Observationally connecting stellar mass and star formation rate to dark matter halo since z~2

HERMES

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- A flood of data charting the cosmic star formation history, stellar mass build-up, BH accretion, etc.

- Measurements of the DM halos in which galaxies reside (galaxy clustering, weak lensing, satellite kinematics, etc.).

Need an observationally-based framework within which to understand the relation between galaxies and halos, and the interconnections between the key aspects of galaxy formation & evolution. No assumptions about the baryonic physics. → **the extended halo model**

The first step is to link both stellar mass and SFR to halos.

Why is such an emprical framework (the extended halo model), i.e. the relation between the luminous and the dark side, useful?

- Understand which physical processes are the main drivers of galaxy formation & evolution.
- Constrain cosmological parameters from galaxy surveys.
- An ideal interface between observations and simulations (hydrodynamical & semi-analytic).

Outline

1. The extended halo model of the local Universe.
   - mathematical framework;
   - observational data;
   - the derived relation between stellar mass, SFR and halo mass.
2. The extended halo model of the high-z Universe.
3. Conclusions.

To build the extended halo model of the local Universe, we start with the **conditional stellar mass function**

(i.e. the distribution of galaxies as a function of stellar mass at fixed halo mass)

$$\Phi(m_{star} \mid M_{halo}) = \Phi_{central} + \Phi_{satellite}$$

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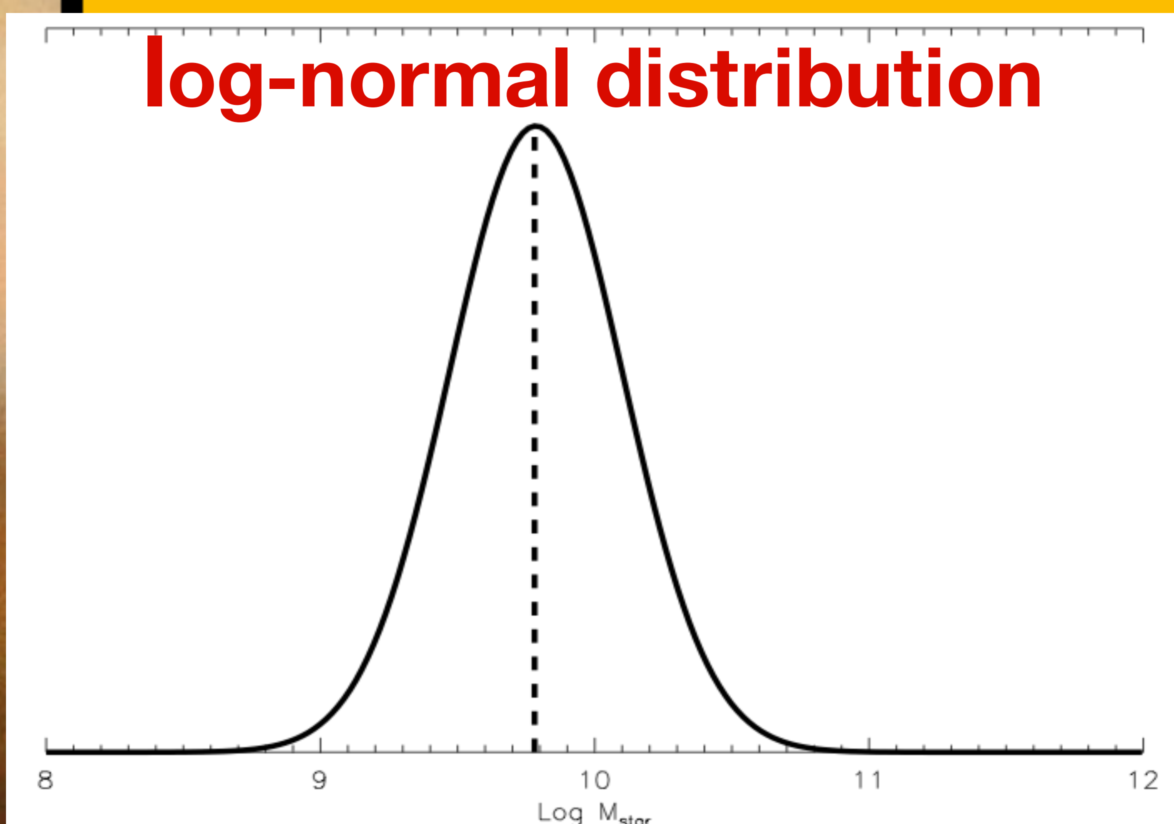
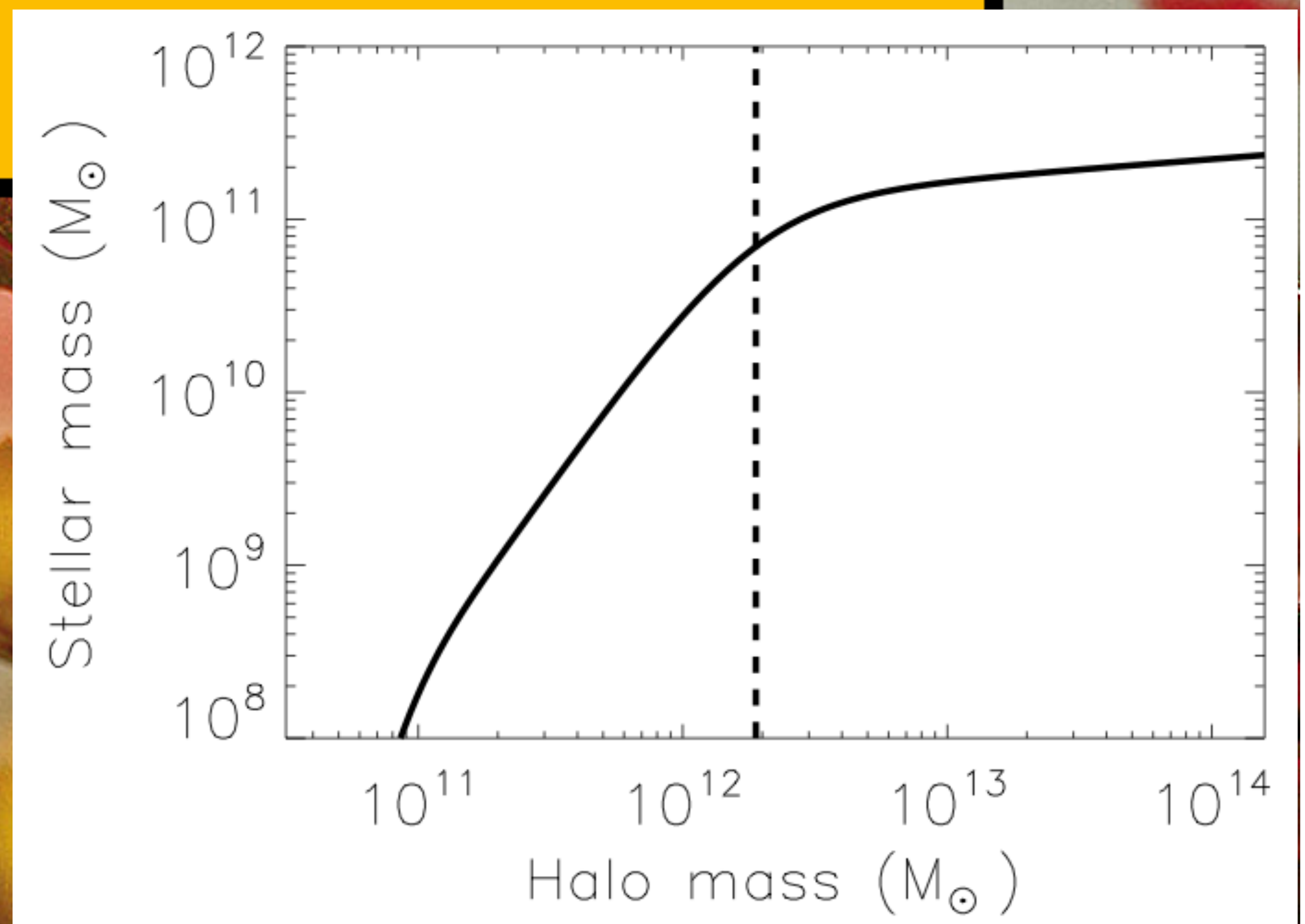
$$\Phi_c(m|M) = \frac{1}{\sqrt{2\pi}\,\ln 10\, m\sigma_c} \exp\left[-\frac{\log^2(m/m_c)}{2\sigma_c^2}\right]$$

Eq. 1

$$m_c(M) = 2M\left(\frac{m_c}{M}\right)_0 \left[\left(\frac{M}{M_{1c}}\right)^{-\beta_c} + \left(\frac{M}{M_{1c}}\right)^{\gamma_c}\right]^{-1}$$

