+ observational detection of assembly bias

time invariance of total stellar mass–cluster mass relation

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with
Bau-Ching Hsieh, Masamune Oguri, and the HSC collaboration
and
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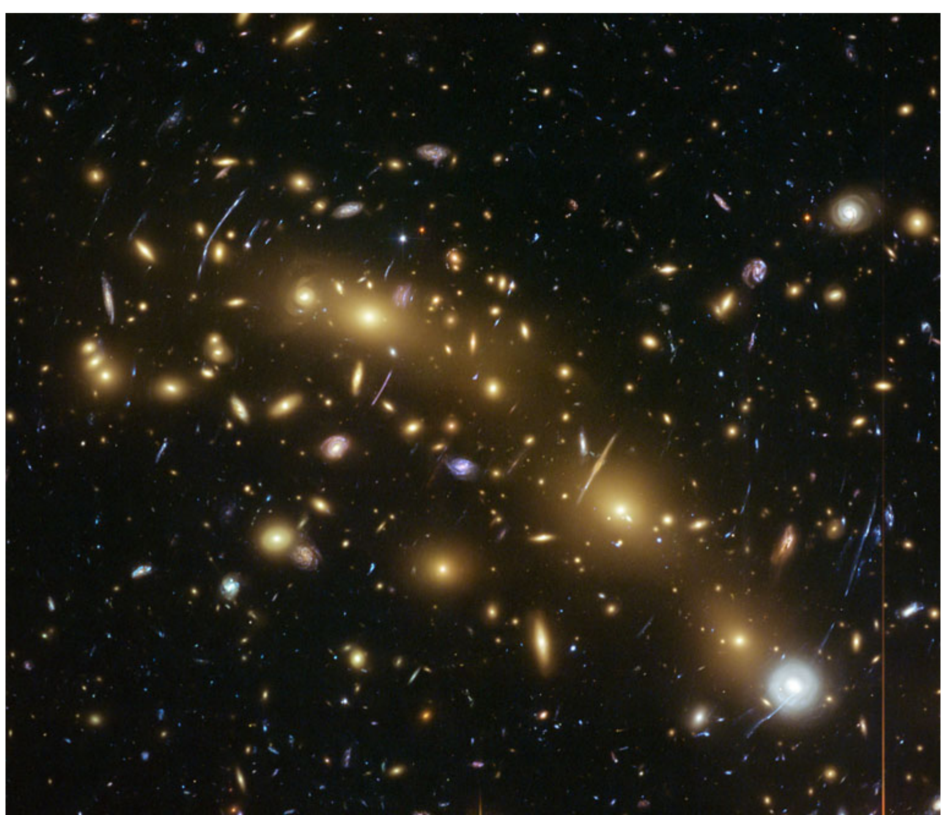
Benedikt Diemer, Andrey Kravtsov, and Neal Dalal

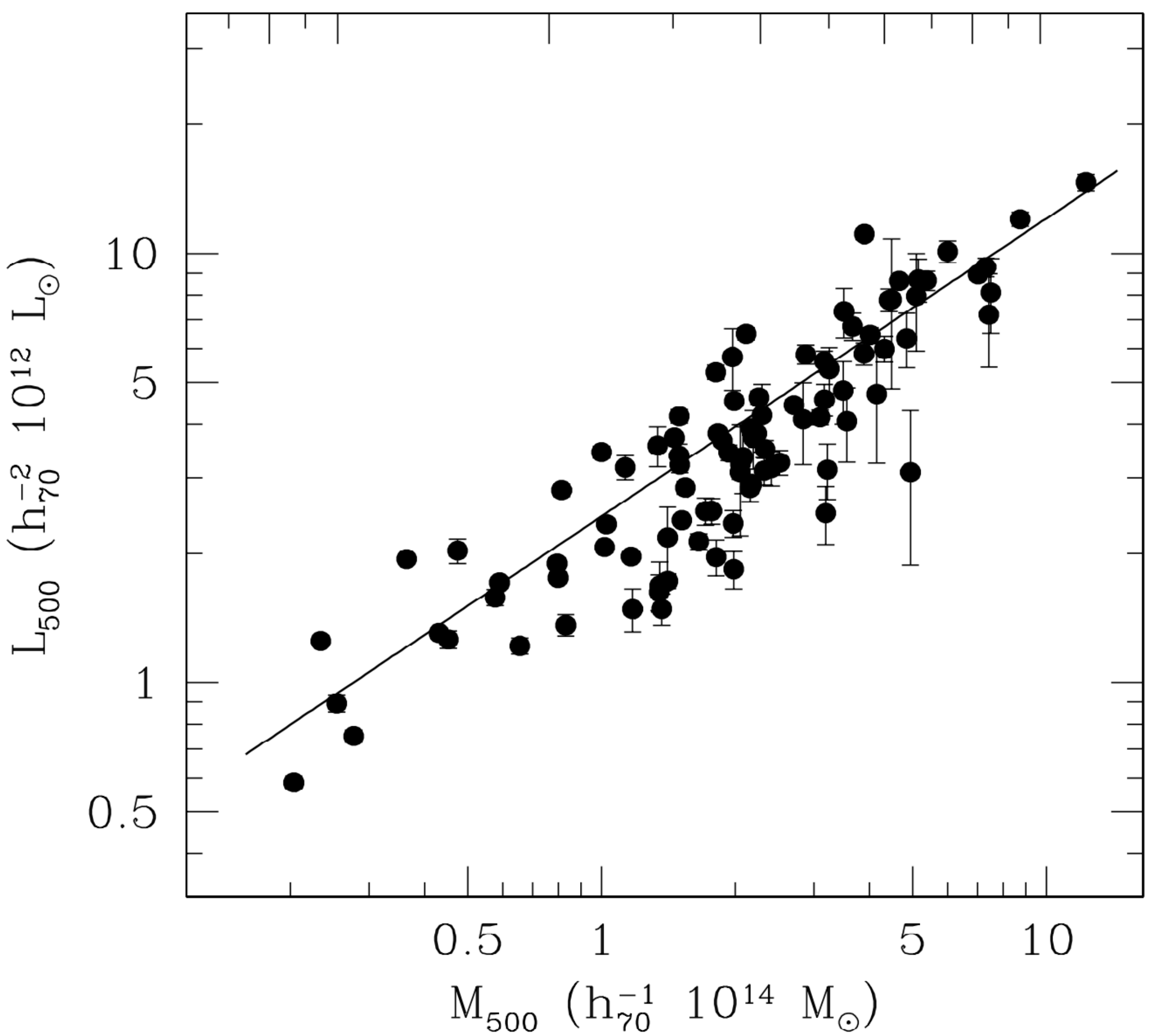
total stellar mass–cluster mass relation

total near-IR K-band light

total stellar mass–cluster mass correlation

- the scaling is far from linear!
- clusters are *not* self-similar — you don't build massive clusters simply by combining smaller ones together
- total galaxy stellar mass per unit halo mass has to decrease as clusters become more massive
  - tidal stripping ⇒ intracluster light?!





$$\frac{L_{200}}{10^{12}\ h_{70}^{-2}\ L_\odot} = 5.64 \pm 0.16 \left(\frac{M_{200}}{2.7 \times 10^{14}\ h_{70}^{-1}\ M_\odot} \right)^{0.72 \pm 0.04}$$

$L_{200} \propto M_{200}^{0.7}$
$(L/M) \propto M^{-0.3}$

Lin+04, HST

total near-IR K-band light

total stellar mass–cluster mass correlation

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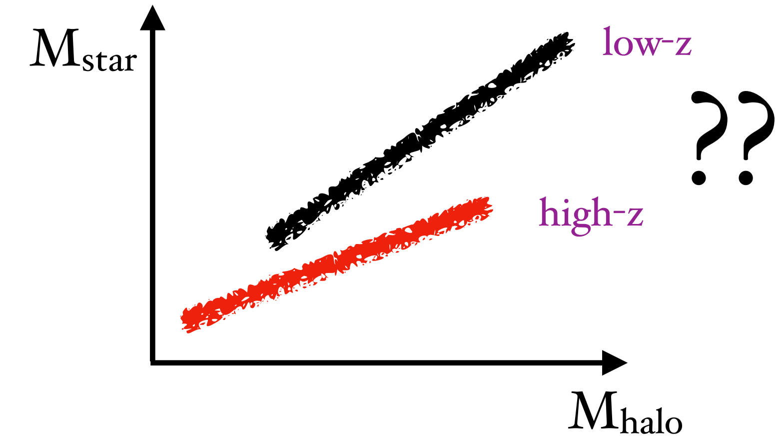
- clusters are *not* self-similar — you don't build massive clusters simply by combining smaller ones together
- total galaxy stellar mass per unit halo mass has to decrease as clusters become more massive
    - tidal stripping ⇒ intracluster light?!
    - perhaps the progenitors of z~0 high-mass clusters (=lower mass clusters at high-z) are different (in terms of L/M) from the low-z low-mass ones?
        - change in the scaling relation may be expected...
        - varying galaxy formation efficiency as a function of cluster mass??

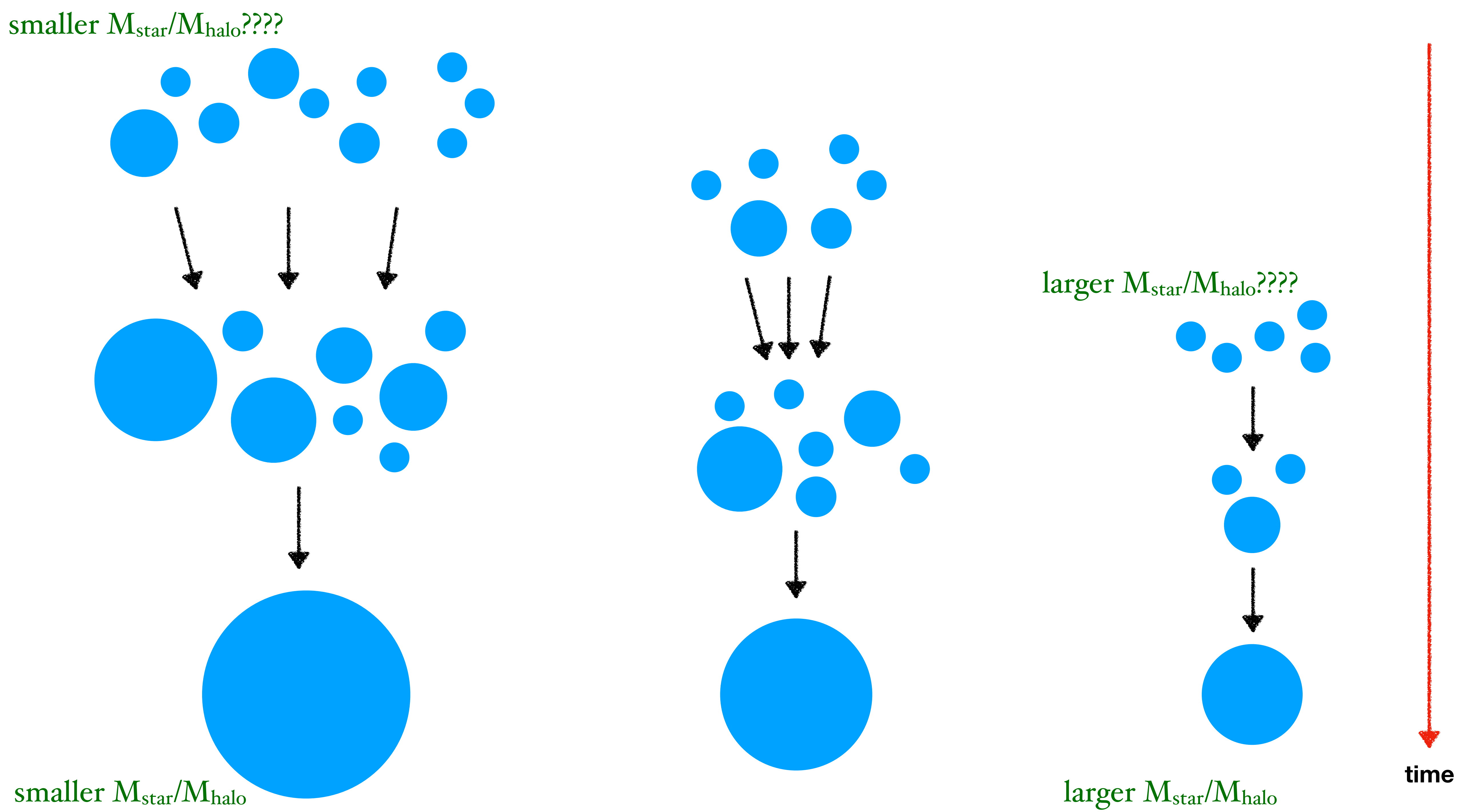
RDCS1252
z=1.24
M_{200}~3x$10^{14}M_{sun}$

Abell2107
z=0.041
M_{200}~3x$10^{14}M_{sun}$

HST, SDSS

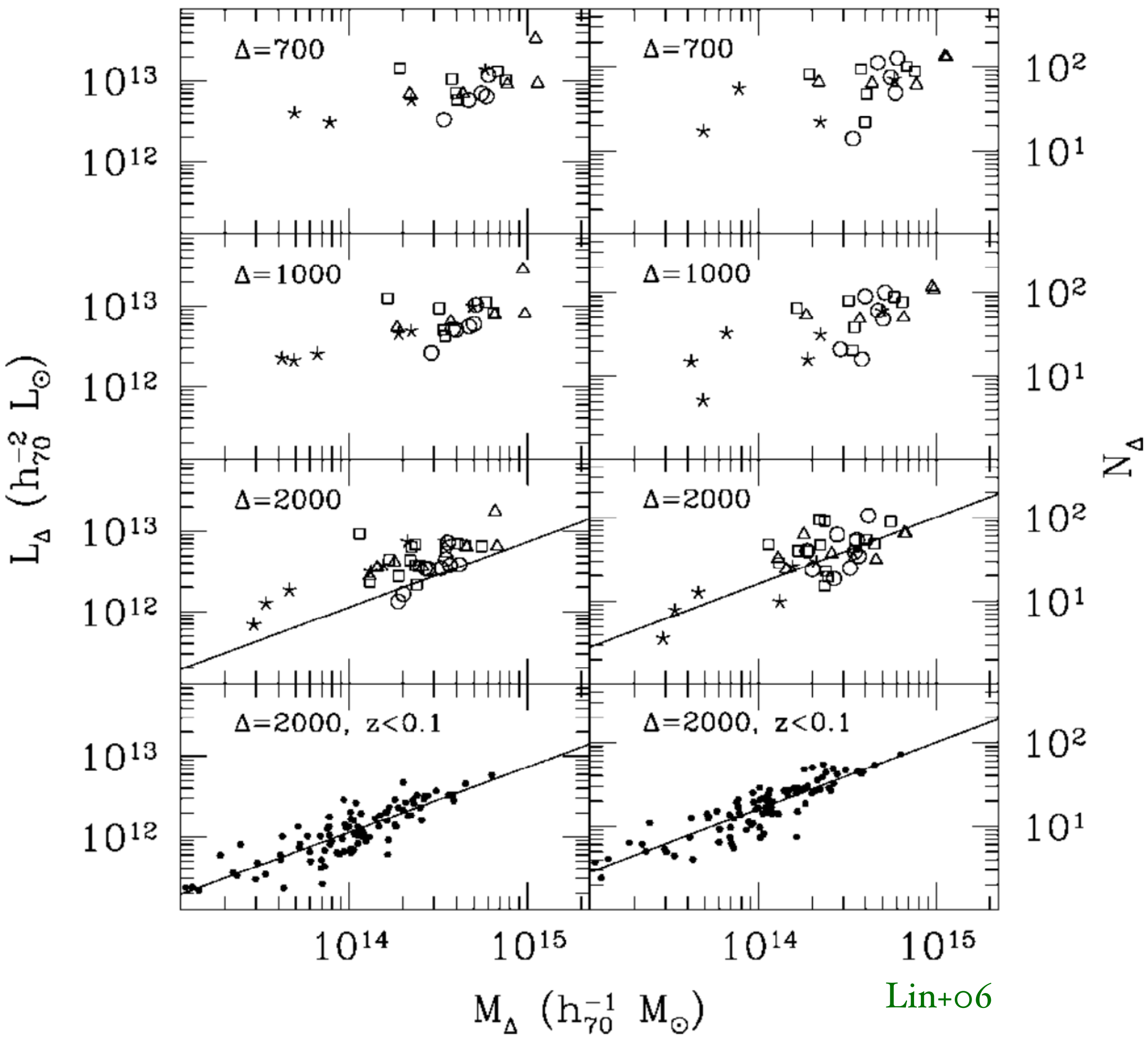
- change in the scaling relation may be expected…
- varying galaxy formation efficiency as a function of cluster mass?? somehow halos must know where/what will they end up with?





does the relation evolve?

27 clusters, z=0-0.9

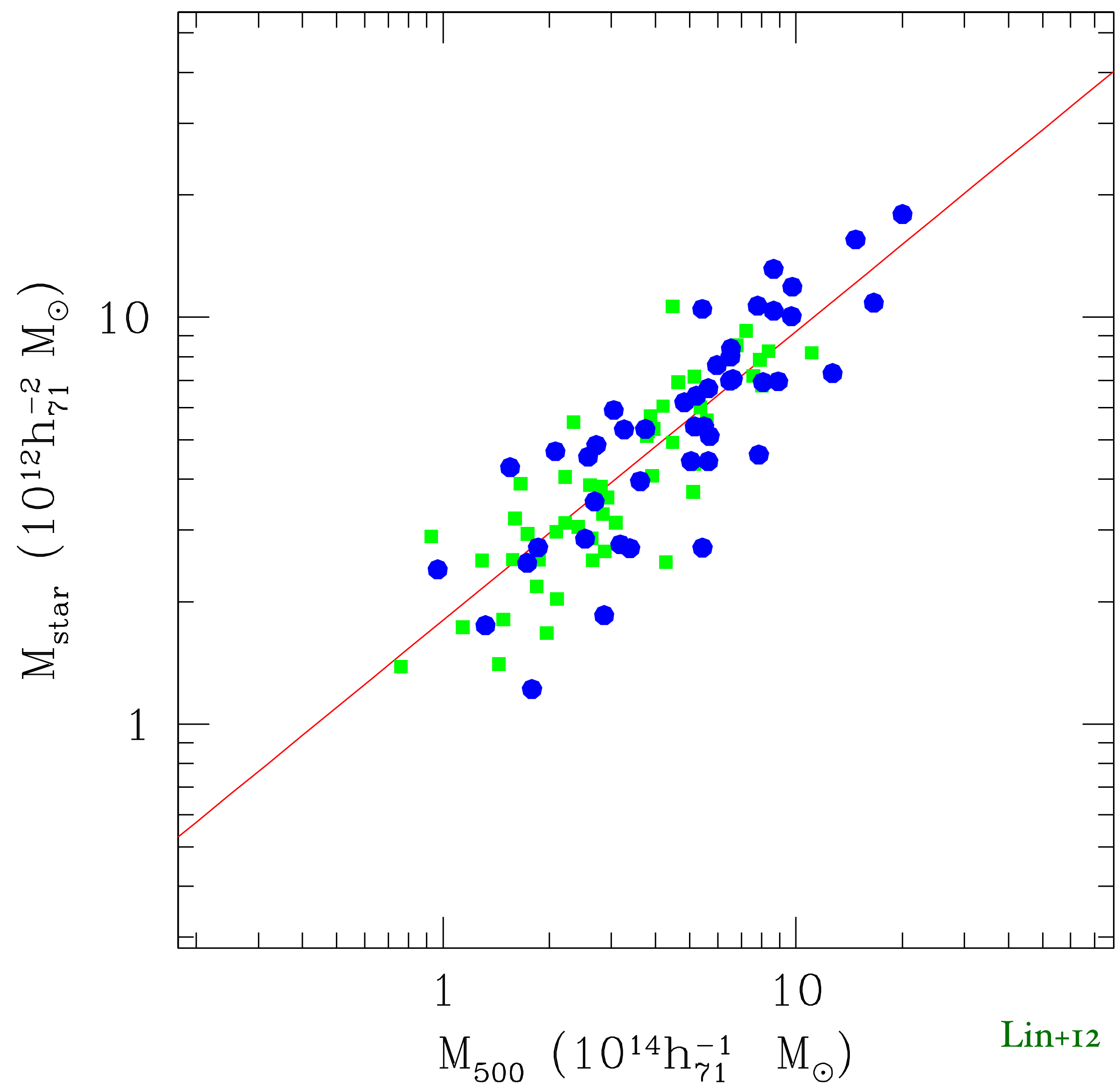


$$N(M, z) = N_0(1 + z)^{\gamma}(M/M_0)^{s}$$

$$\gamma = -0.03 \pm 0.27$$

scaling with near-IR L similar once
passive evolution has been taken into account

