The Galaxy–Dark Matter Connection

constraining cosmology & galaxy formation

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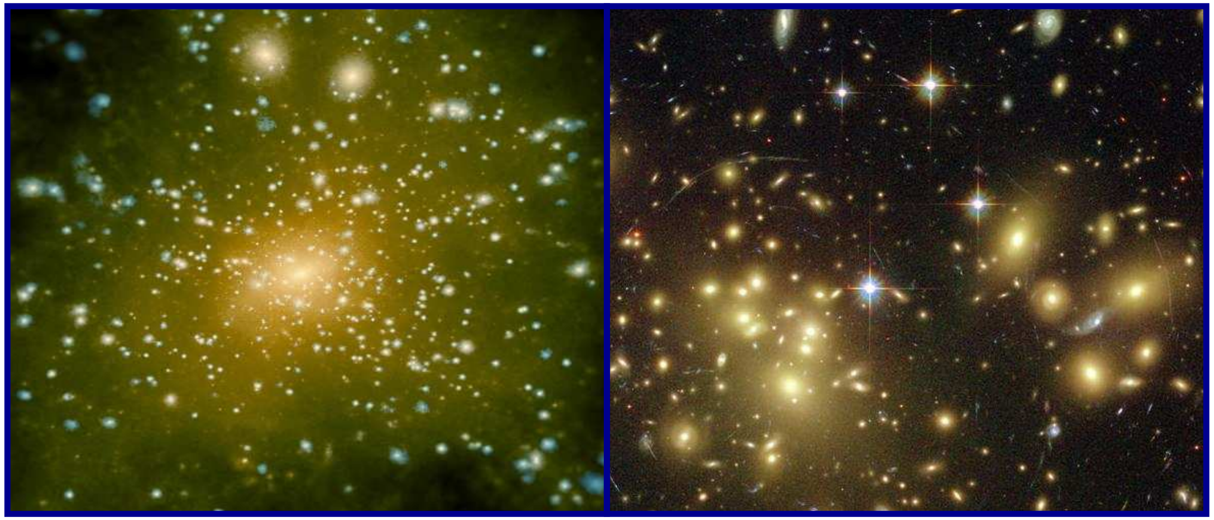
Outline, Motivation & Techniques

Why study the Galaxy-Dark Matter Connection?

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



Four Methods to Constrain Galaxy-Dark Matter Connection

- Group Catalogues
- Satellite Kinematics
- 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 $\Phi(L)$:

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

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 CLF using four different, independent techniques

Galaxy Group Catalogues **Large Scale Structure**

Satellite Kinematics **Galaxy-Galaxy Lensing**

The CLF Model

We split CLF in central and satellite components

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

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

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

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

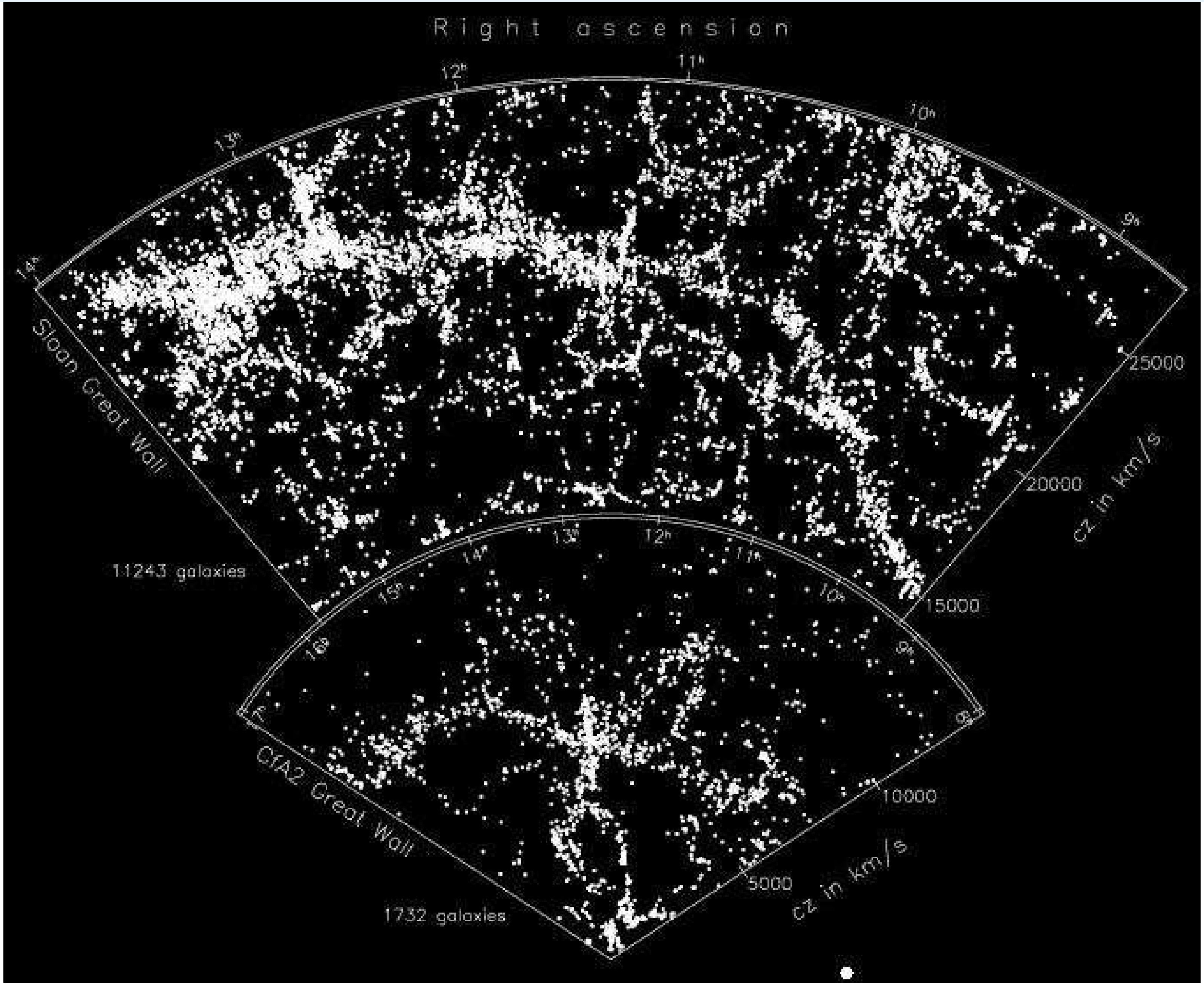
$$\boxed{\Phi_{\mathrm{s}}(L|M)\mathrm{d}L = \frac{\Phi_{\mathrm{s}}}{L_{\mathrm{s}}}\left(\frac{L}{L_{\mathrm{s}}}\right)^{\alpha_{\mathrm{s}}}\exp[-(L/L_{\mathrm{s}})^2]\,\mathrm{d}L}$$

Note that L_{c}, L_{s}, σ_{c}, ϕ_{s} and α_{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

Galaxy Groups from Redshift Surveys



Galaxy Groups from Redshift Surveys

Introduction

Conditional Luminosity Function

Galaxy Group Catalogues
- Galaxy Groups from Redshift Surveys
- The CLF from SDSS Group Catalogue

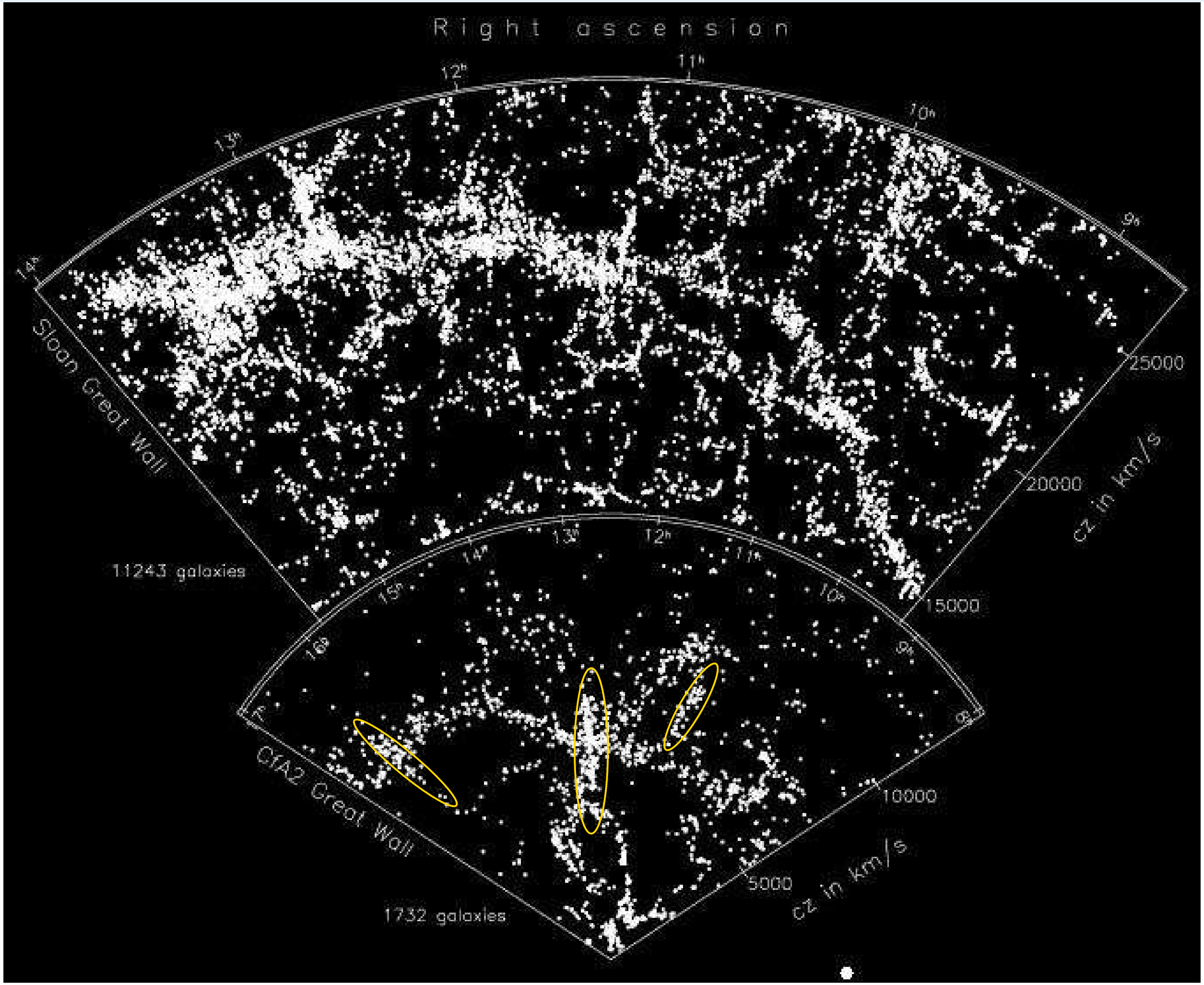
Large Scale Structure

Satellite Kinematics

Galaxy-Galaxy Lensing

Conclusions

Extra Material



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Introduction
Conditional Luminosity Function
Galaxy Group Catalogues
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Large Scale Structure
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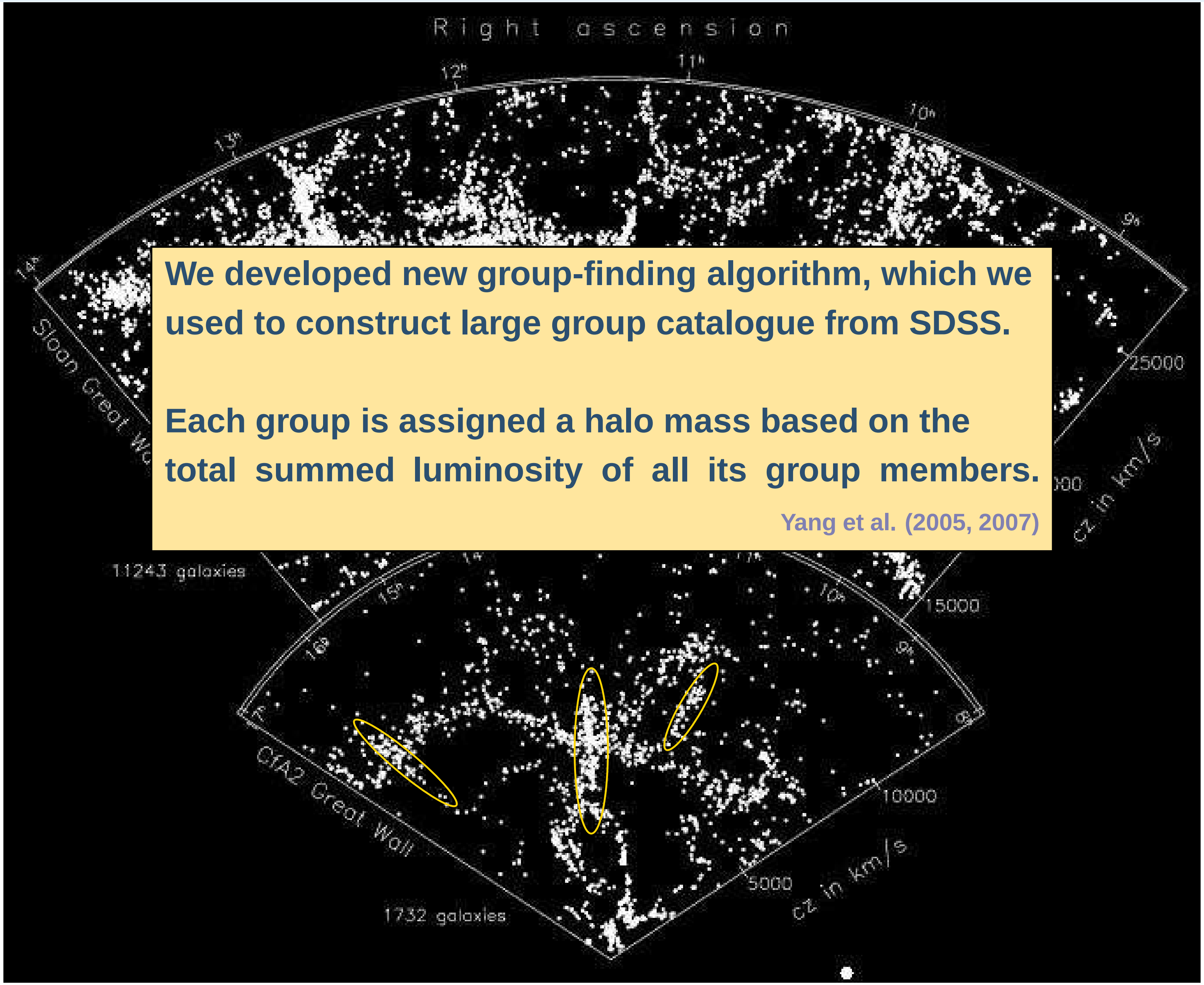
Conclusions
Extra Material



We developed new group-finding algorithm, which we used to construct large group catalogue from SDSS.

Each group is assigned a halo mass based on the total summed luminosity of all its group members.

