Detection of Gravitational Lensing in The CMB

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arXiv:0705.3980, PRD in press

CMB Lensing

- gravitational lensing entails a remapping of the primary CMB anisotropies

$$\tilde{T}(\hat{n}) = T(\hat{n} + \mathbf{d}(\hat{n}))$$

$$\mathbf{d}_a(\hat{n}) = \nabla_a \phi(\hat{n})$$

deflection field (linear theory)

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

Lensing potential

- Deflection $\sigma(d)$~2' coherent on degree scales

blanchard & Schneider 87
zaldarriaga & Seljak 98
Benabed & bernardeau 00
Okamoto & Hu 03
Lewis & challinor 06
...

- Clearly next frontier for CMB studies
  - Could contaminate CMB polarization based primordial gravity wave detection if not "cleaned"
  - also yield unique cosmological constraints (e.g. M_ν=0.04eV with planck alone, lesgourgues et al. 06)
  - different systematics: no overlap between sources and lenses, well defined z source plane (0.09% in z...), well understood PSF...

Can we measure it now with WMAP?

Auto- and cross- Correlations

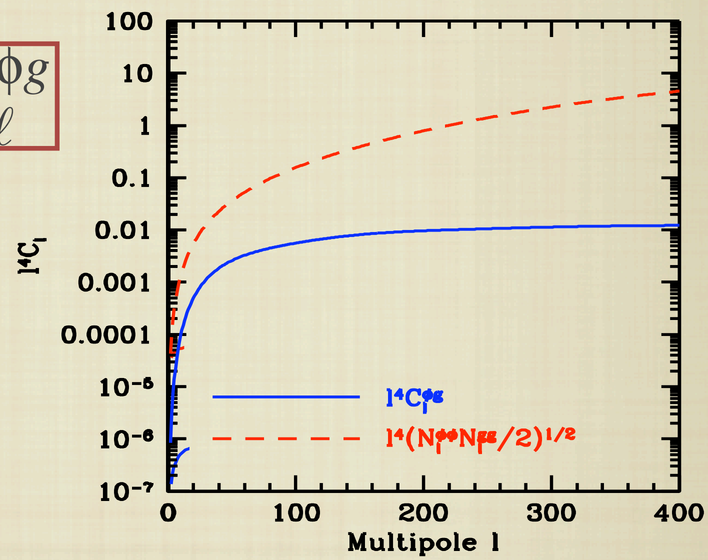
- Gravitational Lensing Effect on the CMB temperature Auto power spectrum is too small to be detected by WMAP (~0.3σ)
- Auto-power spectrum of Φ is not measurable for WMAP (~1σ)...

- ... but Cross-power spectrum of Φ with some tracer of the gravitational potential, eg a galaxy survey, could yield a detection...
- Analogous to the TE signal for CMB analysis

- Cross-correlation is also advantageous in terms of systematics control

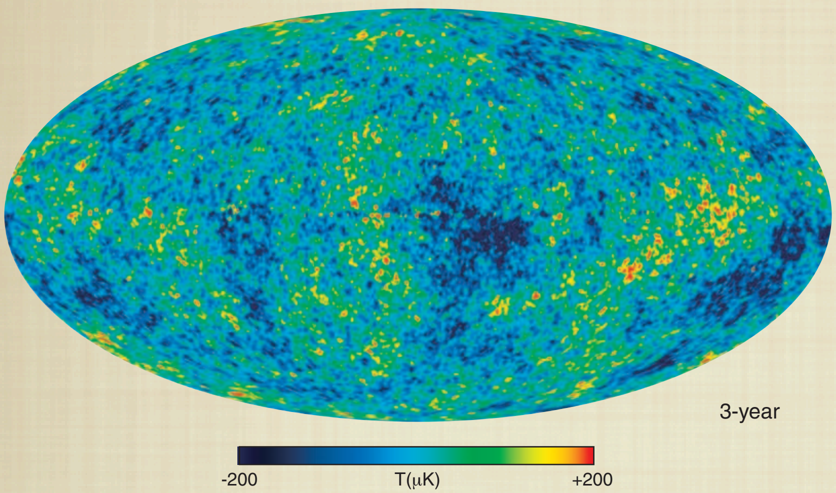
- Approach already studied by Hirata et al. 04 where WMAP-yr1 and SDSS LRGs were used to obtain a 1σ result