94 clusters, z=0-0.6



$$M_{\rm star} \propto M_{500}^{s_2}(1+z)^{\gamma_2}$$

$$s_2 = 0.71 \pm 0.04$$

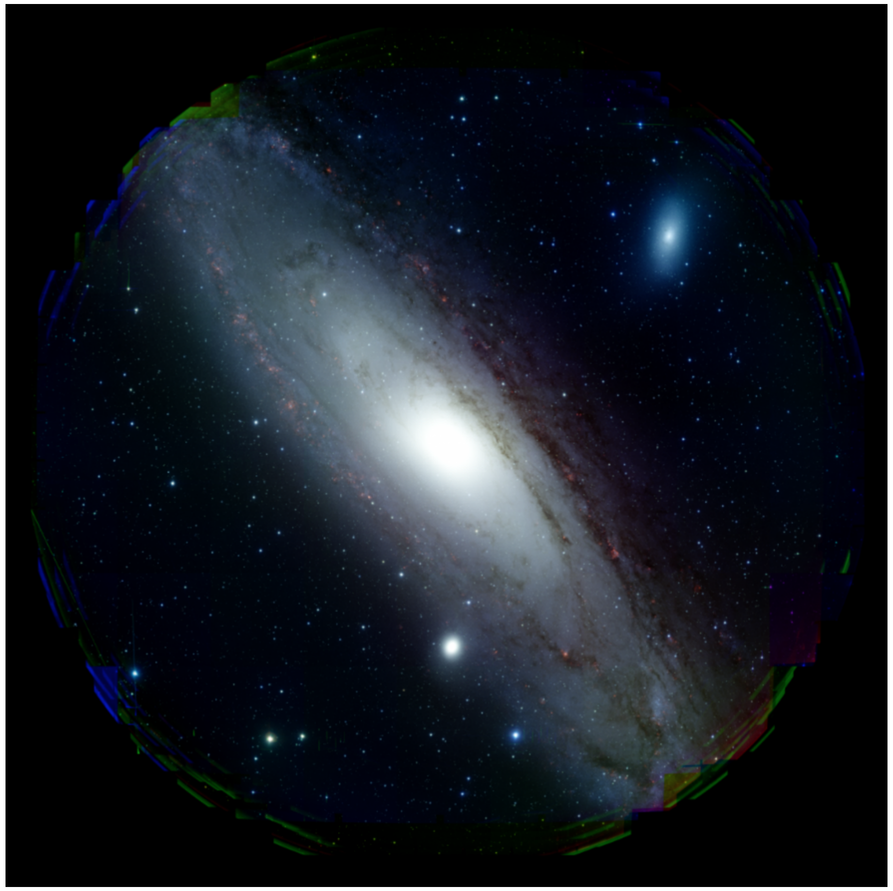
$$\gamma_2 = -0.06 \pm 0.22$$


insights from the HSC survey

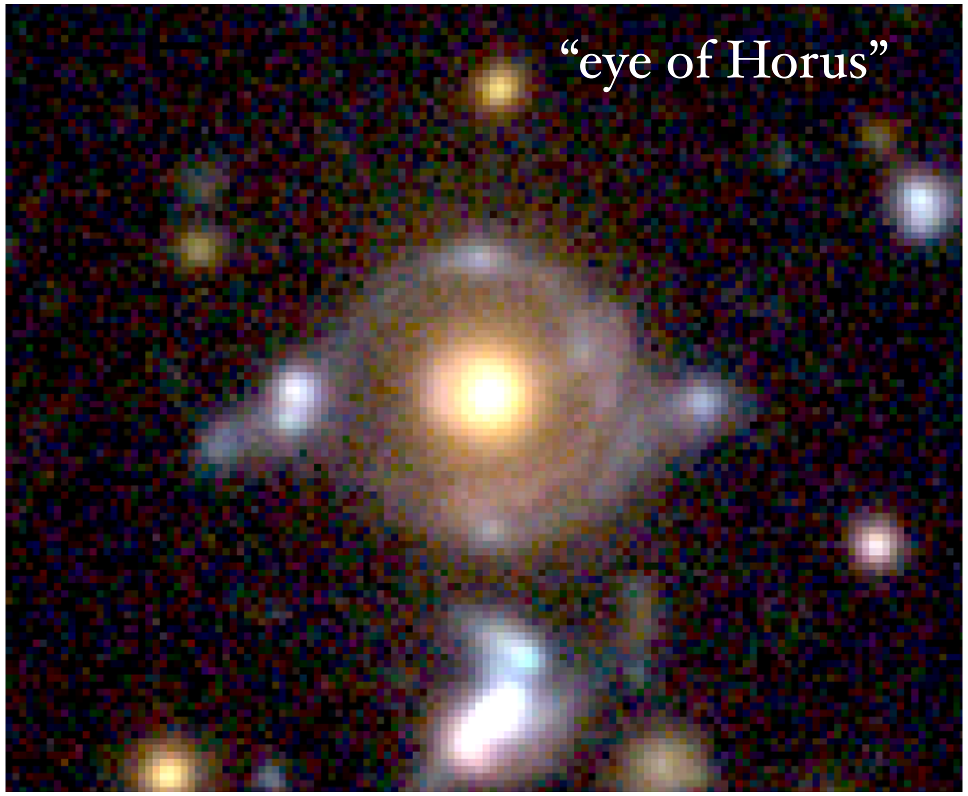
the HSC survey

- not just yet another imaging survey
  - superb imaging quality (median seeing 0.6″)
  - narrow-band filters in deep+ultradeep layers
- complete census of clusters at key phases
  - proto-clusters as Lyman break galaxy overdensities at z=4-6
  - clusters at z=1-2 from broad & narrow bands
  - z<1 clusters from red sequence or shear selection
- 1st public data release in 02/2017; 2nd in mid-2019

Layer	Area [deg^2]	Number of pointings	Filters and depth
Wide	1400	916	*grizy*($i \simeq 26$)
Deep	26	15	*grizy* + 3NBs ($i \simeq 27$)
UltraDeep	3.5	2	*grizy* + 3NBs ($i \simeq 28$)



credit: M. Tanaka, K. Wong, K. Thanjavur



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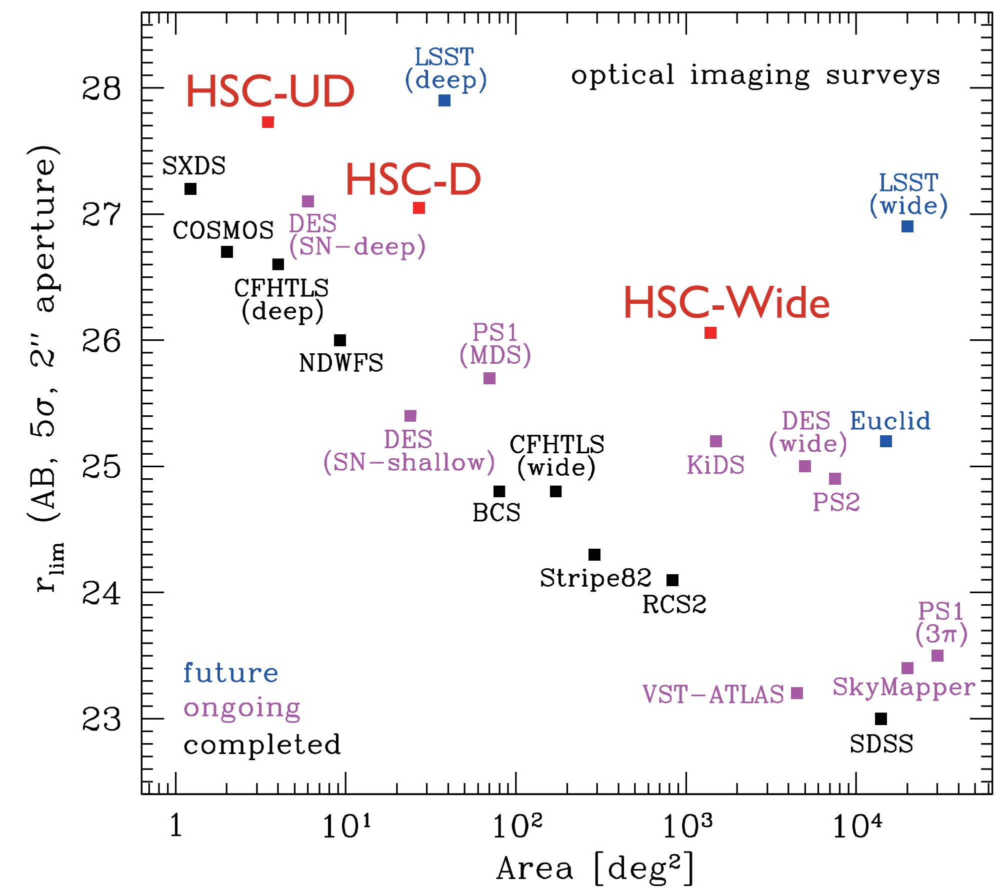

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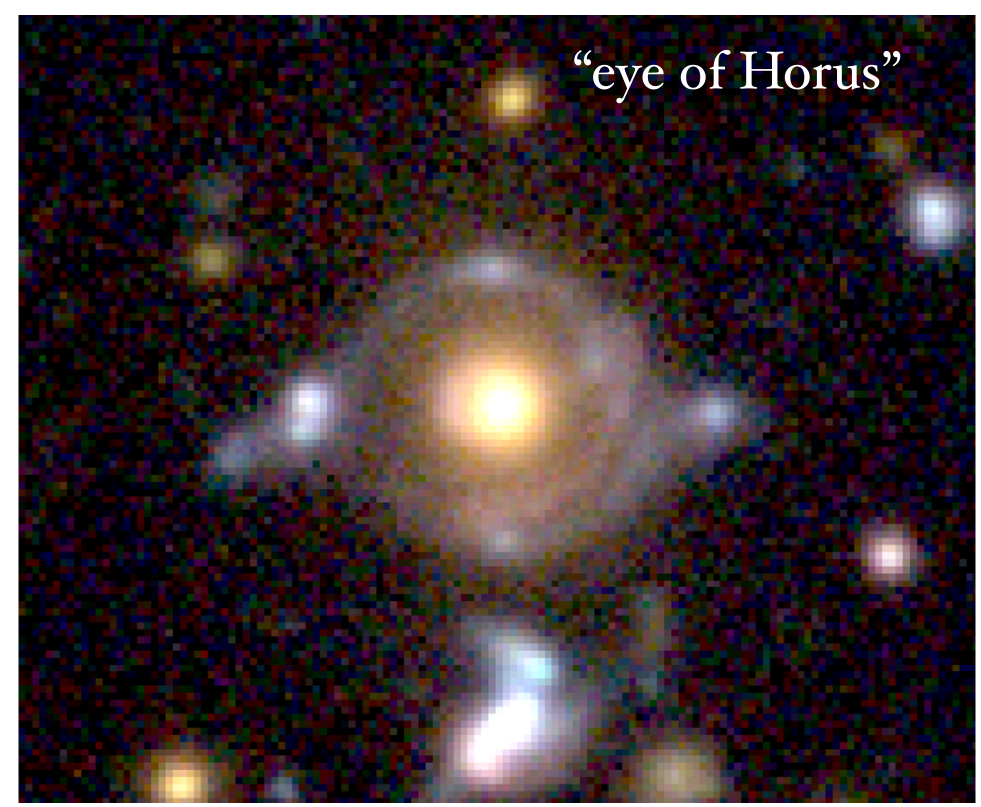

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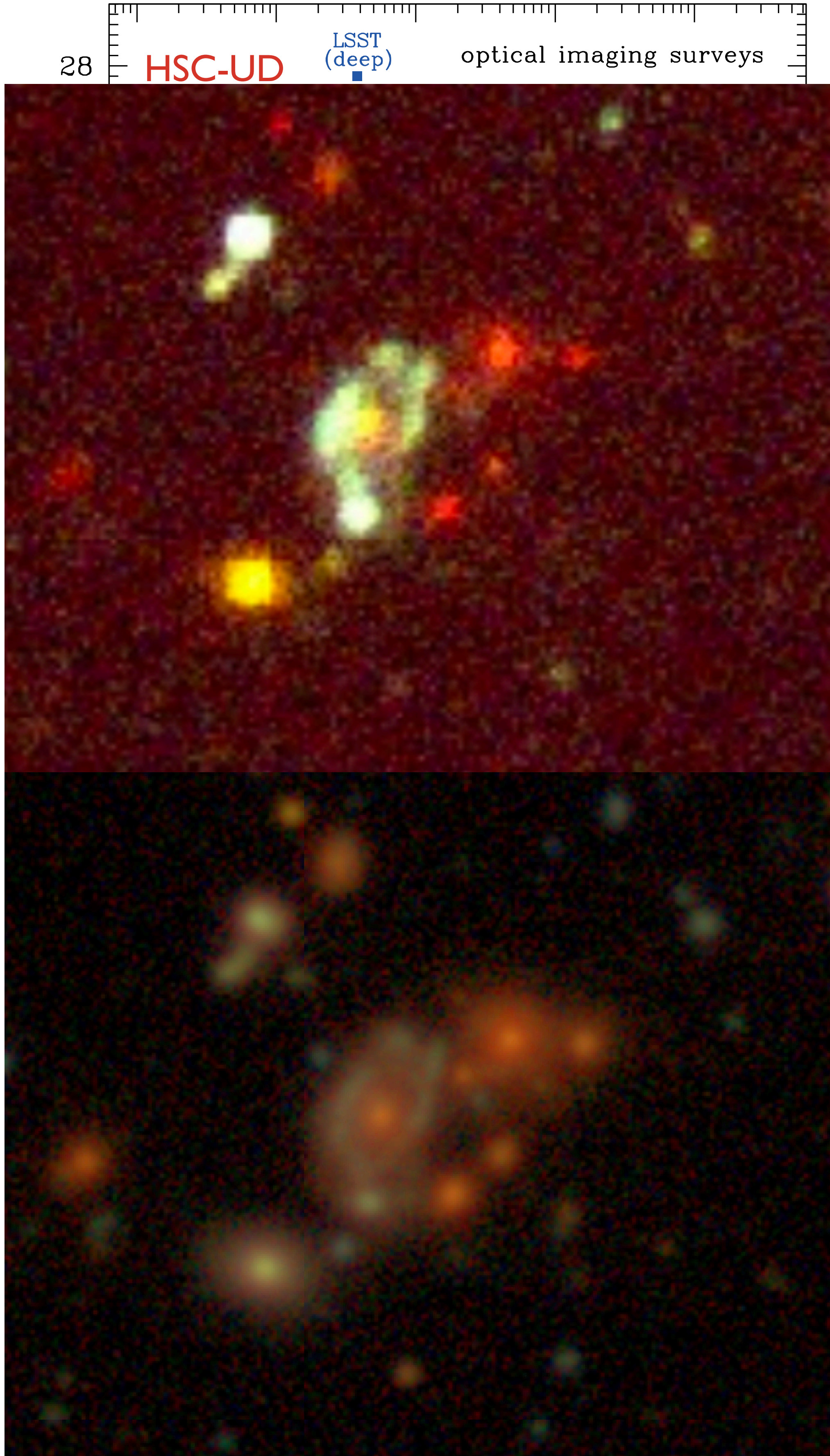
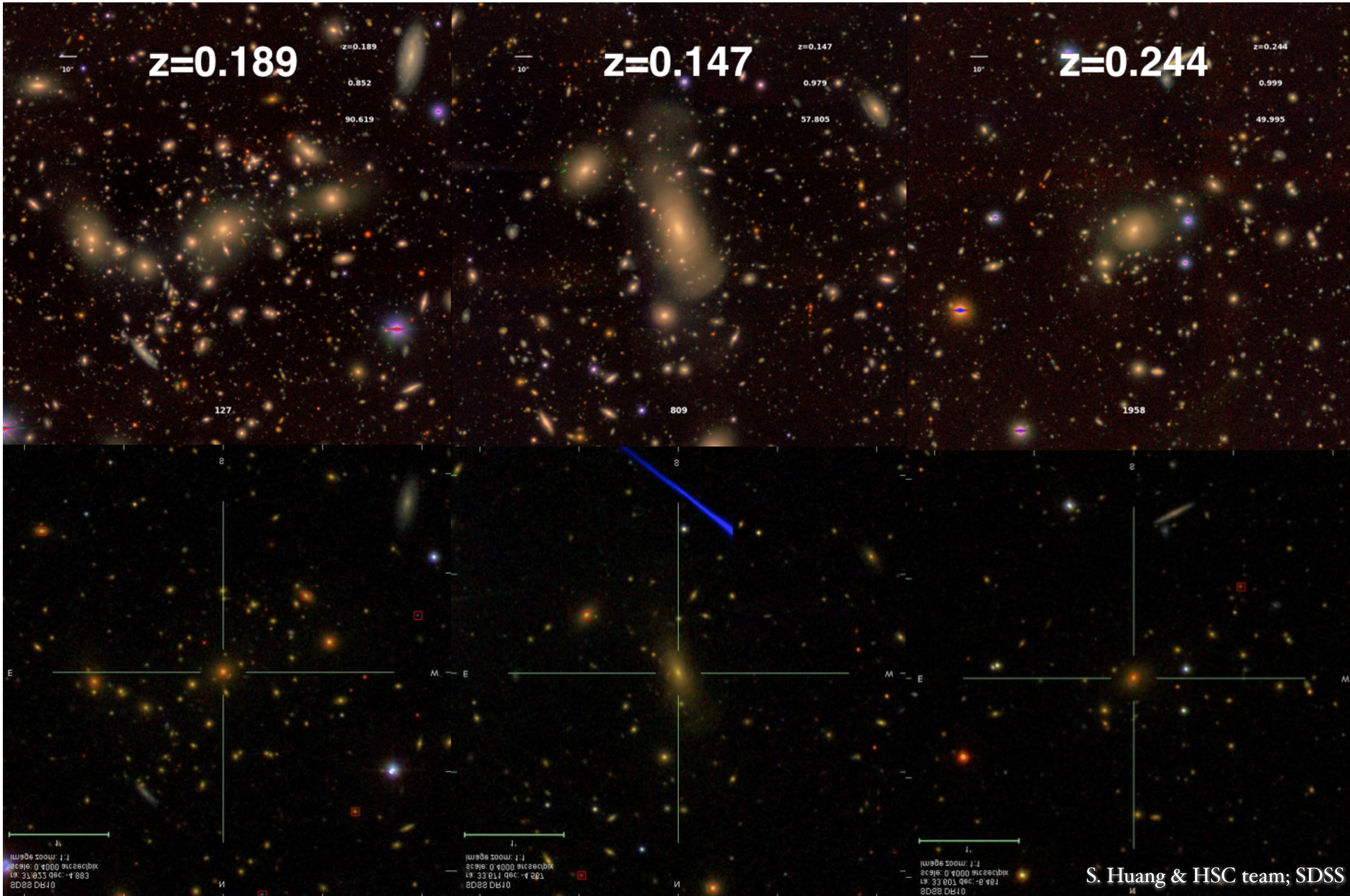


the HSC cluster sample

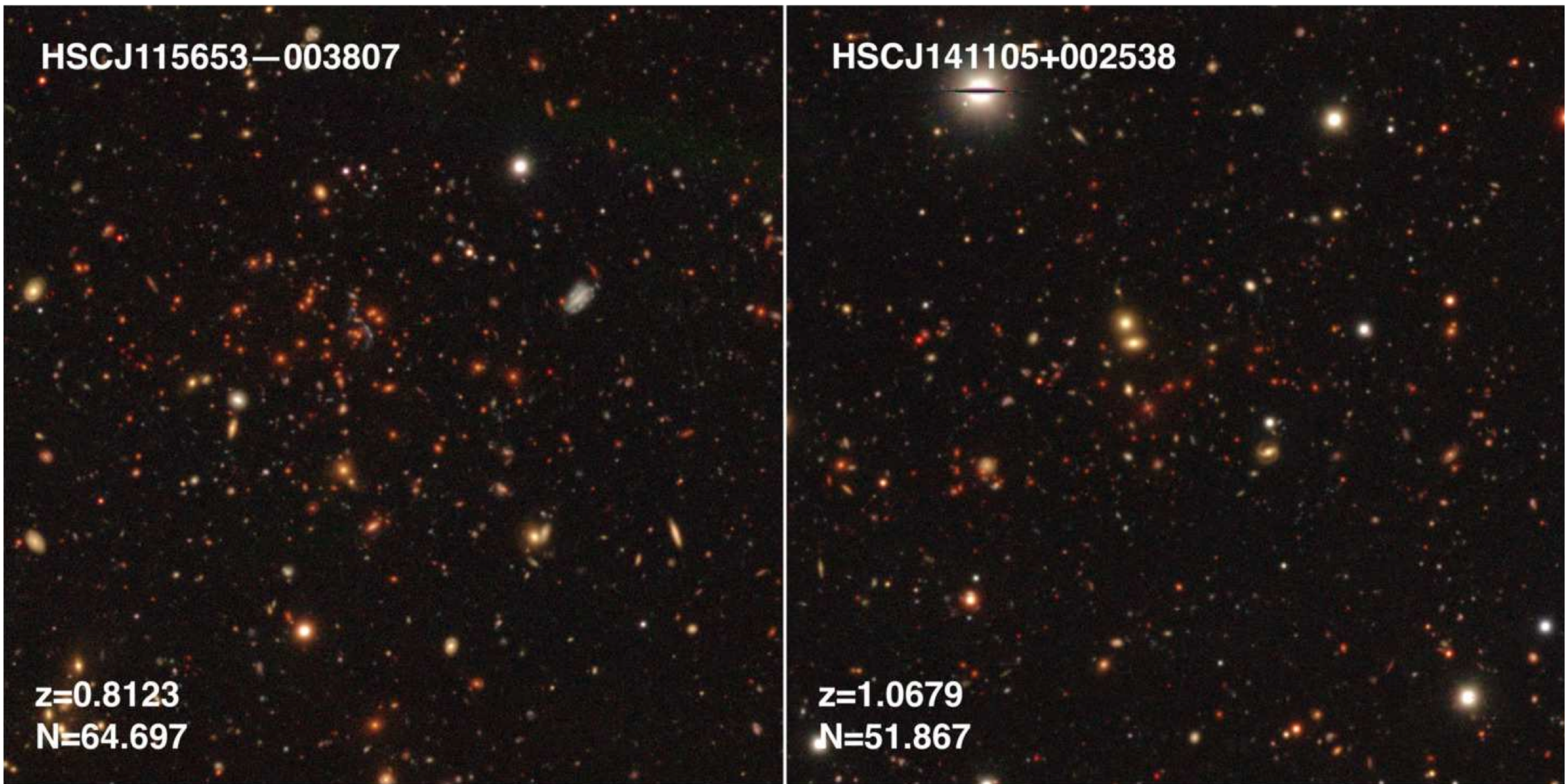


S. Huang & HSC team; SDSS

the HSC cluster sample

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 deg^2 with richness N≥15 in the HSC survey

