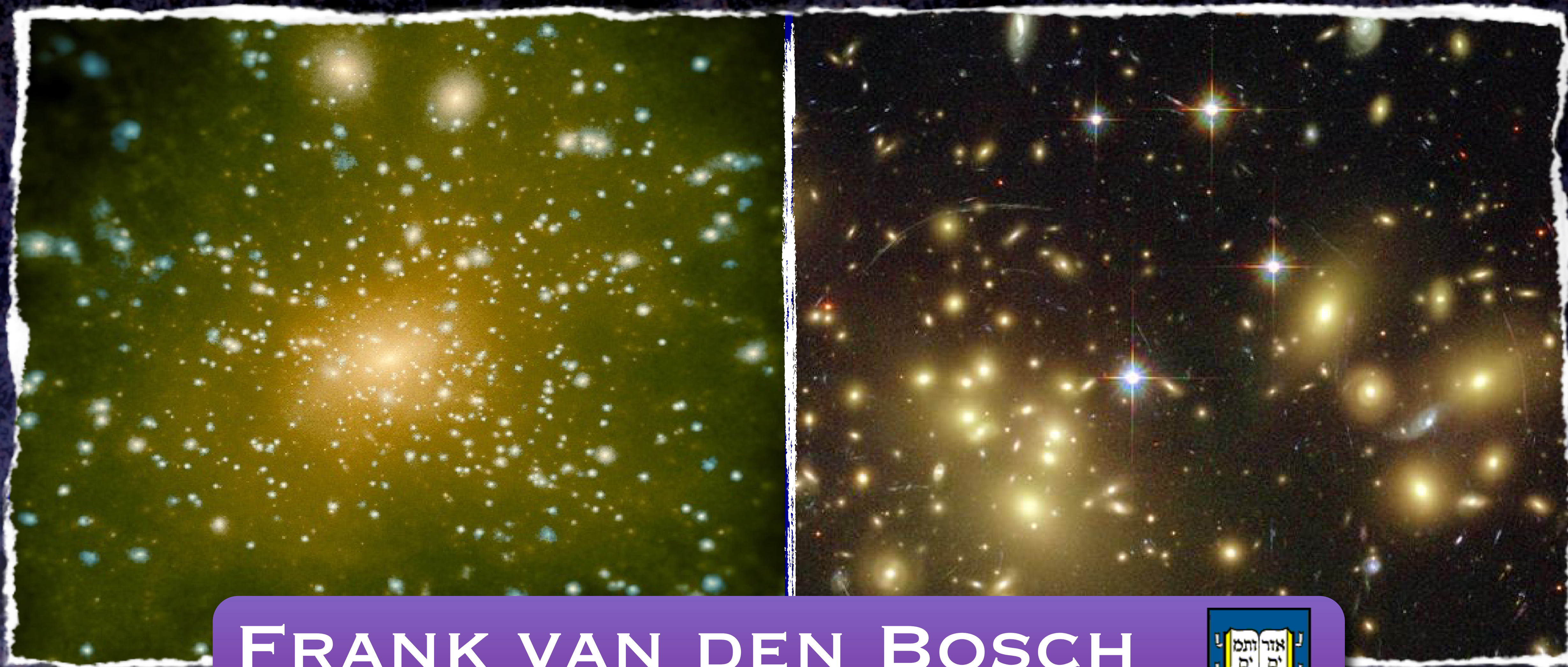
Constraining Cosmological Parameters with Galaxy Clustering and Galaxy-Galaxy Lensing



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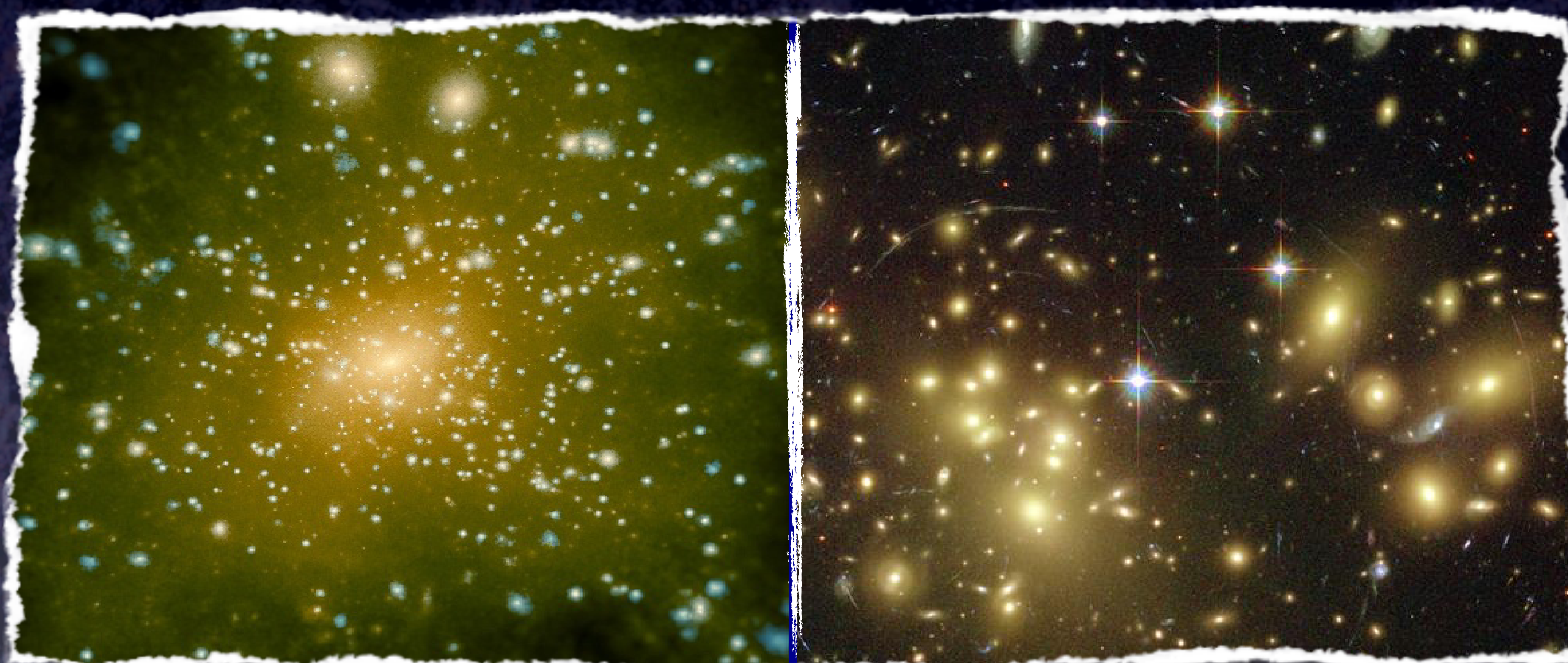
Introduction: Motivation & Goal

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



Different Methods to Constrain Galaxy-Dark Matter Connection:

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

The Halo Model

The halo model describes the dark matter density distribution in terms of its halo building blocks, under the ansatz that all dark matter is partitioned over haloes.

Its ingredients are:

- the halo mass function $n(M)$
- the halo bias function $b(M)$
- the halo density profiles $\rho(r|M) = M u(r|M)$

All of these are (reasonably) well calibrated against numerical simulations. In order to write the dark matter density field, $\rho(\vec{x})$, in terms of these ingredients, imagine that space is divided into many small volumes, ΔV_i , which are so small that none of them contain more than one halo center. Then,

$$\rho(\vec{x}) = \sum_i \mathcal{N}_{\mathrm{h},i} M_i u(\vec{x} - \vec{x}_i | M_i)$$

where $\mathcal{N}_{\mathrm{h},i}$ is the occupation number of volume ΔV_i. Note that $\mathcal{N}_{\mathrm{h},i} = \mathcal{N}_{\mathrm{h},i}^2 =$0 or 1

The Halo Model

$$\rho(\vec{x}) = \sum_i \mathcal{N}_{\mathrm{h},i} M_i u(\vec{x} - \vec{x}_i | M_i)$$

The ensemble average of the density at location $\vec{x}$ can be written as

$$\begin{aligned}
\langle \rho(\vec{x}) \rangle &= \sum_i \langle \mathcal{N}_{\mathrm{h},i} M_i u(\vec{x} - \vec{x}_i | M_i) \rangle \\
&= \sum_i \int \mathrm{d}M \, M \, n(M) \, \Delta V_i \, u(\vec{x} - \vec{x}_i | M) \\
&= \int \mathrm{d}M \, M \, n(M) \int \mathrm{d}^3\vec{x}' \, u(\vec{x} - \vec{x}' | M) = \bar{\rho}
\end{aligned}$$

Using the same methodology, we can work out the 2-point correlation function:

$$\xi(r) \equiv \langle \delta(\vec{x}) \, \delta(\vec{x} + \vec{r}) \rangle = \langle \rho(\vec{x}) \, \rho(\vec{x} + \vec{r}) \rangle - 1$$

where $\delta(\vec{x})$ is the matter overdensity field $\delta(\vec{x}) = \dfrac{\rho(\vec{x})}{\bar{\rho}} - 1$

