CMB lensing and CMBpol

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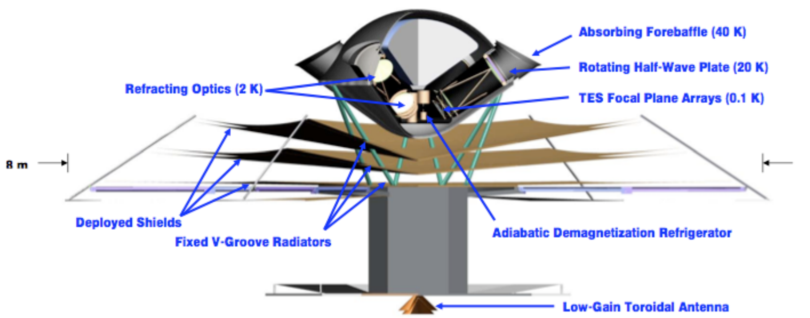
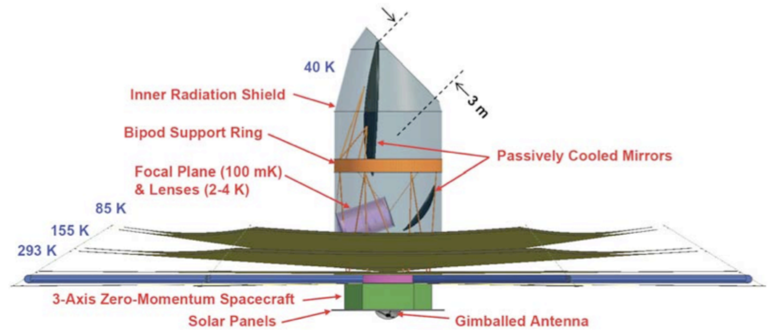
Fermilab

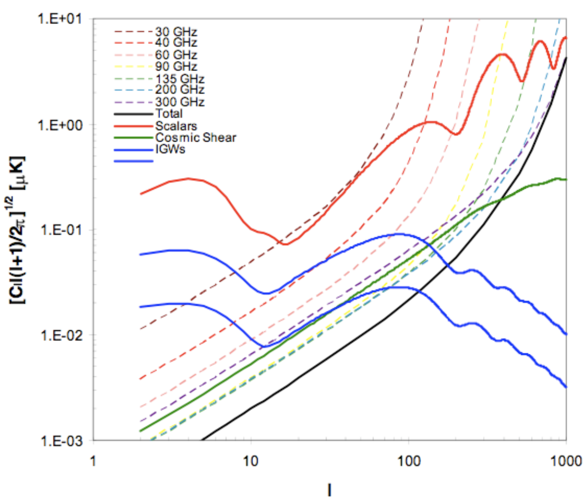
June 26, 2008

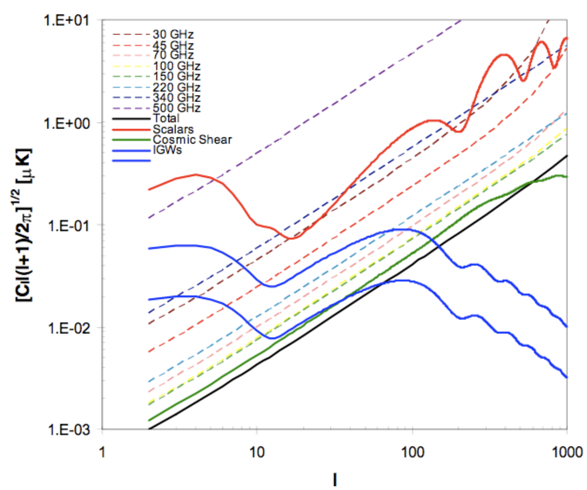
A question for CMBpol…

What do we gain by measuring small-scale polarization?







