B-mode foregrounds removal: LiteBIRD study

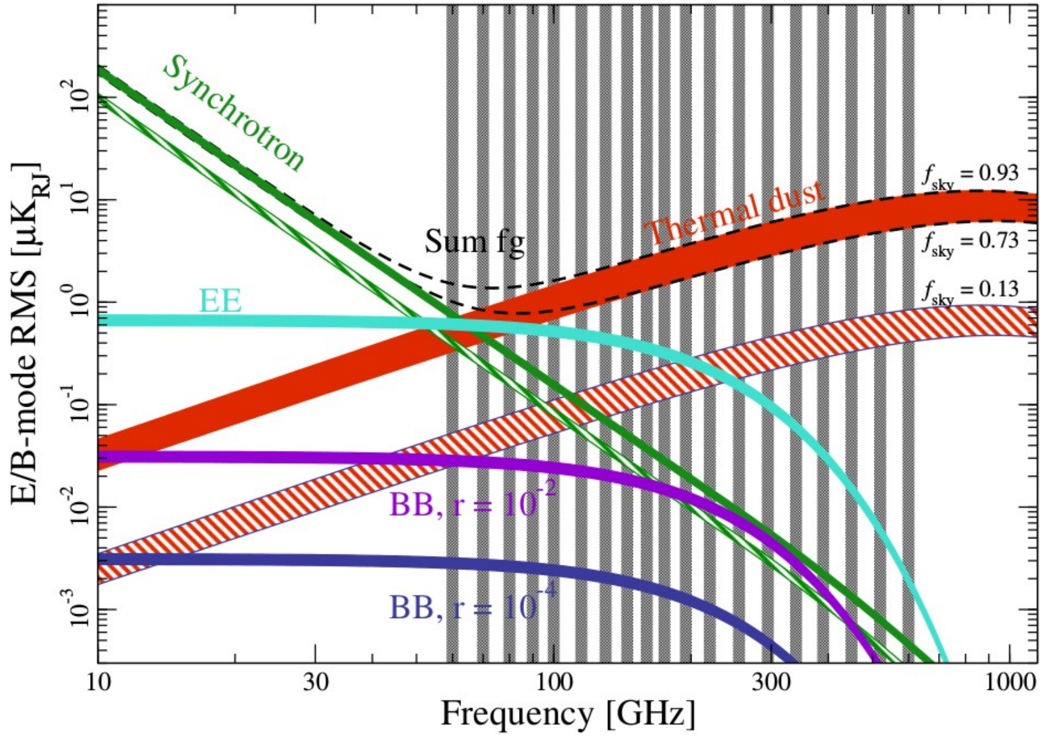
Mathieu Remazeilles

MANCHESTER 1824
The University of Manchester

B-mode from Space workshop
UC Berkeley, USA, 4-6 Dec 2017

CMB B-mode vs foregrounds

Remazeilles, Banday, Baccigalupi, et al,
for the CORE collaboration – JCAP 2017 accepted

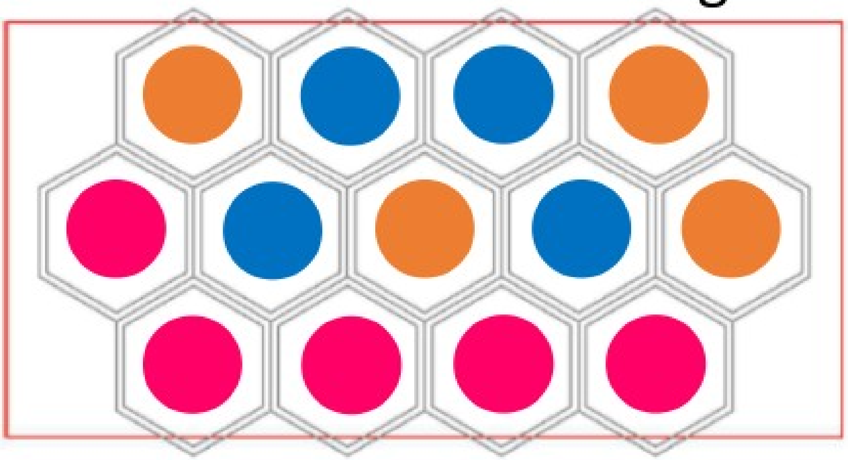


- Polarization **less complex** than intensity (fewer components) but **more challenging:**
  - → larger dynamic range between CMB and foregrounds!
  - → a slight mis-modelling of foregrounds can have a dramatic impact on the CMB B-mode
- **Foregrounds cannot be avoided just by limiting the frequency range of observations:**
  - → At 300 GHz the synchrotron has same amplitude and color than the CMB B-mode r=10^{-2} !
  - → **Broad frequency range is essential** to fight against spectral degeneracies

Example of focal plane for LiteBIRD

cross-Dragone, multi-chroic

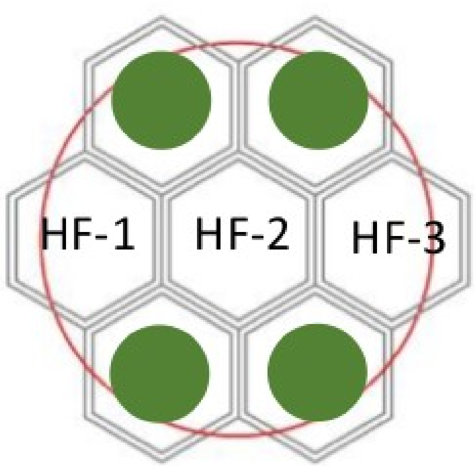
LFT - LF enhanced design



There is still some flexibility on the final design

Band	Center Freq [GHz]	Frac BW	Pixel Diameter [mm]	Num Pix	Num Det	
LF-1	40	0.30	18	[redacted] 95	[redacted]	190
LF-2	50	0.30	18	[redacted] 76	[redacted]	152
LF-3	60	0.23	18	[redacted] 95	[redacted]	190
LF-4	68	0.23	18	[redacted] 76	[redacted]	152
LF-5	78	0.23	18	[redacted] 95	[redacted]	190
LF-6	89	0.23	18	[redacted] 76	[redacted]	152
MF-1	100	0.23	12	148	296	
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	
MF-3	140	0.30	12	148	296	
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	
MF-5	195	0.30	12	148	296	
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	

HFT - LO-HFT300

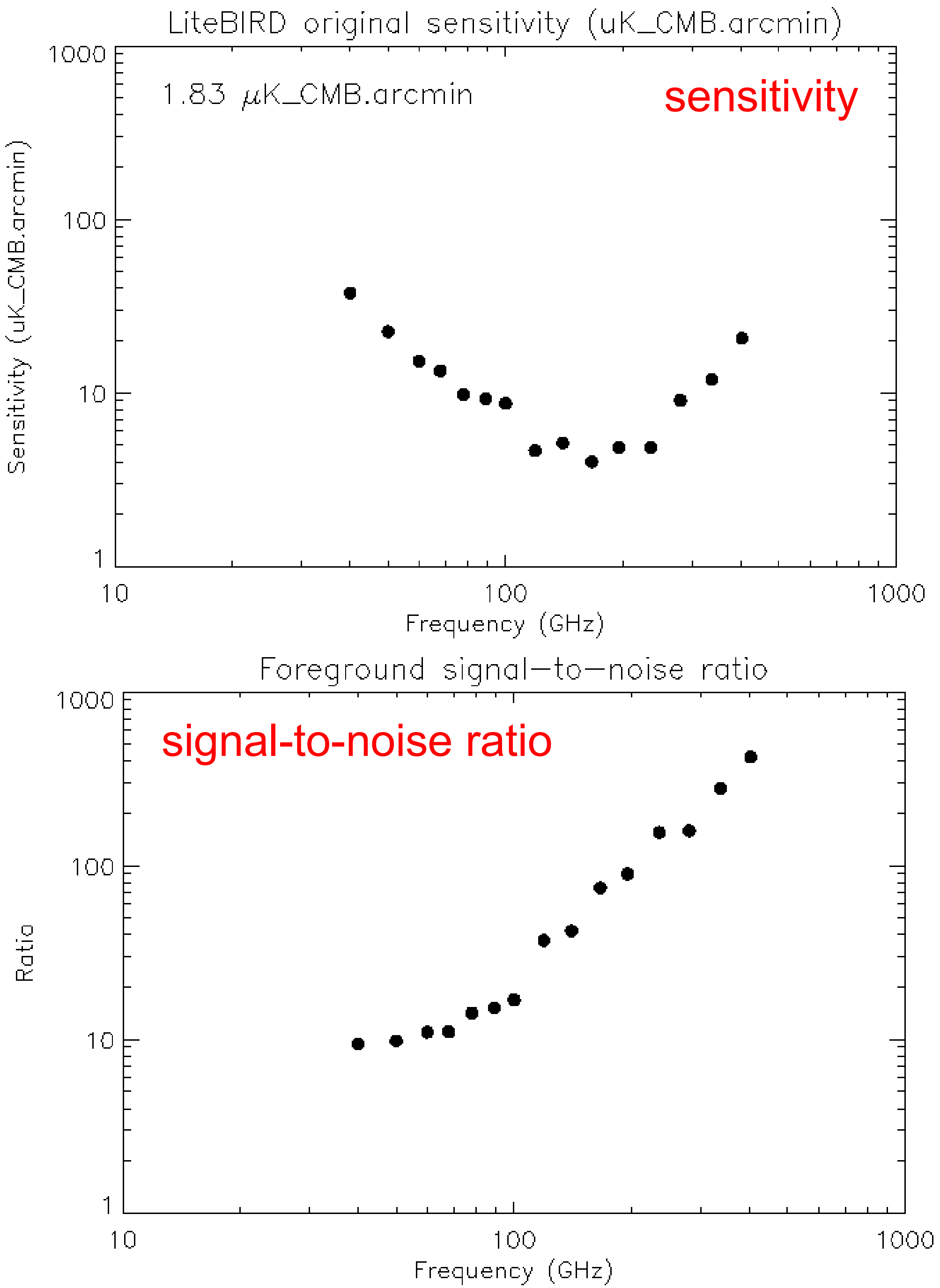


Band	Center Freq [GHz]	Freq BW	Pixel diameter [mm]	Num Pix	Num Det
MF-2	119	0.3	7.7	364	728
MF-4	166	0.3	7.7	364	728
MF-6	235	0.3	7.7	364	728
HF-1	280	0.3	3.9	271	542
HF-2	337	0.3	3.4	331	662
HF-3	402	0.23	2.7	469	938

LiteBIRD sensitivities

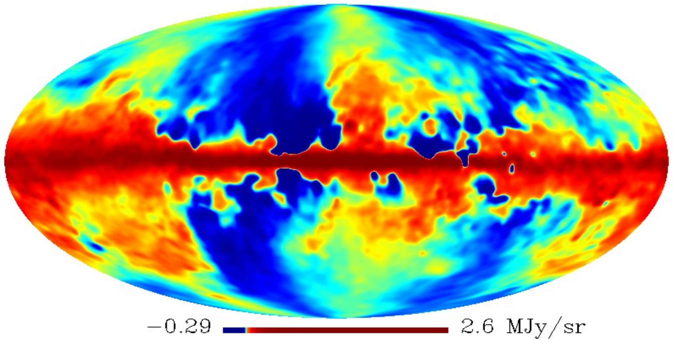
Frequencies [GHz]	Sensitivity in Q,U [µK.arcmin]
40	37.6096
50	22.5819
60	15.2421
68	13.4178
78	9.80981
89	9.219
100	8.70727
119	4.6578
140	5.15081
166	4.00523
195	4.86019
235	4.86446
280	9.05507
337	11.9295
402	20.6931