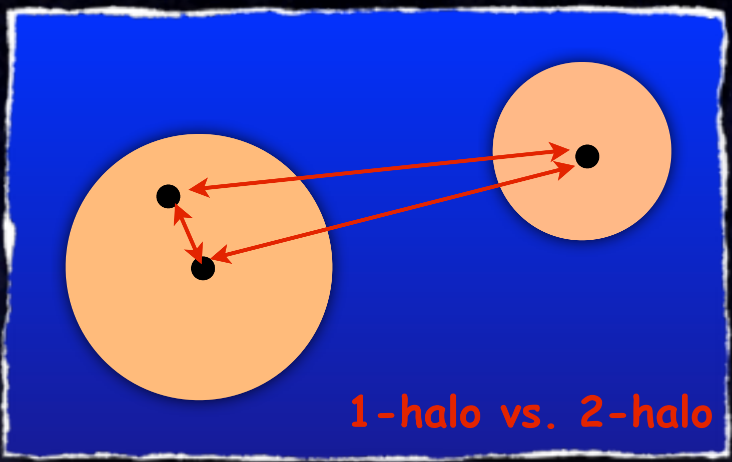
The Halo Model

becomes convolution in real-space

$$1+\xi(r) = \sum_i \sum_j \langle \mathcal{N}_{\mathrm{h},i} \mathcal{N}_{\mathrm{h},j} M_i\, M_j\, u(\vec{x}-\vec{x}_i|M_i)\, u(\vec{x}-\vec{x}_j|M_j)\, \rangle$$

One typically splits this summation in two parts:

- the 1-halo term for which $i=j$
- the 2-halo term for which $i \neq j$



Because of the convolution of the halo profiles, it is advantageous to work in Fourier space; rather than correlation function, $\xi(r)$, we compute the power spectrum, $P(k)$

$$\delta(\vec{x}) \rightarrow \delta(\vec{k}) = \frac{1}{V}\int \delta(\vec{x}) \mathrm{e}^{-i\vec{k}\cdot\vec{x}}\, \mathrm{d}^3\vec{x} = \frac{1}{V}\sum_i \mathcal{N}_{\mathrm{h},i}\, M_i\, \tilde{u}(k|M)\, \mathrm{e}^{-i\vec{k}\cdot\vec{x}}$$

where $\tilde{u}(\vec{k}|M) = \int u(\vec{x}|M)\, \mathrm{e}^{-i\vec{k}\cdot\vec{x}}\, \mathrm{d}^3\vec{x}$ is the FT of the halo density profile

The Halo Model

For the 1-halo term one obtains

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

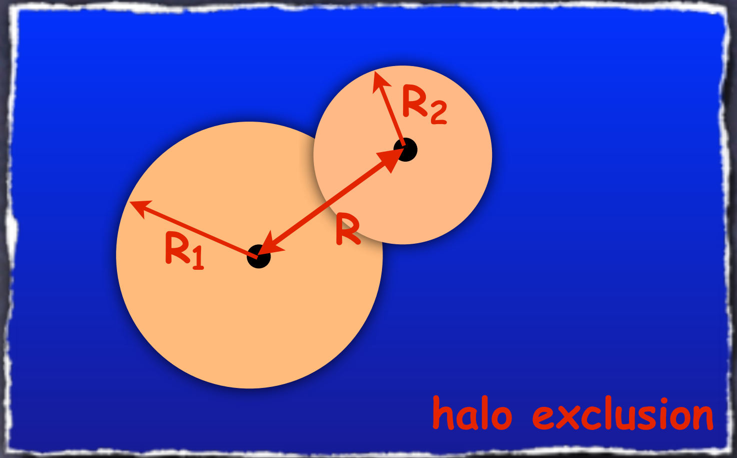
For the 2-halo term one obtains

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

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

describes the fact that dark matter haloes are clustered, as described by the halo-halo correlation function, $\xi_{\rm hh}(r|M_1, M_2)$.

Note that the integration limit $r_{\rm min}$ takes account of halo exclusion: there are no halo pairs with separation $r < r_{\rm min} = r_1(M_1) + r_2(M_2)$



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

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

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

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

The Halo-Halo Correlation Function

For the halo-halo correlation function one can write

$$\xi_{\rm hh}(r|M_1, M_2) = \begin{cases} b(M_1)\, b(M_2)\, \zeta(r)\, \xi_{\rm mm}(r) & r \geq r_{\rm min} \\ -1 & r < r_{\rm min} \end{cases}$$

Here $b(M)$ is the (linear) bias for haloes of mass M, and $\zeta(r)$ is the `radial bias factor' which descibes the deviation from the linear bias model in the quasi-linear regime.

Under the assumption of `deterministic biasing', one can write that

$$\delta_{\rm h}(\vec{x}|M) = \delta_{\rm h}(\delta_{\rm m}) = \sum_{n=1}^{\infty} \frac{b_n(M)}{n!} \delta_{\rm m}^n(\vec{x})$$

Fry & Gaztanaga (1993)

In the linear regime, $\delta_{\rm m} \ll 1$, one has that $\delta_{\rm h} = b_1(M)\delta_{\rm m}$, where $b_1(M) = b(M)$

The radial bias, $\zeta(r)$, captures the higher order moments. Attempts to compute $\zeta(r)$ from first principles have thus far proven insufficiently accurate. We use the `fitting function' of Tinker et al (2005), which is calibrated against numerical simulations: this is the main source of systematic error in our models (~10%)!

The Halo-Halo Correlation Function

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$$\xi_{\rm hh}(r|M_1,M_2) = \begin{cases} b(M_1)\, b(M_2)\, \zeta(r)\, \xi_{\rm mm}(r) & r \geq r_{\rm min} \\ -1 & r < r_{\rm min} \end{cases}$$

Here $b(M)$ is the (linear) bias for haloes of mass M, and $\zeta(r)$ is the `radial bias factor' which descibes the deviation from the linear bias model in the quasi-linear regime.

Under the assumption that $\zeta(r) = 1$, and ignoring halo exclusion, one has that

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

simplifies to

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

This is the approach most often adopted in the literature, but its accuracy is poor (<30%) in the 1-halo/2-halo transition regime (0.5 - 2 Mpc/h)!!

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.

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

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

$$\langle N \rangle_M = \int_{L_{\rm min}}^{\infty} \Phi(L|M) \mathrm{d}L$$

Galaxy luminosity function ($\Phi(L)$)

Halo mass function ($n(M)$)

- Describes occupation statistics of dark matter haloes
- Is direct link between galaxy luminosity function and halo mass function
- Contains 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:

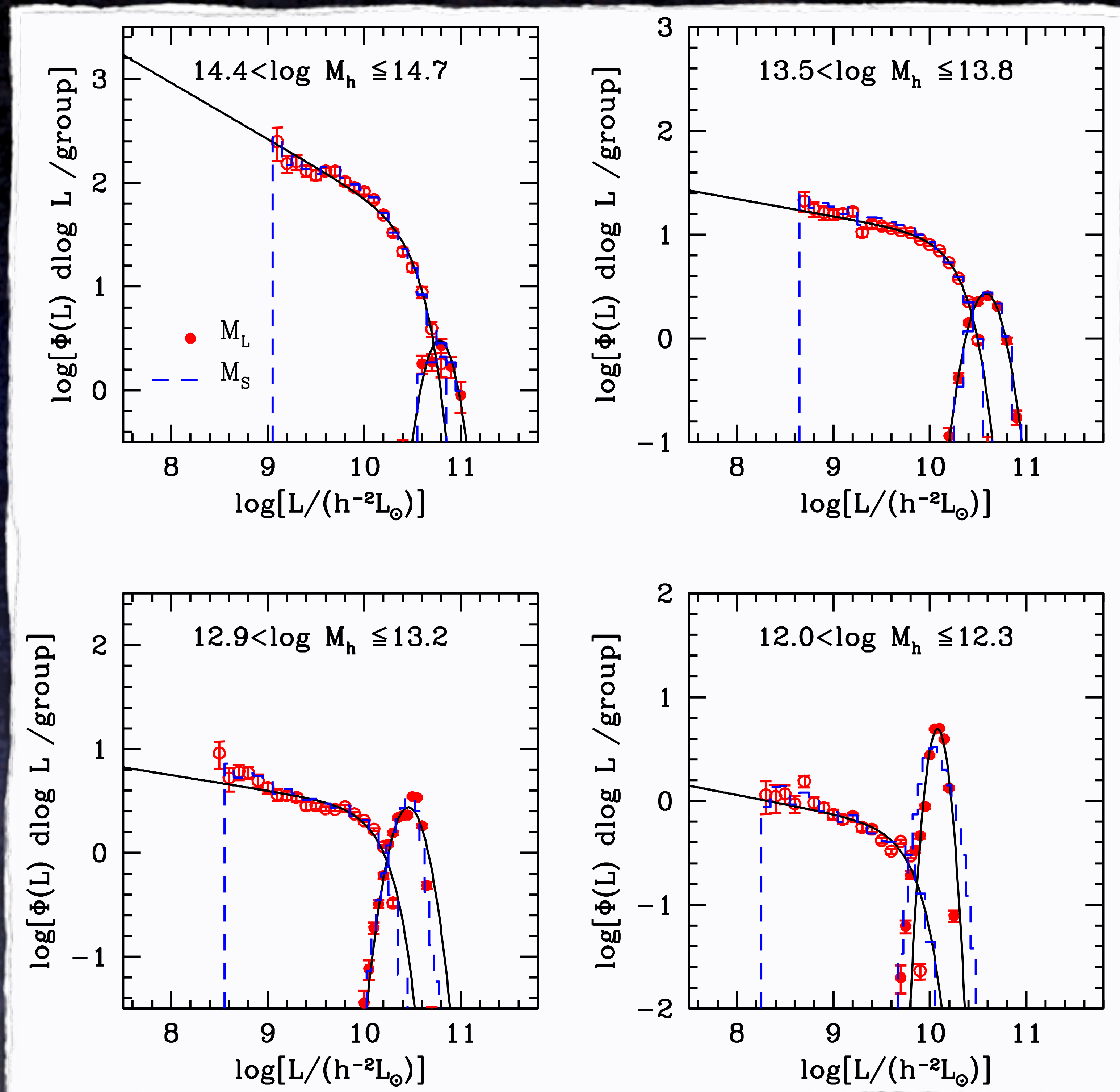
$$\Phi_{\rm s}(L|M){\rm d}L = \frac{\phi_{\rm s}}{L_{\rm s}}\left(\frac{L}{L_{\rm s}}\right)^{\alpha_{\rm s}} \exp\left[-(L/L_{\rm s})^2\right]{\rm d}L$$

