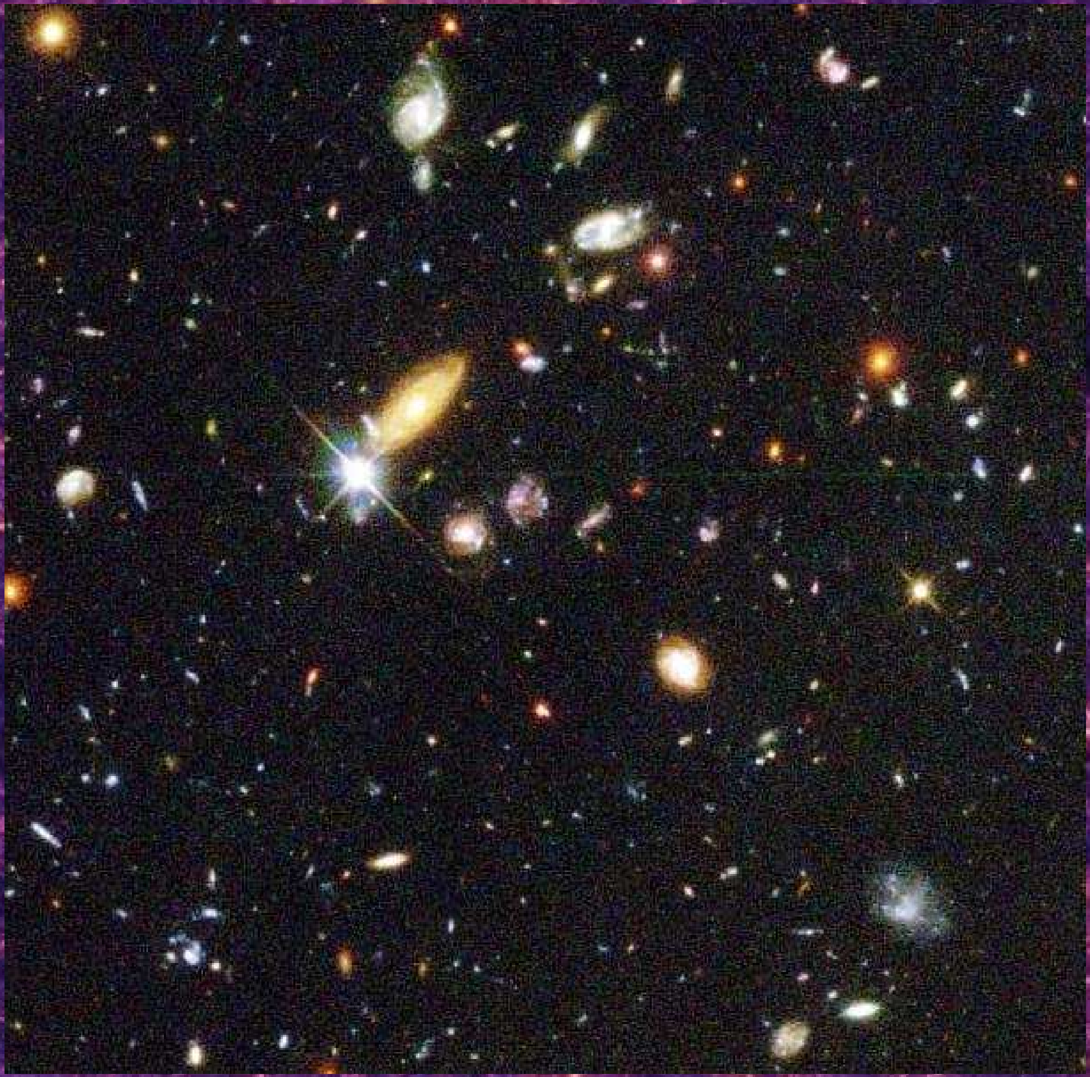
The Galaxy–Dark Matter Connection



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Introduction

PARADIGM: **Galaxies live in extended Cold Dark Matter Haloes.**

QUESTION: **What Galaxy lives in What Halo?**

- **How many galaxies, on average, per halo?**
- **How does $\langle N \rangle$ depend on M and L?**
- **What is $\langle L \rangle (M)$?**
- **How are galaxies distributed (spatially & kinematically) within halo?**

The answers to these questions hold important information regarding

- **Galaxy Formation (cooling/starformation/feedback)**
- **Large Scale Structure (galaxy bias)**
- **Cosmology (Halo mass function/CDM distribution)**

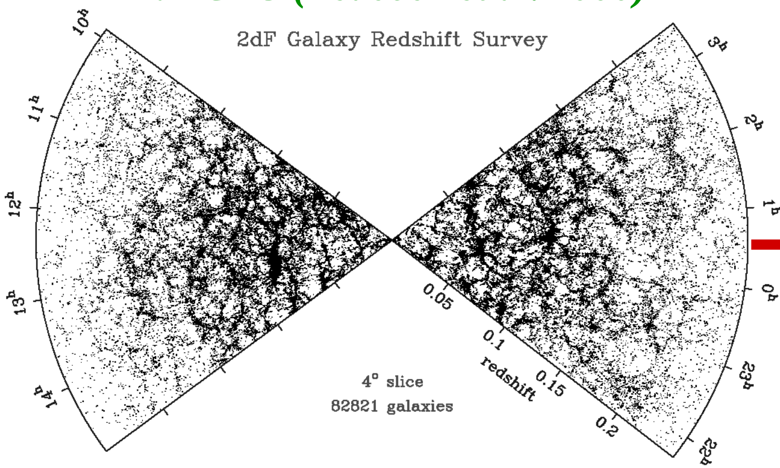
The galaxy-dark matter connection can be studied

