New Constraints on the evolution of the Stellar-to-Dark Matter Connection

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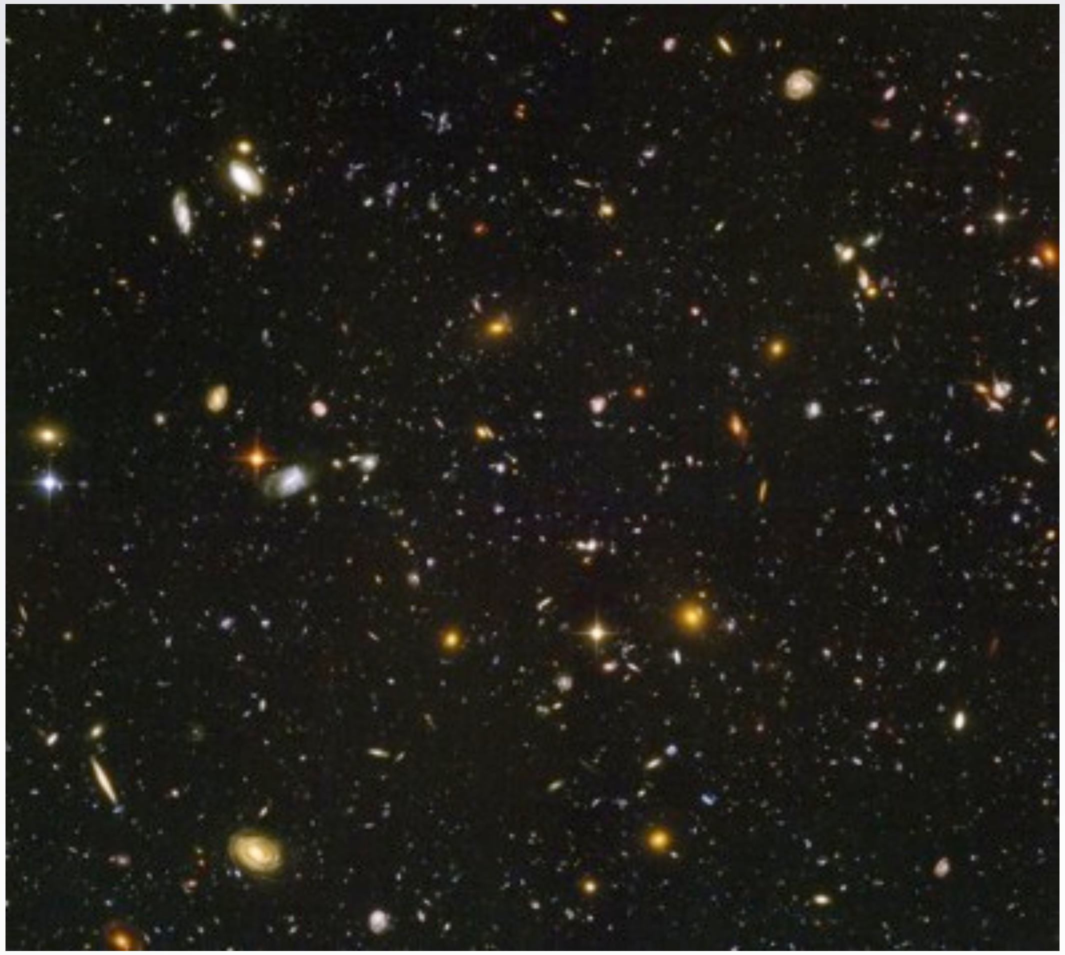
OUTLINE

- Motivation for combining dark matter probes
- Theoretical Framework
- Application to COSMOS data
- Results : Form and Evolution of the Stellar-to-Halo Mass Relation (SHMR).

Motivation for this project

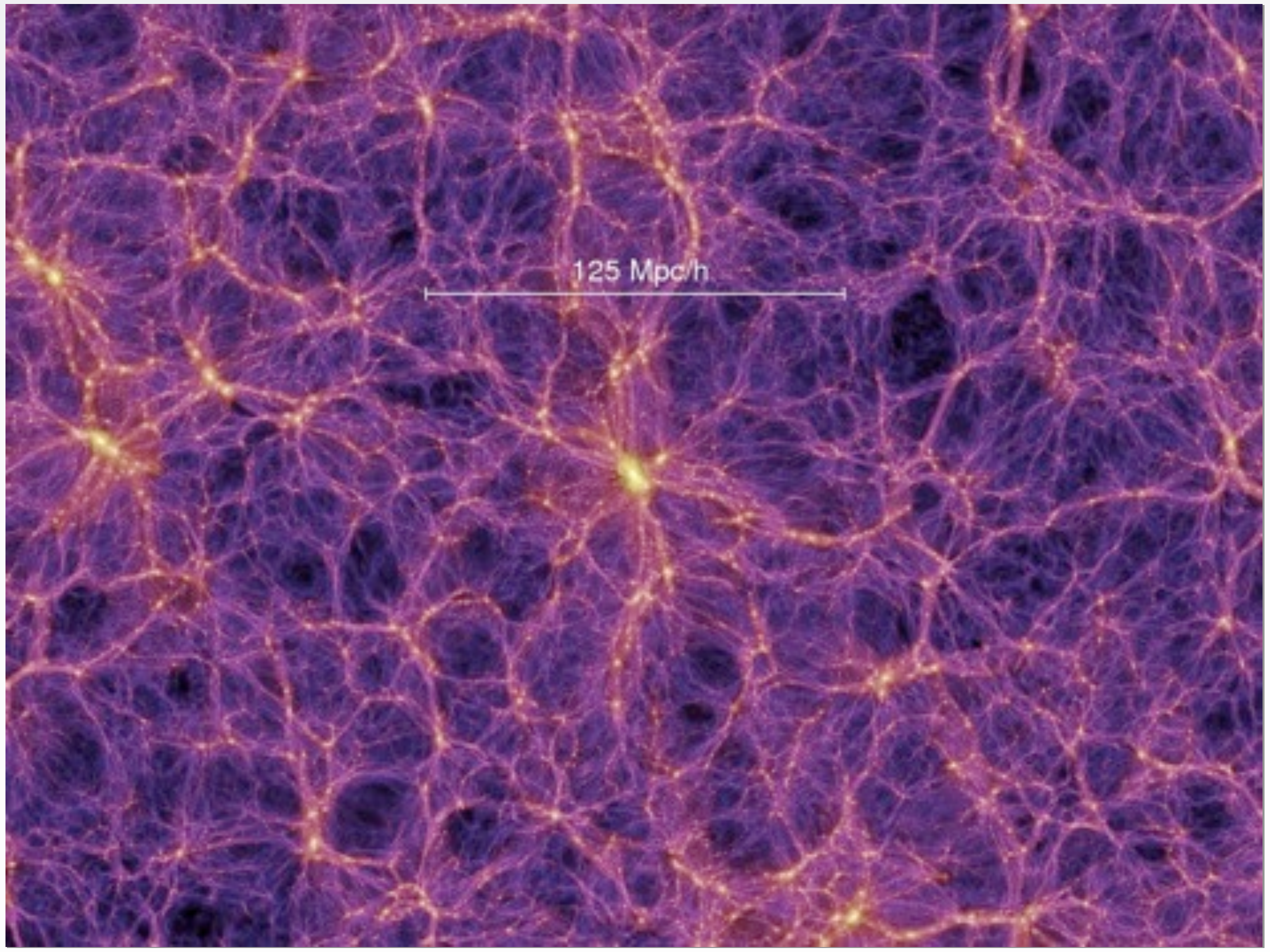
How are galaxies related to the dark matter density field?



Hubble deep field

?

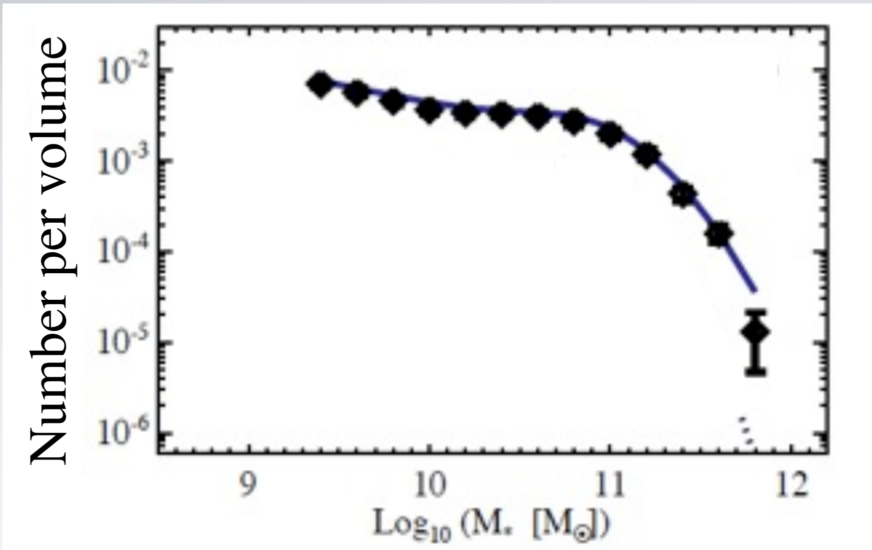
↔



Millenium simulation
Springel et al. 2005

We have several tools for this purpose ...

Three Dark Matter Probes



1

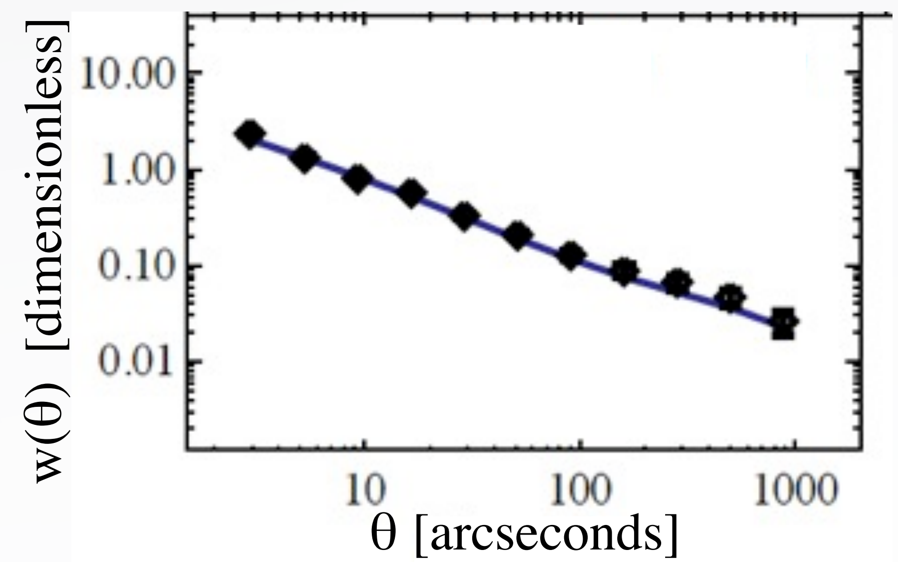
The galaxy stellar mass function :

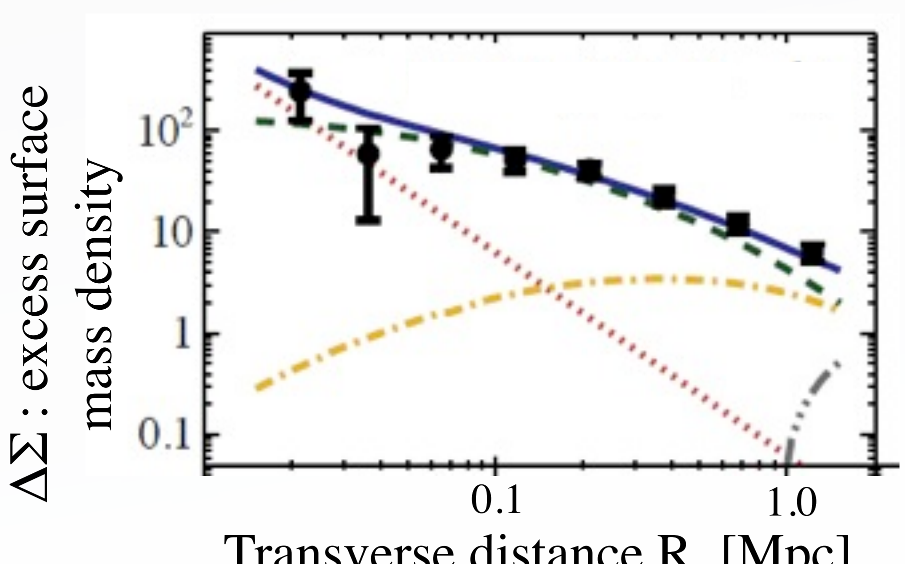
- Number of galaxies per unit volume
- “easy” to calculate
- Typically modelled through “abundance matching”

2

Galaxy auto correlation function :

- Excess probability above random of finding two galaxies with a given separation
- Typically modelled through HOD models





Galaxy-galaxy lensing :

- Measures the galaxy-matter correlation function
- Weak signal that is difficult to measure
- Tells us directly about the galaxy-dark matter connection

3

Combining multiple Dark Matter Probes

- Most studies so far have only ever used one type of probe to study the link between galaxies and dark matter.
- Nonetheless, each probe contains different information. Combining probes makes sense in order to understand the beast :

