The Galaxy–Dark Matter Connection

constraining cosmology & galaxy formation

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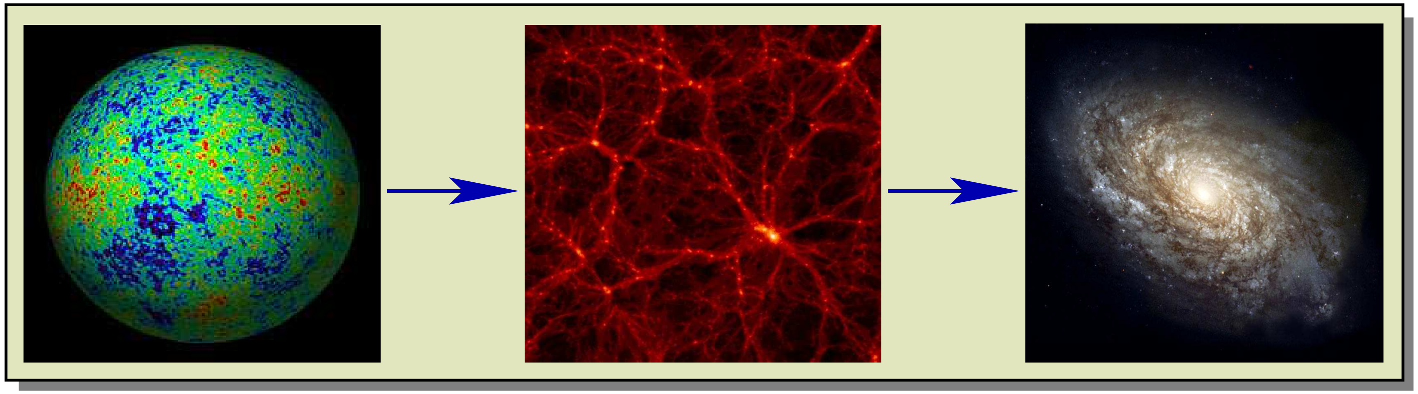
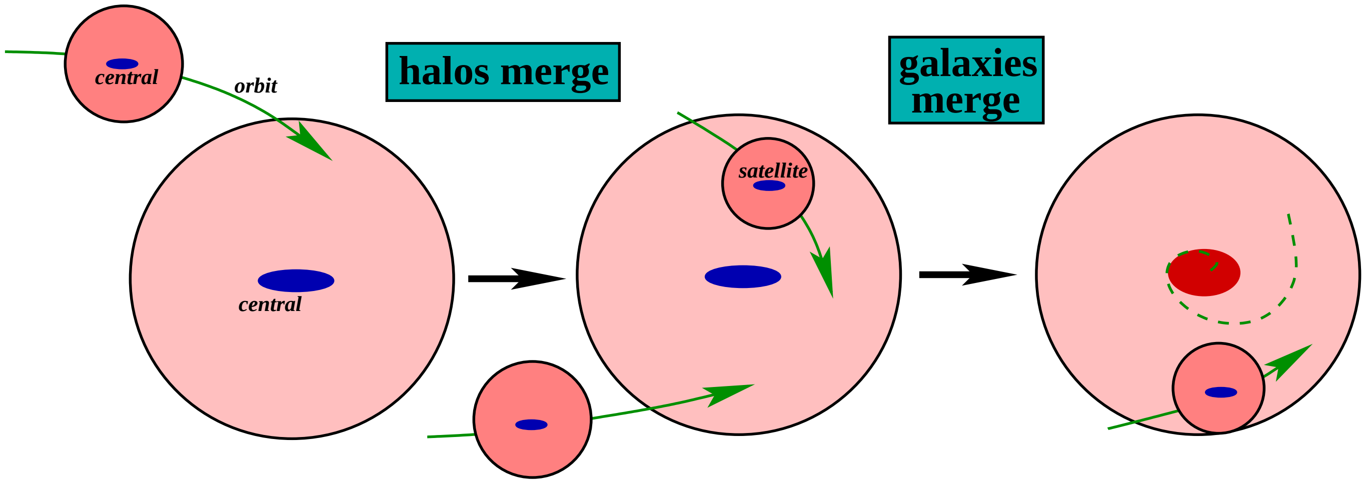
Galaxy Formation in a Nutshell

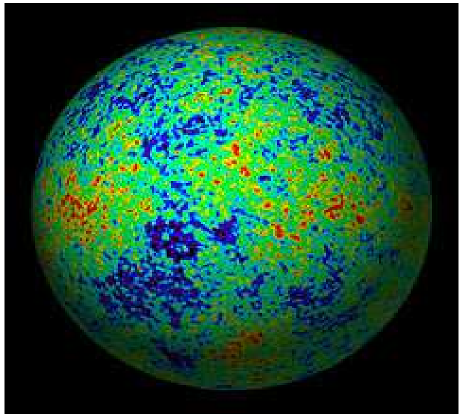


- Perturbations grow due to gravitational instability and collapse to produce (virialized) dark matter halos
- Baryons cool, accumulate at center, and form stars ⇒ galaxy
- Dark matter halos merge, causing hierarchical growth
- Halo mergers create satellite galaxies that orbit halo



Cosmological Parameters

The Cosmic Microwave Background and Supernova Ia have given us precise measurements of most cosmological parameters



$$\Omega_m = 0.27$$
$$\Omega_\Lambda = 0.73$$
$$\Omega_b = 0.04$$
$$H_0 = 72 \text{ km/s/Mpc}$$
$$n_s = 0.95$$
$$\sigma_8 = 0.77$$

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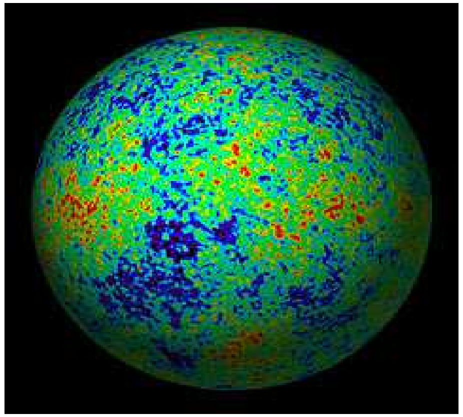

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Open Questions:

- **What is the nature of dark matter; i.e., CDM *vs.* WDM?**
- **What is the nature of dark energy i.e., what is $w = P/\rho$?**
- **What are the properties of the inflaton; i.e., what is $V(\phi)$?**
- **Why do galaxies have the properties they have?**

All these fundamental questions can be addressed probing the matter perturbation field as a function of redshift.

The Issue of Galaxy Bias

An important goal in cosmology is to probe the matter field.

Define the density perturbation field: $$\delta(\vec{x}, z) = \frac{\rho(\vec{x},z) - \bar{\rho}(z)}{\bar{\rho}(z)}$$

An important statistic used to describe the properties of the density field is the two-point correlation function:

$$\xi(r) = \langle \delta(\vec{x}) \delta(\vec{x}+\vec{r}) \rangle$$

It is standard practice to probe $\delta(x)$ using galaxies as tracer population. However, galaxies are a biased tracer of mass distribution.

$$\xi_{\rm gg}(r) = b_{\rm g}^2 \, \xi_{\rm dm}(r) \quad \text{with} \quad b_{\rm g} = \langle \delta_{\rm g} / \delta_{\rm dm} \rangle$$

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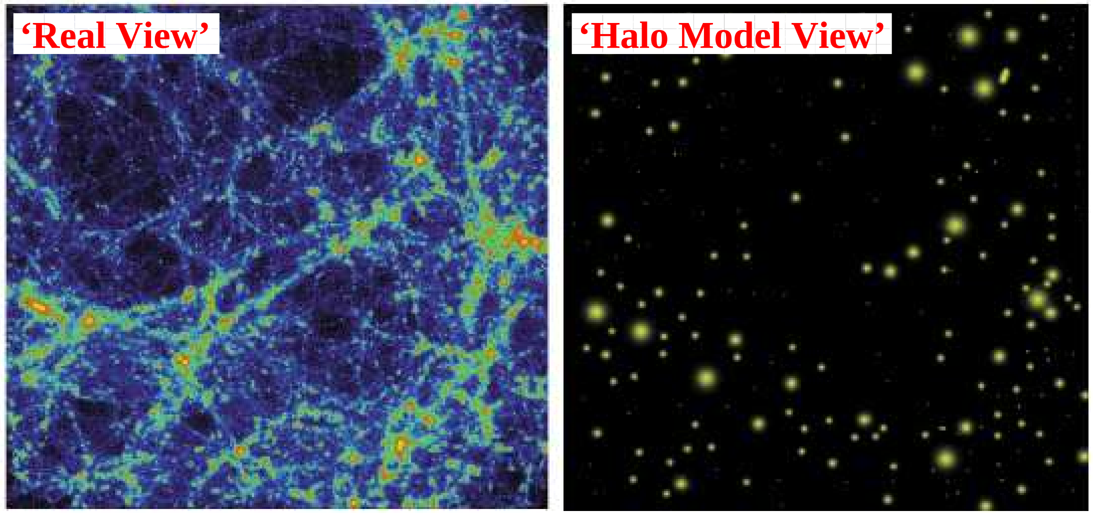
Bias is an imprint of galaxy formation, which is poorly understood.

Consequently, little progress has been made constraining cosmology with Large-Scale Structure, despite several large redshift surveys.

How to constrain and quantify galaxy bias in a convenient way?

How to Handle Bias?

Halo Model: Describe CDM distribution in terms of halo building blocks, assuming that every CDM particle resides in virialized halo



Cooray & Sheth (2002)

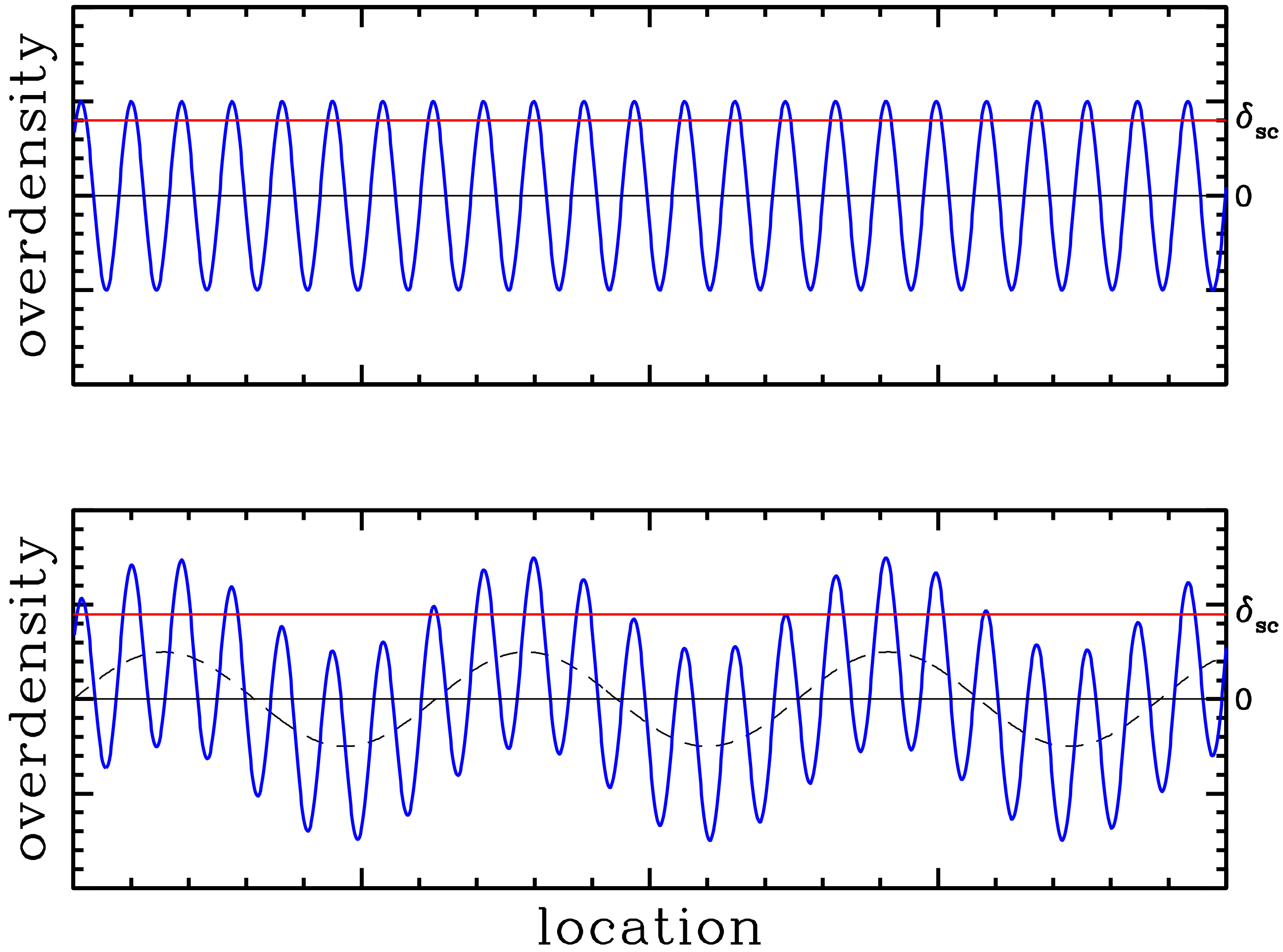
- On small scales: $\delta(\vec{x}) =$ density distribution of halos
- On large scales: $\delta(\vec{x}) =$ spatial distribution of halos

Halo Bias: Dark Matter haloes are biased tracer of mass distribution. More massive haloes are more strongly biased.

Halo Occupation Statistics: A statistical description of how galaxies are distributed over dark matter halos

Galaxy Bias = Halo Bias + Halo Occupation Statistics

The Origin of Halo Bias



Modulation causes statistical bias of peaks (haloes)

Modulation growth causes dynamical enhancement of bias

The Conditional Luminosity Function

To specify Halo Occupation Statistics we introduce Conditional Luminosity Function, $\Phi(L|M)$, which is the direct link between 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 lot of important information, such as:

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

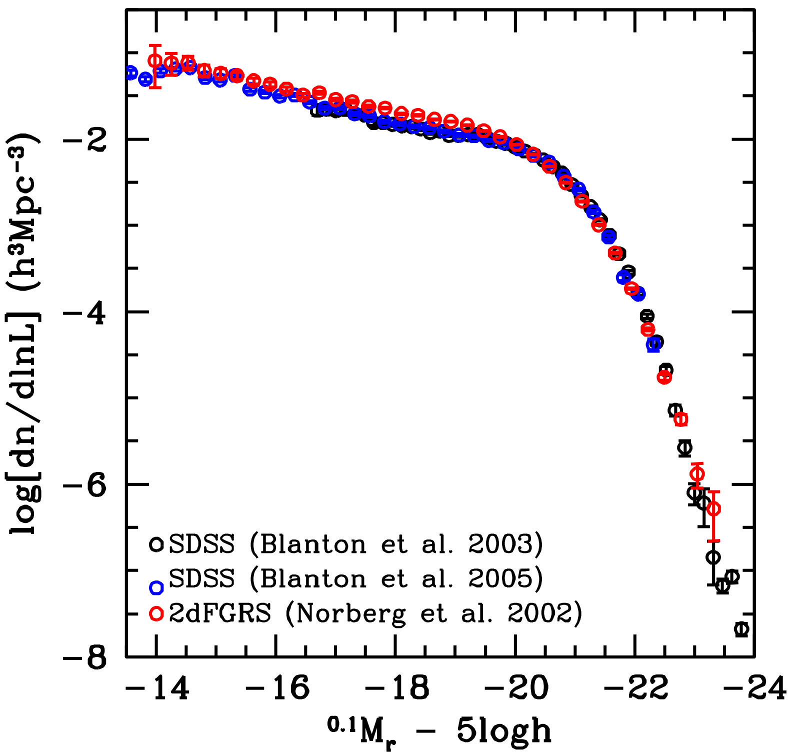
$$\langle L\rangle(M) = \int_0^\infty \Phi(L|M)\, L\, \mathrm{d}L$$