$$\ell^4 C_\ell^{\phi g}$$



DATASETS

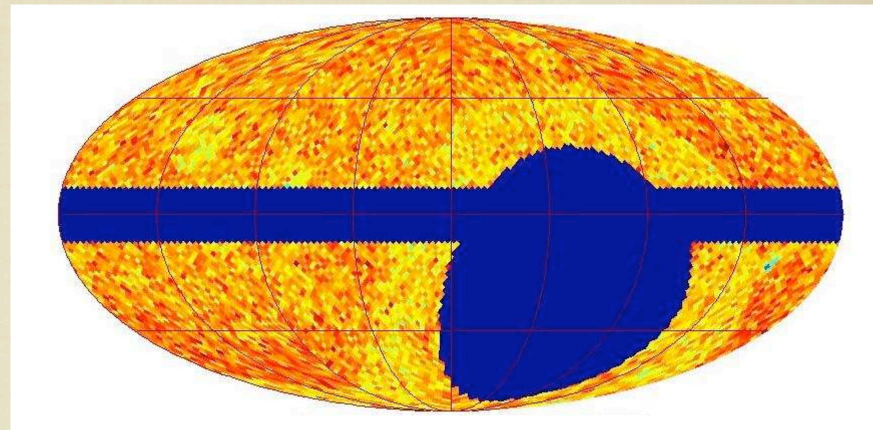
WMAP



- 3 yr public temperature maps
- 3 bands (Q, V and W) combined or not
- Use Kp0 mask to cover 79% of the sky (galactic emissions and pt sources)
- Take into account, for each DA:
  - beam window functions (circular)
  - exact beam patterns
- Exact inhomogeneous noise patterns

Hinshaw et al. 06

NVSS



- NRAO VLA Sky Survey
- 1.4 GHz continuum survey 50% complete at 2.5mJy
- AGN powered radio galaxies, quasars, near star-forming galaxies
- Covers 82% of the sky
- After removing bright objects (>1Jy)and low galactic latitude ($|b|<10$), we ended up using 1.29 10^6 gal., ie 1.6 10^5 gal/steradian
- Redshift distribution has a mean of 0.89 and peaks around 1.

Condon et al. 98

Optimal estimator

- Two stage process

  1- Reconstruction of the lensing potential with a quadratic estimator: divergence of the temperature weighted gradient

$$\alpha(x) = \sum_{\ell m} \tilde{a}_{\ell m} Y_{\ell m}(x)$$

$$\beta(x) = \sum_{\ell m} C_\ell^{TT} \tilde{a}_{\ell m} Y_{\ell m}(x)$$

$$\sum_{\ell m} \tilde{\phi}_{\ell m} Y_{\ell m}(x) = \nabla^a \left[\alpha(x) \nabla_a \beta(x) \right]$$

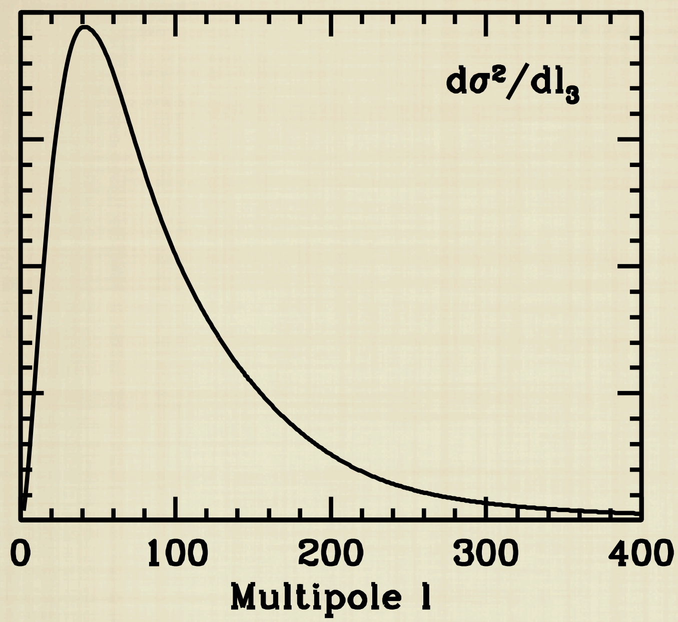
  2- Cross-correlation with the weighted Galaxy density field

$$\hat{C}_b^{\phi g} = \frac{1}{N_b} \sum_{\ell \in b} \sum_{|m| \leq \ell} \frac{1}{\ell^2} \left(\tilde{\phi}_{\ell m} - \langle \tilde{\phi}_{\ell m} \rangle \right)^* \tilde{g}_{\ell m}$$

