



**CANDELS**

Cosmic Assembly Near-infrared Deep Extragalactic Legacy Survey

**CANDELS Meeting @ UCSC - 5 August 2017**

# **The Evolving Galaxy-Halo Connection**

**Joel Primack**

**UCSC**

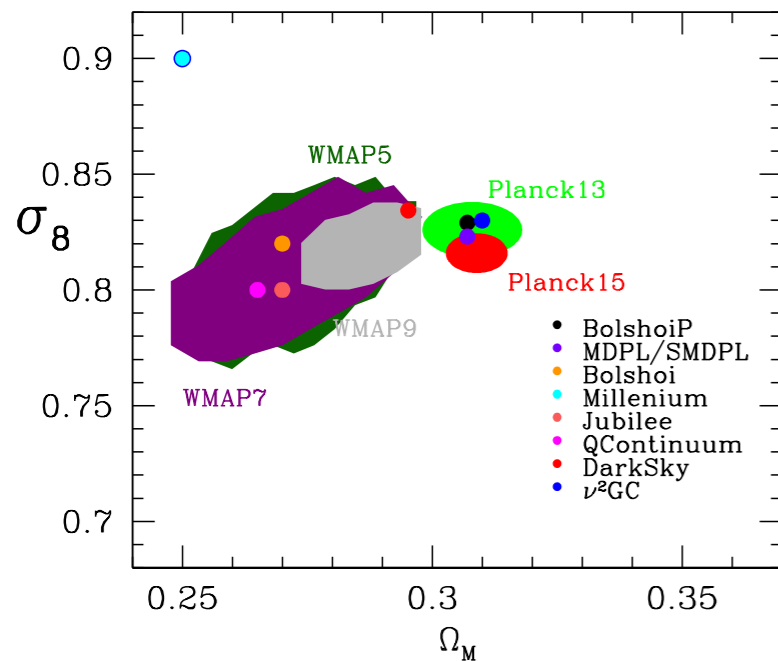
with collaborators including Aldo Rodriguez-Puebla, Christoph Lee, Peter Behroozi, Sandy Faber, Radu Dragomir, Tze Ping Goh, Miguel Aragon Calvo, Doug Hellinger, Anatoly Klypin, Viraj Pandya, Rachel Somerville, & Avishai Dekel

# Halo and Subhalo Demographics with Planck Cosmological Parameters: Bolshoi-Planck and MultiDark-Planck Simulations

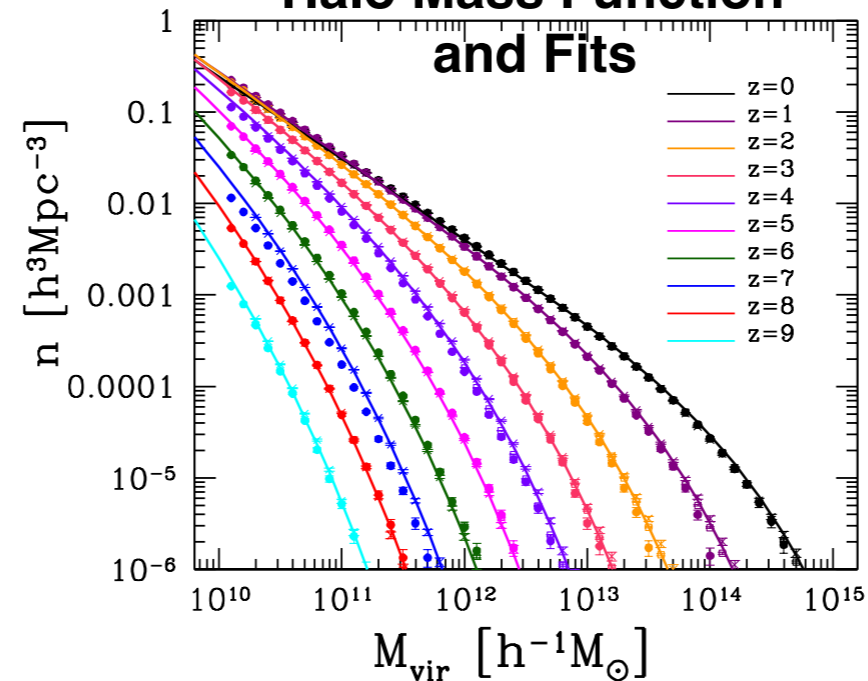
Aldo Rodríguez-Puebla, Peter Behroozi, Joel Primack, Anatoly Klypin, Christoph Lee, Doug Hellinger

MNRAS 2016

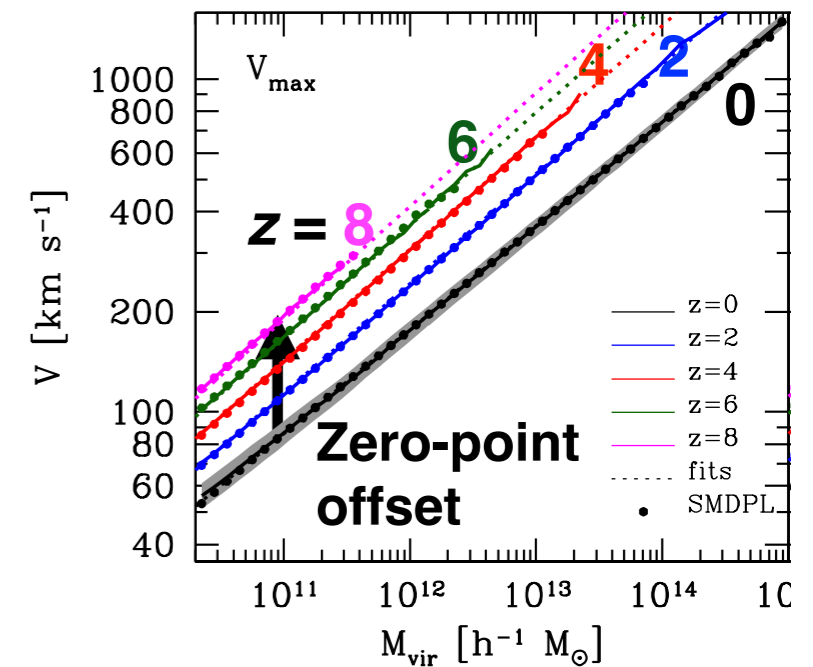
## Cosmological Simulations



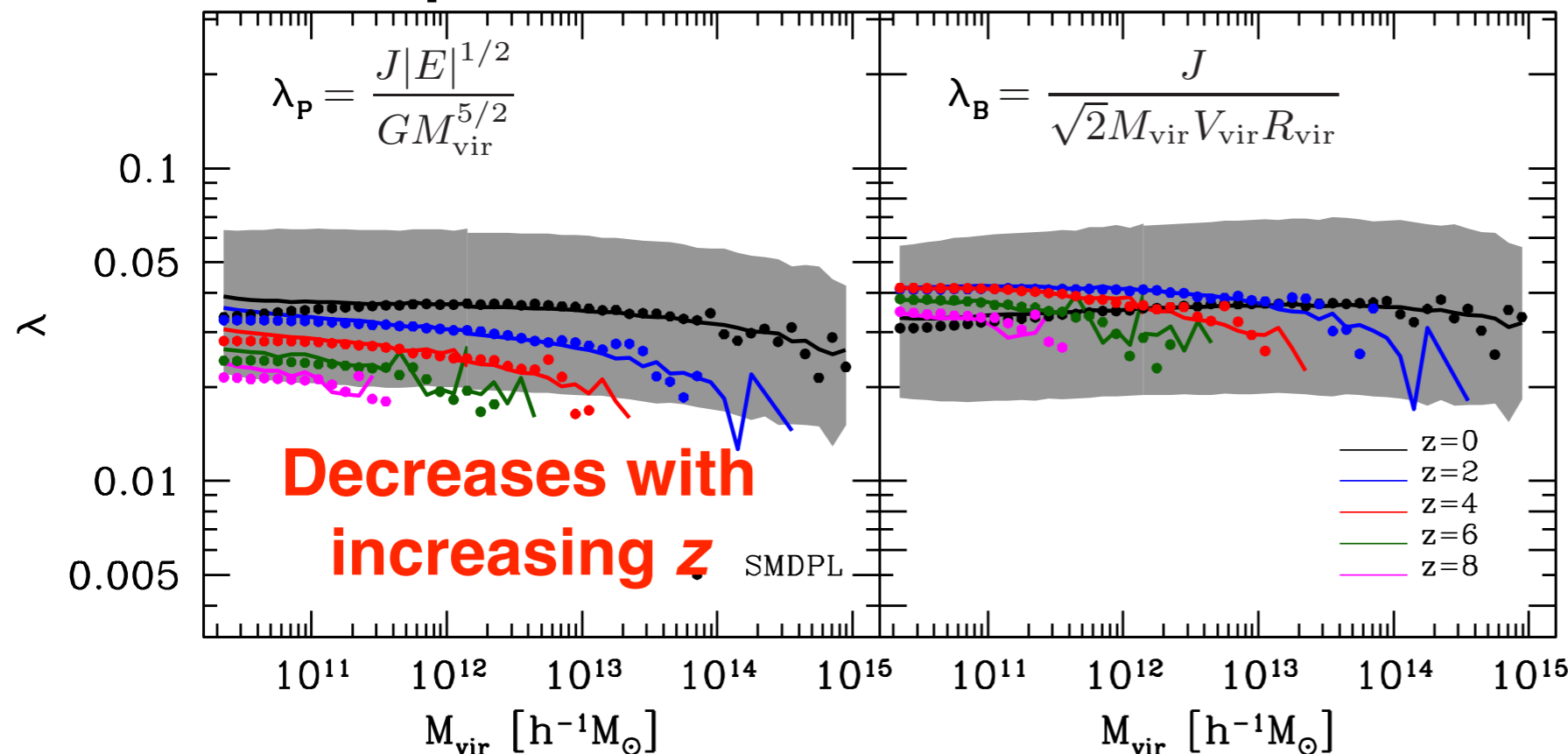
## Halo Mass Function and Fits



## $V_{\text{max}}(M_{\text{vir}}, z)$



## Halo Spin Parameters as a function of $M_{\text{vir}}$



*We have released the halo catalogs and merger trees from Bolshoi-Planck and MultiDark-Planck cosmological simulations. Our paper includes Appendices with instructions for reading these files.*

<http://hipacc.ucsc.edu/Bolshoi/MergerTrees.html>

Medians are shown as the solid lines. At  $z = 0$  the grey area is the 68% range.

# Constraining the Galaxy Halo Connection: Star Formation Histories, Galaxy Mergers, and Structural Properties

Aldo Rodriguez-Puebla, Joel Primack, Vladimir Avila-Reese, Sandra Faber

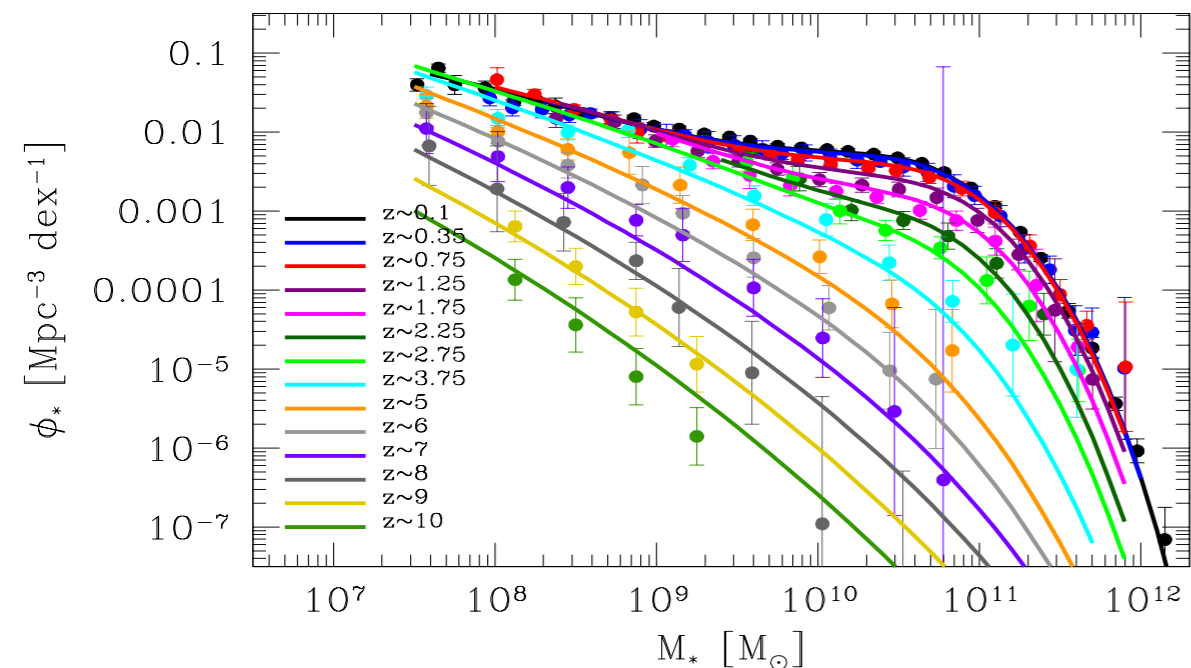
MNRAS 2017

Author	Redshift <sup>a</sup>	$\Omega$ [deg <sup>2</sup> ]	Corrections
Bell et al. (2003)	$z \sim 0.1$	462	I+SP+C
Yang, Mo & van den Bosch (2009a)	$z \sim 0.1$	4681	I+SP+C
Li & White (2009)	$z \sim 0.1$	6437	I+P+C
Bernardi et al. (2010)	$z \sim 0.1$	4681	I+SP+C
Bernardi et al. (2013)	$z \sim 0.1$	7748	I+SP+C
Rodriguez-Puebla et al. in prep	$z \sim 0.1$	7748	S
Drory et al. (2009)	$0 < z < 1$	1.73	SP+C
Moustakas et al. (2013)	$0 < z < 1$	9	SP+D+C
Pérez-González et al. (2008)	$0.2 < z < 2.5$	0.184	I+SP+D+C
Tomczak et al. (2014)	$0.2 < z < 3$	0.0878	C
Ilbert et al. (2013)	$0.2 < z < 4$	2	C
Muzzin et al. (2013)	$0.2 < z < 4$	1.62	I+C
Santini et al. (2012)	$0.6 < z < 4.5$	0.0319	I+C
Mortlock et al. (2011)	$1 < z < 3.5$	0.0125	I+C
Marchesini et al. (2009)	$1.3 < z < 4$	0.142	I+C
Stark et al. (2009)	$z \sim 6$	0.089	I
Lee et al. (2012)	$3 < z < 7$	0.089	I+SP+C
González et al. (2011)	$4 < z < 7$	0.0778	I+C
Duncan et al. (2014)	$4 < z < 7$	0.0778	C
Song et al. (2015)	$4 < z < 8$	0.0778	I
This paper, Appendix D	$4 < z < 10$	0.0778	-

