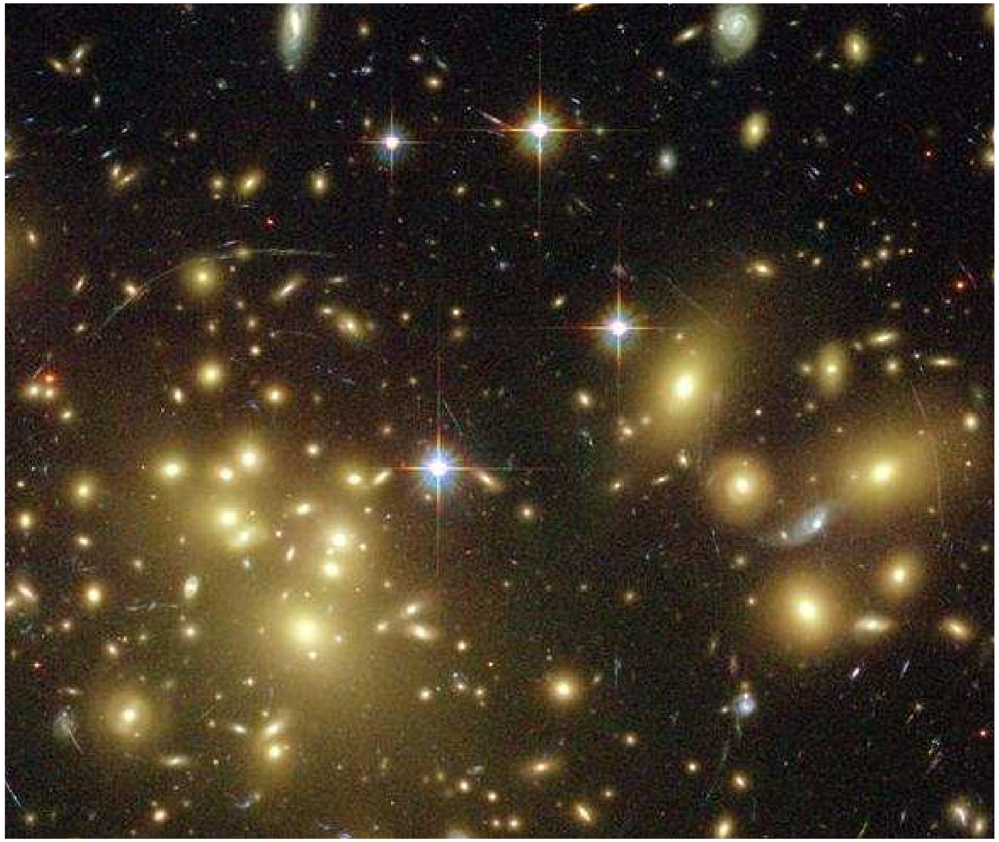
The Galaxy–Dark Matter Connection

cosmology & galaxy formation with the CLF

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Outline

- Basics of Gaussian Random Fields & Press-Schechter Formalism
- Galaxy Bias & The Galaxy-Dark Matter Connection
- Halo Bias & The Halo Model
- Halo Occupation Statistics
- The Conditional Luminosity Function (CLF)
- The Universal Relation between Light and Mass
- Cosmological Constraints & Large Scale Structure
- Galaxy Groups
- Satellite Kinematics
- Brightest Halo Galaxies
- Galaxy Ecology
- Environment Dependence
- Conclusions

Correlation Functions

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

For a Gaussian random field, the one-point probability function is:

$$P(\delta)\mathrm{d}\delta = \frac{1}{\sqrt{2\pi}\sigma}\exp\left[-\frac{\delta^2}{2\sigma^2}\right]\mathrm{d}\delta$$

$$\begin{aligned} \langle\delta\rangle &= \int \delta P(\delta)\mathrm{d}\delta &= 0 \\ \langle\delta^2\rangle &= \int \delta^2 P(\delta)\mathrm{d}\delta &= \sigma^2 \end{aligned}$$

Define n-point probability function: $P_n(\delta_1, \delta_2, \cdots, \delta_n)\ \mathrm{d}\delta_1\,\mathrm{d}\delta_2 \cdots\ \mathrm{d}\delta_n$

Gravity induces correlations between δ_i so that

$$P_n(\delta_1, \delta_2, \cdots, \delta_n) \neq \prod_{i=1}^{n} P(\delta_i)$$

Correlations are specified via n-point correlation function:

$$\langle\delta_1\delta_2\cdots\delta_n\rangle = \int \delta_1\delta_2\cdots\delta_n P_n(\delta_1, \delta_2, \cdots, \delta_n)\ \mathrm{d}\delta_1\,\mathrm{d}\delta_2\cdots\ \mathrm{d}\delta_n$$

In particular, we will often use the two-point correlation function

$$\xi(x) = \langle\delta_1\delta_2\rangle \quad \text{with } x = |\vec{x}_1 - \vec{x}_2|$$

Power Spectrum

It is useful to write $\delta(\vec{x})$ as a Fourier series:

$$\delta(\vec{x}) = \sum_{\vec{k}} \delta_{\vec{k}} \mathrm{e}^{i\vec{k}\cdot\vec{x}} \qquad \delta_{\vec{k}} = \frac{1}{V}\int \delta(\vec{x})\mathrm{e}^{-i\vec{k}\cdot\vec{x}}\mathrm{d}^3\vec{x}$$

Note that $\delta_{\vec{k}}$ are complex quantities: $\delta_{\vec{k}} = |\delta_{\vec{k}}|\mathrm{e}^{i\theta_{\vec{k}}}$

Decomposition in Fourier modes is preserved during linear evolution, so that

$$P_n\left(\delta_{\vec{k}_1}, \delta_{\vec{k}_2}, \cdots, \delta_{\vec{k}_n}\right) = \prod_{i=1}^{n} P(\delta_{\vec{k}_i})$$

Thus, statistical properties of $\delta(\vec{x})$ completely specified by $P(\delta_{\vec{k}})$

A Gaussian random field is completely specified by first two moments:

$$\begin{aligned} \langle \delta_{\vec{k}} \rangle &= 0 \\ \langle |\delta_{\vec{k}}|^2 \rangle &= P(k) \qquad \text{Power Spectrum} \\ \langle \delta_{\vec{k}} \delta_{\vec{p}} \rangle &= 0 \qquad (\text{for } k \neq p) \end{aligned}$$

The power spectrum is Fourier Transform of two-point correlation function:

$$\xi(r) = \frac{1}{(2\pi)^3}\int P(k)e^{i\vec{k}\cdot\vec{r}}\mathrm{d}^3\vec{k} = \frac{1}{2\pi^2}\int_0^\infty P(k)\frac{\sin kr}{kr}k^2\mathrm{d}k$$

Mass Variance

Let $\delta_M(\vec{x})$ be the density field $\delta(\vec{x})$ smoothed (convolved) with a filter of size $R_f \propto [M/\bar{\rho}]^{1/3}$.

Since convolution is multiplication in Fourier space, we have that

$$\delta_M(\vec{x}) = \sum_{\vec{k}} \delta_{\vec{k}} \, \widehat{W}_M(\vec{k}) \, \mathrm{e}^{i\vec{k}\cdot\vec{x}}$$

with $\widehat{W}_M(\vec{k})$ the FT of the filter function $W_M(\vec{x})$.

The mass variance is simply

$$\boxed{\sigma^2(M) = \langle\delta_M^2\rangle = \frac{1}{2\pi^2}\int P(k)\widehat{W}_M^2(k)\, k^2 \mathrm{d}k}$$

Note that $\sigma^2(M) \rightarrow 0$ if $M \rightarrow \infty$.

Press-Schechter Formalism

In CDM universes, density perturbations grow, turn around from Hubble expansion, collapse, and virialize to form dark matter halo.

According to spherical collapse model the collapse occurs when

$$\delta_{\rm lin} = \delta_{\rm sc} \simeq \frac{3}{20}(12\pi)^{2/3} \simeq 1.686$$

$\delta_{\rm lin}$ is linearly extrapolated density perturbation field

$\delta_{\rm sc}$ is critical overdensity for spherical collapse.

Press-Schechter ansatz: if $\delta_{{\rm lin},M}(\vec{x}) > \delta_{\rm sc}$ then $\vec{x}$ is located in a halo with mass $> M$.

The probability that $\vec{x}$ is in a halo of mass $> M$ therefore is

$$P(\delta_{{\rm lin},M} > \delta_{\rm sc}) = \frac{1}{\sqrt{2\pi}\sigma(M)} \int_{\delta_{\rm sc}}^{\infty} \exp\left(-\frac{\delta^2}{2\sigma^2(M)}\right) {\rm d}\delta$$

The Halo Mass Function, then becomes

$$n(M){\rm d}M = \frac{\bar{\rho}}{M}\frac{{\rm d}P}{{\rm d}M}{\rm d}M = \sqrt{\frac{2}{\pi}}\frac{\bar{\rho}}{M^2}\left|\frac{{\rm d}\ln\sigma}{{\rm d}\ln M}\right|\sqrt{\nu}{\rm e}^{-\nu/2}$$

where $\nu = \delta_{\rm sc}^2/\sigma^2(M)$, and a ‘fudge-factor’ 2 has been added.

Galaxy Bias

Consider the distribution of matter and galaxies, smoothed on some scale R

$$\delta(\vec{x}) = \frac{\rho(\vec{x}) - \bar{\rho}}{\bar{\rho}} \qquad \delta_{\rm gal}(\vec{x}) = \frac{n_{\rm gal}(\vec{x}) - \bar{n}_{\rm gal}}{\bar{n}_{\rm gal}}$$

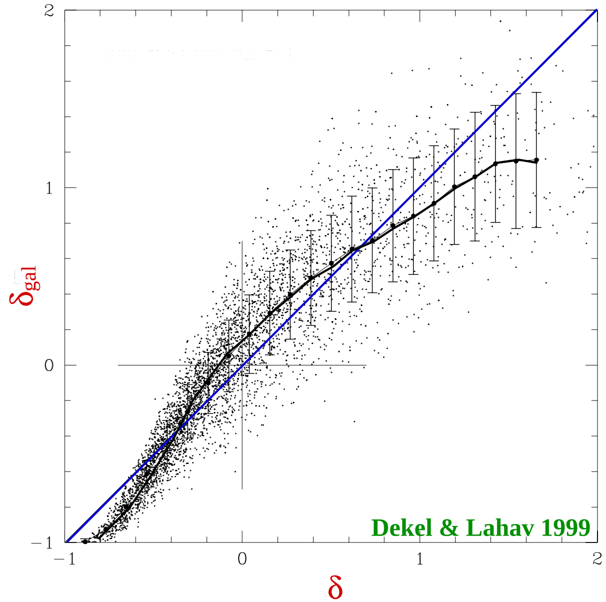
Mass distribution — Galaxy distribution

- There is no good reason why galaxies should trace mass.
- Ratio is galaxy bias: $b(\vec{x}) = \delta_{\rm gal}(\vec{x})/\delta(\vec{x})$
- Bias may depend on smoothing scale R
- One can distinguish various types of bias:

linear, deterministic: $\delta_{\rm gal} = b\,\delta$

non-linear, deterministic: $\delta_{\rm gal} = b(\delta)\,\delta$

stochastic: $\delta_{\rm gal} \neq \langle \delta_{\rm gal} | \delta \rangle$



- Real bias probably non-linear and stochastic
- Since $\delta_{\rm gal} = \delta_{\rm gal}(L, M_*, \ldots)$ bias also depends on galaxy properties

Handling Bias

- **Bias is an imprint of galaxy formation, which is poorly understood**
- **Consequently, little progress constraining cosmology with LSS**

Q: How can we constrain and quantify galaxy bias in a convenient way?

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Q: How can we constrain and quantify galaxy bias in a convenient way?

A: With Halo Model plus Halo Occupation Statistics!

