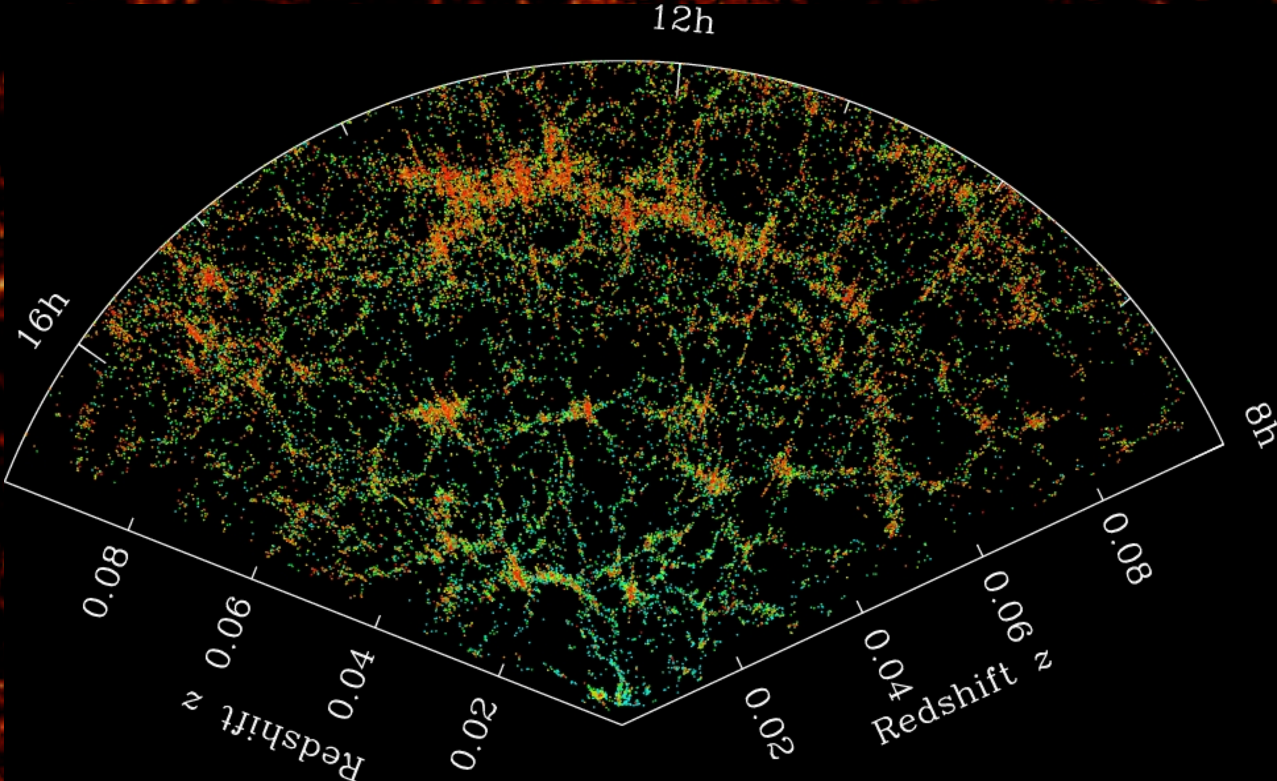
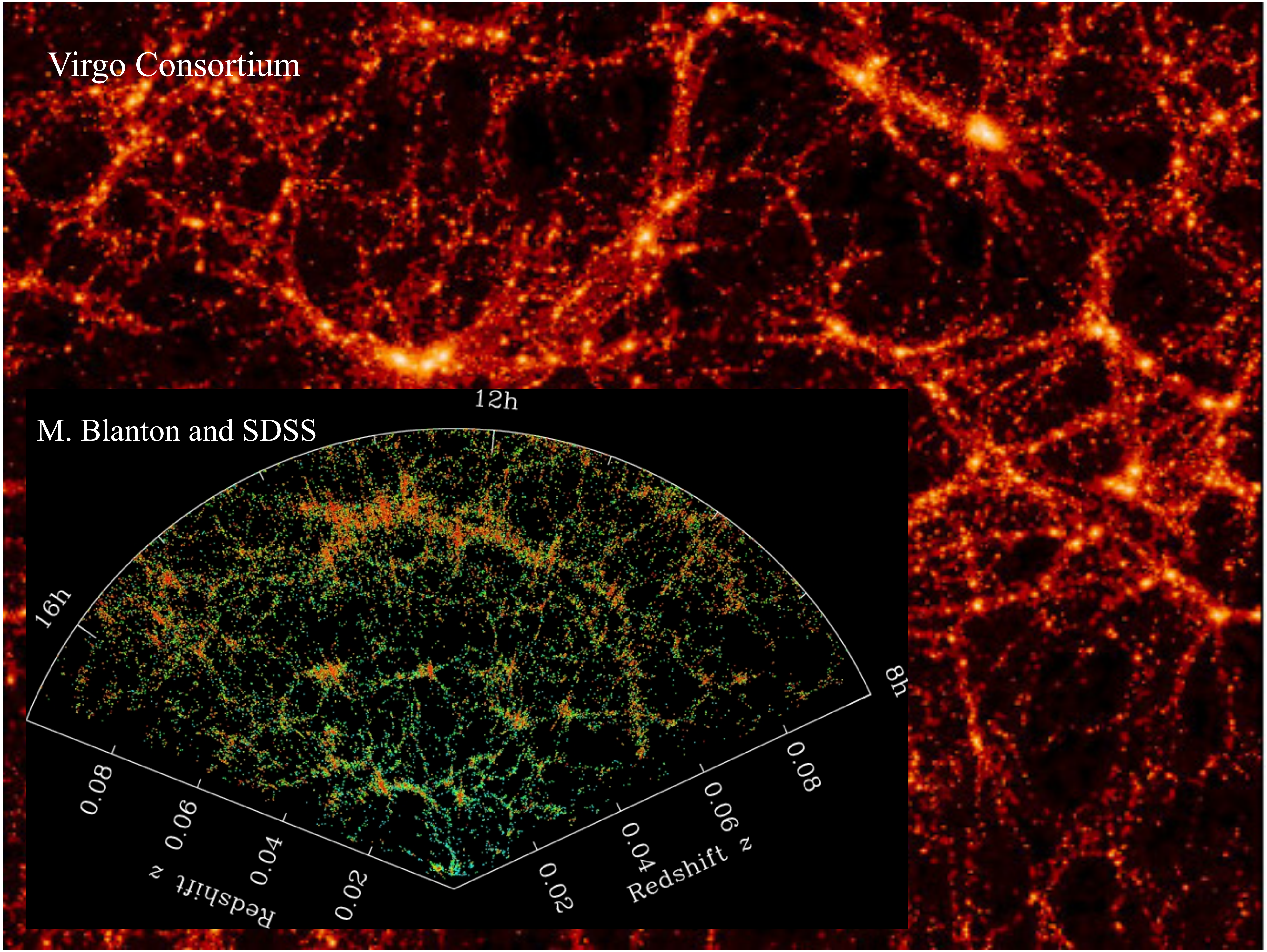
Connecting Galaxies to Dark Matter Halos: HOD, CLF, SHAM, and all that

David Weinberg, Ohio State University

Special thanks to: Andreas Berlind, Zheng Zheng, Jeremy Tinker, Jaiyul Yoo, Vimal Simha, Idit Zehavi




Virgo Consortium
M. Blanton and SDSS
12h
16h
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Redshift z
0.02
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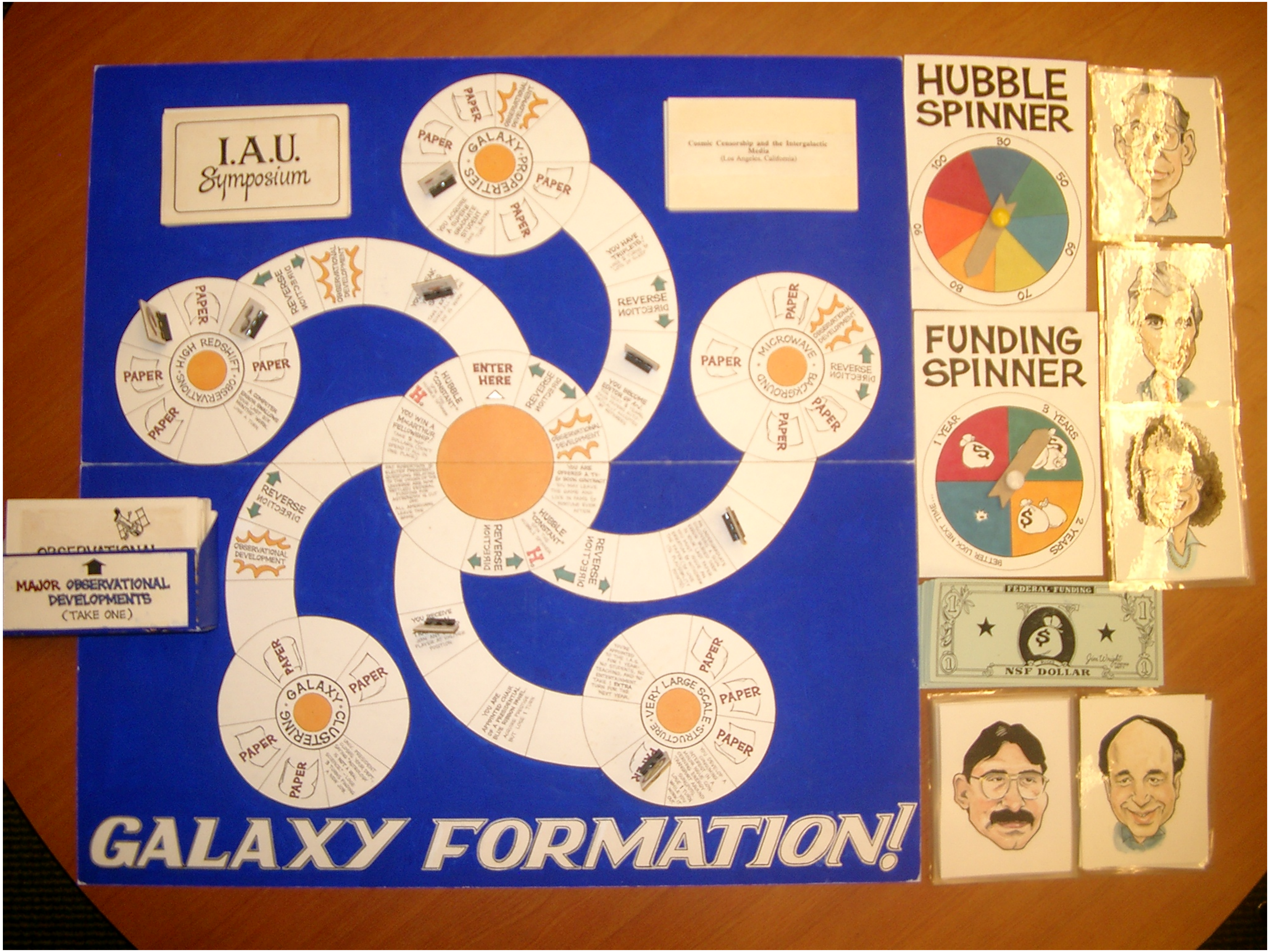
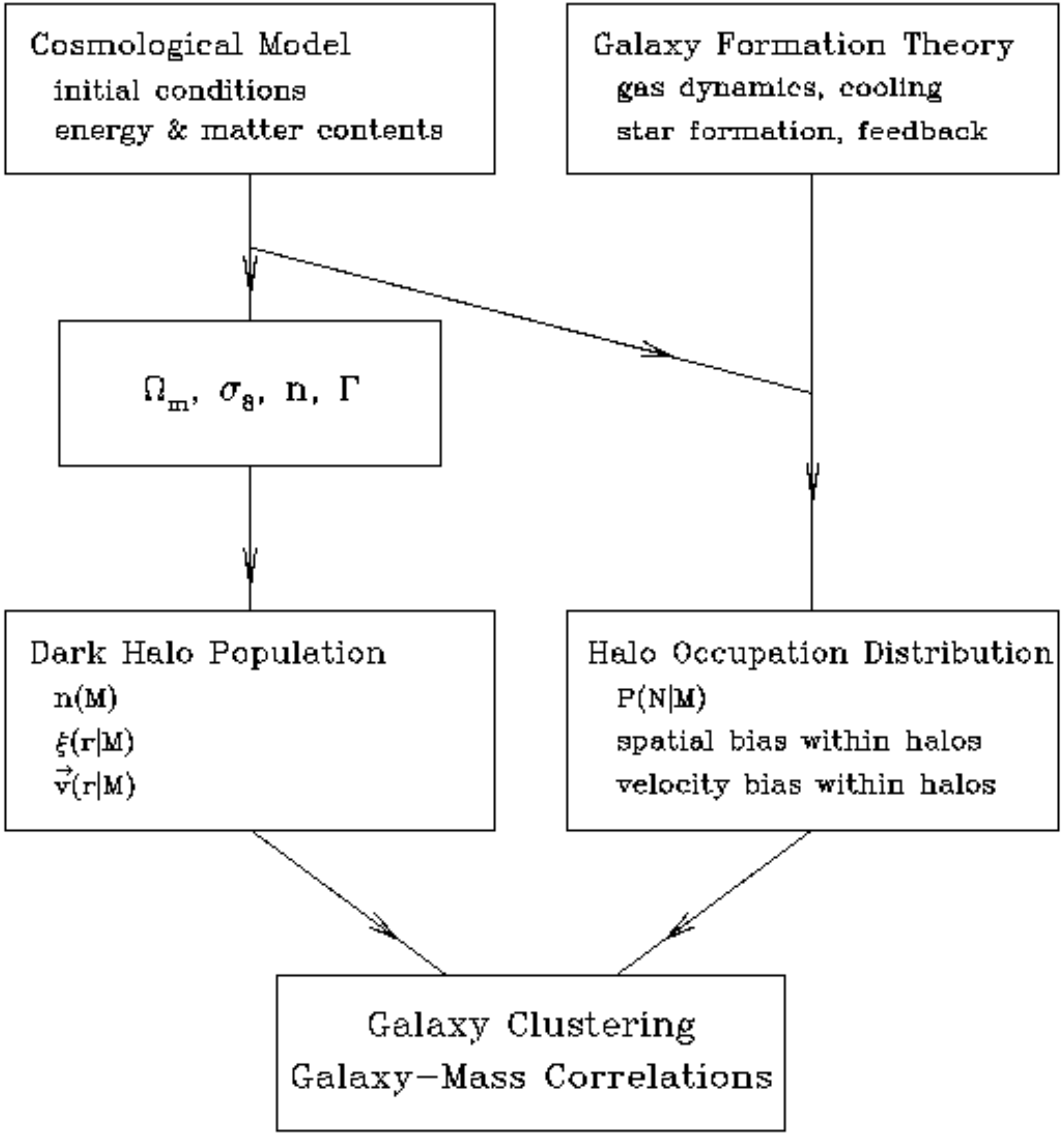
Redshift z


I.A.U.
Symposium
Cosmic Censorship and the Intergalactic Media
(Los Angeles, California)
HUBBLE SPINNER
FUNDING SPINNER
GALAXY PROPERTIES
HIGH REDSHIFT OBSERVATIONS
MICROWAVE BACKGROUND
GALAXY CLUSTERING
VERY LARGE SCALE STRUCTURE
ENTER HERE
HUBBLE CONSTANT
REVERSE DIRECTION
OBSERVATIONAL DEVELOPMENT
PAPER
MAJOR OBSERVATIONAL DEVELOPMENTS
(TAKE ONE)
FEDERAL FUNDING
NSF DOLLAR
BETTER LUCK NEXT TIME
1 YEAR
2 YEARS
3 YEARS
GALAXY FORMATION!

