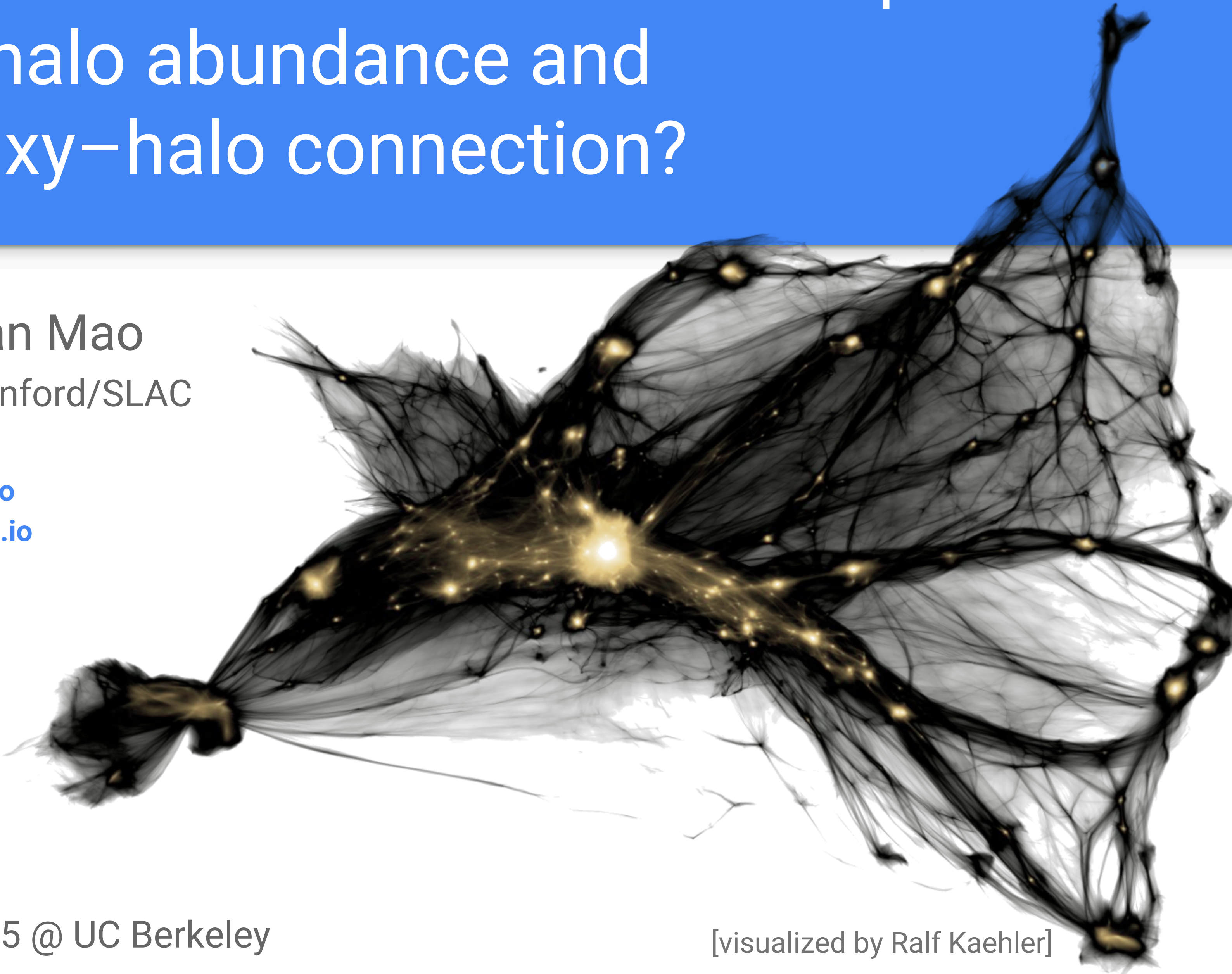
How does halo concentration impact subhalo abundance and galaxy–halo connection?

Yao-Yuan Mao
KIPAC/Stanford/SLAC

@yaoyuanmao
yymao.github.io



10/13/2015 @ UC Berkeley

[visualized by Ralf Kaehler]

What do I do?

- ➔ Run dark matter simulations
- ➔ Extract information from simulations
- ➔ Bridge the gap between simulations and observations by modeling the “unknowns”
- ➔ Use observations to constrain these “unknowns”

What are the questions I want to answer?

Eventually:

➔ Nature of dark matter
➔ Detailed physics involved in galaxy formation

Currently:

➔ How to combine the power from a diverse set of observations
➔ What new observations do we need to answer those “eventually” questions

Simulations and models are the theoretical ground for these questions.

Outline

How does halo concentration impact subhalo abundance and the galaxy–halo connection?

Halo Concentration

Simulations

Subhalo abundance

- ➔ Small-scale scatter
- ➔ Halo-to-halo scatter
- ➔ Model the concentration dependence
- ➔ Implications

Galaxy–halo connection

- ➔ Subhalo Abundance Matching
- ➔ Model the concentration dependence
- ➔ Constraints from galaxy statistics
- ➔ Implications

Outlook

Summary

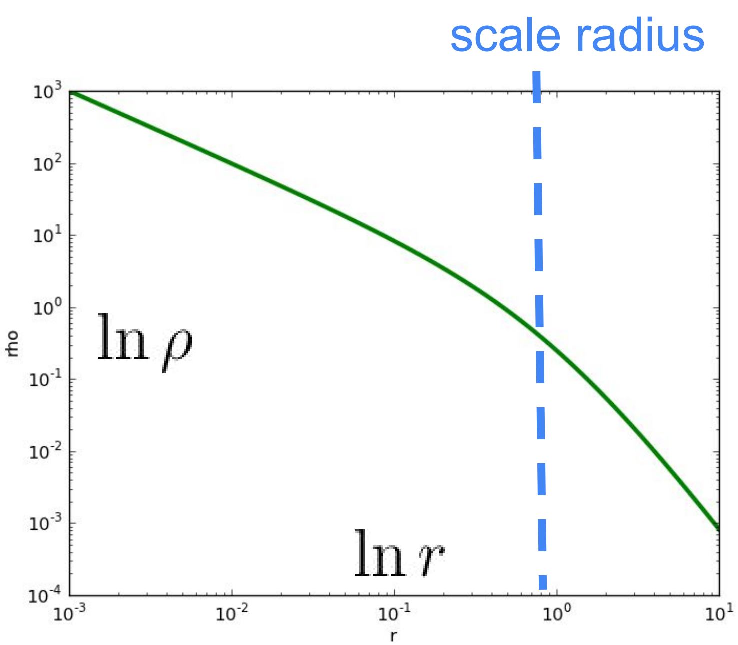
Halo Concentration

Halo concentration

- ➔ A dimensionless parameter characterizing how concentrated the halos are.

- ➔ Concentration is defined as the ratio between the halo radius to the "scale radius"
- ➔ Universal density profiles of DM halos, described by the Navarro–Frenk–White (NFW) profile
- ➔ NFW profile is characterized by a "scale radius"

$$\rho(r) = \frac{\rho_s}{(r/r_s)(1+r/r_s)^2}$$



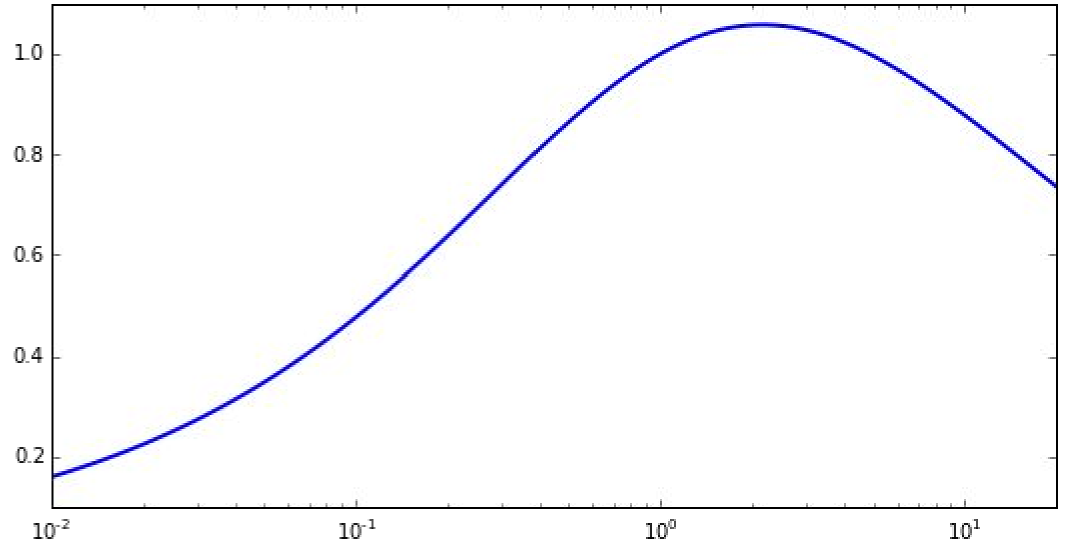
Halo concentration

- Concentration also relates to the maximal circular velocity
- The ratio between "v-max" and "v-vir" is a representation of concentration

- The circular velocity is another way to characterize the density profile

$$v(r) = \sqrt{\frac{GM(<r)}{r}}$$

- For NFW(-like) profile, there is a "maximum circular velocity" (v-max)

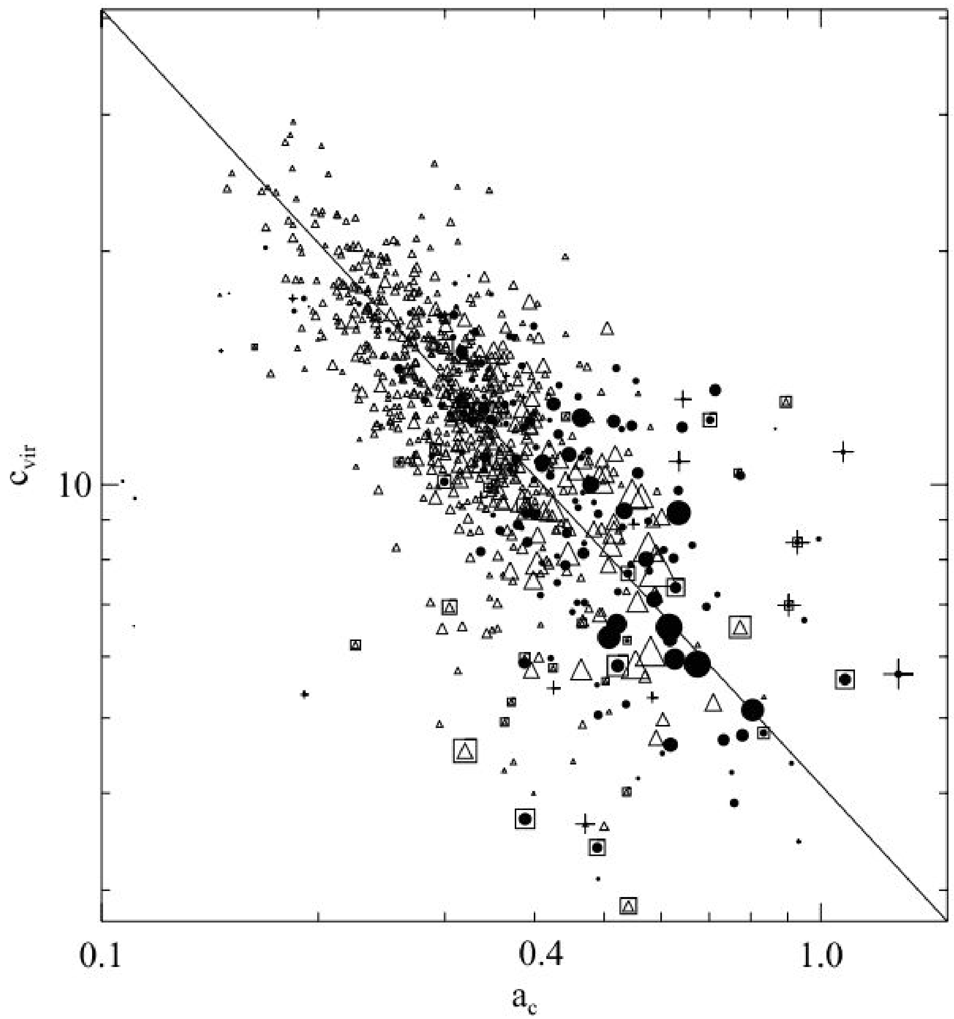


$$\frac{v_{\rm max}}{v_{\rm vir}} = \left[0.2162166\left(\frac{\ln(1+c)}{c} - \frac{1}{1+c}\right)^{-1}\right]^{1/2}$$

Halo concentration

- Halo concentration correlates with halo formation histories, and more generally the environment.

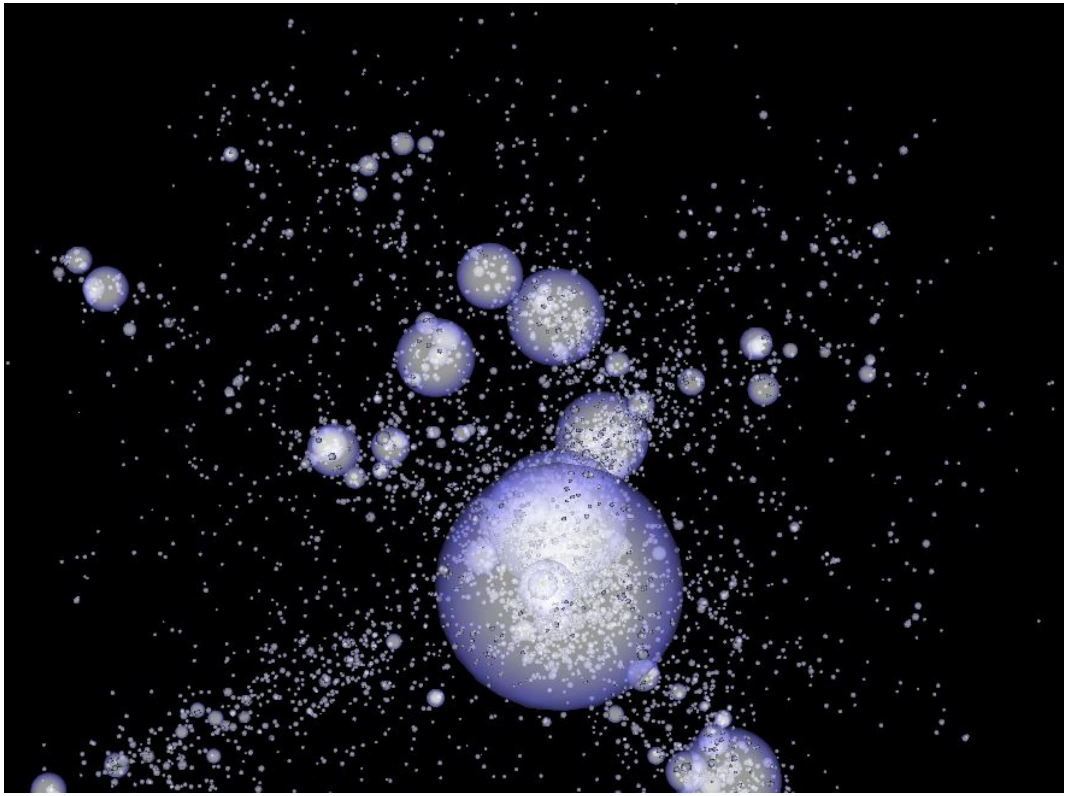
- Halos form early are more concentrated.

