Implication of evolution of massive galaxies from the small-scale galaxy clustering in the BOSS CMASS sample

based on S.S. et al., in prep

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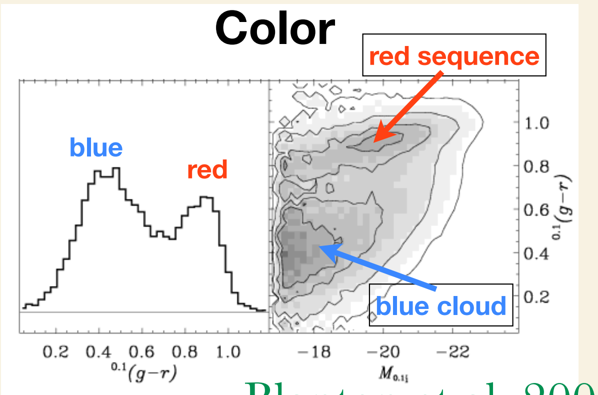
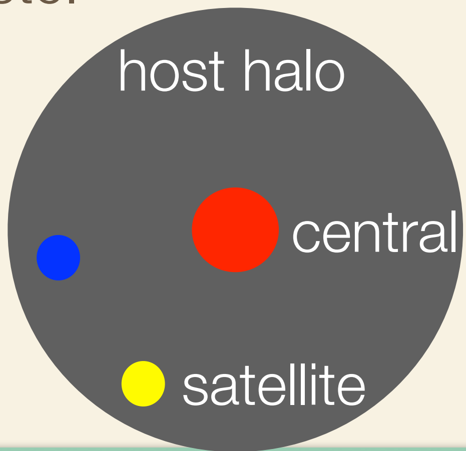
at NAOJ on June 6th in 2014

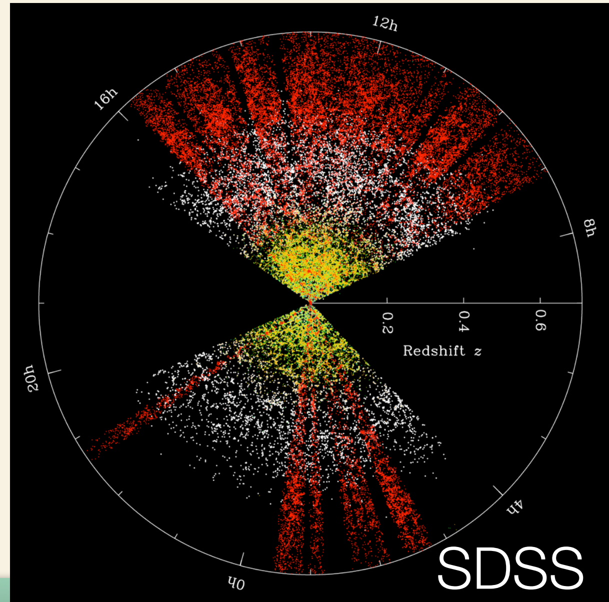
CO-EVOLUTION OF GALAXY & DM HALO

- **Cosmology** via galaxy clustering at large scales, $\mathcal{O}$(10-100Mpc)
  - *Baryon Acoustic Oscillations* → Dark Energy — Anderson, S.S. et al. 2014
  - *Redshift-Space Distortions* → Modified Gravity — Beutler, S.S., Seo et al. 2014; Beutler, S.S., et al. 2014
  - *Shape of galaxy P(k)* → Neutrino Masses — S.S., Takada, Taruya 2011; Zhao, S.S. et al. 2013
- **Galaxy evolution** via galaxy clustering at small scales, $\mathcal{O}$(0.1-10Mpc)
  - sensitive to *how galaxy distributes in a dark matter halo*
  - color- & redshift-dependence of satellite fraction, kinematics etc.



