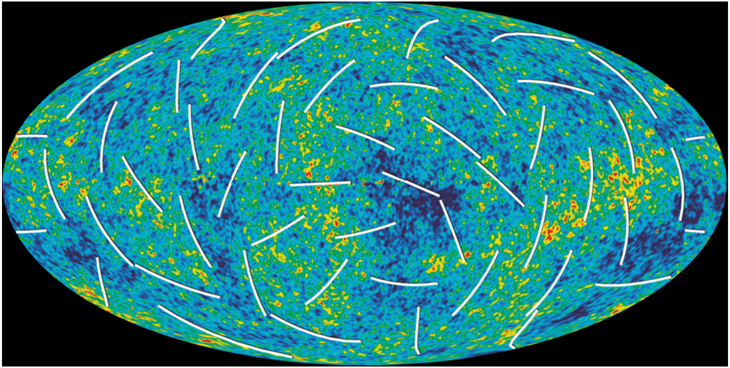
CMB polarization: past, present, and future



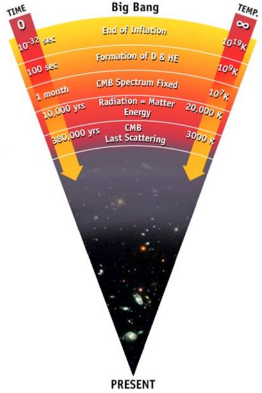
Kendrick Smith
University of Chicago
February 2007, Berkeley

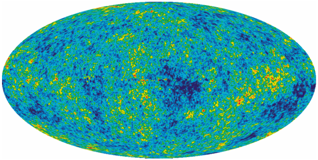
Outline

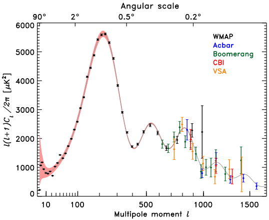
I. Overview; what can be learned from CMB polarization?
II. CAPMAP (2003-2007)
III. QUIET (2007-)
IV. E-B separation

What have we learned from the CMB temperature?

Primary CMB temperature signal: snapshot of acoustic oscillations at recombination ($z \sim 1100$).







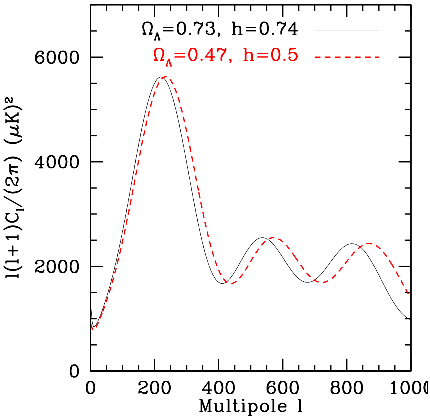
What have we learned from the CMB temperature?

1. Angular scale of acoustic peaks:

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

$\longleftarrow$ Angular diameter distance to recombination

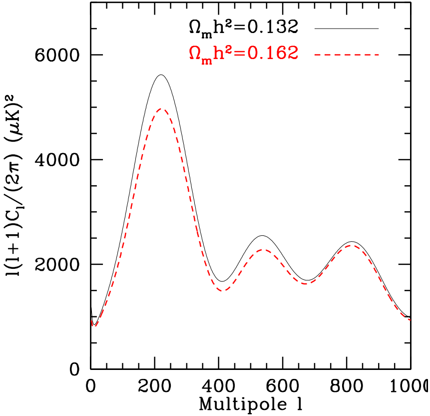
$\longleftarrow$ Distance sound travels before recombination



What have we learned from the CMB temperature?

2. Radiation-matter ratio:

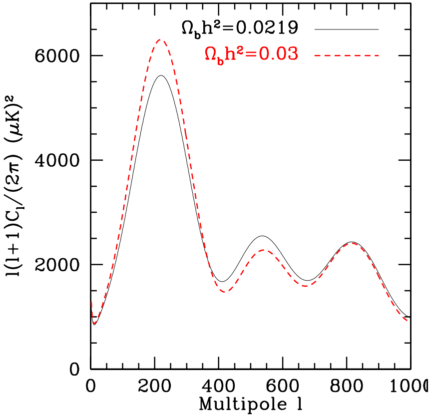
$$r_* = \left(\frac{\rho_r}{\rho_m}\right)_{a_*} \propto (\Omega_m h^2)^{-1}$$



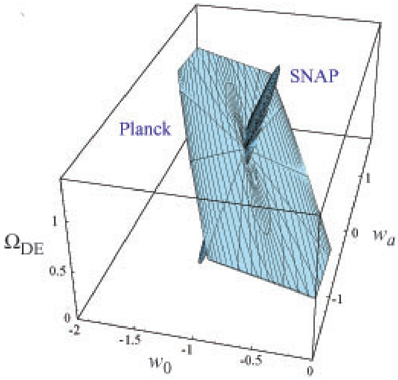
What have we learned from the CMB temperature?

