

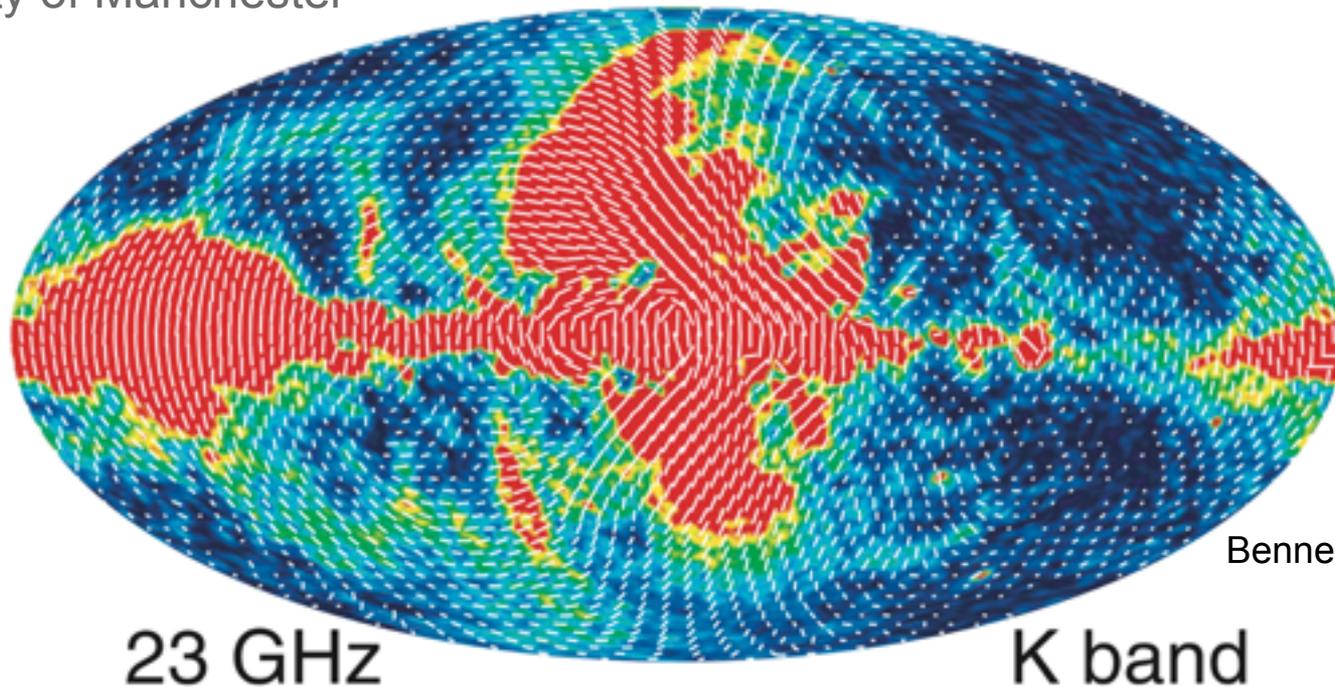
# Challenges of foreground subtraction for (primordial) CMB B-modes

---

Clive Dickinson

Jodrell Bank Centre for Astrophysics

University of Manchester



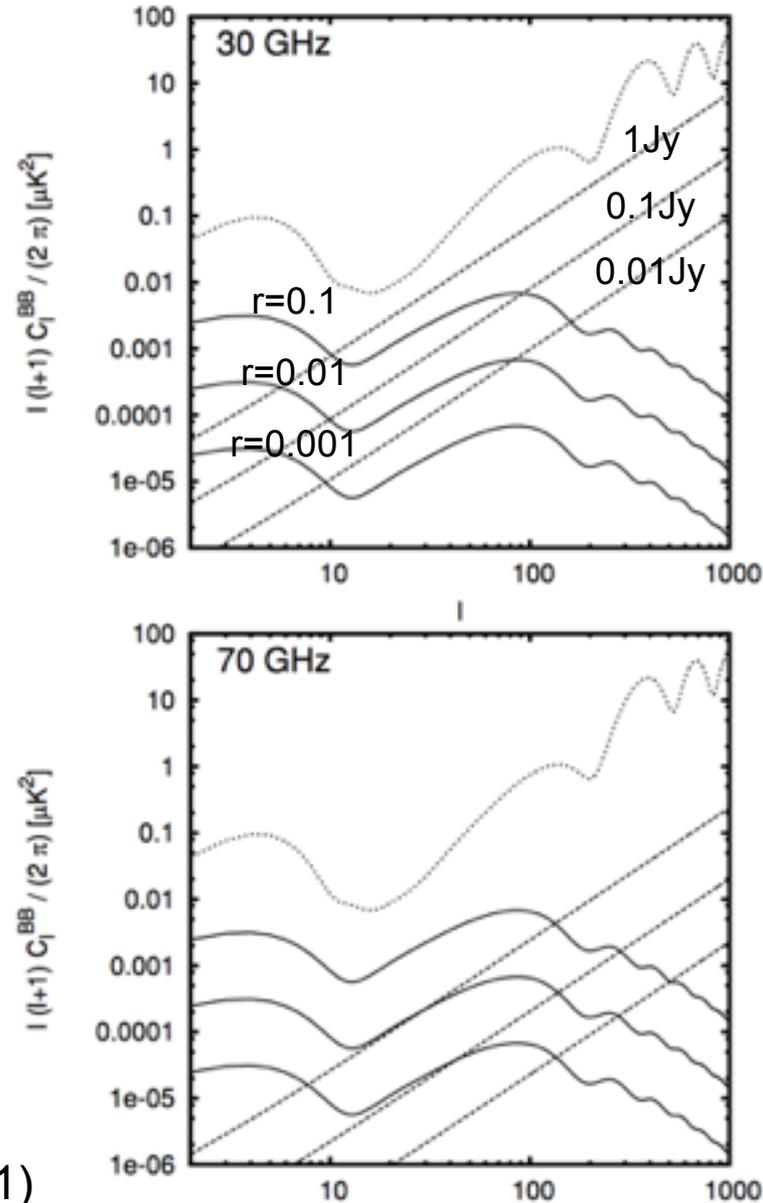
Bennett et al. (2013)