Durham 2001: "A New Era in Cosmology"

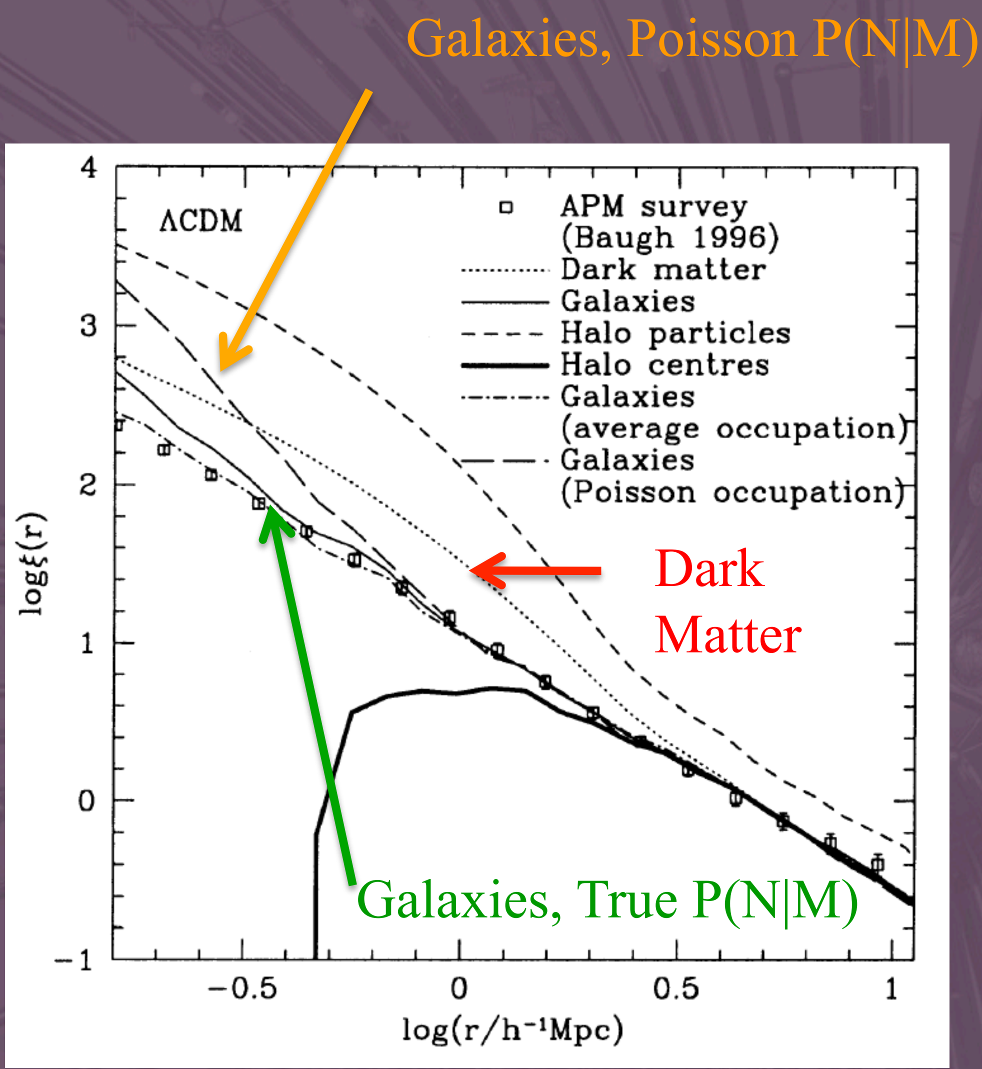


- Kauffmann, Nusser, & Steinmetz 1997: Populate N-body halos with galaxy populations predicted by semi-analytics, compute bias of clustering statistics.

- Jing, Mo, & Börner 1998: Model clustering in Las Campanas redshift survey by populating CDM halos, varying N/M trend.

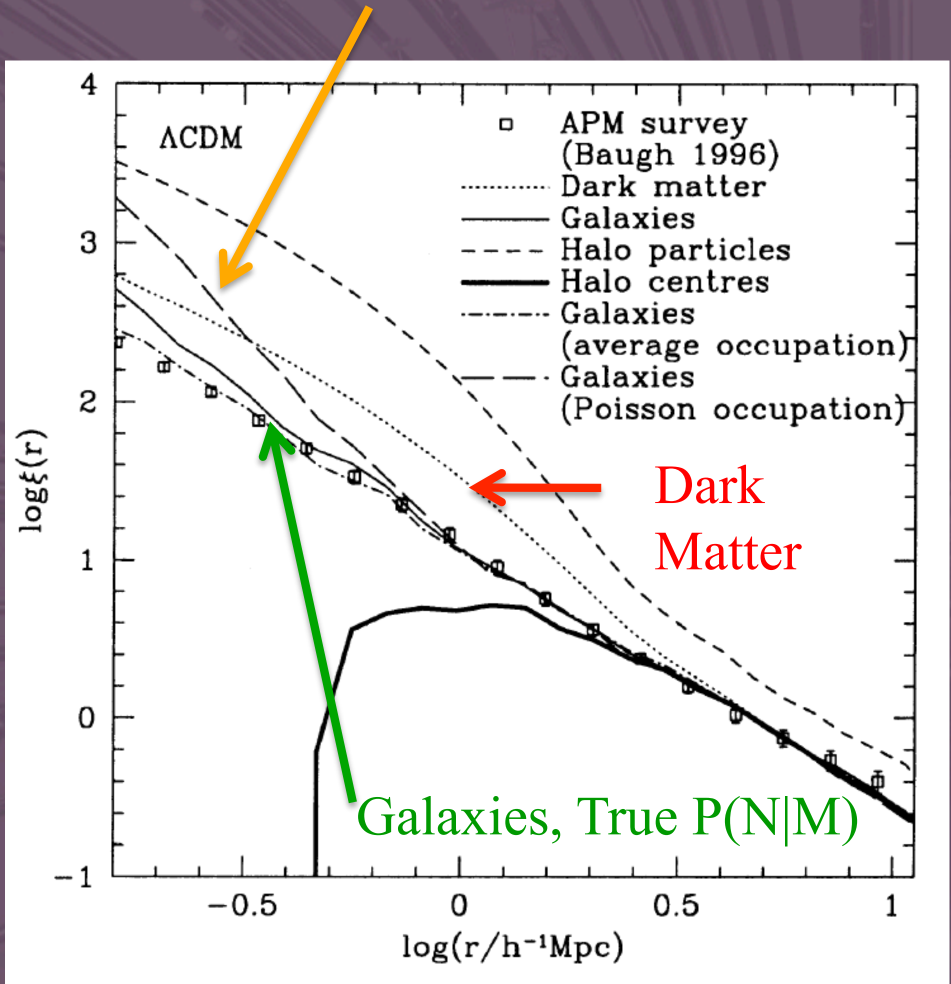
- Colìn, Klypin, Kravtsov, & Khoklov 1999: Compute evolution of clustering and bias of subhalo populations in high-resolution N-body simulations.

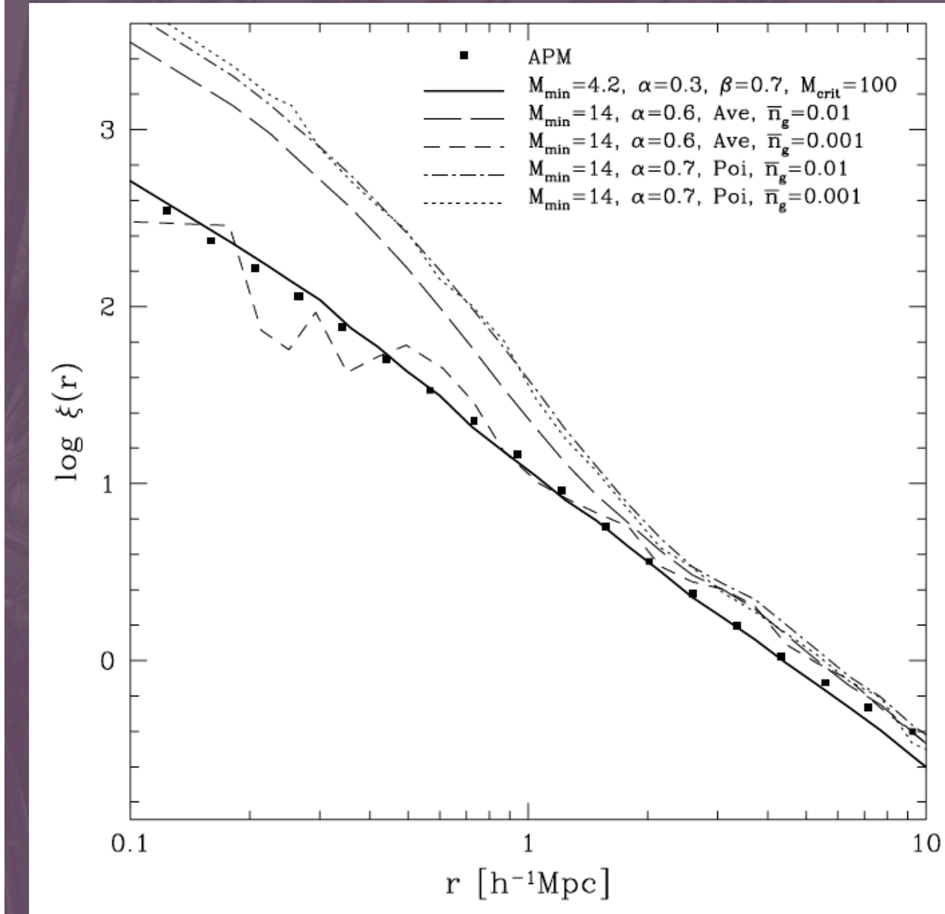
- Benson, Cole, Frenk, Baugh, & Lacey 2000: Predict $P(N|M)$ and clustering statistics by populating N-body halos with semi-analytics. Form of $P(N|M)$ as well as mean trend plays key role in correlation function.



Benson et al. 2000

Galaxies, Poisson P(N|M)





Benson et al. 2000

Berlind & Weinberg 2002

Alphabet Soup

HOD = Halo Occupation Distribution

Fit P(N|M) to observed space density and clustering of a specified galaxy population (volume-limited sample).

CLF = Conditional Luminosity Function

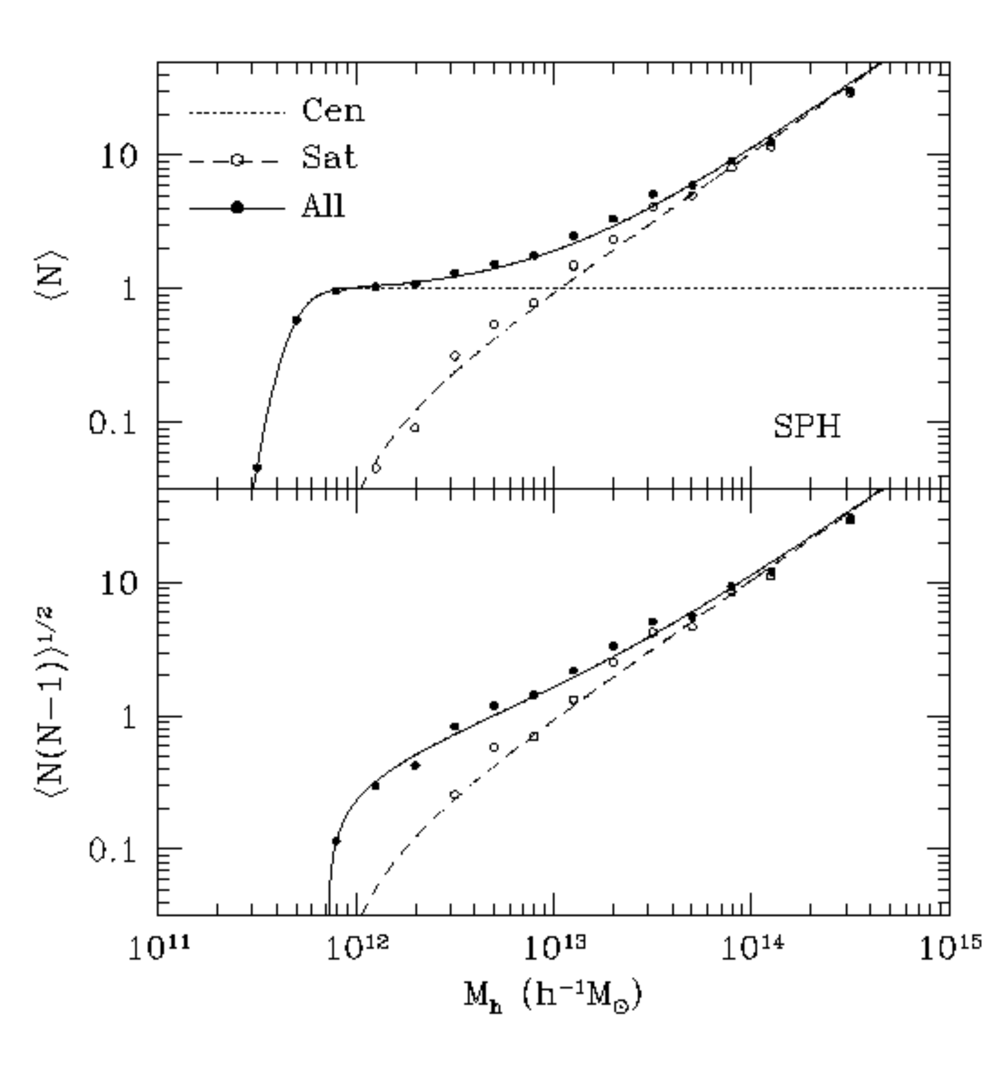
Fit $\Phi(L_{gal}|M_{halo})$ to observed luminosity function and clustering of galaxies (flux-limited sample).

Integrating CLF gives HOD; differencing HOD gives CLF.

SHAM = Sub-Halo Abundance Matching

Monotonically map galaxy luminosity function or stellar mass function to subhalo mass function, to get $L(M_{halo})$ or $M_*(M_{halo})$. Stronger prior than HOD/CLF; needs less data, no free parameters (except cosmological).

HOD: Theoretical Expectations



Zheng, Berlind, Weinberg, Benson, Baugh, Cole, Davé, Frenk, Katz, Lacey 2005

Halo central galaxies usually more massive, older than satellites.

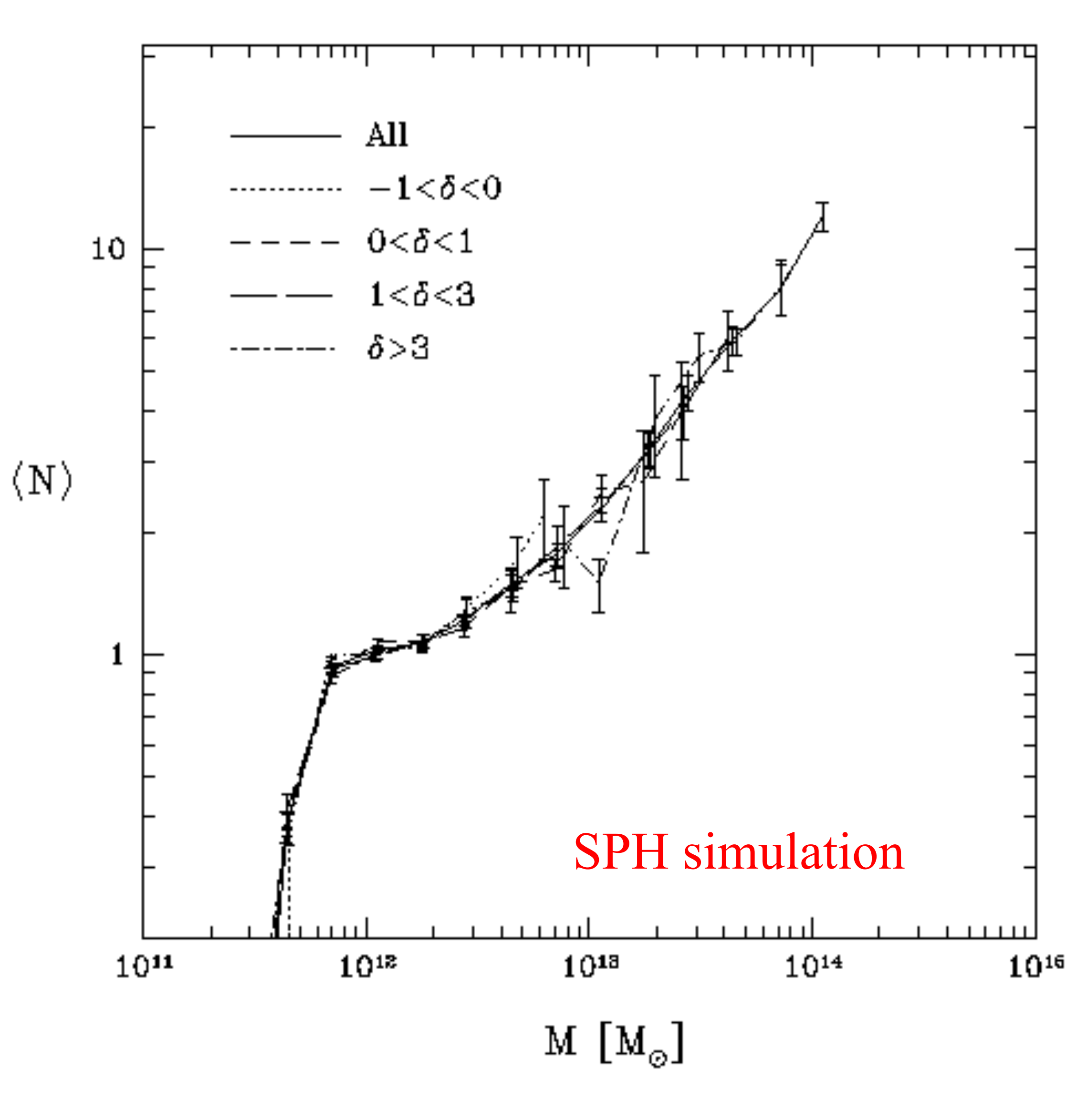
Central: step function

Satellites: truncated power-law, Poisson statistics

(Kravtsov et al. 2004)