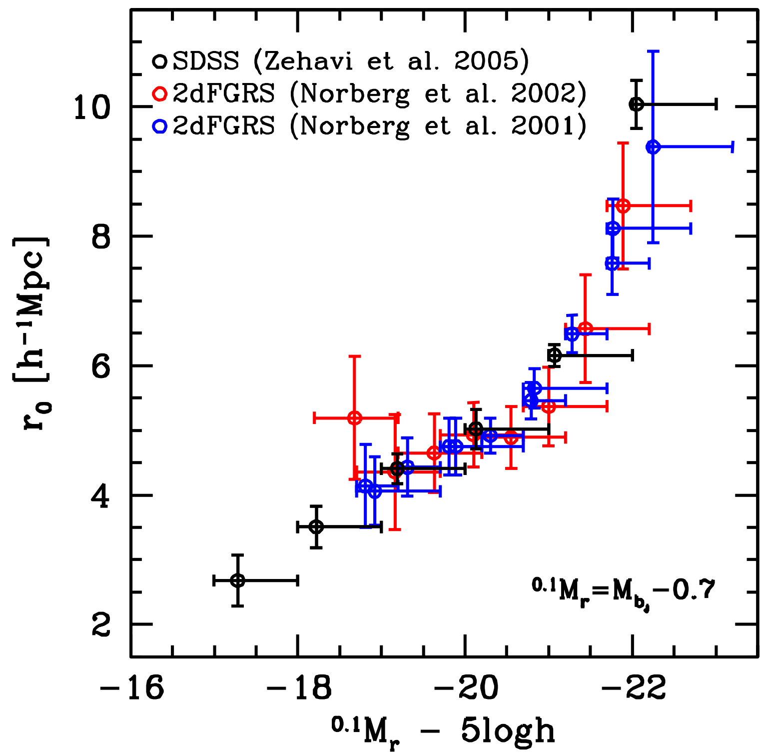
- **The bias of galaxies as function of luminosity:**

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

CLF is ideal statistical tool to specify Galaxy-Dark Matter Connection

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 $\xi(r_0) = 1$

The CLF Model

We split CLF in central and satellite components

$$\Phi(L|M)\mathrm{d}L = \Phi_{\mathrm{cen}}(L|M)\mathrm{d}L + \Phi_{\mathrm{sat}}(L|M)\mathrm{d}L$$

- **For centrals we adopt a log-normal distribution**
- **For satellites we adopt a modified Schechter function**

$$\begin{aligned}\Phi_{\mathrm{cen}}(L|M)\mathrm{d}L &= \frac{1}{\sqrt{2\pi}\,\ln(10)\,\sigma_{\mathrm{c}}}\exp\left[-\left(\frac{\log(L/L_{\mathrm{c}})}{\sqrt{2}\sigma_{\mathrm{c}}}\right)^2\right]\frac{\mathrm{d}L}{L} \\ \Phi_{\mathrm{sat}}(L|M)\mathrm{d}L &= \frac{\Phi_{\mathrm{s}}}{L_{\mathrm{s}}}\left(\frac{L}{L_{\mathrm{s}}}\right)^{\alpha_{\mathrm{s}}}\exp[-(L/L_{\mathrm{s}})^2]\,\mathrm{d}L\end{aligned}$$

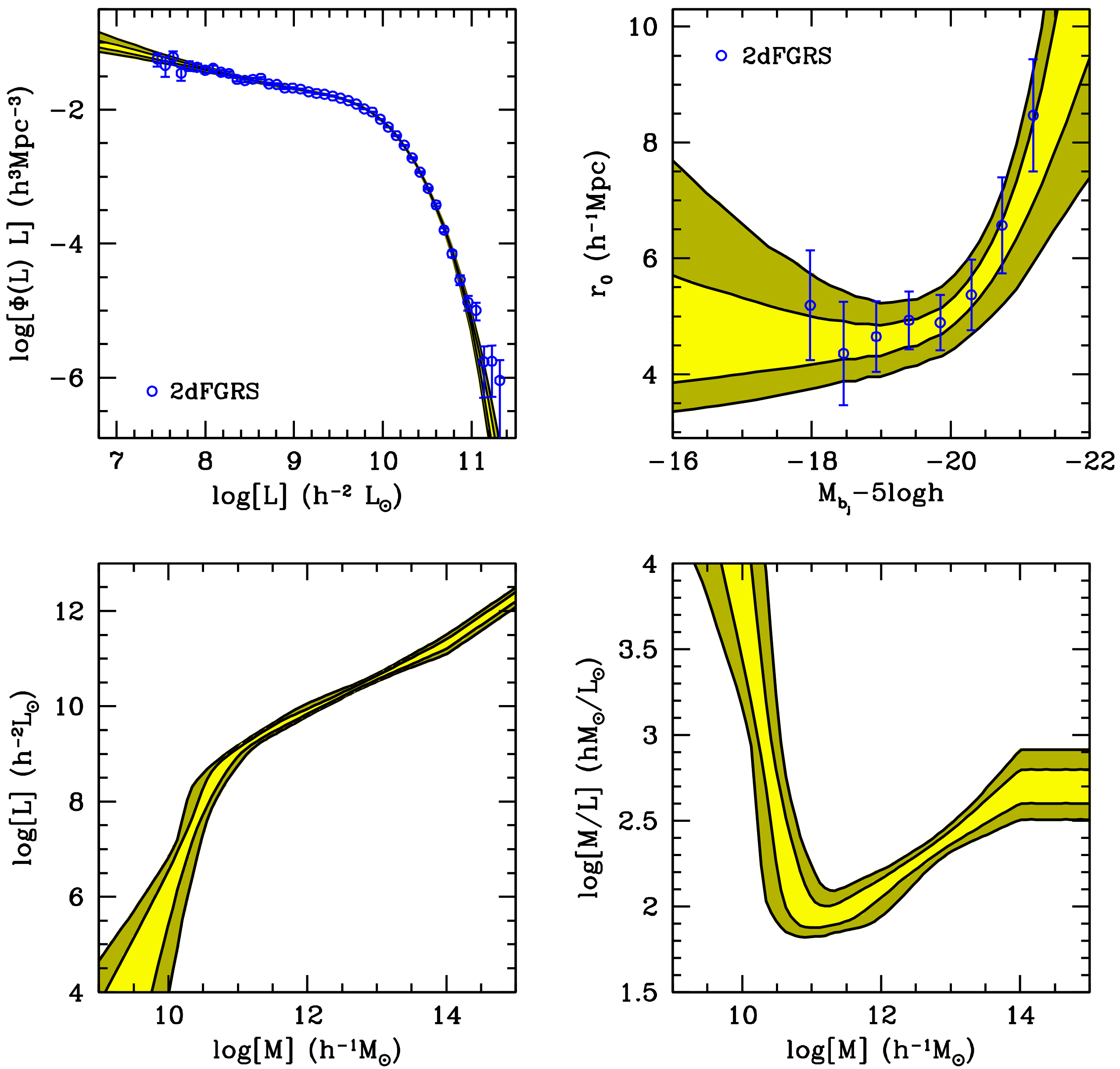
Note that L_{c}, L_{s}, σ_{c}, ϕ_{s} and α_{s} all depend on M

Free parameters are constrained by fitting $\Phi(L)$ and $r_0(L)$.

Construct Monte-Carlo Markov Chain to sample the posterior distribution of free parameters

Use MCMC to put confidence levels on derived quantities such as the average relation between light and mass: $\langle L\rangle(M)$

The Galaxy-Dark Matter Connection



vdB, Yang & Mo (2003); vdB et al. (2005)

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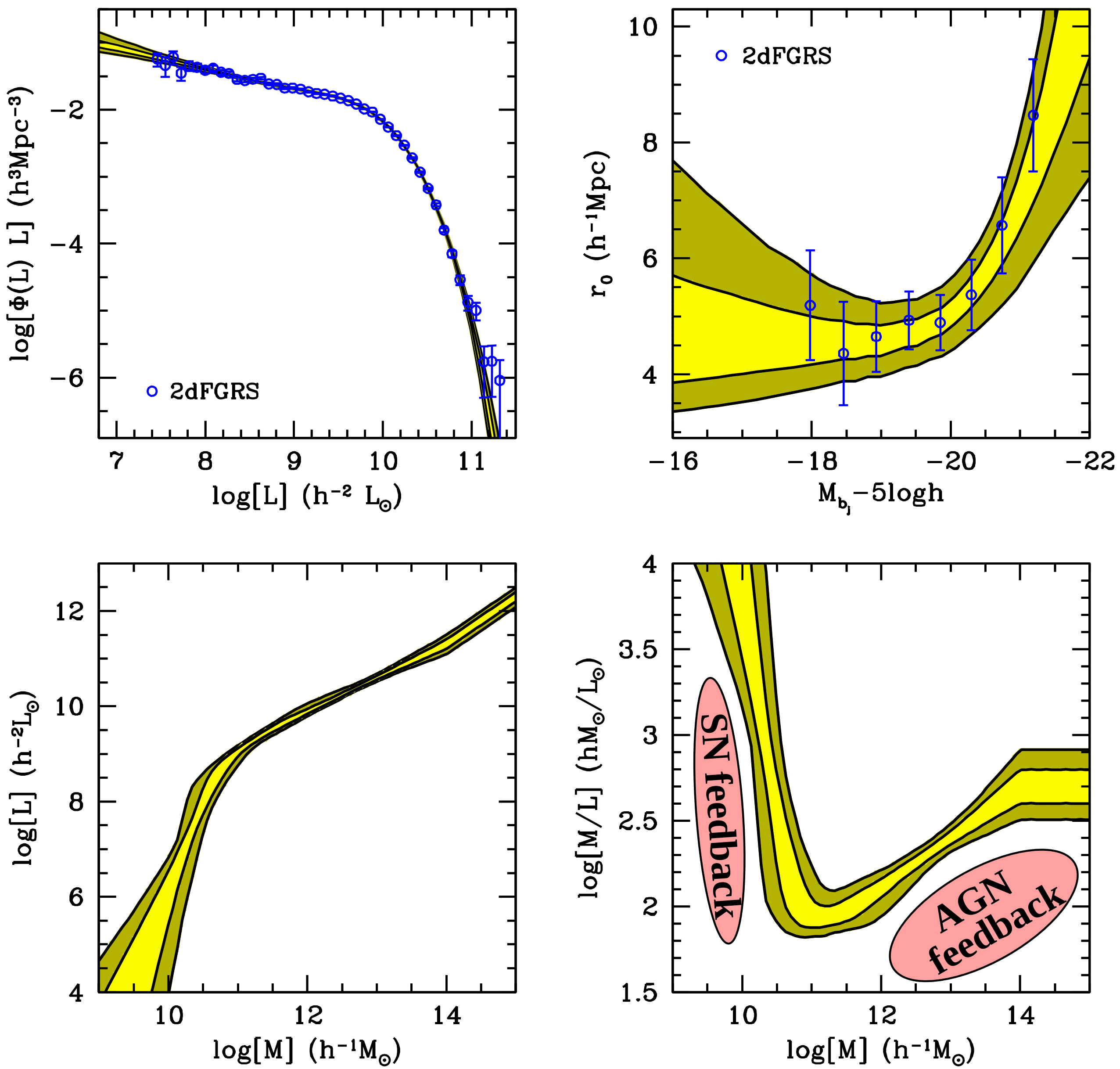

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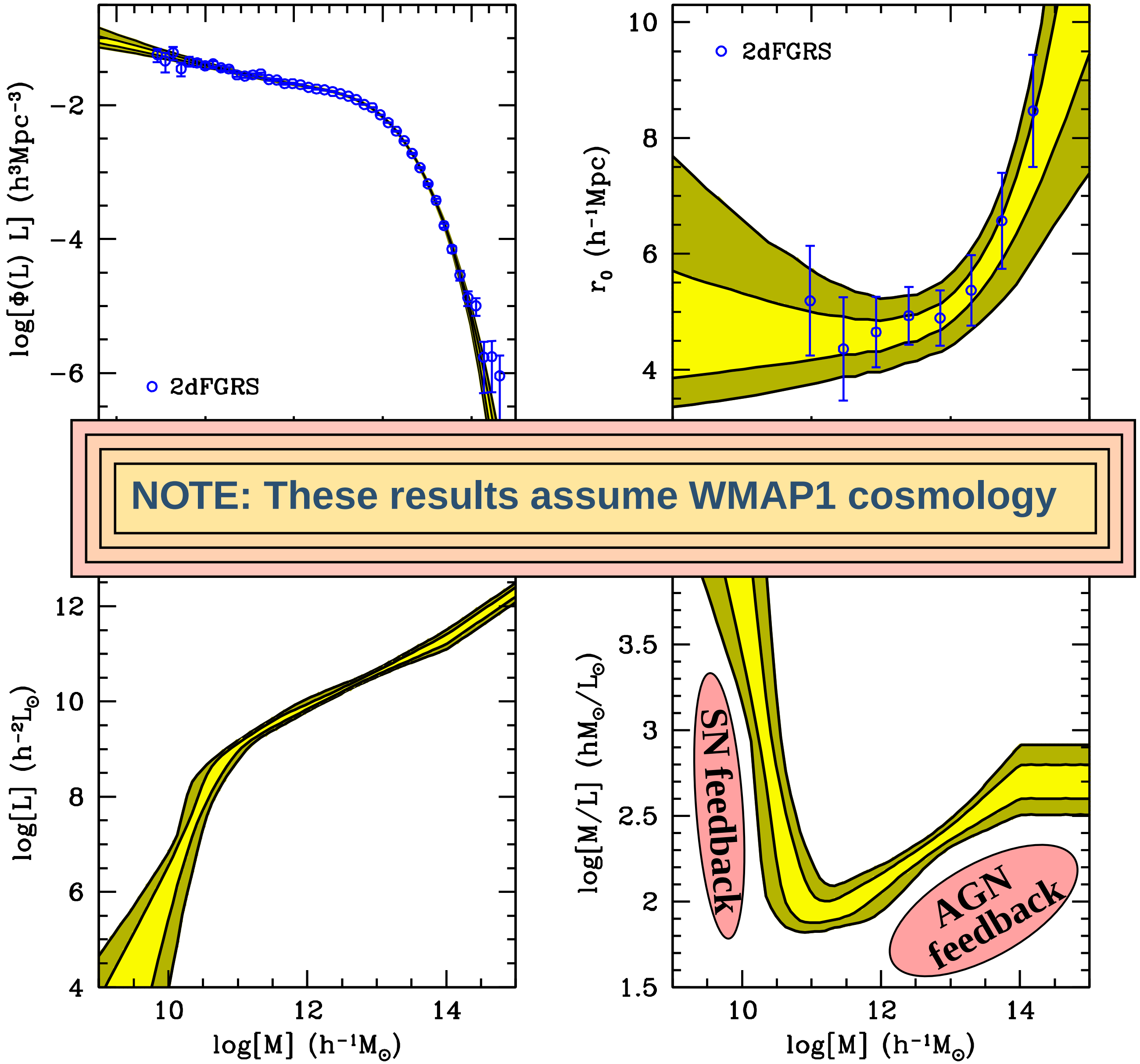
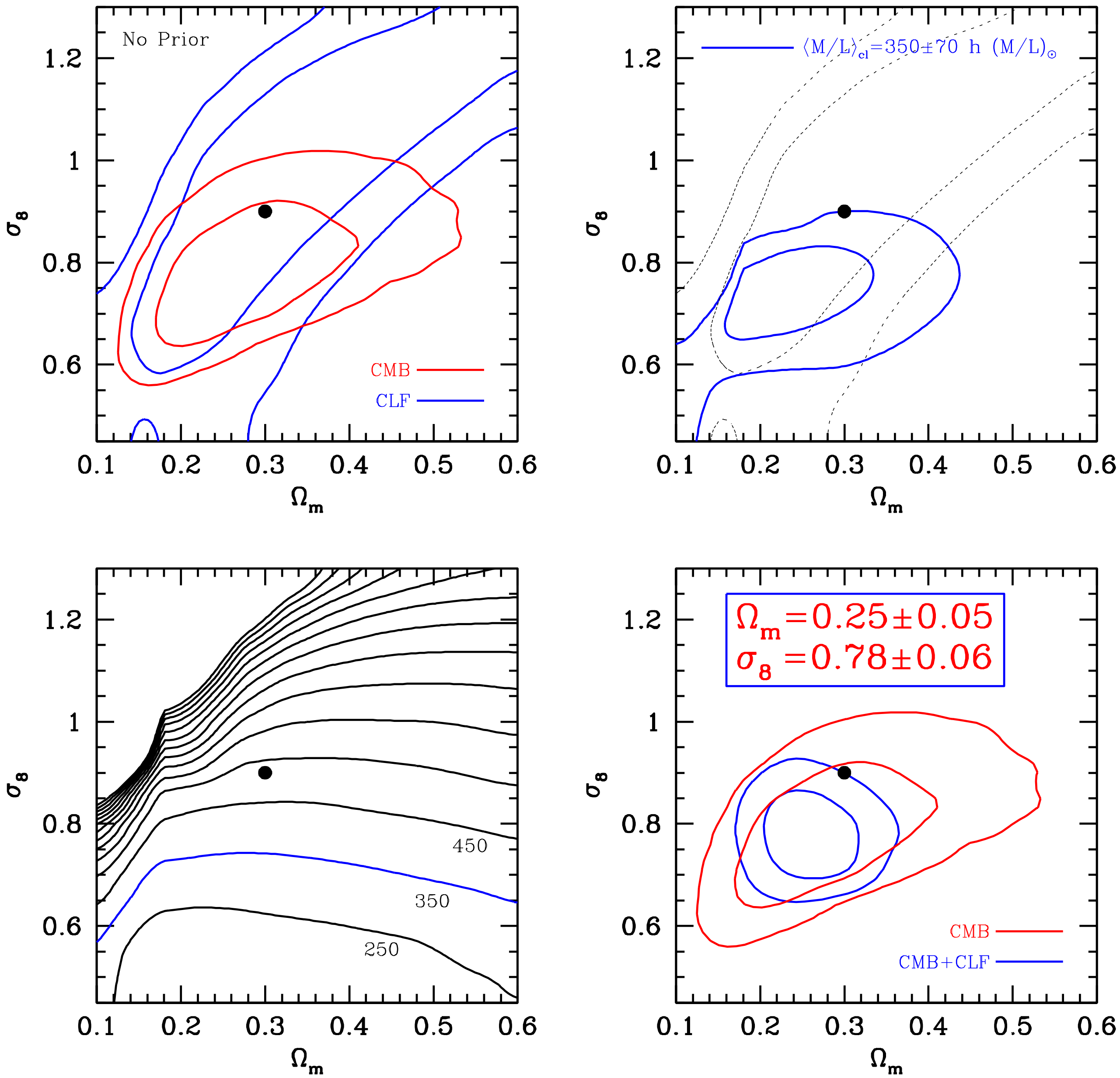


