Interpreting Large Scale Structure

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CfA2 Redshift Survey

(de Lapparent, Geller, & Huchra 1986)
GALAXY FORMATION!
Las Campanas Redshift Survey

Shectman et al. 1996
2dF Galaxy Redshift Survey

3° slice
62559 galaxies
220929 total

Colless et al. 2001
Sloan Digital Sky Survey

Image courtesy of M. Tegmark
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.


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

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

$P_{\text{gal}}(k) = b^2 P(k)$.  
Use $P(k)$ shape for cosmology.

Also:  
Redshift space distortions: constrain $\beta = \Omega_m^{0.6}/b$  
Bispectrum: constrain $b$
Tegmark et al. 2004:

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

$\Omega_m h = 0.213 \pm 0.023$
for $\Omega_b / \Omega_m = 0.17$, $n_s = 1$, $h = 0.72$
SDSS Galaxy Power Spectrum (DR2)

Tegmark et al. 2004
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.
Cole et al. 2005

\[ \Omega_m h = 0.168 \pm 0.016 \]

\[ \Omega_b / \Omega_m = 0.185 \pm 0.046 \]

For \( n_s = 1, \ h = 0.72 \)
$\Omega_m = 0.237 \pm 0.020$
$\Omega_b = 0.041 \pm 0.002$
$h = 0.74 \pm 0.02$
$n_s = 0.954 \pm 0.023$

Sanchez et al. 2005
Consistency?

Cole et al. 2005
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Best-fit parameters linear $P(k)$

Cole et al. 2005

Sanchez et al. 2005
Cole et al. 2005
Tegmark et al. 2004
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: $\Omega_m = 0.3$, $h = 0.7$

Dotted: Sanchez et al. parameters

Padmanabhan et al. 2005
Dark matter clustering is straightforward to predict for specified initial conditions and cosmological parameters. But where are the galaxies?
One solution: add gas dynamics and star formation to simulations.

Weinberg et al. 2004
Galaxies vs. Mass: Beyond Linear Bias

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

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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.
$P(N|M)$, SPH simulation

Mean occupation, SPH & SA

Berlind et al. 2003
P(N|M), SPH simulation

Central-satellite separation

Berlind et al. 2003

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.

Zehavi et al. (2004)
Power-law deviations more pronounced at high redshift.

0-parameter “fit” to Ouchi et al.’s (2005) Subaru data at $z \sim 4$. 

Conroy, Wechsler, & Kravtsov 2005
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.
$\Omega_m = 0.1, \sigma_8 = 0.95$

$\Omega_m = 0.3, \sigma_8 = 0.95$

$\Omega_m = 0.3, \sigma_8 = 0.80$

Tinker et al. (2005)
Cluster mass-to-light ratios

Given $P(k)$ shape, $\sigma_8$, choose HOD parameters to match projected correlation function.

Predict cluster M/L ratios.

These are above or below universal value depending on $\sigma_8/\sigma_{8g}$.

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.

Tinker et al. (2005)
Breaking degeneracy between cosmology and galaxy bias:

Response of clustering observables to cosmological and HOD parameters.

Zheng & Weinberg (2005)
Forecast of joint constraints on $\Omega_m$ and $\sigma_8$, 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

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• 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 $\sigma_8$ and/or $\Omega_m$. 
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• Doing precision cosmology is hard. But interesting.
Sloan Digital Sky Survey

Movie by M. Blanton
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WMAP CMB + SDSS P(k) + SDSS Lyα forest

Seljak et al. 2005:

\( \Omega_m = 0.299 \pm 0.035 \)
\( \Omega_b = 0.048 \pm 0.002 \)
\( h = 0.694 \pm 0.030 \)
\( n_s = 0.971 \pm 0.021 \)
\( \sigma_8 = 0.890 \pm 0.033 \)
Halo central galaxies usually more massive, older than satellites.

Central: step function
Satellites: truncated power-law, Poisson statistics

(Kravtsov et al. 2004)

Zheng et al. 2005
Changing $\Omega_m$ at fixed $\sigma_8$, P(k) shape.

Zheng & Weinberg (2005)