# Component separation for B-modes

- Separate primordial CMB emission from ( $l \sim 5$  and  $l \sim 90$ )
  - **Diffuse Galactic foregrounds**
- Other foregrounds probably dealt with in other ways (e.g. source detection/masking, power spectrum templates, source detection, statistical estimators etc.)
  - Extragalactic sources (Poisson)
  - CIB (clustering)
  - SZ clusters
  - CMB lensing
- Propagate uncertainties to map/power spectra/cosmological parameters
- If possible:
  - Fit for residual monopoles/dipoles
  - Deal with bandpasses (“colour corrections”)
  - Deal with other systematics (e.g. calibration - see e.g. Dick et al. 2011)
  - Separate foregrounds into (multiple) individual components (astrophysics)

# Extragalactic sources

- Extragalactic sources are not very polarized
  - $\sim 3.5\%$  for radio sources (Battye et al. 2011)
  - $< \sim 1\%$  in FIR for star-forming galaxies
    - 1.5% Upper limit of for Arp220 (Seiffert et al. 2006)
- Power is relatively small at freqs  $> 30$  GHz
  - Subtract/mask the brightest sources
  - Statistically correct the residual sources
- N.B. CIB will be  $< 1\%$  polarized but still important
  - Correlated on large angular scales ( $\sim 1$  deg)
  - Polarization does *not* average out (variance does not average)



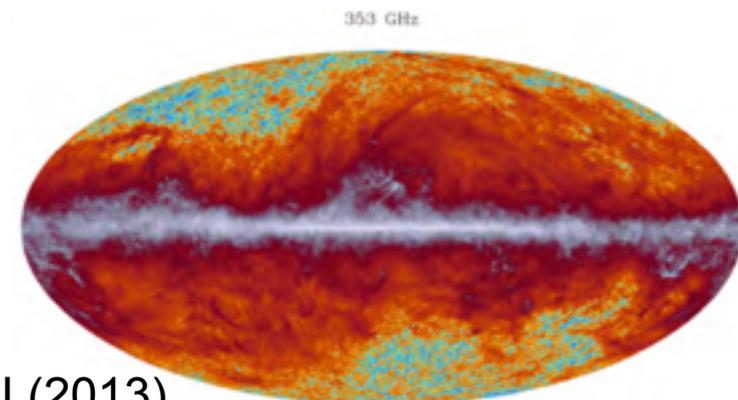
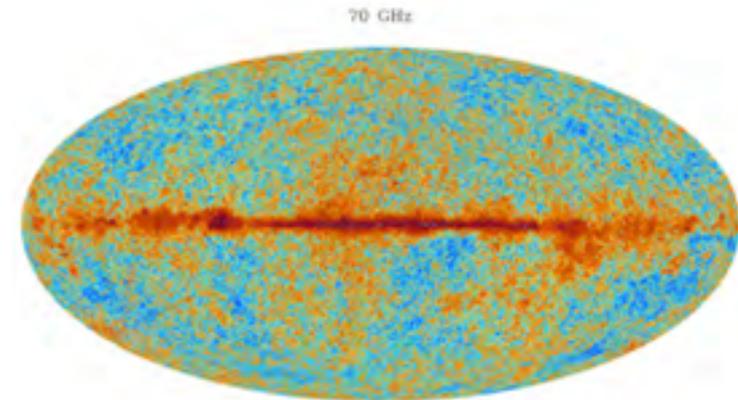
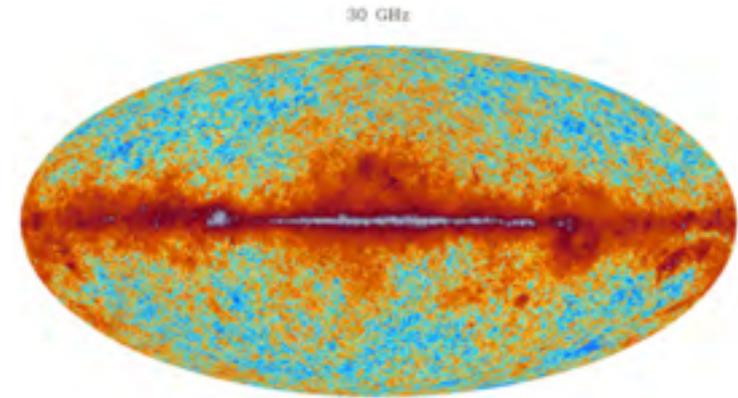
# Large scale polarized foregrounds

