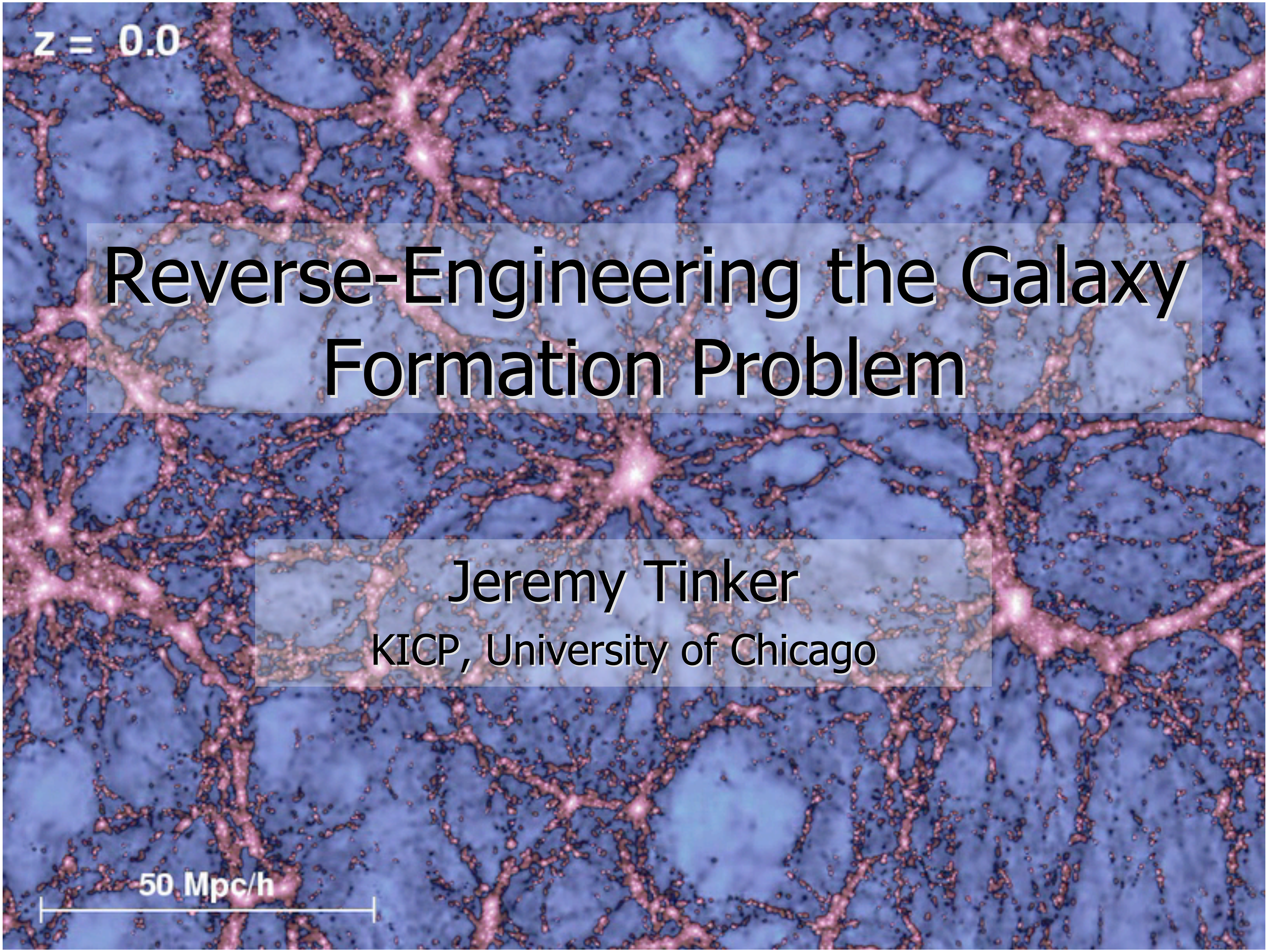
Reverse-Engineering the Galaxy Formation Problem

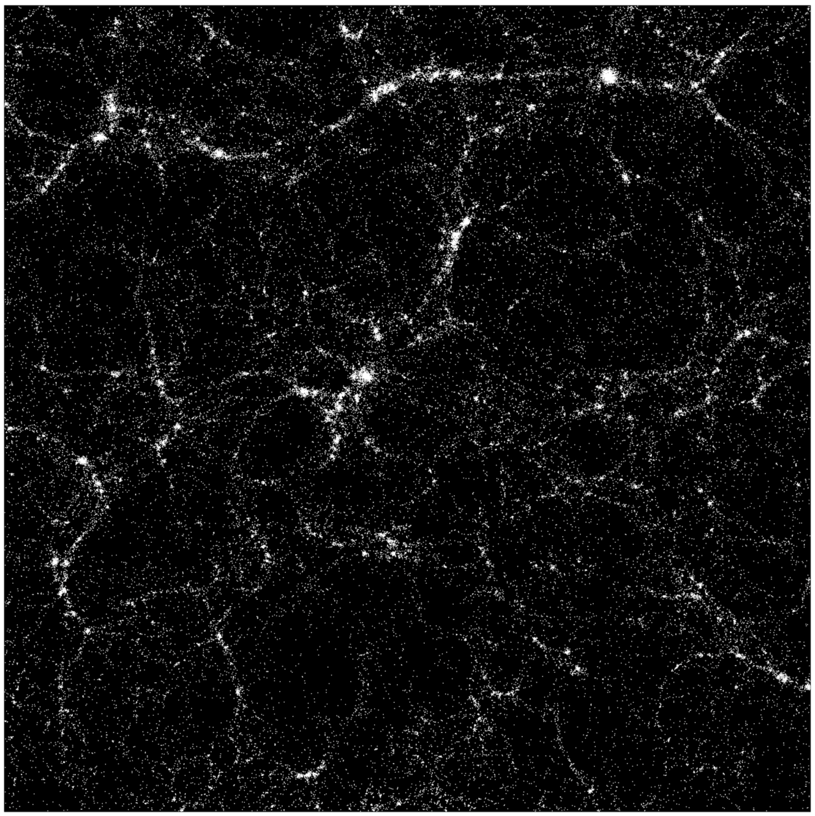
Jeremy Tinker
KICP, University of Chicago



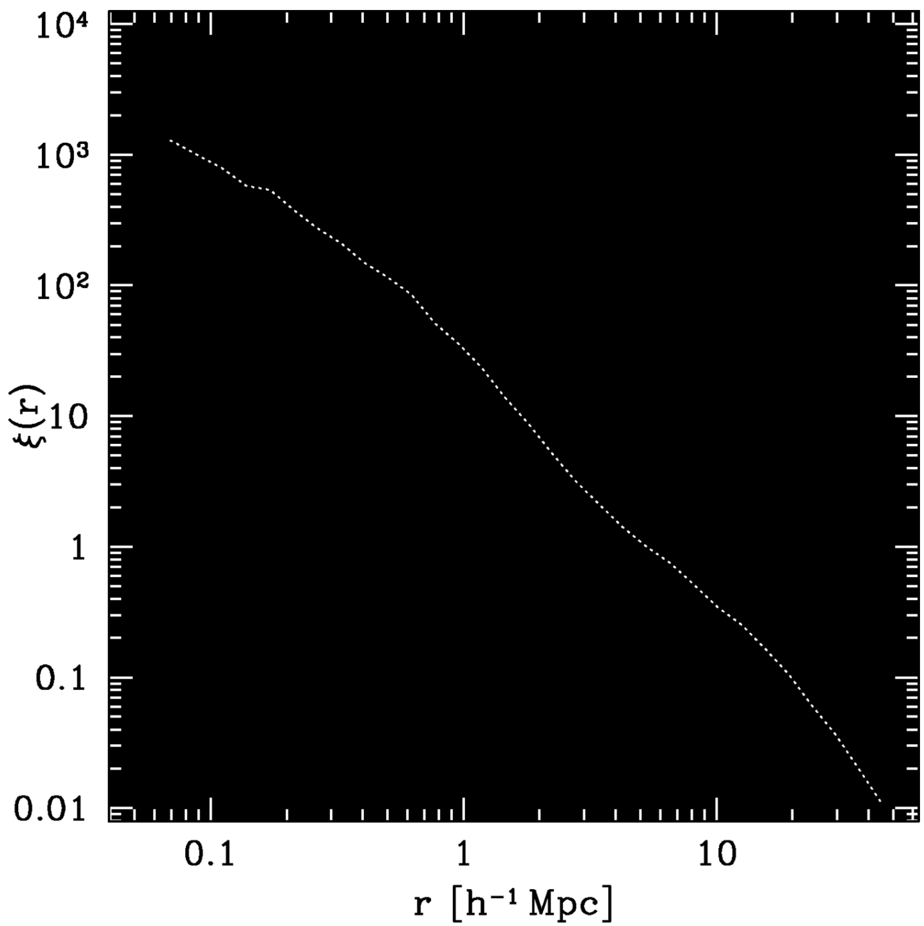
Collaborators

- Galaxy Voids - Charles Conroy, Peder Norberg, Santiago Patiri, David Weinberg, Mike Warren.
  astro-ph/0707.3445
- MgII absorption systems- Hsiao-Wen Chen
  astro-ph/0709.1470

The Universe to a computer.

