Foreground subtraction
&
B-mode reconstruction with PICO

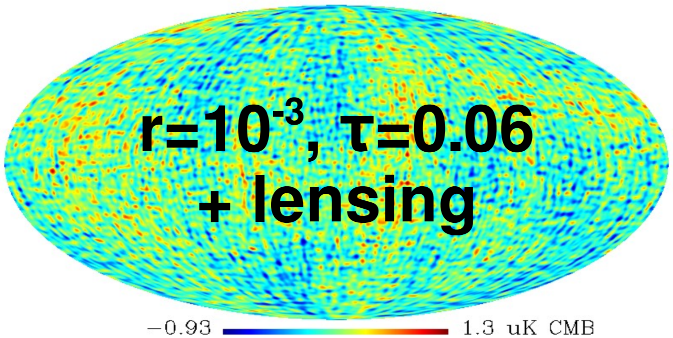
Mathieu Remazeilles

The University of Manchester

PICO Collaboration Science Meeting
Minneapolis, USA, 1-3 May 2018

Sky simulations 1: **PSM**

CMB

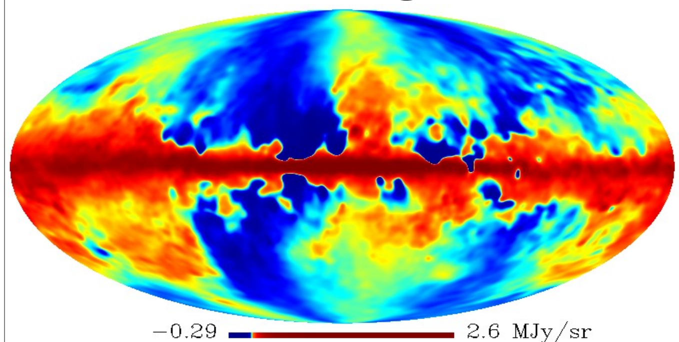


"Simple" sky:

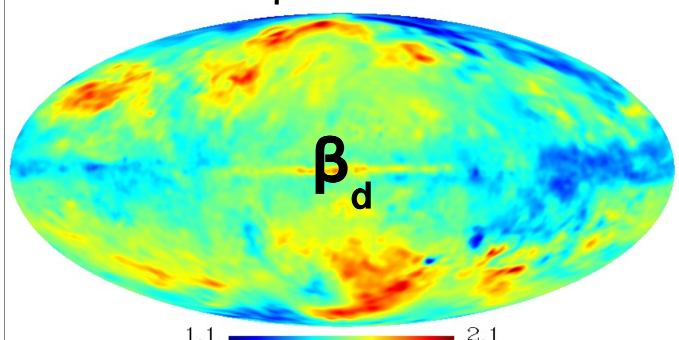
- dust: modified blackbody
- synchrotron: curved power-law
- CMB: r = 10^{-3} + lensing

The PSM tool has been widely used and validated for many years by the Planck collaboration

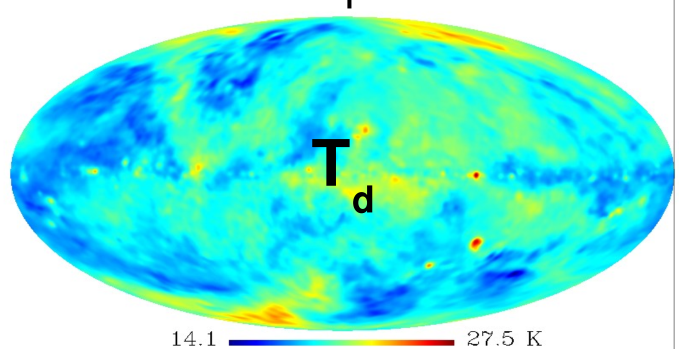
Thermal dust @353 GHz



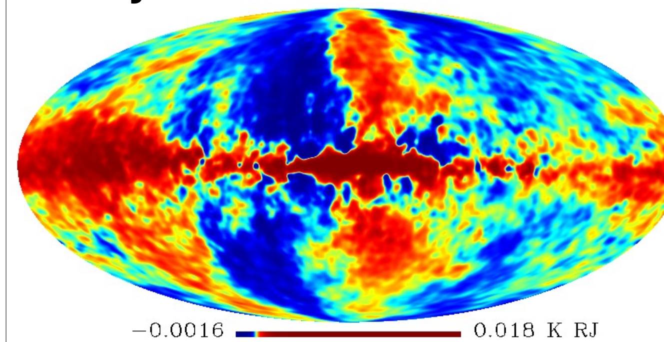
dust spectral index



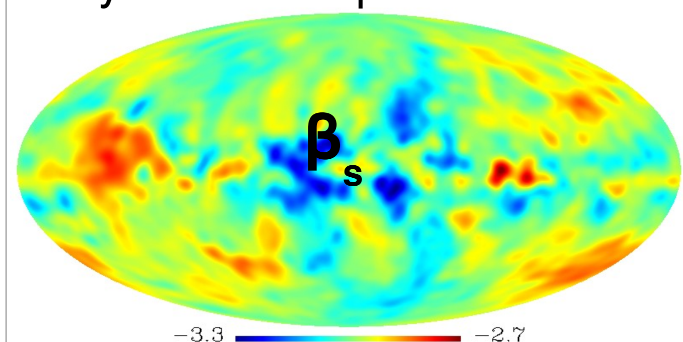
dust temperature



Synchrotron @23 GHz



synchrotron spectral index



Synchrotron curvature

$C_s = 0.3$

smoothed to 1 degree for illustration purposes

Sky simulations 2: **PySM**

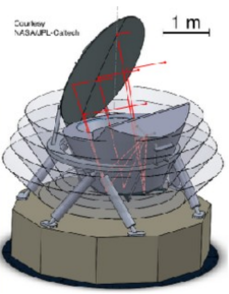
`See C. Pryke's talk`

Series of sky simulations with increasing complexity/realism:
(same set as CMB-S4)

1. **`a1d1f1s1`**: dust single-MBB, synchrotron power-law
2. **`a2d4f1s3`**: dust two-MBB, synchrotron curved power-law, AME
3. **`a2d7f1s3`**: B. Hensley's dust grain model, synchrotron curved power-law, AME
4. B. Hensley's MHD model

→ *Different lensed CMB realisations: both $r = 3 \times 10^{-3}$ and $r = 0$*

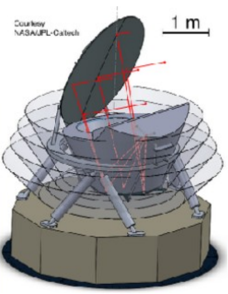
→ *Caveat: no compact radio/IR sources in PySM*



PICO v2-1.4

21- 800 GHz

CMBP						
del nu/nu	0,25		del center	1,2		
nu1	30	GHz				
	nu	**nu_low**	**nu_high**	**del nu**	**FWHM**	**PolWeight**
Band#	**(GHz)**	**(GHz)**	**(GHz)**	**(GHz)**	**(arcmin)**	**(uk*arcmin)**
1	21	18,2	23,4	5,2	40,9	50
2	25	21,9	28,1	6,3	34,1	33
3	30	26,3	33,8	7,5	28,4	22,4
4	36,0	31,5	40,5	9,0	23,7	15
5	43,2	37,8	48,6	10,8	19,7	9,1
6	51,8	45,4	58,3	13,0	16,4	7
7	62,2	54,4	70,0	15,6	13,7	5
8	74,6	65,3	84,0	18,7	11,4	4
9	89,6	78,4	100,8	22,4	9,5	3,2
10	107,5	94,1	120,9	26,9	7,9	2,9
11	129,0	112,9	145,1	32,2	6,6	2,7
12	154,8	135,4	174,1	38,7	5,5	2,6
13	185,8	162,5	209,0	46,4	4,6	3,6
14	222,9	195,0	250,8	55,7	3,8	5,3
15	267,5	234,0	300,9	66,9	3,2	9
16	321,0	280,9	361,1	80,2	2,7	16,0
17	385,2	337,0	433,3	96,3	2,2	32
18	462,2	404,4	520,0	115,6	1,8	75
19	554,7	485,3	624,0	138,7	1,5	220,0
20	665,6	582,4	748,8	166,4	1,3	1100
21	798,7	698,9	898,5	199,7	1,1	10000,0



PICO v3.0

21- 800 GHz

Increased sensitivities!

Band#	nu (GHz)	nu_low (GHz)	nu_high (GHz)	del nu (GHz)	FWHM (arcmin)	PolWeight (uK*arcmin)	Single bolometer NET (uK_CMB)
1	21	18,2	23,4	5,2	38,4	16,3	94,7
2	25	21,9	28,1	6,3	32,0	11,7	86,6
3	30	26,3	33,8	7,5	28,3	7,8	54,9
4	36,0	31,5	40,5	9,0	23,6	5,6	50,2
5	43,2	37,8	48,6	10,8	22,2	5,4	40,3
6	51,8	45,4	58,3	13,0	18,4	4,0	37,1
7	62,2	54,4	70,0	15,6	12,8	3,9	56,5
8	74,6	65,3	84,0	18,7	10,7	3,2	52,7
9	89,6	78,4	100,8	22,4	9,5	2,0	33,8
10	107,5	94,1	120,9	26,9	7,9	1,7	32,1
11	129,0	112,9	145,1	32,3	7,4	1,6	26,7
12	154,8	135,4	174,1	38,7	6,2	1,4	26,3
13	185,8	162,5	209,0	46,5	4,3	2,5	49,9
14	222,9	195,0	250,8	55,7	3,6	3,1	56,0
15	267,5	234,0	300,9	66,9	3,2	2,0	41,7
16	321,0	280,9	361,1	80,3	2,6	3,0	55,3
17	385,2	337,0	433,3	96,3	2,5	3,3	69,0
18	462,2	404,4	520,0	115,6	2,1	7,8	141,0
19	554,7	485,3	624,0	138,7	1,5	44,1	460,5
20	665,6	582,4	748,8	166,4	1,3	176,9	1826,0
21	798,7	698,9	898,5	199,7	1,1	1260,7	10806,1

Component separation methods

- **COMMANDER** – *Eriksen et al 2004, 2008 ; Remazeilles et al 2016, 2017*

  Bayesian multi-component spectral fit in each pixel through Gibbs sampling

  ***M. Remazeilles* (Manchester), H. K. Eriksen, I.K. Wehus (Oslo)**
  foreground cleaning (parametric): YES
  power spectrum reconstruction: YES
  r estimation: YES

- **SEVEM** – *Leach et al 2008 ; Fernandez-Cobos et al 2012*

  Internal template fitting in wavelet space

  ***B. Barreiro*, E. Martinez-Gonzalez, P. Vielva (IFCA)**
  foreground cleaning (blind): YES
  power spectrum reconstruction: (YES)
  r estimation: NO

- **NILC** – *Delabrouille et al 2009 ; Remazeilles et al 2011 ; Basak et al 2012, 2013*

  Minimum-variance internal linear combination in wavelet space

  ***S. Basak* (IISER), C. Baccigalupi (SISSA)**
  foreground cleaning (blind): YES
  power spectrum reconstruction: NO
  r estimation: NO

All these methods already have a strong heritage from Planck data analysis

Component separation methods

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  ***G. Rocha* (JPL)**

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NILC

S. Basak:

*“NILC analysis of PICO simulations is still in progress.
Results are coming soon.”*

SEVEM

B. Barreiro

SEVEM: internal template fitting

R.B. Barreiro, E. Martínez-González, P. Vielva et al.

Instituto de Física de Cantabria

- The reconstructed CMB map is a linear combination of the map to be cleaned and a set of templates that trace the foregrounds

$$\hat{s}_i(x) = d_i(x) - \sum_{i=1}^{N_\nu} \alpha_i t_i(x)$$

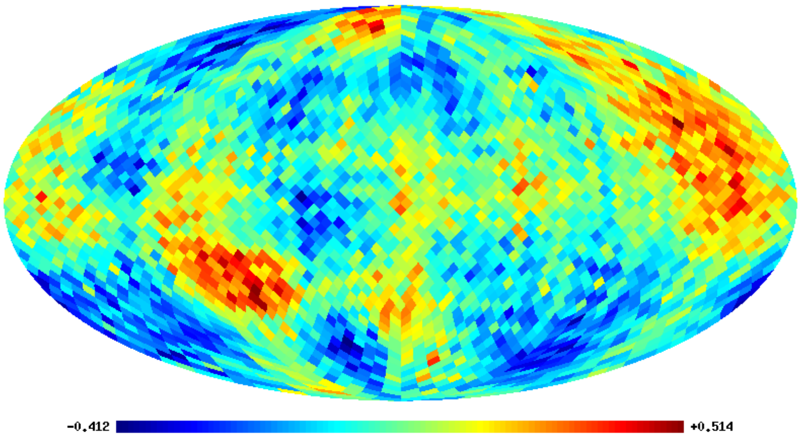
- The templates t_i are typically constructed as the difference between two close frequency channels smoothed at the same resolution (to remove CMB from the templates)
- The linear coefficients α_i are obtained by minimising the variance of the cleaned map outside a given mask
- Fast ⇨ it can work at high resolution
- Robust ⇨ no assumptions about foreground modelling
- It allows to obtain cleaned maps at different frequencies
  - can be combined to improve the signal-to-noise
  - provide additional consistency checks
- Used successfully in Planck to produce intensity and polarization CMB maps

B. Barreiro

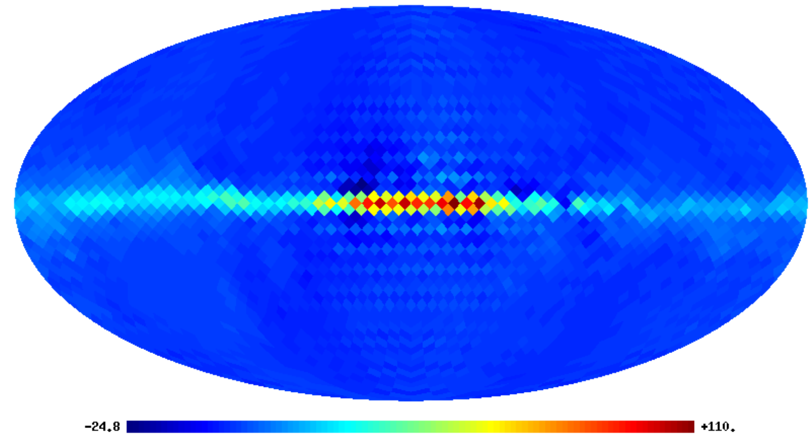
SEVEM: example of cleaned 110 GHz channel (Q)

