New insights on galaxy evolution since z ~ 1.2 from the CFHT Legacy Survey

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Collaborators

JC et al, A&A, vol. 542, A5 (HOD analysis):

- Paris (IAP): H. J. McCracken, Y. Mellier
- Marseille (LAM): O. Ilbert
- CFHT: S. Arnouts
- CEA Saclay: M. Kilbinger
- VVDS & VIPERS teams (Italy, UK, etc.): U. Abbas, S. de la Torre, Y. Goranova, P. Hudelot, J.-P. Kneib, and O. Lefèvre

JC et al, in prep. (gal-gal lensing analysis):

- VIPERS team
- CFHTLenS team
- IPMU: A. Leauthaud
- Taiwan: K. Umetsu, Y.-T. Lin, L. Lin, S. Foucaud, etc.

Overview

- cosmologists have built a “cosmological standard model” able to reproduce observations, but leaving us with fundamental questions regarding the constituents of the Universe
- we face a troubling paradox: the only constituent (also the rarest) we (probably) best know about it, baryonic matter, is observed today in a remarkable diversity of galaxies
- this diversity results from a complex interplay of different physical processes which strongly depends on the host halo mass
- a very interesting - and quite new - approach consists in connecting galaxy properties with those of their halo mass
- we apply two complementary methods to probe the galaxy-halo relationship, based on galaxy clustering and galaxy lensing, in the CFHTLS-Wide survey which remains unmatched in terms of volume at high redshift and image quality

Plan

I. Introduction: cosmological context, galaxy evolution and the halo model

II. CFHTLS-Wide: new insights on galaxy evolution since z ~ 1.2 from galaxy clustering

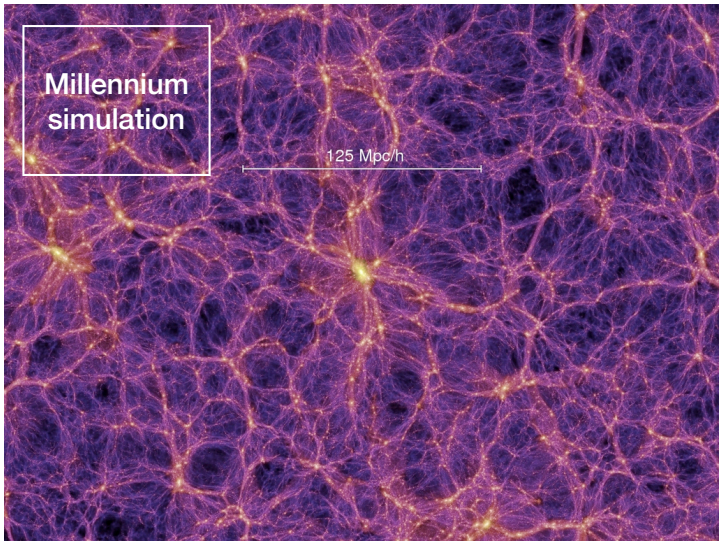
III. CFHTLens/VIPERS: promising results from galaxy-galaxy lensing

IV. Conclusions

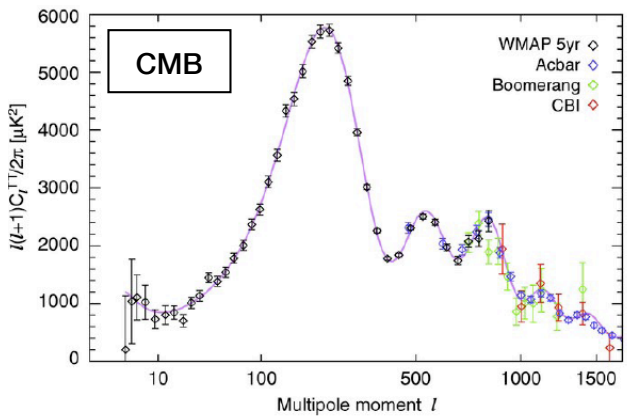
I. Introduction: cosmological context, galaxy evolution and the halo model

The Universe in one slide - The ΛCDM model

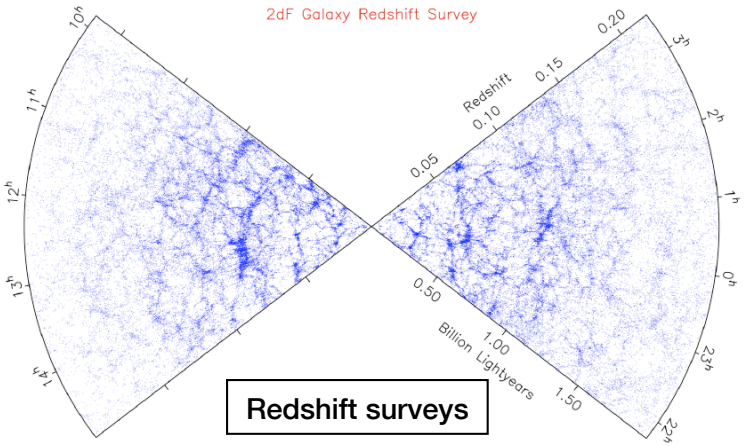
- the Universe is homogeneous and isotropic
- flat
- expanding and accelerating
- is dominated by (cold) dark matter and dark energy
- structures grow by gravitational instabilities of primordial tiny fluctuations that experienced a huge expansion during an early inflation period

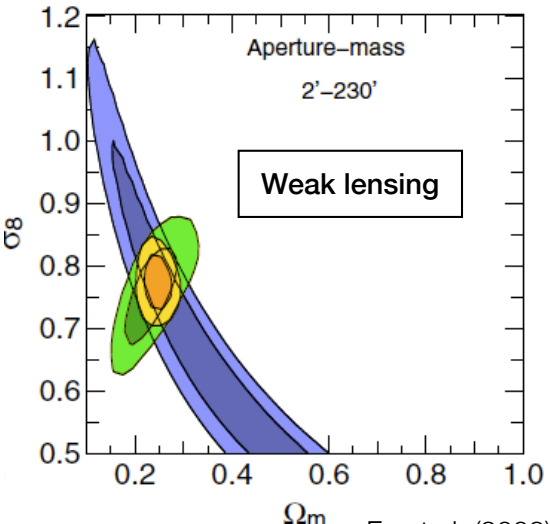


Millenium simulation

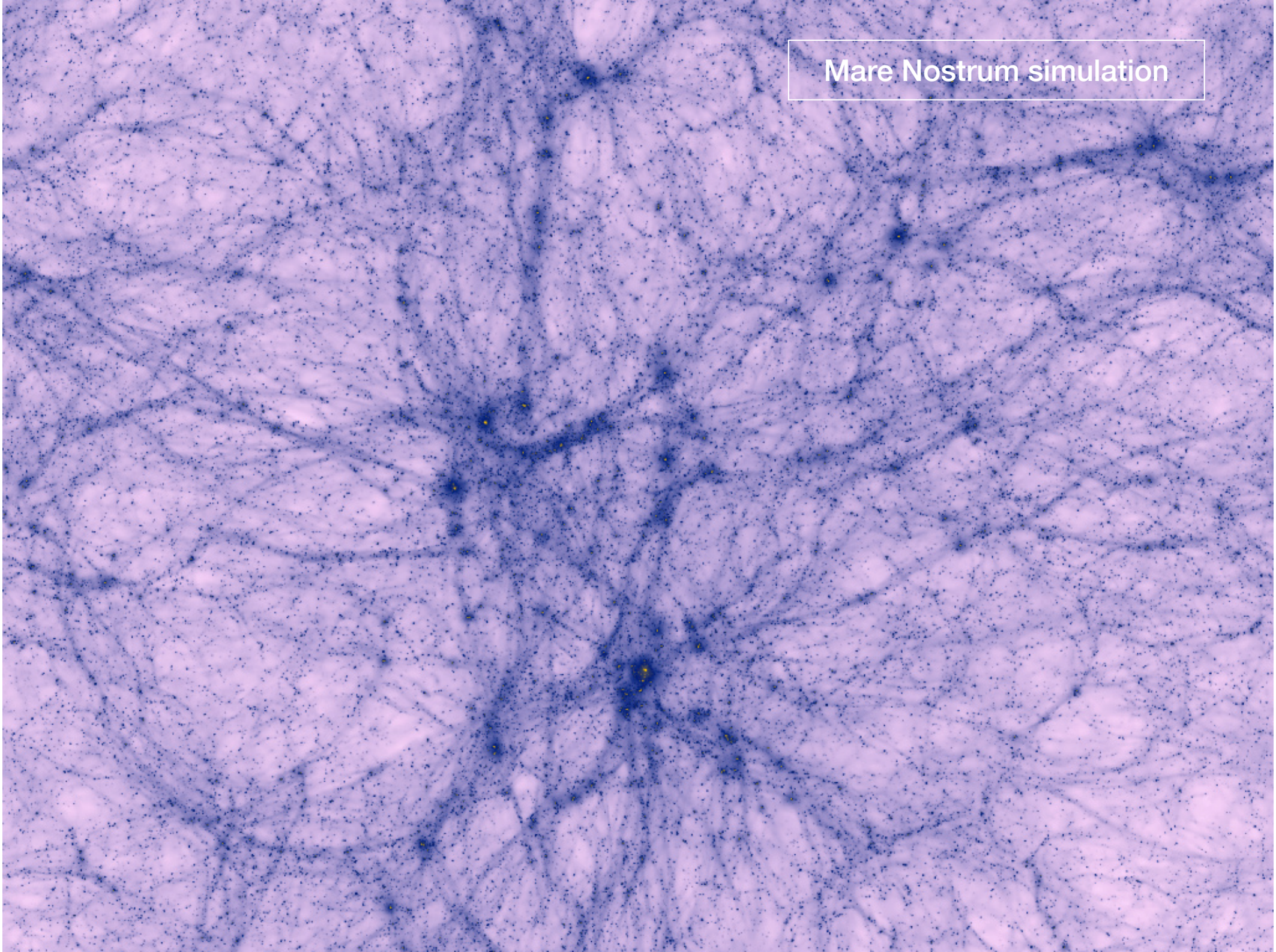


Nolta et al. (2009)





Fu et al. (2008)


Mare Nostrum simulation

The halo model

Cooray & Sheth (2002):

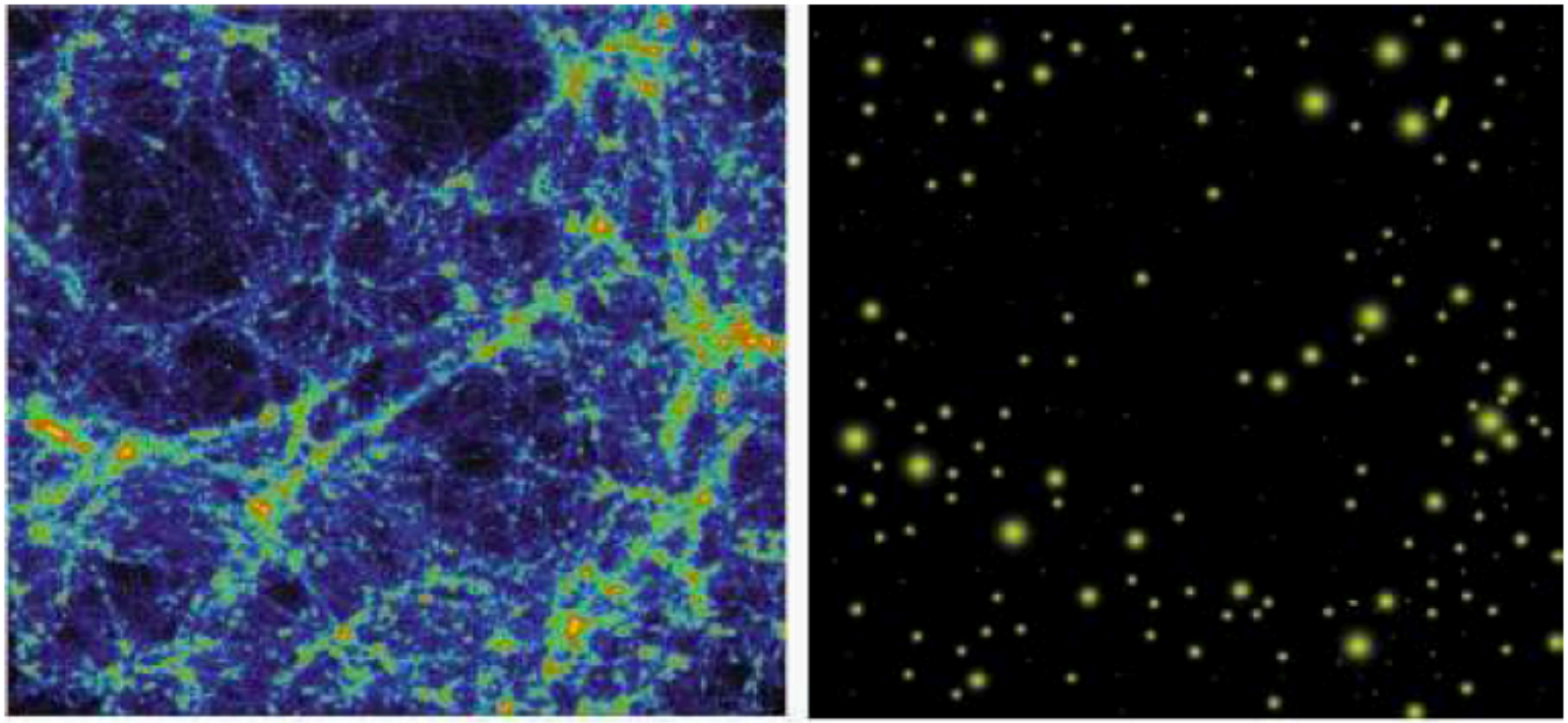
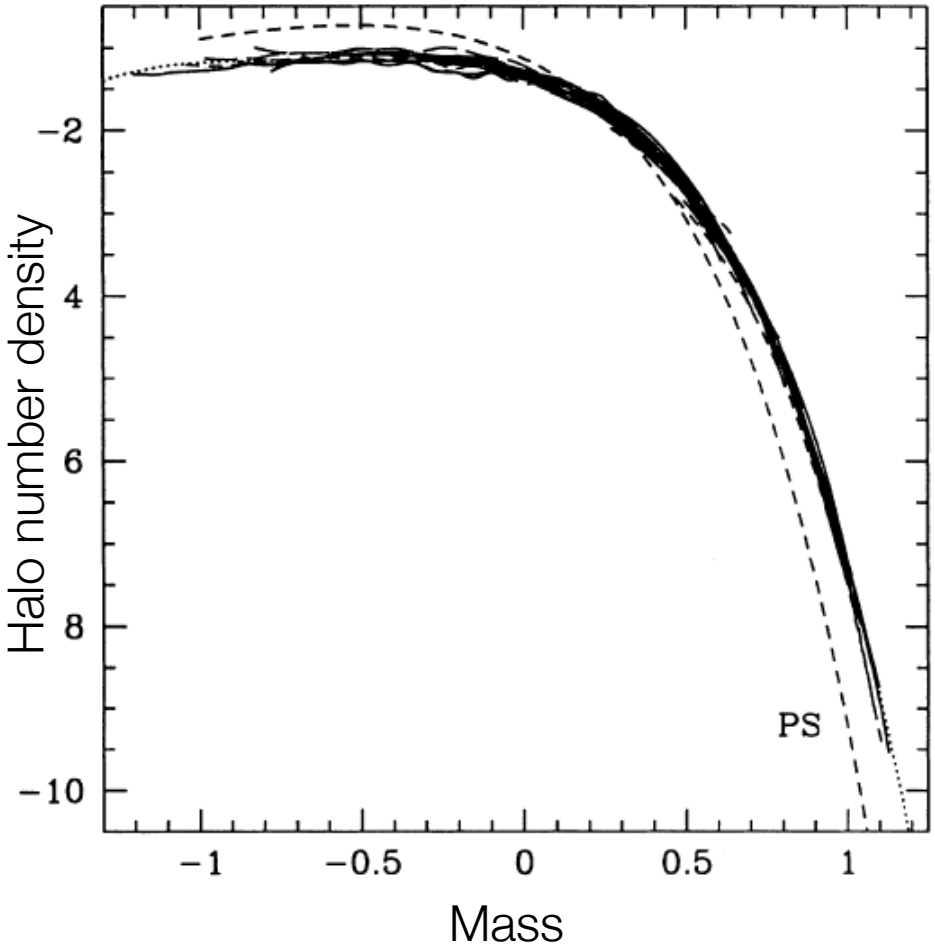


Fig. 1. The complex distribution of dark matter (a) found in numerical simulations can be easily replaced with a distribution of dark matter halos (b) with the mass function following that found in simulations and with a profile for dark matter within halos.

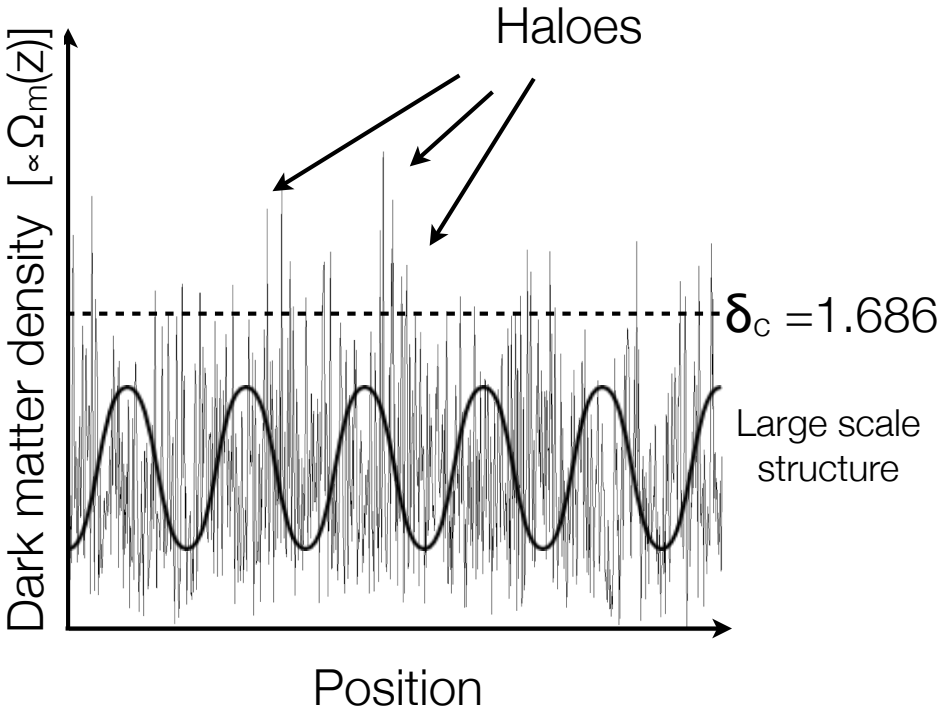
1. The halo mass function

Is the number density of haloes as function of halo mass.