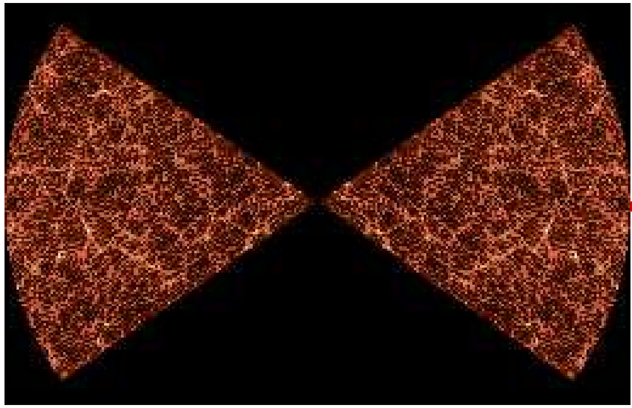
Physically: **Ab initio galaxy formation models (SAMs)**

Statistically: **The Halo Occupation Distributions (HODs)**

The Galaxy-Dark Matter Connection

2dFGRS (Peacock et al. 2000)





CDM simulation (Virgo consortium)

HOD

P(N|M)

Seljak 2000

Scoccimarro et al. 2001

Berlind & Weinberg 2002

Zehavi et al. 2004

Zheng et al. 2004

Tinker et al. 2004

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

It specifies the galaxy bias and links the galaxy-galaxy correlation function, $\xi_{\rm gg}(r)$, to the halo-halo correlation function, $\xi_{\rm hh}(r)$.

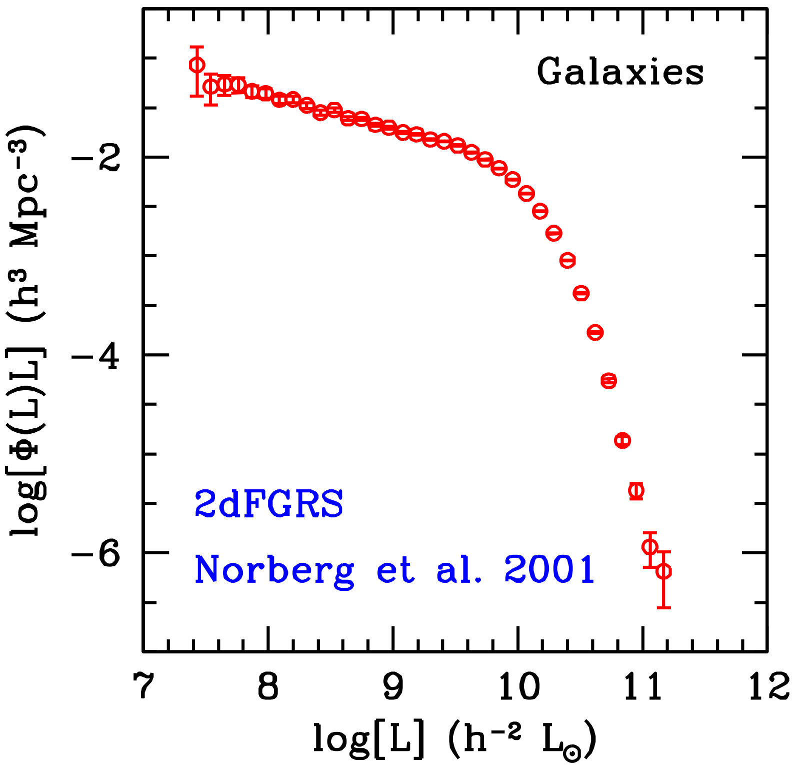
Lighting-Up the Dark Matter

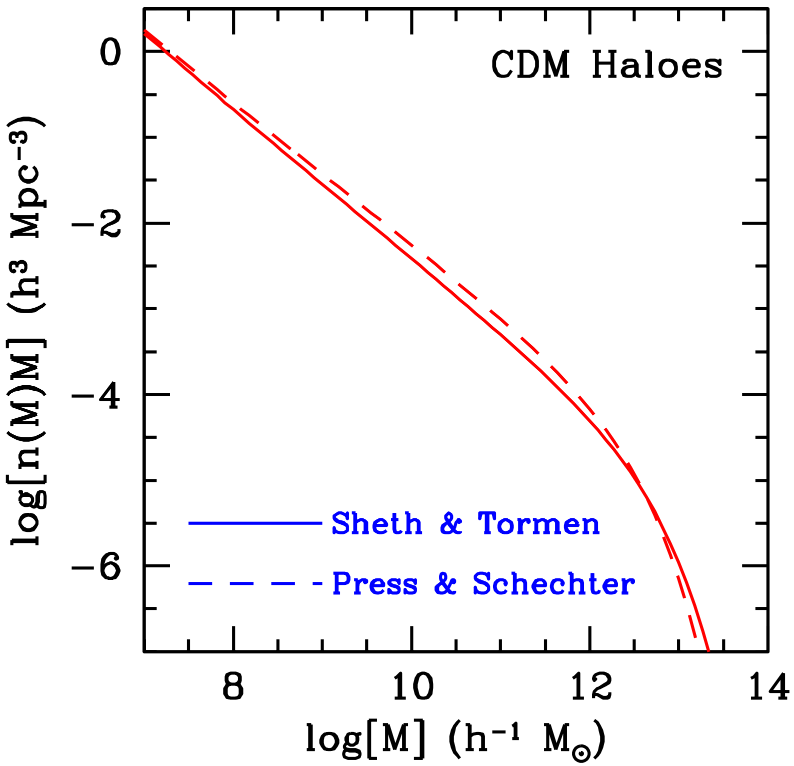
Important Shortcoming: **Galaxy bias depends on galaxy properties:**

$$b_{\rm gal} = b_{\rm gal}(L, \text{type}, ...)$$

This information is not encapsulated in HOD modeling.