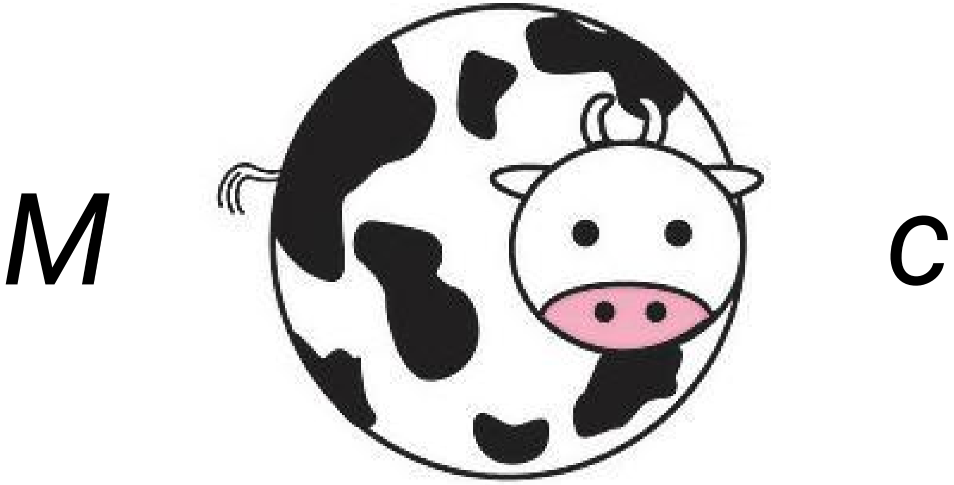


[Wechsler+ 2002]

Halo concentration

→ Mass and concentration are the two most important quantity to describe a halo

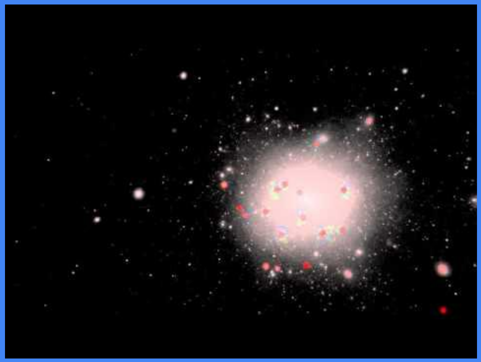




Simulations

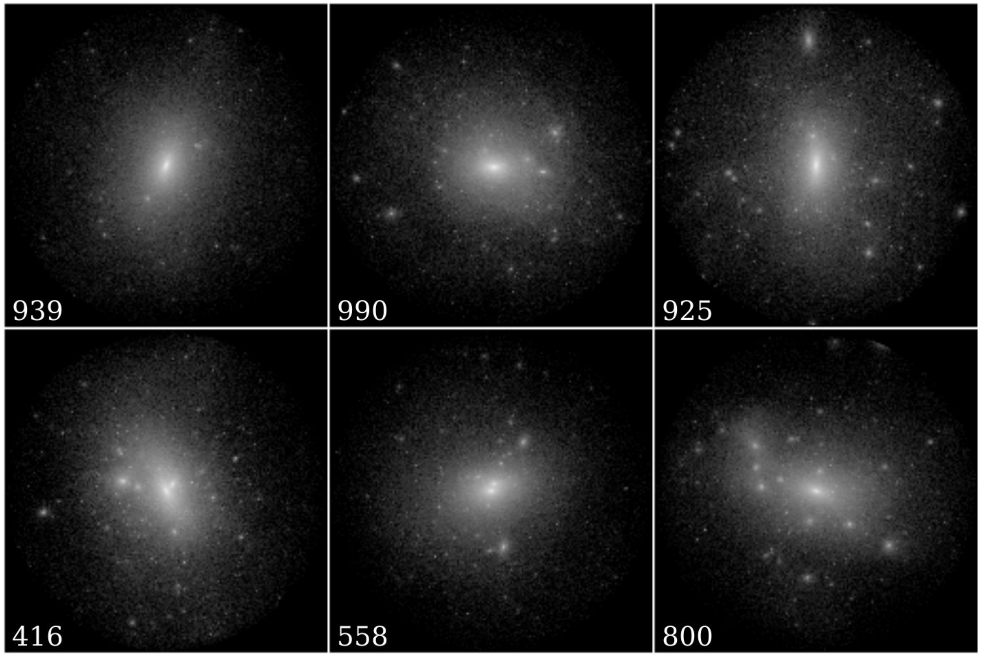
Simulations

- Dark matter only
- Analyzed with Rockstar and Consistent Trees



45 Milky Way-size zoom-in simulations

- mass resolution at $3 \times 10^5\ M_\odot/h$
- selected from a 125 Mpc/h box
- a wide range of accretion histories



Simulations

- ➔ Dark matter only
- ➔ Analyzed with Rockstar and Consistent Trees

Cosmological simulations

"Chinchilla" suite:

- ➔ Run by Matthew Becker, with L-Gadget
- ➔ 2048^3 particles; 125/250/400 Mpc/*h*

"Dark Sky" suite:

- ➔ Run by Skillman, Warren, Turk et al., with 2HOT
- ➔ 4096^3 particles; 400 Mpc/*h*
- ➔ 10240^3 / 2048^3 particles; 1000 Mpc/*h*

"MultiDark" & "Bolshoi"

- ➔ Run by Klypin et al., with L-Gadget and ART
- ➔ 2048^3 particles; 250 Mpc/*h*
- ➔ 3840^3 particles; 1000 Mpc/*h*

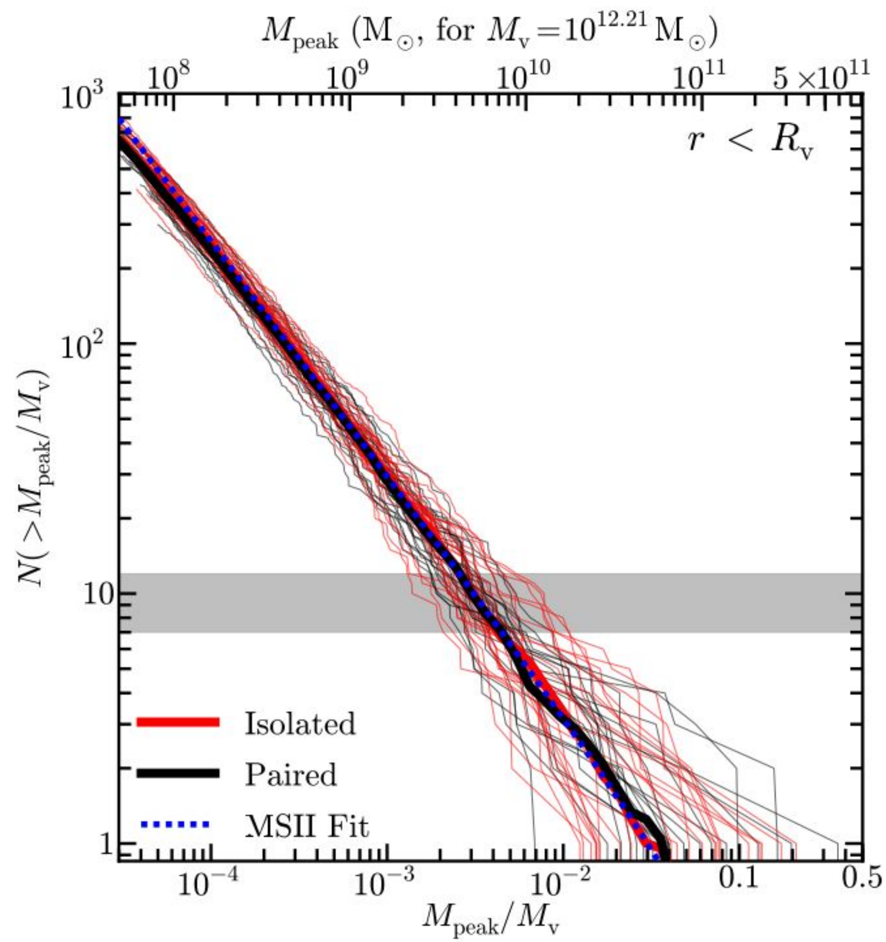
Subhalo abundance

with Marc Williamson and Risa Wechsler

arXiv:1503.02637 (ApJ, 2015)

Subhalo abundance functions

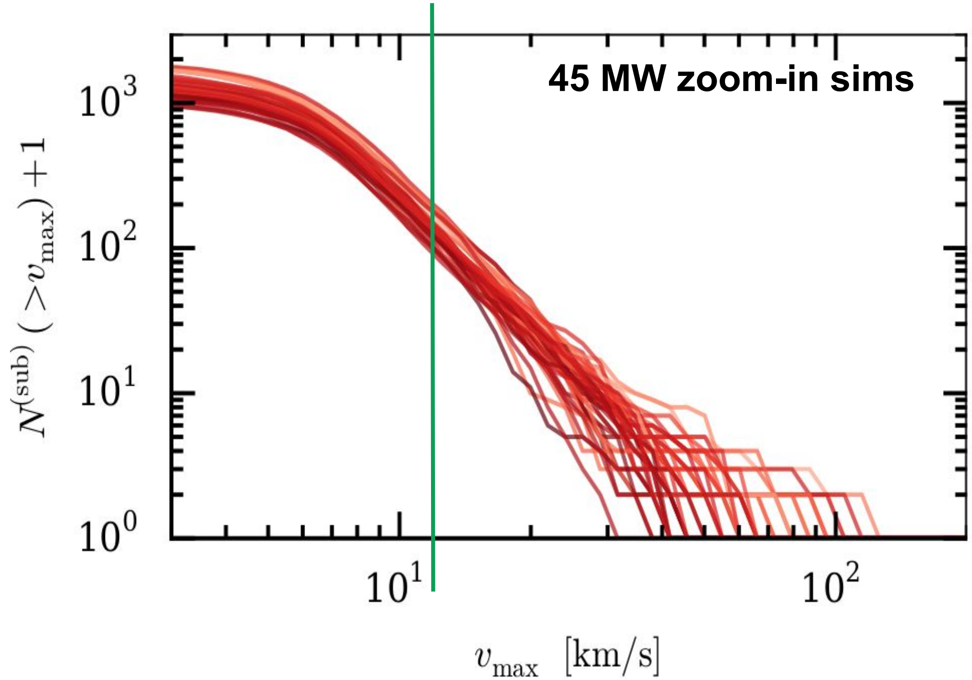
- Subhalo abundance function is the cumulative function of number of subhalos inside a host halo
- Roughly agree with a universal power-law when scaled properly
- Significant halo-to-halo scatter

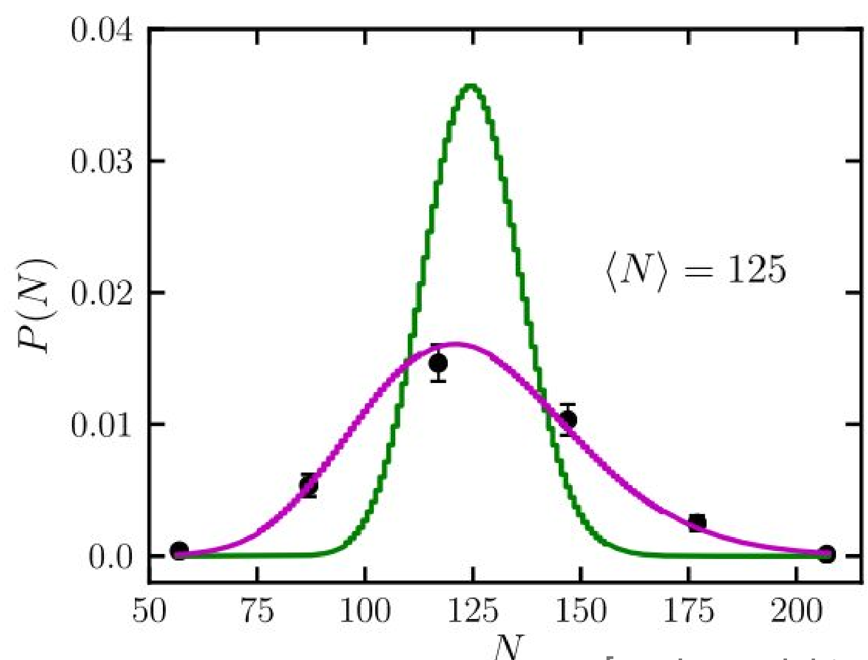


ELVIS [Garrison-Kimmel+ 2014]

Scatter in subhalo abundance

- At a given halo mass, there exists halo-to-halo scatter in subhalo abundance
- This scatter appears to super-Poissonian
- What's the origin of this scatter?

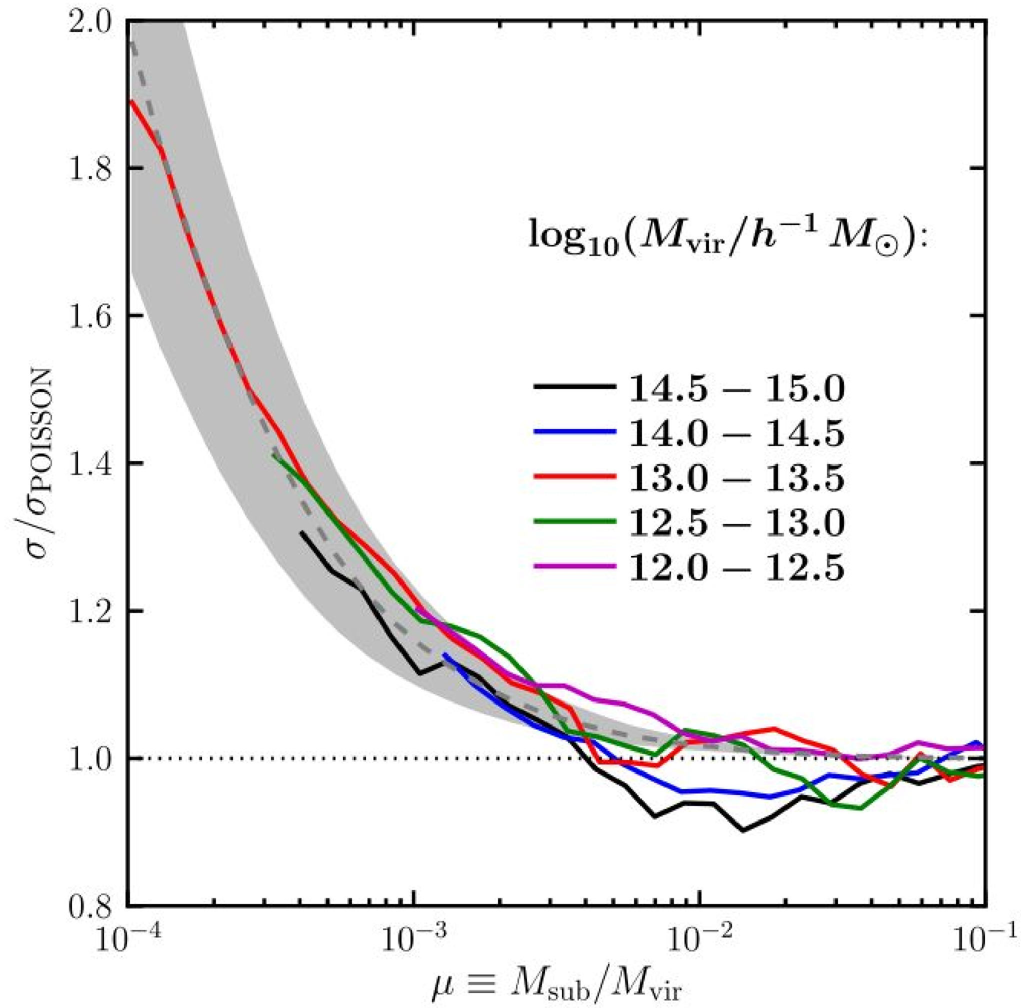




[Boylan-Kolchin+ 2010]

Scatter in subhalo abundance

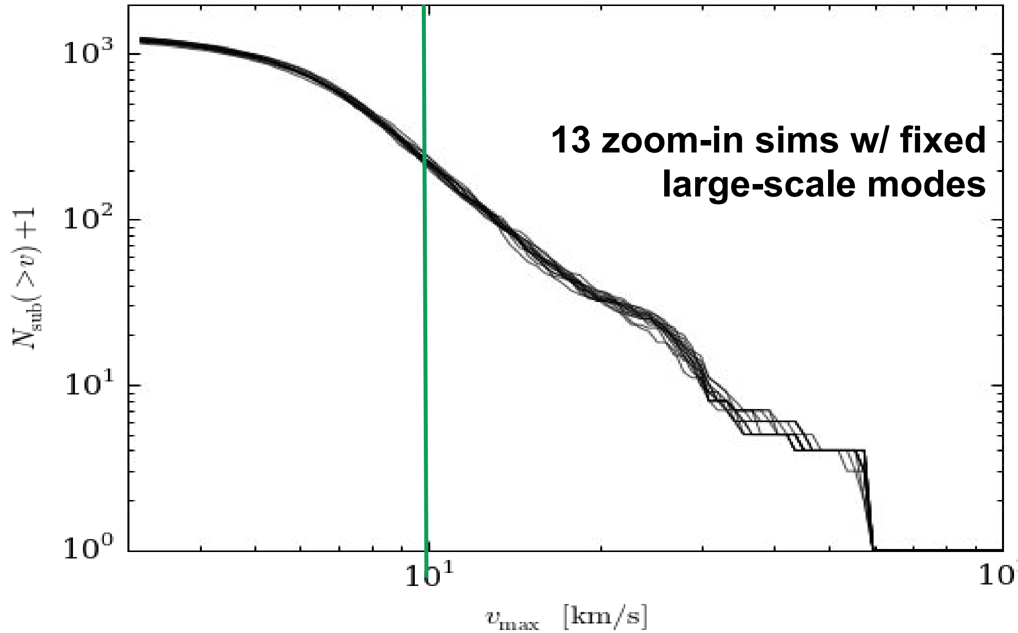
- ➔ At a given halo mass, there exists halo-to-halo scatter in subhalo abundance
- ➔ This scatter appears to super-Poissonian
- ➔ What's the origin of this scatter?

