# Containing Systematics in CMB Polarisation Experiments

Cleaning up the CMB for better estimation of $r$

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# CMB B-modes and r

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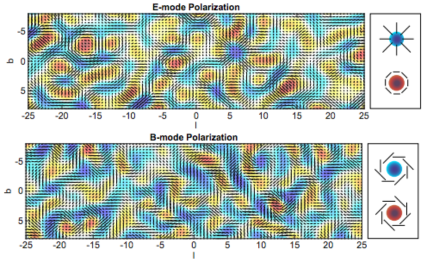
- A CMB telescope observes the microwave sky and provides us the T, Q and U Stokes parameters.
- By convention and convenience we represent the polarisation signal in terms of the quantities E and B

- Through this we have a unique handle on the physics of the early universe and holds the key to understanding inflation

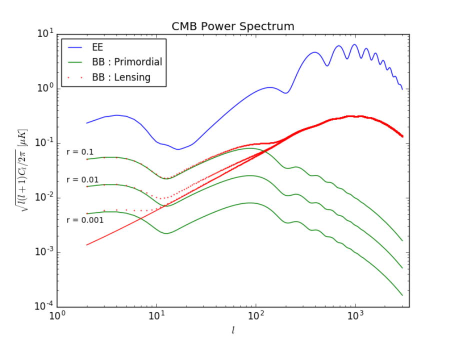


# CMB B-modes and r

- Primordial gravitational waves induce signal in both E and B modes
- Scalar perturbations produce no signal in B

- The tensor to scalar ratio gives us directly the energy scales of Inflation

$$r = \frac{\triangle_h^2}{\triangle_{\Re}^2}$$
$$= 0.1 \frac{V}{[2 \times 10^{16} GeV]^4}$$



# Map Making and Power Spectra Estimation

# Data Compression

- We can think of the process of Map Making and Power Spectrum estimation essentially as stages of data compression.

Time-ordered instrumental data and signal

Several TBs to a few PBs

↓

Sky Maps

Few GBs

↓

Power Spectra

Few thousand data points

# Map Making

- The purpose of map making is to reconstruct the microwave sky from the time-ordered data

We model our data as

$$d_t = \frac{1}{2}\{I_{p(t)} + Q_{p(t)}cos(2\psi_t) + U_{p(t)}sin(2\psi_t)\} + n_t$$
$$d = AS + n$$

In order to estimate S we construct a $\chi^2$ and minimise it to get

$$\chi^2 = (d - AS)^T N^{-1}(d - AS)$$
$$\triangle_S \, \chi^2 = 0$$

And, this give us

$$\widehat{S} = (A^T N^{-1} A)^{-1} A^T N^{-1} d$$

# Power Spectrum Estimation

- Having obtained our T, Q, U maps we wish to construct the CMB power spectra
- Analogous to the Fourier Transform in 1D, we decompose the signal on the spherical sky in a basis of the Legendre polynomials $Y_{lm}$ and ${}_{\pm 2}Y_{lm}$
- On account of being a Gaussian distributed at all scales, all statistical information is contained within the $C_l$

Having obtained the harmonic coefficients, the power spectrum is obtained as

$$C_l^{XY} = \frac{1}{2l+1} \sum_{m=-l}^{m=l} \langle a_{lm}^{*X} a_{lm}^{Y} \rangle$$

The statistical information of the CMB sky is contained in the four spectra $C_l^{TT}$, $C_l^{EE}$, $C_l^{BB}$, $C_l^{TE}$

# Systematics in CMB Observation

# Systematics and signal leakage

- Ideally we would expect all the instruments to be perfect and life would have been easier
- In reality instruments will have certain imperfections

Some of the types of Systematics are

- Asymmetric beam
- Bandpass mismatch
- Pointing error

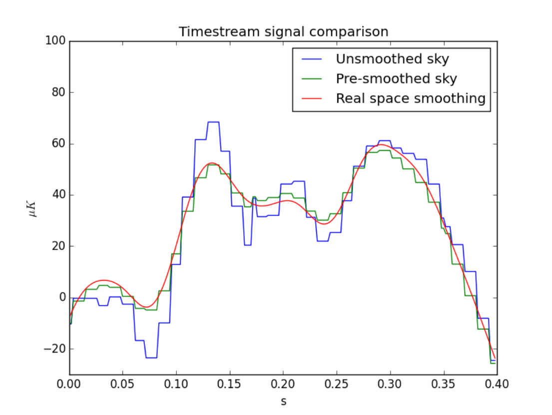
The consequence of such imperfections is the leakage of signal from Temperature to Polarisation. As the Temperature signal is a few orders of magnitude larger than Polarisation, the leakage will swamp out any primordial B-mode signal.

