towards understanding massive galaxy formation

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outline

- focus on $L \geq L^*$ galaxies: brightest cluster galaxies (BCGs), Milky Way-like galaxies
- motivation
  - still discrepancy between theory and observations on the mass assembly history of BCGs
  - $L \geq L^*$ galaxies are mainly *central* galaxies in dark matter halos more massive than ~$10^{12} M_{sun}$: easier to identify progenitors/descendants using knowledge from halo evolution
- research program
  - BCG mass assembly from *top N* cluster selection
  - tracing redshift evolution of clusters and BCGs from z~4 to 0
  - galaxy-halo connection
  - assembly bias
- outlook: Subaru in 2020s

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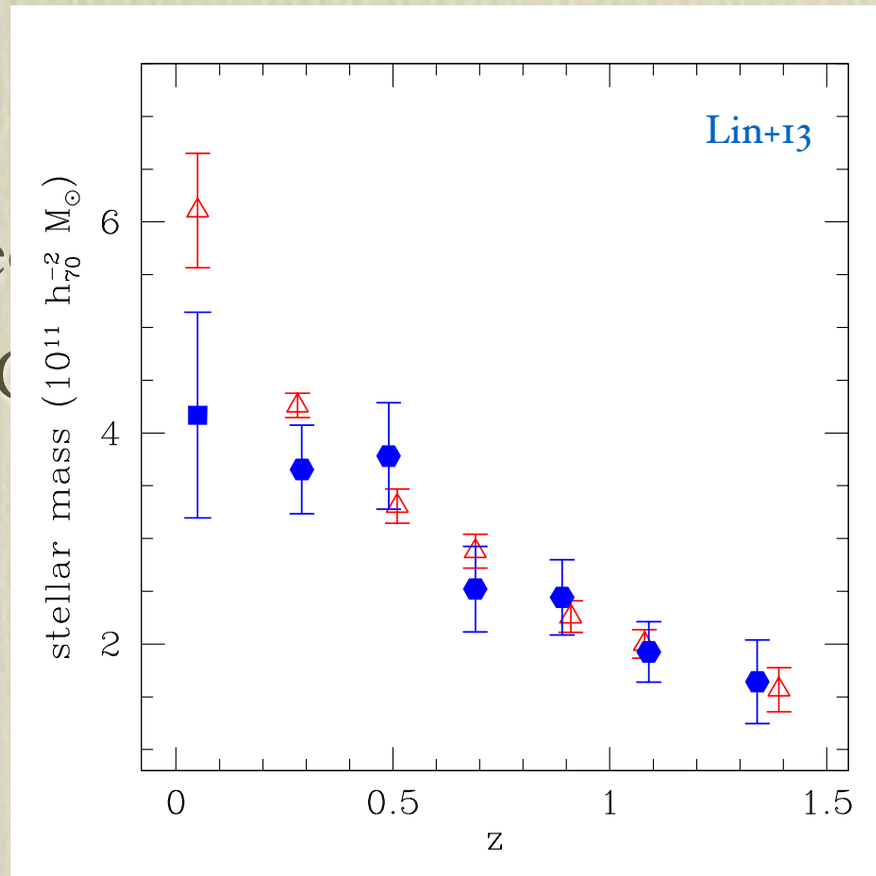

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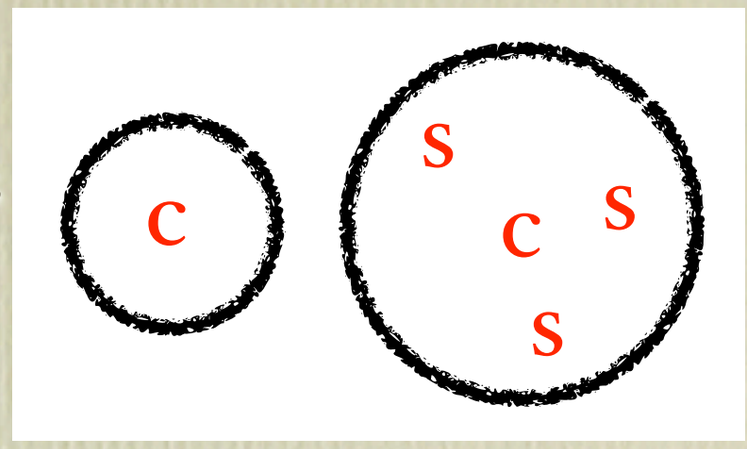

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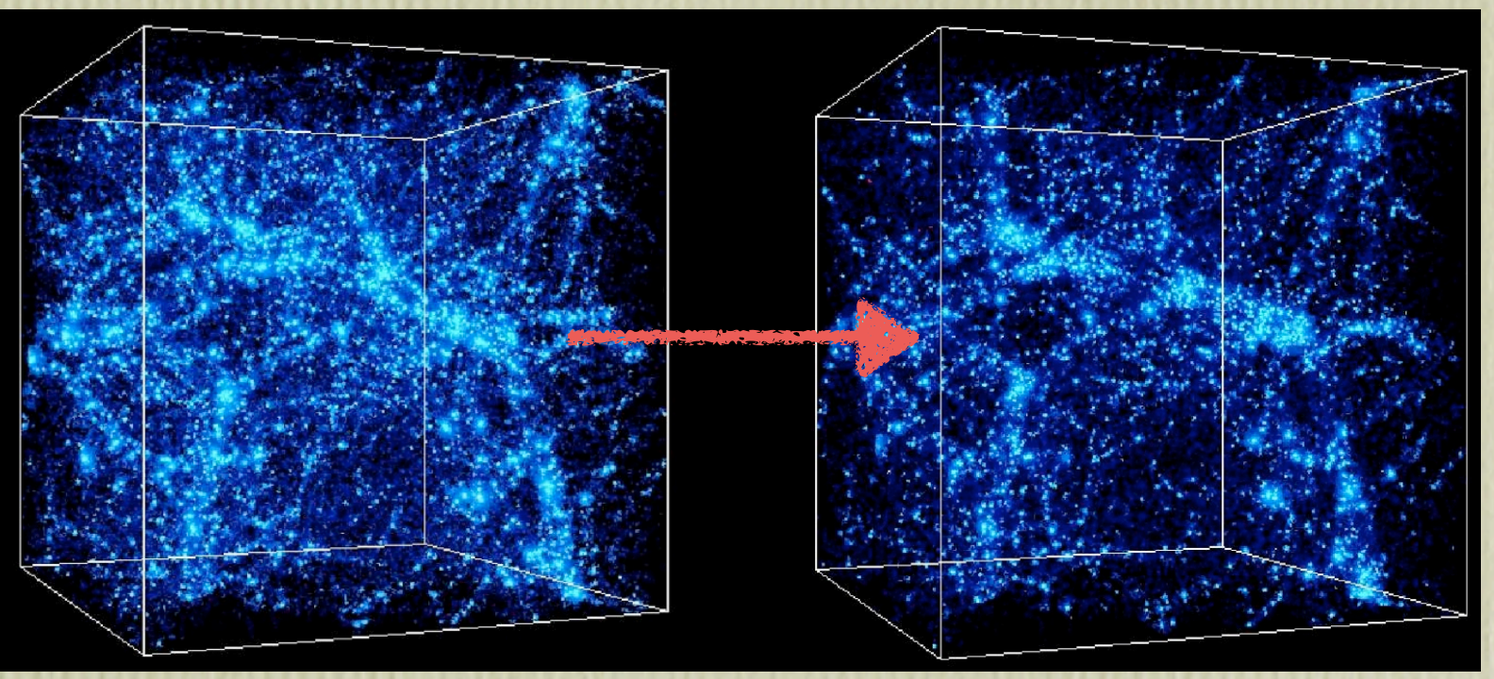
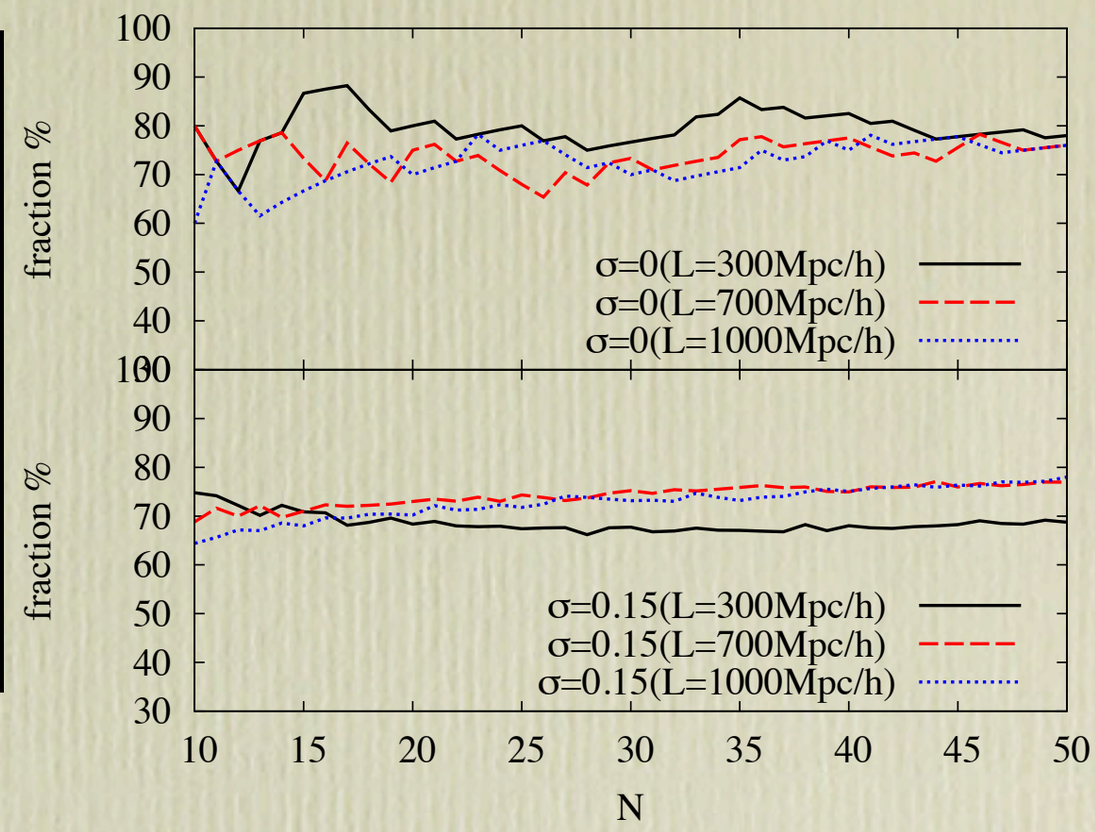
assembly history of BCGs

top N selection of halos



A. Kravtsov

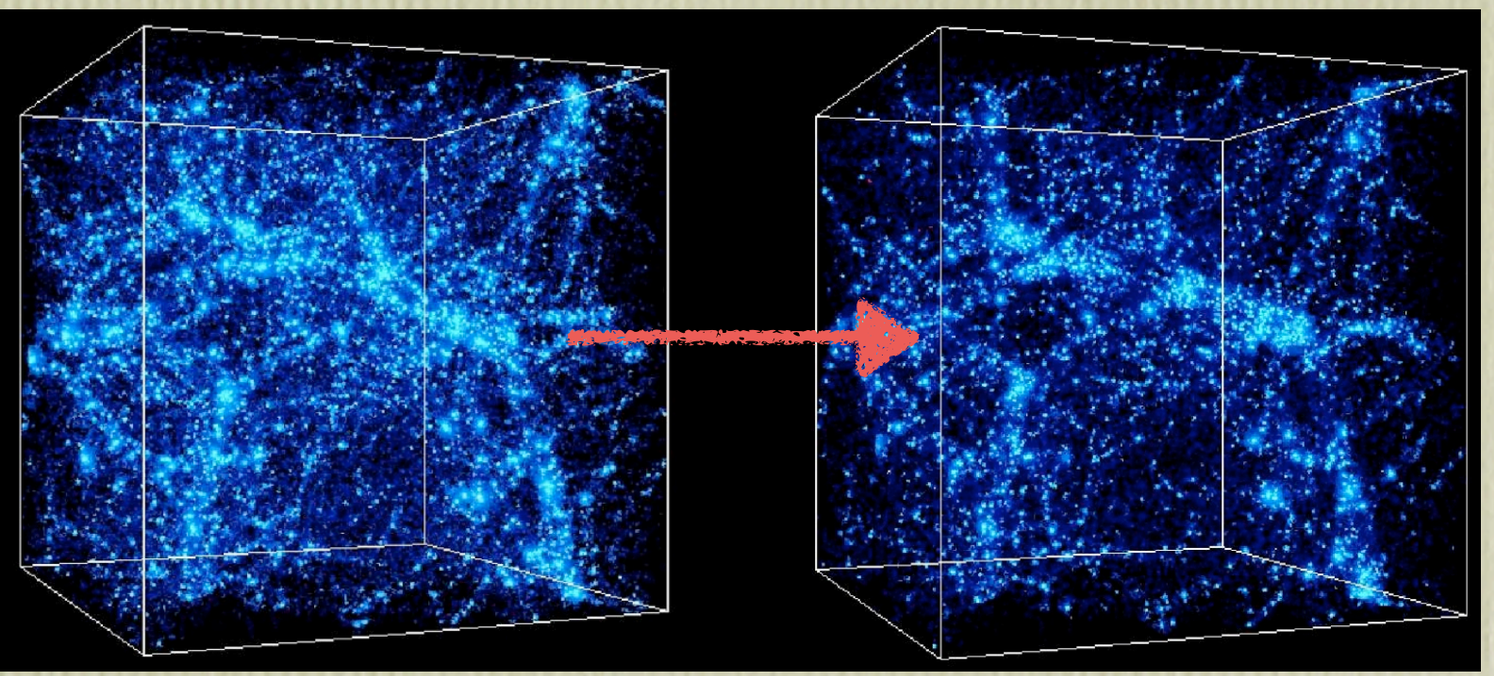


- Ansatz: given comoving volume, the most massive N halos will remain among the most massive N at a later time
- tests with large N-body simulations suggest above holds to ~60-70% (including scatter in mass-observable relation), even with $\Delta z \sim 0.6$
- tests with semi-analytic models show good recovery of galaxy population
- similar in spirit to the fixed cumulative number density selection for field galaxies

