Reconstruction of the primordial CMB B-modes with CORE

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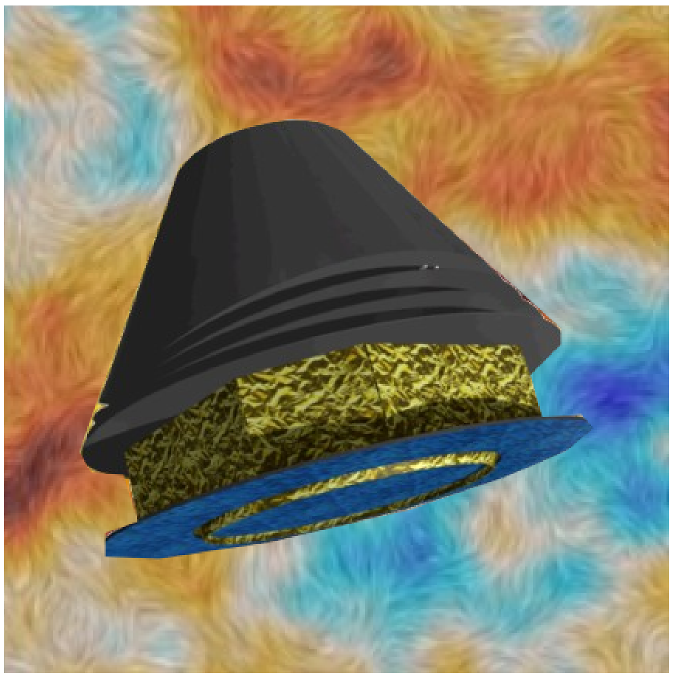
"Exploring Cosmic Origins with CORE : B-mode component separation"

Remazeilles et al., accepted by JCAP (2017)

arXiv:1704.04501

"Inflation and the cosmic microwave background"
Nordita, Stockholm, 17-21 Jul 2017

Primordial B-modes with CORE



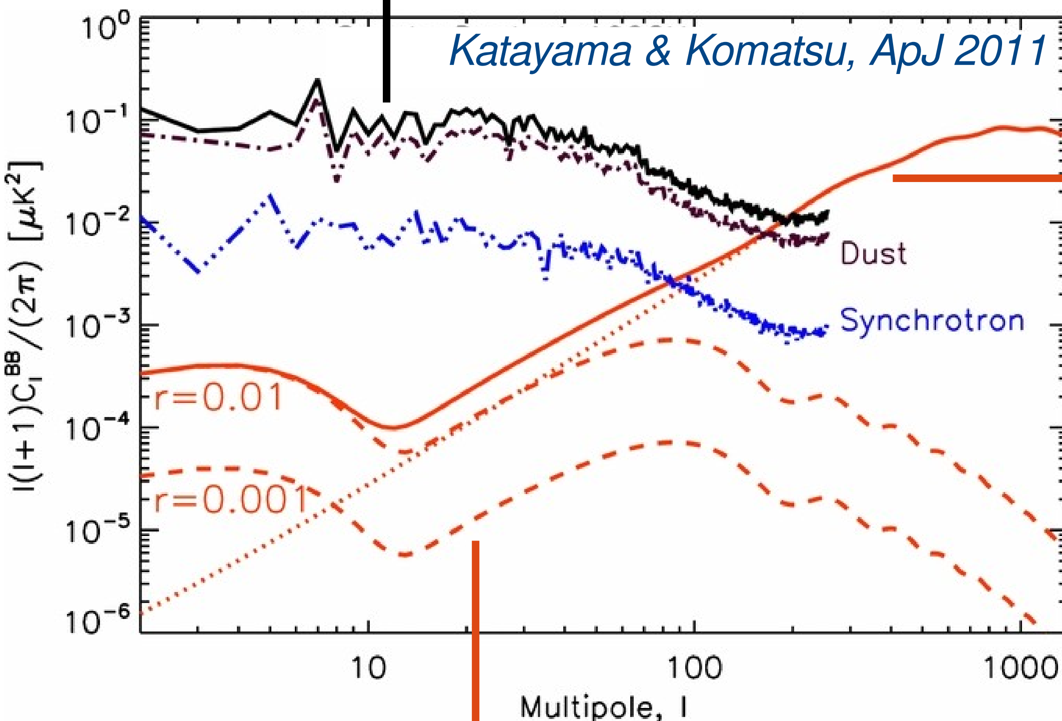
Exploring Cosmic Origins with CORE: B-mode Component Separation