- Diffuse polarized foregrounds dominate at  $l < 100$

| Component                  | Spectrum  | Polarization fraction                  | References  |
|----------------------------|---|--|---|
| <b><u>Synchrotron</u></b>  | Power-law, $\beta \sim -3.1$ , possible curvature   | $\sim 15-20\%$<br>(up to $\sim 50\%$ ) | Page et al. (2007), Kogut et al. (2007), Macellari et al. (2011)  |
| <b><u>Thermal dust</u></b> | Modified black-body, possibly 2 components/flattening at frequencies $< 300$ GHz                  | $\sim 5\%$<br>(up to $\sim 15+\%!$ )   | Ponthieu et al. (2005), Planck Collaboration, ESLAB conference (2013).<br>Planck papers to come out soon!                       |
| Magnetic dipole?           | Similar to thermal dust, but flatter index at frequencies $\sim 100$ GHz                          | Variable<br>(up to $\sim 35\%!?$ )     | Draine & Lazarian (1999), Draine & Hensley (2013)   |
| AME<br>(spinning dust)     | Peaked spectrum $\sim 10-60$ GHz.   | $< \sim 1\%$                           | Lazarian & Draine (2000), Dickinson (2011), Lopez-Caraballo et al. (2011), Macellari et al. (2011), Rubino-Martin et al. (2012) |
| Free-free                  | Power-law $\beta \sim -2.14$ with positive curvature (steepening at frequencies $> \sim 100$ GHz) | $< \sim 1\%$                           | Rybicki & Lightman (1979), Keating et al. (1998), Macellari et al. (2011)   |

# Temperature vs Polarization

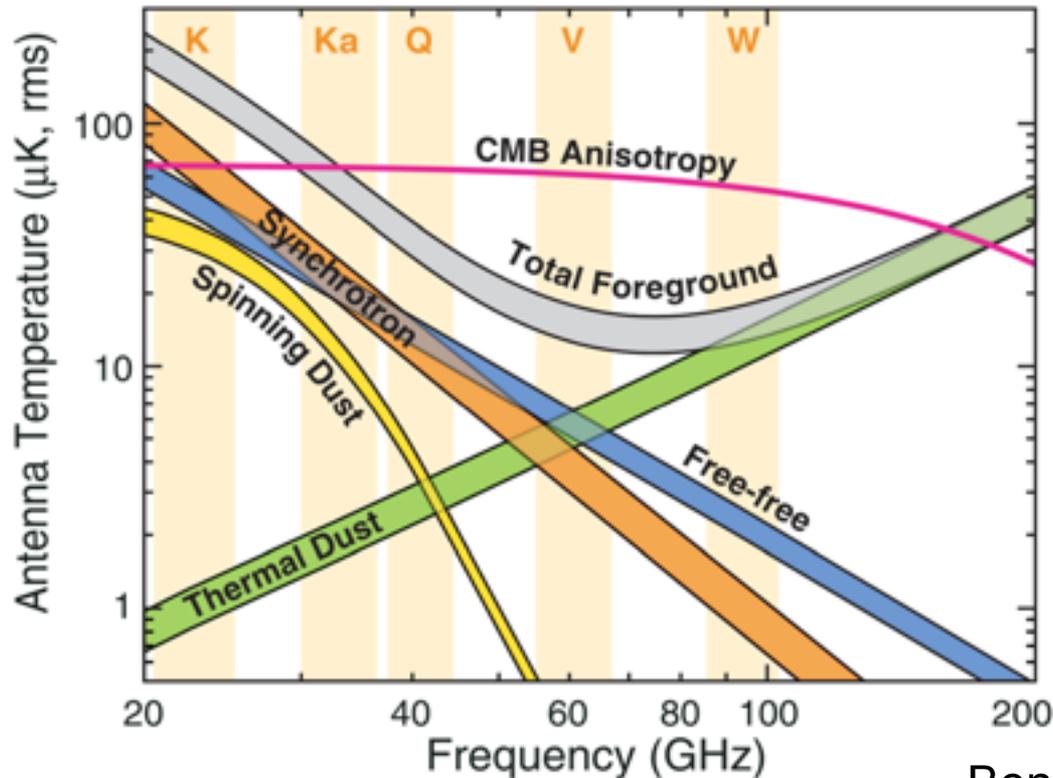
- Foregrounds not a major issue for intensity
  - 40 - 250 GHz relatively clean at high latitudes
  - Still “see” CMB at 20 GHz and 353 GHz !!!
- Similar levels for E-modes
  - CMB and foregrounds polarized at ~10% level
  - Low- $l$  ( $l < 10$ ) significantly contaminated
- CMB B-modes ( $l < 100$ ) much more contaminated by foregrounds
  - CMB  $< 1\%$  polarized
  - Foregrounds  $\sim 10\%$  polarized!