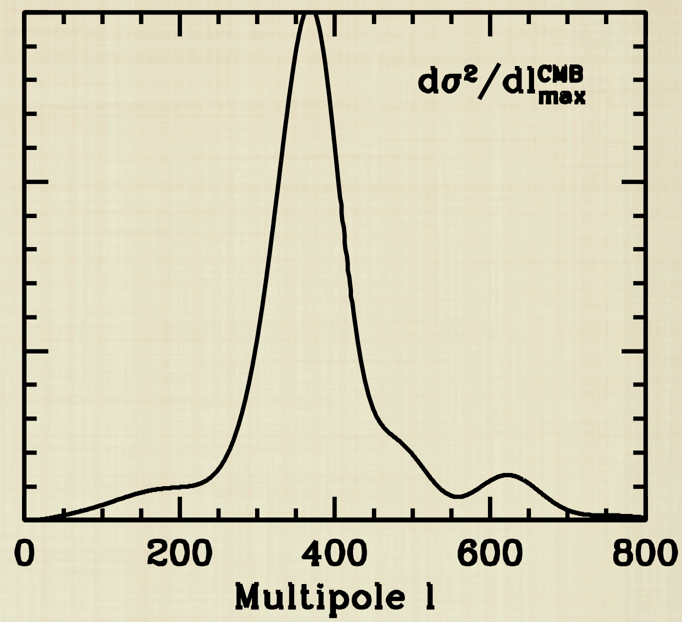
- $(S+N)^{-1}$ Weighting applied to $(7')^2$ pixels masked maps using a Conjugate Gradient algorithm with a multi-grid preconditioner
- Equivalent to the optimal bispectra estimator $\langle T_{LM} T_{LM} G_{LM} \rangle$
- We developed the associated measurement/simulation pipeline (~1 min-cpu/real) (cf Sudeep's talk)

Estimator sensitivity

Mean contribution to the square significance σ^2



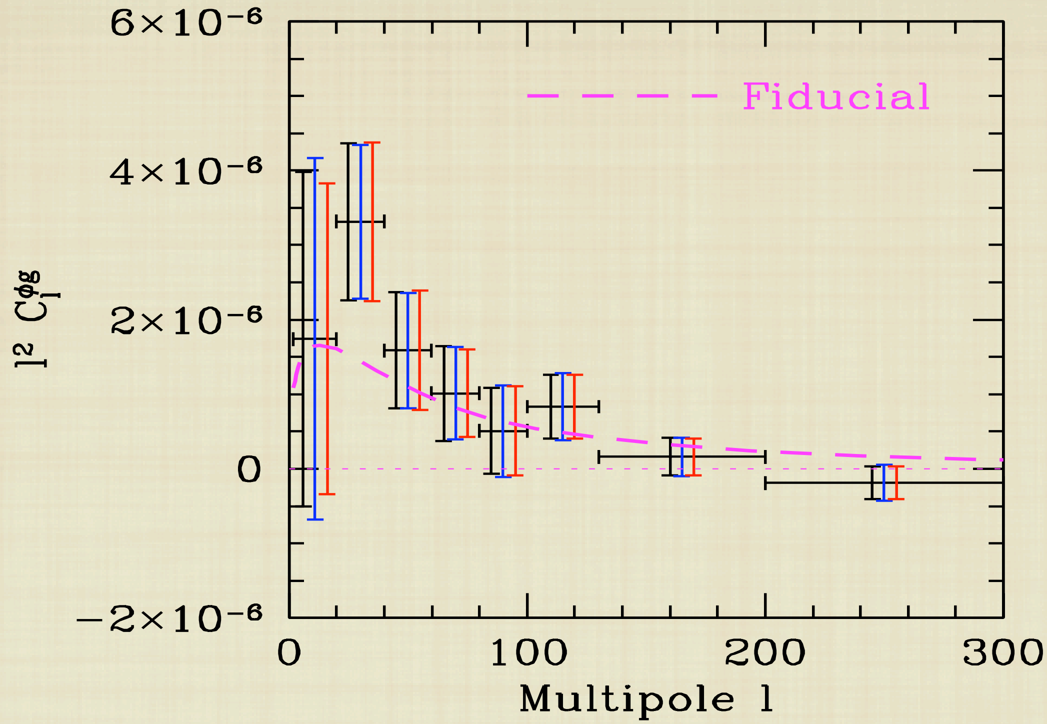
NVSS



CMB

- Most weights come from a coupling between the large scales Galaxy distribution (l~50, ~4 deg.) and smallest angular scales of the CMB (l~400, ~0.5 deg.)

