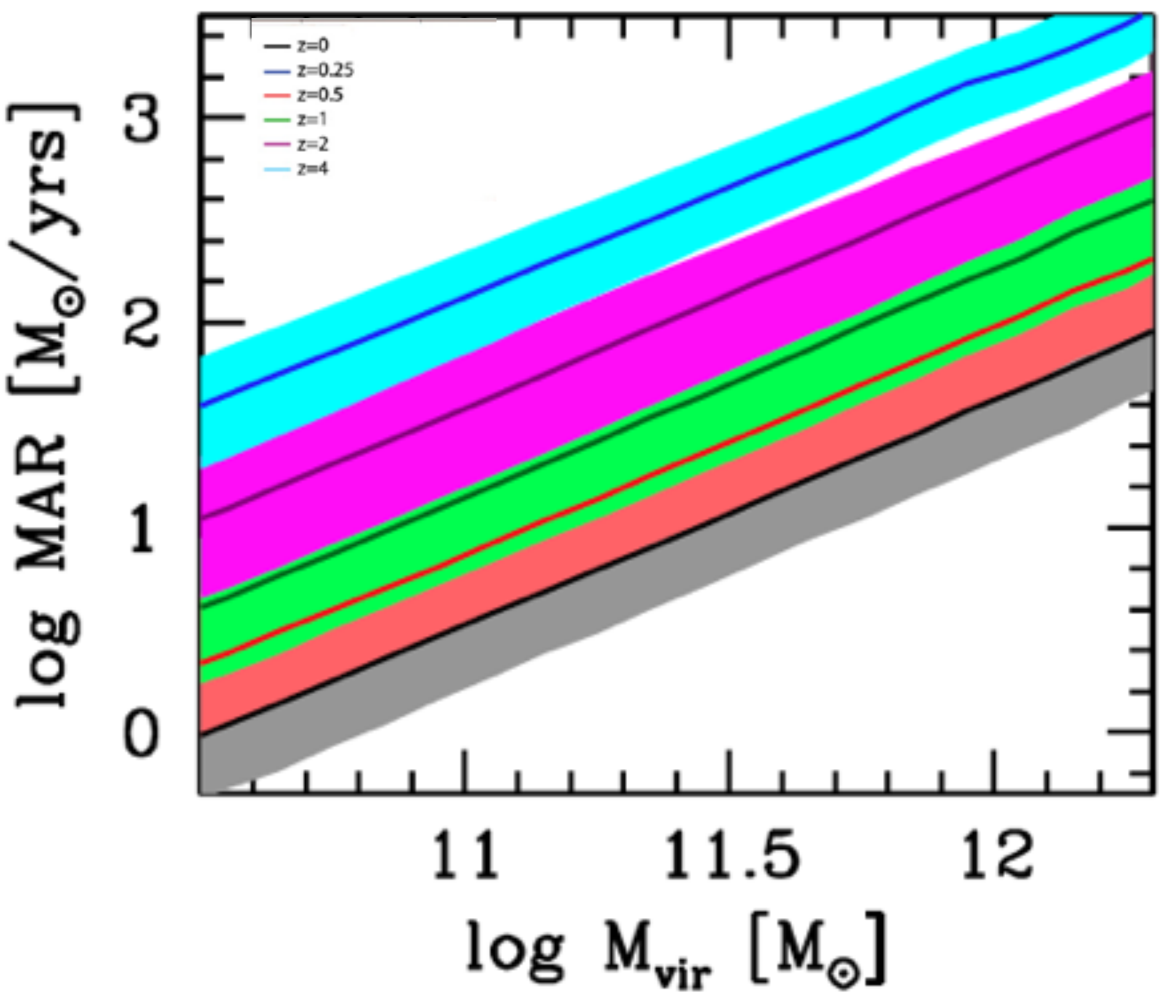
The Galaxy-Halo Connection: Applications to high redshifts

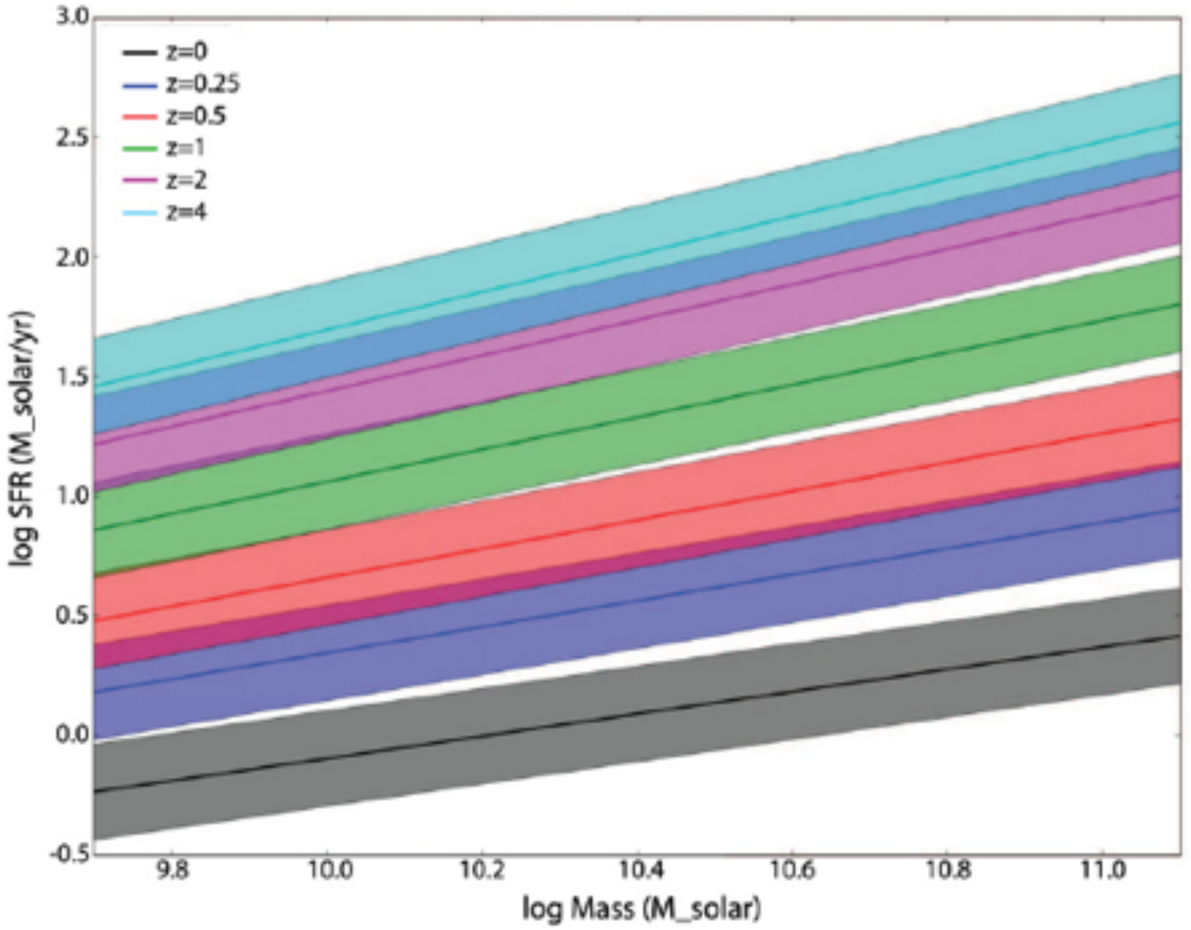
Aldo Rodriguez-Puebla, UCSC

Galaxy workshop UCSC 10/8/16

Halo & Galaxy assembly

$\beta \simeq 1.1$

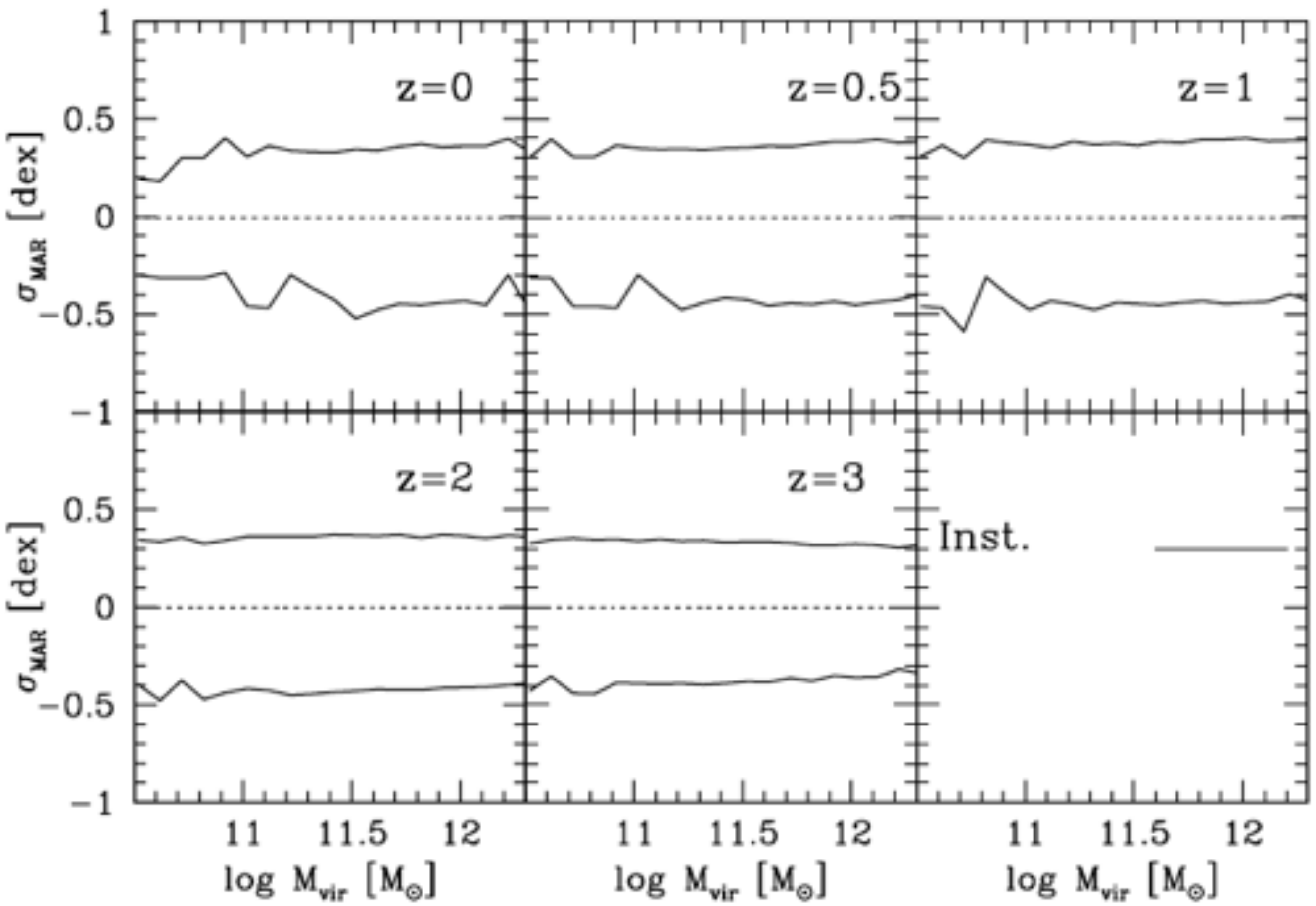




Speagle+2014, and reference therein.

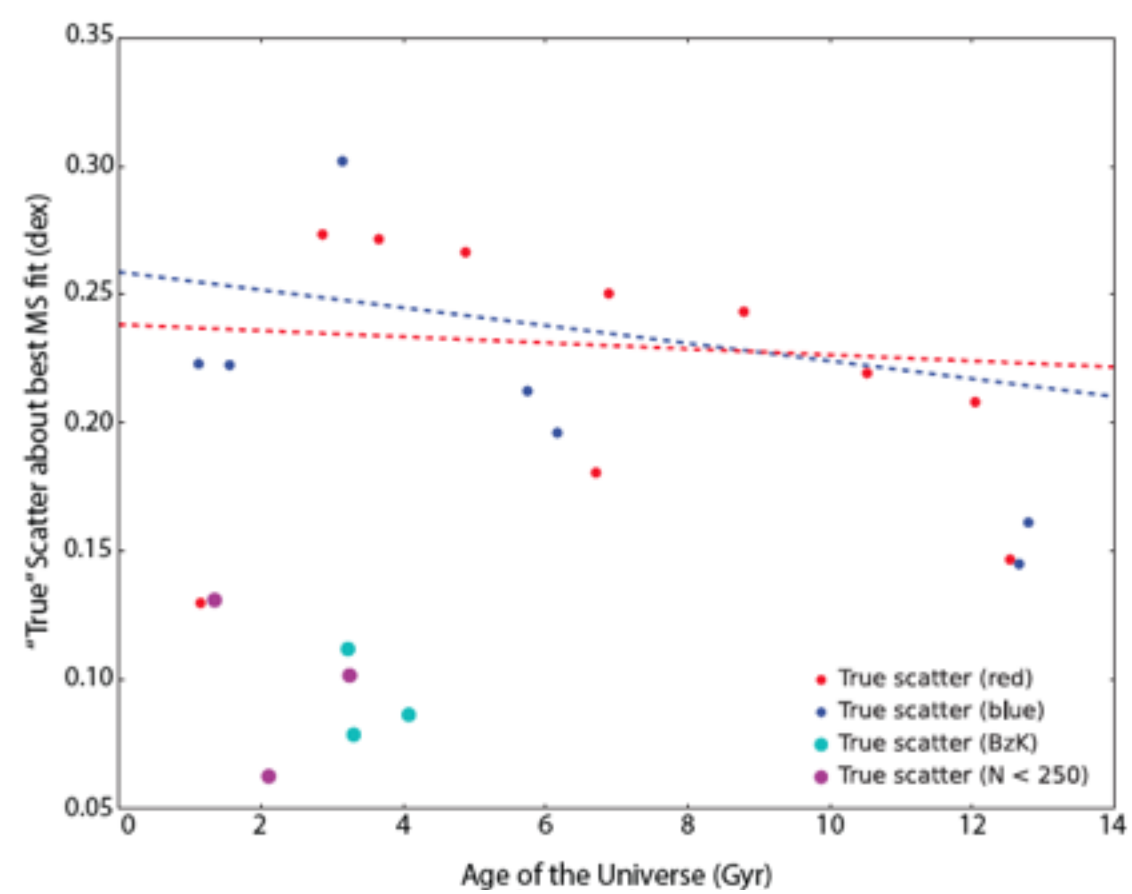
$\beta \simeq 1 - 0.6$

Scatter of the Halo Mass Accretion Rate and the SF-MS

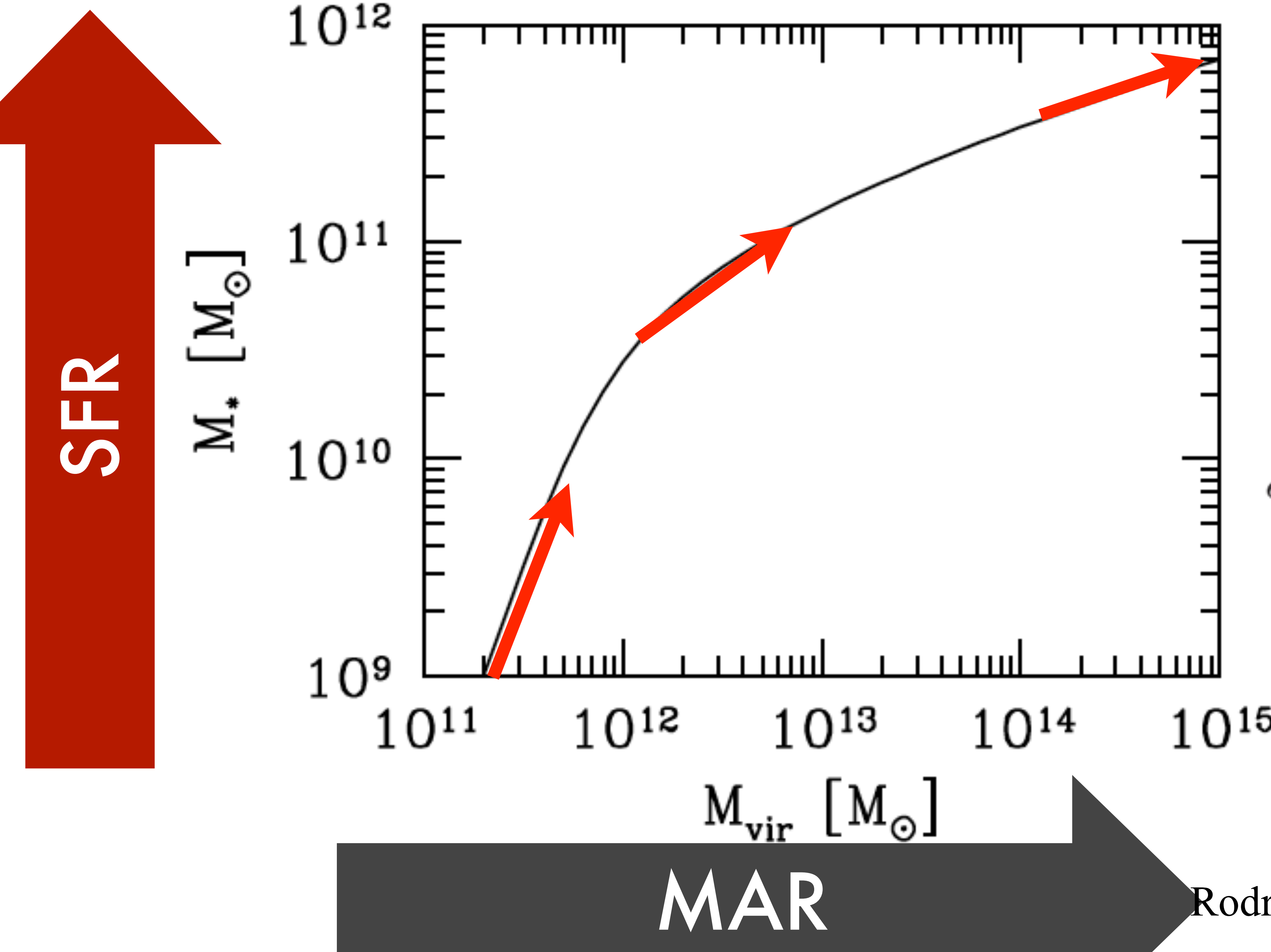


$\sigma \simeq 0.3$-0.4

$\sigma \simeq 0.3$



SHMR for Central galaxies from Bolshoi-Planck sim.



$$M_* = M_*(M_{\rm vir}(t))$$

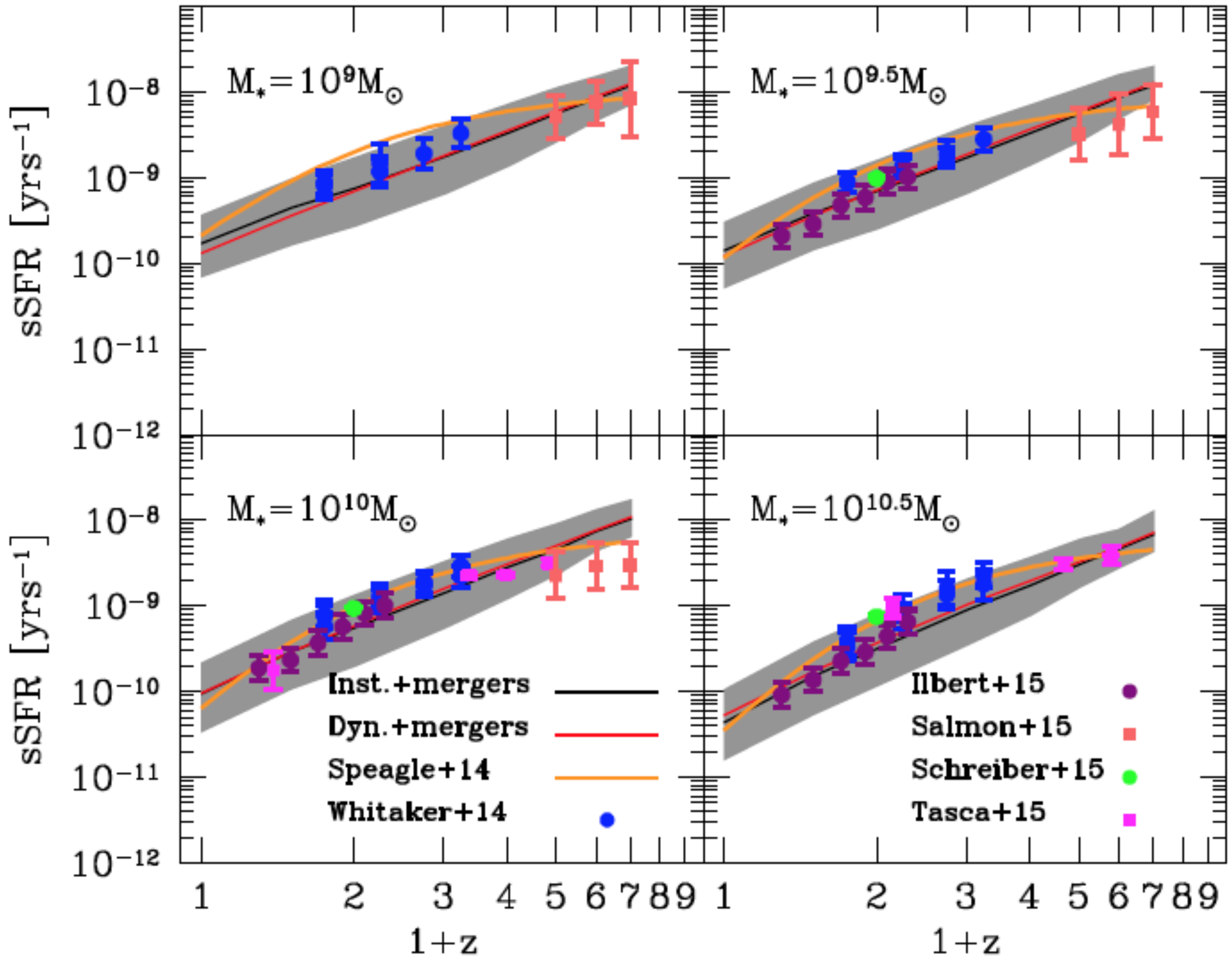
$$\mathrm{SFR} = f_* \times \epsilon \times \dot{M}_{\rm vir}/(1-R)$$

$$f_* = M_*/M_{\rm vir}$$

$$\epsilon = \frac{\dot{M}_*/M_*}{\dot{M}_{\rm vir}/M_{\rm vir}} = \frac{\partial \log M_*}{\partial \log M_{\rm vir}}.$$