Motivation for combining dark matter probes

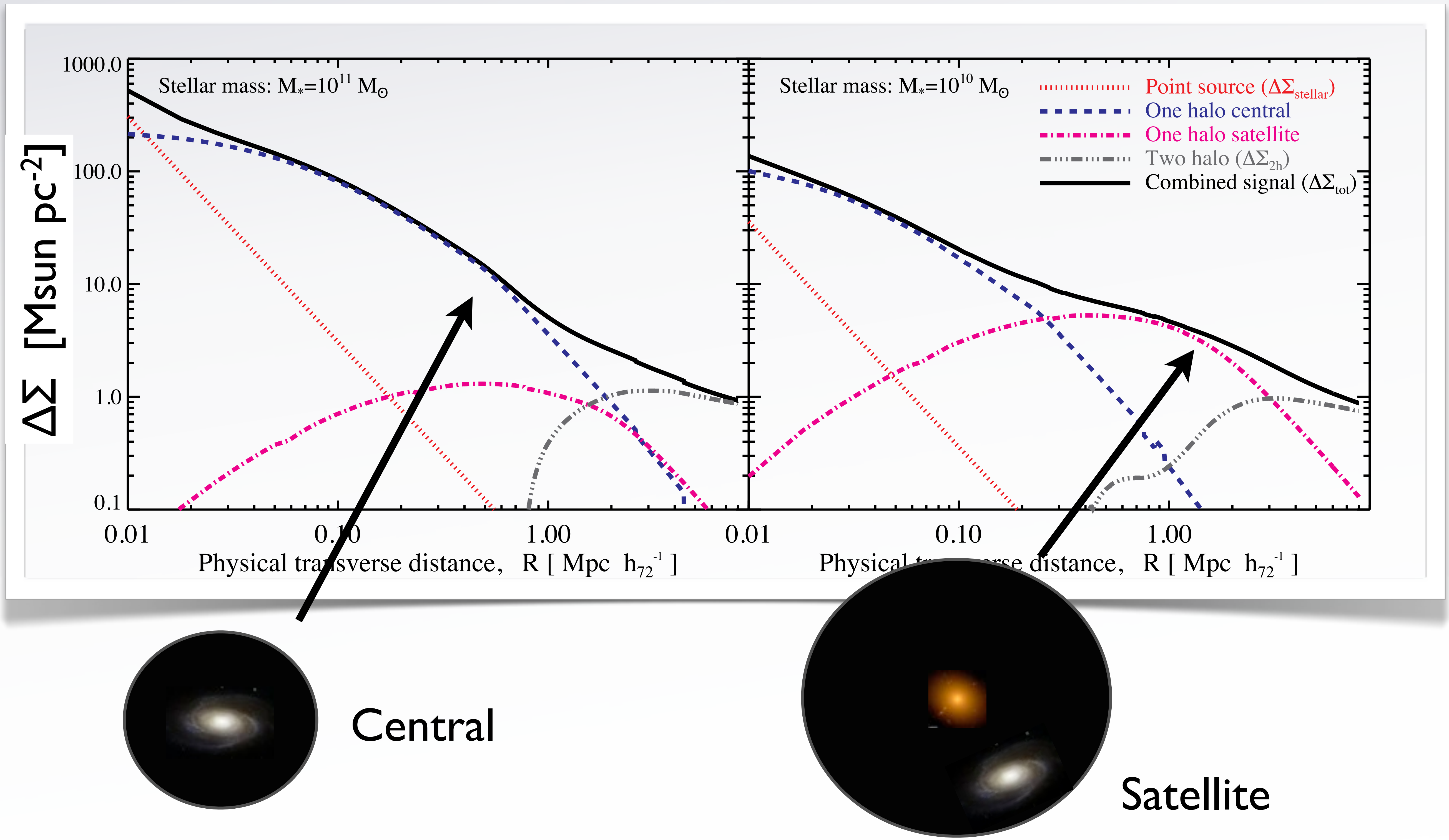
1. **The galaxy-dark matter connection**
   - Building a more robust probe
   - Galaxy formation
   - Informing semi-analytic models

2. **Cosmological parameters: Ω_m, σ_8**
   Yoo *et al.* 2006, Cacciato *et al.* 2009 → the combination of lensing and clustering is a cosmological probe.

3. **Modified gravity as an alternative to Dark Energy**
   Φ: dynamics
   $\Psi + \Phi$: lensing of light around galaxies
   → Screening mechanisms on linear, quasi linear scales.
   Need to understand the galaxy-dark matter connection.

The Galaxy-Galaxy Lensing Signal

ΔΣ: surface mass density contrast



Theoretical Framework

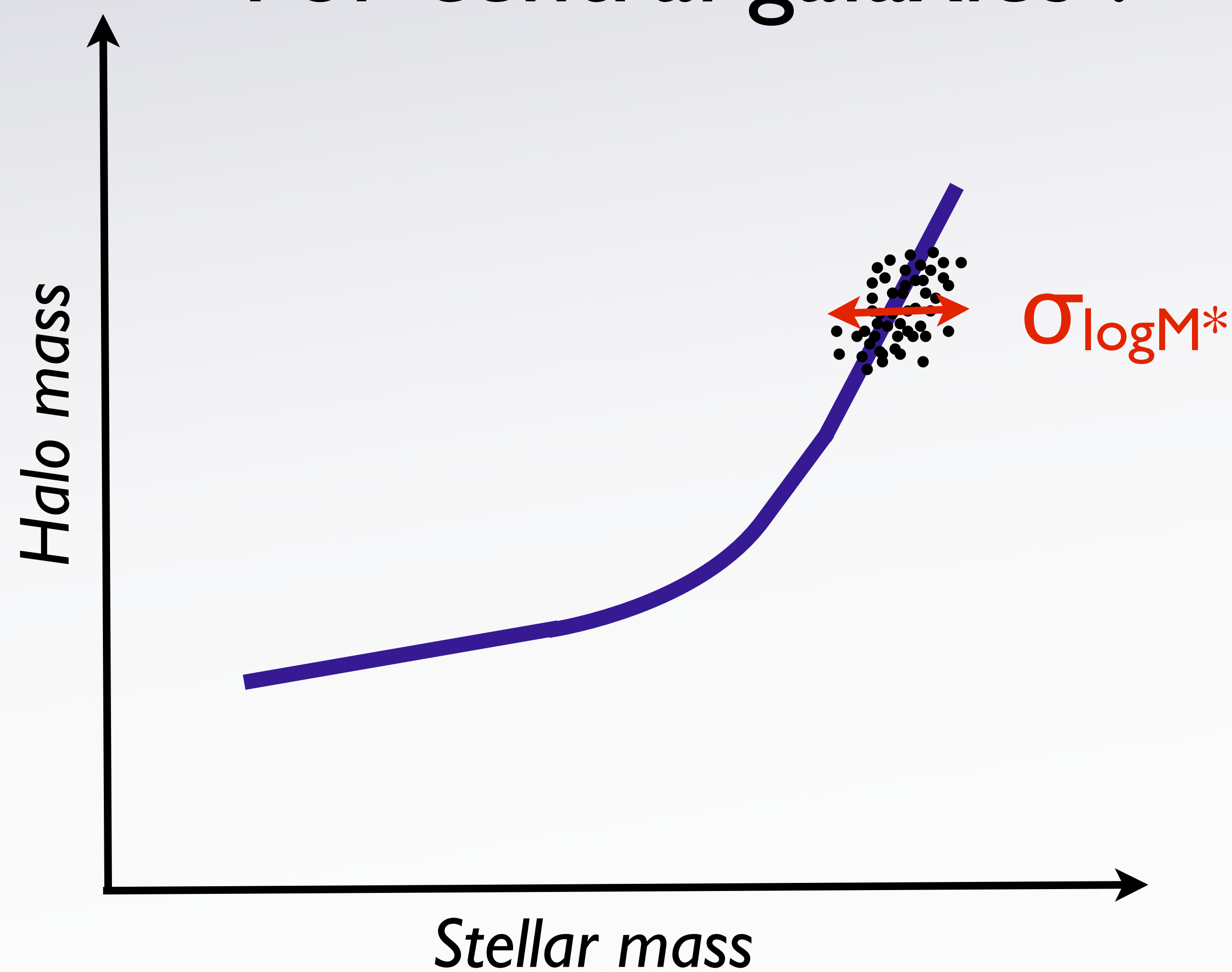
Halo Occupation Distributions (HOD)

- We have developed the theoretical framework necessary to combine galaxy-galaxy lensing, galaxy clustering, and the galaxy stellar mass function
- Our model is an extension to the HOD framework
- Our model enables us to:

  - self consistently model the three observables
  - Fit for the stellar-to-halo mass relation (SHMR)
  - account for intrinsic scatter and measurement error
  - fit data from multiple probes while allowing independent binning schemes for each probe

The Stellar-to-Halo mass relation (SHMR)

For central galaxies :



$P(M_*|M_h)$ is lognormal with :

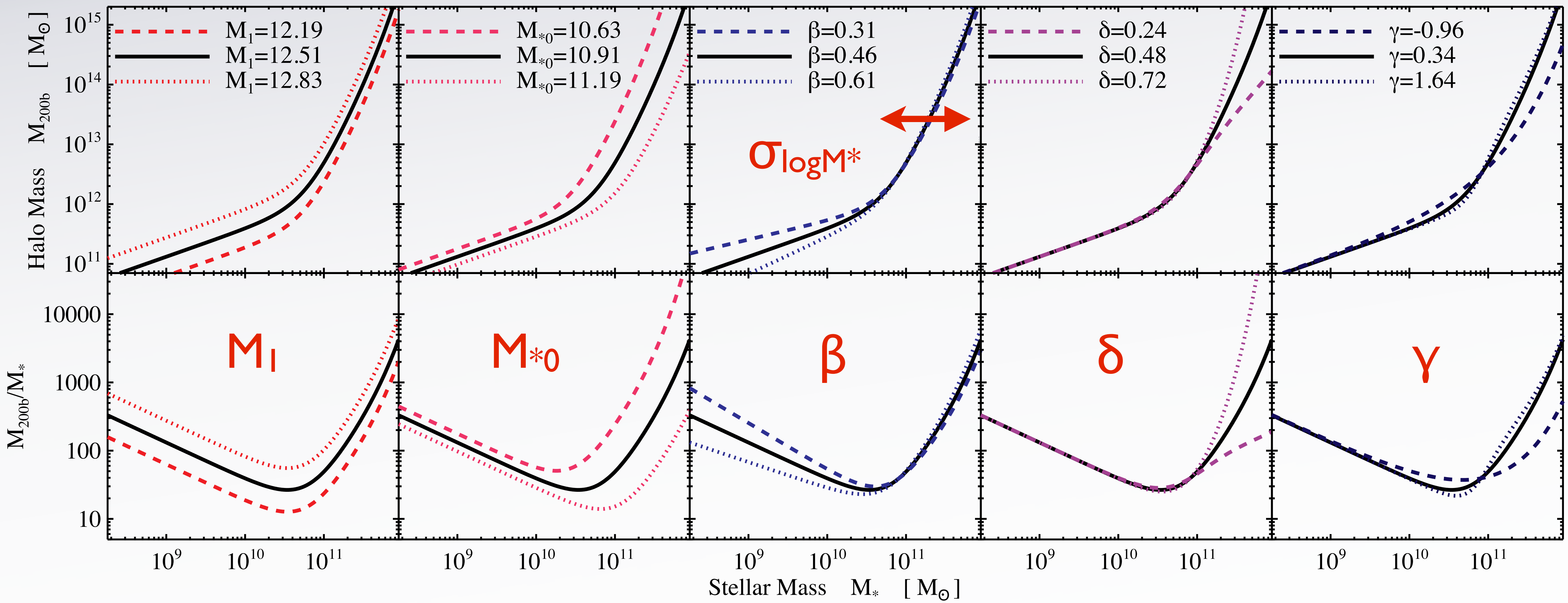
- a mean relation: f_{SHMR}
- a logarithmic scatter: $\sigma_{\log M*}$

$$\log_{10}(\mathbf{f}^{-1}_{\mathrm{SHMR}}(\mathbf{M}_*)) = \log_{10}(\mathbf{M_h}) =$$

$$\log_{10}(\mathbf{M_1}) + \beta\,\log_{10}\left(\frac{\mathbf{M}_*}{\mathbf{M}_{*,0}}\right) + \frac{\left(\frac{\mathbf{M}_*}{\mathbf{M}_{*,0}}\right)^{\delta}}{\mathbf{1} + \left(\frac{\mathbf{M}_*}{\mathbf{M}_{*,0}}\right)^{-\gamma}} - \frac{\mathbf{1}}{\mathbf{2}}$$

Adopted from Behroozi et al. 2010

The Stellar-to-Halo mass relation (SHMR)



M_1 : y-axis (halo mass) normalization

M_{*0} : x-axis (stellar mass) normalization

β : low mass slope

δ : controls high mass sub-exponential behaviour

γ : controls transition regime

Ten Parameter Model

- Parametric form for the stellar-to-halo mass relation (M_1, M_{*0}, β, δ, γ)

$$\log_{10}(f_{\rm SHMR}^{-1}(M_*)) = \log_{10}(M_h) =$$
$$\log_{10}(M_1) + \beta \log_{10}\left(\frac{M_*}{M_{*,0}}\right) + \frac{\left(\frac{M_*}{M_{*,0}}\right)^{\delta}}{1+\left(\frac{M_*}{M_{*,0}}\right)^{-\gamma}} - \frac{1}{2}$$

- Central occupation function ($\sigma_{\log(M^*)}$)

$$\langle N_{\rm cen}(M_h|M_*^{t_1})\rangle =$$
$$\frac{1}{2}\left[1 - \mathrm{erf}\left(\frac{\log_{10}(M_*^{t_1}) - \log_{10}(f_{\rm SHMR}(M_h))}{\sqrt{2}\sigma_{\log M_*}}\right)\right]$$

- Satellite occupation function (B_{cut}, B_{sat}, β_{cut}, β_{sat})

$$\langle N_{\rm sat}(M_h|M_*^{t_1})\rangle = \langle N_{\rm cen}(M_h|M_*^{t_1})\rangle \left(\frac{M_h}{M_{\rm sat}}\right)^{\alpha_{\rm sat}} \exp\left(\frac{-M_{\rm cut}}{M_h}\right)$$

