SDSS and the CMB

Warning: SDSS is *not* WMAP!

- Large Scales: SDSS-WMAP cross-correlation, Galaxy Power Spectrum

Warning: This is a biased account!

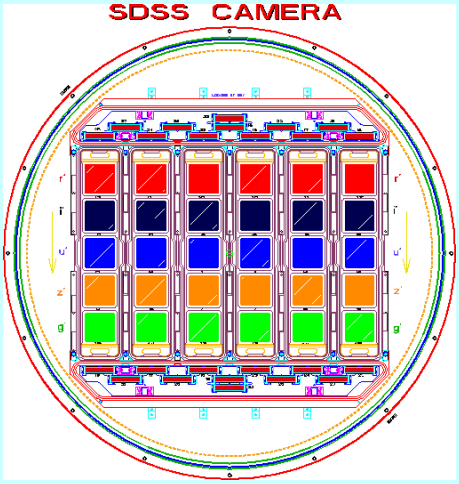
- Medium Scales: Lyman alpha, Clusters
- Small Scales: Dark Matter around Galaxies

Sloan Digital Sky Survey

- 2.5 meter telescope in Apache Point, New Mexico
- Collaboration of: Fermilab, Princeton, U. Chicago, U.Washington, Johns Hopkins, New Mexico State, Max Planck, Japan, Pittsburgh, …
- Scheduled to end in 2005; may be extended until 2007; will cover ¼ of the sky

Two surveys in one

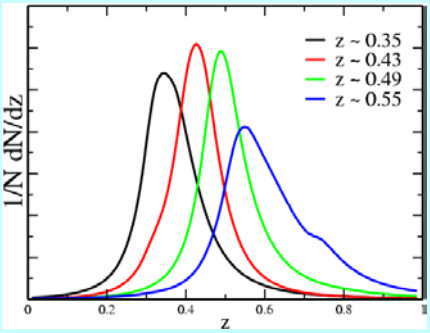
- Photometric survey: hundreds of millions of objects in 5 bands
- Spectroscopic survey: ~1 million objects with spectra
- Spectroscopic survey targets objects found in photometric survey. Reduces systematic effects (typically objects targeted for redshifts are found in different survey, leads to complicated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

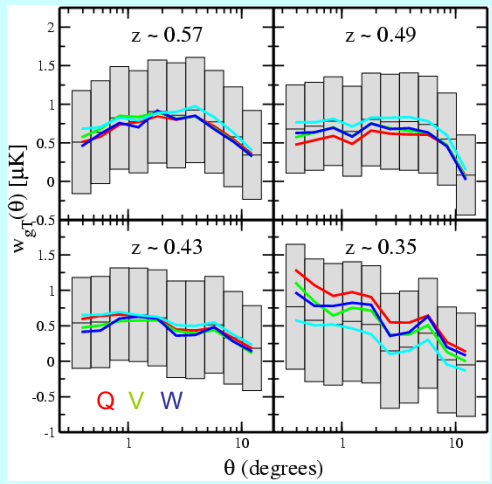


Scranton et al. 2003

CMB responds to $d\phi/dt$, changing potential wells associated with: galaxies and dark energy

Integrated Sachs-Wolfe Effect

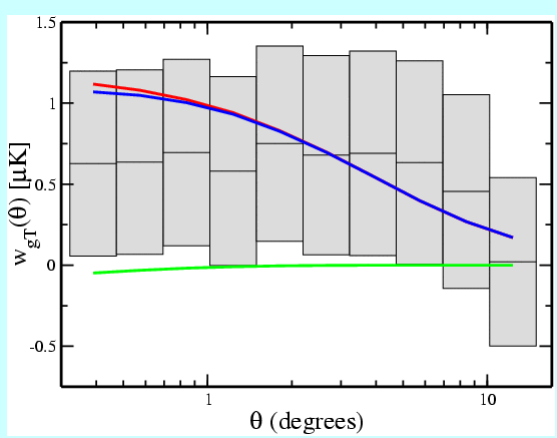
- Detection in three highest redshift bins (lowest contaminated by stars)
- Sign is positive, consistent with ISW, inconsistent with SZ



