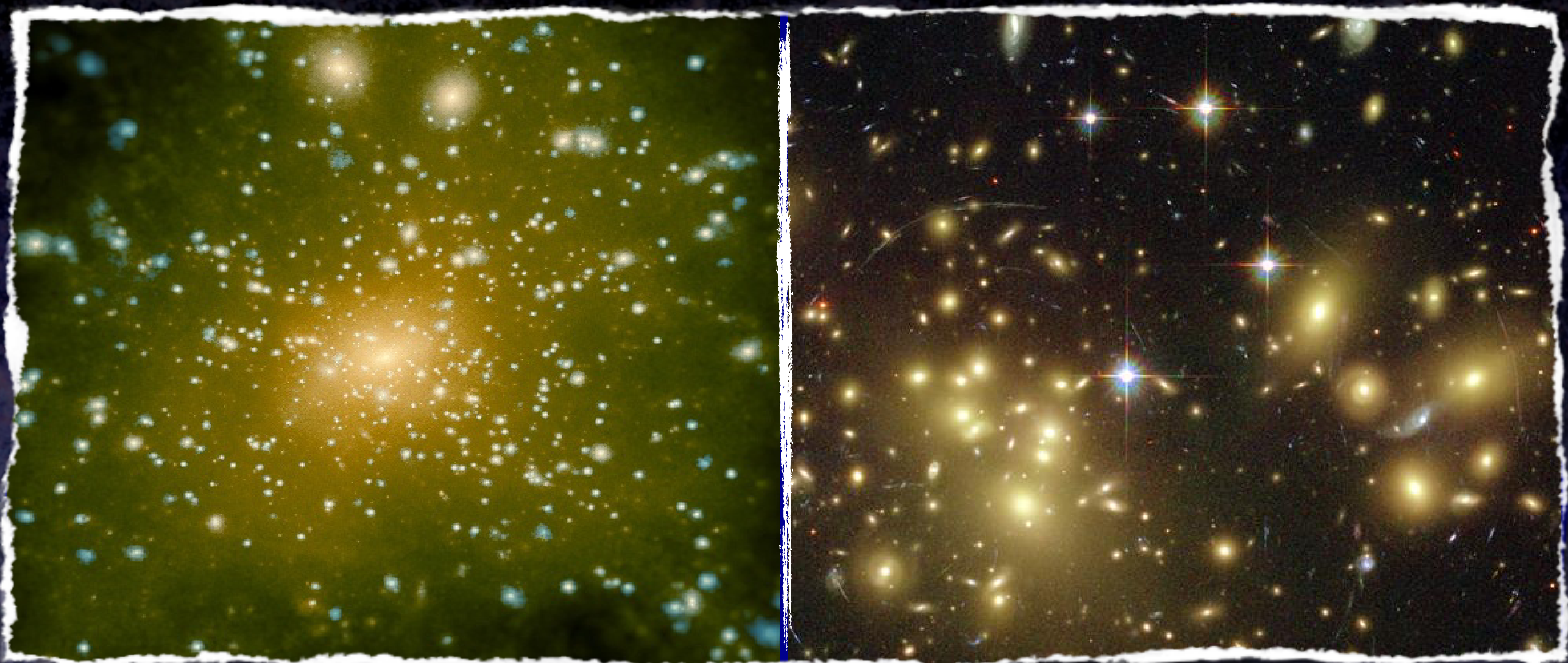
The Galaxy-Dark Matter Connection; from statistical tool to cosmological constraints



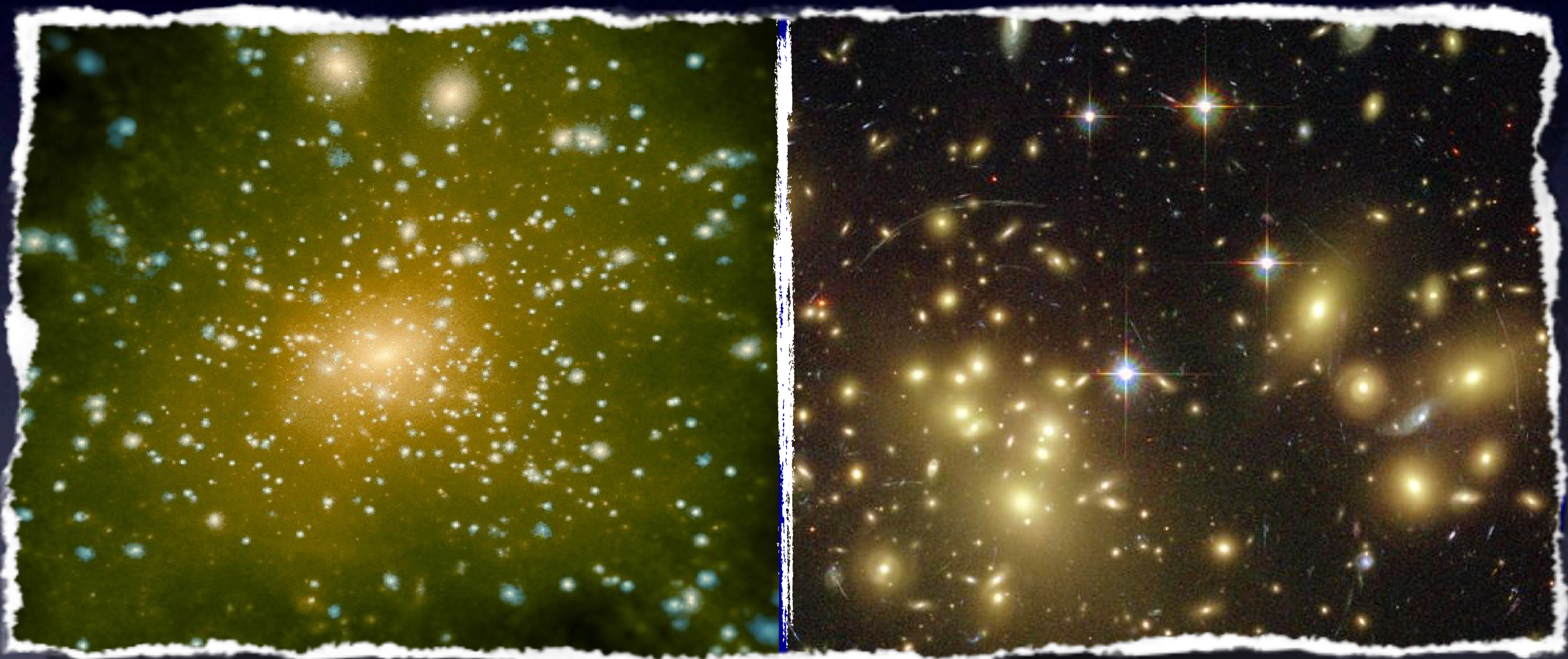
Frank van den Bosch
Yale University

In collaboration with:
Marcello Cacciato (HU), Surhud More (KICP),
Houjun Mo (UMass), Xiaohu Yang (SHAO)

Halo Occupation Modelling: Motivation & Goal

Our main goal is to study the Galaxy-Dark Matter connection;
i.e., what galaxy lives in what halo?

- To constrain the physics of Galaxy Formation
- To constrain cosmological parameters

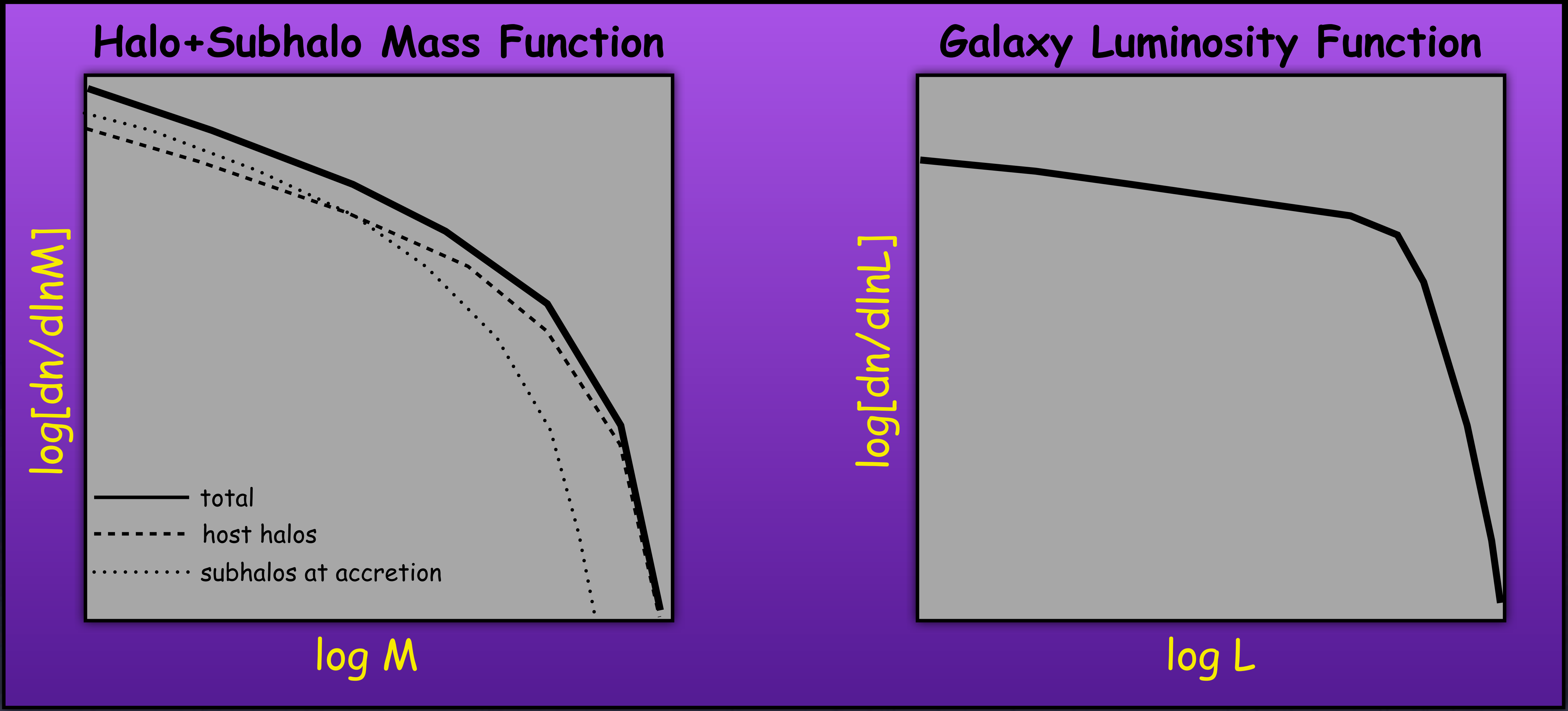


Four Methods to Constrain Galaxy-Dark Matter Connection:

- Large Scale Structure
- Galaxy-Galaxy Lensing
- Satellite Kinematics
- Abundance Matching

(Sub)Halo Abundance Matching

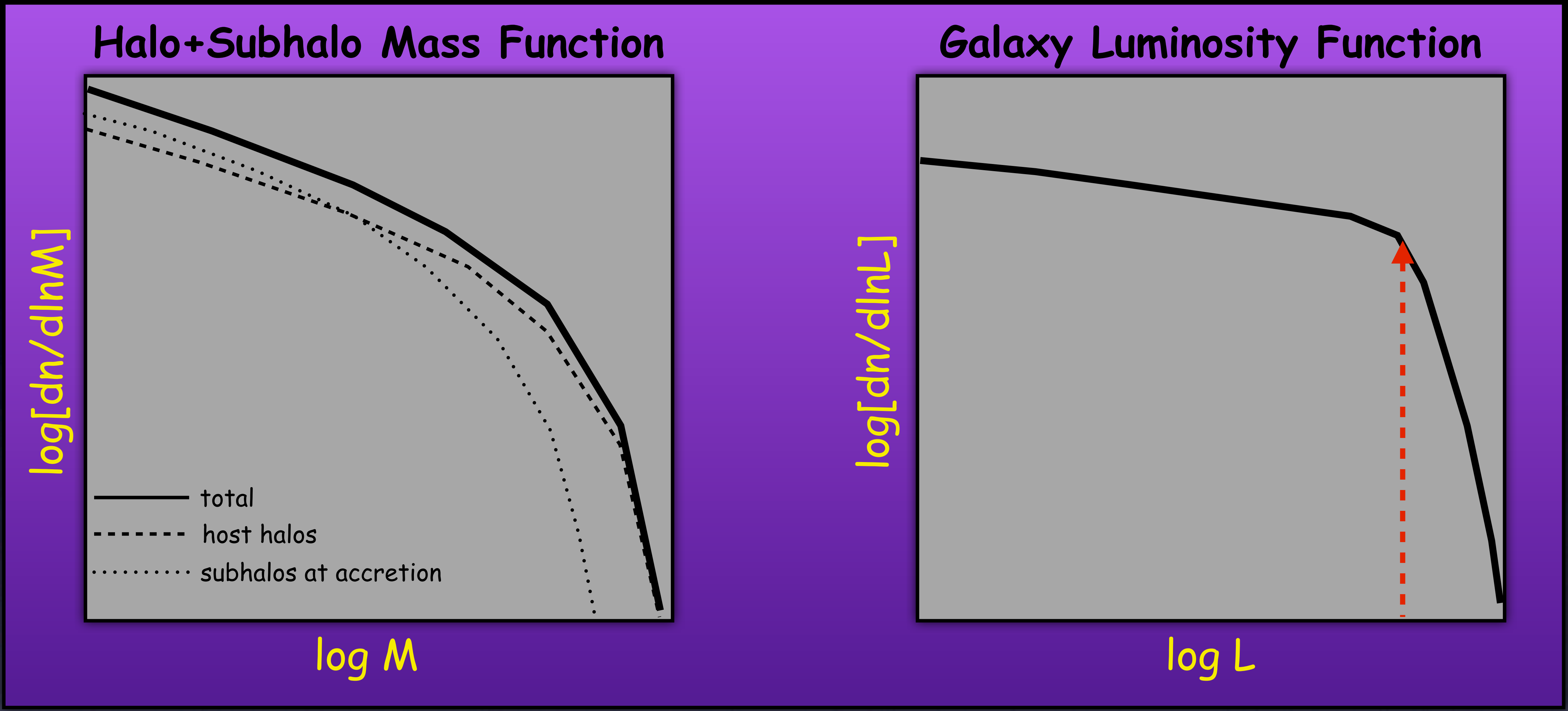
SubHalo Abundance Matching (SHAM)



Establish connection between galaxy luminosity and halo mass by matching their abundances: $n_{\rm g}(>L) = n_{\rm h}(>M) + n_{\rm sh}(>M)$

Mo & Fukugita 1996; Mo, Mao & White 1999; Vale & Ostriker 2004, 2006; Conroy et al. 2006; Shankar et al. 2006; Conroy & Wechsler 2009; Moster et al. 2010; Behroozi et al. 2010; Wetzel & White 2010

SubHalo Abundance Matching (SHAM)

