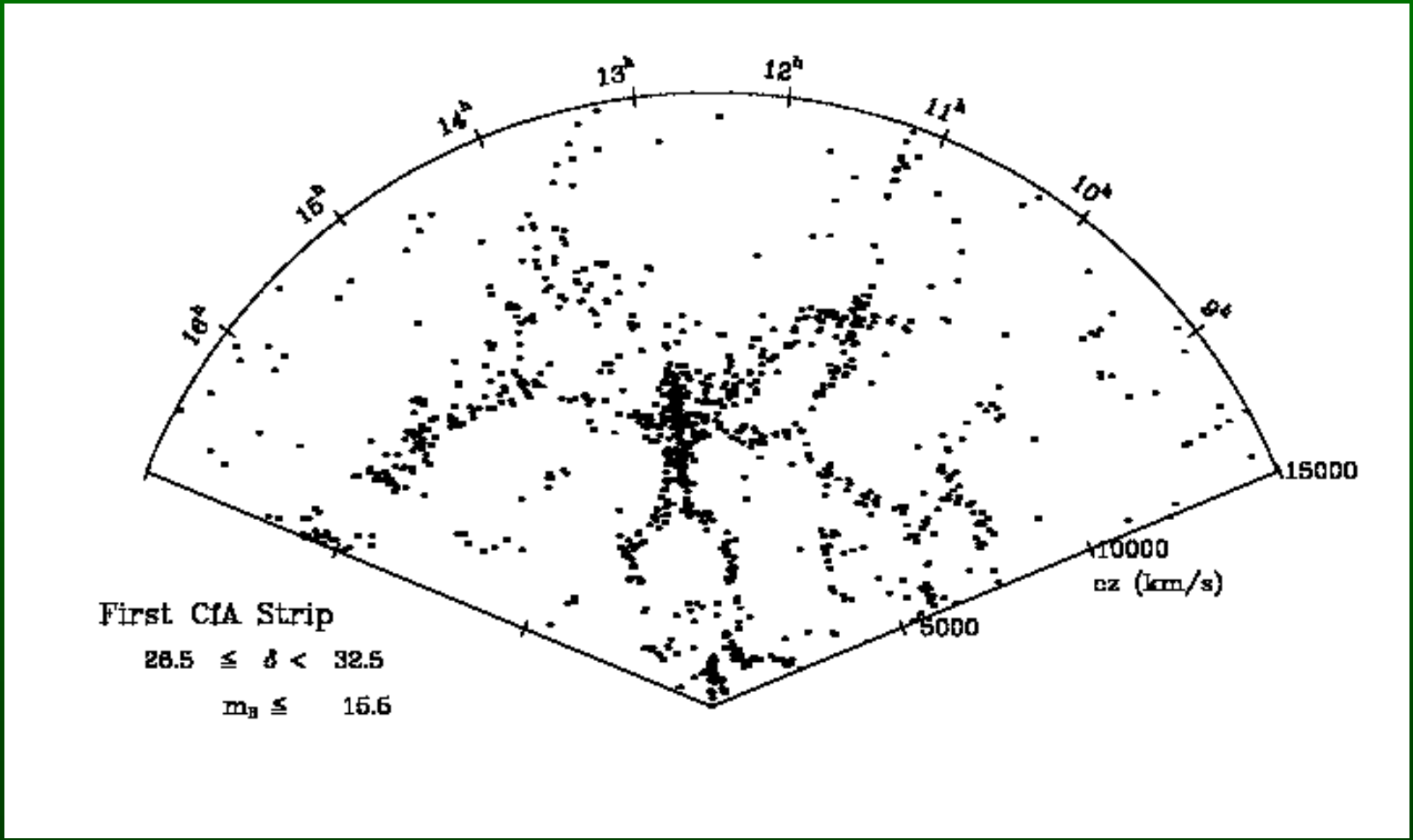
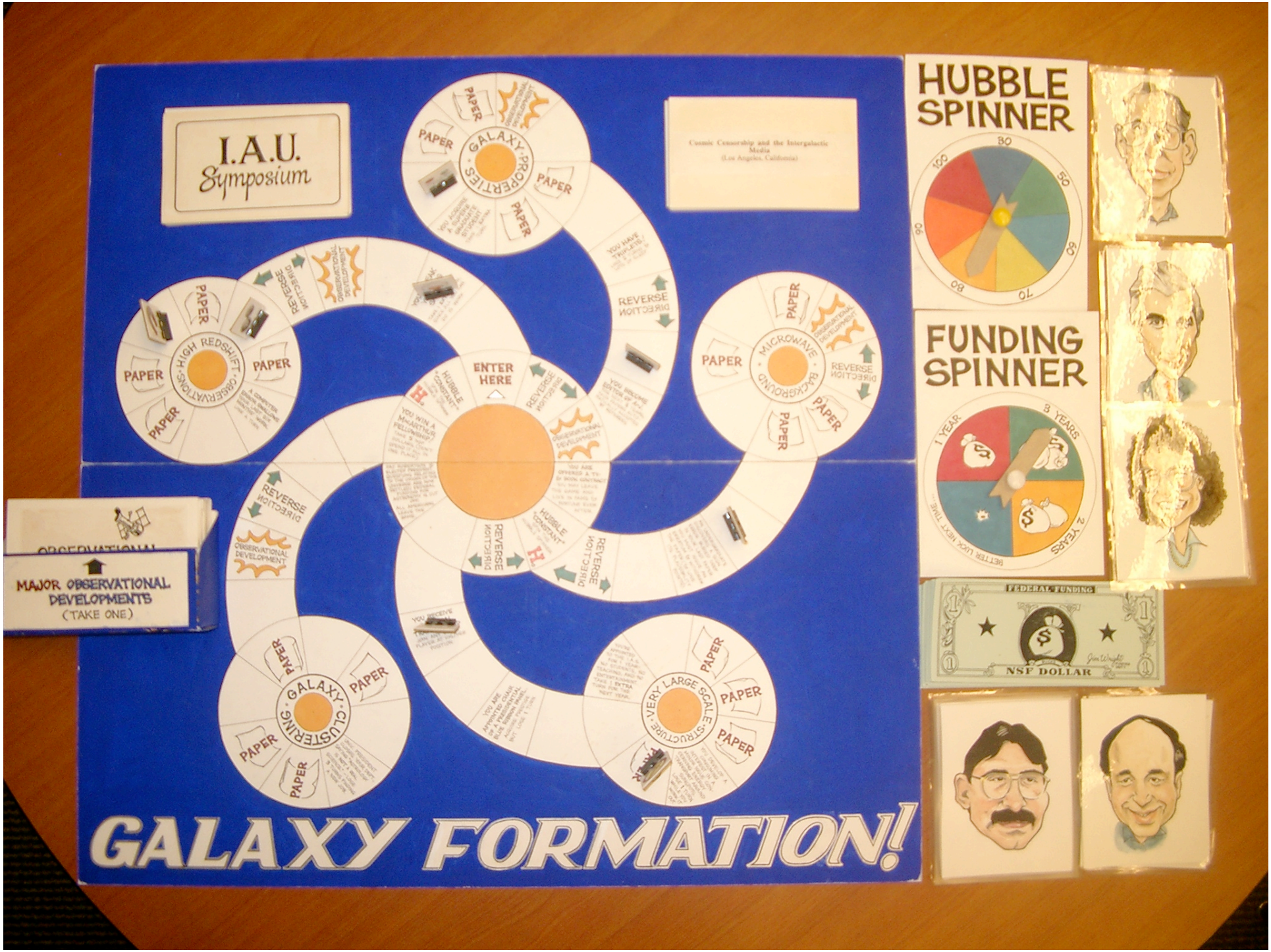
Interpreting Large Scale Structure

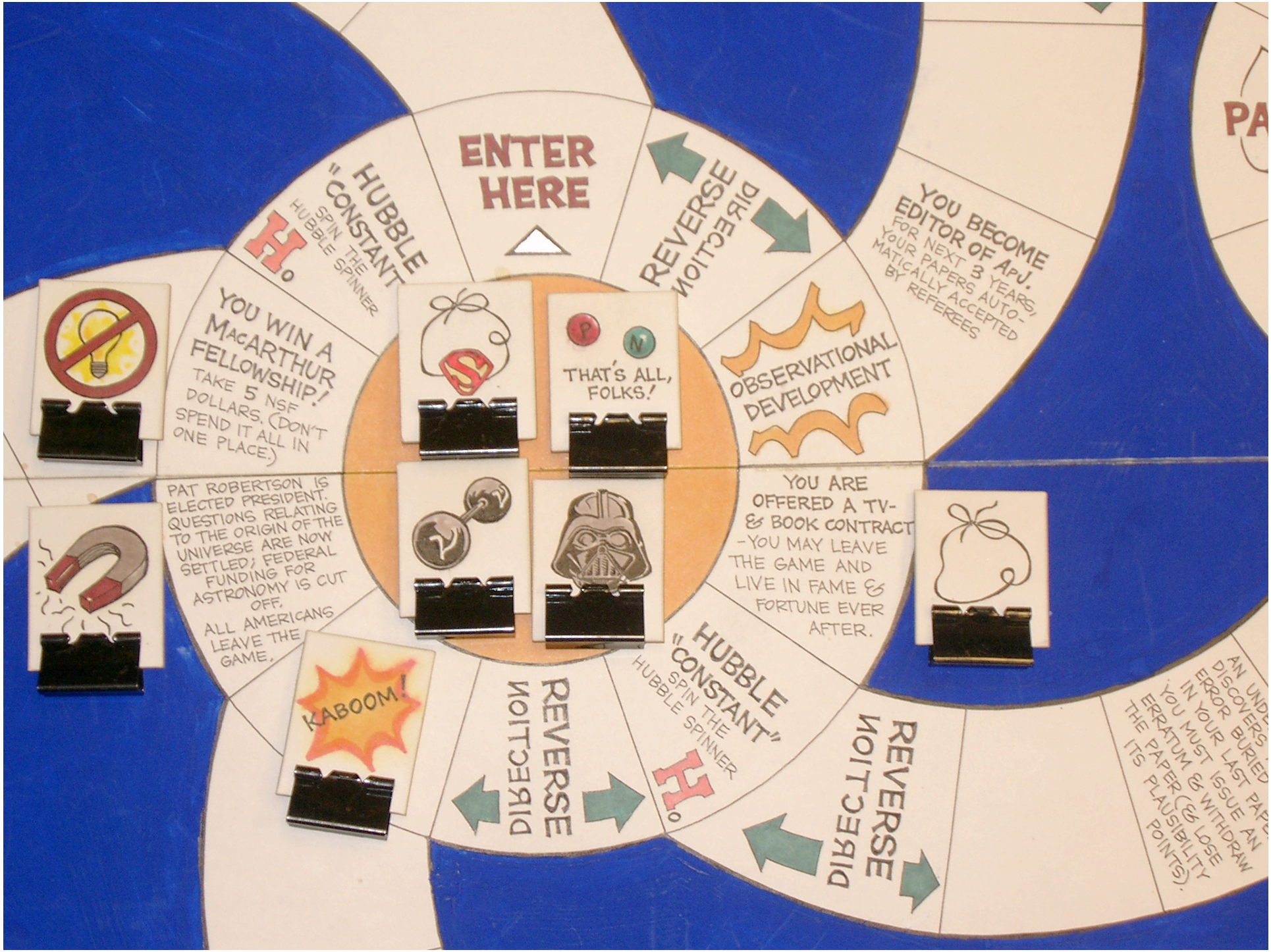
David Weinberg, Ohio State University

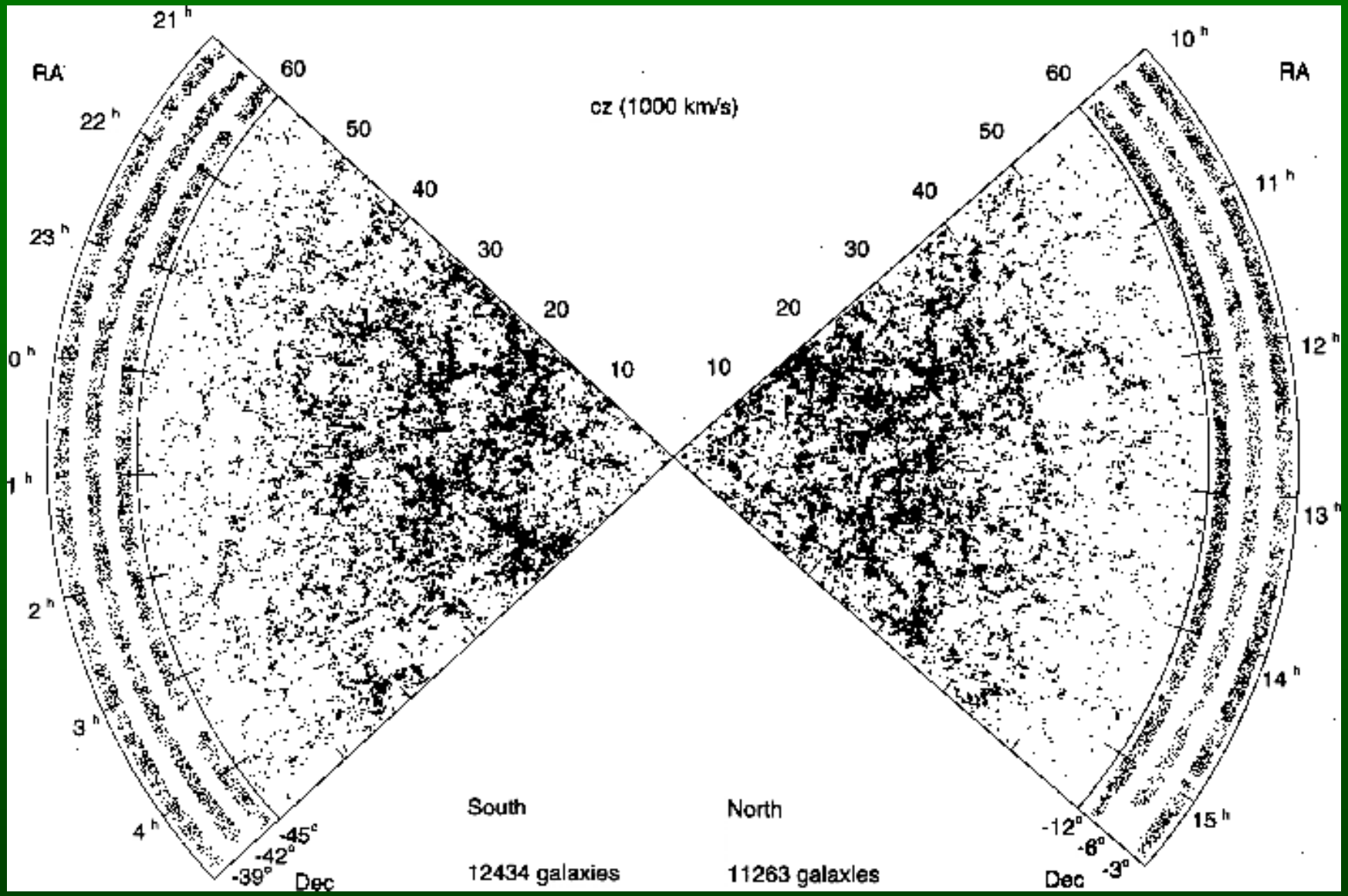


CfA2 Redshift Survey

de Lapparent, Geller, & Huchra 1986

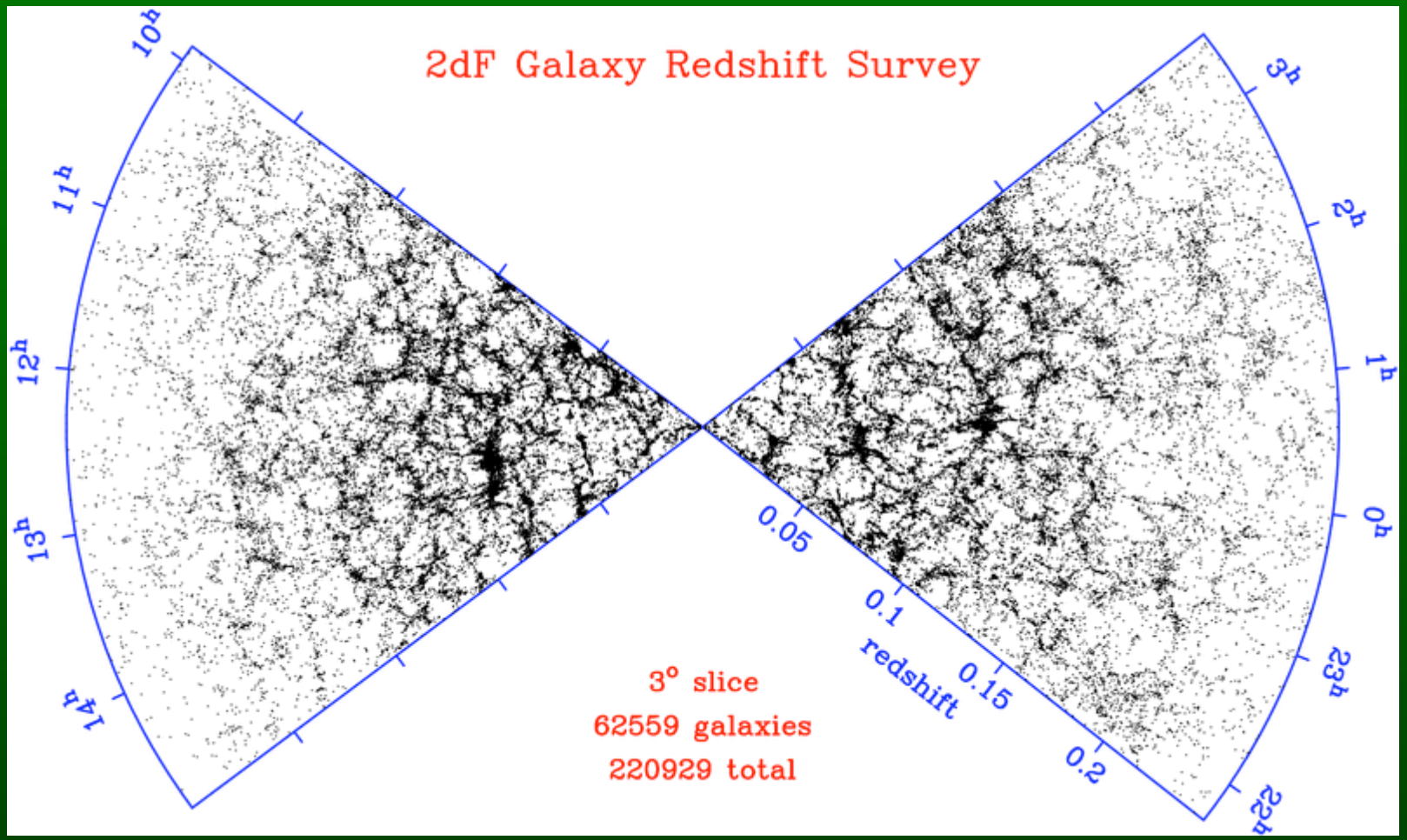

I.A.U.
Symposium
Cosmic Censorship and the Intergalactic Media
(Los Angeles, California)
GALAXY PROPERTIES
HIGH REDSHIFT OBSERVATIONS
MICROWAVE BACKGROUND
GALAXY CLUSTERING
VERY LARGE SCALE STRUCTURE
ENTER HERE
PAPER
REVERSE DIRECTION
OBSERVATIONAL DEVELOPMENT
HUBBLE "CONSTANT"
MAJOR OBSERVATIONAL DEVELOPMENTS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


ENTER HERE
HUBBLE "CONSTANT"
SPIN THE HUBBLE SPINNER
H0
REVERSE DIRECTION
YOU BECOME EDITOR OF ApJ. FOR NEXT 3 YEARS, YOUR PAPERS AUTOMATICALLY ACCEPTED BY REFEREES
OBSERVATIONAL DEVELOPMENT
YOU ARE OFFERED A TV- & BOOK CONTRACT -YOU MAY LEAVE THE GAME AND LIVE IN FAME & FORTUNE EVER AFTER.
REVERSE DIRECTION
HUBBLE "CONSTANT"
SPIN THE HUBBLE SPINNER
H0
REVERSE DIRECTION
AN UNDE
DISCOVERS
ERROR BURIED
IN YOUR LAST PAP
YOU MUST ISSUE AN
ERRATUM & WITHDRAW
THE PAPER (& LOSE
ITS PLAUSIBILITY
POINTS).
PA
P
N
THAT'S ALL, FOLKS!
YOU WIN A MacARTHUR FELLOWSHIP! TAKE 5 NSF DOLLARS. (DON'T SPEND IT ALL IN ONE PLACE.)
PAT ROBERTSON IS ELECTED PRESIDENT. QUESTIONS RELATING TO THE ORIGIN OF THE UNIVERSE ARE NOW SETTLED; FEDERAL FUNDING FOR ASTRONOMY IS CUT OFF. ALL AMERICANS LEAVE THE GAME.
KABOOM!



Las Campanas Redshift Survey

Shectman et al. 1996



Colless et al. 2001

Sloan Digital Sky Survey

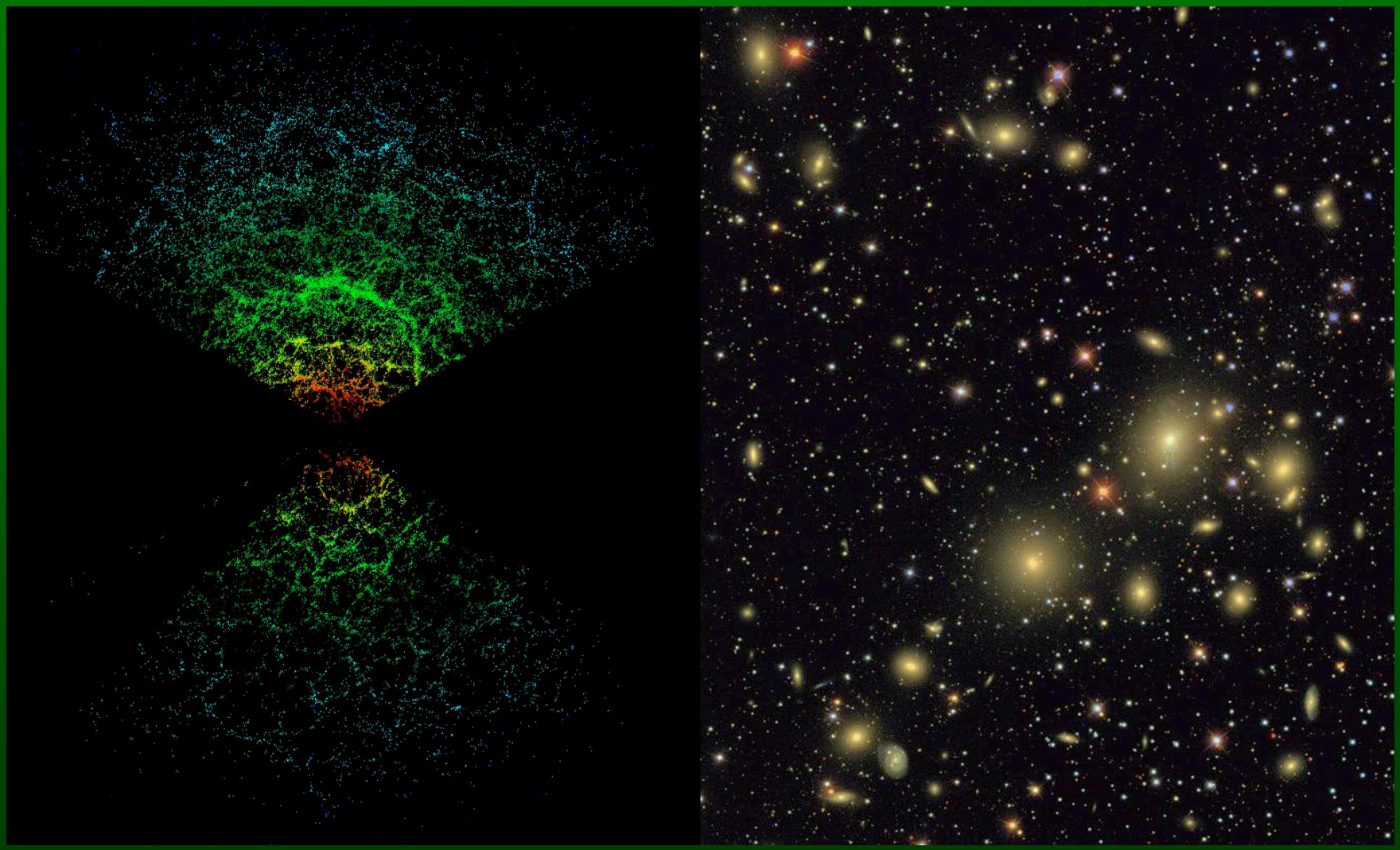
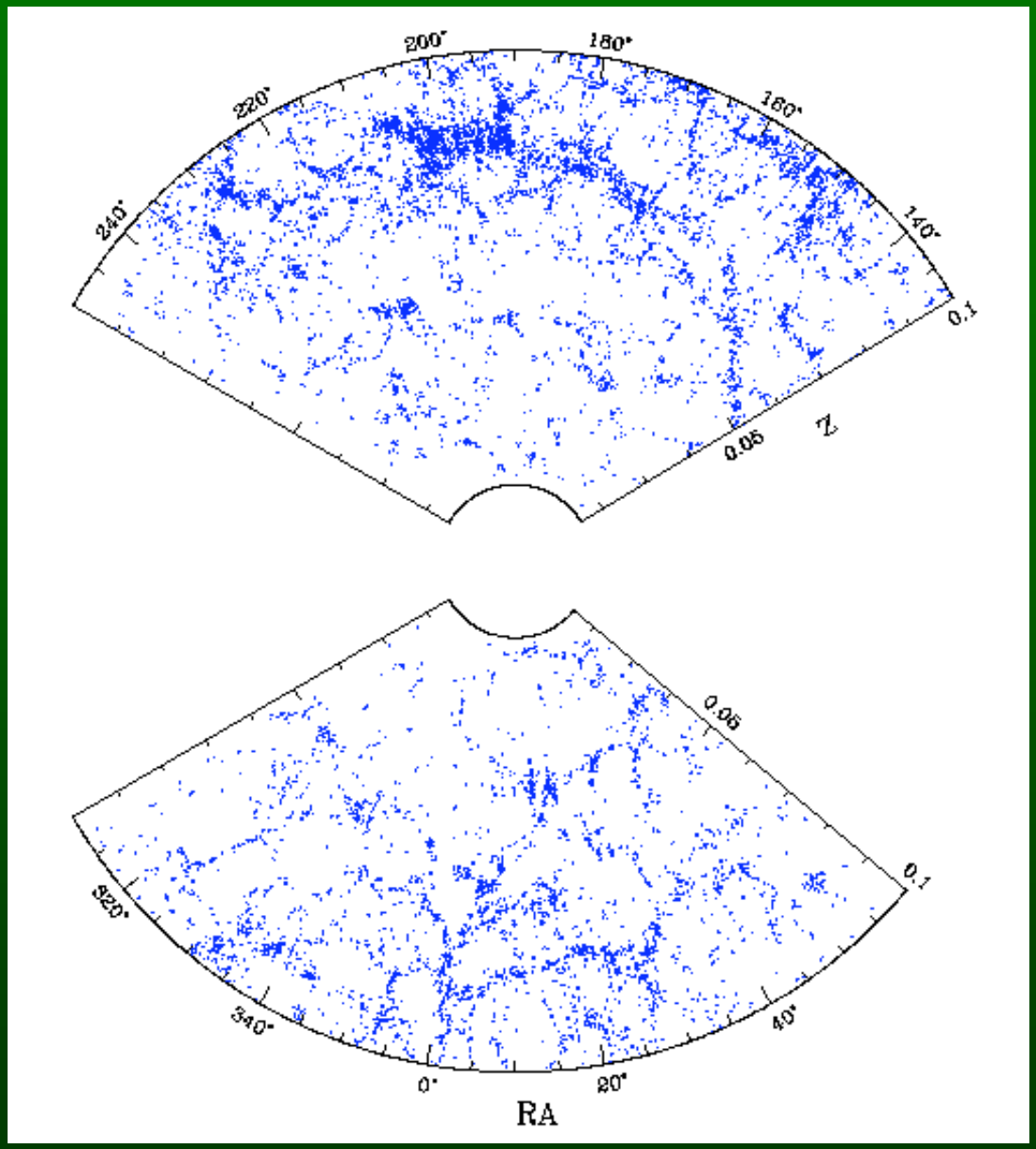


Image courtesy of M. Tegmark

Sloan Digital Sky Survey



Volume-limited sample

$M_r < -20$

Berlind et al. 2005

Important Developments in LSS

1. Large surveys: dynamic range, precision, detail. Precise measurements for well defined classes of galaxies.
2. Combination of LSS constraints with CMB, other cosmological data.
3. Improved modeling of relation between galaxies and dark matter.
4. Weak lensing: galaxy-matter cross-correlation, matter auto-correlation.
5. Galaxy clustering at high redshift.
6. Matter clustering at high redshift from Lyα forest.