NOTE: These results assume WMAP1 cosmology

vdB, Yang & Mo (2003); vdB et al. (2005)

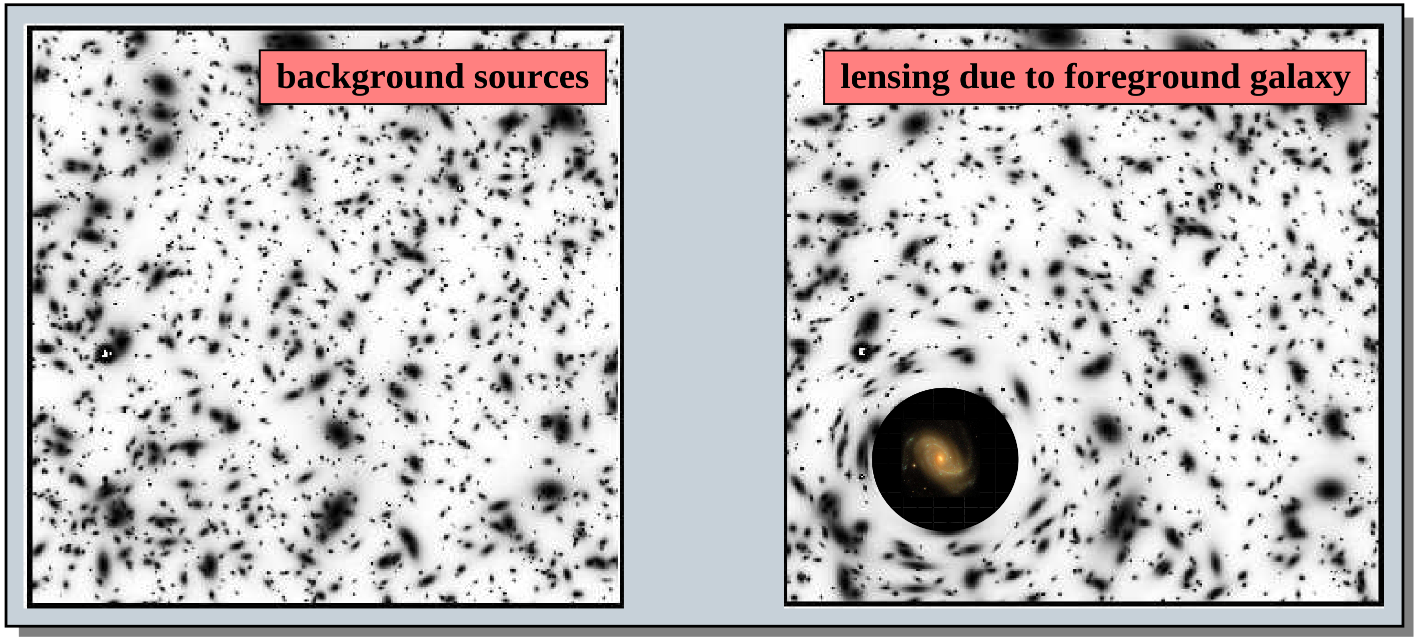
Cosmological Constraints



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

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

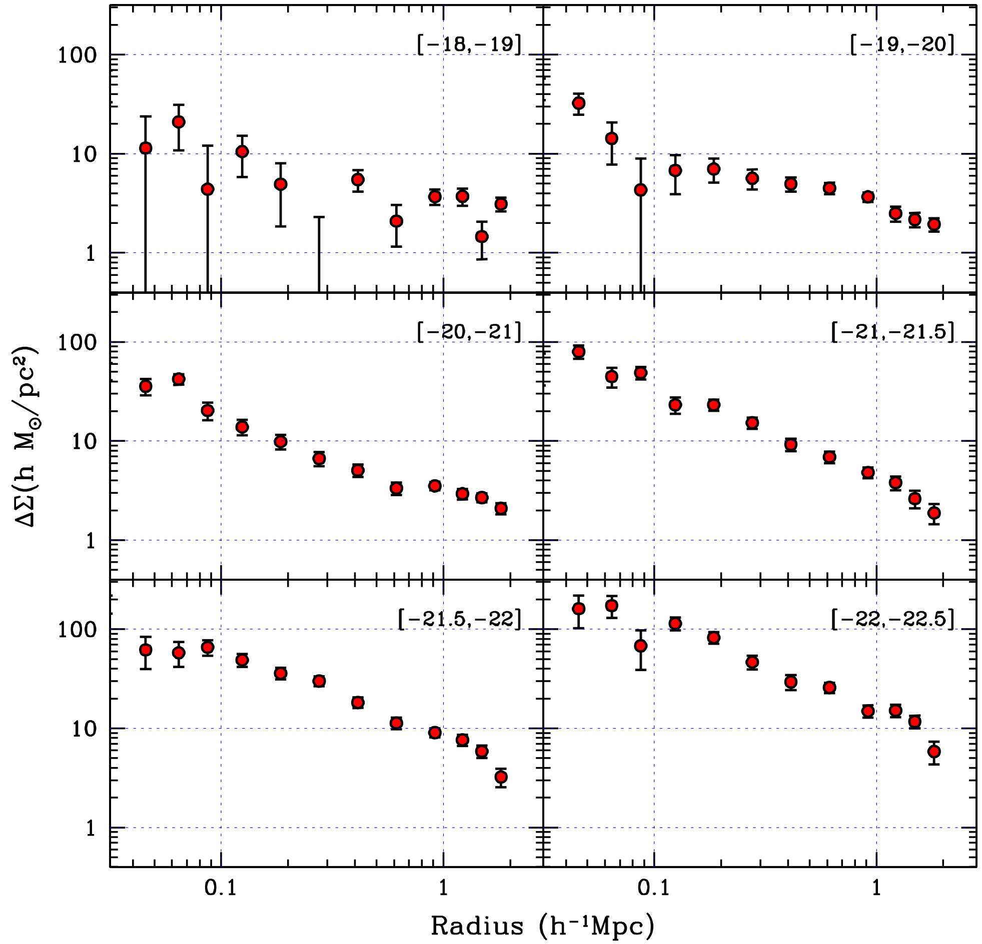
$$\gamma_t(R)\Sigma_{\rm crit} = \Delta\Sigma(R) = \bar{\Sigma}(< R) - \Sigma(R)$$

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

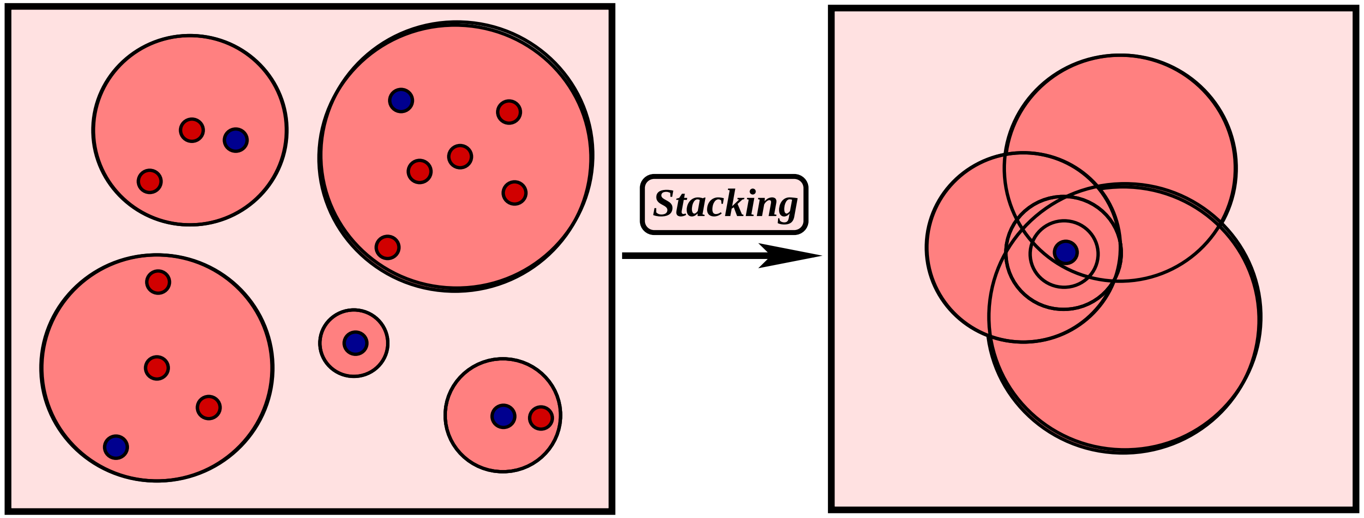
$$\Sigma(R) = \bar{\rho} \int_0^{D_S} [1 + \xi_{\rm g,dm}(r)]\, d\chi$$

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?



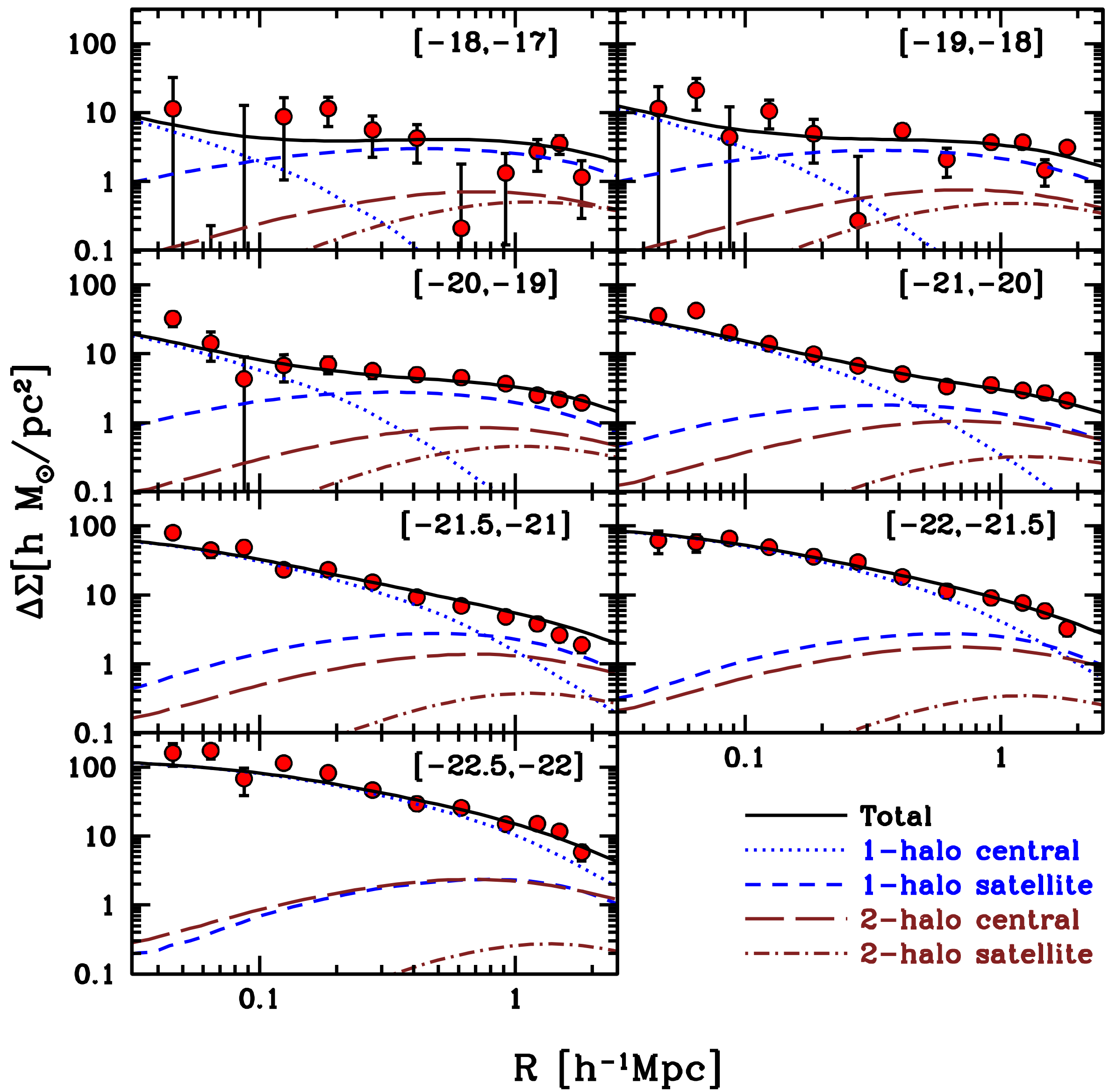
Because of stacking the lensing signal is difficult to interpret

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

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

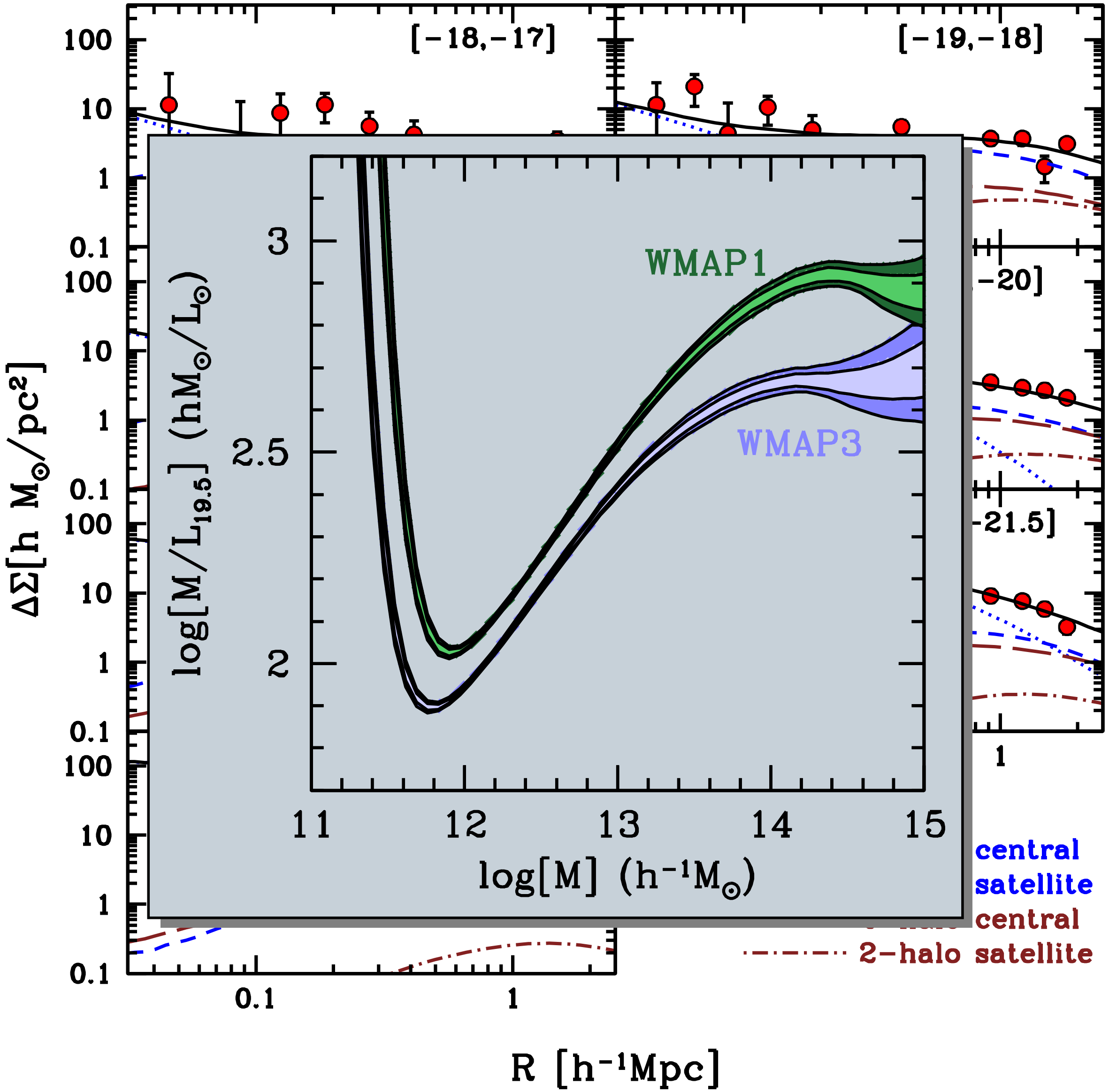
Using $\Phi(L|M)$ **constrained from clustering data, we can predict the lensing signal** $\Delta\Sigma(R|L_1, L_2)$