Inagaki, Lin et al. (2015)

blue: z=0.4 des. of top 100 cl. selected at z=1
red: z=0.4 top 100 cl.

top N selection of halos



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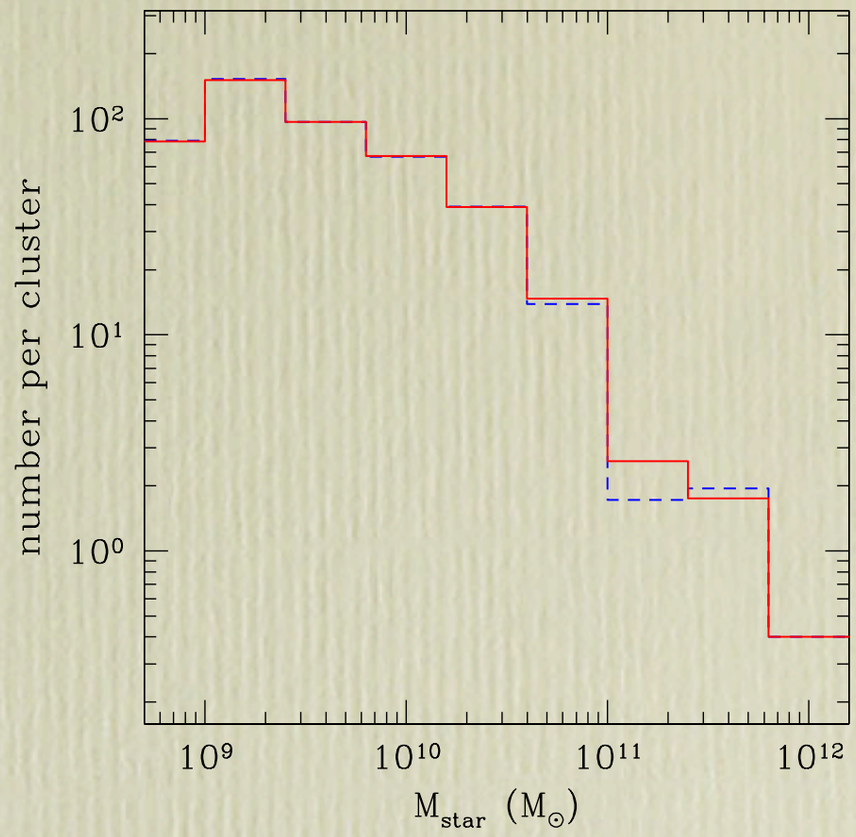

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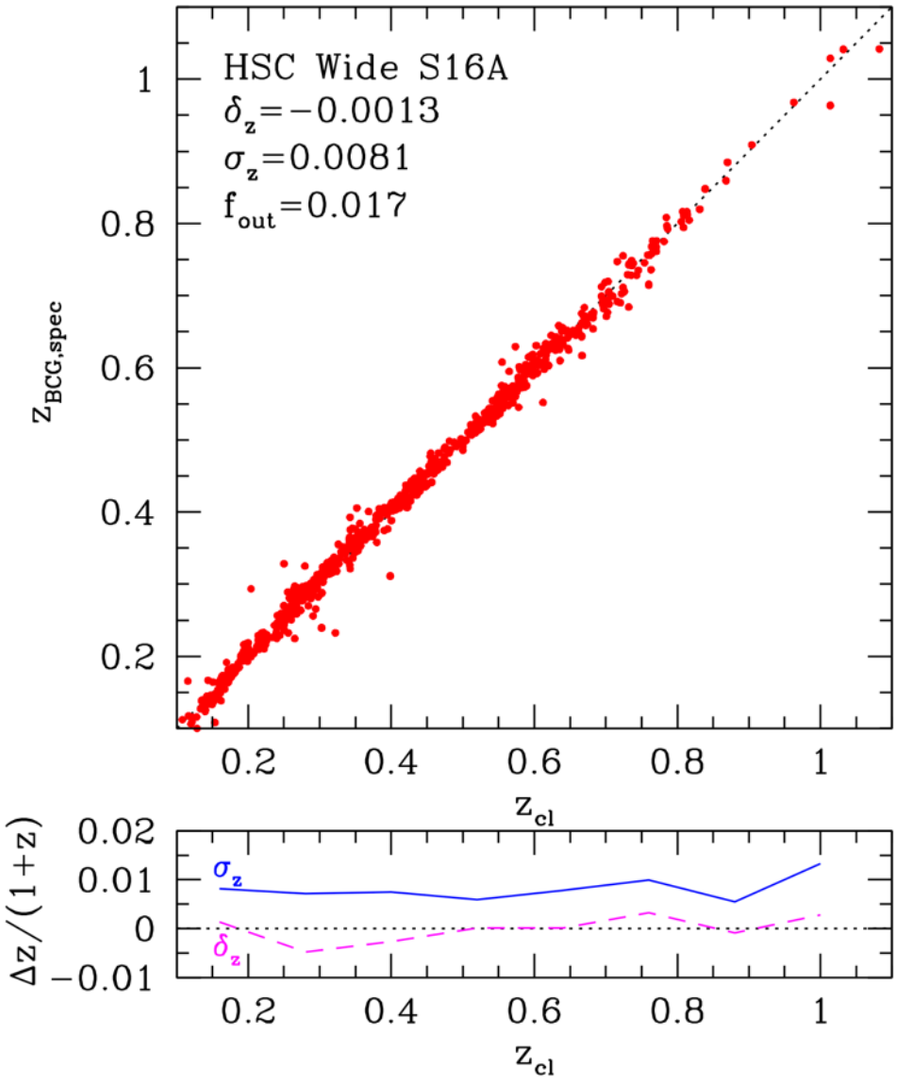
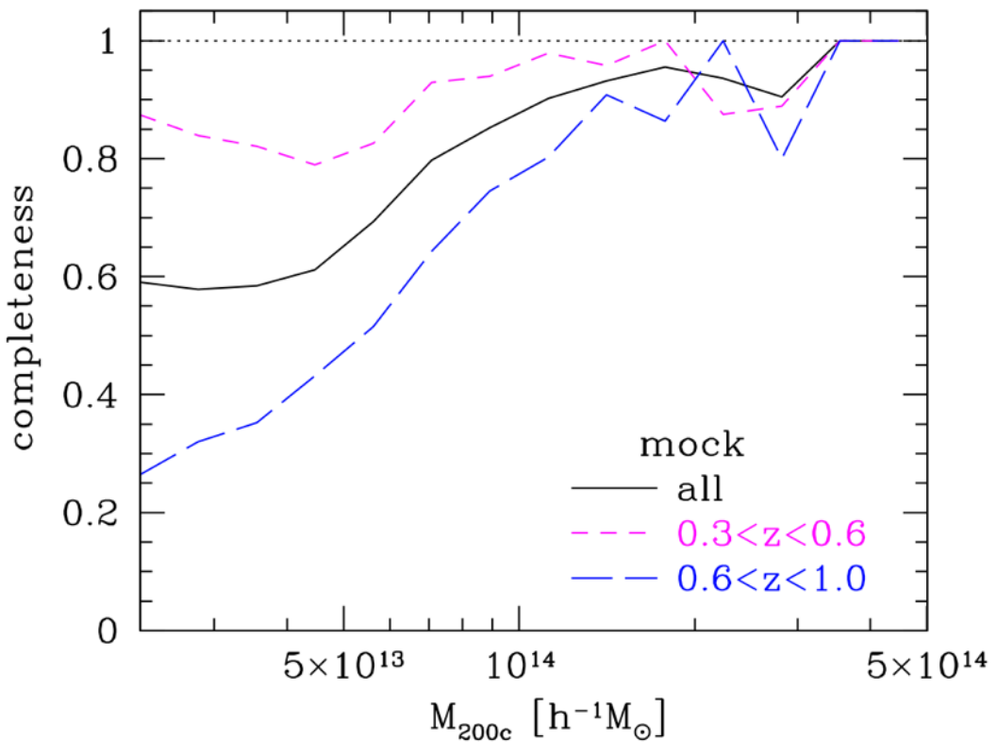
seeing red

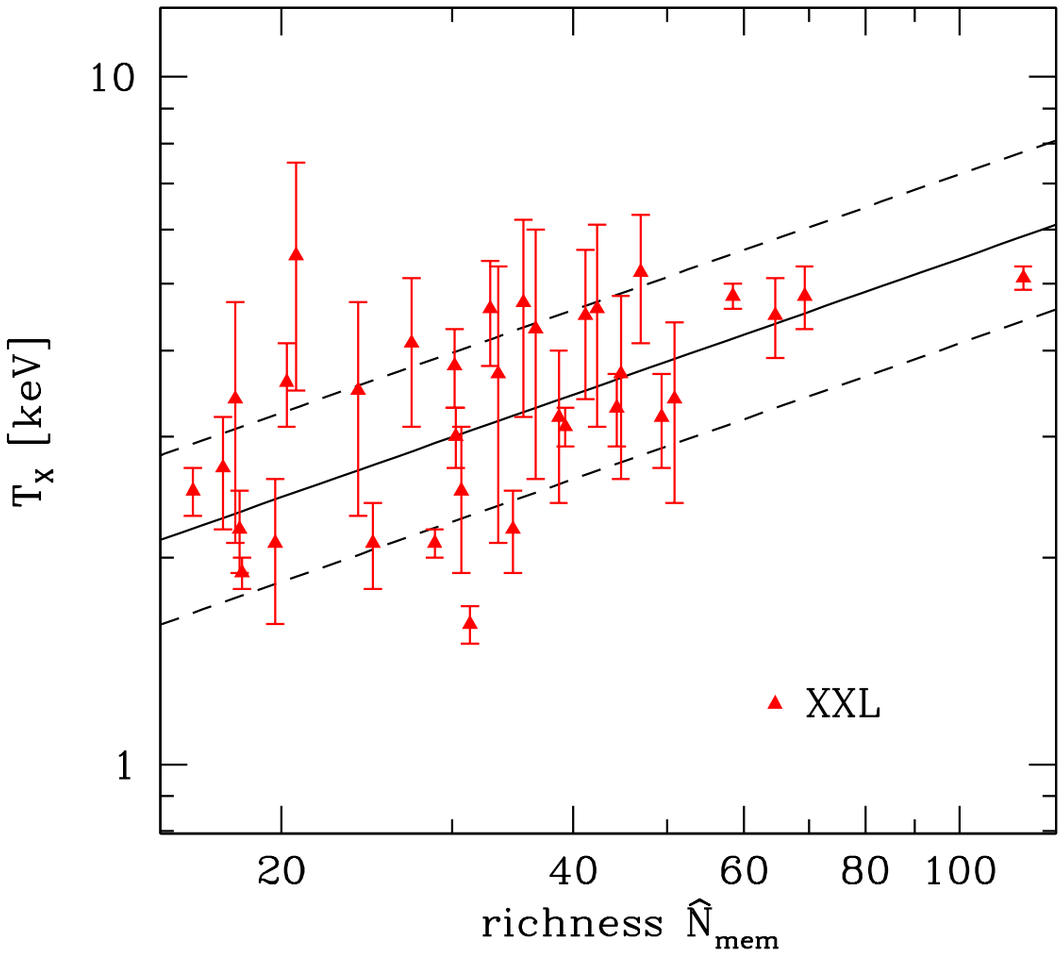
targeting clusters with prominent red sequence, *camira* (**c**luster finding **a**lgorithm based on **m**ulti-band **i**dentification of **r**ed sequence g**a**laxies) has found ~1900 clusters at z=0.1-1.1 over 230 deg² with richness N≥15 in the HSC survey