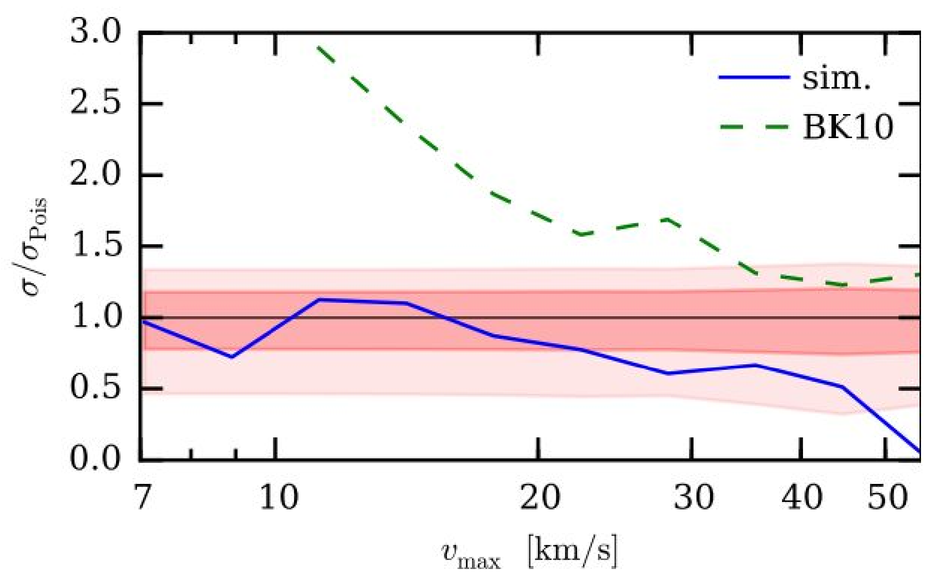


[Boylan-Kolchin+ 2010]

Small-scale scatter

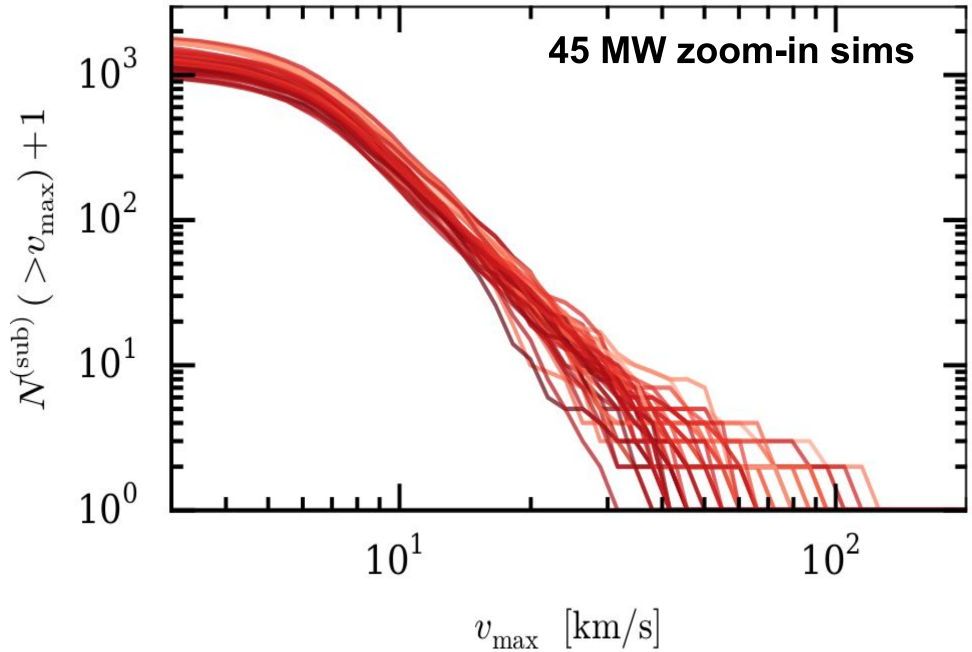
- ➔ In a fixed environment, small-scale perturbations results in Poisson scatter in the subhalo abundance function.

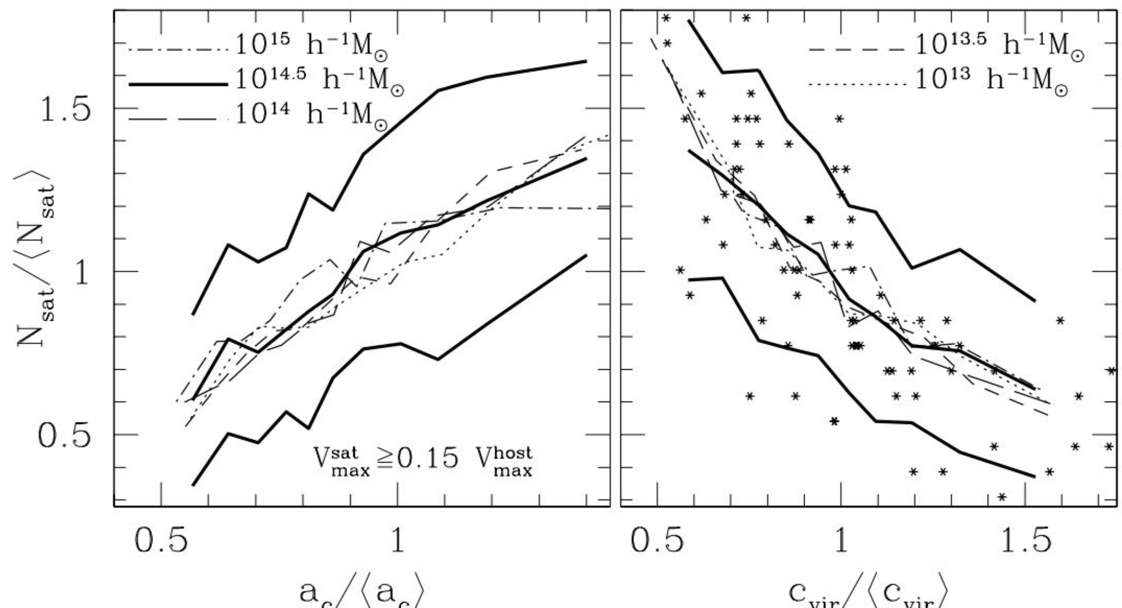




Halo-to-halo scatter

➔ High concentration halos have fewer subhalos, because the subhalos are stripped more.





[Zentner+ 2005]

Modeling the subhalo abundance function

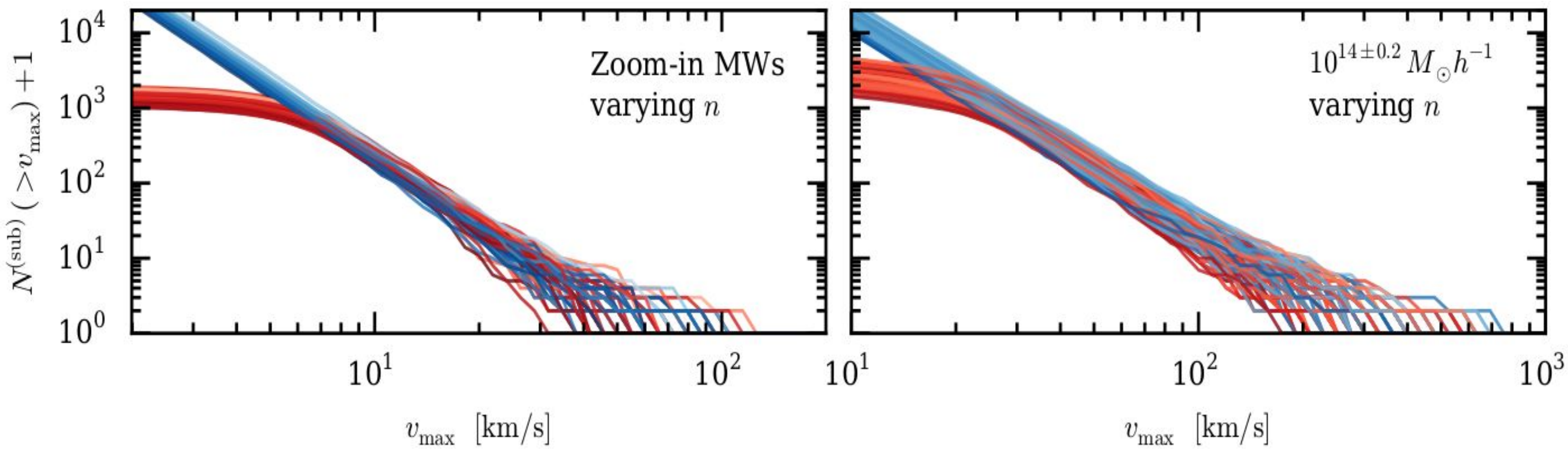
1. Halo-to-halo scatter affects mostly the normalization of the SAF
2. Normalization and host concentration are (anti-)correlated
3. The power-law index is constant (at least in a narrow mass bin)

$$\langle N(v)\rangle = \left(\frac{v}{v_0}\right)^n - \left(\frac{v_{\rm cut}}{v_0}\right)^n .$$

$$v_0 = a\, v_{\rm vir} \qquad v_{\rm cut} = b\, v_{\rm vir} \qquad n = n_0$$

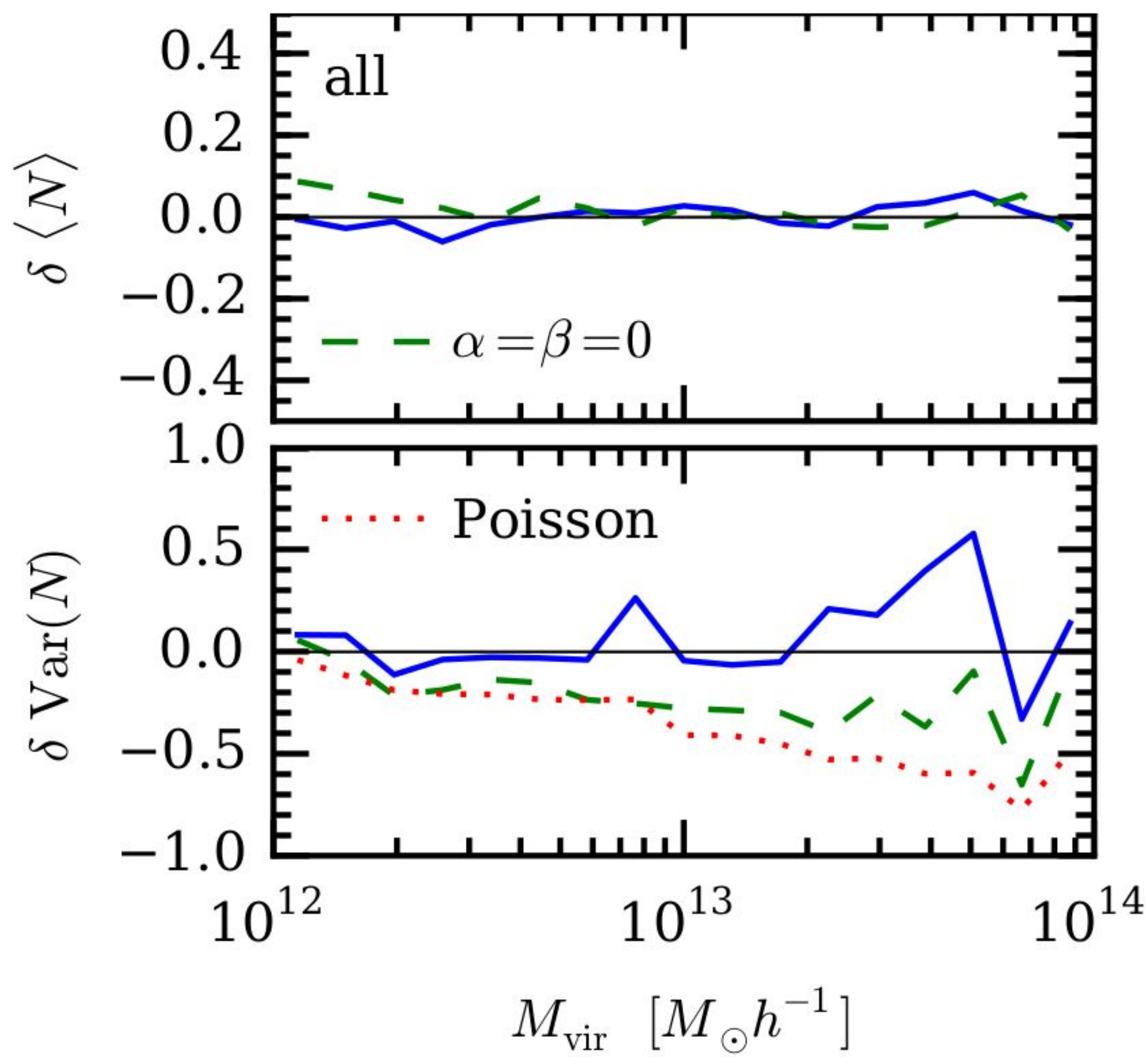
$$a := a_0 \left(\frac{v_{\rm max}}{v_{\rm vir}}\right)^\alpha \qquad b := b_0 \left(\frac{v_{\rm max}}{v_{\rm vir}}\right)^\beta$$