Integrated Sachs-Wolfe Effect

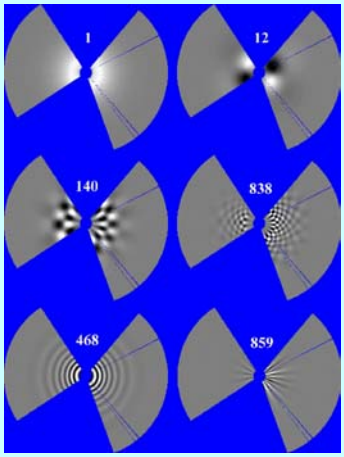
- Simple constant bias model much more likely than null result
- Covariance matrix estimated with jack-knife and simulated CMB
- 14/15 cross-correlations find ISW 95% more likely than null result

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

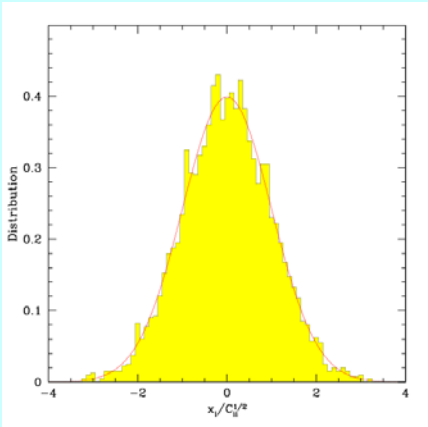
Galaxy Power Spectrum

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

$$\langle x_i \rangle = 0$$

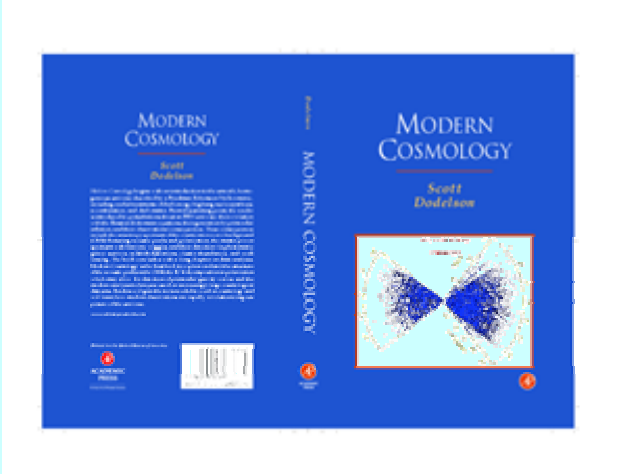
$$\langle x_i x_j \rangle = C_{ij}$$

Distribution is Gaussian! (Sound familiar?)



Tegmark et al. 2003

Consult your favorite cosmology textbook



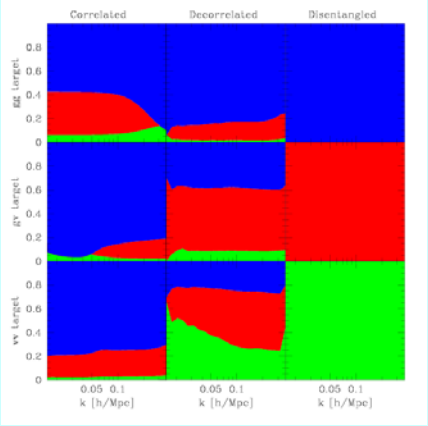
Galaxy Power Spectrum

Redshift Space Distortions

$$\delta_{obs} \square \delta + v$$

$$P_{obs} \square P_{\delta\delta} + 2P_{\delta v} + P_{vv}$$

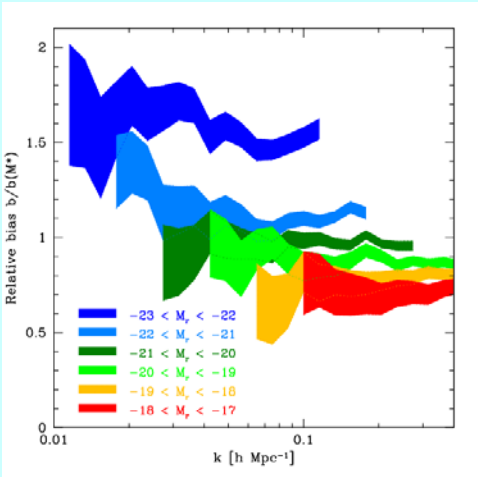
Fit for all three separately, then clean up …