Oguri, Lin+18

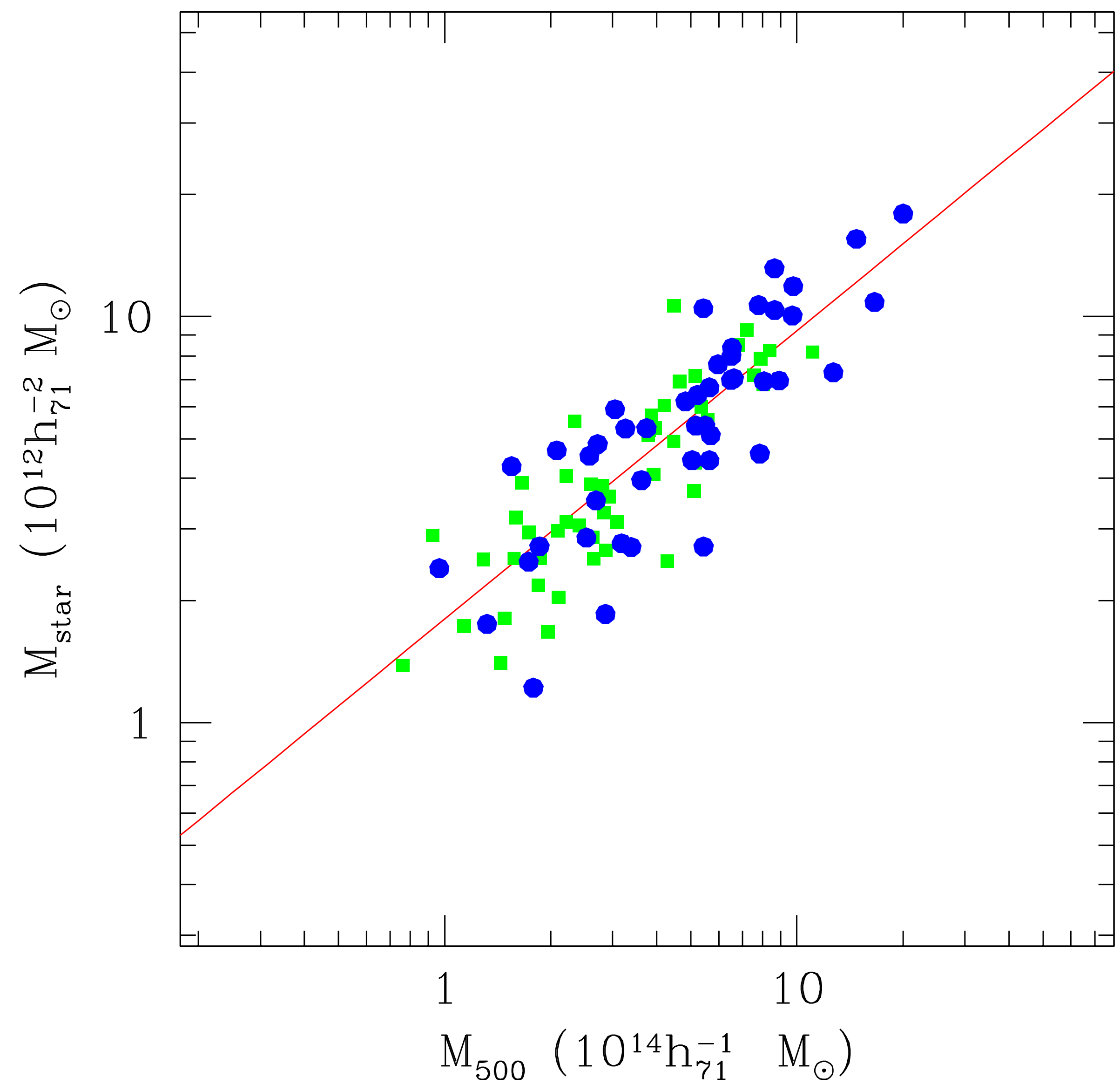


elements of analysis

stellar mass: derived with a machine-learning algorithm

stellar mass distribution: constructed using a statistical background correction scheme

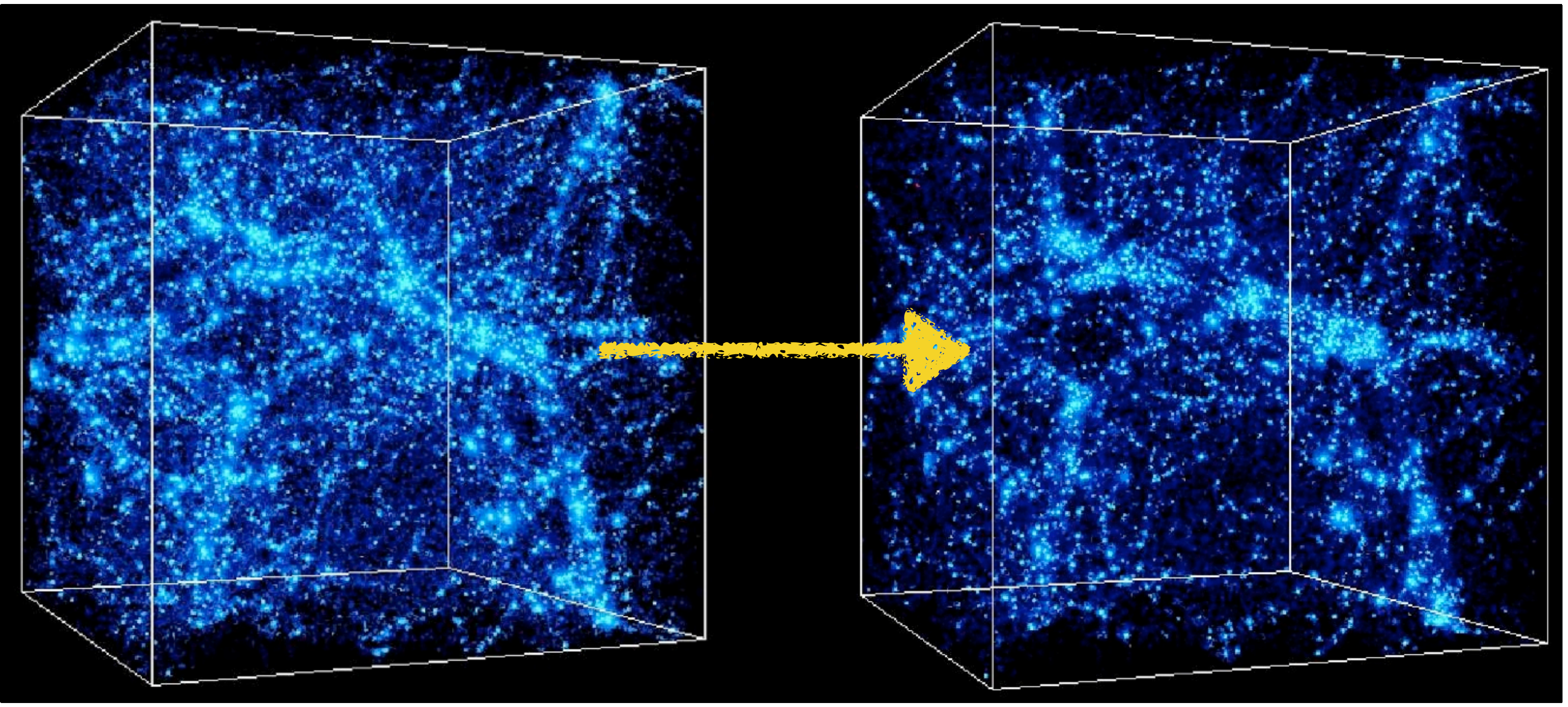
M_{star}: obtained by integrating the SMD



cluster selection: use cluster (sub)samples that can be considered to form an evolutionary sequence: high-z cluster (sub)sample to have properties consistent with progenitors of low-z (sub)samples ⇒ *top N* selection

cluster mass: weak lensing / abundance-based estimates

top N selection of halos



A. Kravtsov

Remaining Fraction (%)

initial z	final z (no scatter)			final z (25% scatter)		
	0.83	0.68	0.45	0.83	0.68	0.45
0.98	86	76	66	62	67	58
0.83	–	86	70	–	64	55
0.68	–	–	79	–	–	58

for N=100 over 60% Millennium volume; 4 redshift bins from 0.3 to 1.02

- construct cluster samples that represent progenitor-descendant relationship *statistically*
- Ansatz: given comoving volume, the most massive N halos will remain among the most massive N at a later time
- similar in spirit to the fixed cumulative number density selection for field galaxies
- tests with Millennium simulation suggest above holds to ~65% (including scatter in mass-observable relation), even with Δz~0.6

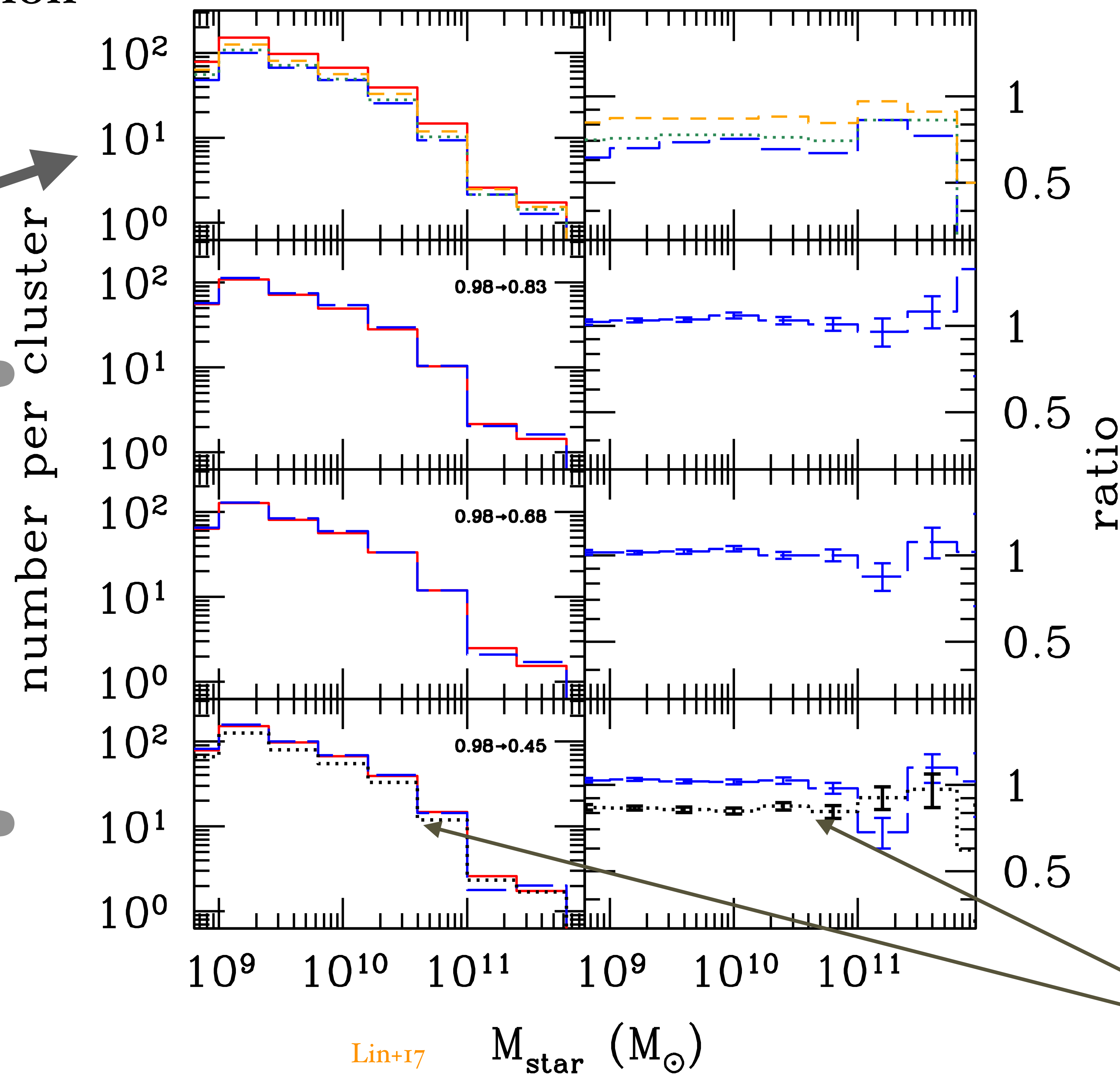
top N selection of halos

tests with semi-analytic models show good recovery of galaxy population

top 100 in 4 bins:
blue: 0.98
green: 0.83
orange: 0.68
red: 0.45

dashed/blue: descendants of top 100 selected at z=0.98

solid/red: top 100 selected at lower-z

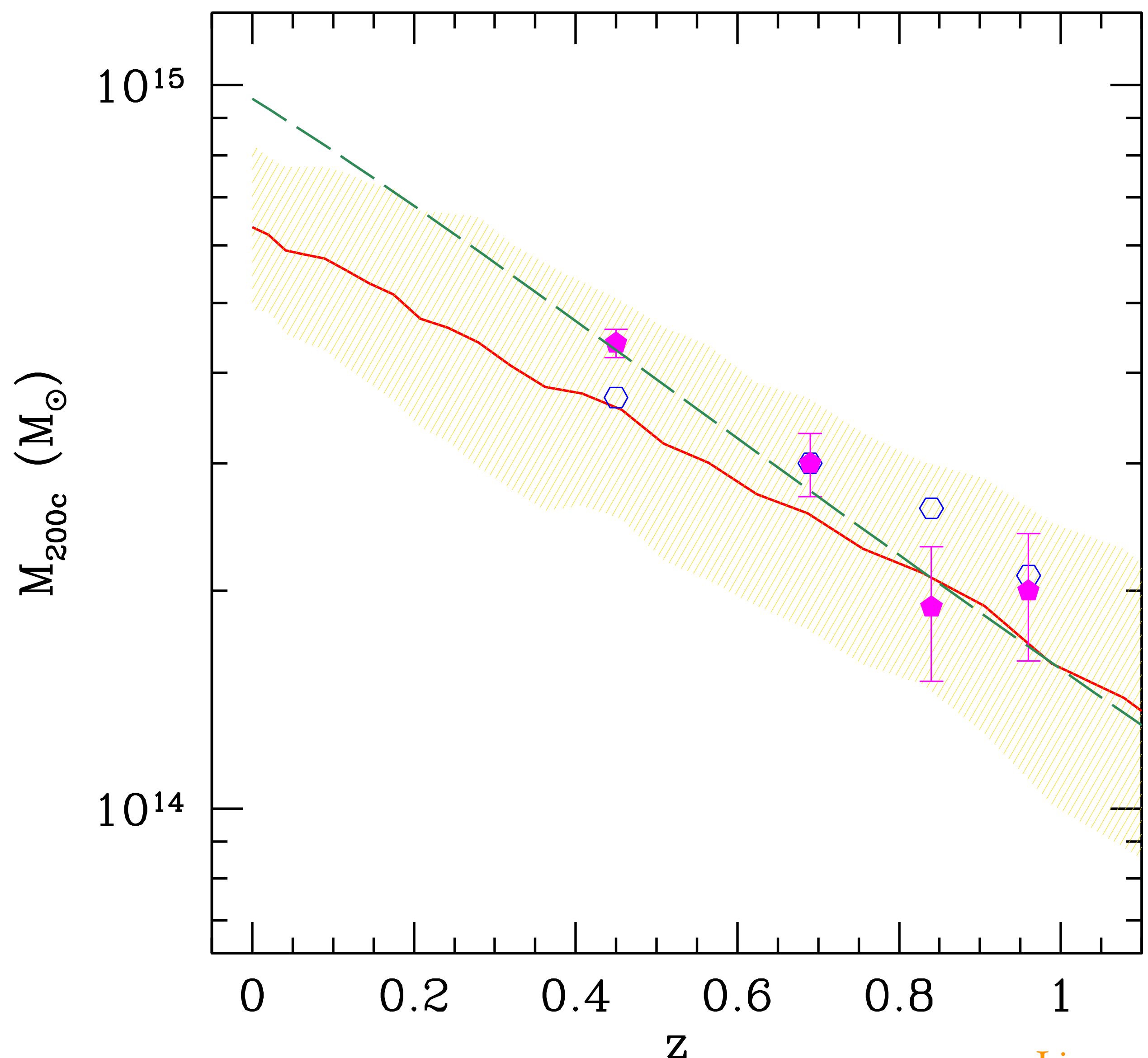


halo mass estimates

- two methods
  - mean mass of top 100 halos over $(420h^{-1}Mpc)^3$ in Millennium, with reasonable assumptions in mass–observable relation (open circles)
  - stacked weak lensing (solid points)
- from $\sim 2\times10^{14}M_{sun}$ at $z\sim1$ to $\sim 4\times10^{14}M_{sun}$ at $z\sim0.45$
- descendant mass at $z\sim0$ likely in $(6\text{-}10)\times10^{14}M_{sun}$