Blanton et al. 2003

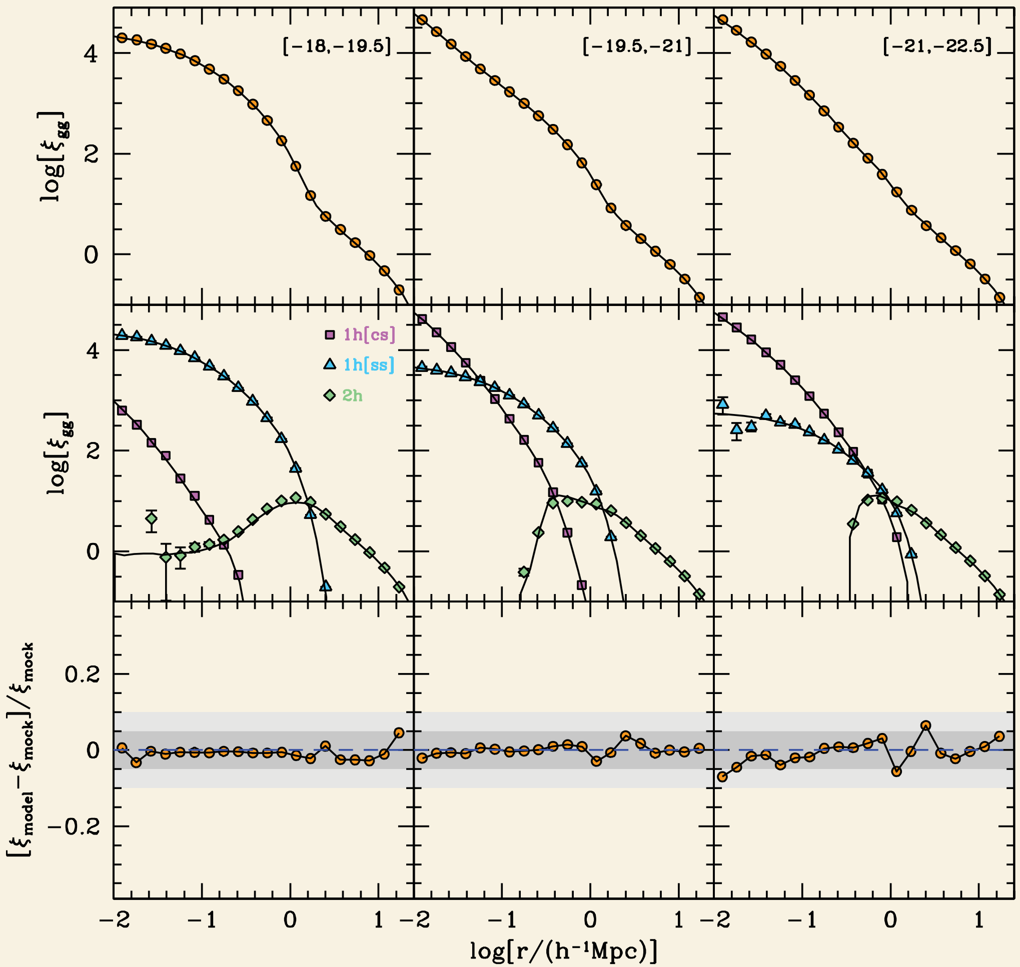




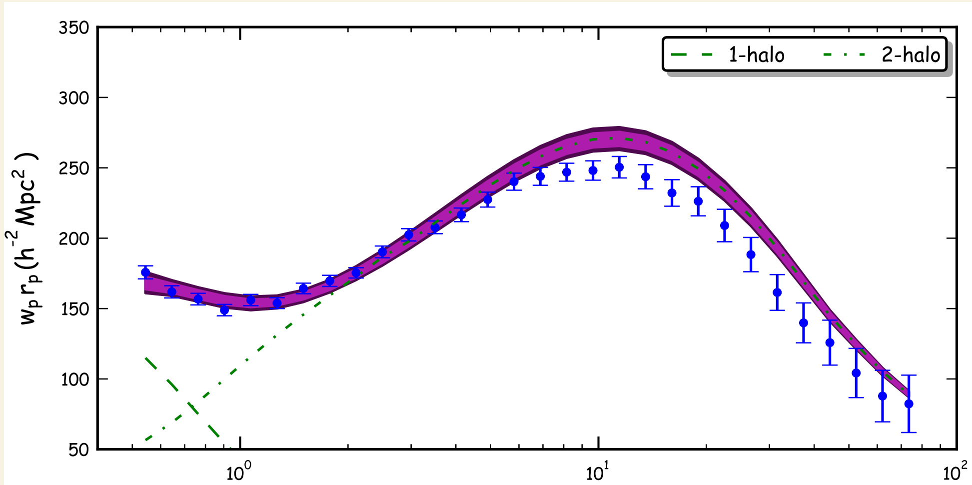
GALAXY CORRELATION FUNCTION

- 3D correlation function $\langle n(\mathbf{x})n(\mathbf{x}+\mathbf{r})\rangle = \overline{n}(\mathbf{x})^2[1+\xi(\mathbf{r})]$
- projected correlation function $w_p(R) = 2\int_0^\infty dZ\,\xi(R,Z)$

van den Bosch et al., 2013



Miyatake et al., 2013



- small-scale clustering is sensitive to 1-halo regime

- less sensitive to RSD

GALAXY-HALO CONNECTION

- need to model nonlinear regime → simulation but…

- *Semi-Analytic Model (SAM)*

  - parametrize galaxy formation with many free parameters   Benson 2014

- *Halo Occupation Distribution (HOD)*   Berlind & Weinberg 2002, Zheng et al. 2005

  - assume a functional form for central and satellite occupation *as a function of the host halo mass M*

  - conditional luminosity function (CLF) is the same

- *Subhalo Abundance Matching (SHAM)*   Kravstov 2004…

  - too simple but the least free parameters
  - assembly bias can be taken into account

SUBHALO ABUNDANCE & AGE MATCHING

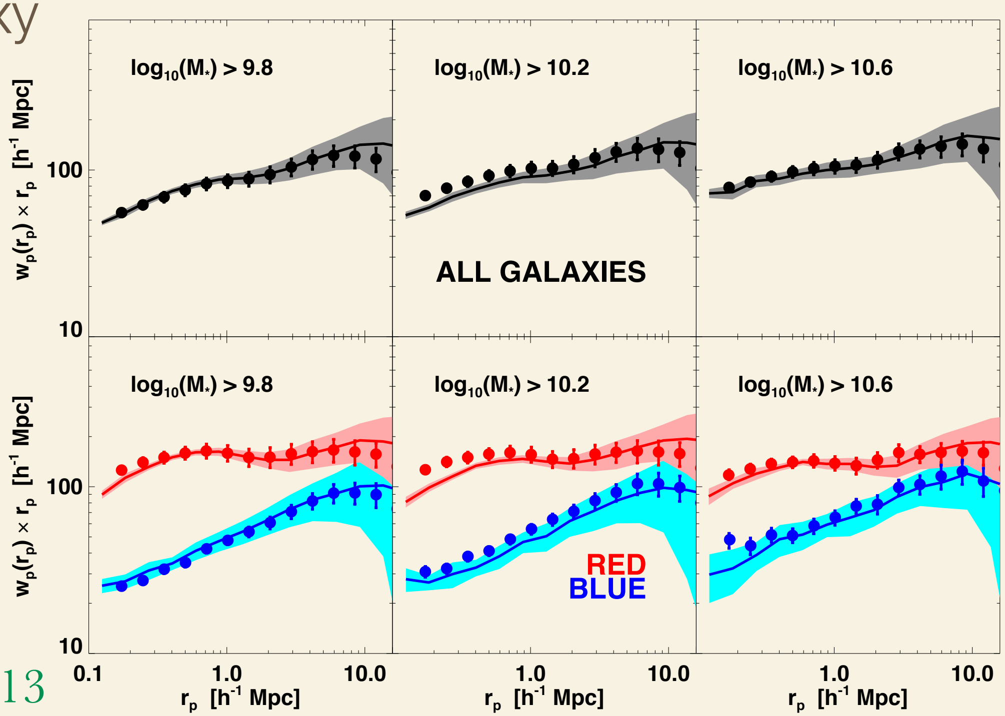
Subhalo Abundance Matching

- A more ***brighter*** galaxy tends to live in a more ***massive*** halo
- Rank-order galaxies by luminosity (or stellar mass), and subhalos by mass (or maximum circular velocity)

Subhalo Age Matching

Hearin et al. 2013abc, Zentner et al. 2013

- At fixed luminosity, an *redder* galaxy tends to live in an *older* halo
- halo formation age is defined by concentration



Hearin et al. 2013

<u>*Goal of this study*</u>

to predict the BOSS CMASS w_p as a function of scale, redshift & color

SIMULATED MOCK HALO CATALOG

- BOSS covers a huge volume (~2.3[(Gpc/h)^3]) with a high number density
  → high resolution with large box size simulation is mandatory!