Instituto de Física de Cantabria

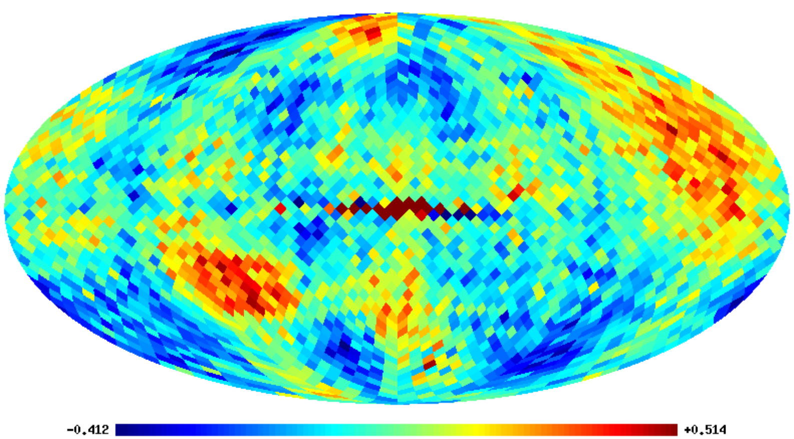
- Simulations from M. Remazeilles (N_{side}=16)
- 12 templates (constructed from 21-52, 270-800 GHz)
- Preliminary results



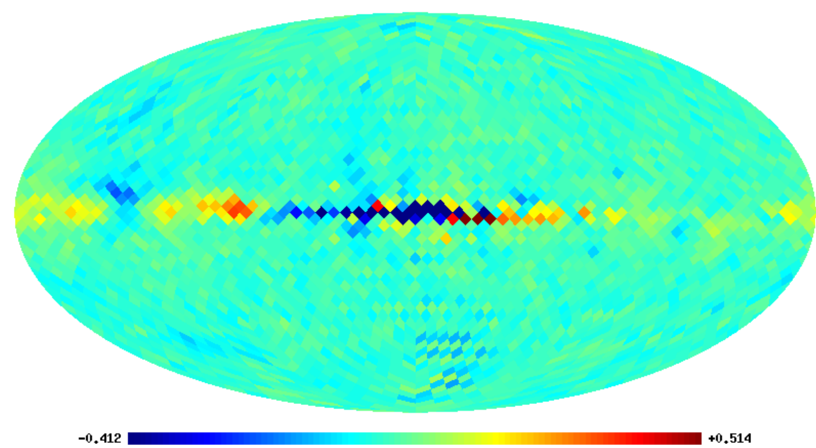
Input CMB



Simulated 110 GHz channel



Cleaned 110 GHz channel



Residuals

B. Barreiro

SEVEM: example of cleaned 110 GHz channel (U)

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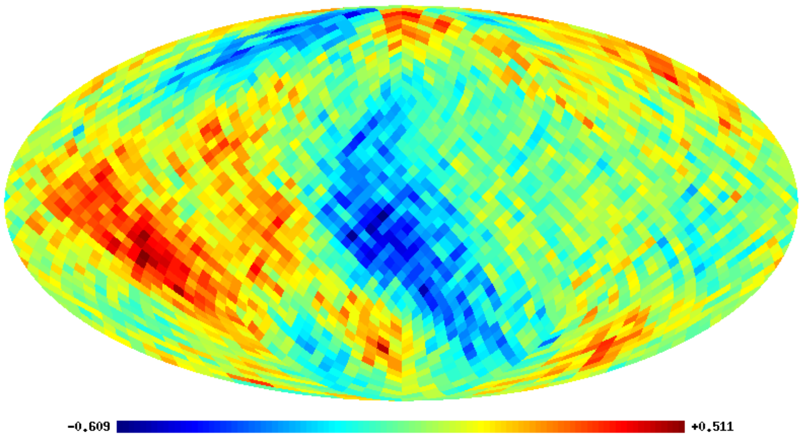
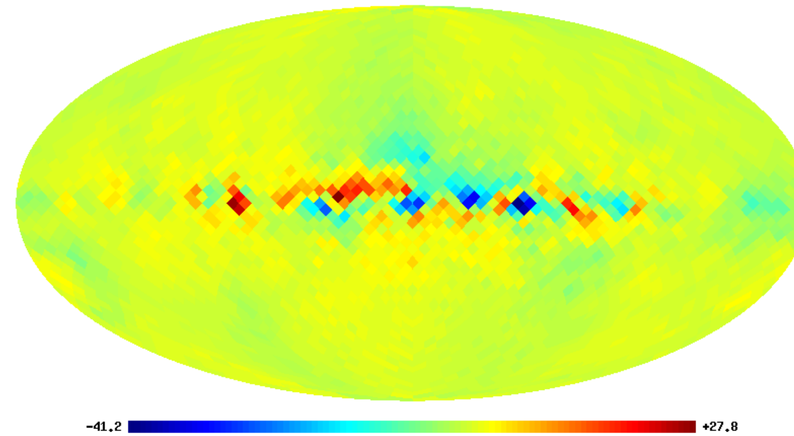
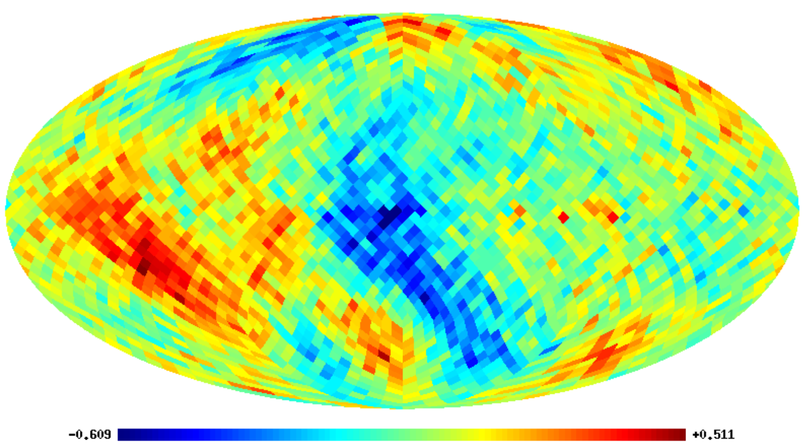
- Preliminary results



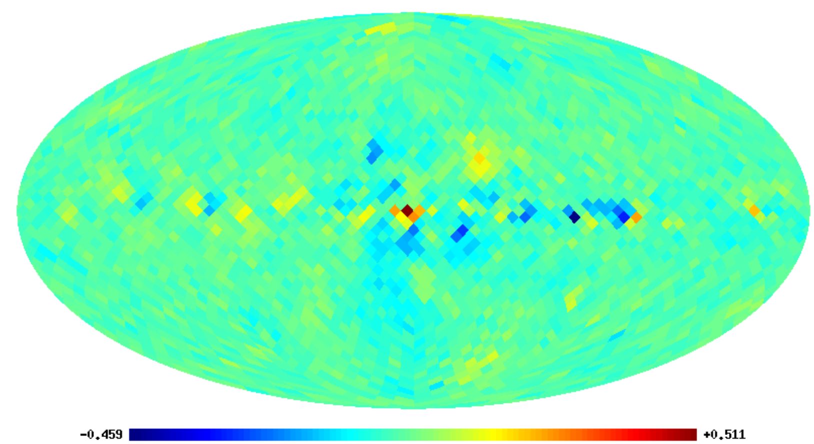
Input CMB



Simulated 110 GHz channel



Cleaned 110 GHz channel



Residuals

B. Barreiro

SEVEM for PICO: status and plans

- Currently studying optimal SEVEM configuration for PICO:
  - Define templates to be constructed
  - Select maps to be cleaned
  - How to combine cleaned maps to improve final result (e.g. weighting by noise, use cross-correlation between cleaned channels…) ?
- Next steps: estimate power spectrum and cosmological parameters from cleaned maps
  - Implementation of QML and MASTER to estimate power spectrum already in place (D. Bilbao-Ahedo, PhD student at IFCA)
  - Go from cleaned maps to full estimation of cosmological parameters (G. Rocha)
- Provide comparison with other methods

B. Barreiro

Commander

M. Remazeilles

Methodology

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

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

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

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

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

2. Likelihood estimation of **r** and **A** $_{\mathbf{lens}}$:

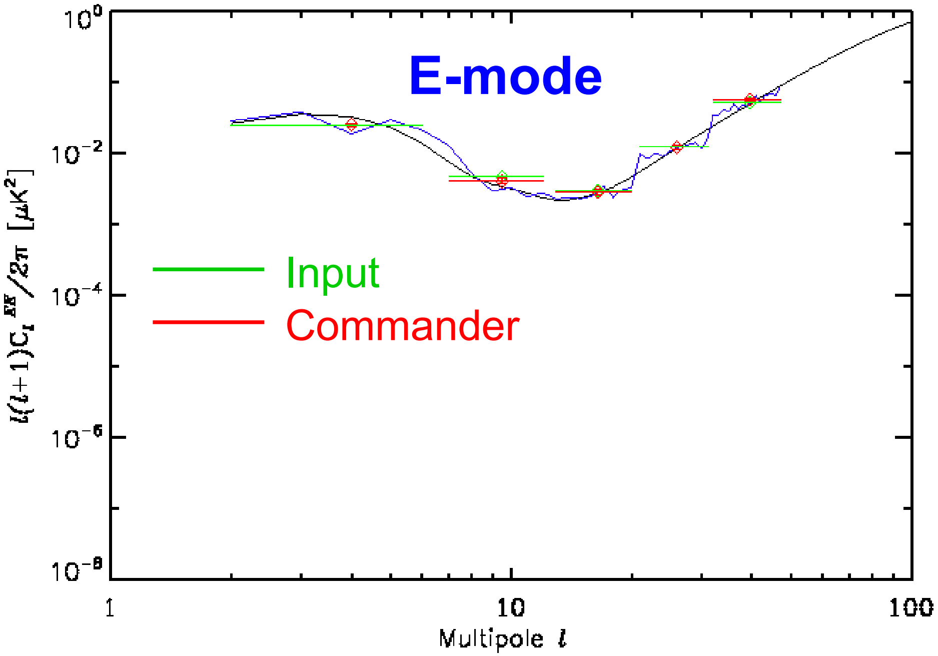
$$-2\ln\mathcal{L}\left[\widehat{C}_\ell|C_\ell^{th}\left(r, A_{lens}\right)\right] = \sum_\ell (2\ell+1)\left[\ln\left(\frac{C_\ell^{th}}{\widehat{C}_\ell}\right) + \frac{C_\ell^{th}}{\widehat{C}_\ell} - 1\right]$$

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

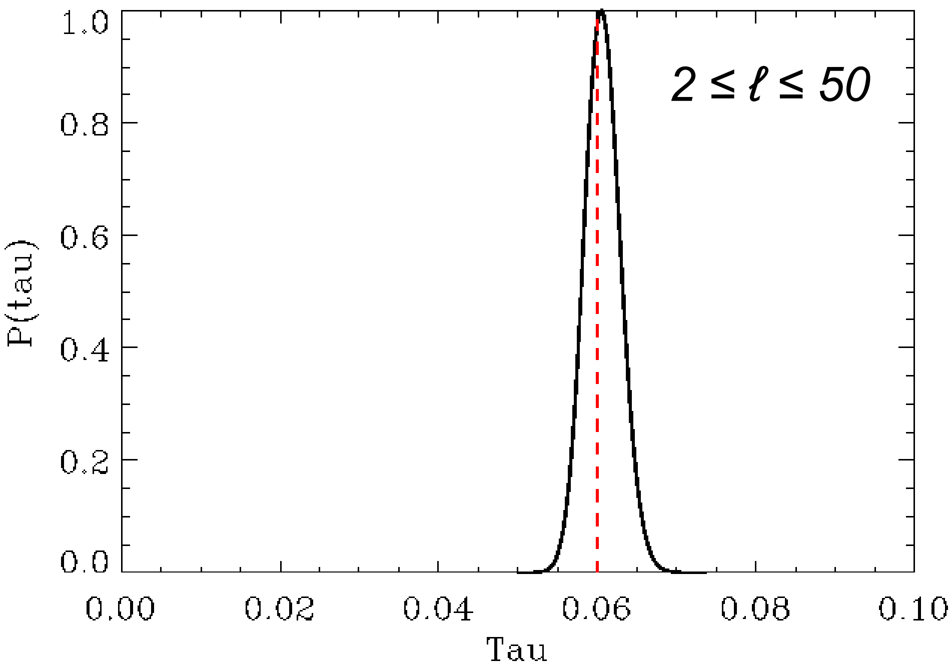
3. Blackwell-Rao posterior: $\mathcal{P}\left(r, A_{lens}\right) \approx \frac{1}{N}\sum_{i=1}^{N}\mathcal{L}\left[\widehat{C}_\ell^i|C_\ell^{th}\left(r, A_{lens}\right)\right]$

The Commander algorithm has strong heritage from real Planck data analysis

Commander reconstruction of CMB E-modes
21 – 800 GHz



τ = 0.0607 ± 0.0023



Foregrounds:

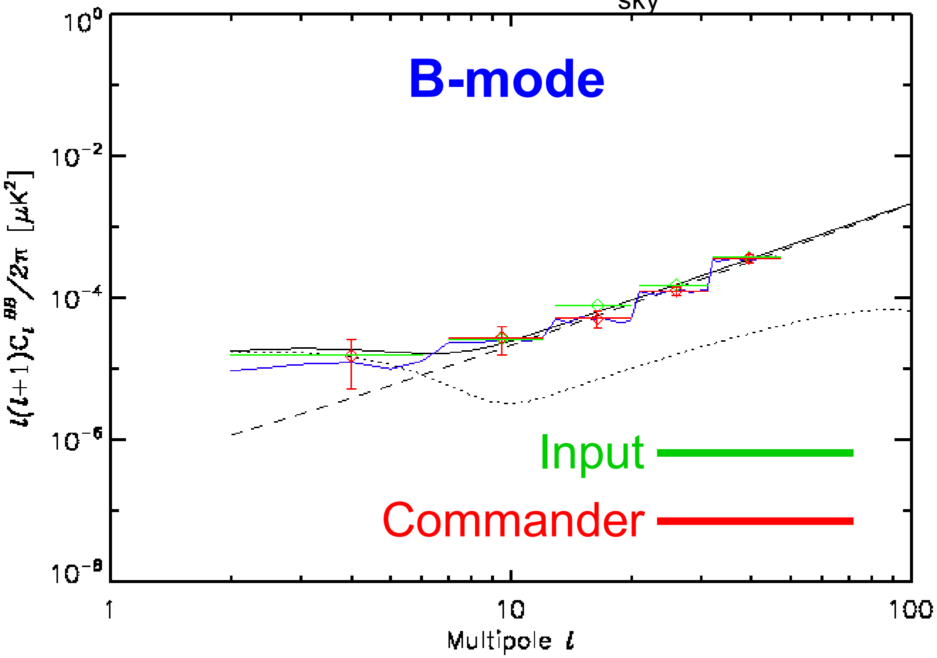
- *Synchrotron power-law with curvature: β_s , C_s*
- *Thermal dust MBB: β_d, T_d*

E-modes serve as a useful validation of the Commander algorithm

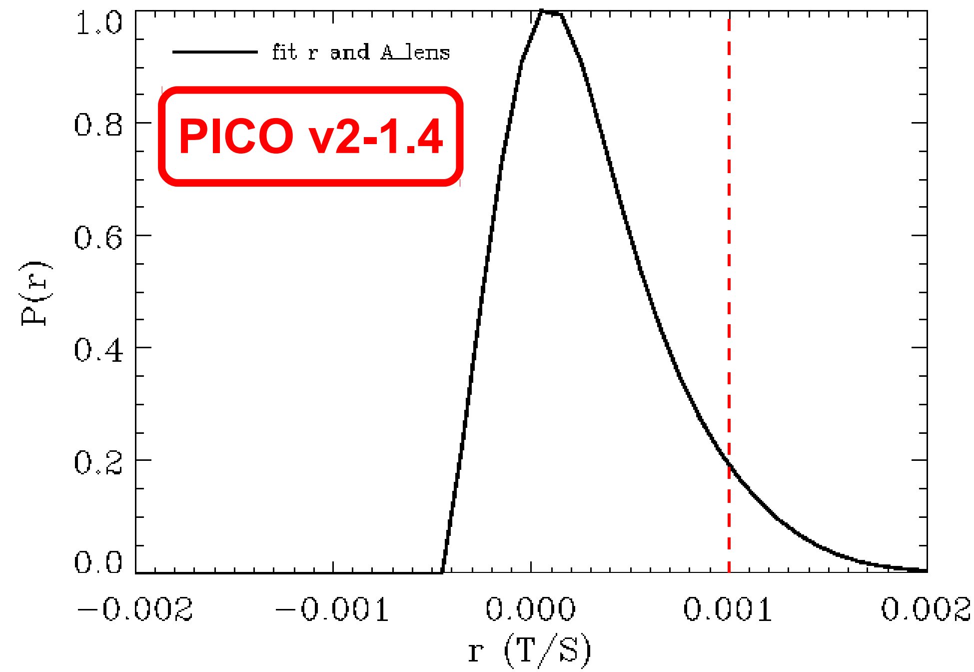
M. Remazeilles

Commander reconstruction of CMB B-modes
21 – 800 GHz

r = 10^{-3} + lensing, f_{sky}=50%



r = (0.30 ± 0.41) × 10^{-3}



$2 \le \ell \le 50$

Foregrounds:

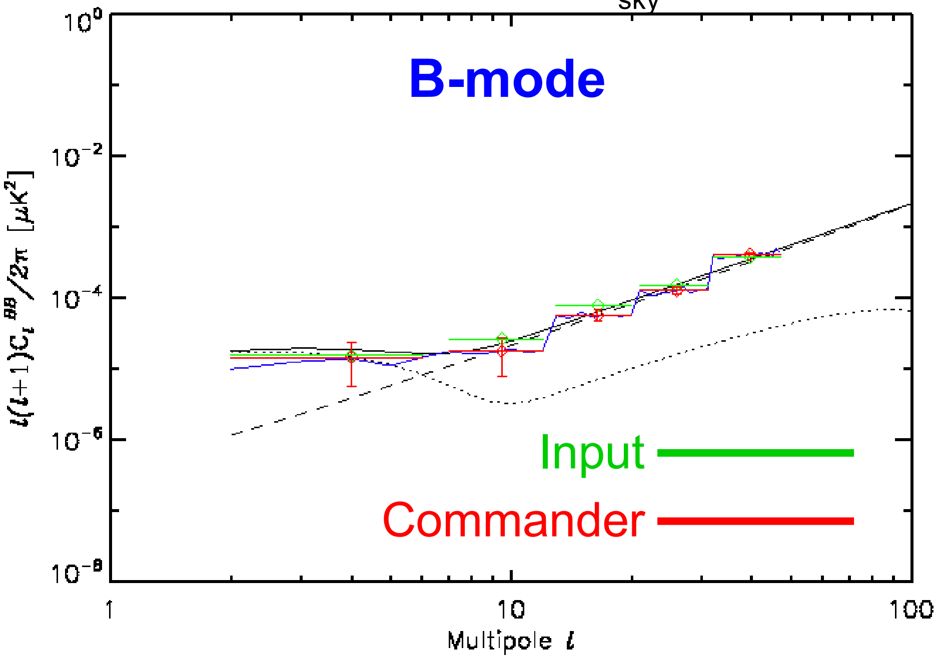
- *Synchrotron power-law with curvature: β_s , C_s*
- *Thermal dust MBB: β_d, T_d*

β_d, T_d, β_s locally fitted in each pixel
C_s globally fitted

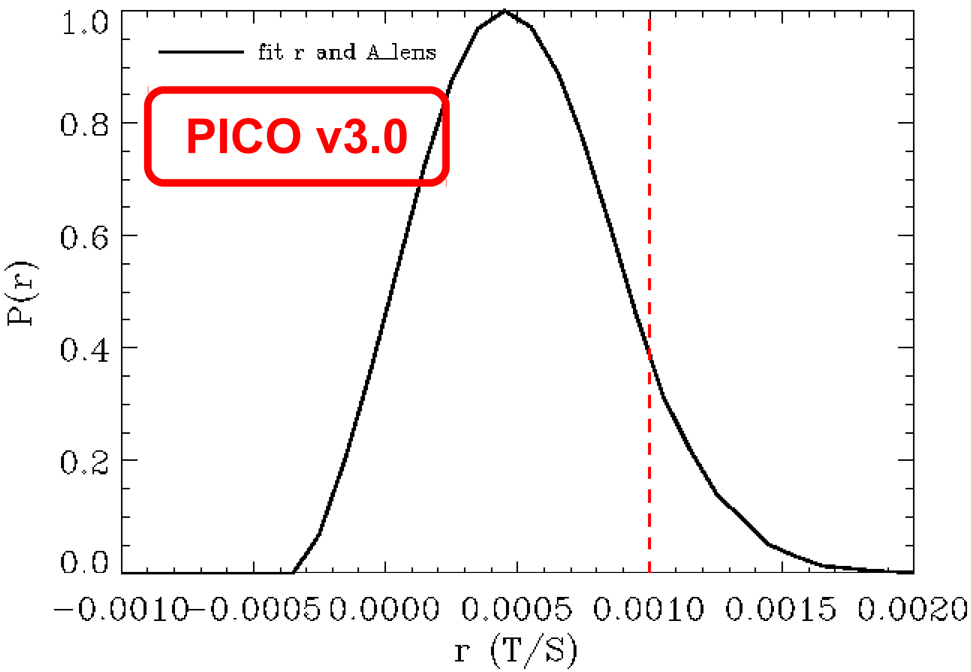
M. Remazeilles

Commander reconstruction of CMB B-modes
21 – 800 GHz

$r = 10^{-3}$ + lensing, f_{sky}=50%



$r = (0.51 \pm 0.36) \times 10^{-3}$



$2 \le \ell \le 50$

Foregrounds:

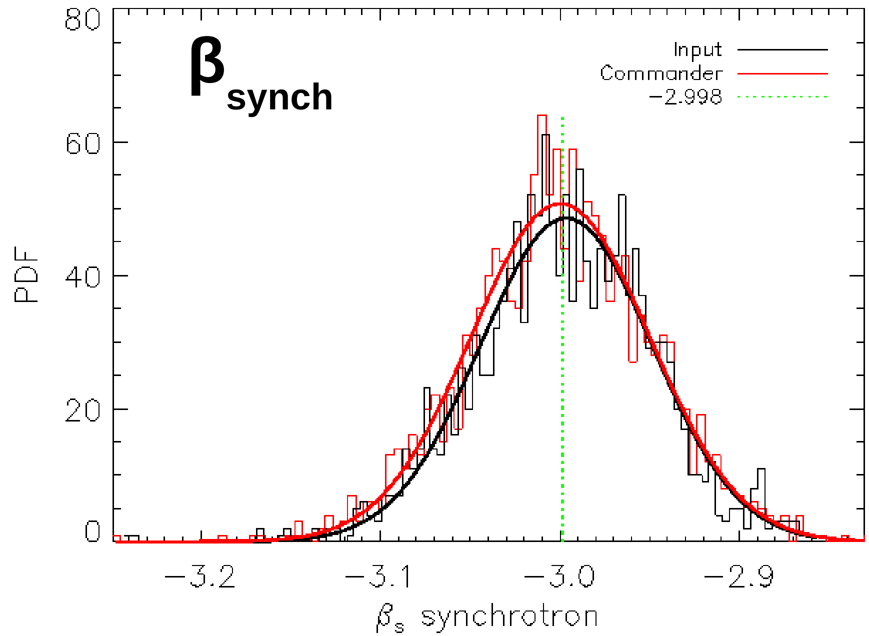
- *Synchrotron power-law with curvature: β_s , C_s*
- *Thermal dust MBB: β_d, T_d*

β_d, T_d, β_s locally fitted in each pixel
C_s globally fitted

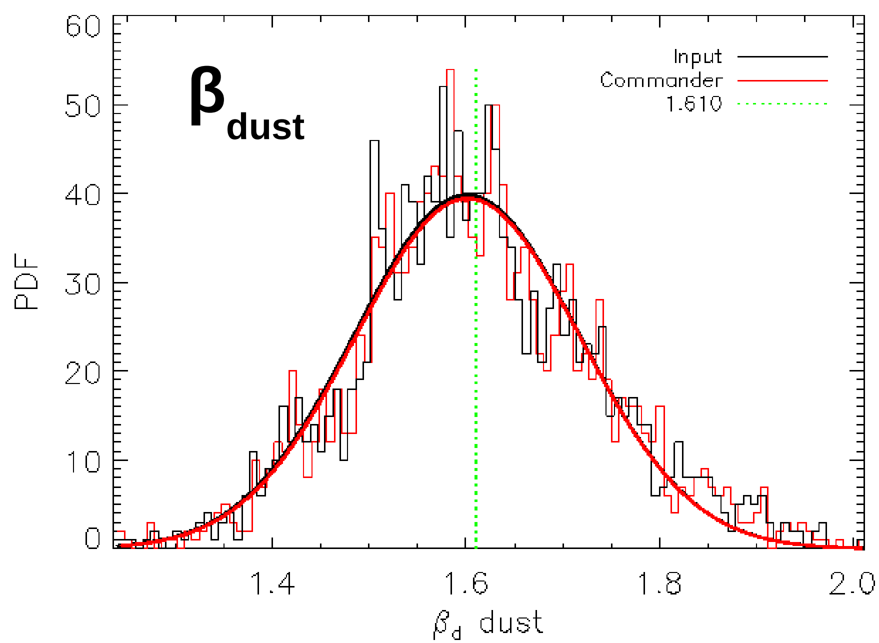
Increased sensitivity reduces σ(r) by 10% only

