Large Scale Structure (Galaxy Correlations)

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“majority of its surface area is only about 10 feet above sea level”
Overview

- Redshift Surveys
- Theoretical expectations
- Statistical measurements of LSS
- Observations of galaxy clustering
- Baryon Acoustic Oscillations (BAO)
- ISW effect

I will borrow heavily from two recent reviews:
2. Nichol et al. 2007 (see my webpage)
P(k) models II

Lack of strong BAO means low baryon fraction

Stronger BAO

Suppression of power
Measuring $\xi(r)$ or $P(k)$

Simple estimator:
$\xi(r) = \frac{DD(r)}{RR(r)} - 1$

Advanced estimator:
$\xi(r) = \frac{(DD-2DR+RR)}{RR}$

The latter does a better job with edge effects, which cause a bias to the mean density of points.

Usually 10x as many random points over SAME area / volume.

Same techniques for $P(k)$ - take Fourier transform of density field relative to a random catalog over same volume. Several techniques for this - see Tegmark et al. and Pope et al. Also “weighted” and mark correlations.
Measuring $\xi(r)$ II

Essential the random catalog looks like the real data!
$\xi(r)$ for LRGs
Errors on $\xi(r)$

Hardest part of estimating these statistics

On small scales, the errors are Poisson

On large scales, errors correlated and typically larger than Poisson

- **Use mocks catalogs**
  - **PROS**: True measure of cosmic variance
  - **CONS**: Hard to include all observational effects and model clustering

- **Use jack-knifes (JK)**
  - **PROS**: Uses the data directly
  - **CONS**: Noisy and unstable matrices
Jack-knife Errors

- Split data into $N$ equal subregions
- Remove each subregion in turn and compute $\xi(r)$
- Measure variance between regions as function of scale

$$\sigma^2 = \frac{(N-1)}{N} \sum_{i=1}^{N} (\xi_i - \bar{\xi})^2$$

Note the (N-1) factor because there are N-1 estimates of mean
Latest $P(k)$ from SDSS

$$k_{eq} \approx 0.075 \Omega_m h^2$$

No turn-over yet seen in data!

$2\sigma$ difference

Depart from “linear” predictions at much lower $k$ than expected

Strongest evidence yet for $\Omega_m << 1$ and therefore, DE
Hindrances

There are two “hindrances” to the full interpretation of the $P(k)$ or $\xi(r)$

- **Redshift distortions**: Helped using modeling & simulations
- **Galaxy biasing**: Helped through higher order correlations
Redshift distortions
We only measure redshifts not distances

Therefore we usually quote $\xi(s)$ as the “redshift-space” correlation function, and $\xi(r)$ as the “real-space” correlation function.

We can compute the 2D correlation function $\xi(\pi, r_p)$, then

$$w(r_p) = 2 \int_0^{\pi_{\text{max}}} \xi(r_p, \pi) d\pi$$

Fingers of God
Expected
Infall around clusters
Biasing

We see galaxies not dark matter

Maximal ignorance

\[ \delta_{gal} = b \delta_{dm} \]

\[ P(k)_{gal} = b^2 P(k)_{dm} \]

However, we know it depends on color & L

Is there also a scale dependence?
Biasing II

Halo model

All galaxies reside in a DM halo

Elegant model to decompose intra-halo physics (biasing) from inter-halo physics (DM clustering)

\[ P(k) = P_{1\text{-halo}} + P_{2\text{-halo}} \]
\[ \langle N_{\text{cent}}(M) \rangle = \exp \left( -\frac{M_{\text{min}}}{M} \right), \]

\[ \langle N_{\text{sat}}(M) \rangle = \exp \left( -\frac{M_{\text{min}}}{M} \right) \left( \frac{M}{M_1} \right)^{\alpha}, \]

\[ \langle N(M) \rangle = \langle N_{\text{cent}}(M) \rangle + \langle N_{\text{sat}}(M) \rangle. \]
Biasing could be helped through use of higher order correlations e.g. 3-point correlation function (bispectrum)

\[ P_{123} = n^3 (1 + \xi_{23} + \xi_{13} + \xi_{12} + \xi_{123}) \, dV^3 \]

