Modeling small-scale 3D clustering of the BOSS CMASS galaxies

斎藤 俊

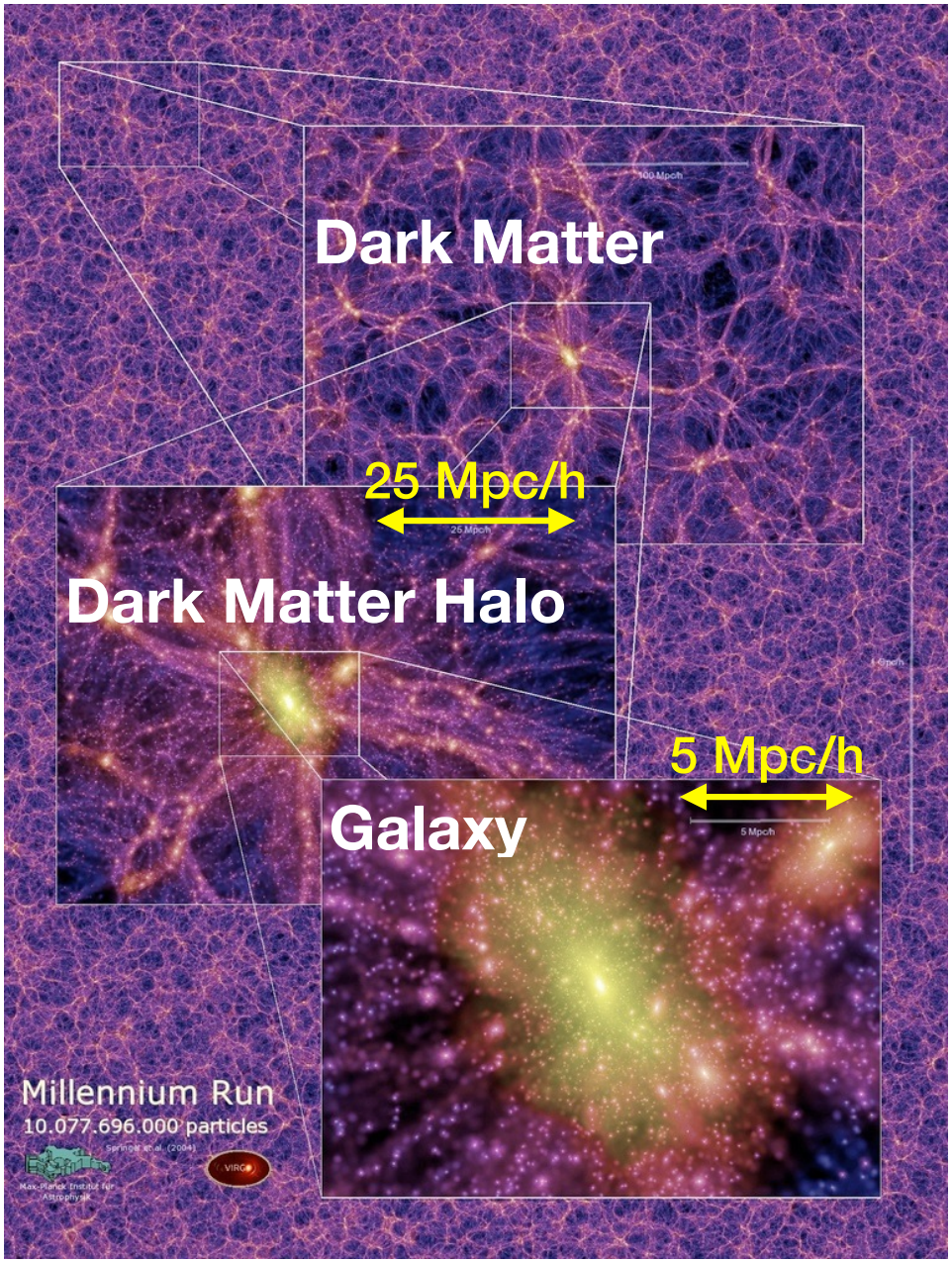
東京大学 カブリ数物連携宇宙研究機構

SS, Leauthaud, Hearin+, submitted to ApJ, arXiv:1509.00482.
Leauthaud, Bundy, **SS**+, submitted to MNRAS, arXiv:1507.04752.
Bundy, Leauthaud, **SS**+, submitted to ApJS, arXiv:1509.01276.
SS, Leauthaud, Hearin+, in prep.
Campbell, **SS**, Hearin+, in prep.

第４回観測的宇宙論ワークショップ@京都大学基礎物理学研究所

2015年11月20日(金)

Galaxies in the Large-Scale Structure



[Textbook: Mo, van den Bosch, White (2010)]

How galaxies spatially gather?

= 3D Galaxy Clustering

LARGE Scale O(10-100Mpc)

trace the DM distribution

- ruled by Gravity

Small Scale O(0.1-1Mpc) ★

galaxy distribution within a virial radii of a DM halo

- Gravity + Baryon physics

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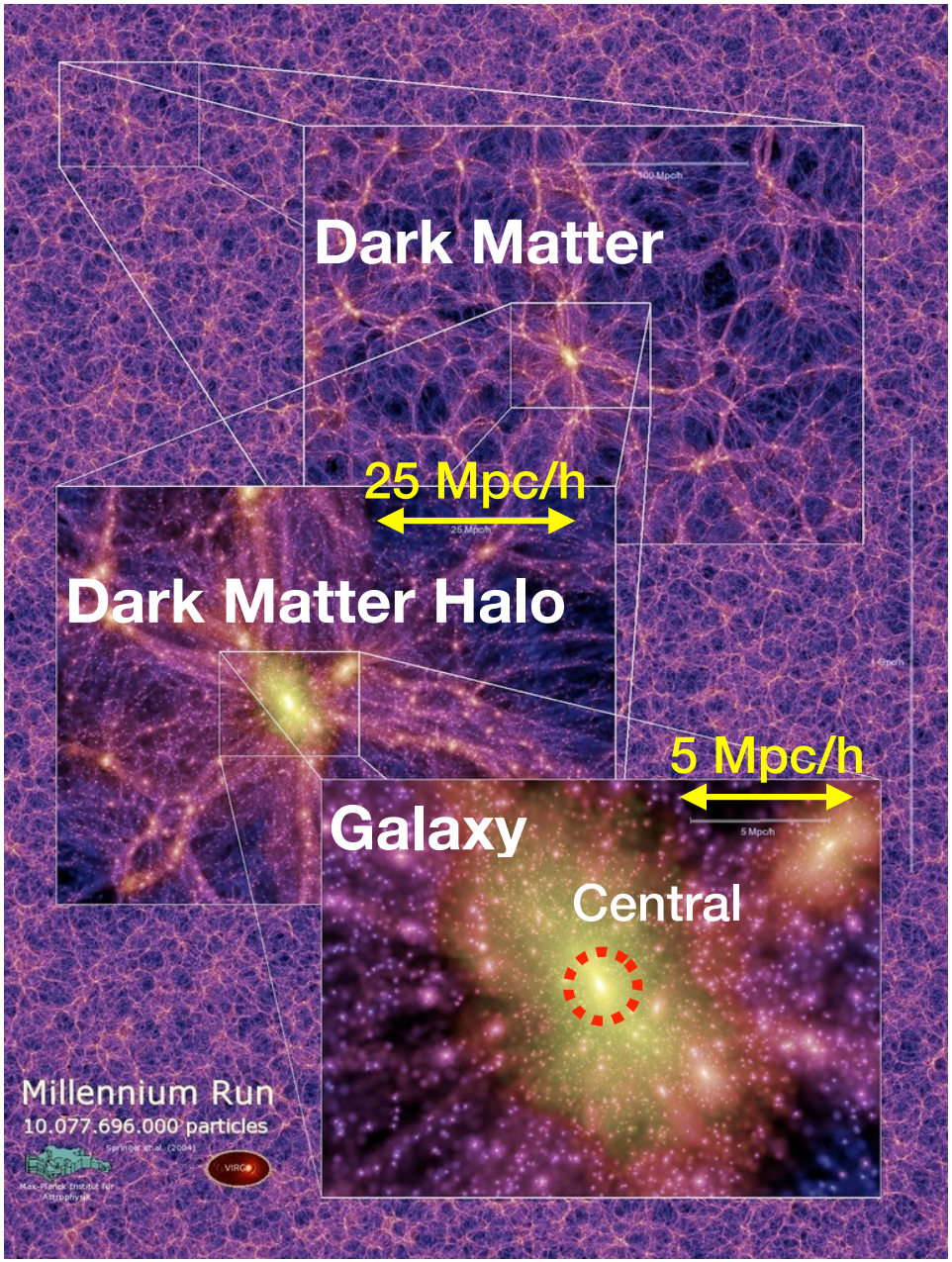

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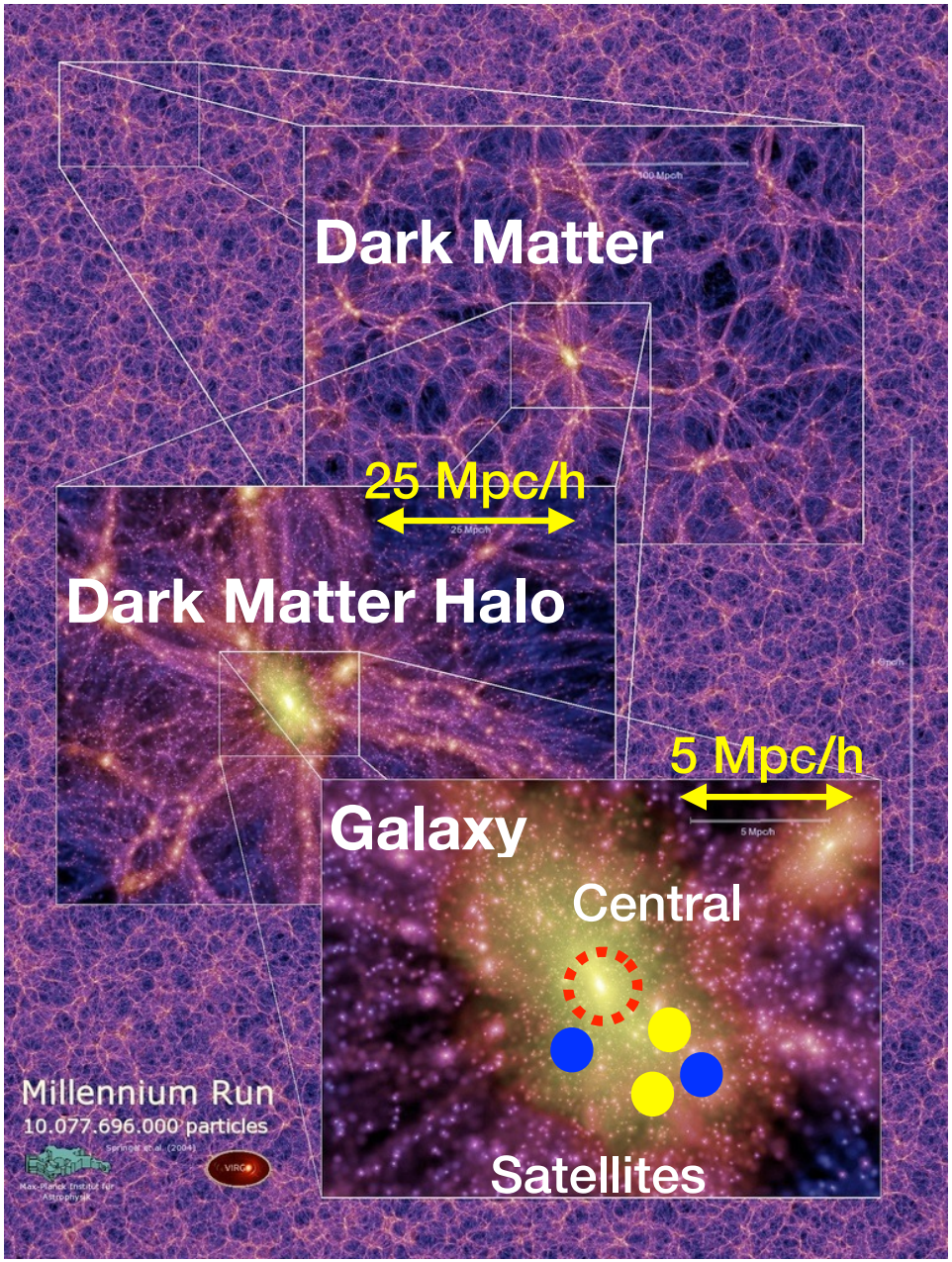

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Measurable Statistics

✦ **2-point statistics:** require more sample than 1pt

- $\xi(\mathbf{s})$: 3D *2pt correlation function* $\quad dP_{12} = \bar{n}^2[1 + \xi(\mathbf{x_1} - \mathbf{x_2})]dV_1 dV_2$

- $\Delta\Sigma(r_\mathrm{p})$: galaxy-galaxy lensing

For convenience,

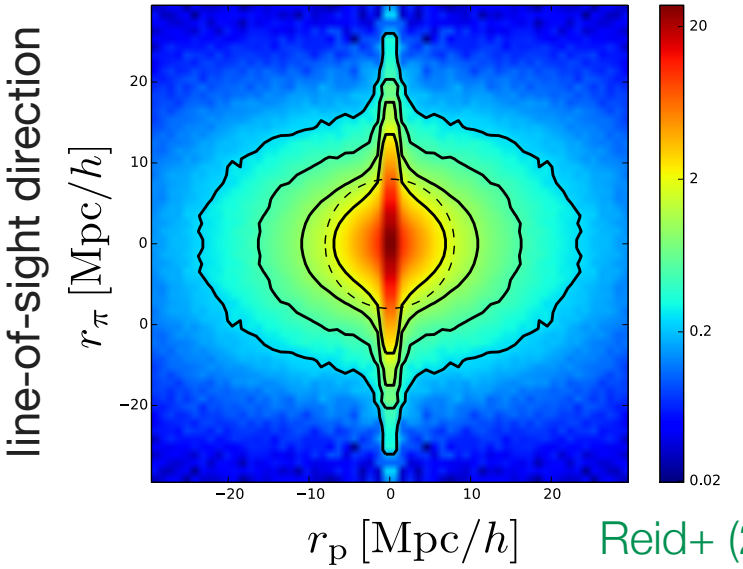
projected correlation function

$$w_p(r_p) = 2\int_0^{r_{\pi,\mathrm{max}}} dr_\pi\, \xi(r_p, r_\pi)$$

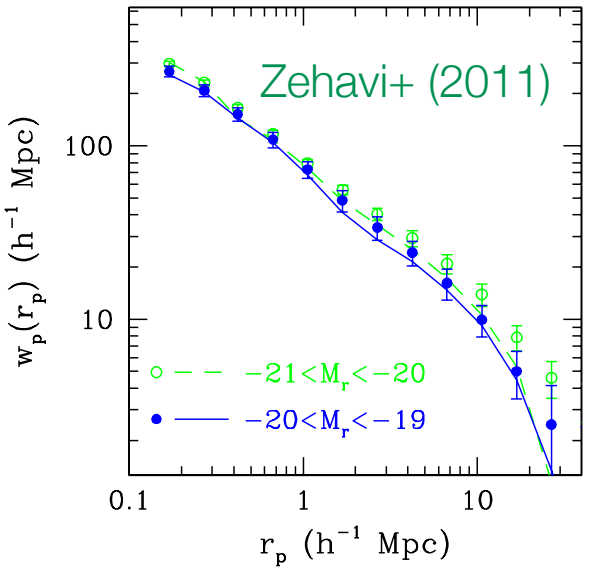
multipole

$$\xi_\ell(s) = \frac{2\ell+1}{2}\int_{-1}^{1} d\mu\, \xi(s,\mu)\mathcal{L}_\ell(\mu)$$

$$s^2 = r_\mathrm{p}^2 + r_\pi^2,\ \mu = \frac{r_\pi}{s}$$



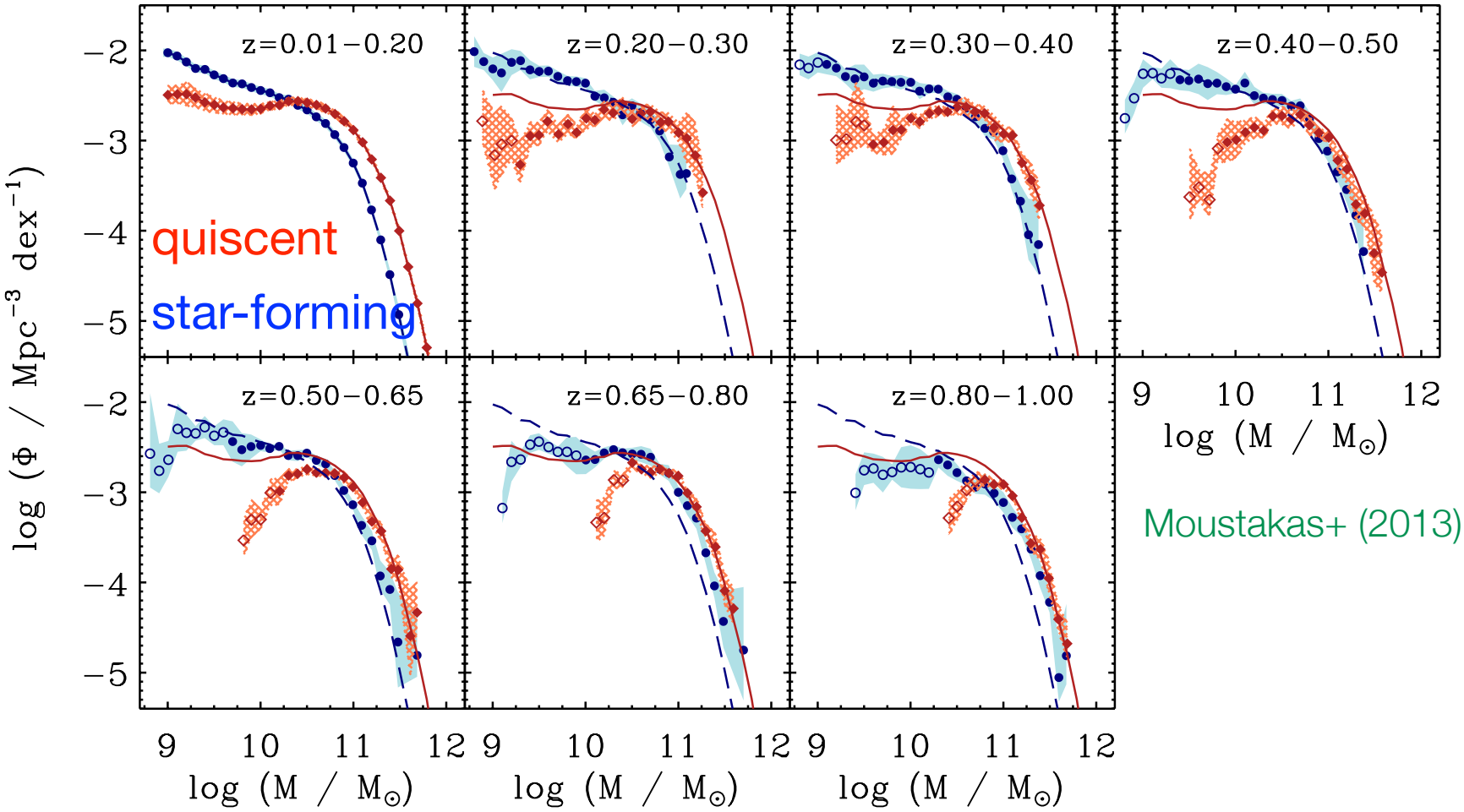
Reid+ (2014)



Measurable Statistics

✦ **1-point statistics:** statistically easy to measure!