3. Photon-baryon ratio:

$$R_* = \left(\frac{3\rho_b}{4\rho_\gamma}\right)_{a_*} \propto (\Omega_b h^2)$$



Importance of the CMB prior



Hu, Huterer & Smith, ApJL (2006)

CMB constraints on

$$\{\Omega_m h^2, \Omega_b h^2, D_*\}$$

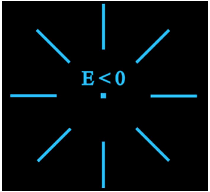
are important for every flavor of cosmological data!

(Supernova example shown here)

In addition, C_ℓ^{TT} contains information about the shape of the initial power spectrum (tilt n_s, running α, etc.)

CMB polarization: E-B decomposition

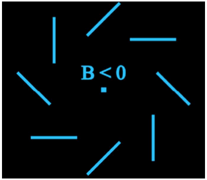
CMB polarization can be decomposed into...



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

- Dominant component: generated by first-order perturbations at recombination and reionization.

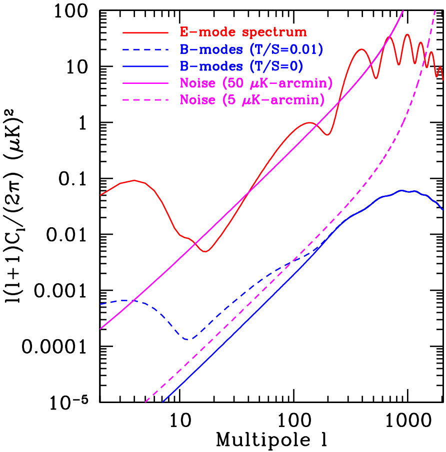
B-modes: $\Pi_{ab} = \left(\frac{1}{2}\epsilon_a{}^c \nabla_b \nabla_c + \frac{1}{2}\epsilon_b{}^c \nabla_a \nabla_c\right)\phi$.



- Generated by second-order effects (mainly gravitational lensing of the larger E-mode signal).
- Also generated by gravitational waves from inflation.

This is the spin-2 analogue of the gradient/curl decomposition for a vector field.

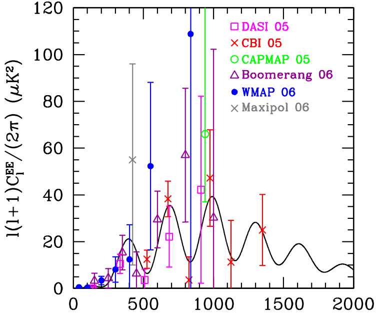
CMB polarization: E-B decomposition



- EE and BB power spectra shown, with noise power spectra for comparison ($\theta_{\rm FWHM} = 10$ arcmin).
- Current experiments (~ 50 μK-arcmin) have detected EE to 10σ, with upper limits on BB.
- Future ground-based experiments (~ 5 μK-arcmin) should make precision measurements of EE and detect B-modes.

CMB polarization: acoustic peaks (C_ℓ^{EE})

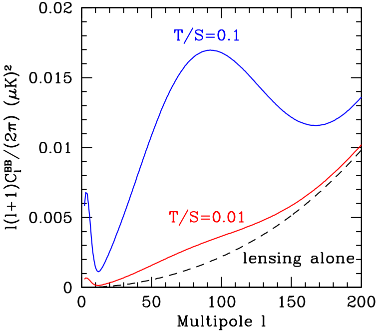
In principle, measuring acoustic peaks in C_ℓ^{EE} can improve errors on $\{\Omega_m h^2, \Omega_b h^2, D_*\}$ by a factor of $\sim \sqrt{2}$. However, for signal-to-noise reasons, C_ℓ^{EE} probably best regarded as predicted by C_ℓ^{TT}...



Exception: polarization is complementary to temperature when estimating the primordial power spectrum $P^{\zeta\zeta}(k)$ (Hu & Okamoto 2003).

Exception: isocurvature modes (Bucher, Moodley & Turok 2000)

CMB polarization: gravity waves (C_ℓ^{BB} at low ℓ)



Low B-mode multipoles ultimately have more sensitivity to gravity waves in the early universe (parameterized by tensor-to-scalar ratio T/S) than any other type of data.

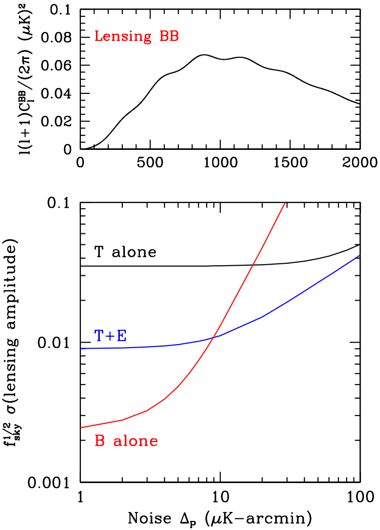
Well-motivated in some inflationary models; observation would rule out others (e.g. ekpyrotic).

