B-mode component separation: lessons from CORE

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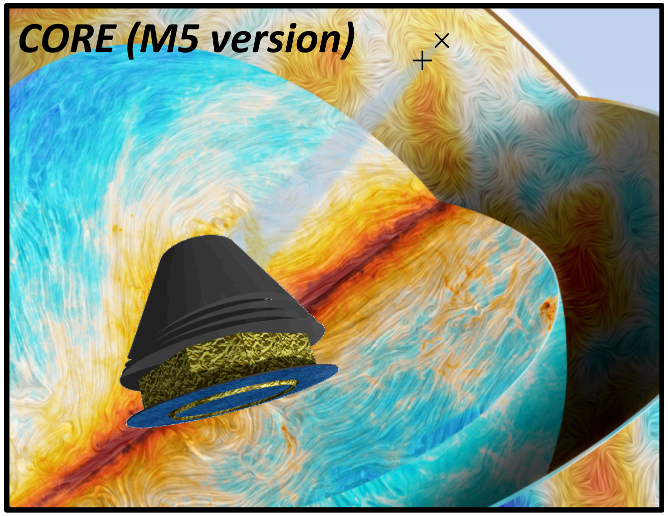
Remazeilles et al, JCAP 04 (2018) 023,
for the CORE Collaboration

“CMB foregrounds for B-mode studies”
Tenerife, 15-18 October 2018

CORE: Cosmic Origins Explorer



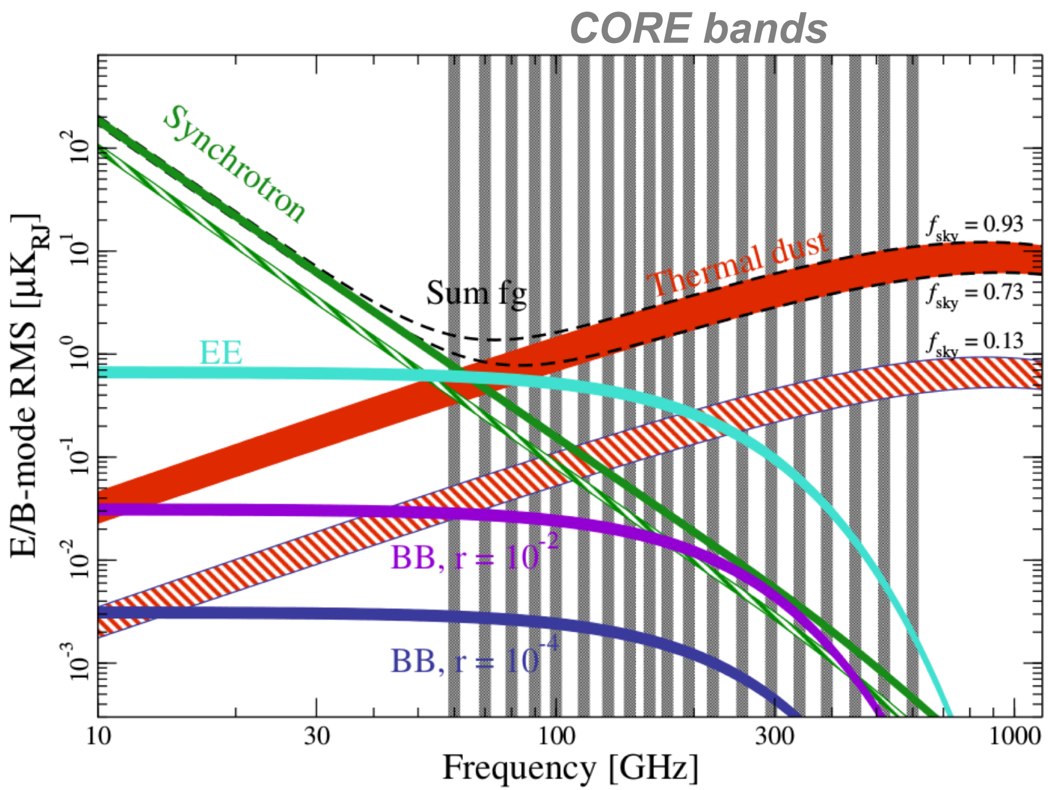
- **100%** of the sky
- **19** frequency bands:
  60 – 600 GHz
- Aggregated sensitivity:
  1.7 μK.arcmin
- **Few arcmin** resolution,
  allowing for 60% delensing

Costs outside ESA M-class envelope (2017)

Frequency [GHz]	Beam [arcmin]	Q and U noise RMS [μK.arcmin]
60	17.87	10.6
70	15.39	10.0
80	13.52	9.6
90	12.08	7.3
100	10.92	7.1
115	9.56	7.0
130	8.51	5.5
145	7.68	5.1
160	7.01	5.2
175	6.45	5.1
195	5.84	4.9
220	5.23	5.4
255	4.57	7.9
295	3.99	10.5
340	3.49	15.7
390	3.06	31.1
450	2.65	64.9
520	2.29	164.8
600	1.98	506.7

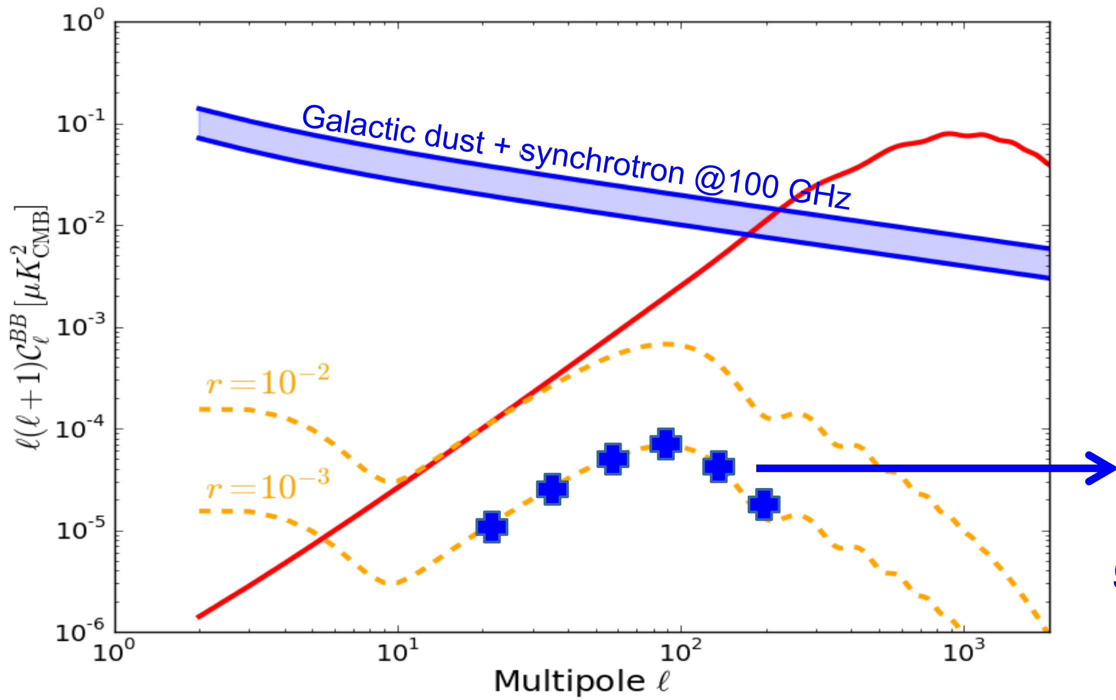
Delabrouille et al, JCAP 04 (2018) 014

CMB B-mode v.s. foregrounds



- **Polarization less complex than intensity (fewer foregrounds) but more challenging (weaker signal):**
  - → *Huge dynamic range between CMB B-mode and foregrounds*
  - → *Component separation thus much more sensitive to foreground uncertainties*
- **Foregrounds can't be avoided by narrowing the frequency range of observations**
  - → *At* ~ 300 GHz, *synchrotron and CMB at* $r = 10^{-2}$ *have similar magnitude and colour!*
  - → *A broad frequency coverage is thus crucial to break spectral degeneracies*

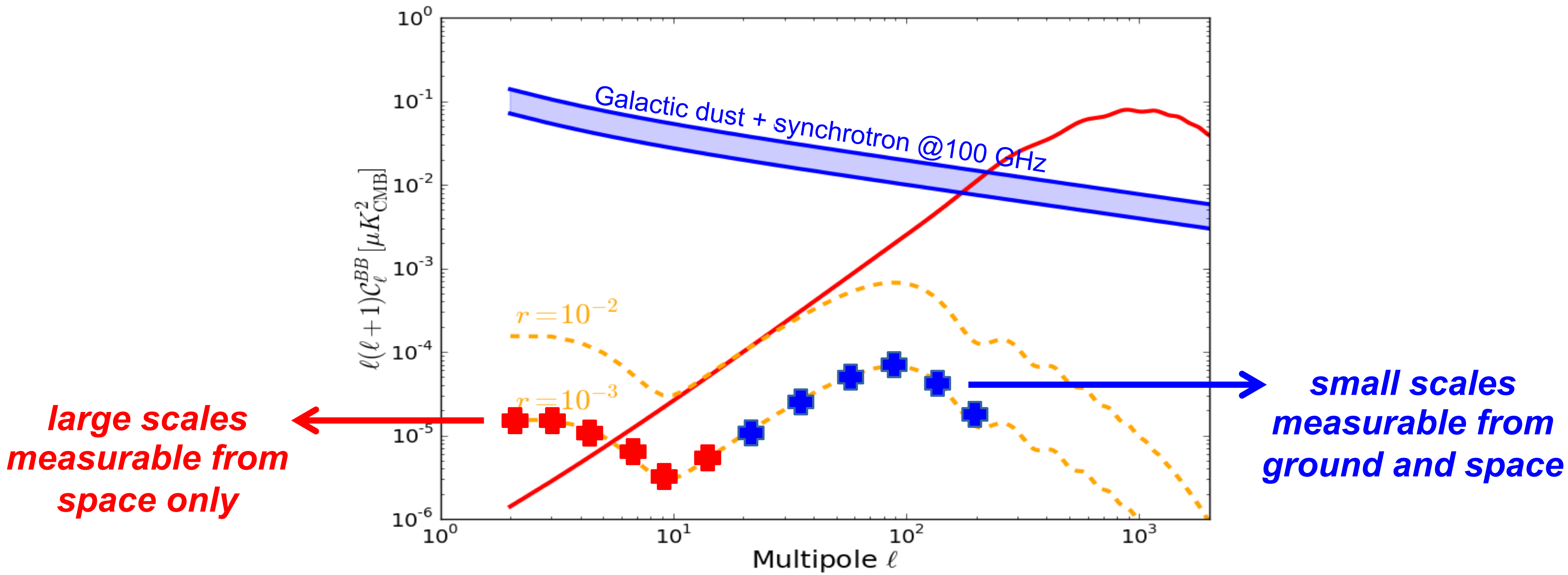
Why going into space?



small scales measurable from ground and space

- *At recombination scales ($20 < \ell < 200$), measurements may be fooled by many kind of <u>power-spectrum degeneracies</u>:*
  primordial B-modes, lensing B-modes, extragalactic sources, and noise have pretty similar slopes

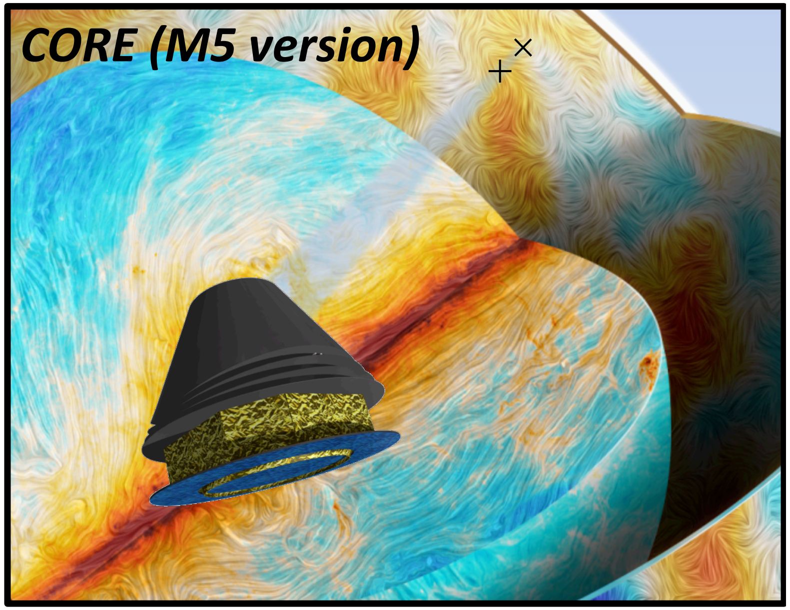
Why going into space?