- MULTIDARK WMAP5 cosmology (MDR1) Riebe et al. 2013

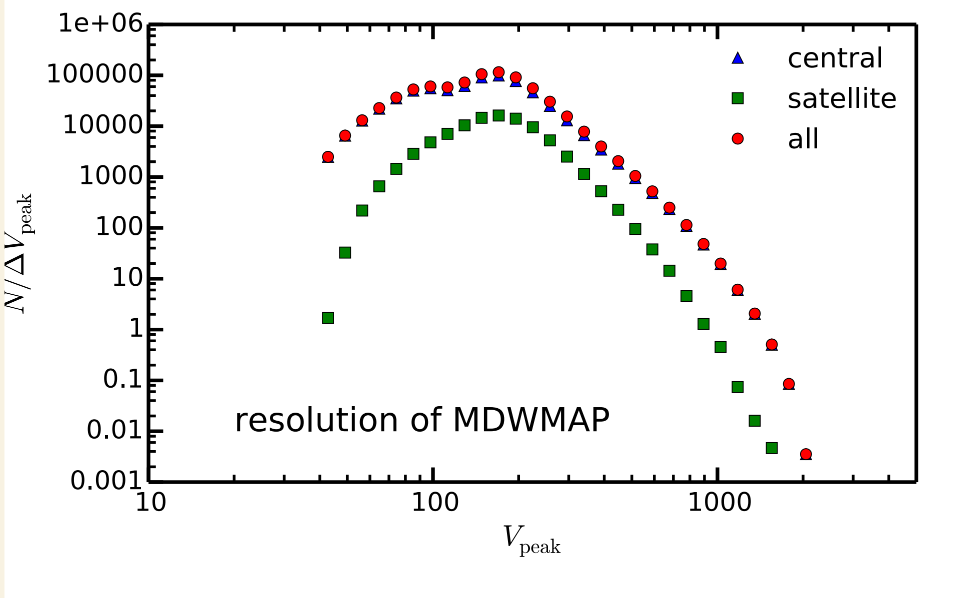
  - Lbox=1Gpc/h, N=2048^3

- ROCKSTAR subhalo finder Behroozi et al. 2013ab

  - utilizes 7D information (position, velocity and time)

  - one of the best subhalo finders Onions et al. 2013

  - halo merger trees are available



OBSERVATIONS

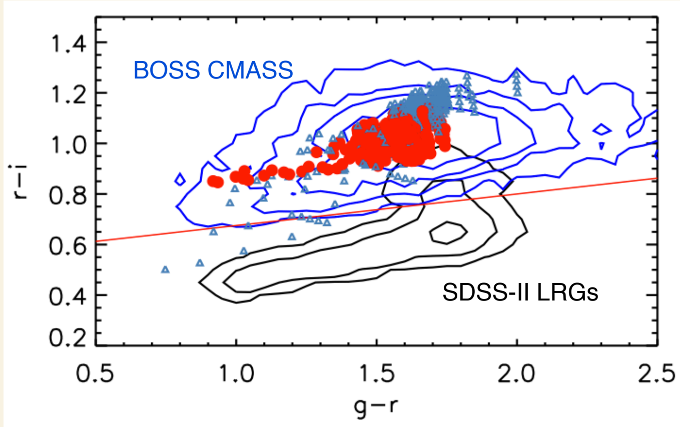
- Baryon Oscillation Spectroscopic Survey (BOSS)

  - a part of Sloan Digital Sky Survey III (SDSS-III, 2009-2014)

  - DR11 covers ~700,000 CMASS galaxies at $0.43<z<0.7$ in ~8,500deg^2

  - CMASS is designed to extend SDSS-II LRGs

BOSS CMASS w_p is the target statistics we want to model!



- We need a complete catalog!

  - CO-ADDS in Stripe 82 Annis et al. 2011, Jiang et al. 2014

  - SDSS photometry combined with UKIDSS near IR bands (over 149deg^2)

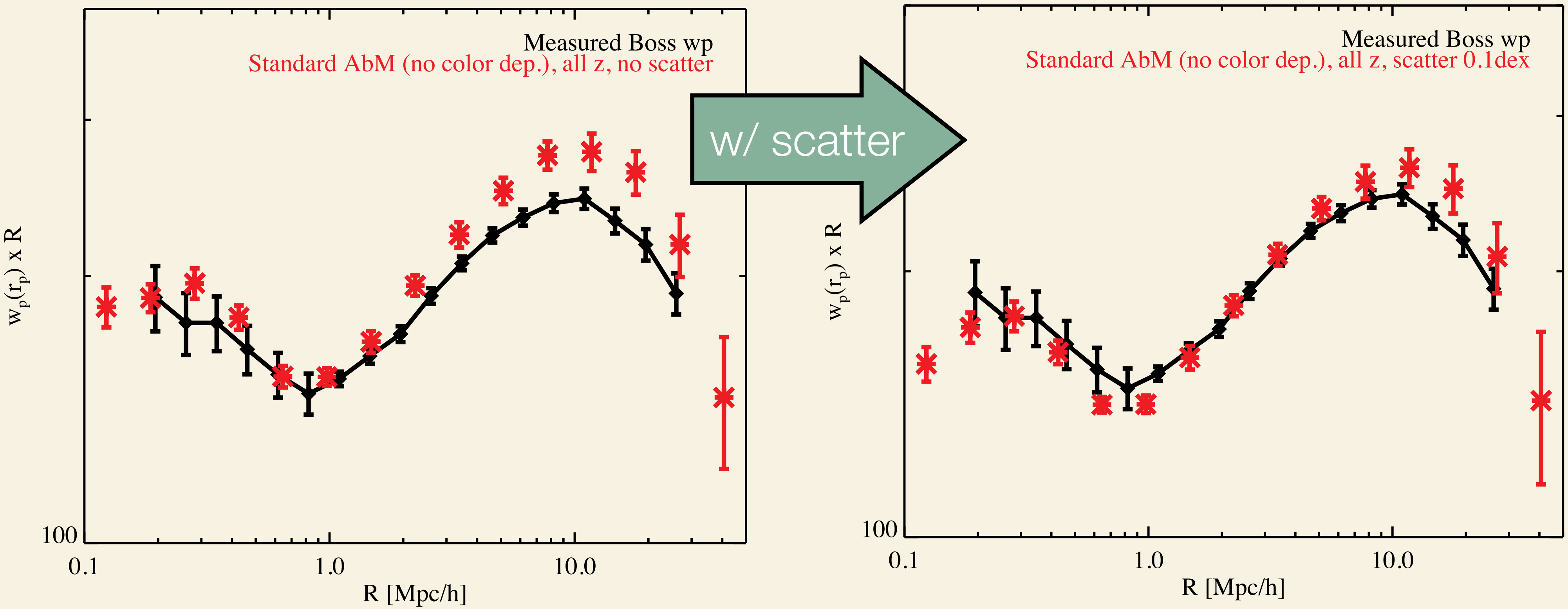
    better photo-z & stellar mass estimates Bundy et al., in prep