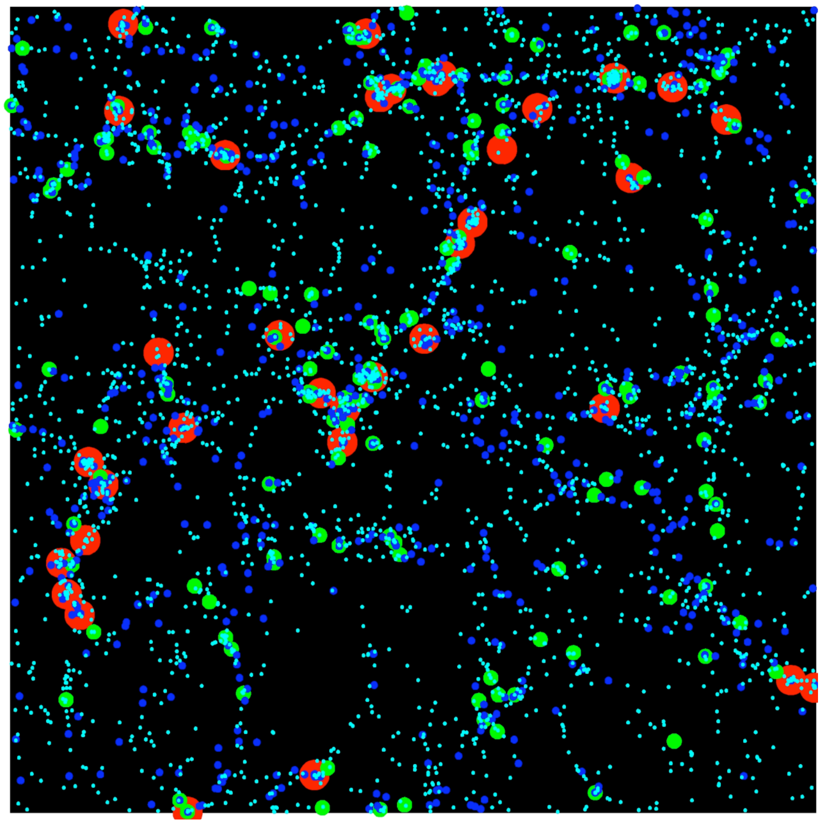


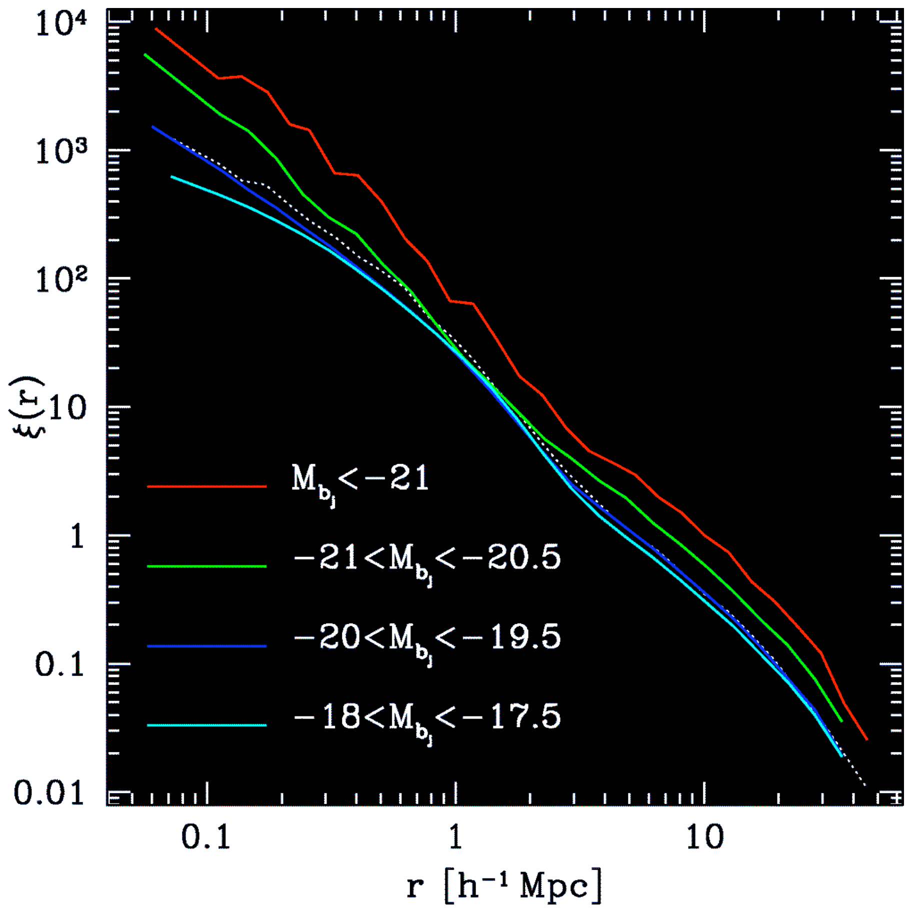
Simulation by Mike Warren



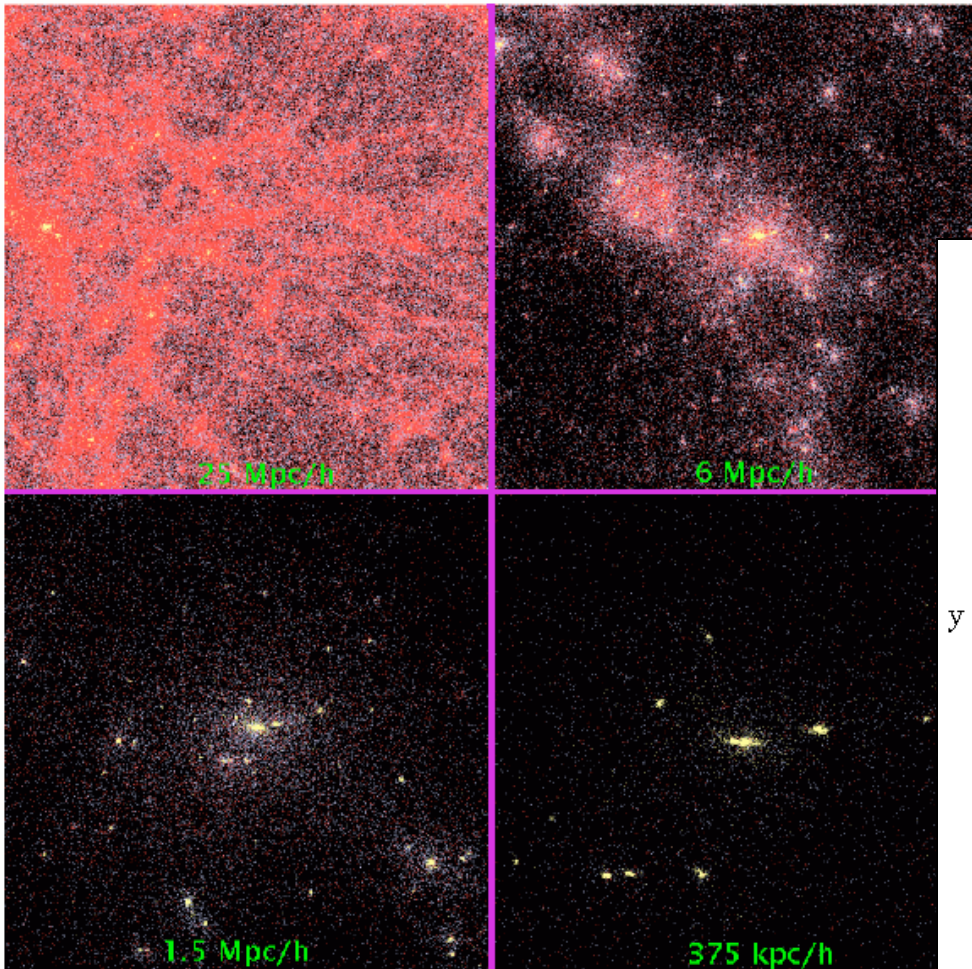
Galaxy Bias

Scale and Luminosity Dependent

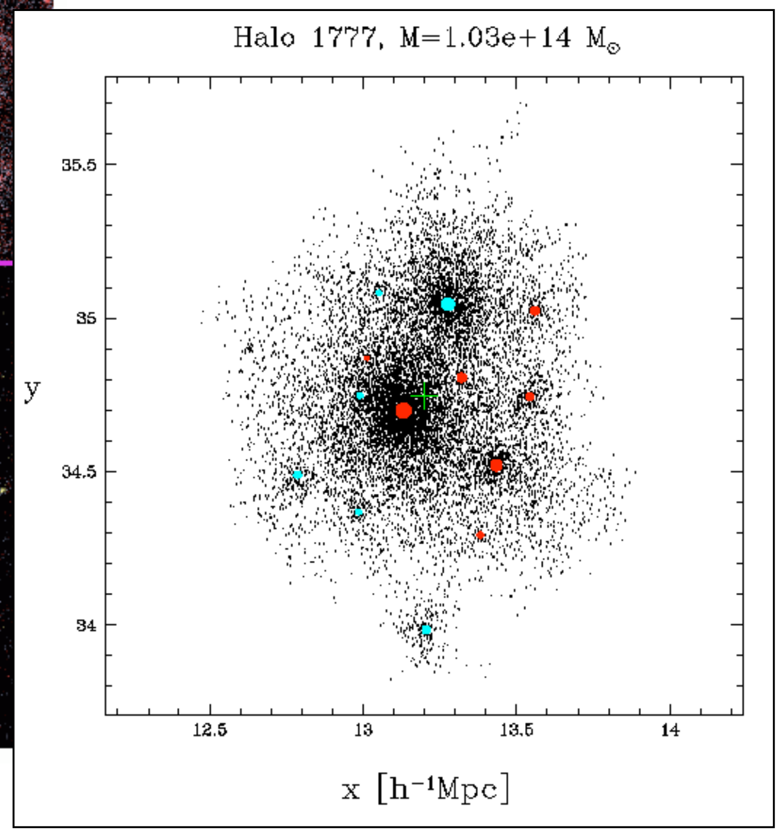




Galaxy Formation
Insights from simulations



Galaxies always form in the halos.



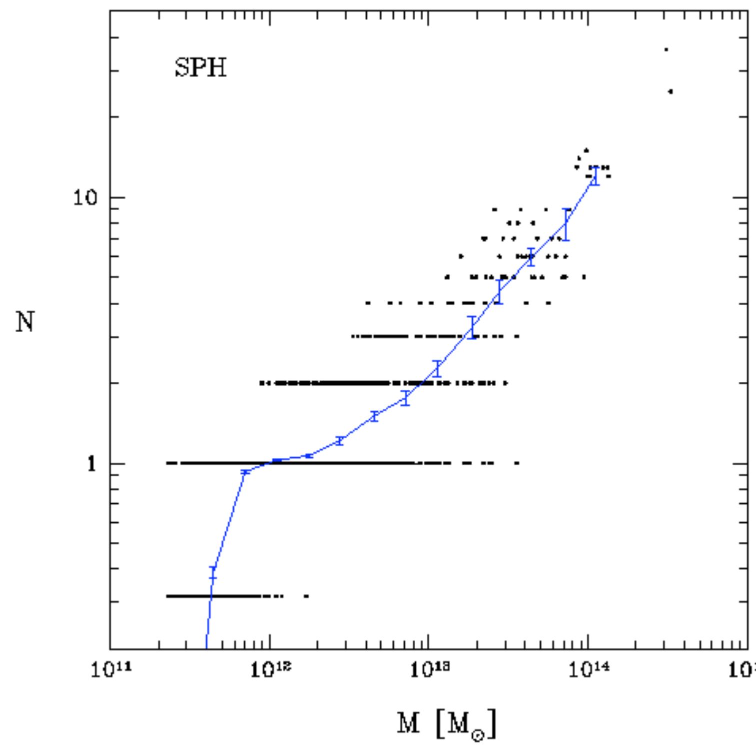
Weinberg et al, 2004

Halo Occupation Distribution

- Statistical prescription for the connection between galaxies and dark matter halos.
- Know <u>all</u> about halos.
- Cons: No galaxy formation physics.
- Pros: No galaxy formation physics. Allows one to 'reverse-engineer' the galaxy formation problem.

P(N|M) - Guts of the HOD

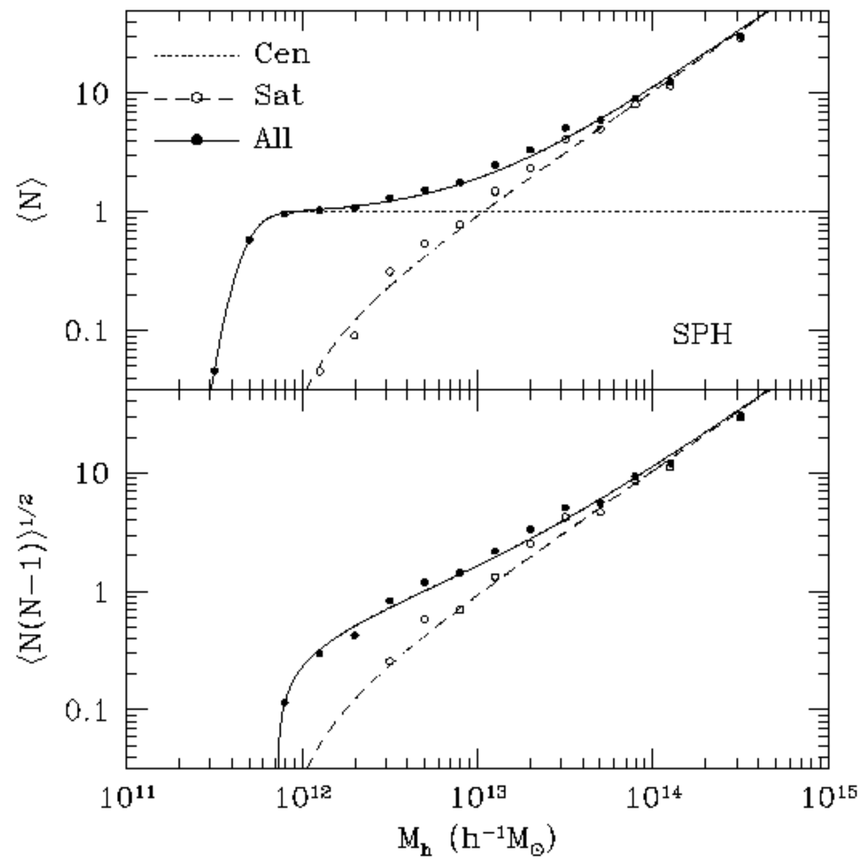
Distribution of galaxies in halos of mass M (Berlind et al, 2003)



Each point is a halo in the simulation

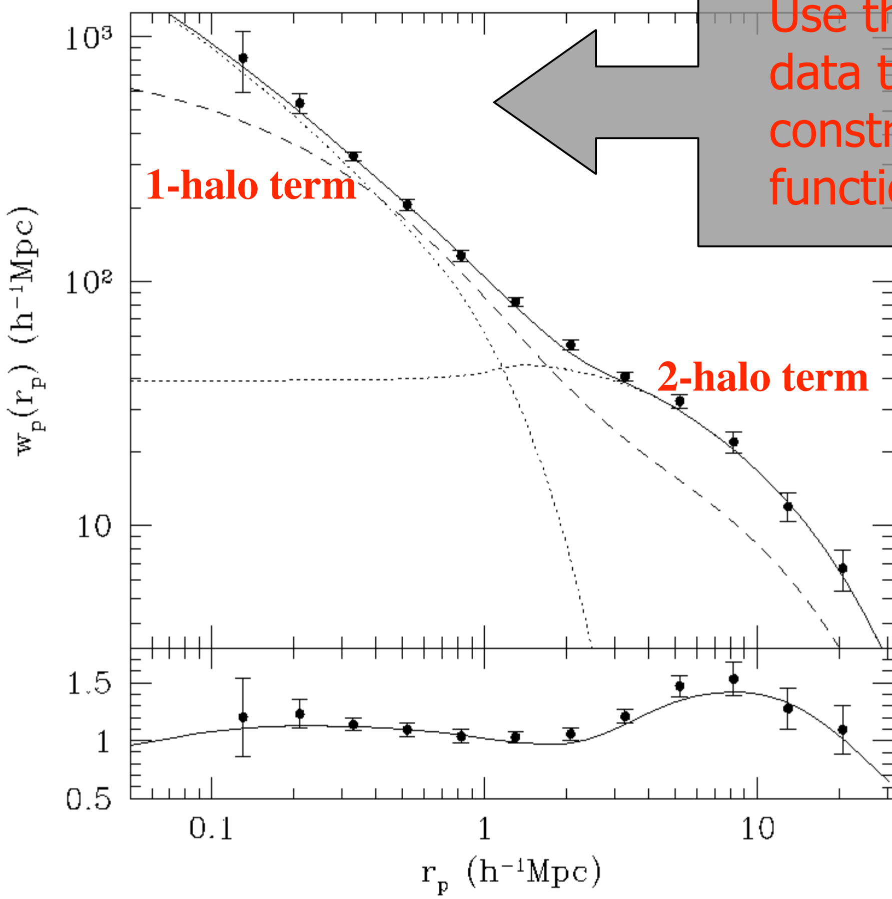
Break the parameterization into two parts: central galaxies and satellites.

(Zheng et al, 2005).

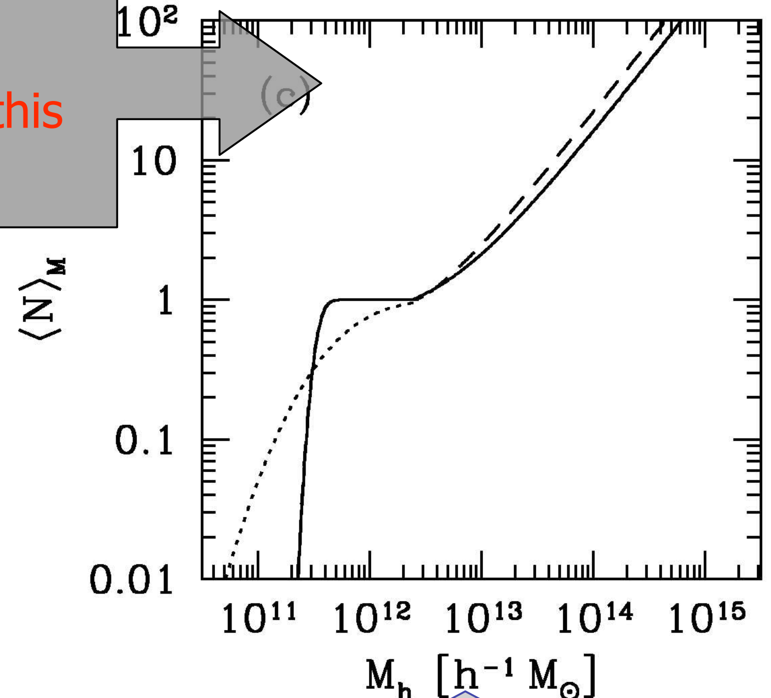


The HOD at work

Zehavi, Weinberg, Zheng et al (2004):
SDSS results



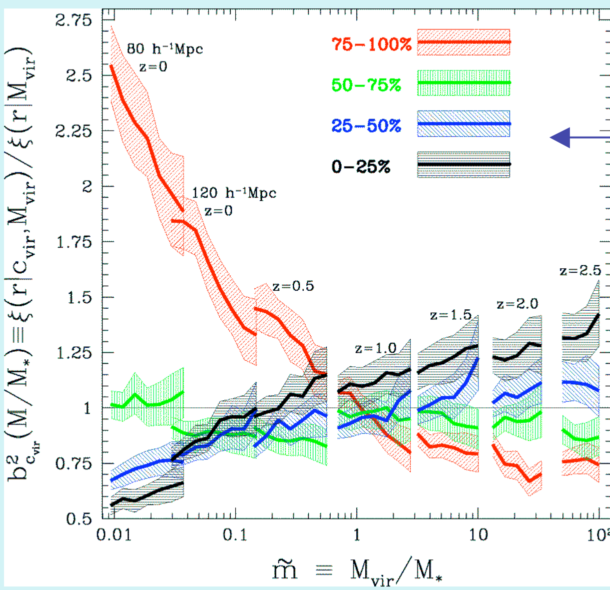
Use these data to constrain this function.



Refer to this as the "occupation function"

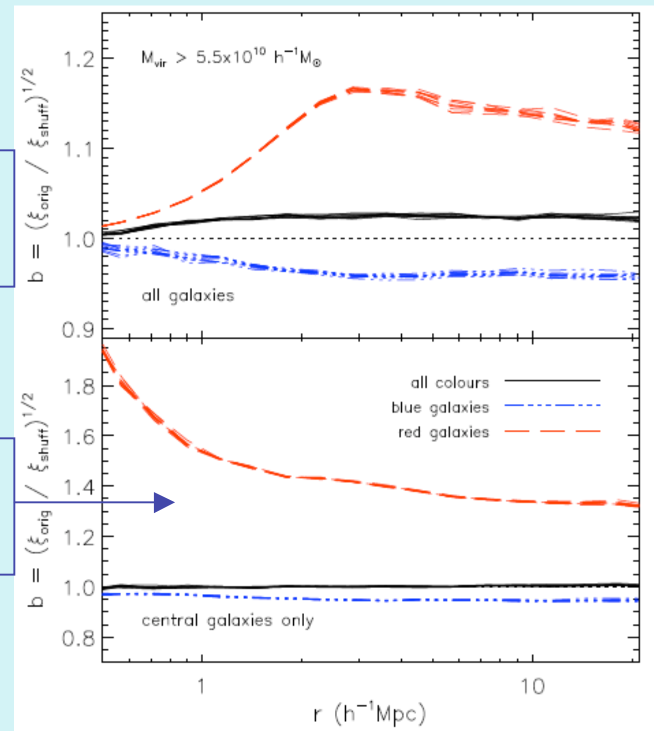
Is the HOD really only P(N|M)?
What about P(N|M,δ)?

- More formally: Are the properties of the galaxies in a halo of mass M determined only by halo mass? What about other halo properties?

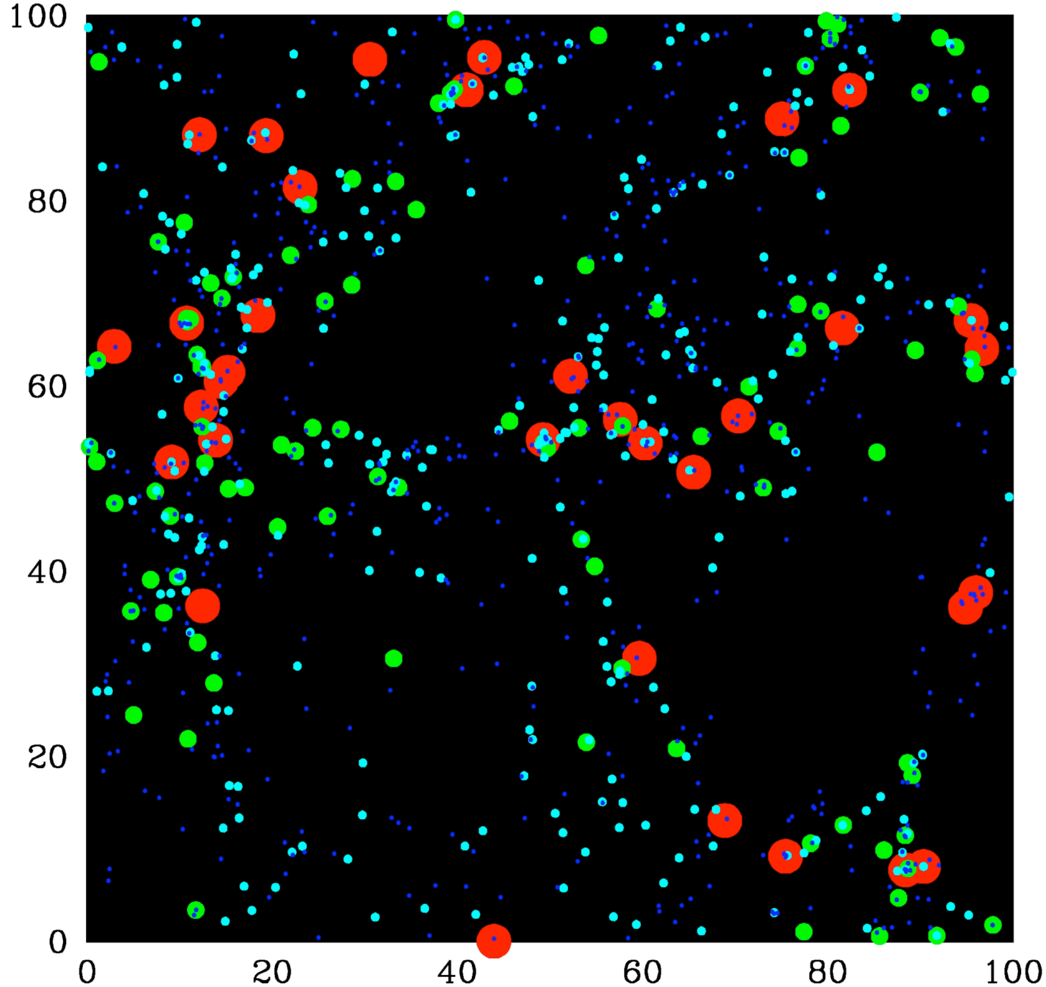


Wechsler et al 2006: halo concentration and environment.