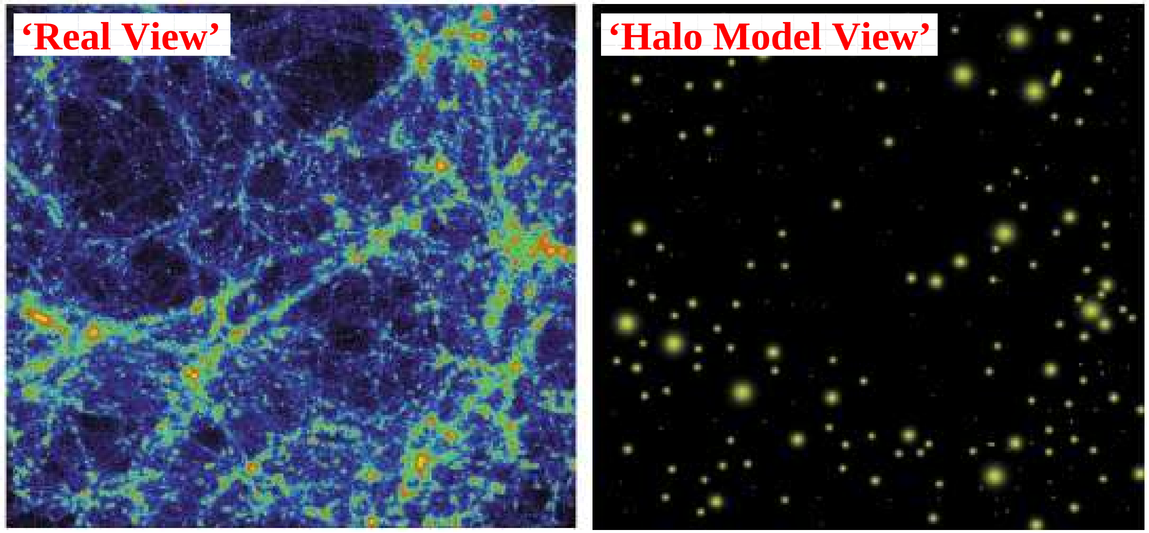
The Halo Model describes CDM distribution in terms of halo building blocks, under assumption that every CDM particle resides in virialized halo

- On small scales: $\delta(\vec{x})$ reflects density distribution of haloes (NFW profiles)
- On large scales: $\delta(\vec{x})$ reflects spatial distribution of haloes (halo bias)

PARADIGM: All galaxies live in Cold Dark Matter Haloes.

galaxy bias = halo bias + halo occupation statistics

Halo Model Ingredients



Cooray & Sheth (2002)

Halo Density Distributions: (Navarro, Frenk & White 1997)

$$\rho(r) = \frac{\rho_s}{(r/r_s)(1+r/r_s)^2}$$

Halo Mass Function: (Press & Schechter 1974)

$$n(m) = \sqrt{\frac{2}{\pi}} \frac{\bar{\rho}}{m^2} \left| \frac{\mathrm{d}\ln\sigma}{\mathrm{d}\ln m} \right| \sqrt{\nu} \mathrm{e}^{-\nu/2}$$

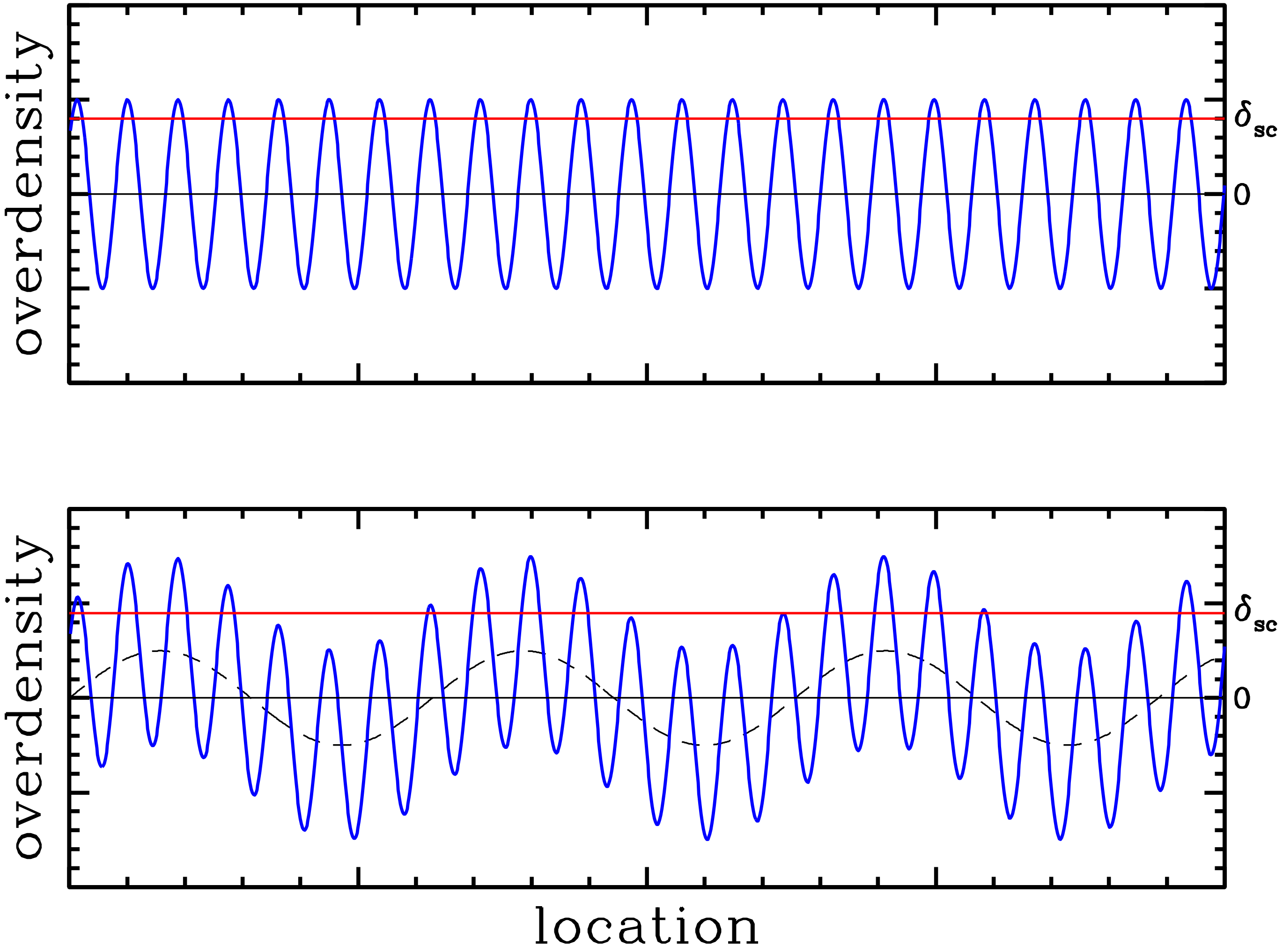
Halo Bias Function: (Kaiser 1994; Mo & White 1996)

$$b(m) \equiv \frac{\delta_h(m)}{\delta} = \frac{n(m|\delta) - n(m)}{n(m)\,\delta} = 1 + \frac{\nu - 1}{\delta_{\rm sc}}$$

$\delta_{\rm sc}$ is critical spherical collapse overdensity, $\sigma^2(m)$ is mass variance, and $\nu = \delta^2_{\rm sc}/\sigma^2(m)$

Statistical Halo Bias

Dark Matter Haloes are a biased tracer of the dark matter mass distribution!



Modulation causes statistical bias of peaks (haloes)

Dynamical Halo Bias

Halo bias has a statistical component plus a dynamical component

Growth of ‘modulation-perturbation’ causes increase in number density of haloes in overdense regions:

Consider a volume V with mass M, and let $M = V\bar{\rho}(1+\delta)$

Here δ is the overdensity of V

At very early times this mass was in a volume V_0 for which $M = V_0\bar{\rho}$

This basically reflects that $\delta_{\rm init} \ll 1$

$$\Rightarrow \quad \boxed{V(1+\delta) = V_0}$$

This reflects the dynamical biasing in the linear regime.

Derivation of Halo Bias I

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

Let $N(m|M,V)$ be the number of haloes of mass m in volume V.

The volume V has an overdensity δ so that $M = V\bar{\rho}(1+\delta)$ and initially was associated with a volume $V_0 = V(1+\delta)$.

The overdensity in the number of haloes of mass m is

$$\delta_h(m) = \frac{N(m|M,V)}{n(m)V} - 1$$

Here $n(m)$ is the (average) halo mass function.

To take account of the dynamical bias we write

$$N(m|M,V) = n(m|M,V)V_0 = n(m|M,V)V(1+\delta)$$

so that

$$\delta_h(m) = \frac{n(m|M,V)}{n(m)}(1+\delta) - 1$$

Derivation of Halo Bias II

PS ansatz: haloes are associates with regions with $\delta > \delta_{\rm sc}$

Therefore, we can compute $n(m|M,V) = n(m|\delta)$ by simply replacing $\delta_{\rm sc}$ with $\delta_{\rm sc} - \delta$ **(Peak-Background split)**.

Using that the **halo bias** is defined as $b(m) = \delta_h(m)/\delta$, one obtains that

$$b(m) = 1 + \frac{\nu - 1}{\delta_{\rm sc}}$$

where $\nu = \nu(m) = \delta_{\rm sc}^2/\sigma^2(m)$

Using that $\sigma(m^*) \equiv \delta_{\rm sc}$ we see that

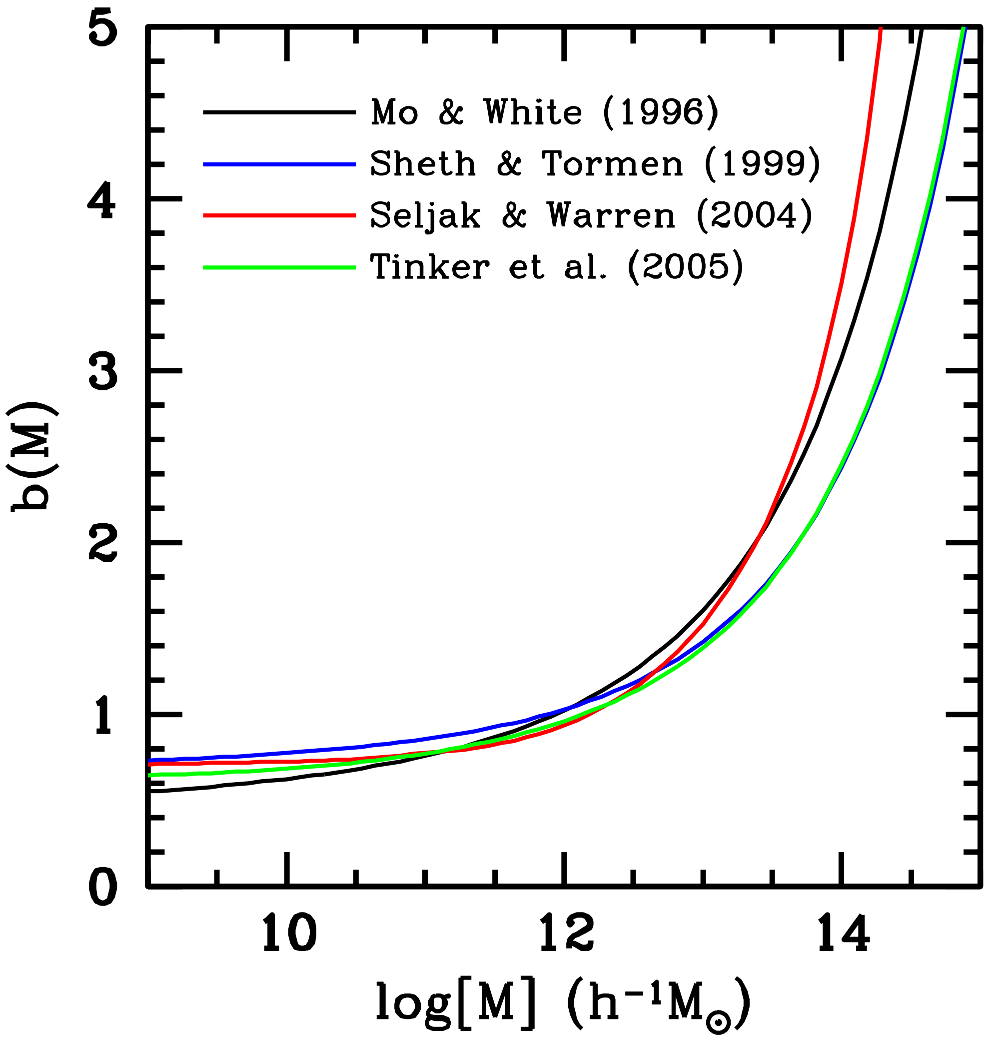
$b(m) > 1$	if $m > m^*$	(biased)
$b(m) = 1$	if $m = m^*$	(unbiased)
$1 - \frac{1}{\delta_{\rm sc}} < b(m) < 1$	if $m < m^*$	(anti-biased)

Note that there is an absolute minimim to the halo bias.

Halo-Halo correlation function:

$$\xi_{\rm hh}(r) \equiv \langle \delta_{h_1} \delta_{h_2} \rangle = b(m_1) b(m_2) \langle \delta_1 \delta_2 \rangle = b(m_1) b(m_2) \xi(r)$$

Fine-Tuning of Halo Bias



Modifications to the derived halo bias have been made based on ellipsoidal collapse corrections, and calibrations against numerical simulations.

Currently, this is one of the main sources of uncertainty in the halo model.

Halo Occupation Statistics

How many galaxies, on average, per halo?

Halo Occupation Distribution: The HOD $P(N|M)$ specifies the probability that a halo of mass M contains N galaxies.

Of particular importance: first moment $\langle N \rangle_M = \sum_{N=0} N\, P(N|M)$

How are galaxies distributed (spatially & kinematically) within halo?

Central Galaxy : located at center of dark matter halo.

Satellite Galaxies: $n_{\rm sat}(r) \propto \rho_{\rm dm}(r) \quad \Longleftrightarrow \quad \sigma_{\rm sat}(r) = \sigma_{\rm dm}(r)$

Supported by distribution of sub-haloes in N-body simulations

What are physical properties of galaxies (luminosity, color, morphology)

One needs separate HOD for each sub-class of galaxies...