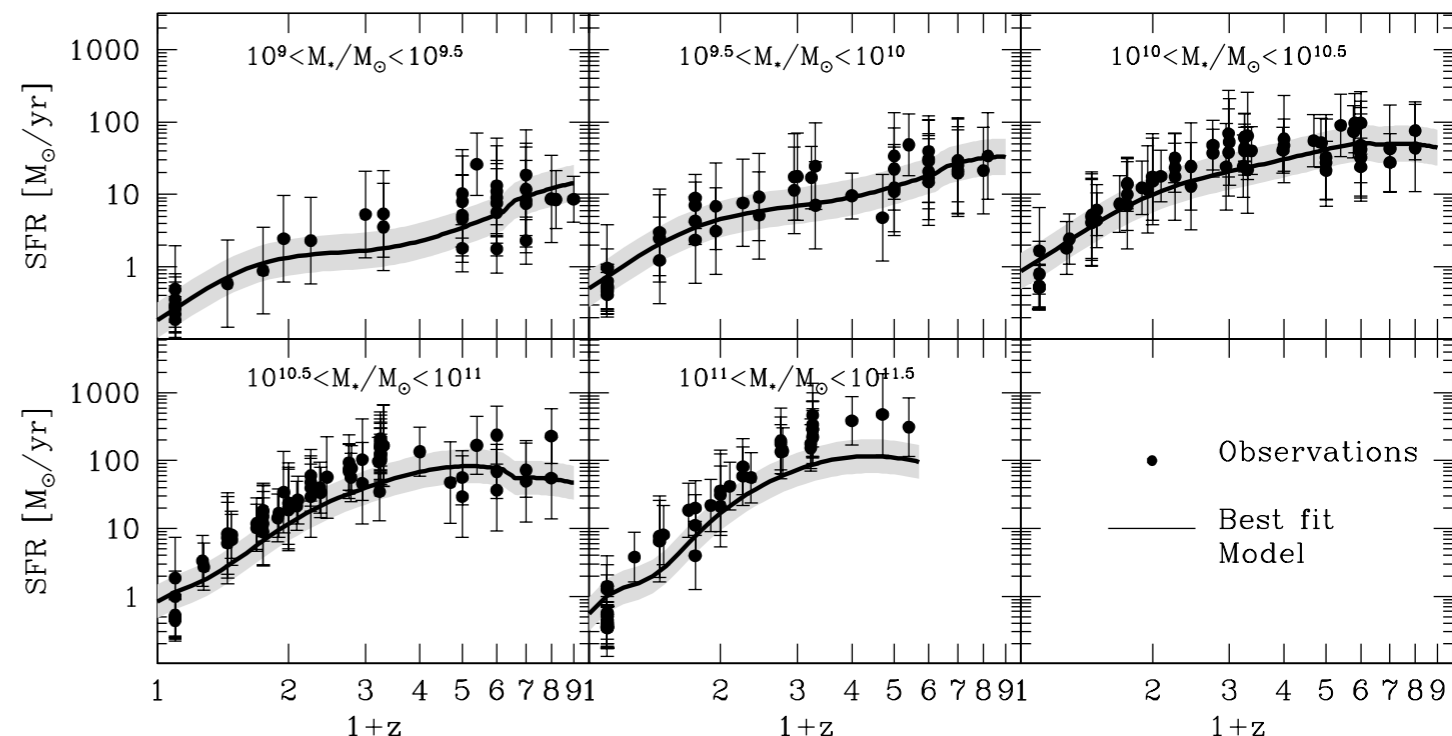
I=IMF; P= photometry corrections; S=Surface Brightness correction; D=Dust model;  
NE= Nebular Emissions; SP = SPS Model; C = Cosmology

Author	Redshift <sup>a</sup>	SFR Estimator	Corrections	Type
Chen et al. (2009)	$z \sim 0.1$	$H_\alpha/H_\beta$	S	All
Salim et al. (2007)	$z \sim 0.1$	UV SED	S	All
Noeske et al. (2007)	$0.2 < z < 1.1$	UV+IR	S	All
Karim et al. (2011)	$0.2 < z < 3$	1.4 GHz	I+S+E	All
Dunne et al. (2009)	$0.45 < z < 2$	1.4 GHz	I+S+E	All
Kajisawa et al. (2010)	$0.5 < z < 3.5$	UV+IR	I	All
Whitaker et al. (2014)	$0.5 < z < 3$	UV+IR	I+S	All
Sobral et al. (2014)	$z \sim 2.23$	$H_\alpha$	I+S+SP	SF
Reddy et al. (2012)	$2.3 < z < 3.7$	UV+IR	I+S+SP	SF
Magdis et al. (2010)	$z \sim 3$	FUV	I+S+SP	SF
Lee et al. (2011)	$3.3 < z < 4.3$	FUV	I+SP	SF
Lee et al. (2012)	$3.9 < z < 5$	FUV	I+SP	SF
González et al. (2012)	$4 < z < 6$	UV+IR	I+NE	SF
Salmon et al. (2015)	$4 < z < 6$	UV SED	I+NE+E	SF
Bouwens et al. (2011)	$4 < z < 7.2$	FUV	I+S	SF
Duncan et al. (2014)	$4 < z < 7$	UV SED	I+NE	SF
Shim et al. (2011)	$z \sim 4.4$	$H_\alpha$	I+S+SP	SF
Steinhardt et al. (2014)	$z \sim 5$	UV SED	I+S	SF
González et al. (2010)	$z = 7.2$	UV+IR	I+NE	SF
This paper, Appendix D	$4 < z < 8$	FUV	I+E+NE	SF

I=IMF; S=Star formation calibration; E=Extinction; NE= Nebular Emissions; SP=SPS Model



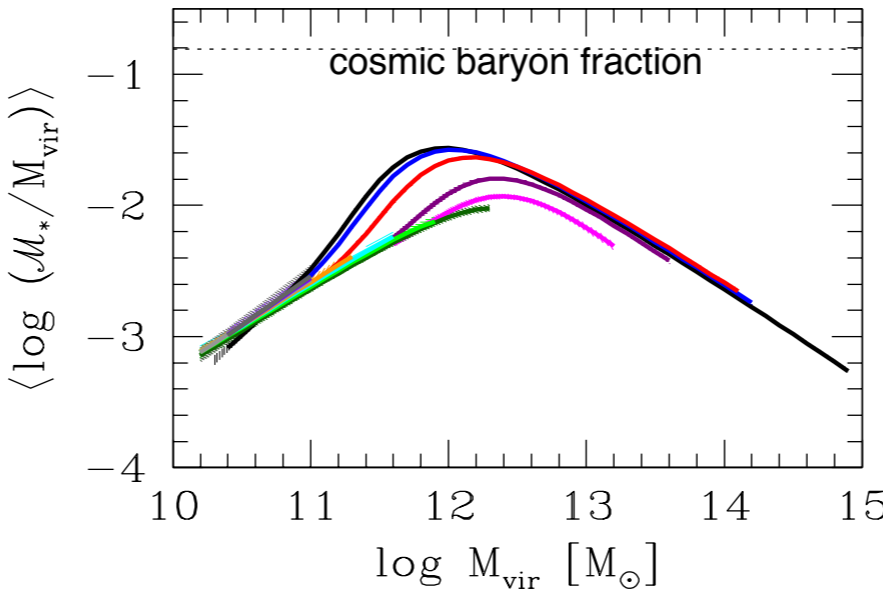
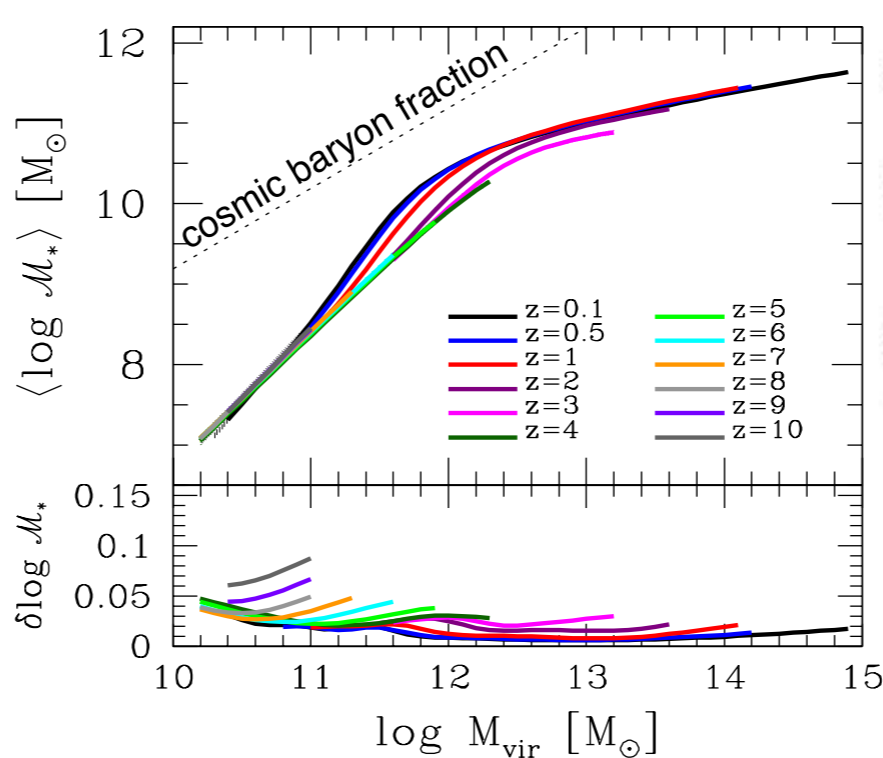
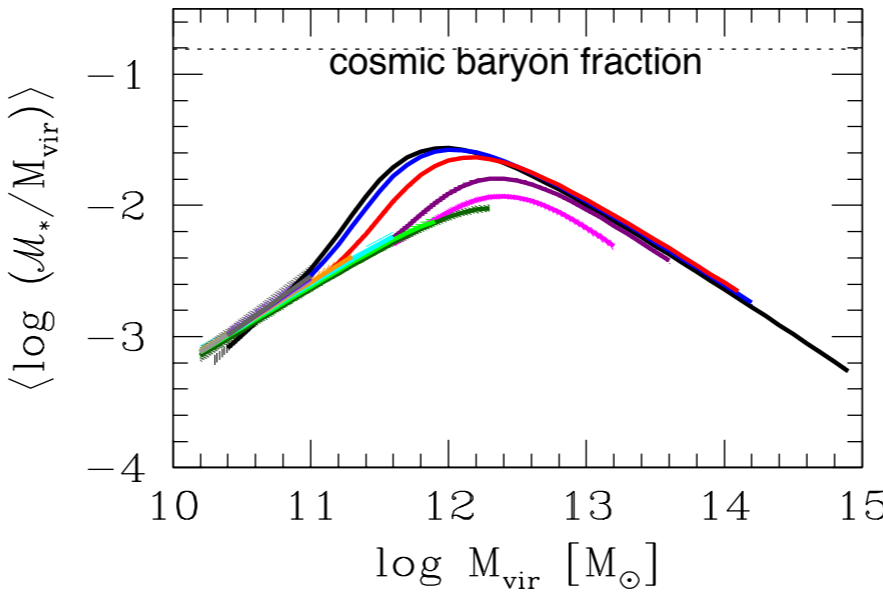
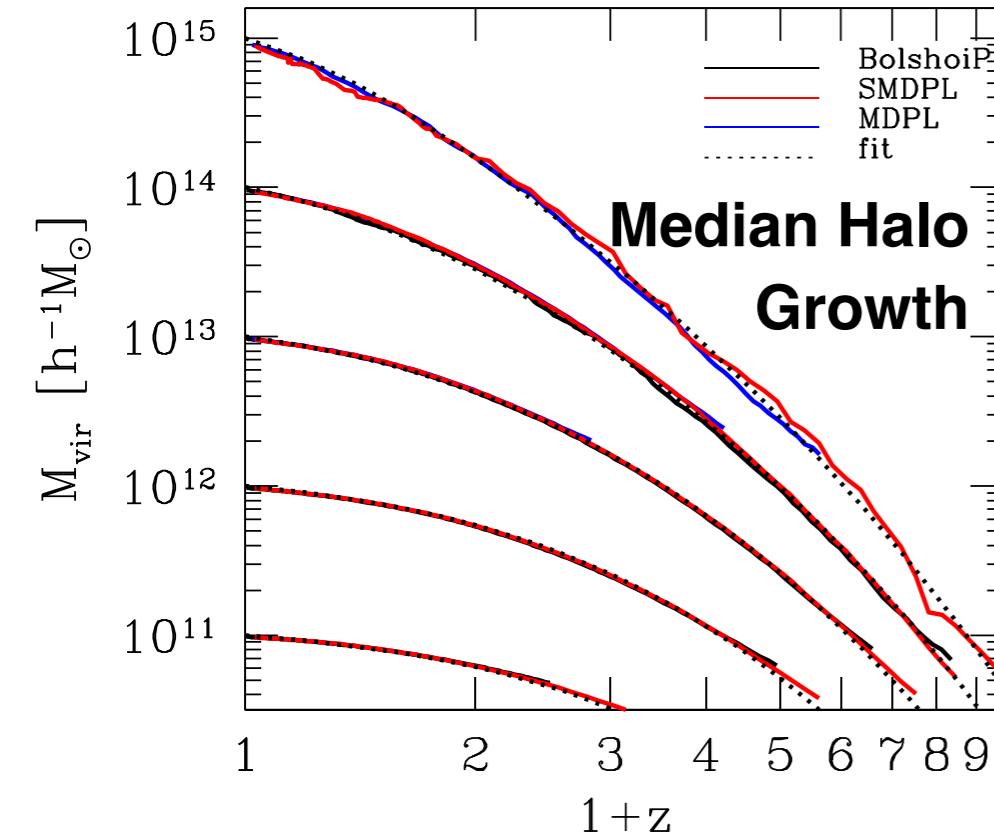
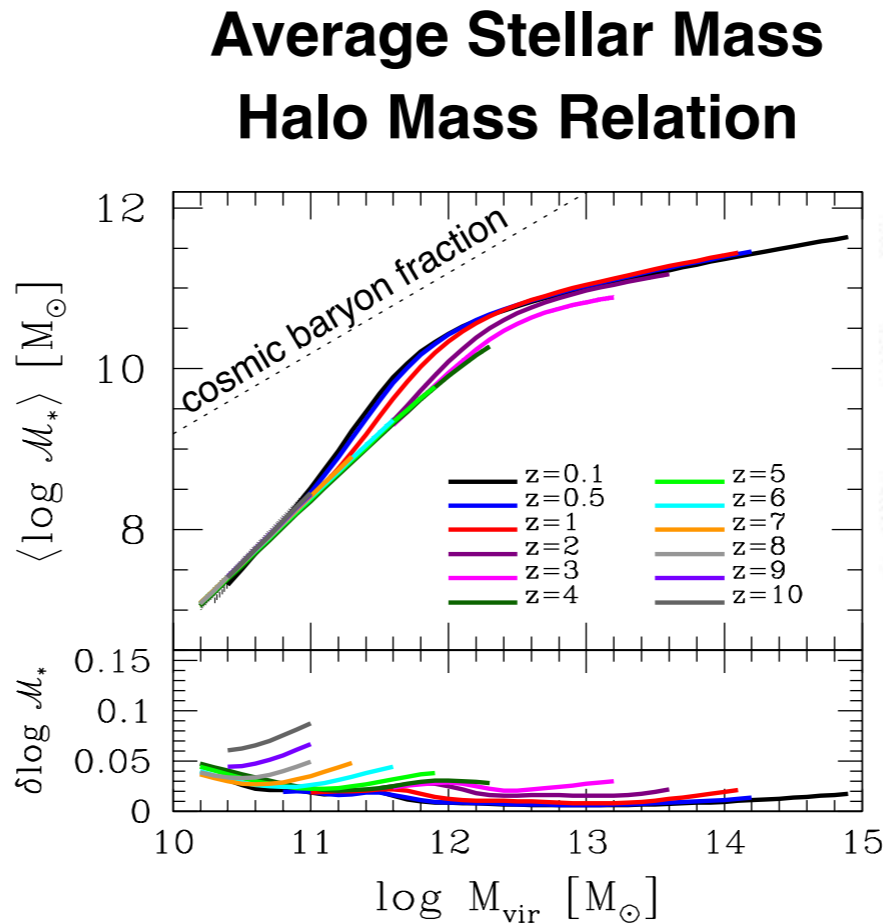
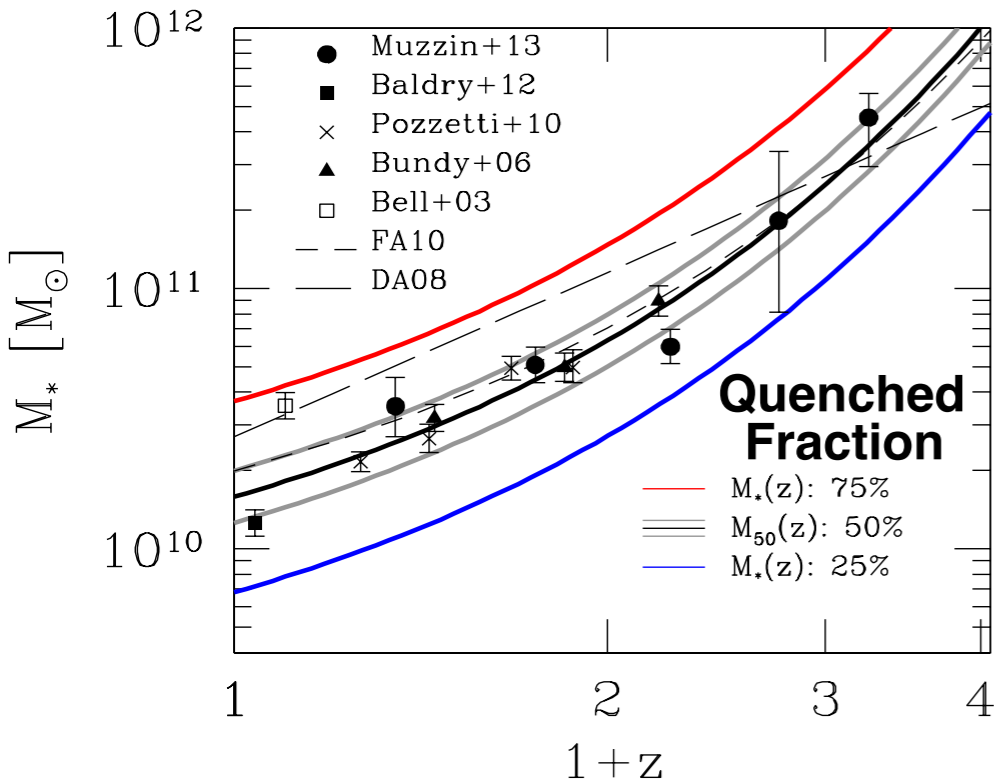
**Redshift evolution from  $z \sim 0.1$  to  $z \sim 10$  of the galaxy stellar mass function derived by using 20 observational samples from the literature and represented by filled circles with error bars. The various data has been corrected for potential systematics that could affect our results. Solid lines are the best fit model from a set of  $3 \times 10^5$  MCMC trials.**