Tegmark et al. 03

Galaxy Power Spectrum

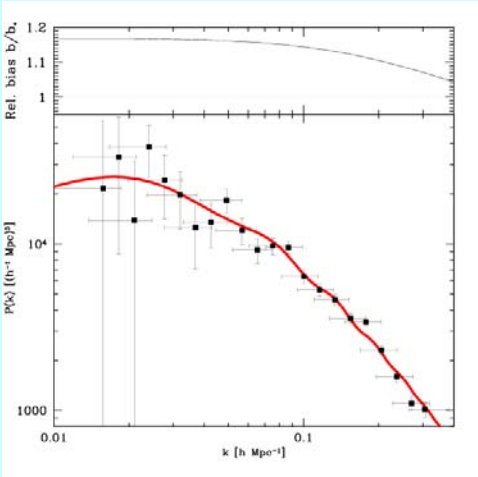
- Brighter galaxies are more clustered than faint galaxies.
- Brighter galaxies are seen from furthest away (smallest k)
- Blind averaging leads to *luminosity bias*



Tegmark et al. 2003

Galaxy Power Spectrum

Ten percent correction over scales of interest.



Tegmark et al. 2003

Cosmological Parameters

Simple formula for estimating effect of systematic errors:

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

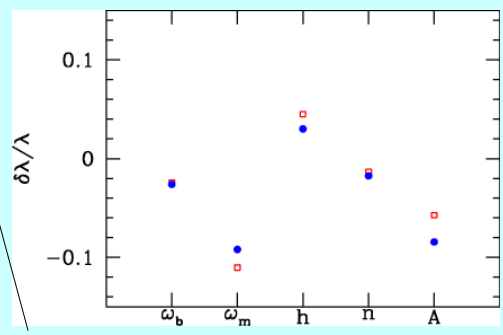
Fisher Matrix

Power Spectrum

Covariance Matrix

Systematic Error in P

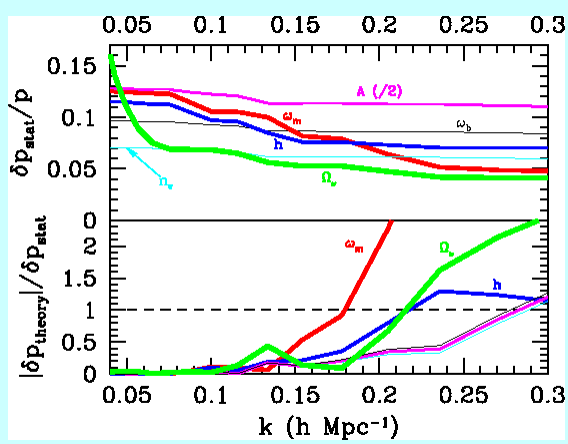
E.g., use linear P instead of NL P



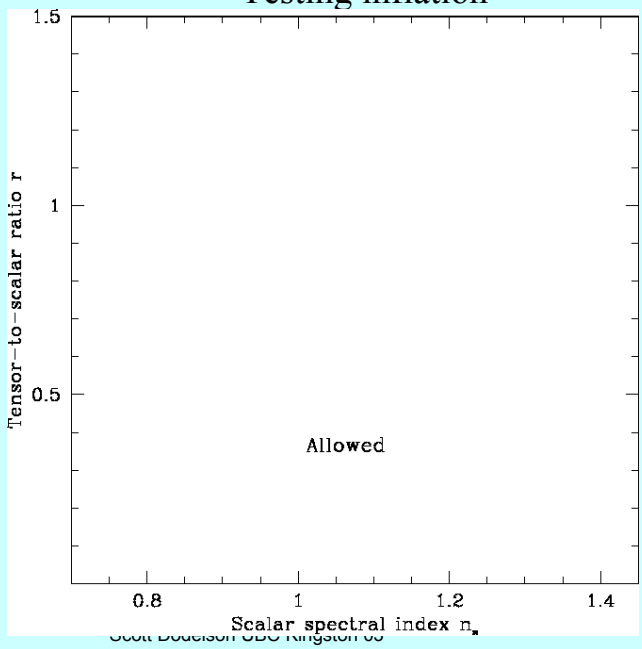
MCMC Formula

Cosmological Parameters

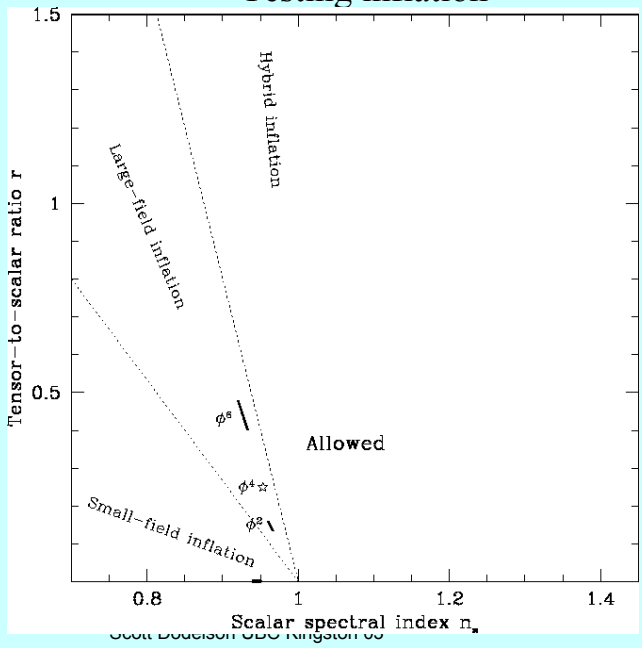
- SDSS helps with neutrinos, matter density, & Hubble constant (out of 7 parameters)
- Very little info from small scales because of 4000 KL modes
- Even ignoring NL effects is OK out to k=.18