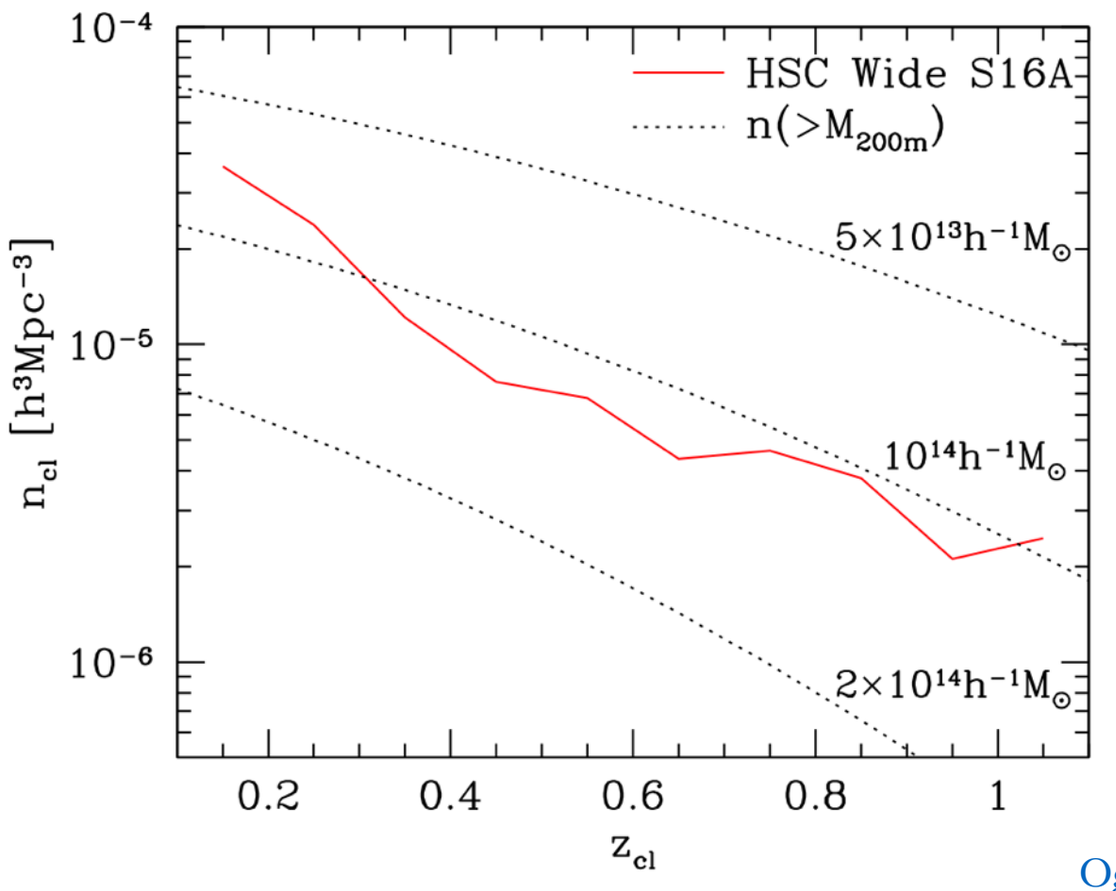
Oguri+17

Oguri, Lin et al. (arxiv:1701.00818)


HSC Wide S16A
δ_z=−0.0013
σ_z=0.0081
f_{out}=0.017
$z_{BCG,spec}$
z_{cl}
$\Delta z/(1+z)$
σ_z
δ_z


completeness
mock
all
0.3<z<0.6
0.6<z<1.0
M_{200c} [$h^{-1}M_\odot$]

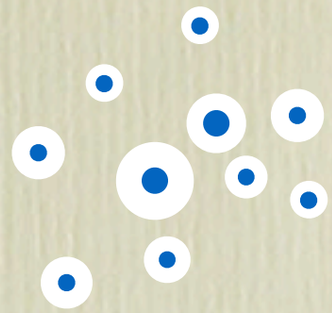

T_x [keV]
XXL
richness $\hat{N}_{mem}$


HSC Wide S16A
$n(>M_{200m})$
$5\times10^{13}h^{-1}M_\odot$
$10^{14}h^{-1}M_\odot$
$2\times10^{14}h^{-1}M_\odot$
n_{cl} [h^3Mpc^{-3}]
z_{cl}

Oguri+17

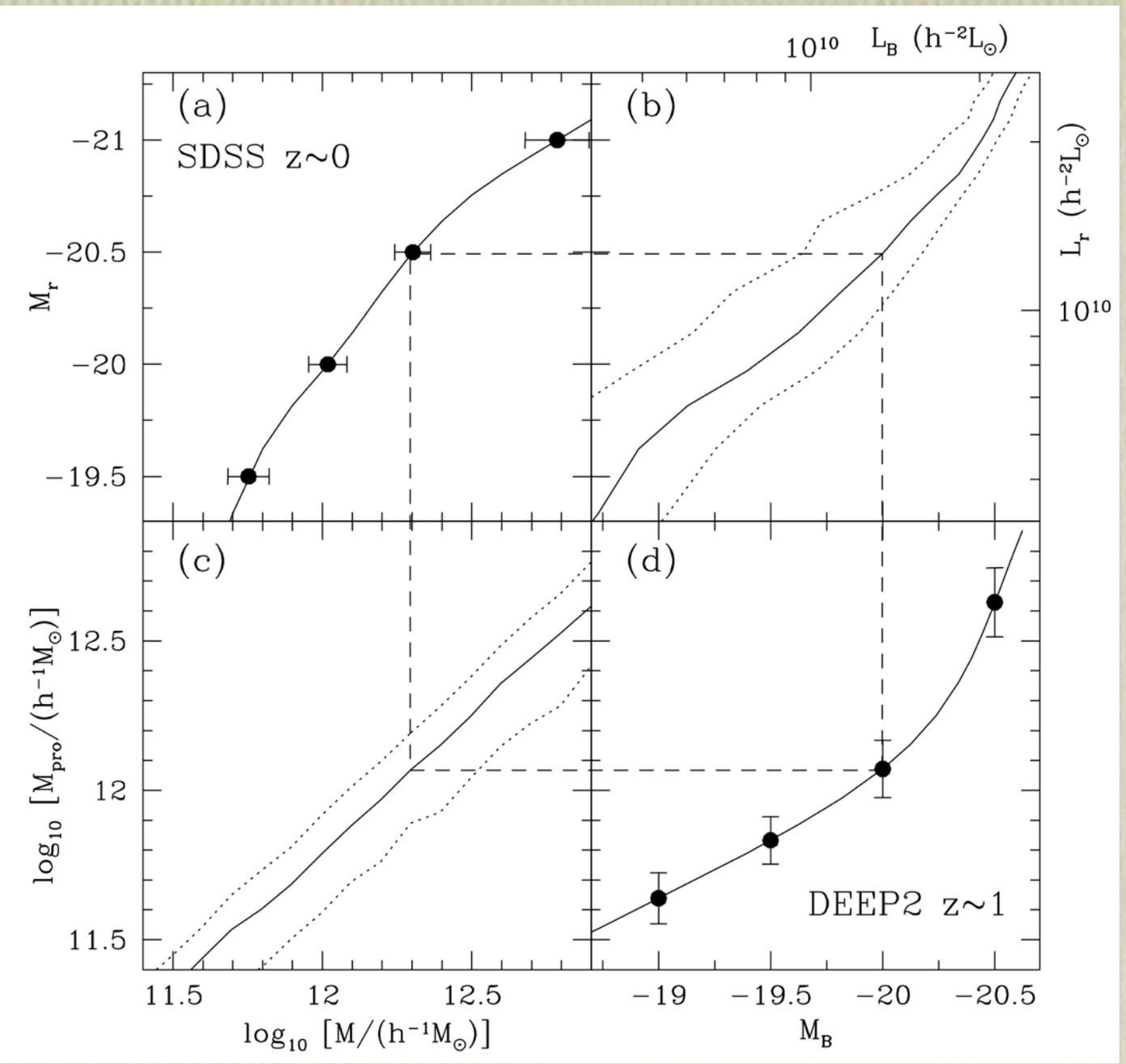
linking proto-cluster with clusters

- using knowledge on galaxy-halo connection derived from galaxy clustering and abundance of Lyman break galaxies (LBGs), we can populate dark matter simulations with mock galaxies
  - need to reproduce the number count, angular correlation function, and luminosity function of LBGs
- run proto-cluster finding on the mock catalog
  - adjust mocks until we obtain reasonable agreement between mocks and observations on clustering and abundance of proto-clusters ⇒ good understanding of the galaxy-halo connection & "definition" of proto-clusters
  - can then infer the large scale bias (=mass) of (the main halos of) proto-clusters
  - use halo merger history to connect them to lower-z
  - can then study the evolution from proto-BCGs to matured BCGs!
  - application to HSC survey



galaxy mass assembly from galaxy-halo connection

galaxy-halo connection vs galaxy assembly

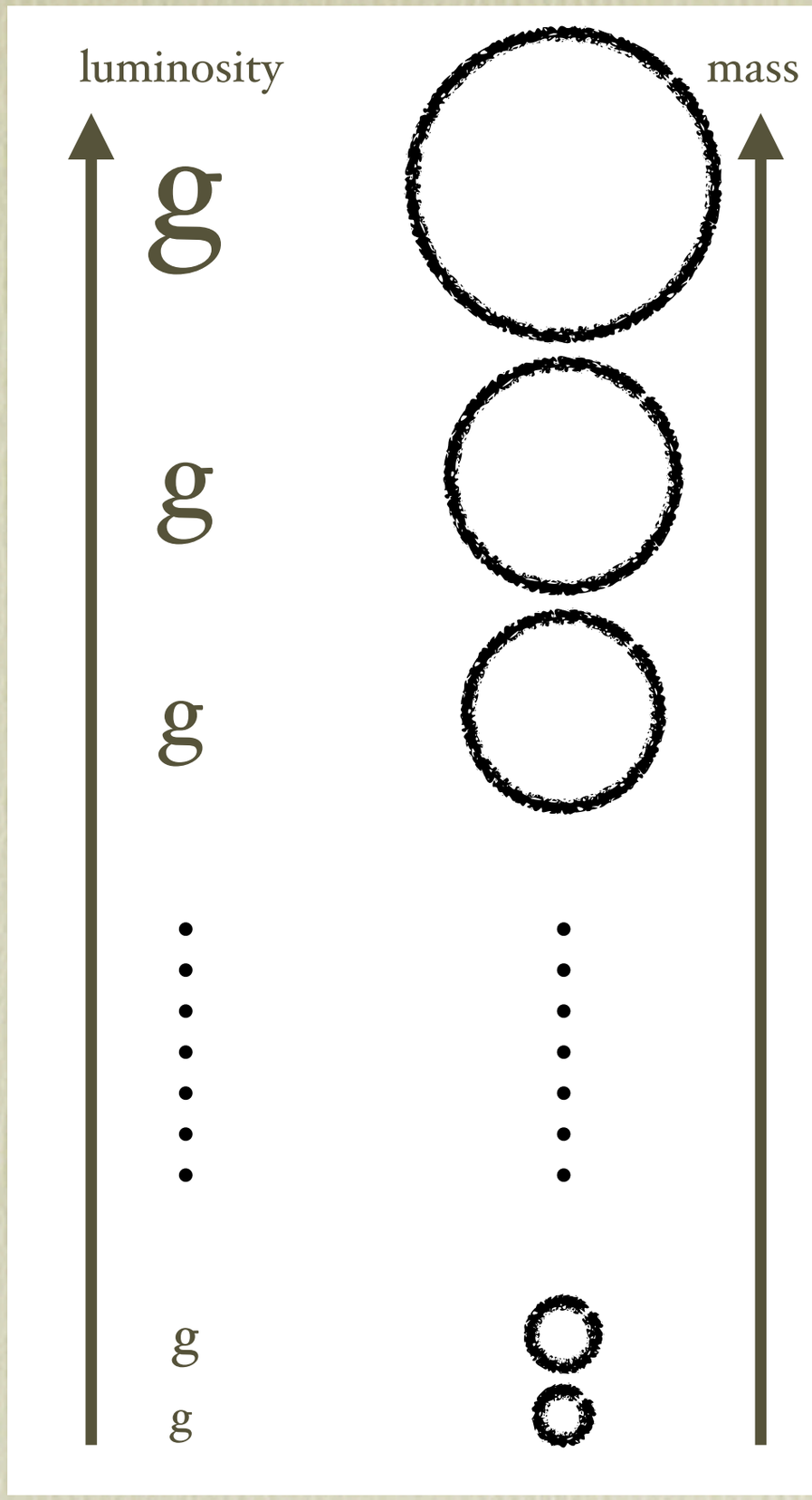


Zheng+07

- it's much easier to study the evolution of halos
- by associating galaxies with halos, it's then possible to study the assembly history of galaxies
- how to get galaxy-halo relation?
- two approaches developed towards realizing this goal
  - first attempt of extending the abundance matching (AM) technique to include color
  - inferring host halo mass of *individual* galaxies based on number of neighboring galaxies

first extension of AM

- goal is to include secondary galaxy properties into AM framework
- use the usual AM to connect halos/subhalos with galaxy luminosity
- then assume color is related to local density of galaxies (densest = reddest)
- can reproduce clustering and lensing results!
- generalizing this approach, and to high-z



