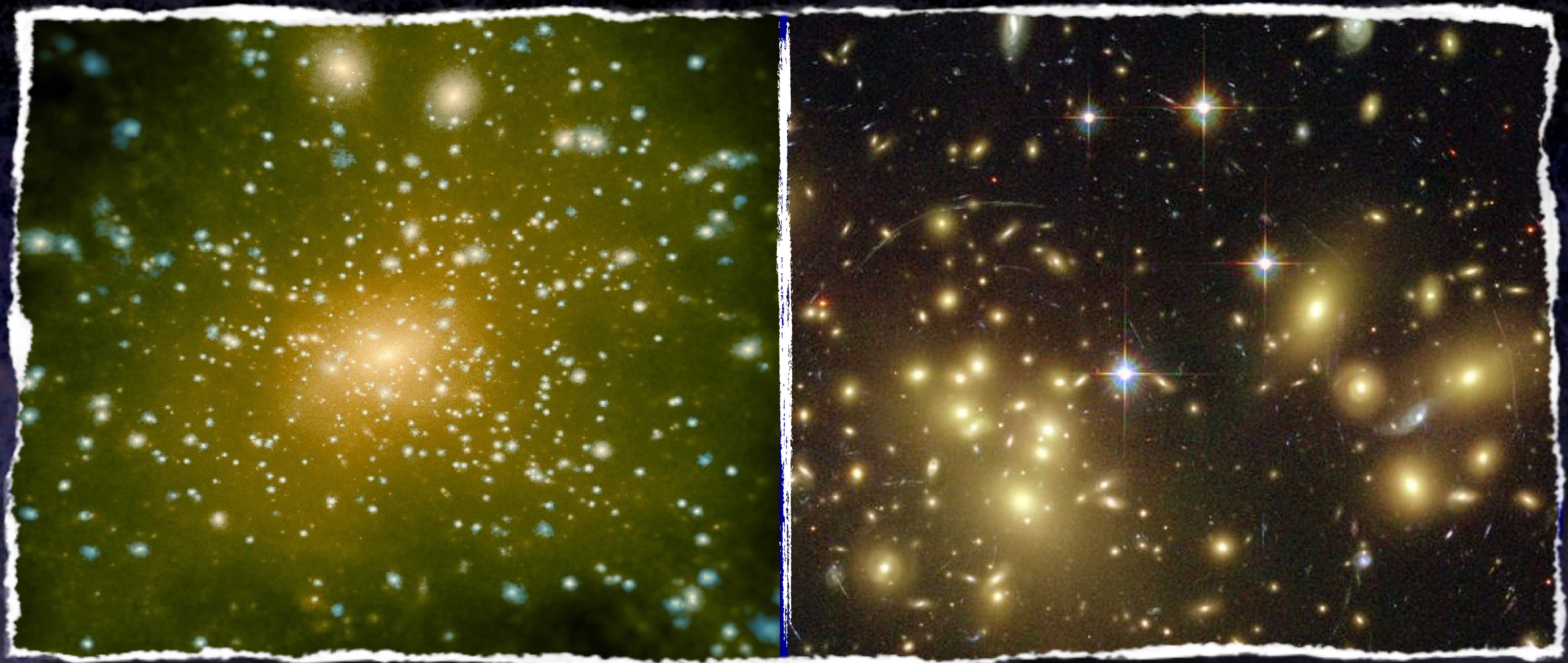
Cosmological Constraints from a Combined Analysis of Clustering & Galaxy-Galaxy Lensing in the SDSS



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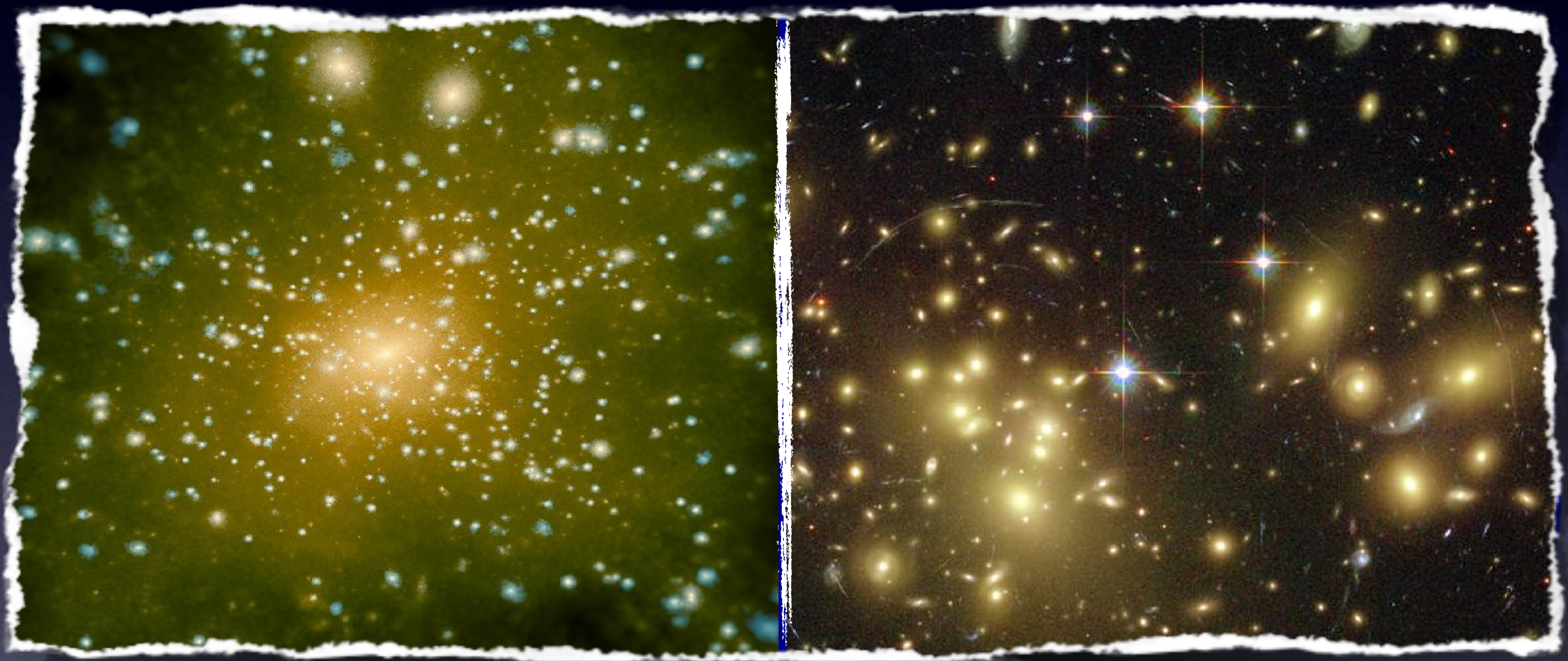
Halo Occupation Modelling: Motivation & Goal

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

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:

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

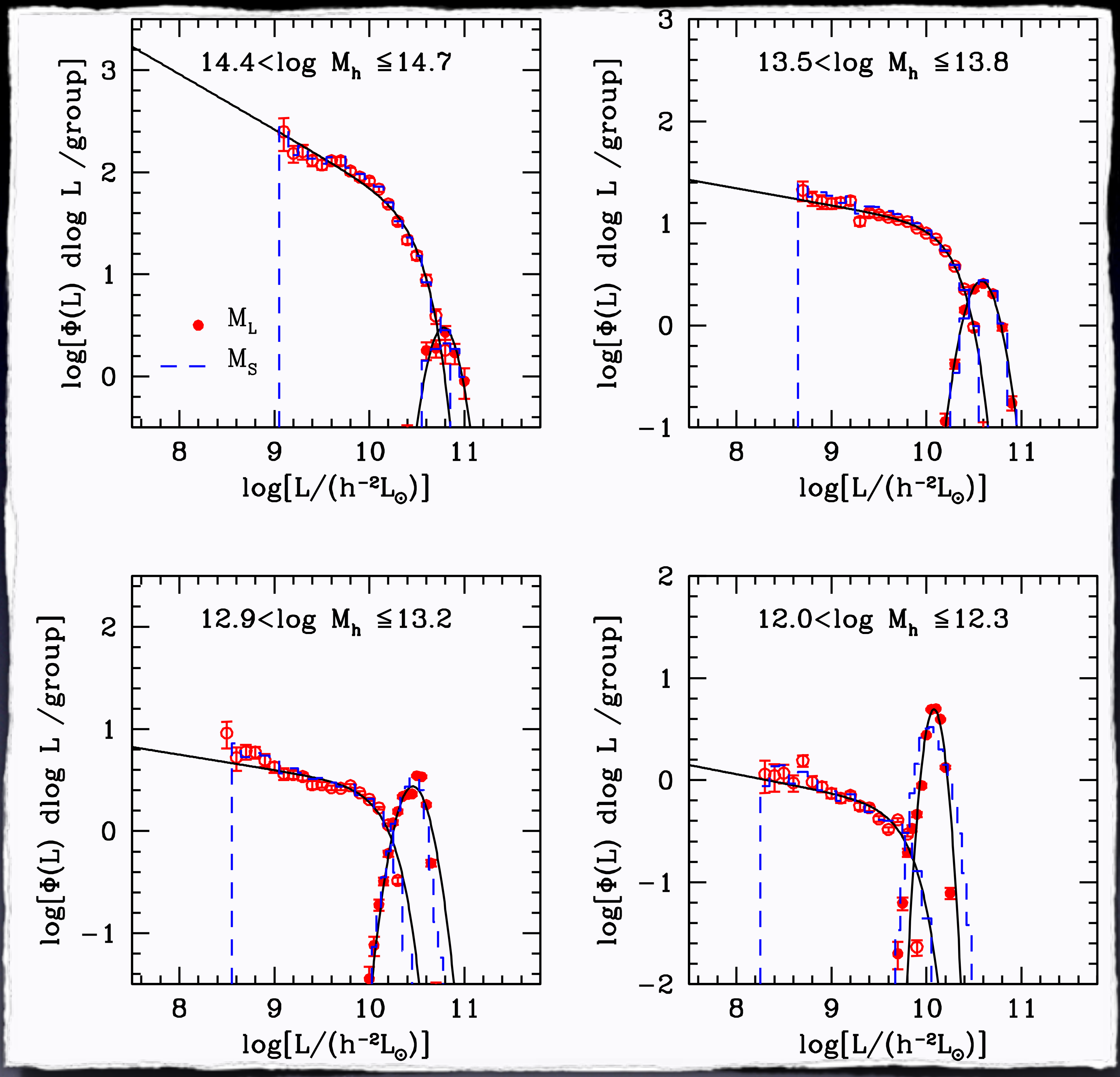
For satellites we adopt a modified Schechter function:

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

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.

CLF Constraints from Group Catalogue

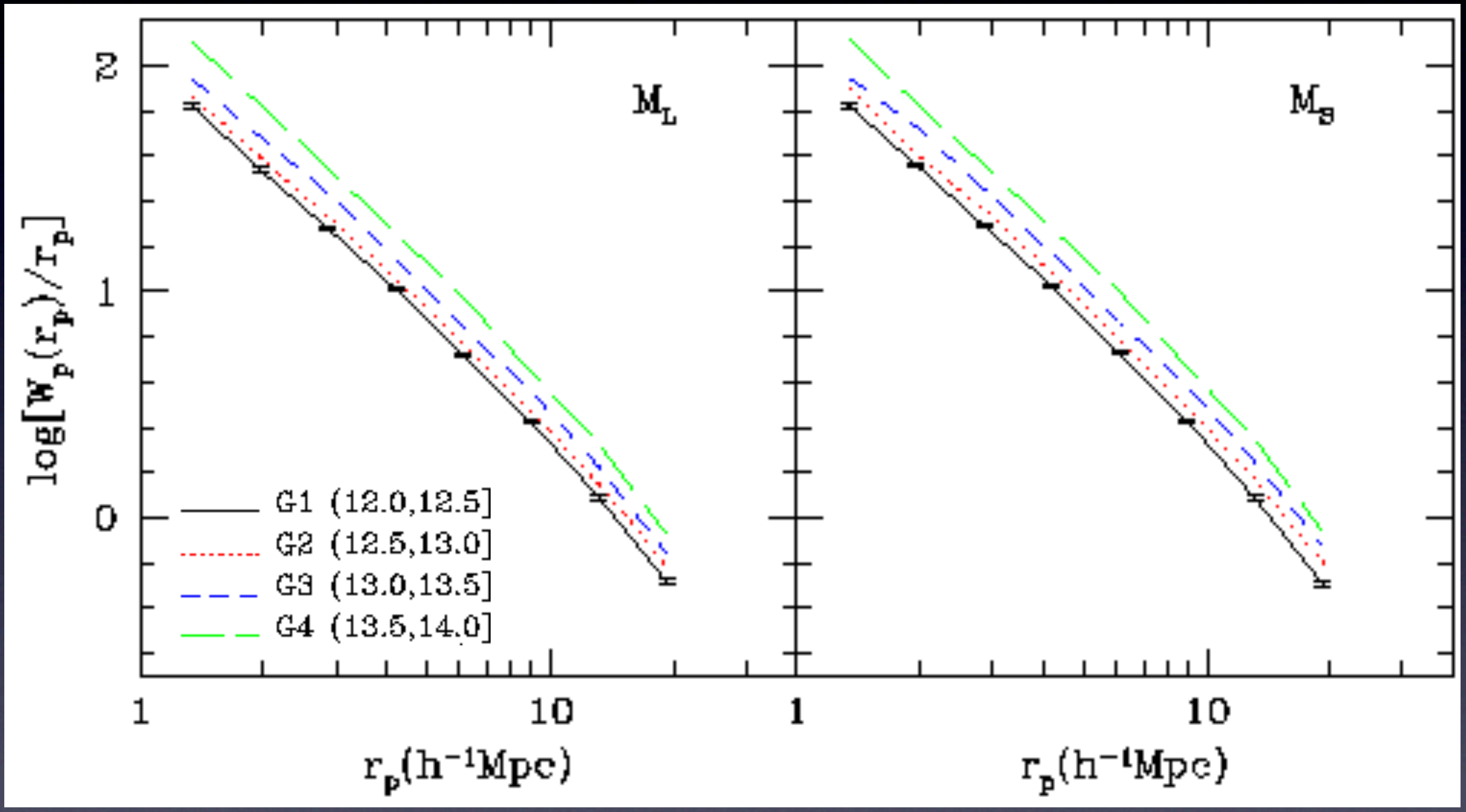


Yang, Mo & vdB (2008)

Clustering of Galaxy Groups

Clustering of groups directly probes clustering of Dark Matter Haloes.

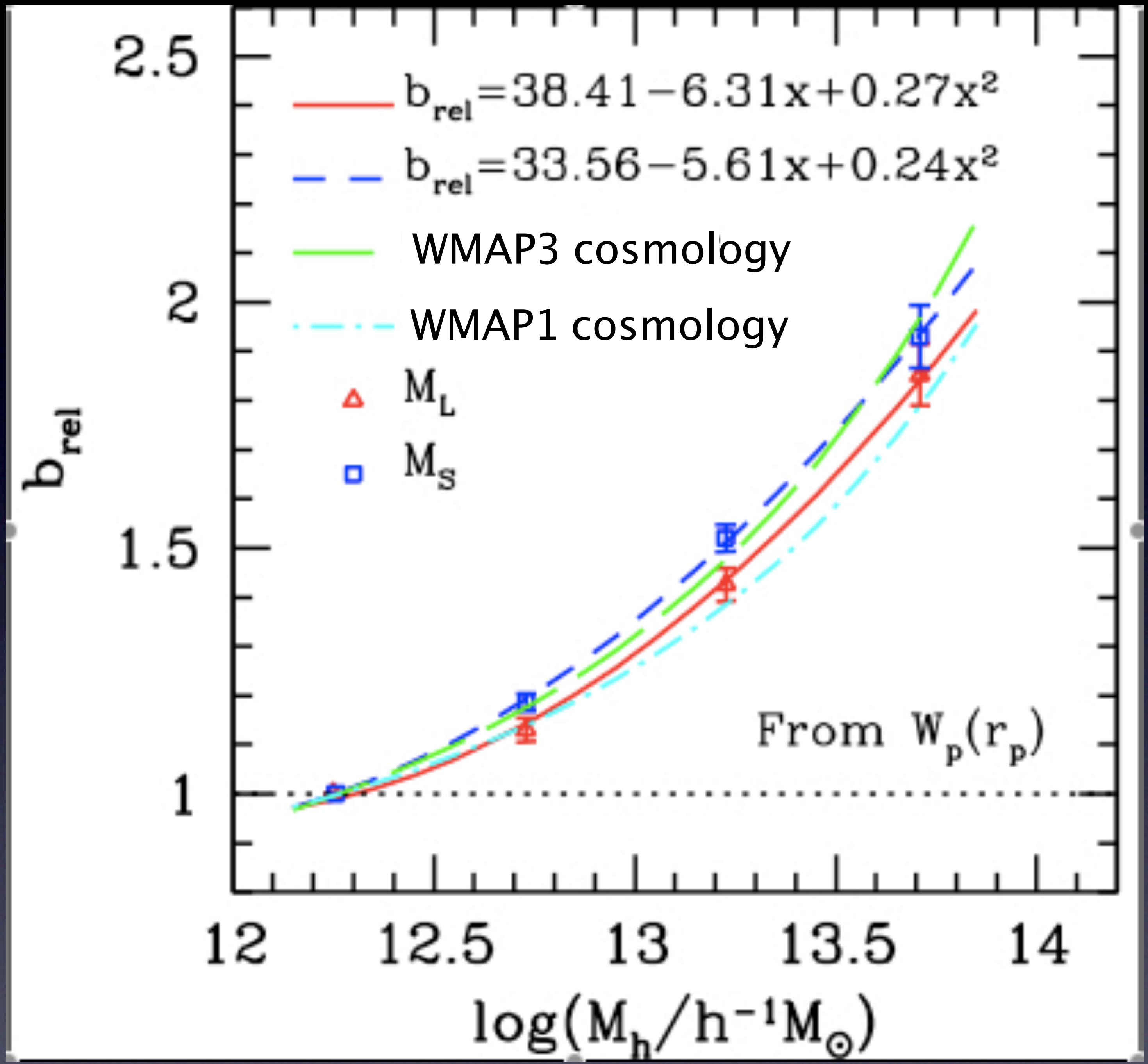
Hierarchical Prediction: More massive haloes are more strongly clustered



Galaxy-Group Cross Correlation confirms prediction!
Results independent of halo-mass indicator.