**Star formation rates as a function of redshift  $z$  in five stellar mass bins. Filled circles with error bars show the observed data. Black solid lines show our best fit model to the SFRs.**

# Constraining the Galaxy Halo Connection: Star Formation Histories, Galaxy Mergers, and Structural Properties

Aldo Rodriguez-Puebla, Joel Primack, Vladimir Avila-Reese, Sandra Faber **MNRAS 2017**

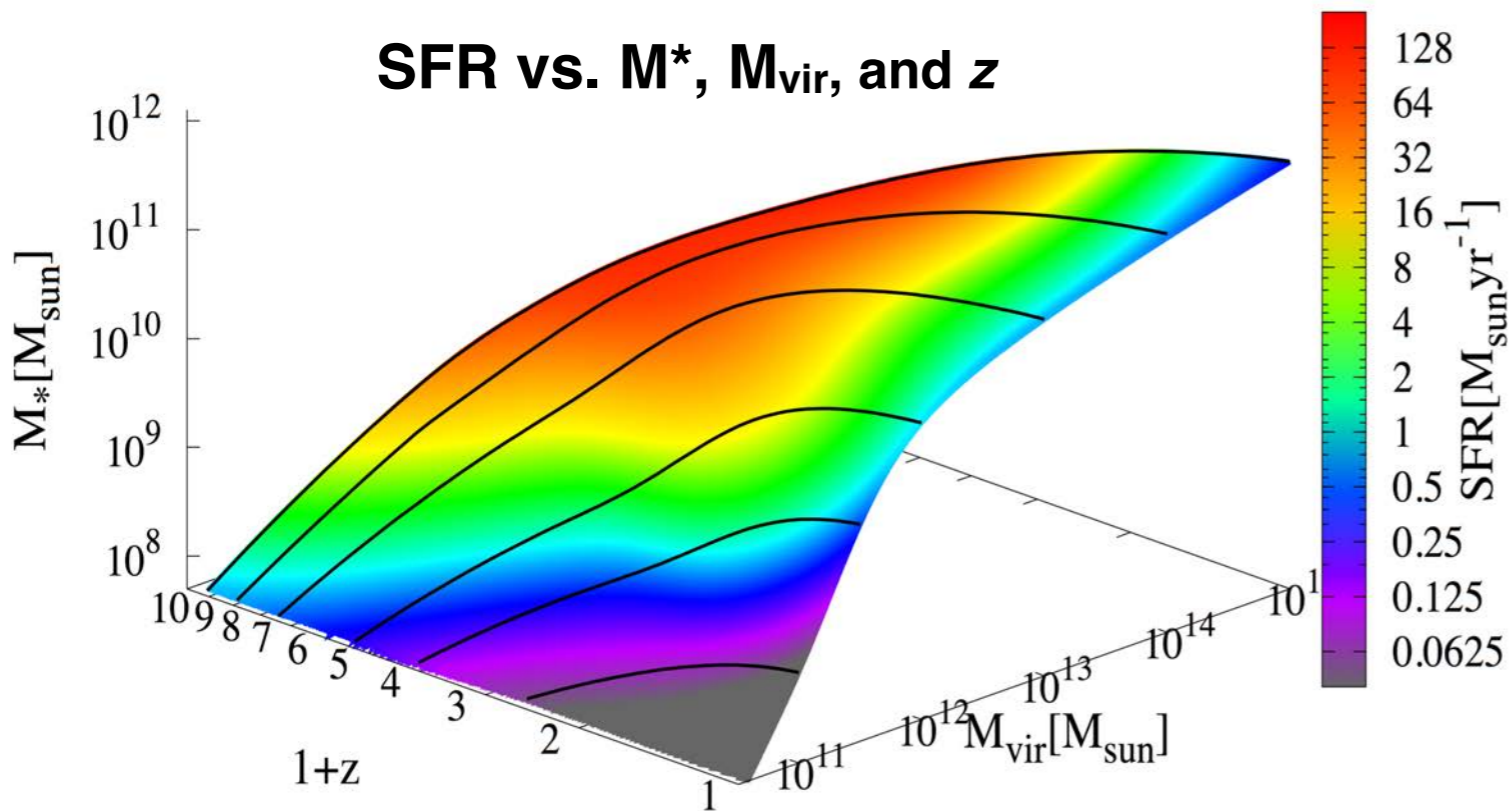


# Constraining the Galaxy Halo Connection:

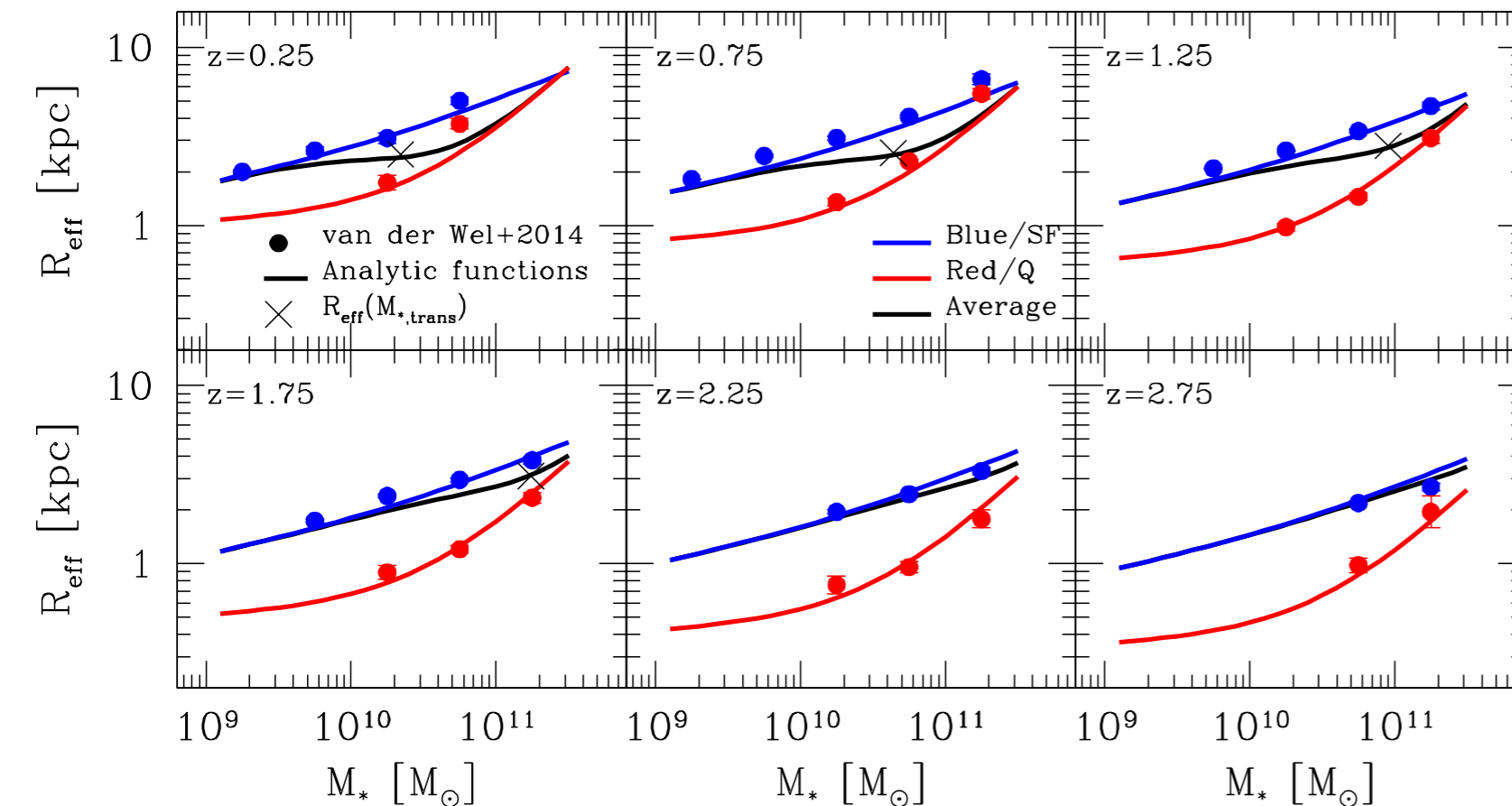
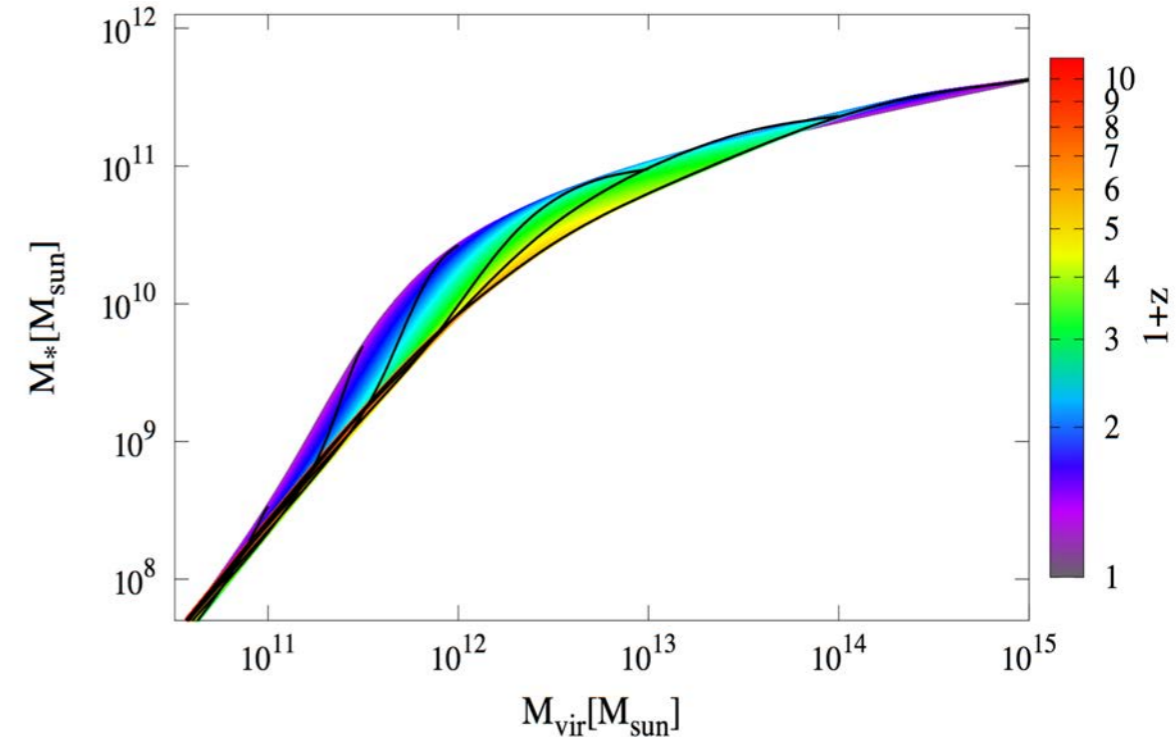
## Star Formation Histories, Galaxy Mergers, and Structural Properties

Aldo Rodriguez-Puebla, Joel Primack, Vladimir Avila-Reese, Sandra Faber

MNRAS 2017



### Stellar Mass-Halo Mass Relation



### Galaxy Radial Stellar Mass Distribution

Solid lines show the redshift dependence for blue and red galaxies of the local relation by Mosleh, Williams & Franx (2013) based on the MPA-JHU SDSS DR7. The black solid lines show the average circularized effective radius as a function of stellar mass. The crosses show the effective radius at  $M_{50}$ , the stellar mass at which the quenched fraction of galaxies is 50%. We utilize the plotted redshift dependences as an input to derive the average galaxy's radial mass distribution as a function of stellar mass by **assuming that blue/star-forming galaxies have a Sersic index  $n = 1$  while red/quenched galaxies have a Sersic index  $n = 4$ .**

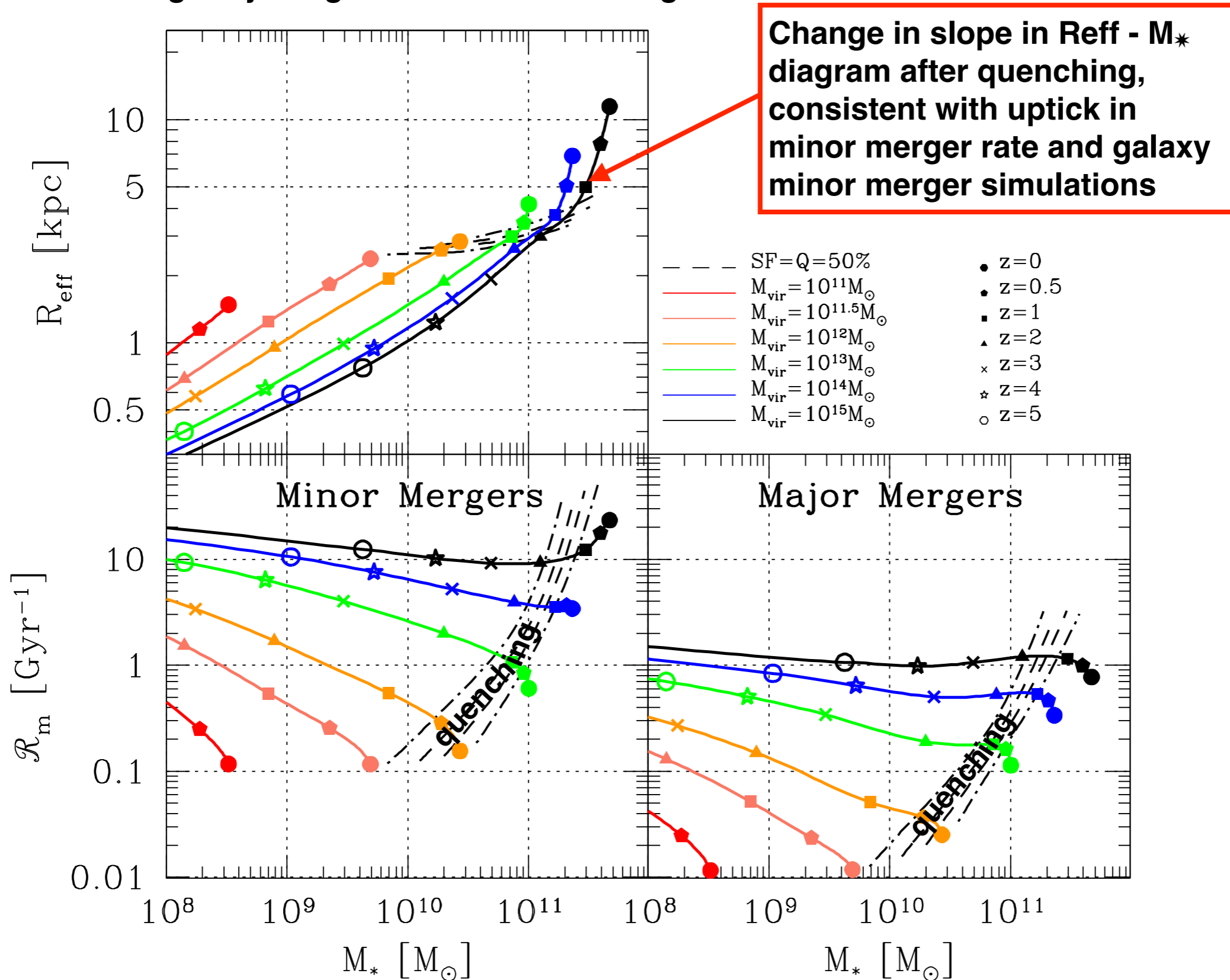
# Constraining the Galaxy Halo Connection:

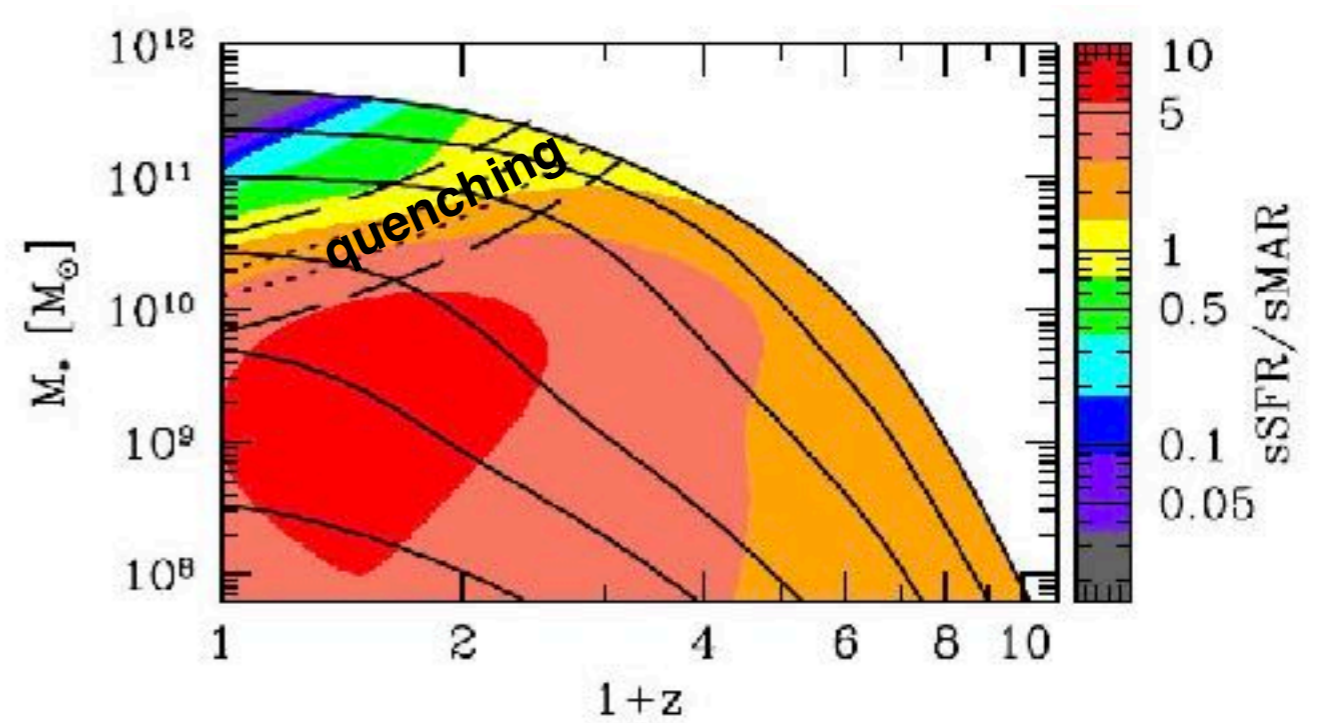
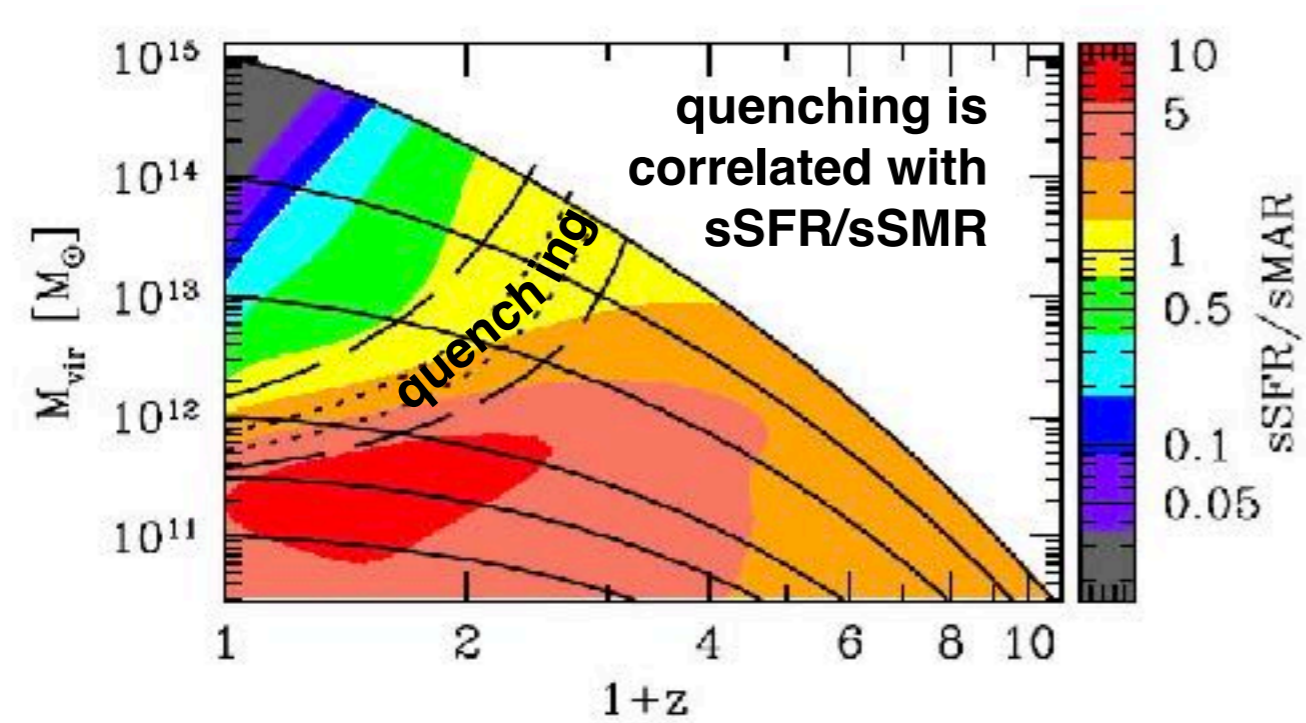
# Star Formation Histories, Galaxy Mergers, and Structural Properties

Aldo Rodriguez-Puebla, Joel Primack, Vladimir Avila-Reese, Sandra Faber

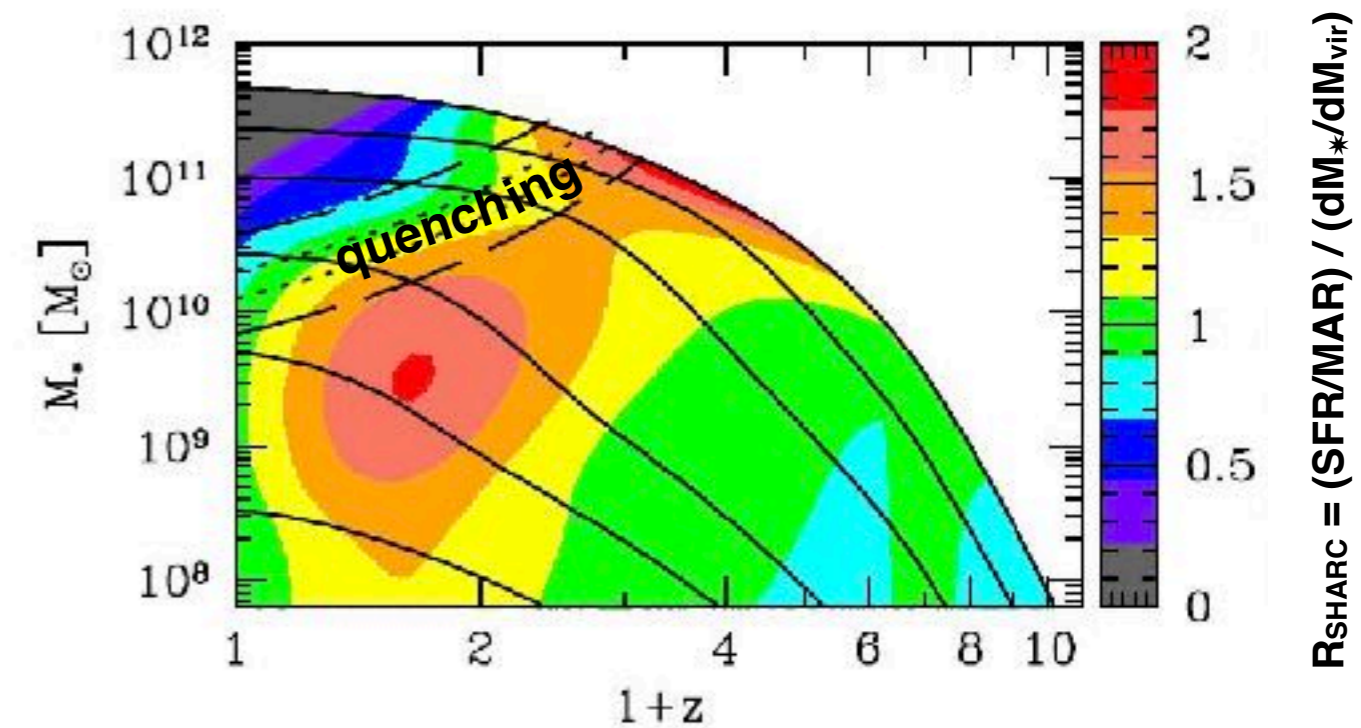
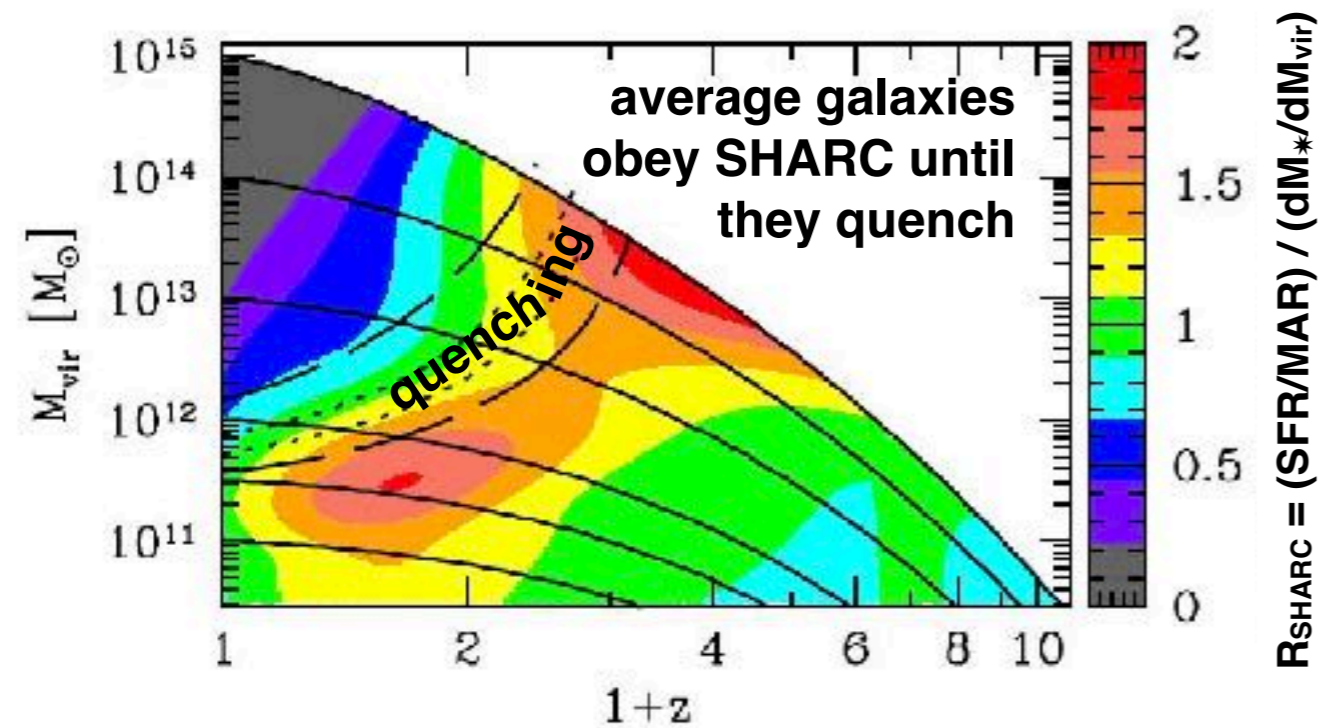
MNRAS 2017

We infer galaxy merger rates from halo mergers





This figure shows that quenching is correlated with  $sSFR/sSMR = t_{halo}/t_*$ , since  $sSFR/sSMR$  and quenching curves are nearly parallel.  $sSFR/sSMR$  - first rises, reaching a peak  $\sim 2$  at  $z \sim 3$  for  $10^{13}$  halos, a peak  $\sim 7$  for  $10^{12}$  halos at  $z \sim 1.5$ , and  $10^{11}$  halos are still at peak  $sSFR/sSMR \sim 10$  - then declines along all  $M_{vir}$  and  $M^*$  progenitor tracks toward  $z=0$ .



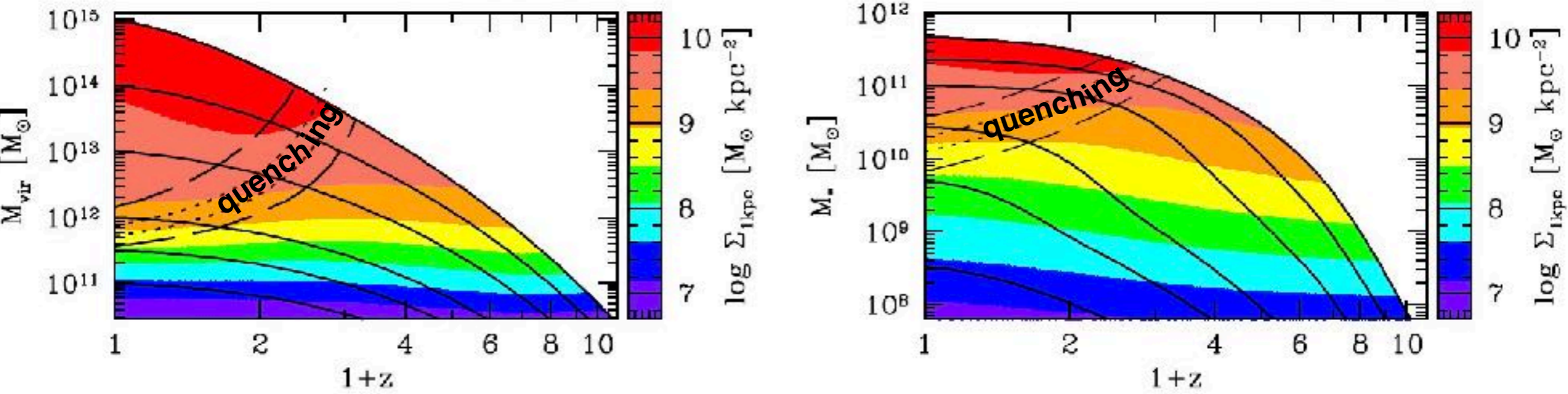
This figure shows that the SHARC approximation is rather well satisfied until quenching, the SHARC ratio  $R_{SHARC} = (SFR / MAR) / (dM_{vir}/d\log M^*)$  having a value of about 1 to 2 along the progenitor trajectories, and then dropping after quenching. This shows quenching is correlated with  $R_{SHARC}$  :

- the fraction of quenched galaxies is  $\sim 50\%$  when  $R_{SHARC} \sim 1$  to 1.5, and the quenched fraction is  $> 75\%$  when  $R_{SHARC}$  drops to  $\sim 1$
- like  $sSFR/sSMR$ ,  $R_{SHARC}$  first rises along all progenitor curves, reaches a peak at higher  $z$  for higher mass ( $M_{vir}$  or  $M^*$ ), and then declines
- unlike  $sSFR/sSMR$ , the peak SHARC ratio is nearly constant between 1.5 and 2 (the SHARC ratio peaks at about 2 for both  $10^{11.5}$  halos at  $z \sim 0.5$  and  $10^{15}$  halos at  $z \sim 3$ , and at about 1.5 for intermediate mass halos).

Note: the SHARC formula is  $SFR = (dM_*/dM_{vir}) MAR$  where  $MAR = dM_{vir}/dt$ . Define  $R_{SHARC} = (SFR / MAR) / (dM_*/dM_{vir})$ , so SHARC  $\implies R_{SHARC} = 1$ .