To address $b_{\rm gal}(L)$ we introduce the Conditional Luminosity Function (CLF)





The CLF, $\Phi(L|M)$, expresses the average number of galaxies with luminosity L that reside in a halo of mass M

The Conditional Luminosity Function

CLF is direct link between galaxy LF, $\Phi(L)$ and halo mass function, $n(M)$:

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

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:

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

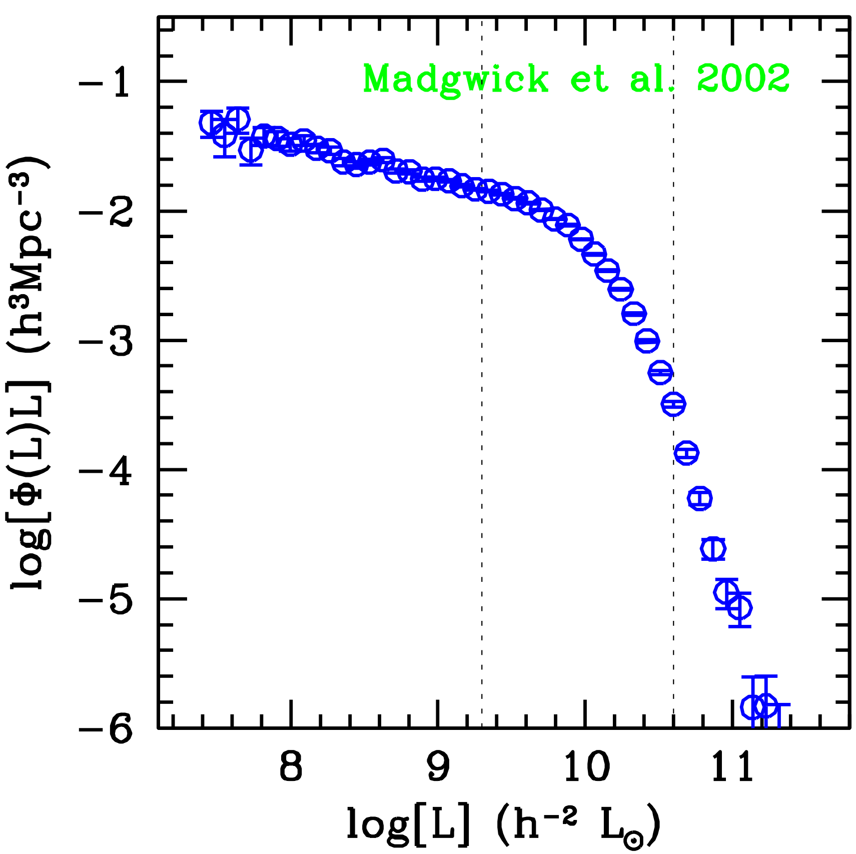
- Galaxy clustering properties as function of luminosity:

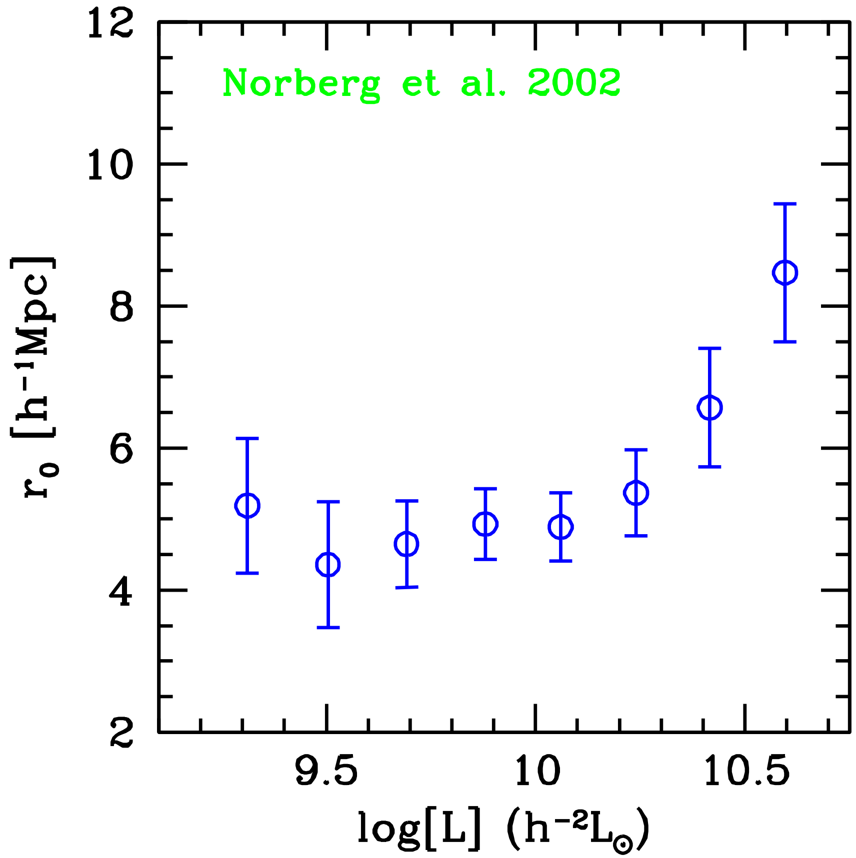
$$\xi_{\mathrm{gg}}(r|L) = b^2(L)\, \xi_{\mathrm{dm}}(r)$$

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

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 Model

- The LFs of clusters are well fit by a Schechter function
- The LF of all field galaxies has a Schechter form
- The halo mass function has a Press-Schechter form