The complete catalog is used in abundance matching!

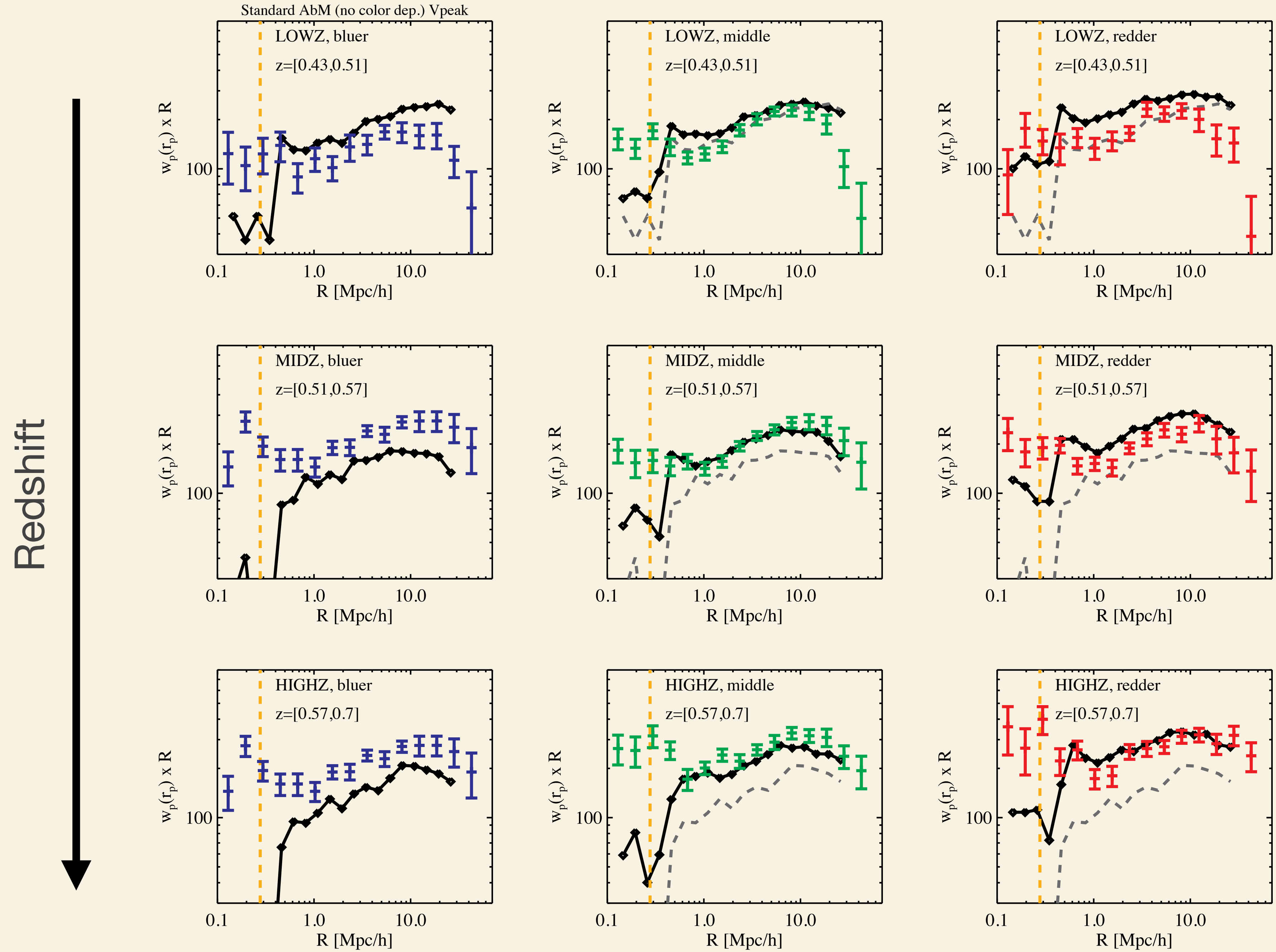
NORMAL ABUNDANCE MATCHING

- assign a galaxy with larger $V_{\rm peak}$ to a subhalo with larger M_*

- We assume the 'global' stellar mass function, and convolved with log-normal scatter with $\sigma_{\log M*} = 0.1$
  → could account for sample variance, photo-z errors etc.