Croton et al 2006: SA galaxies depend on both M, δ.



In what ways are voids useful?

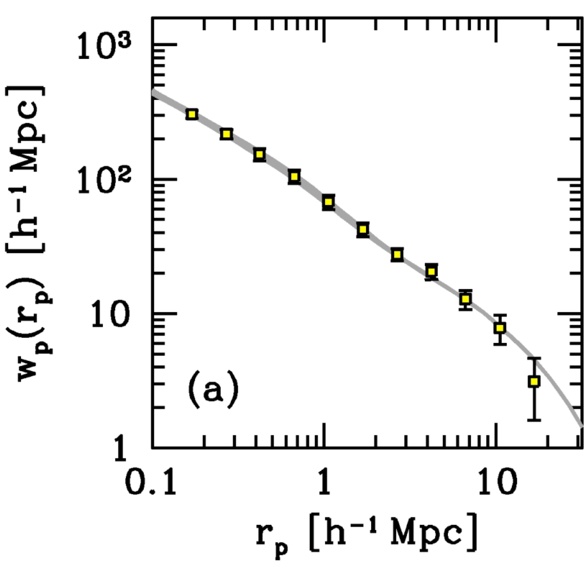


GOOD: Making puns in your astro-ph titles:

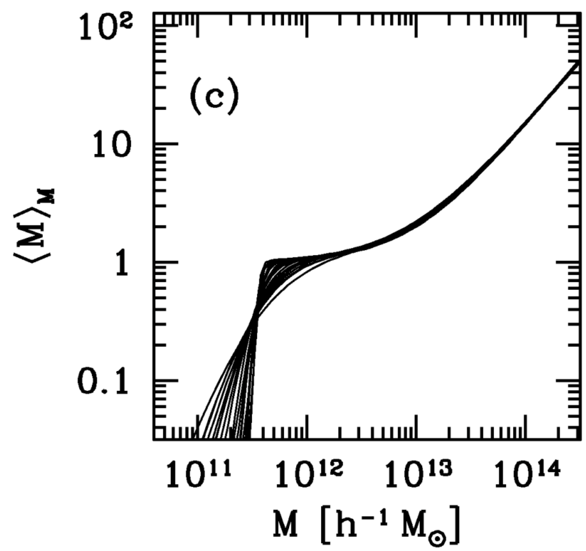
- "Hierarchy of Voids: Much Ado About Nothing"
- "Evidence of Absence: Galaxy Voids in the Excursion Set"
- "A case de*void* of bias: ORS voids and IRAS voids" (my italics)

Also, provide a unique testbed for galaxy formation theories/ processes, since environment is extreme.

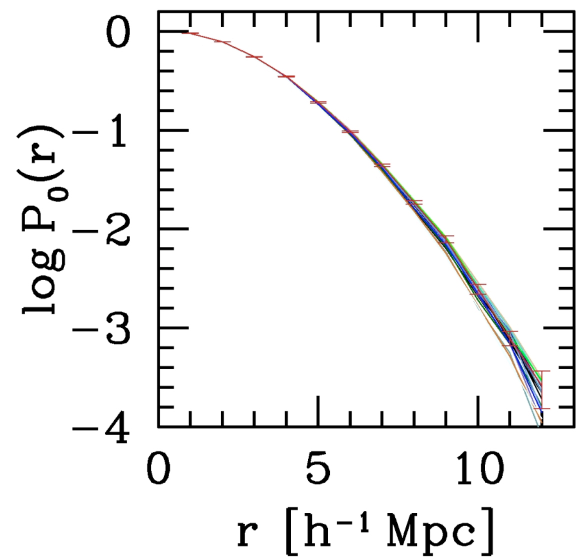
BAD: Void statistics (VPF) don't help constrain bias or cosmology.



20 fits to M_r<-19 SDSS sample.



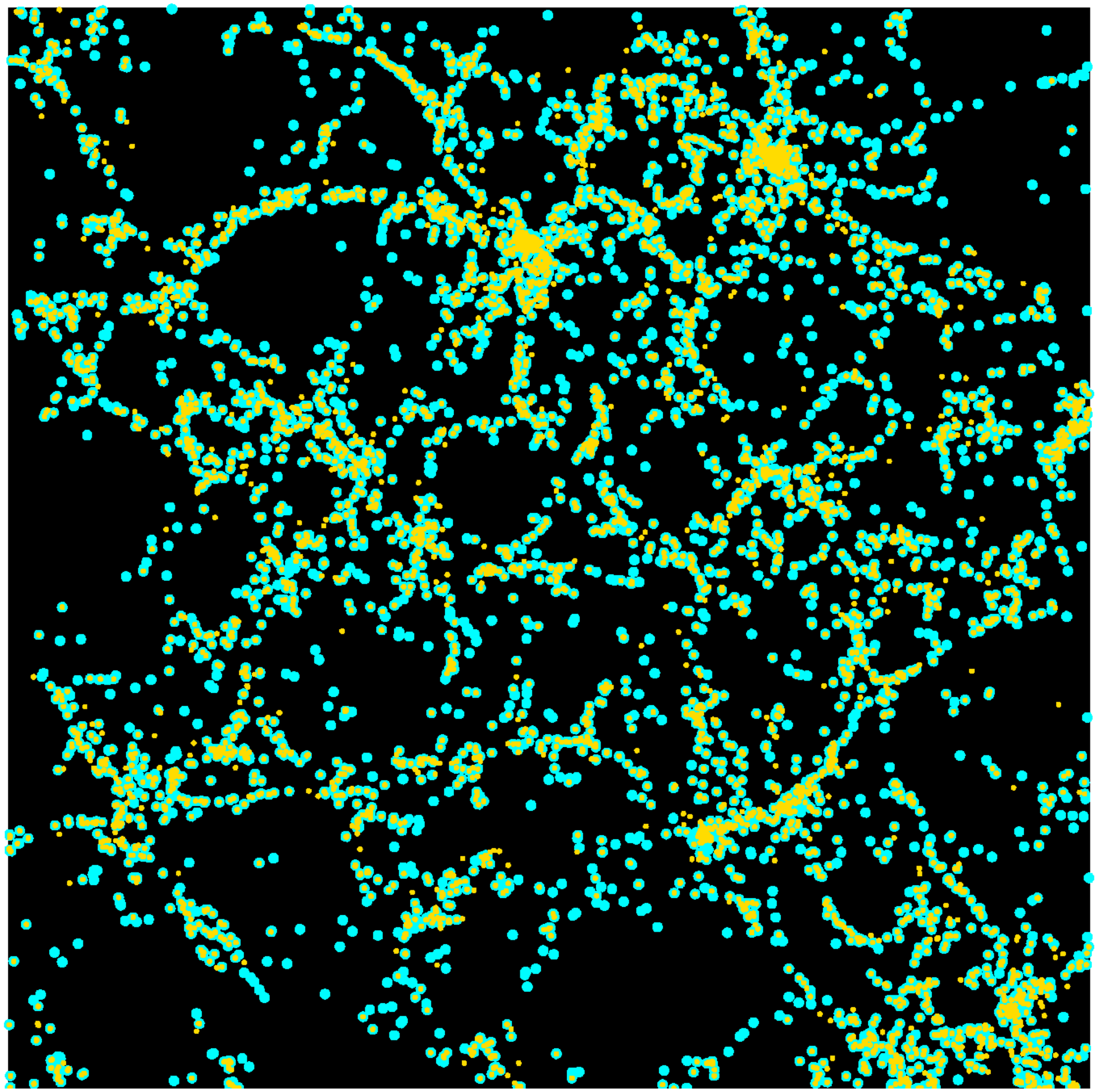
the 20 HODs for those fits.



the 20 VPFs for those HODs.

Tinker, Weinberg, Warren 2006

What if density mattered?

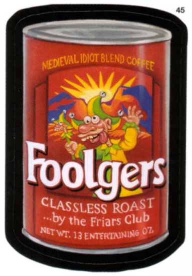


mock SDSS M_r<-19 galaxy samples

Cyan = density-*in*depdendent HOD.

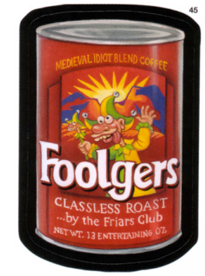
Gold = galaxy formation efficiency goes down at low-δ.

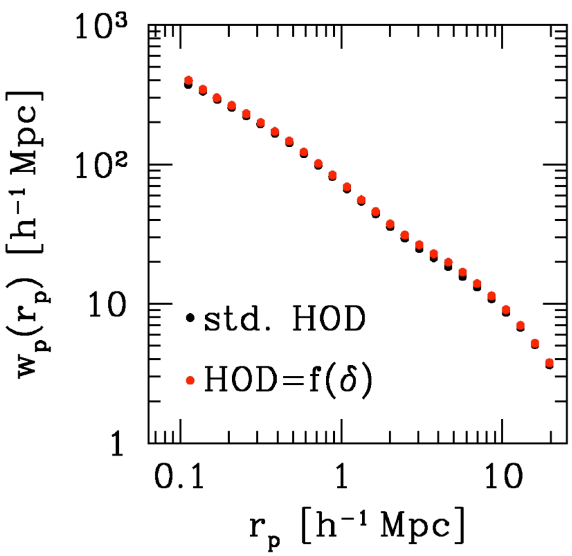
In other words, mass goes up at fixed luminosity (at low-δ).

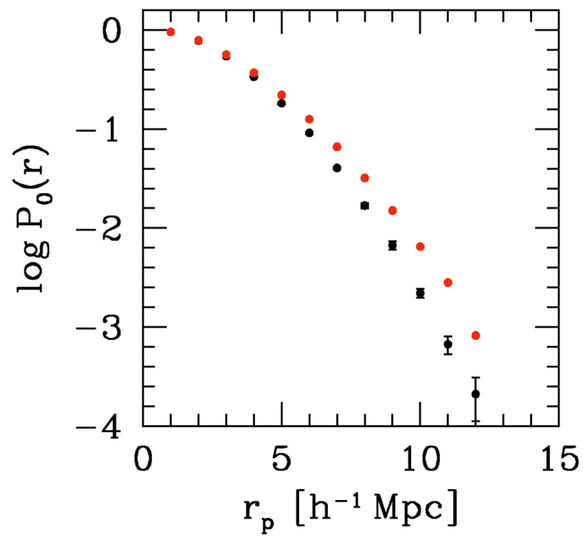


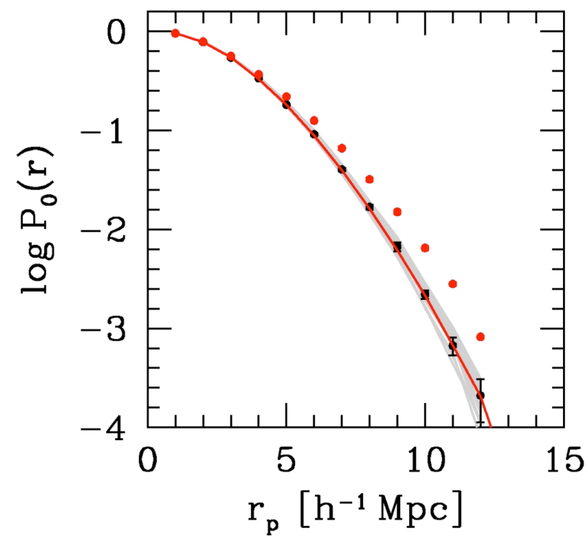
Put the HOD to the test!

We've secretly replaced Tinker's regular HOD with our new δ-dependant model. Let's see if he notices...







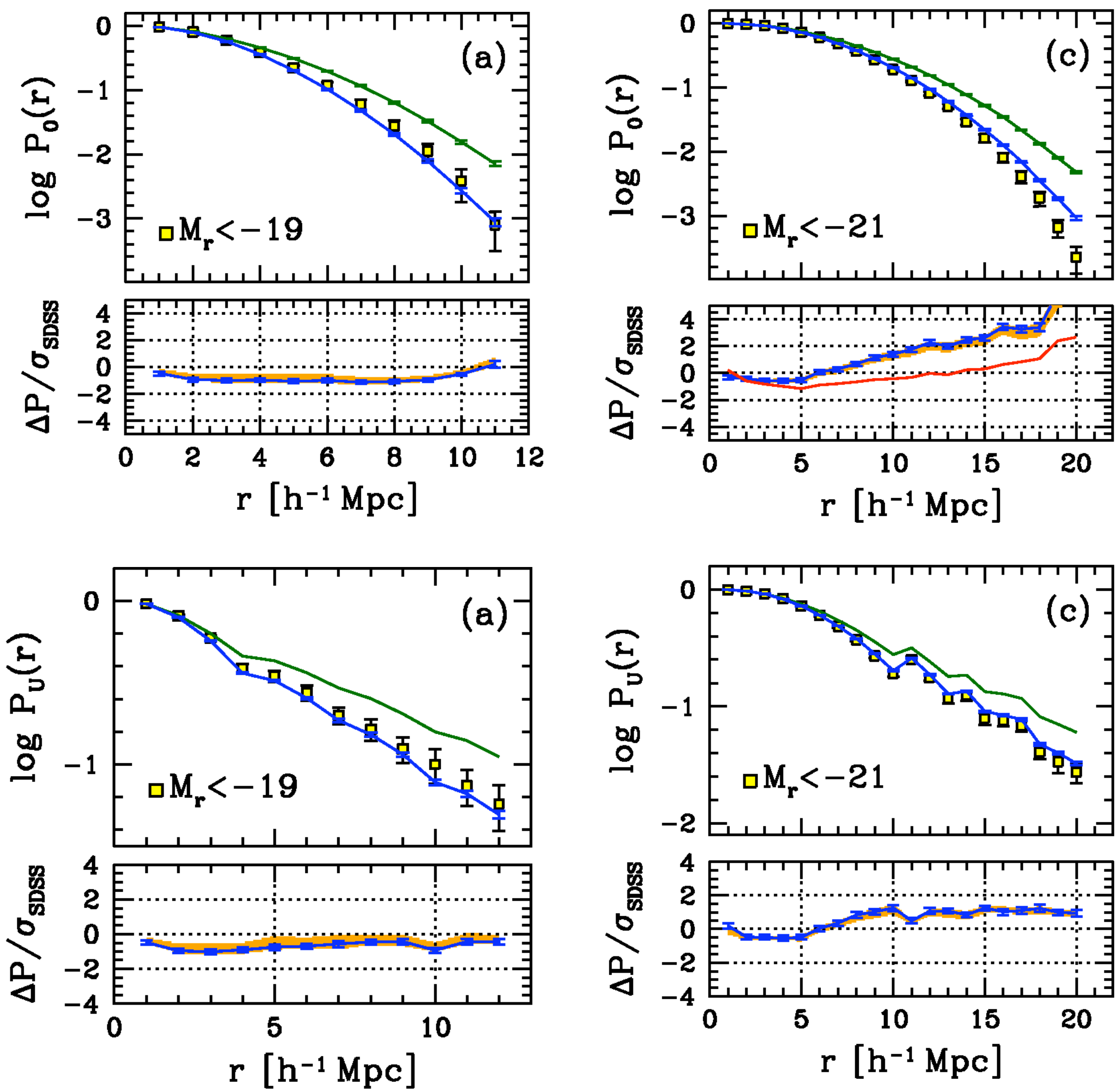


Take two HODs with nearly identical w_p's...

...but the $f(\delta)$ model has larger voids. If I fit the red $w_p(r_p)$ assuming $f(\delta)=0$...