- dN/dz: redshift distribution
- $\phi(M_*)$: ***Stellar Mass Function***: typically ~0.1-0.2dex uncertainty



Moustakas+ (2013)

Galaxy-Halo Connection

✦ **Impossible** to perform hydro simulations in a cosmological volume

- state-of-the-art ***Illustris*** L_{box}=70 Mpc/h c.f.: BOSS V_{survey} ~3(Gpc/h)^3
  Nelson+ (2015)

– ***phenomenological*** way to connect observed gals to halos in *N*-body

- *important even in cosmology* to construct a “realistic” mock catalog

✦ **3 major effective models for galaxy-halo connection**

- Semi-Analytic Model (SAM)

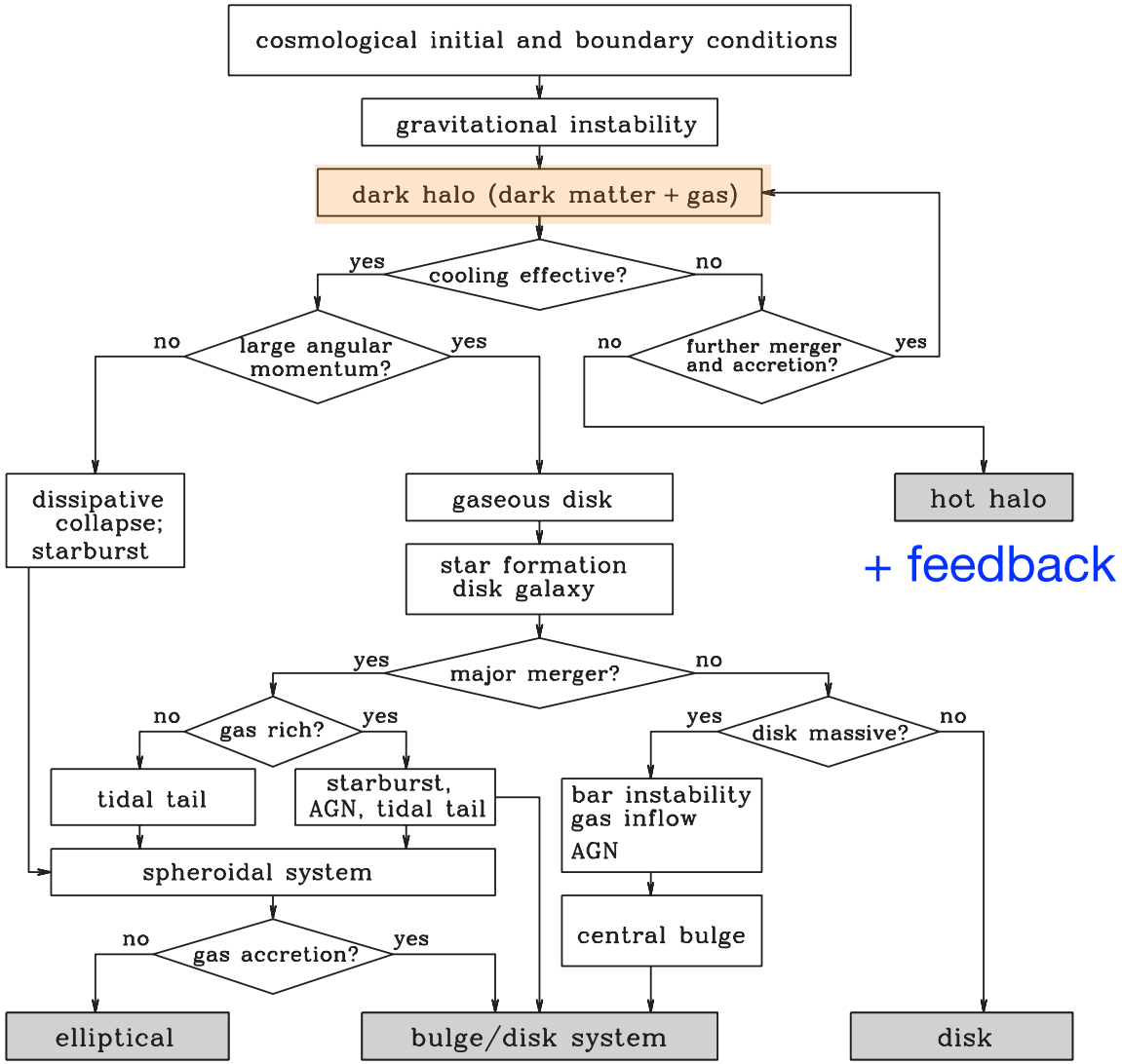
- Halo Occupation Distribution (HOD)

- Subhalo Abundance Matching (SHAM)

Semi-Analytic Model

✦ Introduce baryon physics in halo merging history

but MANY free parameters: e.g., Benson (2012, 2014), Lu et al. (2014) etc



+ feedback

Mo, van den Bosch, White (2010)

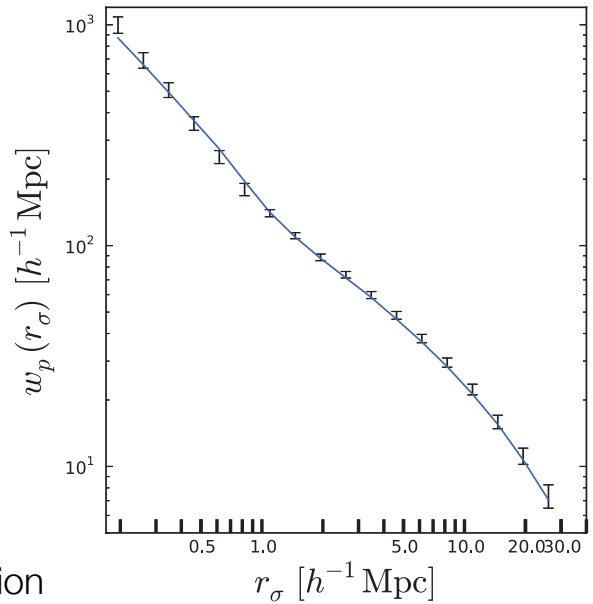
Halo Occupation Distribution (HOD)

✦ The most popular method to link galaxies with halos. Berlind & Weinberg (2002) etc

✦ How it works:

1) assume a functional form P(N_{gal}|$\mathbf{M_{halo}}$) for central and satellite HODs
2) determine the HOD parameters to reproduce
   or 3D correlation function or gal-gal lensing
3) randomly down sample to reproduce dn/dz

$$w_p(r_p) = 2\int_0^{r_{\pi,\max}} dr_\pi\, \xi(r_p, r_\pi)$$



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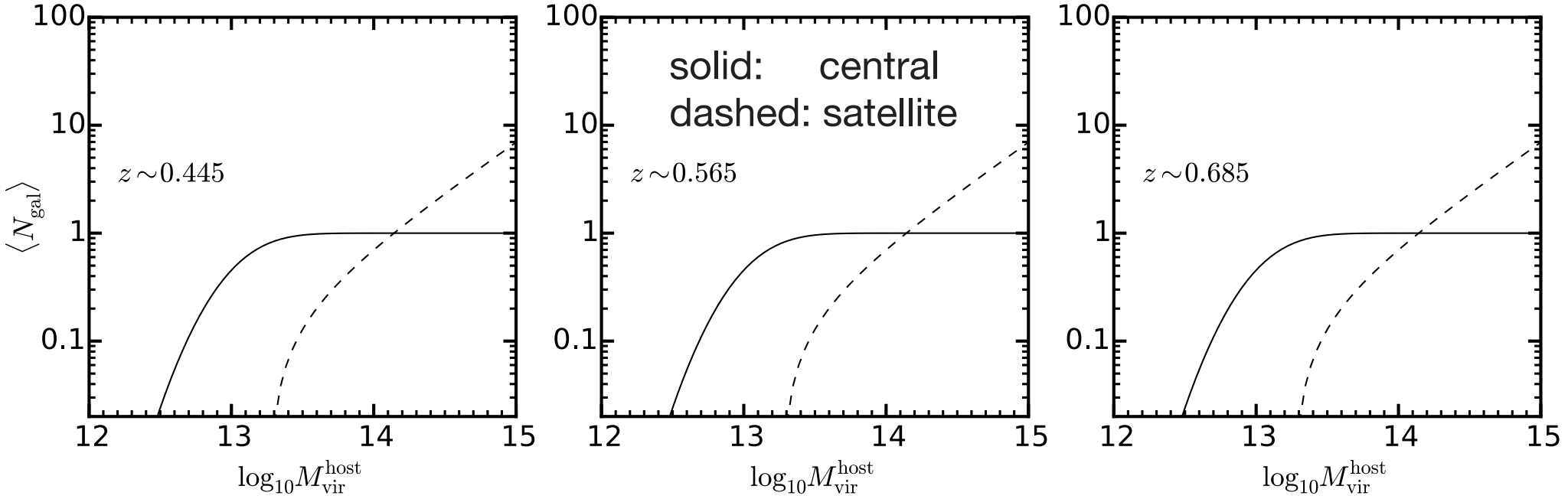

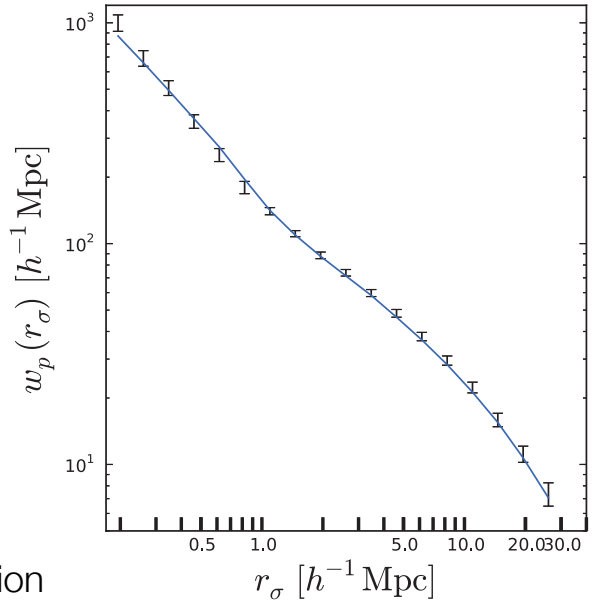

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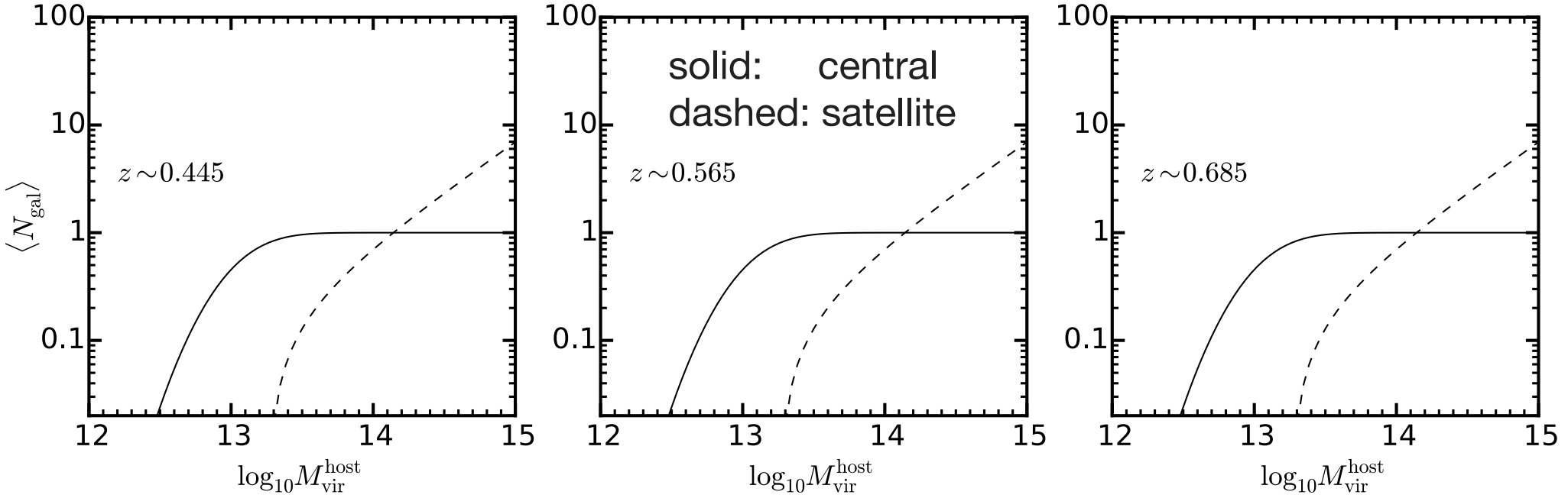

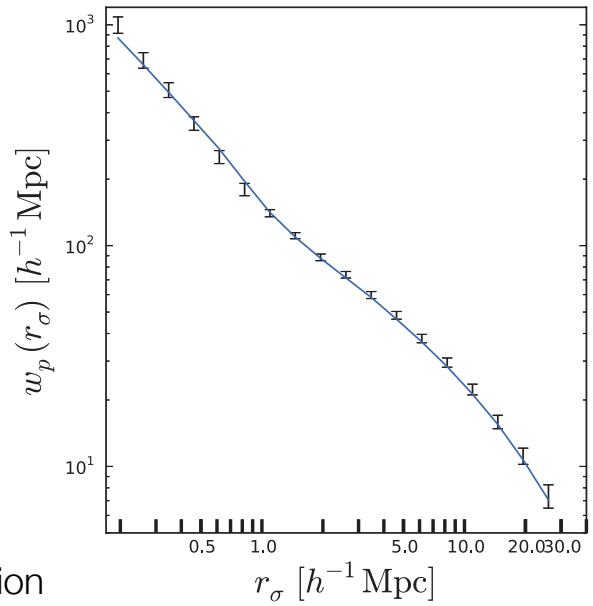

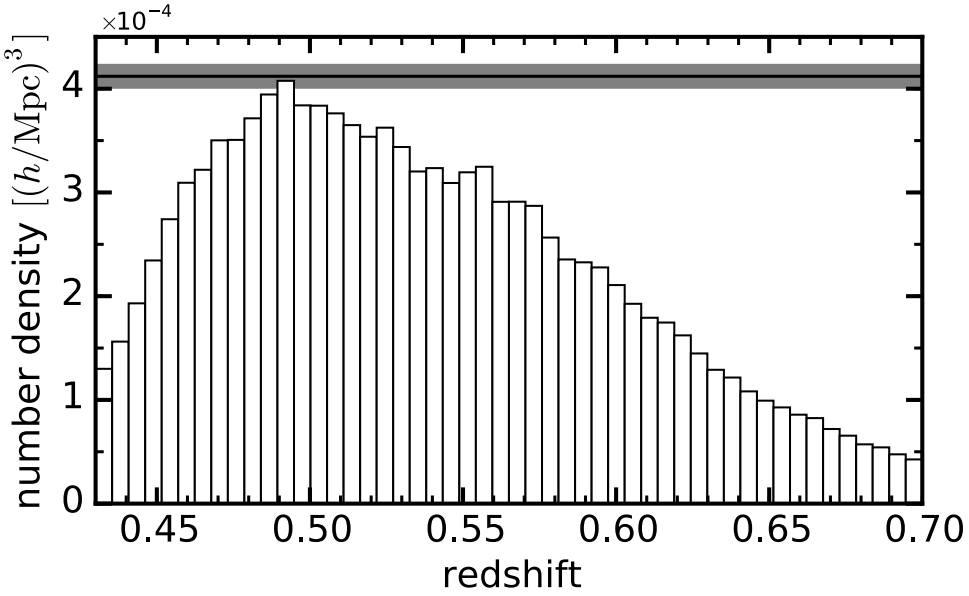

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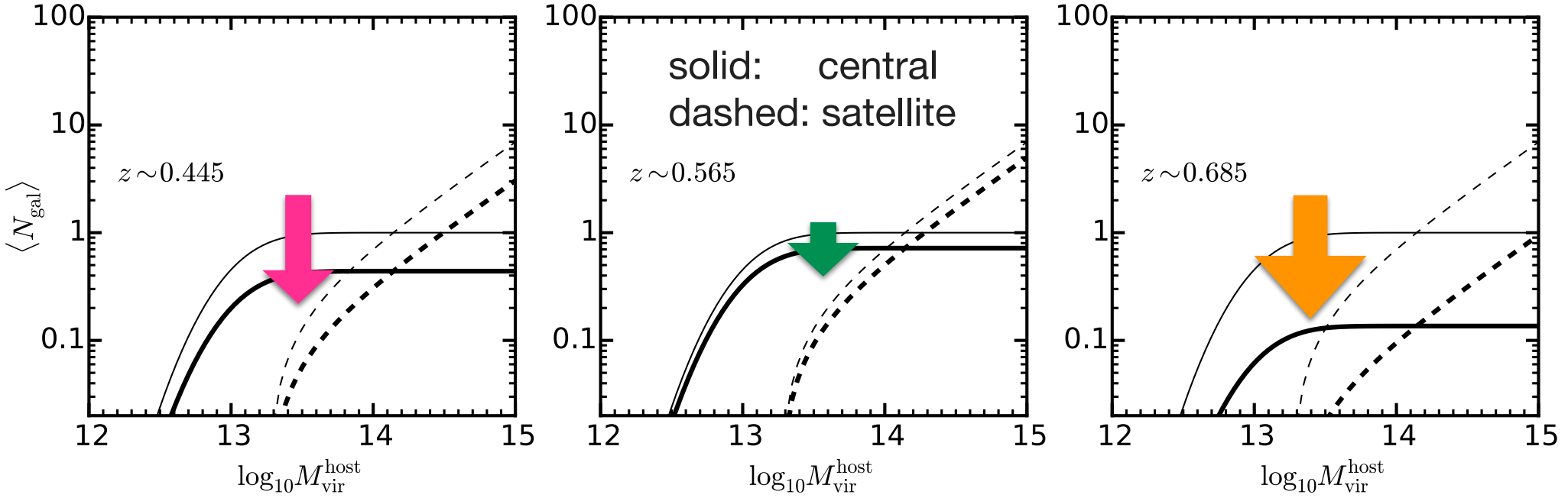
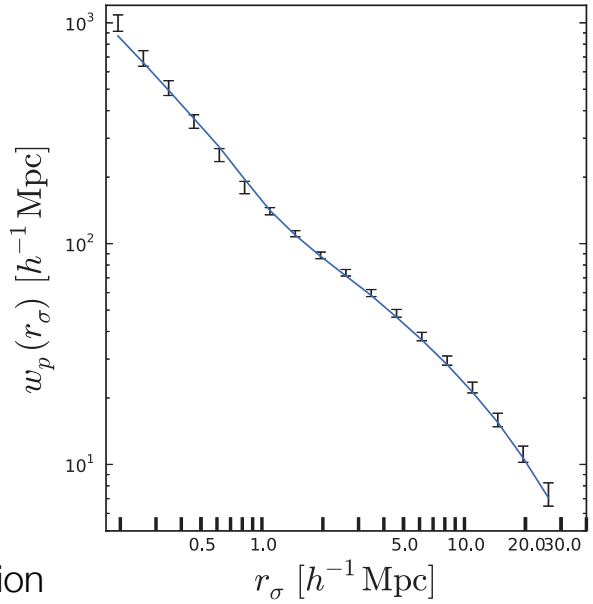
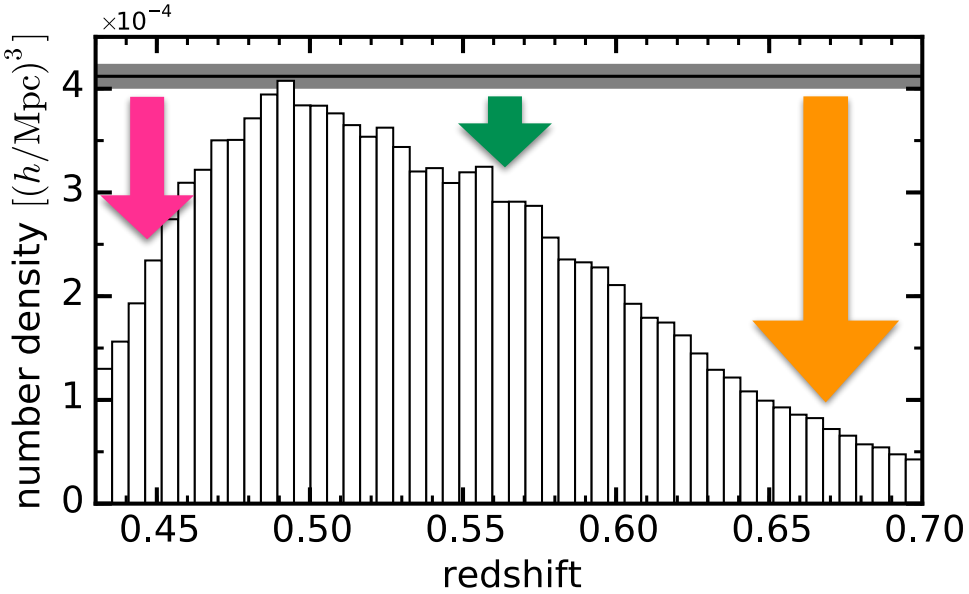






Subhalo Abundance Matching (SHAM)

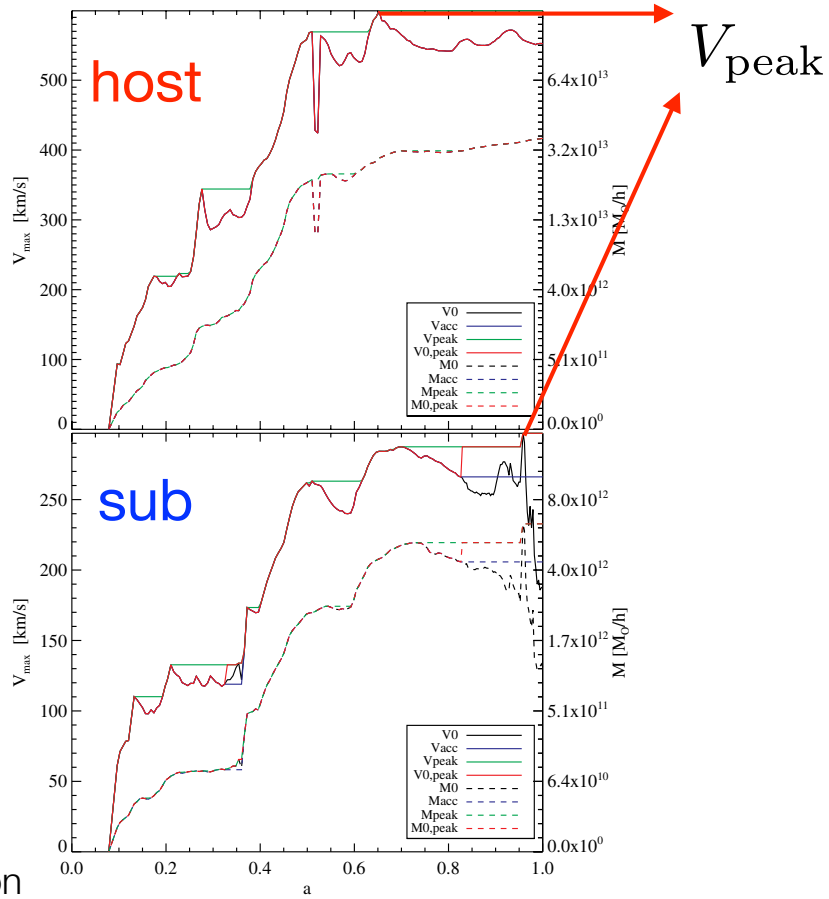
✦ **The Subhalo Abundance Matching (SHAM)** e.g. Kravtsov et al. (2004) etc