- *At recombination scales ($20 < \ell < 200$), measurements may be fooled by many kind of <u>power-spectrum degeneracies</u>: primordial B-modes, lensing B-modes, extragalactic sources, and noise have pretty similar slopes*

- *Detecting the reionization peak ($2 < \ell < 20$) from space will allow to break power-spectrum degeneracies, providing better evidence for detection of primordial CMB B-modes*

CORE



- Mission: *Delabrouille et al, JCAP 04 (2018) 014*
- Instrument: *de Bernardis et al, JCAP 04 (2018) 015*
- Inflation: *Finelli et al, JCAP 04 (2018) 016*
- Parameters: *Di Valentino et al, JCAP 04 (2018) 017*
- Lensing: *Challinor et al, JCAP 04 (2018) 018*
- Clusters: *Melin et al, JCAP 04 (2018) 019*
- Sources: *De Zotti et al, JCAP 04 (2018) 020*
- Velocity: *Burigana et al, JCAP 04 (2018) 021*
- Systematics: *Natoli et al, JCAP 04 (2018) 022*
- Foregrounds: *Remazeilles et al, JCAP 04 (2018) 023*

http://iopscience.iop.org/journal/1475-7516/page/extraproc1

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An IOP and SISSA journal

CORE Special Issue

Exploring cosmic origins with CORE: B-mode component separation

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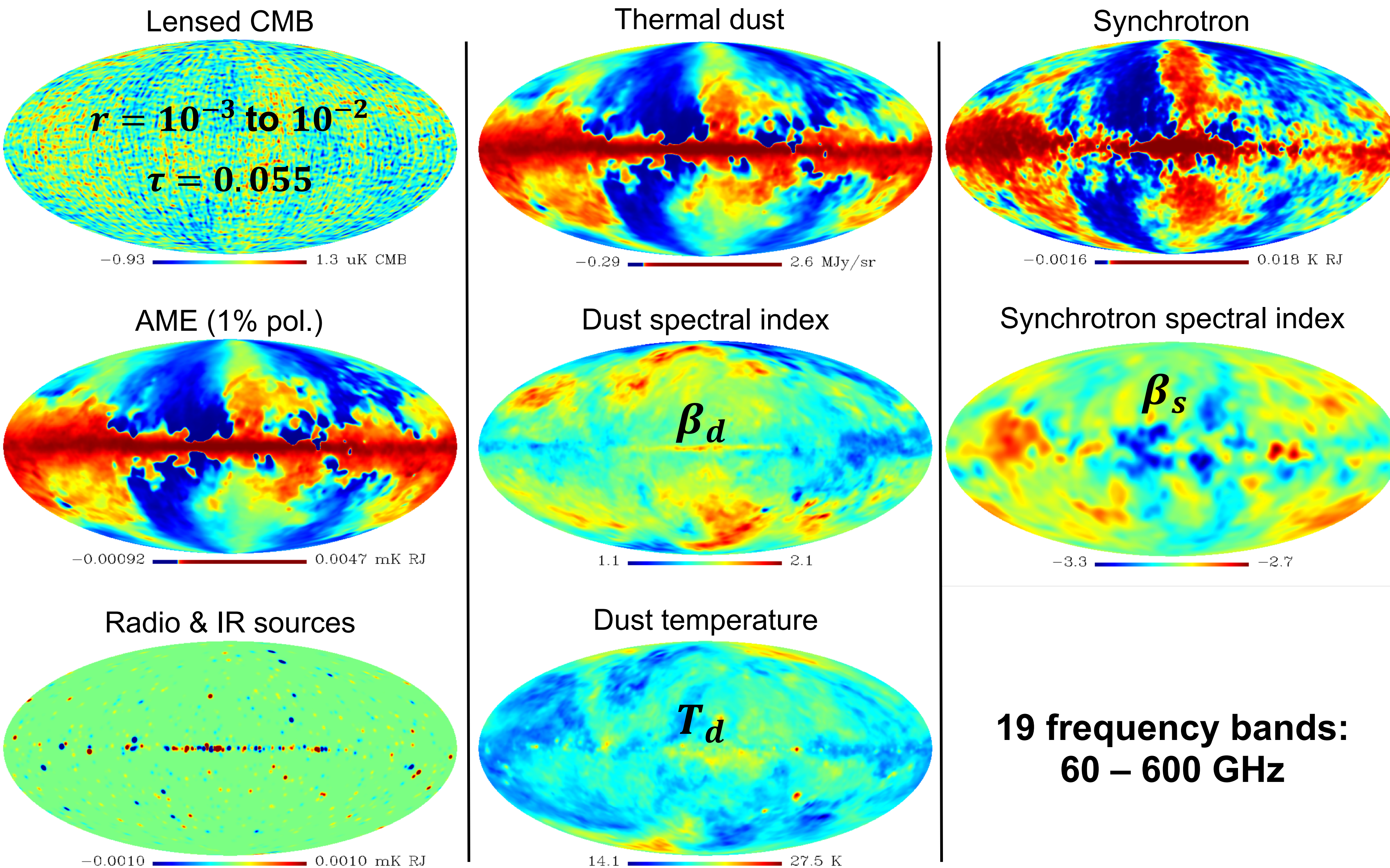
CORE sky simulations: Stokes Q maps



19 frequency bands:
60 – 600 GHz

smoothed to 1° for illustration purposes

Remazeilles et al JCAP 2018

Component separation methods

We have implemented 4 independent techniques (blind and parametric) on the CORE sky simulations:

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

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

- **SMICA** – *Delabrouille et al 2003 ; Cardoso et al 2008*

  Blind independent-component power-spectrum fit in harmonic space

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

  Minimum-variance internal linear combination in wavelet space

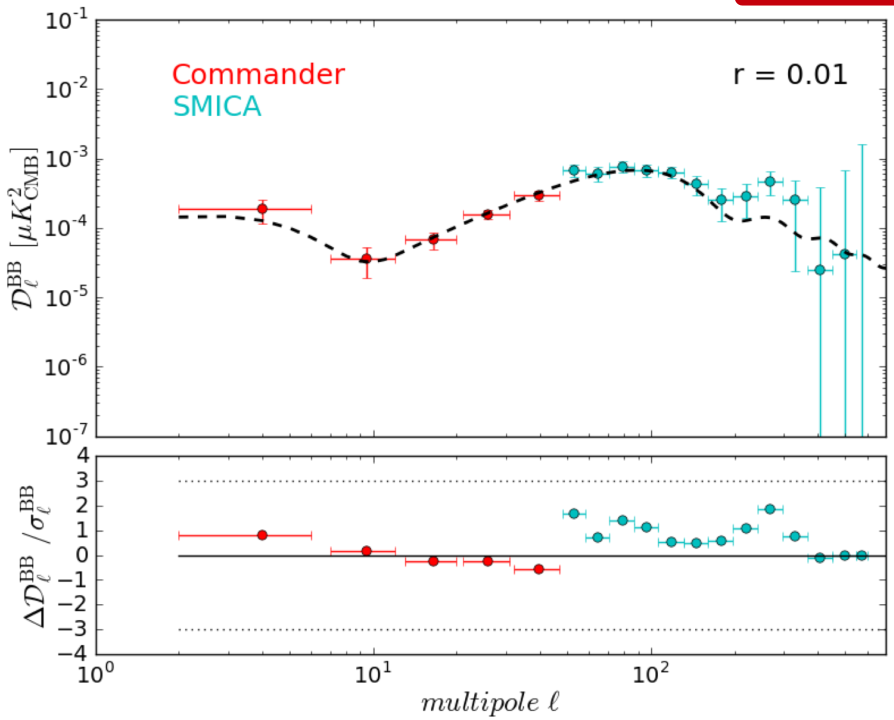
- **X-FORECAST** – *Errard et al 2016 ; Stompor et al 2016*

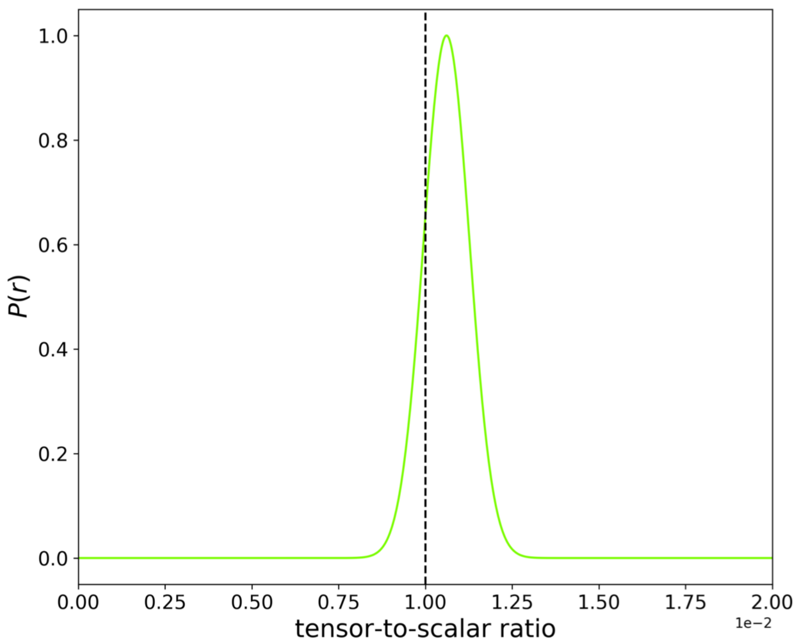
  Maximum-likelihood foreground spectral fit in pixel space + linear combination

Remazeilles et al JCAP 2018

CORE reconstruction of primordial B-modes
– without lensing –

$r = 10^{-2}$



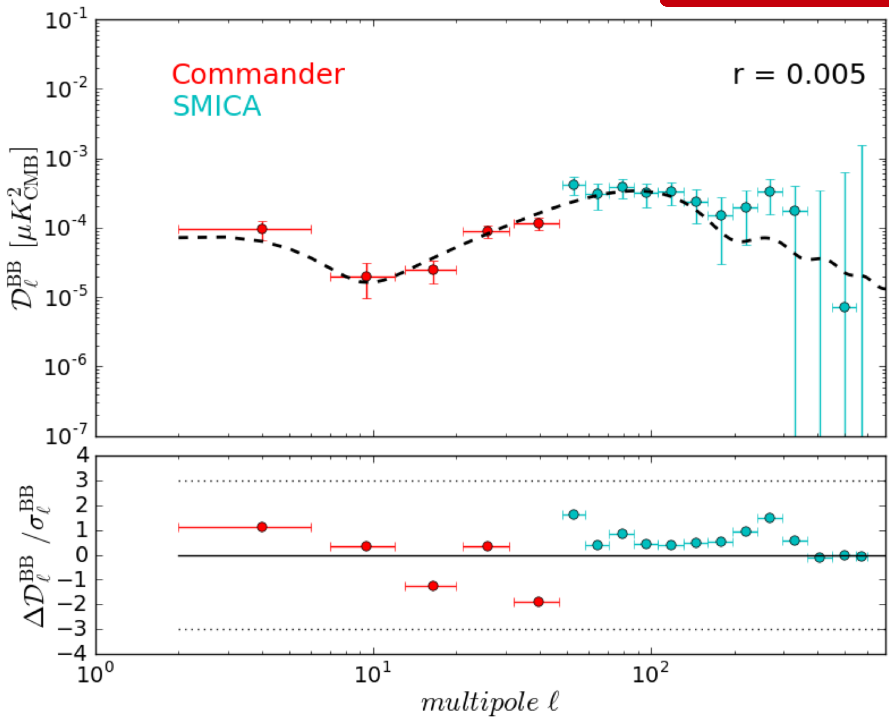


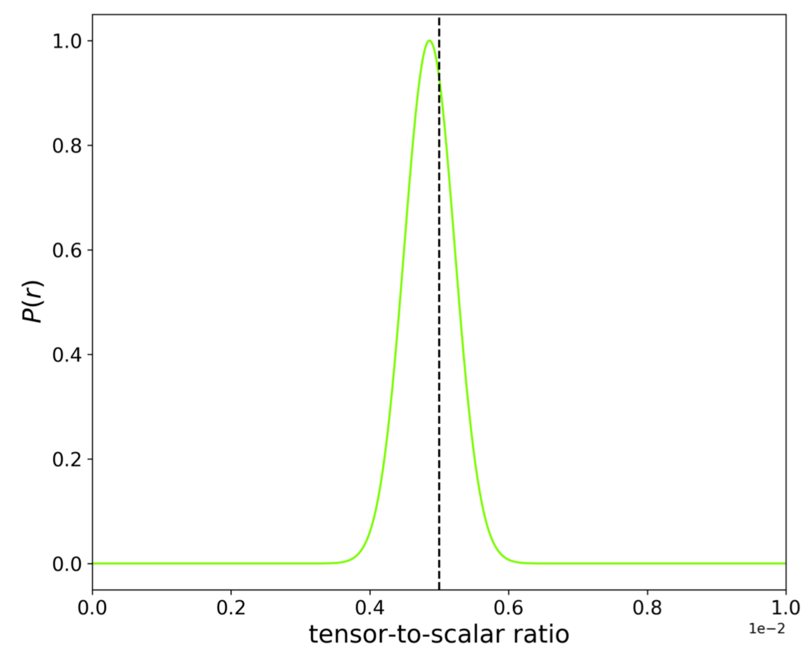
14σ detection of $r = 10^{-2}$ after foreground cleaning