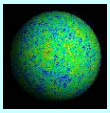


Testing inflation



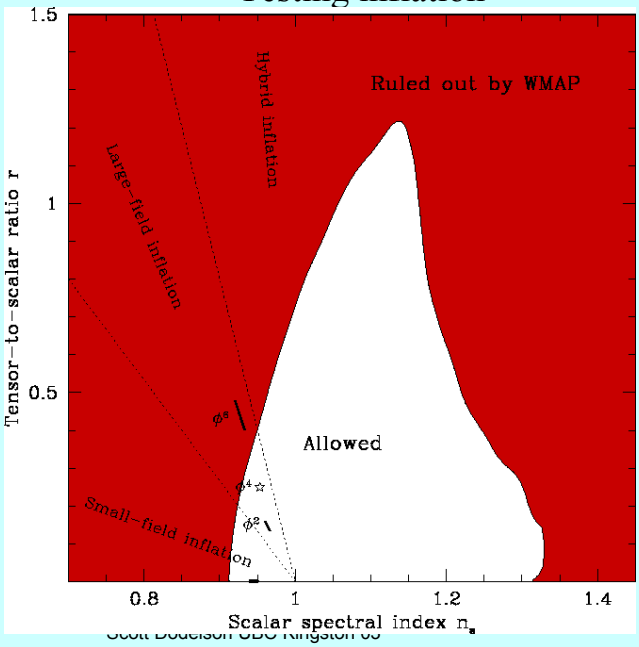
Testing inflation

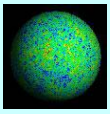




CMB

Testing inflation



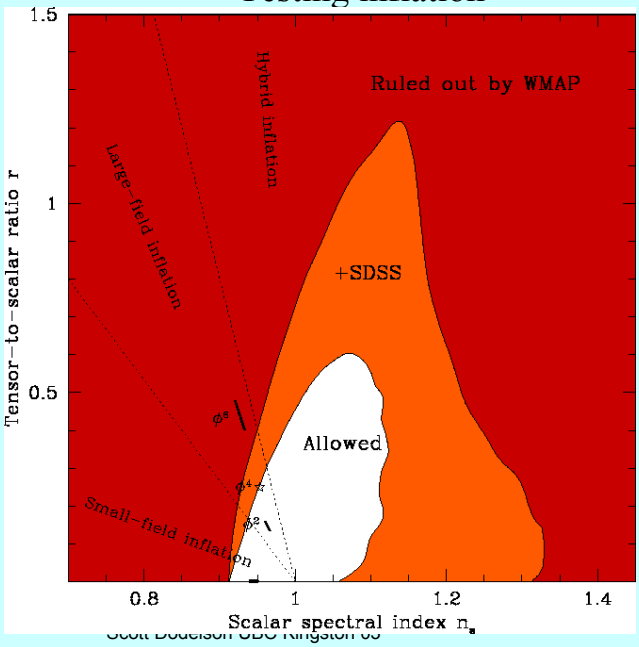


CMB

+

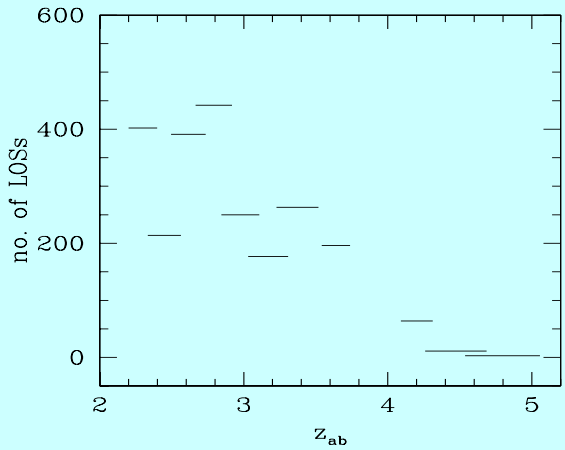
LSS

Testing inflation



Lyman Alpha Forest

3000 QSOs with absorption lines from redshifts 2 to 4.2

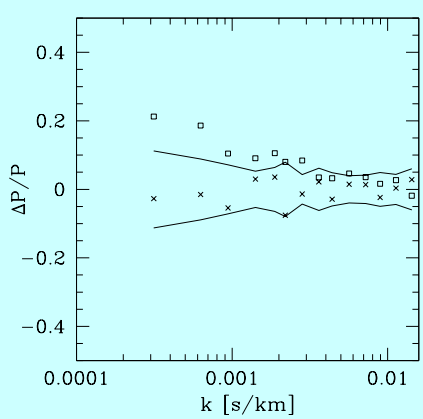