Wang et al., 2008, ApJ, 687, 919

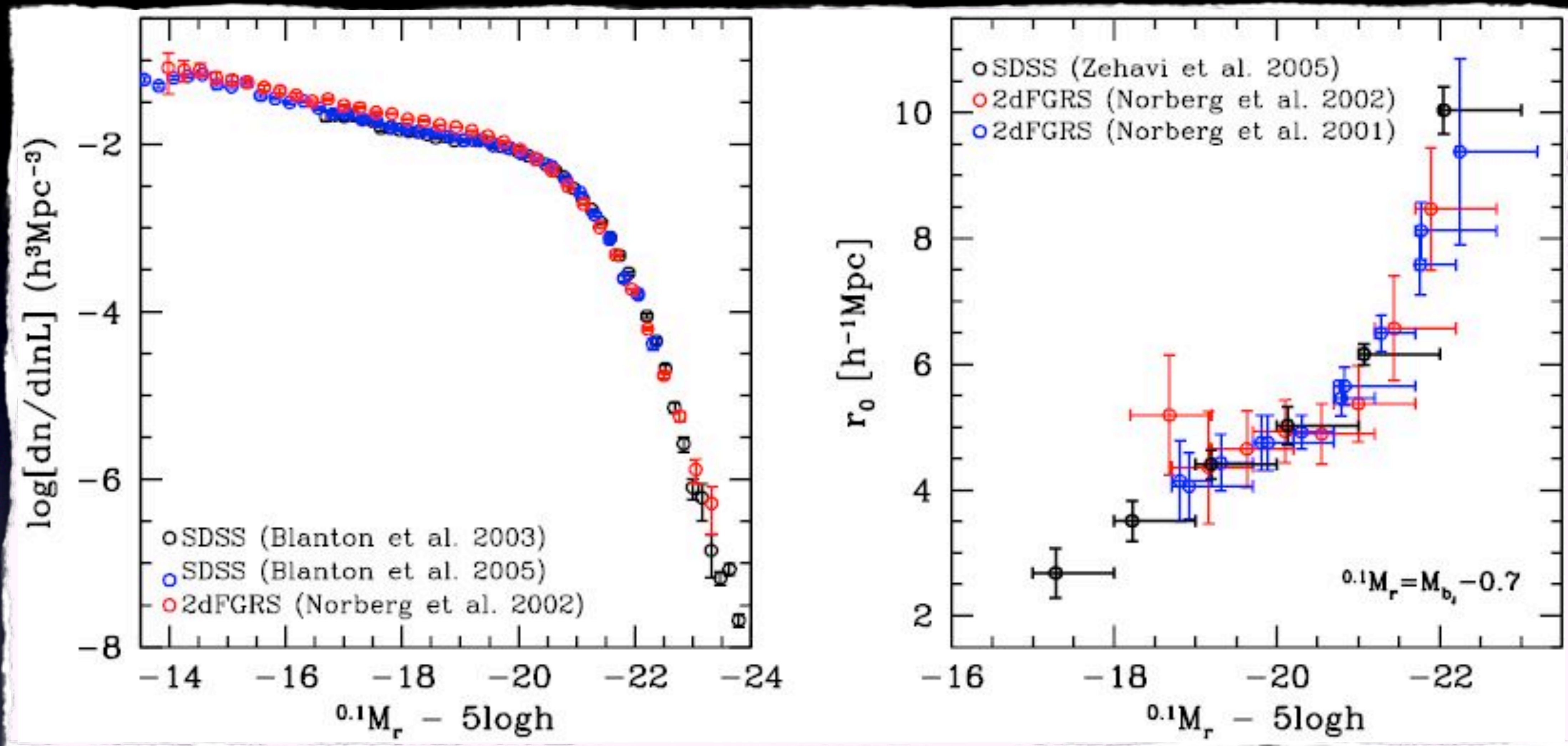
Mass Dependence of Halo Bias



Inferred Halo Bias in good agreement with predictions for concordance cosmology

Wang et al., 2008, ApJ, 687, 919

Luminosity & Correlation Functions

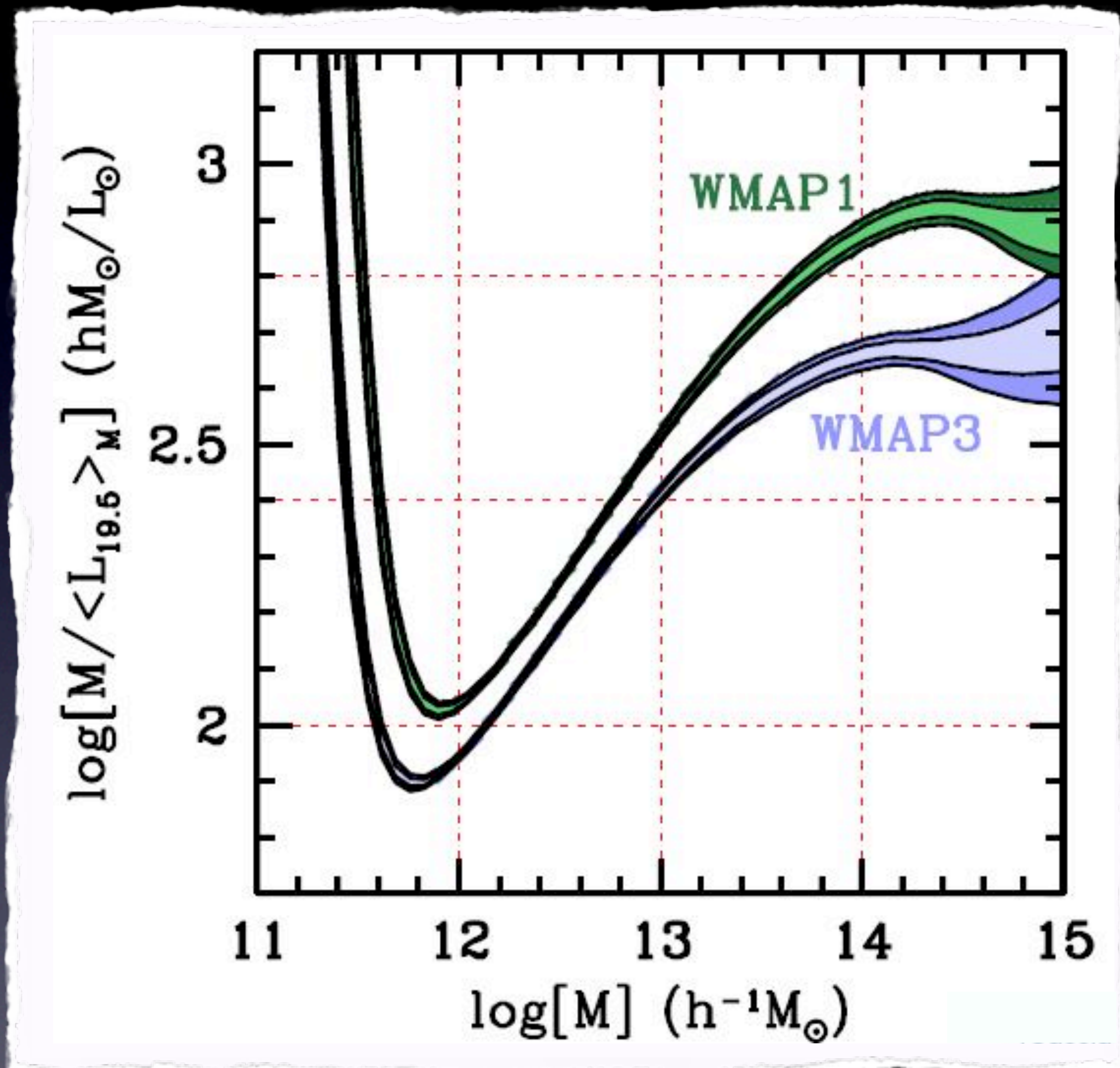


DATA: more luminous galaxies are more strongly clustered

LCDM: more massive halos are more strongly clustered

CONCLUSION: more luminous galaxies reside in more massive halos

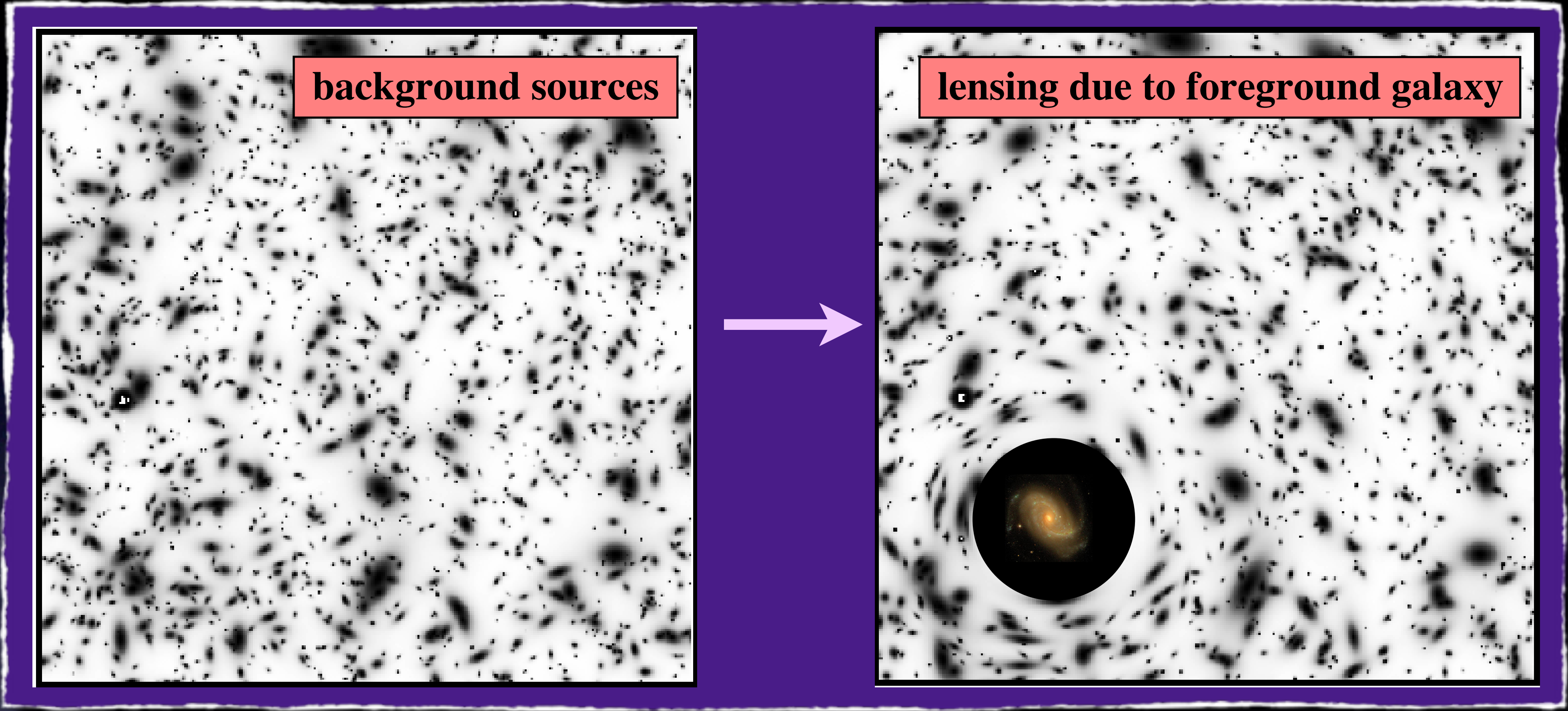
Cosmology Dependence



Cacciato et al. (2009)

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

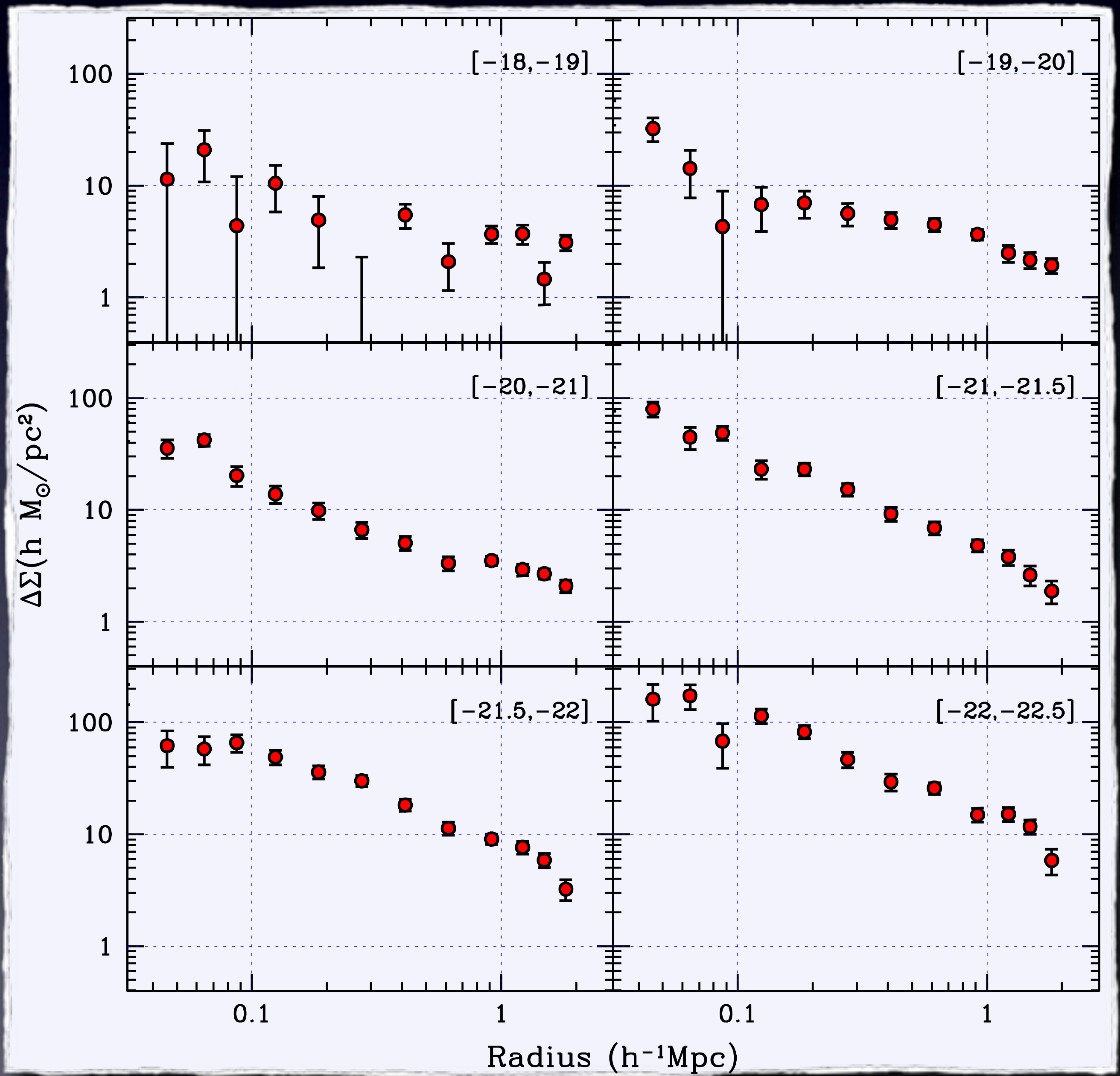
$$\gamma_{\rm t}(R)\Sigma_{\rm crit} = \Delta\Sigma(R) = \bar{\Sigma}(< R) - \Sigma(R)$$