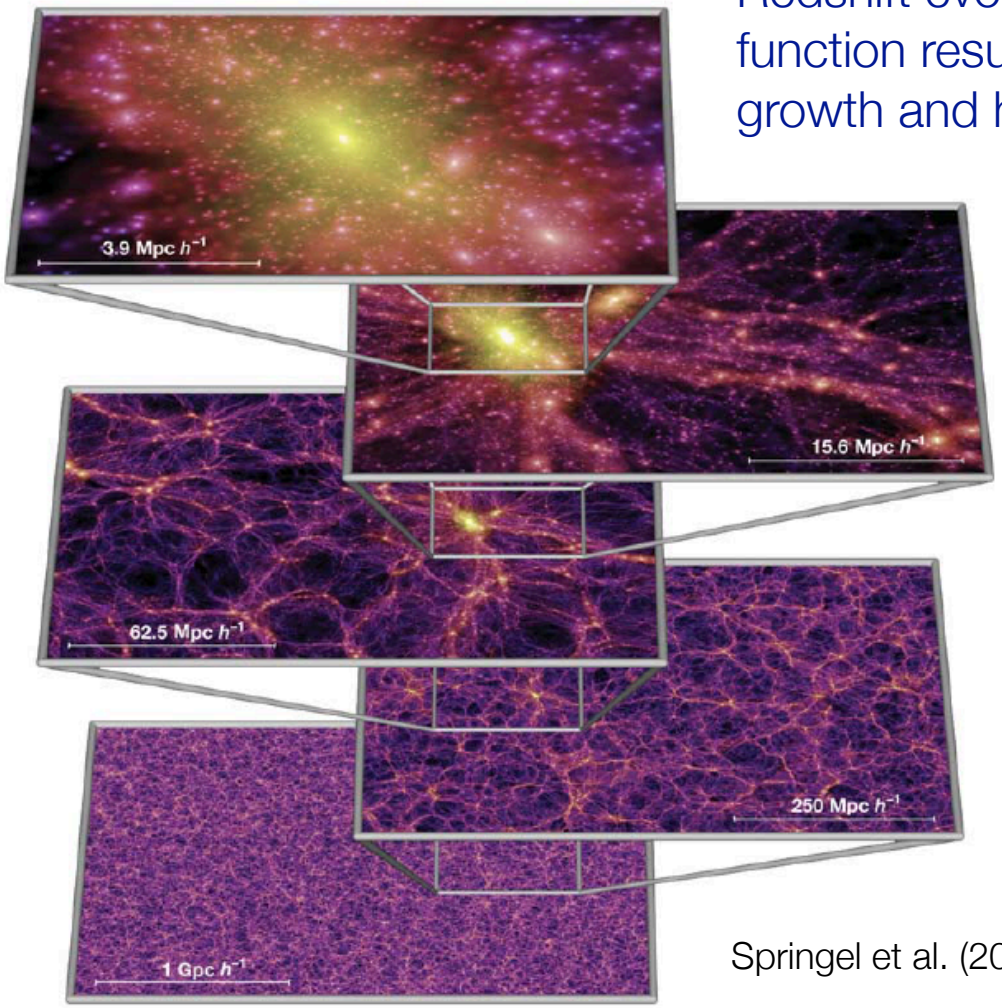
Jenkins et al. (2001):

Press & Schechter (1974) formalism: in a CDM Universe, dark matter collapses in overdense regions above the critical density δ_c to form virialised haloes.

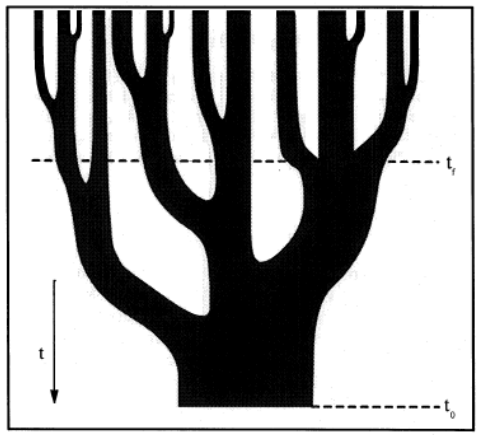


1. The halo mass function (redshift evolution)

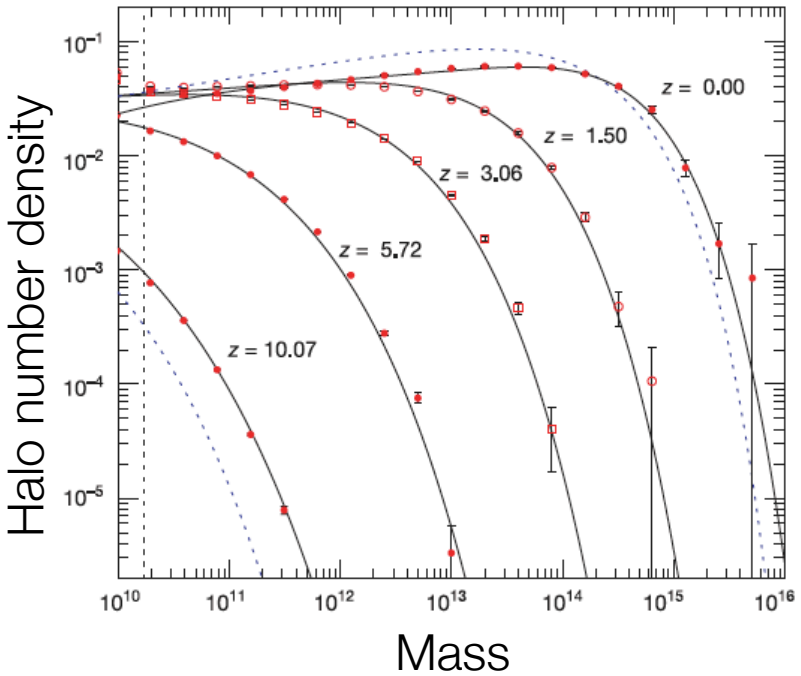
Redshift evolution of the mass function results from structure growth and halo merging.



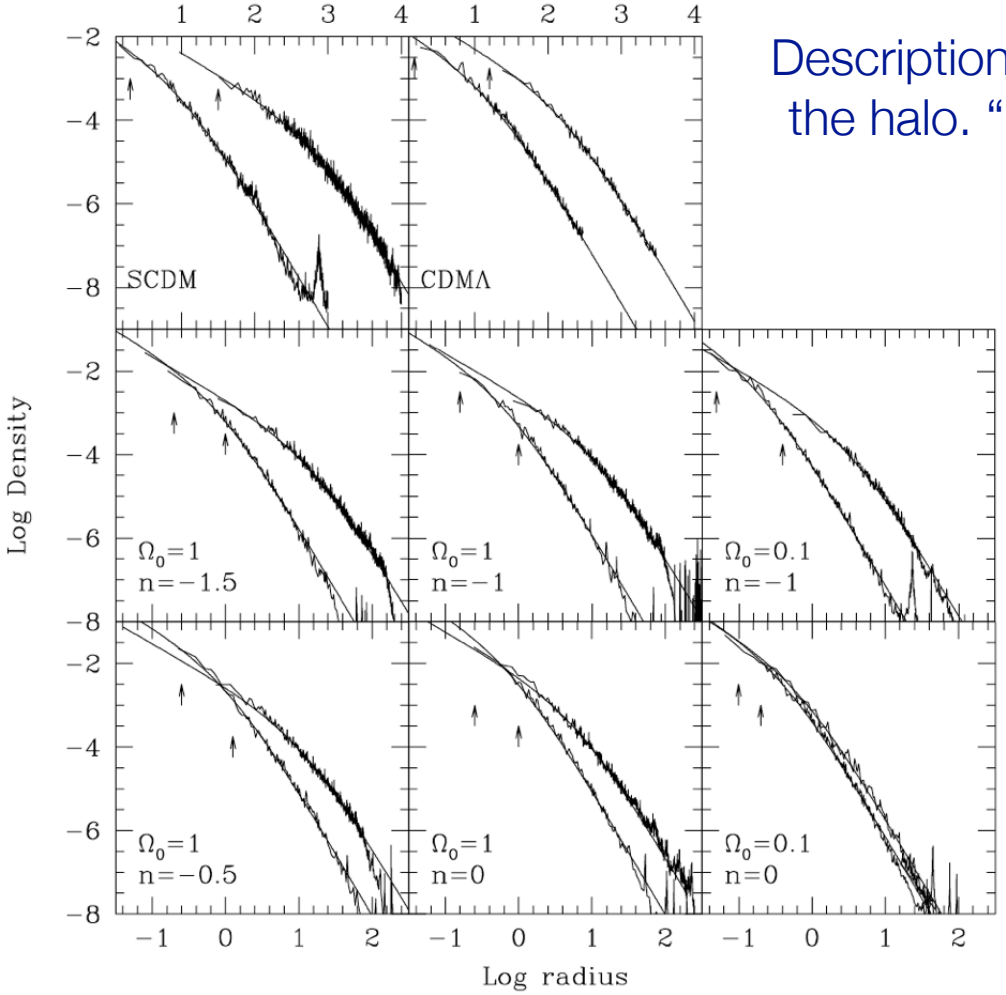
Springel et al. (2005)



Lacey & Cole (1993)



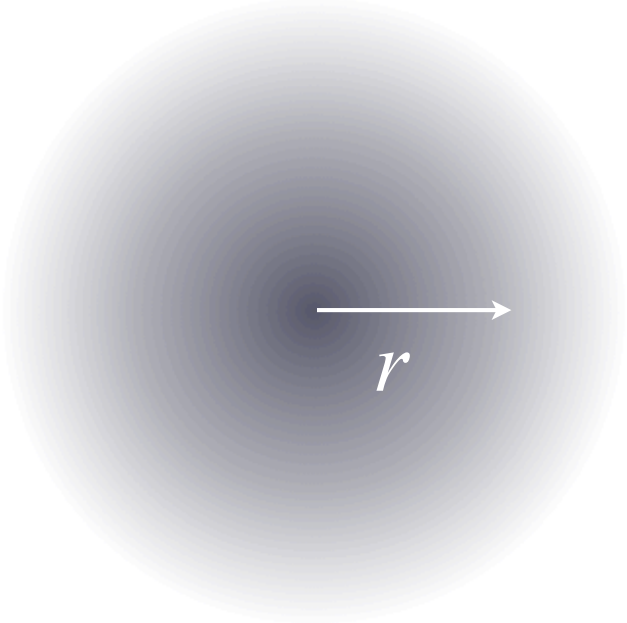
2. Halo density profile



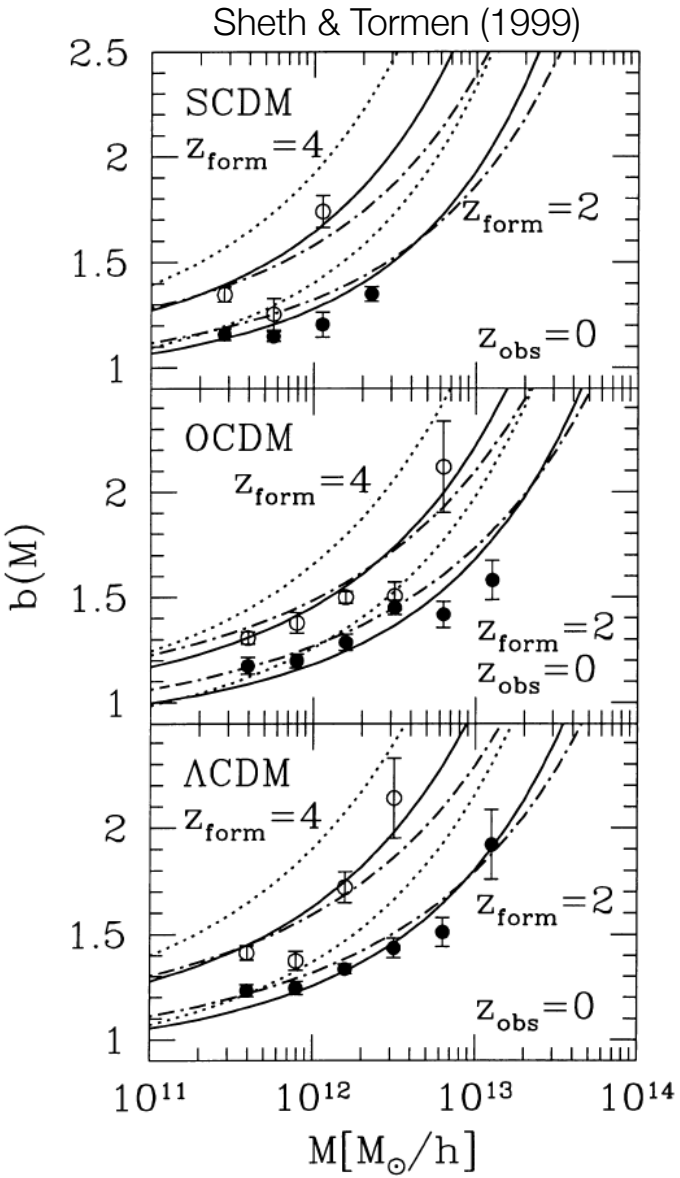
Navarro, Frenk & White (1997)

Description of how dark matter concentrates within the halo. “NFW” profile accurately fits simulations:

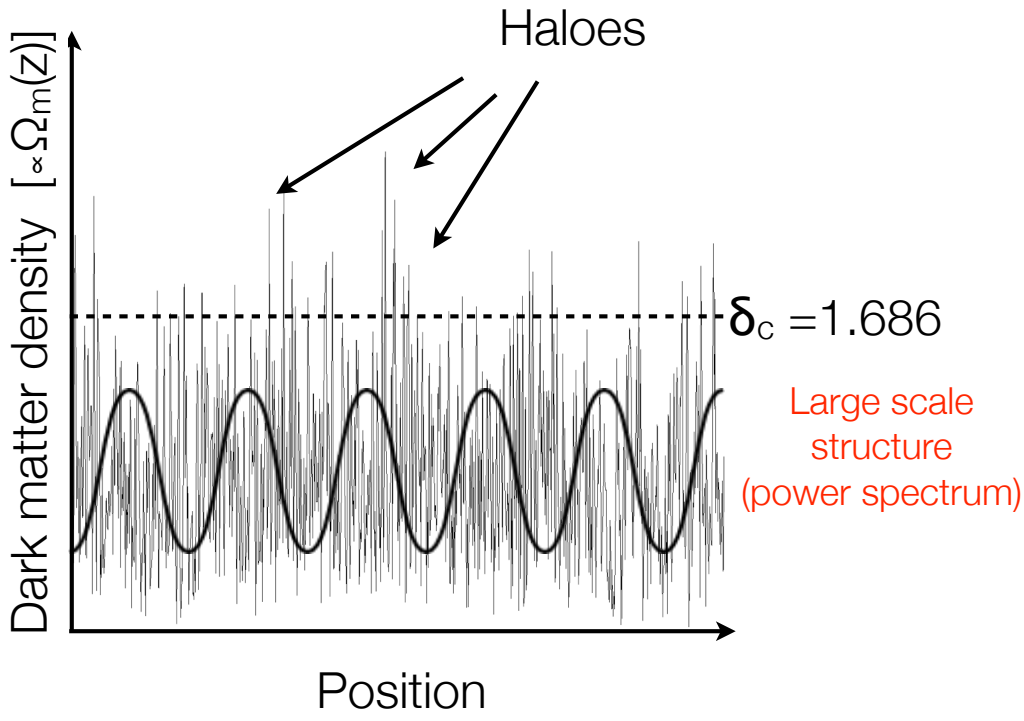
$$\rho_{\rm h}(r|M) = \frac{\rho_{\rm s}}{(r/r_{\rm s})(1+r/r_{\rm s})^2}$$



3. Halo bias

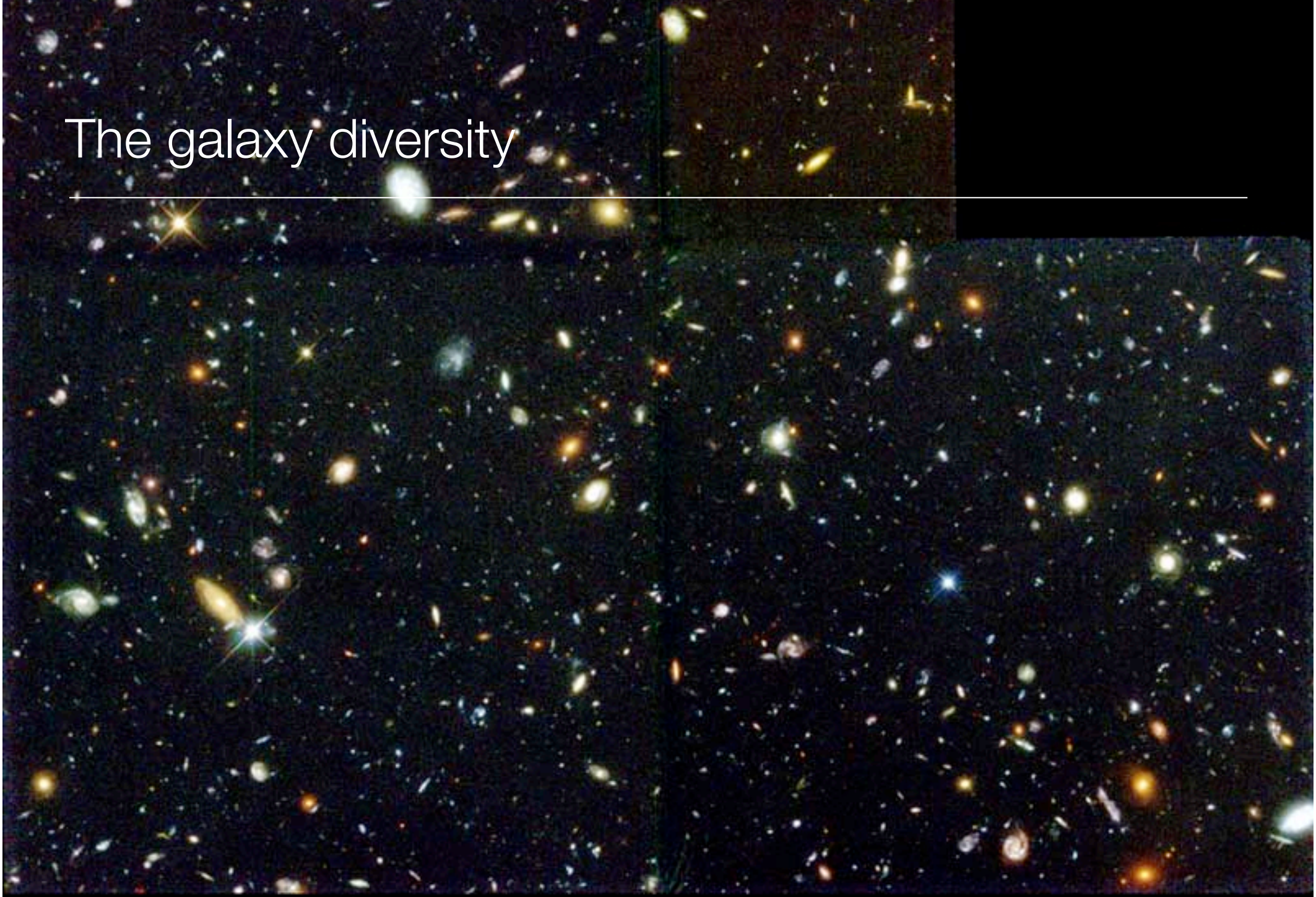


Describes dark matter halo clustering.