Basic Cluster Properties

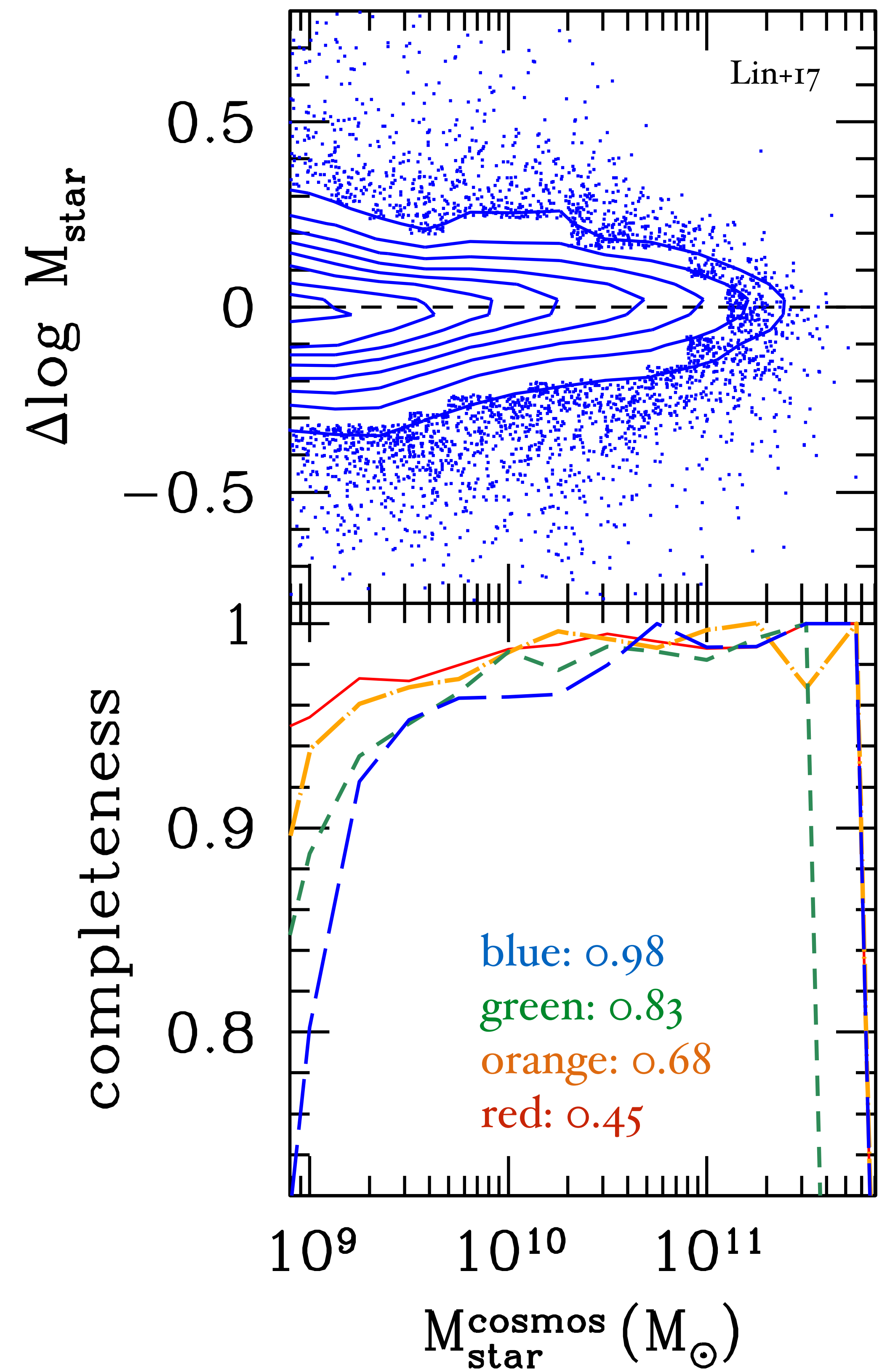
bin	redshift range	mean z	stacked lensing M_{200} ($10^{14} M_\odot$)	stacked lensing r_{200} (Mpc)	abundance M_{200} ($10^{14} M_\odot$)	abundance r_{200} (Mpc)	$\hat{N}_{lim}$
1	0.30 − 0.60	0.45	4.4 ± 0.2	1.33	3.7	1.27	30.0
2	0.60 − 0.77	0.69	3.0 ± 0.3	1.07	3.0	1.09	22.7
3	0.77 − 0.90	0.84	1.9 ± 0.4	0.86	2.6	0.98	21.6
4	0.90 − 1.02	0.96	2.0 ± 0.4	0.84	2.1	0.87	18.0



Lin+17

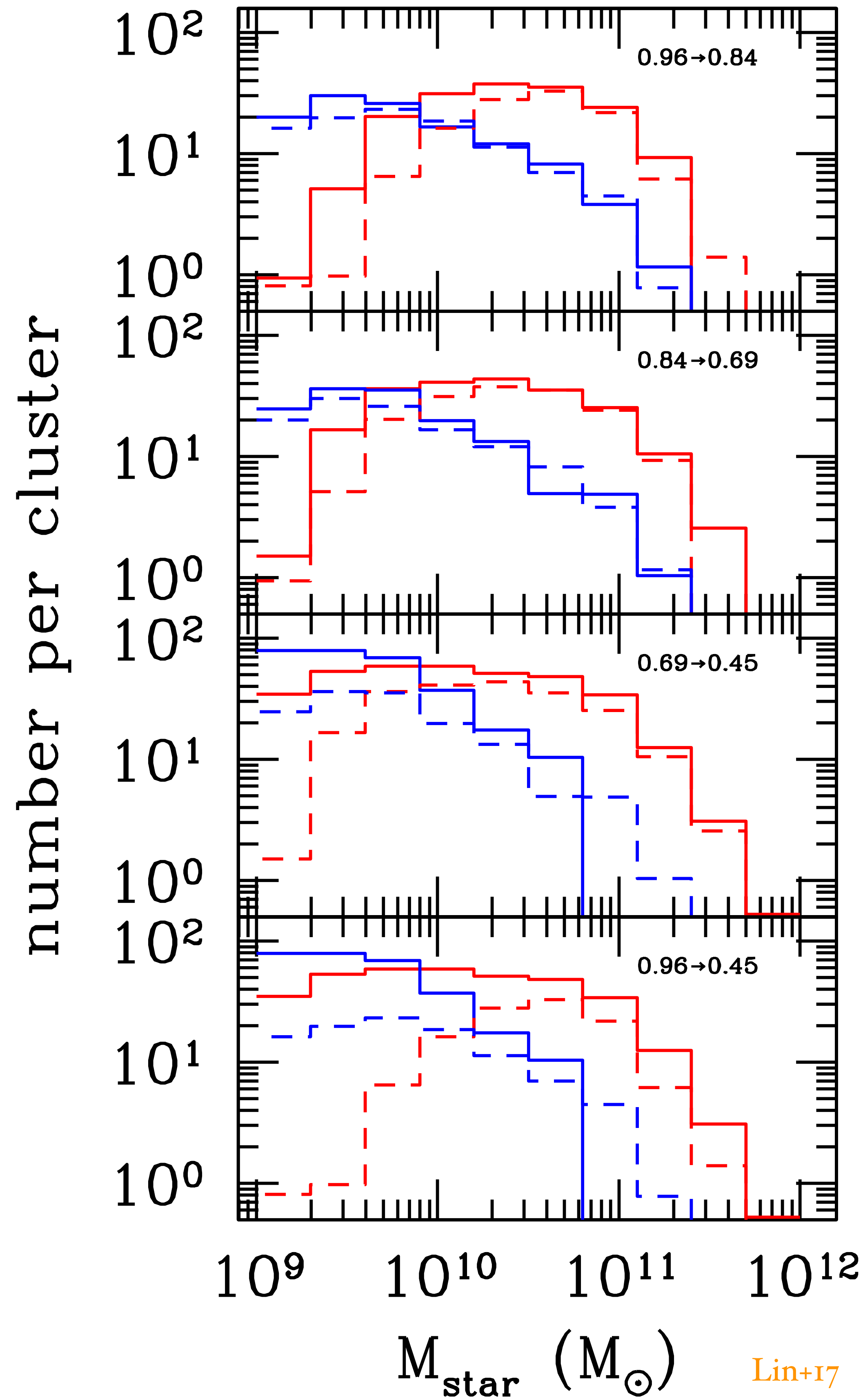
stellar mass estimates

- for galaxies at z>0.8, the HSC *grizy* photometry does not sample much of restframe optical, resulting in biases in stellar mass estimates based on SED fitting
- we thus use a machine learning algorithm, Direct Empirical Method (DEmP, Hsieh & Yee 2014), for the task
- hybrid of linear regression and nearest neighbor
- COSMOS2015 and HSC ultra-deep catalogs used as training set, applied to HSC wide data
- our estimates are unbiased with low scatter
- highly complete above $10^{10} M_{sun}$



stellar mass distribution

- each panel shows pairwise comparison of SMDs (no BCGs) in two redshift bins for red and blue galaxies
  - dashed = higher-z; solid = lower-z
- completeness corrections applied
- apparent growth at both very high mass and low mass ends
  - (except for disappearance of massive blue galaxies)
  - for $M>10^{10}M_{sun}$ red galaxies, abundance at z=0.45 is 2x that at z=0.96
  - for lower mass red galaxies, difference is 7x (down-sizing!)
  - ratios for blue ones are 1.5x and 3x



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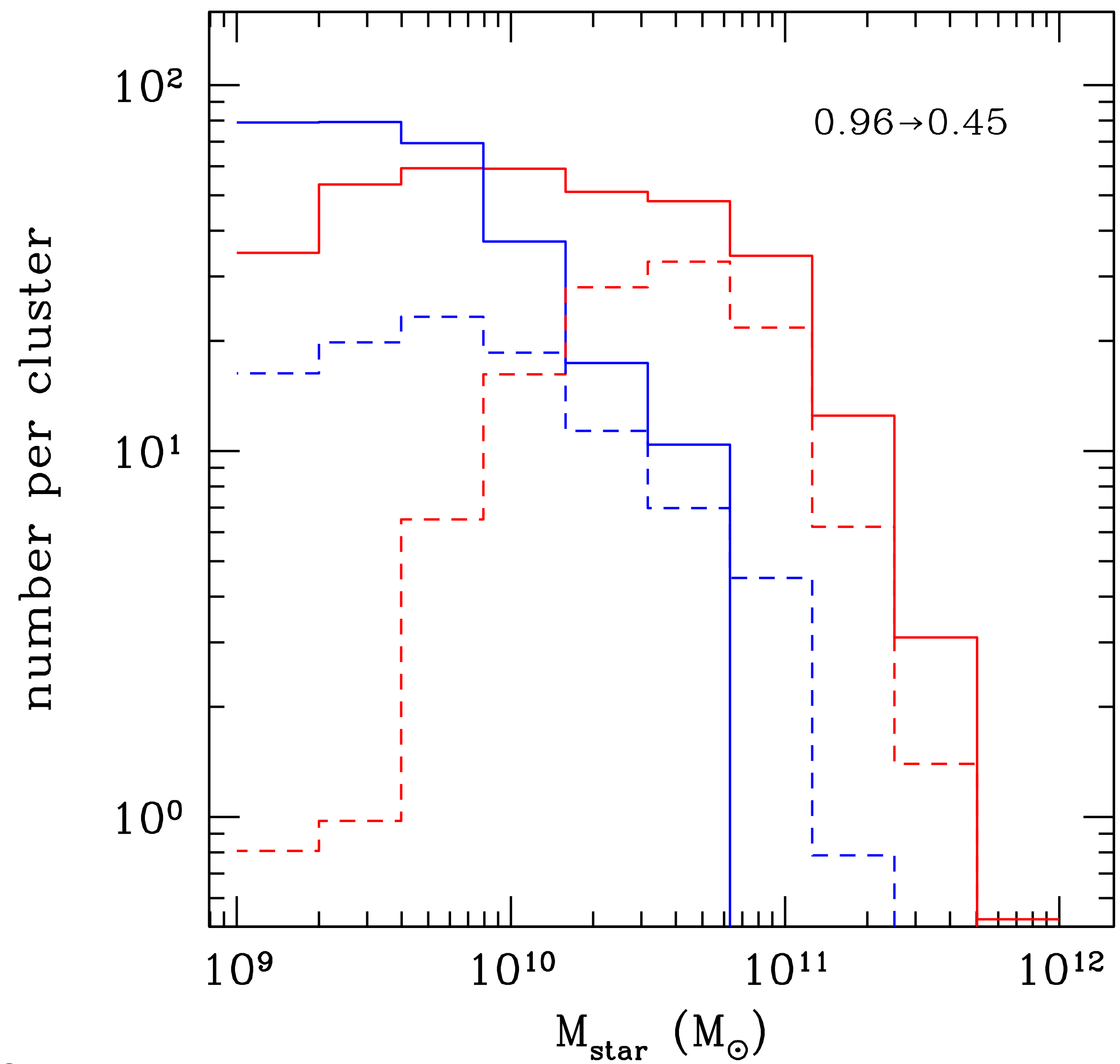
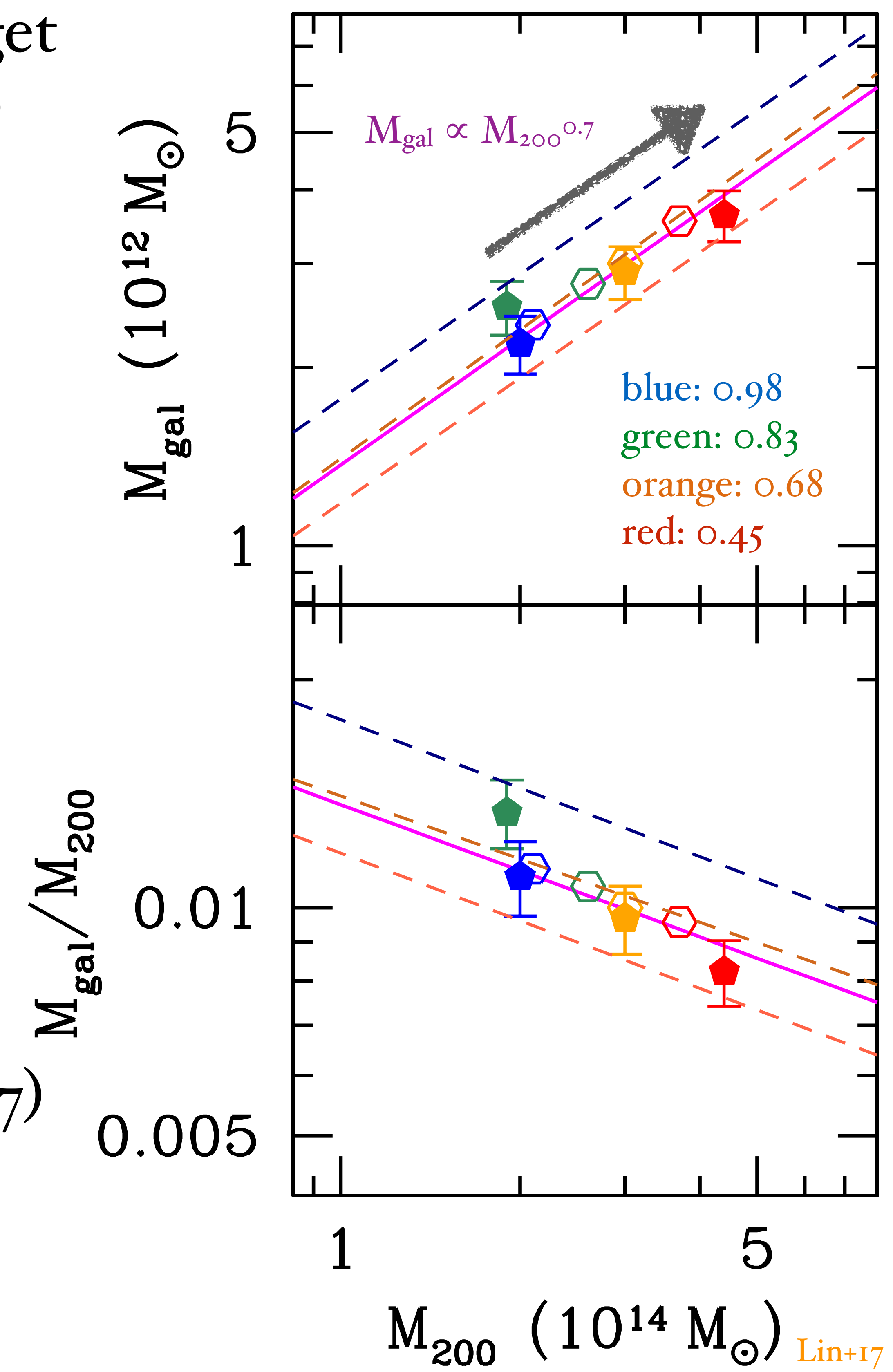


Lin+17

stellar mass contents of clusters

- integrate the SMD down to $10^{10} M_{sun}$ to get "total" stellar mass M_{gal} (including BCGs)
- clusters move along the $M_{gal} \propto M_{200}^{0.7}$ locus (solid line, taken from Lin+12 for a totally different sample)
- why is there no/little evolution of the M_{gal}–M_{200} relation?
  - lots of stripping required?
  - preferentially accreting high M/L objects?
  - operating at all redshifts!
  - would $M_{gal} \propto M_{200}$ at any early epoch?
- also seen in SPT-selected clusters (Chiu+17) & COSMOS groups (Giodini+09)



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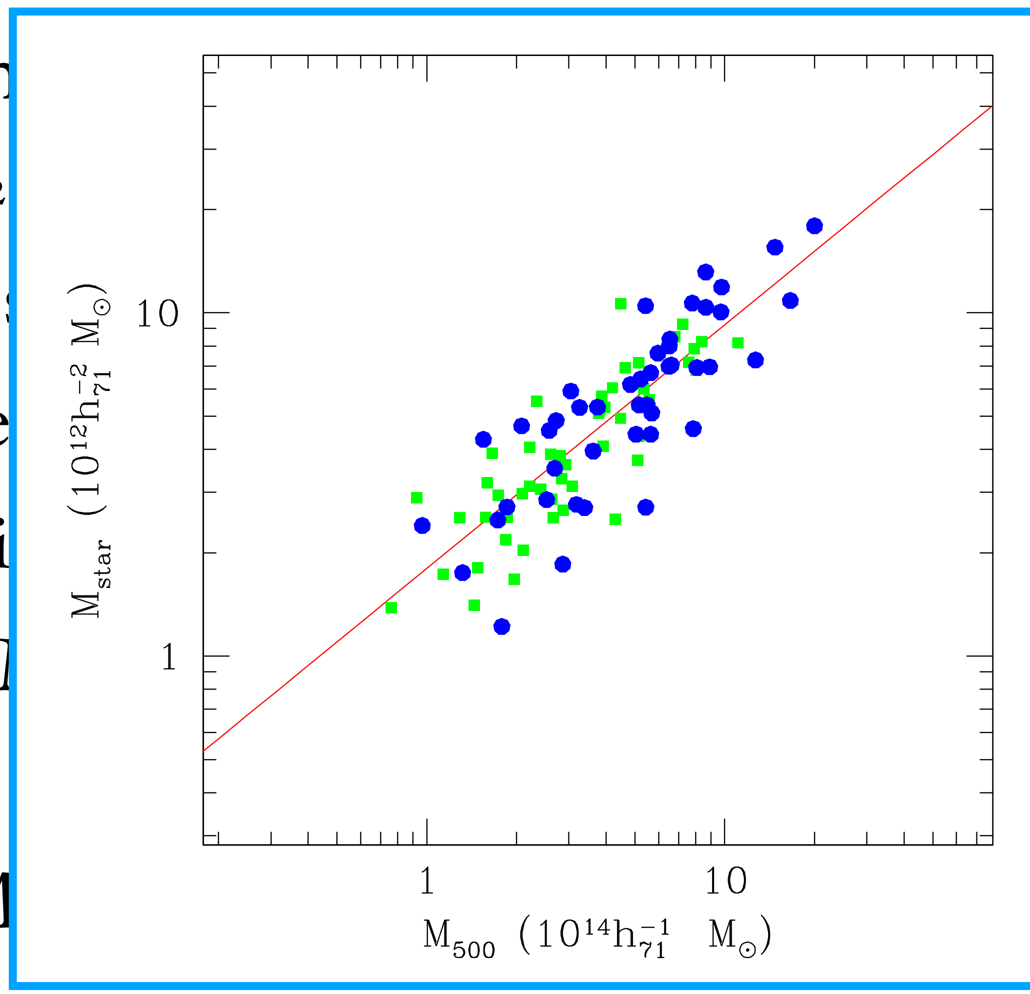
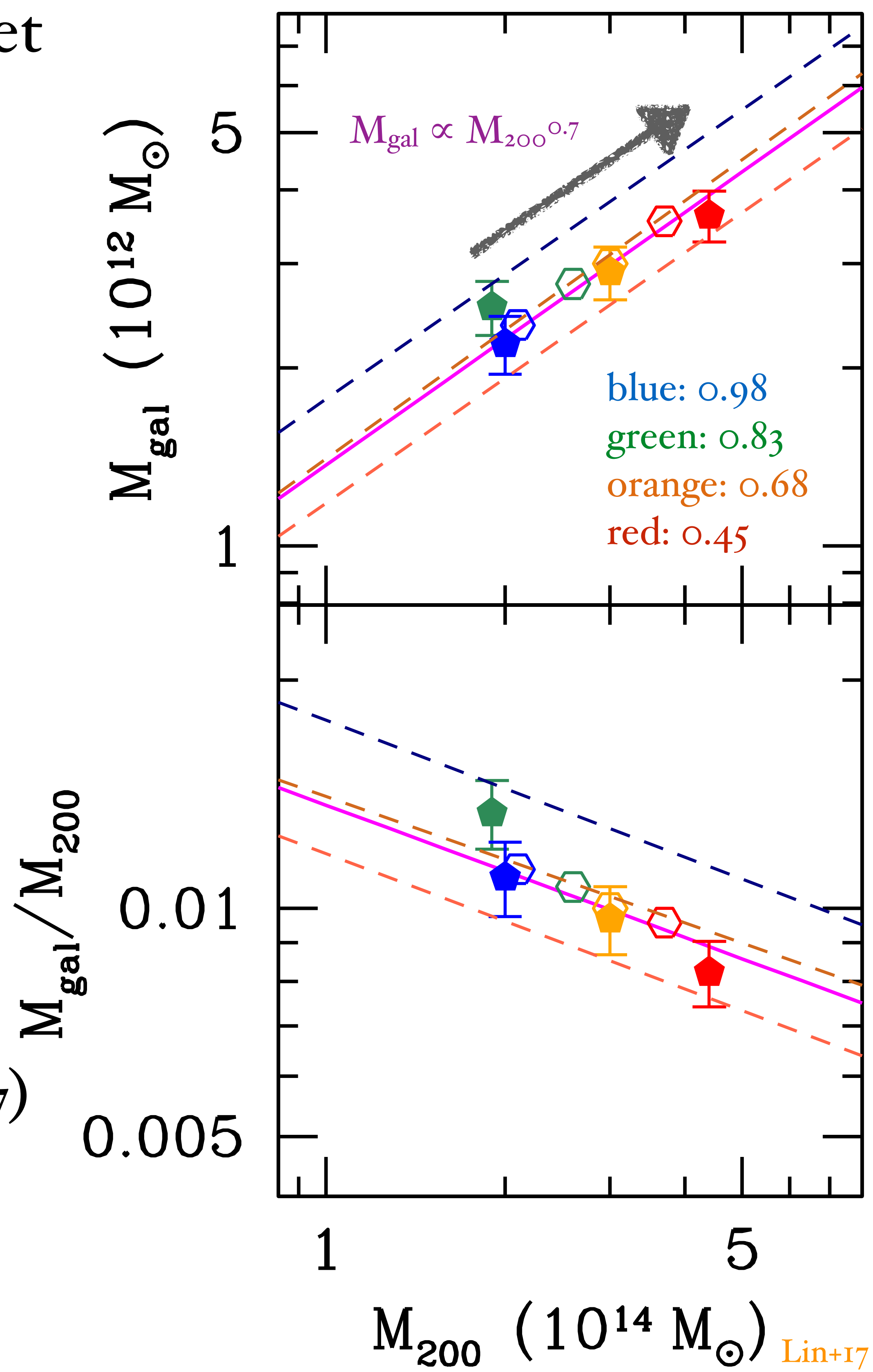
  & COSM