Preliminary measurement



- Q, V and W bands combined
- Statistical 1σ errors only evaluated through Sim x Sim, Data x Sim or Sim x Data (consistency tests)
- ... But this result is just a teaser...

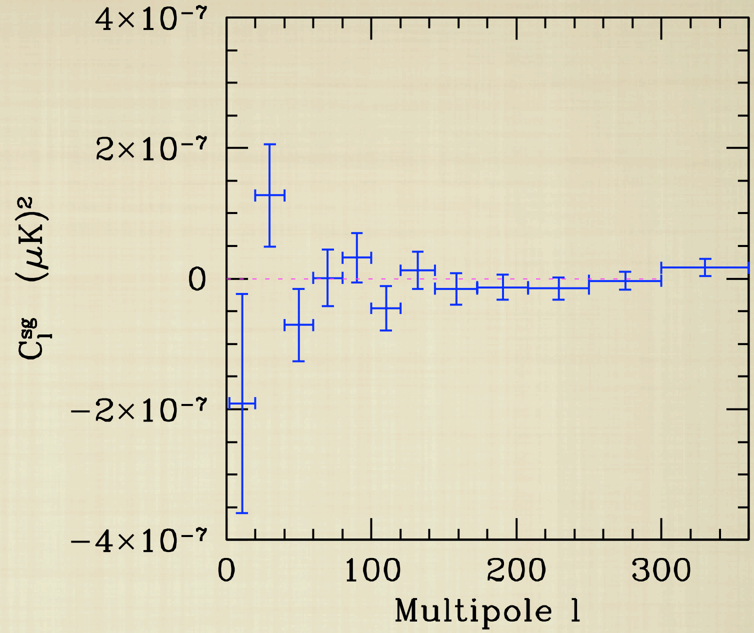
Systematics x Systematics

	WMAP	NVSS
Astrophysical	• Pt sources • SZ clusters • Residual Foregrounds	• (bright) Pt sources • Unknown redshift distribution • unknown bias
Instrumental and/or observational	• Beam uncertainties • Asymmetric Beam effects	• Declination dependancy • ringing around bright sources
Unknown	Bugs, Inconsistencies, etc.	

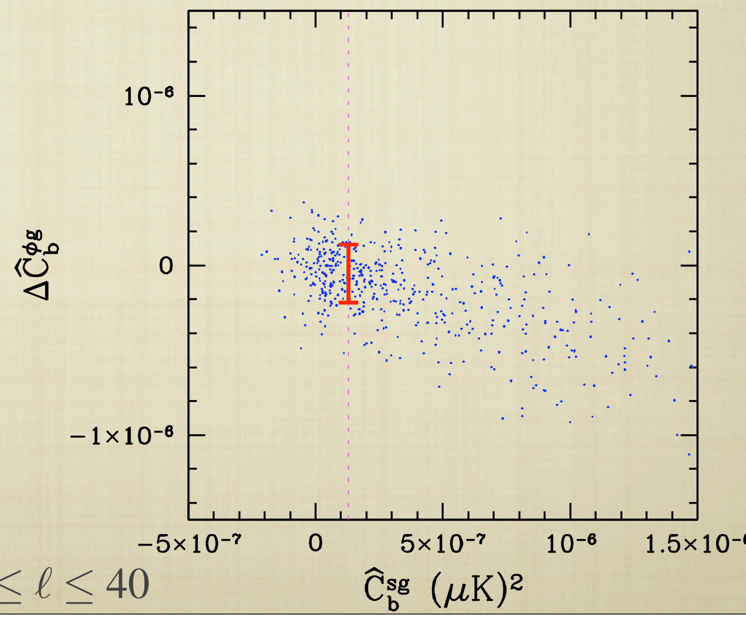
Much less of a tease...

