An Empirical Approach to Understand Star Formation at High Redshifts

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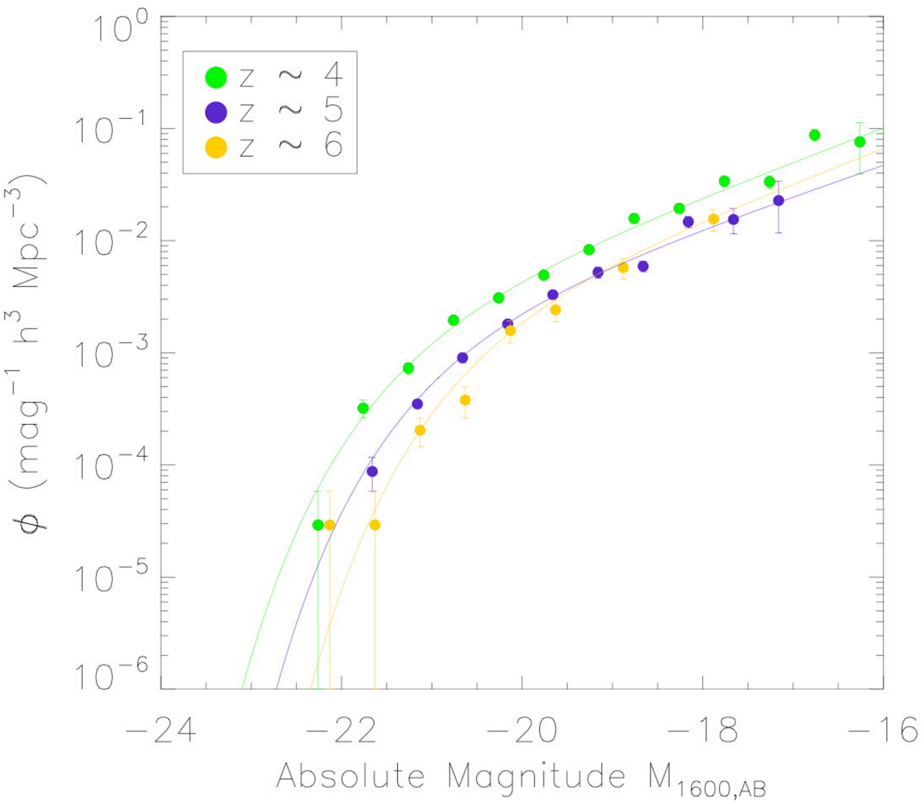
The Evolution of UV Luminosity Function

- Observational constraints of UV luminosity function have improved significantly in recent years (e.g., Giavalisco et al. 2004, Ouchi et al. 2004, Sawicki & Thompson 2006, Bouwens et al. 2007)
- M* brightens with cosmic time, normalization changes little, faint-end slope stays constant (from z~6 to 3)
- What drives the evolution of LF w/ redshifts?

LBG LF measures from Bouwens et al. (2007)

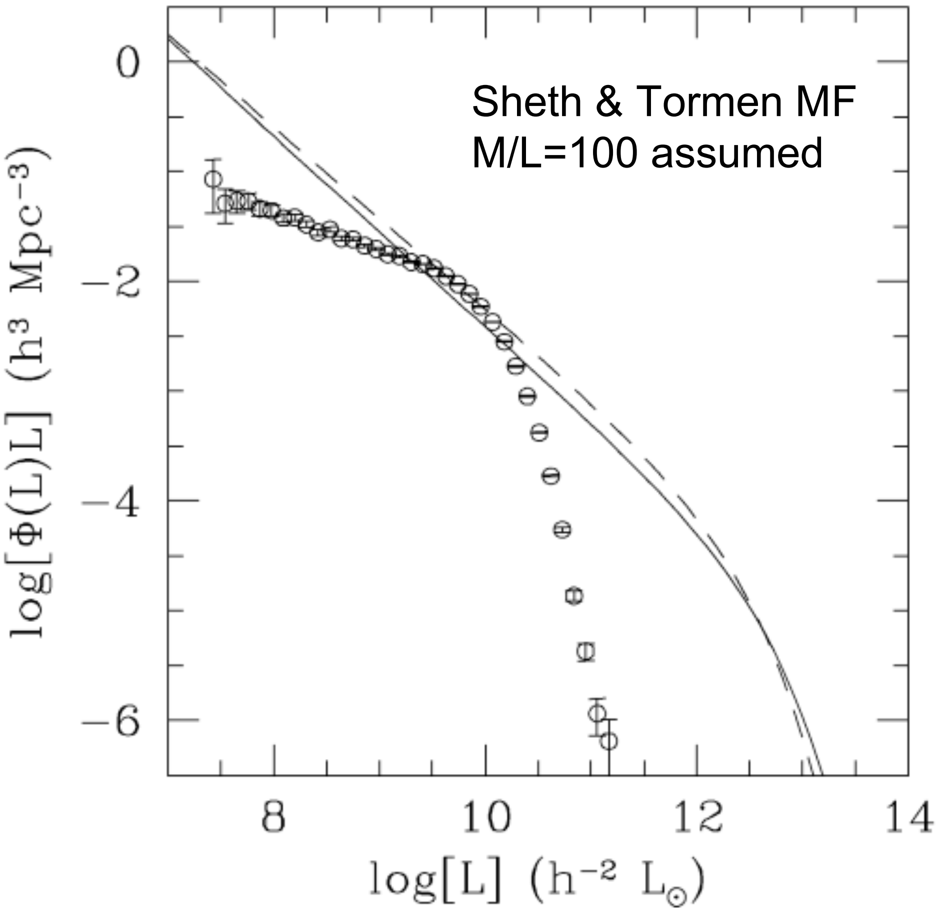


Luminosity Function vs. Mass Function

- **Galaxy LF**: number of galaxies per unit volume per luminosity (or magnitude) -- number counts of galaxies in luminosity space
- **Halo MF**: number of halos per unit volume per mass M

- A suitable L_{UV}-M relation would map one into the other at a given cosmic time

- **Evolution of LF with redshift = Evolution of halo MF (cosmology) + Evolution of L_{UV}-M relation (astrophysics)**

