Report on
COrE+ foreground activities

Mathieu Remazeilles

MANCHESTER 1824
The University of Manchester

on behalf of

C. Baccigalupi, A. Banday, S. Basak, A. Bonaldi, J. Delabrouille, J. Errard, S. Feeney, R. Fernandez-Cobos, C. Hervias, M. Jones, M. Lopez-Caniego, M. Remazeilles, J. A. Rubino Martin, P. Vielva

...

Towards a next space probe for CMB observations and cosmic origins exploration
CERN, 17-20 May 2016

Large scale polarized foregrounds

Component	***Spectrum***	***Polarization fraction***	***References***
Synchrotron	*- Power-law $\beta\sim-3$, variations $\Delta\beta\sim0.2$* *- In theory, curvature C=-0.3* *- Flattening from multiple power-laws / populations of electrons*	*~15-20%* *(up to ~50%)*	*Page et al (2007), Kogut et al (2007), Macellari et al (2011)* *Vidal et al (2015)*
Thermal dust	*- Modified black-body* *- Possibly 2 components/flattening* *at frequencies <300 GHz*	*~5% - 10%* *(up to ~20+%)*	*Ponthieu et al (2005), Planck Collaboration, ESLAB conference (2013).* *Planck intermediate results. XIX*
Magnetic dipole?	*- Similar to thermal dust, but flatter index at frequencies ~100 GHz* *- Not yet detected (70GHz-300 GHz)*	*Variable* *(up to ~35% ?)* *<~5%*	*Draine & Lazarian (1999), Draine & Hensley (2013)* *Hoang & Lazarian (2015)*
spinning dust	*- Peaked spectrum ~10-60 GHz*	*<~1%* *Perseus:0.6+/-0.5%*	*Lazarian & Draine (2000), Dickinson (2011), Lopez-Caraballo et al. (2011), Macellari et al. (2011), Rubino-Martin et al. (2012)* *Planck 2015 results. XXV*
Free-free	*- Power-law $\beta\sim-2.14$ with positive curvature (steepening at frequencies >~100 GHz)*	*Intrisically zero,* *in practice <~1%*	*Rybicki & Lightman (1979), Keating et al. (1998), Macellari et al. (2011)*

Challenging sky simulation

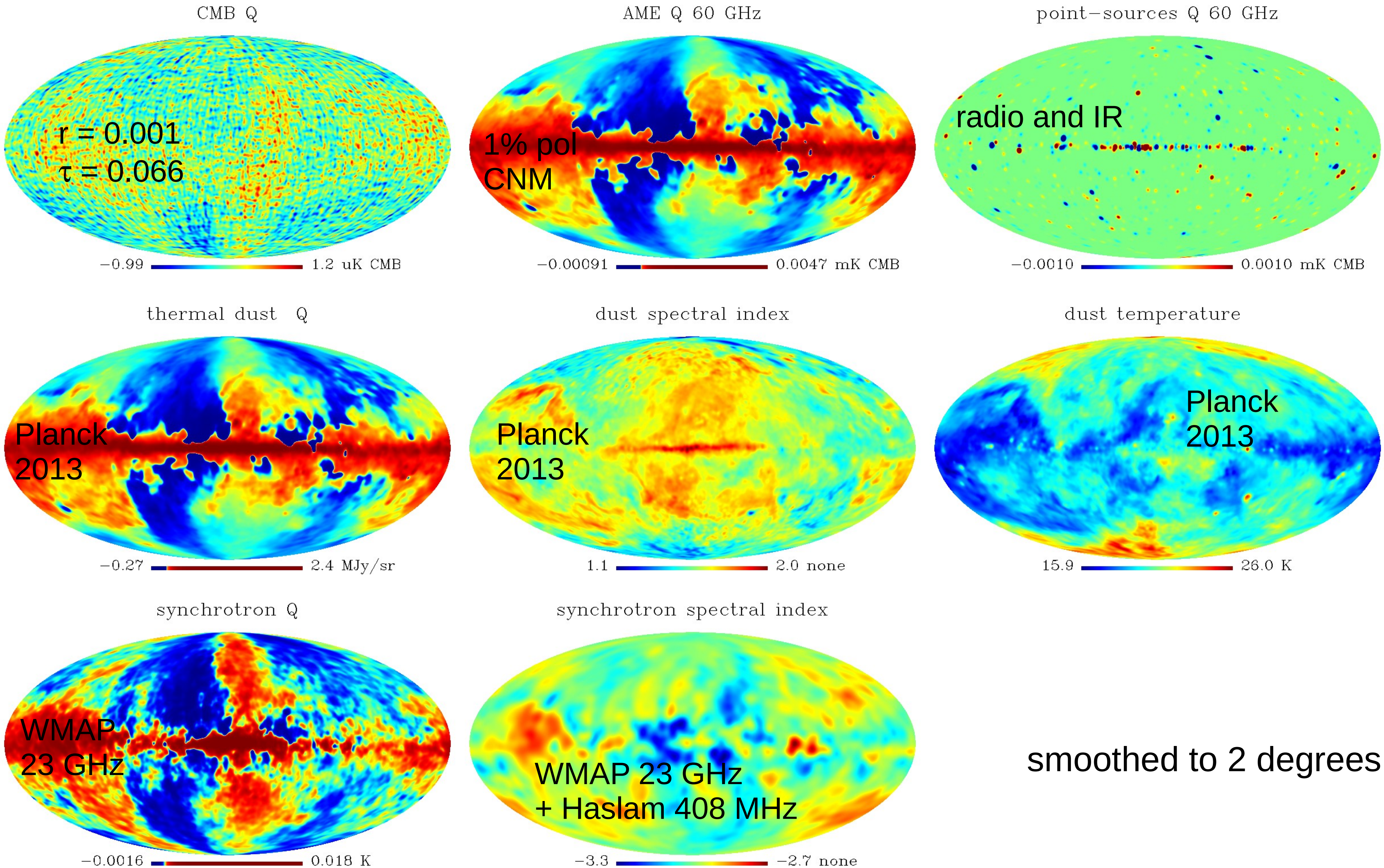
M. Remazeilles,
J. Delabrouille,
C. Dickinson

Modified version of the public Planck Sky Model :

- CMB r = 0.001, τ = 0.066 (to be updated with τ=0.055 from Planck)
- Lensing
- Synchrotron with varying β
- Thermal dust with varying β and T
- AME 1% polarized
- Point-sources (radio and IR)
- white noise / COrE+ and LiteBIRD specs

Challenging sky simulation

M. Remazeilles,
J. Delabrouille,
C. Dickinson



smoothed to 2 degrees

Component separation methods

- COMMANDER – M. Remazeilles, with I. Wehus, H. K. Eriksen, C. Dickinson

  Bayesian parametric fit + Gibbs sampling in pixel space *Eriksen et al 2008*

  Remazeilles et al 2016

- CCA – C. Hervias, A. Bonaldi

  parametric fit of correlated components in harmonic space *Bonaldi et al 2006*

- NILC – S. Basak, C. Baccigalupi

  blind variance minimization of E/B in wavelet space *Basak et al 2012*

- PILC / PRILC – R. Fernandez Cobos, P. Vielva

  blind variance minimization of Q+iU in pixel space *Fernandez-Cobos et al 2016*

- And also,
  Fisher forecast tool, CMB4CAST – J. Errard, S. Feeney *Errard et al 2016*
  MHW point-sources detection / masking – M. Lopez-Caniego

Component separation results:

COMMANDER

Methodology

Eriksen et al, ApJ 2008
Remazeilles et al, MNRAS 2016

1. Separation of components (`COMMANDER` Gibbs sampling) :

$$\boldsymbol{s}^{(i+1)} \leftarrow P\left(\boldsymbol{s} \middle| C_\ell^{(i)}, \boldsymbol{\beta}^{(i)}, \boldsymbol{d}\right),$$ amplitudes

$$C_\ell^{(i+1)} \leftarrow P\left(C_\ell \middle| \boldsymbol{s}^{(i+1)}\right),$$ CMB power spectrum

$$\boldsymbol{\beta}^{(i+1)} \leftarrow P\left(\boldsymbol{\beta} \middle| \boldsymbol{s}^{(i+1)}, \boldsymbol{d}\right),$$ spectral indices

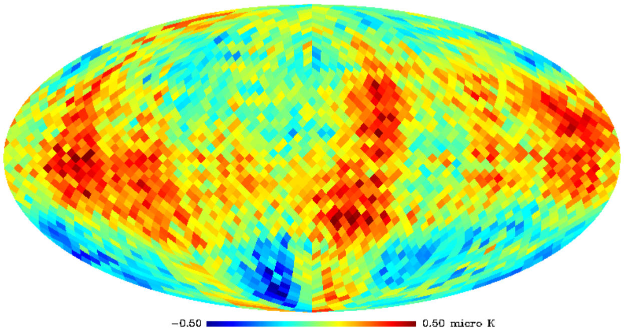
2. Likelihood estimation of r and A_{lens} :

$$-2\ln\mathcal{L}\left[\widehat{C}_\ell | C_\ell^{th}\left(r, A_{lens}\right)\right] = \sum_\ell (2\ell+1)\left[\ln\left(\frac{C_\ell^{th}}{\widehat{C}_\ell}\right) + \frac{C_\ell^{th}}{\widehat{C}_\ell} - 1\right]$$

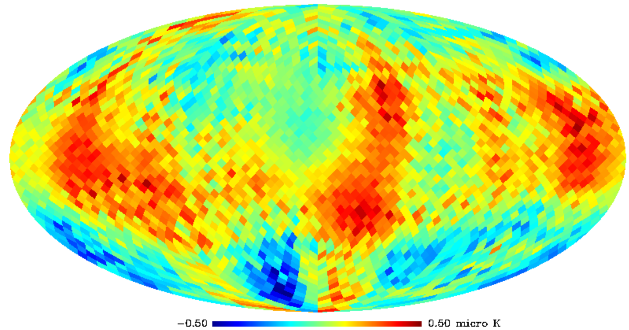
$$C_\ell^{th} = r\, C_\ell^{tensor}(r=1) + A_{lens}\, C_\ell^{lensing}(r=0).$$