Combine this with the small-scale Poisson scatter, the model reproduces SAF

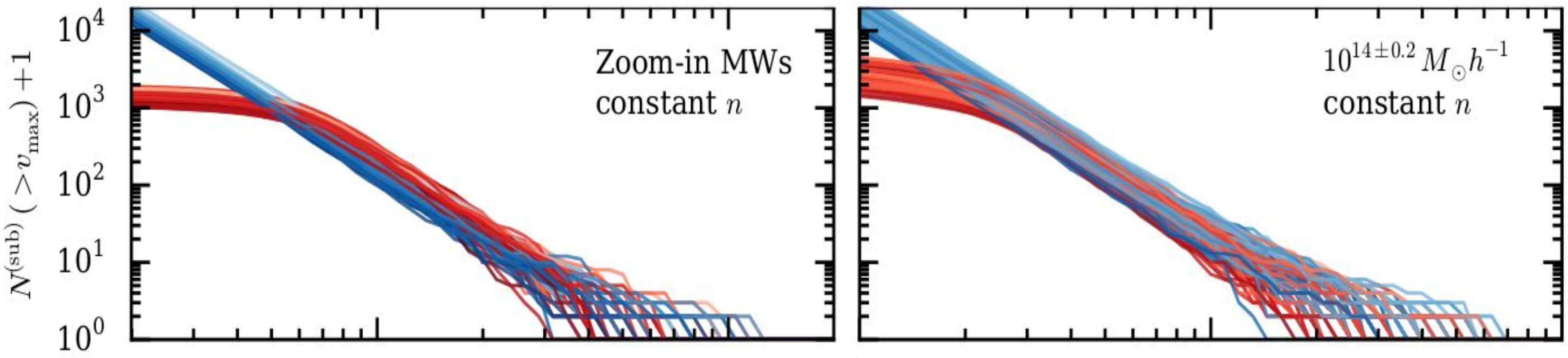


Model prediction

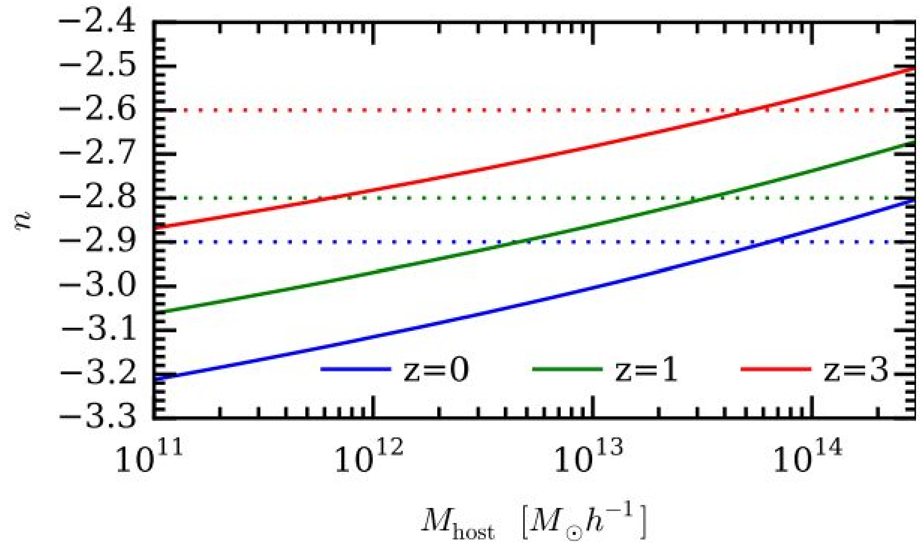
- ➔ With this model, we can match the mean and variance of the subhalo abundance in a wide range of halo mass.



Is the power-law index constant?



➔ A possible dependence of the power-law index on mass and redshift:

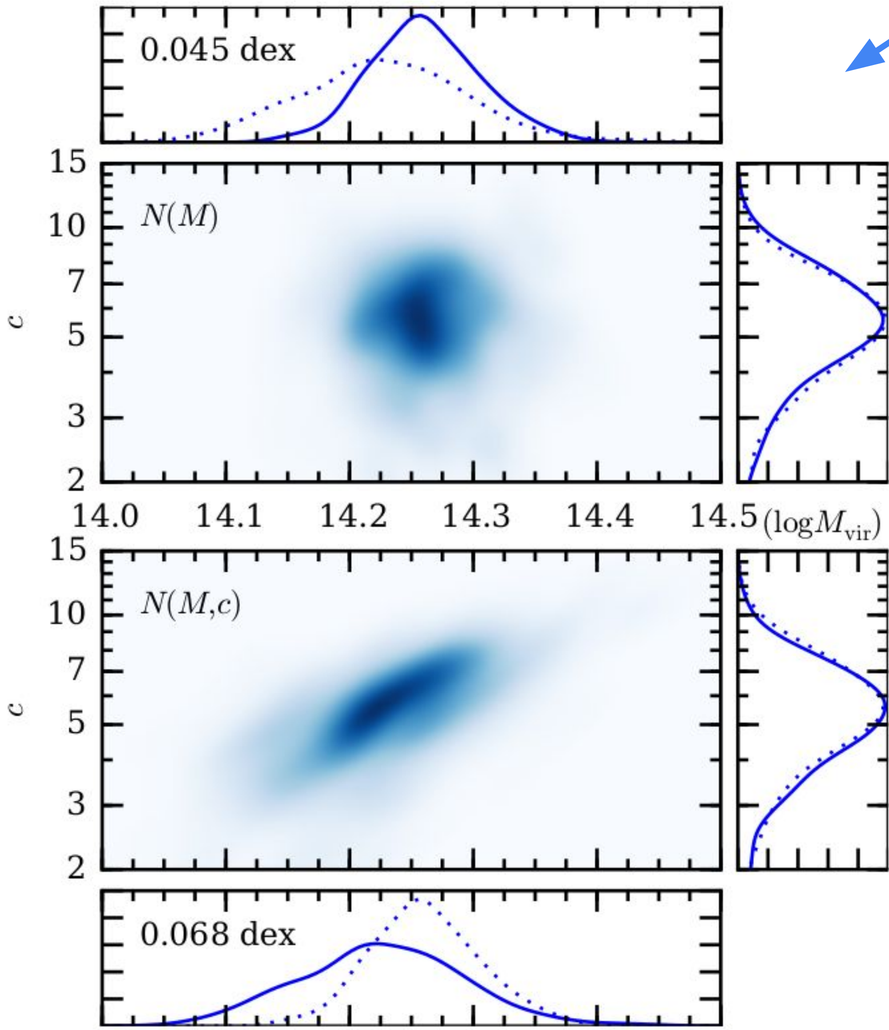


$$n = -3.05\,\nu(M,z)^{-0.1}$$

$$\nu(M,z) = \frac{\delta_c}{\sigma(M)D(z)}$$

Impact on the richness–mass relation

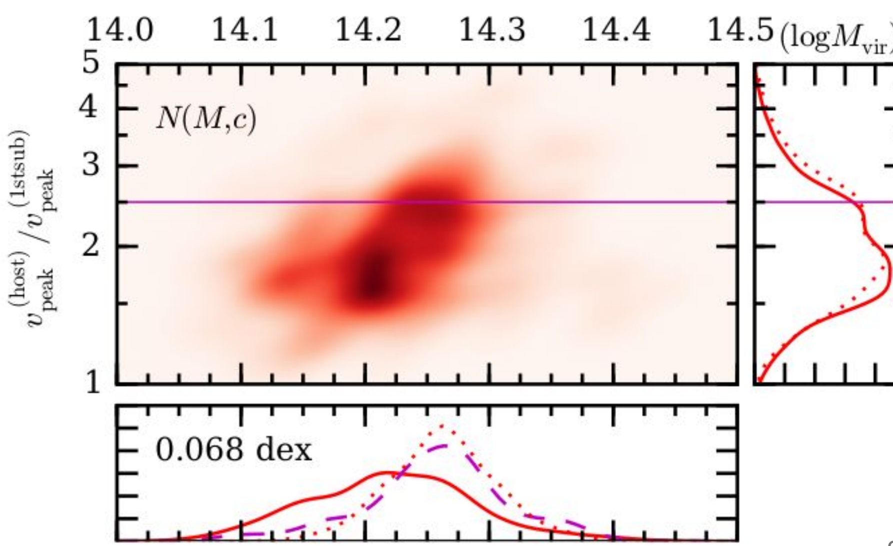
$N\ (v_{max} > 75\ \mathrm{km/s}) = 100$



Concentration–mass distribution for a “fixed-richness” sample

- ➔ Upper panels: model ***without*** concentration dependence
- ➔ Lower panels: model ***with*** concentration dependence

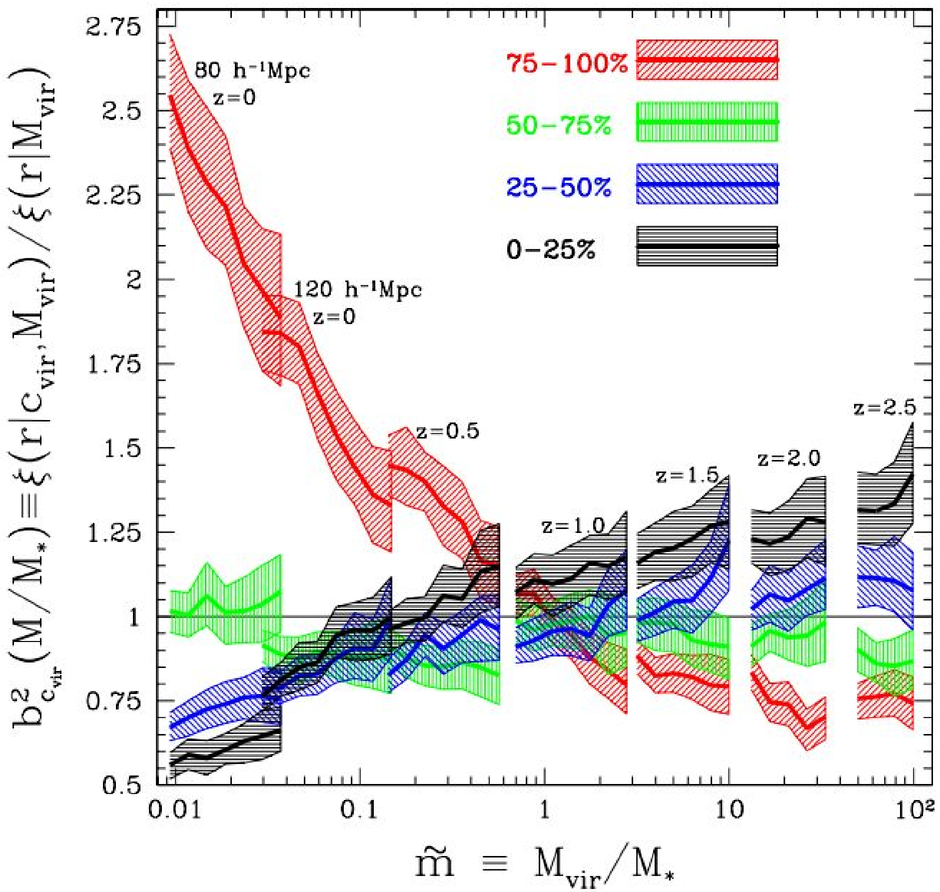
Significant differences appear in the width of predicted halo mass and in the correlation b/w mass and concentration.



Halo assembly bias

- ➔ halos that have different formation histories cluster differently
- ➔ in low-mass regime, high-concentration halos are more clustered

$$b_h(M, c) \neq b_h(M)$$



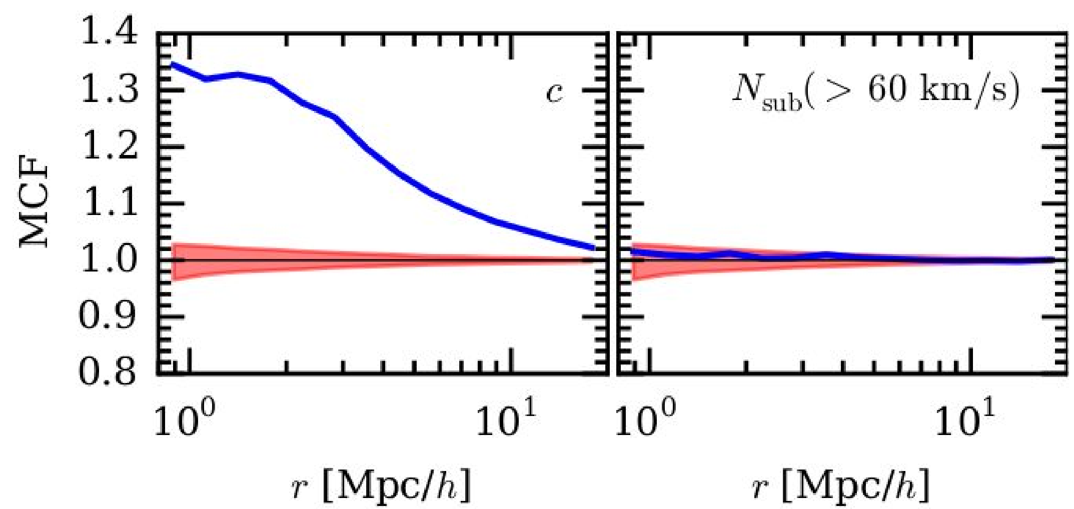
[Wechsler+ 2006]

Probing halo assembly bias

Zentner+ (2005): [...] any correlations between c, Nsat, or subhalo spatial distributions with environment are sufficiently weak that they likely do not have a measurable effect on the correlation function.

$$b_h(M, c) \neq b_h(M)$$

$$P(N_{\rm sub}|M, c) \neq P(N_{\rm sub}|M)$$



➔ Mark correlation function:

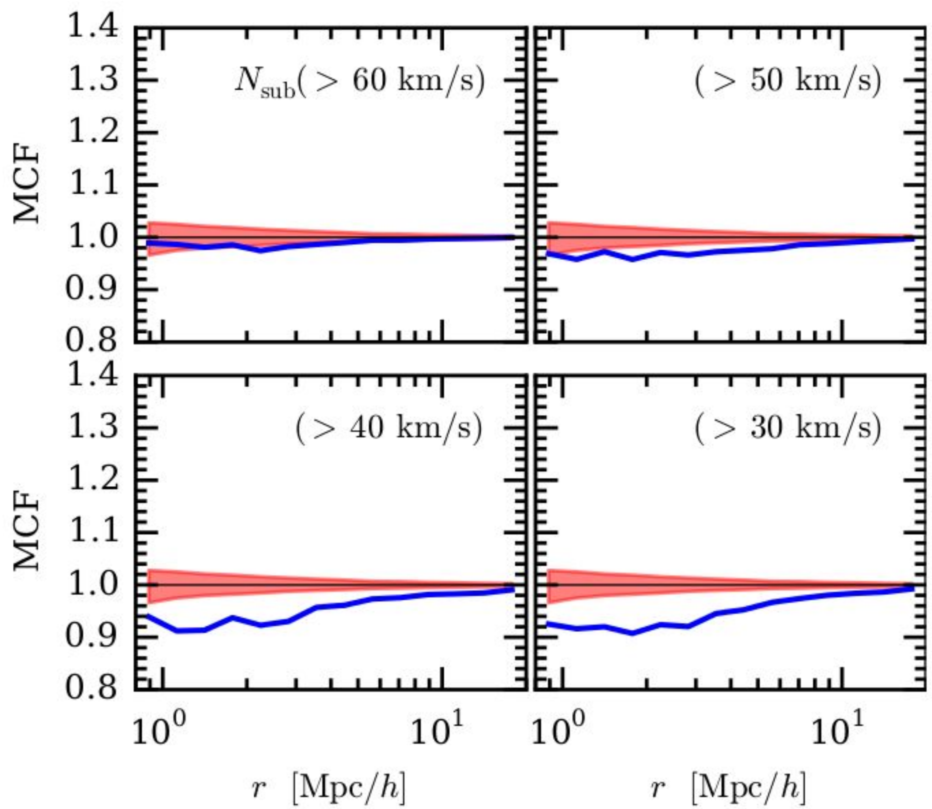
$$\mathrm{MCF}(m, r) = \sum_{(i,j)\in S_r} \frac{m_i m_j}{\bar{m}^2}$$

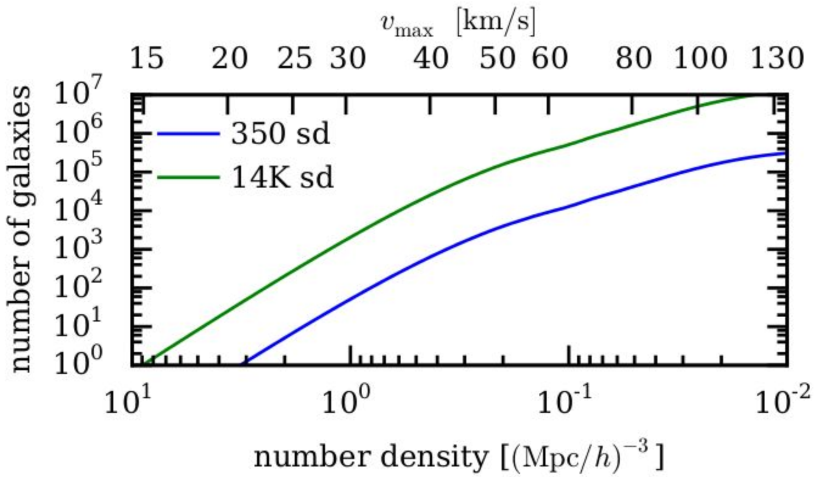
$$S_r = \{(i,j) : |\mathbf{x}_i - \mathbf{x}_j| \in [r, r+dr]\}$$

Probing halo assembly bias

Use the model to predict the MCF of subhalo counts at lower velocity cuts.

