Constrain Galaxy Formation Physics from Large-Scale Structure Measurements and Weak Lensing

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McWilliams Center for Cosmology

IPMU, 2016

More details on **Youtube** and ***arXiv***:

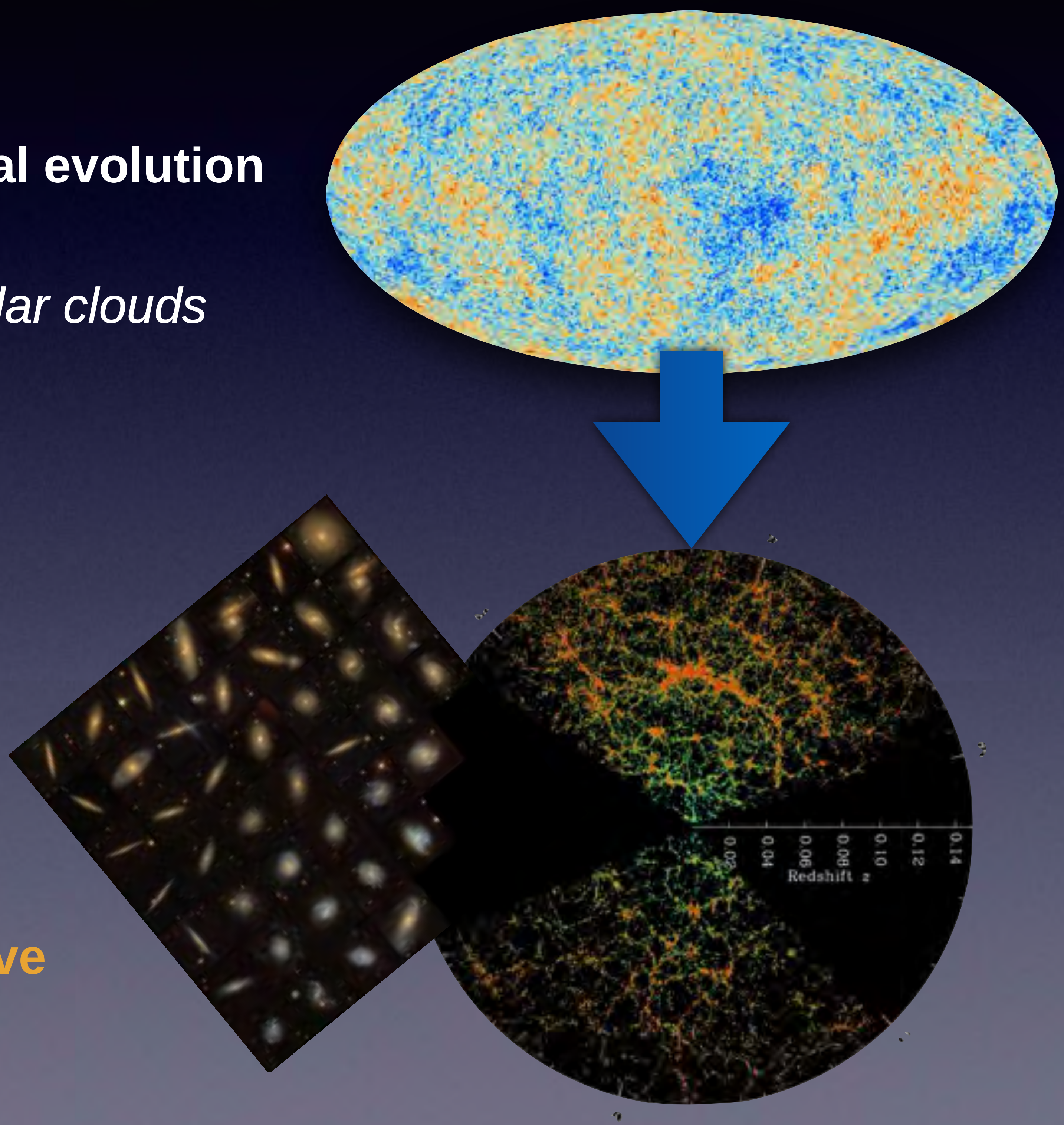
Mandelbaum, Wang, Zu+ (2015), arXiv:1509.06762; in press

Zu & Mandelbaum (2015b), arXiv:1509.06758; in press

Zu & Mandelbaum (2015a), MNRAS, 454, 1161

“Theory of Galaxy Formation”

- **Gravity**
- **Hydrodynamics and the thermal evolution of gas**
- *Star formation from giant molecular clouds*
- *Blackhole growth*
- *Stellar feedback*
- *AGN feedback*
- *Stellar population synthesis*
- *Radiative transfer*
- *Chemical evolution of metals*
- *Magnetic Fields*
- **and the coupling of all the above processes!**

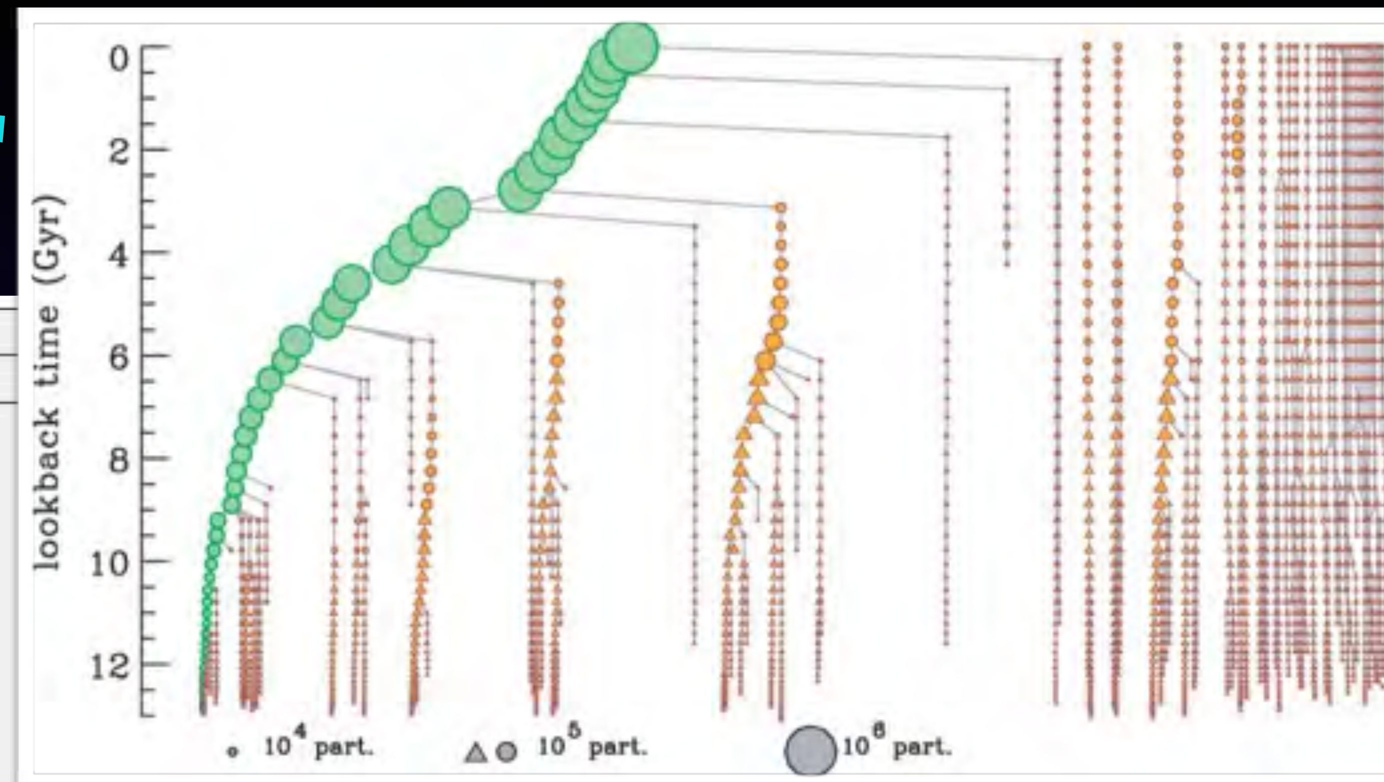


Semi-Analytic Model (SAM)

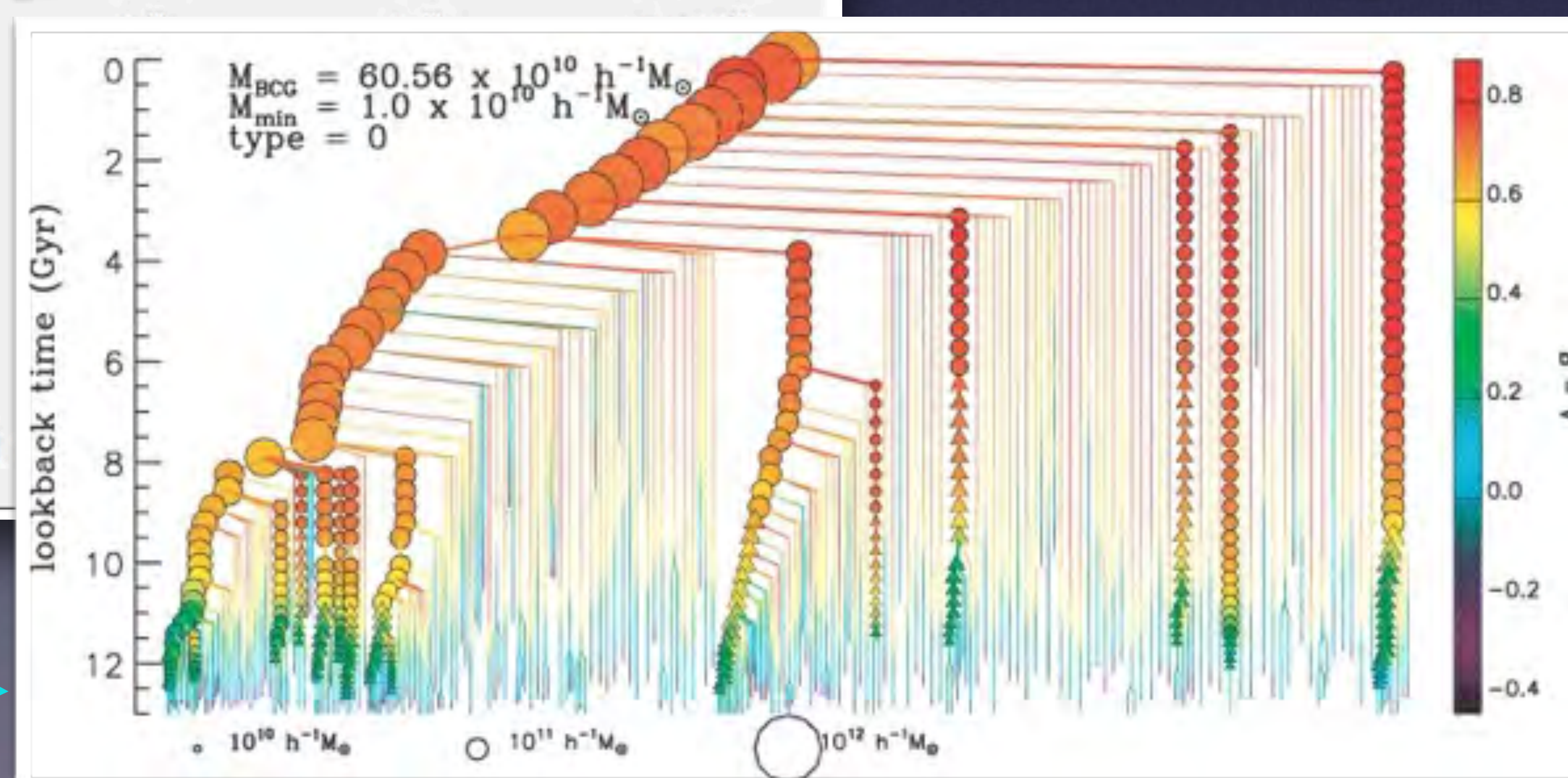
"subgrid physics"

	Model	
	DURHAM[1]	MUNICH[2]
Merger trees		
→ Analytic	Modified ePS[6]	ePS[7]
→ N-body	✓[9]	✓
Halo Profiles	Einasto[10]	Isothermal
Cooling Model		
→ Metal dependent	✓	✓
Star Formation	✓	✓
Feedbacks		
→ SNe	✓	✓
→ AGN	✓[12]	✓
→ Reionization	✓[10]	×
Merging		
→ Substructure[16]	N-body[17]	N-body[17]
→ Substructure–Substructure[19]	✓[20, 10]	×
Environments		
→ Ram pressure stripping	✓[23]	✓[24]
→ Tidal Stripping	✓[10]	×
→ Harassment	×	×
Disks		
→ Disk stability	✓	✓
→ Dynamical friction[27]	✓[28]	×
→ Thickness	✓[28]	×
Sizes		
→ Adiabatic contraction	✓	×
Chemical enrichment	✓[delayed[10]]	✓[instant[29]]
Dust	GRASIL[32]	Screen[33]

Benson (2010)

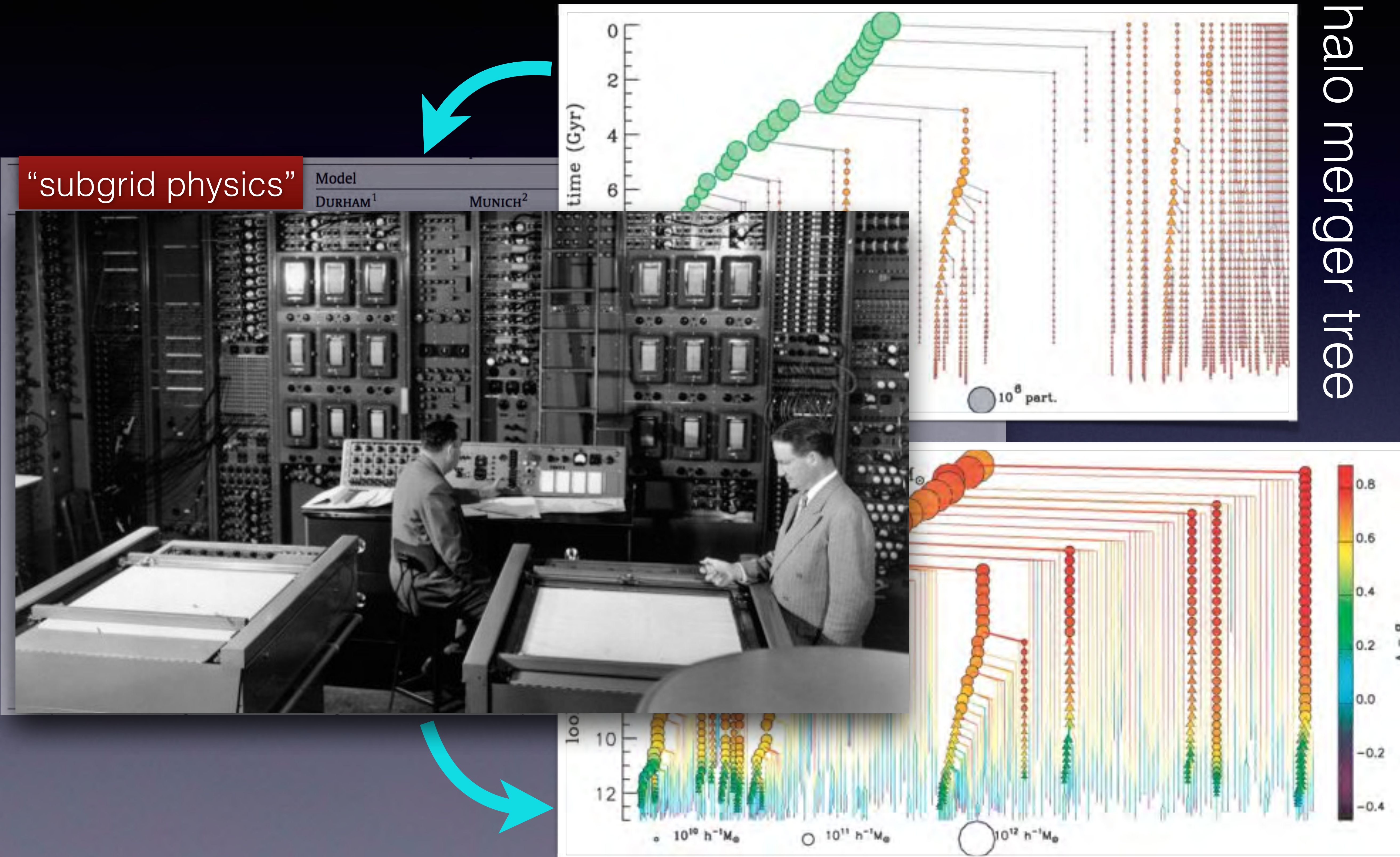


halo merger tree



De Lucia & Blaizot (2007)

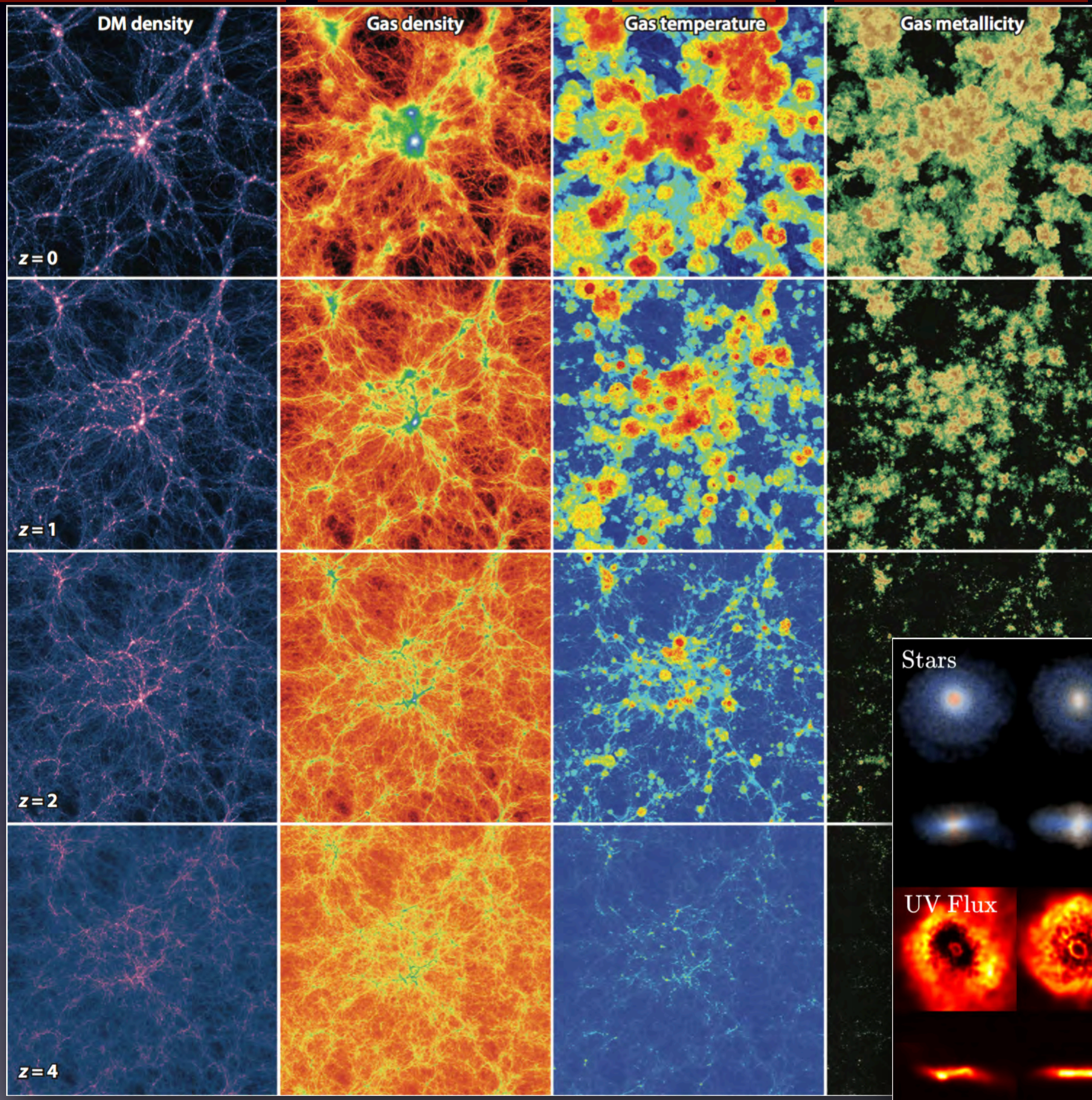
Semi-Analytic Model (SAM)



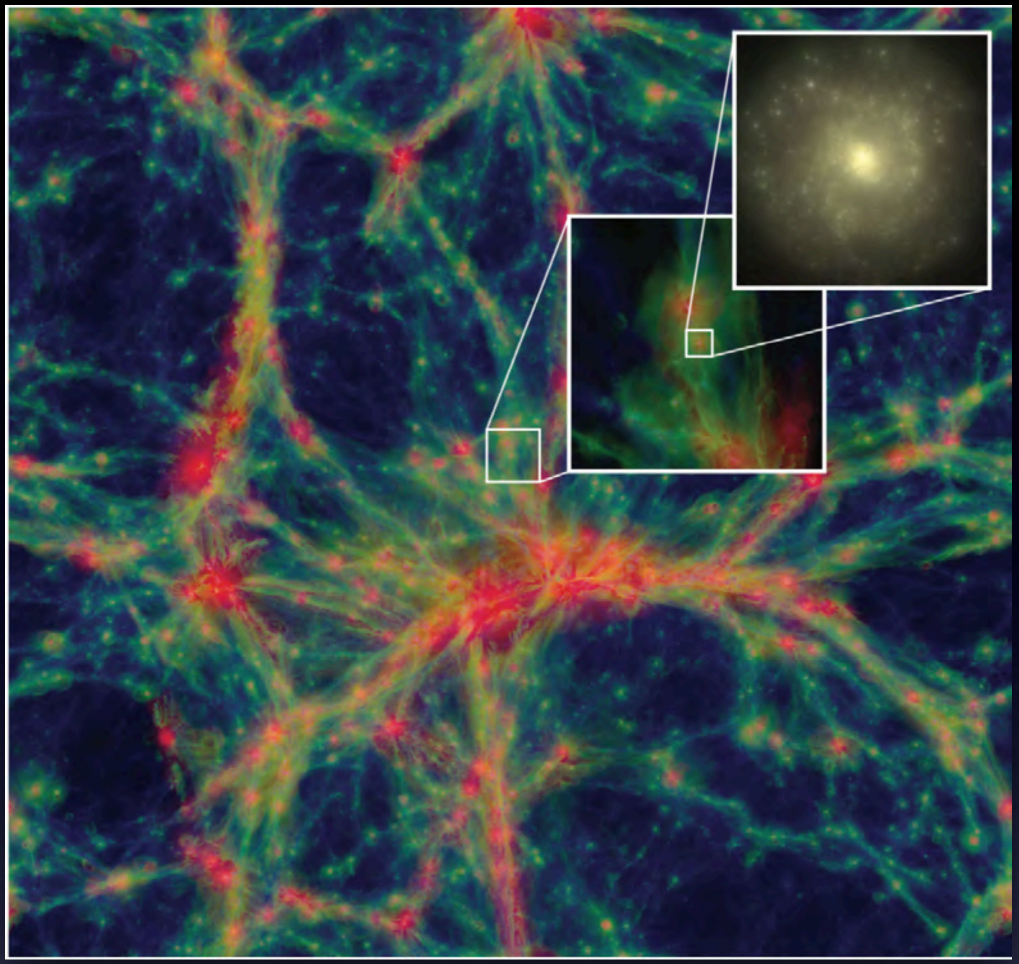
De Lucia & Blaizot (2007)