There is still some flexibility on the final design

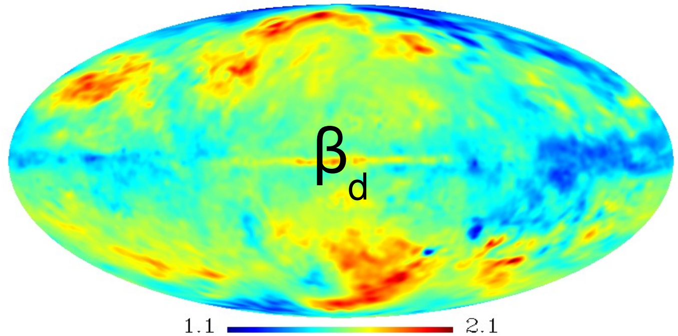


LiteBIRD PSM simulation: Stokes Q maps

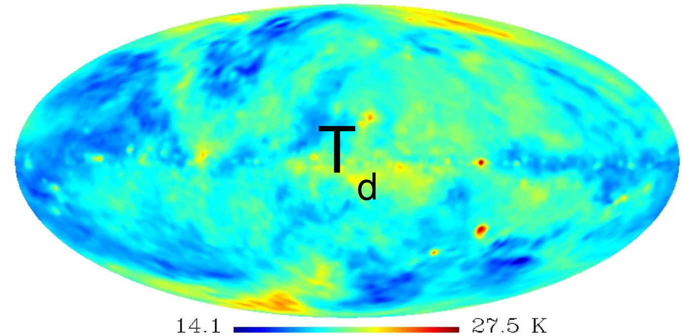
Thermal dust, 353 GHz



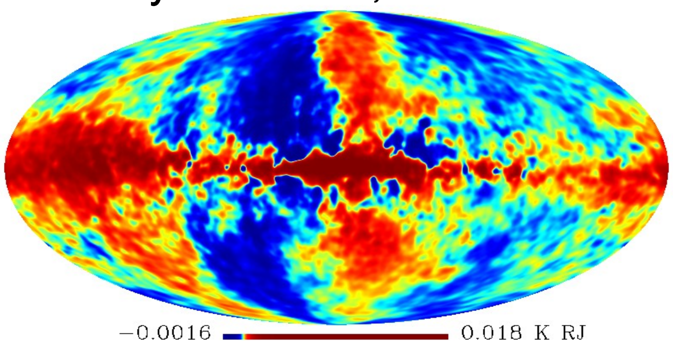
Dust spectral index



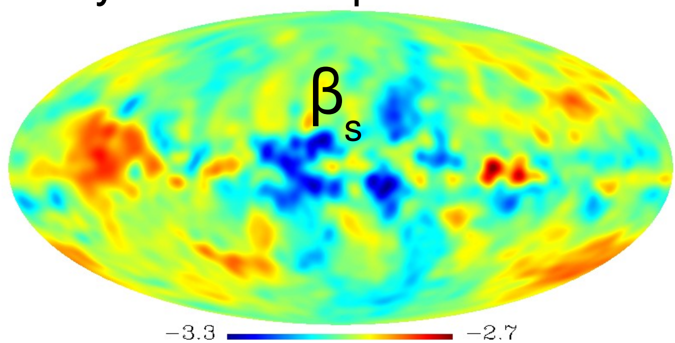
Dust temperature



Synchrotron, 23 GHz



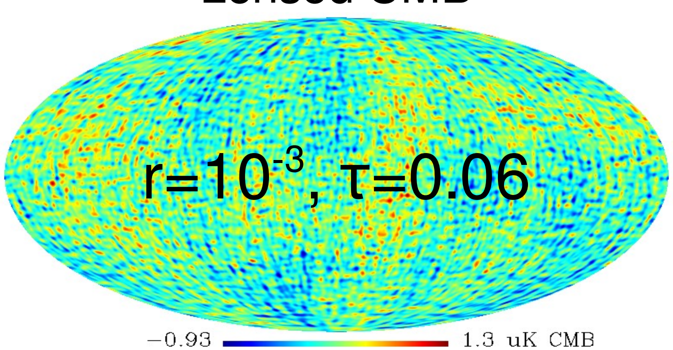
Synchrotron spectral index



Synchrotron curvature

uniform $C_s = 0.3$

Lensed CMB



smoothed to 1°
for illustration purposes

Based on the Planck Sky Model (PSM) – *Delabrouille et al 2013*

Methodology

Eriksen et al 2004, 2008
Remazeilles et al 2016, 2017

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

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

Amplitudes (CMB, foregrounds)

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

Power spectra (CMB)

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

Spectral indices (foregrounds)

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

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

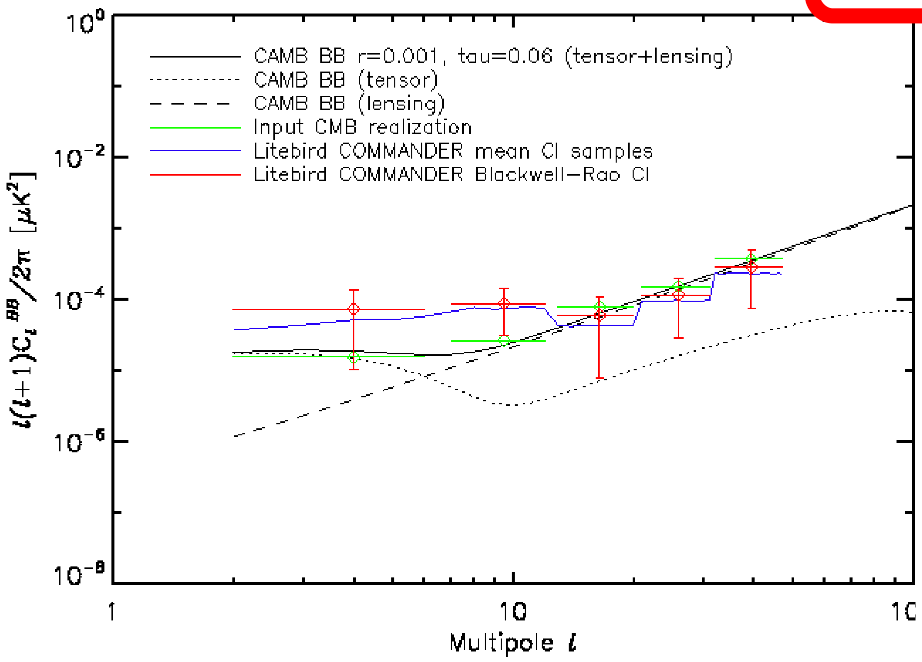
$$C_\ell^{th} = r\, C_\ell^{tensor}(r=1) + A_{lens}\, C_\ell^{lensing}(r=0).$$

3. Blackwell-Rao posterior: $\mathcal{P}\left(r, A_{lens}\right) \approx \frac{1}{N}\sum_{i=1}^{N}\mathcal{L}\left[\widehat{C}_\ell^i | C_\ell^{th}\left(r, A_{lens}\right)\right]$

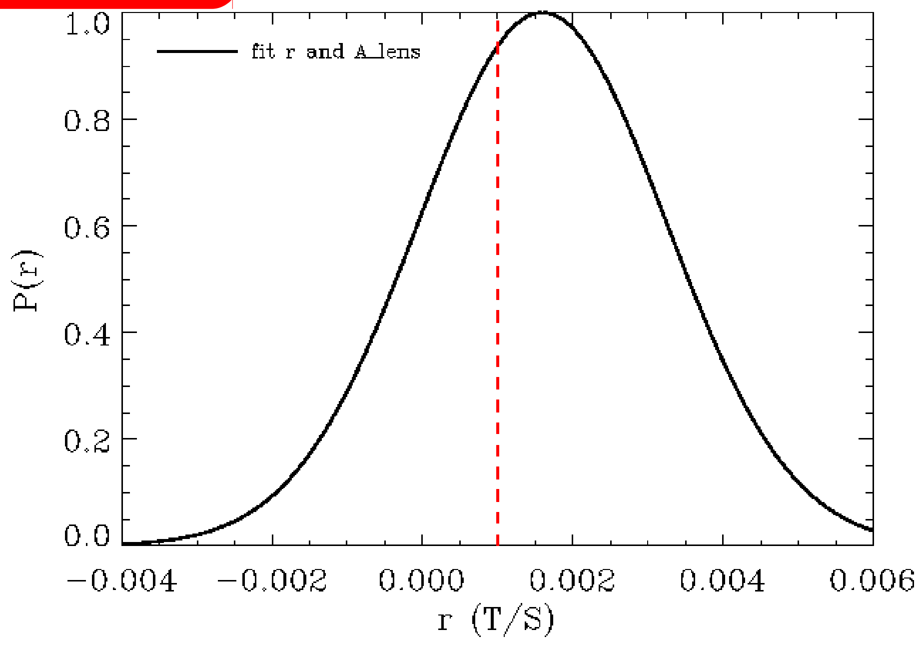
CMB B-mode reconstruction with Commander.
$r = 10^{-3}$, fitting everything

3D foregrounds (no synchrotron curvature)

PRELIMINARY!



$r = (1.6 \pm 1.6) \times 10^{-3}$



β_d, T_d, β_s locally fitted

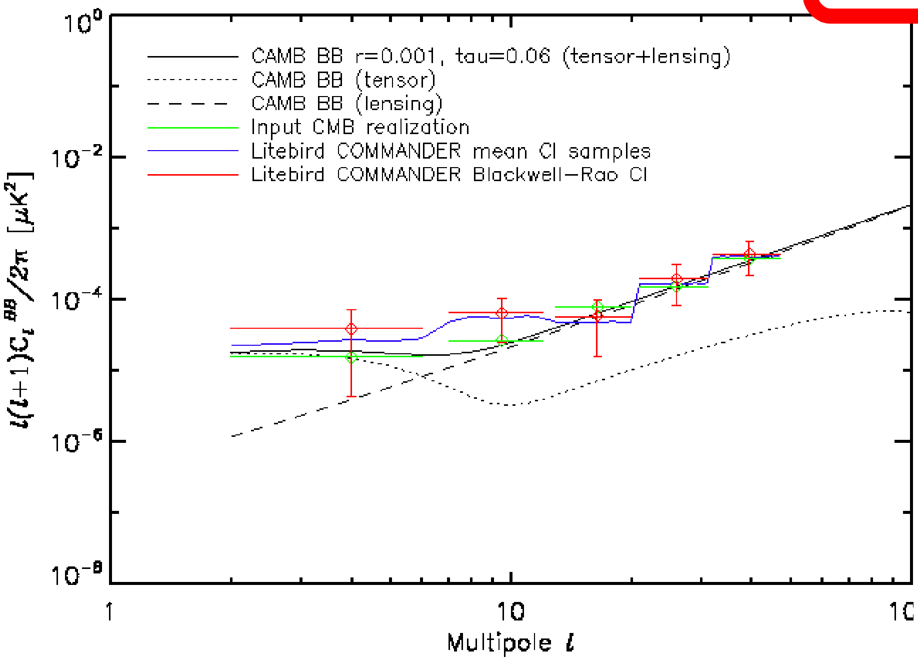
M. Remazeilles

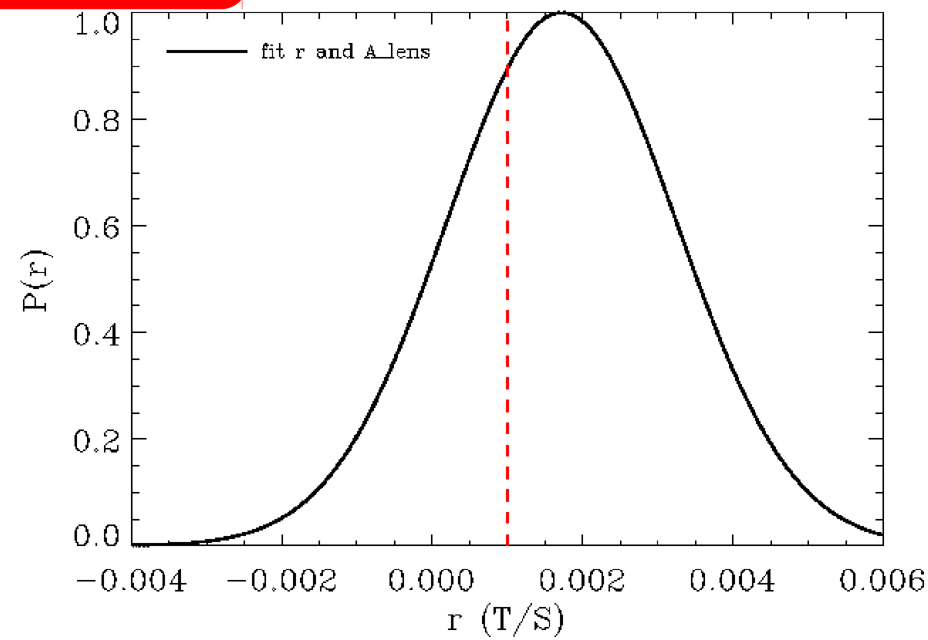
CMB B-mode reconstruction with Commander. $r = 10^{-3}$, fixing β_s and T_d

3D foregrounds (no synchrotron curvature)

PRELIMINARY!

$r = (1.7 \pm 1.5) \times 10^{-3}$





β_s, T_d fixed

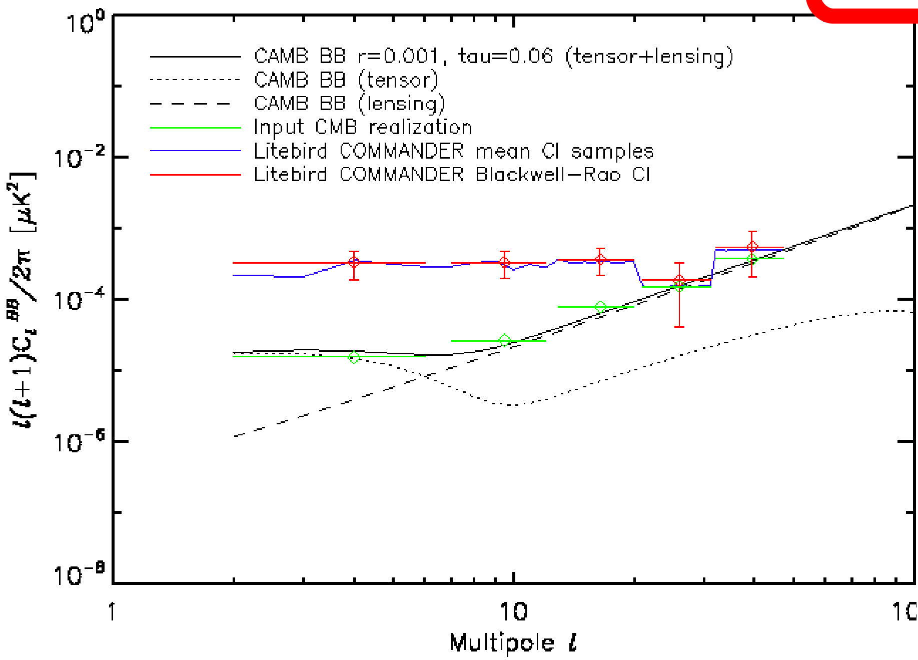
β_d locally fitted

M. Remazeilles

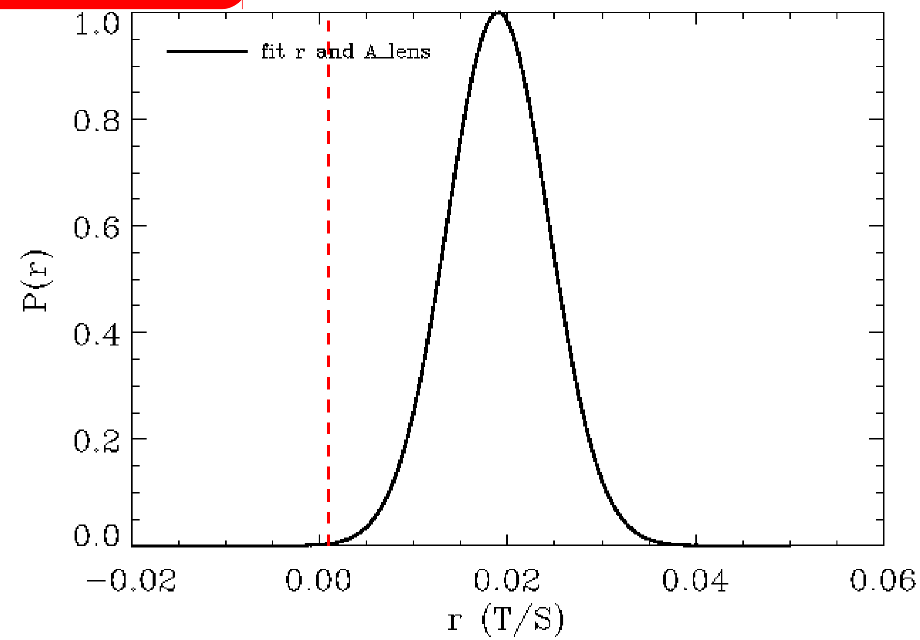
CMB B-mode reconstruction with Commander.
r = 10^{-3}, fitting everything