Remazeilles et al, JCAP 2018

CORE reconstruction of primordial B-modes
– without lensing –

$$r = 5\times10^{-3}$$





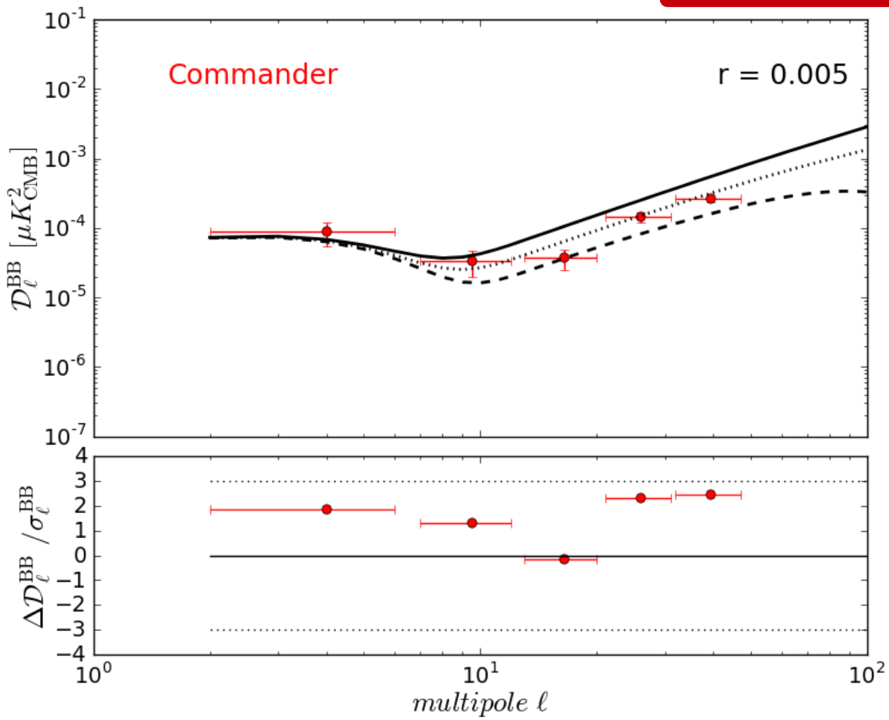
12σ detection of $r = 5\times10^{-3}$ after foreground cleaning

Remazeilles et al, JCAP 2018

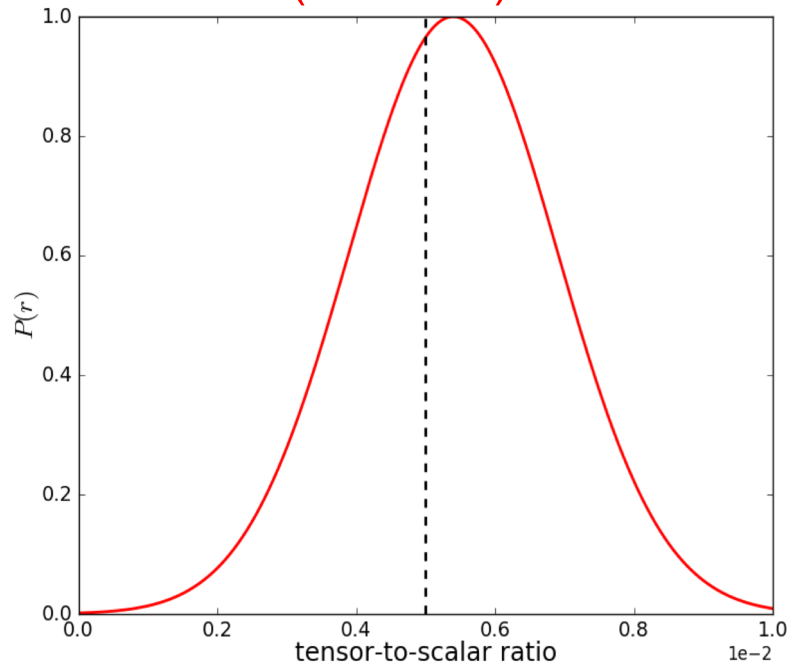
CORE reconstruction of primordial B-modes

– with 40% lensing –

$$r = 5\times10^{-3}$$



r = (5.4 ± 1.5) × 10^{-3}

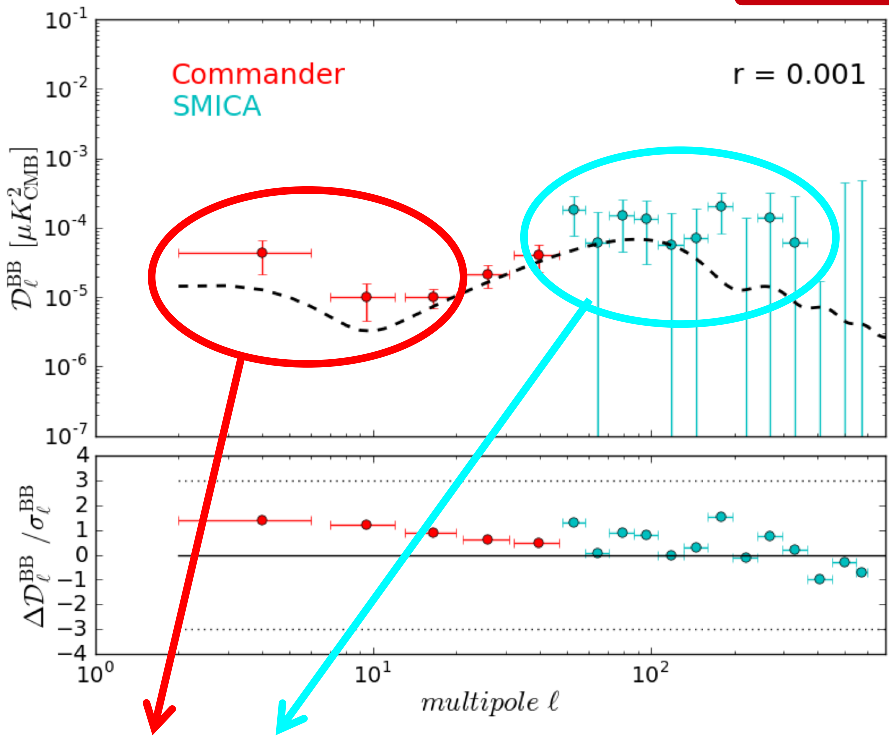


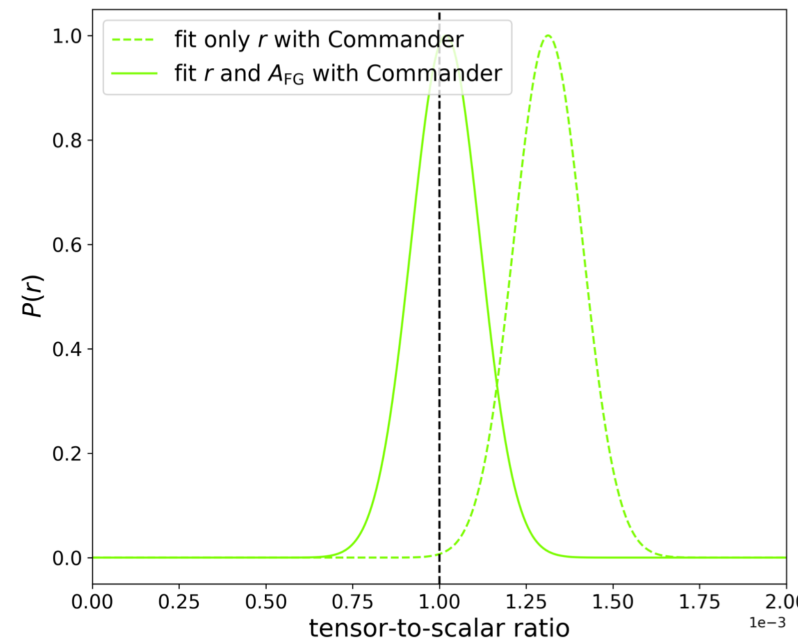
4σ detection of $r = 5\times10^{-3}$
after foreground cleaning and 60% delensing

Remazeilles et al, JCAP 2018

CORE reconstruction of primordial B-modes
– without lensing –

$$r = 10^{-3}$$





foreground residuals!

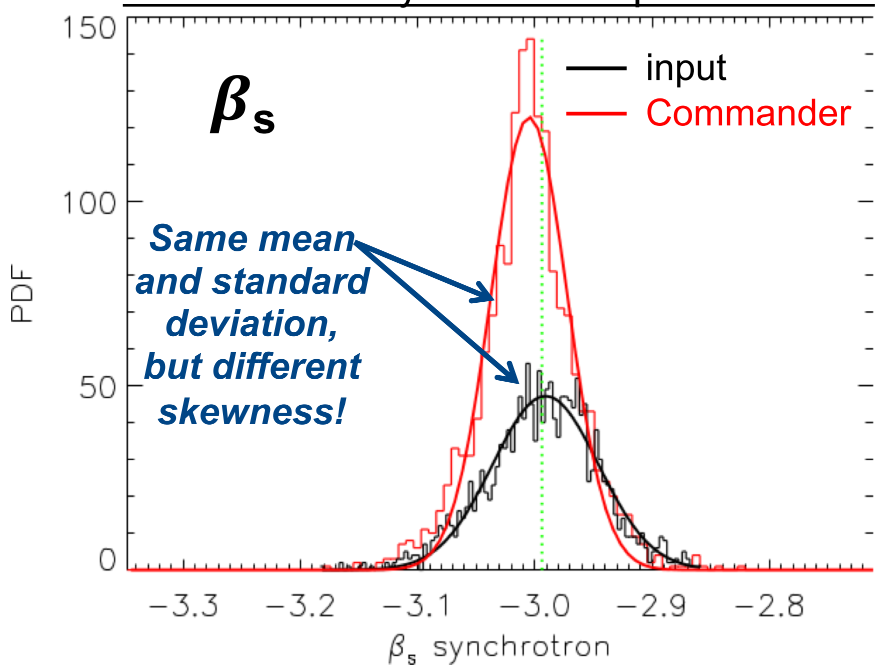
3σ bias on $r = 10^{-3}$ after foreground cleaning

Remazeilles et al, JCAP 2018

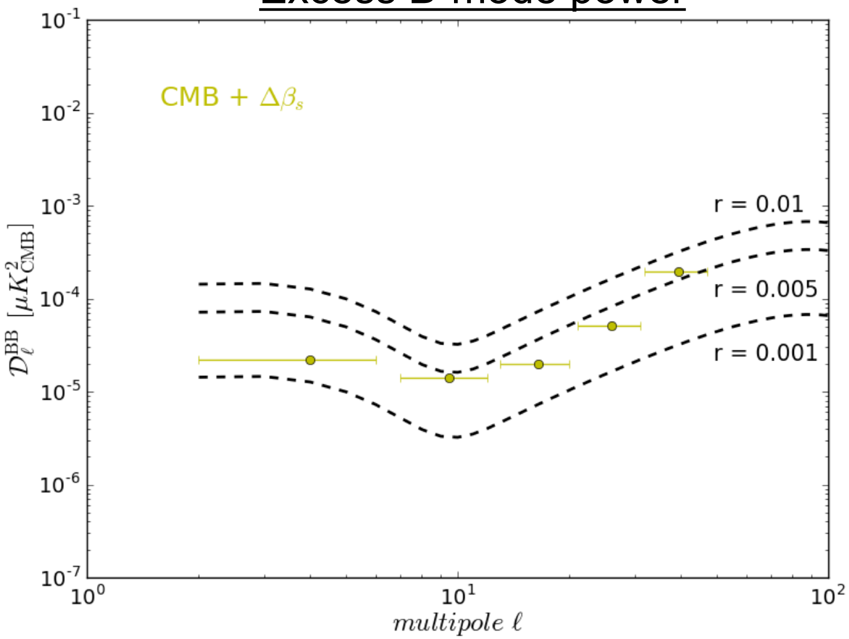
Absence of frequencies below 60 GHz

Errors $\frac{|\beta_s^{out} - \beta_s^{in}|}{\beta_s^{in}} \simeq 2\% \implies$ synchrotron B-mode amplitude shifted by $\Delta r \gtrsim 10^{-3}$ when extrapolated to $\simeq 145$ GHz

Mismatch on synchrotron spectral index



Excess B-mode power



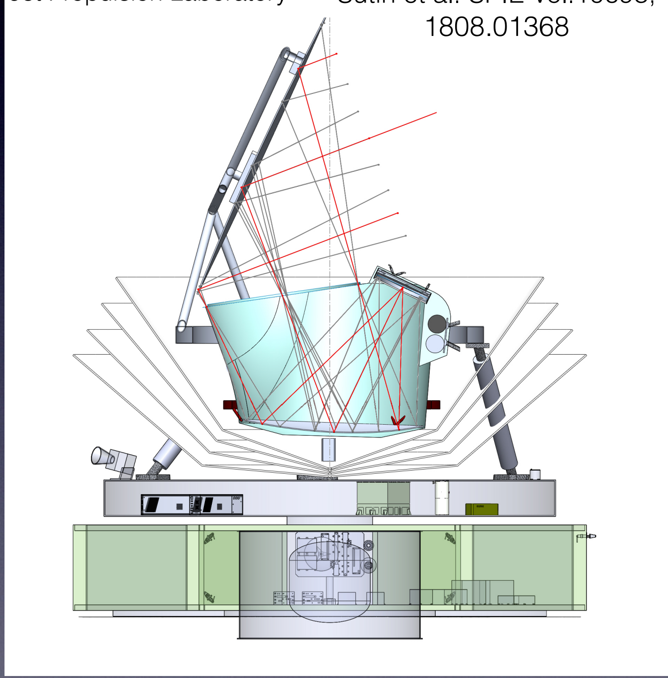
Remazeilles et al JCAP 2018

Sub-percent accuracy on foreground spectral indices is required to allow the detection of CMB B-modes at the level of $r \lesssim 10^{-3}$

On the importance of
a broad frequency coverage

PICO in Brief

- Millimeter/submillimeter-wave, polarimetric survey of the entire sky
- 21 bands between 20 GHz and 800 GHz
- 1.4 m aperture telescope
- Diffraction limited resolution: 38' to 1'
- 13,000 transition edge sensor bolometers
- 5 year survey from L2
- 0.87 uK*arcmin requirement; 0.61 uK*arcmin goal (=CBE)



