Detection of gravitational lensing in the CMB

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University of Chicago
June 2007, "Life Beyond the Gaussian"

Reference: Smith, Zahn, and Doré, 0705.3980

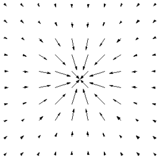
with key contributions from Mike Nolta

Gravitational lensing in the CMB

CMB photons are deflected by gravitational potentials between last scattering and observer. This remaps the CMB while preserving surface brightness:

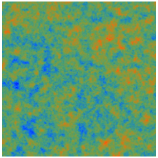
$$T(\widehat{\mathbf{n}}) \to T(\widehat{\mathbf{n}} + \mathbf{d}(\widehat{\mathbf{n}}))$$

where $\mathbf{d}(\widehat{\mathbf{n}})$ is a vector field giving the deflection angle along line of sight $\widehat{\mathbf{n}}$.



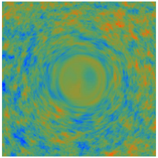
Deflection angles

$+$



Unlensed CMB

$\longrightarrow$



Lensed CMB

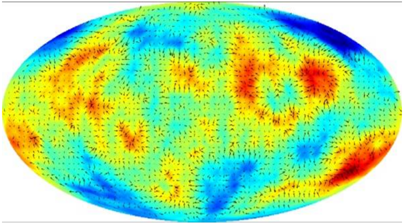
Wayne Hu

Gravitational lensing in the CMB

To first order, deflection angles are a pure gradient field:

$$d_a(\widehat{\mathbf{n}}) = \nabla_a \phi(\widehat{\mathbf{n}})$$

where the lensing potential is given by the line-of-sight integral



Antony Lewis

$$\phi(\widehat{\mathbf{n}}) = -2 \int_0^{\chi_*} d\chi \left(\frac{\chi_* - \chi}{\chi \chi_*} \right) \Psi(\chi \widehat{\mathbf{n}}, \eta_0 - \chi)$$

RMS deflection: $\sim$2.5 arcmin, coherent on degree scales ($\ell \sim 100$)

Scope of talk: We will present a 3.4σ detection from combining WMAP3 with radio galaxy counts from NVSS.

CMB lensing: why bother?

Gravity waves from inflation:

- In polarization, lensing is a contaminant unless removed

Neutrino mass:

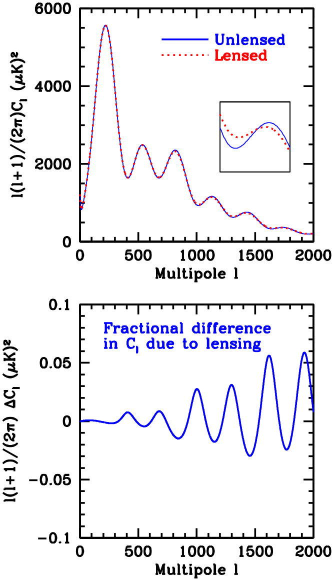
- Complementary to neutrino oscillations ($\sum m_\nu$ vs Δm_ν^2)
- e.g. Planck: ~ 0.14 eV from CMB lensing (Lesgourges et al 2005)

Counterpart to galaxy weak lensing:

- Probes same lensing potential as high-redshift galaxies, but completely different systematics
- CMB: Beam effects, point sources, SZ and other foregrounds
- Galaxies: PSF correction, intrinsic alignments, photo-z errors

Most robust measurement: cross-correlation between the two?

CMB lensing: power spectrum

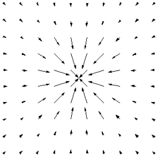


How can CMB lensing be detected in data?

First idea: Try to detect effect of lensing on power spectrum C_ℓ^{TT}.

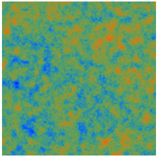
Effect is too small in WMAP: lensing can only be "detected" at $(1/3)\sigma$ directly from power spectrum.