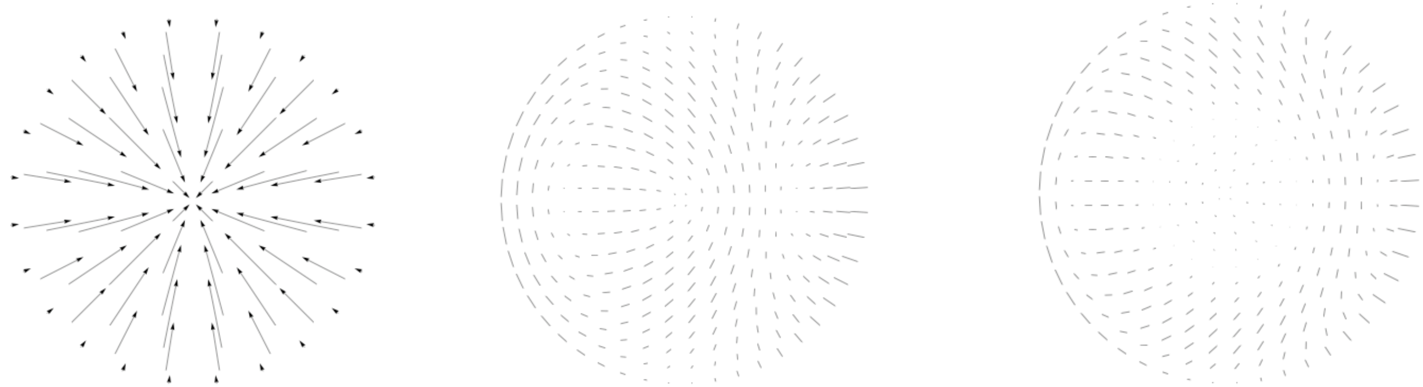


e.g. EPIC "low cost" vs EPIC "comprehensive science"

CMB lensing

Gravitational lensing by large-scale structure "permutes polarization on the sky"

$$\begin{pmatrix} Q(\hat{\mathbf{n}}) \\ U(\hat{\mathbf{n}}) \end{pmatrix}_{\text{lensed}} = \begin{pmatrix} Q(\hat{\mathbf{n}} + \mathbf{d}(\hat{\mathbf{n}})) \\ U(\hat{\mathbf{n}} + \mathbf{d}(\hat{\mathbf{n}})) \end{pmatrix}_{\text{unlensed}}$$



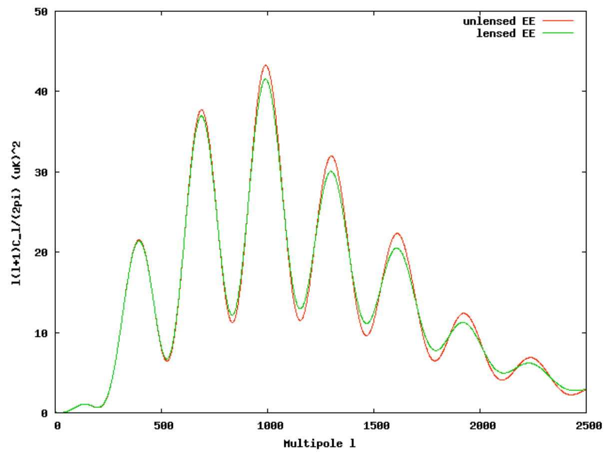
Deflection field + unlensed CMB $\longrightarrow$ Lensed CMB

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

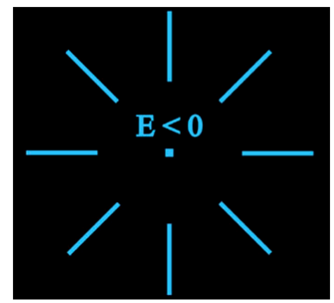
Deflection angles: ~2.5 arcmin RMS, coherent on ~1 deg scales (source redshift ~2.5)

CMB lensing: power spectra

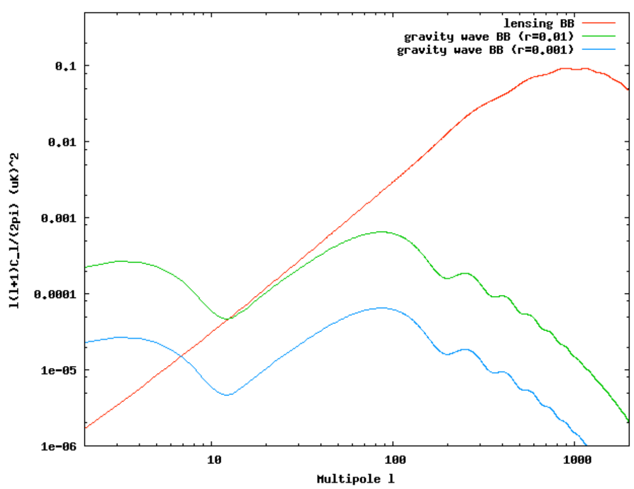
E-modes: scalar sources + linear perturbation theory



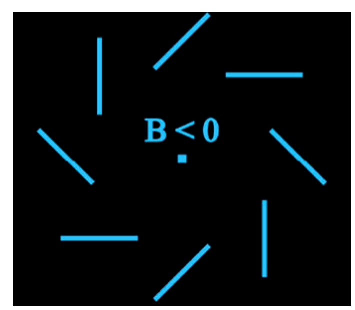
$$\Pi_{ab} = \left(\nabla_a \nabla_b - \frac{1}{2}\delta_{ab}\nabla^2 \right) \phi$$