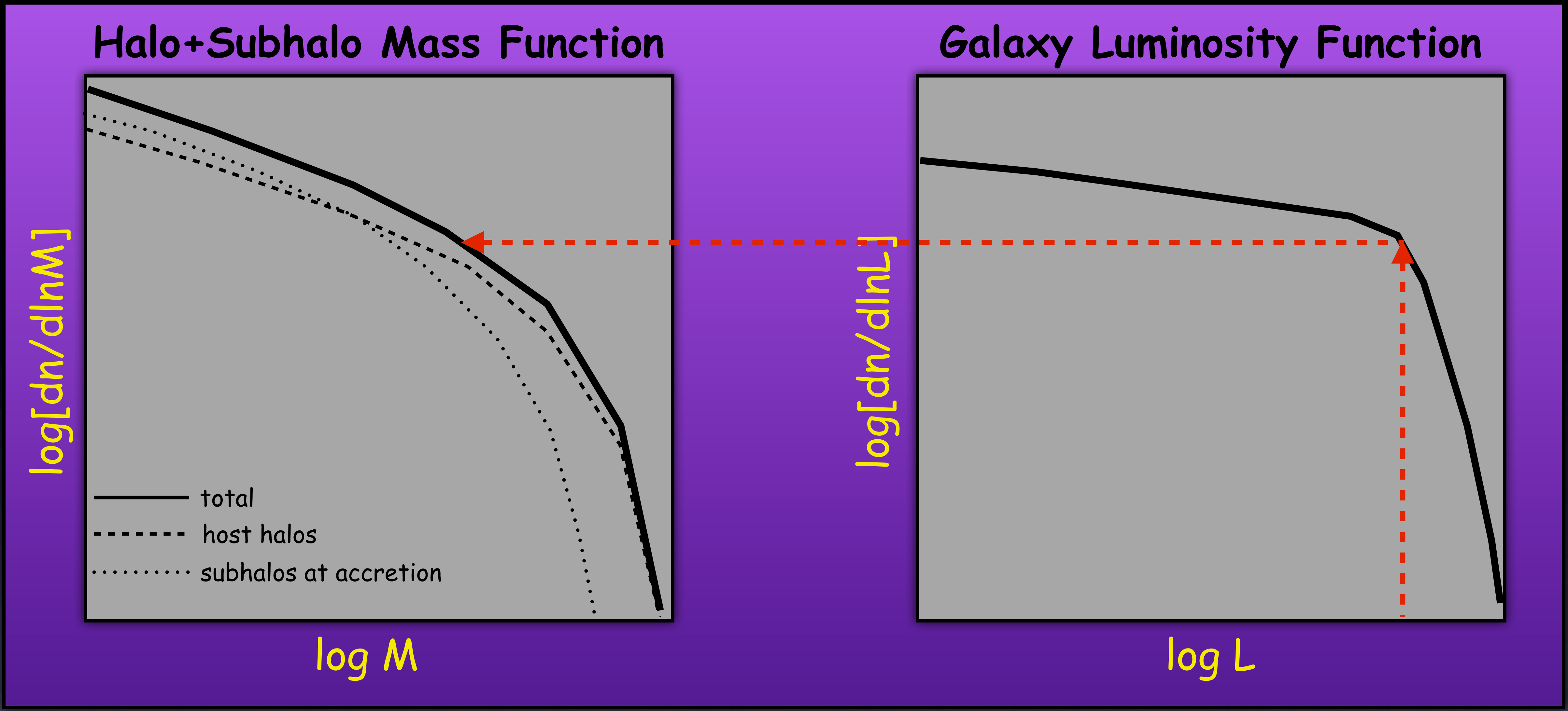


Establish connection between galaxy luminosity and halo mass by matching their abundances:

$$n_{\rm g}(>L) = n_{\rm h}(>M) + n_{\rm sh}(>M)$$

Mo & Fukugita 1996; Mo, Mao & White 1999; Vale & Ostriker 2004, 2006; Conroy et al. 2006; Shankar et al. 2006; Conroy & Wechsler 2009; Moster et al. 2010; Behroozi et al. 2010; Wetzel & White 2010

SubHalo Abundance Matching (SHAM)

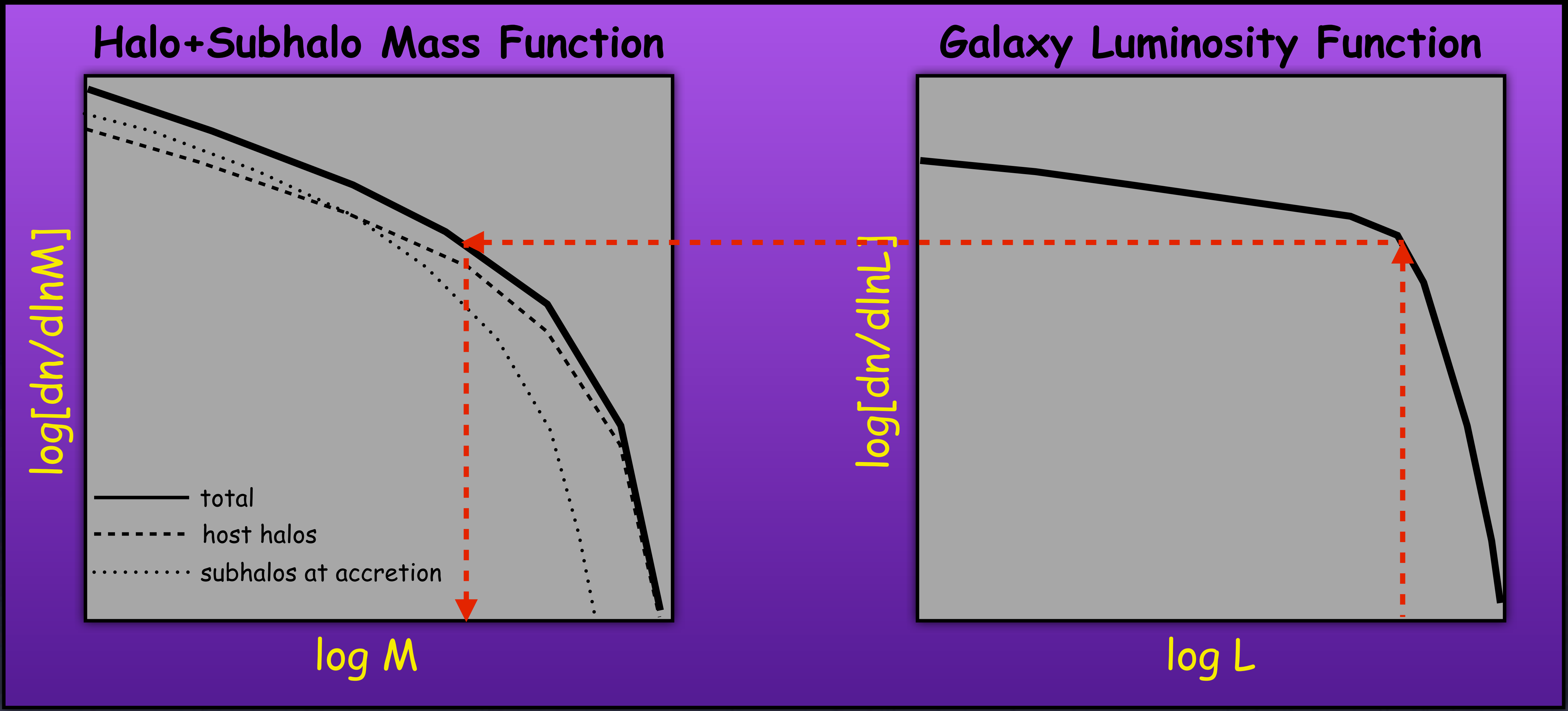


Establish connection between galaxy luminosity and halo mass by matching their abundances:

$$n_{\rm g}(>L) = n_{\rm h}(>M) + n_{\rm sh}(>M)$$

Mo & Fukugita 1996; Mo, Mao & White 1999; Vale & Ostriker 2004, 2006; Conroy et al. 2006; Shankar et al. 2006; Conroy & Wechsler 2009; Moster et al. 2010; Behroozi et al. 2010; Wetzel & White 2010

SubHalo Abundance Matching (SHAM)

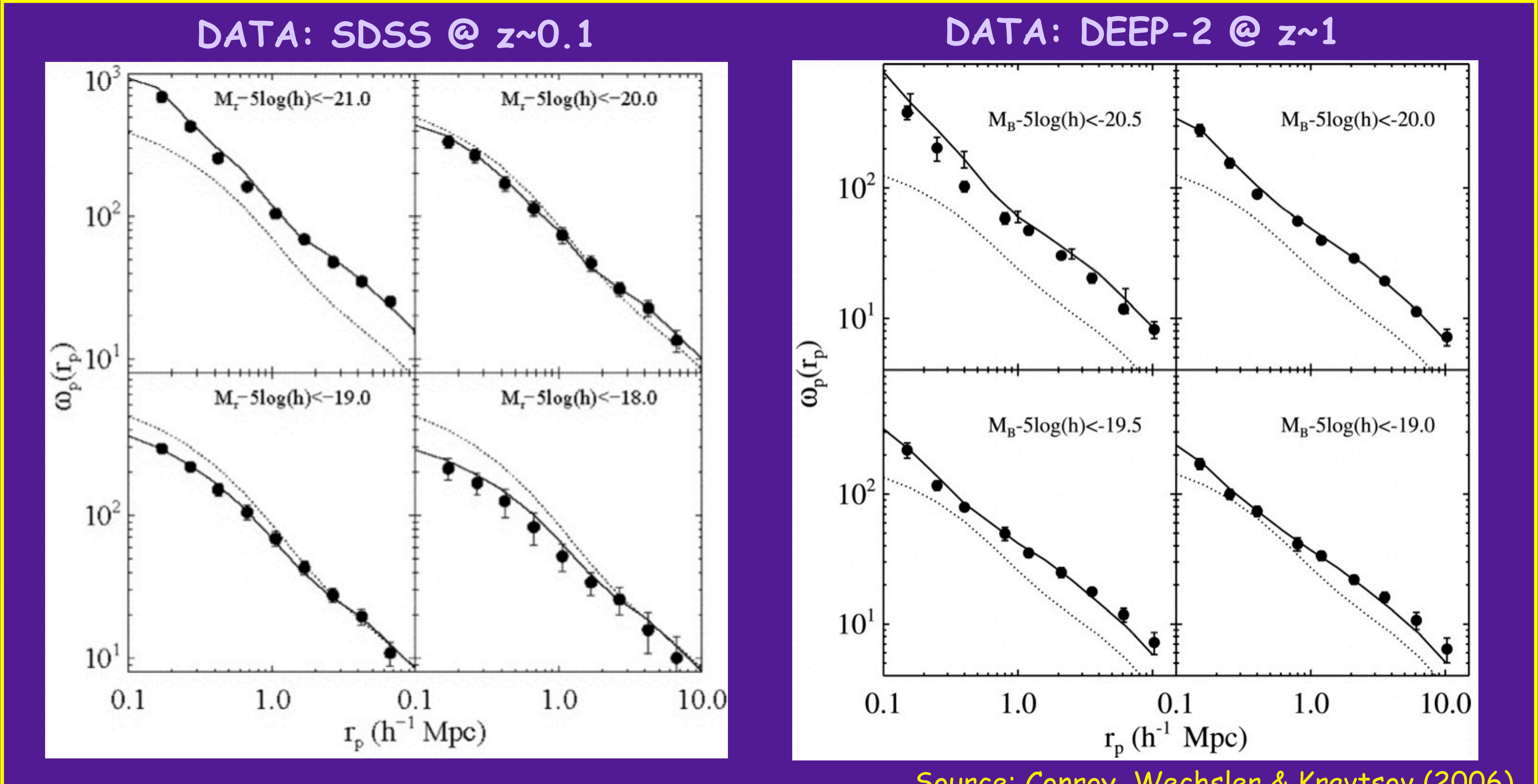


Establish connection between galaxy luminosity and halo mass by matching their abundances: $n_{\rm g}(>L) = n_{\rm h}(>M) + n_{\rm sh}(>M)$

Mo & Fukugita 1996; Mo, Mao & White 1999; Vale & Ostriker 2004, 2006; Conroy et al. 2006; Shankar et al. 2006; Conroy & Wechsler 2009; Moster et al. 2010; Behroozi et al. 2010; Wetzel & White 2010

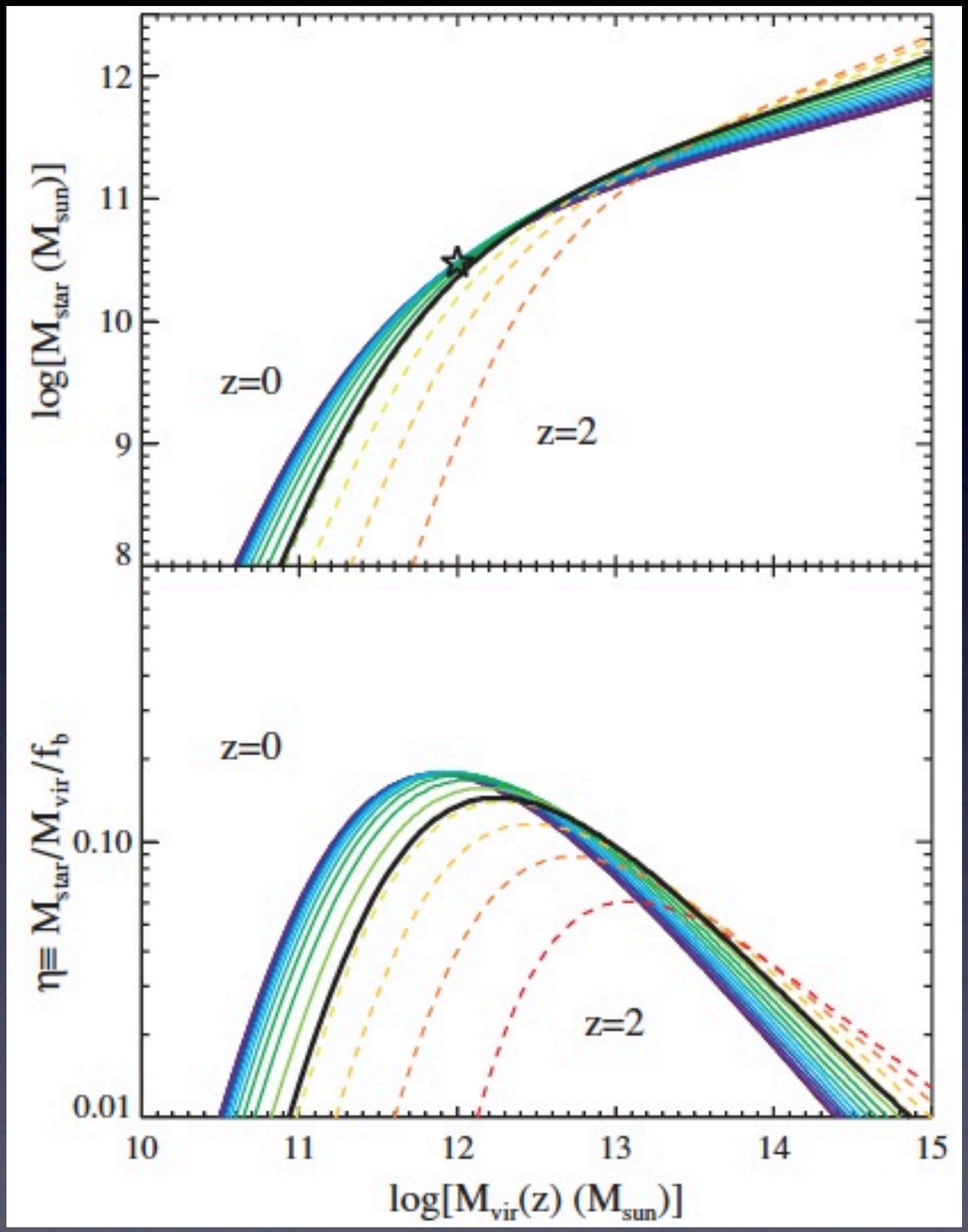
SHAM's Amazing Success

- Has no free parameters (or one; scatter)
- Only requires luminosity (stellar mass) functions
- Fits the observed correlation functions amazingly well!!!
- Cosmology dependent



Source: Conroy, Wechsler & Kravtsov (2006)

SHAM's inconsistency problem



Source: Conroy & Wechsler (2009)

For satellites, SHAM uses (sub)halo mass at accretion, which is treated similar as a host halo of same mass at z=0.