CMB lens reconstruction



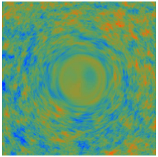
Deflection angles

+



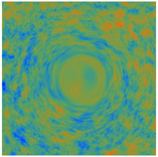
Unlensed CMB

$\longrightarrow$



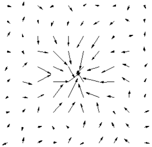
Lensed CMB

Idea: From observed CMB, reconstruct deflection angles (Hu 2001)



Lensed CMB

$\longrightarrow$



Reconstruction + noise

CMB lens reconstruction

Lensing weakly correlates CMB modes with $\mathbf{l} \neq \mathbf{l}'$:

$$\langle T(\mathbf{l}) T(\mathbf{l}')^* \rangle \propto \phi(\mathbf{l} - \mathbf{l}').$$

Reconstructed field $\widehat{\phi}$ is quadratic in CMB temperature:

$$\begin{aligned}
\widehat{\phi}(\widehat{\mathbf{n}}) &= \partial^a \left[\alpha(\widehat{\mathbf{n}}) \partial_a \beta(\widehat{\mathbf{n}}) \right] \\
\alpha(\widehat{\mathbf{n}}) &= \int \frac{d^2 l}{(2\pi)^2} \left(\frac{1}{C_\ell^{TT} + N_\ell^{TT}} \right) T(\mathbf{l}) e^{i \mathbf{l} \cdot \widehat{\mathbf{n}}} \\
\beta(\widehat{\mathbf{n}}) &= \int \frac{d^2 l}{(2\pi)^2} \left(\frac{C_\ell^{TT}}{C_\ell^{TT} + N_\ell^{TT}} \right) T(\mathbf{l}) e^{i \mathbf{l} \cdot \widehat{\mathbf{n}}}
\end{aligned}$$

Second idea for detecting CMB lensing: look for extra power in $\widehat{\phi}$.

Compute $C_\ell^{\phi\phi}$: quadratic in $\widehat{\phi}$, or four-point in CMB.

WMAP3: statistical errors only give 1σ.

In addition, systematics likely to be difficult. . .

CMB lens reconstruction: cross correlation

Third idea for detection: cross-correlate $\widehat{\phi}$ to galaxy counts

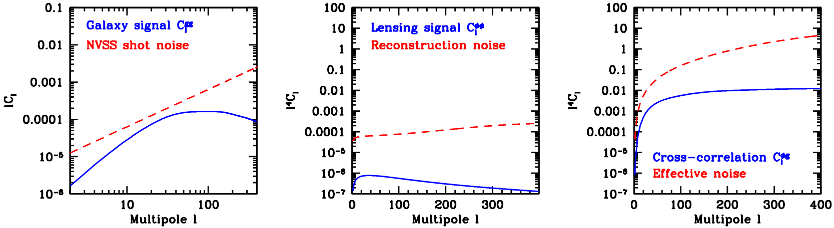
$\Rightarrow$ Highly correlated, so "boosts" signal-to-noise

Systematics also tamer in cross-correlation

Compute $C_\ell^{\phi g}$: three-point estimator

First attempt: LRG's from Sloan, 1σ result (Hirata et al 2004)

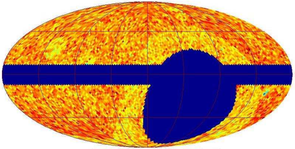
Our approach: Radio galaxies from NVSS.