Eq. 2

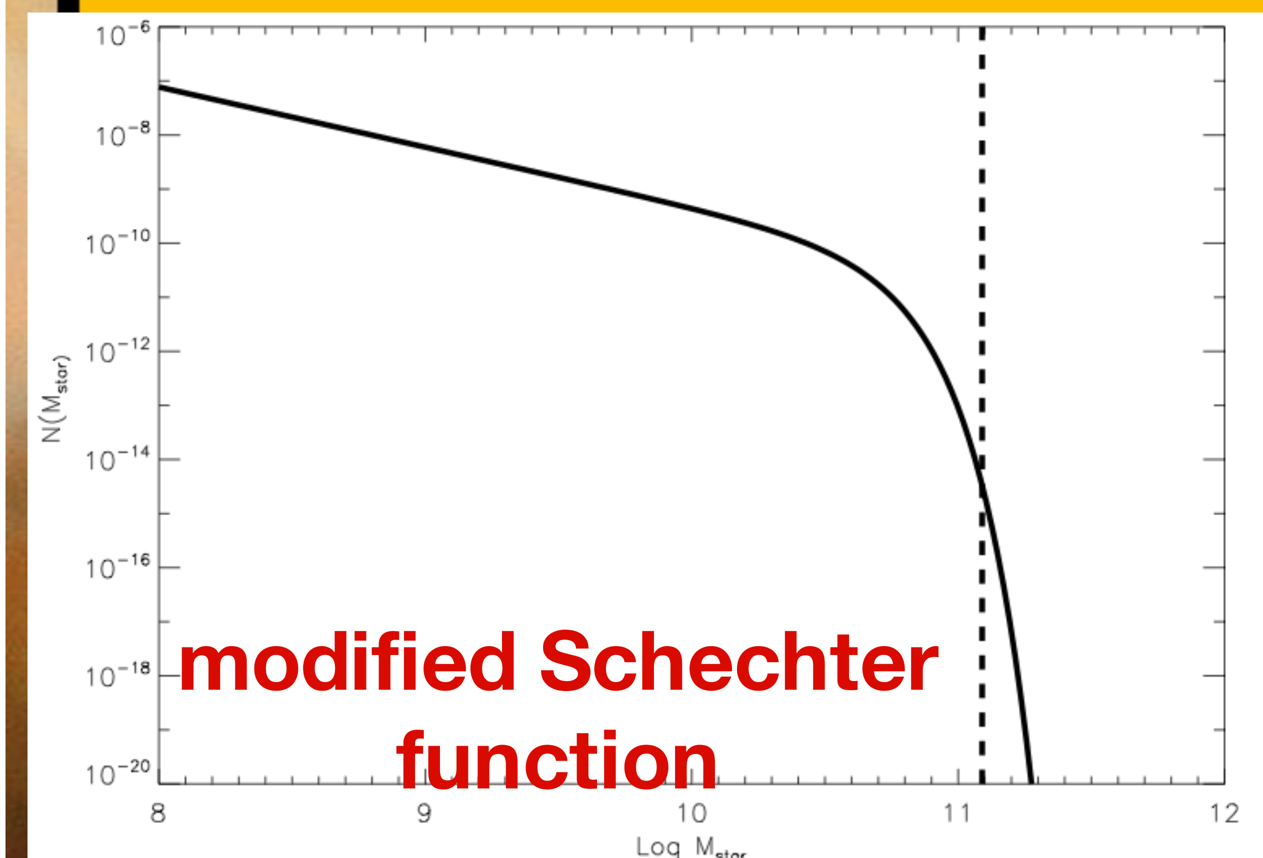


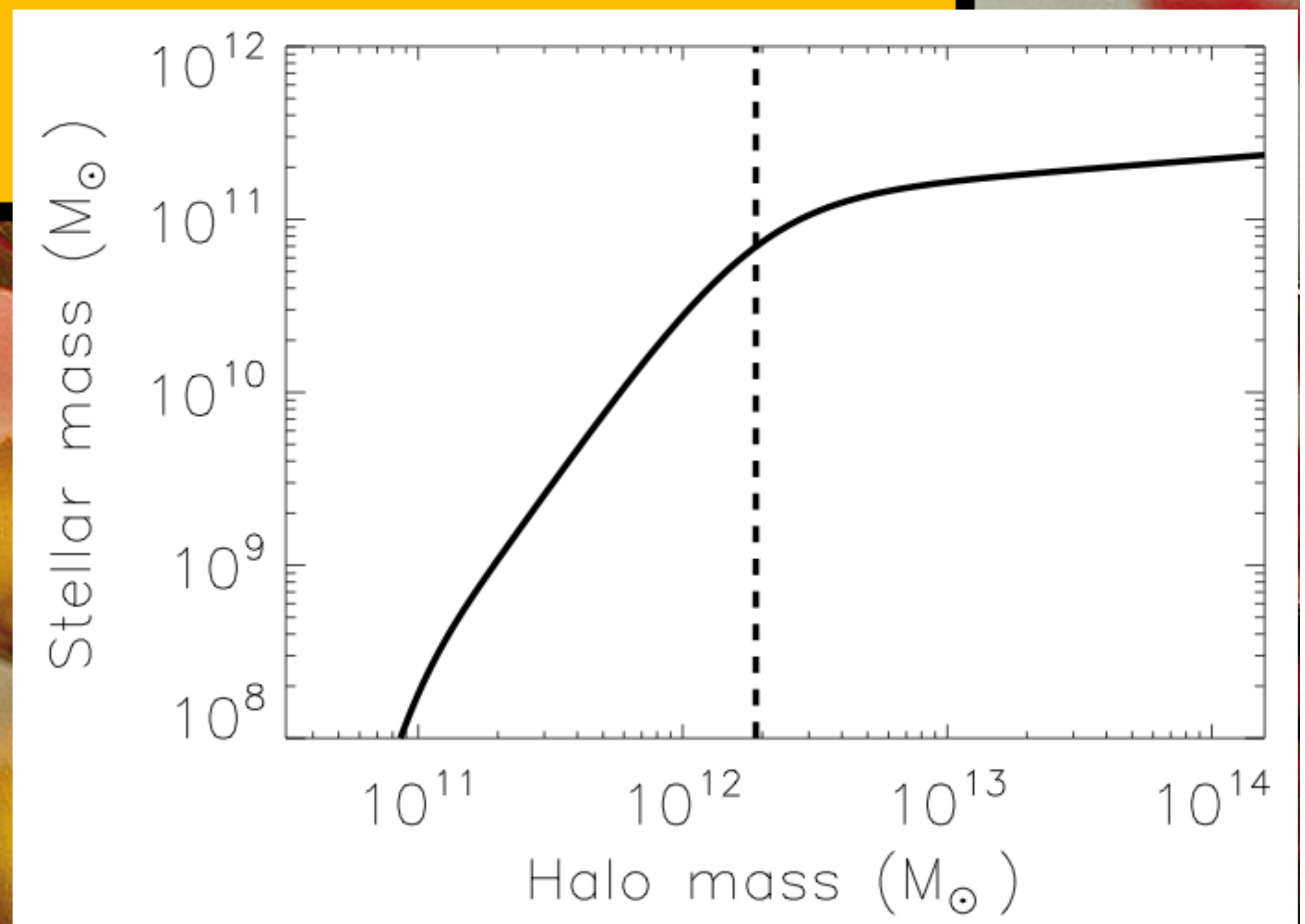


$$\Phi(m_{star} \mid M_{halo}) = \Phi_{central} + \Phi_{satellite}$$

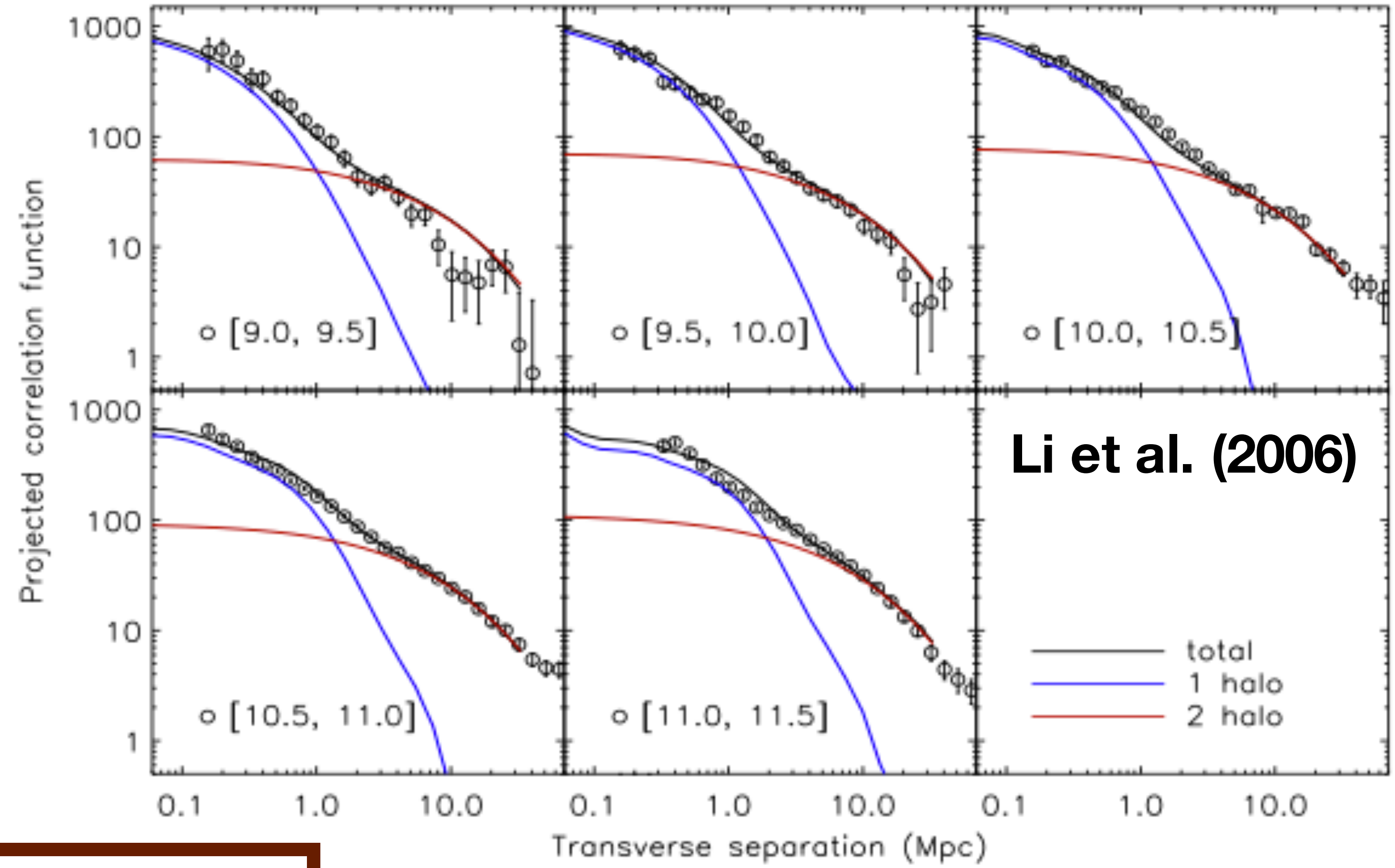
$$\Phi_s(m|M) = \frac{\Phi_s^*}{m_s}\left(\frac{m}{m_s}\right)^{\alpha_s} \exp\left[-\left(\frac{m}{m_s}\right)^2\right] \qquad \text{Eq. 3}$$

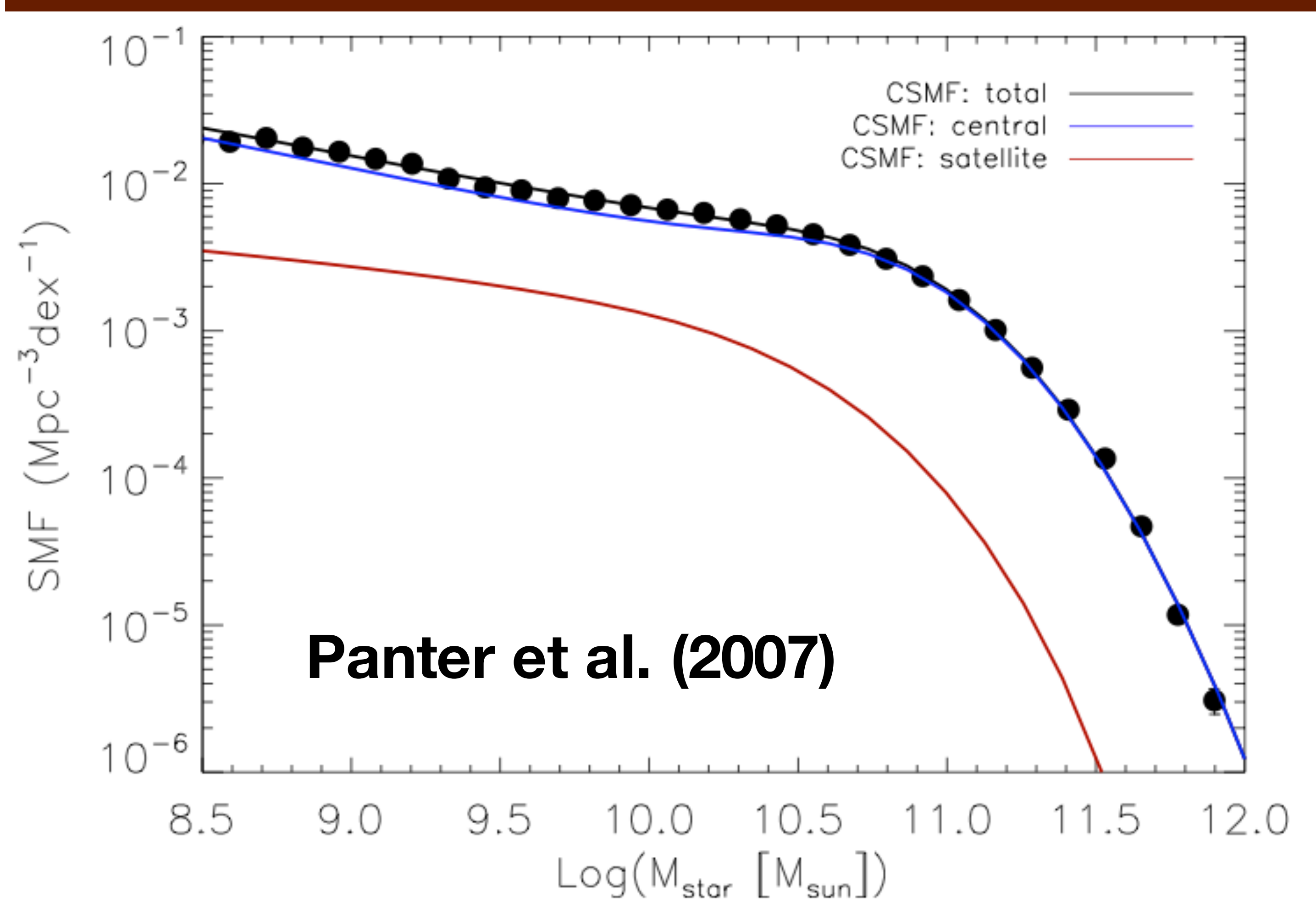