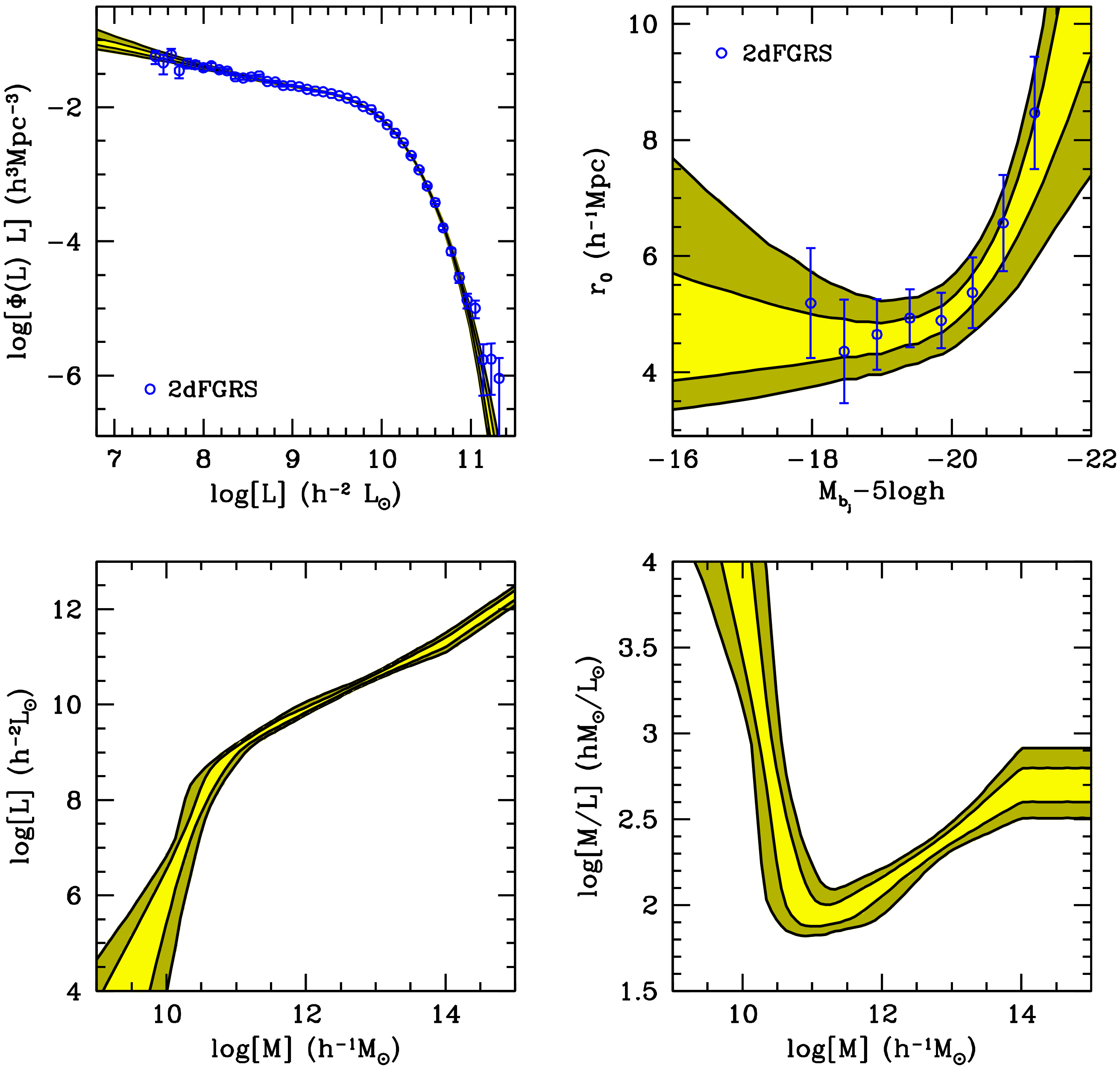
We therefore assume that the CLF also has the Schechter form:

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

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

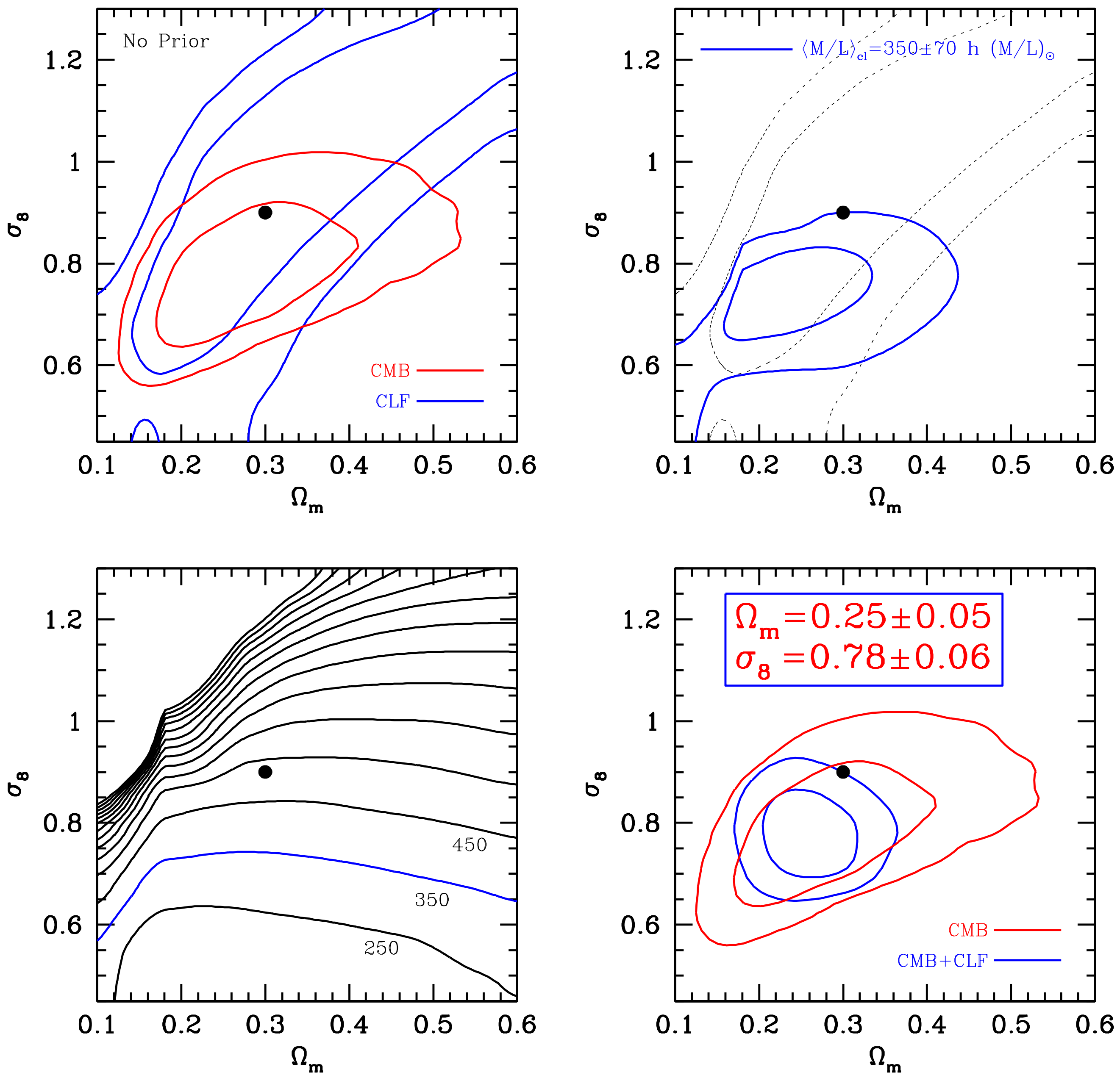
- Parameterize $\tilde{\Phi}^*$, $\tilde{L}^*$ and $\tilde{\alpha}$. In total our model has 8 free parameters
- Construct Monte-Carlo Markov Chain to sample posterior distribution of free parameters. ($N_{\rm eq} = 10^4$, $N_{\rm step} = 4 \times 10^7$, $N_{\rm chain} = 2000$)
- Use MCMC to put confidence levels on derived quantities such as $\langle M/L\rangle(M)$ and $\tilde{\alpha}(M)$.
- Use MCMC to explore degeneracies and correlations between various parameters.