B-modes: non-scalar sources (gravity waves) OR nonlinear effects (lensing)



$$\Pi_{ab} = \left(\frac{1}{2}\epsilon_a{}^c \nabla_b \nabla_c + \frac{1}{2}\epsilon_b{}^c \nabla_a \nabla_c \right) \phi$$



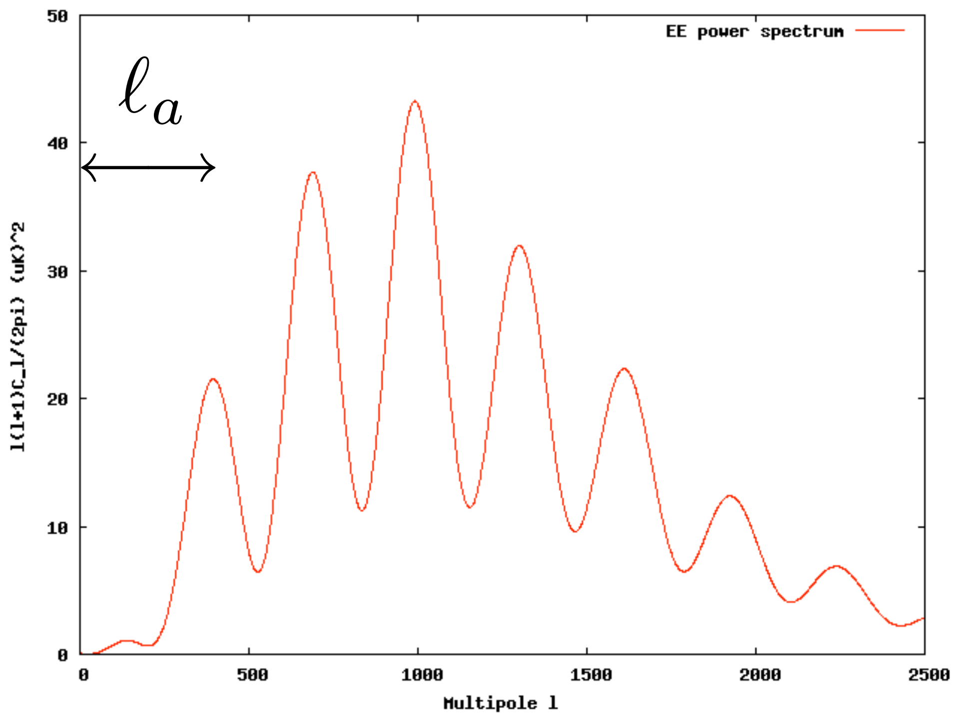
CMB lensing as a source of cosmological information

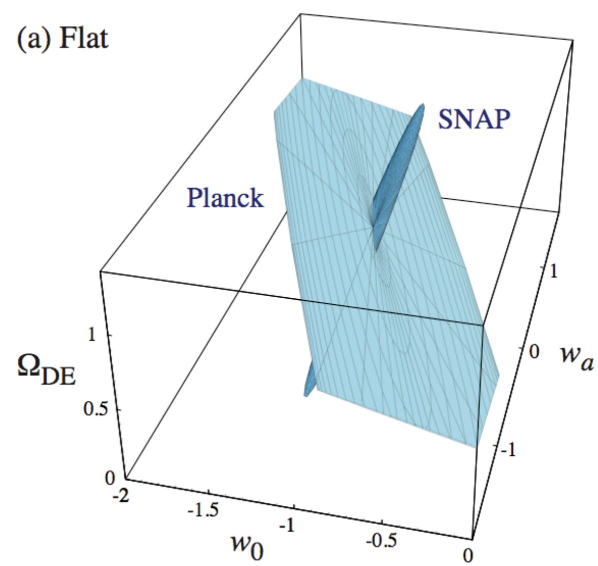
Primary CMB: only sensitive to the late universe via the distance to recombination