Rodriguez-Puebla+2016

sSFR Main Sequence as a Function of Redshift derived from the SHARC assumption



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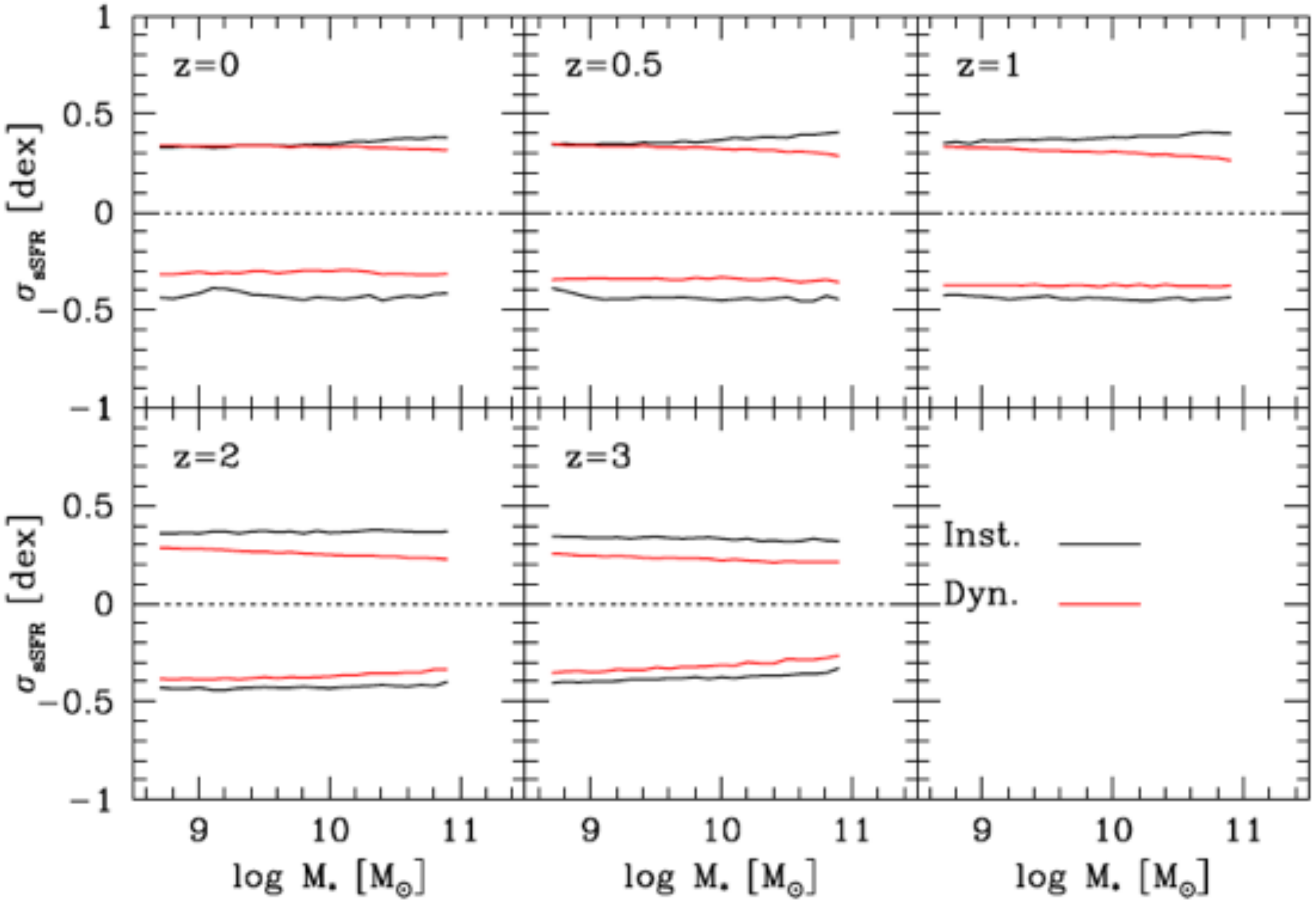
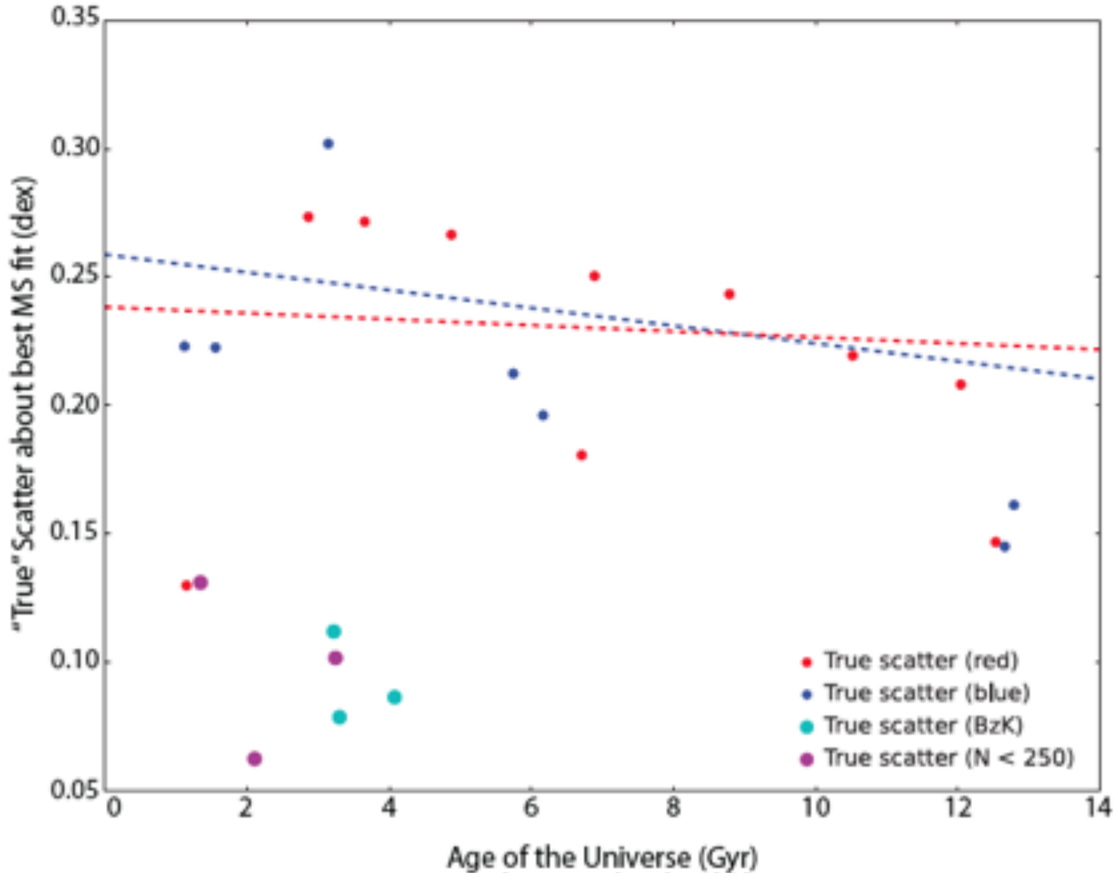
Scatter of the sSFR MS derived from the SHARC assumption



$\sigma \simeq 0.3$



$\sigma \simeq 0.35\text{-}0.45$

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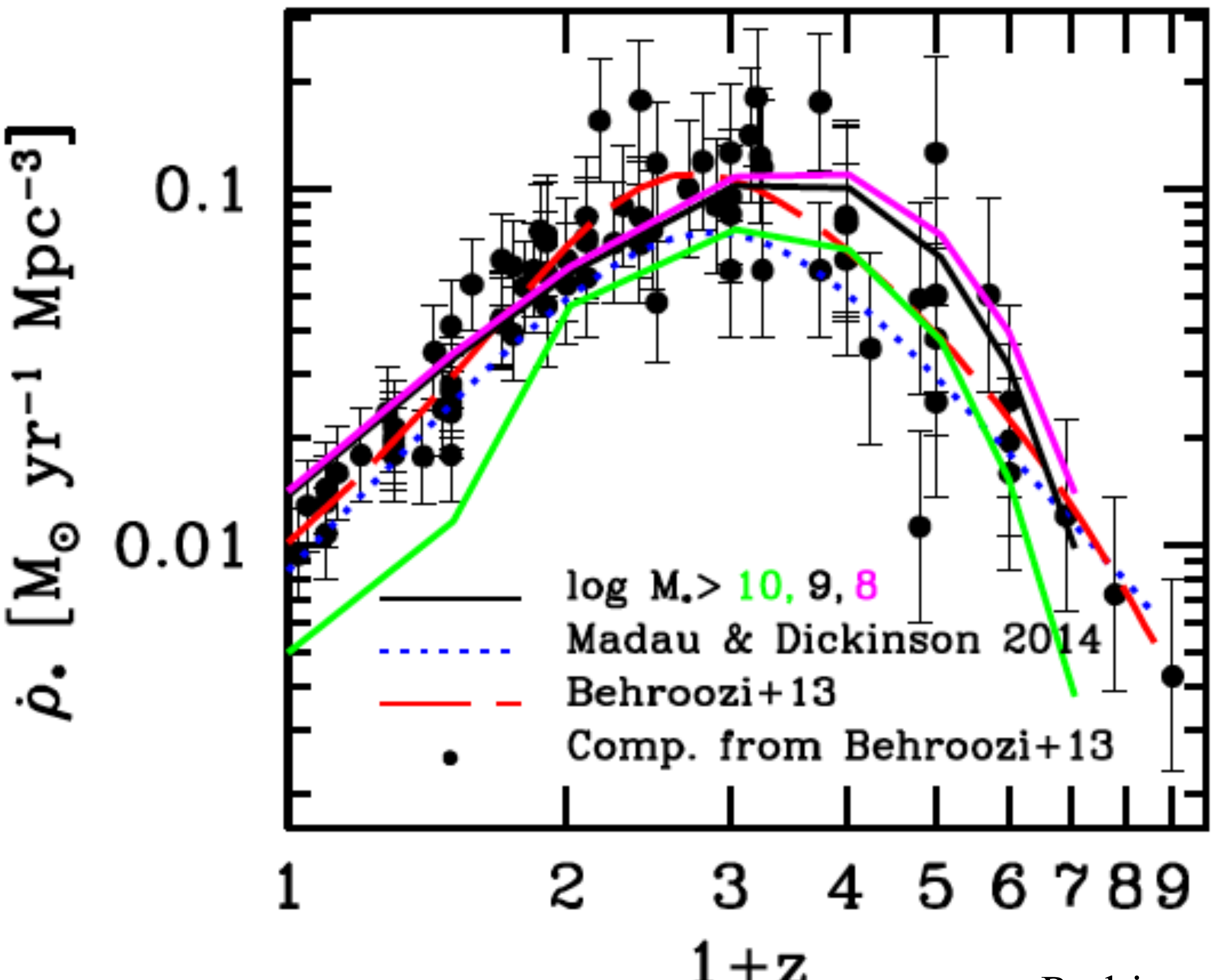
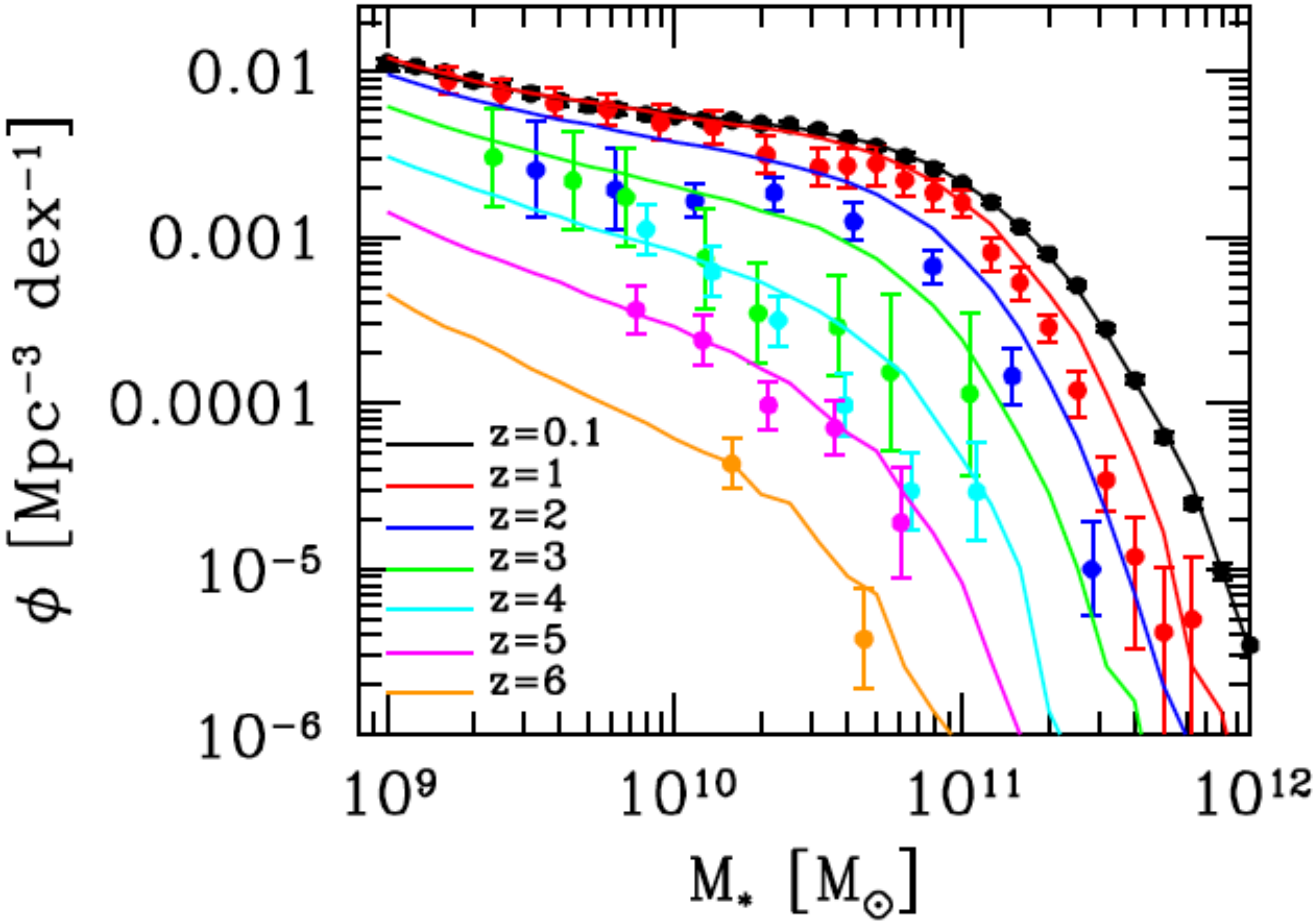
Cosmic Star Formation Rate derived from the SHARC assumption



Rodriguez-Puebla+2016

Evolution of the GSMF derived from the SHARC assumption



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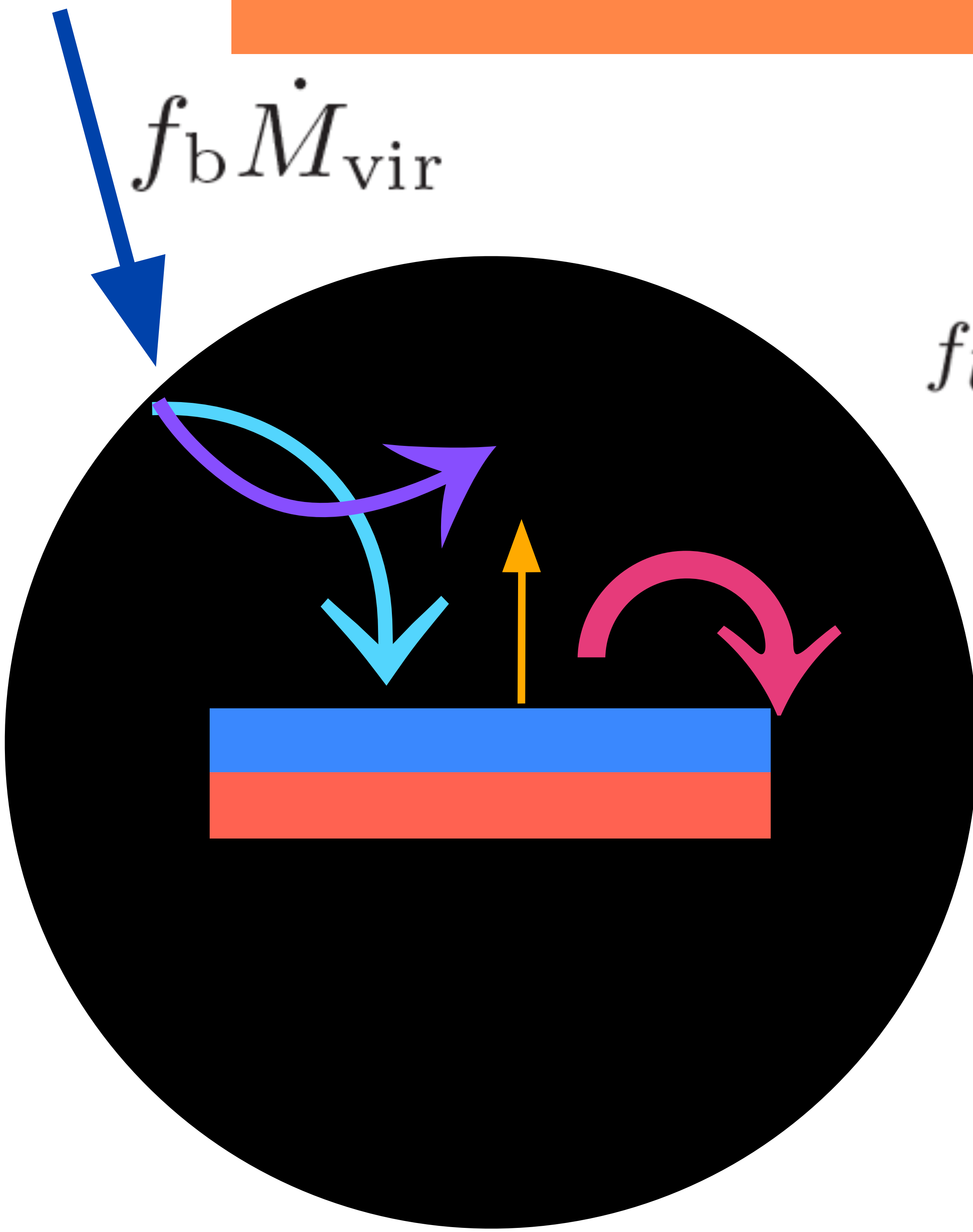
Gas Regulator (Bathtub) Model

$$f_b \dot{M}_{vir}$$



Bouché+11, Davé+11, Krumholz & Dekel 12, Dekel +13, Lilly+13, Dekel & Mandelker 14, Forbes+14, Feldmann+15.

The rate at which:

$f_b(1-\mathcal{E}_{eff})\dot{M}_{vir}$ — the fraction of the baryonic inflowing material that won't reach the ISM

$f_b\mathcal{E}_{eff}\dot{M}_{vir}$ — some fraction of the baryonic inflowing material will reach the ISM

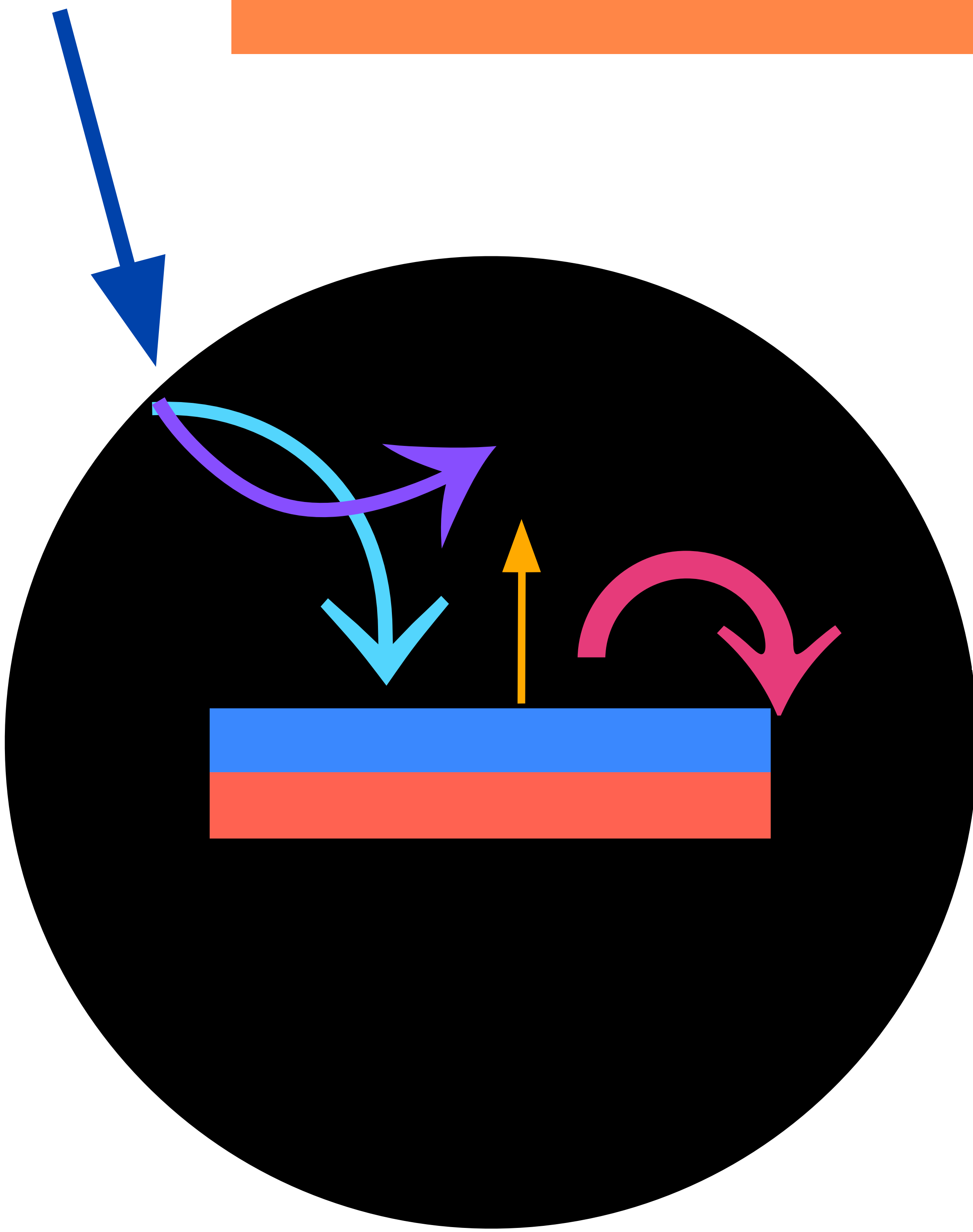
$\dot{M}_{gas,ISM}$ — gas mass change in the ISM

$-\ \eta_{w,ISM}\ \mathrm{SFR}$ — outflowing gas from the ISM

$\eta_{r,ISM}\ \mathrm{SFR}$ — previously ejected gas is re-infalling to the ISM

$-(1-R)\mathrm{SFR}$ — gas mass loss due to SF

Gas Equation for the ISM



$$\dot{M}_{\rm gas,ISM} = f_{\rm b}\mathcal{E}_{\rm eff}\dot{M}_{\rm vir} - (\eta_{\rm w,ISM} - \eta_{\rm r,ISM} + 1 - R){\rm SFR}$$

Bouché+11, Davé+11, Krumholz & Dekel 12, Dekel +13, Lilly+13, Dekel & Mandelker 14, Forbes+14, Feldmann+15.

