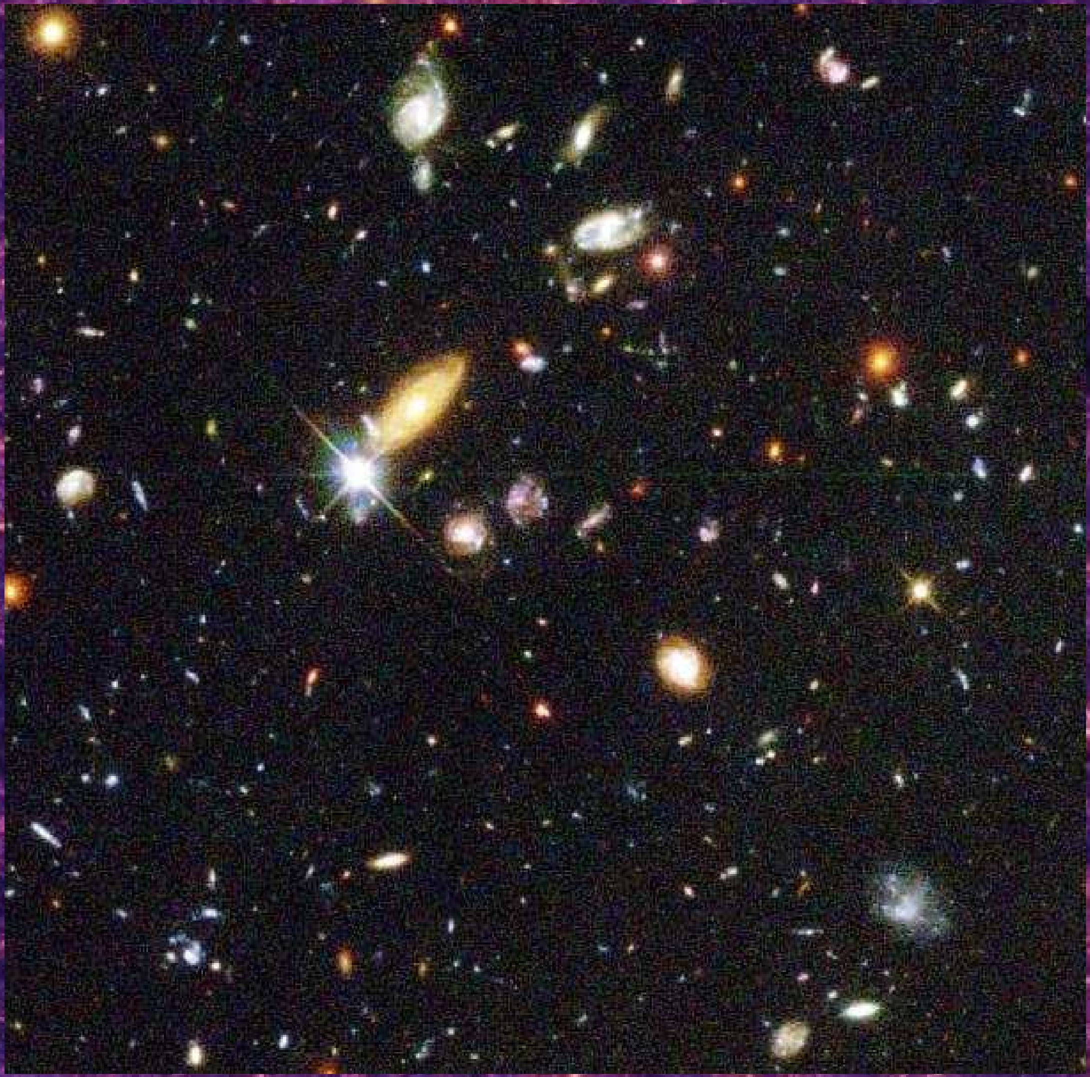
The Galaxy–Dark Matter Connection



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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)**

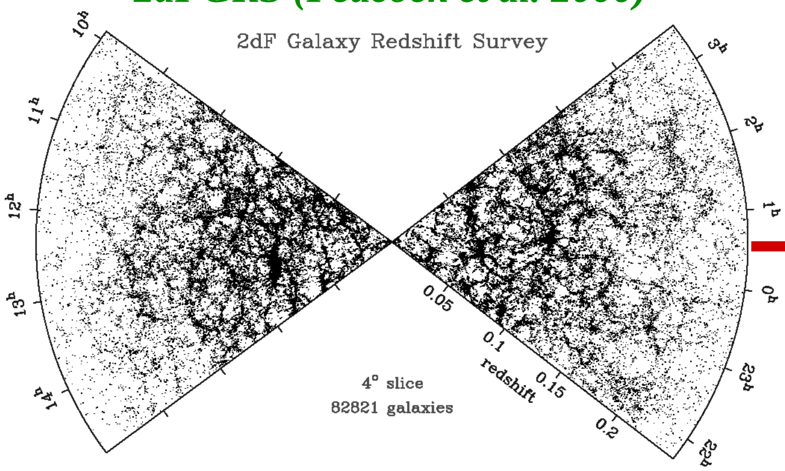
The galaxy-dark matter connection can be studied

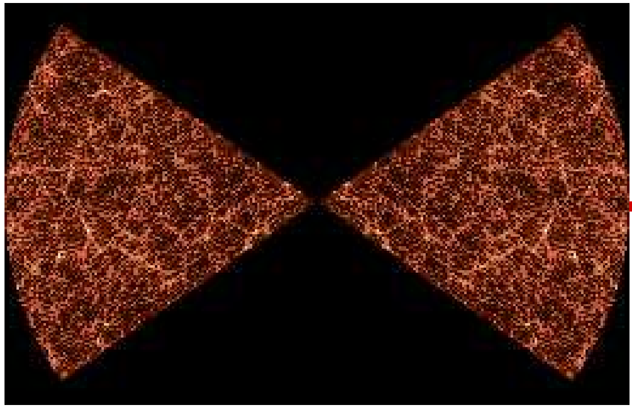
Physically: Ab initio galaxy formation models (SAMs)

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, $\xi_{\rm hh}(r)$.