Hydro-simulations

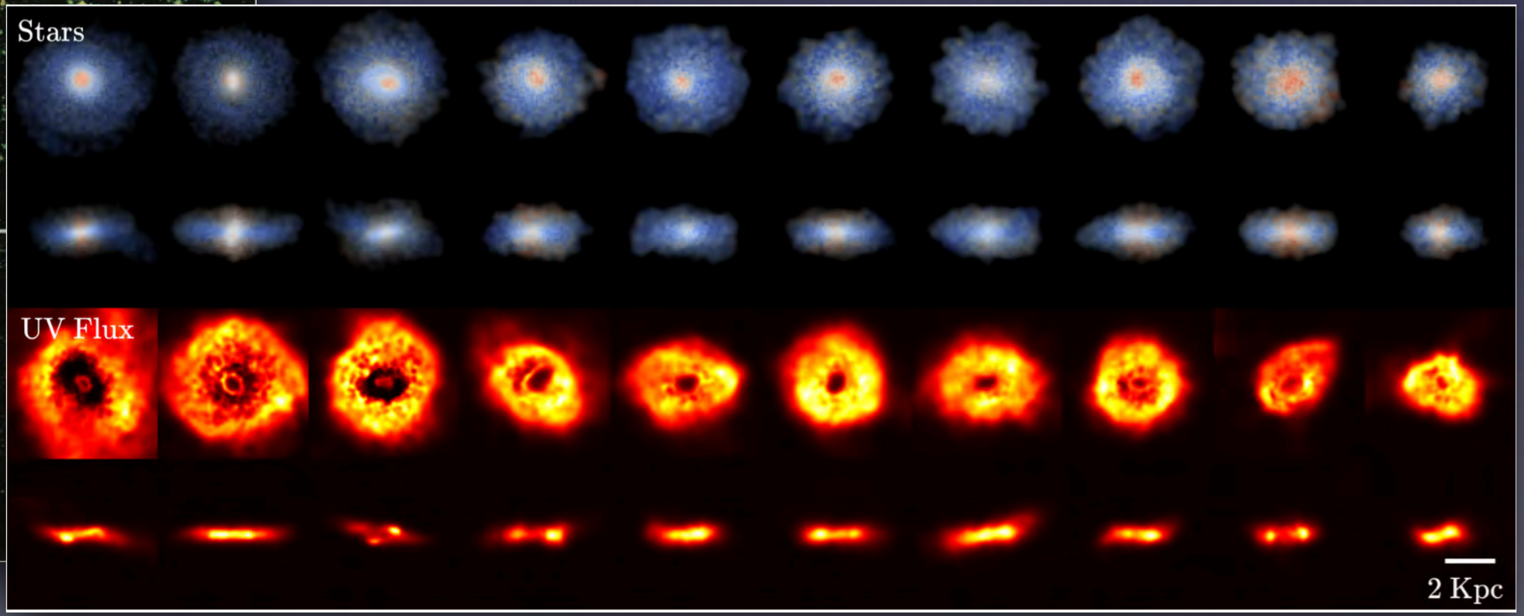
dark matter | rho_gas | T_gas | metallicity



Illustris (Vogelsberger et al. 2014)

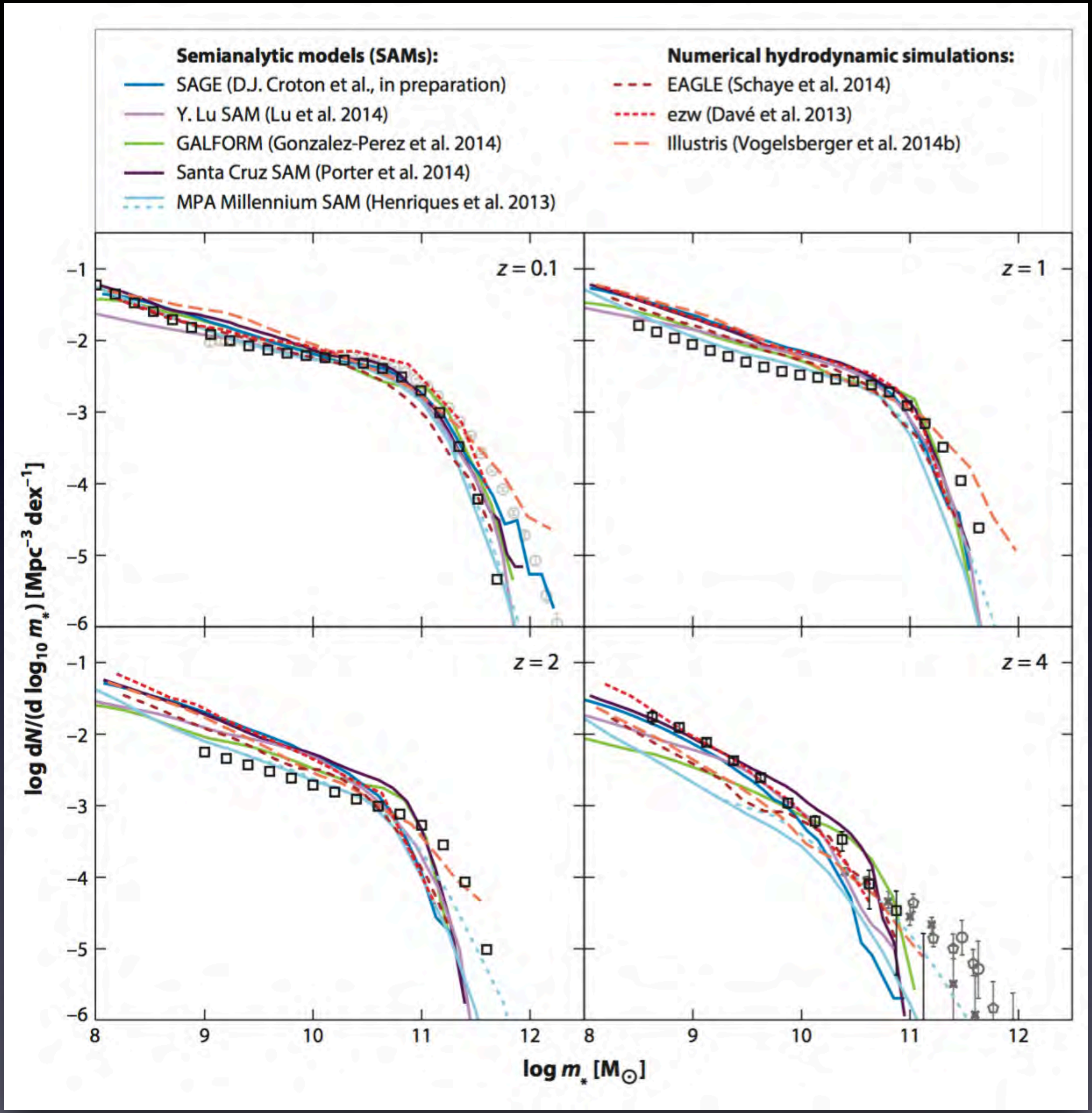


EAGLE (Schaye et al. 2015)

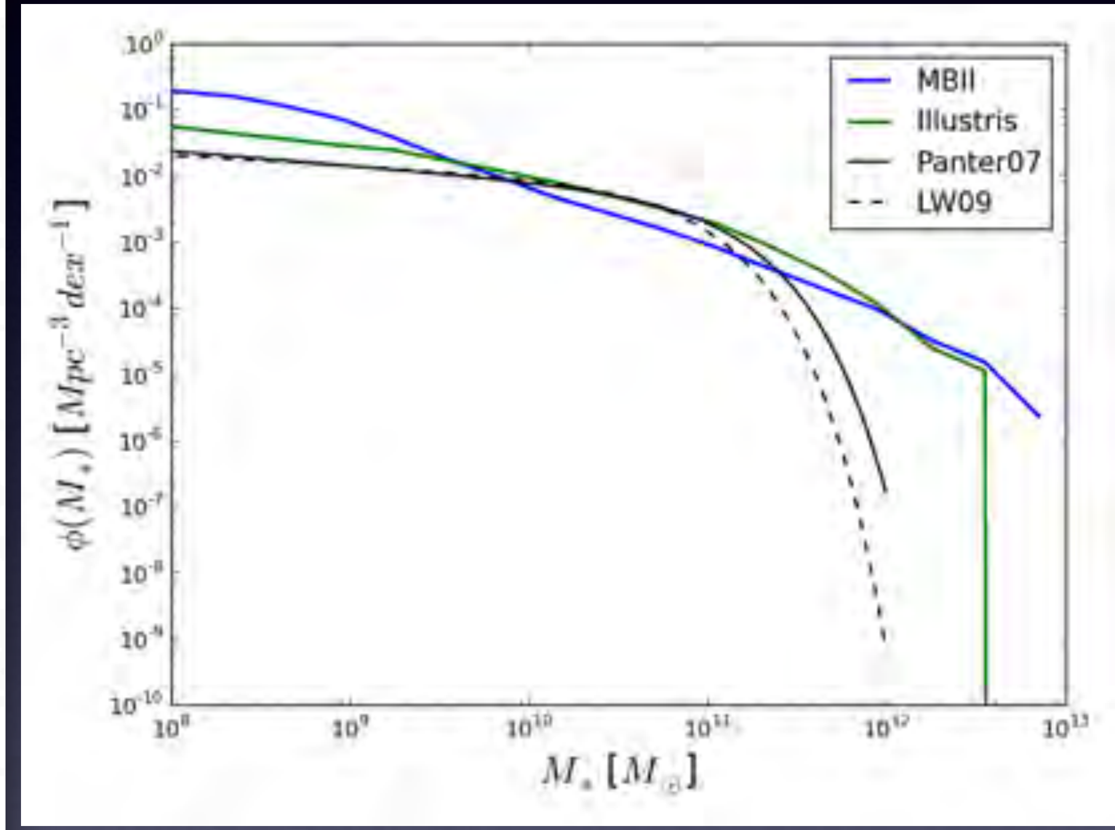


BlueTides (Feng et al. 2015)

galaxy stellar mass functions (SMFs)



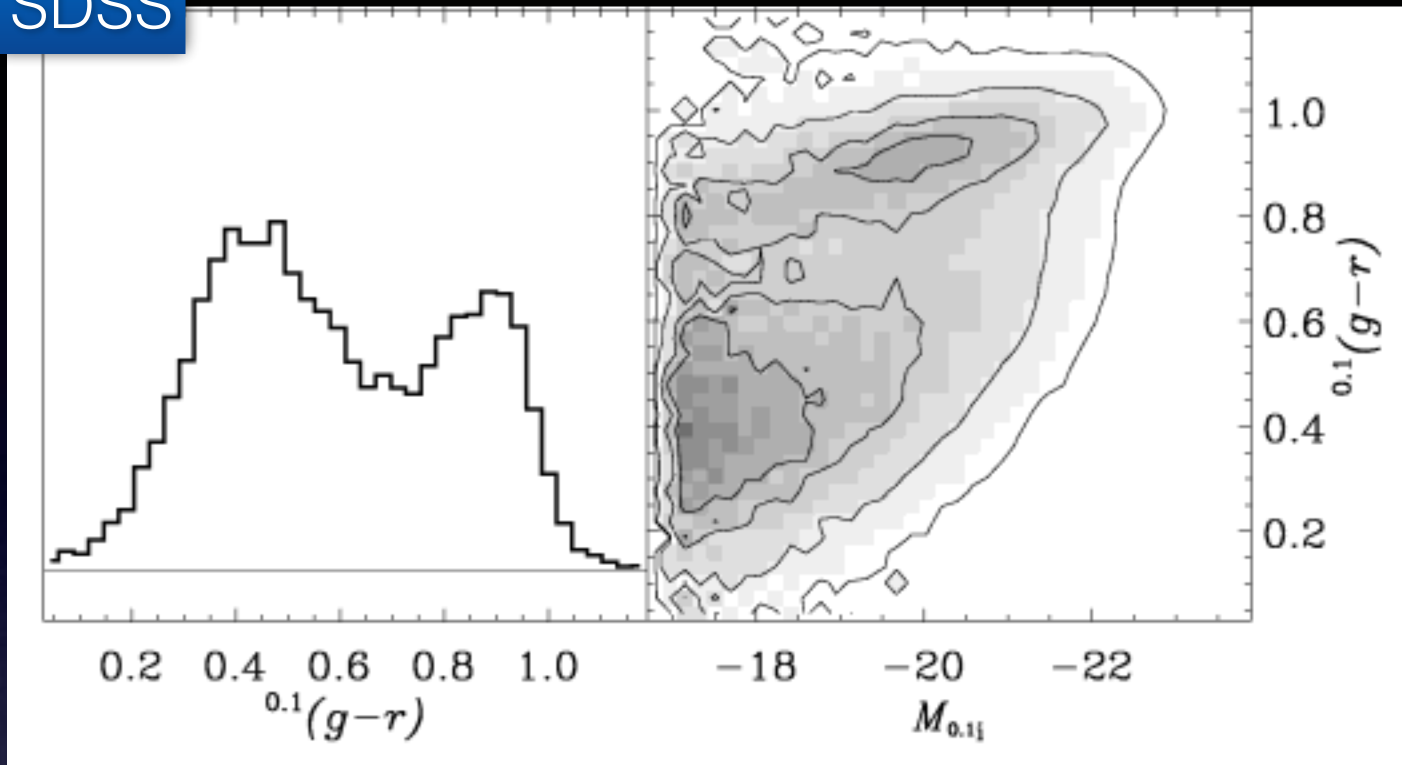
Somerville & Dave (2015)



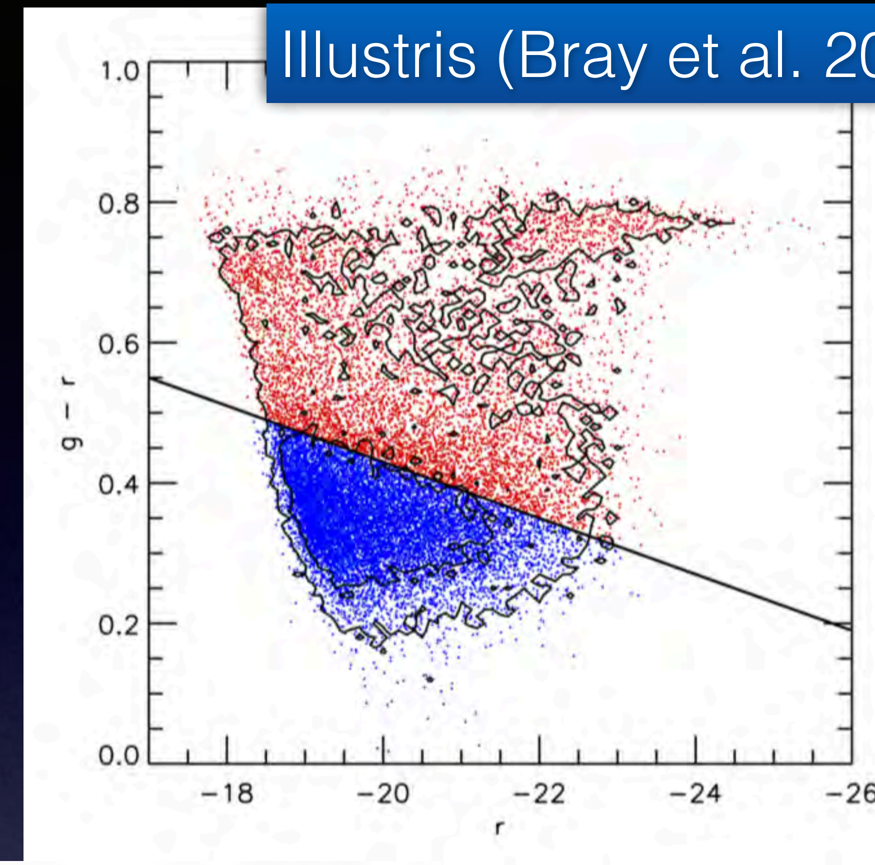
credit: Ananth Tenneti

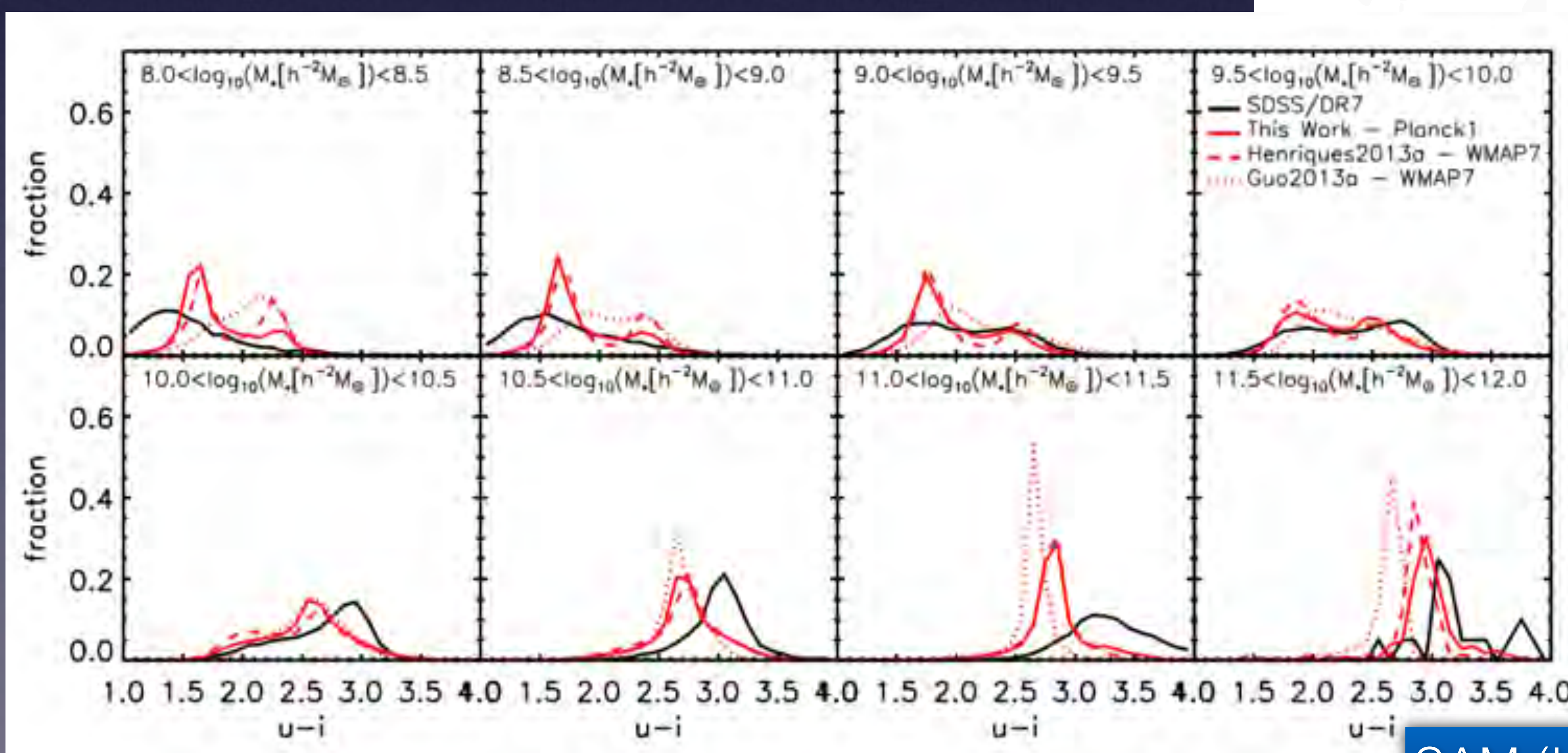
Distributions of galaxy color

SDSS



Illustris (Bray et al. 2015)