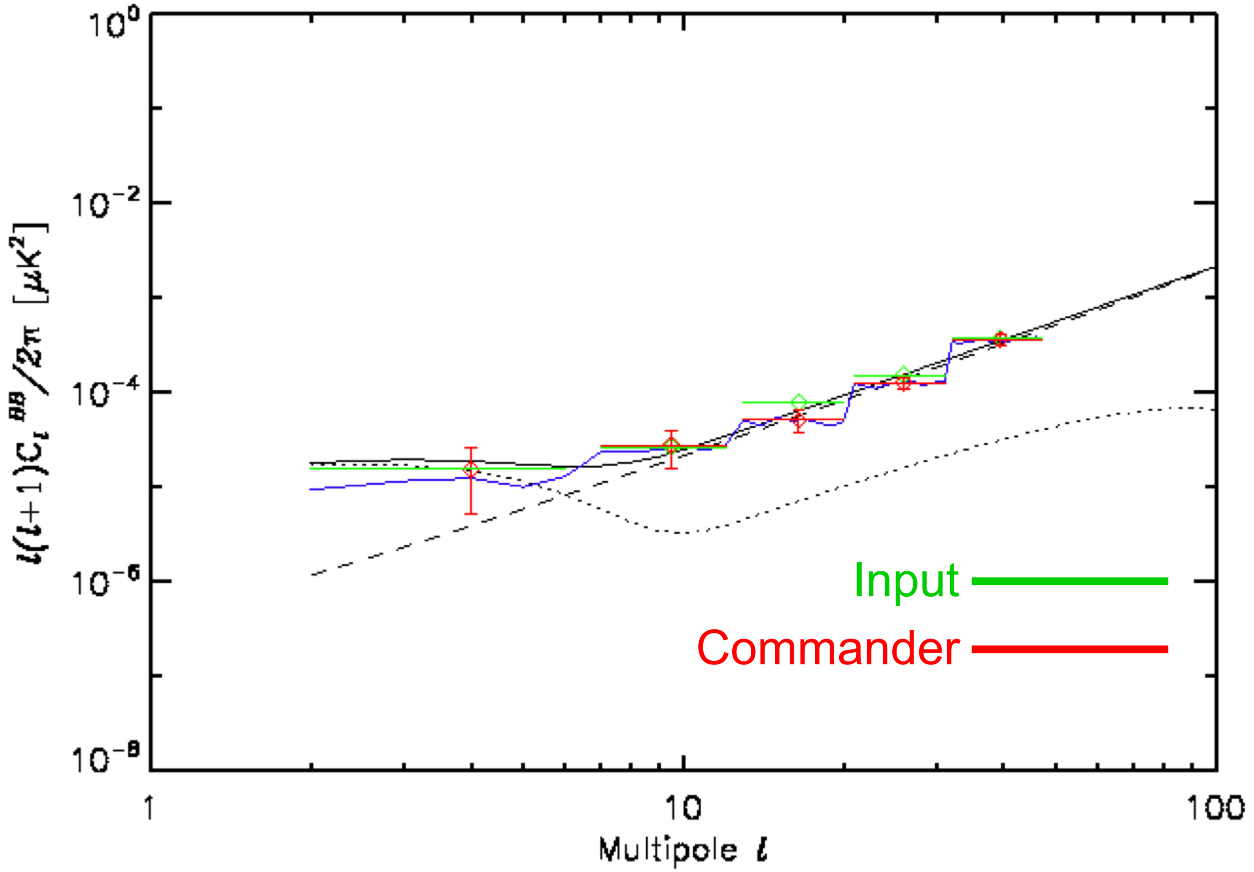
Sutin et al. SPIE Vol.10698; 1808.01368

See talk by Shaul Hanany

PICO reconstruction of primordial B-modes

20 – 800 GHz

$$r = 10^{-3}$$



Foregrounds:

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

$$\sigma(r = 10^{-3}) = 0.4\times10^{-3}$$

after foreground cleaning

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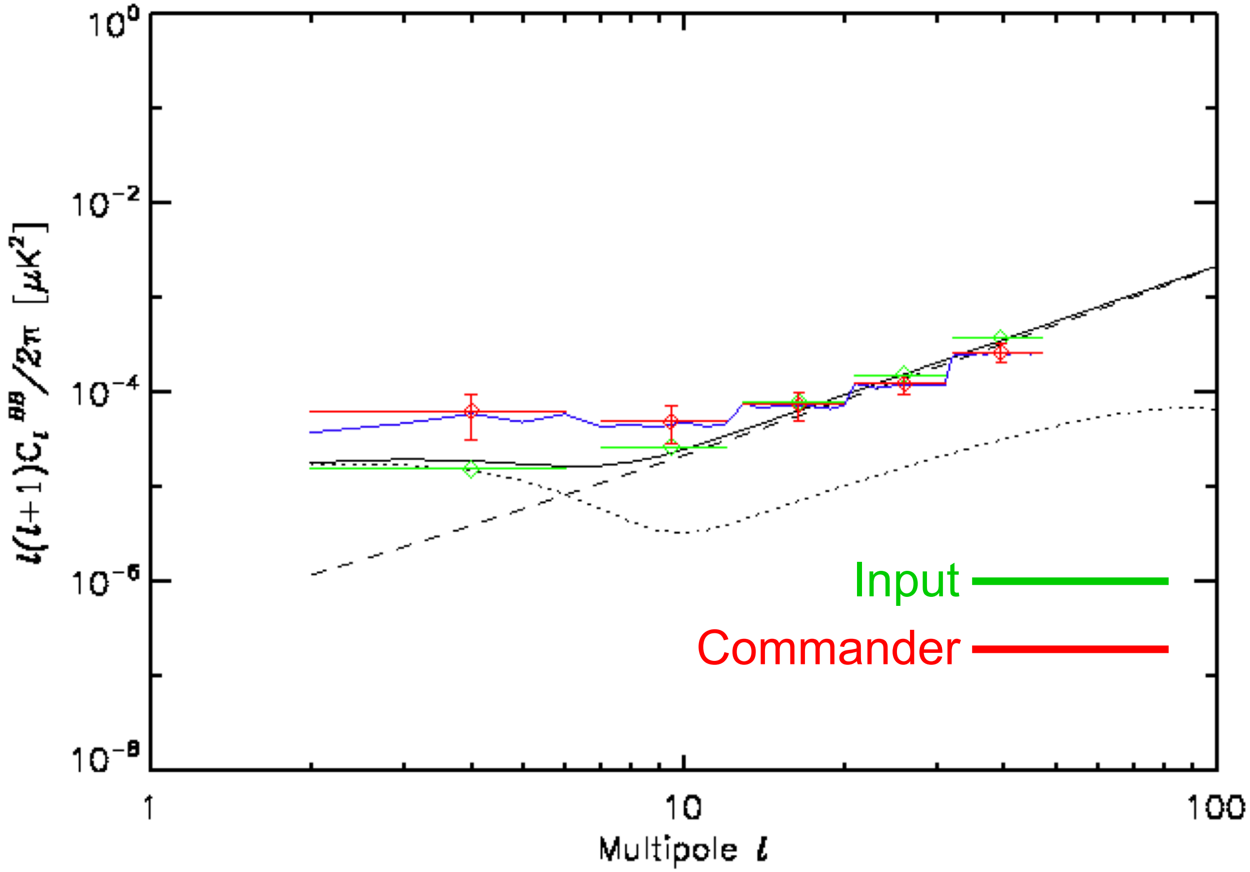
PICO reconstruction of primordial B-modes

43 – 462 GHz

$$r = 10^{-3}$$



Foregrounds:

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

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

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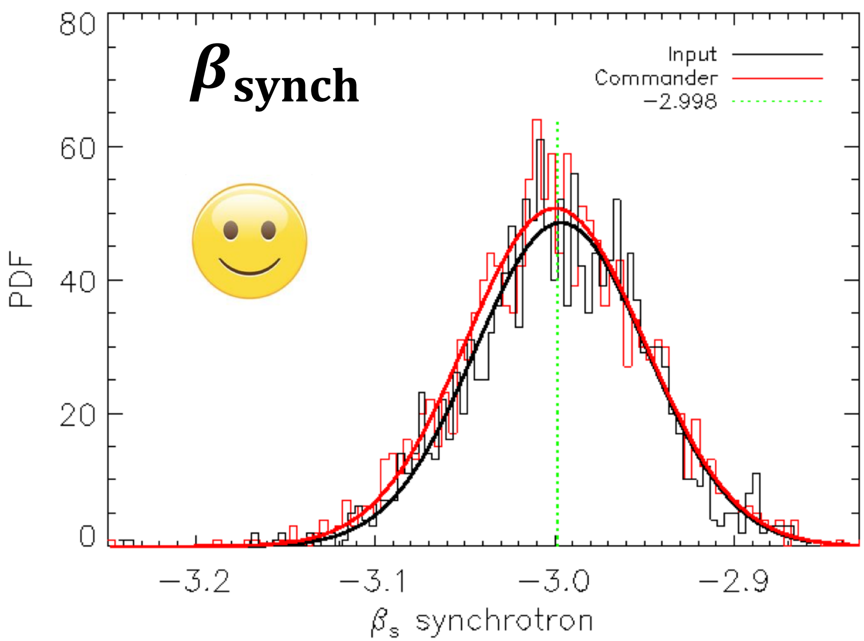
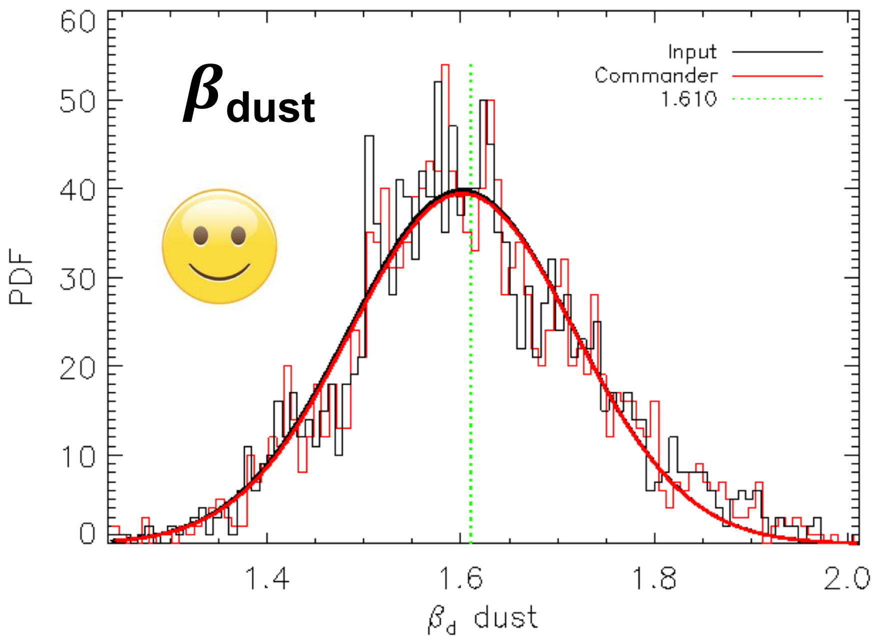
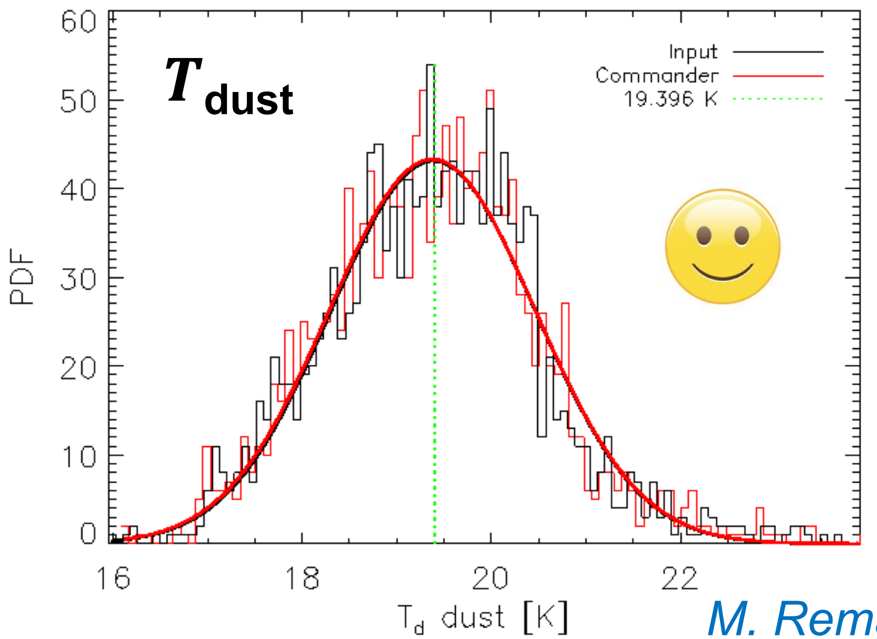
COMMANDER results on foregrounds
PICO **20 – 800 GHz**