High-concentration halos have fewer subhalos, so paired halos on average would have fewer subhalos, if this effect is not diminished by Poisson noise.





Number of subhalos may be used as a robust probe for assembly bias:

- ➔ is less sensitive to the detailed galaxy--halo connection
- ➔ appears in both one- and two-halo terms and has opposite effects to these two terms

Galaxy–Halo Connection

with Ben Lehmann, Matthew Becker, and Risa Wechsler

Galaxy–halo Connection

→ Dark matter-only simulations give us the information about halos, but how about galaxies?

Hydrodynamical simulations

→ computationally expensive

→ include most physics
(but still some subgrid models)

Semi-analytical models

→ build galaxies along the merger histories

→ controlled by “physical” parameters

Empirical models

→ fewer parameters, fits to statistics directly

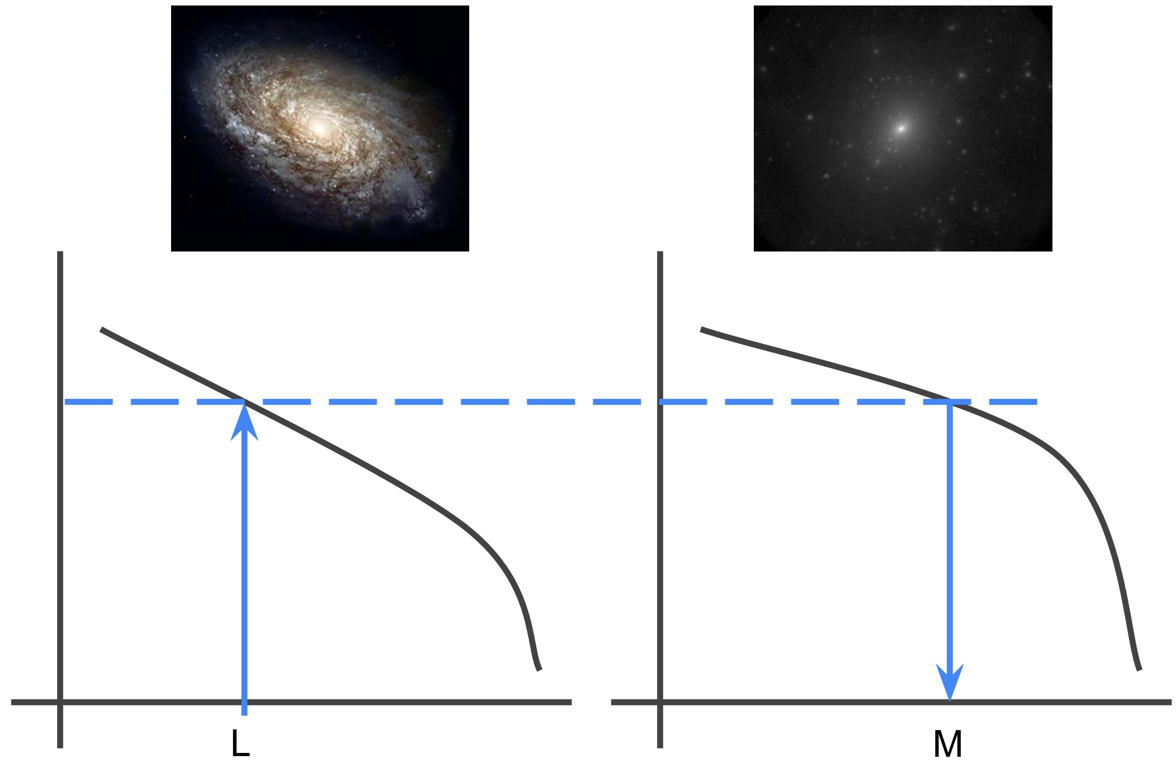
→ Halo Occupation Distribution

→ Abundance Matching

Subhalo Abundance Matching

- ➔ Connects halos galaxies assuming one halo property is strongly correlated with one galaxy property.

Kravtsov+ 2004
Vale & Ostriker 2004, 2006
Conroy+ 2006

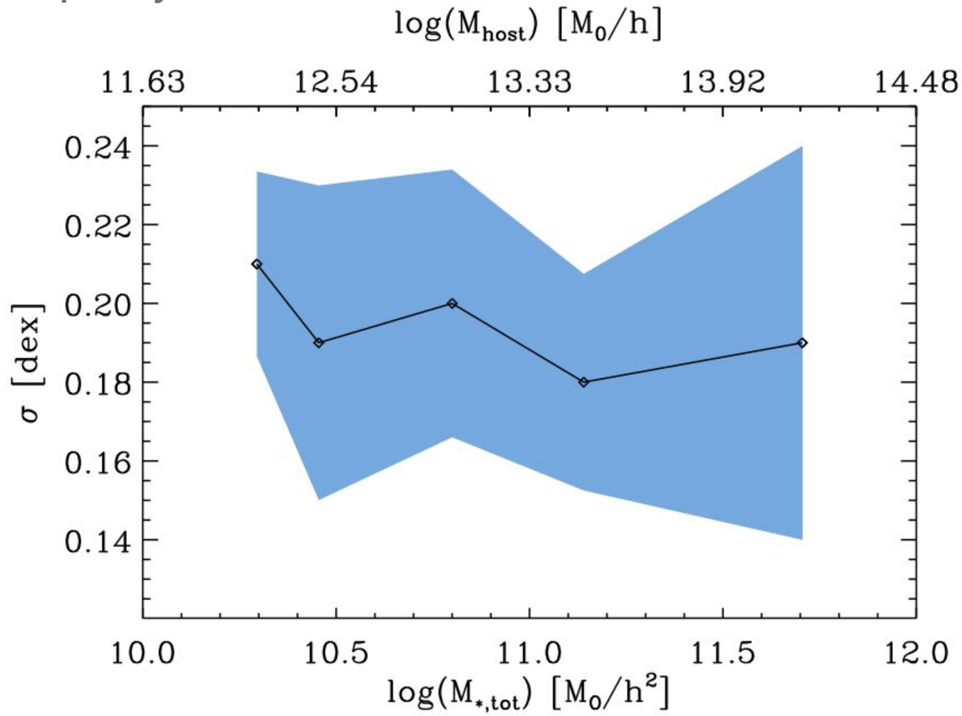


- ➔ Matching the halo proxy with galaxy luminosity (or stellar mass) at the same **number density**.
- ➔ Only the **rank** of the halo proxy matters.
- ➔ Abundance function is matched by construction, but other statistics are *not*

Scatter in SHAM

- ➔ With a constant, Gaussian scatter around 0.2 dex, SHAM provides excellent fits to galaxy statistics.
- ➔ Applying scatter reduces clustering

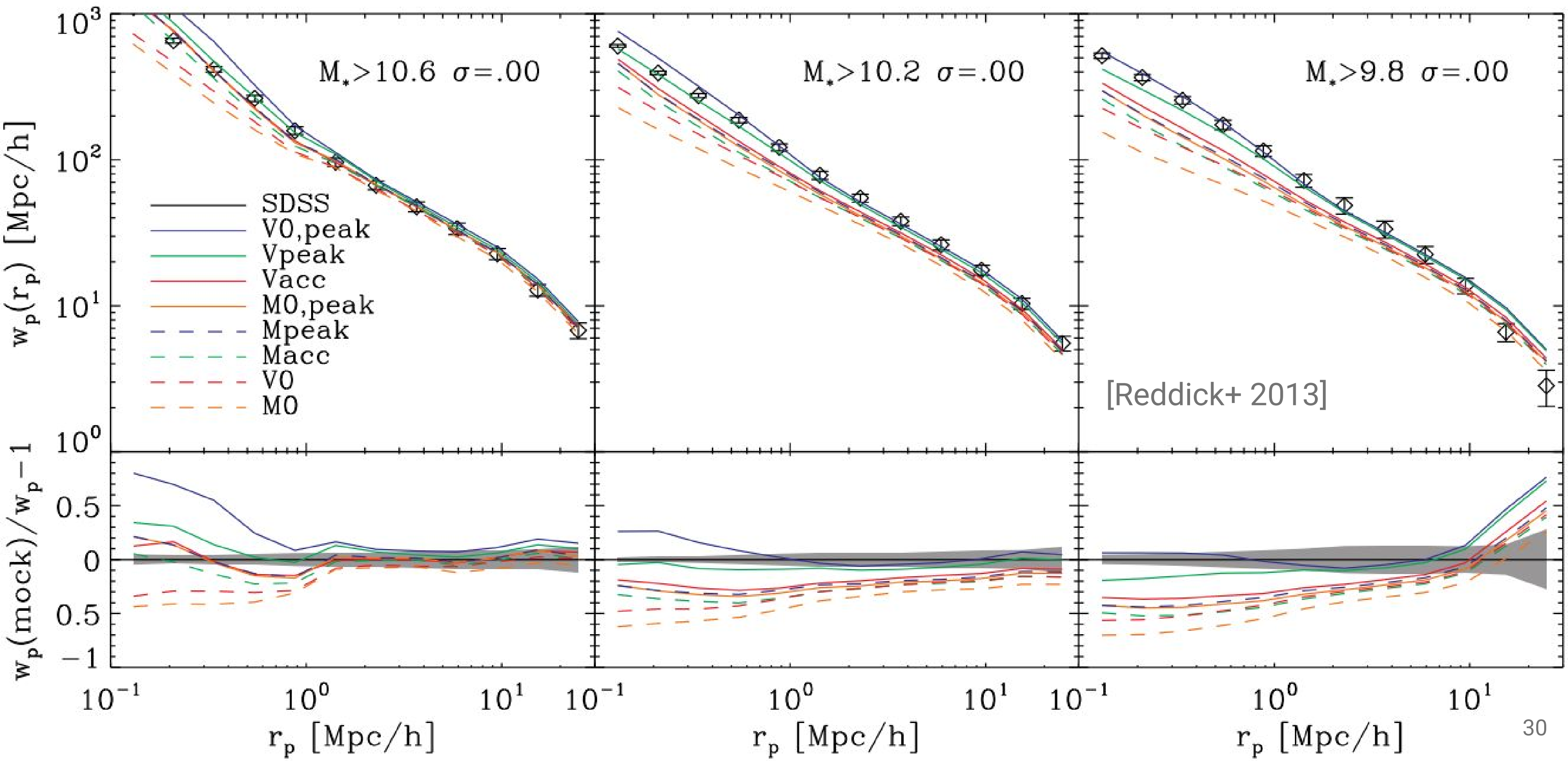
- ➔ Without scatter, the relation between the halo proxy and galaxy luminosity is monotonic and deterministic.
- ➔ Some “scatter” is needed in this galaxy-halo relation to match observed data.
- ➔ Scatter usually expressed in dex of the galaxy property at a given value of the halo proxy



[Reddick+ 2013]

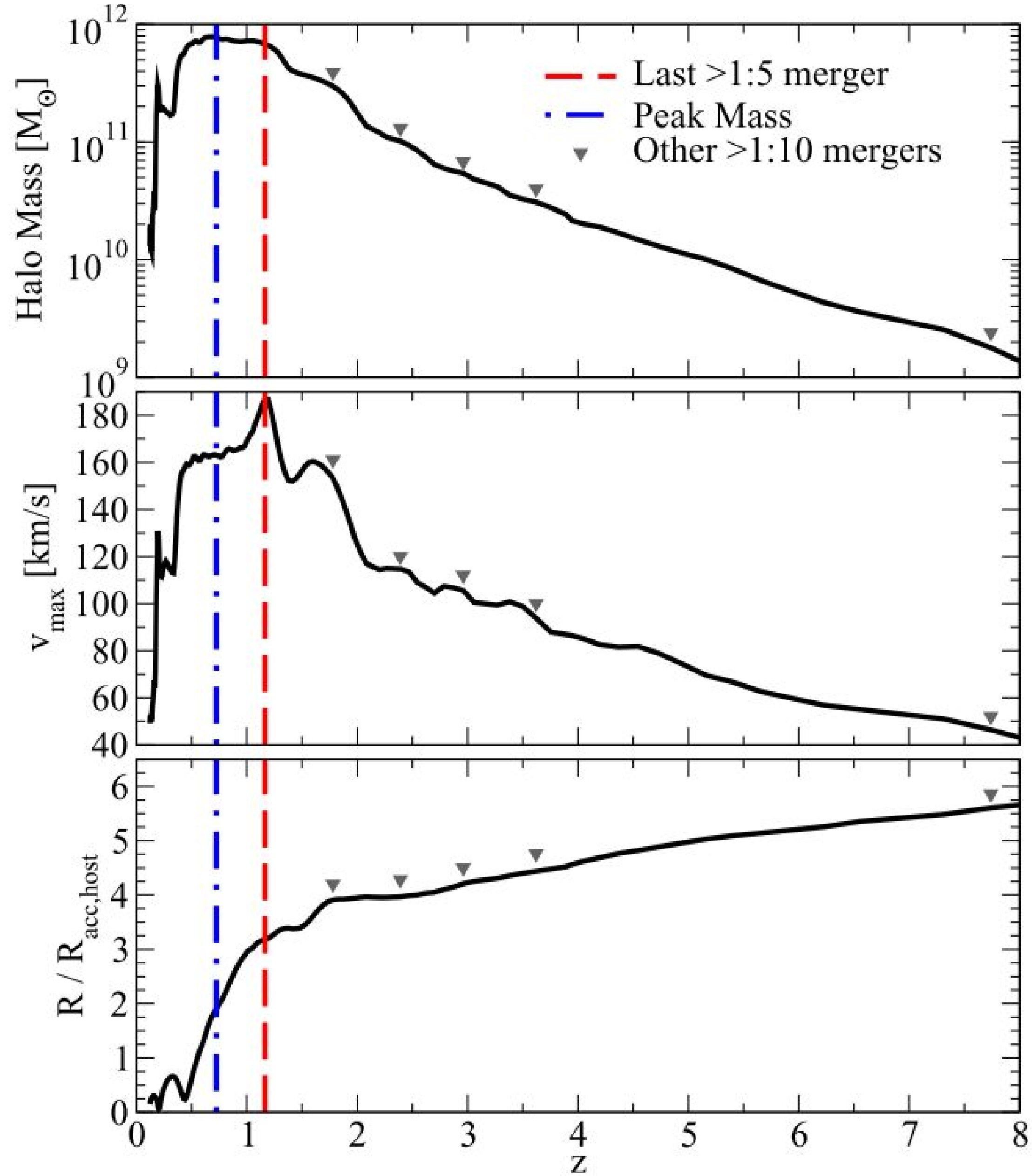
How to choose halo proxy

- ➔ Common choices are mass and circular velocity
- ➔ Reddick+ (2013) found “v-peak” to the best matching proxy