Equilibrium Model: E+SHARC

$$\dot{M}_{\mathrm{gas,ISM}} = f_{\mathrm{b}} \mathcal{E}_{\mathrm{eff}} \dot{M}_{\mathrm{vir}} - (\eta_{\mathrm{w,ISM}} - \eta_{\mathrm{r,ISM}} + 1 - R)\mathrm{SFR}$$

Equilibrium Condition: $\dot{M}_{\mathrm{gas,ISM}} = 0$

$$\dot{M}_{\cancel{\mathrm{gas}},\mathrm{ISM}} = f_{\mathrm{b}} \mathcal{E}_{\mathrm{eff}} \dot{M}_{\mathrm{vir}} - (\eta_{\mathrm{w,ISM}} - \eta_{\mathrm{r,ISM}} + 1 - R)\mathrm{SFR}$$

We define the net mass loading factor: $\eta = \eta_{\mathrm{w,ISM}} - \eta_{\mathrm{r,ISM}}$

$$\mathrm{SFR} = \frac{f_{\mathrm{b}} \mathcal{E}_{\mathrm{eff}}}{\eta + 1 - R} \dot{M}_{\mathrm{vir}}$$

Equilibrium Model: E+SHARC

$$\dot{M}_{\mathrm{gas,ISM}} = f_{\mathrm{b}}\mathcal{E}_{\mathrm{eff}}\dot{M}_{\mathrm{vir}} - (\eta_{\mathrm{w,ISM}} - \eta_{\mathrm{r,ISM}} + 1 - R)\mathrm{SFR}$$

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$$\mathrm{SFR} = \frac{f_{\mathrm{b}}\mathcal{E}_{\mathrm{eff}}}{\eta + 1 - R}\dot{M}_{\mathrm{vir}}$$

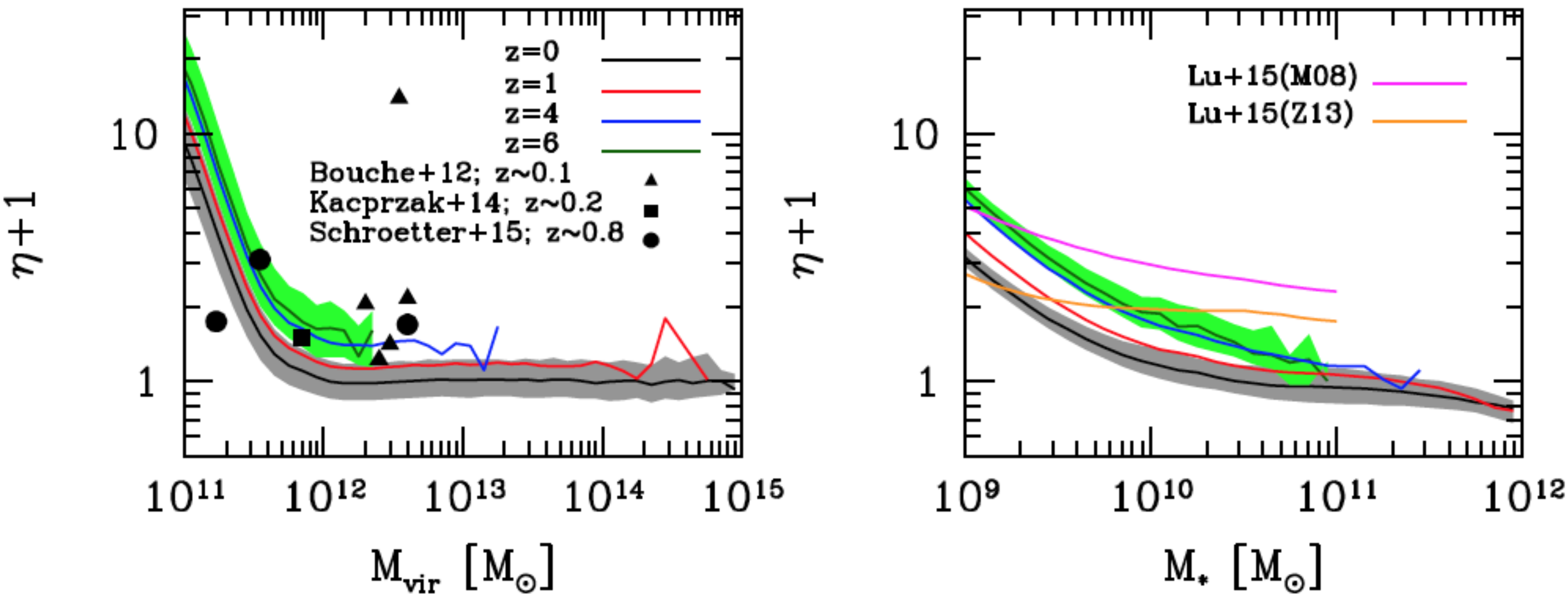
SHARC

$$\mathrm{SFR} = f_* \times \epsilon \times \dot{M}_{\mathrm{vir}}/(1 - R)$$

E+SHARC

Physics $$\frac{f_{\mathrm{b}}\mathcal{E}_{\mathrm{eff}}}{\eta + 1 - R} = \frac{f_*\epsilon}{1 - R}$$ Empirical

Net Mass loading Factor



outflowing gas from the ISM - previously ejected gas is re-infalling to the ISM =

$$\eta = \left[\frac{f_b}{f_*(M_{vir})}\frac{\mathcal{E}_{eff}(M_{vir},z)}{\epsilon(M_{vir})} - 1\right](1-R)$$

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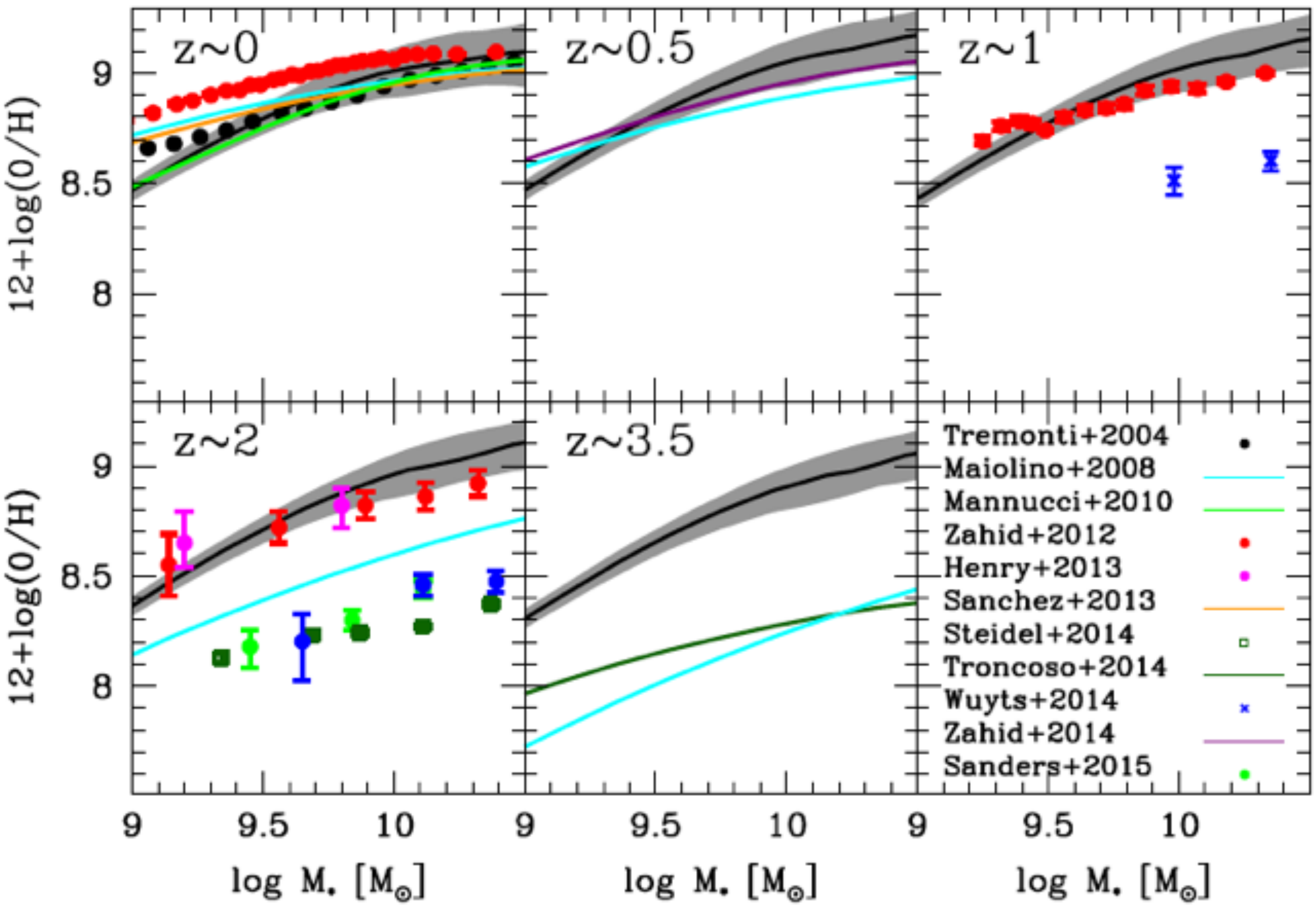
Metallicities



$$Z_{\mathrm{ISM}} = \frac{y}{\eta + 1 - R}$$

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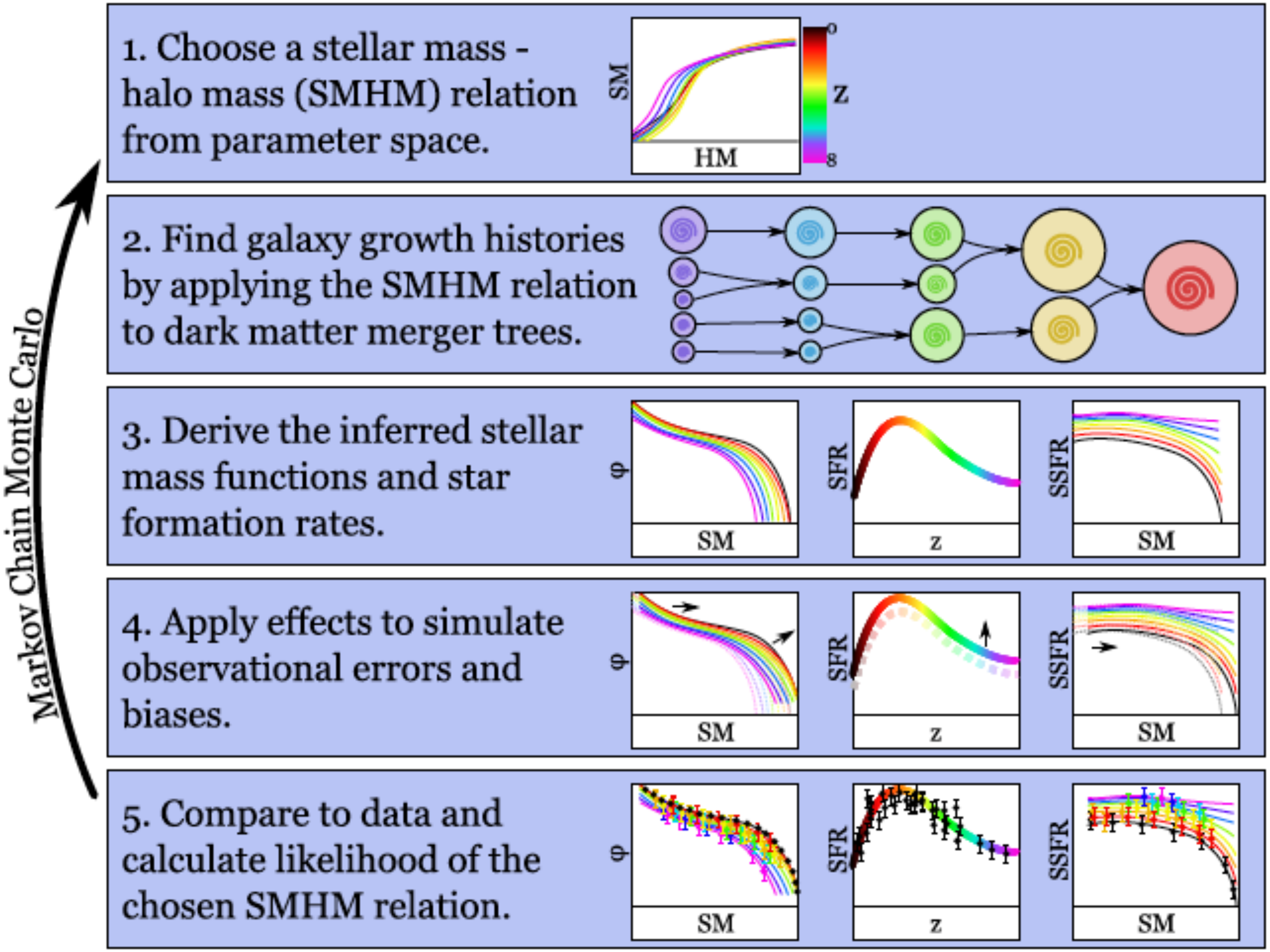
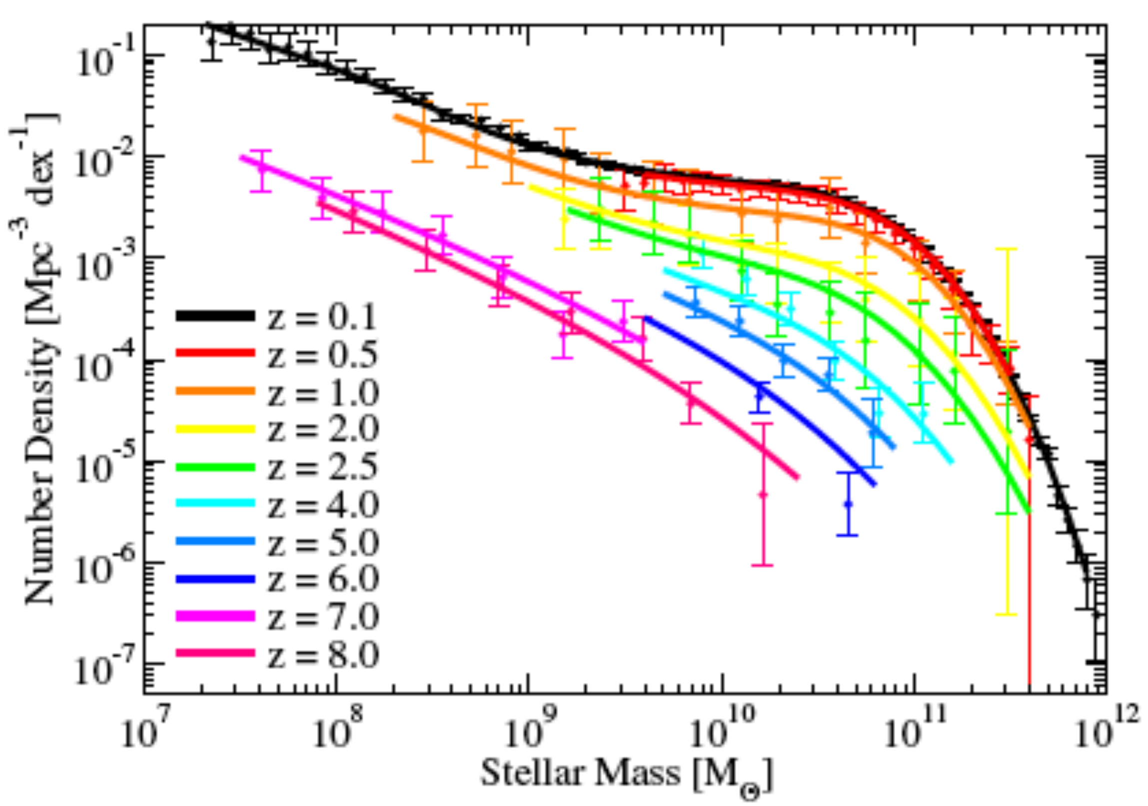
Using information from high redshifts