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

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

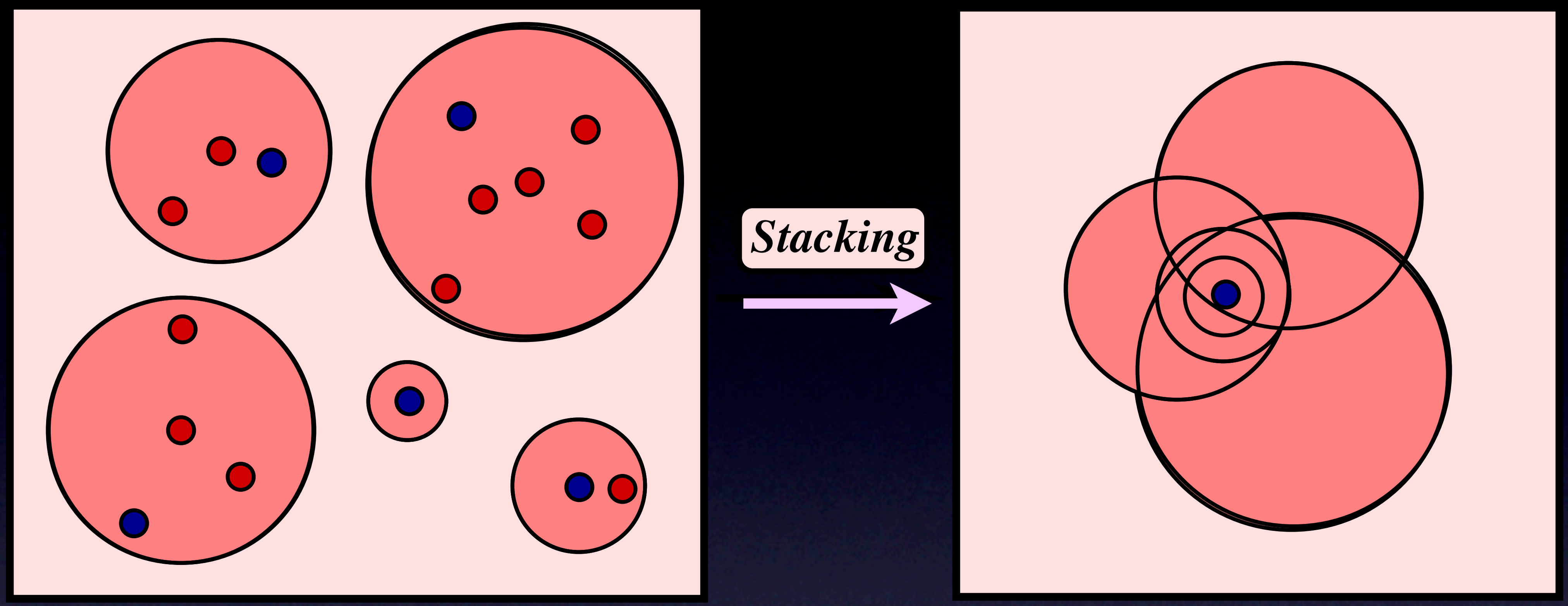
Galaxy-Galaxy Lensing: The Data

- 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:

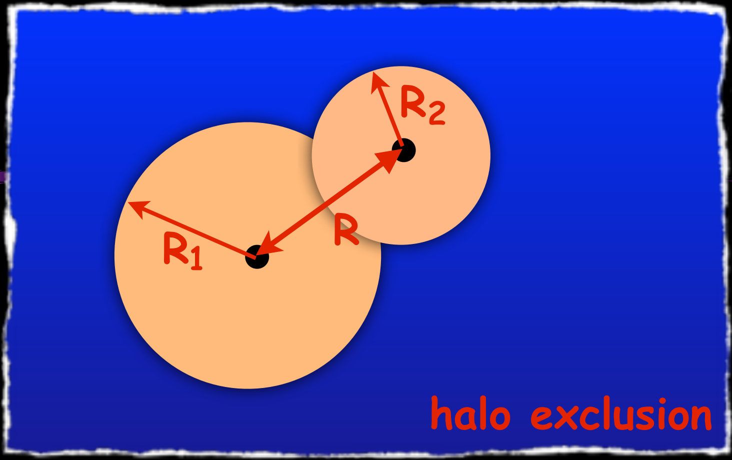
$P_{\rm cen}(M|L)$ $P_{\rm sat}(M|L)$ $f_{\rm sat}(L)$

These can all be computed from the CLF...

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

Constraining Cosmology

Our Version of the Halo Model



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

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

Here $Q(k|M_1, M_2) = 4\pi \int_{r_{\rm min}}^{\infty} [1 + \xi_{\rm hh}(r|M_1, M_2)] \, \frac{\sin kr}{kr} r^2 \mathrm{d}r$

with $1 + \xi_{\rm hh}(r|M_1, M_2) = [1 + b_{\rm h}(M_1) b_{\rm h}(M_2) \zeta(r) \xi_{\rm mm}(r)]\, \Theta(r - r_{\rm min})$

describes the fact that dark matter haloes are clustered, as described by the halo-halo correlation function, $\xi_{\rm hh}(r|M_1, M_2)$, and takes halo exclusion into account by having $r_{\rm min} = R_1 + R_2$

Smith, Scoccimarro & Sheth (2007)
Smith, Desjacques & Marian (2011)

NOTE: $\zeta(r)$ = radial bias function (Tinker et al. 2005)

$\xi_{\rm mm}(r)$ = non-linear matter auto-correlation function (Smith et al. 2003)

Towards a faster halo model...

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

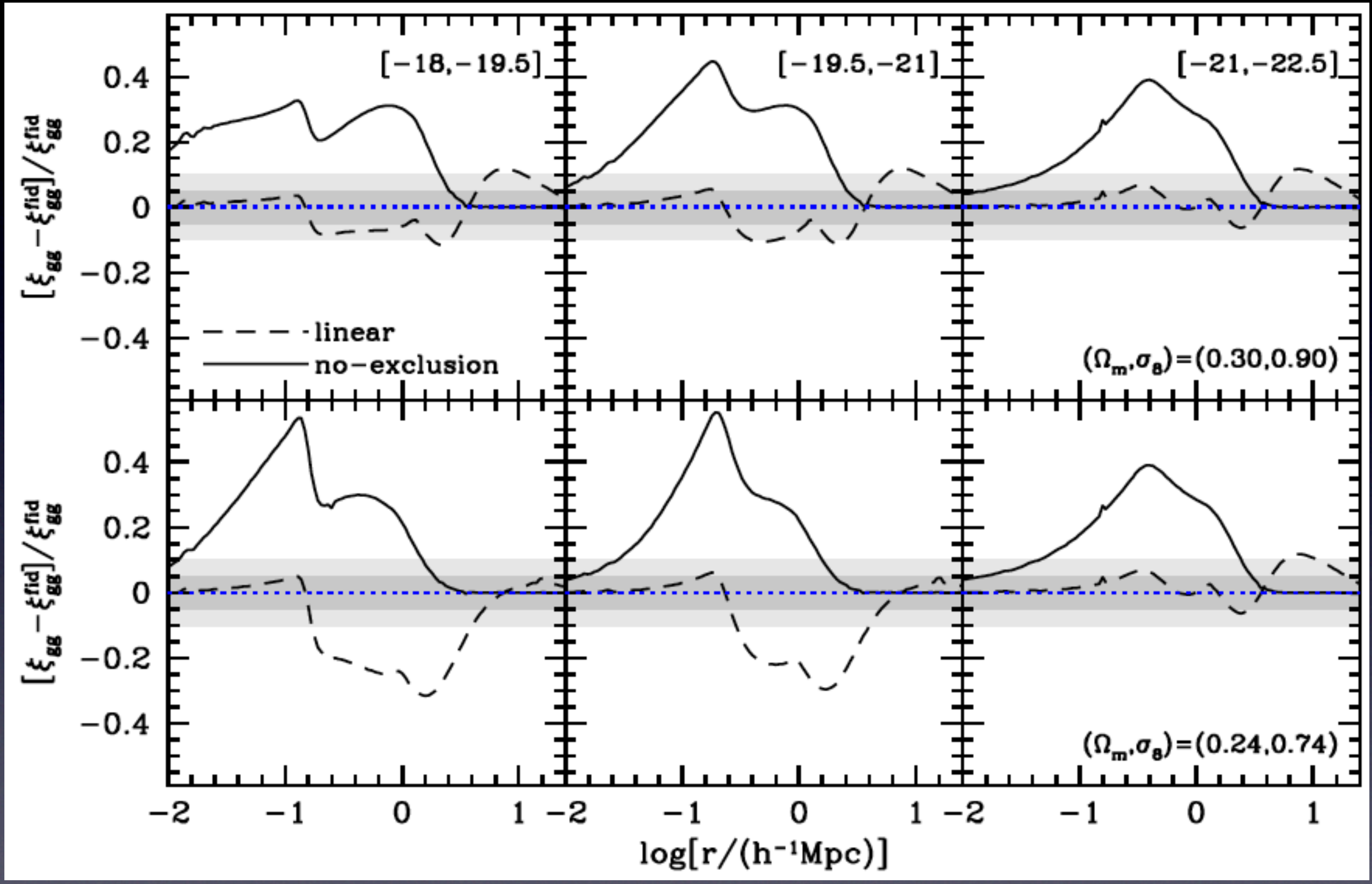
No Halo Exclusion (speed-up: ~10x)

$$P^{2h}(k) = 4\pi \left[\frac{1}{\bar{\rho}} \int \mathrm{d}M\, M\, n(M)\, b_{\mathrm{h}}(M)\, \tilde{u}(k|M)\right]^2 \int \zeta(r)\, \xi_{\mathrm{mm}}(r)\, \frac{\sin kr}{kr}\, r^2\, \mathrm{d}r$$

Use Linear Matter Power Spectrum

$$P^{2h}(k) = \left[\frac{1}{\bar{\rho}} \int \mathrm{d}M\, M\, n(M)\, b_{\mathrm{h}}(M)\, \tilde{u}(k|M)\right]^2 P_{\mathrm{lin}}(k)$$

...but at the loss of accuracy



The Galaxy-Galaxy Correlation Function

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

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

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

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

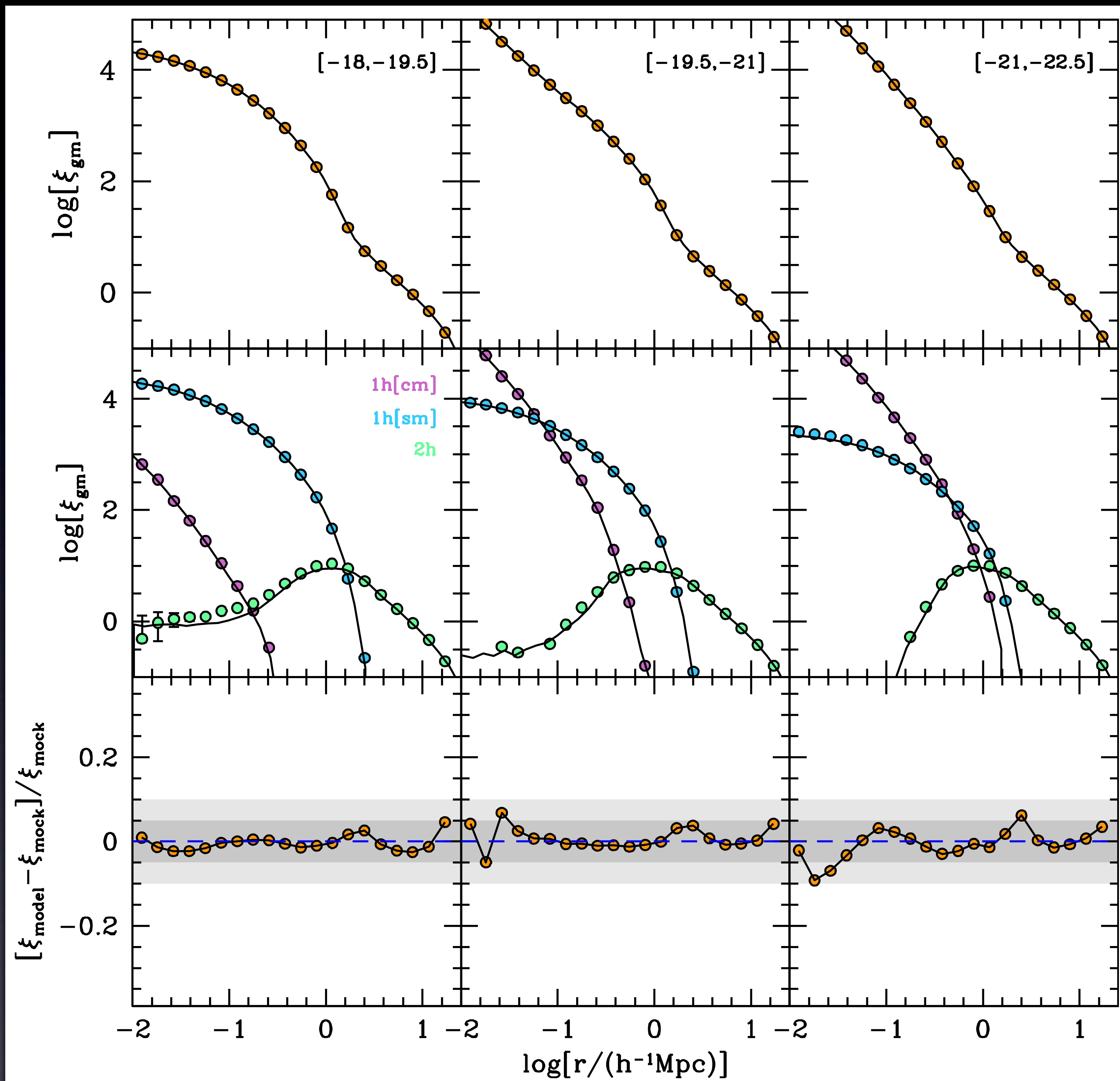
Simply replace

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

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

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 $\xi_{\mathrm{gg}}(r)$

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%

van den Bosch et al. (2013)

Residual Redshift Space Distortions

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

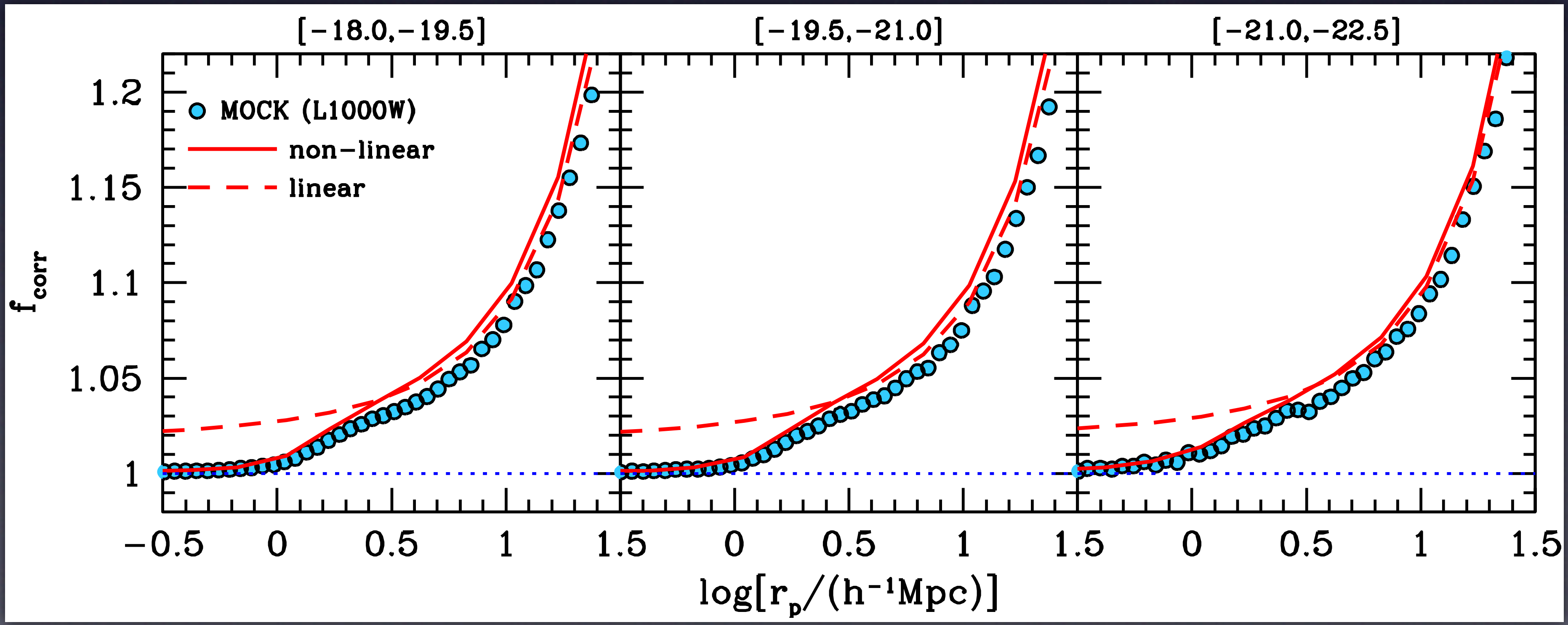
$$w_{\rm p} = 2 \int_0^\infty \xi_{\rm gg}(r_{\rm p}, r_\pi)\, {\rm d}r_\pi = 2 \int_{r_{\rm p}}^\infty \xi_{\rm gg}(r)\, \frac{r\,{\rm d}r}{\sqrt{r^2 - r_{\rm p}^2}}$$