Fundamental Questions

1. What are the matter and energy contents of the universe?
   What is the dark energy accelerating cosmic expansion?
2. What physics produced primordial density fluctuations?
3. Why do galaxies exist?
   What physical processes determine their masses, sizes, luminosities, colors, and morphologies?

Key issue: relation between galaxies and mass

Large scales: $\delta_{gal} = f(\delta_\rho) \sim f'(0)\, \delta_\rho = b\, \delta_\rho$

$[\delta_\rho \equiv (\rho - \langle\rho\rangle)/\langle\rho\rangle]$

$P_{gal}(k) = b^2\, P(k)$.

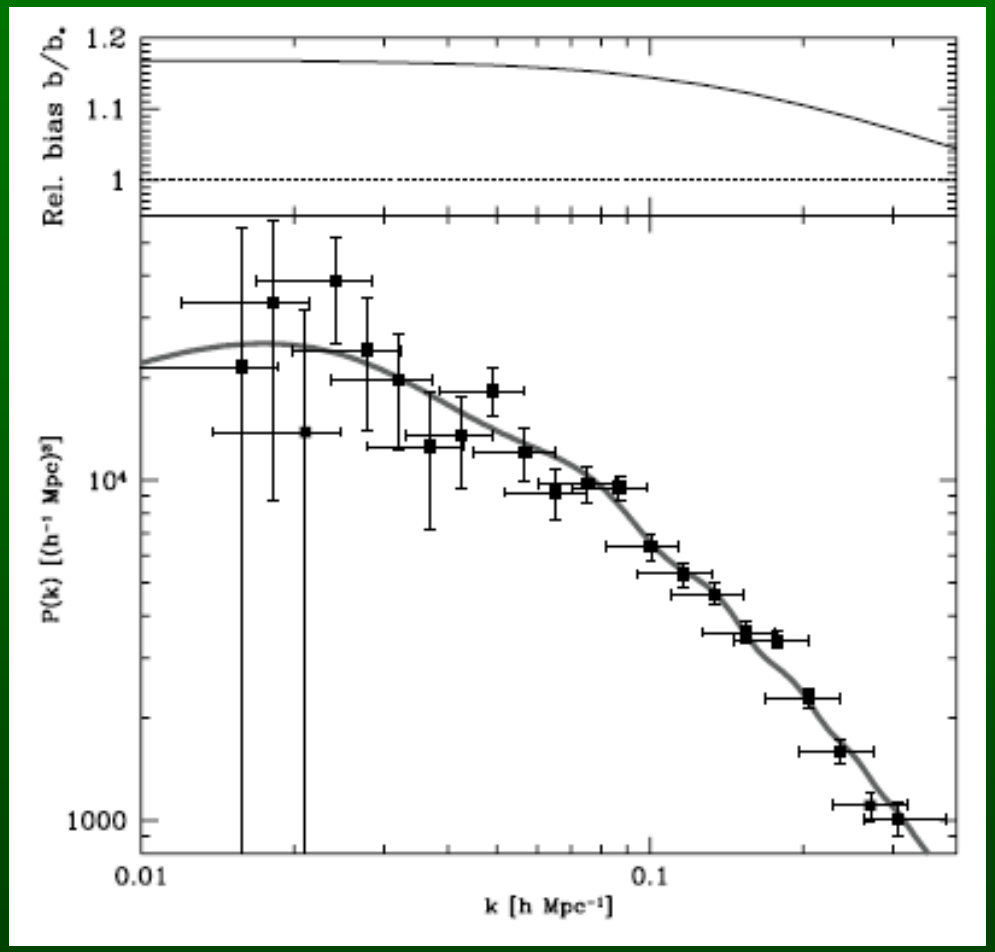
Use P(k) shape for cosmology.

Also:

Redshift space disortions: constrain $\beta = \Omega_m^{0.6} / b$

Bispectrum: constrain b

SDSS Galaxy Power Spectrum (DR2)



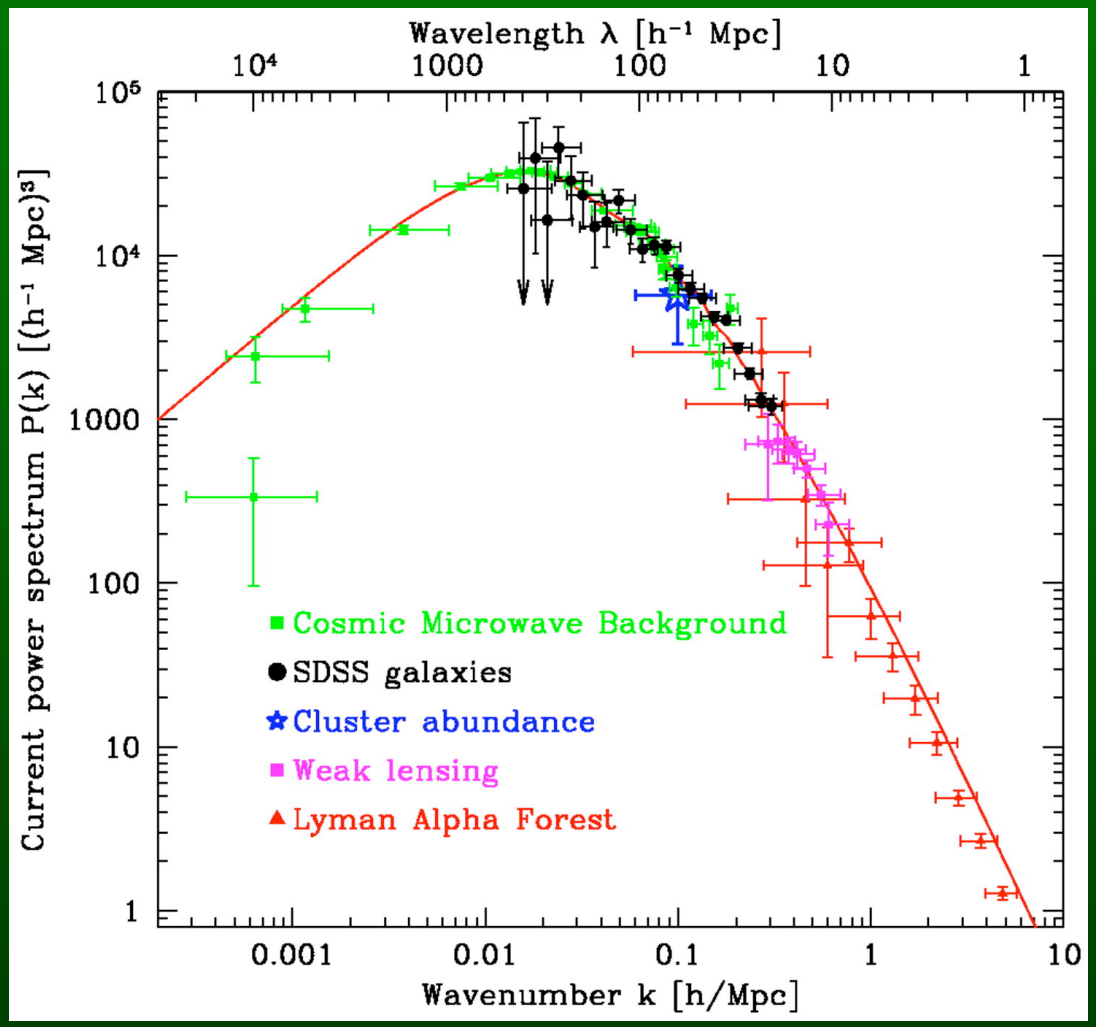
Tegmark et al. 2004

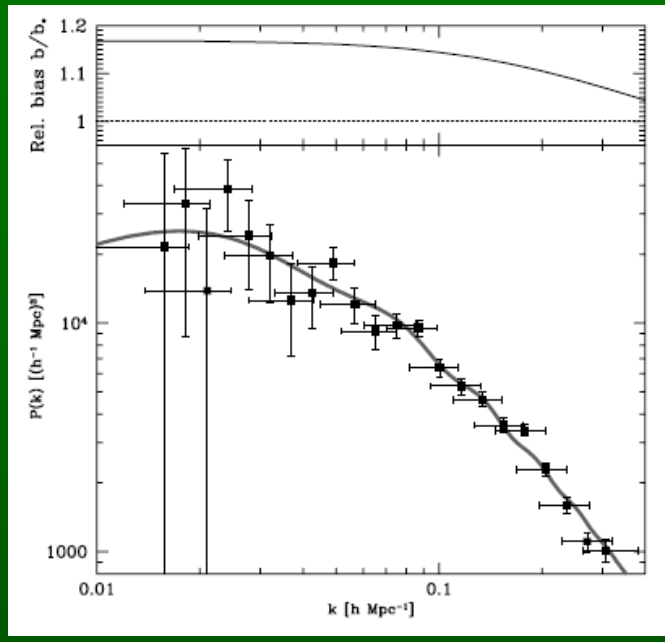
Tegmark et al. 2004:

- Redshift → real space P(k) recovery
- Decorrelated power estimates
- Model with linear bias

$\Omega_m h = 0.213 +/- 0.023$ for $\Omega_b / \Omega_m = 0.17$, $n_s=1$, $h=0.72$

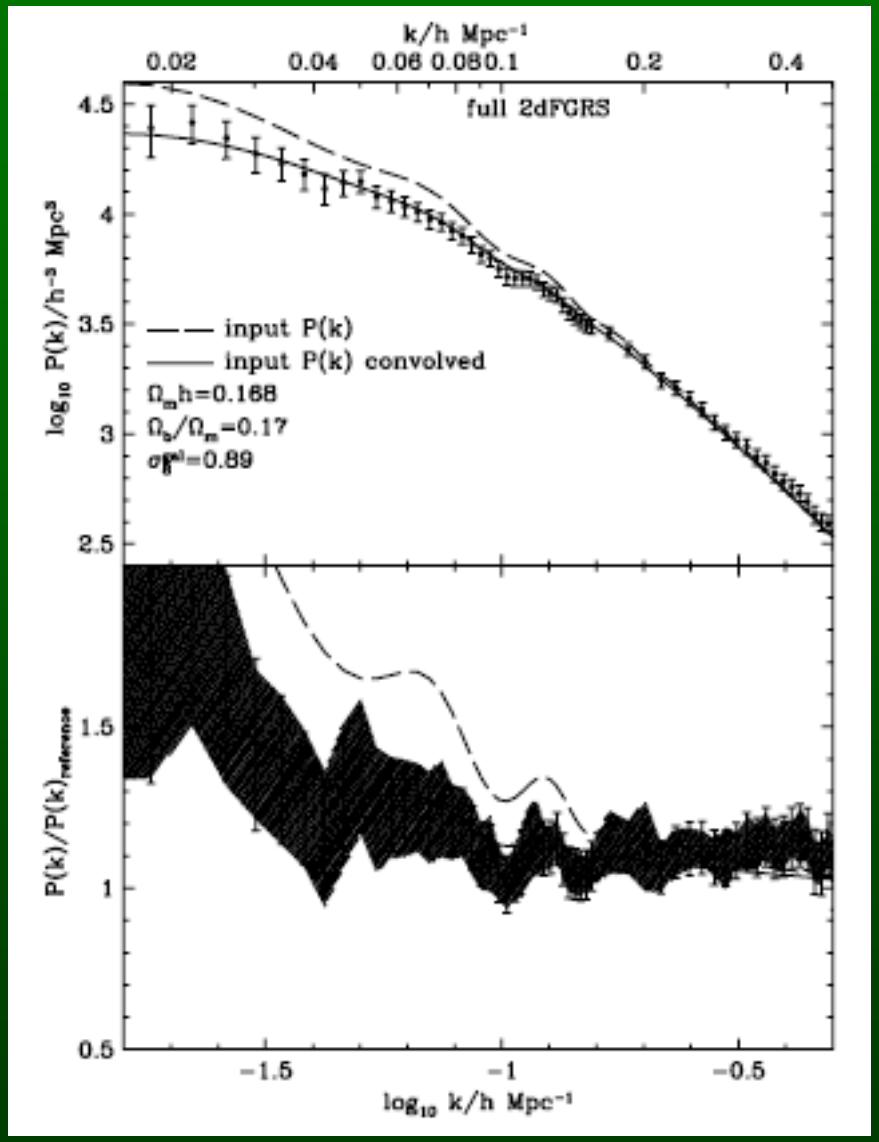
SDSS Galaxy Power Spectrum (DR2)





Tegmark et al. 2004

2dFGRS Galaxy Power Spectrum (final)



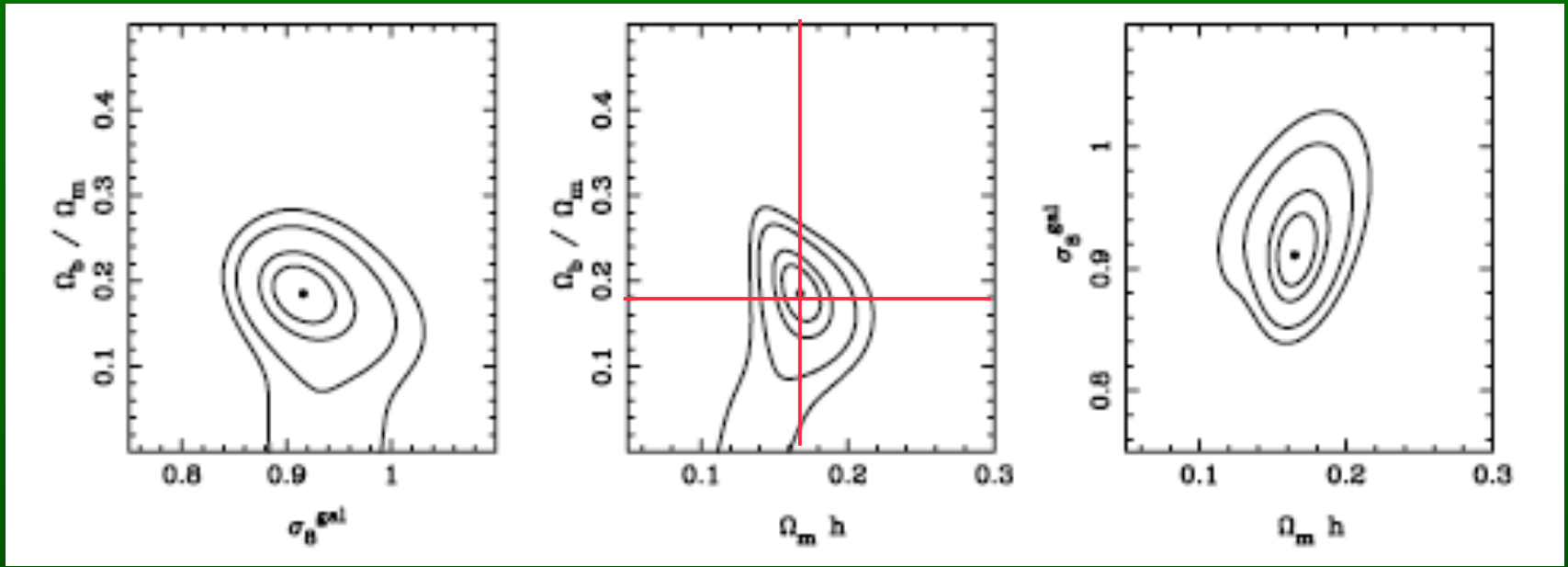
Cole et al. 2005

Cole et al. 2005:

- Angle-averaged redshift space P(k)
- Compare to models convolved with survey window function
- Model scale-dependent bias as $b(k)=(1+Qk^2)(1+Ak)^{-1}$

Theory used to motivate form, give priors on parameter values.

2dFGRS Galaxy Power Spectrum (final)



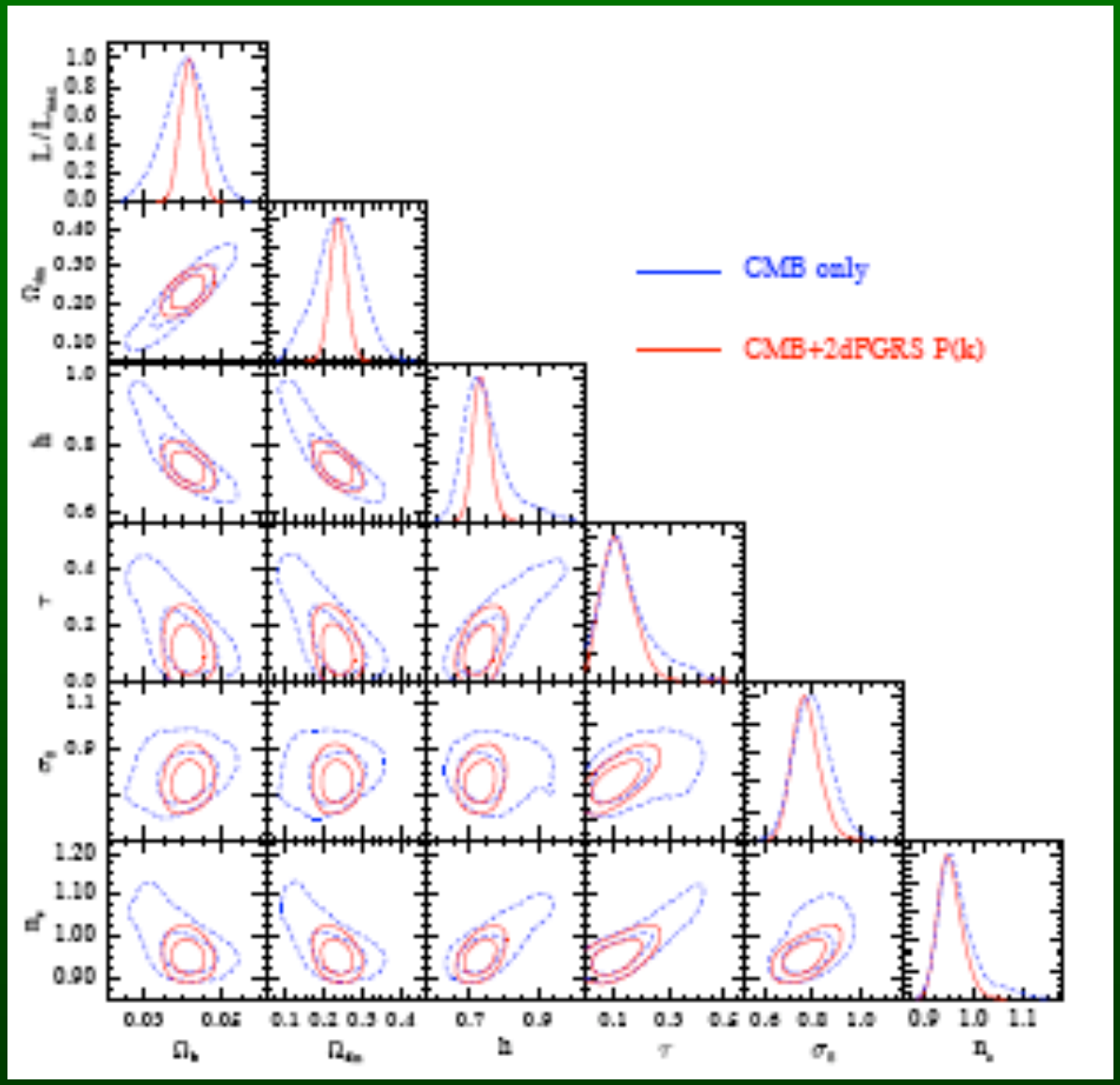
Cole et al. 2005

$\Omega_m h = 0.168 +/- 0.016$

$\Omega_b / \Omega_m = 0.185 +/- 0.046$

For n_s=1, h=0.72

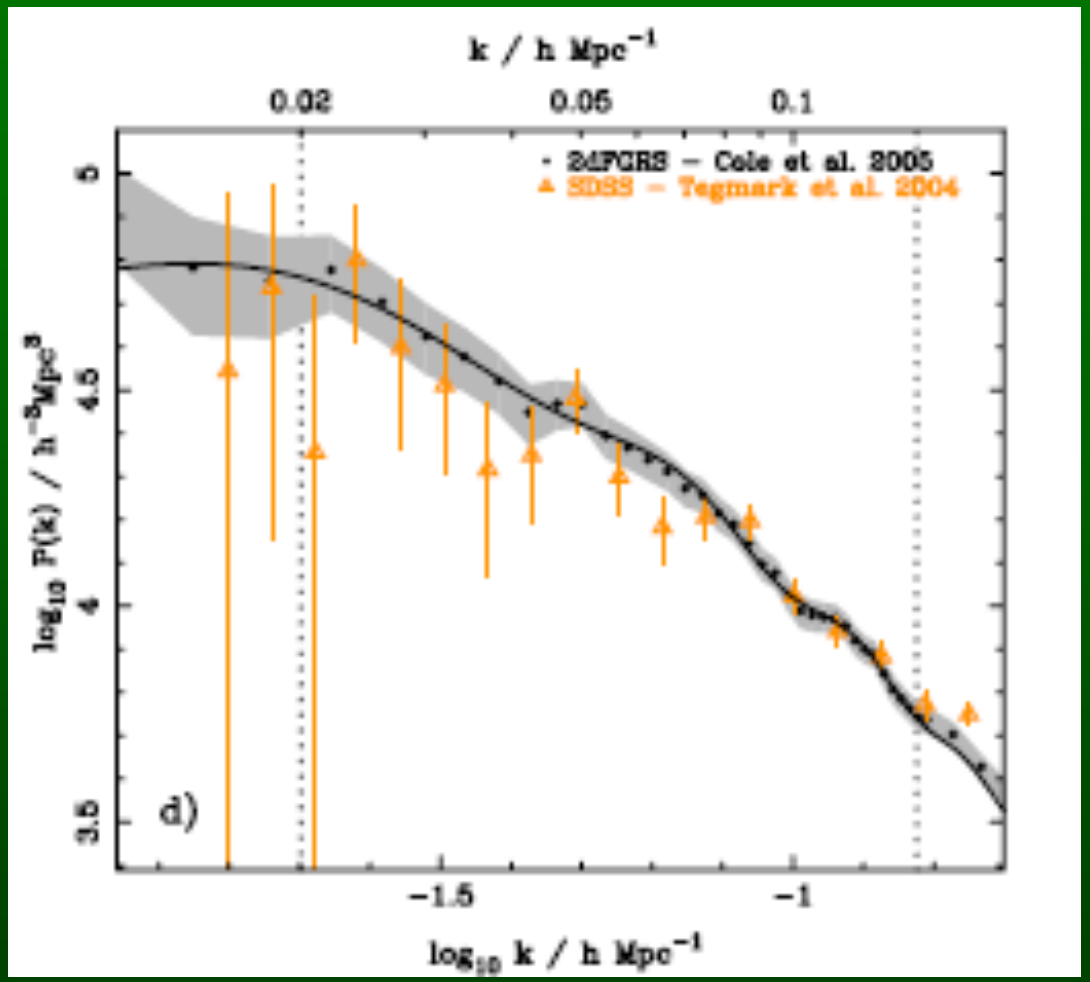
2dFGRS Galaxy Power Spectrum + WMAP CMB



$\Omega_m = 0.237 +/- 0.020$
$\Omega_b = 0.041 +/- 0.002$
$h = 0.74 +/- 0.02$
$n_s = 0.954 +/- 0.023$

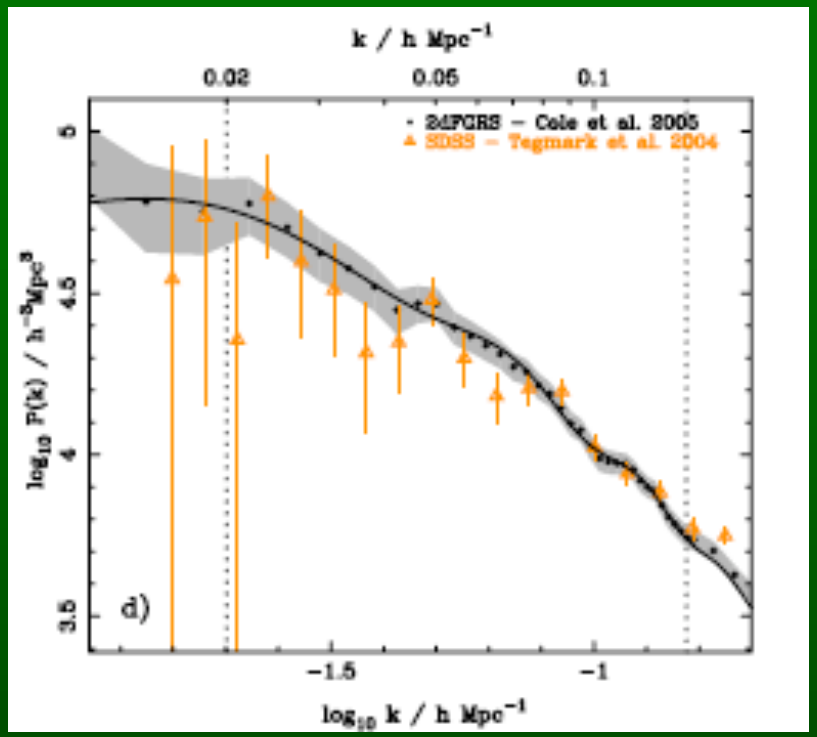
Sanchez et al. 2005

Consistency?



