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

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Collaborators

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Overview

- cosmologists have built a “standard model” relating the dynamics of the Universe to its constituents, but leaving us with unresolved questions regarding their origin
- astronomers 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 we struggle to explain with simple arguments
- the field has known spectacular progresses from deep and large scale surveys, combined with semi-analytic simulations and new analysis techniques
- the halo occupation distribution (HOD) model is based on the well-known dark matter halo model and the simple assumption that the number of galaxies only depends on halo mass to probe the relationship between galaxies and their host haloes
- we applied this new method for the first time to the CFHTLS-Wide survey which remains unmatched in terms of volume at high redshift and image quality

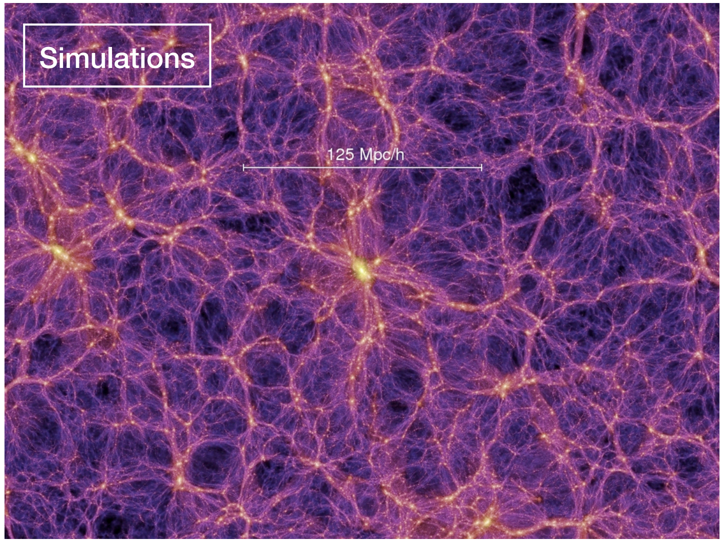
Plan

- I. Introduction: cosmological context and galaxy evolution
- II. Linking the galaxy distribution to Dark Matter: the HOD model
- III. Measurements in the CFHTLS Wide
- IV. Results: new insights on galaxy evolution since z ~ 1.2
- V. Conclusions

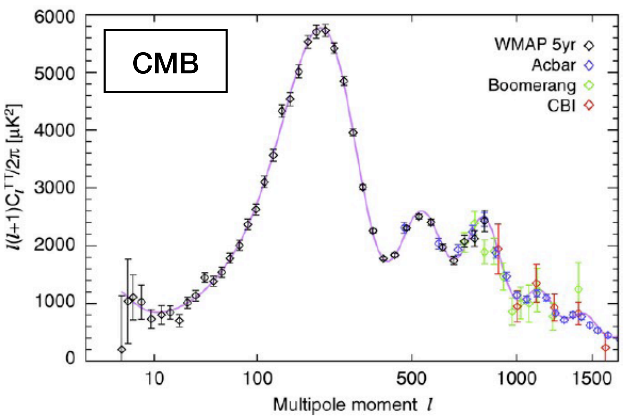
I. Introduction: cosmological context and open questions

The Universe in one slide - The ΛCDM model

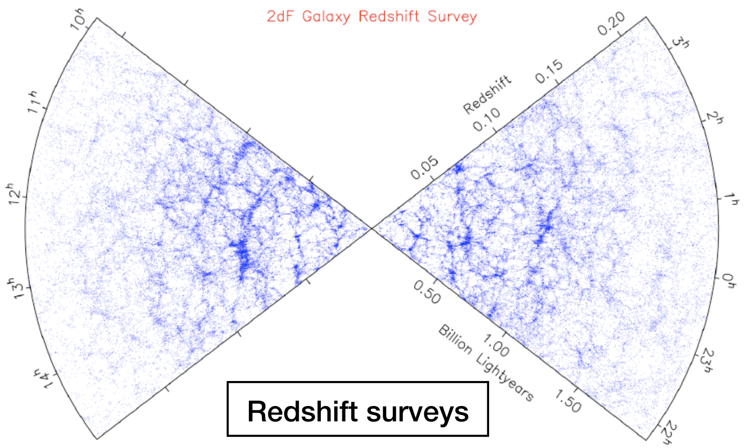
- the Universe is homogeneous and isotropic
- flat
- expanding and accelerating
- is dominated by (cold) dark matter and dark energy
- structures grow by gravitational instabilities of primordial tiny fluctuations that experienced a huge expansion during an early inflation period

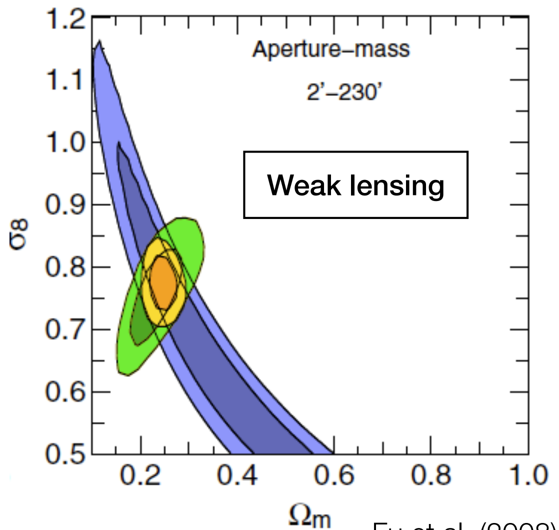


Millenium simulation



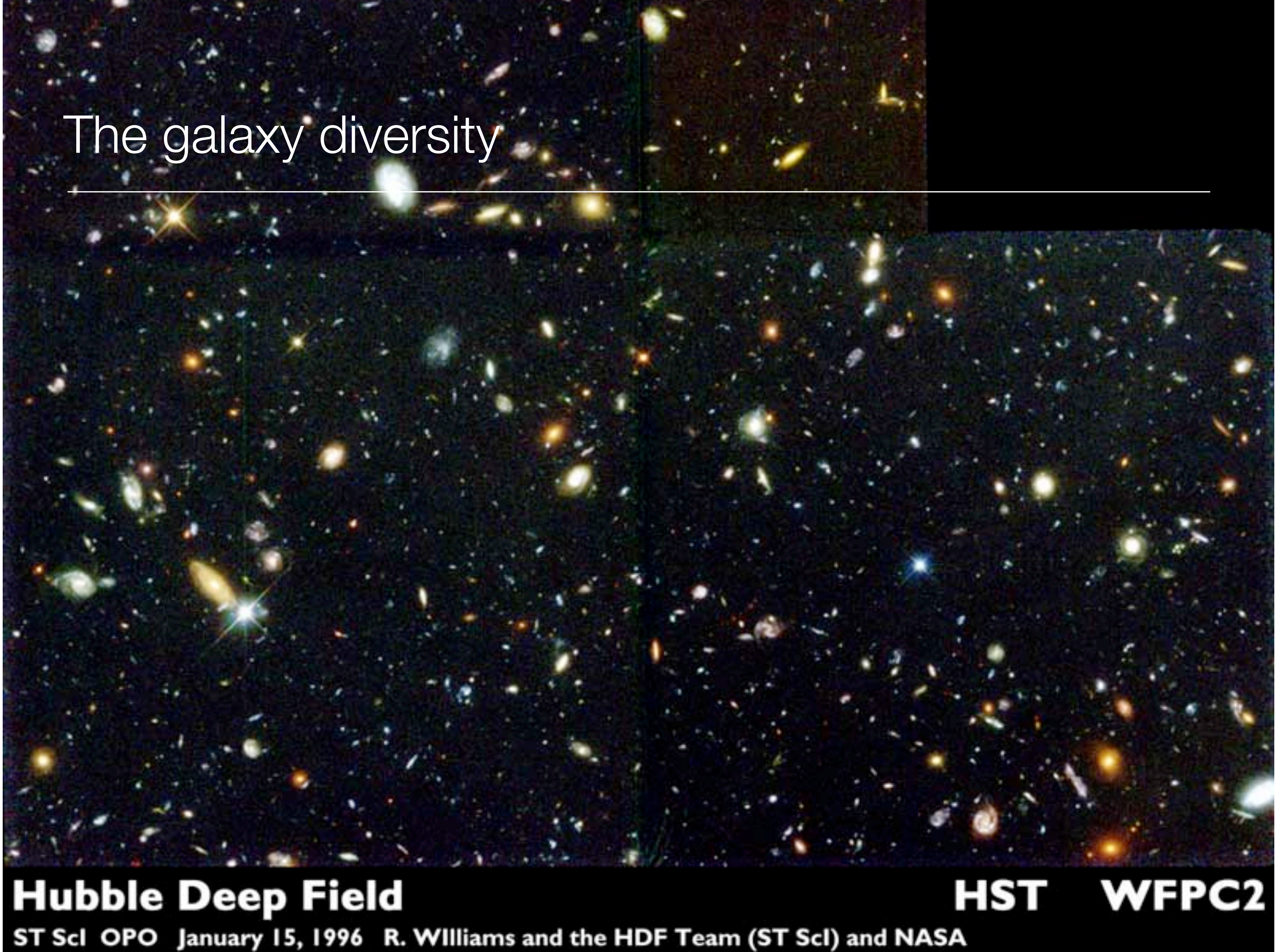
Nolta et al. (2009)



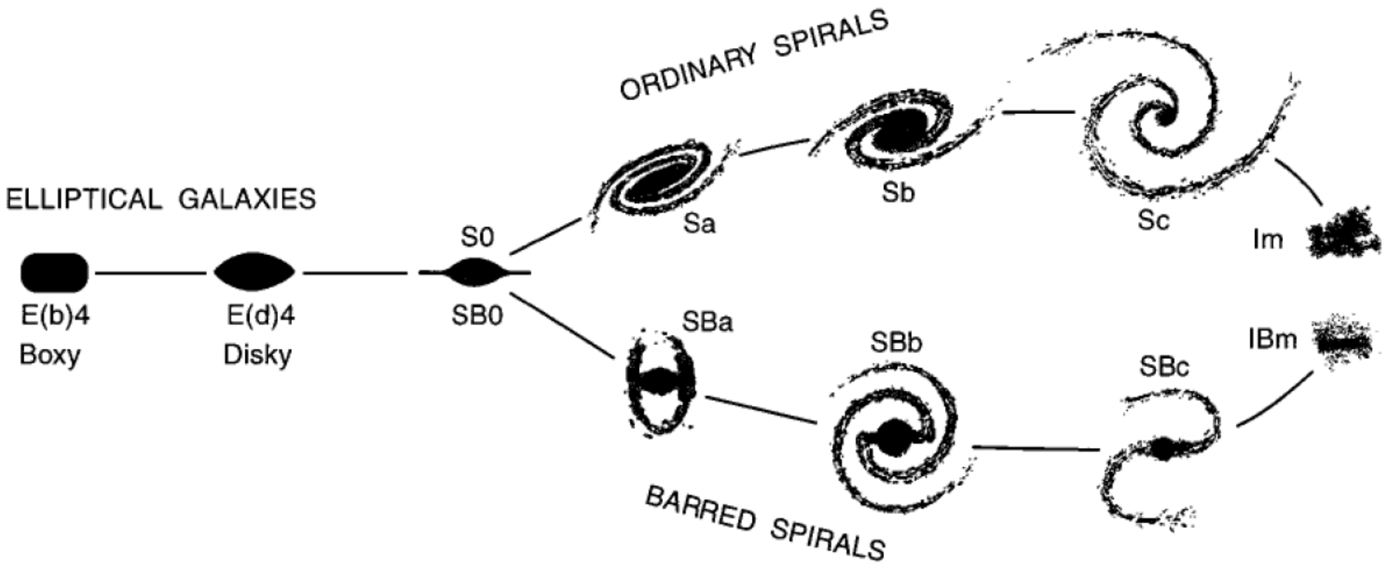


Fu et al. (2008)

The galaxy diversity



The Hubble sequence



dwarf, irregular,
\+ peculiar galaxies and
active galactic nuclei

Kormendy & Bender (1996)

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

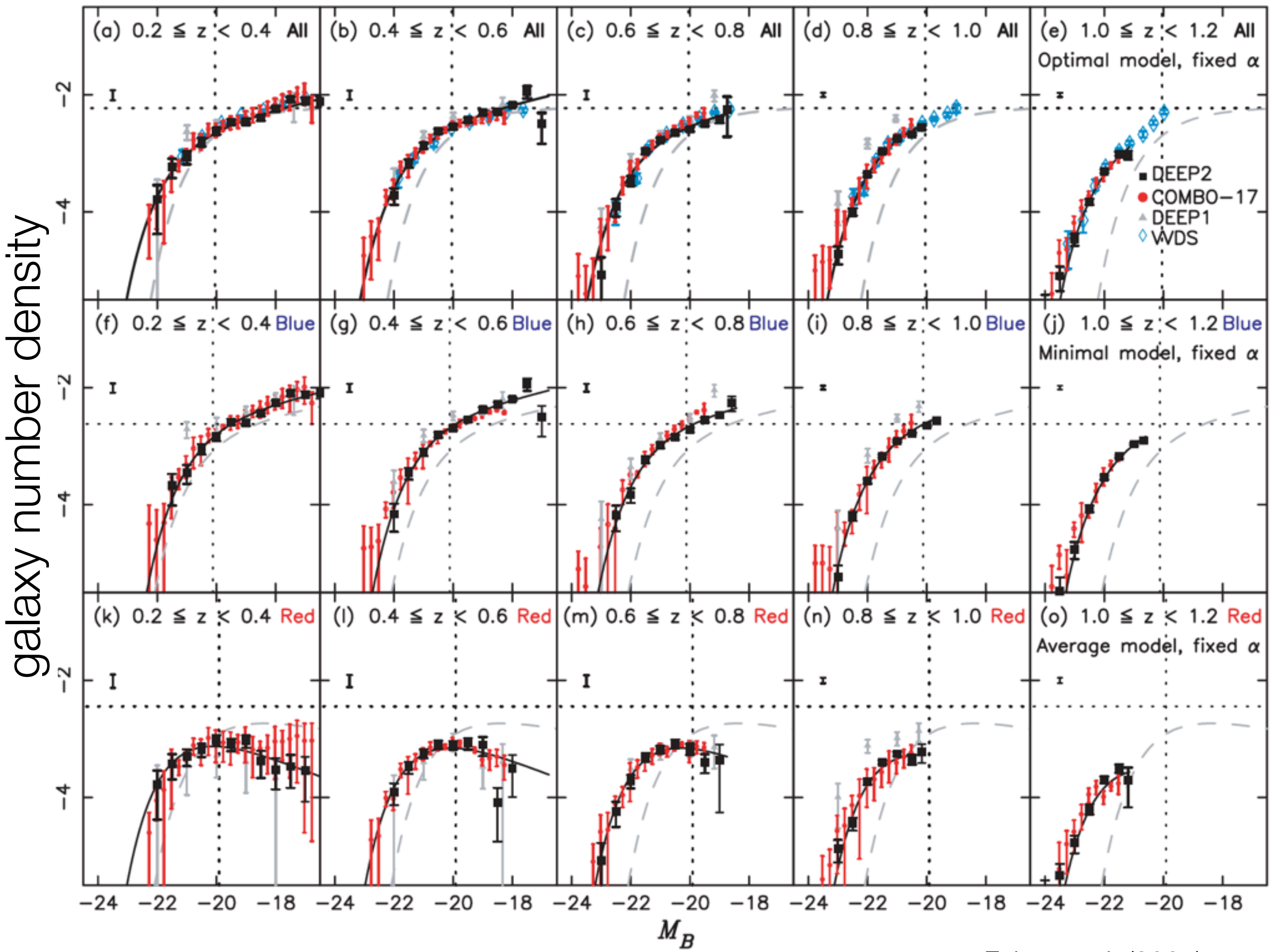
Spiral (disk) galaxies
or late-type galaxies
or “blue” galaxies

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 →



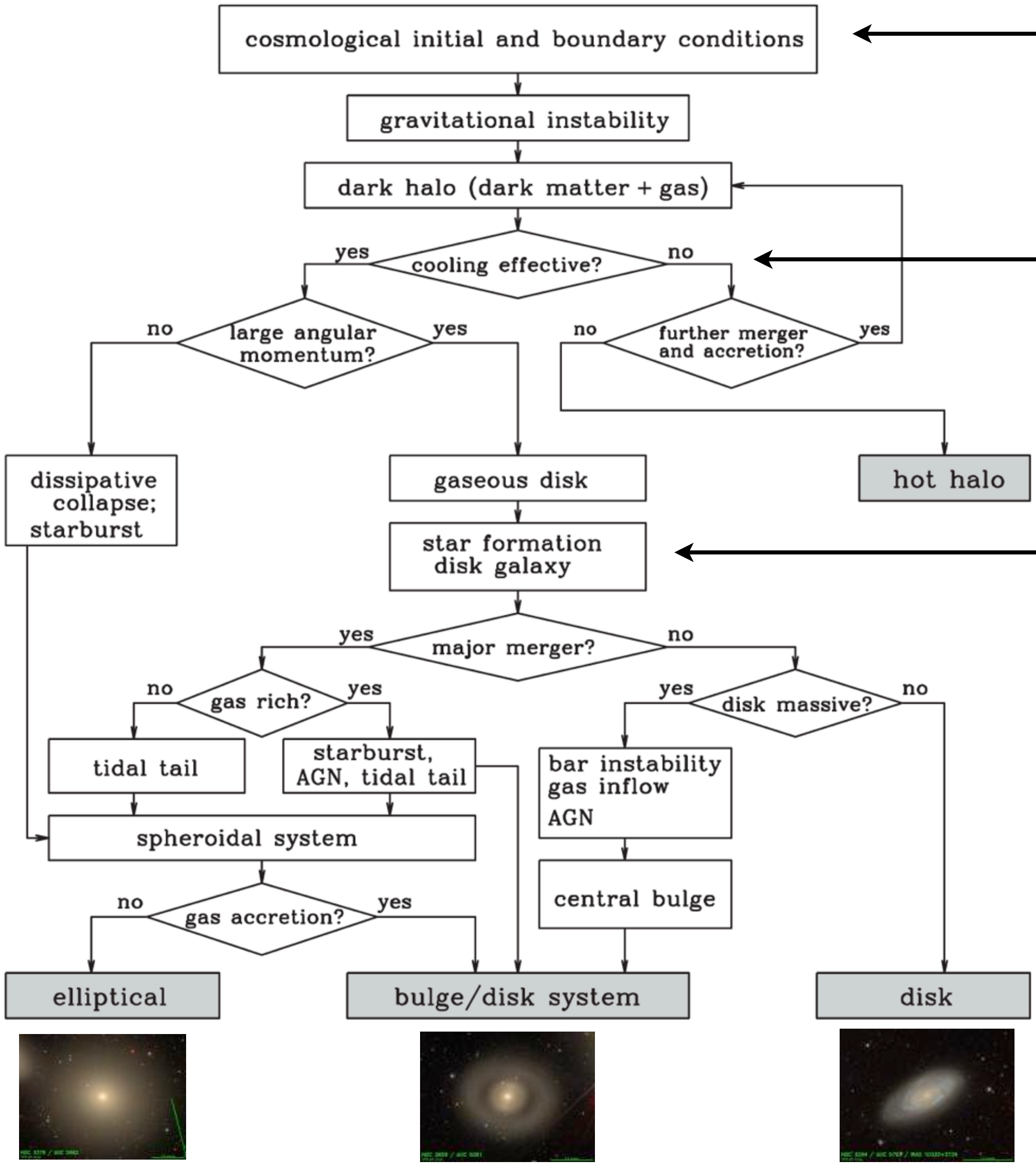
Faber et al. (2007)

- 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?