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

(Padmanabhan+07; Norberg+09; Baldauf+10)



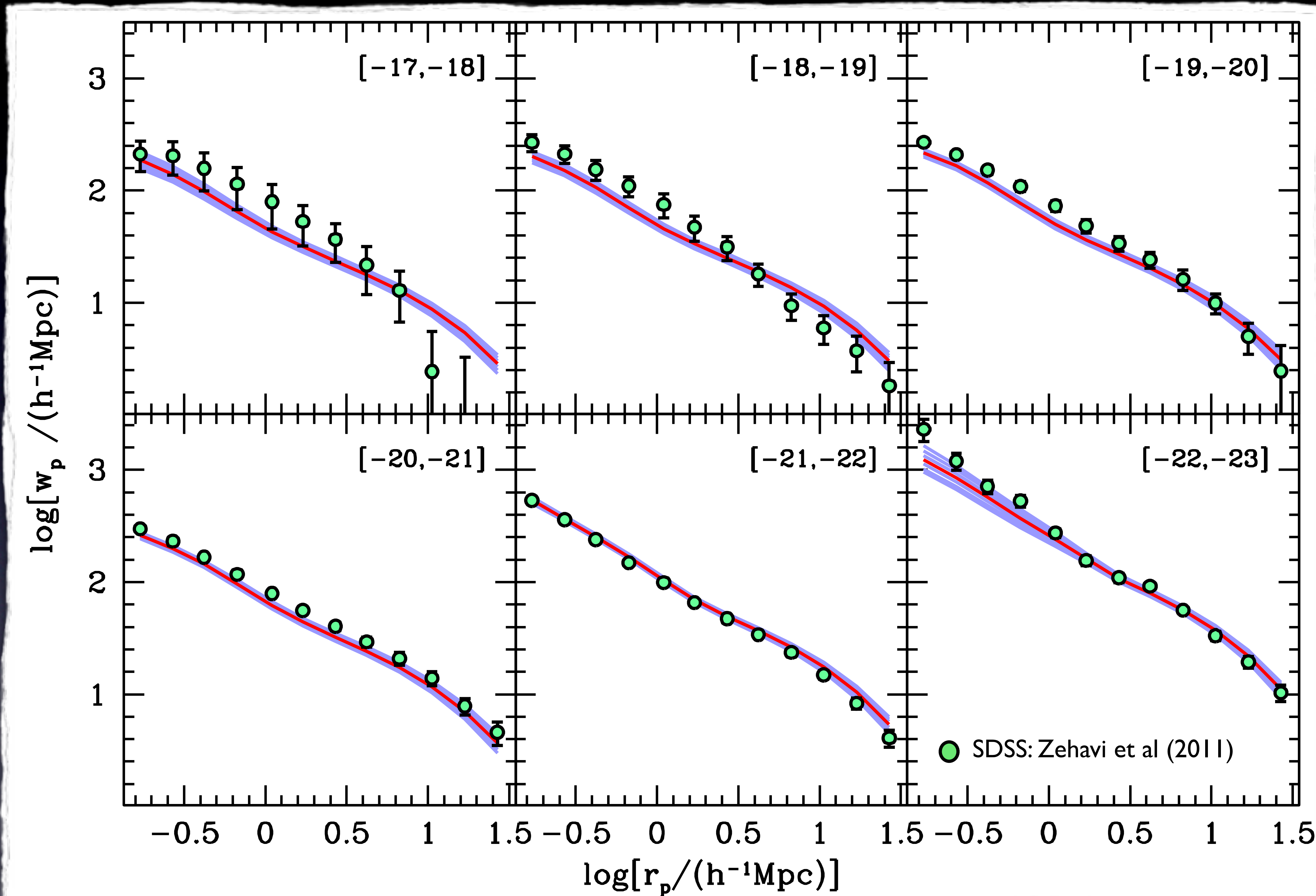
We correct for these residual redshift space distortions using modified Kaiser formalism. This is accurate to better than 2%.

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; ψ , η

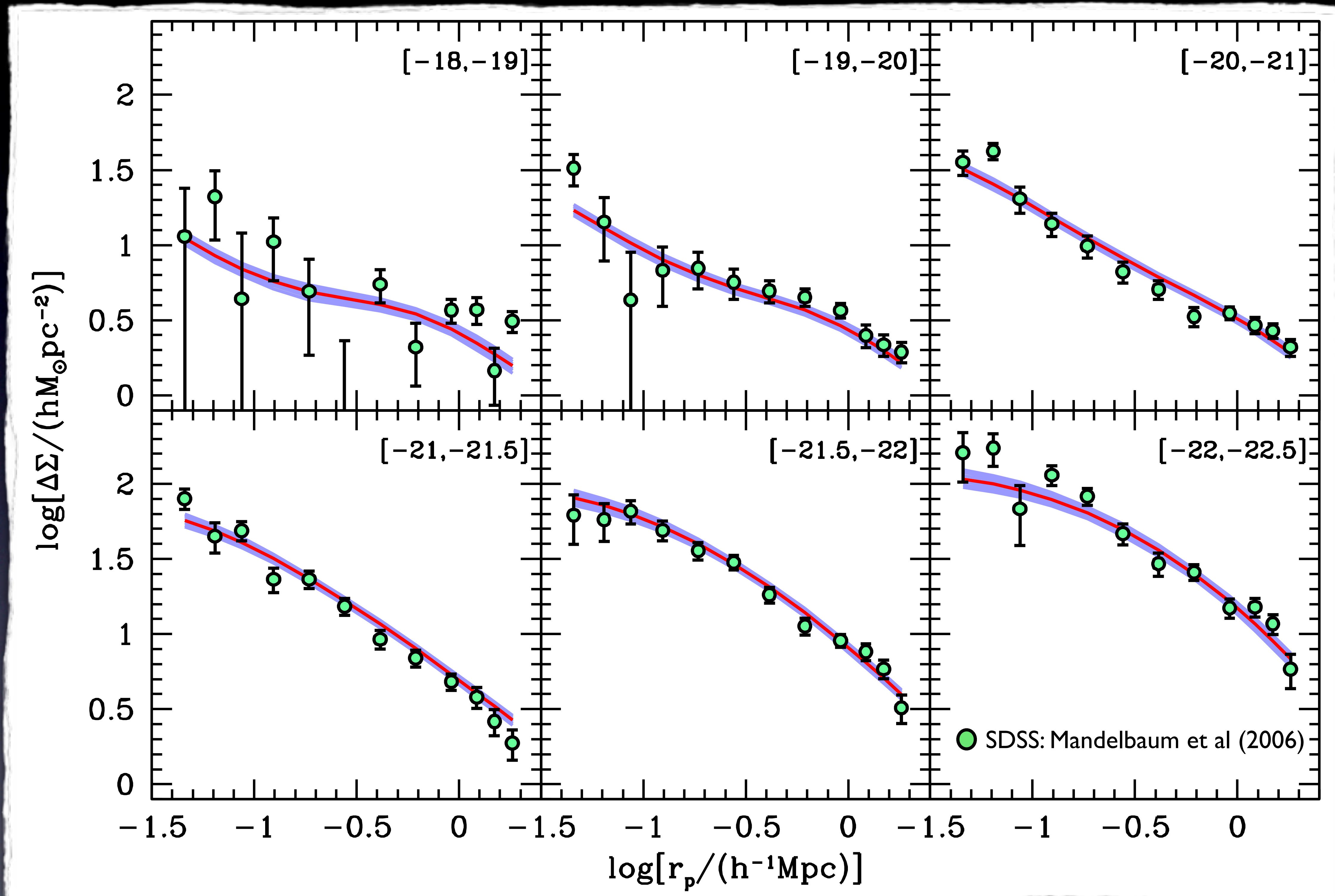
  Total of 176 data points.
- WMAP7 priors on $\Omega_{\rm b}, n_{\rm s}, h$
- Correction for residual redshift space distortions
- Dark matter haloes follow NFW profile
- Radial number density distribution of satellites follows that of dark matter particles.
- Halo mass function, halo bias function and radial bias function fromTinker et al. (2005, 2009, 2010).

Results: Clustering Data



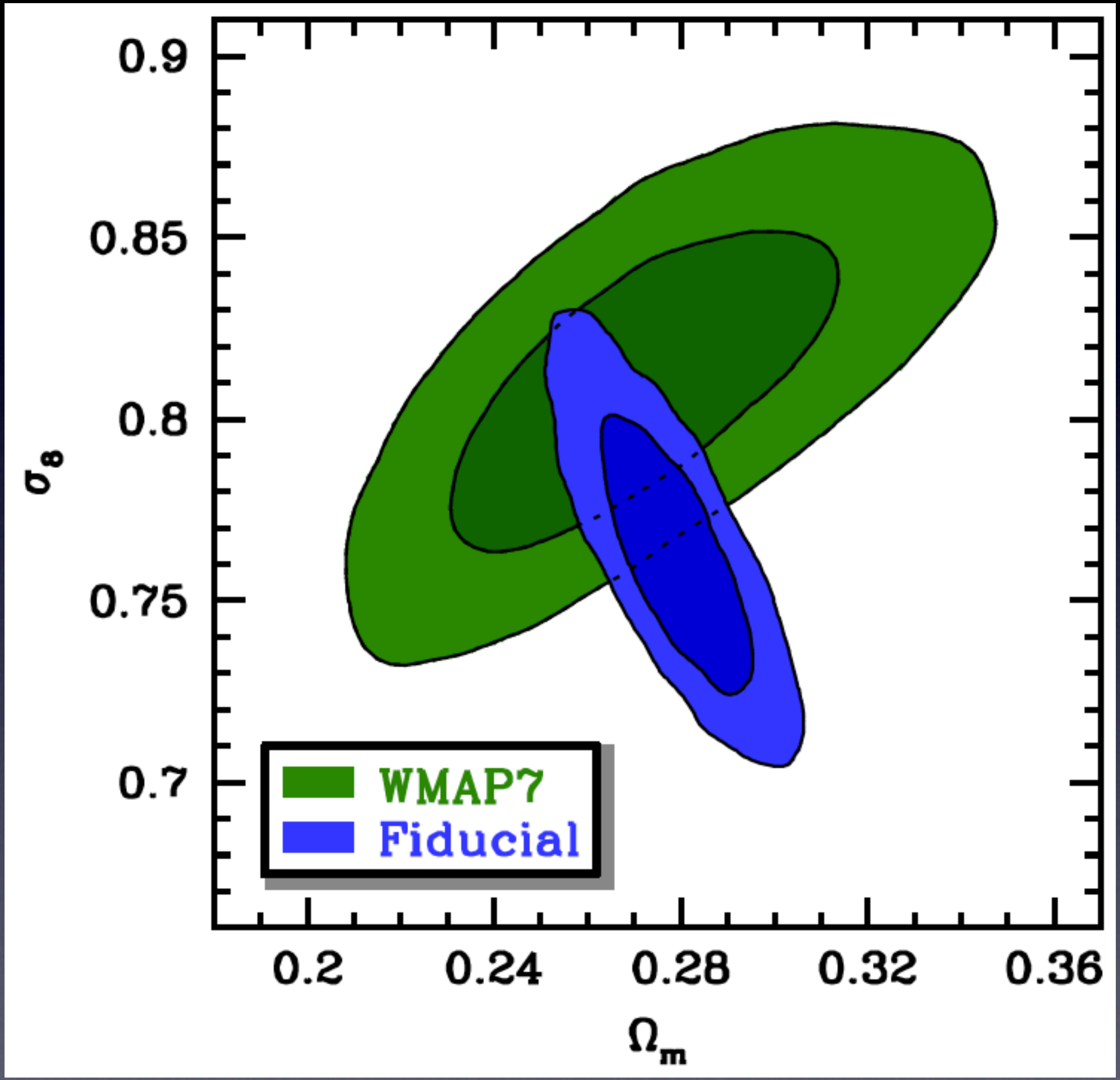
Cacciato et al. (2013)

Results: Lensing Data



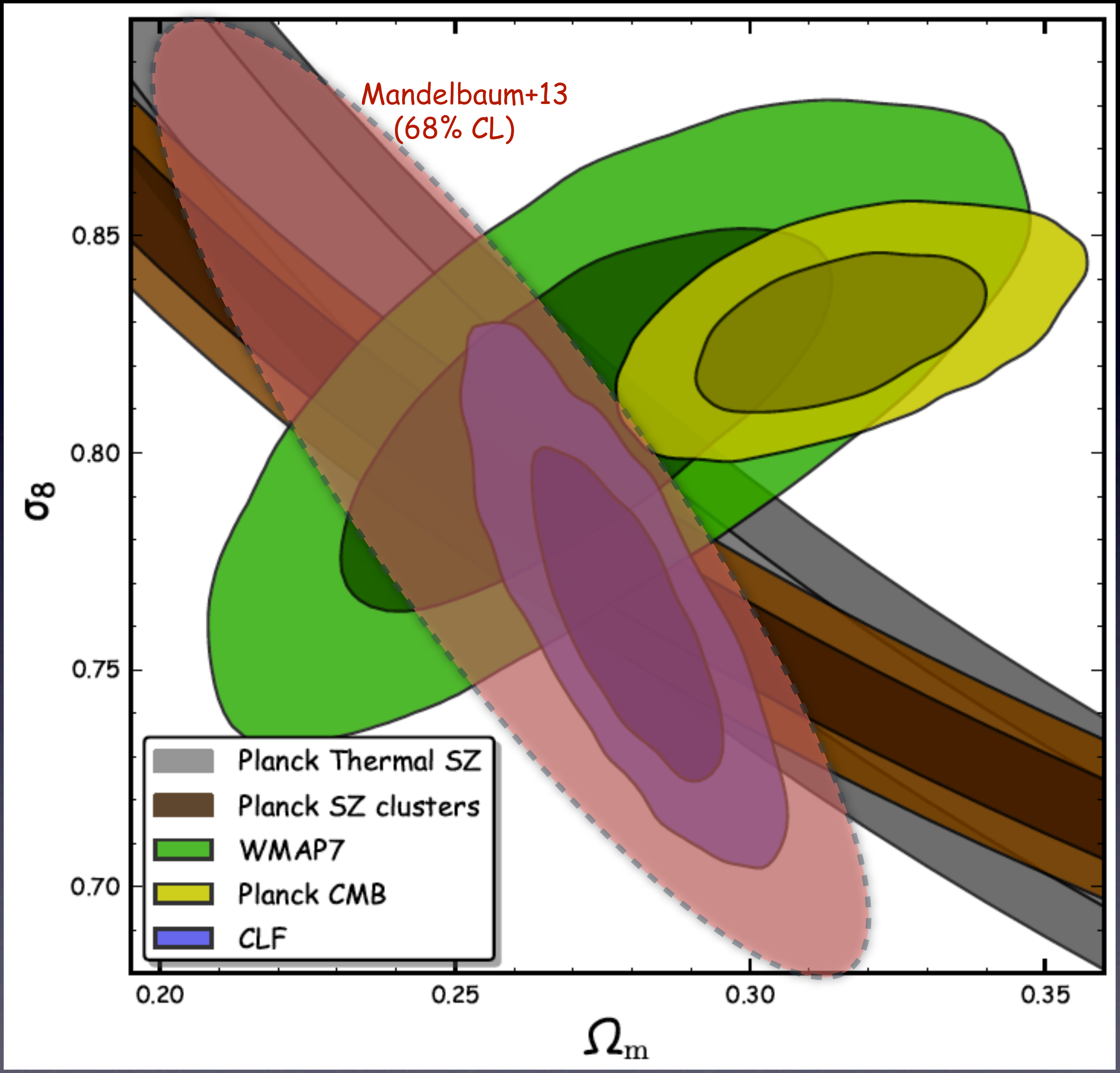
Cacciato et al. (2013)