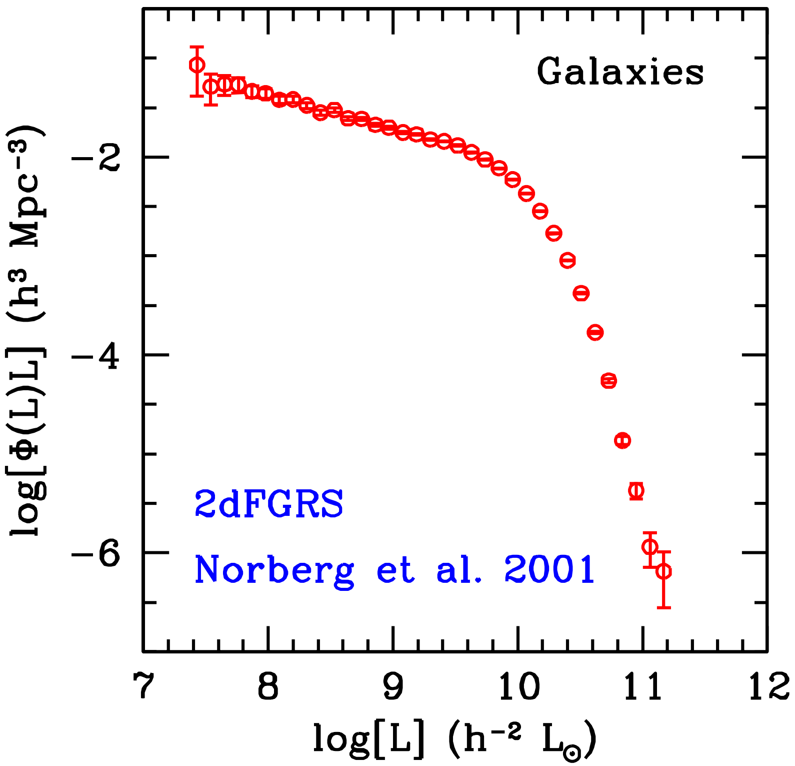
Lighting-Up the Dark Matter

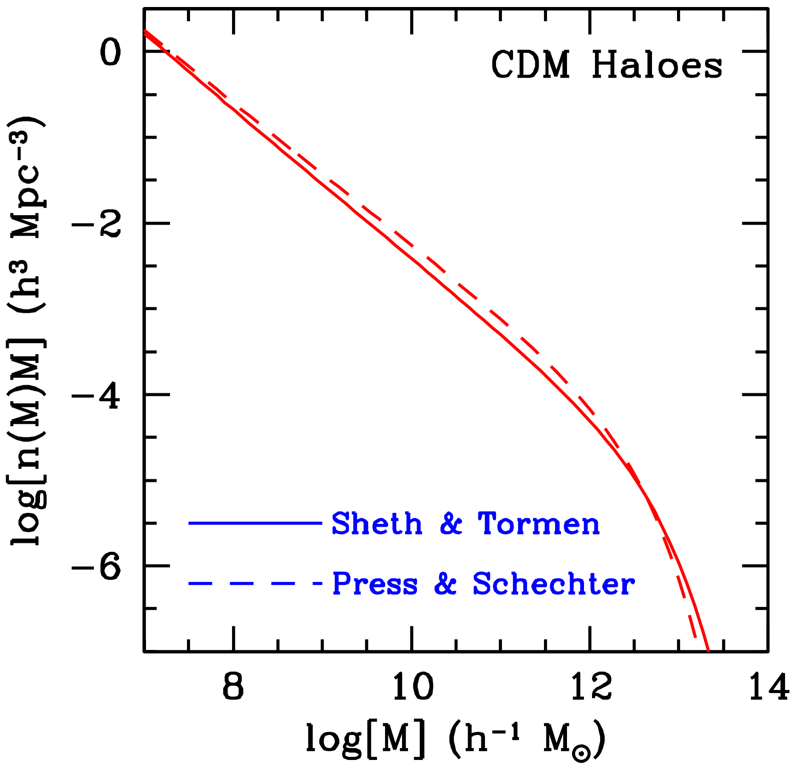
Important Shortcoming: Galaxy bias depends on galaxy properties:

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

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:

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

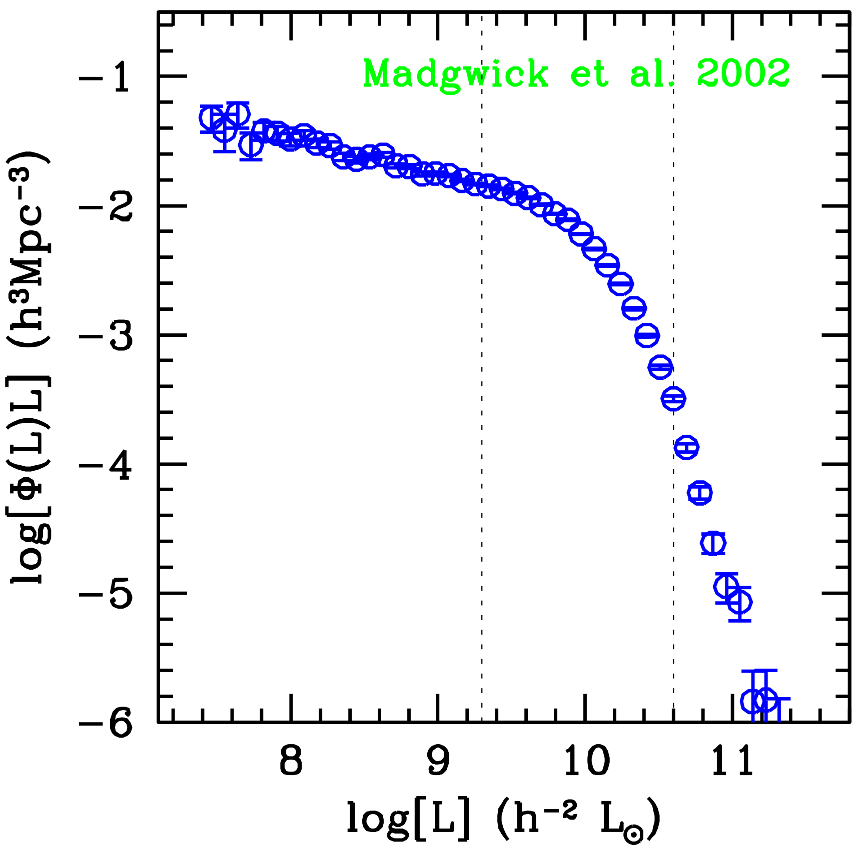
- Galaxy clustering properties as function of luminosity:

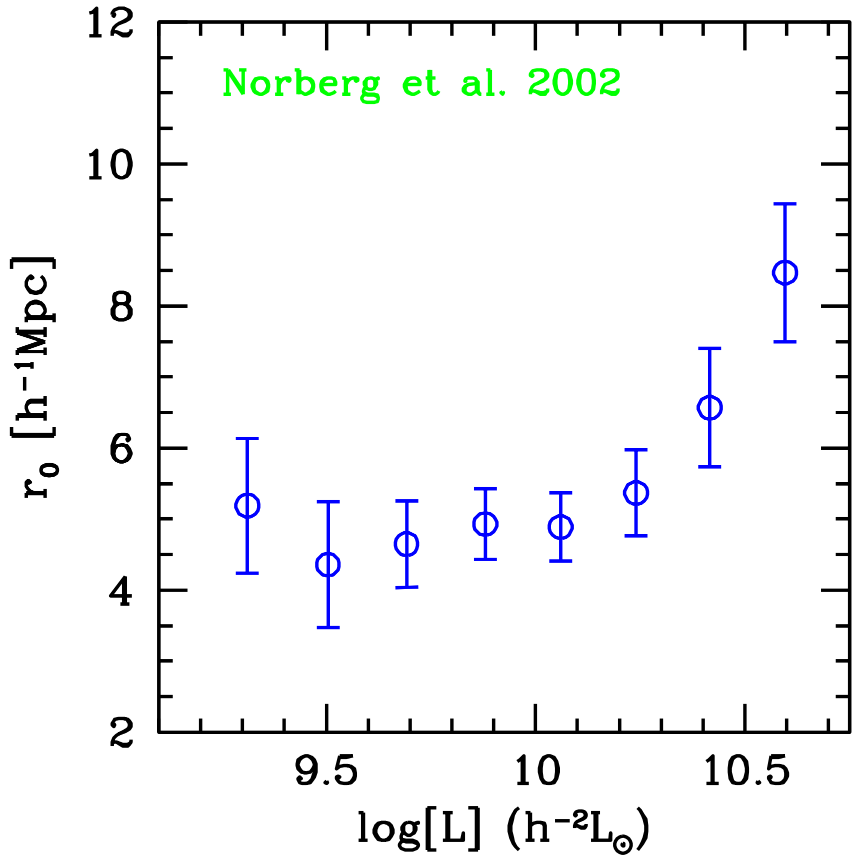
$$\xi_{\mathrm{gg}}(r|L) = b^2(L)\, \xi_{\mathrm{dm}}(r)$$

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

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

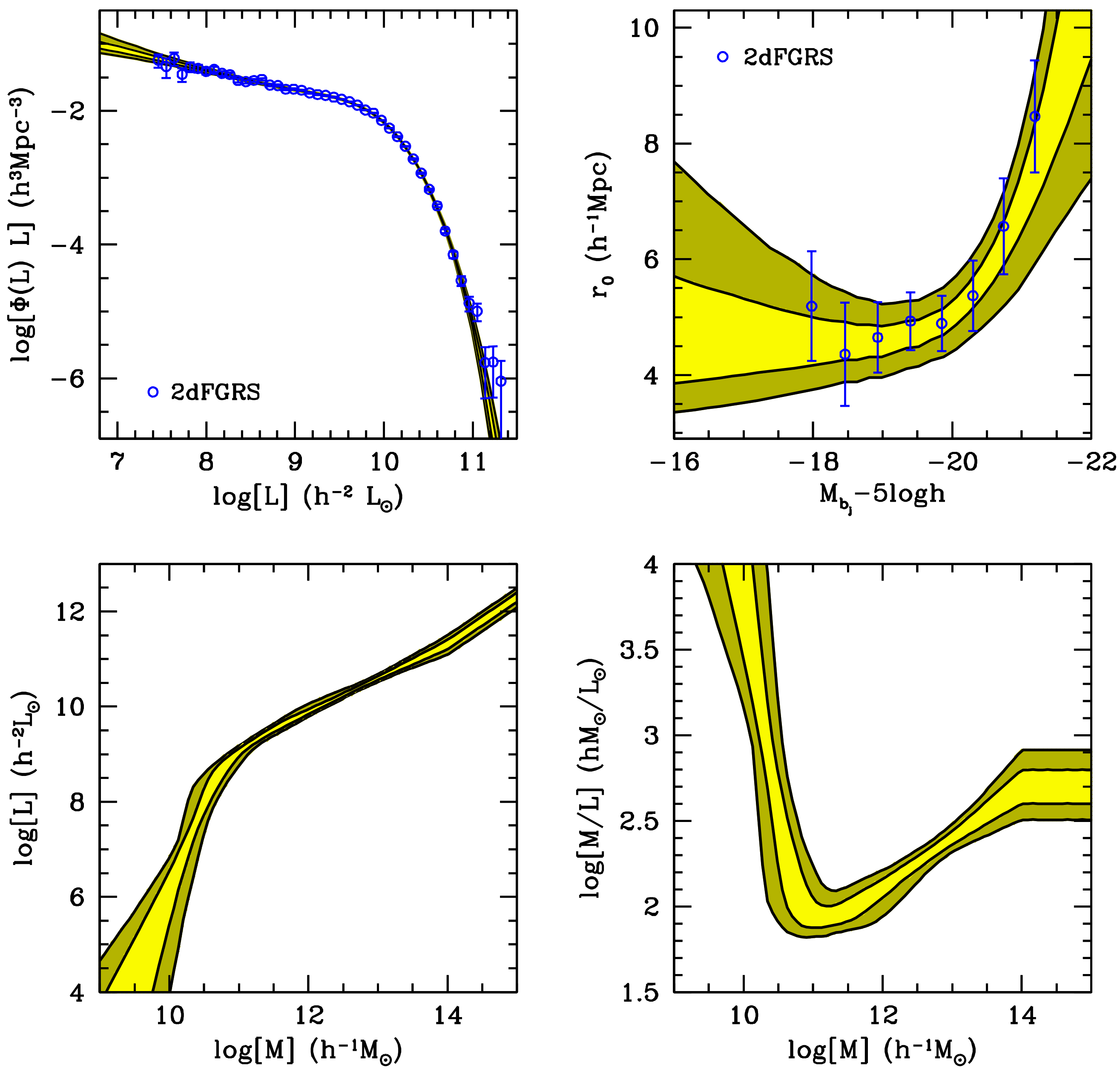
We therefore assume that the CLF also has the Schechter form:

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

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

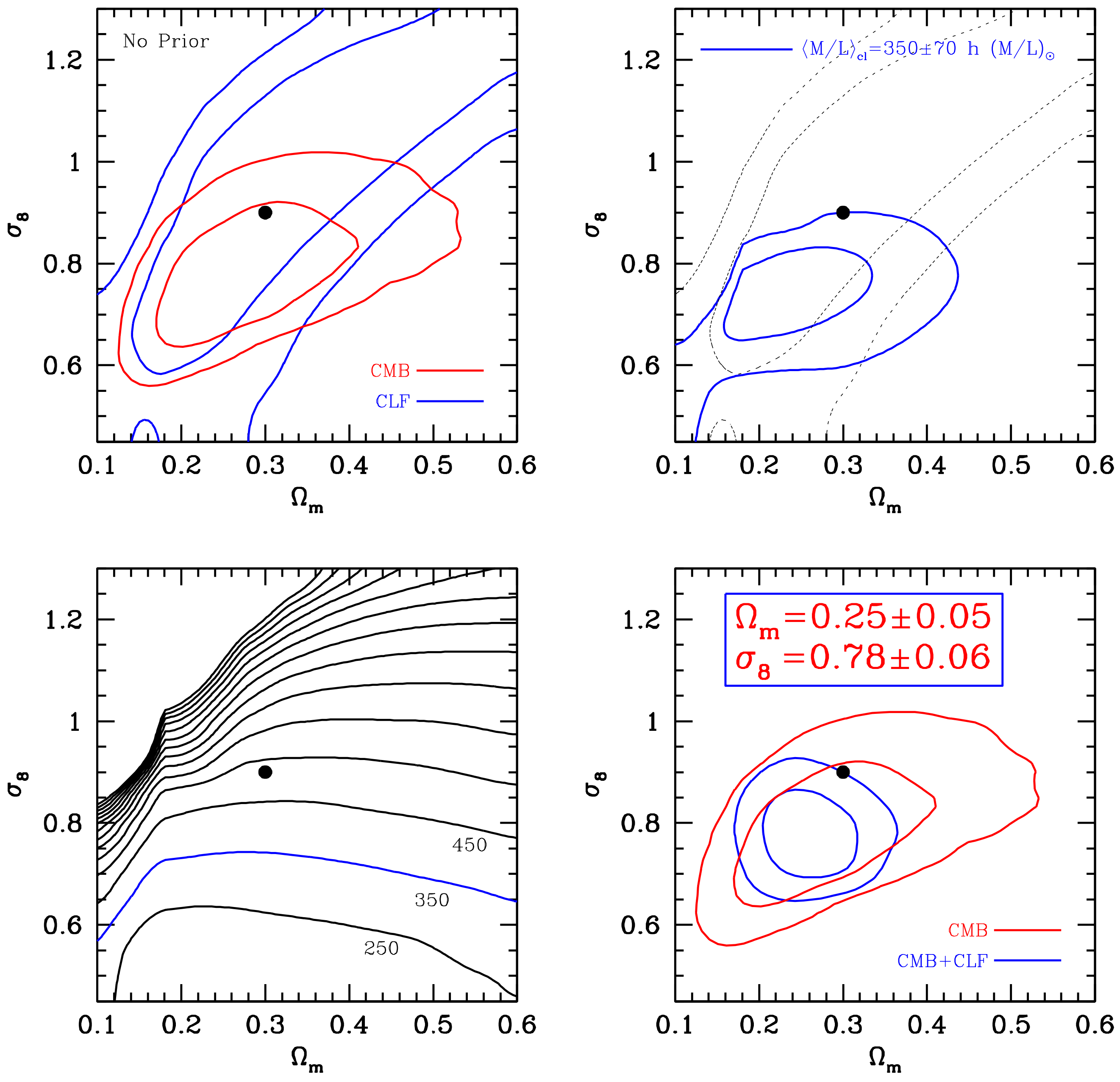
- Parameterize $\tilde{\Phi}^*$, $\tilde{L}^*$ and $\tilde{\alpha}$. In total our model has 8 free parameters
- Construct Monte-Carlo Markov Chain to sample posterior distribution of free parameters. ($N_{\rm eq} = 10^4$, $N_{\rm step} = 4 \times 10^7$, $N_{\rm chain} = 2000$)
- Use MCMC to put confidence 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