Yang et al. (2005, 2007)

The CLF from SDSS Group Catalogue

Introduction
Conditional Luminosity Function
Galaxy Group Catalogues
- Galaxy Groups from Redshift Surveys
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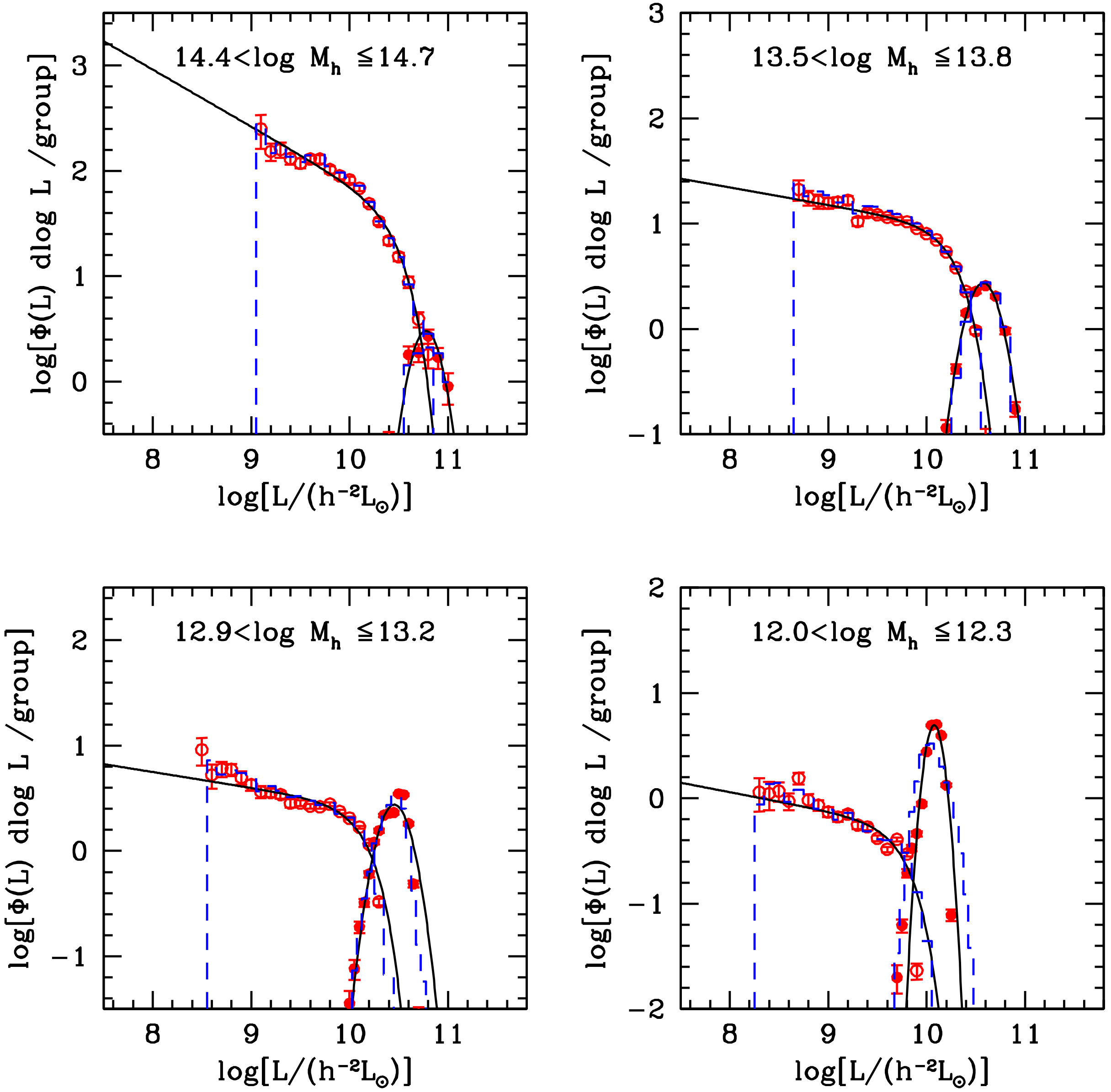
Large Scale Structure
Satellite Kinematics
Galaxy-Galaxy Lensing
Conclusions
Extra Material



Yang, Mo, vdB (2007)

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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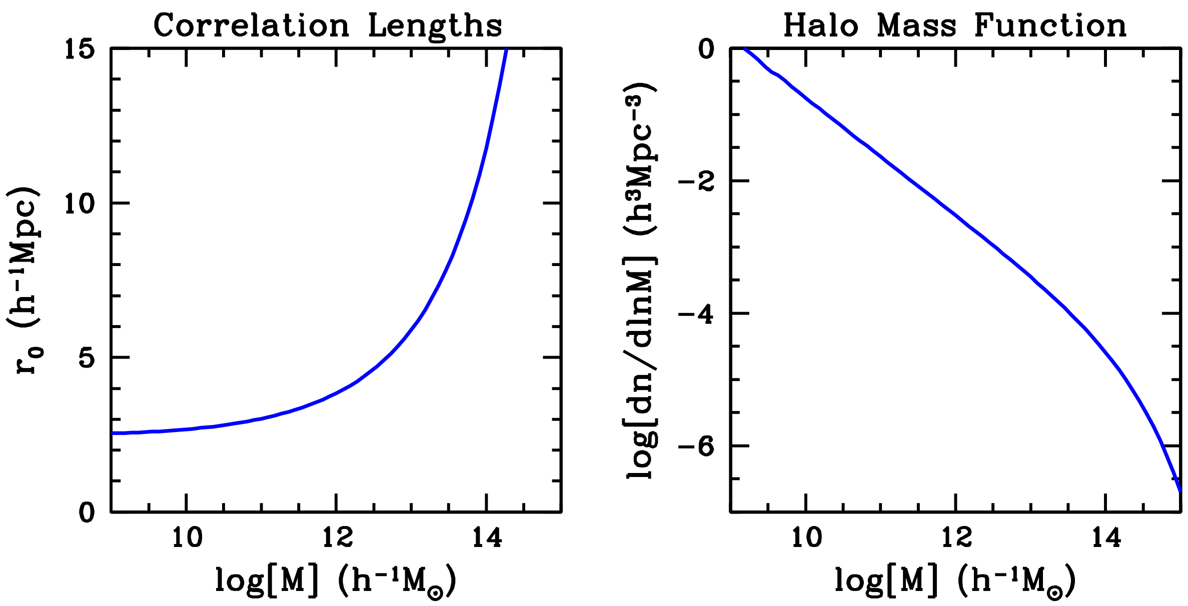

Introduction
Conditional Luminosity Function
Galaxy Group Catalogues
Large Scale Structure
- Occupation Statistics from Clustering
- Luminosity & Correlation Functions
- Results
- Cosmology Dependence

Satellite Kinematics
Galaxy-Galaxy Lensing
Conclusions
Extra Material

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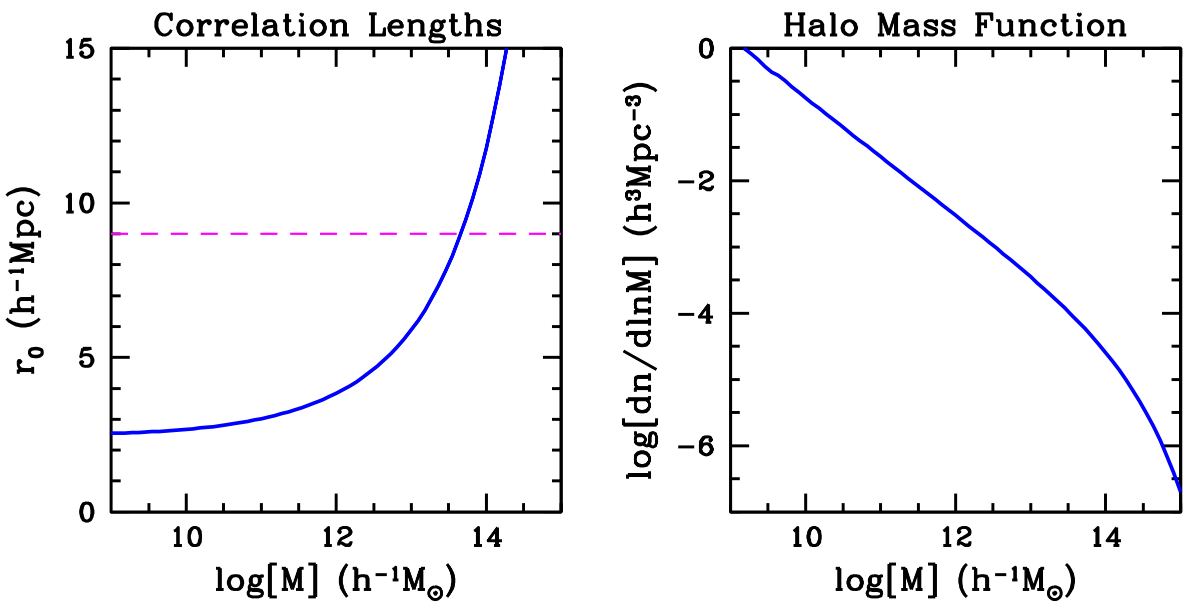

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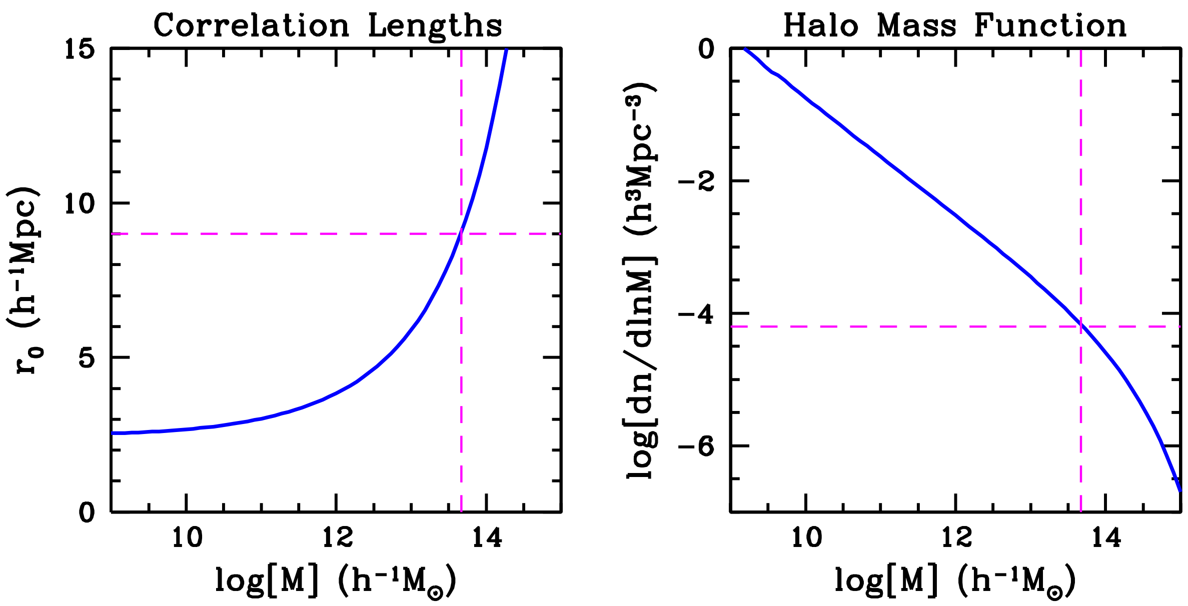

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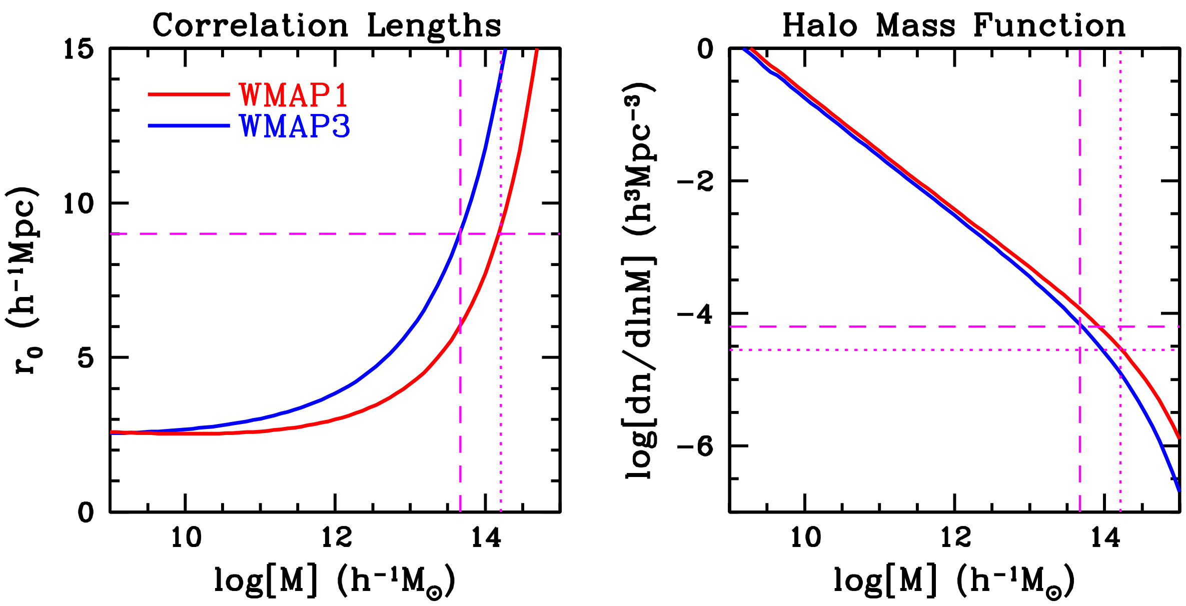