NVSS: NRAO VLA Sky Survey

1.4 GHz sky catalog, 50% complete at 2.5 mJy.

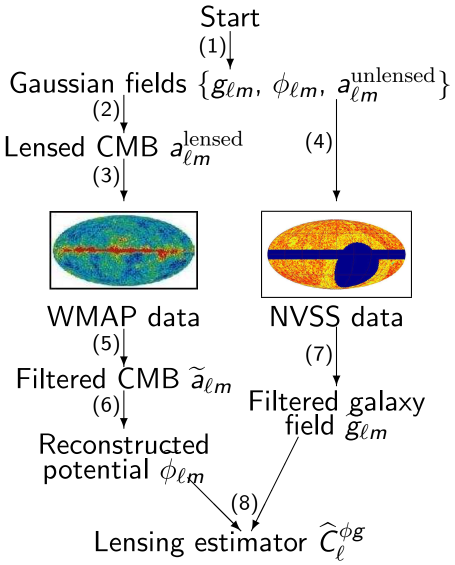
Mostly AGN-powered radio galaxies, quasars, nearby star-forming galaxies



Well-suited for cross-correlating to WMAP lensing potential:

- Nearly full sky coverage ($f_{\rm sky} = 0.82$)
- Low shot noise ($N_{\rm gal} \sim 1.8 \times 10^6$)
- High median redshift ($z \sim 0.9$)

Pipeline



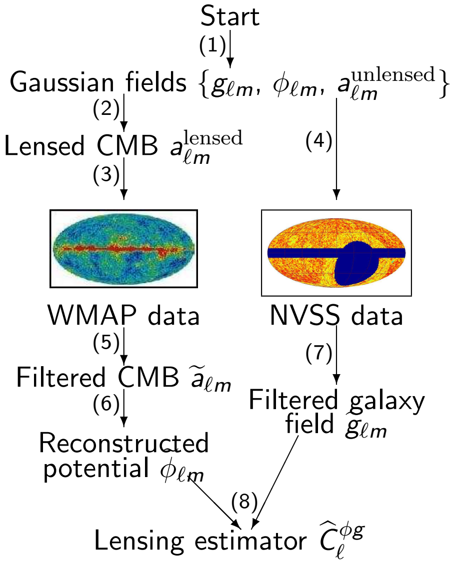
Simulation (steps 1-4):

- Monte Carlo simulations used for calibration, assigning errors

Analysis (steps 5-8):

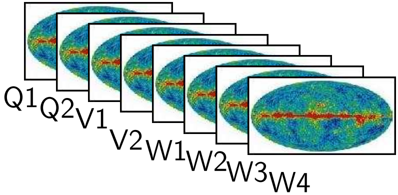
- Filter WMAP (Q-band, V-band, W-band) and NVSS datasets
- Lens reconstruction from WMAP
- Cross-correlate: estimate $C_{\ell}^{\phi g}$ in bands

Pipeline

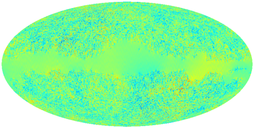


CMB filtering (step 5):

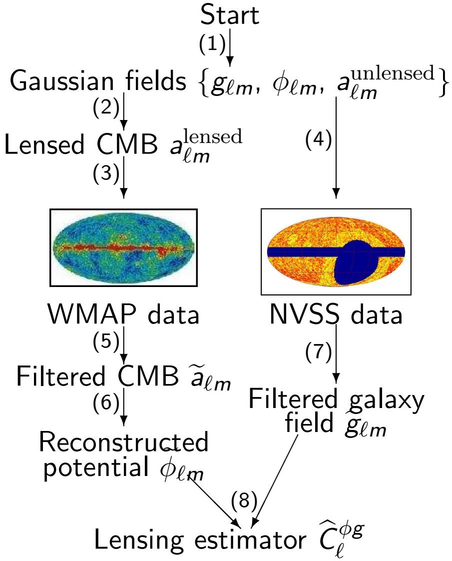
Input: raw WMAP maps



Output: maximum likelihood map obtained by combining all channels

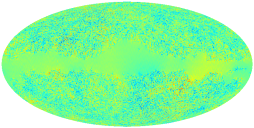


Pipeline

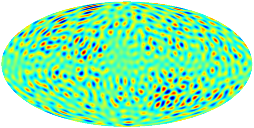


Lens reconstruction (step 6):