Cosmological Constraints

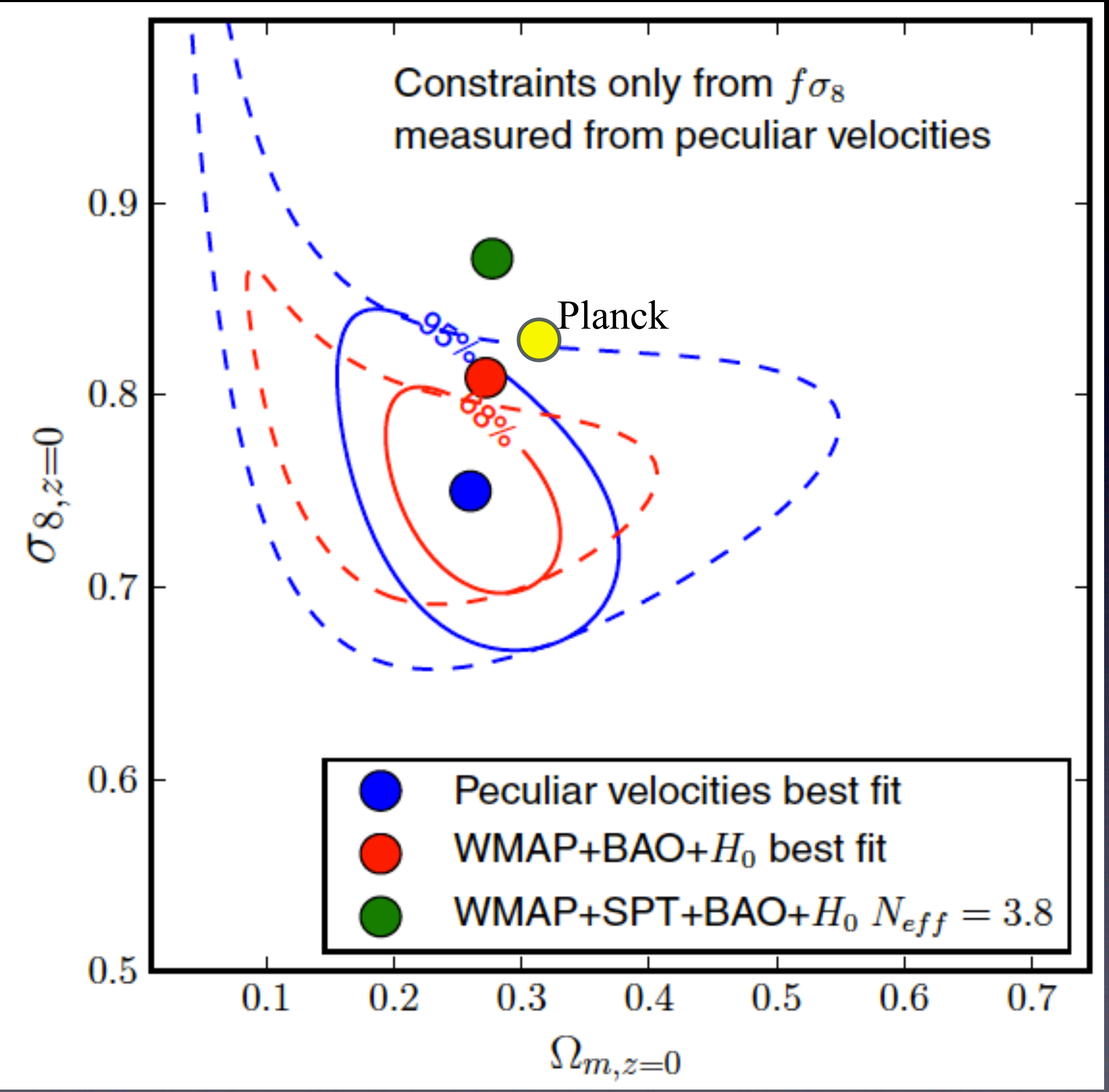


Cacciato et al. (2013)

and then there was Planck...

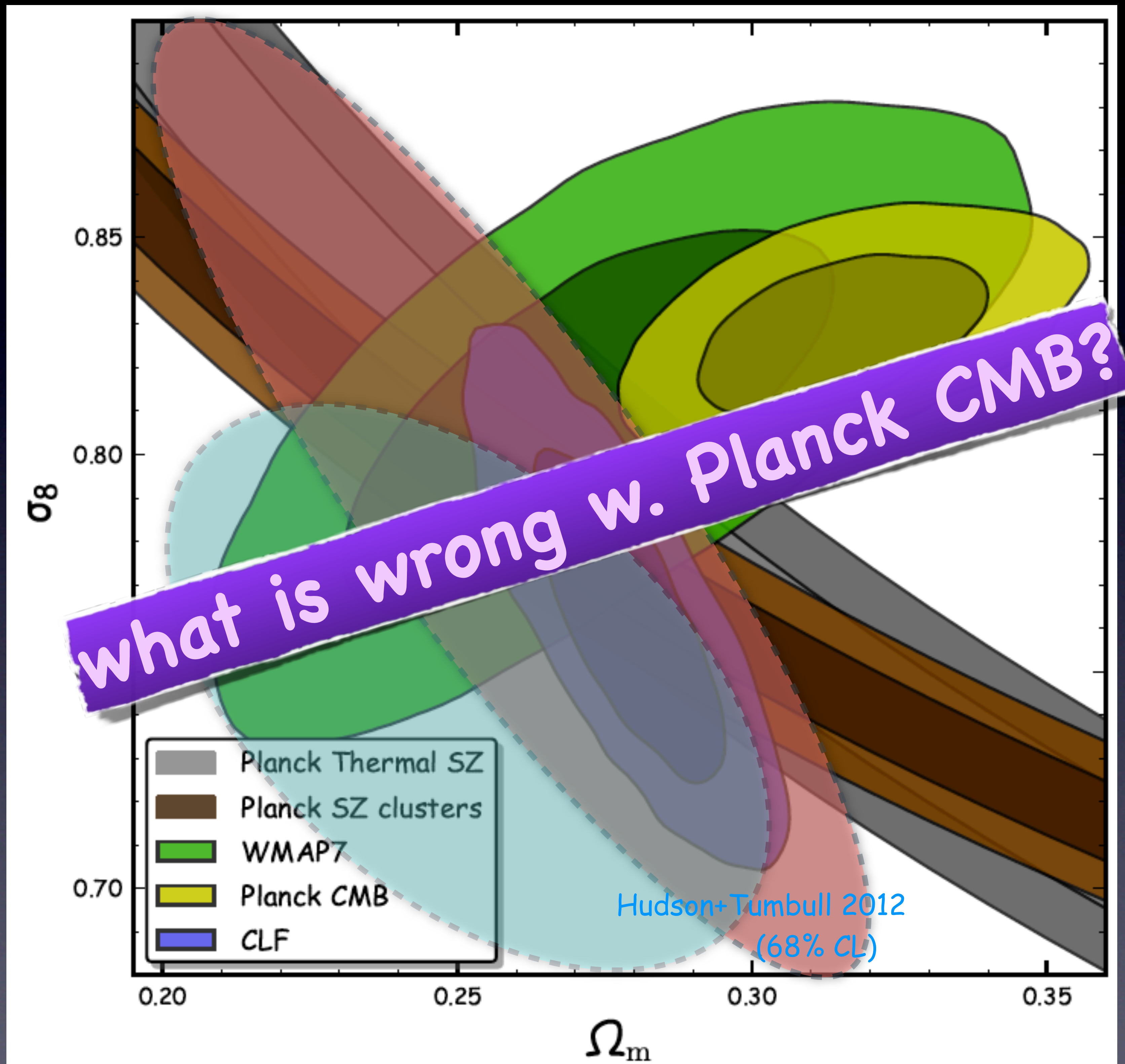


Cosmological Constraints from Peculiar Velocities

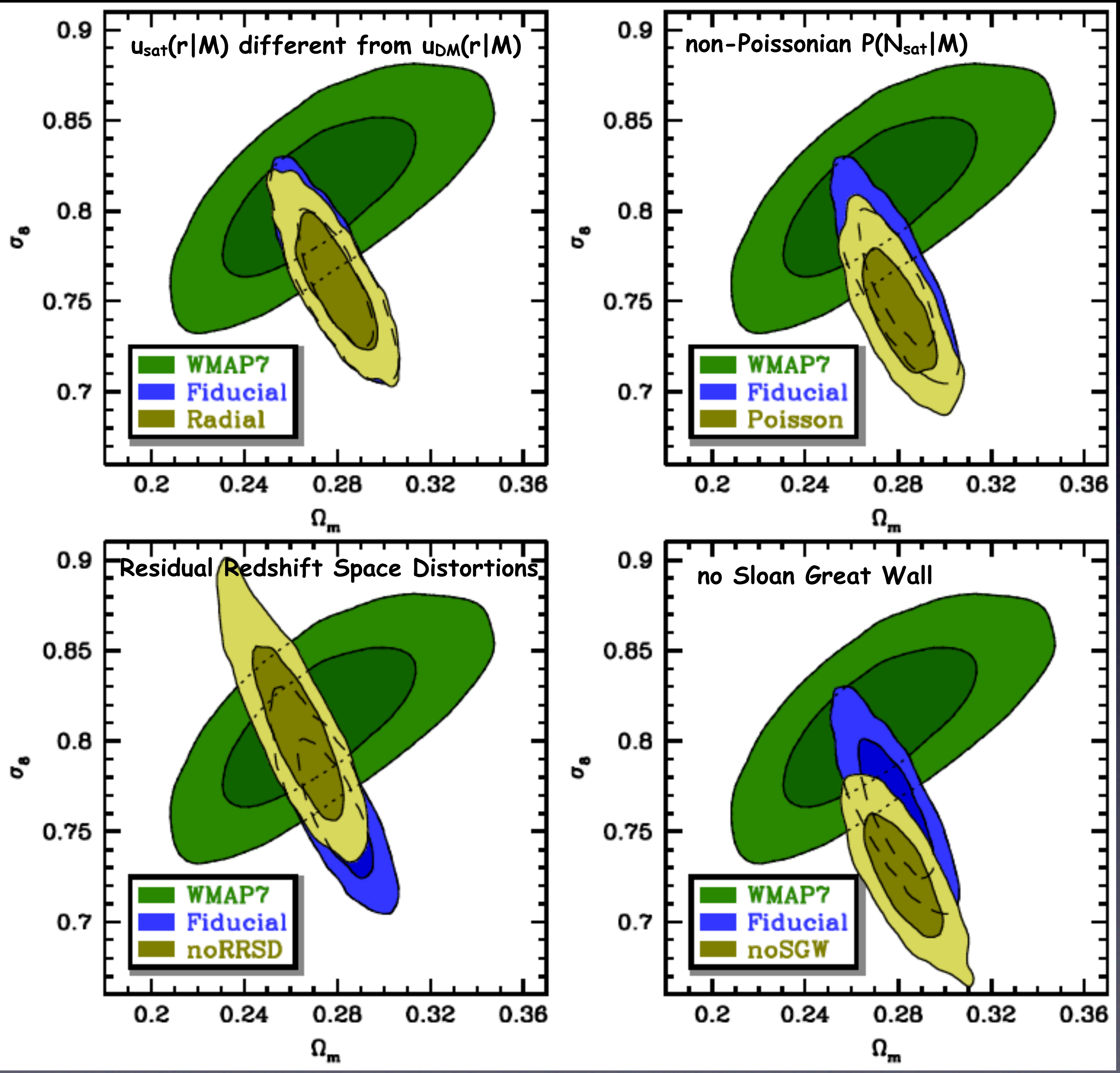


Hudson & Tumbull (2012)

Cosmological Constraints



Degeneracies

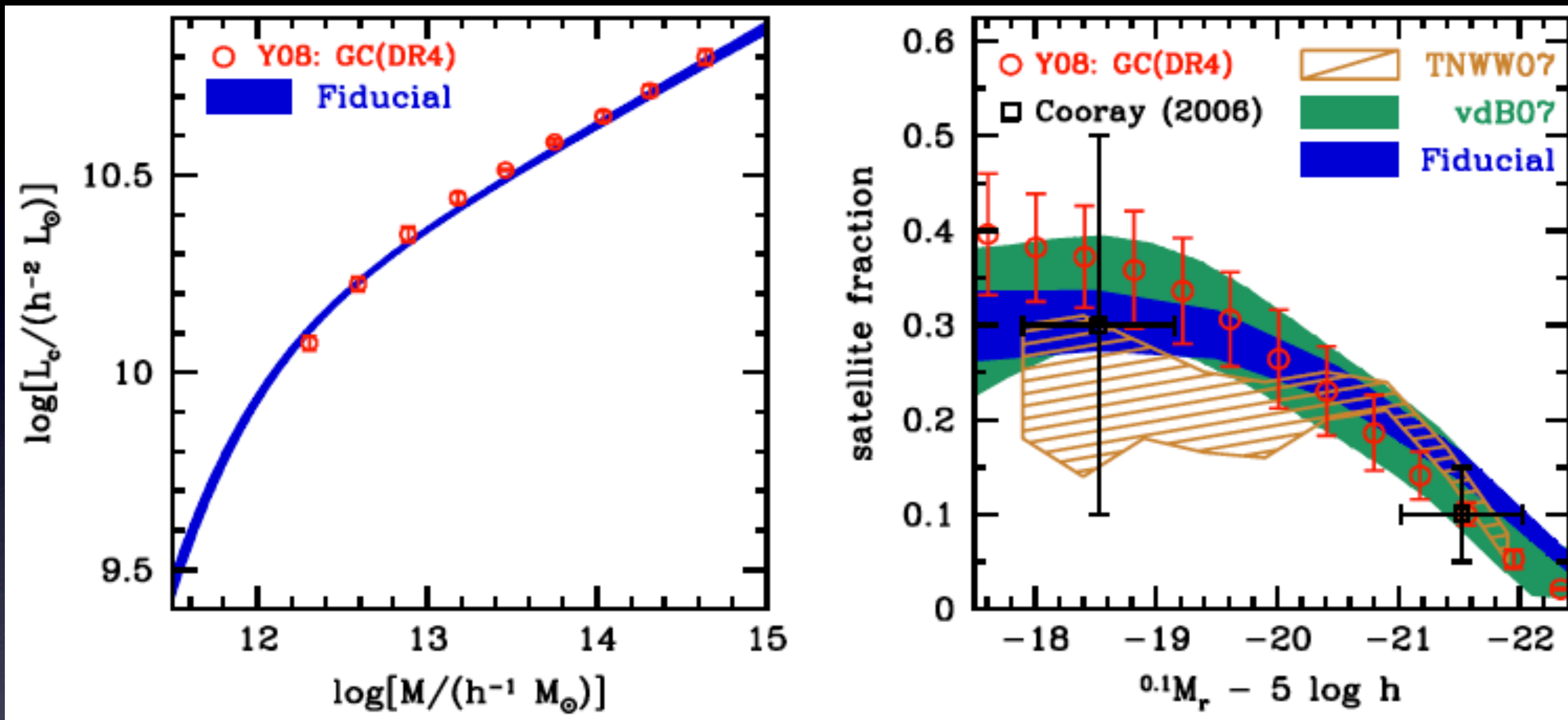


Cacciato et al. (2013)

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.
  - Results in excellent agreement with CMB constraints from WMAP7 with similar analysis by Mandelbaum+12, and with recent peculiar velocity analysis by Hudson &Tumbull 2012... [but tension w. Planck CMB]