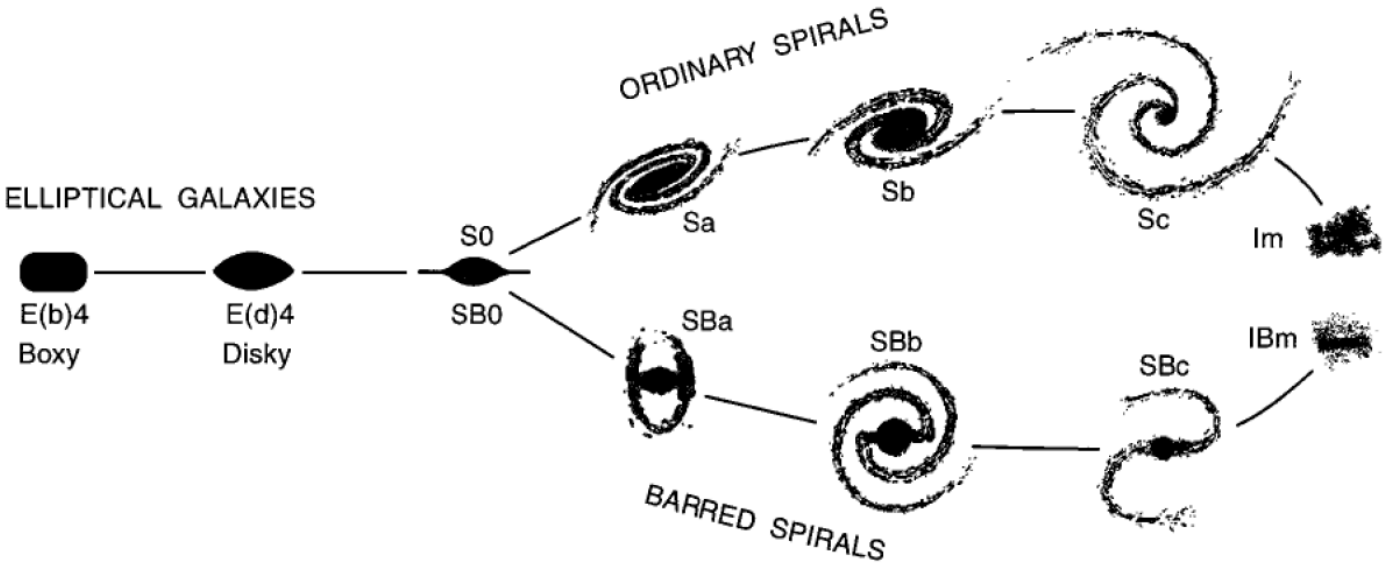


Haloes are “biased” tracers of the matter density fluctuations. b(M) is deduced from “Press & Schechter” formalism and simulations.

The galaxy diversity



The Hubble sequence



Kormendy & Bender (1996)

dwarf, irregular,
+ peculiar galaxies and
active galactic nuclei

Elliptical galaxies
or early-type galaxies
or “red” galaxies

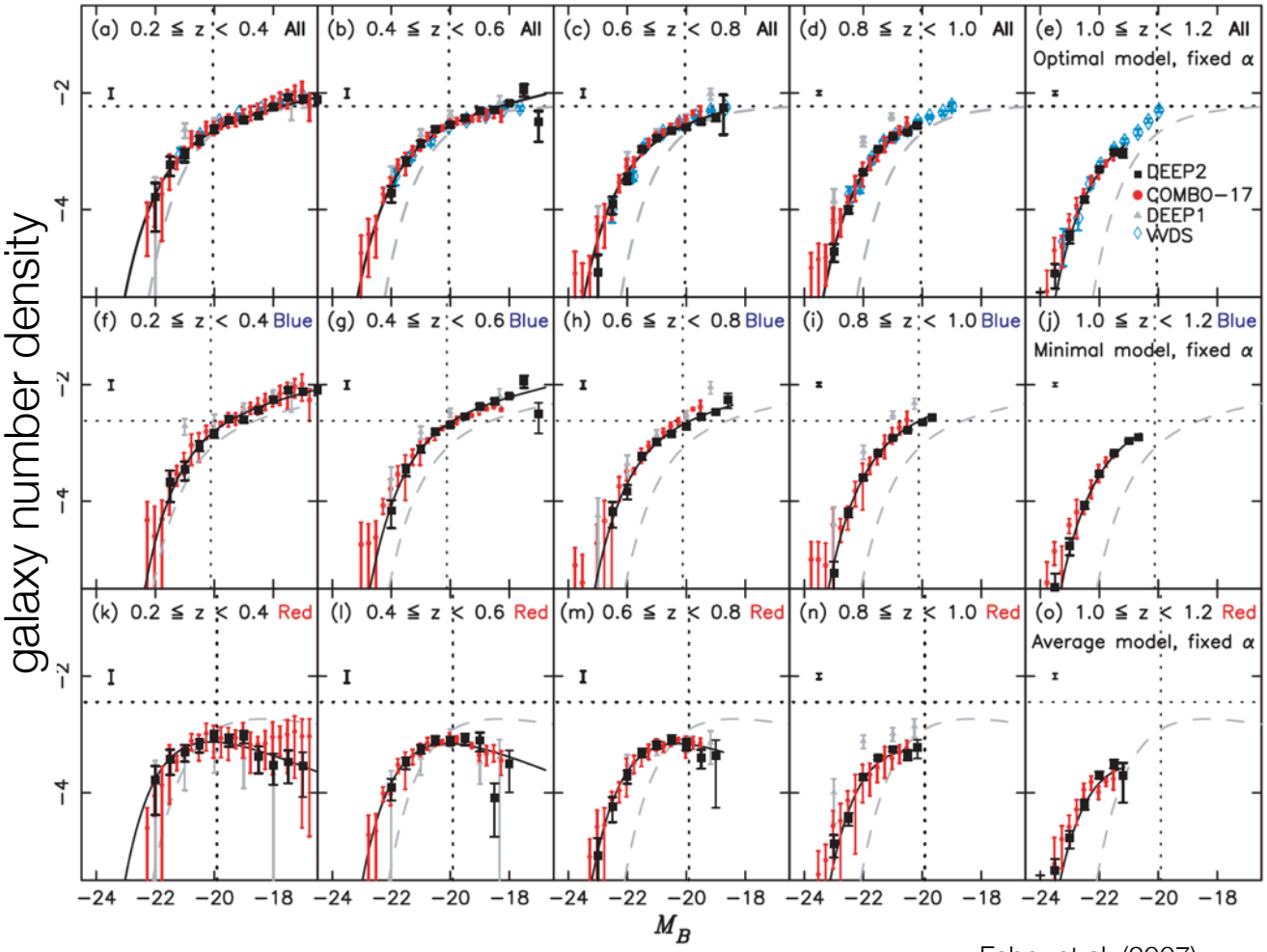
Spiral (disk) galaxies
or late-type galaxies
or “blue” galaxies

rare objects but carry
some precious information
about galaxy evolution

How did galaxies form and evolve from the initial baryon density field to the galaxy diversity as seen today?

Galaxy luminosity function

redshift

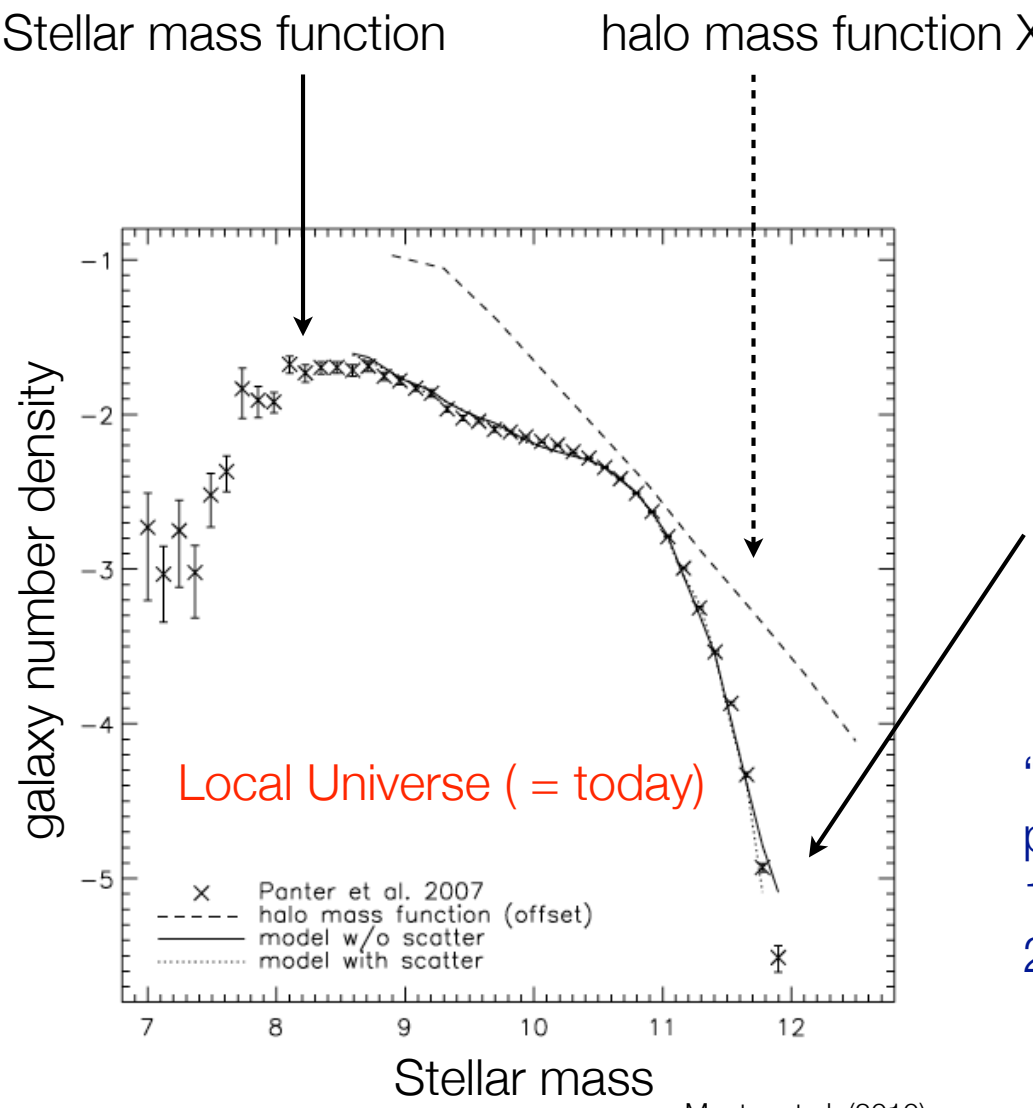


Faber et al. (2007)

- all galaxies. In grey: results from the local Universe (SDSS) -> redshift evolution
- blue galaxies. Dominate at faint luminosity
- red galaxies. Dominate at bright luminosity

WHY?

Star formation efficiency in dark matter haloes



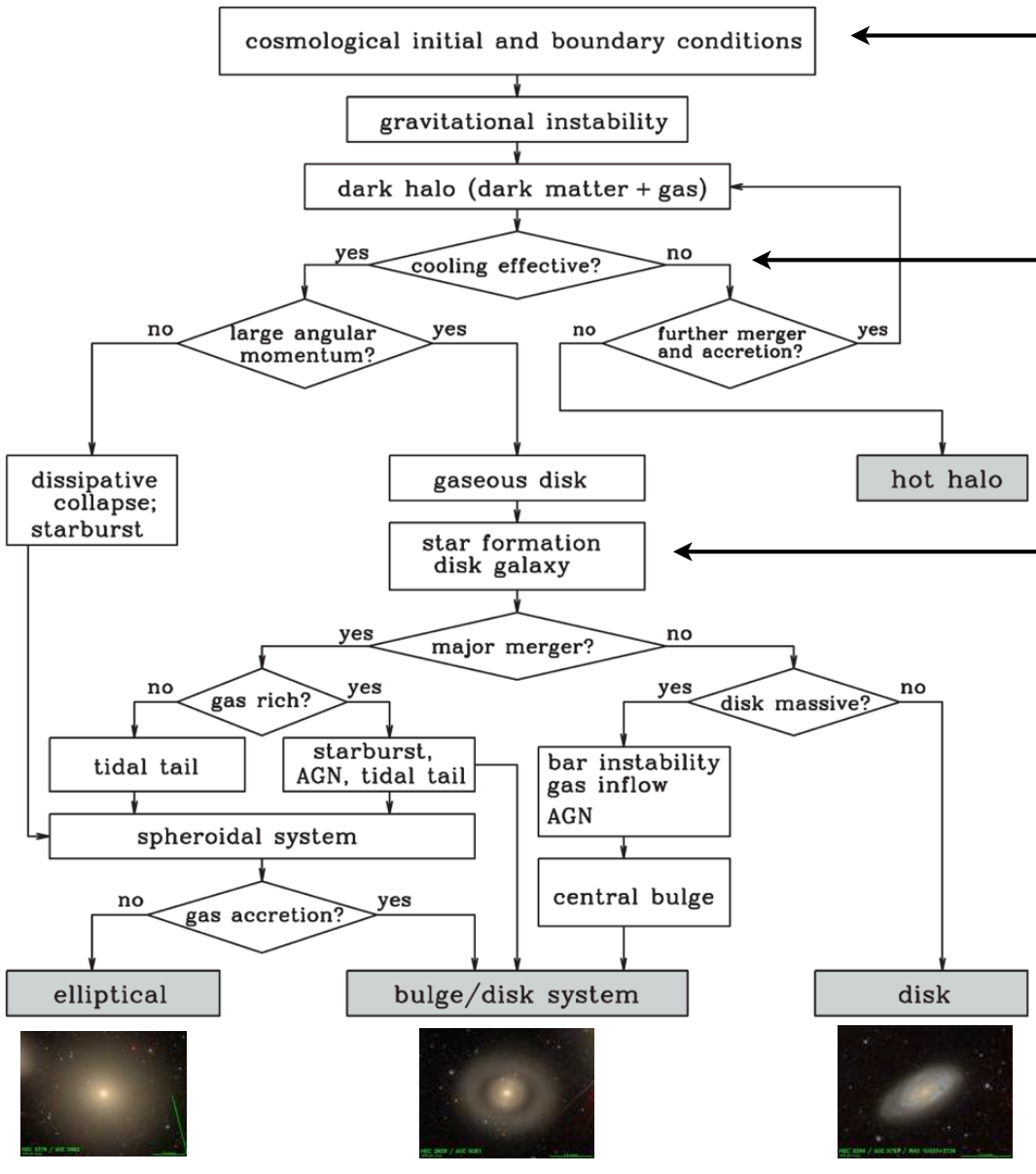
Moster et al. (2010)

star formation efficiency depends on halo mass

"no cooling, no star": there must be physical processes capable of
1. preventing the gas from cooling
2. or reheating the gas

Basics of galaxy formation and evolution

Mo et al. (2011)



ΛCDM cosmology

No cooling, no star

Star formation stops

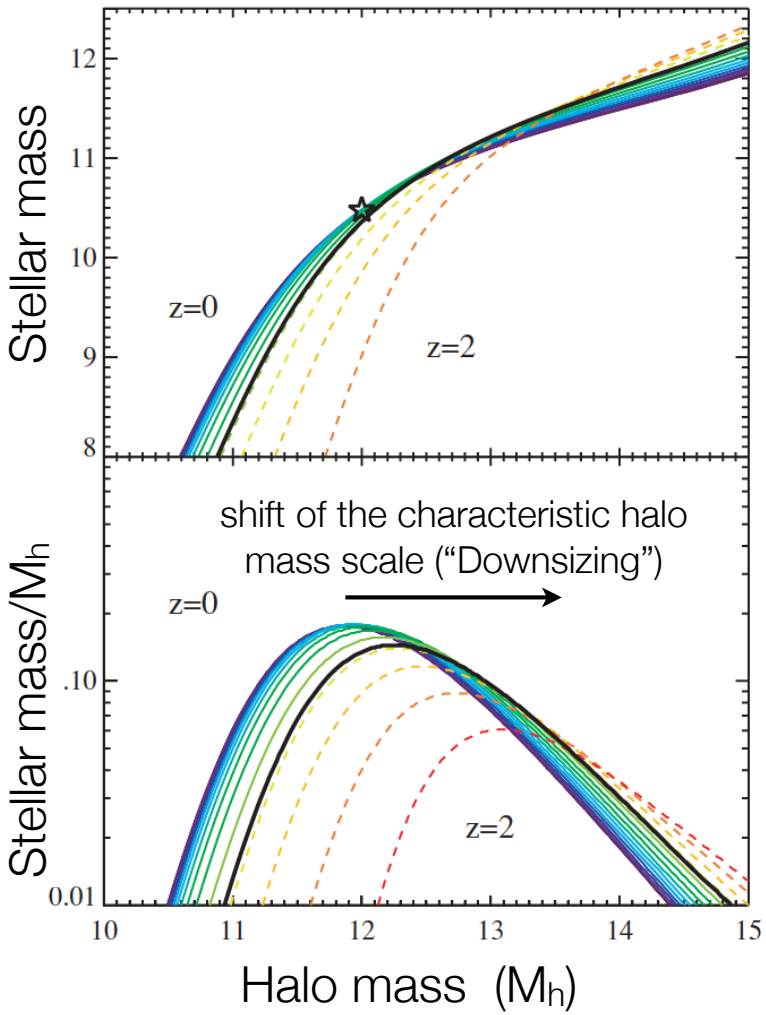
Star formation goes on

Galaxy evolution: depends on halo mass, environment and redshift

Hubble sequence observed today

SDSS, Blanton & Hogg

What drives galaxy evolution?



Conroy & Wechsler (2009)

"Pure" hydrodynamical simulations can't reproduce the observed stellar abundance.