WMAP1

$\Omega_m = 0.30$

$\Omega_\Lambda = 0.70$

$\sigma_8 = 0.90$

WMAP3

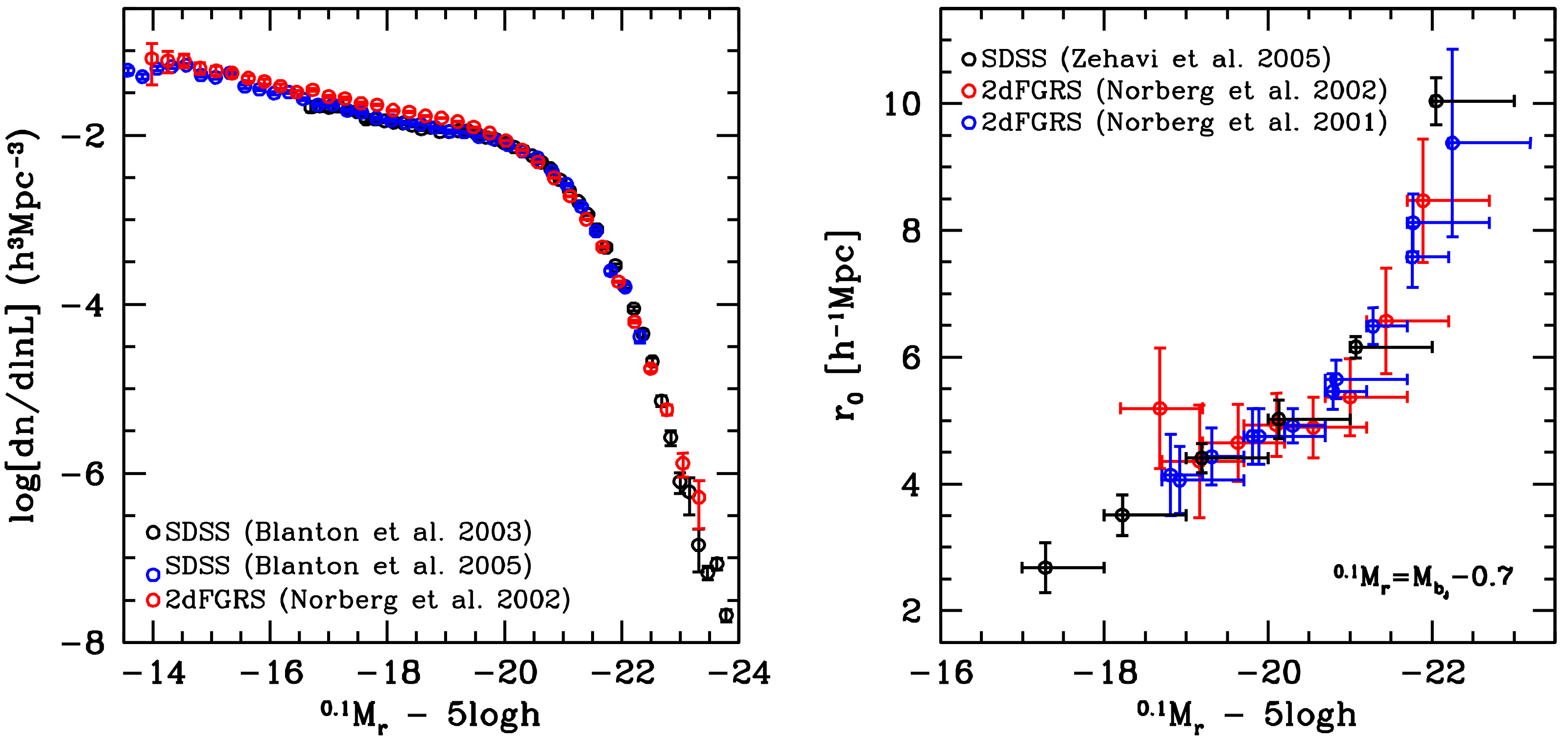
$\Omega_m = 0.24$

$\Omega_\Lambda = 0.76$

$\sigma_8 = 0.74$

CAUTION: Results depend on cosmological parameters

Luminosity & Correlation Functions

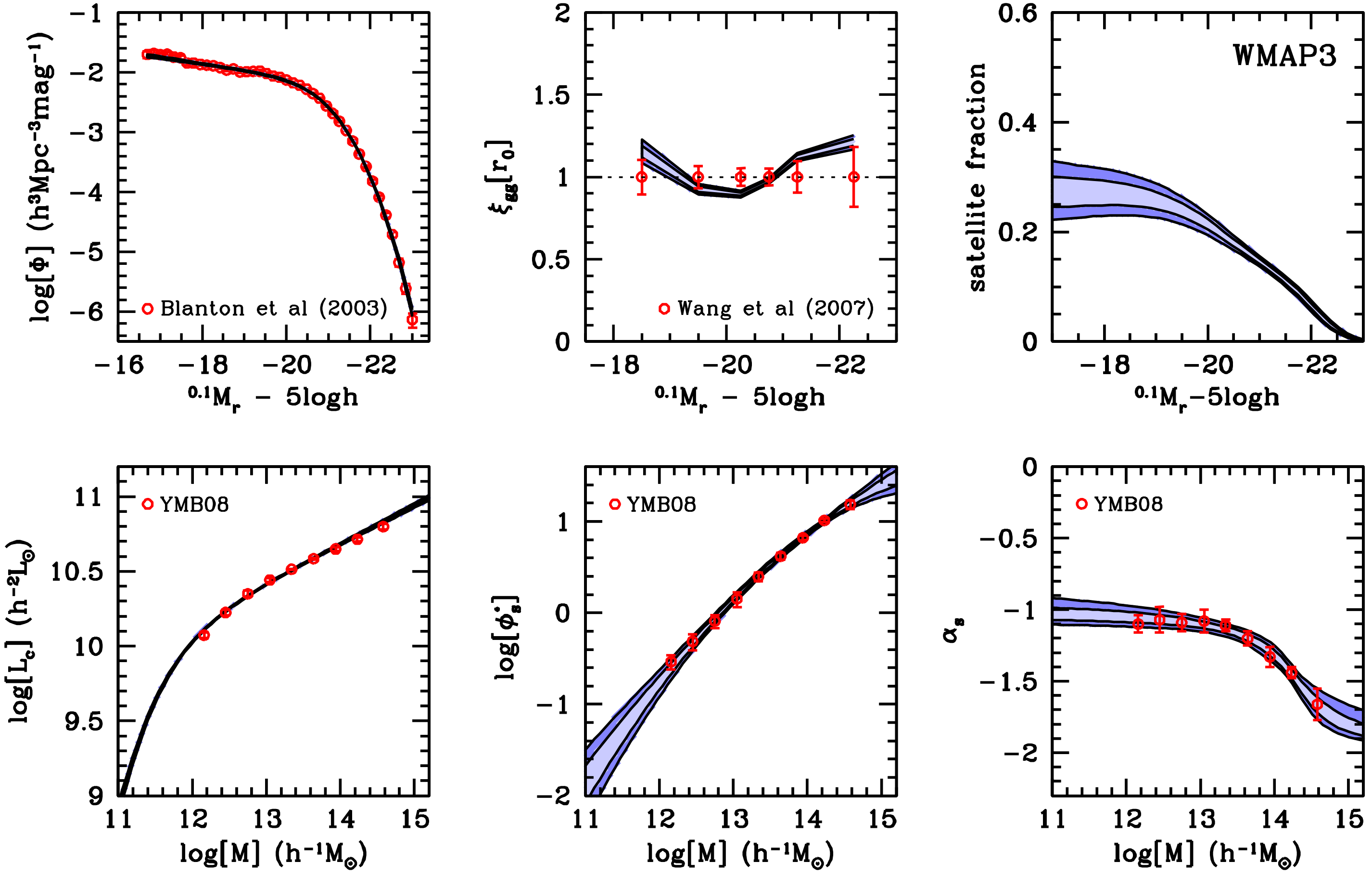


- **DATA:** More luminous galaxies are more strongly clustered.
- **ΛCDM:** More massive haloes are more strongly clustered.

More luminous galaxies reside in more massive haloes

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

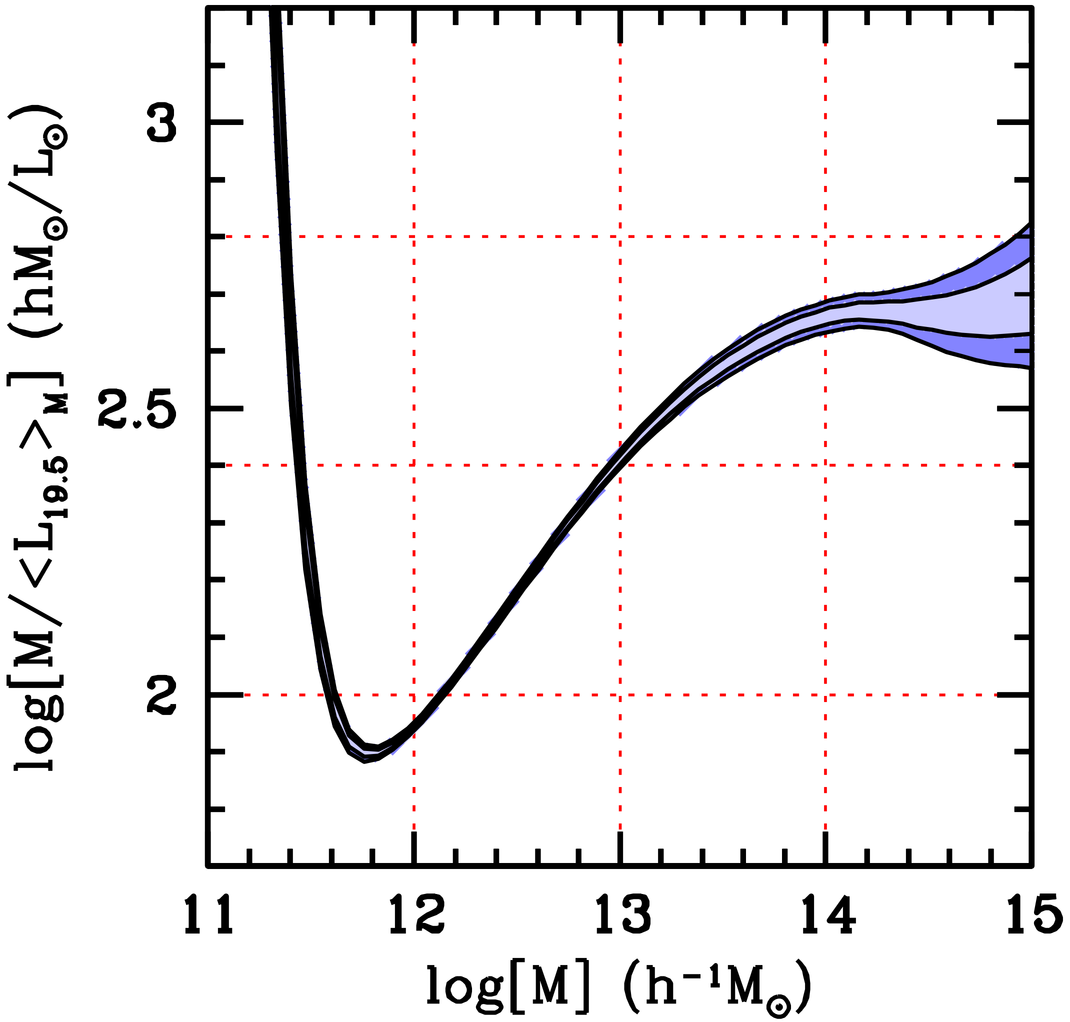
Results



(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



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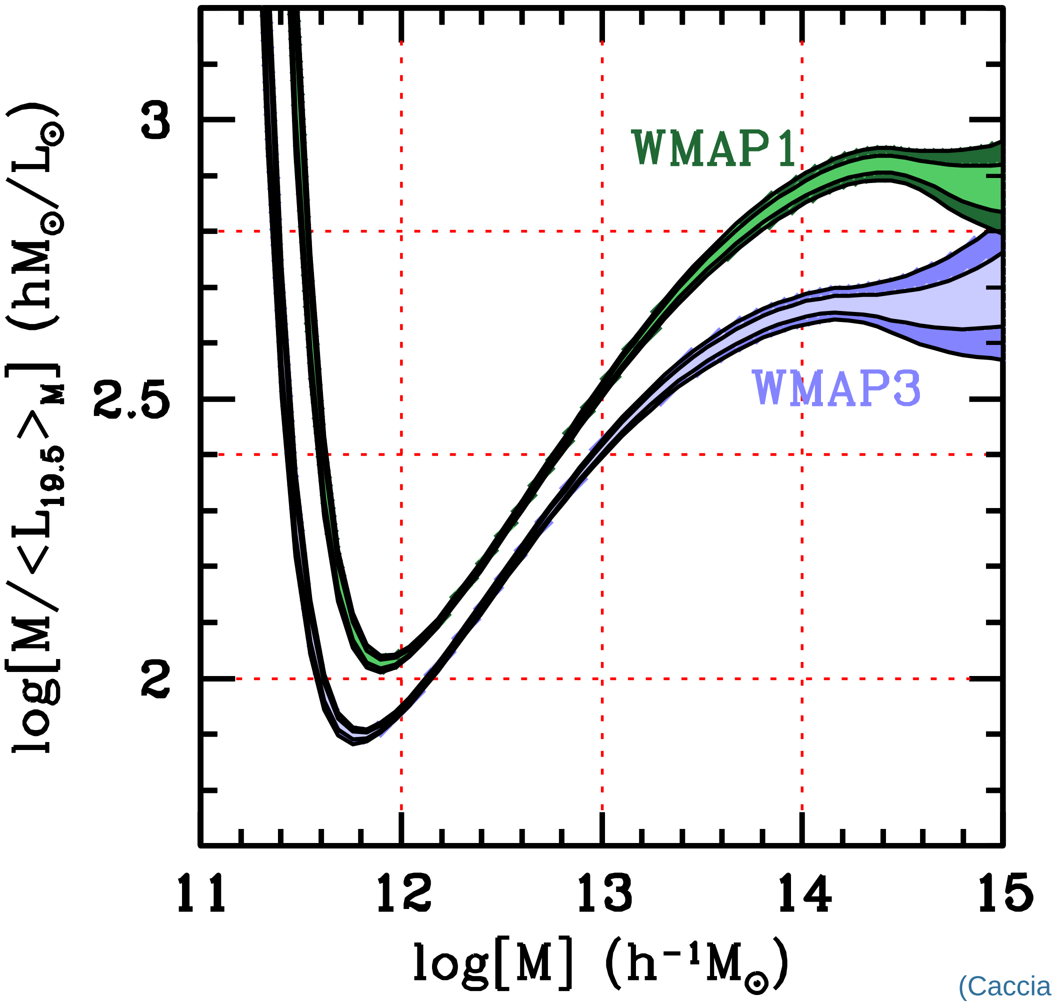


(Cacciato, vdB et al. 2008)

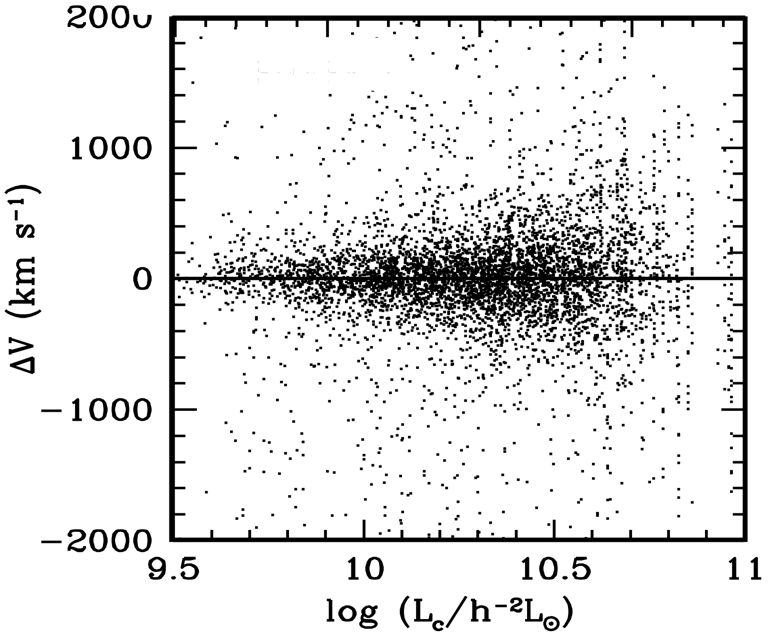
Mass-to-Light ratios tightly constrained, but with strong dependence on cosmology

Satellite Kinematics: Methodology

Introduction
Conditional Luminosity Function
Galaxy Group Catalogues
Large Scale Structure
Satellite Kinematics
● Satellite Kinematics: Methodology
● Satellite Kinematics: Mass Estimates
● Satellite Kinematics in the SDSS
● Modeling Methodology & Results
Galaxy-Galaxy Lensing
Conclusions
Extra Material