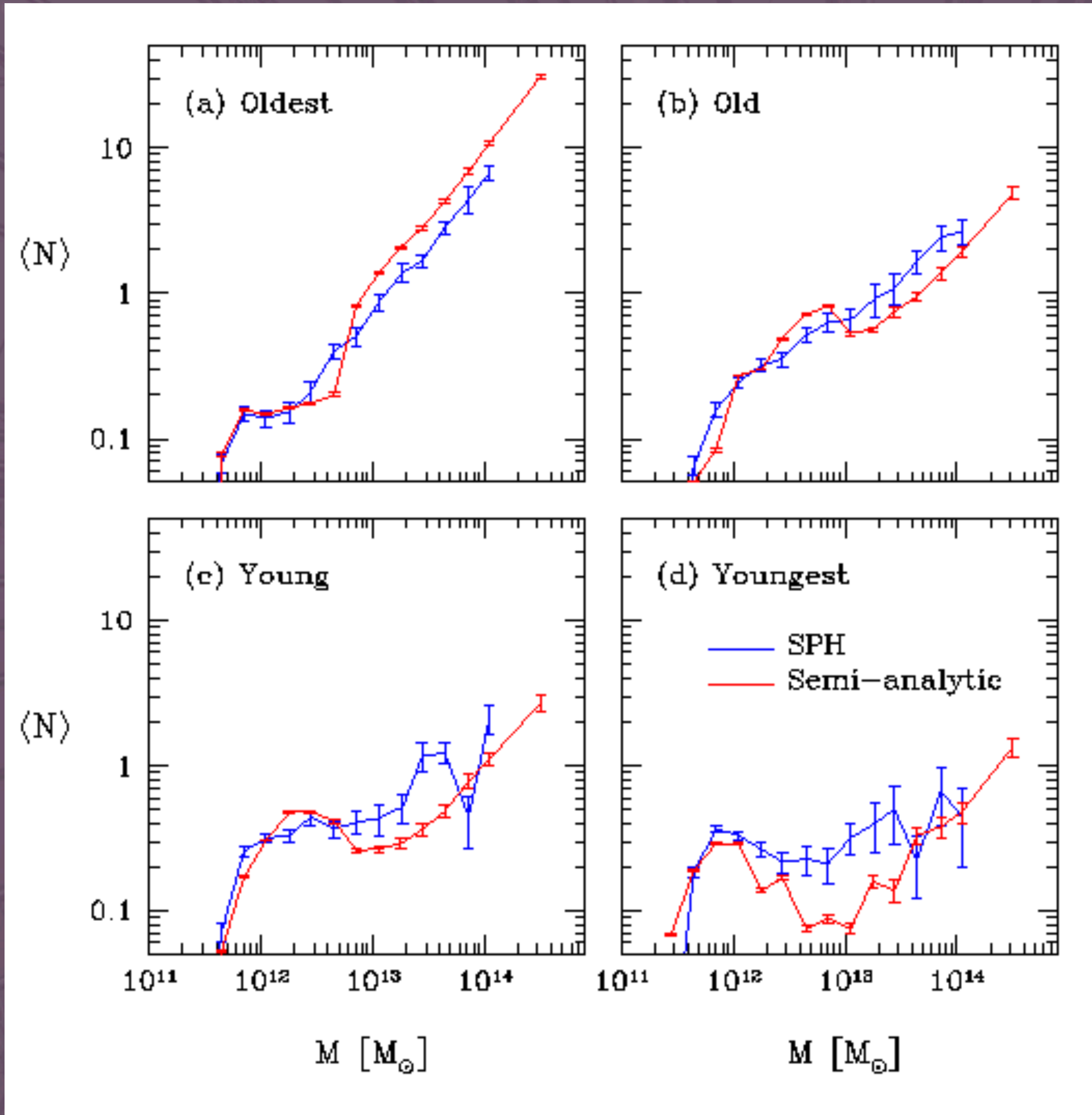
Typically $M_1/M_{min} \approx 20$

Large mass range with sub-Poisson statistics.



Berlind, Weinberg, Benson, Baugh, Cole, Davé, Frenk, Jenkins, Katz, Lacey 2003

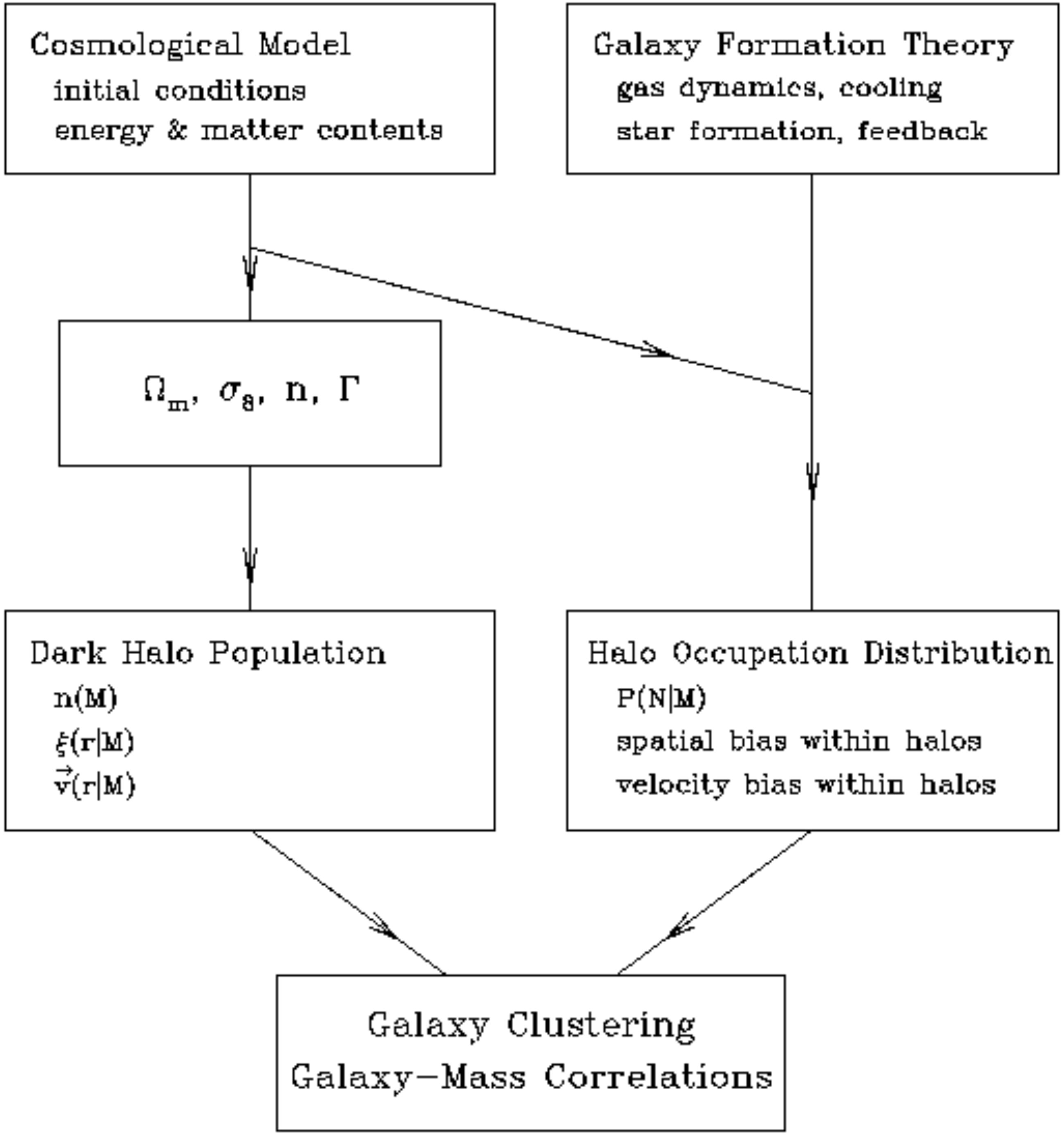
Theory predicts that, to a good approximation, a halo's galaxy content depends (statistically) on its mass, but not on its larger scale environment.



Predicted HOD depends strongly on galaxy's stellar population age.

Environment dependence of halo mass function leads to type-dependence of galaxy clustering (e.g., morphology-density relation).

Berlind et al. 2003



HOD is a complete description of galaxy bias if it is independent of halo's large scale environment

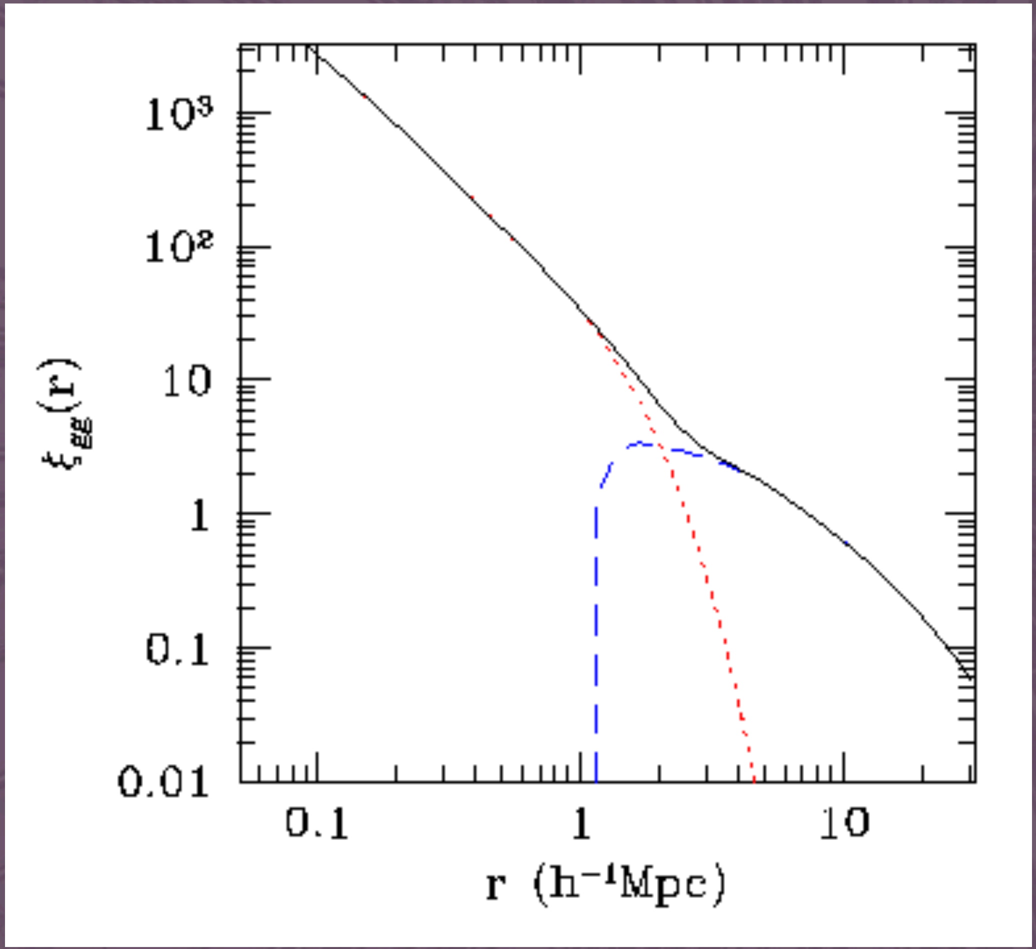
Weinberg 2002

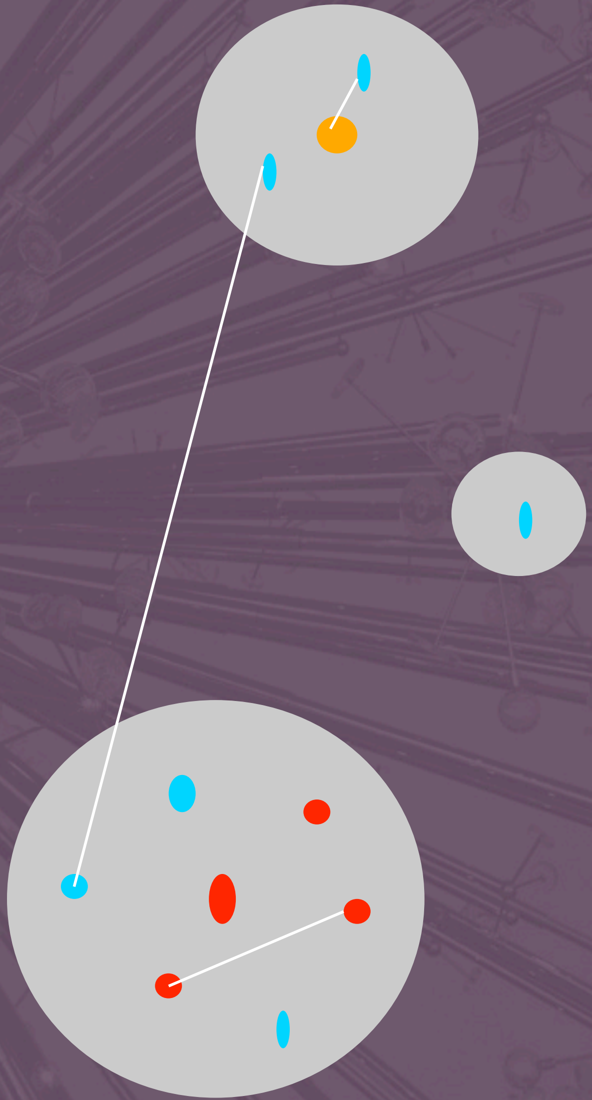
- Empirical successes

- What have we learned ?