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.

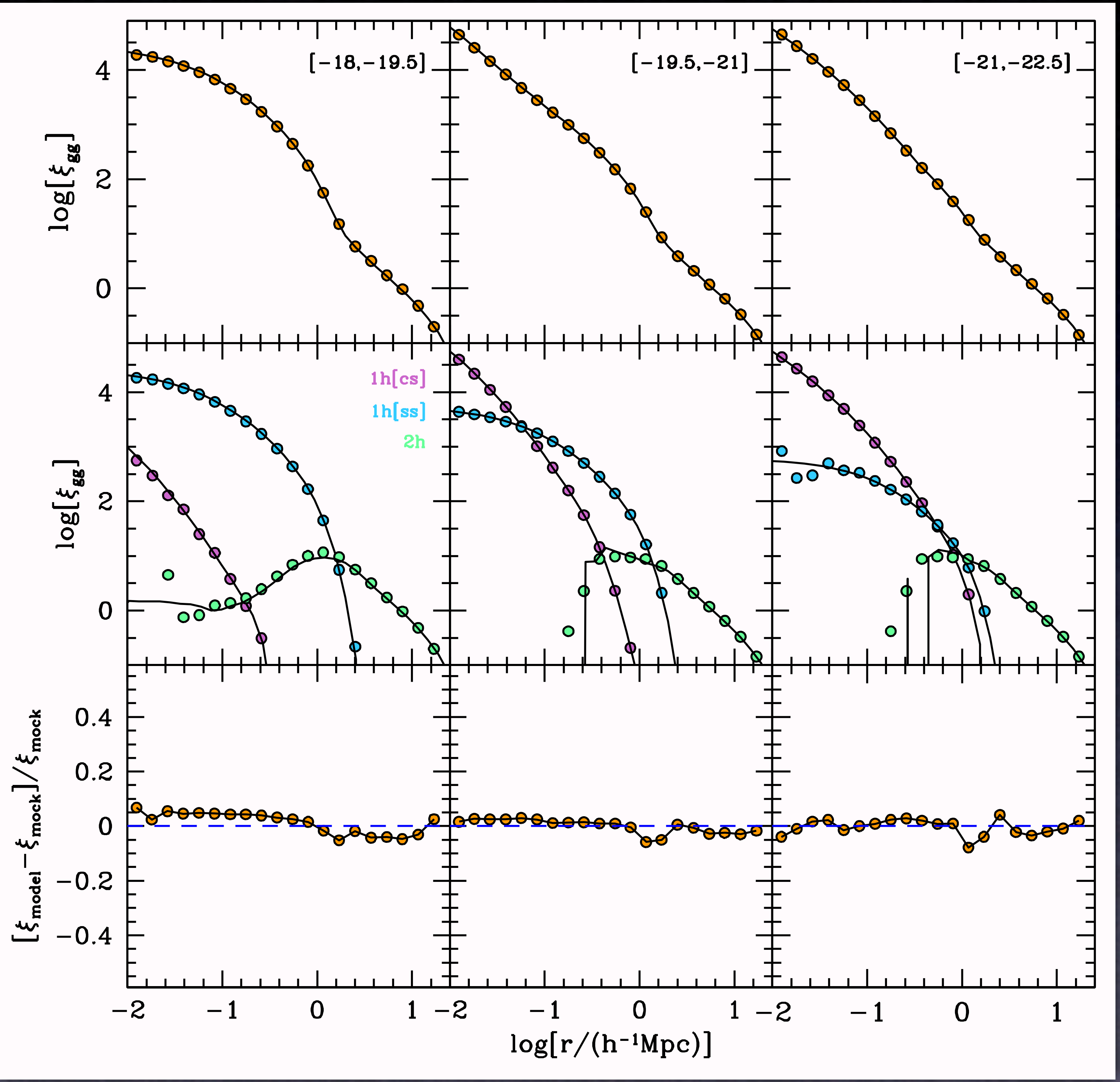
Use Monte-Carlo Markov Chain to sample posterior distributions of free parameters, and to put confidence levels on derived quantities

CLF Constraints from Group Catalogue



Yang, Mo & vdB (2008)