Select centrals and their satellites from a redshift survey

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



Satellite Kinematics: Methodology

Introduction

Conditional Luminosity Function

Galaxy Group Catalogues

Large Scale Structure

Satellite Kinematics

- Satellite Kinematics: Methodology
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Galaxy-Galaxy Lensing

Conclusions

Extra Material

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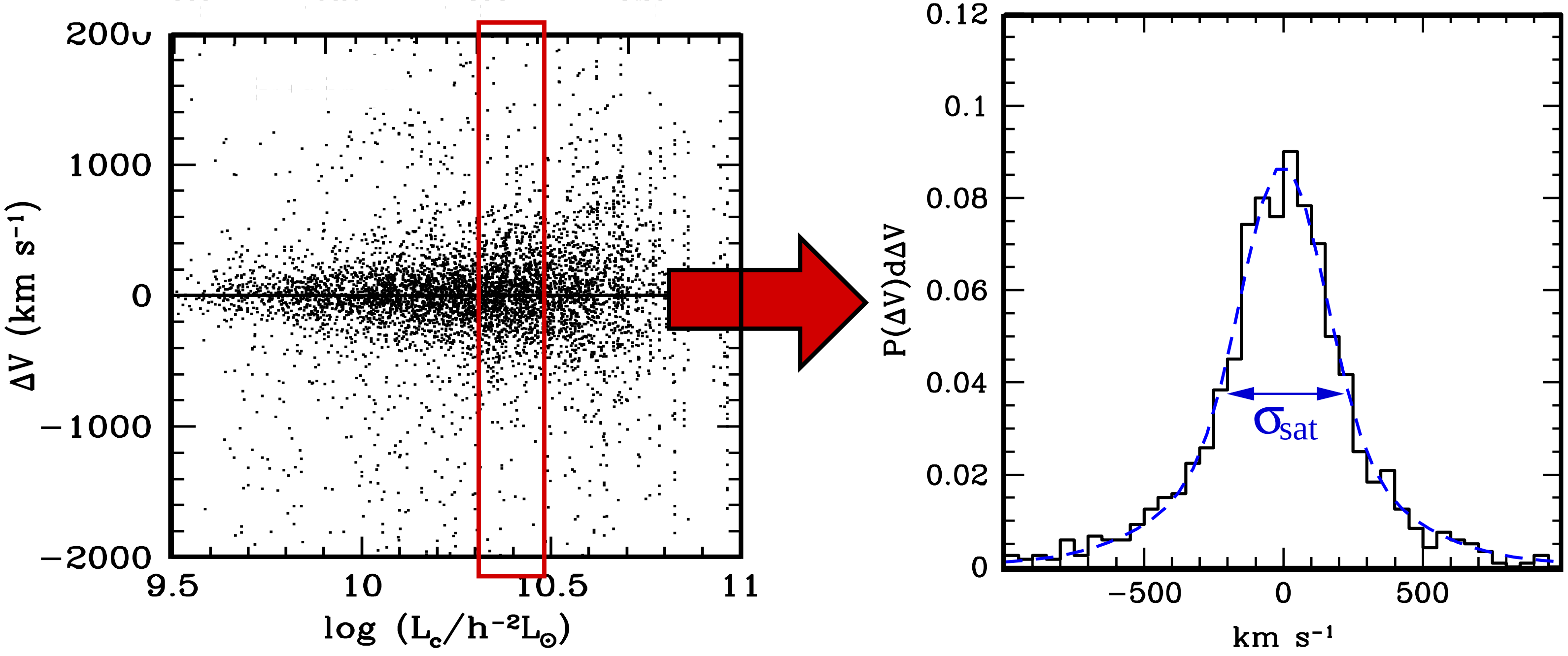
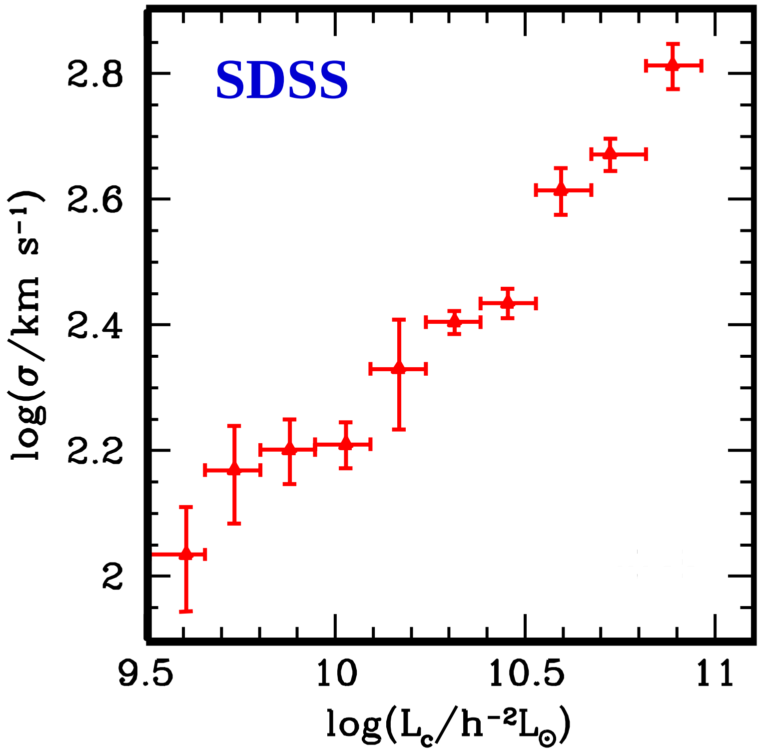


Satellite Kinematics: Methodology

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



(More, vdB et al. 2008)

Brighter centrals reside in more massive haloes.

Satellite Kinematics: Mass Estimates

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

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

Satellite Kinematics: Mass Estimates

Using virial equilibrium and spherical collapse model:

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

On average only ~ 2 satellites per central $\longrightarrow$ 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:

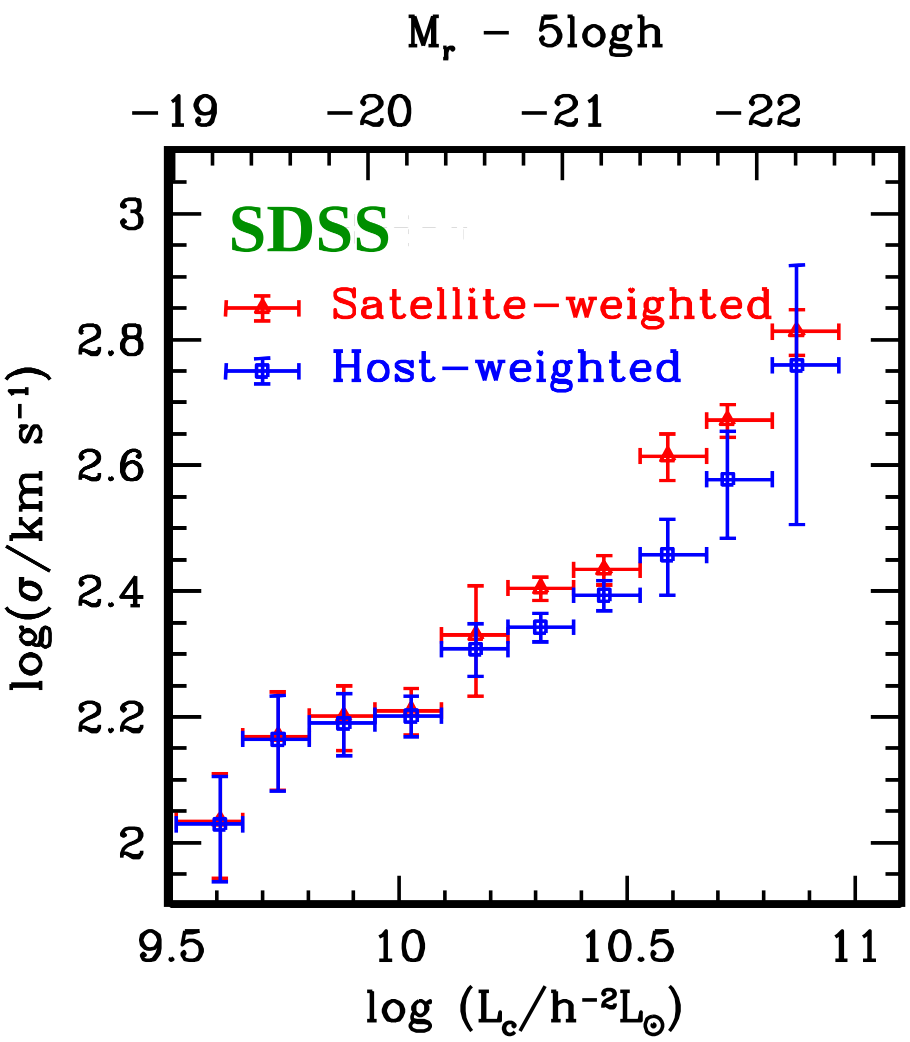
Satellite Weighting: each satellite receives weight of one

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

Host Weighting: each host receives weight of one

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

Satellite Kinematics in the SDSS



Based on SDSS volume-limited sample with

3863 centrals

&

6101 satellites

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

Modeling Methodology & Results

Recall:

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

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

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

Modeling Methodology & Results

Recall:

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

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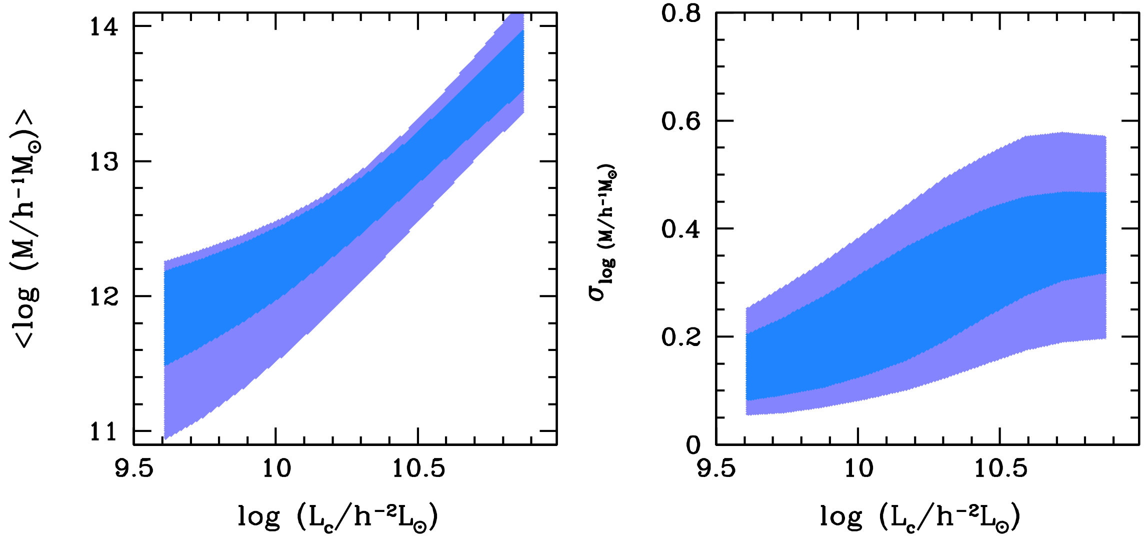

The 68 and 95 percent confidence levels from MCMC

Modeling Methodology & Results

Recall:

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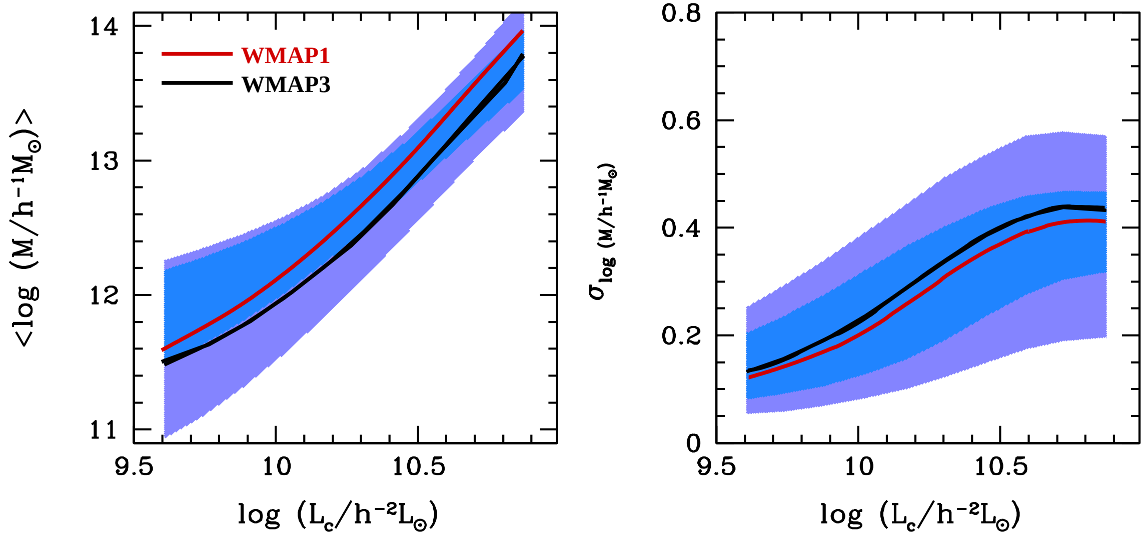
$$\sigma^2_{\rm hw} = \frac{\int P(M|L_{\rm c})\,\sigma^2_{\rm sat}(M)\,{\rm d}M}{\int P(M|L_{\rm c})\,{\rm d}M}$$

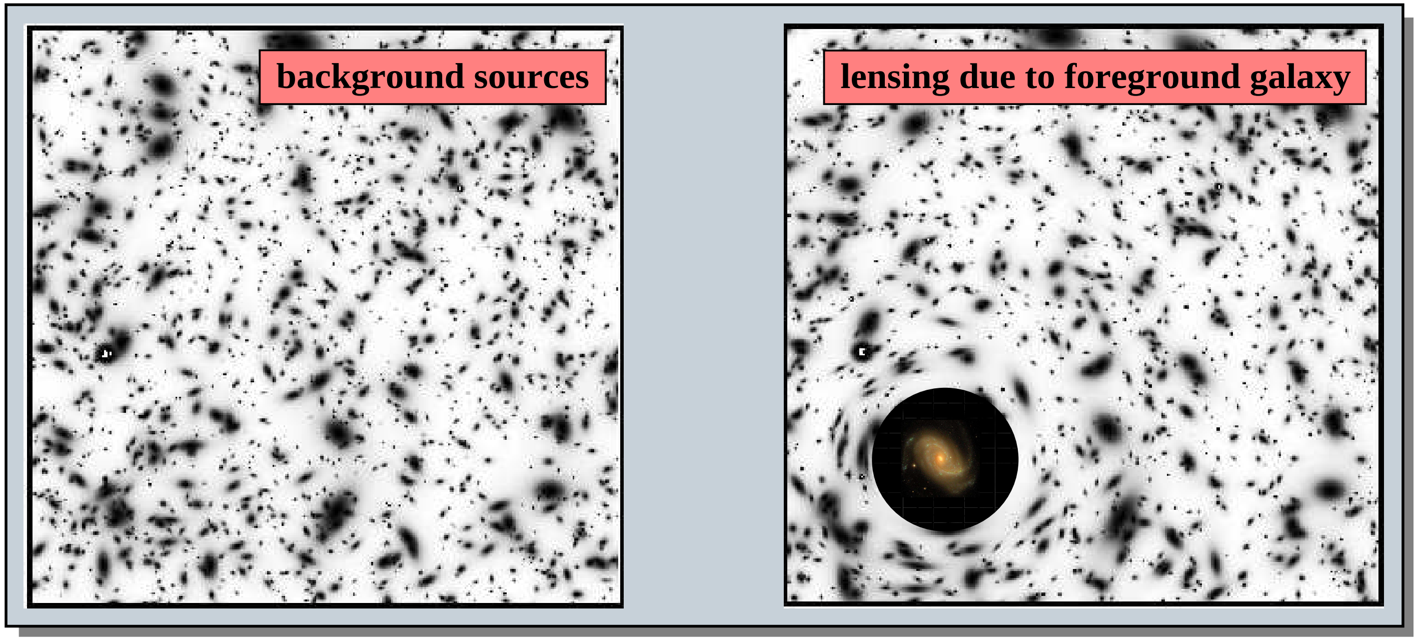
- Jeans equations yield $\sigma^2_{\rm sat}(M)$ for NFW halos
- $P(M|L_{\rm c})$ and $\langle N_{\rm sat}\rangle_M$ follow from CLF
- Constrain CLF model parameters by fitting the observed $\sigma_{\rm sw}(L_{\rm c})$ and $\sigma_{\rm hw}(L_{\rm c})$