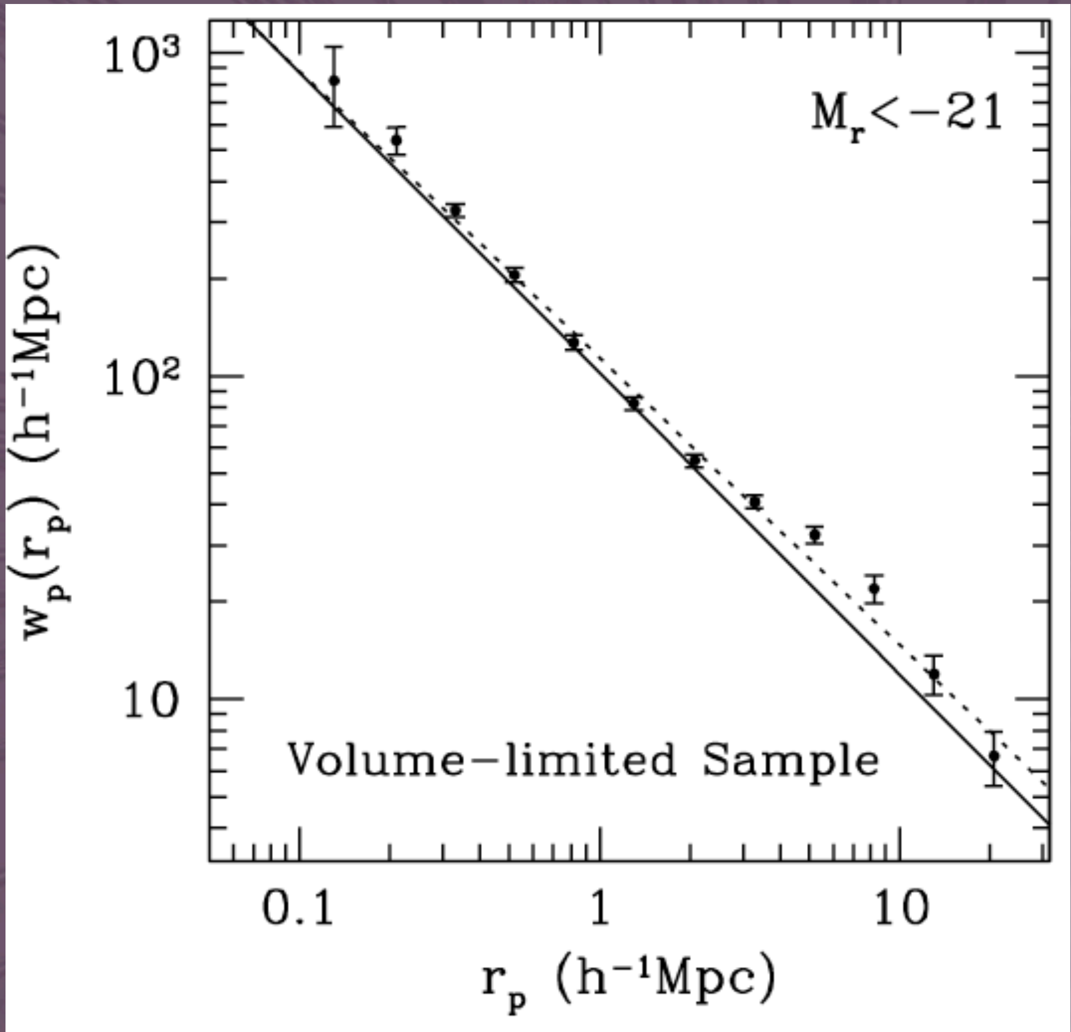
- Some current frontiers

Galaxy correlation function

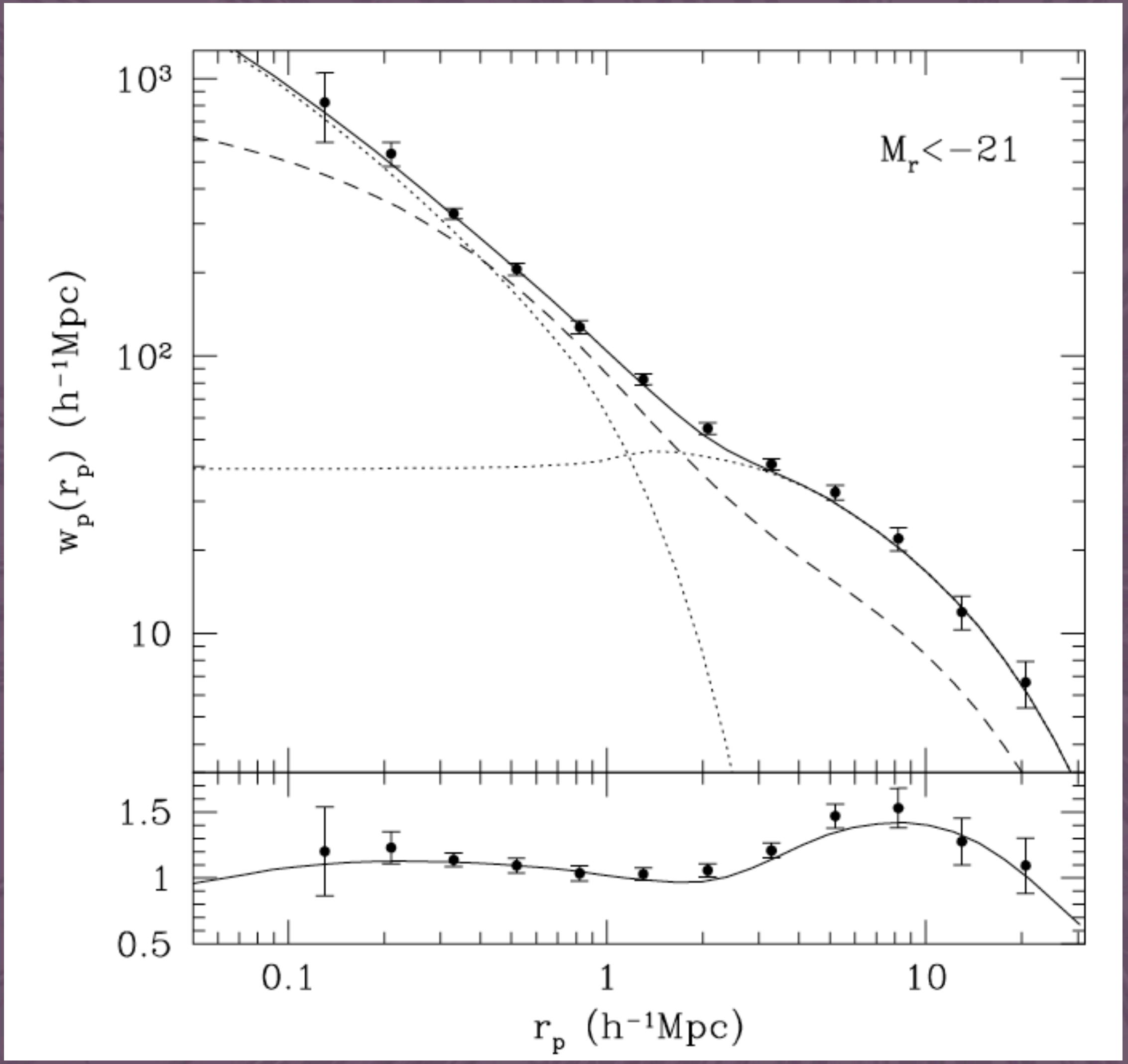


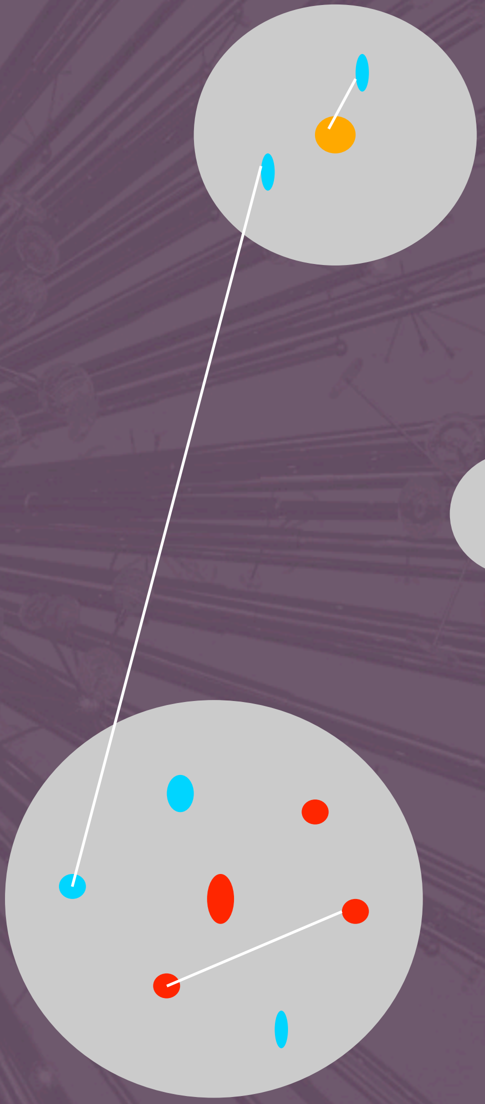


Zehavi, Weinberg, Zheng, Berlind, et al. 2004



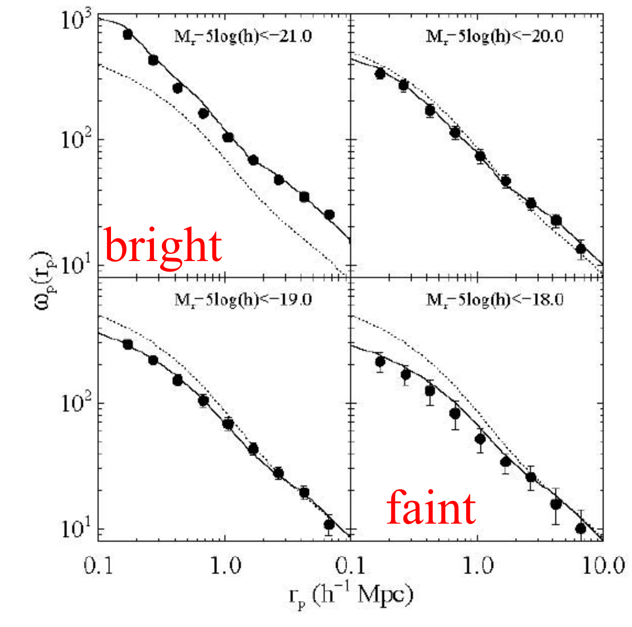
Zehavi, Weinberg, Zheng, Berlind, et al. 2004



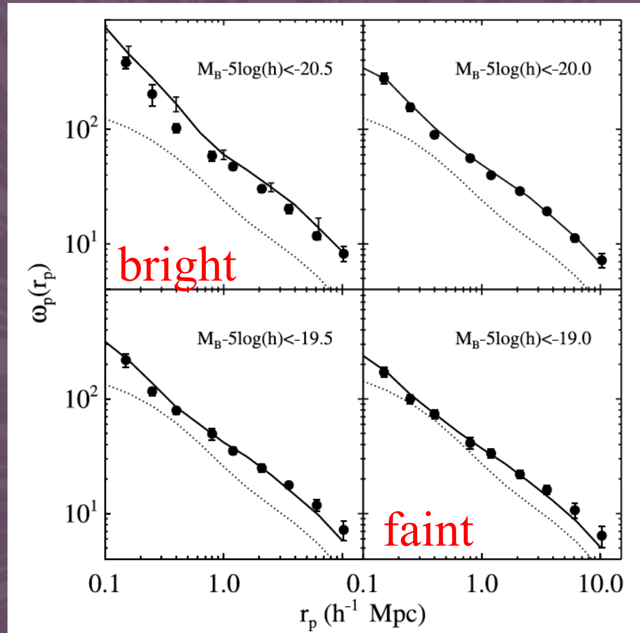


Conroy, Wechsler, & Kratvsov 2006

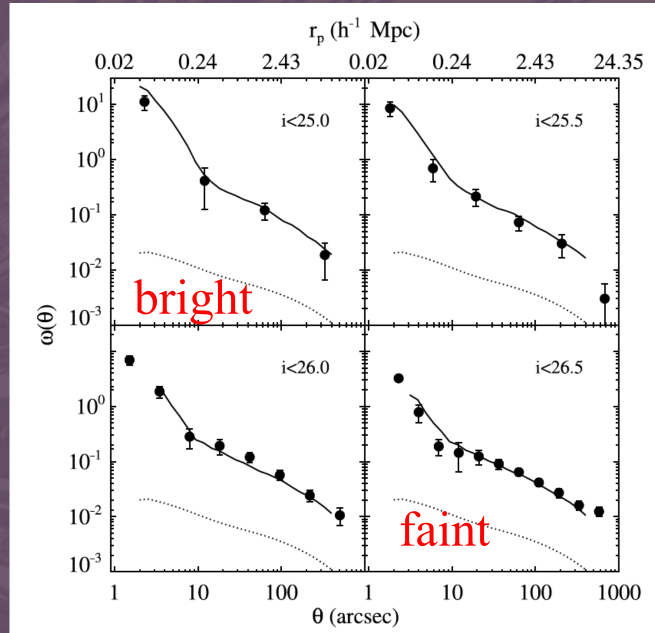
SDSS, z ~ 0



DEEP2, z ~ 1



Subaru LBGs, z ~ 4

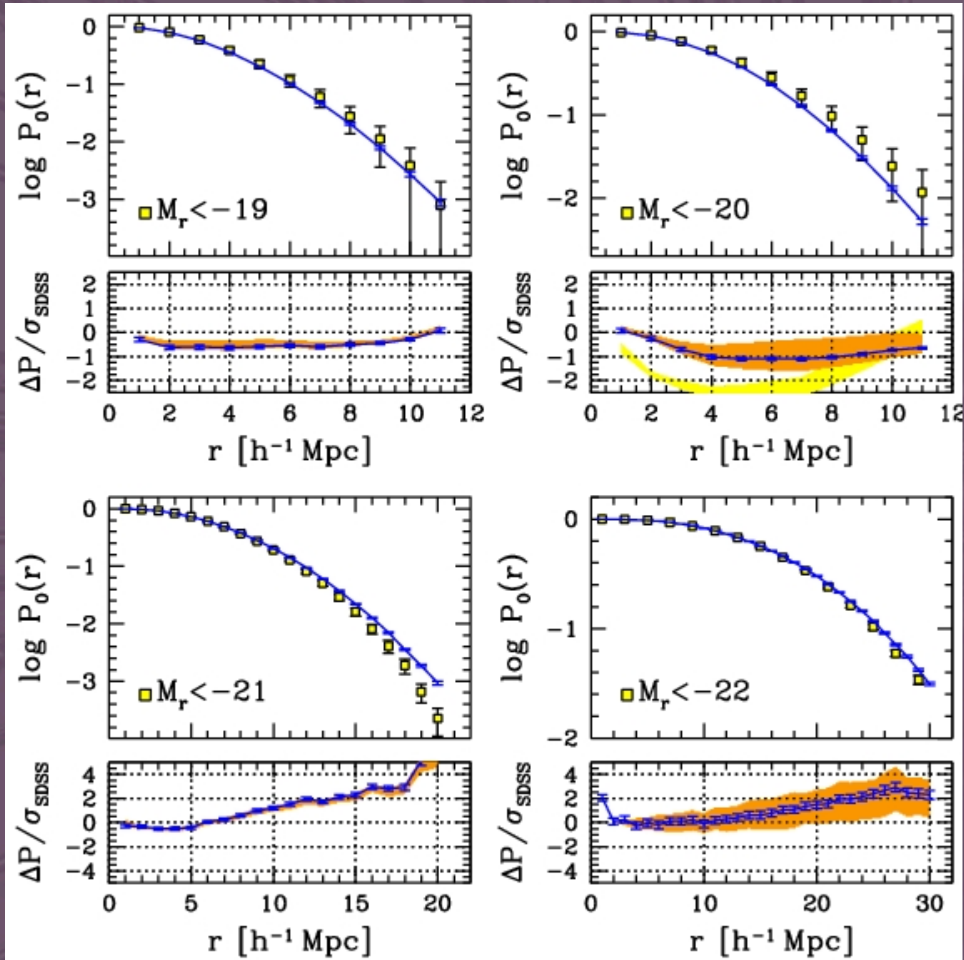


Projected correlation functions, dotted=DM, solid=SHAM, points=data

Zero-parameter model reproduces redshift and luminosity dependence over a remarkable range.

 Booyah!

Tinker, Conroy, Norberg, Patiri, Weinberg, & Warren 2008



Points = SDSS measurements
Curves = HOD predictions

Void probabilities

HOD model fit to galaxy correlation function accurately predicts void probability function $P_0(r)$, for multiple luminosity thresholds.

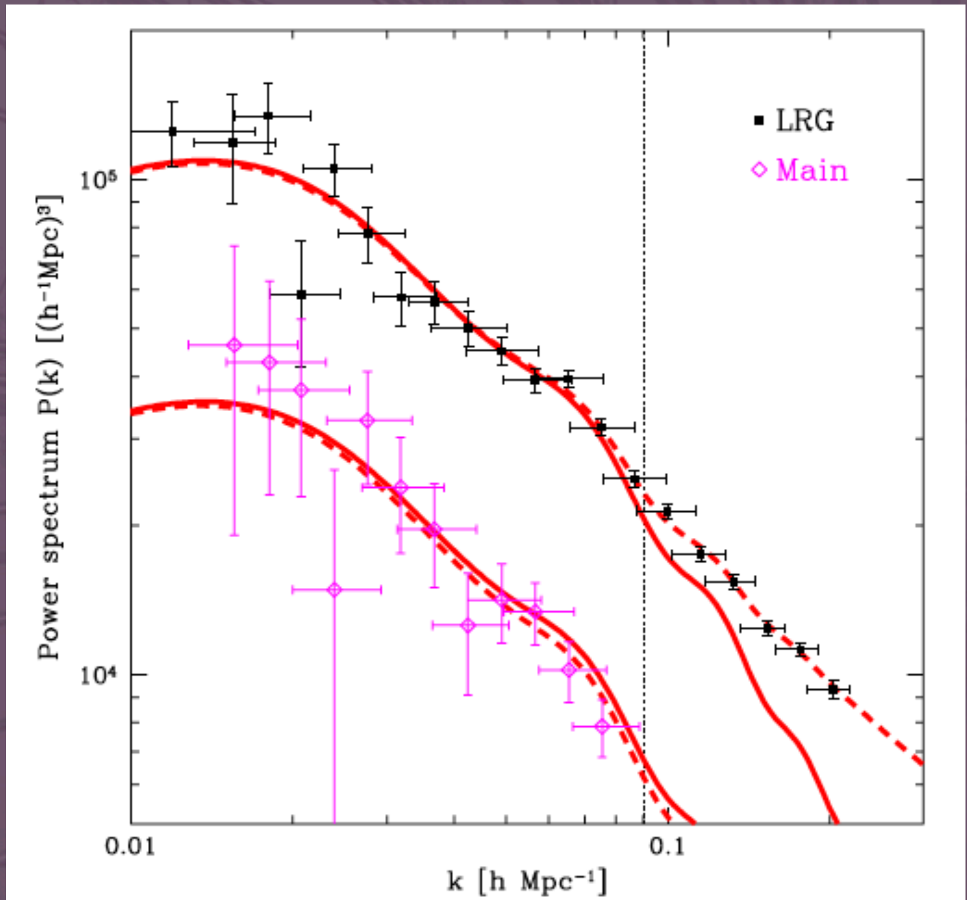
Relies on assumption of environment-independent HOD.