$$m_s(M) = 2M\left(\frac{m_s}{M}\right)_0\left[\left(\frac{M}{M_{1s}}\right)^{-\beta_s} + \left(\frac{M}{M_{1s}}\right)^{\gamma_s}\right]^{-1} \qquad \text{Eq. 4}$$





<u>Local galaxy clustering as a function of stellar mass.</u>





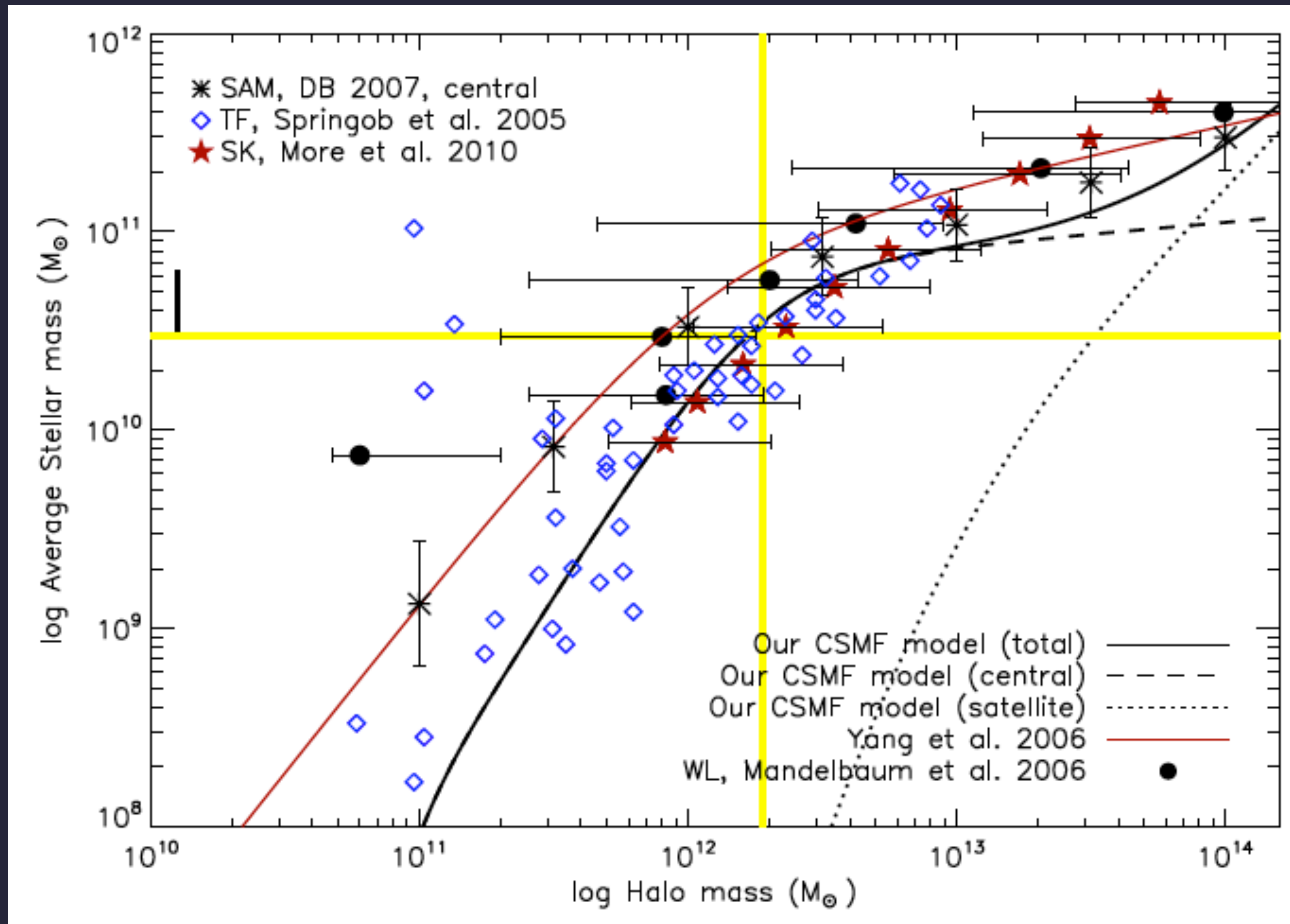
<u>The local stellar mass function (SMF):</u> central galaxis make up 85% of the population with $M_\star$ $>10^{8.5}$ M_Θ.

