Spatial clustering of galaxies as a constraint on galaxy formation and cosmology

or

The Dark Side of the Halo Occupation Distribution

Andrey Kravtsov

Department of Astronomy & Astrophysics
Center for Cosmological Physics, University of Chicago

http://astro.uchicago.edu/~andrey
http://cfcp.uchicago.edu/lss/

Ann Arbor
8 September, 2003
Preporsterous Universe
(Very) Brief History

3 min 3x10^5 yrs 5x10^9 yrs

CMB γ

Nucleo-
Synthesis Last Scattering Galaxy Formation

e P n He

graphics from Wayne Hu (background.uchicago.edu/~whu)
Cosmic Microwave Background (CMB) Temperature Anisotropies

Wilkinson Microwave Anisotropy Probe (WMAP) satellite results circa February 2003
Angular power spectrum of temperature fluctuations

Spergel et al. 2003
Cosmic Pie

- **Dark Energy**: 73%
- **Cold Dark Matter**: 23%
- **Atoms**: 4%
Large-scale structure of the Universe
On even larger scales...
(billions of light years)

2dF Galaxy Redshift Survey

106688 Galaxies
Structure formation in hierarchical cosmology

Hubble Volume Simulation.
[Gus Evrard and VIRGO collaboration]
Clustering of galaxies as a cosmological probe

2-point correlation function

(excess probability to find a pair of galaxies of a given separation)

pair separation in Mpc

Colin, Klypin, Kravtsov, Khokhlov 1999
In the halo model all matter is tied up in halos

$\text{LCDM } 80h^{-1}\text{ Mpc}; \quad m_p = 3.1 \times 10^8 h^{-1} \text{ M}_\odot$
In the halo model all matter is tied up in halos

$\text{LCDM } 80 h^{-1} \text{ Mpc; } m_p = 3.1 \times 10^6 h^{-1} \text{ Msun}$
halo occupation distribution (HOD)
P(N|M) probability for a halo of mass M to harbor N galaxies
galaxy correlation function in the halo model

\[ \text{CF} = \text{one- halo} + \text{two- halo contributions} \]

**Large scales:** All pairs come from separate halos.

\[ \xi_g(r) = b^2 \xi_m(r), \quad b = \bar{n}_g^{-1} \int_0^\infty dM \frac{dn}{dM} \langle N \rangle_{M \leq b(M)} \]

**Small scales:** All pairs come from same halo.

\[ \frac{\bar{n}_g^2}{2} \int_0^r \xi_{th}(r) 4\pi r^2 dr = \int_0^\infty dM \frac{dn}{dM} \langle N(N-1) \rangle_{M \leq b(M)} \frac{2}{2R_{vir}} \]

Berlind & Weinberg 2002
Departures from the power law correlation function as predicted by the Halo Model

Zehavi et al. 2003
HOD in dissipationless simulations

the Bound Density Maxima (BDM) algorithm (Klypin et al. 1999)
Galaxies in CDM models form in massive extended DM halos

DDO 154

(Original HI data from Carignan & Purton, 1999)
Galaxies in a halo: 
central galaxy + a population of satellite galaxies

\[ N(M) = Ns + 1 \]
HOD of galactic halos

Average number of satellites as a function of halo mass the first moment of the HOD
Agreement
with SPH simulations and SAM+N-body models

Berlind et al. 2003
Agreement with observations (SDSS)
Correlation length and CF slope
2-point correlation function of galactic halos
Work in progress: galaxy-mass correlation function

Galaxy-mass correlation function is measured using the SDSS survey

(Sheldon et al. 2003, in preparation)
Conclusion

Darth Vader says:
Don't underestimate the power of the dark side...
Summary

- Clustering of dark matter halos matches the clustering of the overall galaxy population. *Thus gravity appears to be the primary driver of galaxy clustering.*

- The Halo Occupation Distribution is greatly simplified if the population of the halo galaxies is split into the central galaxy and satellites. The shape of the HOD depends only weakly on galaxy mass and time. *This should help us figure out why galaxy correlation function is so close to the power law with amplitude only weakly evolving with time.*