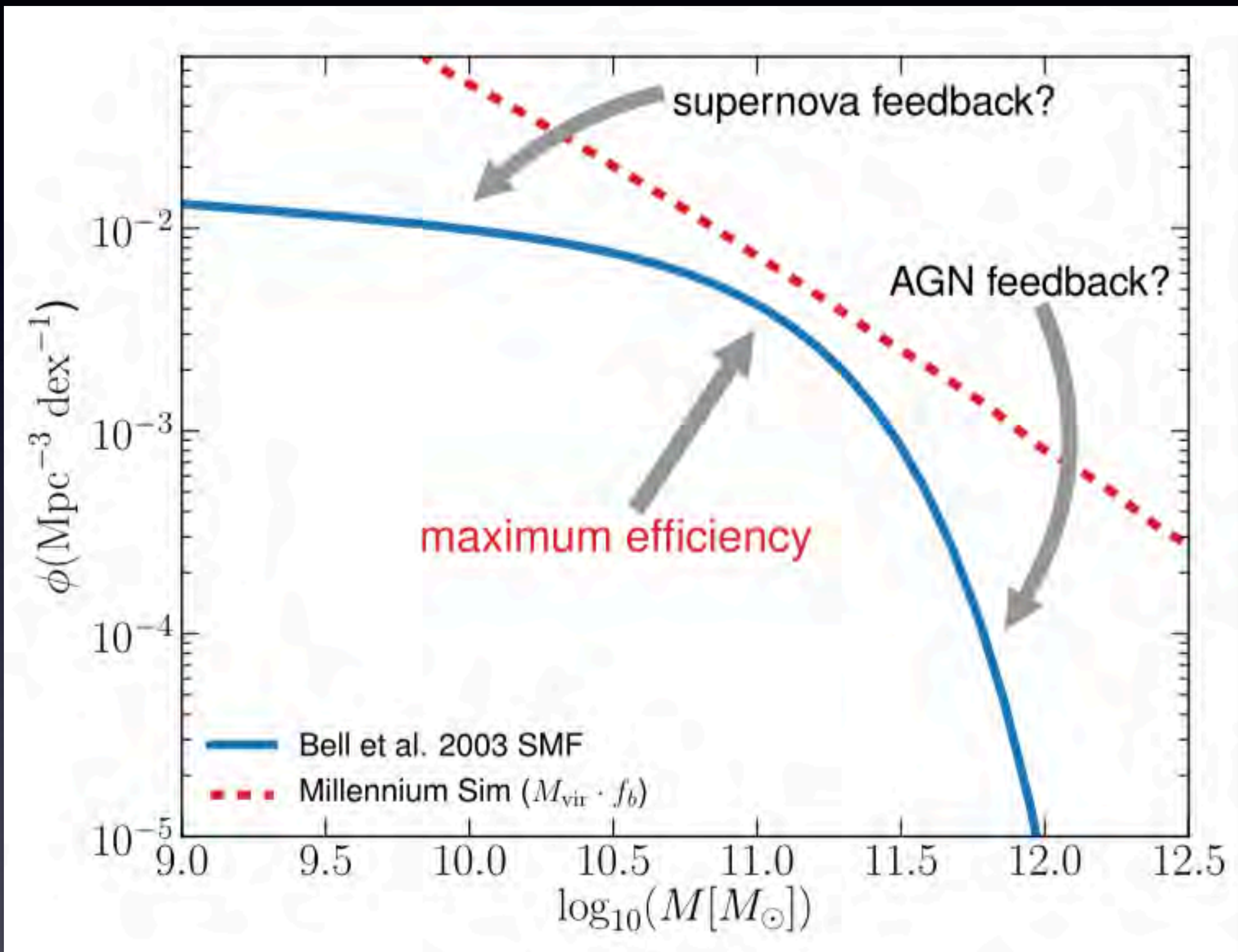




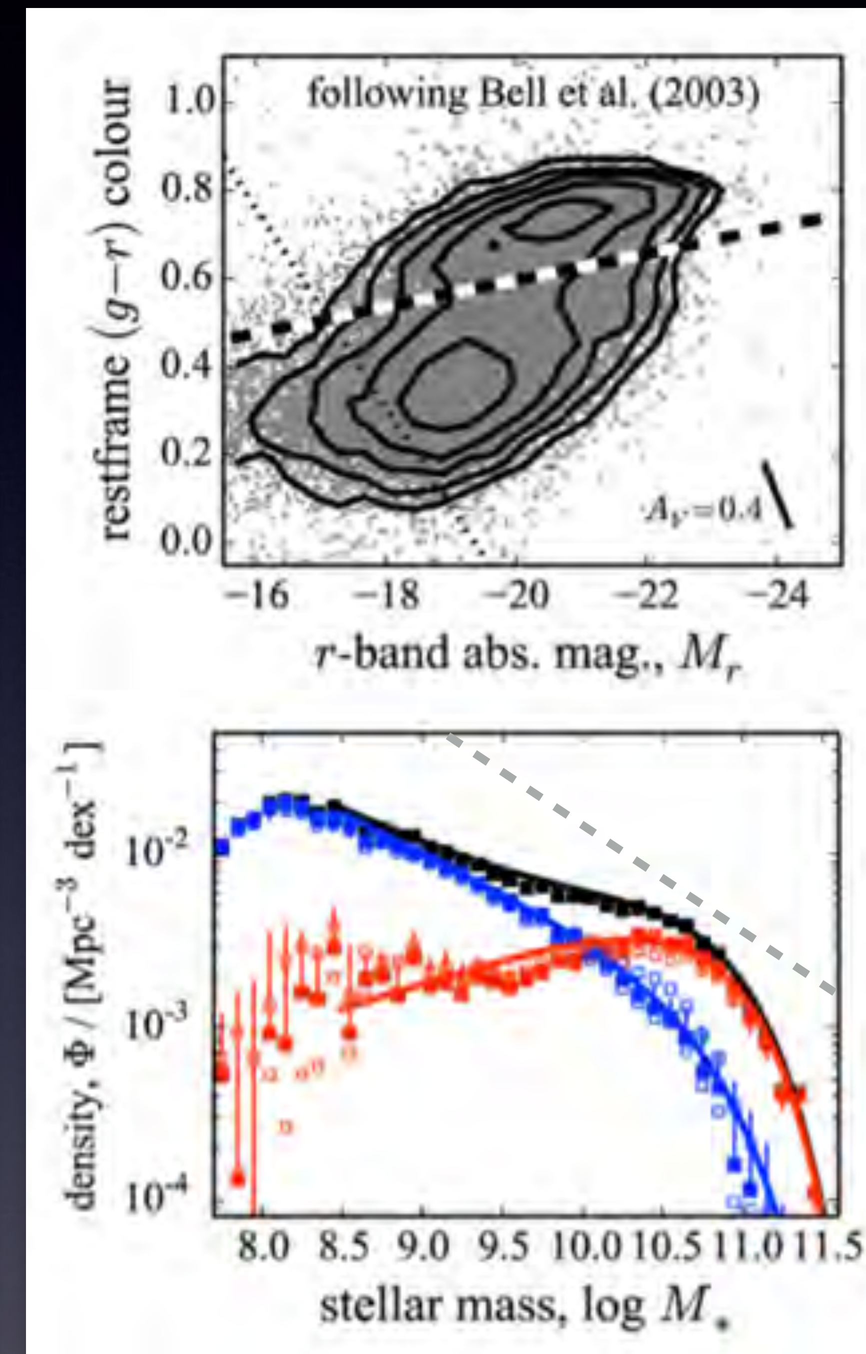
SAM (Henriques et al. 2015)

~~“Theory of Galaxy Formation”~~

“Theory of galaxy stellar mass & color”



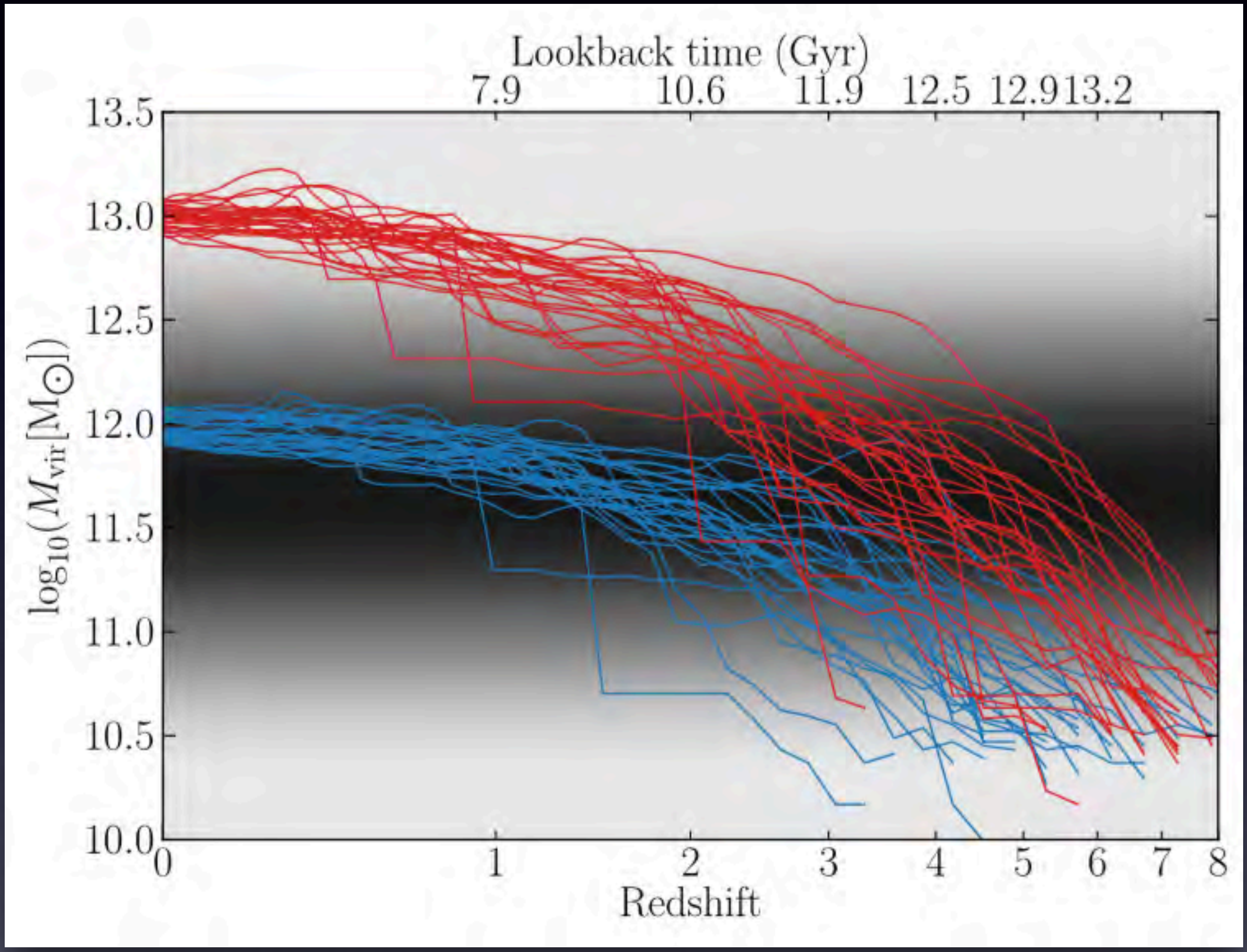
Mutch et al. (2013)



Taylor et al. (2015)

Switching from **predictive** to **probabilistic** models

Alternatively we can constrain $P(\mathbf{g}|\mathbf{h})$, i.e., the probability distribution of galaxies with properties $\mathbf{g}$ within halos with fixed properties $\mathbf{h}$.



Mutch et al. (2013)

Switching from **predictive** to **probabilistic** models

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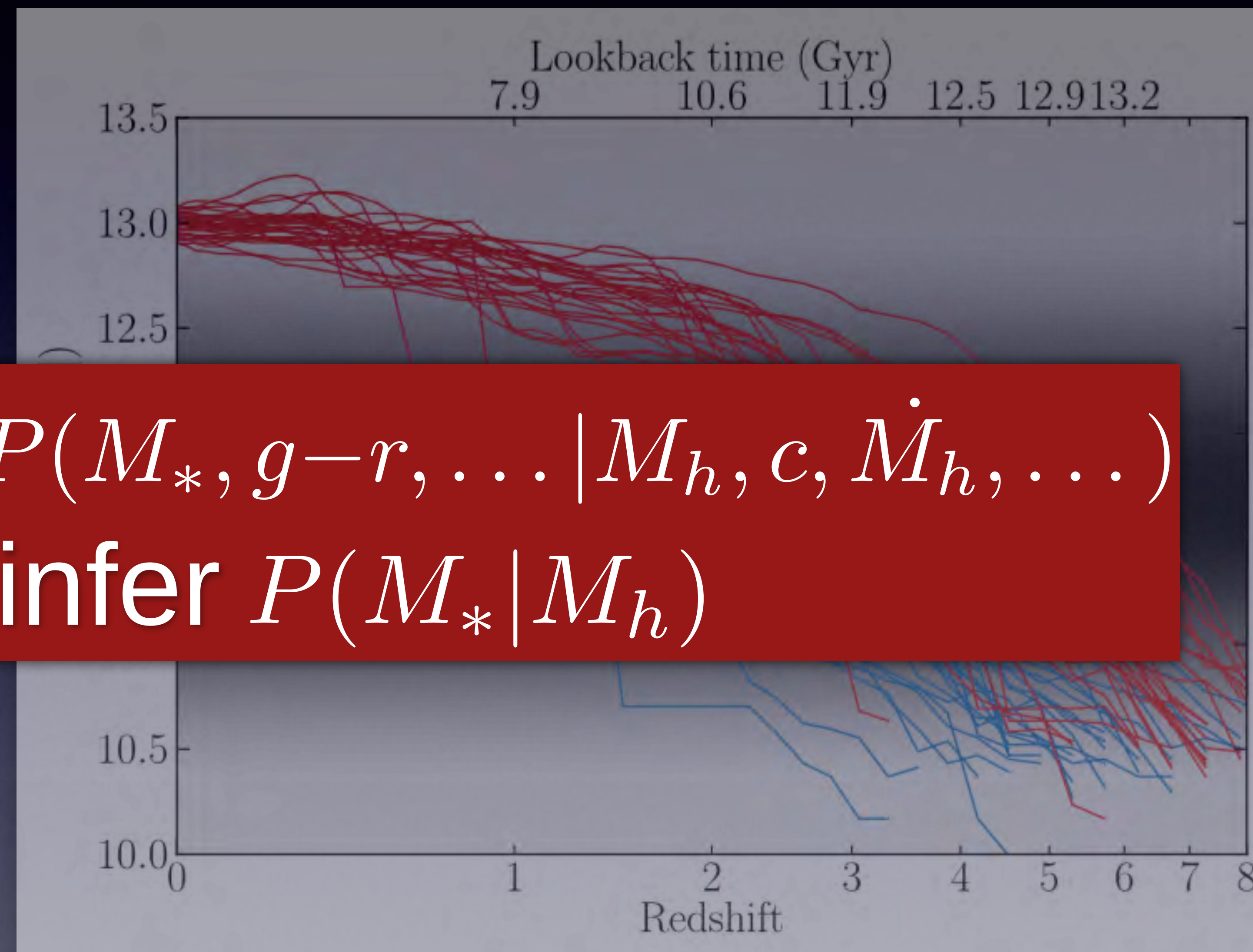


Our goal is to find $P(M_*, g{-}r, \ldots | M_h, c, \dot{M}_h, \ldots)$

The first step is to infer $P(M_* | M_h)$

Mutch et al. (2013)

Large-scale structure probes

- spatial clustering $w_p(r_p) = \int_{-r_{\pi,\max}}^{+r_{\pi,\max}} \xi_{gg}(r_p, r_\pi)\, \mathrm{d}r_\pi$ $\propto \xi_{gg}$
- galaxy-galaxy lensing $\Delta\Sigma(r_p) = \gamma_t(r_p)\Sigma_{\mathrm{crit}}$ $\propto \xi_{gm}$
- marked correlation $M_p = \frac{1 + W_p(r_p)/r_p}{1 + w_p(r_p)/r_p}$

(sensitive to environ. effects)

For a **volume-limited** galaxy sample thresholded in M_*

Halo Occupation Distribution (HOD)

defines $\langle N(M_h) \rangle$ as the number of galaxies as a function of halo mass. Centrals and satellites are modeled separately

$$M_h \rightarrow M_*^{\rm cen}$$

$$M_h \rightarrow \langle N_{\rm sat} \rangle$$

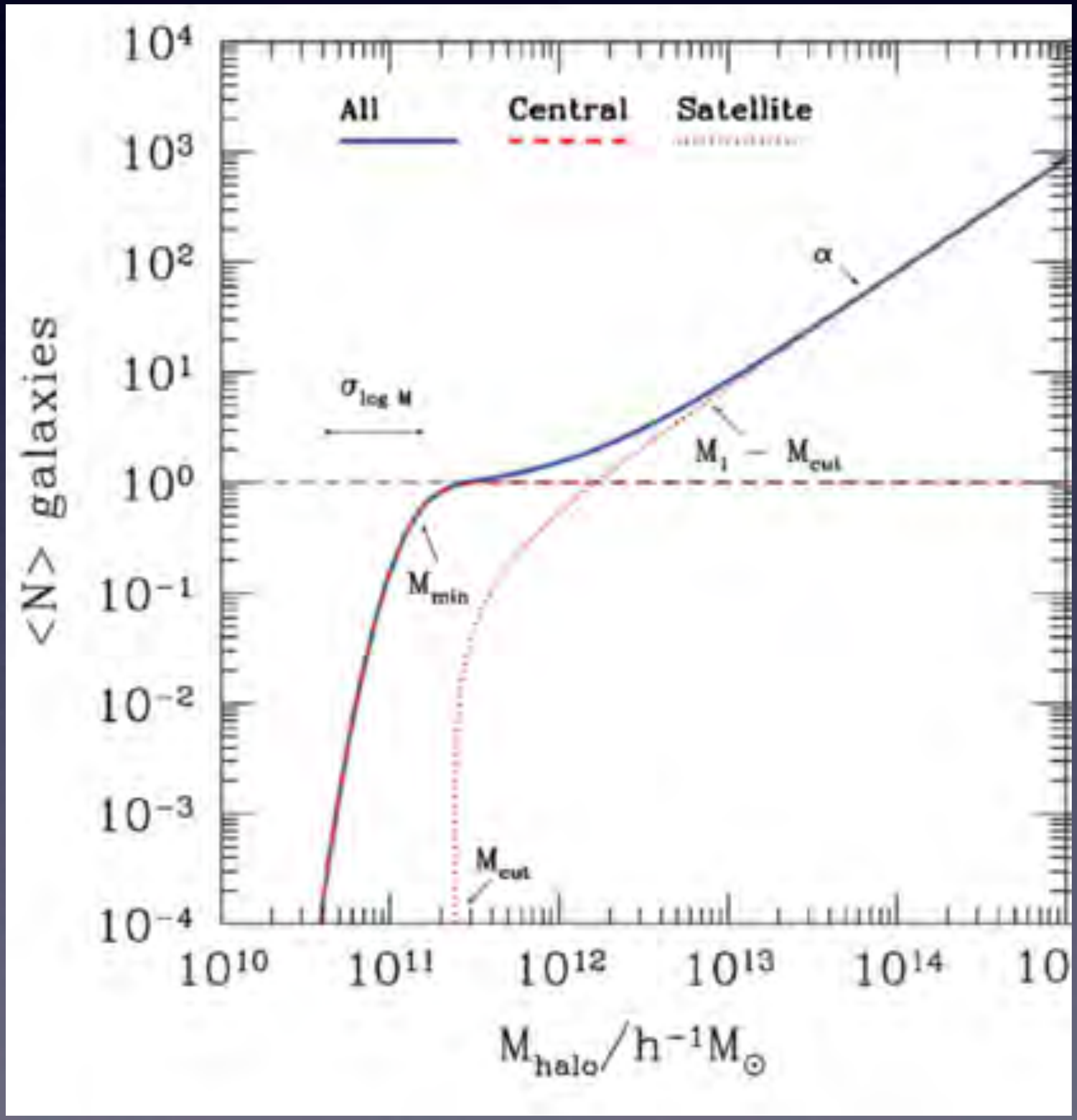
Subhalo Abundance Matching (SHAM)

matches stellar masses to (sub)halos based on their ranking order in some halo mass proxy, e.g., the peak circular velocity:

$$V_{\rm peak} \rightarrow M_*$$

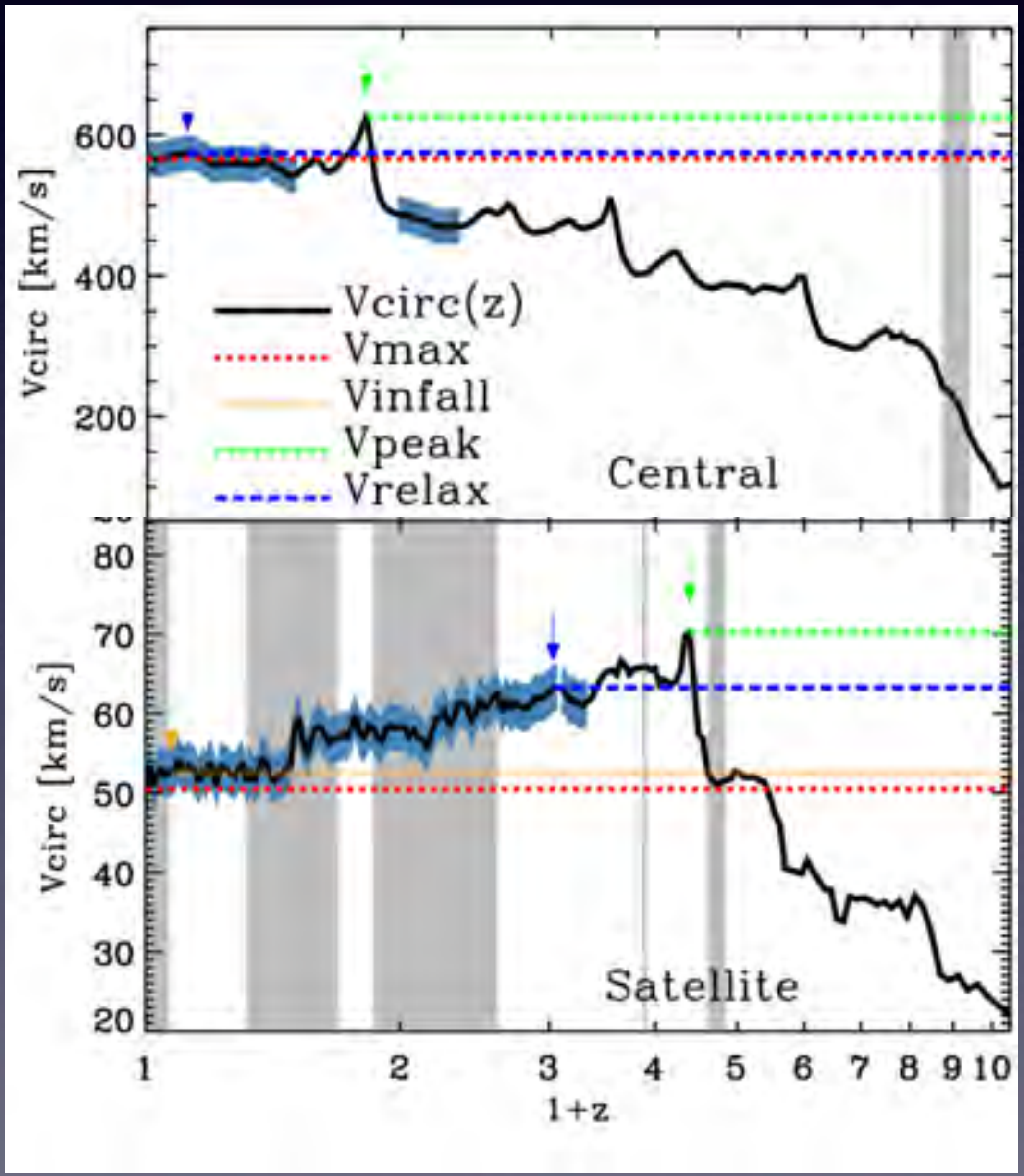
For a **volume-limited** galaxy sample thresholded in M_*

Halo Occupation Distribution (HOD)