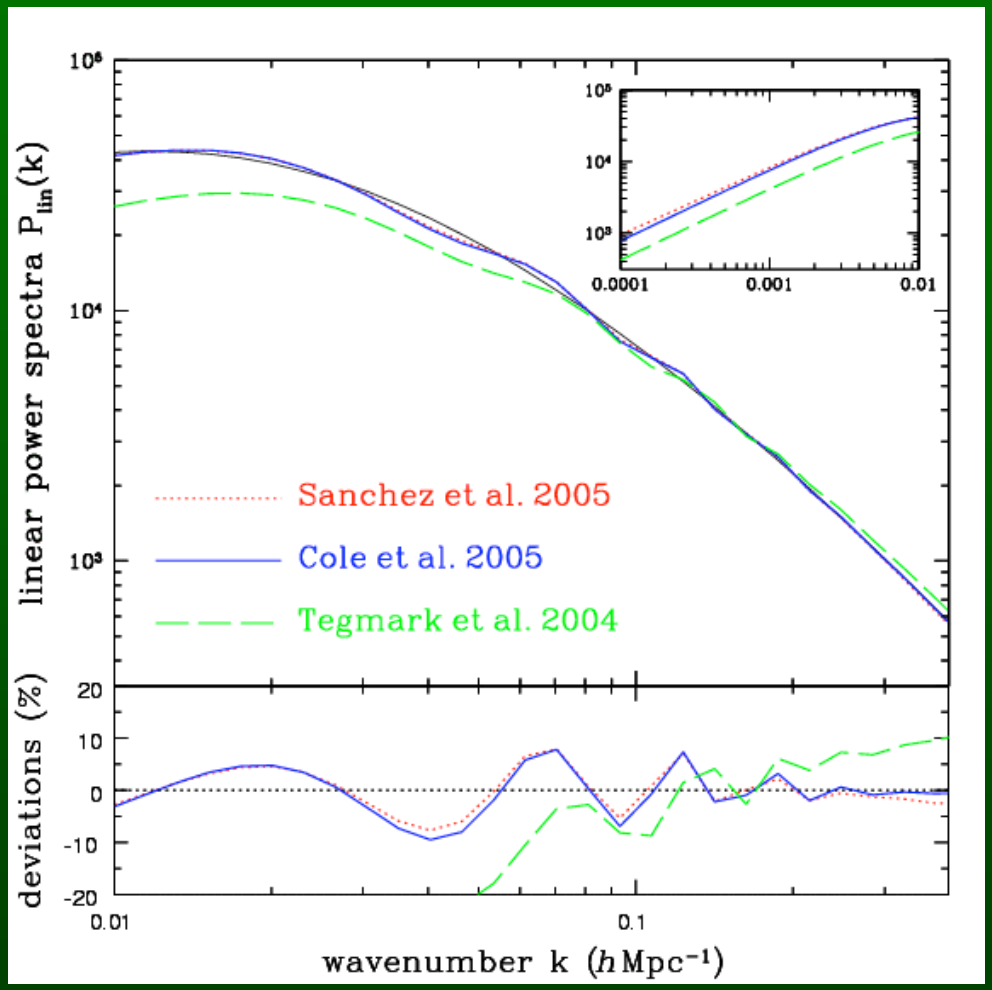
Cole et al. 2005

Consistency?

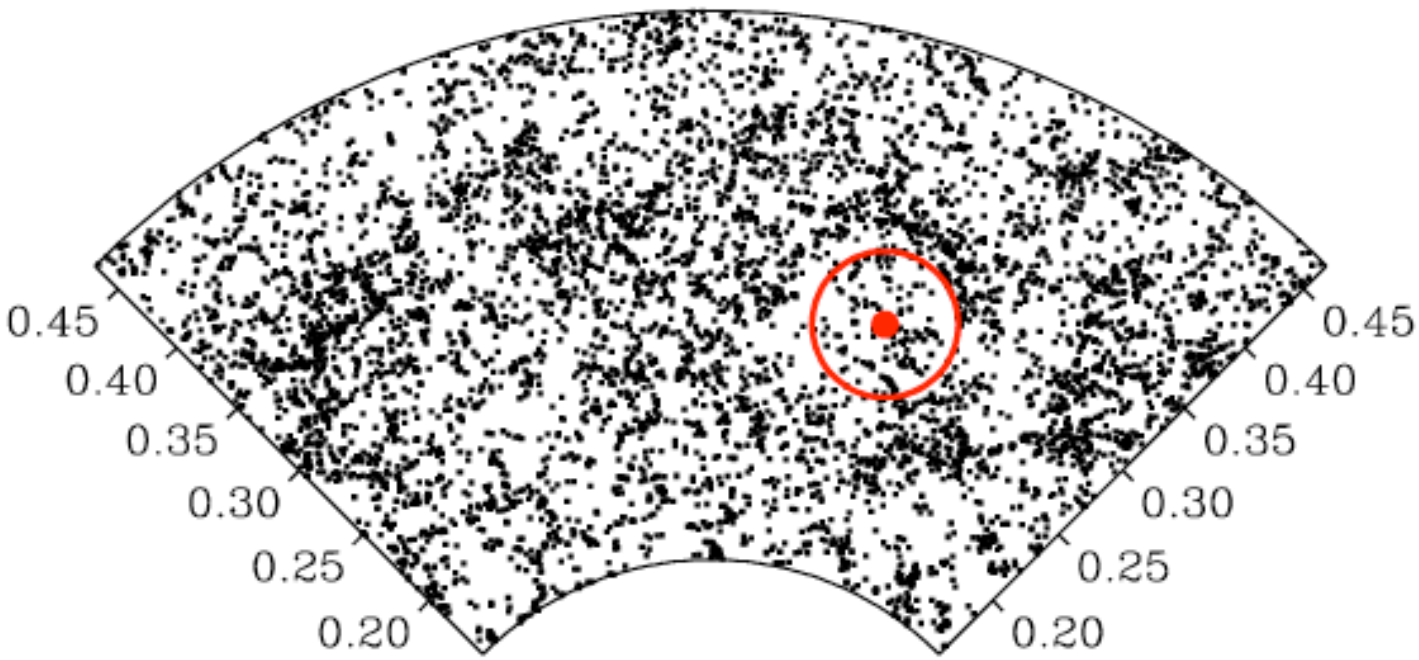


Cole et al. 2005

Best-fit parameters linear P(k)

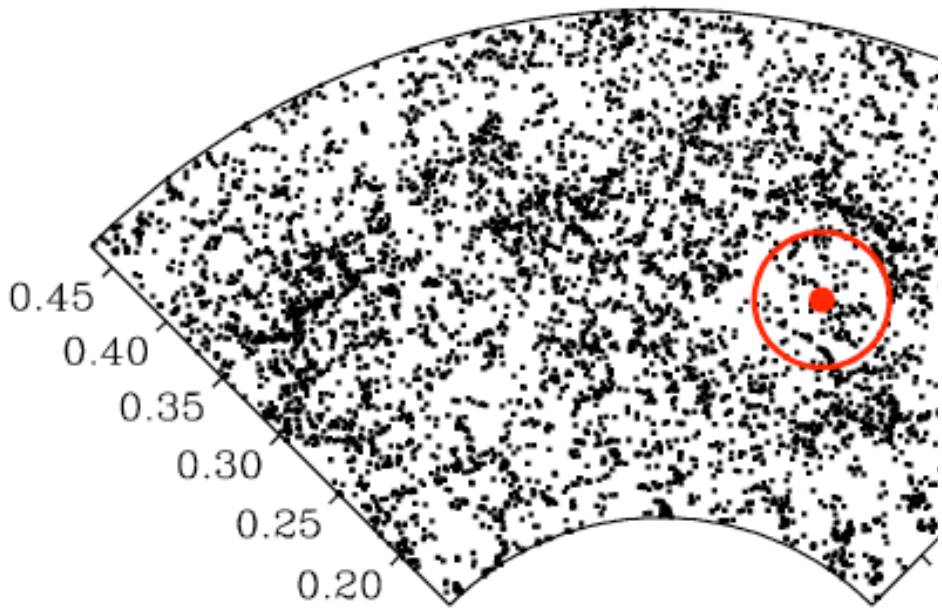


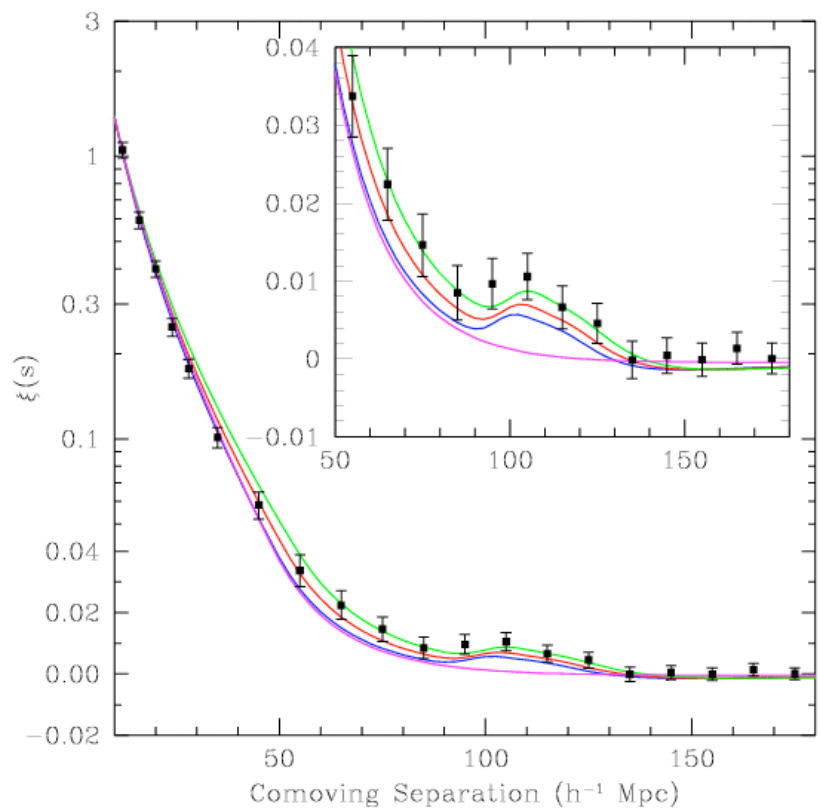
Acoustic Peaks in the SDSS Luminous Red Galaxy Sample



Eisenstein et al. 2005

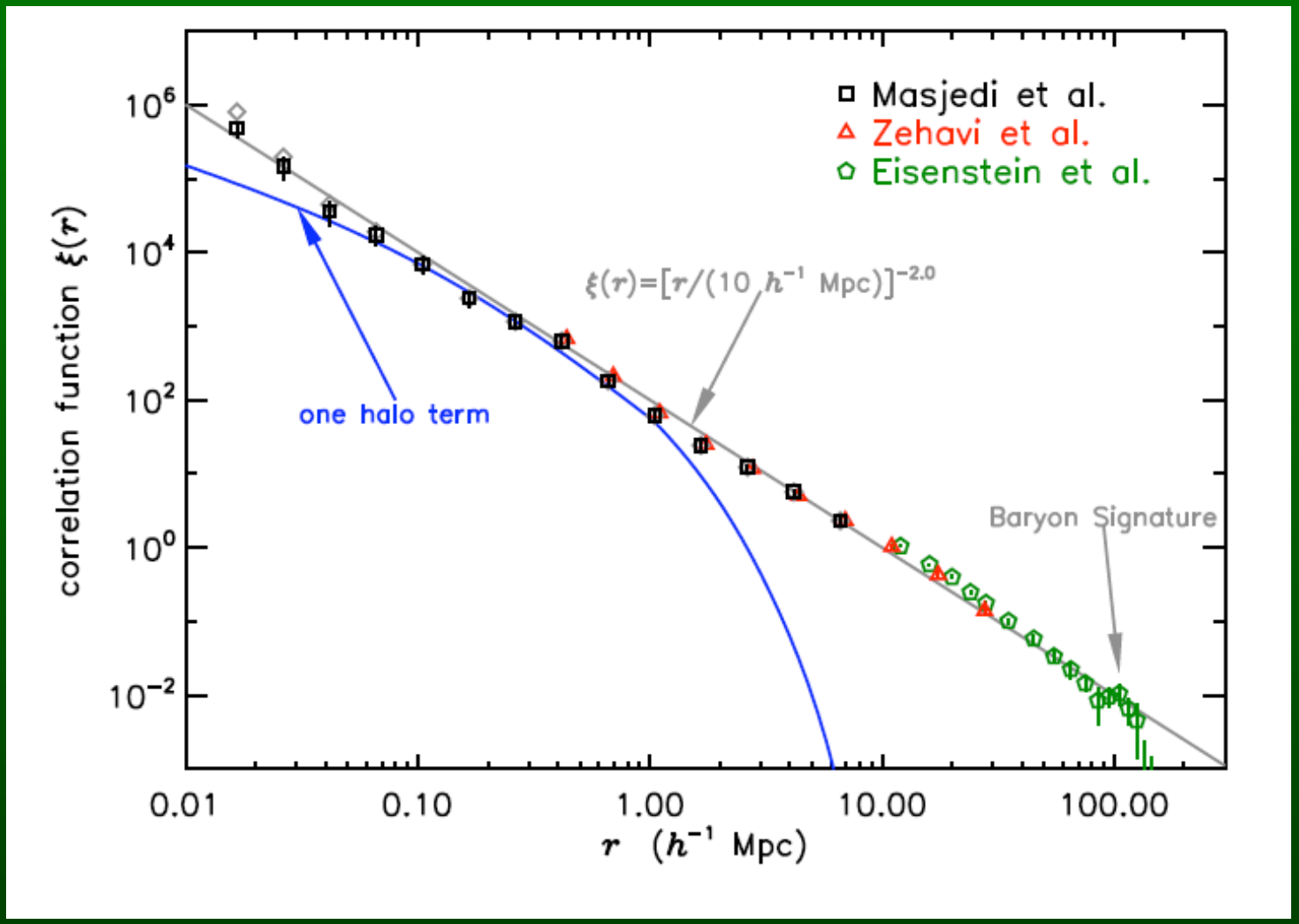
Acoustic Peaks in the SDSS Luminous Red Galaxy Sample





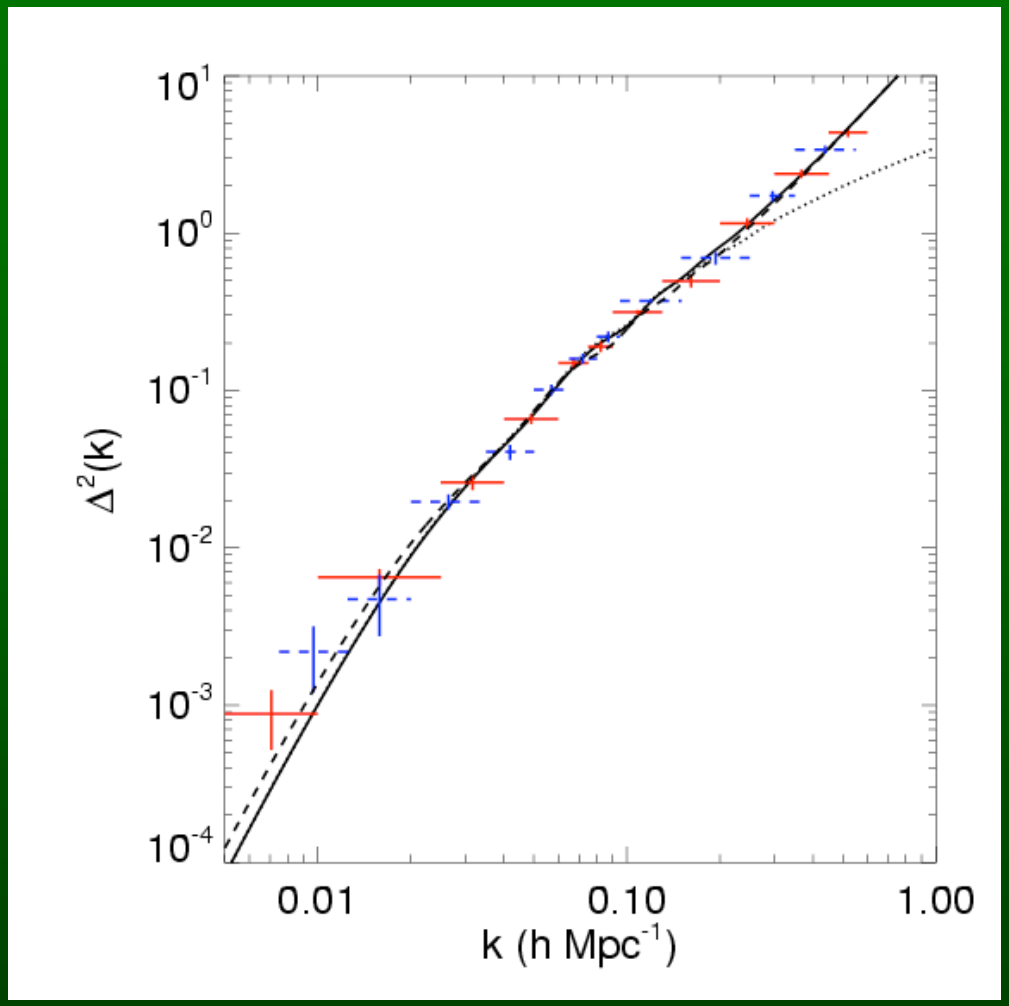
Eisenstein et al. 2005

SDSS LRGs over 4 orders of magnitude in r



Masjedi et al. 2005

SDSS LRGs with Photometric Redshifts

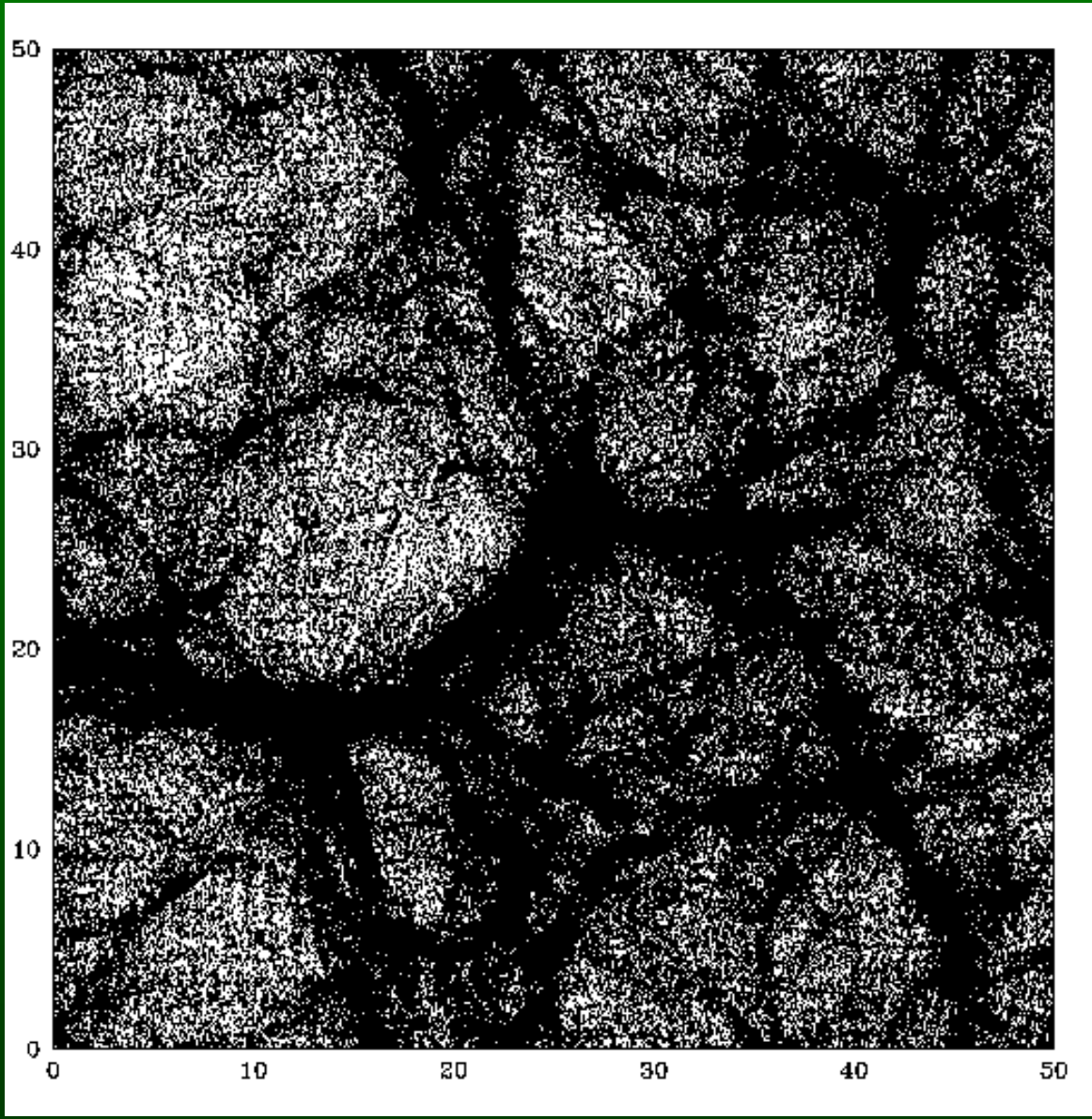


Solid: Ω_m=0.3, h=0.7

Dotted: Sanchez et al. parameters

Padmanabhan et al. 2005

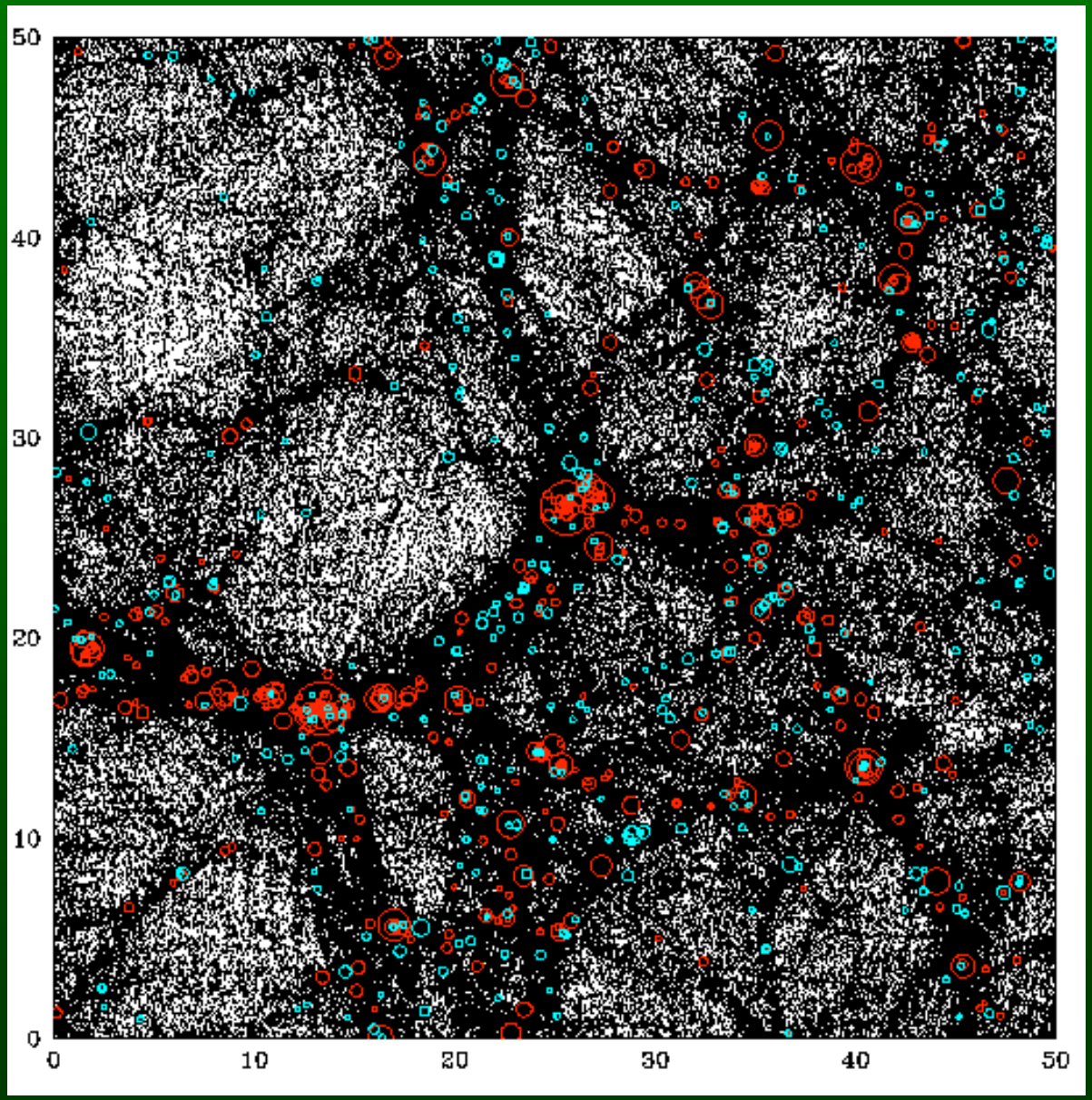
Galaxies vs. Mass: Beyond Linear Bias



Dark matter clustering is straightforward to predict for specified initial conditions and cosmological parameters.