*"a **brighter galaxy** tends to be hosted by a **more massive (sub)halo**"*

$$n_{\rm gal}(>M_*) = n_{\rm halo}(>V_{\rm peak})$$

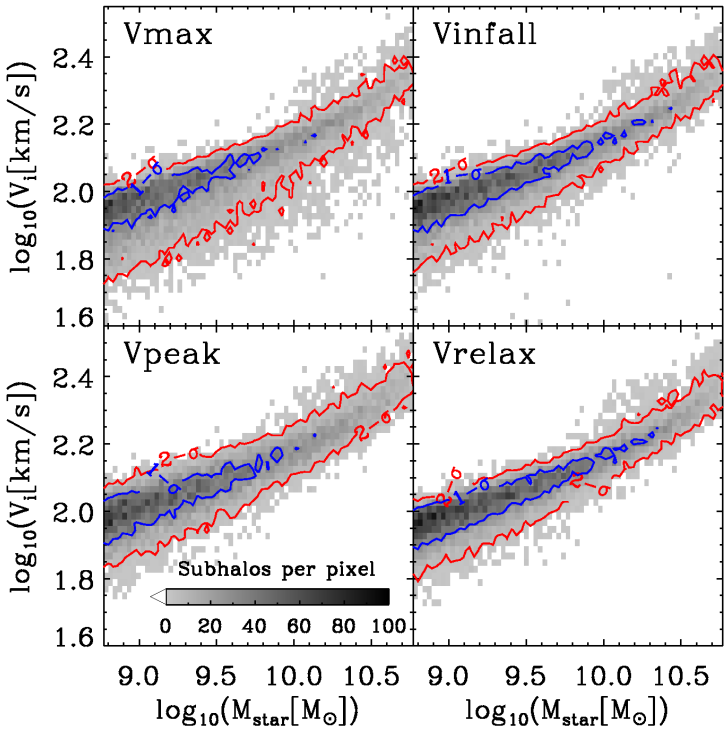
✦ Typical mass history of subhalos

Reddick et al. (2013)



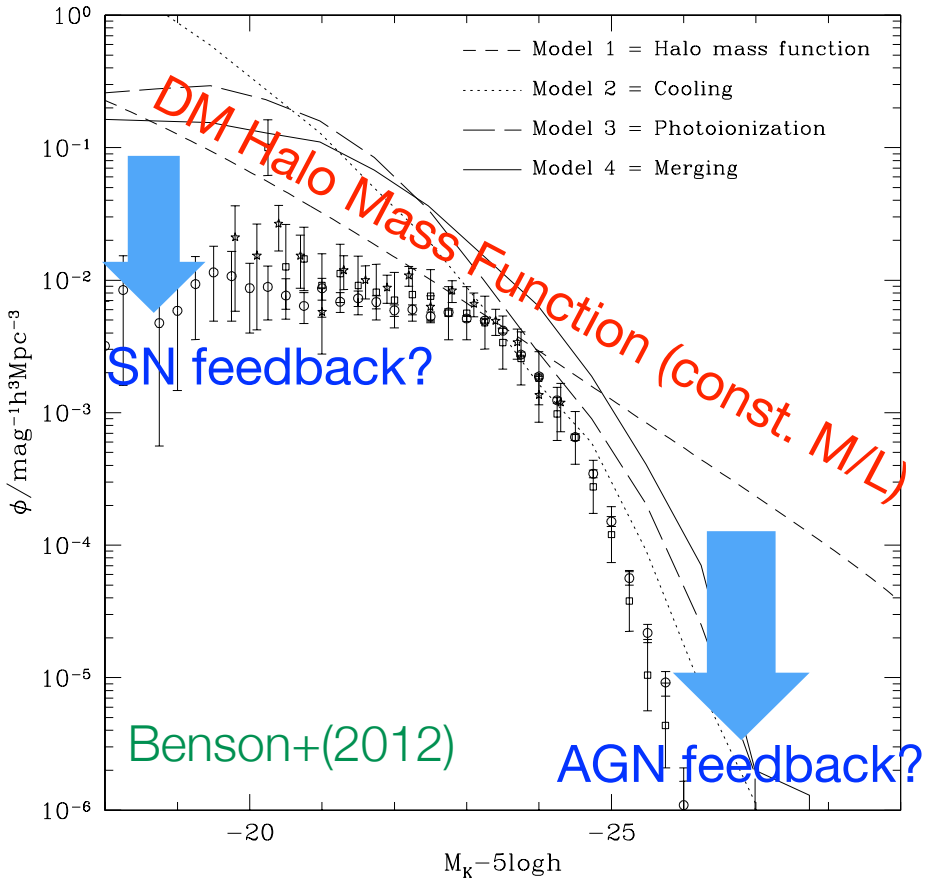
✦ works very well in hydro sim.

EAGLE Chaves-Montero et al. (2015)

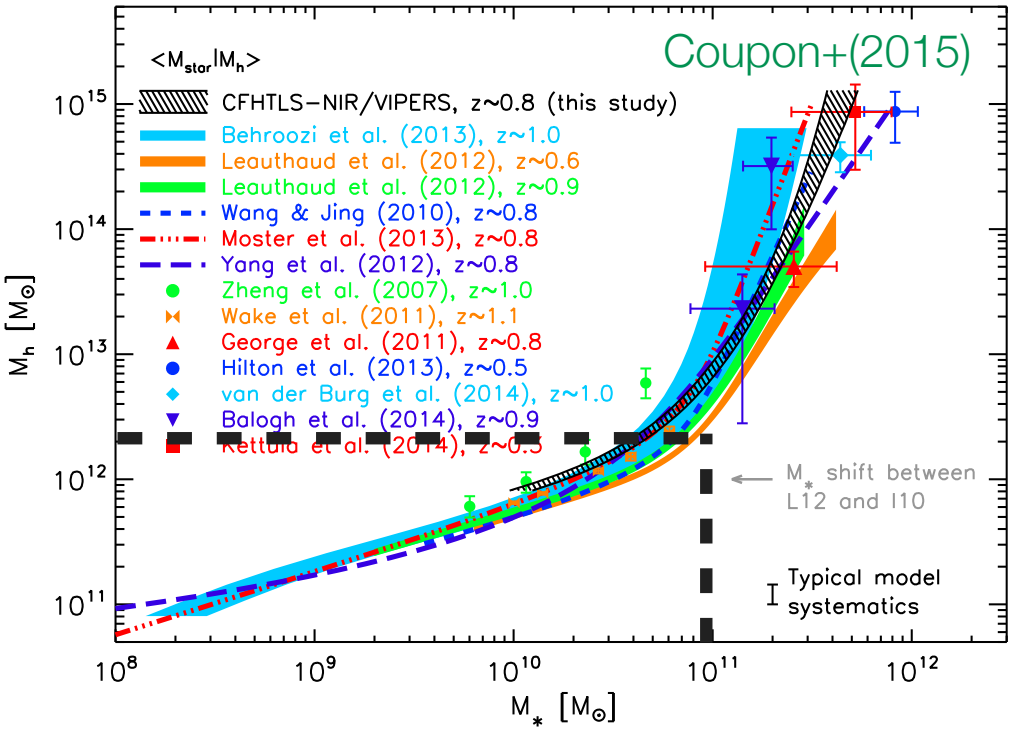


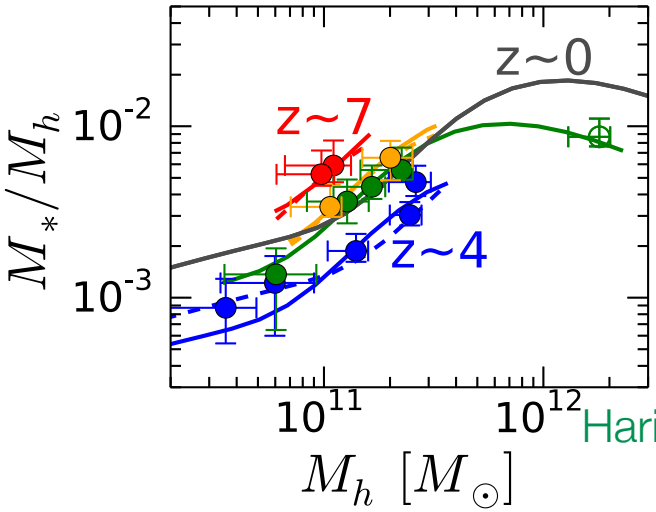
Stellar-to-Halo Mass Relation (SHMR)

✦ A simple model



✦ observation (+HOD/SHAM)





Harikane, **SS** (2015)

Star Formation is most efficient around Milky-Way size galaxy.

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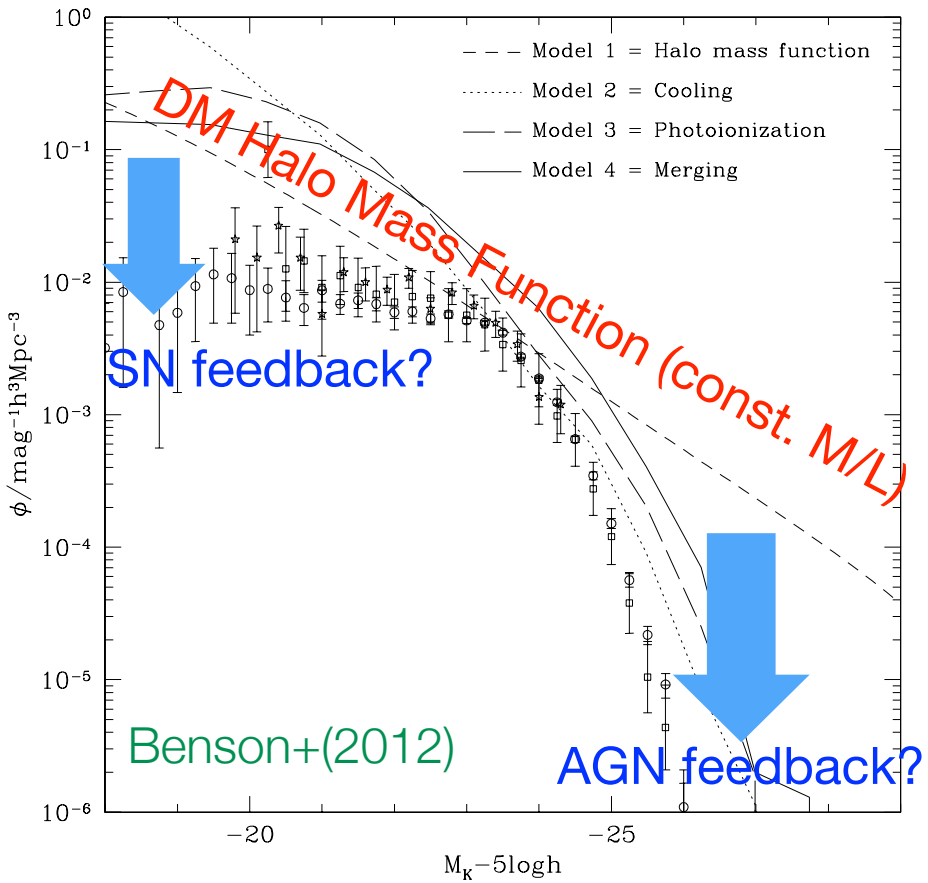

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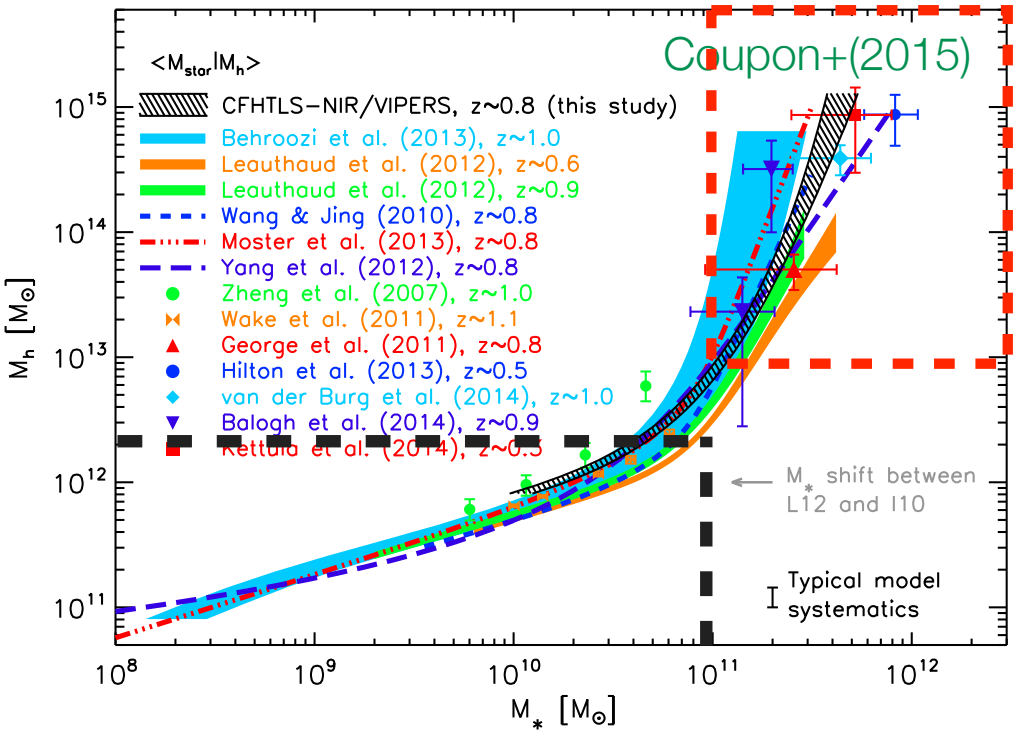

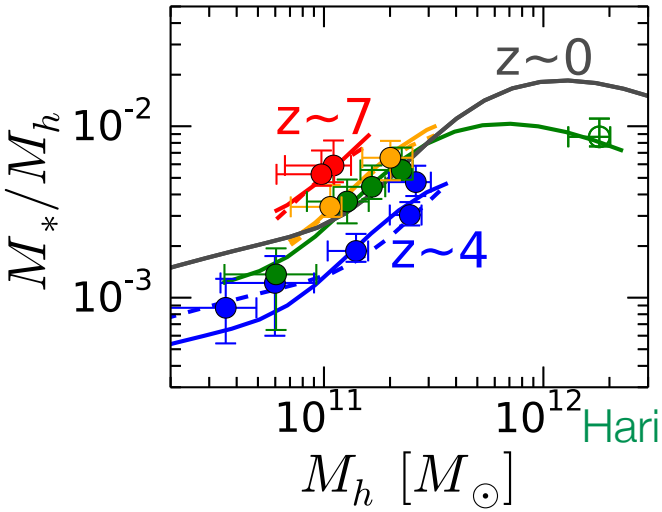

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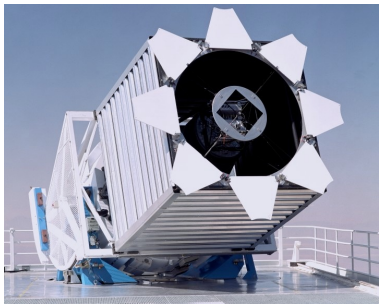
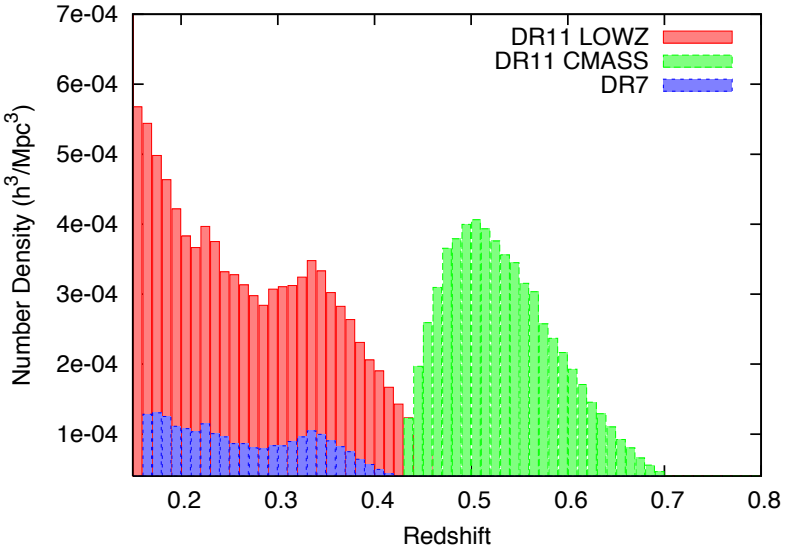
The BOSS CMASS sample



✦ **The Baryon Oscillation Spectroscopic Survey (BOSS)**

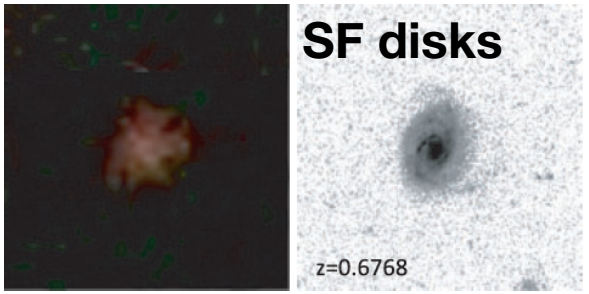
- a part of SDSS-III (2009-2014) Eisenstein et al. (2011)
- Two main cosmological samples:

  LOWZ (z~0.32) & **CMASS** (z~0.57)



✦ **CMASS** : ***"Constant Stellar Mass" sample***

- redshift range: **0.43 < z < 0.70**
- DR12: 836,347 galaxies over 10,252 deg^2
- designed to be *complete* at $\log(M_*/M_\odot) \gtrsim 11.3$ Maraston et al. (2013)
- not all dead and red
  - ~25% has a SF disk Masters et al. (2011)
  - ~37% belongs to an intrinsically blue cloud Montero-Dorta et al. (2014)



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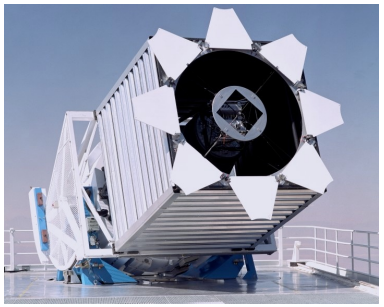

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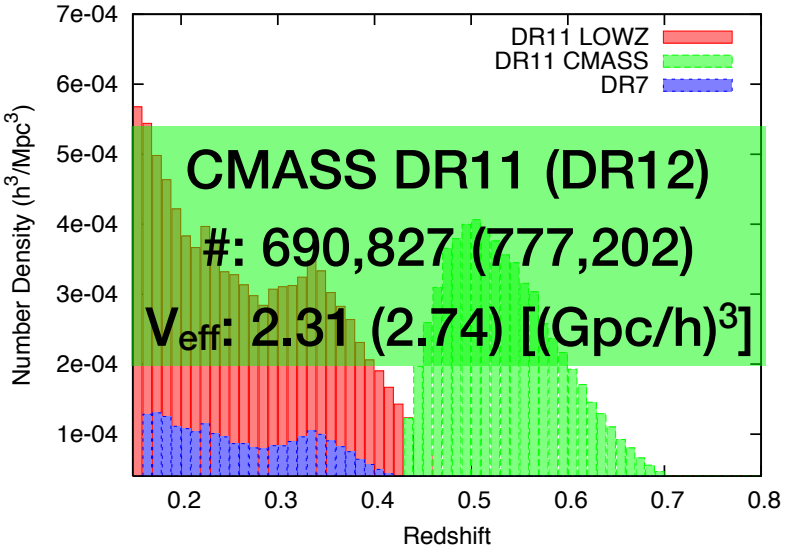