CMB polarization: gravitational lensing

"Guaranteed" B-mode signal from gravitational lensing of the larger E-mode signal.

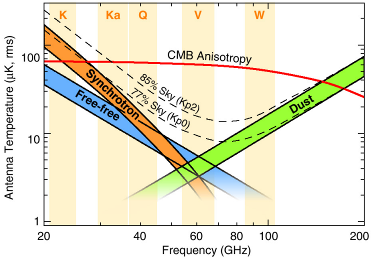
Probes new parameters, e.g. overall lensing amplitude depends on $\sum m_\nu$ by 50% per eV (Eisenstein & Hu 1997)

Gravitational lensing appears in temperature and polarization, but polarization is more sensitive.



Smith, Hu & Kaplinghat, PRD (2005)

Foregrounds

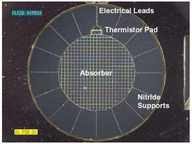


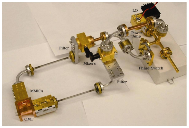
Bennett et al (2003)

Good frequency coverage is essential for controlling foregrounds

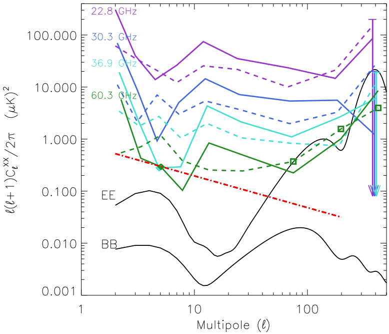
Bolometers ($\nu \geq 100$ GHz)
BICEP, Clover, EBEX, Spider

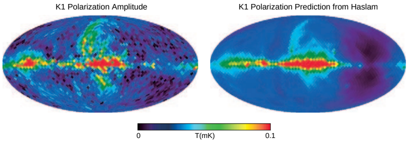
Coherent detectors ($\nu \leq 90$ GHz)
QUIET





Foregrounds





Page et al (2006)

Taken over large regions of sky, foregrounds are comparable to or larger than expected CMB polarization signals

However. . .

To date, polarized foregrounds have not been a significant contaminant for ground-based experiments sampling “clean” patches of sky.

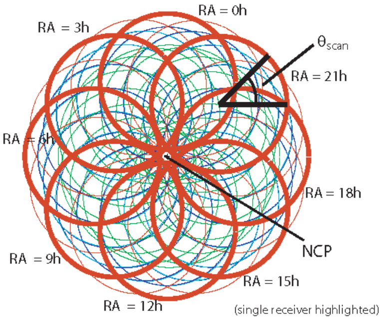
Part II: CAPMAP

Coherent polarimeters + 7m telescope (Crawford Hill, NJ)

First (2003, 4 detectors) observing season resulted in 2σ detection of EE (Barkats et al 2005)

Second (2005, 16 detectors) observing season: soon!

CAPMAP: focal plane



Jeff McMahon

12 W-band (90 GHz) detectors + 4 Q-band (40 Ghz) detectors
Scan small patch near NCP

Total sky area: 7.3 deg^2 (90 GHz), 9.2 deg^2 (40 GHz)

CAPMAP: summary

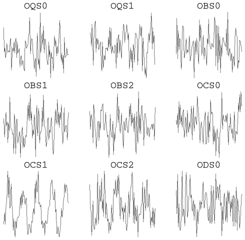
	ν	N_{det}	ΔT	Area	Noise	θ_{FWHM}
CAPMAP I	90 GHz	4	433 hr	2.0 deg^2	100 μK'	4'
CAPMAP II	40 GHz	4	900 hr	9.2 deg^2	70 μK'	6'
	90 GHz	12	900 hr	7.3 deg^2	60 μK'	3.5'

Two independent analysis pipelines:

1. Pipeline 1: represent data in real space (θ, ϕ), noise as dense covariance matrix ($N_{pix} \sim 2500$ for beam size pixels, ~ 10000 for $1/2$ beam size).

2. Pipeline 2: treat noise as azimuthally symmetric and Fourier transform in ϕ (coordinates are now θ, m); big speedup since covariance matrices become block diagonal in m (can easily go to $1/3$ beam size)

CAPMAP: analysis pipeline



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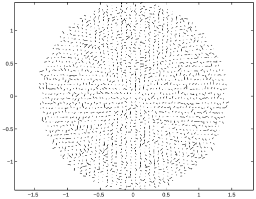
$\longrightarrow$



$$\begin{pmatrix} * & * & \cdots \\ * & * & \cdots \\ \vdots & \vdots & \ddots \end{pmatrix}$$

Timestreams (+ pointing)

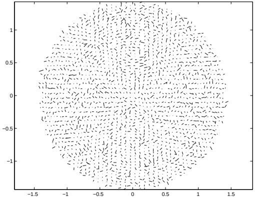
Map + noise covariance

$$N_{map}^{-1} = P N_{tod}^{-1} P^T \quad ; \quad N_{map}^{-1} m = P^T N_{tod}^{-1} t$$

Timestream noise model: white + marginalization over lowest 5 ring modes + ground-synchronous signal.