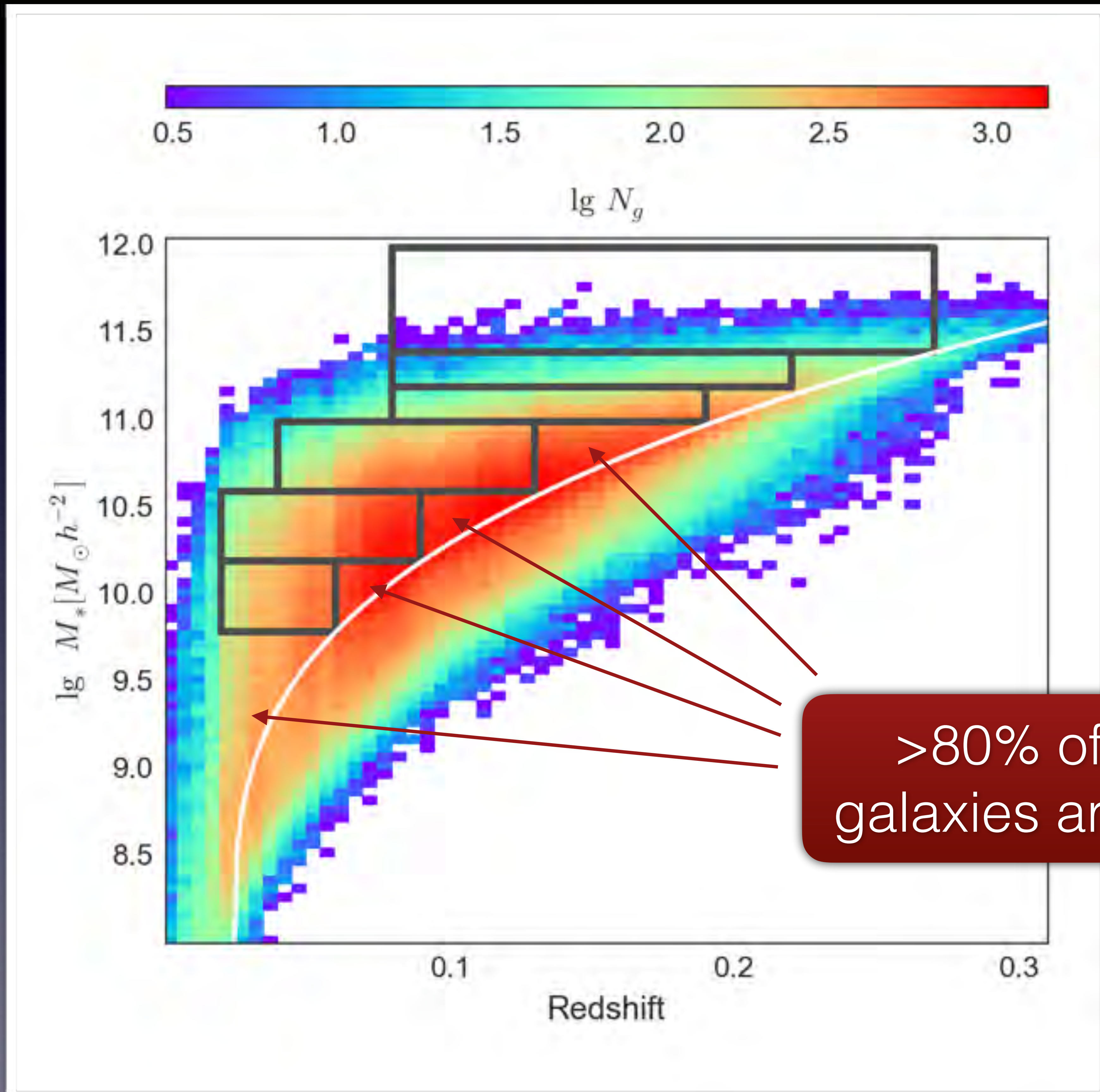
Zheng et al (2005); Contreras et al. (2013)

Subhalo Abundance Matching (SHAM)



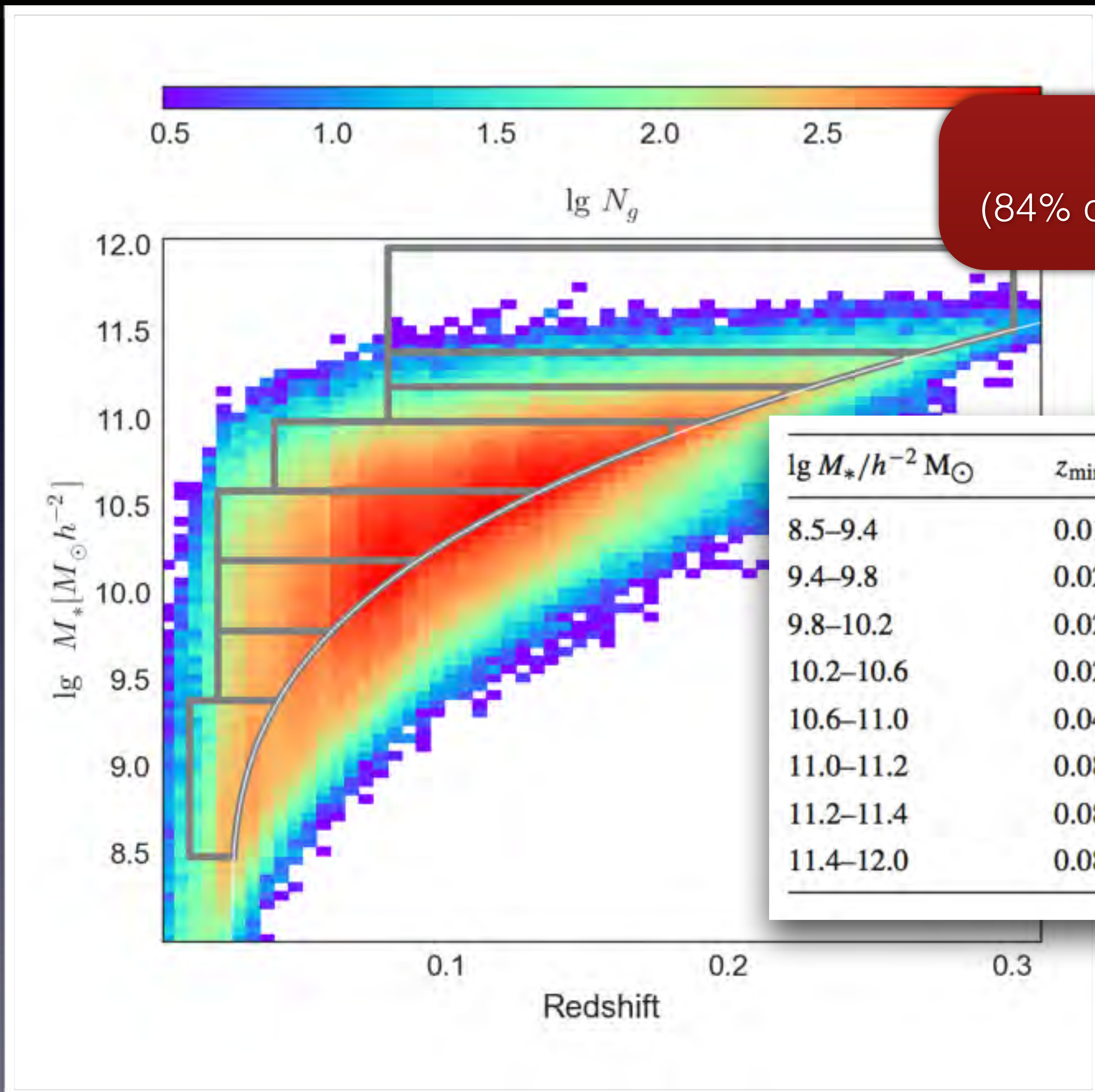
Reddick et al (2013); Lehmann et al.(2015)

volume-limited galaxy samples selected in SDSS DR7



>80% of usable galaxies are wasted!

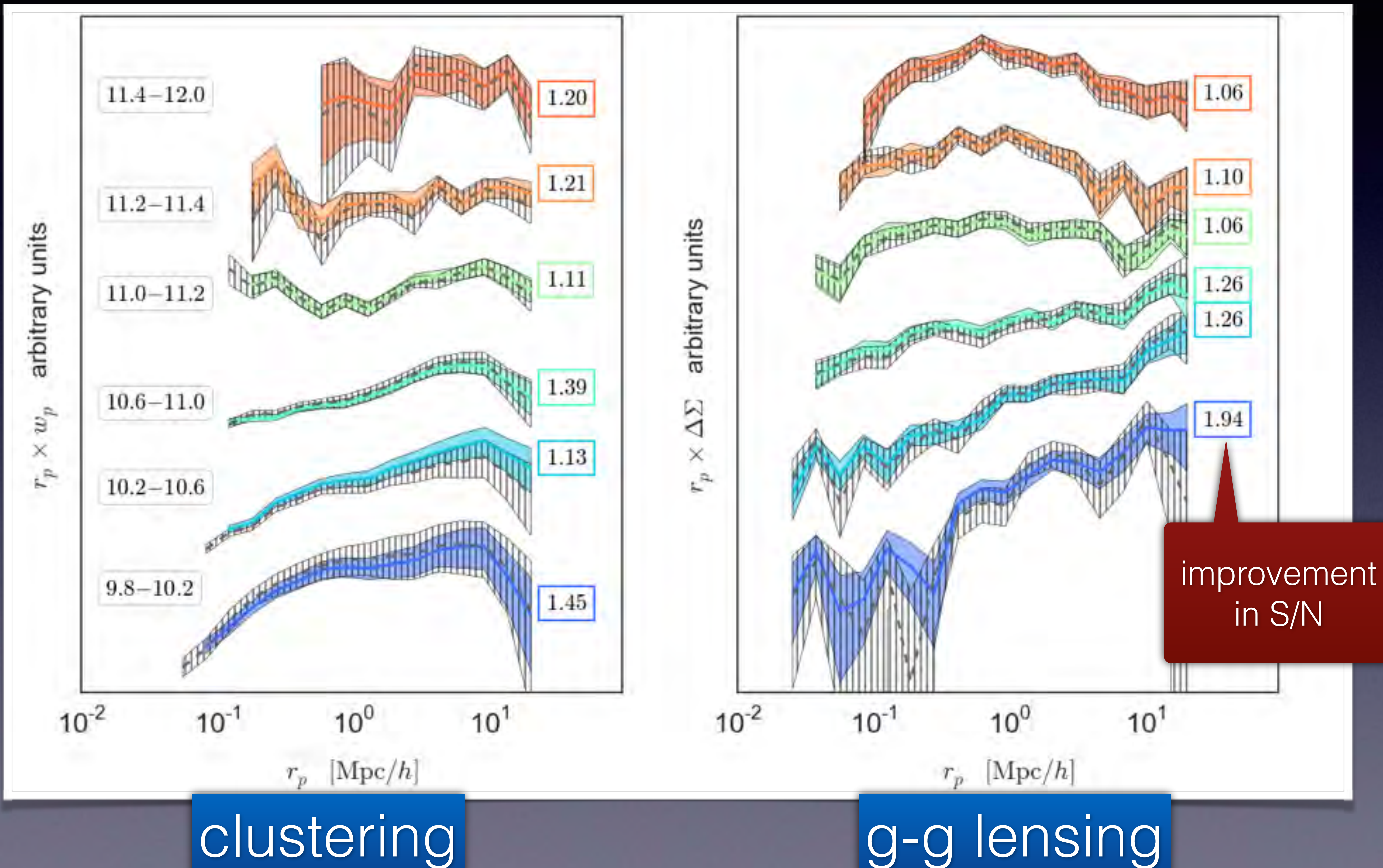
galaxy spectra are expensive!



314,302 vs 170,483
(84% or 143,819 more galaxies!)

lg $M_*/h^{-2}\,\mathrm{M}_\odot$	z_{min}	z_{max}	N_{g}
8.5–9.4	0.01	0.04	13 616
9.4–9.8	0.02	0.06	16 247
9.8–10.2	0.02	0.09 (0.06)	46 910 (22 409)
10.2–10.6	0.02	0.13 (0.09)	96 946 (58 209)
10.6–11.0	0.04	0.18 (0.13)	102 307 (60 283)
11.0–11.2	0.08	0.22 (0.19)	24 908 (19 506)
11.2–11.4	0.08	0.26 (0.22)	10 231 (7427)
11.4–12.0	0.08	0.30 (0.27)	3137 (2649)

more galaxies buy us improved S/N

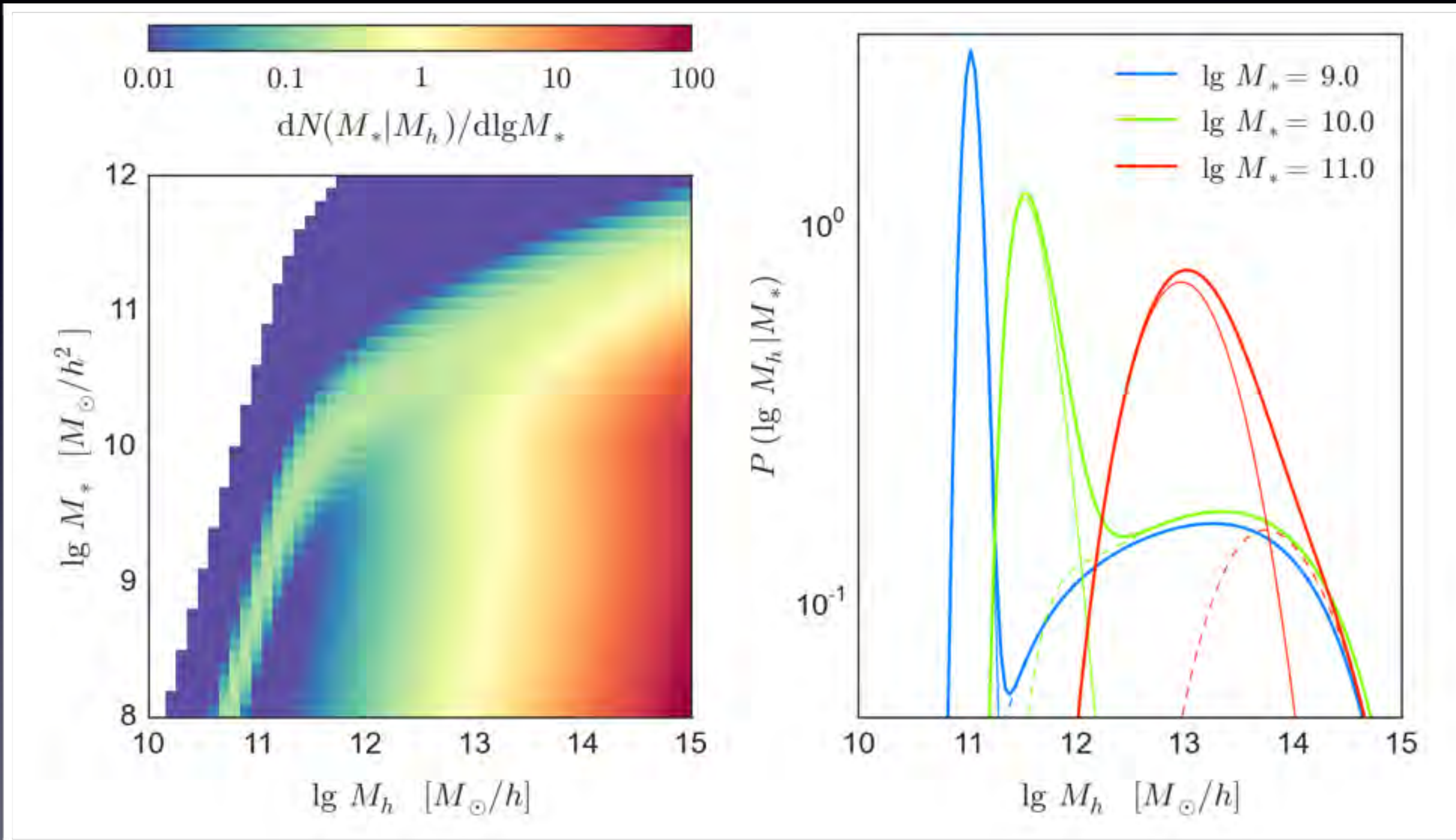


i HOD

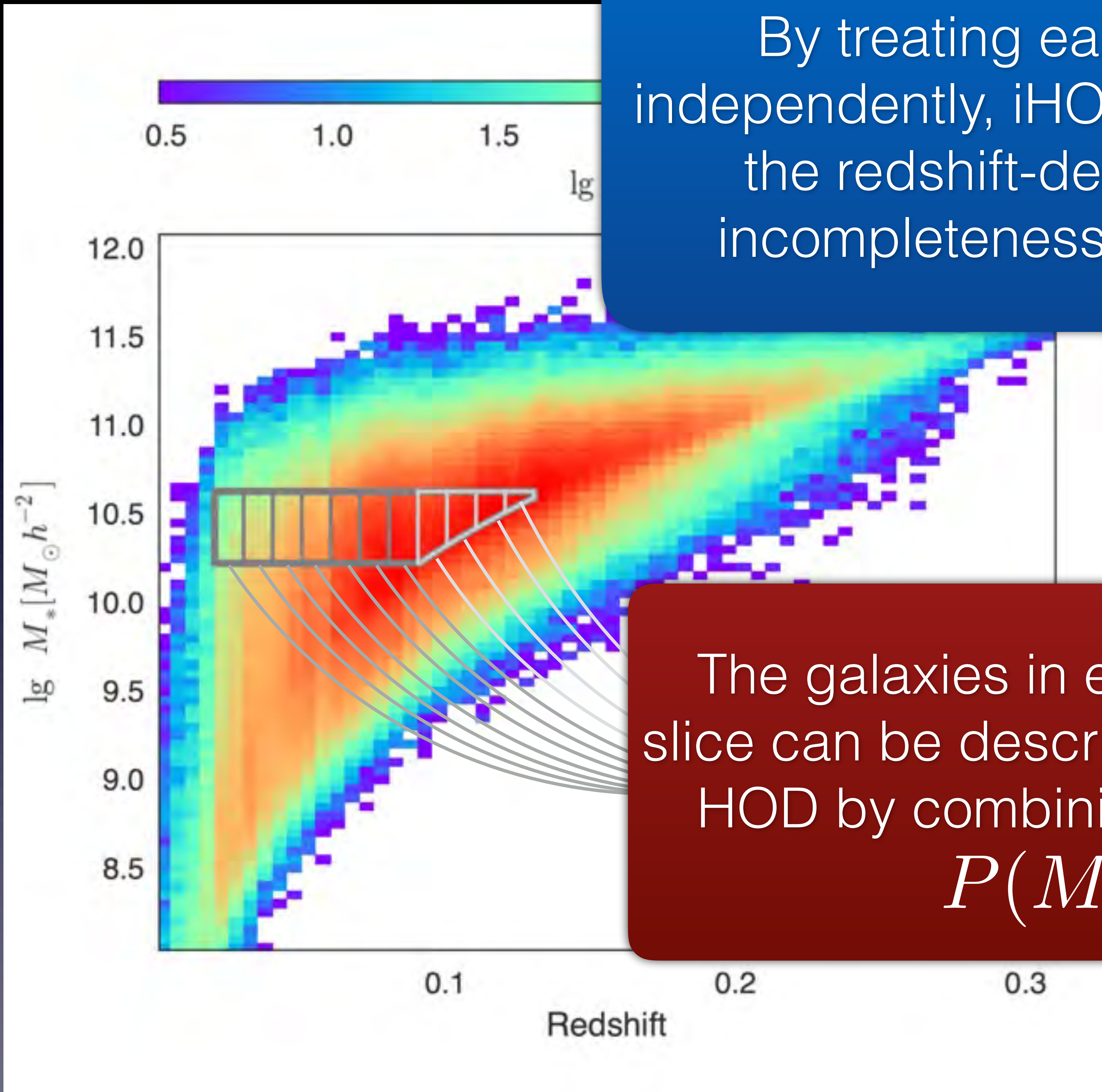
- $P(M_*, M_h)$ defined on the 2D grid of stellar mass and halo mass.
- Central galaxies are described by a mean stellar-to-halo mass relation with a mass-dependent log-scatter.
- Satellite galaxies are described by a halo mass-dependent satellite HOD.
- Derive $P(M_h|M_*)$, i.e., HOD for a single galaxies.

$$P(M_h \mid M_*, z) = \frac{P(M_*, M_h \mid z)}{P(M_* \mid z)} = \frac{P(M_*, M_h \mid z)}{\int P(M_*, M_h \mid z)\, \mathrm{d}M_h}$$

iHOD on the $M_* - M_h$ plane $\qquad P(M_h|M_*)$



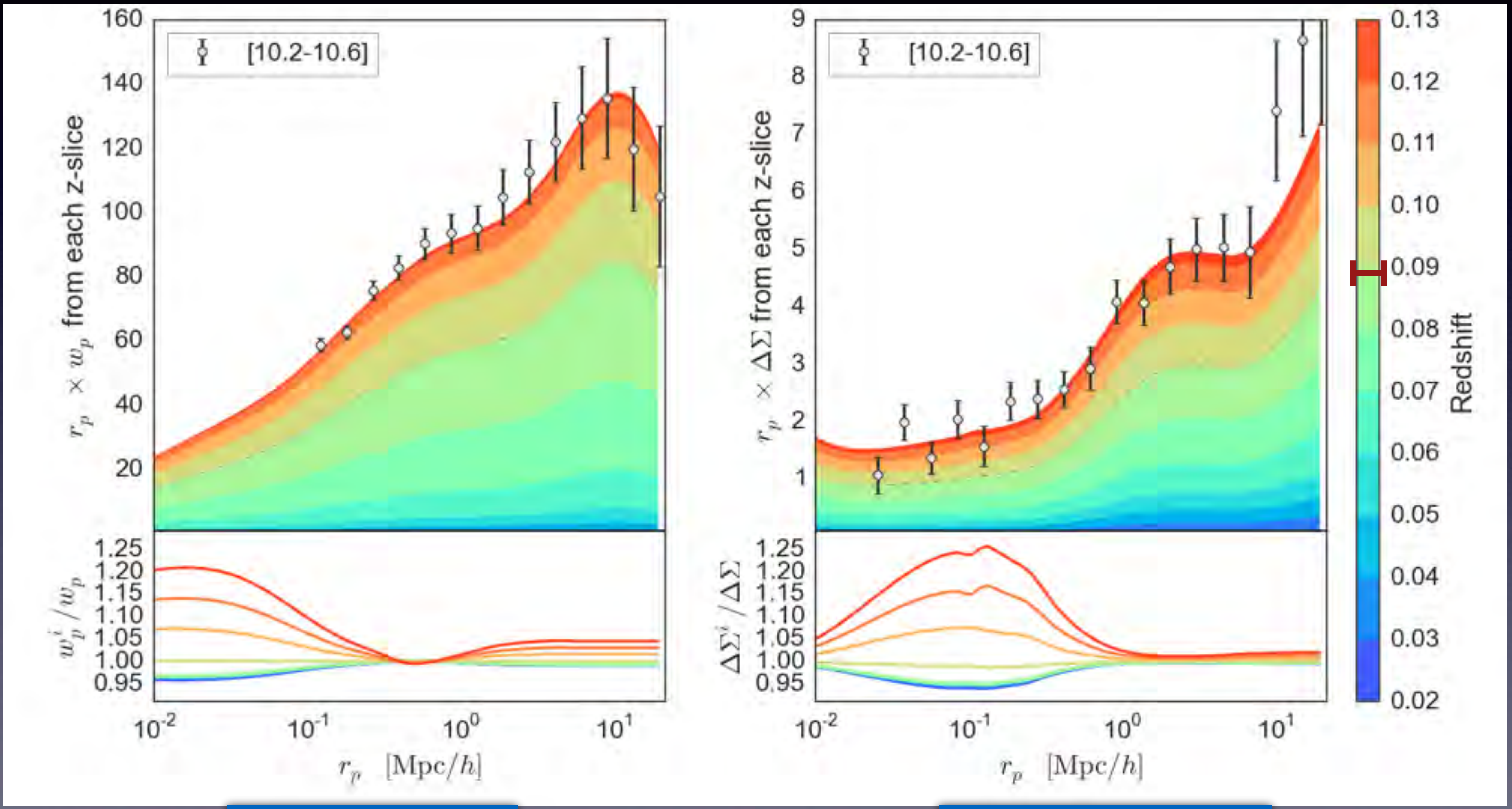
By treating each redshift slice independently, iHOD takes into account the redshift-dependent sample incompleteness self-consistently.