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- clus ... .7 locu ... or a tota
- why ... e M_{ga}
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  - pr ... ects?
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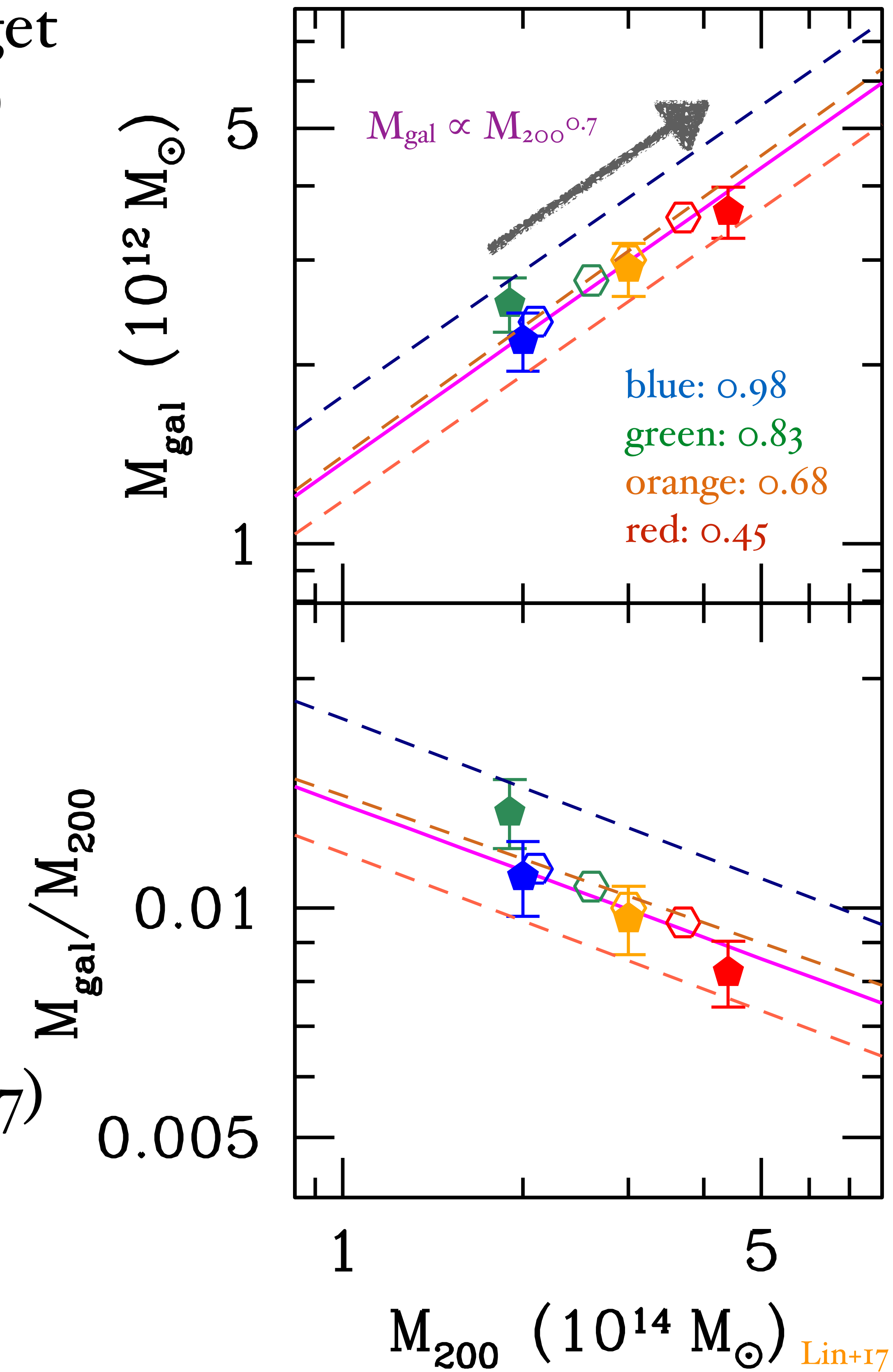
  - w ... ?

Taking merger trees of massive halos from Millennium; for every halo that forms, we assign some stellar mass to it (following a simple M_{star}-M_{halo} prescription). When two halos merge, some fraction f_{loss} of stars are assumed to be lost to intrahalo or interhalo space.

It is found that, to produce a slope of ~0.7, f_{loss}~0.4 is needed; even so, the model cannot produce a constant amplitude of the scaling relation…

- also seen in SPT-selected clusters (Chiu+17) & COSMOS groups (Giodini+09)



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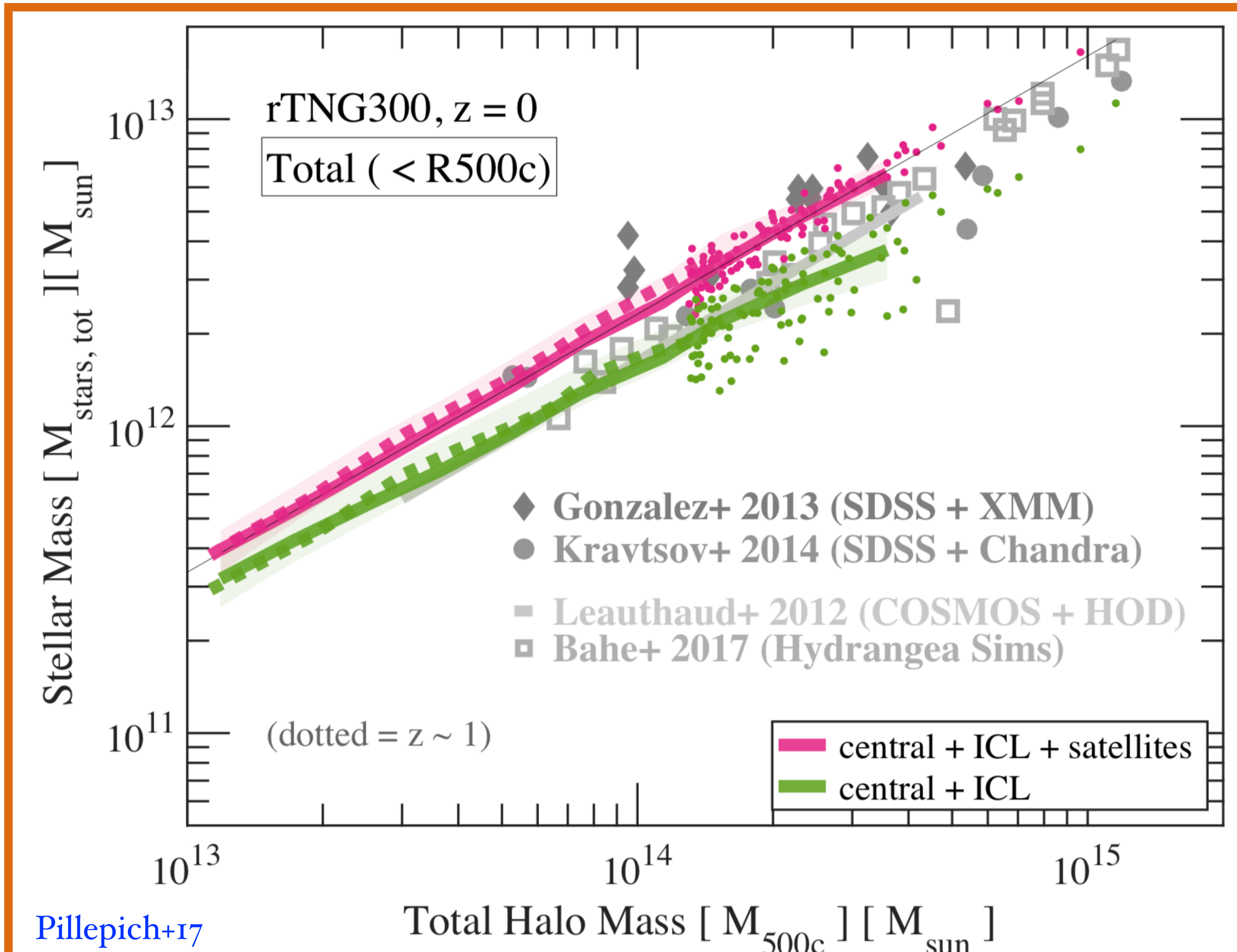
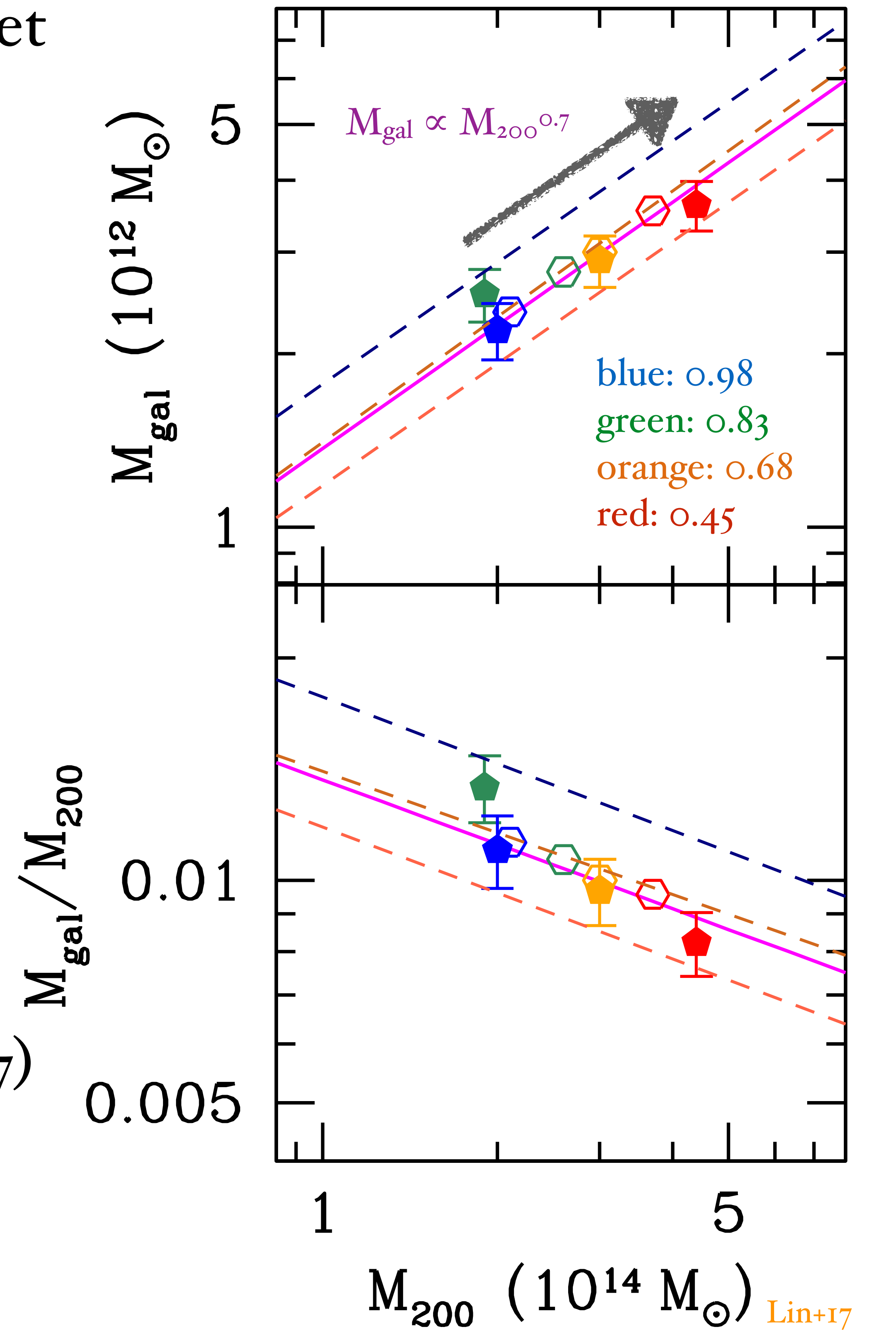
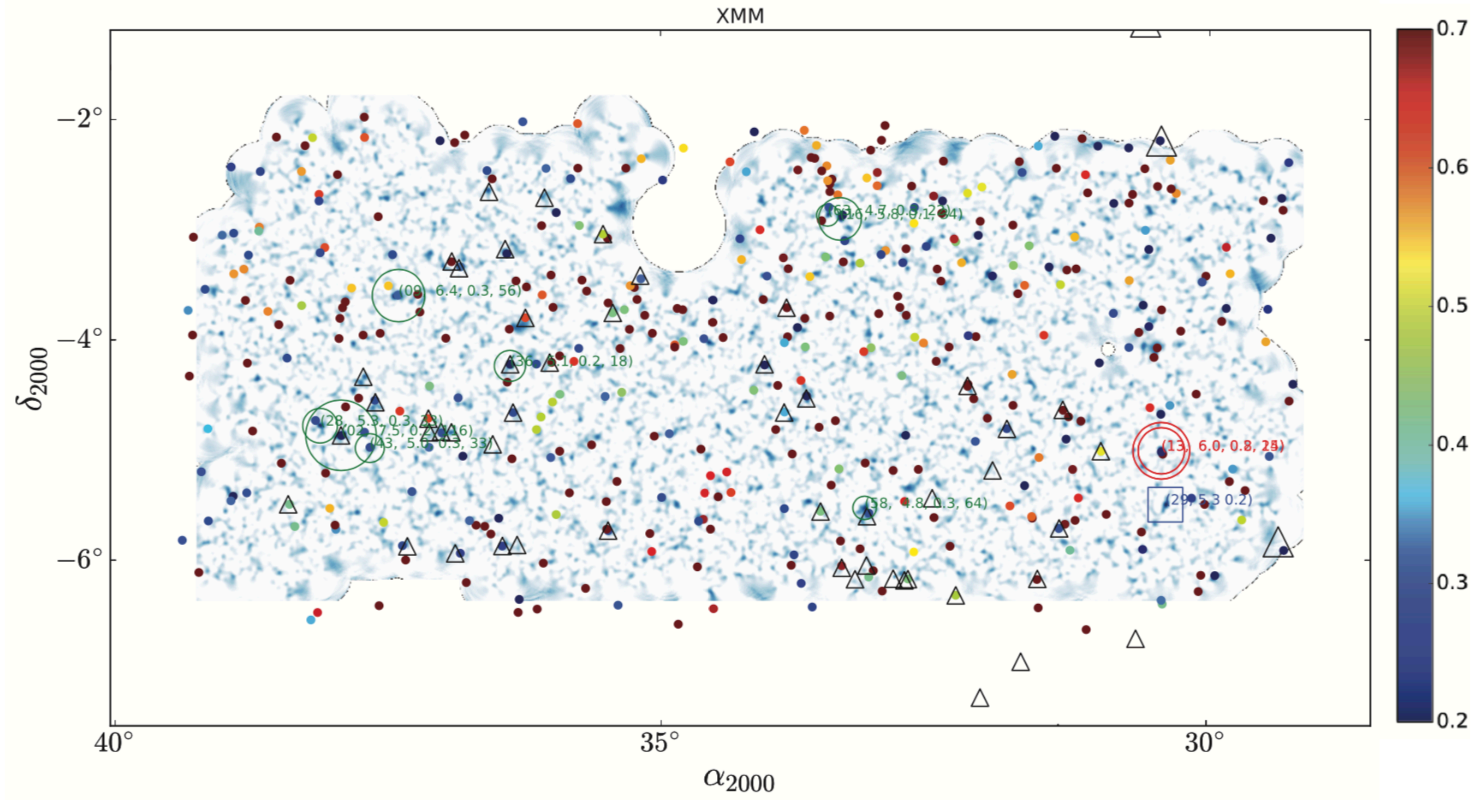


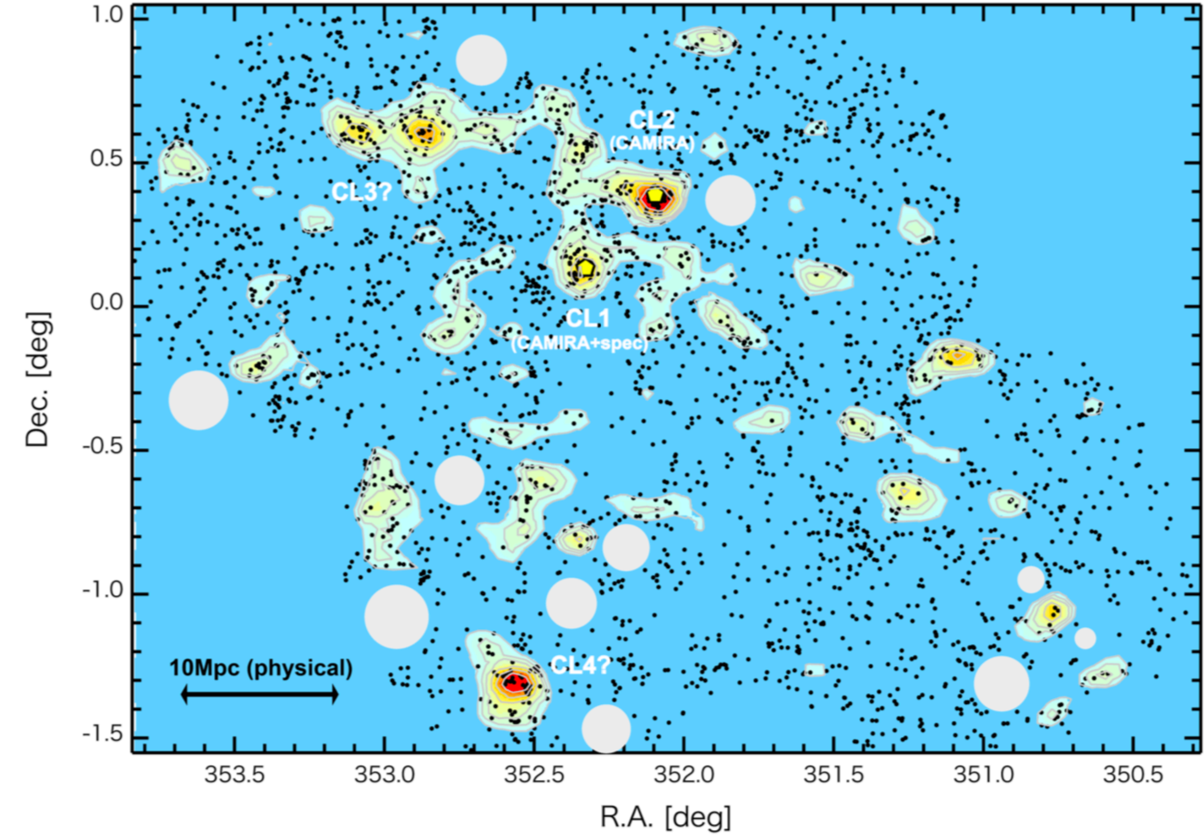
7)

& COSMOS groups (Giodini+09)