$$\ell_a = \pi \frac{D_*}{s_*}$$

$\longleftarrow$ Angular diameter distance to recombination

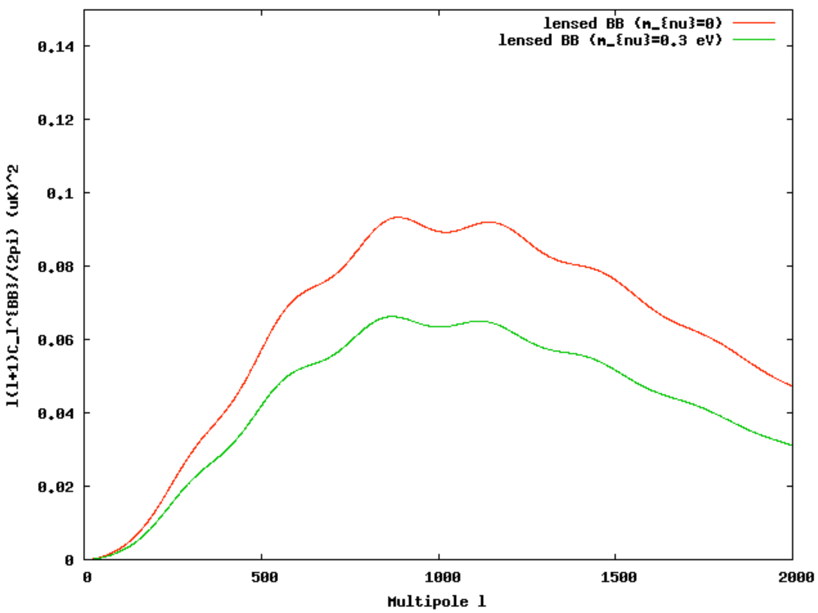
$\longleftarrow$ Distance sound travels before recombination

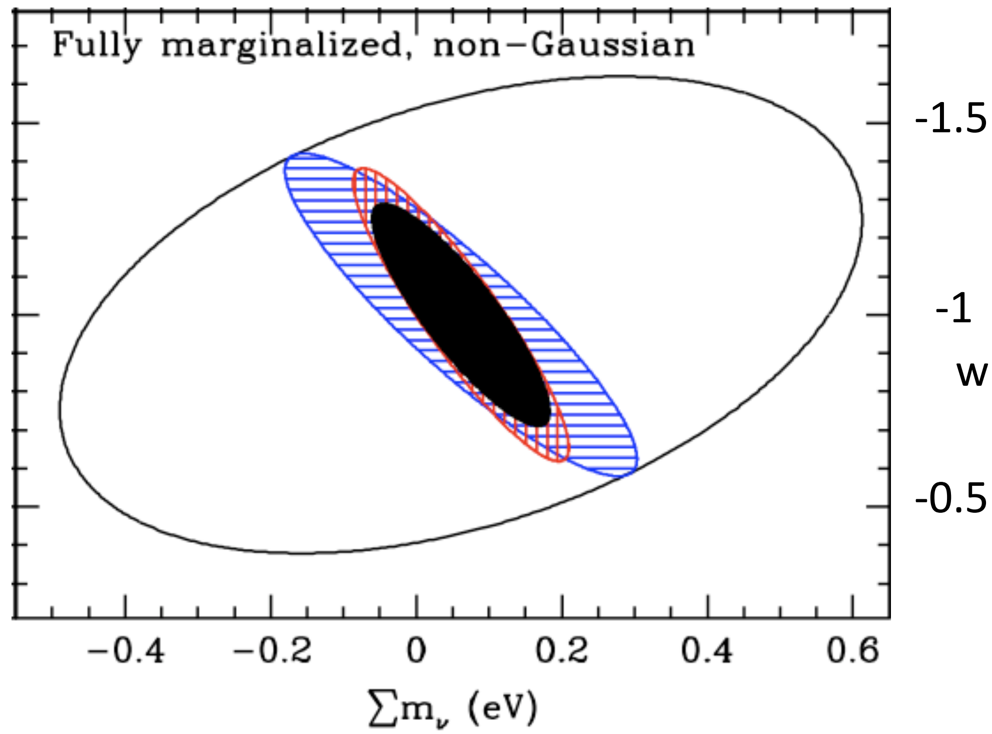




Hu, Huterer & Smith (2006)

CMB lensing as a source of cosmological information





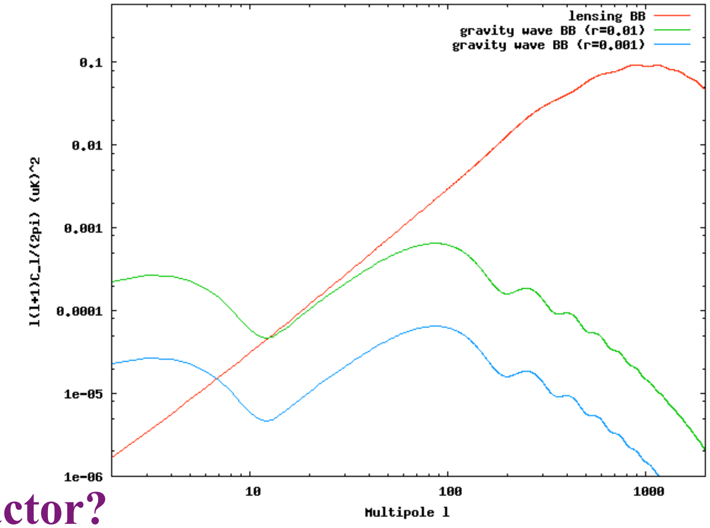
Smith, Kaplinghat & Hu (2006)

B-mode lensing comes from large-scale structure with….
redshift z ~ 2-3 (but with tail going to higher-z)
angular wavenumber l ~ 100-1000 (i.e. k ~ 0.1 h Mpc^{-1})

⇒ CMB lensing is a unique probe, but not "optimized" for neutrino mass or dark energy
"a solution in search of a problem" ?