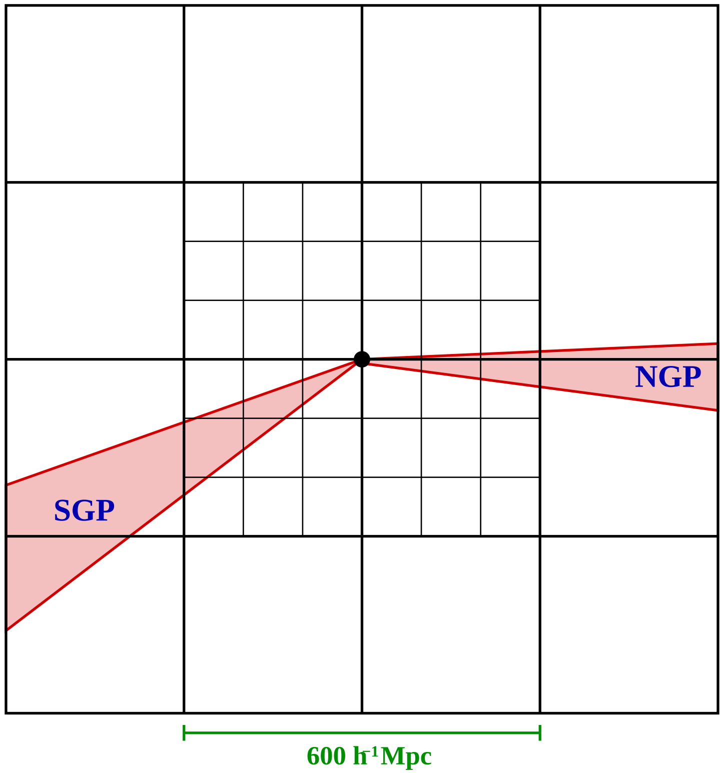
Constraints on Ω_m and σ_8



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

Constructing Mock Surveys

- Run numerical simulations: ΛCDM concordance cosmology; $L_{\rm box} = 100 h^{-1}$ Mpc and $L_{\rm box} = 300 h^{-1}$ 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)



HODs from Galaxy Groups

In addition to using clustering data, Halo Occupation Statistics can also be obtained directly from galaxy groups

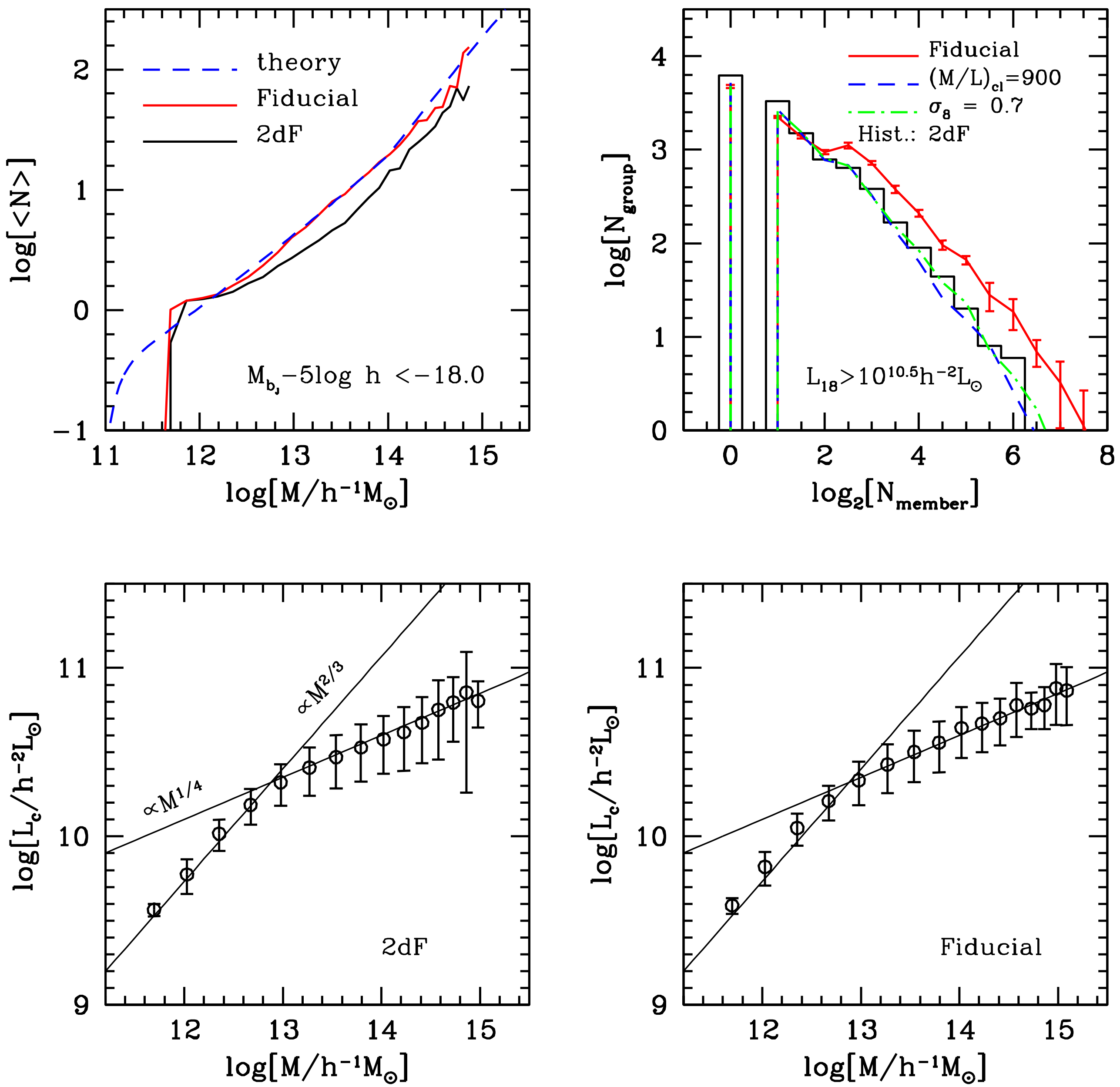
Potential Problems: interlopers, (in)completeness, group mass estimates