Masaki, Lin & Yoshida 13

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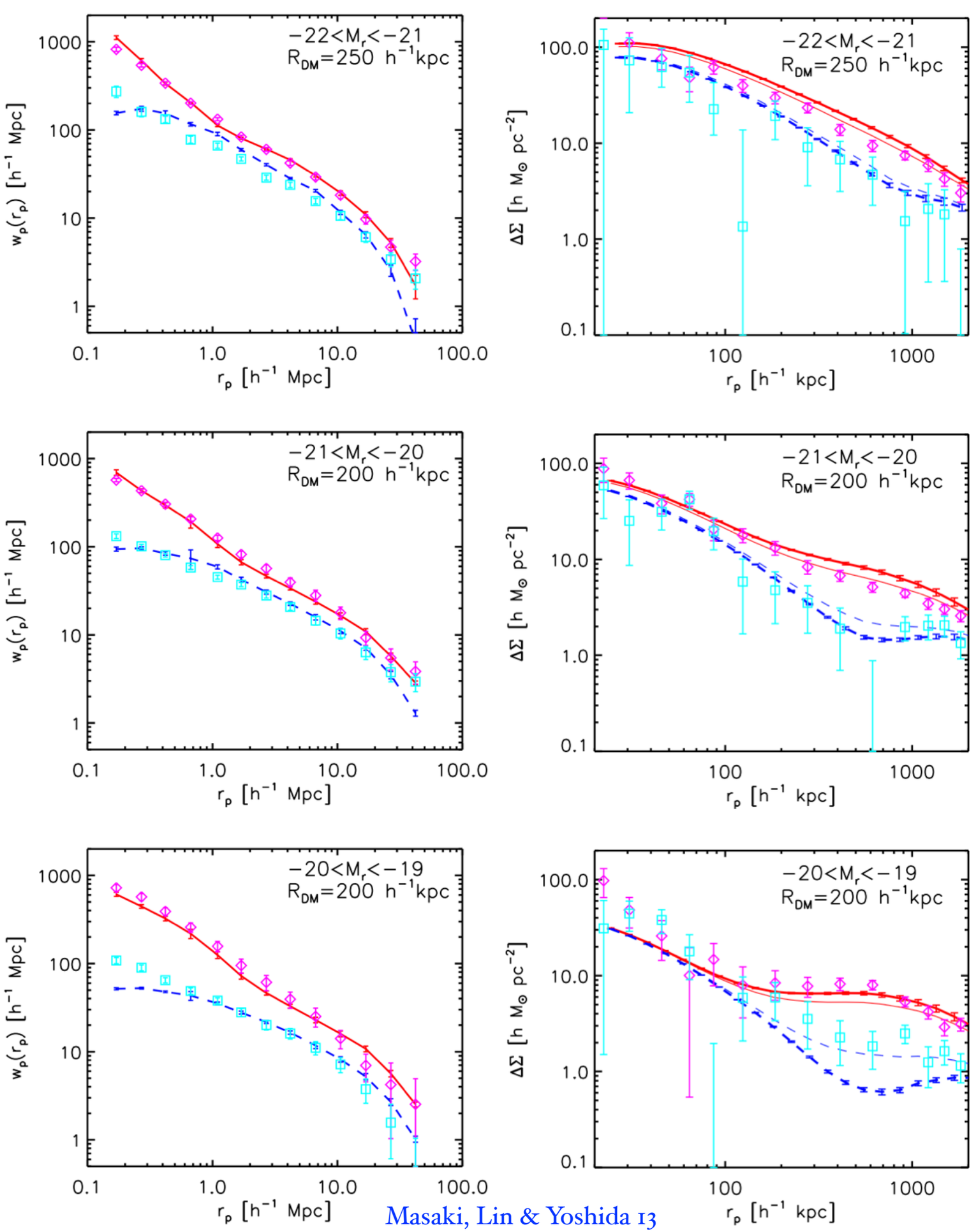
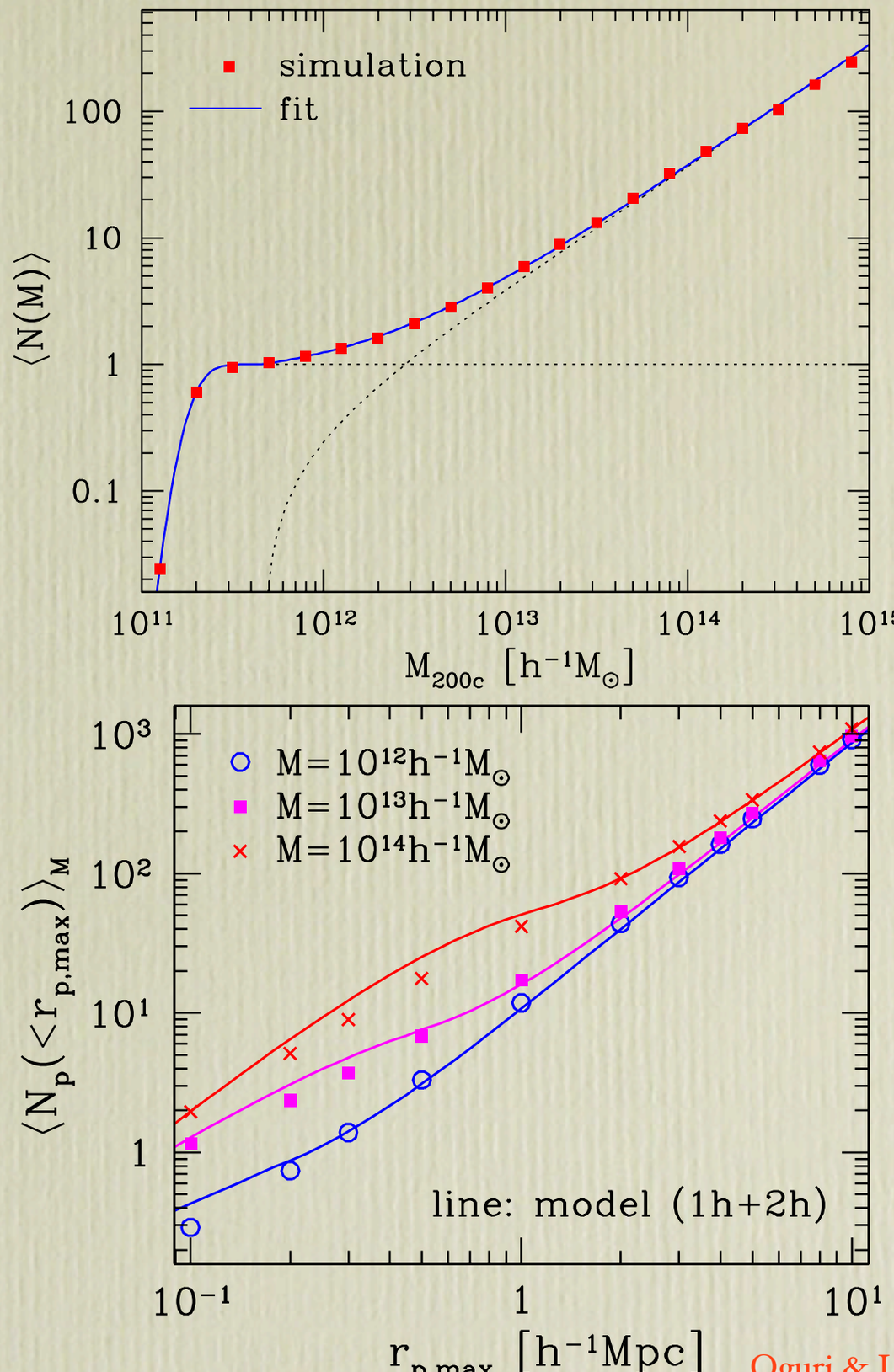


Masaki, Lin & Yoshida 13

new mass estimator: neighbor counts

- halo mass is king!
- estimating halo masses is hard!
- most of existing methods give halo mass in a statistical sense
- for a given galaxy sample, we can infer its halo occupation distribution (HOD), in particular the halo occupation number
- for this sample, we can then infer the number of neighboring galaxies *within the same galaxy sample*
- analytical calculations within the HOD framework, separately for central and satellite galaxies, and for one- and two-halo terms



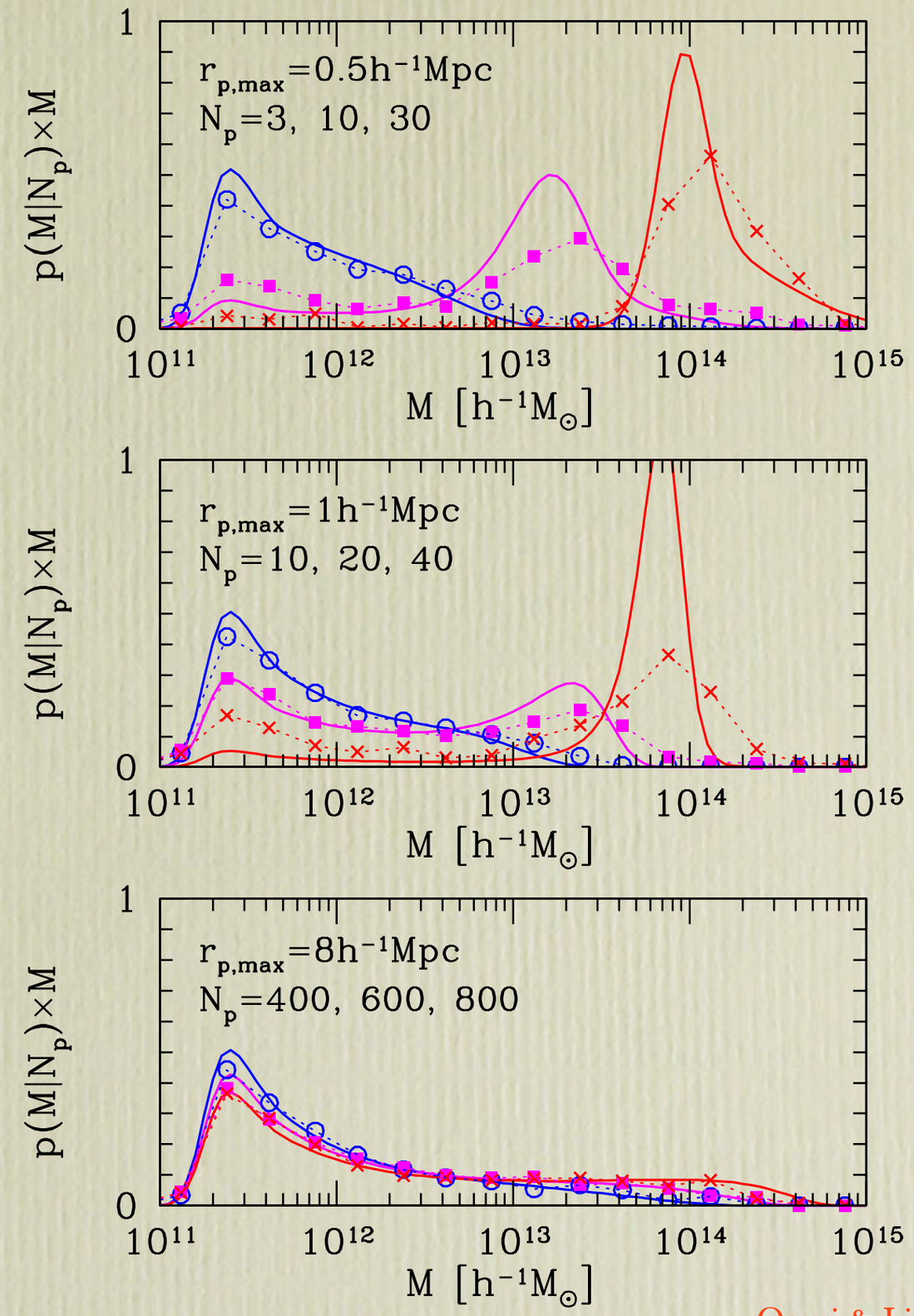
Oguri & Lin 15

halo mass probability distribution

- use Bayes' theorem to infer halo mass probability distribution function (pdf)

$$p(M|N) \propto p(N|M)p(M)$$

- model predictions match well with the mock results
- pdf often bimodal, due to uncorrelated large scale structures
- also gives probability of being a central
- working on extending the method to high redshifts ⇒ high-z galaxy-halo connection!