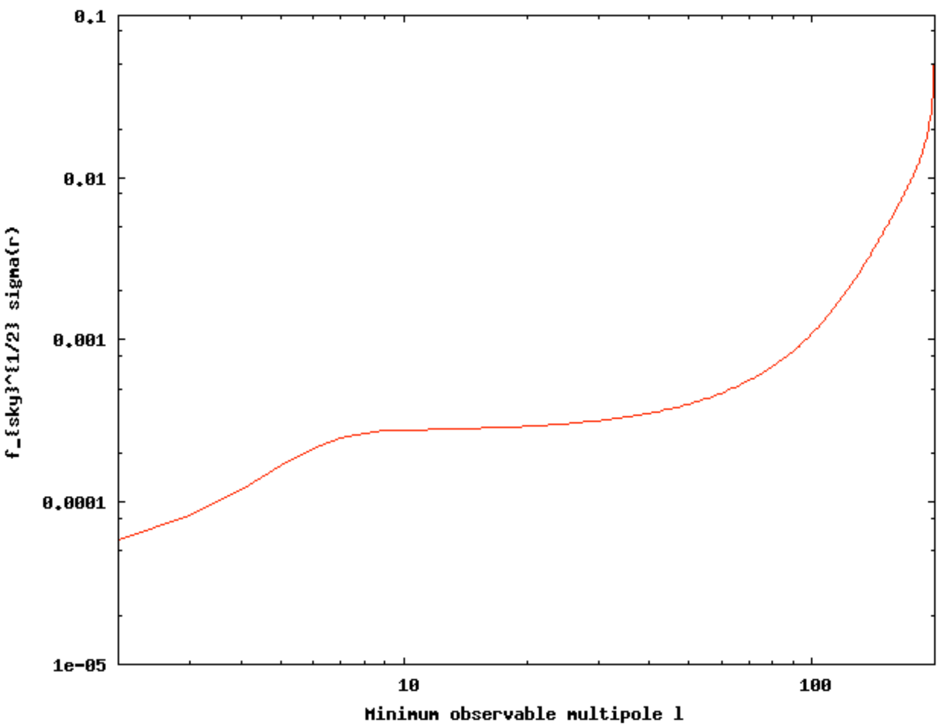
CMB lensing as a contaminant of the gravity wave signal

Magic number: ~5 uK-arcmin noise source



How well can r be measured if lensing is the limiting factor?

Crudely model finite sky coverage:
- assume modes cannot be measured below some lmin
- naive mode-counting above lmin (num. modes = fsky* (2l+1))

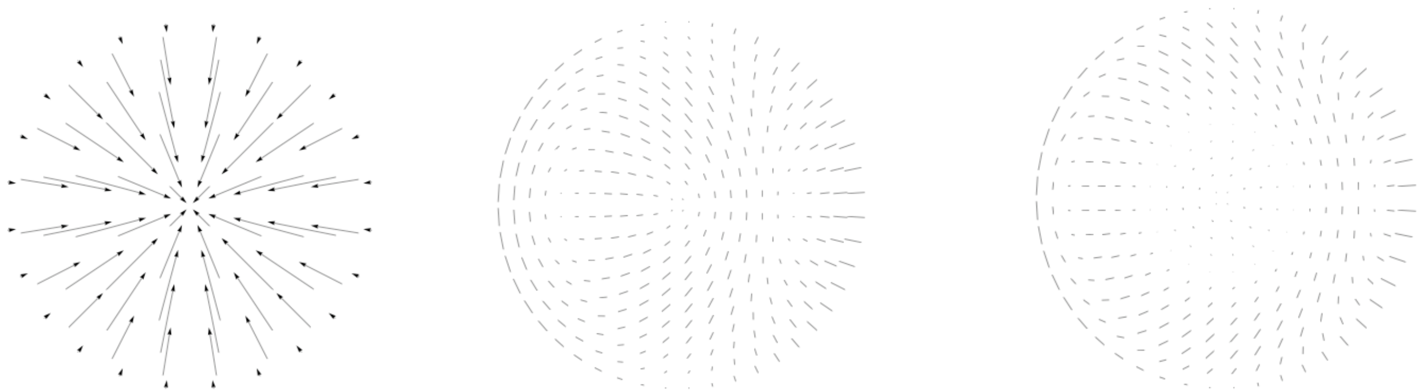


Lensing limit on r:

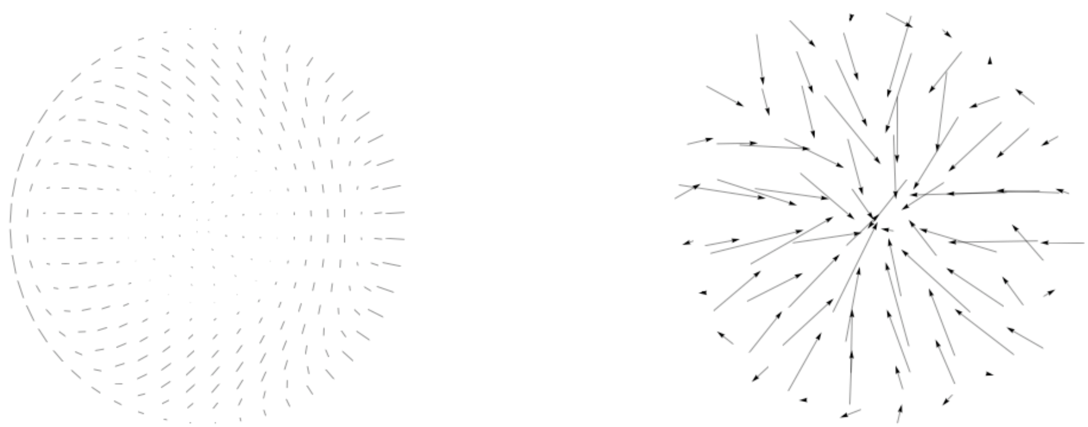
~10^{-4} if reionization bump is measureable

~10^{-3} from the recombination bump alone

CMB lens reconstruction: intuitive idea



Deflection field + unlensed CMB ⟶ Lensed CMB



Lensed CMB ⟶ Deflection field + reconstruction noise

Use background fluctuations to reconstruct lensing deflections mode by mode
Analogous to cosmic shear, but uses CMB as “wallpaper” instead of galaxies

Lens reconstruction: formalism

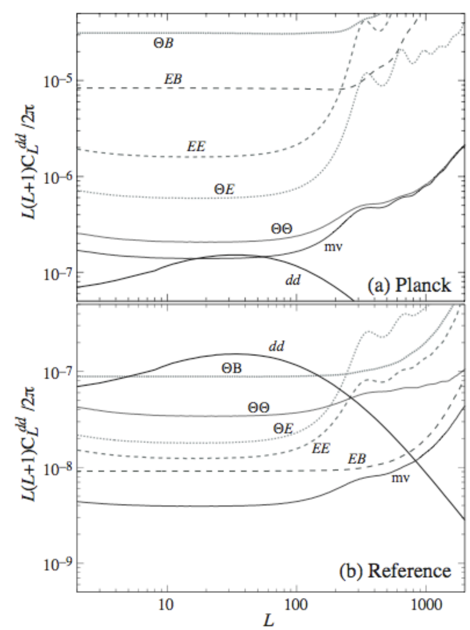
$$\langle E(\mathbf{l})^* B(\mathbf{l}') \rangle = \sin(2\varphi_{\mathbf{l}\mathbf{l}'})[-(\mathbf{l}' - \mathbf{l}) \cdot \mathbf{l}] C_l^{EE} \phi(\mathbf{l}' - \mathbf{l})$$

$$\widehat{\varphi}(\mathbf{l}) = \int \frac{d^2\mathbf{l}'}{(2\pi)^2} \sin(2\varphi_{\mathbf{l}',\mathbf{l}+\mathbf{l}'})[-\mathbf{l} \cdot \mathbf{l}'] C_{l'}^{EE} \frac{E(\mathbf{l}')^* B(\mathbf{l} + \mathbf{l}')}{(C_{l'}^{EE} + N_{l'})(N_{\mathbf{l}+\mathbf{l}'})}$$

Allows “mode by mode” reconstruction of
the lensing potential

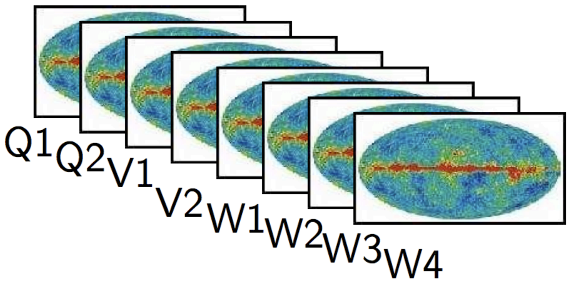
Leads to higher-point statistics
(e.g. power spectrum of phi = 4-point function of CMB)