The galaxies in each narrow redshift slice can be described using a standard HOD by combining all the individual

$$P(M_h|M_*)$$

Signal Contributions from different redshift slices



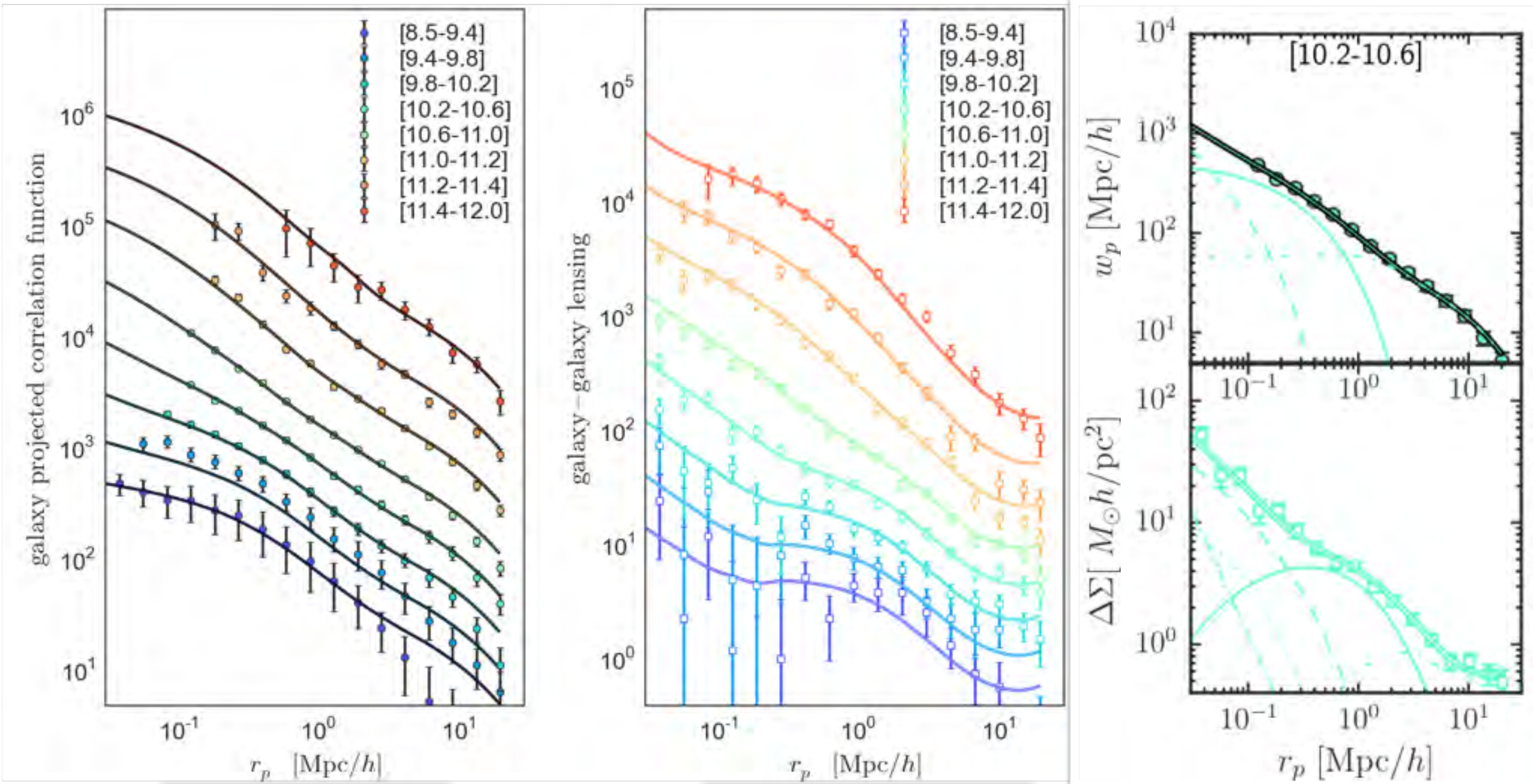
clustering

g-g lensing

parameter constraints

Parameter	Description	Uniform prior range	iHOD	cHOD
$\lg M_{\mathrm{h}}^{1}$	Characteristic halo mass of the SHMR	[9.5, 14.0]	$12.10^{+0.17}_{-0.14}$	$12.32^{+0.29}_{-0.29}$
$\lg M_{*}^{0}$	Characteristic stellar mass of the SHMR	[9.0, 13.0]	$10.31^{+0.10}_{-0.09}$	$10.47^{+0.18}_{-0.21}$
β	Low-mass slope of the SHMR	[0.0, 2.0]	$0.33^{+0.21}_{-0.15}$	$0.54^{+0.29}_{-0.26}$
δ	Controls high-mass slope of the SHMR	[0.0, 1.5]	$0.42^{+0.03}_{-0.04}$	$0.42^{+0.08}_{-0.09}$
γ	Controls intermediate-mass behaviour of the SHMR	[−0.1, 4.9]	$1.21^{+0.18}_{-0.20}$	$1.05^{+0.24}_{-0.26}$
B_{sat}	Normalizes the scaling of M_{sat}	[0.01, 25.0]	$8.98^{+1.18}_{-0.87}$	$11.22^{+2.61}_{-1.99}$
β_{sat}	Slope of the scaling of M_{sat}	[0.1, 1.8]	$0.90^{+0.04}_{-0.05}$	$0.85^{+0.06}_{-0.05}$
B_{cut}	Normalizes the scaling of M_{cut}	[0.0, 6.0]	$0.86^{+0.32}_{-0.37}$	$0.73^{+0.58}_{-0.44}$
β_{cut}	Slope of the scaling of M_{cut}	[−0.05, 1.50]	$0.41^{+0.16}_{-0.15}$	$0.63^{+0.31}_{-0.33}$
α_{sat}	Power-law slope of the satellite HOD	[0.5, 1.5]	$1.00^{+0.03}_{-0.02}$	$1.07^{+0.05}_{-0.05}$
$\sigma_{\ln M_*}$	Low-mass scatter in the SHMR	[0.01, 3.0]	$0.50^{+0.04}_{-0.03}$	$0.42^{+0.07}_{-0.08}$
η	Slope of the scaling of high-mass scatter	[−0.4, 0.4]	$-0.04^{+0.02}_{-0.02}$	$-0.01^{+0.04}_{-0.03}$
f_{c}	Concentration ratio between satellites and dark matter	[0.1, 3.0]	$0.86^{+0.14}_{-0.11}$	$1.06^{+0.32}_{-0.20}$

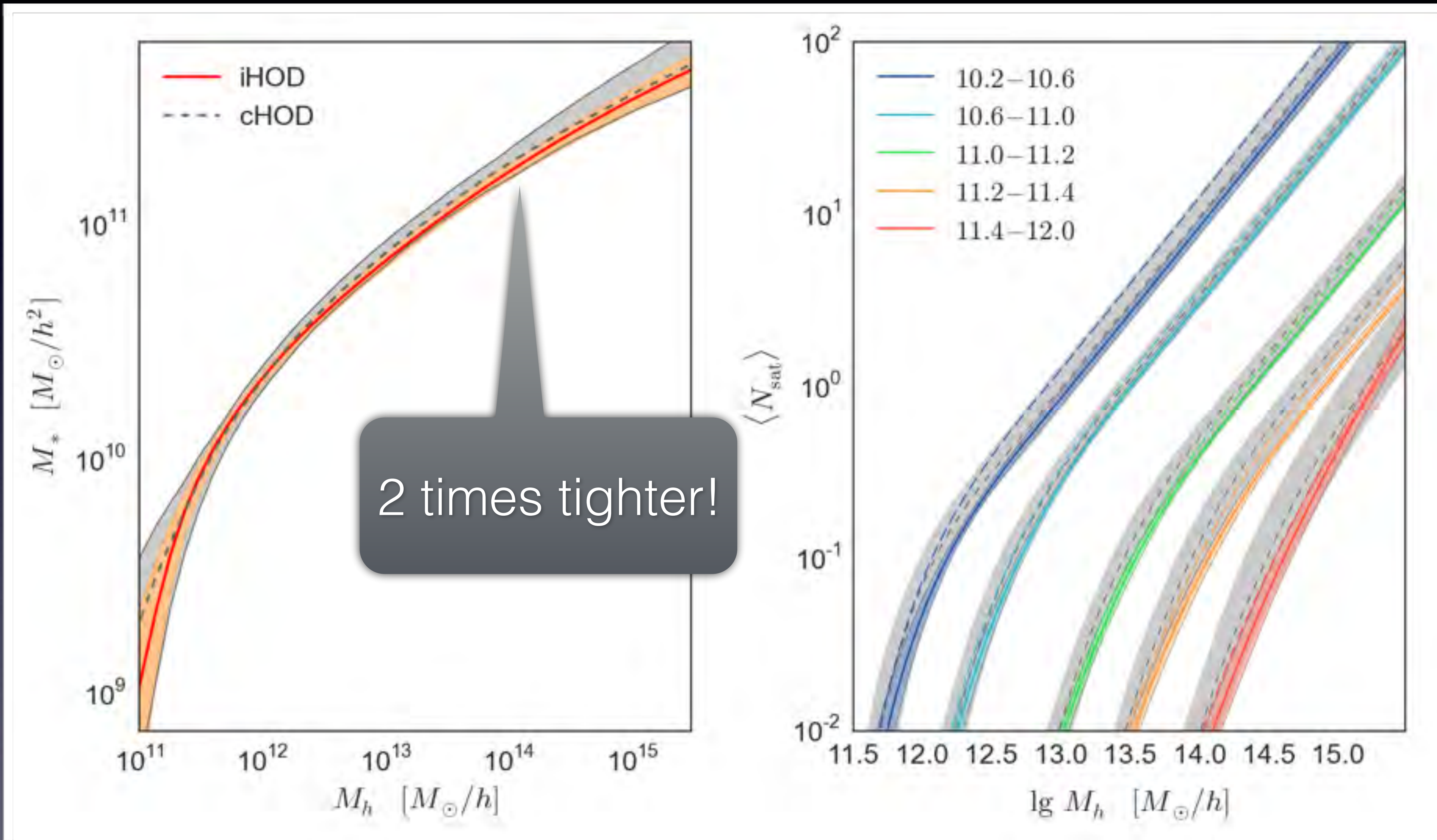
Best-fit model predictions vs. measurements



clustering

g-g lensing

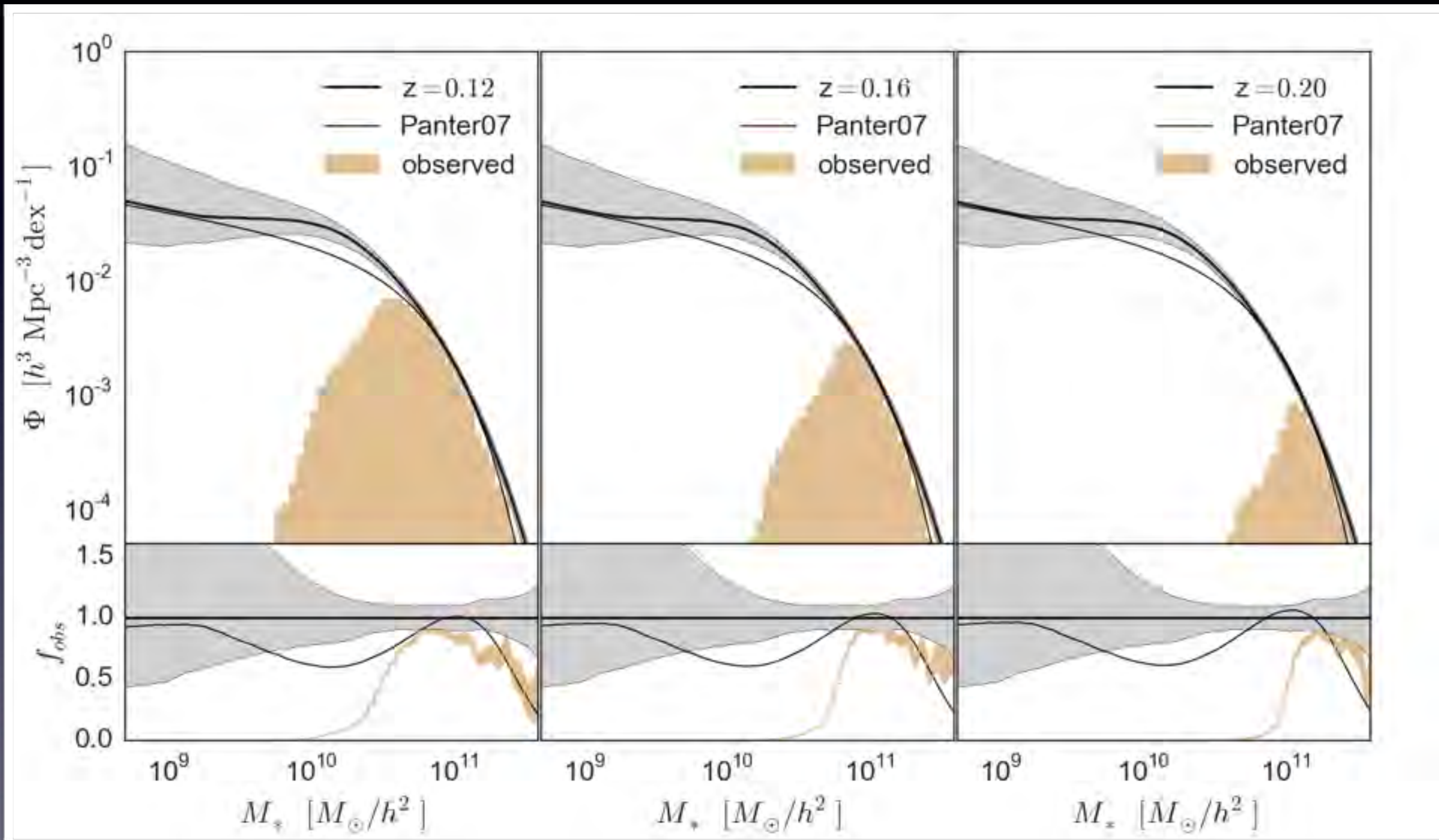
iHOD vs. traditional HOD constraints



Stellar-to-Halo Mass (centrals)

Satellite HODs of five samples

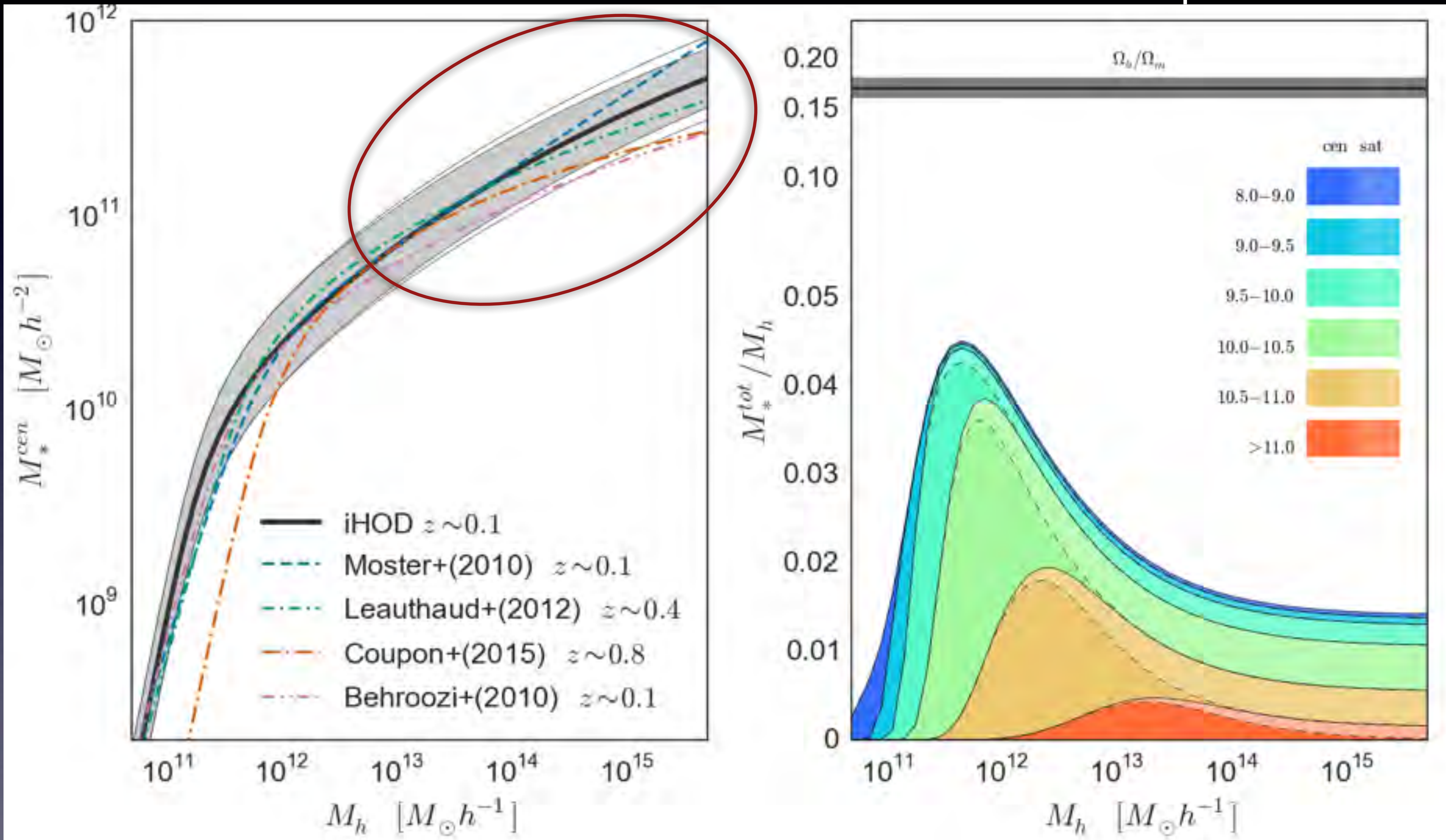
Observed Stellar Mass Functions are reproduced!



Note that SMFs are not used as input to the constraint.

Compare with SHAM

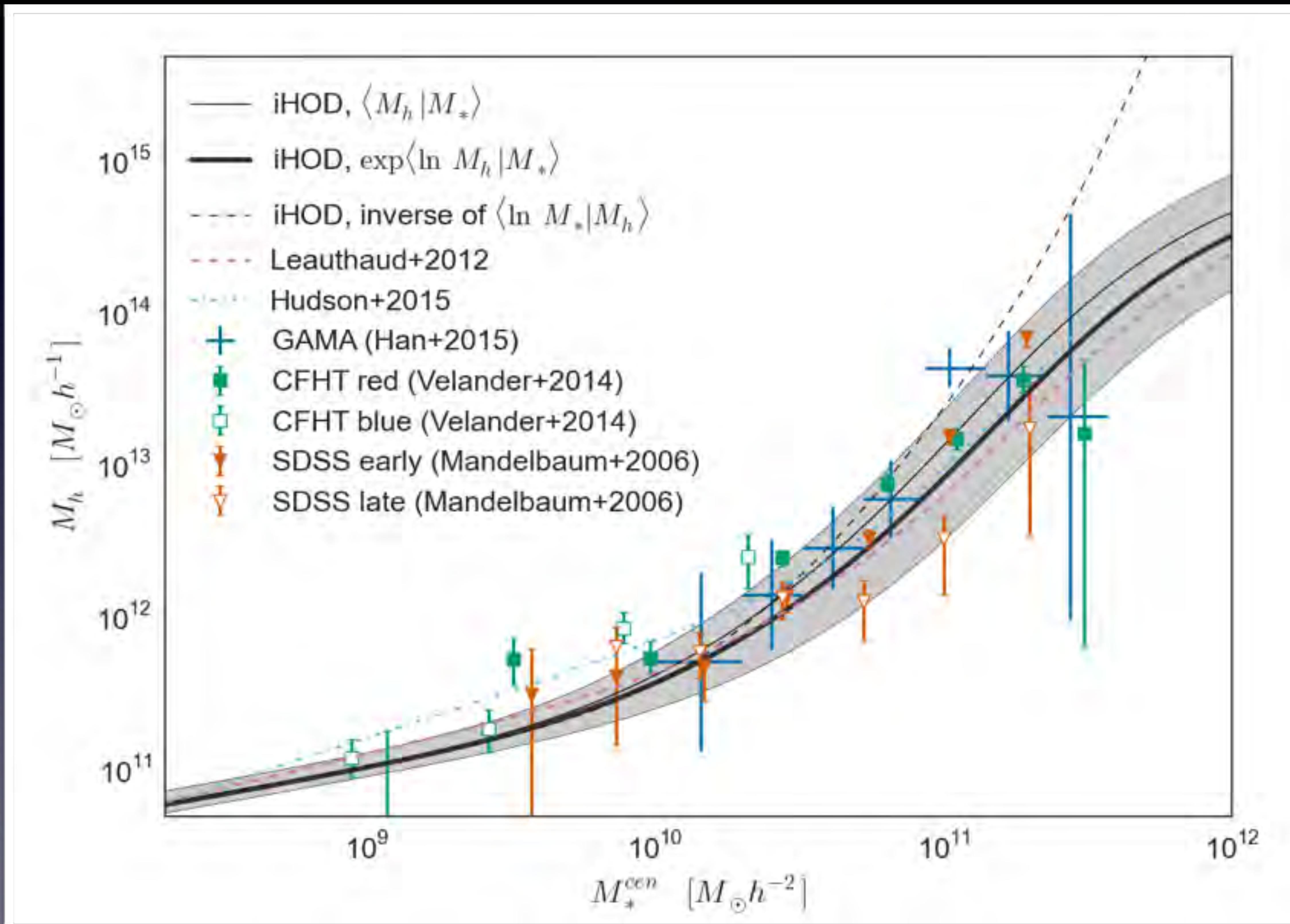
Stellar mass fraction reaches plateau



stellar-to-halo mass relation (centrals)

Stellar mass fraction (cen+sat)

average host halo mass at fixed stellar mass



short summary for paper I

- iHOD is able to extract maximum information from galaxy clustering and lensing measurements, without the need to select volume limited samples.