Comparison with CLF Predictions



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

Comparison with CLF Predictions



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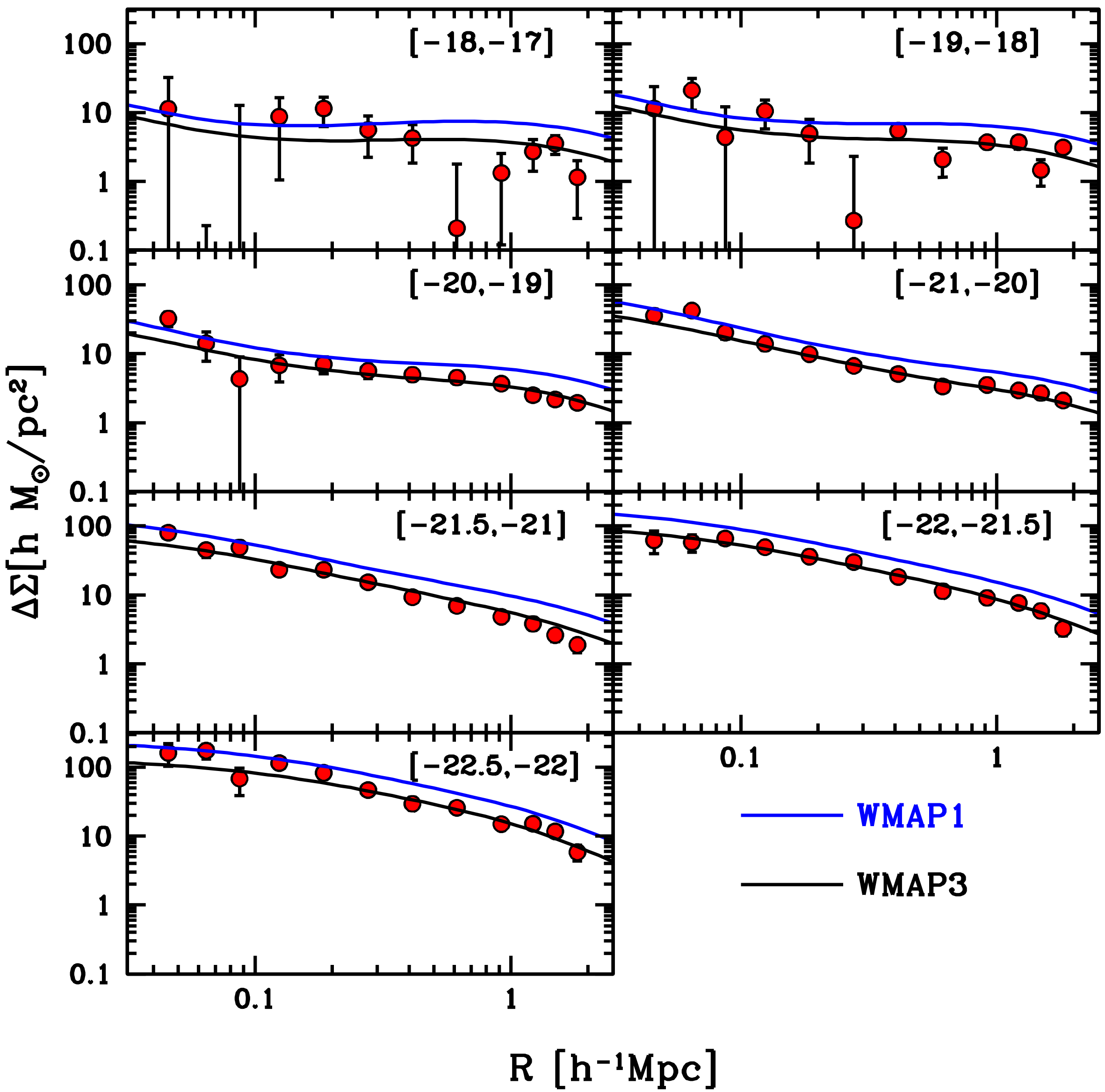


WMAP3 cosmology clearly preferred over WMAP1 cosmology

Conclusions

- **The CLF allows a powerful and consice treatment of galaxy bias.**
- **The CLF quantifies universal relation between light and mass, which puts tight constraints on galaxy formation**
- **The CLF allows for a concise interpretation of galaxy-galaxy lensing**
- **The combination of galaxy clustering and galaxy-galaxy lensing yields tight constraints on cosmological parameters**
- **This is the first time that galaxy distribution on non-linear scales is used to constrain cosmology**
- **All data in excellent agreement with WMAP3 cosmology, but inconsistent with WMAP1 cosmology**

Outlook

Constrain cosmological parameters using clustering & lensing

Cacciato, vdB et al. (in prep)

Test Galaxy-Dark Matter Connection using Satellite Kinematics

vdB et al. (2004), More, vdB et al. (2008)

Study Galaxy-Dark Matter Connection using Galaxy Groups

Yang et al. (2005,2007)

- Probe environment dependence of galaxy formation

  Weinmann et al. (2006a,b), vdB et al. (2007,2008), McIntosh et al. (2008)
- Study galaxy alignments and halo shapes

  Yang et al. (2006), Faltenbacher et al. (2007,2008), Wang et al. (2008)
- Use spatial distribution of groups to reconstruct matter field: cross correlate with CMB and OVI absorbers

  Wang et al. (2008)

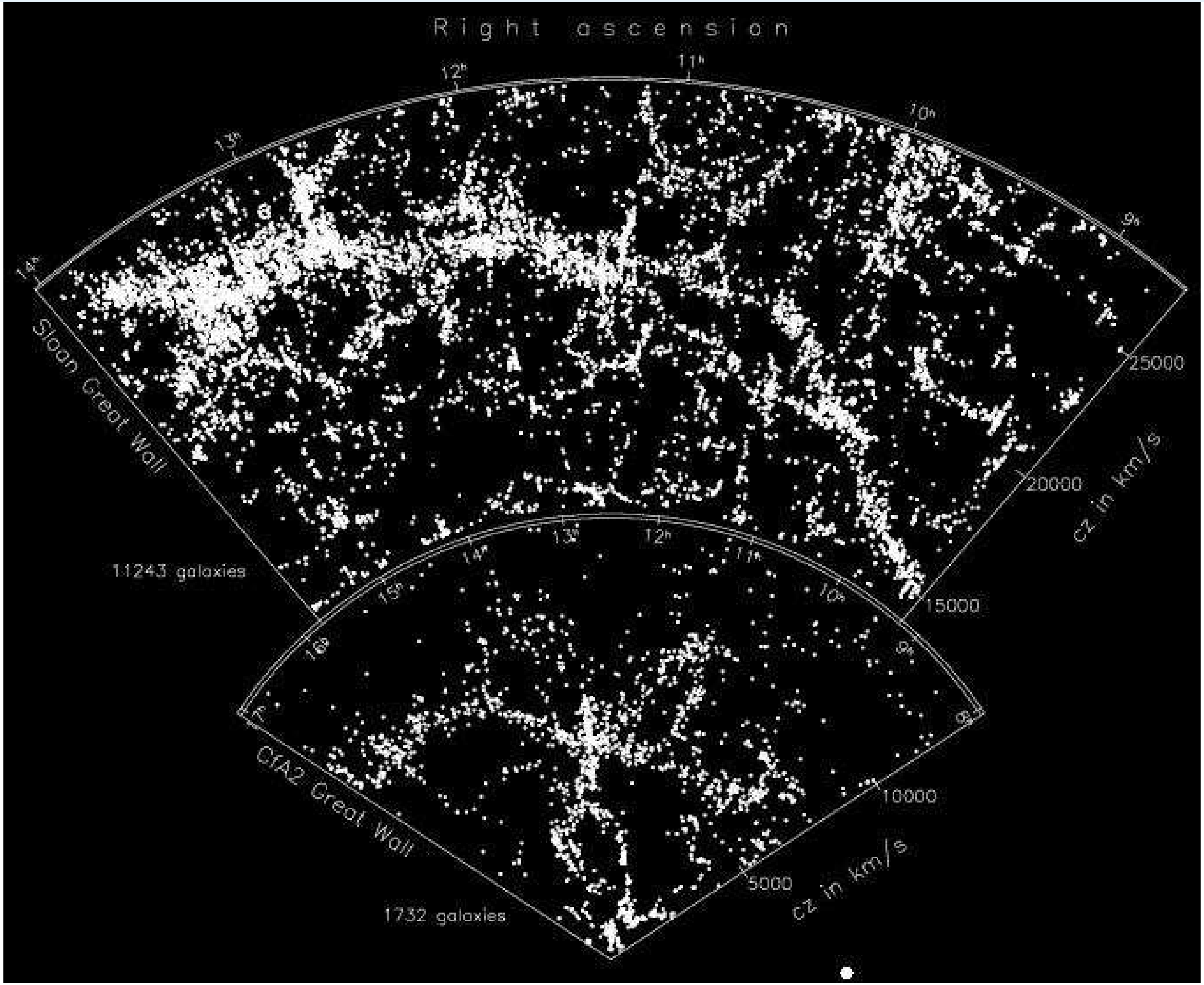
Use CLF to construct detailed Mock Galaxy Redshift Surveys

Yang et al. (2004), vdB et al. (2005)

Extent analysis to higher redshifts (DEEP2, PAN-STARRS, LSST)

- Probe coevolution of galaxies and their dark matter haloes
- Constrain equation-of-state of dark energy

Galaxy Groups from Redshift Surveys



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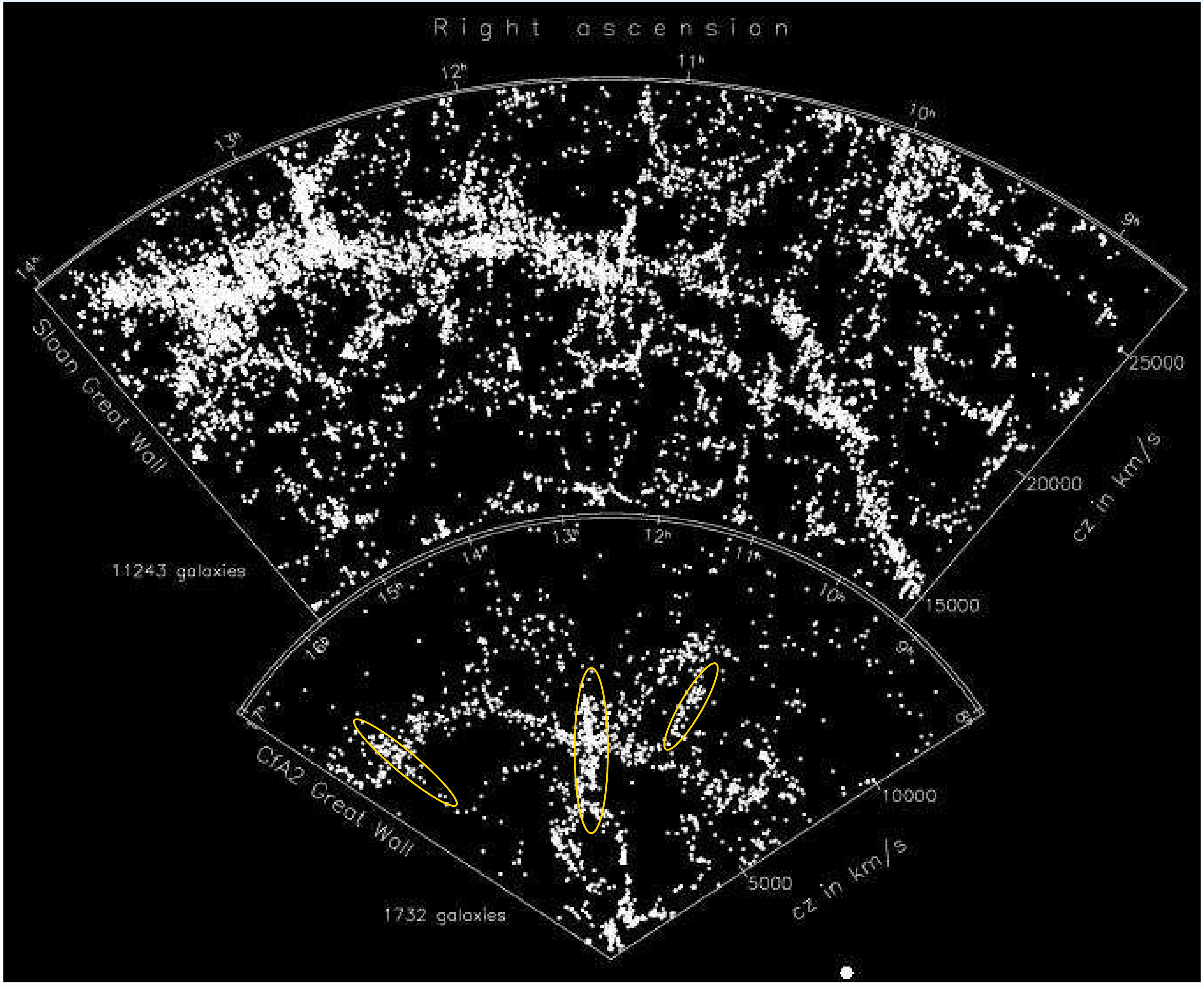

