Galaxy-dark matter halo connections and the assembly of galaxies: I

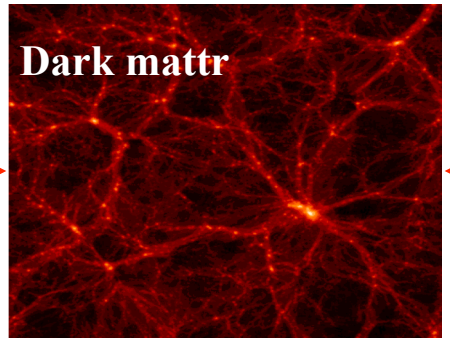
Xiaohu Yang

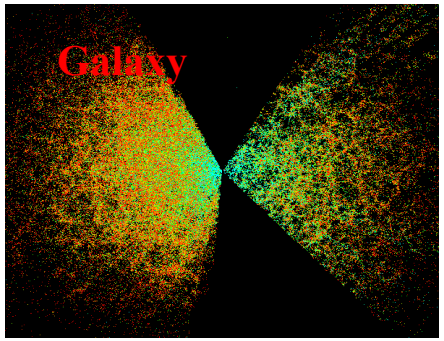
Shanghai Astronomical Observatory

Santa Fe 2012/07/02

Overview of Galaxy Formation in ΛCDM

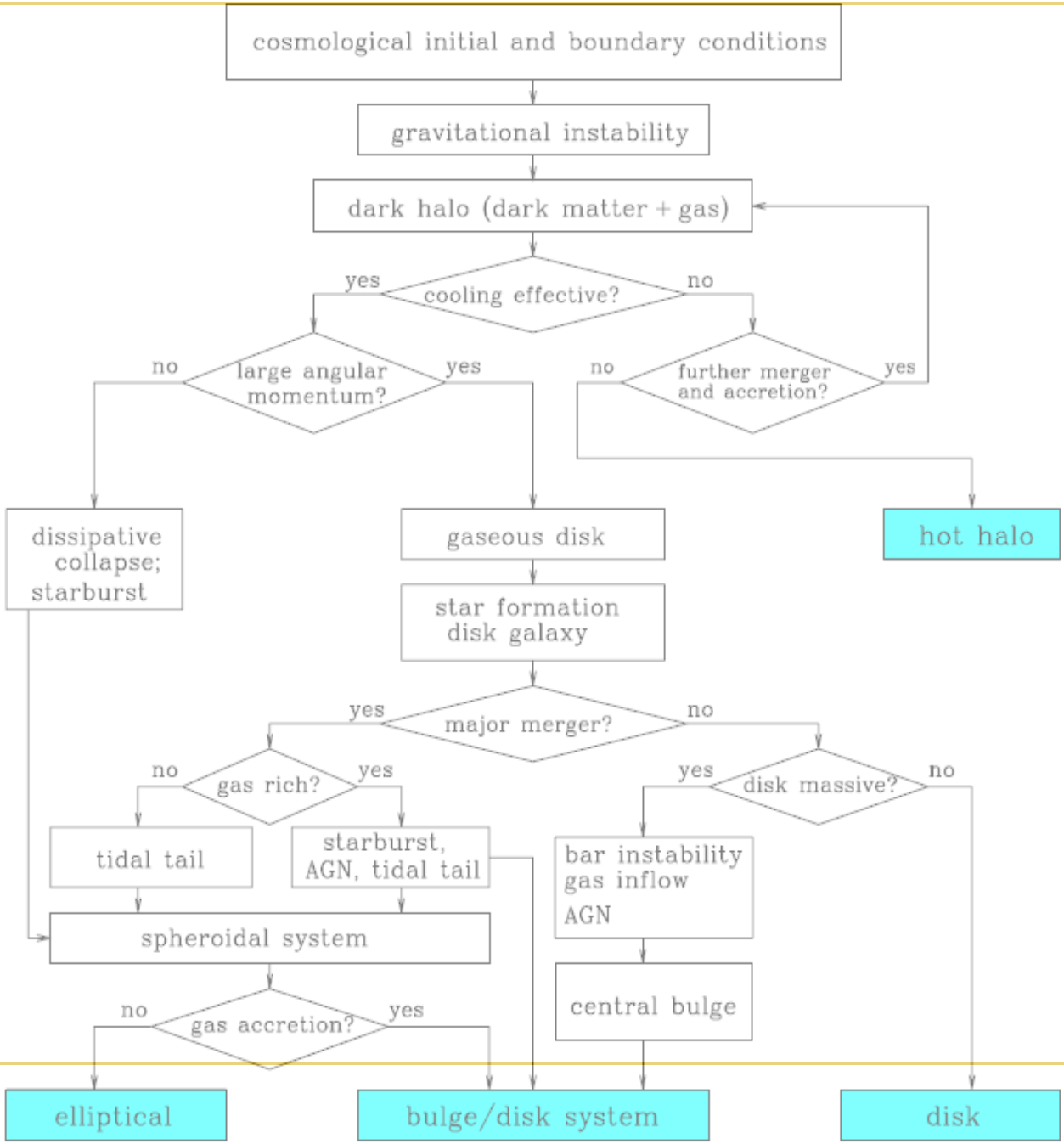
Cosmology：
dark matter: Ω_{dm}
baryons： Ω_b
dark energy： Ω_Λ
Initial： σ_8





- **We live in a *ΛCDM* Universe**
  - ***Ω_0~1, $\Omega_{m,0}$~0.25, $\Omega_{B,0}$~0.025h^{-2}, h~0.7 & σ_8~0.85*** ***(e.g. Spergel et al. 2007)***
- **Galaxies are formed via a two-stage process *(e.g. White & Rees 1978)***
  - ***The first stage of this process is the formation and virialization of dark matter halos:*** *been studied in great detail using the (extended) Press-Schechter formalism (e.g., Press & Schechter 1974), spherical and ellipsoidal collapse (e.g., Sheth, Mo & Tormen 2001) and, most importantly, numerical simulations.*
  - ***The second stage of this process is baryonic cooling and the formation of stars within these dark matter halos:*** *the details are significantly more complex than for halo formation because they rely on the full range of baryonic physical processes (e.g. cooling, star-formation, feedback) in addition to gravity.* ***----still faces several outstanding problems (see Mo et al. 2010 for an up-to-date review)***

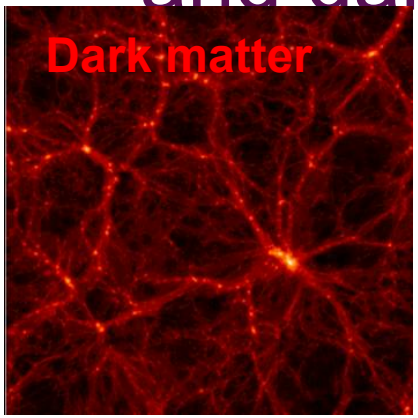
Flowchart of galaxy formation (Mo et al. 2010)

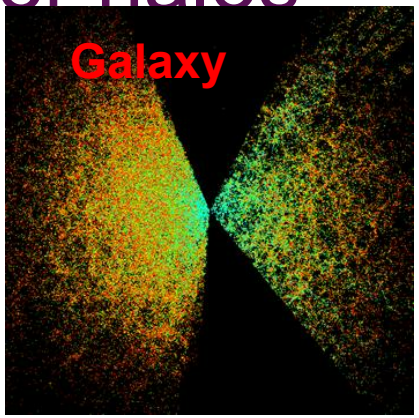


Connecting Galaxies with dark matter halos

- **In general, galaxy formation can be studied using SPH simulations or SAM:**
  - **ASSUME complicated physical processes: gas cooling; star formation; feedbacks by SN, AGN etc.**
- **Or, to build the reliable connections between the galaxies and dark matter halos**
  - **How many galaxies are formed per halo?**
  - **And what is their spatial distribution? (HOD)**
  - **What luminosity does each galaxy have? Color? (CLF)**
  - **Evolution?**
- **The reliable link between galaxies and dark matter halos**
  - **To constrain the galaxy formation processes**
  - **To cosmological parameters**

Establish the reliable links between galaxies and dark matter halos

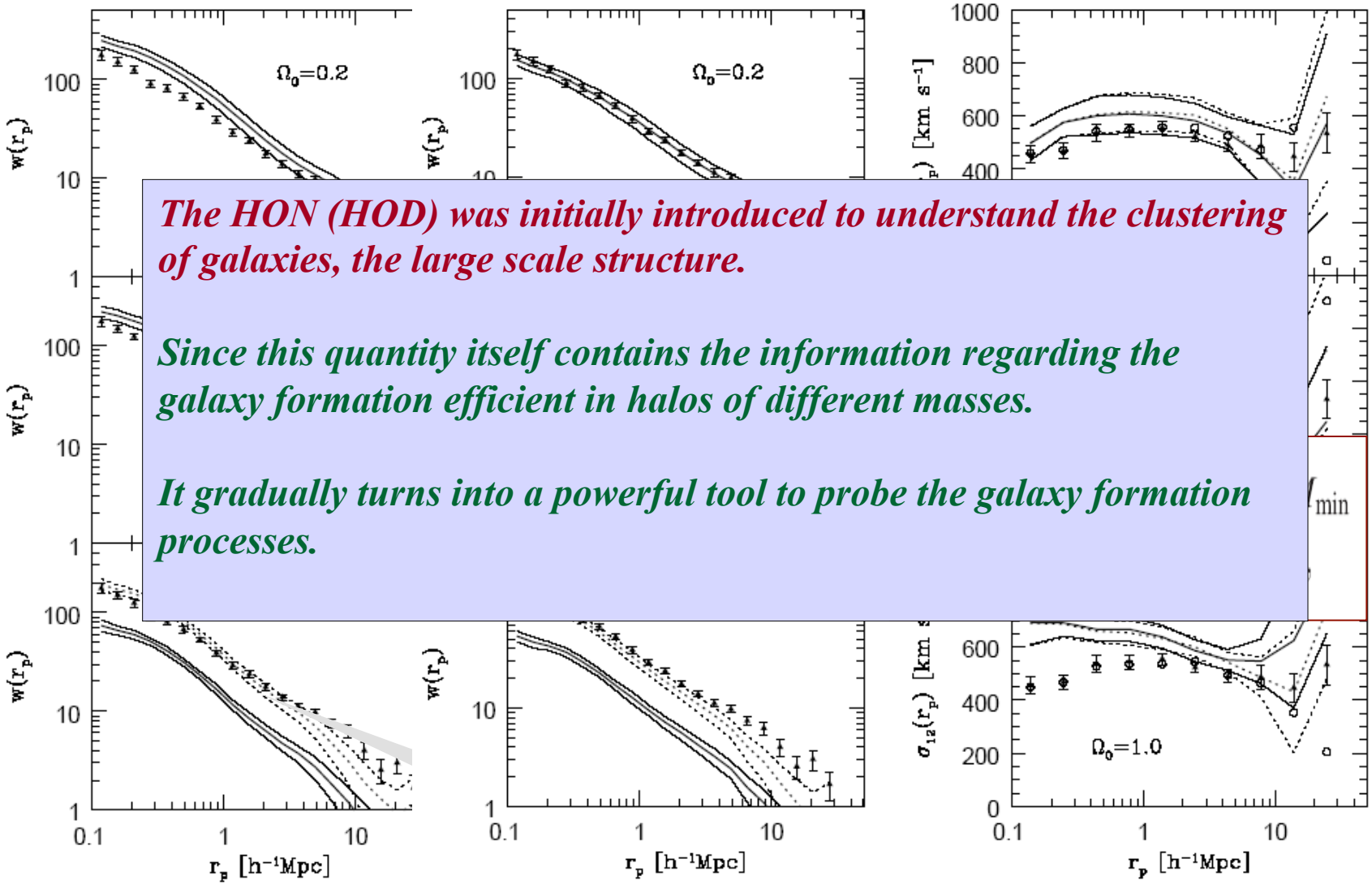




- **Various methods to constrain the galaxy-dark matter connections**
  - ***Large scale structure, → HOD/CLF models***
  - ***Direct measurement from the galaxy groups***
  - ***Galaxy-galaxy lensing***
  - ***(Sub)Halo Abundance matching***
  - ***Satellite kinamatics***
  - ***X-ray clusters***
  - ***Tully-Fisher relation***