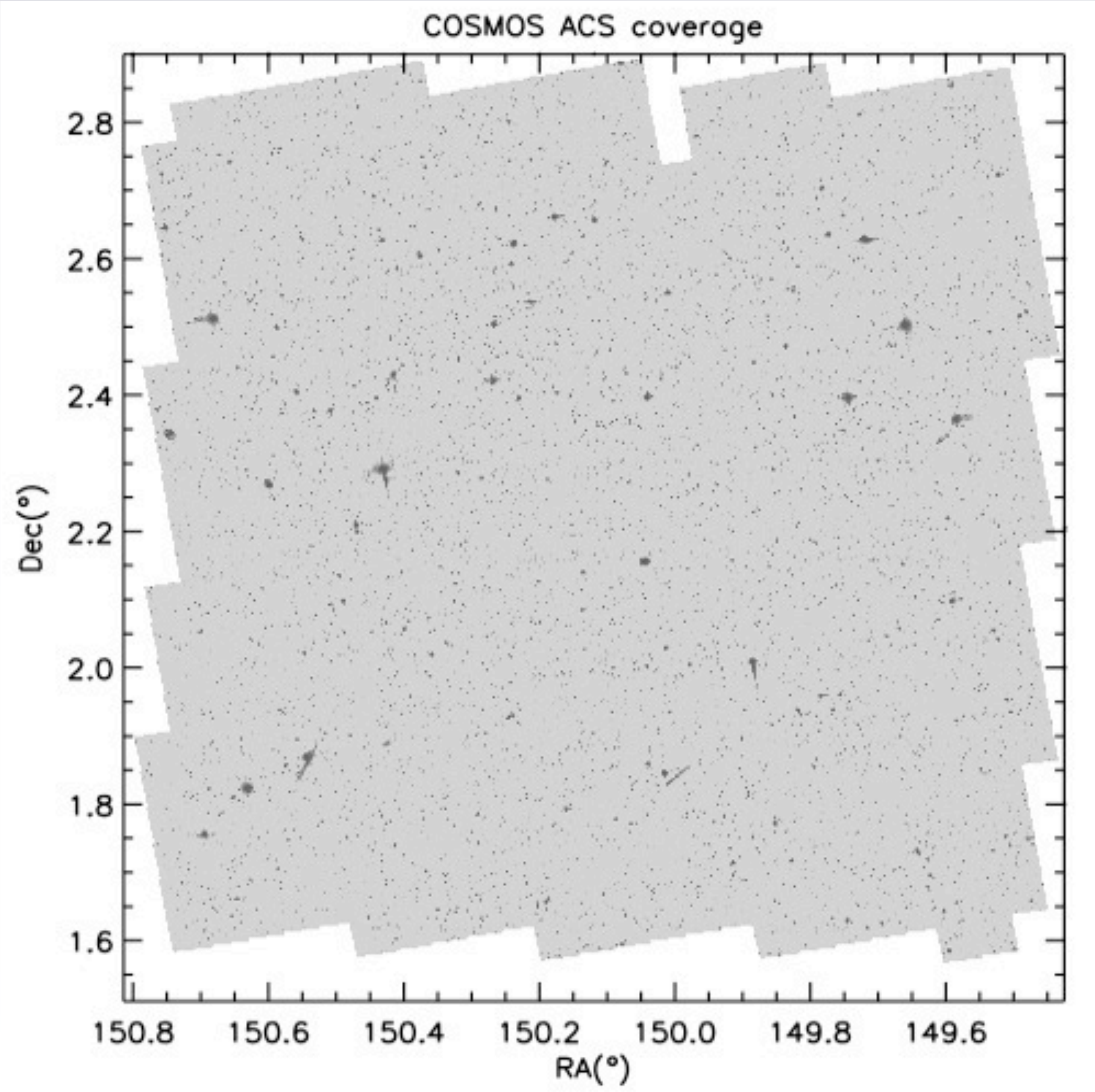
$$\frac{M_{\rm sat}}{10^{12}M_\odot} = B_{\rm sat}\left(\frac{f_{\rm SHMR}^{-1}(M_*^{t_1})}{10^{12}M_\odot}\right)^{\beta_{\rm sat}}$$

$$\frac{M_{\rm cut}}{10^{12}M_\odot} = B_{\rm cut}\left(\frac{f_{\rm SHMR}^{-1}(M_*^{t_1})}{10^{12}M_\odot}\right)^{\beta_{\rm cut}}$$

+ Tinker et al. 2008 halo mass function
+ Tinker et al. 2010 bias function
+ Halo exclusion

Applying this model to Cosmos data

The COSMOS HST survey



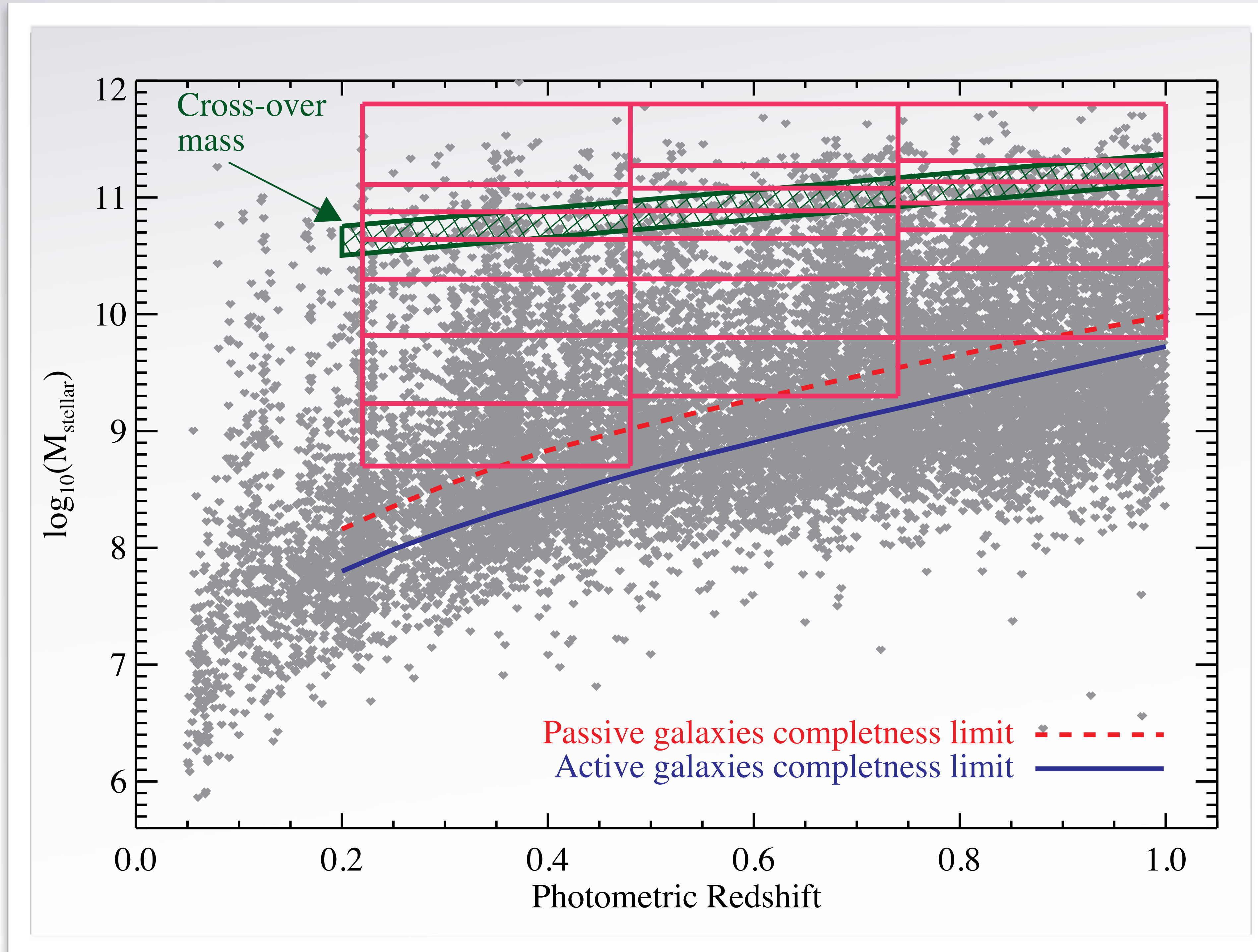
HST ACS
Cycles 12 & 13
590 orbits

✔ Weak lensing

Scoville et al. 2007

Stellar mass distribution in COSMOS

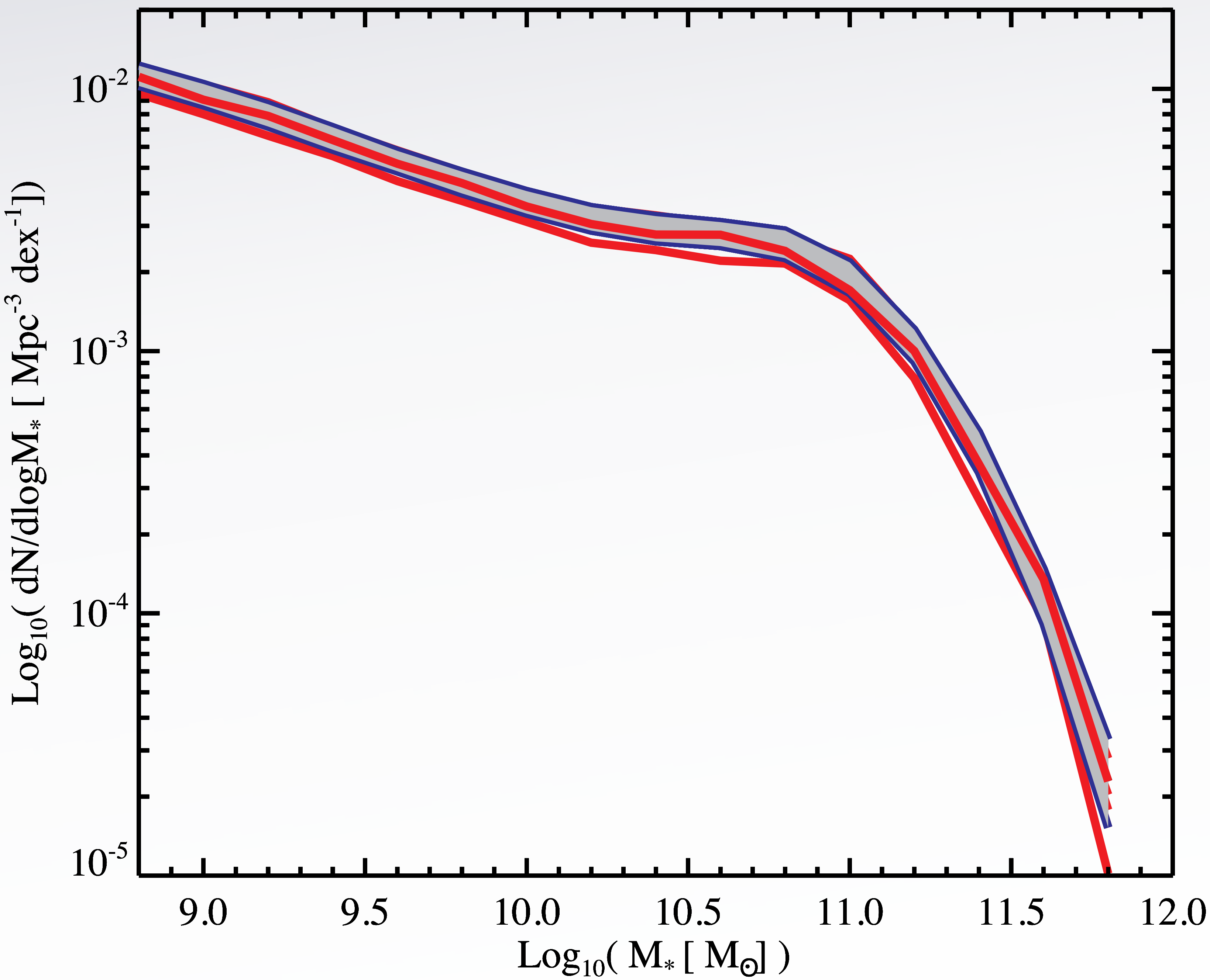
log10(M*)



Photoz

Mock catalogs: sample variance and co-variance

Las Damas "consuelo" box 420 h^{-1}, 1400^3 particles, particle mass=0.1×10^{10} M_{sun}

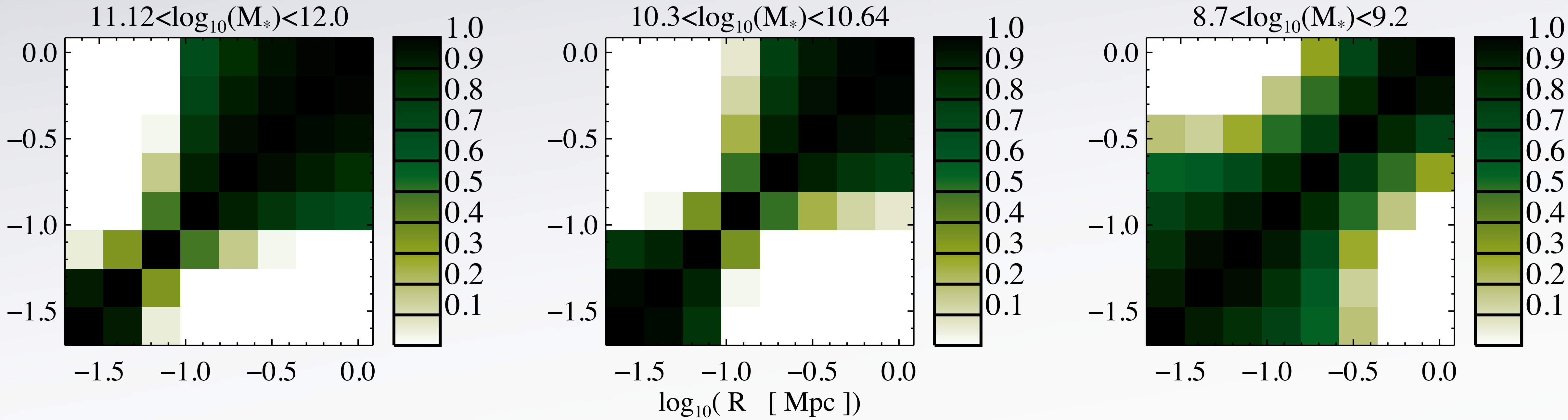


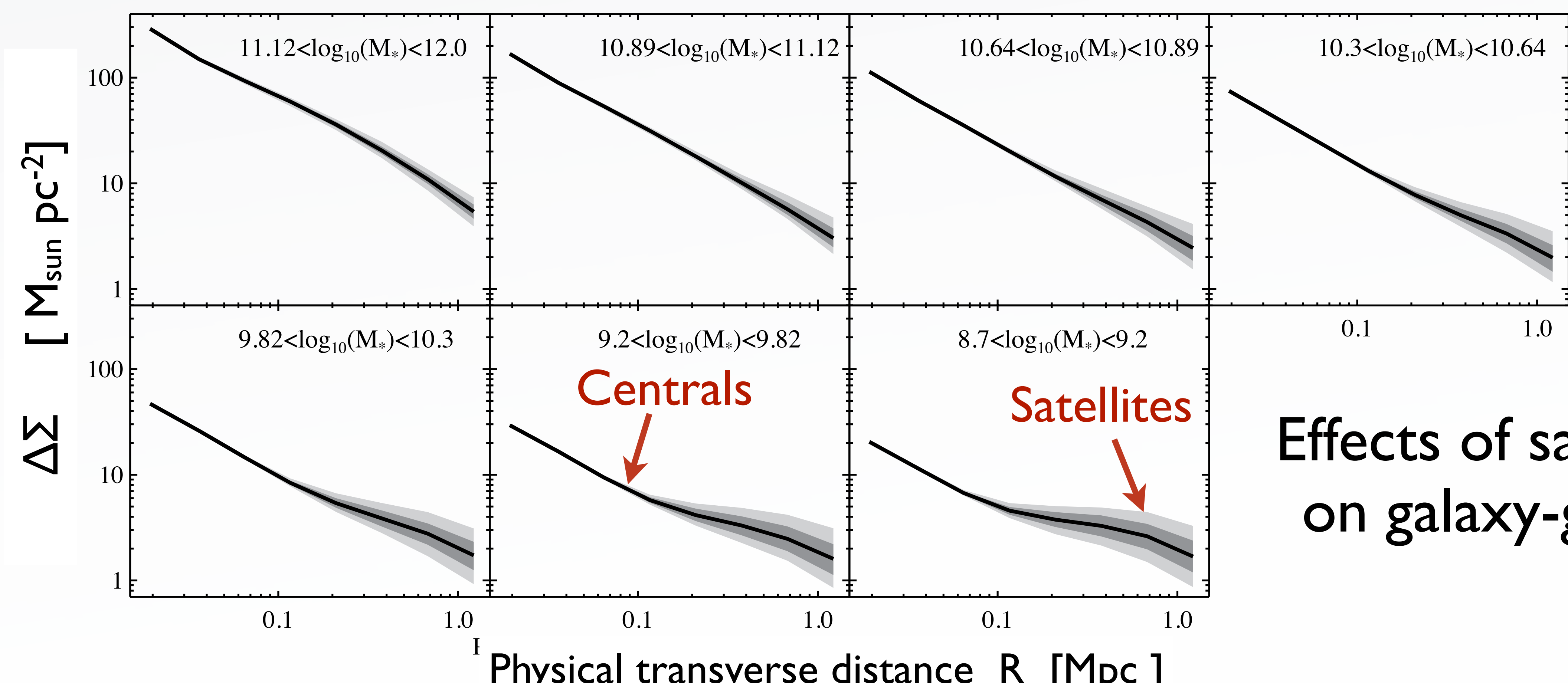
First order effect of sample variance is a global up/down shift in the stellar mass function