Key questions:

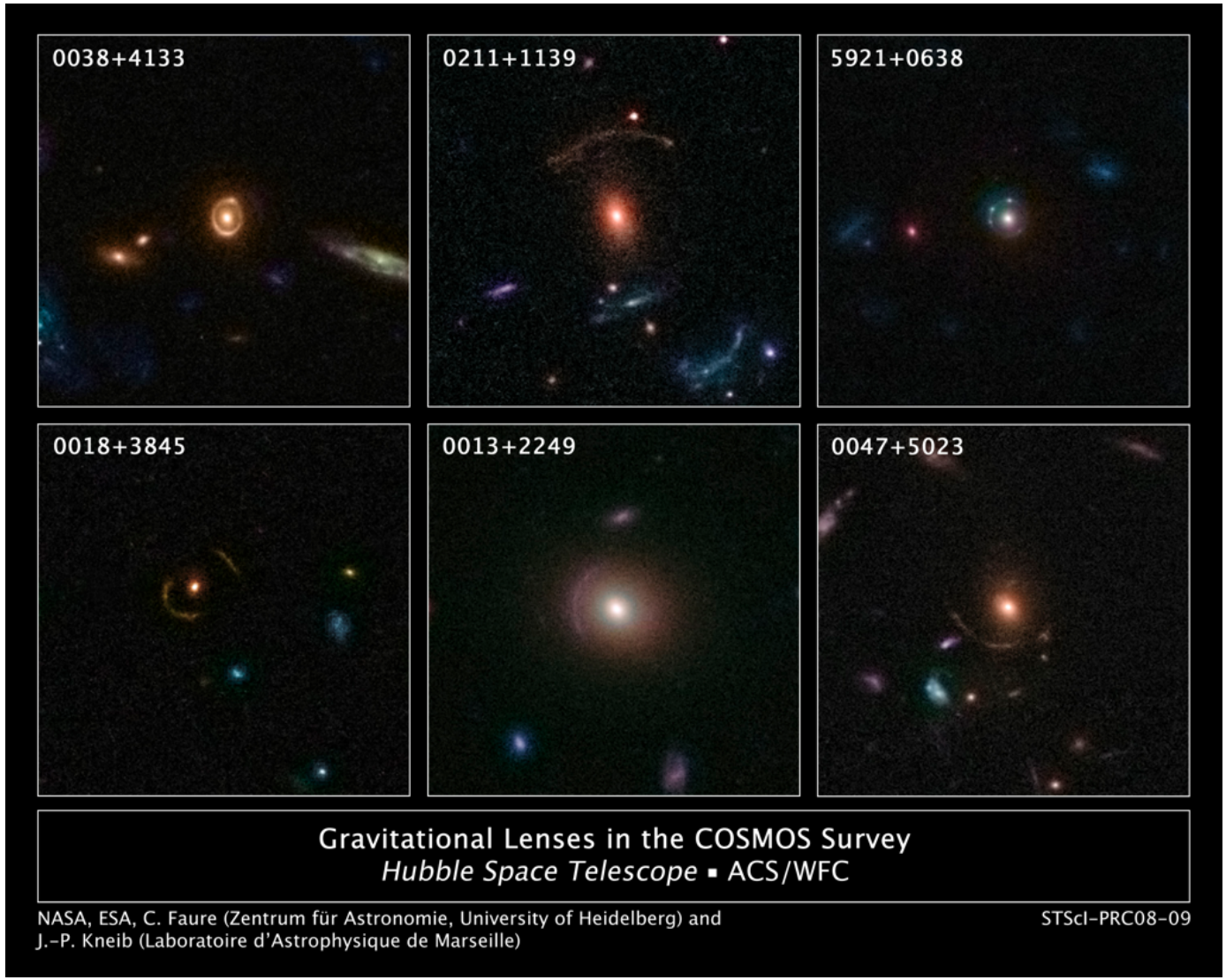
- initial conditions?
- AGN and supernovae feedback processes?
- the role of galaxy merging?
- the importance of the environment?
- impact of a different cosmology?

Strategy:

Observing the stellar-to-halo-mass ratio as function of redshift to compare it with plausible scenarios

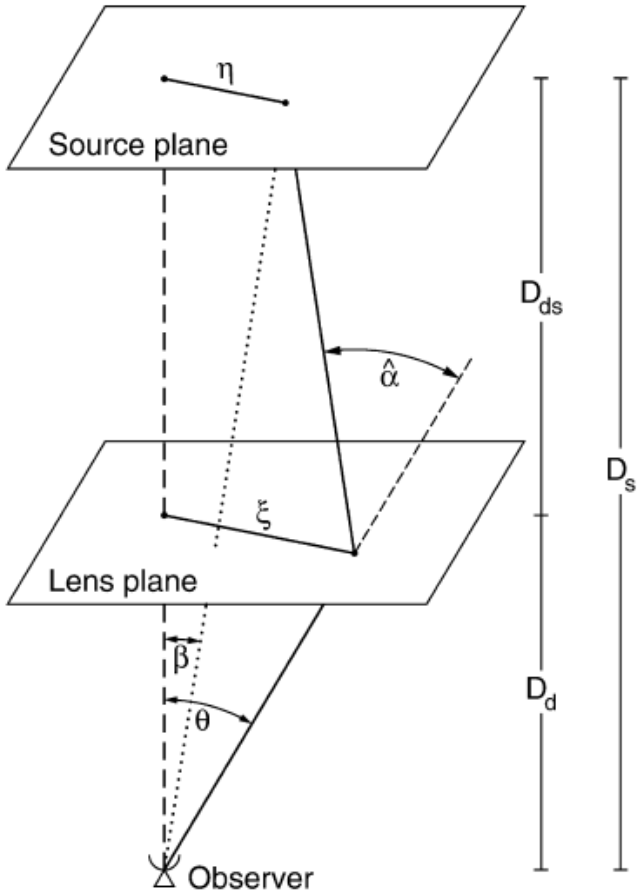
But how to link galaxy properties with halo mass?

1. The ideal case: gravitational lensing



1. The ideal case: gravitational lensing

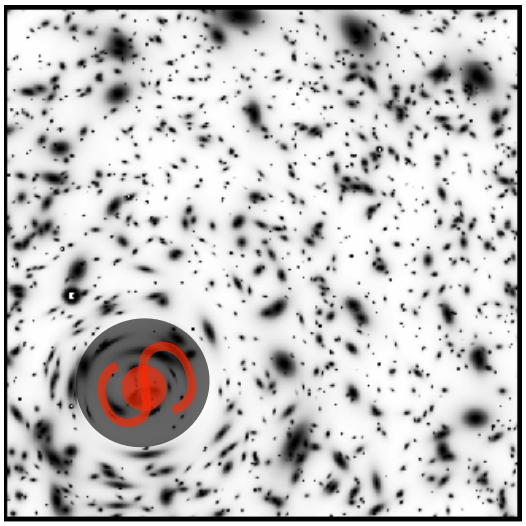
- provides a direct estimate of the mass, but...
- requires rare events such as “Einstein rings” or massive objects
- is limited to relatively low redshift due to less and less background sources at high redshift
- needs some more experience to measure shapes with no systematic errors

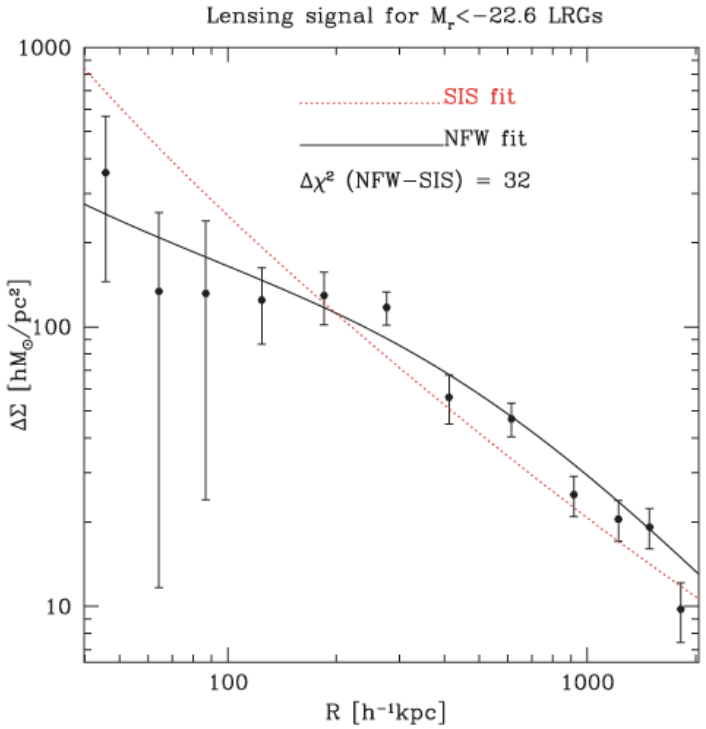


Bartelmann & Schneider (2001)

1. The ideal case: gravitational lensing

Galaxy-galaxy lensing





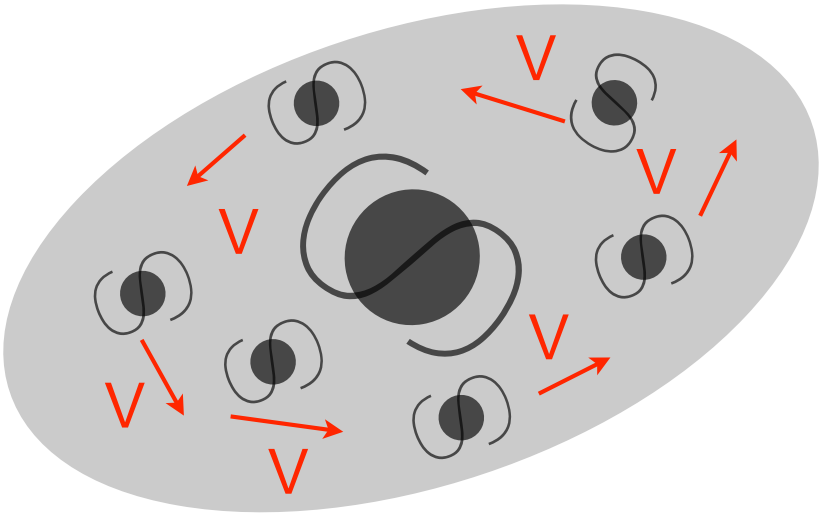
stacked projected density profile from lensing

Mandelbaum et al. (2006)

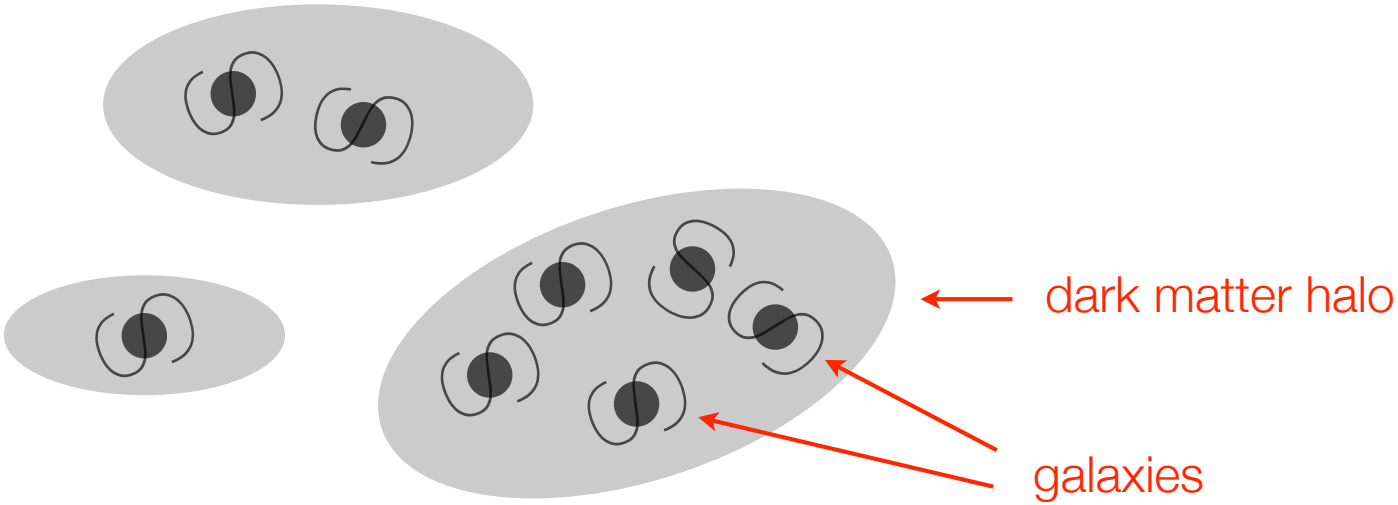
halo mass

2. Satellite kinematics

- also provides a direct estimate of the mass, but...
- requires spectroscopic redshifts
- requires satellites (whereas most galaxies are single)
- and is also limited to relatively low redshift since it relies on faint objects (satellites)

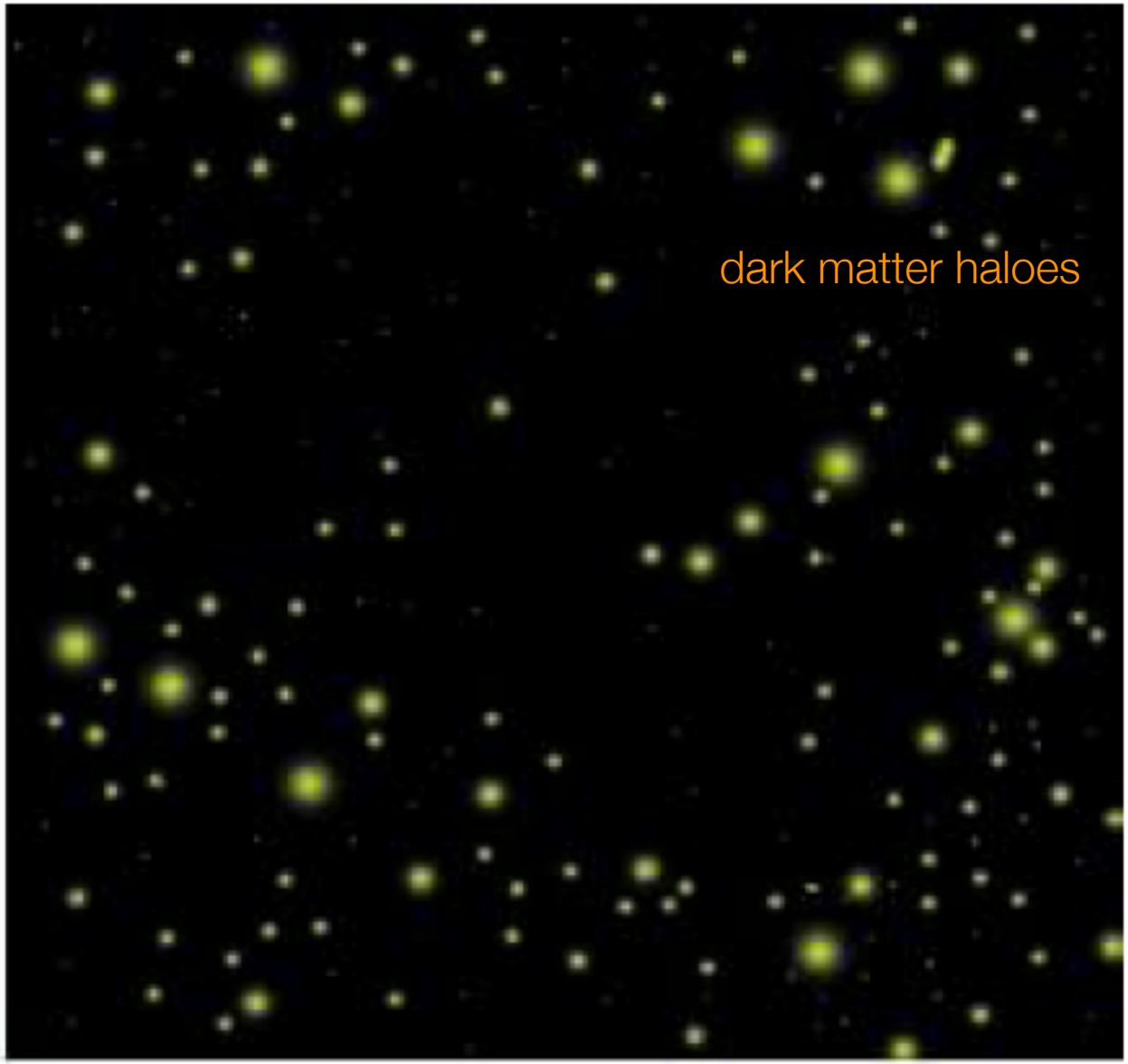


3. The halo occupation distribution model



- dark matter (halo) space distribution is predicted by the halo model
- If one knows how galaxies populate haloes, one can predict
  - the galaxy number density
  - the galaxy distribution (clustering)

3. The halo occupation distribution model



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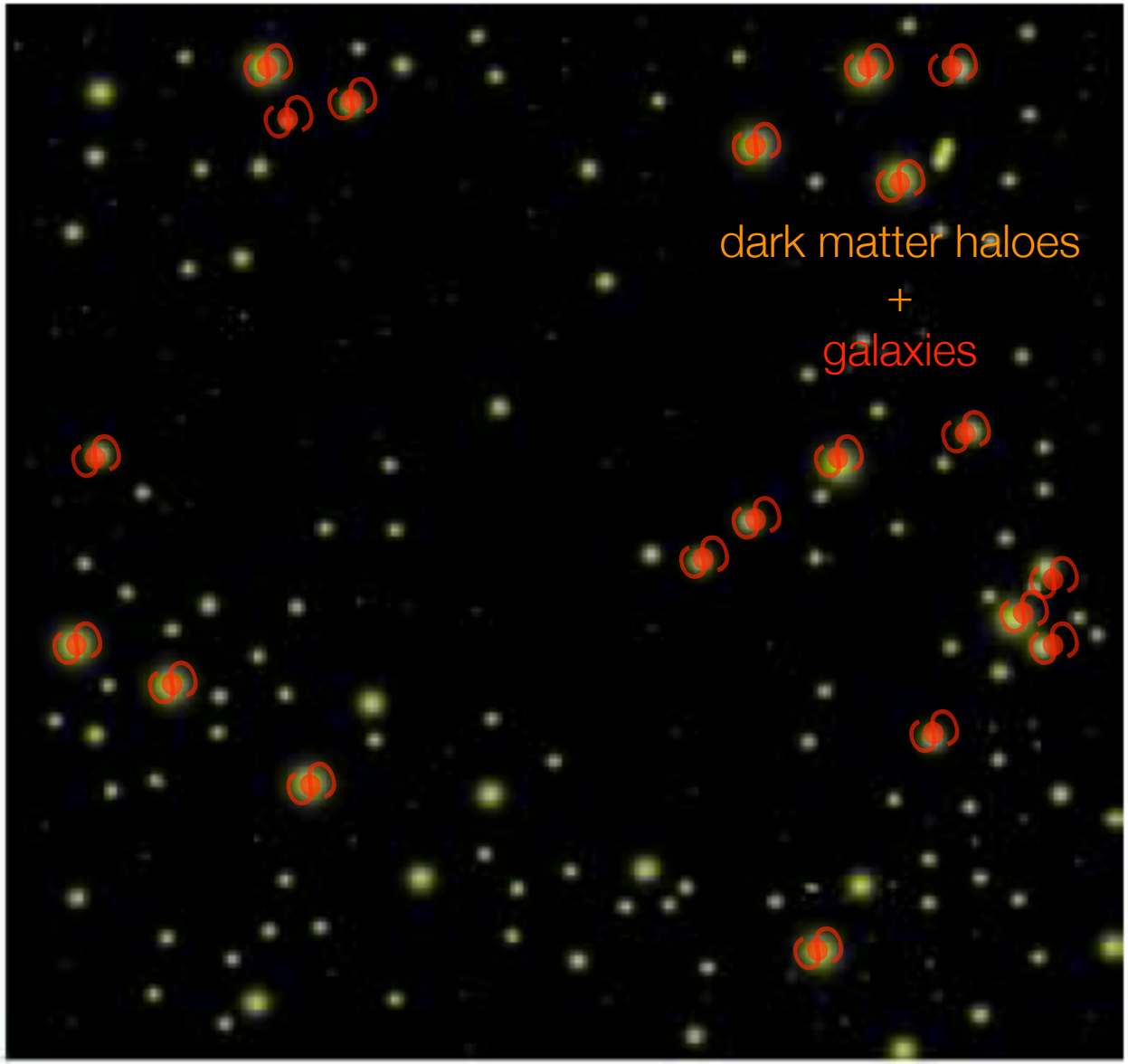