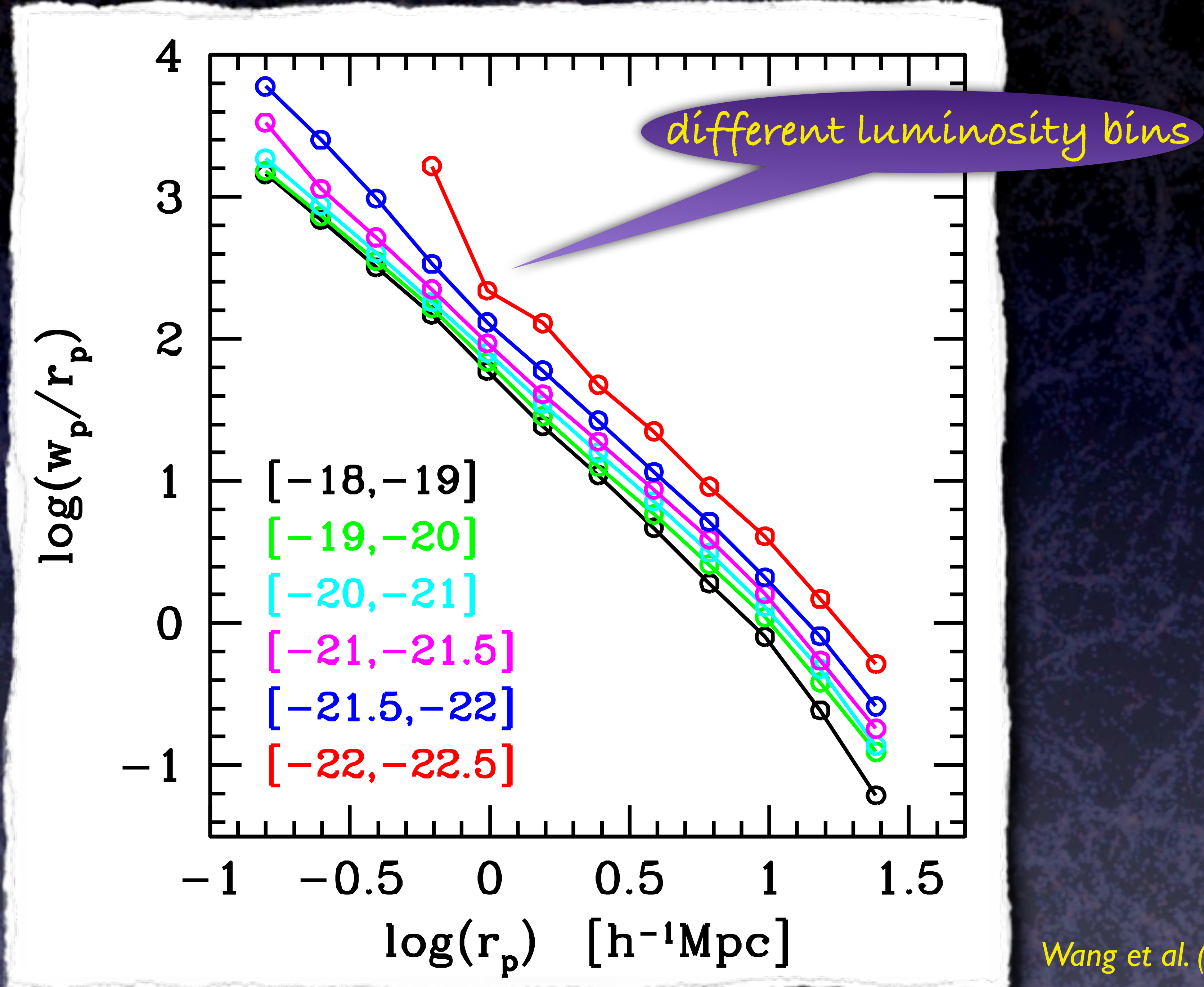
Comparison with Mock Catalogues



- 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 at the 5-10% level

Large Scale Structure: The Data

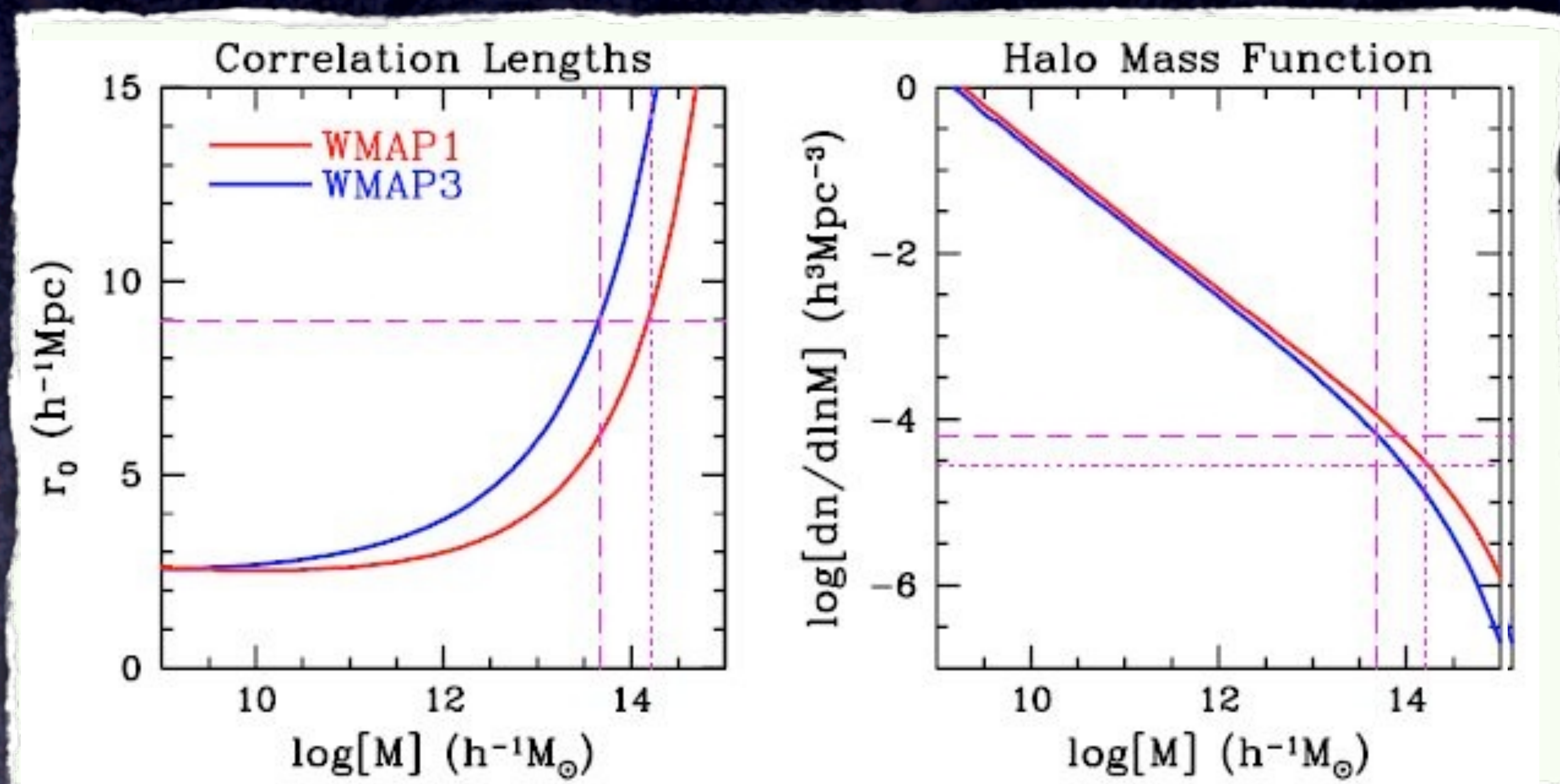


Wang et al. (2007)

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



WMAP1

$\Omega_m = 0.30$

$\Omega_\Lambda = 0.70$

$\sigma_8 = 0.90$

WMAP3

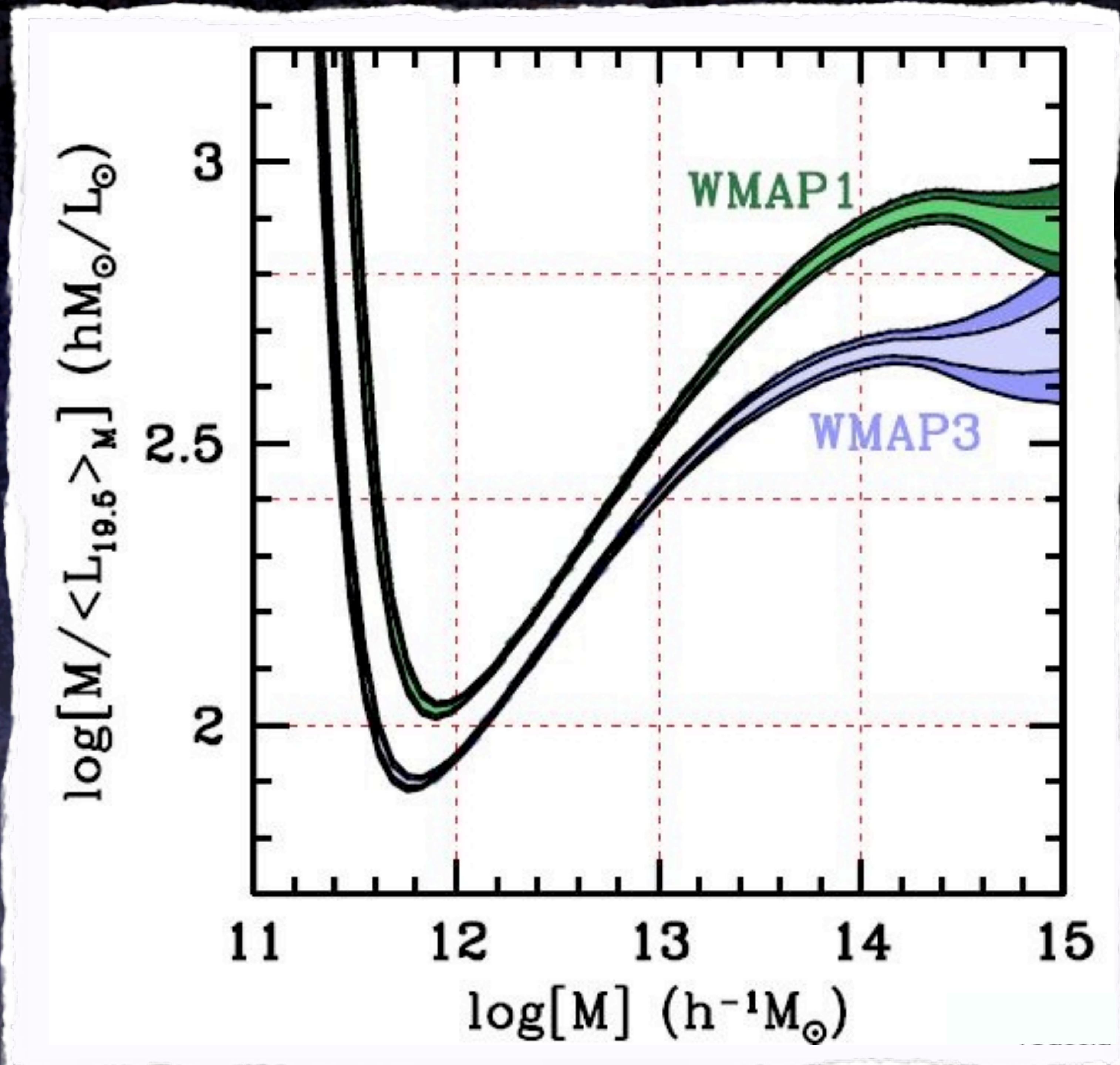
$\Omega_m = 0.24$

$\Omega_\Lambda = 0.76$

$\sigma_8 = 0.74$

...but, results depend strongly on cosmology.