(Simulations show that this filter sufficiently removes $1/f$ noise.)

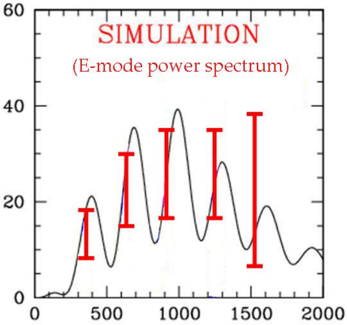
CAPMAP: analysis pipeline



$$\begin{pmatrix} * & * & \cdots \\ * & * & \cdots \\ \vdots & \vdots & \ddots \end{pmatrix}$$

Map + noise covariance

$\longrightarrow$

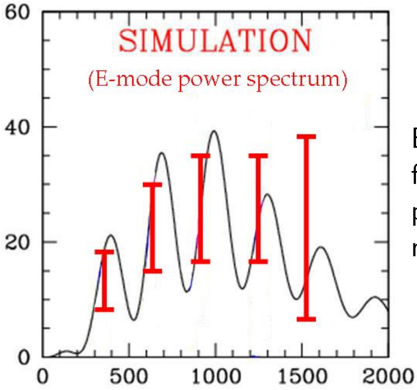


Power spectrum likelihood

Likelihood can be explored in different ways (Newton-Raphson, Markov chain, ...) but each "step" requires a dense matrix operation (Bond, Jaffe & Knox 1997)

Use S/N eigenmode compression to reduce matrix size ($N \sim 2000$ independent of pixel size) (Bond 1994)

CAPMAP: Fisher matrix from full analysis pipeline



Bandpower Fisher matrix computed from noise covariance matrix in real pipeline (equivalent to MC average of many simulations).

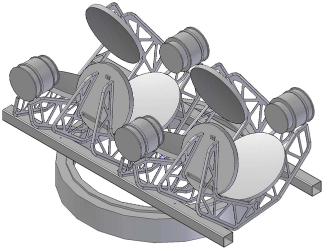
Pipeline also includes null test suite: difference two maps made from disjoint data subsets, analyze power spectrum and compare to zero. (When applied to the two frequency channels, this is a strong test for foregrounds.)

Part III: QUIET (Q/U Imaging ExperimenT)

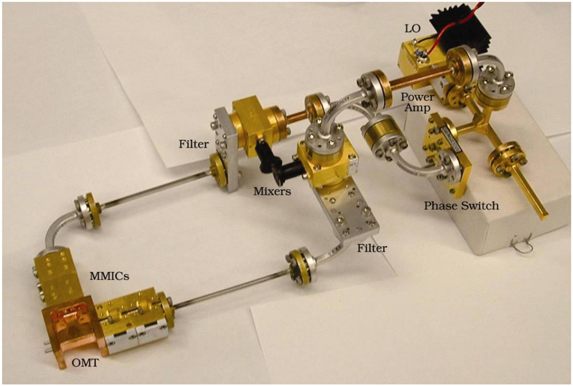
Atacama desert, Chile

Phase I (late 2007):
2m telescope, $\sim$ 100 detectors

Phase II (2010):
2m telescope, $\sim$ 1000 detectors
7m telescope, $\sim$ 500 detectors

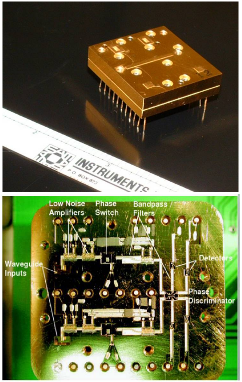


QUIET: “Coherent polarimeter on a chip”



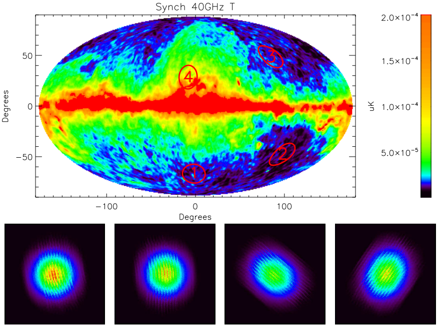
CAPMAP 90GHz polarimeter

→



QUIET 90GHz module

QUIET: Scan strategy



Keith Vanderlinde

Four patches selected for low foreground contamination, distribution around SCP roughly uniform in RA.