Hidden Assumption: M-L relation doesn't evolve!

Inconsistency: SHAM itself shows that M-L relation does evolve!

Solution: Use M-L relation at accretion redshift to populate subhalos with satellites.

Yang et al. (2012) describe a new, self-consistent & dynamical model to describe the evolution of the galaxy-dark matter connection across cosmic time.

(see talk by Xiaohu Yang)

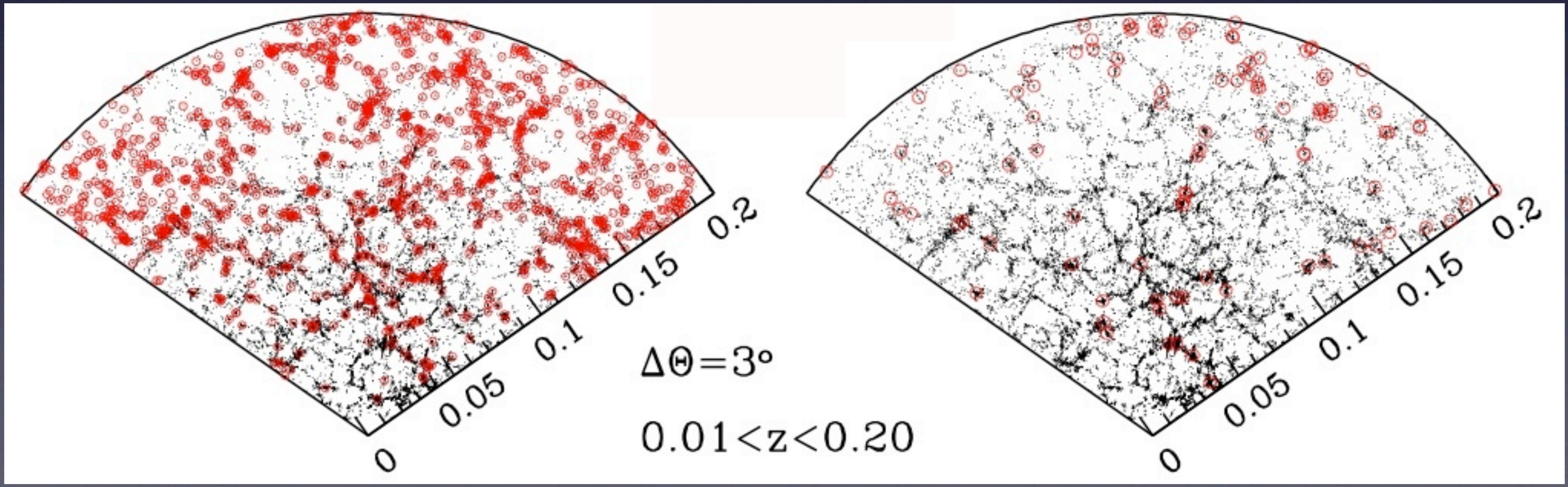
Galaxy Group Catalogues

Constructing Galaxy Group Catalogues

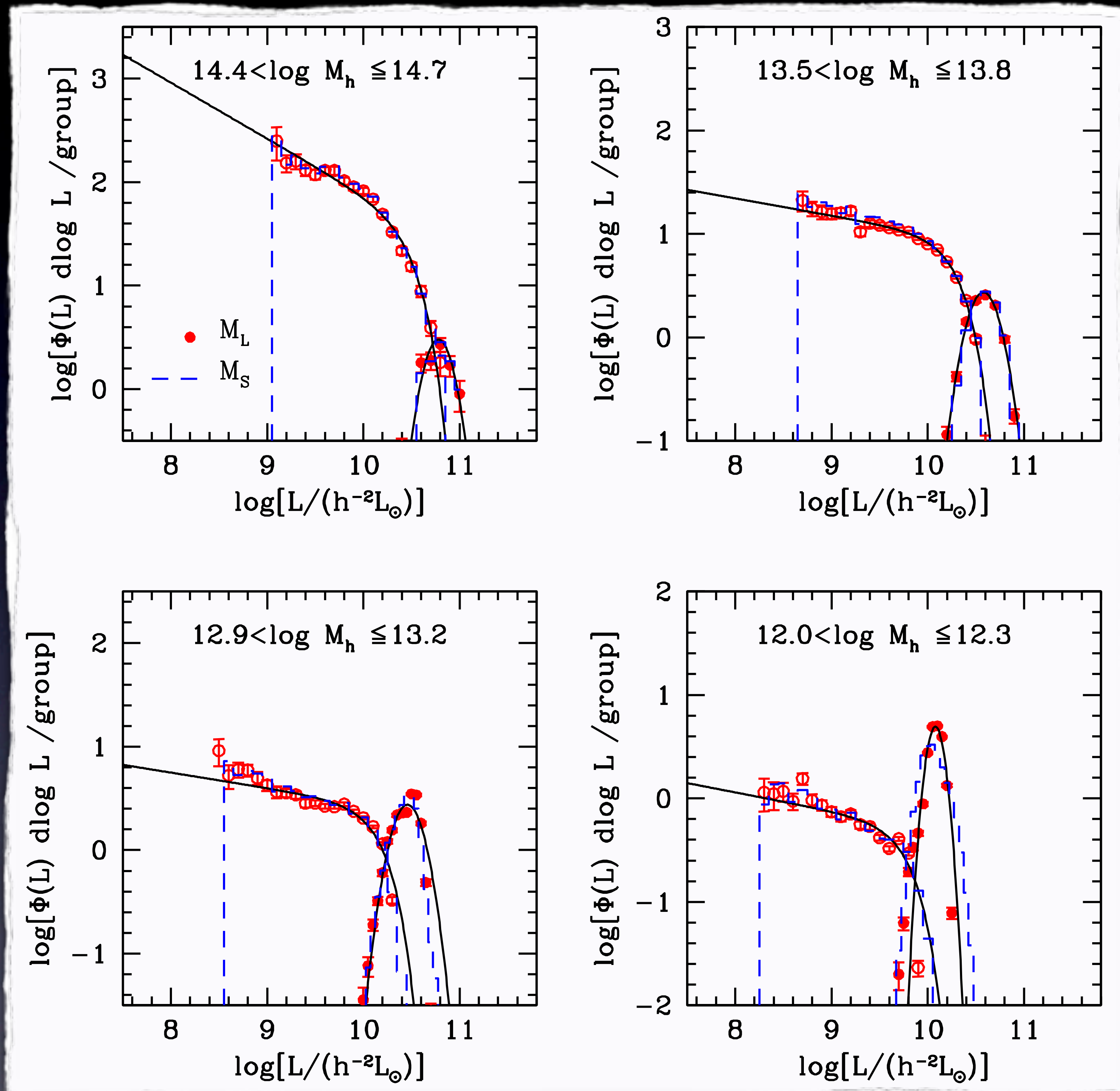
We have developed a new, iterative group finder which uses an adaptive filter modeled after halo virial properties.

- Calibrated & optimized using mock galaxy redshift surveys
- Low interloper fraction (<15%) & high completeness of members (>90%)
- Halo masses estimated from total group luminosity/stellar mass using abundance matching (...cosmology dependent....)
- Can also detect `groups' with single member; large dynamic mass range

For details see Yang et al. (2005) and Yang et al. (2007).



CLF Constraints from Group Catalogue



Yang, Mo & vdB (2008)

The Conditional Luminosity Function

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

$$\Phi(L) = \int \Phi(L|M)\, n(M)\, \mathrm{d}M$$

$$\langle L \rangle_M = \int \Phi(L|M)\, L\, \mathrm{d}L$$

$$\langle N \rangle_M = \int \Phi(L|M)\, \mathrm{d}L$$

- Describes occupation statistics of dark matter haloes
- Links galaxy luminosity function to halo mass function
- Holds information on average relation between light and mass

see Yang, Mo & vdBosch 2003

The CLF Model

We split the CLF in a central and a satellite term:

$$\Phi(L|M) = \Phi_{\rm c}(L|M) + \Phi_{\rm s}(L|M)$$

For centrals we adopt a log-normal distribution:

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

For satellites we adopt a modified Schechter function:

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

Note: $\{L_{\rm c}, L_{\rm s}, \sigma_{\rm c}, \phi_{\rm s}, \alpha_{\rm s}\}$ all depend on halo mass

Free parameters are constrained by fitting data.

Satellite Kinematics

Satellite Kinematics

We use satellite kinematics in the SDSS to probe the relation between stellar mass and halo mass. Using virial equilibrium and spherical collapse:

$$\sigma^2 \propto \frac{GM_{\rm h}}{r_{\rm h}} \qquad M_{\rm h} \propto r_{\rm h}^3 \qquad \sigma \propto M_{\rm h}^{1/3}$$

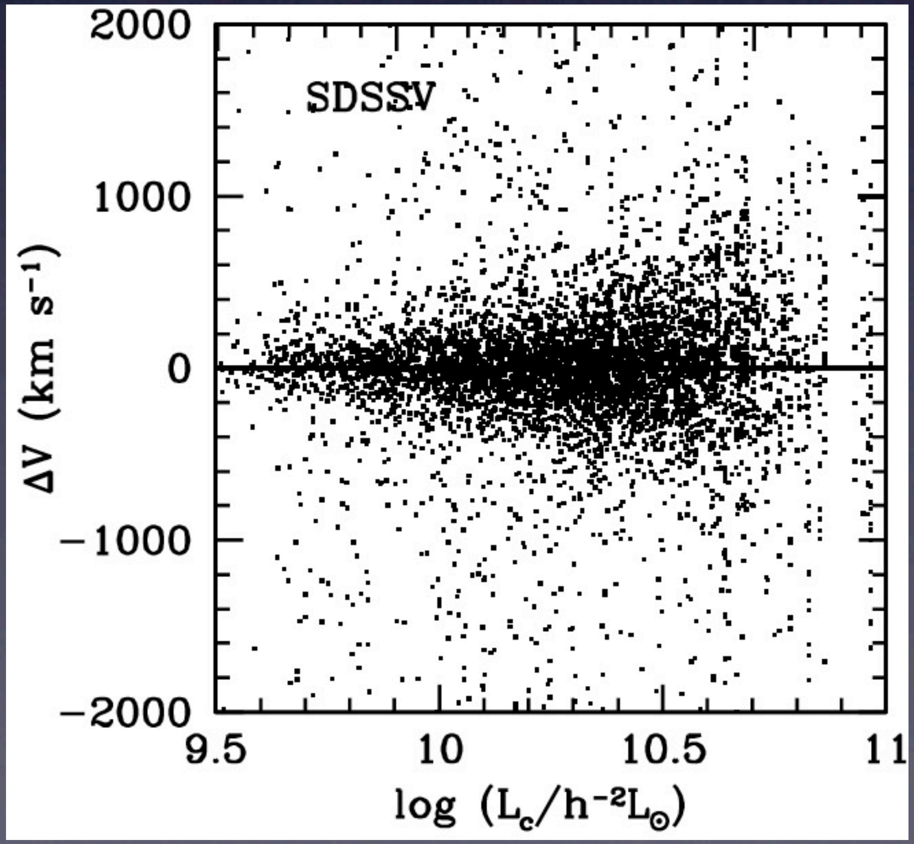
Satellite Kinematics

We use satellite kinematics in the SDSS to probe the relation between stellar mass and halo mass. Using virial equilibrium and spherical collapse:

$$\sigma^2 \propto \frac{GM_\mathrm{h}}{r_\mathrm{h}} \qquad M_\mathrm{h} \propto r_\mathrm{h}^3 \qquad \sigma \propto M_\mathrm{h}^{1/3}$$

On average, only ~2 satellites per central: → **stacking**

- select centrals and satellites from SDSS
- using redshifts, measure $\Delta V = V_\mathrm{sat} - V_\mathrm{cen}$ as function of M_*



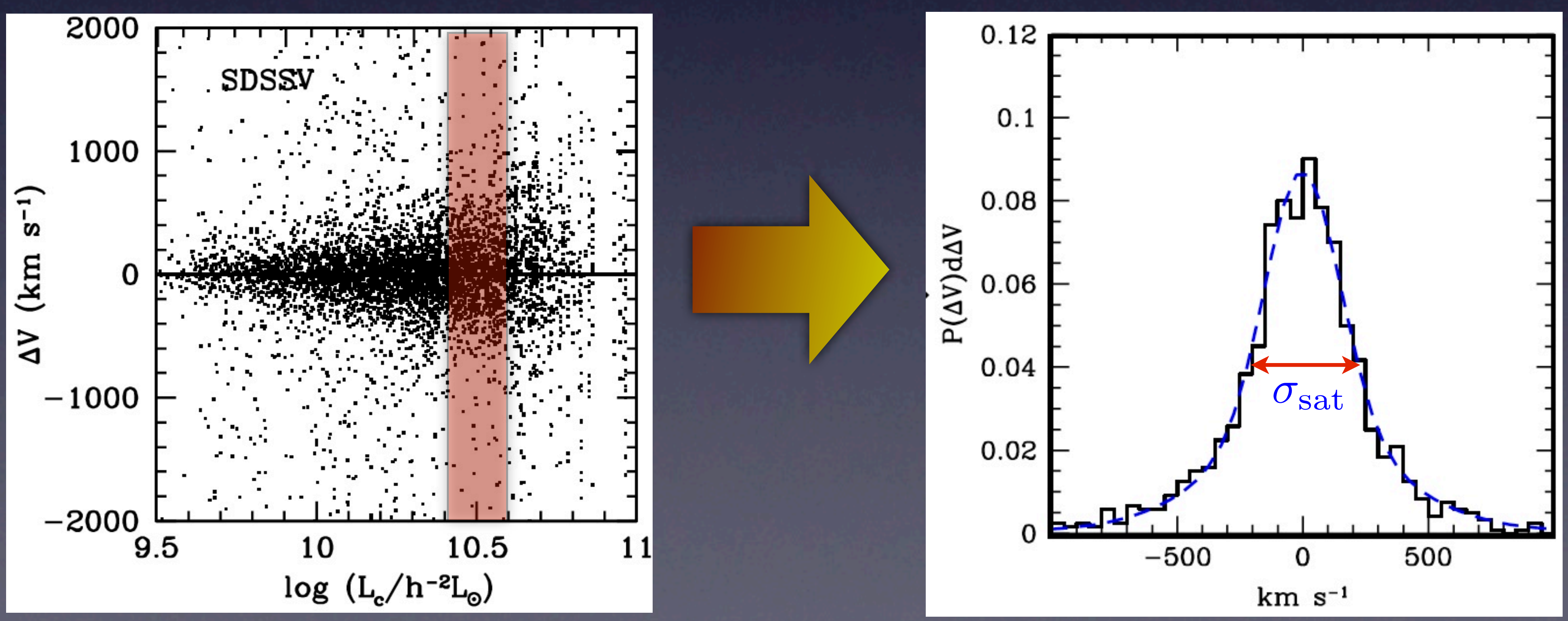
Satellite Kinematics

We use satellite kinematics in the SDSS to probe the relation between stellar mass and halo mass. Using virial equilibrium and spherical collapse:

$$\sigma^2 \propto \frac{GM_{\rm h}}{r_{\rm h}} \qquad M_{\rm h} \propto r_{\rm h}^3 \qquad \sigma \propto M_{\rm h}^{1/3}$$

