Detecting Primordial Gravitational Waves via the Cosmic Microwave Background

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RAS Discussion Meeting

12 Dec 2014

Basic Idea

- High energy phase in the early universe excites quantum density perturbations and gravitational waves
- These seed the formation of structure we see today
- At recombination, $z \approx O(1000)$, and reionization, $z \approx O(10)$, there are free electrons around that can scatter light towards us
  - If they see a quadrupolar intensity pattern around them we see polarized light

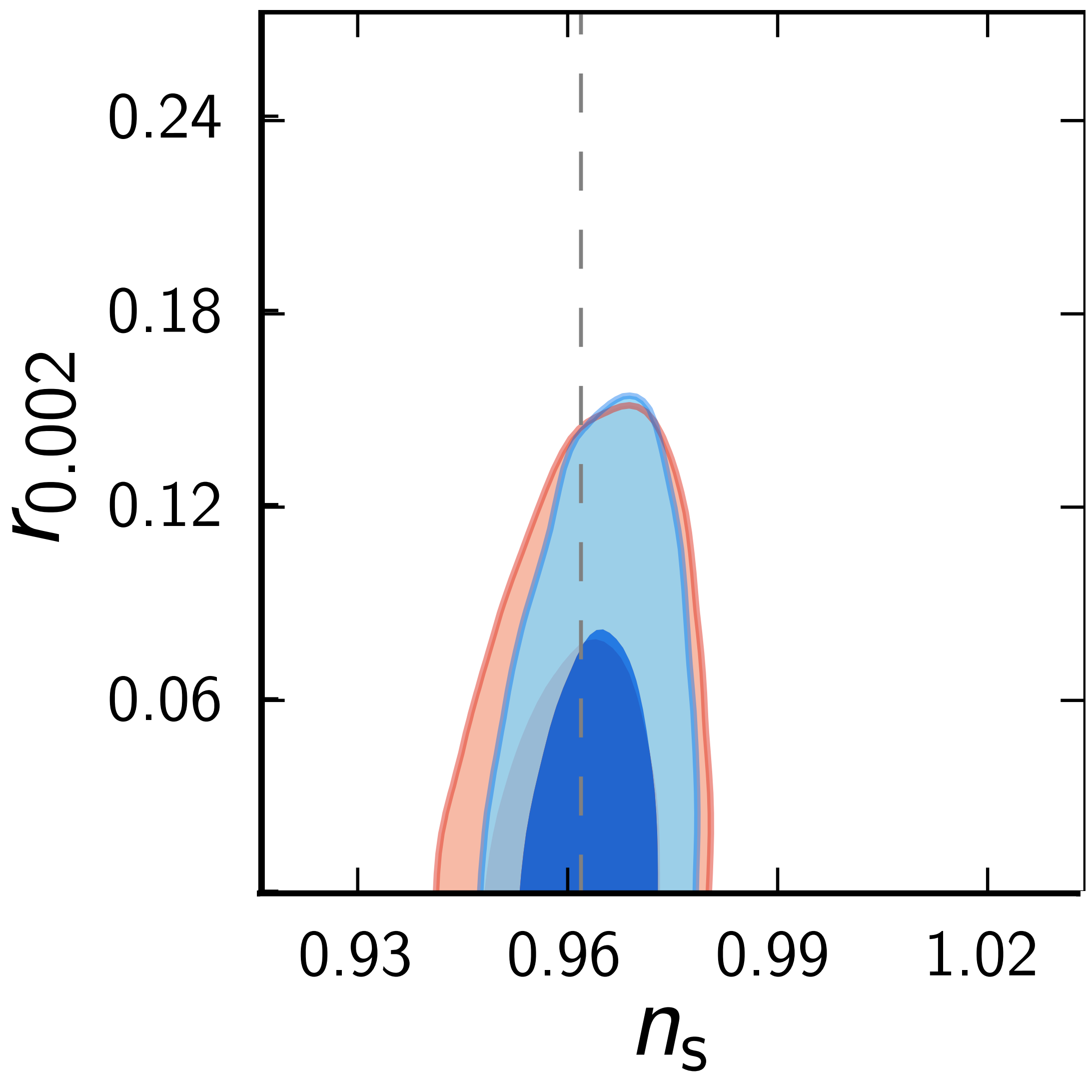
Indirect constraints

- Assume some scalar perturbations
- Define a "tensor to scalar" ratio *r* to set the level of the tensor perturbations
- Compare CMB to predictions