I. From Large scale structure to Halo Occupation Distribution (HOD) and Conditional Luminosity Function (CLF)

HOD: understanding the clustering of galaxies



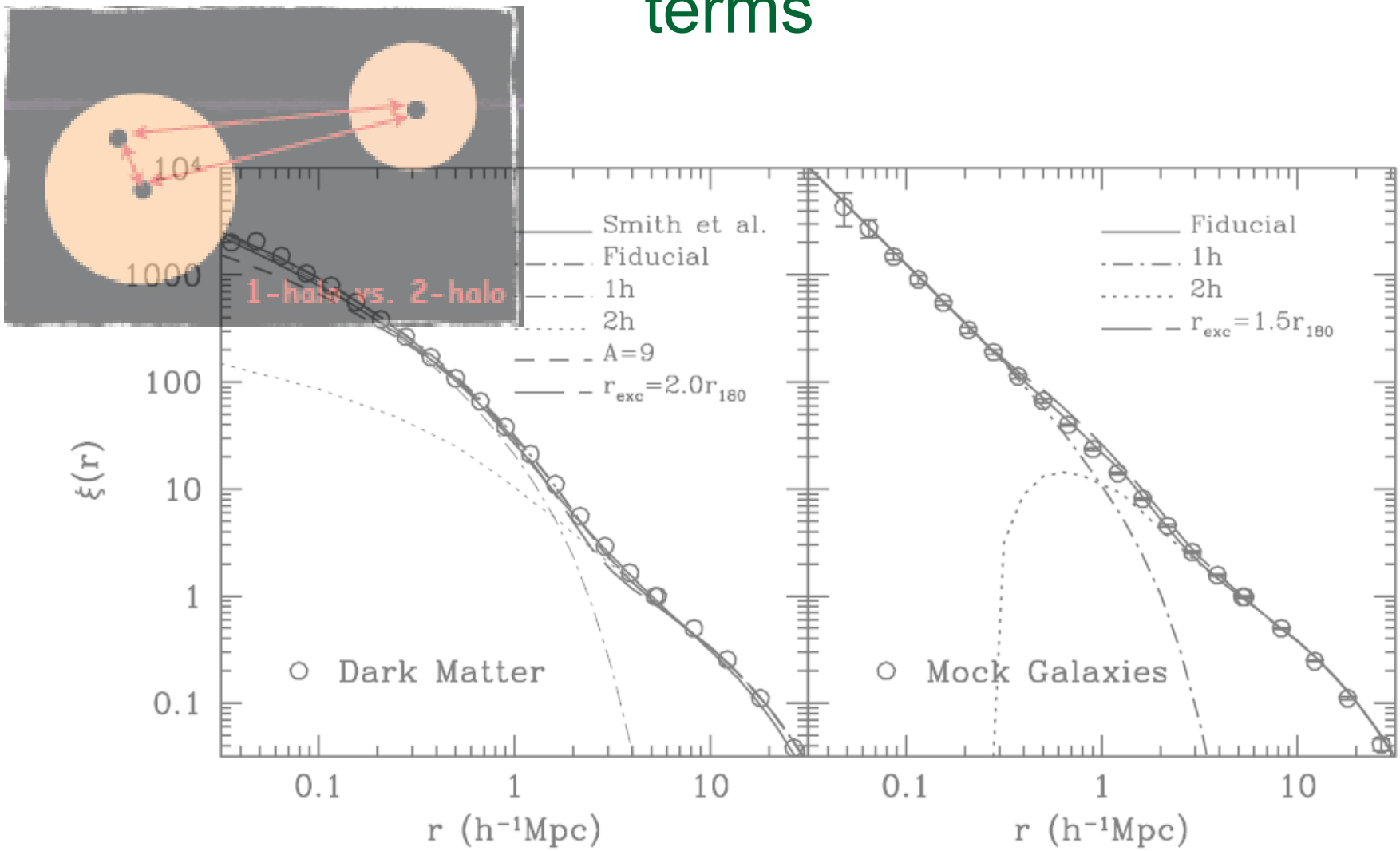
The HON (HOD) was initially introduced to understand the clustering of galaxies, the large scale structure.

Since this quantity itself contains the information regarding the galaxy formation efficient in halos of different masses.

It gradually turns into a powerful tool to probe the galaxy formation processes.

Jing et al. 1998

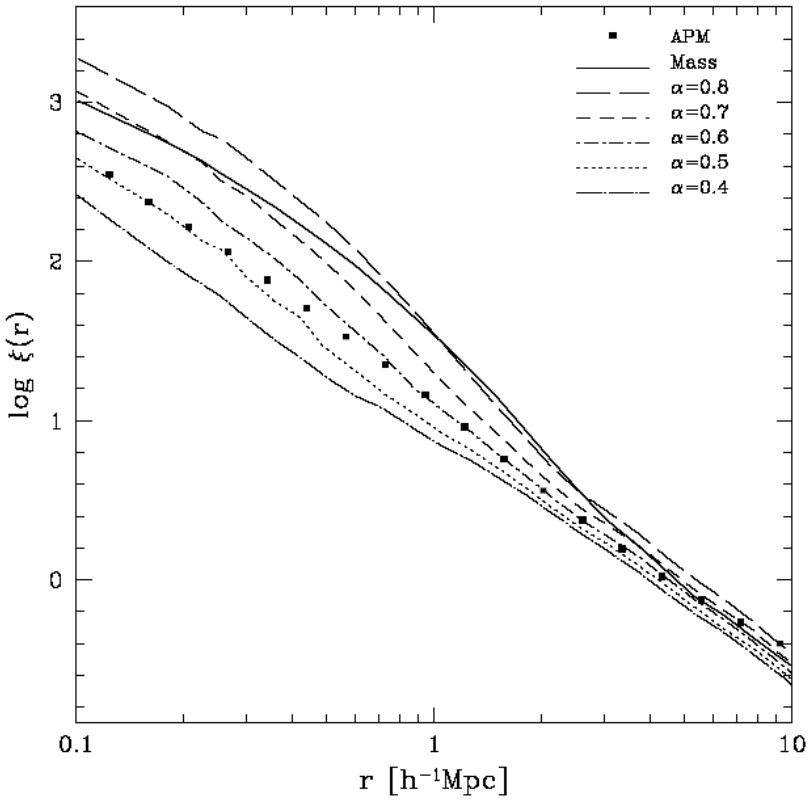
The 2PCF of galaxies: 1-halo and 2-halo terms

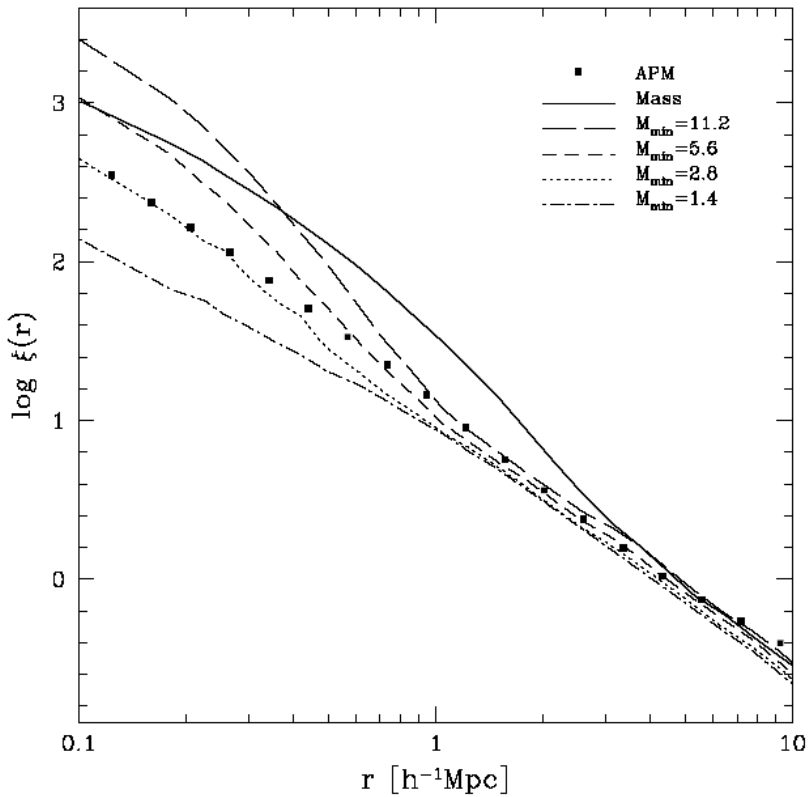


Wang et al. 2004

The clustering can be used to constrain the model

$$N_{\rm avg} = \begin{cases} 0 & \text{if } M < M_{\rm min} \\ (M/M_1)^{\alpha} & \text{if } M_{\rm min} \le M \le M_{\rm crit} \\ (M/M_1')^{\beta} & \text{otherwise ,} \end{cases}$$

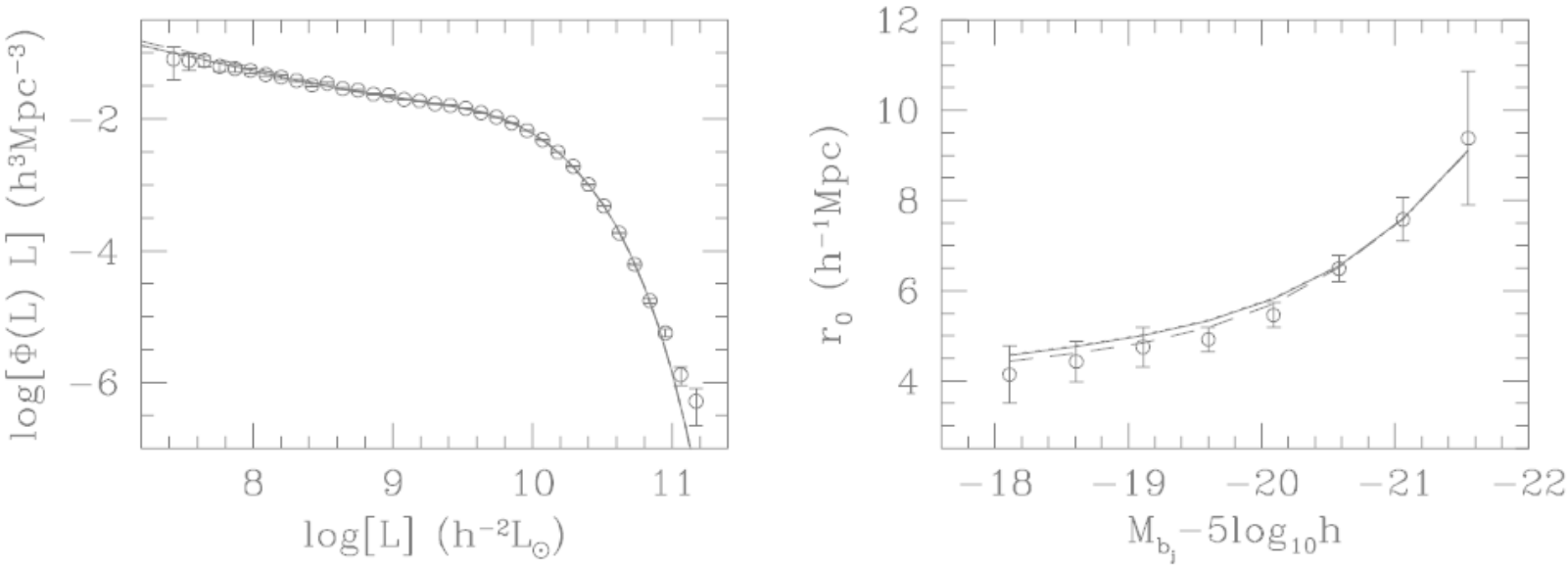




Berlind & Weinberg 2002;
Zheng et al. 2005…

The Conditional Luminosity Function

- **One step further: CLF**
  - ***Galaxies are of different luminosities***
  - ***They are differently clustered.***
  - ***So what is the luminosity distribution of galaxies in halos Φ(L|M)?***
  - ***Use LF and 2PCF to constrain Φ(L|M).***



Yang et al. 2003; van den Bosch et al. 2003; 2007

Some links with CLF $\Phi(L|M)$

The luminosity function:

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

The average luminosity in a halo of mass M:

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

The average number of galaxies in a halo of mass M with $L > L_1$:

$$N_M(L > L_1) = \int_{L_1}^\infty \Phi(L|M)\, \mathrm{d}L$$

Clustering properties of galaxies as function of luminosity:

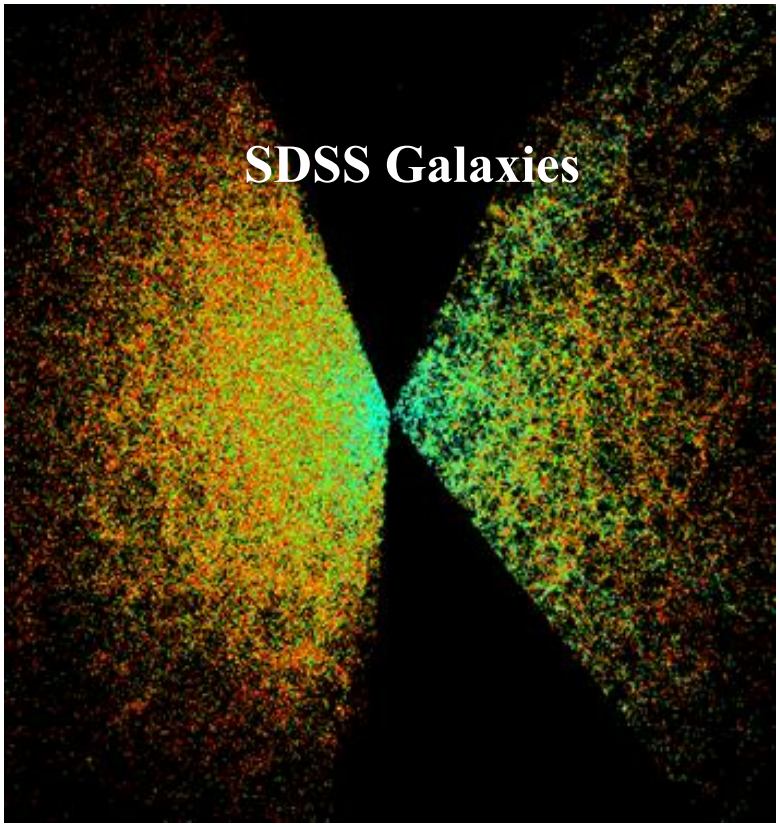
$$\xi_{\mathrm{gg}}(r|L) = b^2(L)\, \xi_{\mathrm{dm}}(r)$$

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

The conditional LF is the ideal statistical 'tool' to link the distributions of dark matter haloes and galaxies.

II. Galaxy groups: the direct measurement of the CLF from the observations

Direct measurement of HOD/CLF?