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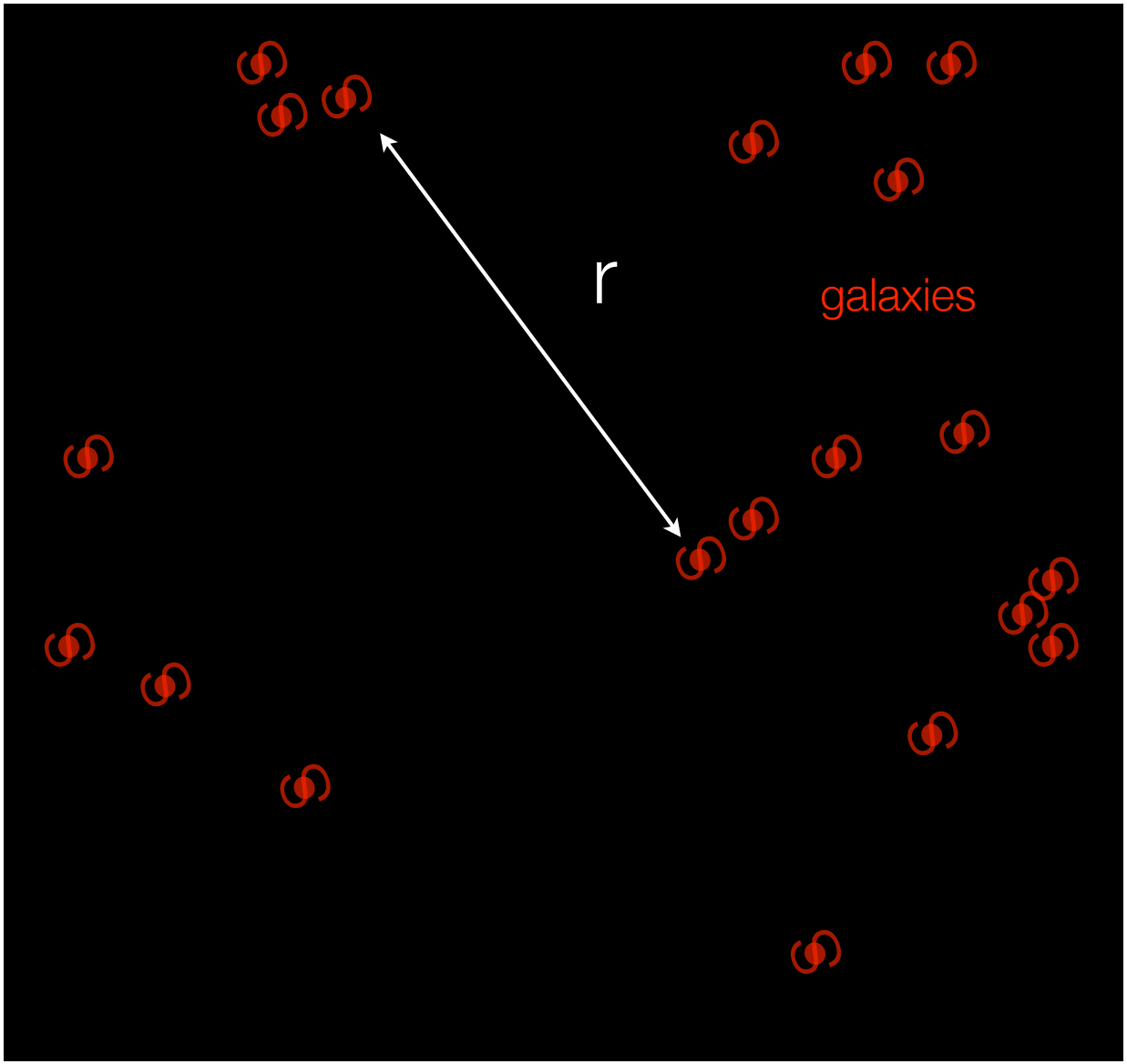


Last step: how do galaxies populate haloes?

Hypotheses:

1: the number of galaxies ONLY depends on halo mass

2: cosmology is fixed (otherwise degenerate with galaxy bias)

$$N \propto M_{\rm h}^{\alpha}$$

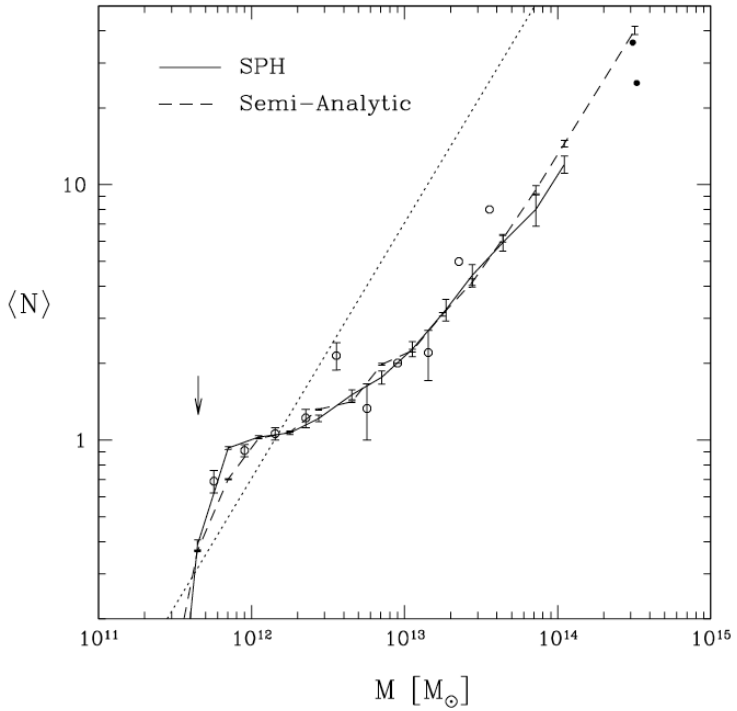
galaxy number (observable)

Halo mass (deduced quantity)

Ref: Berlind & Weinberg (2002, 2003); Kravtsov et al. (2004); Zheng et al. (2005), etc.

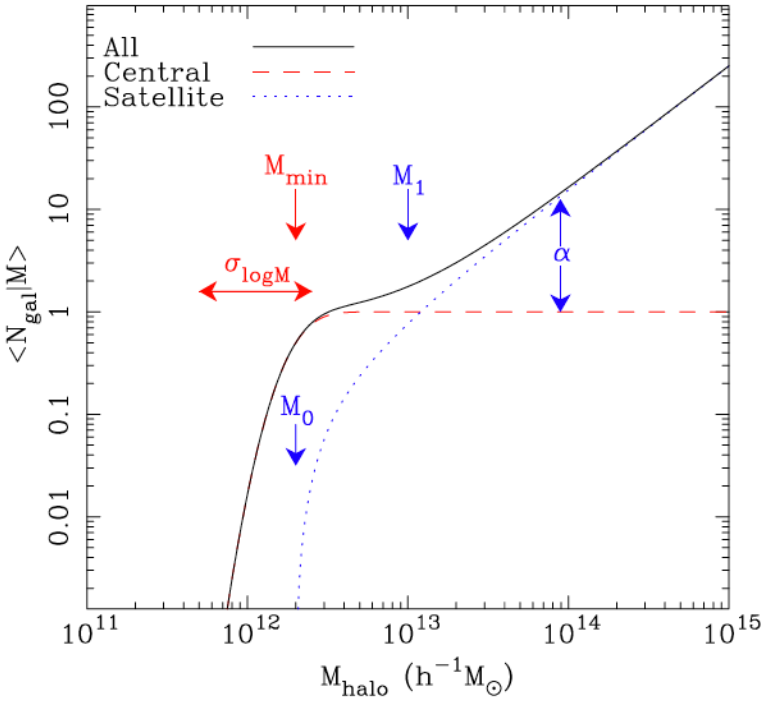
Last step: how do galaxies populate haloes?

Simulations



Berlind & Weinberg (2003)

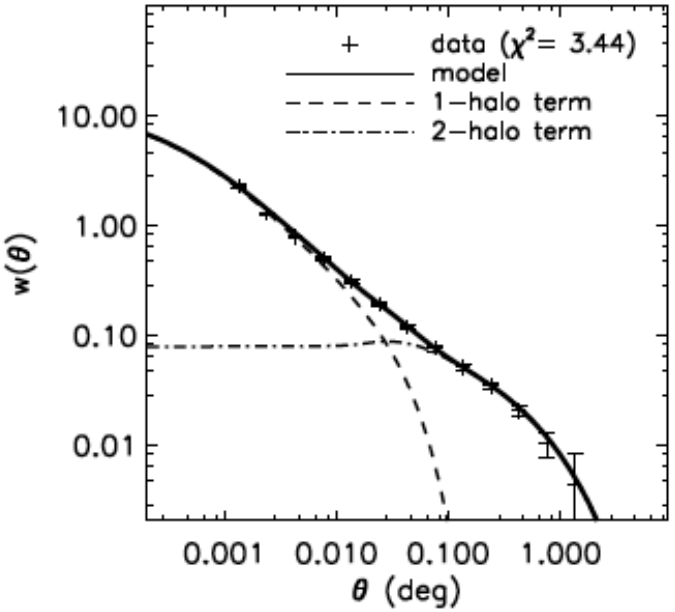
Analytic expression

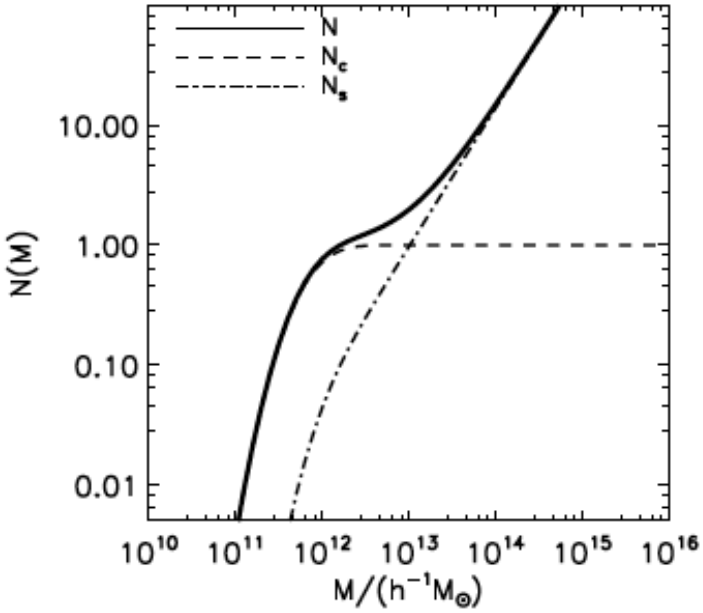


Wake et al. (2011)

In this parameterization, M_{min} is the halo mass of the central galaxy

From HOD to observables: galaxy clustering





Halo density profile convolved with HOD

Halo bias convolved with HOD

Last step: projection of xi(r) with redshift distribution

$$\xi(r) = 1 + \xi_1(r) + \xi_2(r)$$

$$w(\theta) = 2 \int_0^\infty \mathrm{d}x\, f(x)^2 \int_0^\infty \mathrm{d}u\, \xi(r = \sqrt{u^2 + x^2\theta^2})$$

Physical parameters

$$b_{\rm g}(z) = \int {\rm d}M\, b_{\rm h}(M,z)\, n(M,z) \frac{N(M)}{n_{\rm gal}(z)}$$

Galaxy bias

$$\langle M_{\rm halo} \rangle (z) = \int {\rm d}M\, M\, n(M,z) \frac{N(M)}{n_{\rm gal}(z)}$$

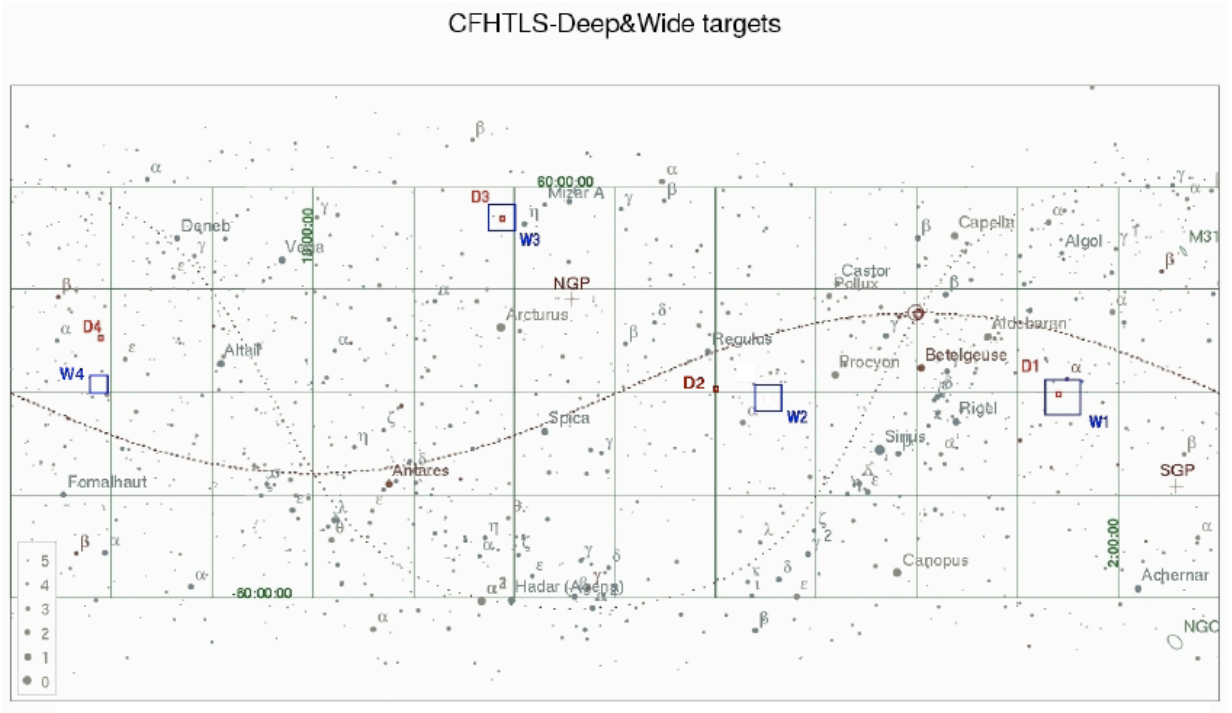
Mean halo mass

$$f_{\rm c}(z) = \int {\rm d}M\, n(M,z) \frac{N_{\rm c}(M)}{n_{\rm gal}(z)}$$

Satellite fraction (1-f_c)

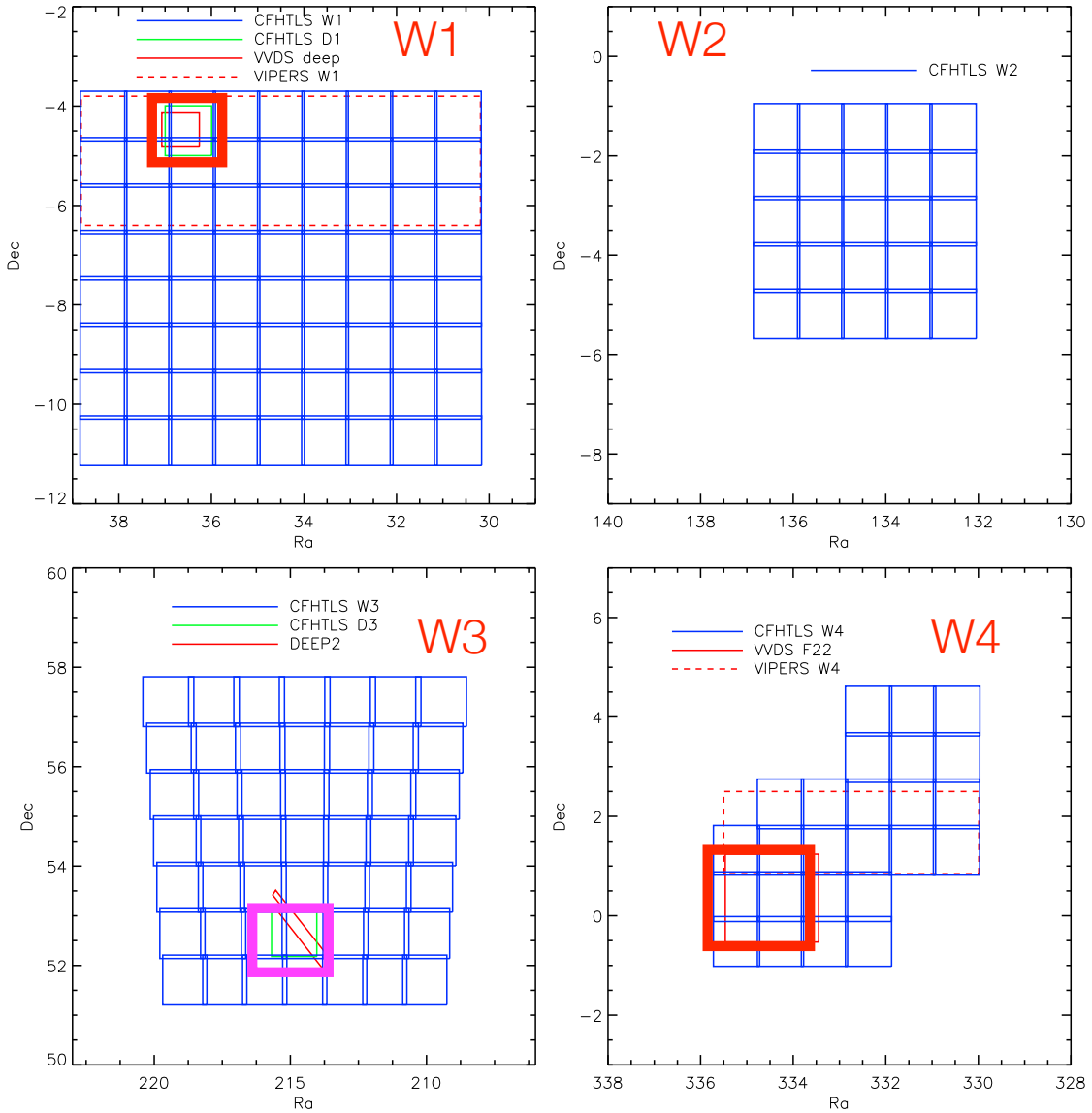
II. CFHTLS-Wide: new insights on galaxy evolution since z ~ 1.2 from galaxy clustering