4D foregrounds (synchrotron curvature fitted locally)

PRELIMINARY!



r = (19 ± 5.4) x 10^{-3}



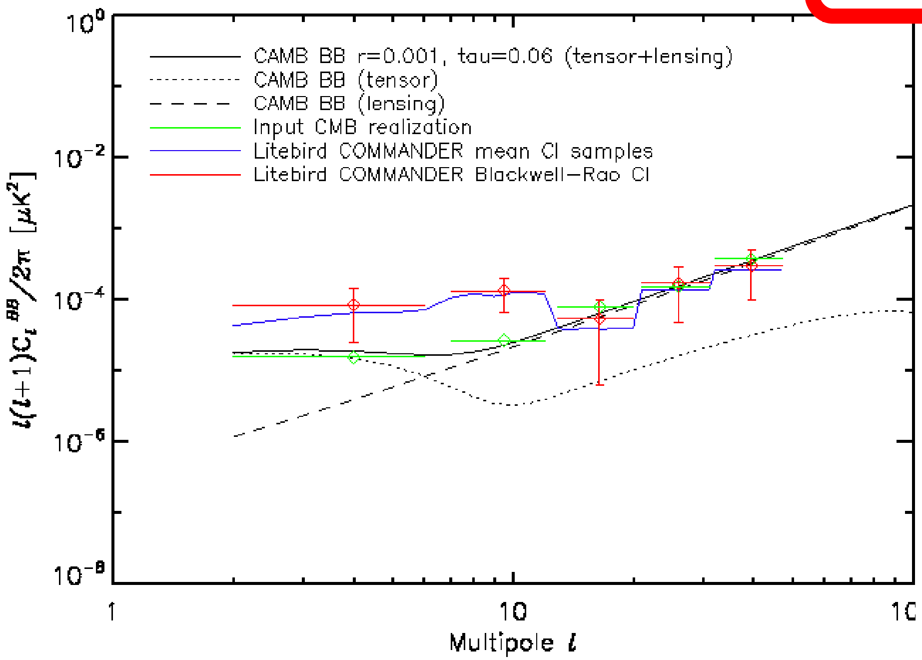
β_d, T_d, β_s, C_s locally fitted

M. Remazeilles

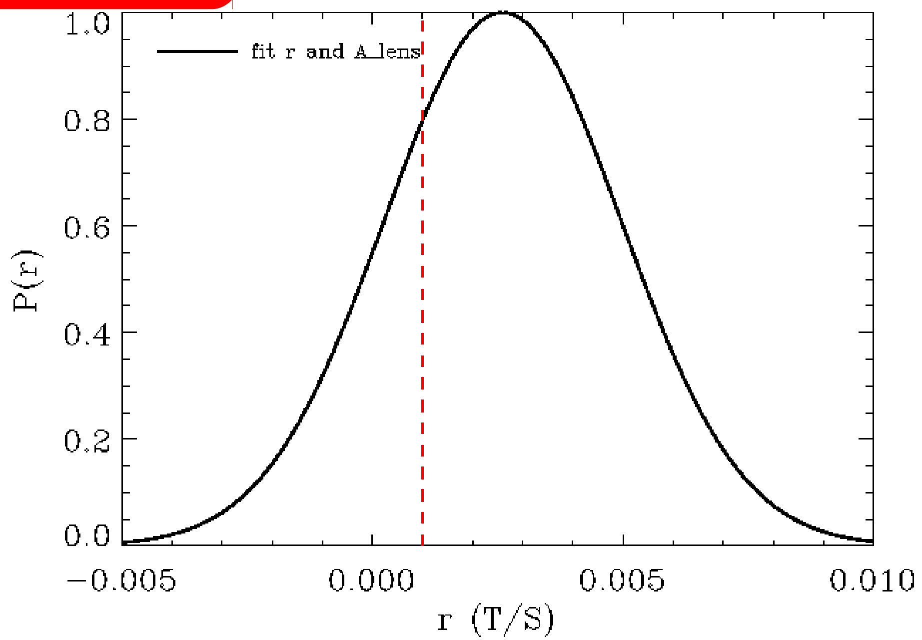
CMB B-mode reconstruction with Commander. $r = 10^{-3}$, fitting everything

4D foregrounds (synchrotron curvature fitted globally)

PRELIMINARY!



$r = (2.6 \pm 2.3) \times 10^{-3}$



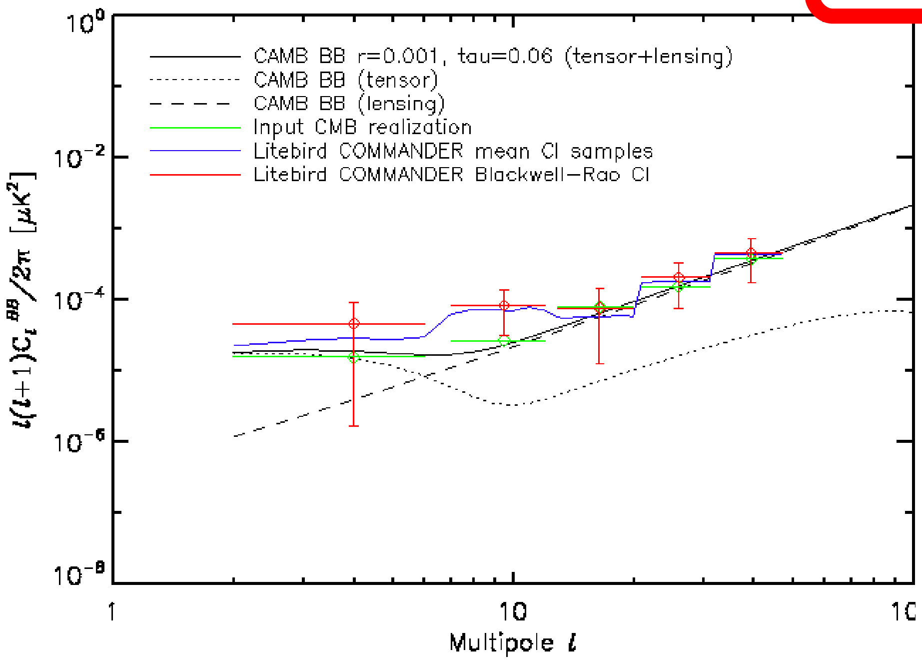
β_d, T_d, β_s locally fitted
C_s globally fitted

M. Remazeilles

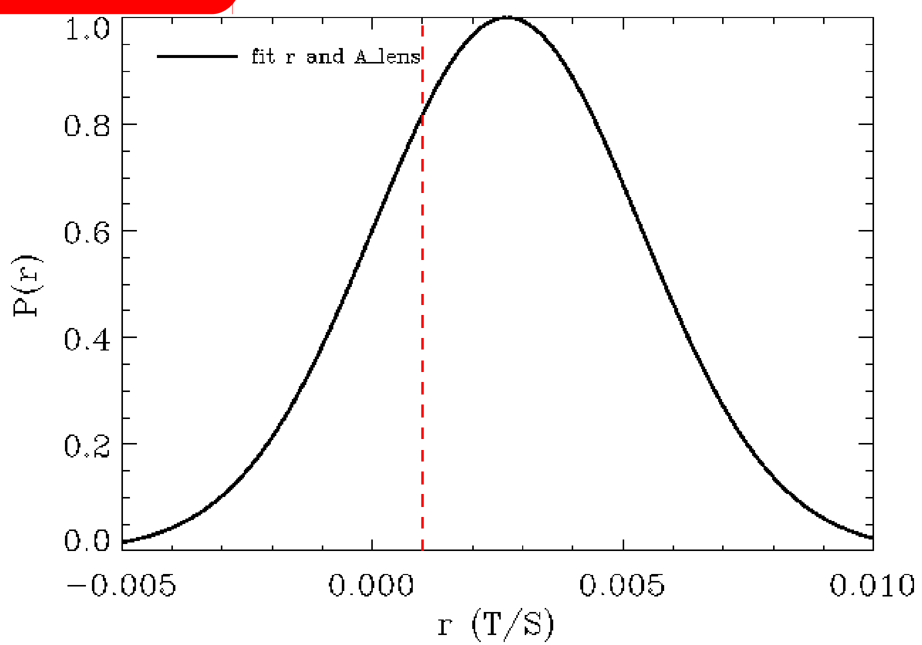
CMB B-mode reconstruction with Commander. $r = 10^{-3}$, fixing β_s and T_d

4D foregrounds (synchrotron curvature fitted globally)

PRELIMINARY!