Hui et al.

Lyman Alpha Forest

Goal: 1D Flux power spectrum

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



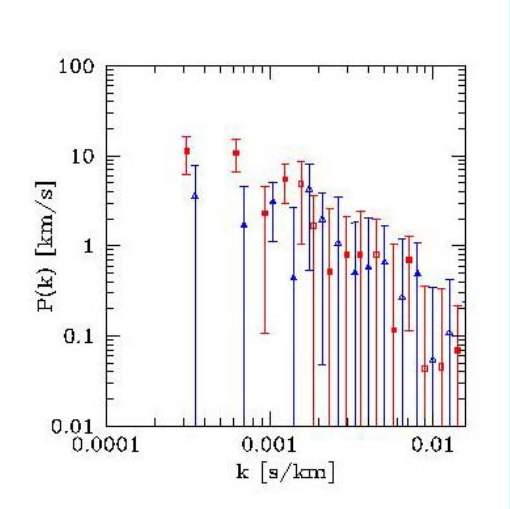
Simple thing works. Composite spectrum works very well.

Lyman Alpha Forest

Systematics Check:

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

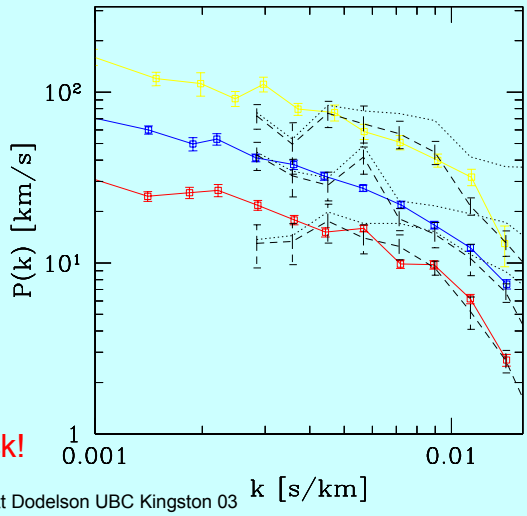
Possible problems on large scales. No problems on small scales.