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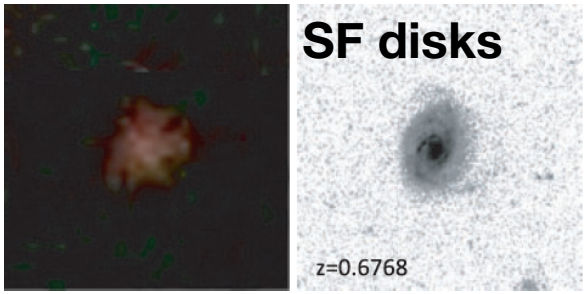
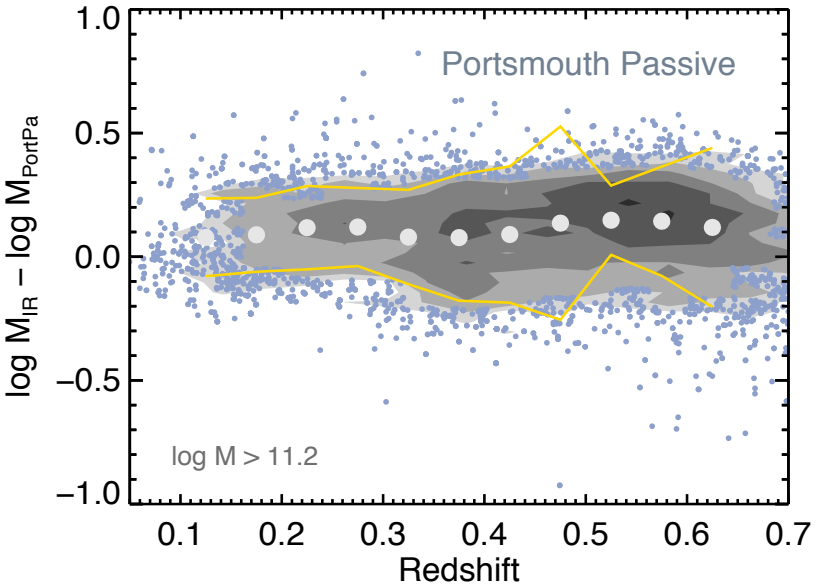


Stripe82 Massive Galaxy Catalog (S82MGC)

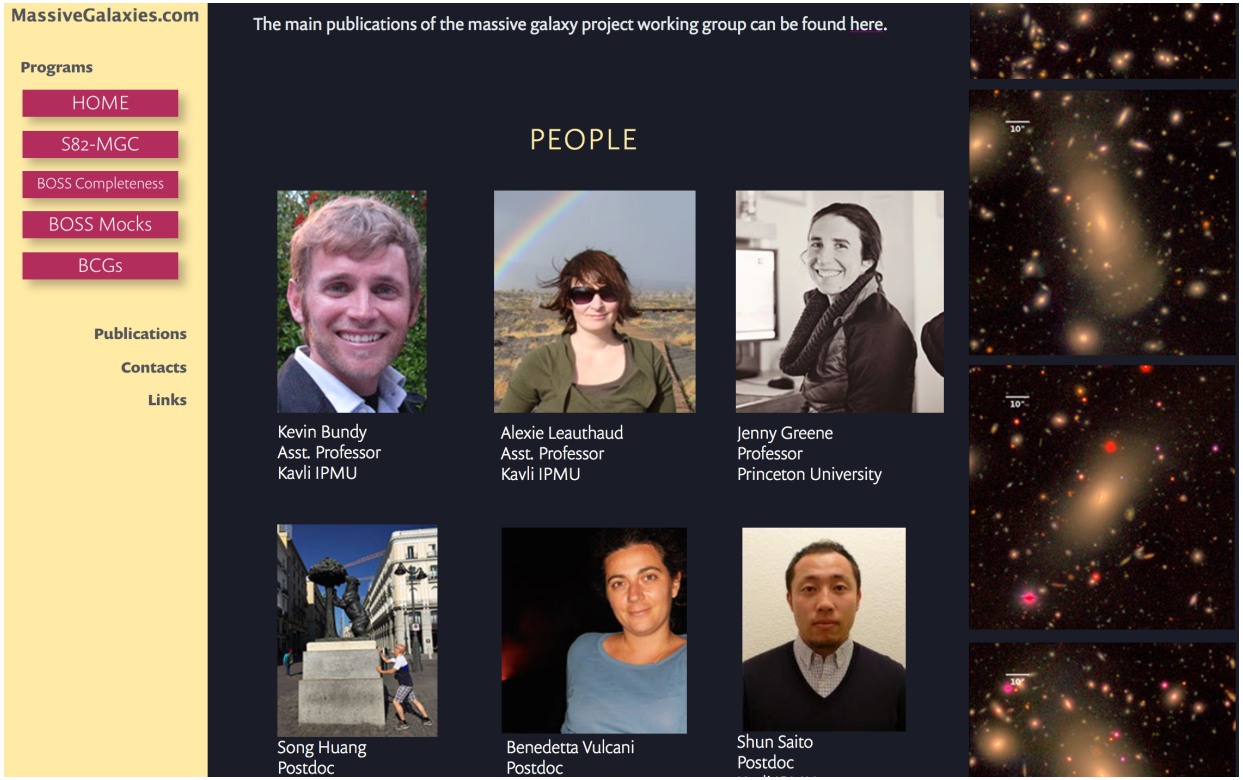
Bundy, Leauthaud, **SS**+ (2015)

- SDSS Co-Adds photometric catalog (~2mag deeper) over 139.4 deg^2

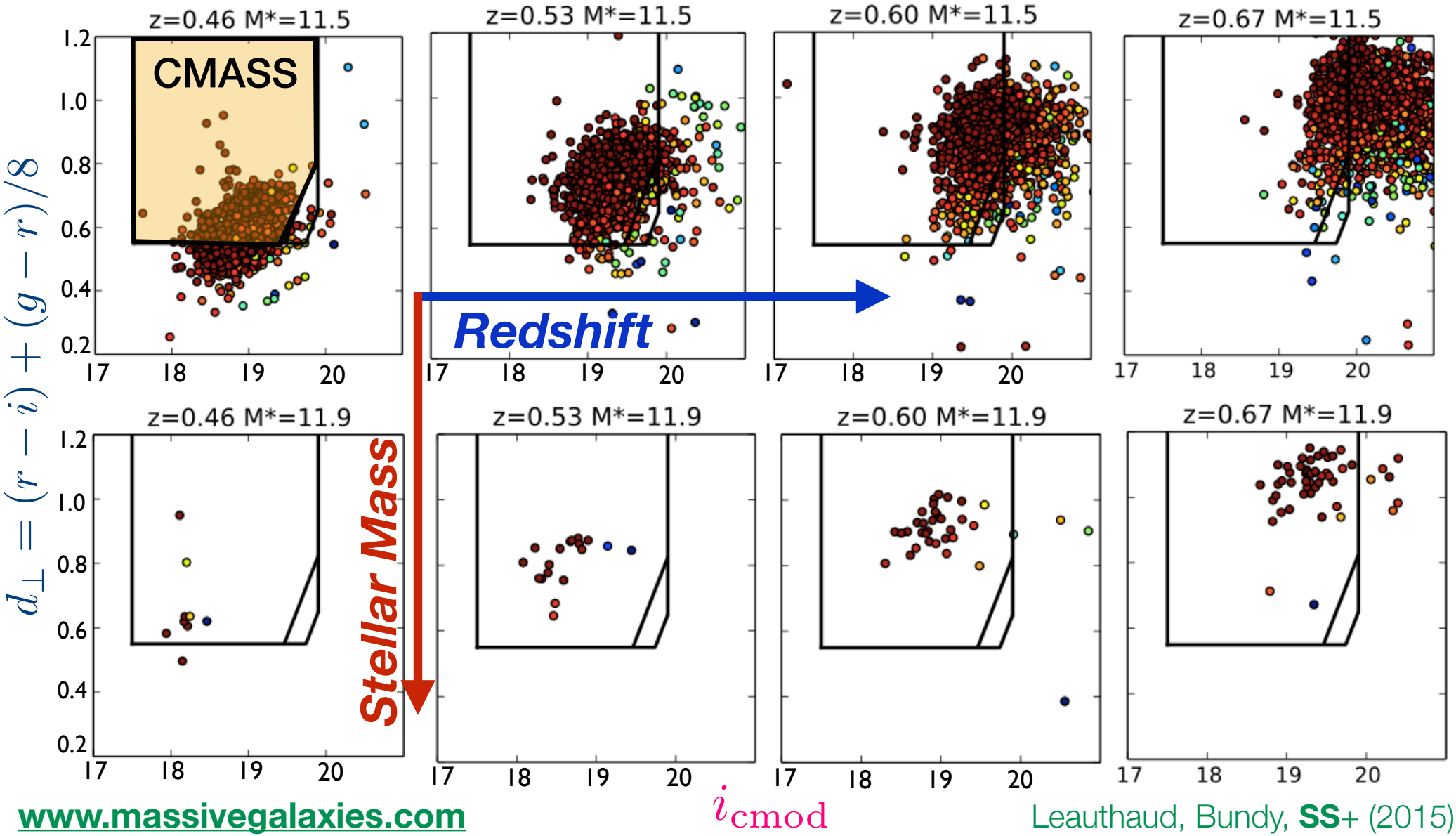
- Combined with UKIDSS NIR bands, obtained more robust M* estimates



www.massivegalaxies.com



The CMASS Selection Function



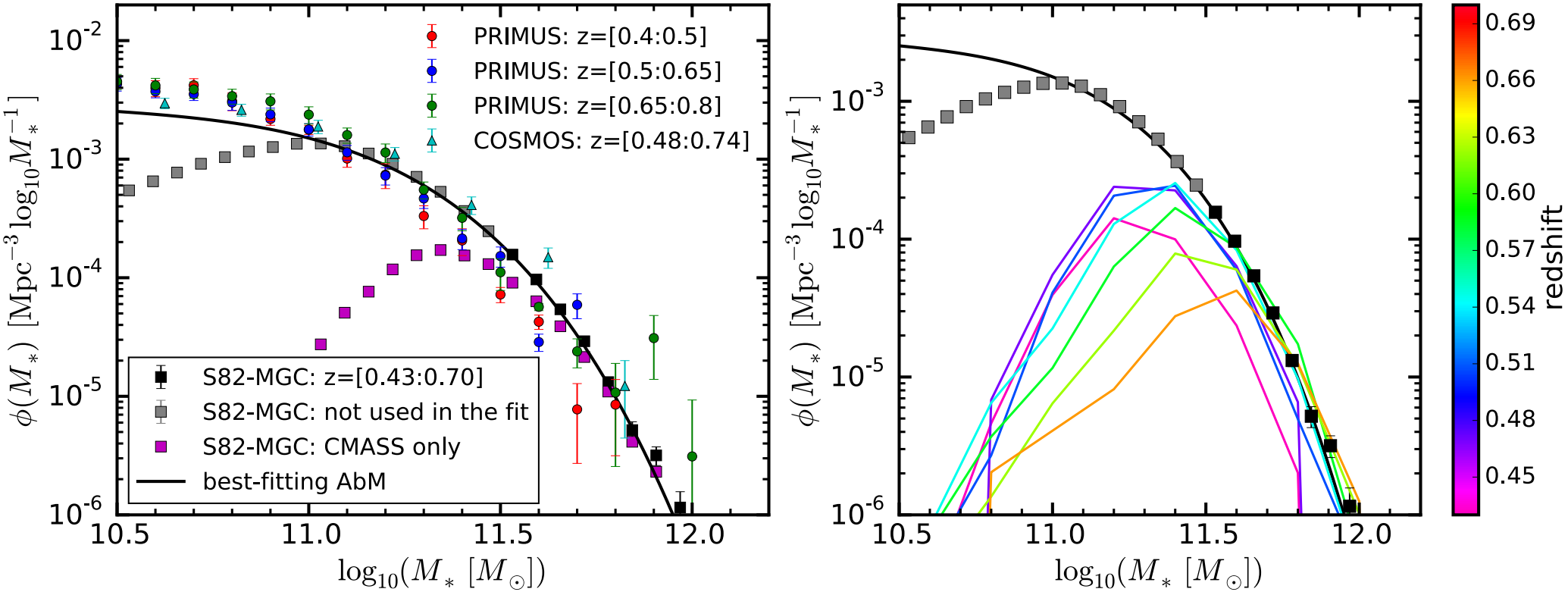
www.massivegalaxies.com

Leauthaud, Bundy, **SS**+ (2015)

low z (high z) is dominated by color cut (luminosity cut).

S82-MGC SMF

SS, Leauthaud+ (2015)



- ***S82-MGC***: best constrain high-mass end, $\log(M_*/M_\odot) \gtrsim 11.5$

  complete at $\log(M_*/M_\odot) \gtrsim 11.3$

- **CMASS ≠ Constant Mass!!** ***redshift-dependent*** completeness

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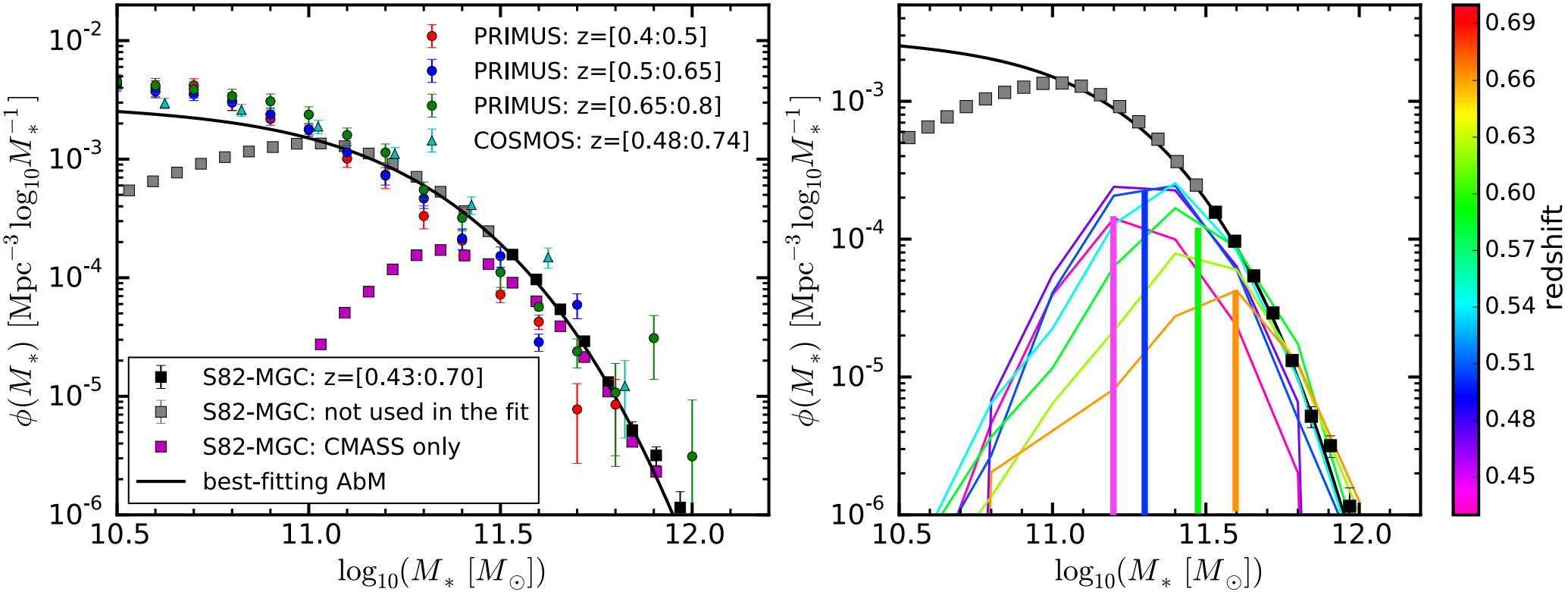

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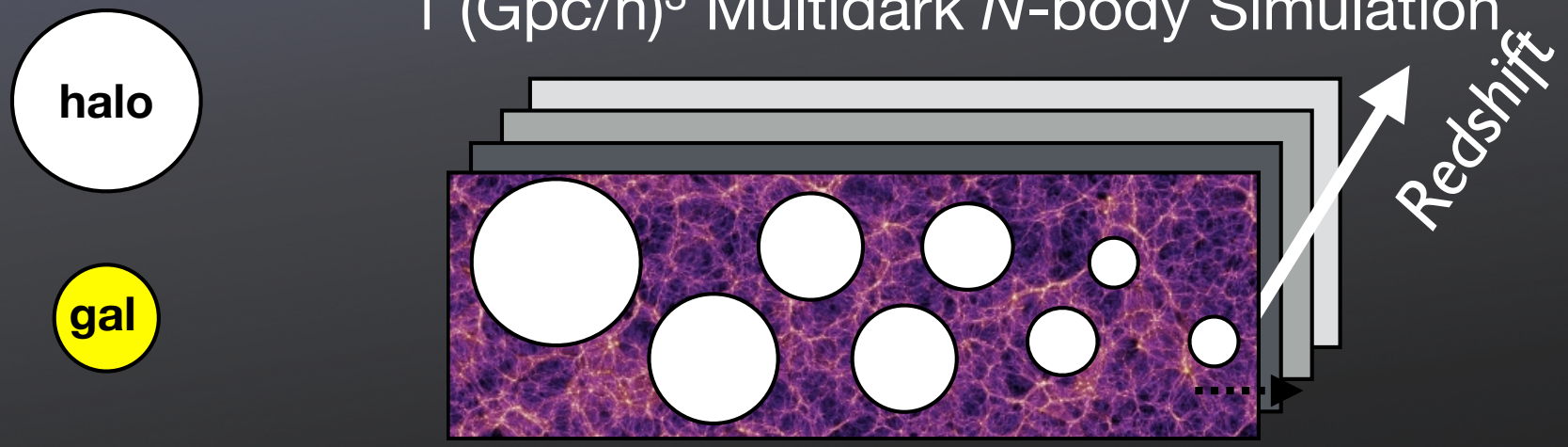
Subhalo Abundance Matching

1 (Gpc/h)^3 Multidark *N*-body Simulation



Subhalo Abundance Matching

halo

gal

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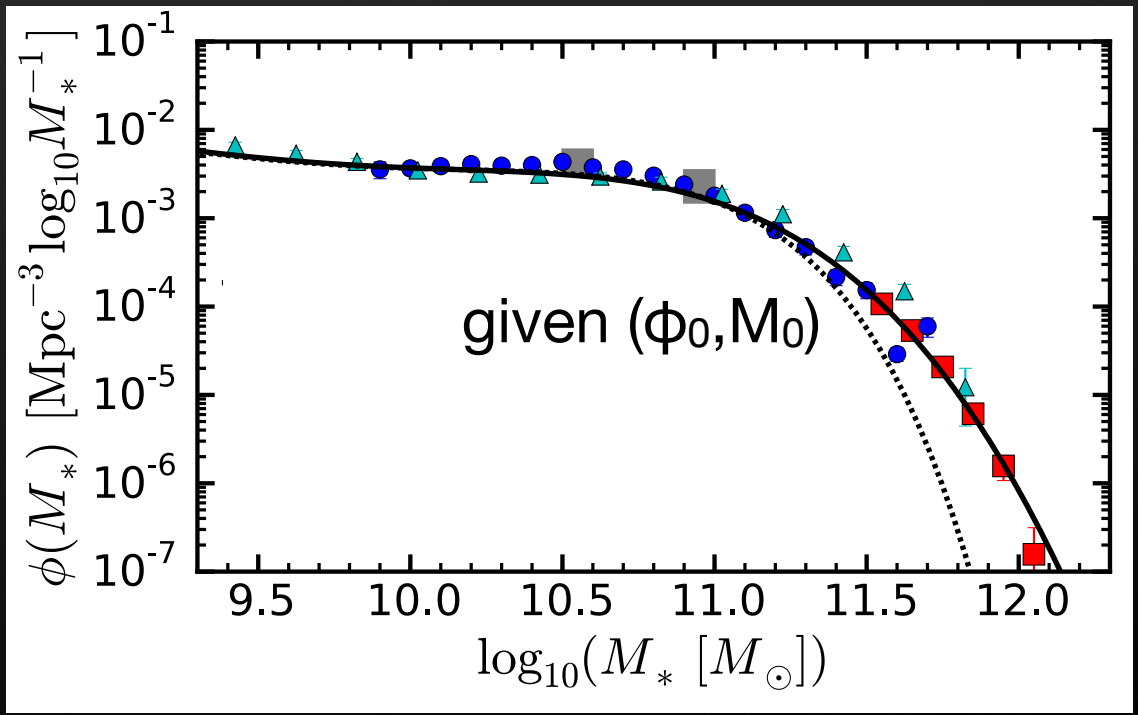
Step 1: Determine Mass Function and abundance match (V_{peak})



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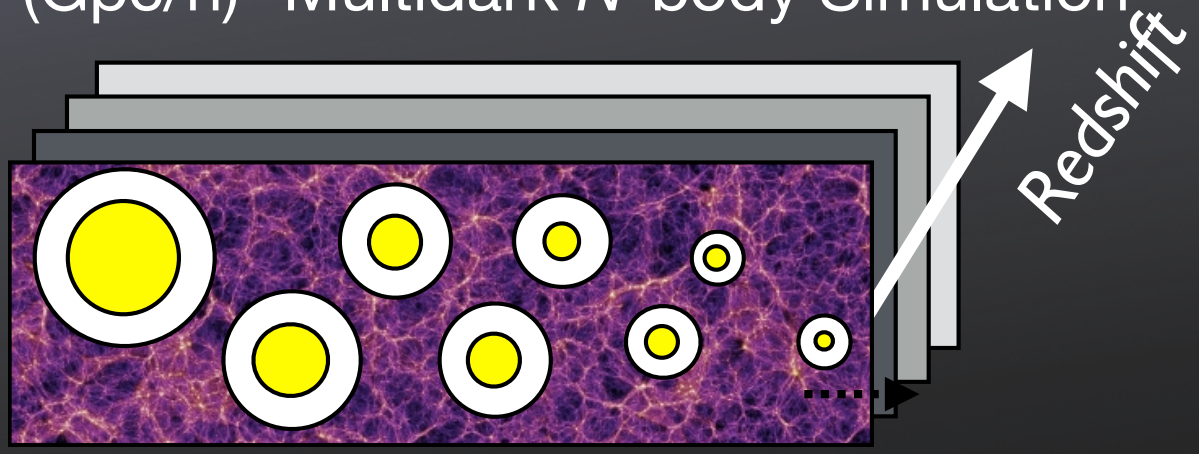