Wang et al. 2011, in

The average stellar mass as a function of halo mass at z ~ 0

$M_\star \sim 3 \times 10^{10}\ M_\odot$

(Kauffmann et al. 2003)



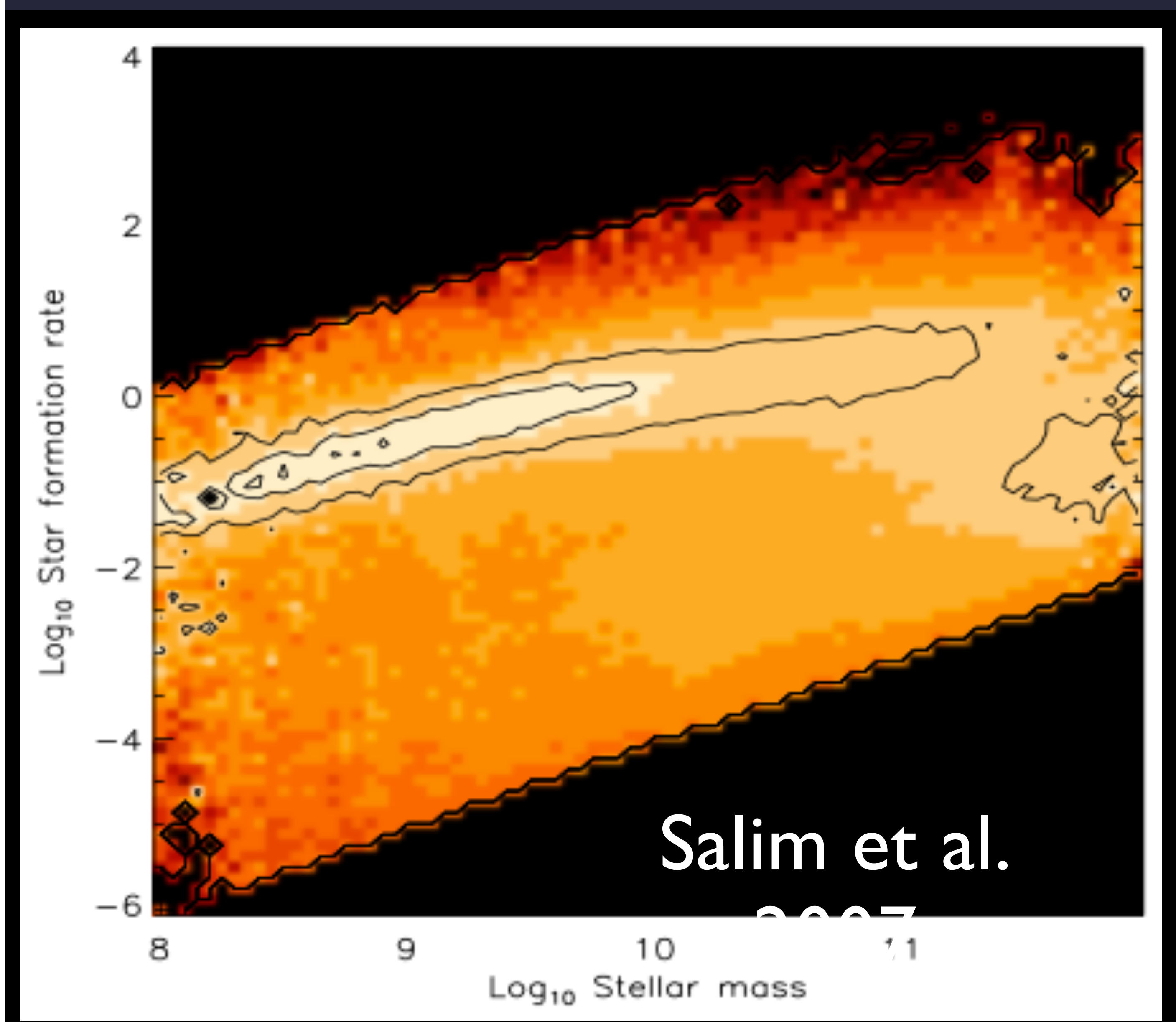
Wang et al. 2011, in

The characteristic halo mass ($2 \times 10^{12}\ M_\odot$) in the stellar-to-halo mass relation

$P(SFR, m_{star} \mid M_{halo}) = P(m_{star} \mid M_{halo}) \times P(SFR \mid m_{star}, M_{halo})$

$P(SFR \mid m_{star}, M_{halo}) =$

$P_{central}(SFR \mid m_{star}, M_{halo}) + P_{satellite}(SFR \mid m_{star}, M_{halo}) =$



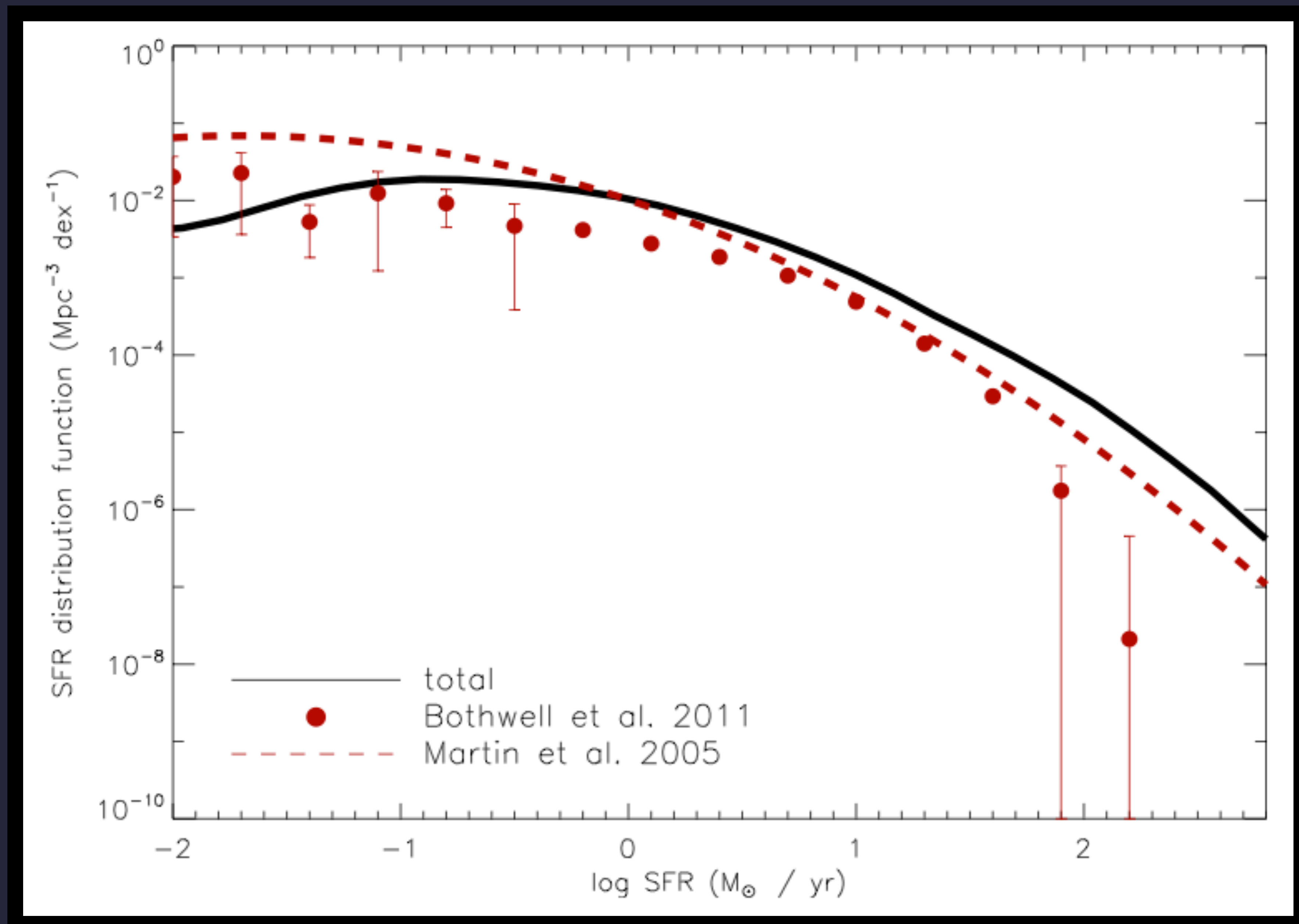
Salim et al.