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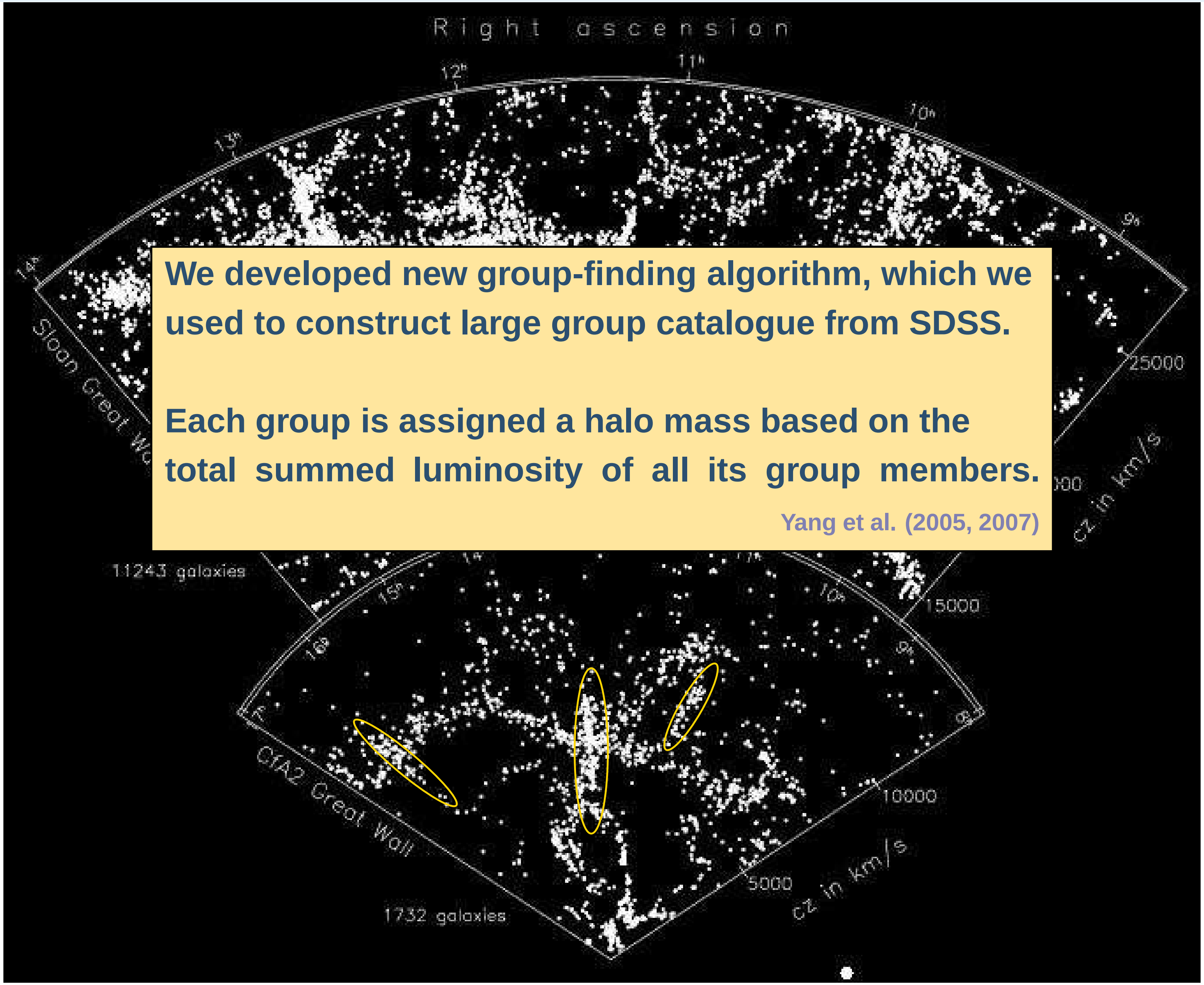
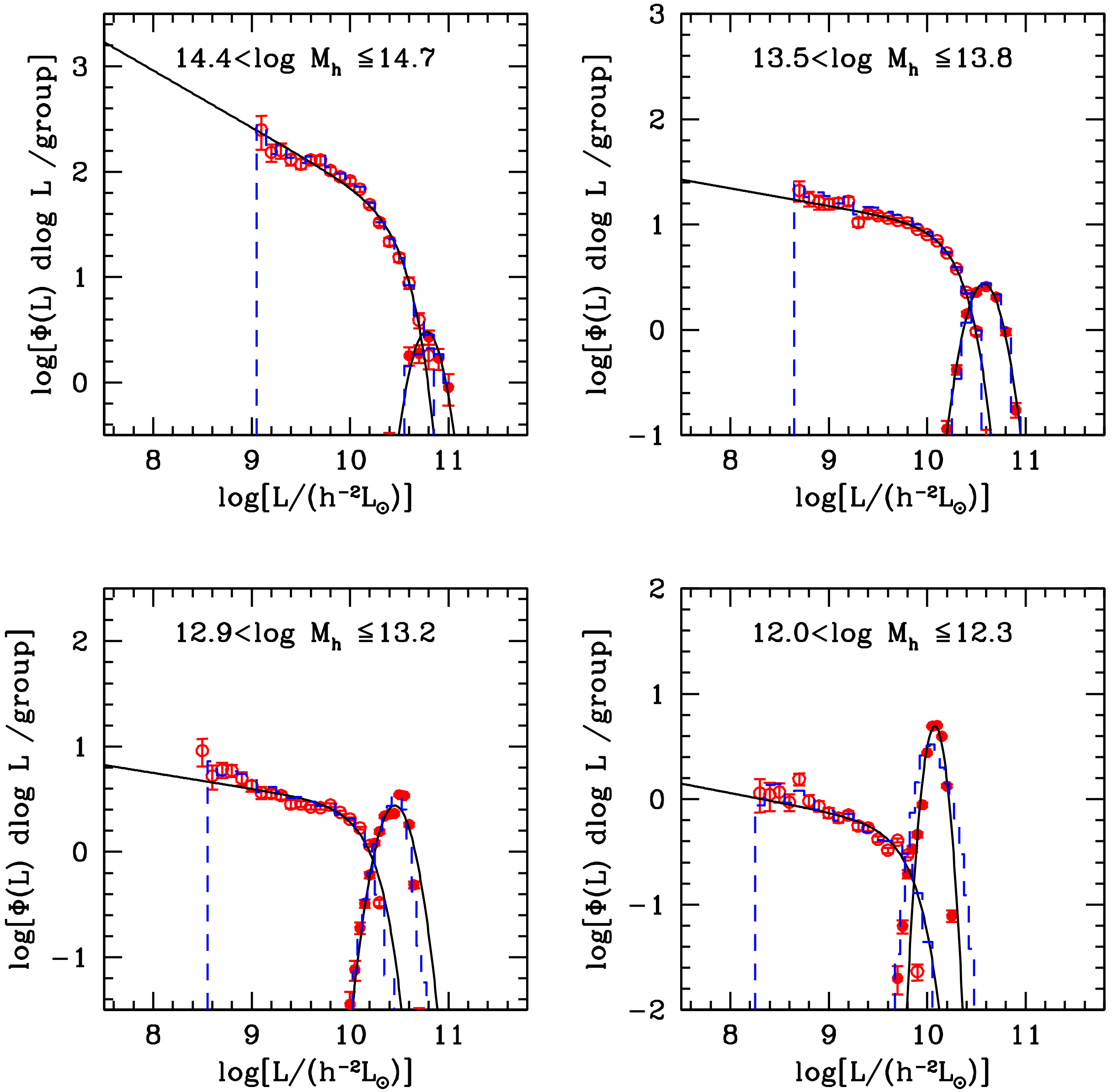


We developed new group-finding algorithm, which we used to construct large group catalogue from SDSS.

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

Yang et al. (2005, 2007)

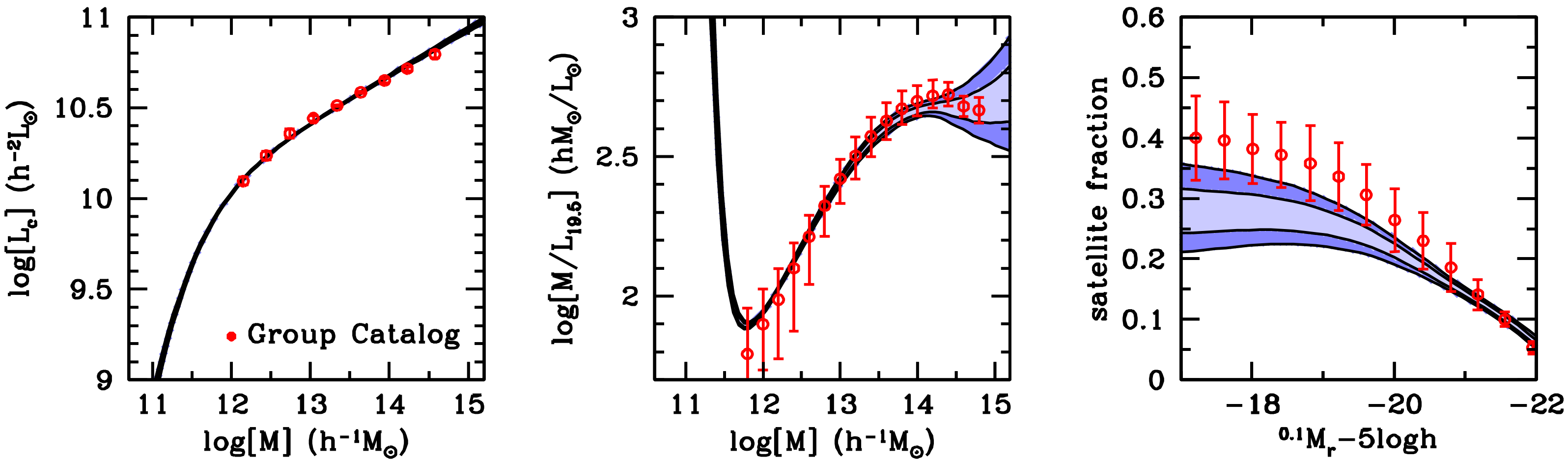
The CLF from SDSS Group Catalogue



Yang, Mo, vdB (2007)

The Galaxy-Dark Matter Connection II

- Constrain the **CLF** using luminosity function, $\Phi(L)$, and galaxy clustering data, $r_0(L)$, obtained from **SDSS**.
- Compare with results obtained from **SDSS group catalogue**.



Excellent agreement between CLF and Group results

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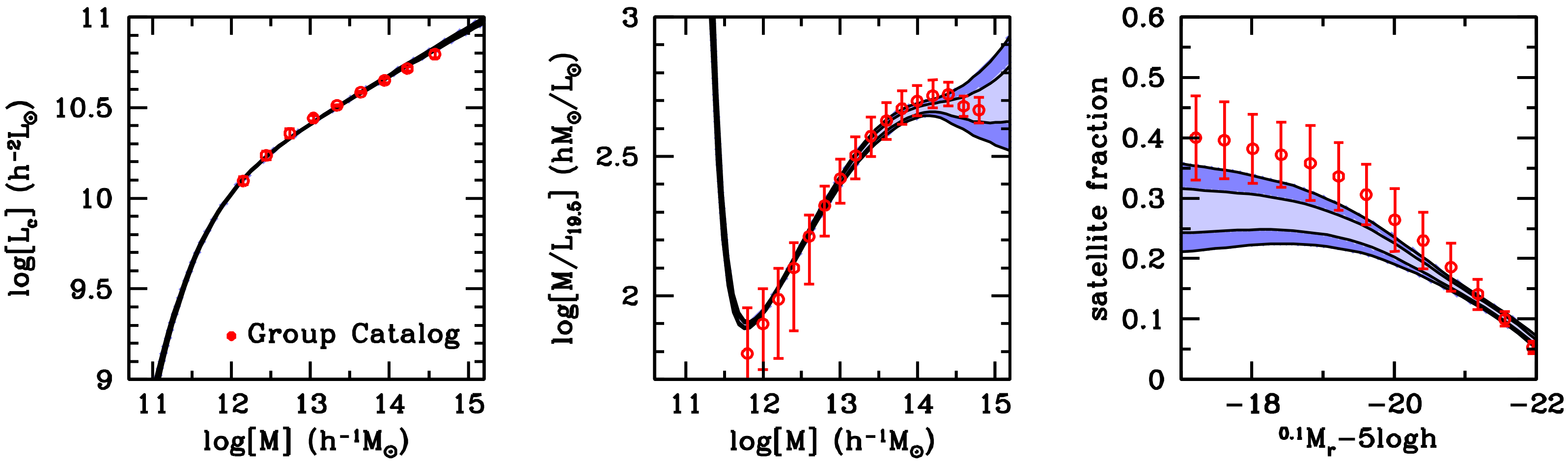
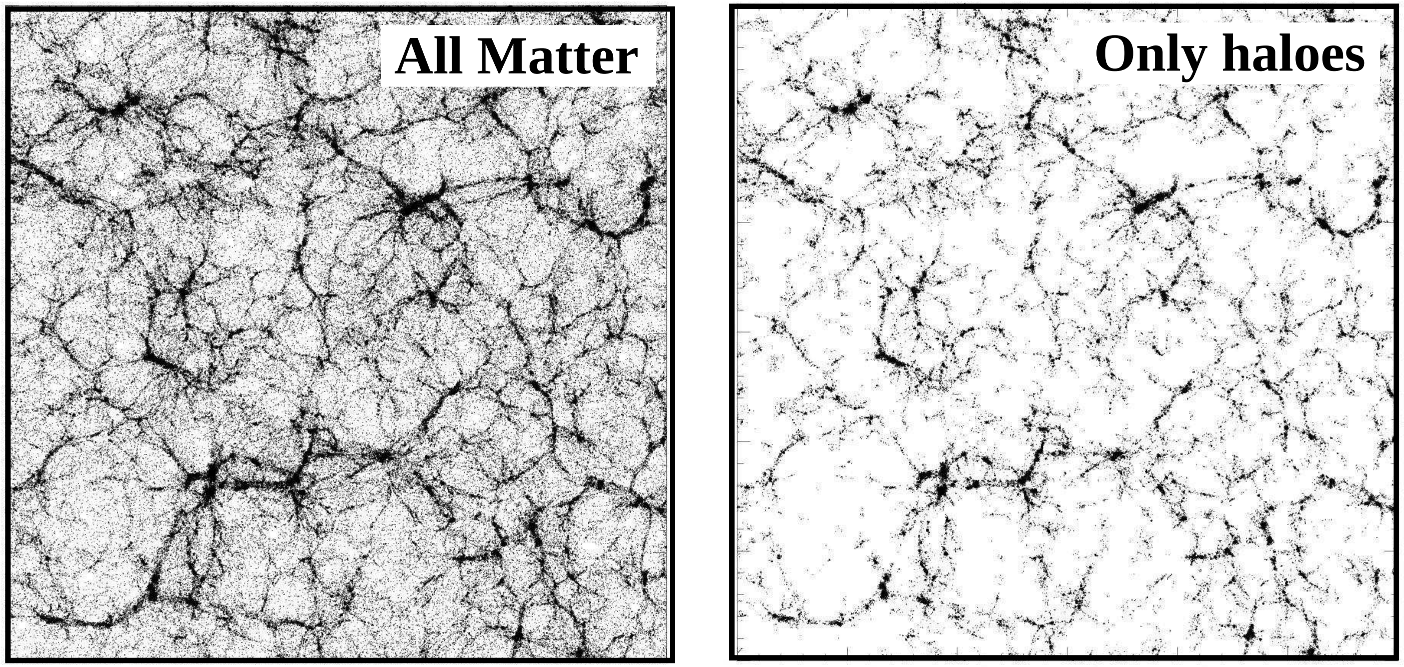
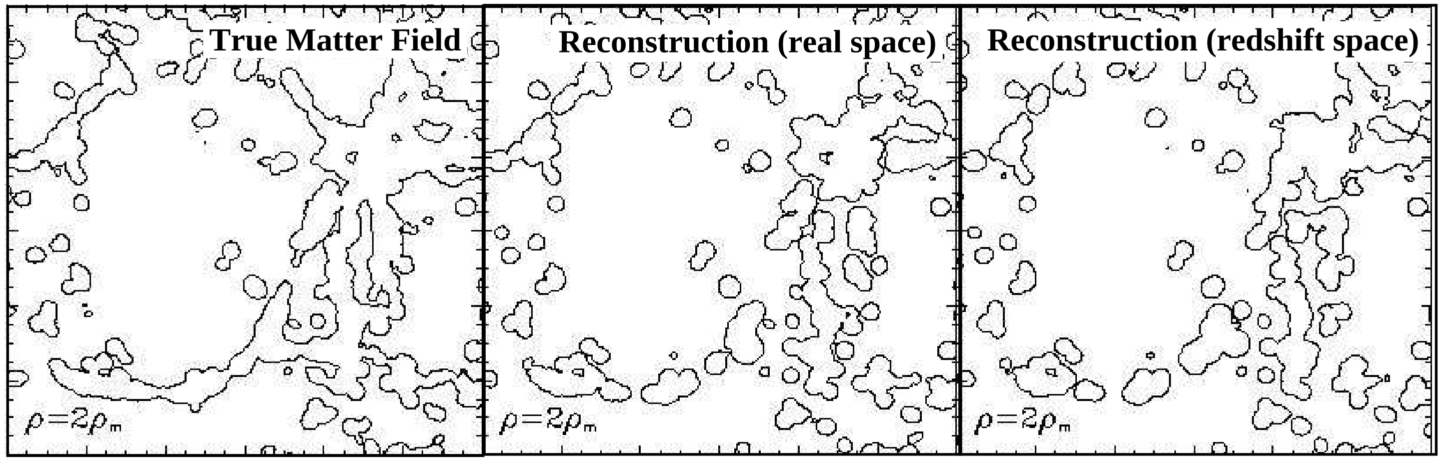


We have accurate, statistical description of how galaxies with different L are distributed over haloes of different M