COMMANDER

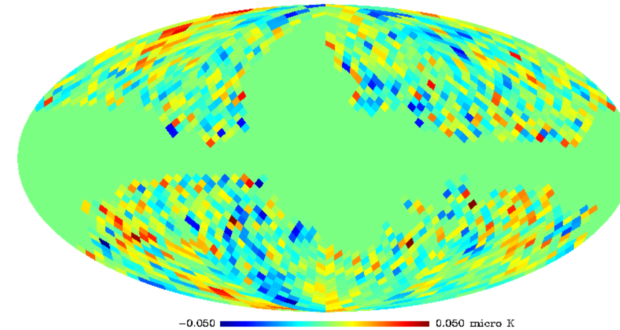
CMB Q INPUT



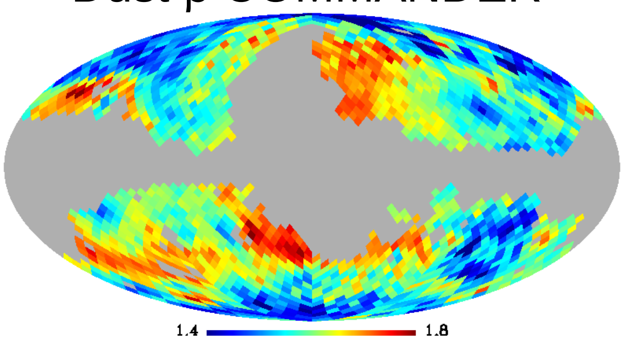
CMB Q COMMANDER



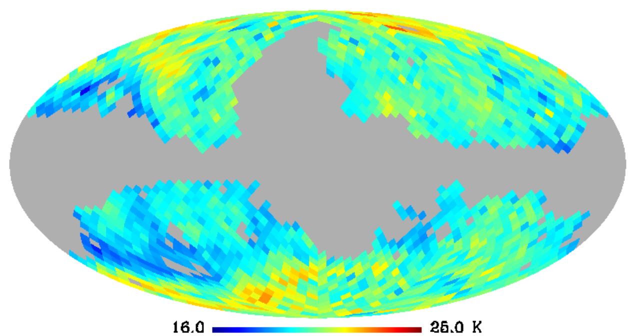
CMB RESIDUALS



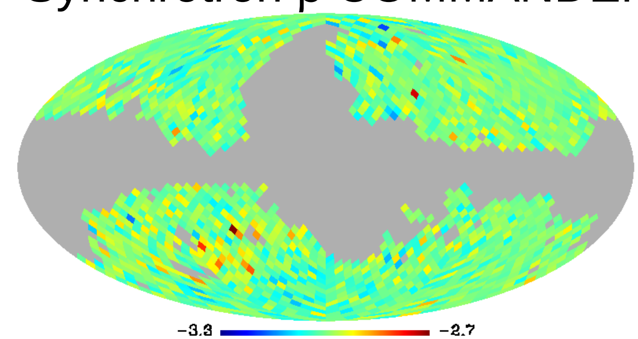
Dust β COMMANDER



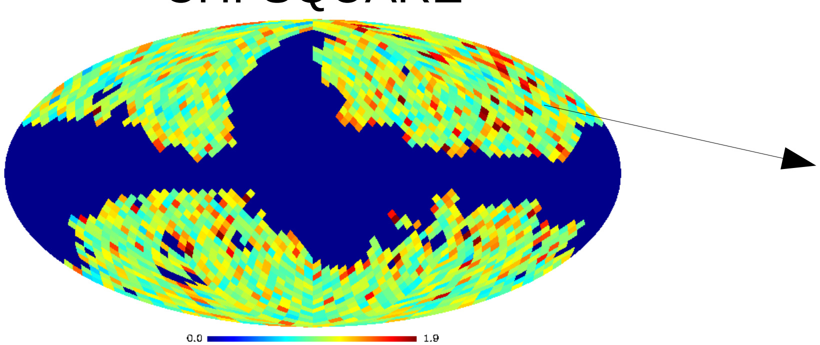
Dust T COMMANDER



Synchrotron β COMMANDER



CHI-SQUARE



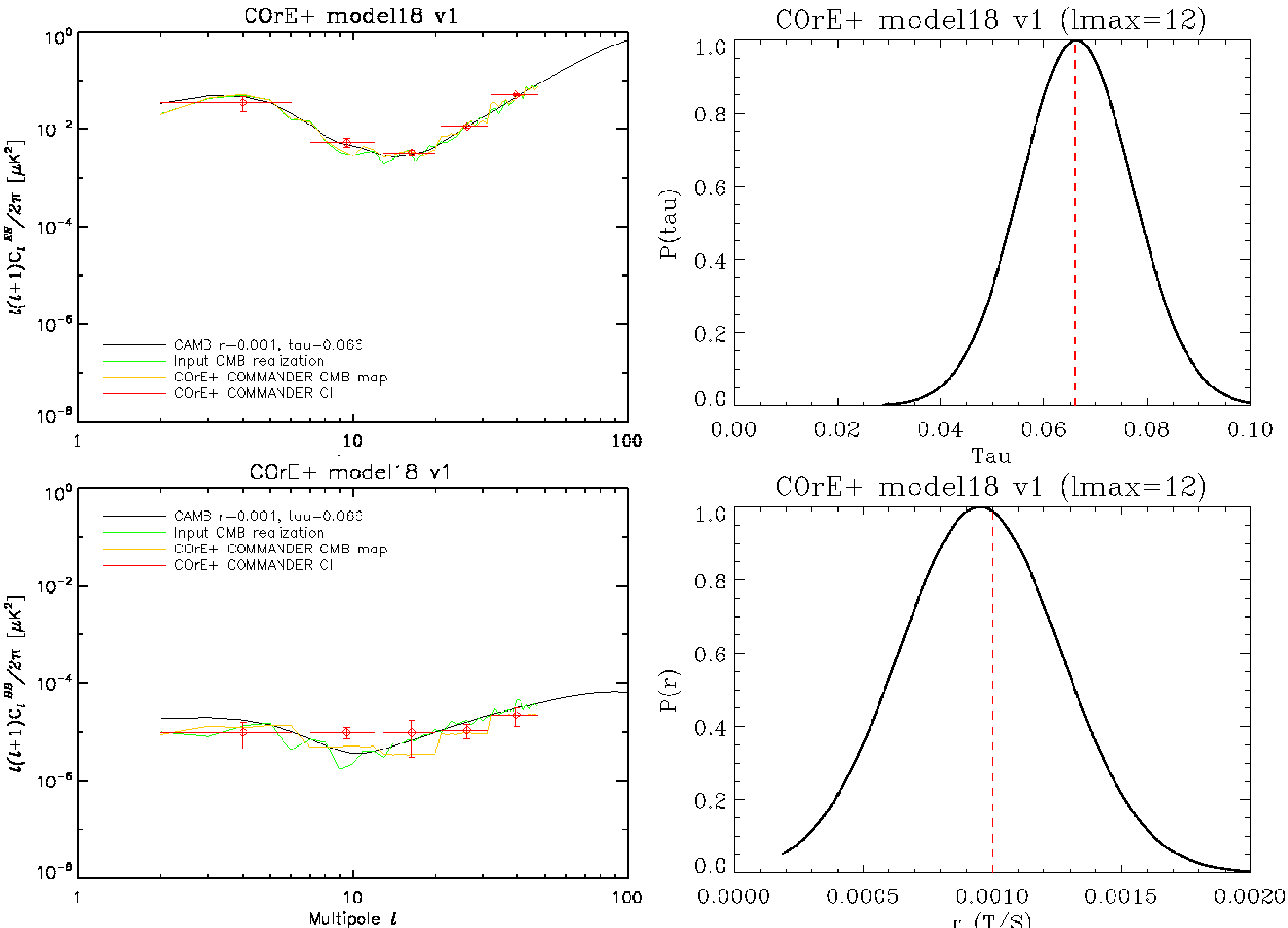
χ^2 statistics over the sky

(i) gives feedback on foreground modelling

(ii) tells where to mask a posteriori

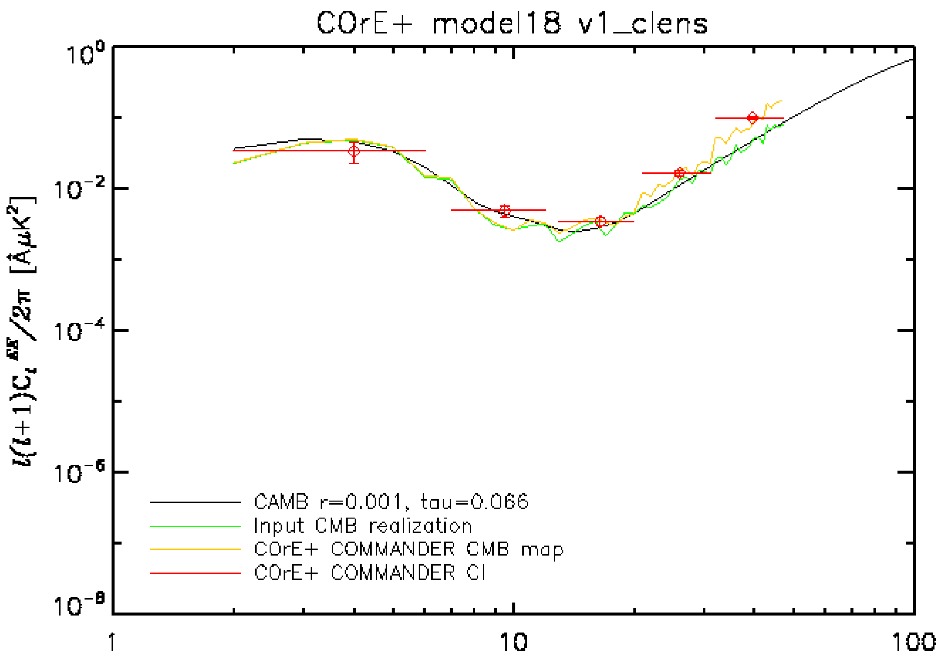
Case 1. constant spectral indices

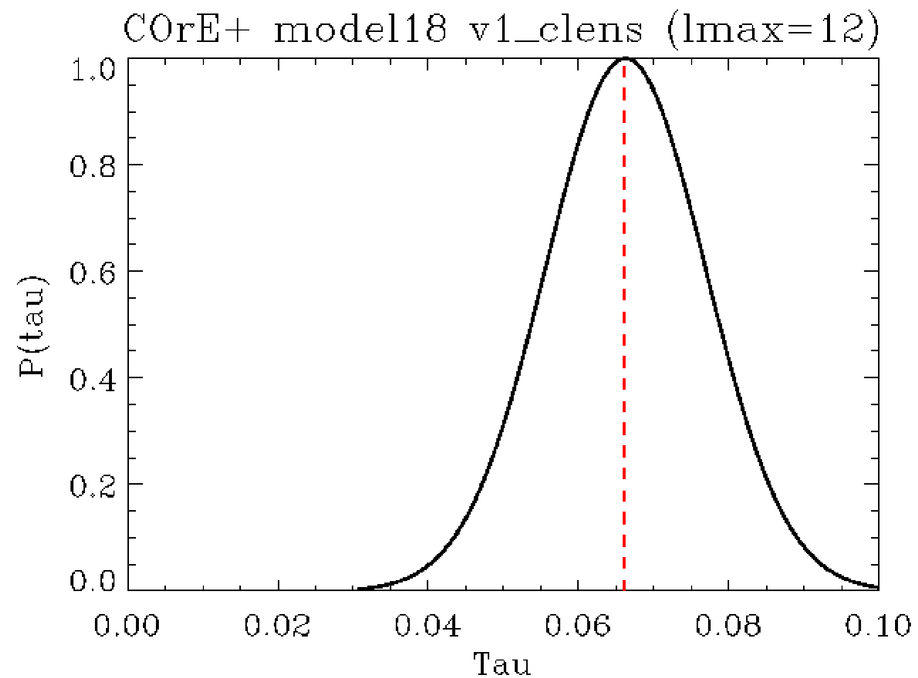
β_{dust} = N (1.6 ± 0.3) in [0.5,4.0], T_{dust} = N (18 ± 0.05) in [10,35], β_{sync} = N (-3 ± 0.1) in [-5.1,-2.3]

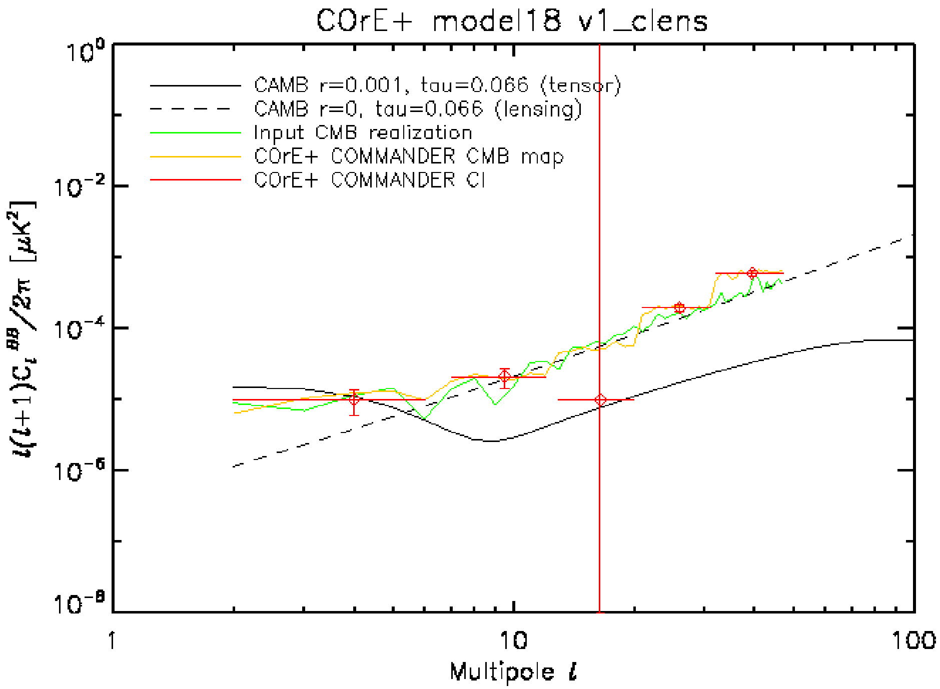


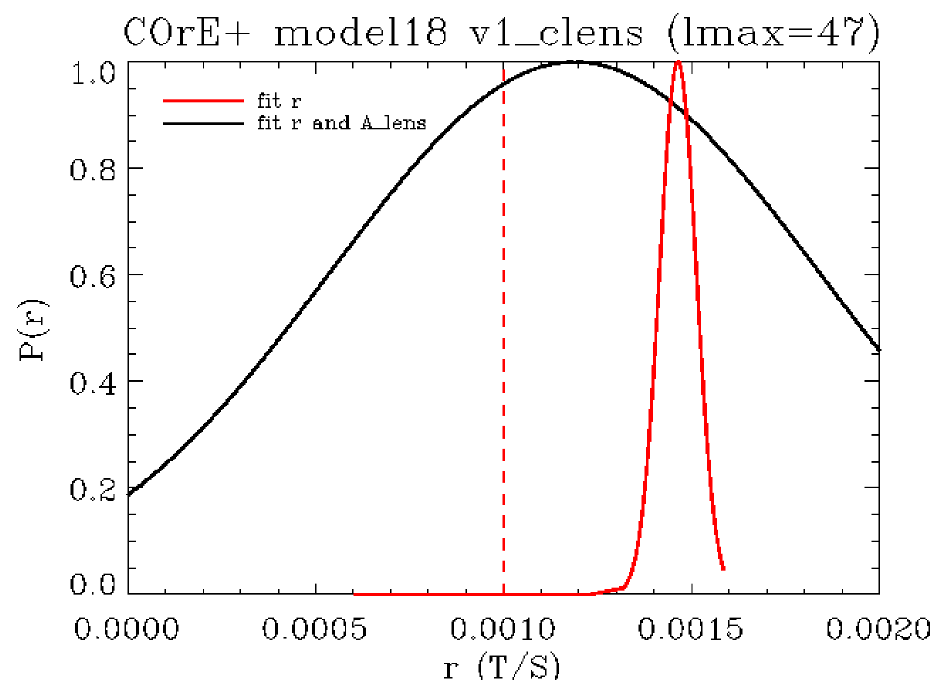
Case 2. constant spectral indices + lensing

β_{dust} = N (1.6 ± 0.3) in [0.5,4.0], T_{dust} = N (18 ± 0.05) in [10,35], β_{sync} = N (-3 ± 0.1) in [-5.1,-2.3]