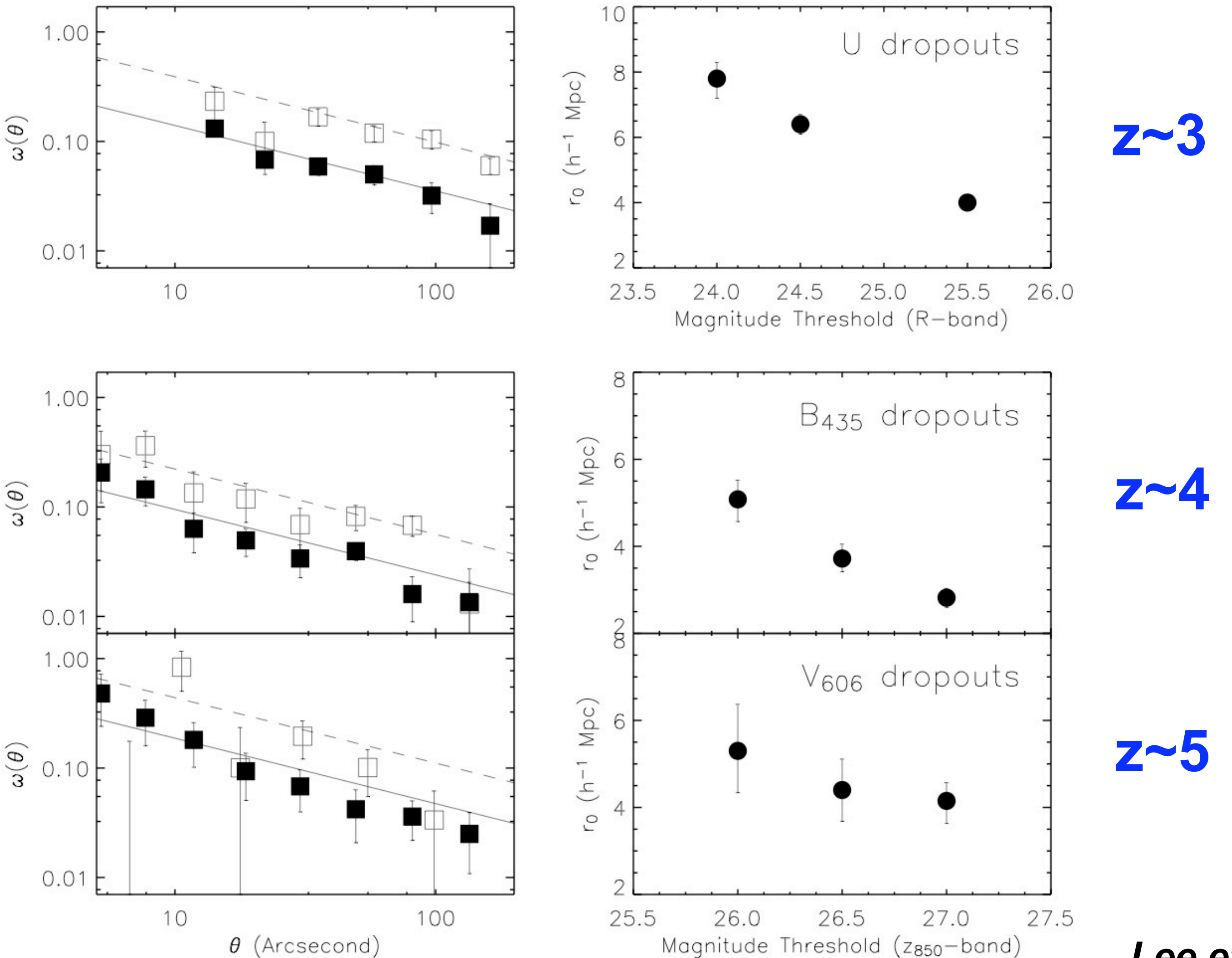


Yang et al. 2003, Monthly Notices

On the Clustering Front…

- Strong L_{UV}-dependence of LBG clustering suggests a correlation between halo mass and UV luminosity (e.g., Giavalisco & Dickinson 2001, Allen et al. 2005, Adelberger et al. 2005, Ouchi et al. 2005, Lee et al. 2006, Hilderbrandt et al. 2007)
- Stochasticity in gas accretion, other star formation processes, and random line of sight (w/ dust) imply scatter in the relation
- L_{UV}-M relation seems to evolve w/ redshift (Lee et al. 2006) - expected from simulations, and confirmed observationally
- Characterize the mean and variance of L_{UV}-M relation -> this should provide us the astrophysical component of LF evolution

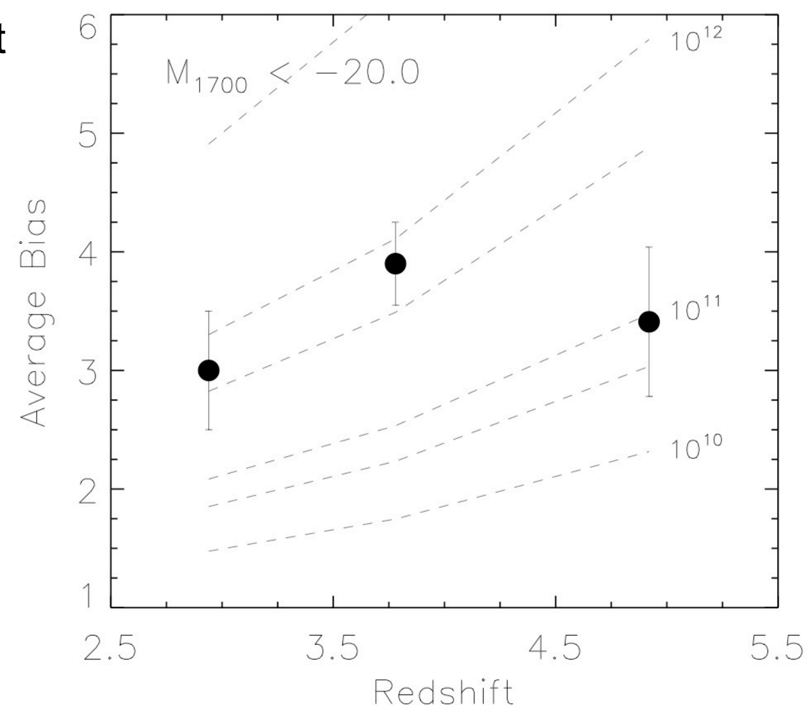
Luminosity-Dependent LBG Clustering



Lee et al. 2006

Evolution of L_{UV}-M_{halo} Relation

- Galaxies at higher redshifts put out more UV photons per halo mass than lower-z counterparts
- More centrally concentrated halos, sharper potential well
- More supplies of gas to form stars