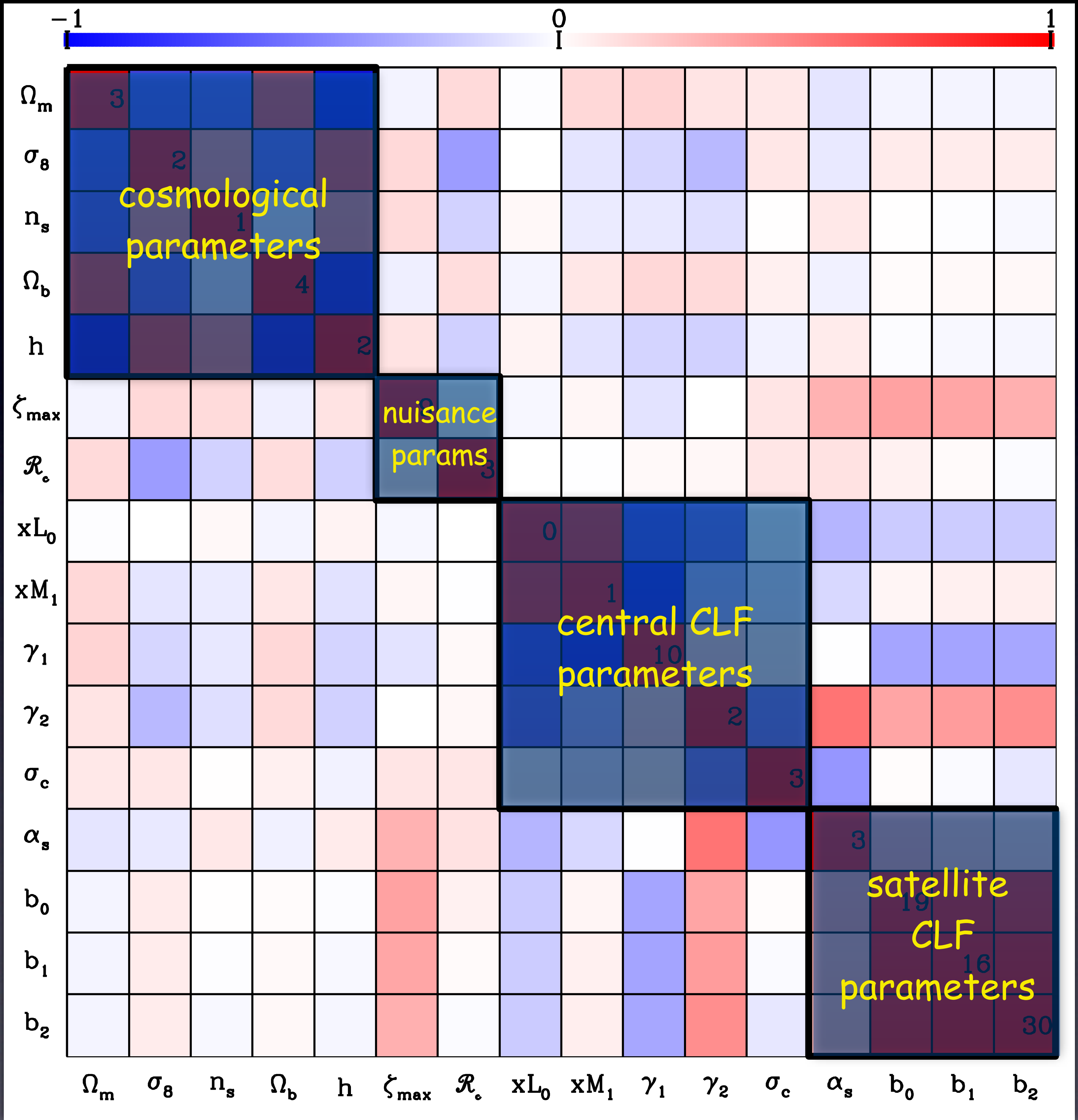
Halo Occupation Statistics



Cacciato et al. (2013)

Posterior on CLF perfectly consistent with results from Galaxy Group Catalogues by Yang, Mo & vdB (2008).

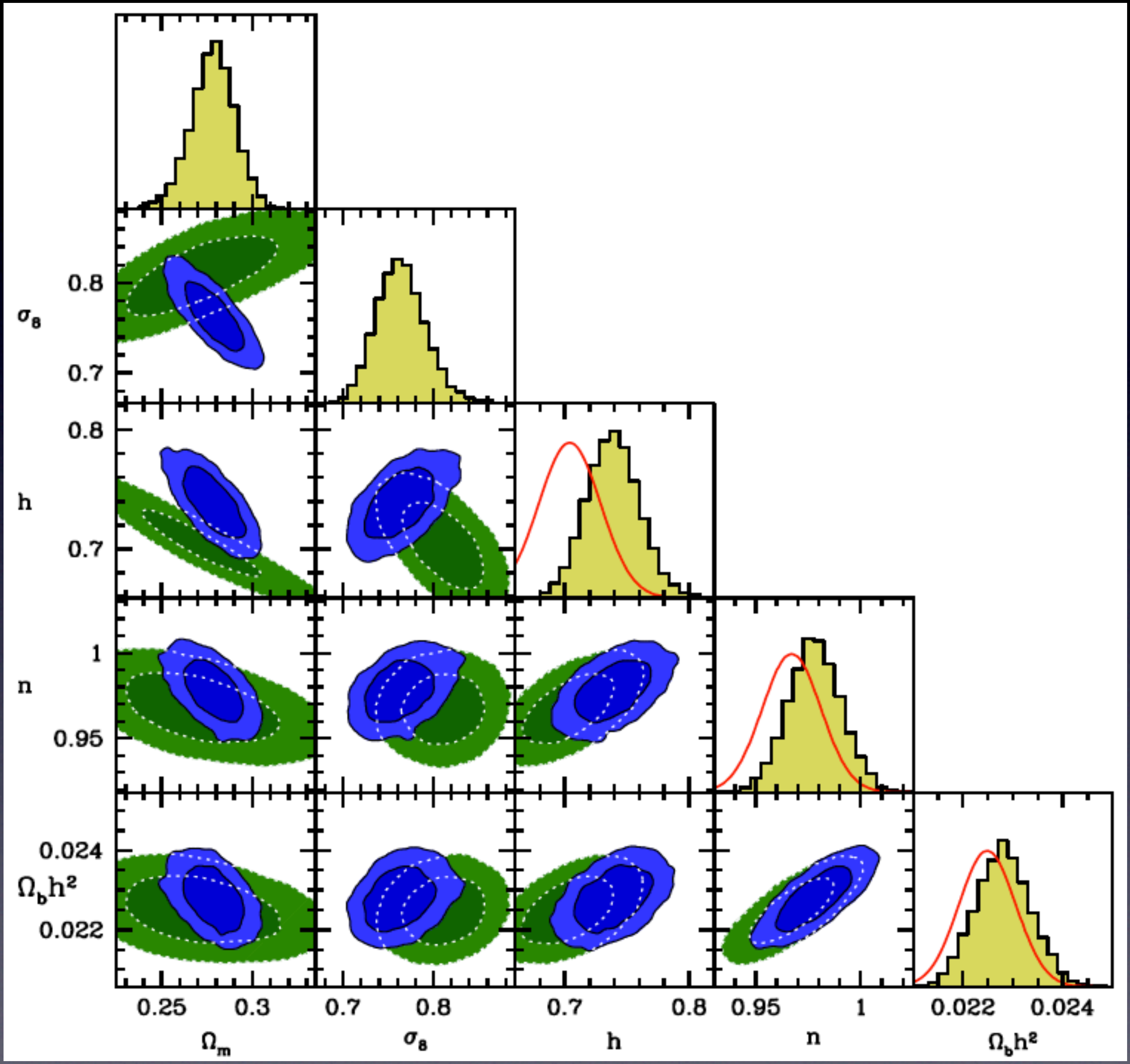
Covariance Matrix



- Covariance matrix has block diagonal form.
- Little correlation between cosmological parameters, and other parameters.
- Nuisance parameters are mainly correlated with the satellite CLF parameters
- Our results are robust to our particular parameterization of the CLF.

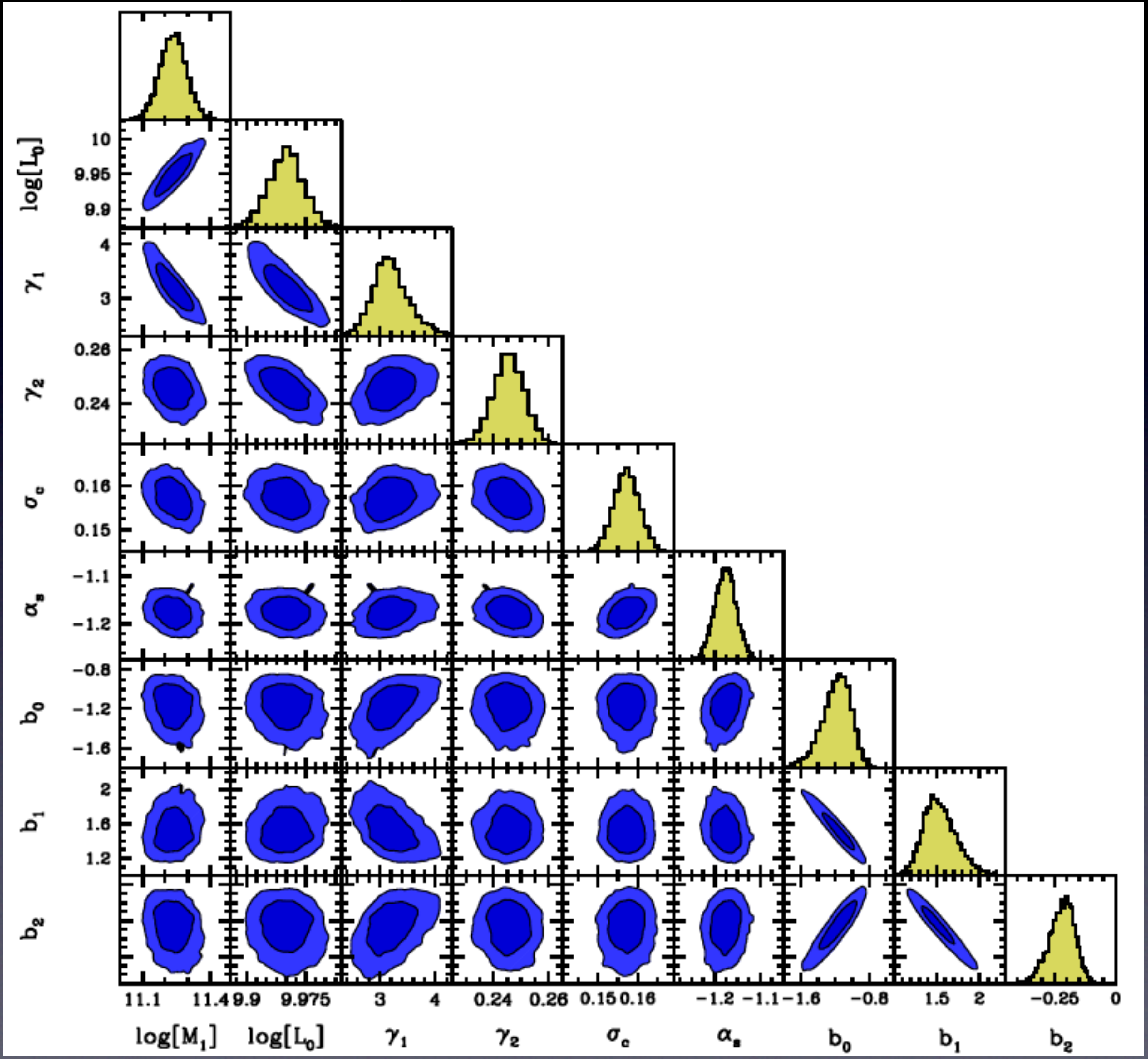
More et al. (2013)

Cosmological Constraints

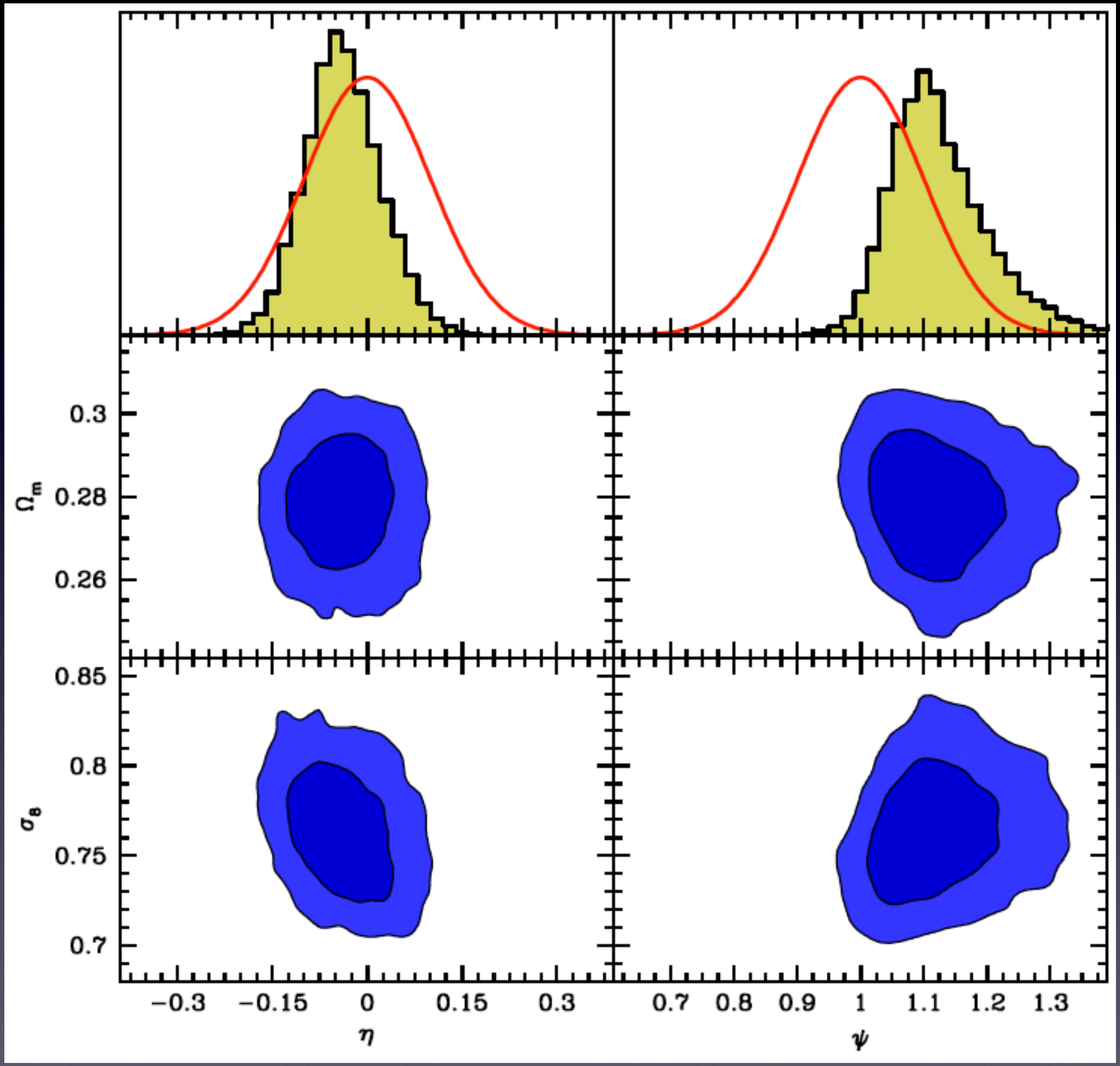


Cacciato et al. (2013)