$(SFR \mid m_{star}) =$

The distribution of SFR in stellar mass bins in the local Universe.

Wang et al. 2011, in

With P(SFR, m_{star} | M_{halo}), we can predict the SFR distribution and compare with the observed local SFR distribution function.

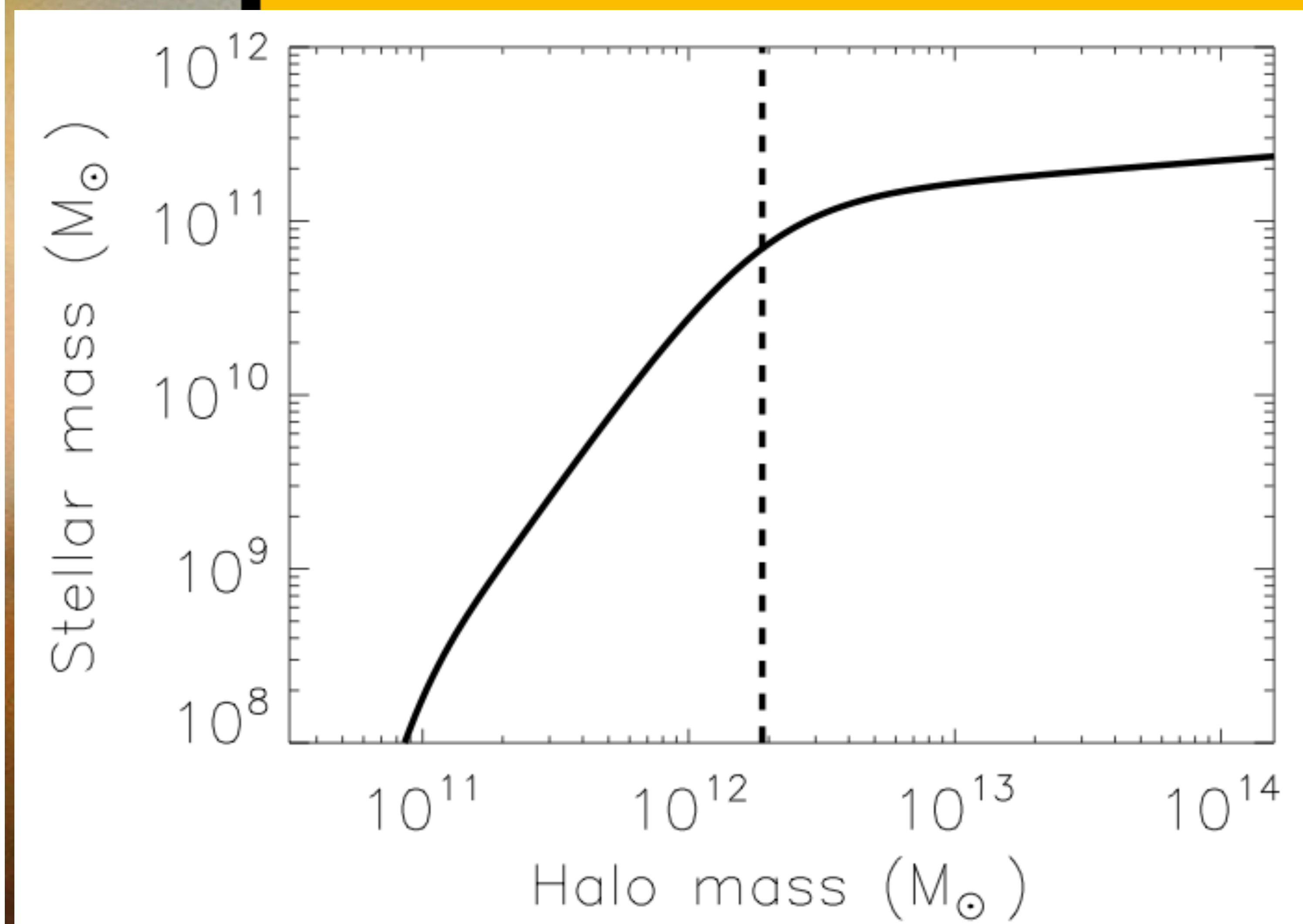


Wang et al. 2011, in

The high-redshift Universe

The evolution in the stellar-to-halo mass relation

$$m_c(M) = 2M\left(\frac{m_c}{M}\right)_0\left[\left(\frac{M}{M_{1c}}\right)^{-\beta_c} + \left(\frac{M}{M_{1c}}\right)^{\gamma_c}\right]^{-1}$$



$$\log M_1(z) = (1+z)^{\mu} \times \log M_1|_{z=0}$$

$$\left(\frac{m}{M}\right)_0(z) = (1+z)^{\nu} \times \left(\frac{m}{M}\right)_0|_{z=0}$$

$$\gamma(z) = (1+z)^{\gamma_1} \times \gamma|_{z=0}$$

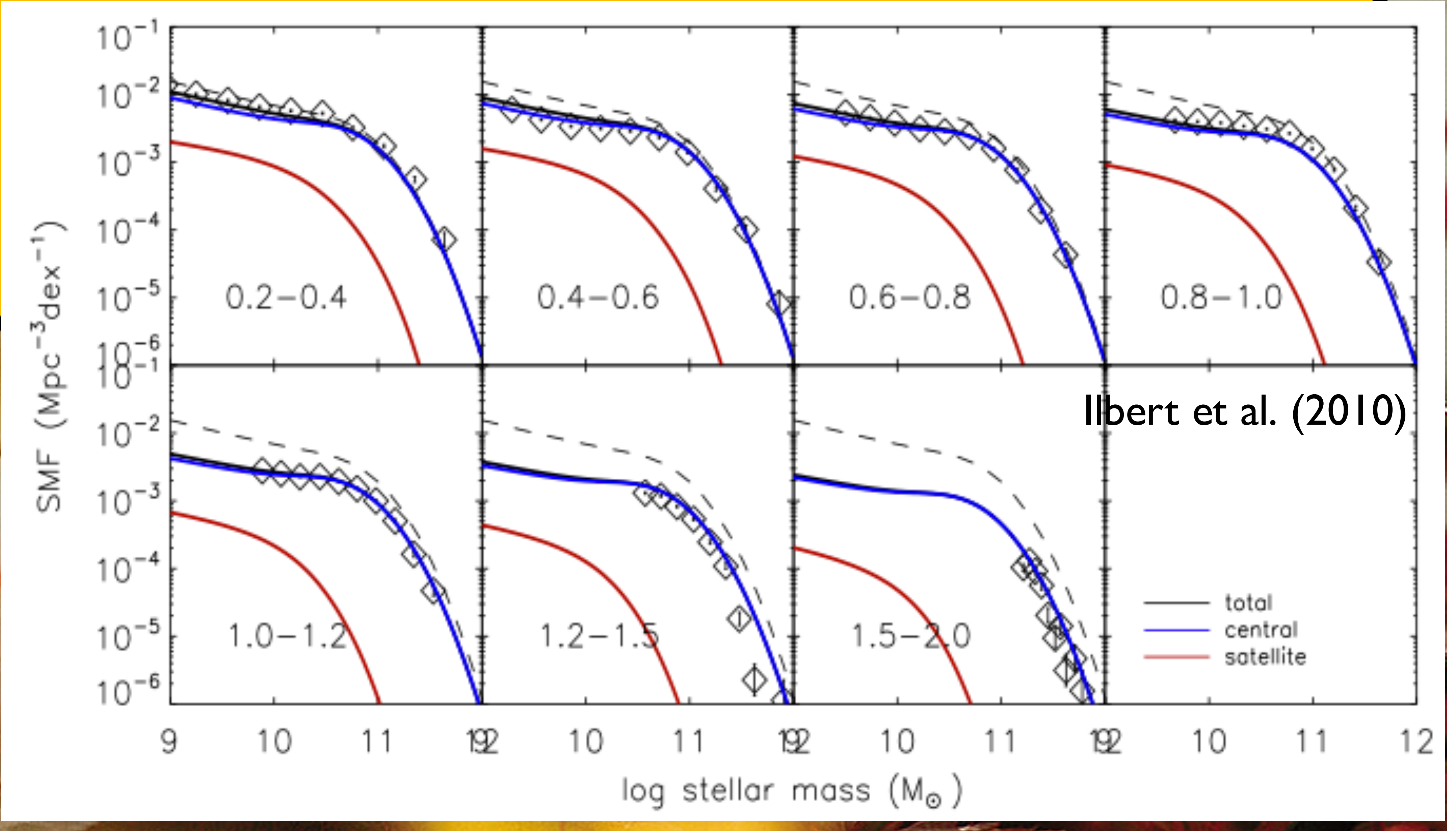
$$\beta(z) = \beta|_{z=0} + \beta_1 \times z$$