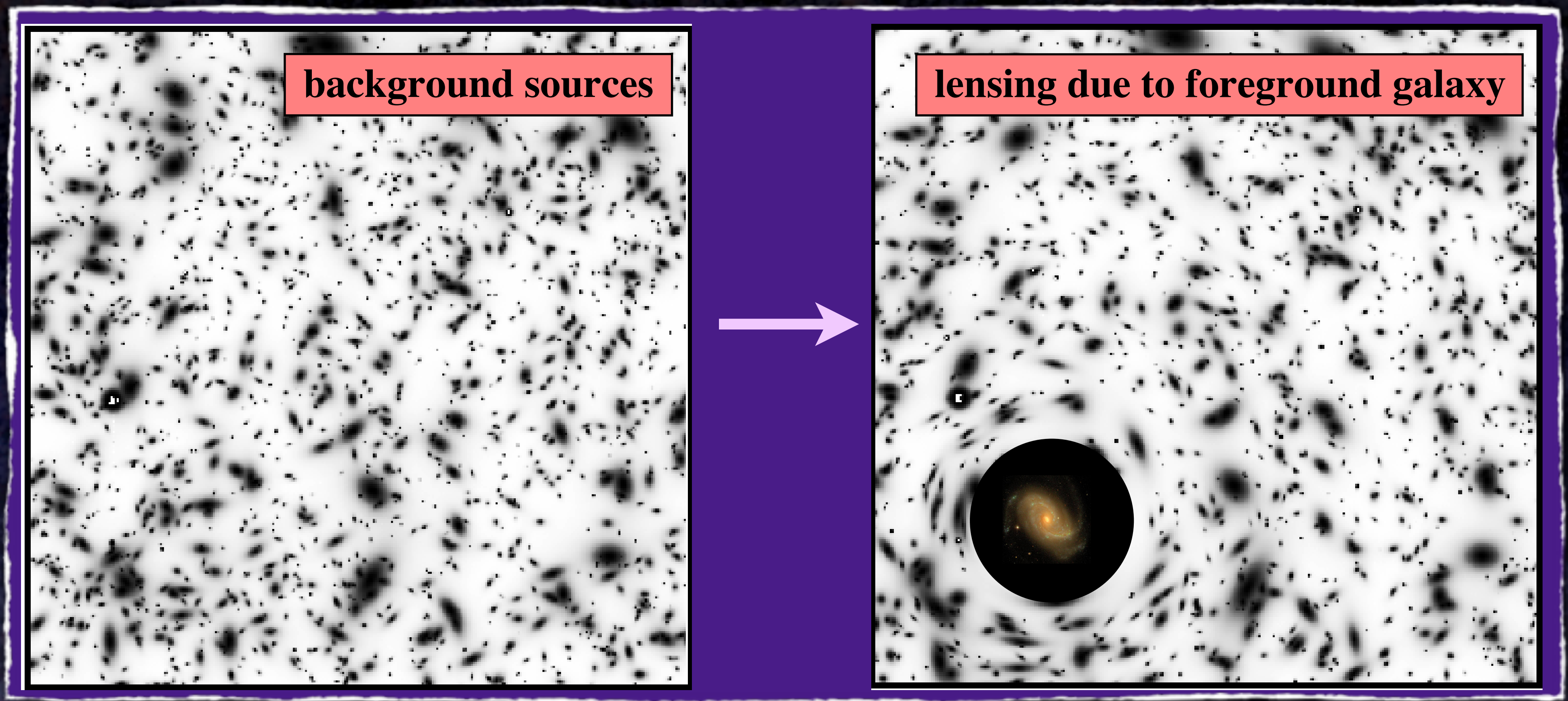
Cosmology Dependence



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

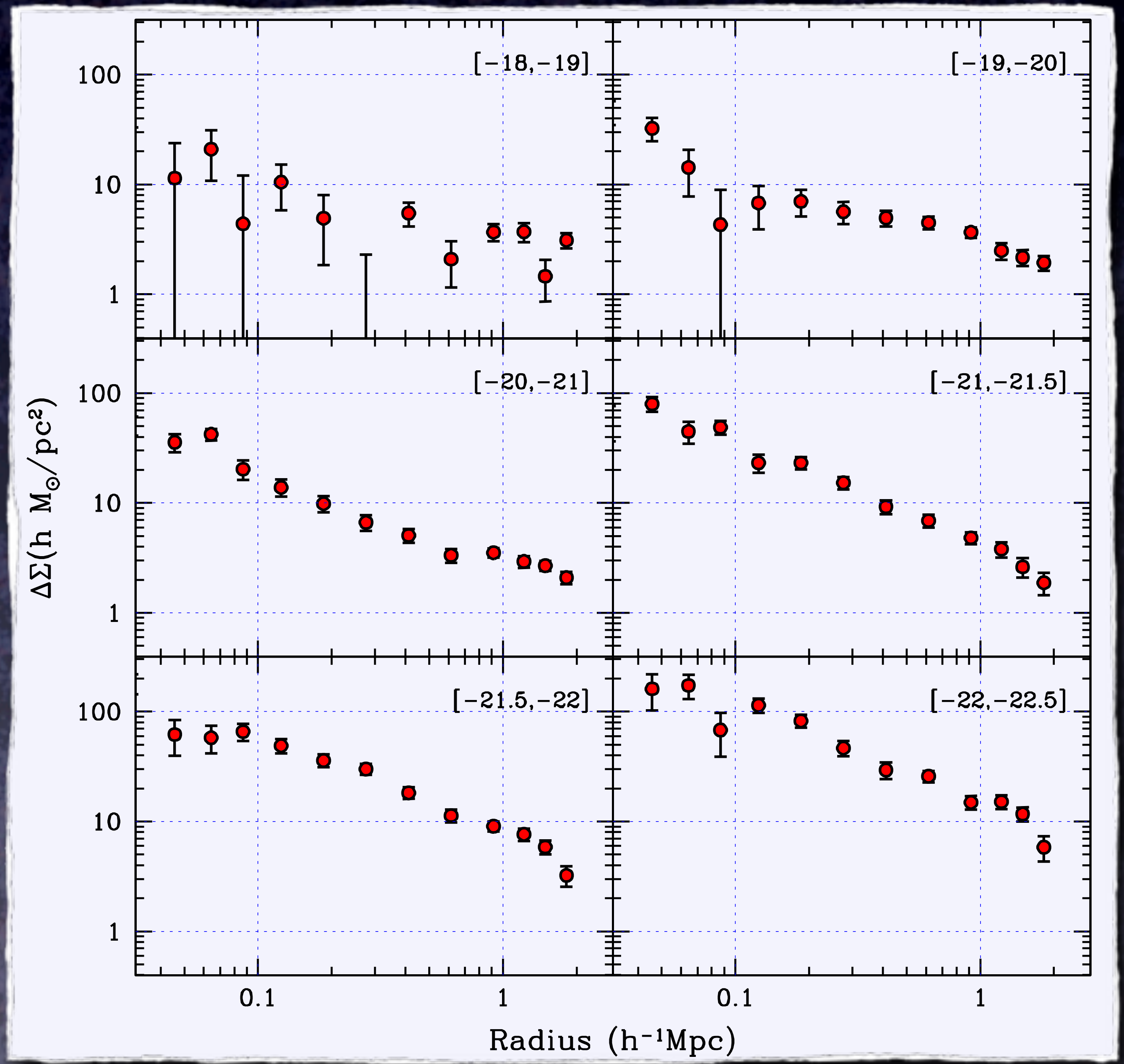
$$\gamma_{\rm t}(R)\Sigma_{\rm crit} = \Delta\Sigma(R) = \bar{\Sigma}(< R) - \Sigma(R)$$

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

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

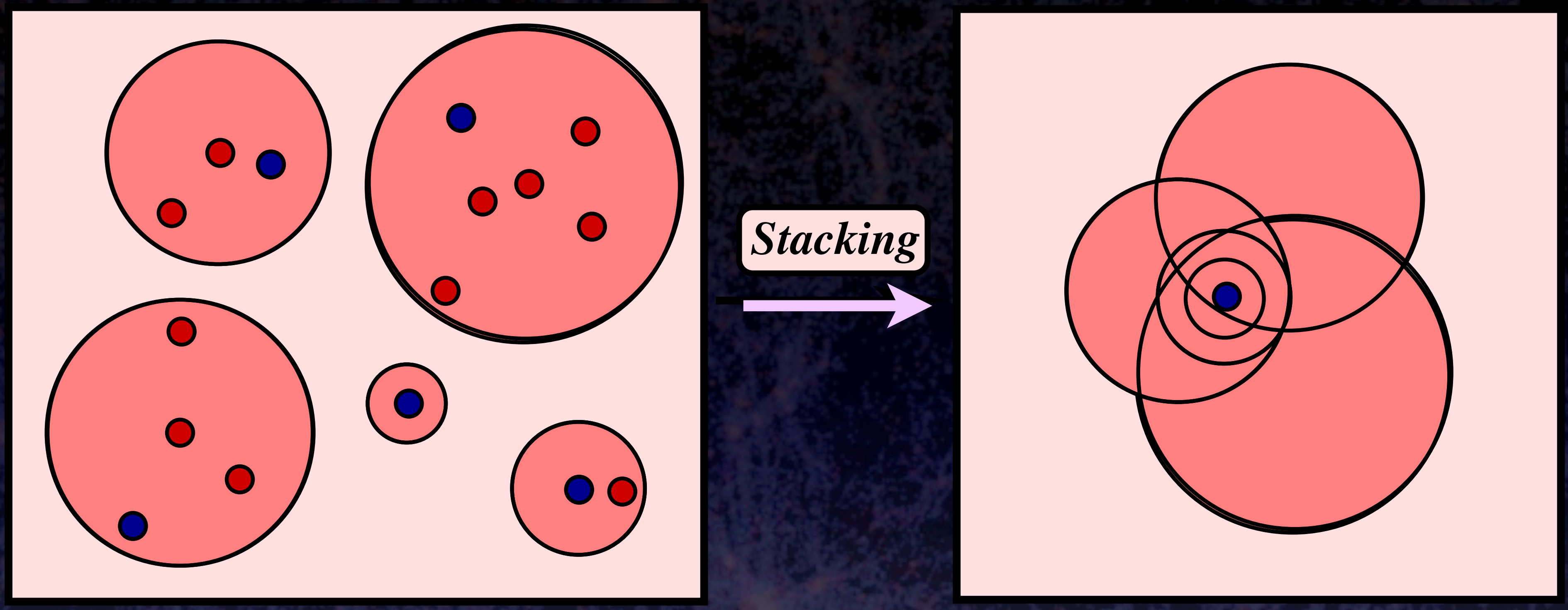
Galaxy-Galaxy Lensing: The Data

- 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:

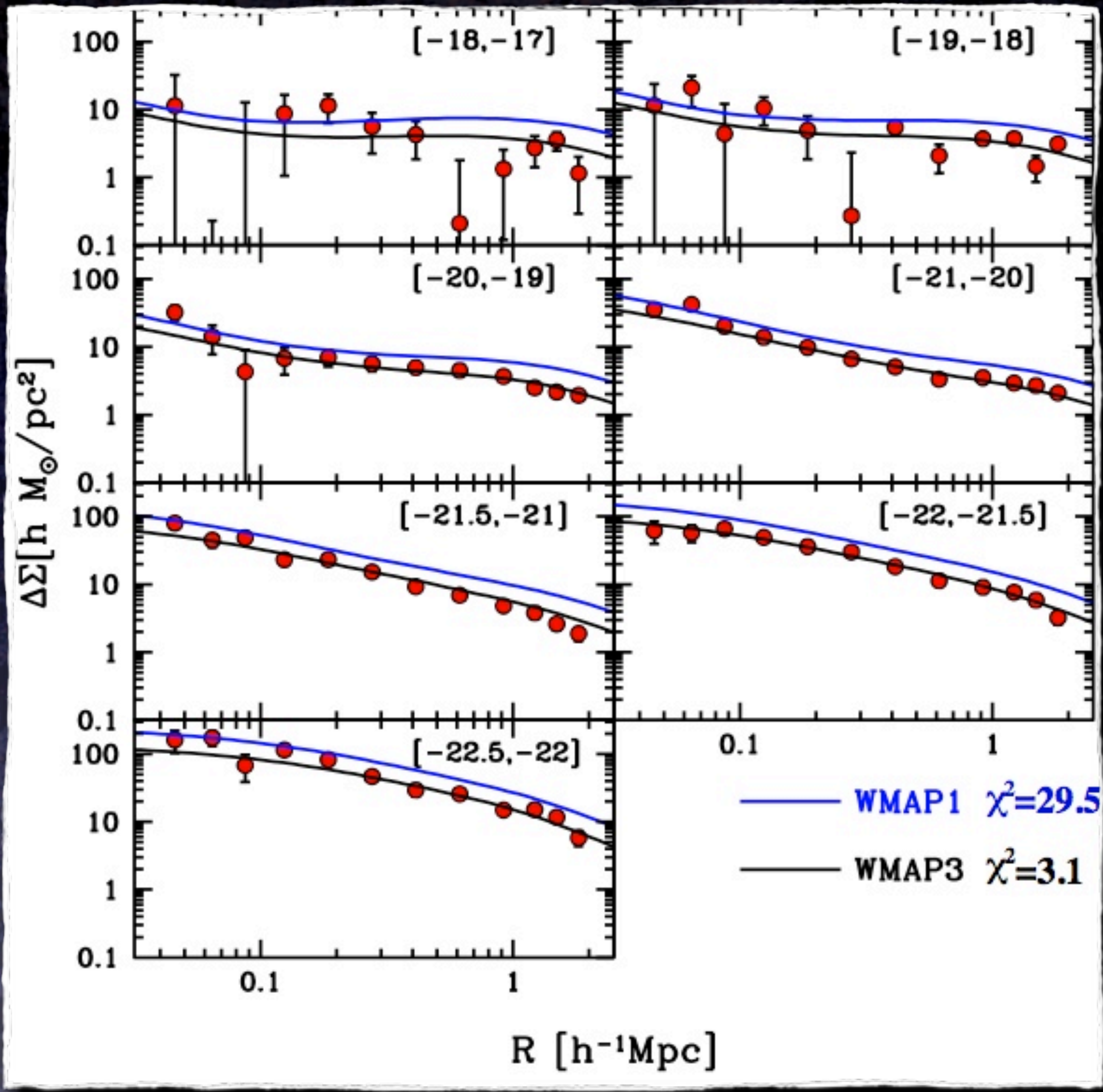
$P_{\rm cen}(M|L)$ $P_{\rm sat}(M|L)$ $f_{\rm sat}(L)$

These can all be computed from the CLF...

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

Combination of $w_{\rm p}(r_{\rm p})$ and $\Delta\Sigma(R|L_1, L_2)$ can constrain cosmology!

Galaxy-Galaxy Lensing: Results



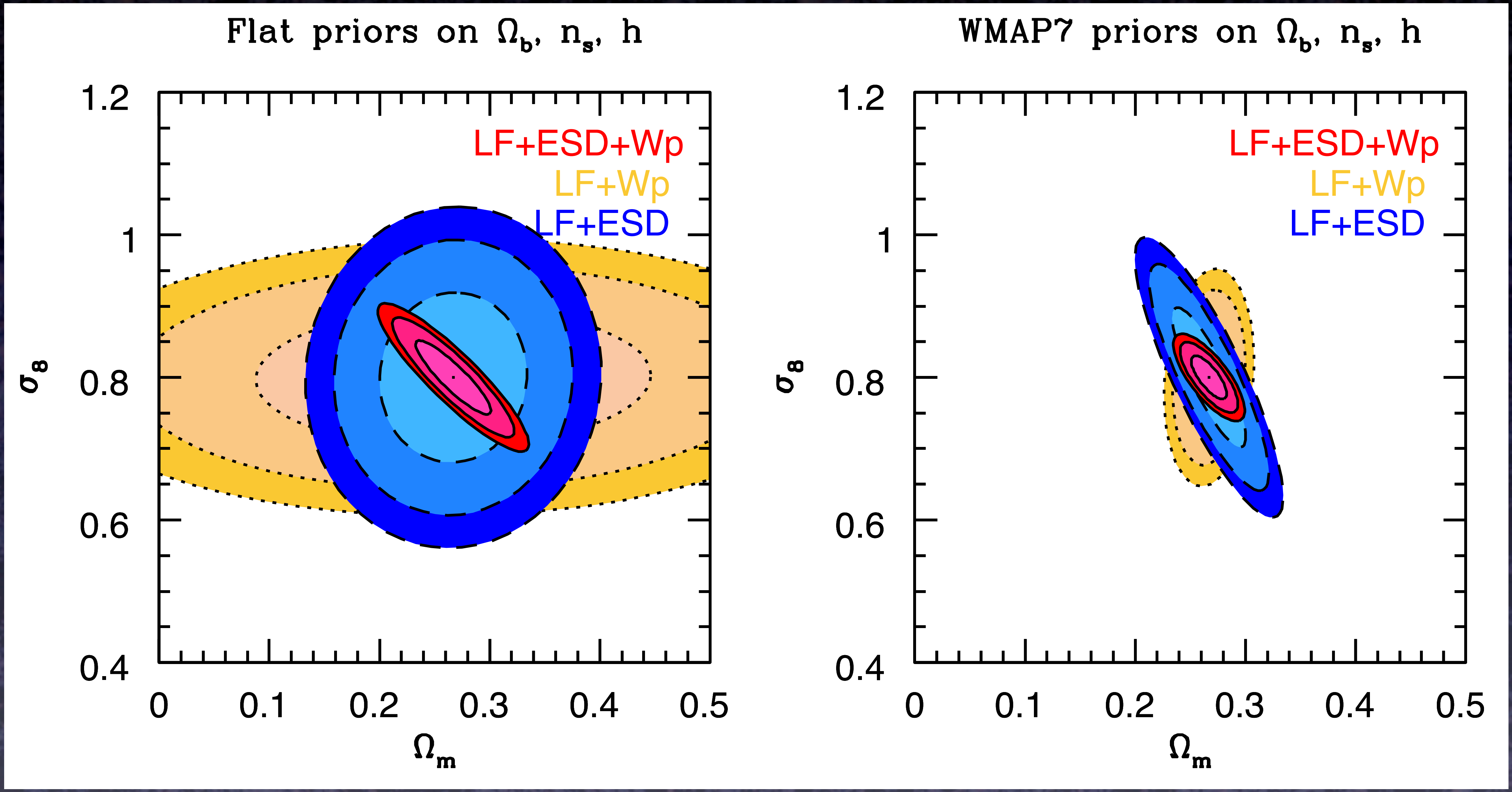
Combination of clustering & lensing can constrain cosmology!!!