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

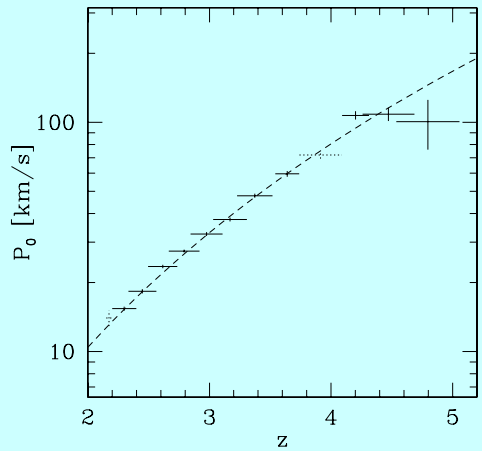
Good agreement with Keck!



Lyman Alpha Forest

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

(Parenthetically: No evidence for Helium reionization)

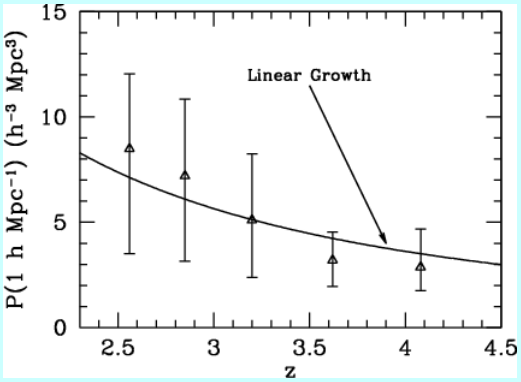


Convert 1D Flux Spectrum to 3D Linear Matter Power Spectrum

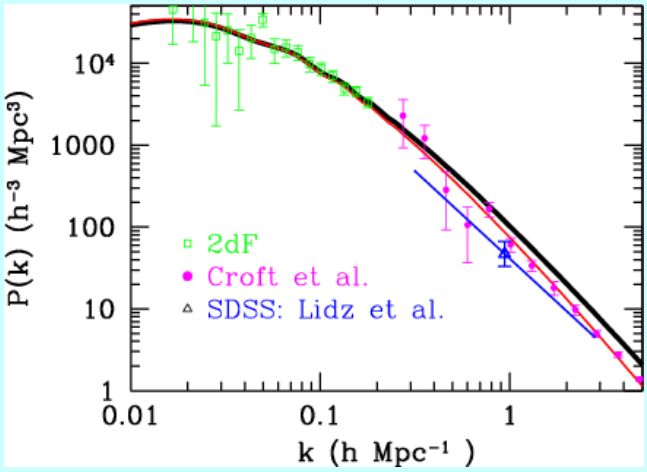
- Run many simulations with CDM-like spectra
- Extract Flux power spectra from each simulation
- Fit amplitude and slope of power at 1 Mpc

Lidz et al.