Pt sources & SZ contribution

- Unresolved WMAP pt sources might appear in NVSS or just be correlated with NVSS pt sources ⇒ spurious correlations
- First To evaluate this signal we construct an optimal estimator to detect this correlation assuming a general ansatz for the bispectra (<TTG>) contribution, $B_{l1,l12,l3}=F_{l3}$
- We do not detect such a pt source contribution

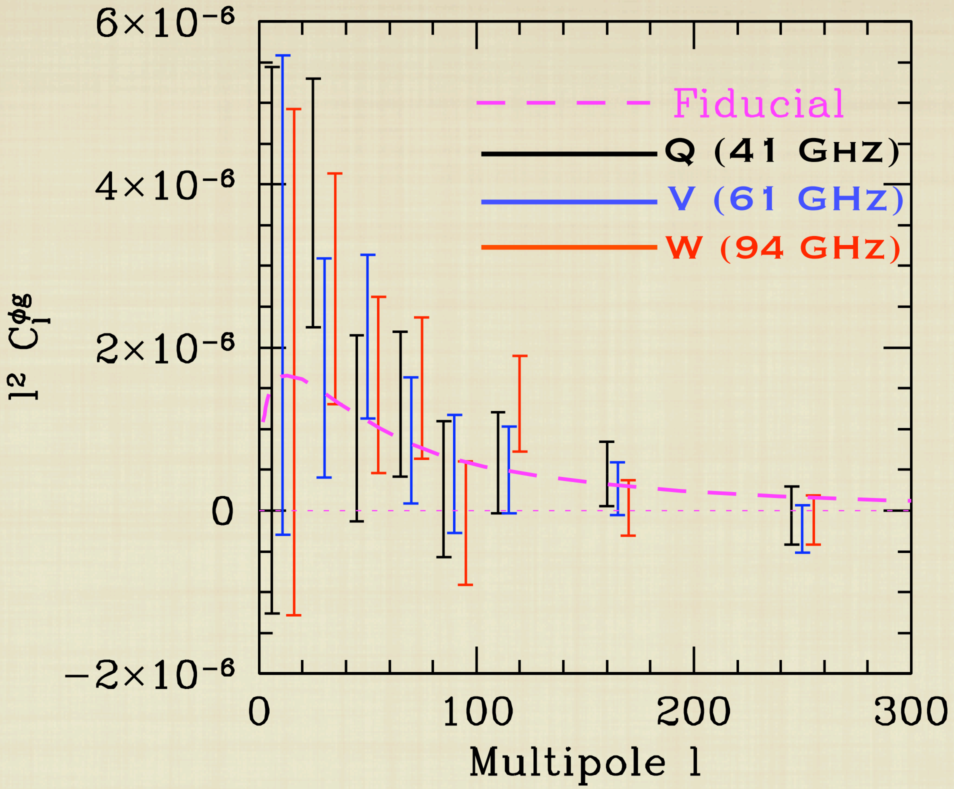


- Second we use this measurement to inform Specific simulations to evaluate the contribution to our lensing estimator
- This contribution will be the dominant since it accounts for about ~27% of the statistical error budget
- Note that this detection also includes SZ clusters since they are not resolved by WMAP beams