Introduce Conditional Luminosity Function, $\Phi(L|M)$, which expresses average number of galaxies with luminosity L that reside in halo of mass M

The Conditional Luminosity Function

The CLF $\Phi(L|M)$ 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:

- **halo occupation numbers as function of luminosity:**

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

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

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

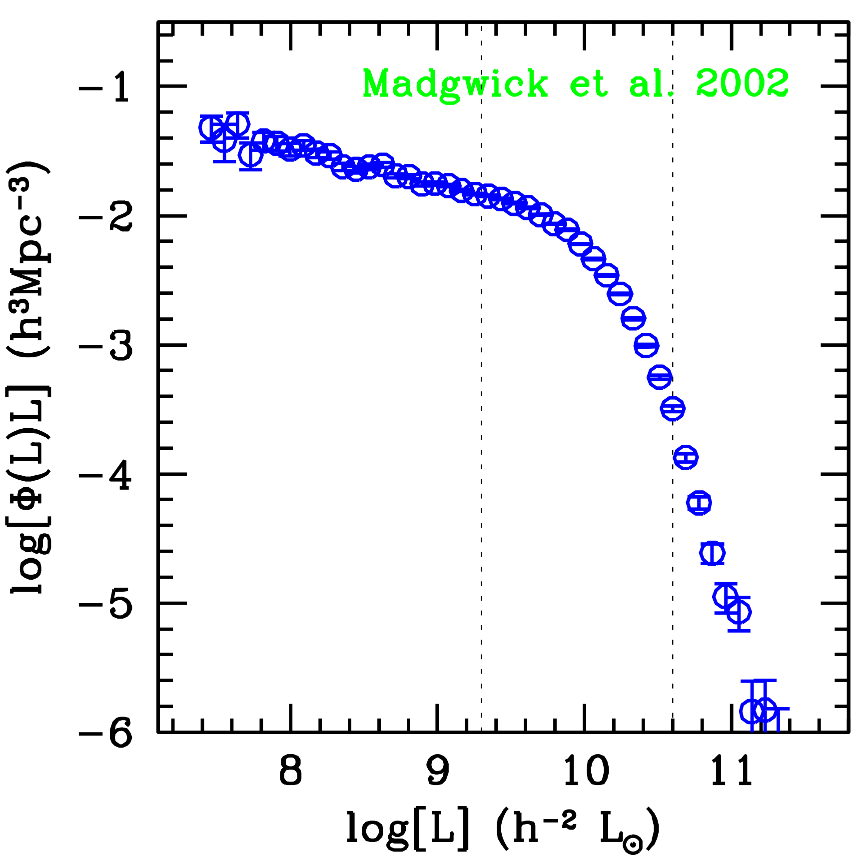
- **The bias of galaxies as function of luminosity:**

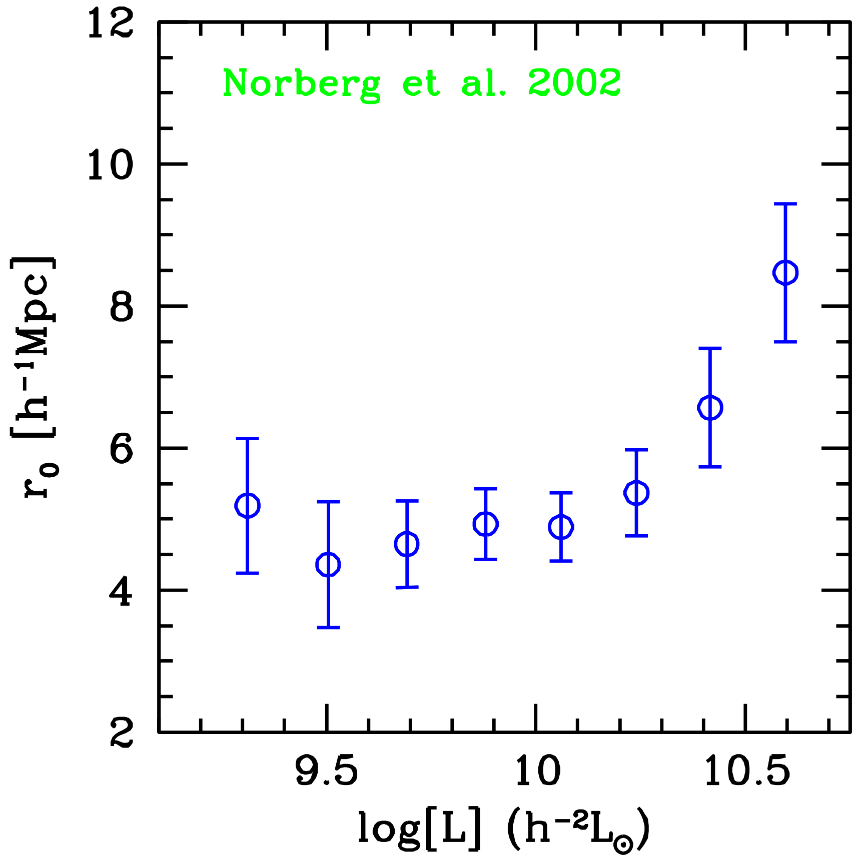
$$\xi_{\rm gg}(r|L) = b^2(L)\, \xi_{\rm dm}(r)$$

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

CLF is ideal statistical ‘tool’ to investigate Galaxy-Dark Matter Connection

Luminosity & Correlation Functions





- **2dFGRS:** 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 assume that the CLF 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.

Use Monte-Carlo Markov Chain to find model that best fits $\Phi(L)$ and $r_0(L)$.
Predict $L_{\rm tot}(M)$ and $L_c(M)$

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

Alternative approach: split CLF in central and satellite components:

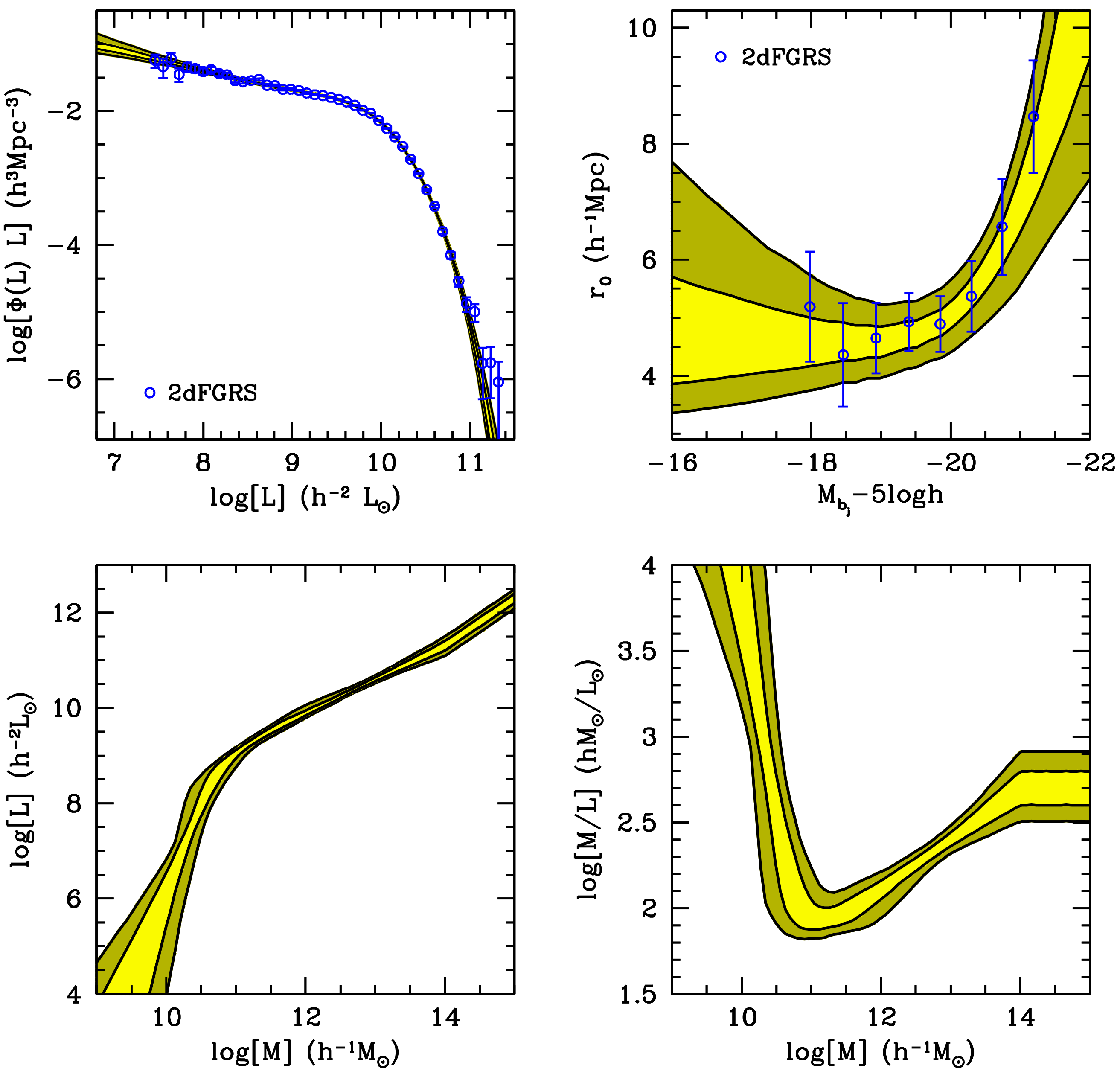
$$\begin{aligned}
\Phi(L|M) &= \Phi_c(L|M) + \Phi_s(L|M) \\
\Phi_c(L|M) &= \frac{\tilde{\Phi}^*_c}{\sqrt{2\pi}\ln(10)\, L\, \sigma_c} \exp\left[-\frac{\log(L/\tilde{L}_c)^2}{2\sigma_c^2}\right] \\
\Phi_s(L|M) &= \tilde{\Phi}^*_s\, L^{\tilde{\alpha}}\, g(L - \tilde{L}_c)
\end{aligned}$$

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

Use direct observational constraints on $L_c(M)$, $L_{\rm tot}(M)$ and $\alpha(M)$
Predict $\Phi(L)$ and $r_0(L)$

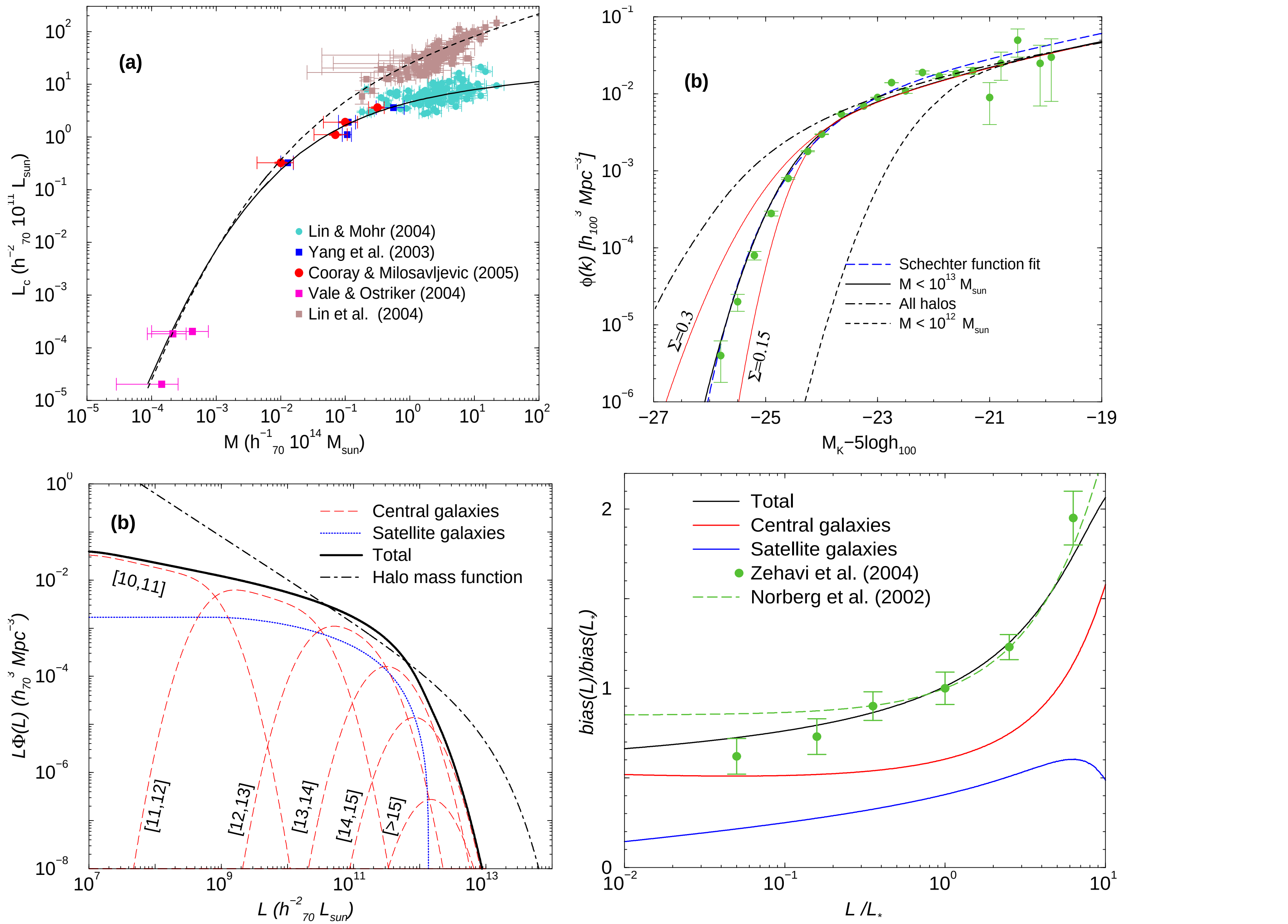
(e.g., Cooray & Milosavljevic 2005; Cooray 2005a,b; Cooray 2006)