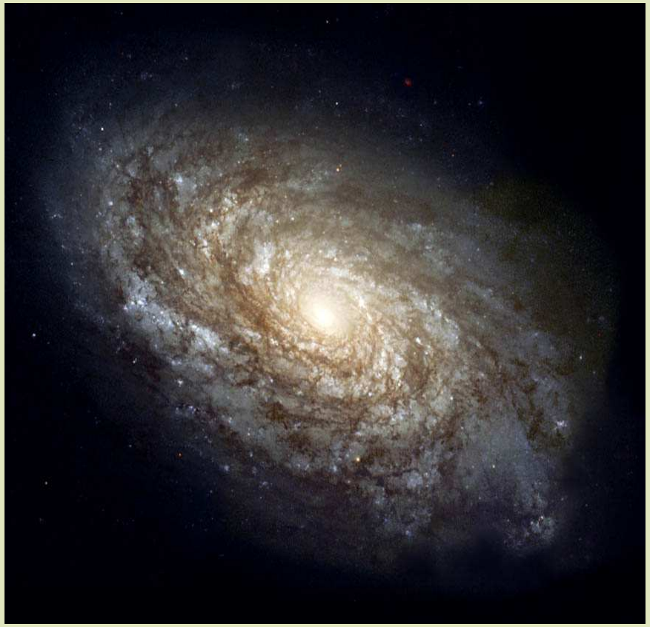
Reconstructing the Density Field





Wang et al. (2007)

The Bi-Modal Distribution of Galaxies

Early-Types	Late-Types
	
Spheroidal Morphology	Disk-like Morphology
Old Stellar Populations	Young Stellar Populations
No or Little Cold Gas	Abundant Cold Gas
Red Colors	Blue colors

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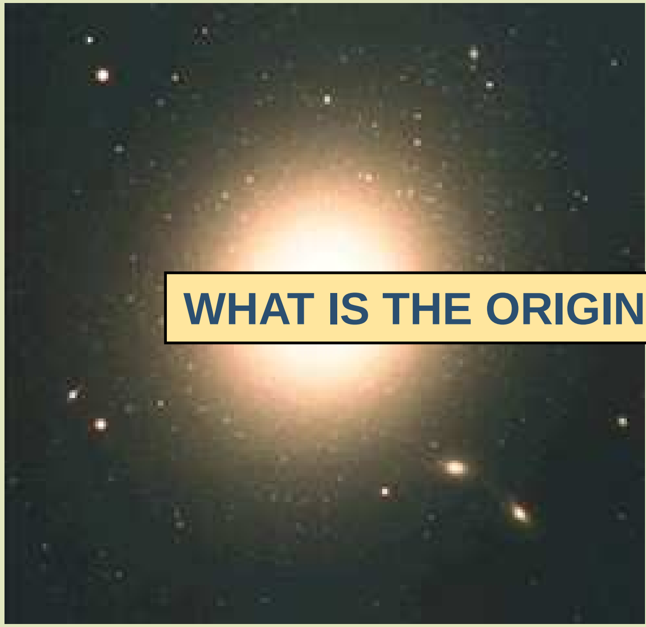	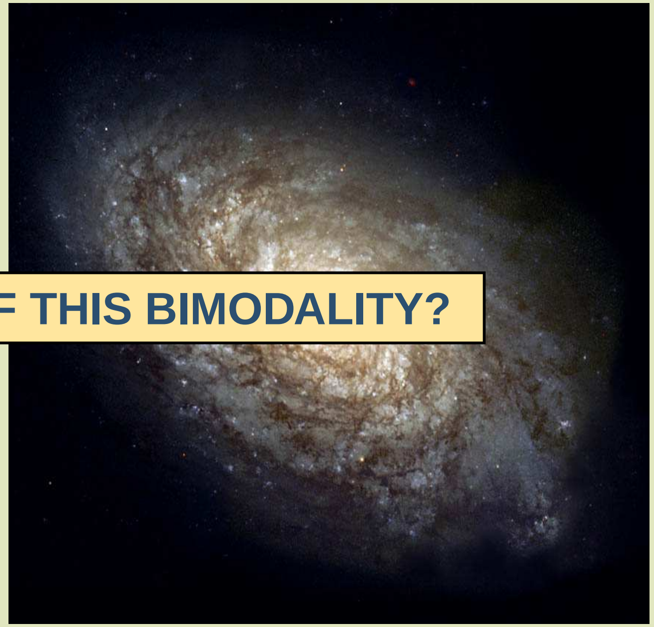
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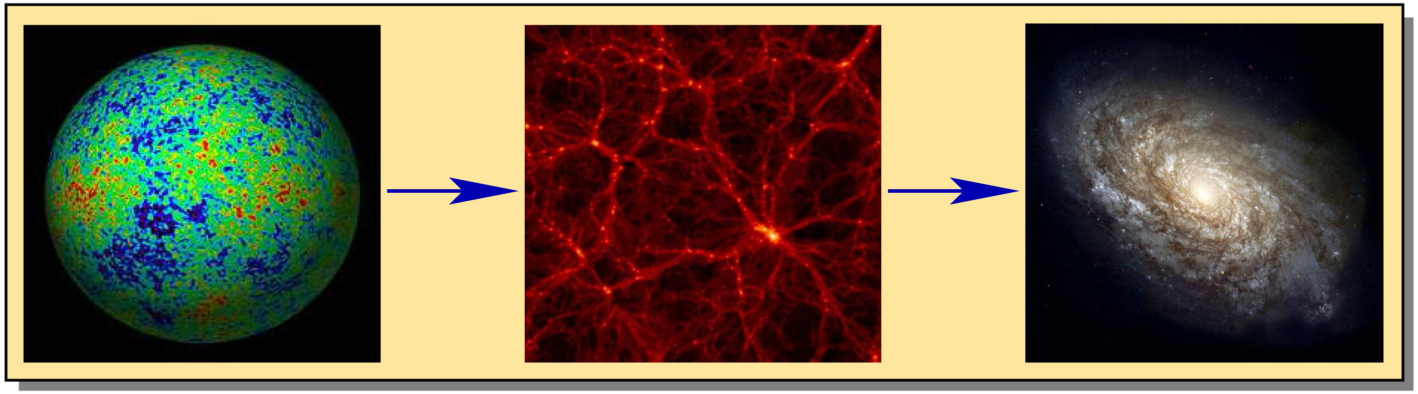
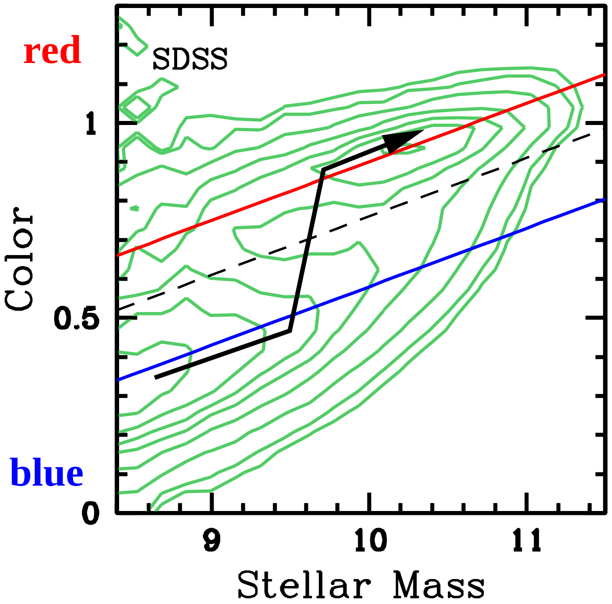
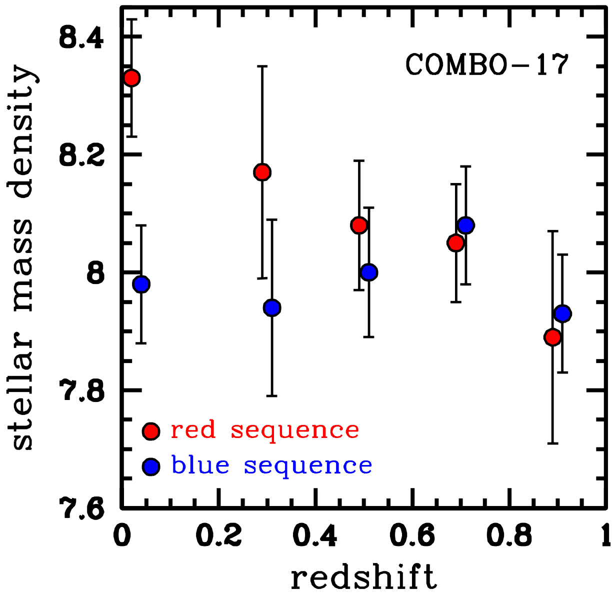
WHAT IS THE ORIGIN OF THIS BIMODALITY?

The Standard Paradigm

PARADIGM: All galaxies originally form as central disk galaxies.

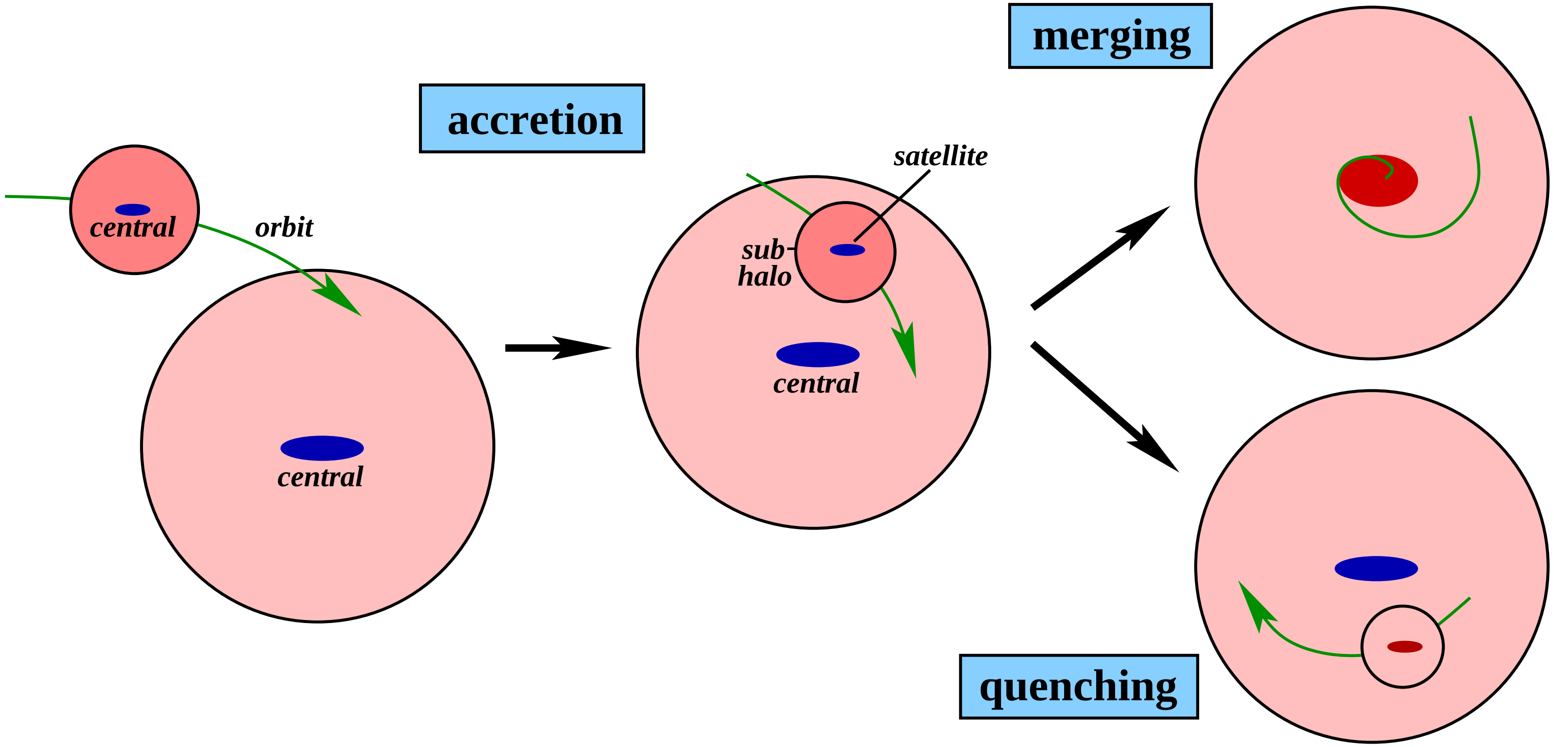






(Wolf et al. 2003; Bell et al. 2004; Borch et al. 2006)

Galaxy Transformations



In ΛCDM cosmology dark matter haloes grow hierarchically.

A major merger between disk galaxies results in an early-type remnant.

There are also several satellite-specific transformation processes:

- **Strangulation** — stripping of hot gas atmosphere
- **Ram-pressure stripping** — stripping of cold gas
- **Galaxy Harassment** — impulsive encounters with other satellites

Outstanding Questions

- **What fraction of the red-sequence satellites underwent their transformation as a satellite?**
- **Which Transformation Process is Most Important?**
- **In what Environment (dark matter halo) do Galaxies undergo their Transformation?**
- **To what extent are Satellite-Specific Transformation Processes responsible for Environment Dependence of Galaxy Population?**

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To address these questions we use our SDSS galaxy group catalog

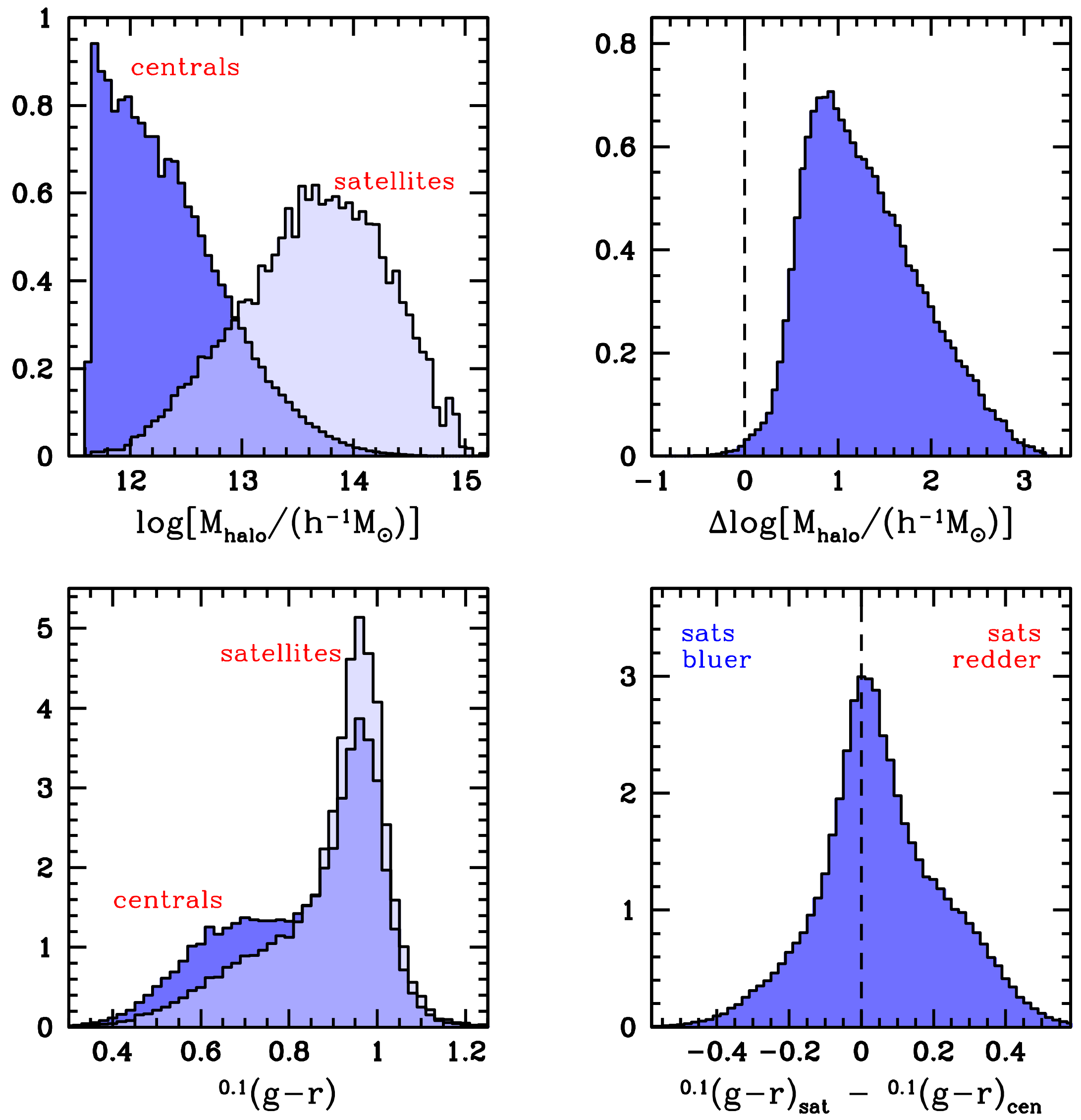
(Yang et al. 2005, 2007)