Wang et al. 2011, in

The SMF as a function of redshift

The SMF increases over time (mostly in lower mass systems).

The fraction of satellite galaxies increases over time.



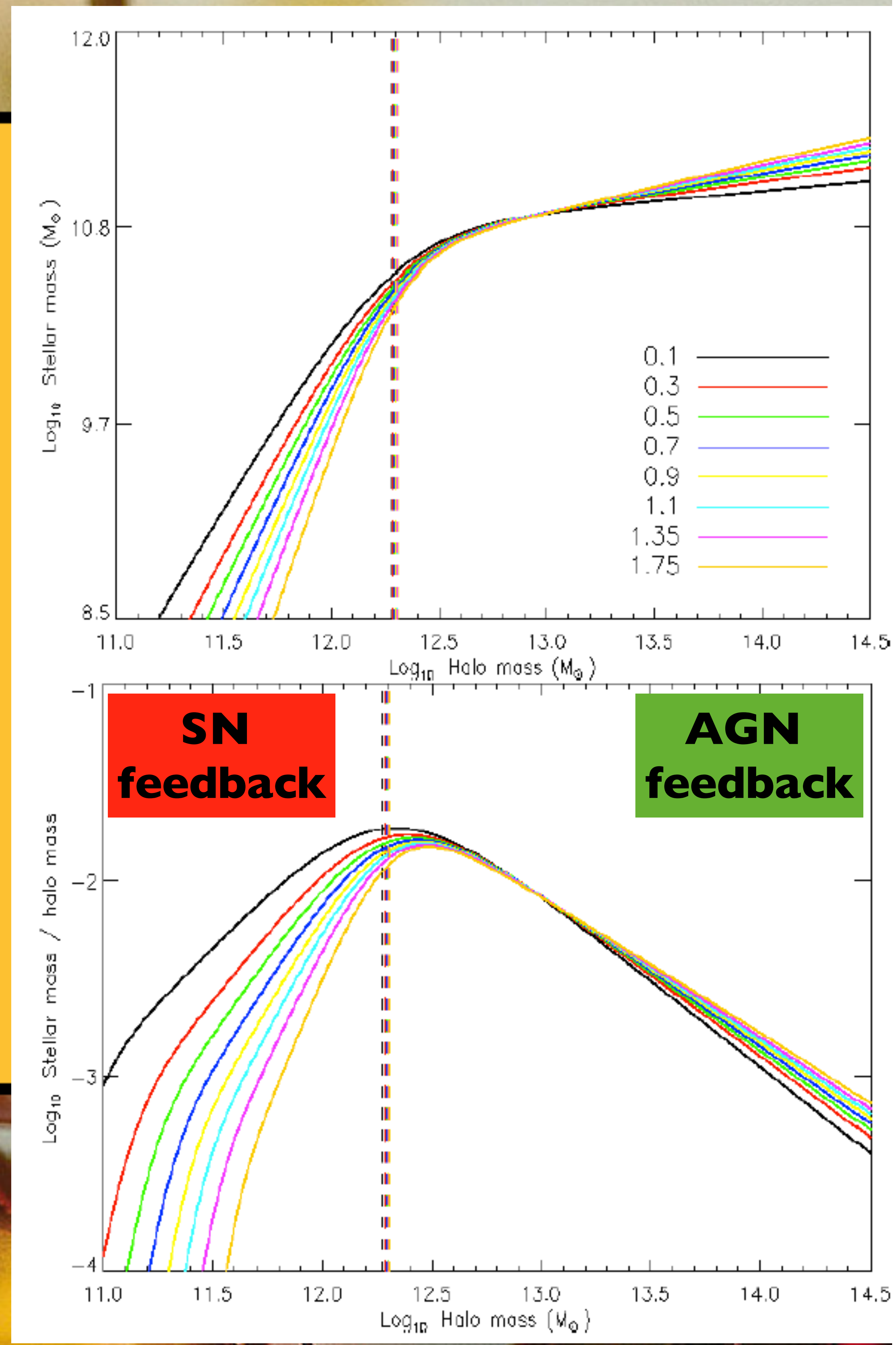
Wang et al. 2011, in

The redshift evolution of the stellar-to-halo mass relation

The characteristic halo mass scale changes very slightly with z.

The stellar-to-halo mass ratio (star formation efficiency) is low in both low-mass and high-mass halos.

The peak in star formation efficiency shifts to lower mass halos over time.

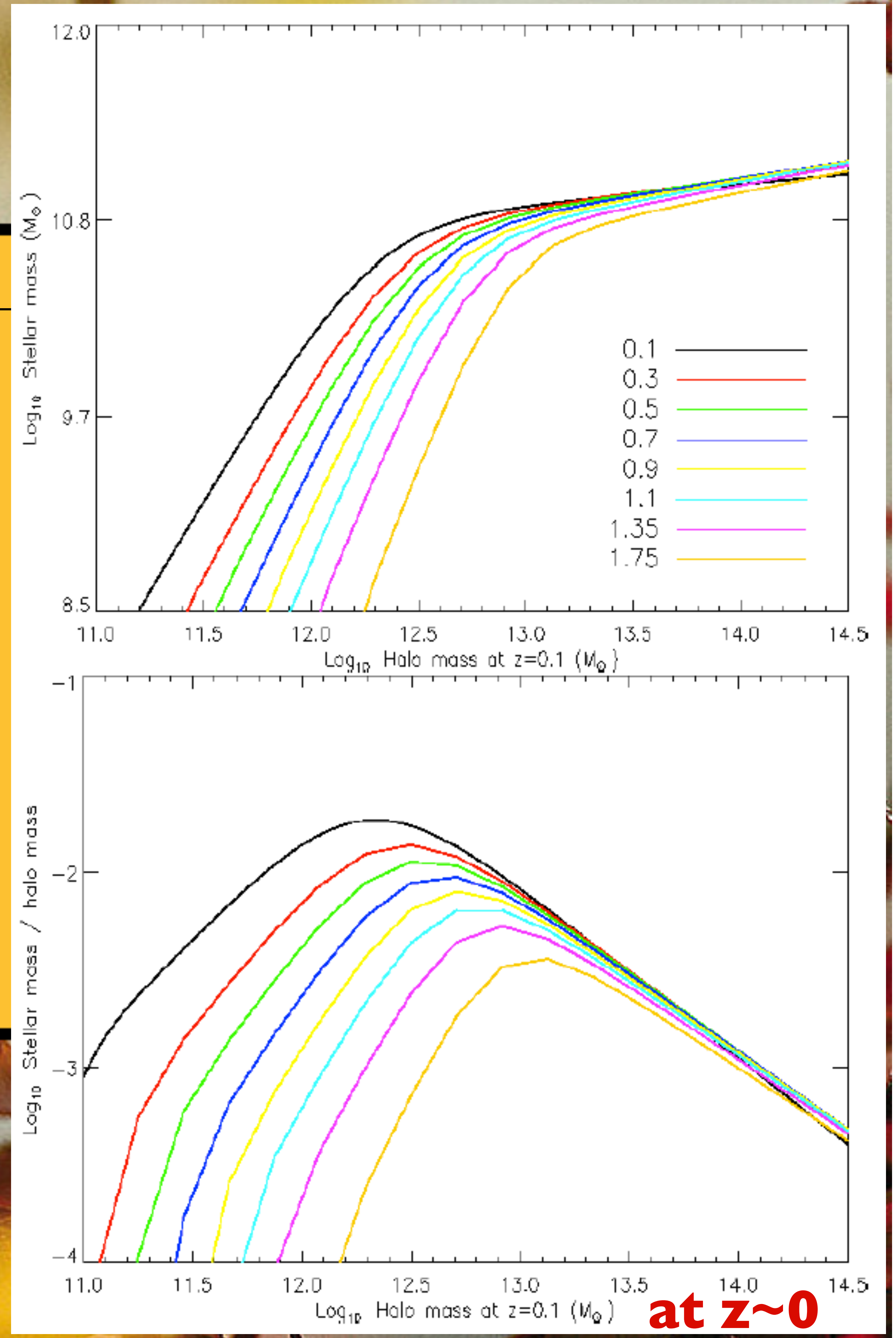


Wang et al. 2011, in

<u>The stellar-to-halo mass relation and its redshift evolution</u>

Stellar mass build-up happened much earlier in more massive halos (cosmic downsizing).