On average, only ~2 satellites per central: → **stacking**

- select centrals and satellites from SDSS
- using redshifts, measure $\Delta V = V_{\rm sat} - V_{\rm cen}$ as function of M_*



Satellite Kinematics

Unless $P(M_\mathrm{h}|M_*)$ is a Dirac Delta function, stacking implies combining haloes of different masses. Consequently, distinguish two schemes:

satellite weighting:

$$\sigma^2_\mathrm{sw}(M_*) = \frac{\int P(M_\mathrm{h}|M_*)\,\langle N_\mathrm{s}|M_\mathrm{h}\rangle\,\sigma^2_\mathrm{sat}(M_\mathrm{h})\,\mathrm{d}M_\mathrm{h}}{\int P(M_\mathrm{h}|M_*)\,\langle N_\mathrm{s}|M_\mathrm{h}\rangle\,\mathrm{d}M_\mathrm{h}}$$

host weighting:

$$\sigma^2_\mathrm{hw}(M_*) = \frac{\int P(M_\mathrm{h}|M_*)\,\sigma^2_\mathrm{sat}(M_\mathrm{h})\,\mathrm{d}M_\mathrm{h}}{\int P(M_\mathrm{h}|M_*)\,\mathrm{d}M_\mathrm{h}}$$

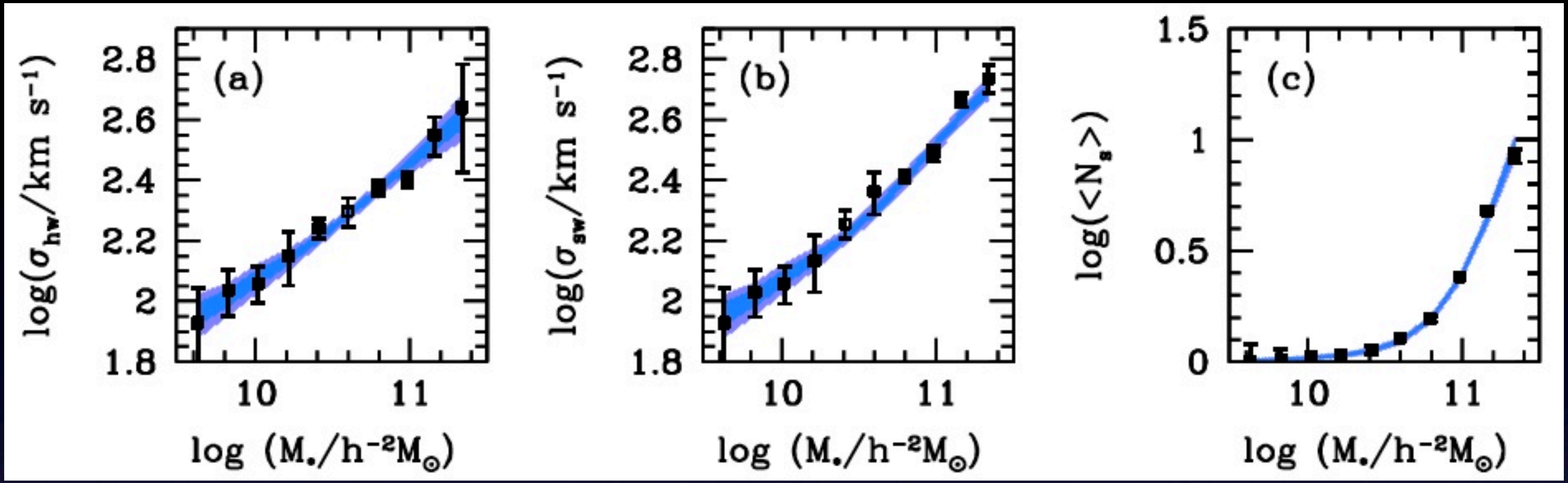
satellites per host:

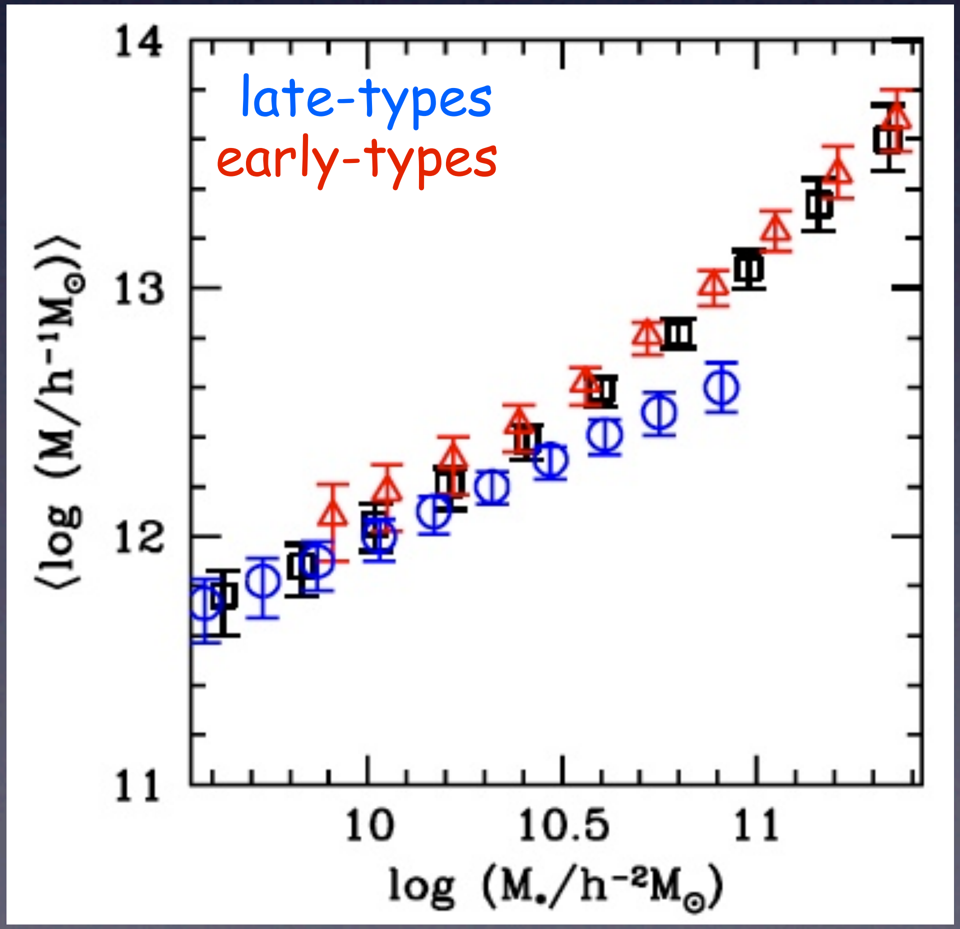
$$\langle N_\mathrm{sat}\rangle(M_*) = \frac{\int P(M_\mathrm{h}|M_*)\,\langle N_\mathrm{s}|M_\mathrm{h}\rangle\,\mathrm{d}M_\mathrm{h}}{\int P(M_\mathrm{h}|M_*)\,\mathrm{d}M_\mathrm{h}}$$

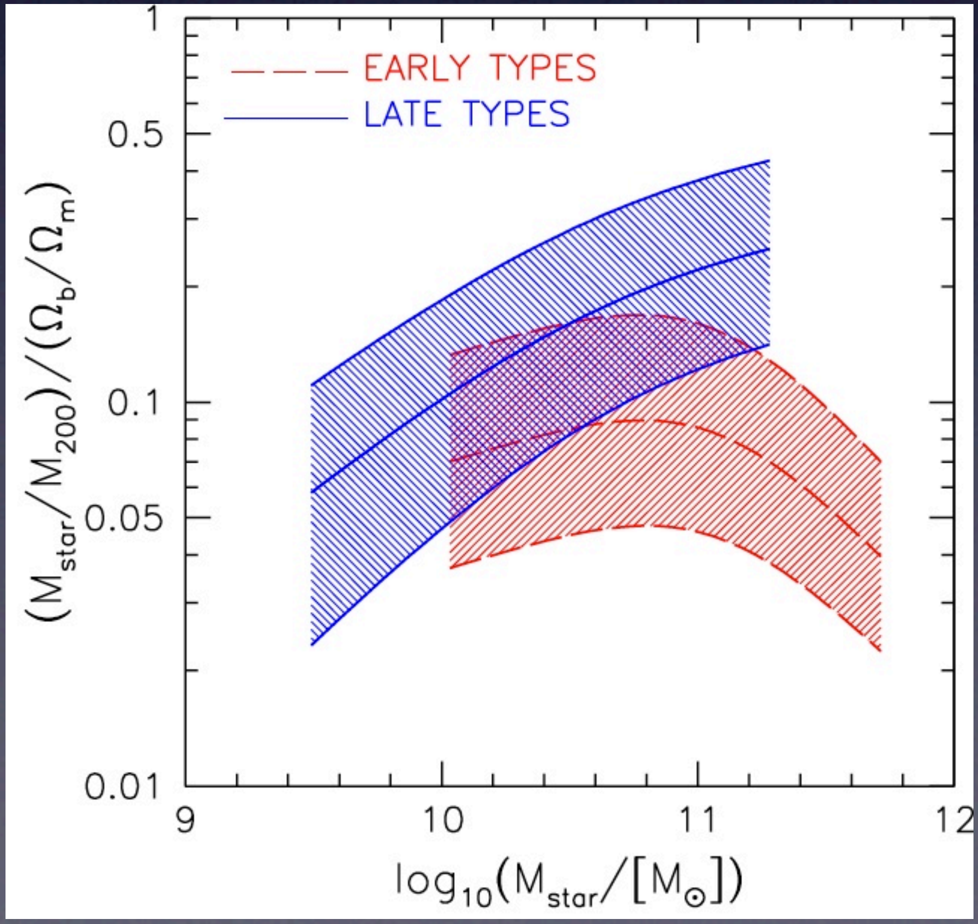
From the measurements of $\sigma^2_\mathrm{sw}(M_*)$, $\sigma^2_\mathrm{hw}(M_*)$, and $\langle N_\mathrm{sat}\rangle(M_*)$ one can determine $P(M_\mathrm{h}|M_*)$.

[More, vdB & Cacciato 2009]

Satellite Kinematics: results







based on ~6300 satellites around ~3800 centrals

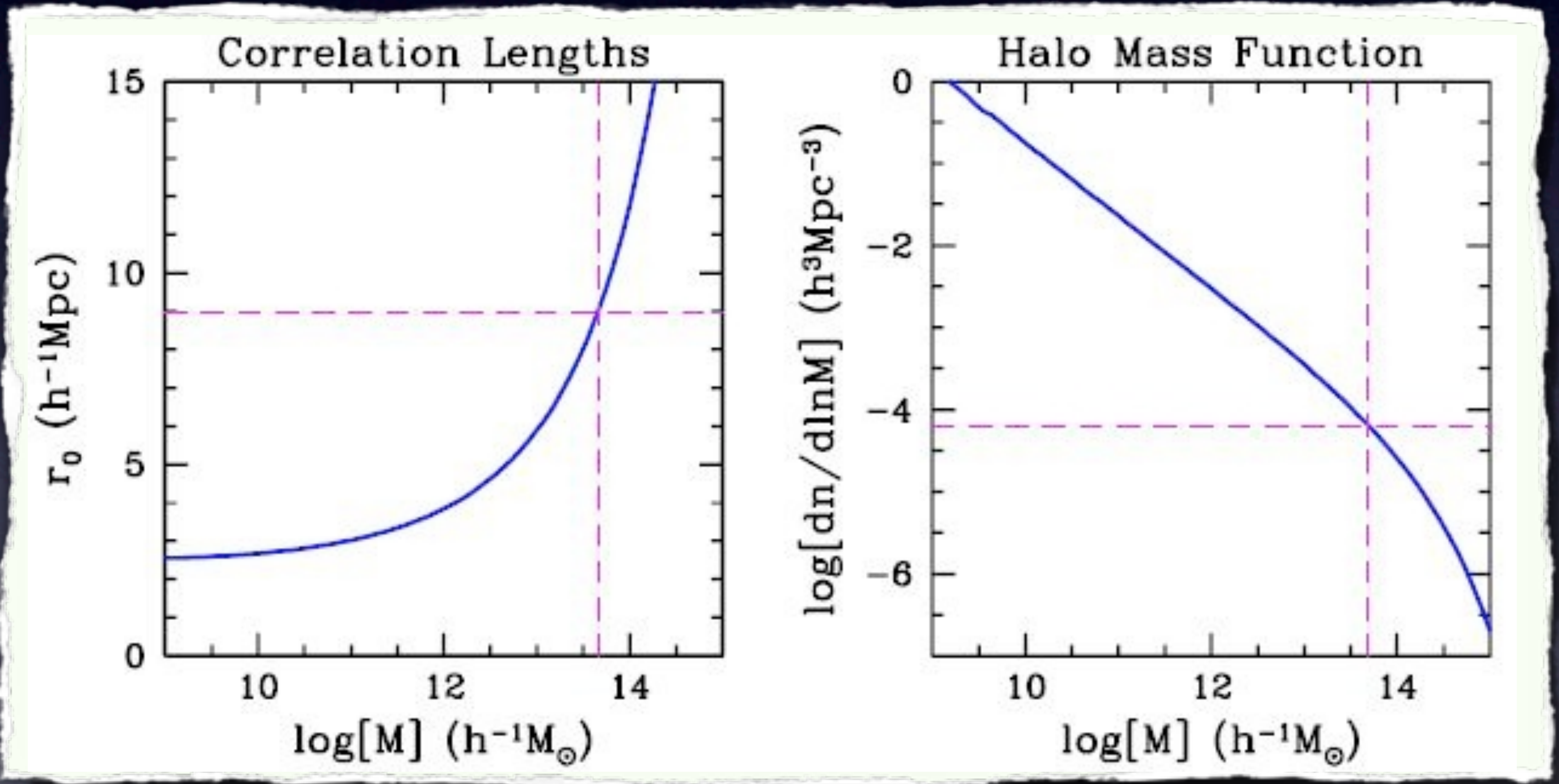
[More et al. 2011]