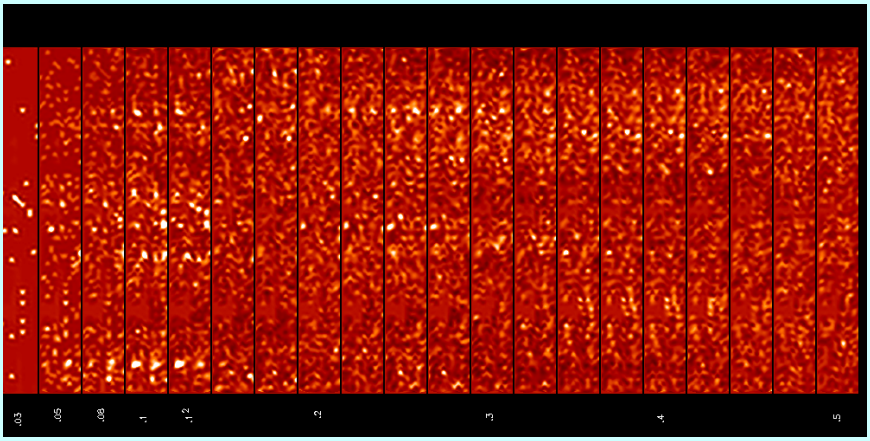
Lyman Alpha Forest



Lyman Alpha Forest

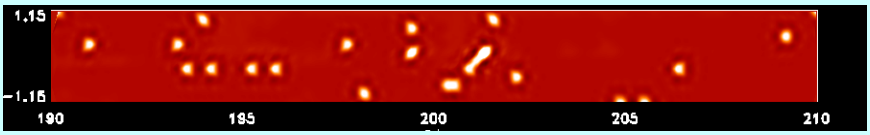


Galaxy Clusters



Scott Dodelson UBC Kingston 03

Galaxy Clusters



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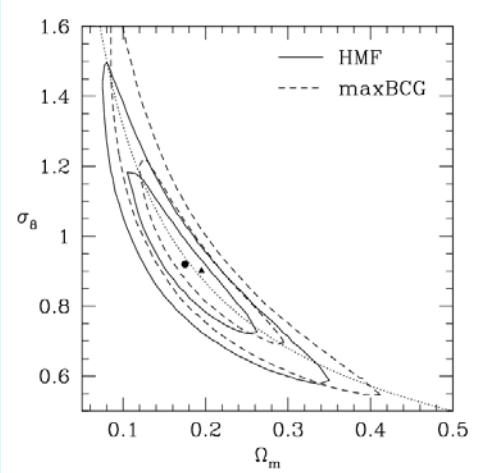
Galaxy Clusters

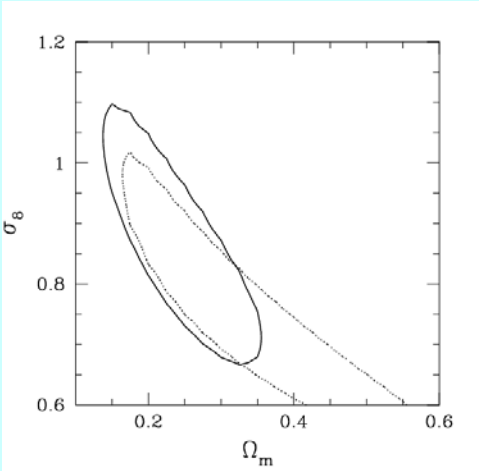
- Two different cluster identification algorithms give very similar cosmological constraints.
- Slightly lower σ_8 than X-ray determinations



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?

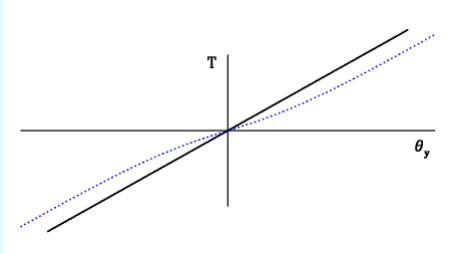


Pierpaoli, Borgani, Scott & White 2003

Galaxy Clusters

Lensing of CMB by Cluster

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



Seljak & Zaldarriaga 1999

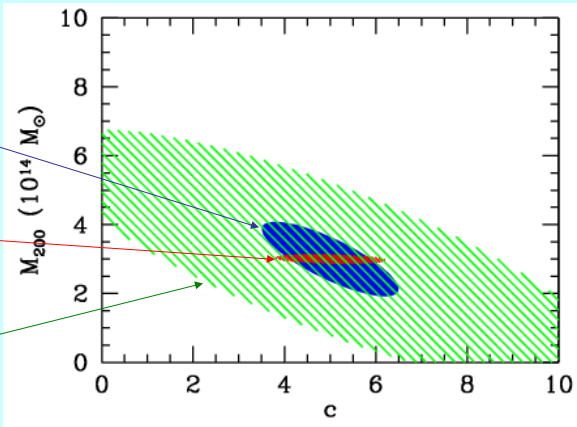
Galaxy Clusters

Fit z=0.3 cluster with NFW profile

Ellipticities of background galaxies

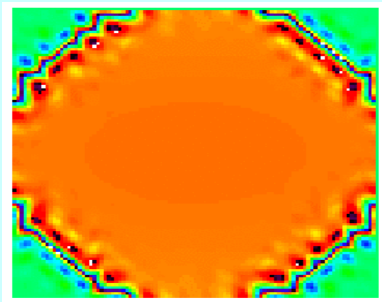
Lensing of CMB (.5' pixels ; 1 μK)