Basics of galaxy formation and evolution

Mo et al. (2011)



ΛCDM cosmology

No cooling, no star

Star formation stops

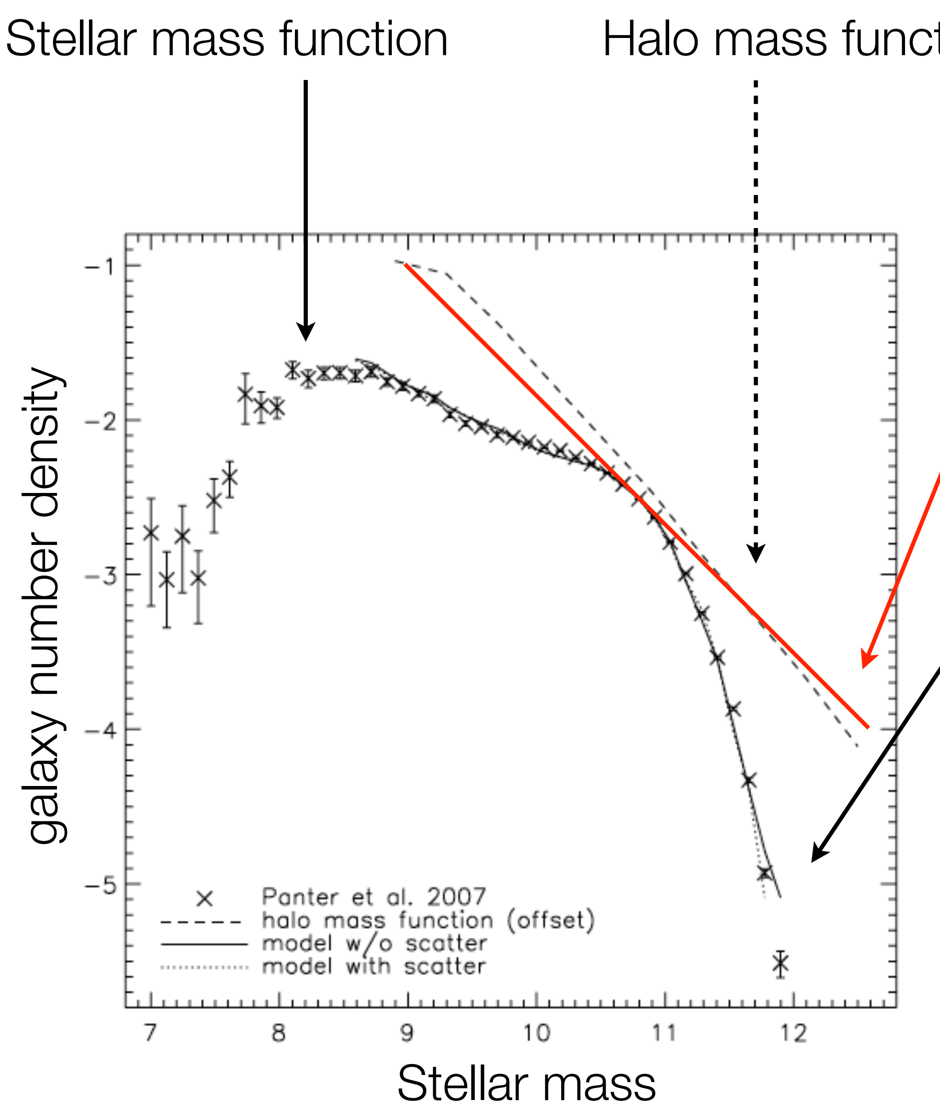
Star formation goes on

Galaxy evolution: depends on halo mass, environment and redshift

Hubble sequence observed today

SDSS, Blanton & Hogg

Star formation efficiency in dark matter haloes



Moster et al. (2010)

- stellar mass function in a naive picture where all baryons are transformed into star
- but 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

Star formation efficiency in dark matter haloes

- stellar mass = only few % of the available baryon “fuel” (Ω_b)
- reaches a maximum of ~ 20% (at z = 0) for galaxies ~ Milky Way
- star formation less efficient in low and high mass haloes

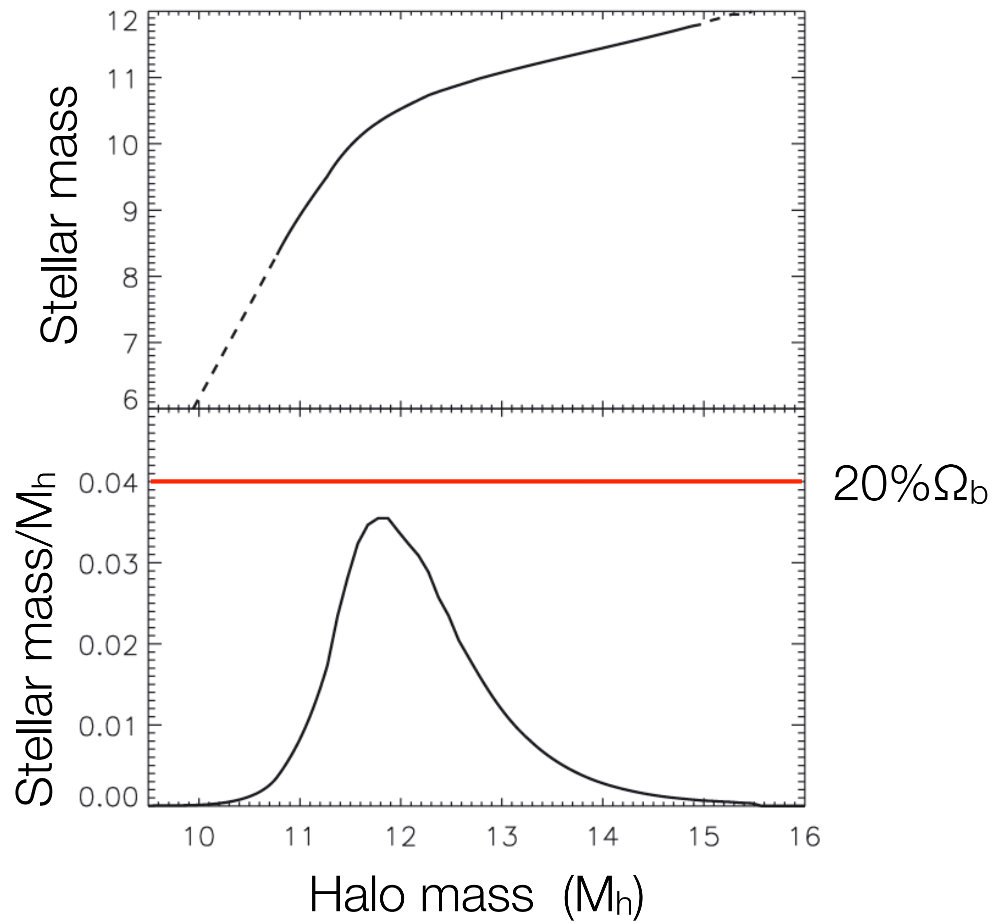
$$M_{\rm star} = f(M_{\rm h})$$

depends on:
- the available gas
- feedback processes “quenching” star formation

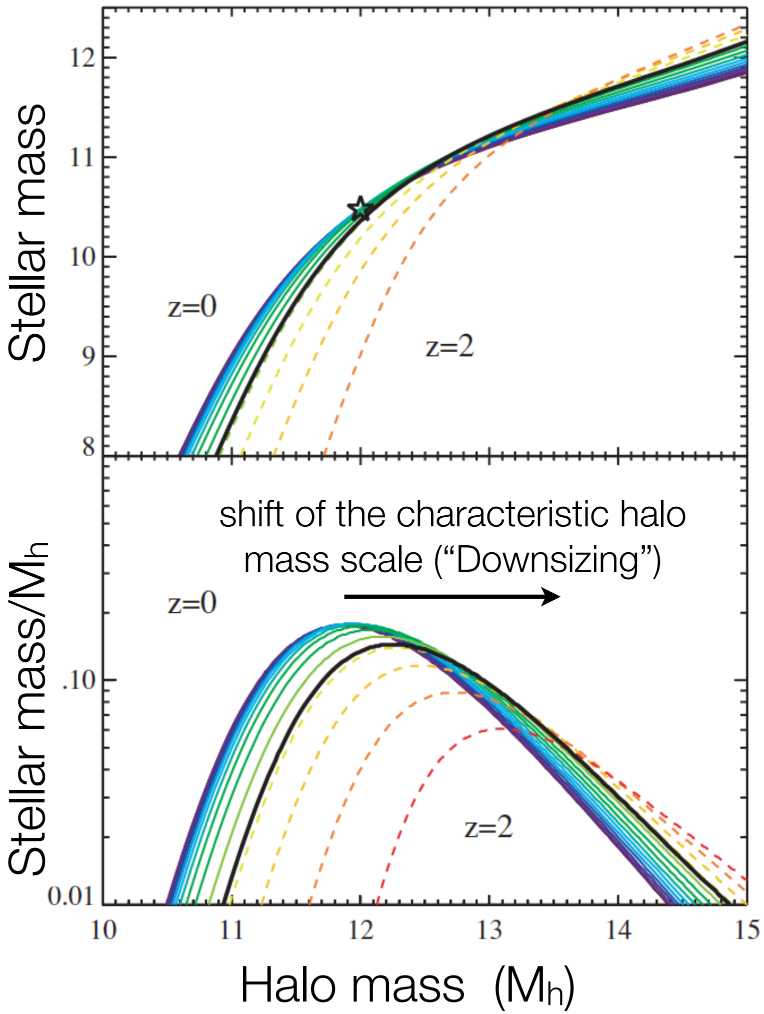
low-mass haloes: supernovae, stellar winds?

high-mass haloes: AGNs?

“abundance matching” Guo et al. (2010)



What drives galaxy evolution?



Conroy & Wechsler (2009)

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

Key questions:

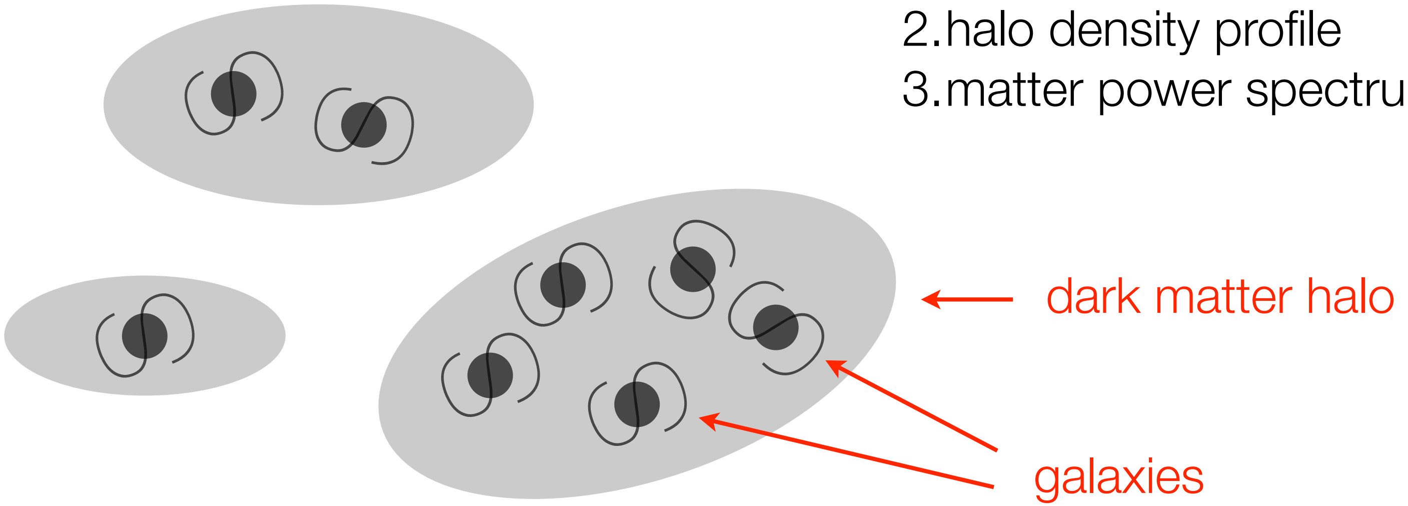
- the role of galaxy merging?
- AGN and supernovae feedback processes?
- the importance of the environment?
- impact of a different cosmology?

☆Strategy☆:

Observing the stellar-to-halo-mass ratio as function of redshift helps to understand the physical processes involved in galaxy evolution.

II. Linking the galaxy distribution to Dark Matter: the HOD model

The halo occupation distribution model



Dark matter distribution defined by:

1. halo mass function
2. halo density profile
3. matter power spectrum (halo bias)

Main hypothesis: the number of galaxies only depends on halo mass: $N \propto M_{\mathrm{h}}^{\alpha}$

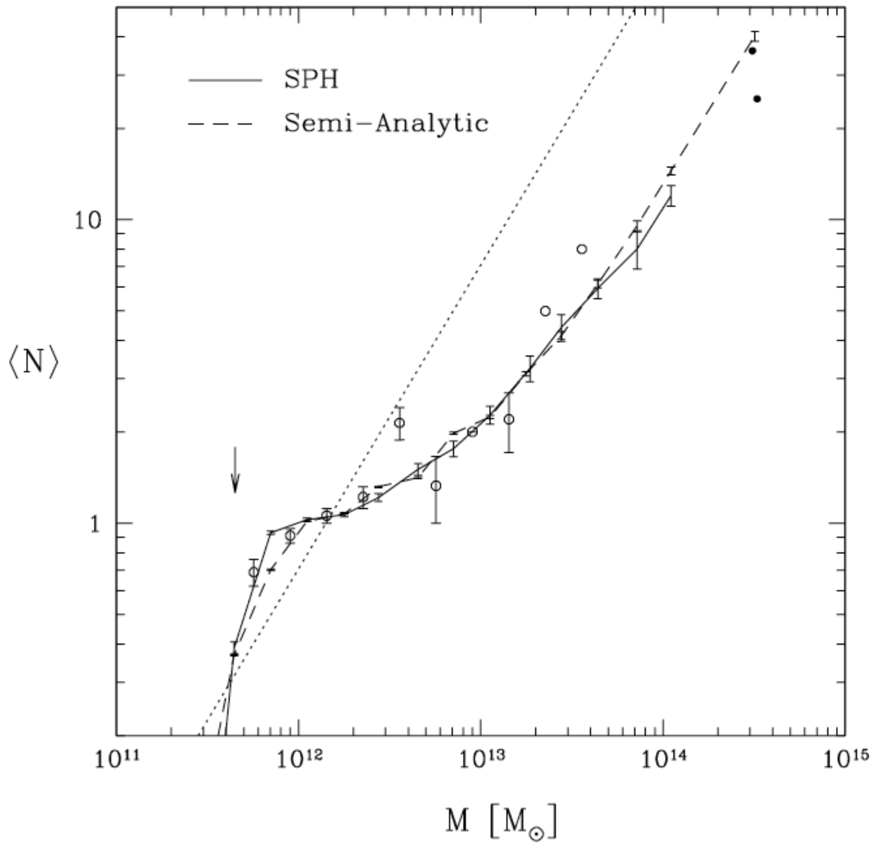
+ dark matter (halo) space distribution, one can predict:

- the galaxy number density
- the galaxy distribution (clustering)

HOD parameterisation

Idea: the number of galaxies ONLY depends on halo mass
(Berlind & Weinberg 2002, 2003; Kravtsov et al. 2004; Zheng et al. 2005).

Berlind & Weinberg (2003)



Semi-analytic simulations:

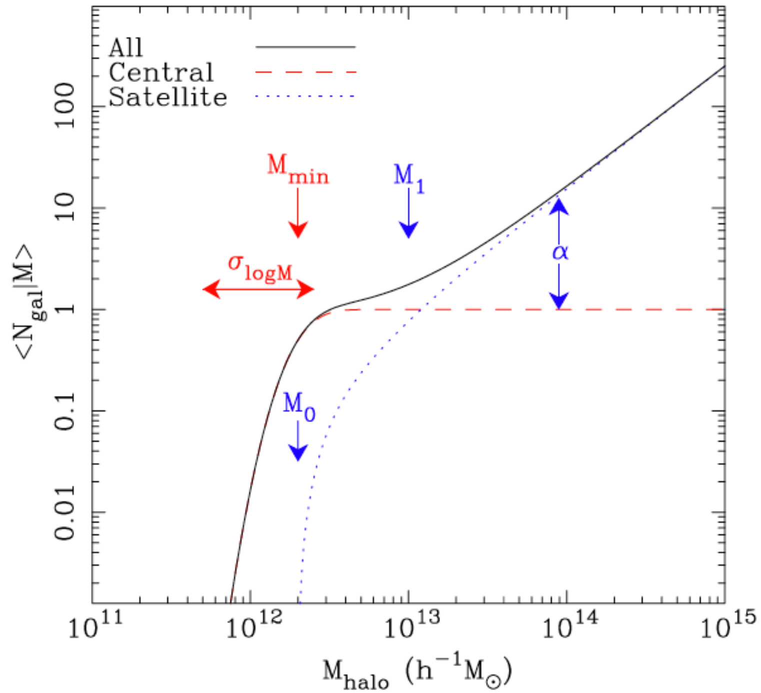
- the number of galaxies only depends on halo mass
- there is a mass below which no galaxy forms
- the number of galaxies then follows a power law as function of halo mass

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

Observable
(galaxy properties)

Halo mass

HOD parameterisation



Wake et al. (2011)

Separation of the contribution from central and satellite galaxies (Zheng et al. 2005, 2007):

$$N_c(M) = \frac{1}{2}\left[1 + \mathrm{erf}\left(\frac{\log M - \log M_{min}}{\sigma_{\log M}}\right)\right],$$

$$N_s(M) = N_c(M) \times \left(\frac{M - M_0}{M_1}\right)^{\alpha}.$$

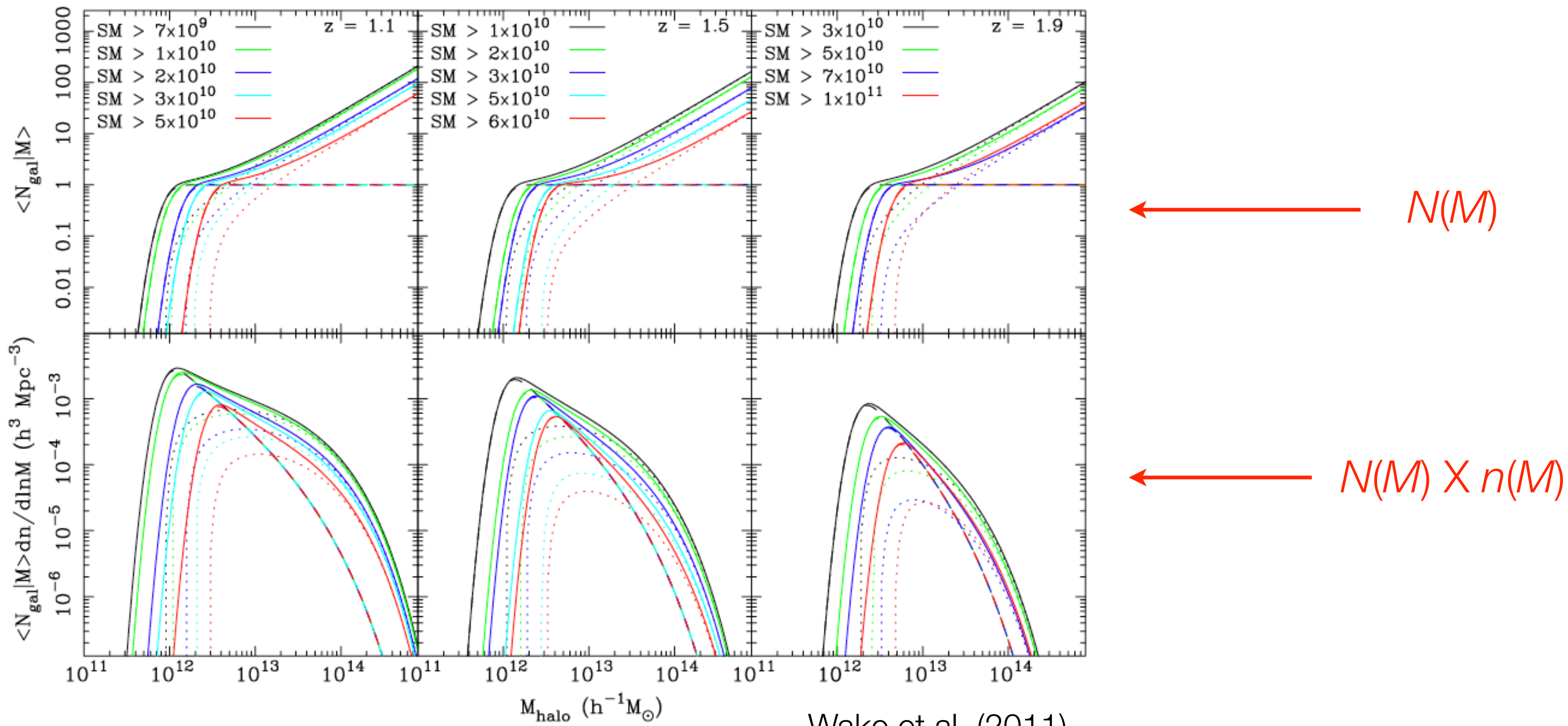
Important assumption: allows to treat central and galaxy contribution separately.