The Relation between Light & Mass



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

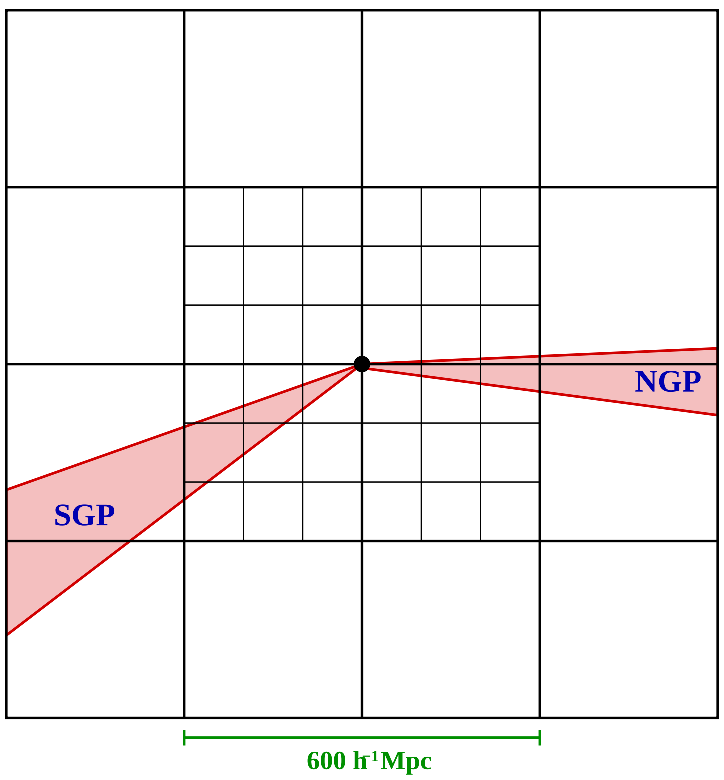
Constraints on Ω_m and σ_8



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

Constructing Mock Surveys

- Run numerical simulations: ΛCDM concordance cosmology; $L_{\rm box} = 100h^{-1}$ Mpc and $L_{\rm box} = 300h^{-1}$ Mpc with 512^3 CDM particles each.
- Identify dark matter haloes (FOF algorithm, $b = 0.2$).
- Populate haloes with galaxies using CLF.
- Stack boxes to create virtual universe and mimick observations (magnitude limit, completeness, geometry)



Large Scale Structure: Theory

Observations 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 $s = \sqrt{r_p^2 + \pi^2}$.