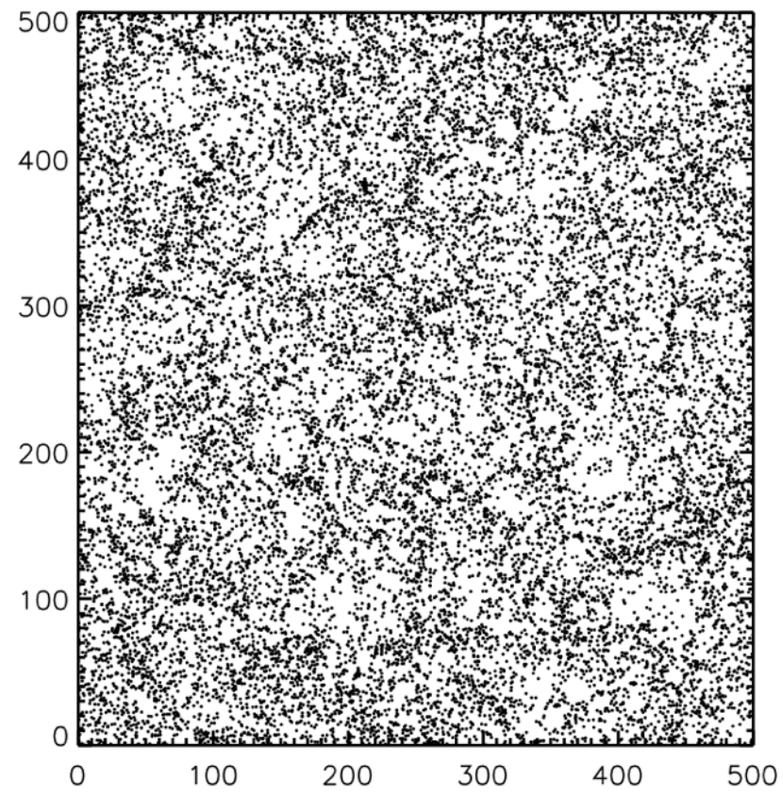
Oguri & Lin 15

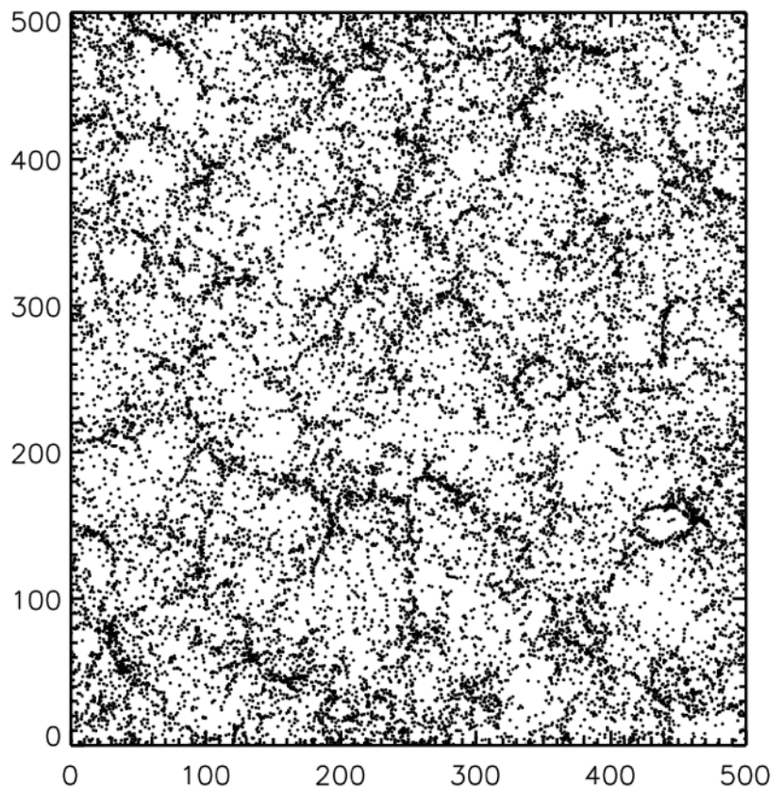
assembly bias: mass is not everything (?)

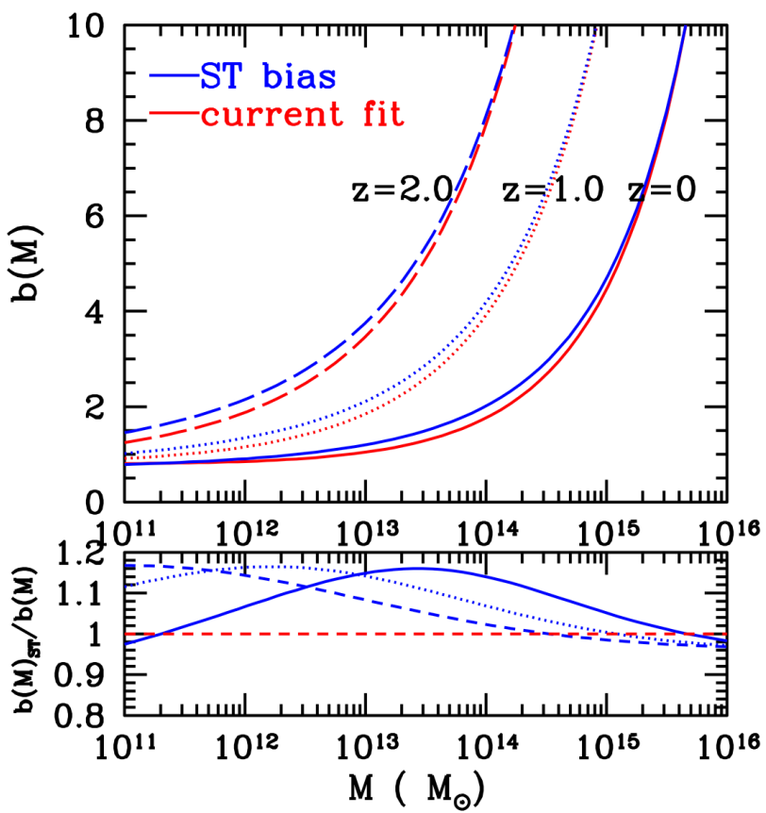
assembly bias?

- dark matter halos also have various degrees of bias, primarily as a function of halo mass
  - more massive halos are more biased
- a secondary effect is *assembly bias*: bias also depends on the halo formation time
  - for low mass halos (~$10^{12}h^{-1}M_{sun}$), those that form earlier would cluster more strongly (having ~40% larger bias)