But where are the galaxies?

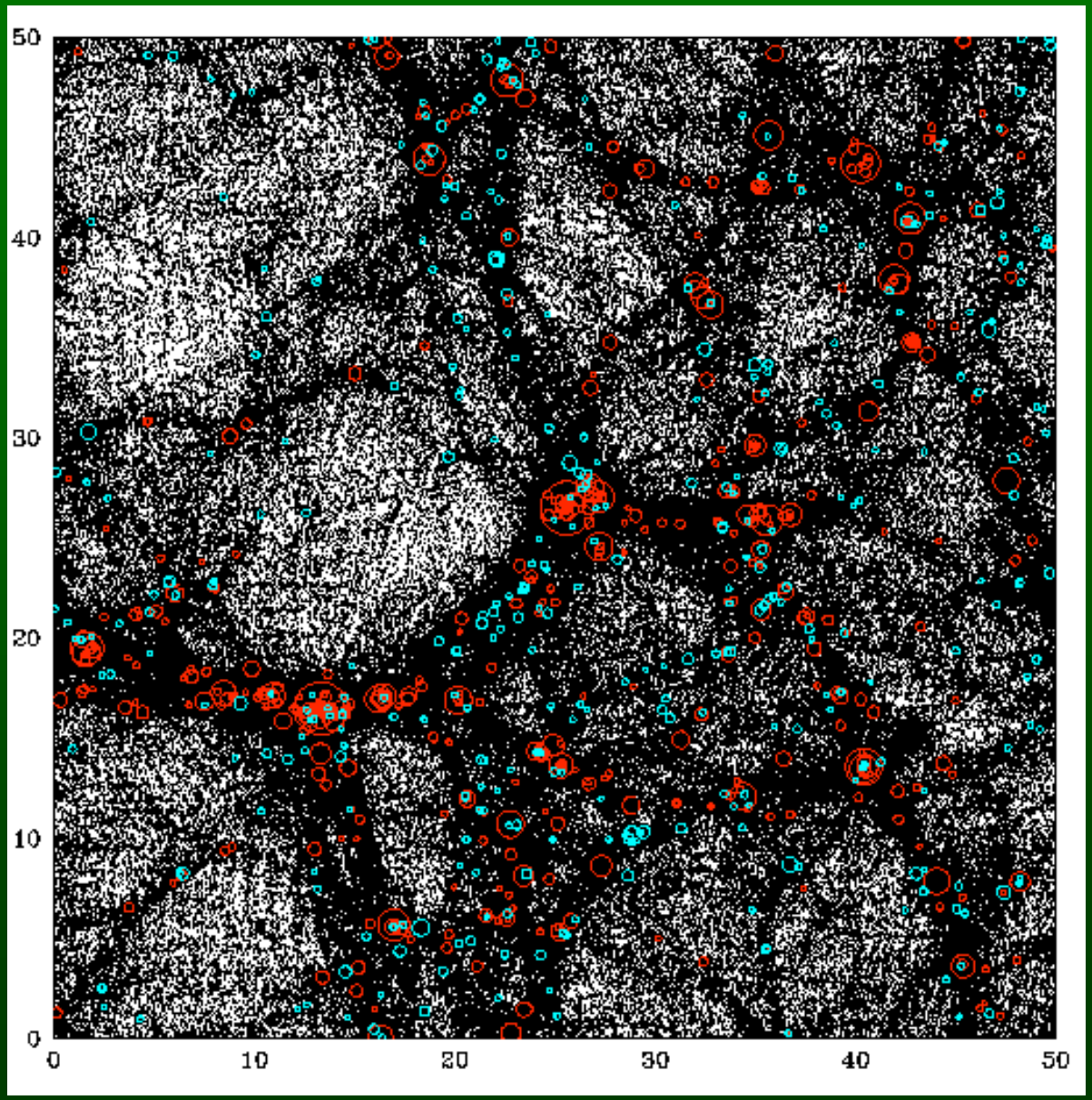
Galaxies vs. Mass: Beyond Linear Bias



One solution: add gas dynamics and star formation to simulations.

Weinberg et al. 2004

Galaxies vs. Mass: Beyond Linear Bias

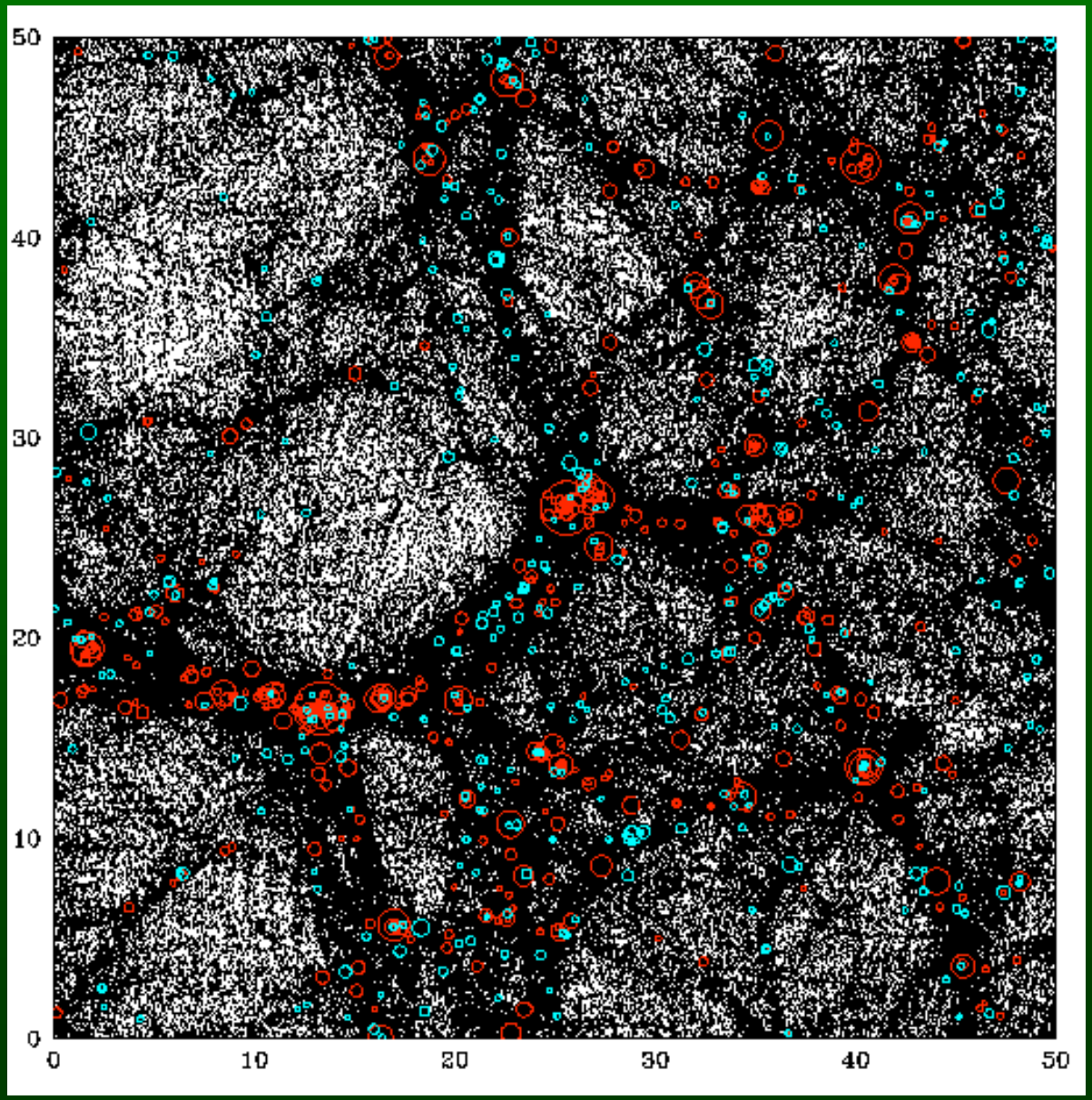


One solution: add gas dynamics and star formation to simulations.

Another solution: add semi-analytic galaxy formation to N-body simulations.

Weinberg et al. 2004

Galaxies vs. Mass: Beyond Linear Bias



One solution: add gas dynamics and star formation to simulations.

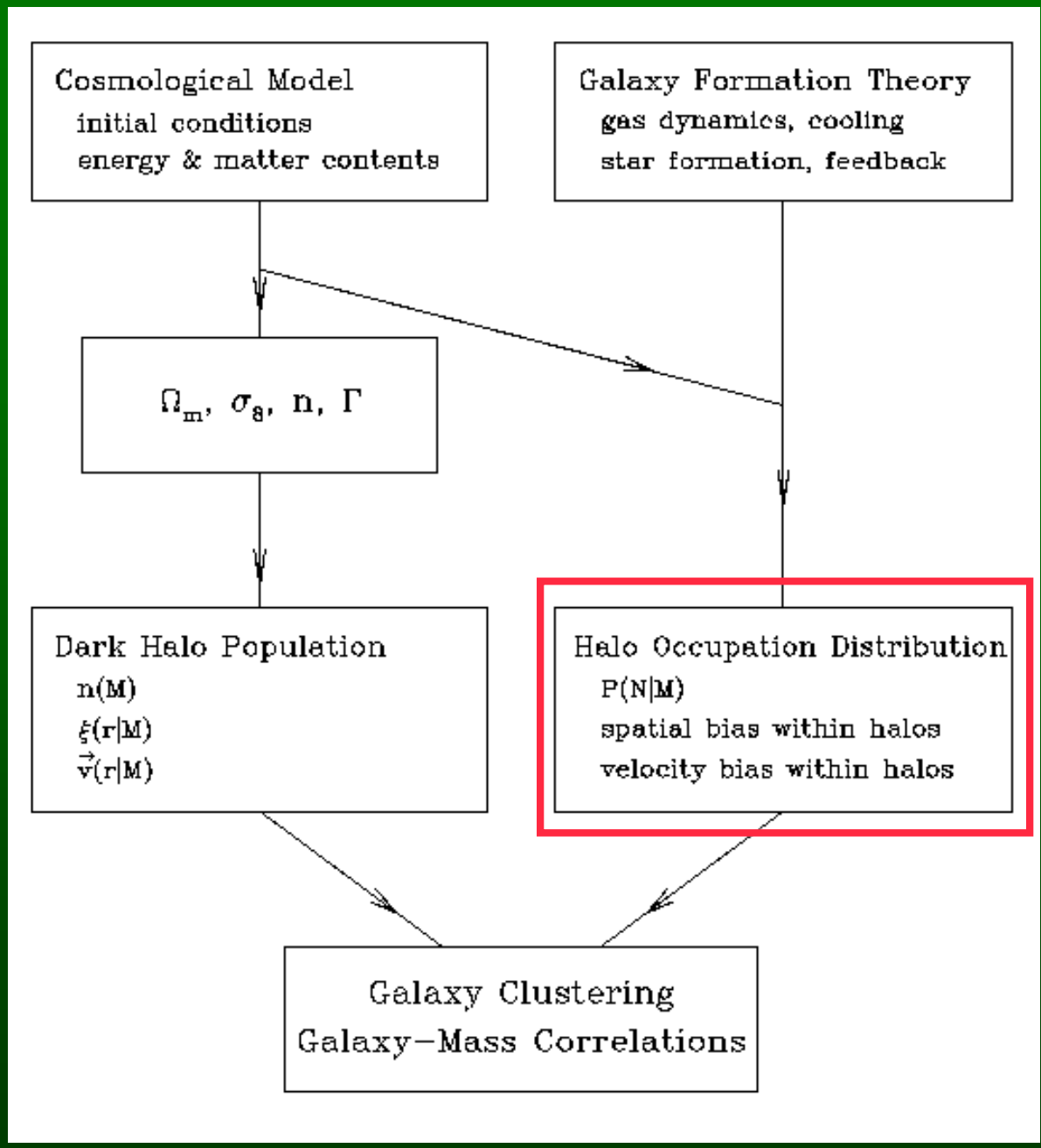
Another solution: add semi-analytic galaxy formation to N-body simulations.

Physical.

Challenging.

Uncertain.

Weinberg et al. 2004



Halo Occupation Distribution (HOD):

Characterize galaxy-dm relation at halo level, by P(N|M).

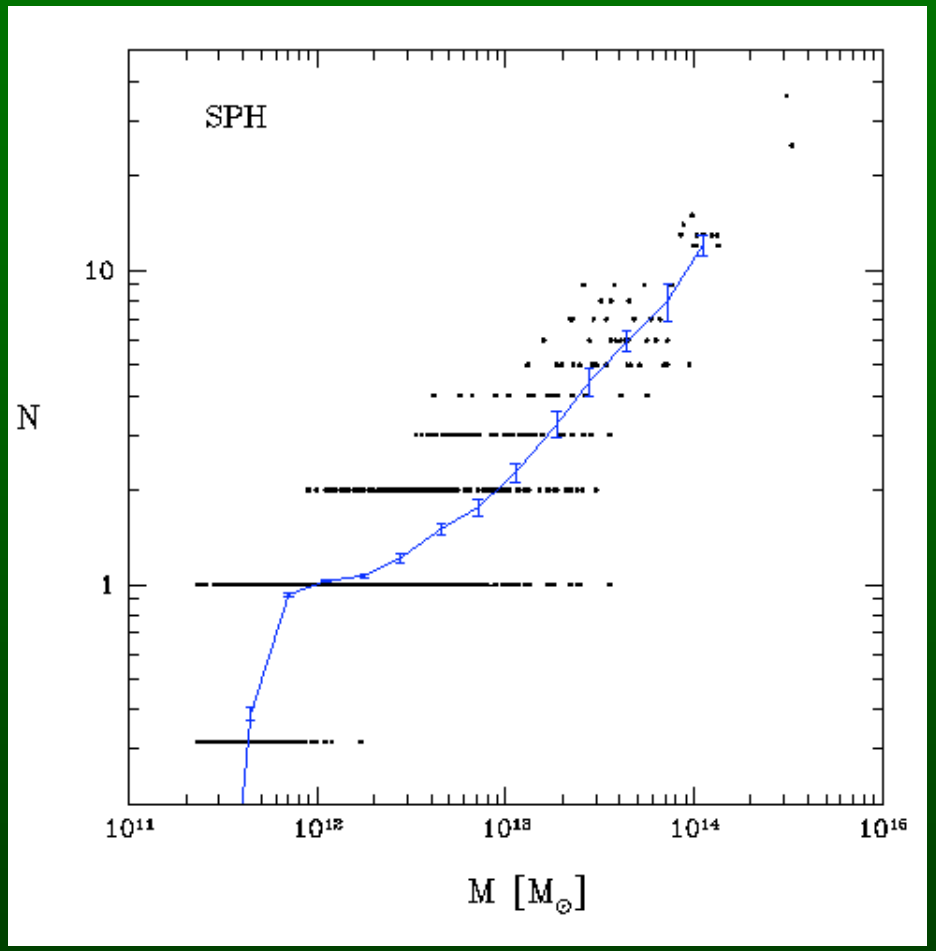
HOD describes bias for all statistics, on all scales.

Predict from theory.

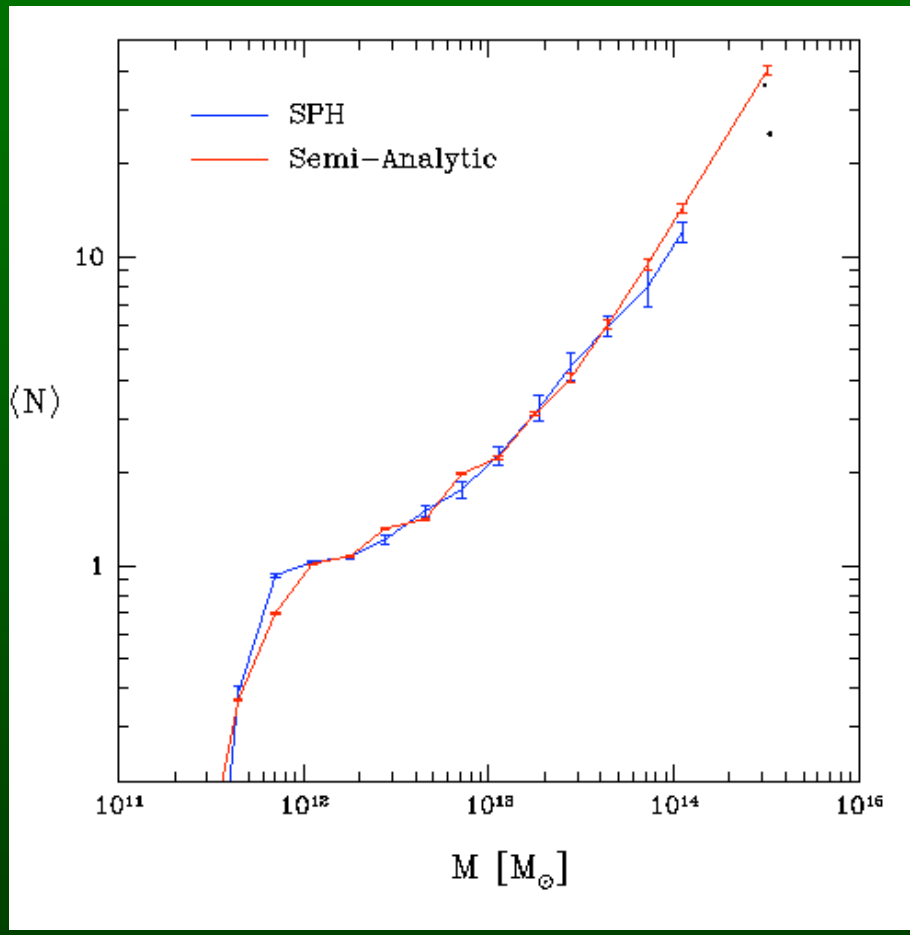
Derive empirically from clustering data.