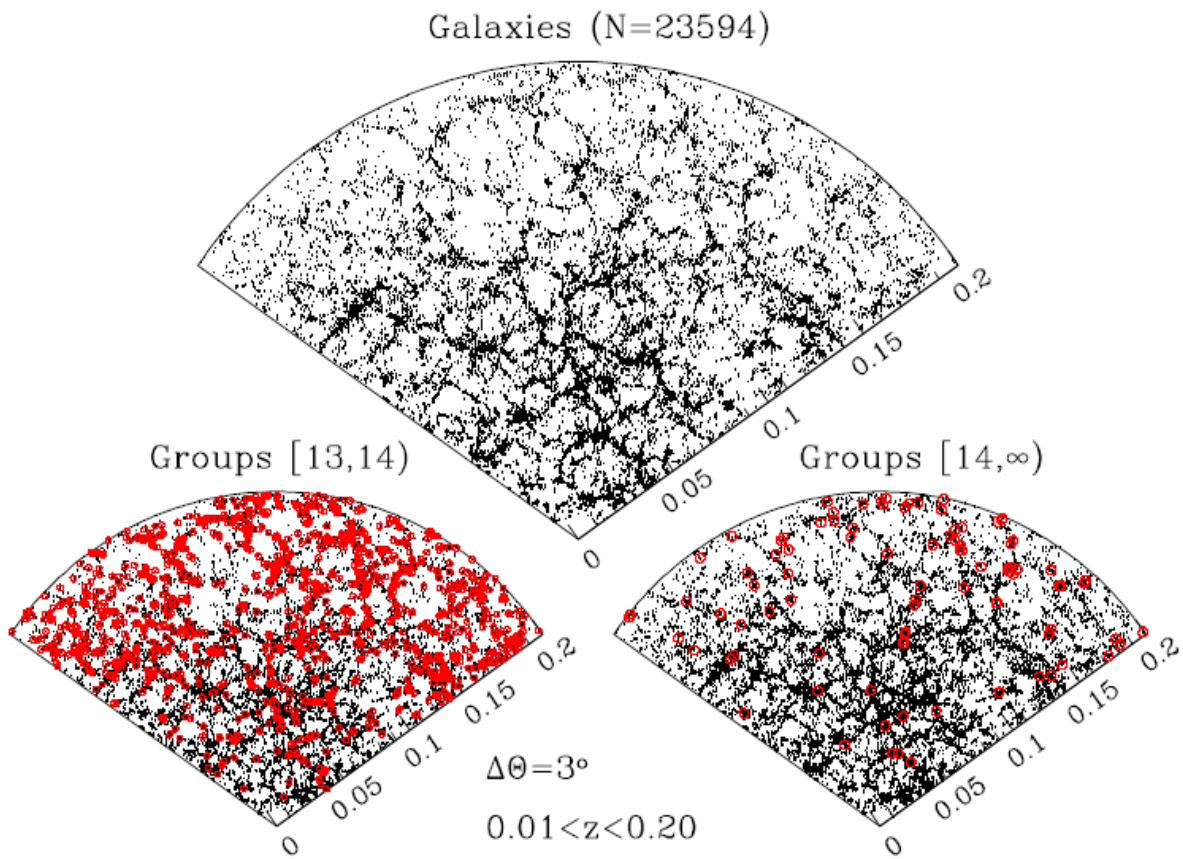
- *(1) Find the galaxies in the same dark matter halos– galaxy groups.*
  - *3D distributions, vary in number density due to magnitude limit*
  - *Redshift distortion affect the distribution along the line-of-sight*
- *(2) To measure the total mass of the group.*
  - *velocity dispersion*
  - *Lensing, X-ray observation*
  - *Abundance match*

Galaxy groups in the SDSS DR4

Sky coverage:
4514 deg^2

Galaxies with redshifts: 369447 (408119)

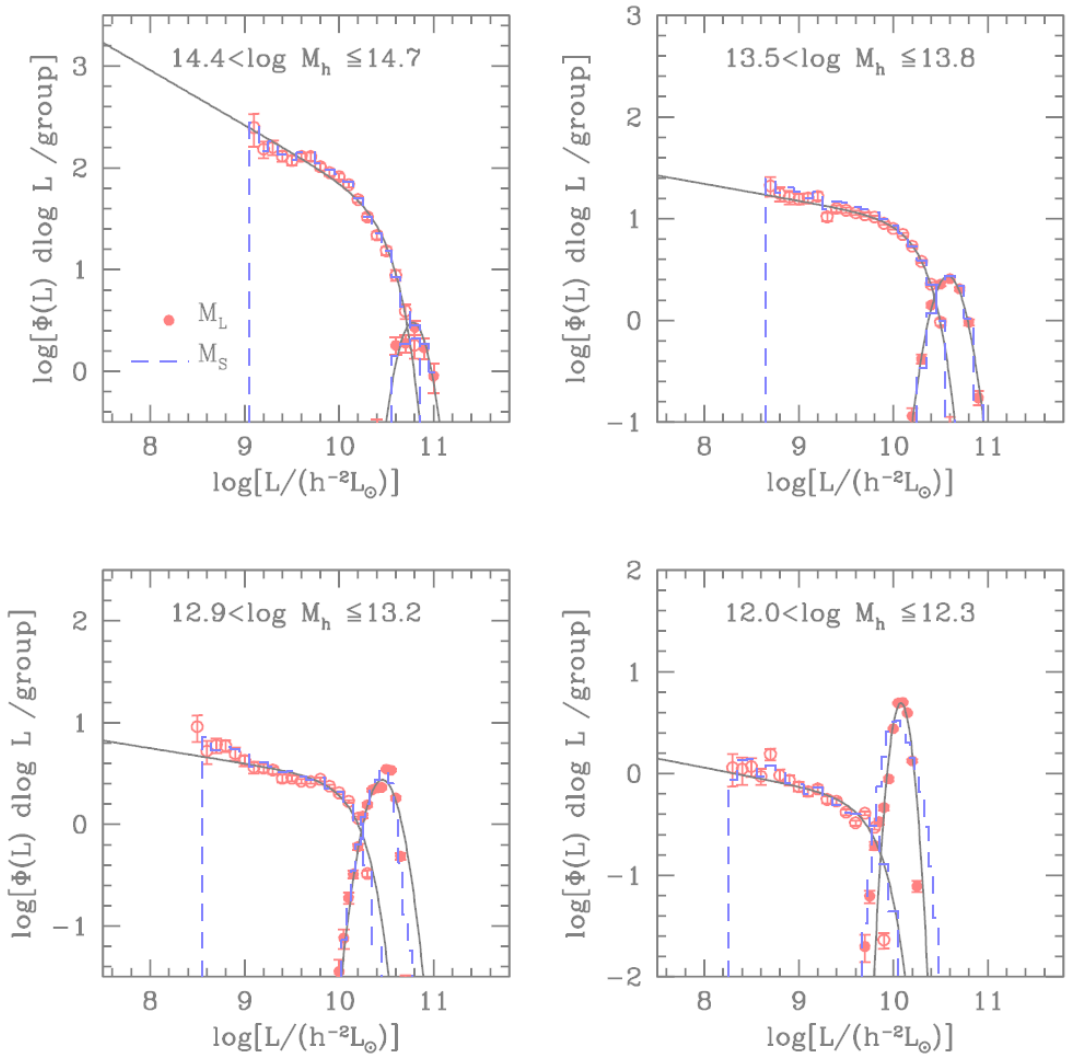
Groups selected: 301237 (300049)



- Galaxies are grouped according to their common halos
- Halo mass is assigned for each group
- The most massive galaxy is defined as the central galaxy

Yang et al. 2007

The direct measurement of CLF from SDSS



Yang et al. 2008

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:

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

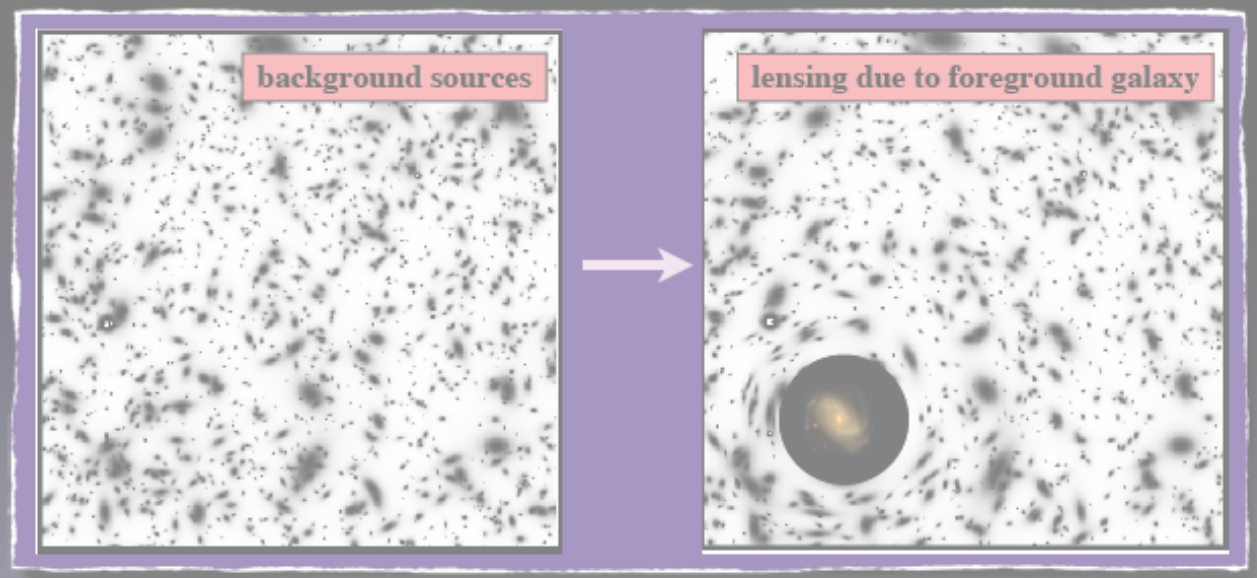
Note: $\{L_{\rm c}, L_{\rm s}, \sigma_{\rm c}, \phi_{\rm s}, \alpha_{\rm s}\}$ all depend on halo mass

Free parameters are constrained by fitting data.

III. Galaxy-galaxy lensing: measure the mass distributions around given galaxies

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

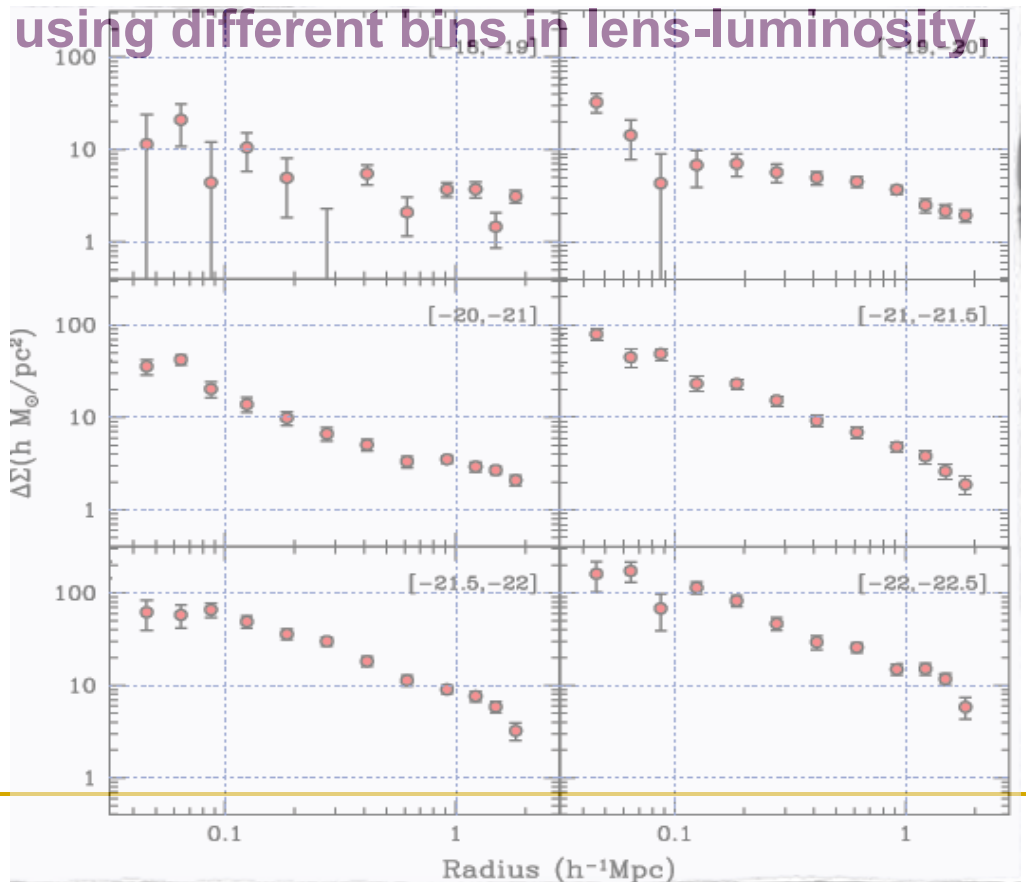
$$\gamma_{\rm t}(R)\Sigma_{\rm crit} = \Delta\Sigma(R) = \bar{\Sigma}(<R) - \Sigma(R)$$