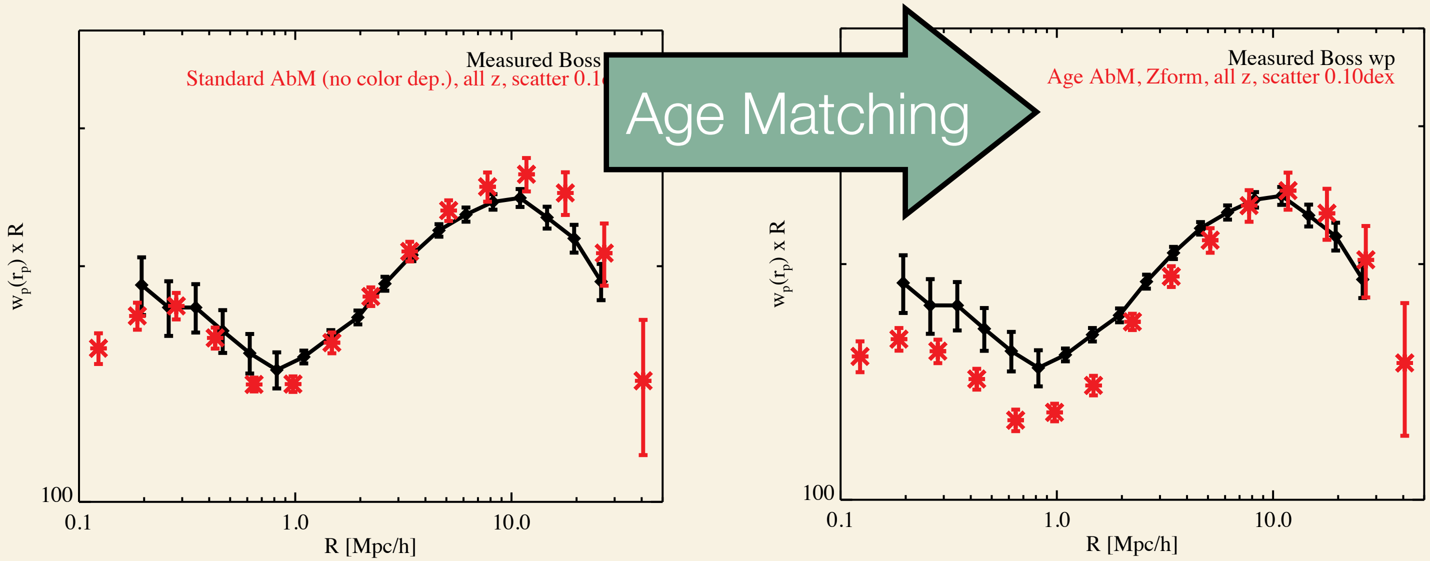
❖ assign other galaxy properties taken from (color, stellar mass)



black points: BOSS CMASS DR11 DATA

AGE MATCHING

- For a fixed M_*, assign a galaxy with larger $r - i$ to a subhalo with larger $c_{\rm vir}$

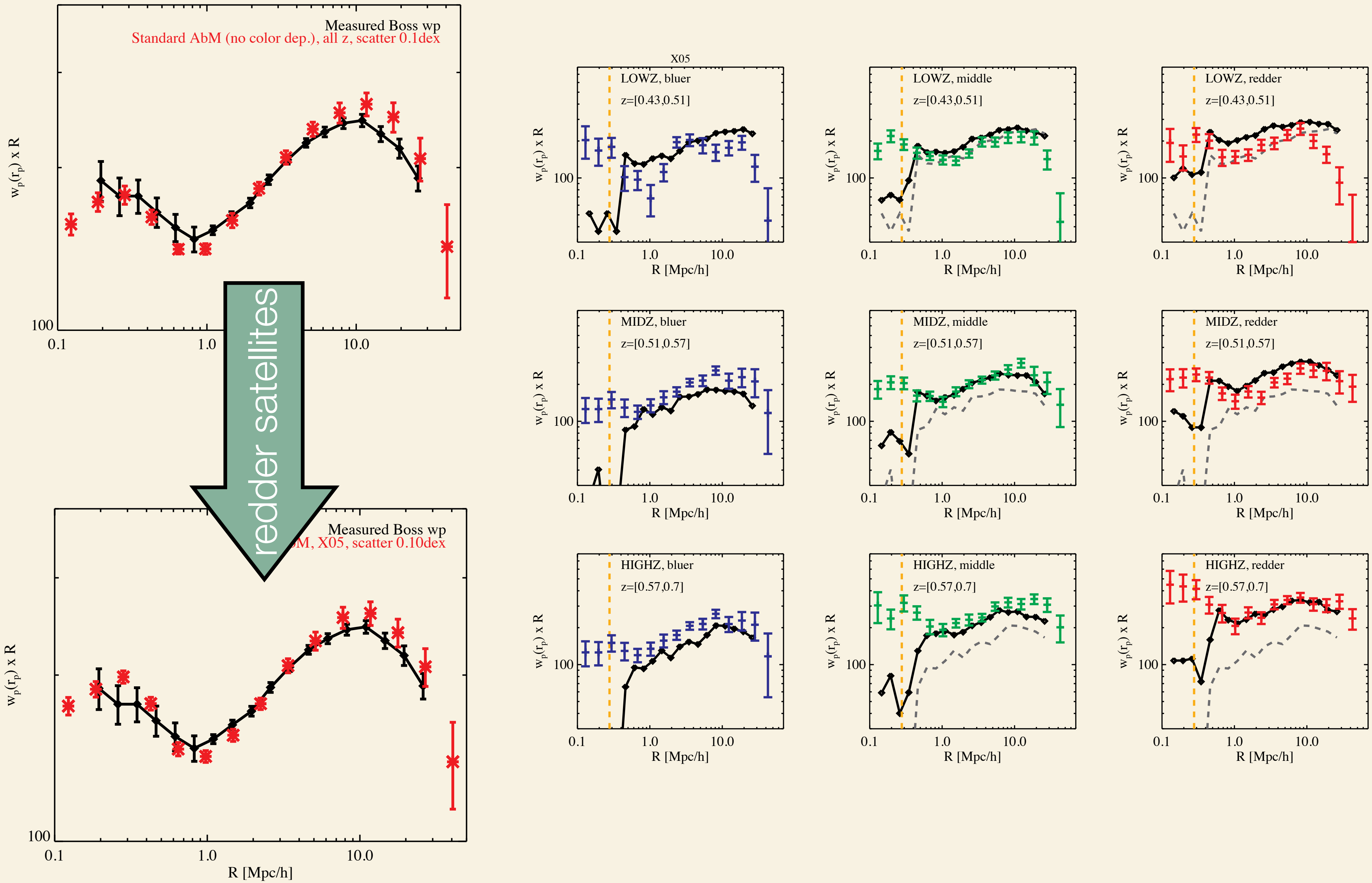


- For M >> M$_{\rm collapse}$, younger (lower $c_{\rm vir}$) halos more strongly clustered
- For M >> M$_{\rm collapse}$, younger halos live in dense environment, meaning that, at fixed M_*, satellites have lower concentration than centrals

Wechsler et al. 2006, Zentner 2007, Daral et al. 2008

- Age Matching puts *blue galaxies* as *less strongly clustered satellites*
  → This is an opposite direction from what we want

MAKE SATELLITES REDDER



SUMMARY

- Subhalo Abundance & Age Matching is a powerful way to model the galaxy-halo connection with fewer free parameters than HOD or SAM.