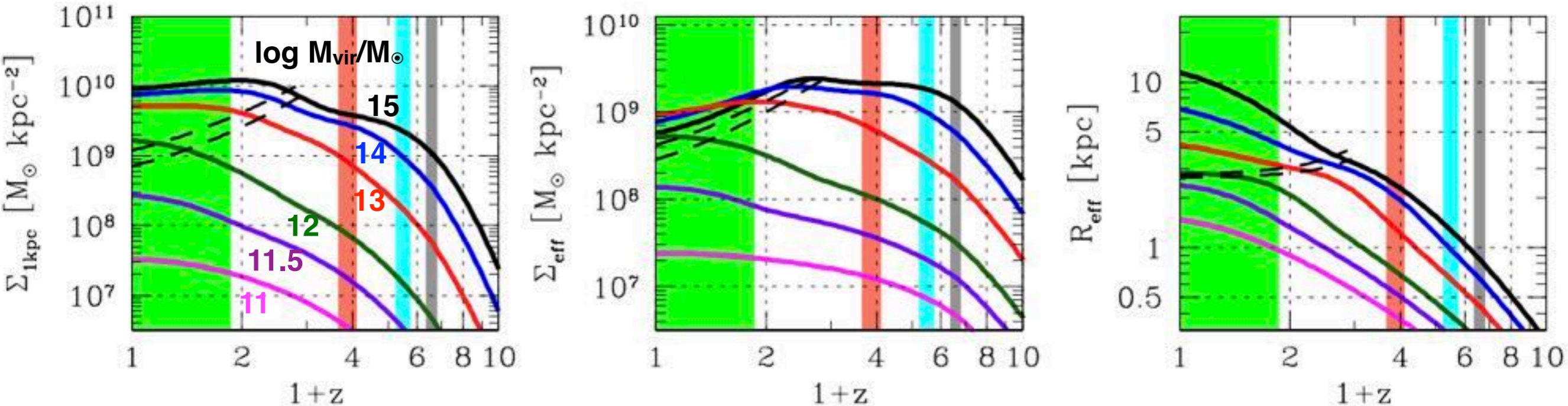
# Constraining the Galaxy Halo Connection: Star Formation Histories, Galaxy Mergers, and Structural Properties

Aldo Rodriguez-Puebla, Joel Primack, Vladimir Avila-Reese, Sandra Faber MNRAS 2017



This figure (and the left panel below) shows that  $\Sigma_1$  reaching a maximum correlates with quenching:

- $\Sigma_1$  at the quenching transition rises steadily with  $M_{vir}$  and reaches maximum at lower  $z$  for lower  $M_{vir}$  — “quenching downsizing”
- That the progenitor tracks are parallel to the trajectory curves shows that  $\Sigma_1$  remains constant after it reaches its maximum



The right panel shows that  $R_{eff}$  steadily rises along halo trajectories, and quenching typically occurs when  $R_{eff} \approx 3$  kpc. Although  $\Sigma_1$  is flat after quenching, the middle panel shows that  $\Sigma_{eff}$  declines after quenching as  $R_{eff}$  increases.



[https://132.248.1.39/galaxy/galaxy\\_halo.html](https://132.248.1.39/galaxy/galaxy_halo.html)

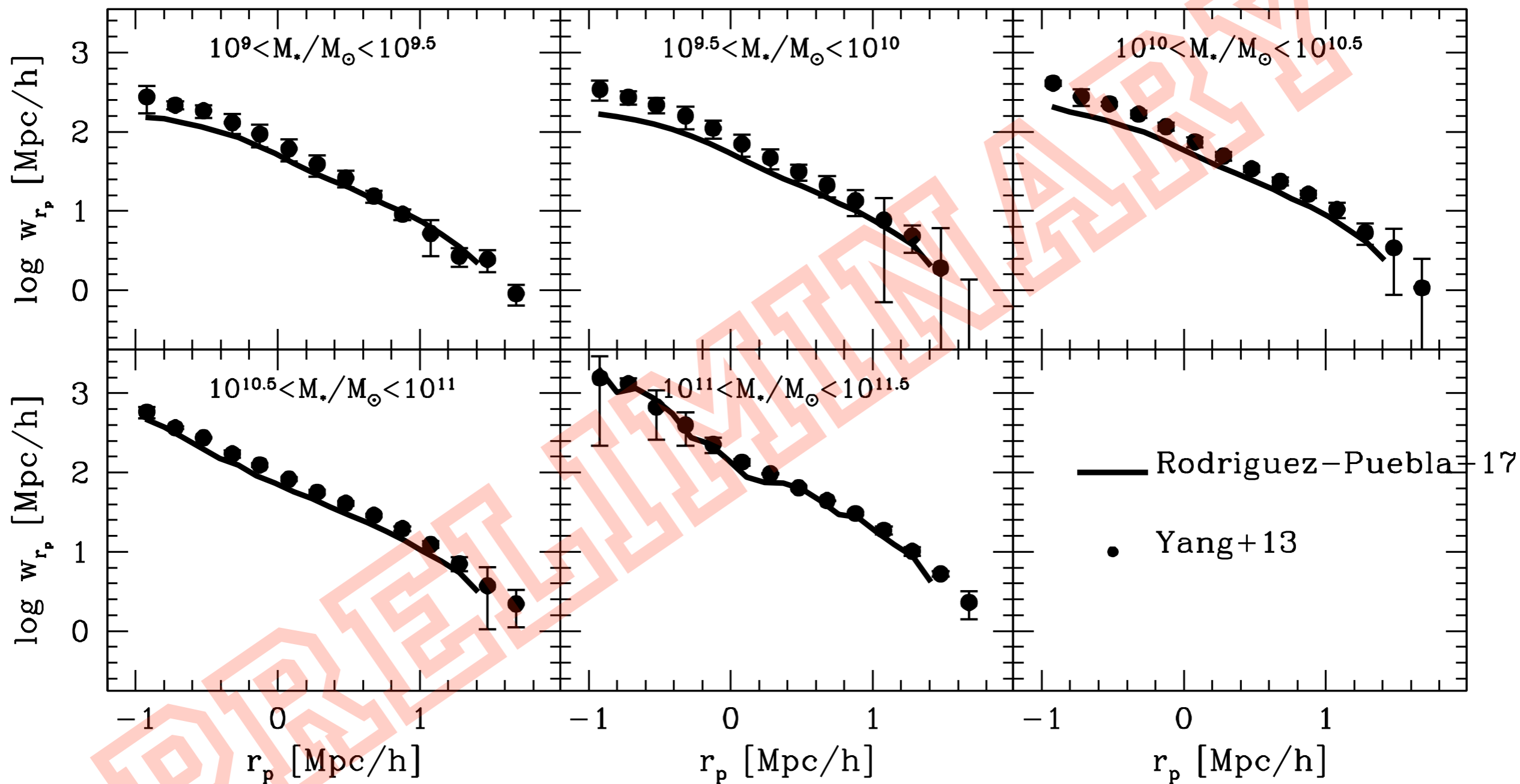
THE  
GALAXY-HALO CONNECTION  
PROJECT

HOW CAN I HELP YOU?

# Constraining the Galaxy Halo Connection: Star Formation Histories, Galaxy Mergers, and Structural Properties

Aldo Rodriguez-Puebla, Joel Primack, Vladimir Avila-Reese, Sandra Faber (RP17) [MNRAS 2017](#)

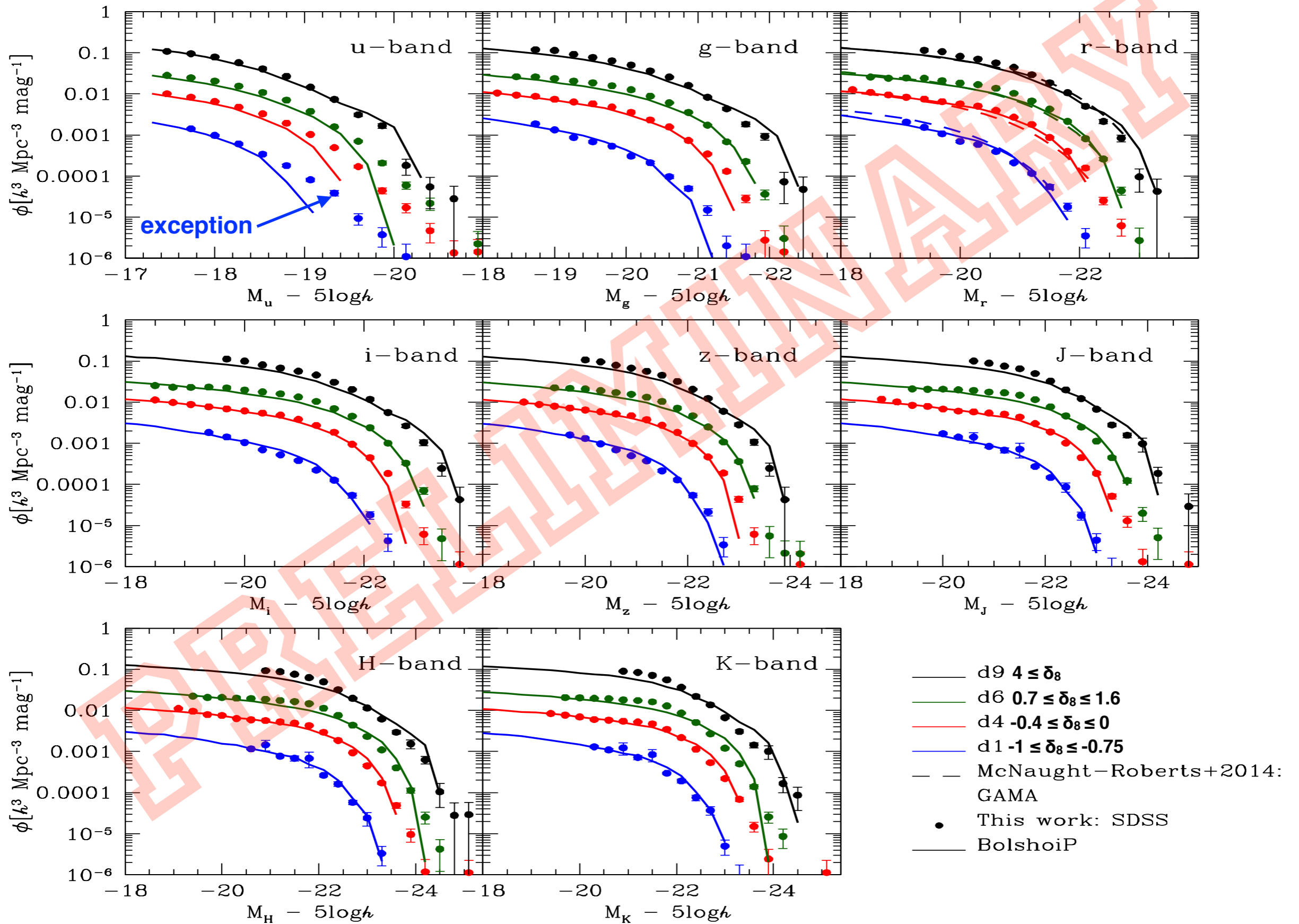
Corresponding 2-point correlation fcns - Rodriguez-Puebla et al. in prep.



Two point correlation function in five stellar mass bins. Solid lines indicate the results of the SHAM result from RP17 while filled circles with error bars is for the SDSS analysis from Yang+12. Note that RP17 used  $M_{\text{vir}}$  for distinct halos and  $M_{\text{peak}}$  for subhalos in their SHAM analysis. The correlation function is known to be underestimated when using  $M_{\text{vir}}$  and  $M_{\text{peak}}$  rather than  $V_{\text{max}}$  and  $V_{\text{peak}}$  in SHAM (e.g., Reddick et al. 2013).

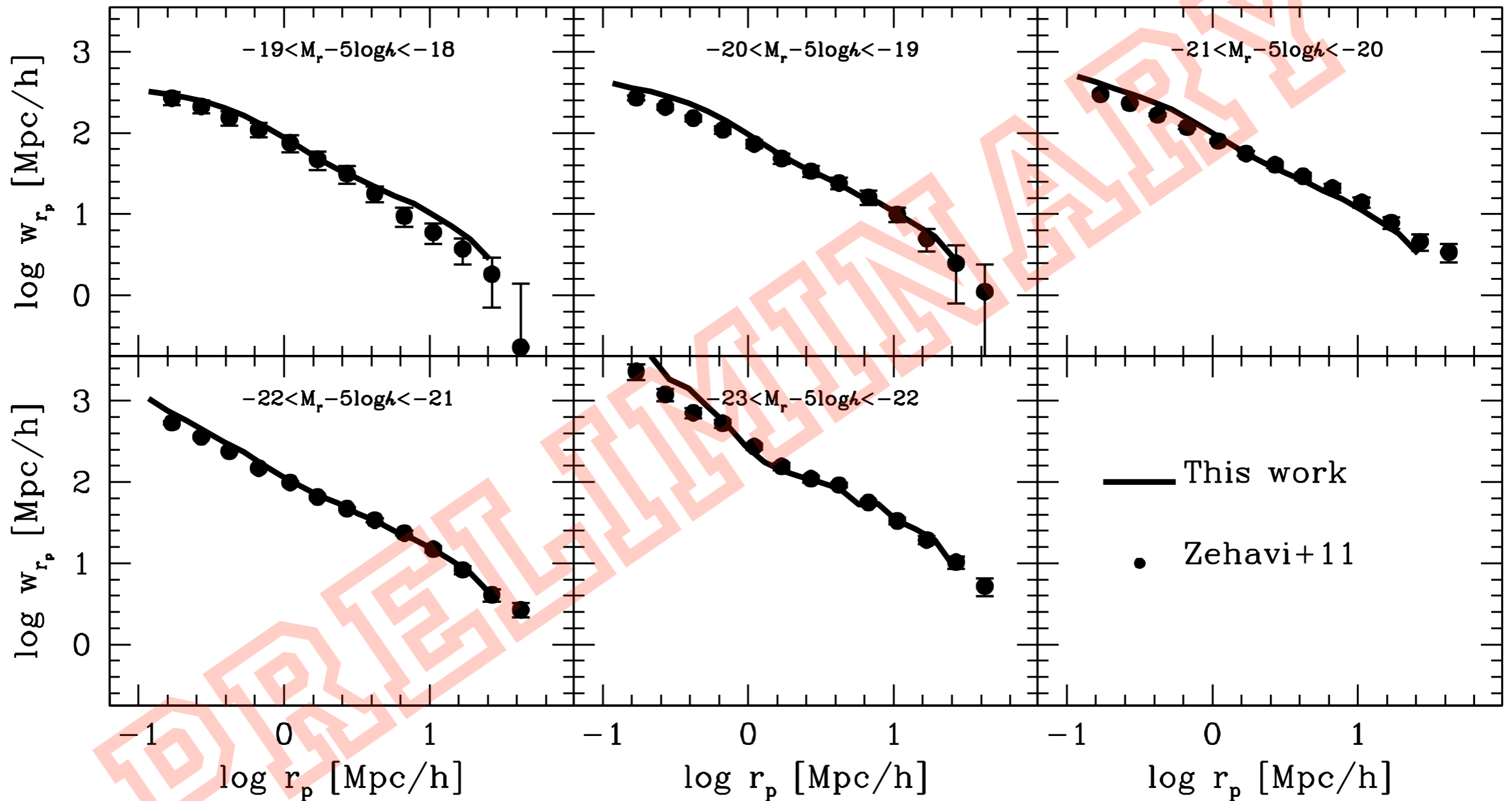
# Abundance Matching LF and MF Are Independent of Density

Radu Dragomir, Aldo Rodríguez-Puebla, Joel R. Primack, Christoph T. Lee, Peter Behroozi, Doug Hellinger, Avishai Dekel (in preparation)