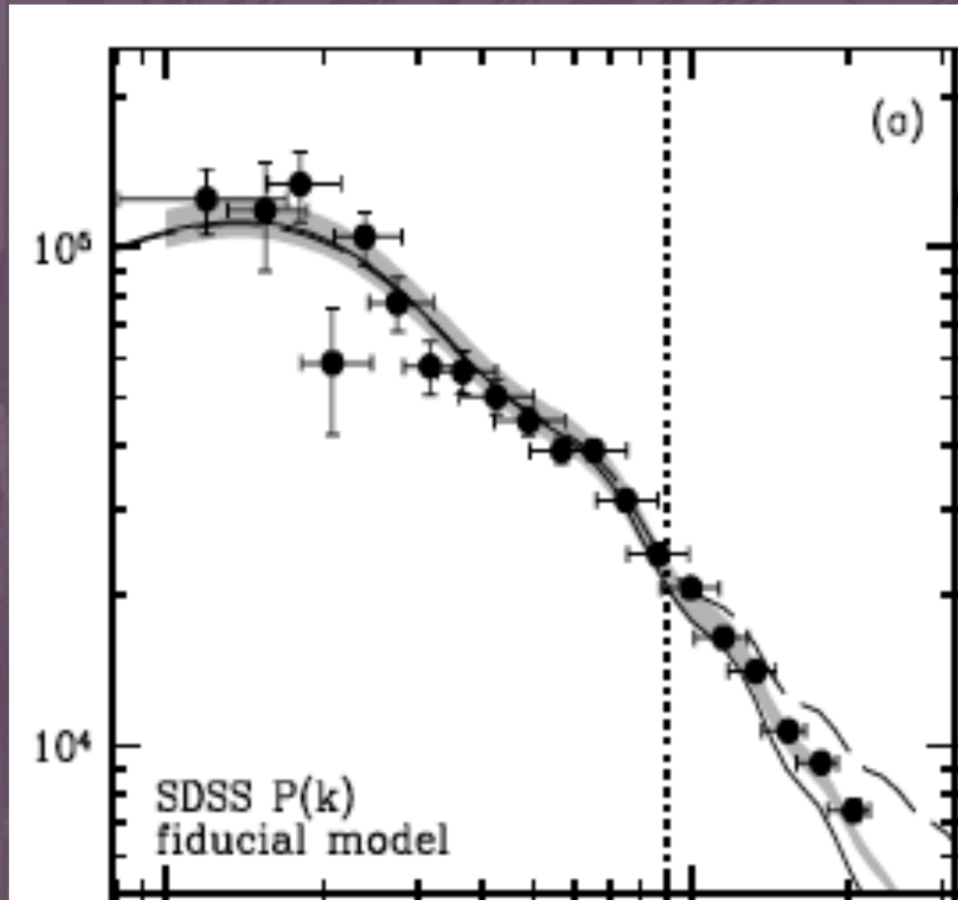
Implies similar luminosities of central galaxies in high and low density environments, for halos $\sim 10^{11.5} - 10^{12.5}$ M_{sun}.

Scale-dependence of bias

Tegmark, Eisenstein, Strauss, Weinberg, et al. 2006

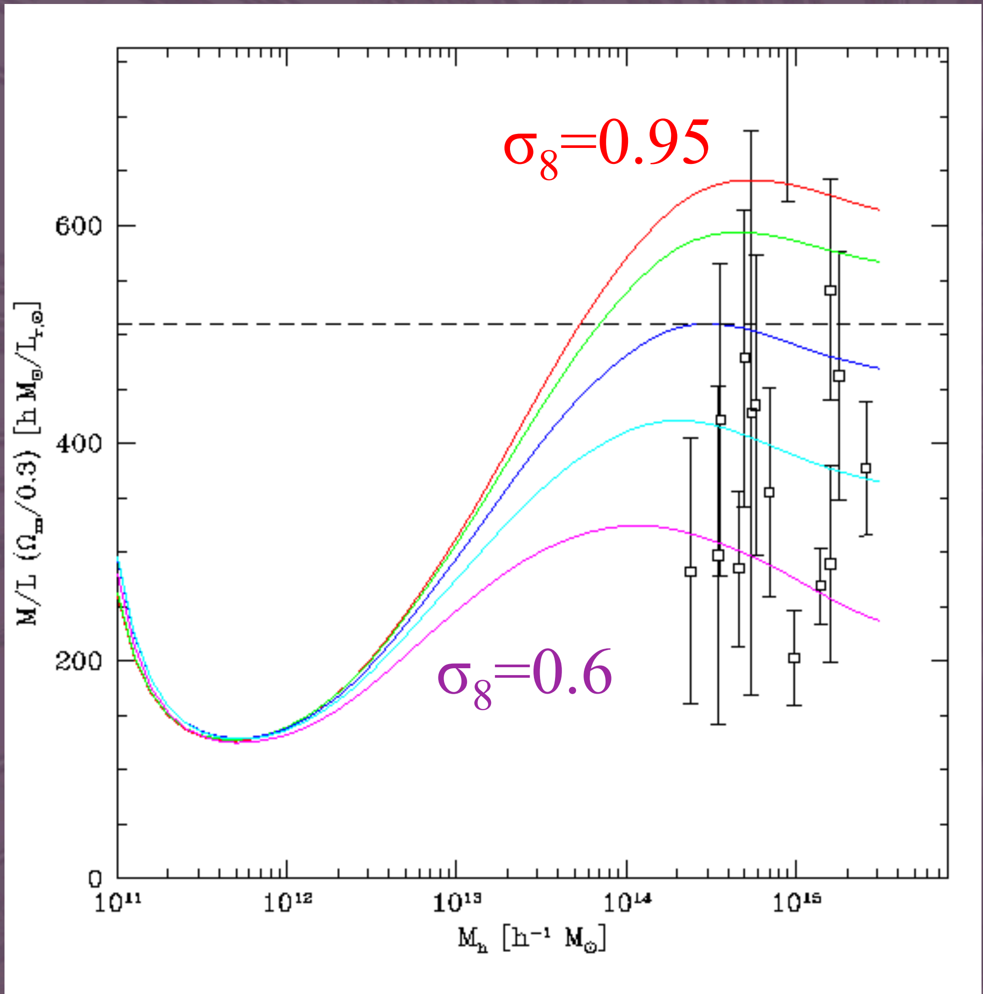
Yoo, Weinberg, Tinker, Zheng, & Warren 2009





HOD model fit to small/intermediate scale clustering of luminous red galaxies correctly predicts the (strong) scale-dependent bias of their power spectrum at k = 0.1-0.2 h / Mpc.

Tinker, Weinberg, Zheng, & Zehavi 2005



M/L ratio

halo mass

Cluster M/L ratios

Fit HOD models to galaxy correlation function. Predicted M/L ratios of halos depend on σ_8, Ω_m.

Matching CNOC M/L's implies

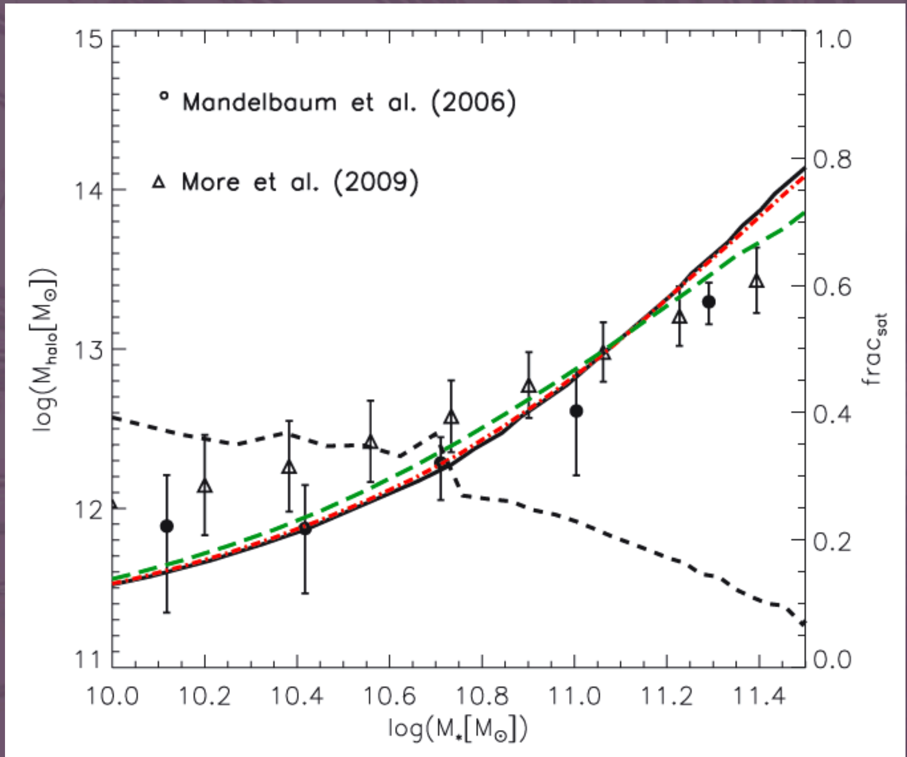
$$(\sigma_8/0.9)(\Omega_m/0.3)^{0.6} = 0.71 \pm 0.05.$$

Similar findings via CLF (van den Bosch et al. 2003) and via SHAM (Vale & Ostriker 2006).

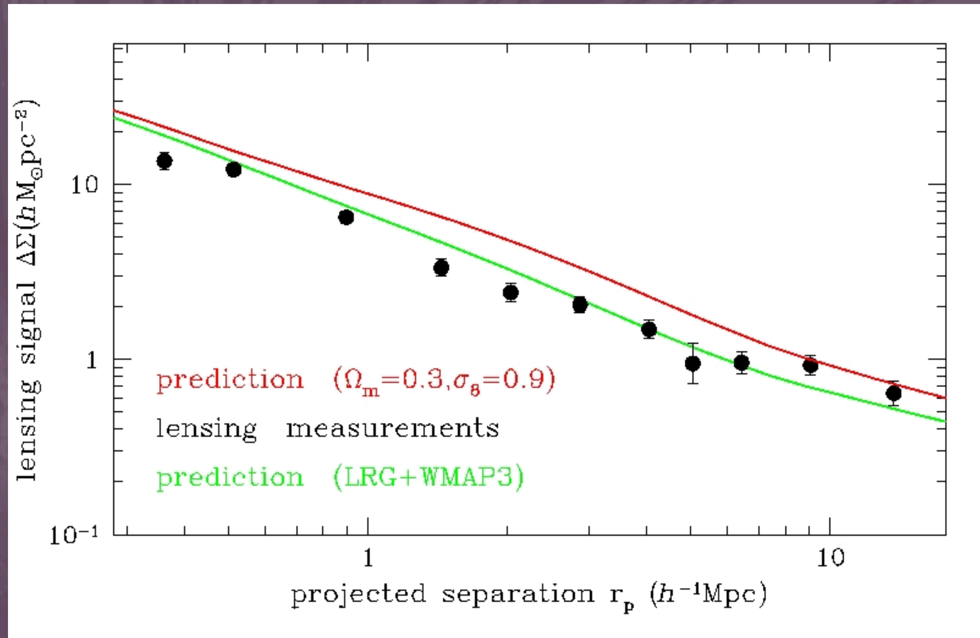
Anticipated change from WMAP1 to WMAP3.

Galaxy-galaxy lensing and satellite kinematics

Guo, White, Li, & Boylan-Kolchin 2010



J. Yoo & R. Mandelbaum



Red curve = SHAM prediction

Points = lensing (filled), satellites (open)

Points = DR4 galaxy-galaxy lensing

Green = HOD model prediction,

$\Omega_m = 0.24$, $\sigma_8 = 0.75$

Red = HOD model, $\Omega_m = 0.3$, $\sigma_8 = 0.9$

HOD models fit to galaxy clustering data correctly predict halo masses and galaxy-mass correlations from weak lensing.

What have we learned?

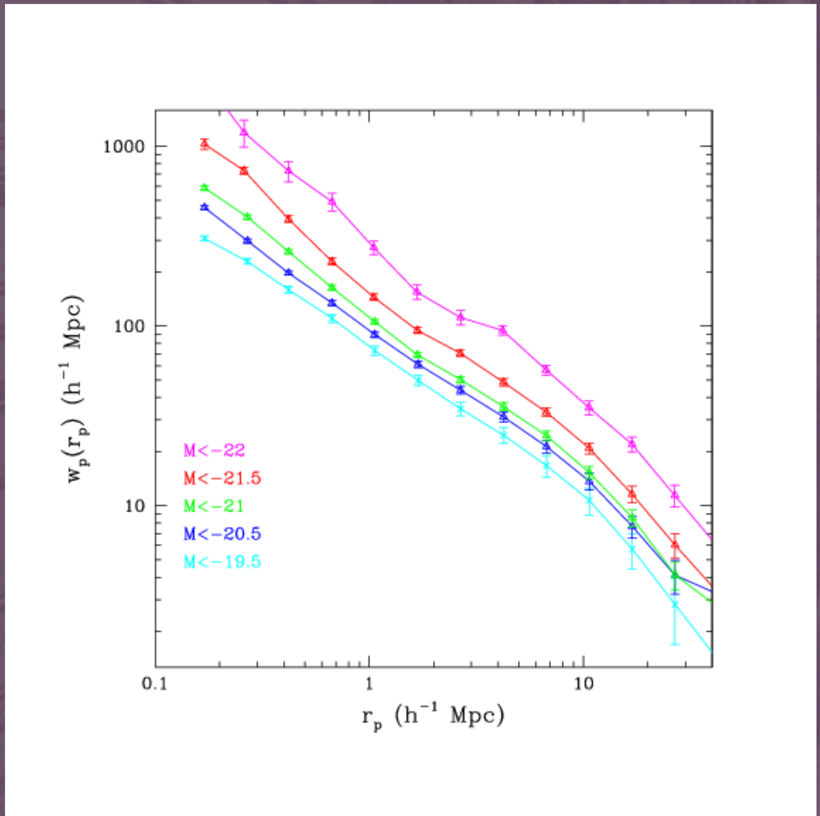
In general terms:

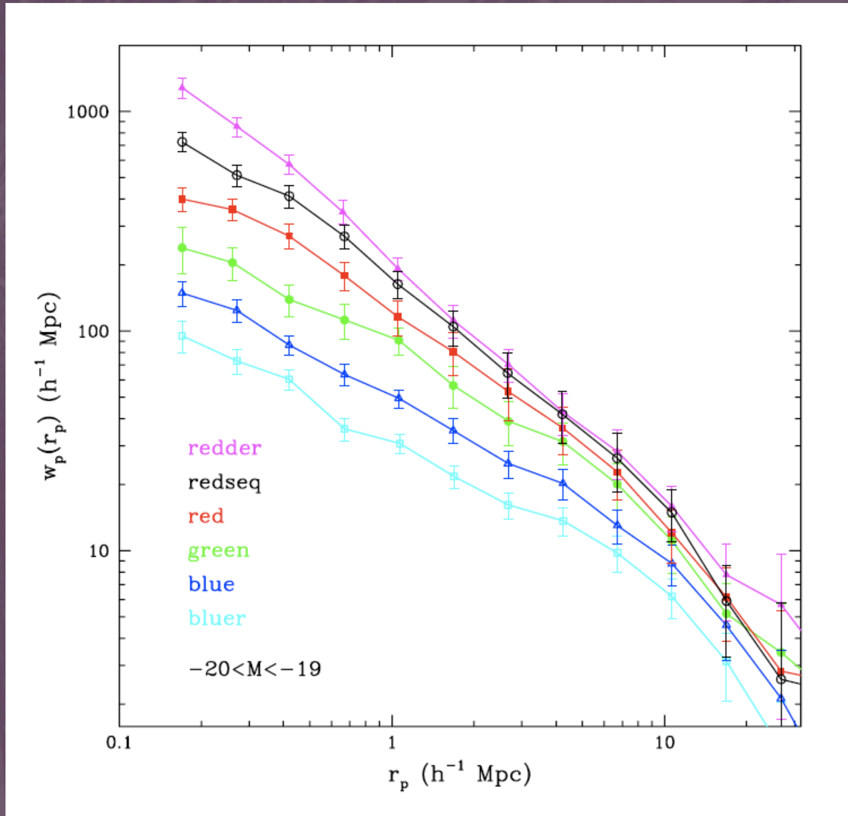
- The relations between galaxies and dark matter halos as a function of galaxy luminosity, color, and redshift.
- The origin of trends with galaxy properties.
- Consistency of ΛCDM + reasonable galaxy formation prescriptions with observed galaxy clustering.
- New cosmological tests, especially for Ω_m, σ_8.