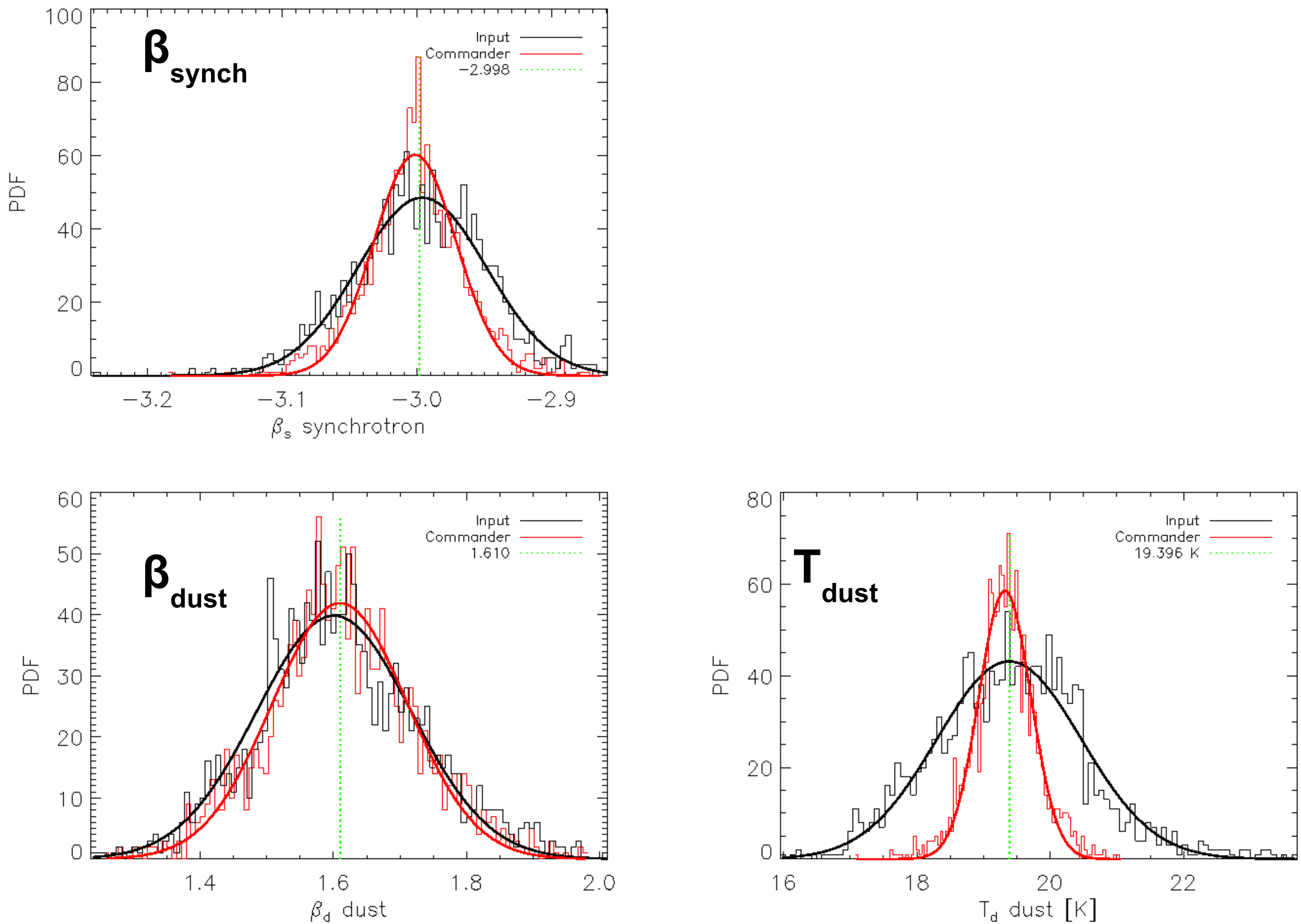
$r = (2.7 \pm 2.6) \times 10^{-3}$



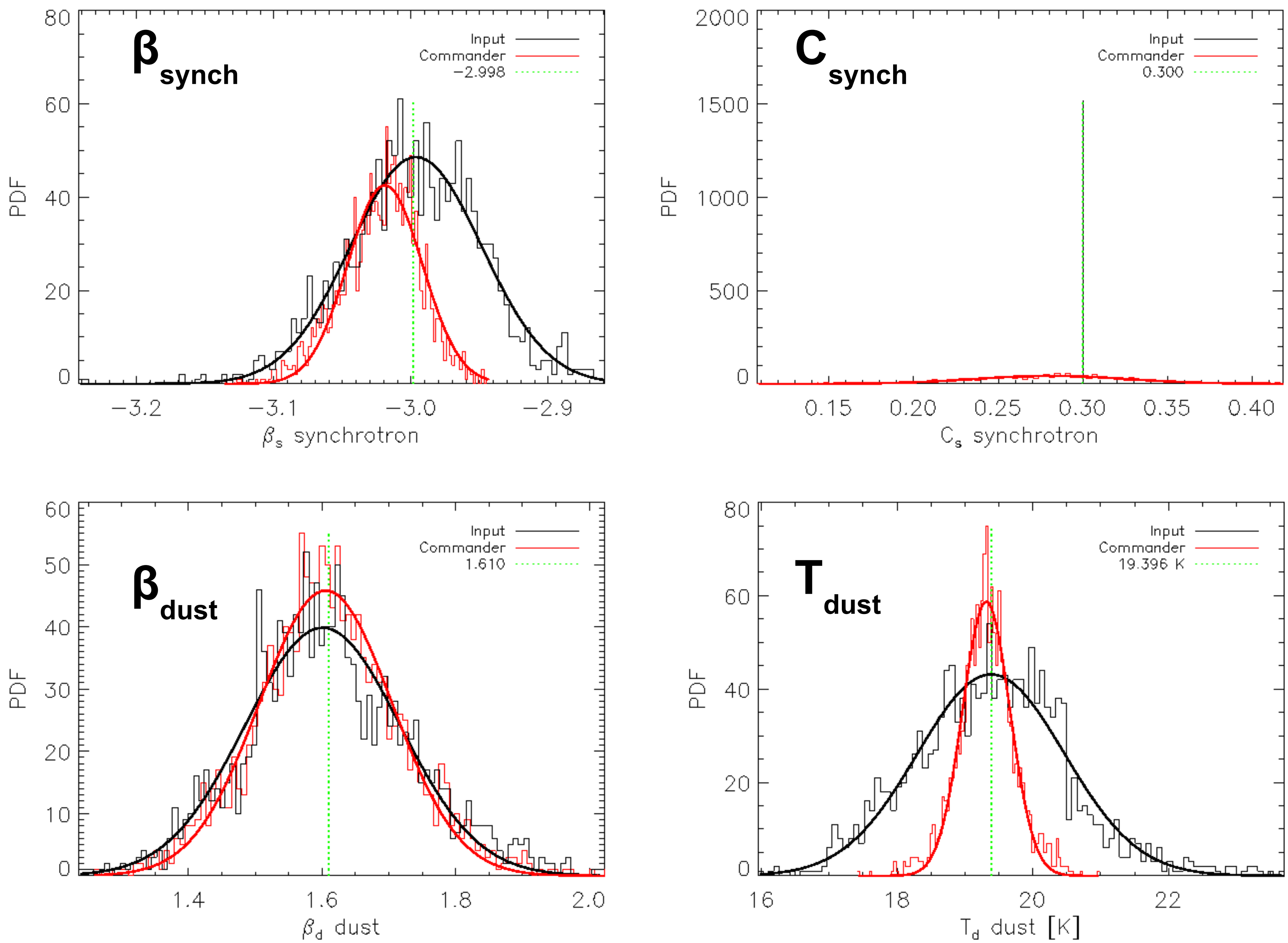
β_s ,T_d fixed
β_d locally fitted
C_s globally fitted

M. Remazeilles

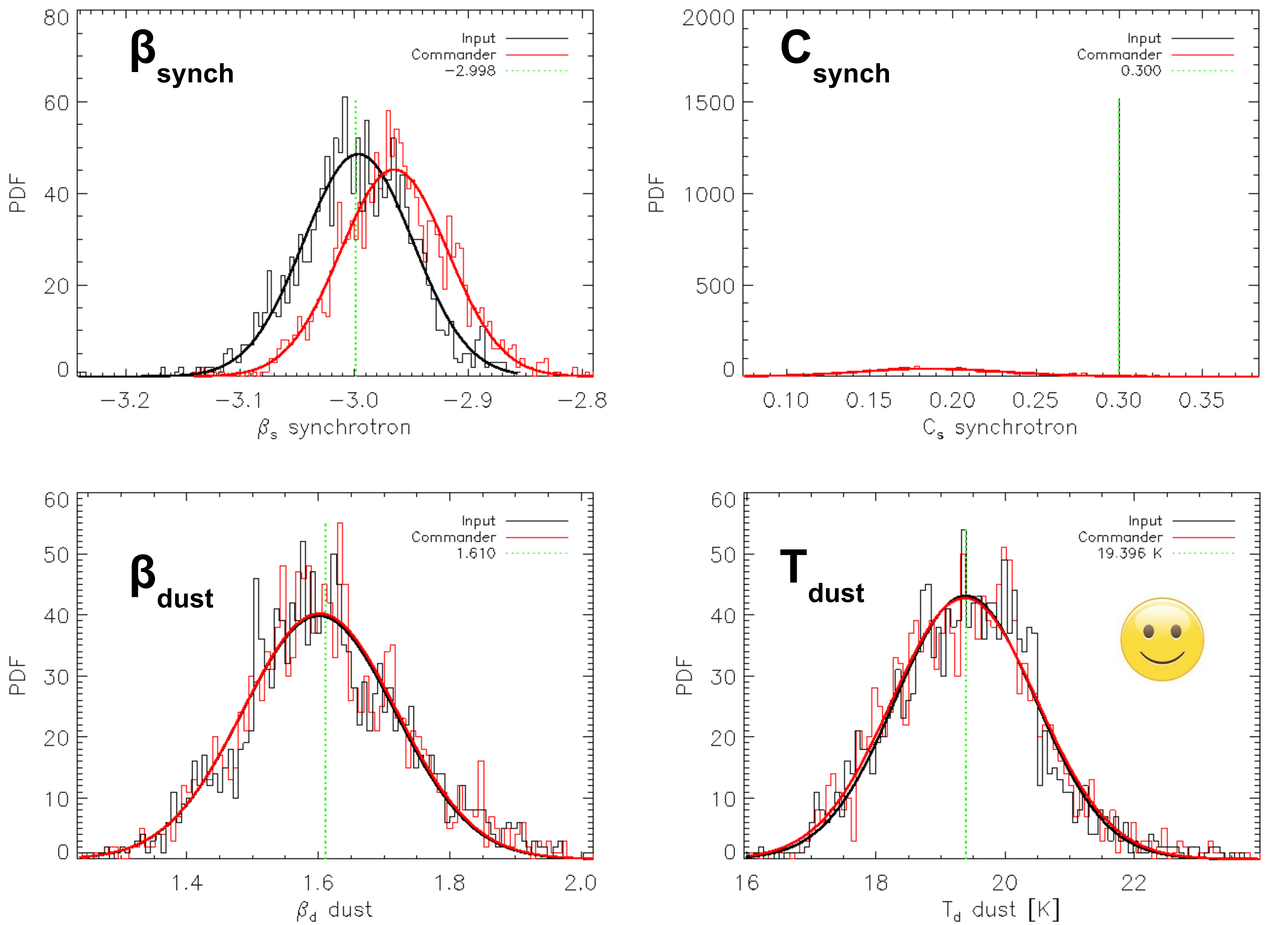
Results for 3D foregrounds



Results for 4D foregrounds

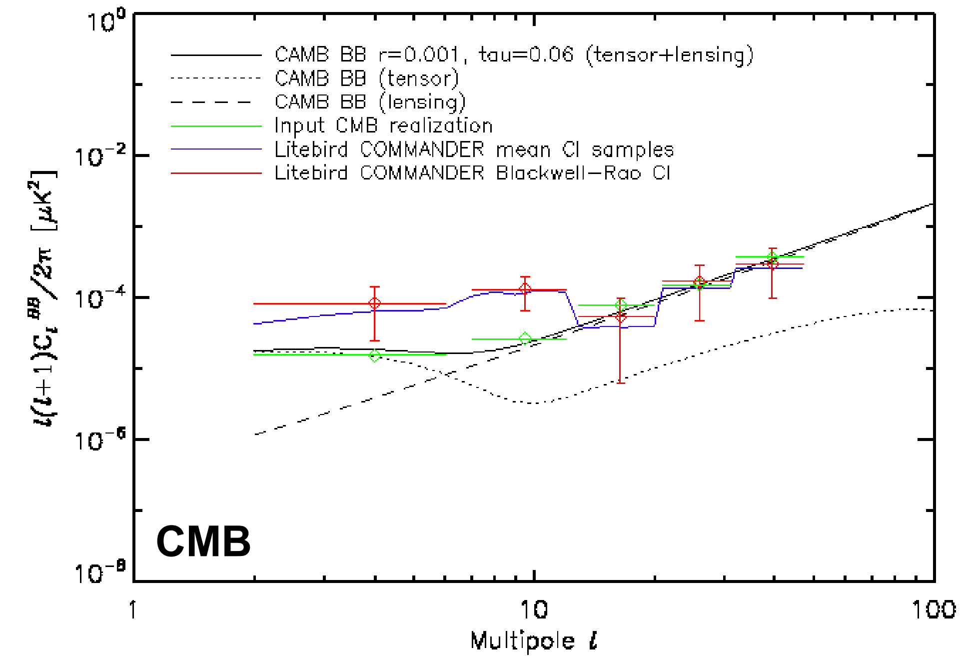


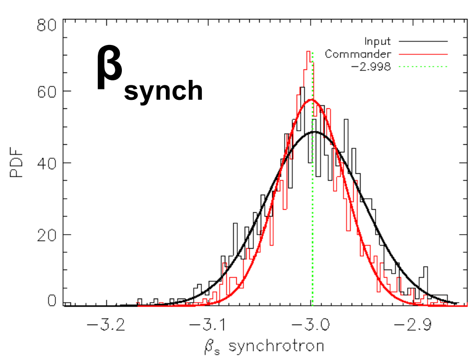
Adding a 600 GHz channel?

