# Establishing the relationship between galaxies and dark matter halos

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## The Cold Dark Matter Paradigm

- The spacetime: the standard cosmology  $\Omega_{\rm m}, \, \Omega_{\Lambda}, \, h$
- Matter content: the universe is dominated by cold dark matter  $\Omega_{CDM}, \Omega_{baryon}, etc$

Initial conditions: density perturbations from inflation ( $P_i(k) = Ak^n$ )
 A(or  $\sigma_8$ ) and n

 $\Omega_m pprox 0.25, \ \Omega_\Lambda pprox 0.75, \ h pprox 0.7, \ \sigma_8 pprox 0.75, \ \Omega_b h^2 pprox 0.022,$ n pprox 0.95.

## Hierarchical formation and CDM halos



- Density perturbations in dark matter collapse into quasi-static clumps (dark matter halos)
- Dark matter halos are well-defined objects:  $\overline{
  ho}_{
  m halo} \sim 350 \overline{
  ho}_{
  m U}$
- Galaxies are assumed to form in dark matter halos

Properties of CDM halos: well understoo

- Mass function: n(M)dM
- Spatial clustering: halo bias b(M)
- Internal structure: density profile, shape, substructure angular momentum, etc

#### Connecting galaxies and dark halos: two ways



- 1. Halo Occupation Distribution: P(N|M), the probability that a halo of mass M contains N galaxies (of given properties)
- 2. Galaxies in groups and clusters

## HOD: Lighting-Up the Dark Matter

 $\Phi(L)dL =$  comoving number density of galaxies with luminosities in the range L, L + dL.



We use the Conditional Luminosity Function to link the distributions of galaxies and CDM halos

 $\Phi(L|M)dL$  = average number of galaxies with luminosities in the range L, L + dL that 'live' in halos of mass M.

## The Conditional Luminosity Function

Yang, Mo, van den Bosch (2003)

The luminosity function:

$$\Phi(L) = \int_0^\infty \Phi(L|M) \, n(M) \, \mathrm{d}M$$

The average luminosity in a halo of mass M:

$$\langle L 
angle(M) = \int_0^\infty \Phi(L|M) \, L \, \mathrm{d}L$$

The average number of galaxies in a halo of mass M with  $L > L_1$ :

$$N_M(L>L_1)=\int_{L_1}^\infty \Phi(L|M)\,\mathrm{d}L$$

Clustering properties of galaxies as function of luminosity:

$$\xi_{
m gg}(r|L) = b^2(L)\,\xi_{
m dm}(r)$$
  
 $\overline{b}(L) = rac{1}{\Phi(L)}\int_0^\infty \Phi(L|M)\,b(M)\,n(M)\,{
m d}M$   
REMINDER:  $n(M)$ ,  $b(M)$ ,  $\xi_{
m dm}(r)$  are well-understood halo properties

The conditional LF is the ideal statistical 'tool' to link the distributions of dark matter halos and galaxies.



We assume that the CLF also has the Schechter form:

$$\Phi(L|M)\mathrm{d}L = rac{ ilde{\Phi}^*}{ ilde{L}^*} \, \left(rac{L}{ ilde{L}^*}
ight)^{ ilde{lpha}} \, \exp(-L/ ilde{L}^*)\,\mathrm{d}L$$

Here  $ilde{\Phi}^*$  ,  $ilde{L}^*$  and  $ilde{lpha}$  all depend on M.

- Parameterize  $ilde{\Phi}^*$ ,  $ilde{L}^*$  and  $ilde{lpha}$ . In total our model has 8 free parameters
- Construct Monte-Carlo Markov Chain to sample posterior distribution of free parameters.

### The Relation between Light and Mass



vdB, Yang, Mo & Norberg, 2004 (astro-ph/0406246)

## Light distribution in the Universe



50% of light is produced in halos  $M \lesssim 2 \times 10^{12} h^{-1} \ {
m M}_{\odot}$ .

#### Constraints on $\Omega_m$ and $\sigma_8$



vdB, Mo & Yang 2003, MNRAS, 345, 923

## Constructing mock catalogs

- Run numerical simulations:  $\Lambda$ CDM concordance cosmology;  $L_{\rm box} = 100h^{-1} {
  m Mpc}$  and  $L_{\rm box} = 300h^{-1} {
  m Mpc}$  with  $512^3 {
  m CDM}$ particles each.
- Identify dark matter halos (FOF algorithm, b = 0.2).
- Populate halos with galaxies using CLF.
- Stack boxes to create virtual universe and mimick observations (magnitude limit, completeness, geometry)