Projected galaxy correlation functions from SDSS DR7

Luminosity: Brighter galaxies are more clustered, on all scales, mainly at highest L

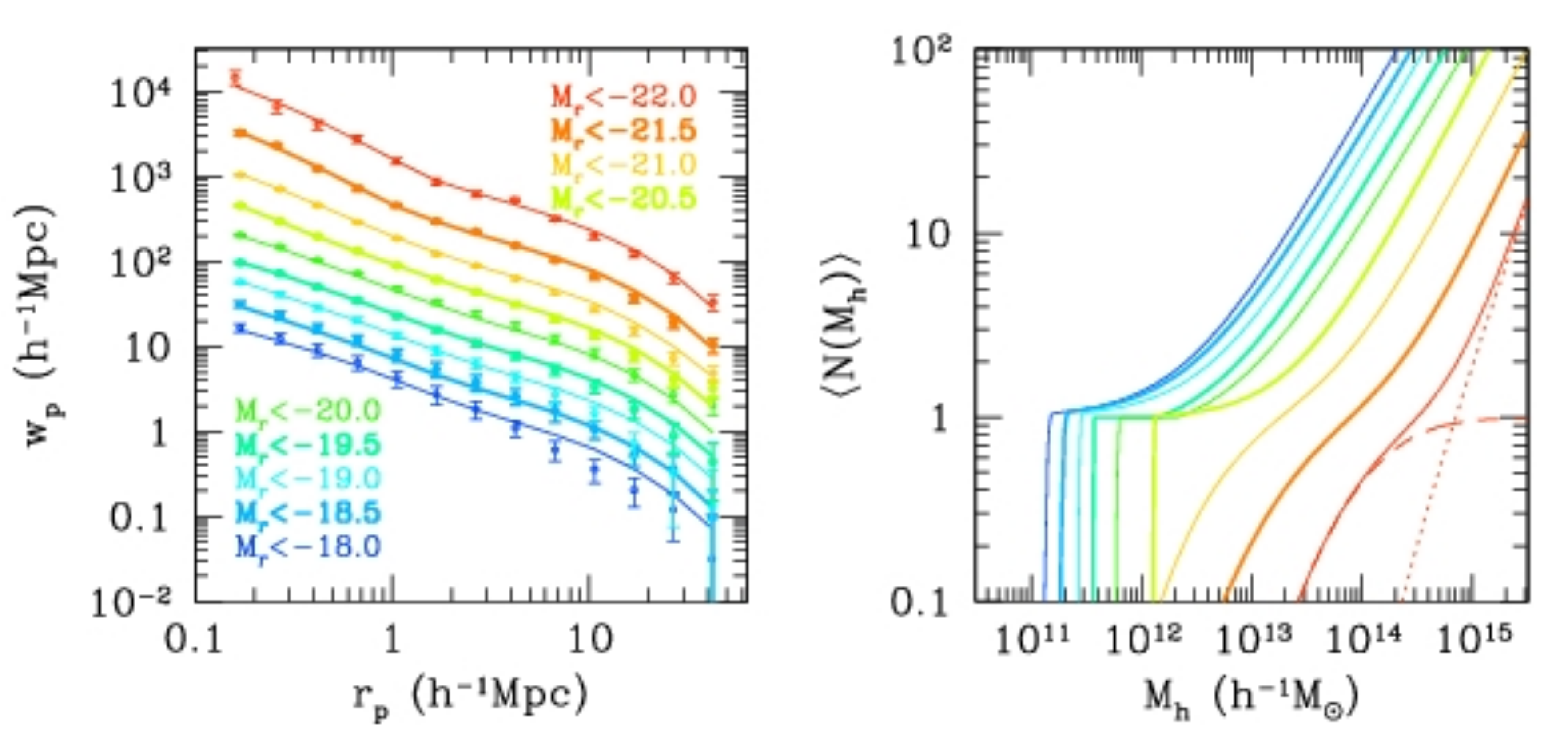
Color: Redder galaxies are more clustered, especially on small scales, continuous trend





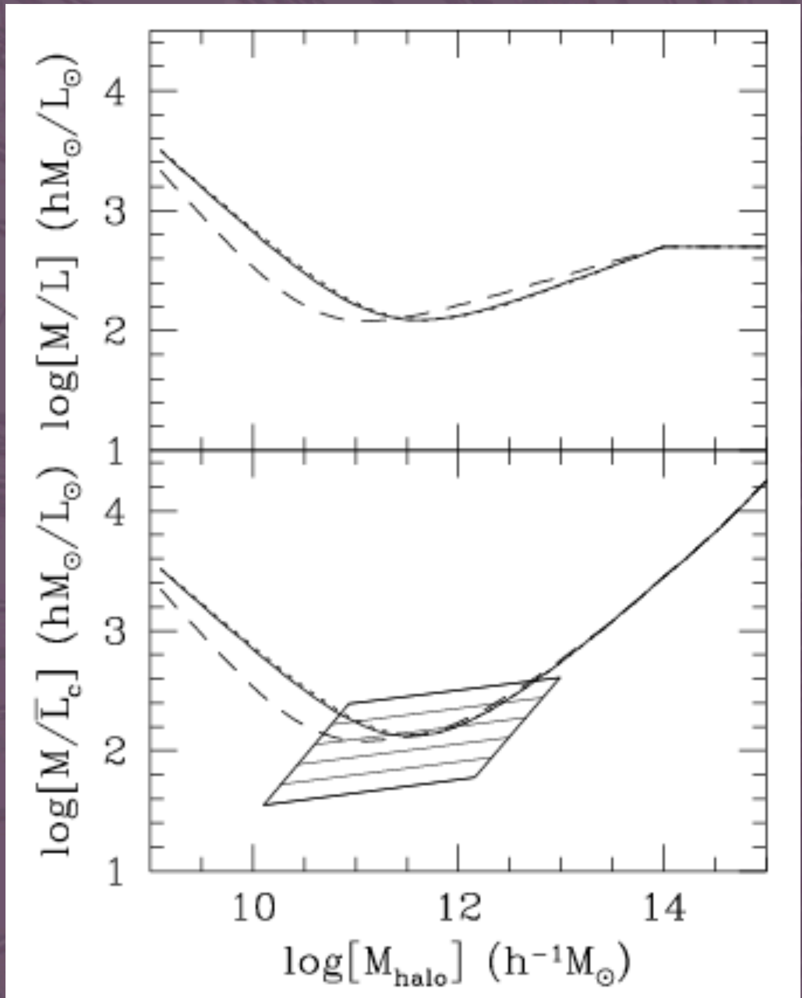
Zehavi, Zheng, Weinberg, et al. 2011

Zehavi, Zheng, Weinberg et al. 2011

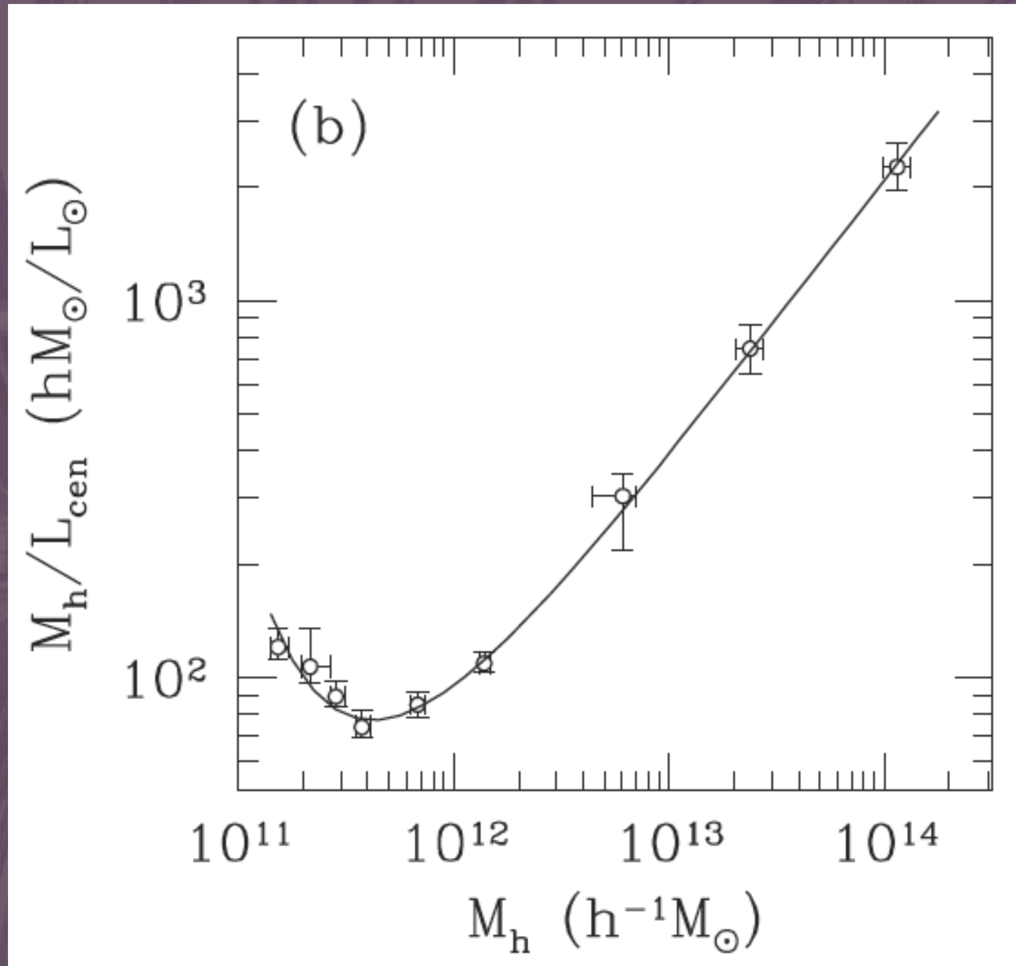


Luminosity dependence explained mainly by overall shift in halo mass scale: brighter galaxies live in more massive halos. Significant scatter between galaxy luminosity and halo mass is required at the high luminosity end.

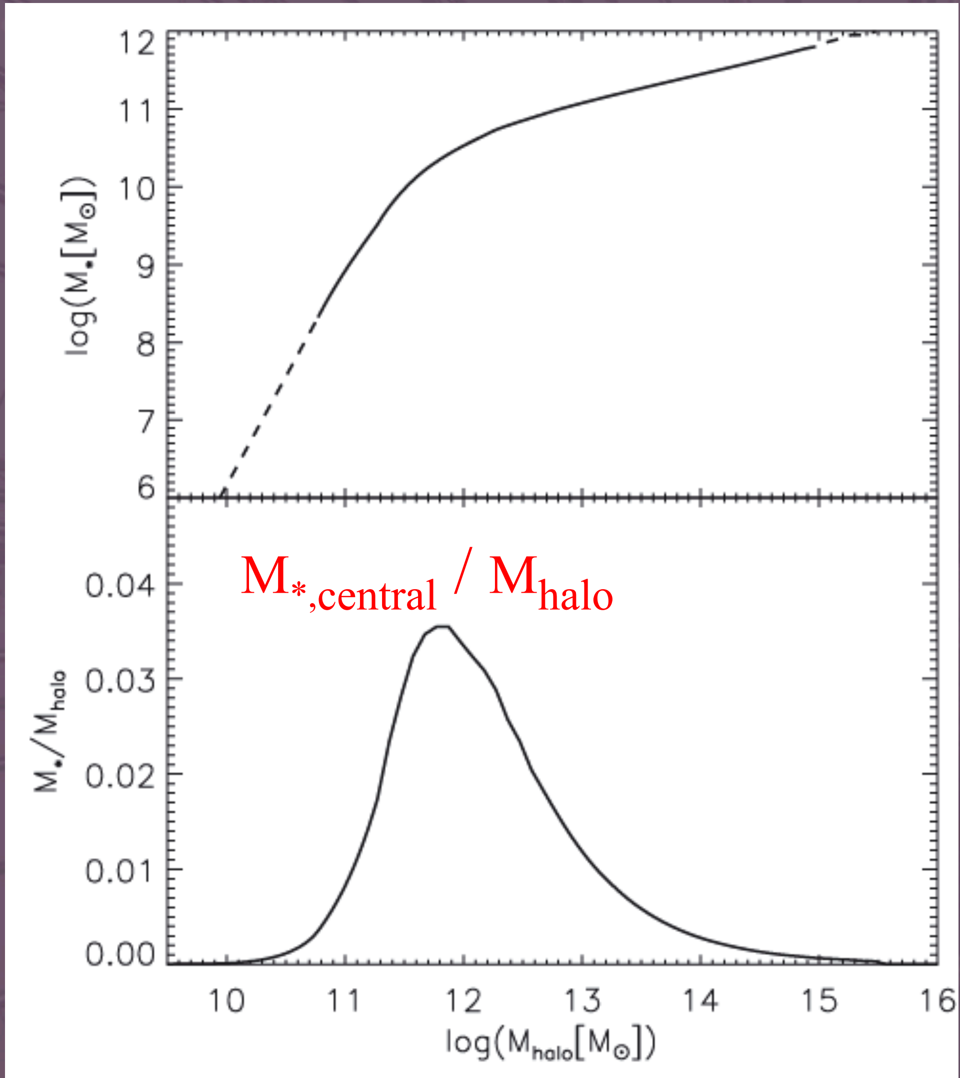
Yang, Mo, & van den Bosch 2003



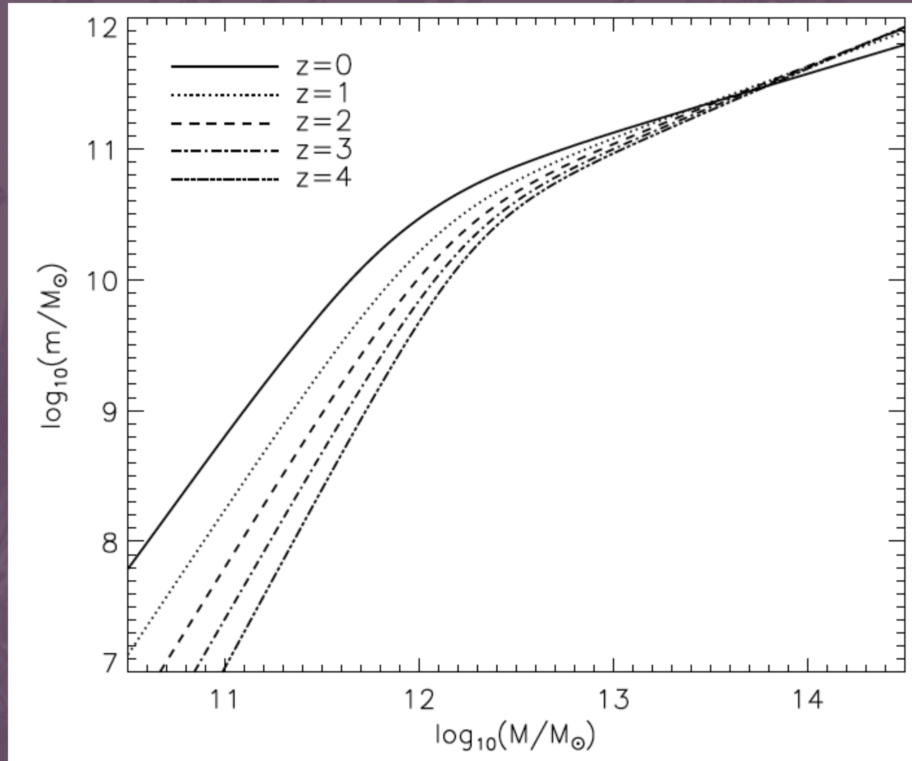
Zehavi, Zheng, Weinberg et al. 2011



Galaxy formation is "maximally efficient" in dark matter halos of mass $M \sim 5 \times 10^{11}\ M_{sun.}$ Tied to transition of stellar feedback to AGN feedback? Cold mode accretion to hot gas halos? Both?