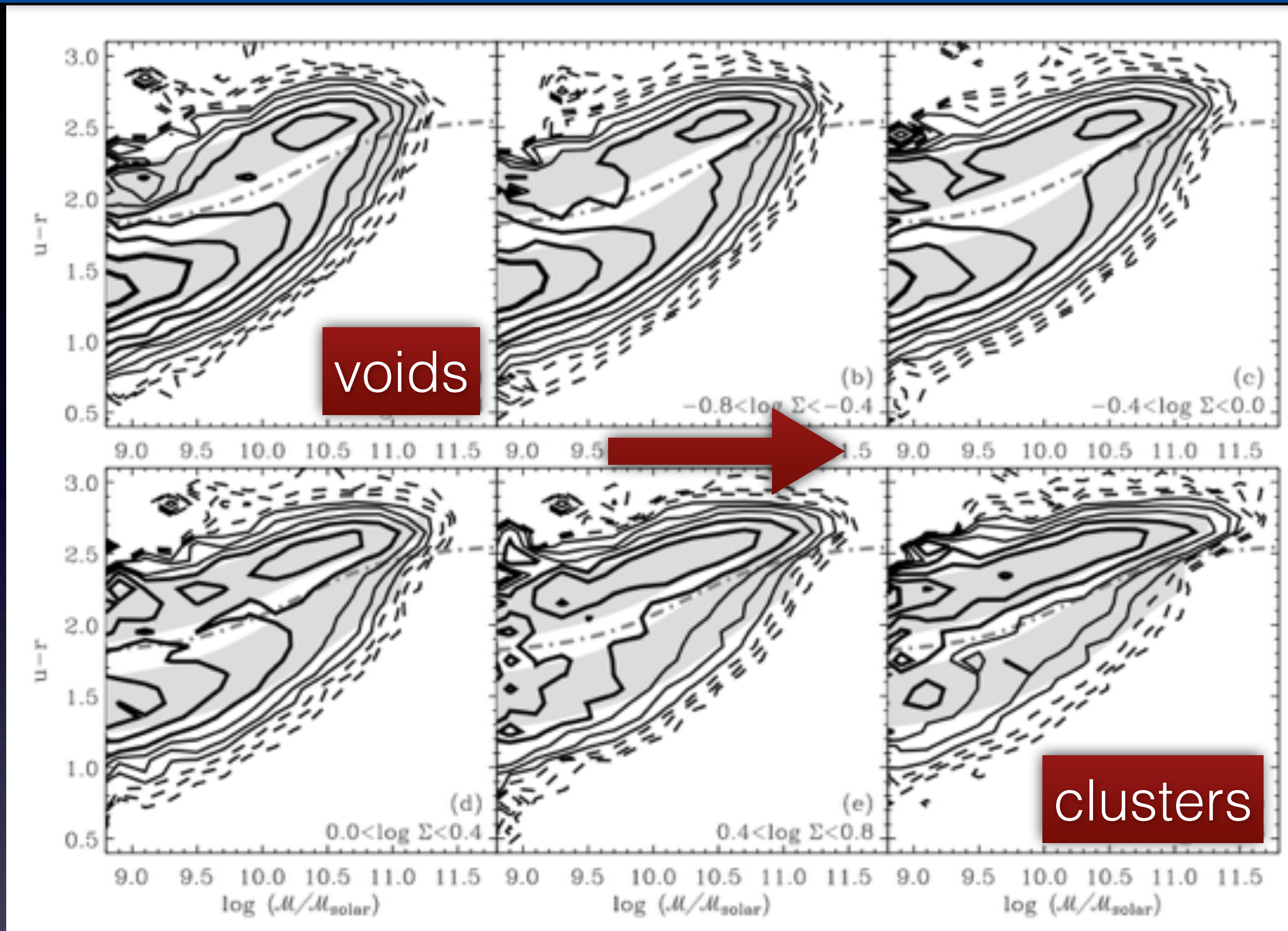
- We obtained tight constraints on the mean and scatter of the stellar-to-halo mass relation.

- The best-fit iHOD not only describes the clustering and lensing over four decades in stellar mass, but also reproduces the SMFs observed by SDSS.

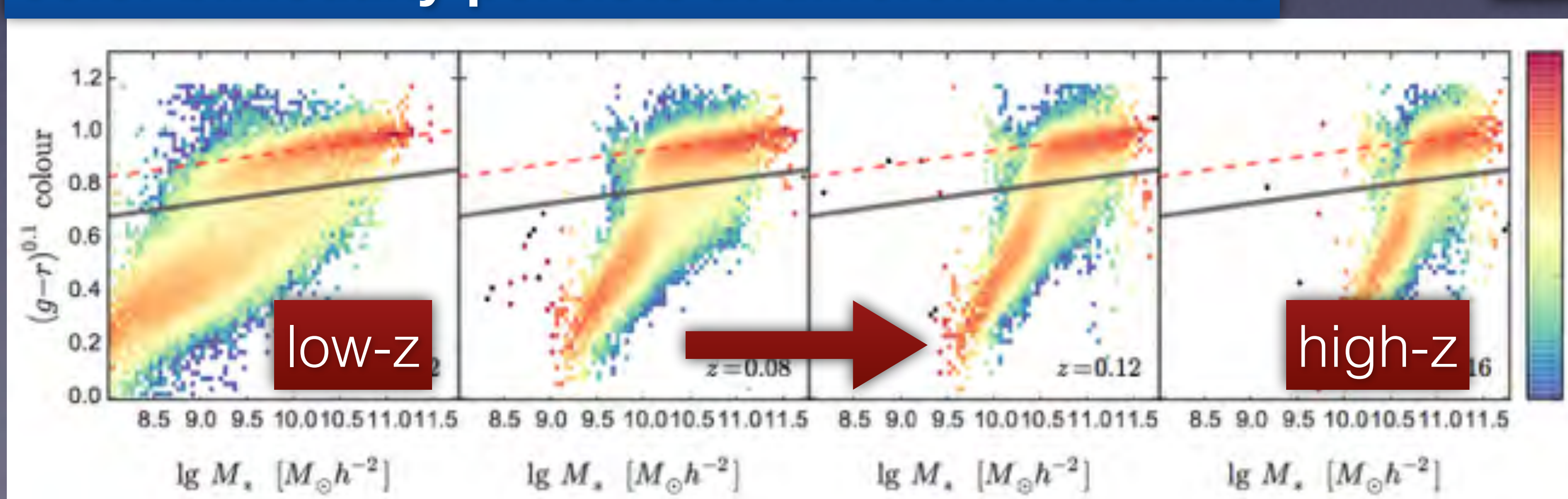
Paper II: What drives quenching

$$P(M_*|M_h) \quad \Rightarrow \quad P(M_*, \mathrm{g{-}r}|M_h, \ldots)$$

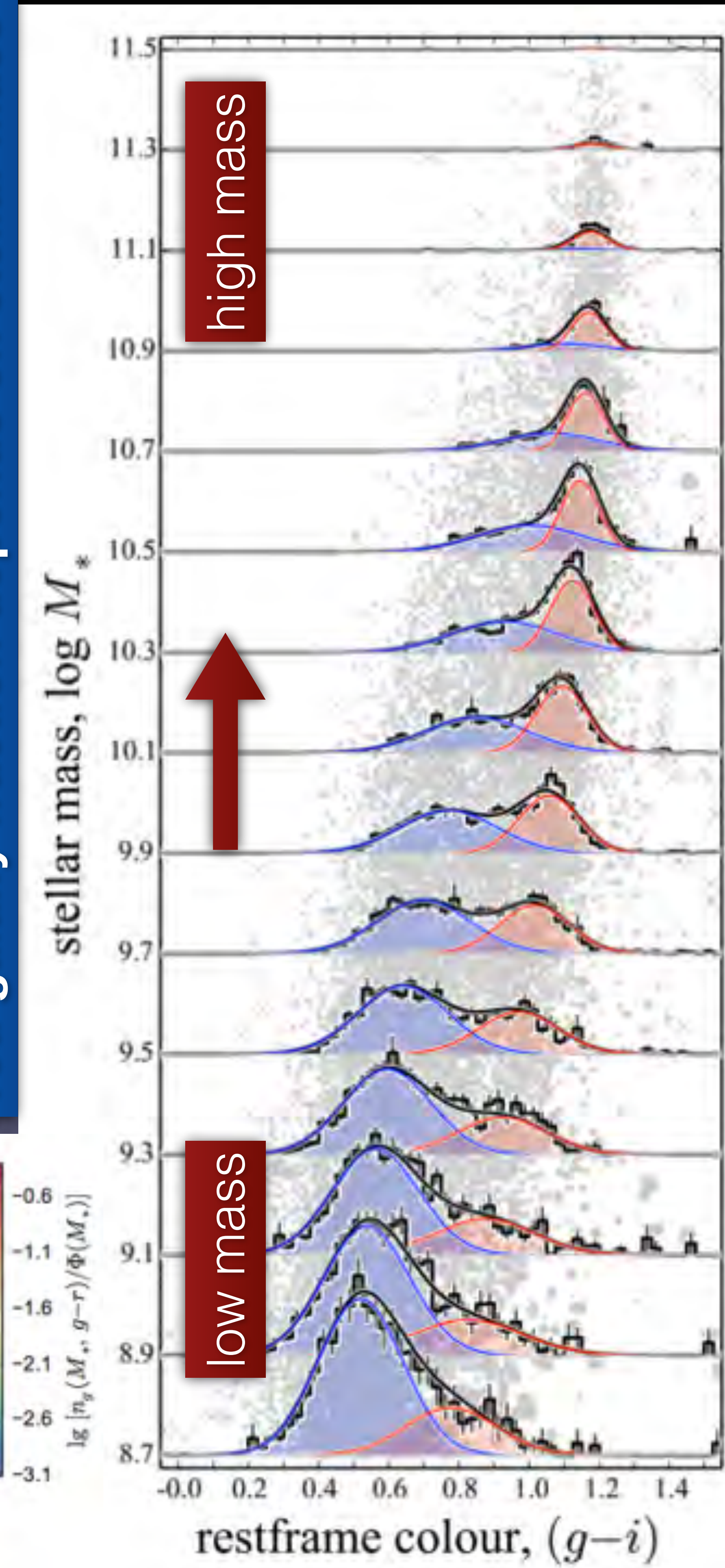
color bimodaity persists in different environments

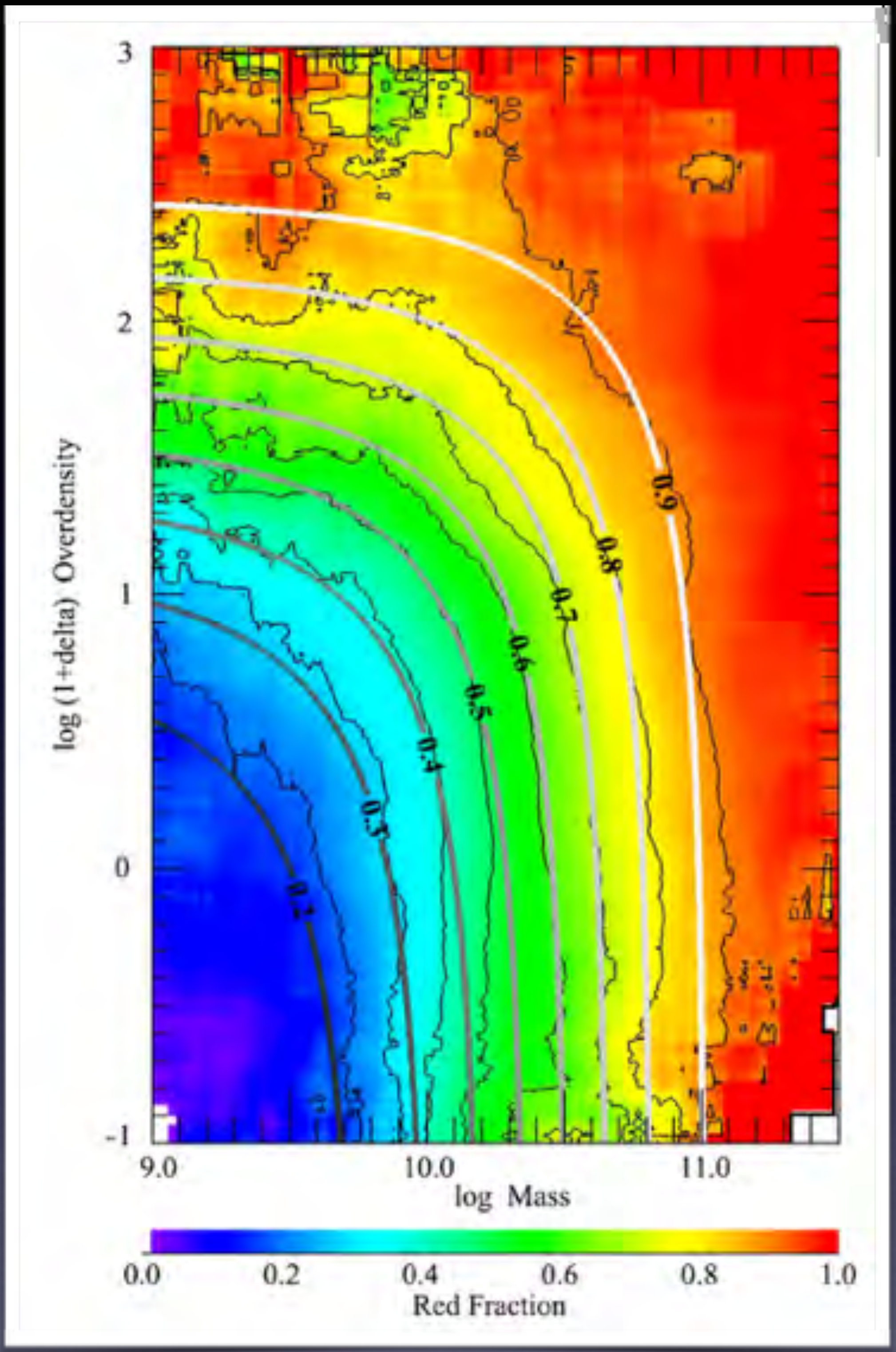


color bimodaity persists at different redshifts



red galaxy fraction depends on stellar mass



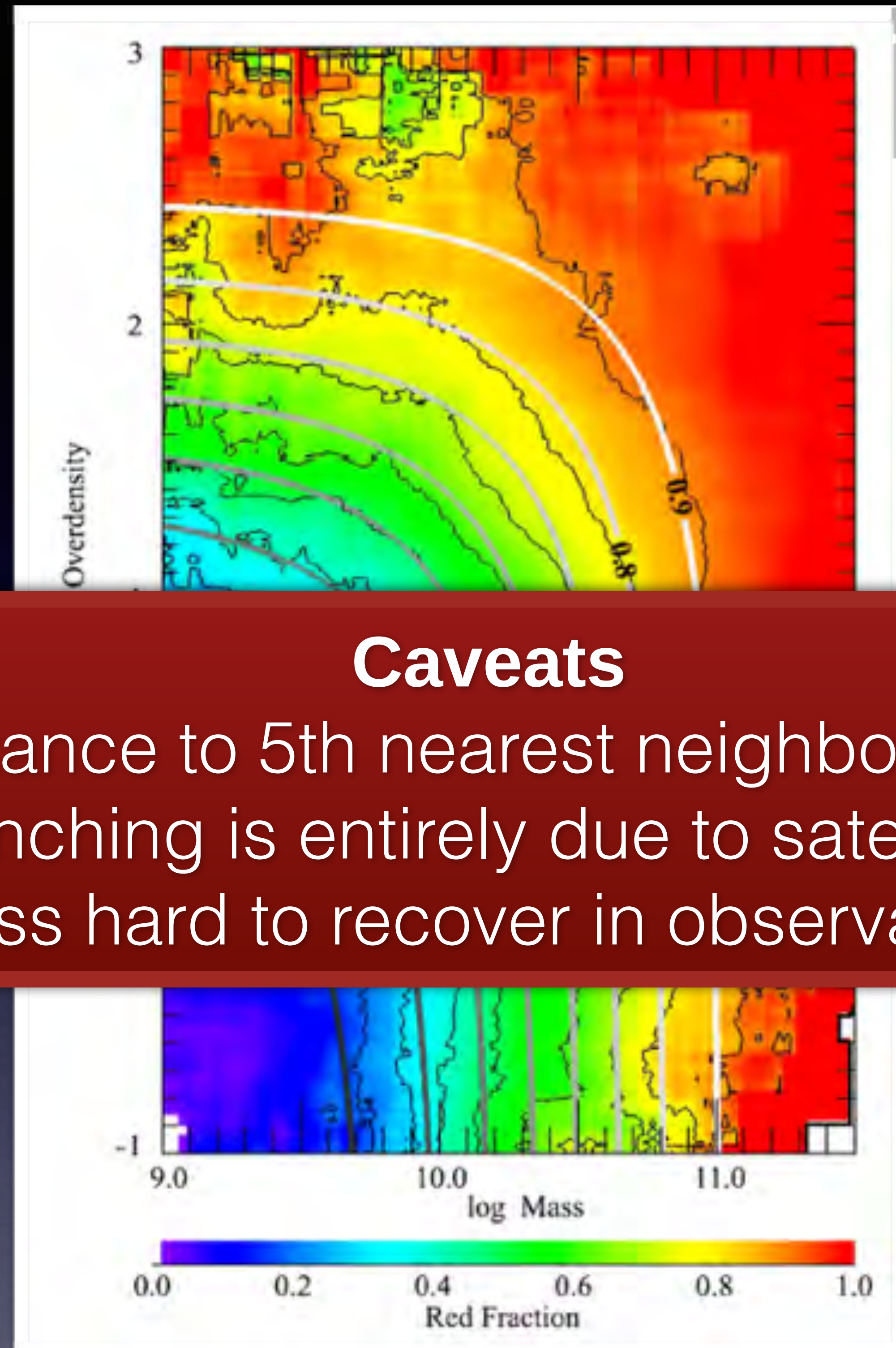


Environment quenching

Stellar Mass quenching

Peng et al. (2010)

Envi quenching

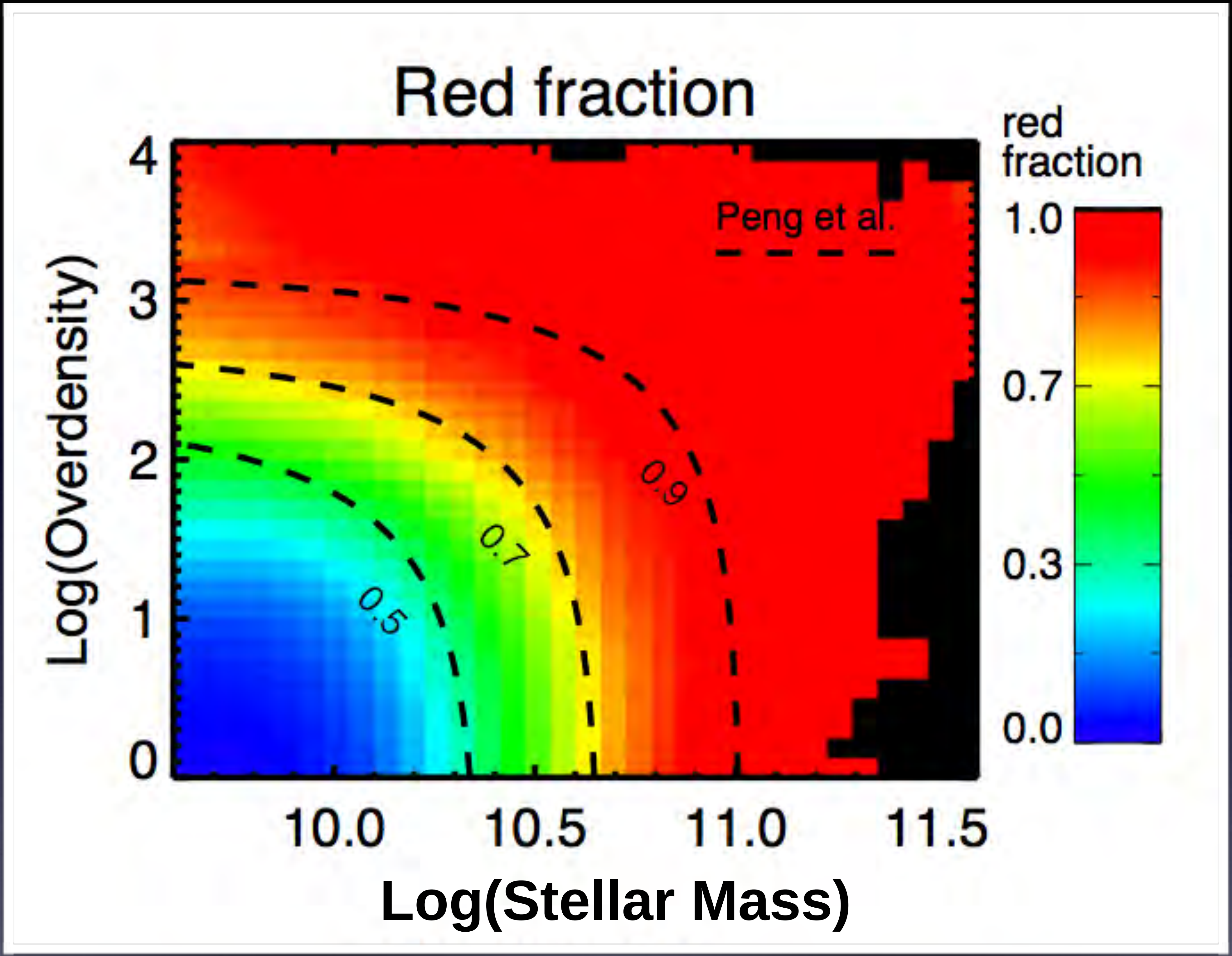


Caveats

- “Environment”: distance to 5th nearest neighbor
- “Environment” quenching is entirely due to satellites (Peng+2012)
- Trend with halo mass hard to recover in observations (Campbell+2015)

Stellar Mass quenching

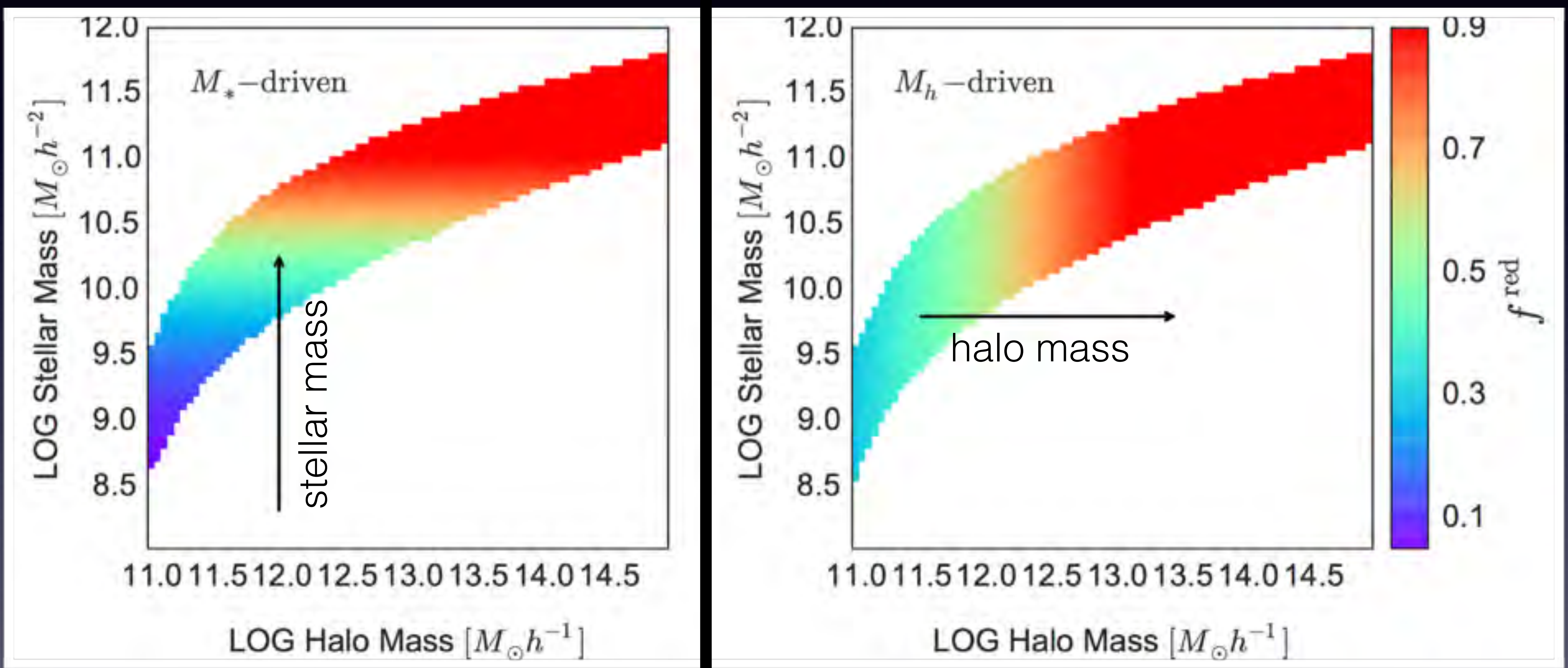
Peng et al. (2010)



Environment and stellar mass trends can be fully explained by **halo mass** quenching.