Weinberg 2002

P(N|M), SPH simulation

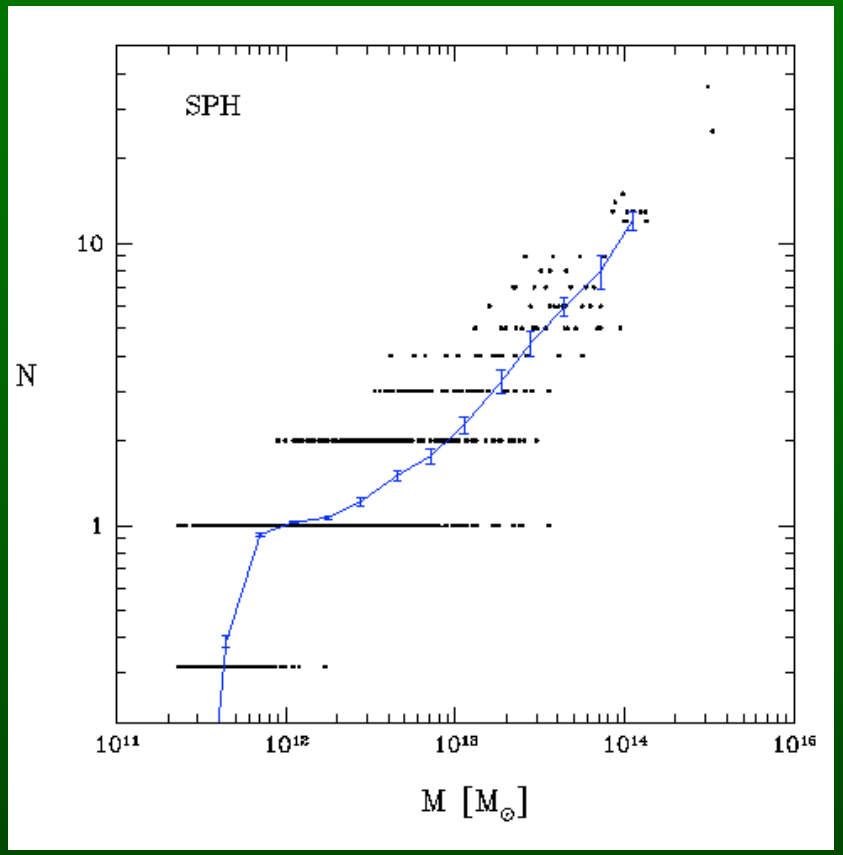


Mean occupation, SPH & SA



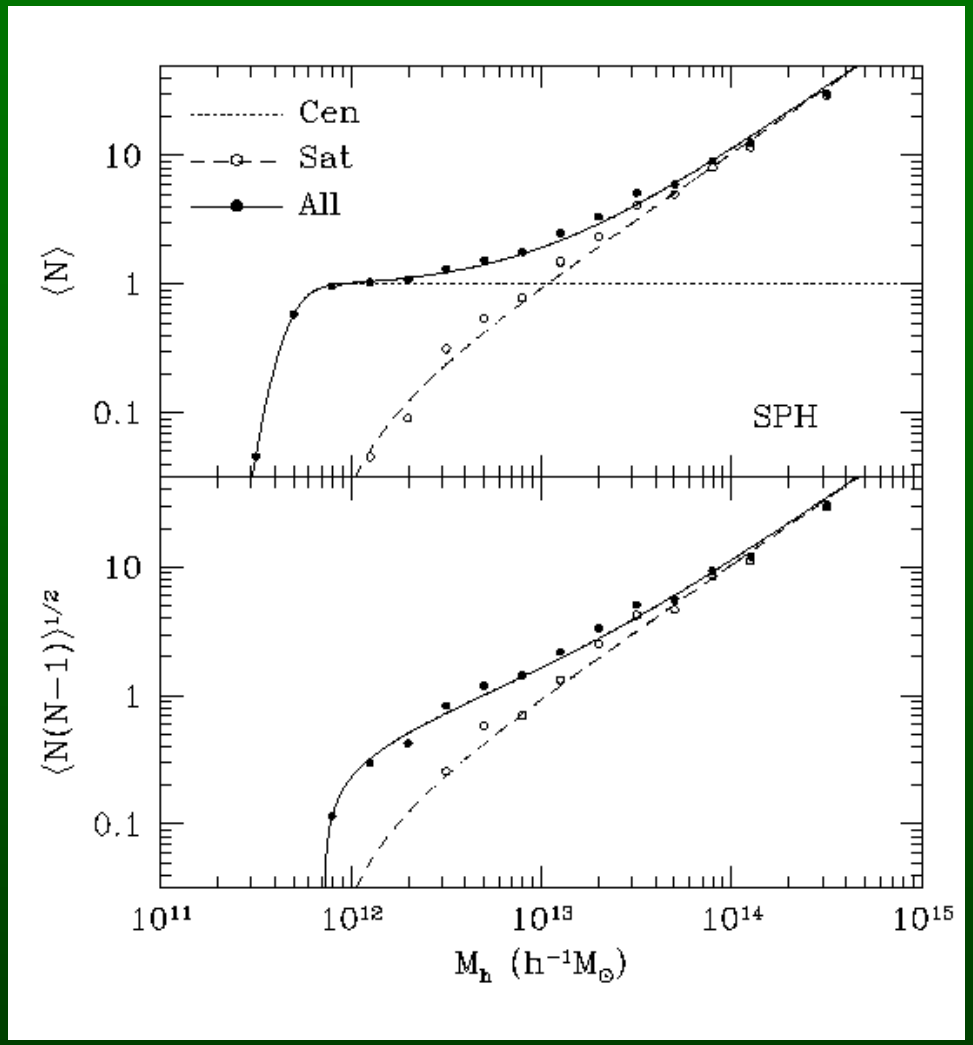
Berlind et al. 2003

P(N|M), SPH simulation

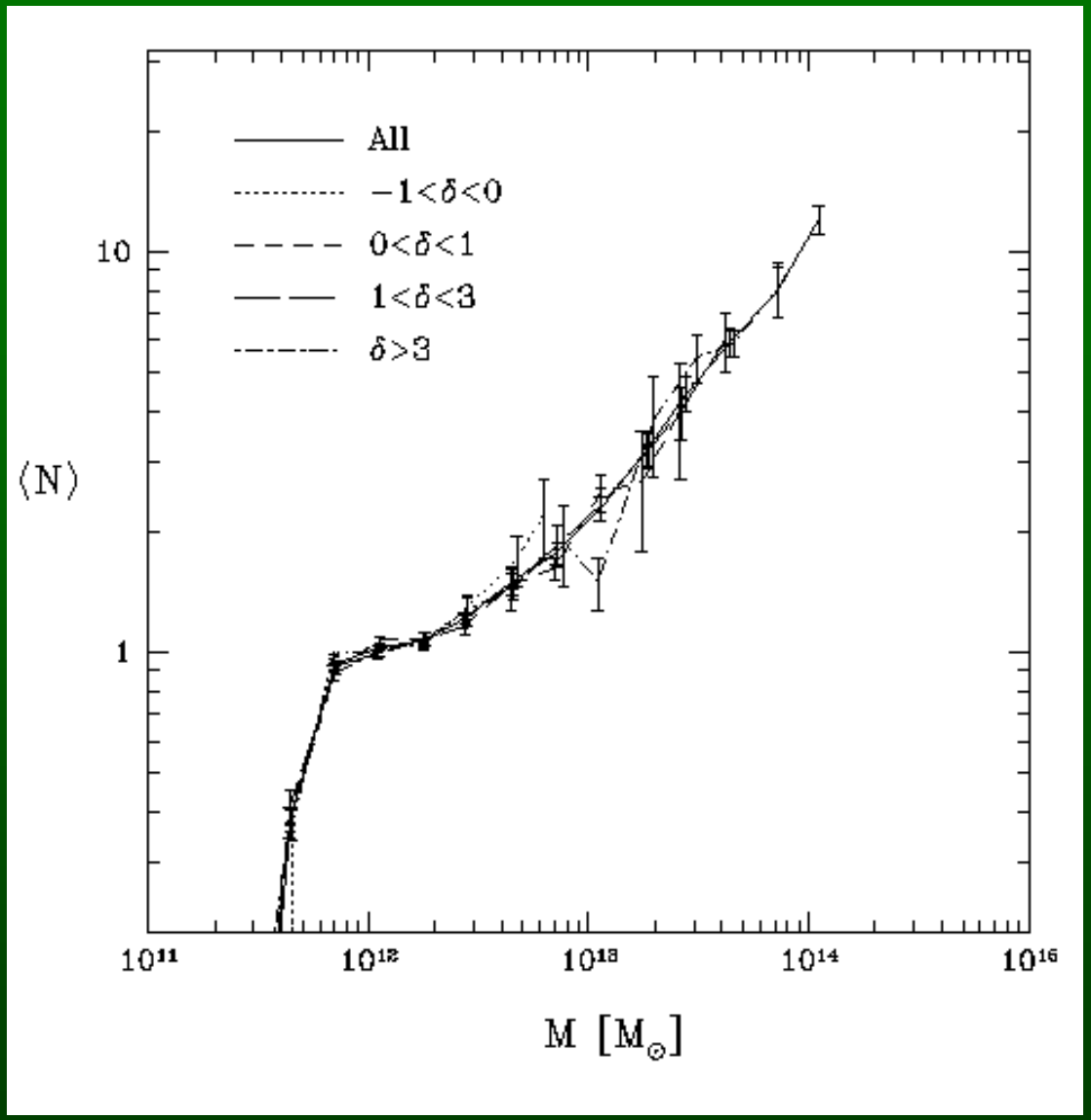


Berlind et al. 2003

Central-satellite separtion

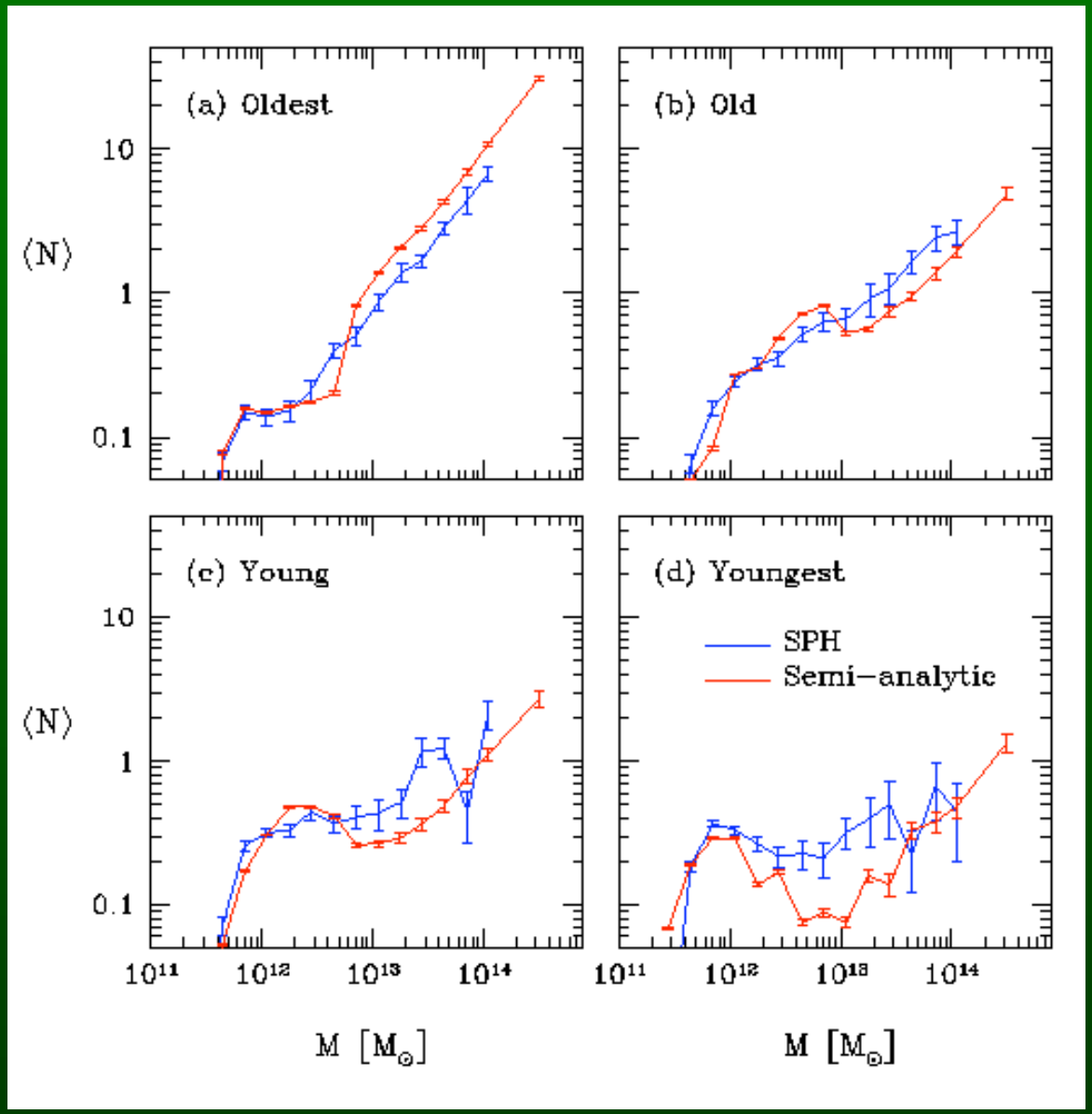


Zheng et al. 2005



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

Berlind et al. 2003



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).

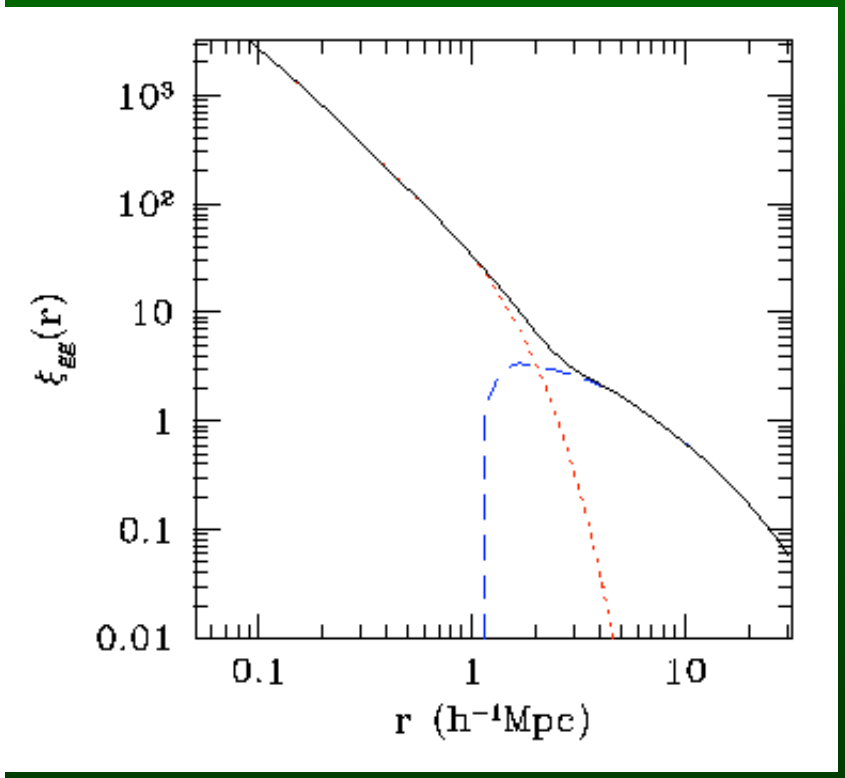
Berlind et al. 2003

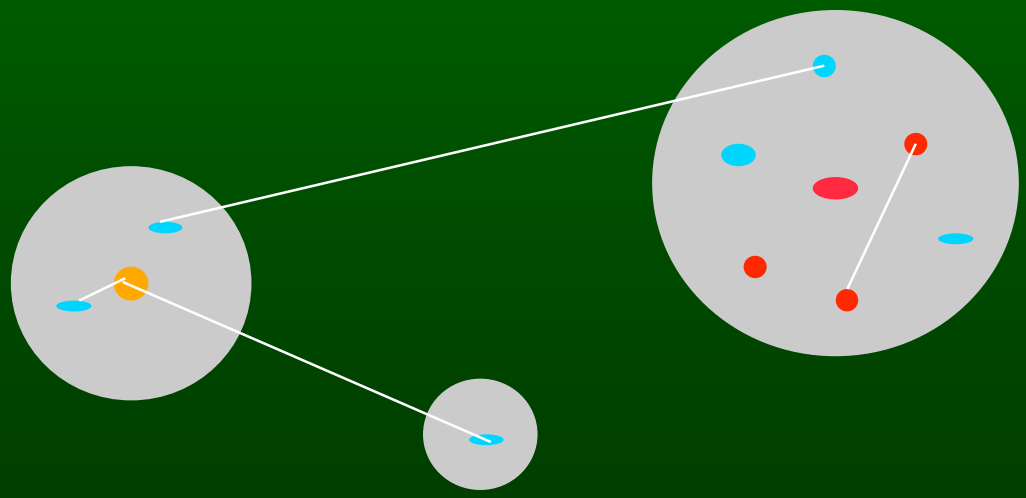
Galaxy 2-point correlation function

$\xi_{gg}(r)$ = excess probability of finding a galaxy a distance r from another galaxy

1-halo term: galaxy pairs in the same halo

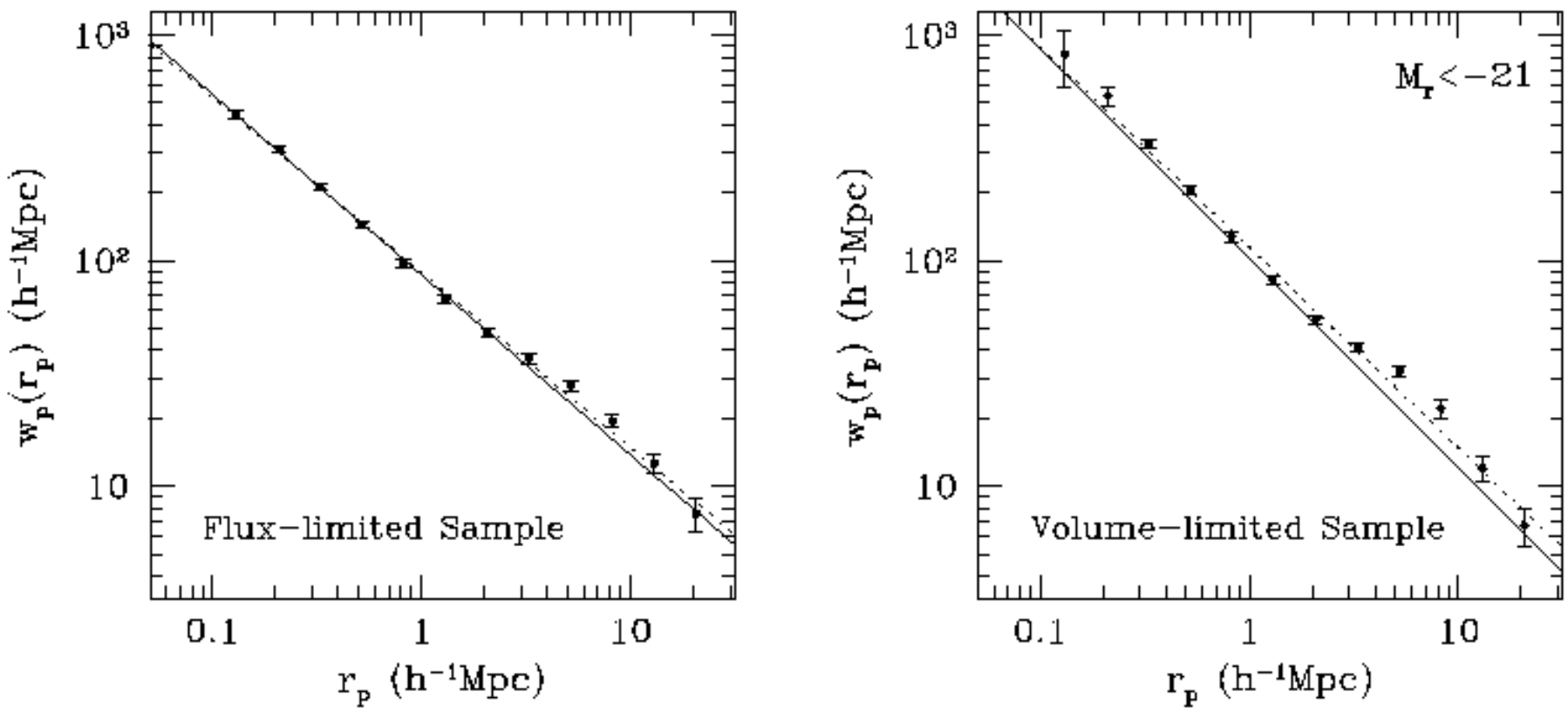
2-halo term: galaxy pairs in separate halos





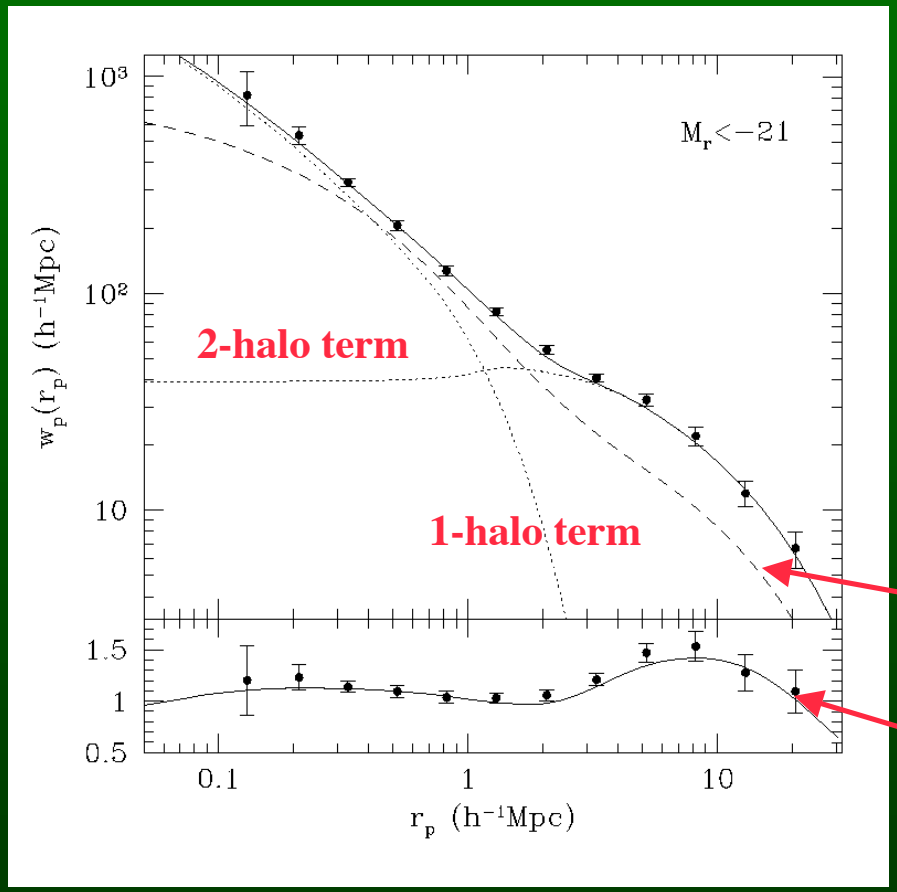
Projected correlation function of SDSS galaxies:

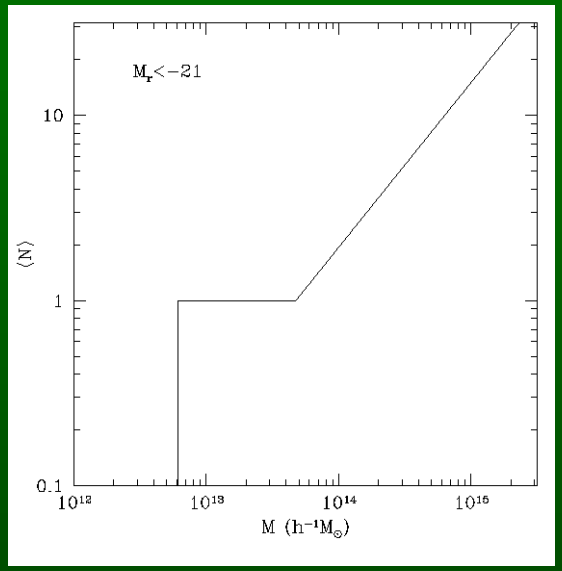
Not quite a power law!



Zehavi et al. (2004a)

Deviation naturally explained by HOD model.

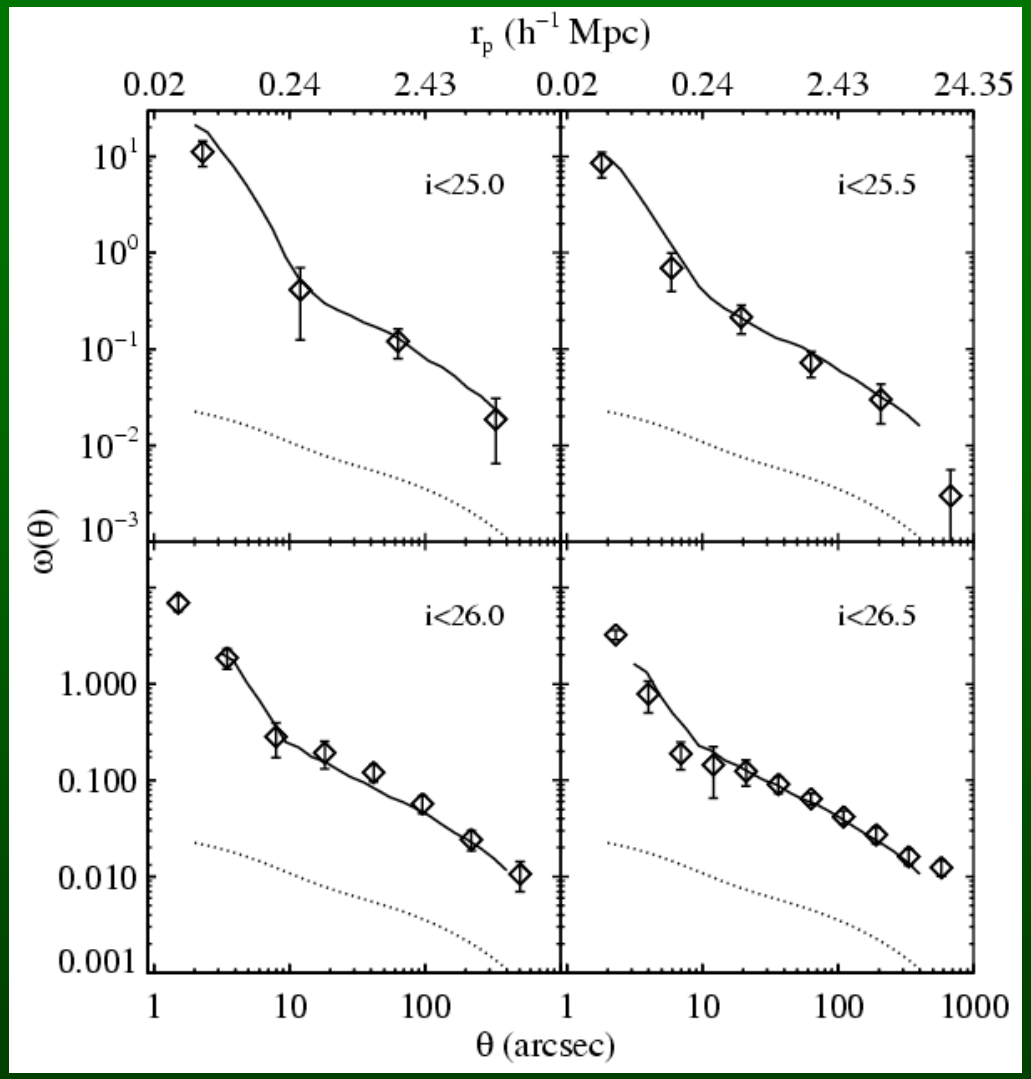




Dark matter correlation function

Divided by the best-fit power law

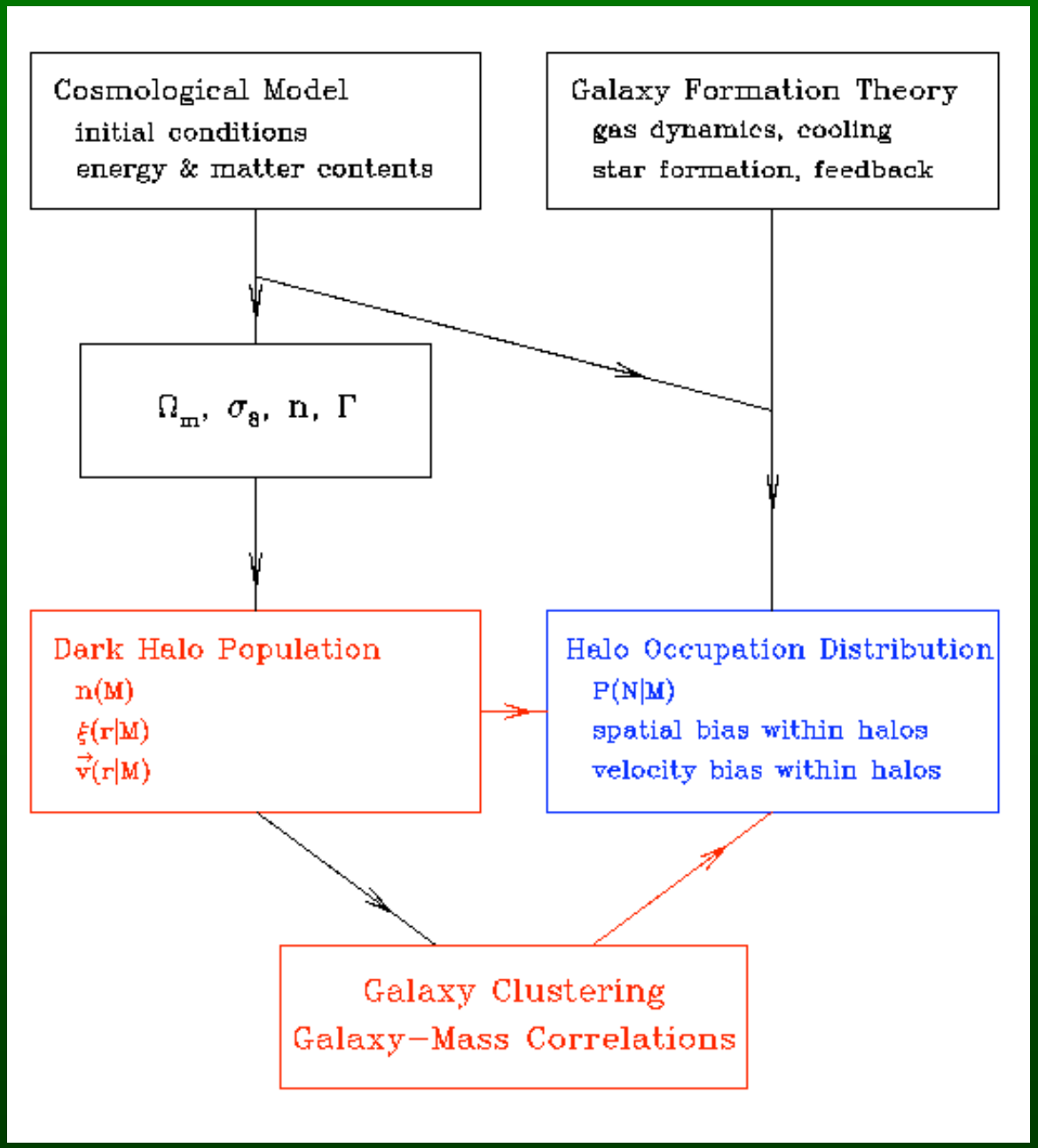
Zehavi et al. (2004)