Fiducial Model

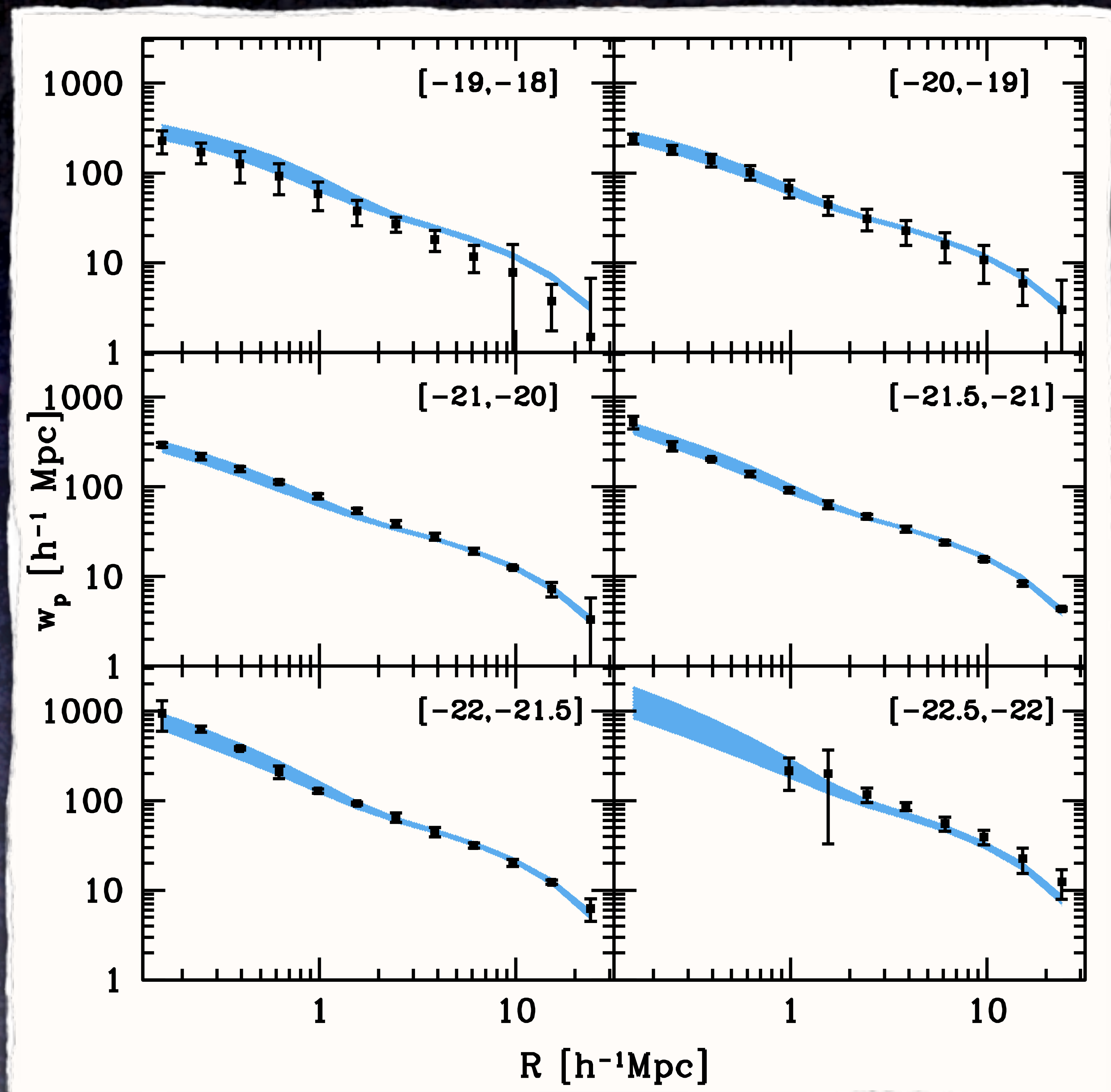
- Total of 13 free parameters:
  - 11 parameters to describe CLF
  - 2 cosmological parameters; $\Omega_{\rm m}$ and σ_8

  Total of 172 data points.
- We use WMAP7 priors on h, $\Omega_{\rm b}$ and $n_{\rm s}$, including their covariance.
- Dark matter haloes follow NFW profile.
- Radial number density distribution of satellites follows that of dark matter particles.
- Halo mass function and halo bias function and radial bias function of Tinker (2008, 2010)