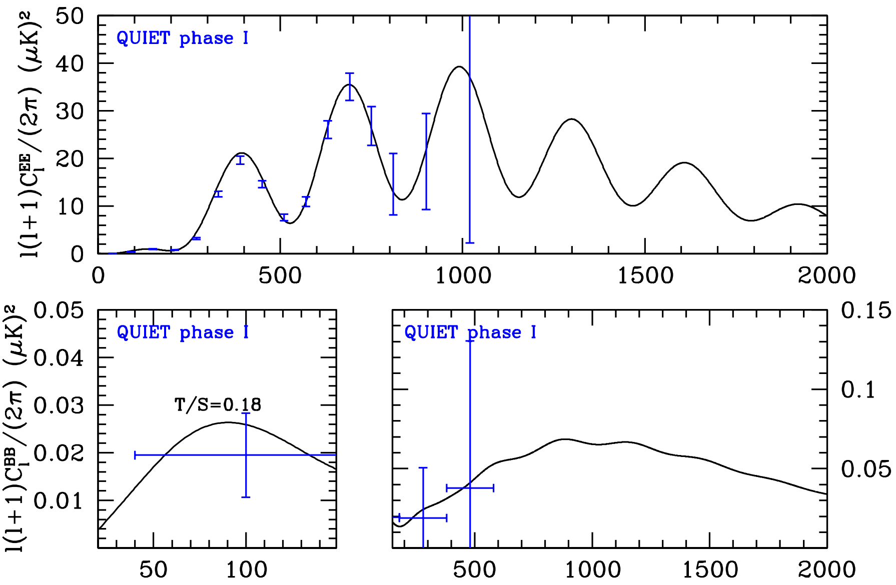
After many repointings, get roughly isotropic coverage and good cross-linking

QUIET: summary

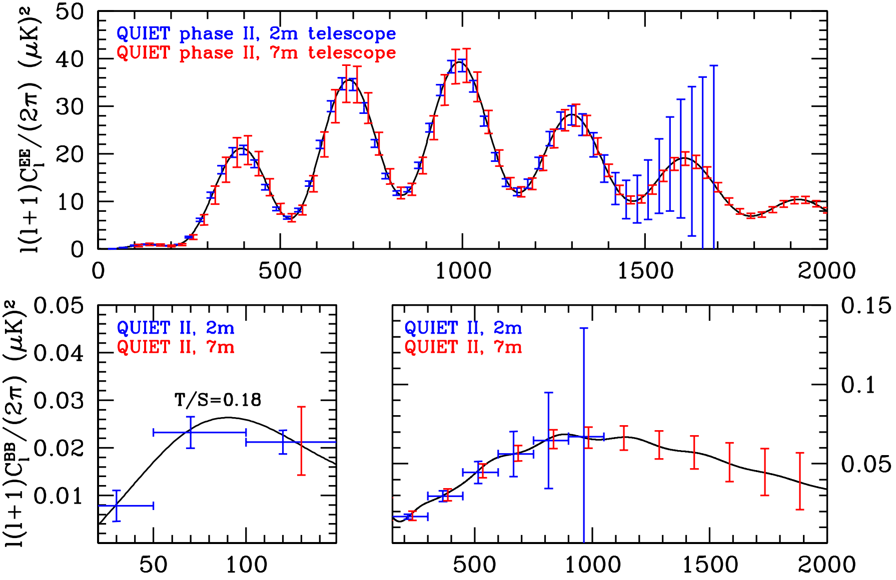
	ν	N_{det}	ΔT	Area	Noise	θ_{FWHM}
CAPMAP I	90 GHz	4	433 hr	2.0 $\deg^2$	100 μK'	4'
CAPMAP II	40 GHz	4	900 hr	9.2 $\deg^2$	70 μK'	6'
	90 GHz	12	900 hr	7.3 $\deg^2$	60 μK'	3.5'
QUIET I	40 GHz	19	4000 hr	1600 $\deg^2$	49 μK'	10'
	90 GHz	83	4000 hr	1600 $\deg^2$	34 μK'	10'
QUIET II (2m)	40 GHz	166	4000 hr	1600 $\deg^2$	9.6 μK'	10'
	90 GHz	714	4000 hr	1600 $\deg^2$	7.3 μK'	10'
QUIET II (7m)	40 GHz	83	8000 hr	160 $\deg^2$	3.2 μK'	6'
	90 GHz	357	8000 hr	160 $\deg^2$	2.5 μK'	3.5'

Forecasting methodology: Compute dense matrix at low ℓ (including scan strategy and mode removal); use simple $f_{\rm sky}$ scaling at high ℓ.

QUIET: phase I forecasts (90 GHz alone)



QUIET: phase II forecasts (90 GHz alone)



QUIET phase I: analysis pipeline

Problem size:

$$
\begin{aligned}
N_{tod} &= (2)(91)(30\ \text{Hz})(10^7\ \text{sec}) = 5.4 \times 10^{10} \\
N_{pix} &= (3)(f_{sky})(12 N_{side}^2) = 3.8 \times 10^5 \qquad (N_{side} = 1024)
\end{aligned}
$$

Unlike CAPMAP, fully optimal analysis seems prohibitive.