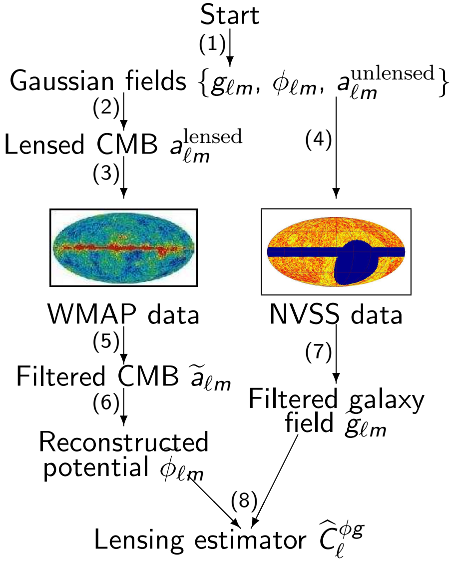
Input: Maximum likelihood CMB map



Output: Reconstructed lensing potential $\widehat{\phi}$ (shown bandlimited to $20 \le \ell \le 40$):

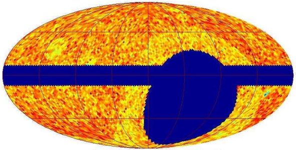


Pipeline

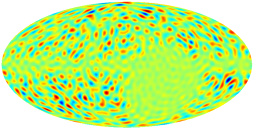


NVSS filtering (step 7):

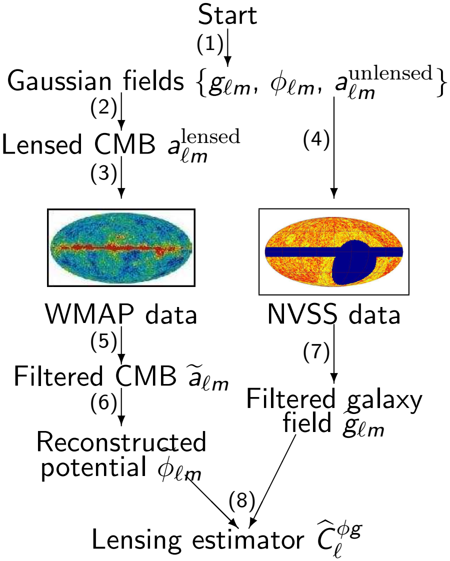
Input: NVSS source catalog



Output: Maximum likelihood galaxy map (shown bandlimited to $20 \leq \ell \leq 40$):

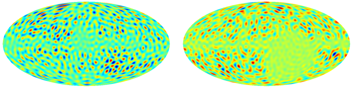


Pipeline



Cross-correlation (step 8):

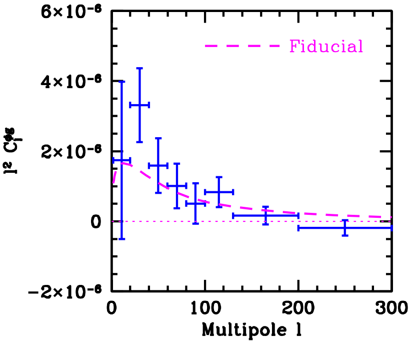
Input: Lensing potential and galaxy fields (shown bandlimited to $20 \leq \ell \leq 40$):



Output: Cross correlation $C_\ell^{\phi g}$, with estimator normalization and statistical errors computed by Monte Carlo

$$\ell^2 C_\ell^{\phi g} = (33.2 \pm 10.5) \times 10^{-7}$$
$$(20 \leq \ell \leq 40, stat.)$$

Main result (statistical errors only)



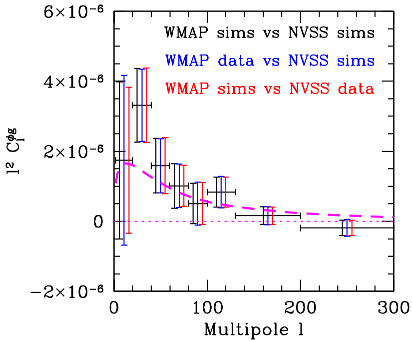
- Values obtained by cross-correlating WMAP and NVSS datasets
- Monte Carlo errors obtained by cross-correlating WMAP and NVSS simulations

Several-sigma (relative to simulations) correlation observed in data

How do we know that the correlation is lensing, rather than something else?