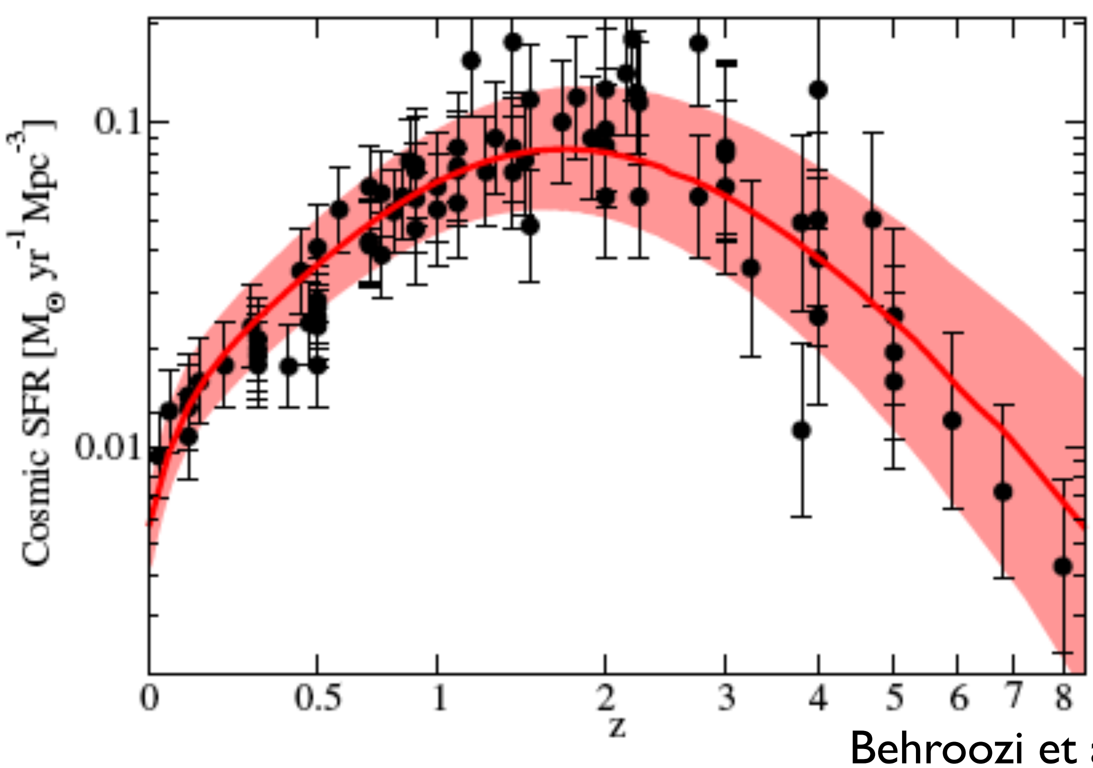
Using information from high redshifts

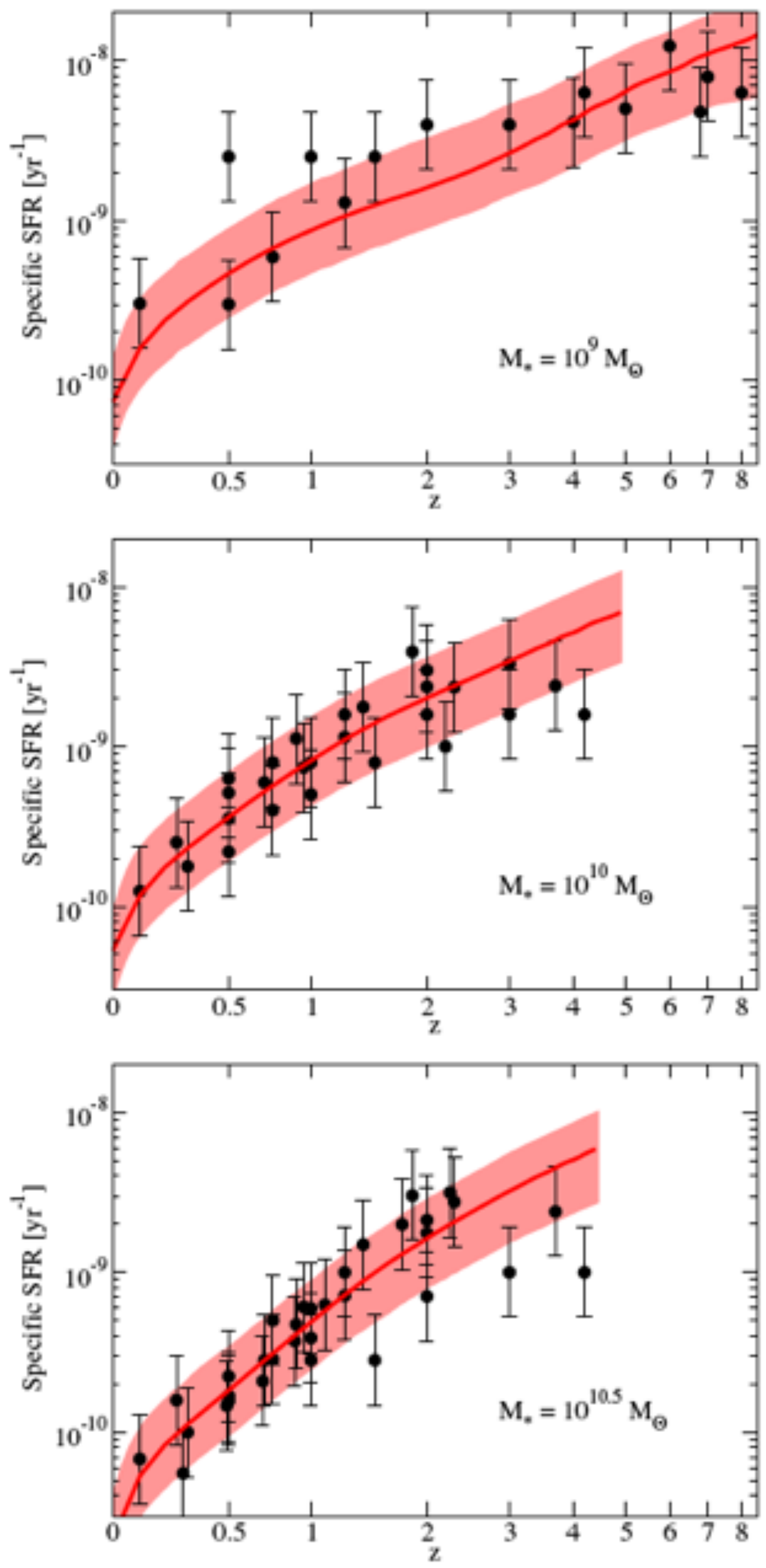
Behroozi et al. 2013



Using information from high redshifts

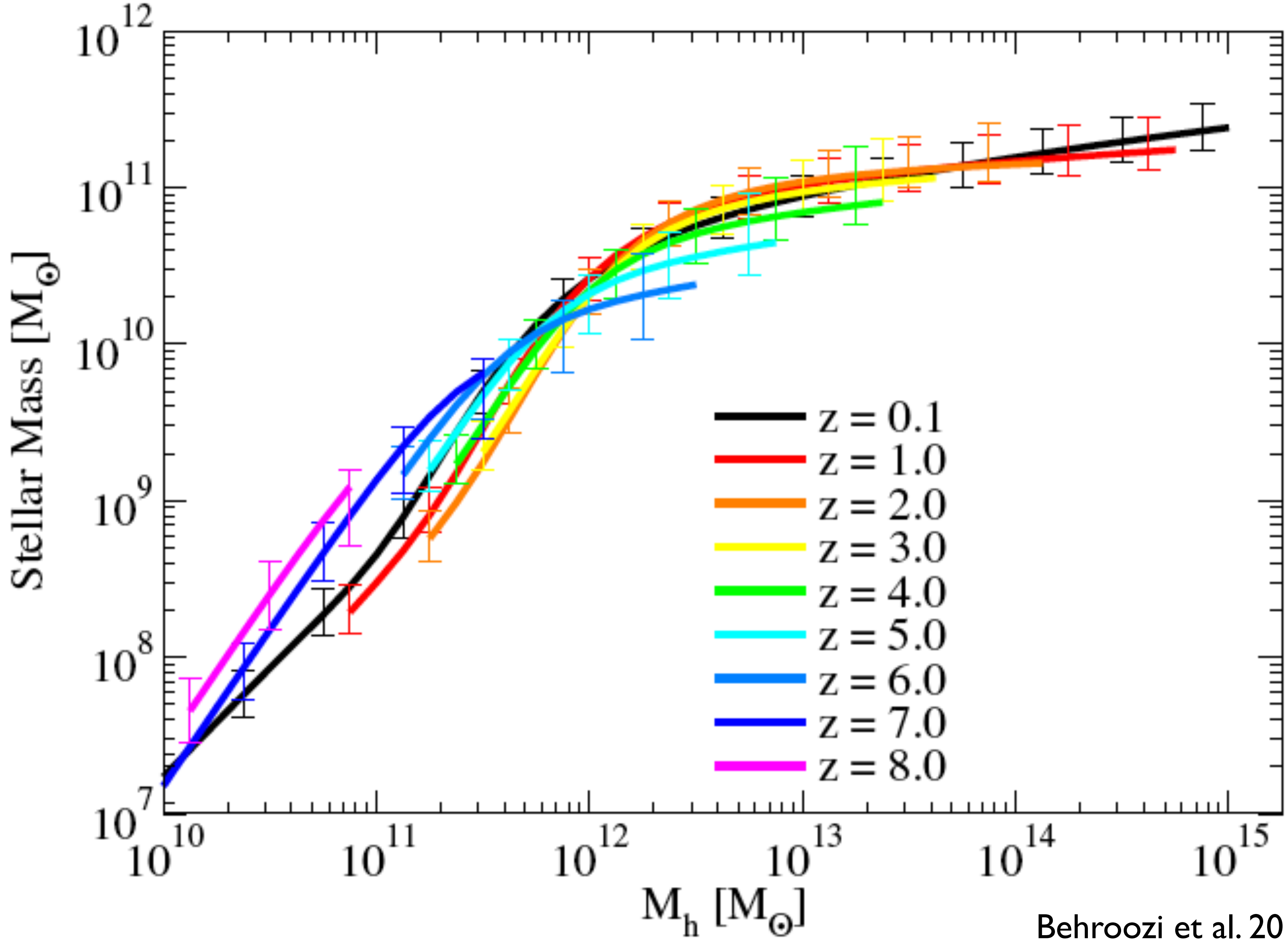






Behroozi et al. 2013

Using information from high redshifts



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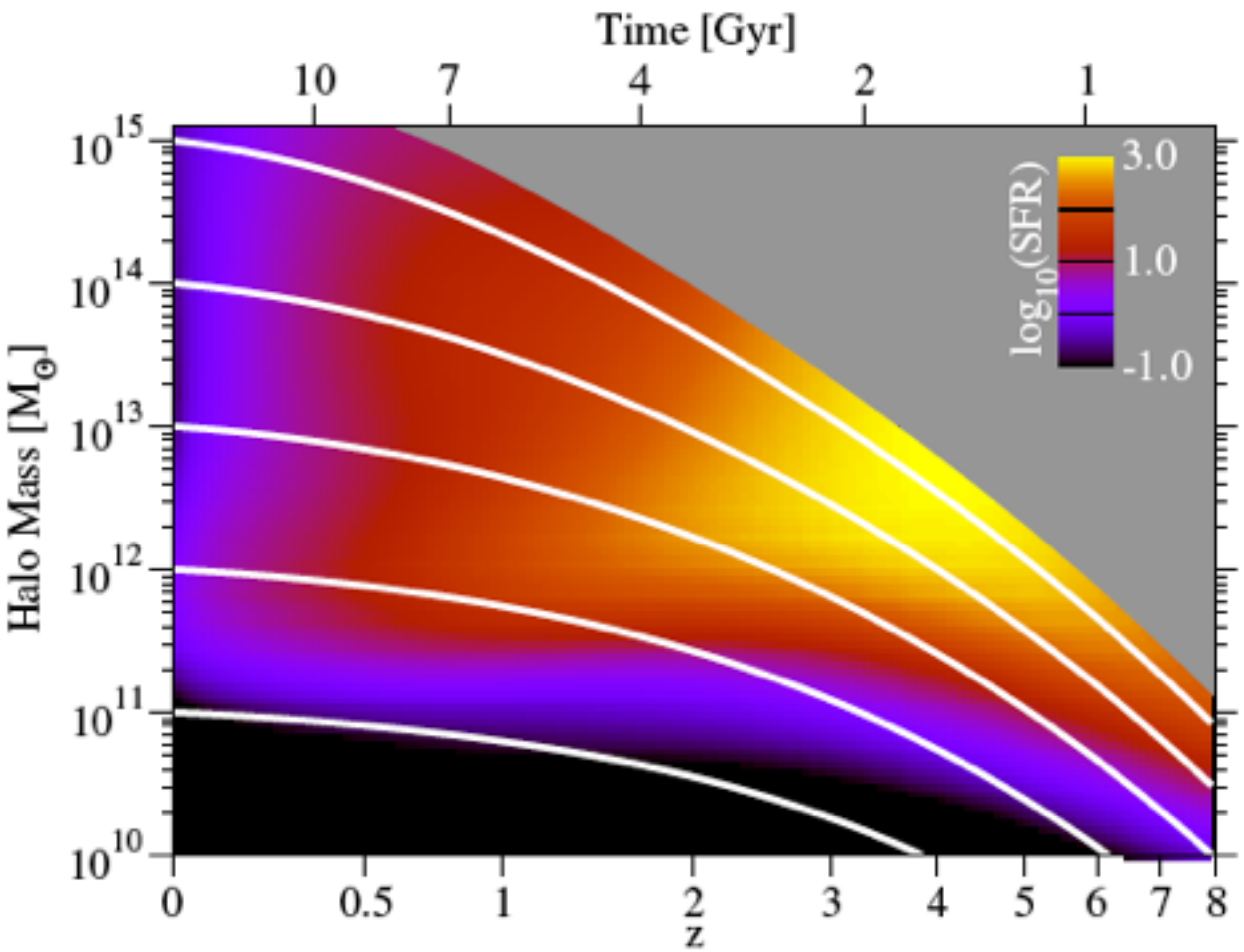
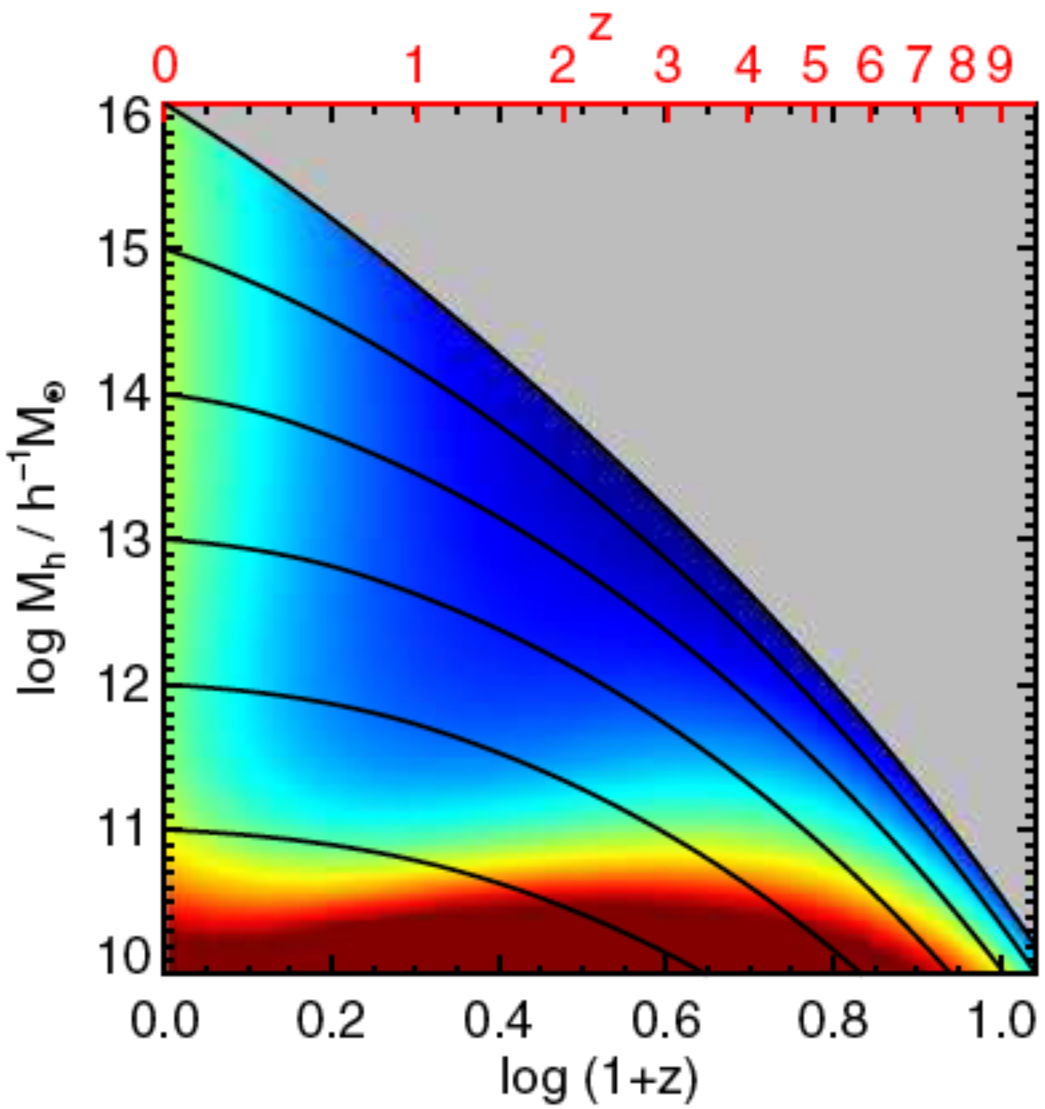
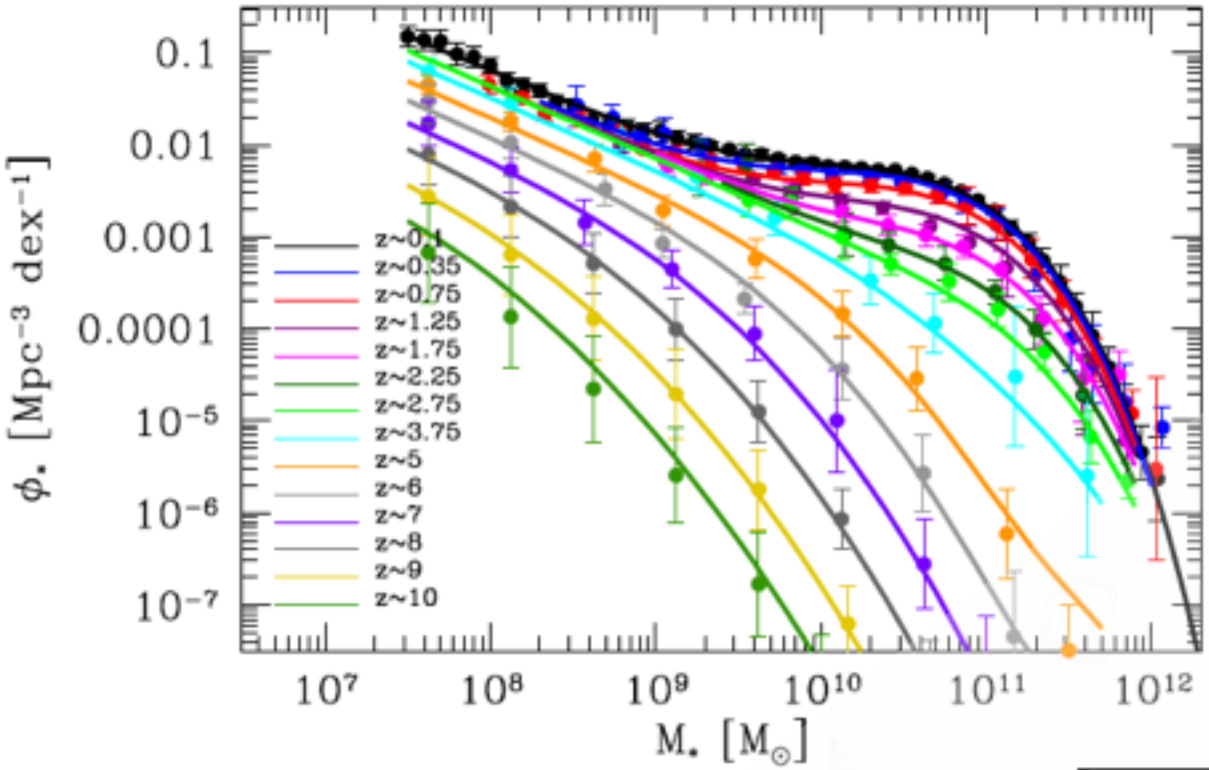


Behroozi et al. 2013

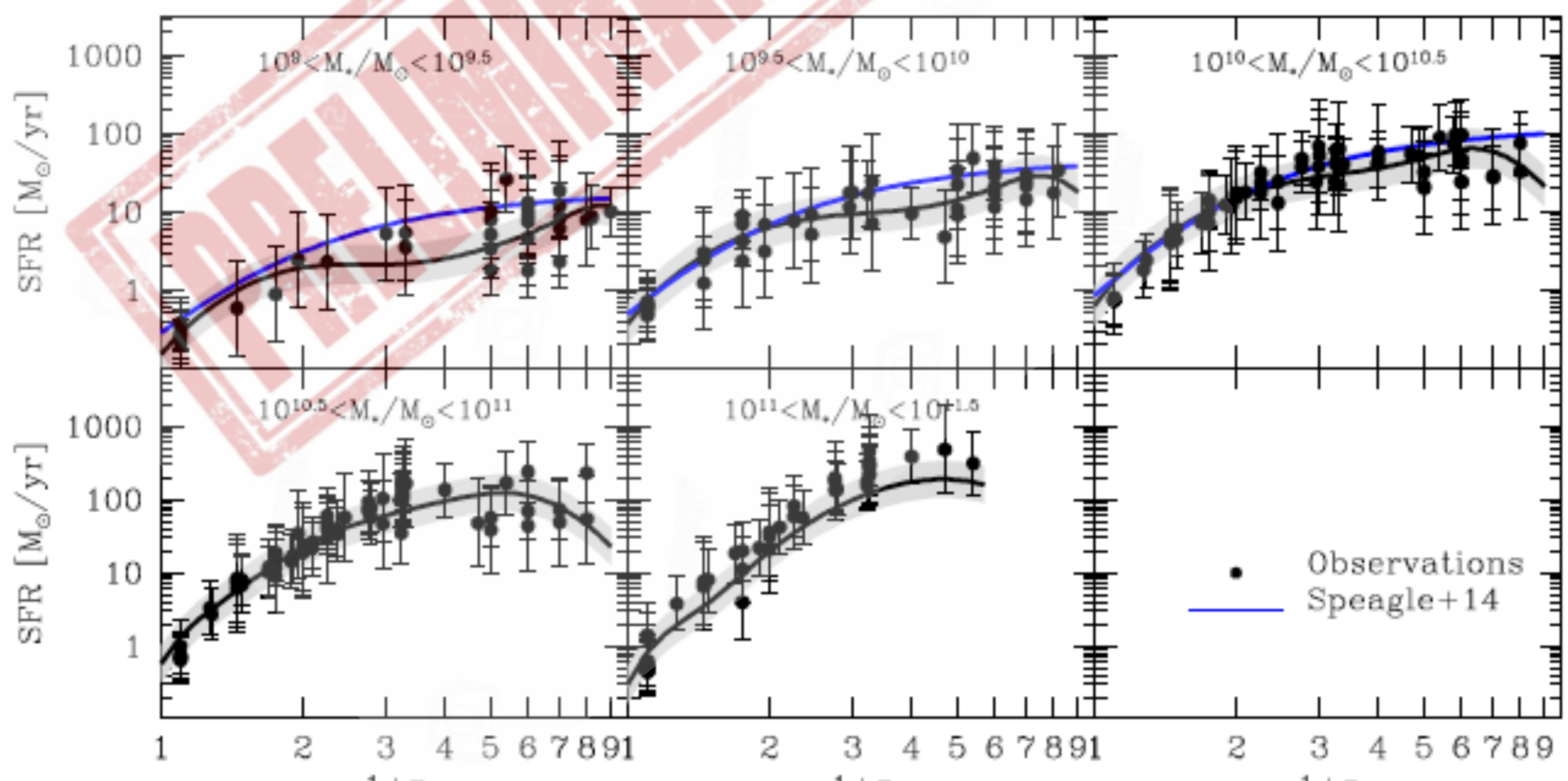


Yang et al. 2013

Using information from high redshifts



Rodriguez-Puebla et al. in prep.



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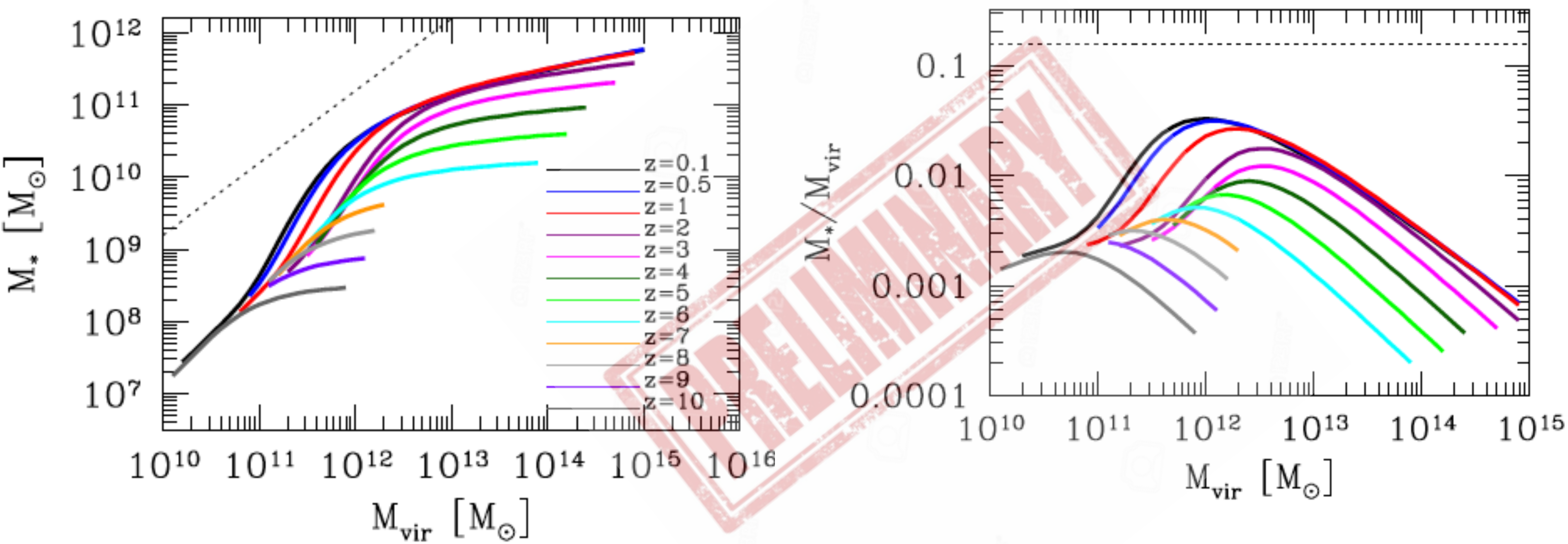