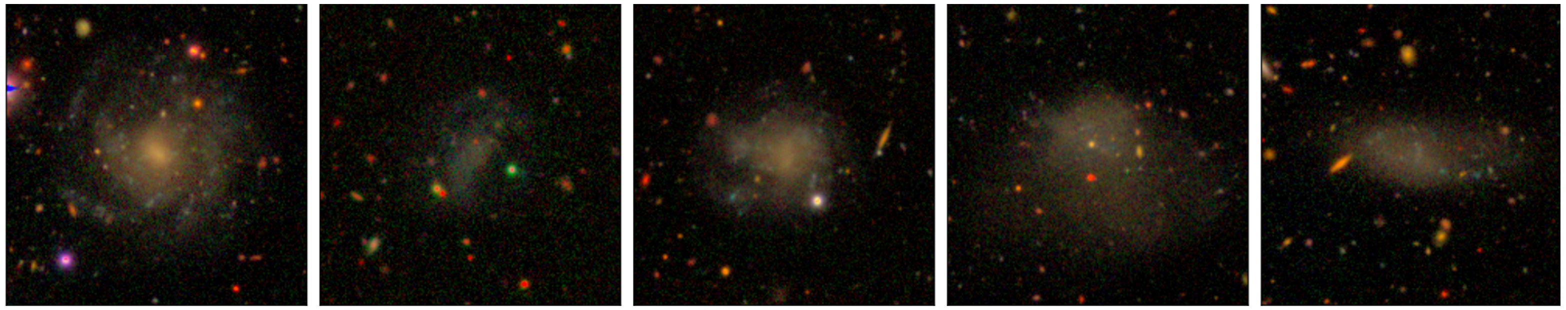




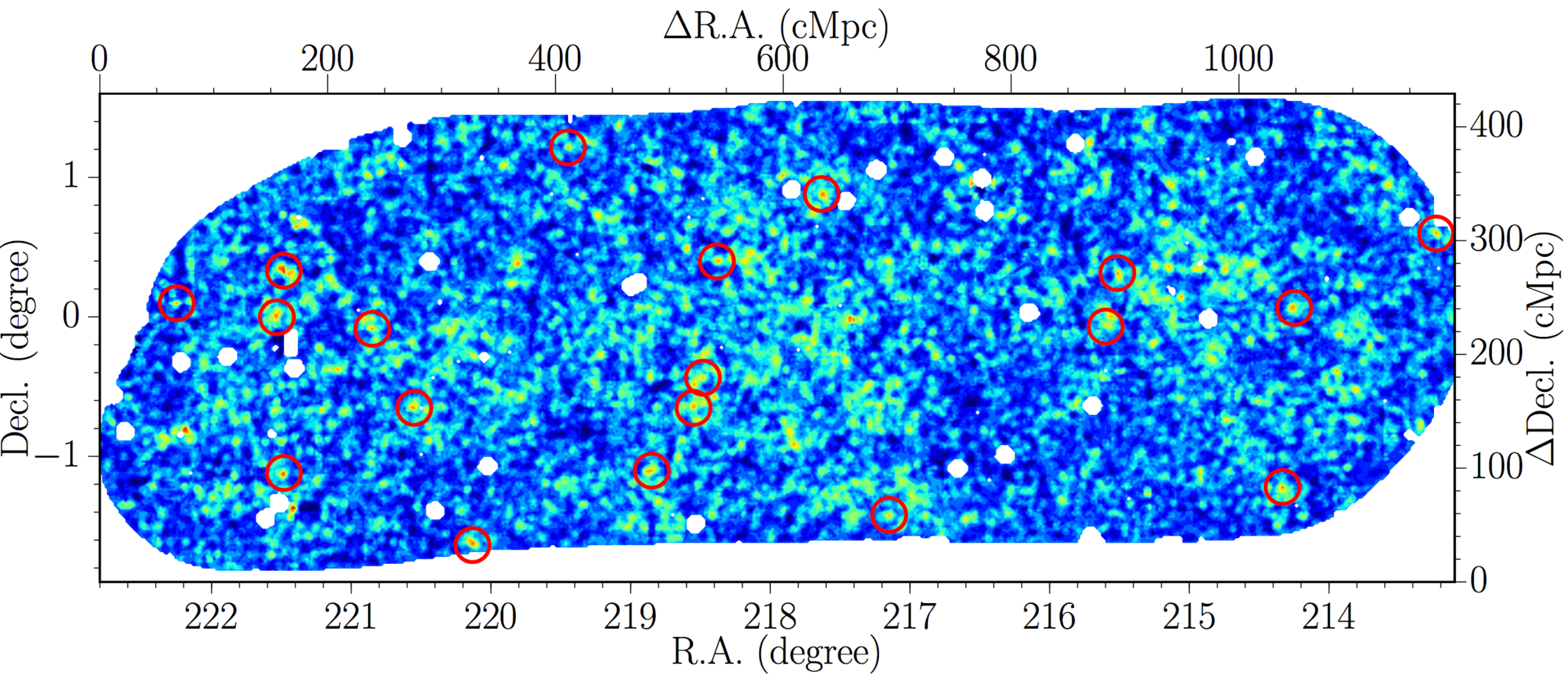
65 mass peaks with S/N>4.7 (Miyazaki+18)



twin cluster at z~0.4 from NBs (Koyama+18)



781 LSBGs (Greco+18)



179 proto-cluster candidates at z~4 as >4σ LBG overdensities (Toshikawa+18)

the next decade

- how to push cluster studies to higher redshift ($z>1.4$), with a large and homogeneously selected sample?
  - eROSITA; next-generation Sunyaev-Zel'dovich surveys
  - Large Synoptic Survey Telescope (LSST)
  - Euclid / WFIRST
  - Subaru Prime Focus Spectrograph (PFS) survey
- with the near-IR coverage, Euclid seems most promising for delivering such a sample
- PFS offers complementary samples
  - overdensities selected from emission line ([OII]) galaxies from cosmological survey (~2000 deg^2)
  - groups and clusters from J-band selected, densely sampled spectroscopic galaxy sample in the galaxy evolution survey (~15 deg^2)

- larger collaboration: Japan, ASIAA, Princeton, JHU, Caltech/JPL, LAM, Brazil, MPA, Chinese participation group, US Northeast participation group
- 1.3 deg diameter FOV
- 2394 fibers with Cobra fiber positioners, <2min reconfigure time
- 380-1260nm spectral coverage
  - 4 spectrographs each with 3 arms
- key sciences
  - cosmology
  - galaxy and AGN evolution
  - Galactic archaeology

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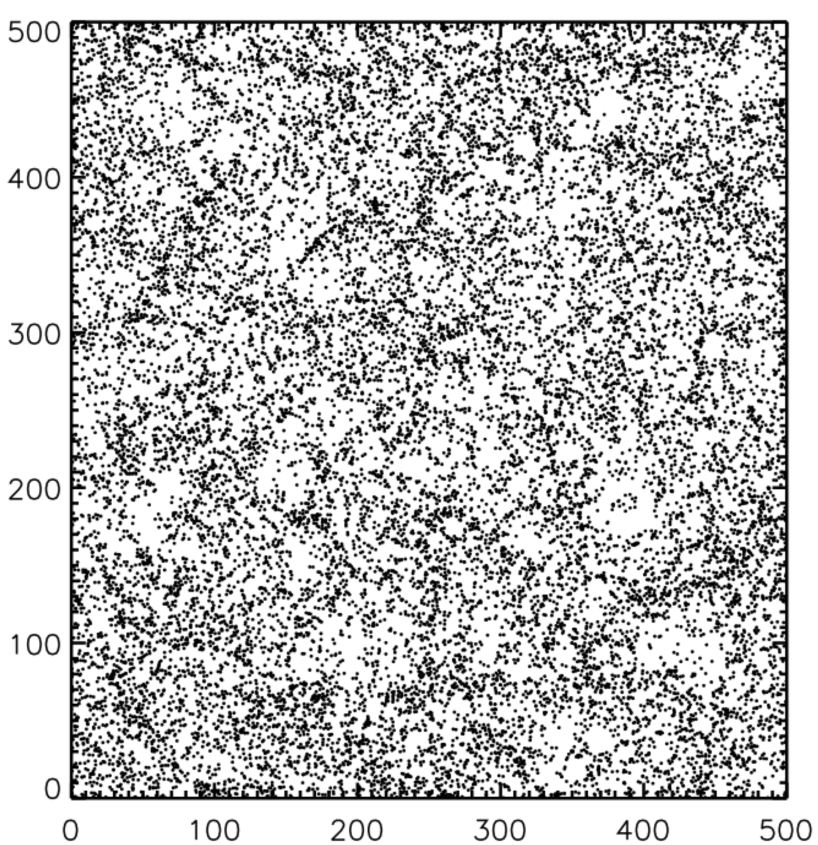
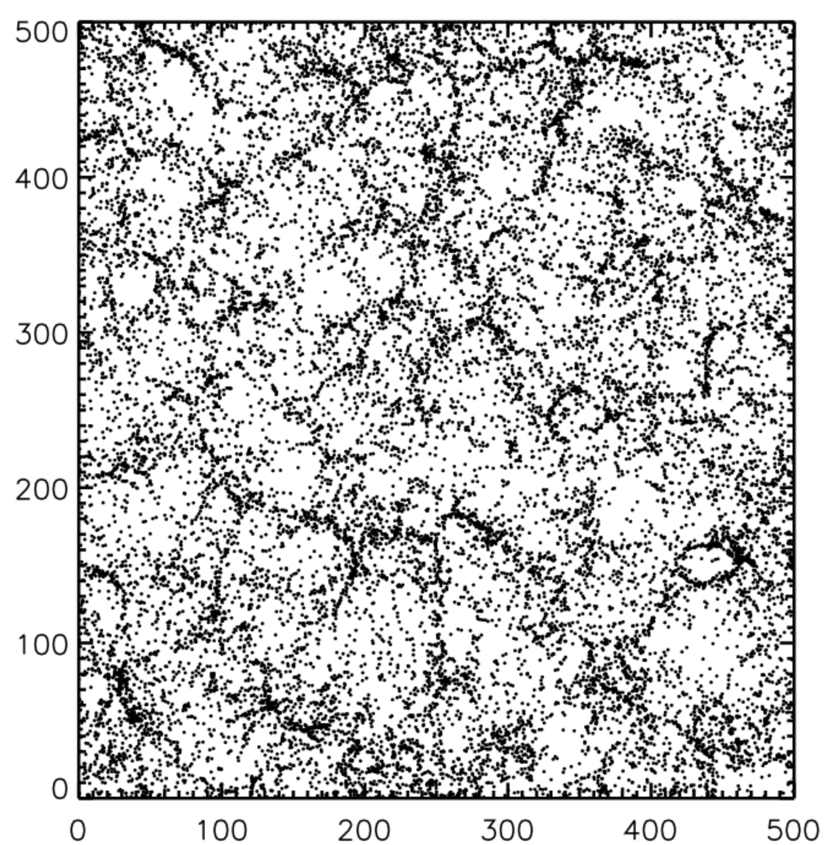
detecting halo assembly bias

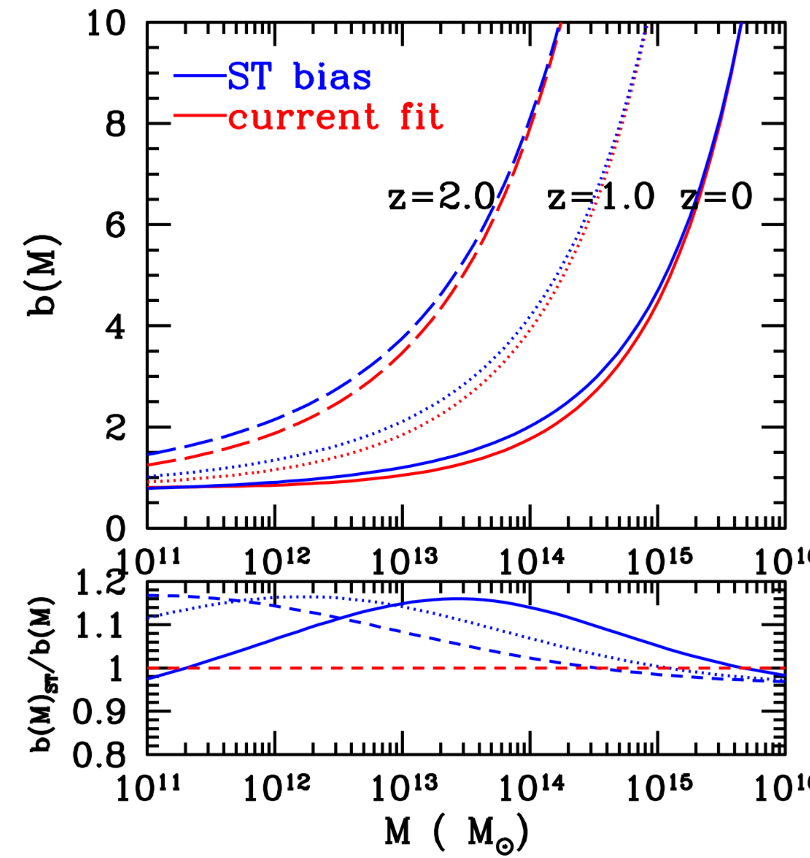
assembly bias?

- dark matter halo bias primarily is 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)
  - for cluster scale halos the amplitude is smaller

Gao+05, Bhattacharya+11

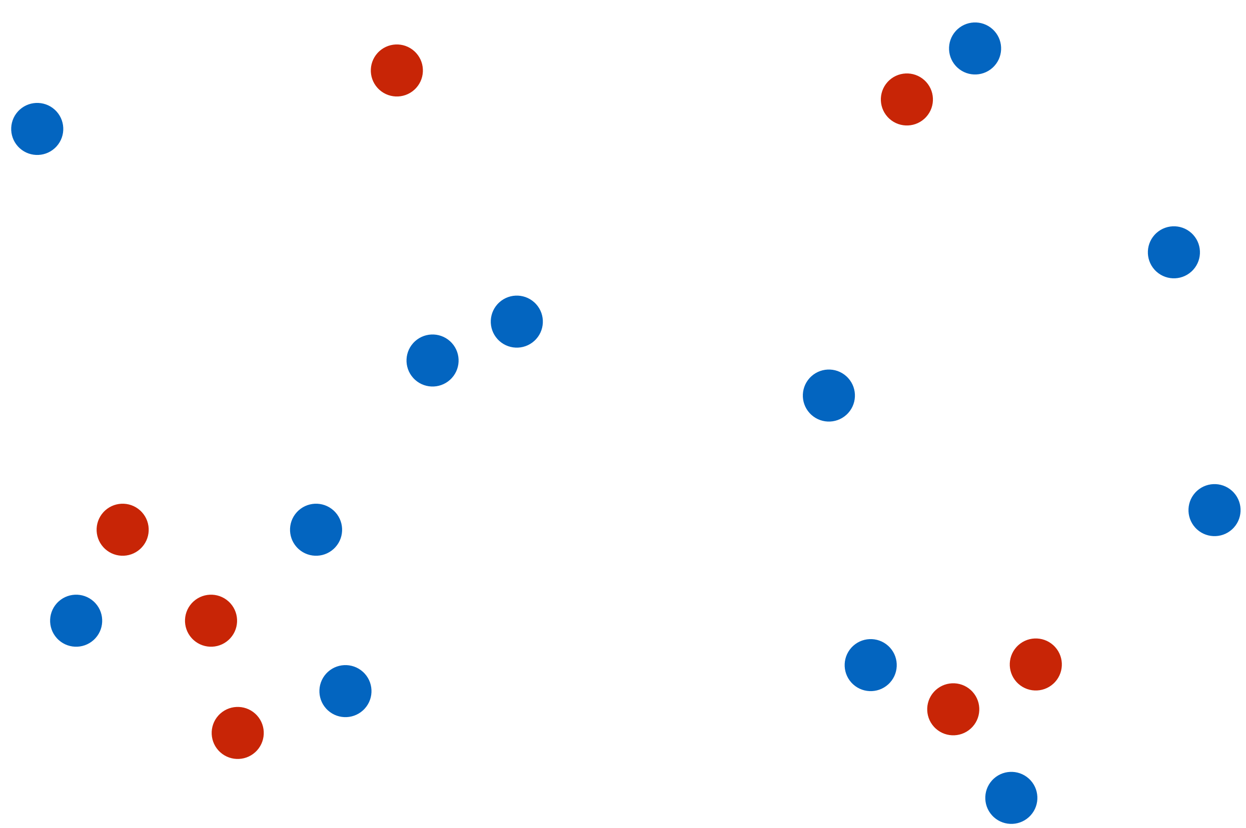


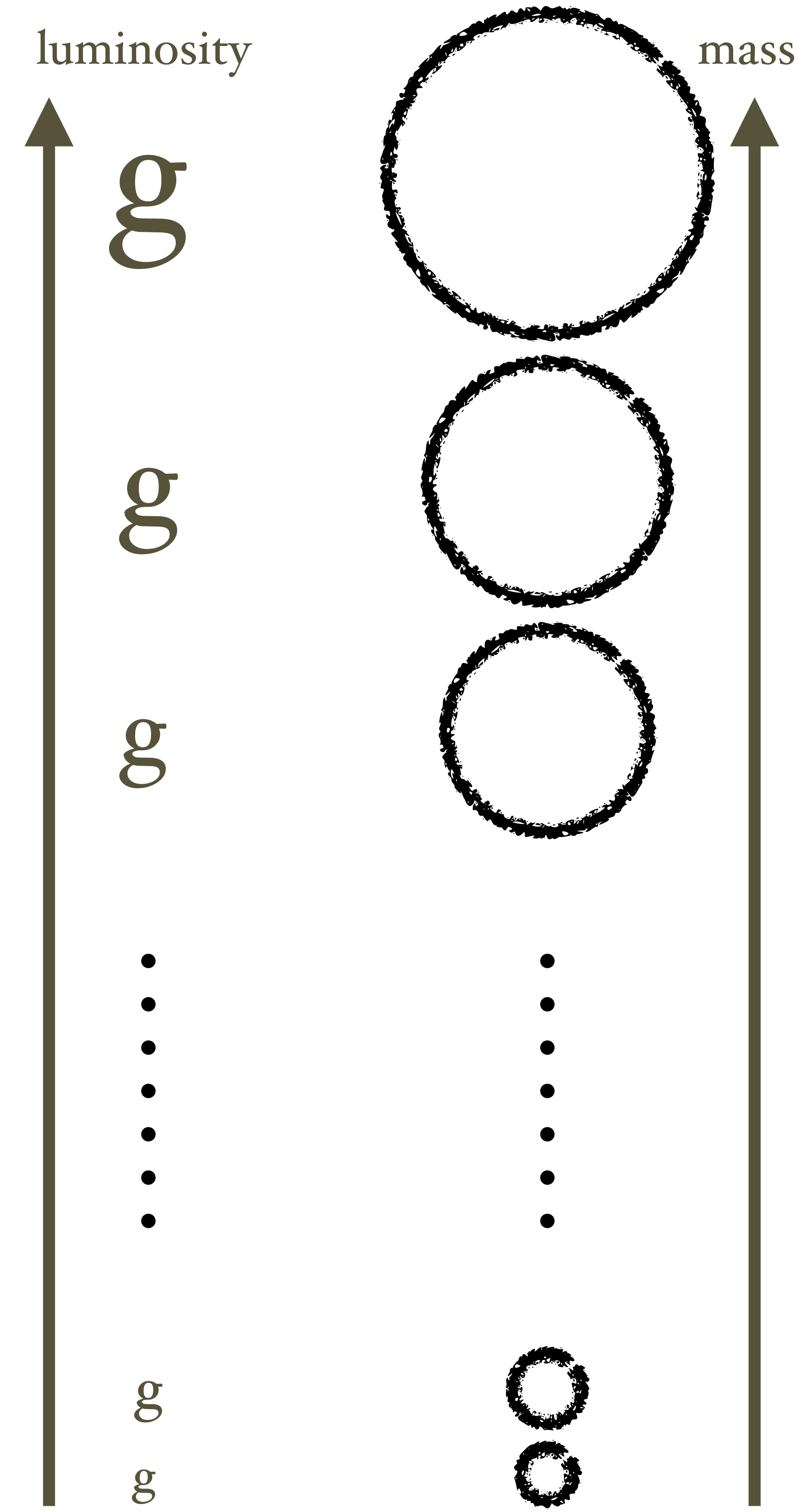




wasn’t this detected long ago?