...I would predict the wrong VPF.

SDSS DR4 results



- Points: DR4 measuremnts.
- Blue Curves: HOD predictions.
- Green curves: δ-HODs

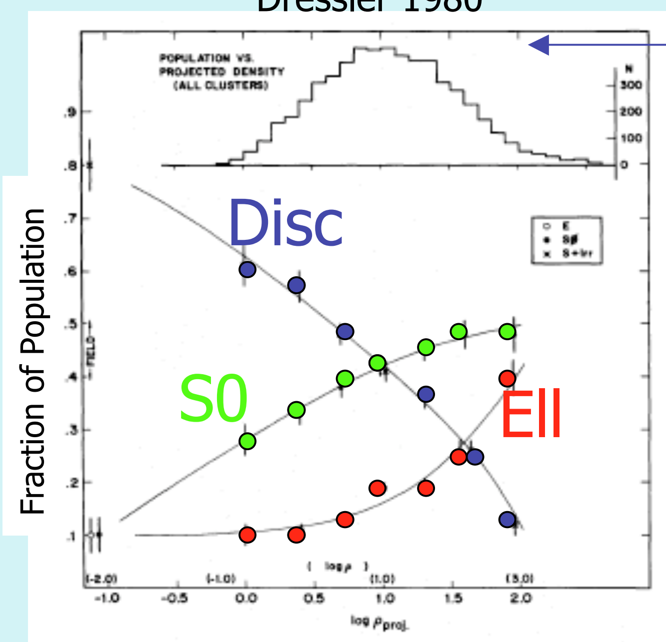
- Luminosity depends only on M, not on halo environment.

Tinker, Conroy, Norberg, Patiri, Weinberg, Warren, 2007, astro-ph/0707.3445

Density-Morphology Relation

- Red, old, elliptical galaxies found in dense environments.

Dressler 1980

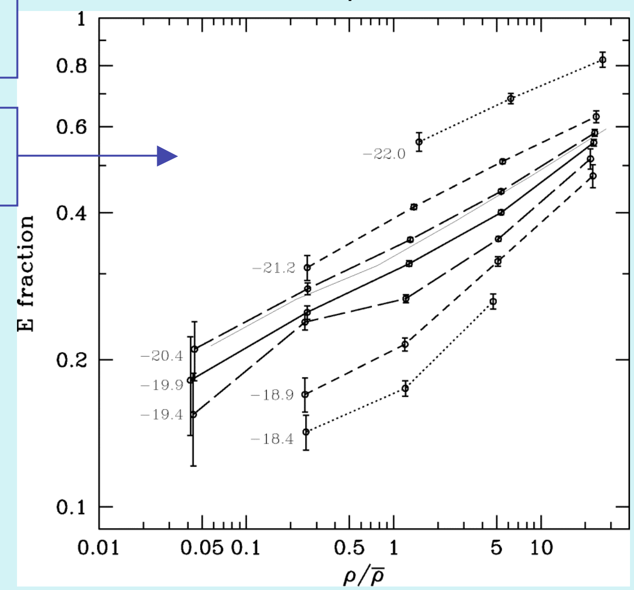


density

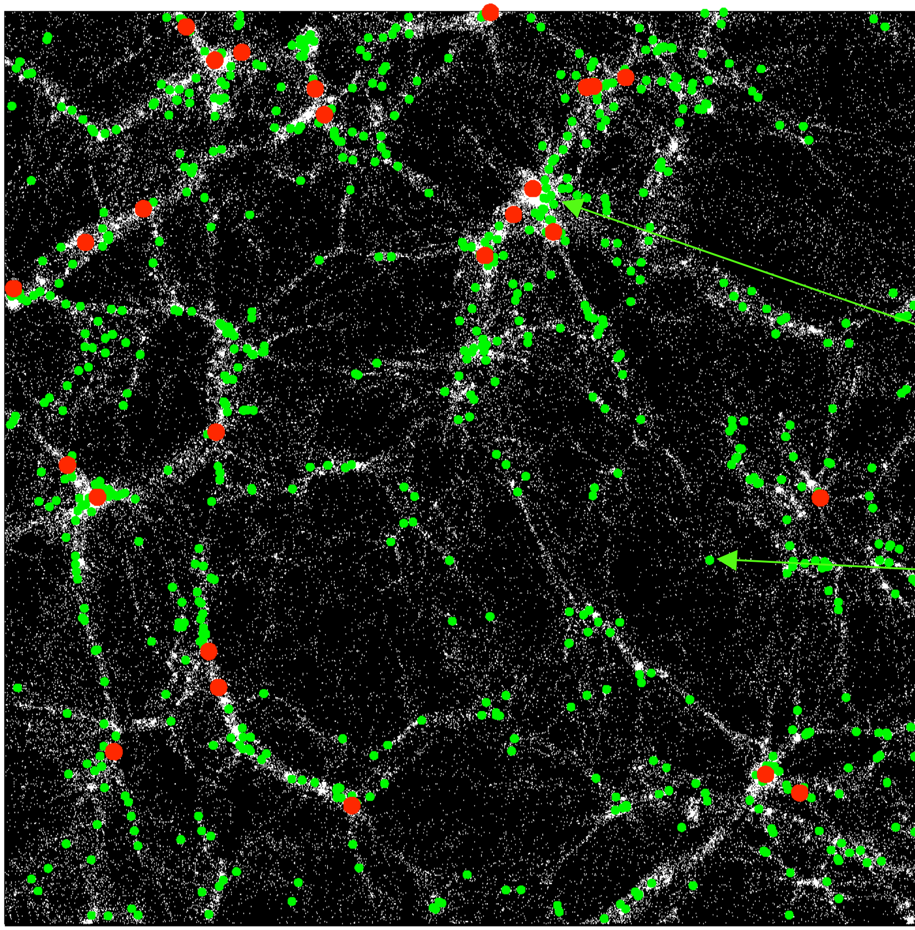
Well-established relation, decades old.

Refined with the statistics of SDSS.

Park et al, 2007



Halo Environment = Galaxy color?



Red=M>10^{13} M_{sol} (group and cluster-size halos)

Green=$5x10^{11}$ M_{sol}-- (mass for -19 central gals)

Should this halo be more likely to house a red galaxy than this halo? ie, P(red)=f(δ)?

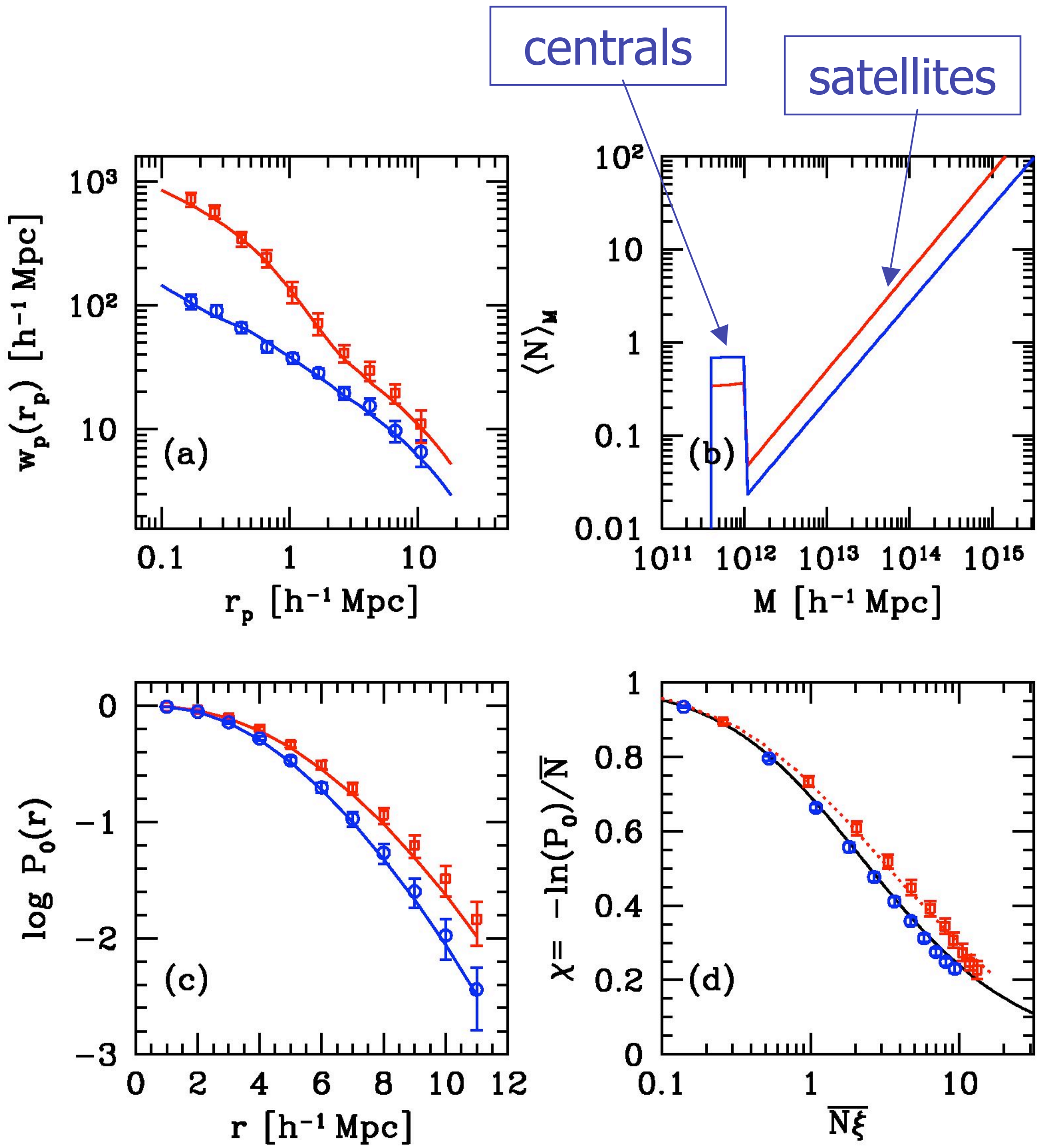
HOD assumption:
P(red)=constant.
Both halos equally likely.

Color Samples: -19>M_r>-20

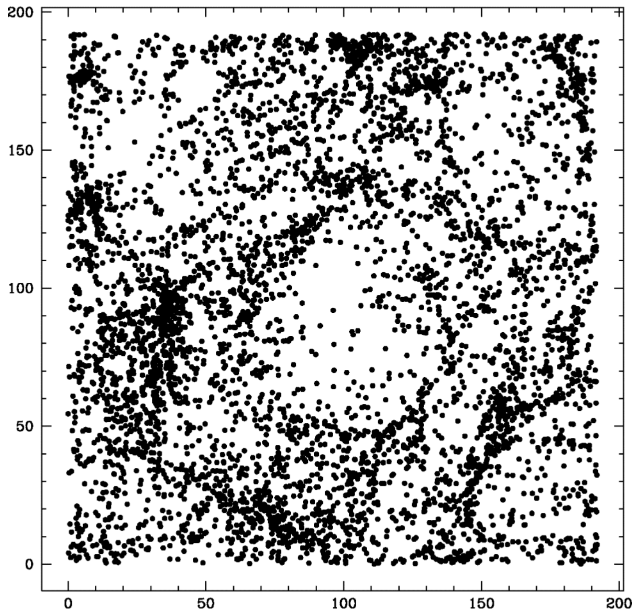
f_{red}(central)~0.3
f_{red}(sats)~0.7

χ^2_{red}=9.9/10
χ^2_{blue}=5.8/10

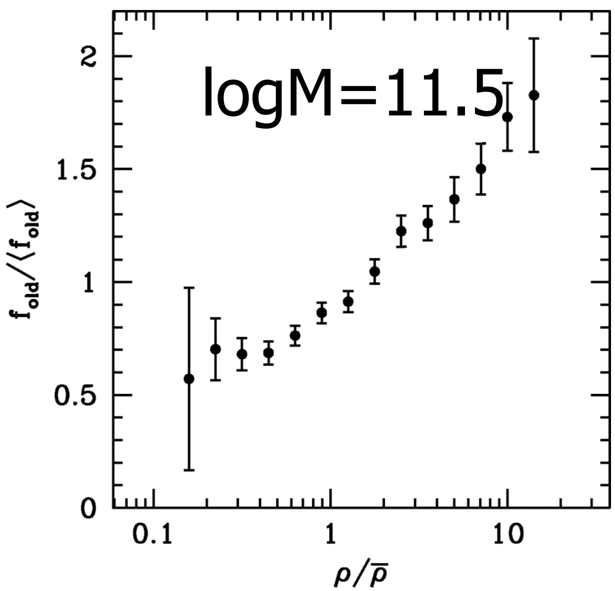
red gals deviate from negative binomial, but HOD prediction is right on.



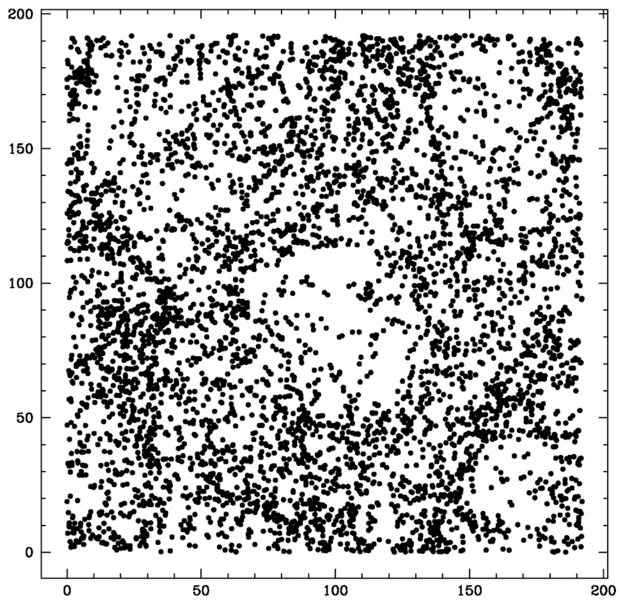
Red galaxies: Implications for halo assembly bias