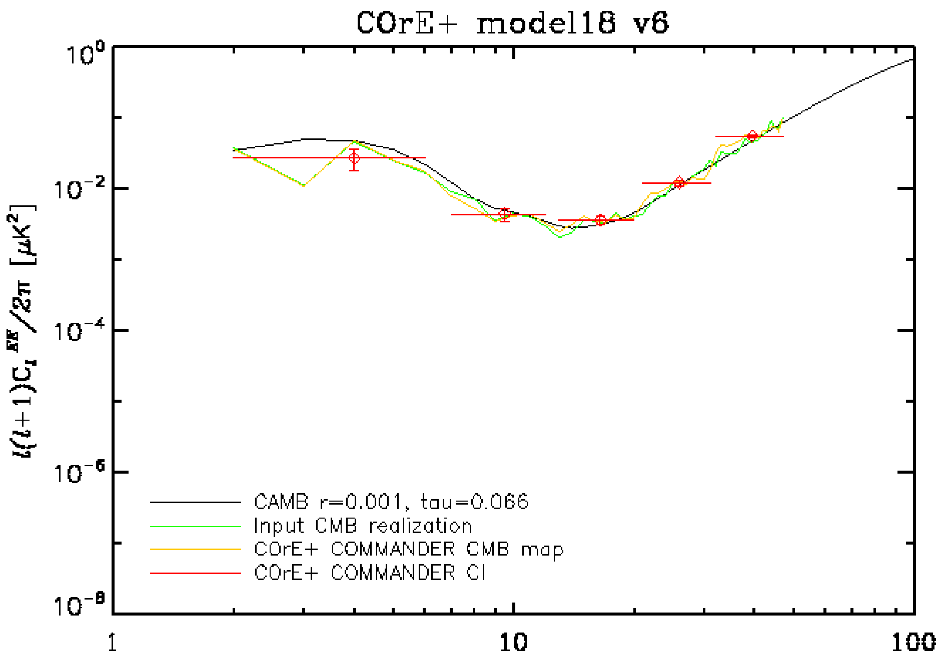


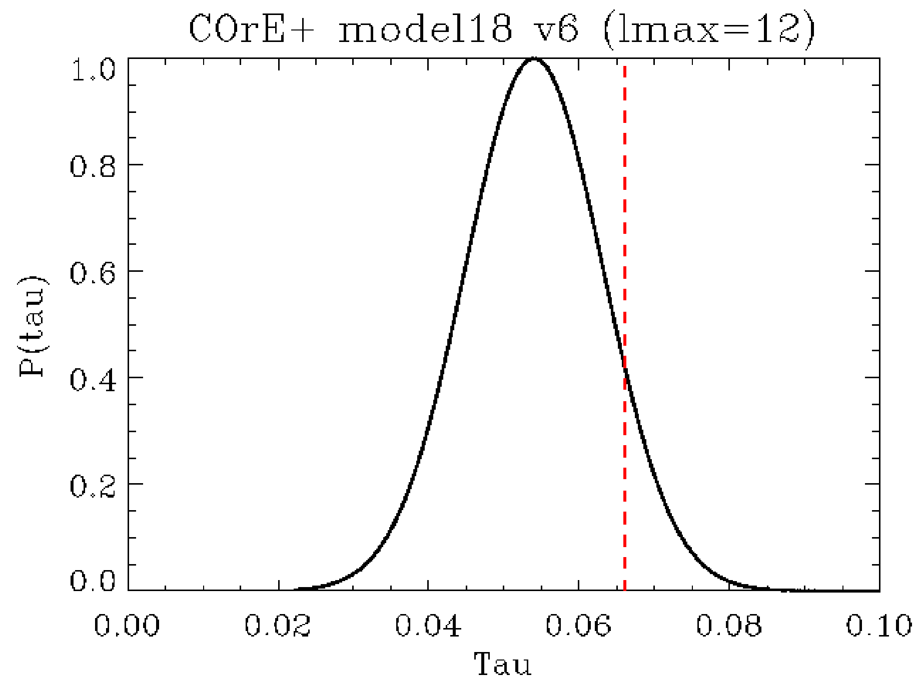


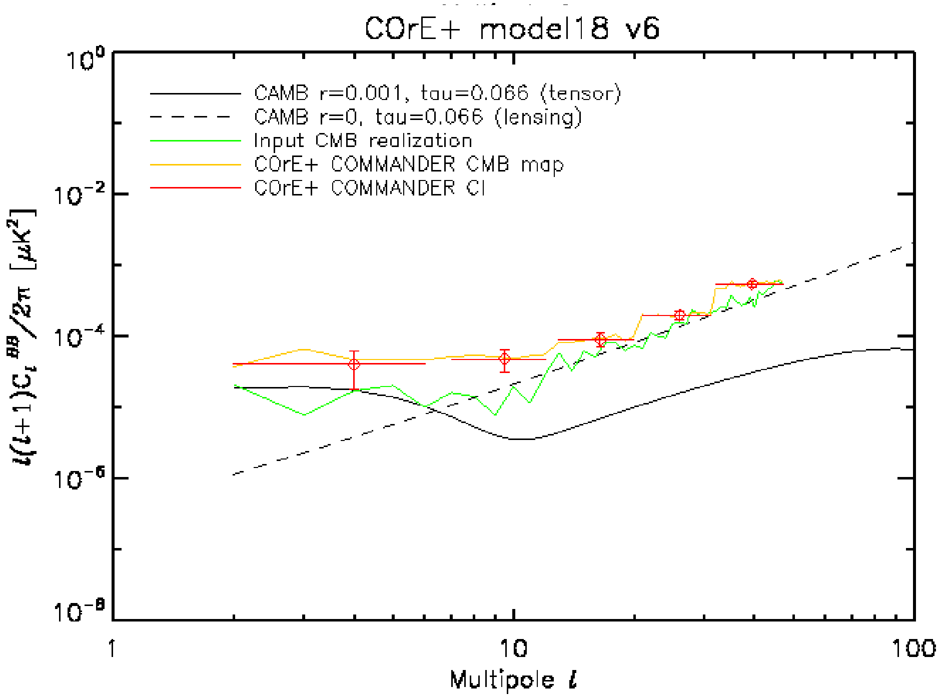


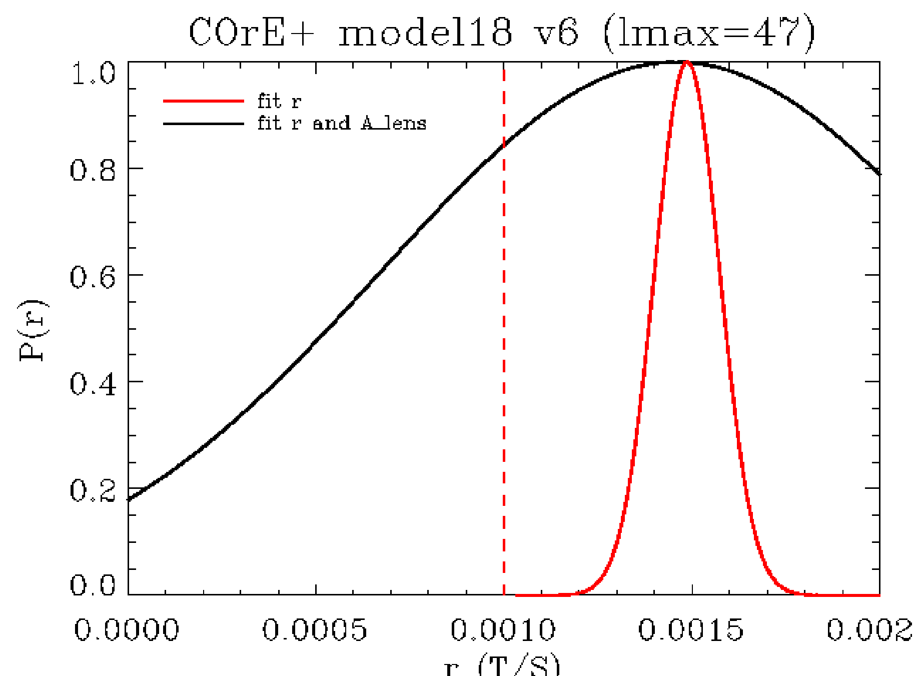
Case 3. variable spectral indices + lensing + AME + PS

β_{dust} = N (1.6 ± 0.3) in [1.0,2.5], T_{dust} = N (19.7 ± 1.5) in [11,50], β_{sync} = N (-3 ± 0.1) in [-5.1,-2.3]





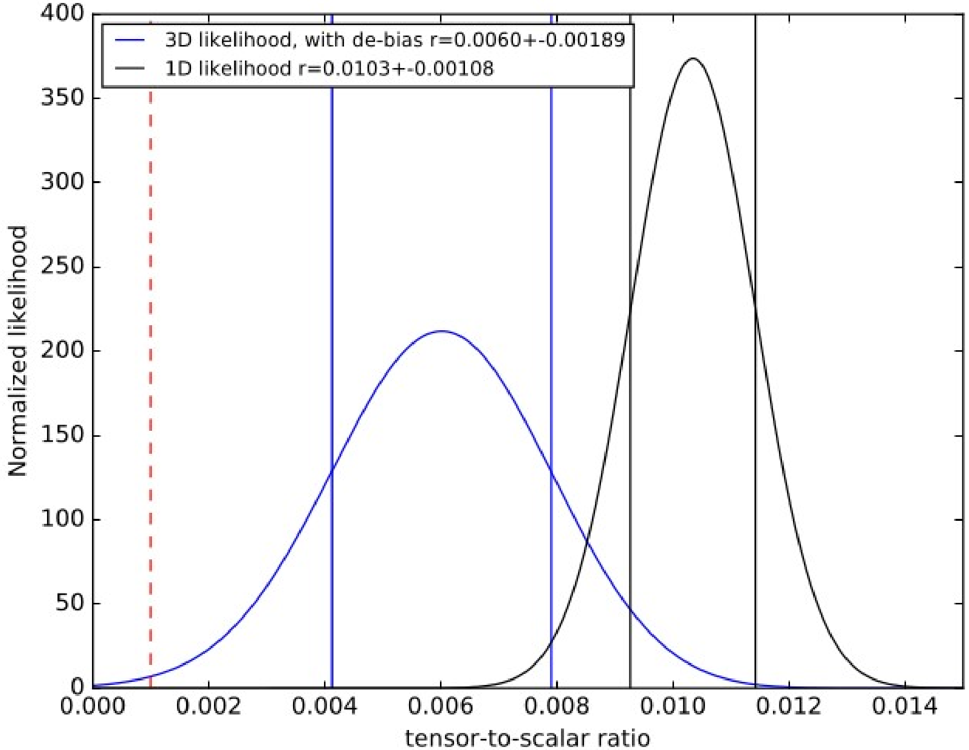


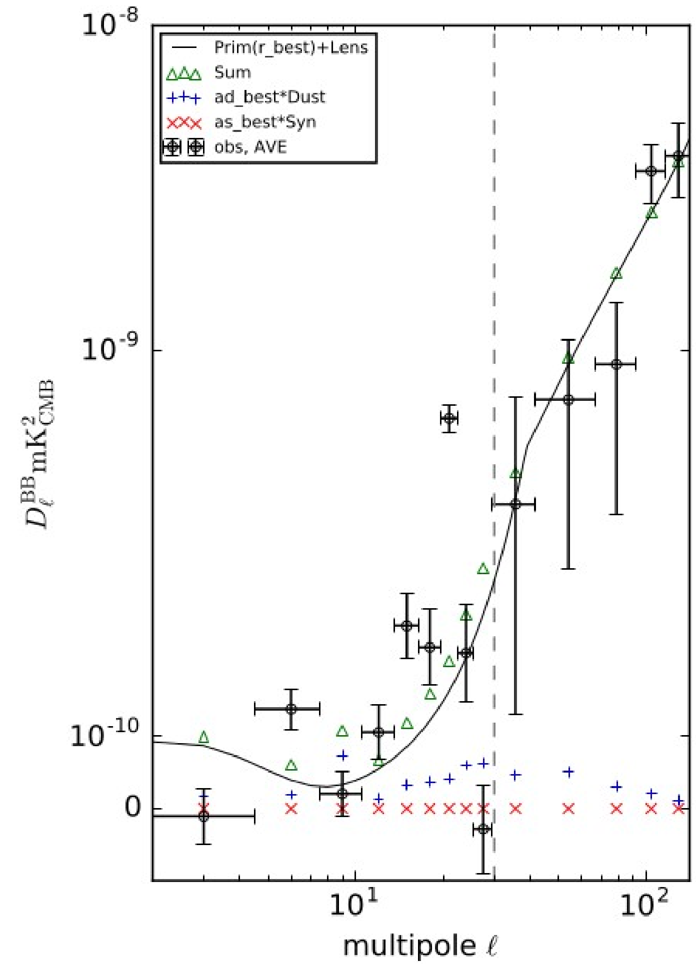


Component separation results:

CCA

Latest COrE+ Results: Likelihoods



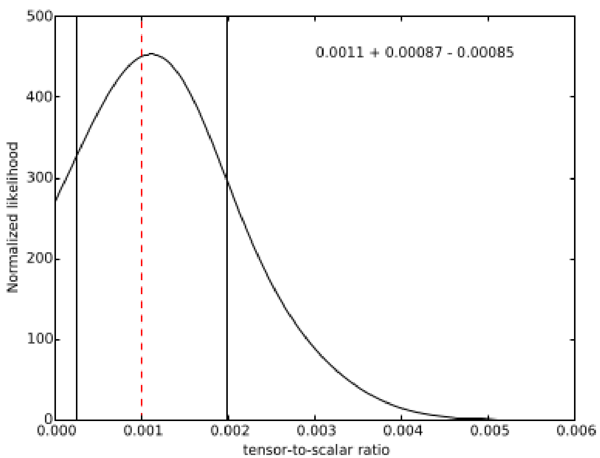


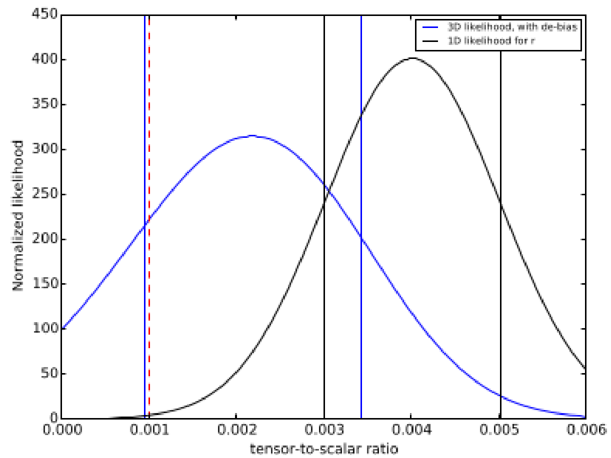
- Likelihood using first 14 bins (lmax=141).
- 1D likelihood (just fitting for r) gives r~0.01. Fitting for 2 extra nuisance foregrounds parameters de-bias to r~0.006, but increases σ_r value.