# Abundance Matching LF and MF Are Independent of Density

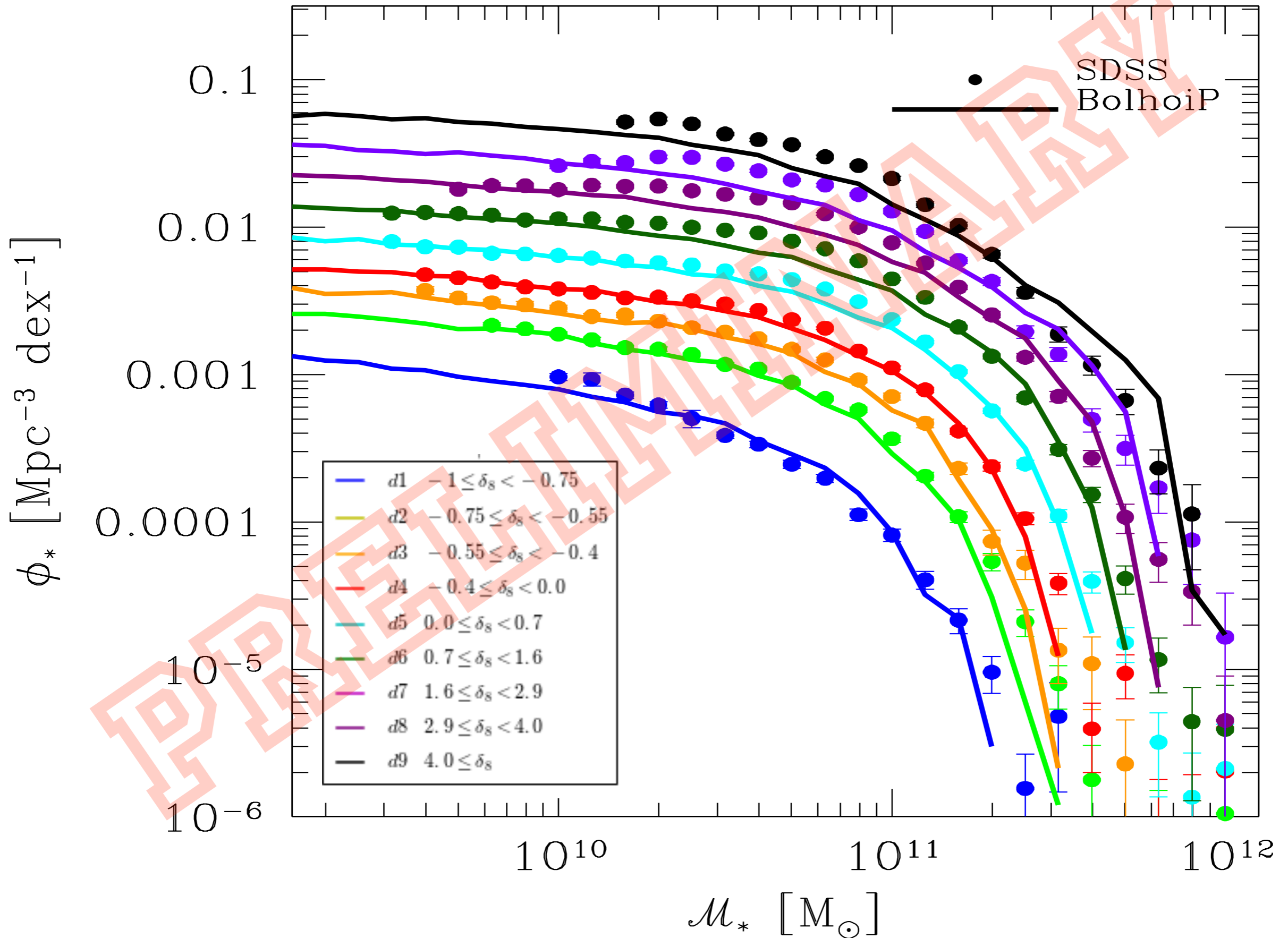
Radu Dragomir, Aldo Rodríguez-Puebla, Joel R. Primack, Christoph T. Lee,  
Peter Behroozi, Doug Hellinger, Avishai Dekel (in preparation)



Two point correlation function in five r-band luminosity bins. Solid lines indicate the results of the SHAM result from Radu Dragomir et al. in prep., while filled circles with error bars are for the SDSS analysis from Zehavi+2011. Dragomir et al. in prep. uses  $V_{\max}$  for distinct halos and  $V_{\text{peak}}$  for subhalos.

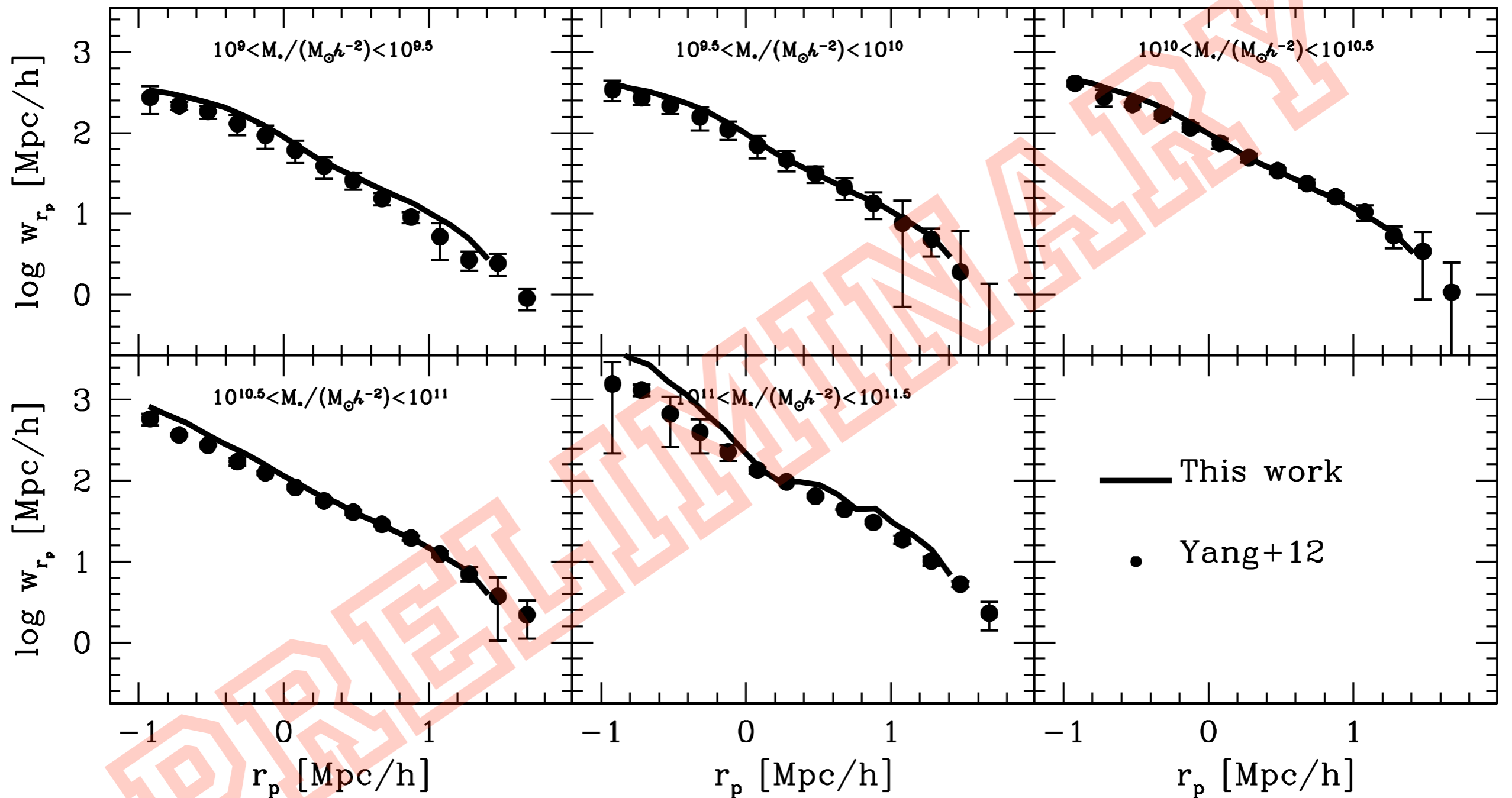
# Abundance Matching LF and MF Are Independent of Density

Radu Dragomir, Aldo Rodríguez-Puebla, Joel R. Primack, Christoph T. Lee,  
Peter Behroozi, Doug Hellinger, Avishai Dekel (in preparation)



# Abundance Matching LF and MF Are Independent of Density

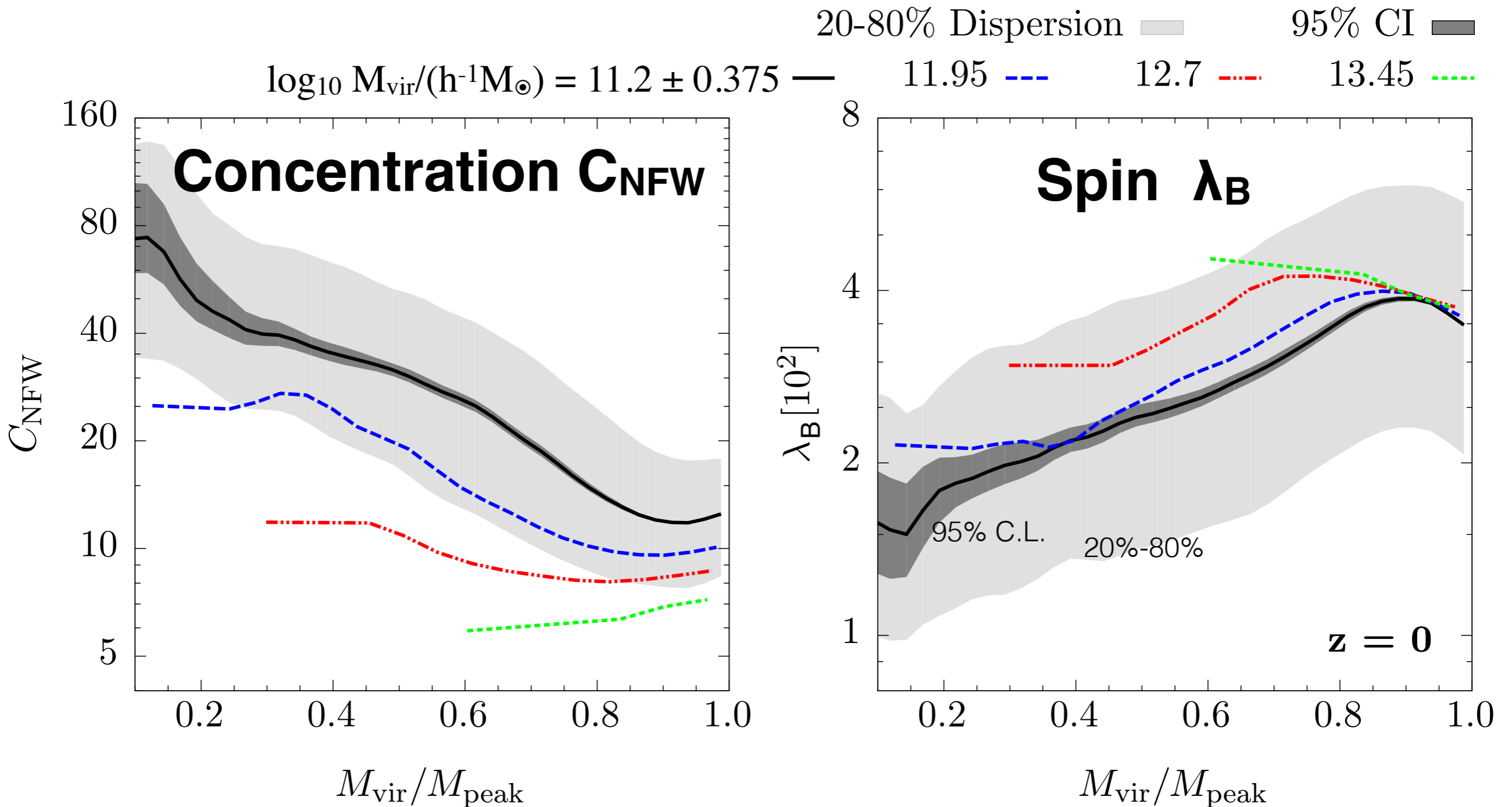
Radu Dragomir, Aldo Rodríguez-Puebla, Joel R. Primack, Christoph T. Lee,  
Peter Behroozi, Doug Hellinger, Avishai Dekel (in preparation)



Two point correlation function in five stellar mass bins. Solid lines indicate the results of the SHAM result from Radu in prep. while filled circles with error bars is for the SDSS analysis from Yang+12. In this case Dragomir et al. in prep. uses  $V_{\max}$  for distinct halos and  $V_{\text{peak}}$  for subhalos in the SHAM analysis. Note that this SHAM reproduces the two point correlation function and the stellar mass function in various environments at the same time.

# Causes & Consequences of Halo Mass Loss

Christoph T. Lee, Joel R. Primack, Peter Behroozi, Aldo Rodríguez-Puebla, Doug Hellinger, Austin Tuan, Jessica Zhu, Avishai Dekel **in final prep.**



- **Most low mass halos in dense regions are significantly stripped**
- **Halos that have lost 5-15% of their mass relative to  $M_{\text{peak}}$  have lower  $C_{\text{NFW}}$ , higher  $\lambda_{\text{B}}$**
- **Halos that have lost more than  $\sim 20\%$  of their mass have higher  $C_{\text{NFW}}$  and lower  $\lambda_{\text{B}}$**

# Causes & Consequences of Halo Mass Loss

Christoph Lee  
GalHalo17-Conference Poster

## Tidal Stripping:

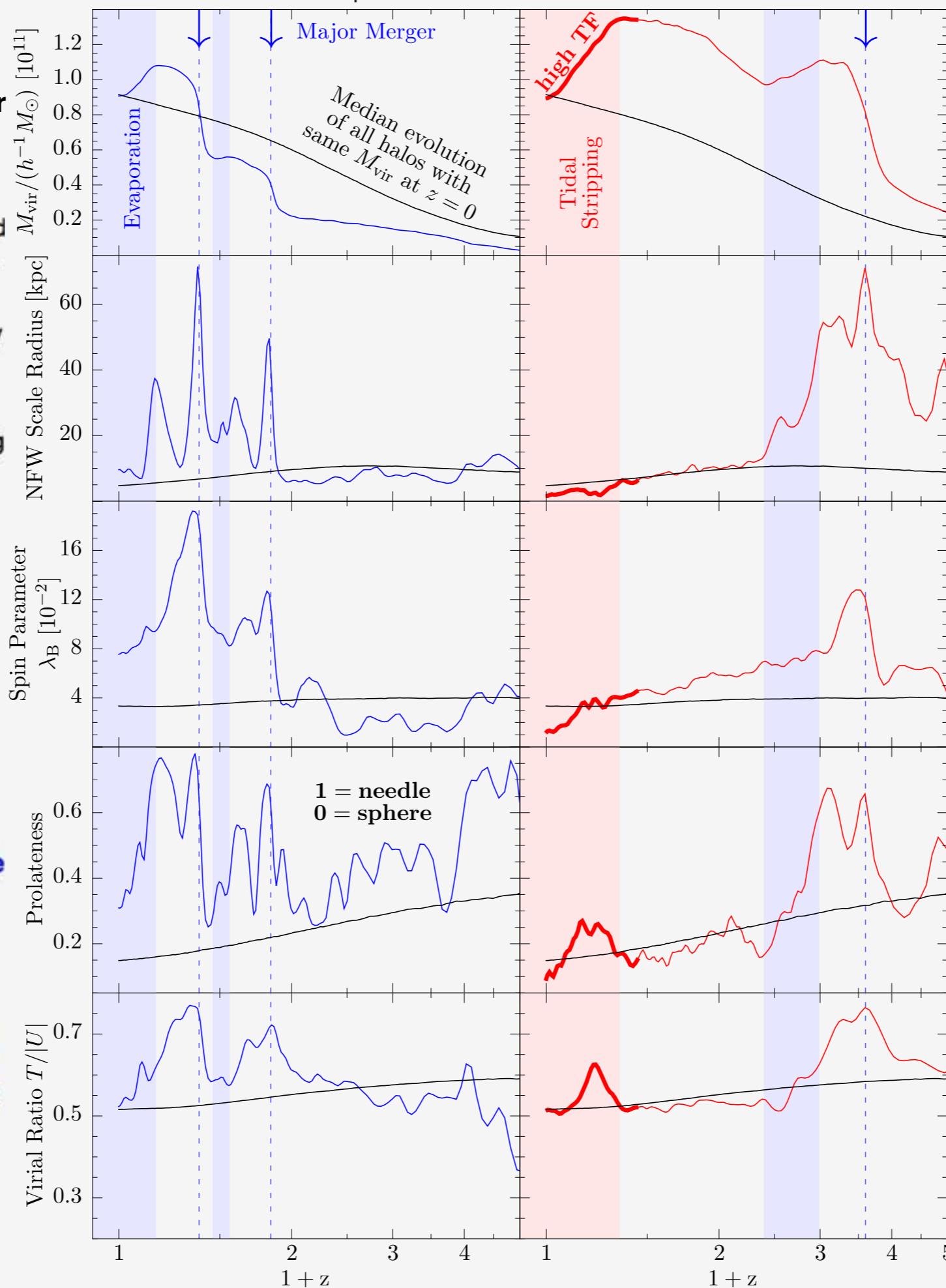
Strong tidal force from a nearby massive halo removes loosely bound particles from a halo. 40% of tidally stripped low mass halos lose more than 20% of their peak mass. Tidally stripped halos develop:

- **Low NFW scale radius** (high concentration) due to steepening outer profile
- **Low spin parameter** due to preferential removal of high angular momentum material
- **Low prolateness** (they become rounder) due to preferential removal of particles on highly elliptical orbits.