The Relation between Light & Mass



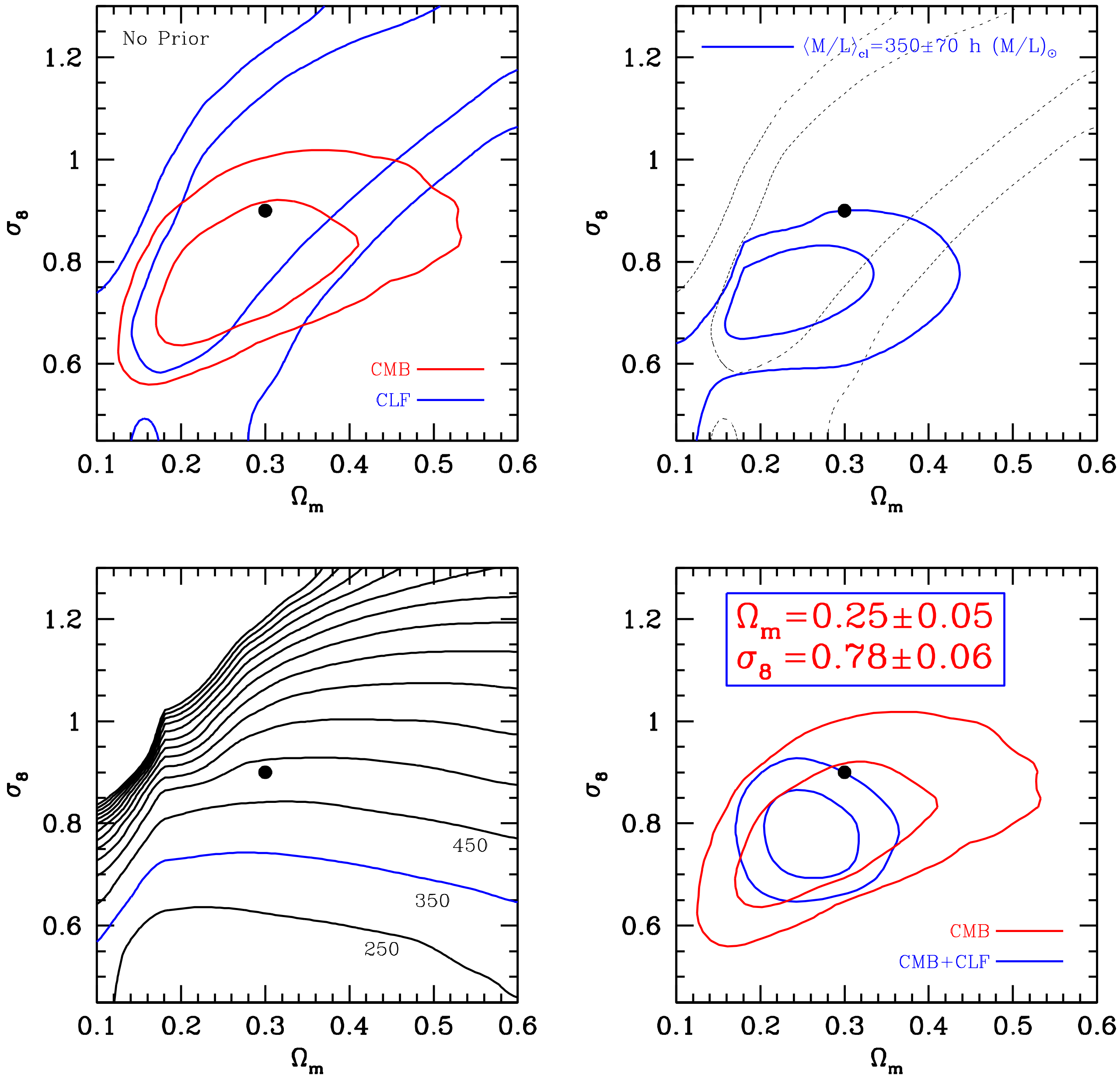
vdB, Yang, Mo & Norberg, 2005, MNRAS, 356, 1233

The Relation between Light & Mass



Cooray & Milosavljevic 2005

Cosmological Constraints



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

See also Tinker et al. 2005; Vale & Ostriker 2005

Large Scale Structure: Theory

Galaxy redshift surveys yield $\xi(r_p, \pi)$ with r_p and π the pair separations perpendicular and parallel to the line-of-sight.

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

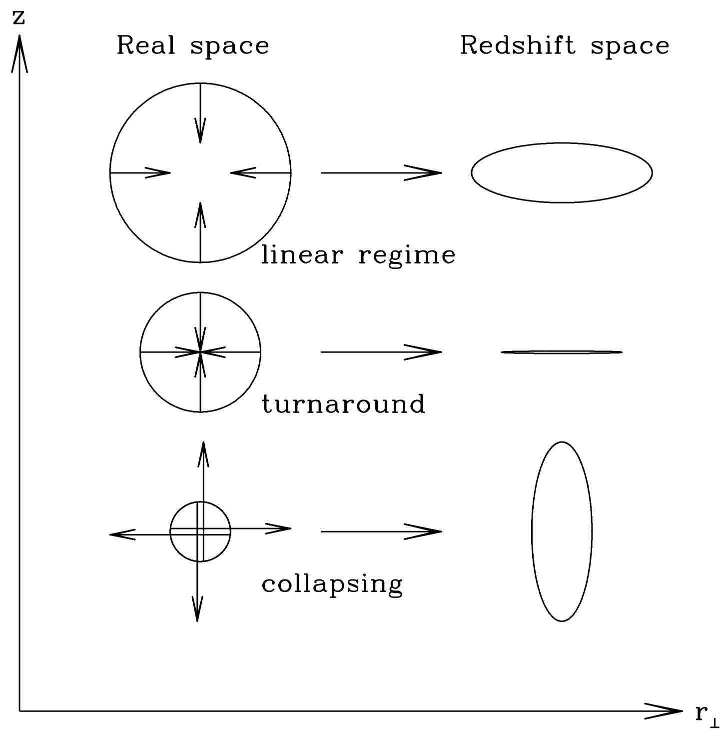
projected CF: $w_p(r_p) = \int_{-\infty}^{\infty} \xi(r_p, \pi) \mathrm{d}\pi = 2 \int_{r_p}^{\infty} \xi(r) \frac{r \, \mathrm{d}r}{\sqrt{r^2 - r_p^2}}$

Peculiar velocities cause $\xi(r_p, \pi)$ to be anisotropic.

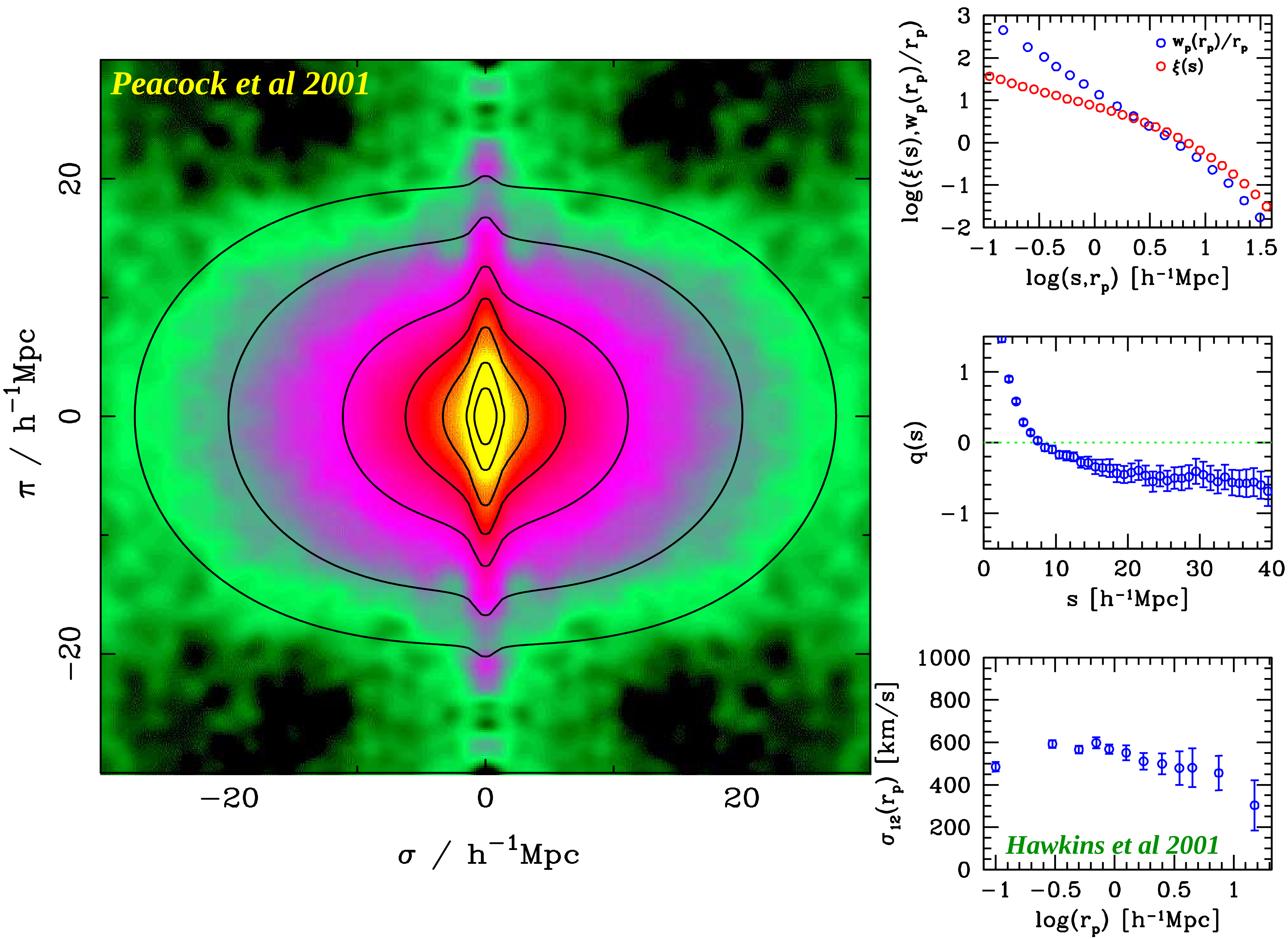
Consequently, $\xi(s) \neq \xi(r)$.

In particular, there are two effects:

- **Large Scales:** Infall (“Kaiser Effect”)
- **Small Scales:** “Finger-of-God-effect”

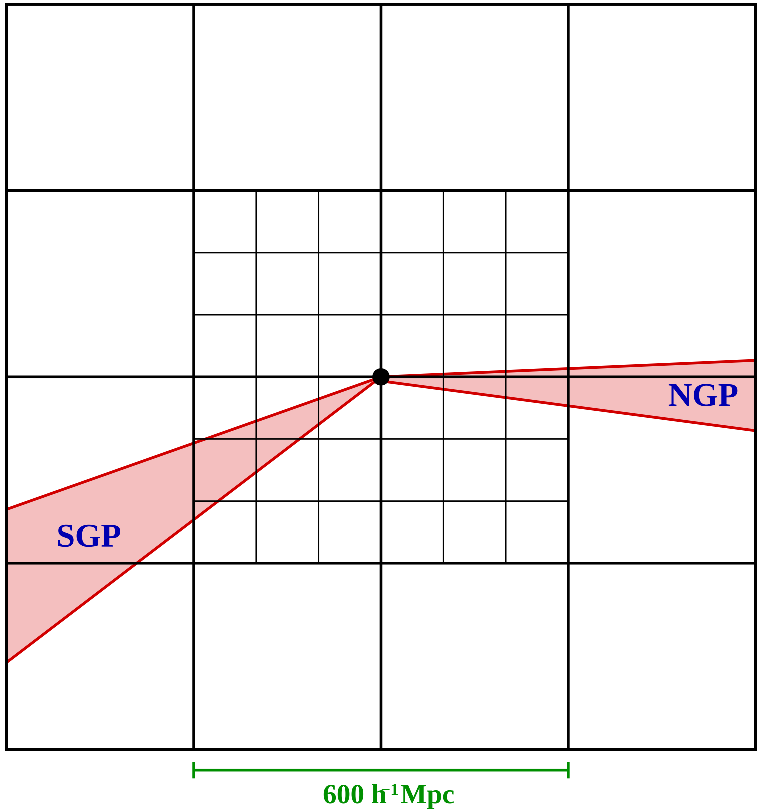


Large Scale Structure: The 2dFGRS

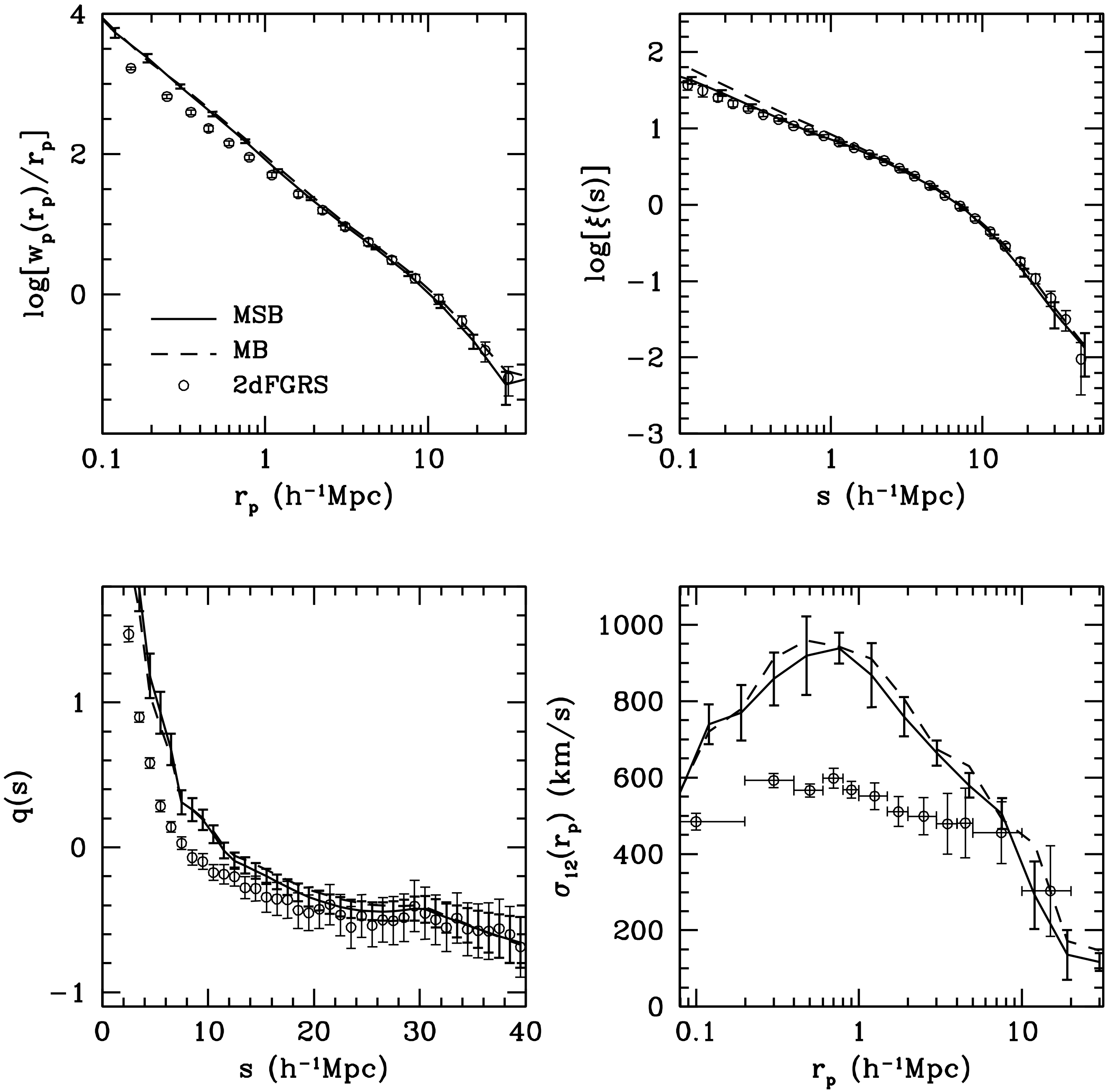


Constructing Mock Surveys

- **Run numerical simulations: ΛCDM concordance cosmology (WMAP1) $L_{\rm box} = 100h^{-1}$ Mpc and $300h^{-1}$ Mpc with 512^3 CDM particles each.**
- **Identify dark matter haloes with (FOF algorithm.**
- **Populate haloes with galaxies using CLF.**
- **Stack boxes to create virtual universe and mimick observations (magnitude limit, completeness, geometry, fiber collisions)**