Gao+05, Bhattacharya+11

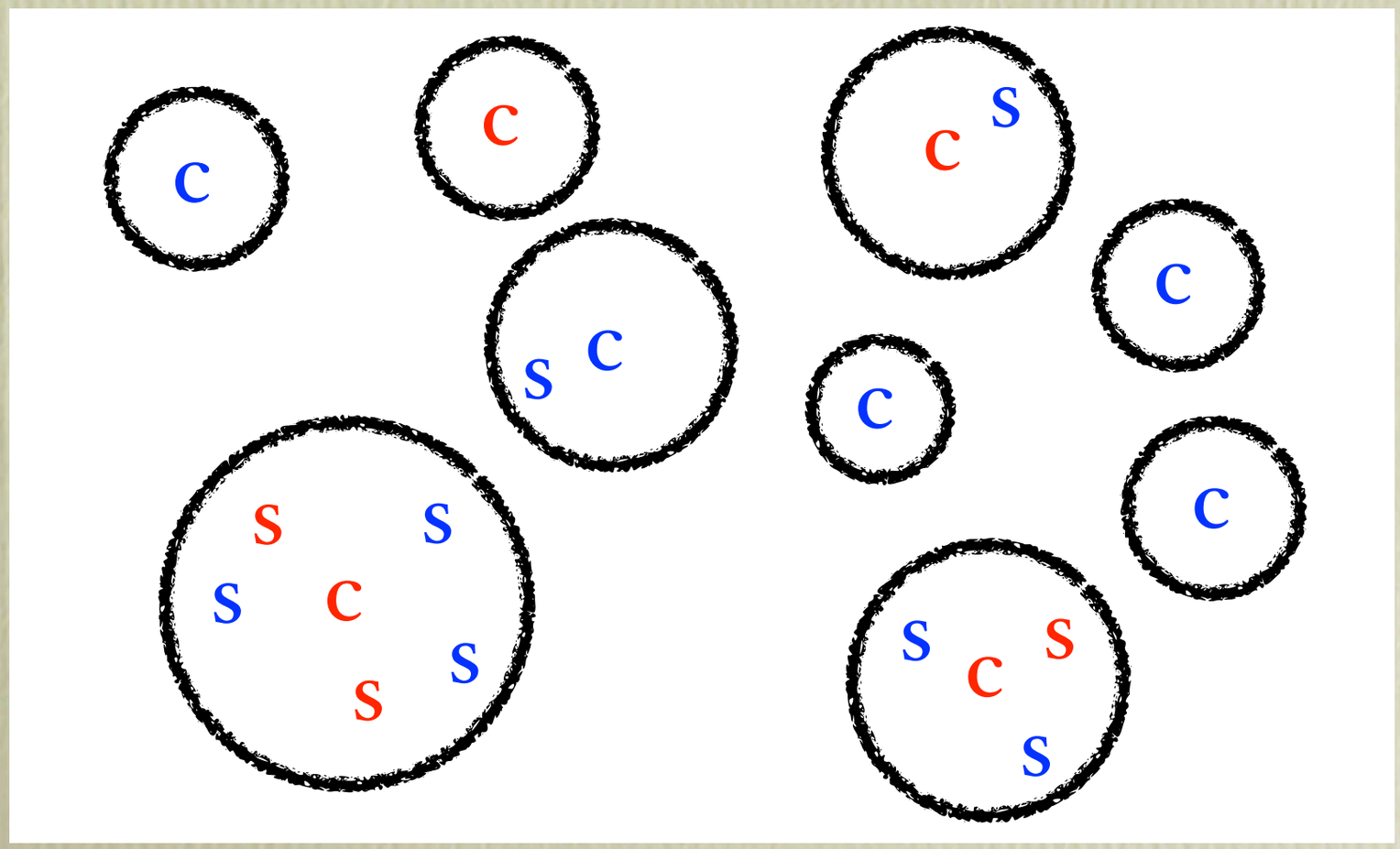


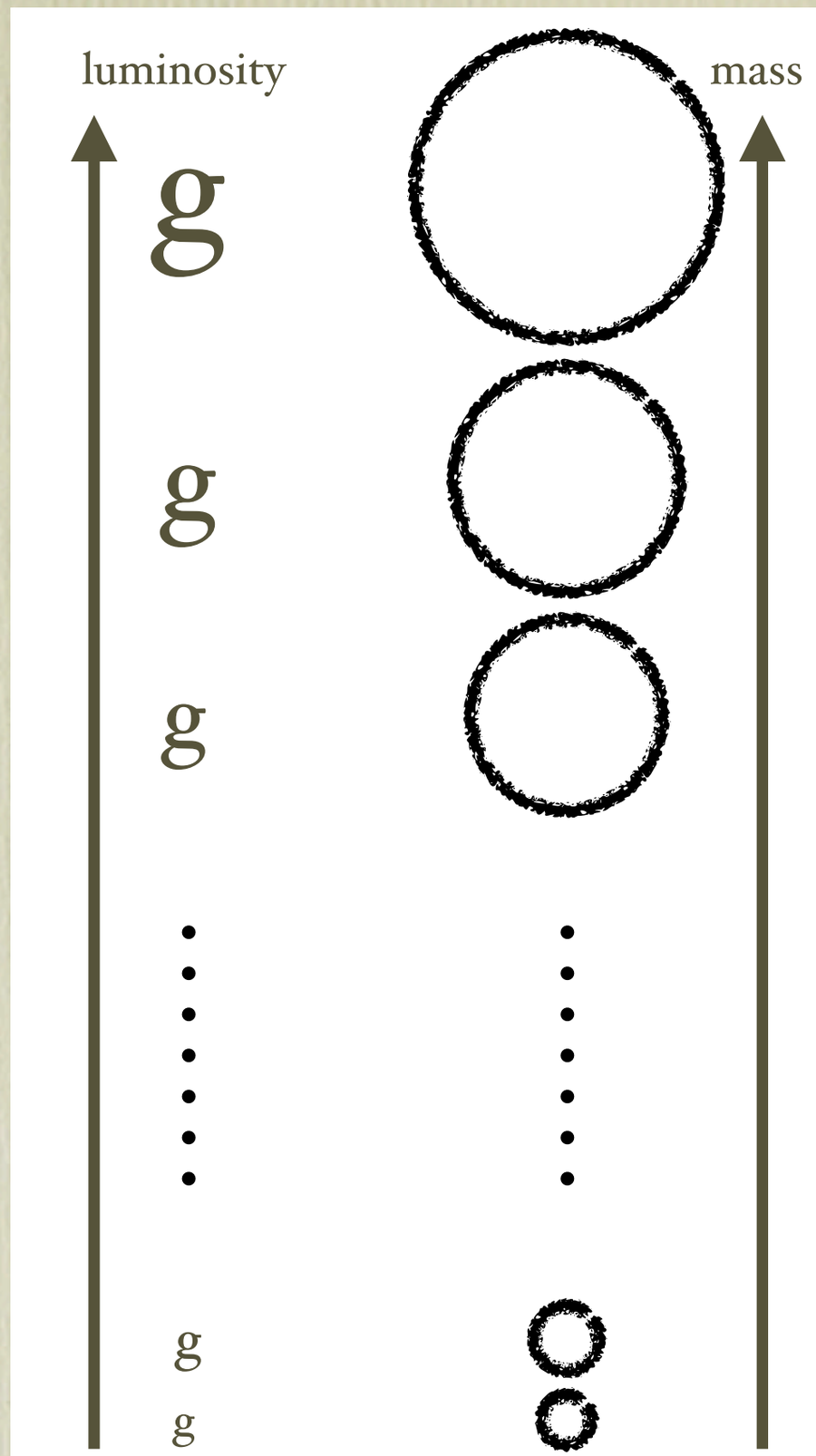




wasn't this detected long ago?

- Yang+06 first claimed detection
  - a catalog that classifies galaxies into single and multiple galactic systems
  - designation of central vs satellite galaxies
  - halo mass *assigned* to each system à la abundance matching technique





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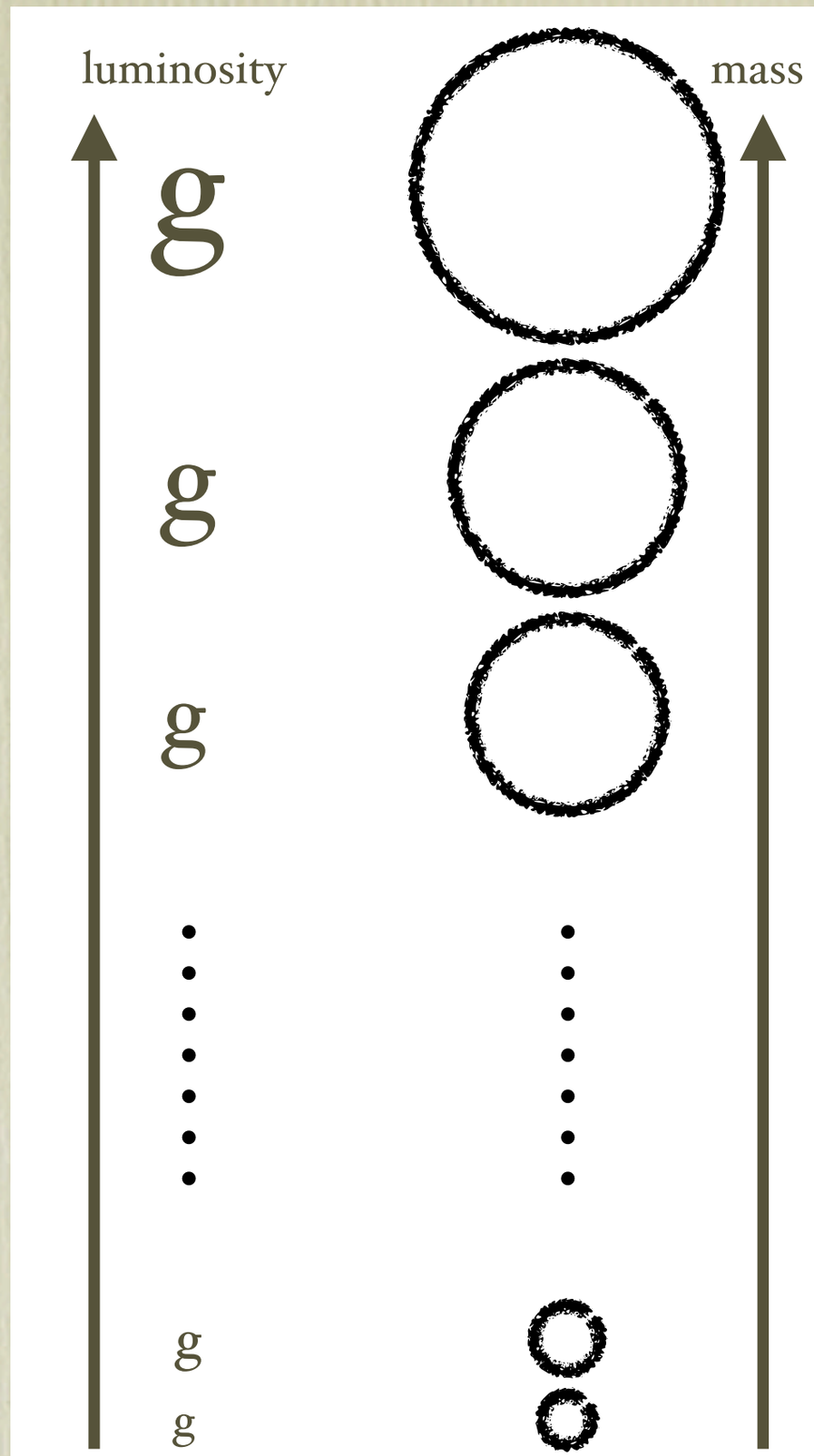
- formation history of central galaxies *assumed* to be closely related to that of the halos
- Yang+06 found that halos with currently passive centrals have larger bias than those with star-forming centrals of the *same* halo mass
  - if passive ↔ old, star-forming ↔ young, then this indicated assembly bias



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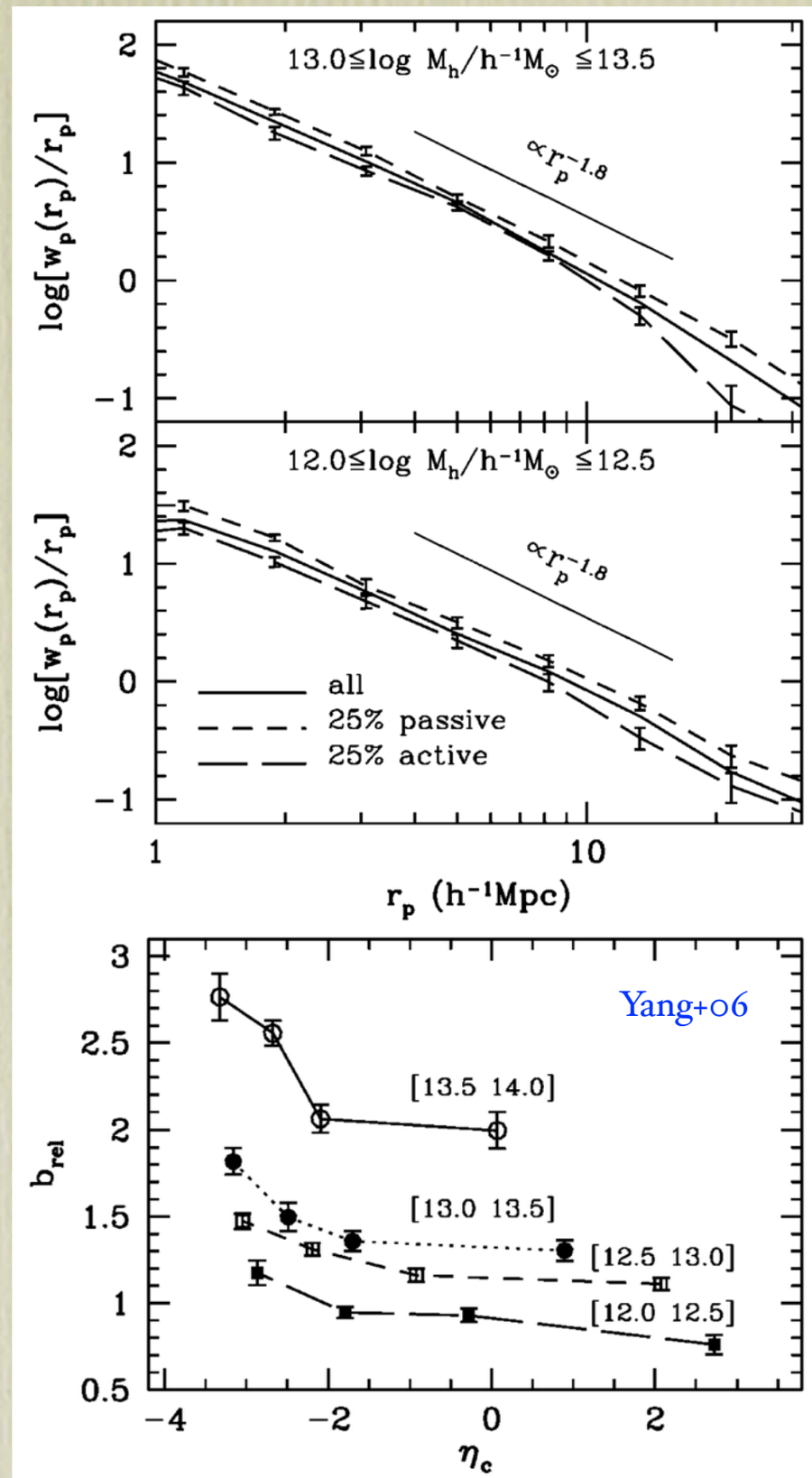
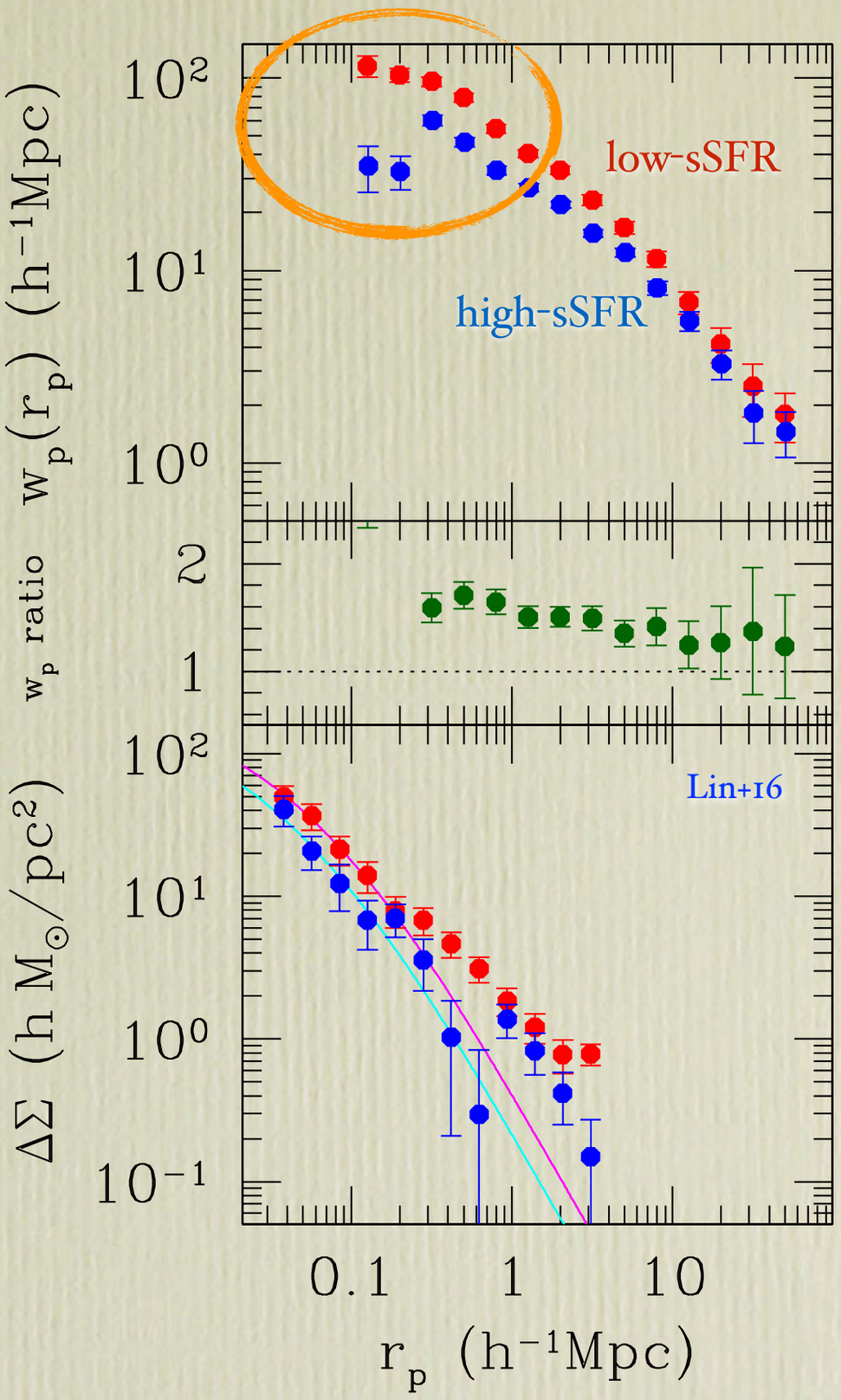