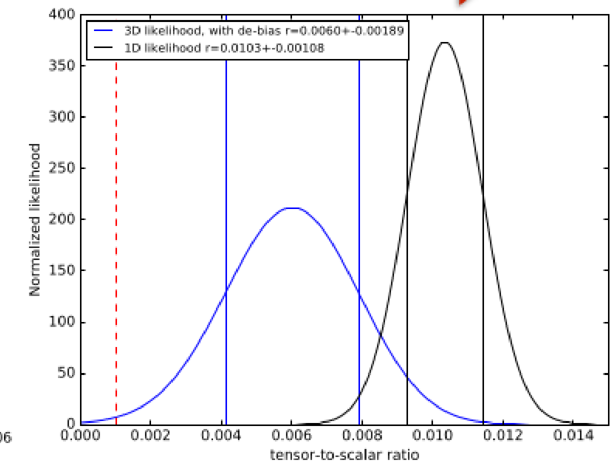
$$C_\ell^{BB}(r) = \frac{r}{r_\star} C_\ell^{BB,\mathrm{prim}}(r_\star) + C_\ell^{BB,\mathrm{lens}} + A_\mathrm{d} C_\ell^{BB,\mathrm{dust}} + A_\mathrm{s} C_\ell^{BB,\mathrm{syn}}$$

Overview of results: Complexity

Increasing complexity of foregrounds







COrE, r=0.001, 100 realizations, only synchrotron and dust, **constant β_{dust} and β_{syn}.**

COrE, r=0.001, 100 realizations, only synchrotron and dust, **variable β_{dust} and β_{syn}.**

COrE+, r=0.001, synchrotron, dust, **AME and PSs**. **variable β_{dust} and β_{syn}.**

Internal simulations for my Phd thesis

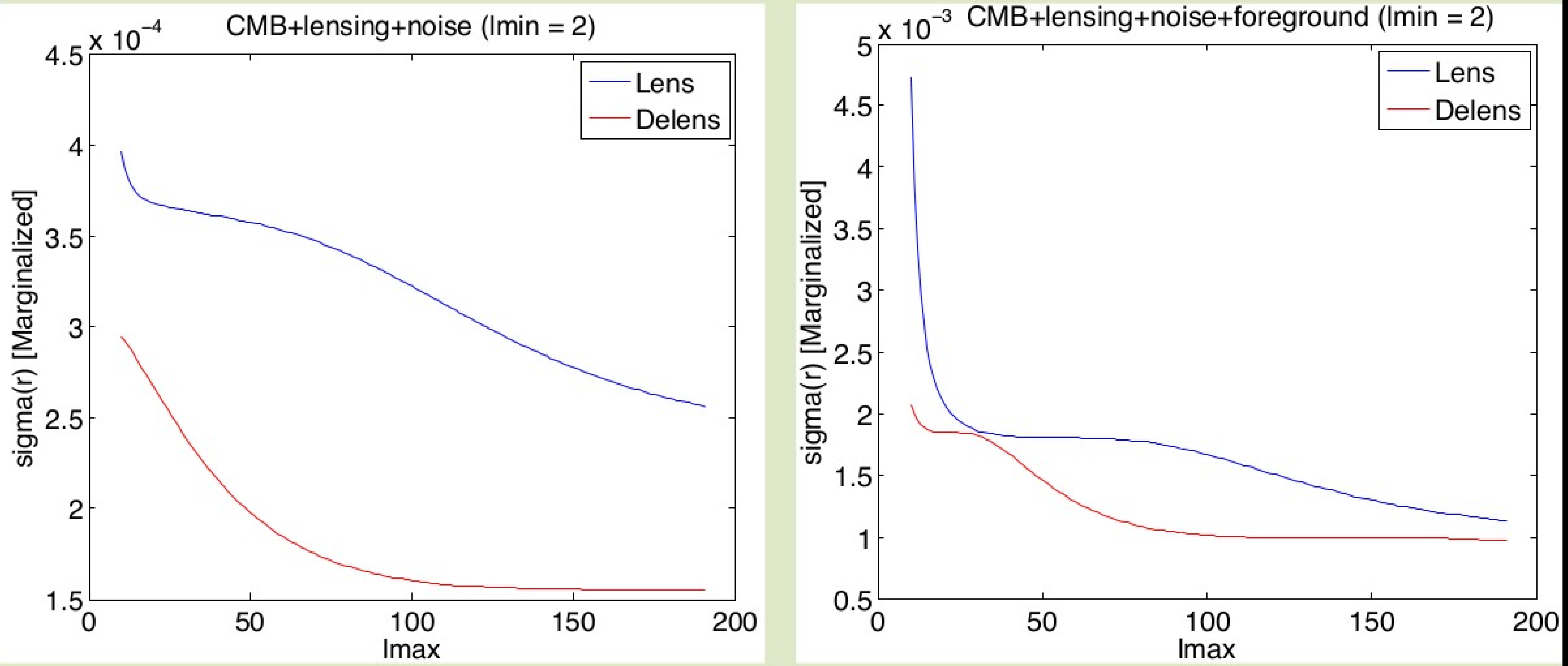
COrE+ simulation

Component separation results:

PILC

PILC

Sensitivity forecast

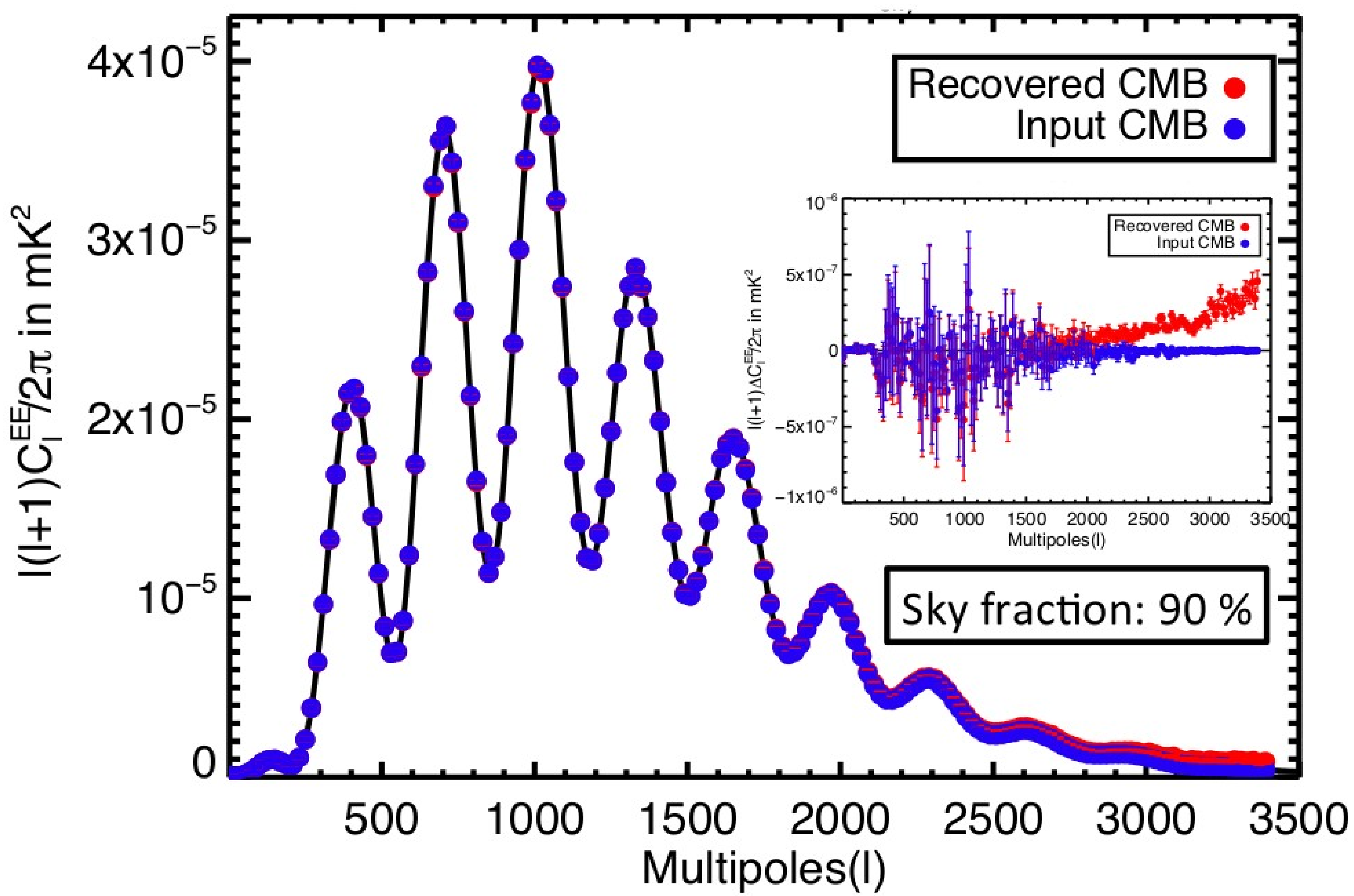


Component separation results:

NILC

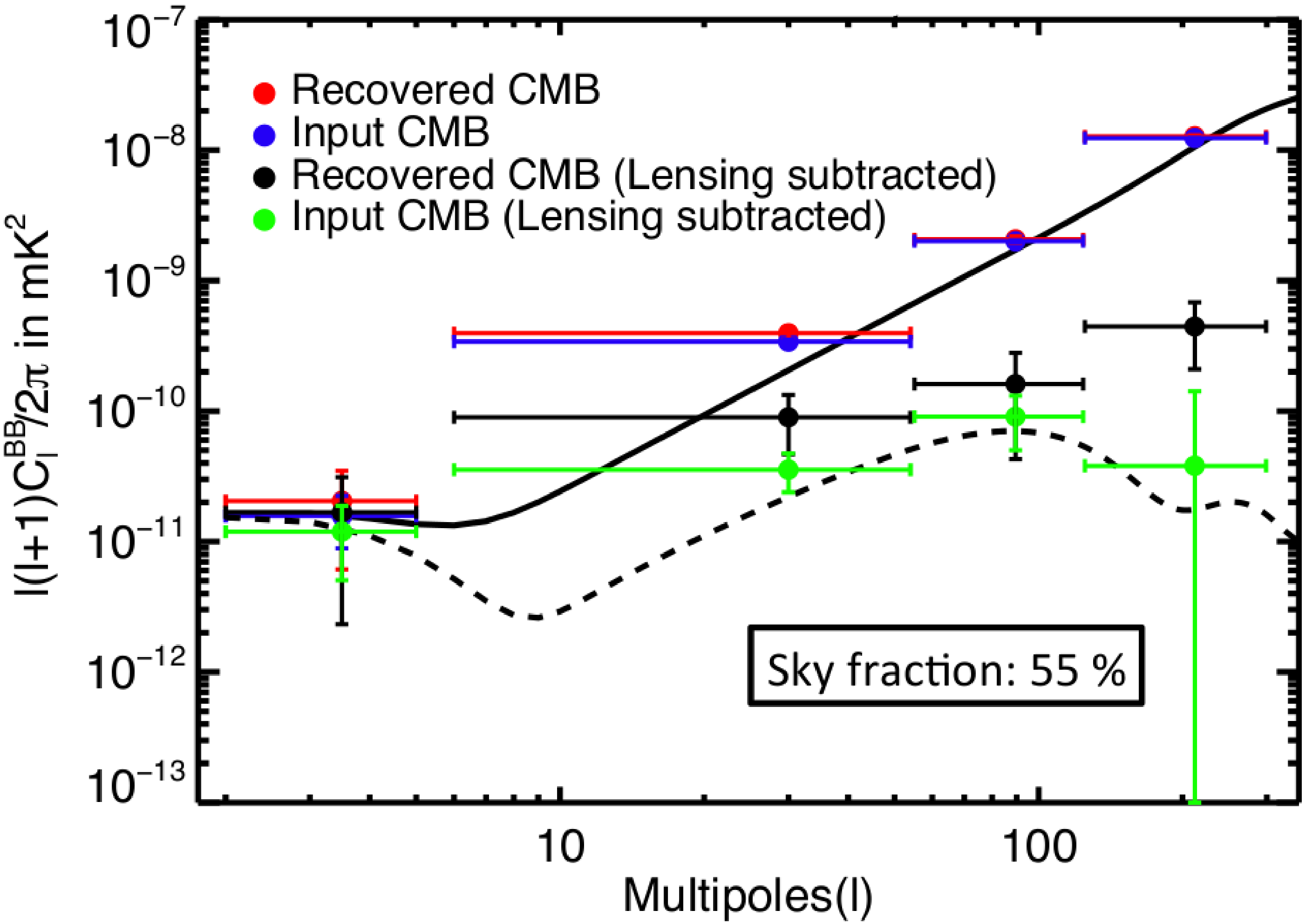
NILC

NILC CMB APS [EE HM1 X HM2]