This will affect the halo mass normalization of the SHMR

Mock catalogs: sample variance and co-variance

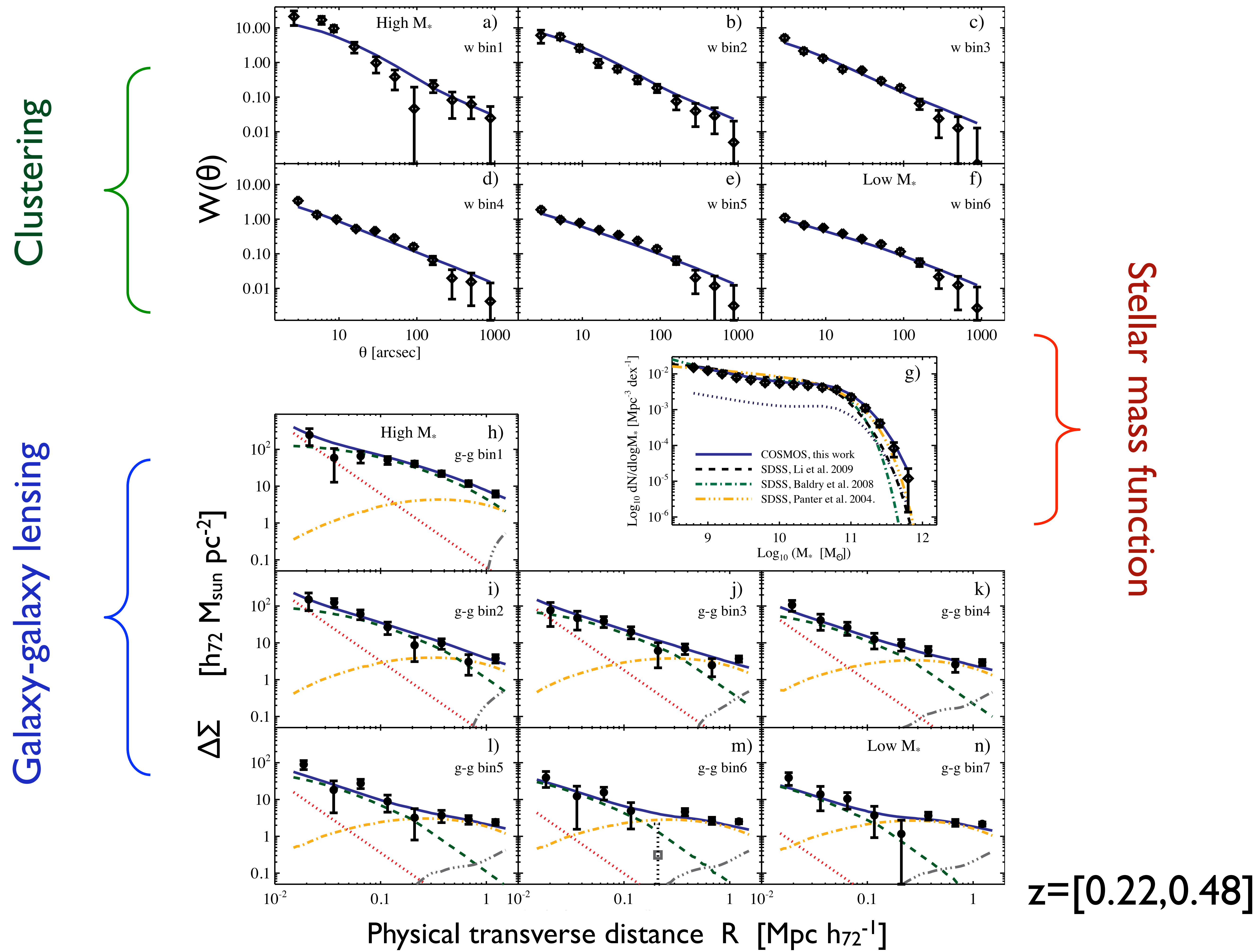
Correlation coefficient matrix:



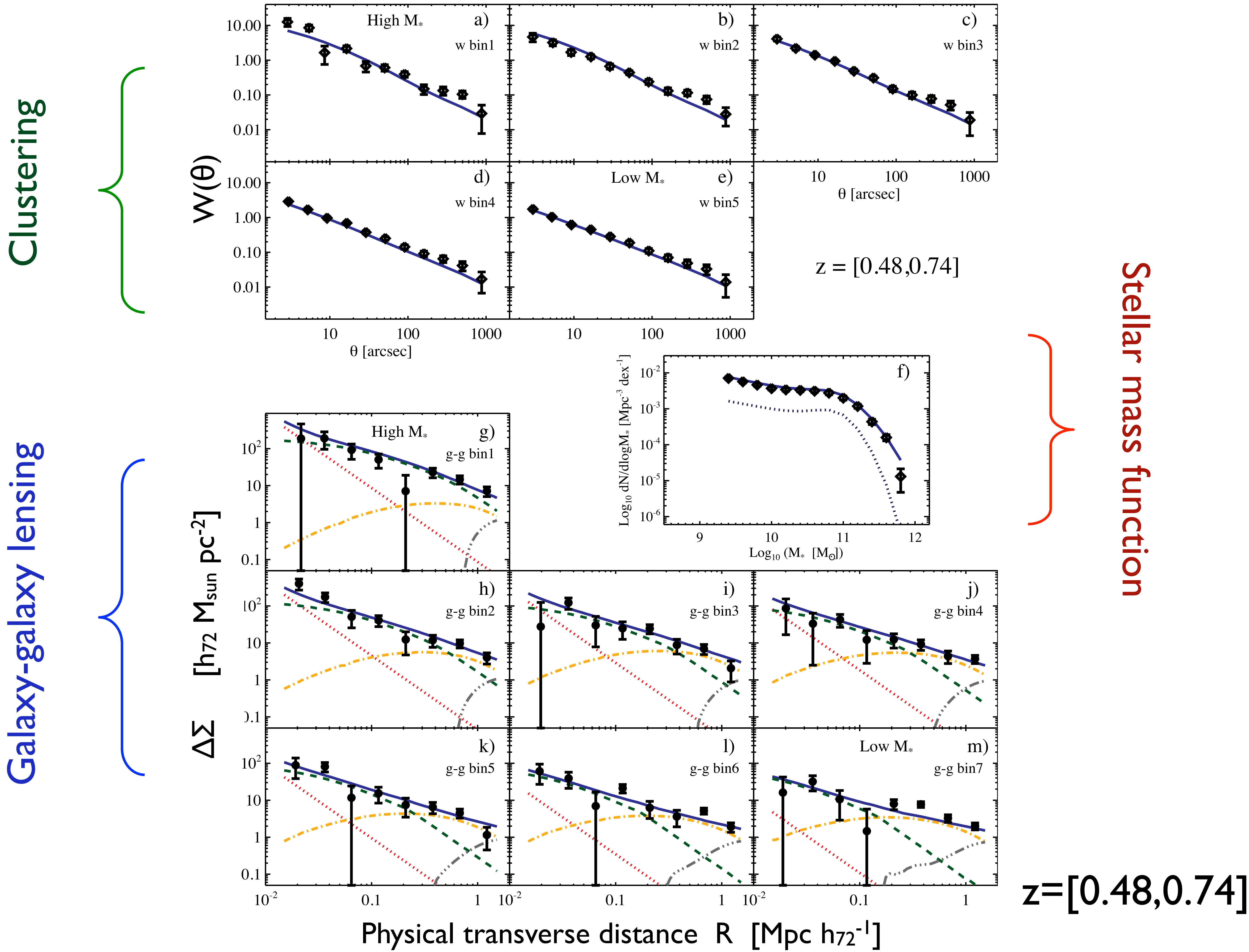


Effects of sample variance on galaxy-galaxy lensing

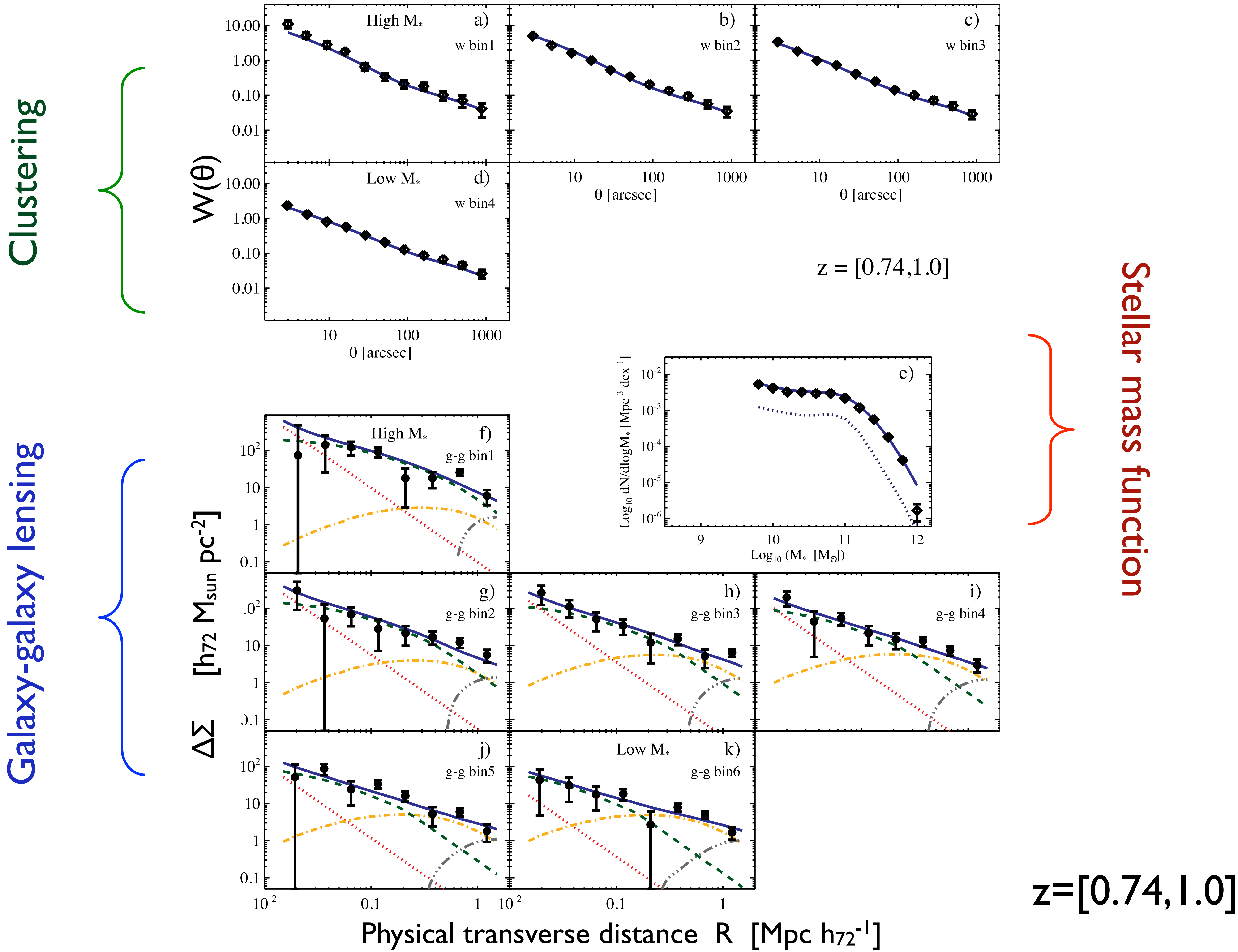
Results :
Form and Evolution of the Stellar-To-Halo Mass Relation



Clustering
W(θ)
High M*
a)
w bin1
b)
w bin2
c)
w bin3
d)
w bin4
e)
w bin5
Low M*
f)
w bin6
θ [arcsec]
Stellar mass function
g)
Log10 dN/dlogM* [Mpc^-3 dex^-1]
COSMOS, this work
SDSS, Li et al. 2009
SDSS, Baldry et al. 2008
SDSS, Panter et al. 2004.
Log10 (M* [M⊙])
Galaxy-galaxy lensing
ΔΣ [h72 Msun pc^-2]
High M*
h)
g-g bin1
i)
g-g bin2
j)
g-g bin3
k)
g-g bin4
l)
g-g bin5
m)
g-g bin6
Low M*
n)
g-g bin7
Physical transverse distance R [Mpc h72^-1]
z=[0.22,0.48]