How to choose halo proxy

- ➔ Subhalos are stripped when/after entering the host halo
- ➔ Stellar content lives in a deeper potential and is less affected

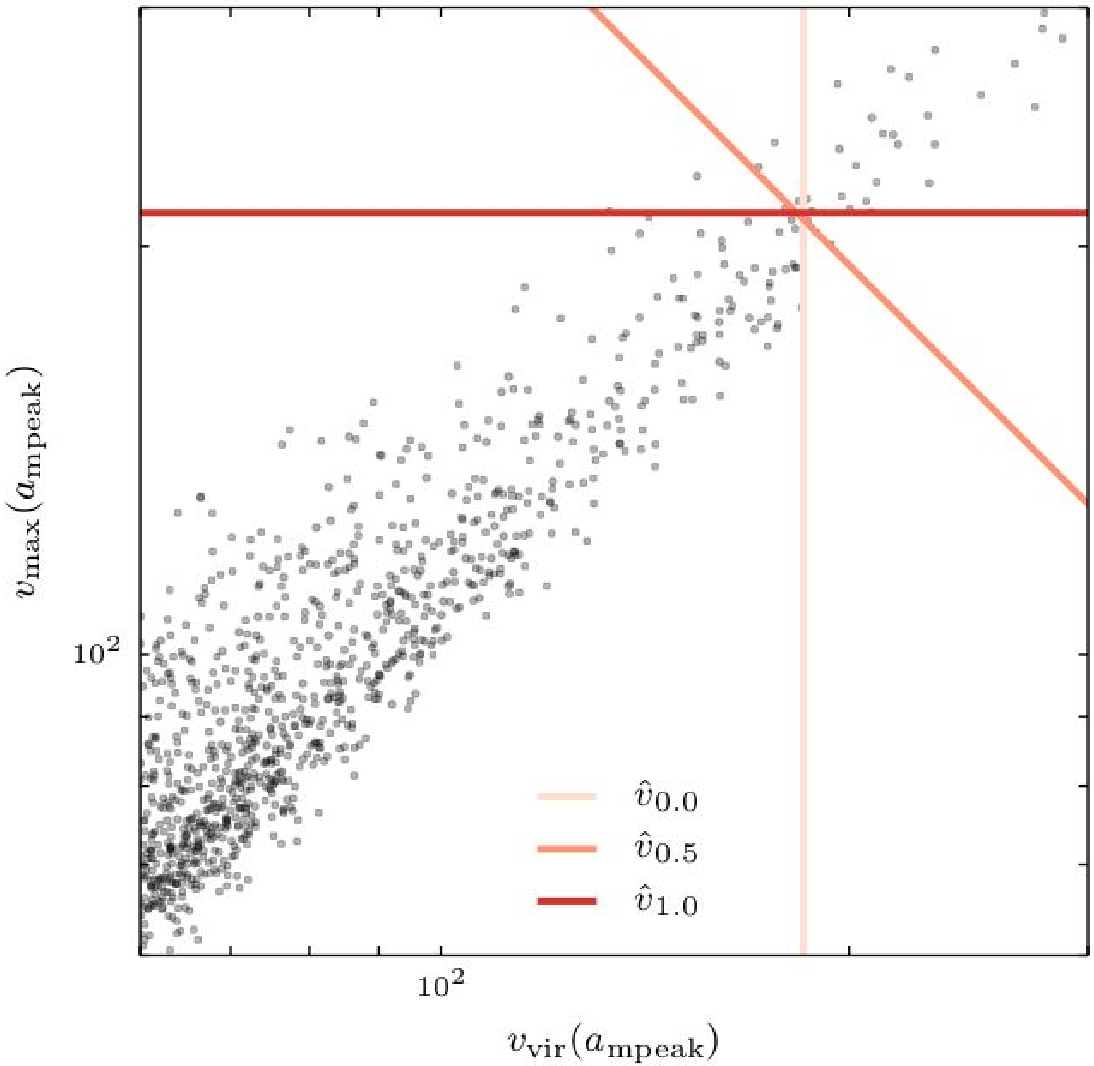


[Behroozi+ 2013]

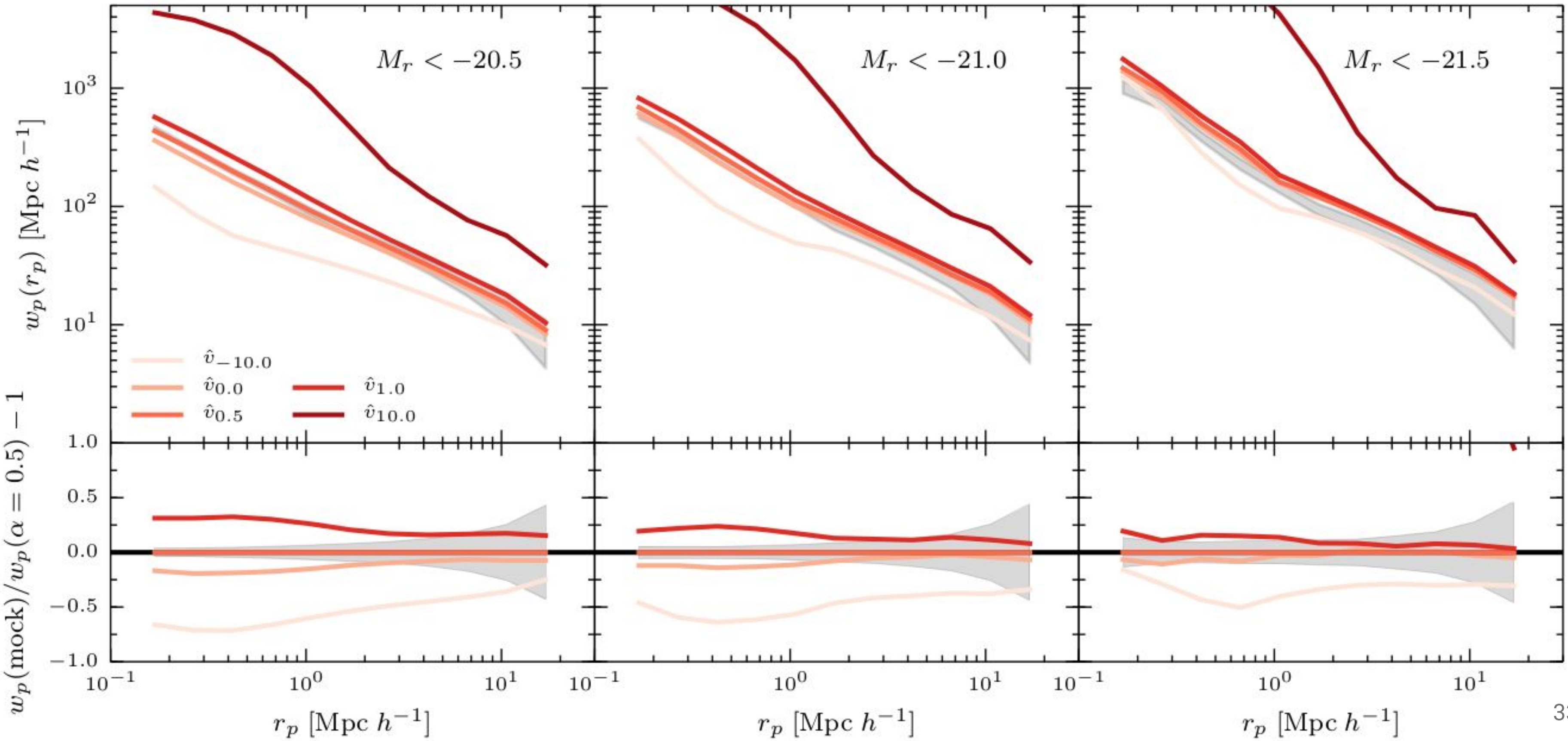
Generalize the matching proxy

- ➔ choosing between “mass” or “circular velocity” *is* changing the concentration dependence

$$v_\alpha := v_{\rm vir}\left(\frac{v_{\rm max}}{v_{\rm vir}}\right)^\alpha$$

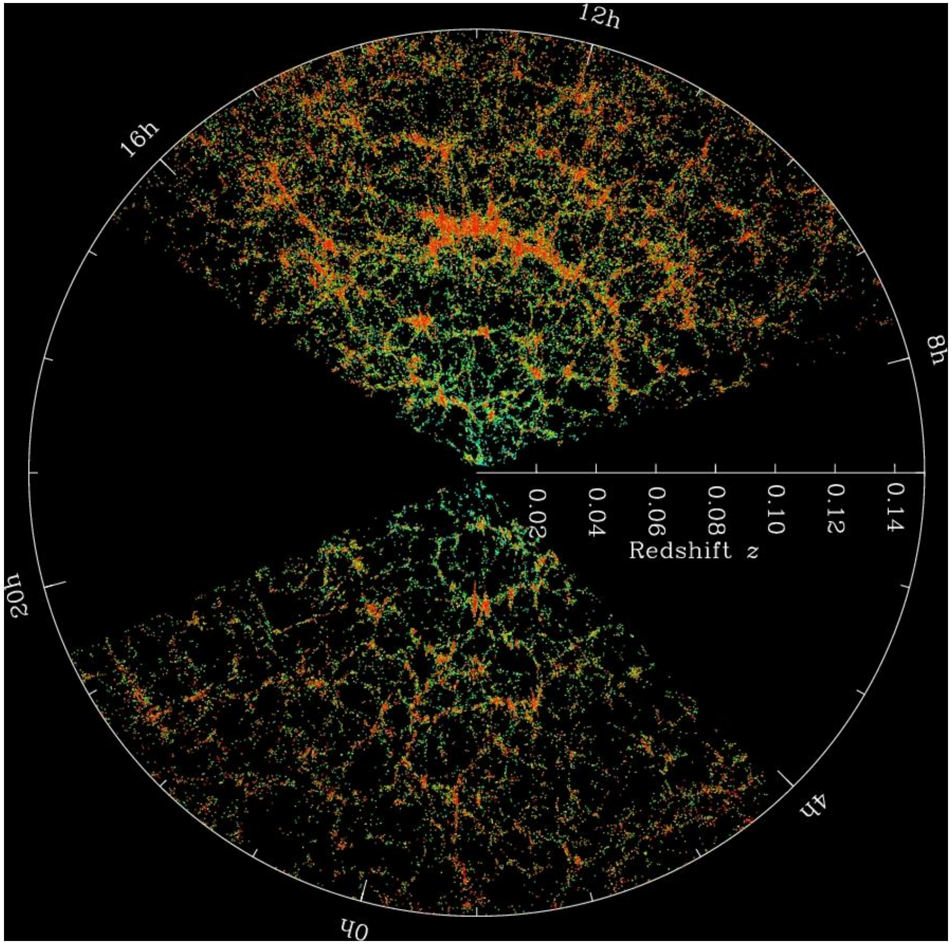


The effect on the projected correlation function of this α parameter



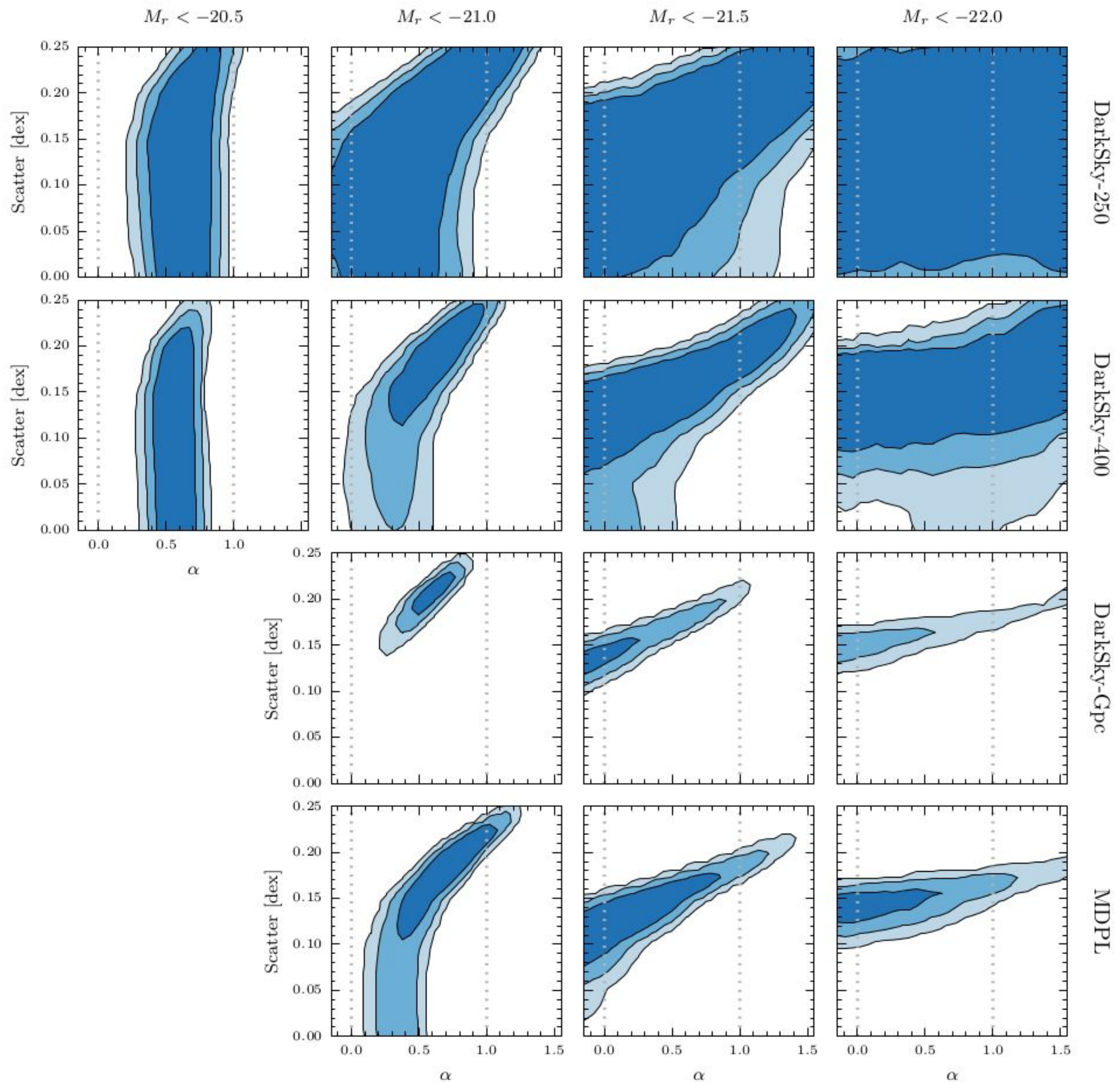
Constraints from large-scale structures

➔ Luminosity-selected sample built from SDSS DR7 [Reddick+ 2013]