Lee et al. 2006

Efficiency of LBGs in Marking Halo sites

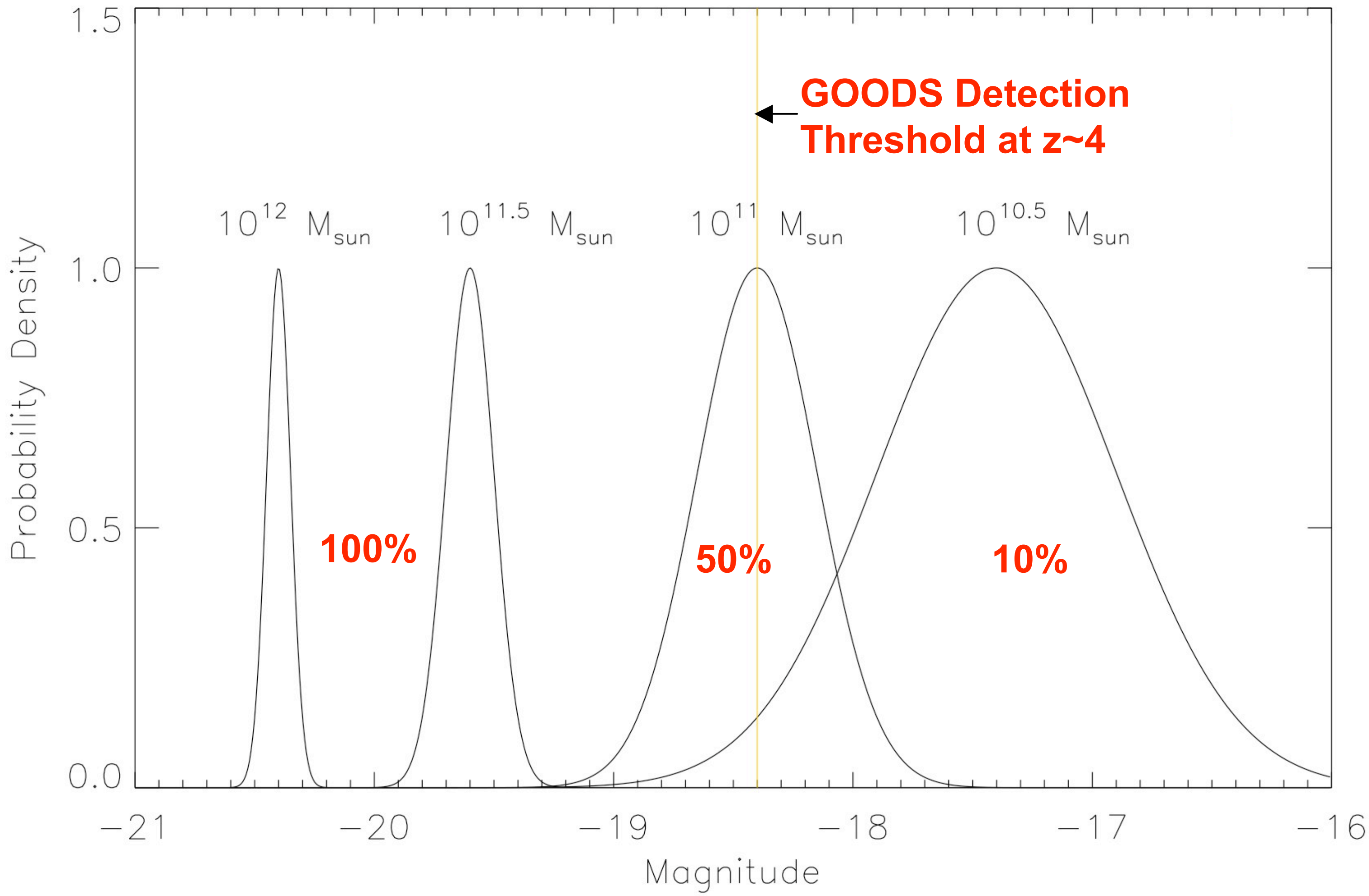
1) **Selection efficiency**: What fraction of general population at a given cosmic epoch is observed as Lyman Break Galaxies?

2) **Duty cycle of SF**: What fraction of galaxies are on at a given time?

3) **Halo occupation efficiency**: Probability of observing galaxy of luminosity L in a halo M. Some halos have visible galaxy, some others don't. The efficiency is mass-dependent

In reality, what we observe includes all of these effects… can we distinguish 2) and 1) from 3)?

Halo Occupation Efficiency



Conventional method to use Clustering: Halo Occupation Distribution (HOD)

- Halo mass function from Sheth & Tormen or Press & Schechter (number density of halos as a function of mass) - clustering as a function of mass M well understood

- Assume a form of HOD that gives the average number of galaxies for a given halo mass M -- $\langle N_g(M) \rangle$ usually modeled as:

$$\langle N_g(M) \rangle = 1 + (M/M_1)^{\alpha} \qquad (M \geq M_{\min})$$

$$\langle N_g(M) \rangle = (M/M_1)^{\alpha} \qquad (M \geq M_{\min})$$

Two free parameters

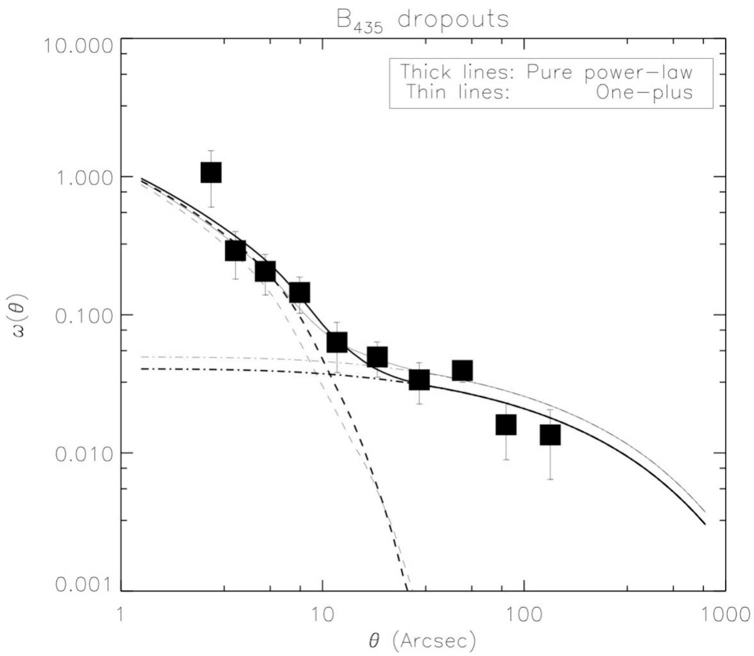
- Assume how galaxies are distributed spatially within the halo (NFW profile like DM), and their pair counts -- $\langle N_g(N_g-1) \rangle$