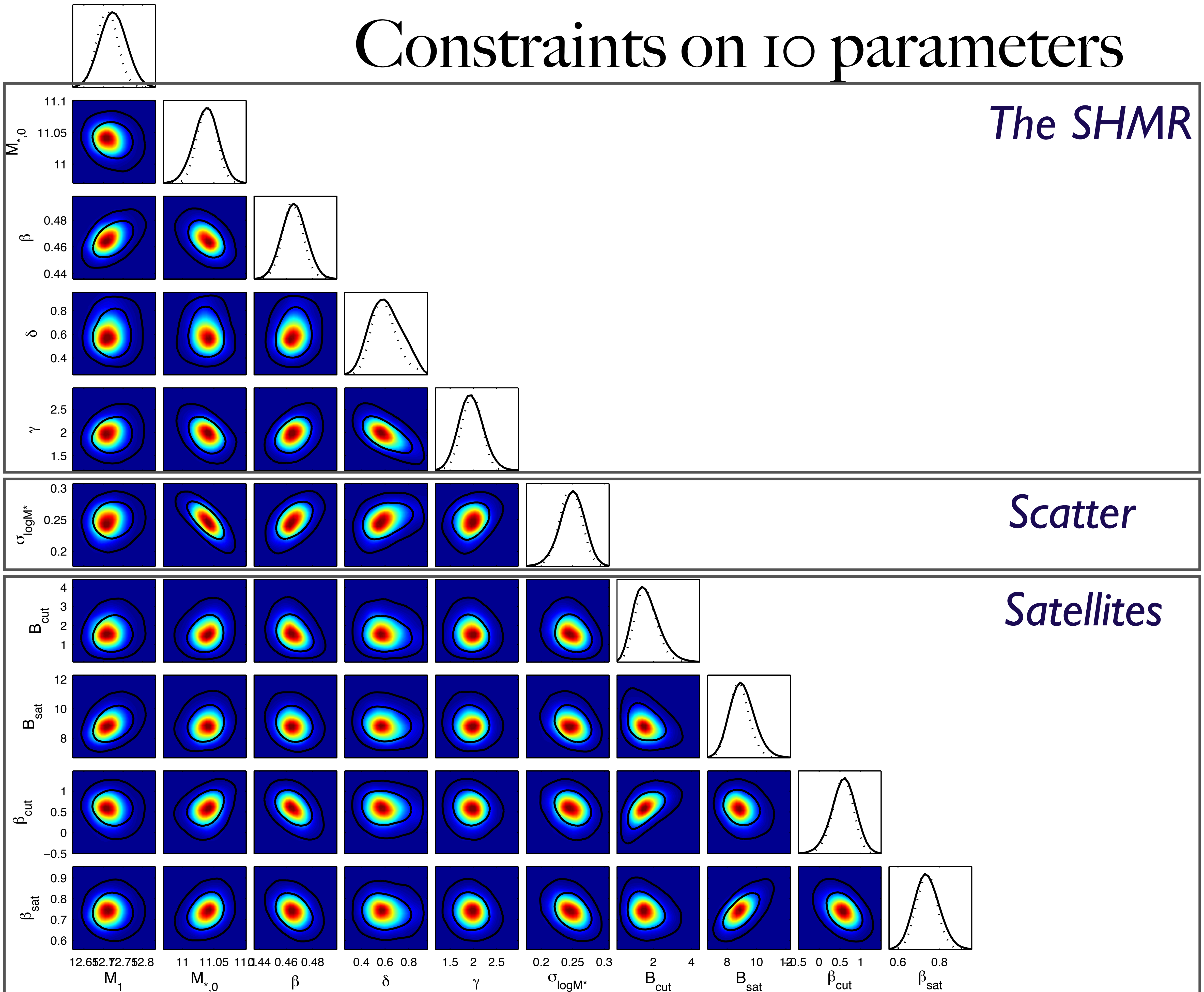


Clustering
Galaxy-galaxy lensing
Stellar mass function
W(θ)
High M*
Low M*
a) w bin1
b) w bin2
c) w bin3
d) w bin4
e) w bin5
θ [arcsec]
z = [0.48,0.74]
f)
Log10 dN/dlogM* [Mpc-3 dex-1]
Log10 (M* [M⊙])
g) g-g bin1
h) g-g bin2
i) g-g bin3
j) g-g bin4
k) g-g bin5
l) g-g bin6
m) g-g bin7
ΔΣ [h72 Msun pc-2]
Physical transverse distance R [Mpc h72-1]
z=[0.48,0.74]

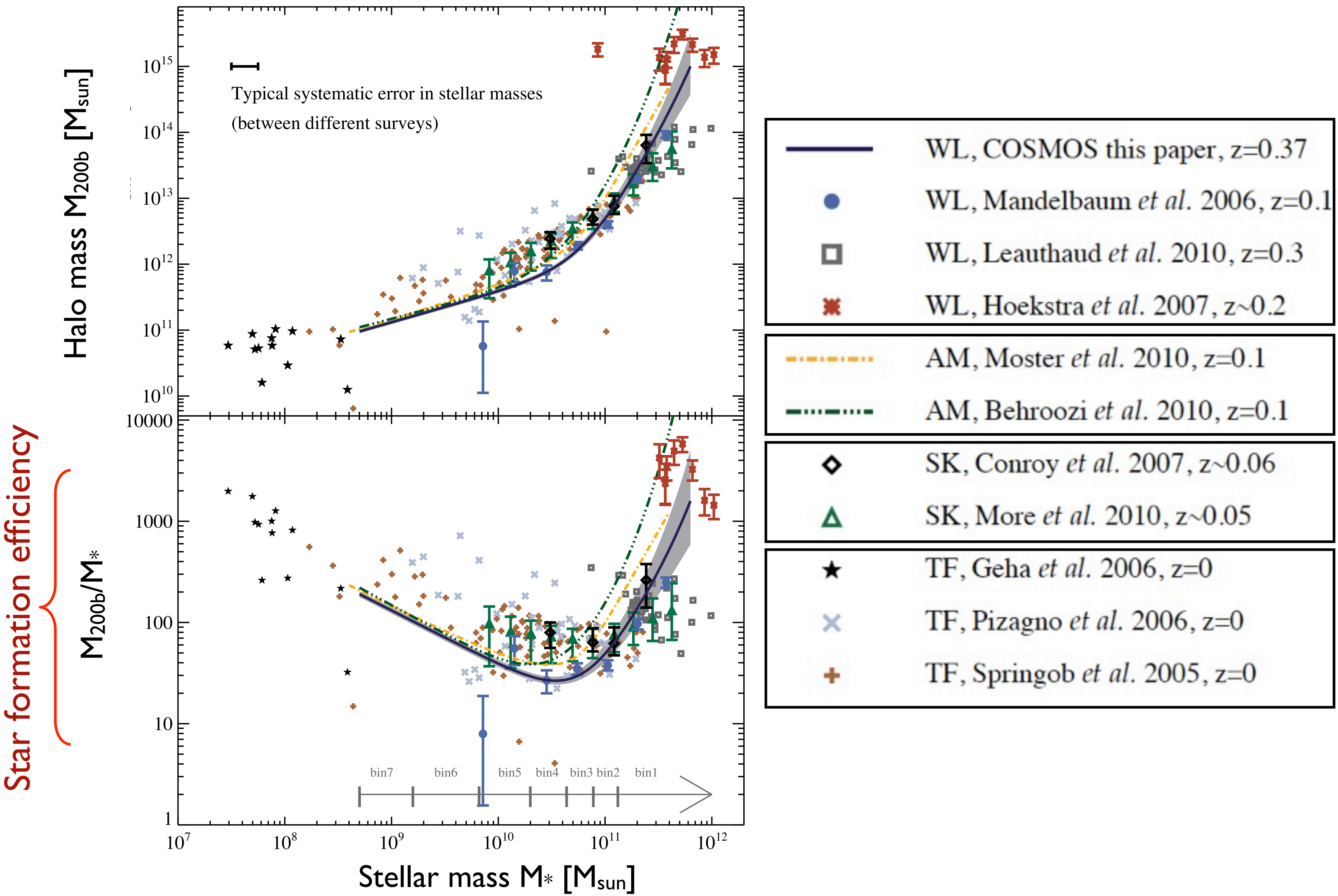


Clustering
Galaxy-galaxy lensing
Stellar mass function
W(θ)
High M*
Low M*
a) w bin1
b) w bin2
c) w bin3
d) w bin4
θ [arcsec]
z = [0.74,1.0]
e)
Log10 dN/dlogM* [Mpc-3 dex-1]
Log10 (M* [M⊙])
f) g-g bin1
g) g-g bin2
h) g-g bin3
i) g-g bin4
j) g-g bin5
k) g-g bin6
ΔΣ [h72 Msun pc-2]
Physical transverse distance R [Mpc h72-1]
z=[0.74,1.0]

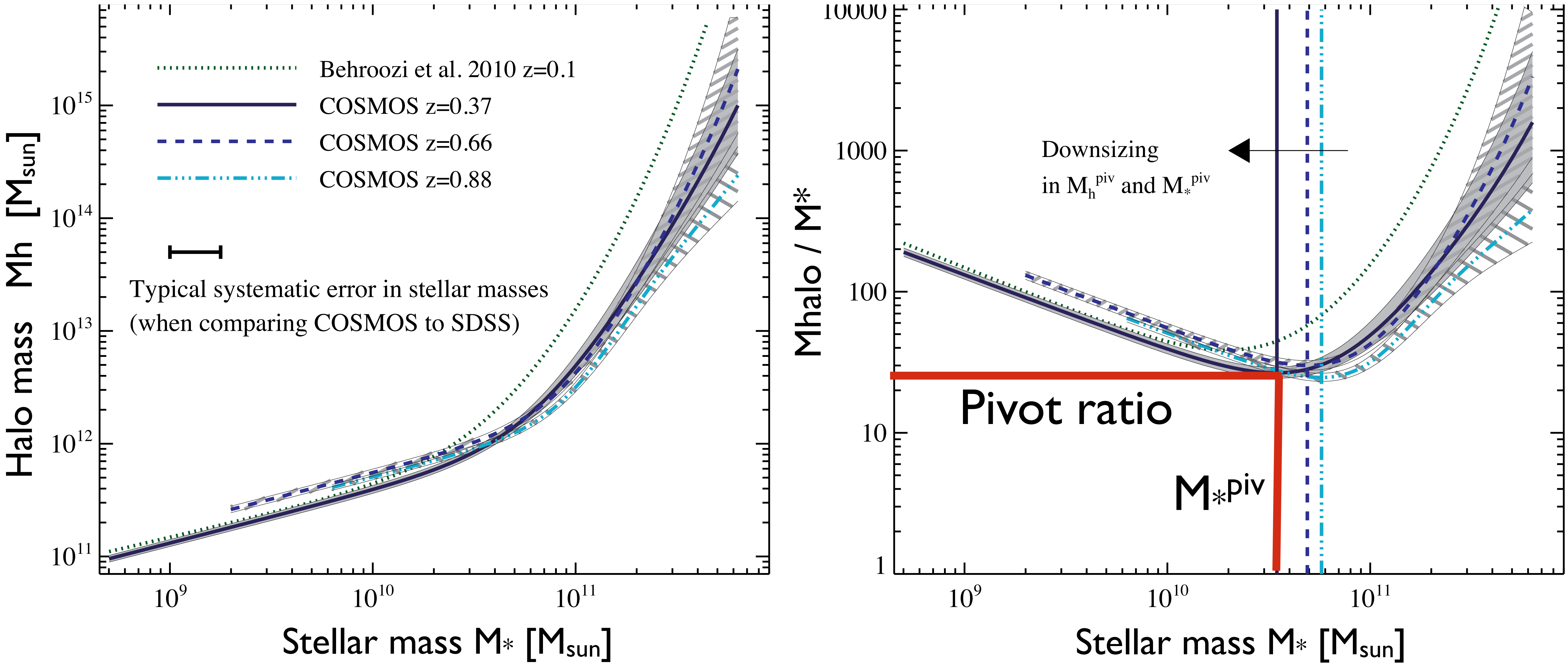
Constraints on 10 parameters



Stellar mass vs Halo mass



Redshift evolution in the SHMR

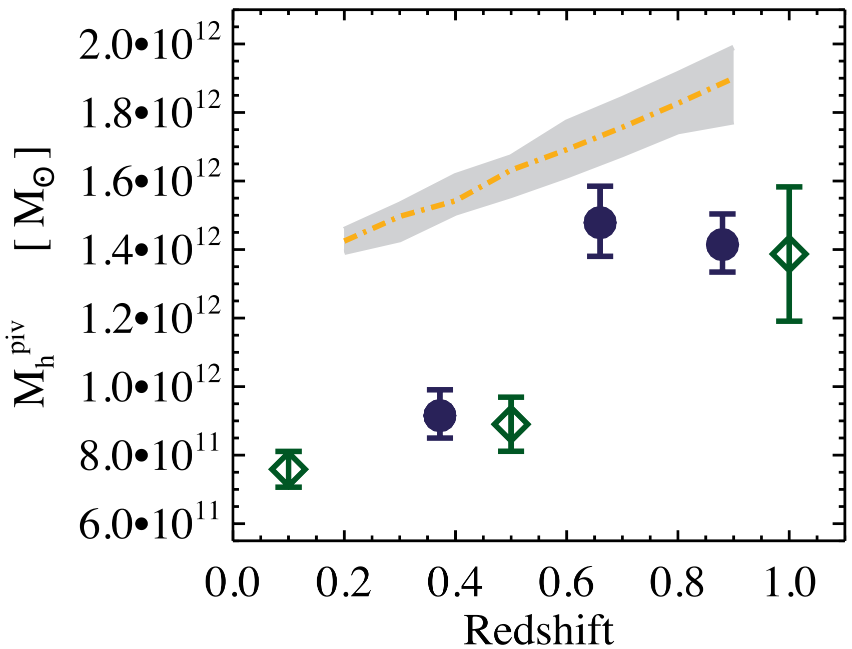


Pivot masses: location of the minimum of M_{200b}/M_* marks the halo mass in which accumulated stellar growth of the central galaxy has been the mode efficient

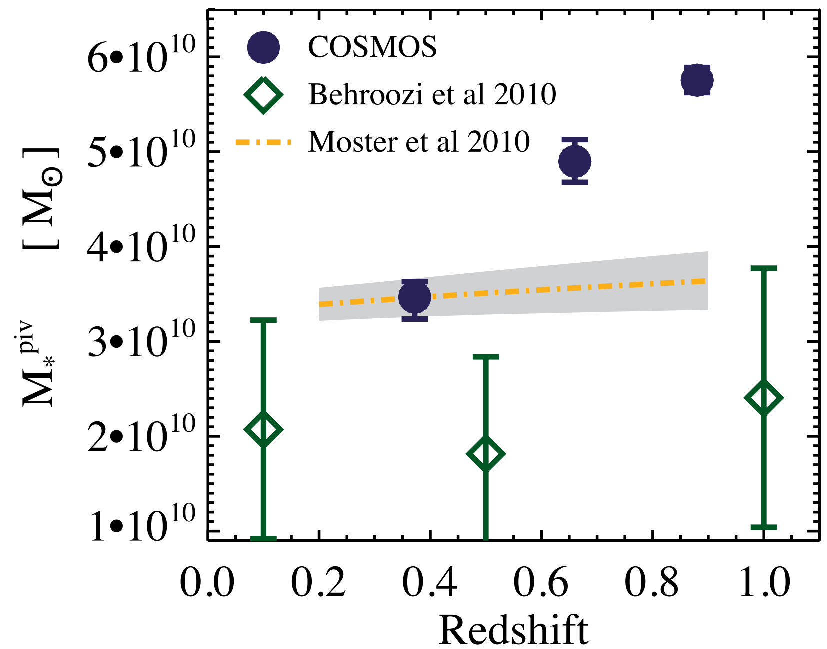
Evolution of the “pivot masses”

We find a downsizing evolution for the pivot stellar mass, and the pivot halo mass. The pivot ratio however remains constant.