This allows us to split galaxy population in centrals and satellites, and to study galaxy properties as function of halo mass

(vdB et al. 2005, 2007; Weinmann et al. 2006; Yang et al. 2006; Moster et al. 2007)

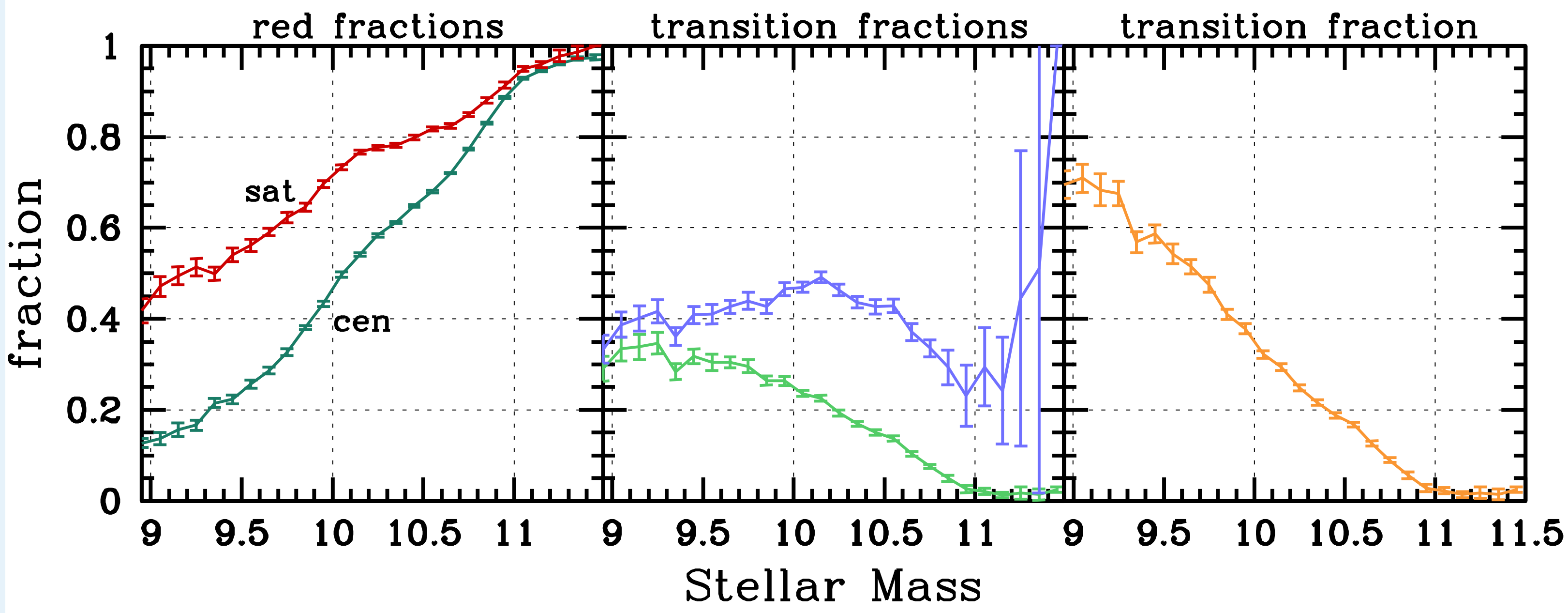
We study impact of satellite-specific transformation processes by comparing satellites to centrals of the same stellar mass, M_*

Centrals vs. Satellites: matched in stellar mass



Sats are marginally redder than centrals of same M_{star}

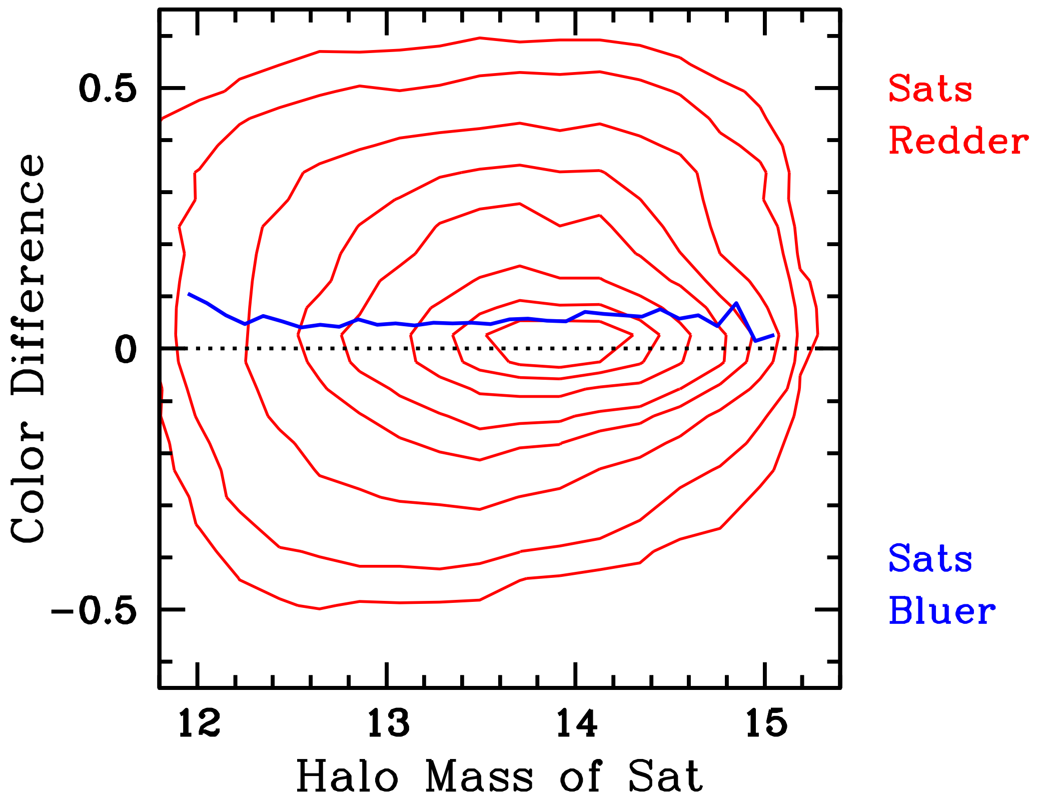
Blue-to-Red Transition Fractions



- The **red** fraction of SATs is higher than that of CENs of same $M_{\rm star}$.
- Roughly 40% of SATs that are **blue** at accretion undergo transition.
- Above $10^{10} h^{-2}\,{\rm M}_{\odot}$ majority of SATs were already **red** at accretion.

Satellite transformation processes only important at low $M_{\rm star}$

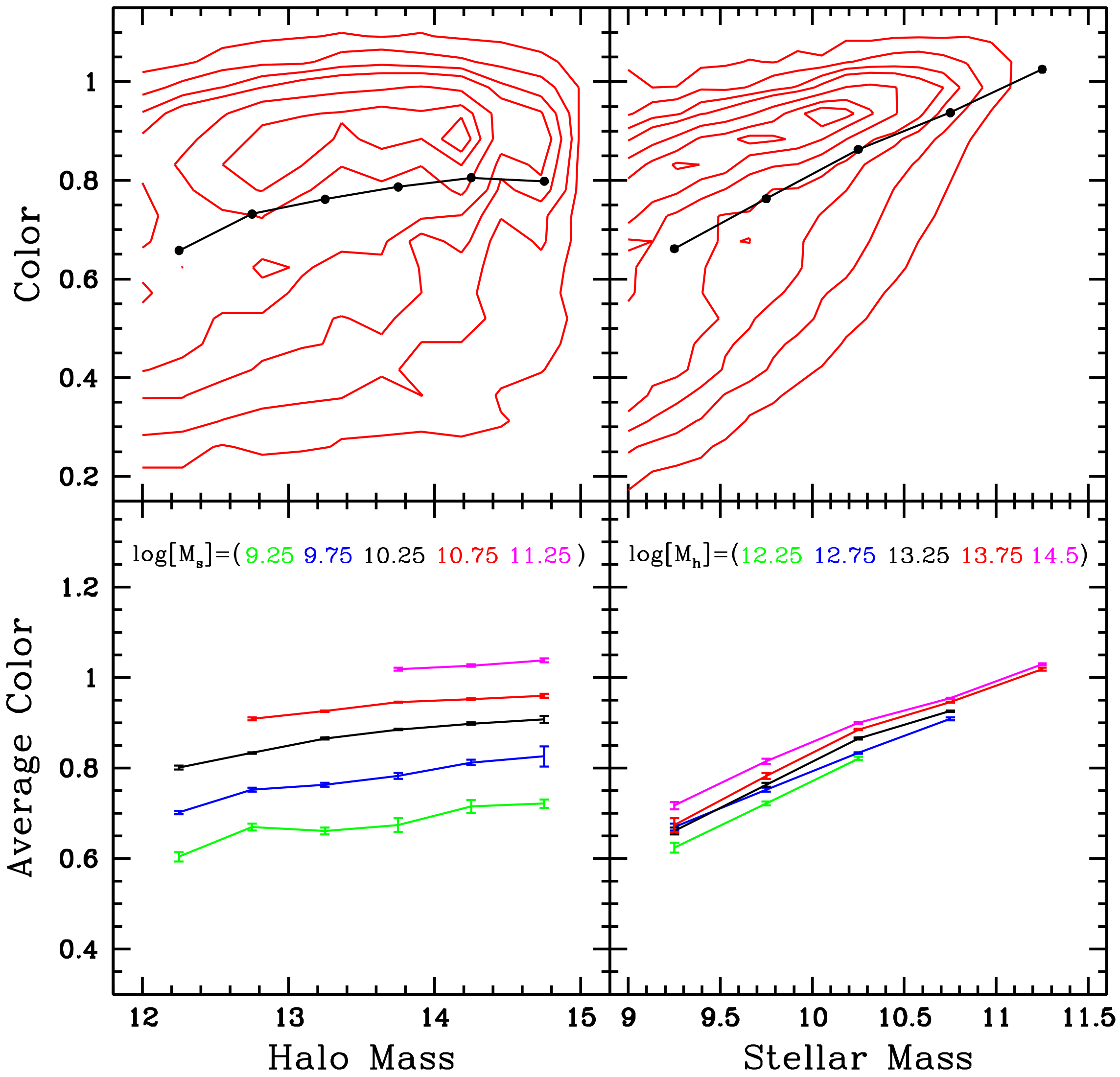
Dependence on Halo Mass



- **Color difference is independent of halo mass of satellite**
- **Transformation efficiency is independent of halo mass**

Strangulation is main satelite-specific transformation mechanism

Satellite Ecology



At fixed $M_{\rm star}$, average satellite color independent of environment

Conclusions

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  From 70% at $\log(M_*) = 9$ to 0% at $\log(M_*) = 11$

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  Strangulation...but needs to be better understood

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- **In what Environment (dark matter halo) do Galaxies undergo their Transformation?**

  In all haloes of all masses

- **To what extent are Satellite-Specific Transformation Processes responsible for Environment Dependence of Galaxy Population?**

Conclusions

- What fraction of the red-sequence satellites underwent their transformation as a satellite?

  From 70% at $\log(M_*) = 9$ to 0% at $\log(M_*) = 11$

- Which Transformation Process is Most Important?

  Strangulation...but needs to be better understood

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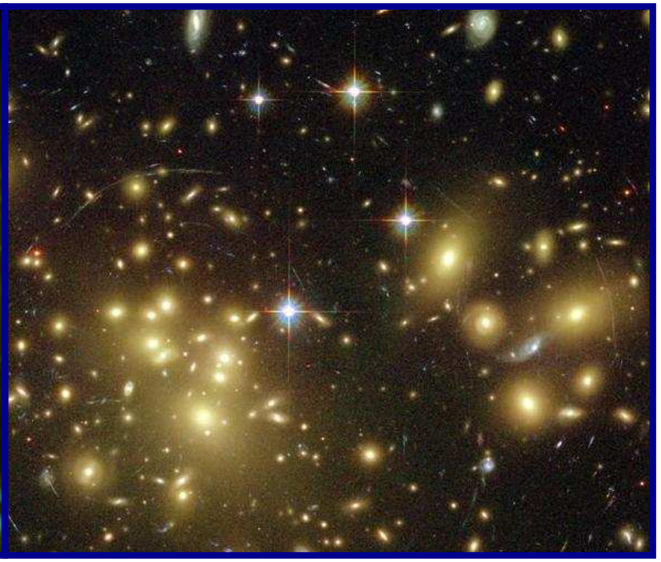
Environment dependence largely vanishes when separating centrals and satellites and when keeping stellar mass fixed.

Motivation and Techniques

Why study the Galaxy-Dark Matter Connection?

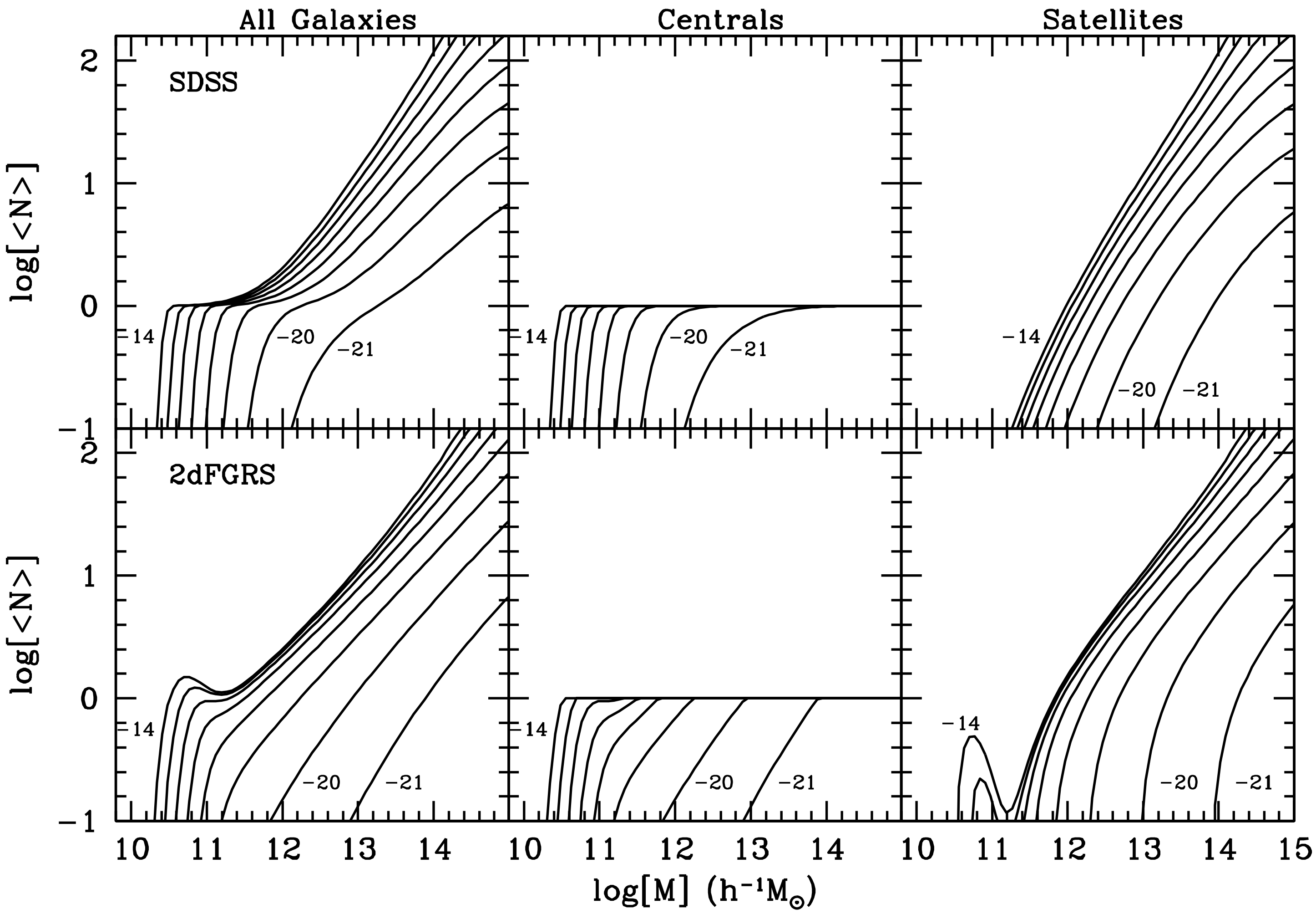
- To constrain the physics of Galaxy Formation
- To constrain Galaxy Bias and Cosmological Parameters
- To interpret Galaxy-Galaxy Lensing and Satellite Kinematics



How to Constrain the Galaxy-Dark Matter Connection?