## Large Scale Structure

**Correlation function in redshift-space:** 

$$\xi(r_p,\pi)=rac{GG(r_p,\pi)}{RR(r_p,\pi)}-1\,,$$

where  $r_p$  and  $\pi$  the pair separations perpendicular and parallel to the line-of-sight.

redshift space CF: 
$$\xi(s)$$
 with  $s = \sqrt{r_p^2 + \pi^2}$ .  
projected CF:  $w_p(r_p) = \int\limits_{-\infty}^{\infty} \xi(r_p, \pi) \mathrm{d}\pi = 2 \int\limits_{r_p}^{\infty} \xi(r) \, rac{r \, \mathrm{d}r}{\sqrt{r^2 - r_p^2}}$ 

Peculiar velocities cause anisotropy of  $\xi(r_p, \pi)$  and differences between  $\xi(s)$  and  $\xi(r)$ . Anisotropy of  $\xi(r_p, \pi)$  is quantified by quadrupole-to-monopole ratio denoted by q(s).



- Large Scales: Infall ("Kaiser Effect"); boosts  $\xi(s)$  w.r.t.  $\xi(r)$ . q(s) is a measure of  $\beta\equiv\sigma_8\Omega_m^{0.6}$
- Small Scales: Virialized motion ("Finger-of-God"); suppresses ξ(s)
   w.r.t. ξ(r). q(s) is a measure for the pairwise velocity dispersions
   (PVDs) denoted by σ<sub>12</sub>.

#### Large Scale Structure: The 2dFGRS



#### Mock versus 2dFGRS: round 1



Yang, Mo, Jing, vdB & Chu, 2004, MNRAS, 350, 1153

#### Mock versus 2dFGRS: round 2



Yang, Mo, Jing, vdB & Chu, 2004, MNRAS, 350, 1153

#### Galaxy Groups: a halo-based group finder

Goal: to group observed galaxies according to common halos

- Assume M/L as function of halo mass
- Select candidate groups using FOF
- Compute group luminosity & estimate halo mass from assumed M/L
- Use corresponding virial quantities, i.e. size and velocity dispersion, to assign group membership
- Iterate until group membership convergence

\* Group catalogue insensitive to initial, assumed M/L

\* Significantly fewer interlopers than with pure FOF selection

\* Galaxy groups are associated with individual dark matter halos

Yang, Mo, vdB, Jing 2004 (astro-ph/0405234)

### Tests with mock catalogs



## Tests with mock catalogs



## Probing Clustering of Dark Matter Halos



Yang, Mo, vdB & Jing 2004 (astro-ph/0406593)

Group correlation matches well halo correlation.

## Galaxy distribution in groups



Galaxy distribution is much less concentrated than dark matter.

## Galaxy Alignment



Orientation of blue centrals follows halo spin.

## Galaxy Properties versus Dark Halos



Two characteristic mass scales:  $M_h \sim 10^{11} h^{-1} M_{\odot}$  (feedback mass scale?)  $M_h \sim 10^{13} h^{-1} M_{\odot}$  (cooling mass scale?)

## Satellite galaxy distribution



Satellites have Poisson distribution

## CLF from Groups



We determined CLF directly from groups in 2dFGRS & mocks.

**Group-sized haloes** have Schechter CLF.

Galaxy-sized haloes reveal Gaussian peak of central galaxies.

Mocks show similar behavior, pointing to an artefact due to mass estimator.

Data is consistent with Schechter CLF!

## Galaxy populations in dark halos

#### Halo mass dependence:



The fractions of early and late type galaxies depend strongly on halo mass. At fixed halo mass, there is virtually no luminosity dependence. The mass dependence is smooth: there is no characteristic mass scale The intermediate type fraction is independent of luminosity and mass.

(Weinmann, vdB, Yang & Mo, 2006)

## Comparison with Semi-Analytical Model

Comparison of Group Occupation Statistics with Semi-Analytical Model of Croton et al. 2006. Includes 'radio-mode' AGN feedback.



- SAM matches global statistics of SDSS
- Luminosity function, bimodal color distribution, and overall blue fraction
- But what about statistics as function of halo mass?

## **Constraining Star Formation Truncation**

To allow for fair comparison, we run our Group Finder over SAM.



Satellites: red fraction too large:  $\triangleright$  strangulation too efficient as modelled Centrals:  $f_{blue}(L|M)$  wrong:  $\triangleright$  AGN feedback has problem

 $f_{
m blue}(L,M)$  useful to constrain SF truncation mechanism



- The conditional luminosity function (CLF) model is a powerful tool to establish the galaxy-dark matter connection
- The halo occupations obtained from the CLF model are in good agreement with those obtained directly from galaxy groups
- Study of how different galaxies occupy different halos can provide vital clues about galaxy formation.