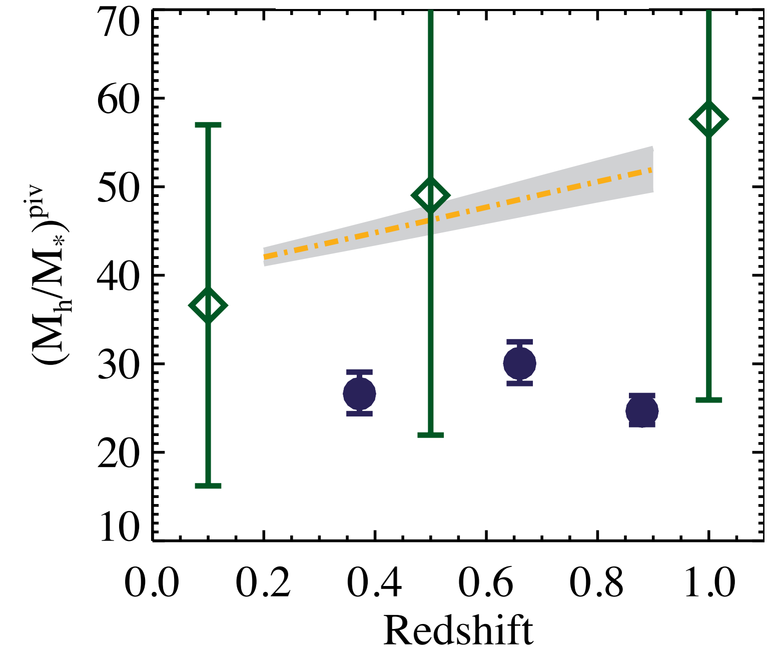
Pivot halo mass



Pivot stellar mass



Pivot ratio



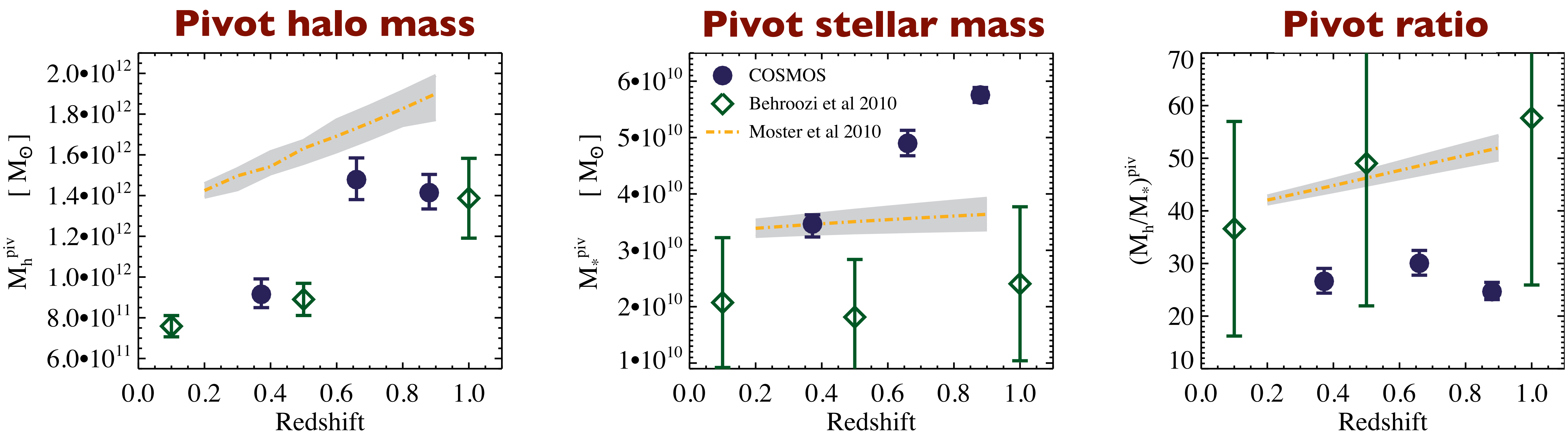
- Most previous results see a downsizing trend in M_h^{piv}
- Normalization difference between Moster et al. 2010 and Behroozi et al. 2010 and our results

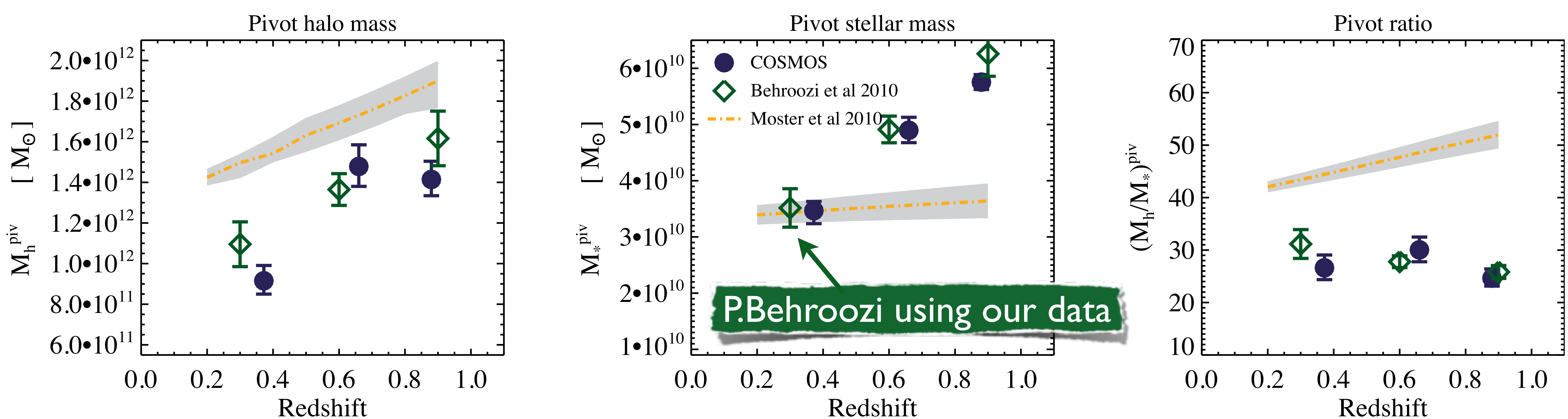
- First study to see a clear downsizing trend for M_*^{piv}
- Systematic errors between stellar mass estimates in distinct surveys: ~ 0.25 dex
- Moster et al 2010 do not account for these errors. Behroozi et al 2010 do account for these errors

- The evolution of M_h^{piv} and M_*^{piv} leaves the pivot ratio constant

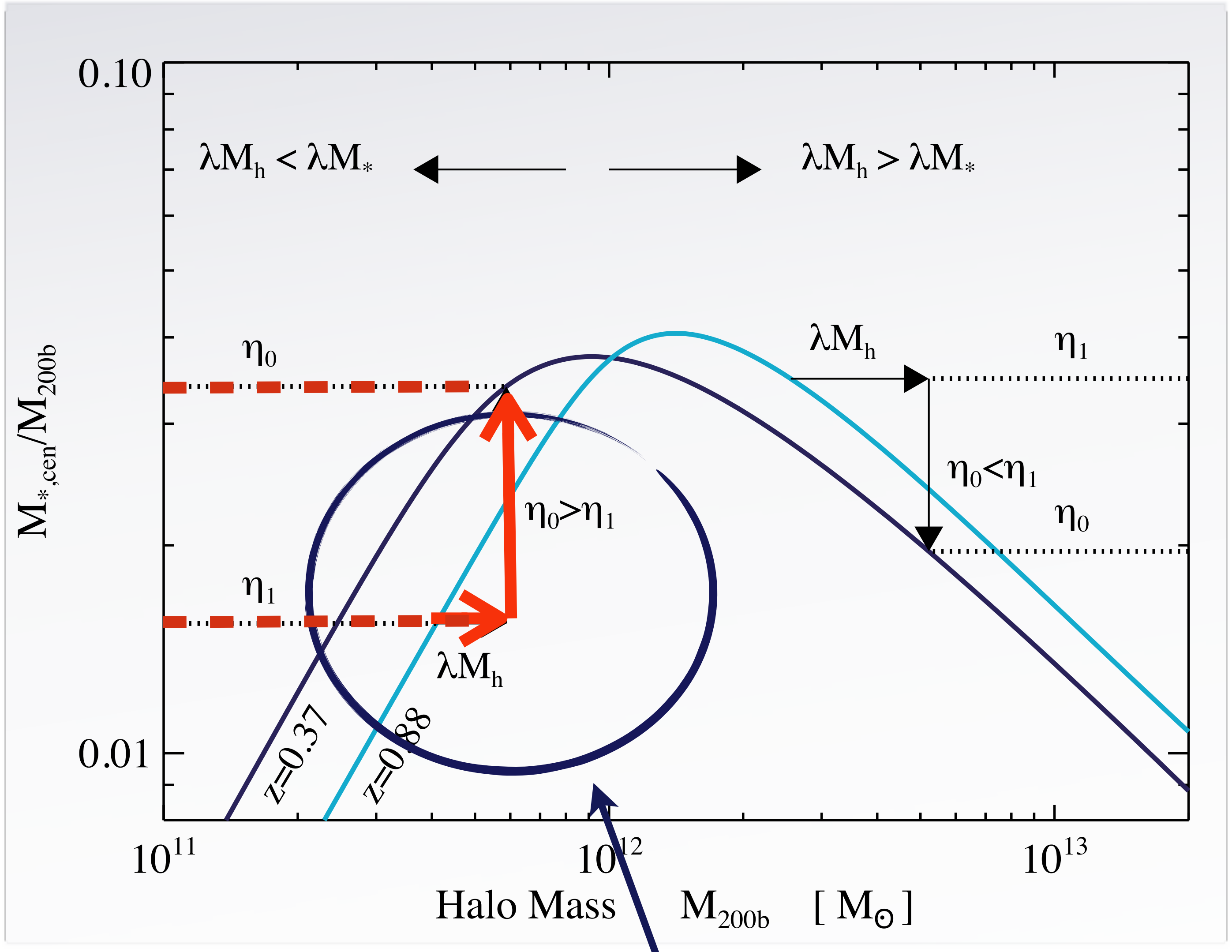
Evolution of the "pivot masses"

We find a downsizing evolution for the pivot stellar mass, and the pivot halo mass. The pivot ratio however remains constant.





Stellar growth versus halo growth



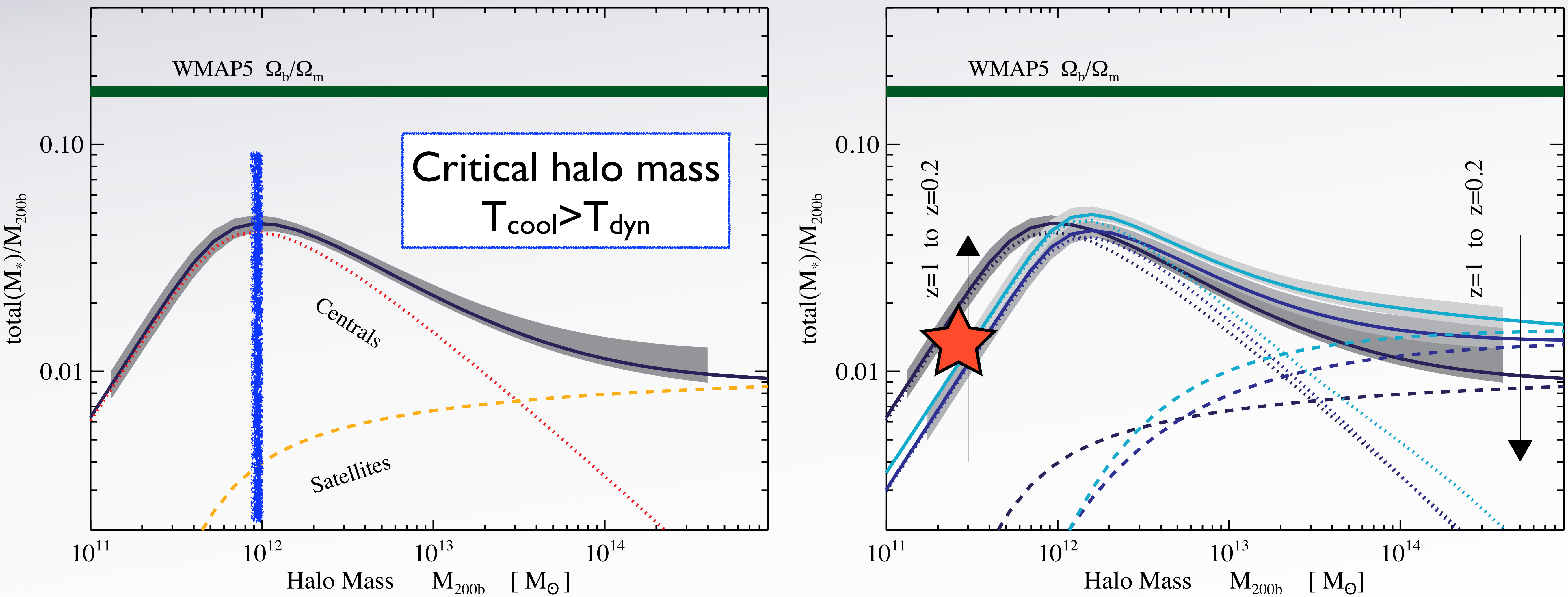
- Halo mass has grown by a factor of λ_{Mh} : $M_h(t_{low}) = \lambda_{Mh} \times M_h(t_{high})$

- Stellar mass has grown by a factor of λ_{M*}: $M_*(t_{low}) = \lambda_{M*} \times M_*(t_{high})$

$$\boxed{\lambda_{M*} = (\eta_0/\eta_1) \times \lambda_{Mh}}$$

The relative growth of the stellar mass has been stronger than the growth of the dark matter: $\lambda_{M*} > \lambda_{Mh}$