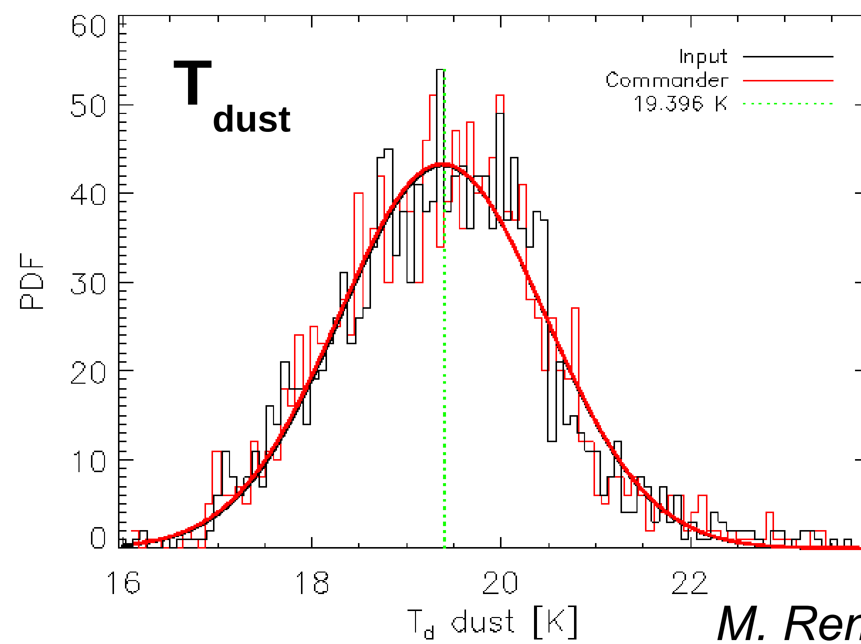
M. Remazeilles

Commander results on foregrounds
PICO v2-1.4



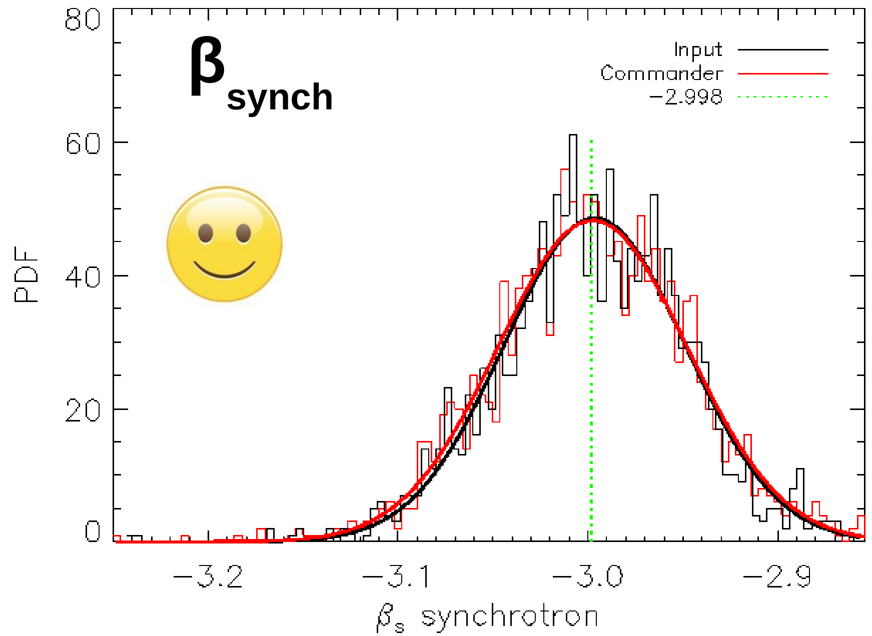
Thanks to the broad frequency range of PICO, dust and synchrotron spectral parameters are all accurately recovered



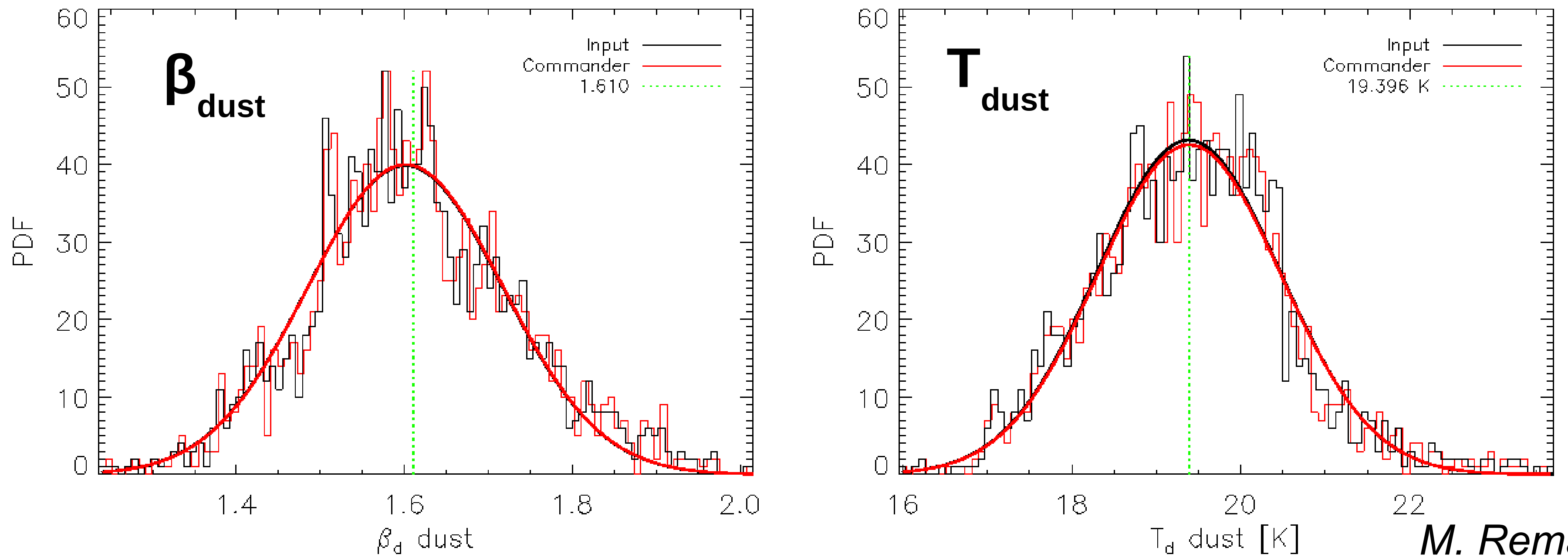


M. Remazeilles

Commander results on foregrounds
PICO v3.0



Increased sensitivities of PICO v3.0 improve the constraints on the synchrotron spectral index



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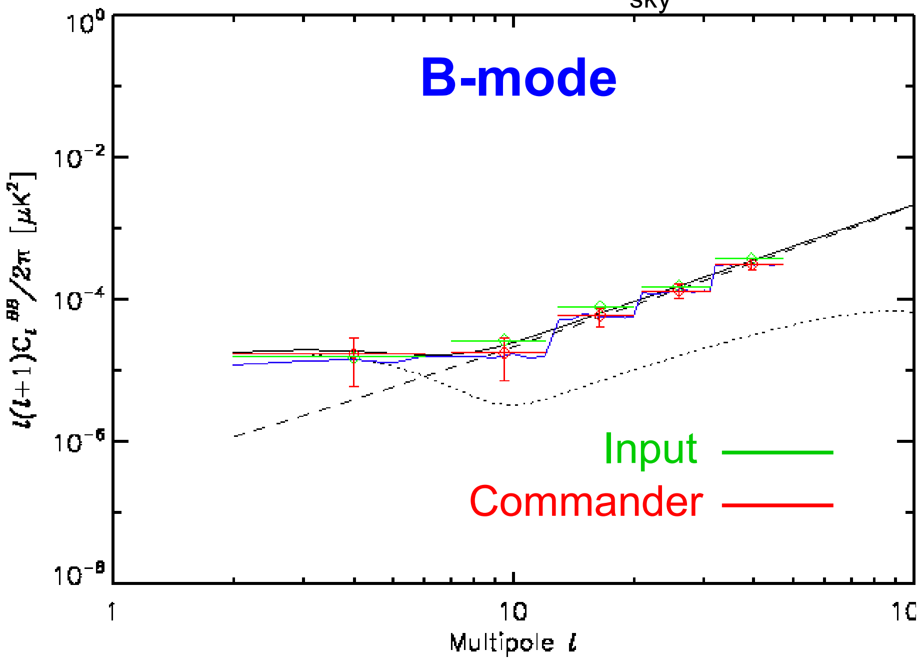
Commander reconstruction of CMB B-modes

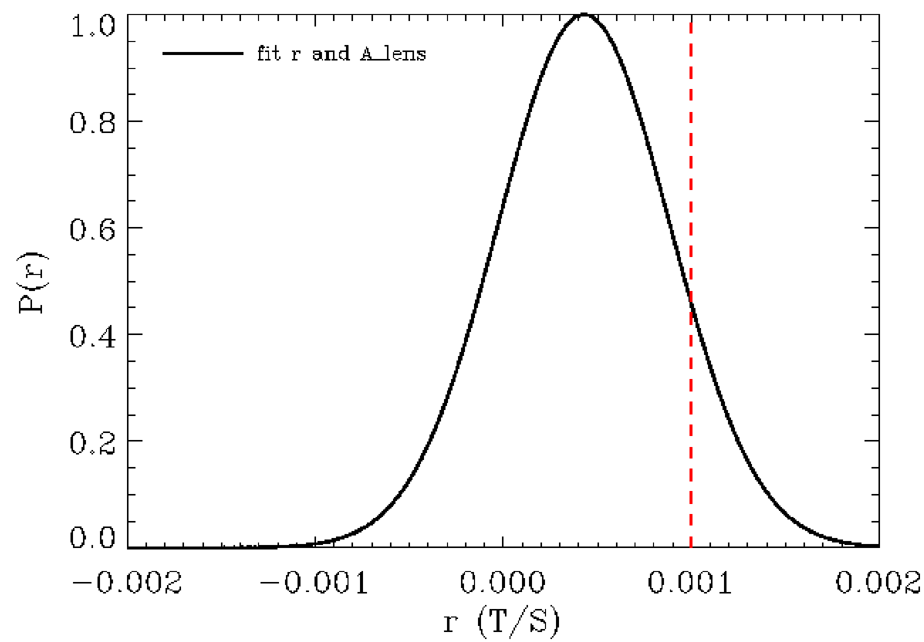
No foregrounds, 50% mask

sample variance + noise
(50% of the sky)

r = 10^{-3} + lensing, f_{sky}=50%



r = (0.6 ± 0.4) × 10^{-3}



Sample variance σ(r = 10^{-3}) = 0.4 x 10^{-3}

That's the minimal uncertainty that can be achieved from $2 \leq \ell \leq 50$ <u>in the absence of foregrounds</u> on 50% of the sky

M. Remazeilles

How σ(r) reduces after foreground cleaning and 60% delensing?

→ **60% delensing is the value quoted by CORE:**

Challinor et al JCAP (2018), 1707.02259

→ **Shortcut adopted for delensing:**

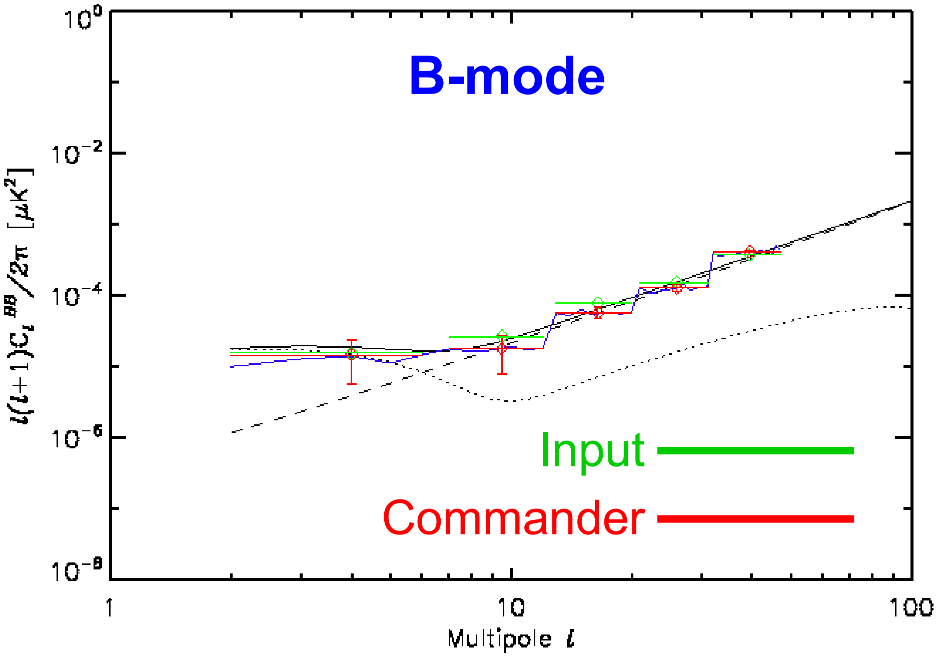
1. *The input CMB map is simulated from the "modified" power spectrum:*

$$\mathbf{C_\ell^{\mathit{BB}}(\mathit{CMB}) = C_\ell^{\mathit{BB}}(\mathit{tensor}) + \mathit{0.40} * \mathit{C_\ell^{BB}}(\mathit{lensing})}$$

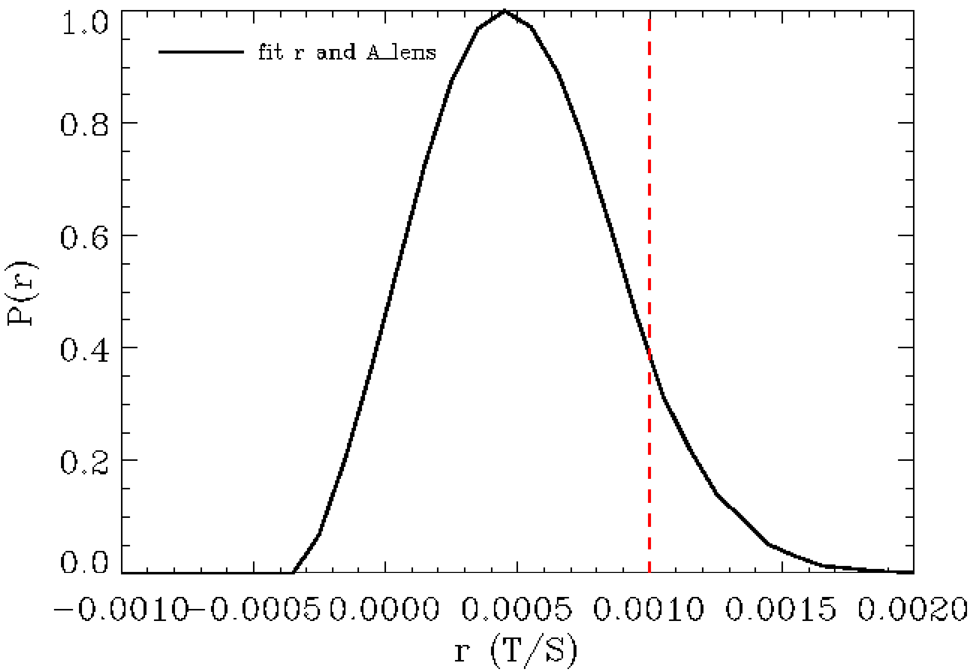
2. *Foreground cleaning is then performed on the "modified" sky simulations*