We have developed a new, iterative group finder, using an adaptive filter modeled after halo virial properties Yang, Mo, vdB, Jing 2005, MNRAS, 356, 1293

- Using detailed Mock Galaxy Redshift Surveys group finder has been optimized to associate galaxies that belong to same dark matter halo.
- Significantly fewer interlopers than with standard (FOF-based) group finders
- Average completeness of individual groups larger than 90 percent.
- The halo masses are estimated from group luminosities. More accurate than using velocity dispersion, especially for low mass groups.
- Group finder can also detect "groups" with single member
  $\Rightarrow$ Large dynamic range in halo masses ($11.5 \lesssim \log[M] \lesssim 15$).

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

Various Statistics of Galaxy Groups



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

Galaxy Ecology

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

(e.g., Oemler 1974; Dressler 1980; Postman & Geller 1984; Dominguez et al. 2002; Kauffmann et al. 2004; Balogh et al. 2004; Goto et al. 2003; Gomez et al. 2003; Hogg et al. 2004; Tanaka et al. 2004)

Environment estimated using galaxy overdensity (projected) to nth nearest neighbour, Σ_n or using fixed, metric aperture, Σ_R.

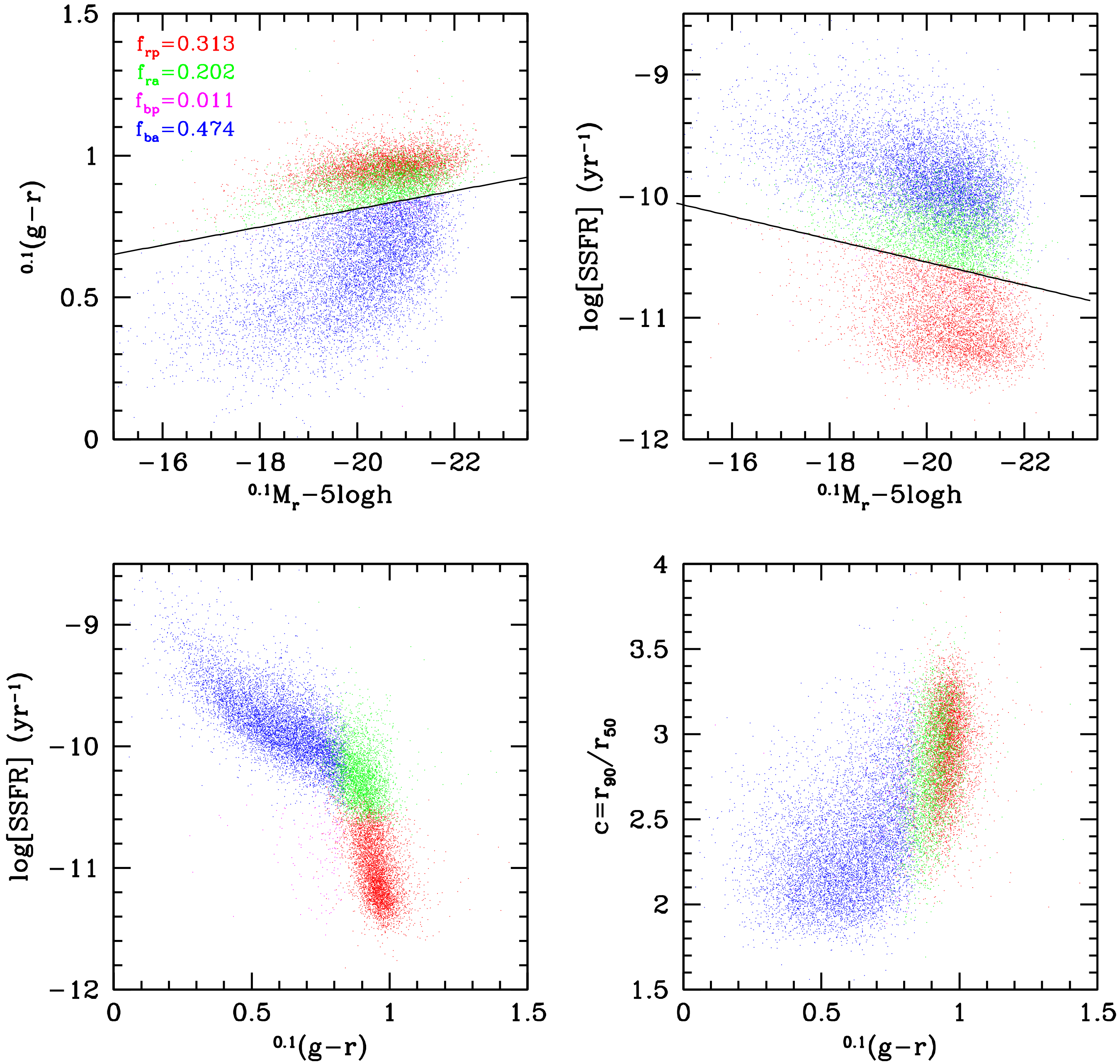
- **Fraction of early types increases with density**
- **There is a characteristic density ($\sim$ group-scale) below which environment dependence vanishes**
- **Groups and Clusters also reveal radial dependence: late type fraction increases with radius**
- **No radial dependence in groups with $M \lesssim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

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.