$20 \leq \ell \leq 40$

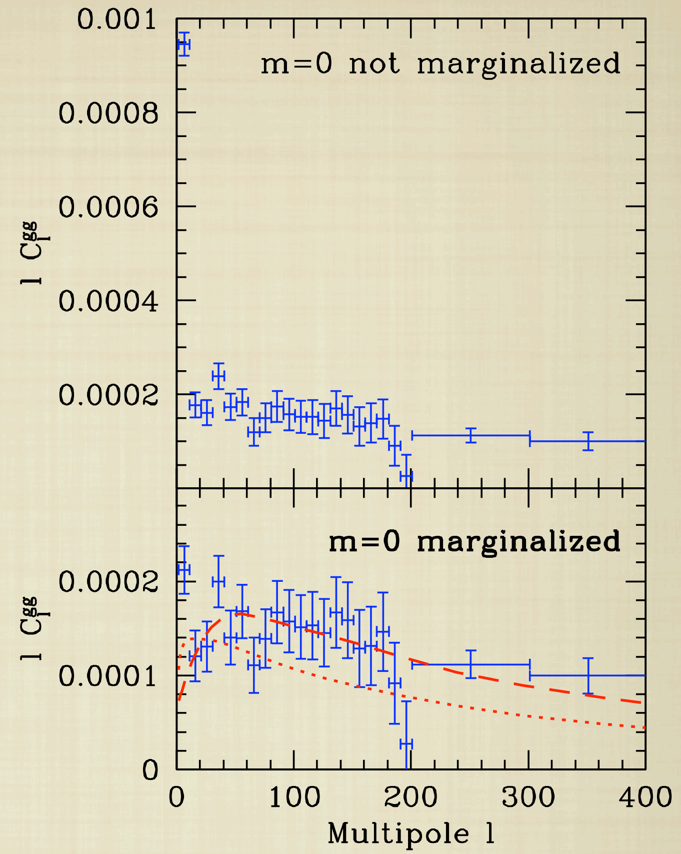
Frequency dependancy



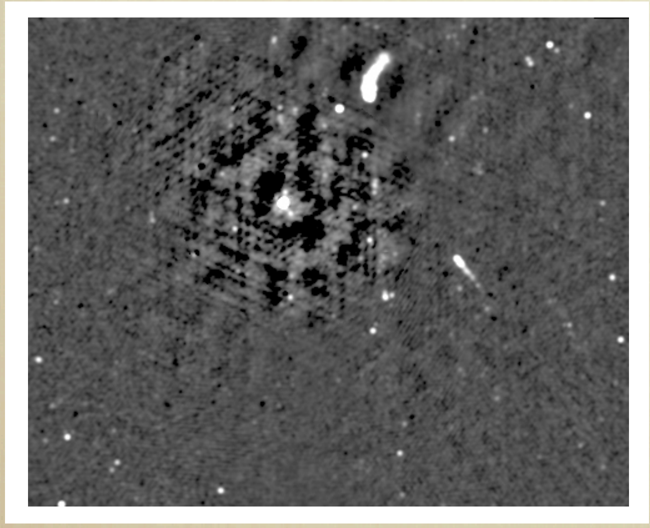
- Strong test for any astrophysical contamination
- no departure from thermal spectrum
- But we still marginalize over foreground templates (free-free and dust) which add ~15% to the statistical error budget

NVSS systematics - I

- Survey depth is a function of declination
- This creates spurious large scale power
- We thus marginalize over azimuthal mode in equatorial coordinates

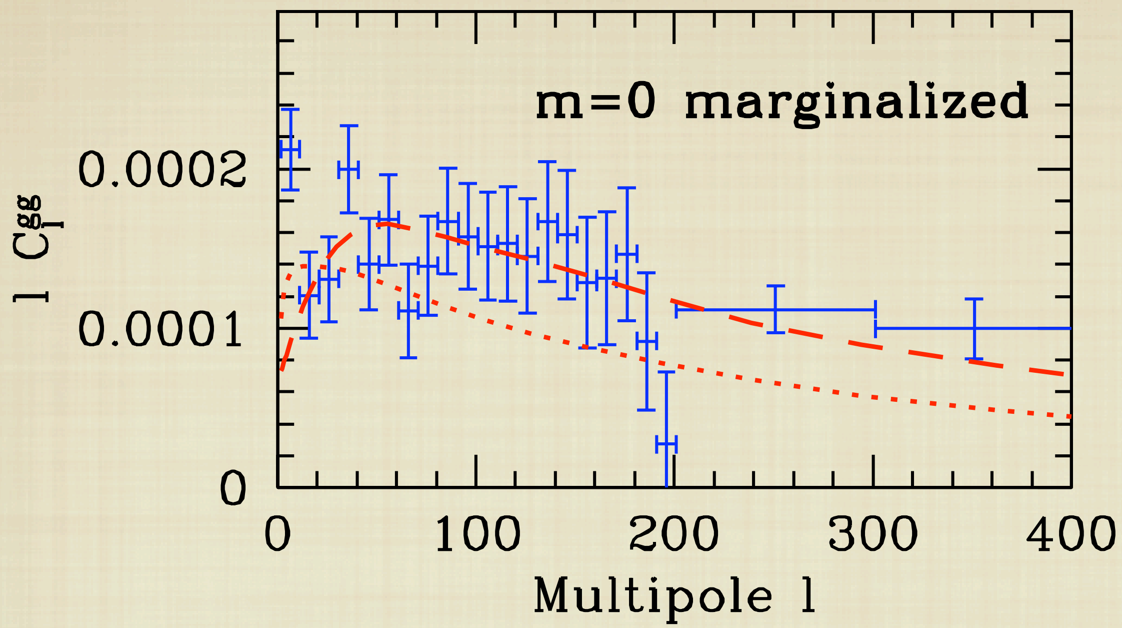


Raw 2°x2° field



- Ringing around bright sources
- We thus mask the bright sources (>1Jy) and 1 deg. disk around them