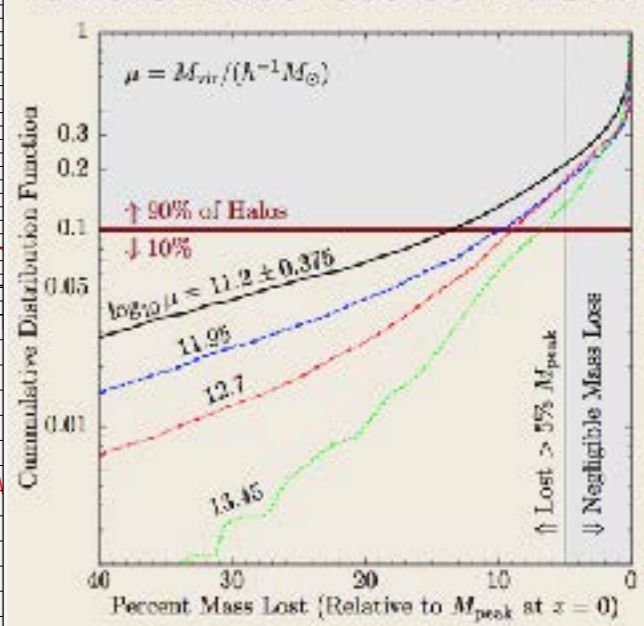
## Evaporation:

Major mergers typically cause **temporary jumps in NFW scale radius, spin parameter, and shape**. As halos relax after a merger, they shed high energy material (evaporate) and **settle back to lower values of scale radius, spin parameter, shape, and virial ratio**. After a major merger, halos typically lose 5-15% of their peak mass through evaporation.

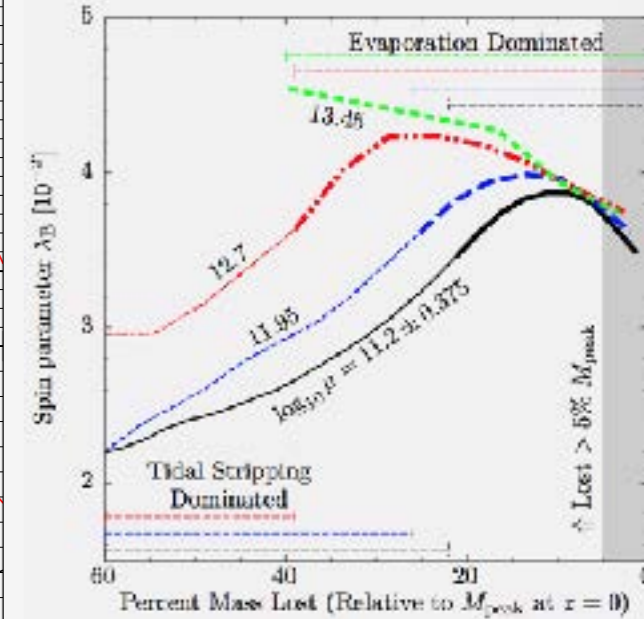
## Examples of individual halo evolution



## Is halo mass loss common?



## Extending this analysis to all halos

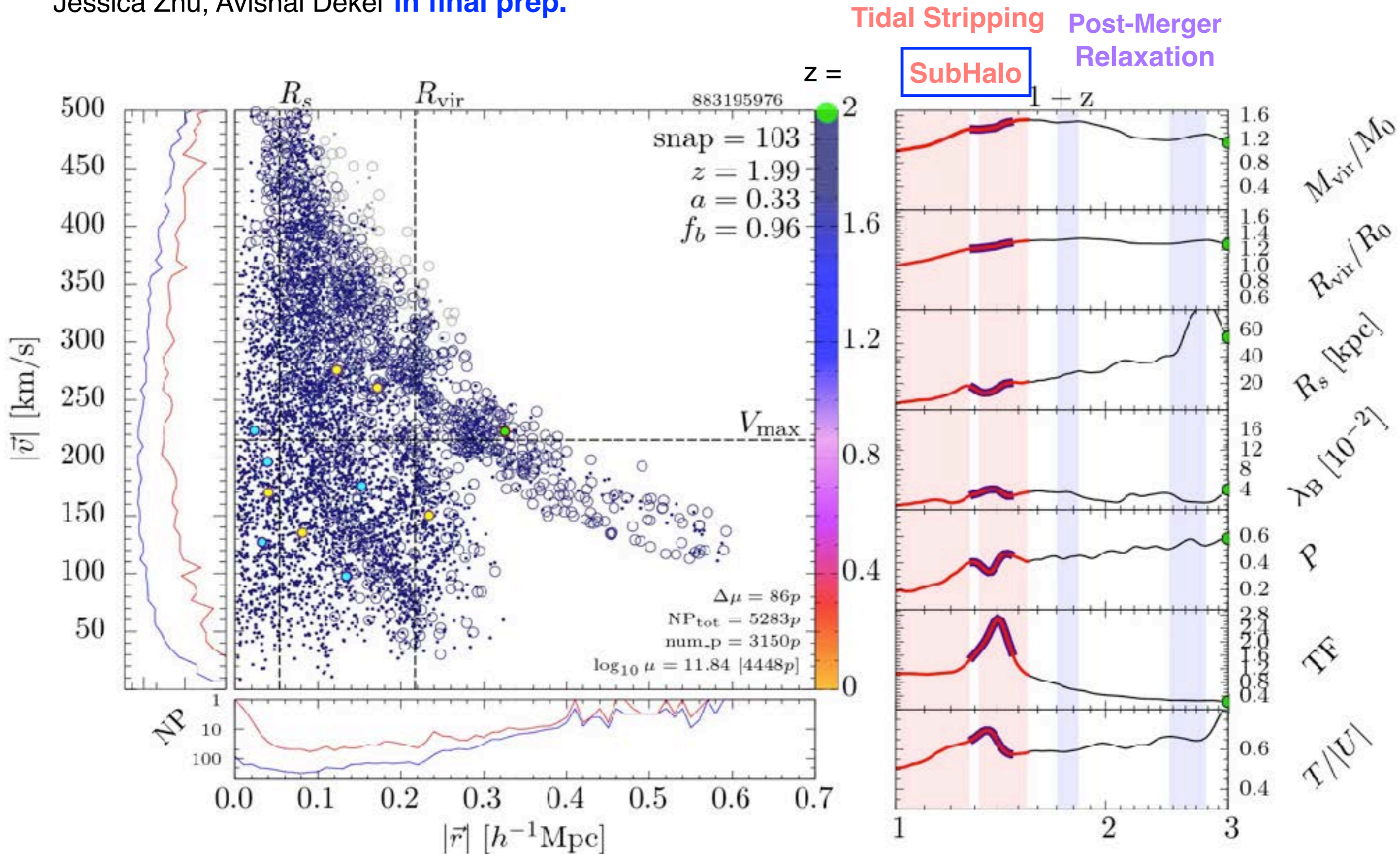


- Low mass halos ( $\log \mu = 11.2$ ) that have lost 5-15% of their peak mass most commonly experienced evaporative mass loss (temporarily high spin parameters).
- Low mass halos that have lost greater than 20% of their peak mass typically are actively being tidally stripped (low spin parameters). More heavily stripped halos have lower spin parameters.
- Some low mass halos are strongly affected by tidal stripping, while high mass halos predominantly experience evaporative mass loss.



# Tidal Stripping and Post-Merger Relaxation: Causes & Consequences of Halo Mass Loss

Christoph T. Lee, Joel R. Primack, Peter Behroozi, Aldo Rodríguez-Puebla, Doug Hellinger, Austin Tuan, Jessica Zhu, Avishai Dekel [in final prep.](#)



# Properties of Dark Matter Haloes: Local Environment Density

Christoph T. Lee, Joel R. Primack, Peter Behroozi, Aldo Rodríguez-Puebla, Doug Hellinger, Avishai Dekel [MNRAS 2017](#)

## Low Mass

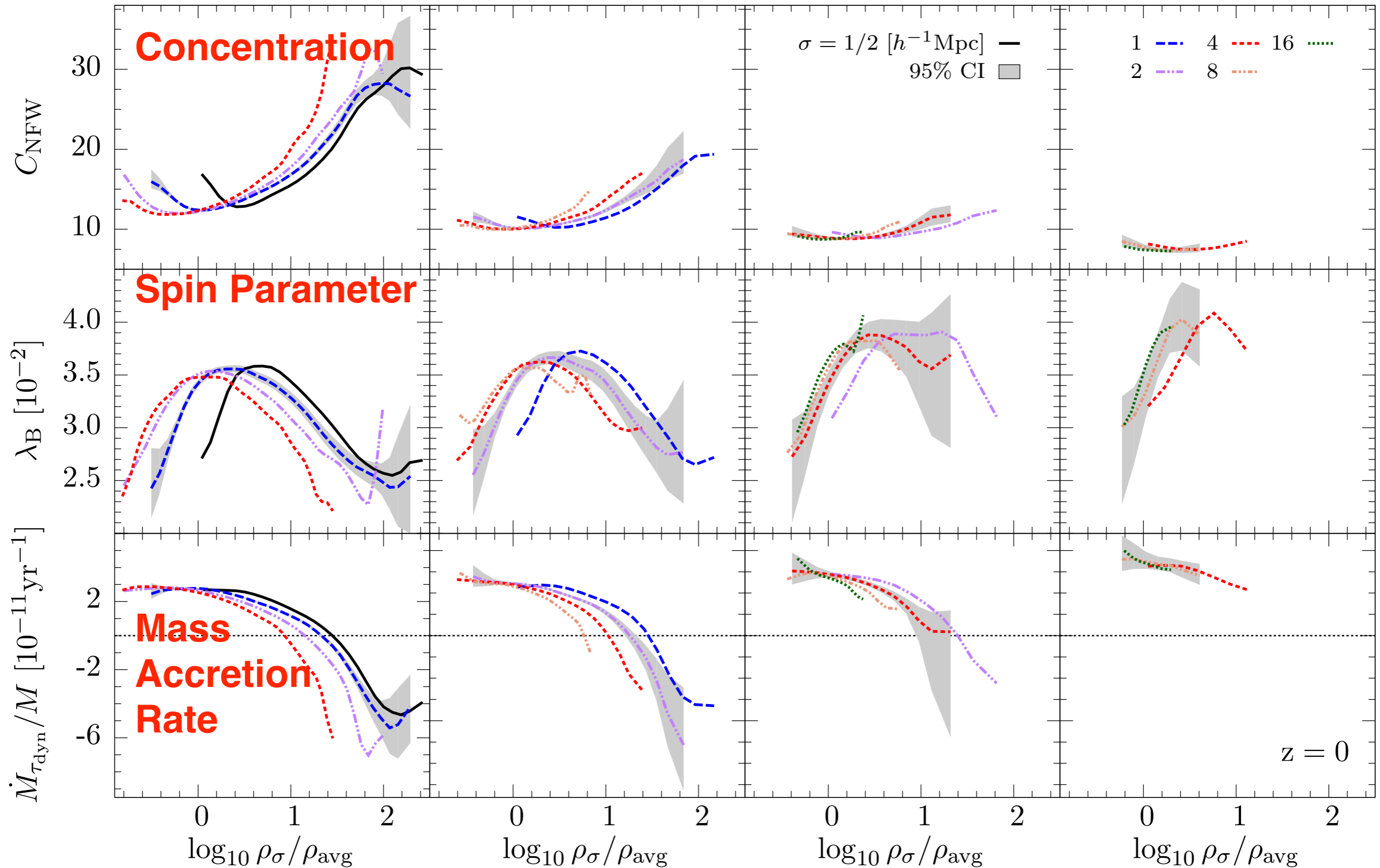
$\log_{10} M_{\text{vir}} / (h^{-1} M_{\odot}) = 11.200 \pm 0.375$

## Intermediate Mass

$11.95 \pm 0.375$

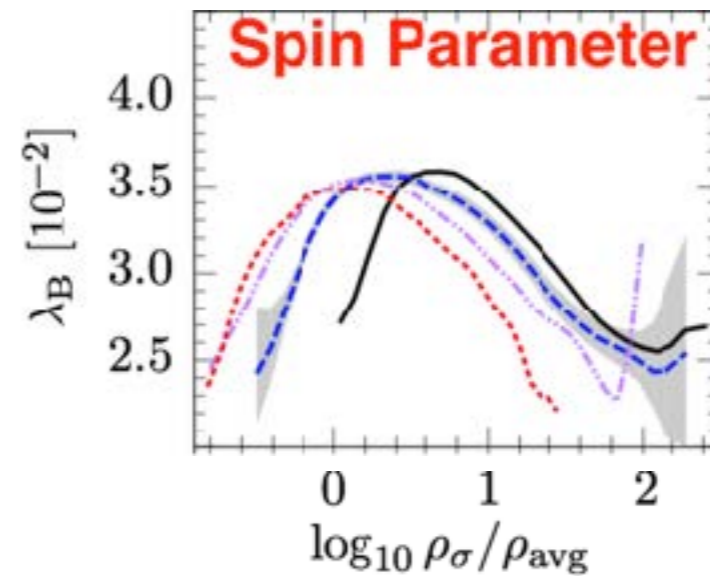
## High Mass

$13.45 \pm 0.375$



# Is Galaxy Radius $R_{3D}^* \propto \lambda R_{halo}$ ?

## Measure $R_{3D}^*$ vs. Local Density!



Huertas-Company+ 2013 found no difference in galaxy size vs. density. Cebrian & Trujillo 2014; Pranger, Trujillo, Kelvin, Cebrian 2017; Yoon, Im, and Kim 2017; and Zhang & Yang 2017 find that galaxies in low-density regions are perhaps slightly larger at the same stellar mass.

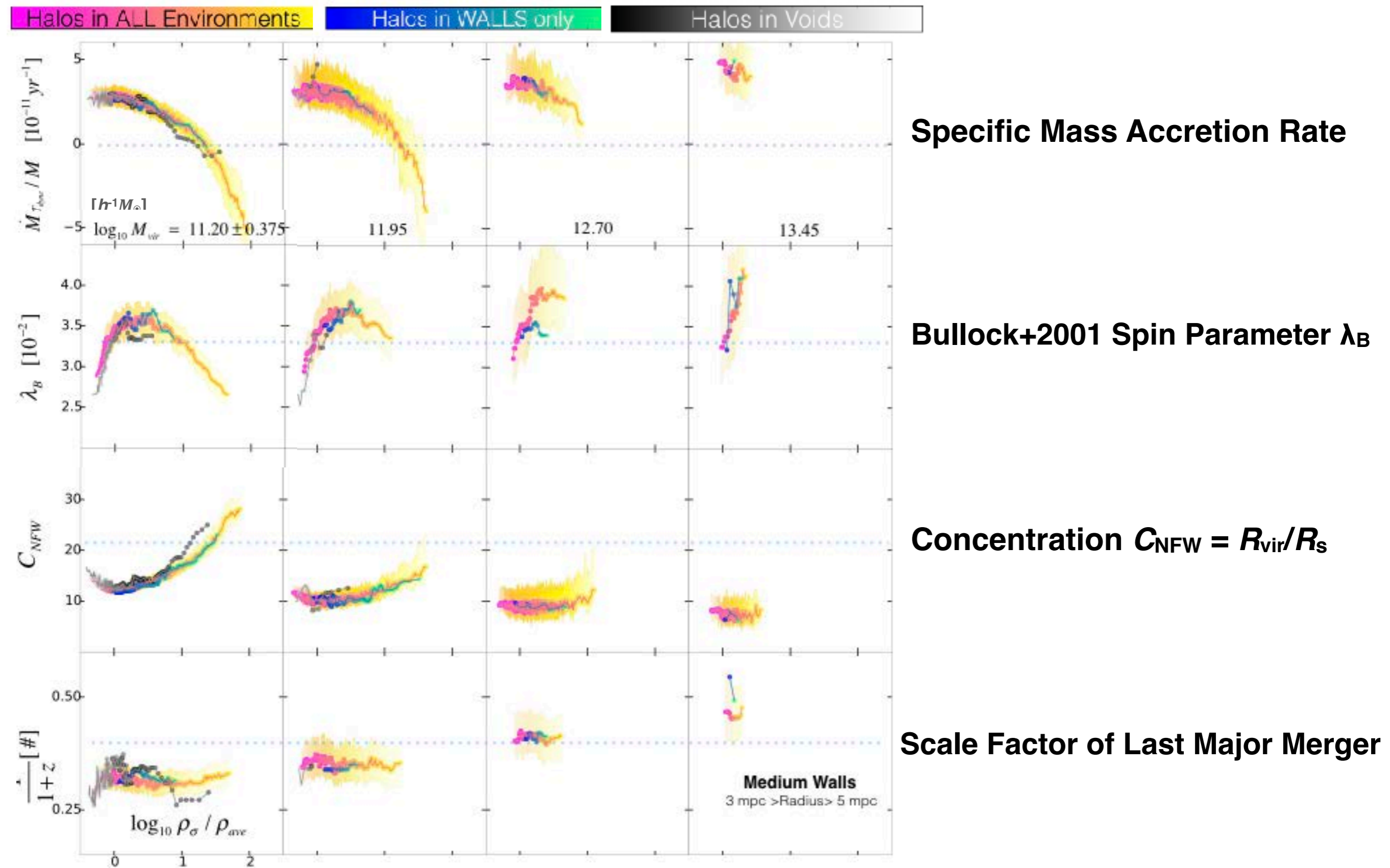
Kravtsov 2013 found that  $\langle R_{3D}^* \rangle \approx 0.015 R_{halo}$  at  $z \sim 0$ , and Somerville+2017 agreed at  $z \sim 0$  using GAMA and found that  $\langle R_{3D}^* \rangle \approx 0.02 R_{halo}$  out to  $z \sim 3$ . But the papers listed above did not attempt to measure  $R_{3D}^*$  nor did they measure density around low-mass galaxies carefully in low-density regions.