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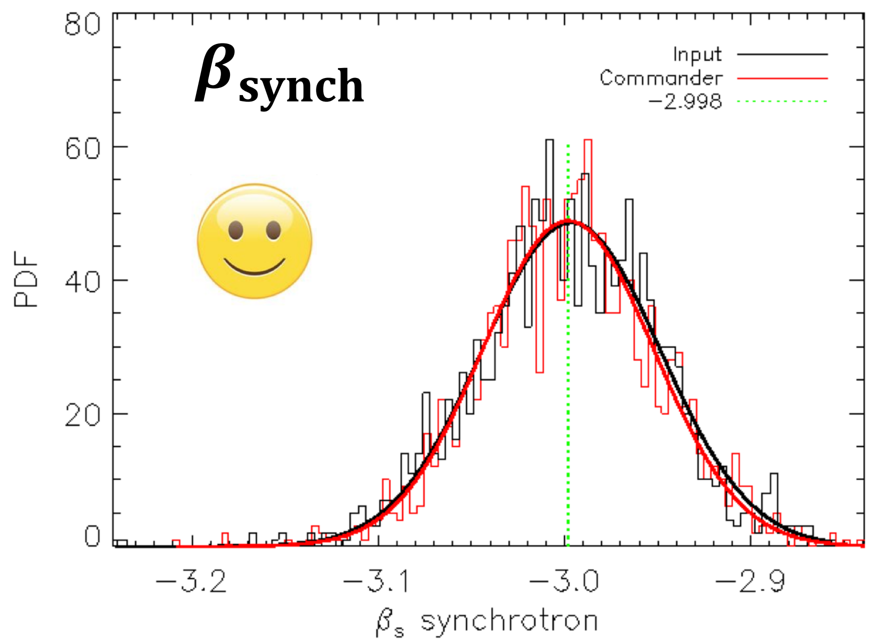
COMMANDER results on foregrounds
PICO **43 – 462 GHz**



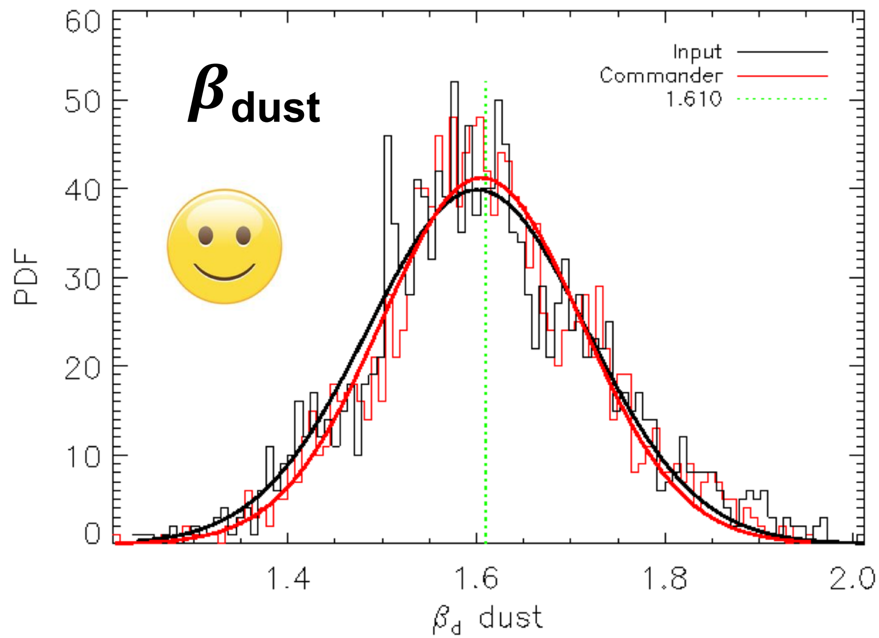
Lack of frequency range / high frequencies

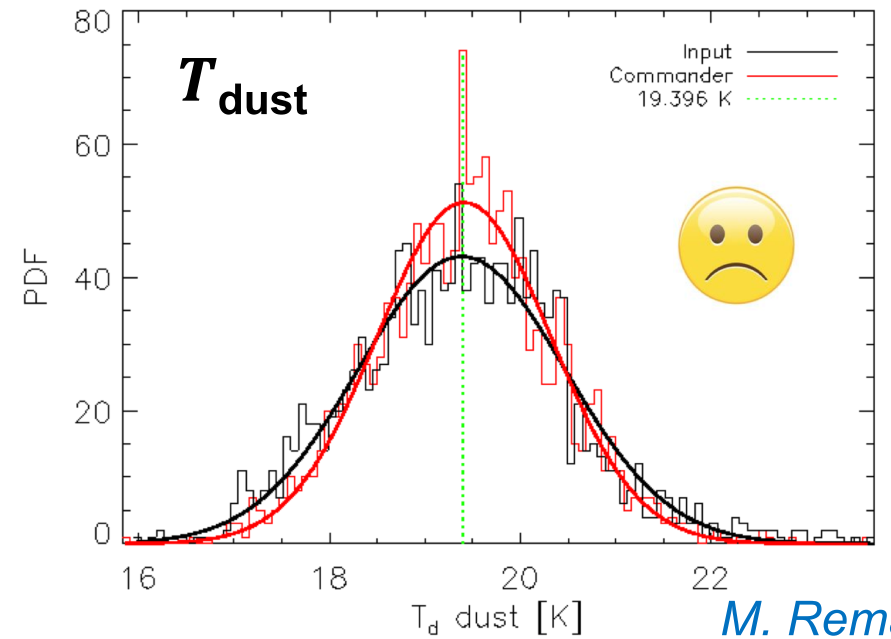
↓

Lack of accuracy / constraint on T_{dust}

↓

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





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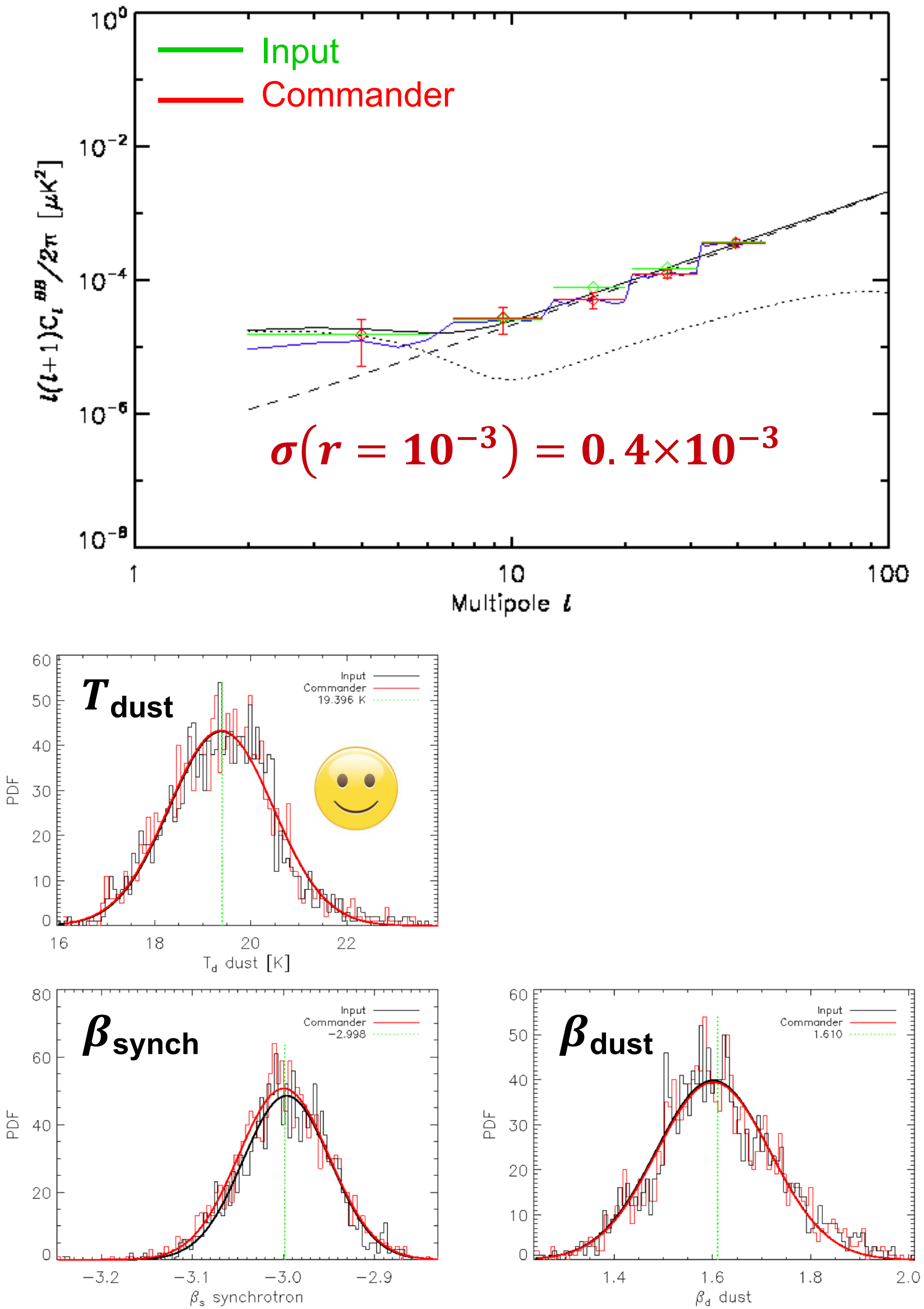
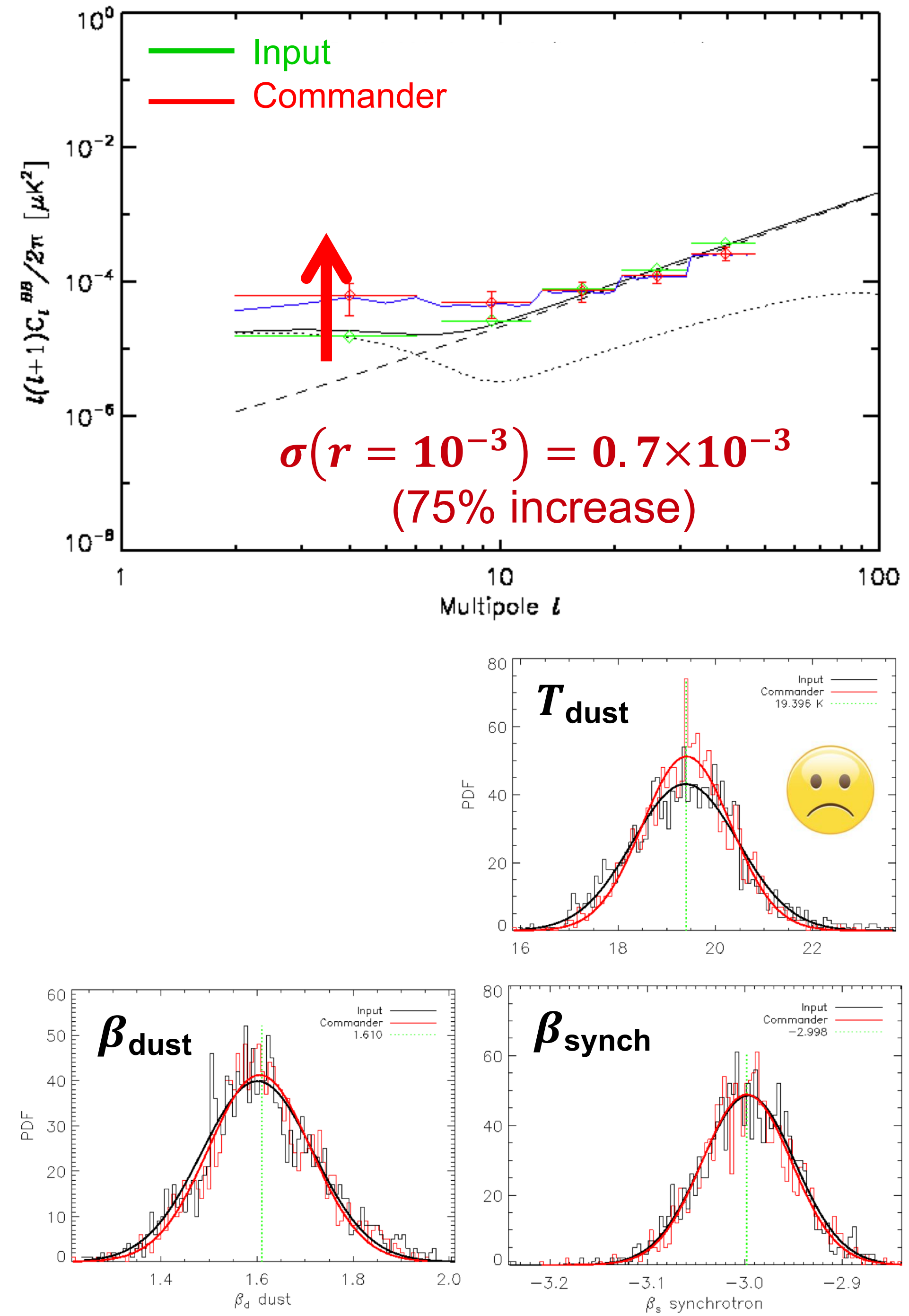
PICO
20 – 800 GHz