# Intensity foregrounds

Details of intensity foregrounds are quite complex! But quite interesting astrophysically speaking!

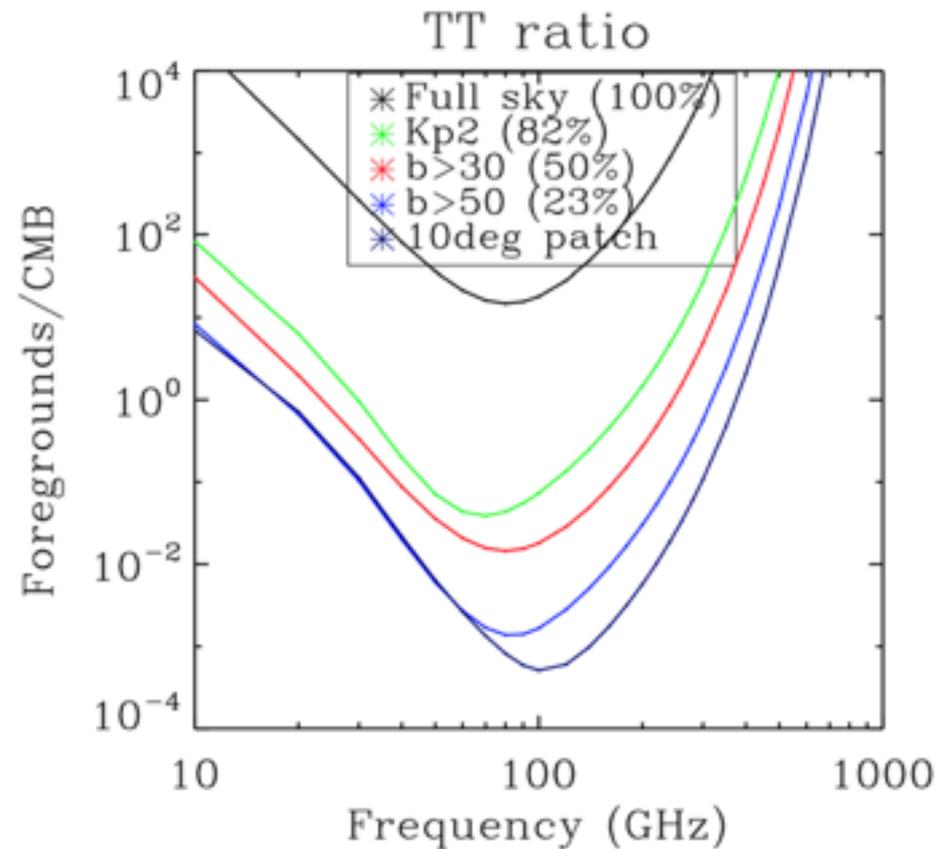
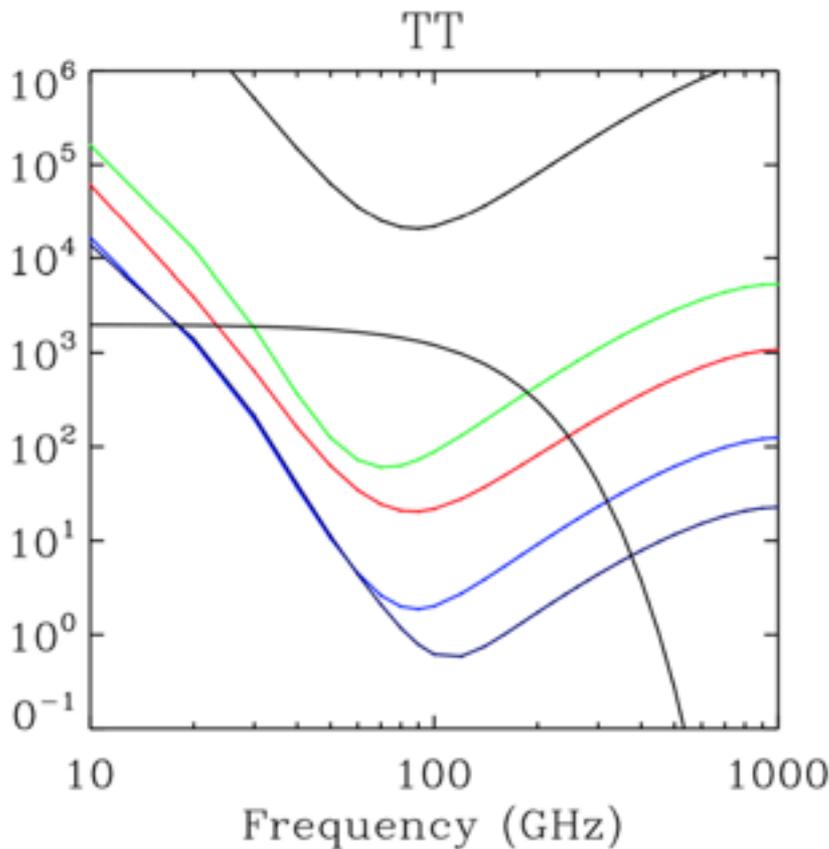
Polarization may well be simpler!?!