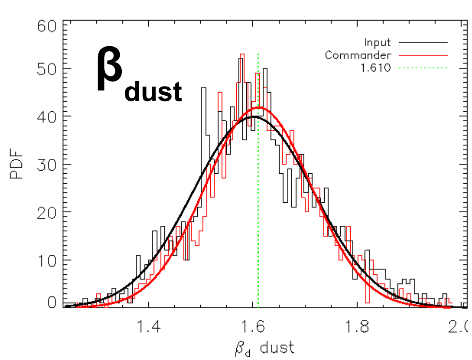


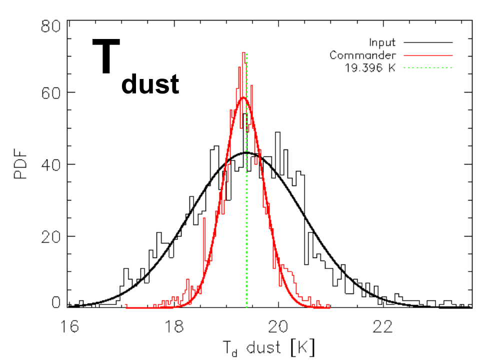
LiteBIRD

40 – 402 GHz

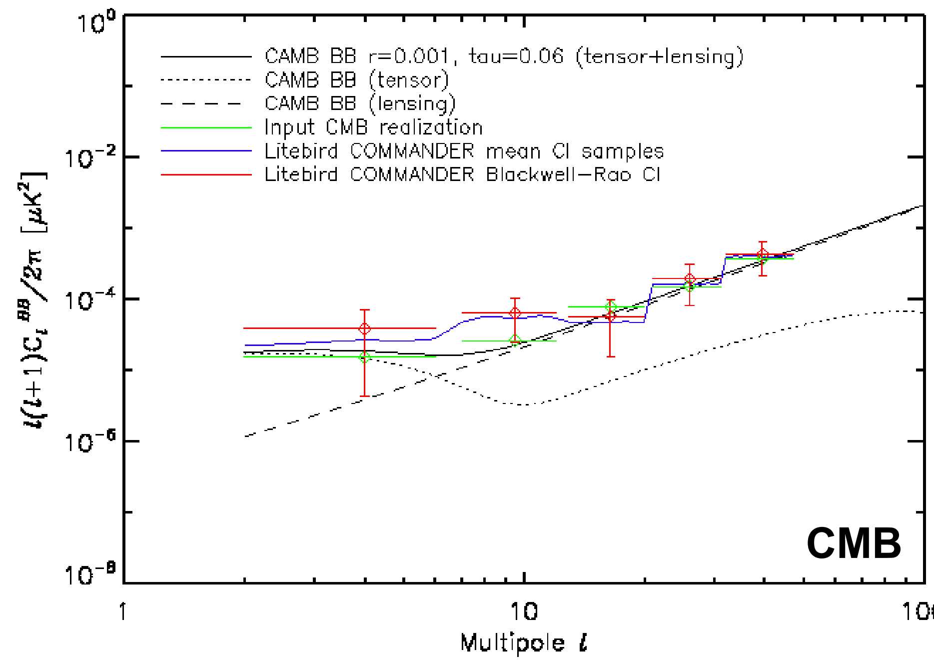


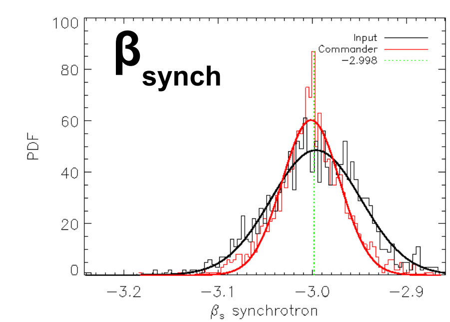


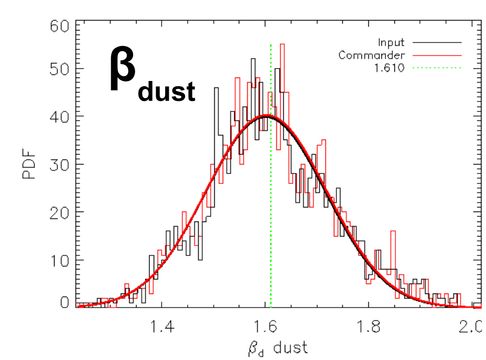


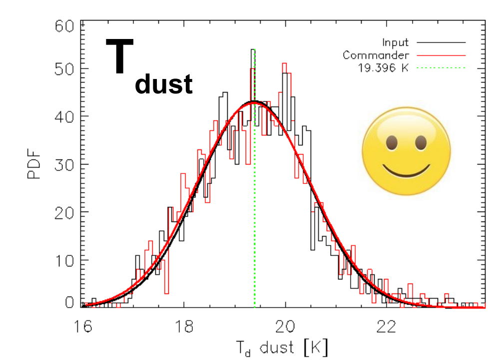


LiteBIRD + 600 GHz

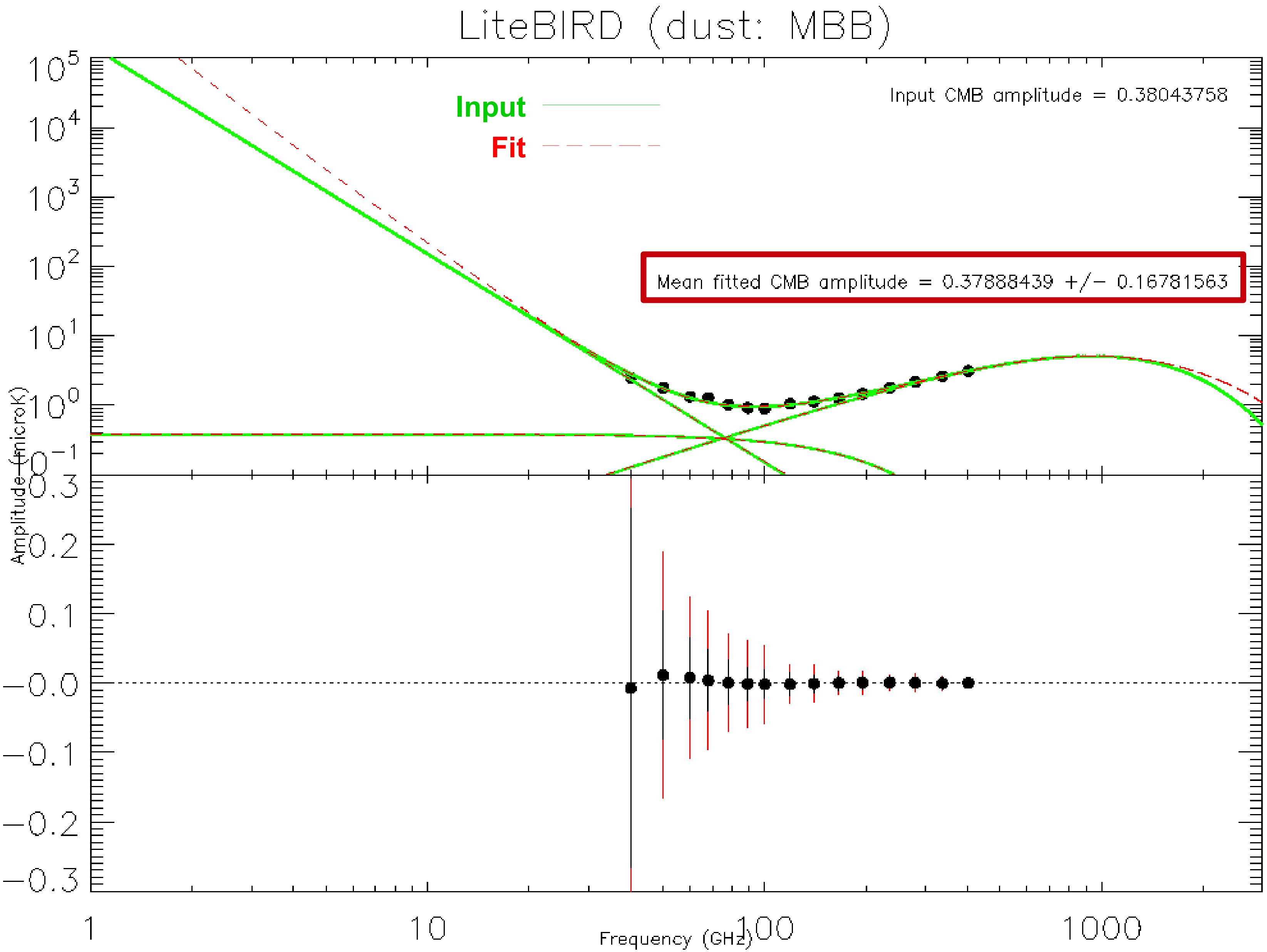






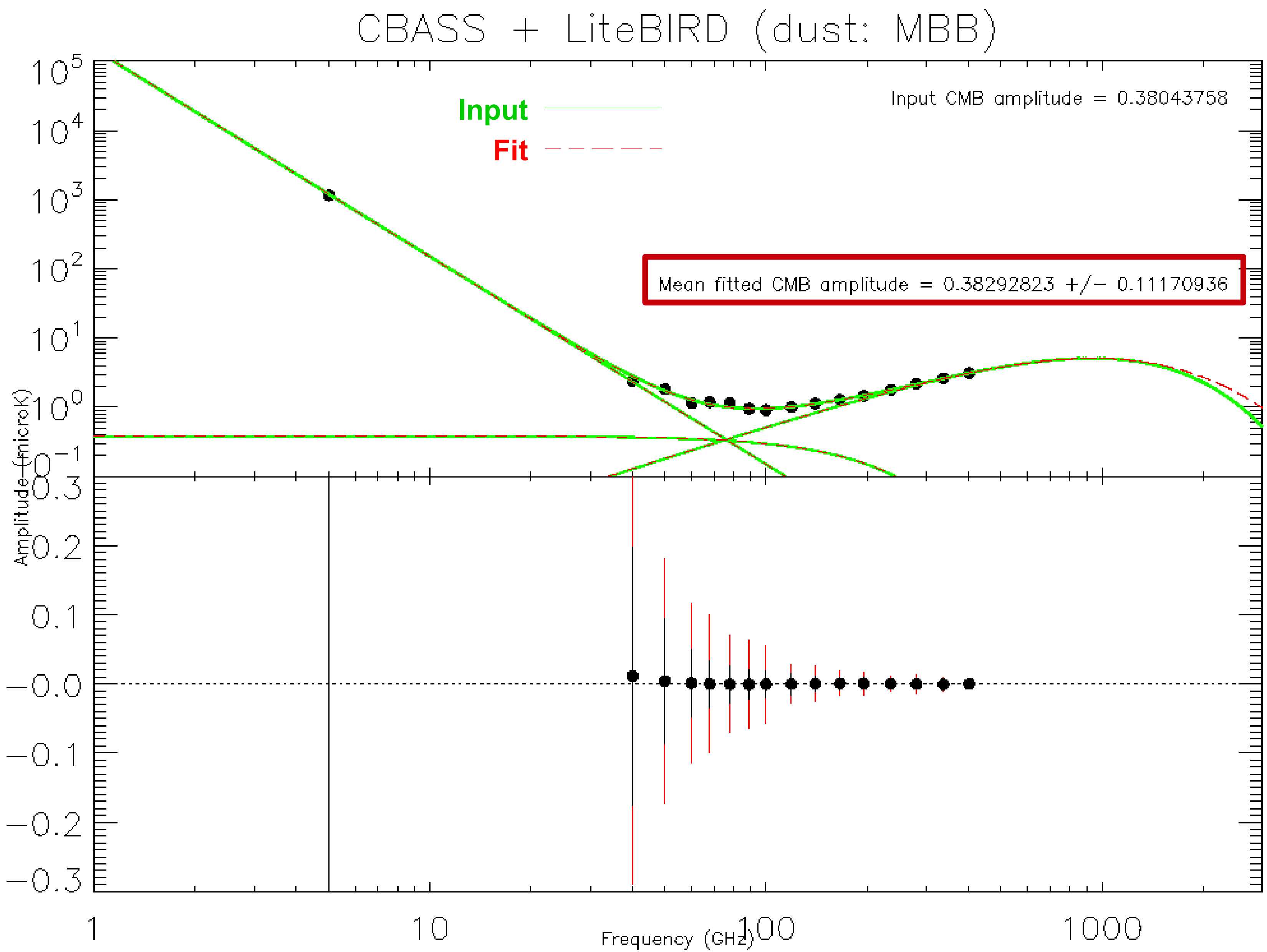


Without C-BASS



M. Remazeilles

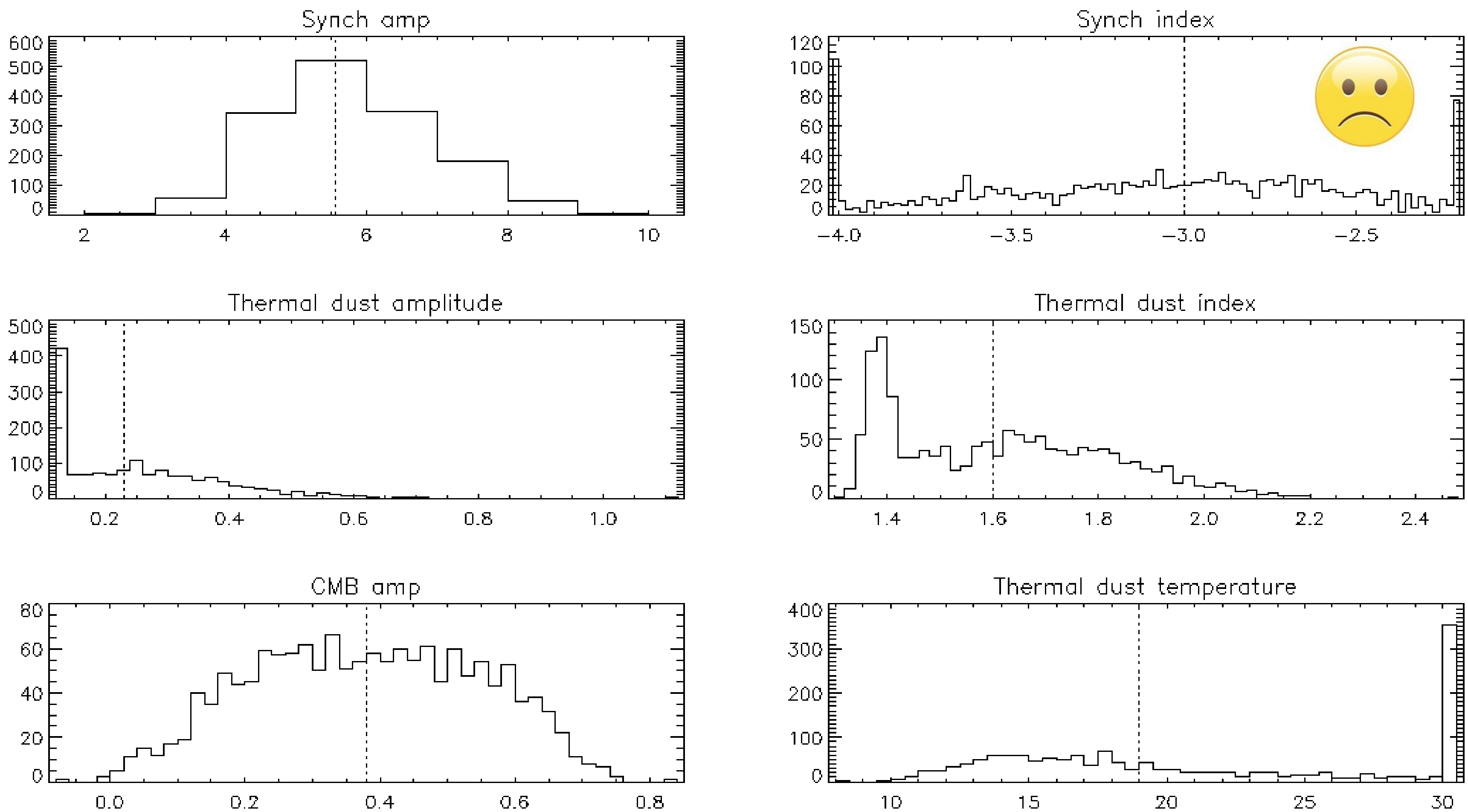
With C-BASS



Uncertainty σ(A_CMB) decreased by 30% !