Conroy, Wechsler, & Kravtsov 2005

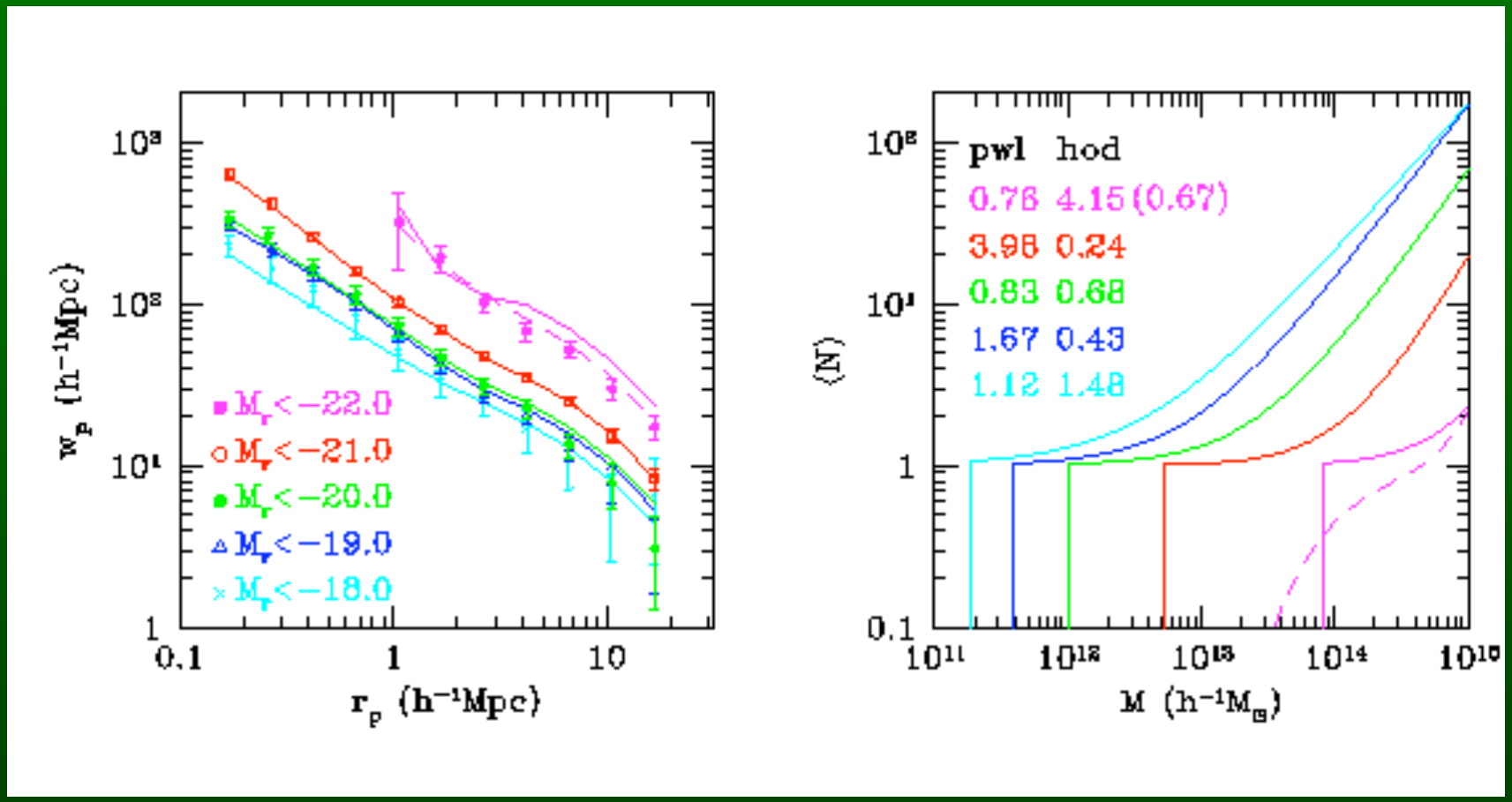
Power-law deviations more pronounced at high redshift.

0-parameter "fit" to Ouchi et al.'s (2005) Subaru data at z ~ 4.



For known cosmology, use observed clustering to derive HOD, learn about galaxy formation.

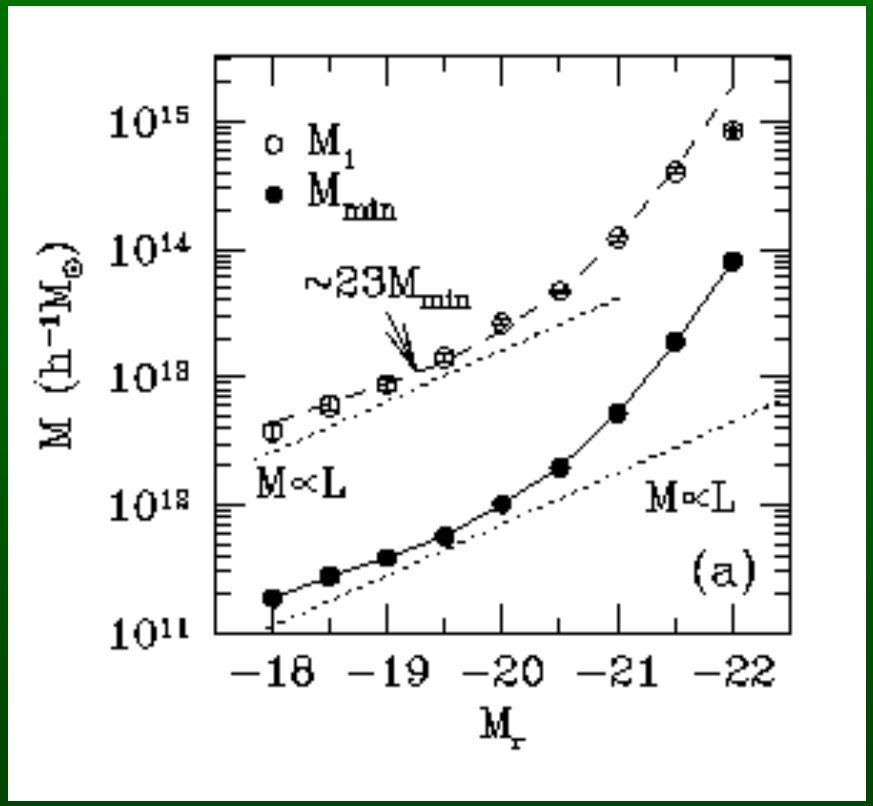
Luminosity dependence of correlation function and HOD



Zehavi et al. (2005)

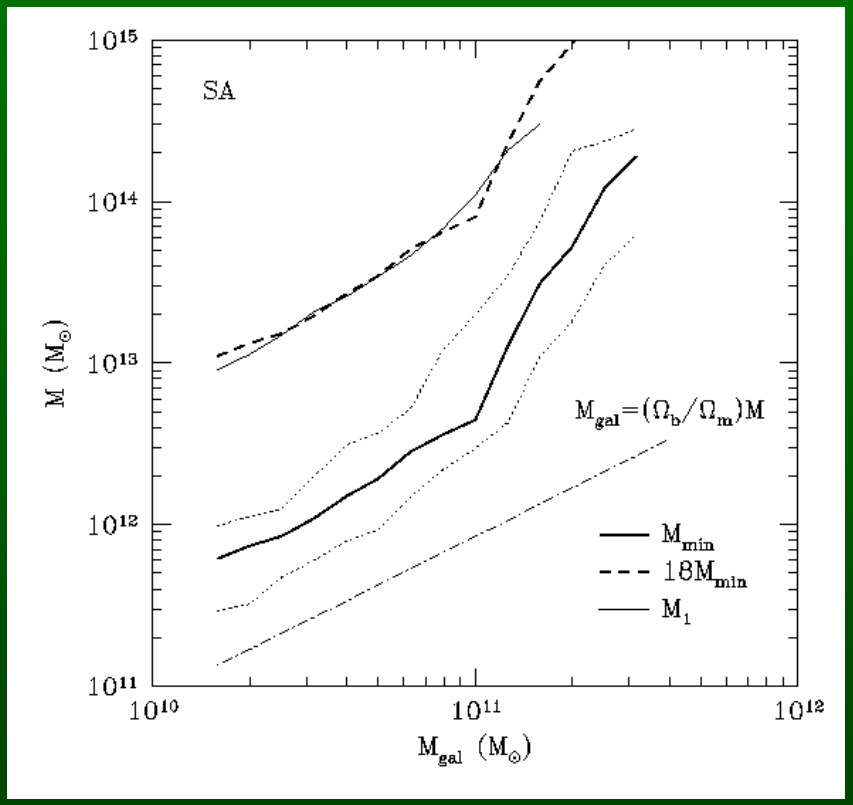
Minimum halo mass vs. luminosity threshold

Observation

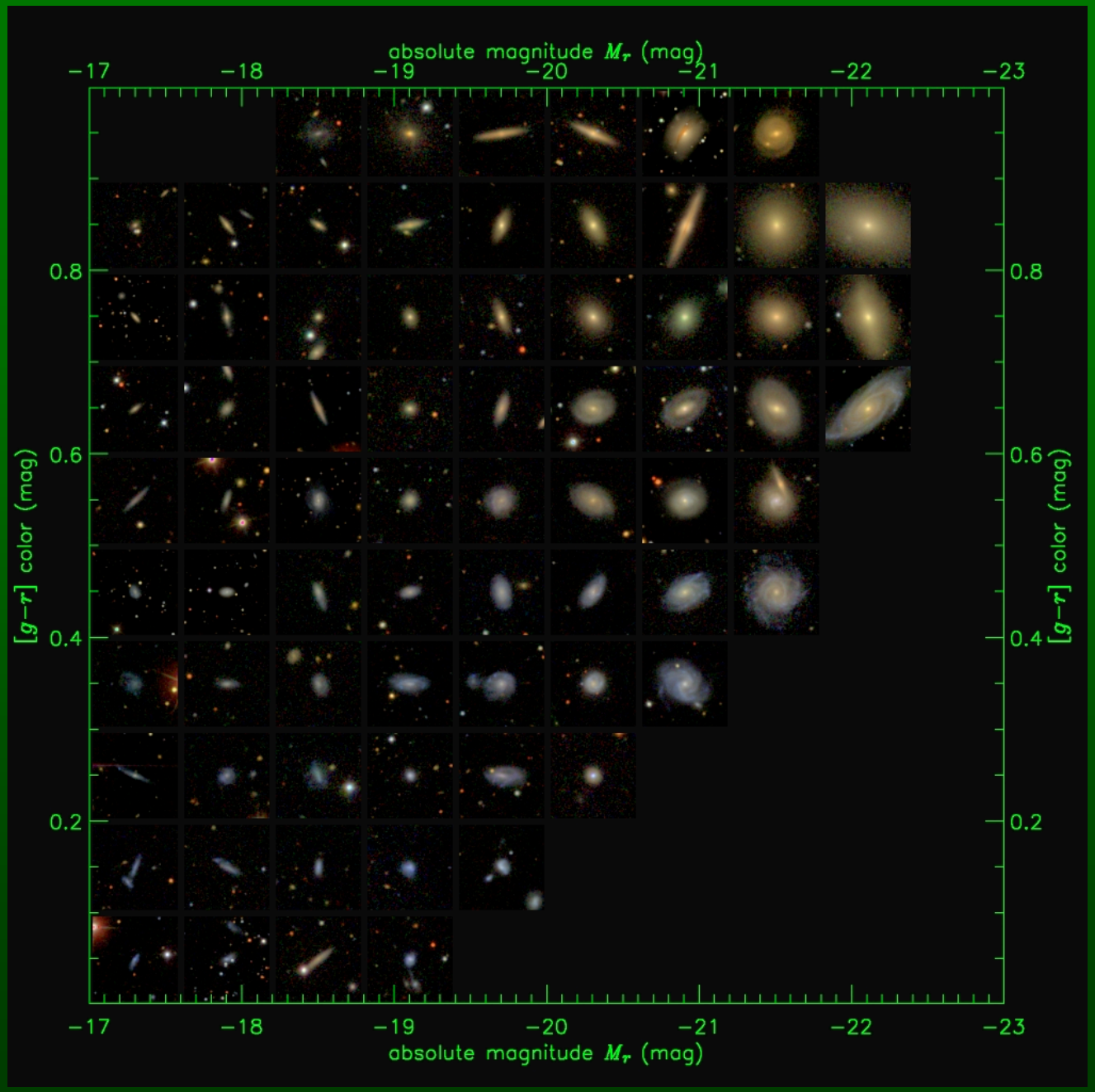


Zehavi et al. (2004b)

Theory

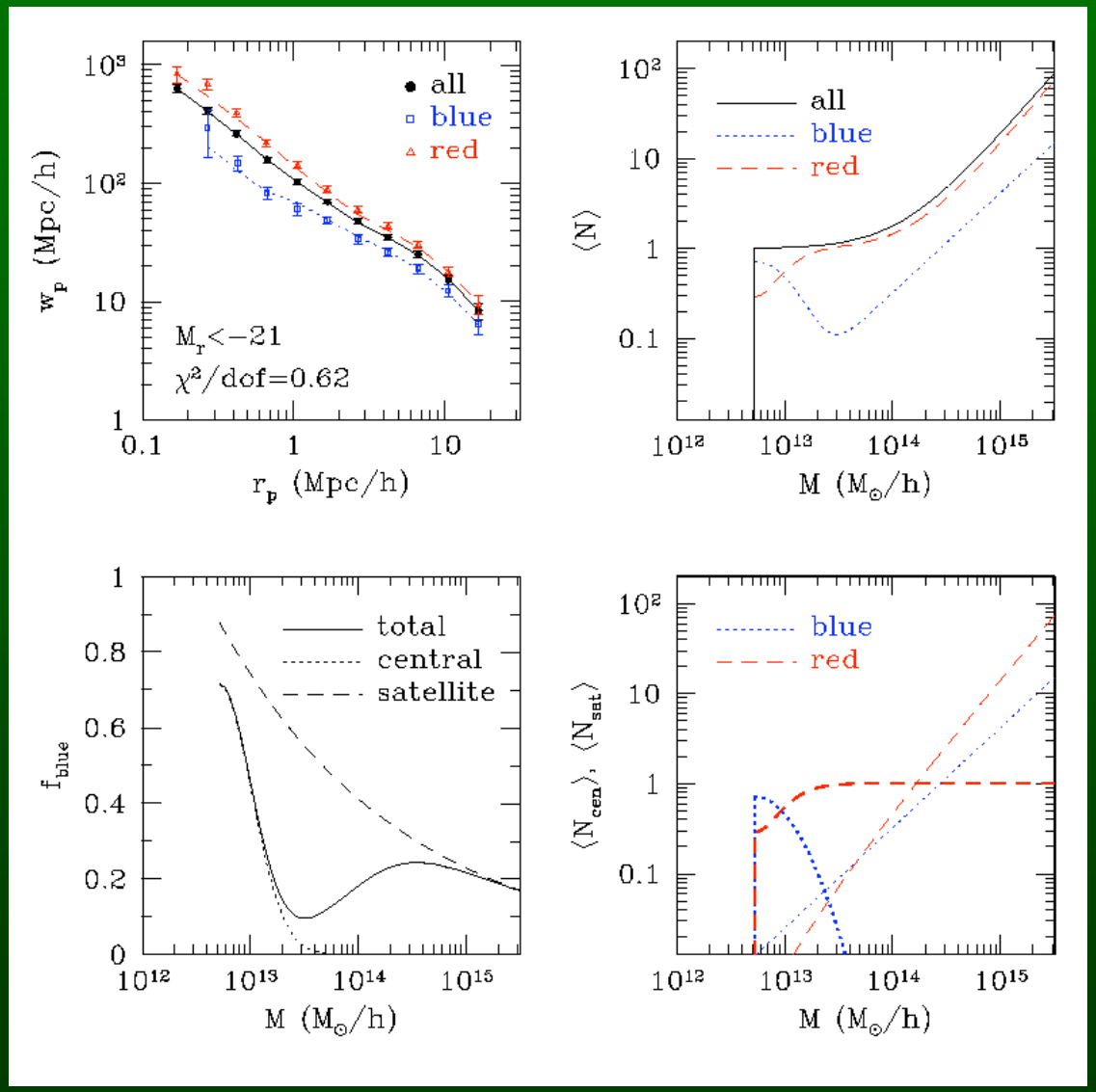


Zheng et al. (2004)



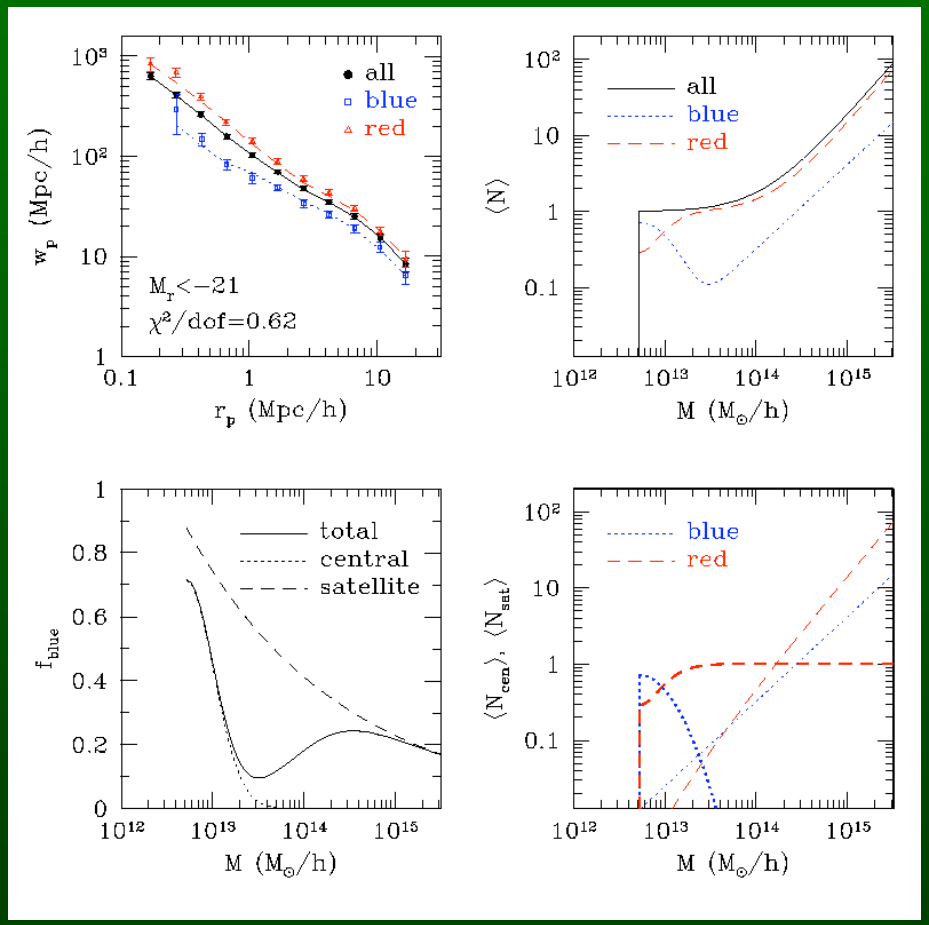
Hogg & Blanton

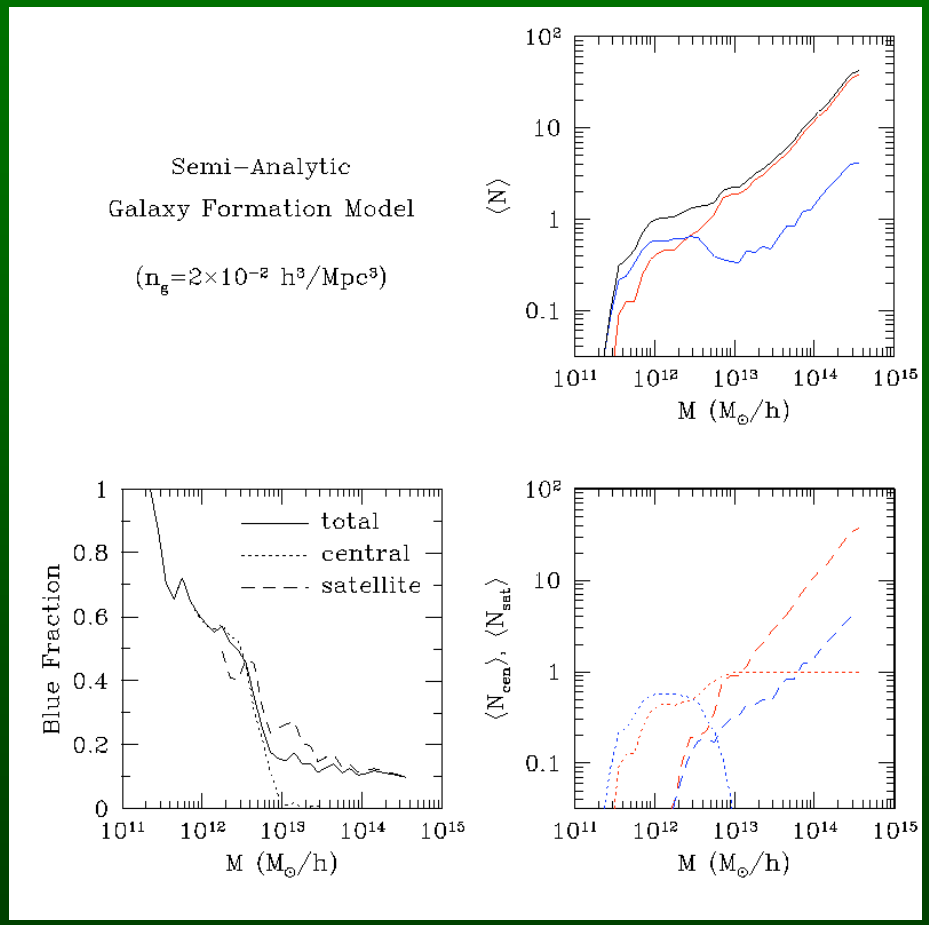
Color dependence of correlation function



Zehavi et al. (2005)

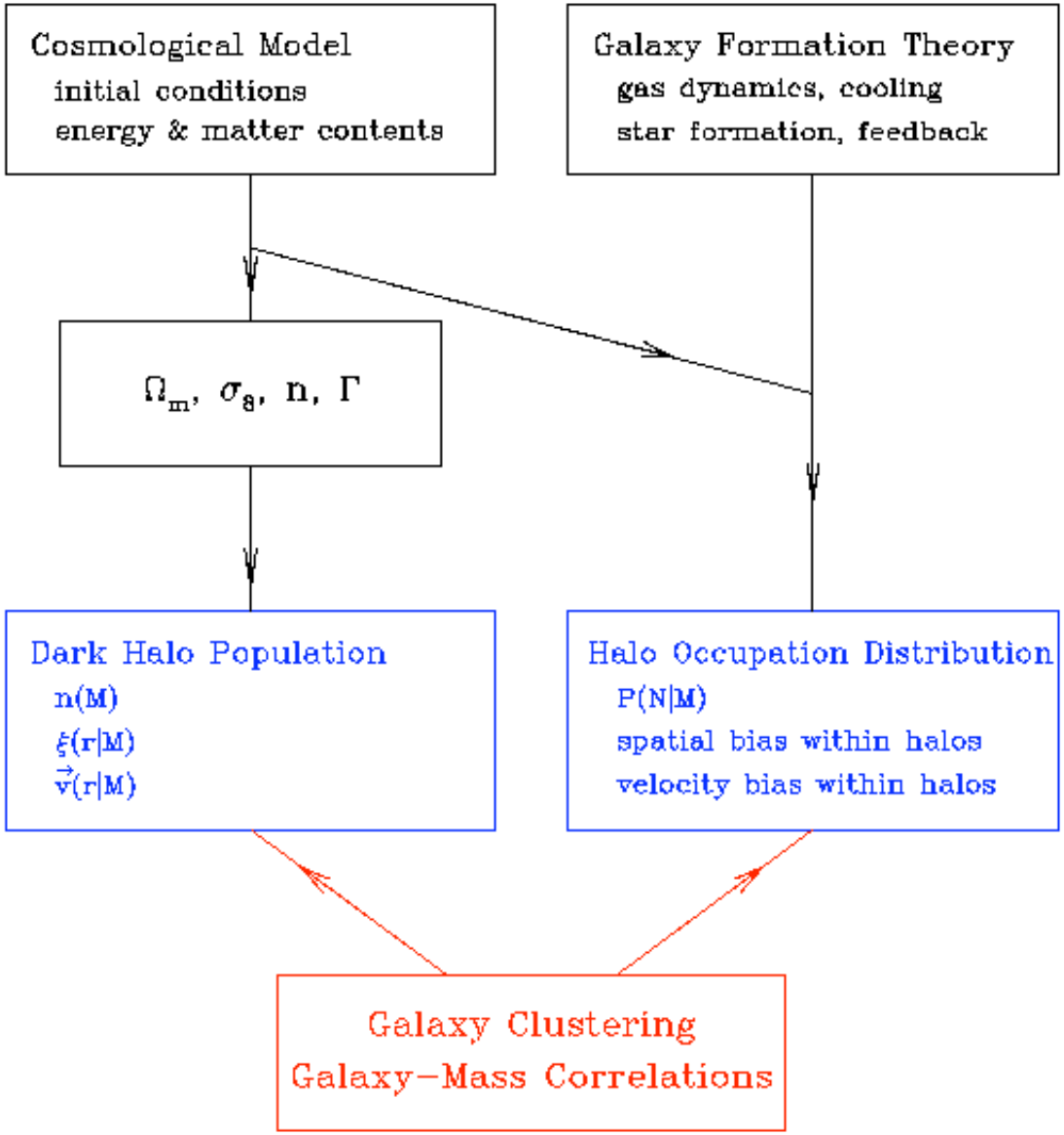
Qualitative agreement with theoretical predictions