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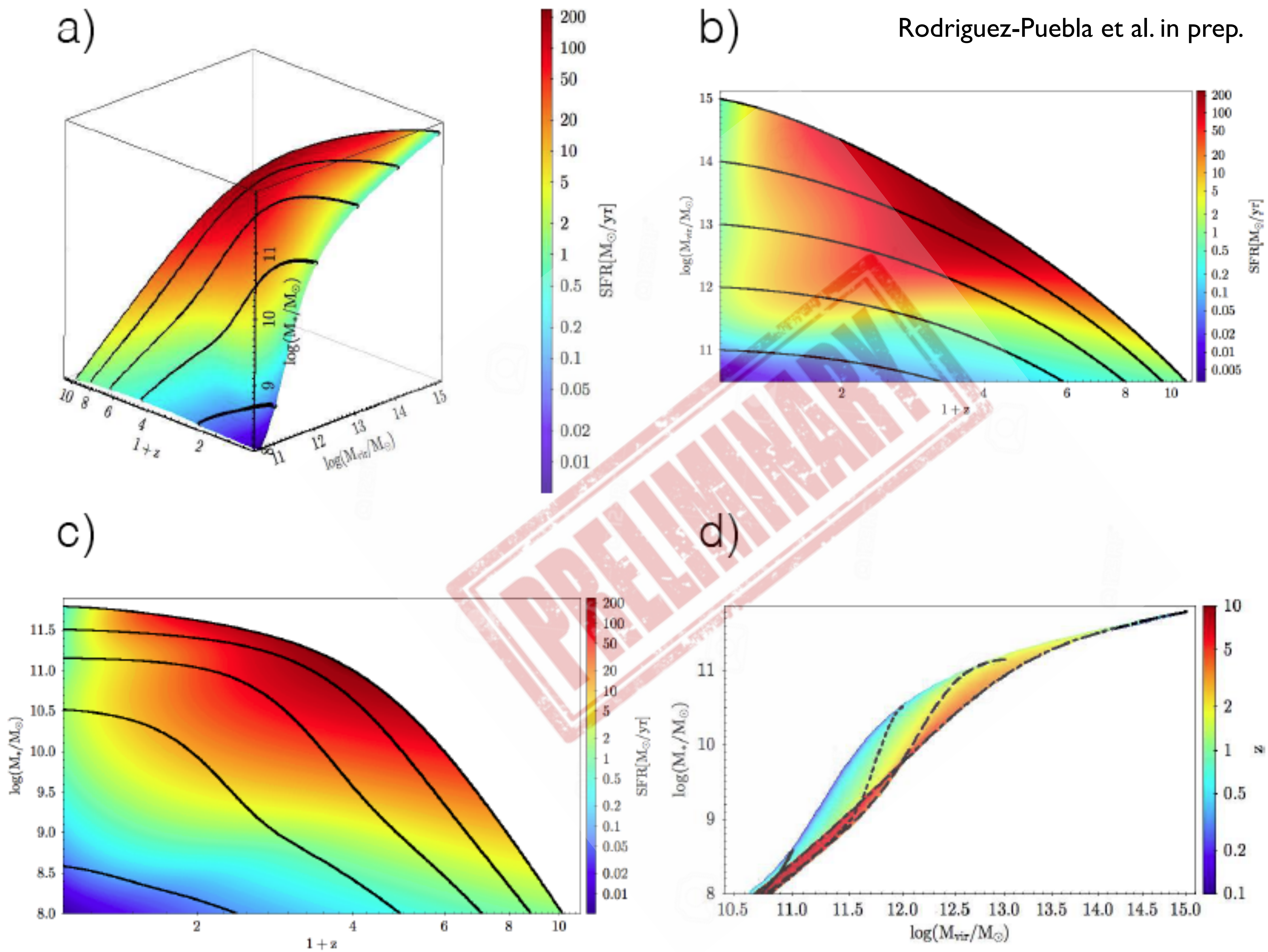
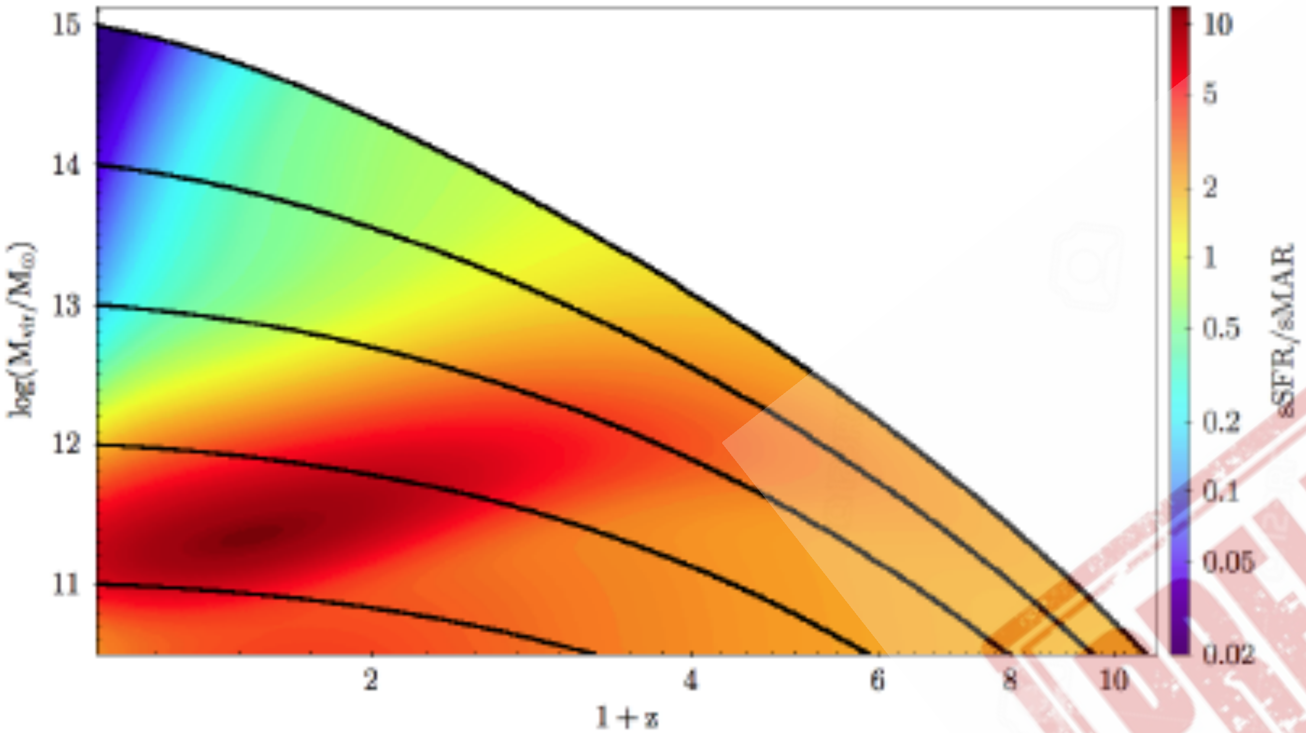
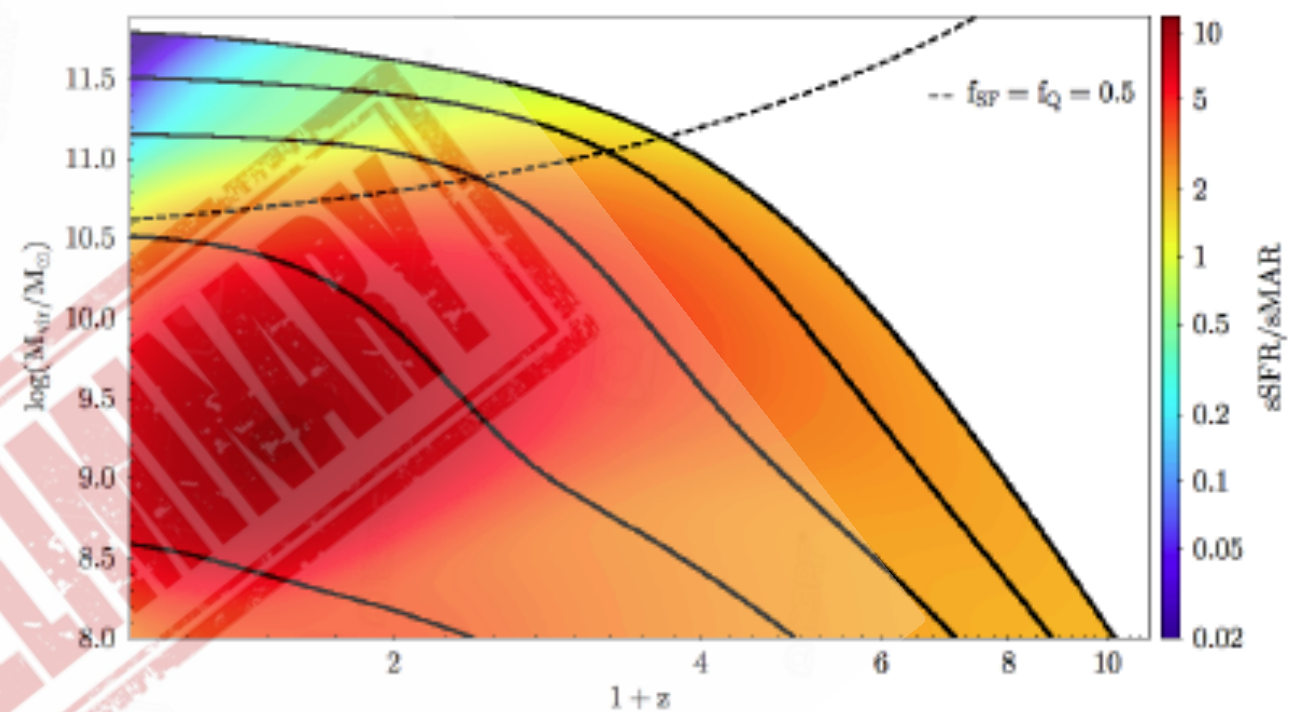


Using information from high redshifts





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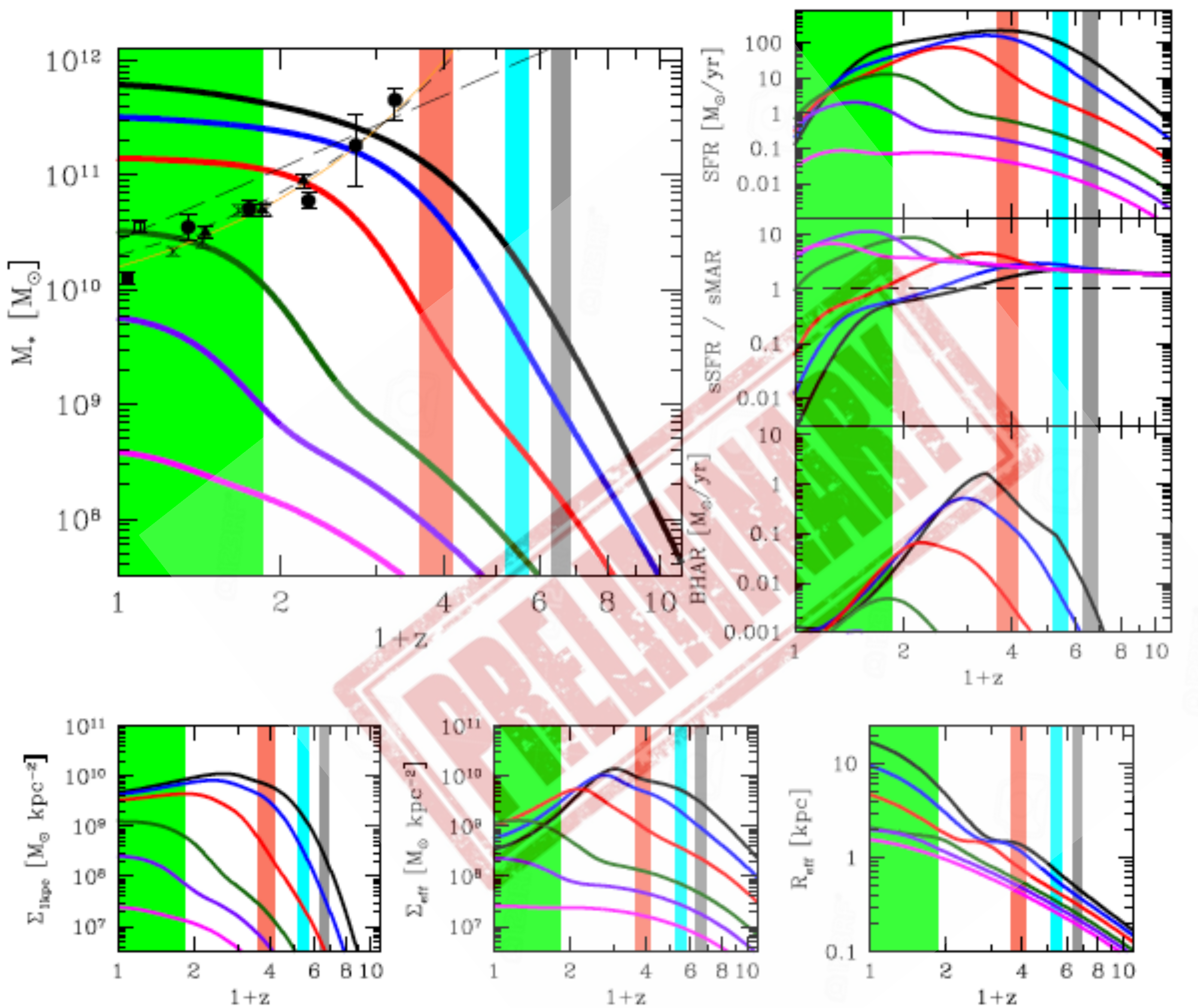

Rodriguez-Puebla et al. in prep.

Uncertainties affecting the Galaxy-Halo Connection

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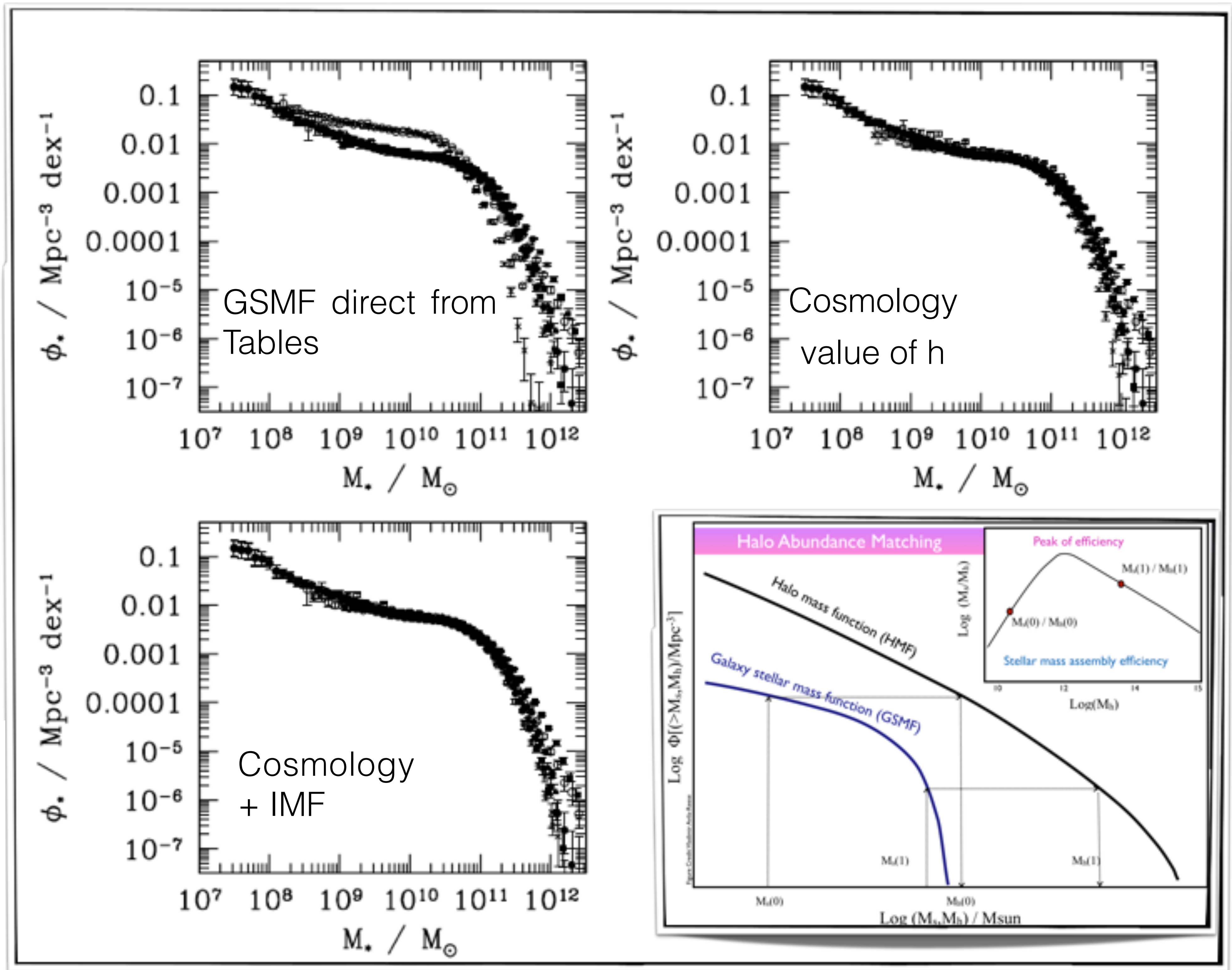
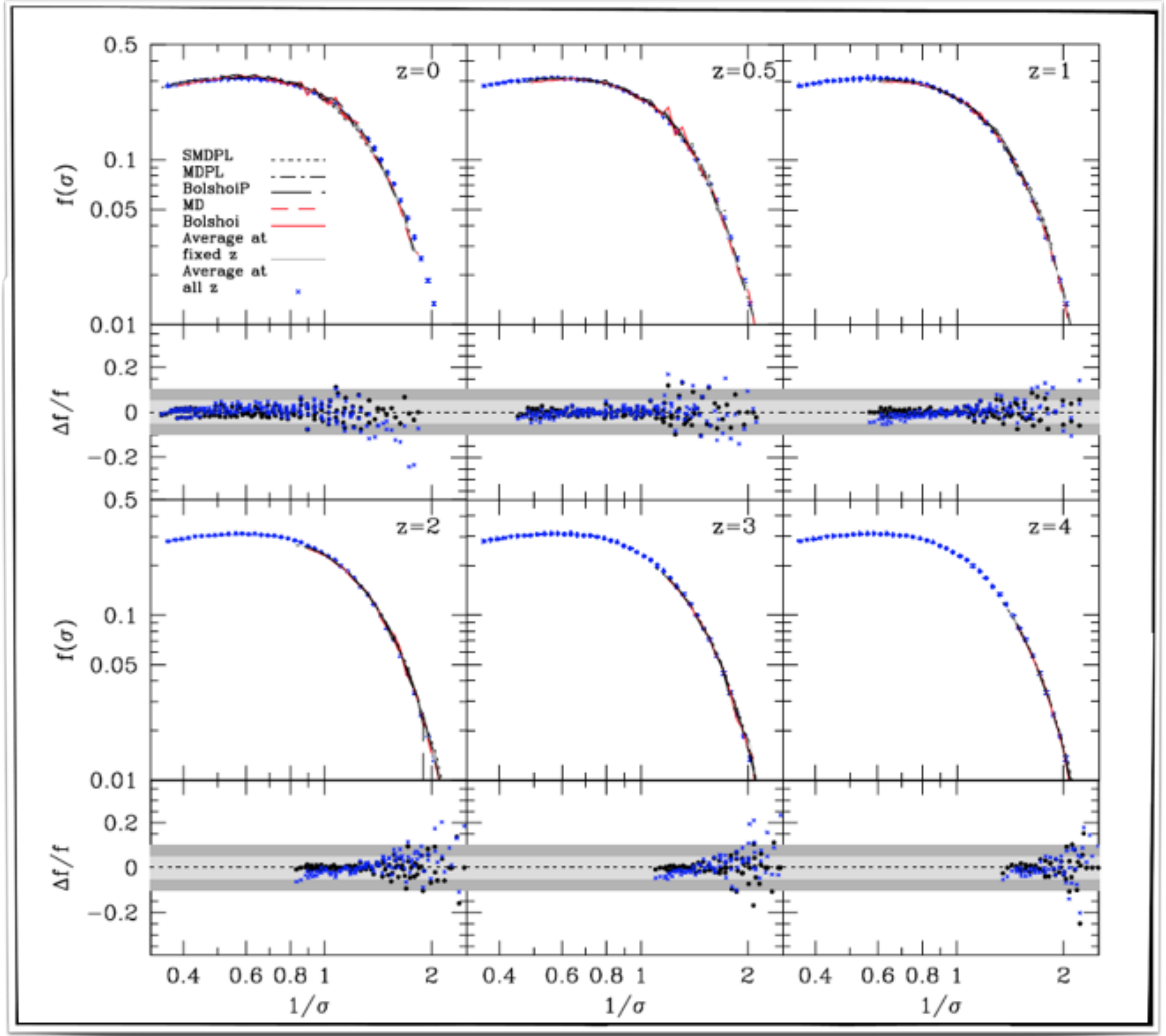


Bernardi et al. 2010

Table 2. M_*/L IMF offsets used in this work. Offset is with respect to the Salpeter (1955) IMF: $\log_{10} M_*/L$ (IMF Salpeter) = $\log_{10} M_*/L$ (IMF reference) + offset.

IMF	Offset (dex)	Reference
Kennicut	0.30	Kennicut (1983)
Scalo	0.25	Scalo (1986)
Diet-Salpeter	0.15	Bell & de Jong (2001)
Pseudo-Kroupa	0.20	Kroupa (2001)
Kroupa	0.30	Kroupa (2002)
Chabrier	0.25	Chabrier (2003)
Baldry & Glazbrook	0.305	Baldry & Glazebrook (2003)

Uncertainties affecting the Galaxy-Halo Connection



$$\frac{dn_{\rm h}}{dM_{\rm vir}} = f(\sigma)\frac{\rho_m}{M_{\rm vir}^2}\left|\frac{d\ln\sigma^{-1}}{d\ln M_{\rm vir}}\right|$$

Uncertainties affecting the Galaxy-Halo Connection: Summary

- Choice of IMF: Introduces a systematic of ~0.3 dex.
- Choice of SPS model: Different models treat stellar evolution differently.
- Parametrization of SHFs: ~0.18 dex.
- Dust attenuation models: ~0.1 dex.
- Statistical errors from individual stellar masses: ~0.1 dex at z~0.1 and ~0.15 at z~1
- Sample variance. Finite regions of the observed universe are susceptible to large scale fluctuations in the number of density galaxies.
- Photometric redshifts.
- Uncertainties on the halo mass function.
- Uncertainties on the cosmology.