**Peebles “Hierarchical Ansatz”**

\[ Q(s, q, \theta) = \frac{\xi_{123}}{\xi_{23} \xi_{13} + \xi_{12} \xi_{13} + \xi_{12} \xi_{23}} \]
Higher order correlations II

Same 2pt, different 3pt

Credit: Alex Szalay
$Q_{\text{galaxies}} = b Q_{\text{darkmatter}}$

Filaments

FOG

Gaztanaga & Scoccimarro 2005
Halo Model
Kulkarni et al. 2007
BAO Measurements
Percival et al. 2006

$\Omega_m = 0.24$ best fit WMAP model


Power spectrum of galaxy clustering. Smooth component removed.
Looking back in time in the Universe

FLAT GEOMETRY

CREDIT: WMAP & SDSS websites
Looking back in time in the Universe

SDSS GALAXIES

OPEN GEOMETRY

CREDIT: WMAP & SDSS websites
Looking back in time in the Universe

CLOSED GEOMETRY

SDSS GALAXIES

CMB

CLOSED GEOMETRY

CREDIT: WMAP & SDSS websites
Cosmological Constraints

Standard ruler (flat, $h=0.73, \Omega_b=0.17$)

\[ \Omega_m = 0.256^{+0.049}_{-0.029} \]

99.74% detection

Best fit $\Omega_m = 0.26$

Percival et al. (2006)
>3σ detection (Hutsi et al., Percival et al)

Measure ratio of volume averaged distance

\[ D_v(z) = \left( \frac{(1 + z)^2 czD_A(z)^2}{H(z)} \right)^{\frac{1}{3}} \]

\[ D_{0.35}/D_{0.2} = 1.812 \pm 0.060 \]

Flat ΛCDM = 1.67

Systematics (damping, BAO fitting) also \( \sim 1\sigma \). Next set of measurements will need to worry about this.
Cosmological Constraints

Flatness assumed, constant $w$

With CMB

Only $D_{0.35}/D_{0.2}$

Favors $w < -1$ at $1.4\sigma$

$1\sigma$  $2\sigma$  $3\sigma$
Cosmological Constraints

Including SNLS constraints

\[ \Omega_m = 0.249 \pm 0.018 \]

\[ w = -1.004 \pm 0.089 \]

\[ D_{0.35} / D_{0.2} = 1.66 \pm 0.01 \]
Discrepancy! What Discrepancy?

• $2.4\sigma$ difference between SN & BAO. The BAO want more acceleration at $z<0.3$ than predicted by $z>0.3$ SNe (revisit with SDSS SNe)

• $\sim 1\sigma$ possible from details of BAO damping - more complex then we thought

• Assumption of flatness and constant $w$ needs to be revisited
Integrated Sachs-Wolfe Effect

Dark Energy effects the rate of growth of structure in Universe

- Poisson equation with dark energy:

\[ k^2 \Phi' = -4 \pi G \frac{d}{d \eta} \left[ a^{-1} (\delta \rho_m + \delta \rho_{DE}) \right] \]

- In a flat, matter-dominated universe (CMB tells us this), then density fluctuations grow as:

\[ \delta \rho_m \propto a \Rightarrow \frac{d \Phi}{d \eta} = 0 \]

- Therefore, curvature or DE gives a change in the gravitational potential
Dilation Effect

blueshift

redshift
Experimental Set-up

Nolta et al, Boughn & Crittenden, Myers et al, Afshordi et al, Fosalba et al., Gaztanaga et al., Rassat et al.
WMAP-SDSS Correlation

No signal in a flat, matter-dominated Universe

Luminous Red Galaxies (LRGs)
ISW Detected
Update of the Scranton et al. (2003) paper

- 6300 sq degrees
- Achromatic
- 3σ detection
Giannantonio et al. (2006)

Cross-correlation of WMAP3 and SDSS quasars

**Detection of DE at z>1**

$0.075 < \Omega_m < 0.45$

$-1.15 < w < -0.76$
Evolution of DE

Consistent with $w = -1$

Rules out models

$\Omega_D \ (z=1.5) > 0.5$
Modified Gravity

Song et al. (2006)