NVSS systematics - II



- Poorly known z distribution and bias of NVSS objects
- Existing models do not fit the auto-power spectrum so well (e.g. Pietrobon 06)
- We proposed a "lopsided Gaussian" which is a better fit (with b_G=1.7)

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

- But not critical for measurements since the CMB lensing kernel is broad

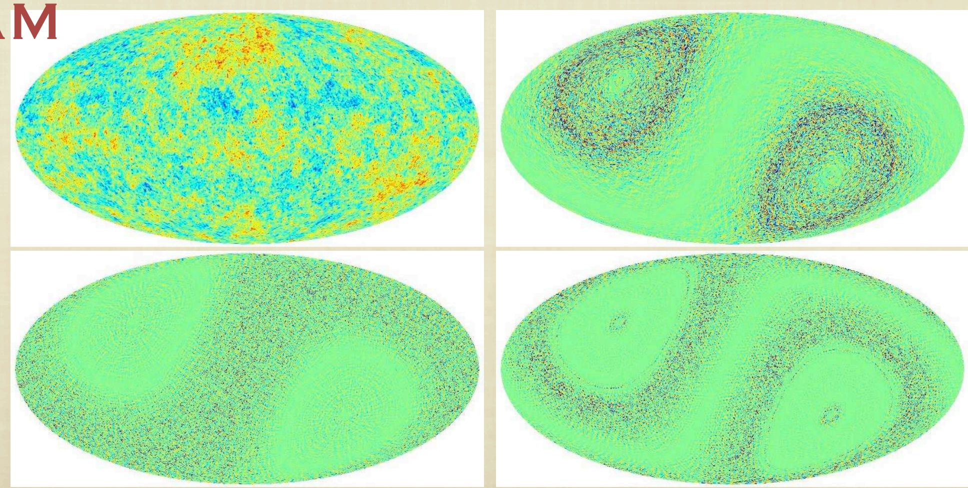
WMAP systematics

- WMAP temperature maps constitute a clean dataset: white noise and foregrounds... (and CMB...)
- we still need to worry about asymetric beam effects
- they are small because of instrumental design (ellipticity>0.8) and scanning strategy (less than 1% on C_L^{TT} for V and W), they can still mimic lensing (shearing cold or hot spots)
- We use the formalism developed in Hinshaw et al. 06 to perform exact simulations of this effect