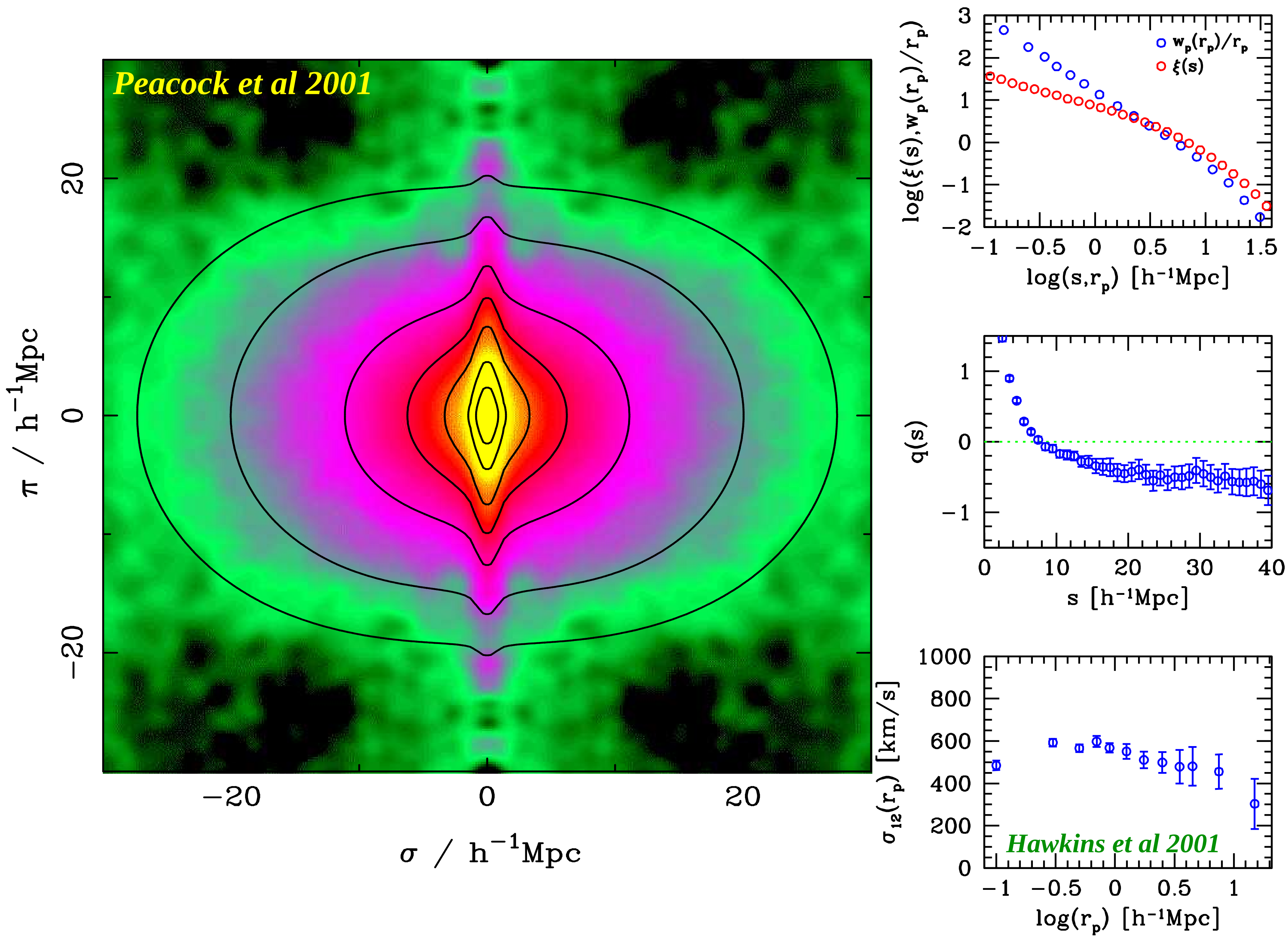
projected CF: $w_p(r_p) = \int_{-\infty}^{\infty} \xi(r_p, \pi) \mathrm{d}\pi = 2 \int_{r_p}^{\infty} \xi(r) \frac{r \, \mathrm{d}r}{\sqrt{r^2 - r_p^2}}$

Peculiar velocities cause anisotropy of $\xi(r_p, \pi)$ and differences between $\xi(s)$ and $\xi(r)$.

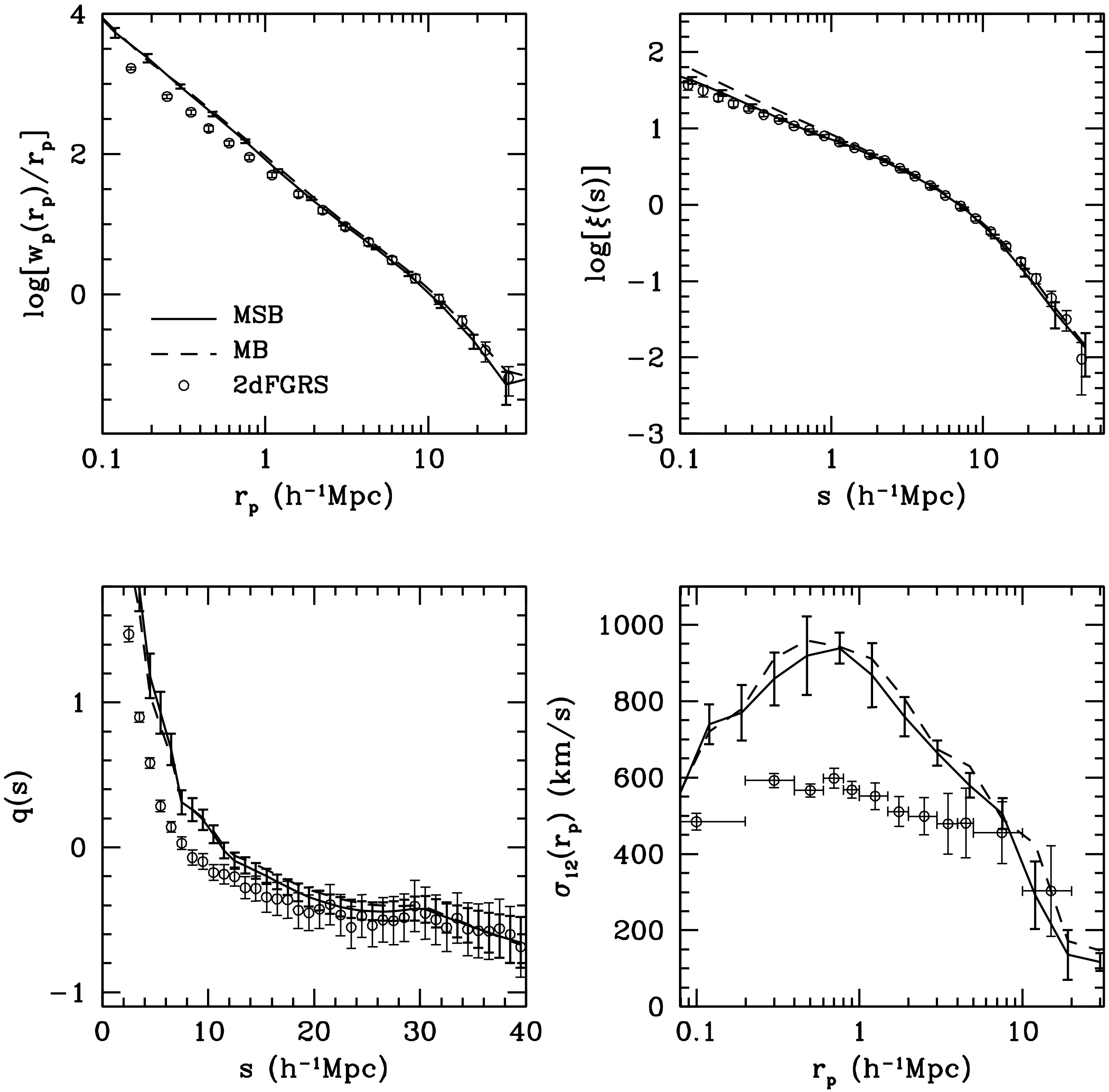
Anisotropy of $\xi(r_p, \pi)$ is quantified by quadrupole-to-monopole ratio denoted by $q(s)$.