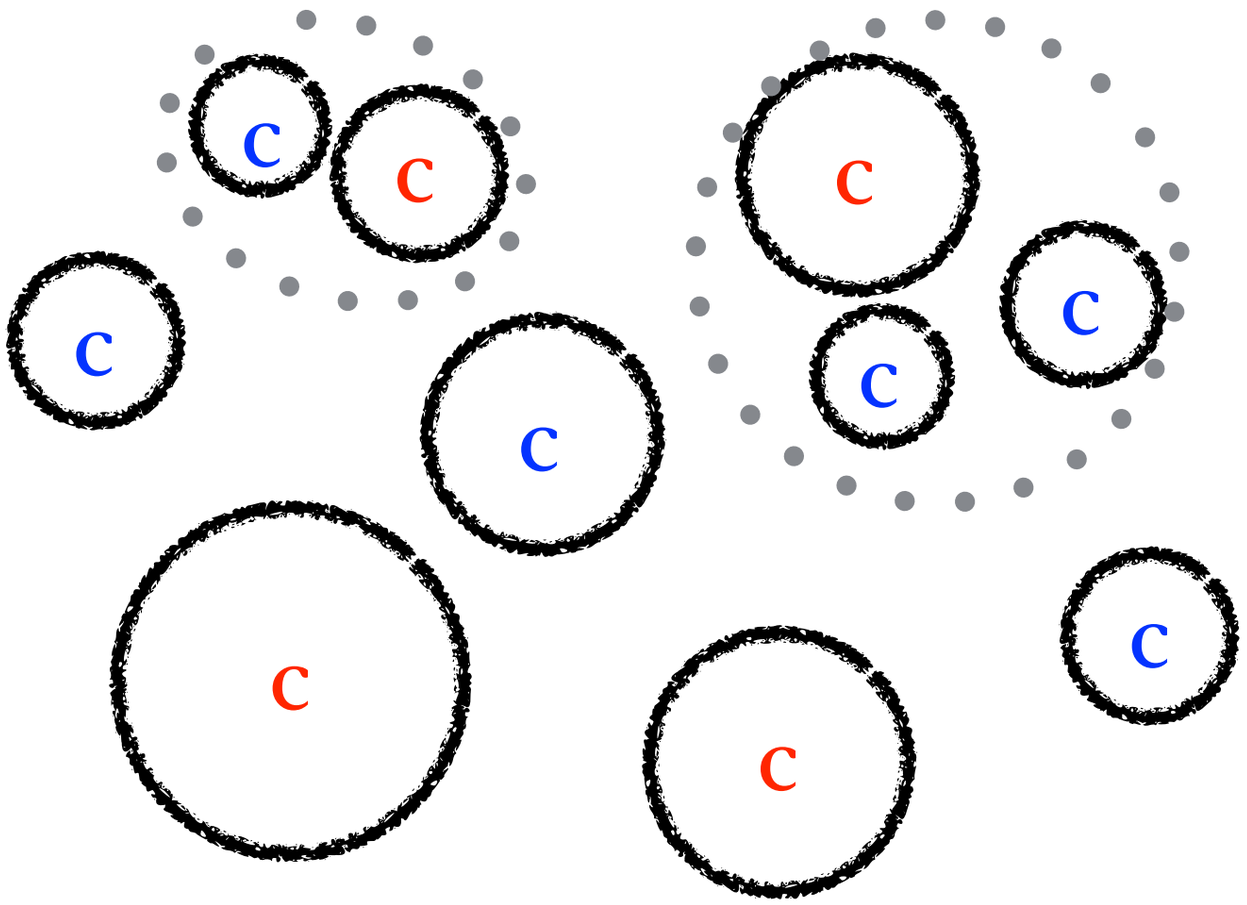
or was it?

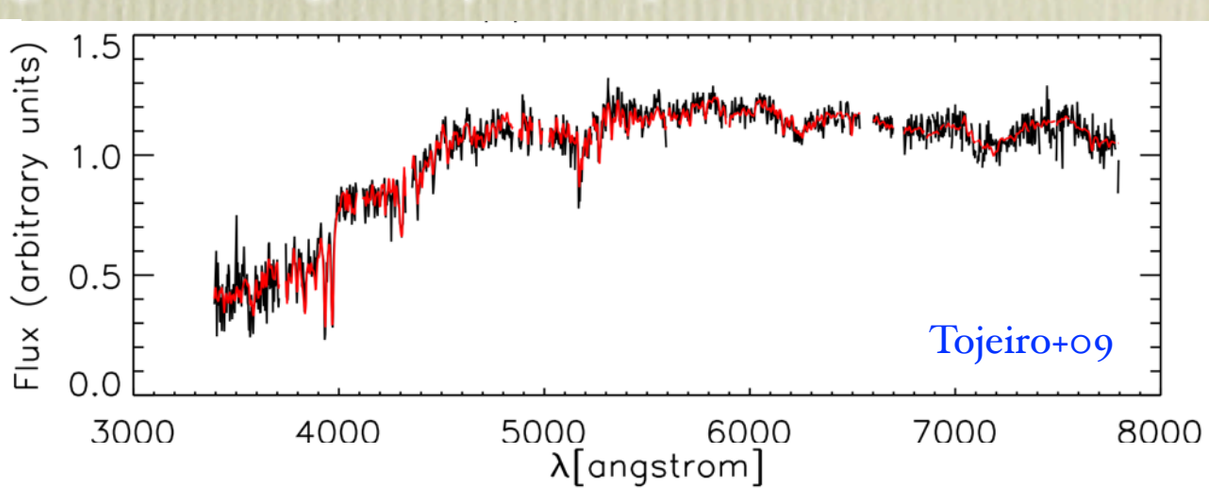
- using SDSS data, we follow the Yang+06 approach and confirm that low-sSFR centrals do cluster more strongly than high-sSFR ones
- however, the difference in bias may be explained by the difference in the mean masses of the two samples, as indicated by stacked weak lensing
- Yang's claim of detection likely false
- Yang et al. halo mass assignment not reliable
- serious contamination from satellite galaxies also detected!

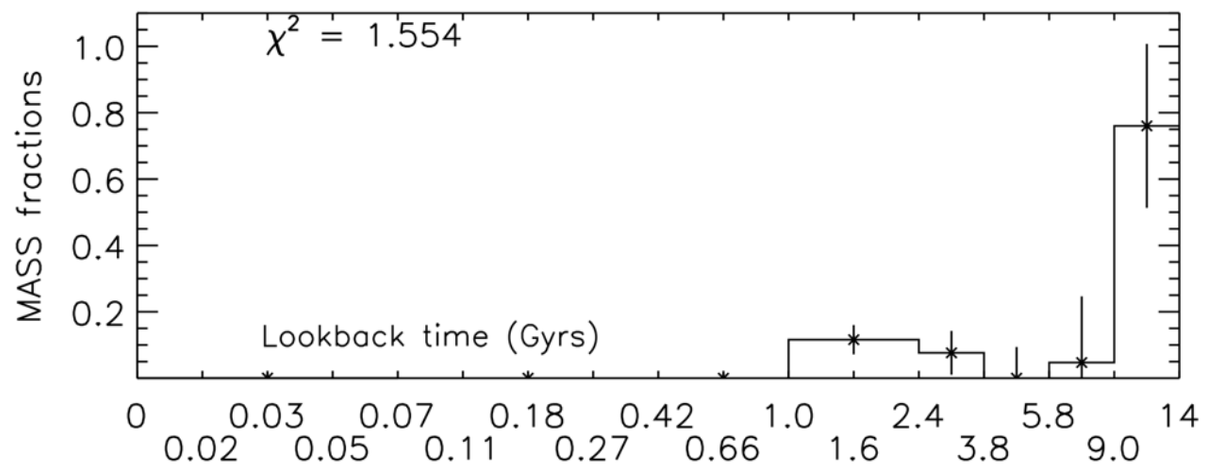


our approach

- still use Yang's central galaxy catalog
  - trim off satellites via a friends-of-friends algorithm
  - use weak lensing to ensure samples of early- and late-forming centrals have similar mean masses
- use resolved star formation history from VESPA algorithm to define early- and late-forming central galaxy samples