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

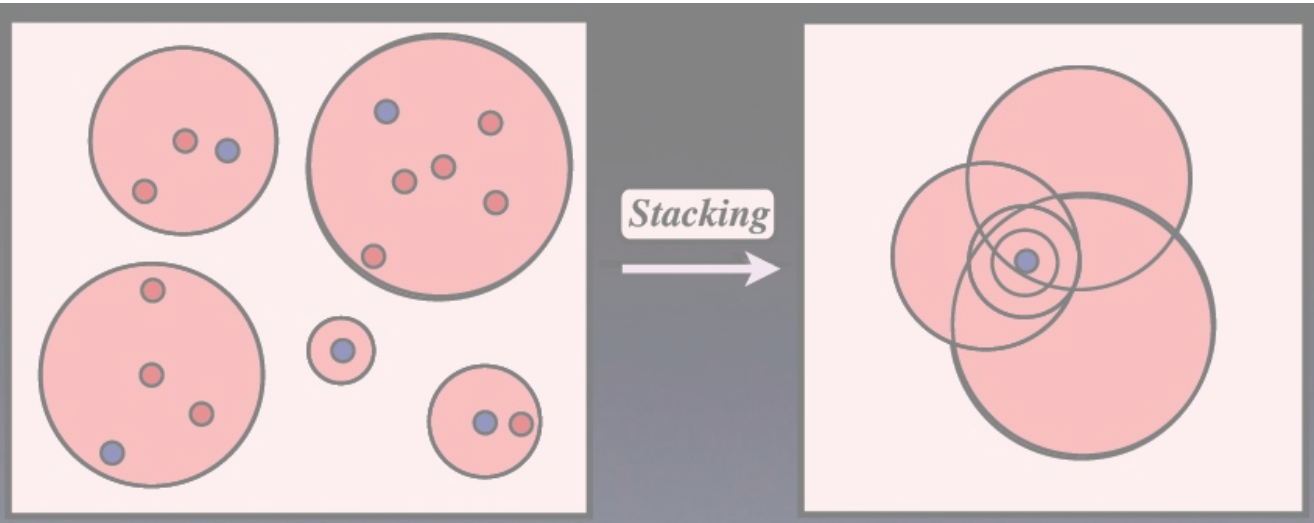
$$\Sigma(R) = \bar{\rho}\int_0^{D_{\rm s}} [1 + \xi_{\rm g,dm}(r)]\,{\rm d}\chi$$

The measurement

- **Number of background sources per lens is limited**
- **Measuring shear with sufficient S/N requires stacking of many lenses**
- **It has been measured using the SDSS by Mandelbaum et al. (2006), using different bins in lens-luminosity.**



Interpret the lensing signals



Because of stacking the lensing signal is difficult to interpret

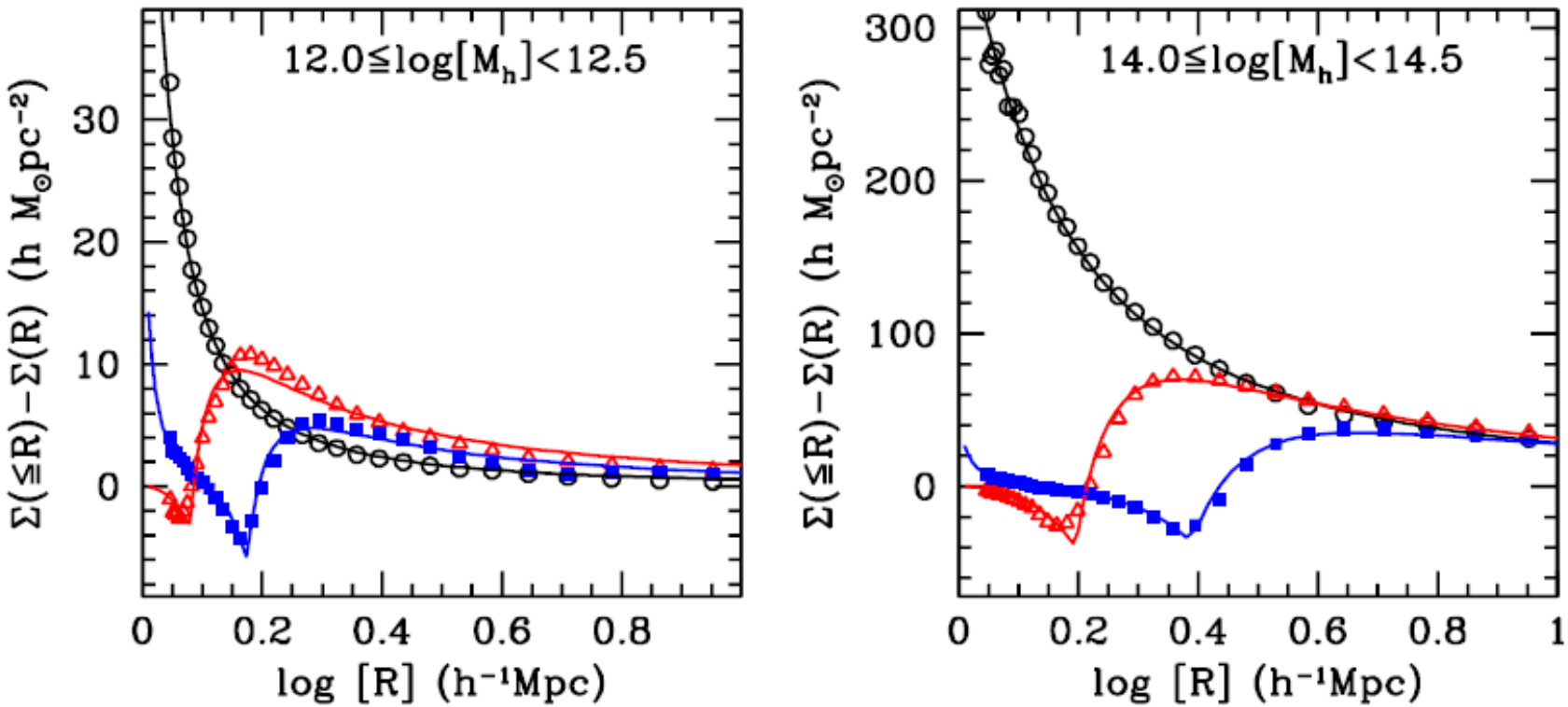
In order to model the data, what is required is:

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

These can all be computed from the CLF...

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

Separating the signals for central and satellite



Yang et al. 2006

IV. (Sub)Halo abundance matching (HAM/SHAM)

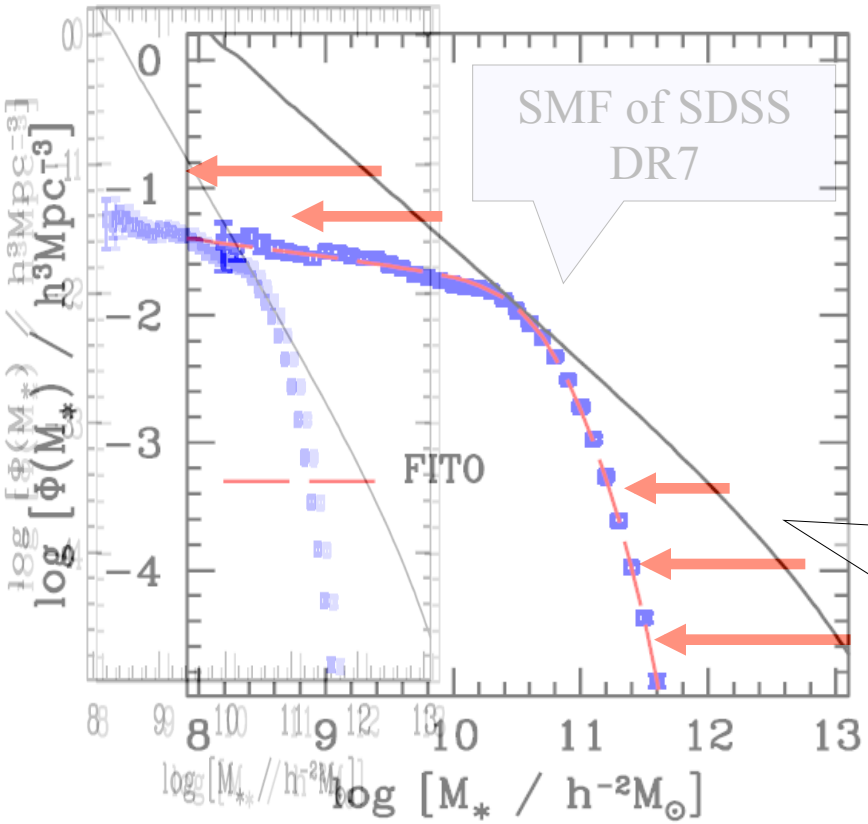
Outline:

- **What is halo abundance matching? How it works?**
- **The accurate subhalo accretion model**
- **The self consistent halo abundance matching with subhalo accretion model**
- **The assembly of galaxies**

Part II

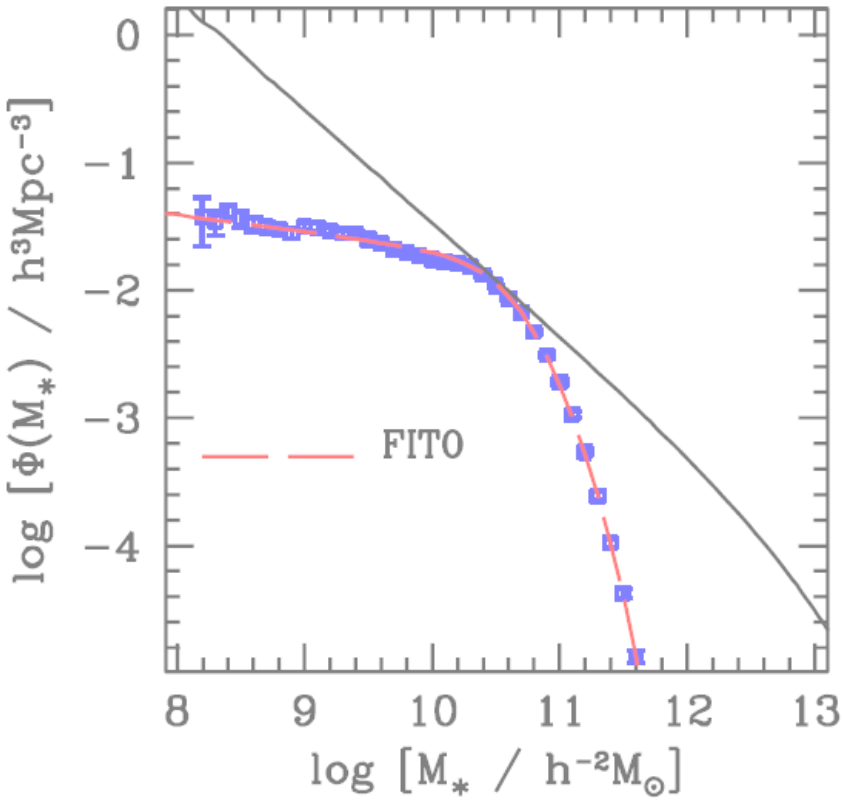
Mo & Fukugita 1996; Mo, Mao & White 1999; Vale & Ostriker 2004, 2006; Conroy et al. 2006; Shankar et al. 2006; Conroy & Wechsler 2009; Moster et al. 2010; Behroozi et al. 2010; Wetzel & White 2010