Galaxy Clustering

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

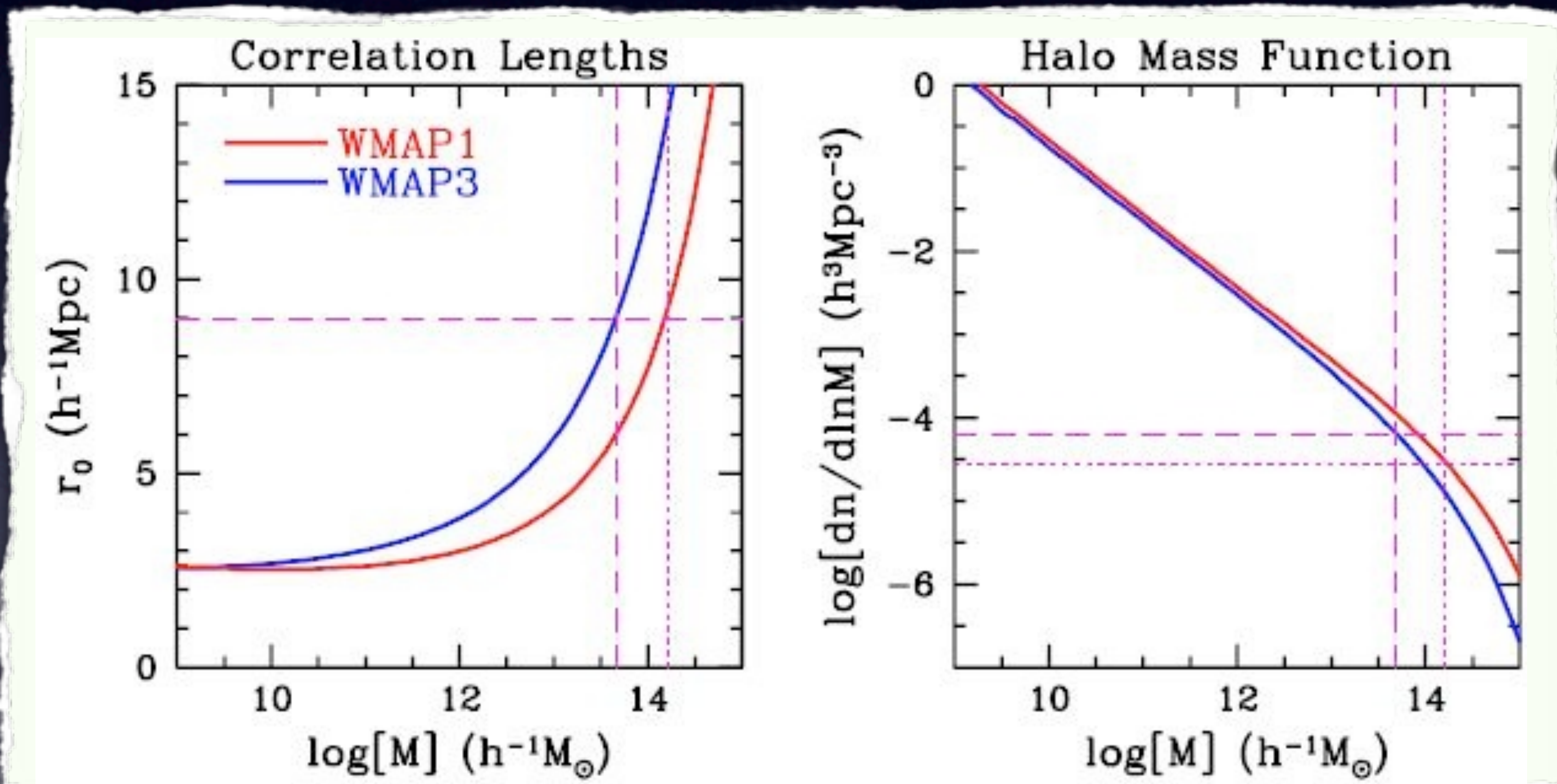
Clustering strength measured by correlation length r_0



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



WMAP1

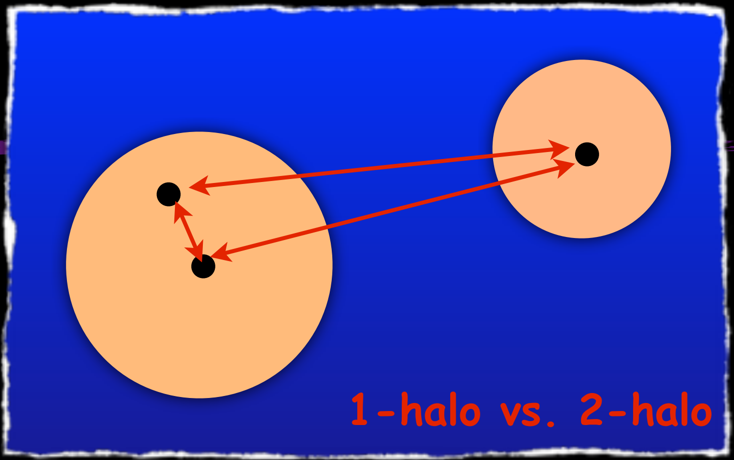
$\Omega_m = 0.30$
$\Omega_\Lambda = 0.70$
$\sigma_8 = 0.90$

WMAP3

$\Omega_m = 0.24$
$\Omega_\Lambda = 0.76$
$\sigma_8 = 0.74$

CAUTION: results depend on cosmology

The Halo Model



$$P^{1h}(k) = \frac{1}{\bar{\rho}^2} \int \mathrm{d}M\, M^2\, n(M)\, |\tilde{u}(k|M)|^2$$

$$P^{2h}(k) = \frac{1}{\bar{\rho}^2} \int \mathrm{d}M_1\, M_1\, n(M_1)\, \tilde{u}(k|M_1) \int \mathrm{d}M_2\, M_2\, n(M_2) \tilde{u}(k|M_2)\, Q(k|M_1, M_2)$$

The above equations describe the non-linear matter power-spectrum.

It is straightforward to use same formalism to compute power spectrum of galaxies:

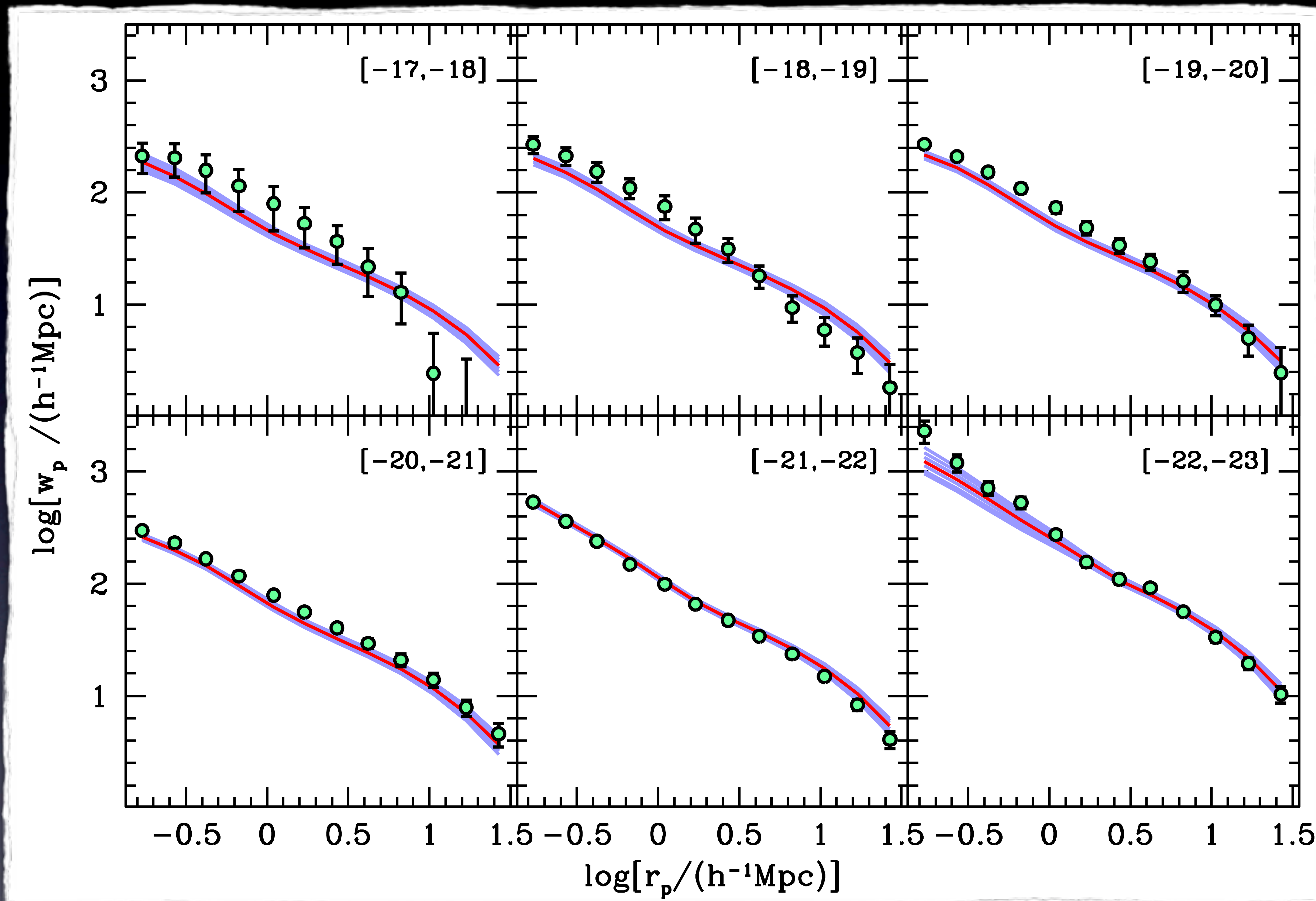
Simply replace

$$\frac{M}{\bar{\rho}_{\rm m}} \rightarrow \frac{\langle N \rangle_M}{\bar{n}_{\rm g}}$$

$$\tilde{u}(k|M) \rightarrow \tilde{u}_{\rm g}(k|M)$$

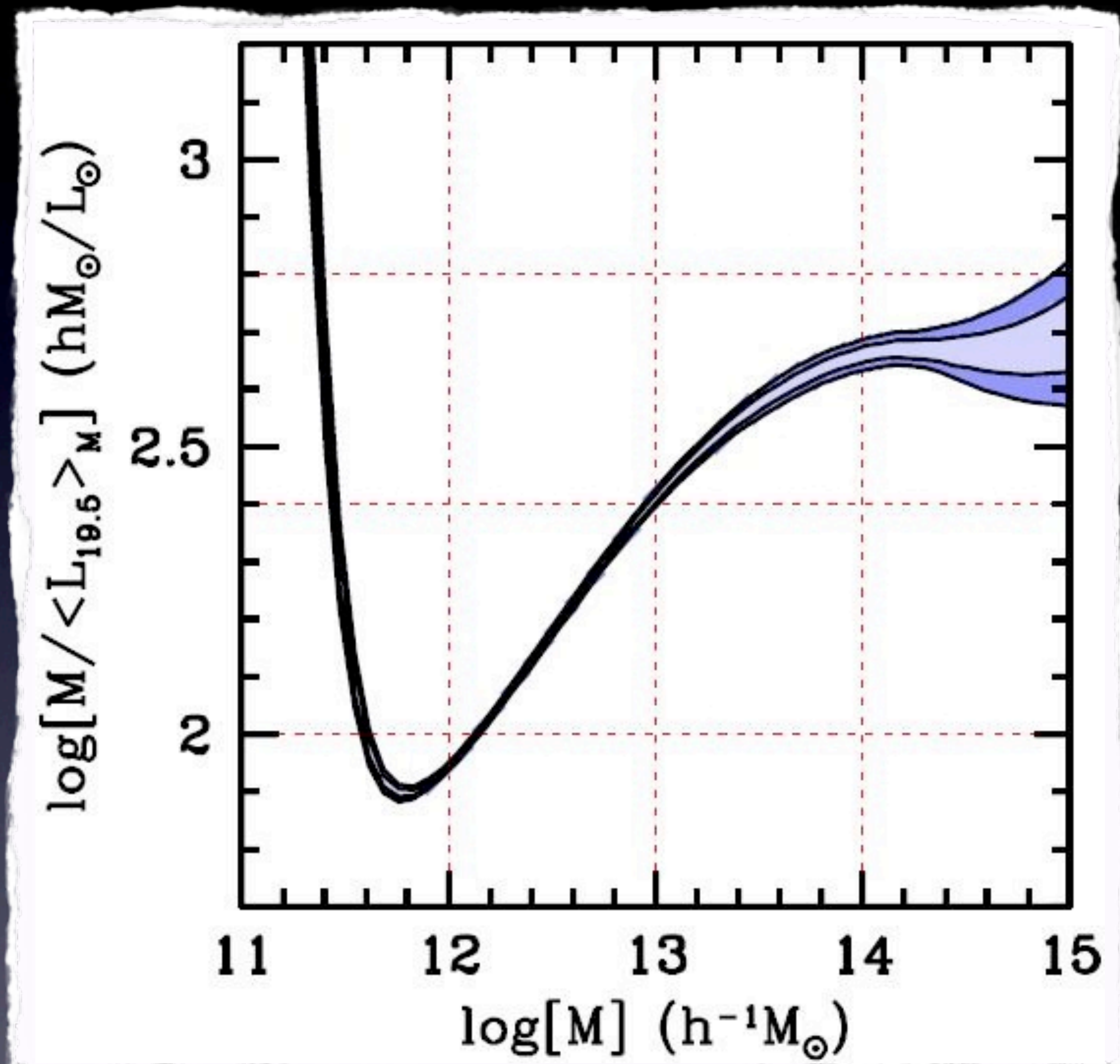
where $\langle N \rangle_M$ describes the average number of galaxies (with certain properties) in a halo of mass M. Thus, the halo model combined with a model for the halo occupation statistics, allows a computation of $\xi_{\rm gg}(r)$

