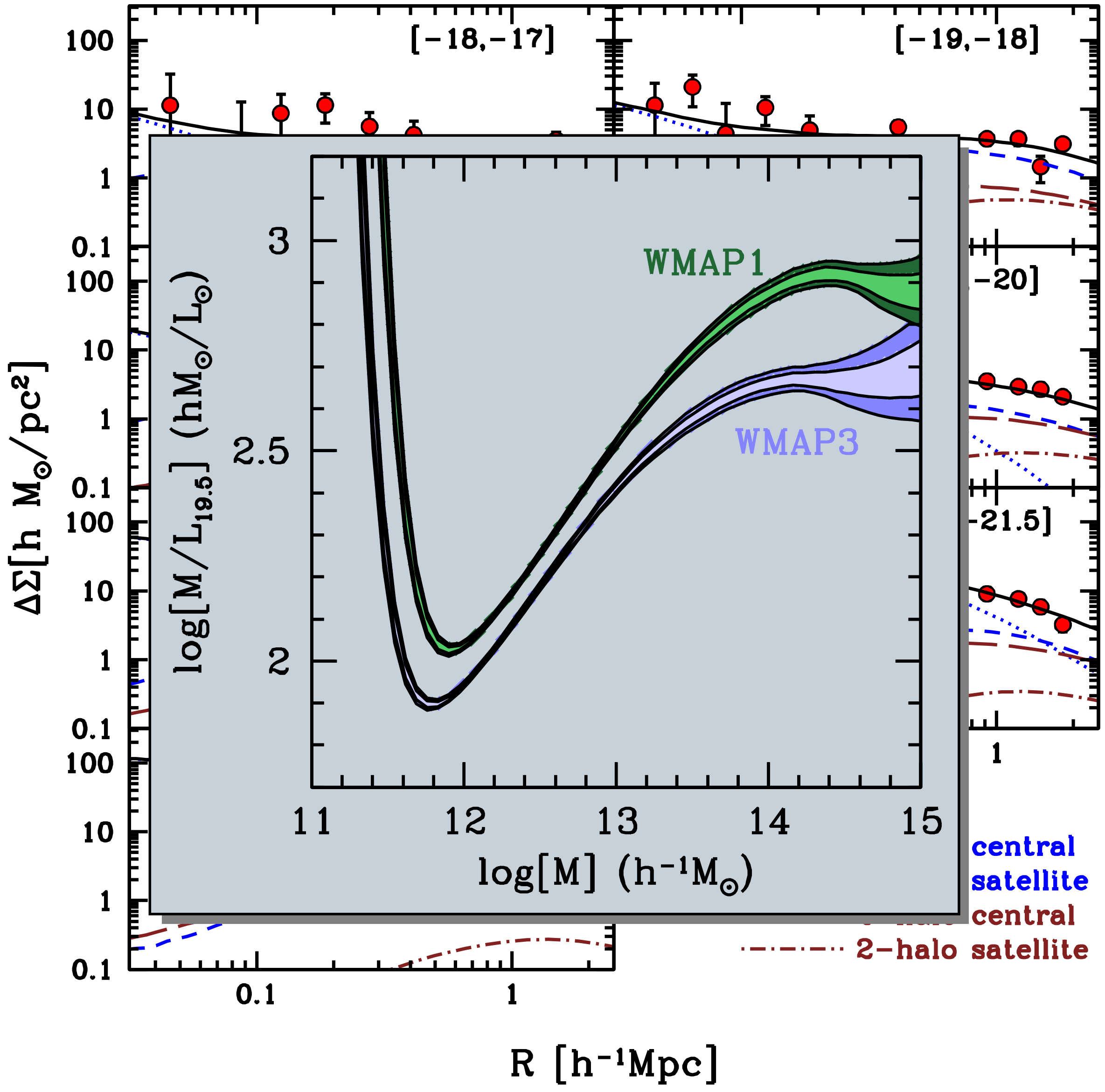

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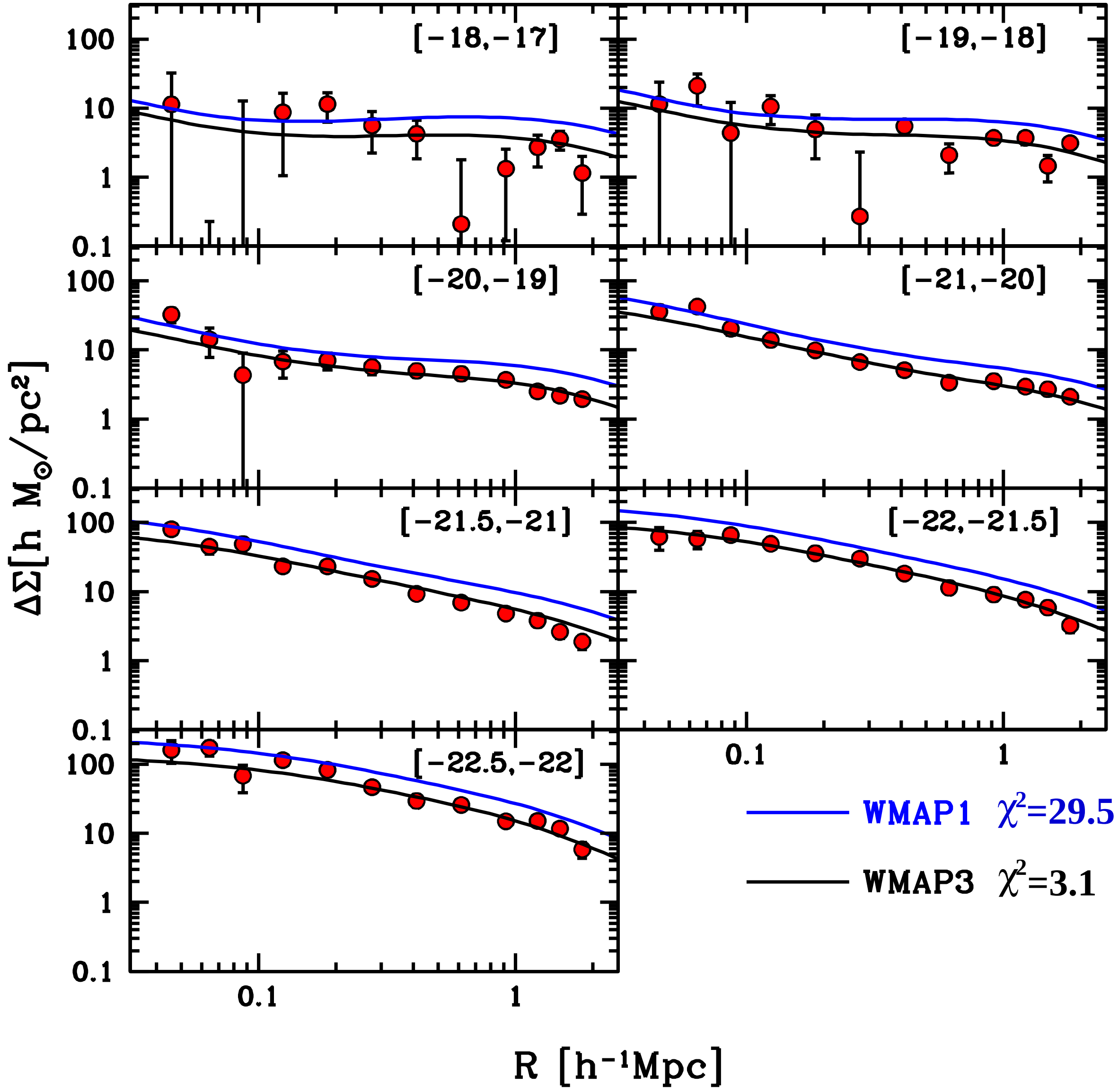
Cosmological Constraints



WMAP3 cosmology clearly preferred over WMAP1 cosmology

Conclusions

Three methods to statistically constrain $P(M|L)$

Clustering | **Satellite Kinematics** | **Galaxy-Galaxy Lensing**

- **Straightforward to constrain $P(M|L)$ with CLF**
- **Accurate constraints from large galaxy redshift surveys**
- **Results are strongly cosmology-dependent**

Conclusions

Three methods to statistically constrain $P(M|L)$

Clustering | **Satellite Kinematics** | **Galaxy-Galaxy Lensing**

- Requires selection of **centrals** and **satellites** from redshift surveys
- Requires **stacking** and is therefore sensitive to **scatter** in $P(M|L)$
- Using **satellite weighting** and **host weighting** simultaneously constrains both mean and scatter of $P(M|L)$
- Scatter in $P(M|L)$ increases strongly with increasing L
- Scatter in $P(L|M)$ is independent of halo mass with $\sigma_{\log L} = 0.16 \pm 0.04$
- **Stochasticity** in galaxy formation well constrained and consistent with model predictions
- Even with large redshift surveys such as SDSS, statistics are limited
- Data not sufficient to discriminate between **WMAP1** and **WMAP3**

Conclusions

Three methods to statistically constrain $P(M|L)$

Clustering | **Satellite Kinematics** | **Galaxy-Galaxy Lensing**

- **Lensing probes masses directly**
- **Requires stacking and is therefore sensitive to scatter in $P(M|L)$**
- **Very sensitive to satellite fractions $f_{\rm sat}(L)$**
- **Most easily interpreted with use of CLF $\Phi(L|M)$**
- **Combination of lensing and clustering holds potential to tightly constrain cosmological parameters**
- **This method is complementary to cosmological constraints from galaxy power spectrum, which only probes linear scales**
- **Current data strongly favors WMAP3 over WMAP1 cosmology**