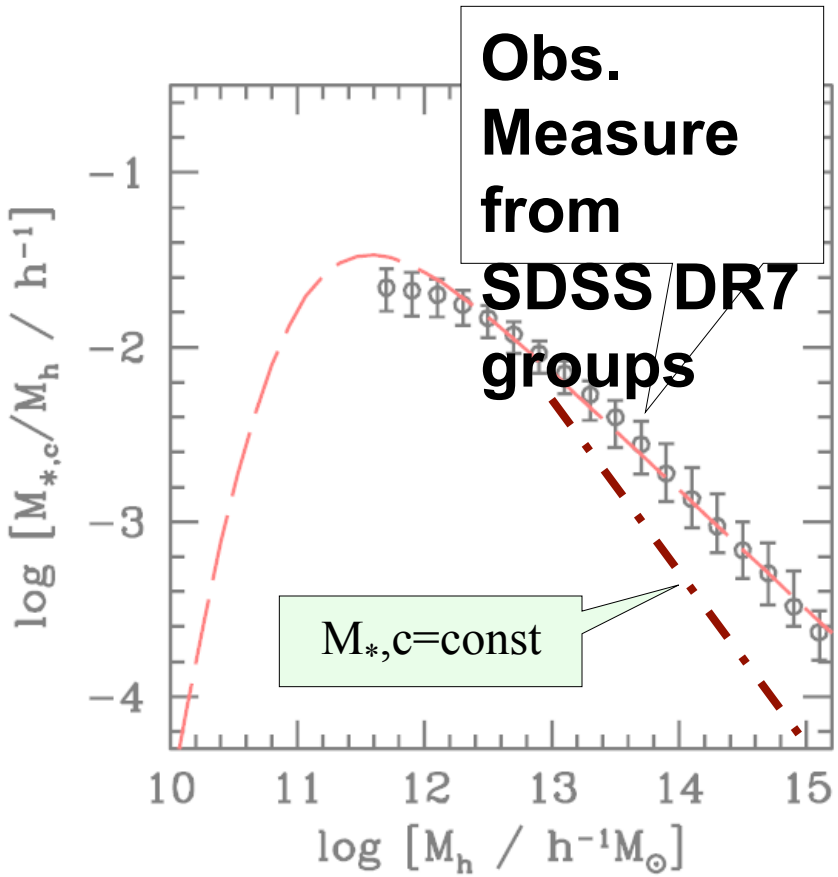
SHAM1: no satellites: FIT0



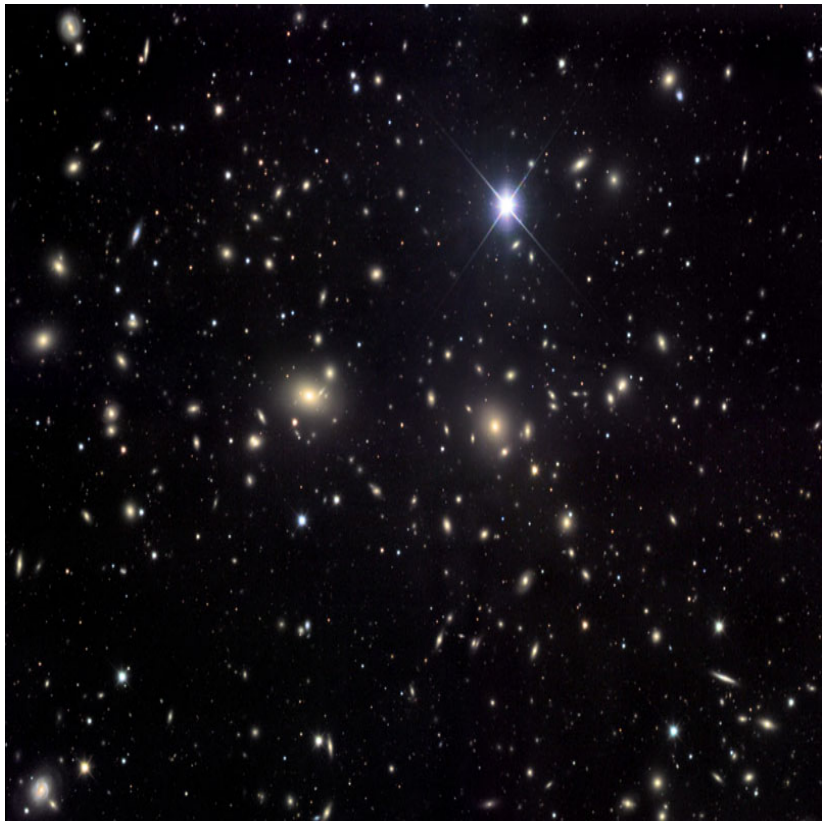
FIT0: Assume there is only one central galaxy in each dark matter halo. → no satellites