Good agreement with CLF clustering results

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

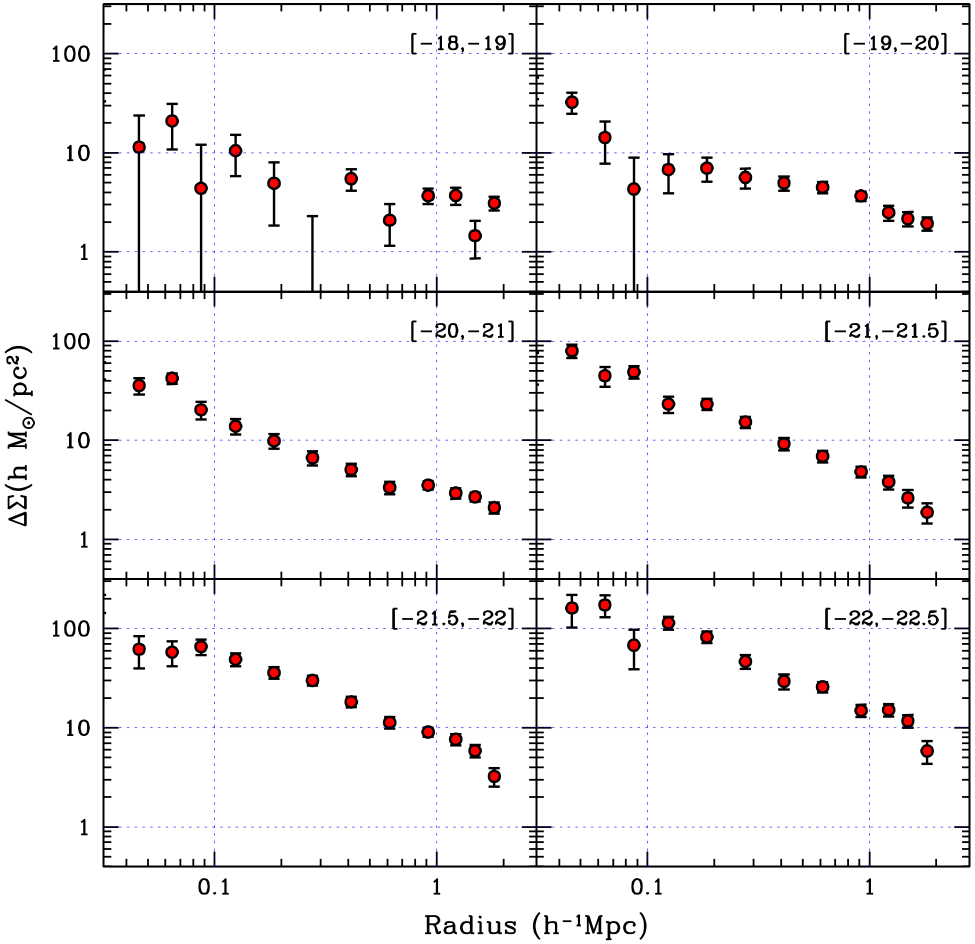
$$\boxed{\gamma_t(R)\Sigma_{\rm crit} = \Delta\Sigma(R) = \bar{\Sigma}(<R) - \Sigma(R)}$$

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

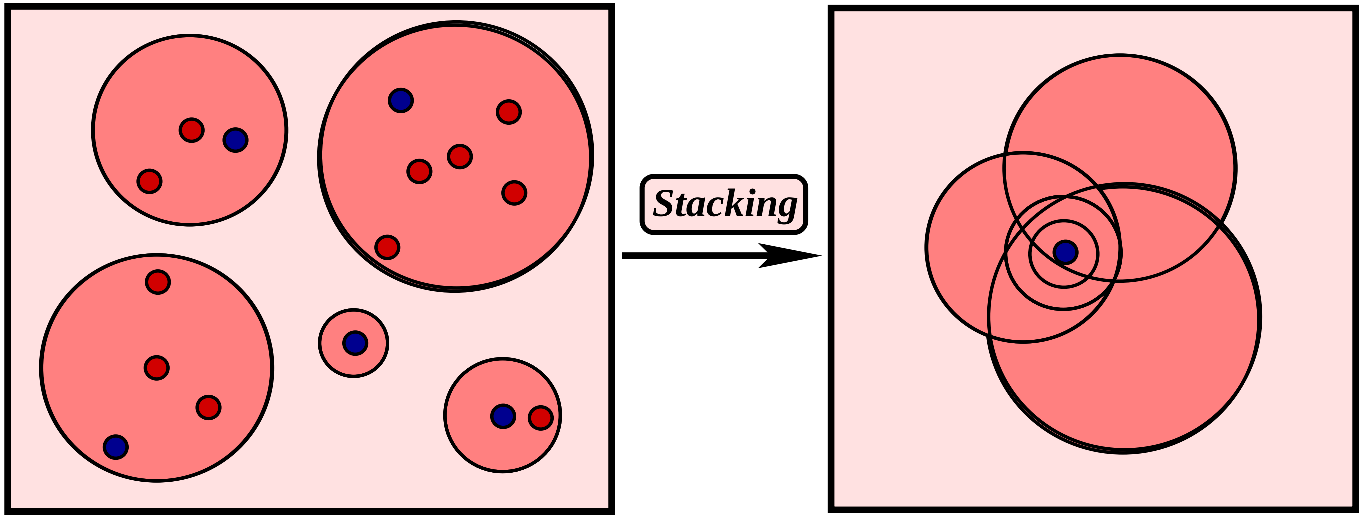
$$\boxed{\Sigma(R) = \bar{\rho}\int_0^{D_S}\left[1+\xi_{\rm g,dm}(r)\right]d\chi}$$

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

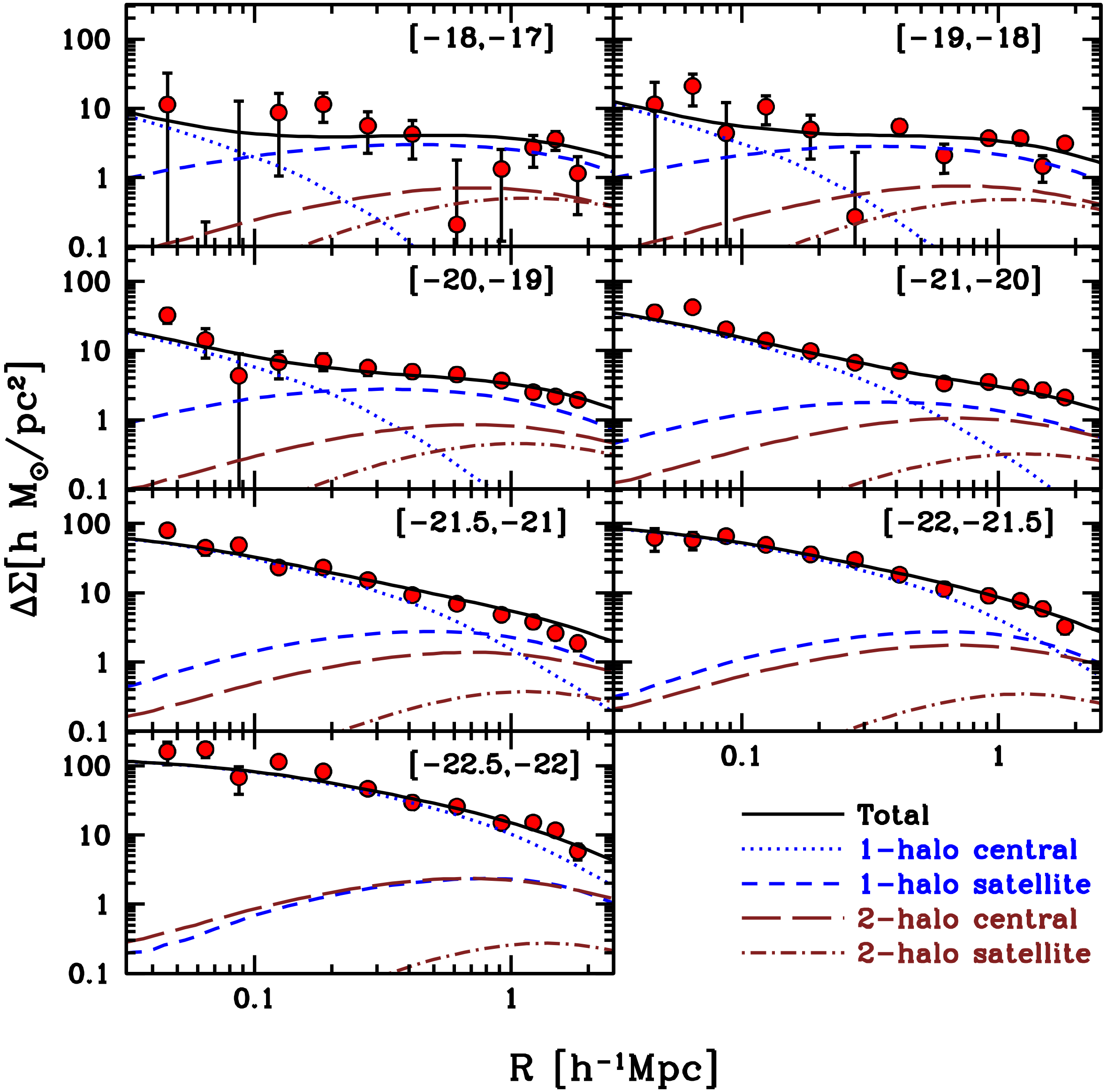
In order to model the data, what is required is:

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

These can all be computed from the CLF

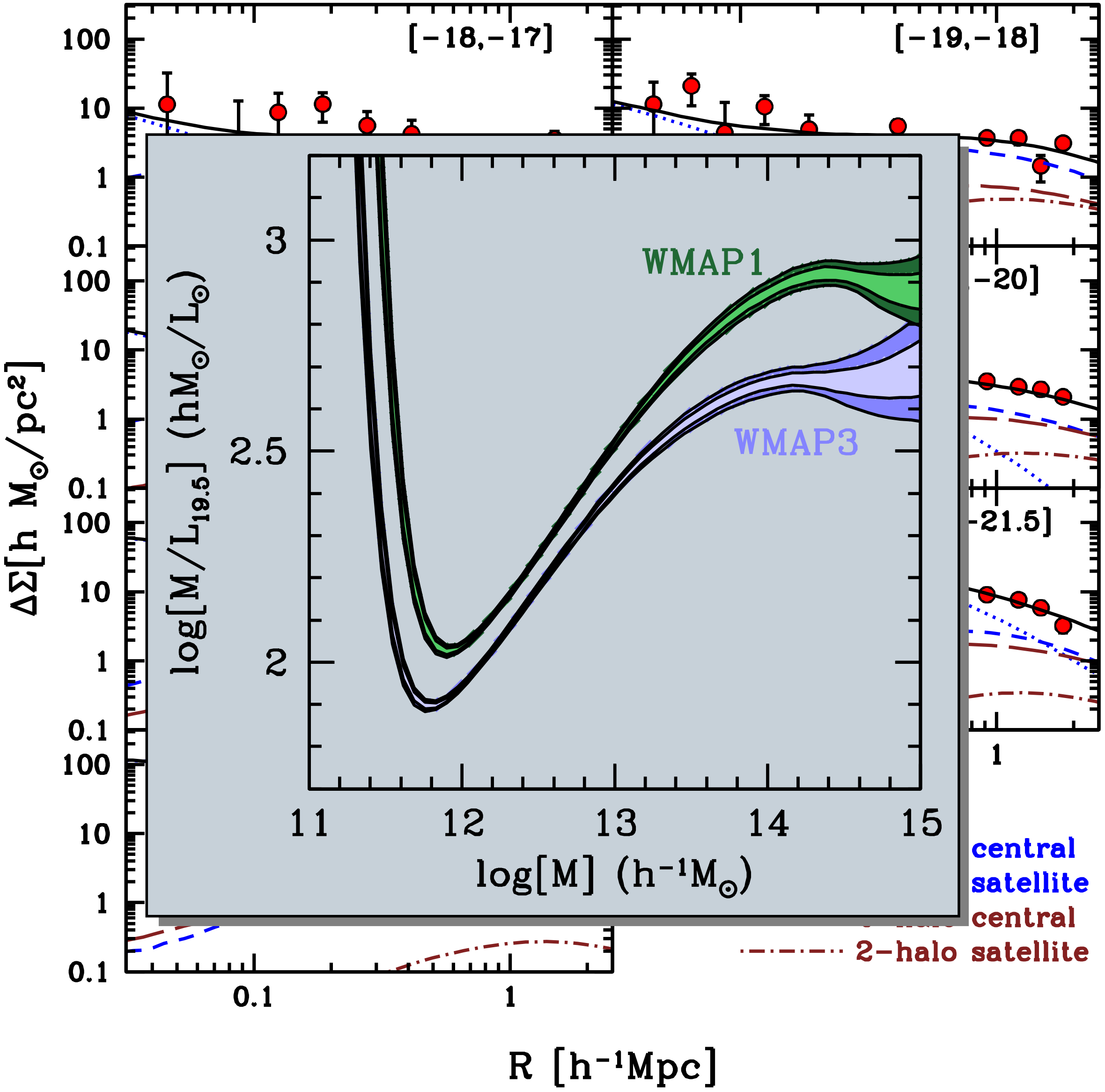
Using $\Phi(L|M)$ constrained from clustering data, we can predict the lensing signal $\Delta\Sigma(R|L_1,L_2)$