old halos

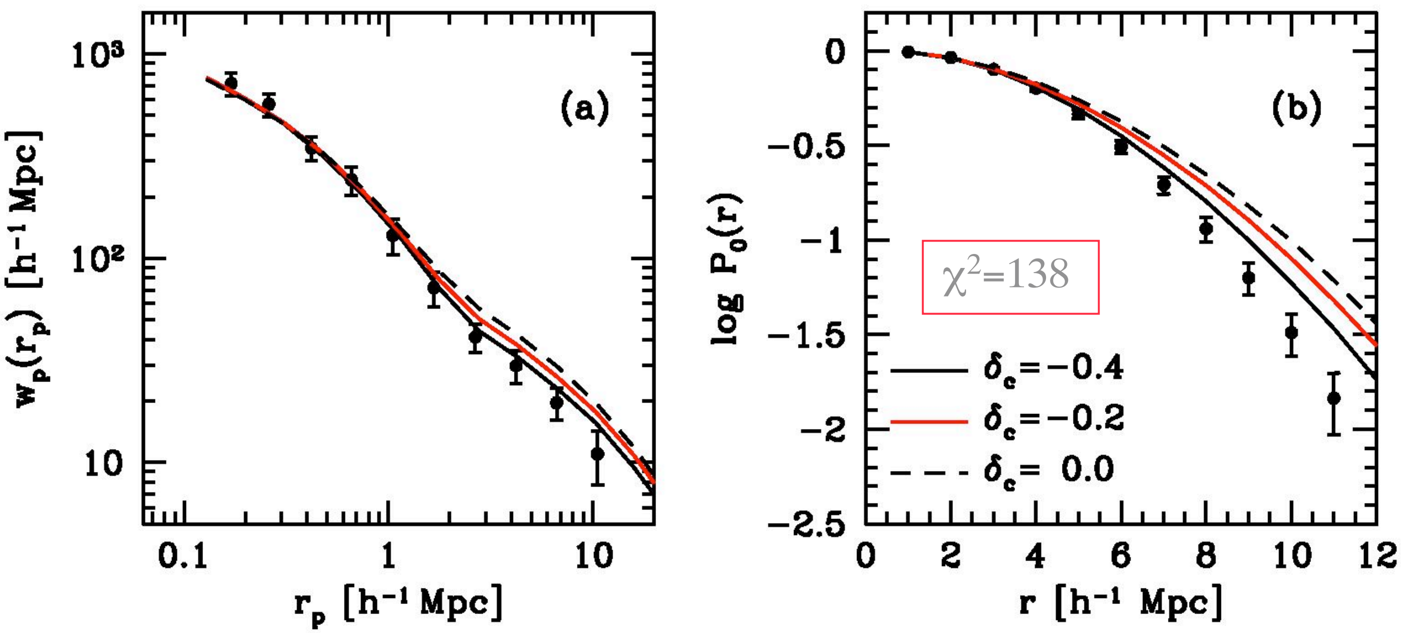


how "old fraction" depends on local environment at **fixed halo mass**



young halos

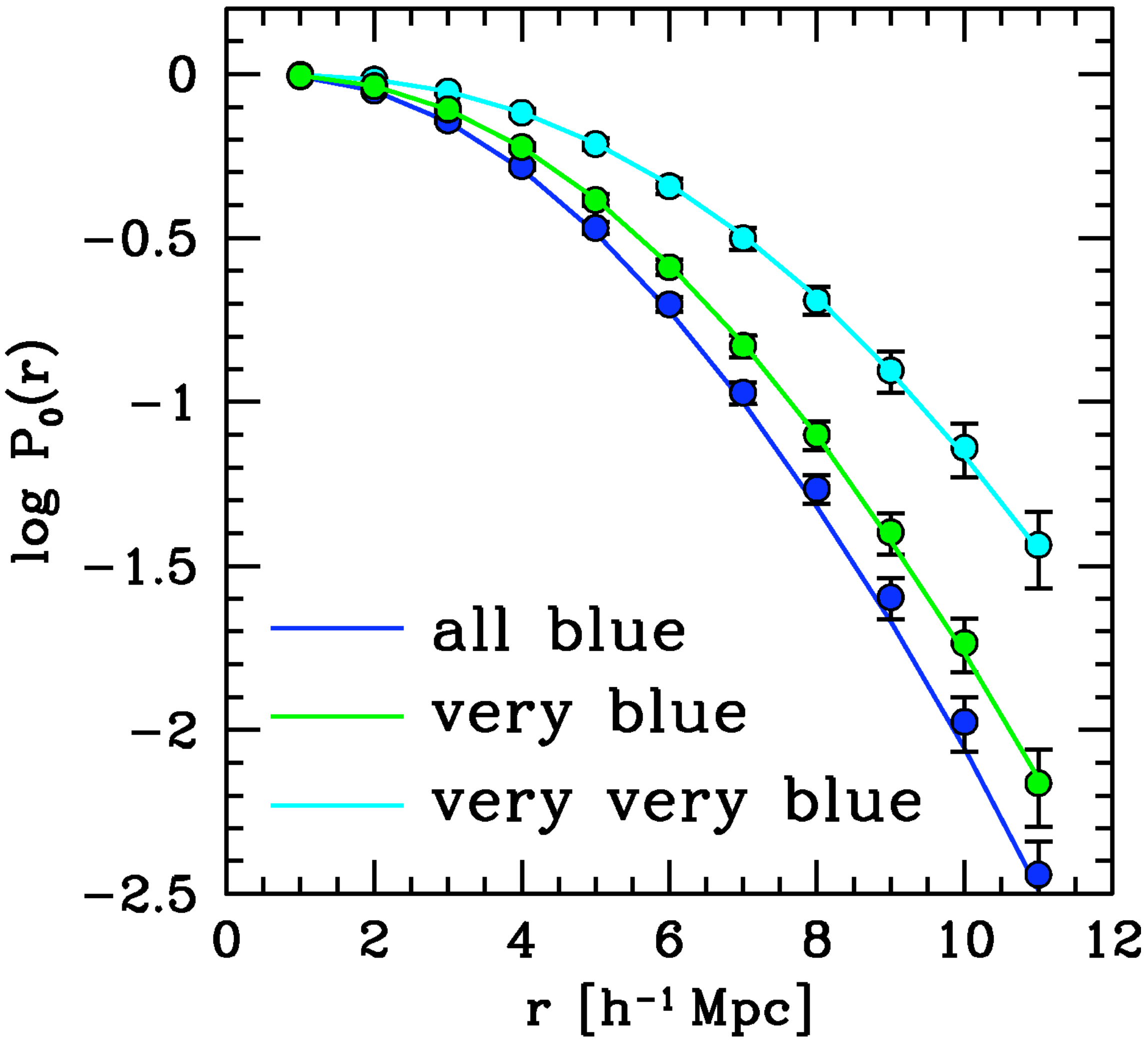
Red galaxies:
Implications for galaxy assembly bias



- Models where red $f_{\mathrm{red,cen}}$ decreases at $\delta<\delta_c$.
- In Croton et al (2005) semi-analytical model, $f_{\mathrm{red,cen}}$ ~1/10 at δ_c ~-0.2. (red line)

- $f_{\mathrm{red,cen}}$ must be nearly constant across all environments (at fixed halo mass).
- SA mechanism (or its trigger) for halting star formation is wrong.

Blue Galaxies: Implications for assembly bias



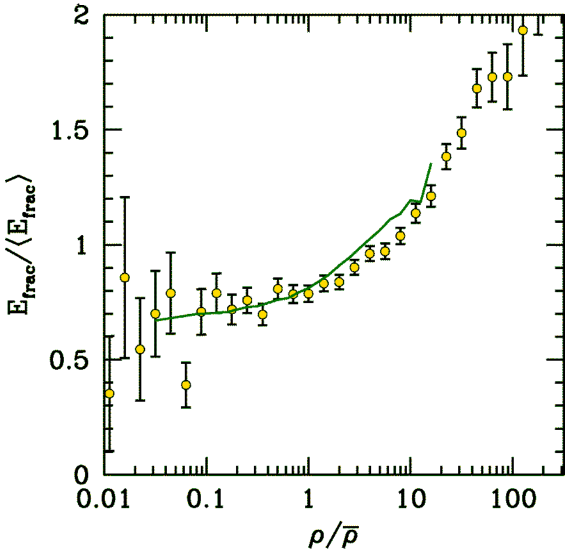
Points: DR4, all blue galaxies (blue points) 0.15 mags bluer (green), 0.3 mags bluer (cyan).

Lines: random sample of blue mocks. (Random sample of halos that host blue galaxies.)

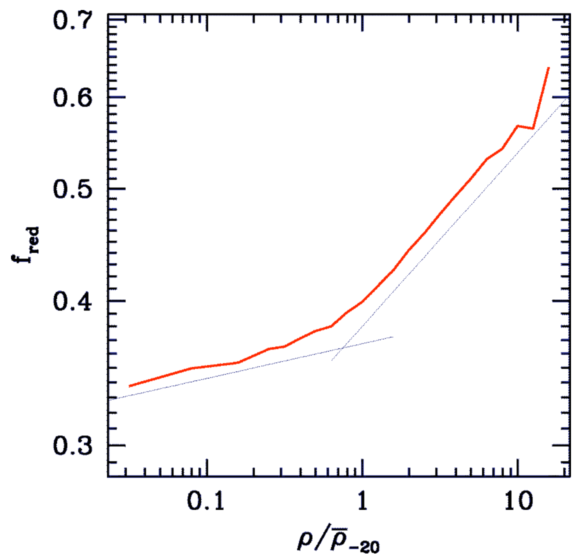
Tinker & Conroy, in prep.

Density-Morphology Redux

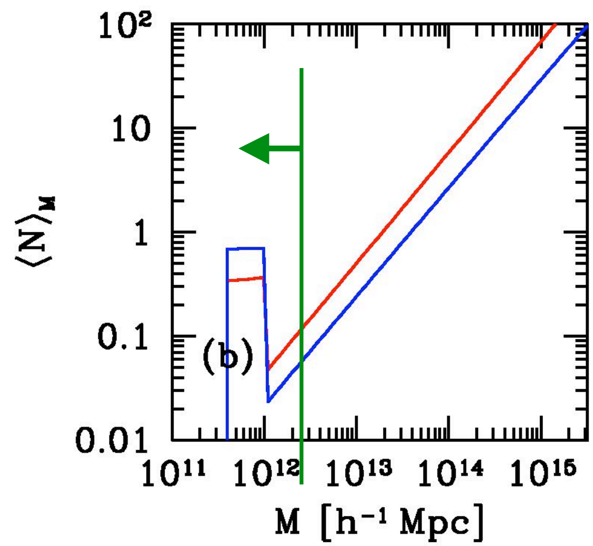
Re-analysis of Park et al data, with HOD comparison.



Denisty-morphology from Park et al (SDSS DR4)



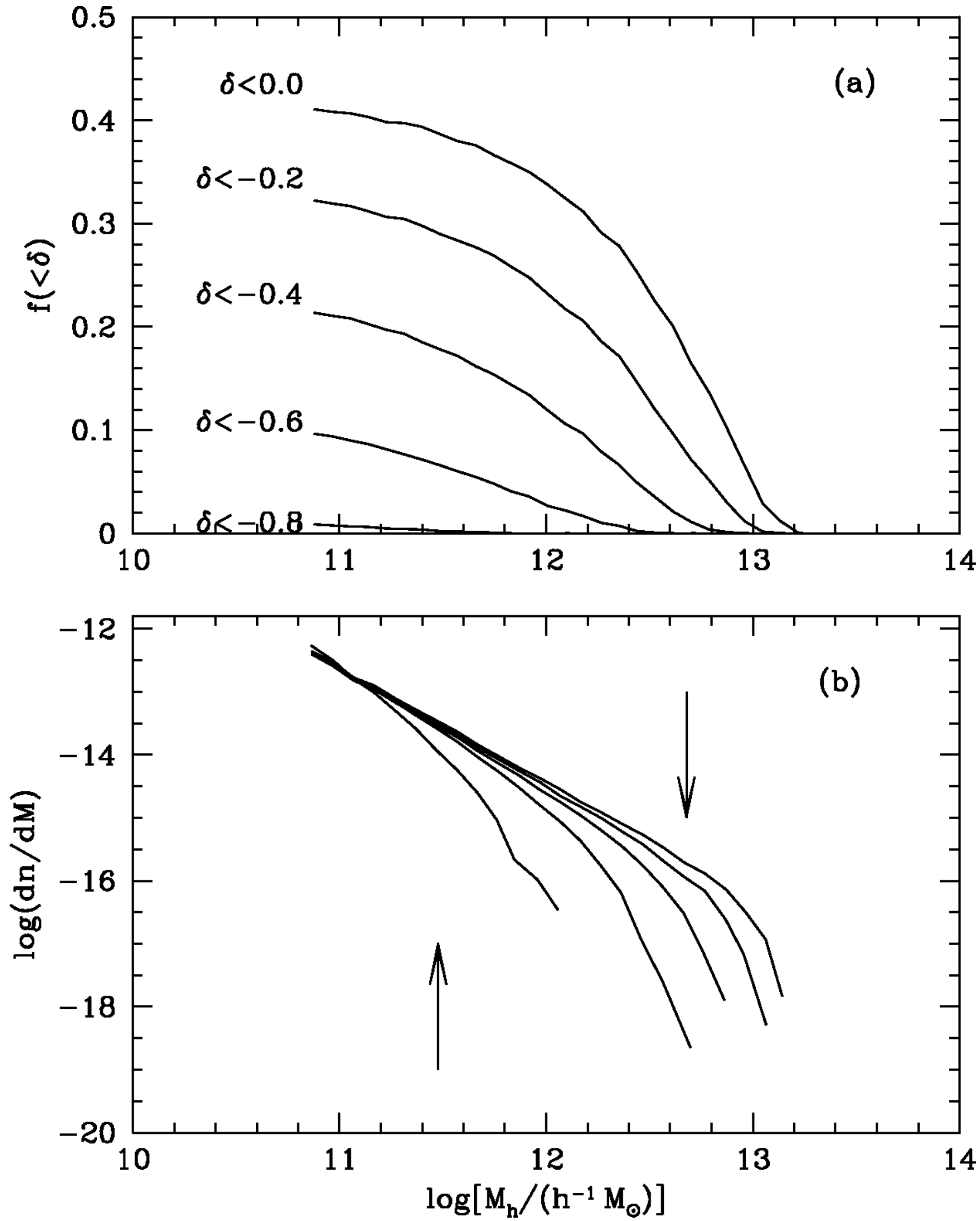
HOD prediction for the density-red fraction relation. Change in mass function with δ creates correlation with density.



HOD assumption is, at low-δ, there is no more density-morphology b/c only $M<10^{12}$ halos exist there. Causes break.

Tinker & Conroy, in prep.

Conditional Mass Function

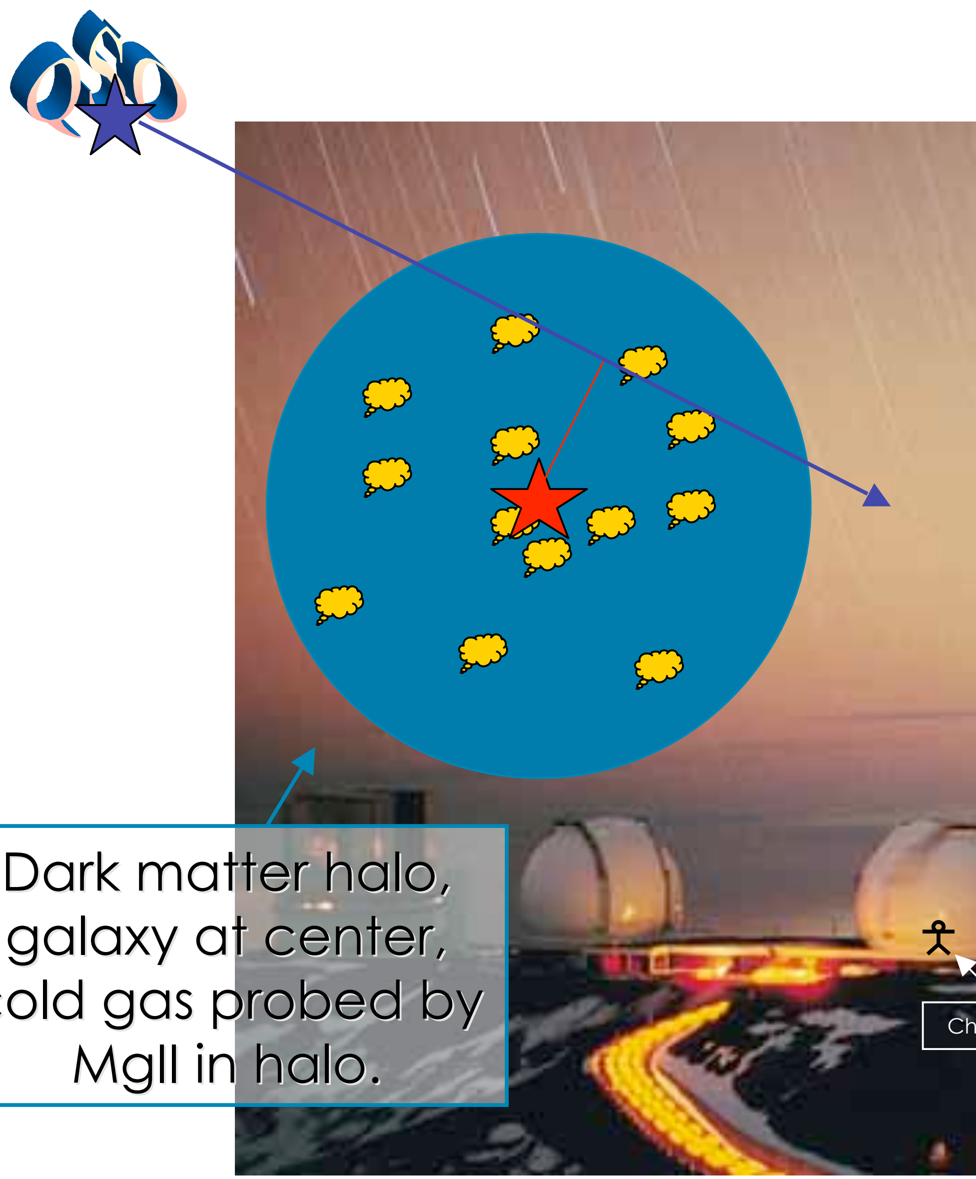


- The mass function changes with local density.
- Top-heavy at high densities.
- Low-mass preferentially in low densities.
- Correlations with environment come from changing mass function

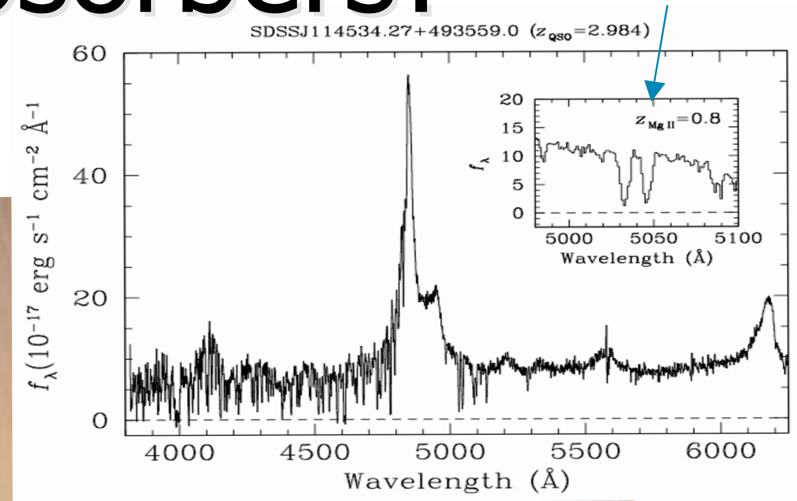
What makes a galaxy? HALO MASS

- Luminosity
- (over four magnitudes in r-band)
- Color
- (even for extremes of the color distribution)
- Morphology
- (mergers don't cause morph. transformation of field galaxies[?])
- Star formation rate? AGN activity?
- (need halo+environment decomposition)

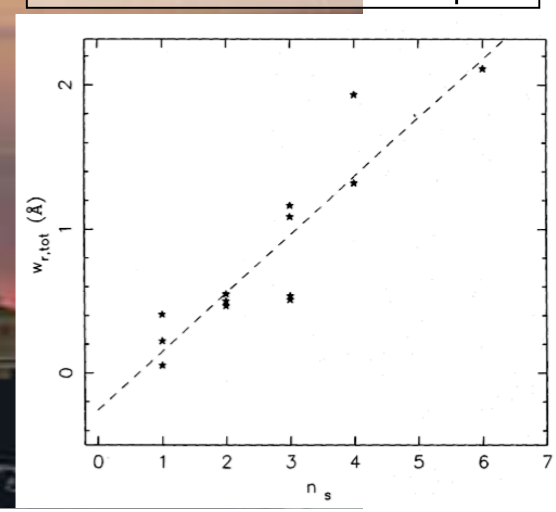
What are MgII Absorbers?