e.g. V1 beam

s=0
σ=88μK

s=1
σ=0.4μK



s=2
σ=1.μK

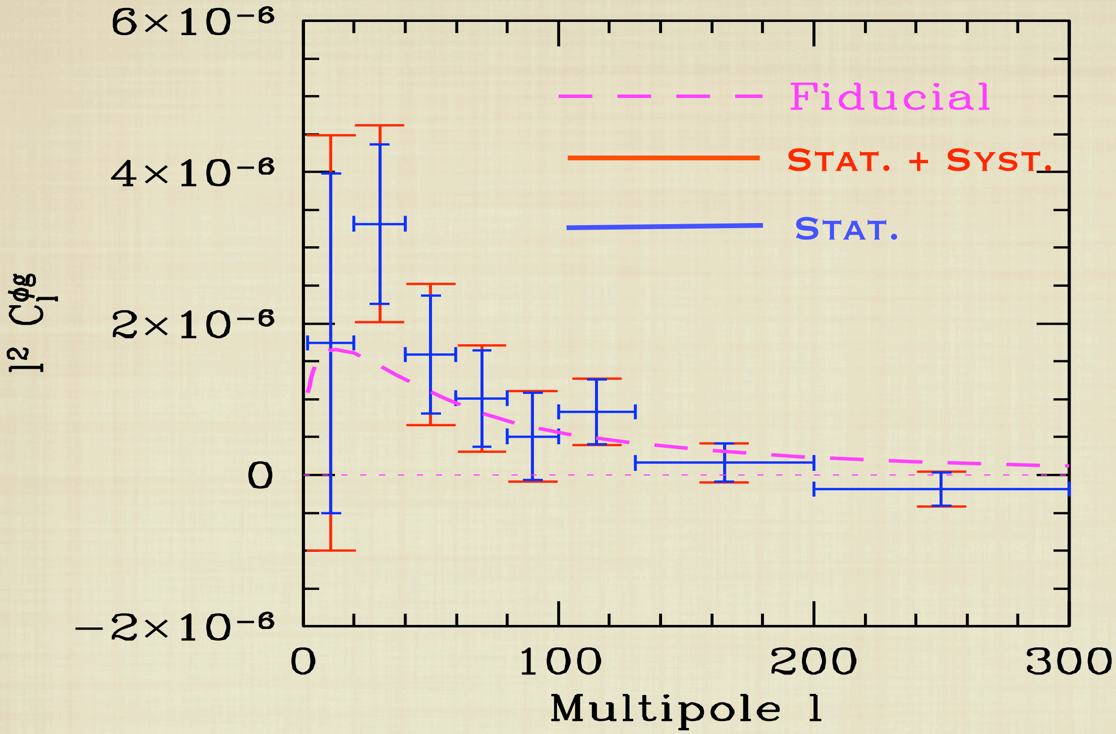
s=3
σ=0.04μK

- Add about ~4% to the statistical error budget

Systematics: best of

(ℓ_{min}, ℓ_{max})	Statistical	Beam			Galactic			Point source + SZ			Stat + systematic
		Asymmetry	Uncertainty	Total	Dust	Free-free	Total	Unresolved	Resolved	Total	
$(2, 20)$	17.4 ± 22.4	± 0.9	± 0.3	± 1.2	± 0.4	± 1.4	± 3.6	± 10.9	± 0.5	± 11.4	17.4 ± 27.4
$(20, 40)$	33.2 ± 10.5	± 0.2	± 0.1	± 0.3	± 0.2	± 0.5	± 1.4	± 4.9	± 1.0	± 5.9	33.2 ± 13.0
$(40, 60)$	15.9 ± 7.8	± 0.1	± 0.1	± 0.2	± 0.2	± 0.3	± 1.0	± 2.8	± 1.5	± 4.3	15.9 ± 9.3
$(60, 80)$	10.1 ± 6.3	± 0.1	± 0.1	± 0.2	± 0.1	± 0.3	± 0.8	± 2.0	± 0.3	± 2.3	10.1 ± 7.0
$(80, 100)$	5.1 ± 5.8	± 0.1	± 0.1	± 0.2	± 0.1	± 0.3	± 0.8	± 1.1	± 0.2	± 1.3	5.1 ± 6.0
$(100, 130)$	8.3 ± 4.3	± 0.1	< 0.1	± 0.2	± 0.1	± 0.2	± 0.6	± 0.6	± 0.2	± 0.8	8.3 ± 4.4
$(130, 200)$	1.6 ± 2.5	< 0.1	< 0.1	± 0.1	± 0.1	± 0.1	± 0.4	± 0.3	± 0.1	± 0.4	1.6 ± 2.6
$(200, 300)$	-1.9 ± 2.2	< 0.1	< 0.1	± 0.1	± 0.1	± 0.1	± 0.4	± 0.3	± 0.1	± 0.4	-1.9 ± 2.3

Final measurement



- Q, V and W combined
- All systematics are combined
- Results are robust wrt systematic effects
- Combined in one single band power:

C = 1.15 ± 0.34, i.e. a 3.4σ signal detection

Conclusions

- We used WMAP 3yr data and NVSS to investigate the signature of gravitational lensing in the CMB
- After a detailed study of systematic effects (Pt sources, SZ, foregrounds, beam effects...) we report a 3.4σ "detection"
- This signal is at the expected level given the currently favored ΛCDM model
- We are currently extending this work to study
  - the cosmological implications (σ_8, Ω_M, ...)
  - the detailed SZ/point sources interplay
- This is just the beginning
  - WMAP will not deliver much more
  - ACT/SPT (see David's talk) and PLANCK will bring CMB lensing to another level ($60\,\sigma$ signal for planck alone..) and will allow unique science to be done
- Thanks Bernard!

FIN