The Canada-France-Hawaii Telescope Legacy Survey (CFHTLS)



- 450 nights observed with Megacam @ CFHT in u,g,r,i,z filters
- Terapix is in charge for the data reduction (latest release T0006)
- the survey is completed since december 2008
- Deep survey: 4 independent fields (total 4 deg2) i < 27.5
- Wide survey: 4 independent fields (total 133 deg2) i < 25.5
- Very Wide survey

CFHTLS-Wide and spectroscopic data



Effective area of the Wide: 133 deg^2
3,000,000 photo-z's in the Wide part
600,000 photo-z's in the deep part
(S/N ~ 40)

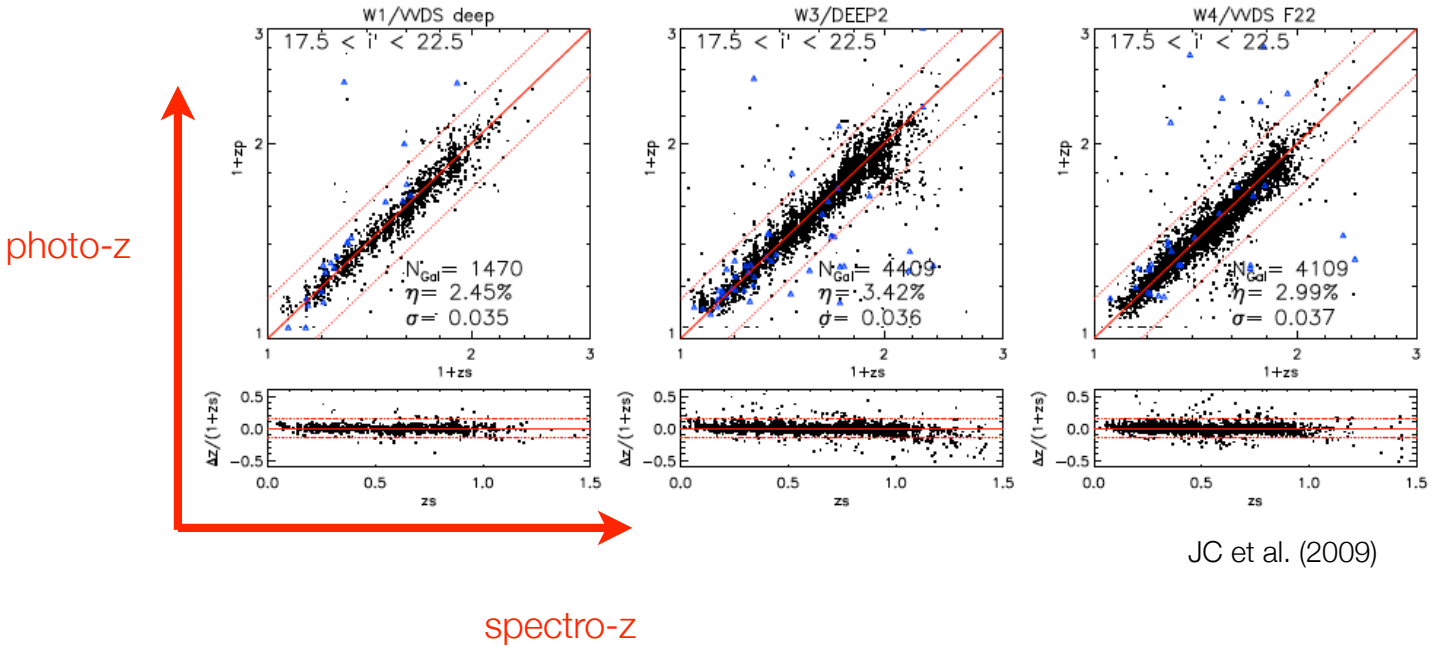
calibrated with 20,000 spectra:

- VVDS Deep (Le Fèvre et al 2005)
- VVDS F22 Wide (Garilli et al 2008)
- DEEP2 (Davis et al 2007)

Photometric redshift accuracy

Photo-z's computed from the Terapix T0006 release using template fitting method and spectro-z calibration (Ilbert et al. 2006, JC et al. 2009):

1. correction of systematic offsets
2. adaptation of templates
3. use of n(z) prior



JC et al. (2009)

Dispersion:
$\sigma = 0.04(1+z)$

Outlier rate: $\eta < 4\%$

The full sample includes 3,000,000 reliable redshifts (i < 22.5) over 4 independent fields covering 155 deg^2 (effective area).

Fast angular correlation function measurements

Landy & Szalay (1993) estimator
(low variance and bias)

PB: classic estimator scales as N^2
would take weeks for ~ 1 000 000 object samples

SOLUTION: for large angular separations, correlate boxes instead of individual objects and build optimised boxes with kd-tree (scale as NlogN)

adaptive approximation ~ 0.5

$\alpha_w = \theta / d_b$

size of the box

angular separation

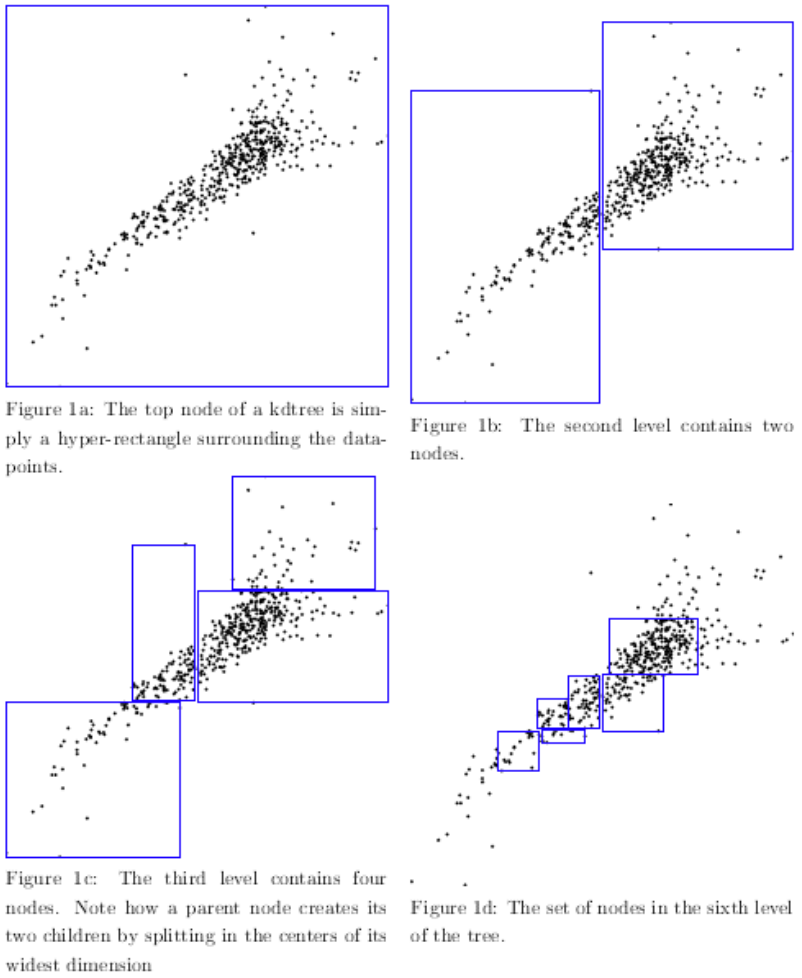


Figure 1a: The top node of a kdtree is simply a hyper-rectangle surrounding the data-points.

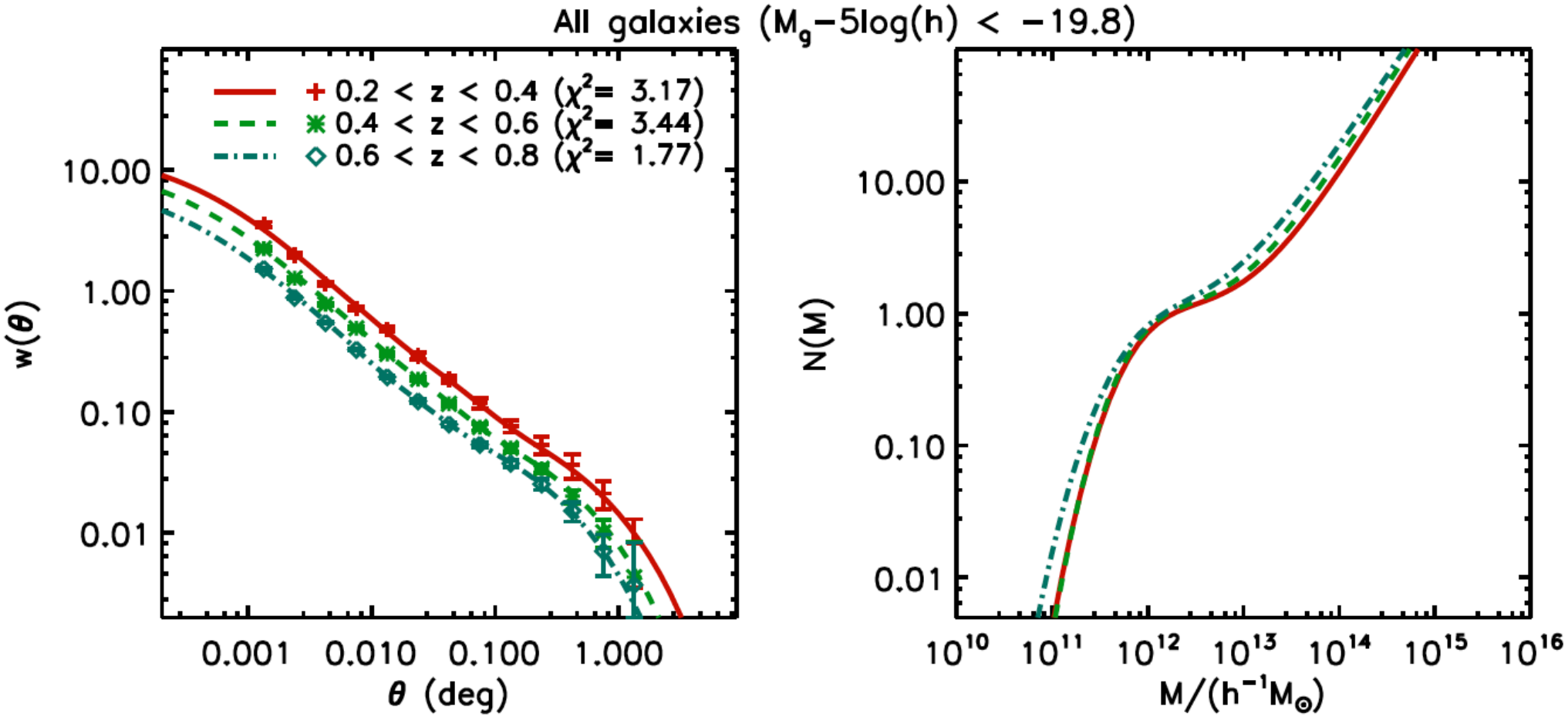
Figure 1b: The second level contains two nodes.

Figure 1c: The third level contains four nodes. Note how a parent node creates its two children by splitting in the centers of its widest dimension

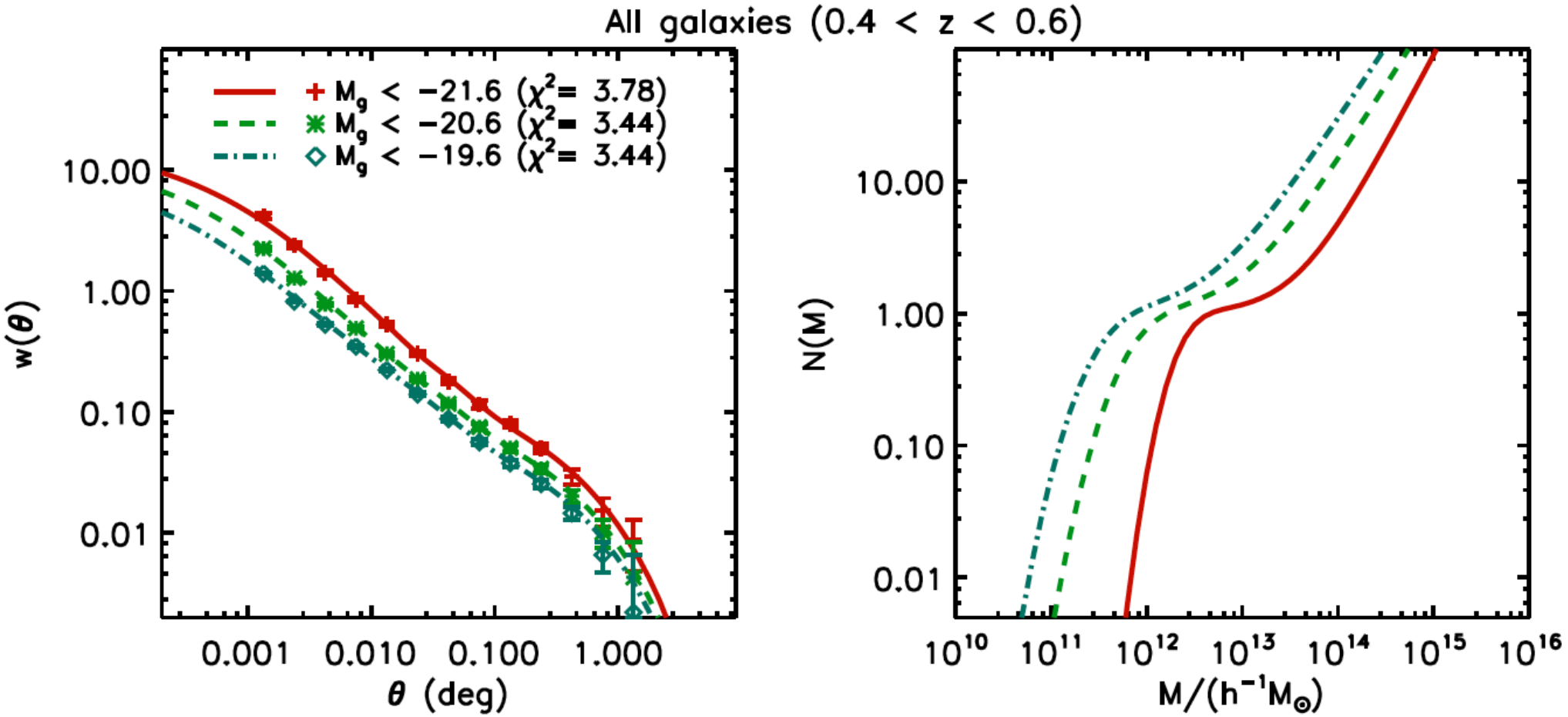
Figure 1d: The set of nodes in the sixth level of the tree.

Moore et al. (2001)