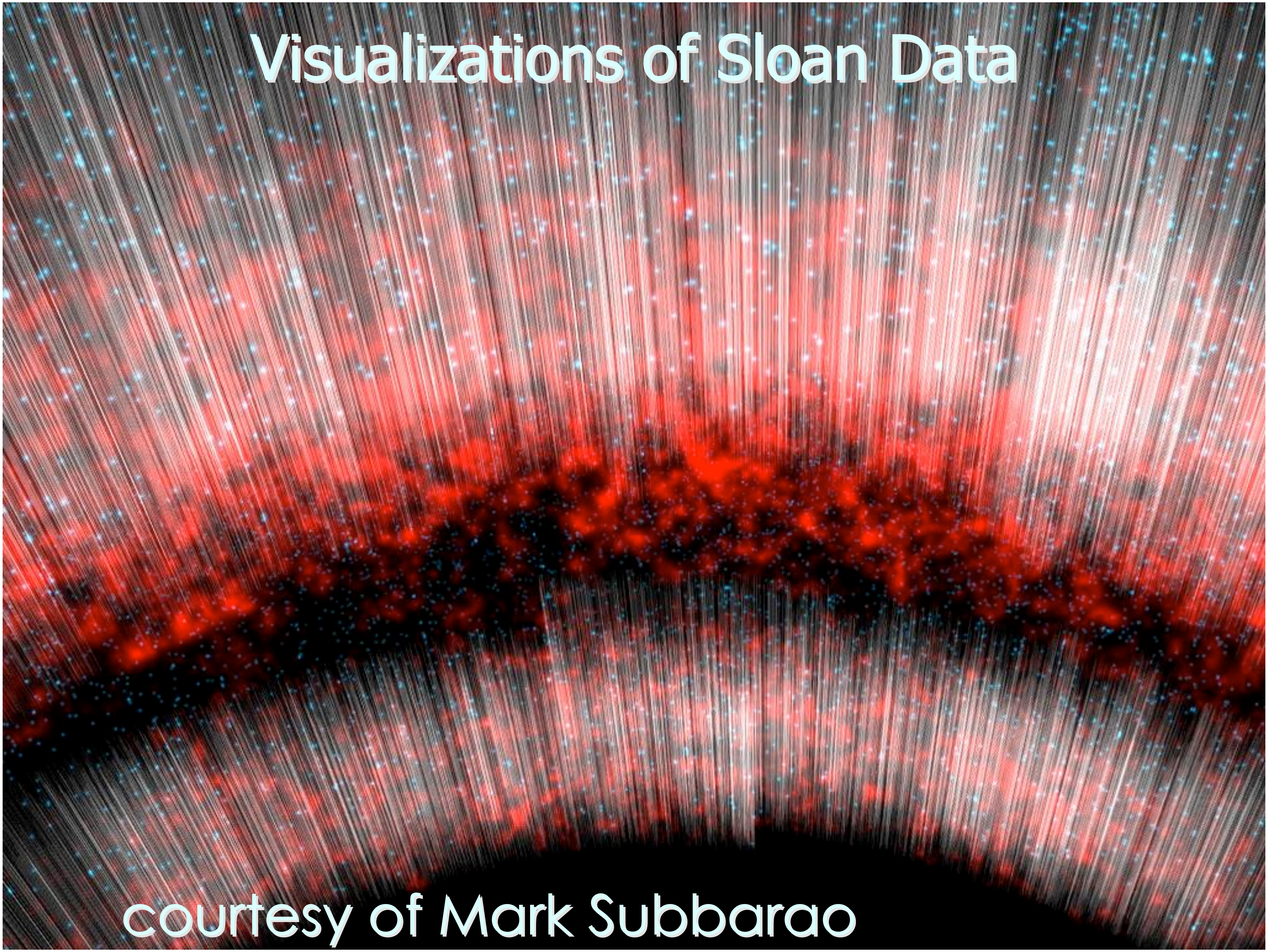
2796, 2803



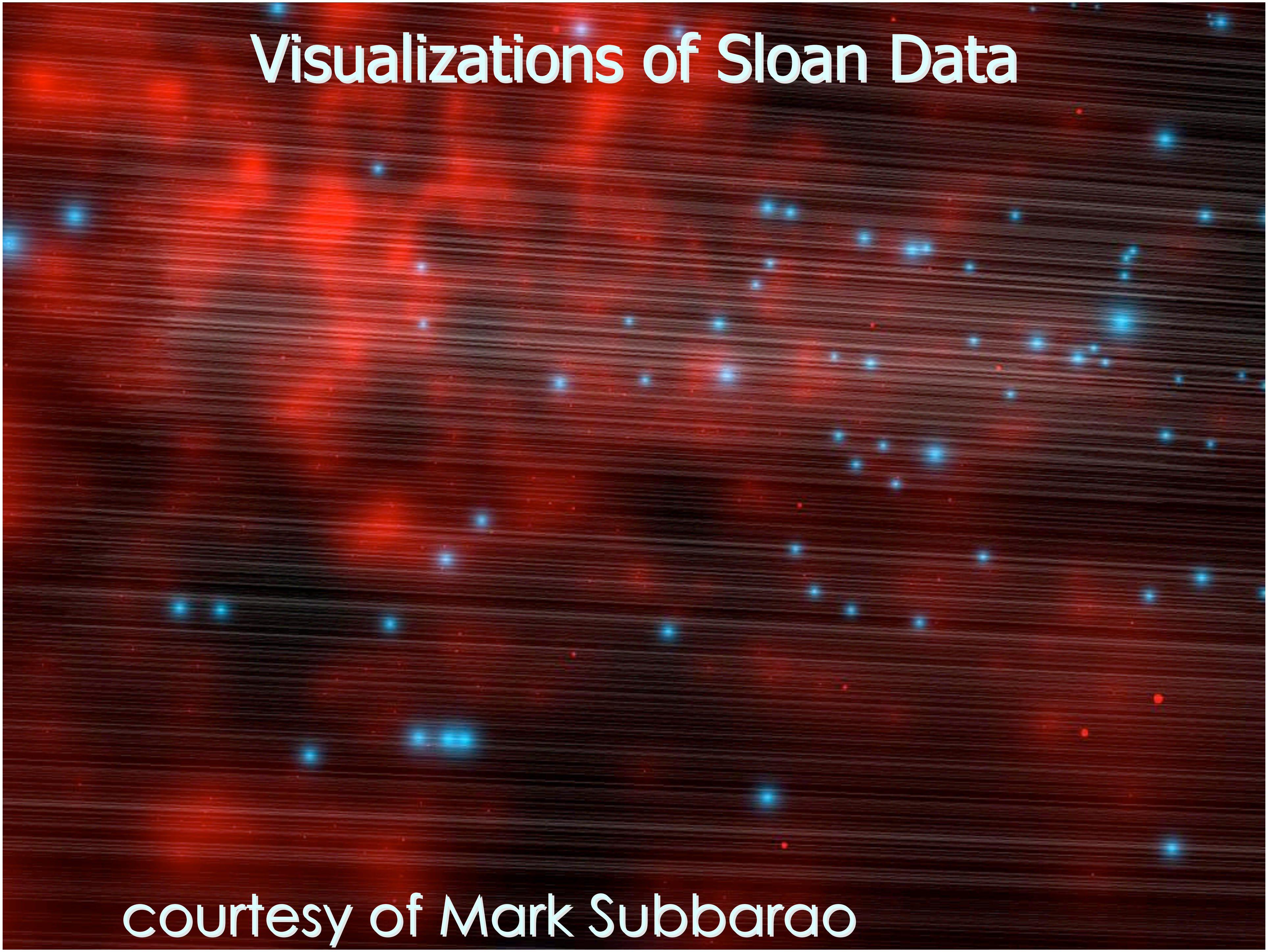
High-res analysis shows $W_r \sim N_{comp}$



Dark matter halo, galaxy at center, cold gas probed by MgII in halo.


Visualizations of Sloan Data
courtesy of Mark Subbarao

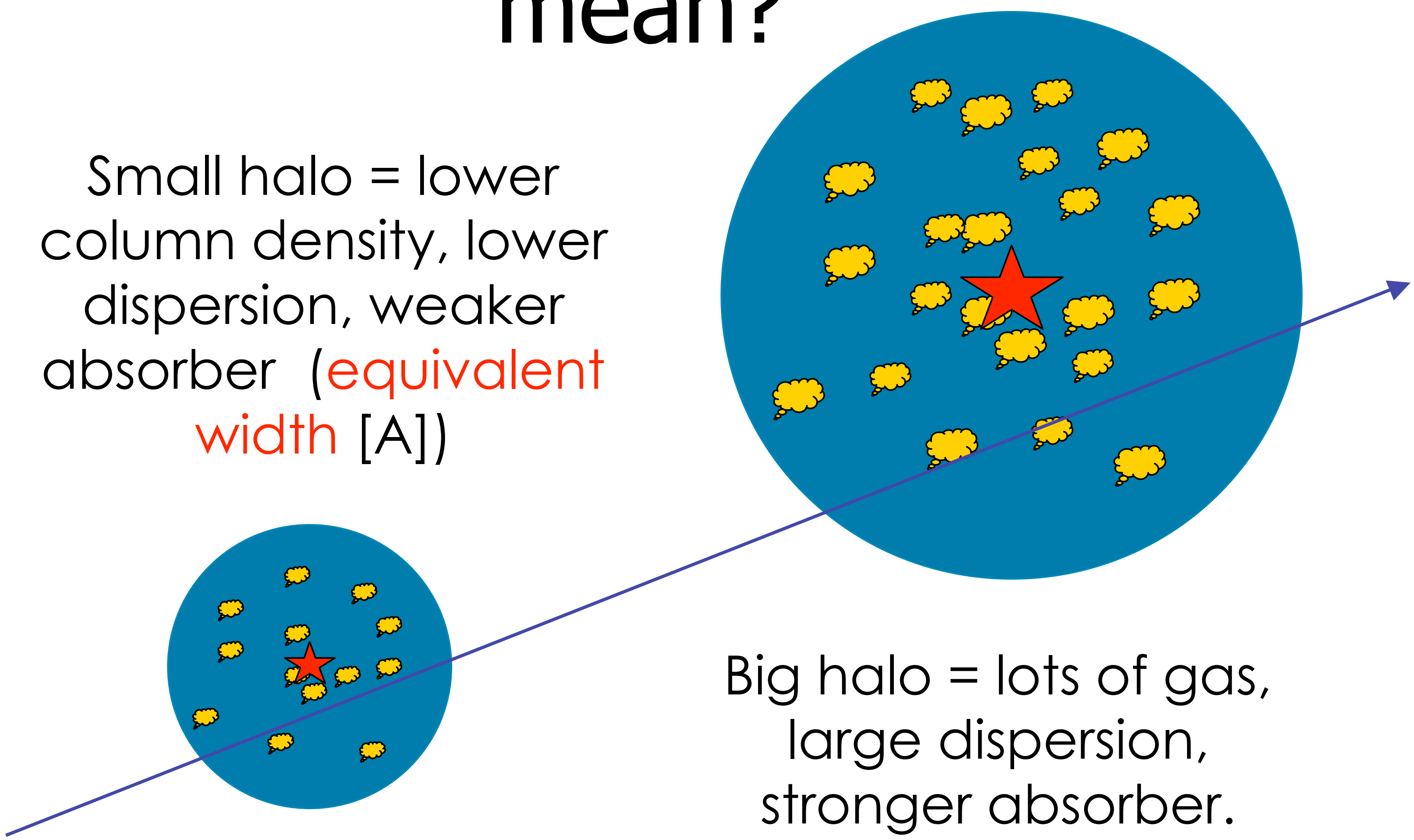
Visualizations of Sloan Data



courtesy of Mark Subbarao

What do (we think) they mean?

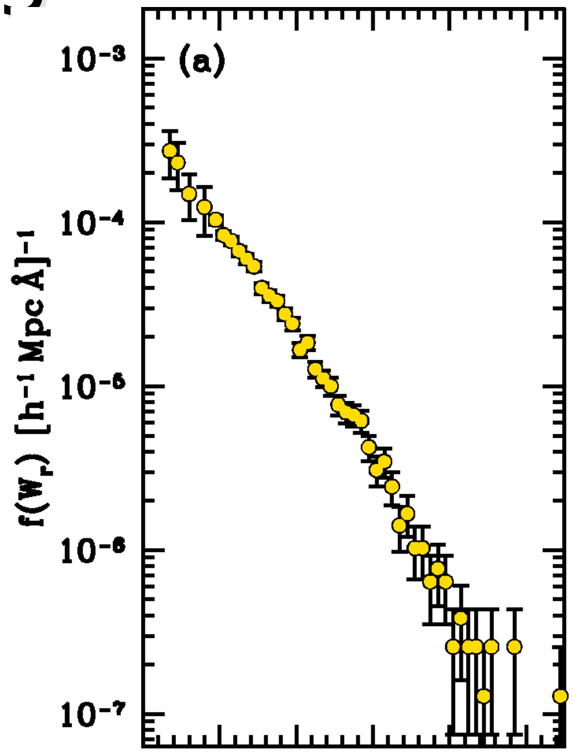
Small halo = lower column density, lower dispersion, weaker absorber (equivalent width [A])

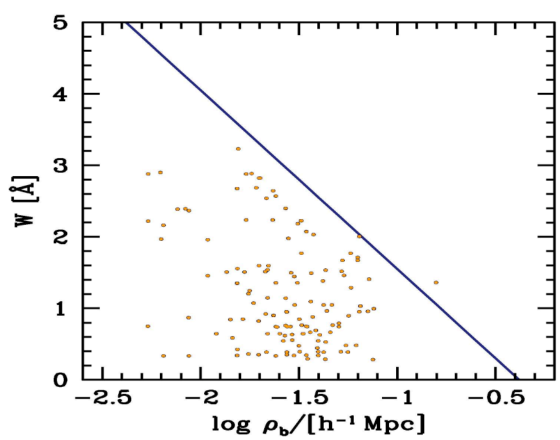


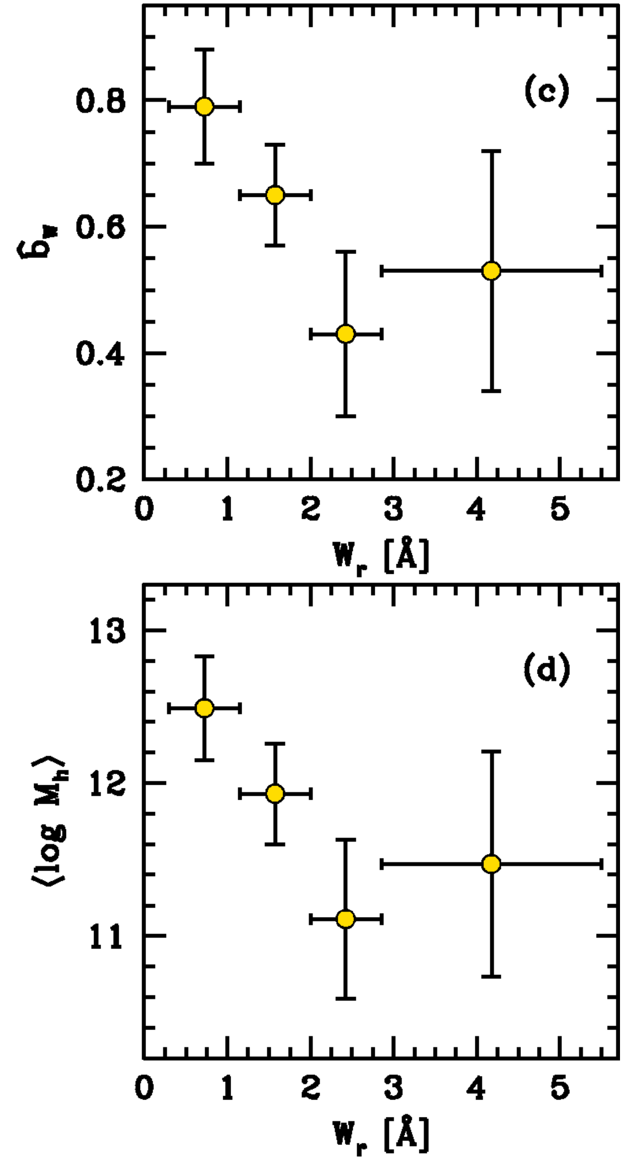
Big halo = lots of gas, large dispersion, stronger absorber.