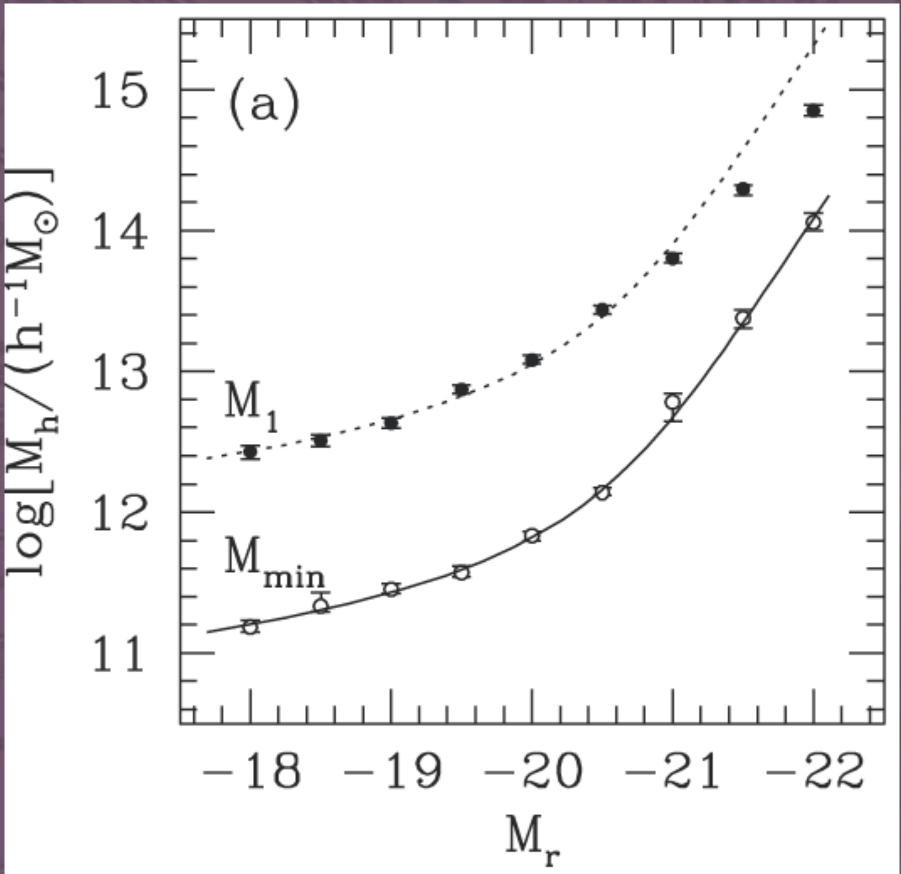
Guo, White, Li, & Boylan-Kolchin 2010



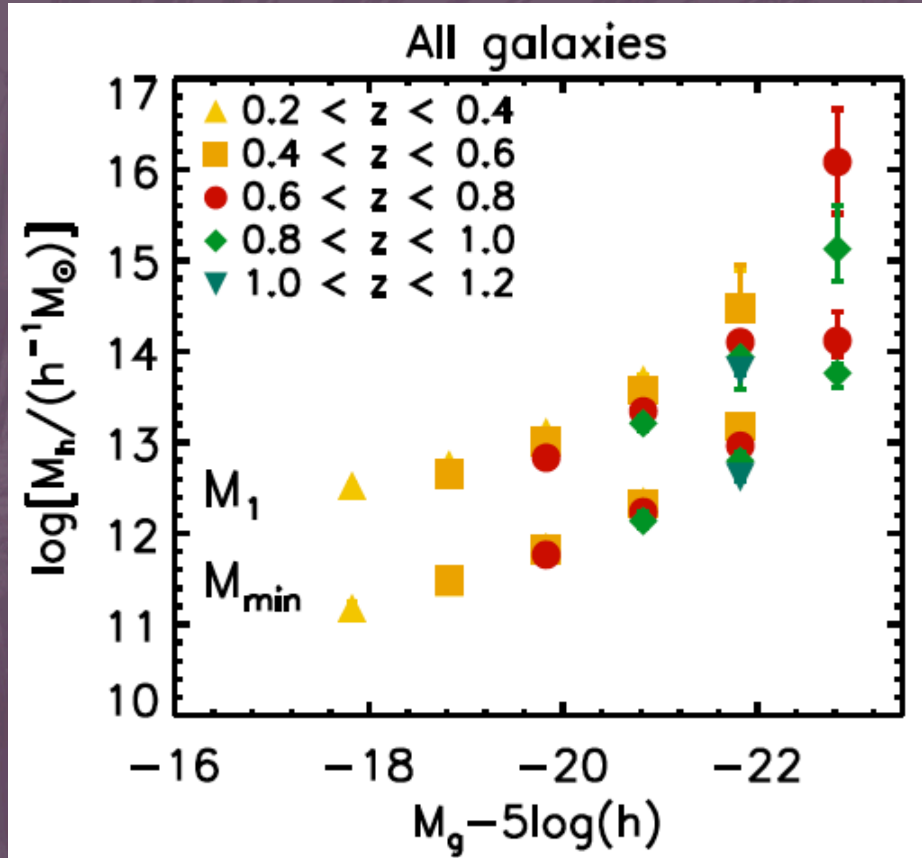
Moster, Somerville, Maulbetsch, van den Bosch, Maccio, Naab, Oser 2010

Little evolution of “peak efficiency halo mass” with redshift.

Zehavi, Zheng, Weinberg et al. 2011

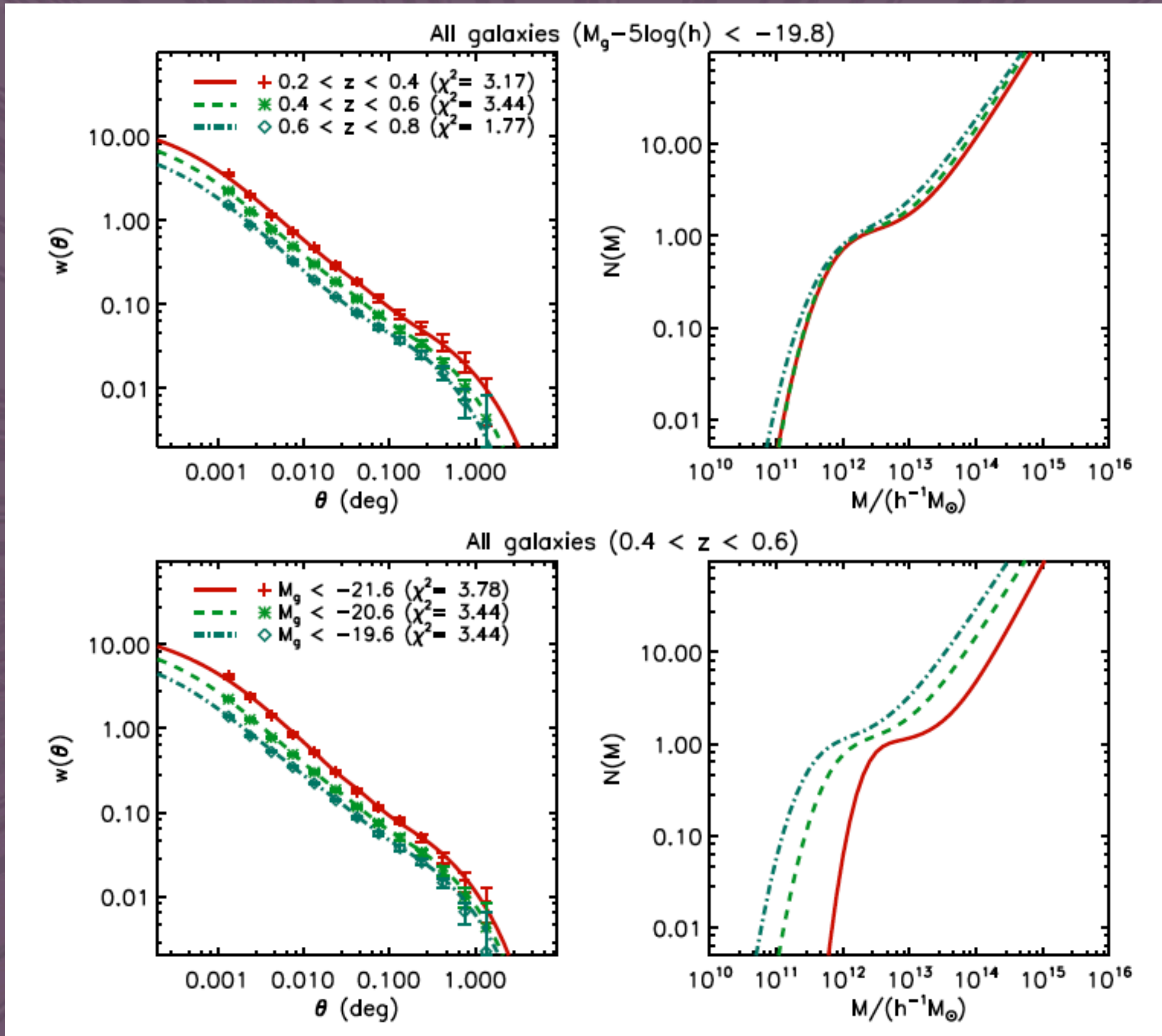


Coupon, Kilbinger, McCracken et al. 2011

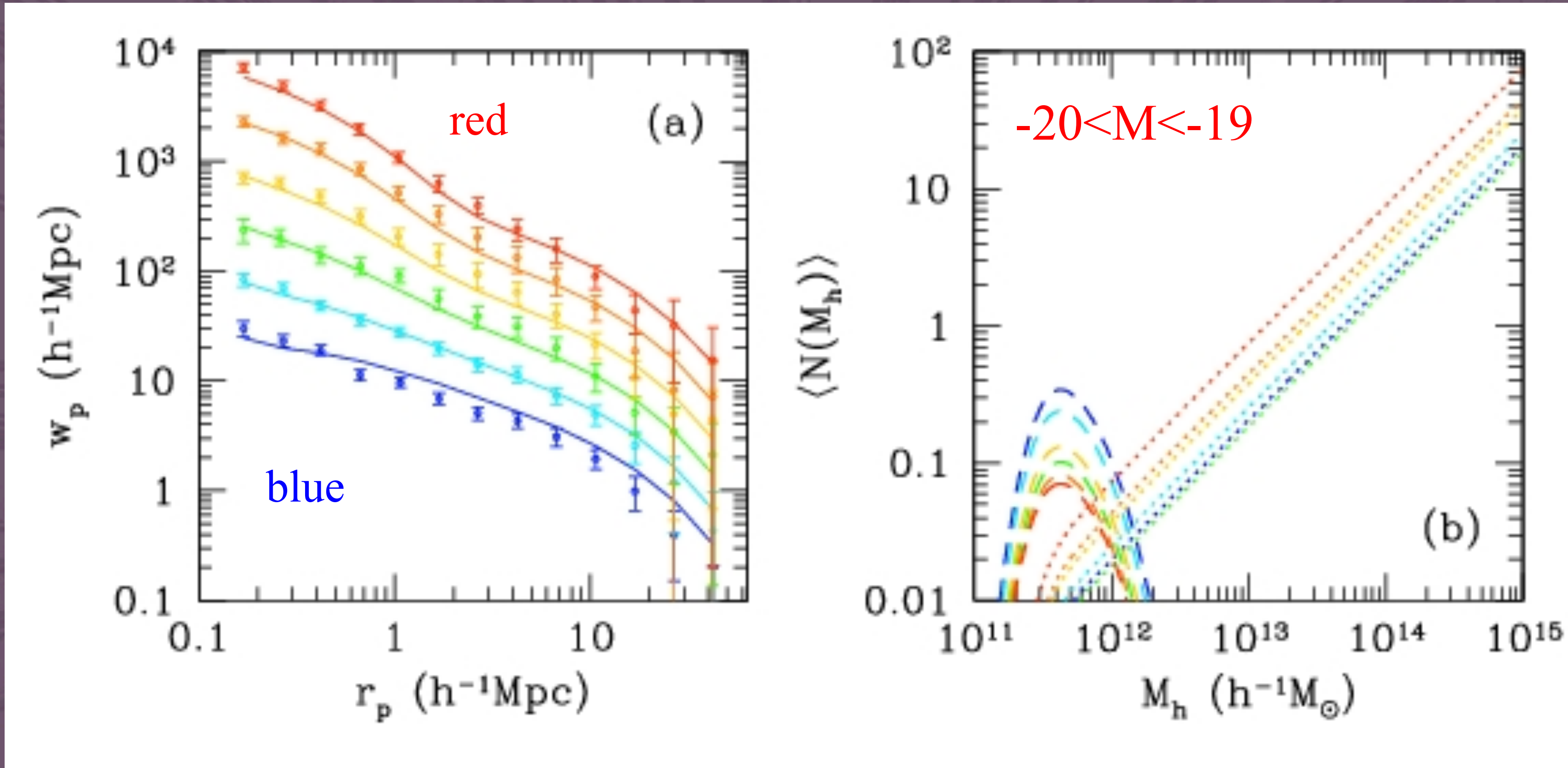


Ratio of M_1 (halo mass for first satellite) to M_{min} (halo mass for central) is ~ 15-20, over a wide range in luminosity and redshift. Probably tied to halo merger statistics + dynamical friction times.

Coupon, Kilbinger, McCracken et al. 2011

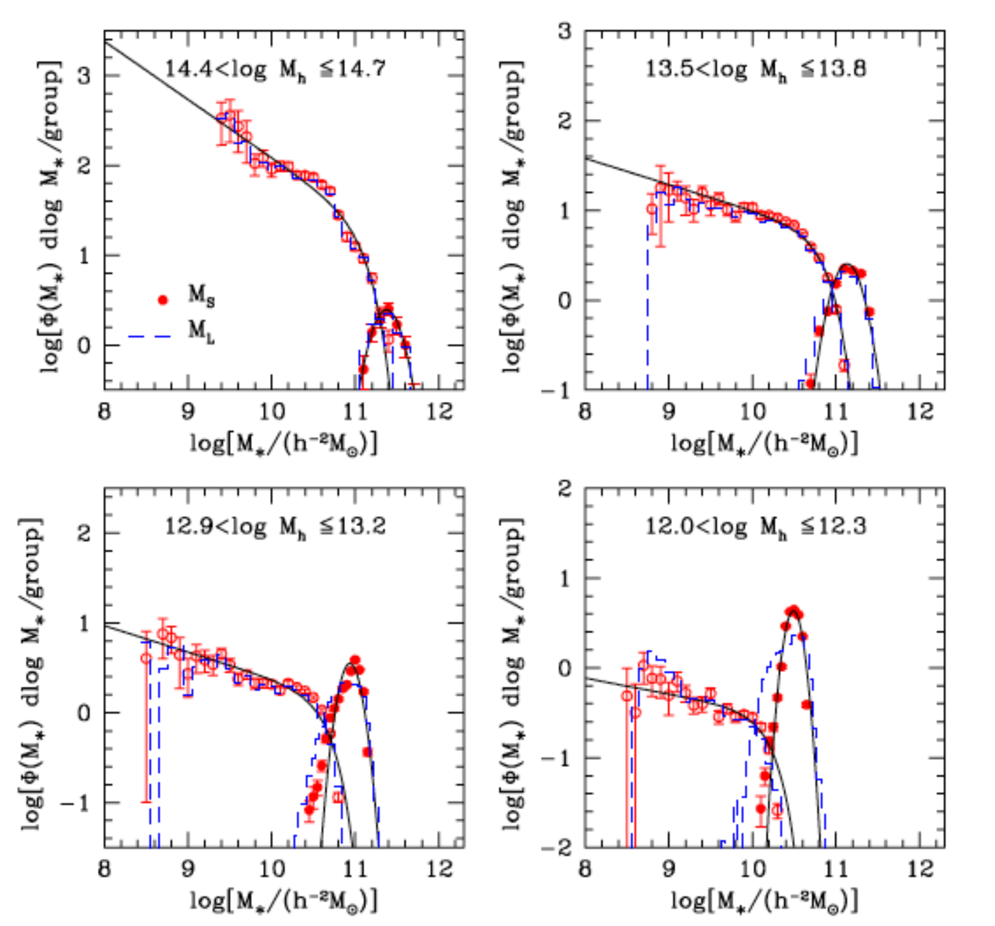


Zehavi, Zheng, Weinberg et al. 2011



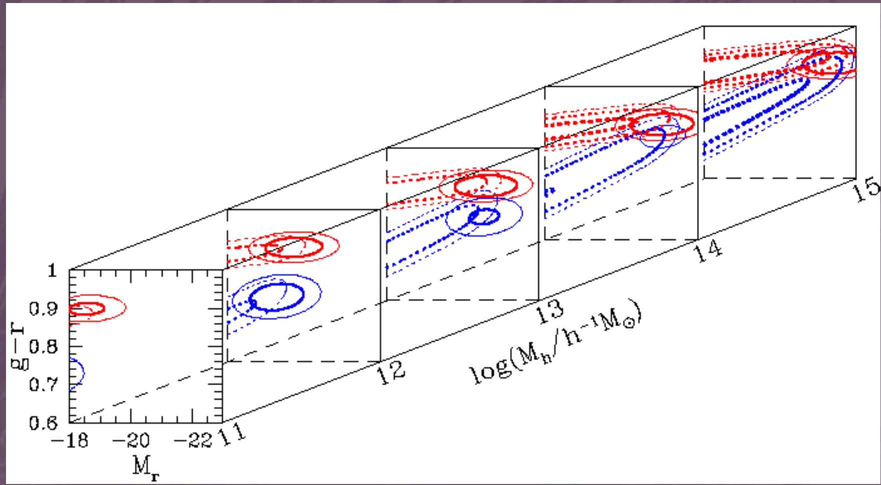
Color dependence explained mainly by change in ratio of central galaxies in low mass halos (predominantly blue) to satellites in high mass halos (predominantly red).