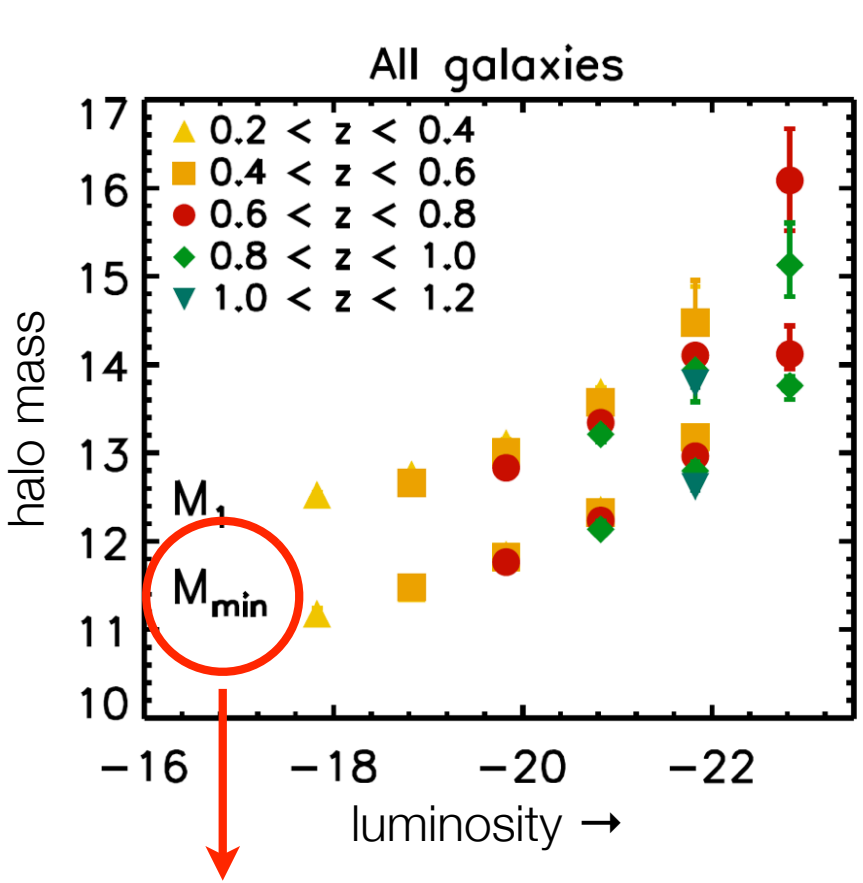
Redshift evolution - all galaxies



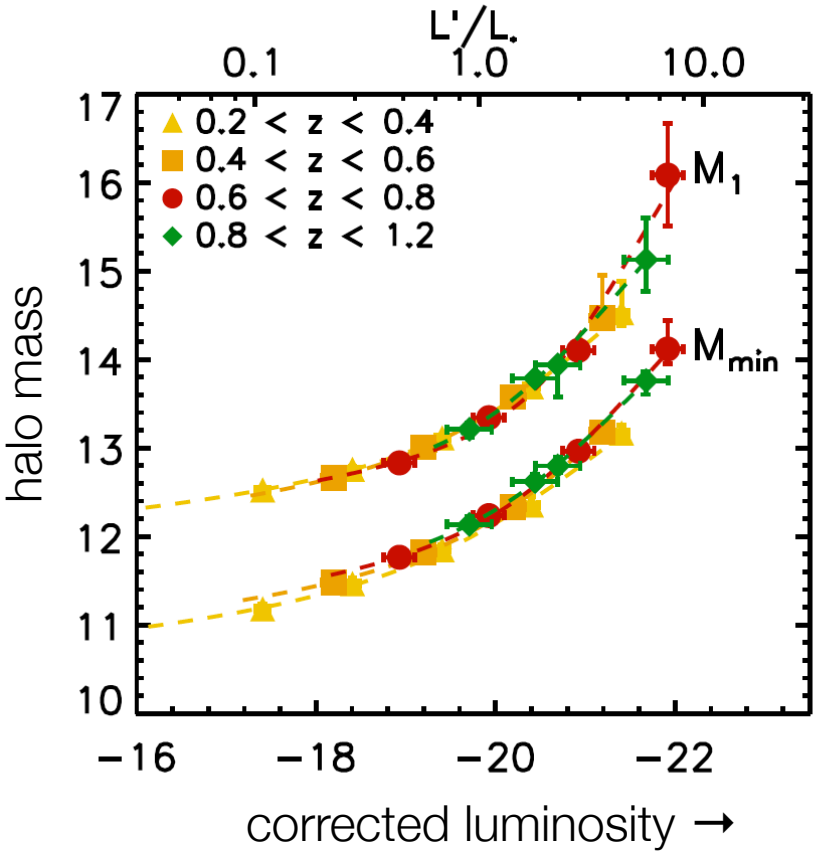
Luminosity dependence - all galaxies



Stellar-to-halo mass relationship - all galaxies



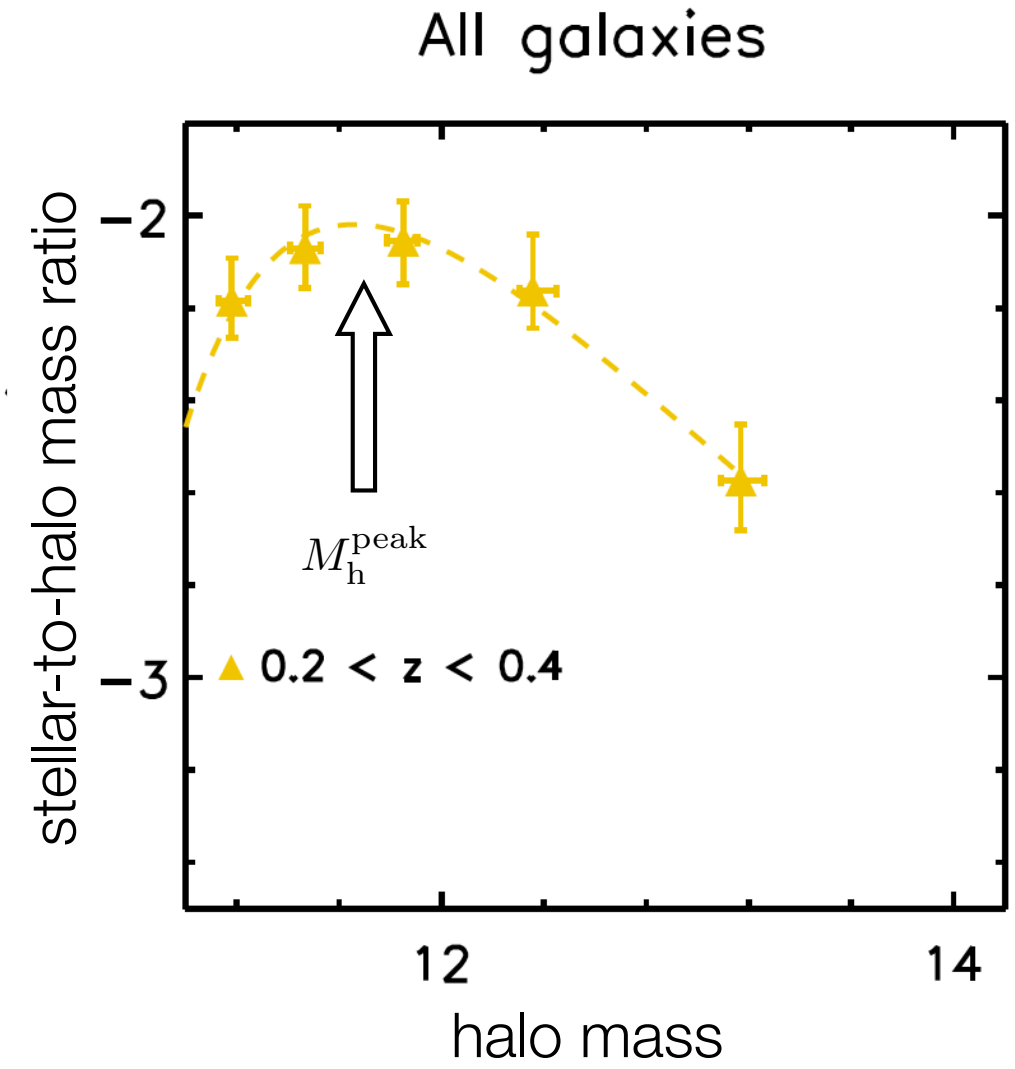
Halo mass for central galaxies



Correct for luminosity evolution
= stellar mass proxy

JC et al. (2012)

Stellar-to-halo mass ratio vs halo mass



We can re-write

$$\frac{L'_{\rm c}}{L_*} = A\left(\frac{M_{\rm h}}{M_{\rm t}}\right)^{\alpha_M}\exp\left(-\frac{M_{\rm t}}{M_{\rm h}}+1\right)$$

into

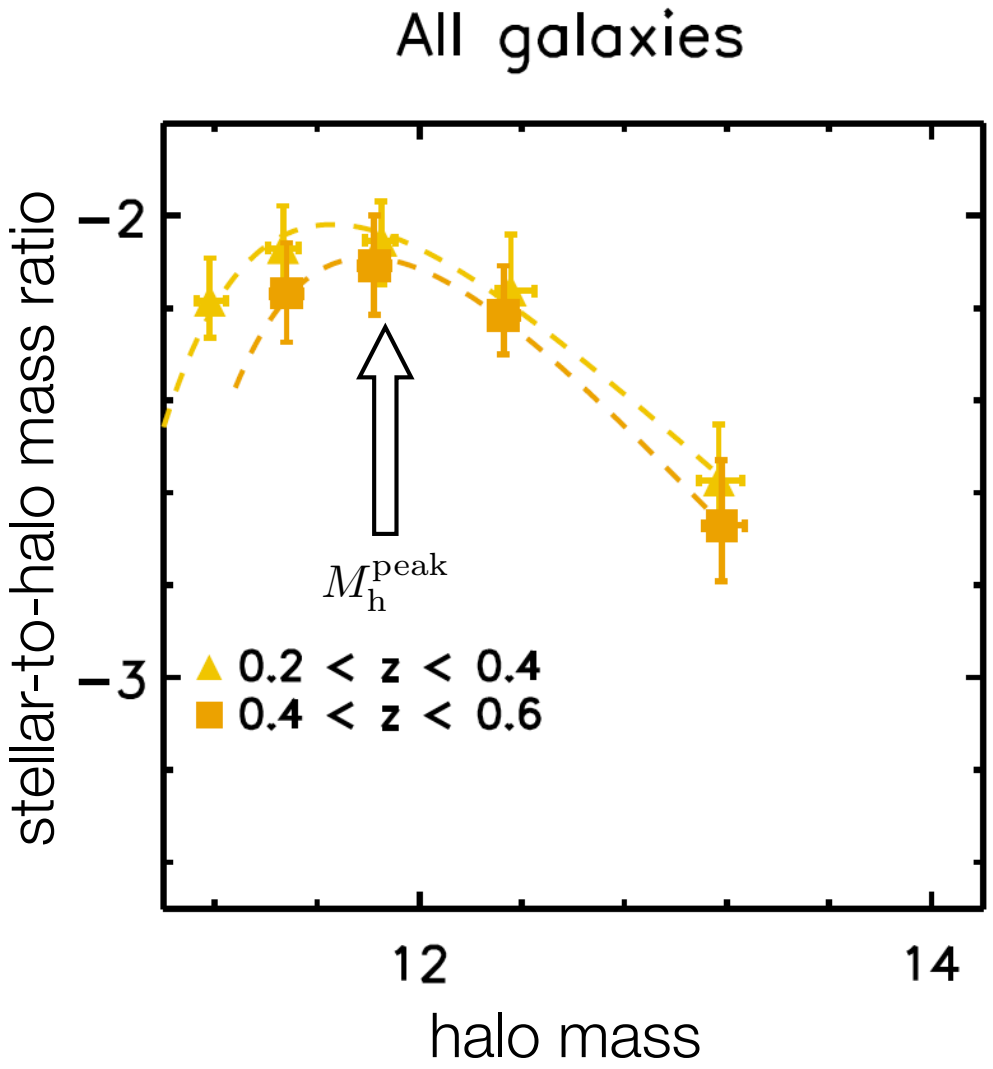
$$\frac{L'_{\rm c}}{M_{\rm h}} = A\,\frac{L_*}{M_{\rm t}}\left(\frac{M_{\rm h}}{M_{\rm t}}\right)^{\alpha_M-1}\exp\left(-\frac{M_{\rm t}}{M_{\rm h}}+1\right)$$

⇔ stellar-to-halo mass ratio as function of halo mass

$$M_{\rm h}^{\rm peak} \sim 10^{12}h^{-1}M_\odot$$

JC et al. (2012)

Stellar-to-halo mass ratio vs halo mass

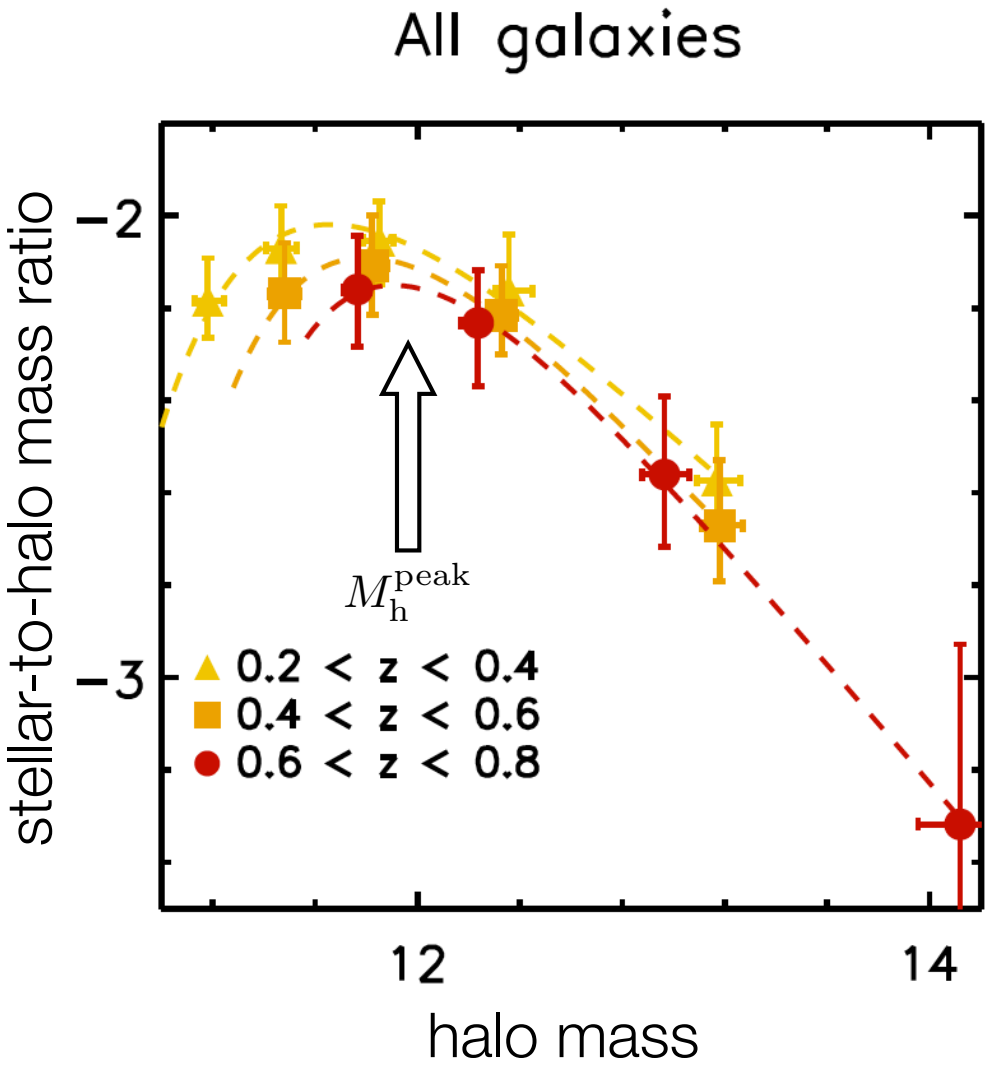


Redshift evolution:

- $M_{\rm h,peak}$ shifts at higher mass
- $M_{\rm star}/M_{\rm h}$ decreases with redshift

JC et al. (2012)

Stellar-to-halo mass ratio vs halo mass

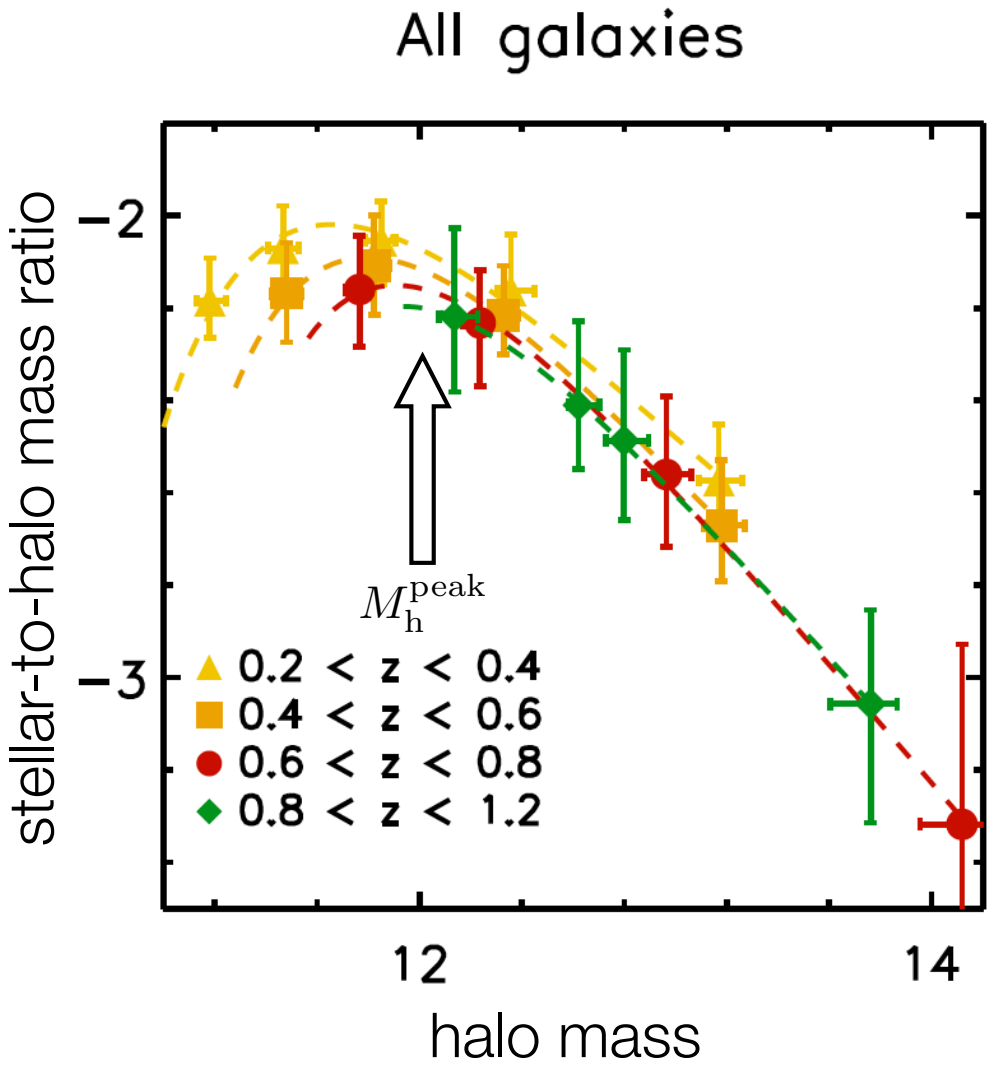


Redshift evolution:

- trends confirmed at higher redshift
- the position of the peak does not depend on L→$M_{\rm star}$
- the amplitude variation depends on L→$M_{\rm star}$ (larger variation expected)

JC et al. (2012)

Stellar-to-halo mass ratio vs halo mass



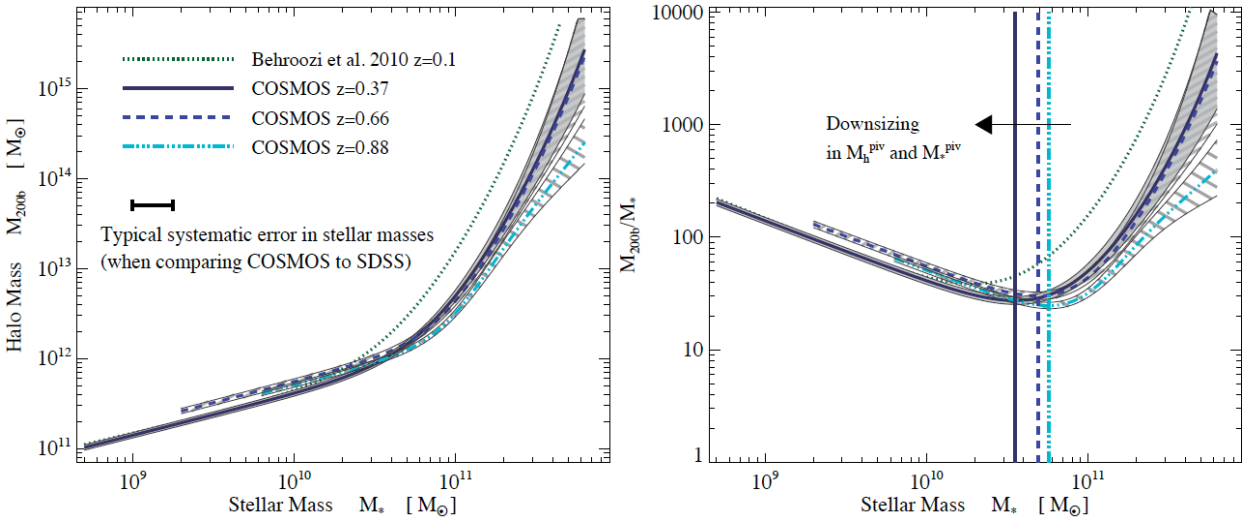
Redshift evolution:

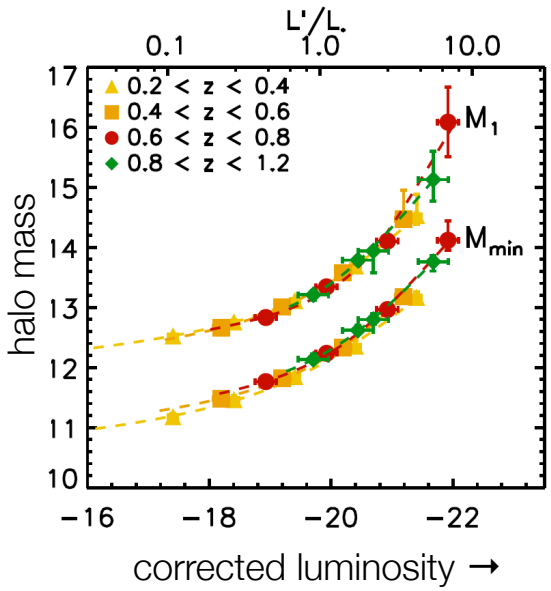
- the peak is poorly constrained in the highest redshift bin
- stronger evolution seen in low-mass haloes than in high-mass ones

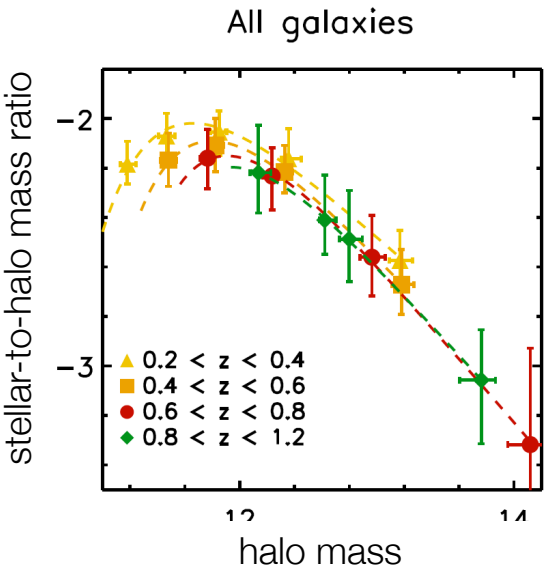
JC et al. (2012)

Comparison with COSMOS

Leauthaud et al. (2011)

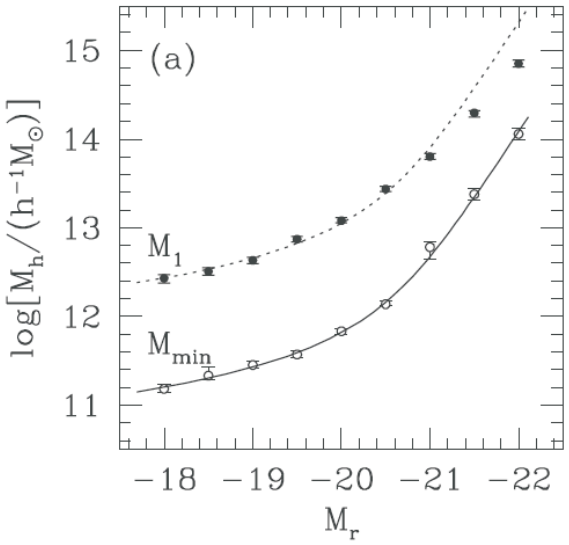


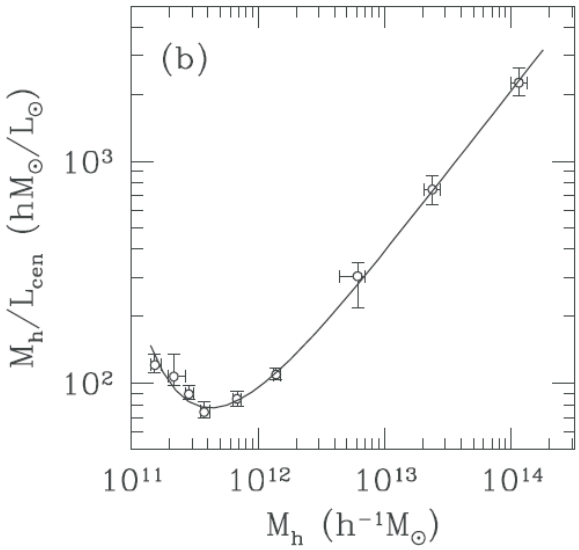


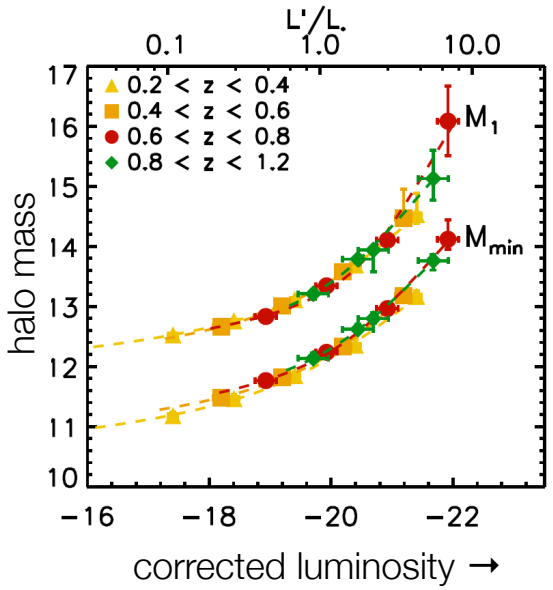


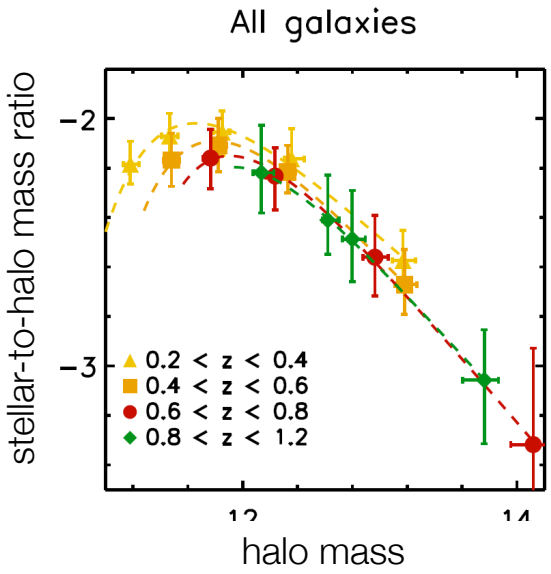
Comparison with the local Universe

Zehavi et al. (2010)

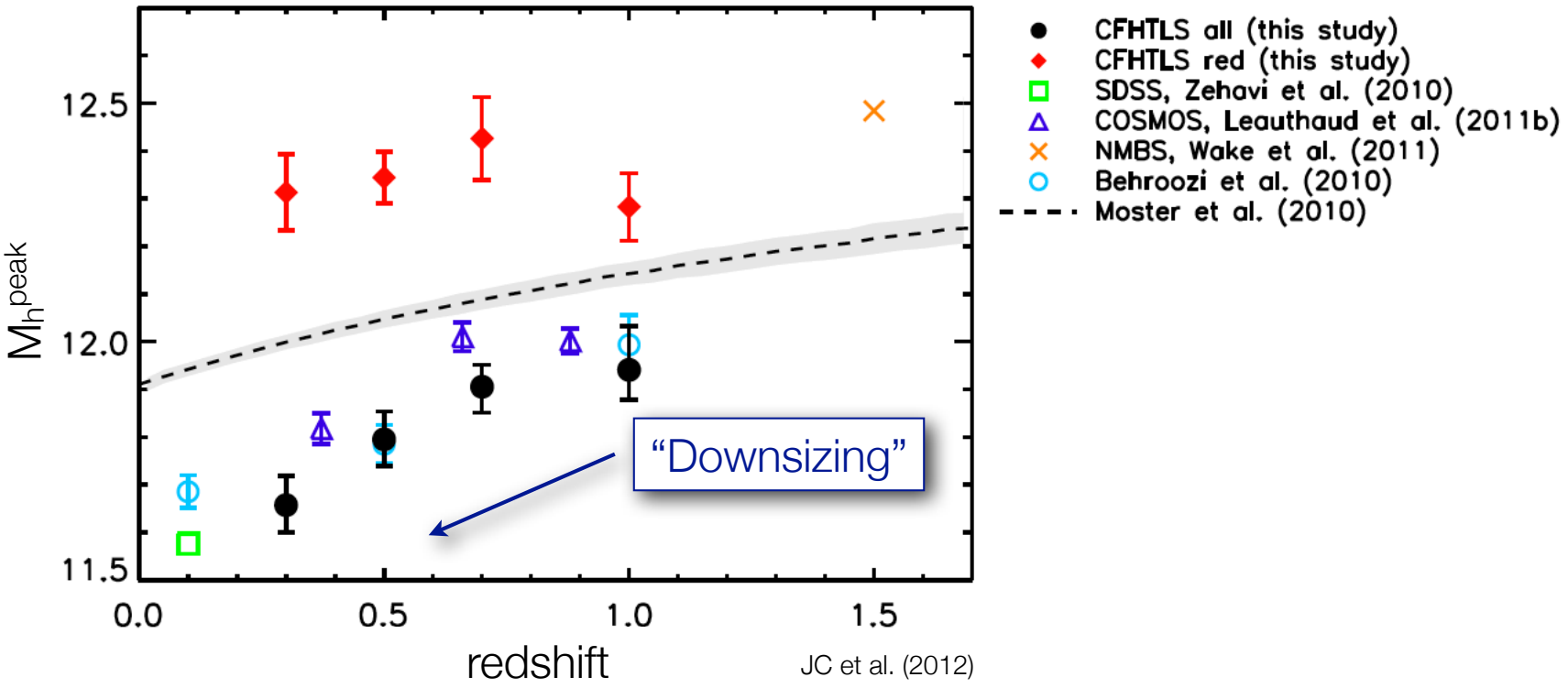








Comparison with the literature



- Similar trend for observations and semi-analytic simulations
- Excellent agreement with SDSS
- Lower value than in COSMOS (cosmic variance issue?)

III. CFHTLens/VIPERS: promising results from galaxy-galaxy lensing

Star-forming vs passive galaxies

- we have related luminosity/stellar masses to the host halo mass
- how about other physical parameters?
- star formation rate is a also a fundamental measure since it shows the instantaneous star formation processes (whereas stellar mass is an integrated SFR)

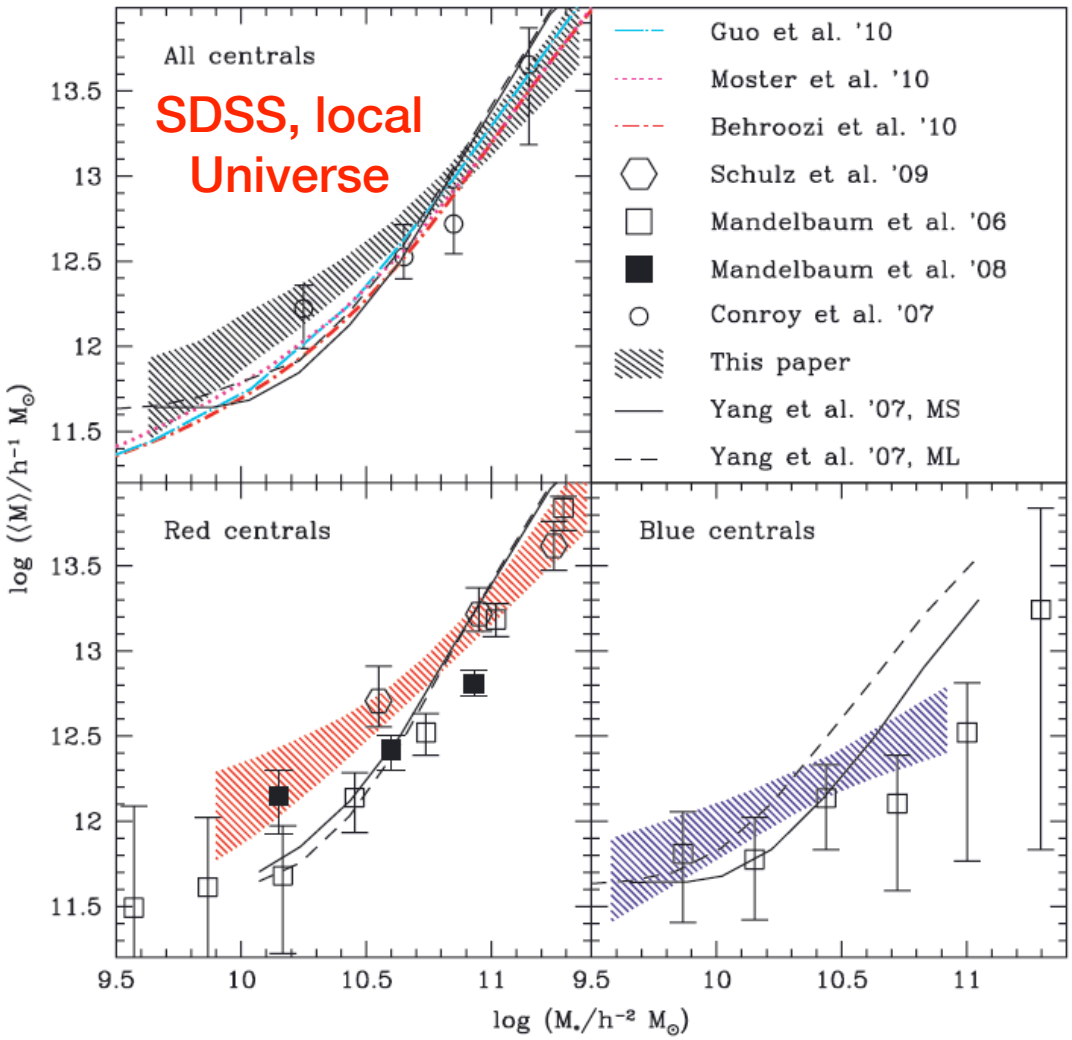
what we know:

- passive galaxies increase in number and grow in mass with time
- in the local Universe, massive star forming galaxies are rare and seem to live in less massive haloes

what we don't know:

- how massive passive galaxies accumulate more mass (mergers, gas accretion?)
- how does the stellar-to-halo mass ratio evolve with redshift for massive star-forming galaxies

SHMR in the local Universe

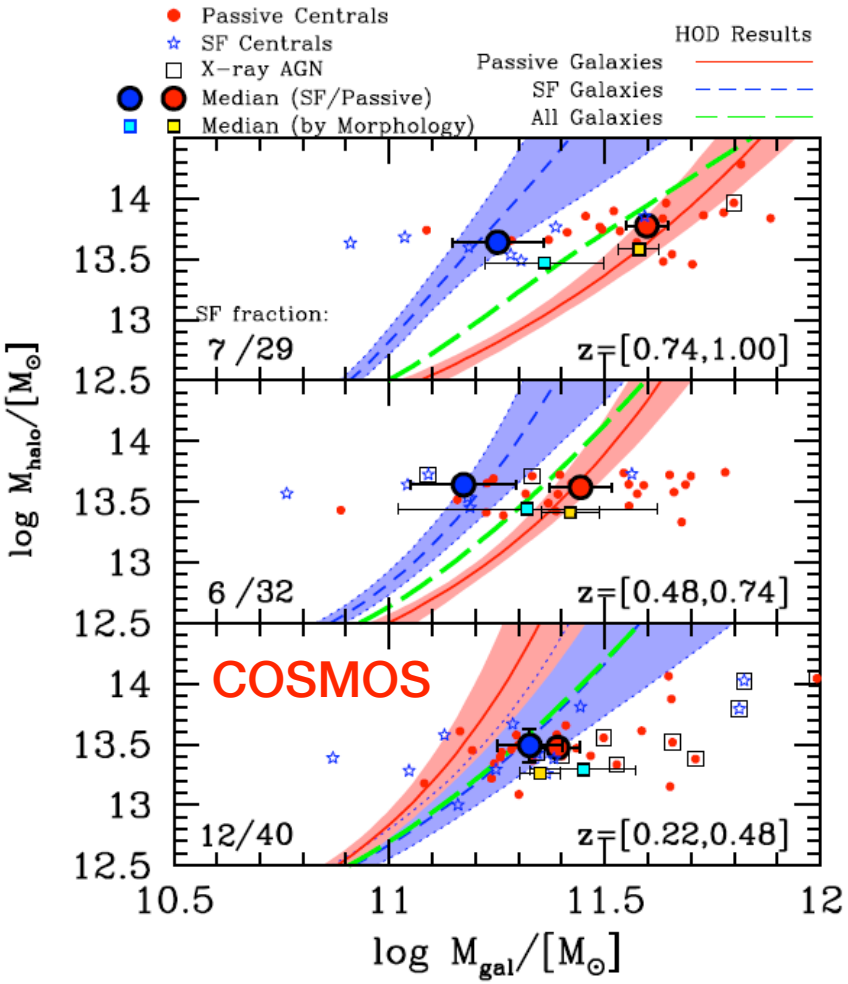


- blue galaxies live in less massive haloes than red ones
- no very massive blue galaxies

CAVEAT: some (very dusty) star-forming have red colors

More et al. (2011), satellite kinematics

SHMR evolution for active galaxies



Intriguing result:

- star forming galaxies seem to live in more massive haloes than passive one
- the trend reverses at low redshift (consistent with SDSS results)
- but COSMOS is limited by cosmic variance...

Tinker et al. (2012), gg-lensing+clustering

Conclusions

- for the full sample, $M_{h,\,peak}$ = 4.5 10^11 M_{sun} and moves towards higher halo masses at higher redshifts, suggesting that the bulk of star-formation activity migrates from higher halo mass at high redshifts (z~1.2) to lower halo mass haloes at lower redshifts (z~0)

- red galaxies do not evolve significantly but experience passive evolution

- for galaxies in haloes < 10^12 M_{sun}, we observed a increase in satellite fraction of about 2, which is consistent with a pictures where galaxy mergers do not play a significant role for galaxy evolution

- an important step further is to better understand the physical processes responsible for the evolution of galaxies

- future observations with accurate stellar masses and a better model for blue galaxy clustering will be necessary to complete this study