Constraints on α and scatter

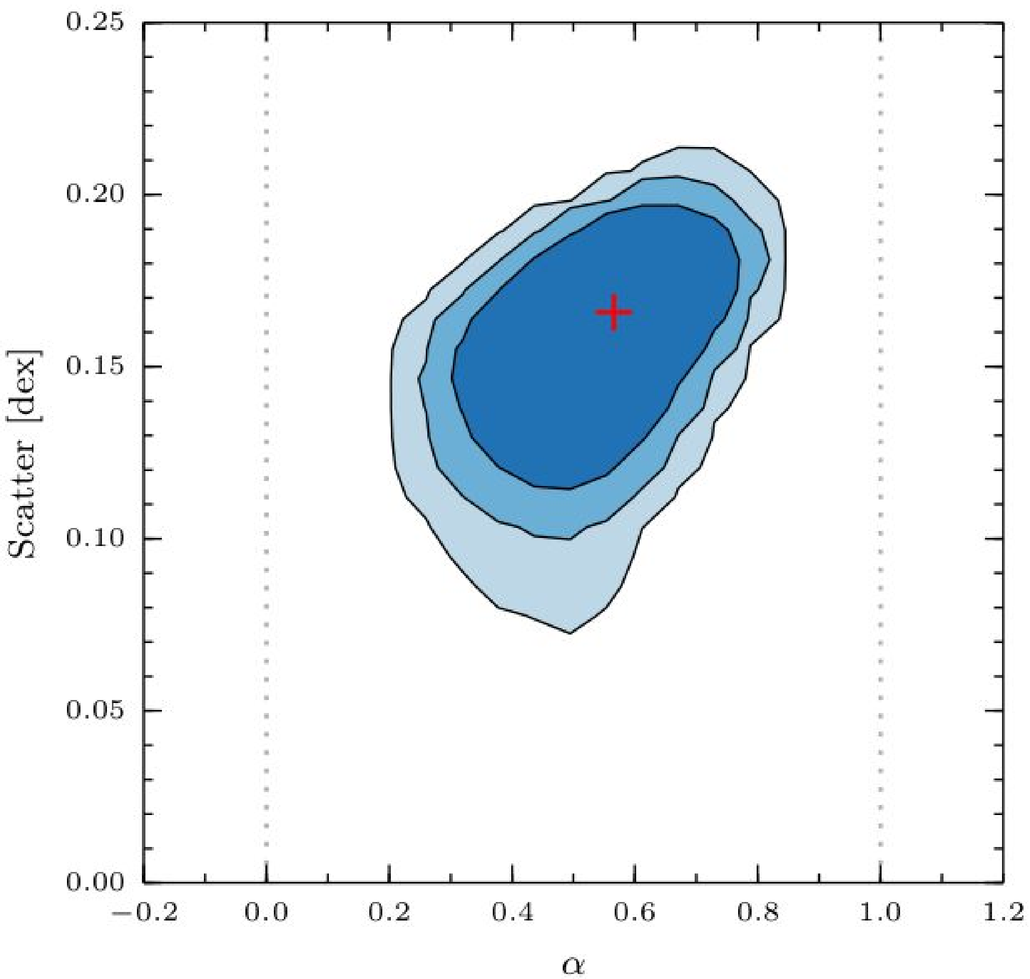
- bright sample constrains scatter more; dim sample constrains α more
- α and scatter are degenerate
- larger boxes give tighter constraints



Constraints on α and scatter

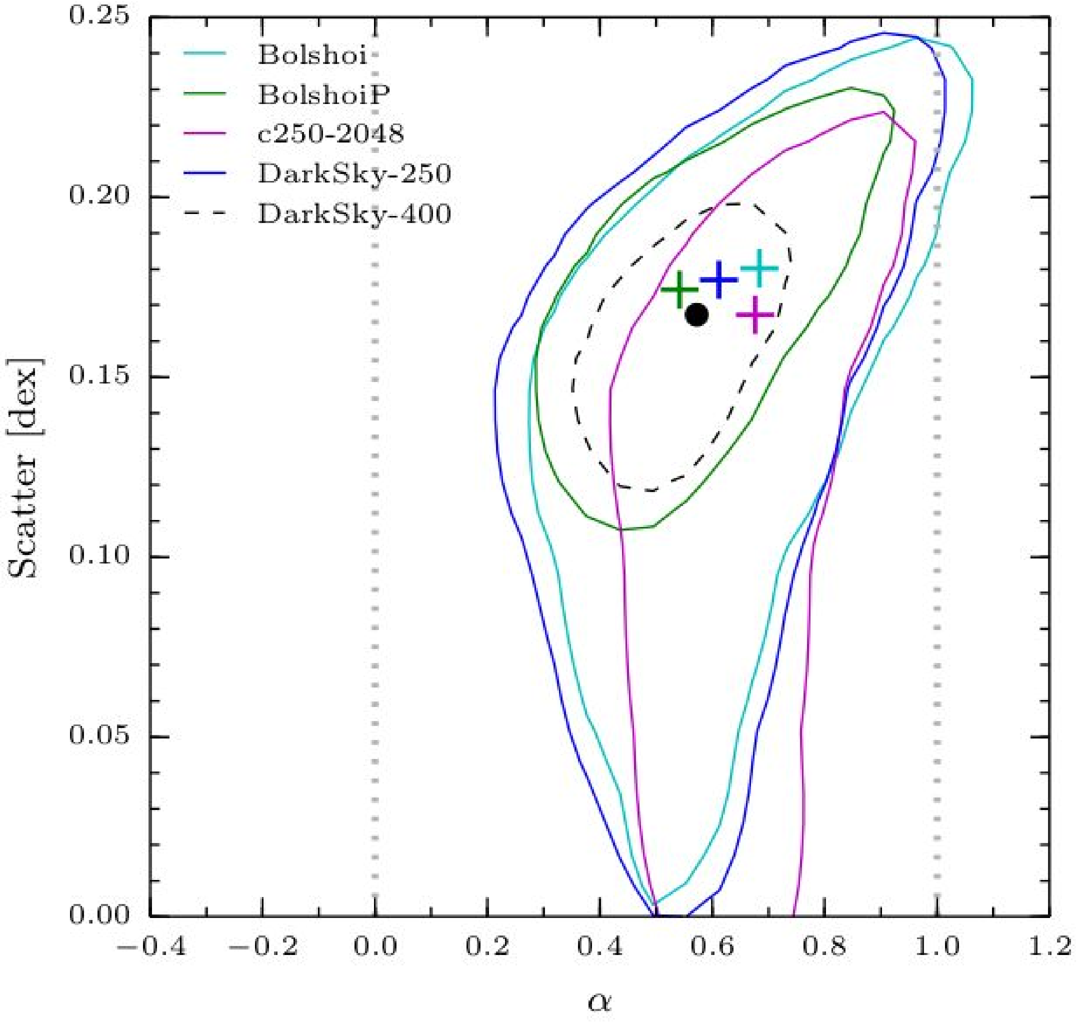
- excludes "m-peak" and "v-peak"
- best-fit α ~ 0.6
- best-fit scatter consistent with previous studies

Joint constraint on α and scatter from four luminosity-selected samples, with the Dark Sky-400 box

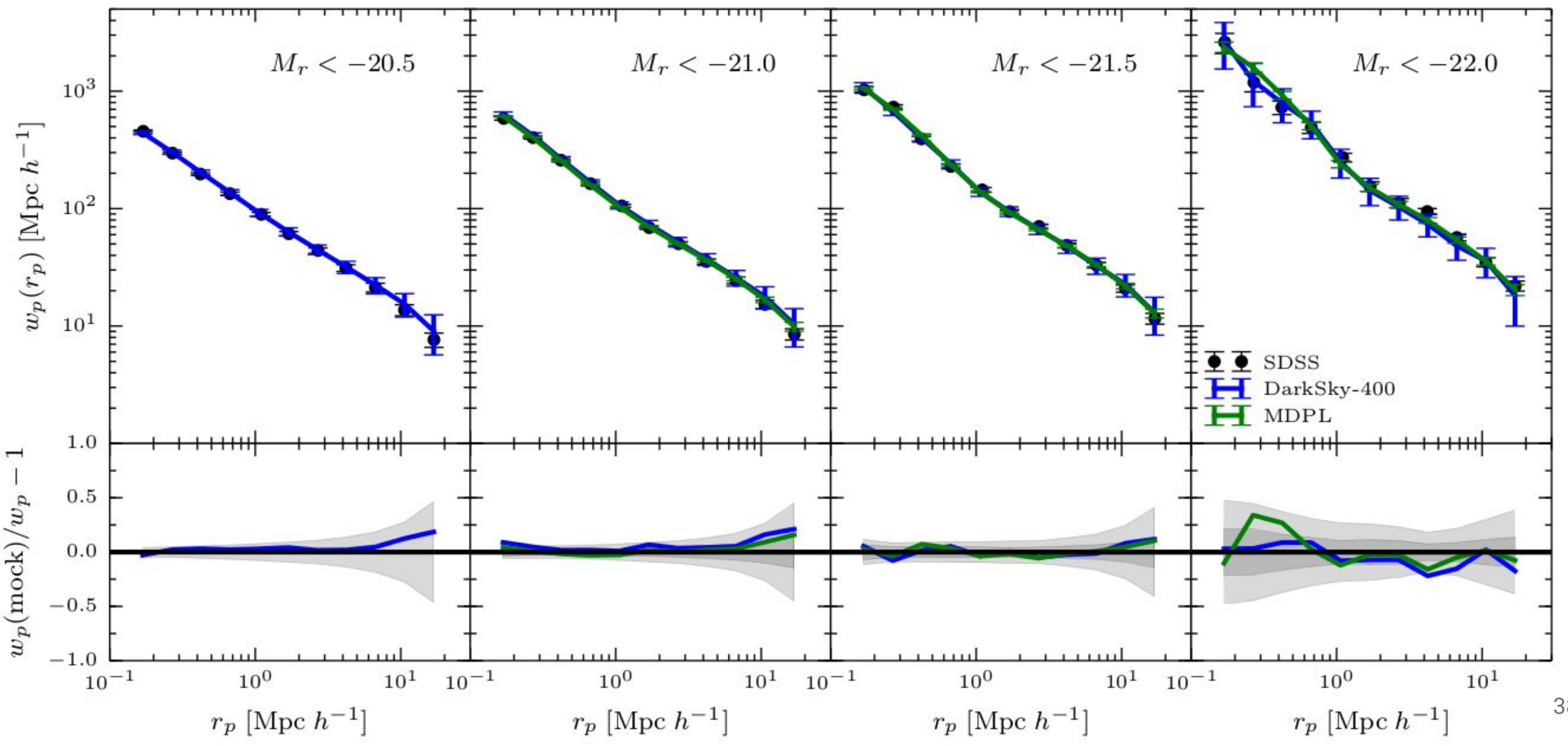


Constraints on α and scatter

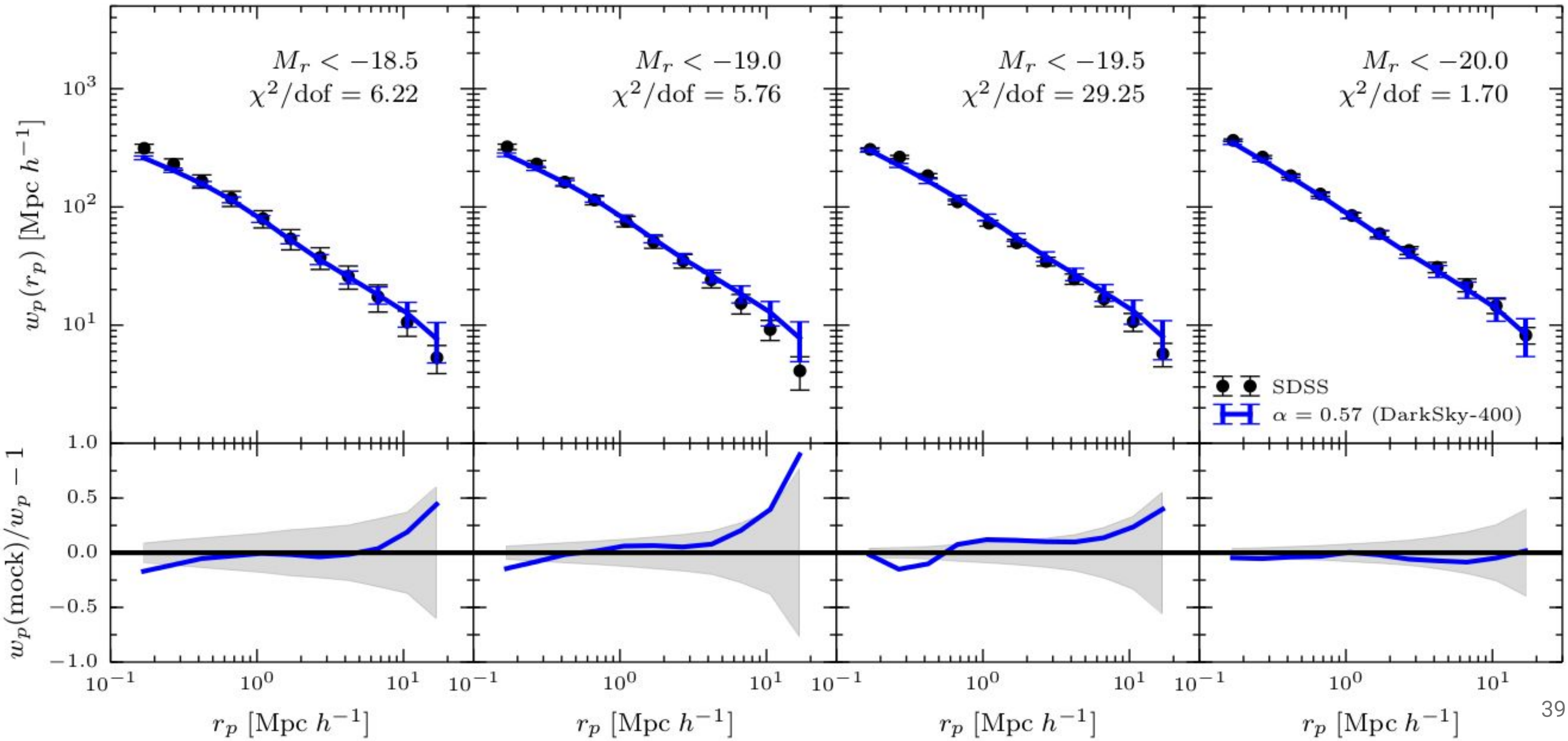
- ➔ results hold in different boxes with slightly different cosmologies
- ➔ previous studies on SHAM commonly used 250 Mpc/*h* boxes