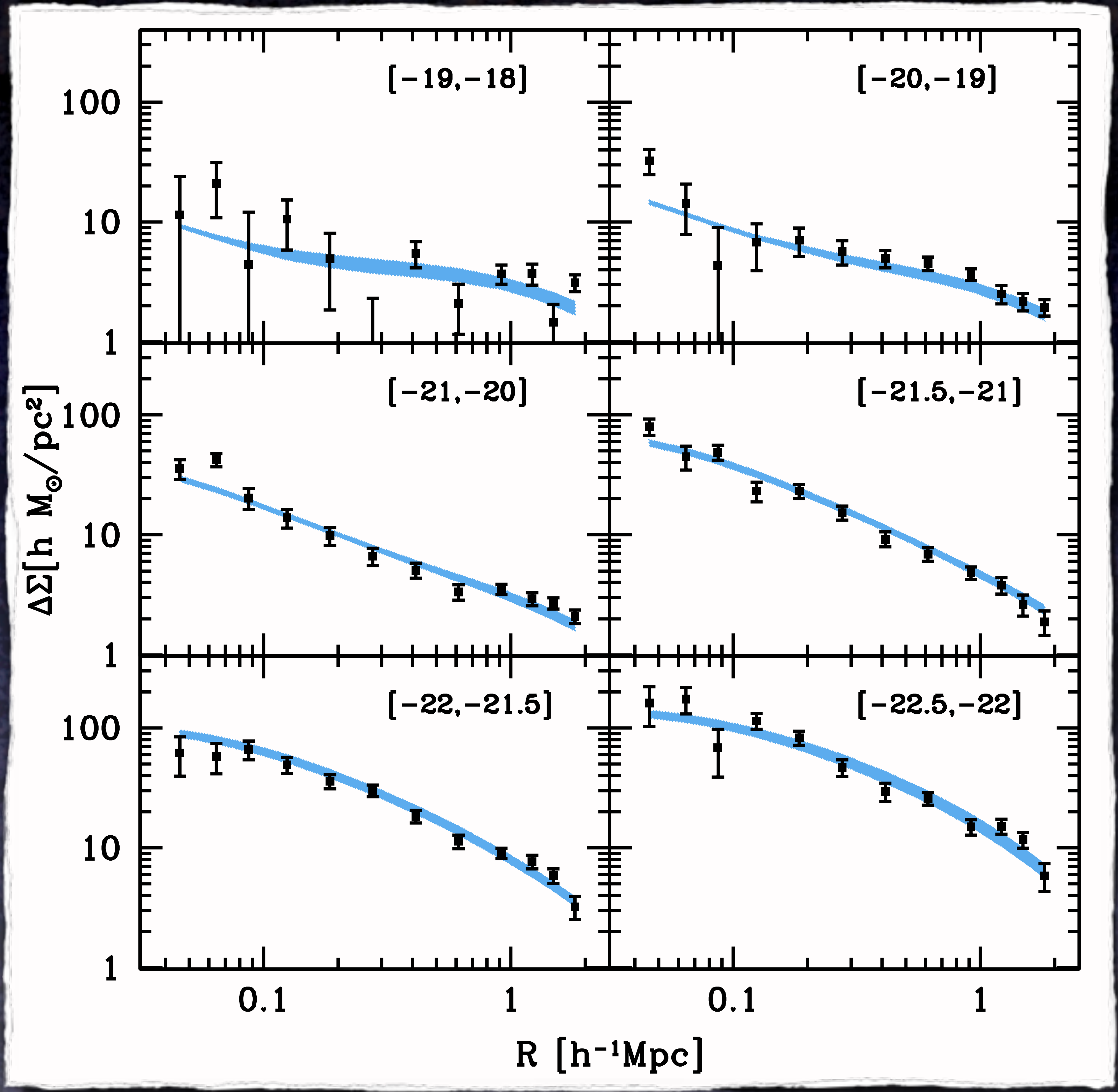
Fisher Forecasting



Results: Clustering Data

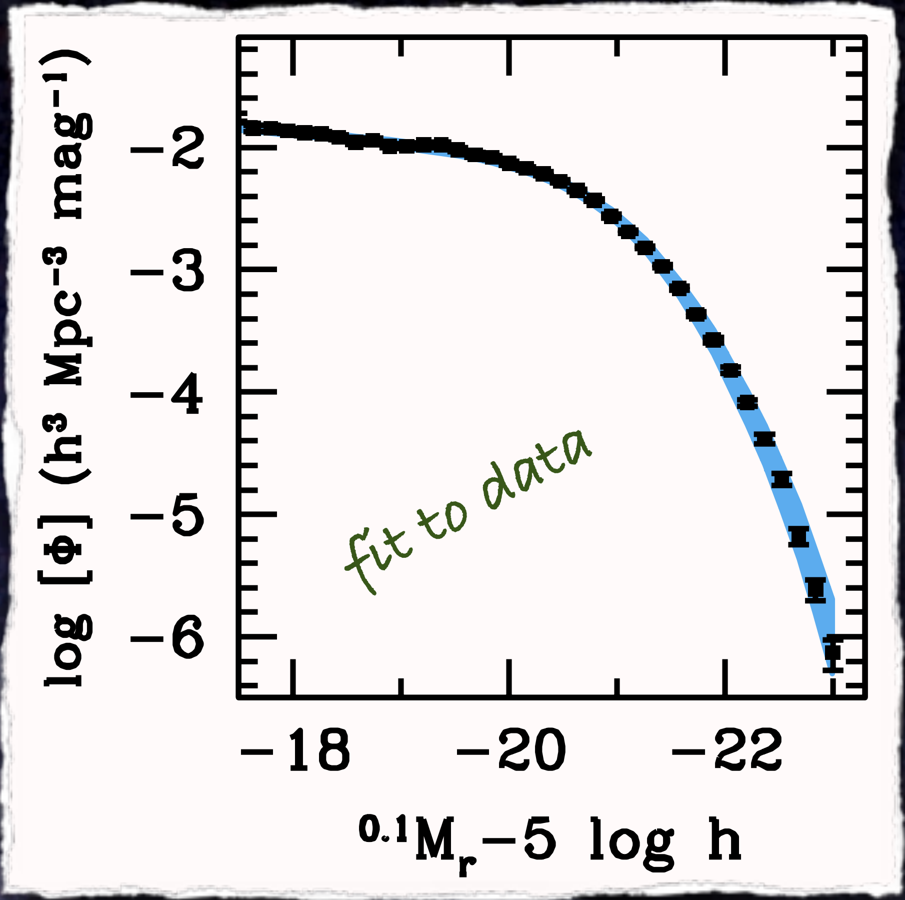


Results: Lensing Data

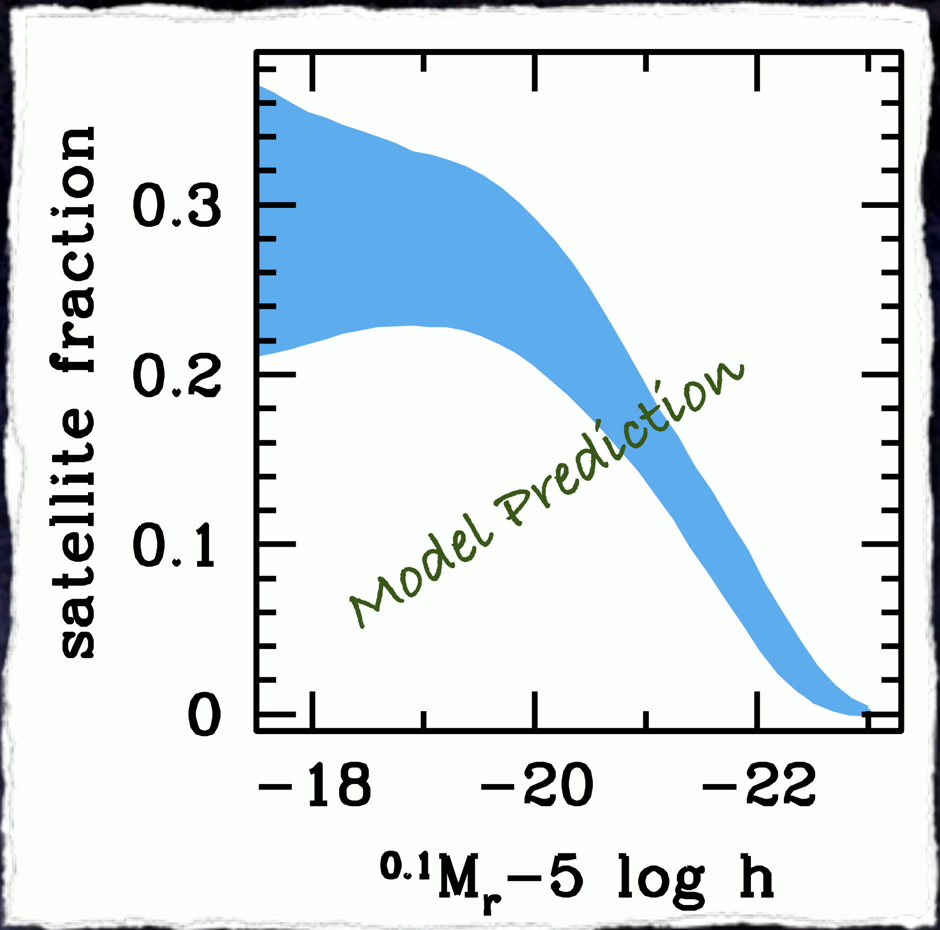


Luminosity Function & Satellite Fractions

Luminosity Function

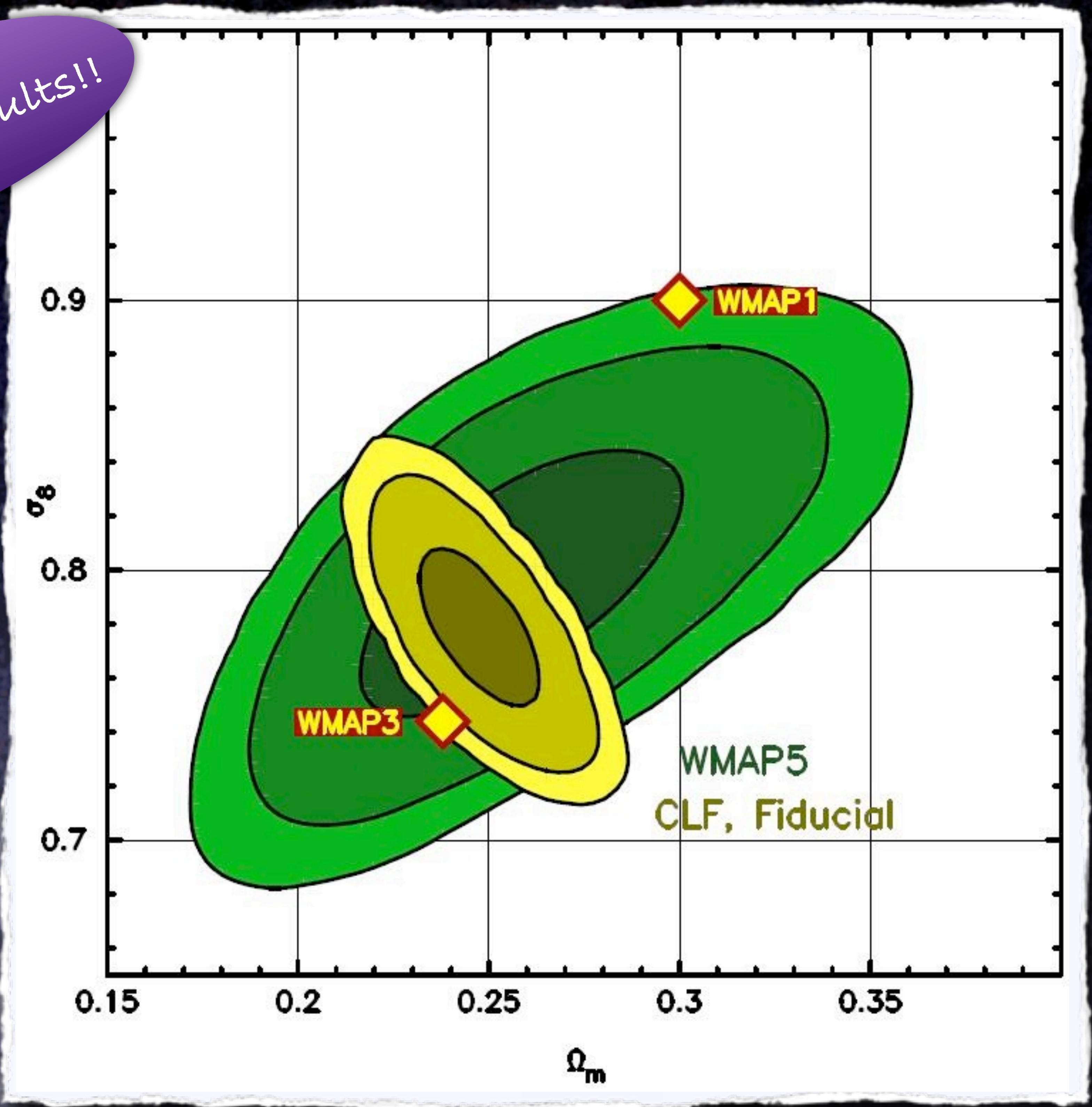


Satellite Fractions



Cosmological Constraints

WARNING: preliminary results!!



Conclusions

- Conditional Luminosity Function (CLF) is powerful statistic to describe galaxy-dark matter connection.
- 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.
- Main systematic uncertainties (~10%) related to radial bias, redshift space distortions and halo bias.
- Preliminary results are in excellent agreement with CMB constraints from WMAP5