- 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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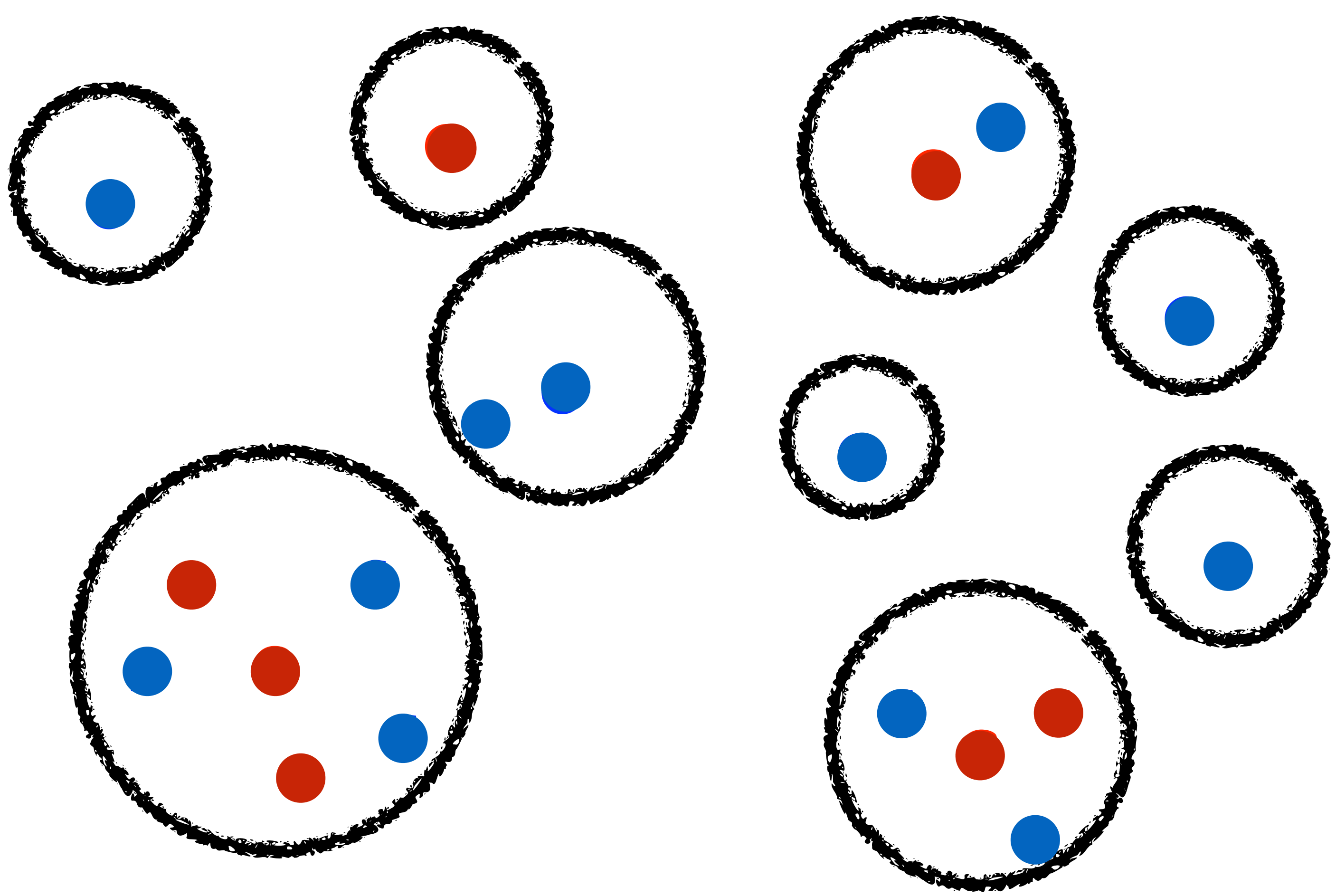

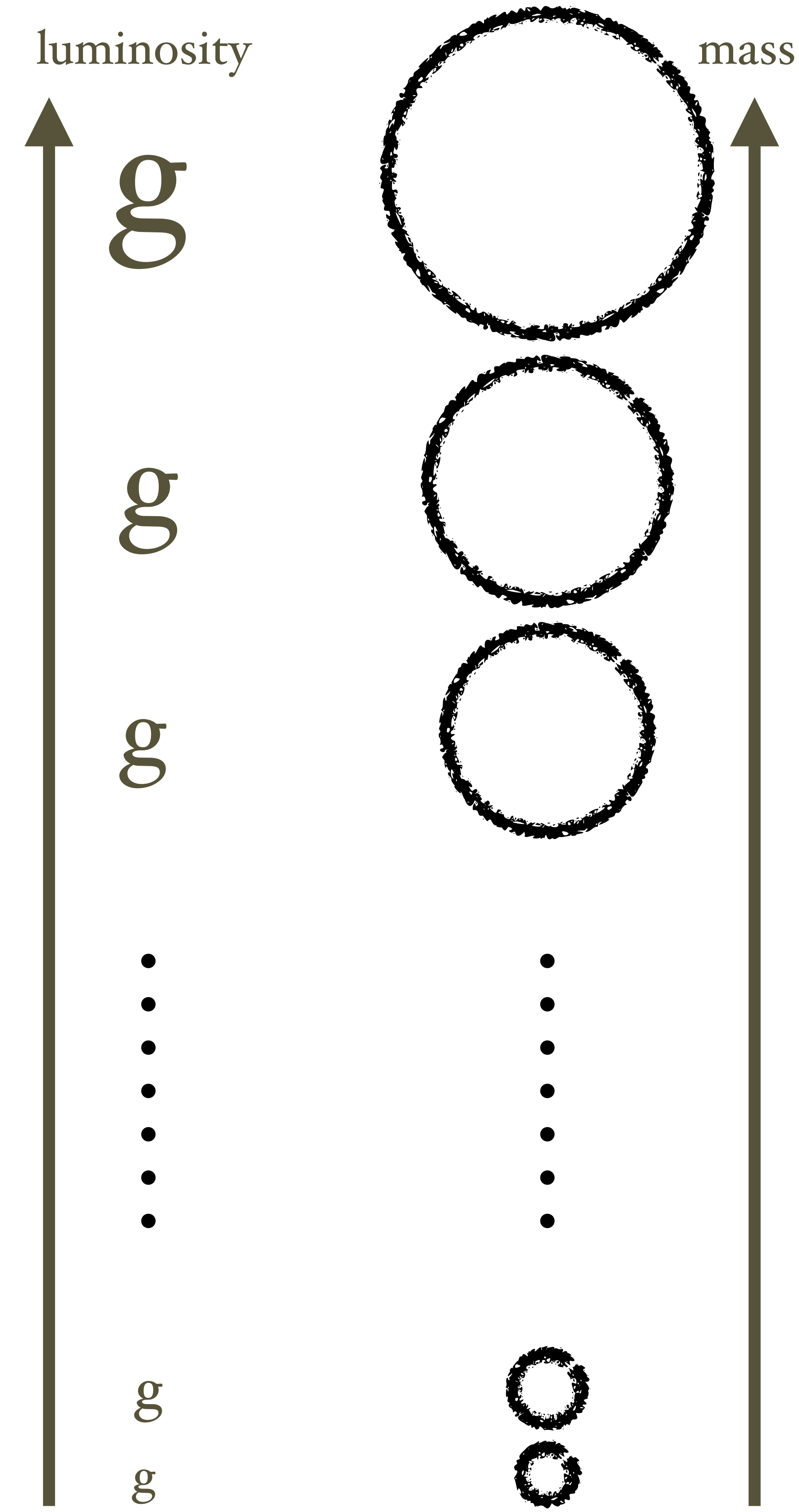

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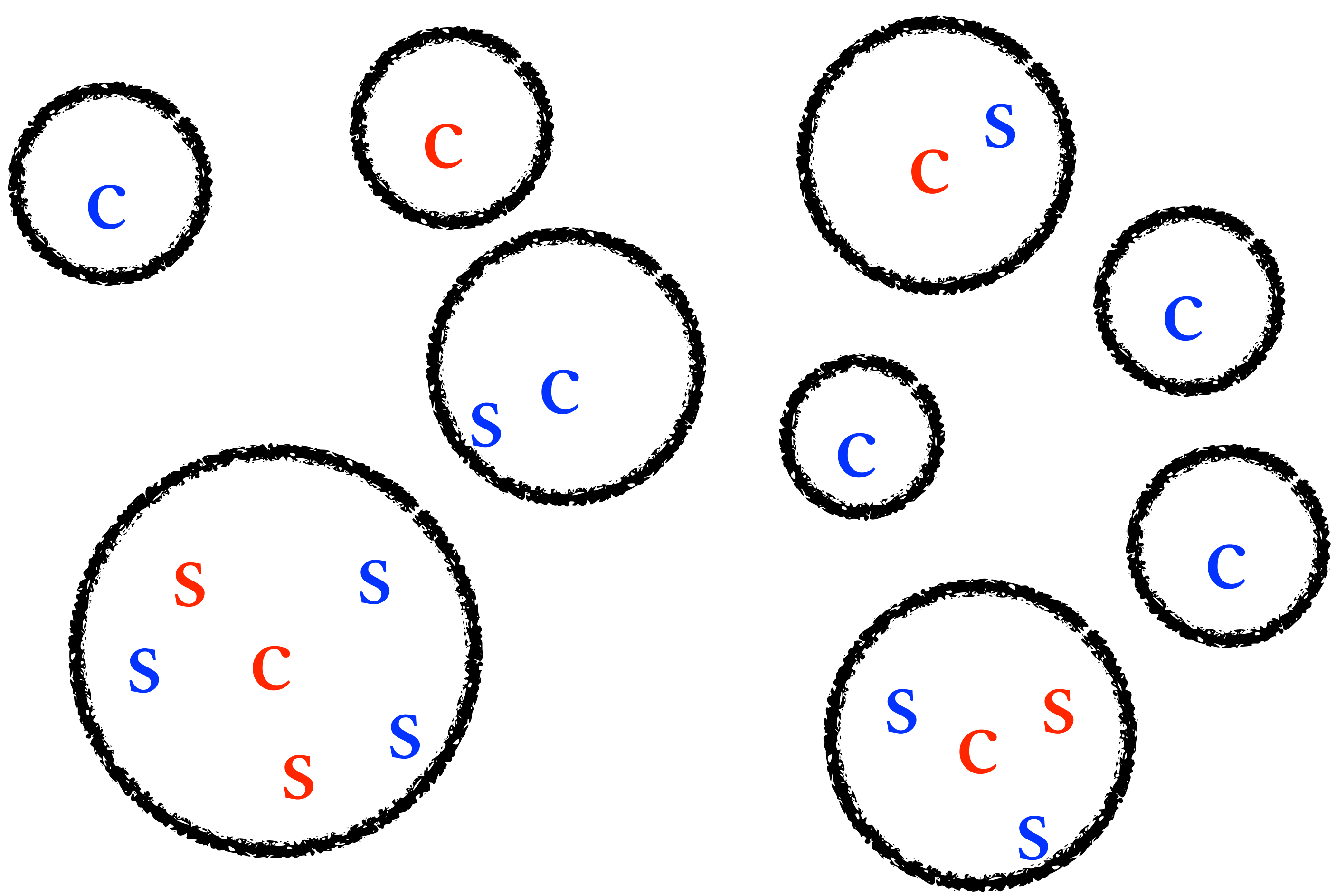
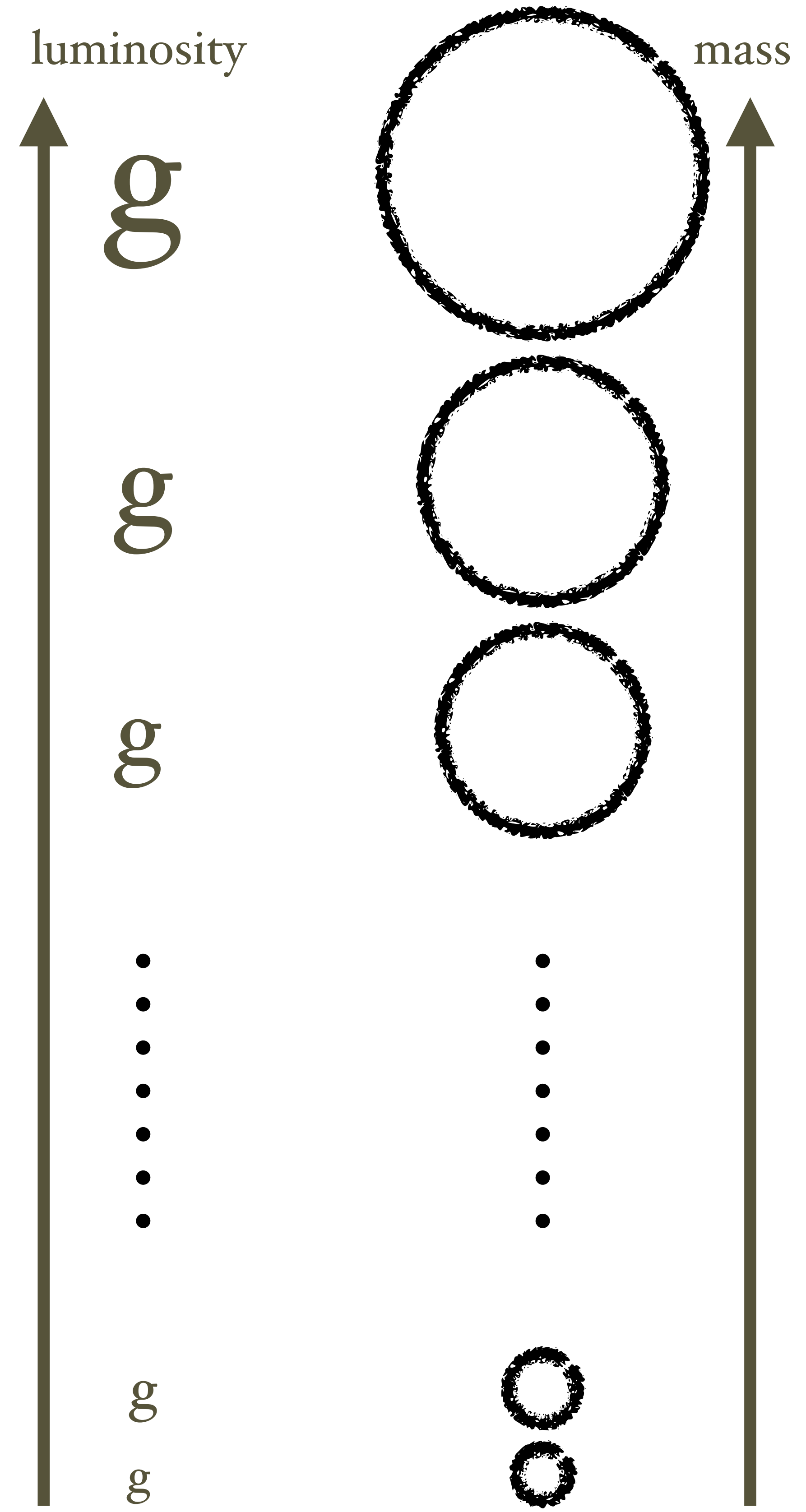
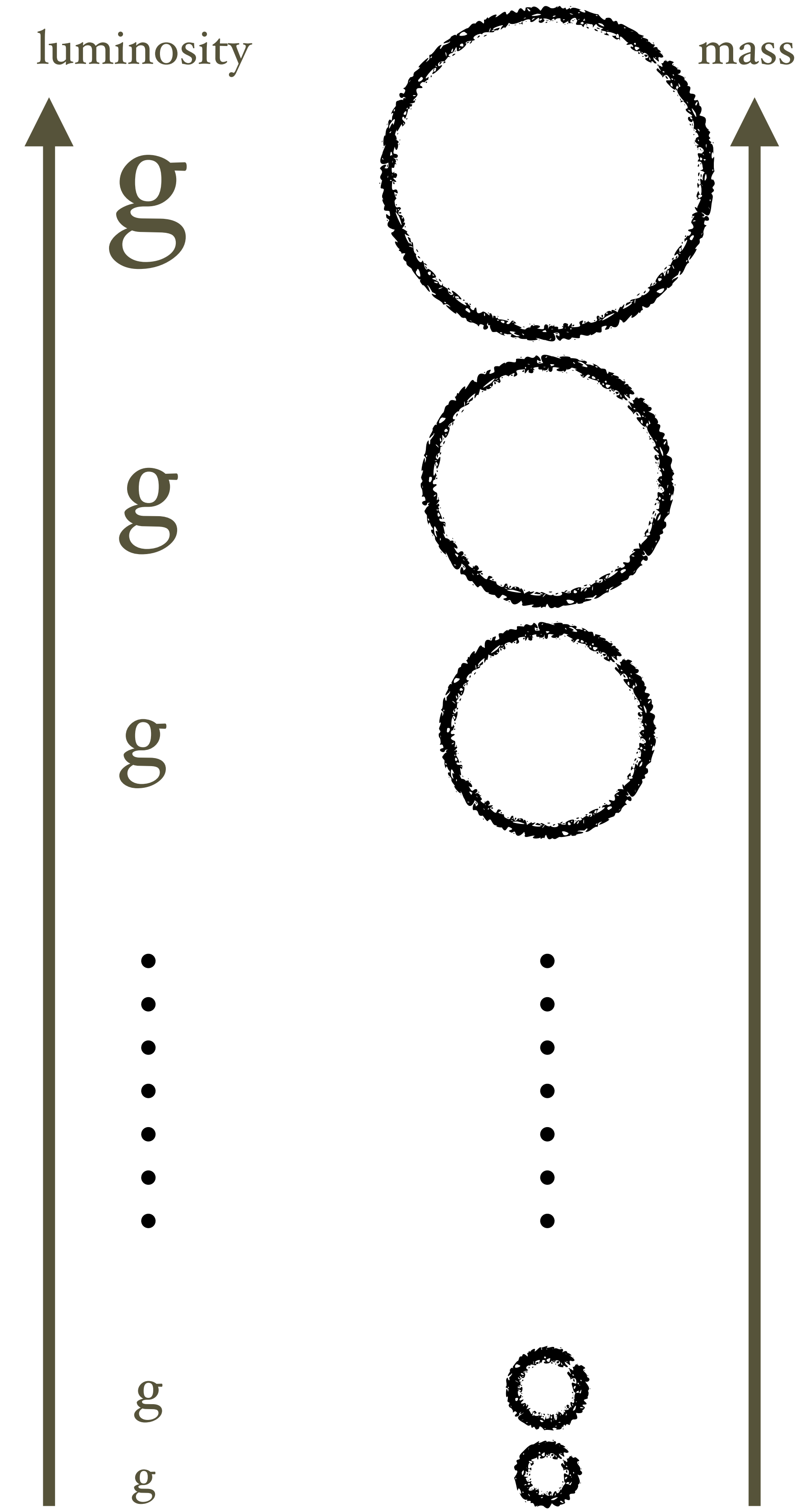




wasn't this detected long ago?