Fit to the projected correlation functions



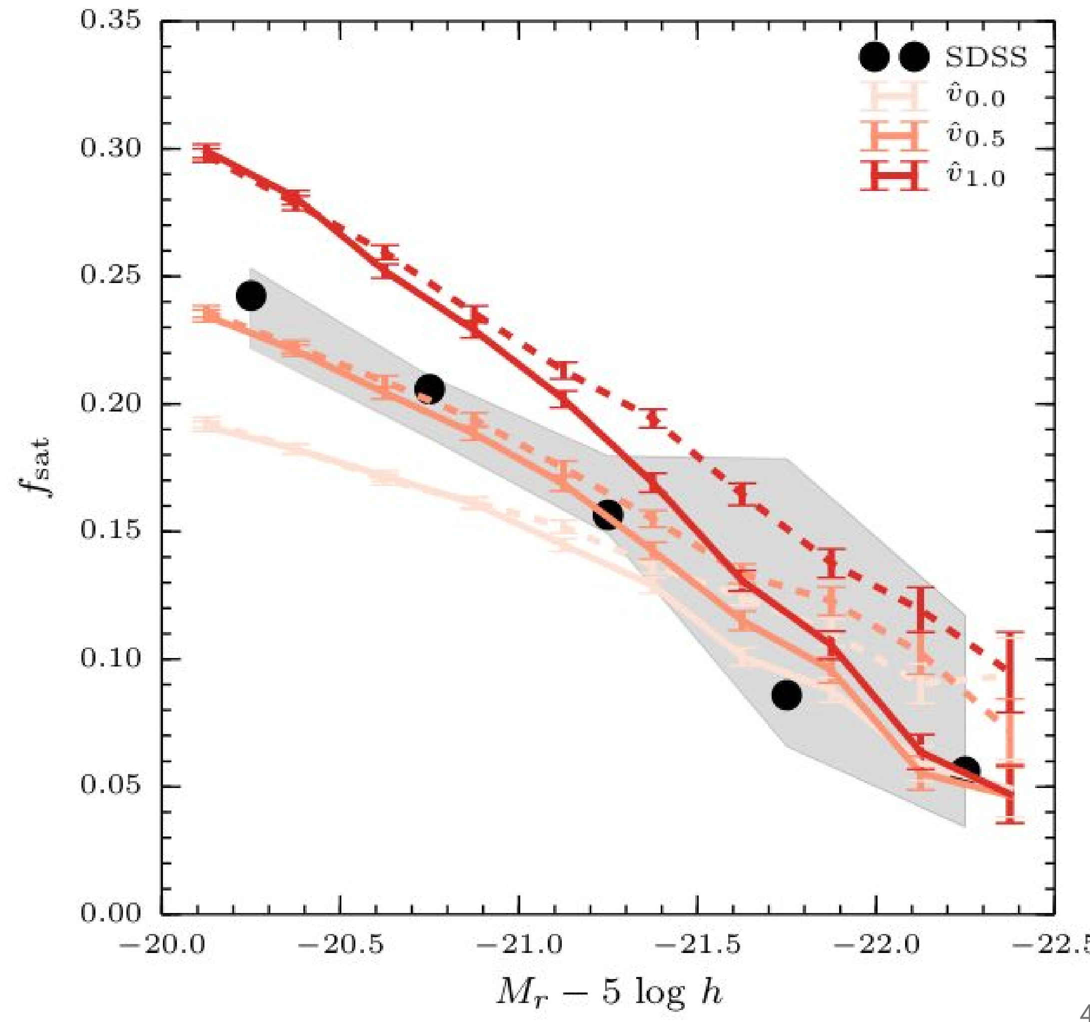
Fit to the projected correlation functions (dimmer samples)



Satellite Fraction

- At a number density, fraction of satellite "galaxies".
- Provides independent constraints in addition to correlation statistics

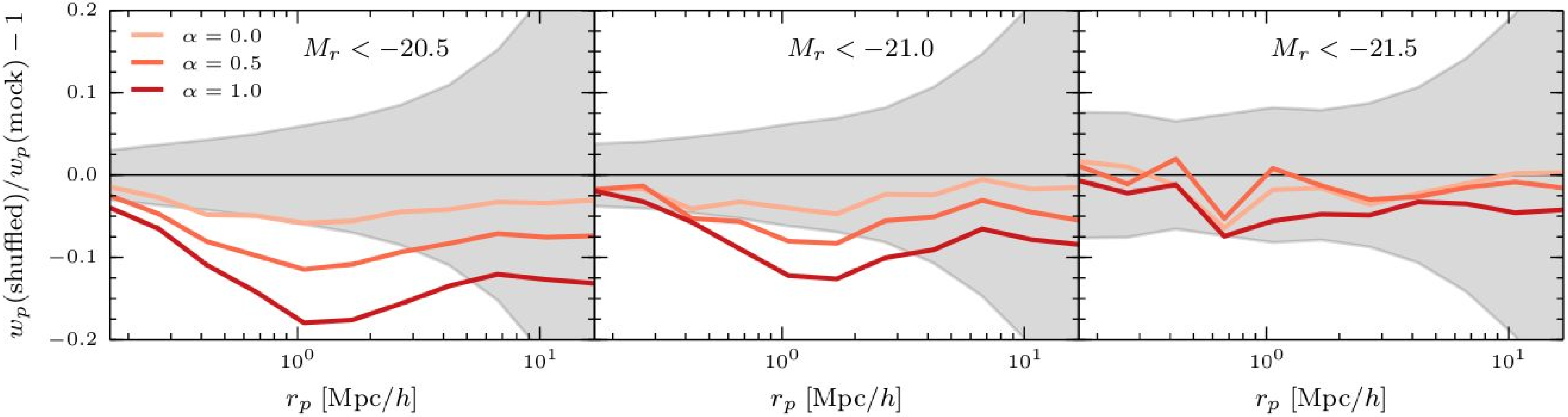
- Subhalos are more concentrated (when compared with host halos of the same mass), so larger α results in higher satellite fraction.



Assembly Bias

➔ Concentration dependence directly impacts assembly bias in the catalog

➔ To demonstrate the “amount” of assembly bias in the catalog, we “shuffle” the catalog in bins of halo mass (following the procedure in Zentner+ 2014)



➔ High-concentration halos (below M*) are more clustered, so larger α results in larger difference between shuffled and unshuffled catalogs.

Outlook

Exploring the “freedom” in SHAM

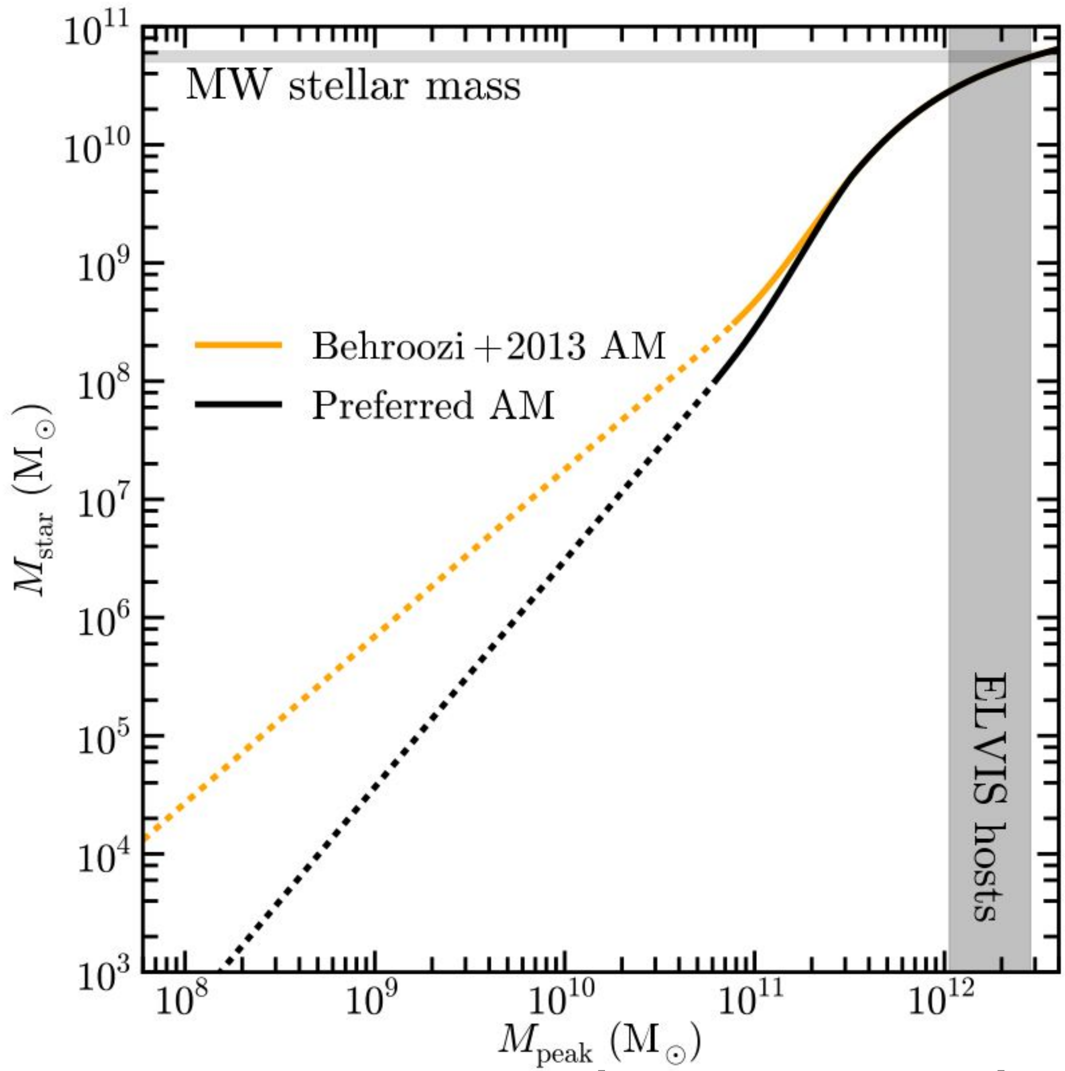
- ➔ Abundance matching is *not* parameter-free
- ➔ Parameters in abundance matching provide insights to galaxy formation

- ➔ Empirical models provide a layer in between physical models (hydrodynamical simulations, SAMs) and observables.
- ➔ Different observations can jointly constrain the empirical models.
- ➔ Empirical models then constrain physical models.
  [See e.g. Chaves-Montero 2015 with EAGLE simulations]

Dimmer samples

- ➔ Resolution requirements for the empirical models are still unclear
- ➔ Extrapolate the current SHAM scheme to the very faint regime

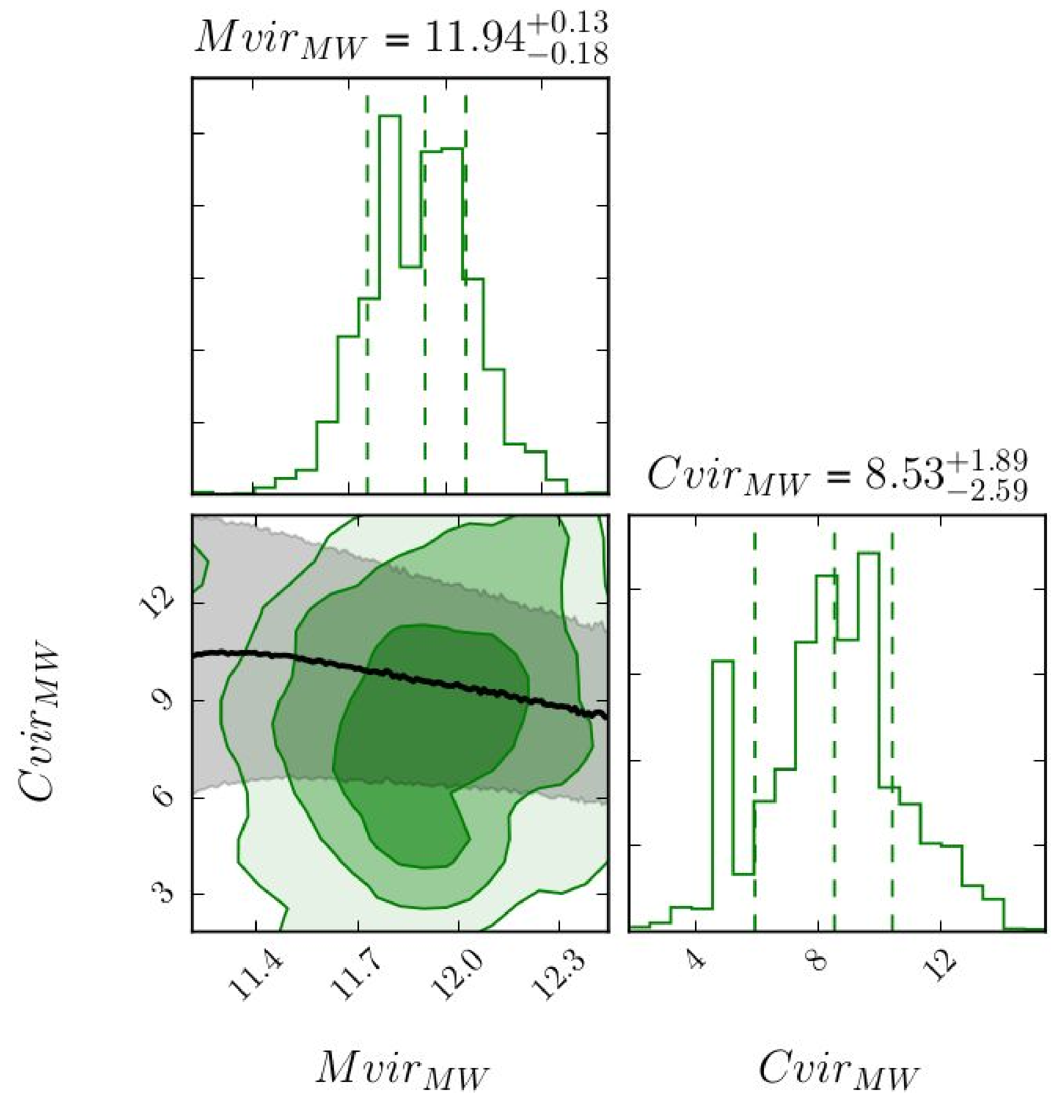
➔ Dwarf galaxies in the Milky Way (or similar systems) are in a regime where SHAM has not been fully tested.



[Garrison-Kimmel+ 2014]

Applications to dwarf galaxies

➔ When comparing the real Milky Way with simulations/model prediction, it is important to understand the *prior* on mass and concentration.



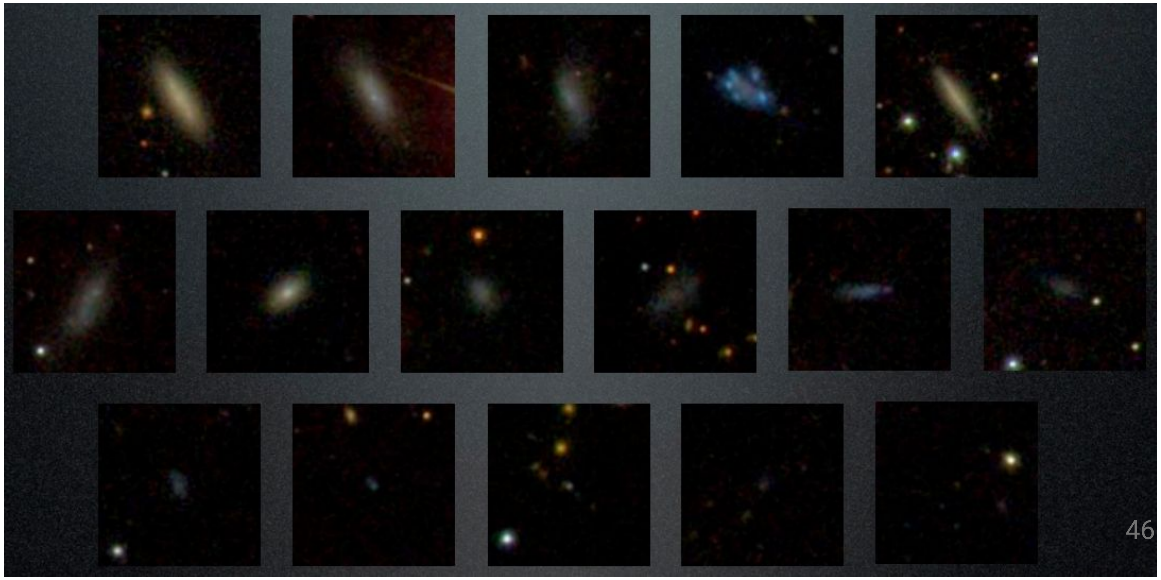
[Williamson, YYM+ in prep]

SAGA Survey

- "Satellites Around Galactic Analogs" led by M. Geha and R. Wechsler
- helps to quantify the scatter in the faint-end galaxy-halo connection
- helps to understand the Milky Way in a cosmological context

- host galaxy sample: ~80 isolated L* galaxies from SDSS + 2MASS, with 20 < D < 45 Mpc, -23 < K < 24.6

- 17 satellites from the SAGA Survey



Summary

- Concentration is the most important parameter, other than mass, that describes a halo.
- Subhalo abundance depends on both halo mass and concentration.
- Concentration dependence in abundance matching can be parameterized and constrained by data.
- Empirical models of galaxy–halo connection can bridge galaxy formation theory and observations.