- We aim at modeling the BOSS CMASS galaxy clustering at 0.1-10 Mpc/*h*

- Normal Subhalo Abundance Matching

  - works well to predict the whole CMASS w_p

  - under-predict clustering of red, over-predict clustering of blue

- Age Matching

  - in this massive regime, the matching against concentration doesn't work

  - inversely, *making satellites redder* seems to be an answer

FUTURE PROSPECTS

- Questions I would like to ask the audience

  - physical argument of *making massive satellite galaxies redder*

  - velocity information should be available via RSDs Reid et al. 2014
    Guo et al. 2014

  - galaxy-galaxy lensing pushes smaller scale

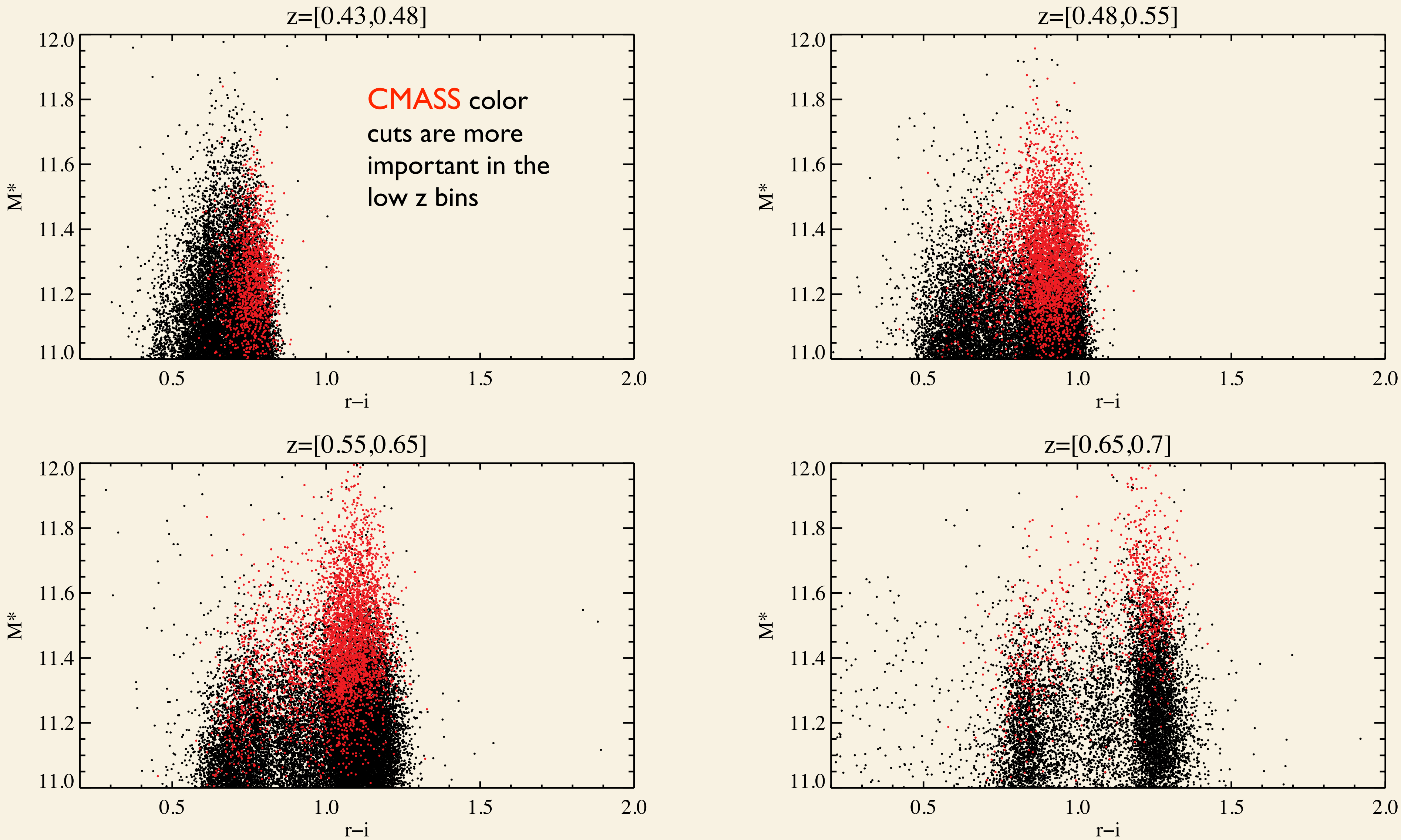
- Future prospects in 20's

  - a bunch of data is available
    photo-z (HSC, DES, LSST) + spec-z (PFS, DESI, Euclid)