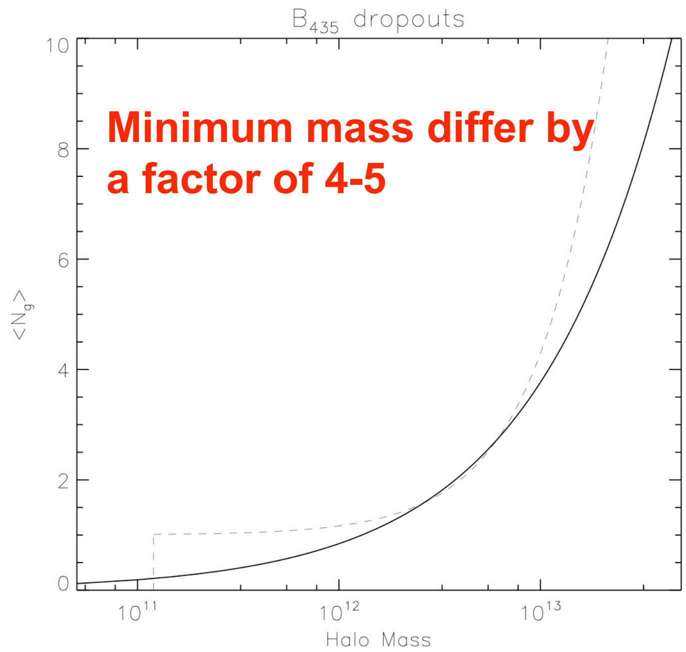
- Vary HOD parameters until it agrees with the observed $w(\theta)$ measures

- Obtain best-fit parameters for each luminosity subsample -> mean physical parameters for the galaxy sample ($M_{min,1,2,3}$, $\alpha_{1,2,3}$, $M_{1,1,2,3}$ for $L_{1,2,3}$)

Why is HOD model not enough at high-z?

- With unknown duty-cycle and halo occupation efficiency, the form of HOD is not known - degeneracy in the derived physical parameters (*e.g.*, minimum halo mass to host galaxy, average host halo mass, etc.)
- HOD model contains little information on the L_{UV}-M relation, constrains only in *cumulative* sense.





Lee et al. 2006

Luminosity Function as an extra constraint

- LF and CFs are derived from the same galaxies, and therefore same halos and subhalos, so taking the observed LF measures explicitly into the model….
  - keeps in check the type of degeneracy inherent in HOD model
  - Ties correlation function measures of different luminosity subsamples in a self-consistent way
  - No need to know the shape of HOD *a priori* - HOD comes naturally out of the best-fit L-M model
  - Can use the state-of-the-art simulations to correctly input DM halo/subhalo properties into the model

Modeling L_{UV}-M relation

- **Ingredients**: total halo/subhalo mass function, observed luminosity function, correlation functions for luminosity subsamples

- For a fixed halo mass M, we model the probability of a galaxy to have luminosity L as a lognormal distribution (simplest model w/ least # of parameters):

$$P(L,M)d\ln L = \frac{0 < dc < 1}{\sqrt{2\pi}\sigma(L/\breve{L}(M))}\exp[-(\ln L - \ln \breve{L}(M))/2\sigma^2]d\ln L$$

- Total Halo Occupation Efficiency (M)= $\int_{Lthresh} P(L,M)d\ln L$

- Peak luminosity is a smoothly rising function (more massive halos are likely to have more gas accretion) -- double power-law like

- Fractional scatter σ is a declining function of mass (halo occupation efficiency is lower for fainter galaxies)

Modeling L_{UV}-M relation (continued)

- The probability density of finding a galaxy of luminosity L in a halo/subhalo M is:

$$\pi(L,M)\,d\ln L\,d\ln M = \frac{dn_T}{d\ln M} P(\ln L,\ln M)\,\delta(\ln L - \ln \breve{L}(M))\,d\ln L\,d\ln M$$

- <u>**Luminosity Function**</u>

Total mass function

$$\phi(M_{1700}) = \frac{\ln 10}{2.5}\int d\ln M\,\frac{dn_T}{d\ln M} P(\ln L, M)$$

- <u>**HOD $\langle N_g(M)\rangle$**</u> **for a sample with luminosity threshold L_0**

Number of subhalo of mass m In a parent halo M

$$\langle N_h(M)\rangle_{L\geq L_0} = \int_{\ln L_0}^{\infty} d\ln L\; P(\ln L, M)$$

$$\langle N_{sh}(M)\rangle_{L\geq L_0} = \int_{\ln L_0}^{\infty} d\ln L \int_{m}^{fM} dm\, P(\ln L, M) N(m\,|\,M)$$

$$\langle N_g(M)\rangle_{L\geq L_0} = \langle N_h(M)\rangle_{L\geq L_0} + \langle N_{sh}(M)\rangle_{L\geq L_0}$$