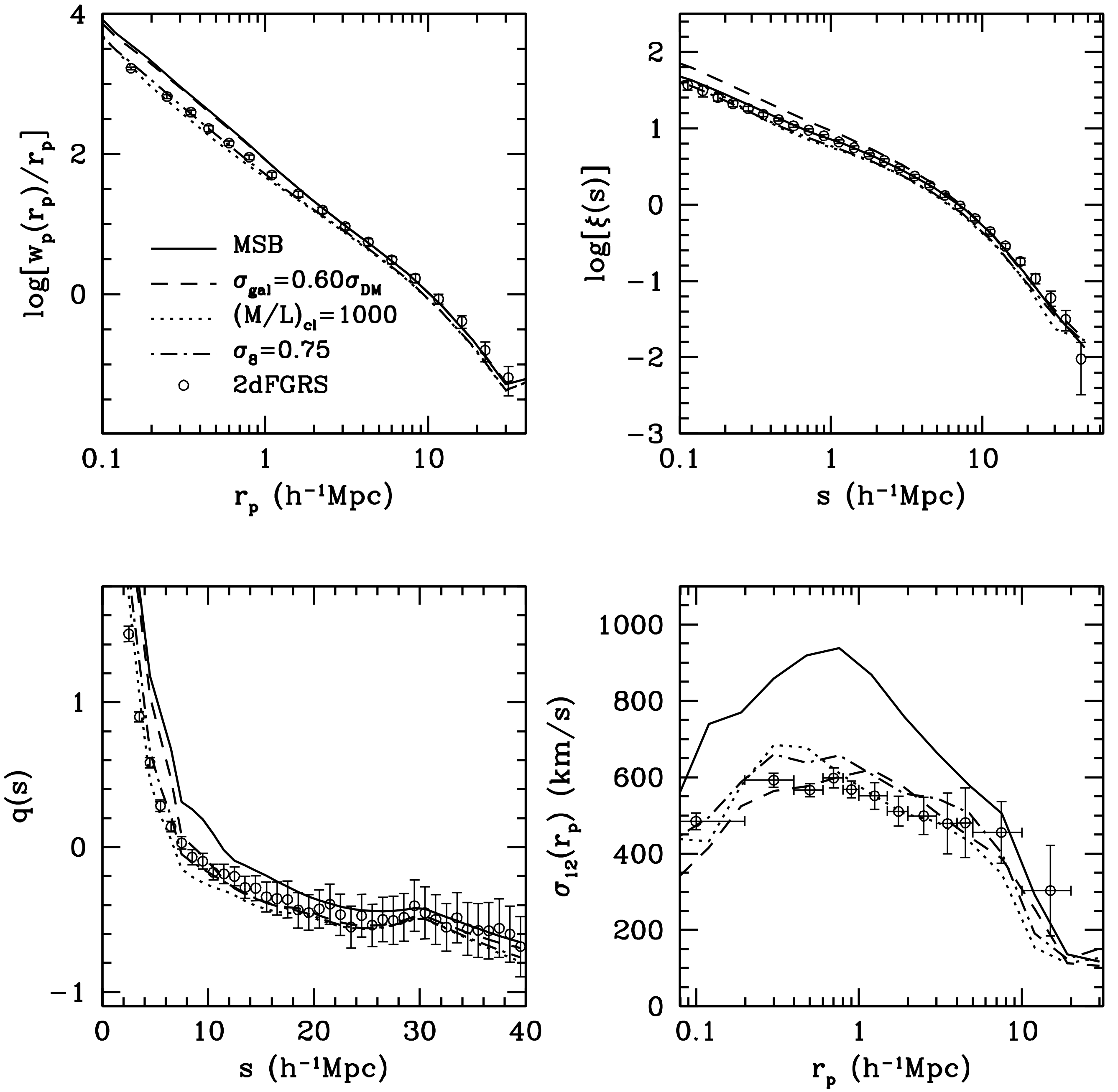


Mock versus 2dFGRS: round 1



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

Mock versus 2dFGRS: round 2



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

HODs from Galaxy Groups

Halo Occupation Statistics can also be obtained directly from galaxy groups

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

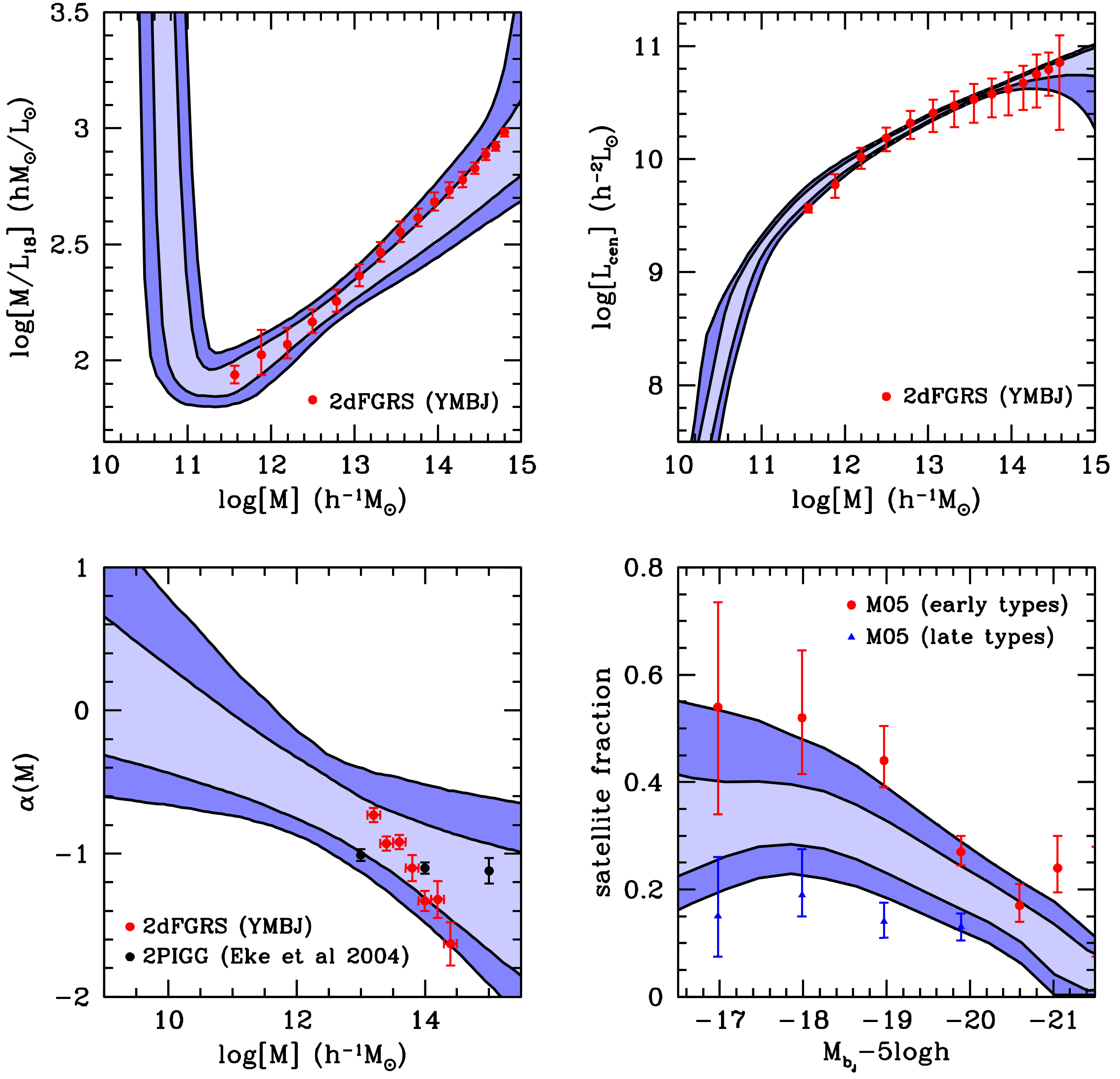
We developed new, iterative group finder, using an adaptive filter modeled after halo virial properties

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.
  More accurate than using velocity dispersion of members.
- Can also detect “groups” with single member
  ▷ Large dynamic range ($11.5 \lesssim \log[M] \lesssim 15$).

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

The Relation between Light & Mass

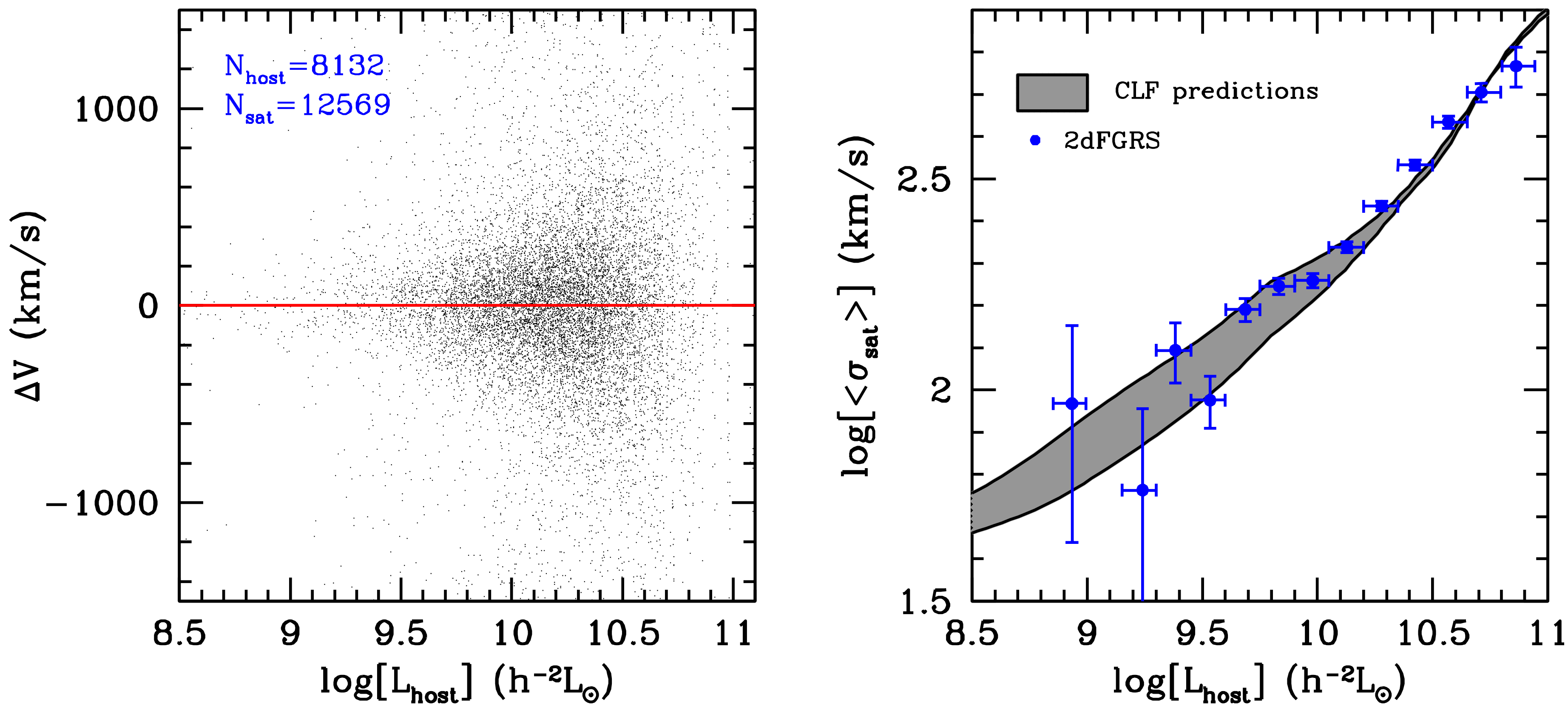


YMBJ = Yang, Mo, vdB & Jing, 2005

vdB et al. 2006, in prep.