Results: Clustering Data

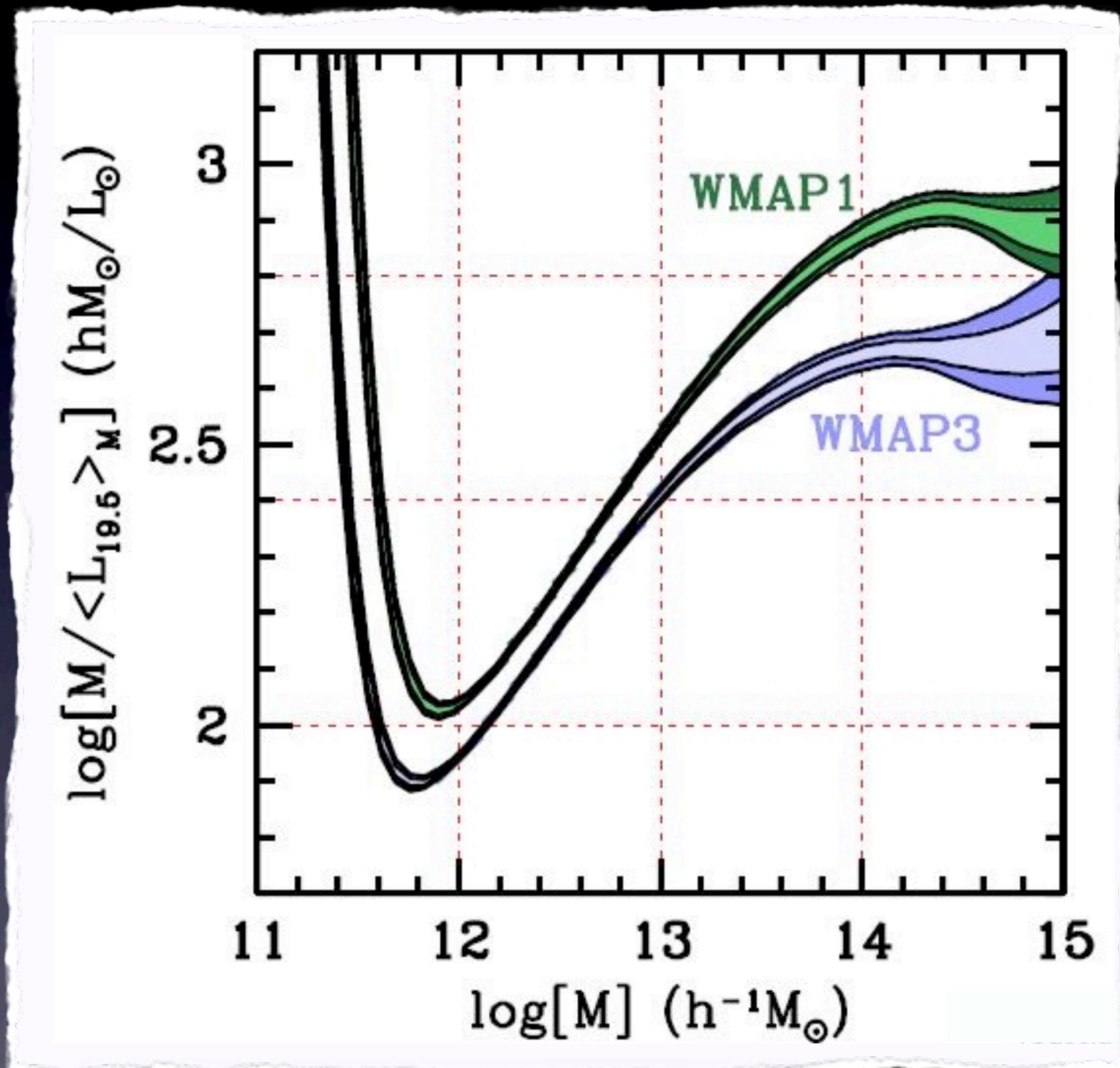


[data from Zehavi, Zheng et al. 2011]

Cosmology Dependence



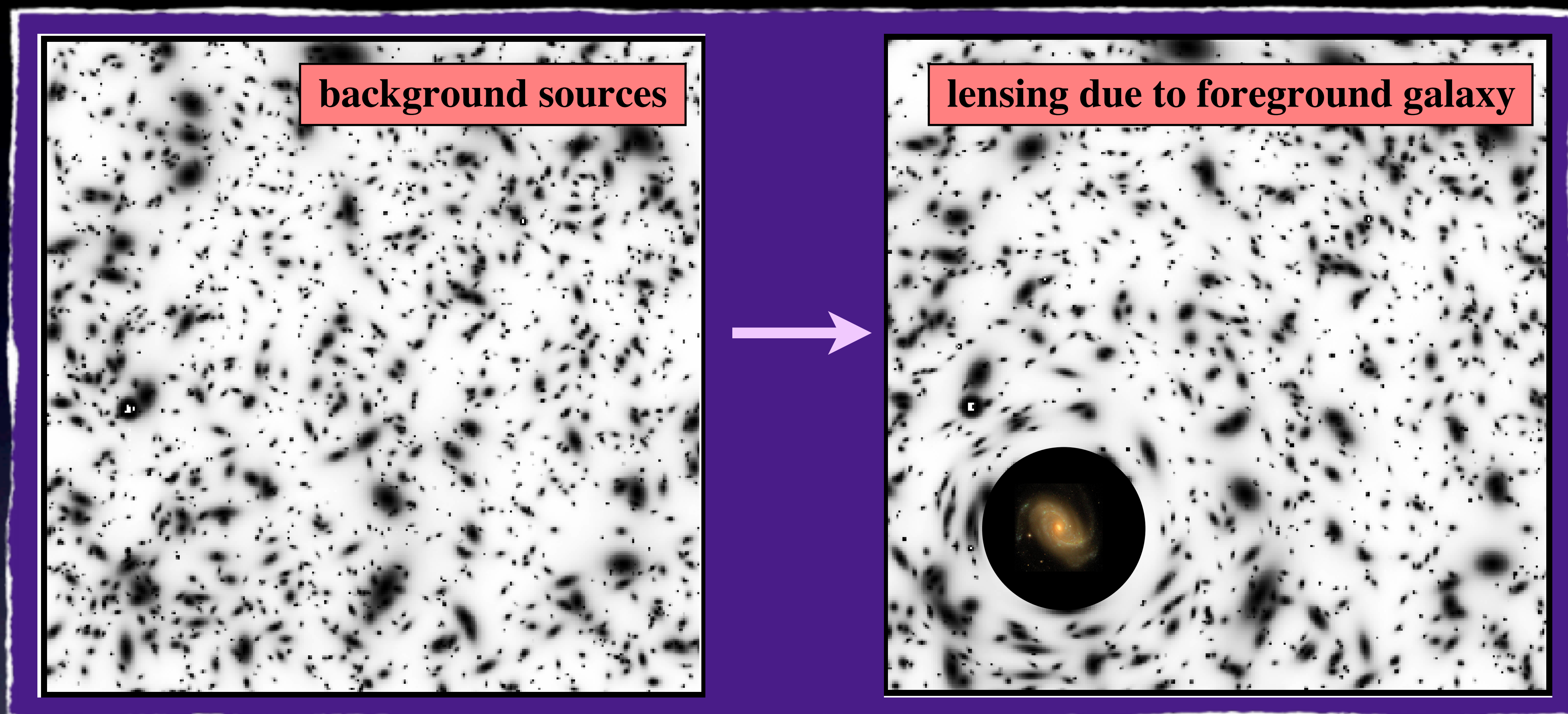
Cosmology Dependence



Galaxy-Galaxy Lensing

Galaxy-Galaxy Lensing

The mass associated with galaxies lenses background galaxies



Lensing causes correlated ellipticities, the tangential shear, $\gamma_{\rm t}$, which is related to the excess surface density, $\Delta\Sigma$, according to

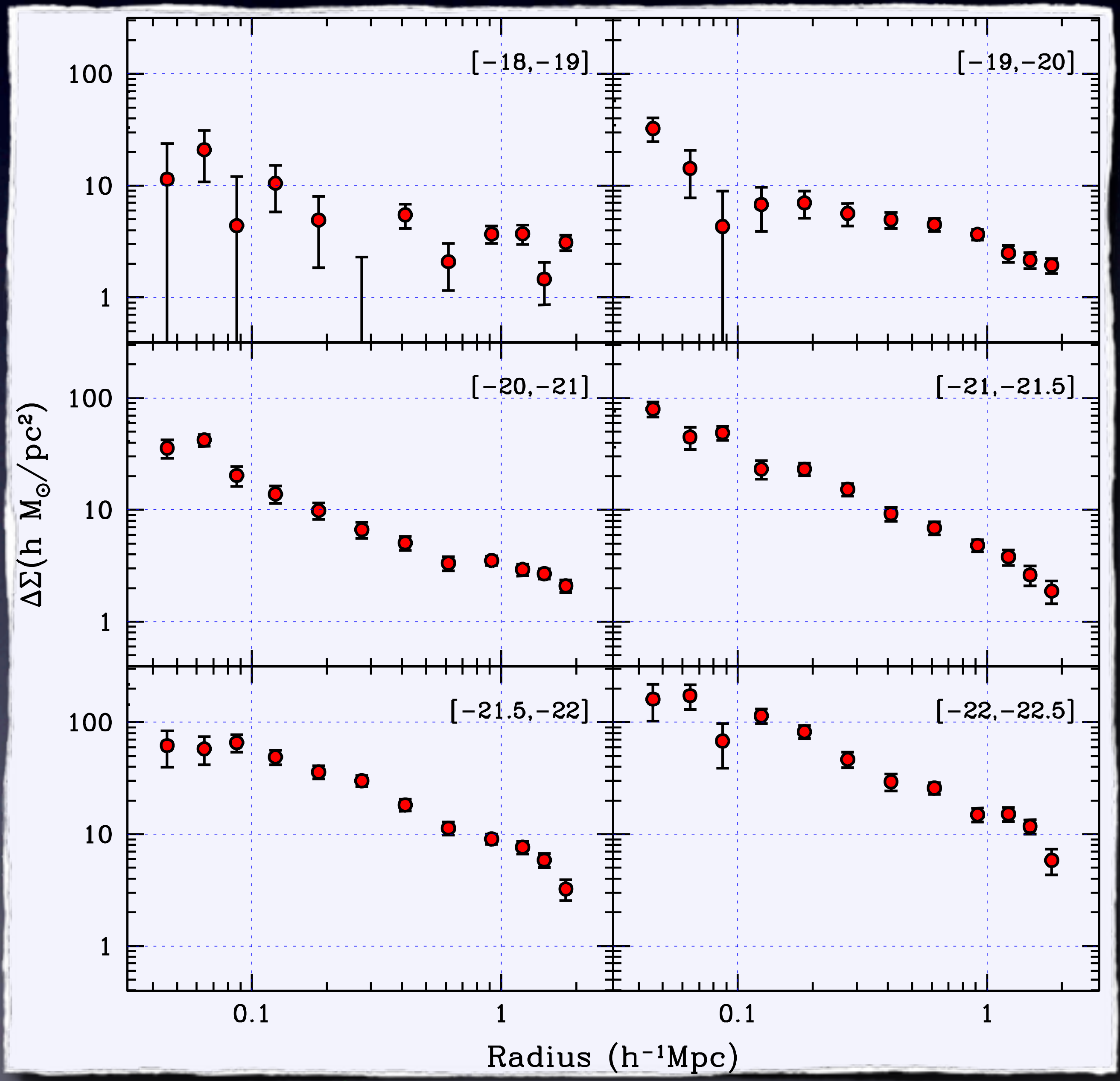
$$\gamma_{\rm t}(R)\Sigma_{\rm crit} = \Delta\Sigma(R) = \bar{\Sigma}(< R) - \Sigma(R)$$

$\Delta\Sigma$ is line-of-sight projection of galaxy-matter cross correlation

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

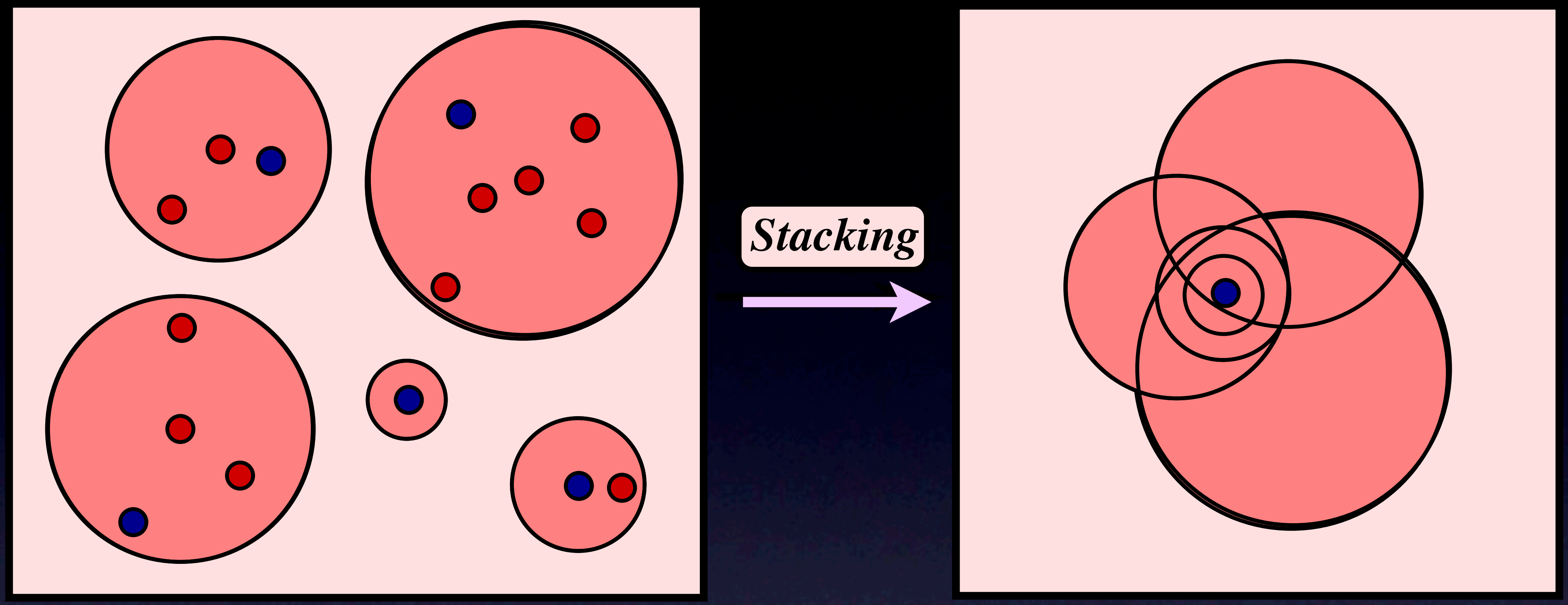
Galaxy-Galaxy Lensing: The Data

- Number of background sources per lens is limited
- Measuring shear 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. (2006), using different bins in lens-luminosity



Mandelbaum et al. (2006)

How to interpret the signal?