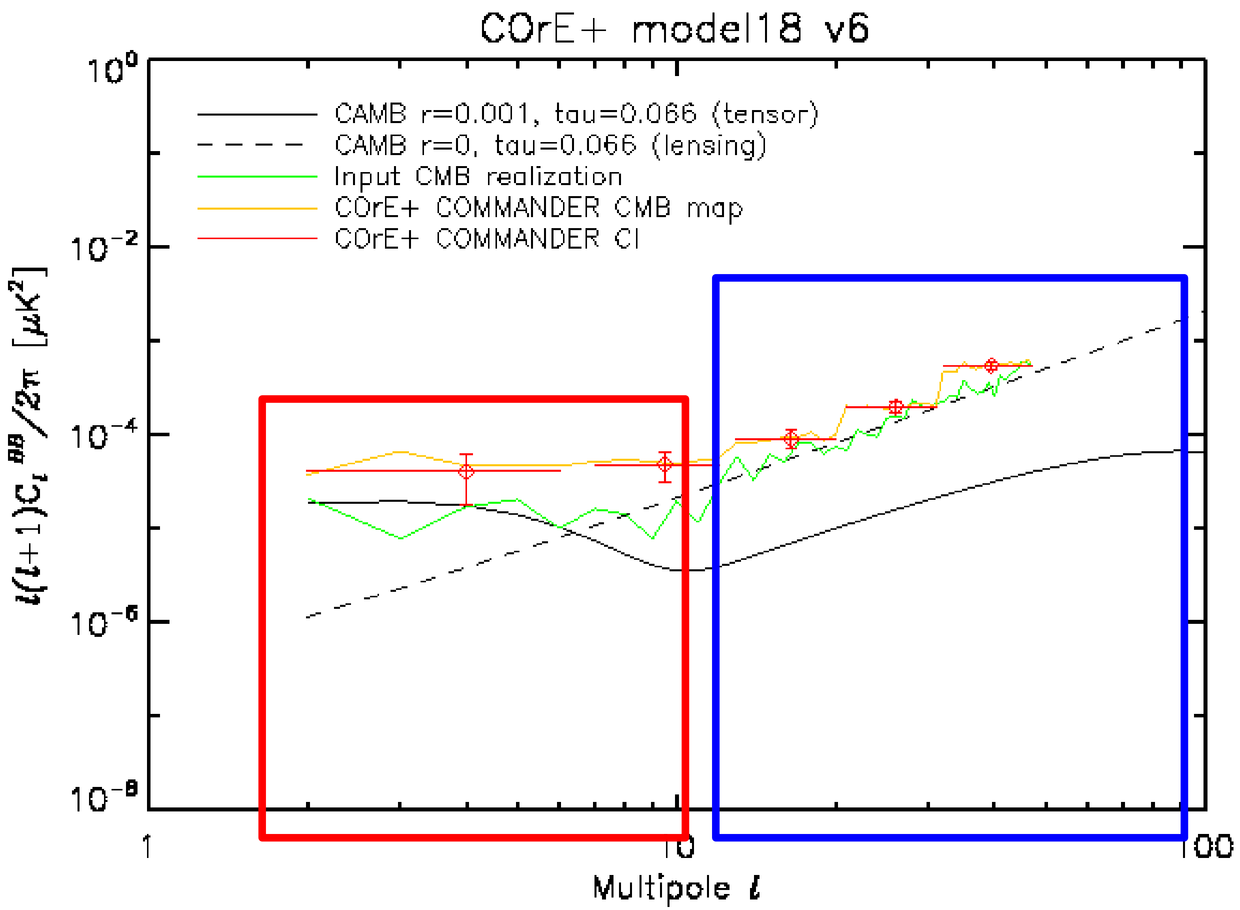


NILC

NILC CMB APS [BB HM1 X HM2]



We do need to control foregrounds at ℓ < 12 (reionization bump) to disentangle tensor B-modes and lensing B-modes !



$r = 10^{-3}$

“ Detecting the reionization bump is a must-have when we claim for a satellite mission ”

R. Mandolesi

Key issues

Issue 1. Why r is biased ?

- Imperfect foreground modelling ?

  i.e., too challenging polarized sky
  (low r, low τ, complex foregrounds)

- Lack of low / high frequency channels ?

Bias on r: imperfect foreground modelling ?

- At which precision the foreground parameters need to be known ?

$$\Delta\beta = ? \rightarrow \Delta r = 10^{-4} \text{ without bias}$$

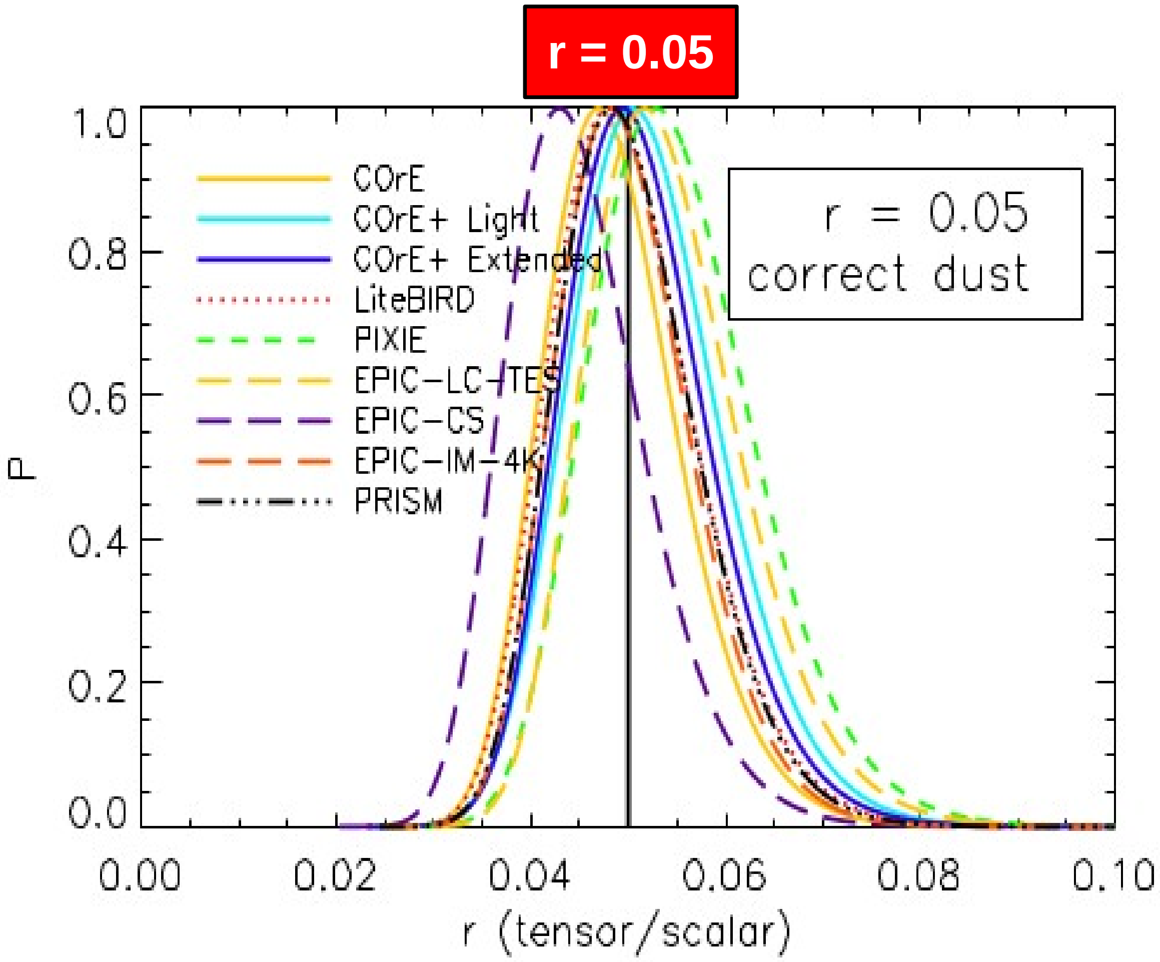
- Optimal galactic masking ?

→ masks can be constructed a posteriori
from chi-square / residual maps
→ Then reiterate component separation with new mask

Blind ILC methods have intrinsic limit on reducing the variance
(unless if infinite # modes/channels)

Parametric fitting methods have intrinsic limit on modelling the sky
(unless if infinite precision on foreground parameters)

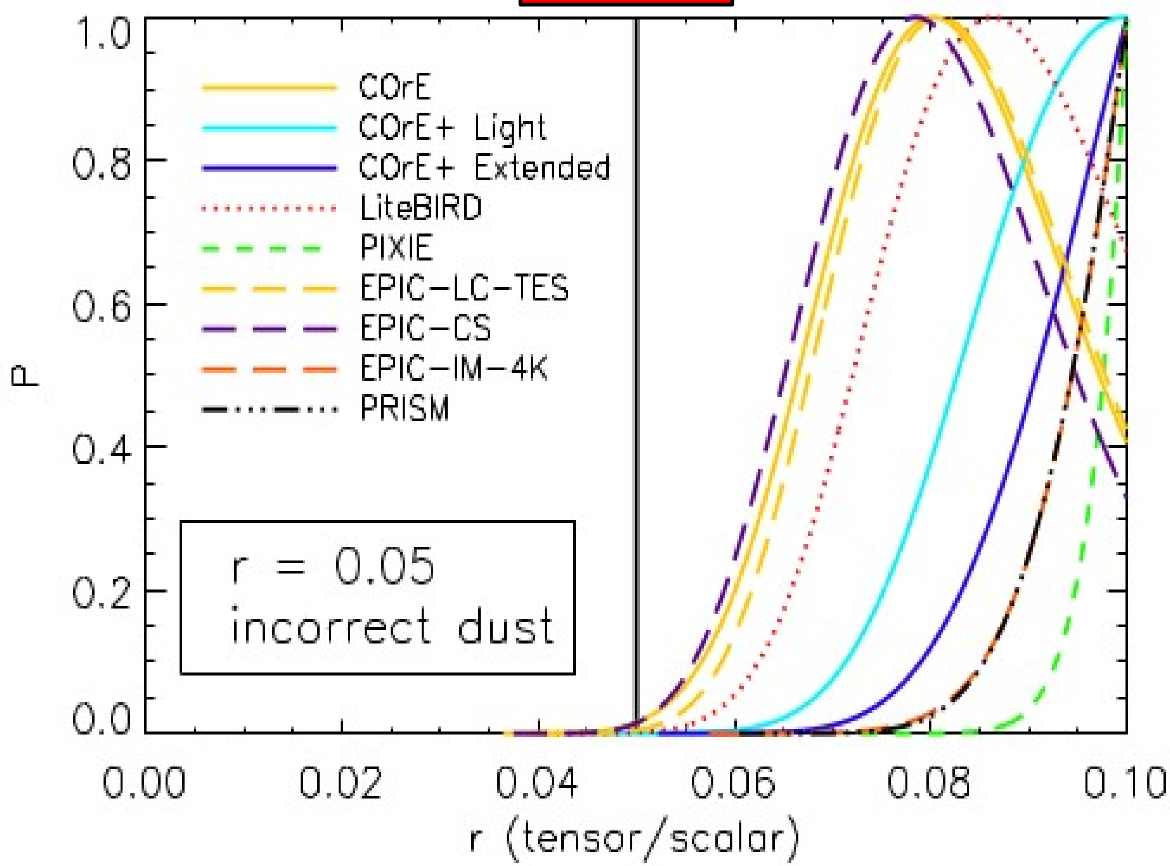
Correct foreground modelling



Remazeilles, Dickinson, Eriksen, Wehus, MNRAS 2016

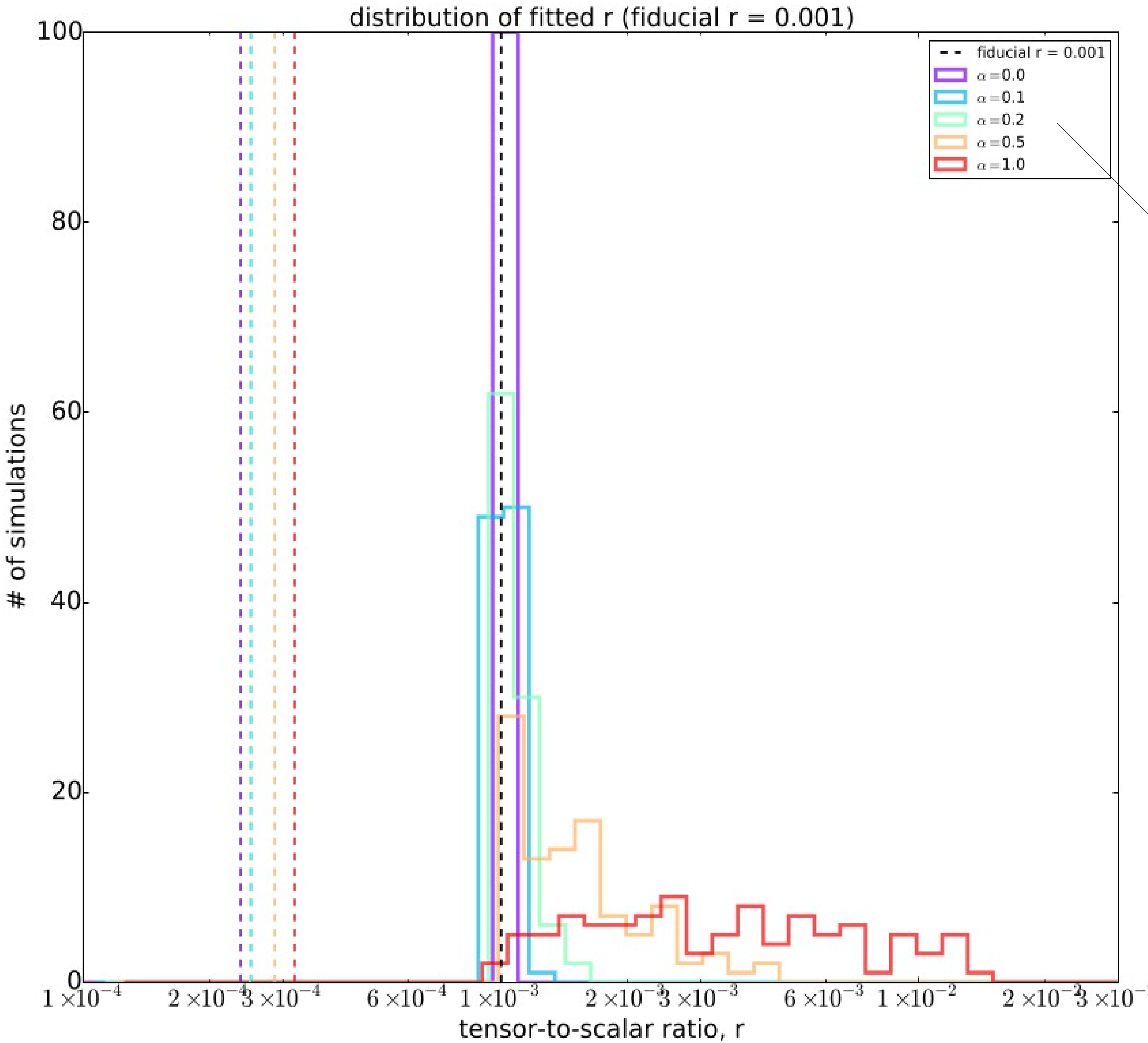
Impact of foreground mis-modelling : omitting one dust greybody