- the smooth transition takes into account the scatter in galaxy formation
- M_{min} corresponds to the halo mass of central galaxies
- M_1, α describe the satellite abundance

From HOD to observables: galaxy number density

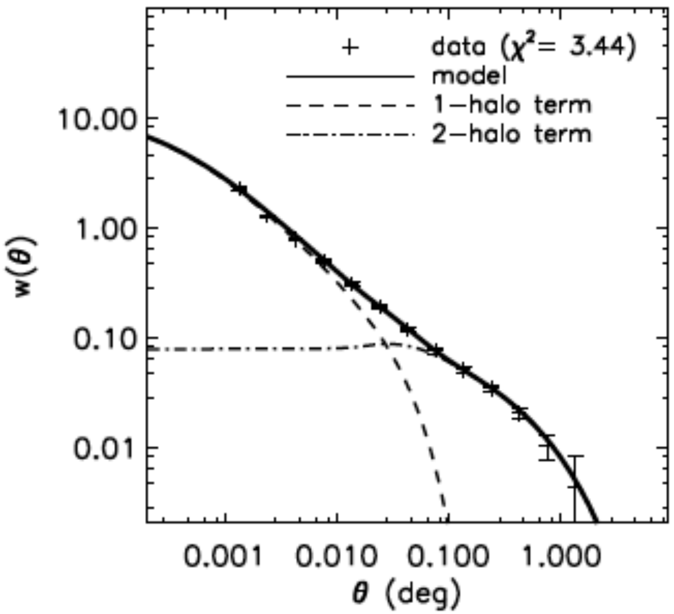
Convolution between halo mass function and HOD:

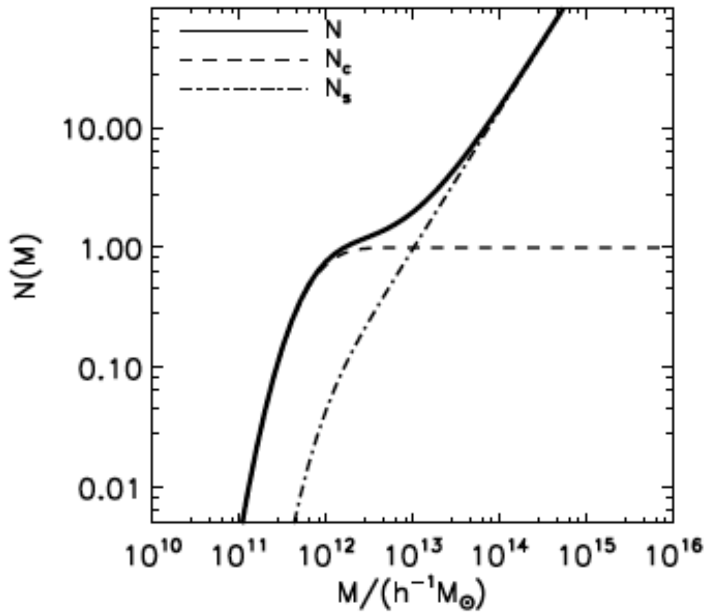
$$n_{\rm gal}(z) = \int N(M)\, n(M, z)\, {\rm d}M$$



Wake et al. (2011)

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

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

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

Physical parameters

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

Galaxy bias

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

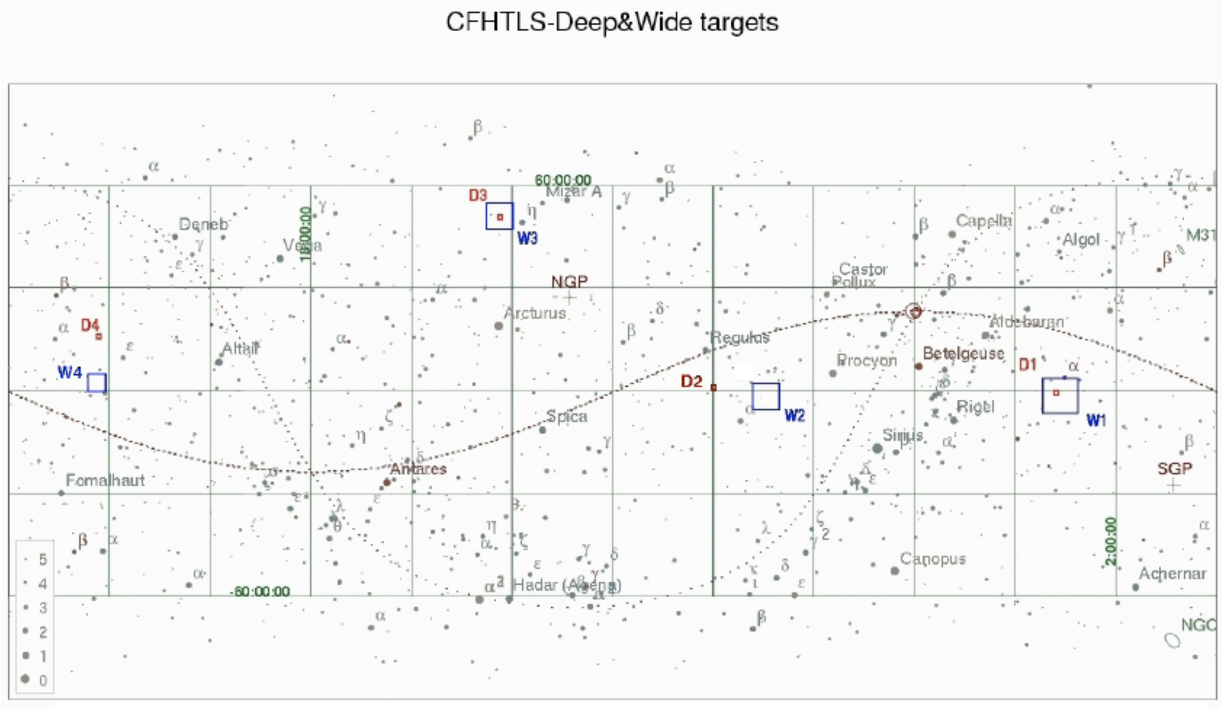
Mean halo mass

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

Satellite fraction ($1-f_c$)

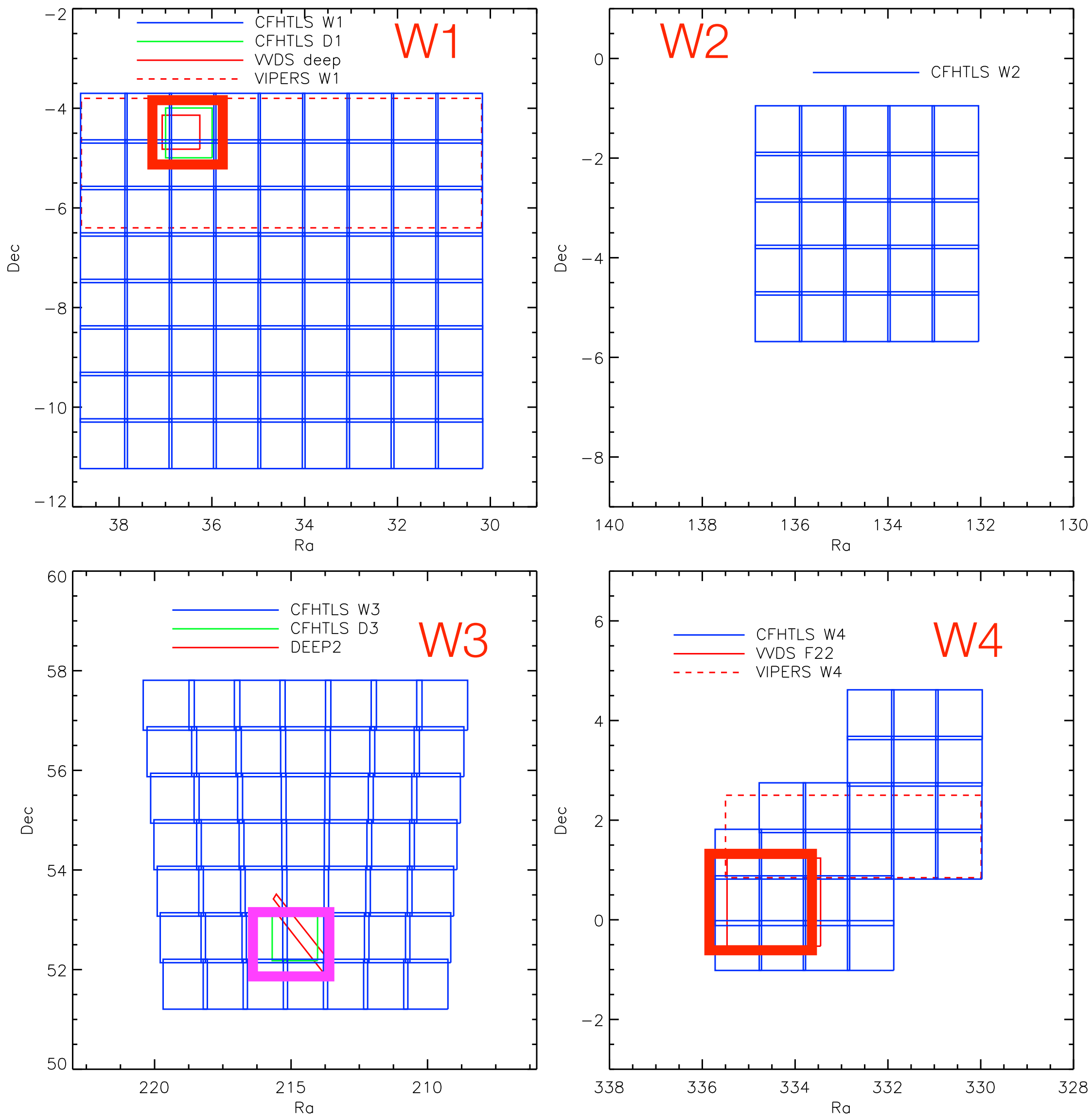
III. Measuring galaxy clustering in the CFHTLS Wide

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:

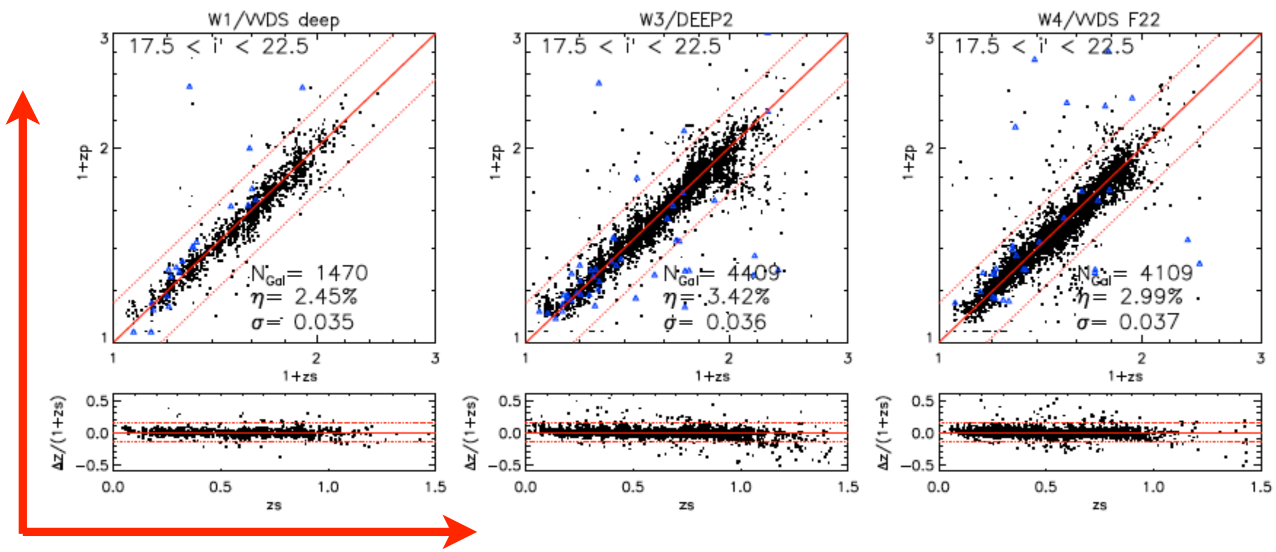
- VVDS Deep (Le Fèvre et al 2005)
- VVDS F22 Wide (Garilli et al 2008)
- DEEP2 (Davis et al 2007)

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

photo-z



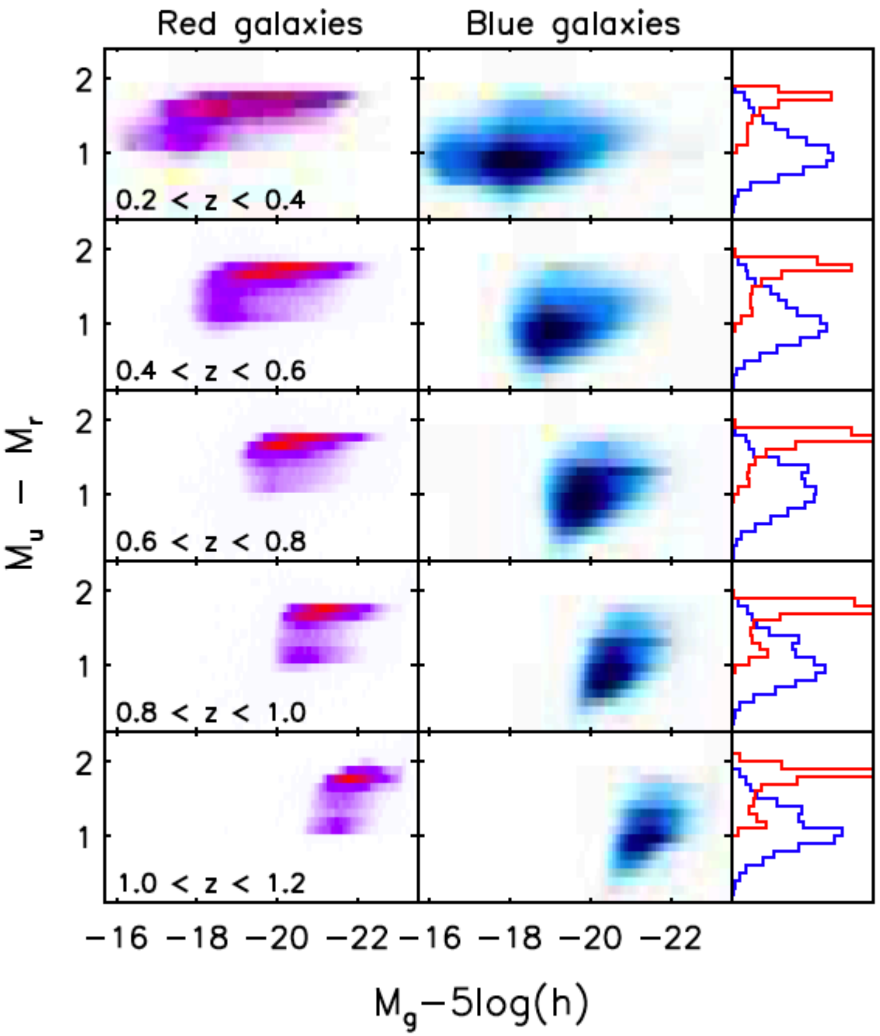
spectro-z

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).

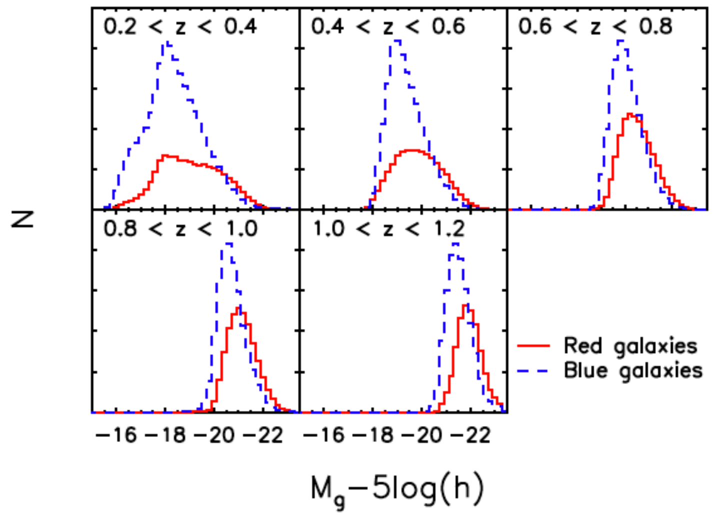
Sample selection - galaxy type



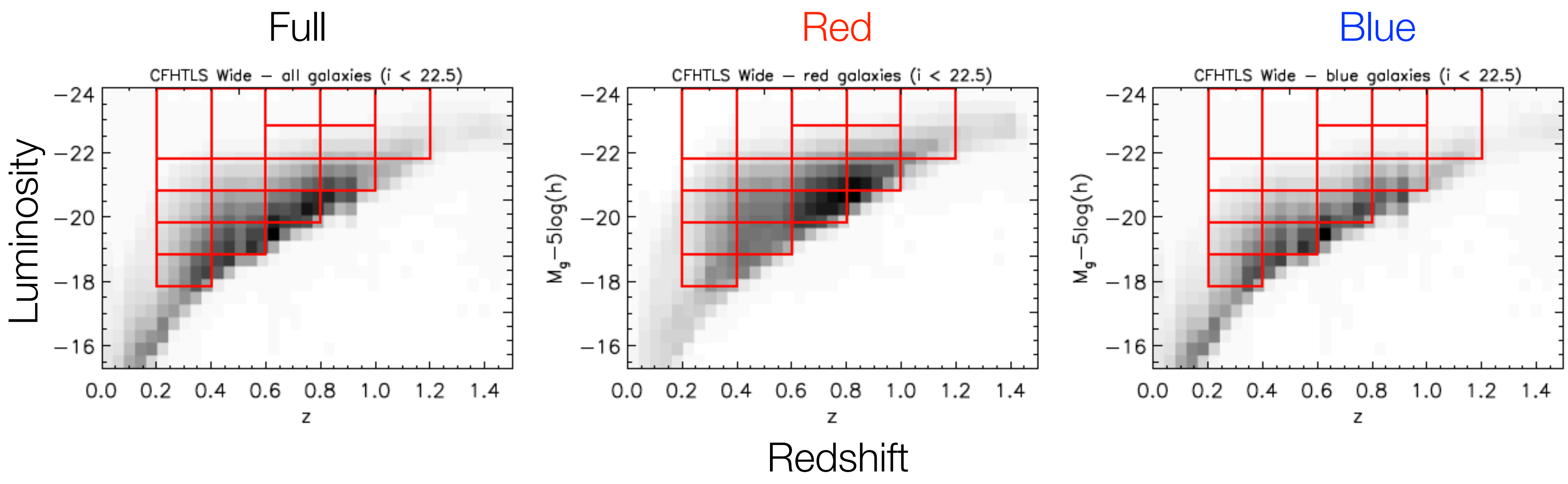
Total sample (i < 22.5): 3 000 000 galaxies divided into:

- red galaxies: El, Sbc
- blue galaxies: Sbc, Scd, Im, SB1, SB2

(equivalent to a colour selection)



Sample selection - redshift/luminosity



- threshold samples (guarantees the presence of central galaxies)
- five redshift bins, $0.2 < z < 1.2$
- 45 samples
- blue bright samples are discarded (weak clustering signal)
- larger samples have over 1 000 000 galaxies
- galaxy number density estimate: N_{total}/volume: $n_{\rm gal}^{\rm obs} = N_{\rm total} / \left[\Omega \int_{z_{\rm min}}^{z_{\rm max}} \frac{{\rm d}V}{{\rm d}z} \, {\rm d}z \right]$,

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

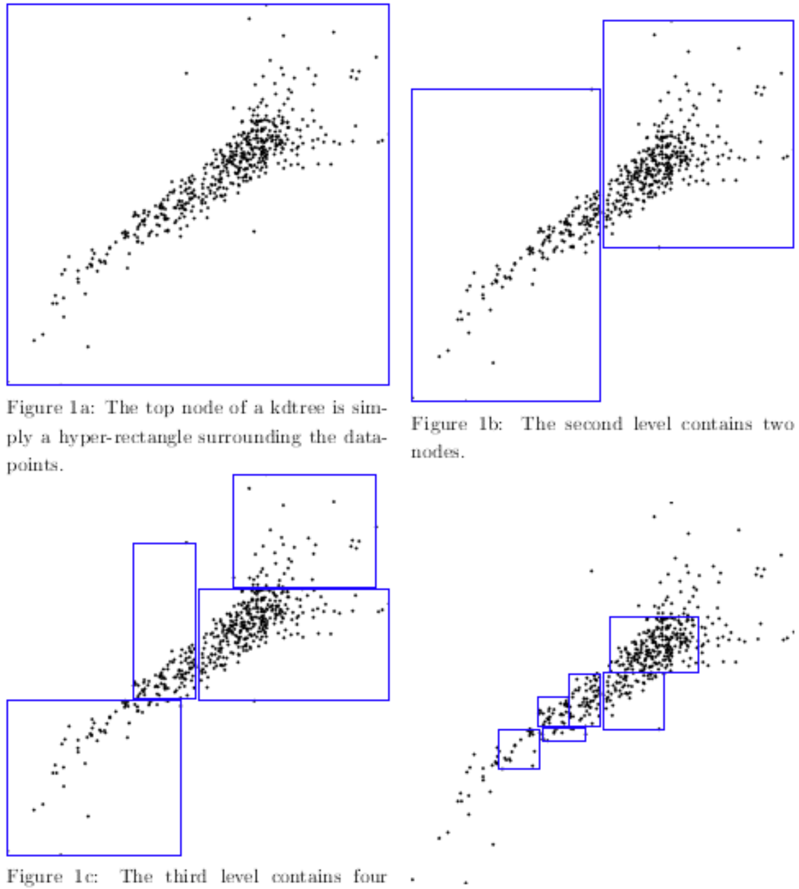


Figure 1a: The top node of a kdtree is simply a hyper-rectangle surrounding the datapoints.