Total stellar content as a function of halo mass



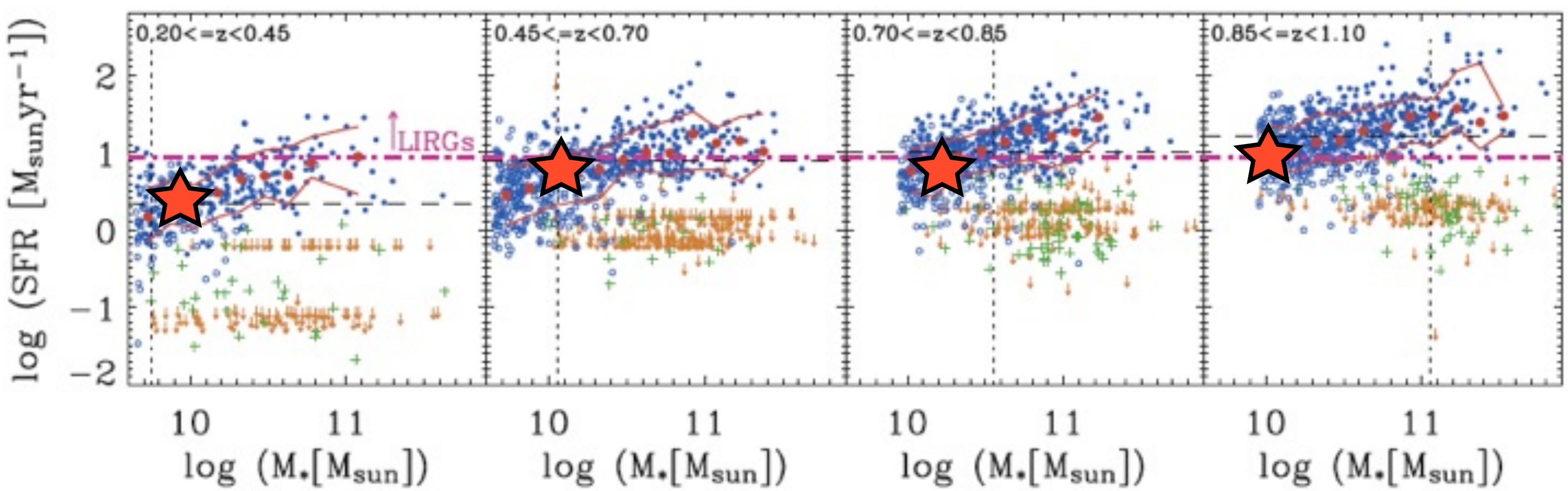
- Centrals dominate the total stellar content at $M_h < 2x10^{13}$ M_{sun}
- Satellites dominate the total stellar content at $M_h > 2x10^{13}$ M_{sun}
- At $M_h < 10^{12}$ M_{sun}: stellar growth outpaces halo growth
- At $M_h > 10^{12}$ M_{sun}: halo growth outpaces stellar growth (smooth accretion)

Also see Conroy and Wechsler 2009

A rough calculation of λ_{M*} and λ_{Mh}

A halo of 2×10^{11} M_{sun} hosts a central galaxy of $M_* \approx 10^{10} M_{sun}$

Star formation rate :



- SFR ~ 2-7 M_{sun} yr^{-1}
- 3.2 Gyr between bins
- λ_{M*} ~ 2-3

Noeske et al. 2007

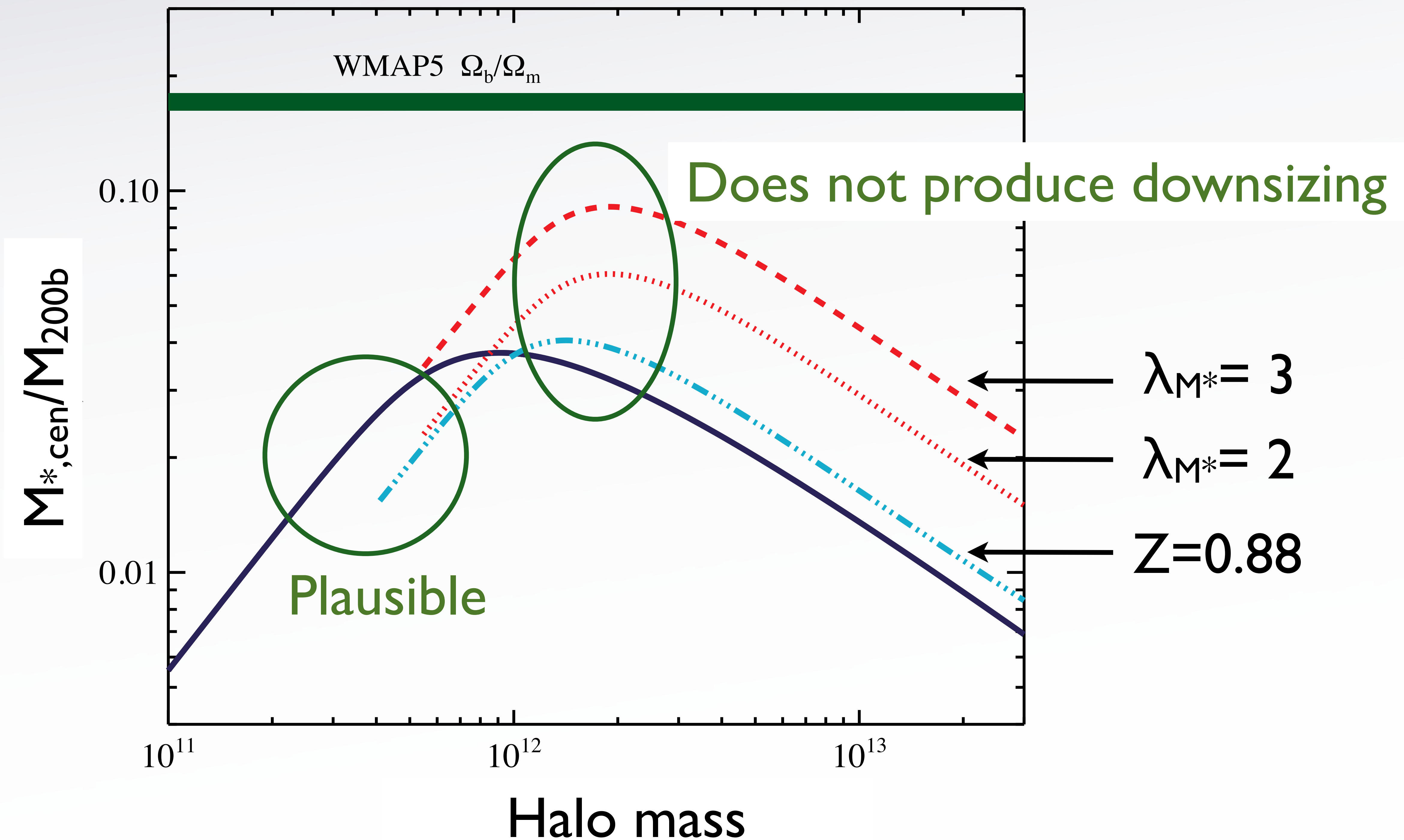
Halo growth rate :

$$\langle \dot{M}_{tot} \rangle = 42\, M_\odot \mathrm{yr}^{-1} \left(\frac{M}{10^{12} M_\odot} \right)^{1.127} \times (1 + 1.17z) \sqrt{\Omega_m (1+z)^3 + \Omega_\Lambda}\,.$$

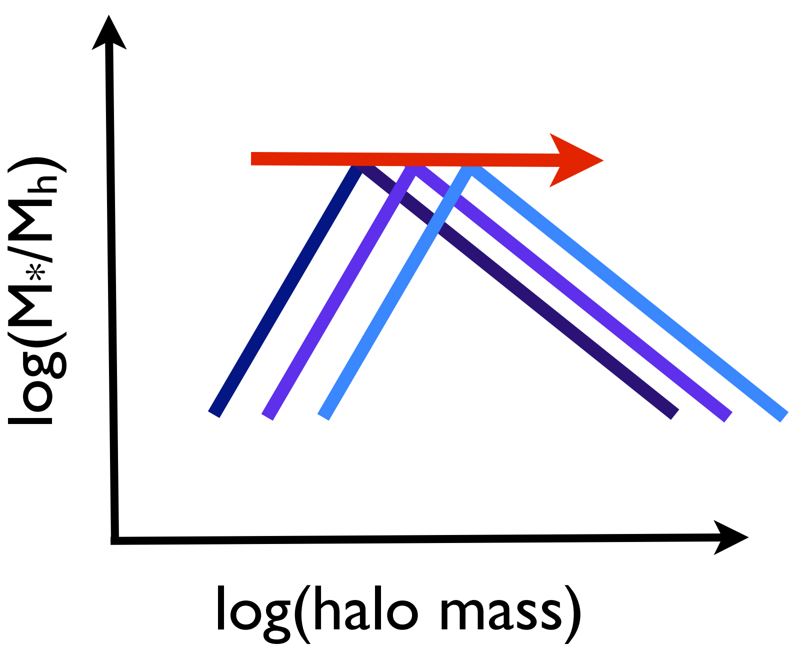
- growth ~ 22 M_{sun} yr^{-1}
- 3.2 Gyr between bins
- λ_{Mh} ~ 1.34

Fakhouri et al. 2010

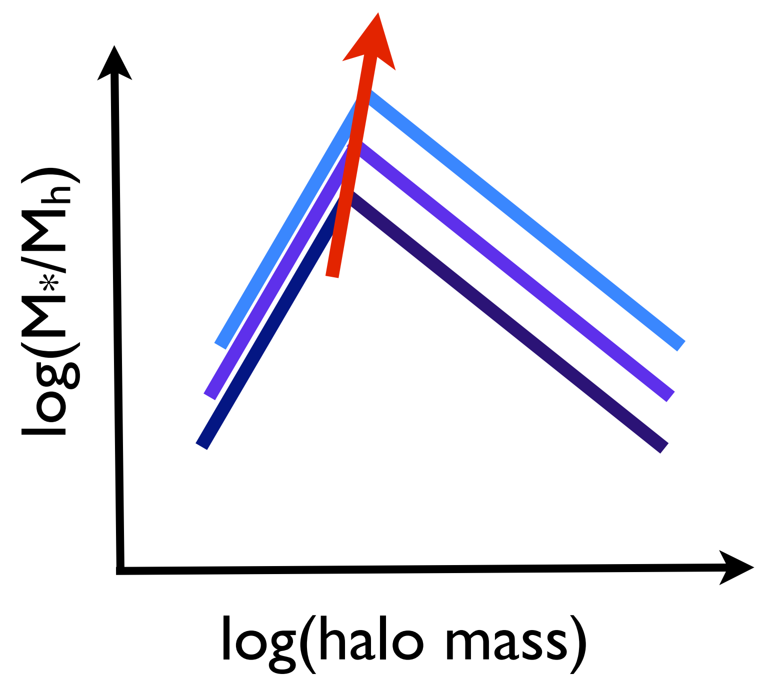
Using this naive calculation :