Decomposition of CMB

- Temperature fluctuations T
- Polarization fluctuations
  - Stokes parameters Q & U
  - Rewrite as a “gradient” or “E-mode” pattern and “curl” or “B-mode” pattern

Planck 2013: n_s and r



Planck 2014

- Planck 2014 results due soon
- Preliminary results were presented at a recent conference; many talks available online at:
  - http://www.cosmos.esa.int/web/planck/ferrara2014
- Parameter constraints now come from a likelihood that optionally includes high-/ TE and EE spectra in addition to TT

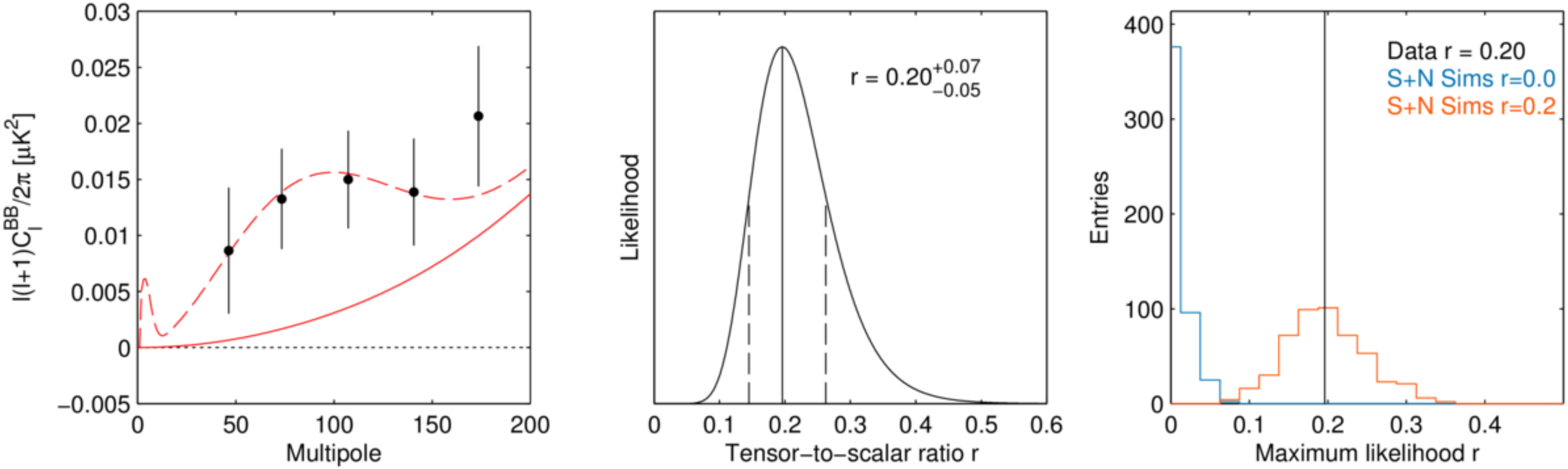
- in G. Efstathiou's Ferrara talk, see:
  - preliminary 2014 TT, TE & EE power spectra
  - preliminary 2014 r vs n_s plot

Less indirect constraints

- Density waves have a symmetry that stops them producing a “curl” or “B-mode” pattern in the CMB polarization, they only make a “gradient” or “E-mode” pattern

- Gravity waves produce both E- and B- mode patterns in the CMB polarization…

BICEP 2014: B-modes at 150 GHz!