Because of stacking the lensing signal is difficult to interpret

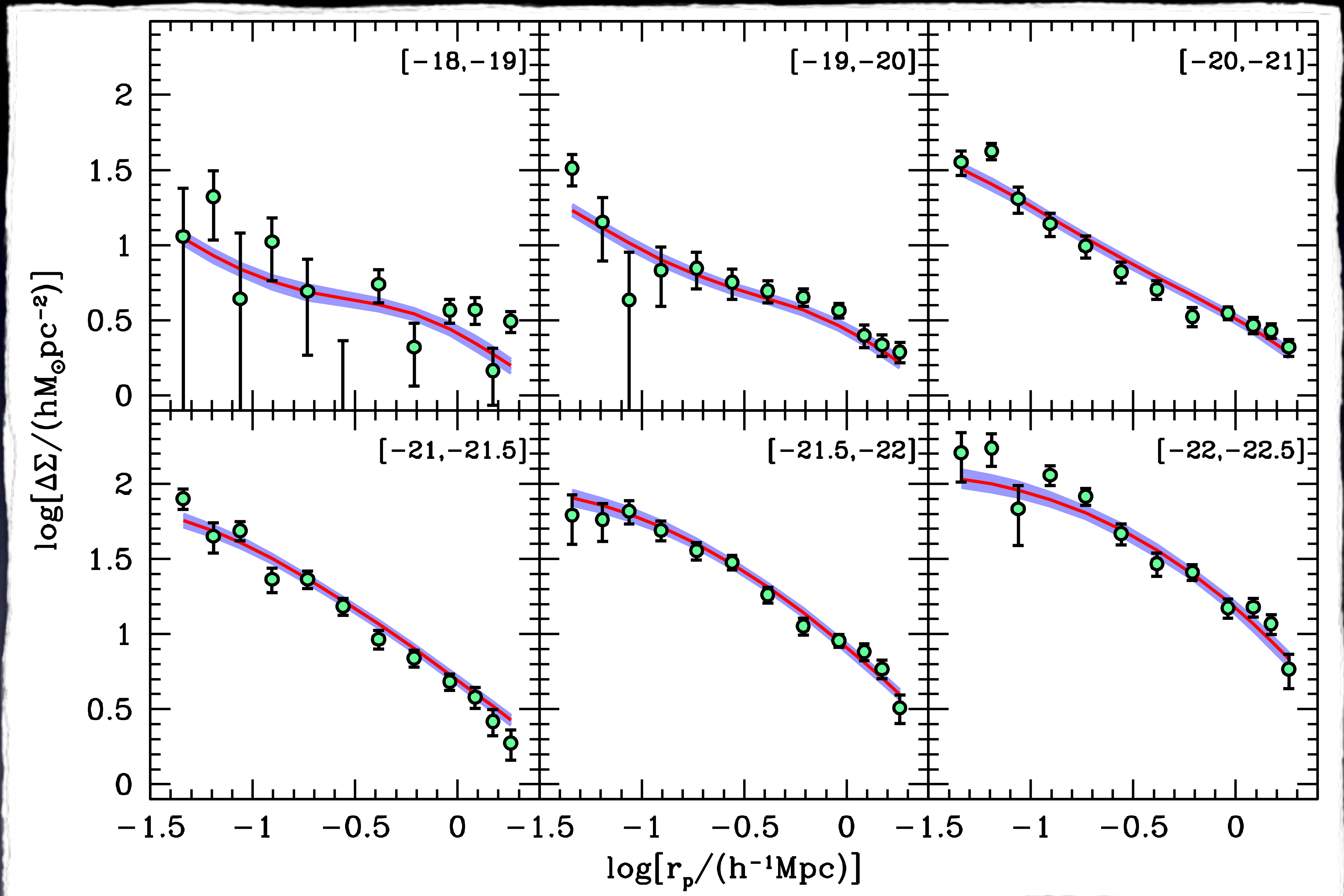
In order to model the data, what is required is:

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

These can all be computed from the CLF...

For a given $\Phi(L|M)$ we can predict the lensing signal $\Delta\Sigma(R|L_1, L_2)$

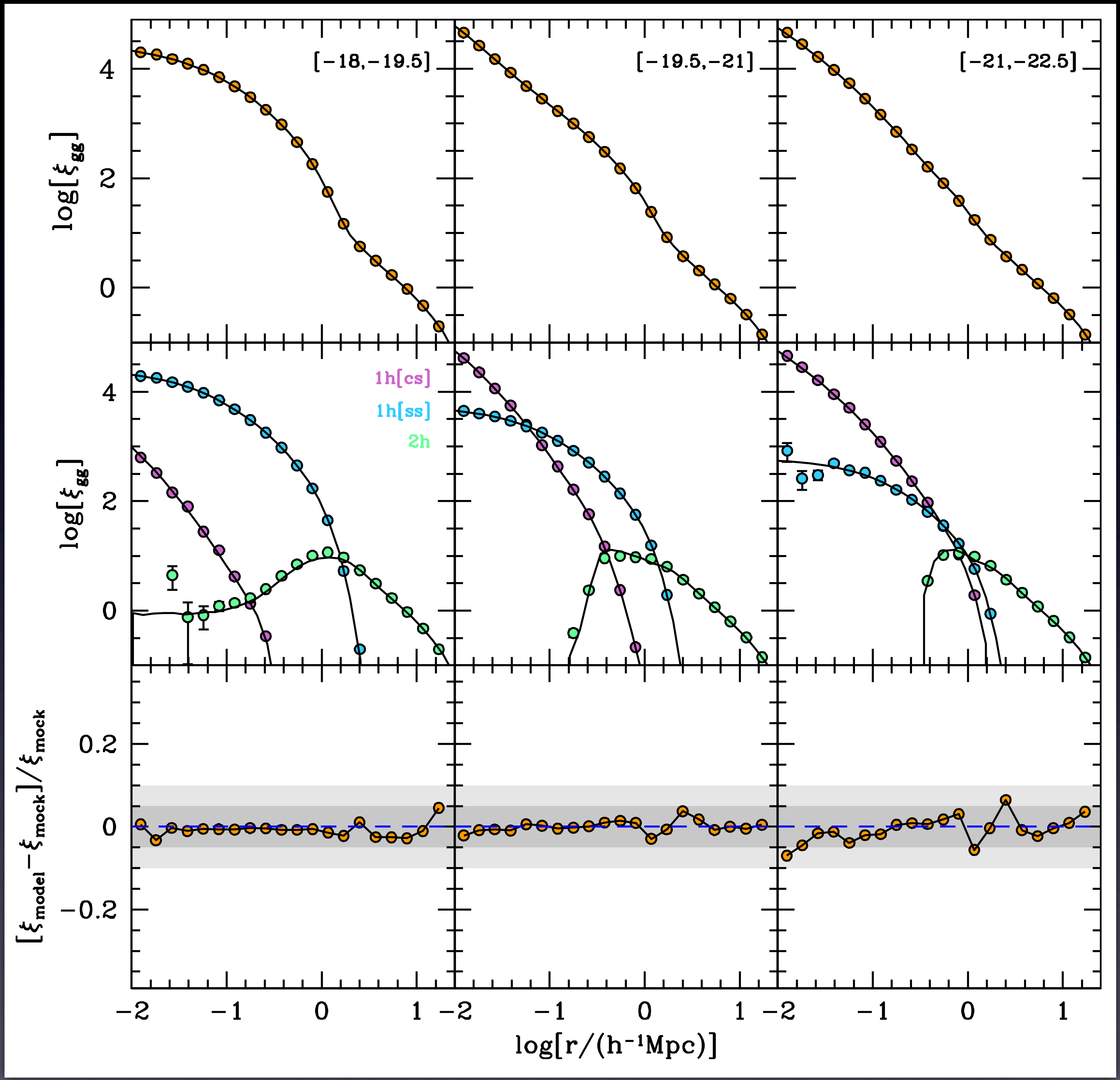
Results: Lensing Data



[data from Mandelbaum et al. 2006]

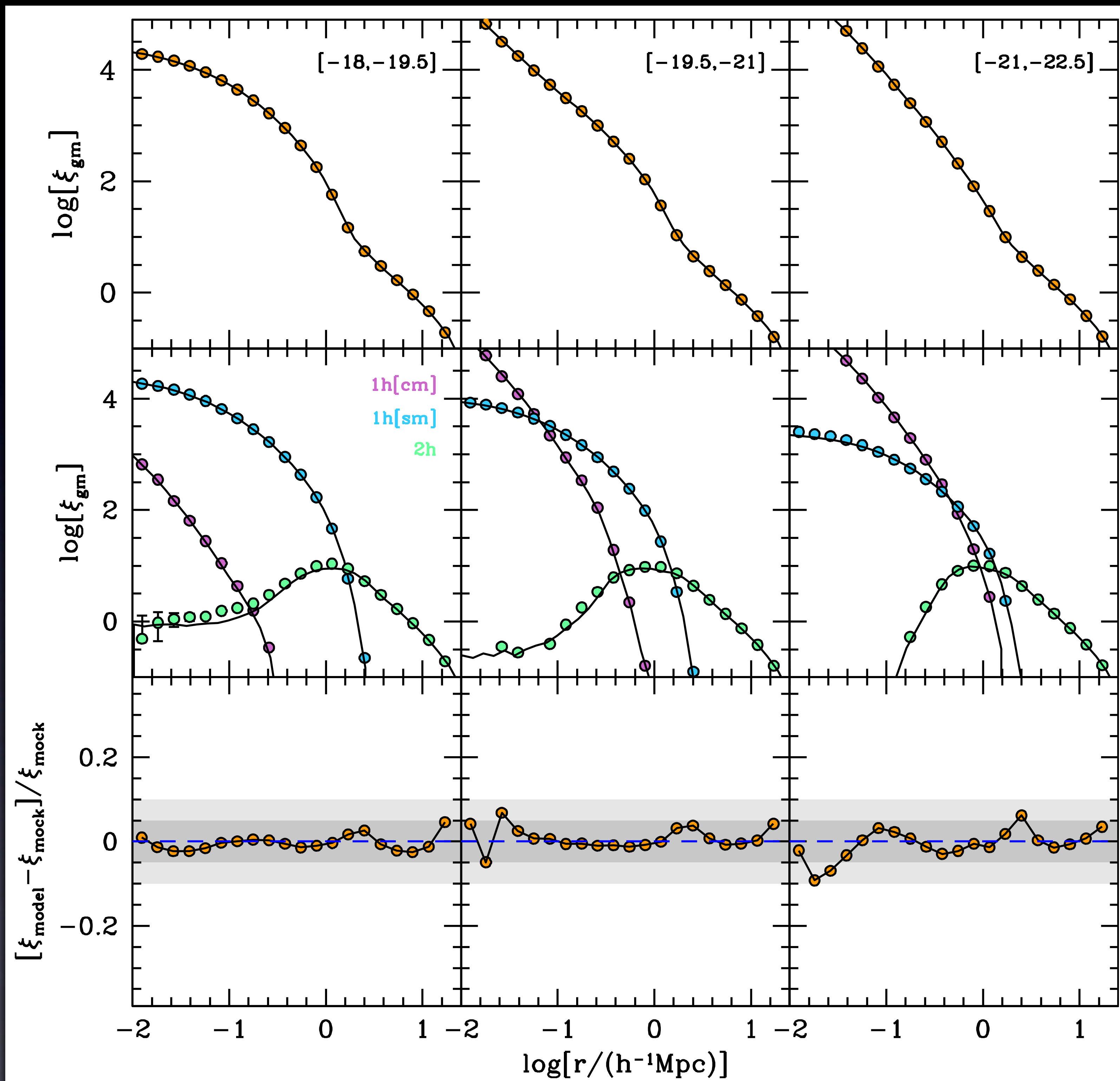
Constraining Cosmology

Comparison with Mock Catalogues



- Run numerical simulation of structure formation (DM only)
- Identify DM haloes, and populate them with galaxies using a model for the CLF.
- Compute galaxy-galaxy correlation functions for various luminosity bins.
- Use analytical model to compute the same, using the same model for the CLF.

Comparison with Mock Catalogues



- Run numerical simulation of structure formation (DM only)
- Identify DM haloes, and populate them with galaxies using a model for the CLF.
- Compute galaxy-galaxy correlation functions for various luminosity bins.
- Use analytical model to compute the same, using the same model for the CLF.

Our model is accurate to better than ~5%

Residual Redshift Space Distortions

To avoid redshift space distortions, one typically uses projected correlation function

$$w_{\rm p} = 2 \int_0^\infty \xi_{\rm gg}(r_{\rm p}, r_\pi)\, {\rm d}r_\pi = 2 \int_{r_{\rm p}}^\infty \xi_{\rm gg}(r)\, \frac{r\, {\rm d}r}{\sqrt{r^2 - r_{\rm p}^2}}$$

Residual Redshift Space Distortions

To avoid redshift space distortions, one typically uses projected correlation function

$$w_{\rm p} = 2\int_0^{\infty} \xi_{\rm gg}(r_{\rm p}, r_\pi)\,{\rm d}r_\pi = 2\int_{r_{\rm p}}^{\infty} \xi_{\rm gg}(r)\,\frac{r\,{\rm d}r}{\sqrt{r^2 - r_{\rm p}^2}}$$

Because of limitations of data, one can only integrate out to finite radius, $r_{\rm max}$

$$w_{\rm p} = 2\int_0^{r_{\rm max}} \xi_{\rm gg}(r_{\rm p}, r_\pi)\,{\rm d}r_\pi \neq 2\int_{r_{\rm p}}^{\sqrt{r_{\rm p}^2+r_{\rm max}^2}} \xi_{\rm gg}(r)\,\frac{r\,{\rm d}r}{\sqrt{r^2 - r_{\rm p}^2}}$$

Residual Redshift Space Distortions

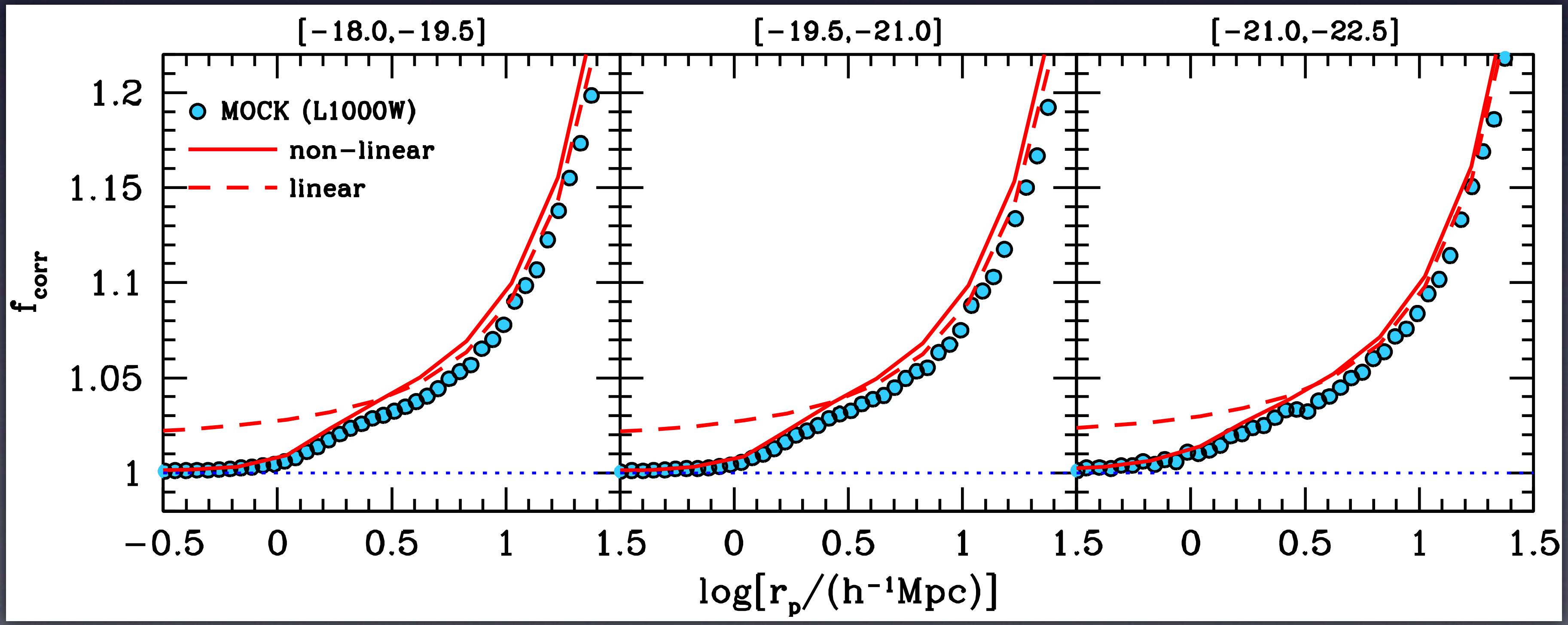
To avoid redshift space distortions, one typically uses projected correlation function

$$w_{\rm p} = 2\int_0^\infty \xi_{\rm gg}(r_{\rm p}, r_\pi)\, {\rm d}r_\pi = 2\int_{r_{\rm p}}^\infty \xi_{\rm gg}(r)\, \frac{r\, {\rm d}r}{\sqrt{r^2 - r_{\rm p}^2}}$$

Because of limitations of data, one can only integrate out to finite radius, $r_{\rm max}$

$$w_{\rm p} = 2\int_0^{r_{\rm max}} \xi_{\rm gg}(r_{\rm p}, r_\pi)\, {\rm d}r_\pi \neq 2\int_{r_{\rm p}}^{\sqrt{r_{\rm p}^2 + r_{\rm max}^2}} \xi_{\rm gg}(r)\, \frac{r\, {\rm d}r}{\sqrt{r^2 - r_{\rm p}^2}}$$

The resulting, residual z-space distortions easily exceed 20% at r_p ~20 Mpc/h (Norberg et al. 2009).