Bennett et al. (2013)

# Intensity foregrounds vs CMB

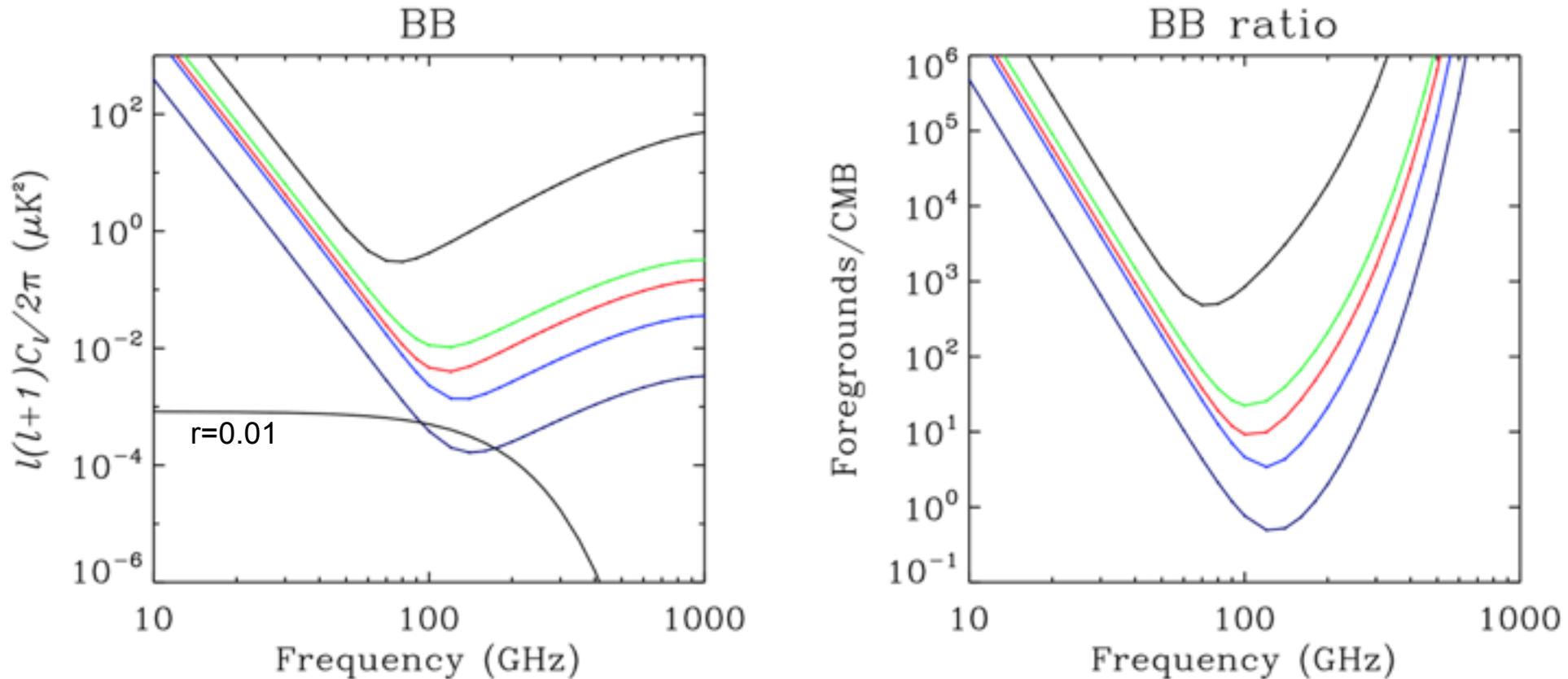
Only very largest scales, including Galactic plane, which are strongly affected by diffuse foregrounds (TT)