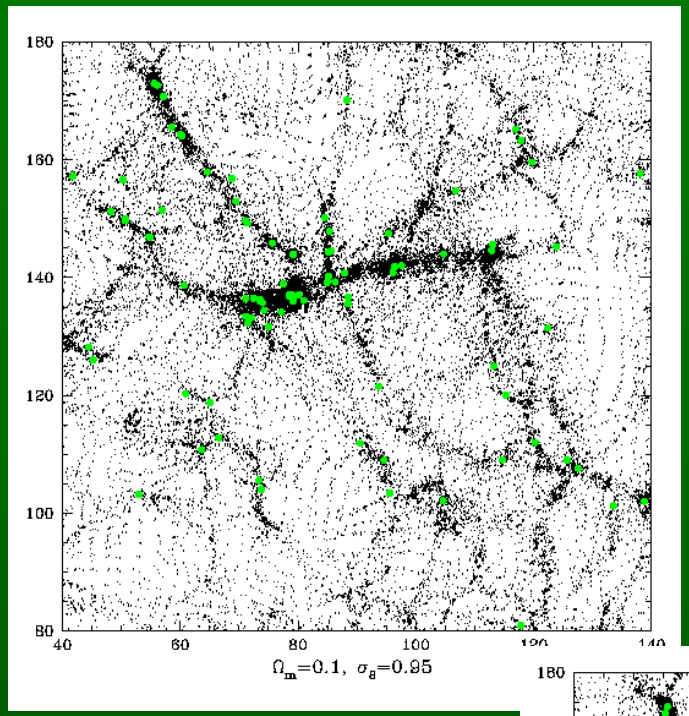


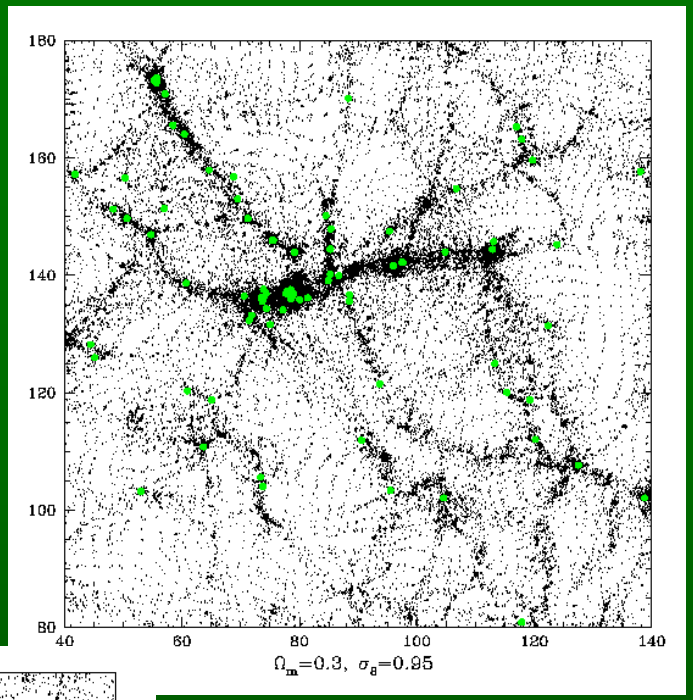
Zehavi et al. (2005)

Berlind et al. (2003), Zheng et al. (2005)



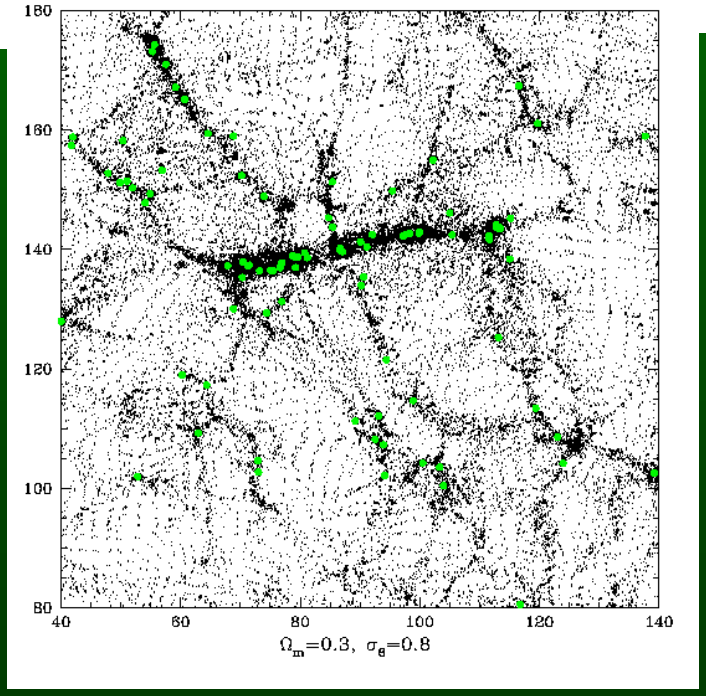
Constrain HOD and cosmological parameters simultaneously. Use intermediate and small scale clustering to break degeneracy between cosmology and galaxy bias.





$\Omega_m = 0.1, \sigma_8 = 0.95$

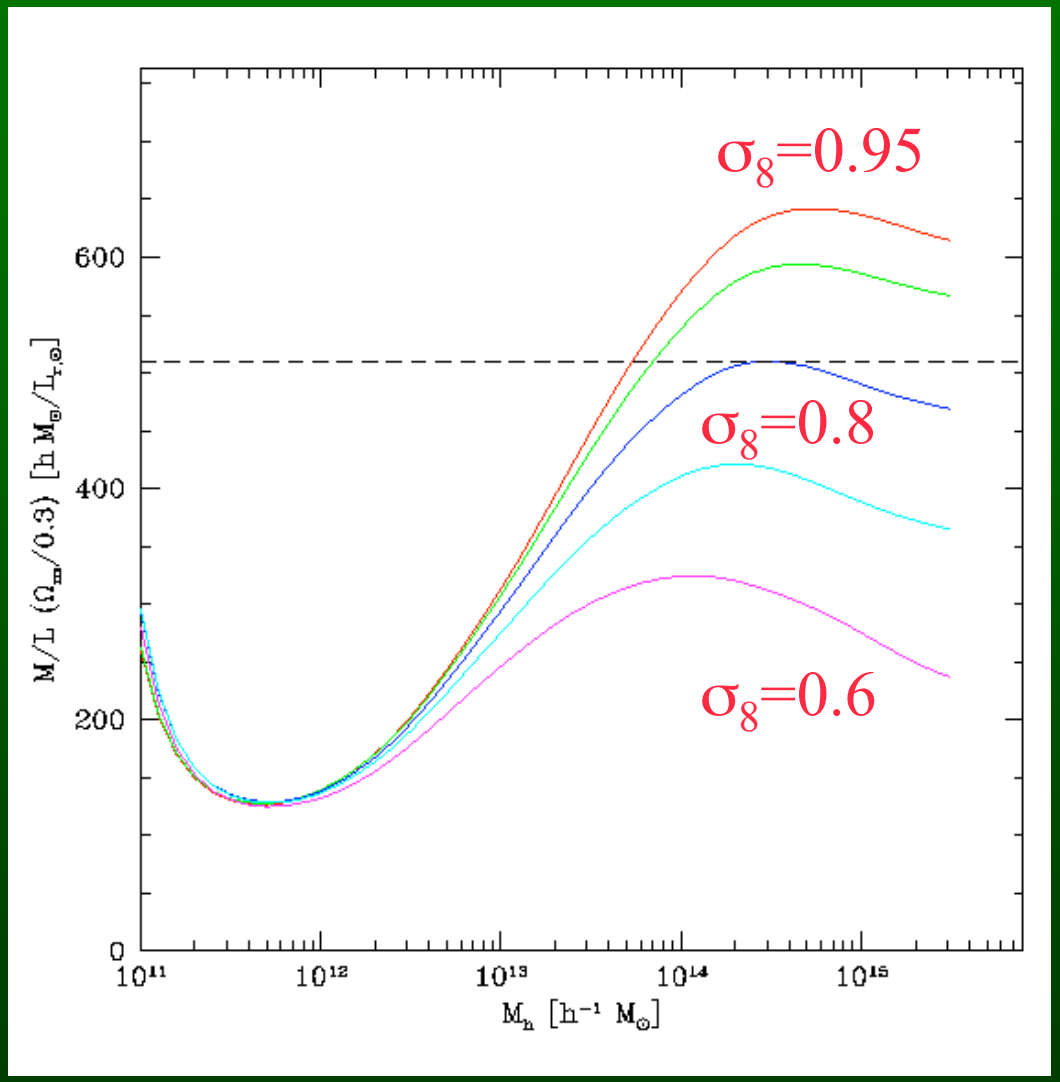
$\Omega_m = 0.3, \sigma_8 = 0.95$



Tinker et al. (2005)

$\Omega_m = 0.3, \sigma_8 = 0.80$

Cluster mass-to-light ratios



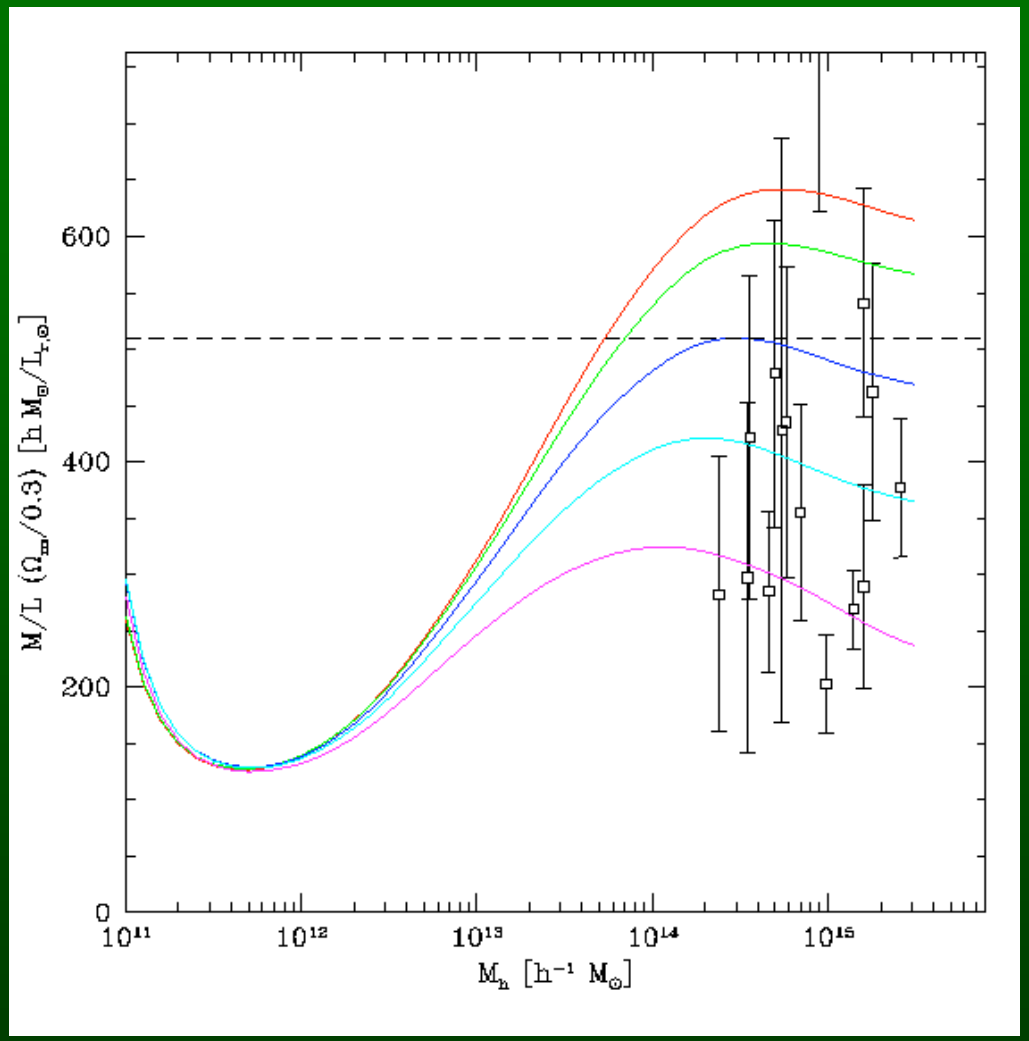
Given P(k) shape, σ_8 , choose HOD parameters to match projected correlation function.

Predict cluster M/L ratios.

These are above or below universal value depending on σ_8 / σ_{8g} .

Tinker et al. (2005)

Cluster mass-to-light ratios



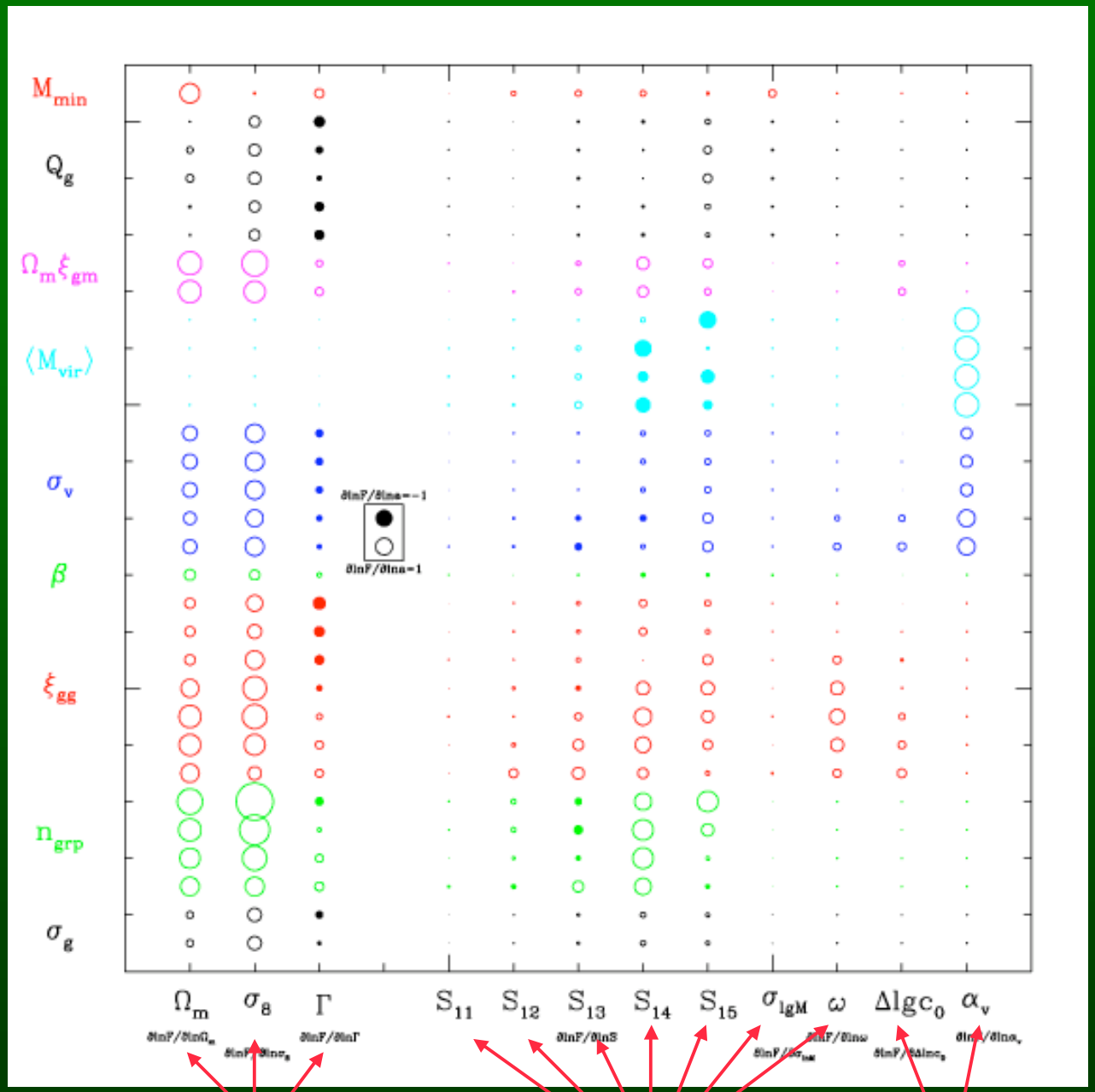
Tinker et al. (2005)

Matching CNOC M/L's implies

$(\sigma_8/0.9)(\Omega_m/0.3)^{0.6} =$

$0.71 \pm 0.05.$

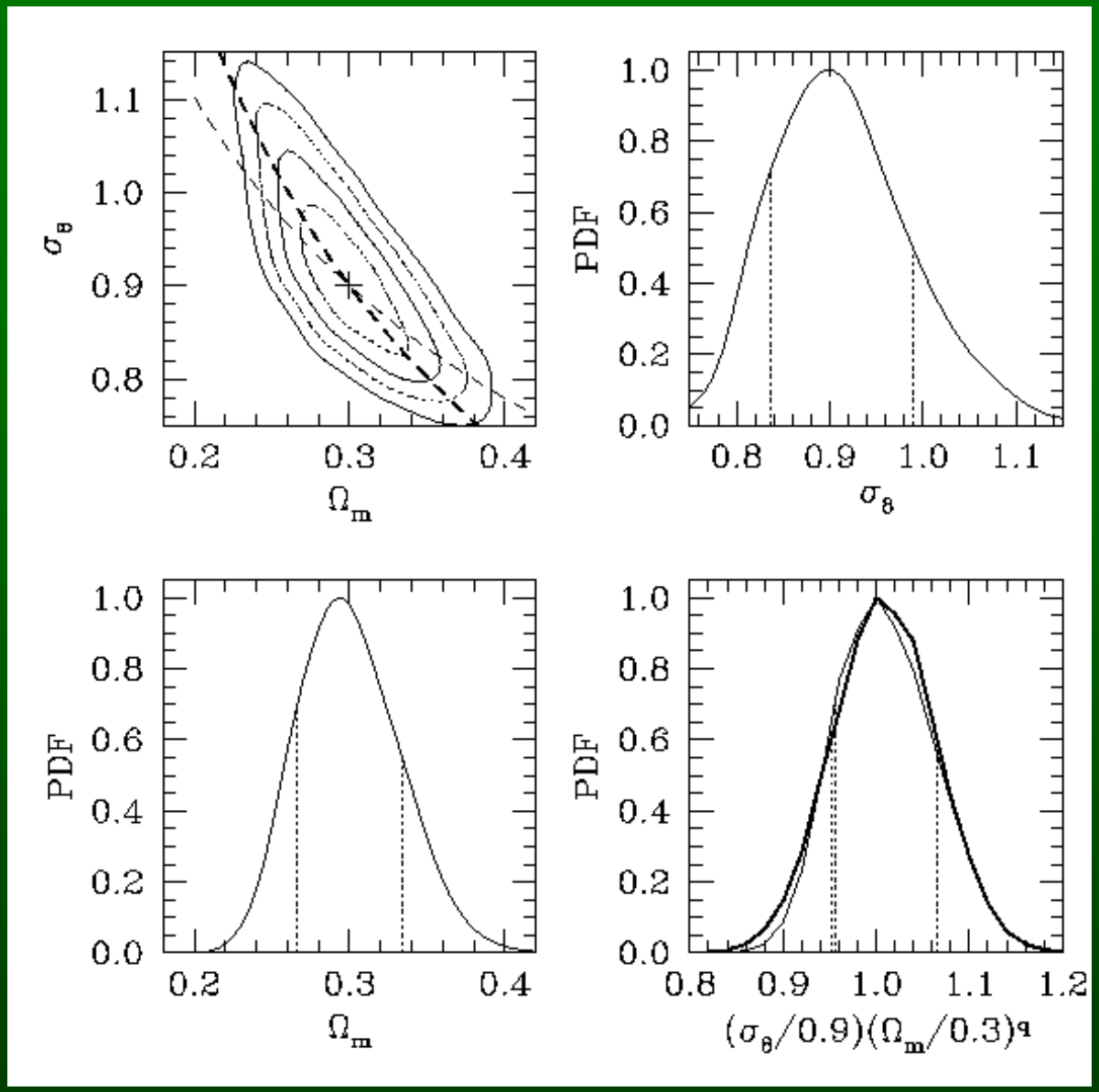
Similar results by van den Bosch et al., modeling 2dFGRS.



Breaking degeneracy between cosmology and galaxy bias:

Response of clustering observables to cosmological and HOD parameters.

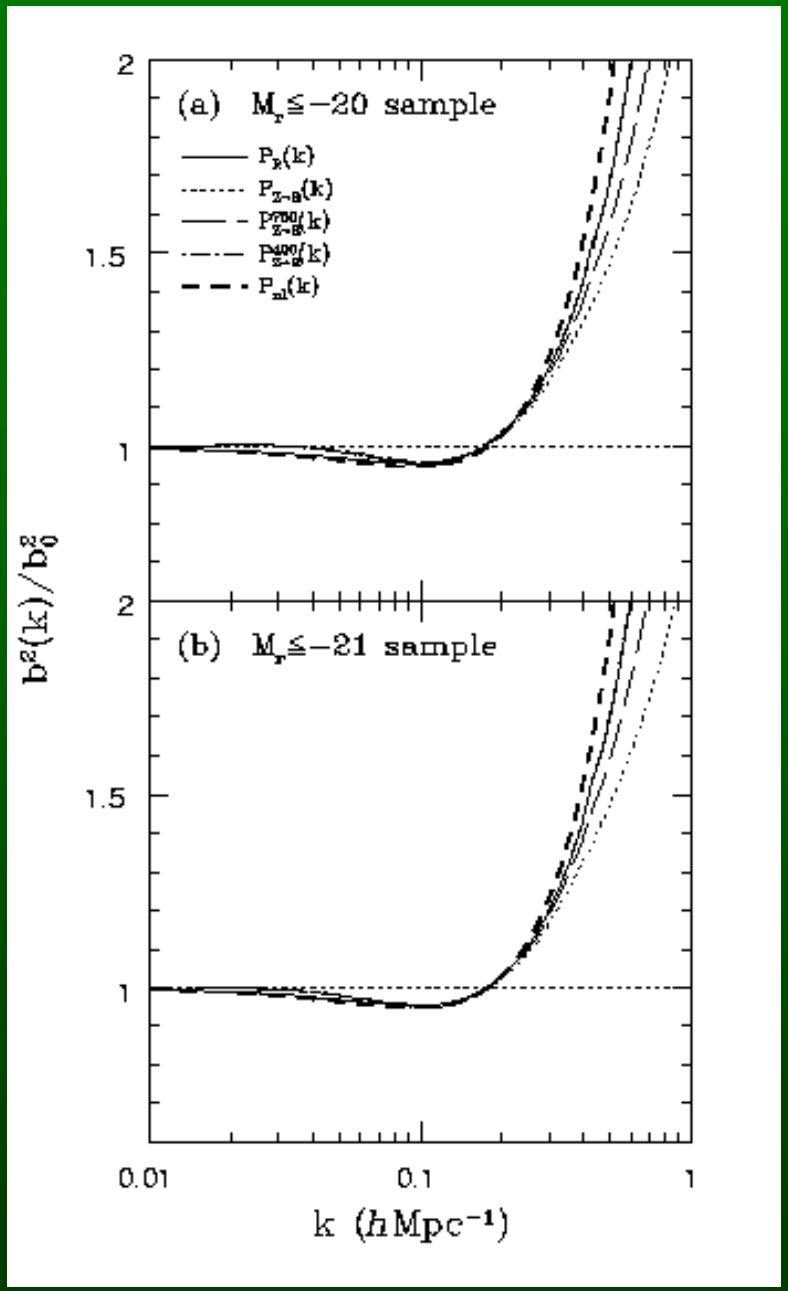
Zheng & Weinberg (2005)



Forecast of joint constraints on Ω_m and σ_8, for fixed P(k) shape.

Eight clustering statistics, 30 "observables", each with 10% fractional error.