r = 0.05



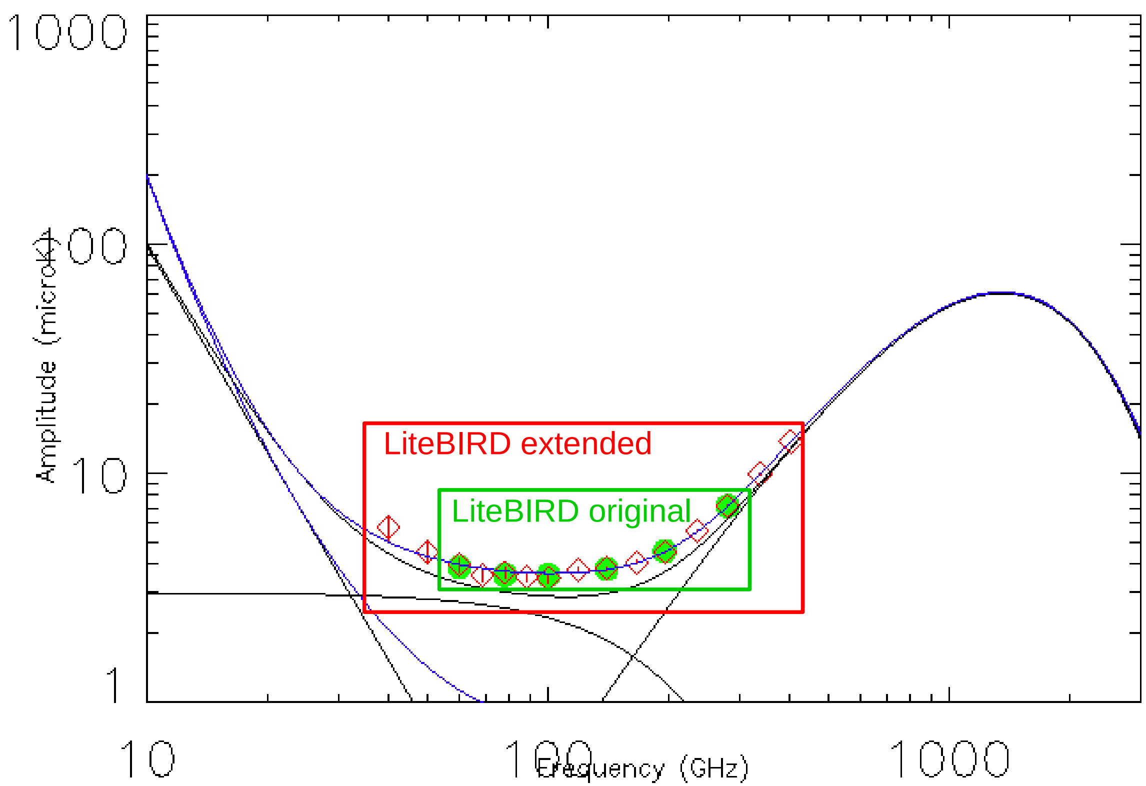
Remazeilles, Dickinson, Eriksen, Wehus, MNRAS 2016

impact on the estimation of tensor-to-scalar ratio (II)



α: dispersion around fiducial foreground scaling laws

Do we need extra channels < 60 GHz ?



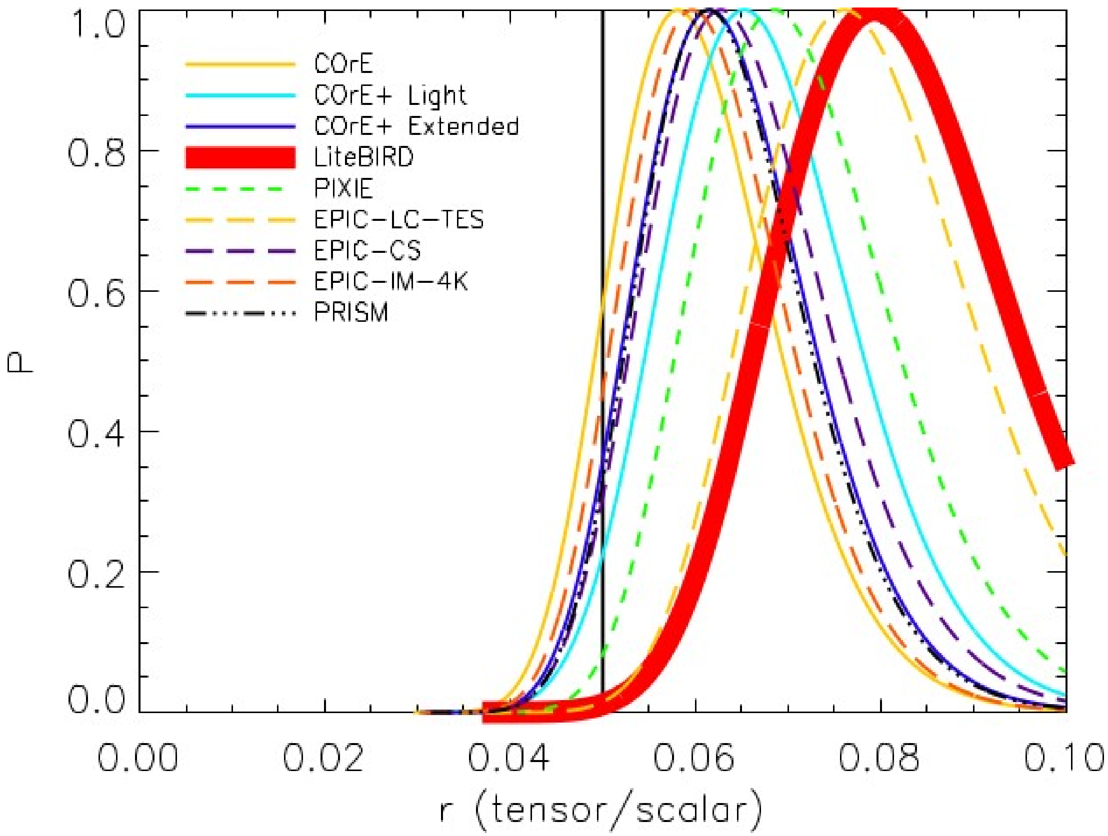
Index curvature can make synchrotron spectrum less orthogonal to CMB spectrum

<u>Over a restricted frequency range</u>, spectral flattening may prevent component separation techniques from distinguishing between CMB and synchrotron B-modes

i.e. global sky is correctly fitted ($\chi^2 \sim 1$) but individual synchrotron and CMB components not correctly splitted (r biased)

Impact of mis-modelling synchrotron : neglecting index curvature

r = 0.05



LiteBIRD original

χ^2	r	
1.00	0.06756 ± 0.01027	COrE+ Light
1.01	0.06390 ± 0.00946	COrE+ Extended
1.01	0.06074 ± 0.00920	COrE
1.01	0.07988 ± 0.01027	LiteBIRD
1.01	0.07122 ± 0.01027	PIXIE
1.09	0.07769 ± 0.01029	EPIC-LC-TES
0.99	0.06558 ± 0.01004	EPIC-CS
1.30	0.06205 ± 0.00906	EPIC-IM-4K
1.12	0.06386 ± 0.00925	PRISM

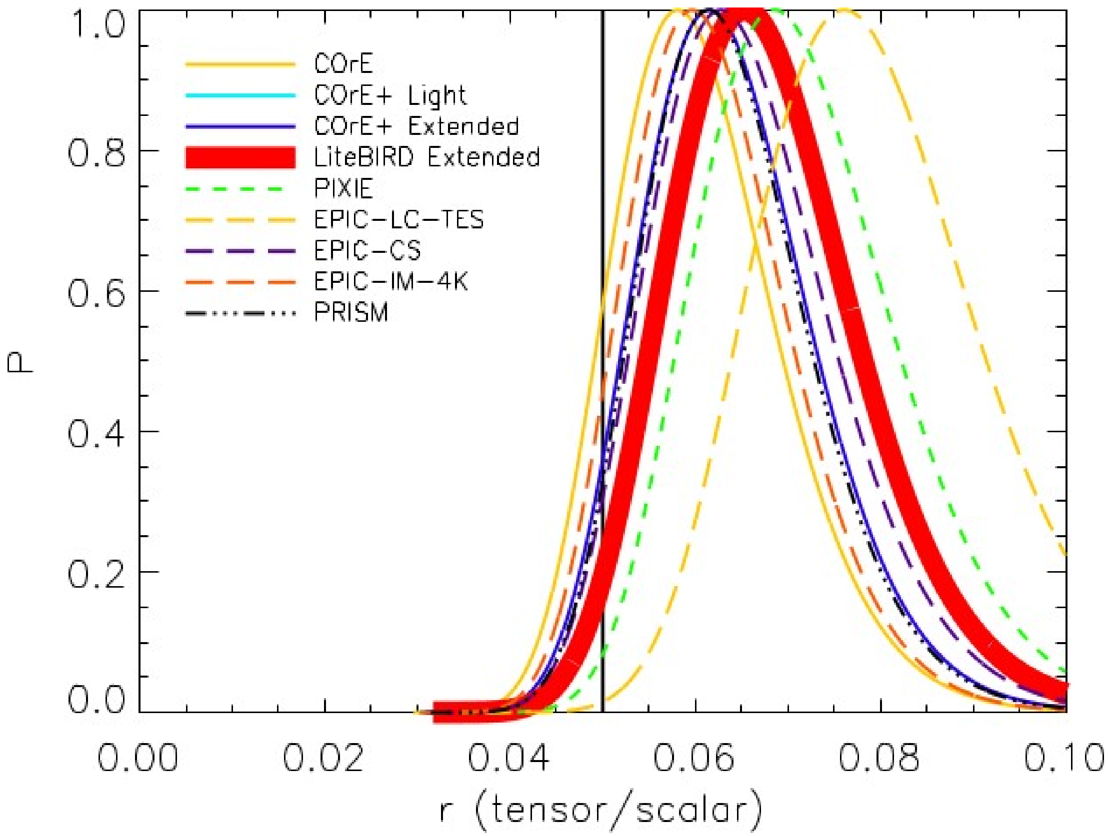
extra bias: false r detection with no χ^2 evidence !

→ lack of low-frequency channels

Remazeilles, Dickinson, Eriksen, Wehus, MNRAS 2016

Impact of mis-modelling synchrotron : neglecting index curvature

r = 0.05



LiteBIRD extended

Remazeilles, Dickinson, Eriksen, Wehus, MNRAS 2016

Bias on r: do we need extra frequencies ?

- In terms of cost optimization for M5 proposal,
  better use ancillary data (C-BASS, QUIJOTE, WMAP)
  that will be available at that time when COrE will be launched

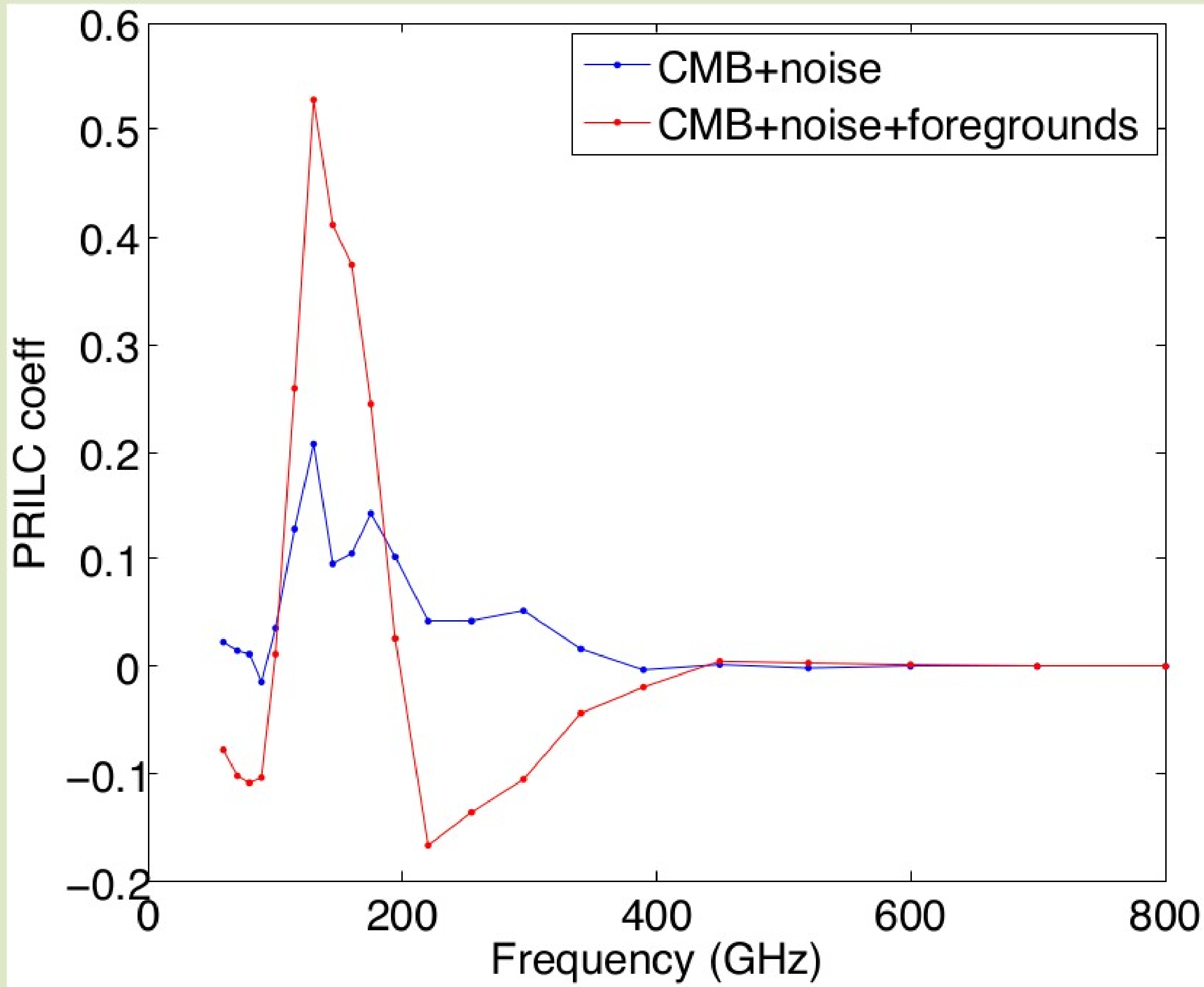
- Plan for the ECO paper:
  We will produce a new simulation with COrE frequencies
  + C-BASS 5 GHz
  + QUIJOTE frequencies
  + WMAP 23 GHz

  to see if extra frequencies help in reducing the bias on r
  at the reionization bump