M05 = Mandelbaum et al. 2005

Satellite Kinematics in the 2dFGRS

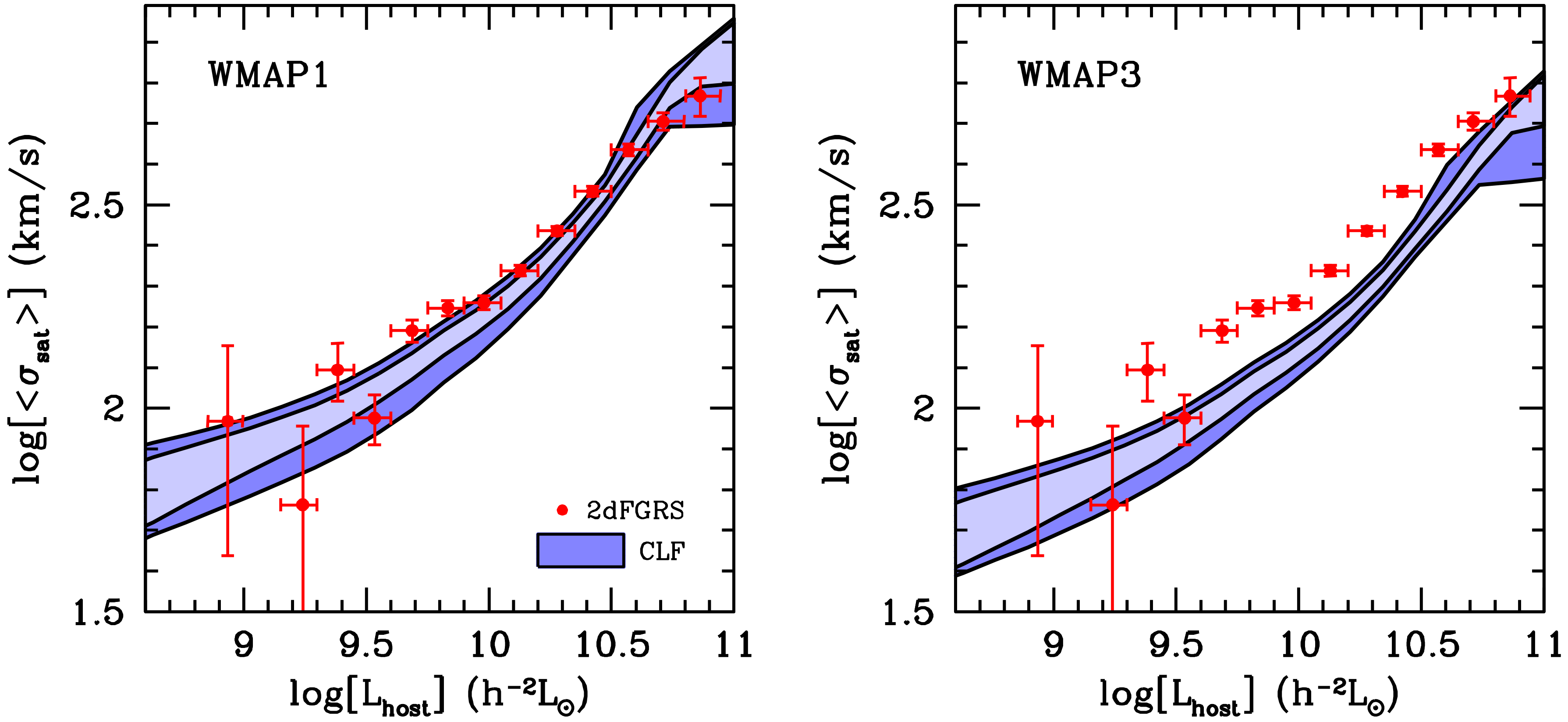


- **Mocks are used to optimize host-satellite selection criteria**
- **Using an iterative, adaptive selection criterion minimizes interlopers**
- **Application to 2dFGRS yields 12569 satellites & 8132 hosts**
- **Independent dynamical evidence to support WMAP1-CLF results**

vdB, Norberg, Mo & Yang, 2004, MNRAS, 352, 1302

vdB, Yang, Mo & Norberg, 2005, MNRAS, 356, 1233

Problems for the WMAP3 Cosmology?



- In **WMAP3** cosmology, haloes have lower mass-to-light ratios and are less concentrated.
- **WMAP3-CLF** underpredicts satellite velocity dispersions by $\sim 30\%$
- But, $L_{\rm cen}(M)$ in good agreement with group-data....
- Central galaxies do **not** reside at rest at center of halo.

vdB et al. 2006, in preparation

Brightest Halo Galaxies

Paradigm: Brightest Galaxy in halo resides at rest at center

In order to test this **Central Galaxy Paradigm**, we compare the velocity of central galaxy to the average velocity of the satellites. Define

$$\mathcal{R} = \frac{N_s(v_c - \bar{v}_s)}{\hat{\sigma}_s}$$

with $\bar{v}_s = \frac{1}{N_s}\sum_{i=1}^{N_s} v_i$ and $\hat{\sigma}_s = \sqrt{\frac{1}{N_s - 1}\sum_{i=1}^{N_s}(v_i - \bar{v}_s)^2}$.

If **Central Galaxy Paradigm** is correct, $P(\mathcal{R})$ follows a Student t-distribution with $N_s - 1$ degrees of freedom

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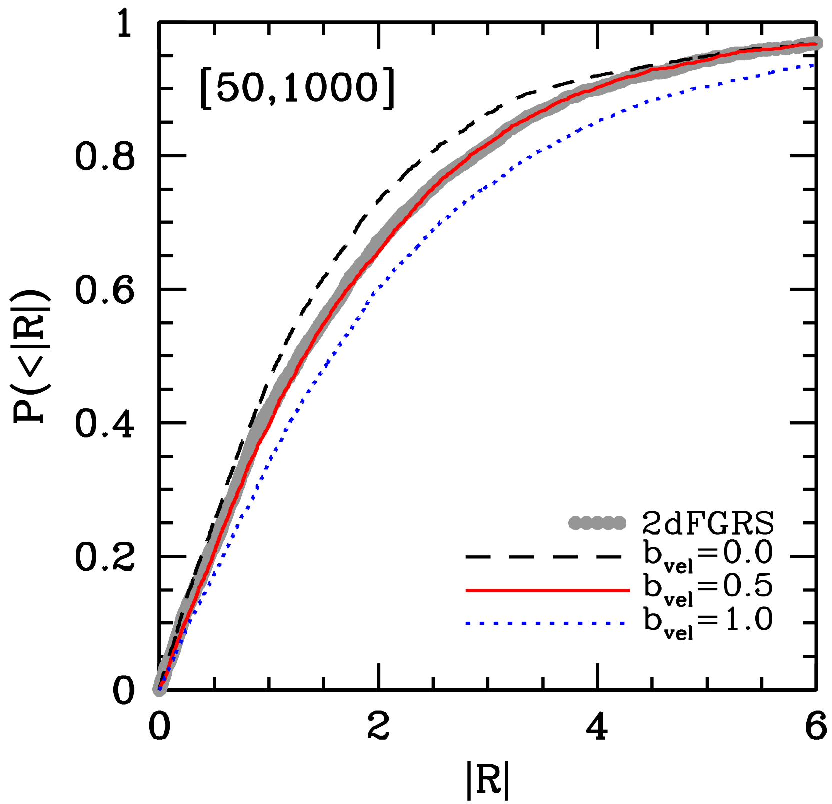
IMPORTANT: Applicability of this $\mathcal{R}$-test depends strongly on ability to find those galaxies that belong to same halo.

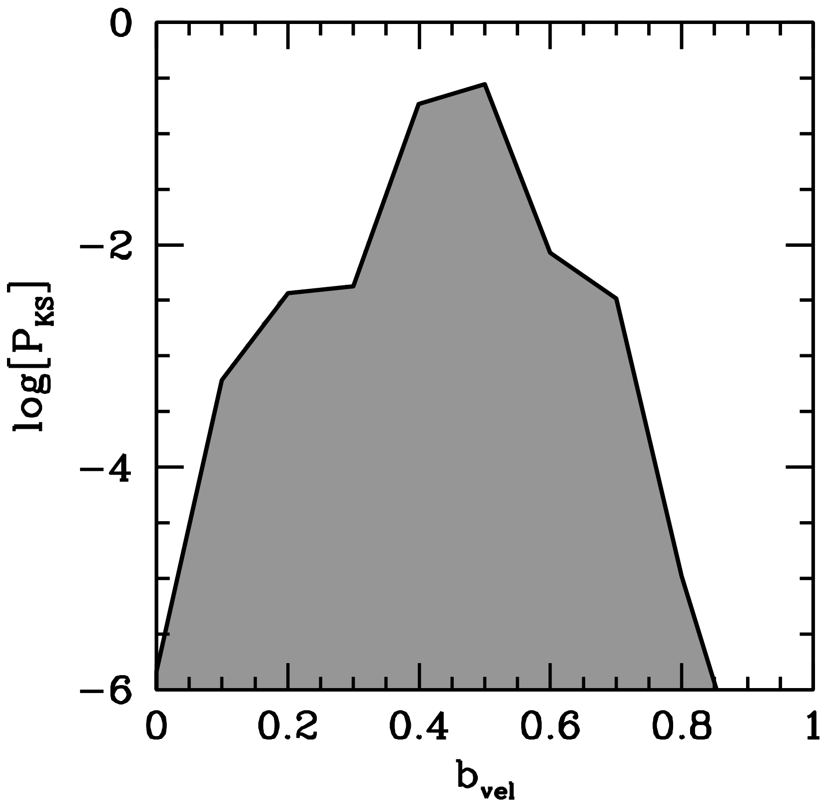
PROBLEM: Interlopers and incompleteness effects

SOLUTION: Use halo-based group finder and mock galaxy redshift surveys

DATA: Both 2dFGRS (Final Data Release) and SDSS (DR2, NYU-VAGC)

Evidence against Central Galaxy Paradigm

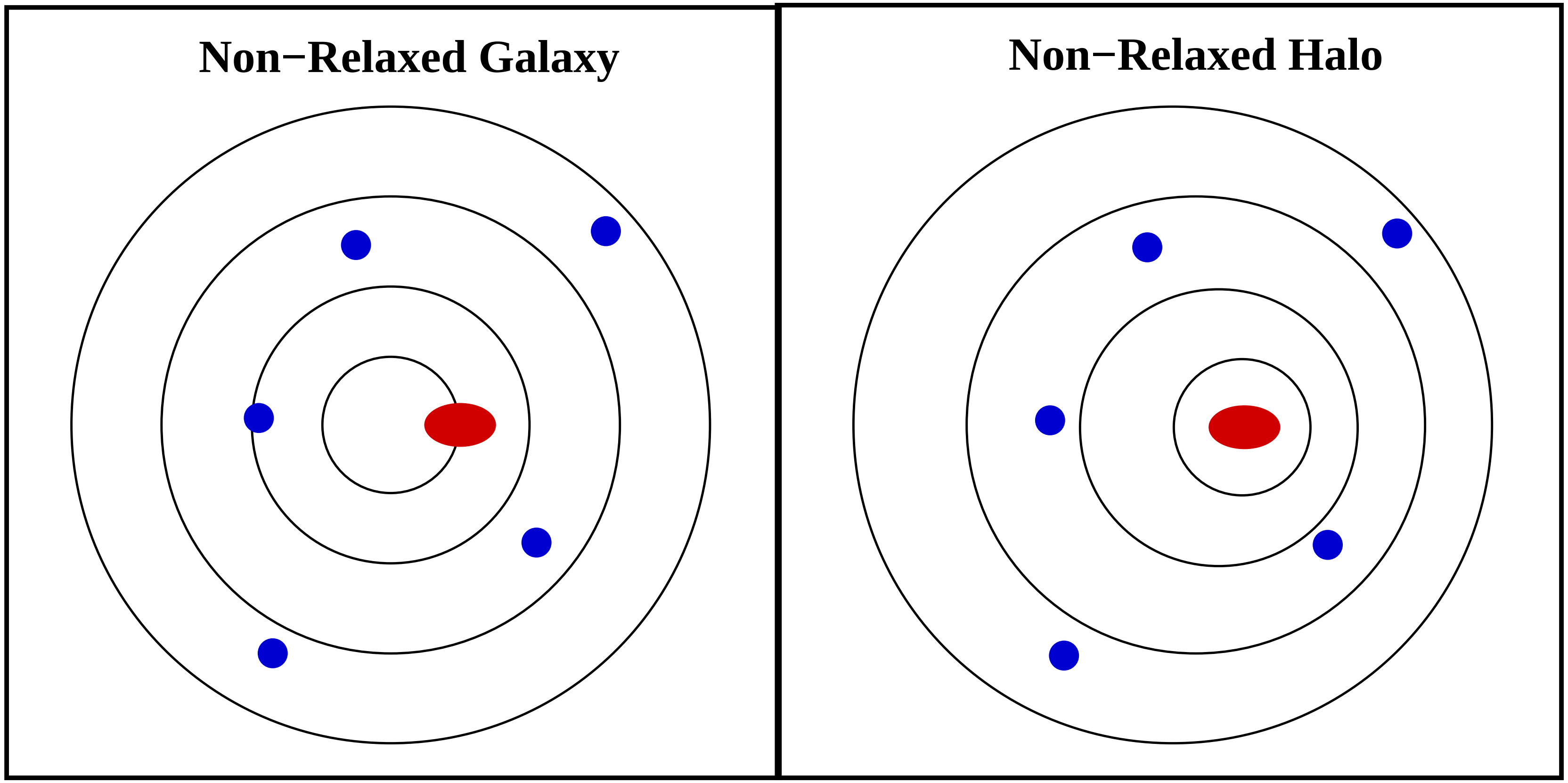




- We construct ten MGRSs, that only differ in the velocity bias ($b_{\rm vel}$) of the brightest halo galaxy
- The $P(\mathcal{R})$ of 2dFGRS is best reproduced by MGRS with $b_{\rm vel} = 0.5$
- The null-hypothesis of the Central Galaxy Paradigm is ruled out at strong confidence: $P_{\rm KS} = 1.5 \times 10^{-6}$
- Best-fit value of $b_{\rm vel} = 0.5$ suggests that specific kinetic energy of central galaxies is $\sim 25\%$ of that of satellites

vdB et al. 2005, MNRAS, 361, 1203

Implications



- Brightest halo galaxy either oscillates in relaxed halo, or resides at potential minimum of non-relaxed halo.
- Strong gravitational lensing (external shear?)
- Distortions in disk galaxies (lopsidedness & bars)
- Satellite kinematics $\sigma_{\rm sat} = \sqrt{1 + b_{\rm vel}}\, \sigma_{\rm dm}$

Galaxy Ecology

Many studies have investigated relation between various galaxy properties (morphology / SFR / colour) and environment

(e.g., Dressler 1980; Balogh et al. 2004; Goto et al. 2003; Hogg et al. 2004)

Environment estimated using galaxy overdensity (projected) to $n^{\rm th}$ nearest neighbour, Σ_n or using fixed, metric aperture, Σ_R.