Comparison with CLF Predictions



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

Comparison with CLF Predictions



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Introduction

Conditional Luminosity Function

Galaxy Group Catalogues

Large Scale Structure

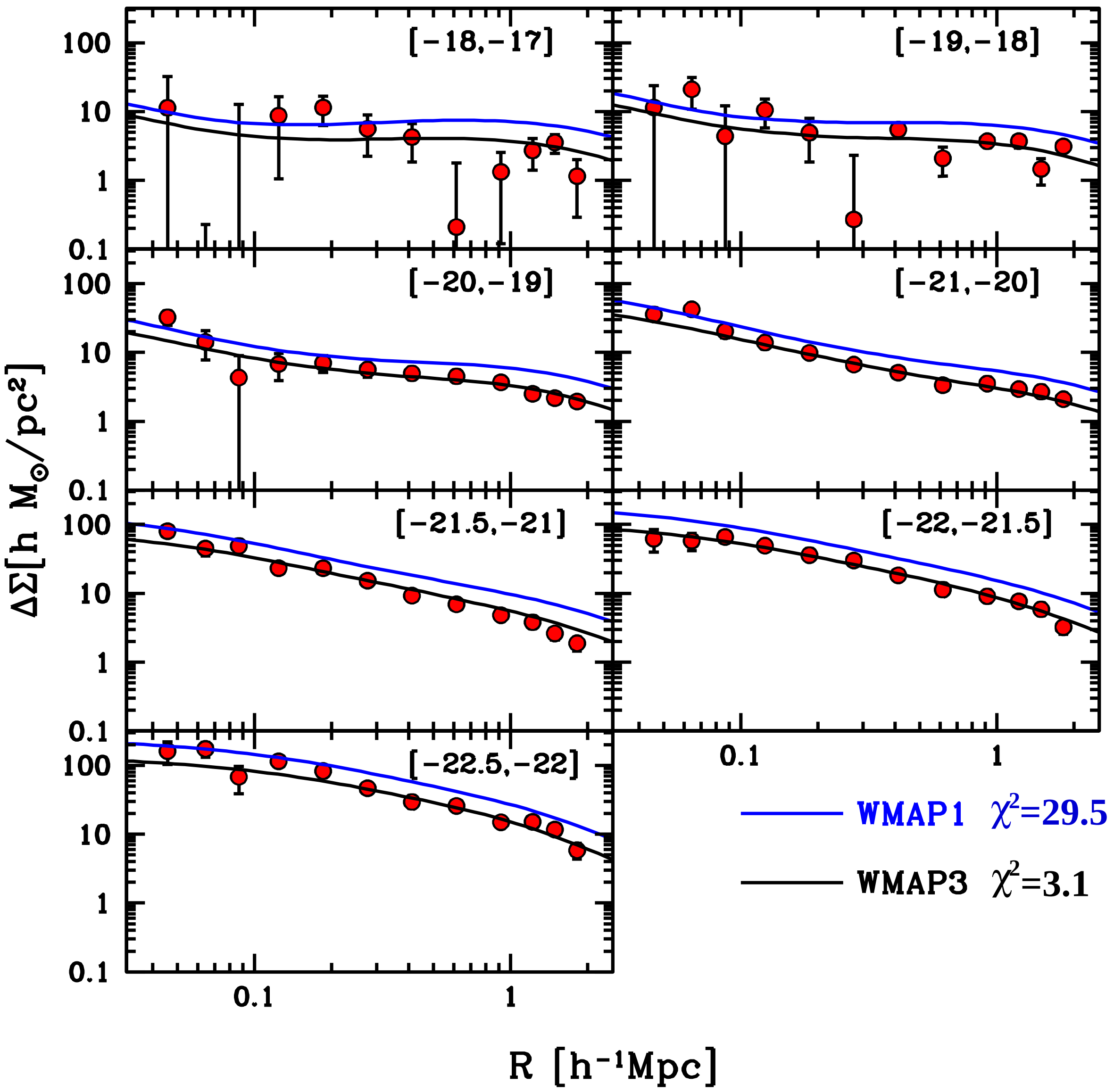
Satellite Kinematics

Galaxy-Galaxy Lensing
- Galaxy-Galaxy Lensing
- The Measurements
- How to interpret the signal?
- Comparison with CLF Predictions
- WMAP3 vs. WMAP1
- Cosmological Constraints

Conclusions

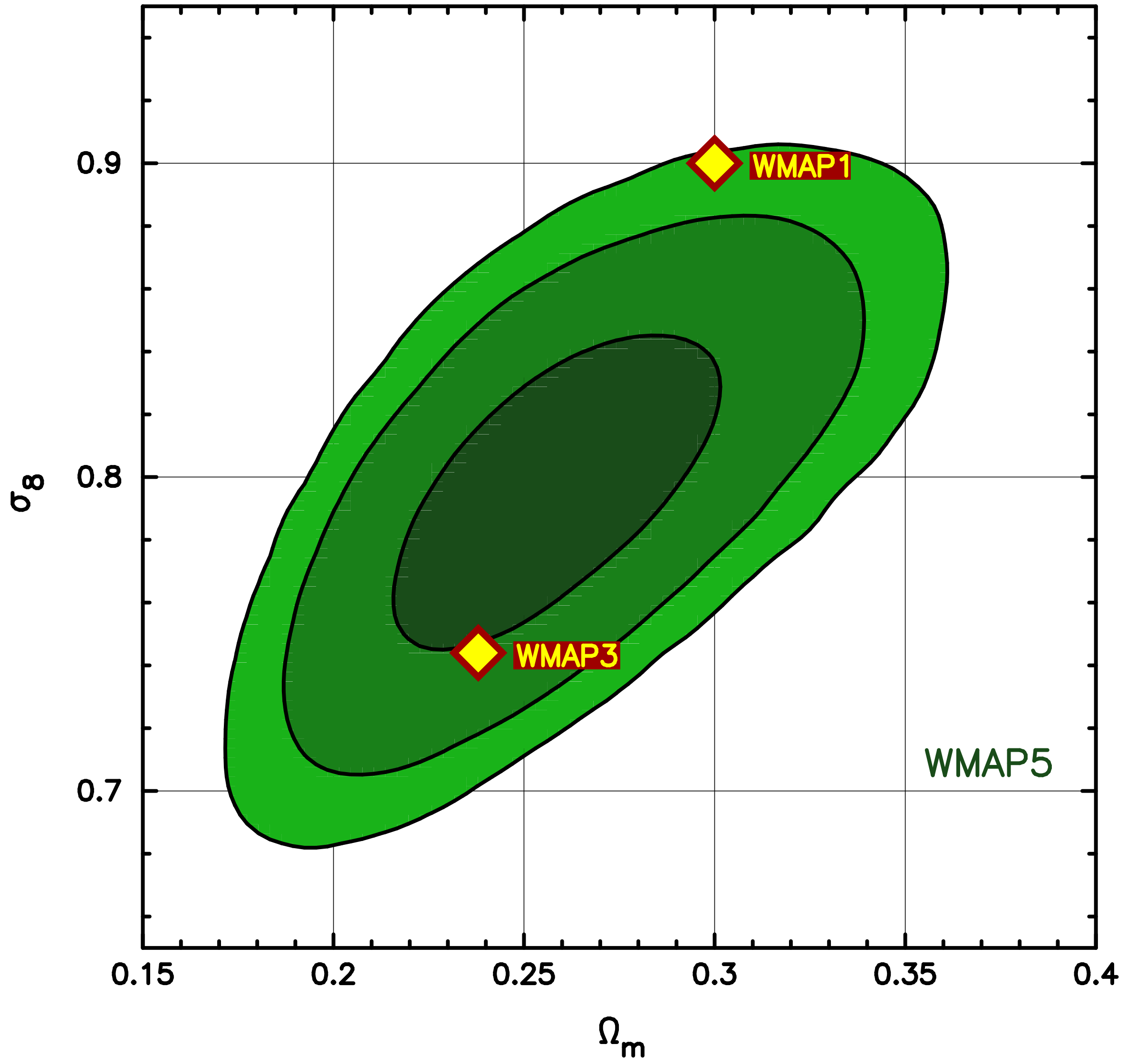
Extra Material

WMAP3 vs. WMAP1



WMAP3 cosmology clearly preferred over WMAP1 cosmology

Cosmological Constraints



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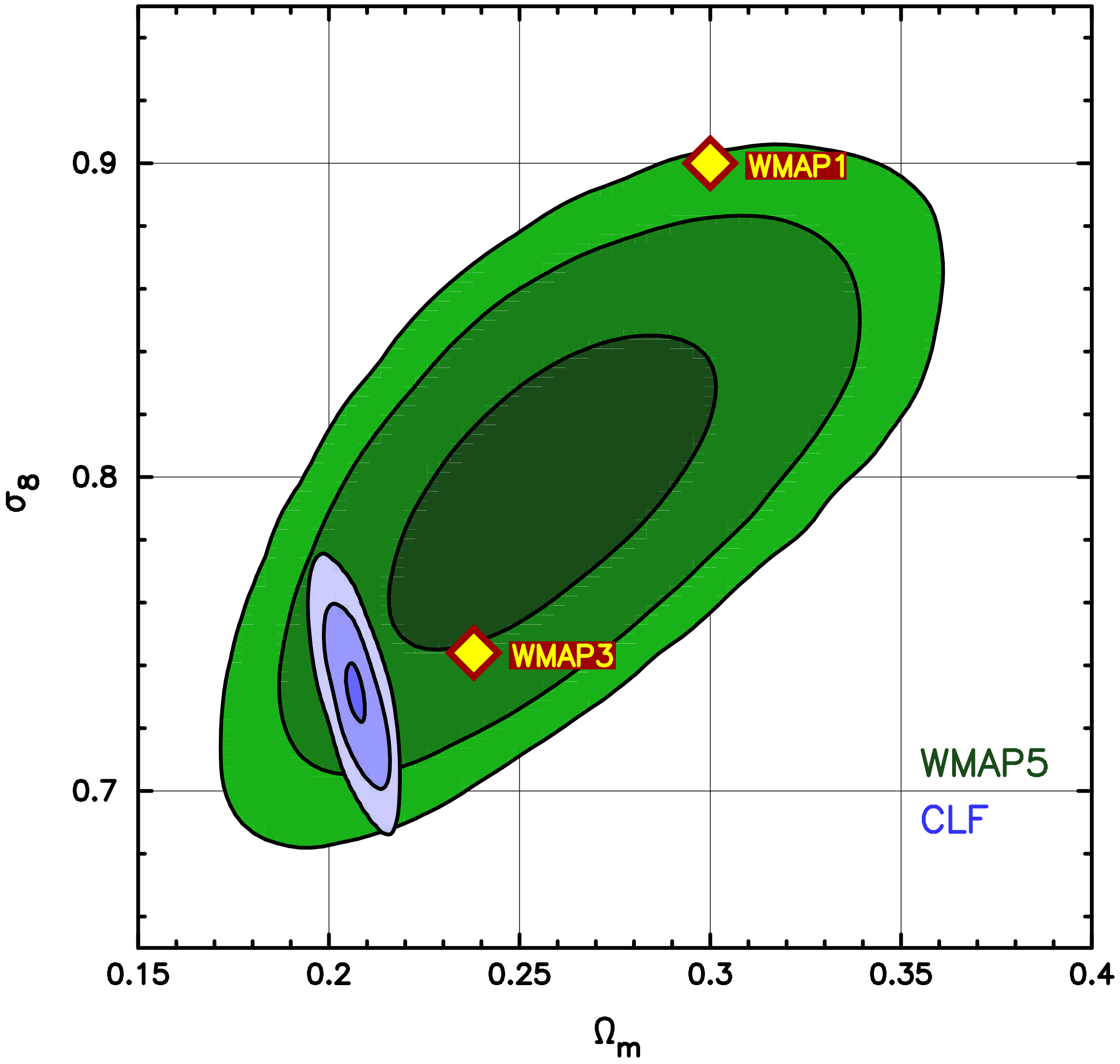
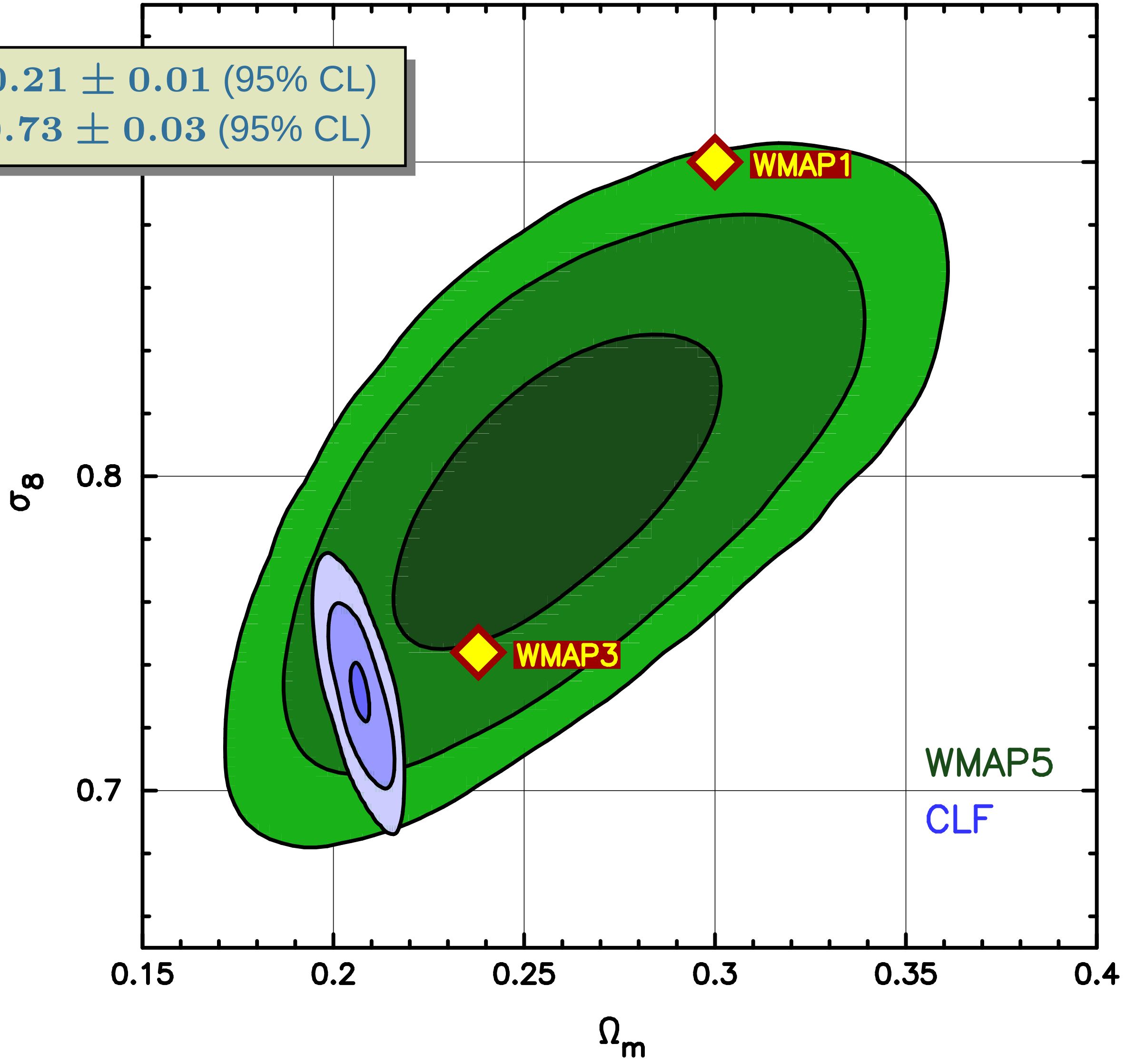


Precision Cosmology using non-linear structure!!