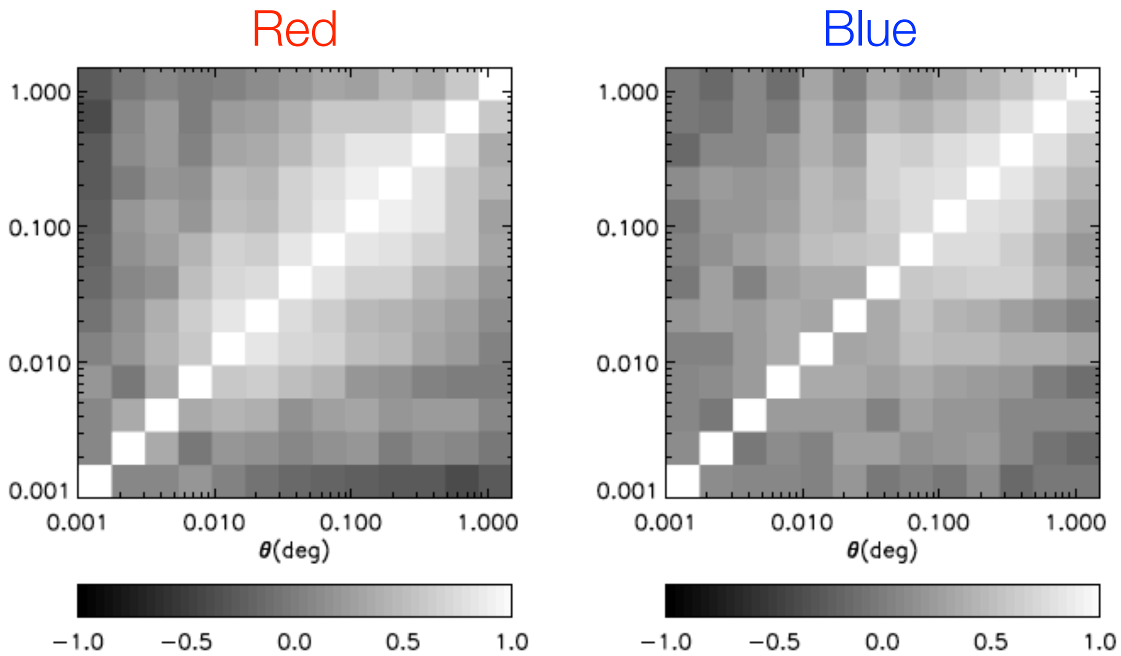
Figure 1b: The second level contains two nodes.

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)

Estimating errors - w(θ)



$$C(w_i, w_j) = \frac{N-1}{N}\sum_{l=1}^{N}(w_i^l - \overline{w}_i)(w_j^l - \overline{w}_j)$$

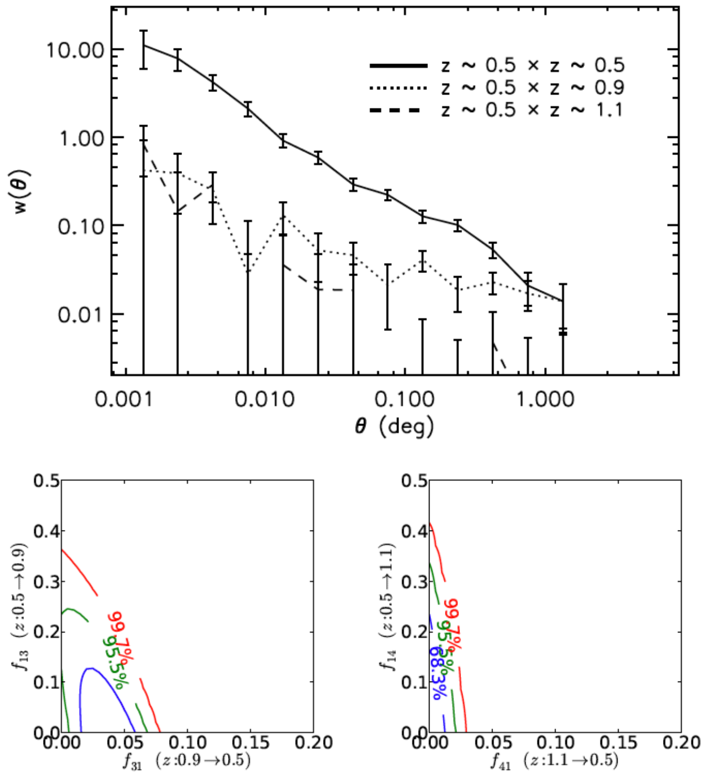
+ Error on n_{gal} from the field-to-field variance

Covariance matrices estimated from Jackknife estimator using 62 realisations. 4 independent fields allow a non-biased (although noisy) cosmic variance estimate

- large scales highly correlated
- small scales correlated for red galaxies

Estimating errors - photometric redshifts

- photo-z error estimated from PDF (cf previous slide)
- ξ(r) projected using redshift distribution of photo-z convolved with photo-z error
- cross-correlation check (a la Benjamin et al 2010): photo-z contamination should create a positive cross-correlation between redshift bins



results:

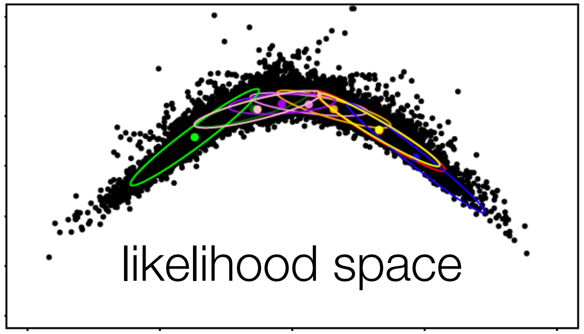
- small cross-correlation between adjacent bins likely due to the large-scale structure
- no significant contamination found between distant field
- red samples (better photo-z) perform the best

IV. Results: new insights on galaxy evolution since z ~ 1.2

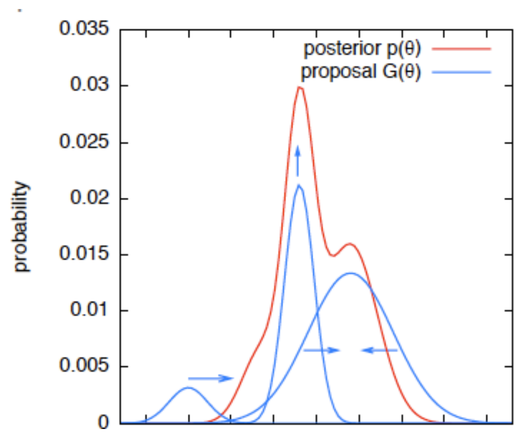
Fitting HOD parameters

Likelihood: $$\chi^2 = \sum_{i,j} \left[w^{\rm obs}(\theta_i) - w^{\rm model}(\theta_i)\right] \left(C^{-1}\right)_{ij} \left[w^{\rm obs}(\theta_j) - w^{\rm model}(\theta_j)\right] + \frac{\left[n_{\rm gal}^{\rm obs} - n_{\rm gal}^{\rm model}\right]^2}{\sigma^2_{n_{\rm gal}}}$$

- constraints from w(θ) + galaxy number density
- population monte carlo (PMC): likelihood space is sampled from a proposal (importance sampling method, see Cappé et al. 2004)
- the proposal is iteratively adapted to match the posterior (convergence: “perplexity” → 1)
- same results as MCMC but not point is rejected and the method is easy to parallelize (10 times faster)



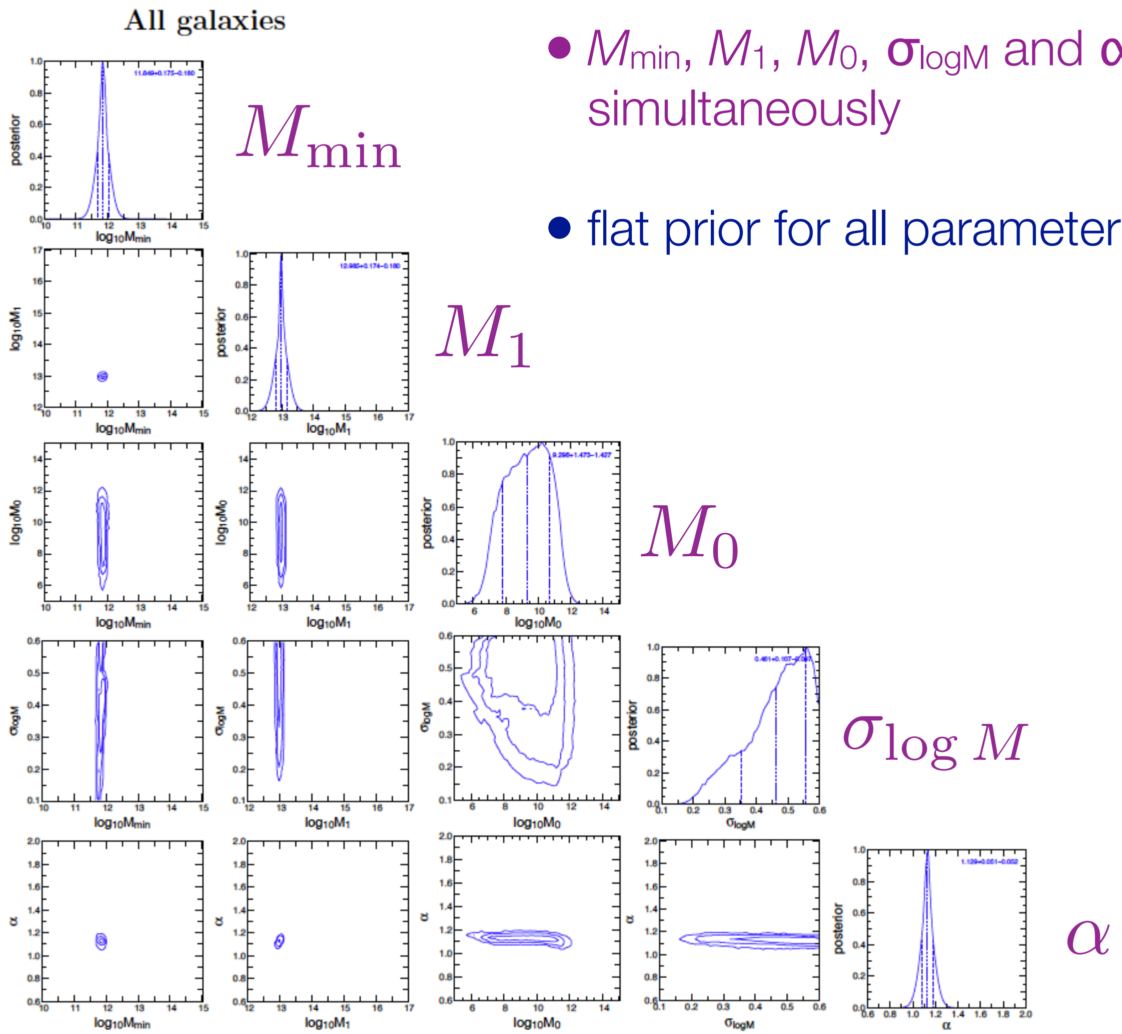
Wraith et al. (2009)

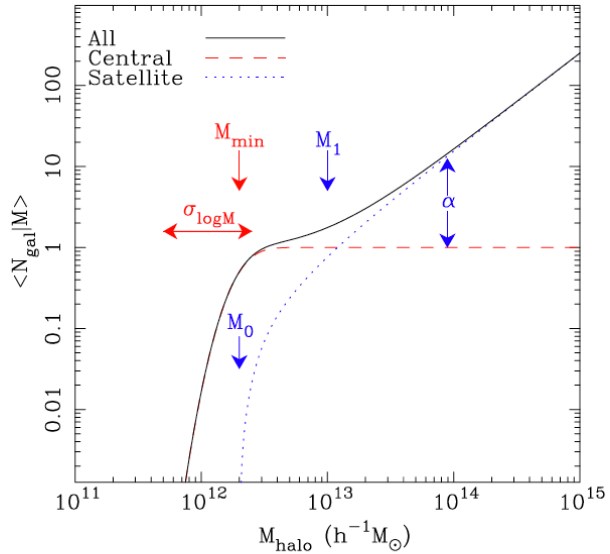


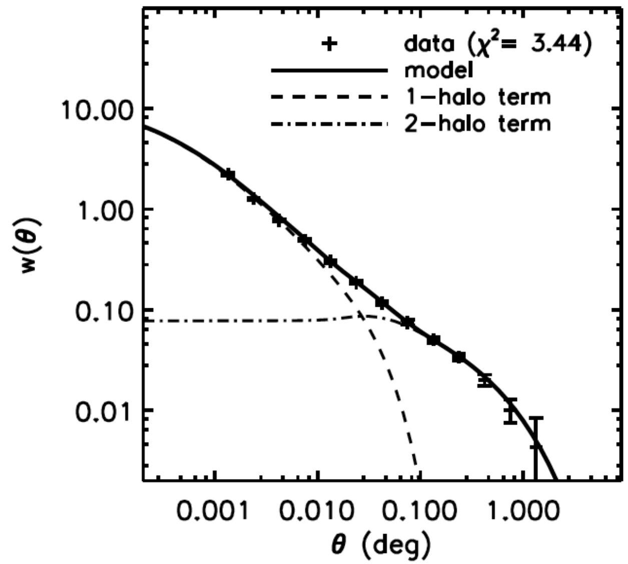
(M. Kilbinger)

Fitting HOD parameters

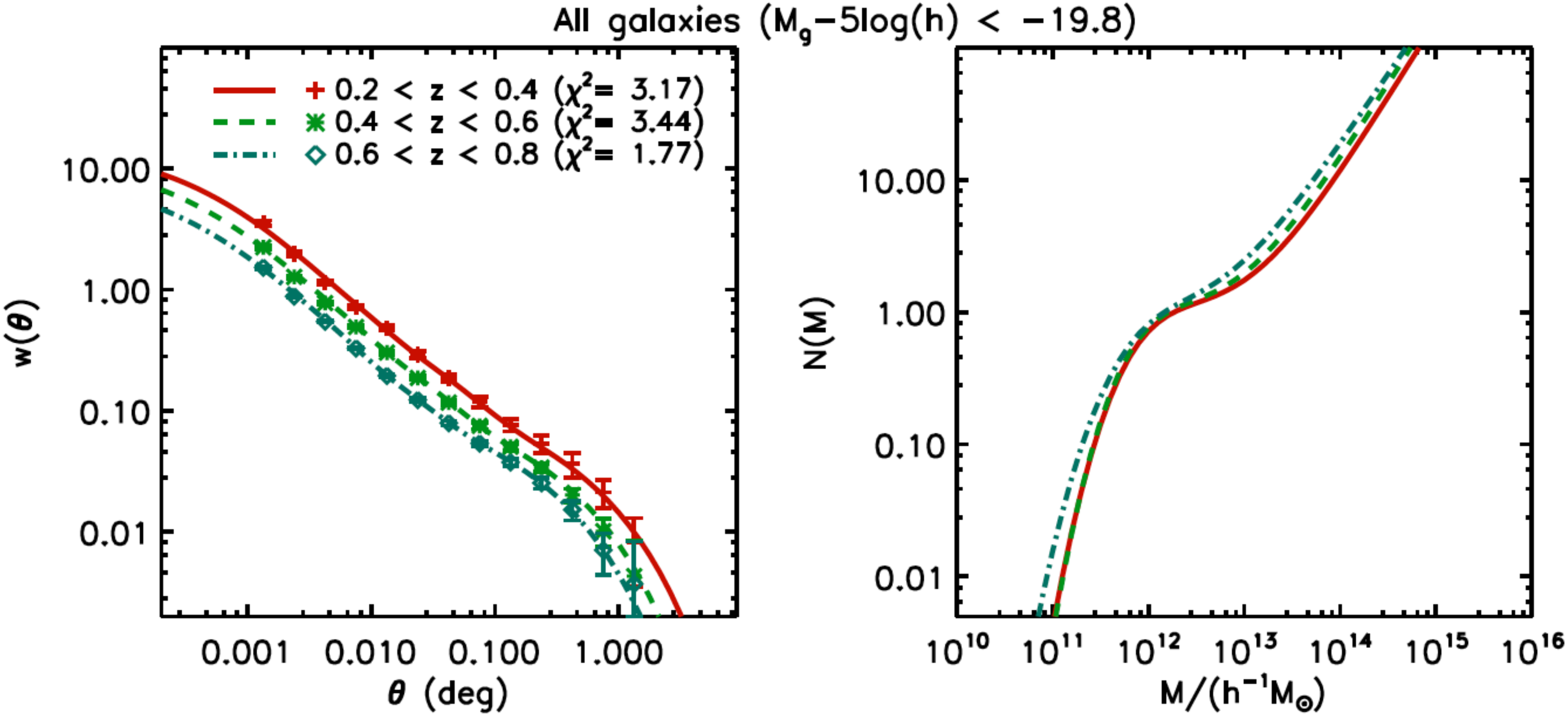
- M_{min}, M_1, M_0, σ_{logM} and α fit simultaneously
- flat prior for all parameters