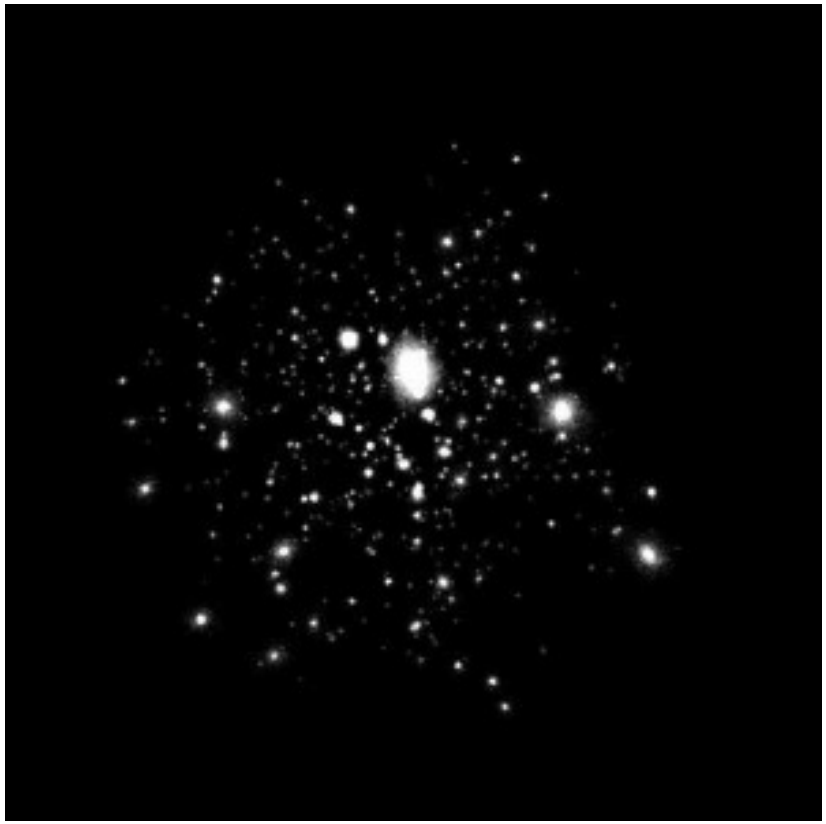
SHAM1: no satellites FIT0



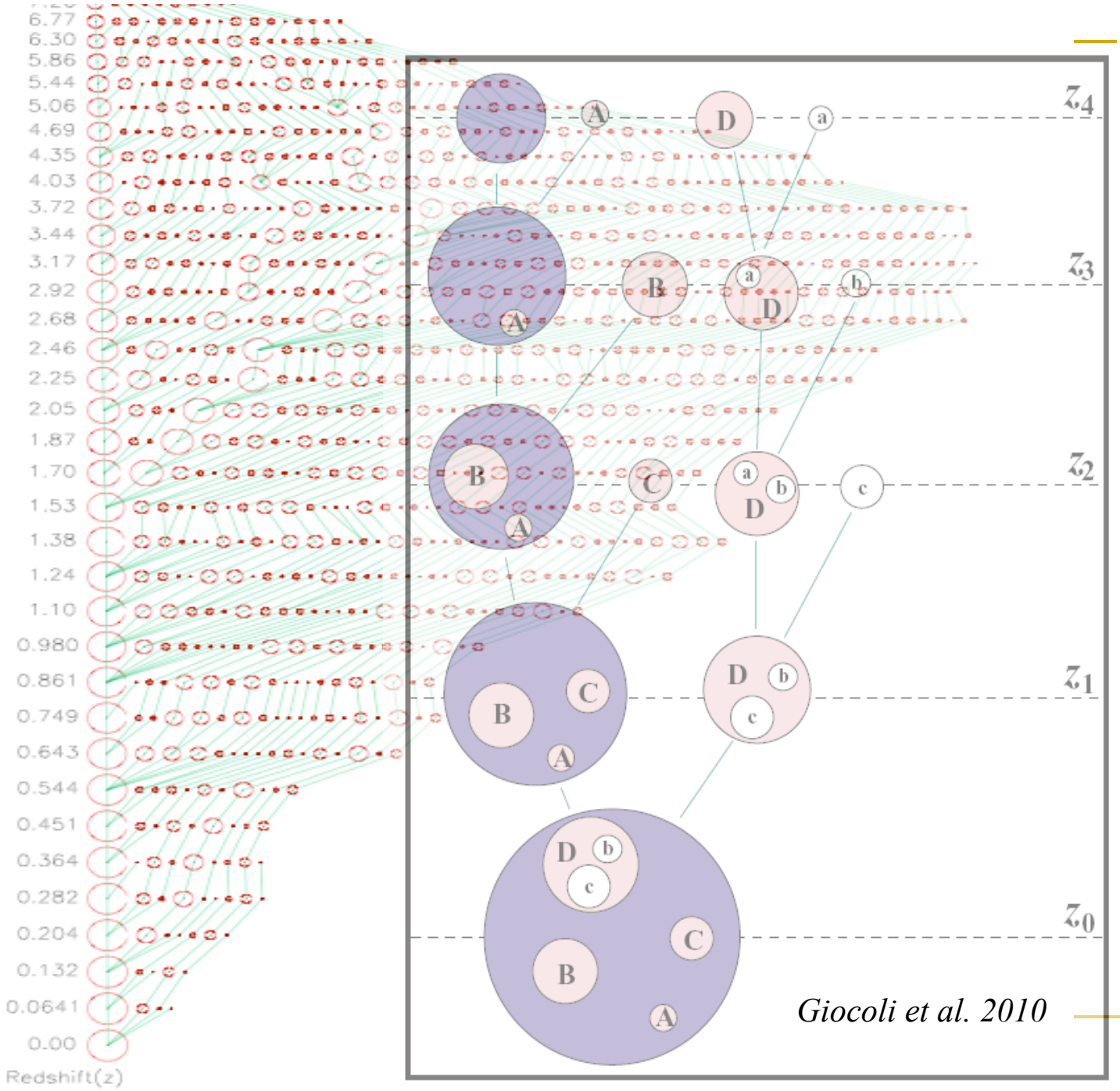


Satellite galaxies and subhalos



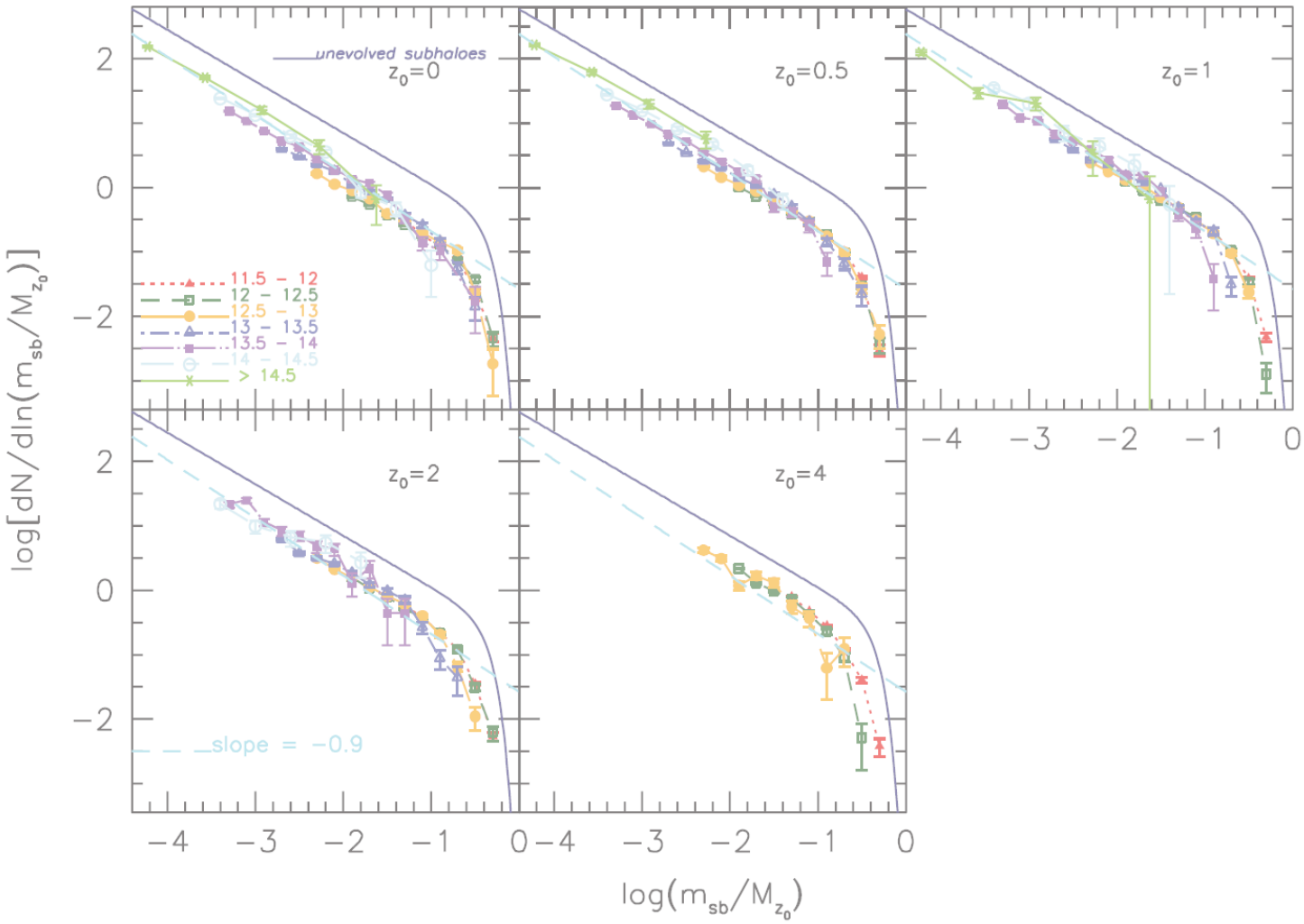


Halo merger tree



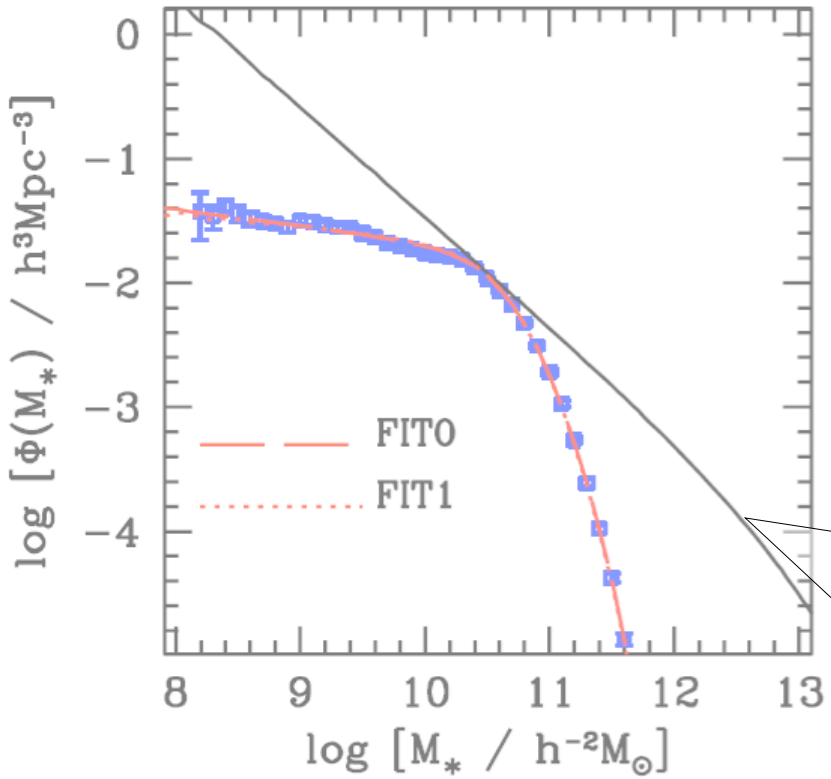
Giocoli et al. 2010

The unevolved subhalo mass function



Giocoli et al. 2010

SHAM2: no evolution, no disruption, FIT1

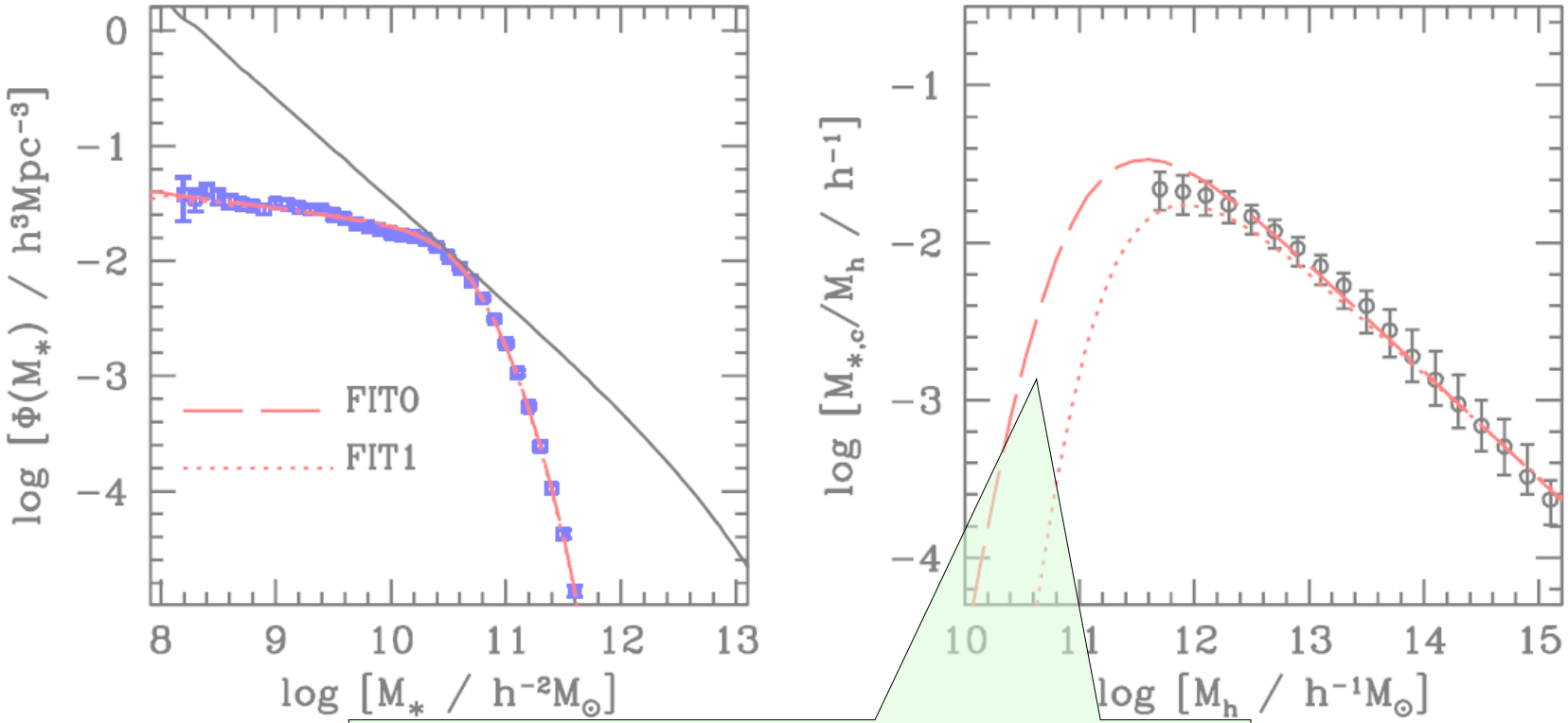


FIT1:

(1)Assume subhalos have the same central-host halo relation.

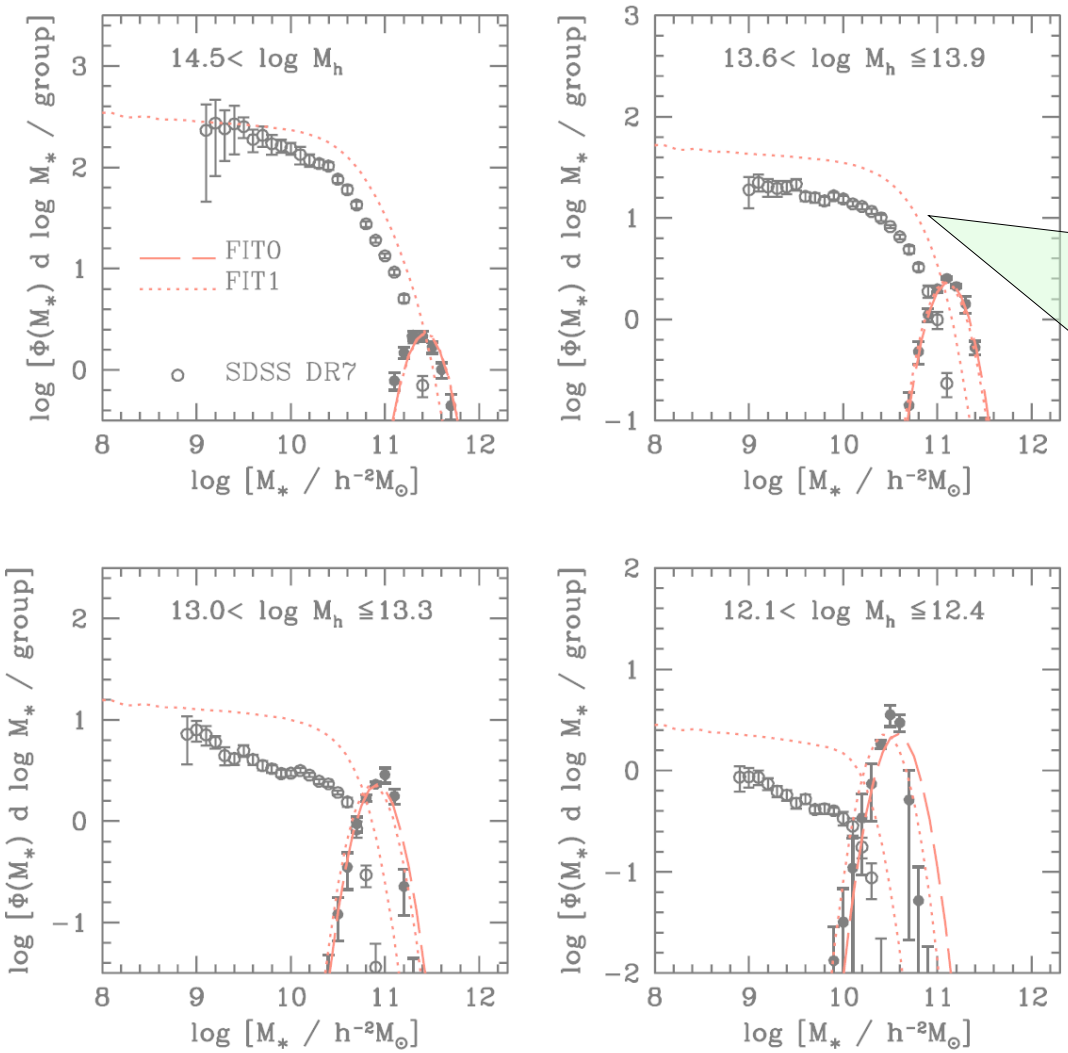
(2)Add up all the subhalos aver been

SHAM2:



The two extreme cases only differ significantly in low mass halos → for central galaxies

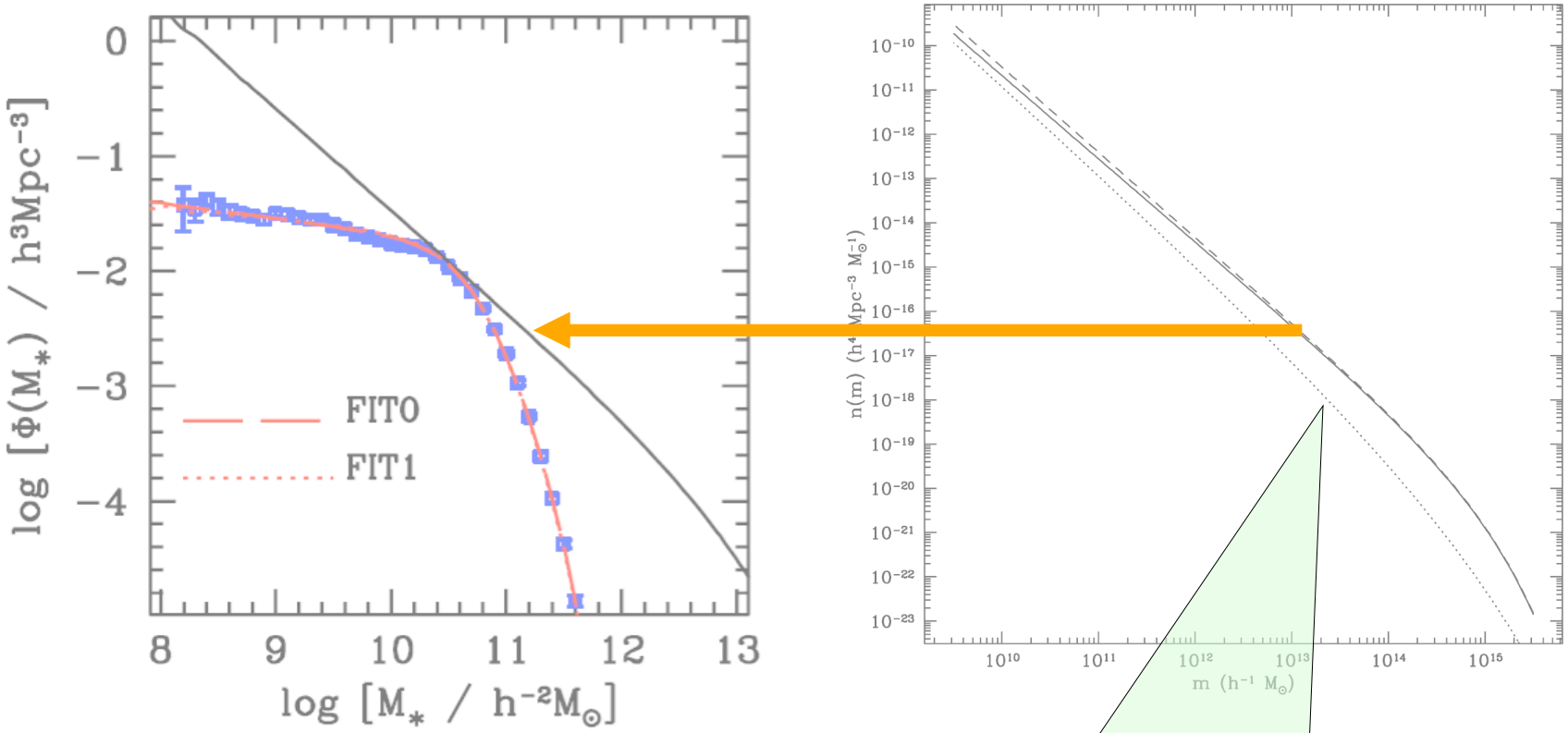
SHAM2: over predicted satellite population



The two extreme cases have dramatically different predictions of satellite galaxies

Yang et al. 2009

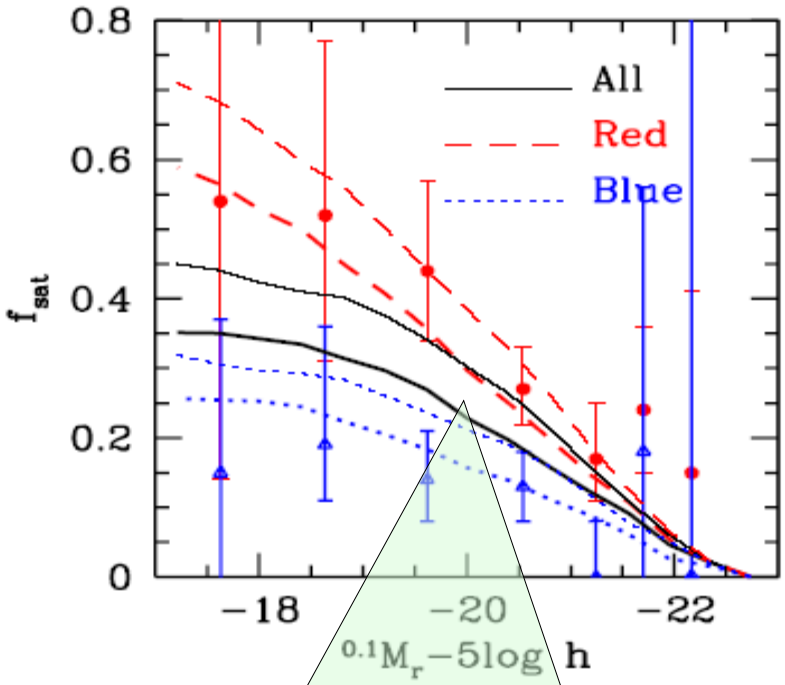
SHAM3: more realistic, – add survived subhalos

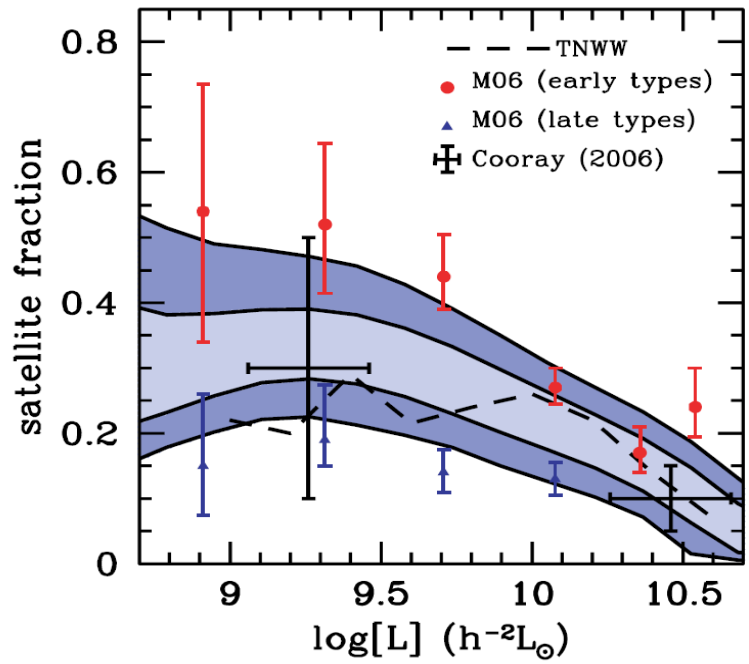


The satellite fraction is about 10-20%

Mo et al. 1999; Vale & Ostriker 2004

The fraction of satellite galaxies.