- <u>**Correlation Function w(θ)**</u> **for luminosity threshold L_0**

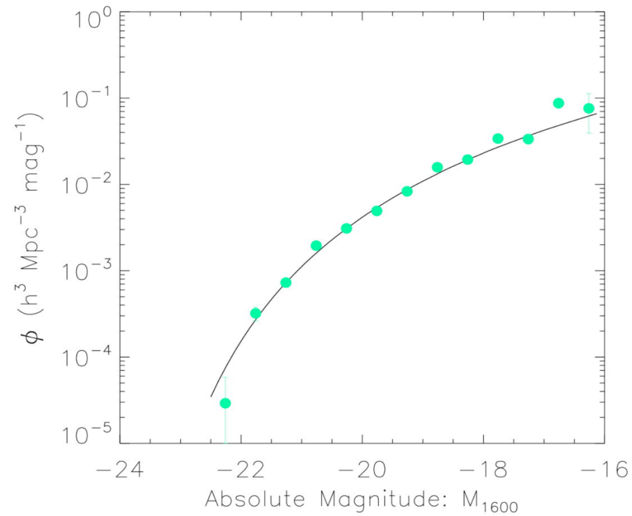
  Can be calculated using the HOD $\langle N_g(M)\rangle$ computed above

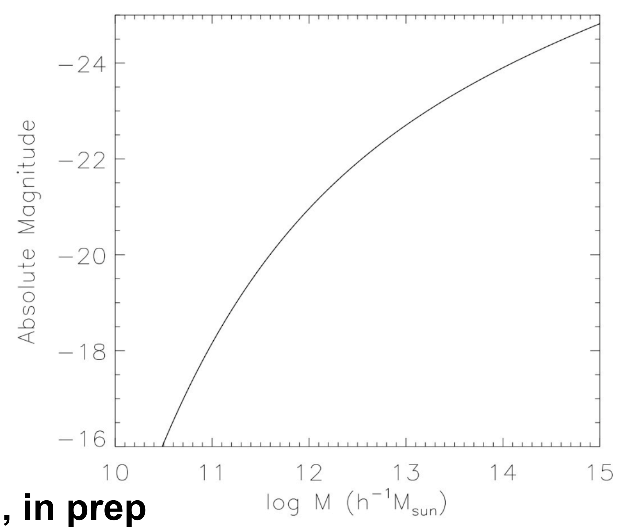
Model Predictions I - no scatter

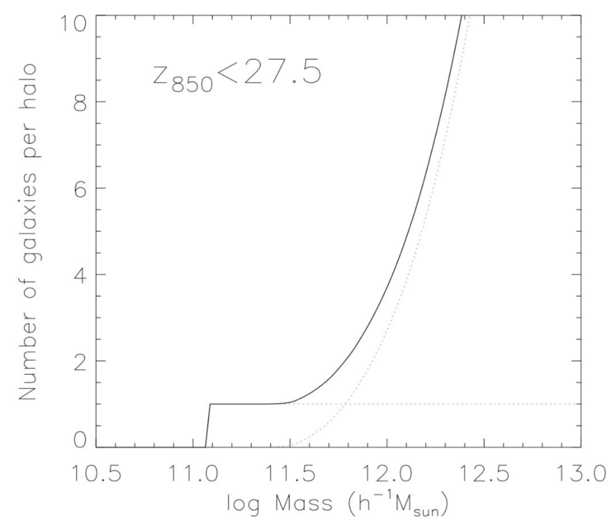
- one-to-one mapping between halo mass and luminosity (halo occupation efficiency = unity, no scatter)
- L_{UV}-M relation can be uniquely determined by comparing total mass function and luminosity function non-parametrically (Vale & Ostriker 2006)

$$\frac{dn_T}{d\ln M} d\ln M = \phi(\ln L) d\ln L$$

LBG LF at z~4 Bouwens et al. 2007



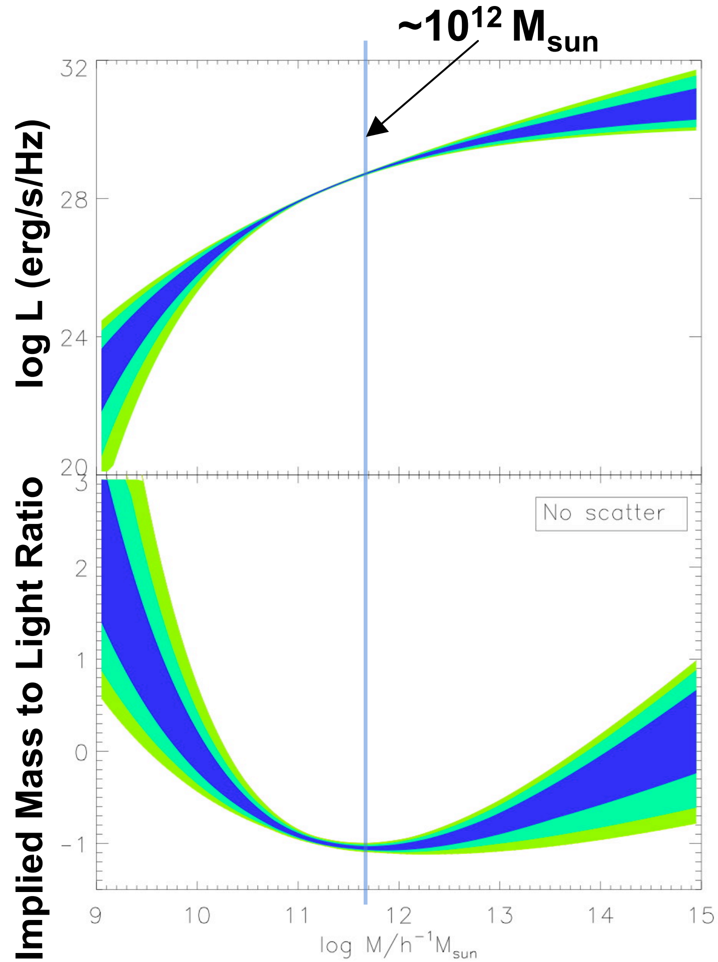




K.-S. Lee et al., in prep

Model Predictions I - no scatter (continued)

- A range of L_{UV}-M consistent with the observed luminosity function at z~4 when no scatter is assumed (1,2,3 sigma)
- The common feature is that there is a minimum M/L_{UV} around $10^{11.5}$ -10^{12} M_{sun} to account for the observed faint-end slope much shallower than the halo mass function
- But that's not the end of the story…..