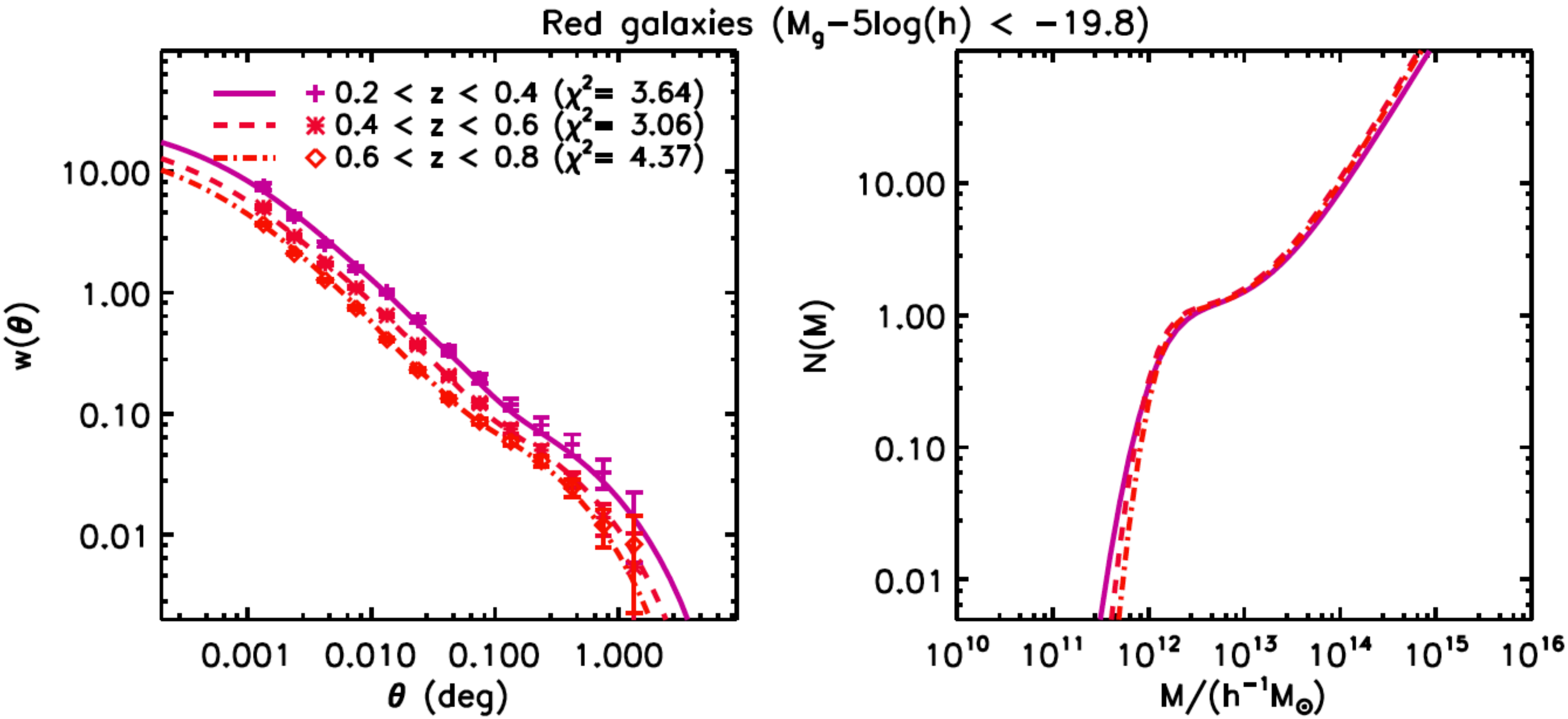




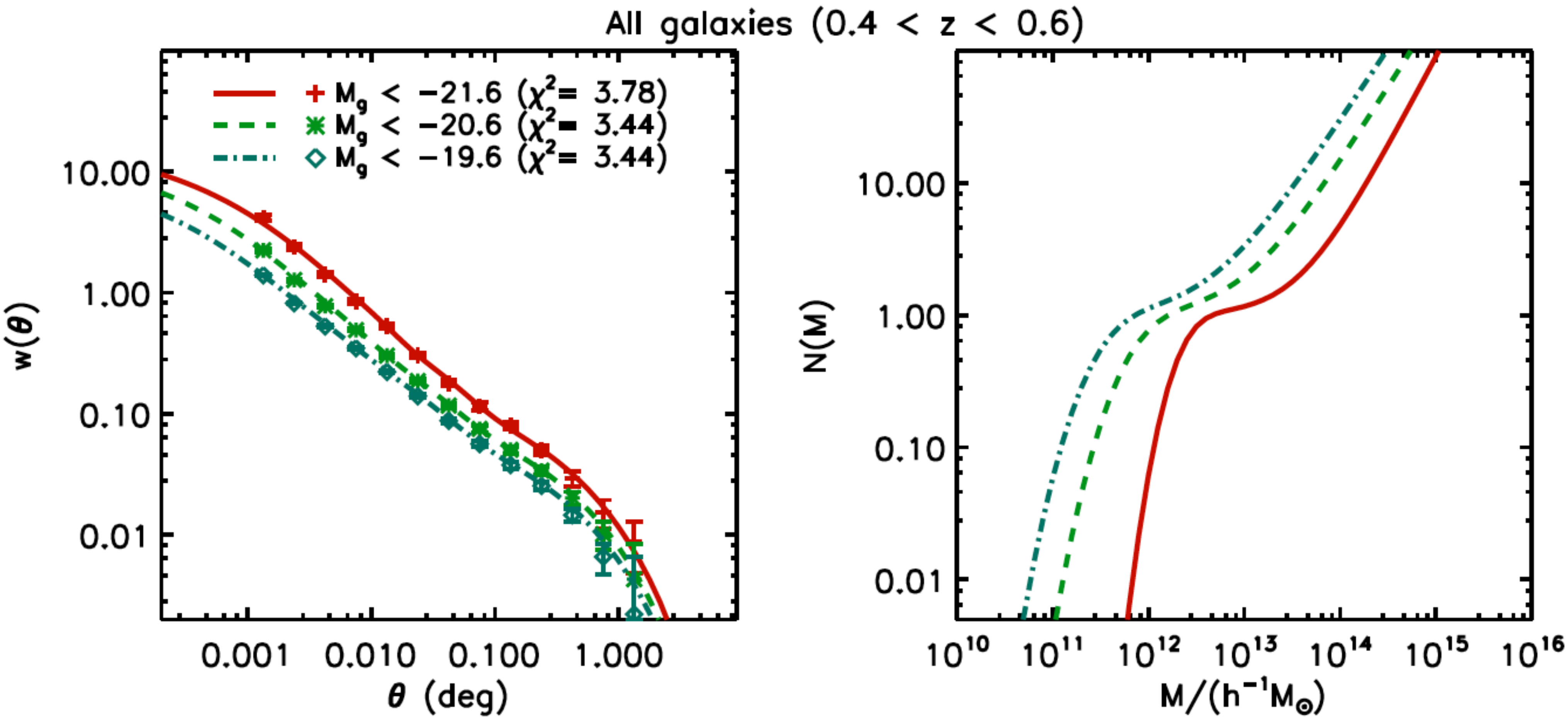
Redshift evolution - all galaxies



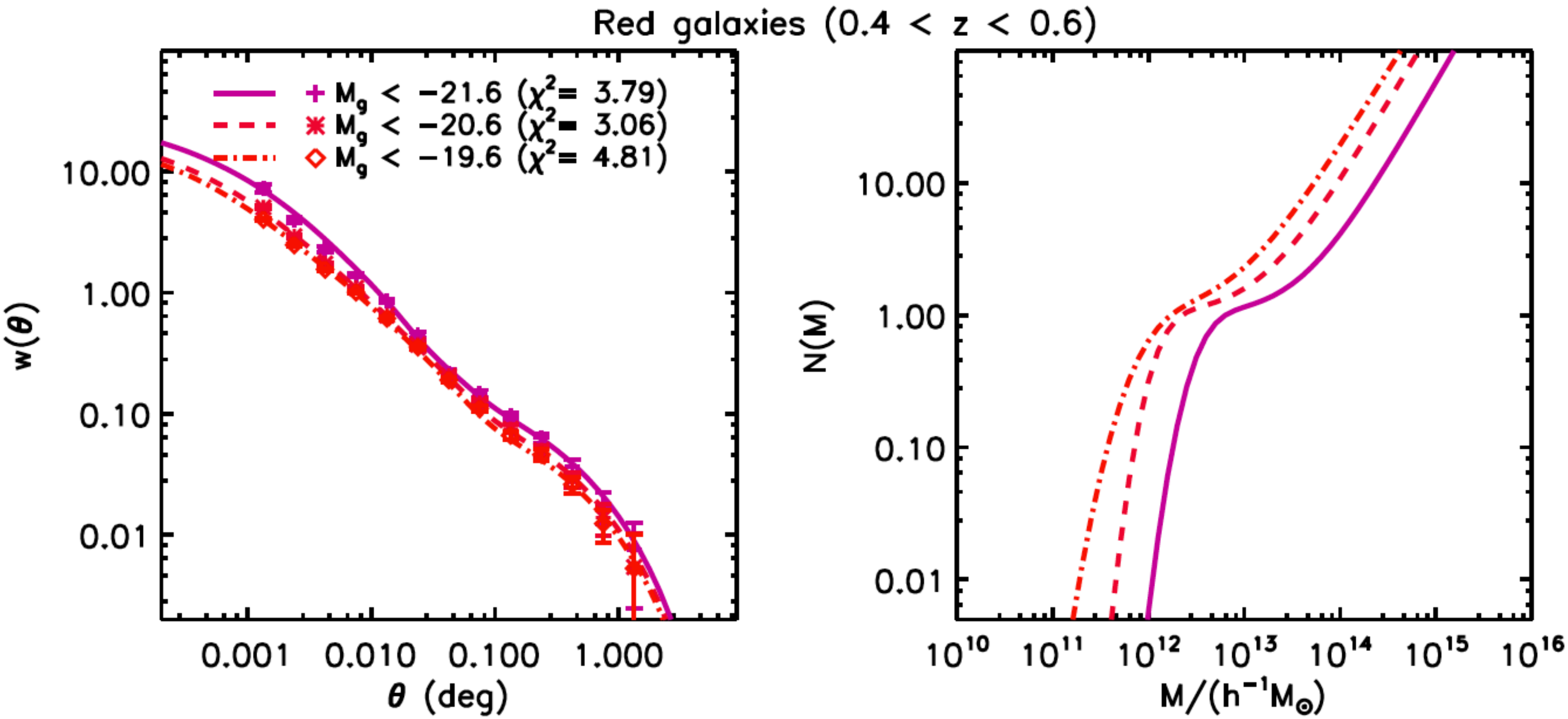
Redshift evolution - red galaxies



Luminosity dependence - all galaxies

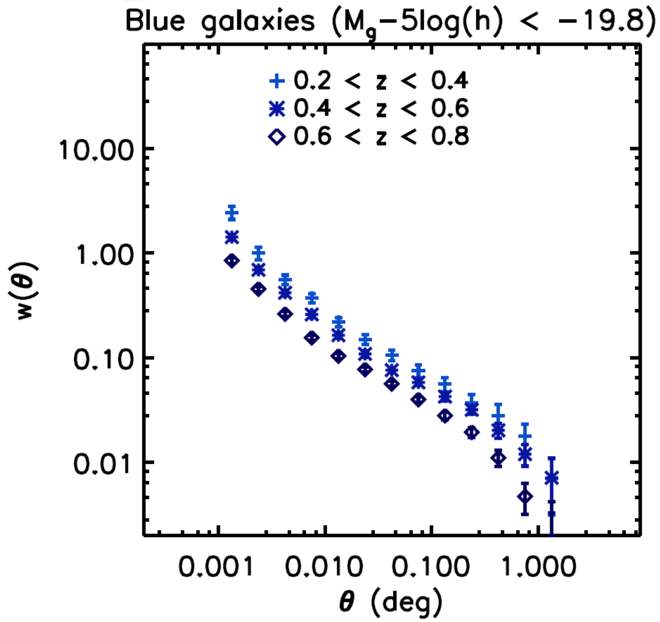


Luminosity dependence - red galaxies

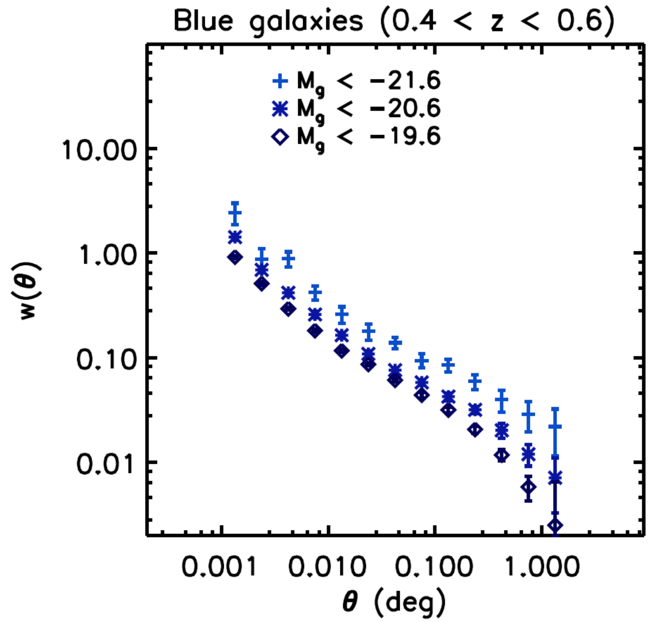


Clustering measurements - blue galaxies

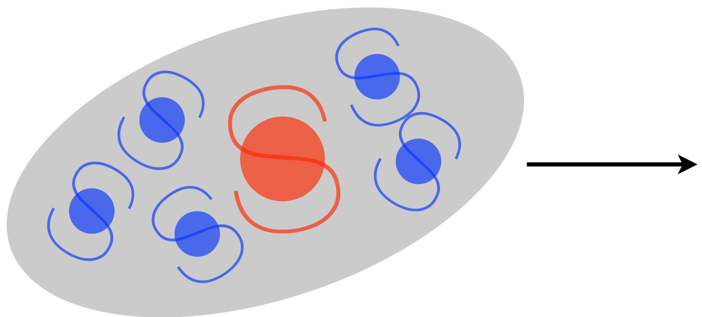
redshift evolution



Luminosity dependence

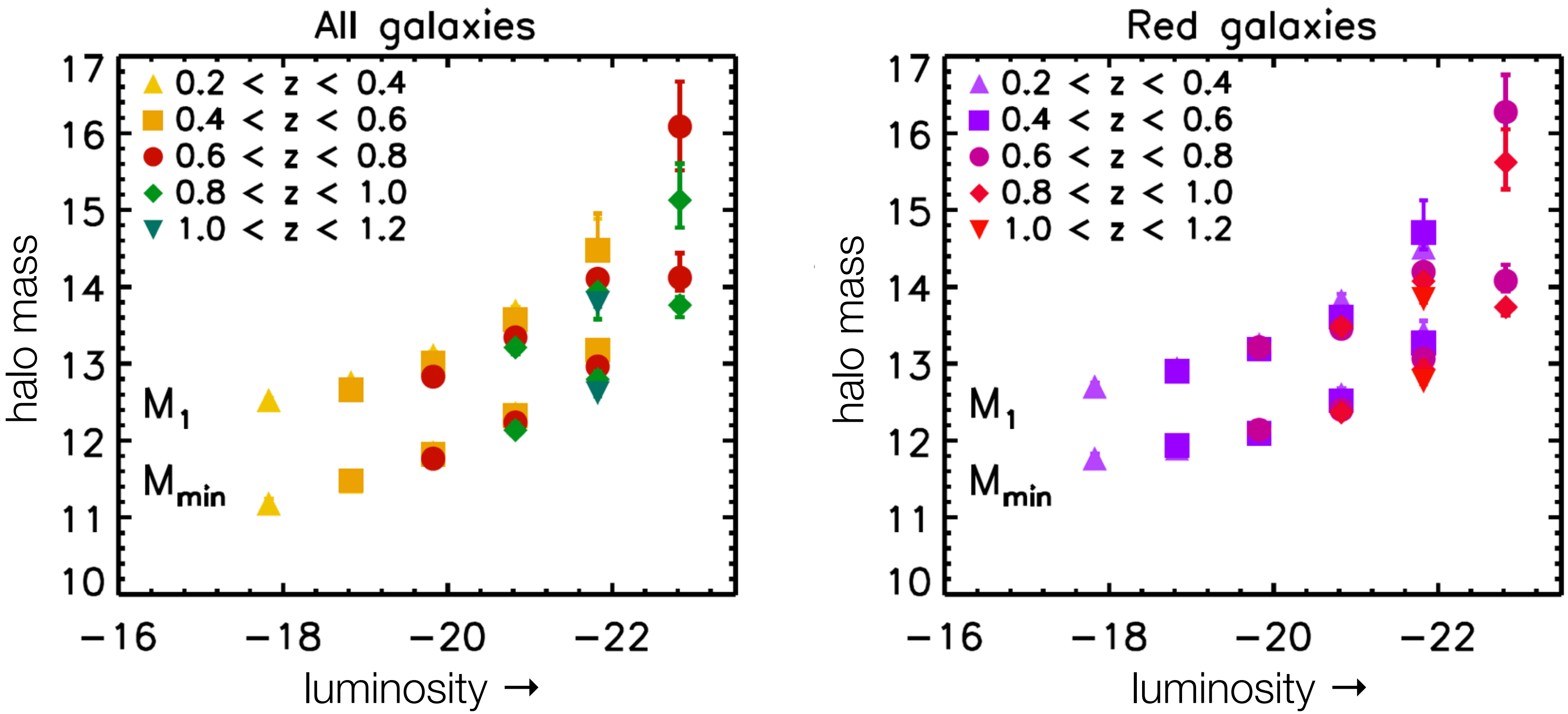


CAVEAT: blue satellite galaxies may belong to a red central galaxy.



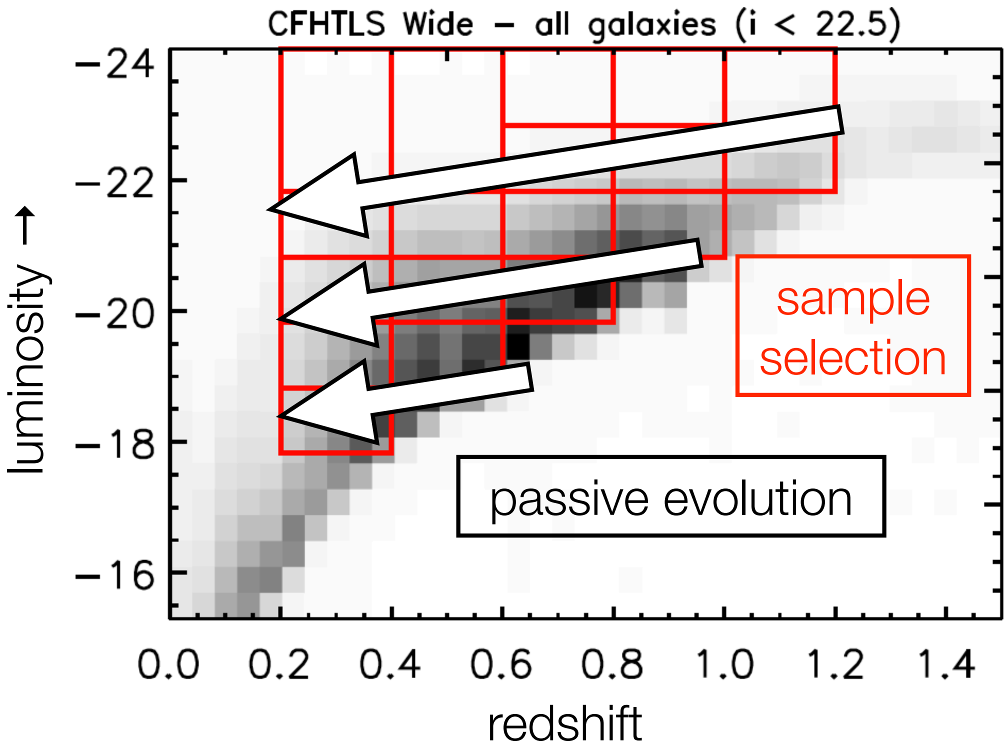
The model based on the separation central/satellite breaks down. No HOD fitting for blue samples.

Halo mass vs galaxy luminosity



- brighter galaxies reside in more massive haloes
- halo masses decrease with redshift
- red galaxies reside in more massive haloes than blue ones

Redshift evolution of L/M_h?

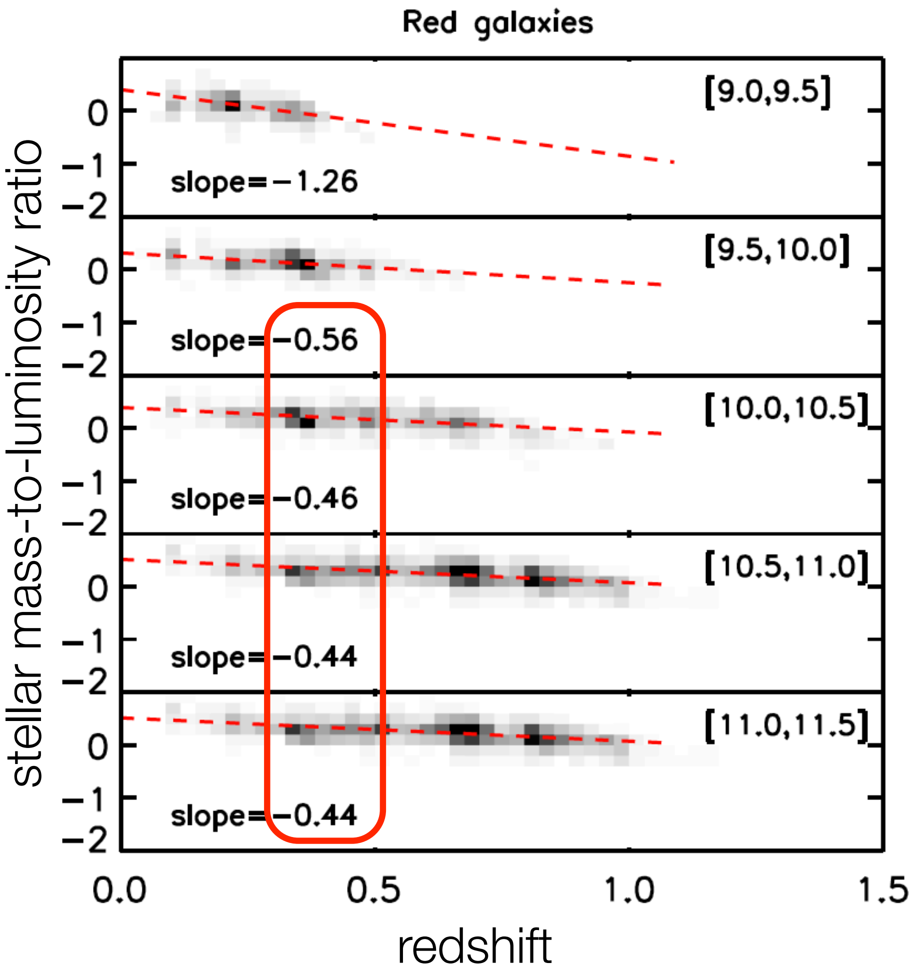


- **PB**: galaxies experience passive evolution (due to stellar population ageing)
- a constant luminosity selection "sees" different populations at different redshifts
- **consequence**: we observe less massive galaxies at higher redshift

decrease of M_h is partially due to this selection effect

Transforming luminosity into stellar mass

COSMOS 30-band stellar masses vs L_B:



From Ilbert et al. (2010)

No stellar masses (yet) in CFHTLS, but luminosity to stellar mass relation derived from COSMOS

For red galaxies:

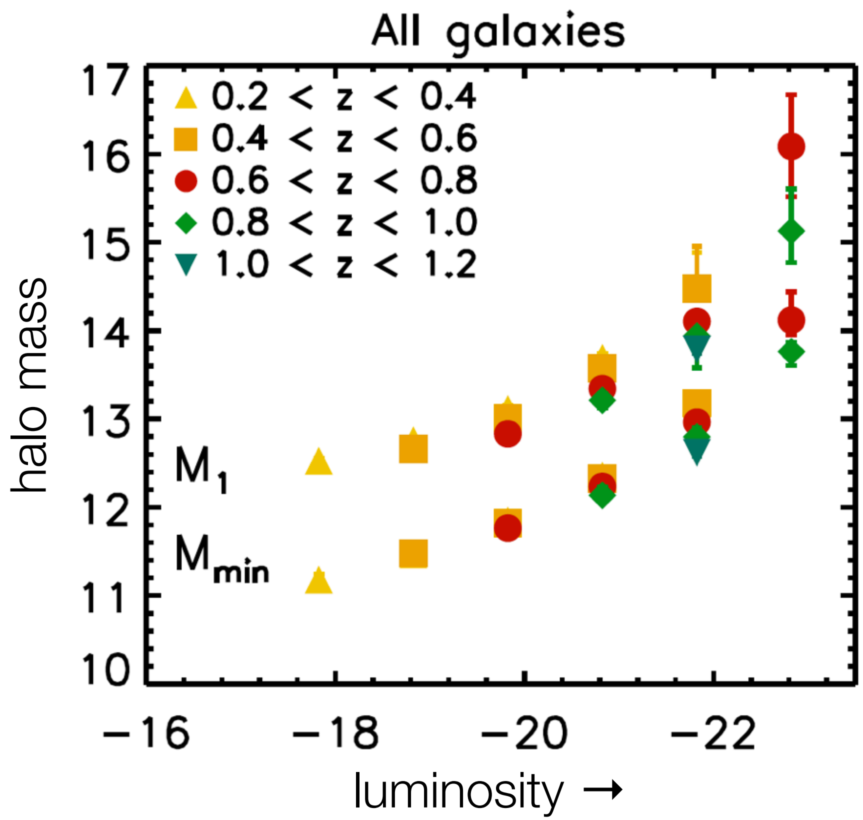
- stellar mass proportional to luminosity:

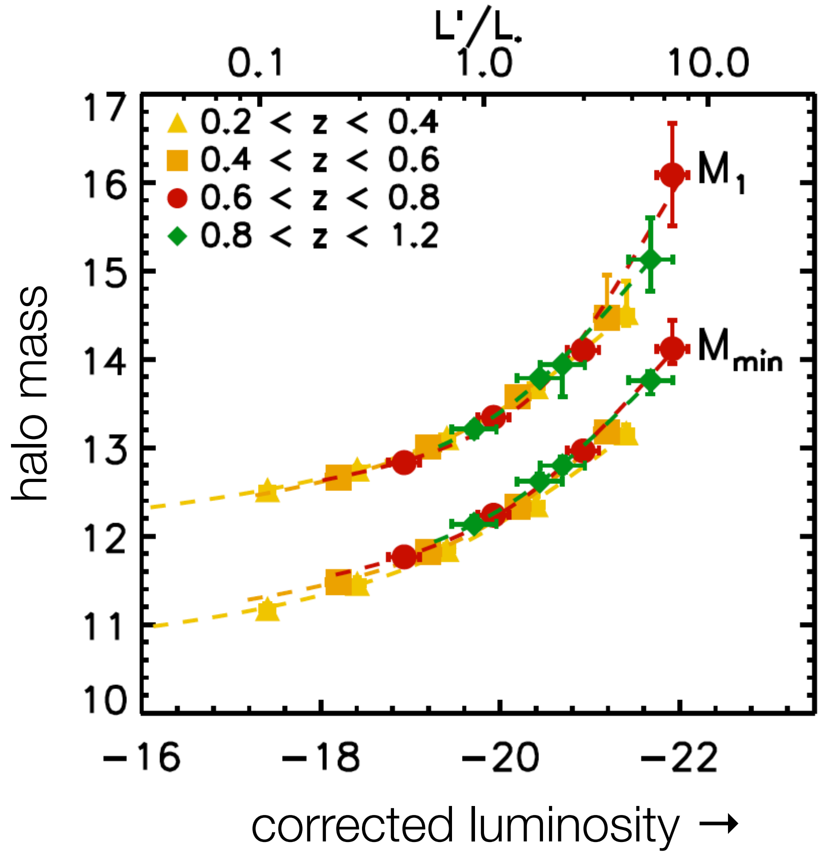
$$\log\left(\frac{M_{\rm star}}{L_B}\right)_{\rm red} = \log\left(\frac{M_{\rm star}}{L_B}\right)_{{\rm red},z=0} - 0.5\times z$$

For all galaxies:

- non trivial relation due to the mixing of red and blue galaxies
- applied the “red” correction but probably underestimates the faint luminosity evolution

Stellar-to-halo mass relationship - all galaxies





stellar mass proxy

JC et al. (arXiv:1107.0616)

Stellar-to-halo mass relationship - all galaxies

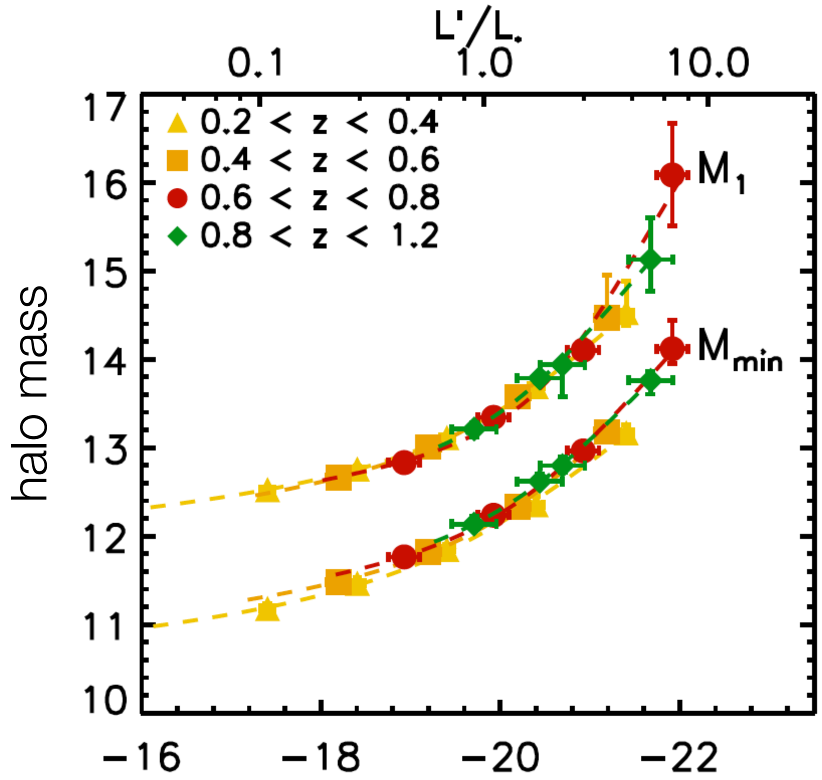
- relation between halo mass and central galaxy stellar mass
- redshift evolution of M_{star}/M_h
- but uncertainties at faint luminosity (where blue galaxies dominate)
- parameterised relation between luminosity and halo mass:

(Zehavi et al. 2010)

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

stellar mass proxy

halo mass

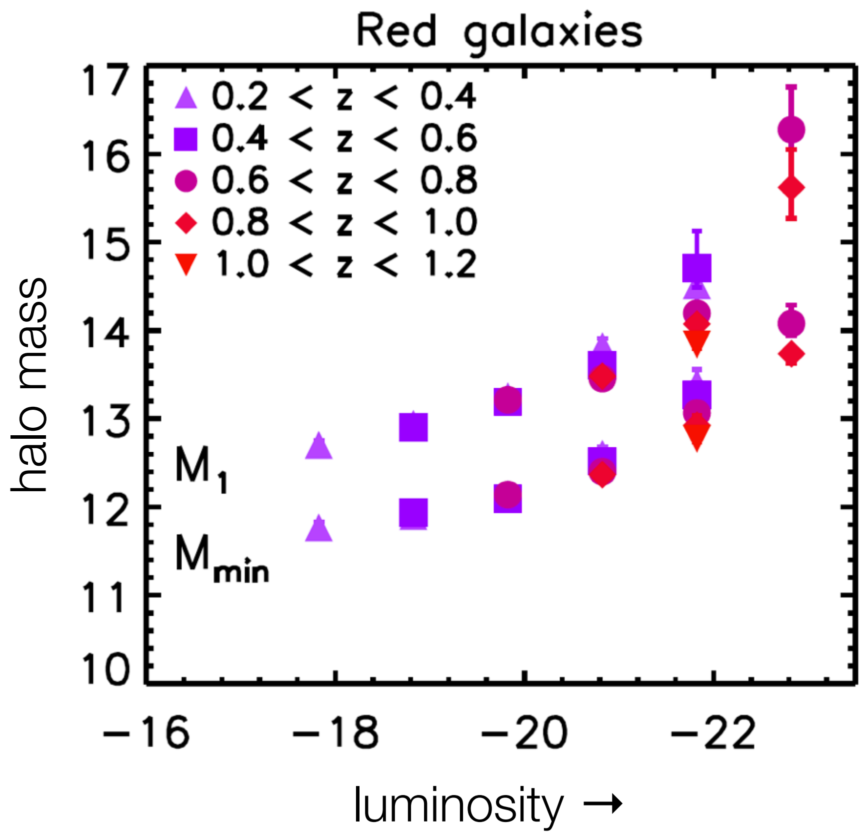


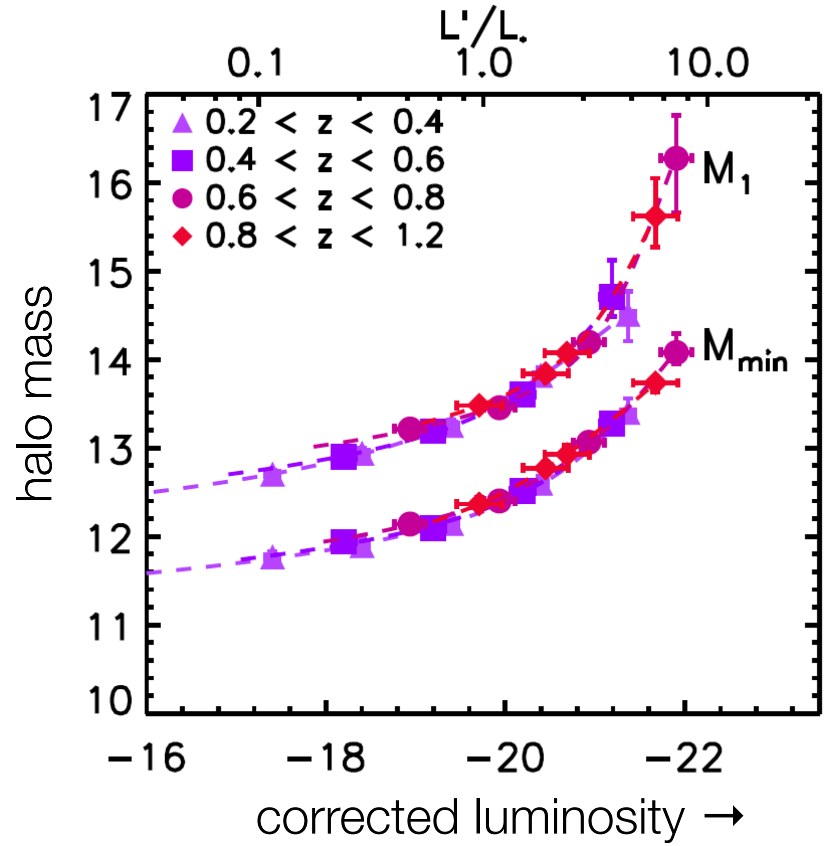
corrected luminosity →

stellar mass proxy

JC et al. (arXiv:1107.0616)

Stellar-to-halo mass relationship - red galaxies



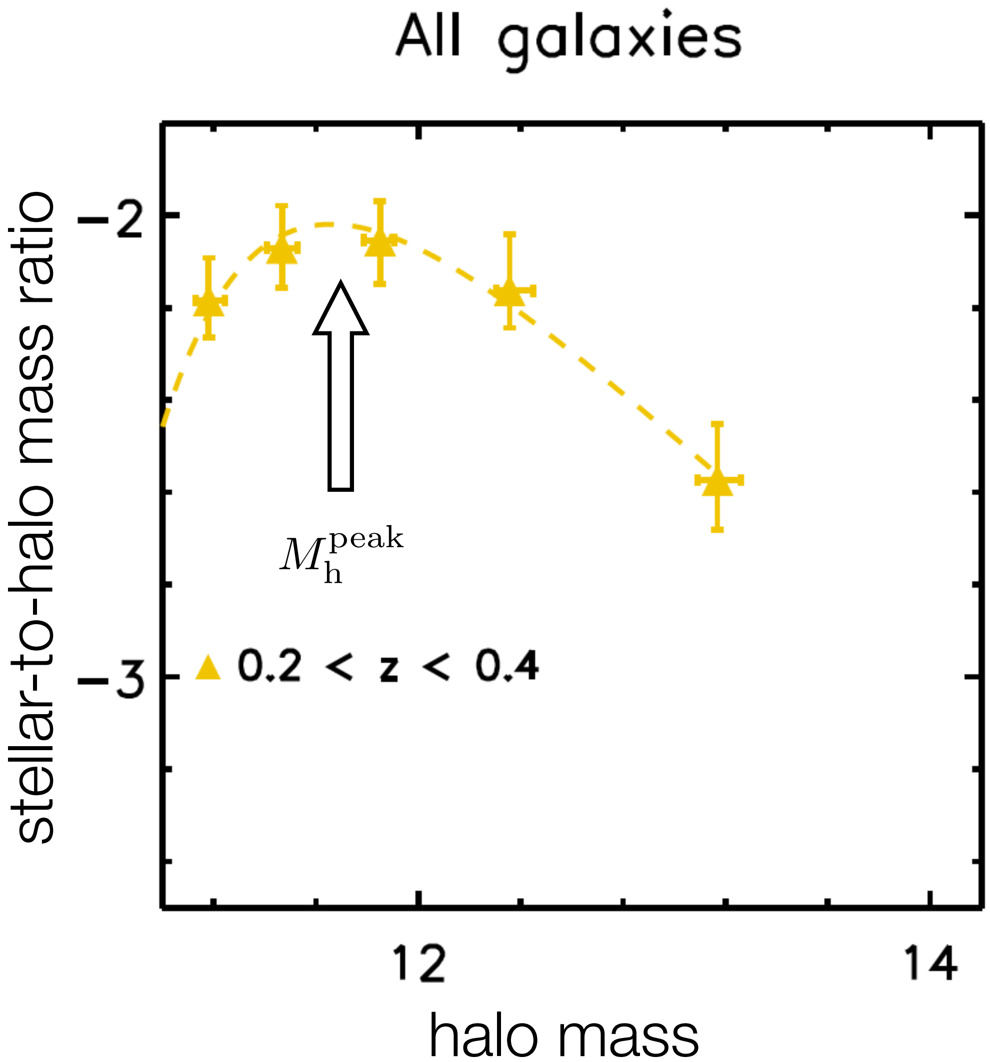


stellar mass proxy

- robust relation between halo mass and stellar mass
- weak redshift evolution of M_{star}/M_h

JC et al. (arXiv:1107.0616)

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

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

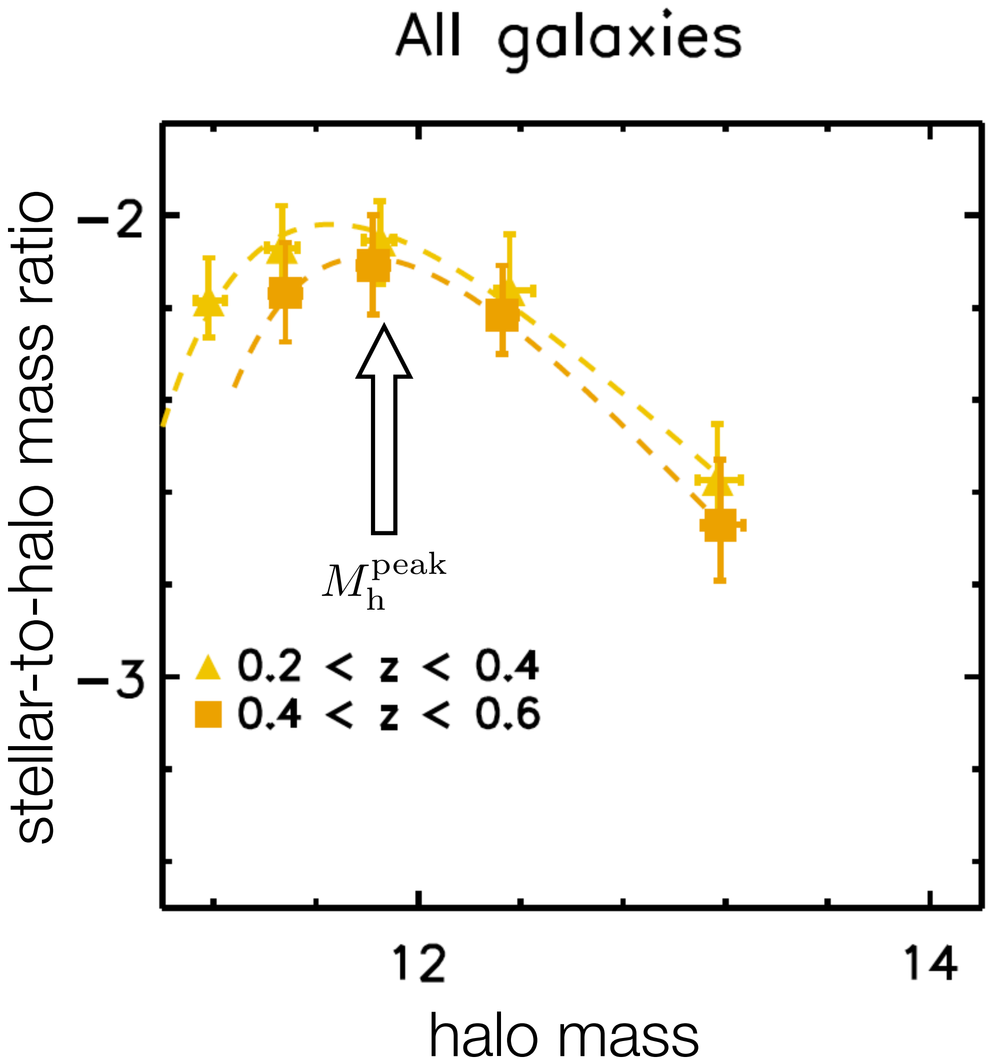
⇔ stellar-to-halo mass ratio

as function of halo mass

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

JC et al. (arXiv:1107.0616)

Stellar-to-halo mass ratio vs halo mass

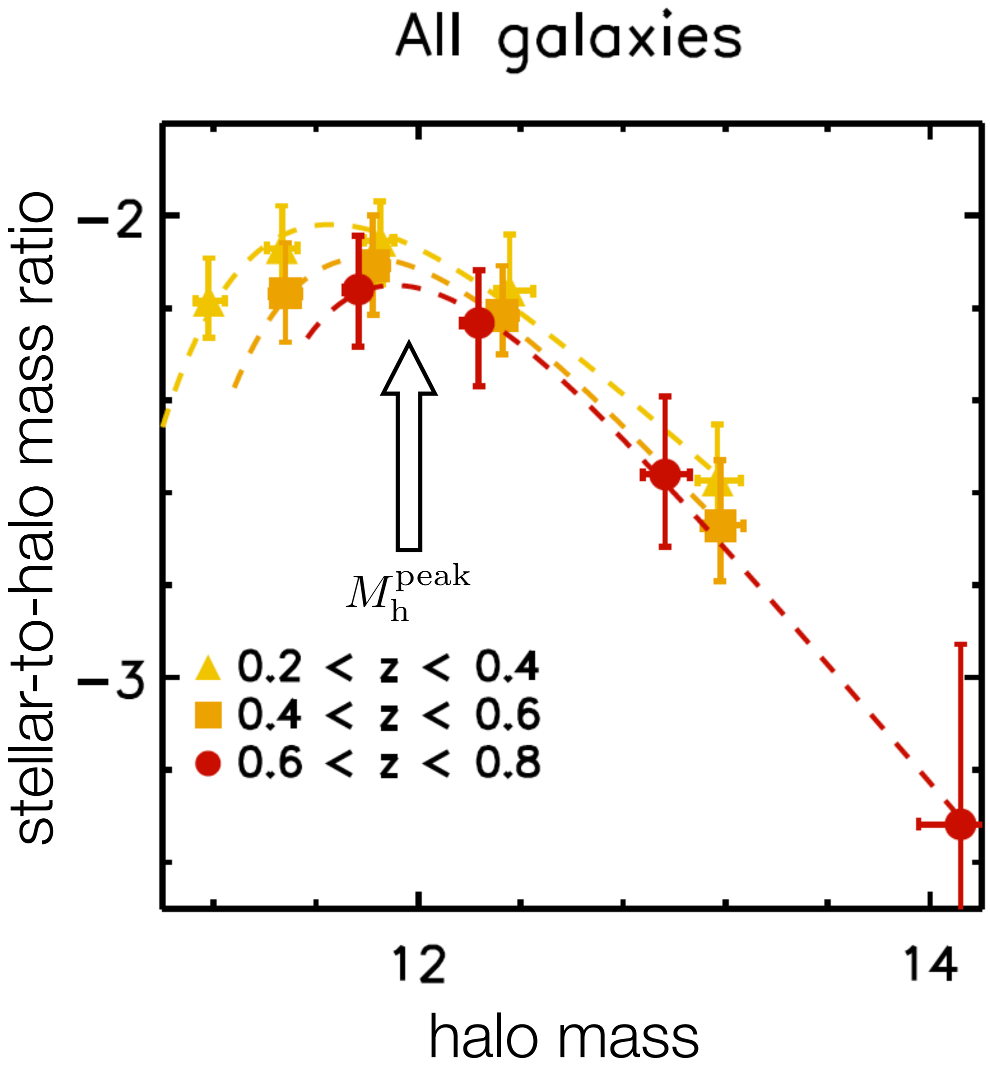


Redshift evolution:

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

JC et al. (arXiv:1107.0616)

Stellar-to-halo mass ratio vs halo mass

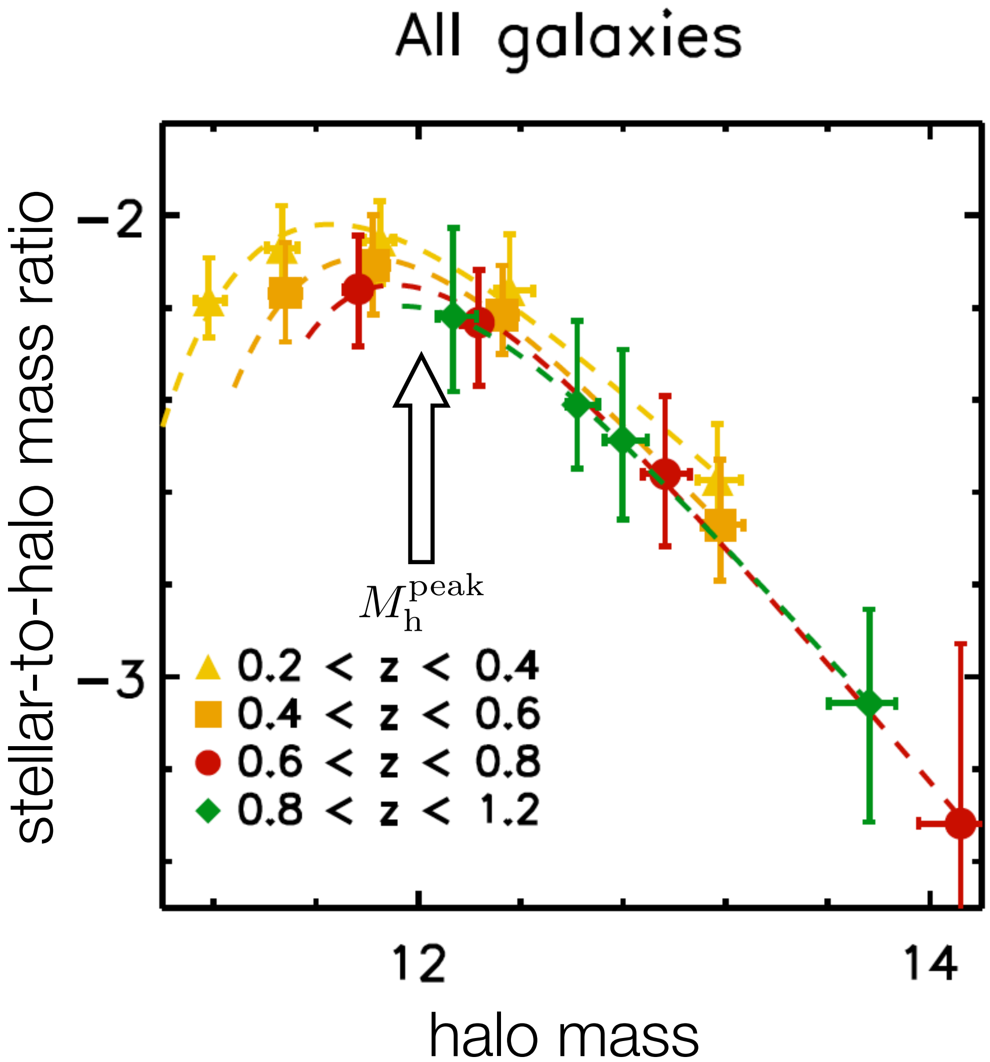


Redshift evolution:

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

JC et al. (arXiv:1107.0616)

Stellar-to-halo mass ratio vs halo mass



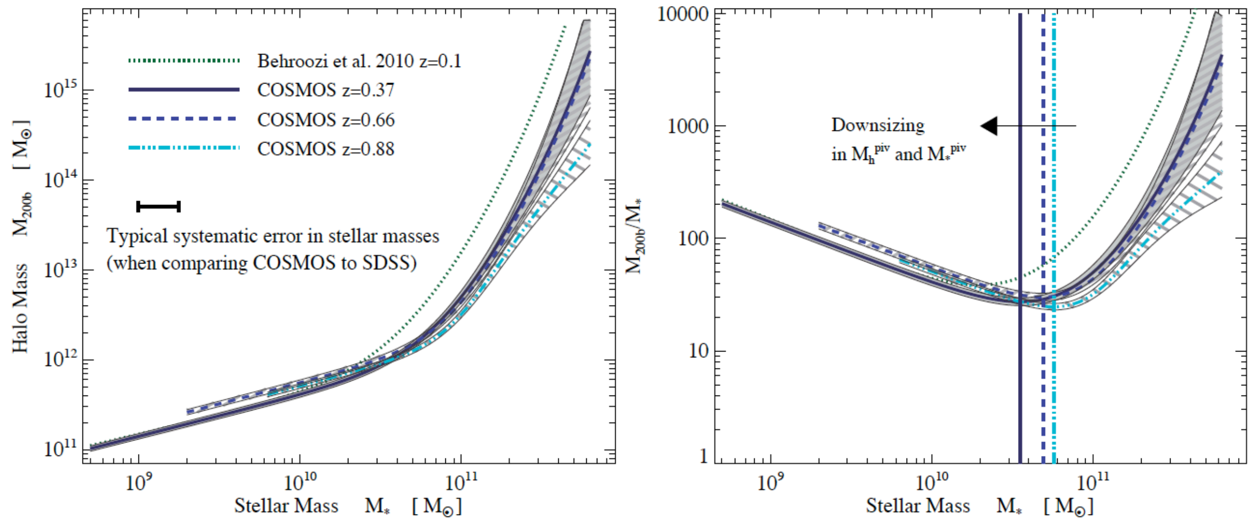
Redshift evolution:

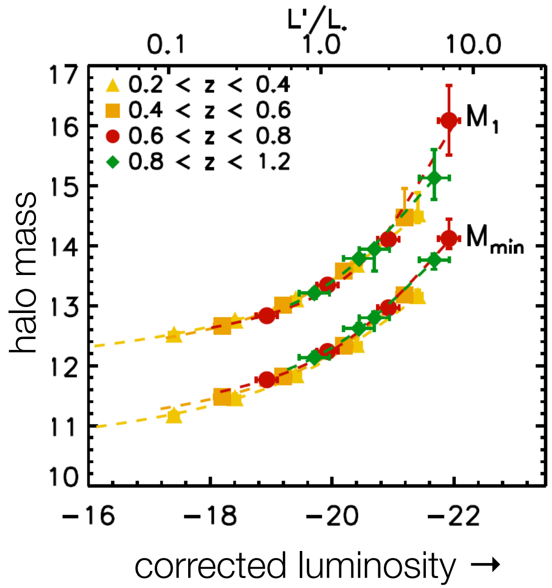
- the peak is poorly constrained in the highest redshift bin
- stronger evolution seen in low-mass haloes than in high-mass ones

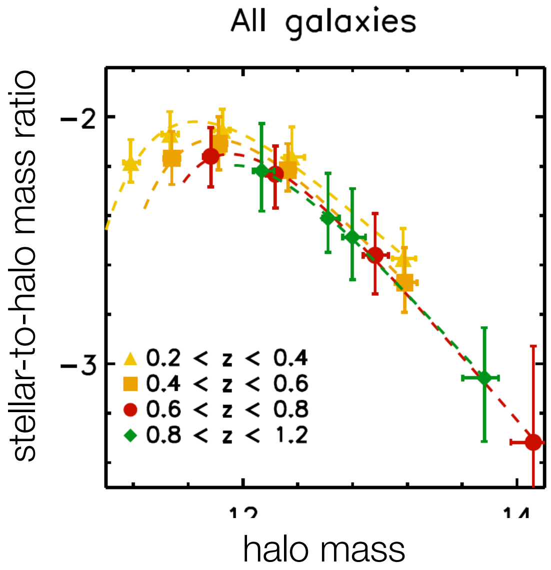
JC et al. (arXiv:1107.0616)

Comparison with COSMOS

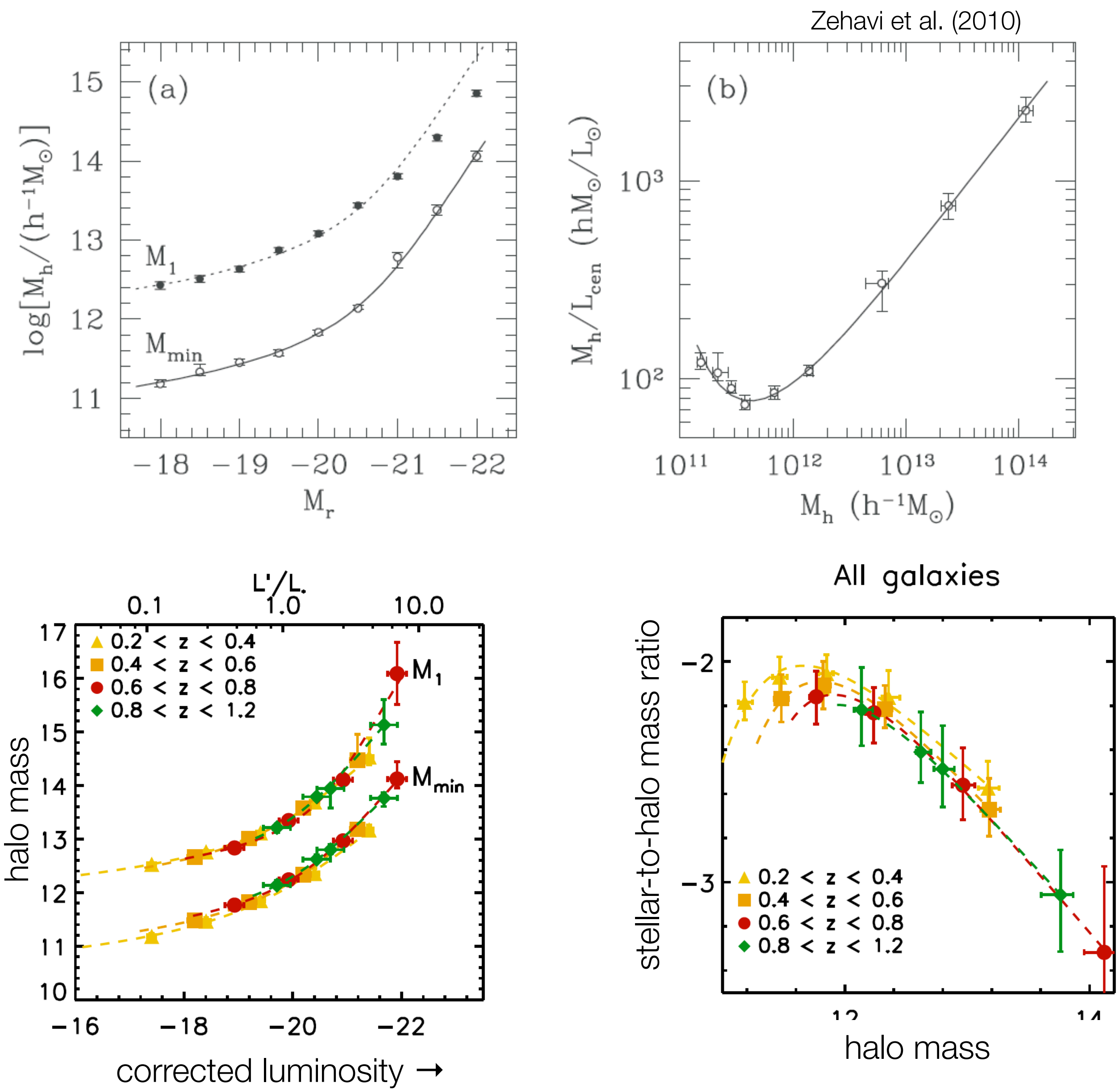
Leauthaud et al. (2011)



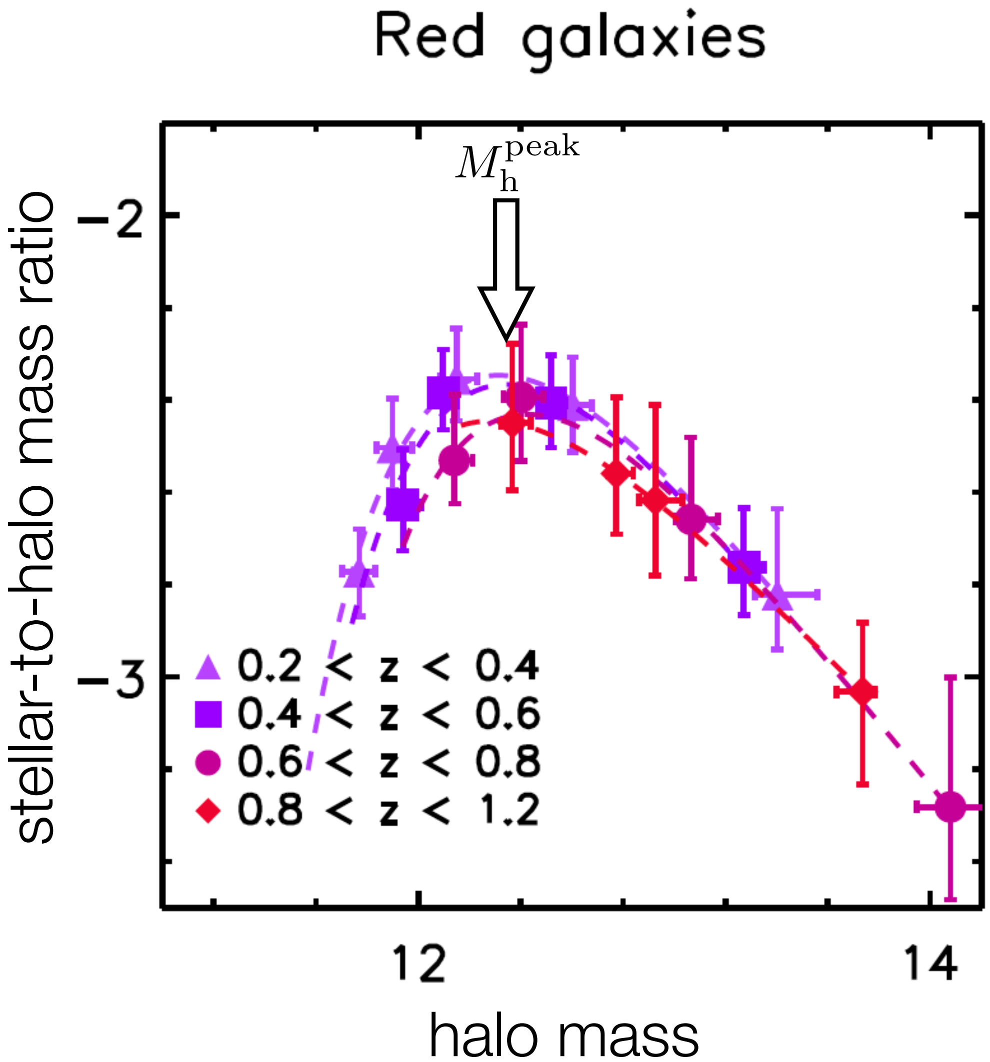




Comparison with the local Universe



Stellar-to-halo mass ratio vs halo mass



Red galaxies

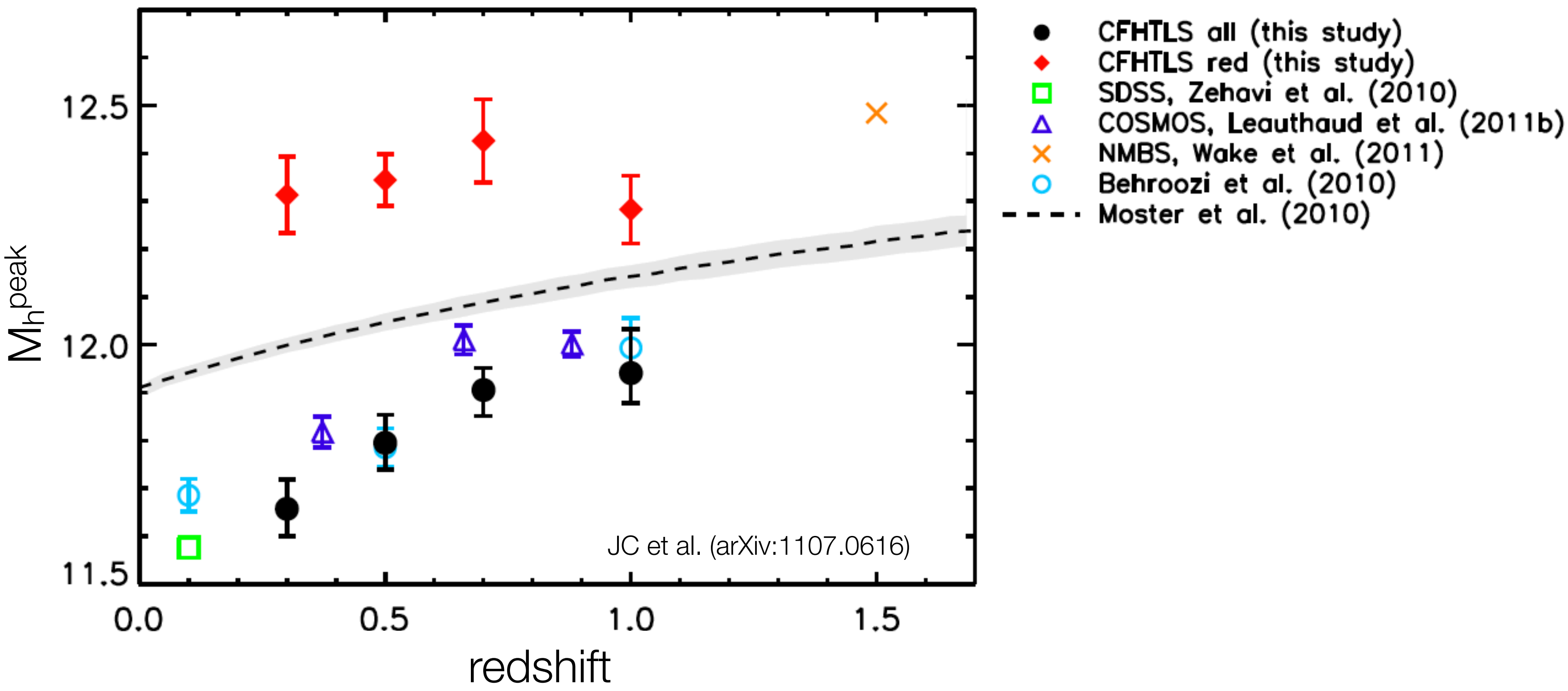
- the peak is at higher mass
- slower redshift evolution in low-mass haloes

JC et al. (arXiv:1107.0616)