- 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
- 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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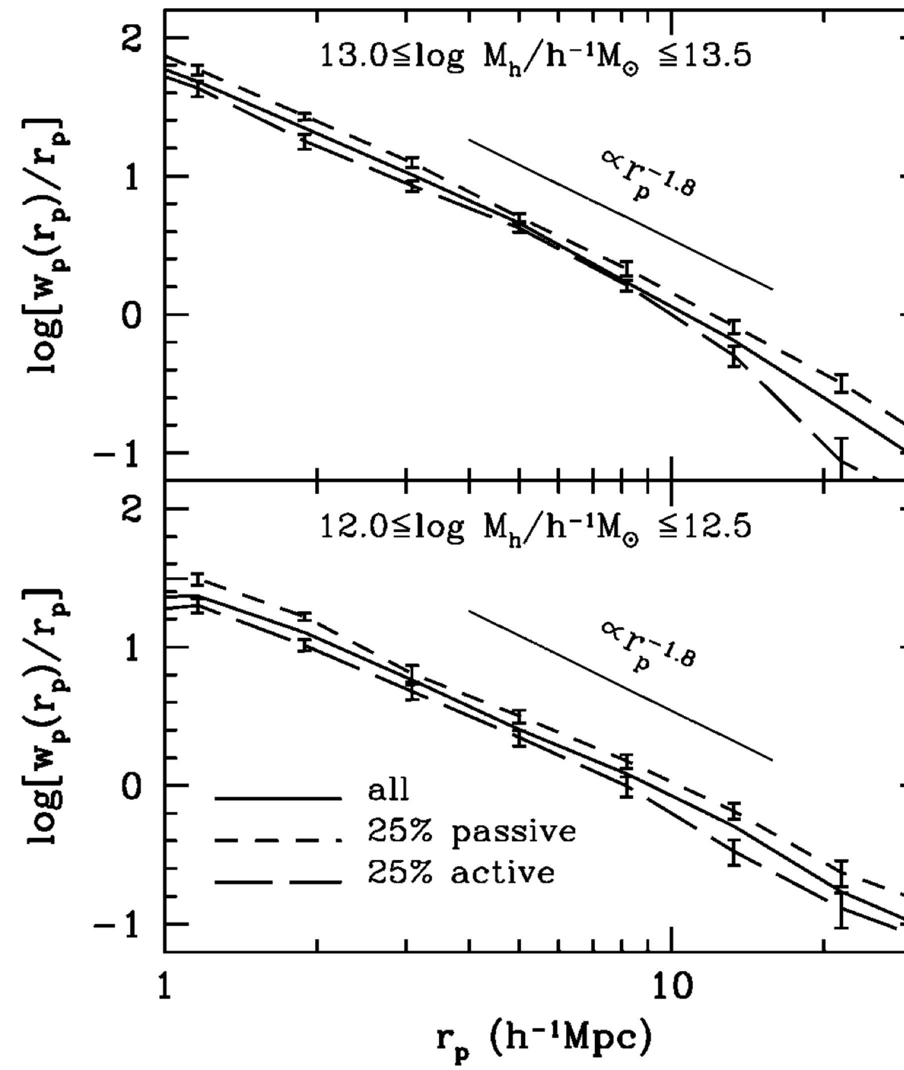
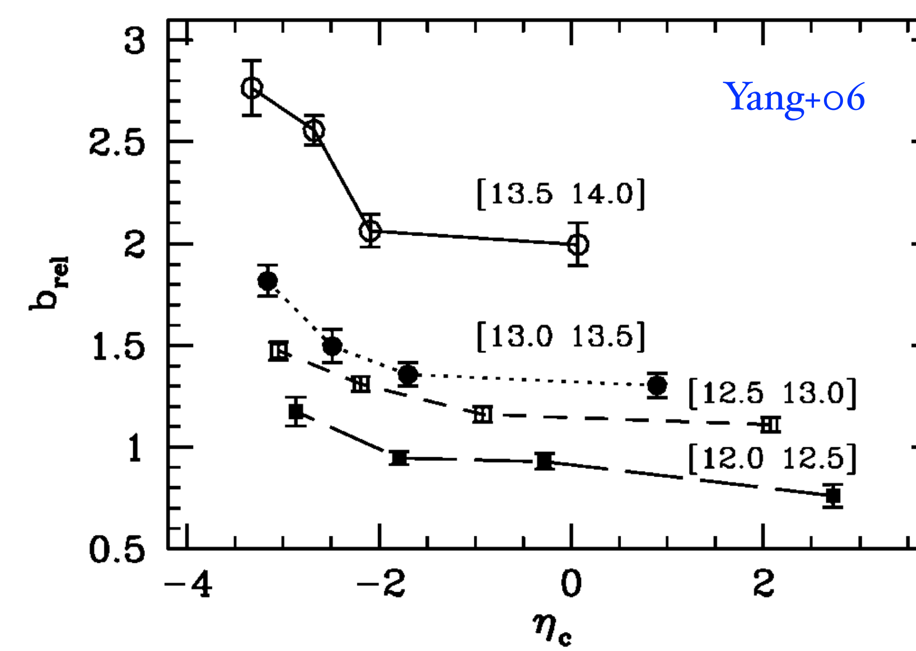
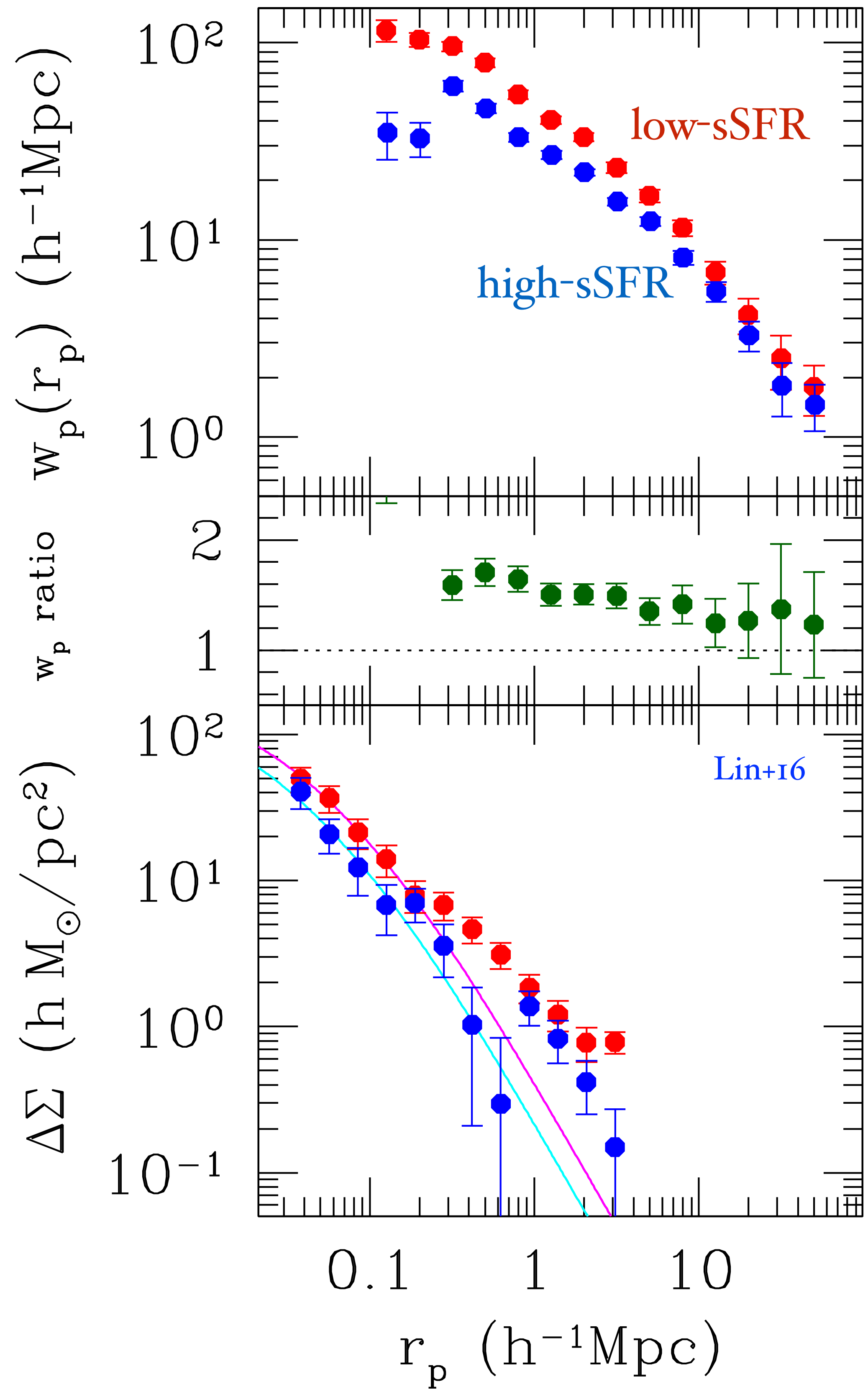




or was it?

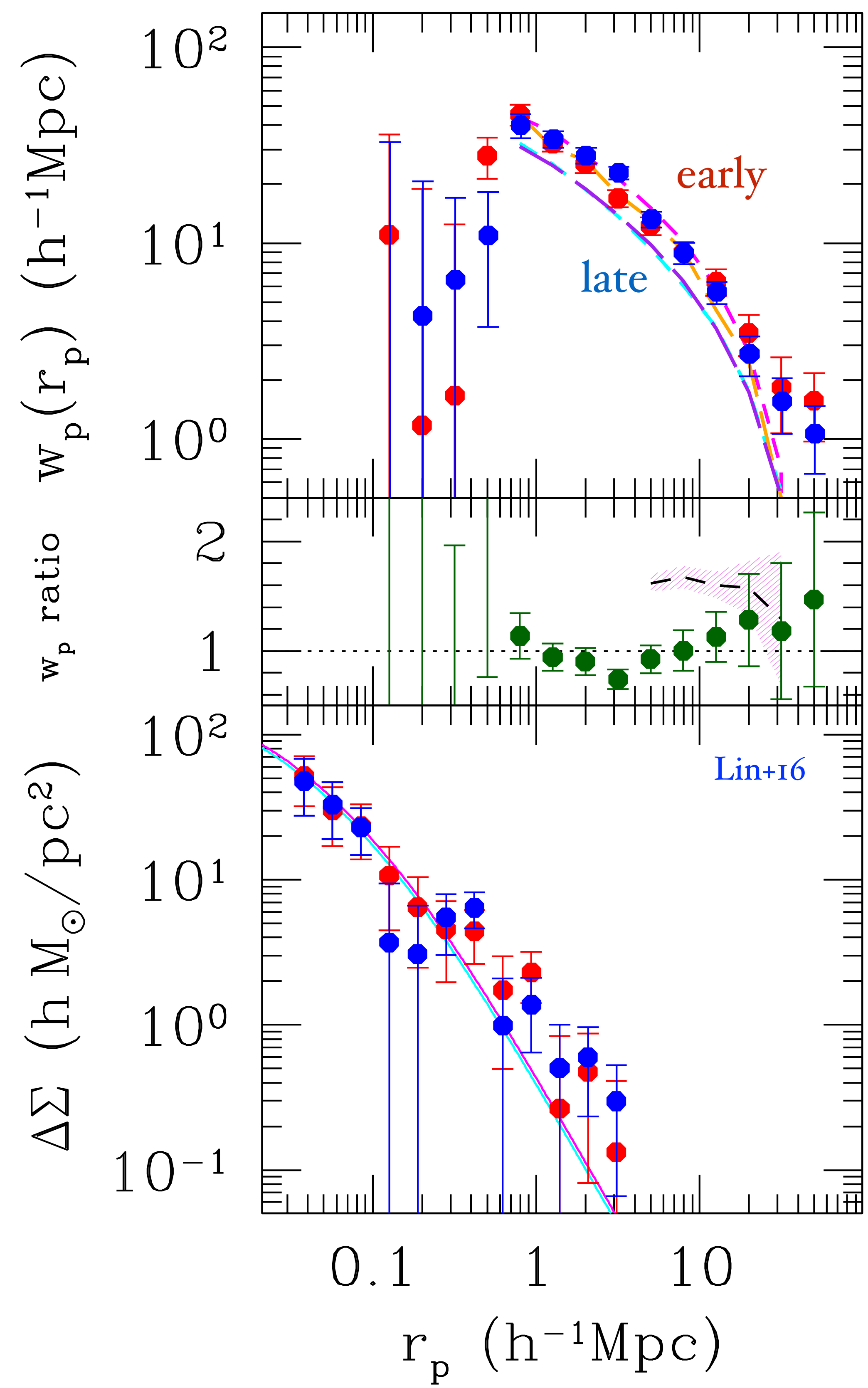
- using SDSS data, we follow the Yang+06 approach and confirm that low-sSFR centrals do cluster more strongly than high-sSFR ones sSFR=specific star formation rate
  - only central galaxies are used
- however, the difference in bias may be explained by the difference in the mean masses of the two samples, as indicated by stacked weak lensing
- the previous claim of detection likely false
- Yang et al. halo mass assignment not reliable (at such low mass scales)
- serious contamination from satellite galaxies also seen



in Milky Way-like halos

non-detection of assembly bias

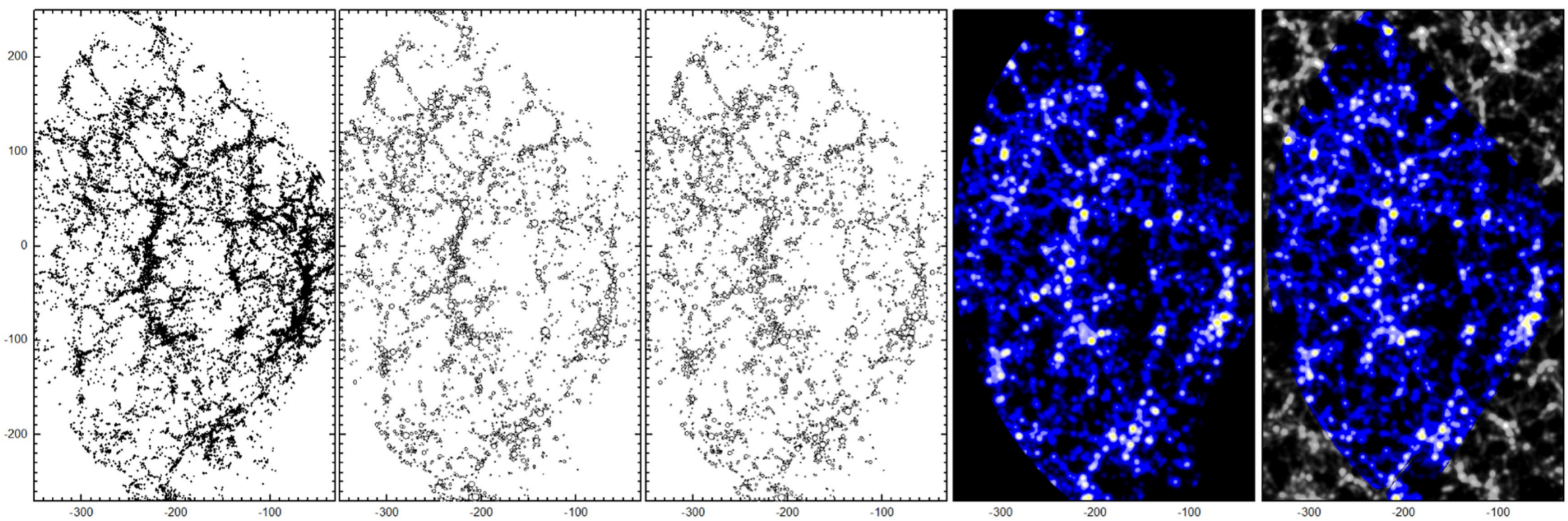
- we have constructed a pair of early- and late-forming central samples (selected by star formation history) for which the satellite contamination is minimal
- masses are $(9\pm2)\times10^{11} h^{-1} M_{sun}$ and $(8\pm2)\times10^{11} h^{-1} M_{sun}$
- theoretical expectation derived from high resolution N-body simulations, taking into account uncertainties in halo mass distribution
  - log-normal form assumed
  - probable values of centroid & width allowed by measured lensing signal
- probability for theory to be consistent with observation is 2×10^{-6}



assembly bias at cluster scales?

- what is the best proxy/indicator for the halo formation time?
- concentration may work, but difficult to measure in practice
- what if we have the mass accretion history (MAH) of the clusters?
- using the group catalog of Yang et al., H.-Y. Wang et al. (2016) have run a constrained simulation (CS) of the local Universe (SDSS DR7, z<0.12) called *Elucid*

Wang+16



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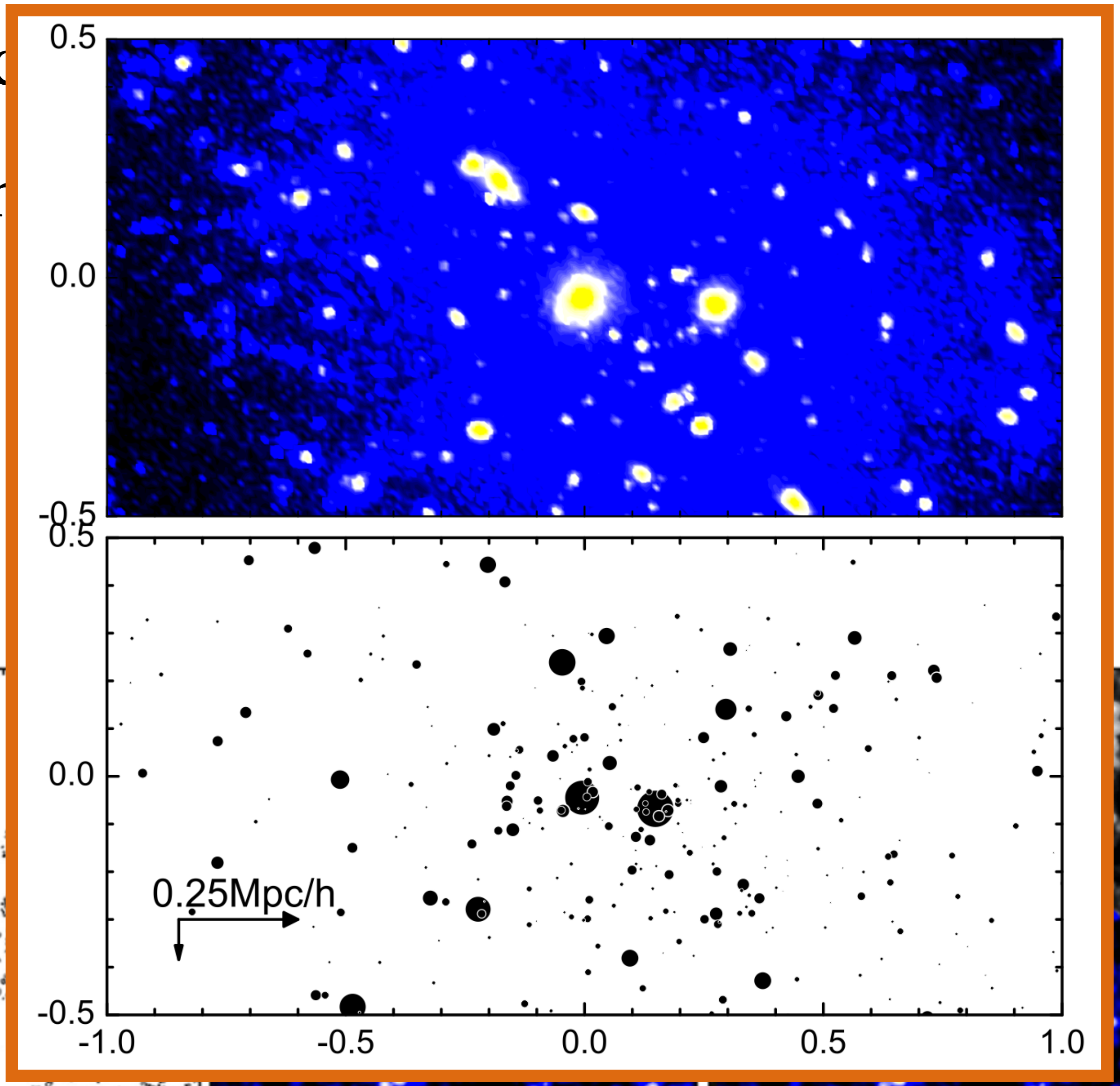

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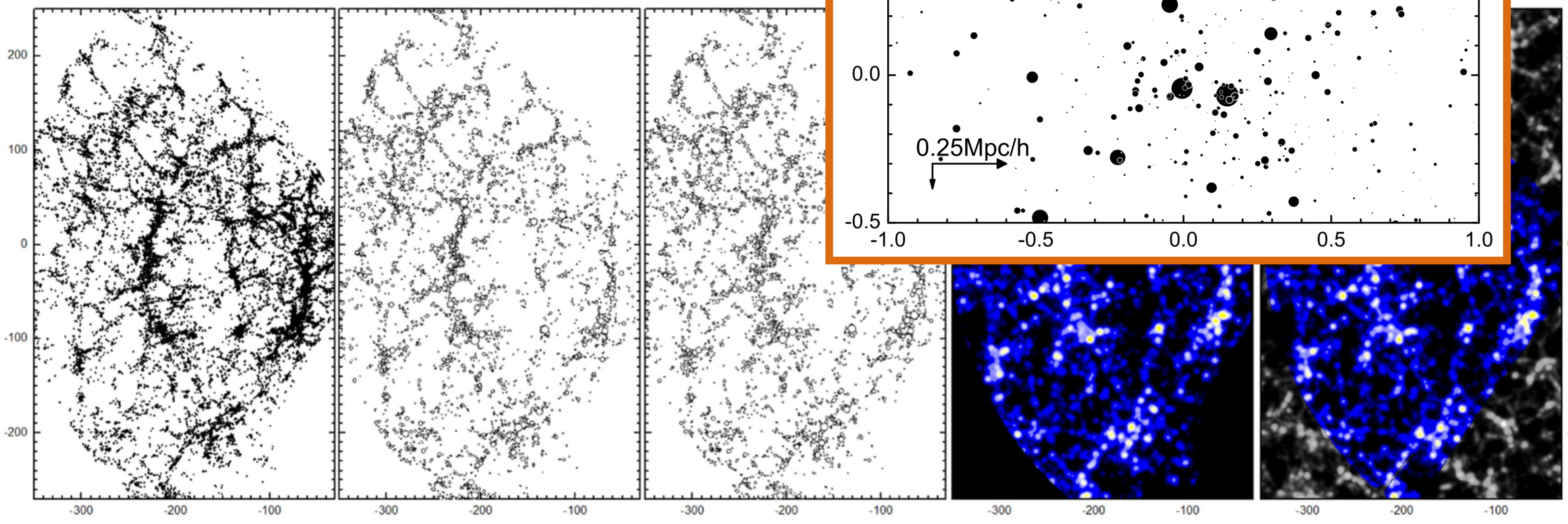

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- for structures larger than ~2Mpc/h, there is very good correspondence between SDSS LSS and Elucid structures
- we have selected top 600 most massive clusters at $z<0.12$ from Yang's catalog
- MAH for each cluster is given by the counterpart halo in Elucid

conclusion

- it remains a puzzle as to why the total stellar mass–cluster mass relation does not evolve with time
  - should include intracluster light in the measurements of "total" stellar mass
  - should measure this relation in bins of optical richness at several redshifts, to really constrain the (no-)evolution
- HSC data is great for a wide array of topics in galaxy/cluster formation and cosmology
  - stay tuned for the next public data release (May 2019)!
- forward-modeling techniques have great potential for understanding galaxy/cluster formation (assembly bias, splashback radius, stellar mass–cluster mass relation, etc)
  - extending such approaches to high-z (from DESI, PFS, Euclid?) would be exciting!