M. Remazeilles

Commander reconstruction of CMB B-modes
no delensing



$r = (0.51 \pm 0.36) \times 10^{-3}$



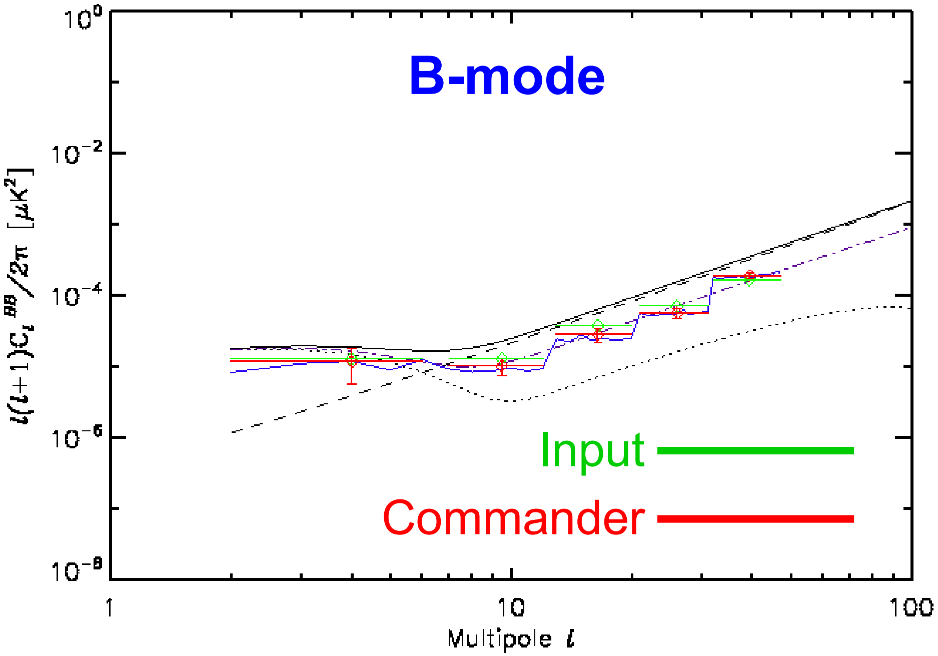
$2 \leq \ell \leq 50$

<u>Foregrounds</u>:

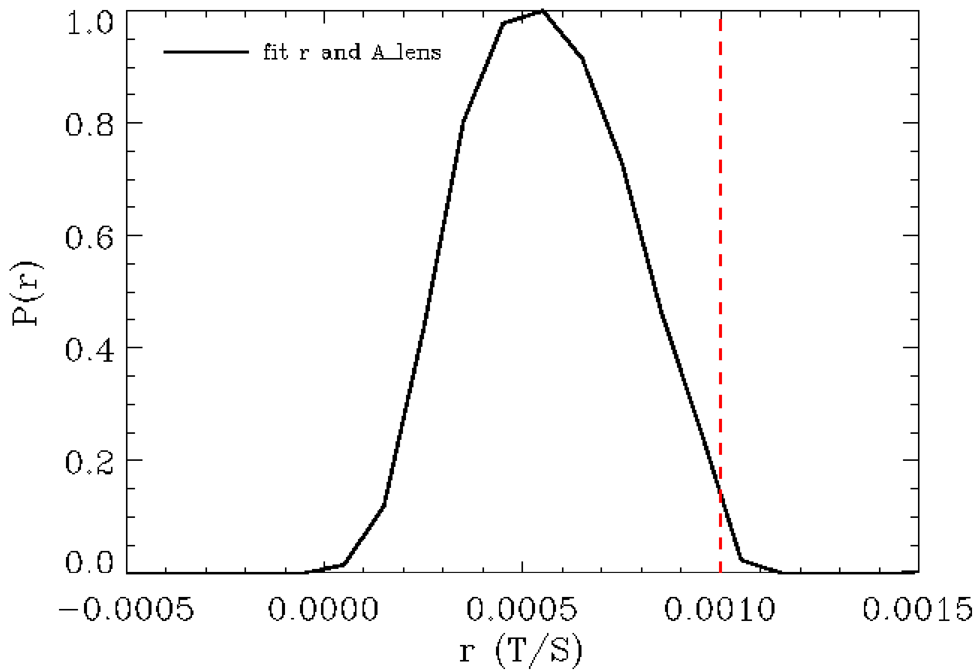
- *Synchrotron power-law with curvature: β_s , C_s*
- *Thermal dust MBB: β_d, T_d*

M. Remazeilles

Commander reconstruction of CMB B-modes
60% delensing



$r = (0.57 \pm 0.24) \times 10^{-3}$



$2 \leq \ell \leq 50$

Foregrounds:

- *Synchrotron power-law with curvature: β_s , C_s*
- *Thermal dust MBB: β_d, T_d*

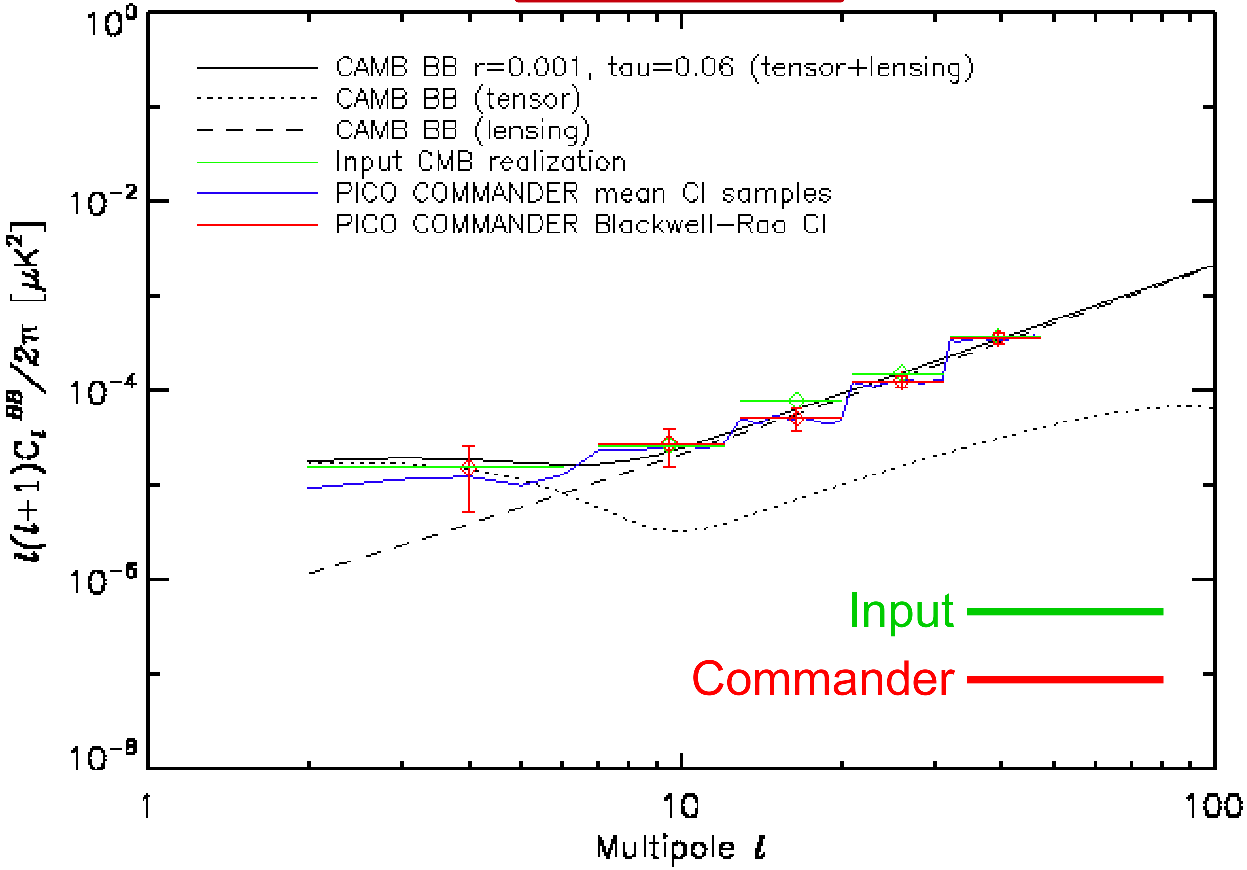
M. Remazeilles

Discarding PICO frequencies?

Commander reconstruction of CMB B-modes

21 – 800 GHz

$r = 10^{-3}$



Foregrounds:

- *Synchrotron (power-law with curvature)*
- *Thermal dust (MBB)*

$\sigma(r = 10^{-3}) = 0.4 \times 10^{-3}$

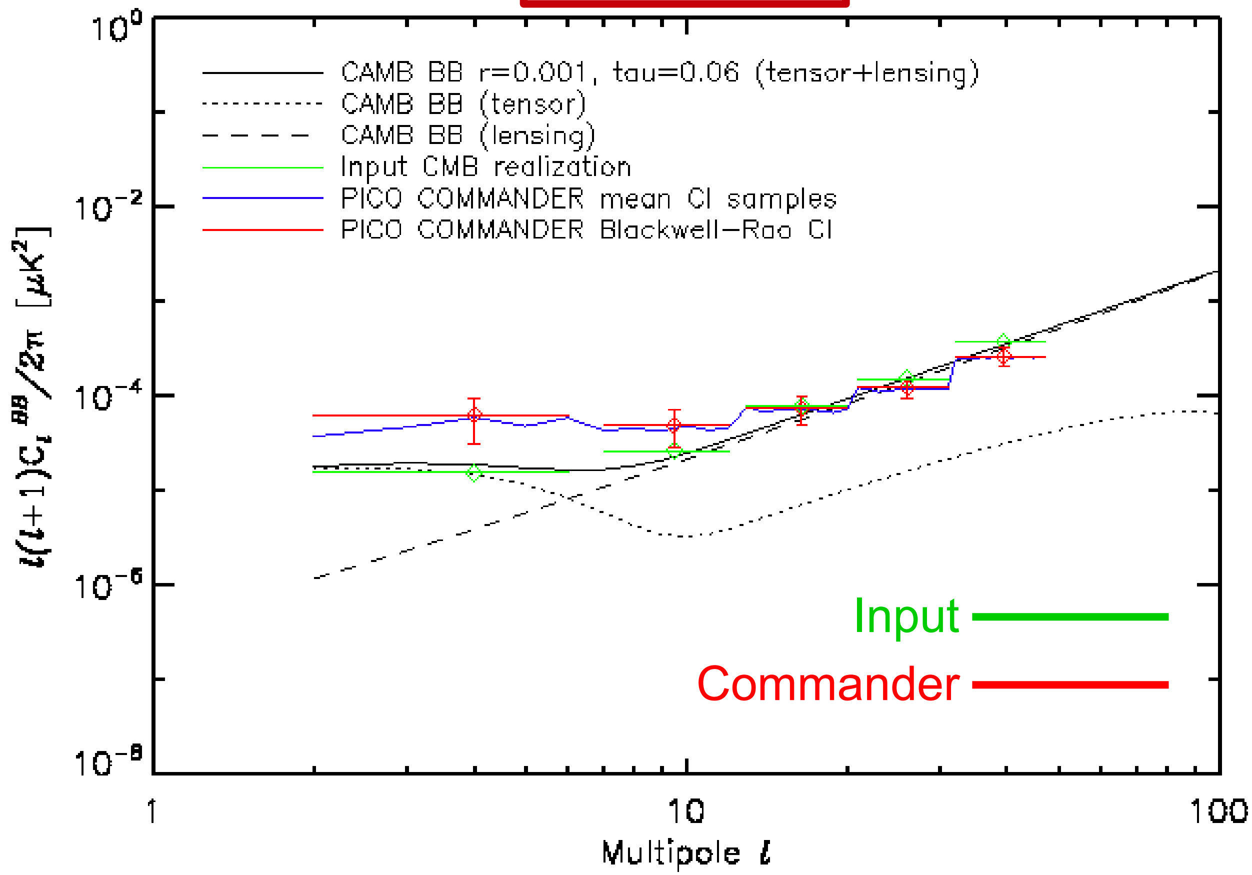
after foreground cleaning

M. Remazeilles

Commander reconstruction of CMB B-modes

43 – 462 GHz

r = 10^{-3}



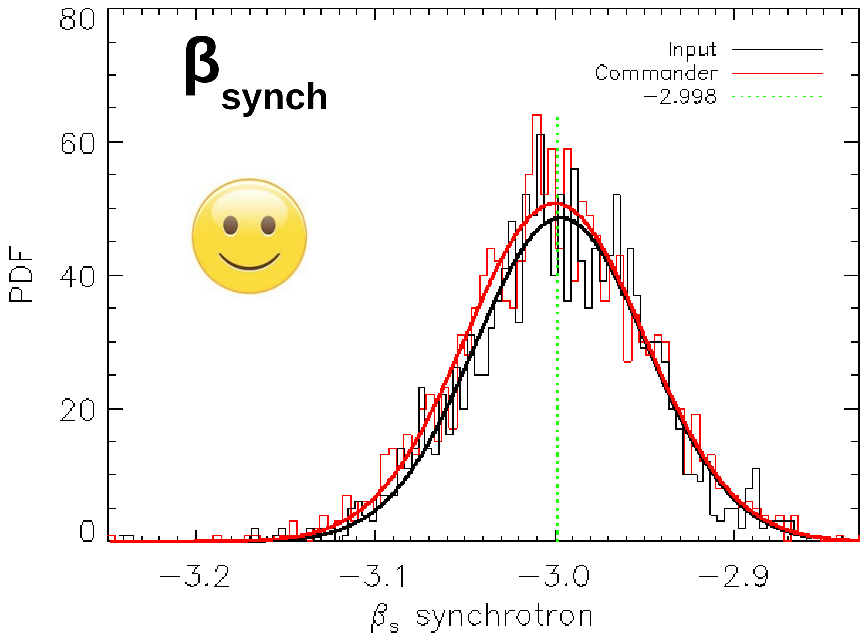
Foregrounds:

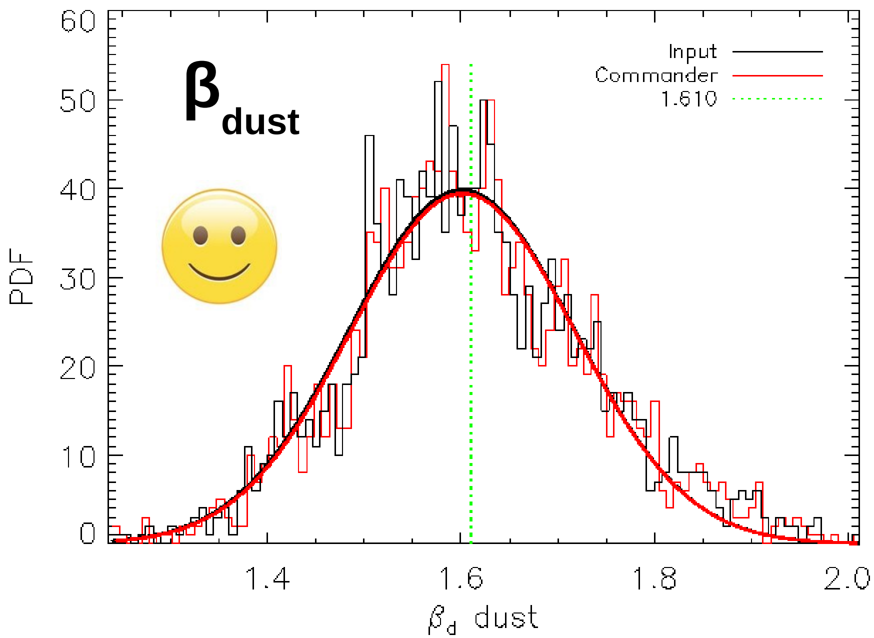
- *Synchrotron (power-law with curvature)*
- *Thermal dust (MBB)*

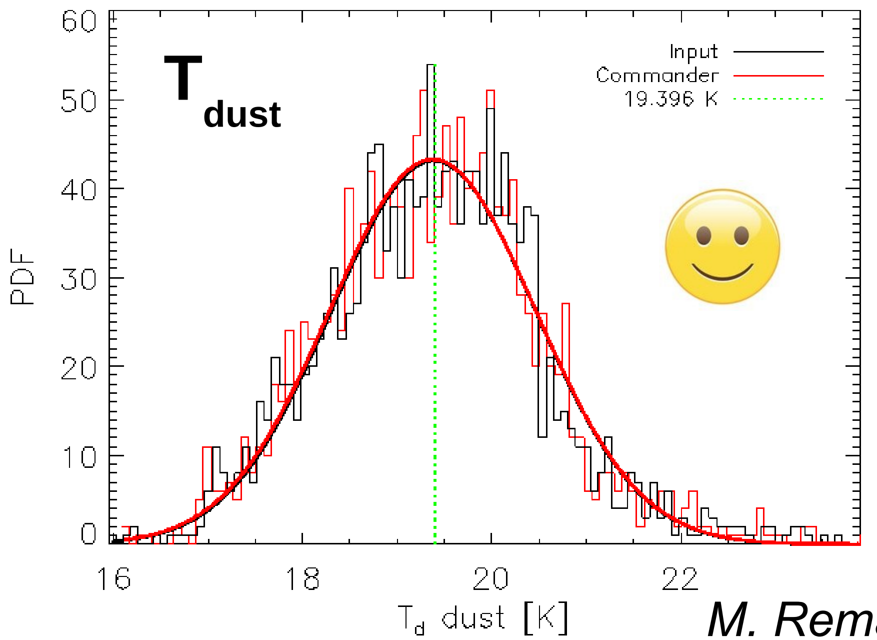
Narrowing the frequency range of observations causes biases on large-scales due to foregrounds

M. Remazeilles

COMMANDER results on foregrounds
PICO **21 – 800 GHz**

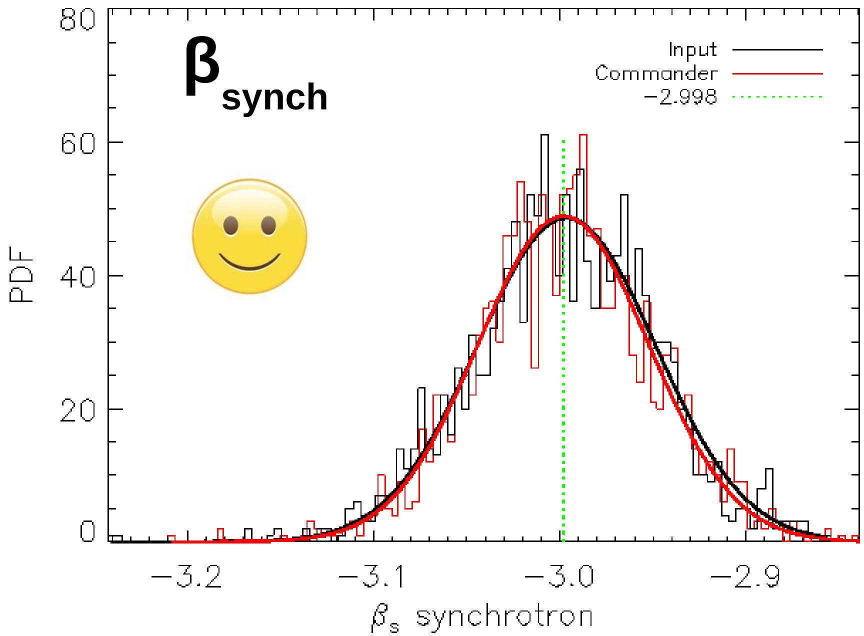






M. Remazeilles

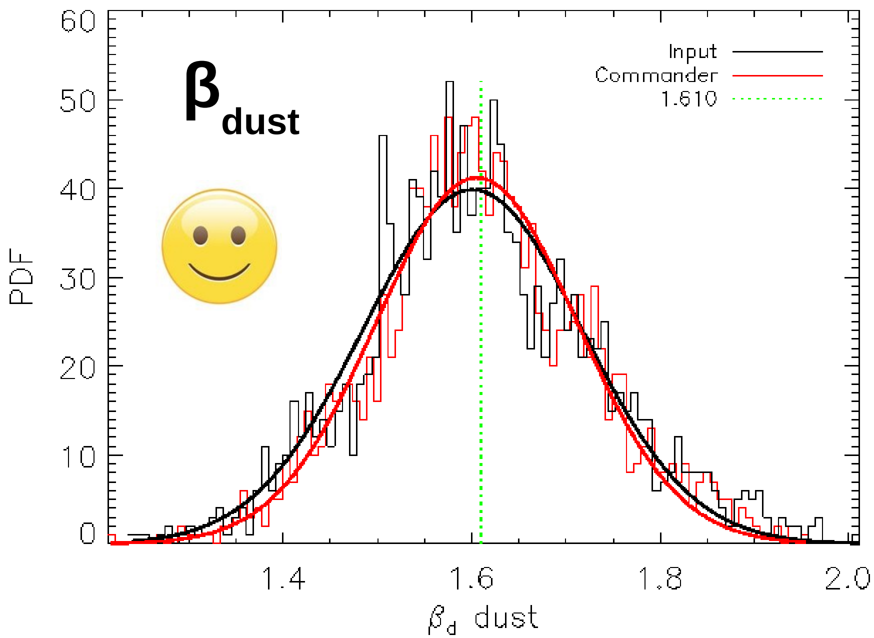
COMMANDER results on foregrounds
PICO **43 – 462 GHz**

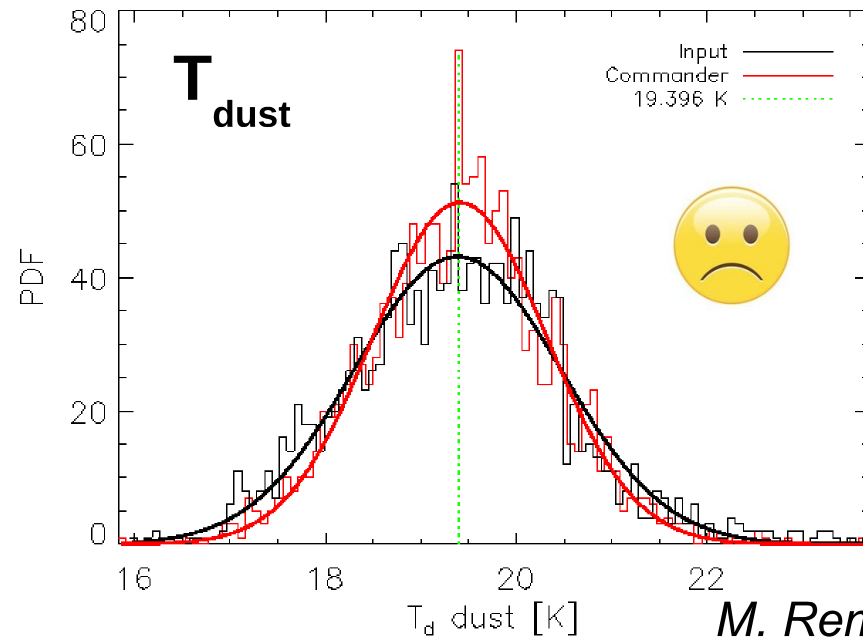


Lack of frequency range / high frequencies

Lack of precision/constraint on T_{dust}

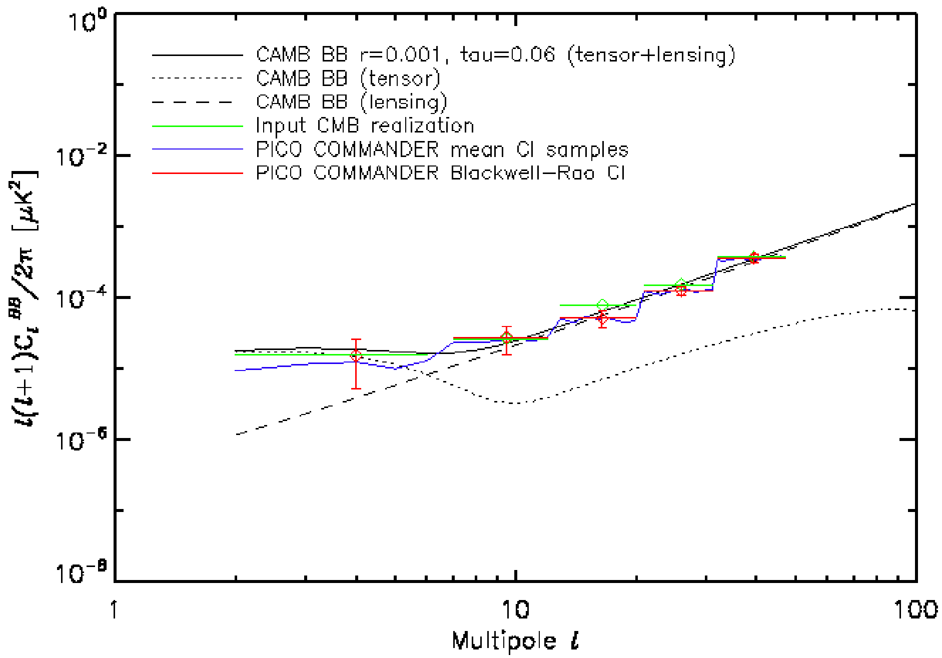
Translates into a bias on CMB B-mode
by extrapolation towards CMB frequencies