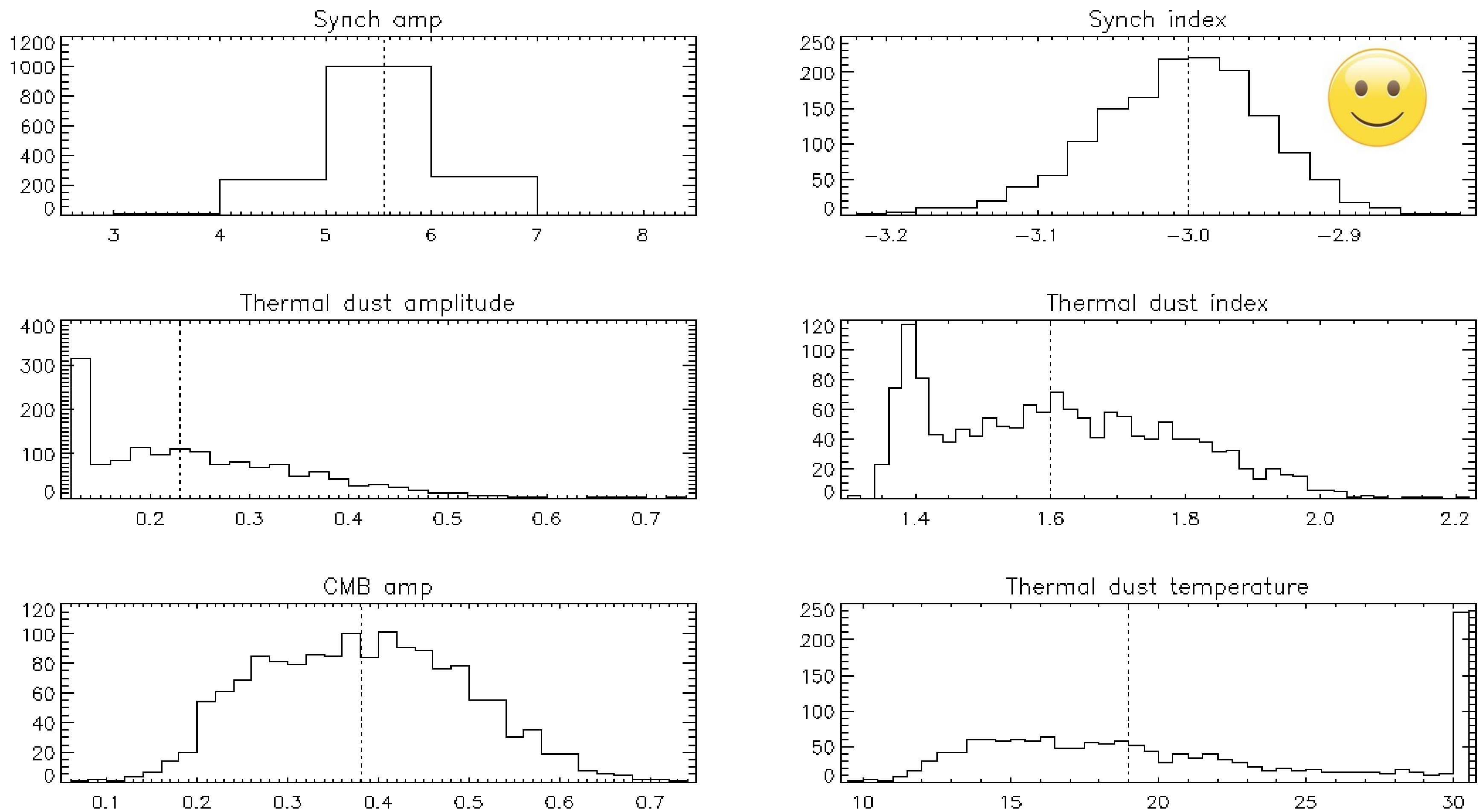
M. Remazeilles

Without C-BASS



M. Remazeilles

With C-BASS



Synchrotron index is much better constrained with C-BASS 5GHz band, so the CMB is.

M. Remazeilles

Physics versus Mathematics

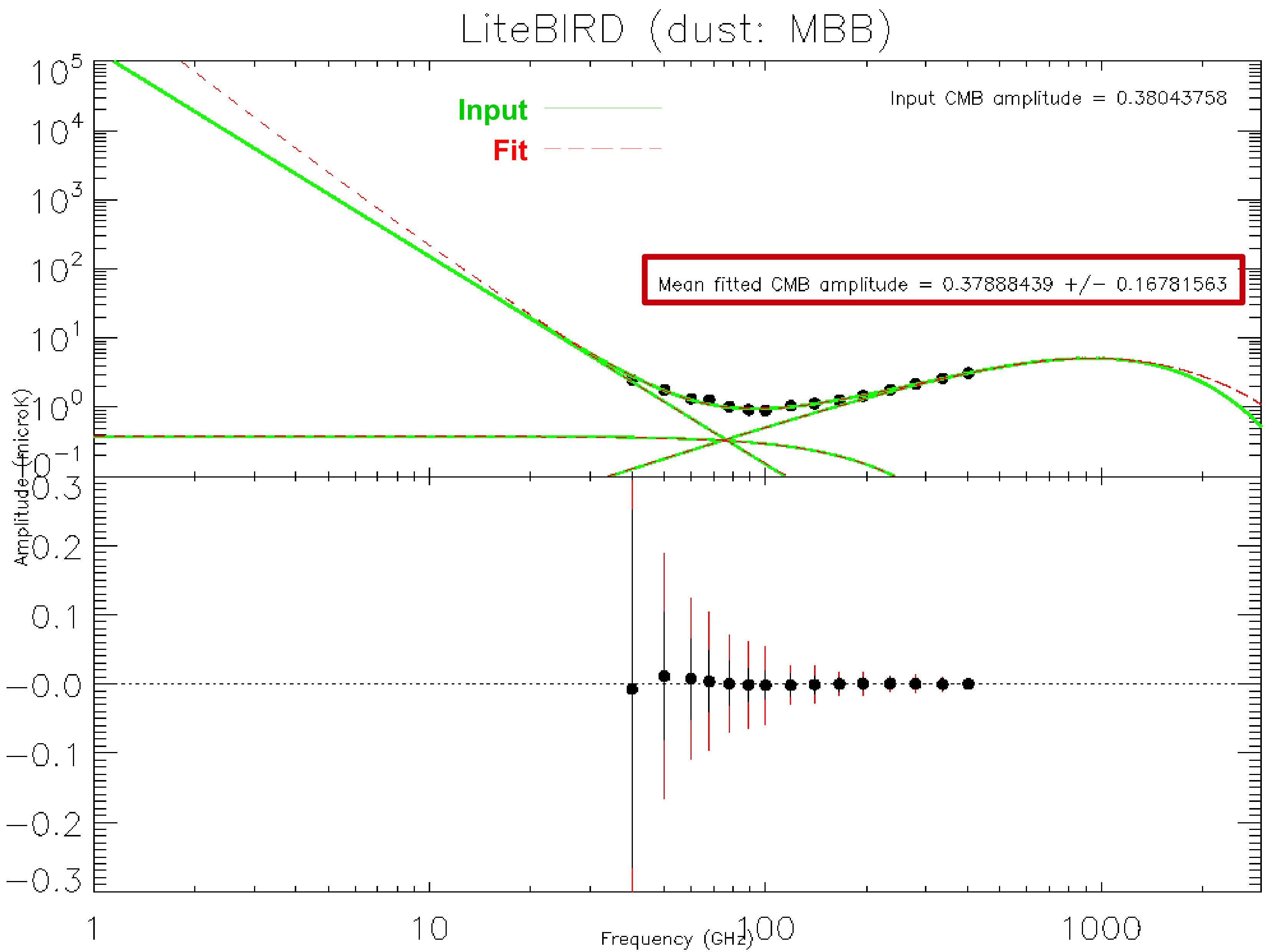
How to deal with foreground complexity over a limited frequency range?

- Over a limited frequency range, we suffer from a lack of high-frequency data points to constrain the dust temperature T_{dust} at the required precision $\sigma(r) < 10^{-3}$

  → This translates into a biased CMB B-mode by extrapolation.

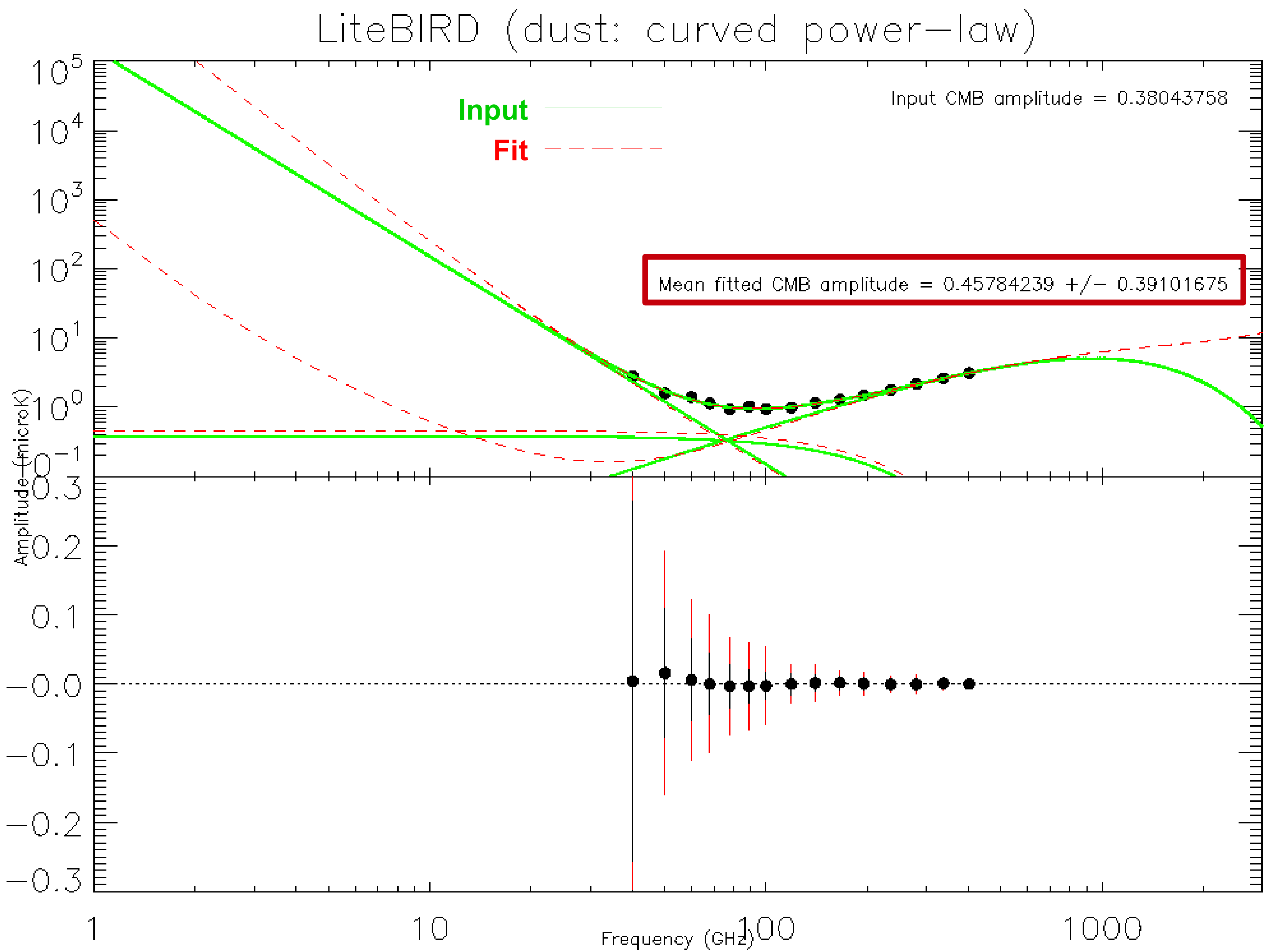
- Can we get more <u>precision</u> by fitting a dust <u>curvature</u> (local) instead of a dust <u>temperature</u> (non-local) over the limited frequency range, without lack of <u>accuracy</u>?

LiteBIRD dust: fit a MBB



M. Remazeilles

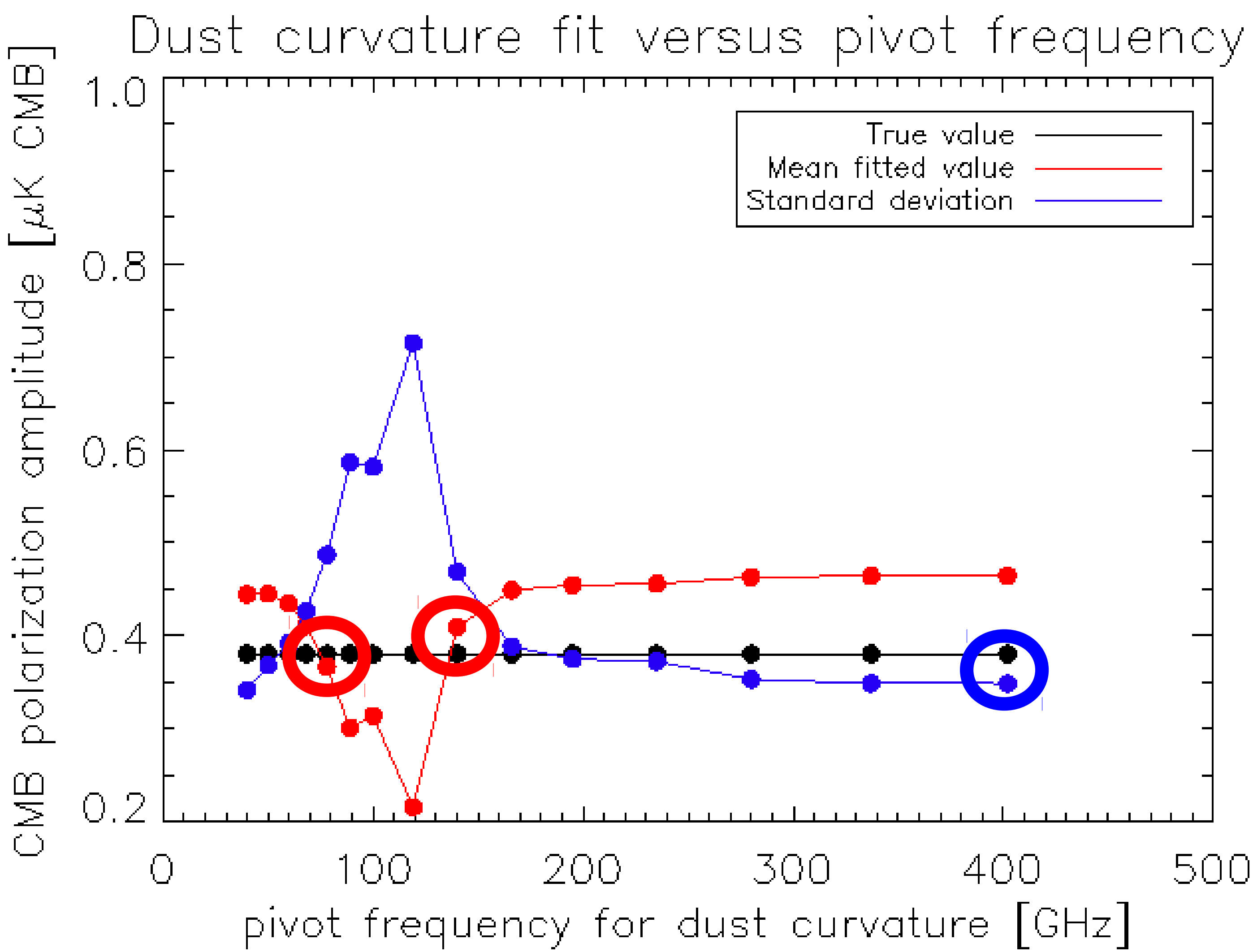
LiteBIRD dust: fit a curved power-law



Pivot frequency: 400 GHz

M. Remazeilles

What's the best pivot frequency?