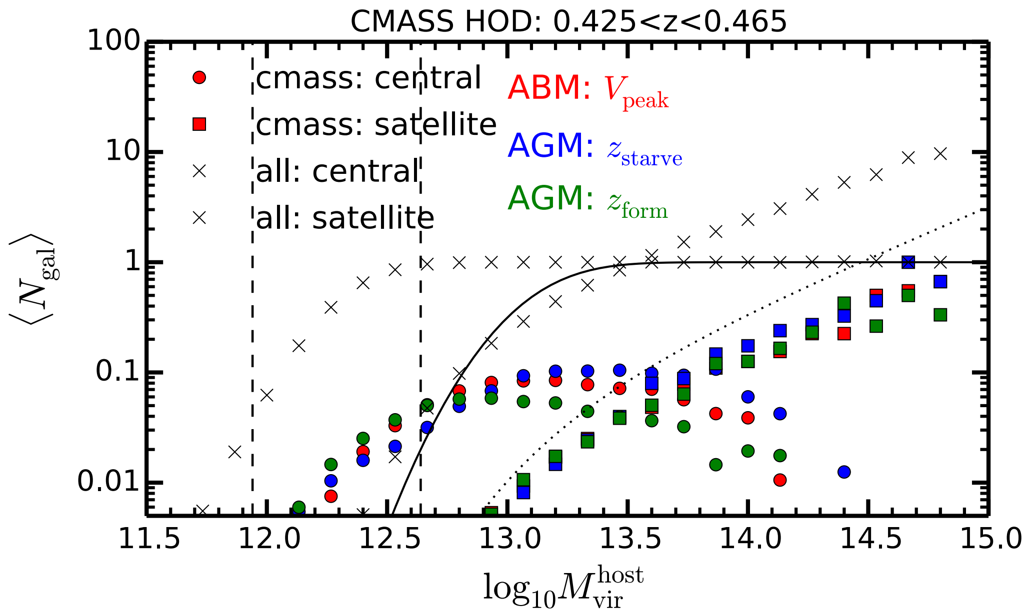
  - could establish the galaxy-halo connection model
    beyond mass (or HOD)! Tinker et al. 2013
    feedback to galaxy formation combined with simulation studies

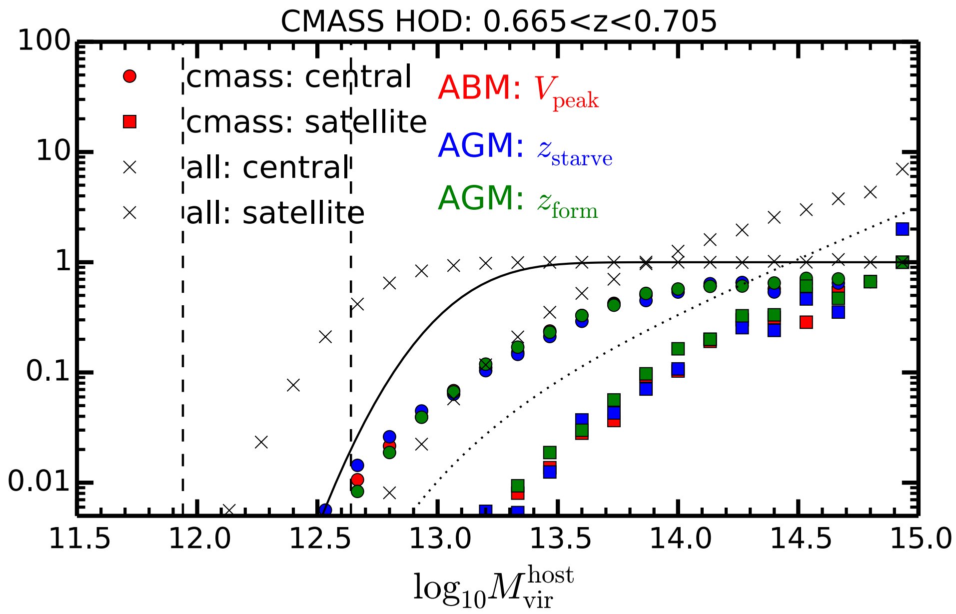
APPENDIX

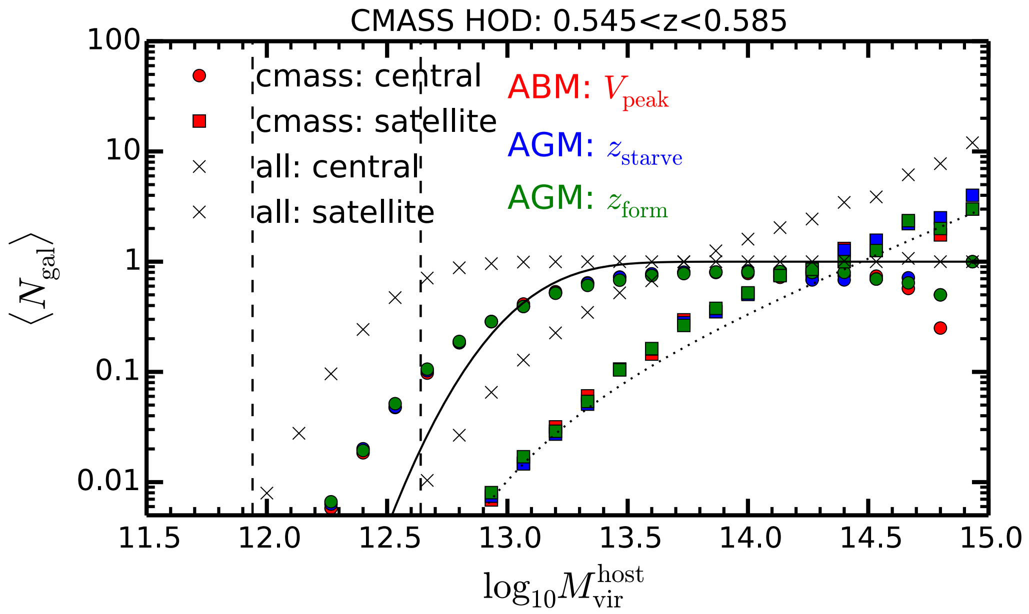
COLOR & COMPLETENESS



PREDICTED HOD







- HOD functional form

$$N_{\rm cen}(M) = \frac{1}{2}\,{\rm erfc}\left[\frac{\ln(M_{\rm cut}/M)}{\sqrt{2}\sigma}\right]$$