Implications for galaxy evolution

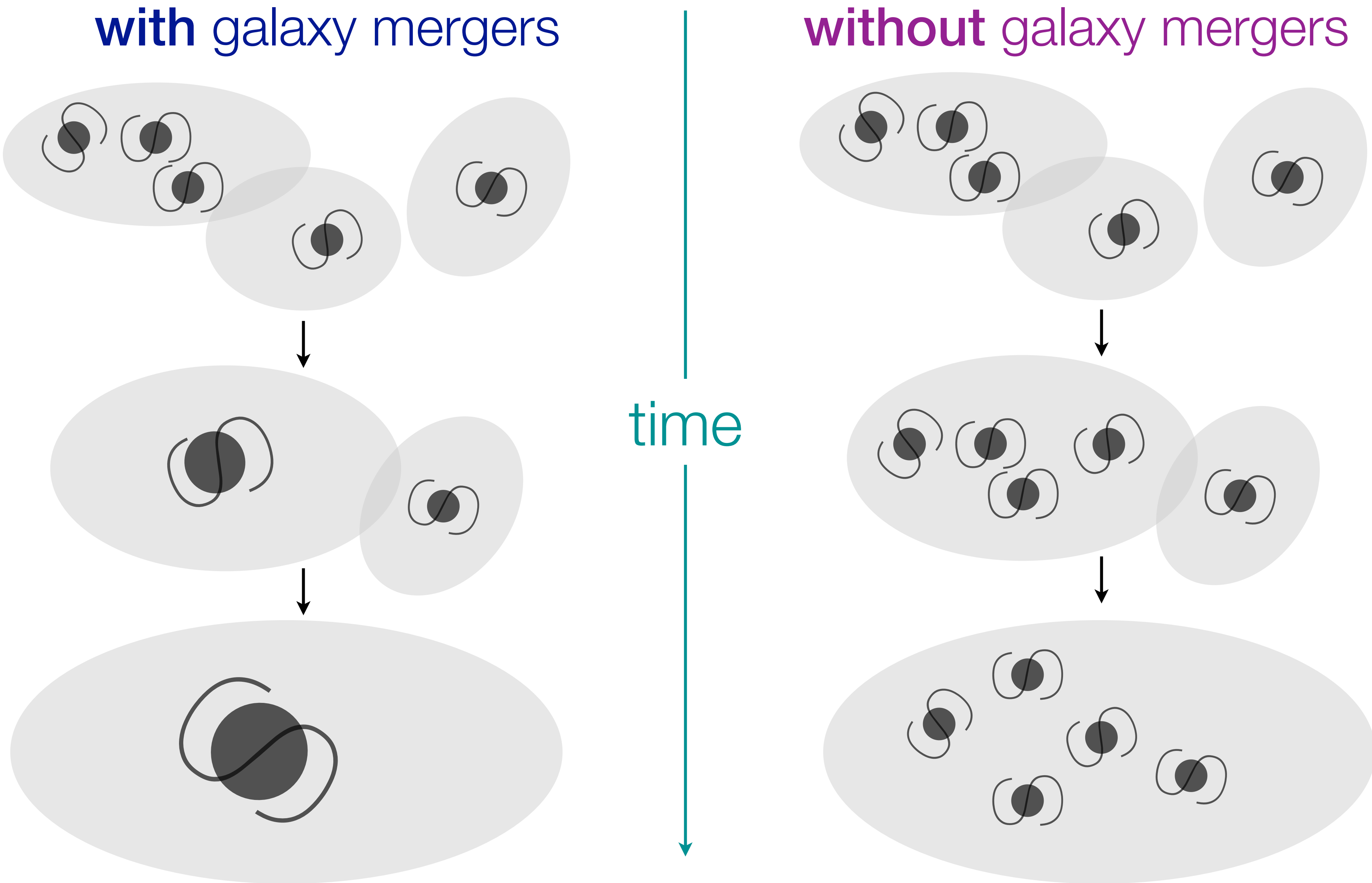
- in the local Universe, the stellar content has been most efficiently accumulated in haloes of mass (M_{peak}) ~ 10^{12} M_{sun}
- star formation is “quenched” by feedback processes at both halo mass limits
- the shift of the peak with redshift is caused by a differential evolution in low- and high-mass haloes (“downsizing” effect)
- in the full sample the evolution is more rapid in low-mass haloes (samples dominated by blue galaxies)
- active star formation raises the SMHR with time (decreases with redshift)
- red galaxy SMHR do not show significant evolution, consistent with passive evolution

Comparison with the literature

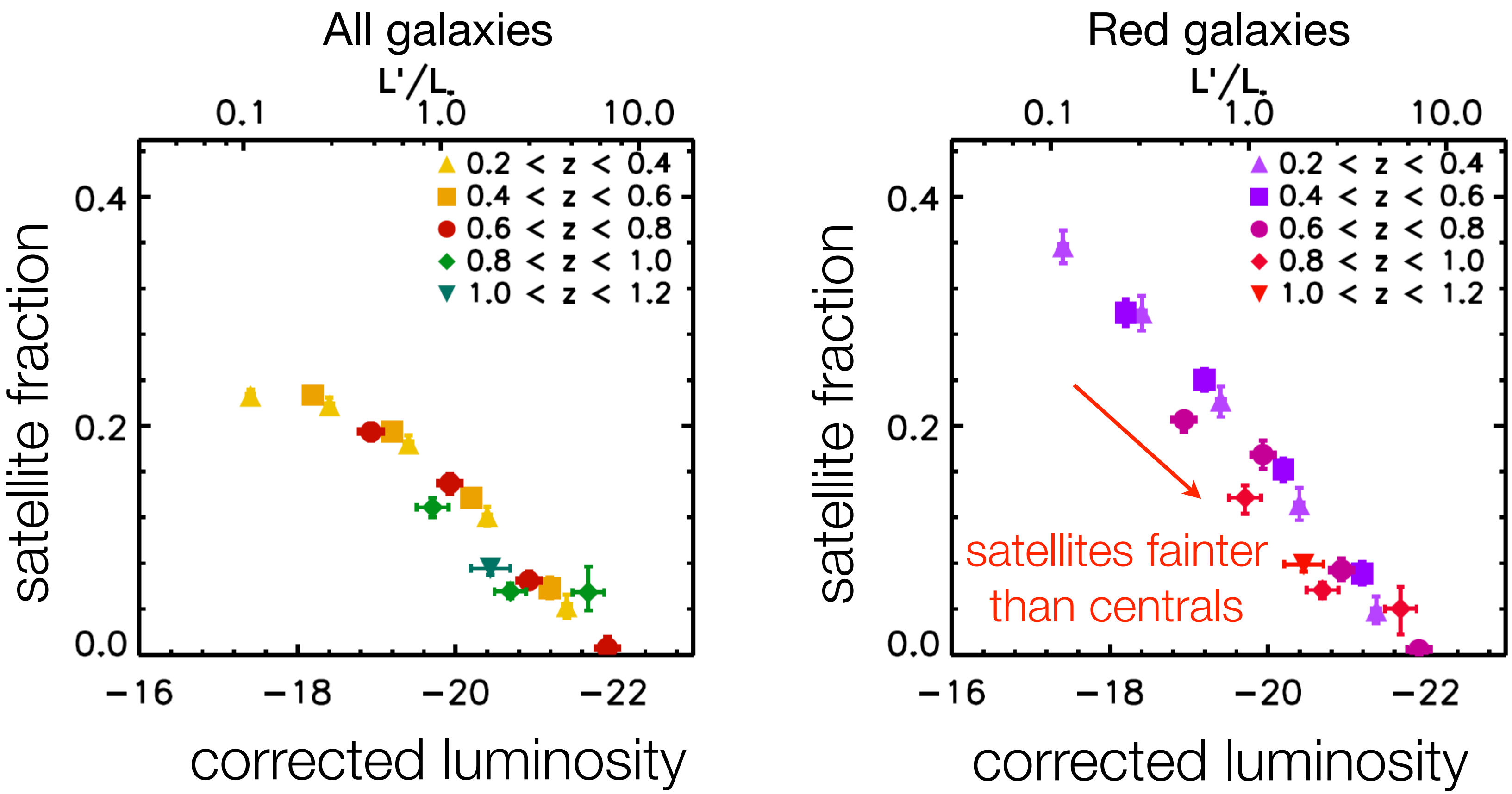


- Similar trend for observations and semi-analytic simulations
- Excellent agreement with SDSS
- Lower value than in COSMOS (cosmic variance issue?)
- no significant evolution for red galaxies: passive evolution since z ~ 1.2?

The importance of mergers in galaxy evolution



Satellite galaxy fraction

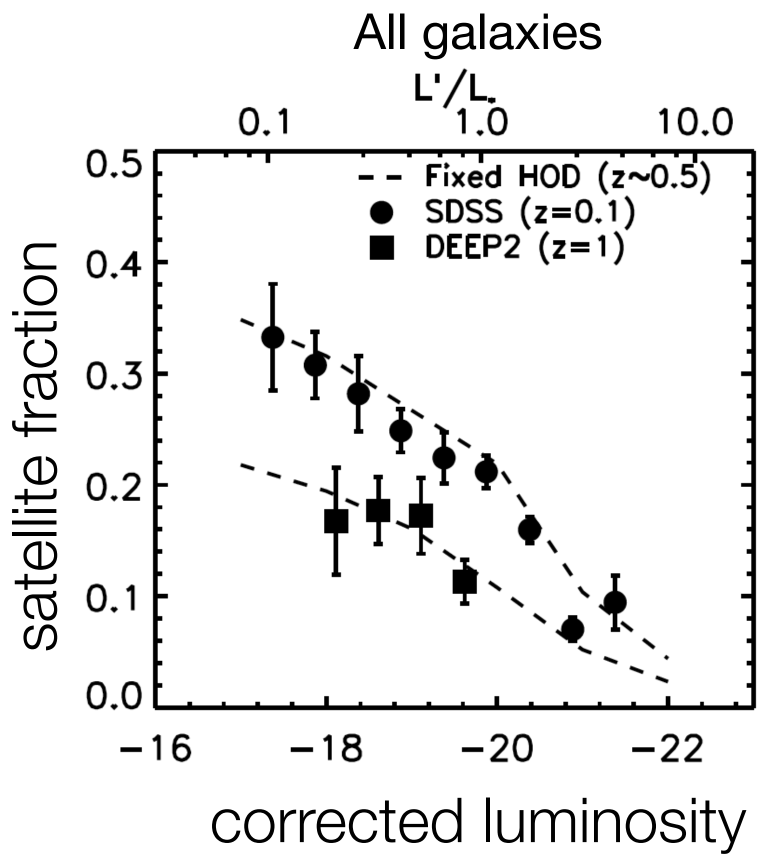


- number of red satellites is larger than in full sample

JC et al. (arXiv:1107.0616)

- increases (decreases) with time (redshift)
- flattens at high luminosity (larger number of small haloes with single galaxies)

Satellite galaxy fraction - redshift evolution



$$f_{\rm sat} \equiv n(M,z) \otimes N_{\rm sat}(M)$$

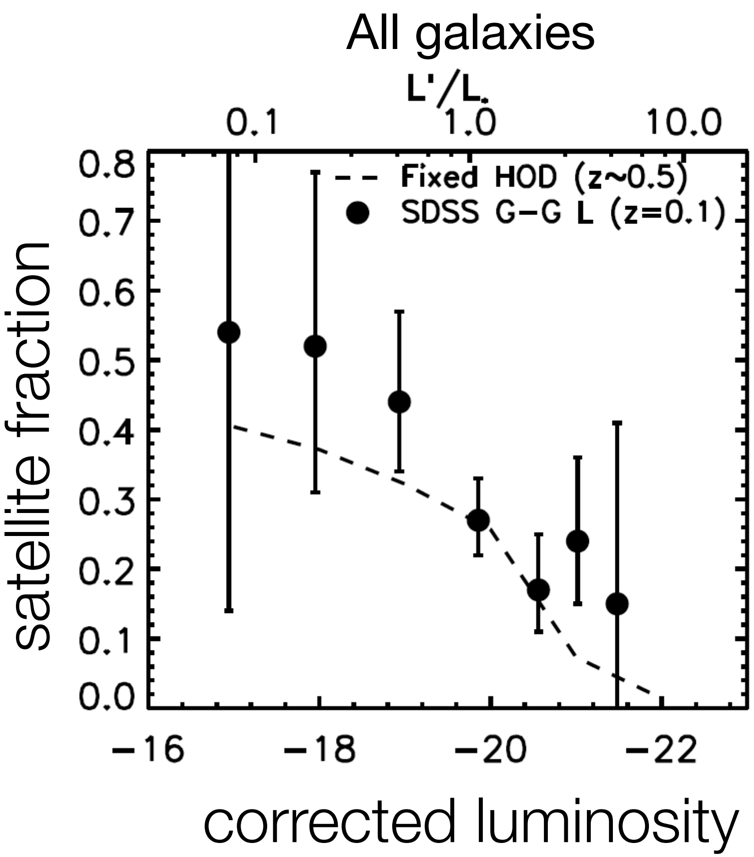
halo mass function (M,z)

HOD [=f(z)?]

- keeping HOD fixed (z~0.5 values), we extrapolated $f_{\rm sat}$ in luminosity and redshift
- no significant departures with local Universe measurements

→ consistent with HOD(z) ~ cst. Minor role of galaxy mergers?

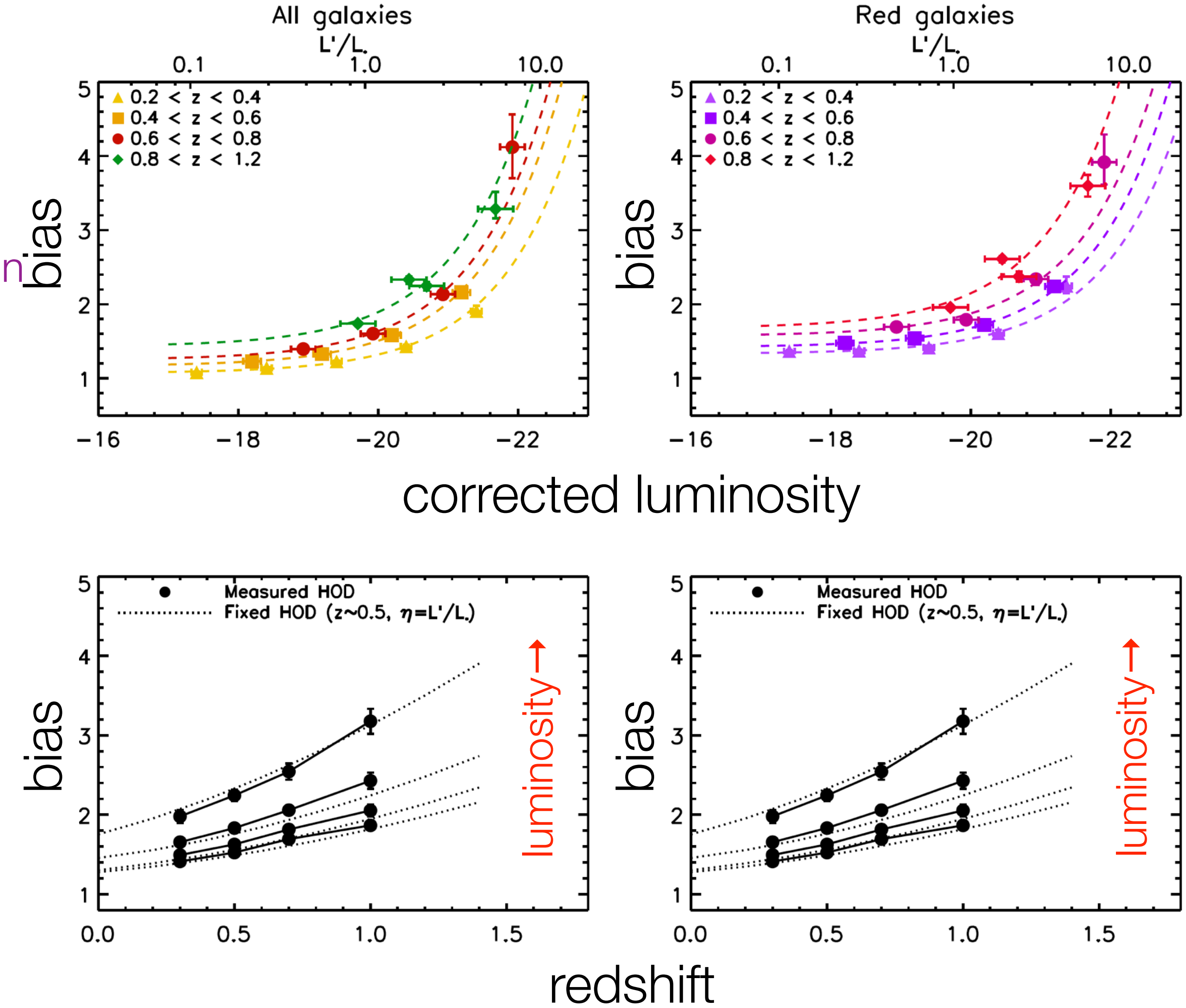
Satellite galaxy fraction - red galaxies



- good agreement with local Gal-Gal lensing (Mandelbaum et al. 2006)
- White et al. (2007): deficit of red satellites found at later time?

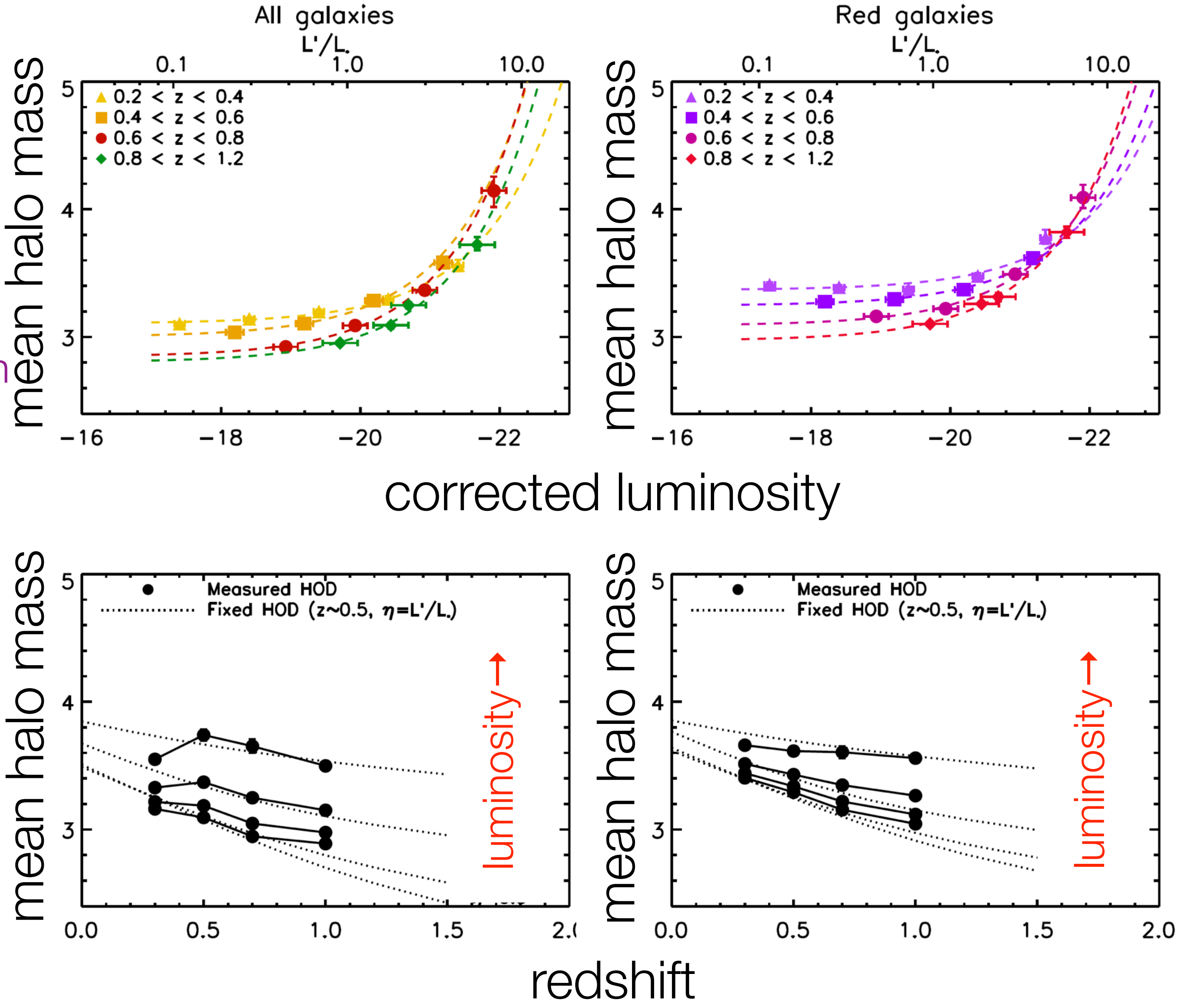
Galaxy bias

- bias increases with luminosity and redshift
- brighter galaxies reside in more massive haloes
- bright samples depart from "HOD (z) = cst" model



Mean halo mass

- mean halo mass increases with luminosity but decreases with redshift
- brighter galaxies reside in more massive haloes
- bright samples strongly depart from “HOD (z) = cst” model



V. Conclusions

Conclusions

- understanding galaxy formation and evolution is challenging
- the HOD formalism, a powerful combination of the halo model and simple assumptions, brings valuable hints on the relationship between galaxy and dark matter
- the CFHT Legacy Survey is a unique combination of depth, area and image quality
- we measured the galaxy clustering using advanced tools in the CFHTLS Wide and checked that no systematic would dominate our error budget
- when applying the HOD model to the CFHTLS, we were able to derive precise constraints on galaxy evolution

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