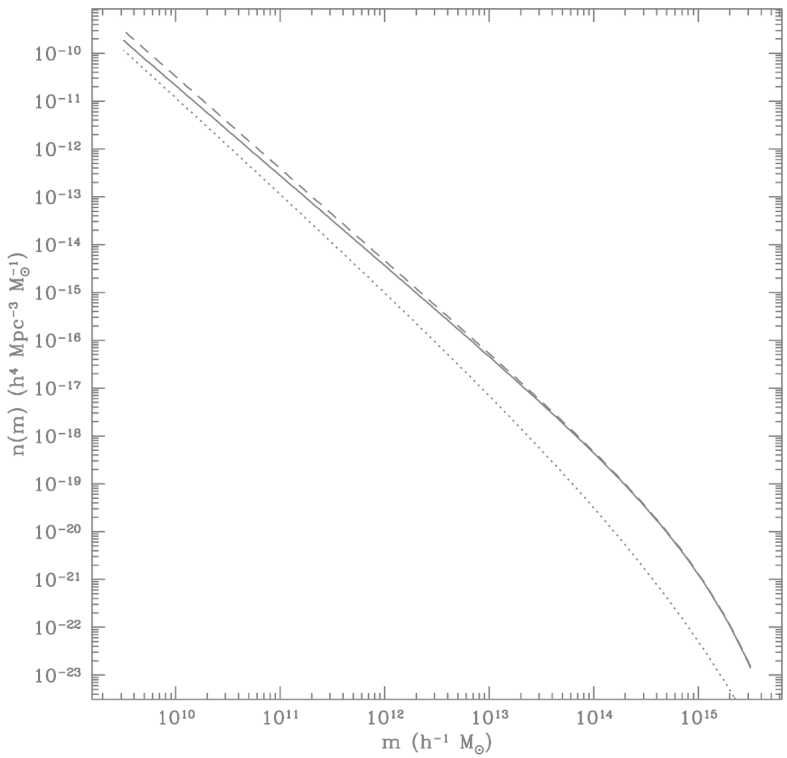


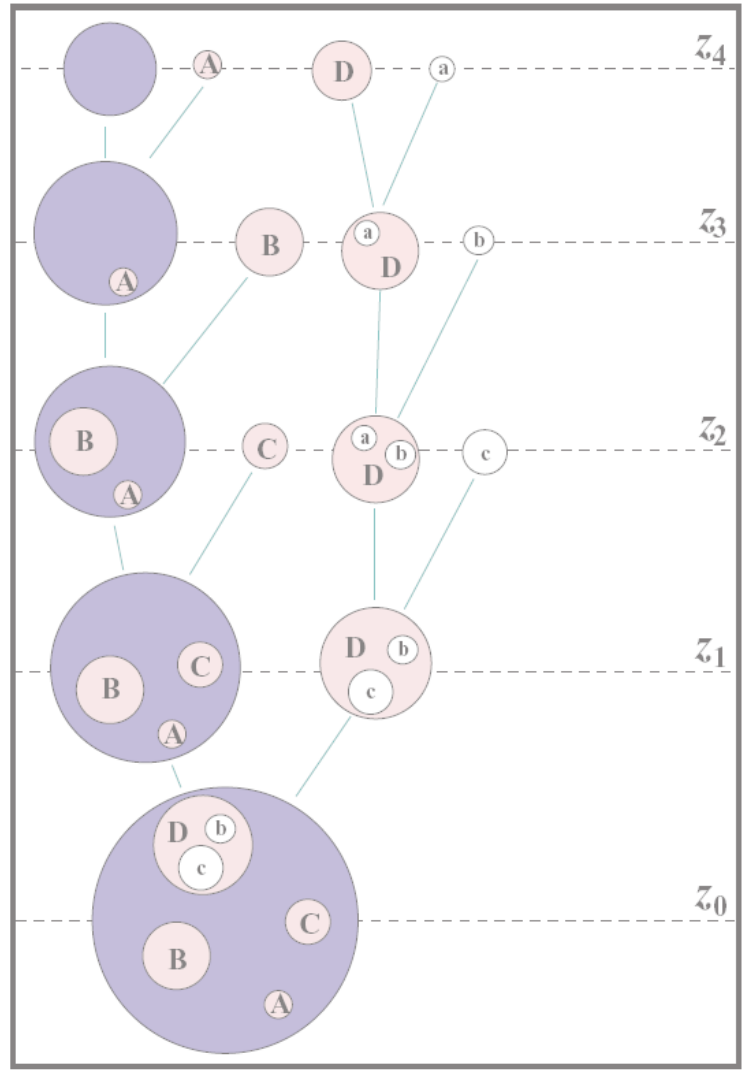


Obs. measure of the satellite fraction is
about 20-40%

Yang et al. 2007

SHAM4 –survived subhalos but with accreted masses





Vale & Ostriker 2006; Conroy et al. 2006; Moster et al. 2010…

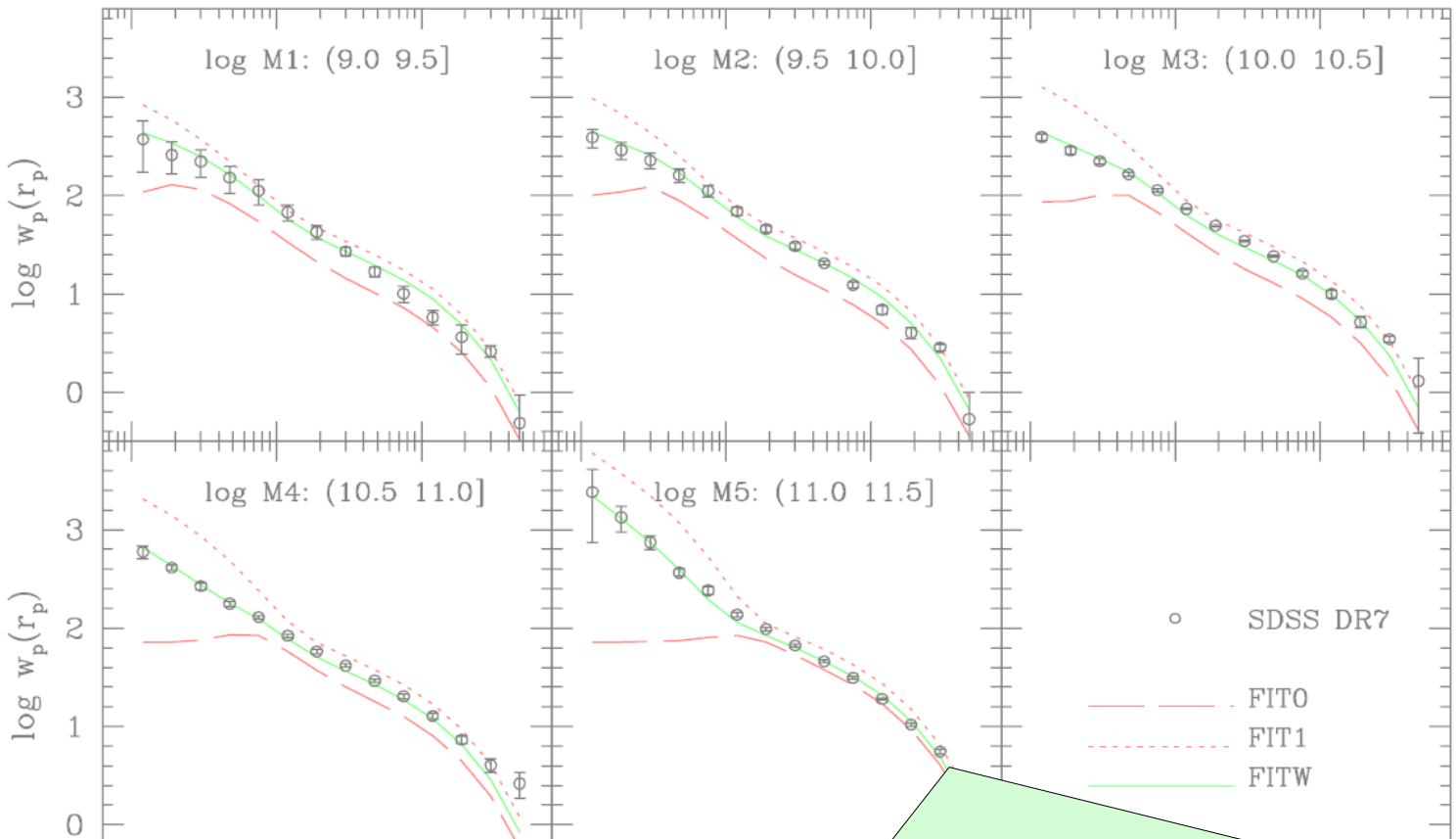
HAM: with LF/SMF only

- Different approaches:
  - SHAM1: No subhalos (satellite galaxies) → *impossible*
  - SHAM2: The accreted progenitors → *too many satellites, should be stripped*
  - SHAM3: The survived population found by different sub finder → *too few satellite galaxies survived*

With LF/SMF alone, one can somehow make reasonable prediction of central-halo relation, however the subhalo-satellite connection is poorly understood.

- **→ the latter two suffer from simulation resolution effect: no orphan satellite**

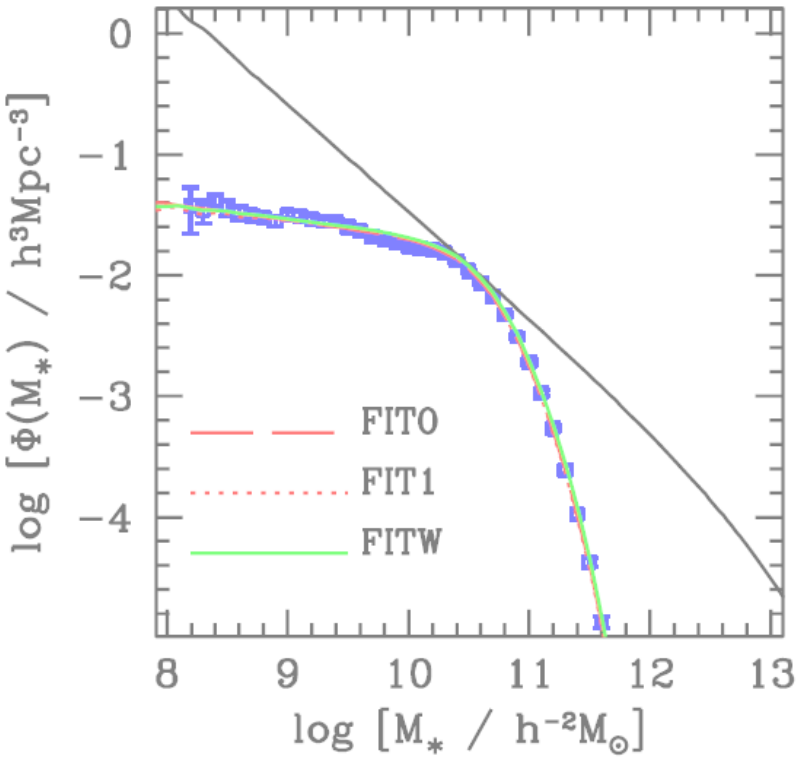
Accurate constraining of the satellite population

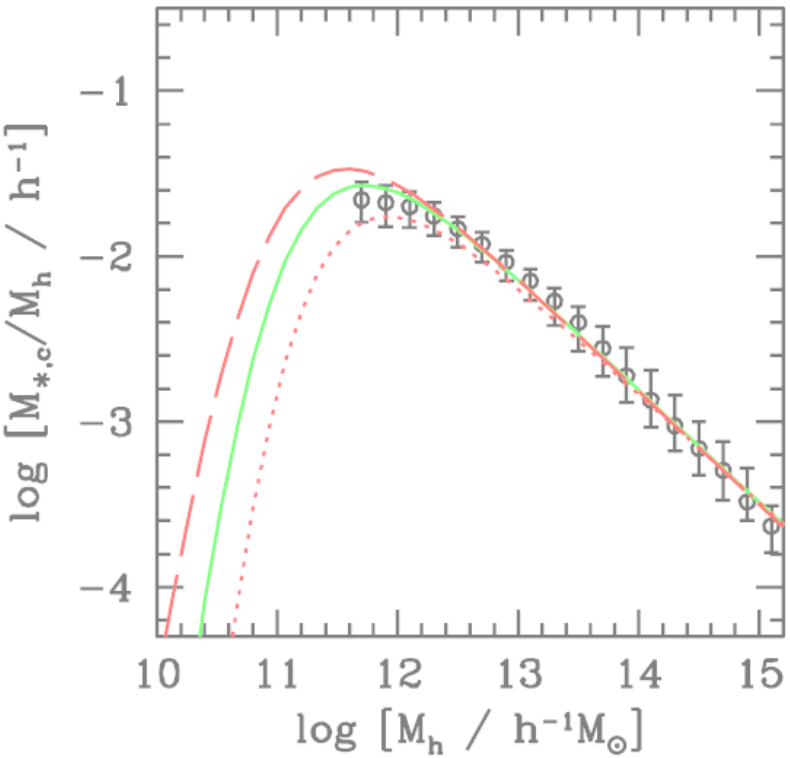


Such approaches of using clusterings to constrain the number of satellite galaxies (and of different luminosities) are so called Halo Occupation Distribution (HOD) and Conditional Luminosity Function (CLF) models.