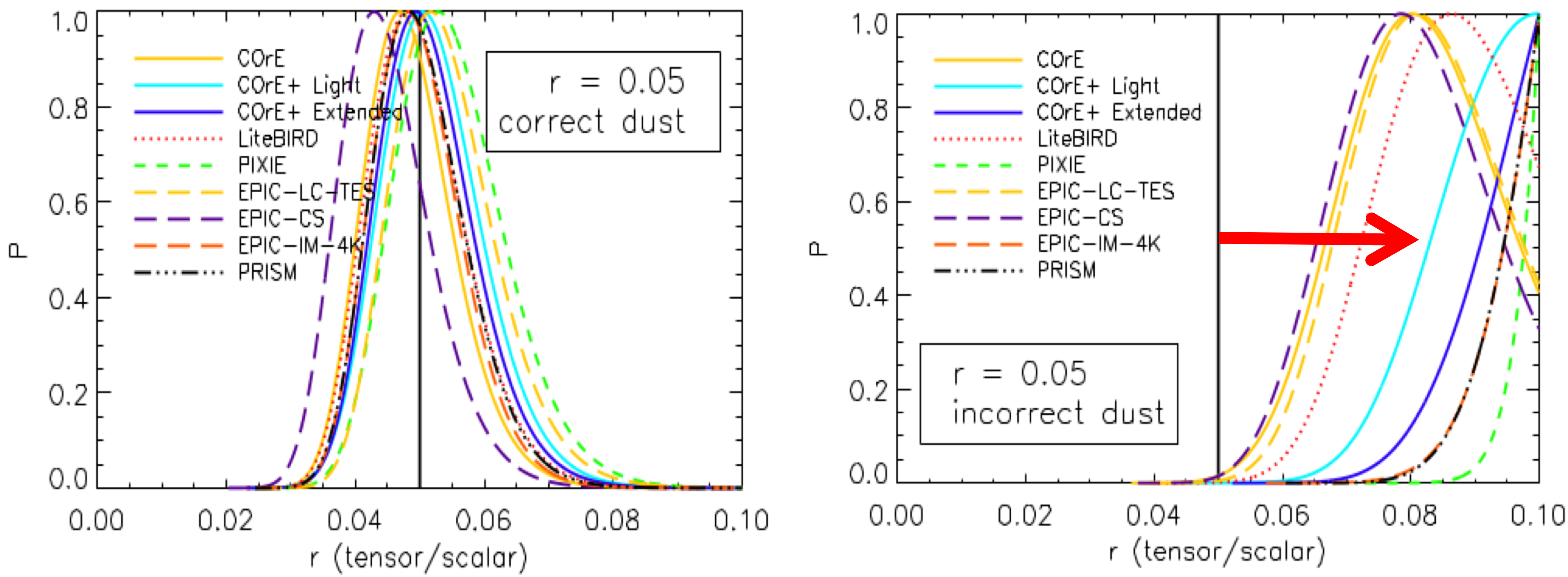
PICO
43 – 462 GHz



Subtle issues for B-mode component separation

#1. Foreground mismodeling

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

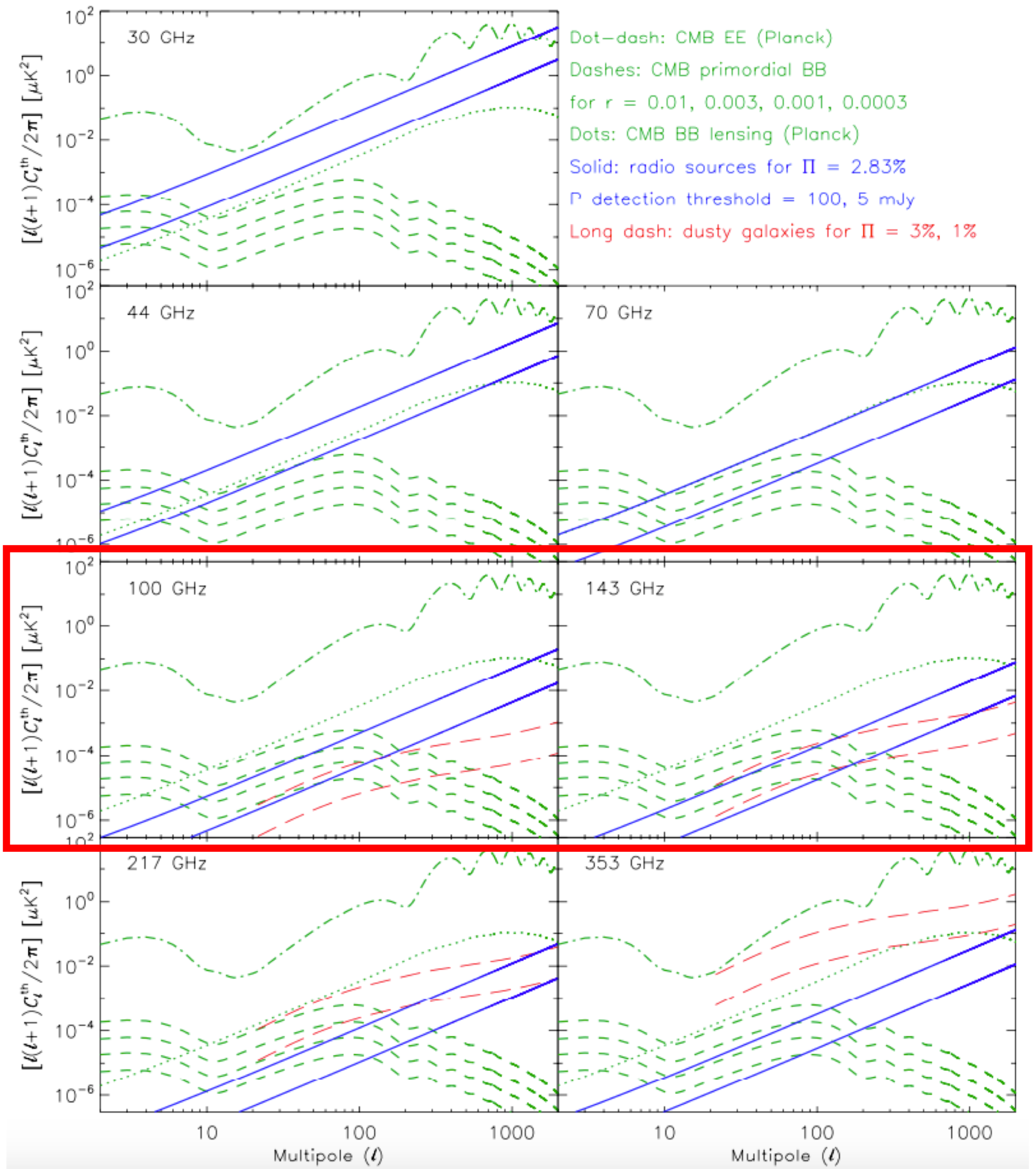


Remazeilles, Dickinson, Eriksen, Wehus, MNRAS (2016)

The Sneaky Point:

CMB experiments with narrow frequency ranges < 400 GHz show no evidence ($\chi^2 \simeq 1$) for incorrect foreground models!

#2. Extragalactic sources cannot be ignored even at large scales



Radio and IR sources at ~100-140 GHz exceed primordial CMB B-mode power ($r = 10^{-3}$) at angular scales $\ell \gtrsim 50$

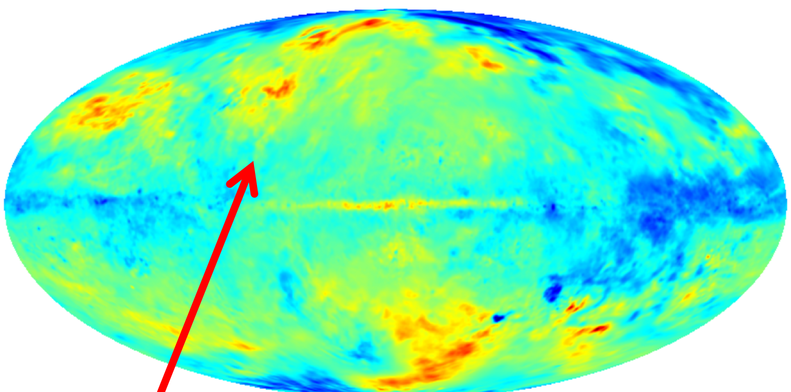
Trombetti, Burigana, De Zotti, Galluzzi, Massardi, A&A 2018

#3. Averaging effects

Actual foreground SED <u>on the maps</u> may differ from 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

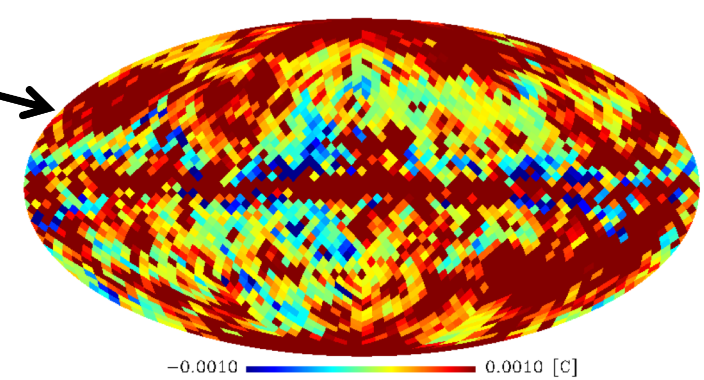
many values β_{dust} per pixel

→ ***effective SED:*** $\sum_i \nu^{\beta_i} = \nu^{\alpha + C\, log(\nu) + \dots}$

Remazeilles et al JCAP 2018:

Pixelization / averaging creates spurious curvature on the dust spectral index across frequencies!

→ **Bias of $\Delta r \simeq 10^{-3}$ if the effective dust curvature is ignored in the parametric fit**



New approaches?

- Most of our efforts so far have been in developing component separation methods tailored to deal with CMB temperature data (see beautiful Planck results), for which the "signal-to-foreground" ratio was relatively large
- With the new challenges to overcome on B-modes, and the entering in the new era of faint "signal-to-foreground" regimes, it is timely to design novel component separation methods
- Some alternative approaches might provide interesting avenues:

1. Parametric:

   Moment expansion / effective modeling of the foreground SED instead of fitting astrophysical models

   Chluba et al 2017 *(see talks by A. Mangilli and A. Rotti)*

2. Blind:

   GNILC: minimize variance of foregrounds instead of foreground + noise

   Remazeilles et al 2011

Alternative methods #1: moment expansion / effective modeling

Moment expansion of the foreground SEDs:

$$\left(\frac{\nu}{\nu_0}\right)^{\beta}\left[1 + C_1\,\left(\ln\left(\frac{\nu}{\nu_0}\right)\right)^2 + C_2\left(\ln\left(\frac{\nu}{\nu_0}\right)\right)^3 + \cdots\right]$$

Chluba, Hill, Abitbol, 2017

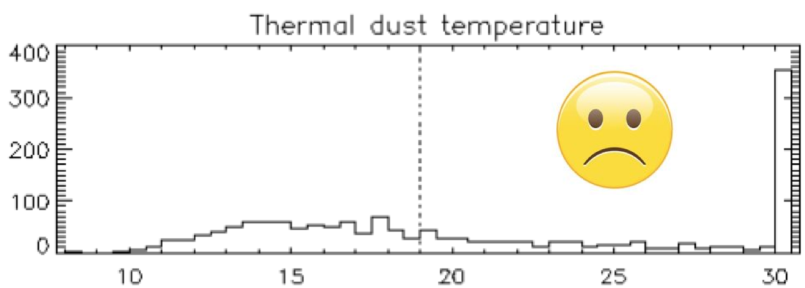
See talks by Aditya Rotti & Anna Mangilli

Moment expansion / effective modeling: dust temperature v.s. dust curvature

Example on LiteBIRD 40 – 400 GHz:

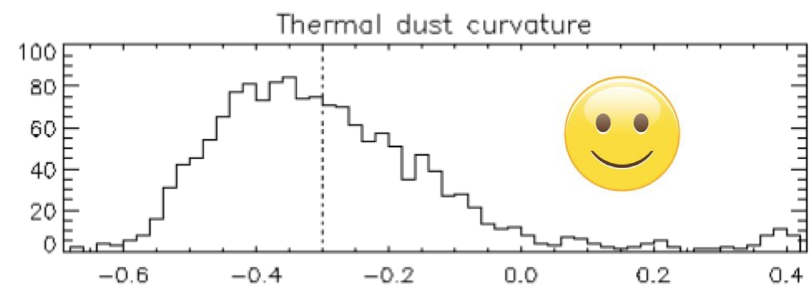
Modified blackbody

$$\left(\frac{\nu}{\nu_0}\right)^{\beta} B(\nu, \boldsymbol{T})$$



Curved power-law

$$\left(\frac{\nu}{\nu_0}\right)^{\beta}\left[1 + \boldsymbol{C}\left(\ln\left(\frac{\nu}{\nu_0}\right)\right)^2 + \cdots\right]$$



- *Without pivot frequencies* > 400 GHz, *dust temperature is not well constrained*
- *Curvature is local, thus better constrained than temperature over a narrow frequency range*

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Alternative methods #2: GNILC

Remazeilles, Delabrouille, Cardoso (2011)

Basic idea:

- Look for independent (not physical) foreground degrees of freedom over the sky and over the angular scales

  ⟶ *foreground subspaces*

- Focus ILC variance minimization into foreground subspaces instead of minimizing the variance of foregrounds + noise

Basic properties:

- Blind (no assumption on foregrounds)

  ⟶ *fairly insensitive to decorrelation / averaging effects*

- Local over the sky and over the scales (based on wavelets)

- Generalization of ILC: use not only spectral but also spatial information (angular power spectrum)

PICO data challenge:
A series of non-trivial sky simulations

Probe Mission Study Wiki

Recent changes Media Manager Sitemap

You are here: CMB Probe Mission Study Wiki » **20180424_dc_maps**

20180424_dc_maps

Data Challenge Maps I

Apr 24 2018, Clem Pryke

For CMB-S4 project we have made simulations using a number of different foreground models plus lensed-LCDM, noise and tensors. These are described at Data challenge summary page and in a series of logbook postings.