: Lower bias for pivot frequencies 89 GHz and 143 GHz, i.e. in the CMB range.

: Lower uncertainty for pivot frequency 402 GHz, i.e. in the dust range.

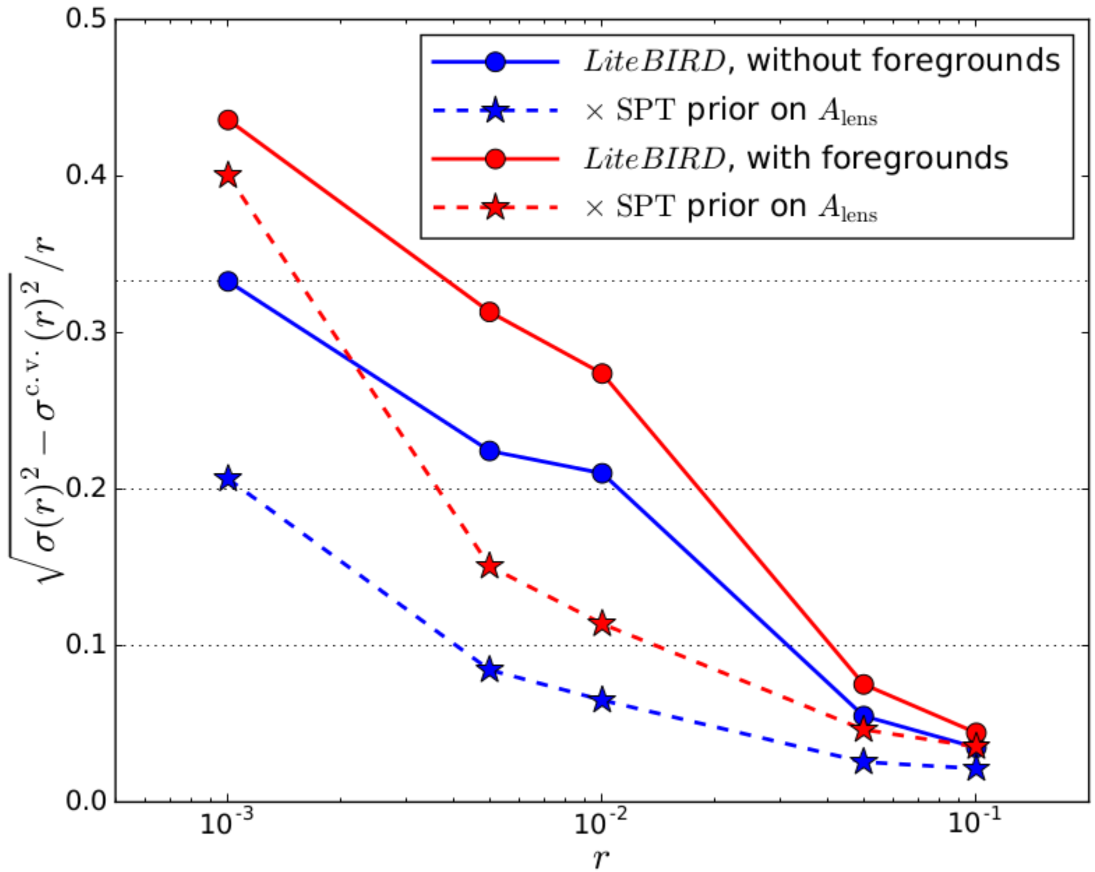
→ **no ideal choice of pivot frequency!**

M. Remazeilles

Joint Bayesian estimation of tensor, lensing, and foreground B-modes

Remazeilles, Dickinson, Eriksen, Wehus, MNRAS 2017

arXiv:1707.02981

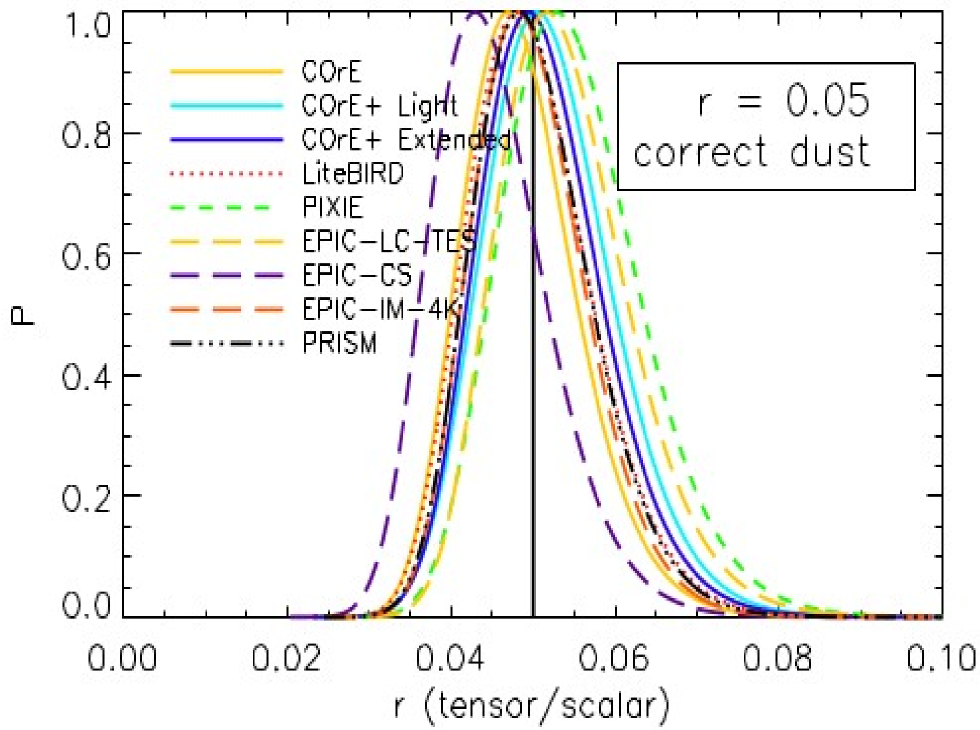


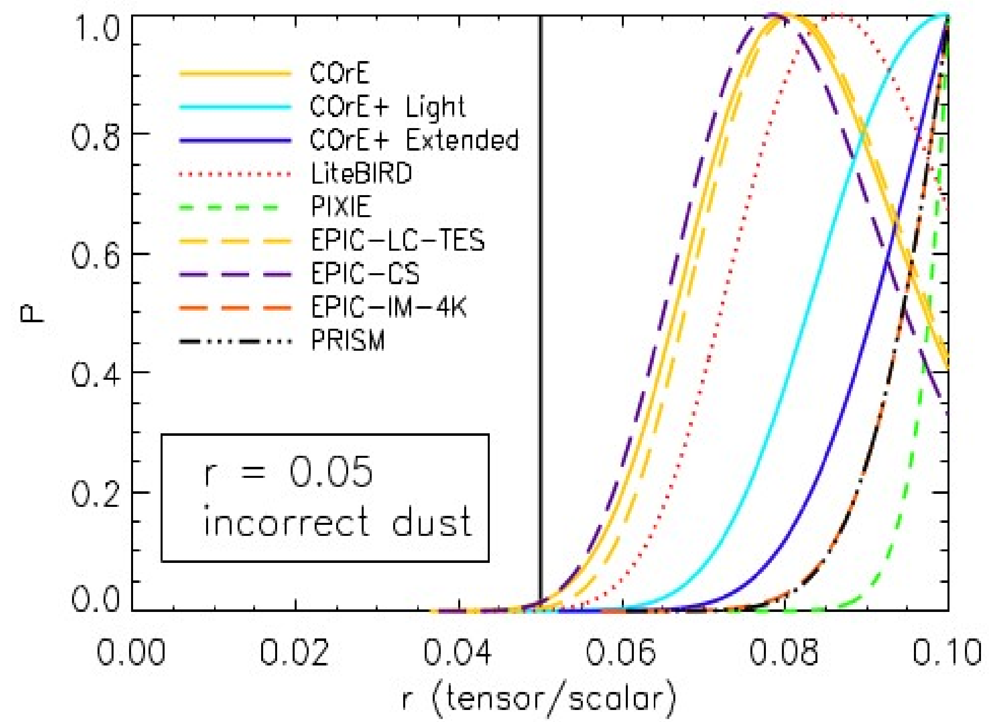
$$\mathcal{P}\left(r, A_{lens}\right) \approx \frac{1}{N} \sum_{i=1}^{N} \mathcal{L}\left[\widehat{C}_\ell^i | C_\ell^{th}\left(r, A_{lens}\right)\right] \mathcal{P}^{prior}\left(A_{lens}\right)$$

Subtle issues on B-mode foregrounds

#1. Impact on r of foreground mismodelling

Impact of mismodelling 2 MBB dust components as a single MBB component:



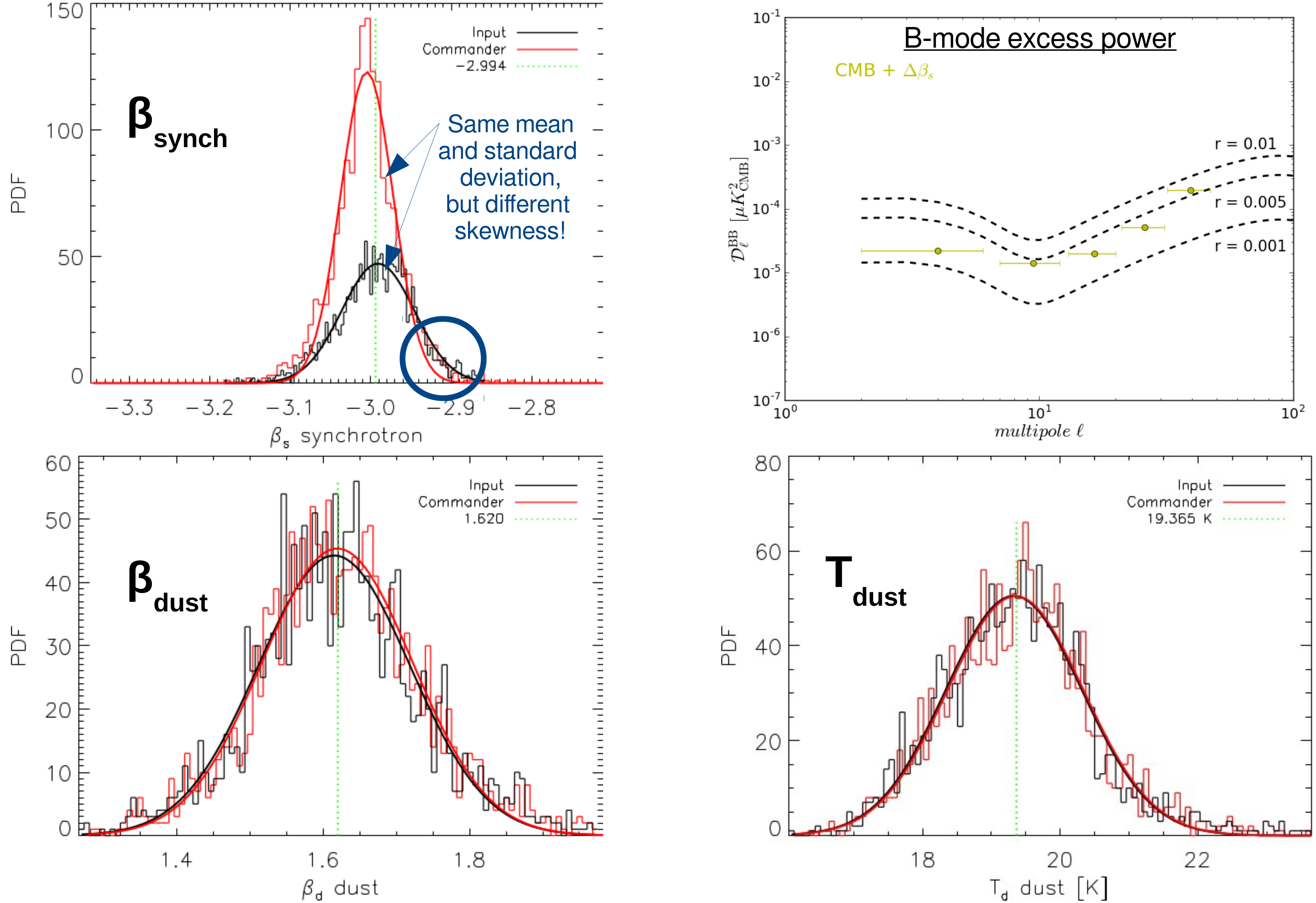


Remazeilles et al, MNRAS 2016

- **How many dust components in the sky? But do we really care?**
- **<u>Most important</u>, what is the actual dust spectrum in the 70 – 140 GHz frequency range?**
- **Any extrapolation is obsolete because of decorrelation effects**

#2. Lack of frequency range / sensitivity to β_s, T_d

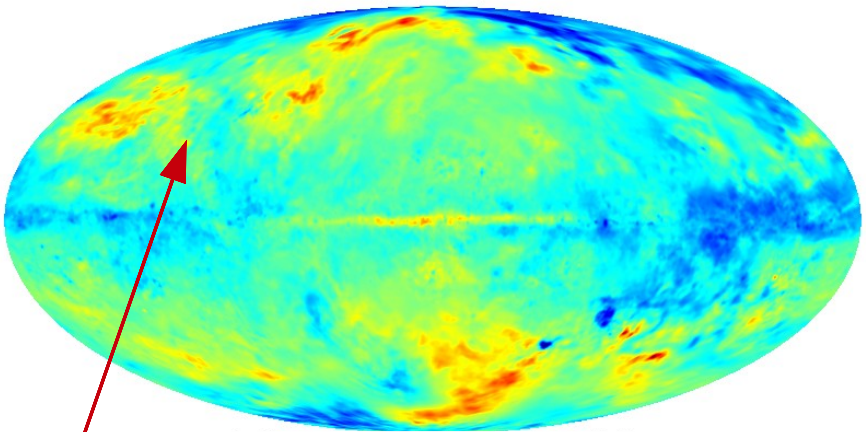
Error $\Delta\beta_{synch} \sim 0.02 \Rightarrow$ error $\Delta r \sim 10^{-3}$ when extrapolated from 23 to 145 GHz !