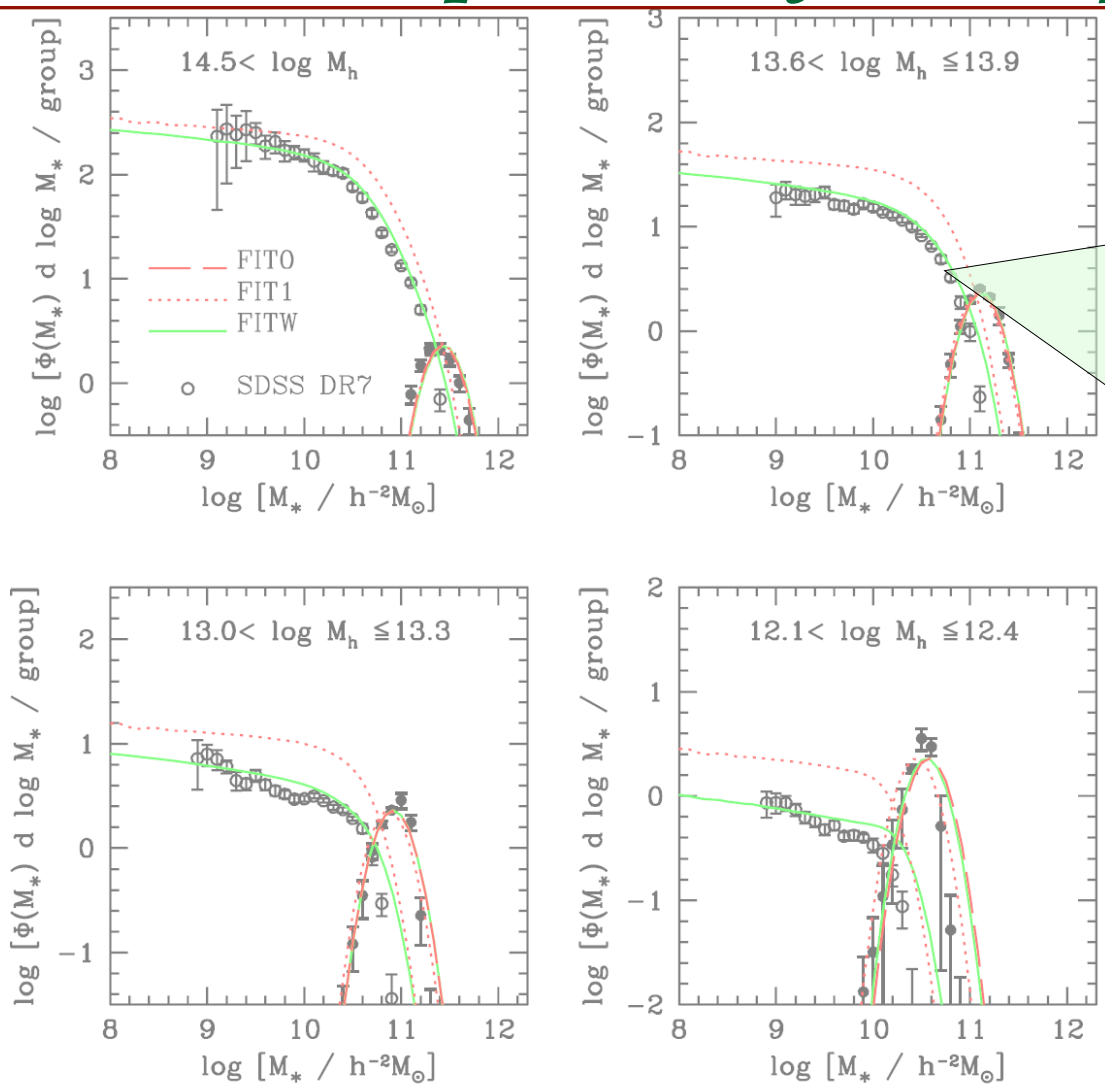
Yang et al. 2003; ven den Bosch et al. 2003; Zheng et al. 2005...

HOD and CLF constrain





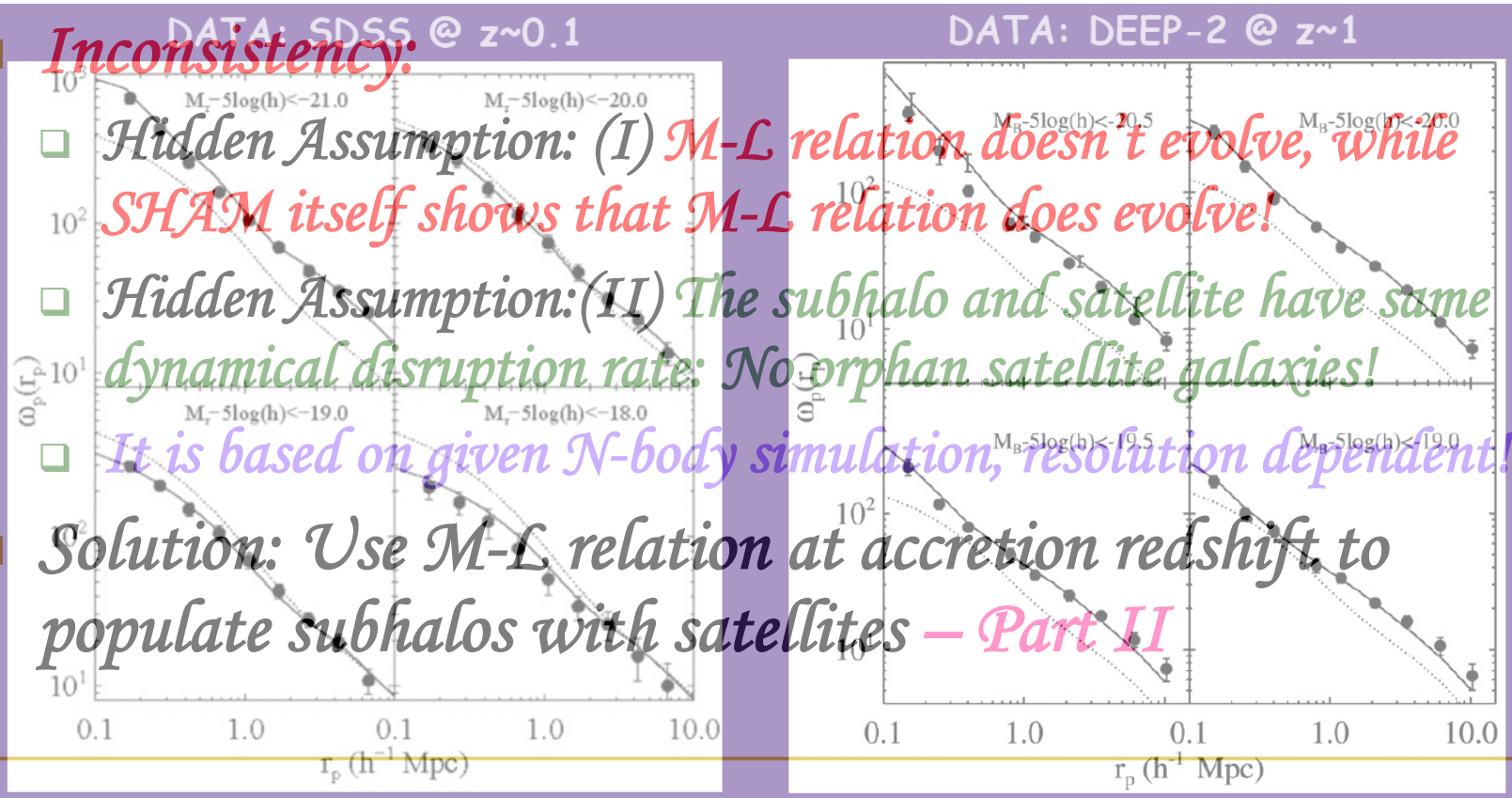
The reliable prediction of satellite population



The accurate clustering measures of galaxies can be used to make reliable constraints of satellite population in halos of different masses! → HOD/CLF

Success and inconsistency of SHAM

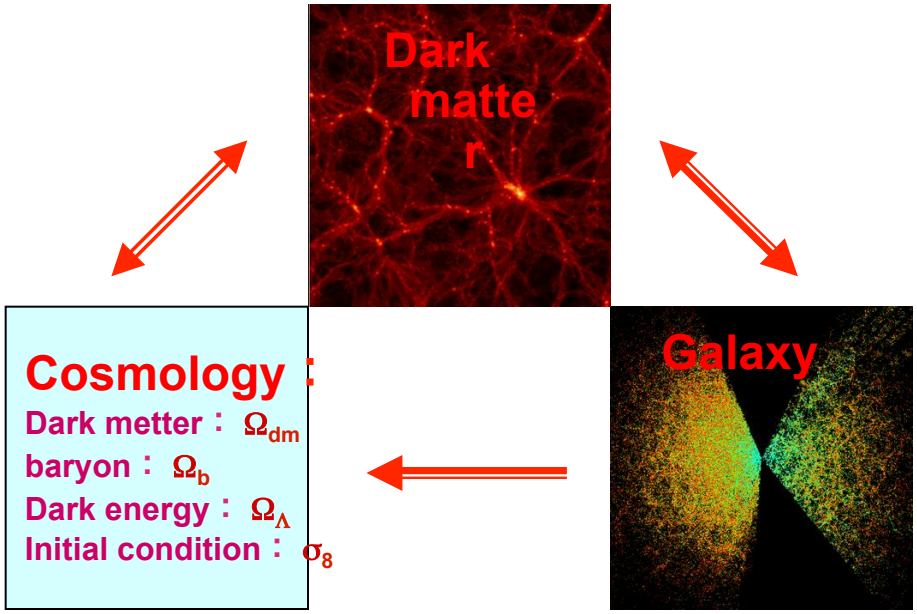
- **Success:** SHAM provides similar predictions of the central and satellite galaxies as HOD/CLF, yet it only uses the LF alone!
- **Inconsistency:**
  - Hidden Assumption: (I) M-L relation doesn't evolve, while SHAM itself shows that M-L relation does evolve!
  - Hidden Assumption: (II) The subhalo and satellite have same dynamical disruption rate: No orphan satellite galaxies!
  - It is based on given N-body simulation, resolution dependent!
- Solution: Use M-L relation at accretion redshift to populate subhalos with satellites – Part II



Source: Conroy, Wechsler & Kravtsov (2006)

Success and inconsistency of SHAM

- *Success: SHAM provides similar predictions of the central and satellite galaxies as HOD/CLF, yet it only uses the LF alone!*
- *Inconsistency:*
  - *Hidden Assumption: (I) M-L relation doesn't evolve, while SHAM itself shows that M-L relation does evolve!*
  - *Hidden Assumption:(II) The subhalo and satellite have same dynamical disruption rate: No orphan satellite galaxies!*
  - *It is based on given N-body simulation, resolution dependent!*
- *Solution: Use M-L relation at accretion redshift to populate subhalos with satellites – Part II*



Local universe: With the reiable link between galaxies and dark matter halos being established using HOD/CLF, it has been used for various purposes: understanding/constraining the galaxy formation processes, the large scale structure of Universe, the cosmological parameters, etc. *Jing et al. 1998;Berlind & Weinberg 2002; Yang et al. 2003;2004;2012;van den Bosch et al. 2003a; 2003b; 2007; 2012; Vale & Ostriker 2004; Cooray 2006; Zehavi et al. 2005; Zheng et al. 2005; 2007*

Summary

- **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**

Cosmological probes!

- *CLF + M/L: van den Bosch et al. 2003*
- *CLF + PVD: Yang et al. 2004*
- *HOD + M/L: Tinker et al. (2005)*
- *CLF + Lensing: Li et al. (2009); More et al. (2009)*
- *GC + PVD: Li et al. 2012*
- *CLF + Lensing + Clustering: van den Bosch et al. 2012; More et al. 2012…*