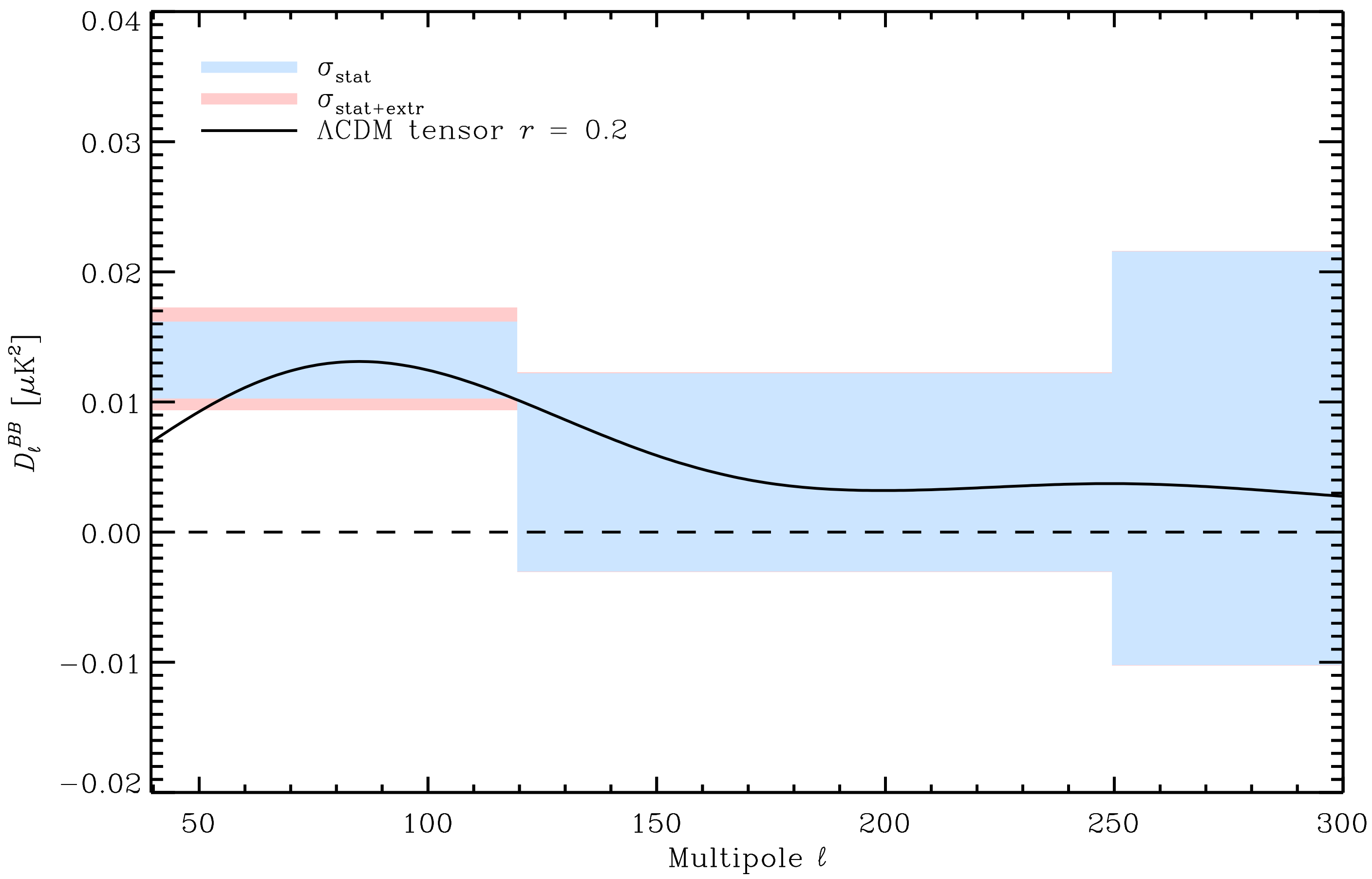


Bicep 2 Results Paper 2014

But is it primordial?

- A main challenge…

Planck PIP30: Dust is important!



BICEP+Planck

- Cross-correlation analysis to try and disentangle a primordial signal from dust

- …Wait and see!

Main Challenges: Foregrounds

- Next generation of ground-based B-mode experiments will observe at multiple frequencies
  - See e.g. L. Page's talk from Ferrara
- Balloons can cover more frequencies
  - Less atmosphere
- Also of course space
  - LiteBIRD
  - COrE+

Foreground Mitigation Techniques

- Choose clean areas of the sky! Then mask
- Template-based cleaning
  - Do foregrounds significantly decorrelate across frequencies though?
- Parametric modelling
  - E.g. via Gibbs sampling with Commander
  - But what about priors?