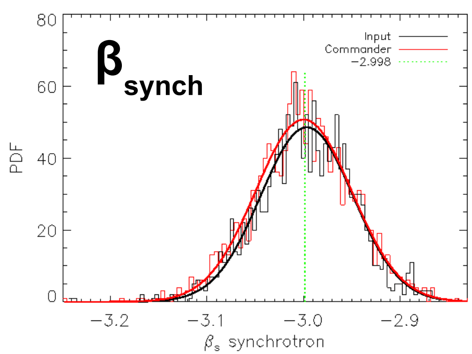


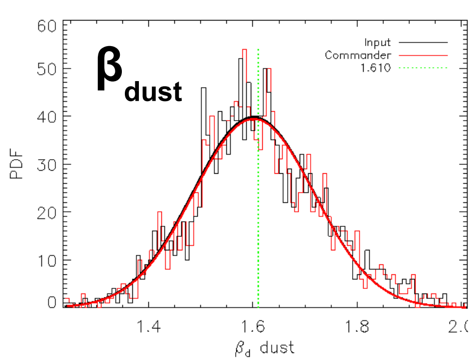


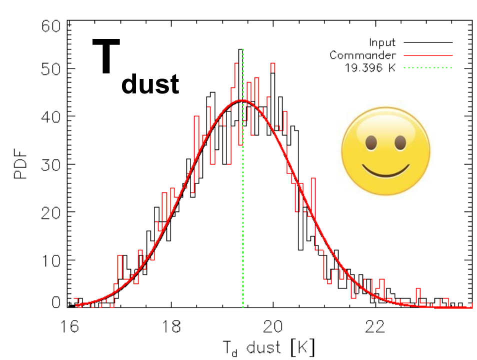
M. Remazeilles

PICO
21 – 800 GHz



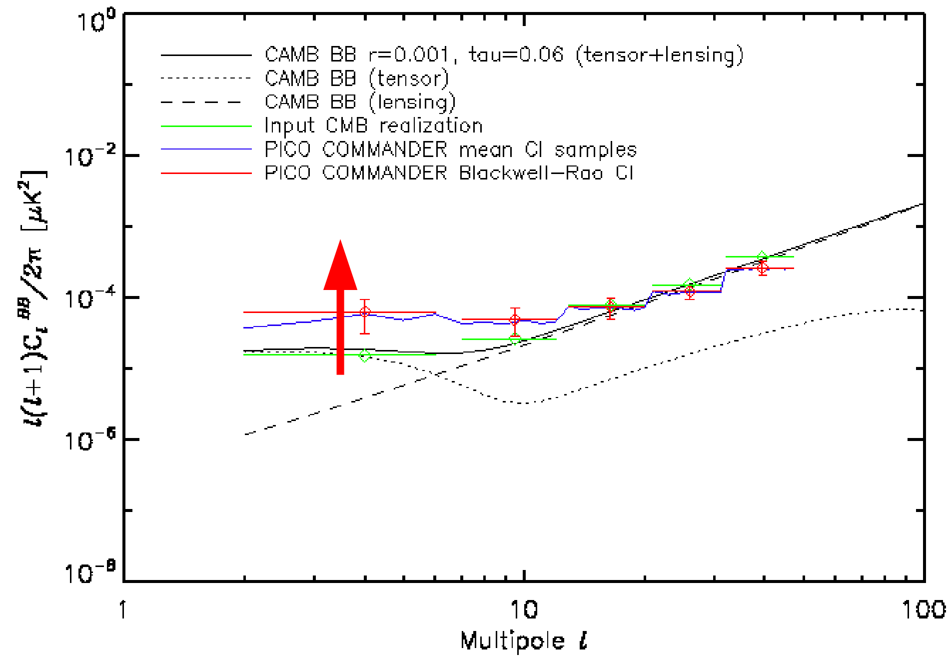






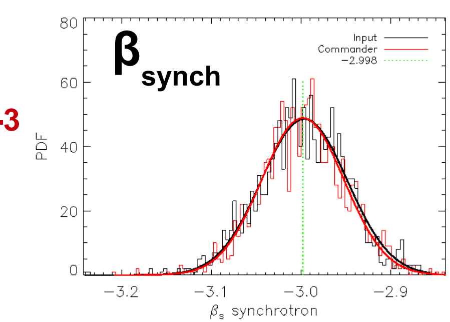
σ(r=10^{-3}) = 0.4 × 10^{-3}

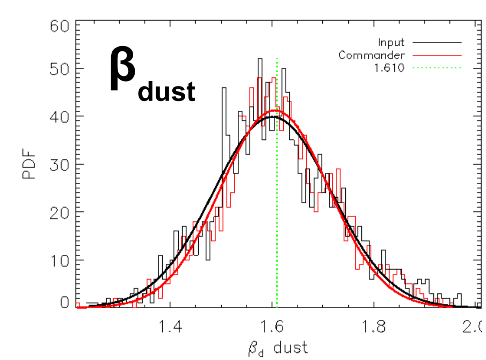
PICO
43 – 462 GHz

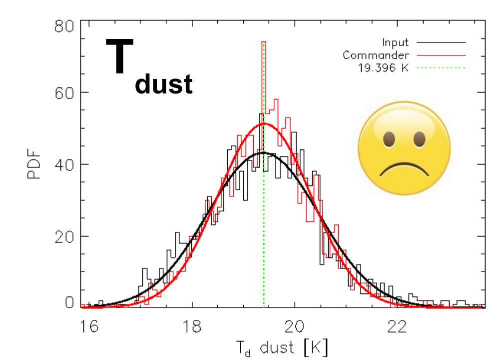


σ(r=10^{-3}) = 0.7 × 10^{-3}

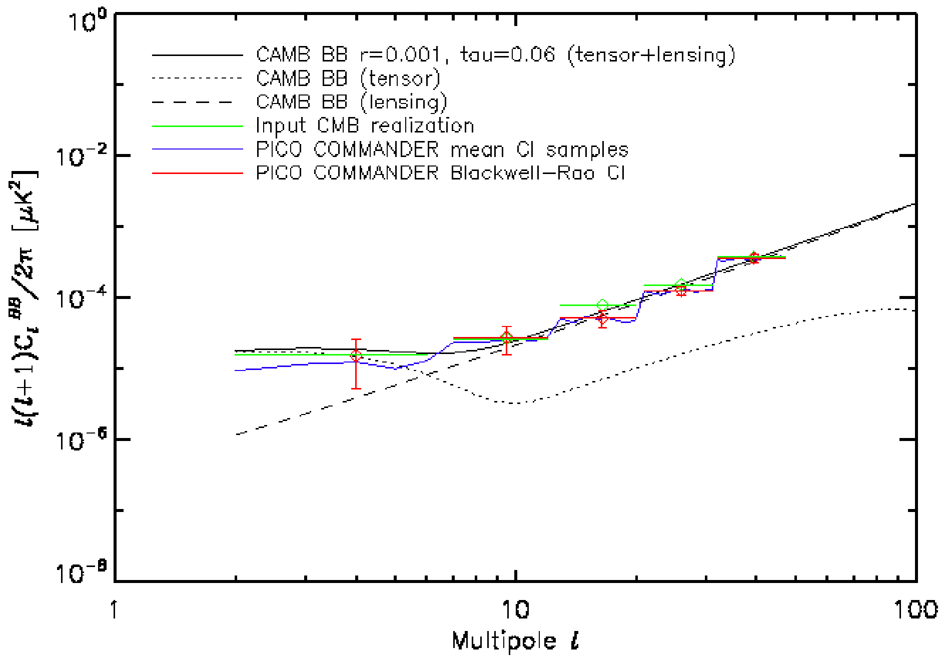
(75% increase)

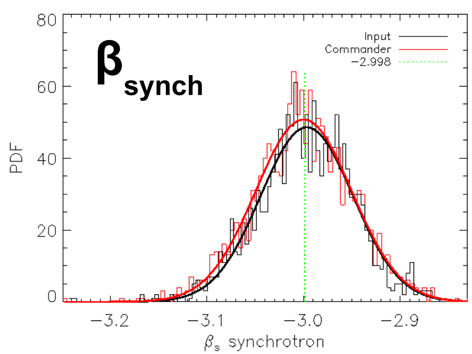




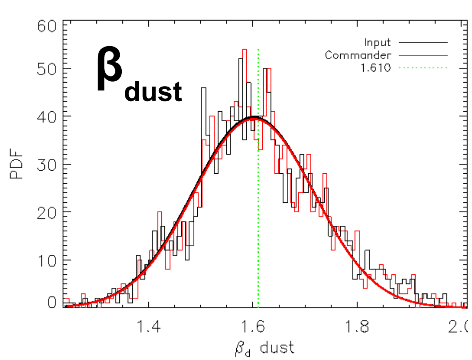


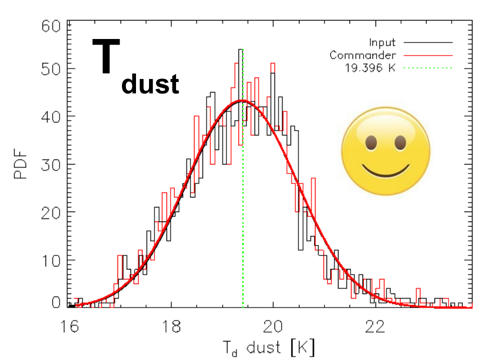
PICO
21 – 800 GHz



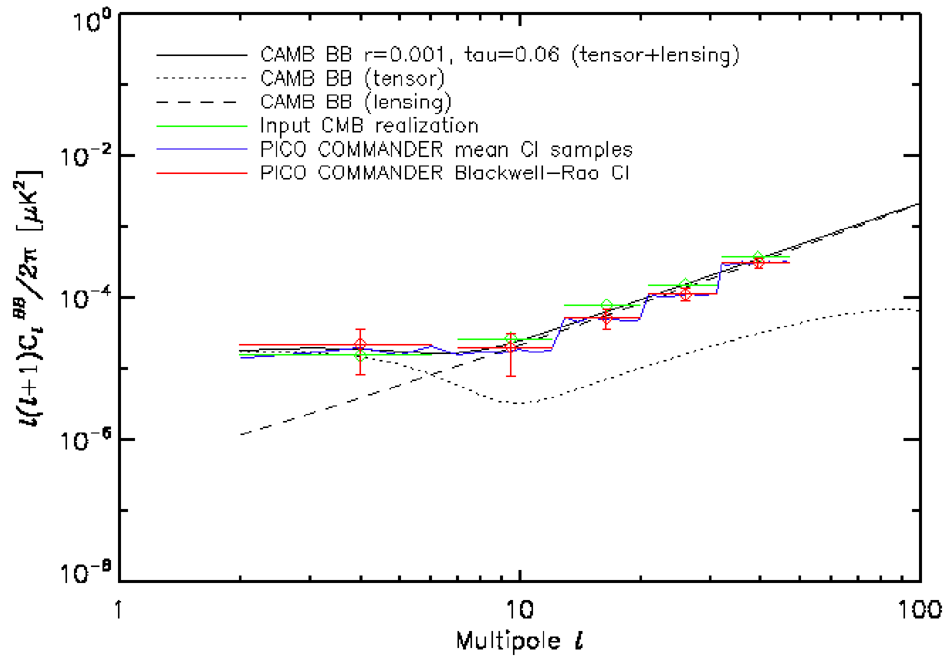


σ(r=10^{-3}) = 0.4 × 10^{-3}



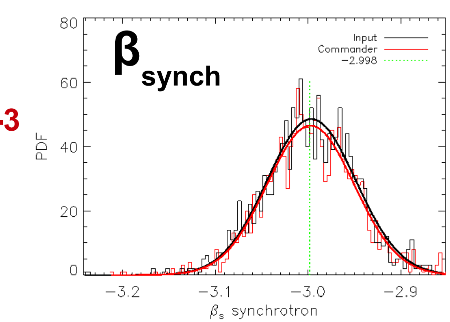


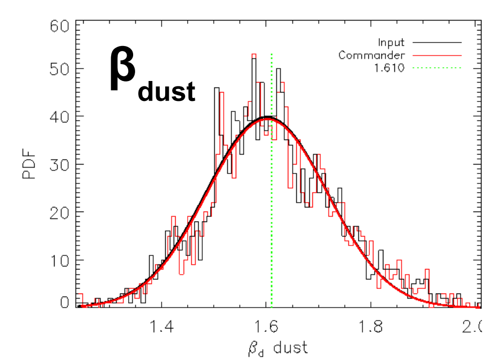
PICO
43 – 800 GHz

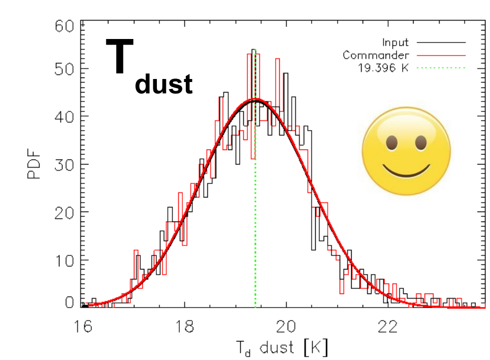


σ(r=10^{-3}) = 0.5 × 10^{-3}

(25% increase)







Summary for PICO

	estimated r [× 10^{-3}]	σ(r=10^{-3}) [× 10^{-3}]
• **21 – 800 GHz, no foregrounds, 50% mask**	0.6	**0.4**
• **21 – 800 GHz, with foregrounds, 50% mask**		
PICO v2-1.4	0.30	**0.41**
PICO v3.0 **PICO v3.0 + 60% delensing**	0.51 0.57	**0.36** **0.24**
• **43 – 800 GHz, with foregrounds, 50% mask**	0.4	**0.5**
• **43 – 462 GHz, with foregrounds, 50% mask**	1.3	**0.7**

These results are for 2 ≤ ℓ ≤ 50.

We should be able to reduce σ(r) by going to higher multipoles, e.g. by combining COMMANDER at low-ℓ and NILC/SEVEM at high-ℓ

M. Remazeilles

Path forward with foregrounds 1/2

- High-ell power-spectrum / r estimation still needed for blind methods NILC, SEVEM

  → *Manpower: power spectrum estimators, likelihoods (G. Rocha, R. Flauger?)*

- More complex simulations

  → Current results still based on a “quite simple” sky model:

  - *Single-MBB dust ; no decorrelation ; no bandpasses*
  - *Single spectral index per N_{side}=16 pixel (no SED mixing/averaging issue)*

  → Real challenge for parametric methods

  - *Alternatives? e.g. moment expansion (Chluba et al 2017)*
    Still needs to prove itself on sky simulations
  - *Blind approaches (NILC, SEVEM) more robust to unknown foregrounds?*

- Perform multi-instrument component separation, e.g. C-BASS + PICO

  J. Hill-Valer's talk

Path forward with foregrounds

- Foregrounds + systematics cross-talk in the simulations

  → Calibration uncertainties, asymmetric beams, bandpass mismatch

- Real delensing on foreground-cleaned CMB maps (manpower?)