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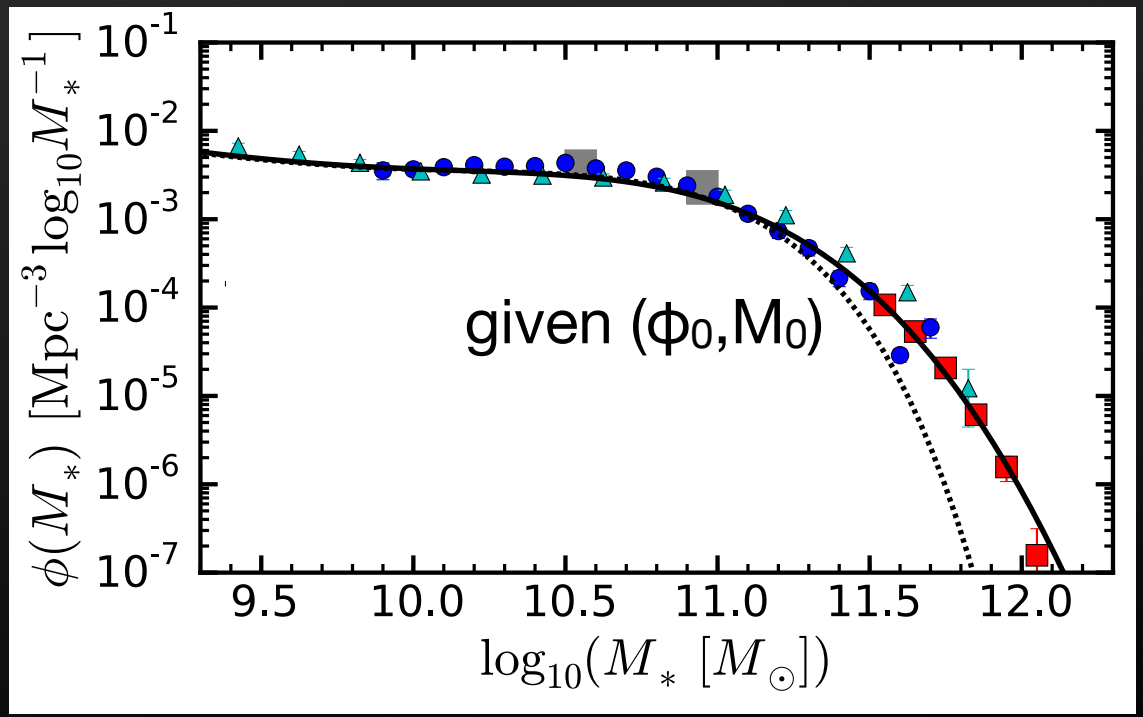

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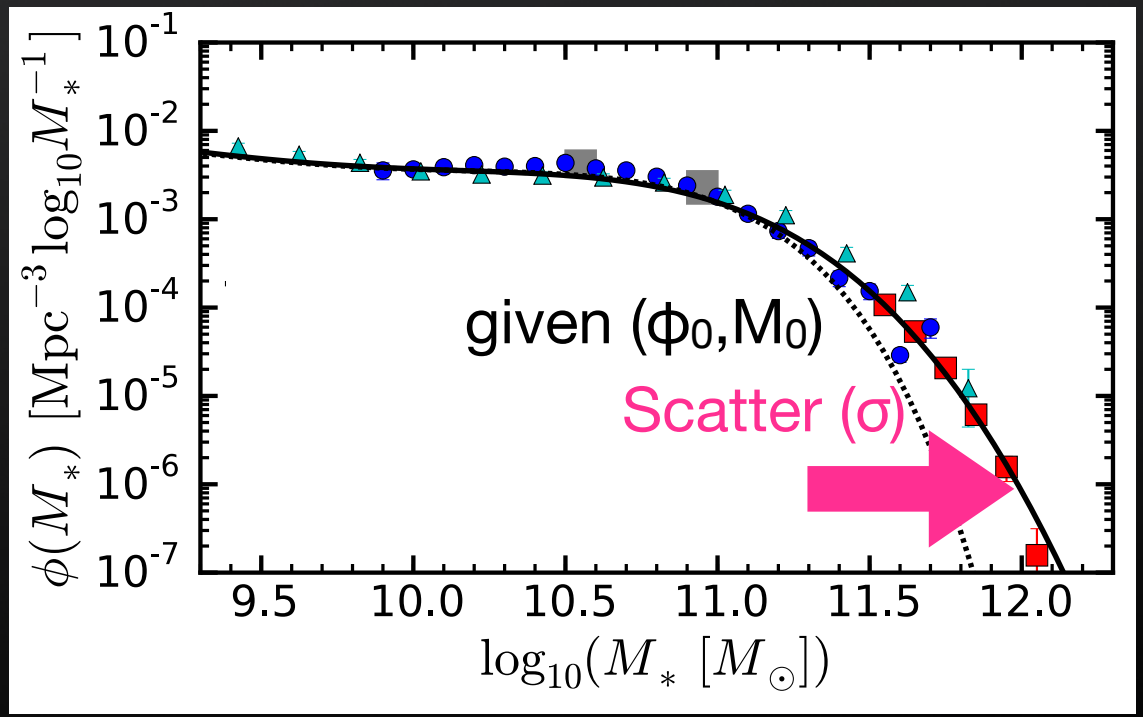

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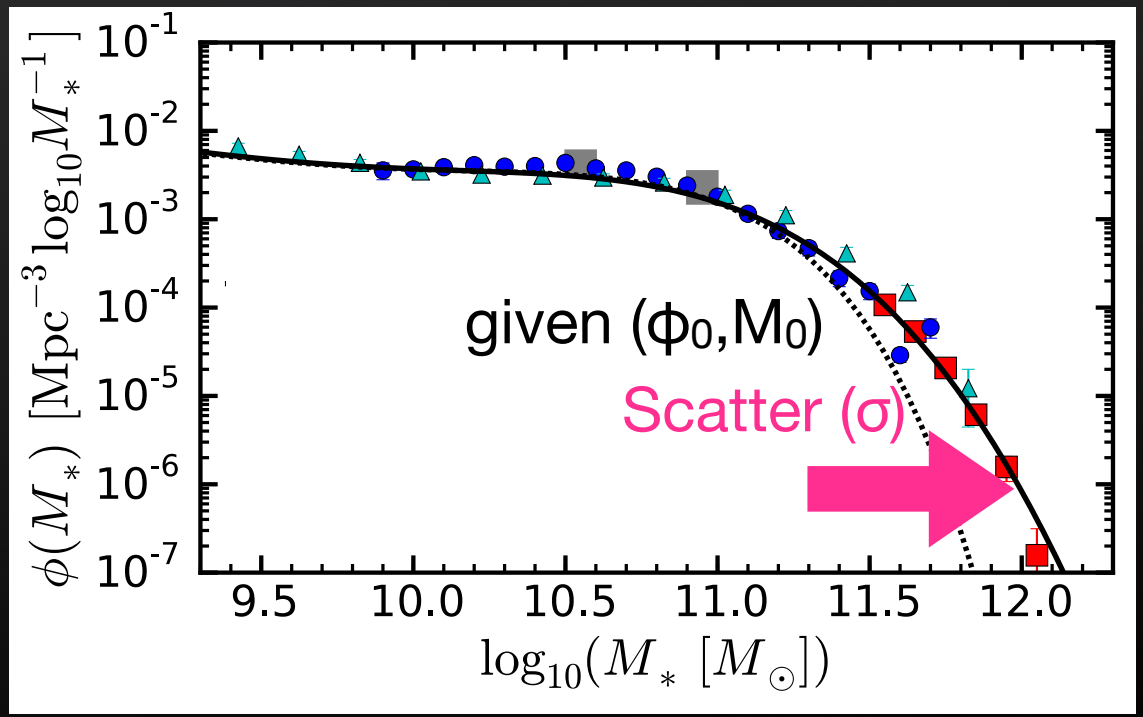

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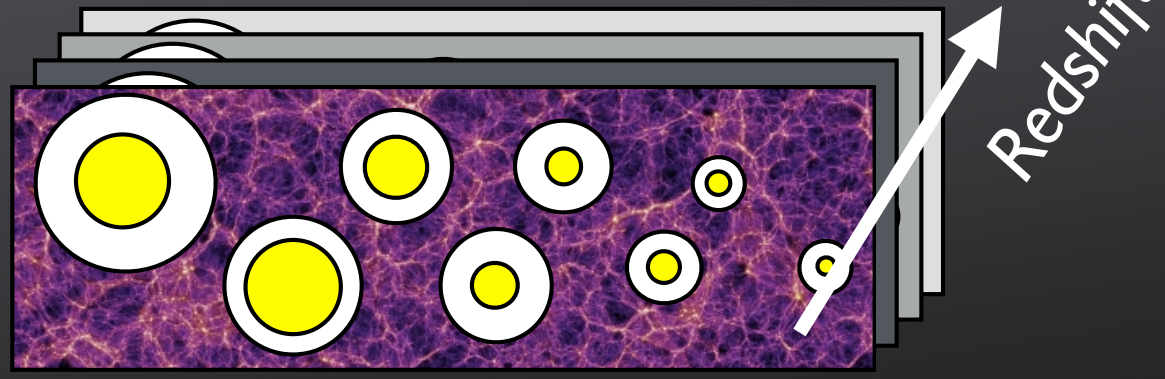
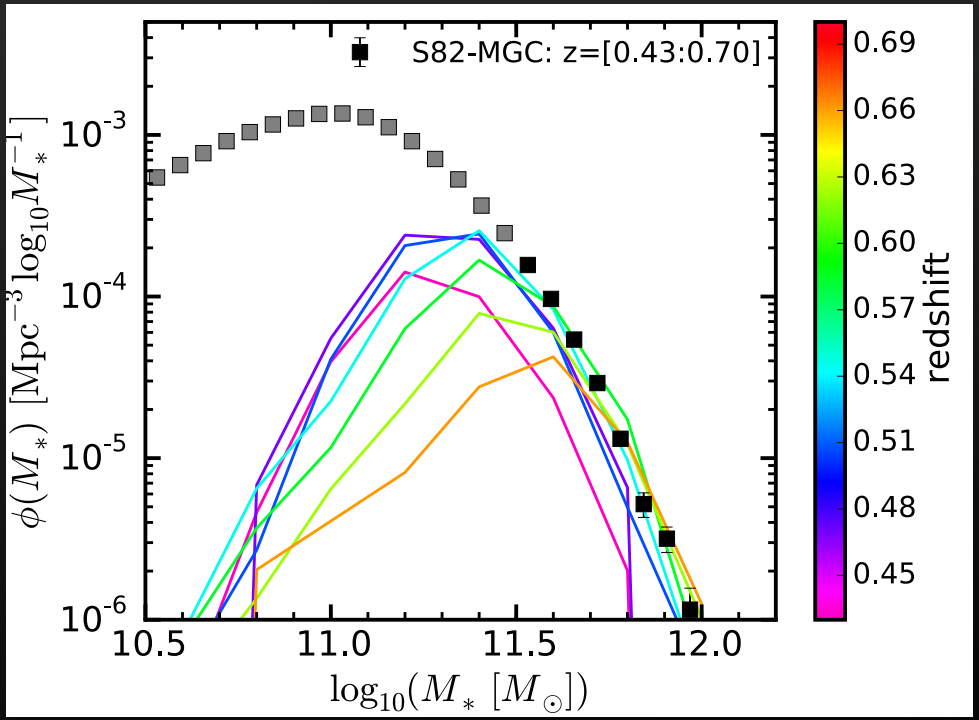
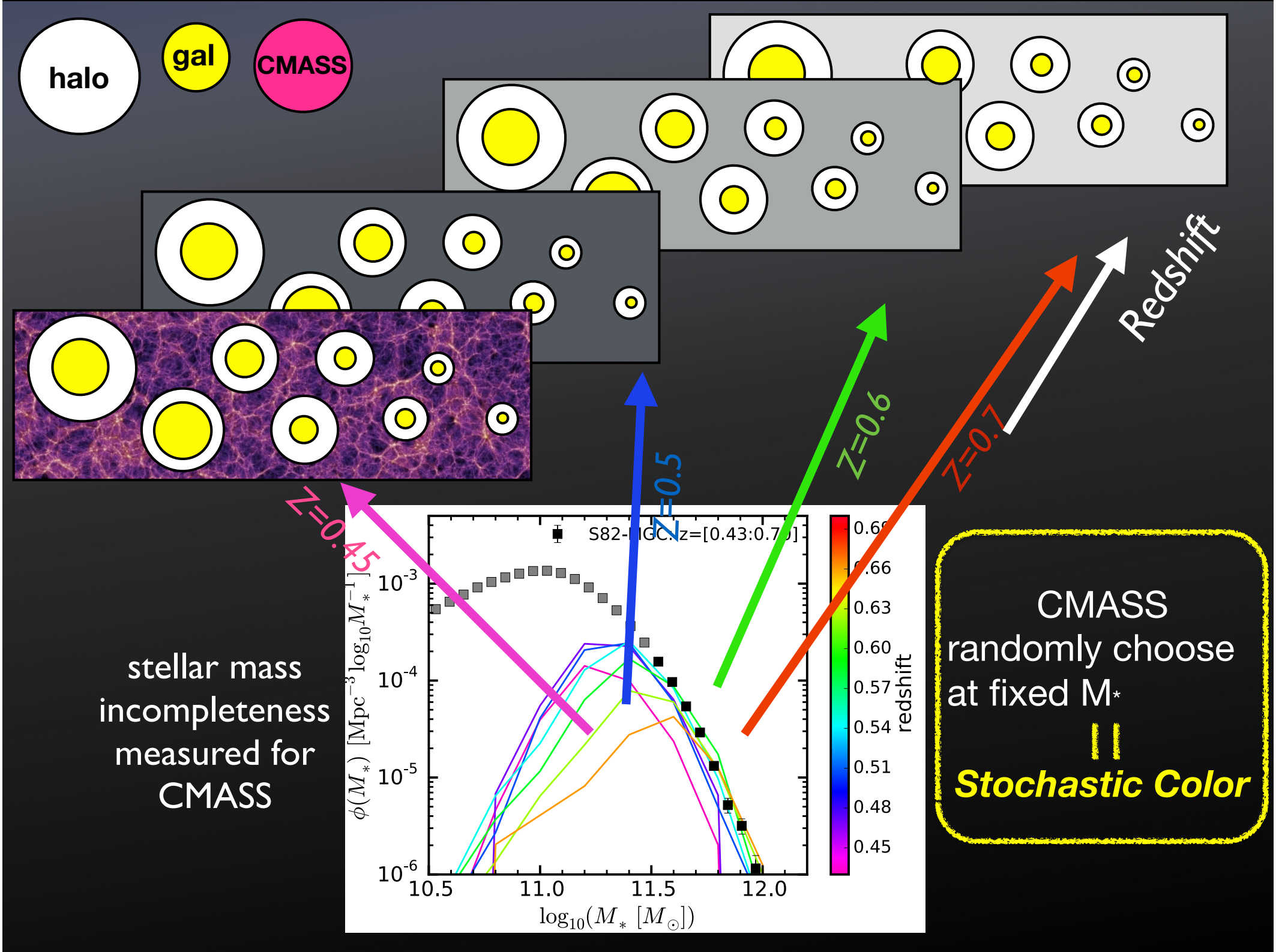
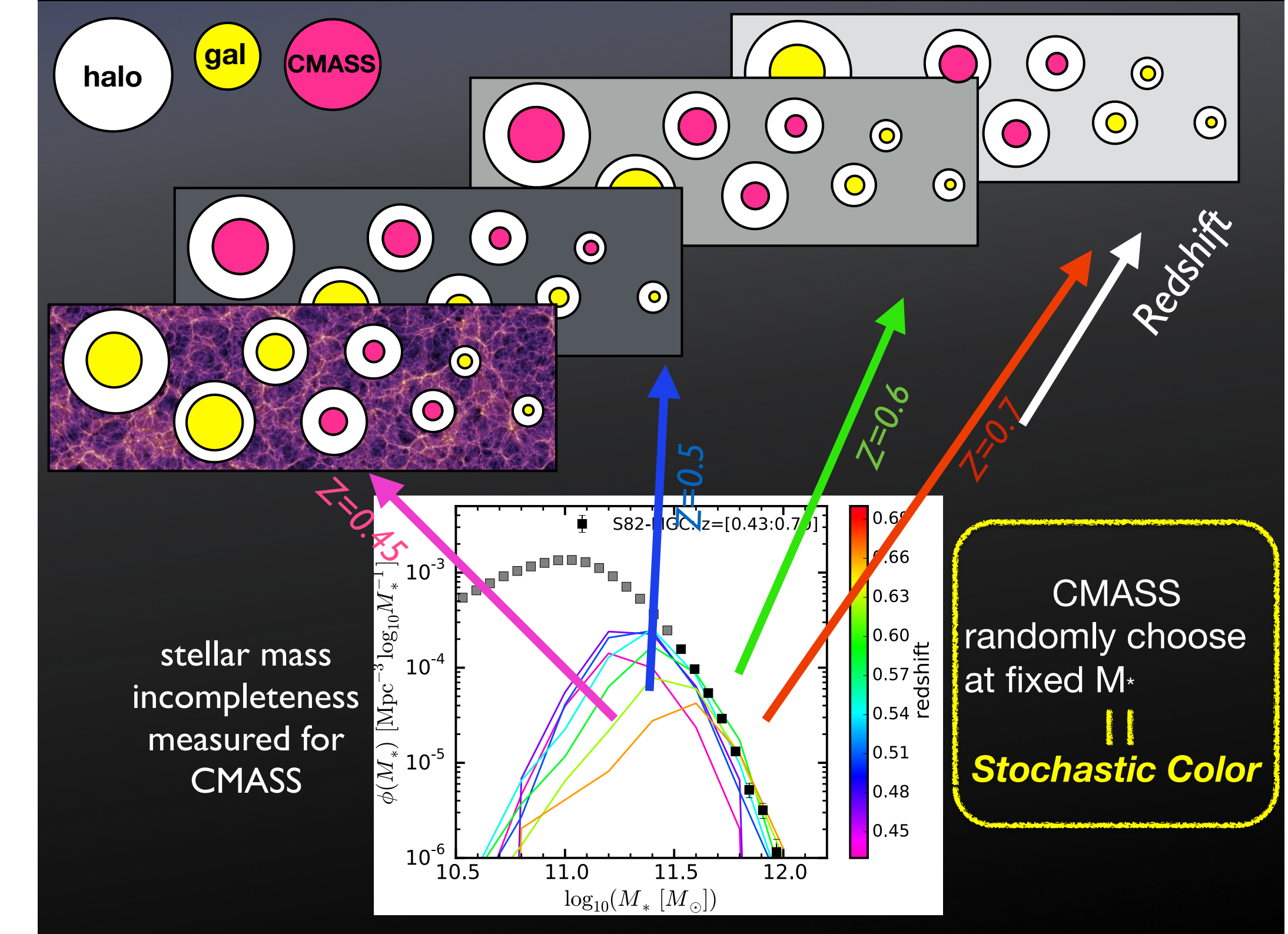


Step 2 : Redshift dependence of stellar-mass completeness




halo
gal
CMASS
Redshift
Z=0.45
Z=0.5
Z=0.6
Z=0.7
S82-[illegible]GC: z=[0.43:0.7[illegible]]
$\phi(M_*)$ [Mpc^{-3}log$_{10}M_*^{-1}$]
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10.5
11.0
11.5
12.0
log$_{10}(M_*$ [$M_\odot$])
redshift
0.69
0.66
0.63
0.60
0.57
0.54
0.51
0.48
0.45
stellar mass incompleteness measured for CMASS
CMASS randomly choose at fixed M*
=
Stochastic Color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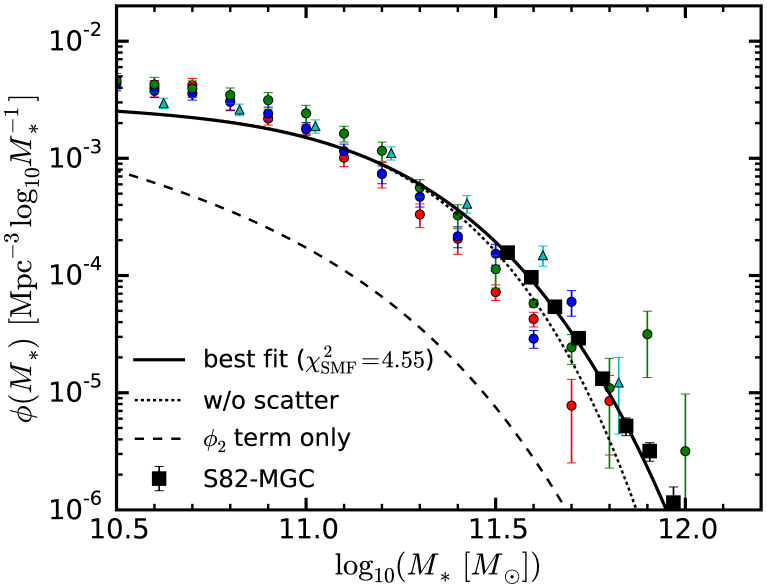
CMASS randomly choose at fixed M*
=
Stochastic Color