# Simulation Pipeline

- To facilitate the study of Systematics and data analysis techniques it was essential to build a scalable and efficient simulation and map-making pipeline
- The simulation code is optimised for a COrE like scan strategy
- Coded in python using optimised libraries.
- MPI parallelised to be scalable and run over several processes.
- Capable of performing an efficient real space beam convolution for beams of any shape.

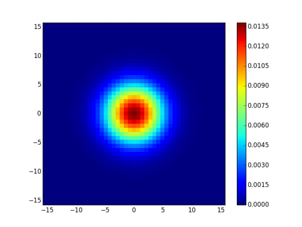
# Real space convolution

- With our pixel space convolution we get a superior simulated signal as compared to scanning from pre-smoothed maps.
- We have better control over pixelisation issues and pointing at different points within the same Healpix pixel.

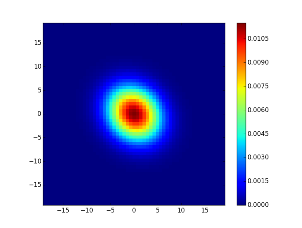


# Asymmetric Beams - Pixelised Beam Maps

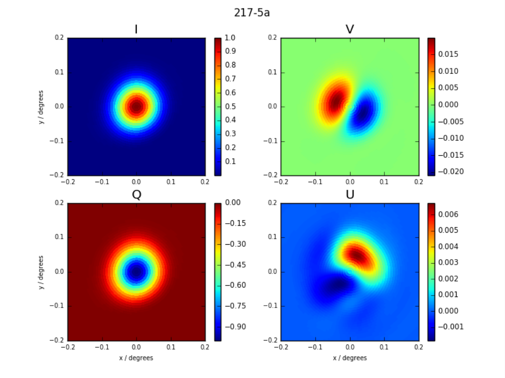
8′ symmetric beam



8′, 10% elliptic beam

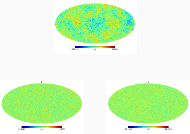


Realistic 7.68′′ beam. Court. Mark Ashdown

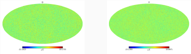


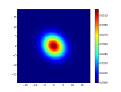
# Leakage estimation pipeline : Summary

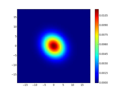
Input map



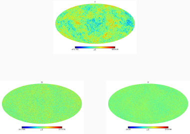
Estimated leakage map





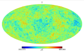


Convolved map

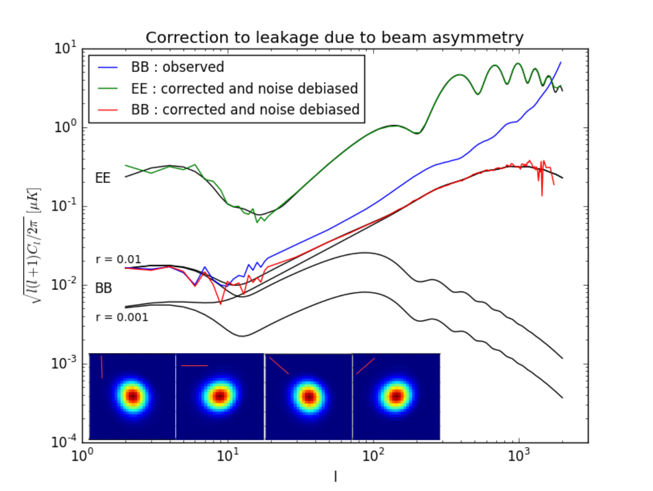


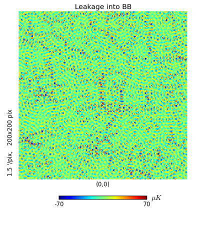
Deconvolve for circular beam in harmonic space