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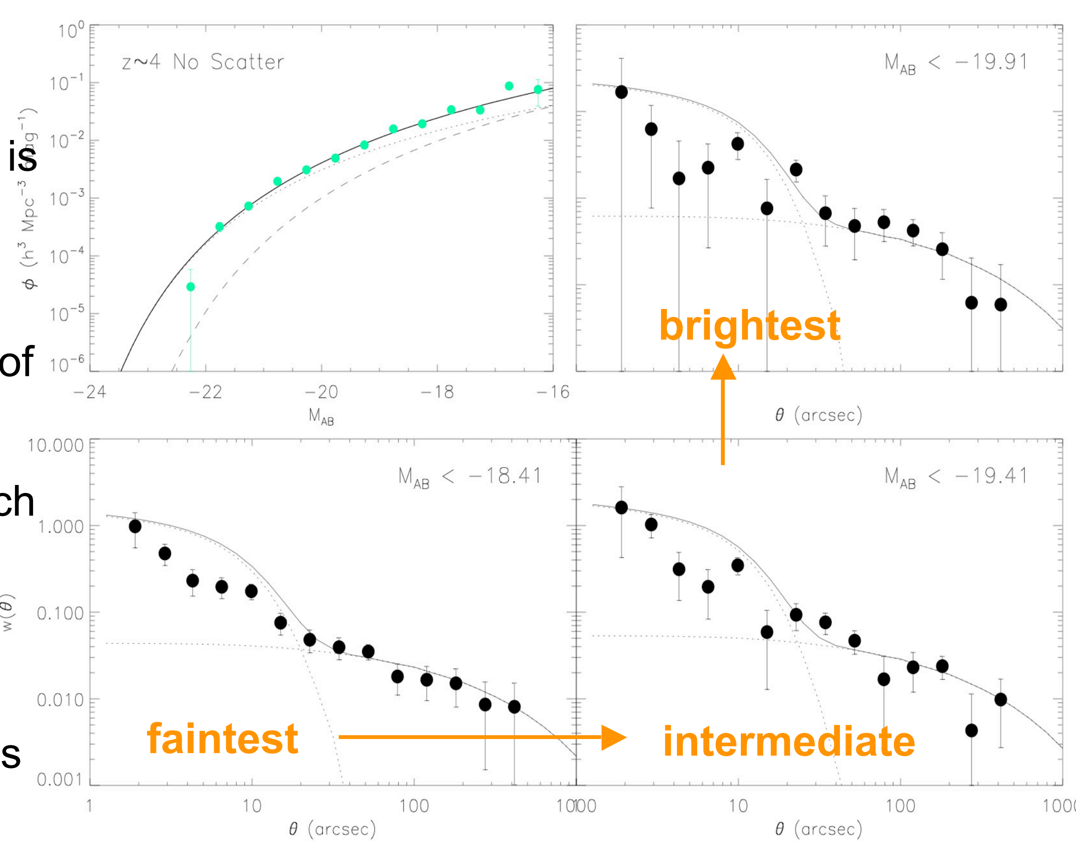
Model Predictions I - no scatter (continued)

- All the L_{UV}-M models that provide good fits to the LF over-predict small-scale clustering when no scatter is assumed
- Introduction of scatter suppresses the amplitude of one-halo term (θ<10-20 arcsec) by including many lower-mass halos with much less substructures
- In addition, the model prediction of the L_{UV}-dependence at large scales somewhat shallower than observed values

LF at z~4 from Bouwens et al. 2007



Angular correlation function at z~4 from GOODS v1.9

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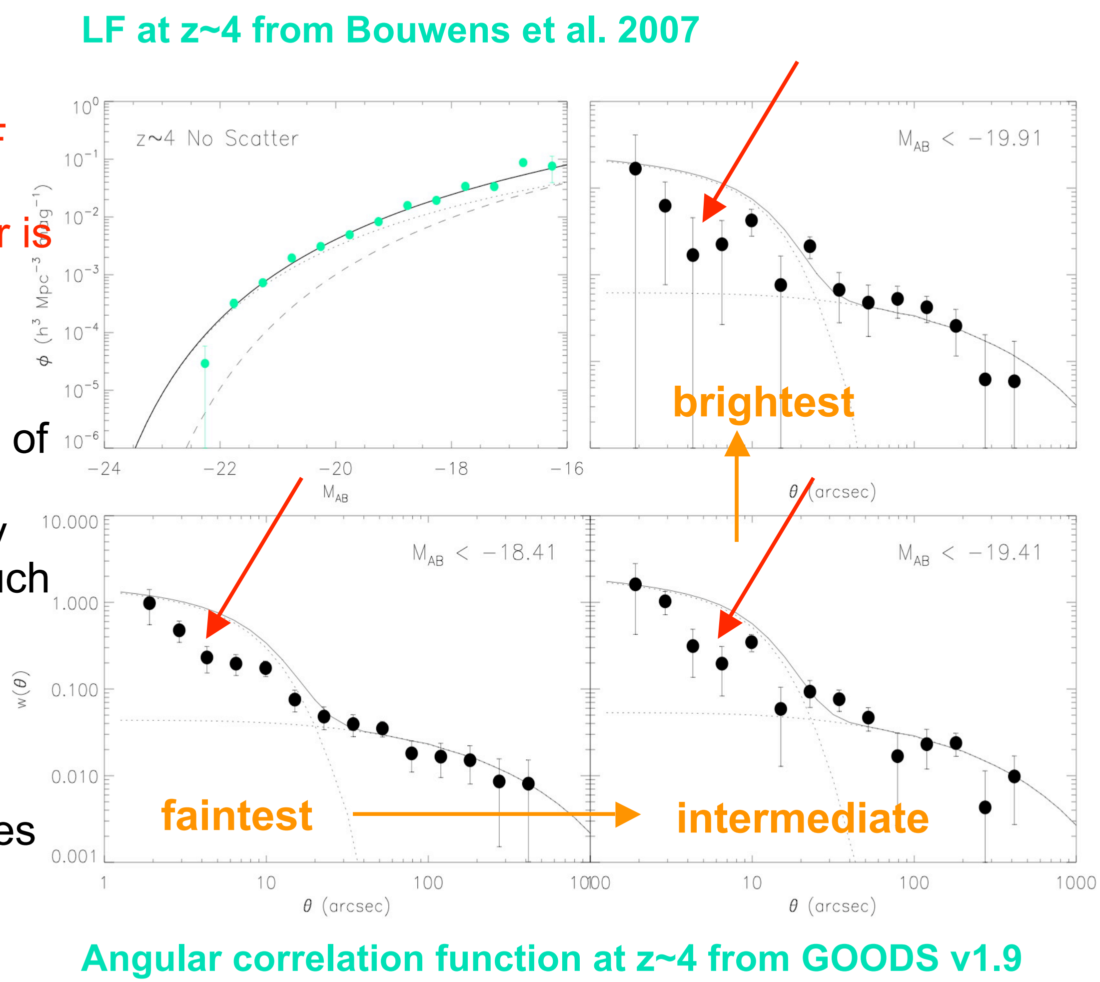