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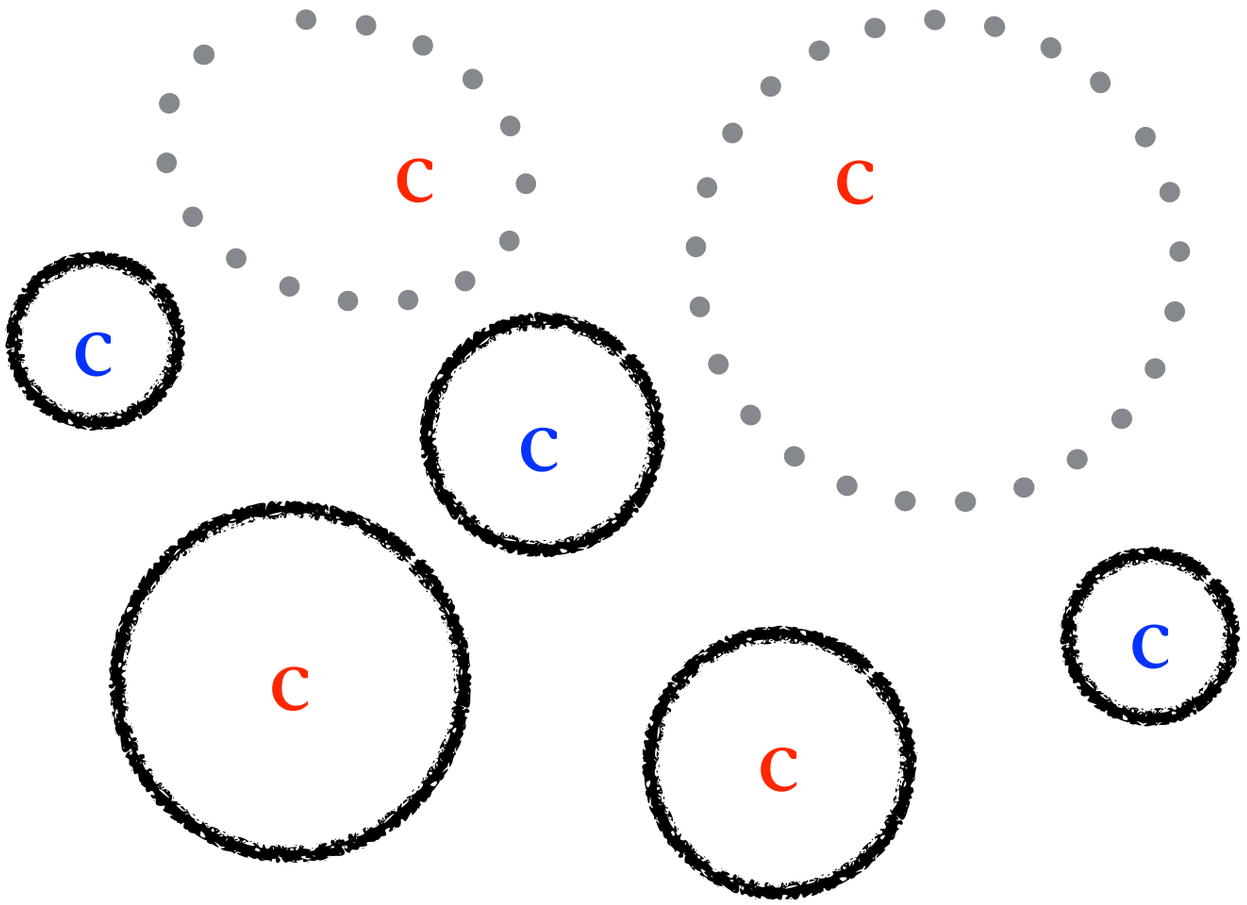
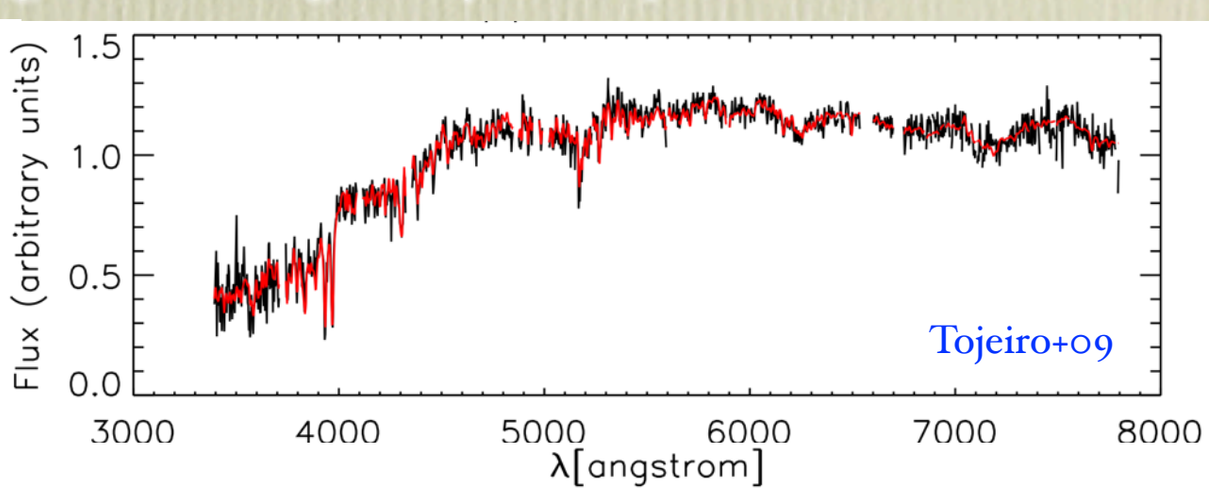
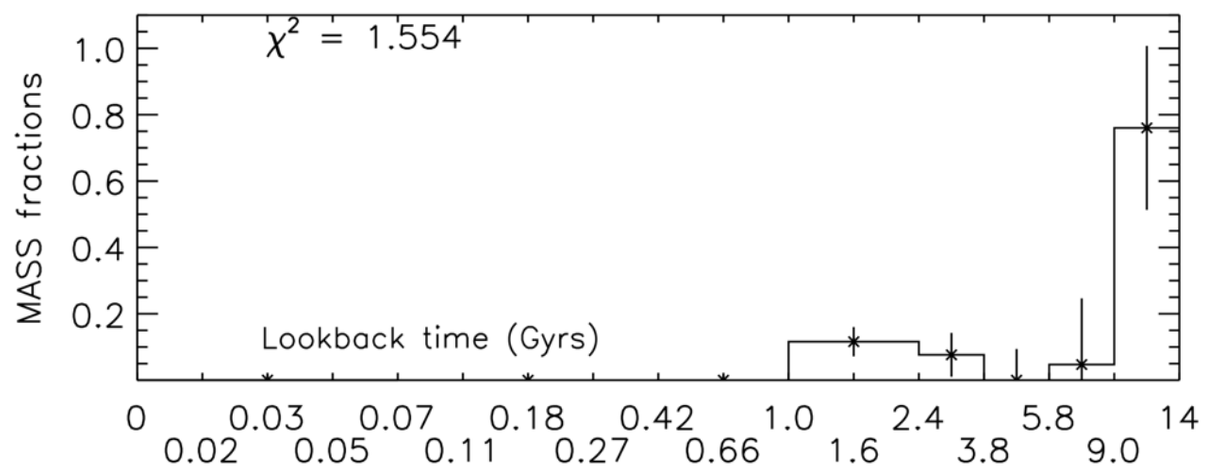
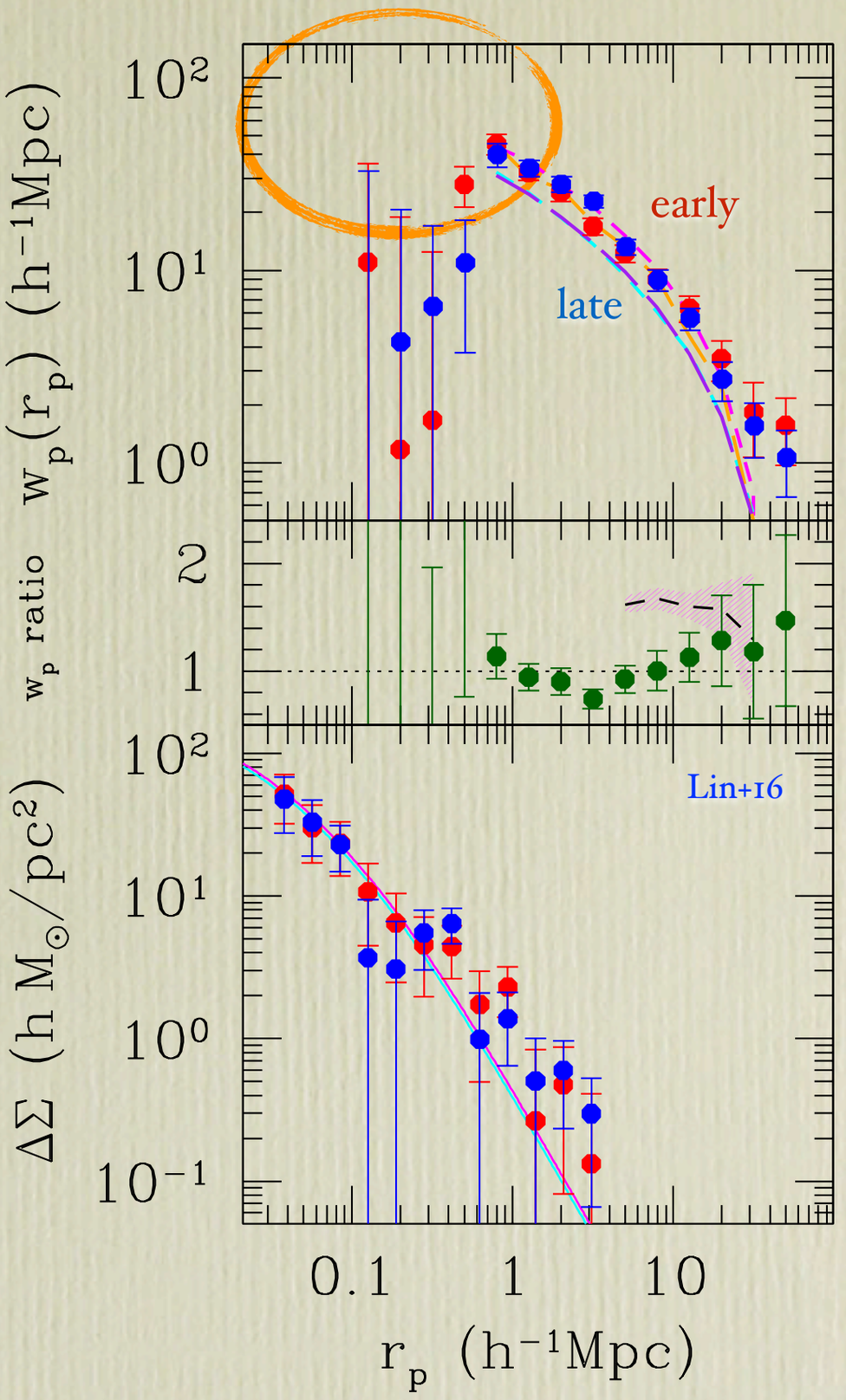






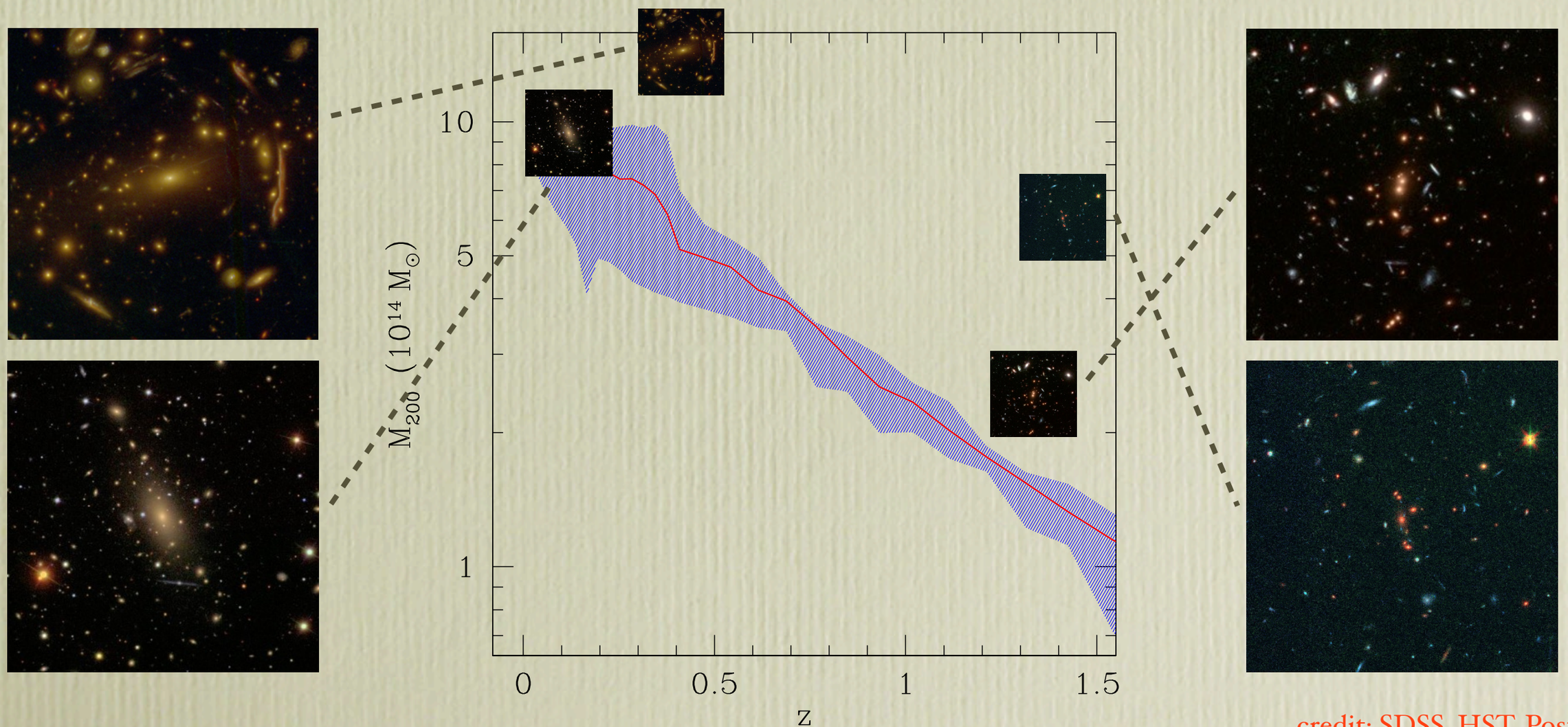
non-detection of assembly bias

- we have constructed a pair of early- and late-forming central samples for which the satellite contamination is minimal
- masses are $(9\pm2)\times10^{11}h^{-1}M_{sun}$ and $(8\pm2)\times10^{11}h^{-1}M_{sun}$
- theoretical expectation derived from high resolution N-body simulations, taking into account uncertainties in halo mass distribution
- probability for theory to be consistent with observation is 2×10^{-6}
- higher S/N spectra needed to recover the SFH/mean age?
- better proxy for halo formation time?



looking ahead: BCGs & clusters

- we need to move beyond simple halo mass consideration for linking clusters at different epochs
  - halo concentration/accretion mode (e.g., splashback radius) to be considered as well for linking clusters
  - should study sizes, color, metallicity when linking BCGs



credit: SDSS, HST, Postman+12

looking ahead: galaxy-halo connection

- Yang's approach to build group/cluster sample in SDSS is very influential, even though central-satellite classification, and halo mass estimates still need to be improved
- would be wonderful to repeat such efforts out to z~1-2
  - dense sampling to ~sub-L_* galaxies; GAMA at z~1?
  - in HSC-D fields (26 deg^2), supplementing PFS-GE survey
    - halo mass calibration via magnification bias from HSC
- can study assembly bias, galactic conformity, density reconstruction; application of Oguri & Lin (2015) method
- or, a program to get high quality spectra at $z<0.3$ for better quantification of stellar populations (PFS or MSE?!)