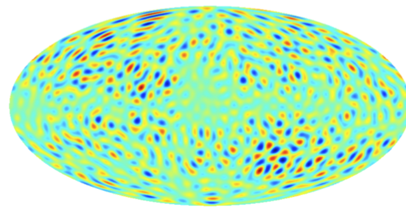
A stronger source of lensing information
than the CMB power spectra

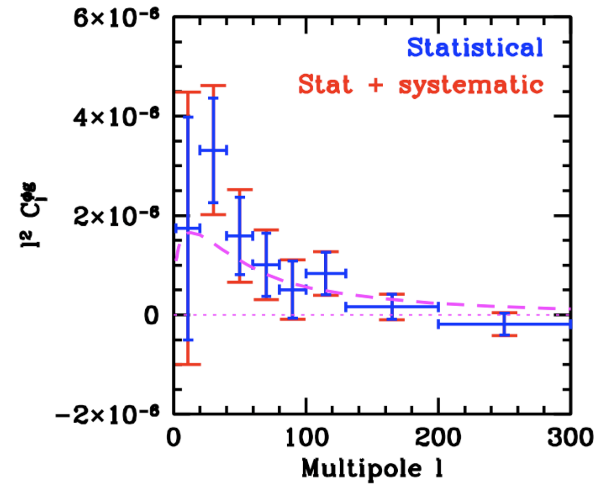


Hu & Okamoto 2003

Lens reconstruction in WMAP3







		Beam			Galactic			Point source + SZ			
$(\ell_{\min}, \ell_{\max})$	Statistical	Asymmetry	Uncertainty	Total	Dust	Free-free	Total	Unresolved	Resolved	Total	Stat + systematic
$(2, 20)$	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

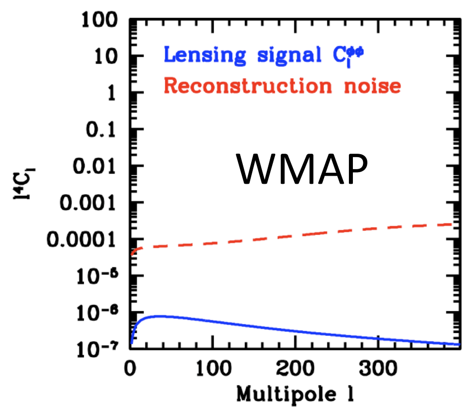
TABLE I: Final estimated $C_b^{\phi g}$ bandpowers, together with statistical uncertainties and systematic errors from point sources. All entries in the table are $\ell^2 C_\ell^{\phi g}$ in multiples of 10^{-7}.

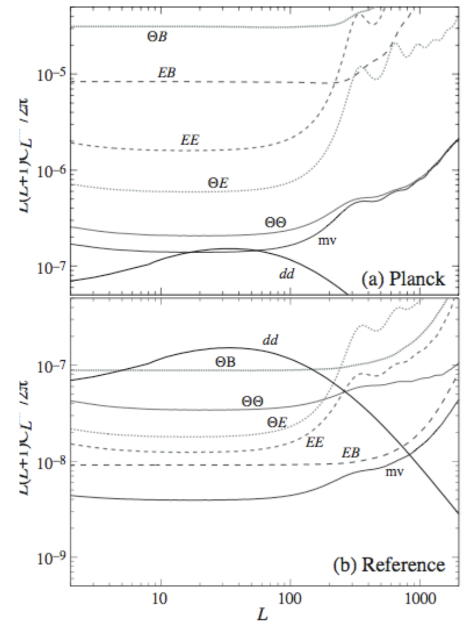
3.4 sigma detection (in cross-correlation with NVSS)

Smith, Zahn, Dore & Nolta 2007

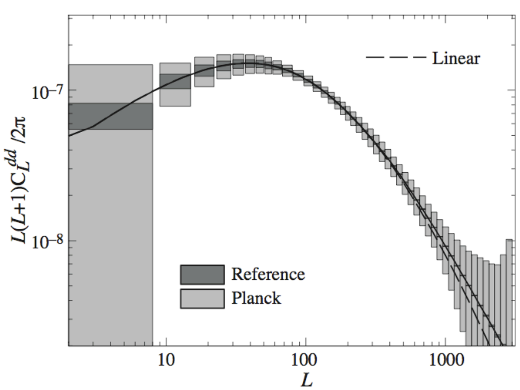
Lens reconstruction: future prospects

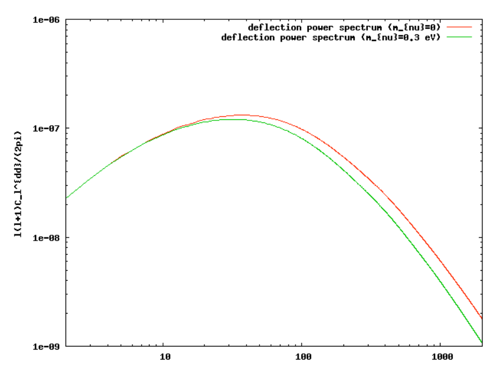
Upcoming small-scale CMB experiments (Planck, SPT, ACT, …) will shortly bring us Into the high signal-to-noise regime:



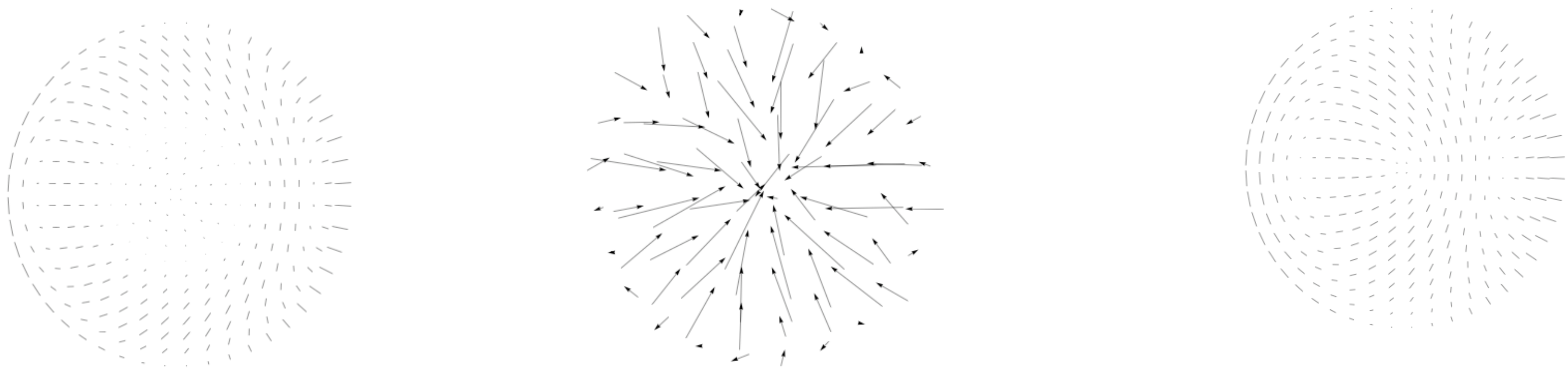


We are entering the era where each small-scale CMB experiment will "contain" a lensing experiment:





A futuristic application: gravity wave “cleaning”

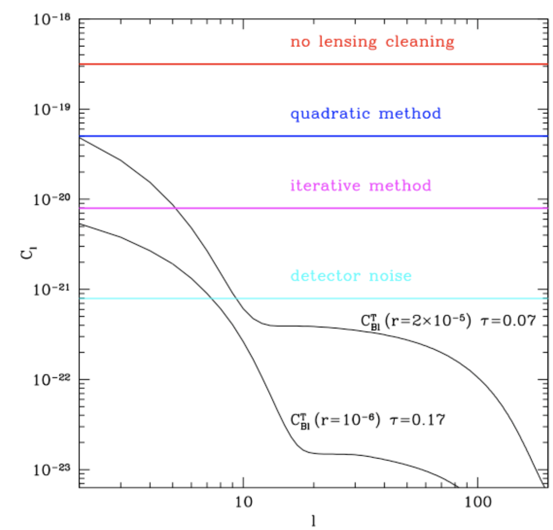


Lensed CMB $\longrightarrow$ Deflection field + reconstruction noise $\longrightarrow$ Unlensed CMB

Allows separation of gravity wave and lensing B-modes

Uses small-scale B-modes (l~10^3) to “clean” the gravity wave signal at l~10^2

Futuristic, but ultimately necessary if we want to beat the r ~ 10^{-3} limit from CMB lensing.



Hirata & Seljak 2003

More questions for CMBpol….

1. What cosmological information can be gained by measuring the lensing power spectrum?
   Can we add anything In the JDEM/LSST era?

2. How much do we gain from gravity wave “cleaning”?
   Is an “internal” lens reconstruction from small-scale CMB polarization the only option?
      small-scale CMB temperature?
      large-scale structure (all-sky cosmic shear / galaxy counts)?

3. Can we expect CMB lens reconstruction to be robust in the presence of
   Instrumental systematics?
   Foregrounds? (extragalactic point sources)