Main Challenges: Systematics

- T->P leakage
- E<->B mixing coming from finite sky patches
- …

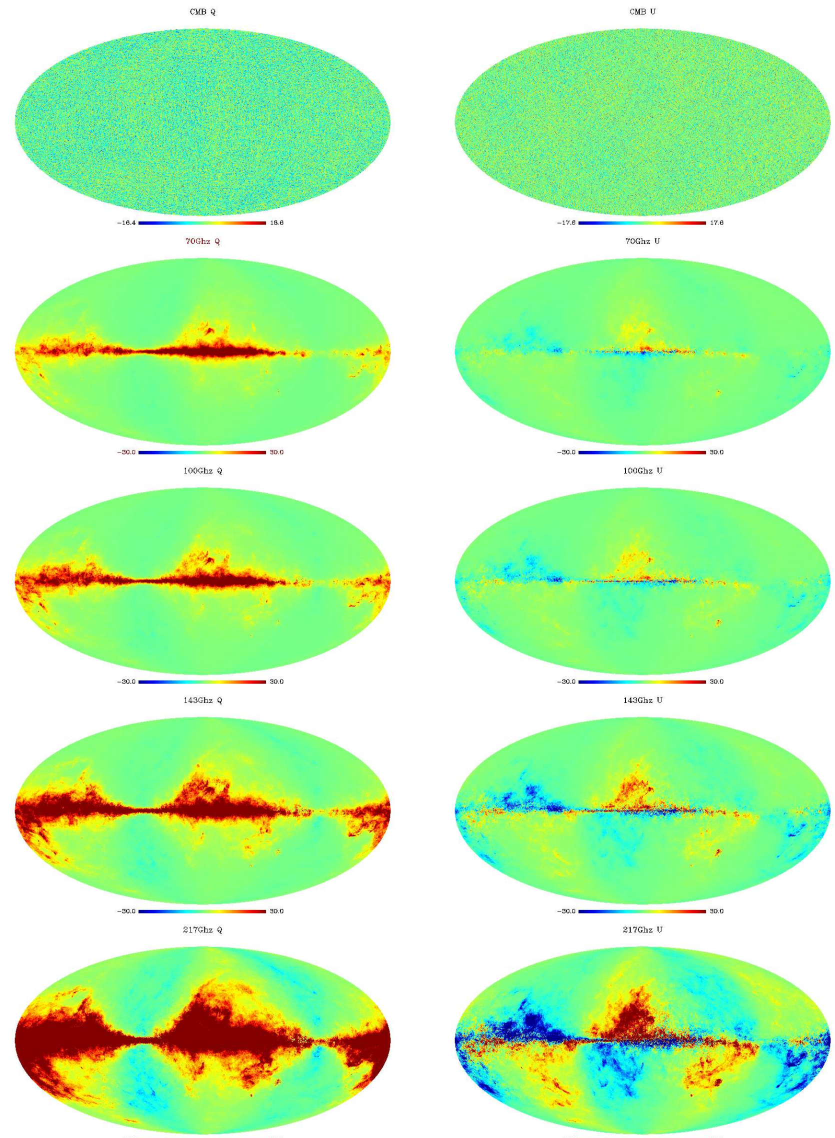
The future

- Might be able to "de-lens" the CMB to remove the lensing contribution
  - In principle allows one to push to much lower *r*, ultimately perhaps to 10^{-6}!
  - This uses high-*l* information to reconstruct the lensing potential
  - See Lewis & Challinor, Phys Rep 429 (2006) 1, for a discussion and original references