**We are measuring  $R_{3D}^*$  vs. density in SDSS using several methods (galaxy counts within 2 Mpc projected, distance to nth nearest galaxy, Voronoi volume), and spin  $\lambda$  vs. density by the exact same methods in mock catalogs from Bolshoi-Planck and MultiDark-Planck.**

**We are also determining how to measure  $R_{3D}^*$  from the optical images.**

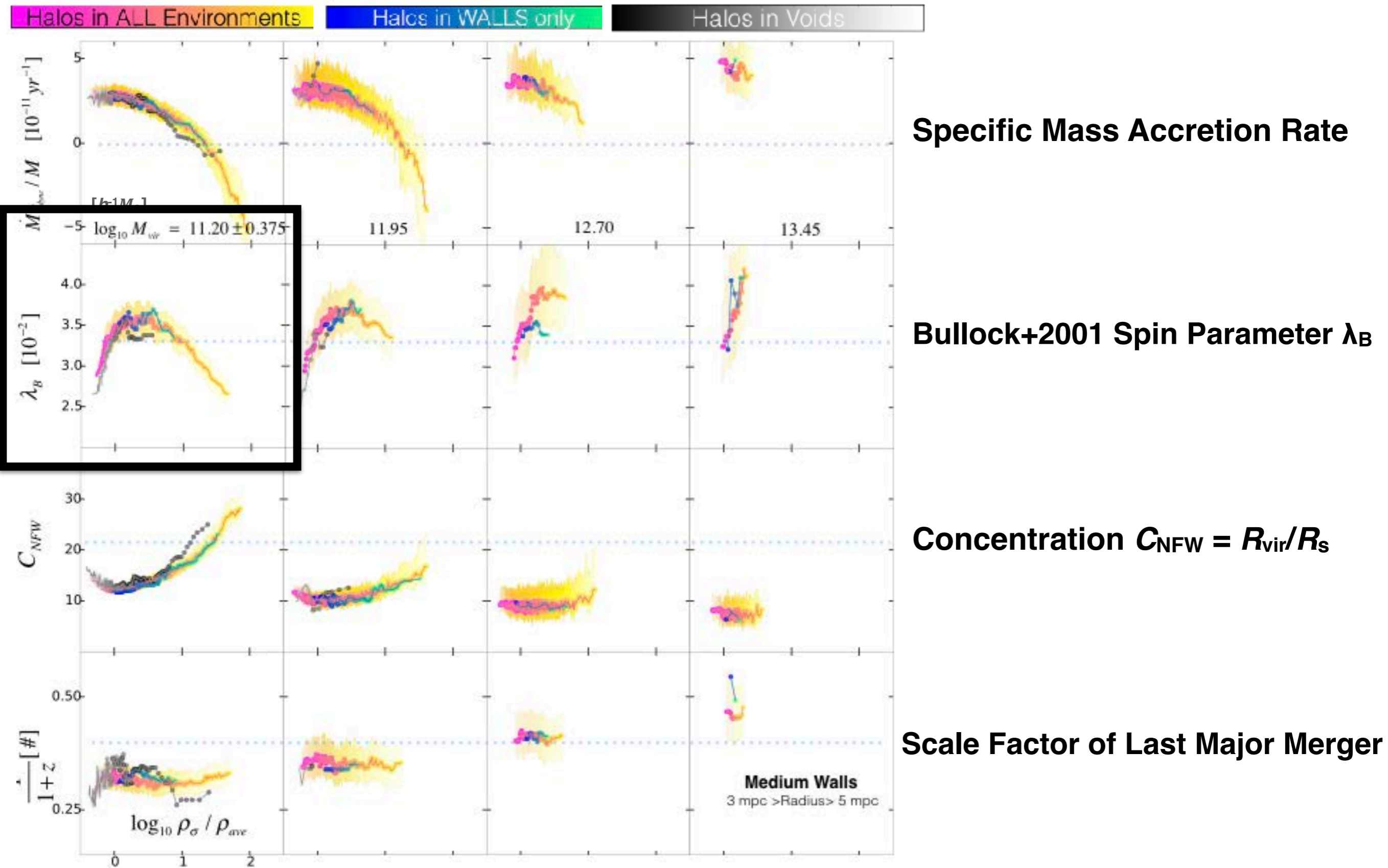
# Halo Properties Independent of Web Location at the Same Density

Tze Ping Goh, Christoph T. Lee, Joel R. Primack, Miguel Aragon Calvo, Peter Behroozi, Aldo Rodríguez-Puebla, Doug Hellinger, Avishai Dekel, Kathryn Johnston (in preparation)



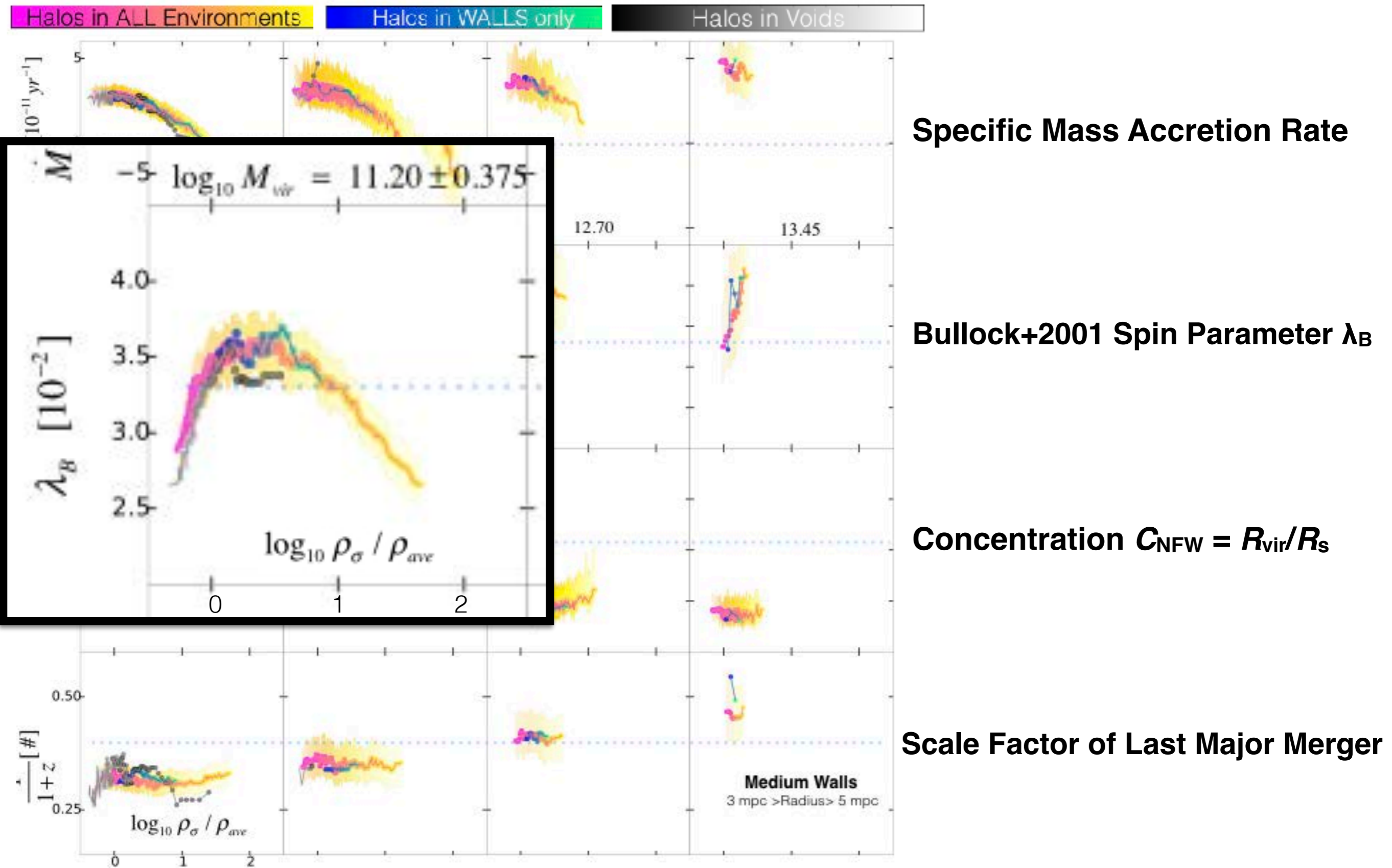
# Halo Properties Independent of Web Location at the Same Density

Tze Ping Goh, Christoph T. Lee, Joel R. Primack, Miguel Aragon Calvo, Peter Behroozi, Aldo Rodríguez-Puebla, Doug Hellinger, Avishai Dekel, Kathryn Johnston (in preparation)



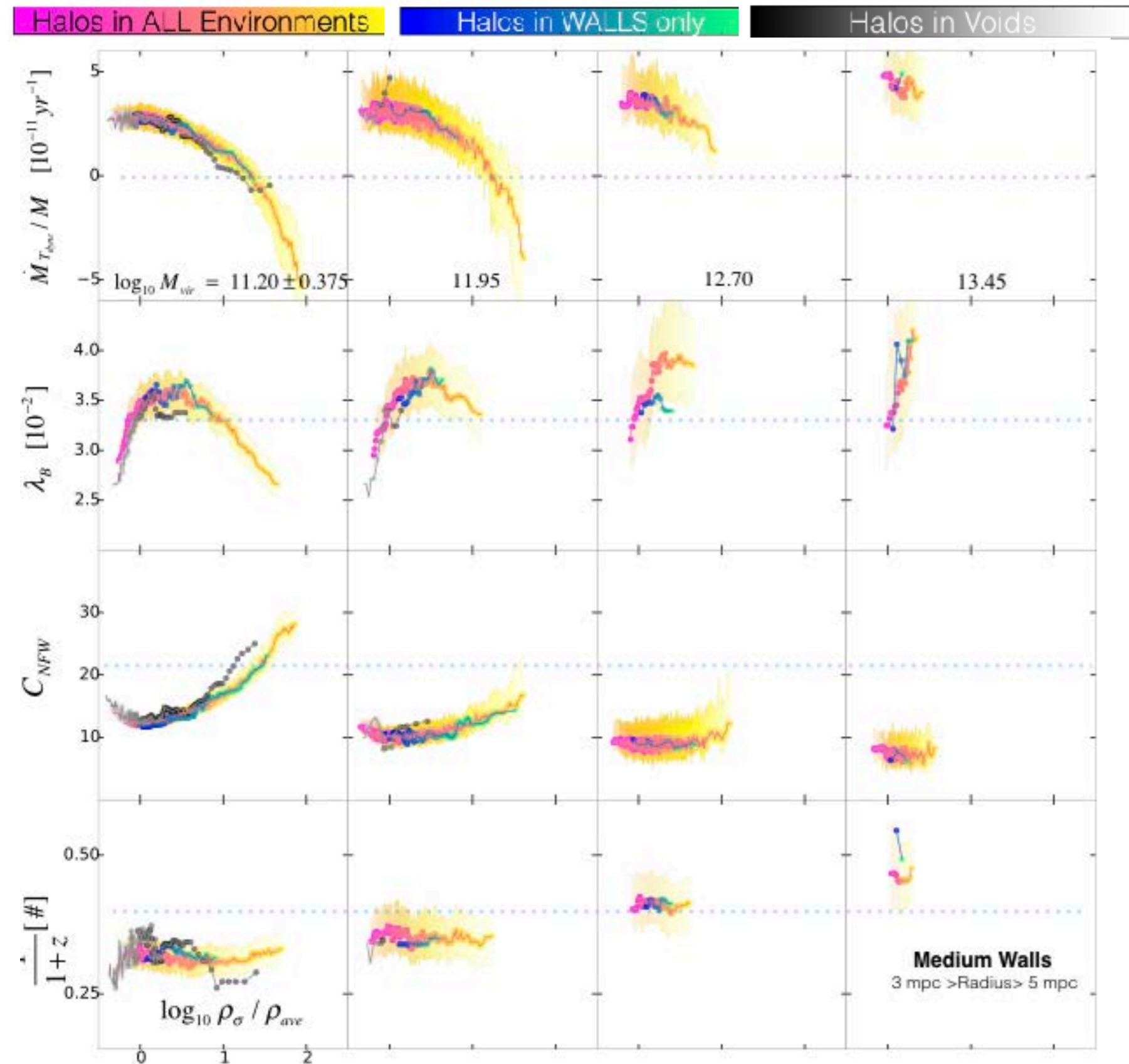
# Halo Properties Independent of Web Location at the Same Density

Tze Ping Goh, Christoph T. Lee, Joel R. Primack, Miguel Aragon Calvo, Peter Behroozi, Aldo Rodríguez-Puebla, Doug Hellinger, Avishai Dekel, Kathryn Johnston (in preparation)



# Halo Properties Independent of Web Location at the Same Density

Tze Ping Goh, Christoph T. Lee, Joel R. Primack, Miguel Aragon Calvo, Peter Behroozi, Aldo Rodríguez-Puebla, Doug Hellinger, Avishai Dekel, Kathryn Johnston (in preparation)



**At the same environmental density, halo properties are independent of cosmic web location.** It doesn't matter whether a halo is in a cosmic void, wall, or filament, what matters is the halo's environmental density. The properties studied are mass accretion rate, spin, halo concentration, scale factor of the last major merger, and prolateness. We had expected that a web's cosmic web location would matter for at least some of these halo properties. That it does not is a significant discovery.

SDSS galaxy mass and size are independent of web environment at fixed density (Yan, Fan, White 2013). GAMA data show that the galaxy luminosity function is also independent of web environment at fixed density (Eardley et al. MNRAS 2015). This contrasts with the finding that the halo mass function is dependent on web location at the same density using the v-web (Metuki, Liebeskind, Hoffman 2016).

**CANDELS Meeting @ UCSC - 5 August 2017****The Evolving Galaxy-Halo Connection****Joel Primack****UCSC**

- **Abundance matching with radii & mergers**  $\Rightarrow R^* \sim M^{*1/3}$  goes to  $R^* \sim M^{*2}$  after quenching, & **quenching downsizing:  $\Sigma_1$  grows till quenching,  $\Sigma_{1,quench}$  larger & at higher  $z$  for higher  $M^*$**
- **2-pt Correlation Functions for SHAM with  $M_{vir}$  &  $M_{peak}$  (OK) and  $V_{max}$  &  $V_{peak}$  (better)**
- **Halo properties  $\dot{M}/M$ ,  $\lambda$ ,  $C_{NFW}$ ,  $a_{LMM}$ , shape depend on environmental density**
- **Spin  $\lambda$  30% smaller at low density tests whether galaxy  $R^*$  is determined by host halo  $\lambda$**
- **Halo properties  $\dot{M}/M$ ,  $\lambda$ ,  $C_{NFW}$ ,  $a_{LMM}$ , shape don't depend on web location at fixed density**
- **Galaxy Luminosity-Halo Mass, Stellar Mass-Halo Mass relations are independent of density**
- **Halo Mass Loss: Relaxation after Merger  $\Rightarrow C_{NFW} \downarrow$  &  $\lambda \uparrow$ , Tidal Stripping  $\Rightarrow C_{NFW} \uparrow$  &  $\lambda \downarrow$**