- **Large Scales: Infall ("Kaiser Effect"); boosts $\xi(s)$ w.r.t. $\xi(r)$. $q(s)$ is negative and a measure of $\beta \equiv \Omega_m^{0.6}/b$.**
- **Small Scales: Virialized motion ("Finger-of-God"); suppresses $\xi(s)$ w.r.t. $\xi(r)$. $q(s)$ is positive and a measure for the pairwise velocity dispersions (PVDs) denoted by σ_{12}.**

Large Scale Structure: The 2dFGRS

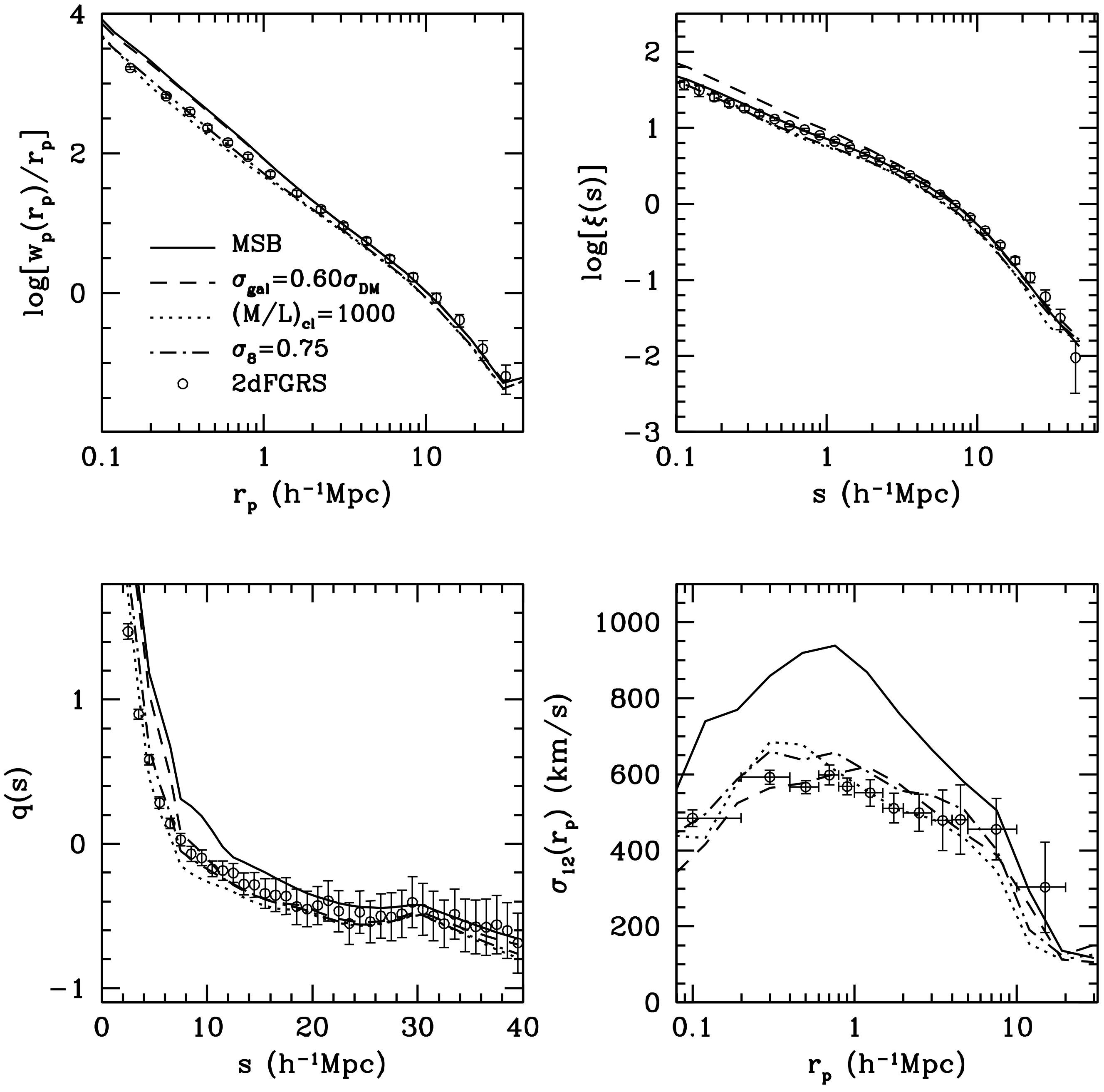


Mock versus 2dFGRS: round 1



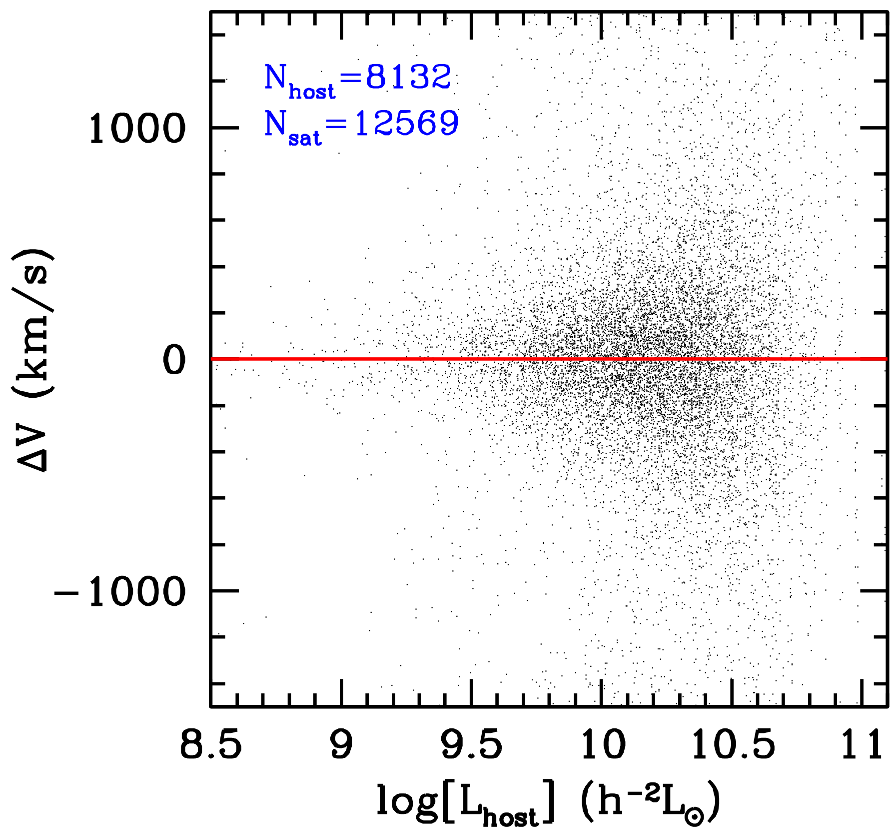
Yang, Mo, Jing, vdB & Chu, 2004, MNRAS, 350, 1153

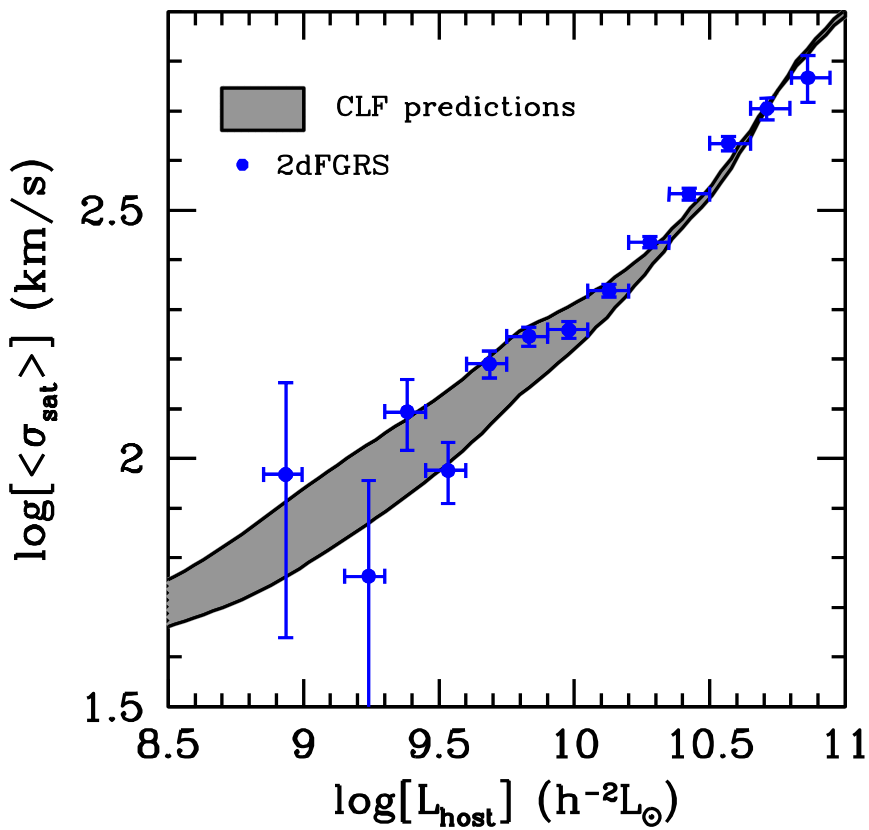
Mock versus 2dFGRS: round 2



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

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 CLF results

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

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

Conclusions: CLF

- $\Phi(L|M)$ is a powerful statistical tool. It is strongly constrained by $\Phi(L)$ and $r_0(L)$ (Yang, Mo & vdB 2003)
- $\Phi(L|M)$ yields mass-to-light ratios $\langle M/L\rangle(M)$ and galaxy bias as function of luminosity, type, etc (vdB, Yang & Mo 2003)
- Relation between mass and light inferred from $\Phi(L|M)$ in excellent agreement with satellite kinematics (vdB, Norberg, Mo & Yang 2004)
- $\Phi(L|M)$ ideal to construct mock galaxy redshift surveys and to study large scale structure (Yang, Mo, Jing, vdB & Chu 2004)
- There are two characteristic scales in Galaxy Formation, at $\sim 10^{11} h^{-1}\ \mathrm{M}_\odot$ and $\sim 10^{13} h^{-1}\ \mathrm{M}_\odot$.
  (vdB, Yang, Mo & Norberg 2005; Yang, Mo, vdB & Jing 2005)

The ΛCDM concordance cosmology predicts too many massive clusters, unless $\langle M/L\rangle_{\mathrm{cl}} \simeq 1000h\ (\mathrm{M/L})_\odot$ or $\sigma_8 \simeq 0.75$.