Conditional luminosity function

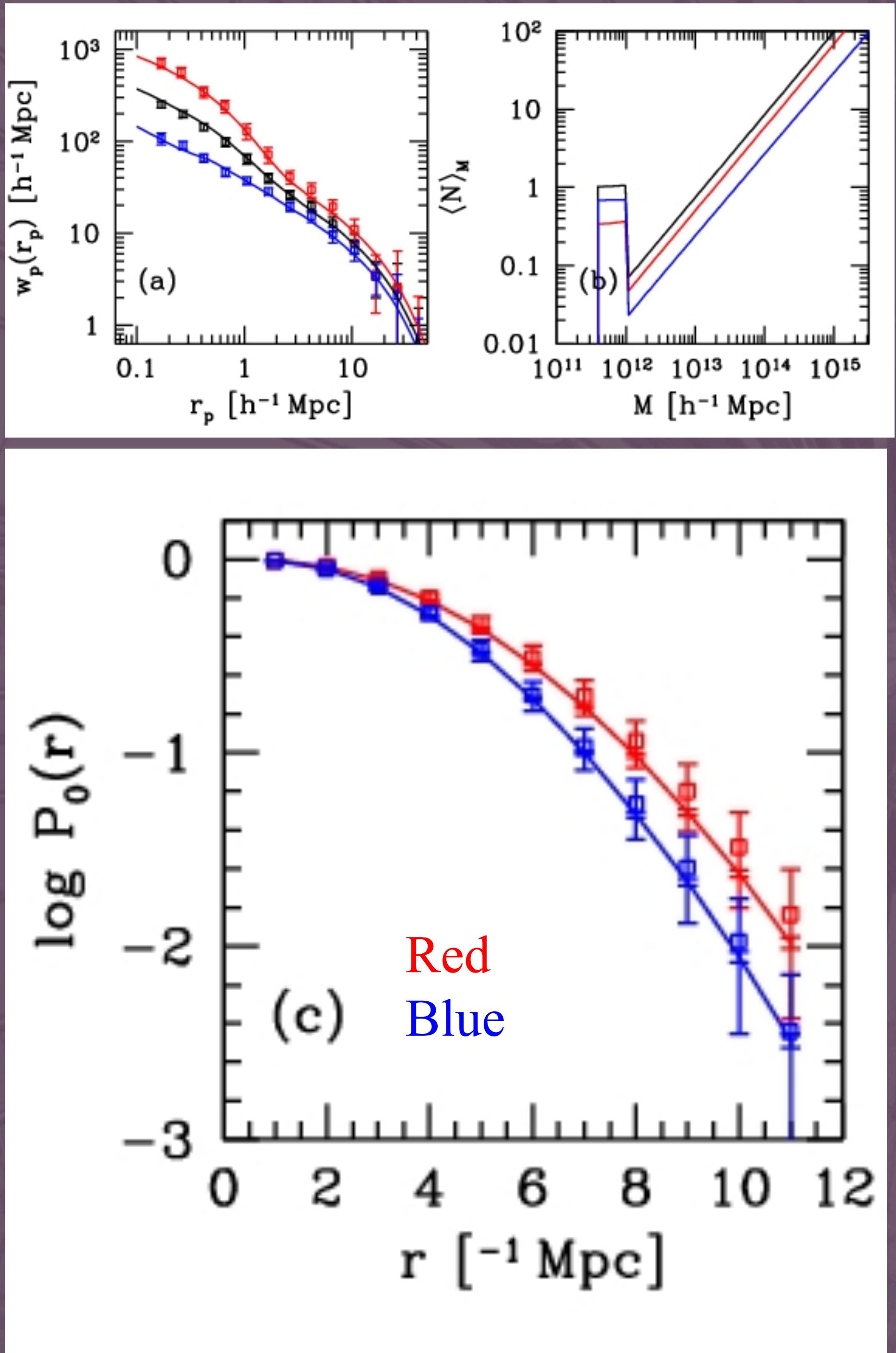


Yang, Mo, & van den Bosch 2008

Conditional color-mag diagram



Zheng et al., in prep.



HOD models fit to correlation functions of red and blue galaxies correctly predict void statistics of red and blue galaxies.

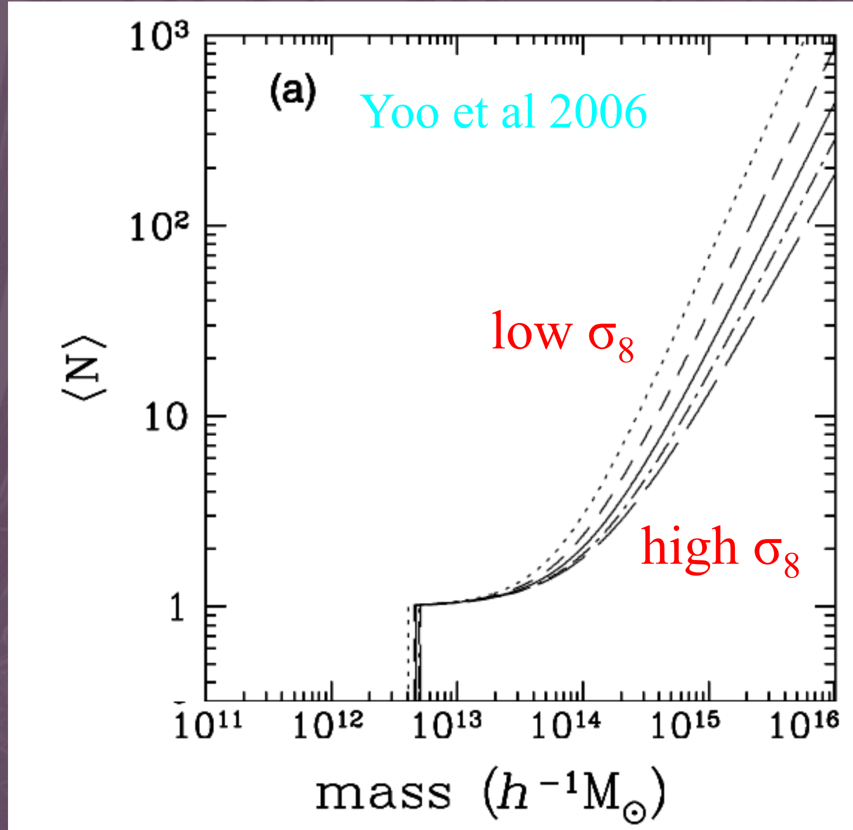
For ~ 10^{12} M_{sun} halos, color distribution of central galaxies is similar in dense and underdense environments.

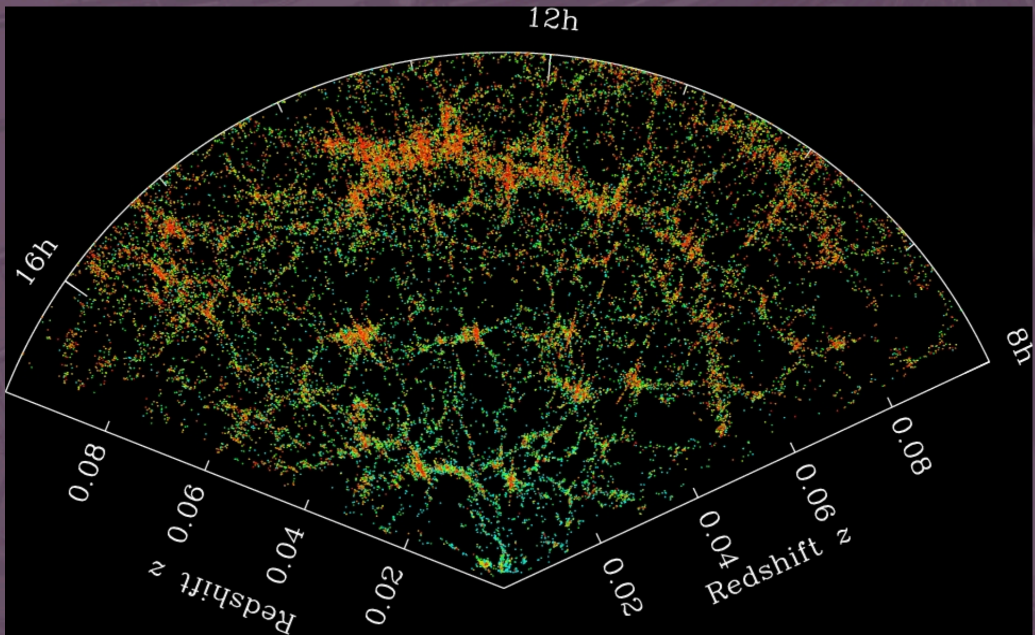
(See Tinker talk at this meeting, Tinker, Wetzel, Conroy, in prep.)

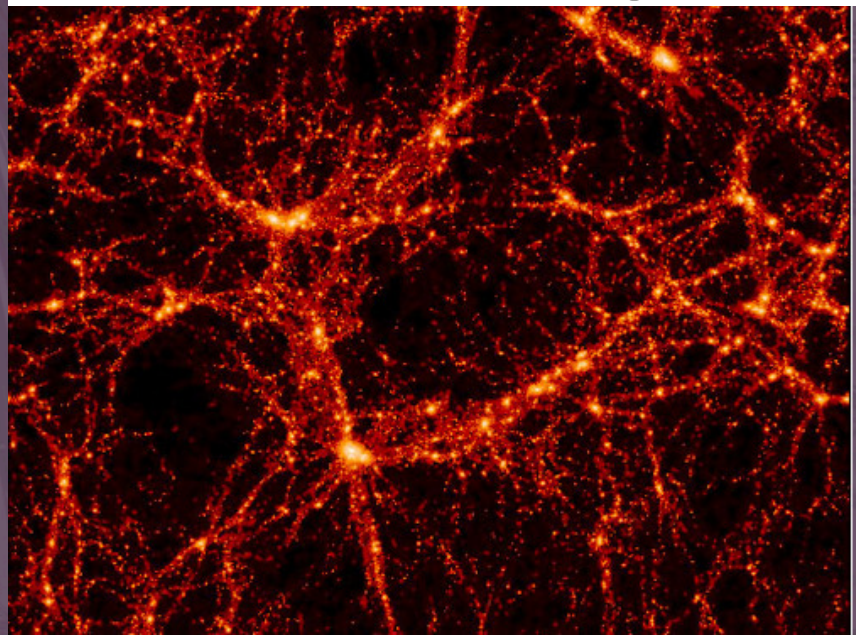
Tinker, Conroy, Norberg, Patiri, Weinberg, Warren 2008

Fitting observed galaxy correlation function in a model with stronger matter clustering (higher σ_8) or higher matter density (Ω_m) requires putting galaxies higher mass halos:

- Higher M at given <N>.
- Higher M/L ratios of clusters.
- Larger galaxy peculiar velocities.
- Stronger galaxy-galaxy lensing.



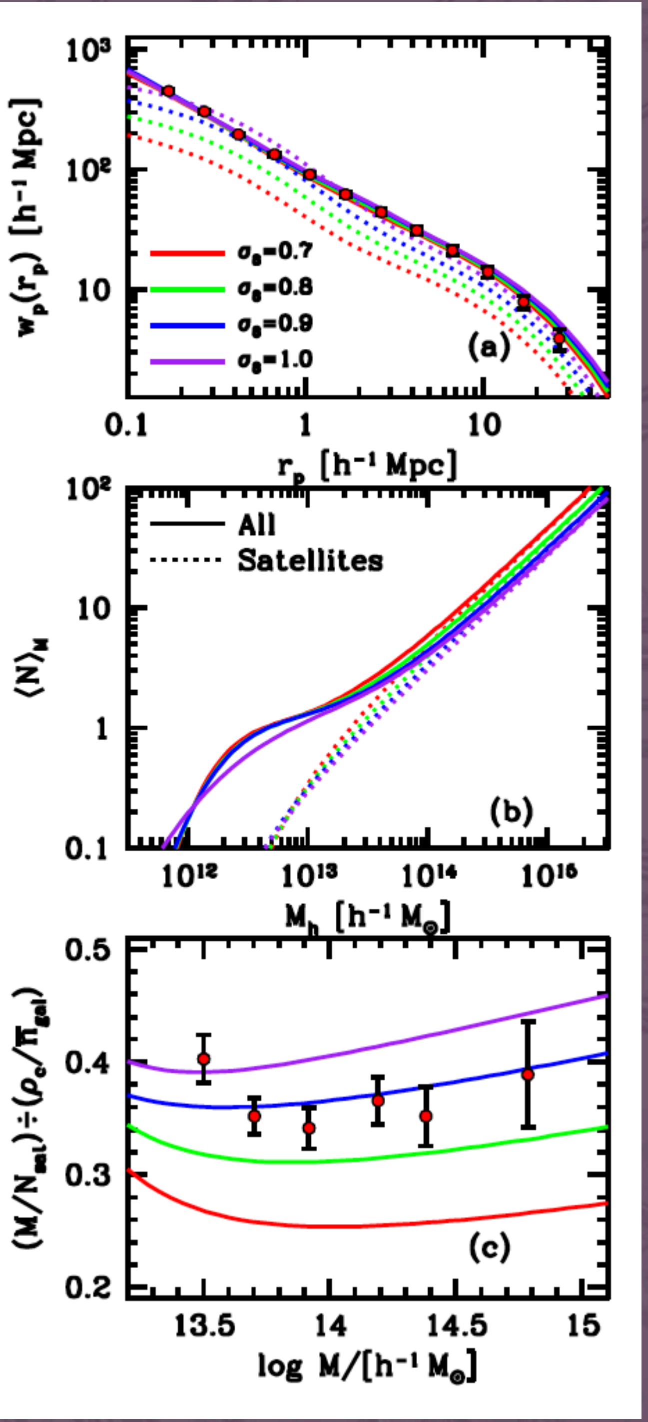




Cluster mass-to-number ratios

Joint fit of HOD model to galaxy correlation function (SDSS DR7) and M/N_{gal} ratios of maxBCG clusters, with stacked weak lensing masses.

Higher M/N for higher σ_8 or Ω_m .



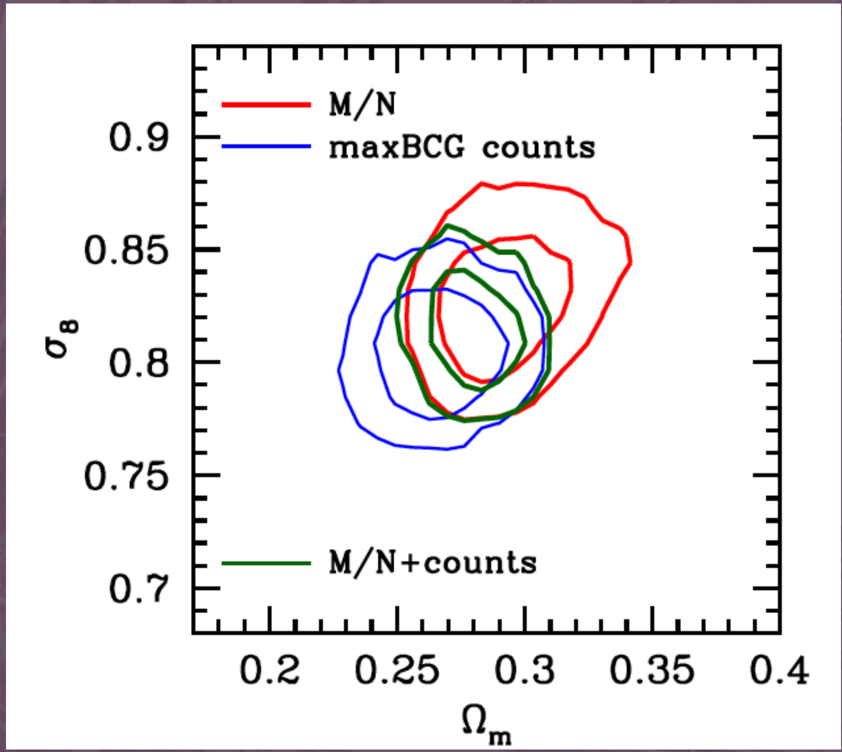
Tinker, Sheldon, Wechsler et al. 2011

Tinker, Sheldon, Wechsler et al. 2011

Cluster mass-to-number ratios

Joint fit of HOD model to galaxy correlation function (SDSS DR7) and M/N_{gal} ratios of maxBCG clusters, with stacked weak lensing masses.

$\sigma_8 = 0.826 \pm 0.020, \ \Omega_m = 0.290 \pm 0.016$



Red = M/N
Blue = cluster abundance (Rozo et al. 2010)
Both incorporate (but significantly tighten) WMAP7 priors.

Main uncertainties:

- halo bias formula
- LF evolution from z=0.1 to z=0.25
- HOD evolution from z=0.1 to z=0.25

Factor of two error reduction is readily achievable with current measurements.

Results consistent with cluster abundance, but systematics nearly orthogonal.

Some frontiers of the field

Environmental variations of the HOD

Most observational evidence to date favors little/no variation, but it should be present at some level.

Environment dependence is a nuisance for cosmological analysis but valuable for understanding galaxy formation.

Redshift-space distortions

A potentially powerful probe of dark energy, gravity.

In principle, HOD method allows accurate modeling from non-linear to linear regime, best accuracy and use of information.

Developing an accurate and flexible analytic model is hard.

Redshift evolution of halo occupations

Adds clustering to the empirical studies of galaxy evolution.

New observational results coming in rapidly.

Interesting theoretical models under development.

Summary

Empirical successes:

Shape and amplitude of galaxy $\xi(r)$ vs. luminosity and redshift.
Successful predictions of void statistics, galaxy-galaxy lensing, scale-dependent bias of LRG power spectrum.
Early discovery of "WMAP3" Ω_m, σ_8.

What have we learned?

Peak of galaxy formation efficiency at $M_{halo} \sim 10^{12} M_{sun}$.
Luminosity dependence of clustering driven by M_{min} of centrals.
Substantial L-M_{halo} scatter for high luminosity galaxies.
Near-constant ratio of $M_1 / M_{min} \sim 15$-20.
Color dependence of clustering driven by satellite fraction.
Same central galaxy colors for $10^{12} M_{sun}$ in voids and dense regions.
Cluster M/N +WMAP: $\sigma_8 = 0.826 \pm 0.020$, $\Omega_m = 0.290 \pm 0.016$

Some frontiers of the field:

Environmental variations, Redshift-space distortions, Evolution