LCDM

DGP
DETF Terminology

- **Stage II** are experiments going on now (most are still limited by statistics and systematics)
- **Stage III** are next generation (before end of decade). Investigate systematics and gain factor of >3
- **Stage IV** are next decade and gain factor of 10
After SDSSII (AS2)  
Baryon Oscillation Spectroscopic Survey (BOSS)

- Measure distance to \(~1\%\) at \(z=0.35\) and \(z=0.6\)
- 10000 deg\(^2\) with 1.5m LRGs to \(0.2<z<0.8\)
- 160k quasars at \(2.3<z<2.8\)
- Starting 2009
- \(h\) to \(1\%\) with SDSS SNe

2SLAQ (www.2slaq.info)
Dark Energy Survey (DES)

- 5000 sq deg multiband (g,r,i,z) survey of SGP using CTIO Blanco with a new wide-field camera
- 9 sq deg time domain search for SNe

<table>
<thead>
<tr>
<th>Method</th>
<th>$\sigma (\Omega_{DE})$</th>
<th>$\sigma (w_0)$</th>
<th>$\sigma (w_a)$</th>
<th>$z_p$</th>
<th>$\sigma (w_p)$</th>
<th>$[\sigma (w_a)\sigma (w_p)]^{-1}$</th>
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<tbody>
<tr>
<td>BAO</td>
<td>0.010</td>
<td>0.097</td>
<td>0.408</td>
<td>0.29</td>
<td>0.034</td>
<td>72.8</td>
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<tr>
<td>Clusters</td>
<td>0.006</td>
<td>0.083</td>
<td>0.287</td>
<td>0.38</td>
<td>0.023</td>
<td>152.4</td>
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<tr>
<td>Weak Lensing</td>
<td>0.007</td>
<td>0.077</td>
<td>0.252</td>
<td>0.40</td>
<td>0.025</td>
<td>155.8</td>
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<tr>
<td>Supernovae</td>
<td>0.008</td>
<td>0.094</td>
<td>0.401</td>
<td>0.29</td>
<td>0.023</td>
<td>107.5</td>
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<tr>
<td>Combined DES</td>
<td>0.004</td>
<td>0.061</td>
<td>0.217</td>
<td>0.37</td>
<td>0.018</td>
<td>263.7</td>
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<tr>
<td>DETF Stage II Combined</td>
<td>0.012</td>
<td>0.112</td>
<td>0.498</td>
<td>0.27</td>
<td>0.035</td>
<td>57.9</td>
</tr>
</tbody>
</table>

Table 1: 68% CL marginalized forecast errorbars for the 4 DES probes on the dark energy density and equation of state parameters, in each case including Planck priors and the DETF Stage II constraints. The last column is the DETF FoM; $z_p$ is the pivot redshift. Stage II constraints used here agree with those in the DETF report to better than 10%.
DES Photo-z’s

DES science relies on good photometric estimates of the 300 million expected galaxies.

Simulated DES

Simulated DES+VISTA

u-band from VST could remove the low-z errors (ugrizJk)
Proposed MOS on Subaru via an international collaboration of Gemini and Japanese astronomers

- 1.5deg FOV with 4500 fibres feeding 10 low-res spectrographs and 1 high-res spectrograph
- ~20000 spectra a night (*2dfGRS at z~1 in 10 nights*)
- DE science, Galactic archeology, galaxy formation studies and lots of ancillary science from database
- Design studies underway; on-sky by 2013
- Next Generation VLT instruments; meetings in Garching
- Combine with an imager and do “SDSS at z=1”
DE Science

Measure BAO at $z \sim 1$ and $z \sim 3$ to determine $w(z)$
Galaxy Evolution: Every galaxy in Coma (M_r < -11)
IGM and Quasars: Simultaneously observing QSOs and galaxies in the same fields
Calibrate photo-z’s: LSST and DES require > a few 10^5 unbiased redshifts (Abdalla et al. 2007)