In halos > $10^{13.5}$ $M_{\Theta,}$ over 70% of the stellar mass is already in place at z~2.

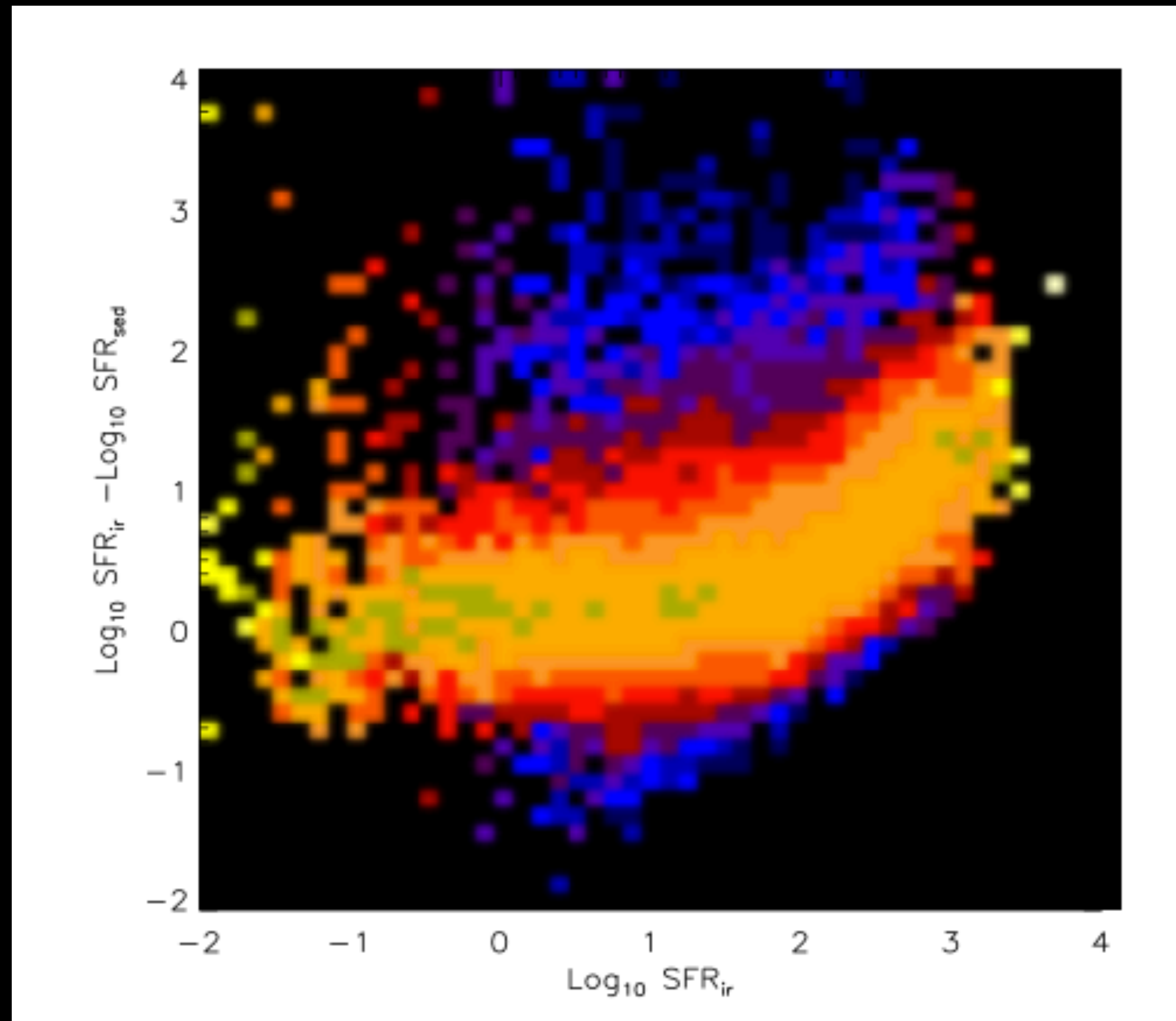


at z~0

Wang et al. 2011, in

Link the stellar mass and SFR to DM halo in the high-z Universe

Herschel-SPIRE data crucial for estimating SFRs in the high-z Universe

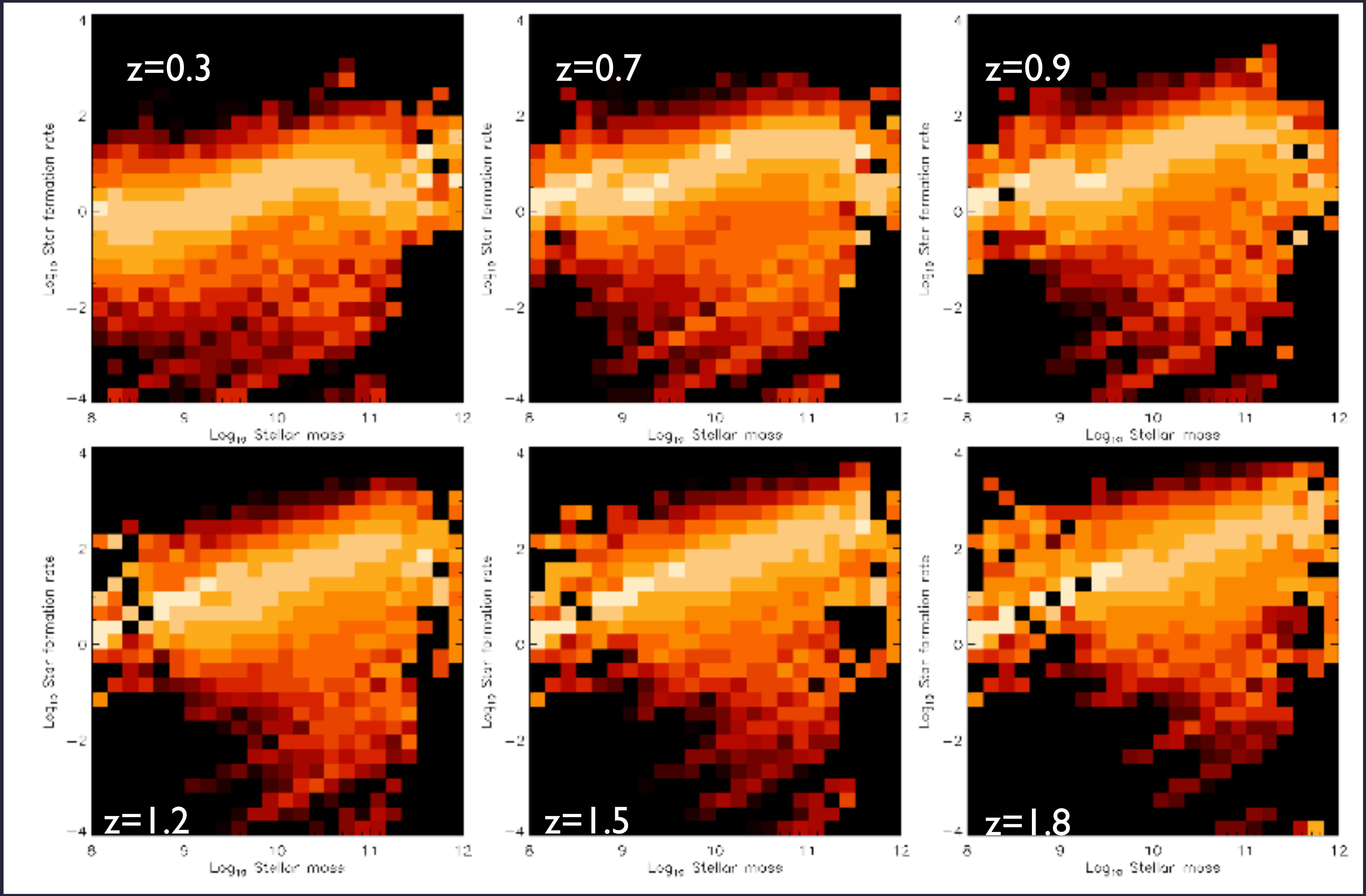


Infrared SFR vs (infrared SFR - UV to NIR SED SFR)

Wang et al. 2011, in prep.