Weight of the frequency channels

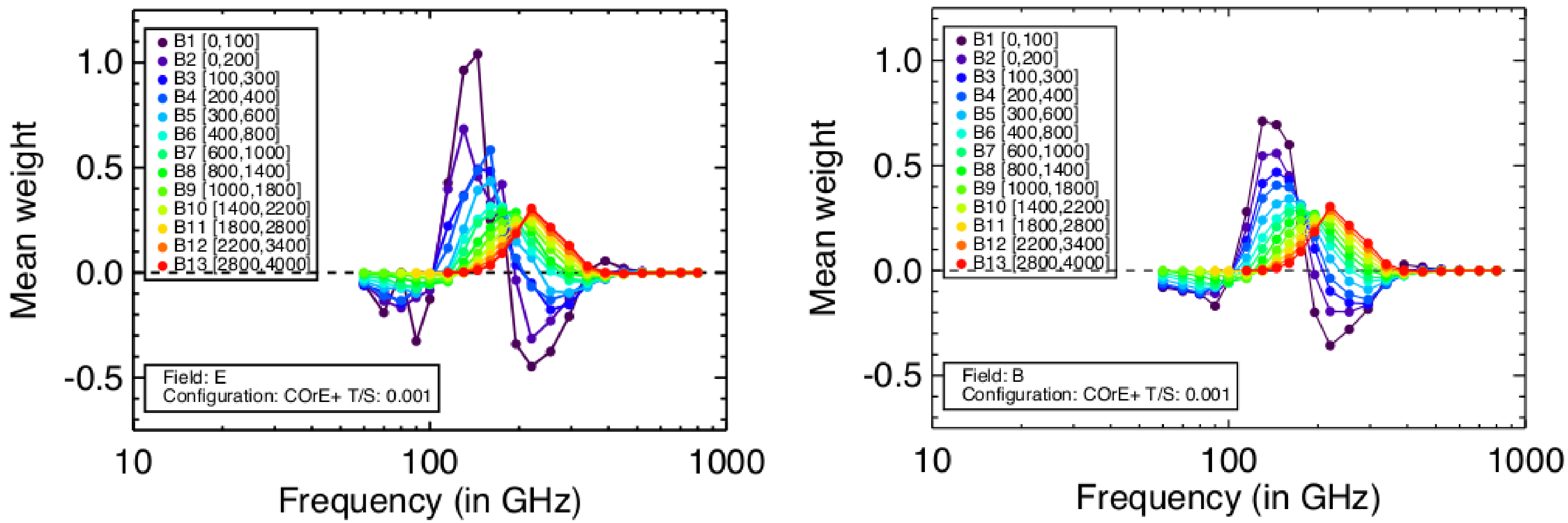
PILC

Relative weight of the different channels



Weight of the frequency channels

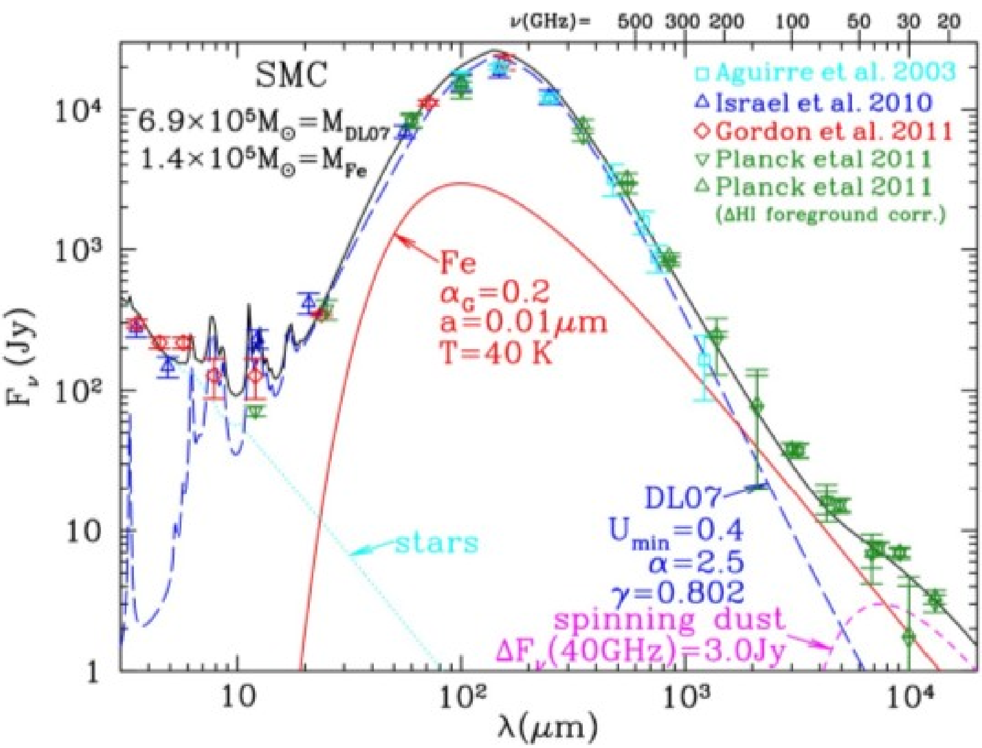
NILC weights



Frequency channels around 150 and 220 GHz have contributed the most to the final reconstruction of CMB polarization maps

Issue 2. Magnetic dust

- The frequency spectrum of magnetic dust is degenerate with the CMB spectrum (blackbody) ?



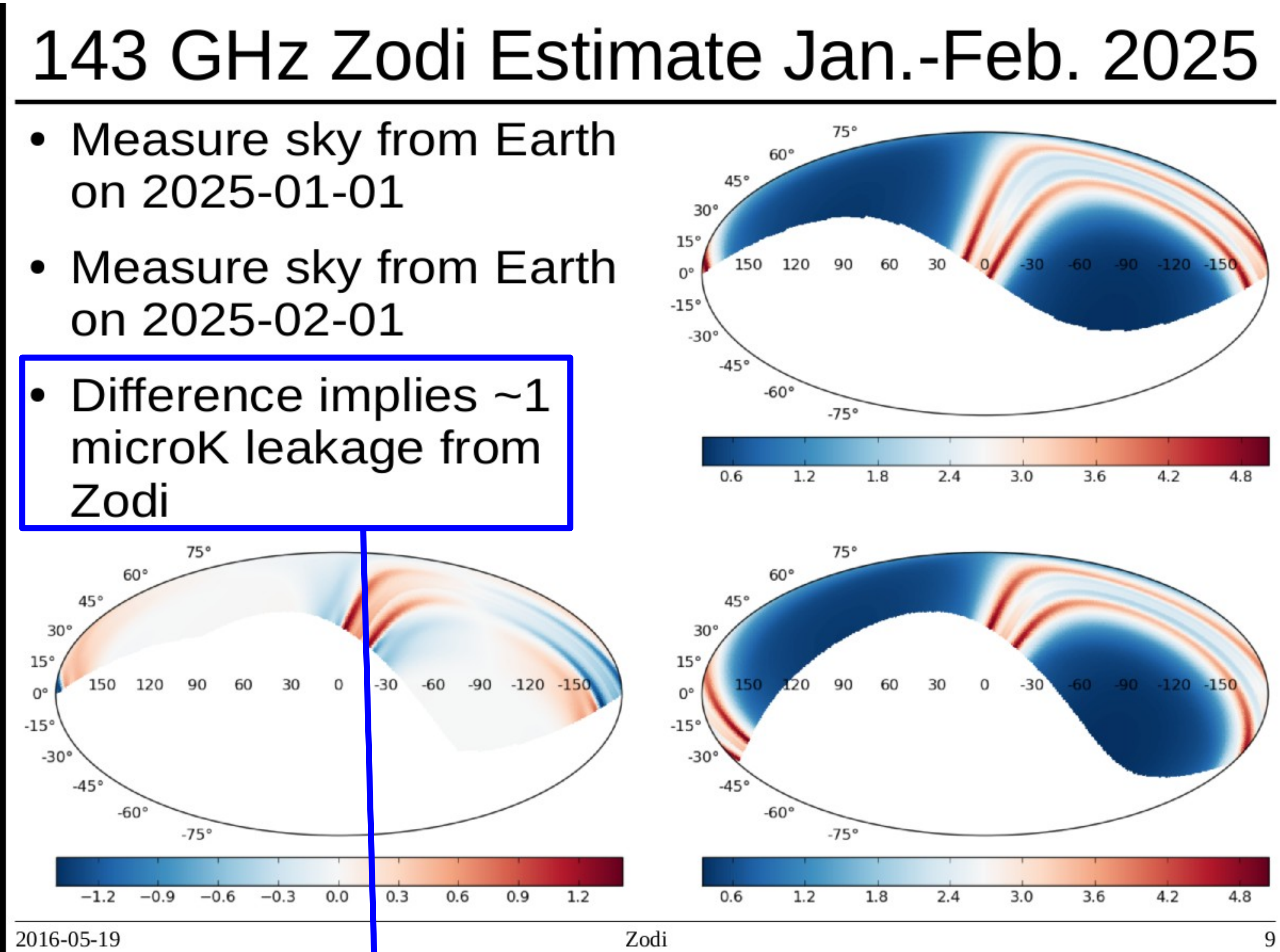
Draine & Hensley (2013)

- It could be highly polarized (35 %)

- We still need observations of diffuse magnetic dust

Issue 3. Zodiacal light

K. Ganga



“ Huge for COrE, given the sensitivity and the target $r = 10^{-3}$ ”

Issue 4. How to characterize residuals ?

- No chi-square evidence of fake detection of r for restricted frequency ranges !

  i.e., good fit of the global sky,
  but still incorrect split of CMB and foreground B-modes

- If no chi-square evidence then how to detect foreground B-mode residuals?

  → check stability of P(r) with subsets of channels

  → check stability of P(r) with varying masks

Issue 5. Sharing information on foreground residuals with the Science Working Groups

- E.g., neutrino mass forecasts (J. Lesgourgues ' talk) :
  " $\sigma (\Sigma M_\nu)$ shows stability across COrE, Litecore, Litebird "

  Is it still true when considering foreground errors ? Given that these experiments have different frequencies and sensitivities

- We need to provide to Science WGs a C(ℓ) of the residual foregrounds after component separation, for each experiment

Errard, Feeney, Peiris and Jaffe (JCAP, 2016)

→ http://portal.nersc.gov/project/mp107/index.html

CMB4CAST GROUNDS

Fisher forecast tool including:
(i) foreground cleaning
(ii) delensing
(iii) cosmological parameter estimation

It can help us to investigate:

- a larger number of models/simulations
- other cosmological parameters

Progress on PSM

J. Delabrouille

Summary

- The PSM is in a quick development phase for generating simulations for COrE (and other experiments: CMB-S4, LiteBIRD, etc ...).
- A tool for the CMB community, but person-power limited
- NEW features since "pre-launch" model
  - New templates for galactic temperature and polarisation
  - Several emission laws for synchrotron and dust
  - Polarised spinning dust
  - New random galactic emission + development of 3D galaxy
  - New CMB x CIB x Lensing (x SZ), dust contamination in clusters
- Send-in your wish-list, give a hand if you can, and stay tuned !

Conclusions

The foreground WG has done a lot of work so far
→ we have produced simulations: http://www.jb.man.ac.uk/~cdickins/exchange/bpol_sims/Mathieu/
→ we have produced component separation results and forecasts

- Can we detect the reionization bump at $r = 10^{-3}$?
- Is the observed bias on r due to
  - too challenging B-mode sky / imperfect foreground modelling ?
  - a lack of frequency channels ?
- Importance of characterization of the residuals
  Also need to provide level of foreground residuals to Science WG
- Optimal masking ?
- Is the magnetic dust a killer ?
- Plan of the ECO paper: 2 baseline simulations
  - a “simple one” with <u>constant spectral indices</u> (+ lensing + AME + PS)
  - a “realistic one” with <u>variable spectral indices</u> (+ lensing + AME + PS)

Main questions we intend to address

- Can we detect the reionization peak at r = 0.001 ?
  What are the bias and 1σ uncertainty on r = 0.001 ?