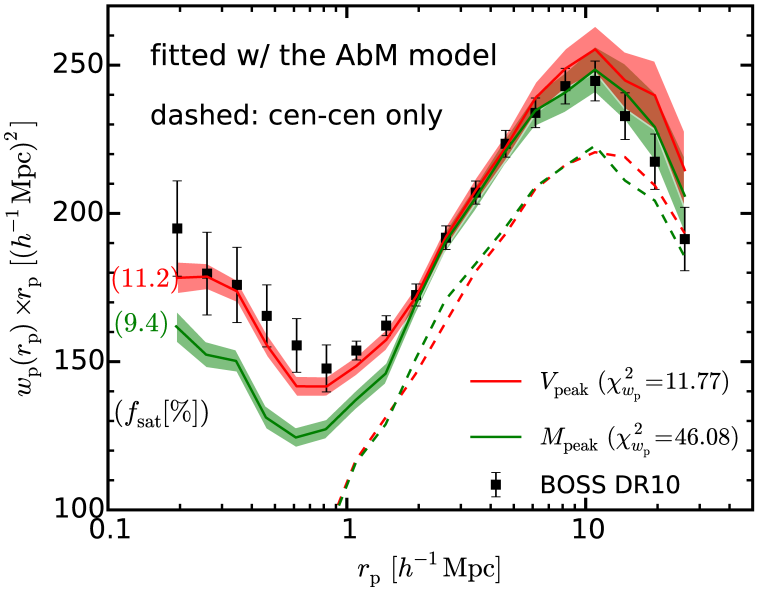
Result

SS, Leauthaud+ (2015)

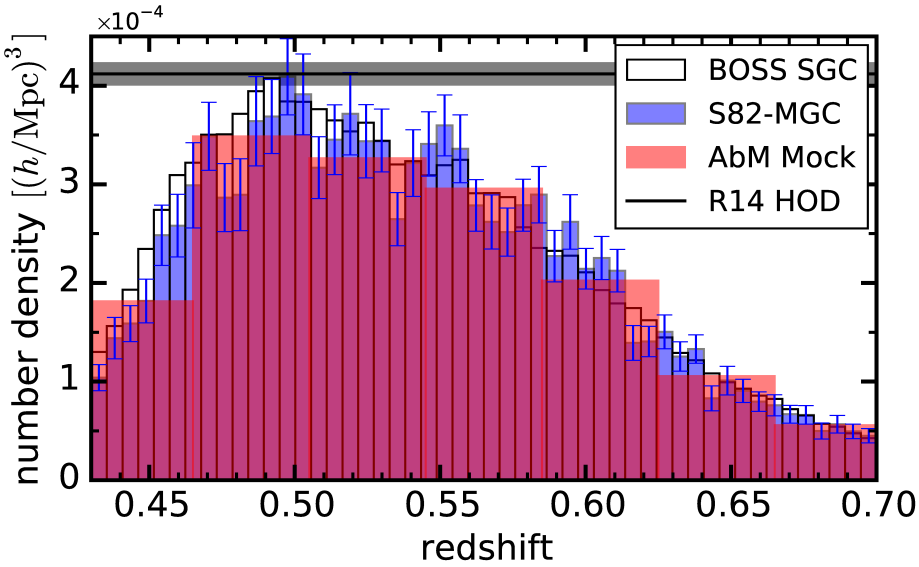
$$\sigma(\log M_*|V_{\rm peak}) = 0.1$$

- can simultaneously explain SMF & w_p



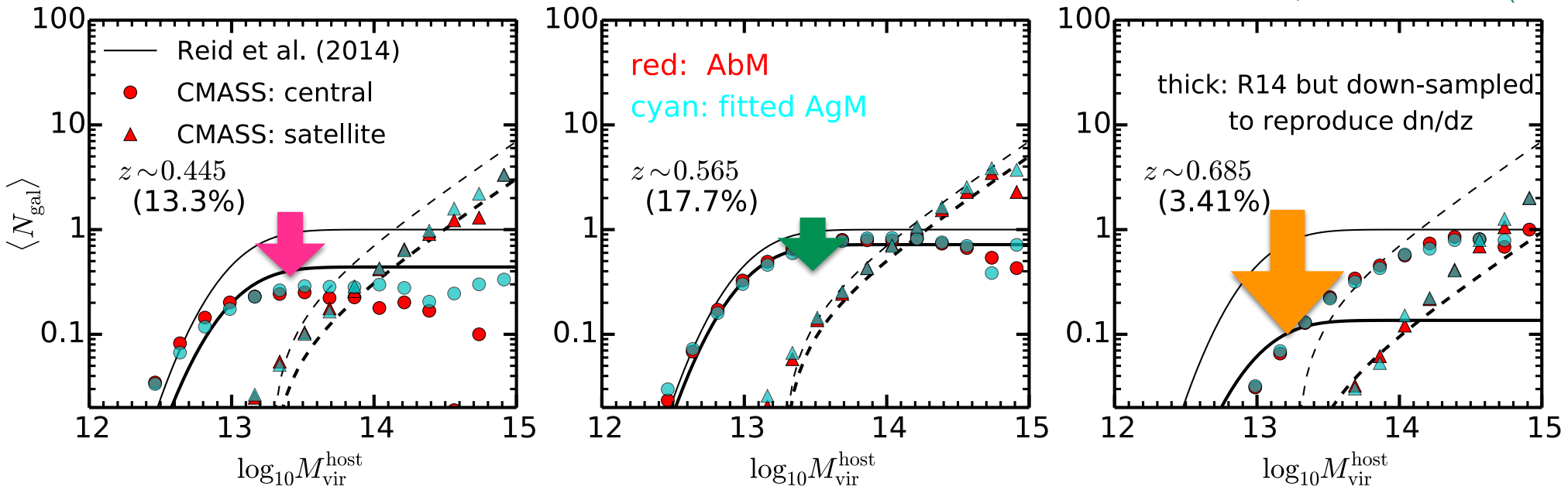


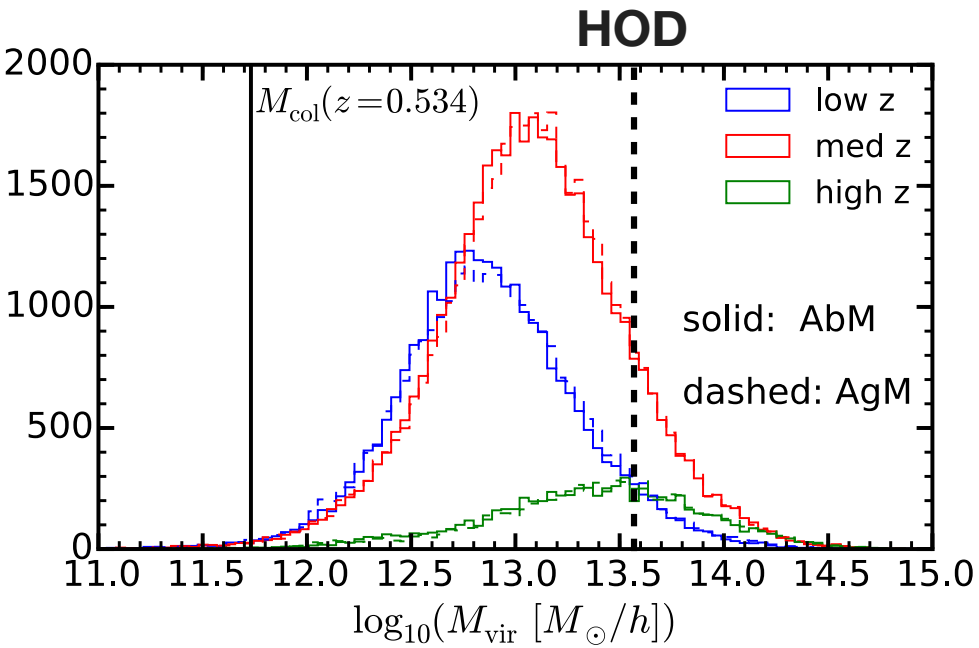
- explain dN/dz by design

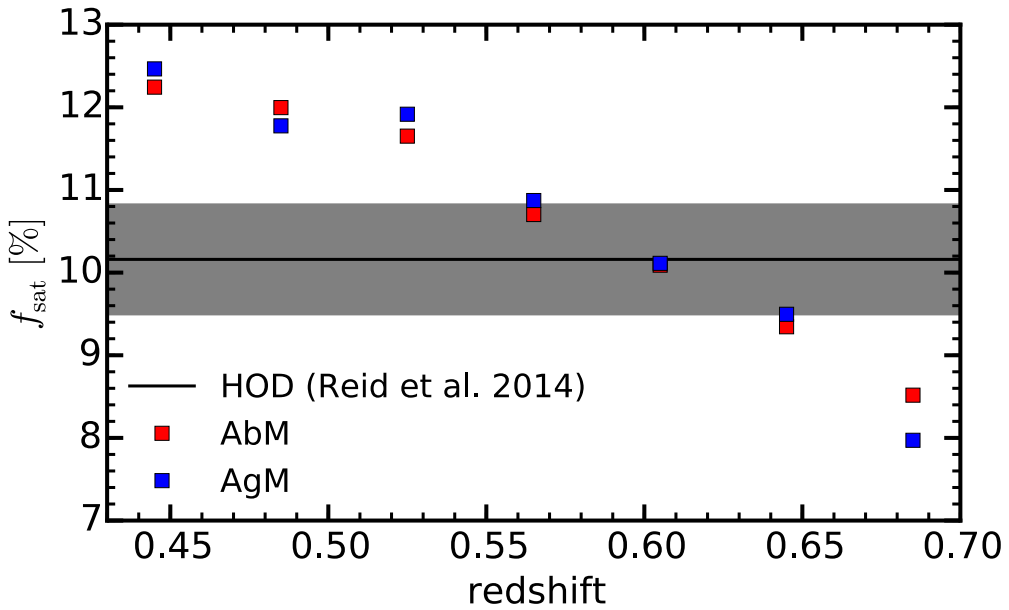


Evolution of HOD with Redshift

SS, Leauthaud+ (2015)

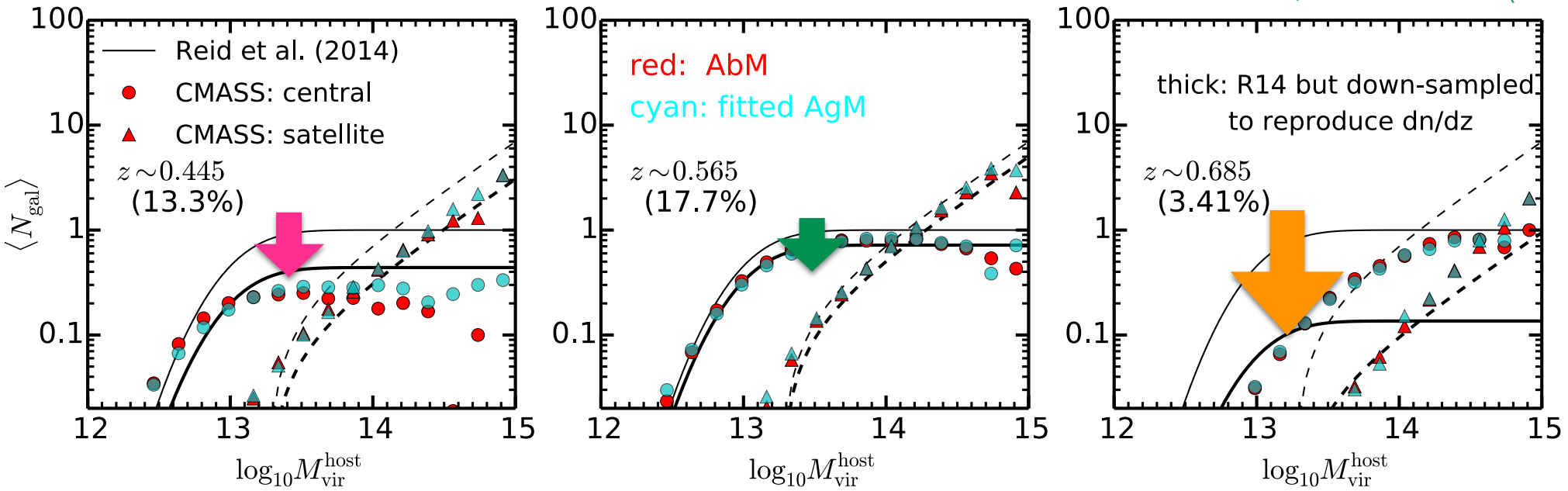


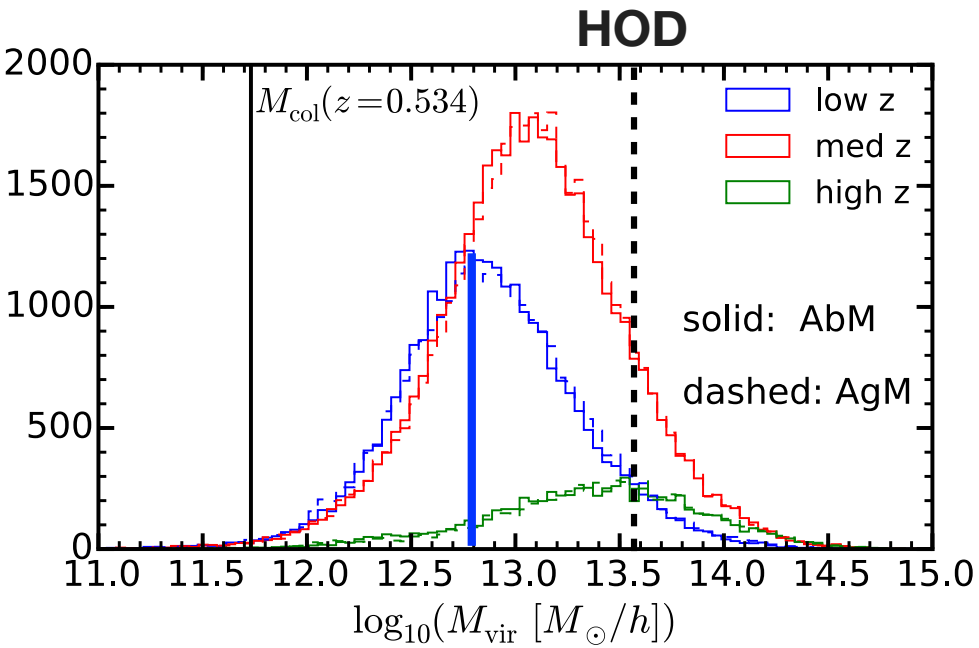


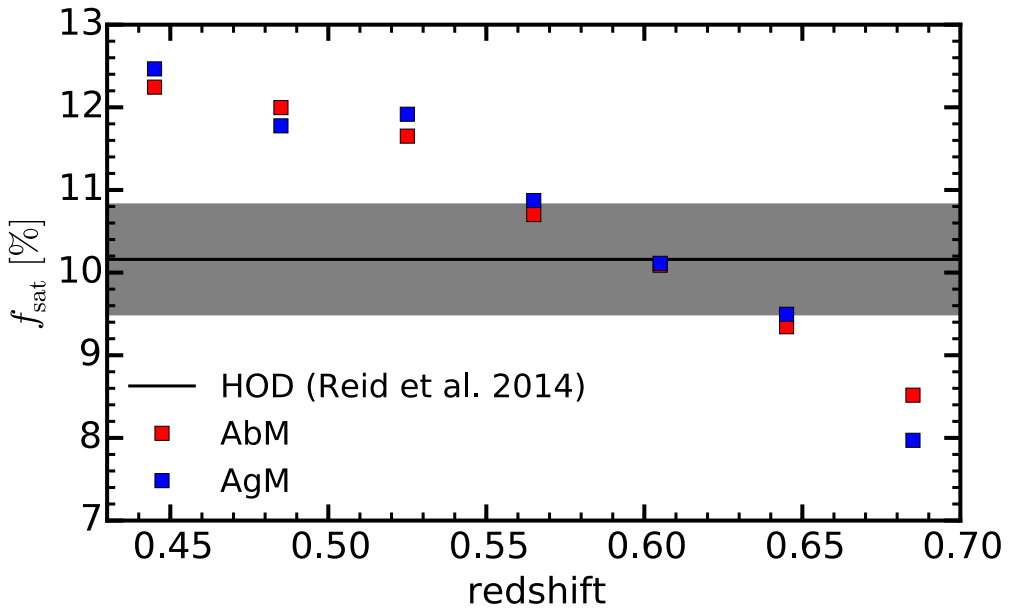


Evolution of HOD with Redshift

SS, Leauthaud+ (2015)