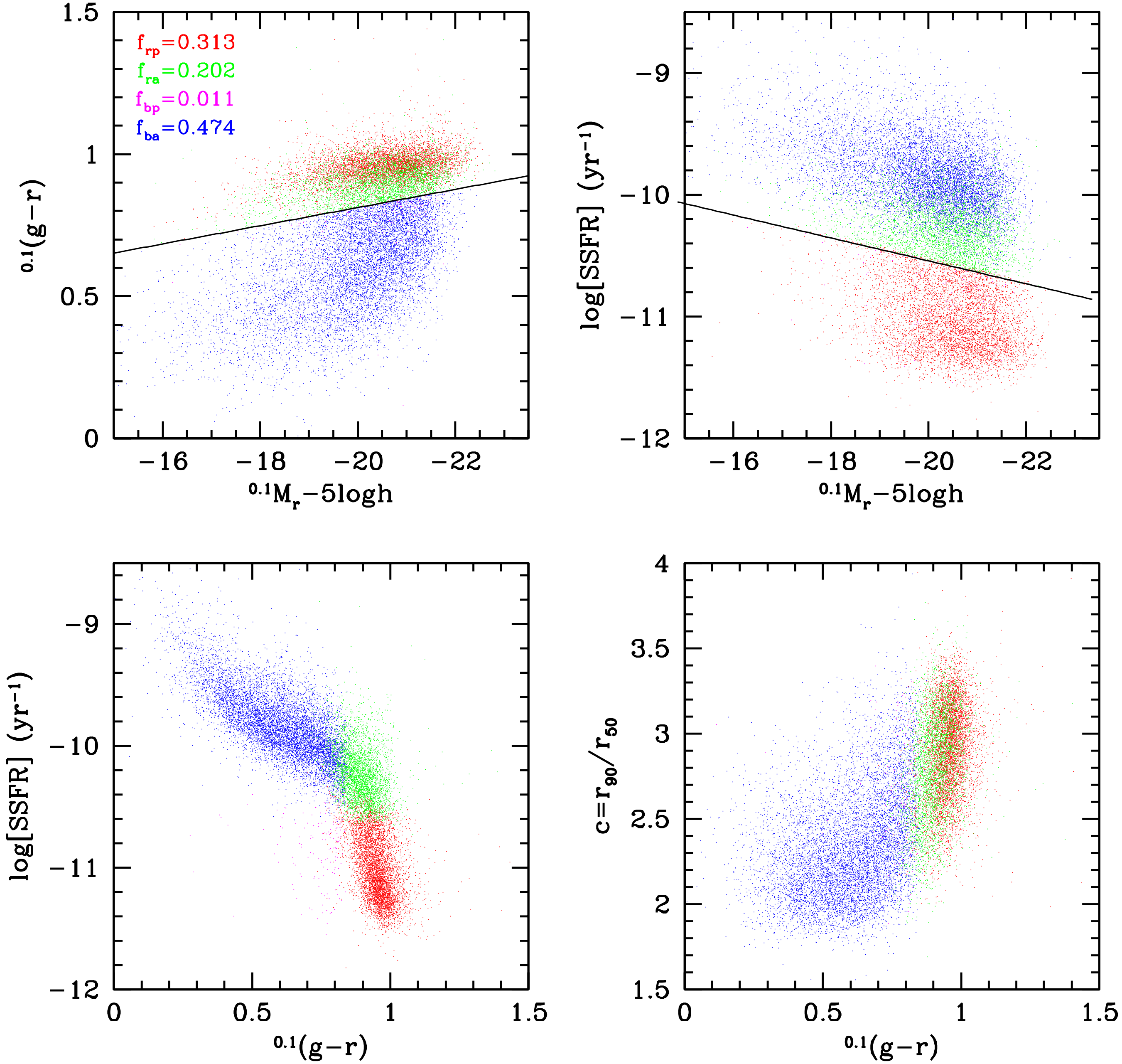
- **Fraction of early types increases with density**
- **There is a characteristic density ($\sim$ group-scale) below which environment dependence vanishes**
- **Groups and Clusters reveal radial dependence: late type fraction increases with radius**
- **No radial dependence in groups with $M \lesssim 10^{13.5} h^{-1}\, {\rm M}_{\odot}$**

Danger: Physical meaning of Σ_n and Σ_R depends on environment.

Physically more meaningful to investigate halo mass dependence of galaxy properties. This requires galaxy group catalogues.

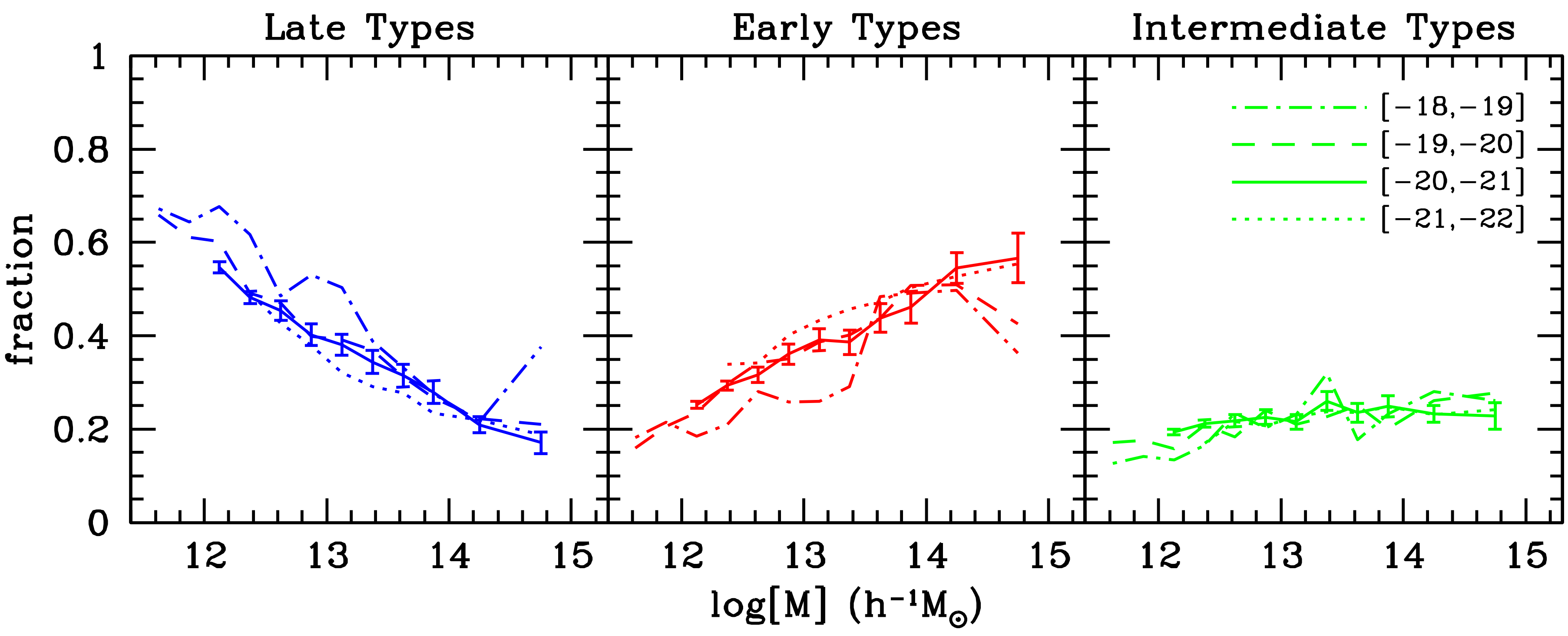
Important: Separate luminosity dependence from halo mass dependence.

Defining Galaxy Types



Data from NYU-VAGC (Blanton et al. 2005): SSFRs from Kauffmann et al. (2003) and Brinchmann et al. (2004)

Halo Mass Dependence



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

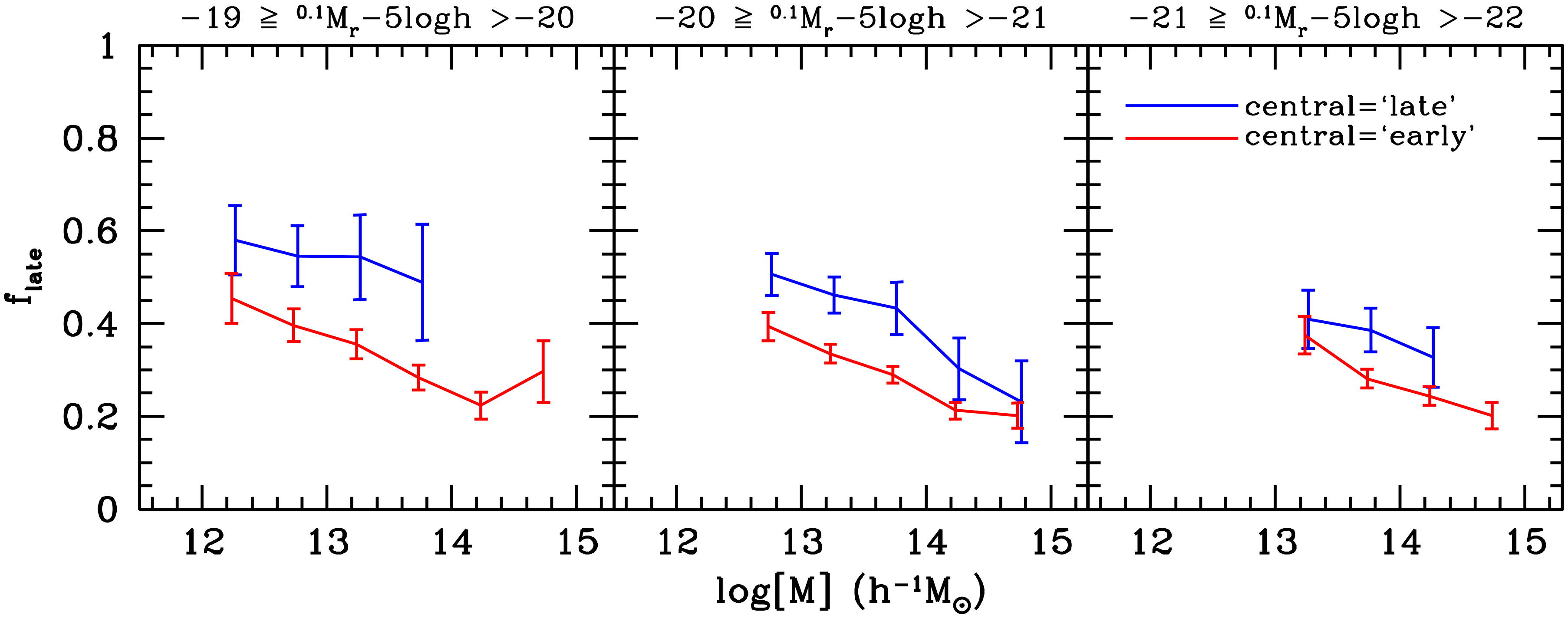
At fixed halo mass, there is virtually no luminosity dependence.

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)

Galactic Conformity



Late type 'centrals' have preferentially late type satellites, and vice versa.