Dunkley et al. (2009) U.S. Decadal review white paper  
(based on Planck Sky Model simulations; see Delabrouille et al. (2013))

# Polarized foregrounds vs CMB B-modes

For  $r=0.01$ , foregrounds dominate CMB almost everywhere at all frequencies on scales  $>1$  deg



Dunkley et al. (2009) U.S. Decadal review white paper  
(based on Planck Sky Model simulations; see Delabrouille et al. (2013))

# Component separation methods

- Many methods/algorithms/codes out there! (see next slide)
  - 3 broad categories
    - 1. Parametric / non-blind (e.g. pixel fitting, external template fitting)
    - 2. Semi-blind (use some external info but not reliant e.g. SMICA, CCA)
    - 3. Blind (e.g. ILC, ICA, PCA, Neural networks)
- Most successful / popular so far have been simple ones!
  - Template fitting, ILC, parametric fitting...
  - Do not want to change noise properties of maps
  - **Important to fully propagate errors (using likelihood)**
  - Simple, linear methods are preferred! (see Komatsu talk)
- But times are changing...
  - c.f. Planck Collaboration XII (2013): SMICA, GMCA, NILC, Commander-Ruler

# (some) Component separation methods

DISCLAIMER: this list is not comprehensive and some algorithms grouped together (but are quite different)

| Type                                   | Codes / implementations                       | Method / assumptions  | References   |
|--|---|---|--|
| ILC                                    | Pixel based ILC, NILC, Constrained ILC, MILCA | Internal Linear Combination - CMB spectrum conserved  | Bennett et al. (2003), Delabrouille et al. (2007), Remazeilles et al. (2011), Hurier et al. (2010) |
| ICA                                    | FastICA, AltICA, JADE                         | Independent Component Analysis - Gaussian CMB/non-Gaussian foregrounds  | Hyvarinen (1999), Cardoso (1999), Maino et al. (2002)  |
| Sparsity                               | GMCA, PCA, Neural networks                    | Foregrounds described by few numbers in certain basis set (e.g. PCA)  | Bobin et al. (2007, 2013), Leach et al. (2005), Norgard-Nielsen (2008)                             |
| Template fitting                       | Linear sum of spatial templates, WIFIT, SEVEM | Linear sum of spatial templates (external or internal templates)  | Bennet et al. (2003), Page et al. (2007), Hansen et al. (2006), Martinez-Gonzalez et al. (2003)    |
| Spectral matching                      | SMICA   | Estimates model parameters (mixing coefficients/power spectrum) using 2nd order statistics (correlations). Then Wiener filtering. | Delabrouille et al. (2003), Cardoso et al. (2008)  |
| Correlated Components                  | CCA   | Correlations used to estimate mixing matrix, then Wiener filtering solution   | Bedini et al. (2003), Bonaldi et al. (2006)  |
| Pixel-based frequency spectral fitting | Commander, MEM, Miramare, Galclean (MCMC)     | Pixel-based parametric fitting. Simple models in frequency space. MCMC/Gibbs sampling.  | Eriksen et al. (2006, 2008), Leach et al. (2008), Stompor et al. (2009), Dunkley et al. (2009)     |
| Power spectrum fitting                 | FastMEM, Planck likelihood fitting            | Mask and then fit power-law in the power spectrum   | Hobson et al. (1998), Stolyrov et al. (2002), Planck Collaboration (2013)                          |
| Hierarchical Bayesian fitting          | Hierarchical Bayesian fitting                 | a   | Morishima poster   |

Blind (green), semi-blind (yellow) and non-blind (orange)