CLF parameters



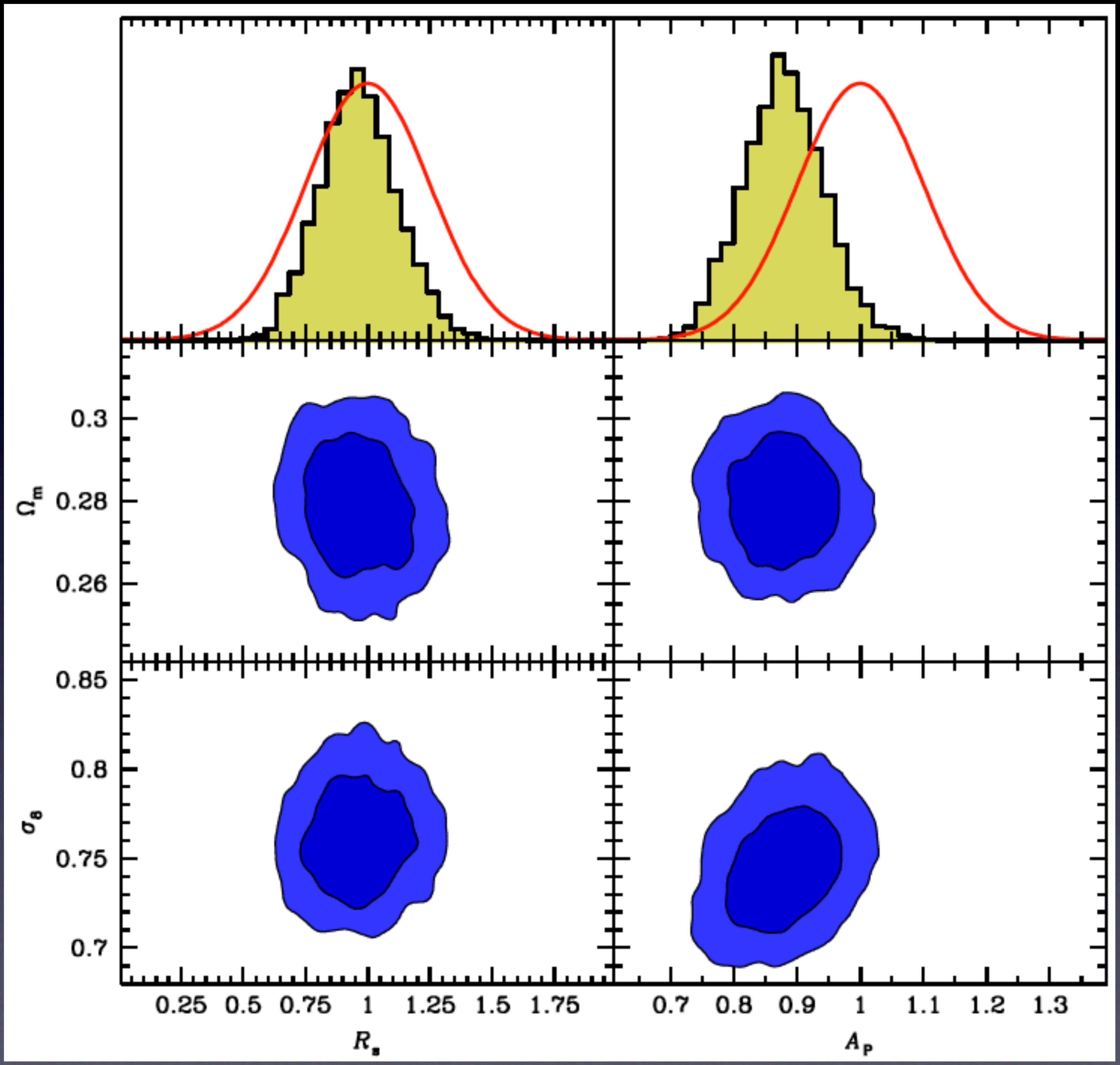
Nuisance Parameters



Cacciato et al. (2013)

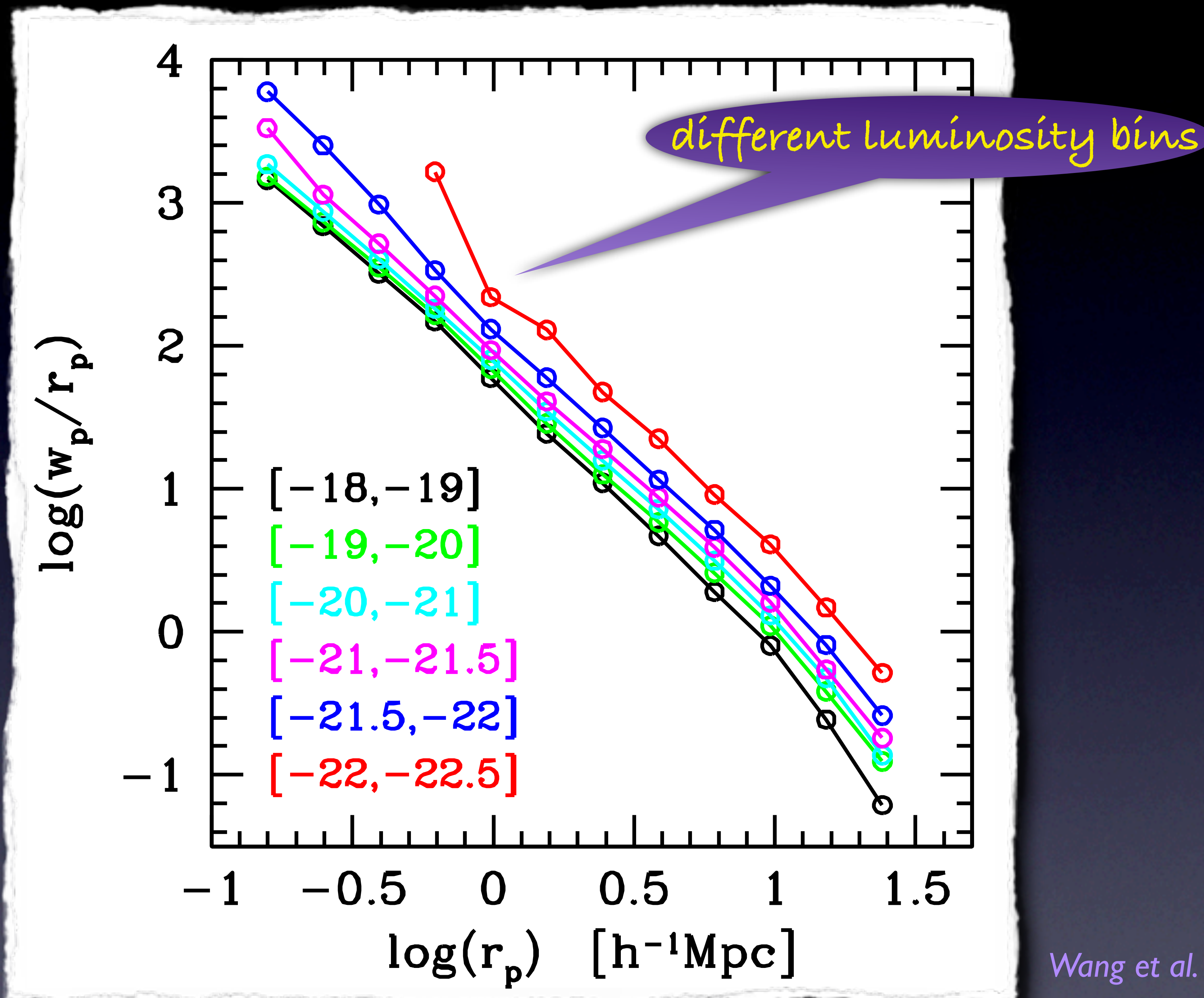
$c(M, z) = (1 + \eta)\, \bar{c}(M, z)$ *Non-linear (radial) halo bias*

Title



0.3
0.28
0.26
Ω_m
0.85
0.8
0.75
0.7
σ_8
0.25 0.5 0.75 1 1.25 1.5 1.75
R_s
0.7 0.8 0.9 1 1.1 1.2 1.3
A_P

Galaxy Clustering: The Data



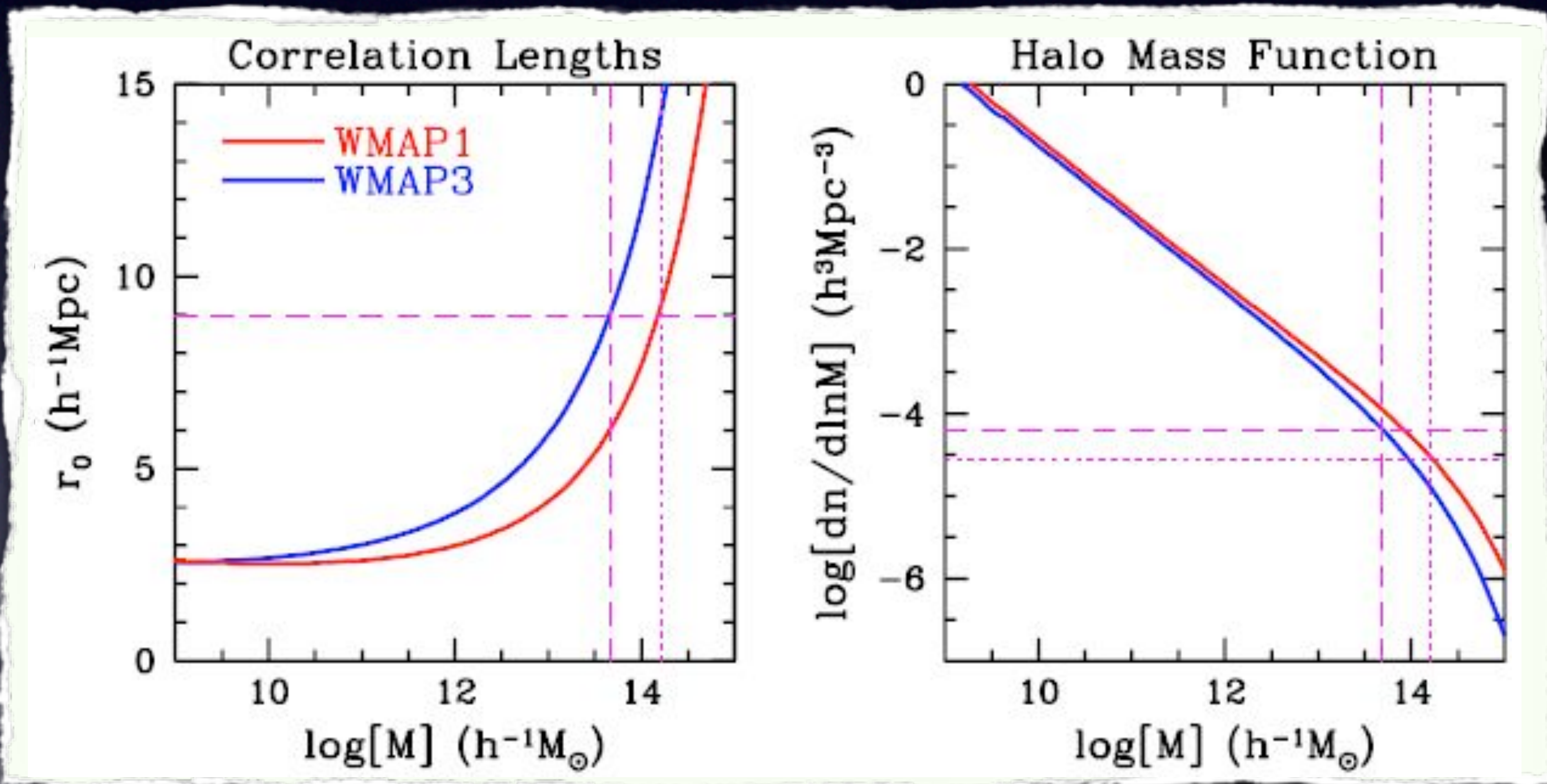
Wang et al. (2007)

More luminous galaxies are more strongly clustered

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

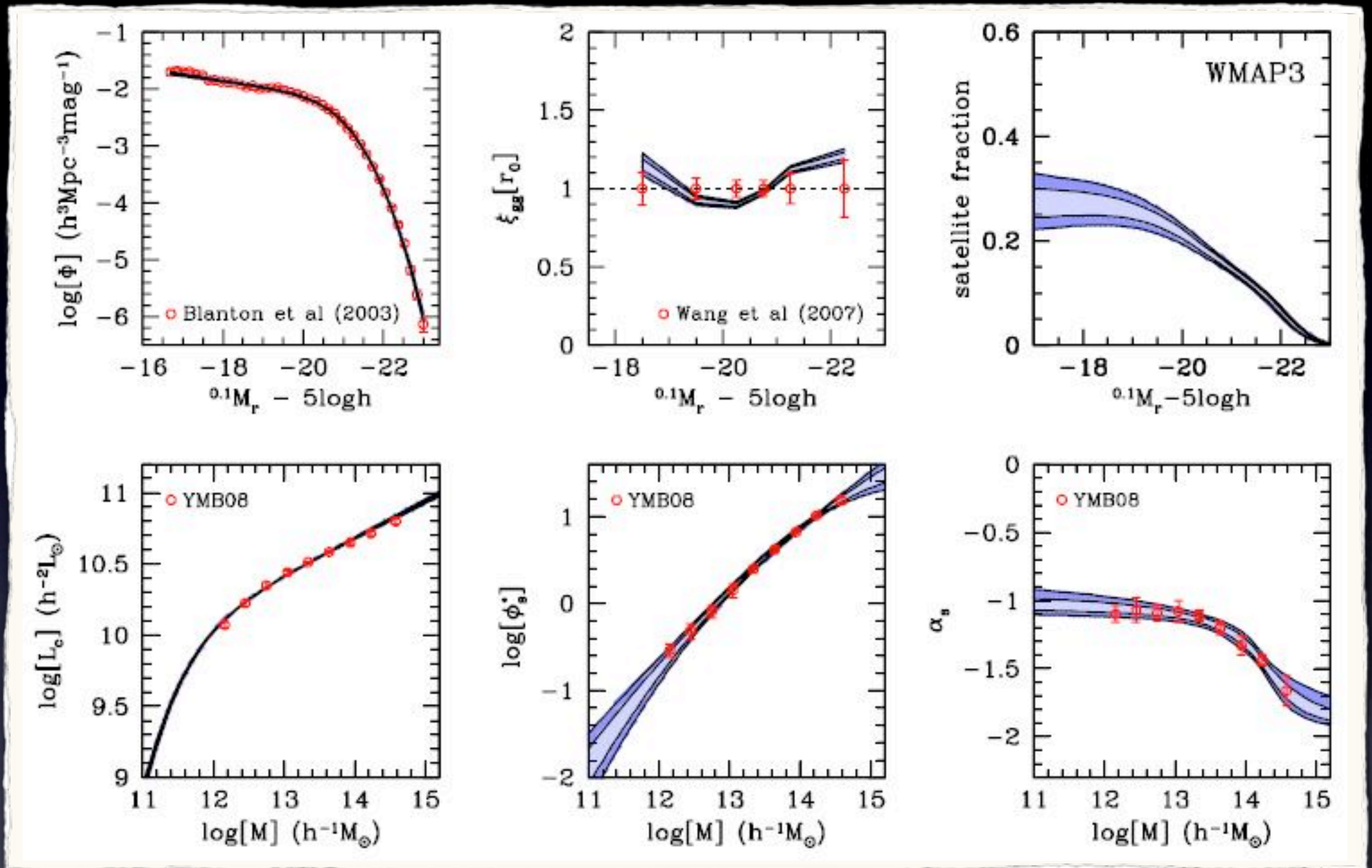
$\Omega_m = 0.24$

$\Omega_\Lambda = 0.76$

$\sigma_8 = 0.74$

CAUTION: results depend on cosmology

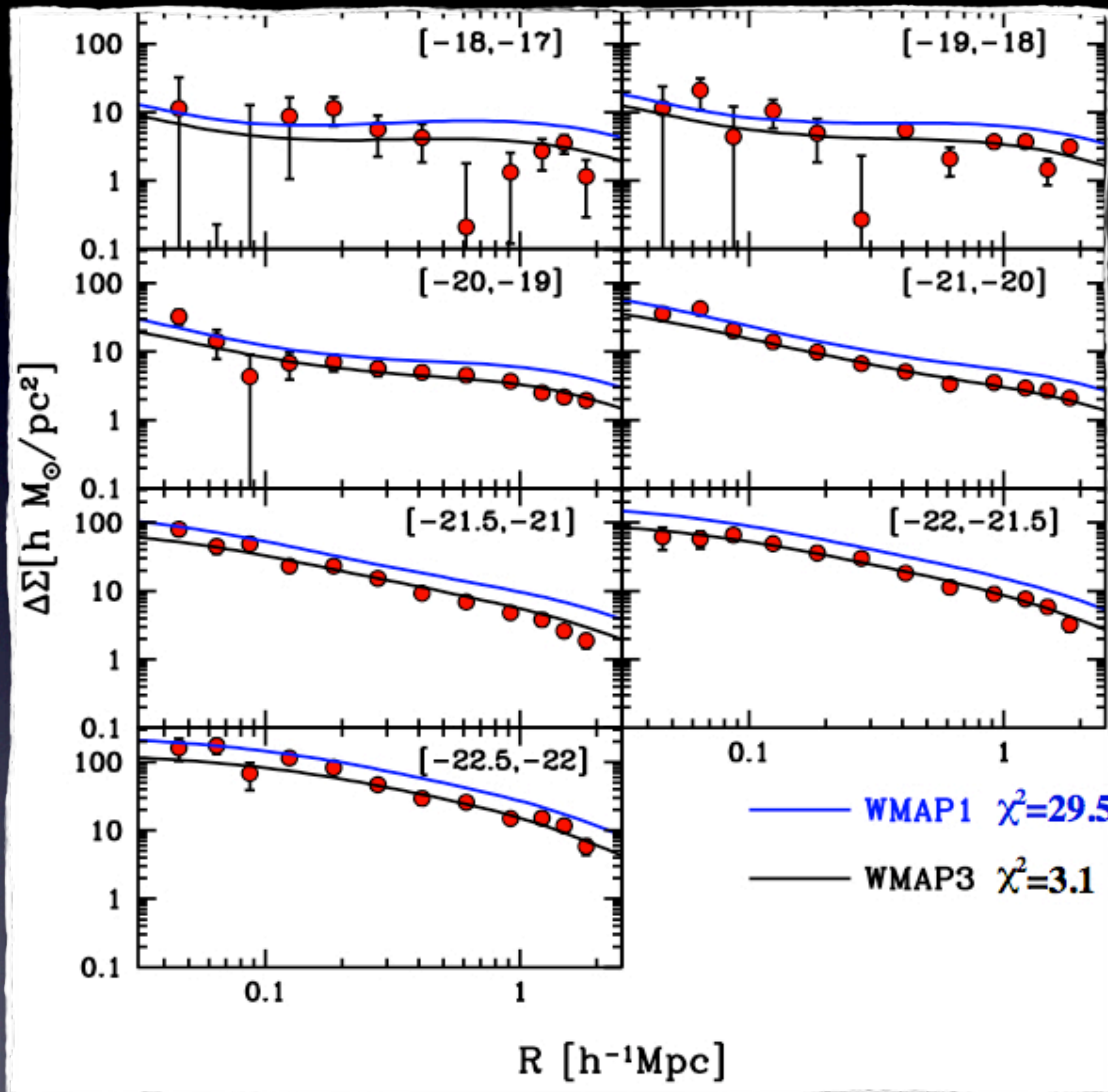
Results from MCMC Analysis



Cacciato, vdB et al. (2009)