Residual Redshift Space Distortions

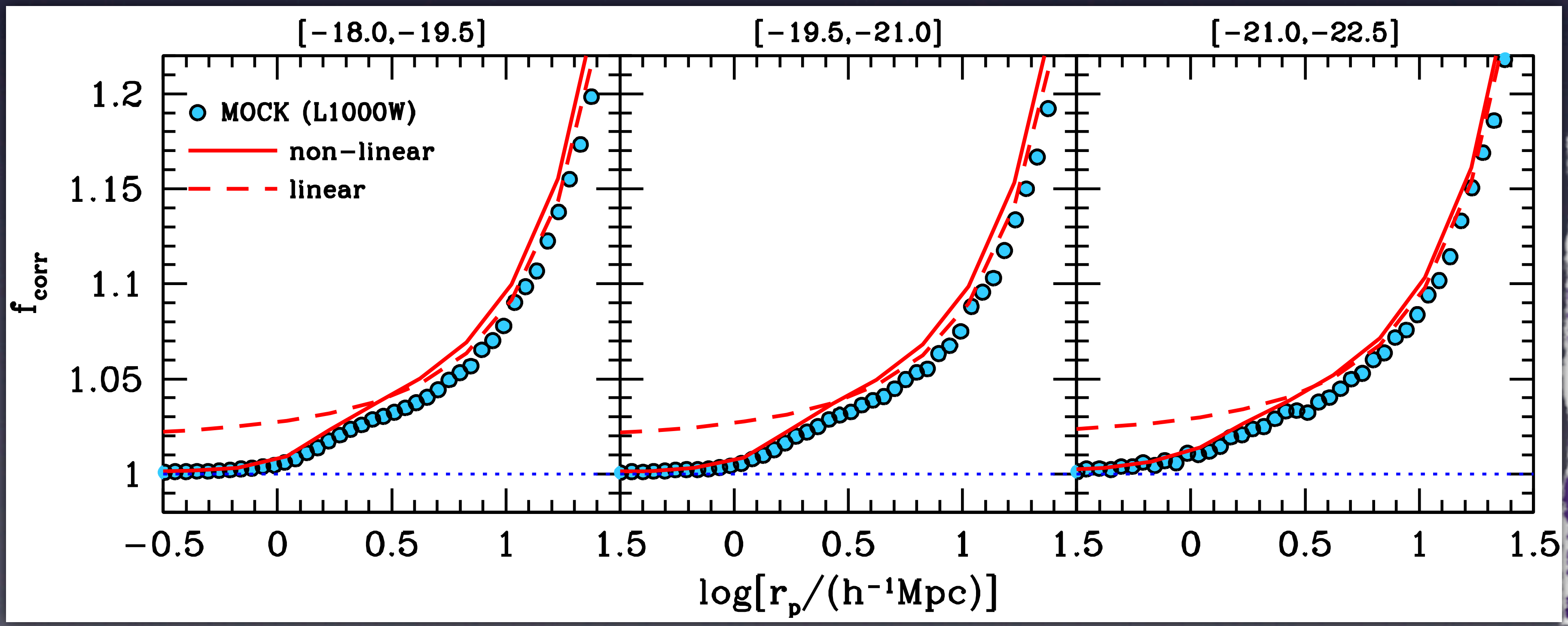
To avoid redshift space distortions, one typically uses projected correlation function

$$w_{\rm p} = 2\int_0^{\infty} \xi_{\rm gg}(r_{\rm p}, r_\pi)\,{\rm d}r_\pi = 2\int_{r_{\rm p}}^{\infty} \xi_{\rm gg}(r)\,\frac{r\,{\rm d}r}{\sqrt{r^2 - r_{\rm p}^2}}$$

Because of limitations of data, one can only integrate out to finite radius, $r_{\rm max}$

$$w_{\rm p} = 2\int_0^{r_{\rm max}} \xi_{\rm gg}(r_{\rm p}, r_\pi)\,{\rm d}r_\pi \neq 2\int_{r_{\rm p}}^{\sqrt{r_{\rm p}^2 + r_{\rm max}^2}} \xi_{\rm gg}(r)\,\frac{r\,{\rm d}r}{\sqrt{r^2 - r_{\rm p}^2}}$$

The resulting, residual z-space distortions easily exceed 20% at r_p ~20 Mpc/h (Norberg et al. 2009).



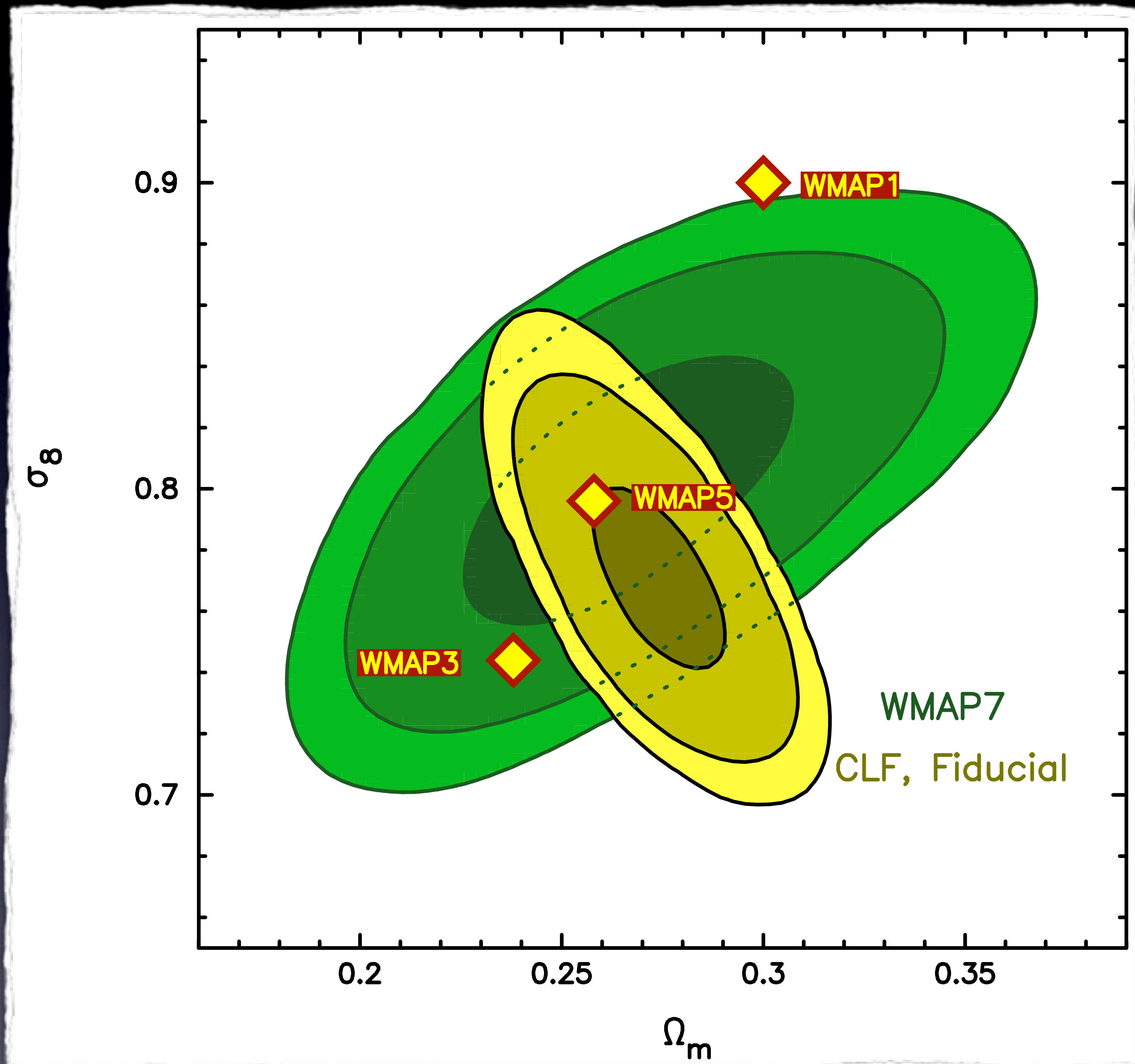
We correct for these residual redshift space distortions using modified Kaiser formalism. Mocks show that this is accurate to few percent.

Fiducial Model

- Total of 16 free parameters:
  - 9 parameters to describe CLF
  - 5 cosmological parameters; $\Omega_{\rm m}, \Omega_{\rm b}, \sigma_8, n_{\rm s}, h$
  - 2 nuisance parameters; $\zeta_{\rm max}, \mathcal{R}_{\rm c}$

  Total of 176 data points.
- WMAP7 priors on $\Omega_{\rm b}, n_{\rm s}, h$
- Correction for residual redshift space distortions
- Dark matter haloes follow NFW profile + marginalize over 10% uncertainty in c(M) relation
- Radial number density distribution of satellites follows that of dark matter particles.
- Halo mass function and halo bias function of Tinker et al. (2009,2010).

Cosmological Constraints

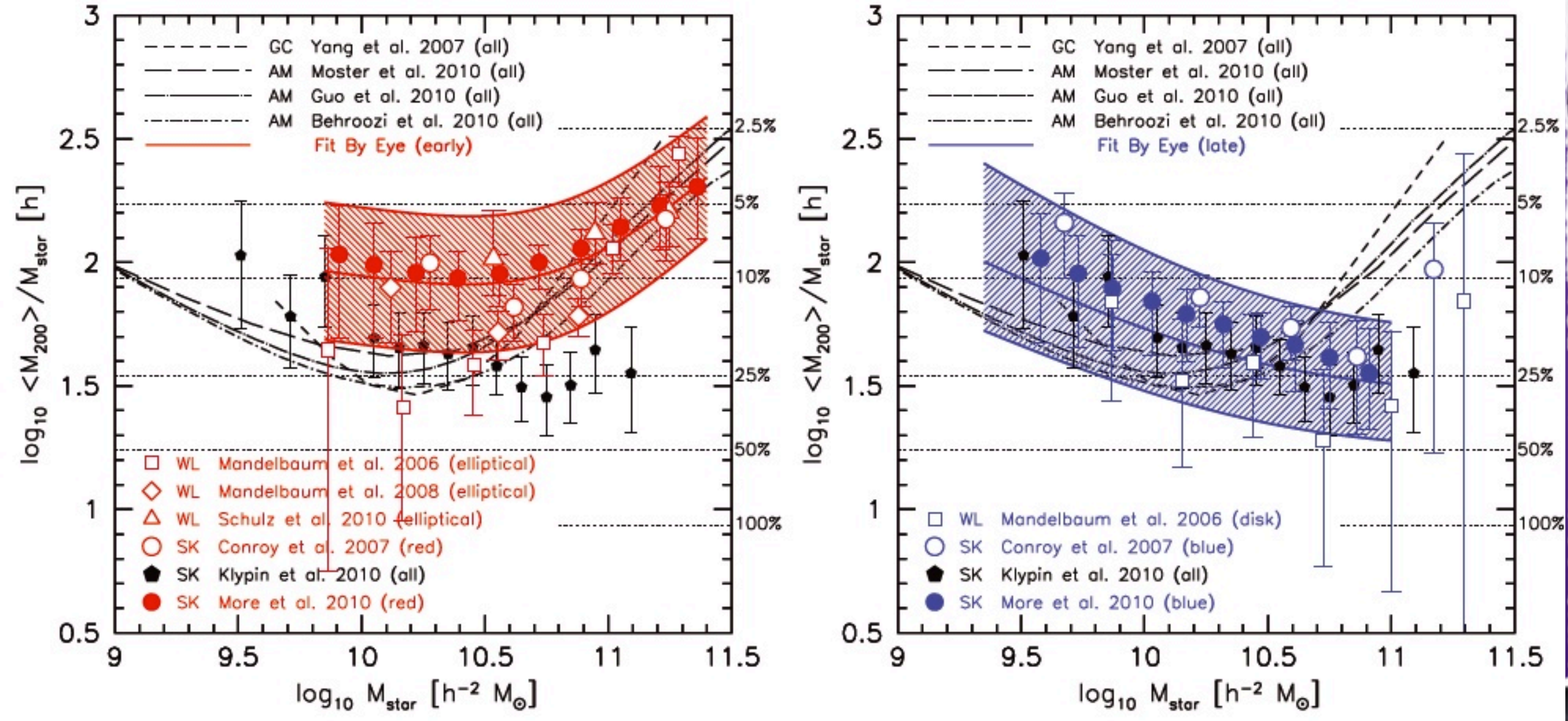


Conclusions

- Recent years have seen enormous progress in establishing the galaxy-dark matter connection, including its scatter!
- Different methods (group catalogues, satellite kinematics, galaxy-galaxy lensing, clustering & abundance matching) now all yield results in good mutual agreement.
- Combination of galaxy clustering and galaxy-galaxy lensing can constrain cosmological parameters.
    - This method is complementary to and competitive with BAO, cosmic shear, SNIa & cluster abundances.
    - Preliminary results are in excellent agreement with CMB constraints from WMAP7
    - Forecasting for constraints on neutrino mass, WDM and modified gravity very promising.

Conclusions

- Recent years have seen enormous progress in establishing the galaxy-dark matter connection, including its scatter!
- Different methods (group catalogues, satellite kinematics, galaxy-galaxy lensing, clustering & abundance matching) now all yield results in good mutual agreement.



[Dutton et al. 2010]

Conclusions

- Recent years have seen enormous progress in establishing the galaxy-dark matter connection, including its scatter!
- Different methods (group catalogues, satellite kinematics, galaxy-galaxy lensing, clustering & abundance matching) now all yield results in good mutual agreement.
- Combination of galaxy clustering and galaxy-galaxy lensing can constrain cosmological parameters.
    - This method is complementary to and competitive with BAO, cosmic shear, SNIa & cluster abundances.
    - Preliminary results are in excellent agreement with CMB constraints from WMAP7
    - Forecasting for constraints on neutrino mass, WDM and modified gravity very promising.

The End