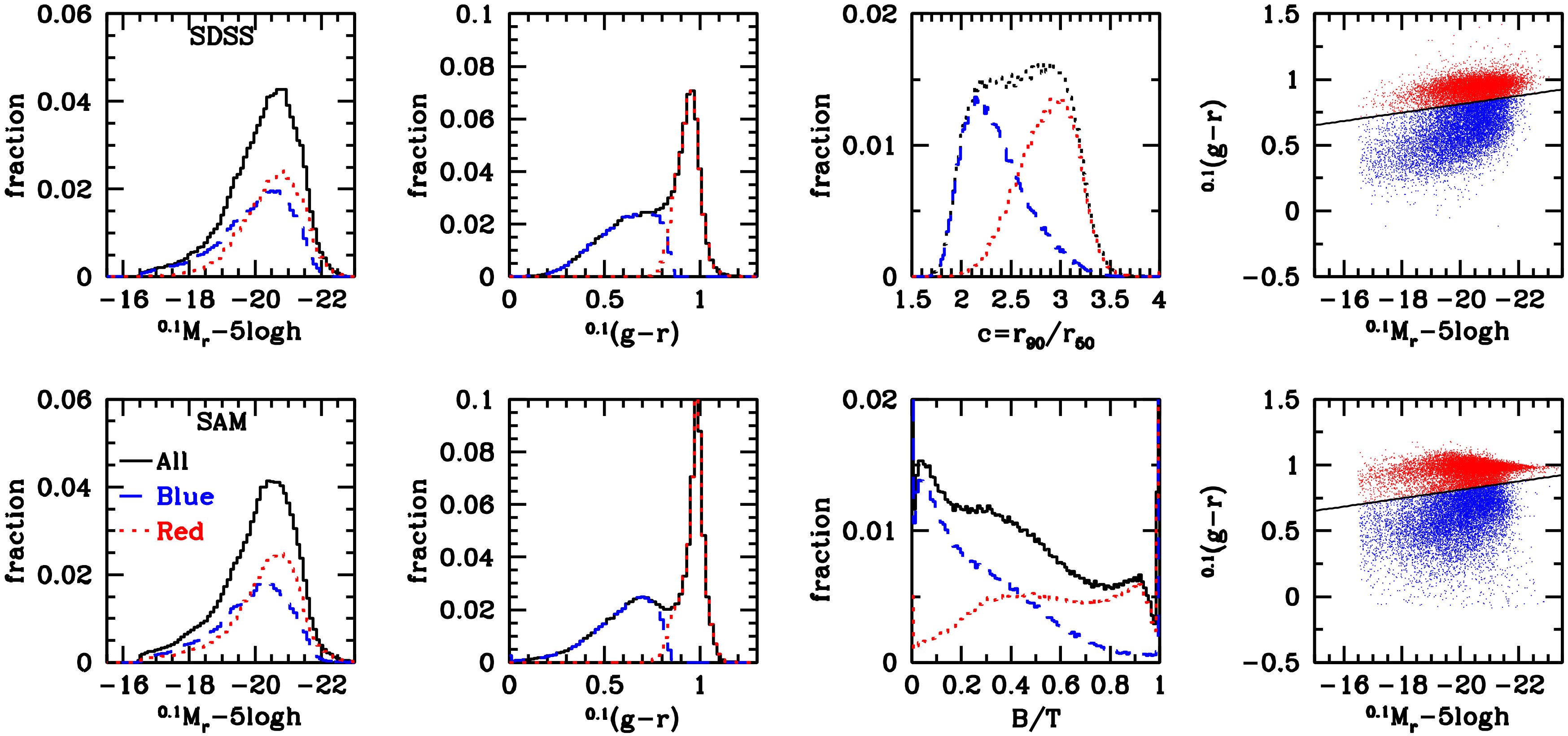
Satellite galaxies 'adjust' themselves to properties of their central galaxy

Galactic Conformity present over large ranges in luminosity and halo mass.

(Weinmann, vdB, Yang & Mo, 2006)

Comparison with Semi-Analytical Model

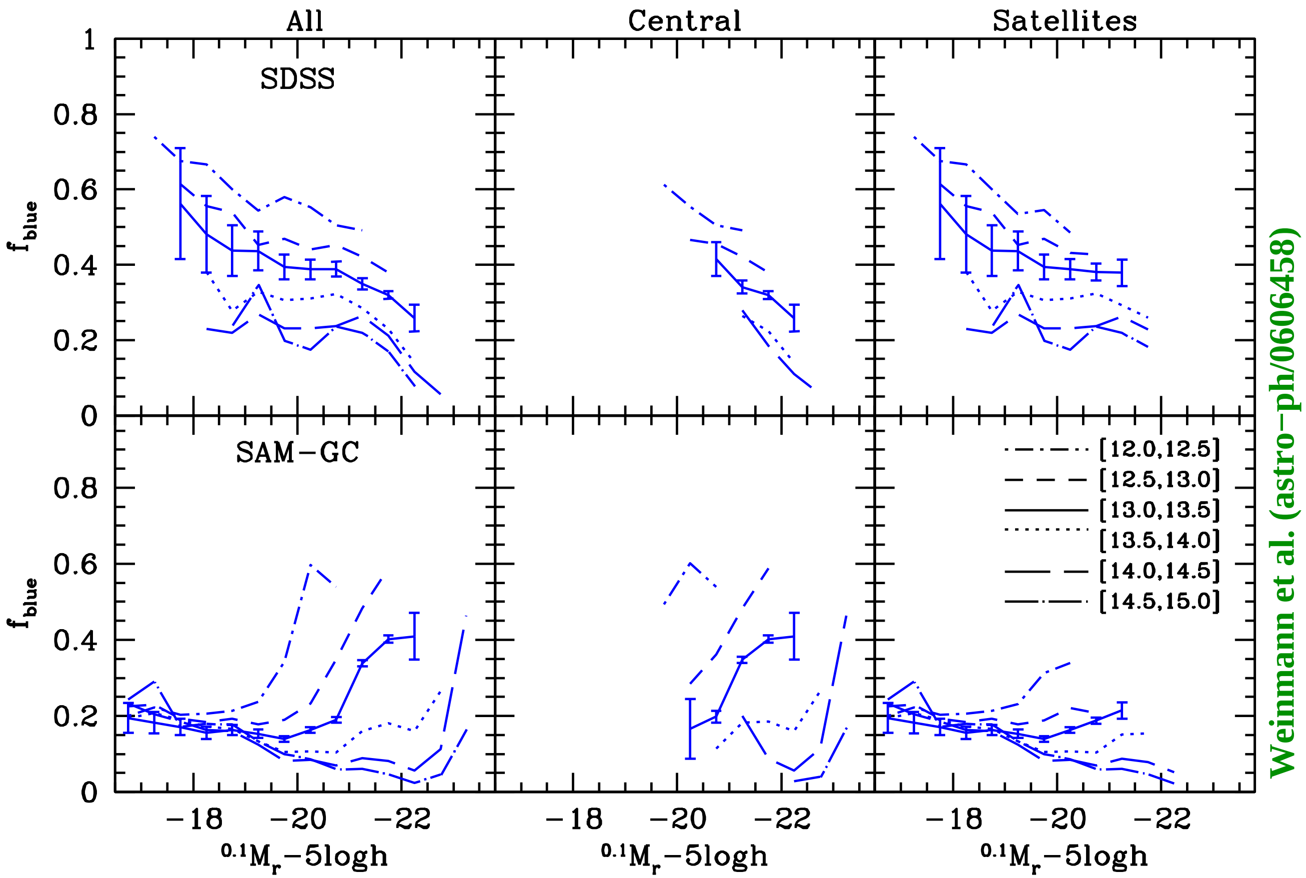
Comparison of Group Occupation Statistics with Semi-Analytical Model of Croton et al. 2006. Includes 'radio-mode' AGN feedback.



- **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**

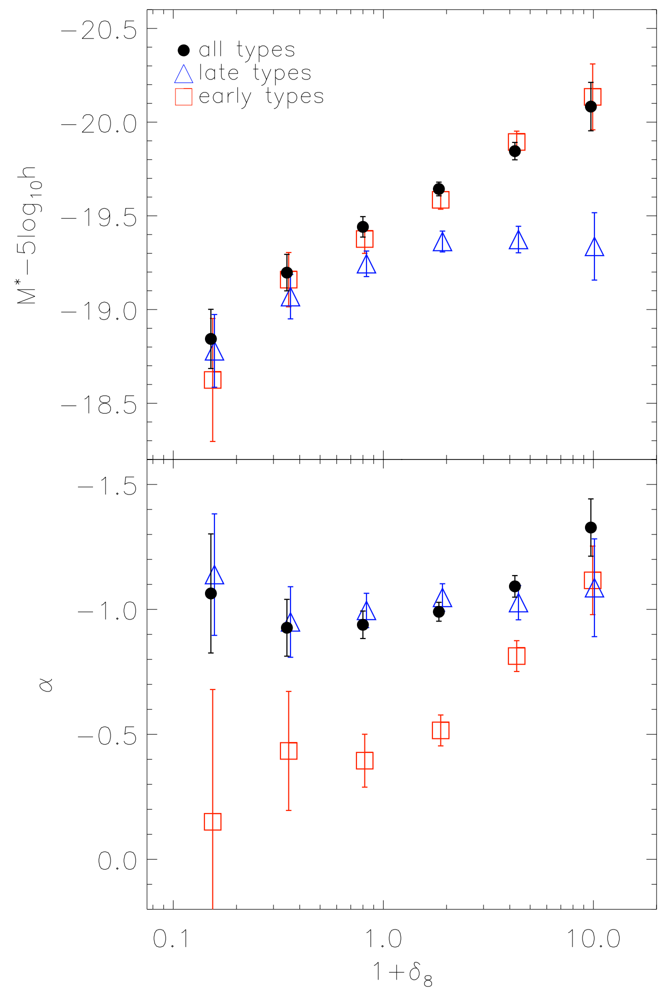
Centrals: $f_{\rm blue}(L|M)$ **wrong:** ▷ **AGN feedback/dust modelling wrong**

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

Large-Scale Environment Dependence

Inherent to CLF formalism is assumption that L depends only on M.

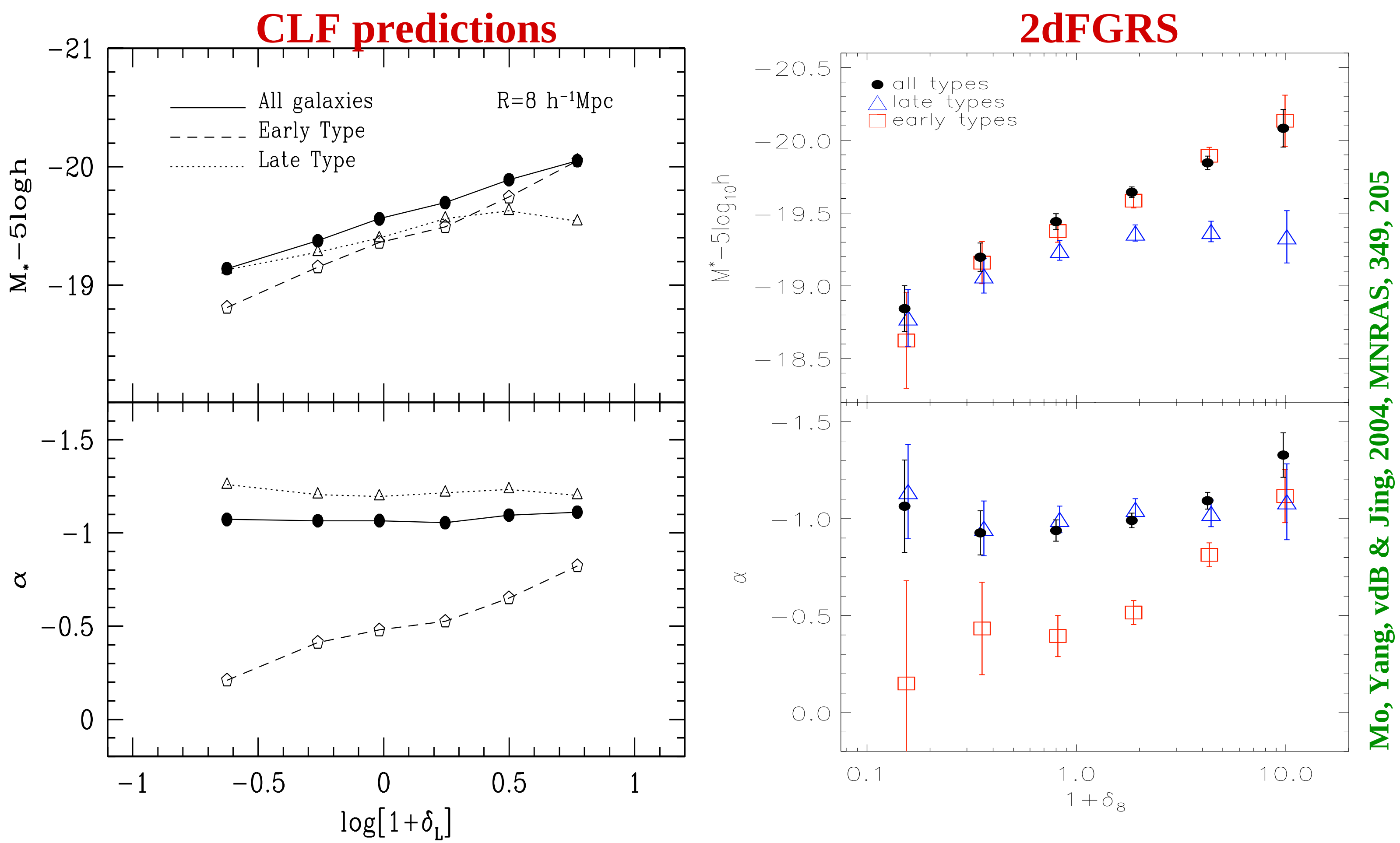
But $\Phi(L)$ has been shown to depend on large scale environment



Croton et al. 2005

Does this violate the implicit assumptions of the CLF formalism?

Large-Scale Environment Dependence



Populate haloes in N-body simulations with galaxies using $\Phi(L|M)$

Compute $\Phi(L)$ as function of environment and type as in Croton et al. (2005)

Because $n(M)$ depends on environment, we reproduce observed trend

There is no environment dependence, only halo-mass dependence

Theoretical Expectations

From the fact that

$$\delta_h(m) \equiv \frac{n(m|\delta)}{n(m)} - 1 = b(m)\delta$$

we obtain that

$$\boxed{n(m|\delta) = [1 + b(m)\delta]\ n(m)}$$

Since the halo bias $b(m)$ is an increasing function of halo mass, the abundance of more massive haloes is more strongly boosted in overdense regions than that of less massive haloes

In other words; massive haloes live in overdense regions

If more massive haloes host more luminous galaxies, we thus expect that the luminosity function of galaxies also depends on environment

Conclusions

Galaxy Bias = Halo Bias + Halo Occupation Statistics

Halo Occupation Statistics can be modeled & constrained using:

- **Halo Occupation Distribution (HOD)** $P(N|M)$
- **Conditional Luminosity Function (CLF)** $\Phi(L|M)$

or it can be 'measured' directly using galaxy groups

Halo Model and/or Halo Occupation Statistics can:

- **Constrain Cosmological Parameters**
- **Constrain Galaxy Formation**

In the near future we will be able to

- **Constrain galaxy bias as function of redshift**
- **Obtain independent constraints from galaxy-galaxy lensing**