# Forecasts for B-modes

- Planck should be able to detect  $r \sim 0.05-0.1$  (Efstathiou & Gratton 2009, Betoule et al. 2009, Bonaldi & Ricciardi 2011, Armitage-Caplan et al. 2011)
- Foregrounds become significant limitation for  $r < 0.1$ 
  - Typically 30-100% increase in errors due to component separation
- BUT, several studies have shown  $r \sim 0.001$  can be reached (Dunkley et al. 2009, Betoule et al. 2009, Katayama & Komatsu 2011)

| Method     | Average dust<br>pol fraction (%) | Description            | $\ell < 15$ | $\ell < 150$ |
|------------|----------------------------------|------------------------|-------------|--------------|
| Fisher     | 0                                | No foregrounds         | 0.0015      | 0.00046      |
| Fisher     | 5                                | 10% residual           | 0.014       | 0.00052      |
| Parametric | 1                                | Fixed spectral indices | 0.0015      | 0.0005       |
| Parametric | 1                                | Power-law indices      | 0.0025      | —            |
| Parametric | 5                                | Power-law indices      | 0.003       | —            |
| Blind      | 4                                | SMICA                  | —           | 0.00055      |

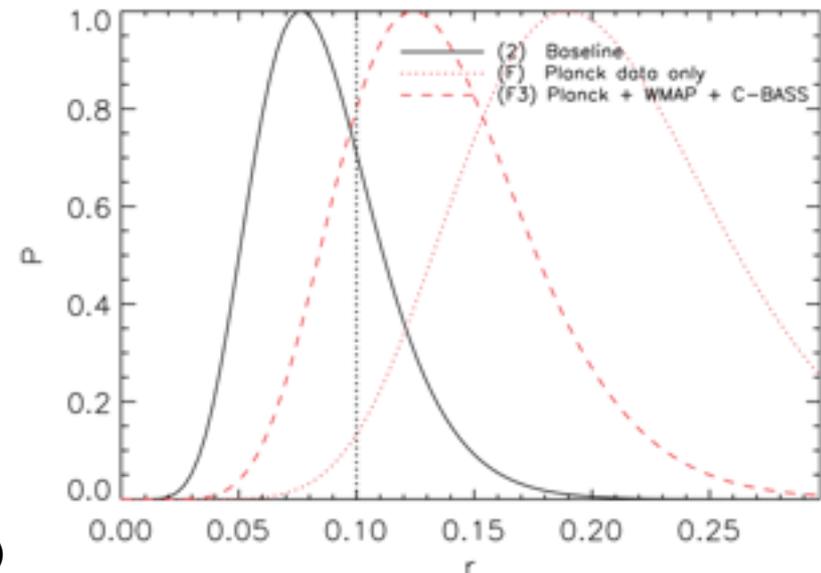
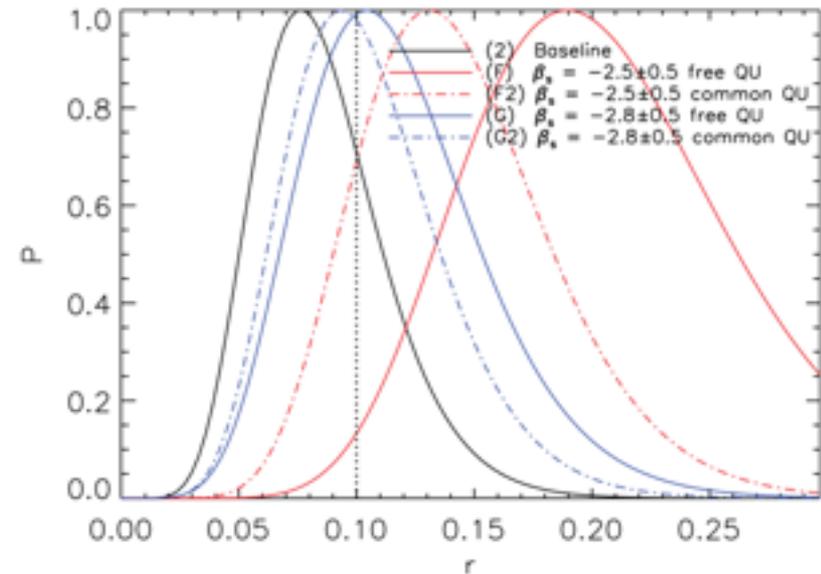
# Potential issues

- Are polarized foregrounds so simple?
  - Thermal dust polarization possibly more polarized than first thought
  - Subtle spectral variations in synchrotron/dust
  - AME polarization
  - Magnetic dust polarization
- Calibration
  - Gain calibration (e.g. Dick et al. 2011)
  - Offsets (e.g. Eriksen et al. 2008)
  - Bandpass mis-match
  - Effective frequencies (colour corrections)
- Other systematics
  - Line contamination! (c.f. CO for Planck!)
  - Polarization leakage (I- $\rightarrow$ Q,U)
  - Polarization angle calibration
  - 1/f (striations)
  - Spillover (sidelobes)
  - .....