- Luminosity Dependent Clustering
- Galaxy Group Catalogues
- Galaxy-Galaxy Lensing

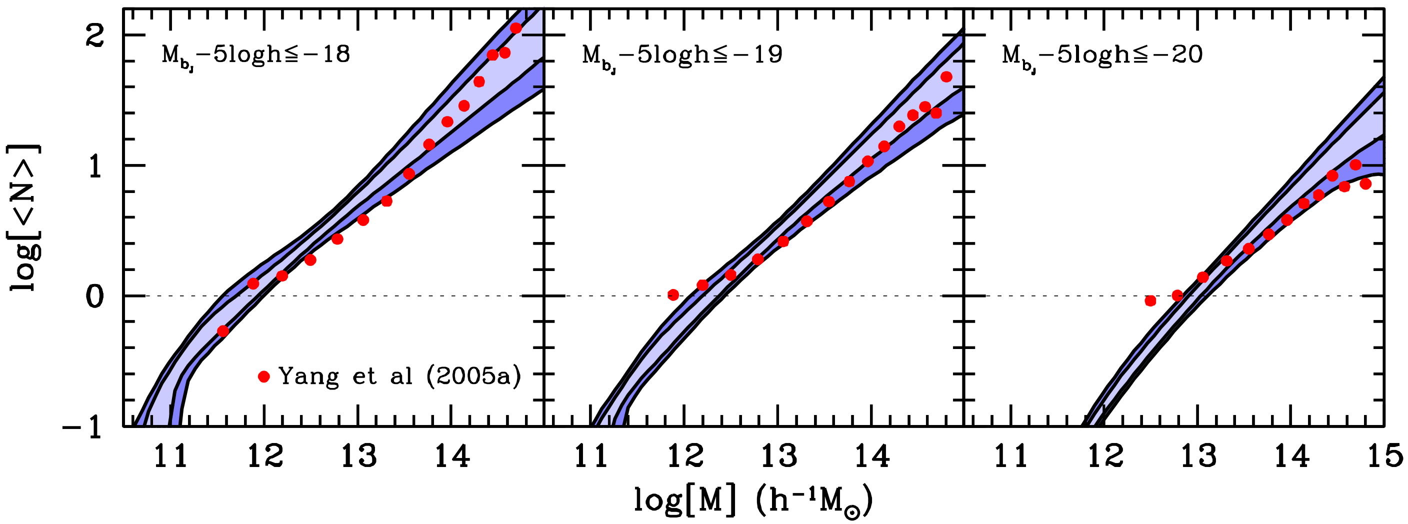
Halo Occupation Numbers



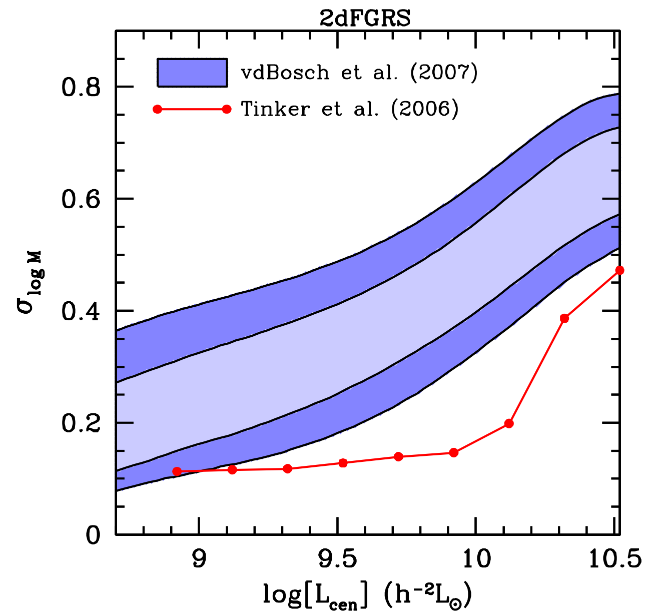
- **Unlike 2dFGRS, the SDSS reveals clear shoulders at $\langle N \rangle_M = 1$**
- **Most likely this is an ‘artefact’ of the functional form of the CLF**

HOD results for 2dFGRS

Comparison of 2dFGRS HOD from CLF and from Group Catalogue:

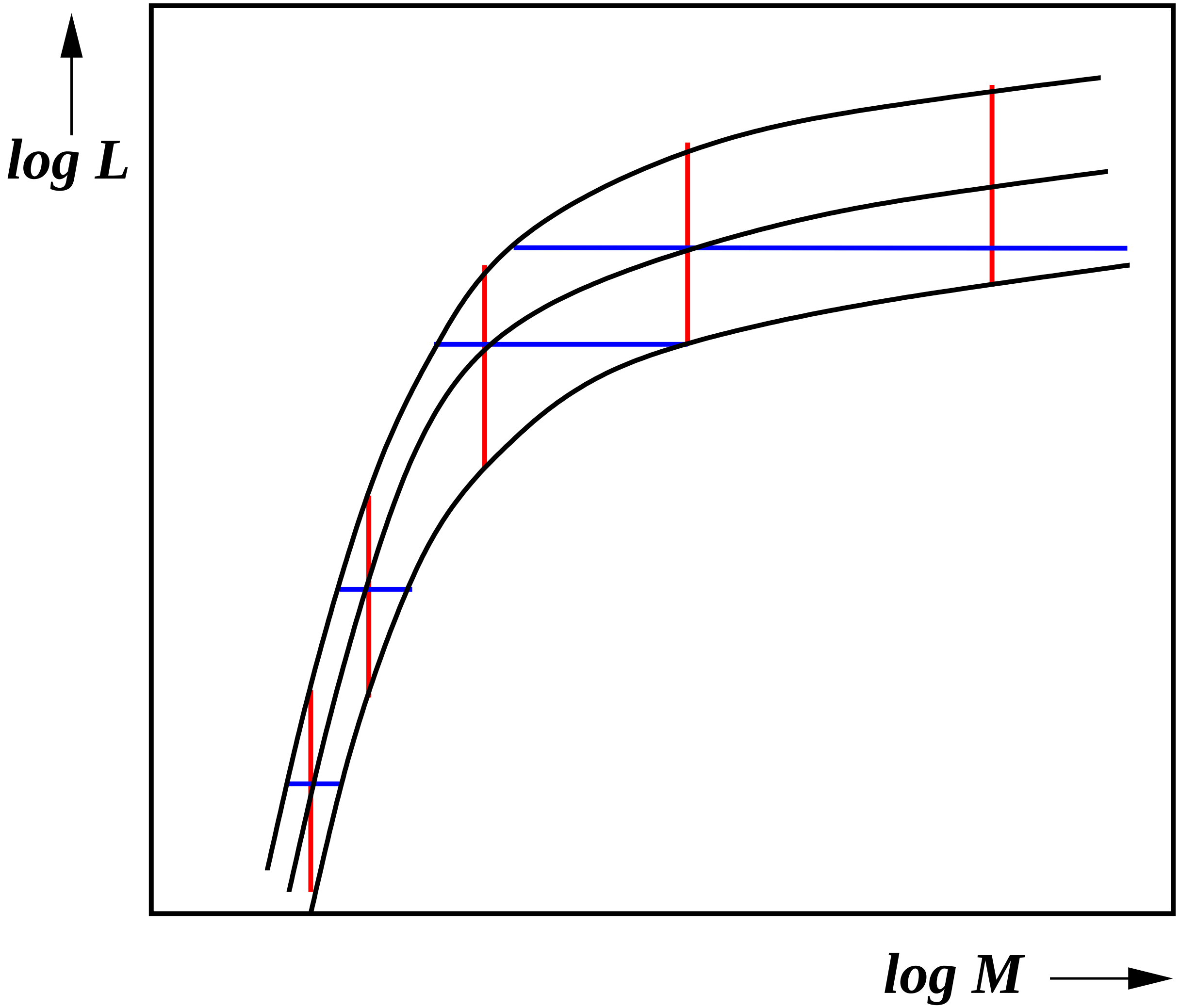


The transition $\langle N \rangle_M = 0 \rightarrow 1$ is 'smooth', indicating that $P(M|L_{\rm cen})$ is broad.



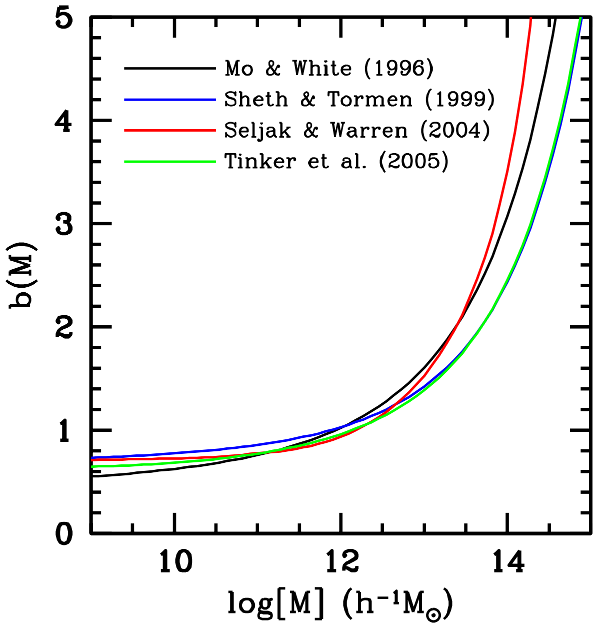
Very different from most HOD models, which often model transition as step-function, which corresponds to $P(M|L_{\rm cen}) = \delta[M - \langle M \rangle(L_{\rm cen})]$

The origin of $\sigma_{\log M}(L)$



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

Analytical Description of Halo Bias



Define **halo bias** as $b(m) = \langle \delta_h(m)/\delta \rangle$

Then the halo-halo correlation function for haloes of mass m can be written as

$$\xi_{\rm hh}(r) \equiv \langle \delta_{h_1} \delta_{h_2} \rangle = b^2(m)\xi(r)$$

More massive dark matter haloes are more strongly clustered

Clustering strength of galaxies is a measure of the mass of the haloes in which they reside

Halo Occupation Statistics completely specifies Halo Bias

Halo Occupation Statistics also constrain **Galaxy Formation**

The CLF Model

For 2dFGRS we assume that CLF has Schechter form:

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

Here Φ^*, L^* and α all depend on M.

(e.g., Yang et al. 2003; vdB et al. 2003, 2005)

For SDSS we split CLF in central and satellite components:

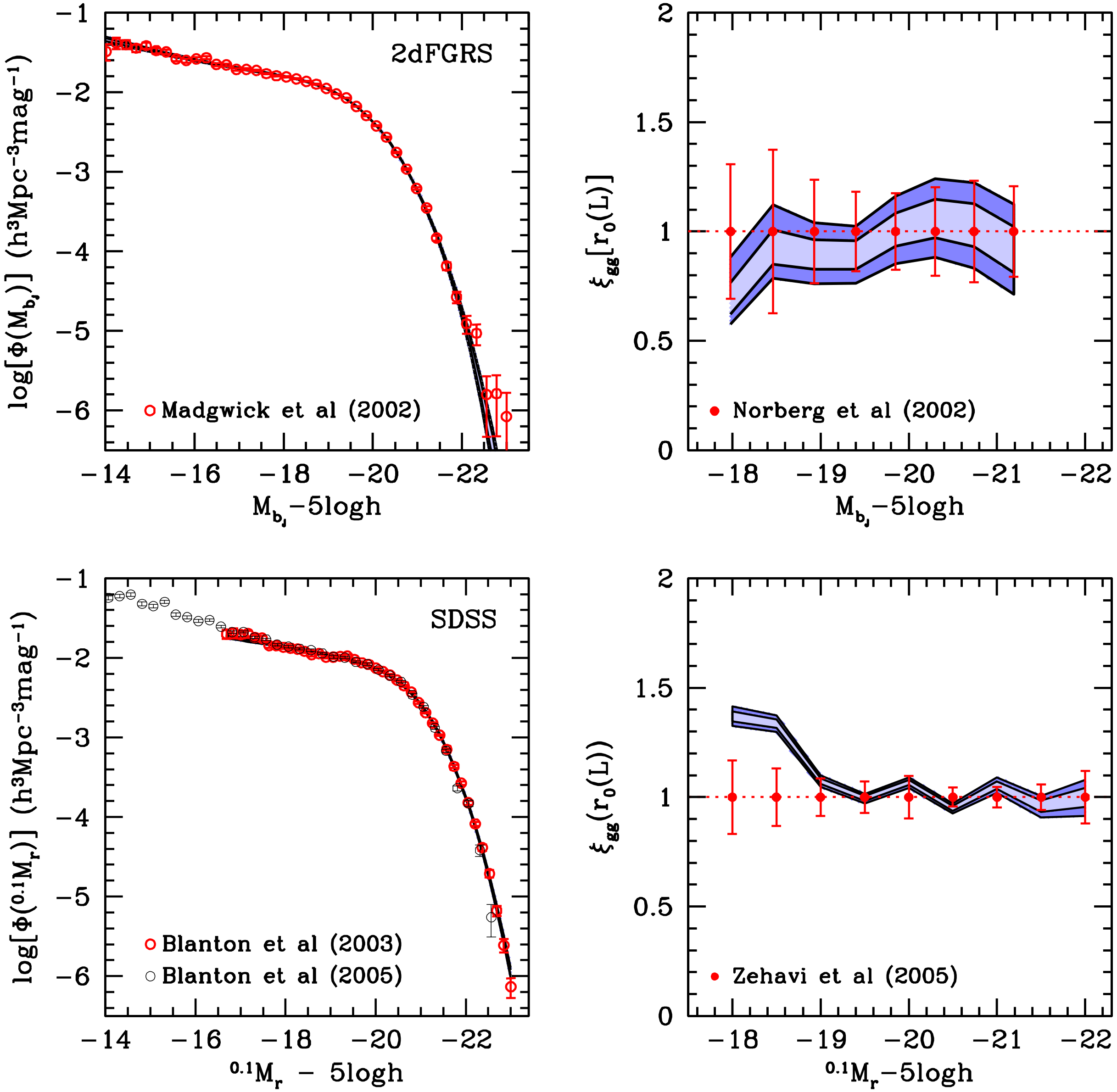
$$\begin{aligned}
\Phi(L|M)\mathrm{d}L &= \Phi_c(L|M)\mathrm{d}L + \Phi_s(L|M)\mathrm{d}L \\
\Phi_c(L|M)\mathrm{d}L &= \frac{1}{\sqrt{2\pi}\,\ln(10)\,\sigma_c} \exp\left[-\left(\frac{\log(L/L_c)}{\sqrt{2}\sigma_c}\right)^2\right] \frac{\mathrm{d}L}{L} \\
\Phi_s(L|M)\mathrm{d}L &= \frac{\Phi_s}{L_s} \left(\frac{L}{L_s}\right)^{\alpha_s} \exp[-(L/L_s)^2]\,\mathrm{d}L
\end{aligned}$$

Here L_c, L_s, σ_c, ϕ_s and α_s all depend on M

(e.g., Cooray & Milosavljevic 2005; Cooray 2005, 2006; vdB et al. 2007)

Use Monte-Carlo Markov Chain to constrain free parameters by fitting to $\Phi(L)$ and $r_0(L)$.

Best-Fit Models



2dFGRS: vdB et al. 2006 (astro-ph/0610686)

SDSS: vdB et al. 2007 (in preparation)

Constructing Galaxy Group Catalogues

Galaxy-Dark Matter connection can be studied more directly by measuring the occupation statistics of galaxy groups.

Potential Problems: interlopers, (in)completeness, mass estimates

We have developed a new, iterative group finder which uses an adaptive filter modeled after halo virial properties

Yang, Mo, vdB, Jing 2005, MNRAS, 356, 1293

- **Calibrated & Optimized with Mock Galaxy Redshift Surveys**
- **Low interloper fraction ($\lesssim 20\%$).**
- **High completeness of members ($\gtrsim 90\%$).**
- **Masses estimated from group luminosities/stellar masses. More accurate than using velocity dispersion of members.**
- **Can also detect "groups" with single member**
  - ▷ **Large dynamic range ($11.5 \lesssim \log[M/\mathrm{M}_\odot] \lesssim 15$).**

Group finder has been applied to both the 2dFGRS (completed survey) and to the SDSS (NYU-VAGC DR2 + DR4; Blanton et al. 2005)