Uncertainties affecting the Galaxy-Halo Connection: Formalism

Abundance matching:

$$\phi_{\rm direct}(M_*) \equiv \phi_h(M_h(M_*)) \frac{d \log M_h}{d \log M_*},$$

Including scatter on the M*-Mvir relation

$$\phi_{\rm true}(M_*) = \int_{-\infty}^{\infty} \phi_{\rm direct}(10^y)\, P_s(y - \log_{10} M_*) dy$$

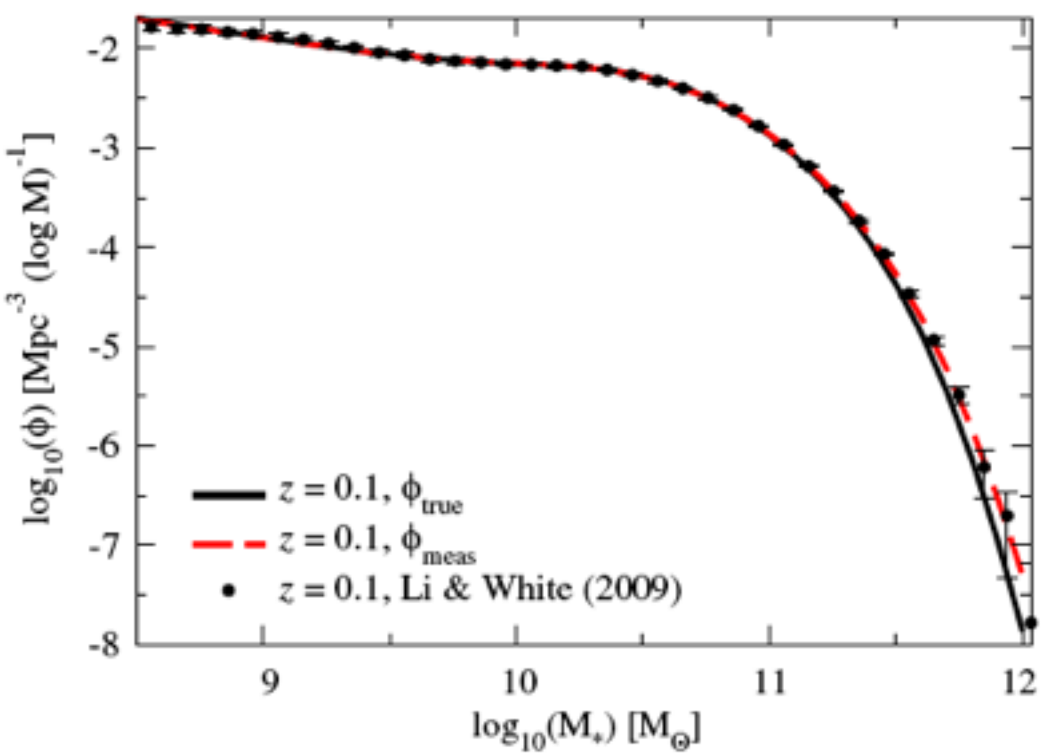
Modelling the observed GSMF

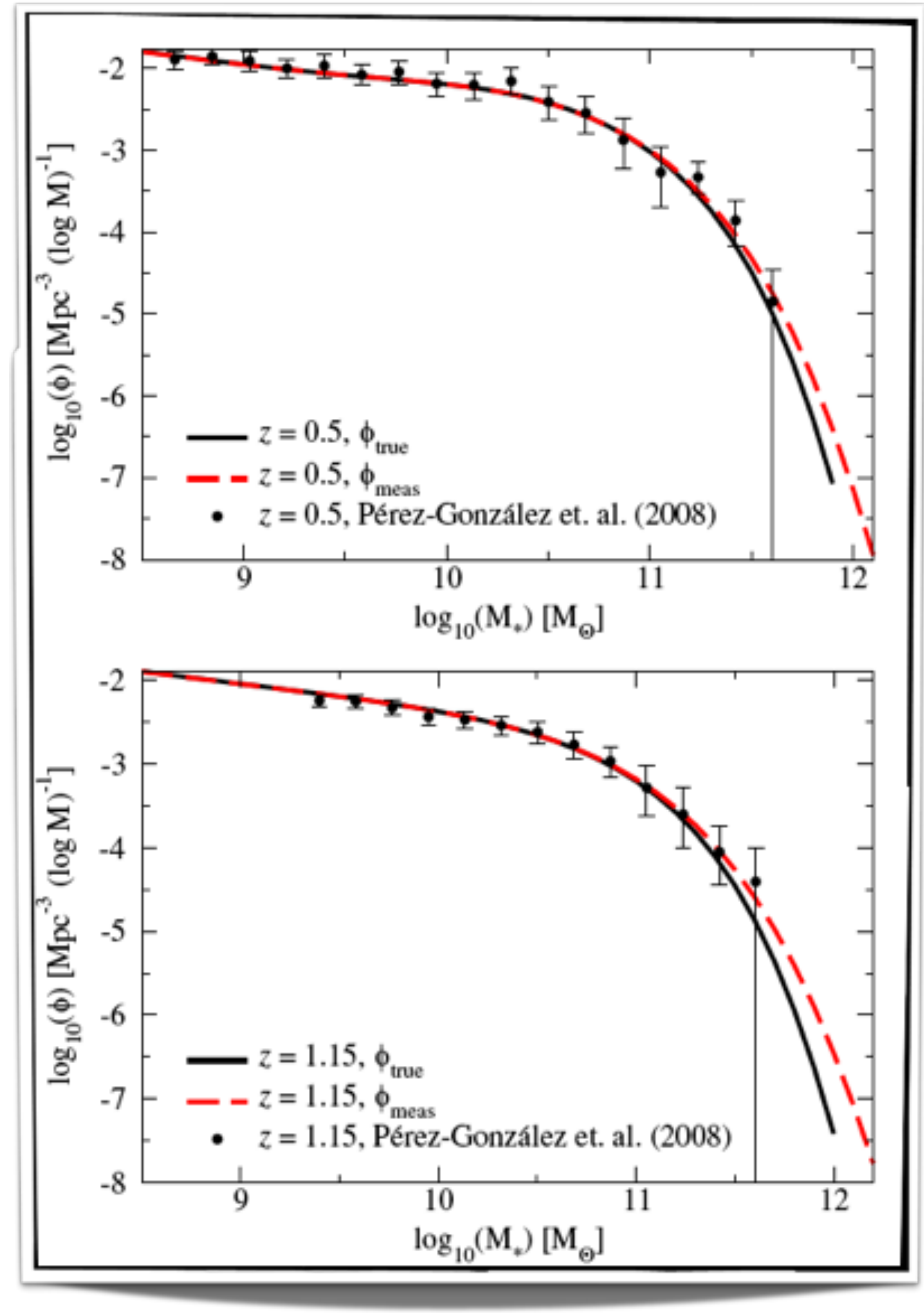
$$\phi_{\rm meas}(M) = \int_{-\infty}^{\infty} \phi_{\rm true}(10^y)\, P(y - \log_{10}(M)) dy,$$

$$\phi_{\rm meas}(M_*) = \phi_{\rm direct}(M_*) \circ P_s(\Delta \log_{10} M_*) \circ P(\Delta \log_{10} M_*)$$

Uncertainties affecting the Galaxy-Halo Connection: Impact on the GSMF

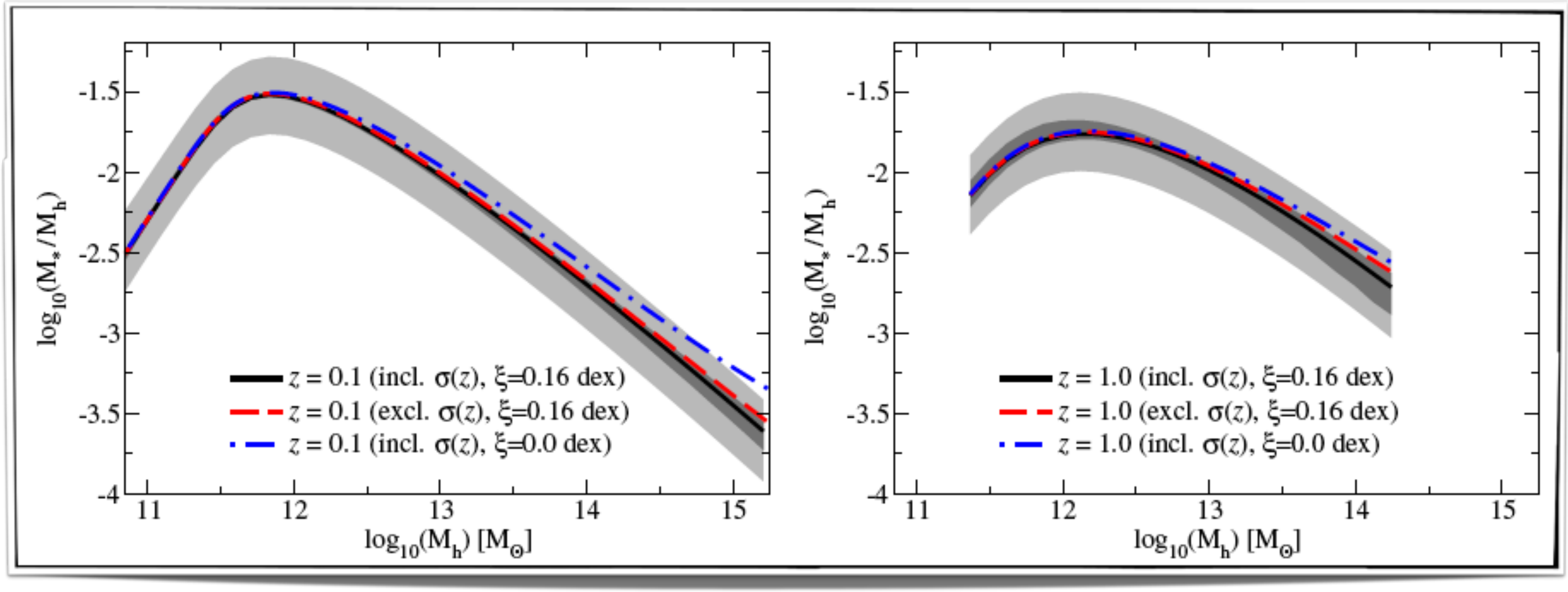
Behroozi et al. 2010





Uncertainties affecting the Galaxy-Halo Connection: M*-Mvir relation

Behroozi et al. 2010



Uncertainties affecting the Galaxy-Halo Connection: M*-Mvir relation

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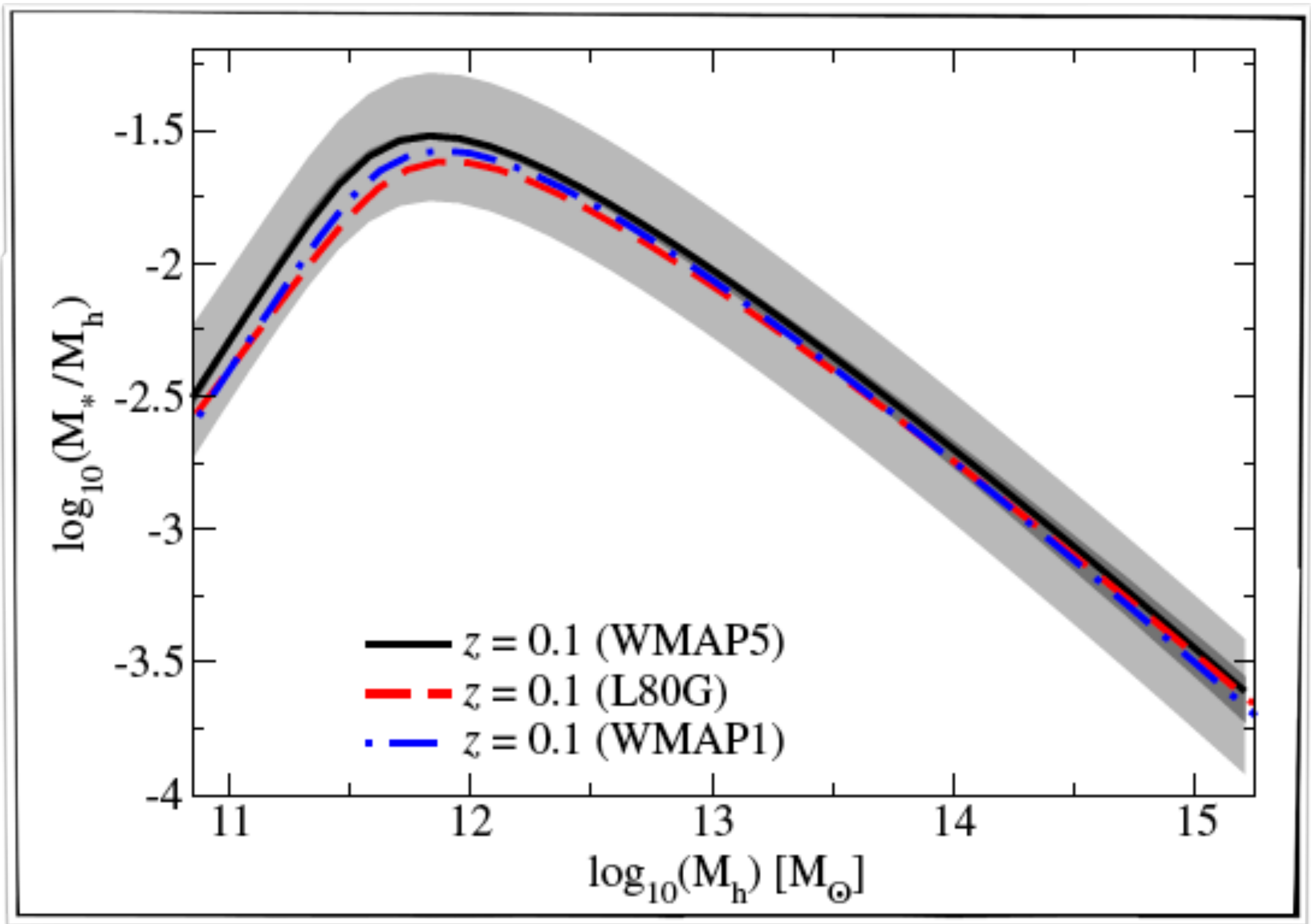
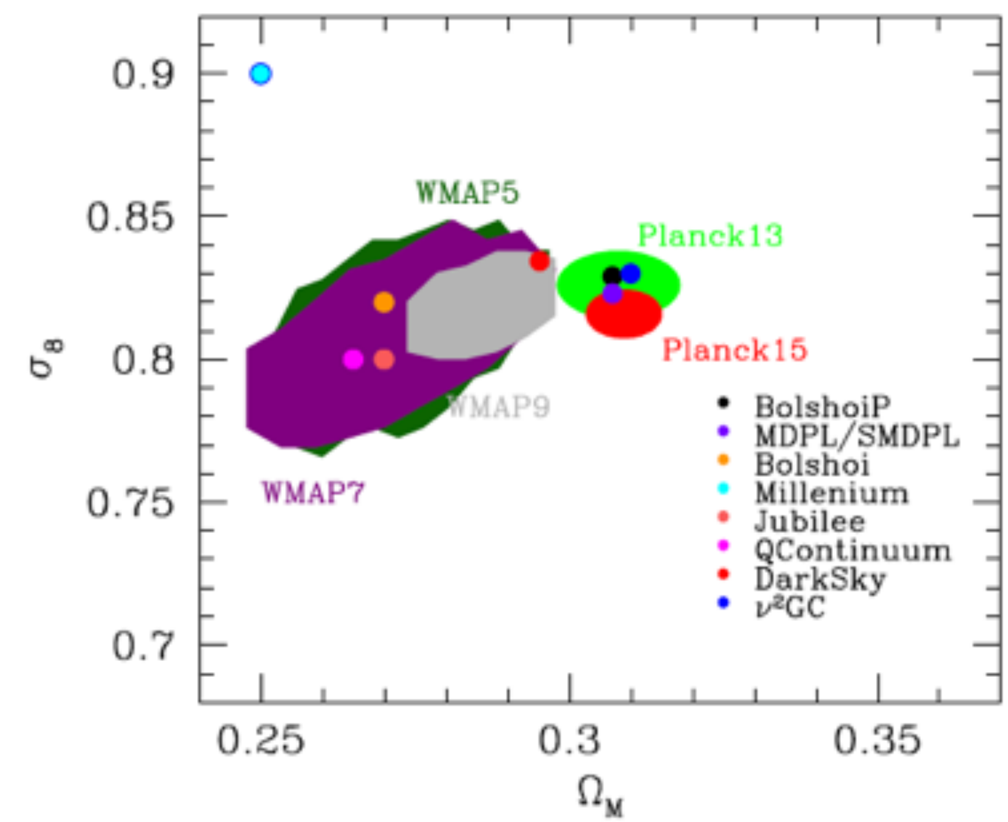
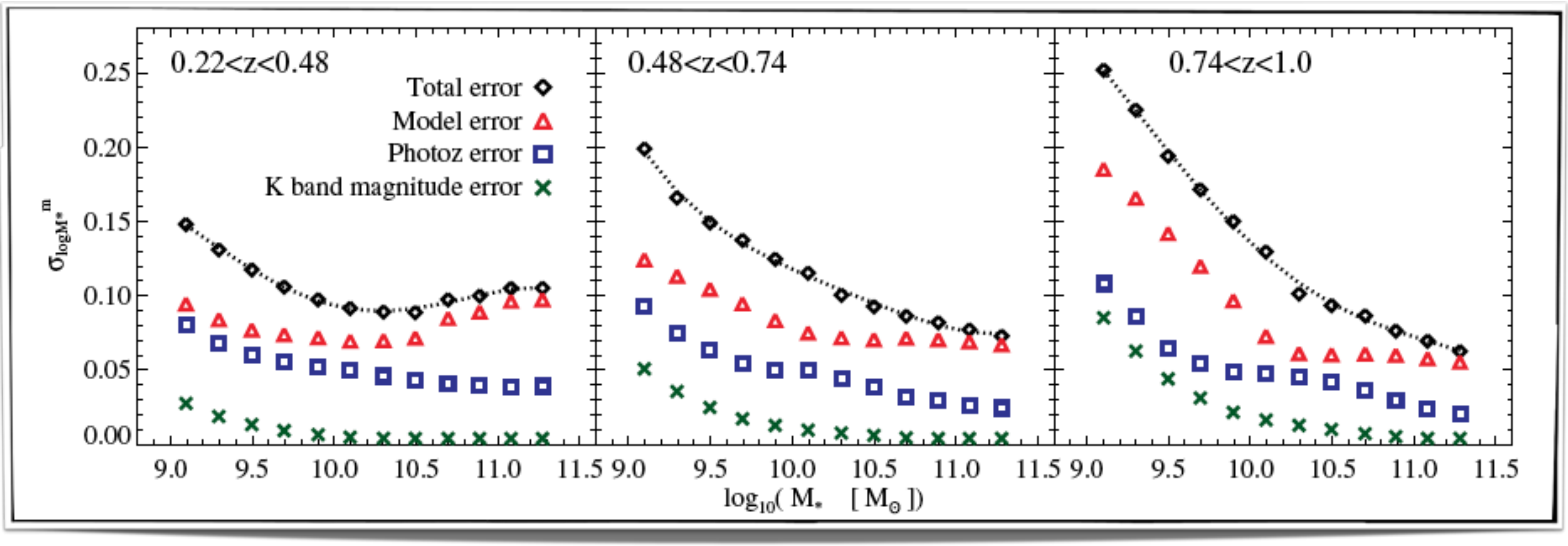


Rodriguez-Puebal et al. 2016b



Uncertainties affecting the Galaxy-Halo Connection: M*-Mvir relation

Leauthaud et al. 2012

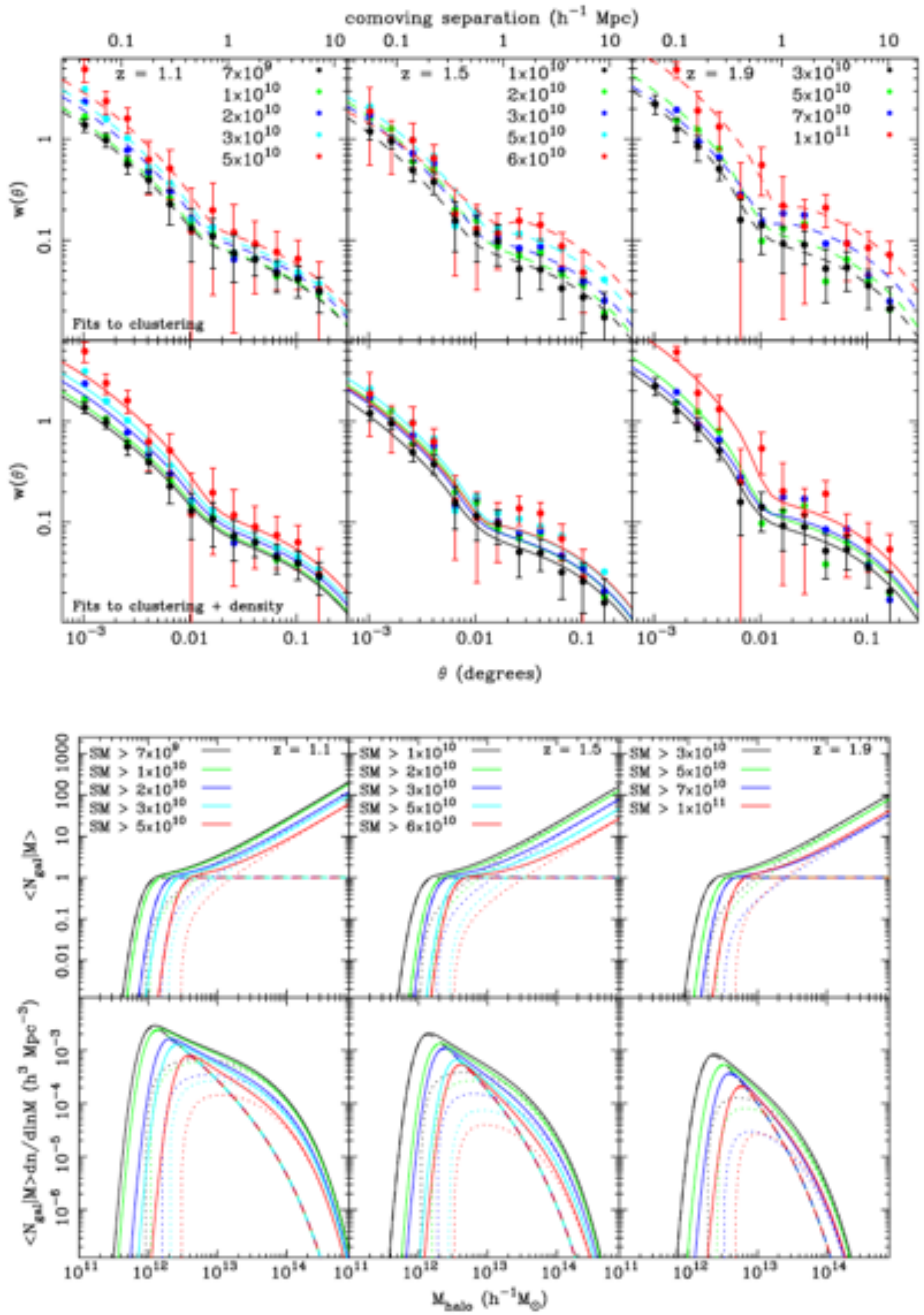


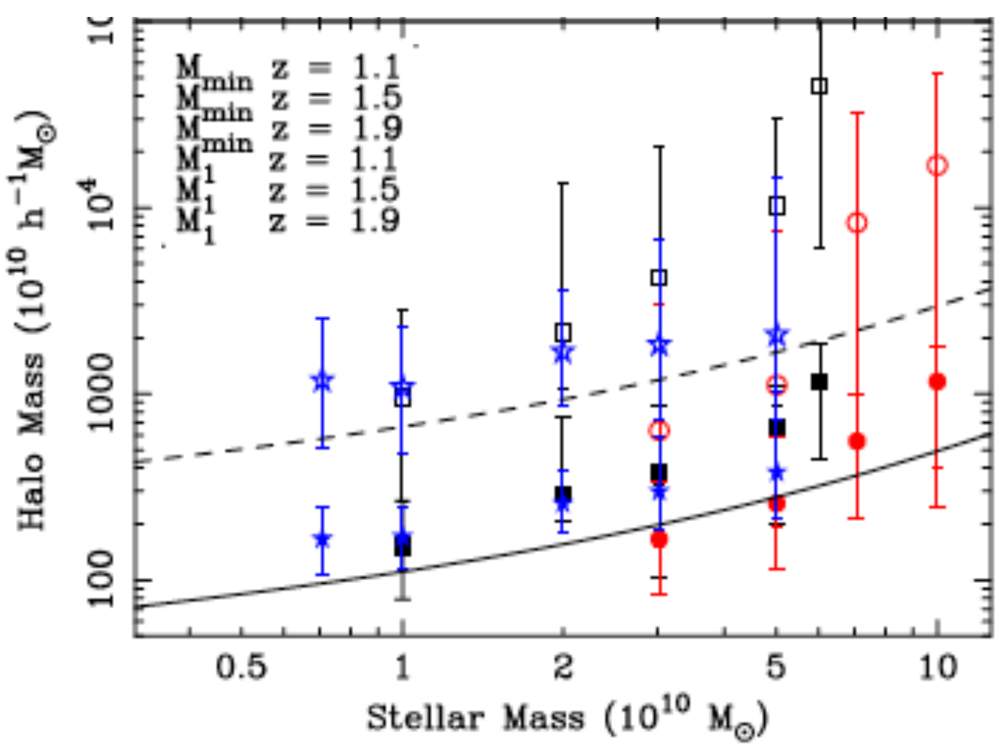
Three contributions to the stellar mass error budget. i) Model error is given by the 68% confidence interval of the mass probability distribution determined for each stellar mass galaxy. ii) Photoz error with derives from the uncertainty in the luminosity distance owing to the error on a given photometric redshift. iii) Photometric uncertainty on the observed K-band magnitude.