Zheng & Weinberg (2005)



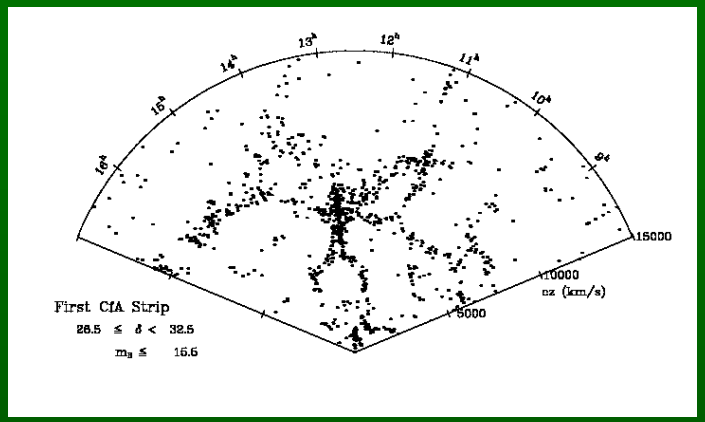
Constrain HOD by fitting $w_p(r_p)$. Use derived HOD to calculate scale-dependent bias for large scale P(k).

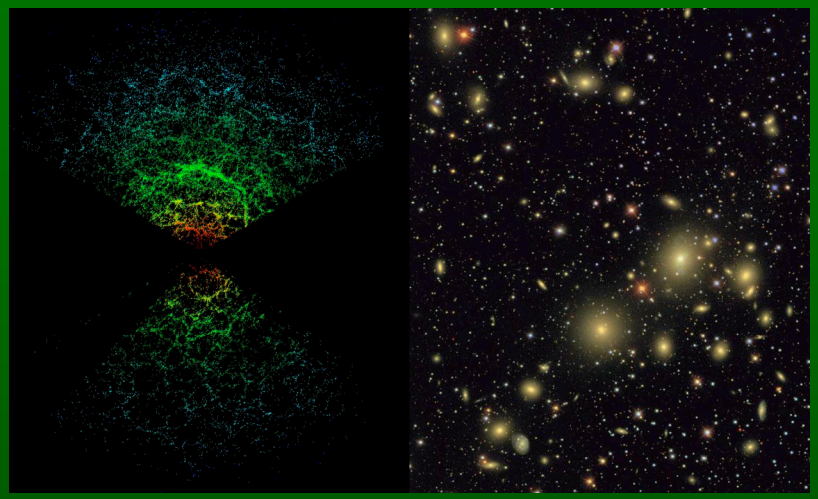
Can also use HOD to improve modeling of large scale redshift-space distortions.

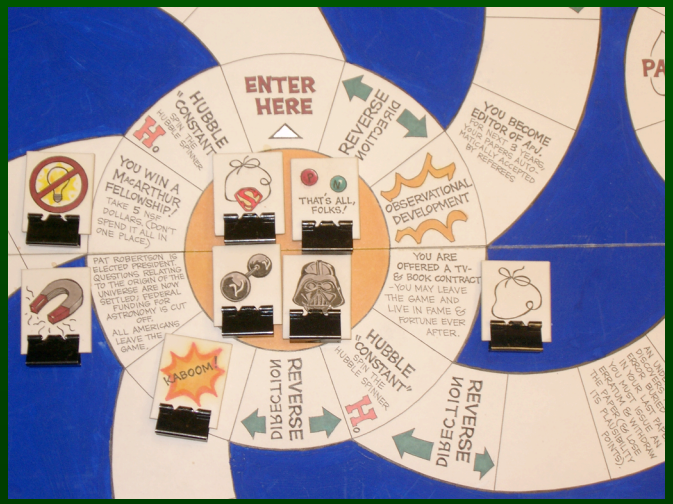
Yoo, Weinberg, Tinker, in prep.

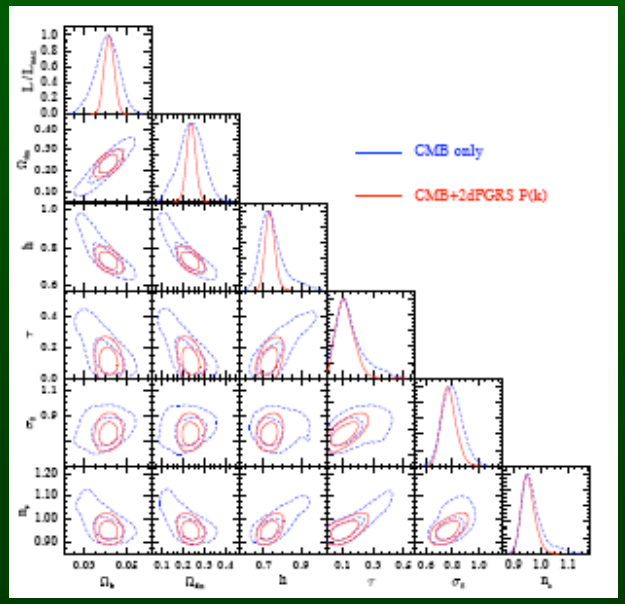
Conclusions

- We've come a long way since 1986









Conclusions

- We've come a long way since 1986
- Large scale P(k) + CMB + etc.
  - Convergence of results? What parameter values?
- HOD framework:
  - Connects clustering to galaxy formation physics.
  - Explains power-law deviations in $\xi(r)$.
  - Qualitative agreement with theory on luminosity, color dependence.
  - Use small/intermediate scale clustering to pin down galaxy bias for given cosmology.
  - Dynamical evidence suggests low σ_8 and/or Ω_m.

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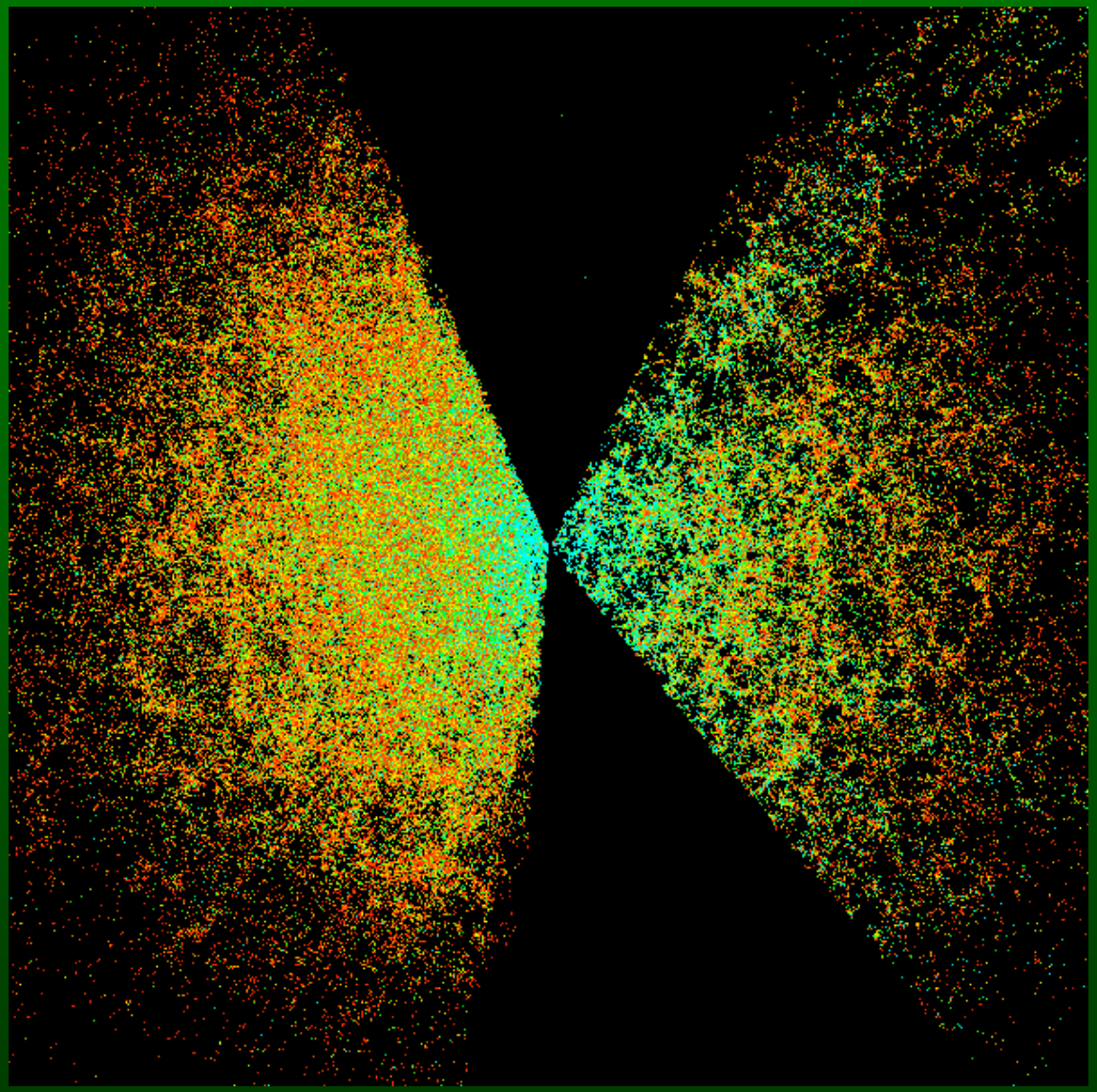
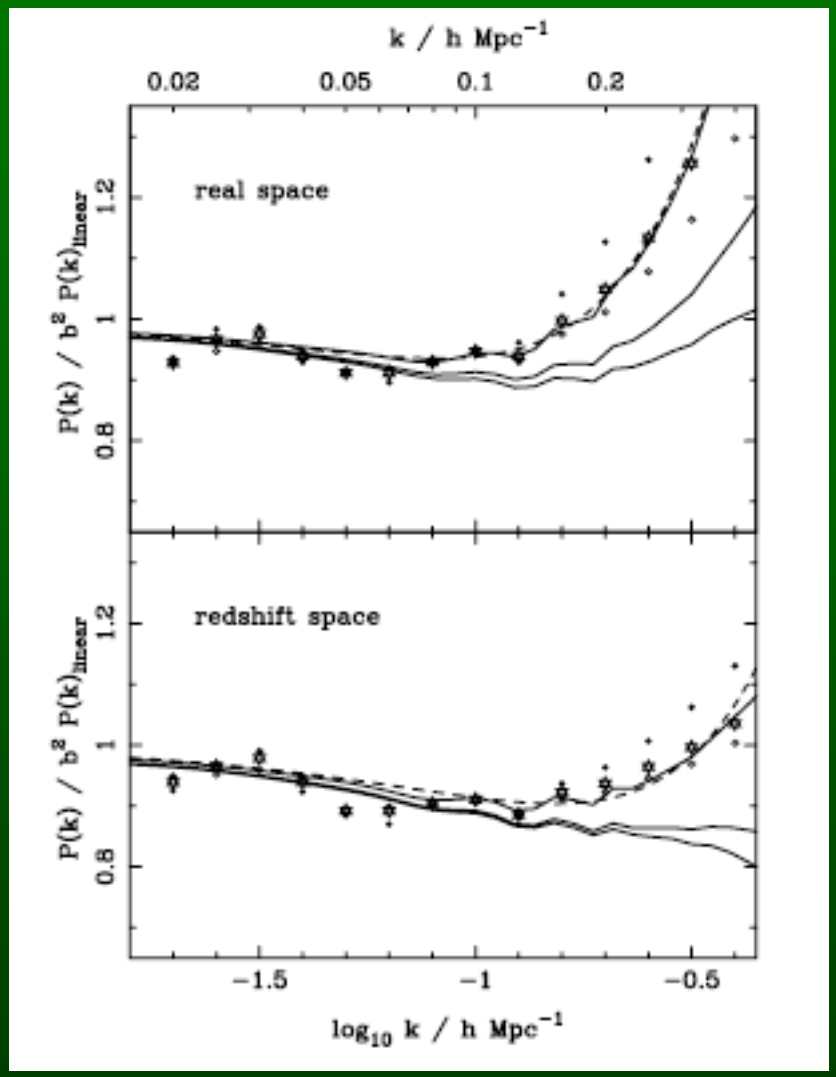
Sloan Digital Sky Survey



Movie by M. Blanton

2dFGRS Galaxy Power Spectrum (final)



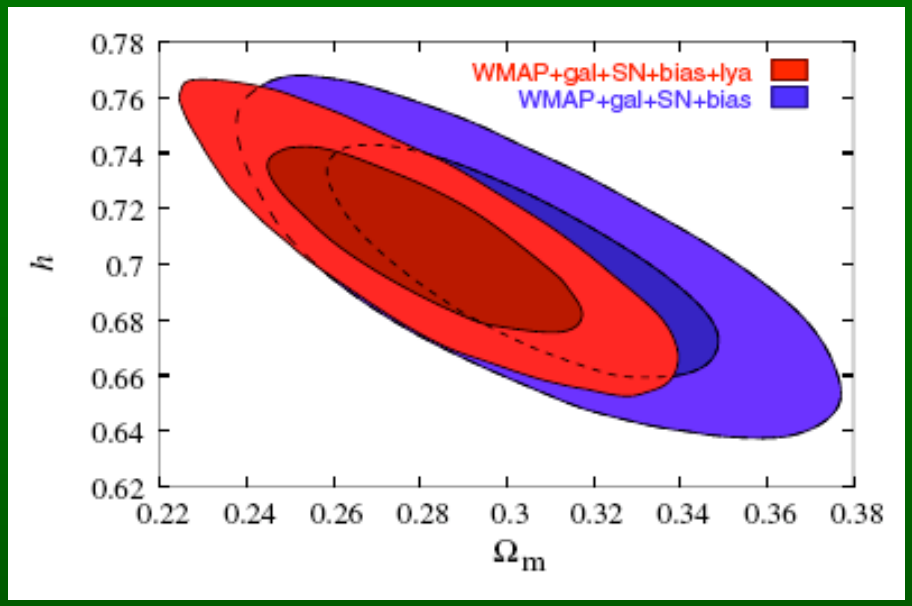
Cole et al. 2005

Cole et al. 2005:

- Angle-averaged redshift space P(k)
- Compare to models convolved with survey window function
- Model scale-dependent bias as $b(k)=(1+Qk^2)(1+Ak)^{-1}$

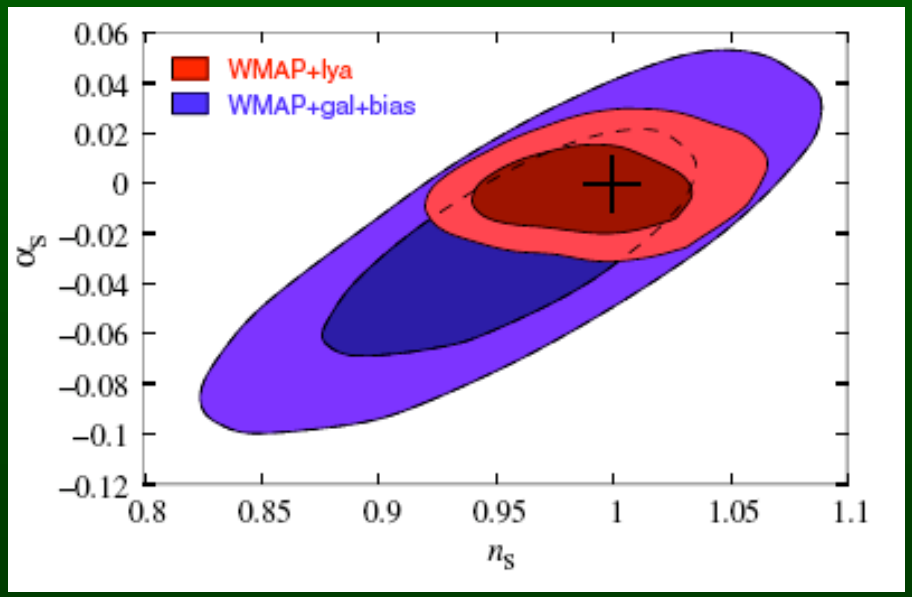
Theory used to motivate form, give priors on parameter values.

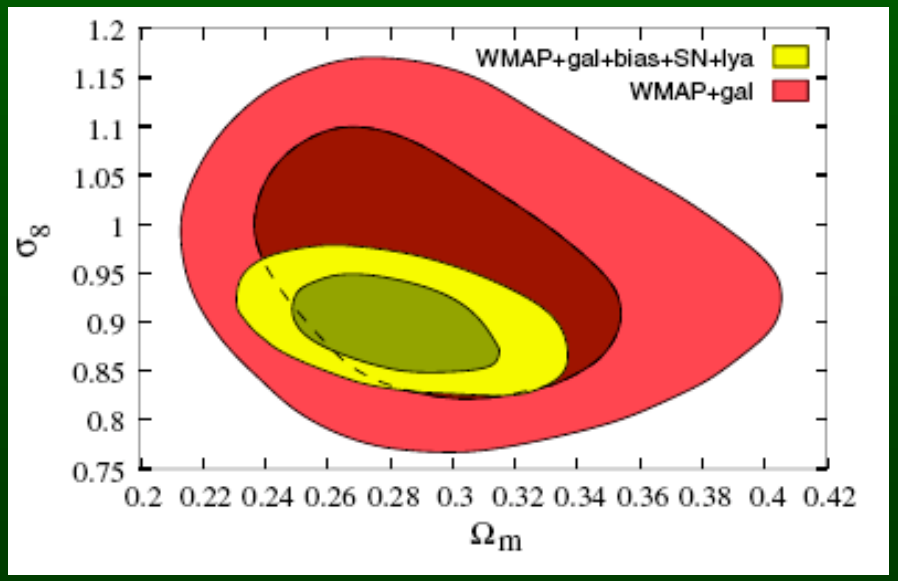
WMAP CMB + SDSS P(k) + SDSS Lyα forest

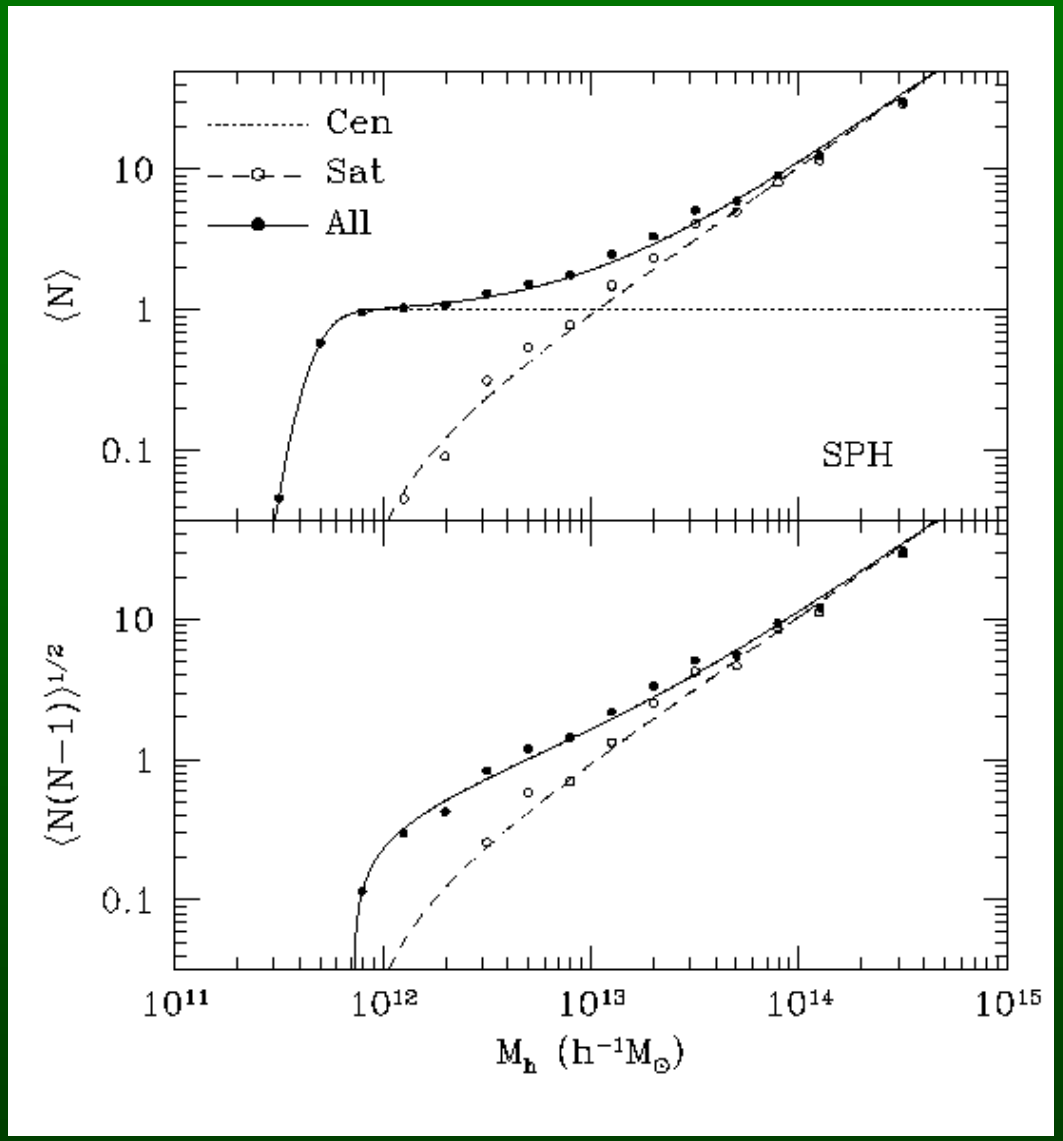


Seljak et al. 2005:

$\Omega_m = 0.299 +/- 0.035$
$\Omega_b = 0.048 +/- 0.002$
$h = 0.694 +/- 0.030$
$n_s = 0.971 +/- 0.021$
$\sigma_8 = 0.890 +/- 0.033$







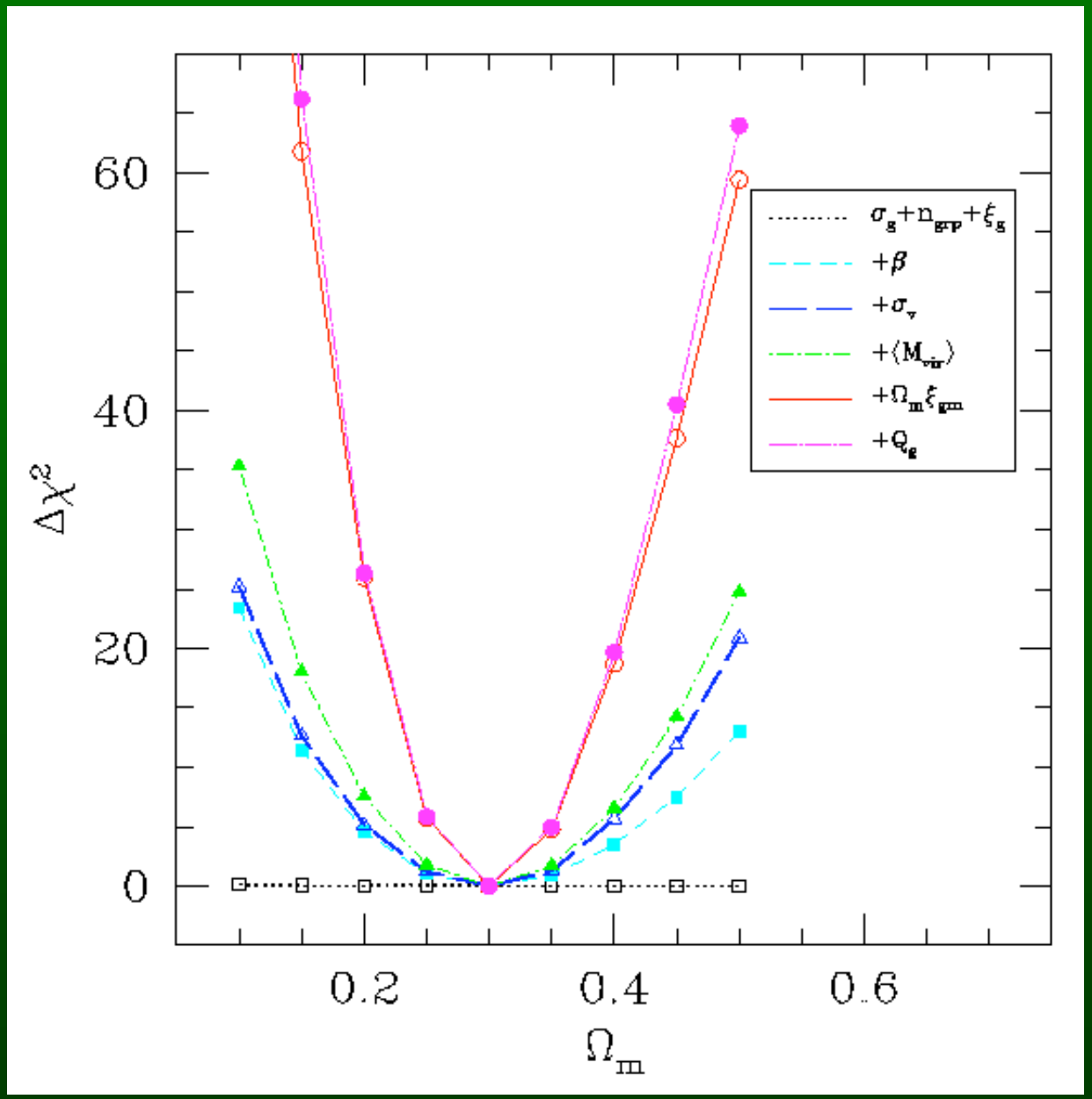
Zheng et al. 2005

Halo central galaxies usually more massive, older than satellites.

Central: step function

Satellites: truncated power-law, Poisson statistics

(Kravtsov et al. 2004)



Changing Ω_m at fixed σ_8, P(k) shape.

Zheng & Weinberg (2005)