Exploring Monte Carlo based alternatives:

- Map-making: destriping
- Map-making: MASTER approach (high-pass + binning)
- Power spectrum estimation: pseudo-C_ℓ

Computational cost: probably $\sim 10^4$ CPU-hours for a full analysis

Running problem: E-B mixing

Part IV: E-B mixing

How are E-mode and B-mode power spectra estimated from data?

- Under the simplifying assumption of all-sky isotropic noise, estimating C_ℓ^{EE}, C_ℓ^{BB} from a noisy map Π_{ab} is straightforward:

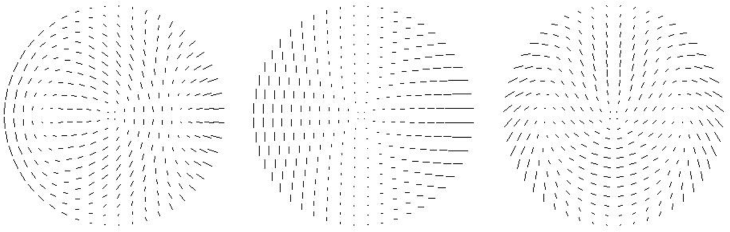
$$a^E_{\ell m} = \int d^2x\, \Pi^{ab}(x) Y^E_{(\ell m)ab}(x) \qquad a^B_{\ell m} = \int d^2x\, \Pi^{ab}(x) Y^B_{(\ell m)ab}(x)$$

$$\widehat{C}_\ell^{EE} = \frac{1}{2\ell+1} \sum_{m=-\ell}^{\ell} a^E_{\ell m} a^{E*}_{\ell m} \qquad \widehat{C}_\ell^{BB} = \frac{1}{2\ell+1} \sum_{m=-\ell}^{\ell} a^B_{\ell m} a^{B*}_{\ell m}$$

- The E-mode and B-mode spherical harmonics $Y^E_{\ell m}(x)$, $Y^B_{\ell m}(x)$ provide a complete basis for E-mode and B-mode power on the sky, and are decoupled from each other.

What is the E-B mixing problem?

- In the presence of sky cuts or inhomogeneous noise, the E/B decomposition becomes more complicated:

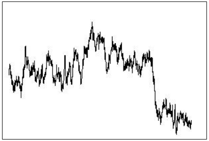


pure E-mode ambiguous mode pure B-mode

- Pure E-modes and B-modes are expensive to compute directly
- Challenge: Find a B-mode estimator which only receives contributions from pure B-modes, and is computationally fast.

Pseudo-C_ℓ power spectrum estimation: 1-D analogy

- Start with timeseries on a finite interval:
- Take FFT, and estimate power spectra, as if the timeseries were periodic on a larger interval:



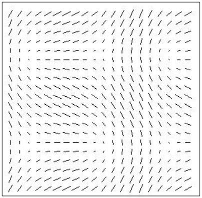
$$\begin{aligned} \widetilde{f}(\omega) &= \int dt\, f(t) W(t) \exp(i\omega t) \\ \widetilde{P}(\omega) &= |\widetilde{f}(\omega)|^2 \end{aligned}$$

- Final step: fix up the normalization

$$\widehat{P}(\omega) = \frac{1}{K} \widetilde{P}(\omega)$$

Pseudo-C_ℓ power spectrum estimation: 2-D version

- Start with CMB polarization on a finite patch:
- Take spherical transform, and estimate power spectrum, as if the polarization were defined all-sky:



$$\tilde{a}^E_{\ell m} = \int \Pi^{ab}(x) W(x) Y^{E*}_{(\ell m)ab}(x) \qquad \tilde{a}^B_{\ell m} = \int \Pi^{ab}(x) W(x) Y^{B*}_{(\ell m)ab}(x)$$

$$\tilde{C}^{EE}_\ell = \frac{1}{2\ell+1} \sum_{m=-\ell}^{\ell} \tilde{a}^E_{\ell m} \tilde{a}^{E*}_{\ell m} \qquad \tilde{C}^{BB}_\ell = \frac{1}{2\ell+1} \sum_{m=-\ell}^{\ell} \tilde{a}^B_{\ell m} \tilde{a}^{B*}_{\ell m}$$

- Final step: debias

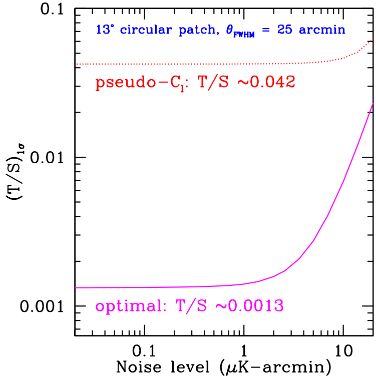
$$\begin{pmatrix} \hat{C}^{EE}_\ell \\ \hat{C}^{BB}_\ell \end{pmatrix} = \begin{pmatrix} K^+_{\ell\ell'} & K^-_{\ell\ell'} \\ K^-_{\ell\ell'} & K^+_{\ell\ell'} \end{pmatrix}^{-1} \begin{pmatrix} \tilde{C}^{EE}_{\ell'} - \langle \tilde{C}^{EE}_{\ell'} \rangle_{\rm noise} \\ \tilde{C}^{BB}_{\ell'} - \langle \tilde{C}^{BB}_{\ell'} \rangle_{\rm noise} \end{pmatrix}$$