Evolution of HOD with Redshift

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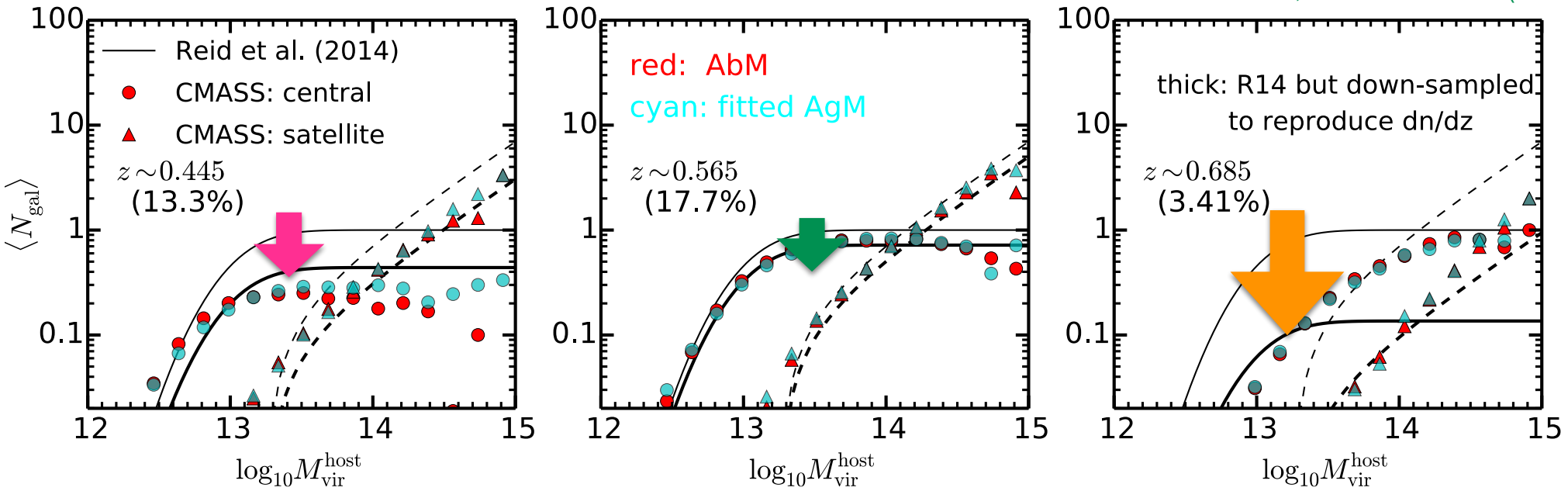
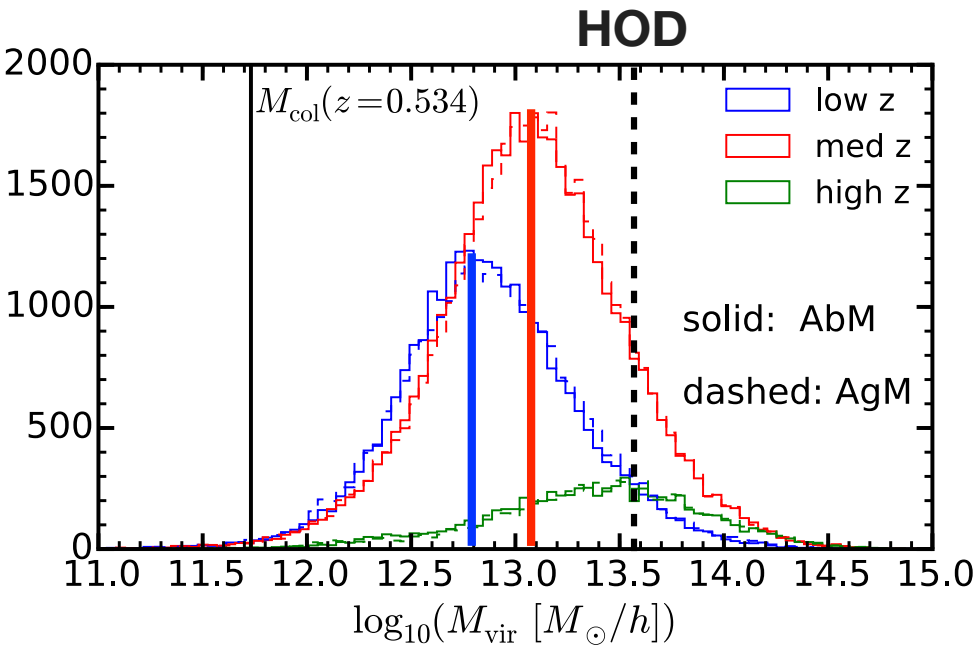
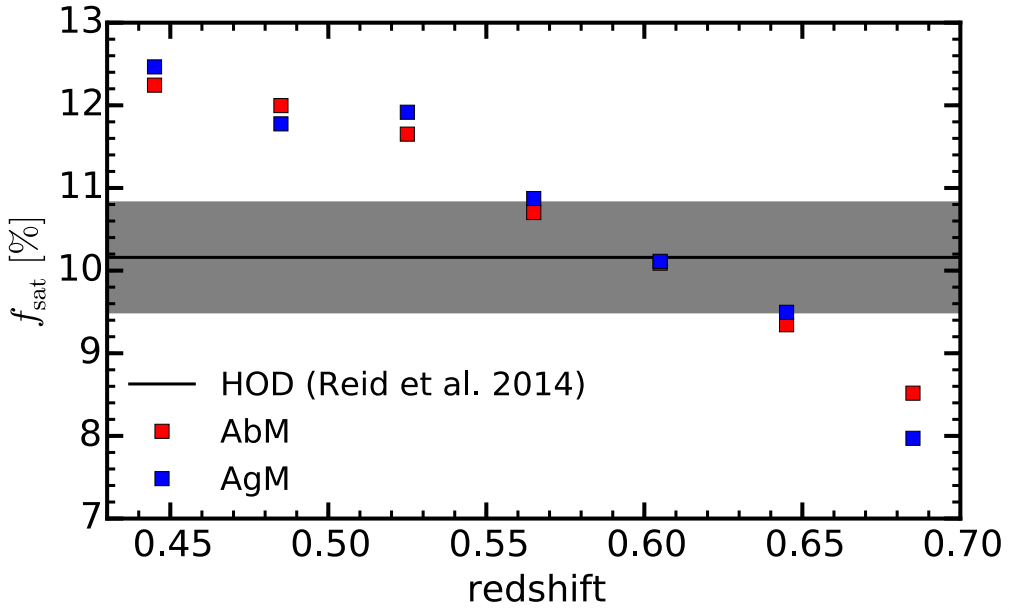
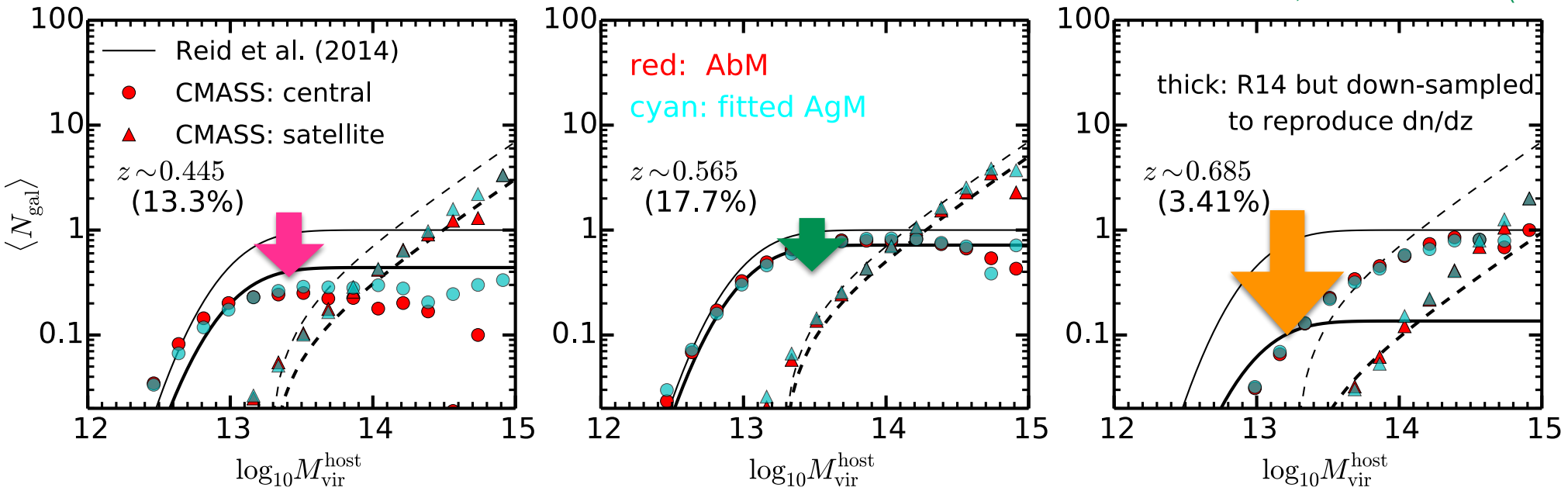


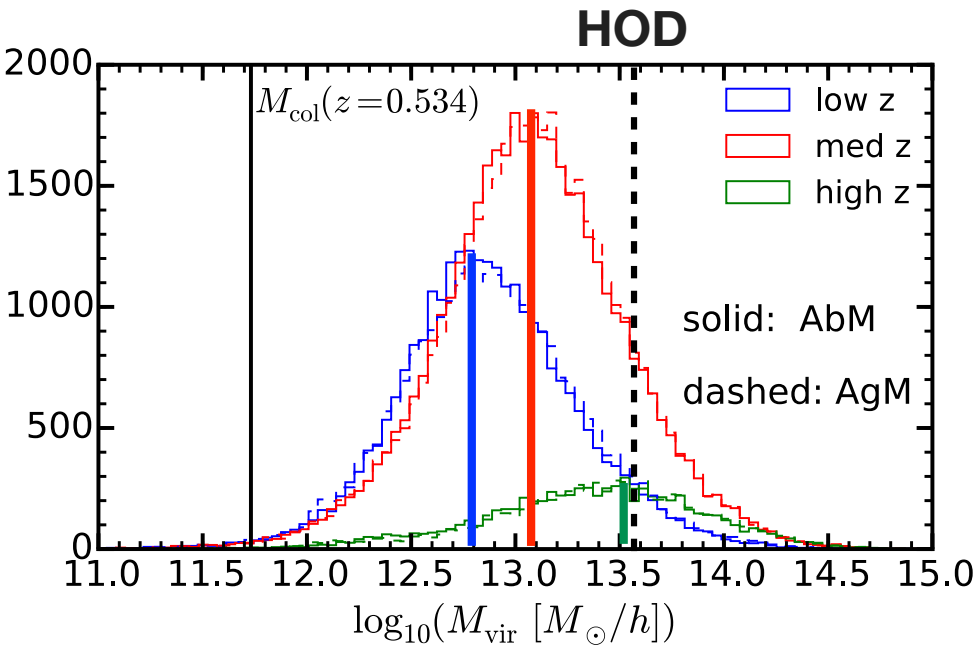


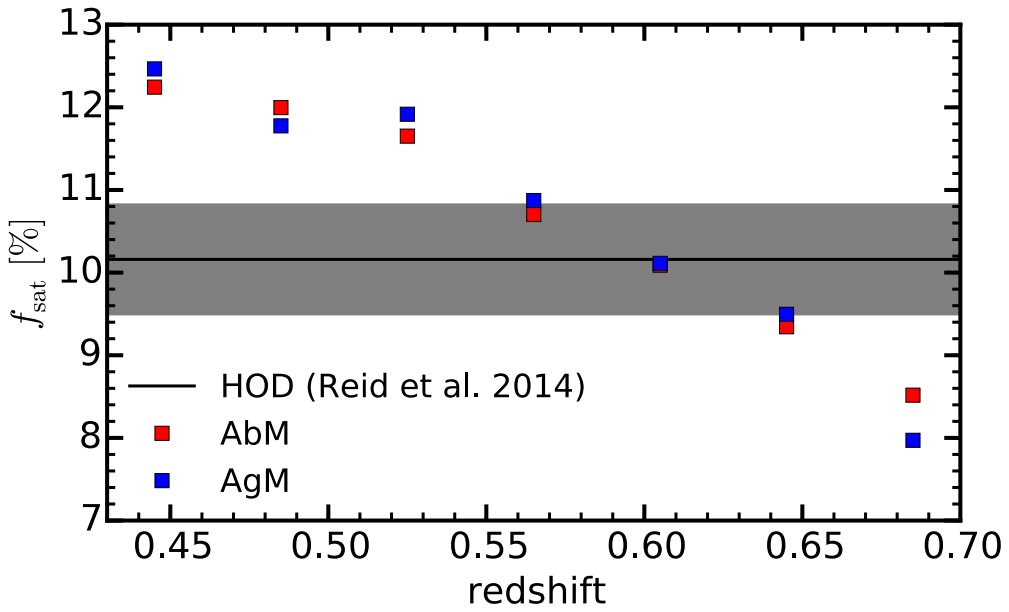


Evolution of HOD with Redshift

SS, Leauthaud+ (2015)



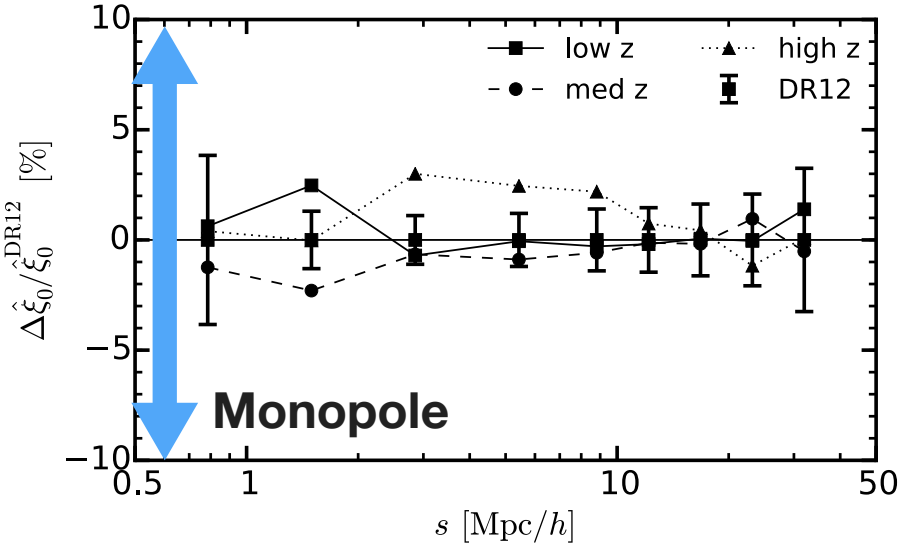


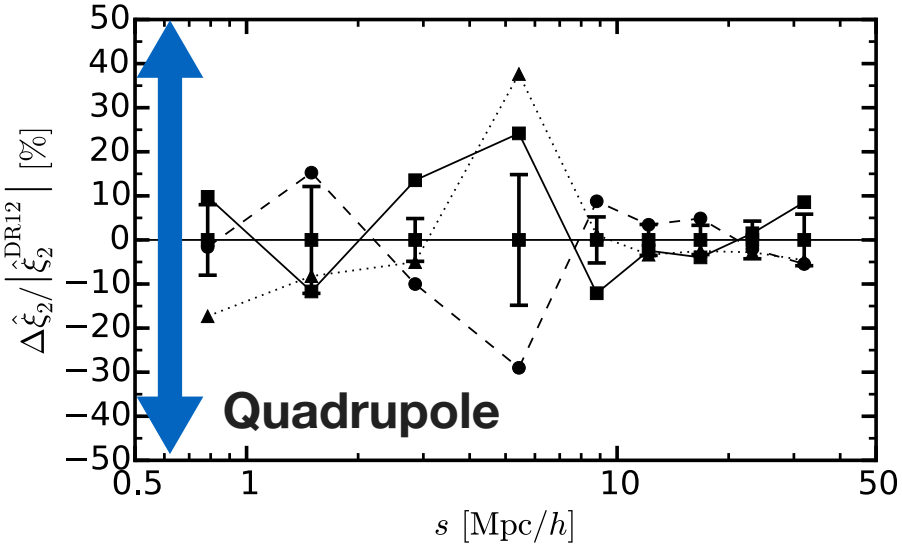


But …fails for 3D Clustering Signal

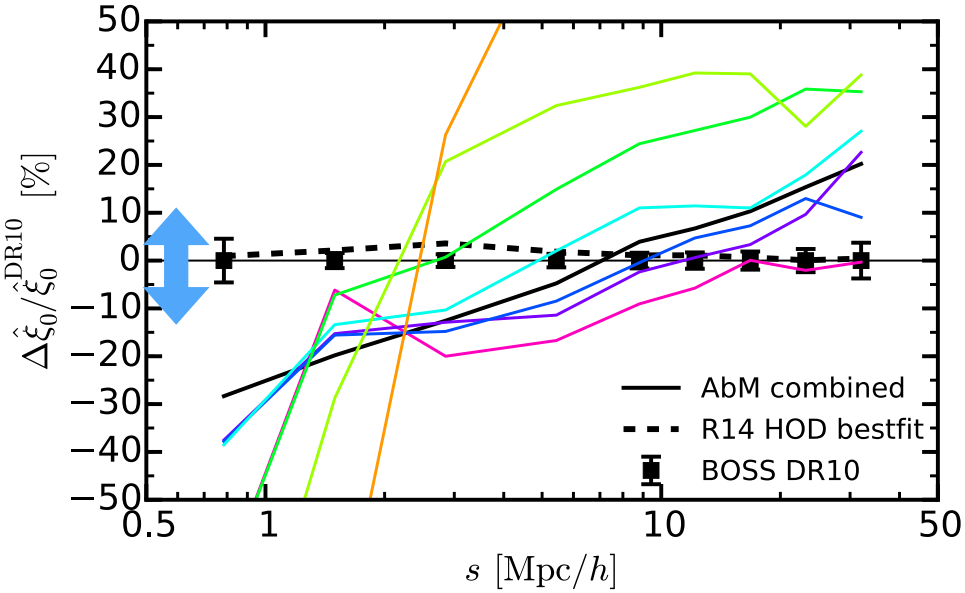
✦ The measurements show **NO** redshift evolution

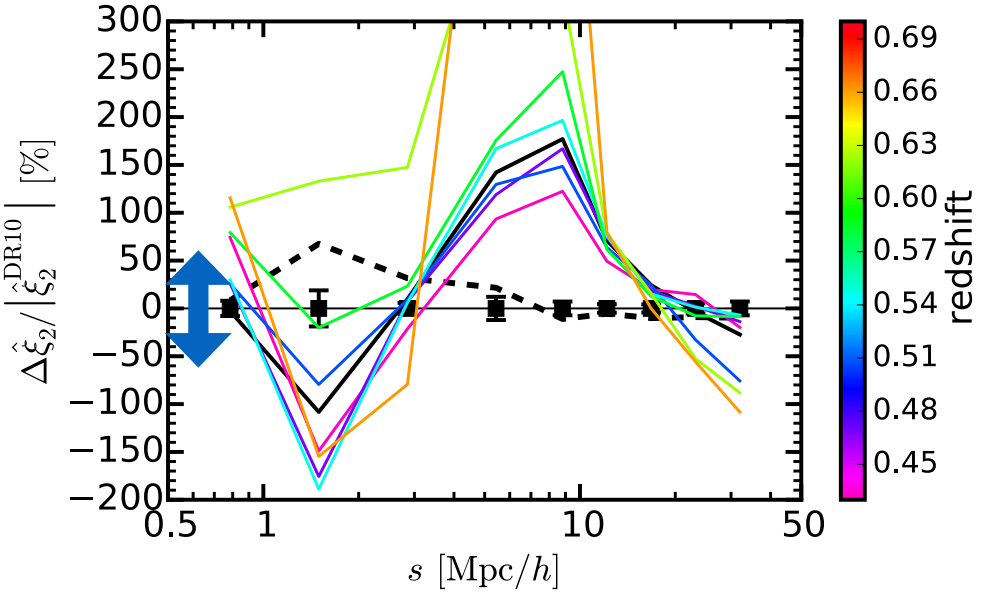
SS, Leauthaud+ (2015)



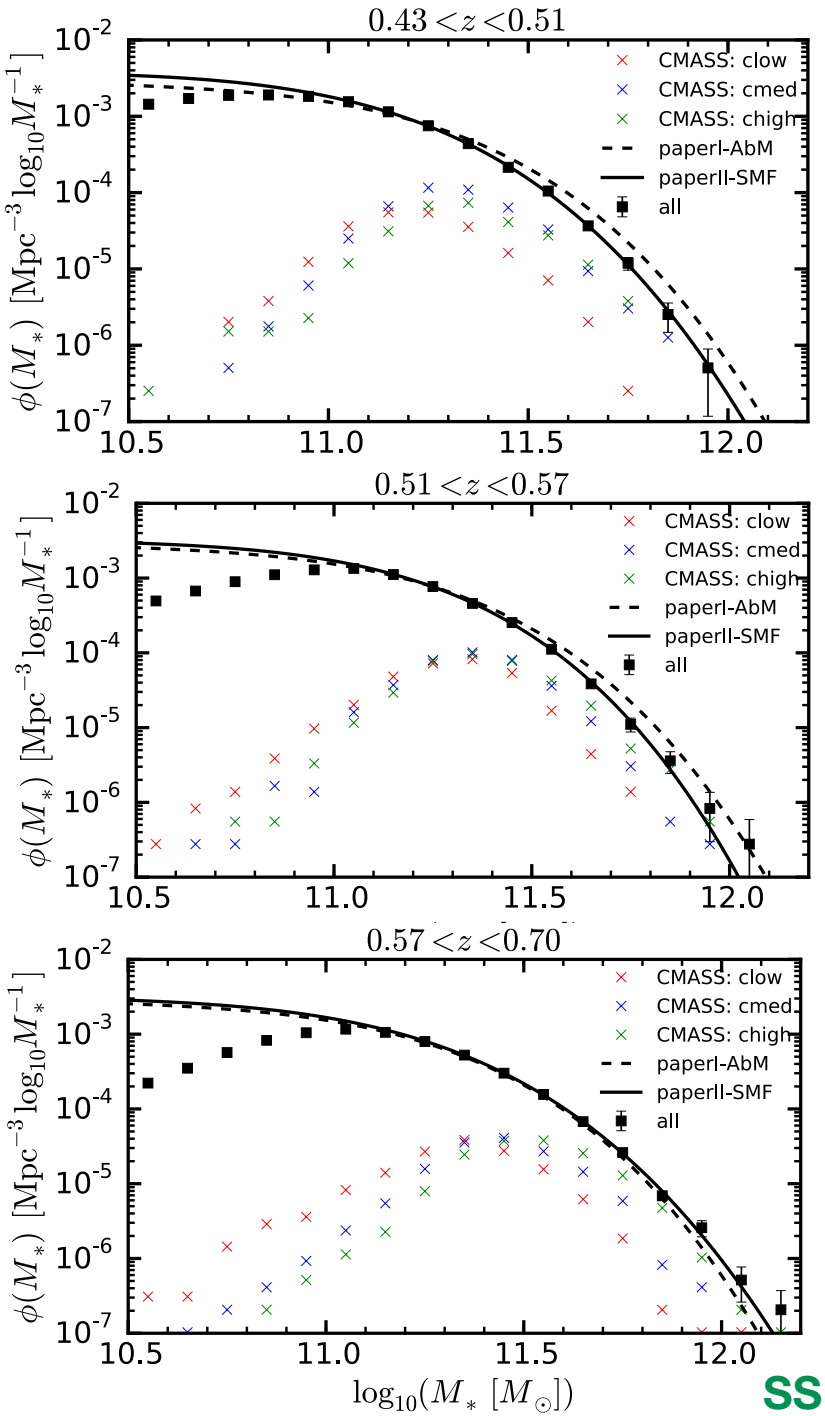


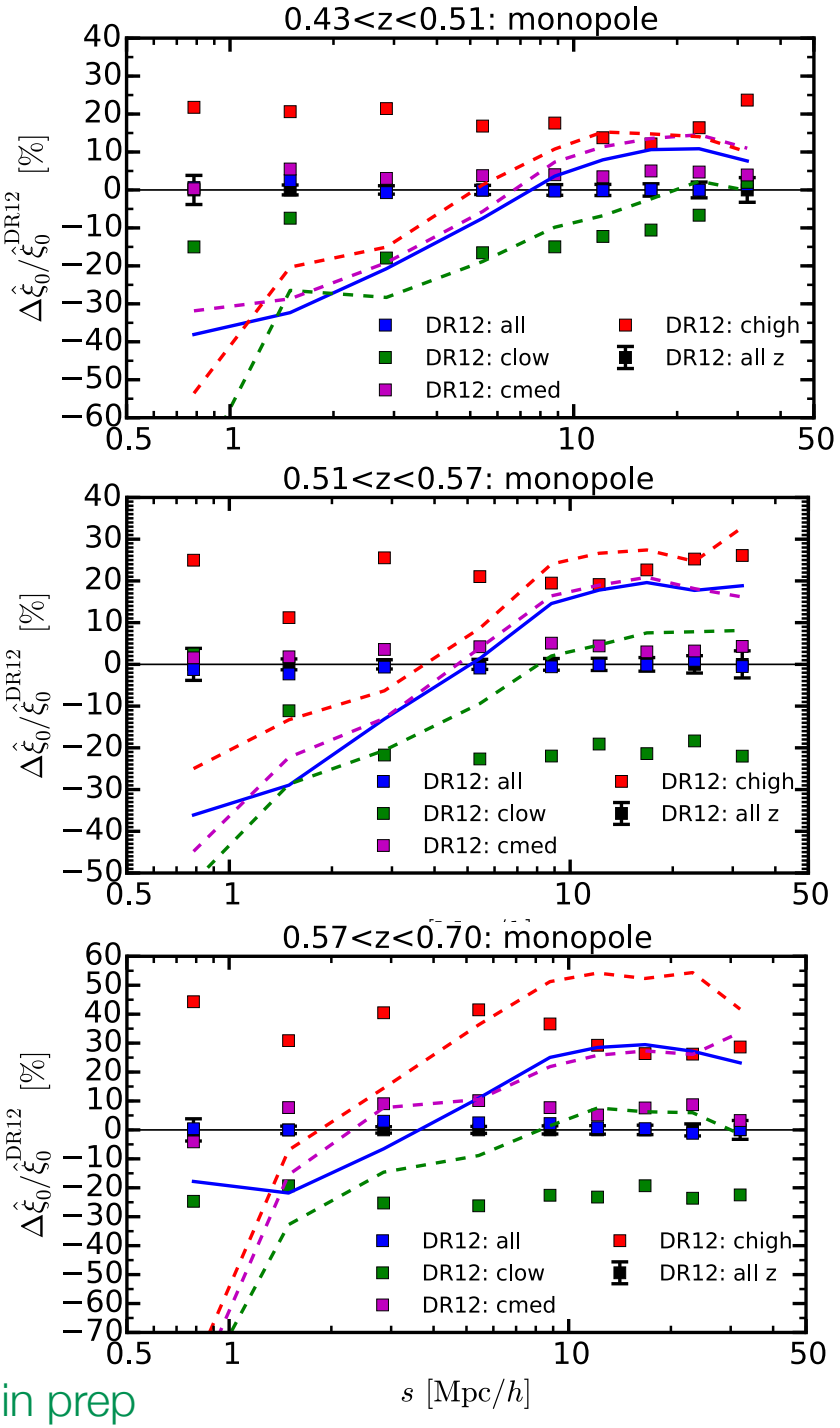
✦ Our “Stochastic Color” model





Redshift- & Color-dependence





SS, Leauthaud+, in prep

Failure of "Stochastic Color" model

- "Stochastic Color" model is highly ruled out by the data
  - CMASS SMFs show a higher $\overline{M}_*$ at higher redshift
  - therefore, $\overline{M}_{\rm halo}$ also evolves with time
  - However, data shows NO redshift evolution