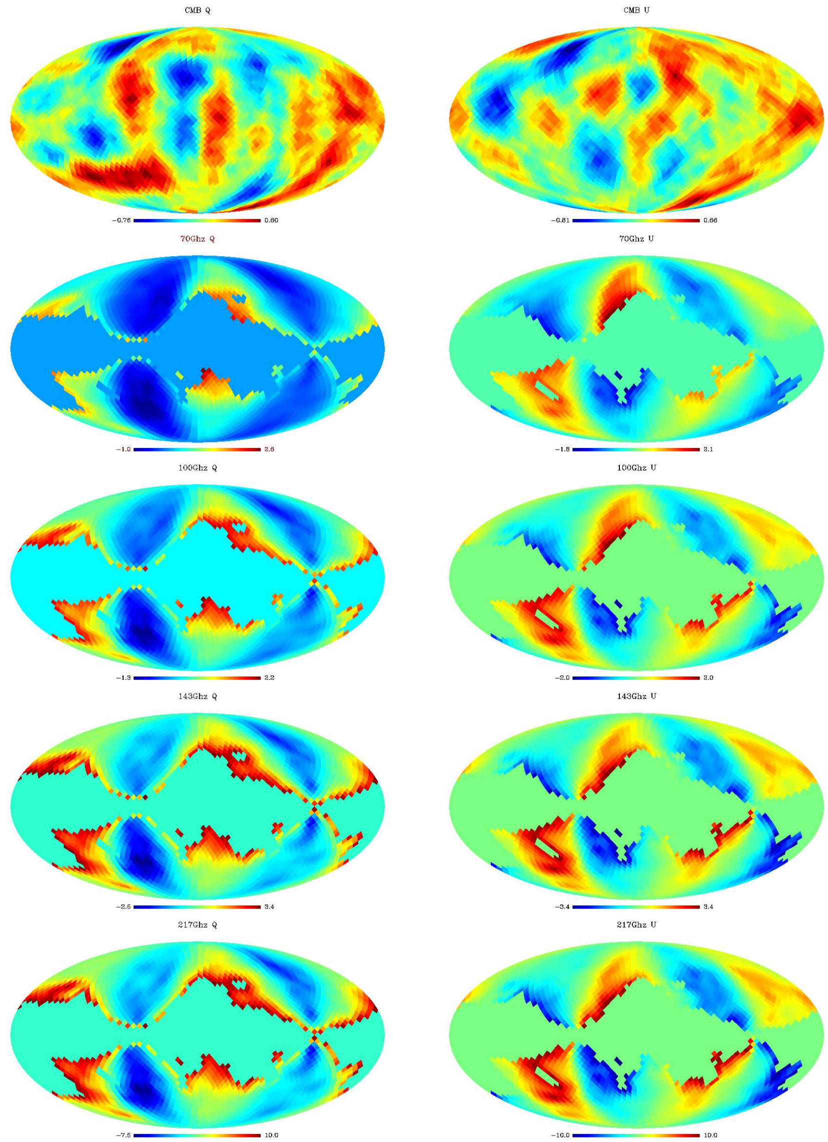
More on template cleaning…

- Following Efstathiou, SG & Paci 2009
  - Based on simulations, now seems very optimistic!
- Focus on “reionization” B-modes

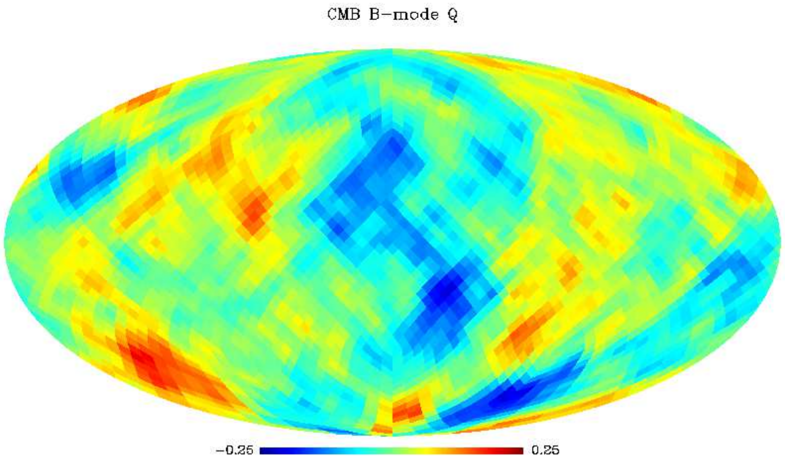
Simulated inputs…

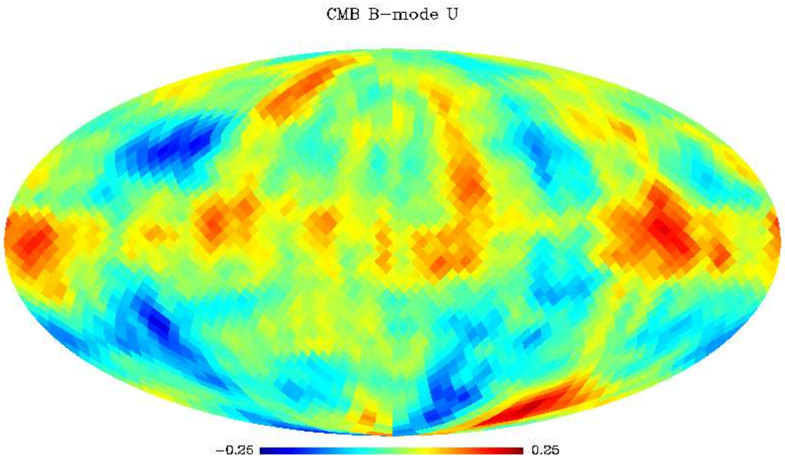


Mask and smooth



Cf. the r=0.1 input contribution





- Model data as:

$$\mathbf{x} = \mathbf{s} + \mathbf{F}\boldsymbol{\beta} + \mathbf{n}$$

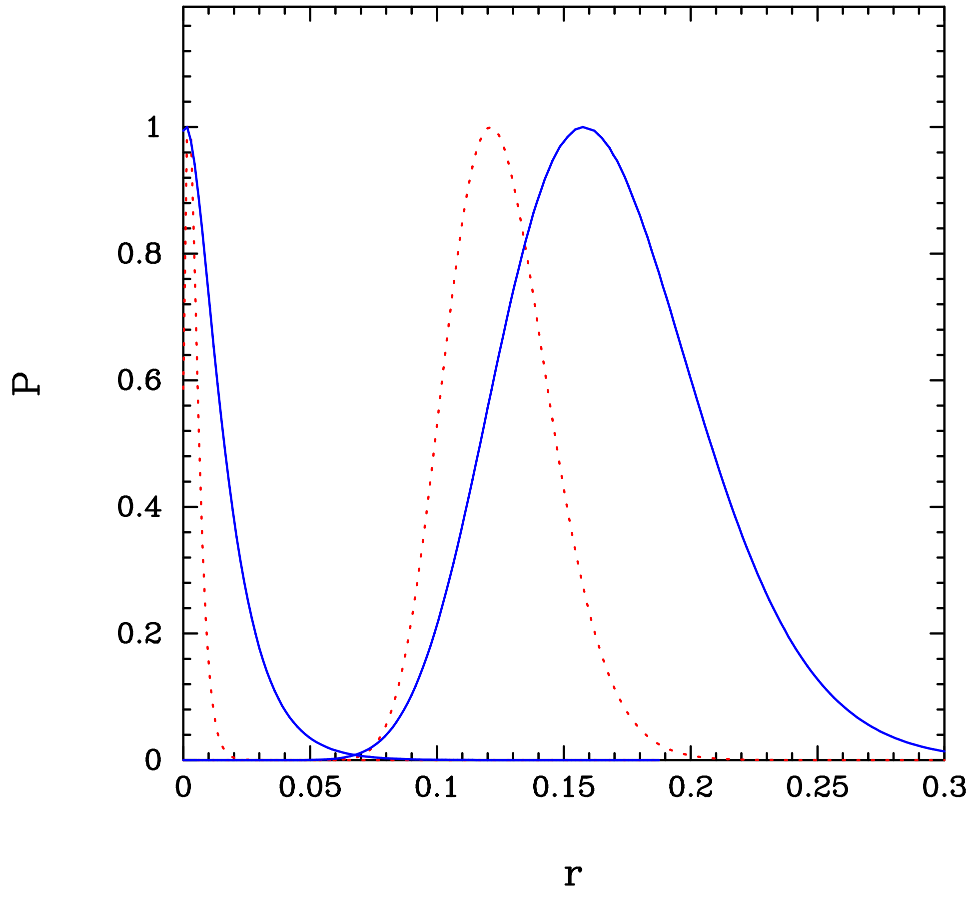
- Find coeffs by minimizing:

$$\chi^2 = (\mathbf{x} - \mathbf{F}\boldsymbol{\beta})^T \mathbf{C}^{-1} (\mathbf{x} - \mathbf{F}\boldsymbol{\beta})$$

- Soln is:

$$\boldsymbol{\beta} = (\mathbf{F}^T \mathbf{C}^{-1} \mathbf{F})^{-1} (\mathbf{F}^T \mathbf{C}^{-1} \mathbf{x})$$

Clean afresh for every model…



Comparing methods…

Scheme	cross-correlation offset	foreground mismatch
Blind (e.g. ILC)	Significant	Small (given enough frequency bands)
Semi-blind (e.g. template fitting)	Small	Small (given enough templates)
Unblind (e.g. model fitting)	Small (if model is correct)	Small (if model is correct)

- Explicit “pixel-based” likelihood scheme
- Involves inverting O(10k x 10k) matrices

- One could in principle do a similar thing for hi-resolution ground-based experiments that look for the “recombination” modes, with bigger matrices
  - Is this feasible/desirable compared to power spectrum methods?

Conclusions

- Very exciting time
  - Bicep-Planck due soon
  - Expect massive ground-based progress in the next few years
- Challenges remain
  - Handling foregrounds
  - Modelling systematics
  - Likelihood computations