Rest of talk: Null tests, systematics.

Check: different ways of computing Monte Carlo errors



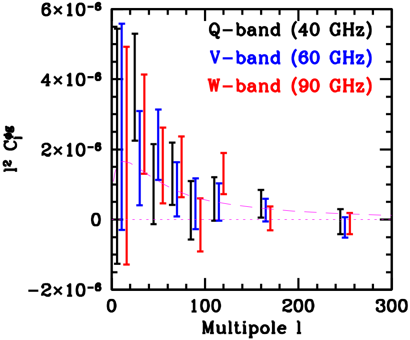
Our default procedure is to correlate pairs of sims, but could also:

- Correlate WMAP data with NVSS sims
- Correlate WMAP sims with NVSS data

Three-way consistency is an important check

Shows that result only depends on correctness of one of the simulation pipelines

Check: frequency dependence



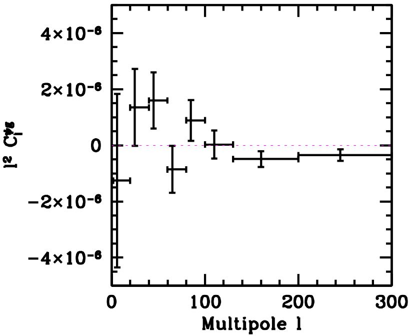
Analyze each frequency channel in WMAP separately

Results consistent between frequencies

Because different frequencies are correlated, cannot combine three sets of error bars in a straightforward way.

Best overall result obtained from Q+V+W combined map as shown previously

Check: curl null test



Lensing potential is expected to be a pure gradient:

$$d_a(\widehat{\mathbf{n}}) = \nabla_a \phi(\widehat{\mathbf{n}})$$

but consider ficticious curl component instead:

$$d_a(\widehat{\mathbf{n}}) = \epsilon_{ab} \nabla^b \psi(\widehat{\mathbf{n}})$$

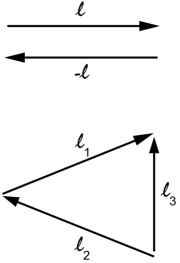
Null test: Should get $C_\ell^{\psi g} = 0$.

$\chi^2 = 12.1/8$: high at 1σ, so $C_\ell^{\psi g}$ null test passes.

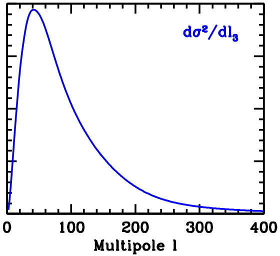
Null test cannot monitor parity-invariant contaminants (e.g. point sources), analagous to $C_\ell^{EB} = 0$ in CMB polarization experiments.

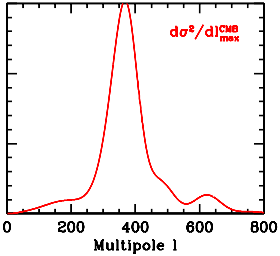
Bispectrum perspective

Alternate approach to lensing estimator $C_\ell^{\phi g}$: optimal estimator for 3-point signal $b_{\ell_1 \ell_2 \ell_3}$ induced by gravitational lensing.



Bispectrum: depends on triple $\ell_1 \ell_2 \ell_3$ (power spectrum C_ℓ depends on single ℓ).