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

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

Group Catalogues	**Clustering**
Satellite Kinematics	**Galaxy-Galaxy Lensing**

- **Requires somewhat arbitrary group-finder**
- **We used well-tested Halo Based Group Finder of Yang et al (2005)**
- **Ideal for studying environment dependence of galaxy formation**
- **Mass assignments is cosmology-dependent**
- **Correlation function of groups is direct reflection of that of dark matter haloes**

Conclusions

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

Group Catalogues	**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

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

Group Catalogues	**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 $P(M|L)$**
- **Even with large redshift surveys such as SDSS, statistics are limited**
- **Data not sufficient to discriminate between WMAP1 and WMAP3**

Conclusions

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

Group Catalogues	**Clustering**
Satellite Kinematics	**Galaxy-Galaxy Lensing**

- **Lensing probes masses directly**
- **Requires stacking and is therefore sensitive to scatter in $P(M|L)$**
- **Also 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**

Cosmological Conclusions

Cosmological constraints obtained from non-linear structure (clustering + lensing + group catalogue) are in excellent agreement with CMB constraints

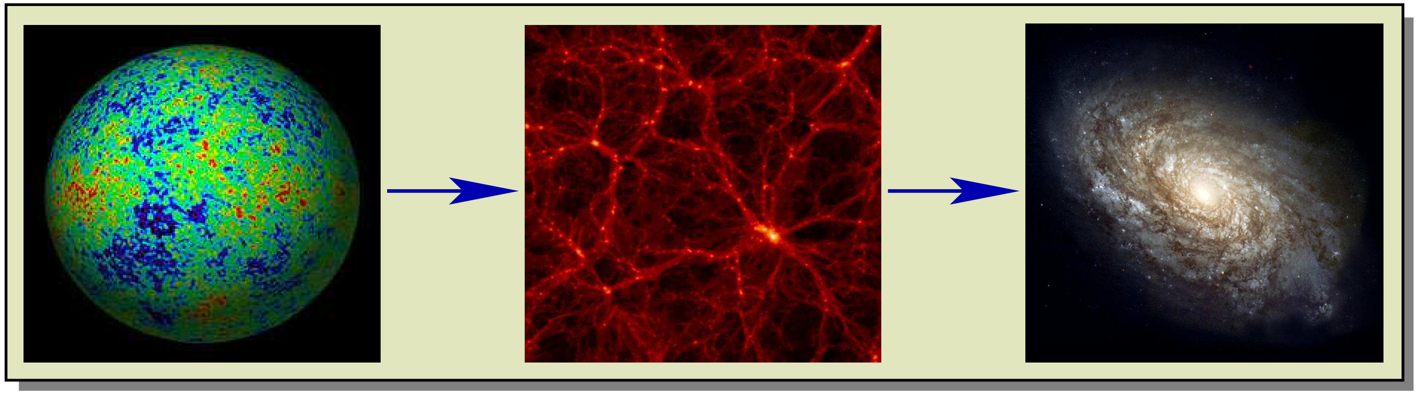
Current (preliminary) results suggest

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

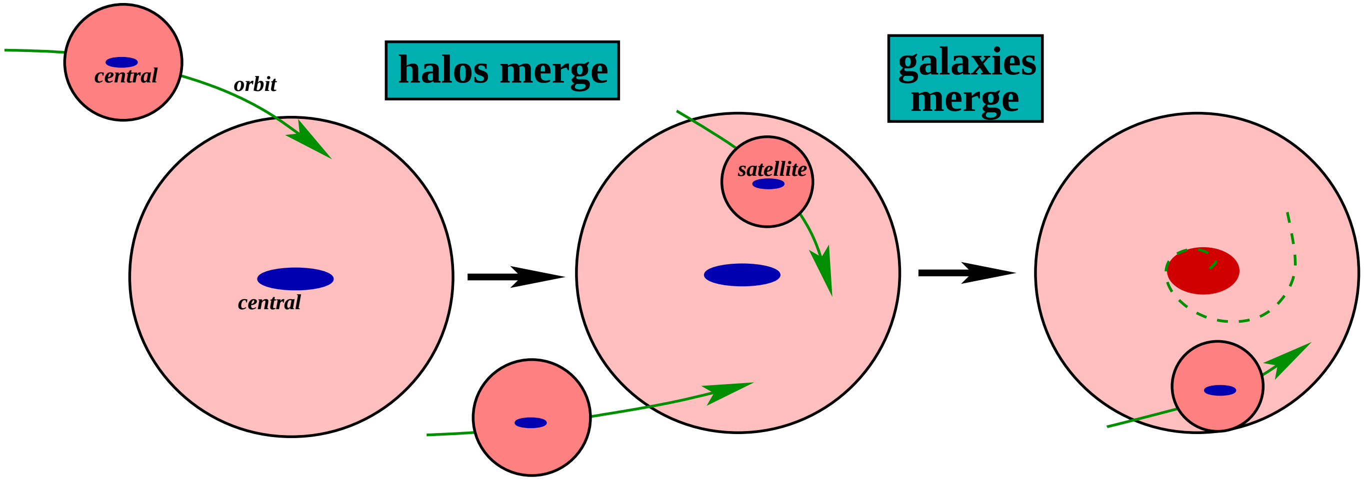
This technique is competative with and complementary to BAO, cosmic shear, SNIa and Lyα forest

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 ⇒ 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

Galaxy Group Catalogues

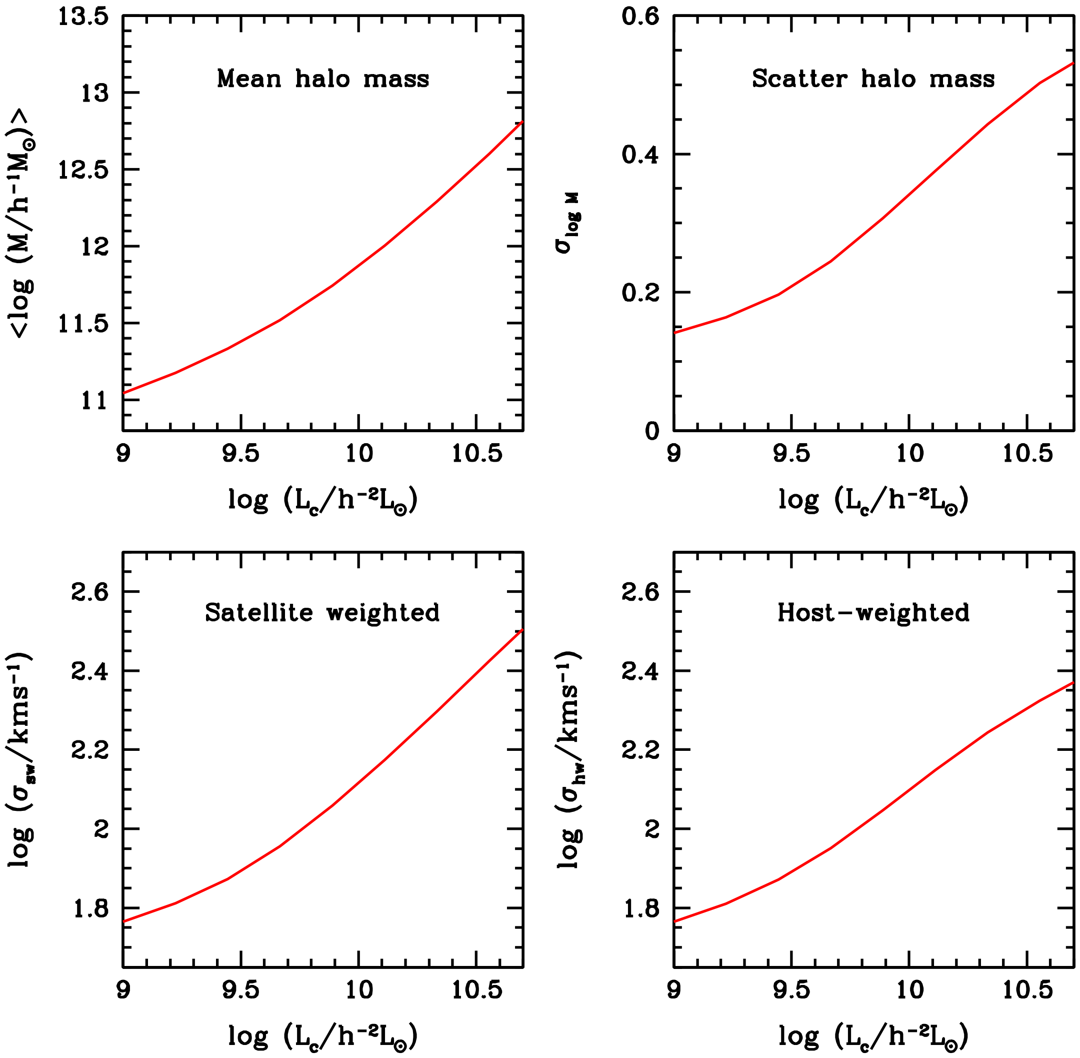
Large Scale Structure

Satellite Kinematics

Galaxy-Galaxy Lensing

Conclusions

Extra Material
- Galaxy Formation in a Nutshell
- Satellite Weighting or Host Weighting?
- Implications for Galaxy Formation Stochasticity
- Comparison with other Constraints
- Halo Occupation Numbers



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Introduction
Conditional Luminosity Function
Galaxy Group Catalogues
Large Scale Structure
Satellite Kinematics
Galaxy-Galaxy Lensing
Conclusions
Extra Material
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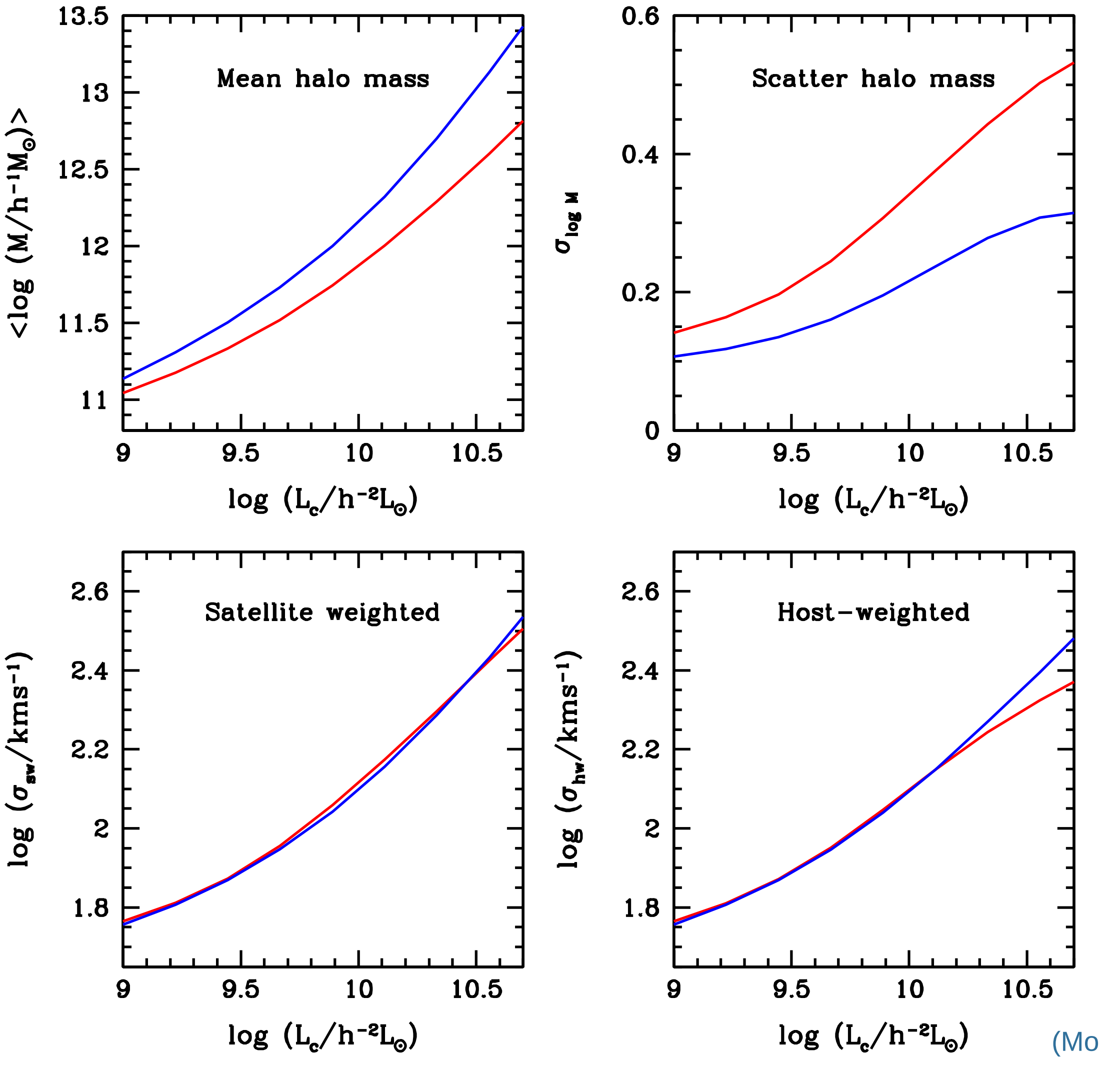
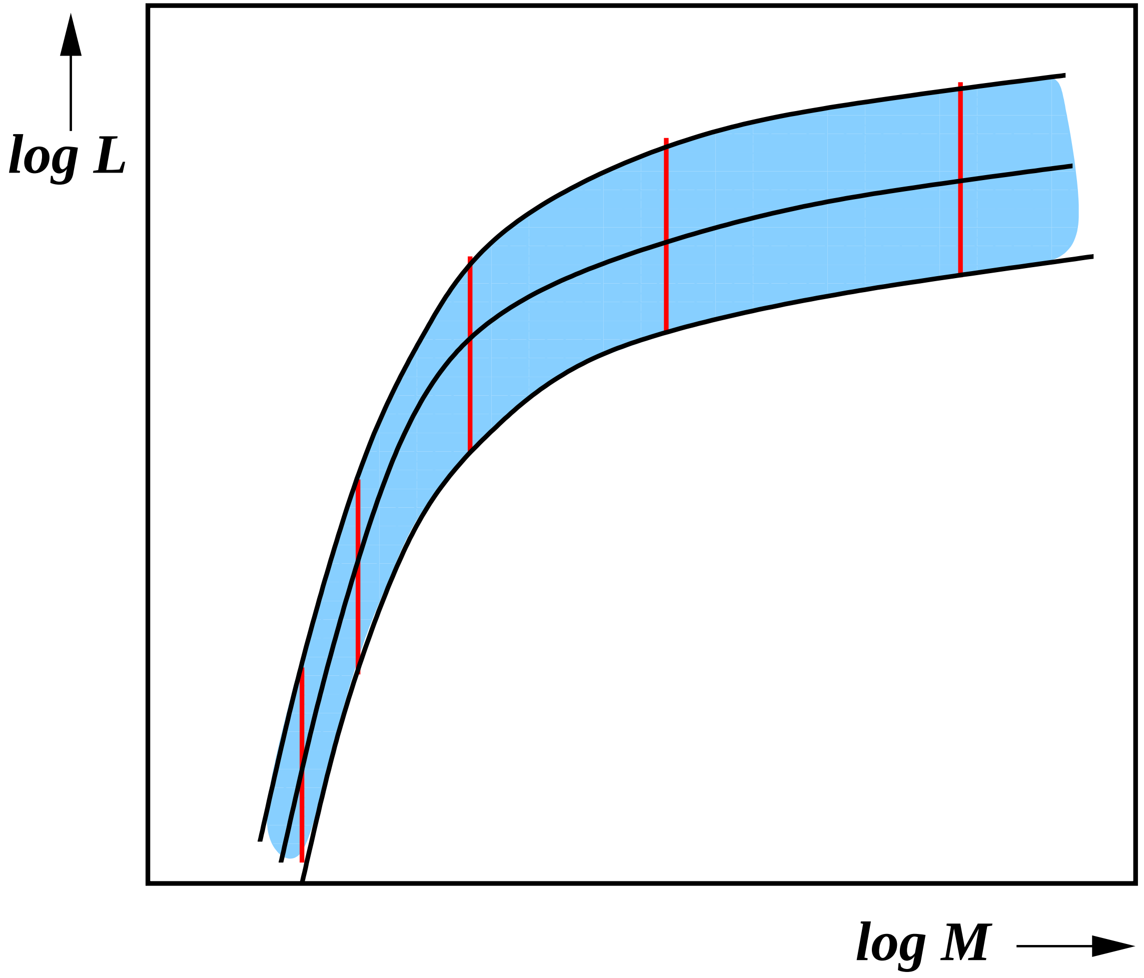