Statistics of MgII Systems

- Frequency function: $d^2N/(dLdW)$ from Prochter etal (2006).
- Bias: Bouche et al (2006) measure bias relative to LRGs as a function of W: anti-correlation!
- Distribution of impact parameters: "strong absorbers preferentially at low impact parameters."





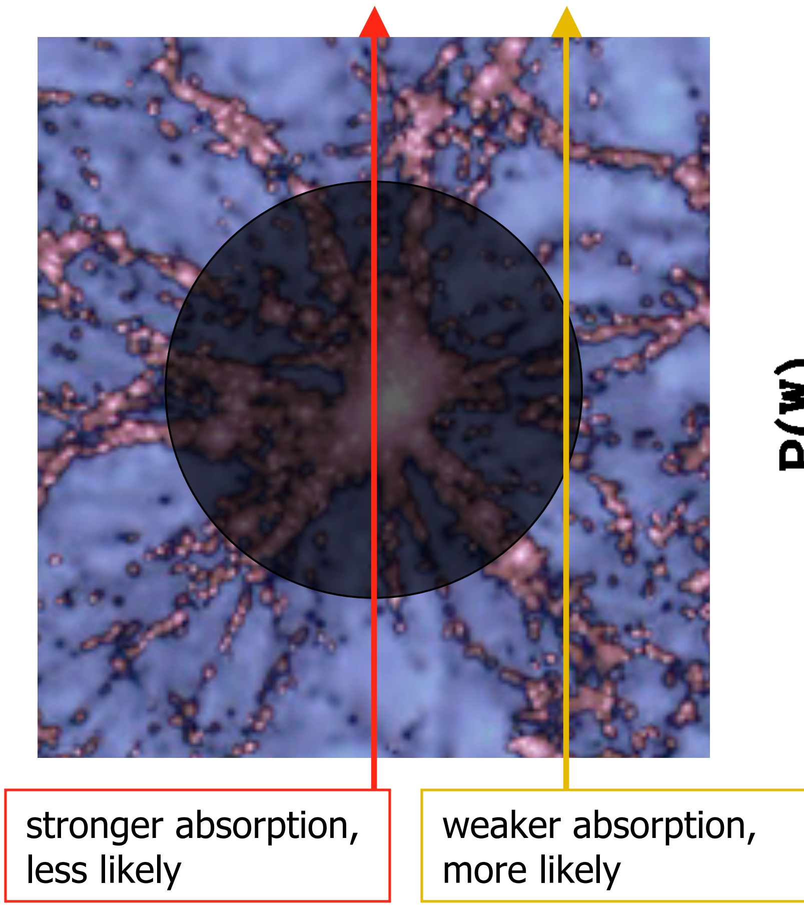


Why are they important?

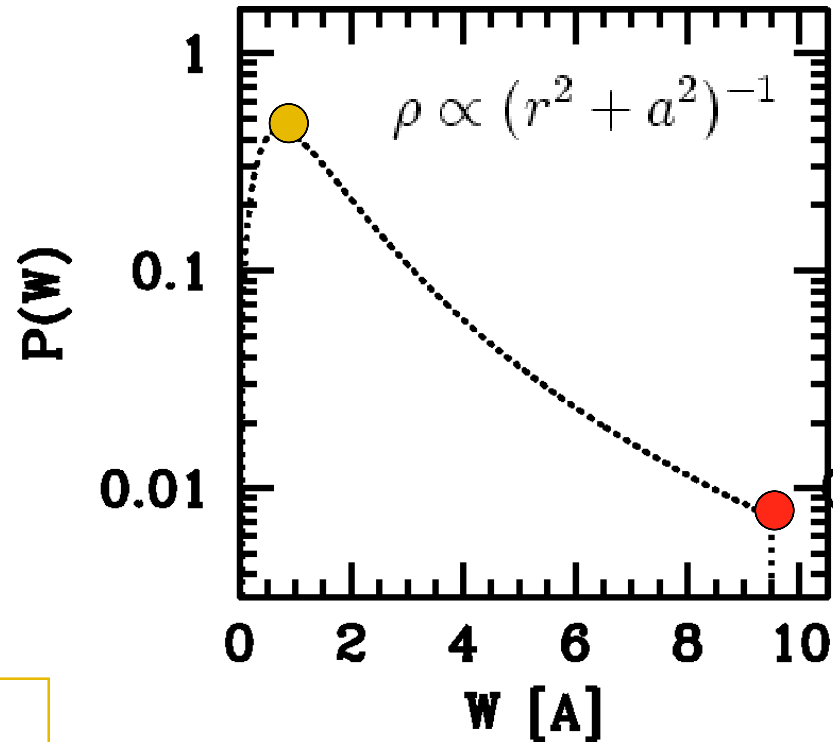
- This gas dominates the total baryon budget of the universe.
- Direct window into high-z galaxy formation.

- Are they ubiquitous, or a special subset of dark matter halos?
- What is the distribution of halo masses for the gas?
- Is a non-gravitational process required for the anti-correlation?

Halo-Based Model: $P(W_r|M)$



$$\boxed{P(s) \propto s}$$

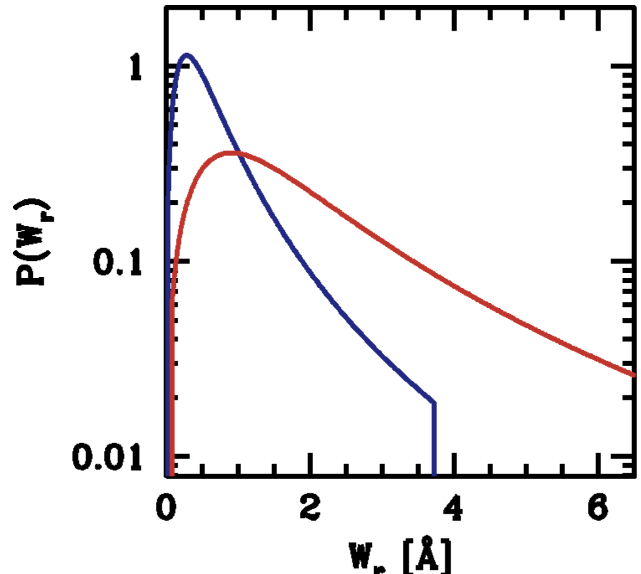


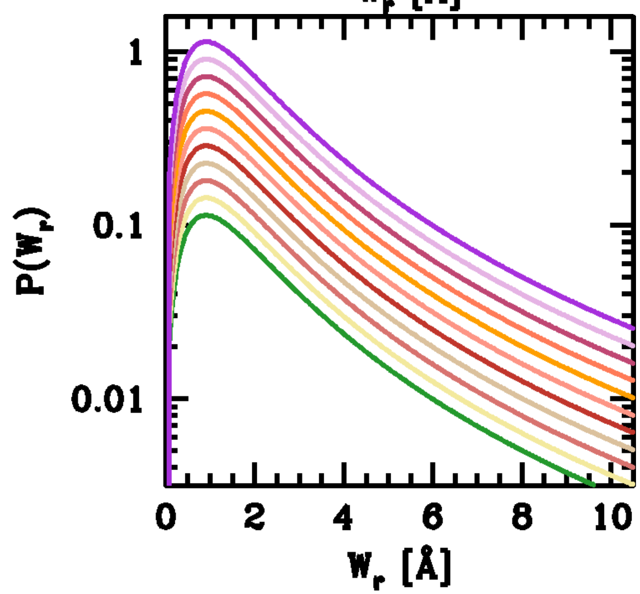
Halo-Based Model: $P(W_r|M)$

FREE PARAMETERS:

- $A_W(M)$ - absorption/g-cm^2.
  cold gas fraction
  cold cloud properties
  natural scaling - $W_r \sim M^{1/3}$

- $\kappa_g(M)$ - incidence of absorption.
  -covering factor - sightlines may not hit any cold gas
  -incidence of gaseous halos - what if MgII is a subset of halos?
- Model 1: Vary smoothly with halo mass.

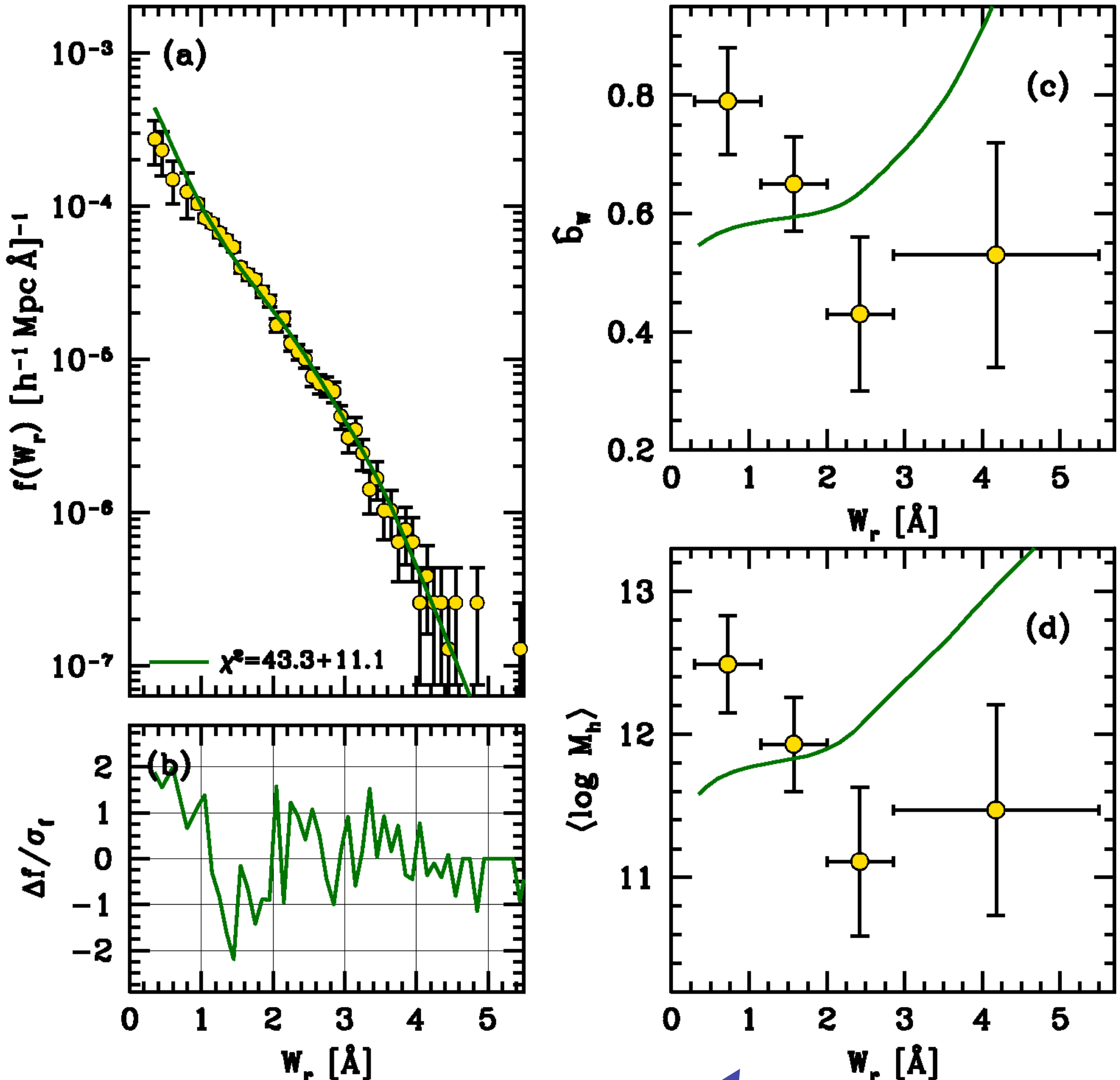




Results

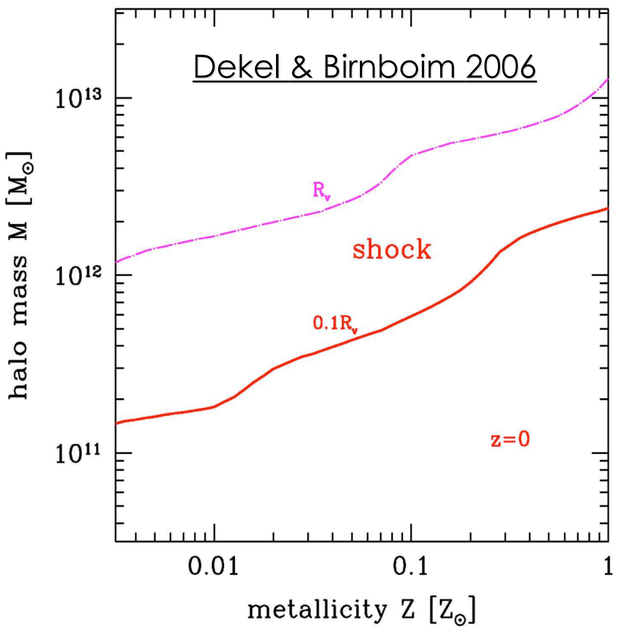
-Model: Gas content varies smoothly as a function of halo mass. "Classical picture".

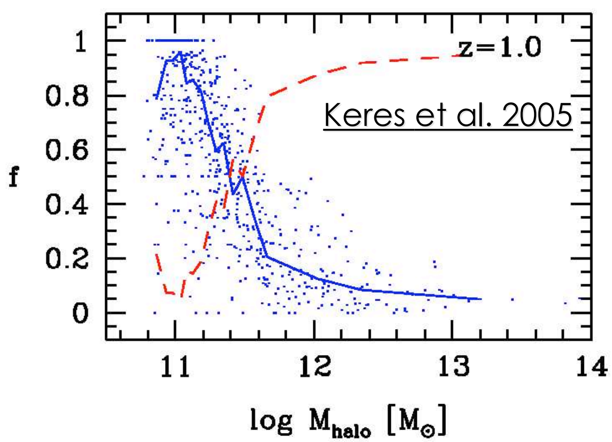
- Seven free parameters.



Mass points are estimated by Bouche et al from b(w). Not used in model fitting.