Constraints at high redshift

Constraints at high redshift

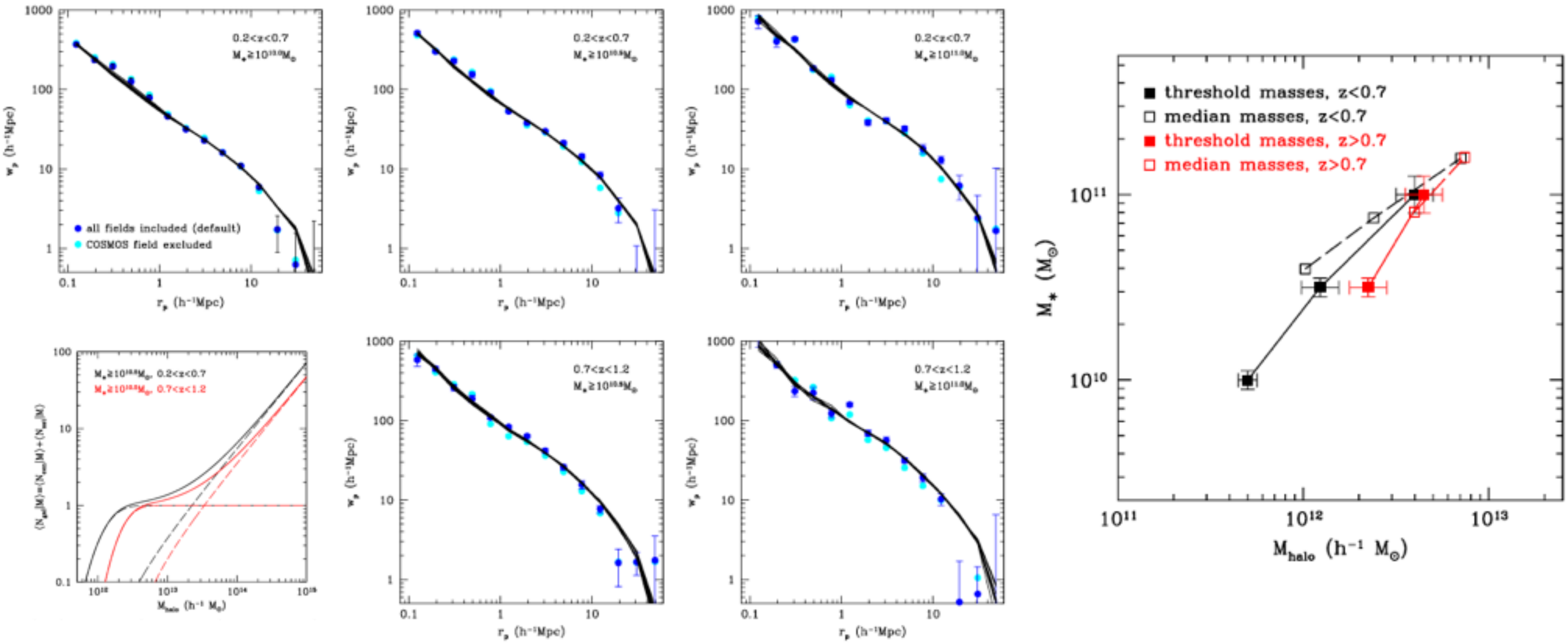
Wake et al. 2012





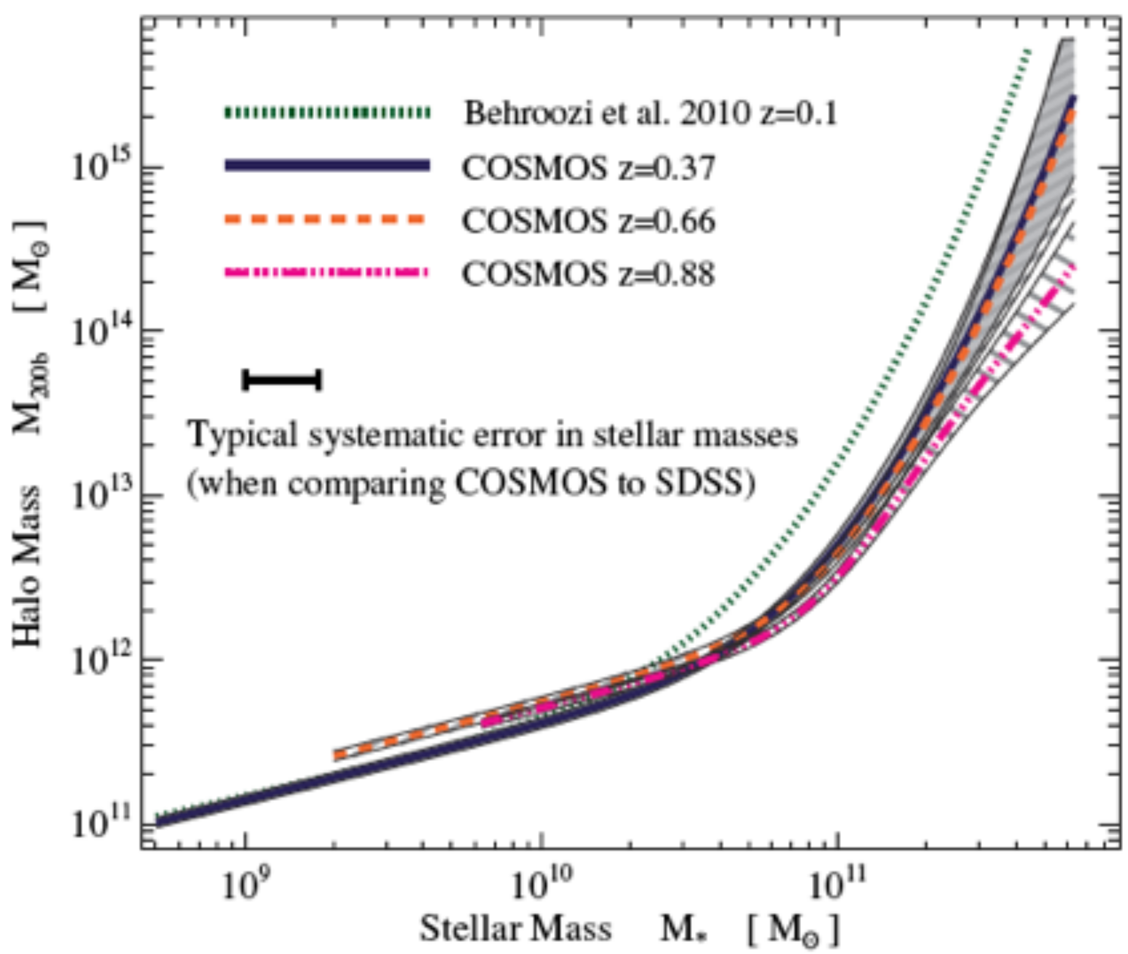
Constraints at high redshift

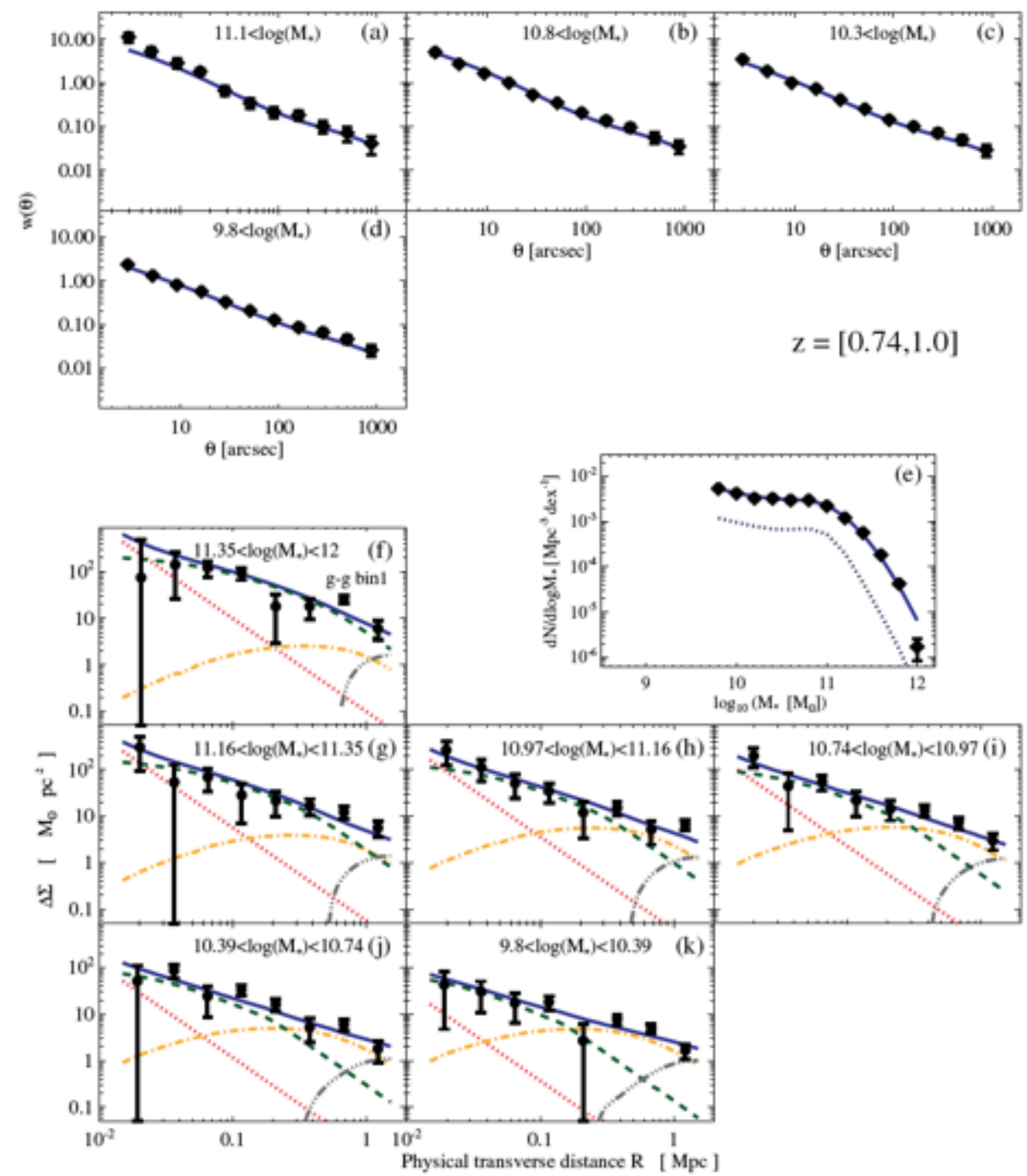
Skibba et al. 2015



Constraints at high redshift

Leauthaud et al. 2012

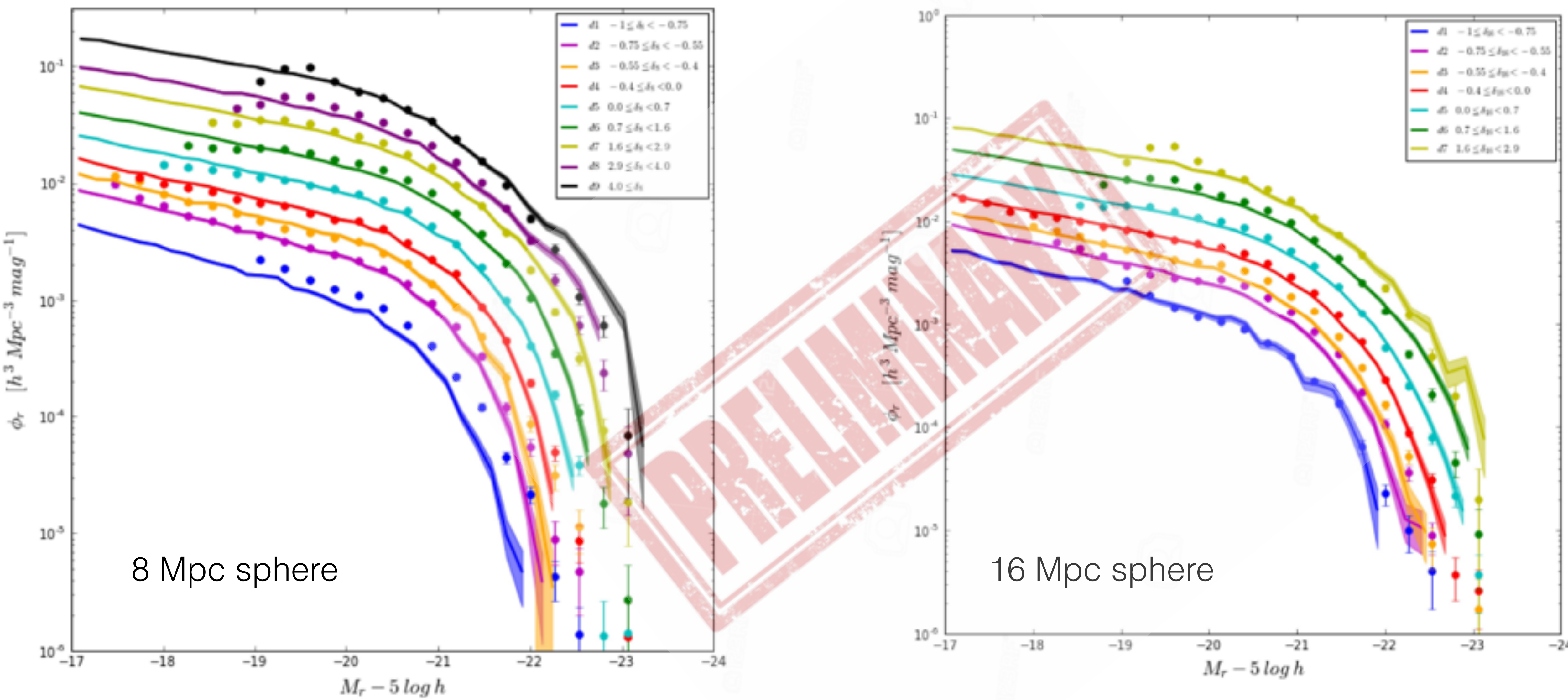




Environment dependence on the Galaxy-Halo connection

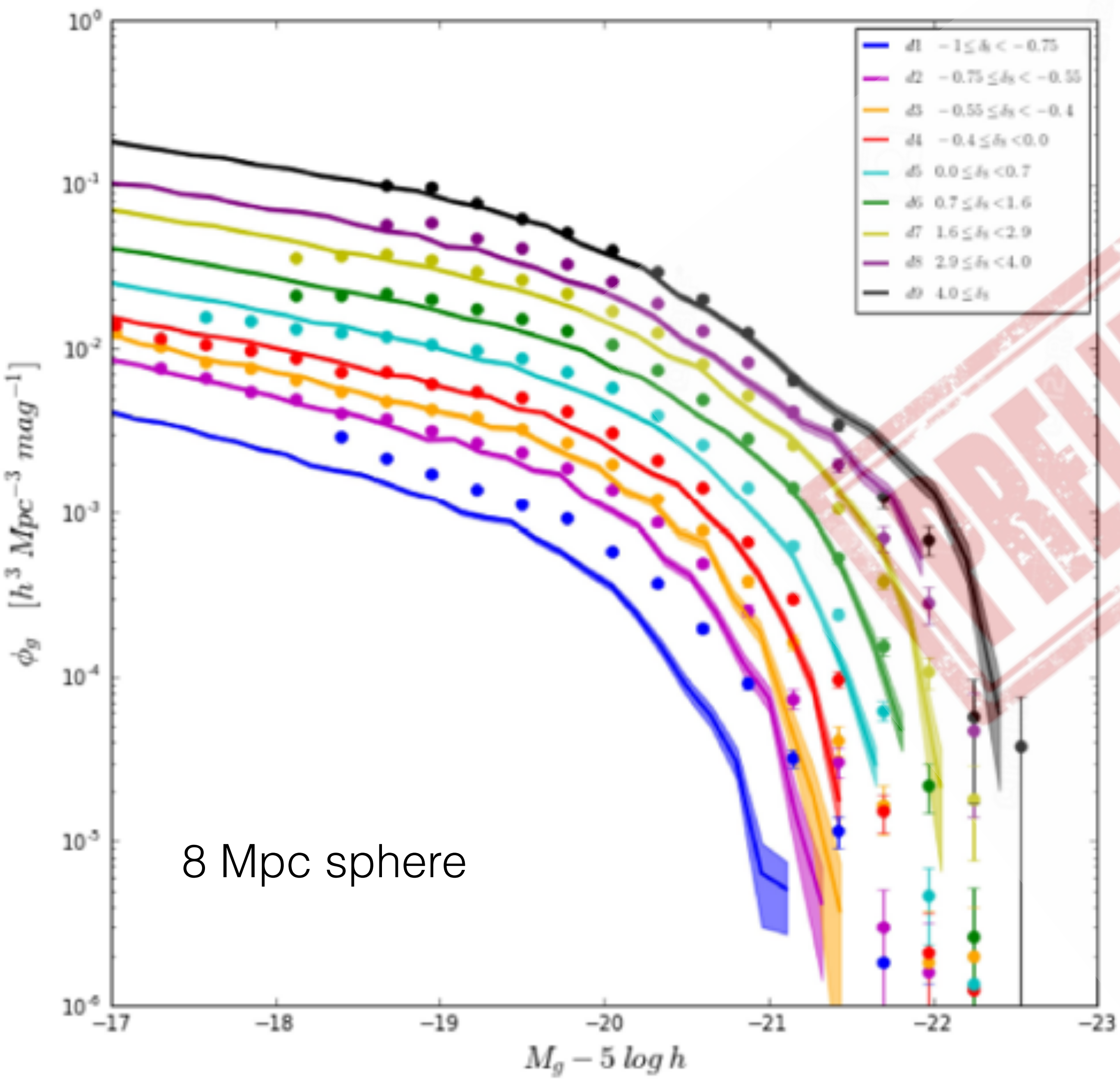
Environment dependence on the Galaxy-Halo connection

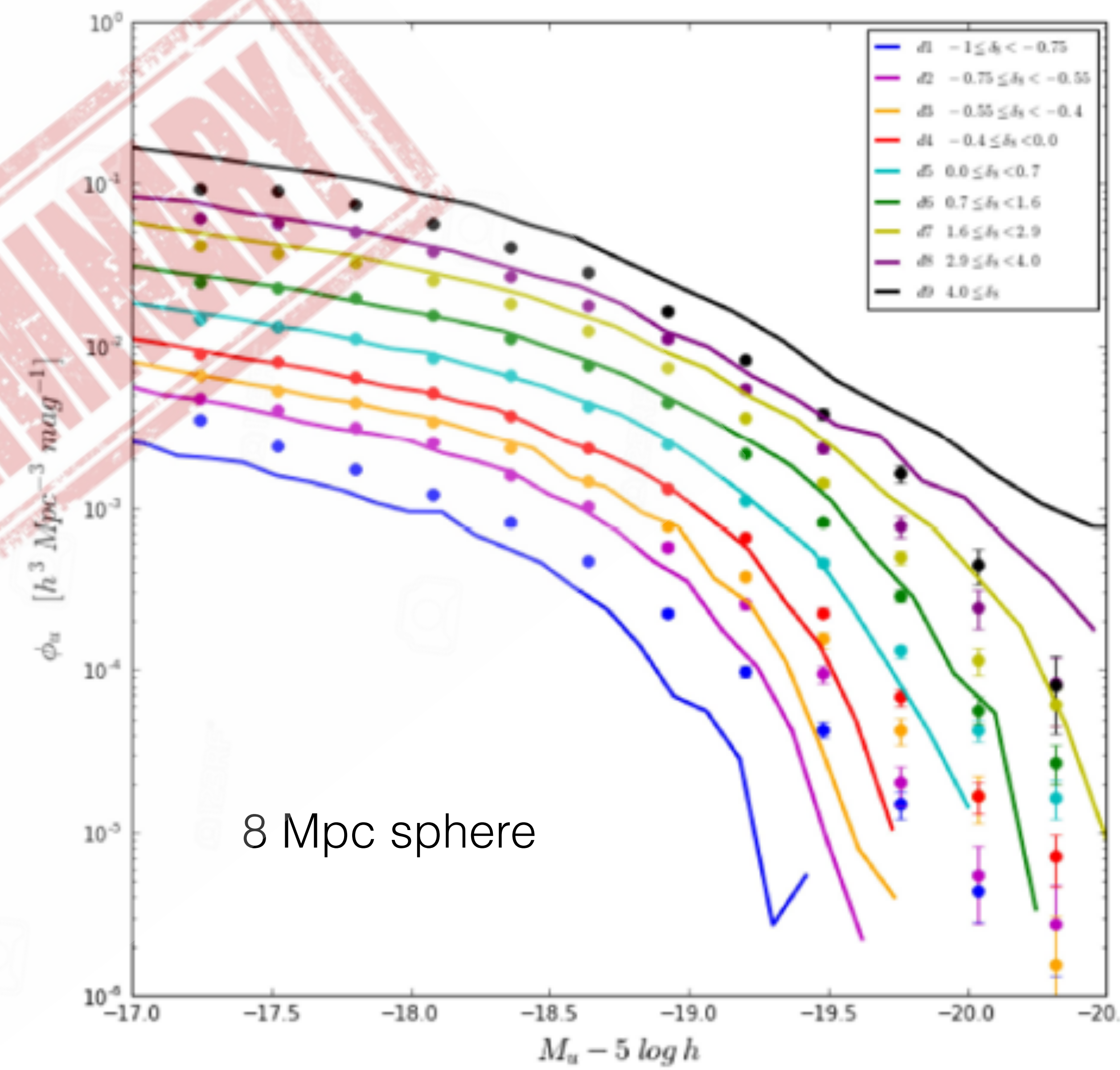
Dragomir, Rodriguez-Puebla et al. in prep.