  - with complex polarized foregrounds,
  - with gravitational lensing effect,
  - with COrE+ and LiteBIRD specs.

- Are 1% polarized foregrounds (e.g. AME) relevant for r = 0.001 ?

- Impact of the variation of foreground spectral indices ?

- Impact of polarized point-sources ?

current simulation

Main questions we intend to address

- Can we reconstruct the CMB B-mode at r = 0.001 ?
  What are the bias and 1σ uncertainty on r = 0.001 ?

  - with complex polarized foregrounds,
  - with gravitational lensing effect,
  - with COrE+ and LiteBIRD specs.

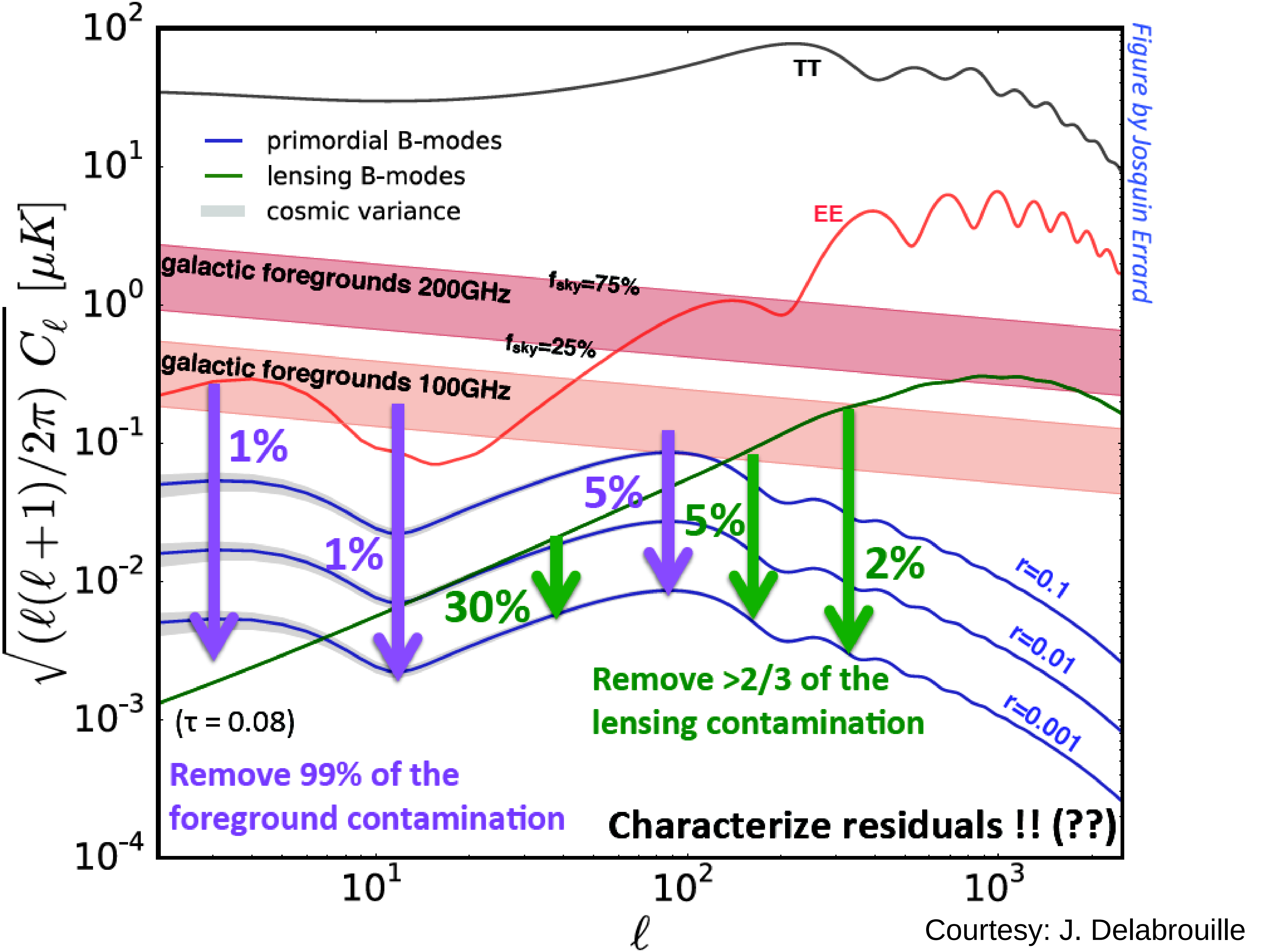
- Are 1% polarized foregrounds (e.g. AME) relevant for r = 0.001 ?
- Impact of the variation of foreground spectral indices ?
- Impact of polarized point-sources ?

current simulation

- What is the impact of systematics on the foreground removal ?
- How COrE+, LiteCOrE, LiteBIRD perform in this respect ?

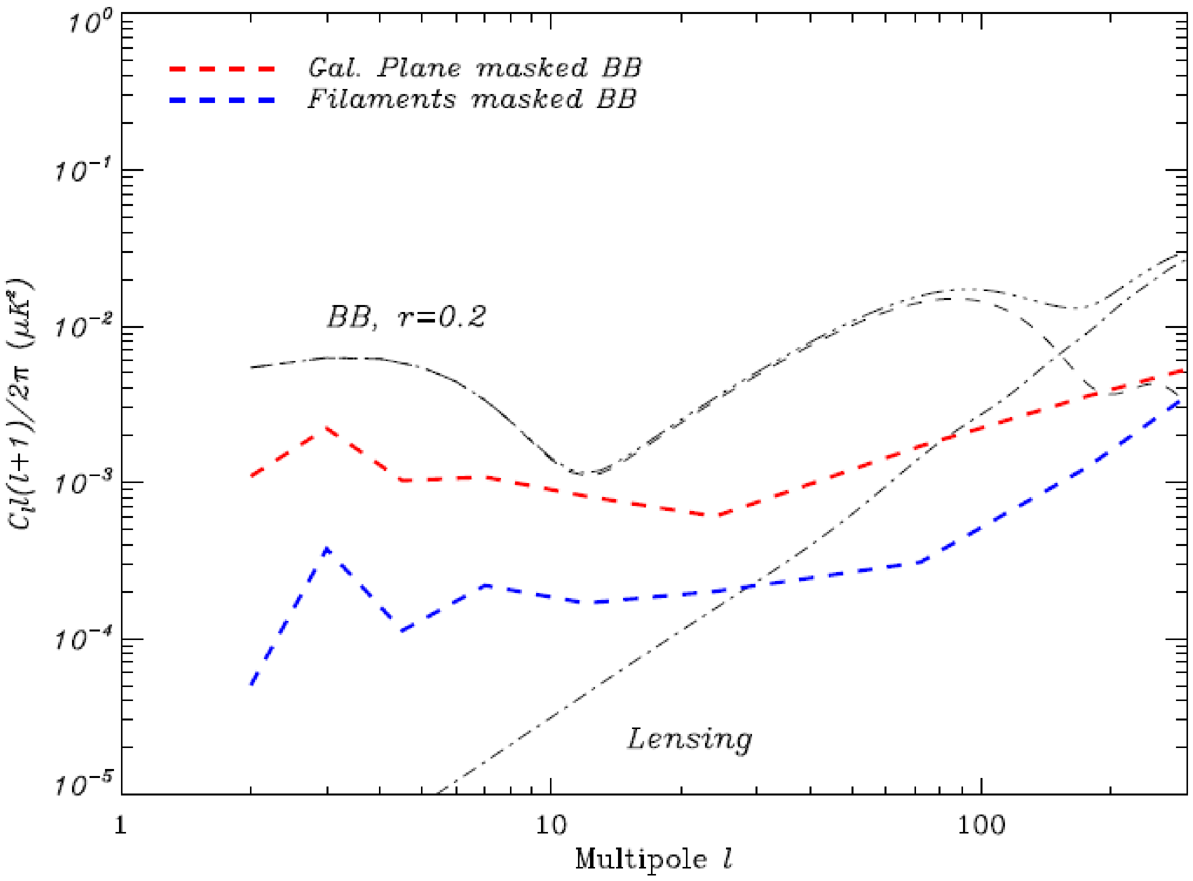
(long term) we still need a simulation mixing both systematics (bandpass, beams) and foregrounds

Backup slides



Courtesy: J. Delabrouille

Synchrotron



Vidal, Dickinson, Davies, Leahy, MNRAS 2015

On larger scales and large areas synchrotron is much more of a problem:

more polarization in the filaments (40%) than in the Galactic plane !

Galactic masking won't help !

Impact on component separation of calibration errors

 MNRAS 2010

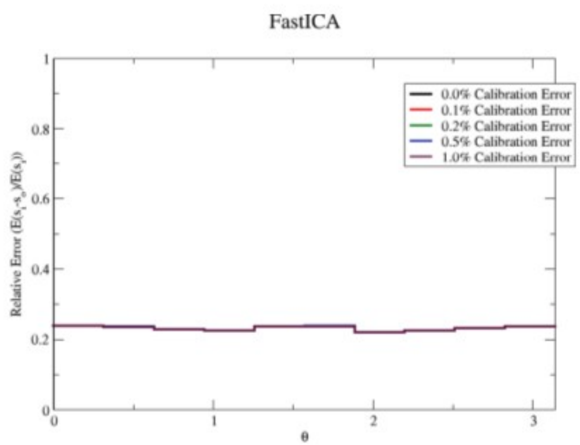
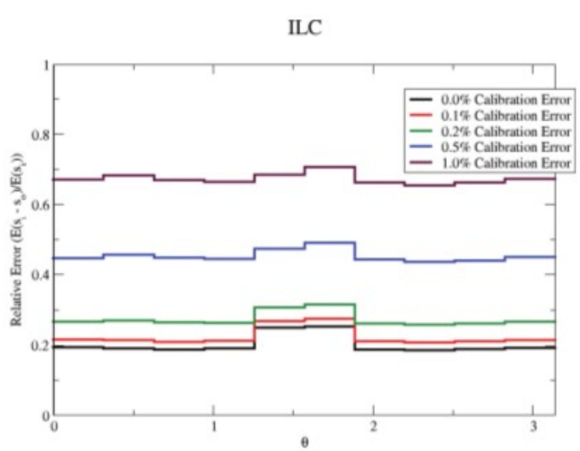


Figure 2. Plot of the relative error of FastICA as a function of the galactic latitude. Generated using 128 simulations for each case. As expected, the relative error of FastICA has very little dependence upon the calibration error.



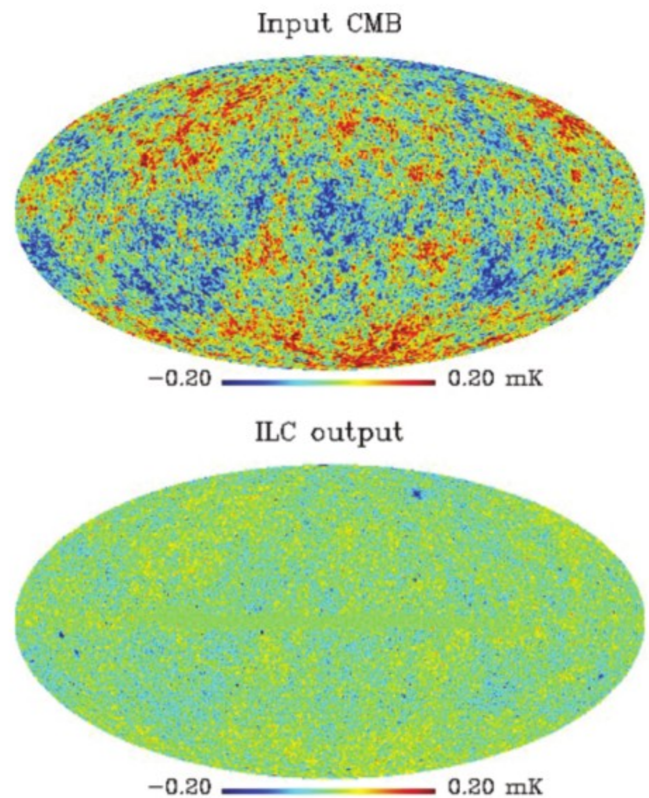


Figure 4. Input CMB- and ILC-estimated CMB plotted on a 0.2 mK scale for one realization at 1 per cent calibration error with particularly bad output (relative error near 1.0). Note that the variance of the ILC output is far below the input CMB, indicating that the input CMB was largely cancelled.

performed especially poorly, compared with the input CMB plotted on the same scale. The variance of the ILC output is much lower

`ILC` weights discrepant with actual CMB calibration
→ variance minimization kills the CMB !

Instrument specs

COrE+ ext.

frequency [GHz]	beam [arcminute]	P-noise [μK.degree]
60	14.0	0.342
70	12.0	0.233
80	10.5	0.160
90	9.3	0.123
100	8.4	0.098
115	7.3	0.073
130	6.5	0.057
145	5.8	0.057
160	5.3	0.057
175	4.8	0.058
195	4.3	0.063
220	3.8 (4.0)	0.090
255	3.3 (4.0)	0.152
295	2.9 (4.0)	0.220
340	2.5 (4.0)	0.422
390	2.2 (4.0)	0.790
450	1.9 (4.0)	1.982
520	1.6 (4.0)	5.632
600	1.4 (4.0)	20.050
700	1.2 (4.0)	93.500
800	1.1 (4.0)	203.333

LiteBIRD ext.

frequency [GHz]	beam [arcminute]	P-noise [μK.degree]
40.0	108.0	0.708
50.0	86.0	0.433
60.0	72.0	0.333
68.4	63.0	0.258
78.0	55.0	0.208
88.5	49.0	0.167
100.0	43.0	0.200
118.9	36.0	0.158
140.0	31.0	0.125
166.0	26.0	0.117
195.0	22.0	0.083
234.9	18.0	0.108
280.0	37.0	0.167
337.4	31.0	0.167
402.1	26.0	0.317