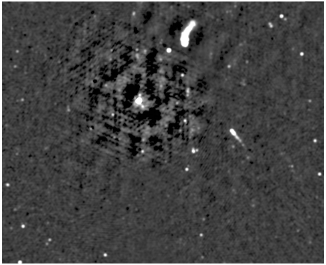
NVSS systematics: bright sources

NVSS maps show "ringing" near bright sources

We treat this by masking ~ 2000 sources > 1 Jy

Source mask included in statistical errors

We include the mask in all results, but neither C_ℓ^{gg} nor $C_\ell^{\phi g}$ changes significantly.



NVSS raw map: $2^\circ \times 2^\circ$

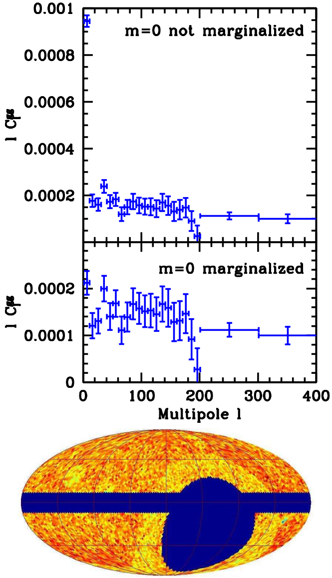
NVSS systematics: declination gradients

Consider NVSS galaxy power spectrum C_ℓ^{gg}.

If analyzed straightforwardly, obvious systematic contamination at low ℓ

Known systematic effect: equatorial striping (excess power for $\ell \lesssim 100$)

Projecting out $m = 0$ modes appears to remove contaminant (no evidence for higher values of m)

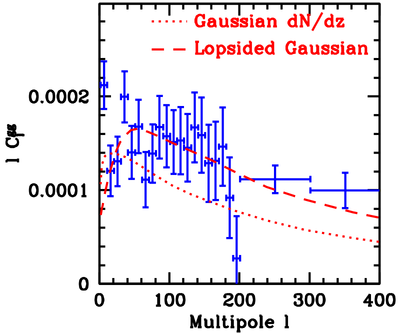


NVSS systematics: modeling uncertainty

NVSS redshift distribution is not known very well; we found that existing models, e.g. Gaussian (Pietrobon 2006)

$$\frac{dN}{dz} \propto \exp\left(-\frac{(z-1.1)^2}{2(0.8)^2}\right)$$

did not fit C_ℓ^{gg} well.



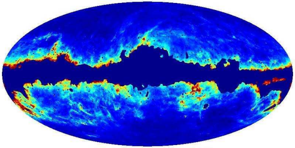
However a small tweak, e.g. "lopsided Gaussian":

$$\frac{dN}{dz} \propto \begin{cases} \exp\left(-\frac{(z-1.1)^2}{2(0.8)^2}\right) & (z < 1.1) \\ \exp\left(-\frac{(z-1.1)^2}{2(0.3)^2}\right) & (z > 1.1) \end{cases}$$

results in a good fit. (Exception: $\ell \leq 10$.)

WMAP systematics: galactic foregrounds

Most of the foreground signal excluded by Kp0 mask: galactic plane, $\sim$ 700 resolved point sources.



Dust: use FDS template (Finkbeiner et al 1999)

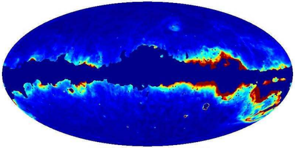
Frequency dependence $\propto \nu^2$

V-band (60 GHz) RMS: 6.4 μK.

Free-free emission: use $H\alpha$ template (Finkbeiner 2003, Bennett et al 2003)

Frequency dependence $\propto \nu^{-2.14}$

V-band (60 GHz) RMS: 4.8 μK.