- What about intensity component separation? Lots of exciting targets:

  → Relativistic SZ mapping

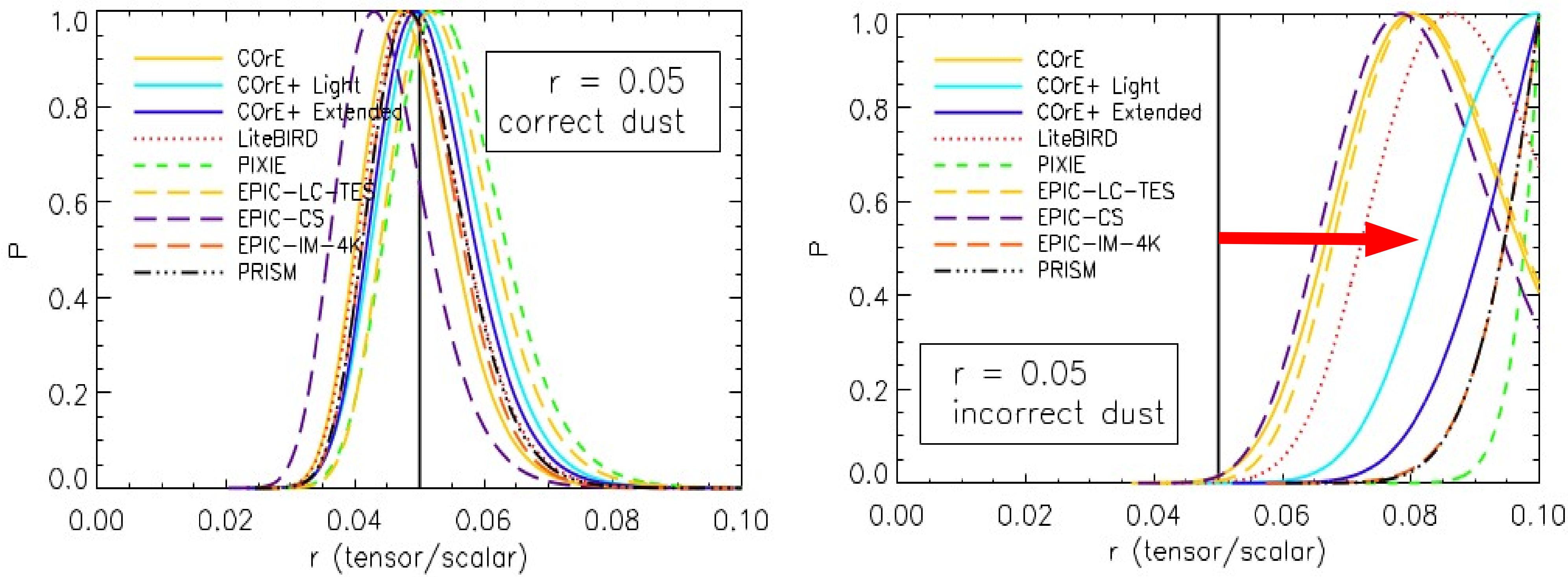
  → Anisotropic μ-distortions (Remazeilles & Chluba, MNRAS 2018)

  → CIB mapping

Backup slides

#1. Foreground mismodelling

Impact on r of mismodelling two MBB dust components as a single MBB component:



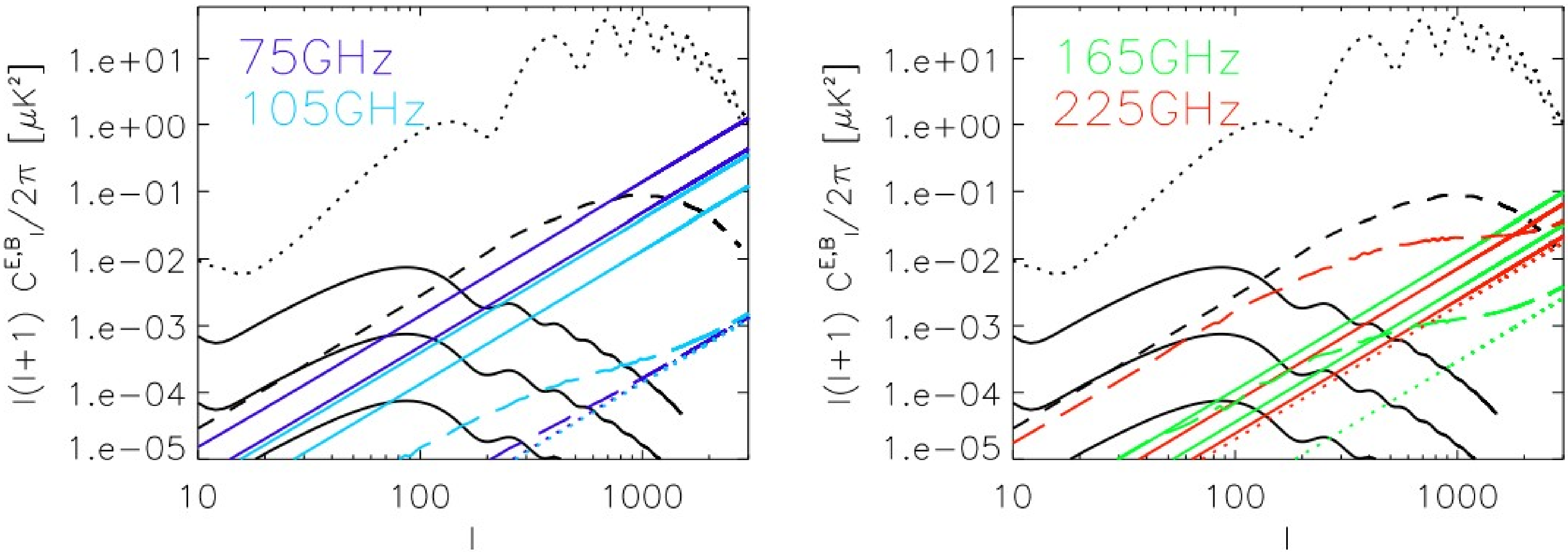
Remazeilles, Dickinson, Eriksen, Wehus, MNRAS (2016)

The Sneaky Point:

CMB experiments with narrow frequency range < 400 GHz show no evidence (χ2 ~ 1) for incorrect foreground modelling!

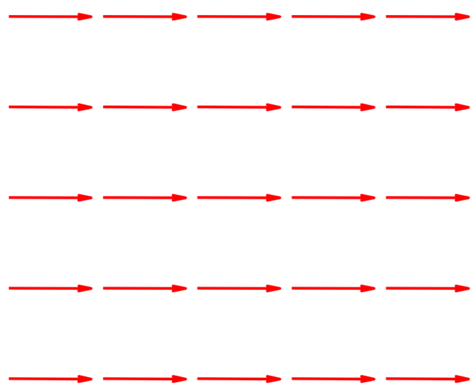
#2. Extragalactic compact foregrounds cannot be ignored

Polarized Radio and IR compact sources at ~ 100 GHz dominate the primordial CMB B-mode at $r = 10^{-3}$ on angular scales $\ell \gtrsim 50$



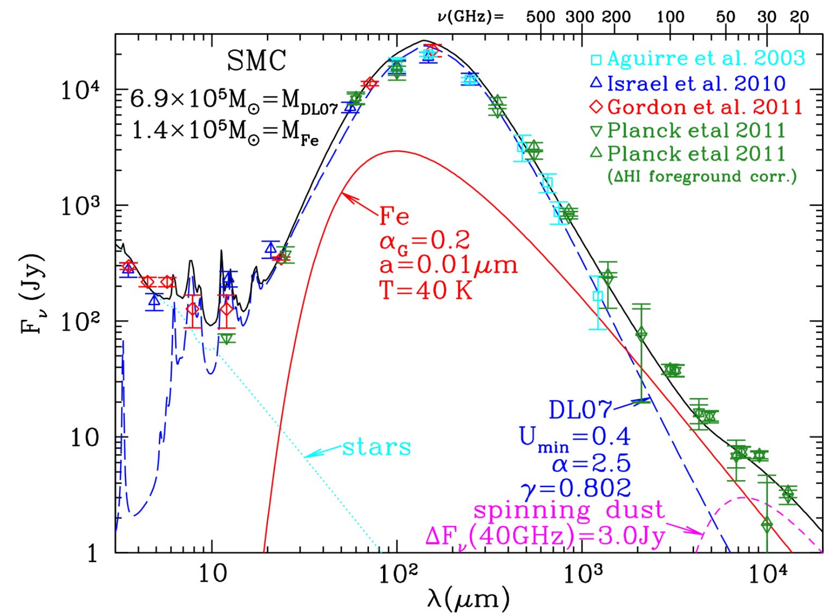
Curto et al 2013

#3. 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!**
- **In theory, MD might be highly polarized ~35%**
- **Spectral degeneracy at ~ 100 GHz between CMB and MD**

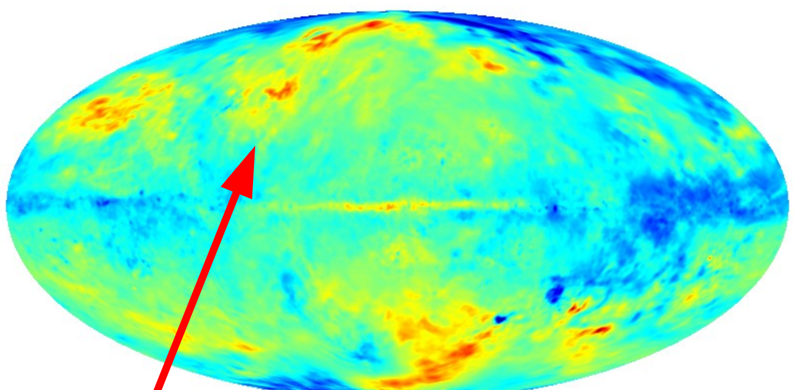
  → ***can be a killer for component separation***

#4. Averaging effects

The actual foreground SED <u>on the maps</u> differs from the real SED <u>in the sky</u> !

Chluba, Hill, Abitbol, 2017

Dust spectral indices in the sky



one value β_{dust} per line-of-sight

Mapping / pixelization

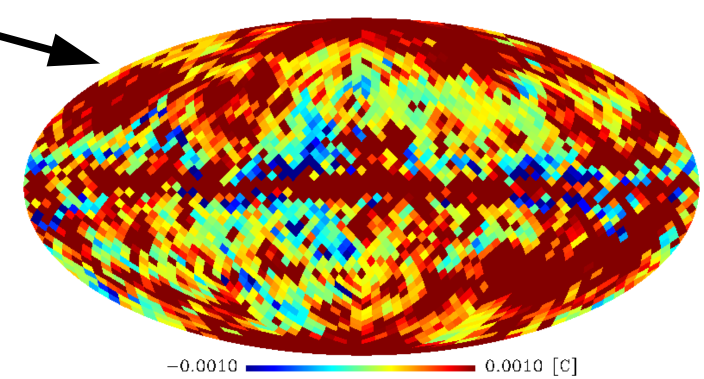
many values β_{dust} per pixel

(effective SED: $\sum_i \nu^{\beta i} = \nu^{\beta + C\,Log(\nu) + \dots}$)

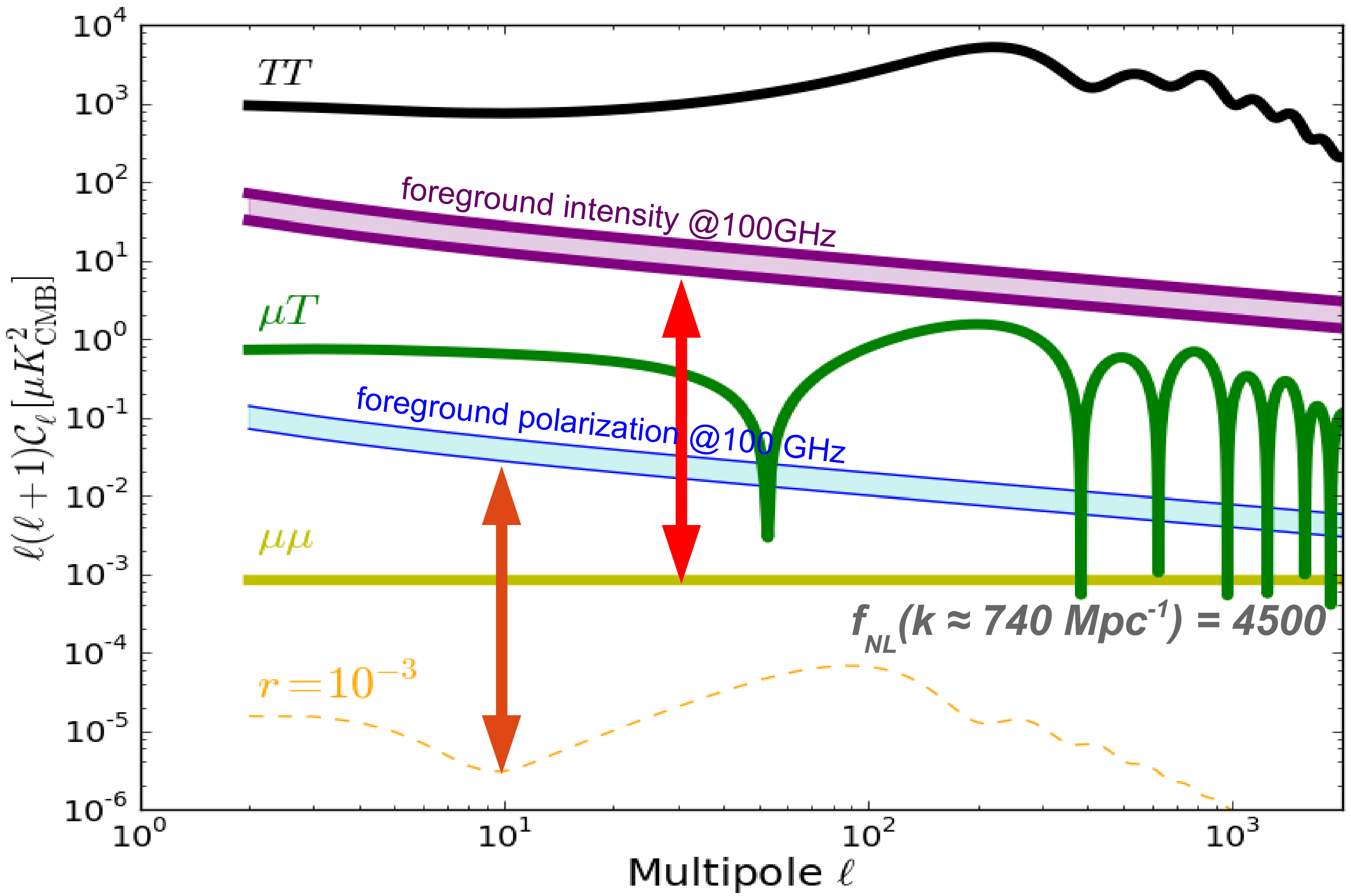
Pixelization/averaging creates spurious curvatures on the foreground SED!

→ Bias of $\Delta r \approx 10^{-3}$ if ignored in the parametric fitting

Remazeilles et al 2017,
for the CORE collaboration



Anisotropic μ-type distortions at $z > 10^4$



μ-T correlation signal between CMB temperature and μ-distortion anisotropies

→ ***accessible signal, allowing to constrain $f_{NL}(k \approx 740\ \mathrm{Mpc}^{-1})$***

→ ***to be definitely considered by future CMB satellites!***

More details in Remazeilles & Chluba, MNRAS (2018): arXiv:1802.10101