- Next step:
  - There must be an effect which can compensate the evolution
  - At fixed stellar mass, introduce correlation galaxy color with
    - halo formation epoch (or age)
    - halo recent merger
    - local density (or environment)
  - Goal: explain DR12 $\hat{\xi}_\ell(s; color, z)$ & lensing

Conditional SHAM: **Age Matching**

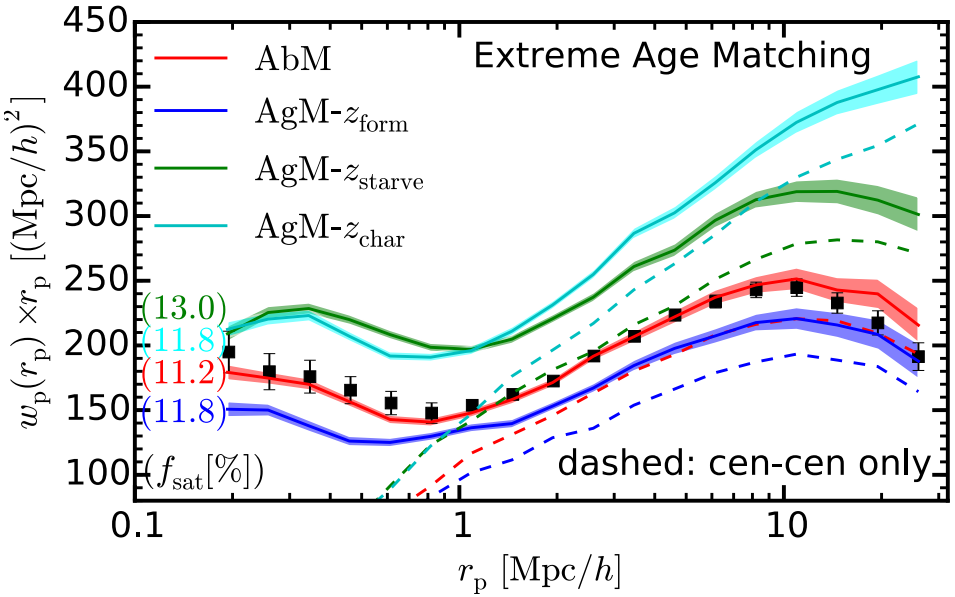
✦ At fixed stellar mass, "a ***redder*** galaxy tends to be hosted by an ***older*** halo"

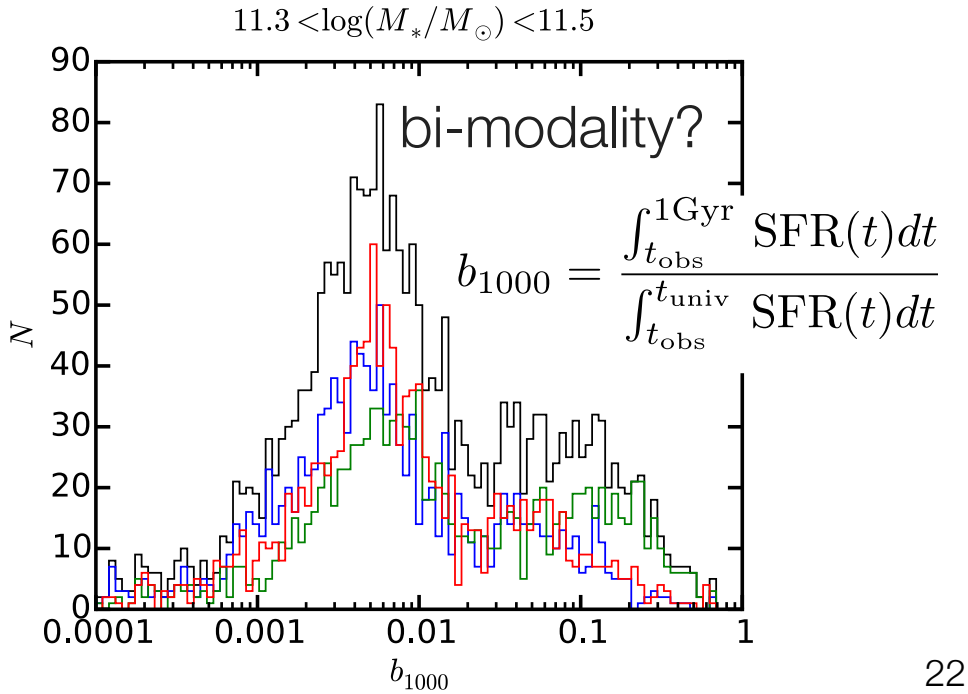
$$P(M_*|V_{\rm peak}) \rightarrow P(M_*, color|V_{\rm peak}, z_{\rm starve})$$ Hearin et al. (2013)

✦ 3 components in $z_{\rm starve}$

- $z_{\rm form}$: (sub)halo's concentration c.f., Miyatake et al. (2015)
- $z_{\rm char}$: when a (sub)halo get mass of 10^{12} $M_{\rm sun}$
- $z_{\rm acc}$: when a subhalo accreted onto its host halo

✦ The effect of **assembly bias** depends on definition of formation time





What is Peculiar Velocity of Galaxies?

✦ Difference b/w **our SHAM model** & **HOD** (Reid et al. 2014)

1) velocity of central

Rockstar: core velocity defined within [0-0.1] r_{vir}

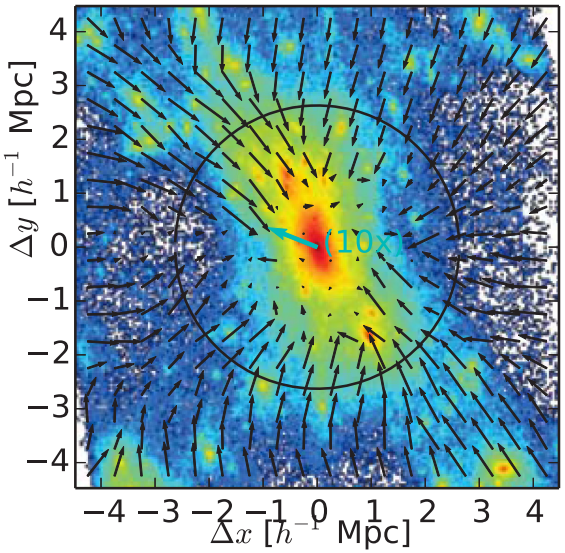
SO halos: core velocity defined within [0-0.33] r_{vir}

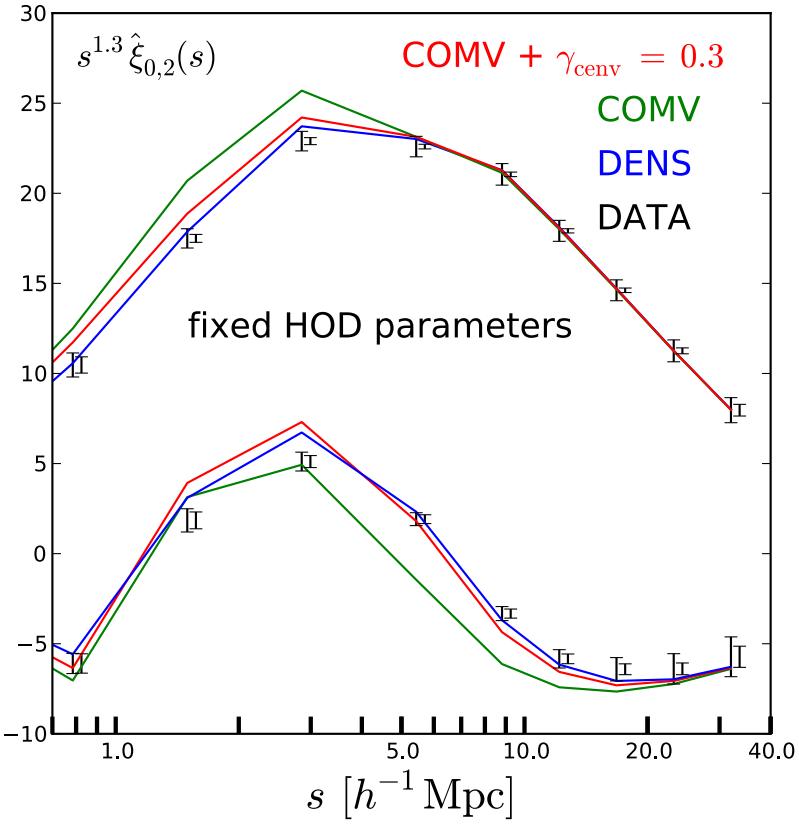
c.f.) Guo et al. (2014): defined within [0-0.22] r_{vir} + velocity bias

2) velocity of satellites

SHAM: the same as central

Reid et al. (2014): velocity of DM





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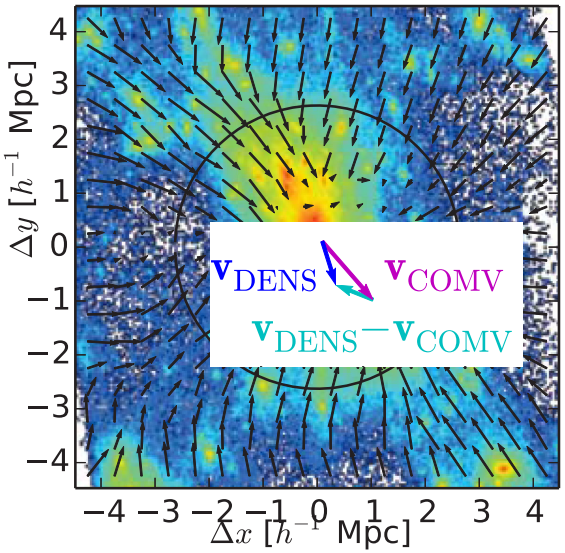
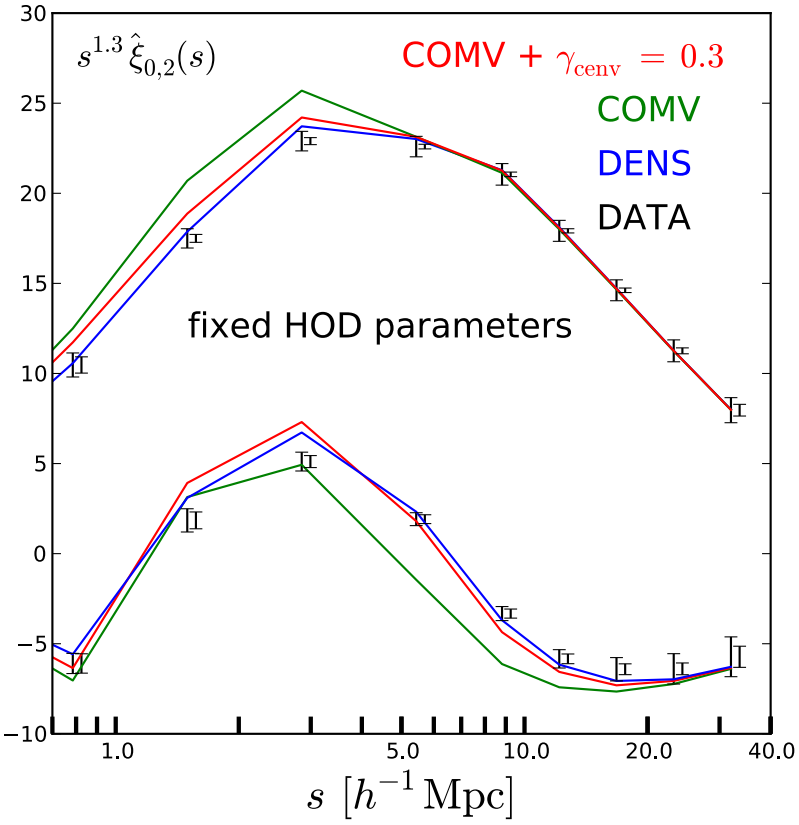


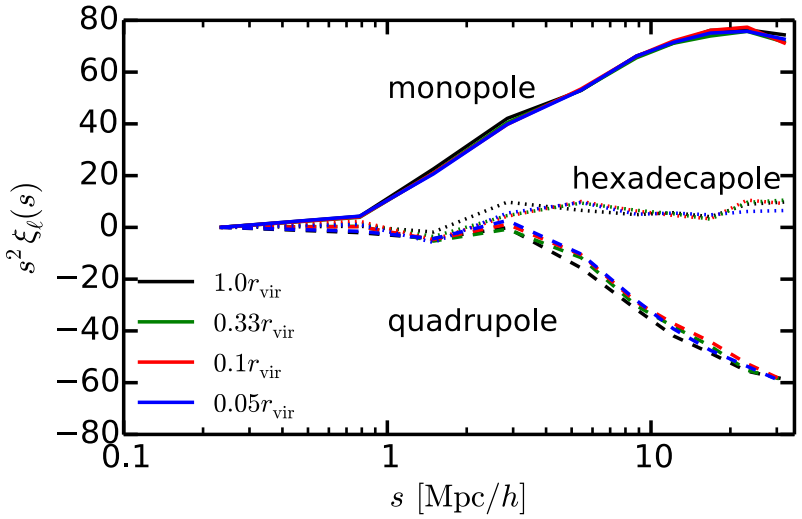


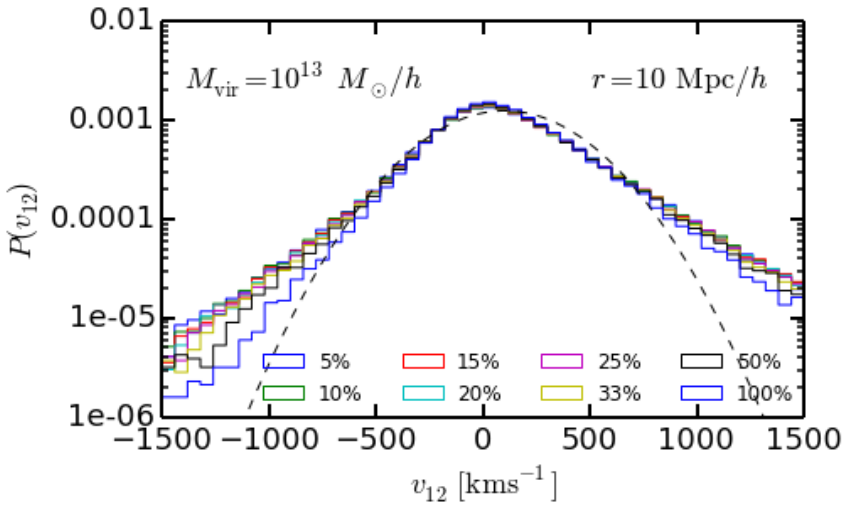
Impact of velocity definition

✦ Negligible in cen-cen pairs

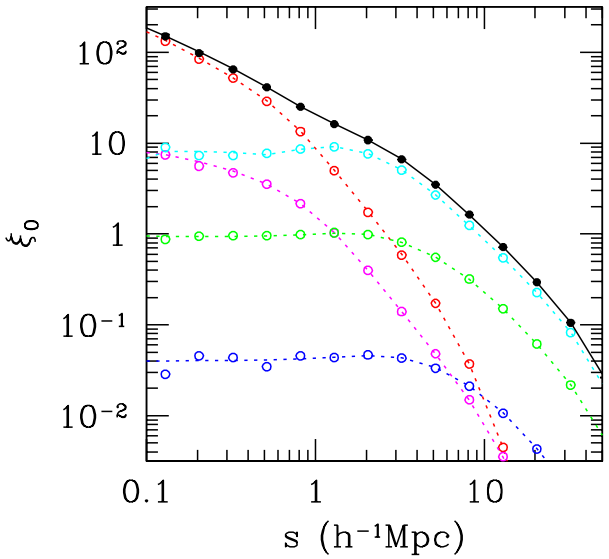
Campbell, **SS**, Hearin+, in prep

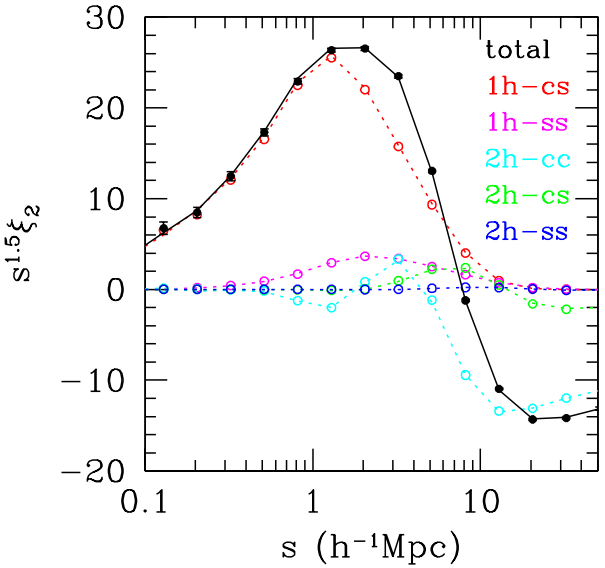
$$1+\xi(r_{\rm p},\pi)=\int dy[1+\xi(r)]\mathcal{P}(v_{12},\mathbf{r})$$





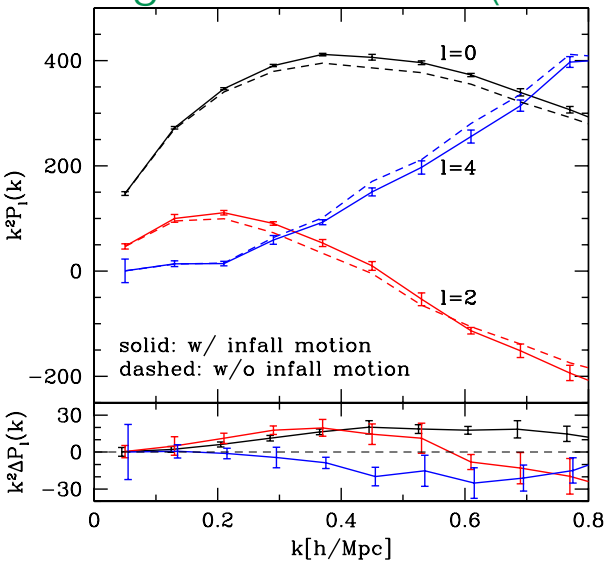
✦ cen-sat pairs? Zheng & Guo (2015)





✦ subhalo infall

Hikage & Yamamoto (2015)



Summary

- A realistic model of the CMASS-Halo connection is essential

- The CMASS SMFs in S82MGC varies as a function of z, therefore a simple SHAM ('Stochastic Color') model is ruled out

- Hope is a conditional SHAM such as *age matching* by introducing correlation b/w galaxy color & halo formation epoch

- However, there are caveats at massive end:
  - no unique definition of "halo age"
  - ambiguity to define "velocity" of subhalo (or galaxy)

Stay Tuned!