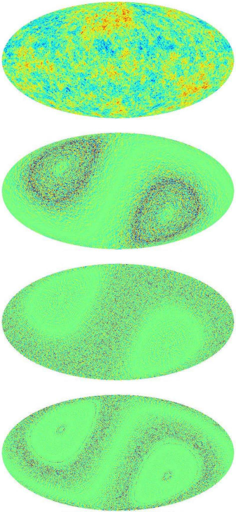
WMAP systematics: galactic foregrounds

Synchrotron: templates available on degree scales (Haslam 408 MHz, WMAP K – Ka), but not on CMB scales ($\ell \sim 400$) used for lensing.

Assume systematic errors from synchrotron equal to dust + free-free!

$(\ell_{\rm min}, \ell_{\rm max})$	Statistical	Galactic Dust	Galactic Free-free	Galactic Total
$(2, 20)$	17.4 ± 22.4	± 0.4	± 1.4	± 3.6
$(20, 40)$	33.2 ± 10.5	± 0.2	± 0.5	± 1.4
$(40, 60)$	15.9 ± 7.8	± 0.2	± 0.3	± 1.0
$(60, 80)$	10.1 ± 6.3	± 0.1	± 0.3	± 0.8
$(80, 100)$	5.1 ± 5.8	± 0.1	± 0.3	± 0.8
$(100, 130)$	8.3 ± 4.3	± 0.1	± 0.2	± 0.6
$(130, 200)$	1.6 ± 2.5	± 0.1	± 0.1	± 0.4
$(200, 300)$	-1.9 ± 2.2	± 0.1	± 0.1	± 0.4

WMAP systematics: beam asymmetry



WMAP beams are asymmetric, but treated as isotropic in pipeline

(Q-band: 20% elliptical, V,W-band: 10-20 dB substructure)

- Include beam asymmetry in simulations, treat as source of systematic error.
- Multipole expansion of beam ($s = 0$ isotropic, $s = 1$ dipole, ...)
- Convolution with higher-s multipoles includes sky-varying kernel which depends on scan strategy

WMAP systematics: beam uncertainty

After beam asymmetry, the only beam effect is uncertainty in the isotropic part

$(\ell_{\min}, \ell_{\max})$	Statistical	Asymmetry	Beam Uncertainty	Total
$(2, 20)$	17.4 ± 22.4	± 0.9	± 0.3	± 1.2
$(20, 40)$	33.2 ± 10.5	± 0.2	± 0.1	± 0.3
$(40, 60)$	15.9 ± 7.8	± 0.1	± 0.1	± 0.2
$(60, 80)$	10.1 ± 6.3	± 0.1	± 0.1	± 0.2
$(80, 100)$	5.1 ± 5.8	± 0.1	± 0.1	± 0.2
$(100, 130)$	8.3 ± 4.3	± 0.1	< 0.1	± 0.2
$(130, 200)$	1.6 ± 2.5	< 0.1	< 0.1	± 0.1
$(200, 300)$	-1.9 ± 2.2	< 0.1	< 0.1	± 0.1

Point sources: approach

Only CMB point sources which are correlated to NVSS contribute

Too difficult to estimate point source contibution from models!

Approach: estimate level of point source contamination from data

Cross spectrum C_ℓ^{Tg} has wrong scaling; must estimate bispectrum

$$\Delta C_\ell^{Tg} \propto \sum_i S_i n_i \qquad b_{\ell_1 \ell_2 \ell_3} \propto \sum_i S_i^2 n_i$$

Most general bispectrum considered: $b_{\ell_1 \ell_2 \ell_3} = F(\ell_3)$

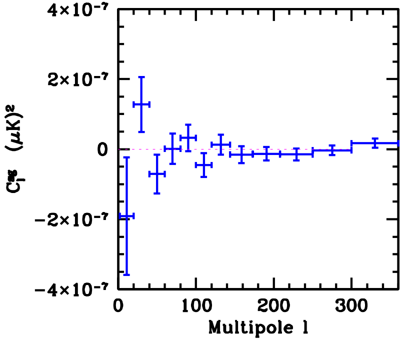
- Allows arbitrary point source clustering on degree scales
- Assumes clustering negligible on CMB scales ($\ell \sim 400$)
- Nonlinear evolution neglected

Point sources: estimator

Optimal estimator for point source bispectrum:

- "Quadratic reconstruction" $s(\widehat{\mathbf{n}})$ for point source power in CMB
- Cross-correlate to NVSS: C_ℓ^{sg}.