Deconvolved map



# $7.68'$ fwhm beam, 4 bolos



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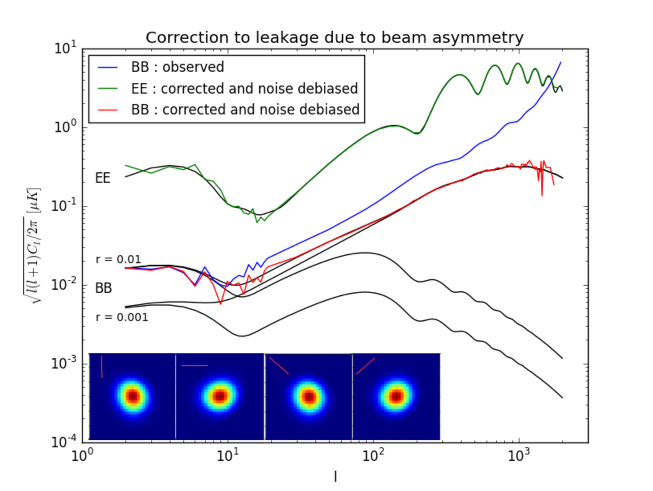
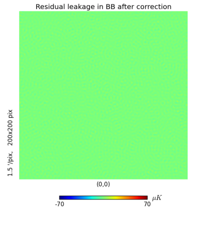
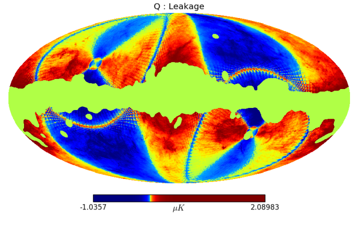
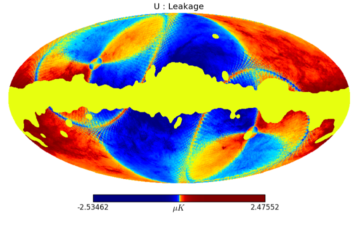


# Leakage due to Bandpass mismatch

- The bolometers observing the sky have a frequency response which gives rise to a bandpass over which the sky signal is integrated
- In reality the bolometers will have slightly different band edges, centres and shapes.
- This gives rise to leakage from Temperature to Polarisation and is detrimental to the measurement of r



# Modeling the Leakage

An interesting way to model the leakage is to take the difference of signal from orthogonal detectors

$$
\begin{aligned}
d_t &= \frac{1}{2}\{d_t^{(a)} - d_t^{(b)}\} \\
&= \frac{1}{2}\{Q_{p(t)} cos(2\psi_t) + U_{p(t)} sin(2\psi_t)\}_{CMB} \\
&+ \frac{1}{4}\left[\{I_{p(t)}^{(a)} - I_{p(t)}^{(b)}\} + \{Q_{p(t)}^{(a)} + Q_{p(t)}^{(b)}\} cos(2\psi_t) + \{U_{p(t)}^{(a)} + U_{p(t)}^{(b)}\} sin(2\psi_t)\right]_{GAL} \\
&= \frac{1}{2}\{Qcos(2\psi_t) + Usin(2\psi_t)\} + \frac{1}{4} \triangle \alpha I_{GAL}^{(0)} \\
&= As + Ty
\end{aligned}
$$

Here, we try to model the leakage as a template times an amplitude where the template is a Thermal Dust T map at a certain frequency. We attempt to find the amplitude of this template so that we can subtract it from the timestream.

# Correcting the leakage

We construct the $\chi^2$ and iteratively by first estimating $\S$, substituting it back and then estimating $y$. This gives us

$$\chi^2 = (d - As - Ty)^T(d - As - Ty)$$
$$\widehat{S} : \triangle_S \chi^2 = 0$$
$$\widehat{y} : \triangle_y \chi^2 = 0$$

and this give us.

$$\widehat{y} = (T^T F_S T)^{-1} T^T F_S d$$
$$F_S = \{1 - A(A^T A)^{-1} A^T\}$$

We can now correct for the leakage by

$$\widehat{S} = (A^T A)^{-1} A^T (d - y I_{GAL}^{(0)})$$

Note : Few bugs in the template estimation pipeline, so no plots on correction yet

# Putting it all together

- We hope to model most of the leakage terms due to systematics.
- Once we have a suitable model we will be able to apply the same technique as for bandpass leakage.
- Instead of one parameter $y$, we end up with an array of scalars $\overline{y}$.