SDSS and the CMB

- Large Scales: SDSS-WMAP cross-correlation, Galaxy Power Spectrum
  - **Warning:** SDSS is not WMAP!
- Medium Scales: Lyman alpha, Clusters
- Small Scales: Dark Matter around Galaxies

Warning: This is a biased account!

Sloan Digital Sky Survey

- 2.5 meter telescope in Apache Point, New Mexico
- Scheduled to end in 2005; may be extended until 2007; will cover ¼ of the sky

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Two surveys in one

- Photometric survey: hundreds of millions of objects in 5 bands
- Spectroscopic survey: ~1 million objects with spectra
- Spectroscopic survey targets objects found in photometric survey. Reduces systematic effects (typically objects targeted for redshifts are found in different survey, leads to complicated selection function).

Integrated Sachs-Wolfe Effect

Large Red Galaxies selection + photo-z leads to 4 redshift distributions: 3400 sq deg, 2 Million galaxies

WMAP Q,V,W channels + “Clean” map

CMB responds to \( \frac{d\phi}{dt} \), changing potential wells associated with: galaxies and dark energy
Integrated Sachs-Wolfe Effect

• Detection in three highest redshift bins (lowest contaminated by stars)
• Sign is positive, consistent with ISW, inconsistent with SZ

• Simple constant bias model much more likely than null result
• Covariance matrix estimated with jack-knife and simulated CMB
• 14/15 cross-correlations find ISW 95% more likely than null result

See also: Diego et al., Nolta et al., Boughn & Crittenden, Fosalba & Gaztanaga, Myers et al., Afshordi et al.
Galaxy Power Spectrum

- 3D positions of 200k galaxies
- Remove FOG’s with tunable parameter
- Use linear combination of pixel-overdensities: Karhunen-Loeve modes.
- Lowest modes probe largest scale structure
- Compression of 3x200,000 numbers into 4000 (lose small scale information)

Tegmark et al. 2003

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Galaxy Power Spectrum

KL modes have mean zero and (almost diagonal) variance due to Poisson noise and clustering

\[
\langle x_i \rangle = 0
\]

\[
\langle x_i x_j \rangle = C_{ij}
\]

Distribution is Gaussian! (Sound familiar?)

Tegmark et al. 2003
Consult your favorite cosmology textbook

Galaxy Power Spectrum

Redshift Space Distortions

\[ \delta_{\text{obs}} \sqsubset \delta + v \]
\[ P_{\text{obs}} \sqsubset P_{\delta\delta} + 2P_{\delta v} + P_{vv} \]

Fit for all three separately, then clean up …
Brighter galaxies are more clustered than faint galaxies.
Brighter galaxies are seen from furthest away (smallest $k$)
Blind averaging leads to luminosity bias

Ten percent correction over scales of interest.
Cosmological Parameters

Simple formula for estimating effect of systematic errors:

$$\delta \lambda_\alpha = F^{-1}_{\alpha \beta} \frac{\partial P_i}{\partial \lambda_\beta} C^{-1}_{ij} \delta P_j$$

E.g., use linear $P$ instead of NL $P$

Fisher Matrix

Power Spectrum

Covariance Matrix

Systematic Error in $P$

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Cosmological Parameters

- SDSS helps with neutrinos, matter density, & Hubble constant (out of 7 parameters)
- Very little info from small scales because of 4000 KL modes
- Even ignoring NL effects is OK out to $k=.18$

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Testing inflation

CMB

CMB + LSS
Lyman Alpha Forest

3000 QSOs with absorption lines from redshifts 2 to 4.2

Goal: 1D Flux power spectrum

- Subtract mean flux and divide by mean flux. This gives $\delta$ [open squares]
- Composite QSO spectrum [crosses]
- Principle Component Analysis: Allow each QSO spectrum to vary: linear combination of training set [reference points]

Simple thing works. Composite spectrum works very well.
Lyman Alpha Forest

Systematics Check:
Cross-correlate distant lines of sight. No intrinsic correlations: any observed must be due to improper continuum fitting.

Possible problems on large scales. No problems on small scales.

Lyman Alpha Forest

• Dashed lines are from Keck; solid from SDSS
• 3 sets of curves from low (bottom) to high (top) redshift
• SDSS goes to larger scales, but doesn’t have small scales resolution

Good agreement with Keck!
Lyman Alpha Forest

Parameterize with amplitude at every redshift: scales as \((1+z)^4\)

(Parenthetically: No evidence for Helium reionization)

Convert 1D Flux Spectrum to 3D Linear Matter Power Spectrum

- Run many simulations with CDM-like spectra
- Extract Flux power spectra from each simulation
- Fit amplitude and slope of power at 1 Mpc

Lidz et al.
Galaxy Clusters

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Galaxy Clusters

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Galaxy Clusters

- Two different cluster identification algorithms give very similar cosmological constraints.
- Slightly lower $\sigma_8$ than X-ray determinations.

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Bahcall et al. 2003

Galaxy Clusters

- X-Ray temperature and X-Ray Luminosity Function give similar cosmological constraints.
- Largest systematic uncertainty comes from scatter (two types) in M-T relationship.
- Can lensing do better?

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Pierpaoli, Borgani, Scott & White 2003
Galaxy Clusters

Lensing of CMB by Cluster

- CMB is pure gradient on cluster scales
- Distinct signature, with amplitude of order 10 $\mu$K
- Can high resolution, low noise CMB experiment resolve uncertainty in cluster masses?

Seljak & Zaldarriaga 1999

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Galaxy Clusters

Fit z=0.3 cluster with NFW profile

Ellipticities of background galaxies

Lensng of CMB (.5' pixels ; 1 $\mu$K)

CMB Lensing including projection effects

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Galaxy Clusters

Why is projection so damaging? Large scale structure affects long wavelength modes, precisely those for which there is signal.

Galaxies & Matter

- 9 million source galaxies, all with photo-z’s with < 10% errors
- 127,000 lens galaxies, all with spectroscopic redshifts
- Noise per lens: $\sigma_{SN}/N^{1/2} \sim 0.4/8.5 \sim 0.05$, factor of ten greater than the signal
- Need to average over many lenses

Sheldon et al. 2003

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Galaxies & Matter

• Measure azimuthally averaged tangential shear as a function of radius

• Systematic check: No B-mode

![Graph](Sheldon et al. 2003)

Galaxies & Matter

• Invert to get 3D cross-correlation function

• Comparing to galaxy-galaxy correlation function (with same sample!), constant bias (actually r/b) fits well.

![Graph](Sheldon et al. 2003)
Galaxies & Matter

\[ \delta T = \frac{\partial T}{\partial y} \delta \theta_y \]

Deflection due to massive galaxy at \( z = 1 \)

Observed anisotropy
Gradient of primordial CMB, mean zero and rms 0.22 \( \mu K/\text{arcsec} \)
Deflection angle

Dodelson & Starkman 2003
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Galaxies & Matter

• Need to average over many galaxies, with S/N per galaxy of \( \sim 0.1 \)
• Very similar to galaxy-galaxy lensing
• In principle probes galaxy/matter correlation at higher redshift

Dodelson & Starkman 2003
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Conclusions

**Microwave/Optical link strengthening**

- Cross-correlation (**Dark Energy**)
- Complementarity (**Neutrinos, Inflation**)
- Multiple mass indicators for clusters (**Dark Energy**)
- Mass & Galaxies (**Galaxy formation**)