Remazeilles et al, for the CORE collaboration, JCAP 2017

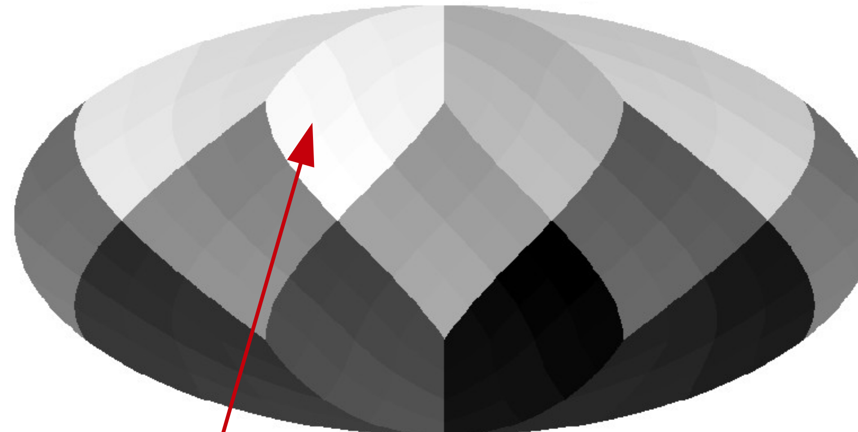
#3. Averaging effects of spectral indices within pixels / beams

Dust spectral indices in the sky



One value β_{dust} per line-of-sight

Map pixelization



Many values β_{dust} per pixel

(effective SED: $\sum_i \nu^{\beta i} \neq \nu^{\beta}$)

- **Averaging / pixelization creates spurious curvatures on the foreground SED !**
- **The assumed SED might differ from the effective SED in the maps!**

→ source of bias on $r = 10^{-3}$ for parametric / template fitting methods

→ similar to decorrelation effects, but not physical

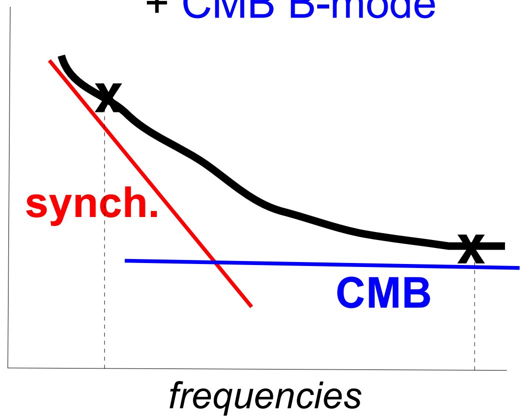
Chluba, Hill, Abitbol, 2017

Remazeilles et al 2017, for the CORE collaboration

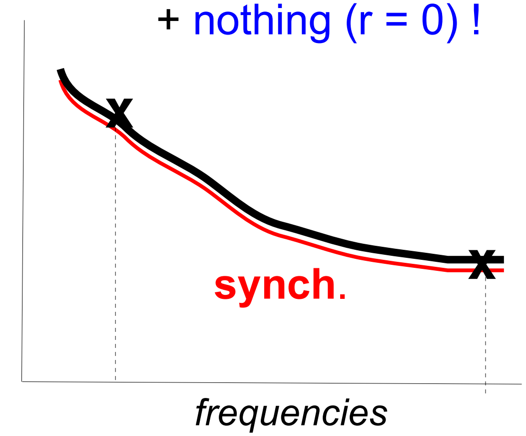
#4. Frequency range & spectral degeneracies

- **A bias on r may result from a lack of frequency bands**

(a) Total fit = synchrotron
+ CMB B-mode

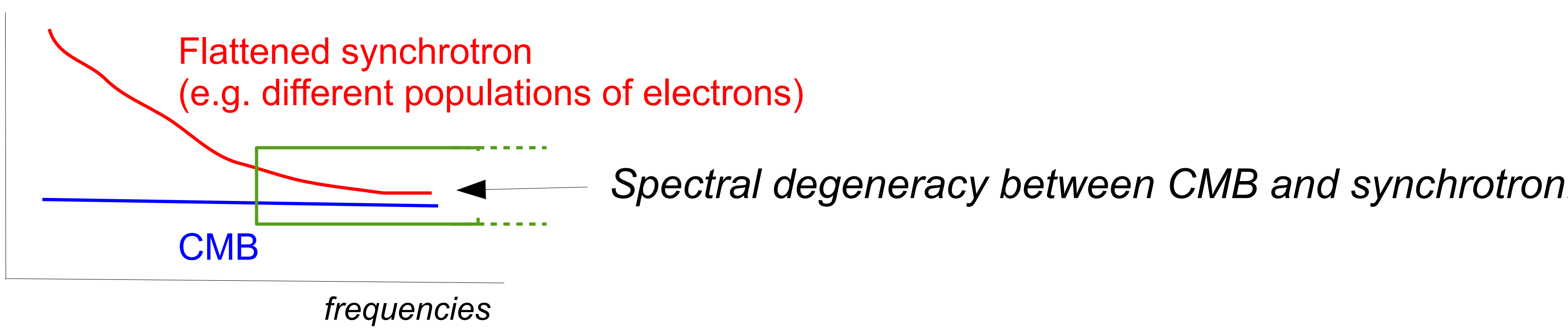


(b) Total fit = curved synchrotron
+ nothing (r = 0) !

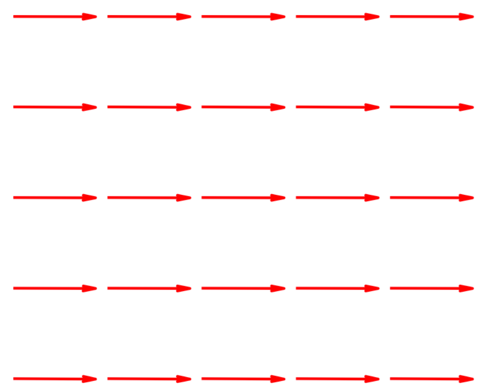


→ *Same goodness-of-fit and no chi-square evidence for incorrect modelling!*
→ *Accurate fit of the total sky emission does not mean correct CMB fit!*

- **A bias on r may result from a limited frequency range**



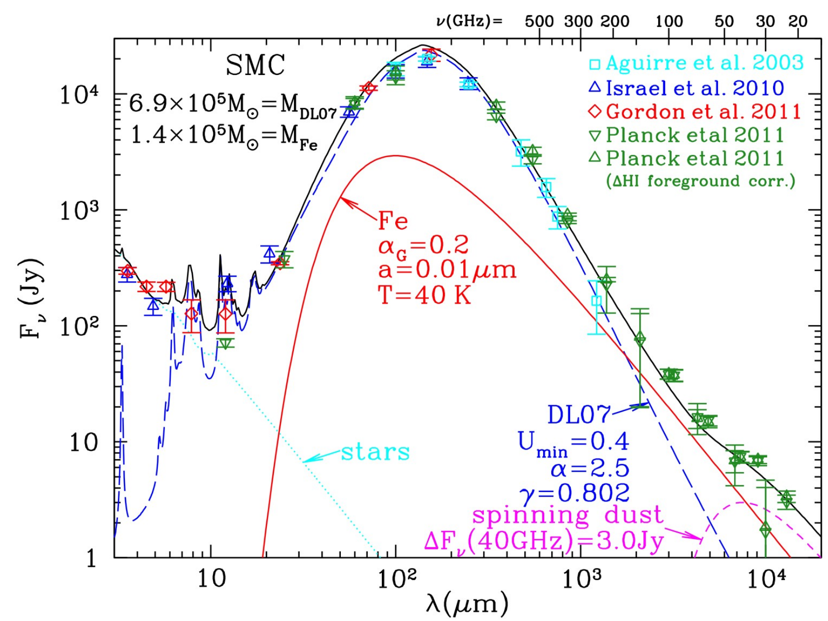
#5. What about magnetic dust (MD)?



Ferromagnetic lattice with spins aligned.

Thermal fluctuations will move them away, producing magnetic dipole radiation

Draine & Hensley 2013



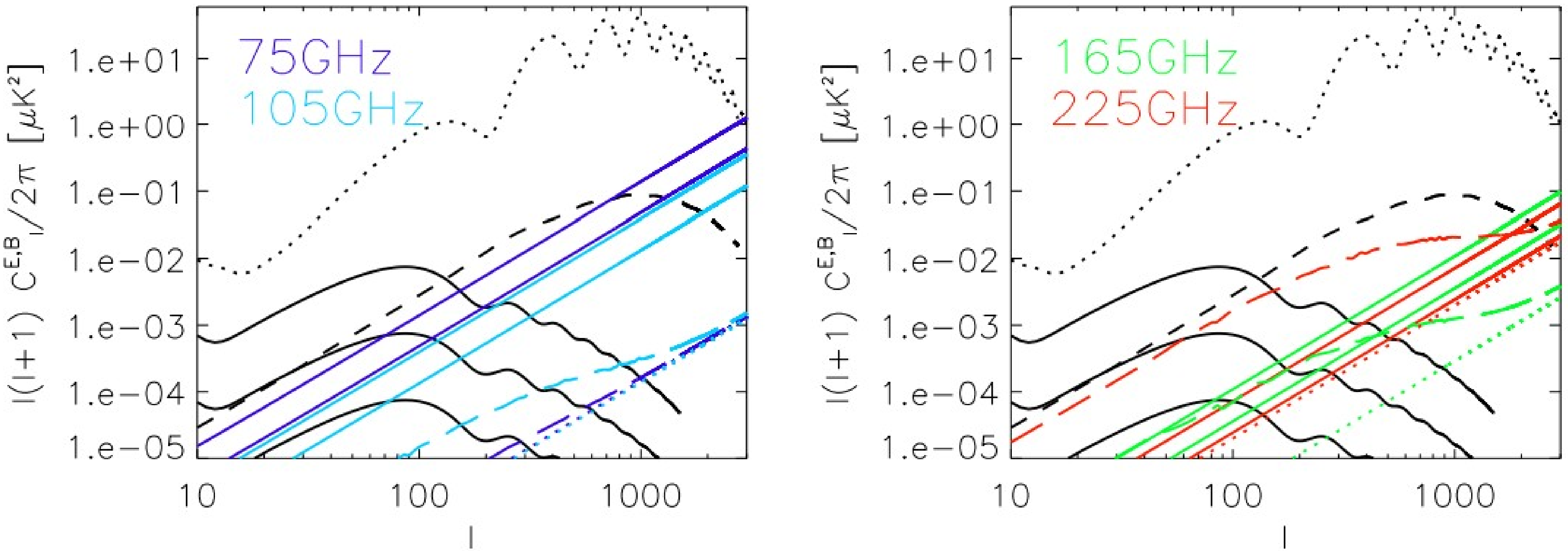
- **Diffuse MD not yet observed!**
- **Theoretically, MD is <u>highly polarized</u> ~35%**
- **MD shows <u>spectral degeneracy with the CMB</u> around 100 GHz!**

  → can be a killer for component separation

#6. Extragalactic compact foregrounds

Polarized radio and IR compact sources at ~100 GHz dominate the primordial CMB B-mode at r = 10^{-3} on large angular scales ℓ ≳ 50 !

Curto et al 2013



- Detect compact sources in intensity (easier), mask the relevant ones in polarization?
- “Inpainting” of sources in frequency maps prior to component separation?

A few remarks

To claim for a robust detection of the primordial B-mode, we will need:

→ to recover the reionization (l ~ 12) and the recombination (l ~ 100) peaks in order to recognize false detections due to power spectra degeneracies between CMB and foreground residuals

→ to check that the recovered signal is stable when varying the Galactic masking and / or the set of frequency channels

→ to get consistent results between independent component separation techniques (parametric and blind)

How to deal with foreground complexity?

→ On a limited frequency range, we have a lack of data points to constrain the dust temperature T_{dust} at the required precision for $\sigma(r) < 10^{-3}$

→ This translates into a bias on the CMB B-mode by extrapolation

→ So can we get more precision by fitting a dust curvature (local) instead of a dust temperature (non-local) on a limited frequency range, without lack of accuracy?