I have exploited this work for PICO to make equivalent sims.

Everything below is available on NERSC under /project/projectdirs/pico/

I first made PySM input maps for the PICO band centers as listed in the v3.2 spreadsheet at imageroptions. I did this for delta function bandwidths to keep things simple. Everything is nside=512.

Under sky_yy we have the sky models where yy designates the sky model number:

- 91=PySM a1d1f1s1
- 92=PySM a2d4f1s3
- 93=PySM a2d7f1s3
- 96=Brandon's MHD model taken from /global/homes/b/bhensley/mhd_maps/maps_v1 on 180424
- cmb = links to the cl's and alm's from which the LCDM component are generated (shared with Plank ffp10 sims)

Under expt_xx we just have single file 90/params.dat which specifies the instrument parameters for this round as taken from the v3.2 spreadsheet.

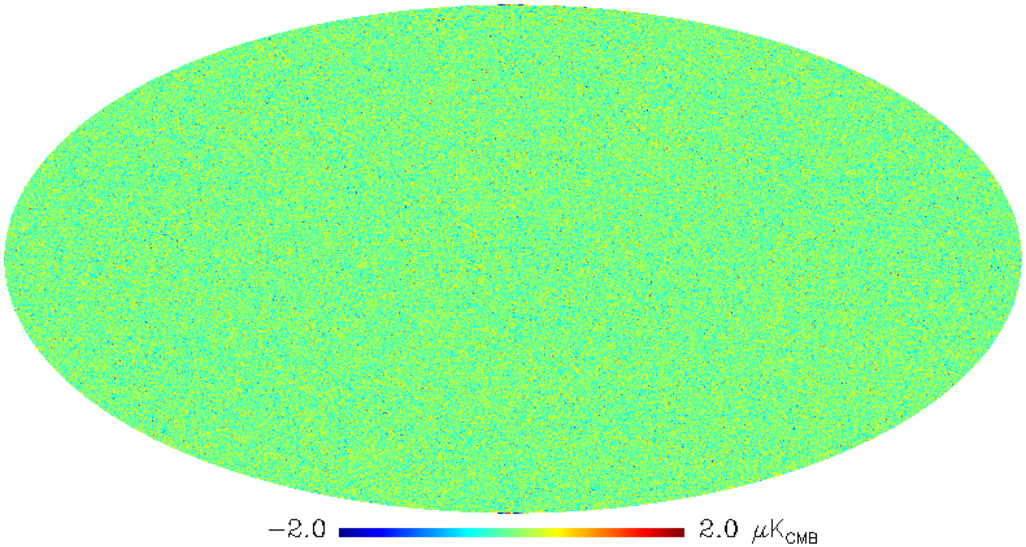
Under data_xx.yy we have the sets of simulated experimental maps. 90.00 contains the lensed-LCDM (llcdm), noise (noise) and tensor (tenso) components for each band. Noise levels are also as per the v3.2 spreadsheet. The signal components have beam smoothing applied with beam widths as per the v3.2 spreadsheet. There are also combined lLCDM+noise+foreground+tensor maps (comb). These come as four flavors. Straight “comb” has full lensing signal. The “comb_AL” variants have the lensing signal artificially suppressed to the given levels of lensing power. So “comb_AL0p15” is the amount of lensing PICO is supposed to have post de-lensing. “comb_AL0p1” and “comb_AL0p03” are also provided and might be useful.

For the 90.00 case the “foreground” is just Gaussian realizations of dust and synchrotron with uniform amplitude over the whole sky set to equal the observed amplitude in the BICEP/Keck patch. This is not a serious model and is intended only for test purposes. In particular it enables: a) To run full sky (unmasked) harmonic analysis - no need to deal with E/B mixing problems. b) The dust and synchrotron SED's are simple and uniform over the full sky so they can be fit as such. beta_dust=1.6, T_dust=19.6K, beta_sync=-3.1.

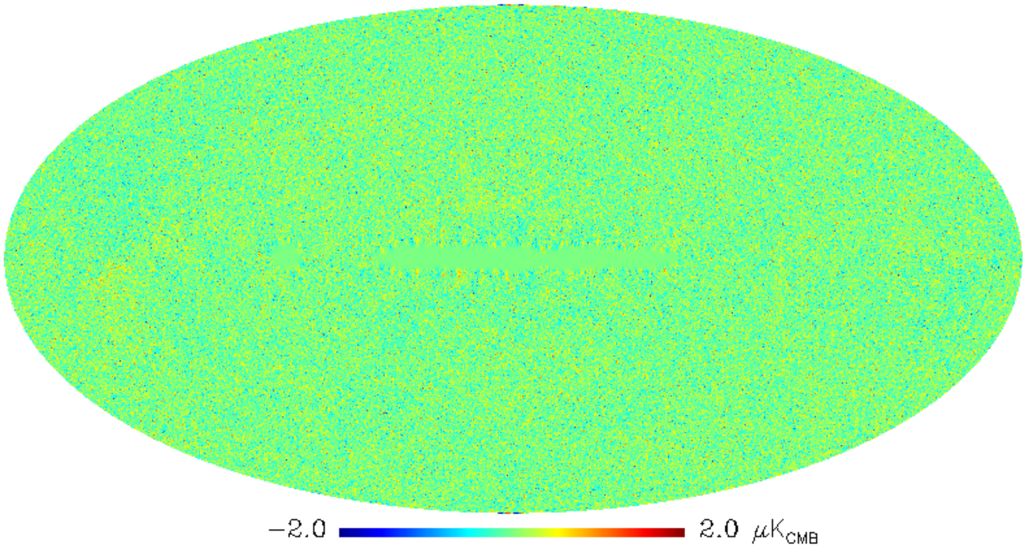
90.91, 90.92, 90.93 and 90.96 contains the combined maps for the proper sky models.