CMB Lensing including projection effects

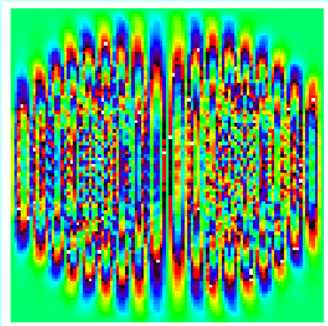


Galaxy Clusters

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



Mode most contaminated by LSS



Mode least contaminated by LSS

Galaxies & Matter

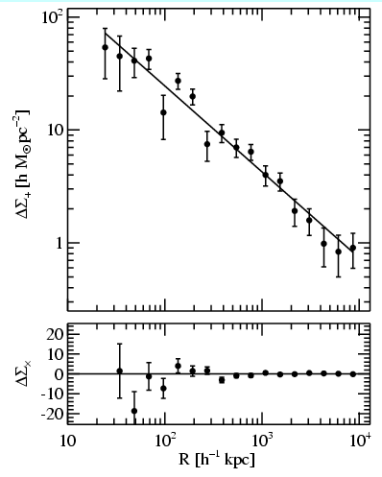
Sheldon et al. 2003

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

Galaxies & Matter

- Measure azimuthally averaged tangential shear as a function of radius

- Systematic check: No B-mode

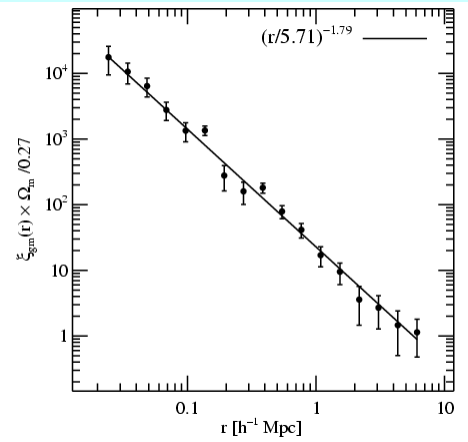


Sheldon et al. 2003

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.



Sheldon et al. 2003

Galaxies & Matter

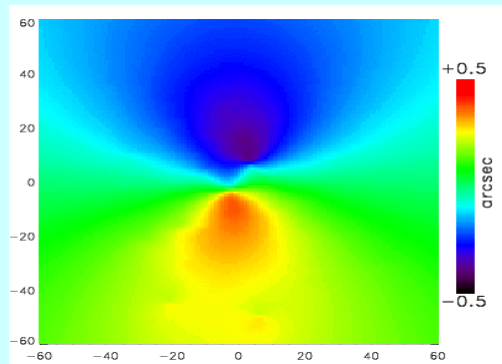
$$\delta T = \frac{\partial T}{\partial y}\delta\theta_y$$

Observed anisotropy

Gradient of primordial CMB, mean zero and rms 0.22 μK/arcsec

Deflection angle

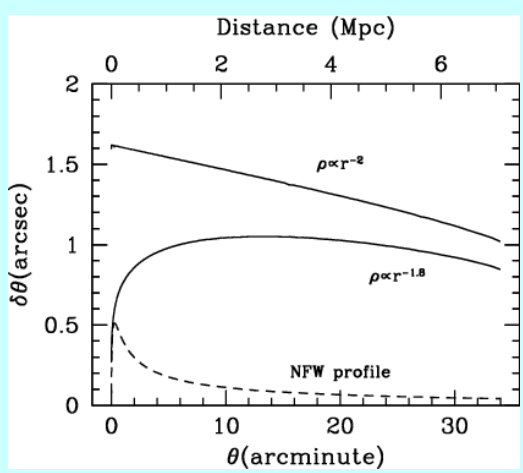
Deflection due to massive galaxy at z=1



Dodelson & Starkman 2003

Galaxies & Matter

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



Dodelson & Starkman 2003

Conclusions

Microwave/Optical link strengthening

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