Pseudo-C_ℓ power spectrum estimation: tradeoffs

- Pseudo-C_ℓ: suboptimal but very fast
- Practial problem: how to choose pixel weight function $W(x)$?
- For B-modes, there is a more fundamental problem: the estimator mixes E and B and therefore limits B-mode sensitivity at low noise levels.

$$\widetilde{a}^B_{\ell m} = \int \Pi^{ab}(x) W(x) Y^B_{(\ell m)ab}(x)$$

Pseudo-C_ℓ power spectrum estimation: EB mixing



Smith (2005)

- Challinor & Chon (2004): For $f_{\rm sky} \sim 0.01$, pseudo-C_ℓ limits the gravity wave signal which can be detected to $(T/S) \sim 0.05$.
- In the pseudo-C_ℓ method, $E \to B$ mixing is treated like noise: can subtract bias, but extra variance remains.

$$\begin{pmatrix} \widehat{C}_\ell^{EE} \\ \widehat{C}_\ell^{BB} \end{pmatrix} = \begin{pmatrix} K^+_{\ell\ell'} & K^-_{\ell\ell'} \\ K^-_{\ell\ell'} & K^+_{\ell\ell'} \end{pmatrix}^{-1} \begin{pmatrix} \widetilde{C}_{\ell'}^{EE} - \langle \widetilde{C}_{\ell'}^{EE} \rangle_{\rm noise} \\ \widetilde{C}_{\ell'}^{BB} - \langle \widetilde{C}_{\ell'}^{BB} \rangle_{\rm noise} \end{pmatrix}$$

A "pure" pseudo-C_ℓ estimator:

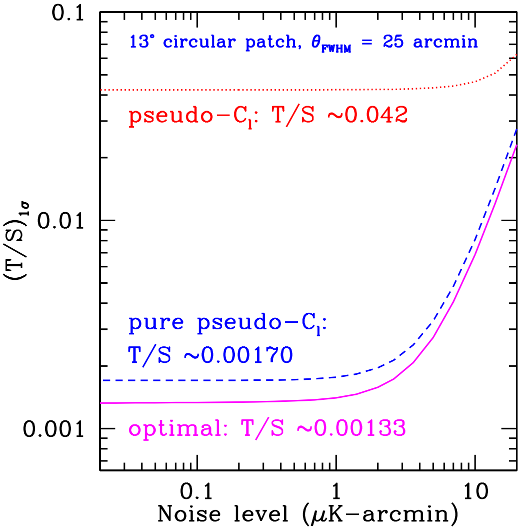
Proposal: Add higher-spin weights W_a, W_{ab} and counterterms to cancel the E-B mixing (Smith 2005)

$$\tilde{a}^B_{\ell m} = \int d^2x\, \Pi^{ab}(x) \Big[W(x) Y^{B*}_{(\ell m)ab} + \epsilon_a{}^c \frac{W_b(x) Y^{G*}_{(\ell m)c} + W_c(x) Y^{G*}_{(\ell m)b}}{\sqrt{(\ell-1)(\ell+2)}} + \frac{\epsilon_a{}^c W_{bc}(x) Y^*_{\ell m}}{\sqrt{(\ell-1)\ell(\ell+1)(\ell+2)}} \Big]$$

Also proposed algorithmic approach for choosing $W(x)$, $W_a(x)$, $W_{ab}(x)$ (Smith and Zaldarriaga 2006).

Based on variational principle: minimize "average power" $\langle \widetilde{C}_\ell \rangle$ satisfying normalization constraint $\sum_x W(x) = 1$.

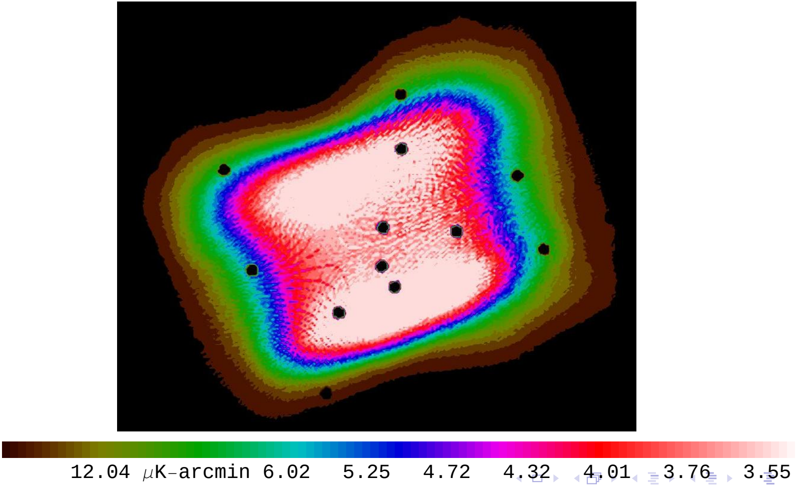
Pure pseudo-C_ℓ estimator: EB mixing



Smith (2005)