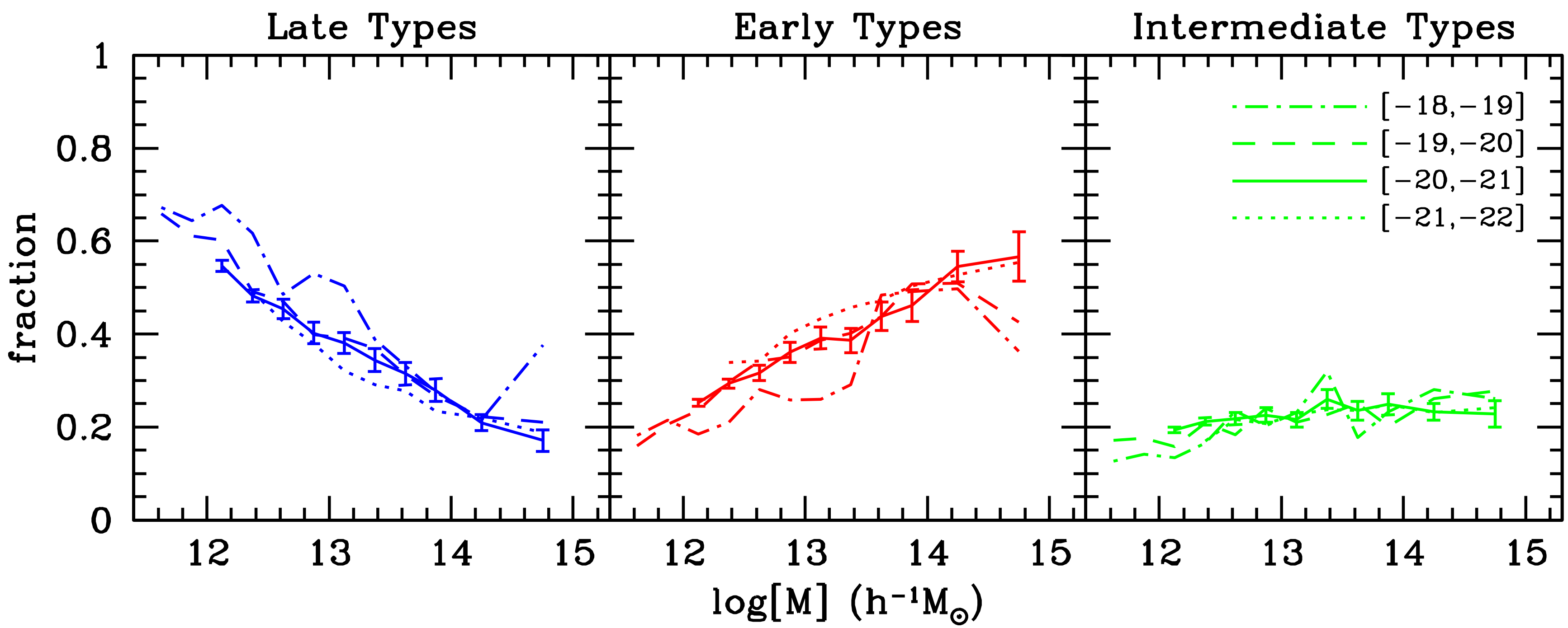
Important: Separate luminosity dependence from halo mass dependence.

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.

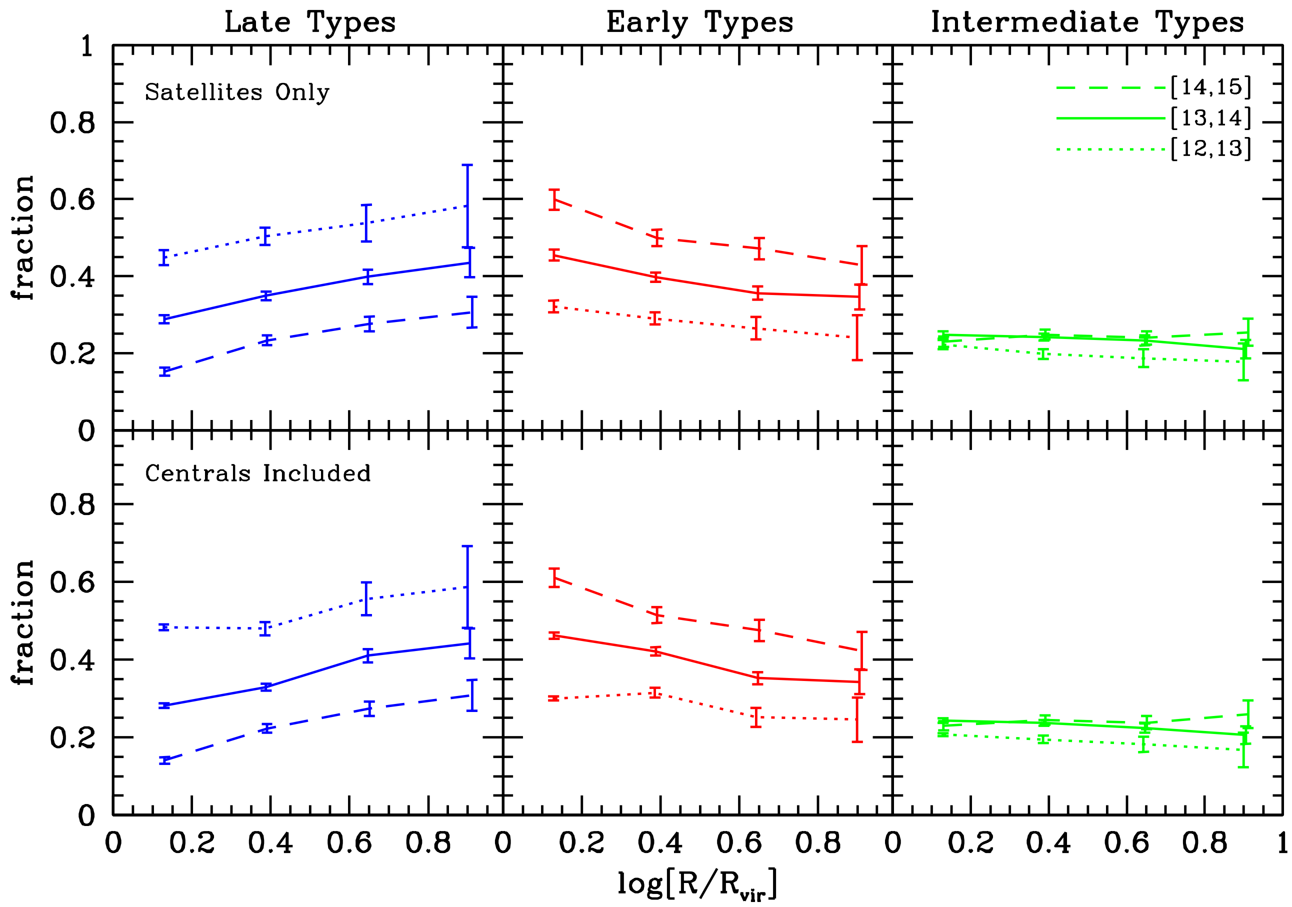
At fixed halo mass, there is virtually no luminosity dependence.