Gabor & Dave (2015)

Distinguishing the Two Scenarios

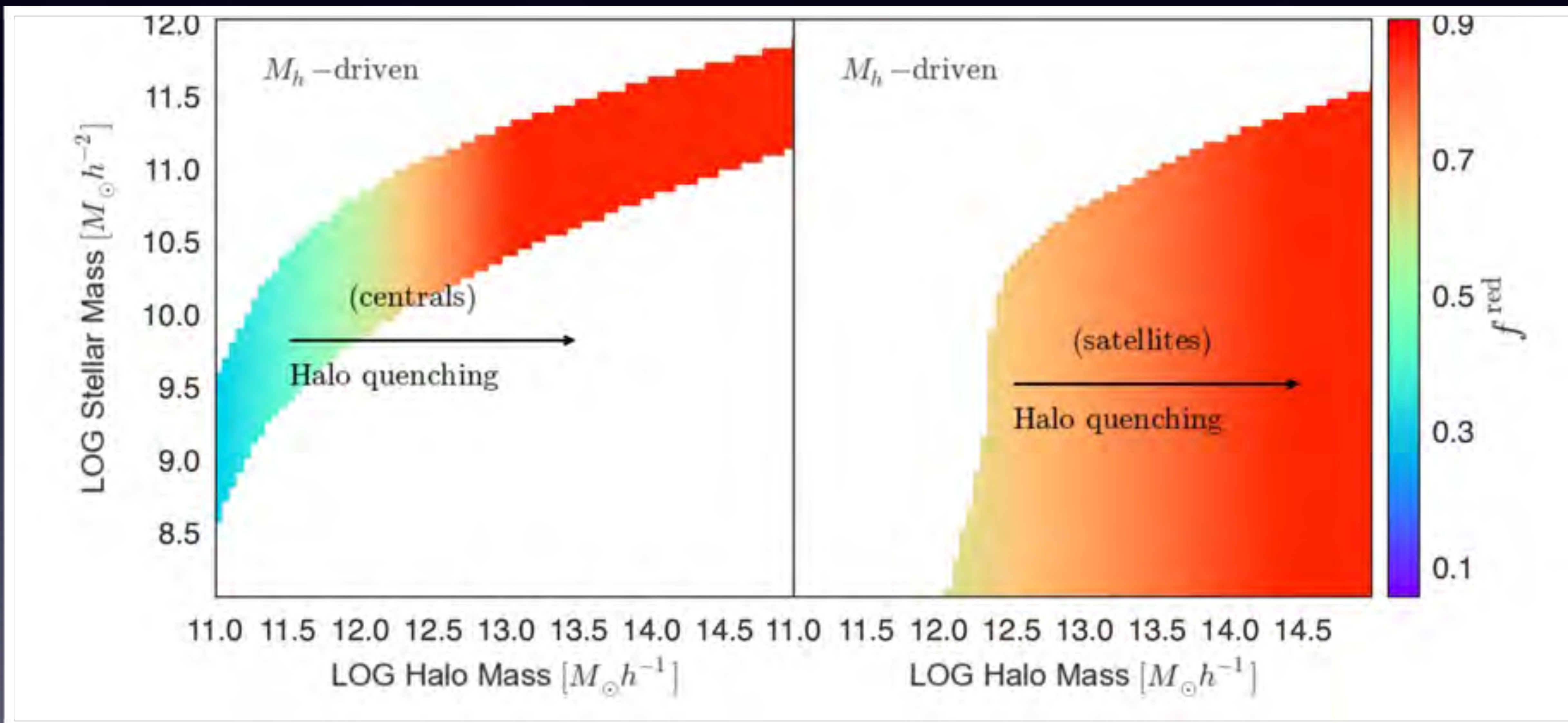


bands: stellar vs. halo mass of **central** galaxies

The two scenarios should predict different color split in galaxy clustering and g-g lensing.

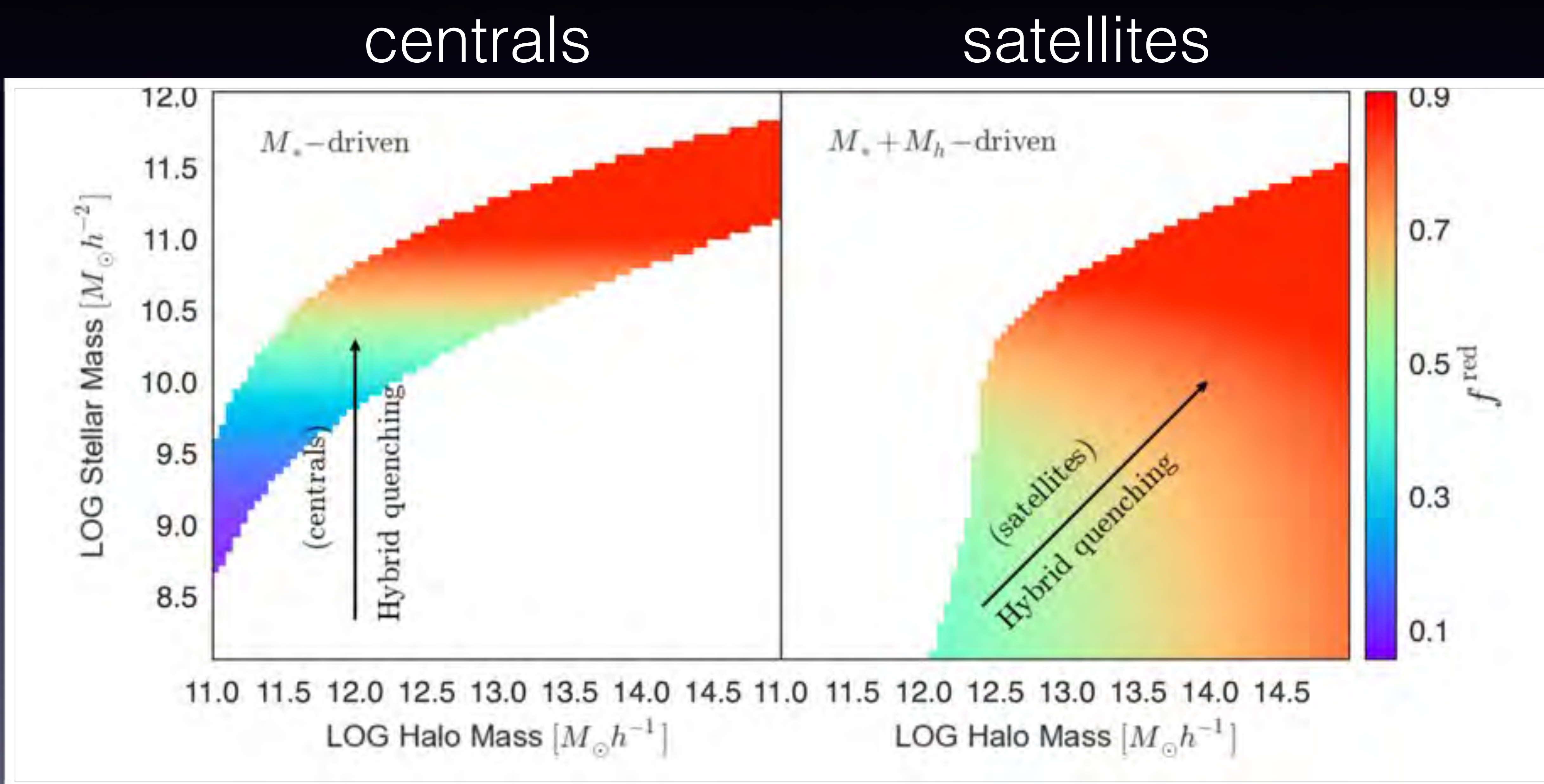
Halo quenching model

centrals satellites



Red fraction is tied to **halo mass** for both centrals and satellites.

Hybrid quenching model



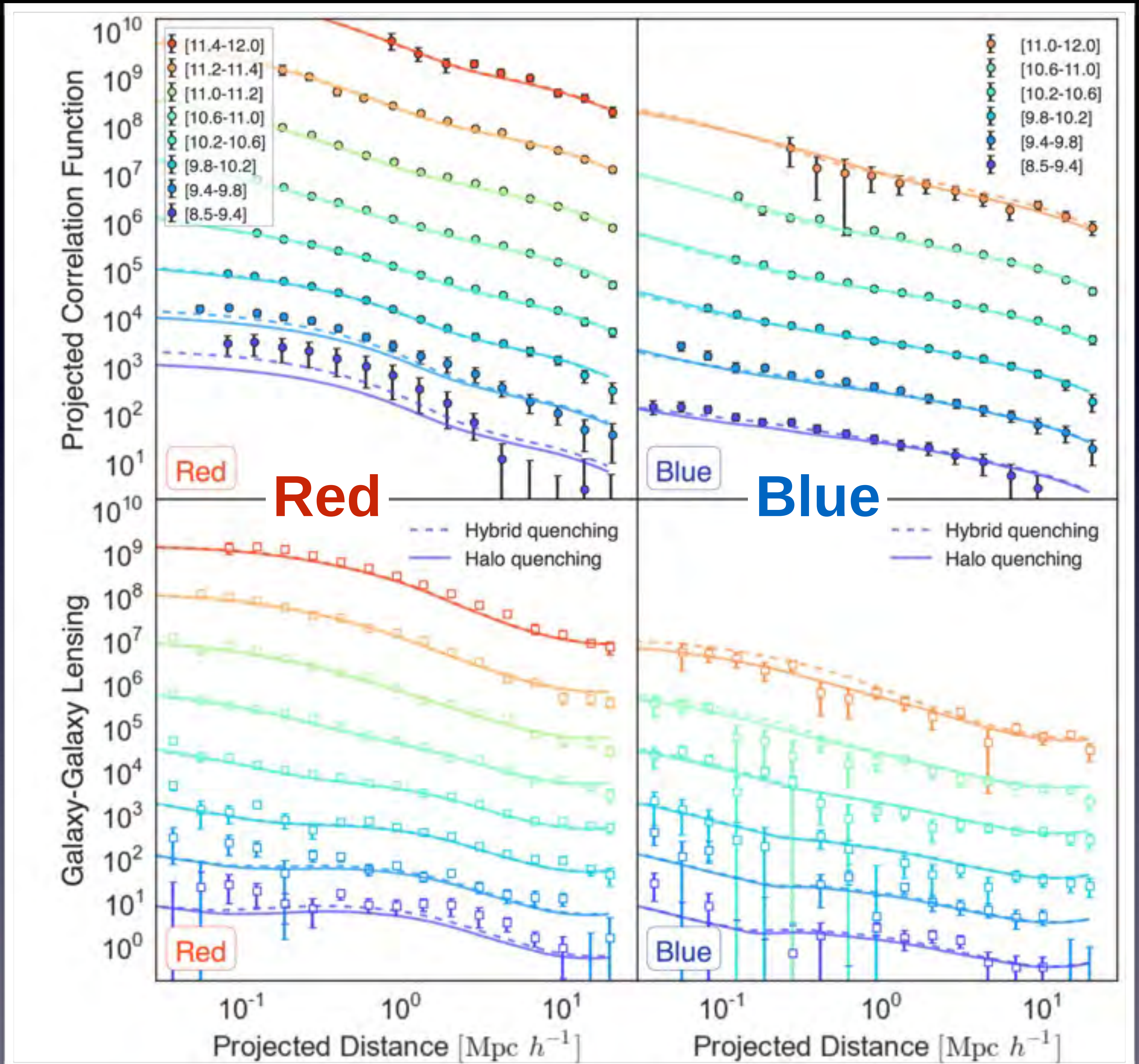
Red fraction is tied to **stellar mass** for all galaxies, while satellite quenching has an extra dependence on halo mass

Red fraction to Signal prediction

- The best-fit iHOD of overall galaxies is kept fixed.
- We split the overall iHOD into red & blue, using only four parameters for each quenching model (*traditional HODs require ~15-20*).
- Red & blue clustering and g-g lensing signals can be predicted from respective iHODs in each quenching model.
- Again, the **84%** more galaxies helped tremendously!