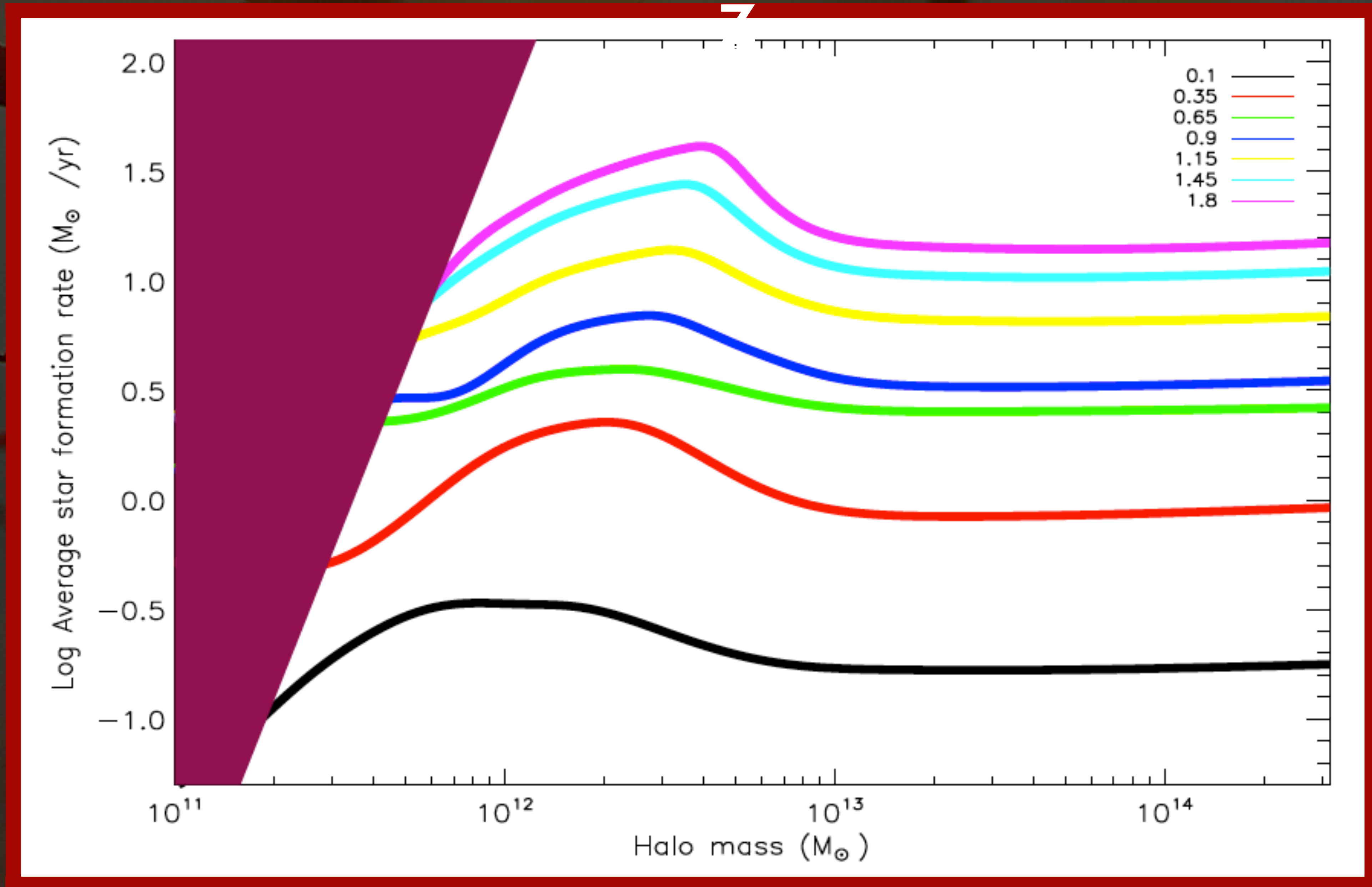
P(SFR | Mstar) in different redshift bins

(averaged over COSMOS, ECDFS & EGS)



Wang et al. 2011, in

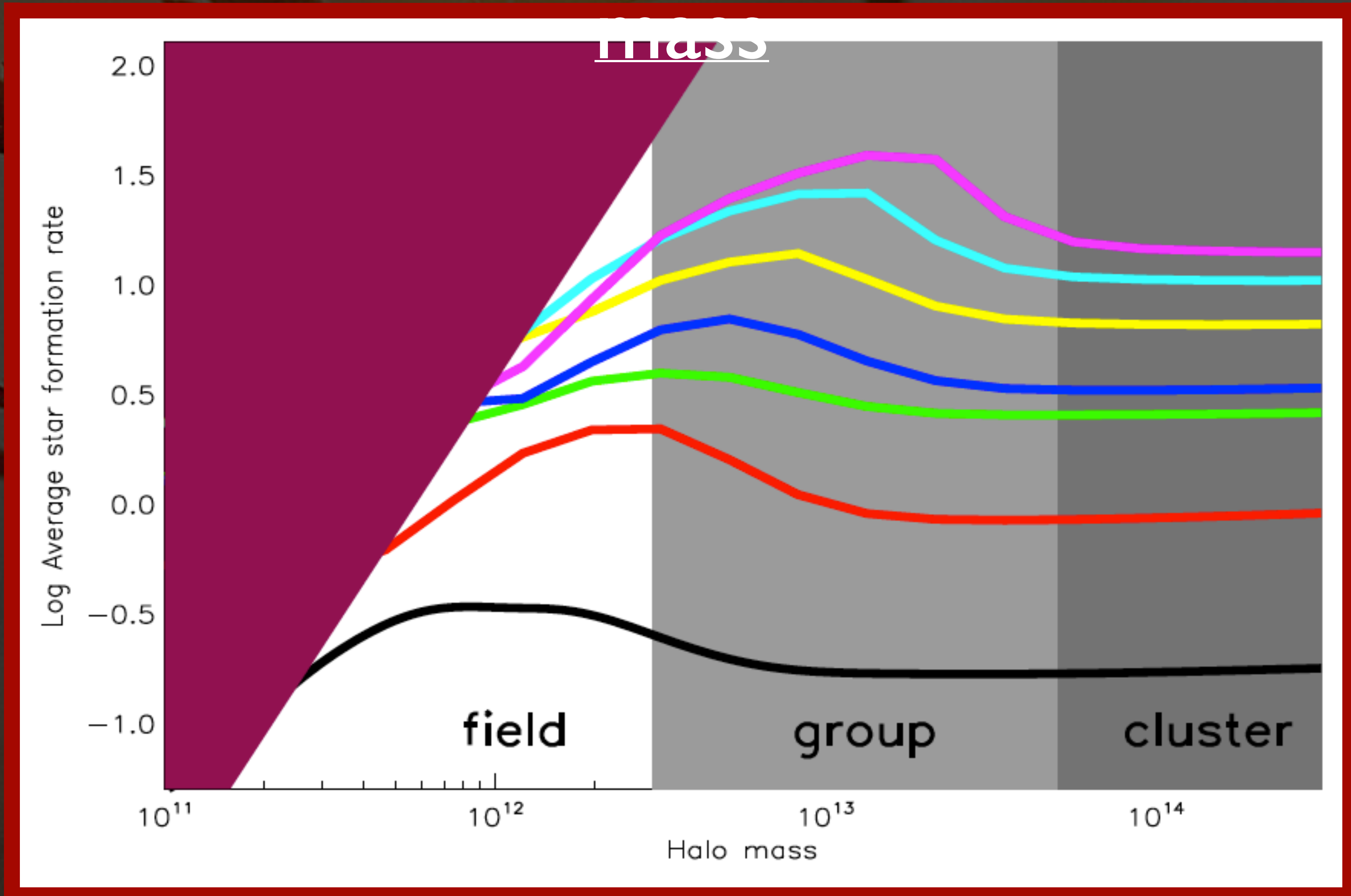
The average SFR as a function of halo mass and z



The level of star-forming activity has steadily decreased over time.
At a given redshift, SFR peaks in a relatively narrow range of halo mass.
The peak of SFR shifts to lower mass halos over time.

Wang et al. 2011, in

Trace the evolution of SFR as a function of halo mass



DM halo accretion history + the extended halo model as a function of z = galaxy evolution (identify progenitors / descendants of different galaxy populations).

Most actively star-forming galaxies at z~2 have evolved into quiescent galaxies in today's group environment.

Conclusions

- This is the first time we are able to statistically build the dependence of SFR on halo mass and z.
- The level of star-forming activity has steadily decreased over time, dropping by ~ 2 orders of magnitude.
- At a given redshift, SFR peaks in a relatively narrow range of halo mass.
- The peak of SFR shifts to less massive halos at z decreases.
- Most actively star-forming galaxies at z~2 have evolved into quiescent galaxies in today's group-like environment.

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