Cold vs. Hot Halo Gas





Low Mass = Cold Gas ($T \sim 10^4$ K)

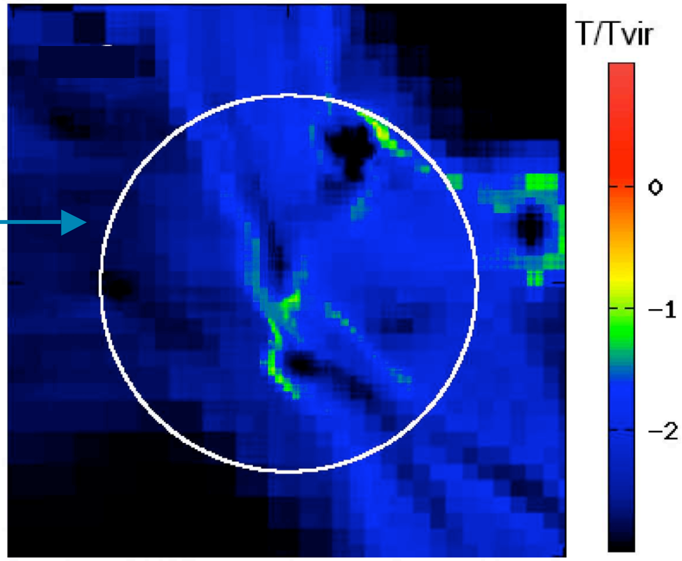
High Mass = Hot Gas ($T > 10^6$ K) no MgII

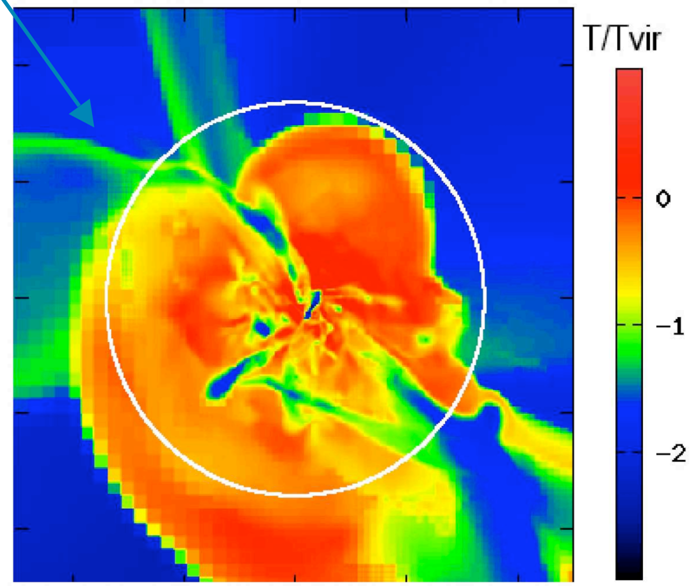
Transition mass scale: shock heating occurs as an inside-out process.

Simulations predict that this process occurs over 1-2 dex in halo mass.

In the hot mode, some cold gas still exists.

Dekel & Birnboim 2006





Results

-"Transiton" Model: 8 free parameters.

-transition mass

-transition width

-cold fraction

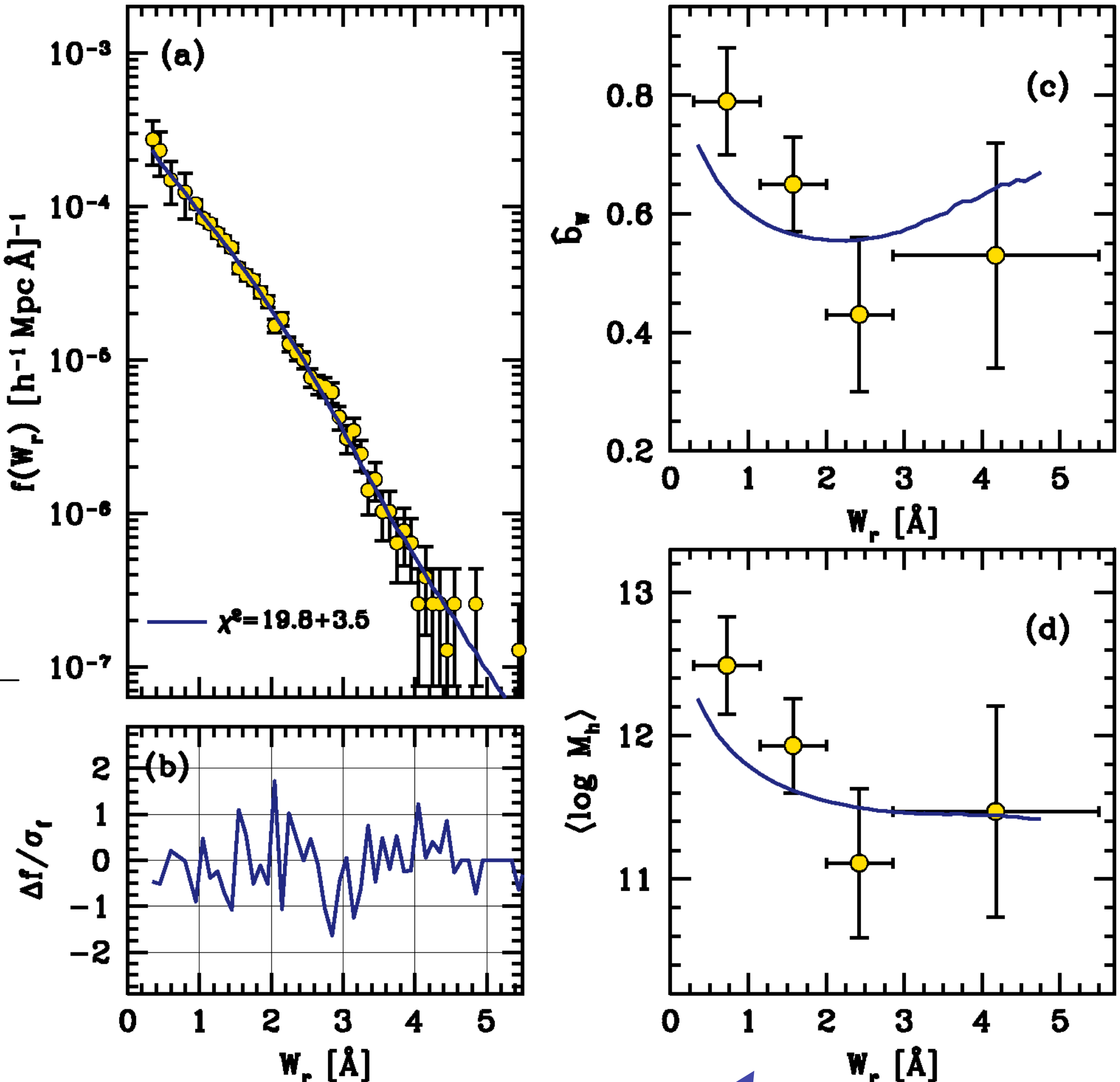
-f_{cold} = 6%

-$10^{11.5}$ transition mass

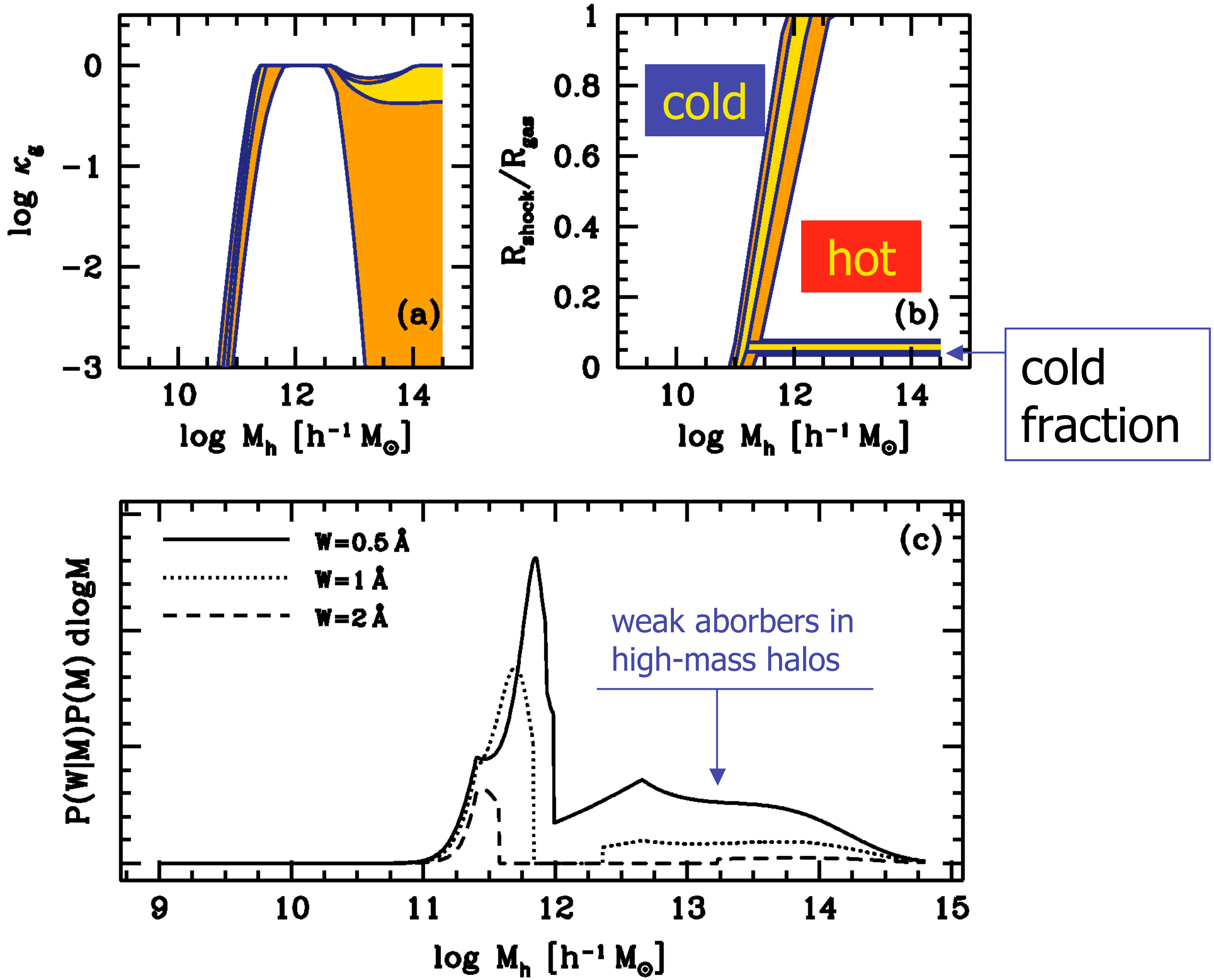
-transition width of 1.0 dex in mass.

$$R_{shock} = R_0 + \alpha_{shock} \log(M/10^{12})$$

$$f_{cold} \rightarrow R \leq R_{shock}$$



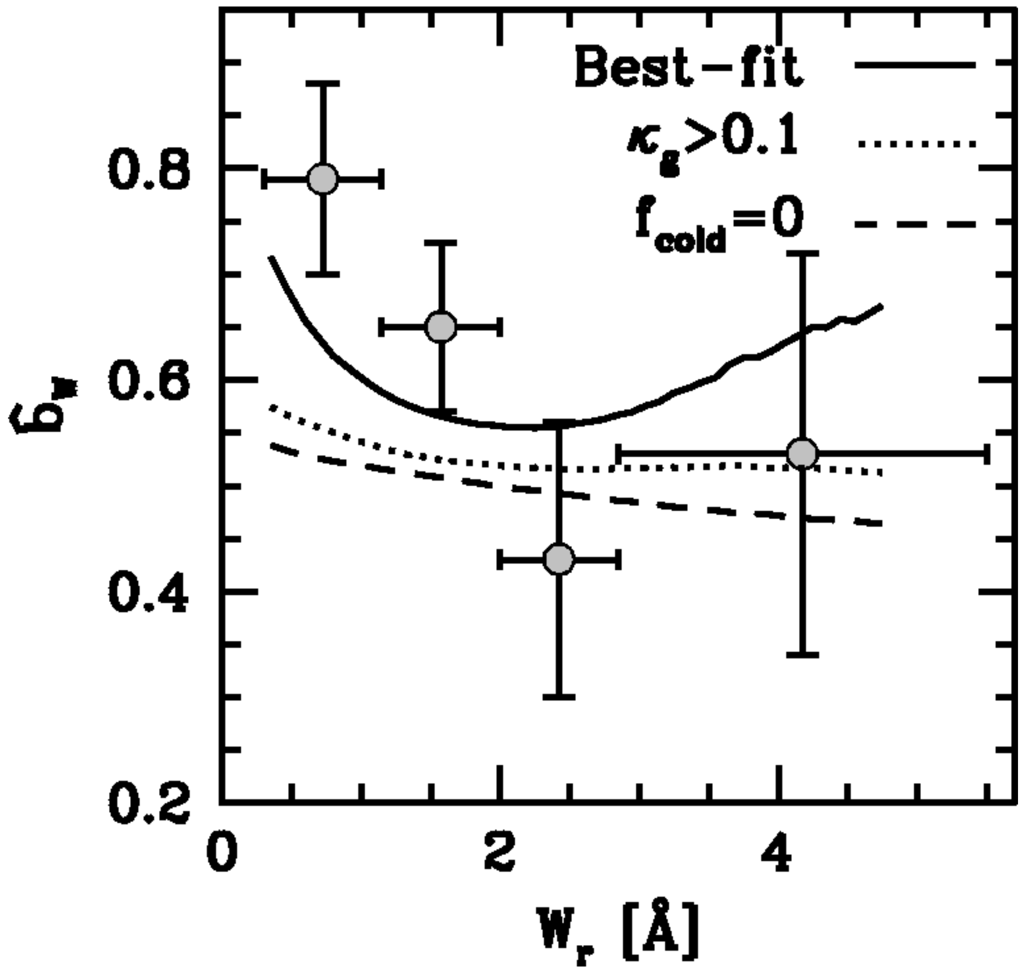
Mass points are estimated by Bouche et al from b(w). Not used in model fitting.



log κ_g
0
−1
−2
−3
10
12
14
log M_h [$h^{-1} M_\odot$]
(a)
R_{shock}/R_{gas}
1
0.8
0.6
0.4
0.2
0
cold
hot
(b)
cold fraction
P(W|M)P(M) dlogM
W=0.5 Å
W=1 Å
W=2 Å
(c)
weak aborbers in
high-mass halos
9
10
11
12
13
14
15
log M_h [$h^{-1} M_\odot$]

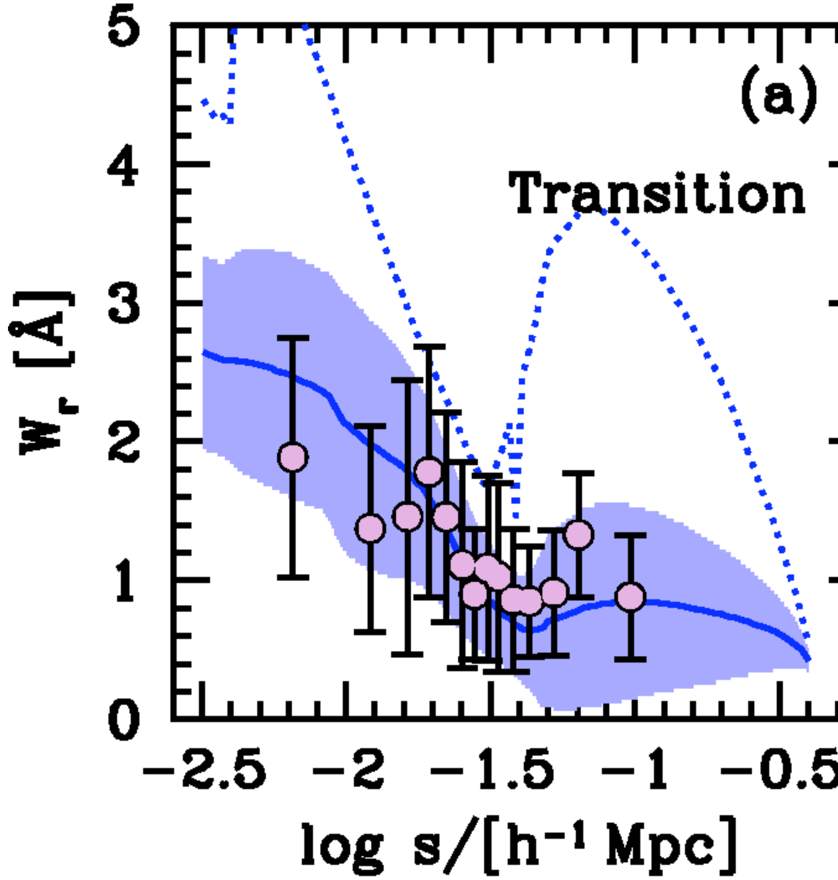
Wherefore the anti-correlation?

- Starbursts yield strong absorbers in low-mass halos.
- Not necessary: $10^{11}\ M_{sol}/h \sim 2$ Ang.
- BUT, anti-correlation comes from weak systems in high-mass halos.
- One-halo term in LRG-W_r x-corr proves massive galaxies host weak absorbers.



Impact Parameters

- Points+bars are mean and dispersion for every ten data points.
- Line+shade are mean and dispersion of model (note: these are model predictions).
- Dotted line = 99% upper bound on $P(W|\rho_b)$.
- NB! - take these data with grain of salt: incomplete at low ρ_b and possibly biased. Use for consistency check.



Absorber Summary

- Can model with absorber statistics with halo-based model, and constrain the parameters.

- High κ_g means absorbers are representative of all galaxies, $M>10^{11}$.

- Bias anti-correlation can only be fit with a hot/cold transition.

- Starbursts/superwinds <u>do not</u> create an anti-correlation.

- Combine galaxy HOD with absorber occupation to make predictions for absorber-galaxy connection.