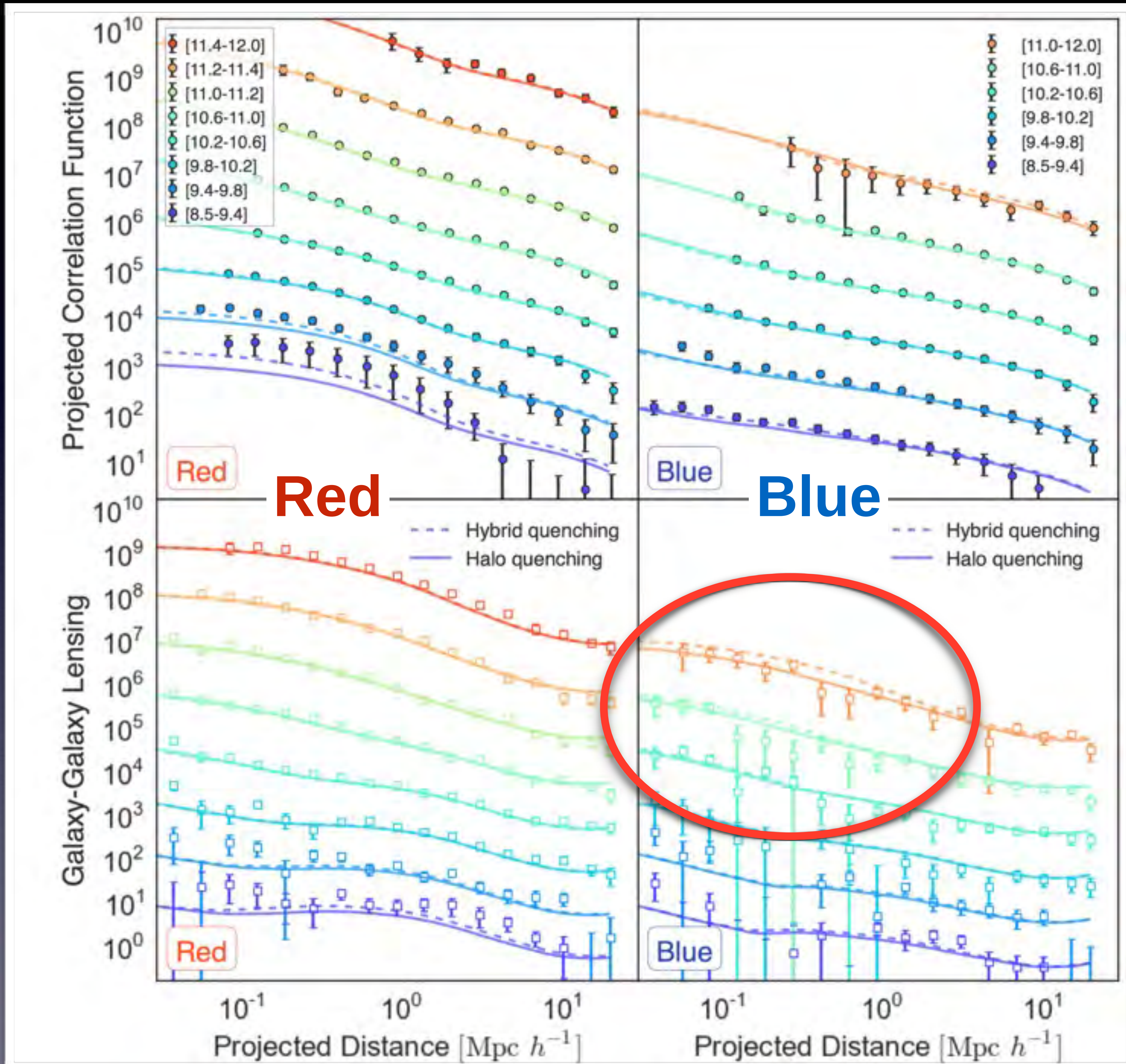
clustering

g-g lensing



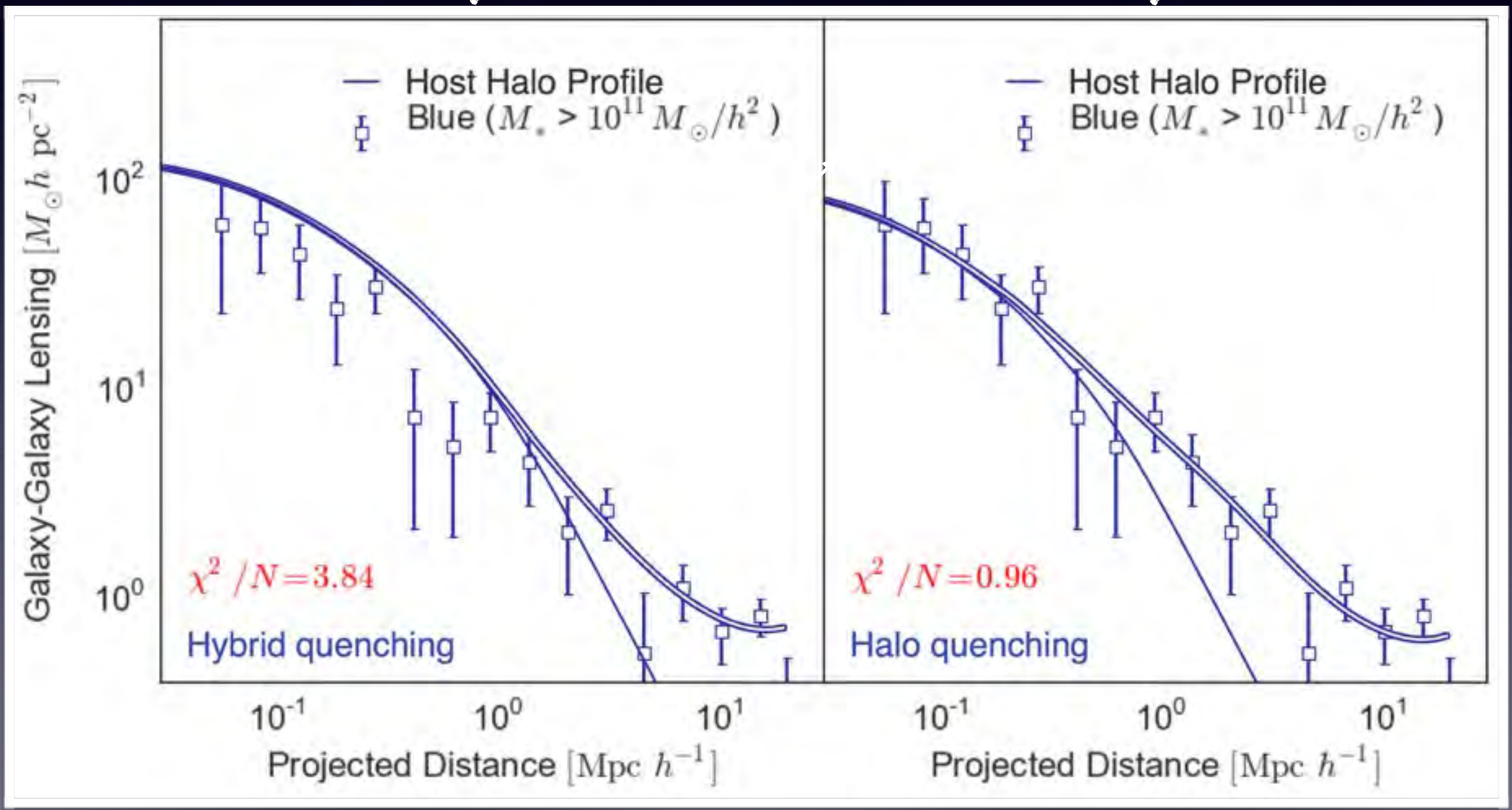
clustering

g-g lensing

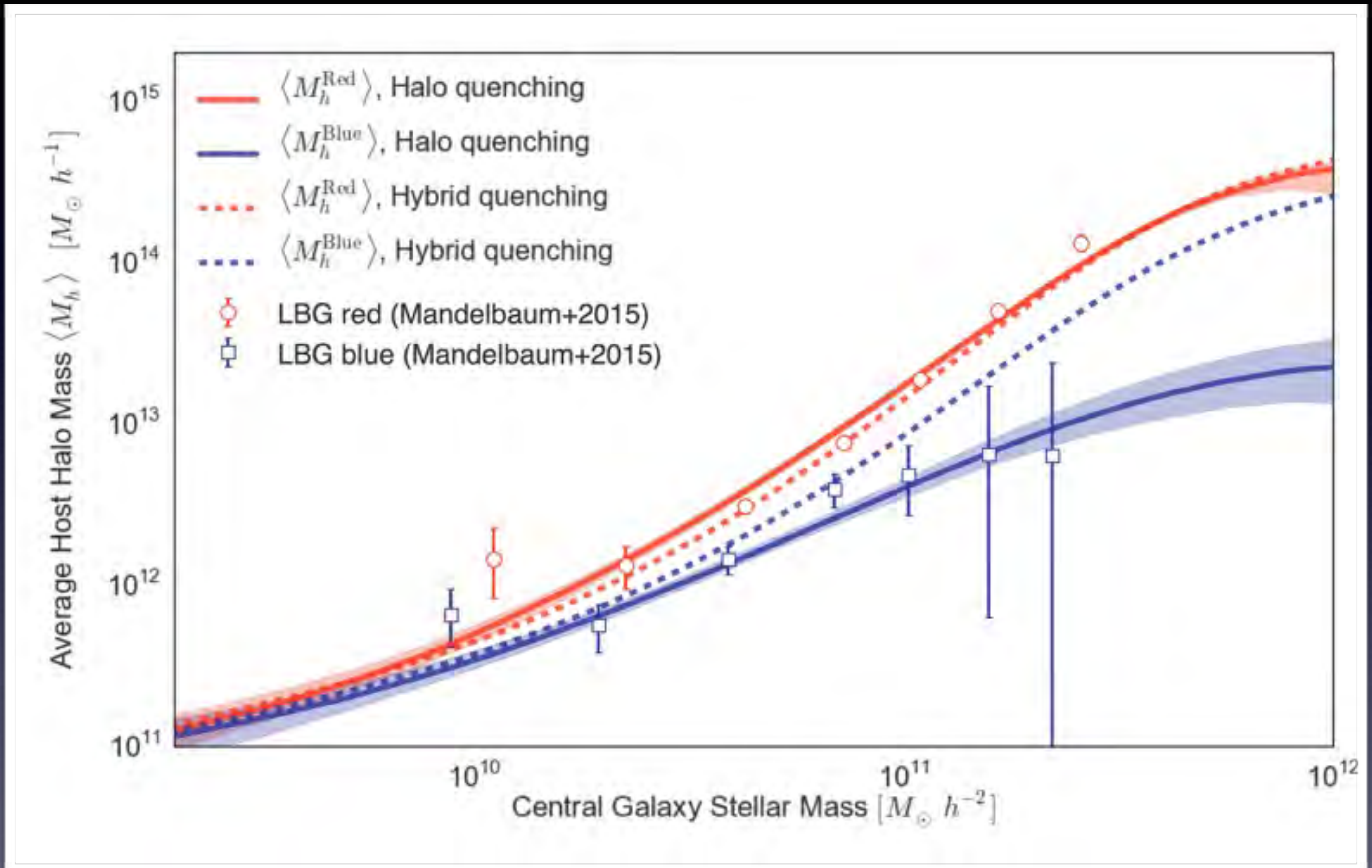


Key Discriminator: Lensing of Massive Blue Galaxies

Hybrid **quenching** | ***Halo*** **quenching**



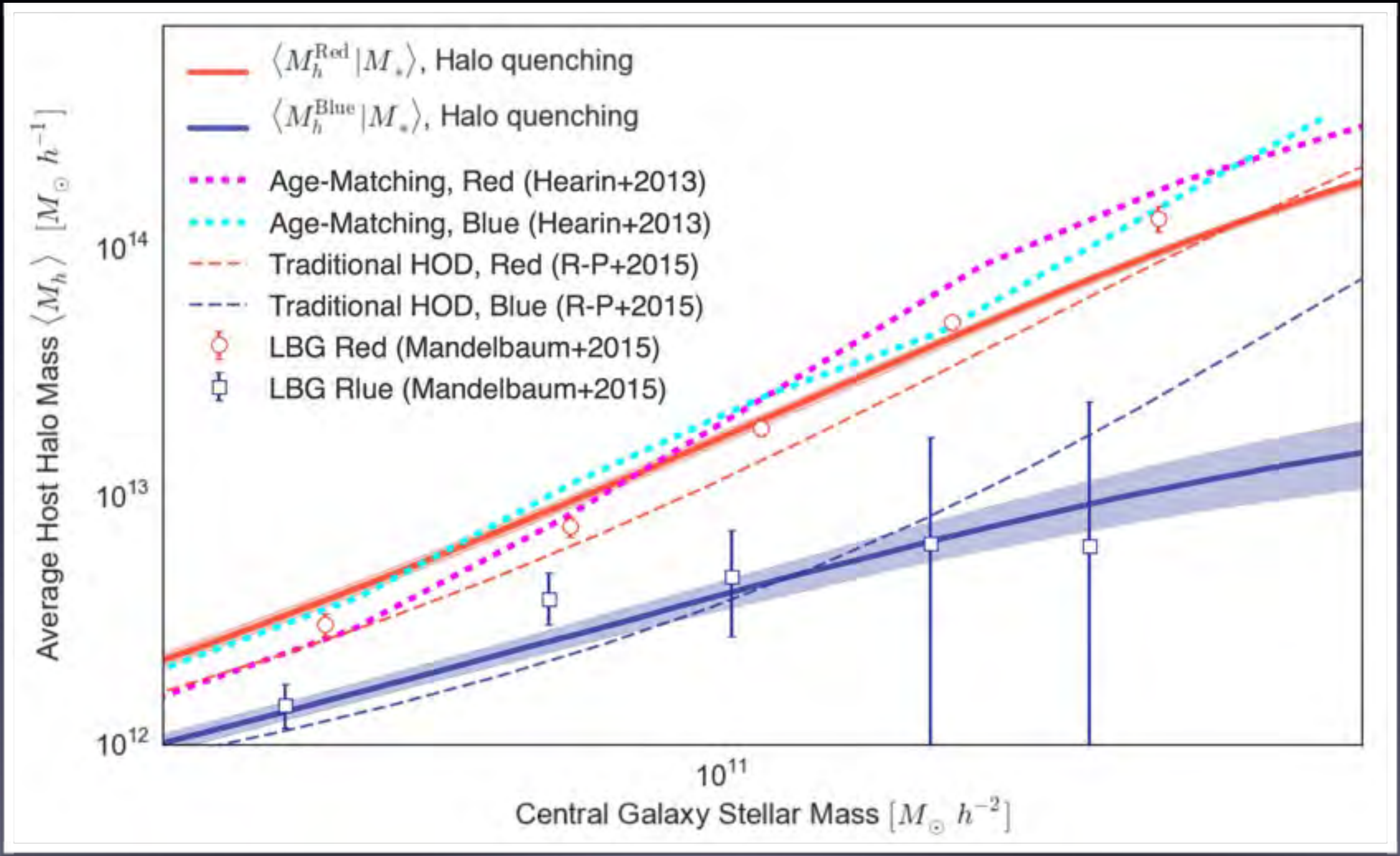
Average Host Halo Mass of Red and Blue Centrals



locally brightest galaxies (**LBG**s): centrals with high purity

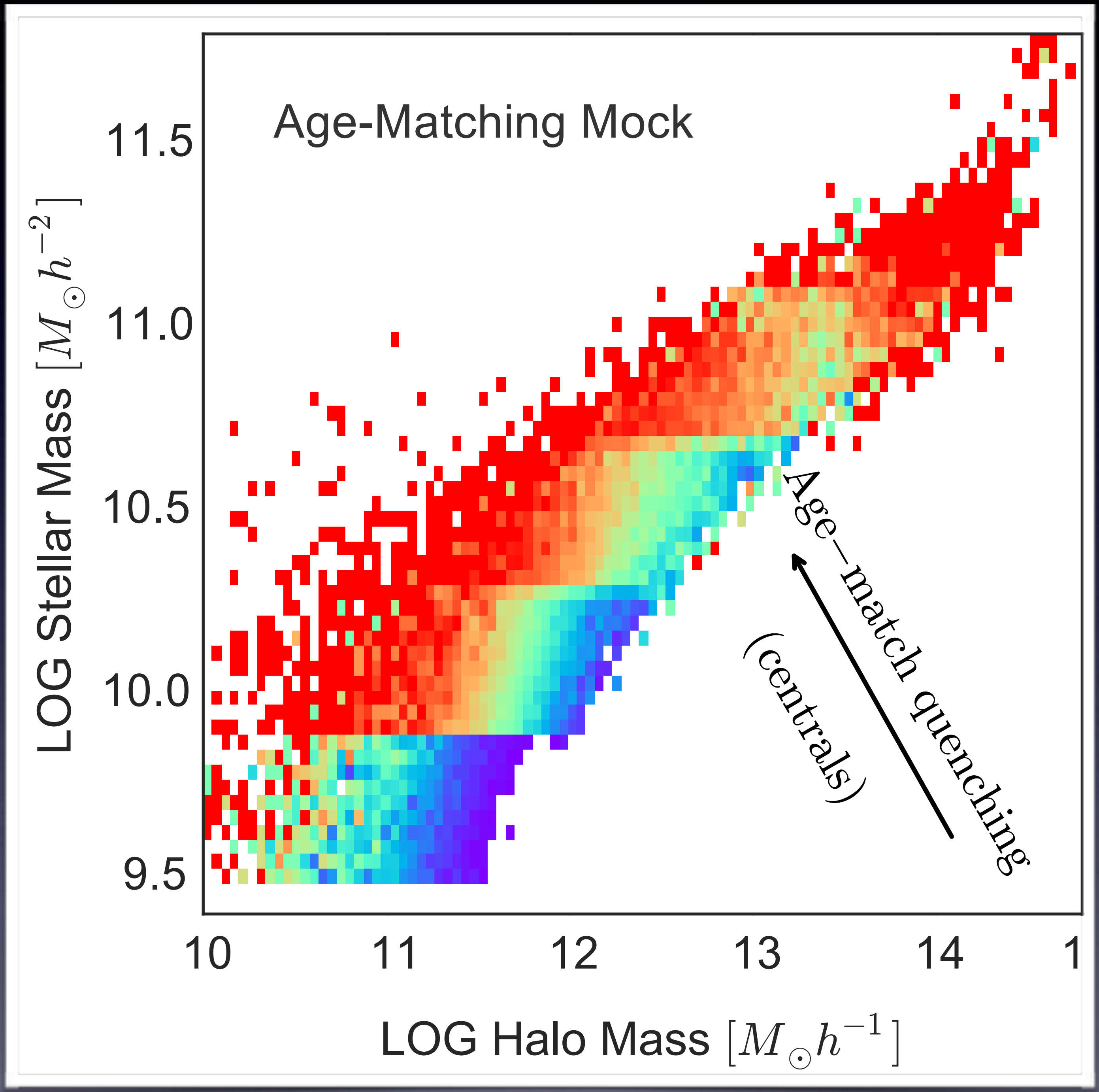
Mandelbaum, Wang, Zu, White, Henriques, More (2015)

Compare to traditional HOD and Age-matching



Strong bimodality in the host halo mass of centrals!

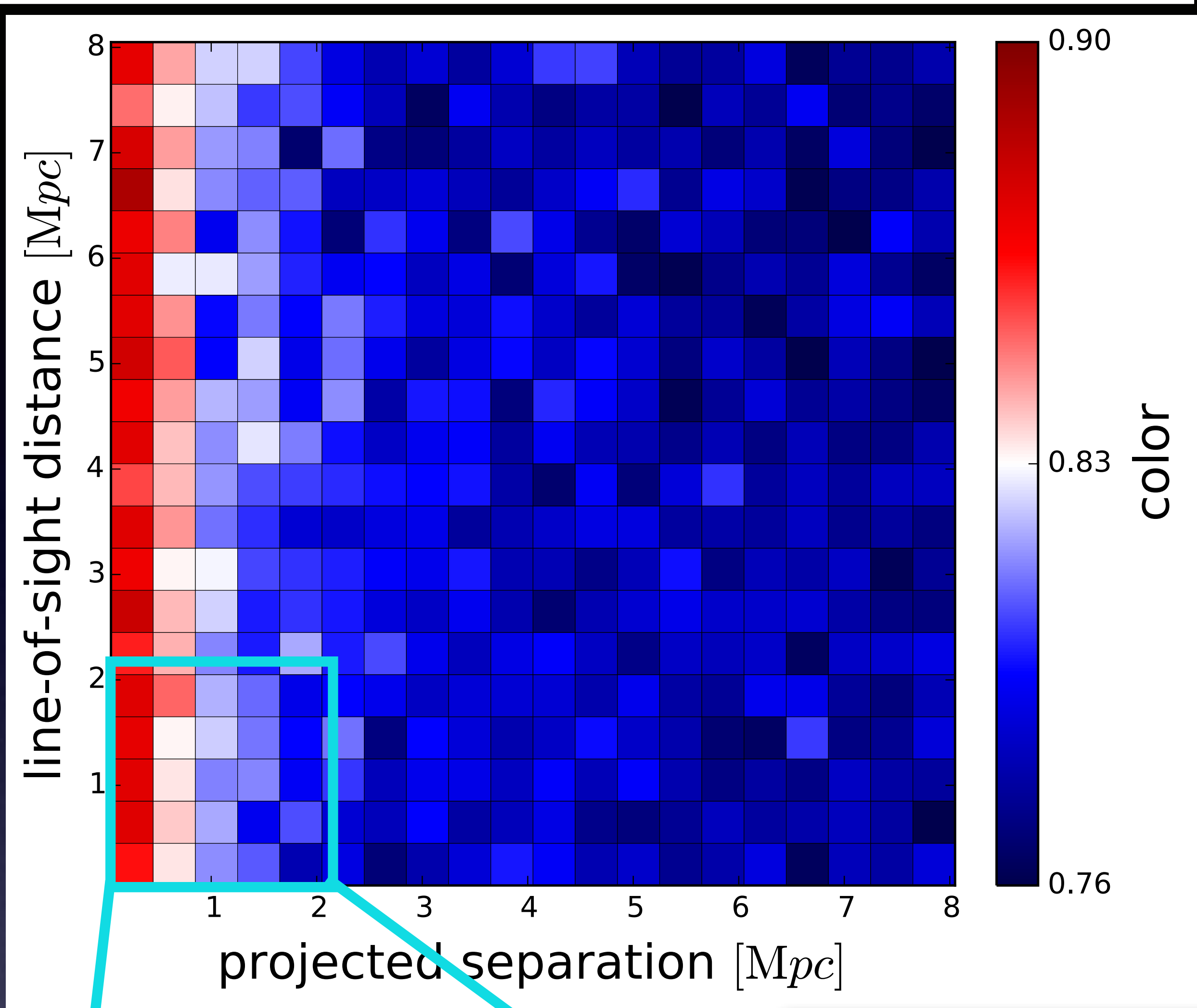
central galaxy quenching in age-matching



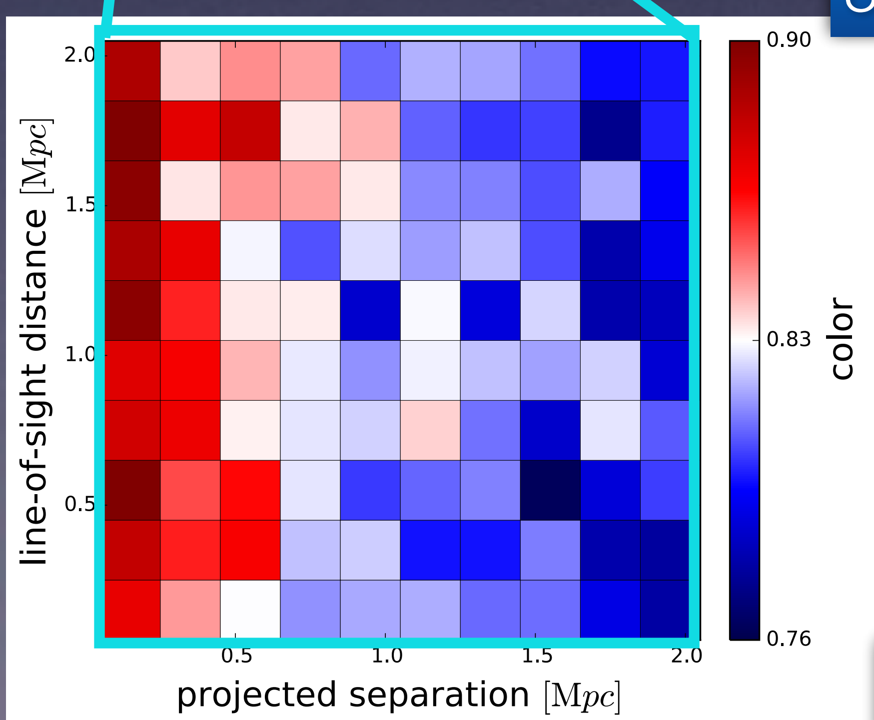
bluer centrals at fixed stellar mass are put in younger (thus higher mass) halos

satellite quenching timescales

average color around group centers

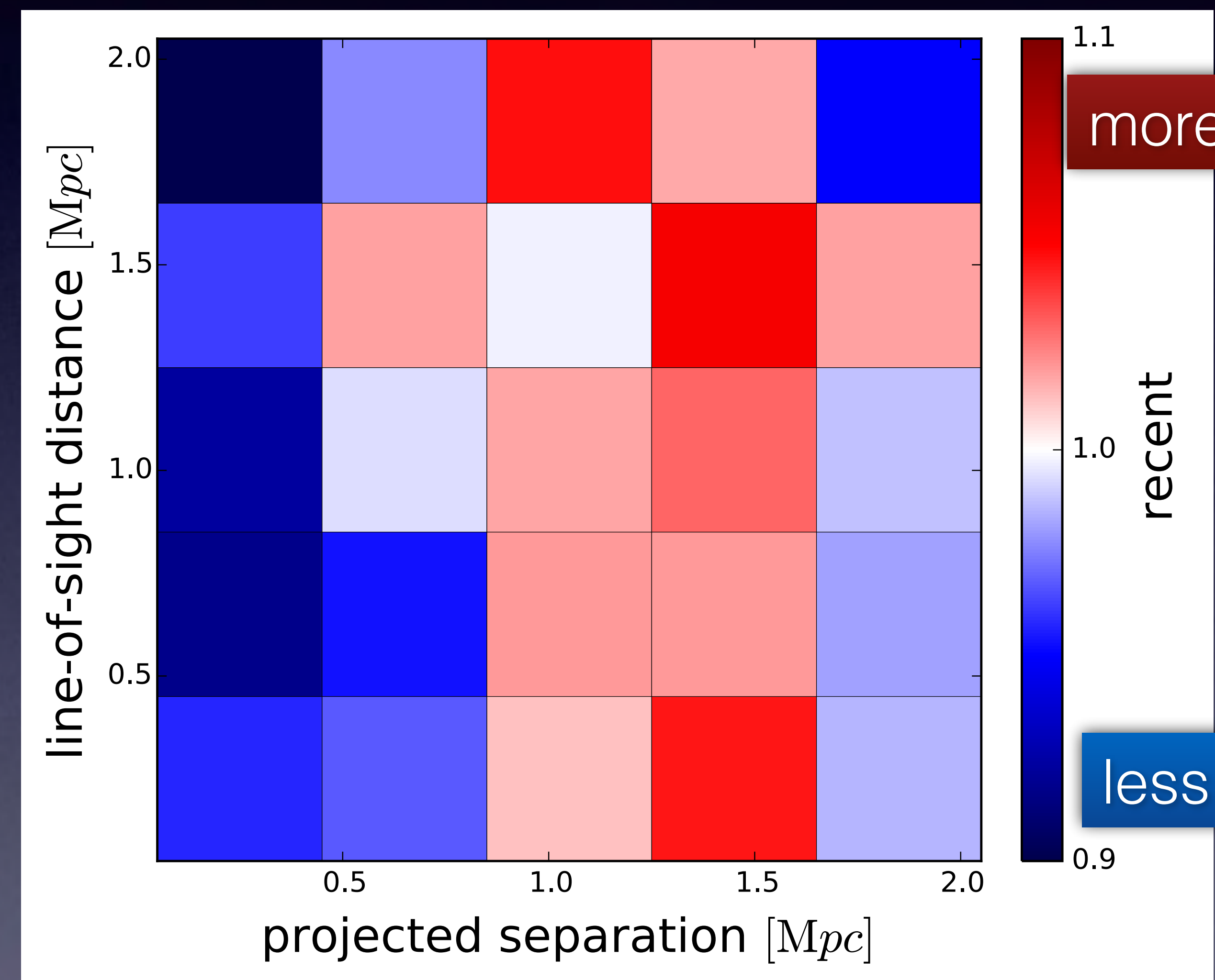


8 Mpc x 8 Mpc



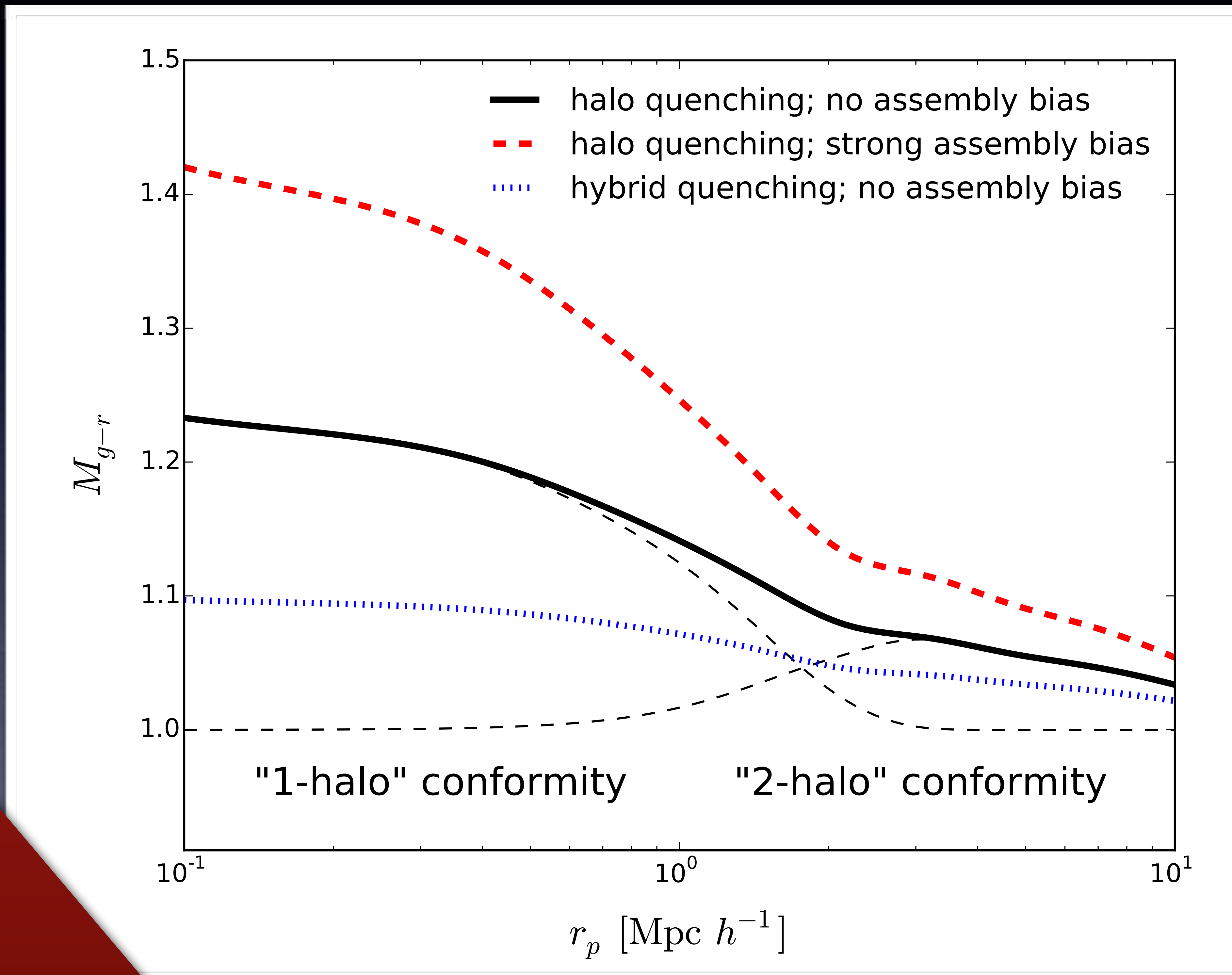
2 Mpc x 2 Mpc

How recent is the latest star-formation episode in quiescent galaxies around group centers



2 Mpc x 2 Mpc

Marked Correlation: Conformity, & Assembly Bias



preliminary

Conclusions

- The **iHOD** is a powerful formalism that can be easily applied to ongoing and future surveys.
- The clustering and g-g lensing of red and blue galaxies in SDSS point to the necessity of having a dominant halo quenching effect in the low-redshift Universe. **No 2nd variable needed so far.**
- The inferred critical masses for the quenching of centrals and satellites are both around $1.5 \times 10^{12} M_{\odot}/h$, consistent with the value expected in the canonical **halo quenching theory**.
- Models without halo quenching, e.g., the **age-matching** model, fail to reproduce the **strong bimodality** observed in the weak lensing mass of host halos between red and blue centrals.
- Marked correlations will be the key observable for constraining conformity and assembly bias. **Is a 2nd variable needed?**