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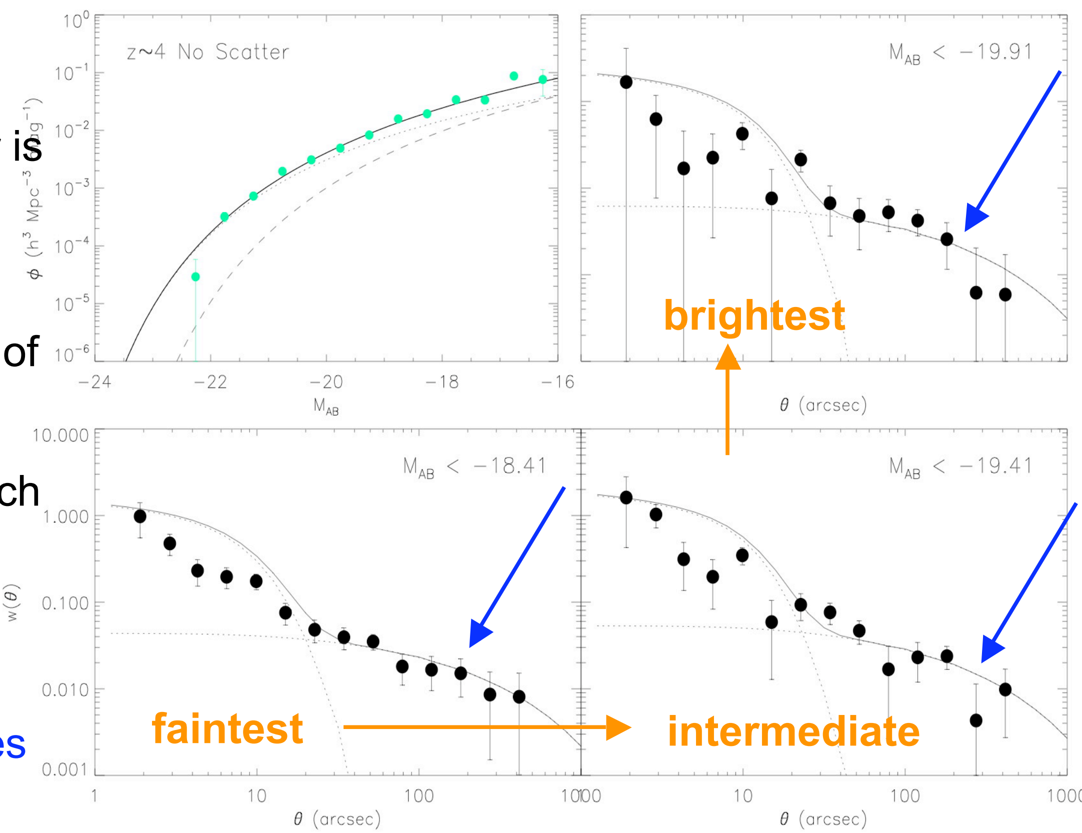


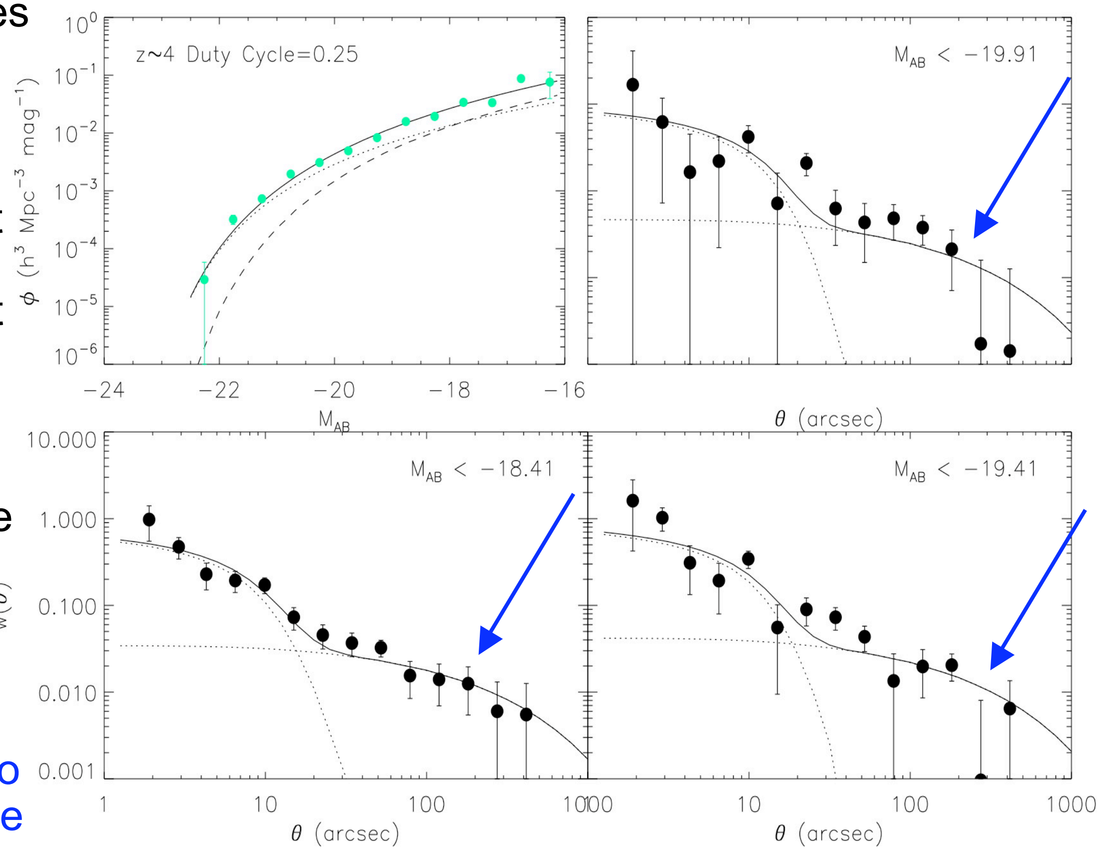
Angular correlation function at z~4 from GOODS v1.9