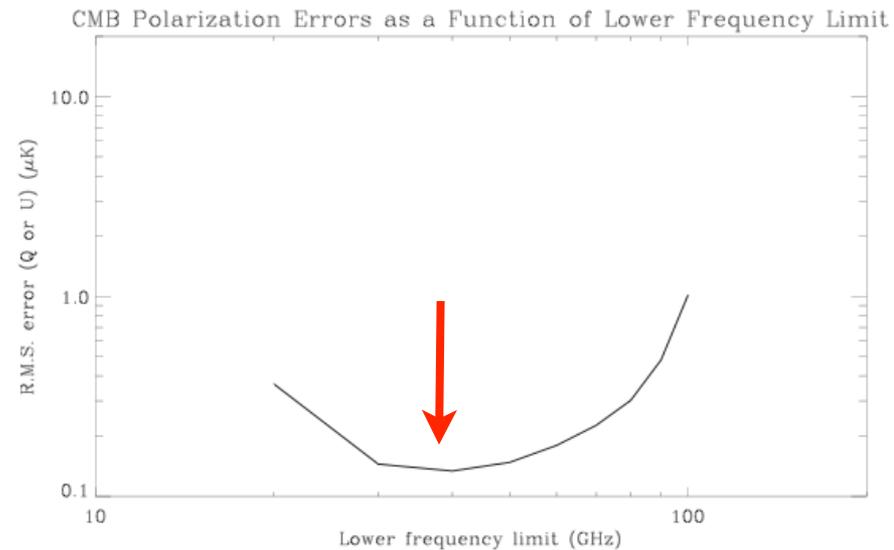
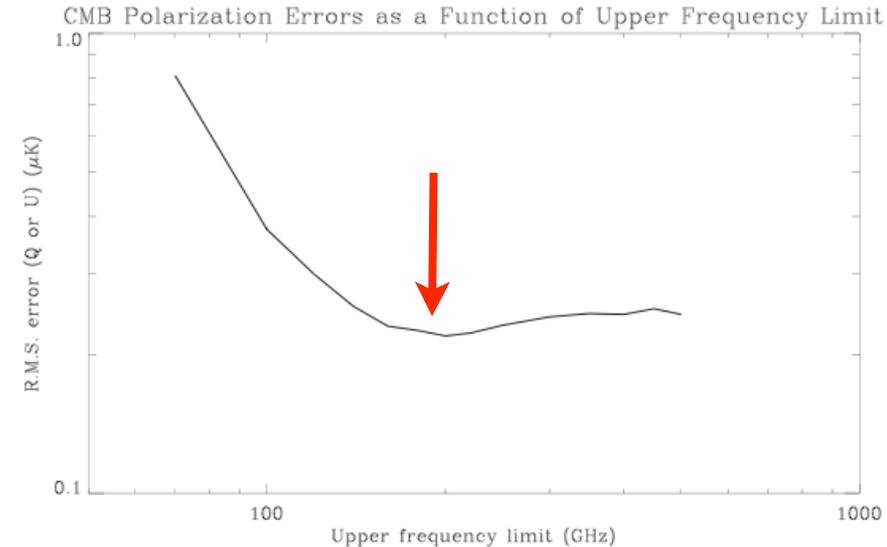
# Foreground modelling examples

- For Planck (Armitage-Caplan et al. 2011):
  - $\sim 1\%$  polarized free-free or spinning dust has negligible effect on Planck
  - Curvature of synchrotron can bias  $r$  by  $\sim 1\sigma$  ( $r \sim 0.03$ )
  - Mis-matches in synchrotron spectral index can bias  $r$  by up to  $\sim 3\sigma$
- For CMBpol/EPIC/CORE/LiteBird etc. we will be much more sensitive to foreground modelling errors!
  - see also Betoule et al. (2009)



# Optimization of future CMBpol missions

- Important to design future missions so not to be limited by foregrounds
- Want to minimise final error after component separation step
  - No. channels:  $>6$
  - Narrow bands are better (avoid bright lines, frequencies better defined...)
  - Frequency range: 40-250 GHz or more!
  - Low frequencies from ground/balloon
  - Few GHz up to  $\sim 20$  GHz
  - SPASS, CBASS, QUIJOTE, COFE/LATTE....
  - No. detectors per band



# Conclusions

- CMB/foregrounds component separation is a very active field of research
  - Important for cosmology and astrophysics
- Planck should be able to detect  $r \sim 0.1$  or possibly below
- Planck HFI data (esp 353 GHz) will provide vital information on polarized dust
- Future CMB polarization mission should be aiming for  $r \sim 0.001$ , possibly even below
  - Optimization important
  - High quality ground/balloon data, esp. low frequencies ( $\sim$ few GHz to 20 GHz) is very important!
- Many methods out there!
  - We will need several independent methods to achieve convincing detection of  $r$
  - Simple methods preferred e.g. template fitting!
- More work needed in this area!
  - Error bar propagation (forming likelihood)
  - Dealing with systematics (bandpasses, calibration etc)
  - Understanding foreground modelling errors