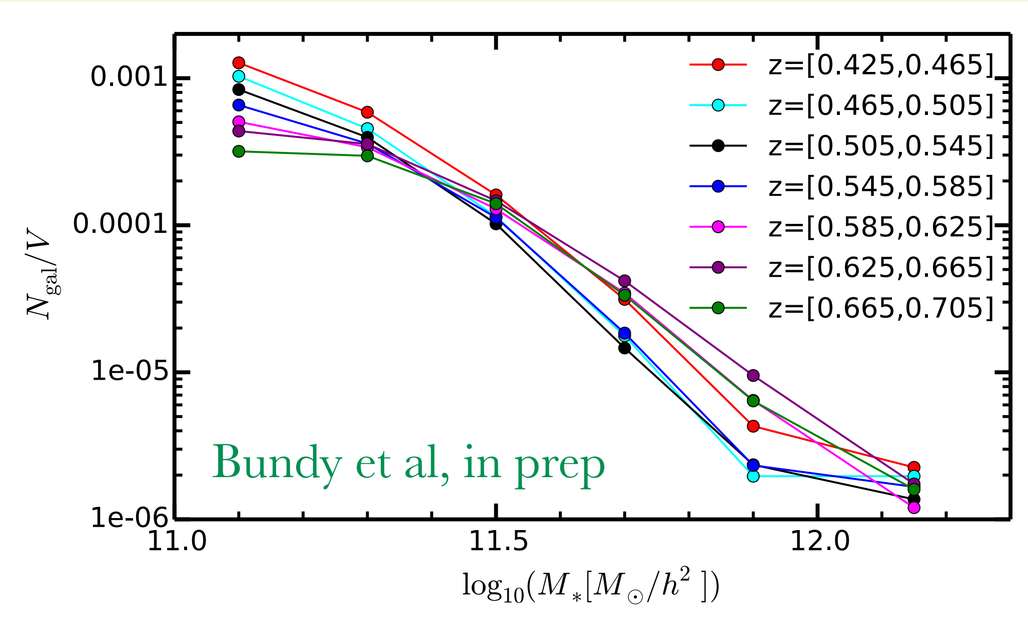
$$N_{\rm sat}(M) = N_{\rm cen}\left(\frac{M - \kappa M_{\rm cut}}{M_1}\right)^{\alpha}$$

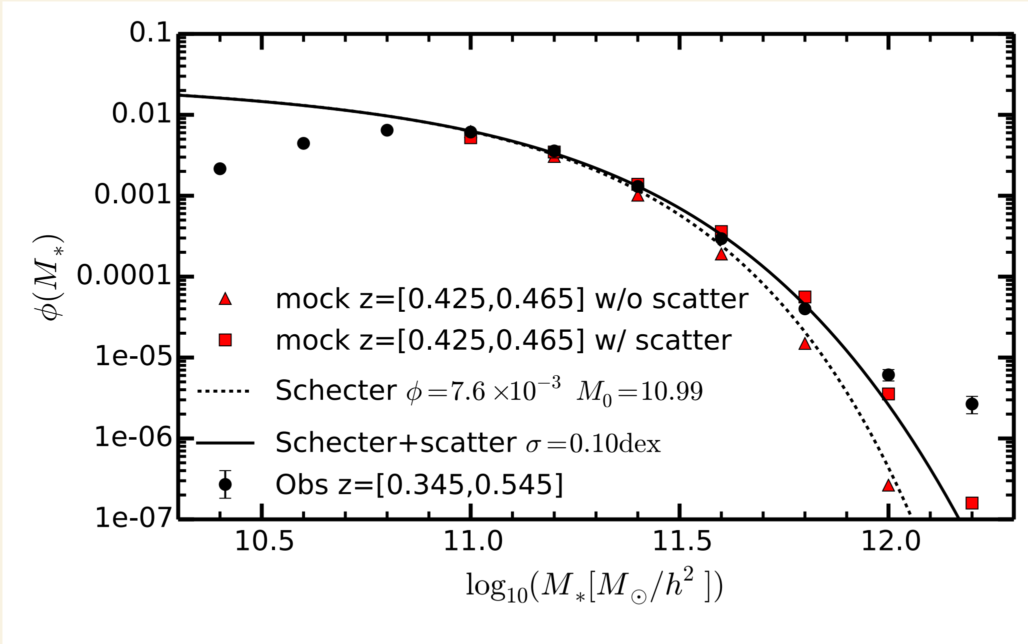
SCATTER IN ABM

- Sample variance in the observed SMF can be reduced by introducing scatter

  Behroozi et al. 2010, Reddick et al. 2012

- We assume the observed SMF is a 'global' one convolved with $\sigma_{\log M*} = 0.1$
  - The global SMF is fitted with the Schecter function Lin & White 2009
  - Abundance Matching is done against the global SMF

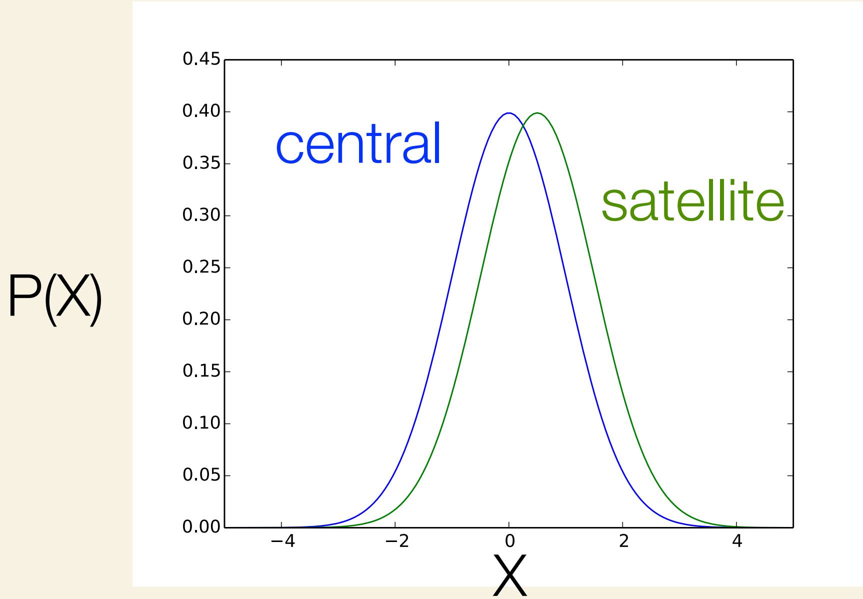




ARTIFICIAL EXPERIMENT

- In order to see how well making satellite only redder works, we did the following experiment.

- We artificially prepare the halo property 'X' whose distribution is Gaussian but satellites has bigger mean (μ=0.5 with σ=1.0).



- Then do Age Matching against 'X'. Again note that this is not base on physics and just an artificial experiment.
- We call this the "X0.5" model. μ can be tweaked to match small scale clustering.