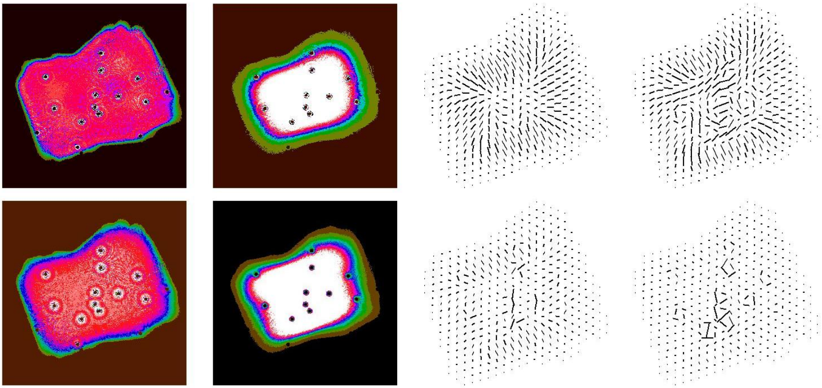
Fiducial experiment: hitcount map

- Fiducial experiment: average noise $\sim 5.75\ \mu$K-arcmin, $\theta_{\rm FWHM} = 8$ arcmin, randomly generated point source mask, noise distribution based on preliminary EBEX simulations.

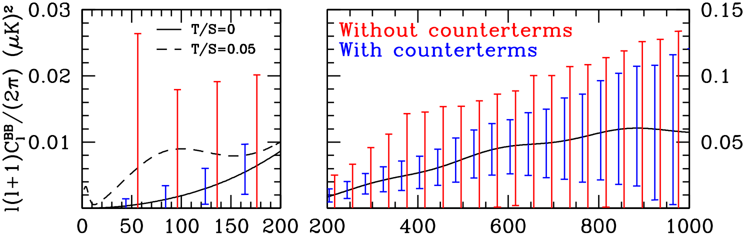


Fiducial experiment: weight functions

- Optimized weight function depends on ℓ band; shown here for $(\ell_{\min}, \ell_{\max}) = (30, 70)$ (top row) and $(510, 550)$ (bottom).
- Each "weight function" consists of four pieces (left to right): E-mode weight function $W_E(x)$, scalar piece of B-mode weight $W(x)$, and two B-mode counterterms $W_a(x)$, $W_{ab}(x)$.



Fiducial experiment: power spectrum errors



Smith & Zaldarriaga, astro-ph/0610059

- Adding counterterms significantly improves BB power spectrum errors for the fiducial experiment
- Gravity wave signal: $\sigma(T/S)$ $0.054 \rightarrow 0.0056$.
- Lensing amplitude: $\sigma(A_{\rm lens})$ $0.258 \rightarrow 0.085$.

Concluding thoughts

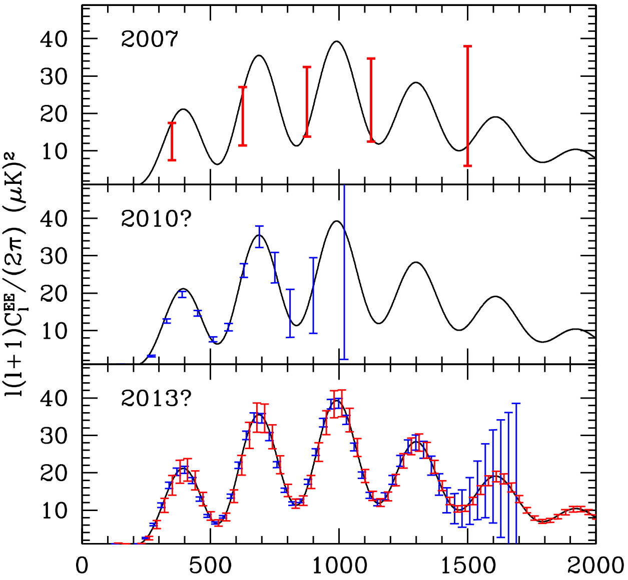
Estimator gives good E-B separation while also solving an outstanding practical problem: choosing the weight function.

Estimator performance seems convincing for “real-world” distribution of white noise, but full QUIET noise model will be more complicated ($1/f$ noise, ground synchronous modes...)

Related: this only solves half the EB separation problem for Monte Carlo CMB pipelines!

Map-making also mixes E and B...

Concluding thoughts



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