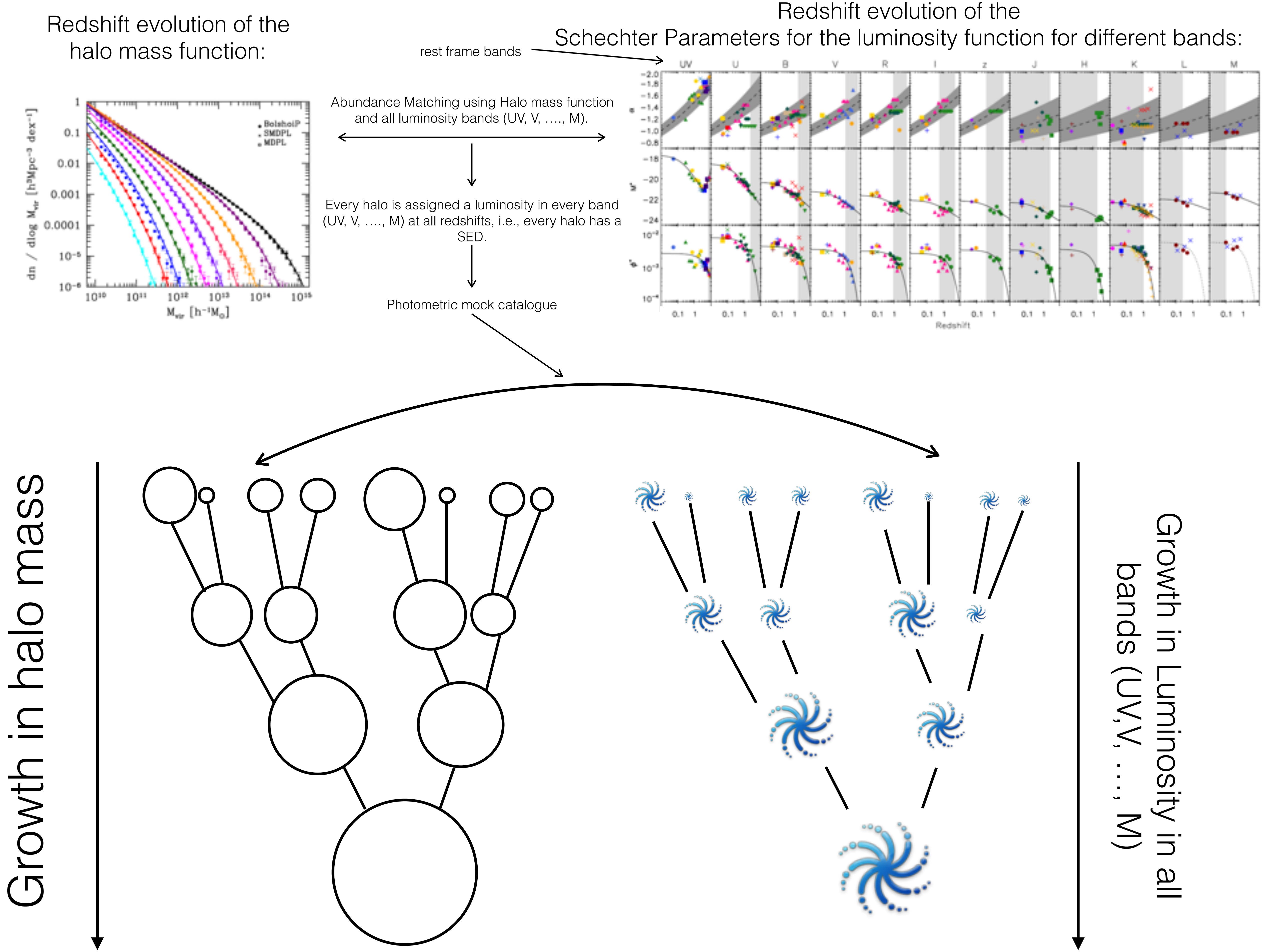


Environment dependence on the Galaxy-Halo connection

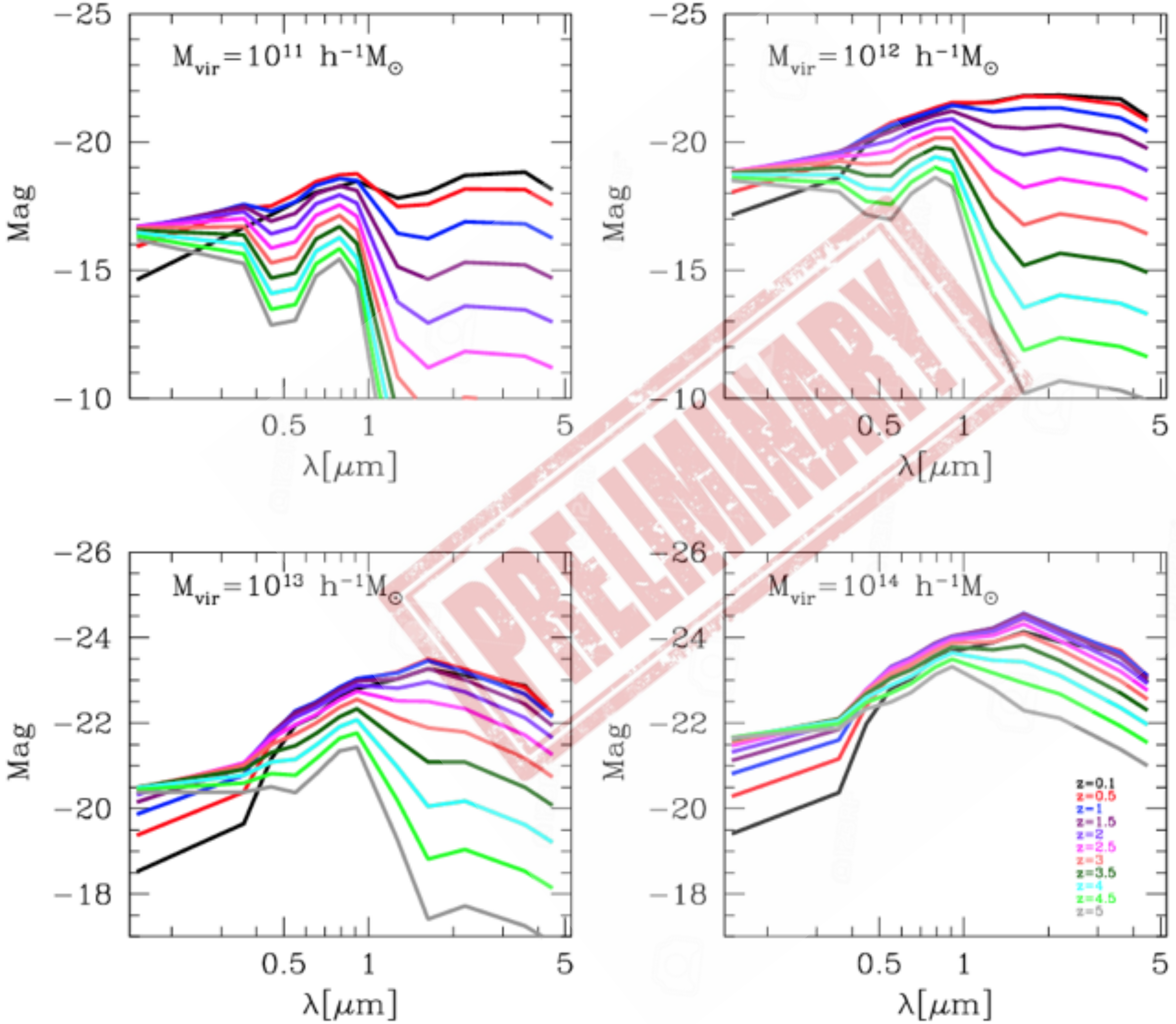
Dragormir, Rodriguez-Puebla et al. in prep.





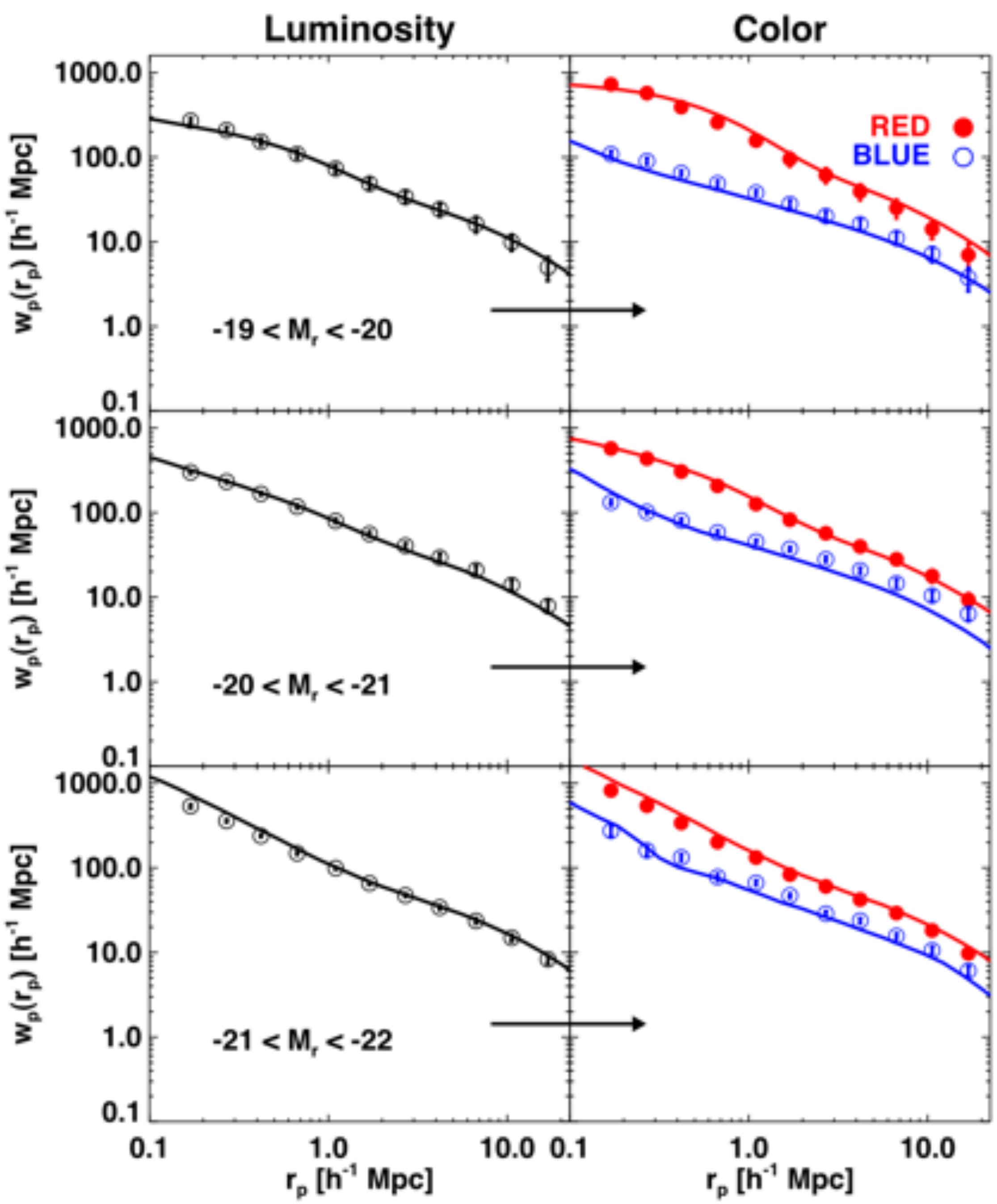

Redshift evolution of the
halo mass function:
Redshift evolution of the
Schechter Parameters for the luminosity function for different bands:
rest frame bands
Abundance Matching using Halo mass function
and all luminosity bands (UV, V, …., M).
Every halo is assigned a luminosity in every band
(UV, V, …., M) at all redshifts, i.e., every halo has a
SED.
Photometric mock catalogue
Growth in halo mass
Growth in Luminosity in all
bands (UV,V, …, M)

Environment dependence on the Galaxy-Halo connection



Beyond Halo Mass

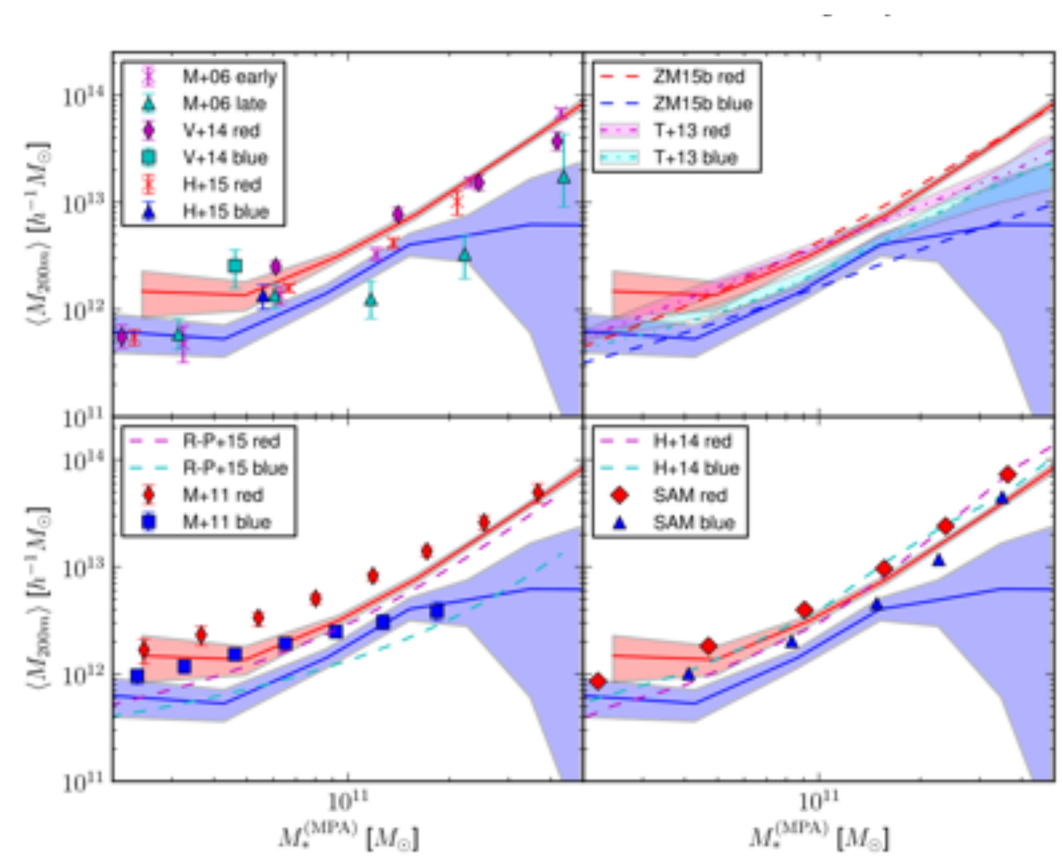
Comparison to Age Matching



Hearin & Watson et al. 2013

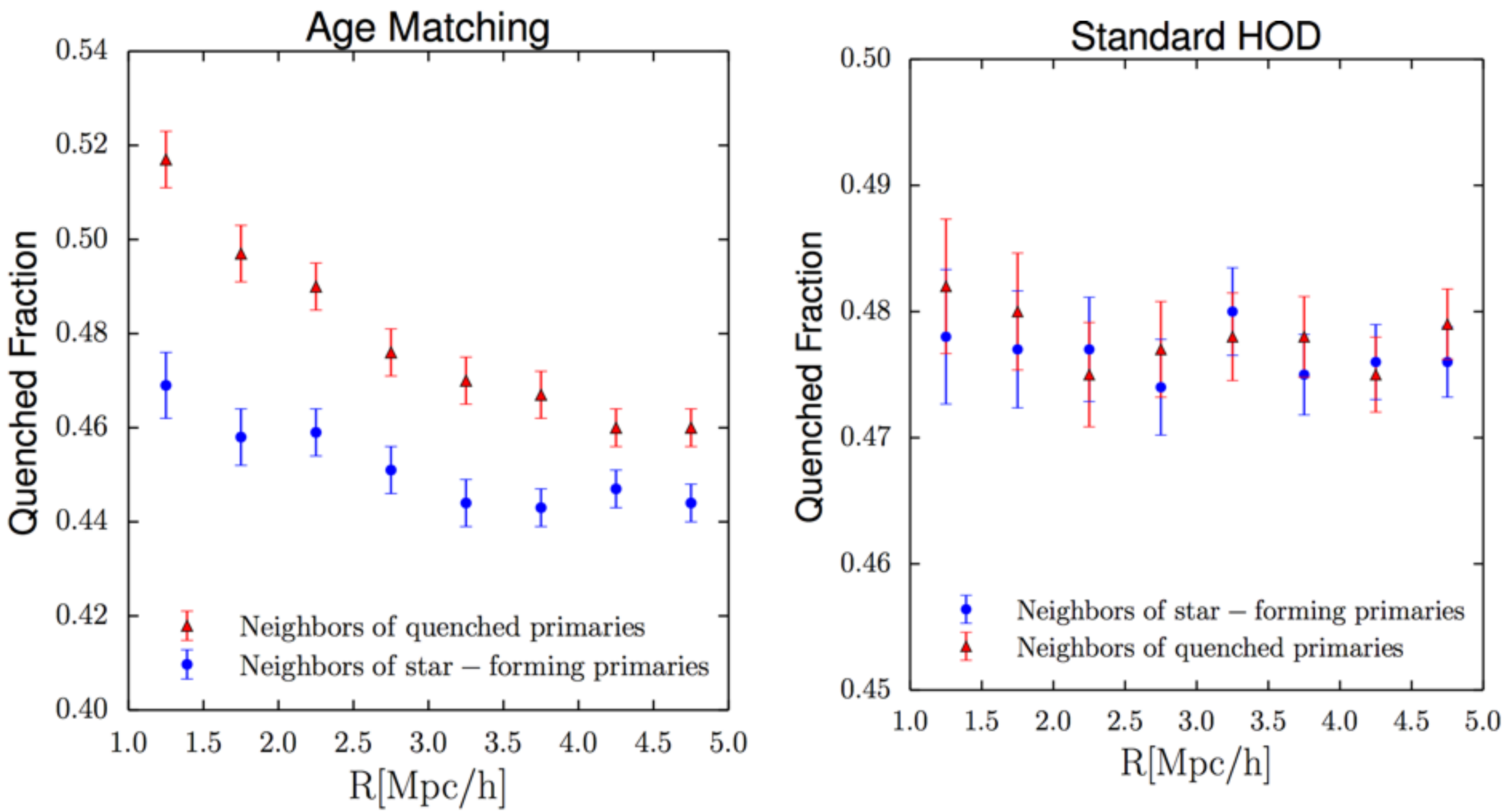
1) AMT

2) zstarve = Max{z_{acc}, z_{12}, z_{form}}



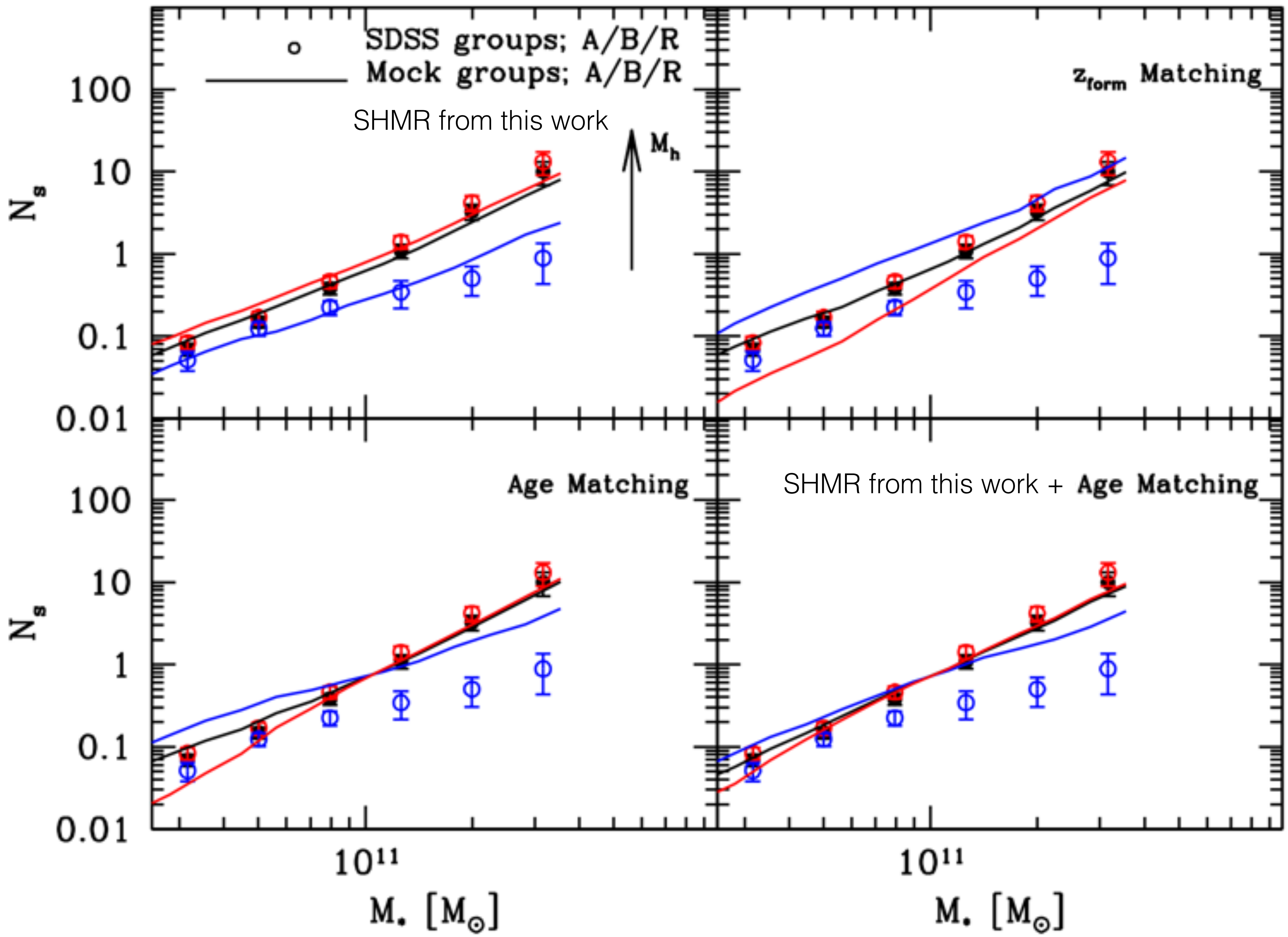
Mandelbaum et al. 2016

Comparison to Age Matching



Hearin & Watson et al. 2015

Comparison to Age Matching



Summary

The Empirical modelling allow us to construct self-consistent models with the data and our standard structure formation model without invoking any physics of galaxy formation.

Empirical modelling constraints indirectly the galaxy-halo connection.

Understanding systematics and errors in observations is vital in order to interpret correctly results from the empirical models.

The Rock says that you can gain insights on the physics of galaxy formation using empirical modelling.

Don’t replace empirical modelling with galaxy formation models.