- Model fits data extremely well with
- Same model in excellent agreement with results from SDSS galaxy group catalogue

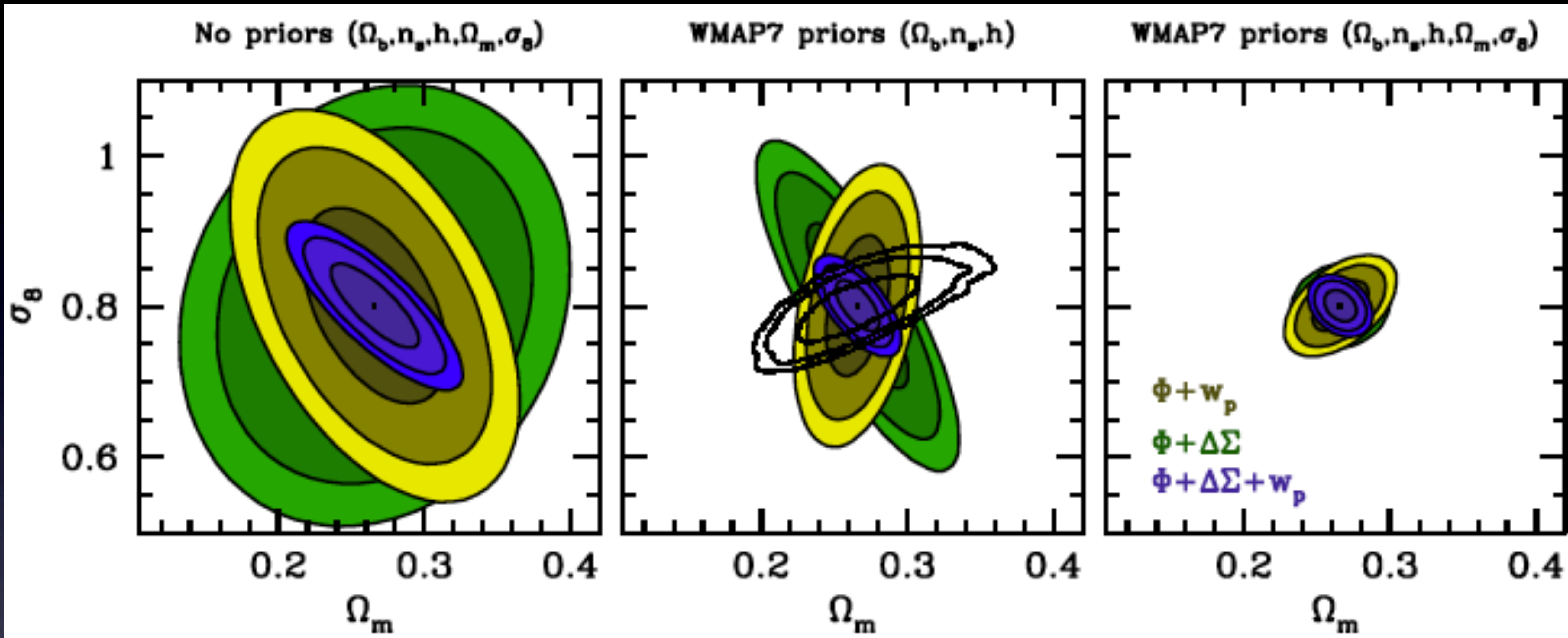
Galaxy-Galaxy Lensing: Results



Cacciato et al. (2009)

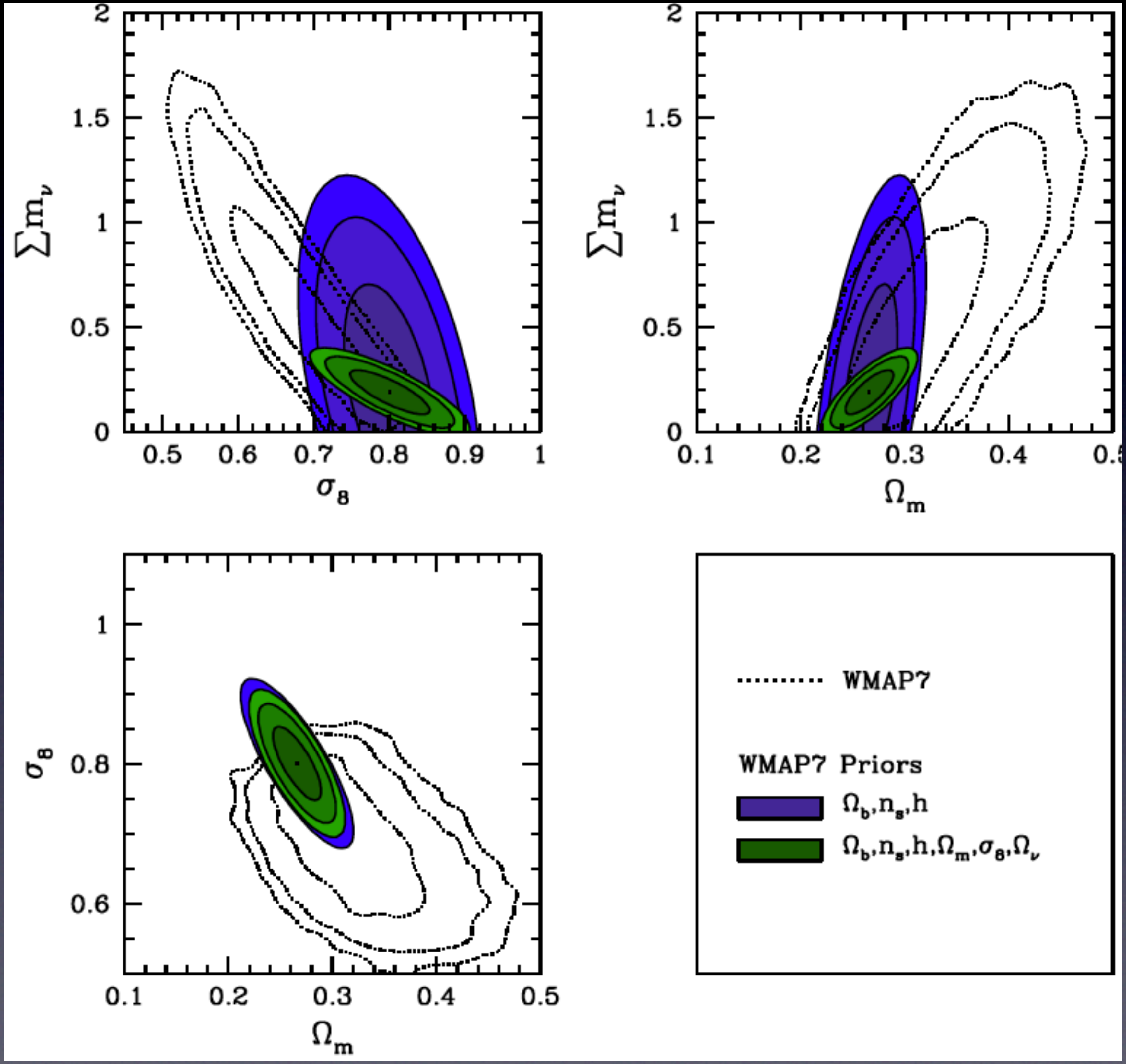
Combination of clustering & lensing can constrain cosmology!!!

Fisher-Forecasting

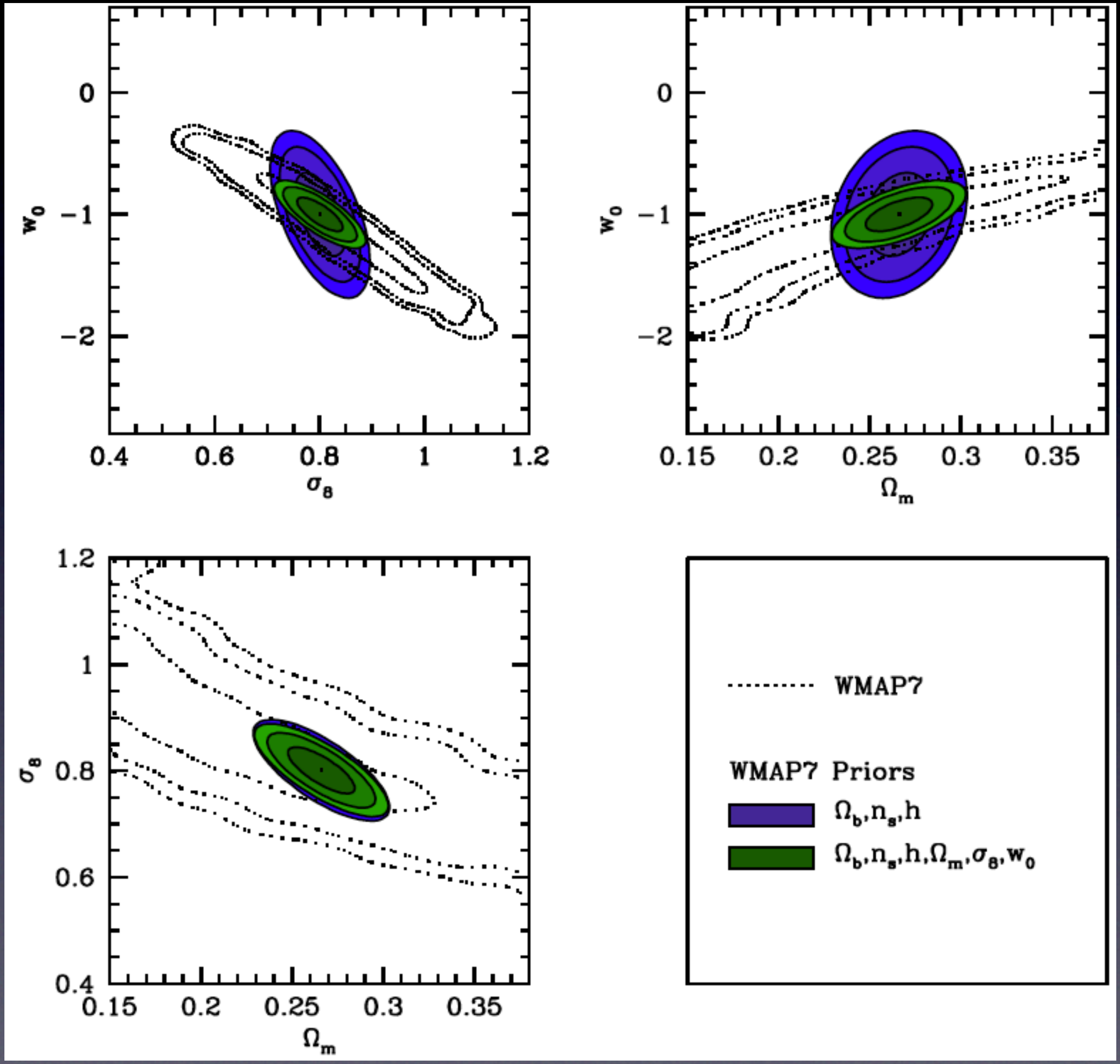


More et al. (2013)

Neutrino Mass

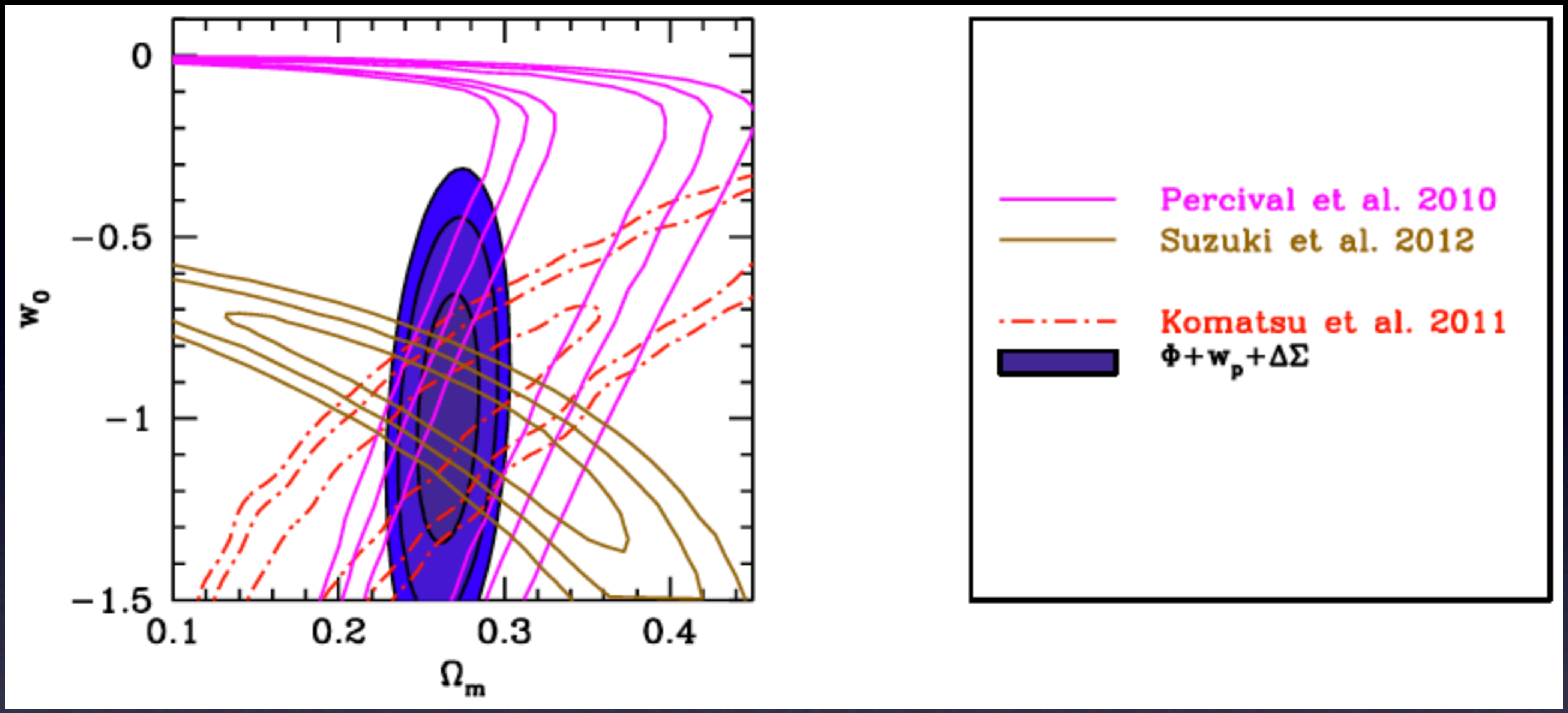


Dark Energy



0
−1
−2
w_0
0.4
0.6
0.8
1
1.2
σ_8
0
−1
−2
w_0
0.15
0.2
0.25
0.3
0.35
Ω_m
1.2
1
0.8
0.6
0.4
σ_8
0.15
0.2
0.25
0.3
0.35
Ω_m
WMAP7
WMAP7 Priors
Ω_b, n_s, h
$\Omega_b, n_s, h, \Omega_m, \sigma_8, w_0$

Dark Energy



0
−0.5
−1
−1.5
w_0
0.1
0.2
0.3
0.4
Ω_m
Percival et al. 2010
Suzuki et al. 2012
Komatsu et al. 2011
$\Phi+w_p+\Delta\Sigma$

Comparison with other methods