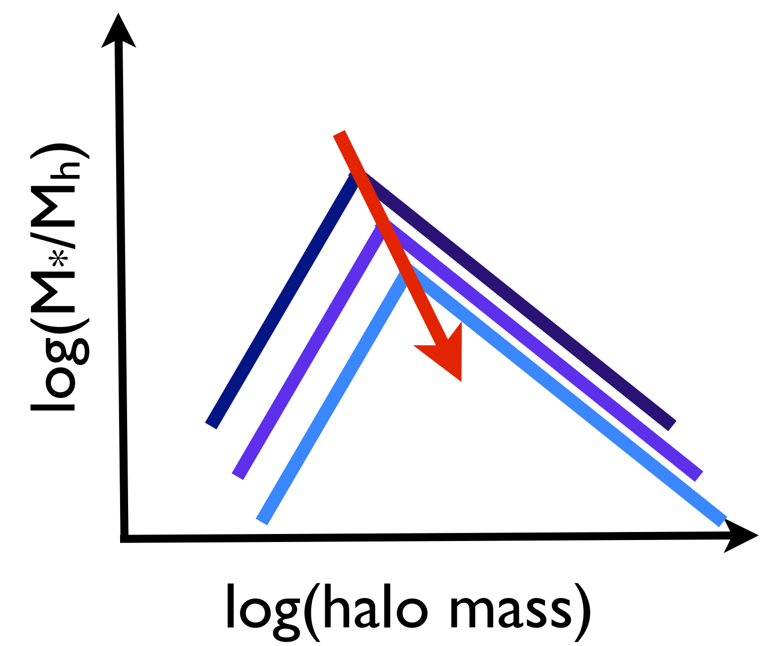
The most simple evolution scenario



$\boxed{\lambda_{M*} = \lambda_{Mh}}$

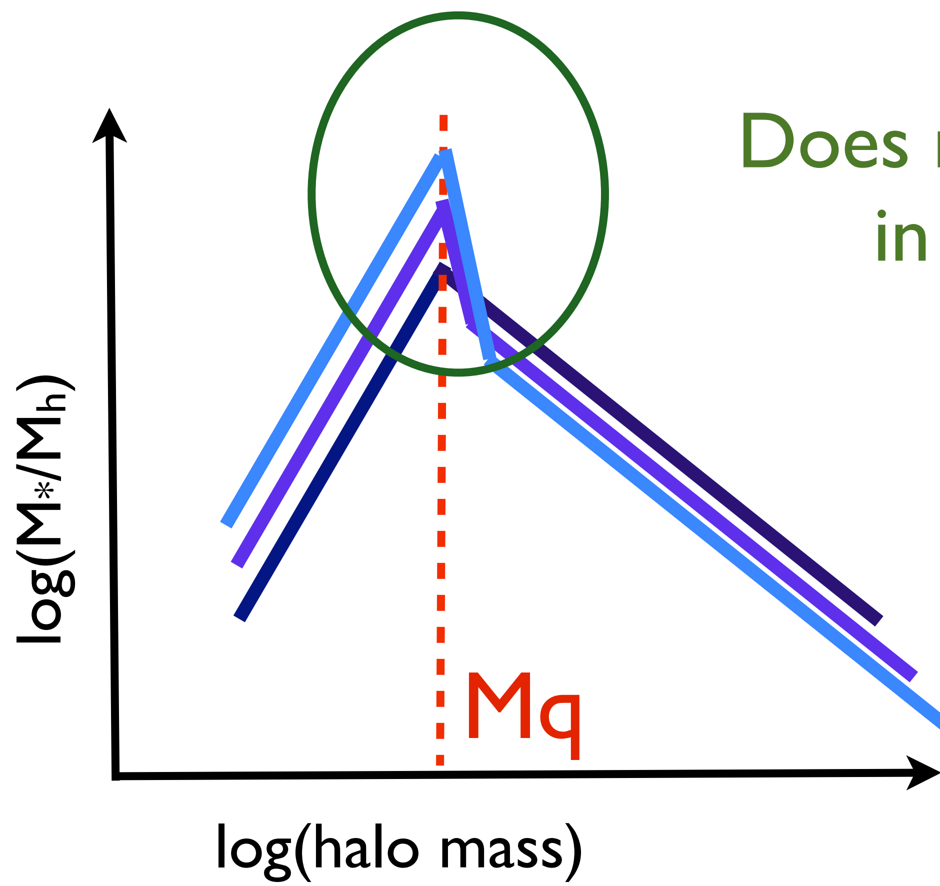


$\boxed{\lambda_{M*} > \lambda_{Mh}}$



$\boxed{\lambda_{M*} < \lambda_{Mh}}$

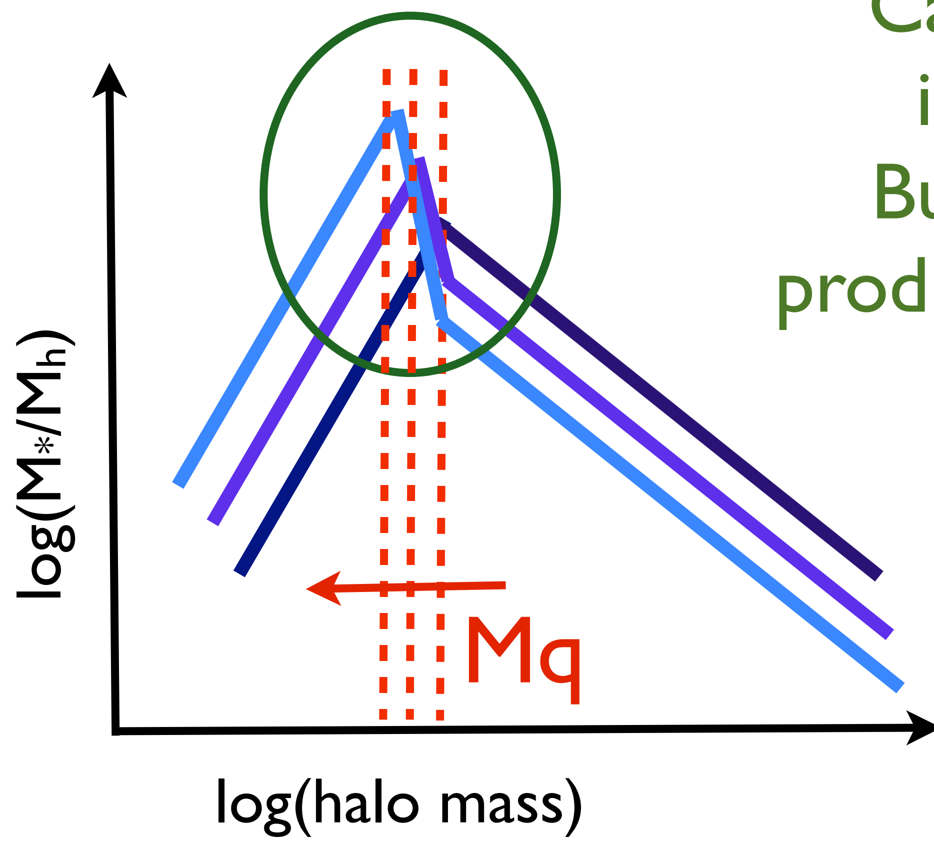
Fixed halo mass (Mq) above which star formation is quenched



Does not produce downsizing in the pivot quantities

$\lambda_{M*} > \lambda_{Mh}$
for $M_h < M_q$

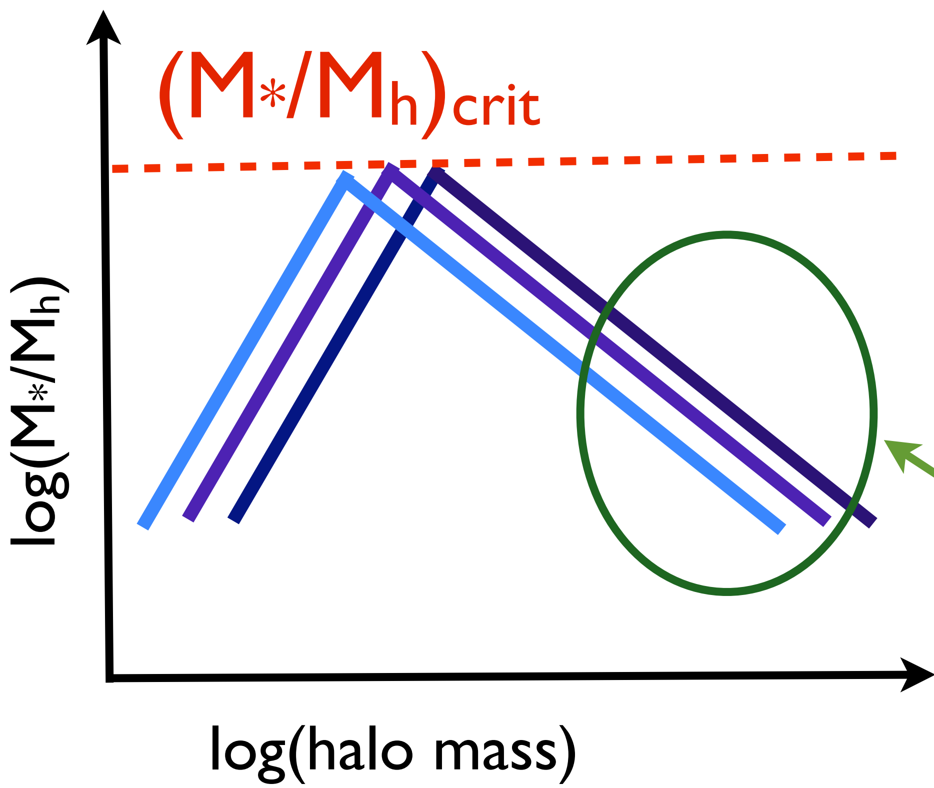
Evolving pivot mass (Mq) above which star formation is quenched



Can produce downsizing
in the pivot quantities
But does not necessarily
produce a constant pivot ratio

$\lambda_{M*} > \lambda_{Mh}$
for $M_h < M_q$

Fixed (M_*/M_h) limit above which star formation is quenched

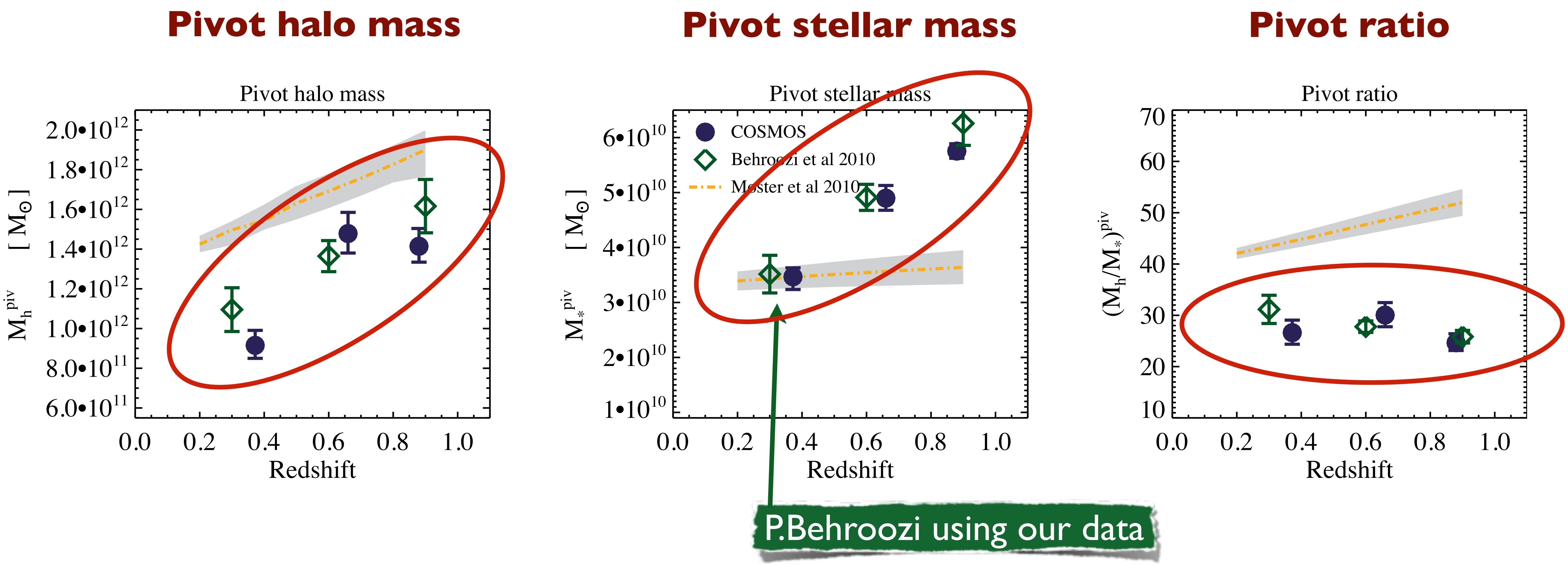


A critical pivot ratio, coupled with $\lambda_{M*} > \lambda_{Mh}$ naturally leads to downsizing

Still need maintenance mode feedback to prevent growth in higher mass halos

$\lambda_{M*} > \lambda_{Mh}$
for $M_h < M_q$

Evolution of the "pivot masses"



The mechanism(s) that regulate the quenching of star formation may have a physical dependance on M_*/M_h and not simply on M_h

Mechanisms that might depend on M_*/M_h ?

Speculative !!

- Disk instabilities : if the mass of the disk dominates the gravitational potential, the system is unstable to perturbations.

$$V_{max}/(GM_{disk}/R_{disk})^{0.5} < 1$$

Efstathiou et al. 1982

- AGN feedback → a) halo of hot gas to which AGN jets can couple b) a sufficiently large BH to offset cooling in the halo

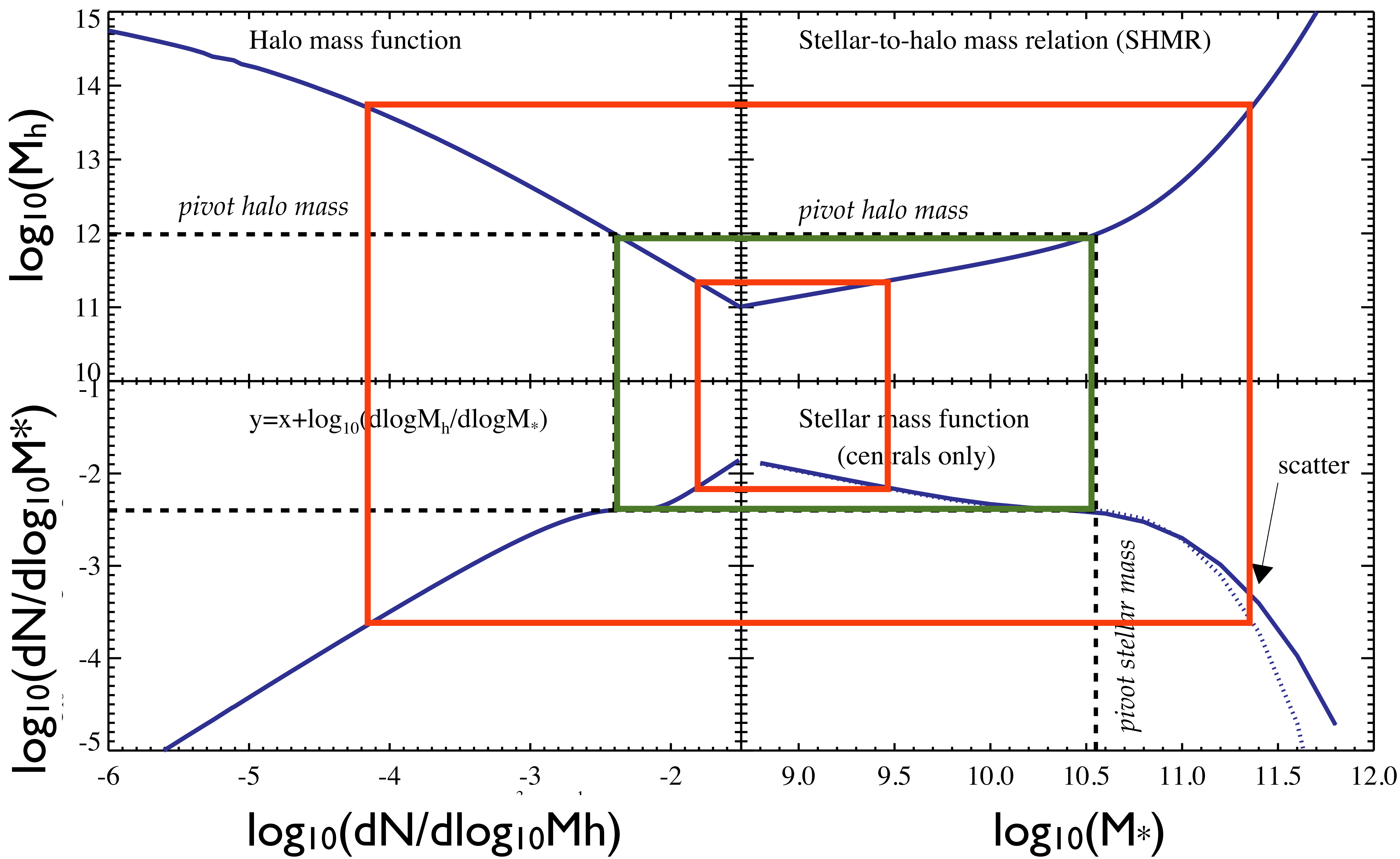
$$L_{heat}/L_{cool} \approx 10^3(\Delta/200)^{-1/3}(\Omega_m/0.25)^{-1/3}(f_{gas}/0.15)^{-1}(\tau_{cool}/Gyr)(M_h/10^{12}M_{sun})^{-2/3}(\varepsilon/0.01)\underline{(M_*/M_h)}$$

From A.Benson

  - $M_*/M_h=1/27$ → $L_{heat}=37 \times L_{cool}$
  - uncertainties in f_{gas}, ε, ...

- others ??

The link between halo and stellar-mass



Summary

- We have build a method to combine galaxy-galaxy lensing, galaxy clustering, and number densities into a more robust probe of the galaxy-dark matter connection
- We have applied this technique to the COSMOS field and studied the SHMR from z=0.2 to z=1.0
- We find a downsizing behaviour for the "pivot masses" but the "pivot ratio" remains remarkably constant
- This coincidence raises the intriguing possibility that the quenching of star-formation may have a physical dependance on M_h/M_*

Work in Progress and future plans

- Calculation of the total amount of stars locked up in galaxies, implications for the baryon fraction in groups
- Comparison between HOD models and abundance matching methods
- Comparisons with semi-analytic models such as Galacticus with A. Benson
- Application to larger data sets (e.g. BOSS, HSC)
- Cosmology and GR tests