K.-S. Lee et al., in prep

Model Predictions II - Constant Duty-cycle

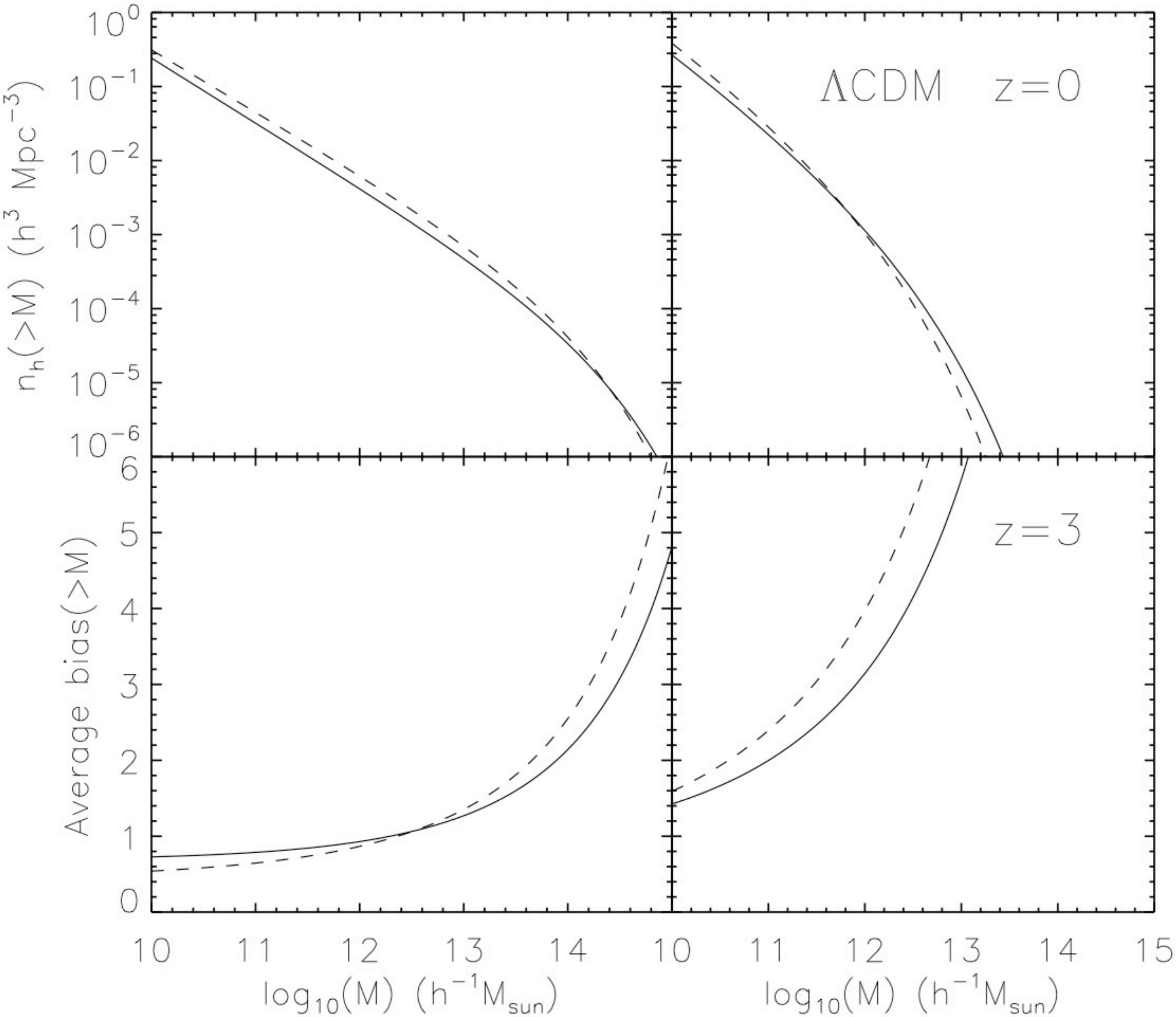
- When a constant duty-cycle is assumed, the model does a lot better
- There is still a one-to-one rel'n b/w L_{UV} and M except that only one in every four halos have UV counterpart (others remain invisible)
- The model does poorly in reproducing the large scale clustering
- L_{UV}-dependence becomes less pronounced as the average mass halo/subhalo sample decreases -> hence the bias factor

LBG LF at z~4 from Bouwens et al. 2007
With Duty-Cycle 25%



ACF at z~4 from GOODS v1.9 data

K.-S. Lee et al., in prep



ΛCDM z=0
z=3
$n_h(>M)$ (h^3 Mpc^{-3})
Average bias(>M)
$\log_{10}(M)$ ($h^{-1}M_{sun}$)
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
0 1 2 3 4 5 6
10 11 12 13 14
10 11 12 13 14 15

What have we learned?
What more do we need?

- Mass-dependent scatter is really needed to reproduce the amplitude of the luminosity dependence of clustering

- Duty-cycle (at least in a simple case) can be distinguished from galaxy occupation efficiency

- Need to go wider to constrain the luminosity-dependent clustering at higher luminosity (L>L*) e.g., COSMOS 2-deg^2 survey (KSL, MG, et al. in prep), CFHTLS, SXDS, etc.

- With large surveys, one can check, as an additional test, cross-correlation function of independent luminosity samples -> provides further constraints to the model

- Go deeper: ACS GTO archival data set, many one-pointing fields with multi-wavelength observations with depth comparable to GOODS, or deeper (UDF, UDF-Ps, UGC10214)

Summary

- Joint analyses of clustering properties and LF is the key to unambiguously constraining the evolution of the L_{UV}-M relation and galaxy duty cycle, and to understanding the observed evolution of UV LF at these cosmic epochs
- Current data suggest that not only scatter between mass and UV light is needed but also it has to be mass dependent to match the observed luminosity-dependent clustering
- Constant duty-cycle (independent of mass) alone does not reproduce the observed amplitude of luminosity dependence of clustering (bias does not change significantly for low-mass halos)
- Larger area surveys and deeper surveys are needed to explore wider range of luminosities and carry out independent checks