The mass dependence is smooth: there is no characteristic mass scale; i.e., no indication that something special happens at the group or cluster scales.

The intermediate type fraction is independent of luminosity and mass.

(Weinmann, vdB, Yang & Mo, 2005)

Dependence on Group-centric Radius



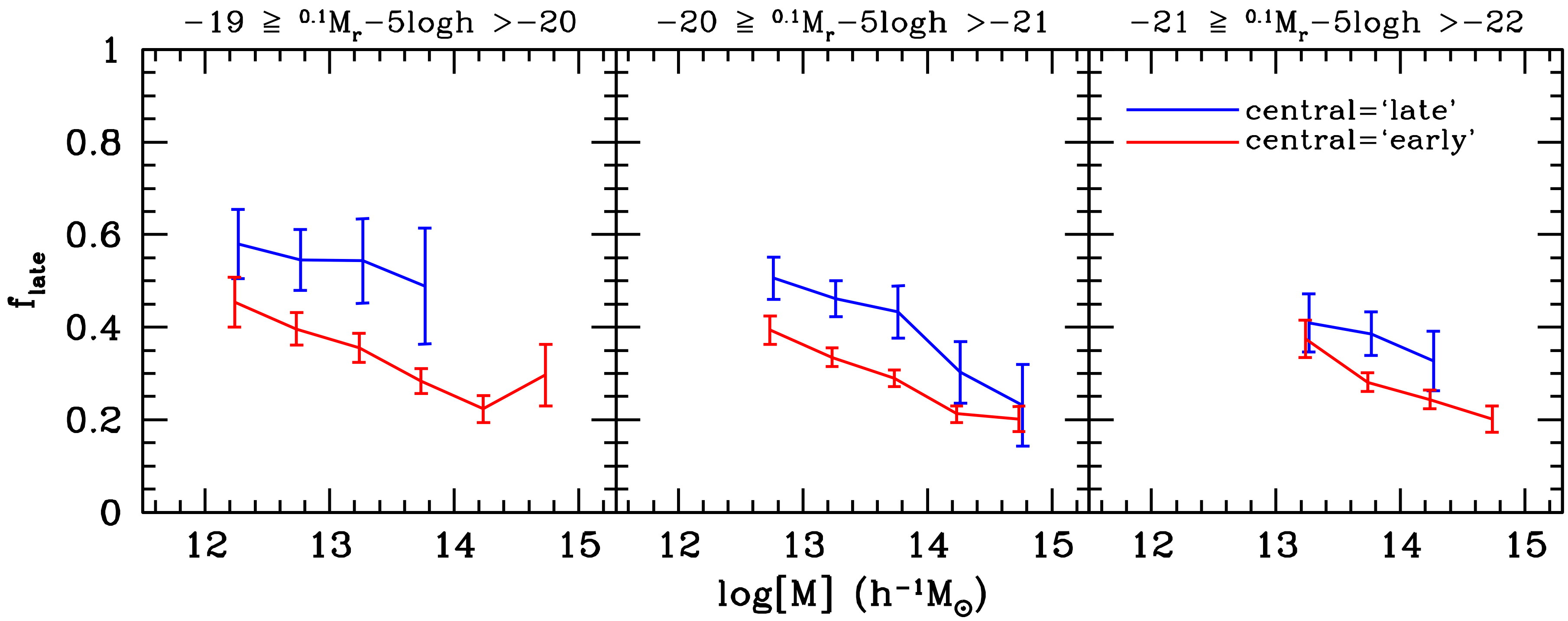
As noticed before, the late type fraction of satellites increases with radius.
This trend is independent of halo mass!

Inconsistent with previous studies, but these included central galaxies.

Our results rule out group- and cluster-specific processes such as ram-pressure stripping and harassment: nature rather than nurture!

(Weinmann, vdB, Yang & Mo, 2005)

Galactic Conformity



Satellite galaxies ‘adjust’ themselves to properties of their central galaxy: late type ‘centrals’ have preferentially late type satellites, and vice versa.

This has been noticed before, but only for small samples of loose groups (Wirth 1983; Ramella et al. 1987; Osmond & Ponmon 2004).

Our results indicate that this Galactic Conformity is present over large ranges in luminosity and halo mass. **(Weinmann, vdB, Yang & Mo, 2005)**

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 $\langle M/L\rangle_{\rm cl} \simeq 1000h\ (\mathrm{M/L})_\odot$ or $\sigma_8 \simeq 0.75$.

Conclusions: Ecology

- Galaxy properties scale smoothly with halo mass. There is no indication for a specific transition at either group or cluster scale.
- Galaxy type (early vs. late) is determined by the mass of the halo in which the galaxy lives. Not by the mass (or luminosity) of the galaxy.
- Late type fractions increase with halo-centric radius, independent of halo mass. This rules out ram-pressure stripping and harassment as physical causes, and favors a ‘nature’ scenario instead.
- Satellite galaxies ‘adjust’ their properties to those of their central galaxy: Galactic Conformity (Weinmann, vdB, Yang & Mo 2005)