No evidence for point sources seen in data: $\chi^2 = 11.7/12$.



Allows tight systematic errors: any point source contribution must be hidden beneath the detection threshhold

Point sources: systematic errors

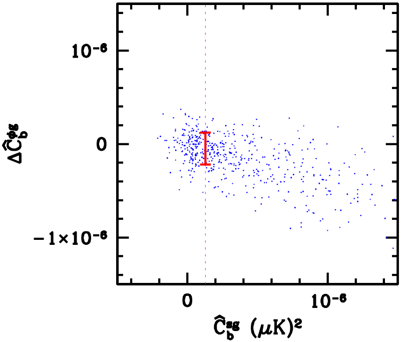
Consider ensemble of simulations with varying point source levels

Restrict to simulations with same observed point source level as data

Point source contribution to lensing:

$$\Delta \widehat{C}_\ell^{\phi g} = (-0.5 \pm 1.7) \times 10^{-7}$$

Treat shift as part of systematic error: $\pm 2.2 \times 10^{-7}$.



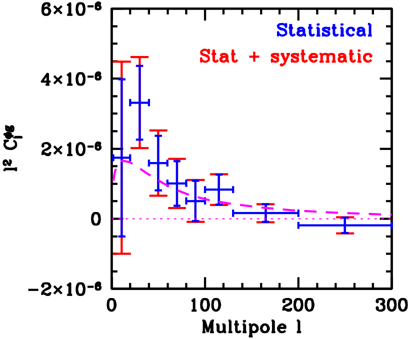
One final detail: Sunyaev-Zeldovich effect can be treated as part of point source contribution for WMAP (SZ clusters not resolved by WMAP beam).

Point sources: bottom line

Point sources are largest source of systematic error:

$(\ell_{\min}, \ell_{\max})$	Statistical	Point source + SZ Unresolved	Resolved	Total
$(2, 20)$	17.4 ± 22.4	± 10.9	± 0.5	± 11.4
$(20, 40)$	33.2 ± 10.5	± 4.9	± 1.0	± 5.9
$(40, 60)$	15.9 ± 7.8	± 2.8	± 1.5	± 4.3
$(60, 80)$	10.1 ± 6.3	± 2.0	± 0.3	± 2.3
$(80, 100)$	5.1 ± 5.8	± 1.1	± 0.2	± 1.3
$(100, 130)$	8.3 ± 4.3	± 0.6	± 0.2	± 0.8
$(130, 200)$	1.6 ± 2.5	± 0.3	± 0.1	± 0.4
$(200, 300)$	-1.9 ± 2.2	± 0.3	± 0.1	± 0.4

Final result (including systematic errors)



Combine statistical errors with systematic errors considered previously:

- WMAP beam effects
- Galactic CMB foregrounds
- Point sources + SZ

To assess total statistical significance: fit to one large bandpower in multiple of fiducial $C_\ell^{\phi g}$.

Result: 1.15 ± 0.34, i.e. a 3.4σ detection, consistent with the fiducial model.

Conclusions

- Milestone: 3.4σ detection, not enough for precision cosmology but in agreement with the predicted level.
- Future prospects: unlikely to exceed 5σ in next few years; different story after Planck/SPT/ACT (e.g. Hu 2001: $\sim 60\sigma$ from Planck alone).
- Many systematic checks: "sims vs data", frequency dependence, curl null test, WMAP beam effects, point sources + SZ
- Systematics largely unexplored outside WMAP/NVSS datasets: point source + SZ contamination seems to be the biggest problem (in particular, beam effects are small) but this may not apply to upcoming higher-resolution surveys.