(More, vdB et al. 2008)

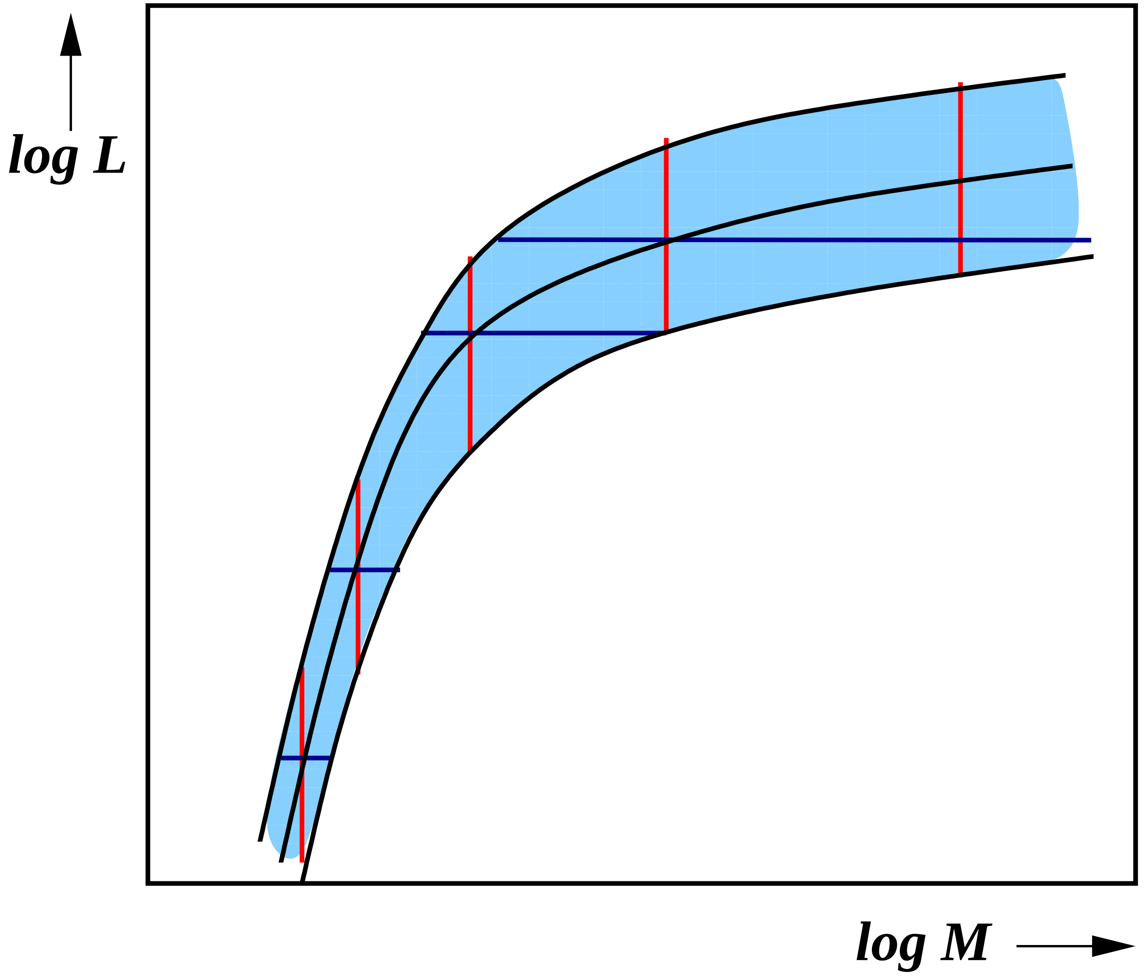
The combination of $\sigma_{\rm sw}$ and $\sigma_{\rm sw}$ allows one to determine mean and scatter of $P(M|L_{\rm c})$

Implications for Galaxy Formation Stochasticity



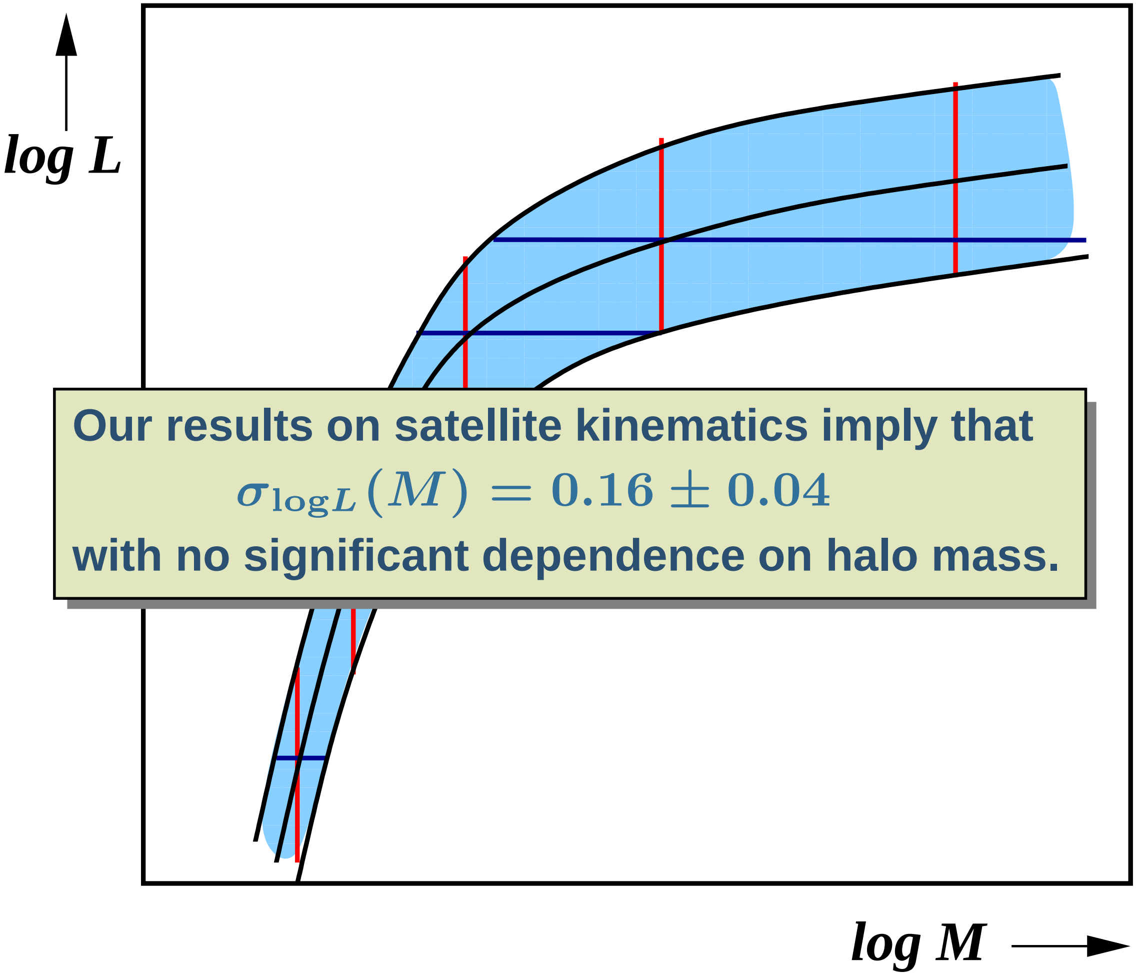
- **The scatter in $P(L_{\rm cen}|M)$ is independent of M**

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



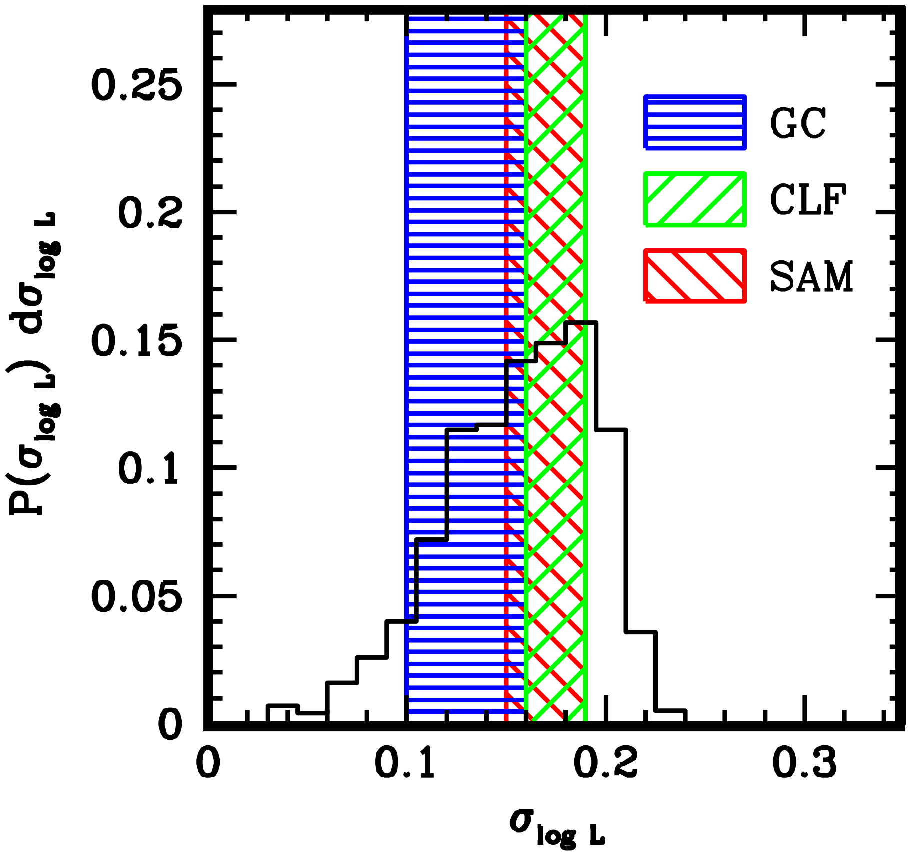
Our results on satellite kinematics imply that

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

with no significant dependence on halo mass.

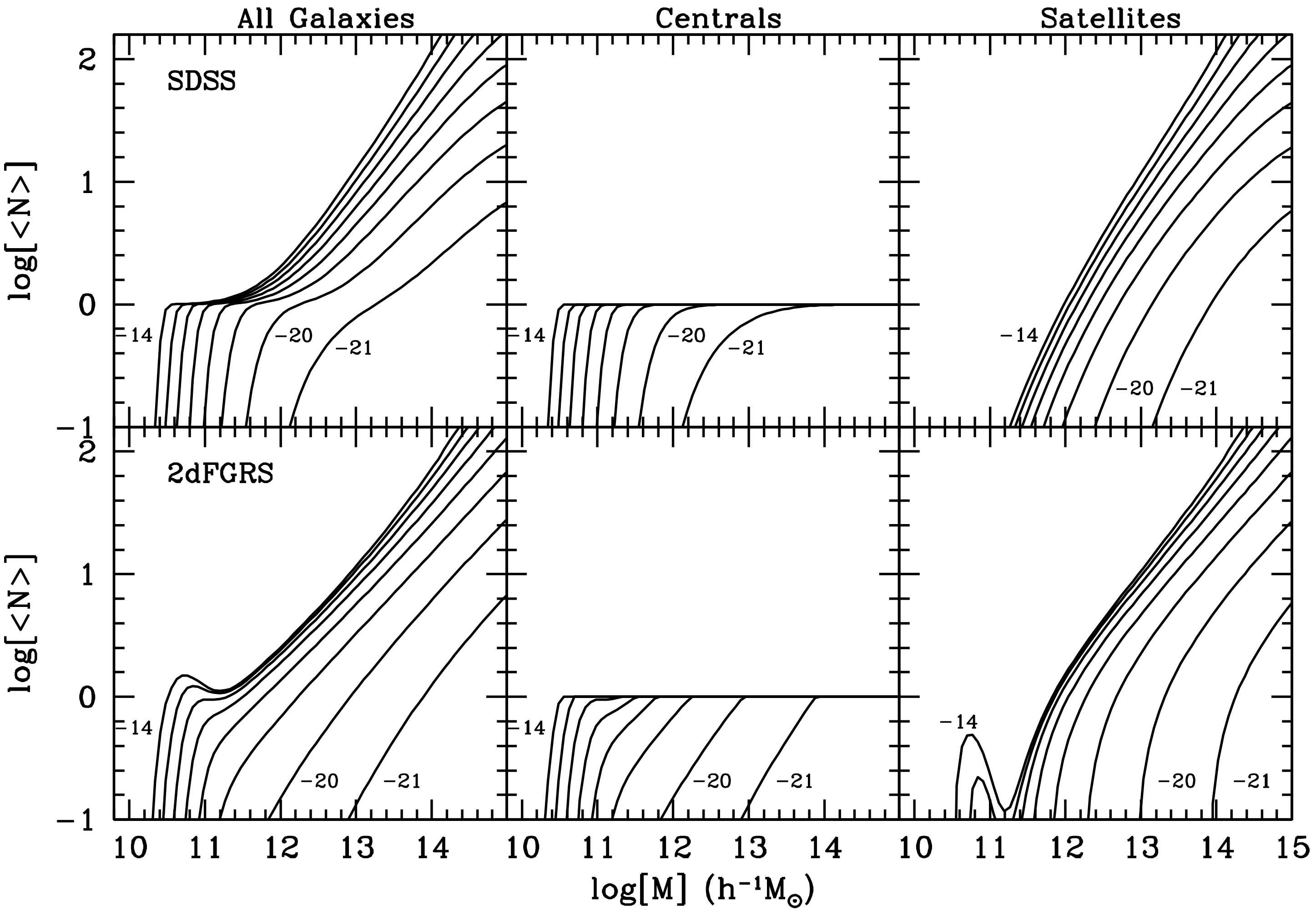
- **The scatter in $P(L_{\rm cen}|M)$ is independent of M**
- **The scatter in $P(M|L_{\rm cen})$ increases strongly with $L_{\rm cen}$**

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**