GNILC results on PICO 90.91 sim
5’ resolution

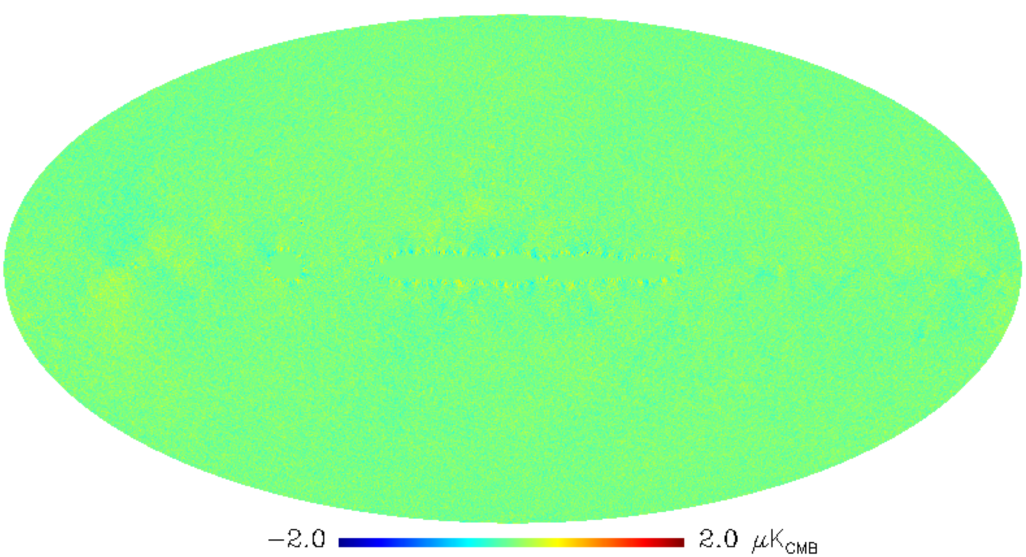
Input CMB B-mode map



GNILC CMB B-mode map



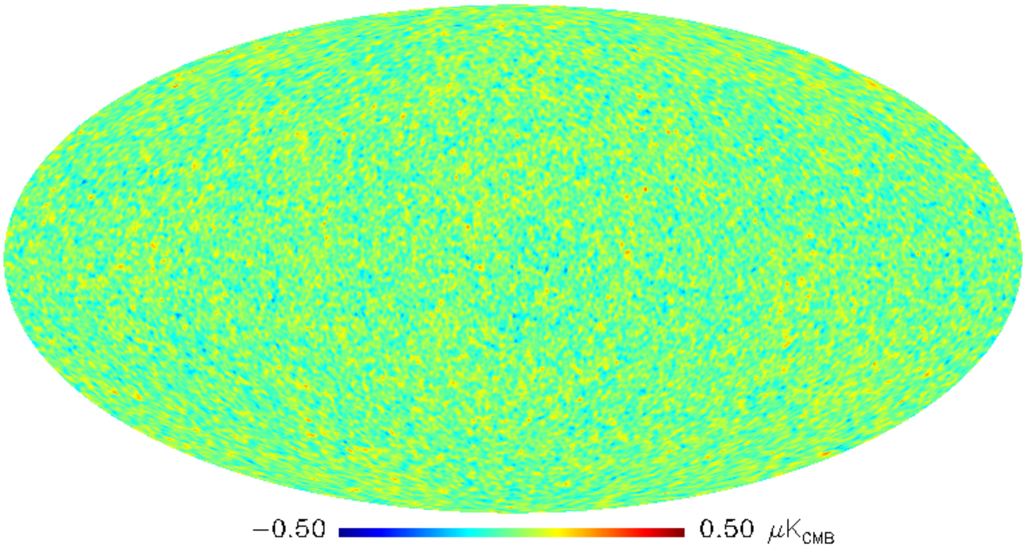
Residuals



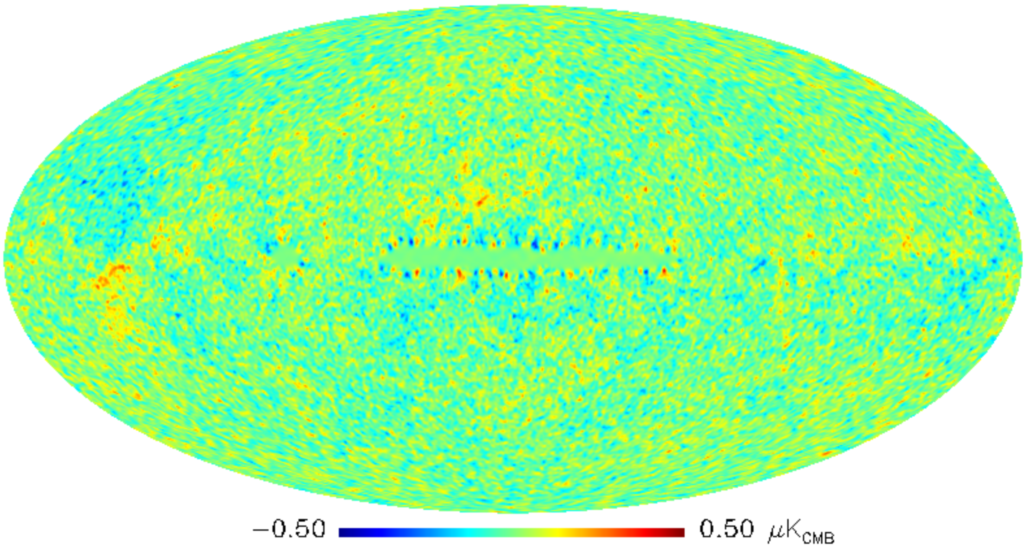
M. Remazeilles

GNILC results on PICO 90.91 sim
1 degree resolution

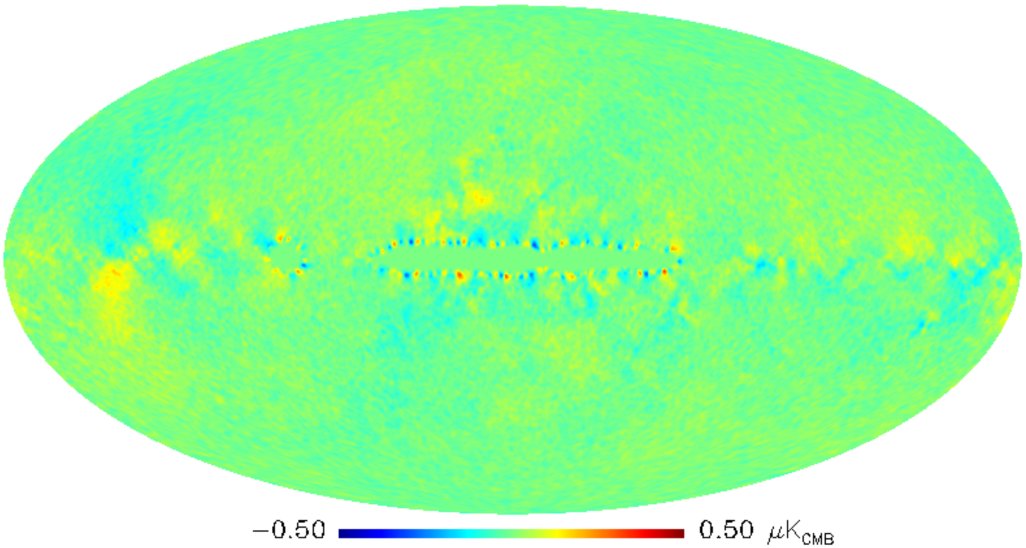
Input CMB B-mode map



GNILC CMB B-mode map



Residuals



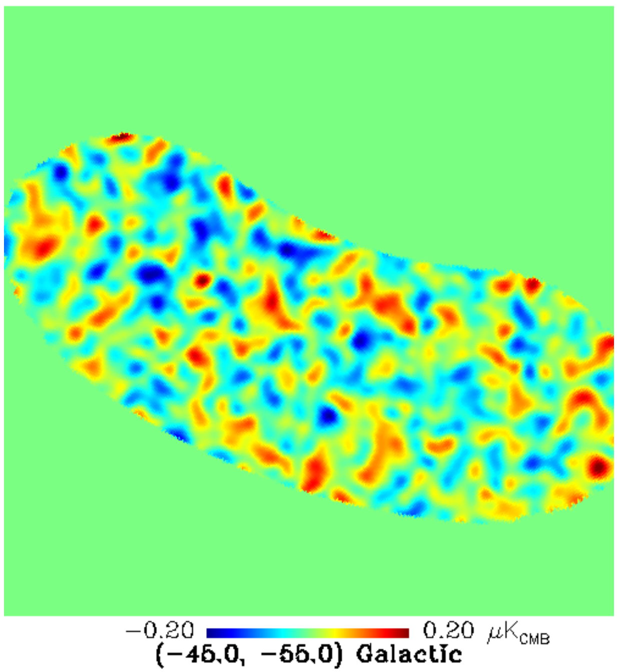
M. Remazeilles

GNILC results on PICO 90.91 sim

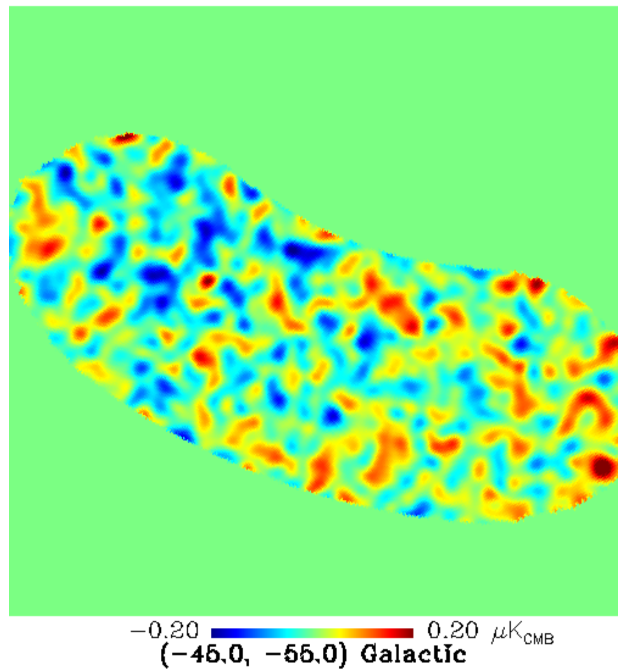
1 degree resolution

(zoom in BICEP2 field)

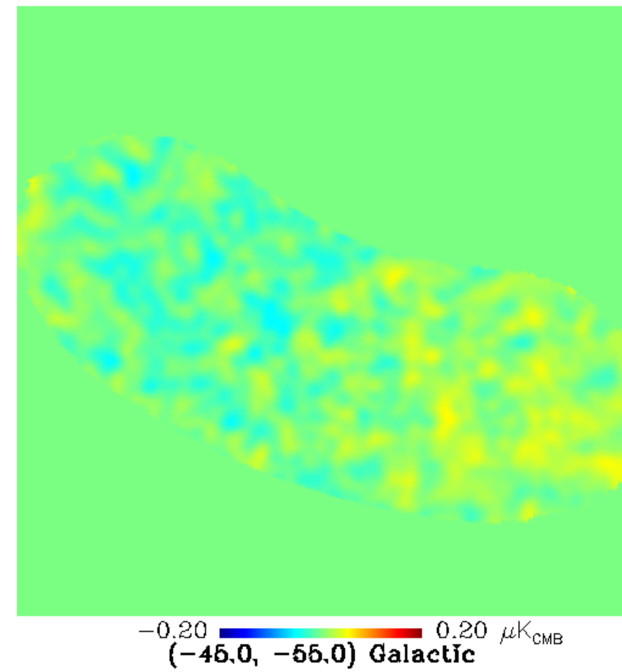
Input CMB B-modes



GNILC CMB B-modes

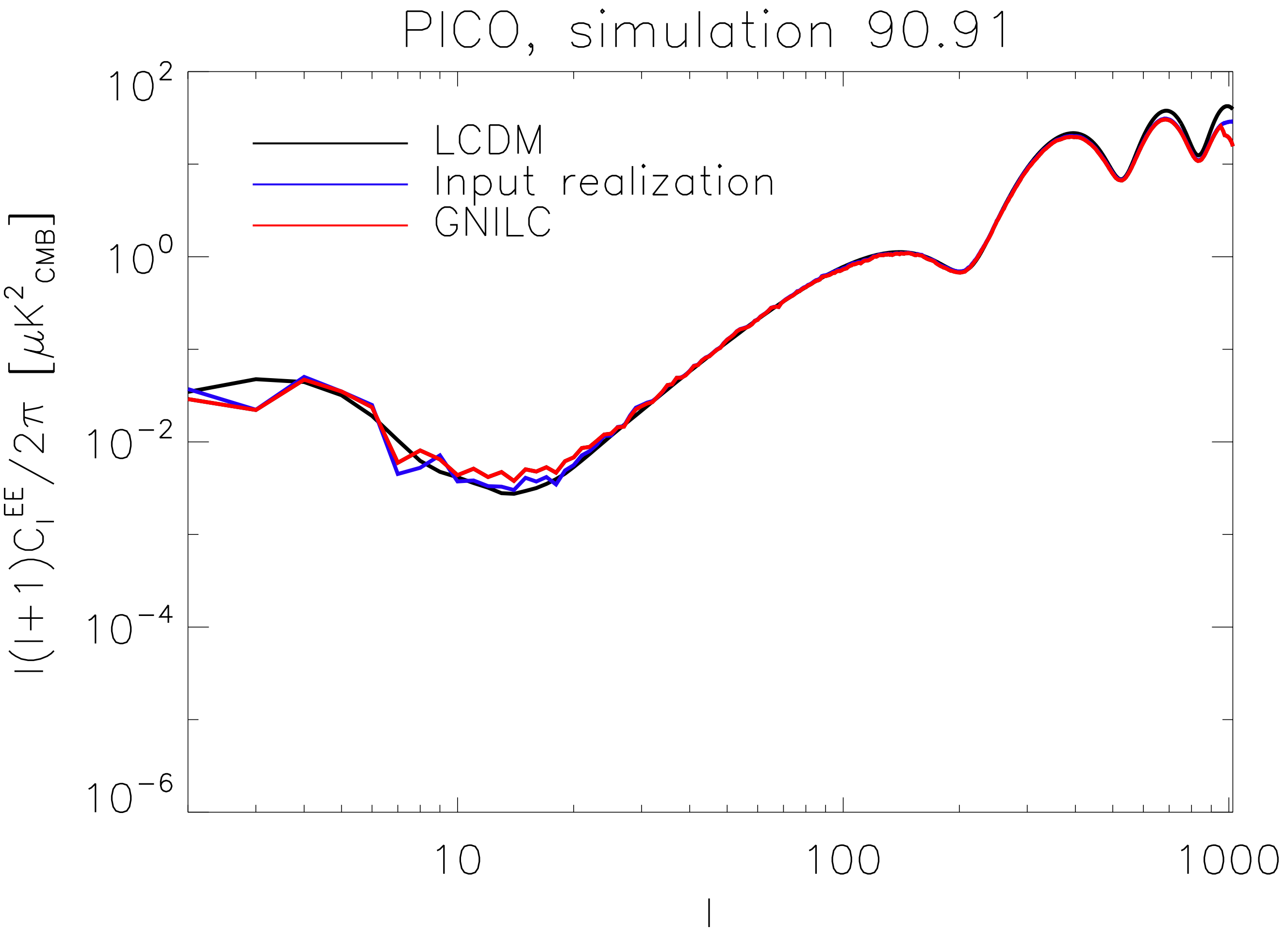


Residuals



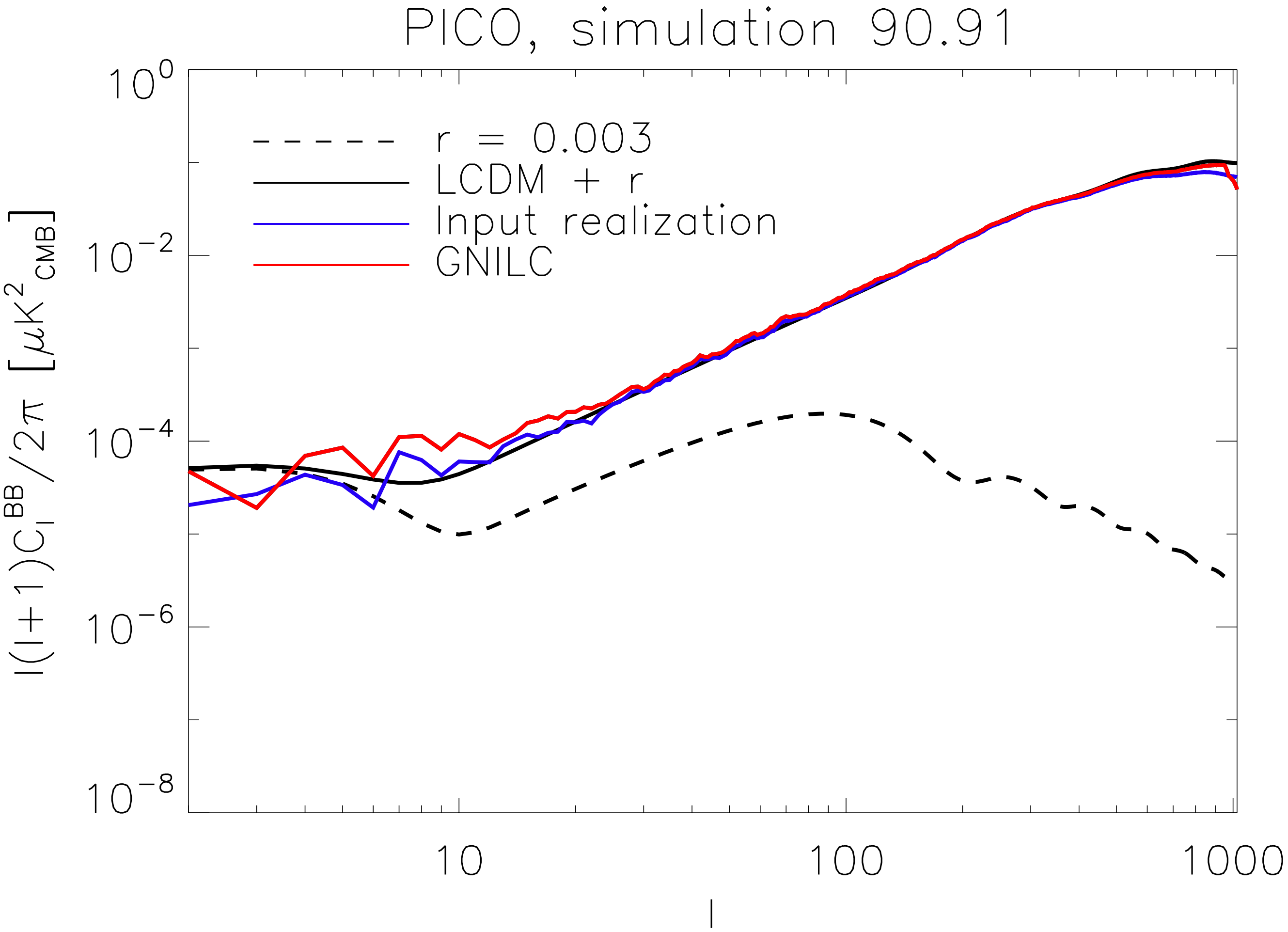
M. Remazeilles

GNILC EE reconstruction with PICO (90.91)



M. Remazeilles

GNILC BB reconstruction with PICO (90.91)



M. Remazeilles

Summary

After foregrounds cleaning (COMMANDER + SMICA / NILC) and 60% delensing,

- CORE (60-600 GHz) able to reconstruct the primordial CMB B-mode power spectrum at $r = 5\times10^{-3}$ on both reionization and recombination peaks without bias.
- CORE (60-600 GHz) able to detect $r = 5\times10^{-3}$ at 4σ significance without bias.
  → *allows to constrain Starobinsky's R^2 inflation model*

After foregrounds cleaning (COMMANDER),

- PICO (21-800 GHz) able to detect $r = 10^{-3}$ at 2.5σ significance without bias.
- Descoped PICO (43 – 462 GHz) fails to detect $r = 10^{-3}$ without post-marginalization over foreground residuals in the likelihood

General issues that future CMB B-mode experiments might be facing:

- Foreground mismodelling: omitting curvature, AME, dust components, decorrelation
- Lack of frequency range and spectral degeneracies: how to detect false detections of r ?
  → external low / high frequency data from ground / balloons might help in this case
- Averaging effects of foreground SEDs by pixelization / beam convolution

Need novel alternative approaches for new challenges: Moment expansion, GNILC, …

Thanks for your attention!