M. Remazeilles,[1] A. J. Banday,[2,3] C. Baccigalupi,[4,5] S. Basak,[6,4] A. Bonaldi,[1] G. De Zotti,[7] J. Delabrouille,[8] C. Dickinson,[1] H. K. Eriksen,[9] J. Errard,[10] R. Fernandez-Cobos,[11] U. Fuskeland,[9] C. Hervías-Caimapo,[1] M. López-Caniego,[12] E. Martinez-González,[11] M. Roman,[13] P. Vielva,[11] I. Wehus,[9] A. Achucarro,[14,15] P. Ade,[16] R. Allison,[17] M. Ashdown,[18,19] M. Ballardini,[20,21,22] R. Banerji,[8] N. Bartolo,[23,24,7] J. Bartlett,[8] D. Baumann,[25] M. Bersanelli,[26,27] M. Bonato,[28,4] J. Borrill,[29] F. Bouchet,[30] F. Boulanger,[31] T. Brinckmann,[32] M. Bucher,[8] C. Burigana,[21,33,22] A. Buzzelli,[34,35,36] Z.-Y. Cai,[37] M. Calvo,[38] C.-S. Carvalho,[39] G. Castellano,[40] A. Challinor,[25] J. Chluba,[1] S. Clesse,[32] I. Colantoni,[40] A. Coppolecchia,[34,41] M. Crook,[42] G. D'Alessandro,[34,41] P. de Bernardis,[34,41] G. de Gasperis,[34,36] J.-M. Diego,[11] E. Di Valentino,[30,43] S. Feeney,[18,44] S. Ferraro,[45] F. Finelli,[21,22] F. Forastieri,[46] S. Galli,[30] R. Genova-Santos,[47,48] M. Gerbino,[49,50] J. González-Nuevo,[51] S. Grandis,[52,53] J. Greenslade,[18] S. Hagstotz,[52,53] S. Hanany,[54] W. Handley,[18,19] C. Hernandez-Monteagudo,[55] M. Hills,[42] E. Hivon,[30] K. Kiiveri,[56,57] T. Kisner,[29] T. Kitching,[58] M. Kunz,[59] H. Kurki-Suonio,[56,57] L. Lamagna,[34,41] A. Lasenby,[18,19] M. Lattanzi,[46] J. Lesgourgues,[32] A. Lewis,[60] M. Liguori,[23,24,7] V. Lindholm,[56,57] G. Luzzi,[34] B. Maffei,[31] C.J.A.P. Martins,[61] S. Masi,[34,41] D. McCarthy,[62] J.-B. Melin,[63] A. Melchiorri,[34,41] D. Molinari,[33,46,21] A. Monfardini,[38] P. Natoli,[33,46] M. Negrello,[16] A. Notari,[64] A. Paiella,[34,41] D. Paoletti,[21] G. Patanchon,[8] M. Piat,[8] G. Pisano,[16] L. Polastri,[33,45] G. Polenta,[65,66] A. Pollo,[67] V. Poulin,[32,68] M. Quartin,[69,70] J.-A. Rubino-Martin,[47,48] L. Salvati,[34,41] A. Tartari,[8] M. Tomasi,[26] D. Tramonte,[47] N. Trappe,[62] T. Trombetti,[21,33,22] C. Tucker,[16] J. Valiviita,[56,57] R. Van de Weijgaert,[71,72] B. van Tent,[73] V. Vennin,[74] N. Vittorio,[35,36] K. Young,[54] and M. Zannoni,[75,76] for the CORE collaboration.

Accepted by JCAP (2017)

Primordial CMB B-mode power spectrum

Astrophysical foregrounds



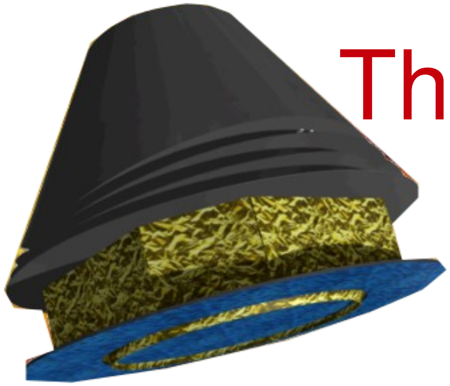
Gravitational lensing

Gravitational waves

- *r.m.s. fluctuations < 0.1 μK*
- *Obscured by very bright Galactic foregrounds*
- *Spurious lensing B-modes*

- CMB B-modes on large scales = signature of primordial gravitational waves predicted by inflation
- The amplitude (tensor-to-scalar ratio) depends on the energy scale of inflation:

$$r = 0.008 \times (E_{inf} / 10^{16}\ \text{GeV})^4$$



The space mission concept CORE

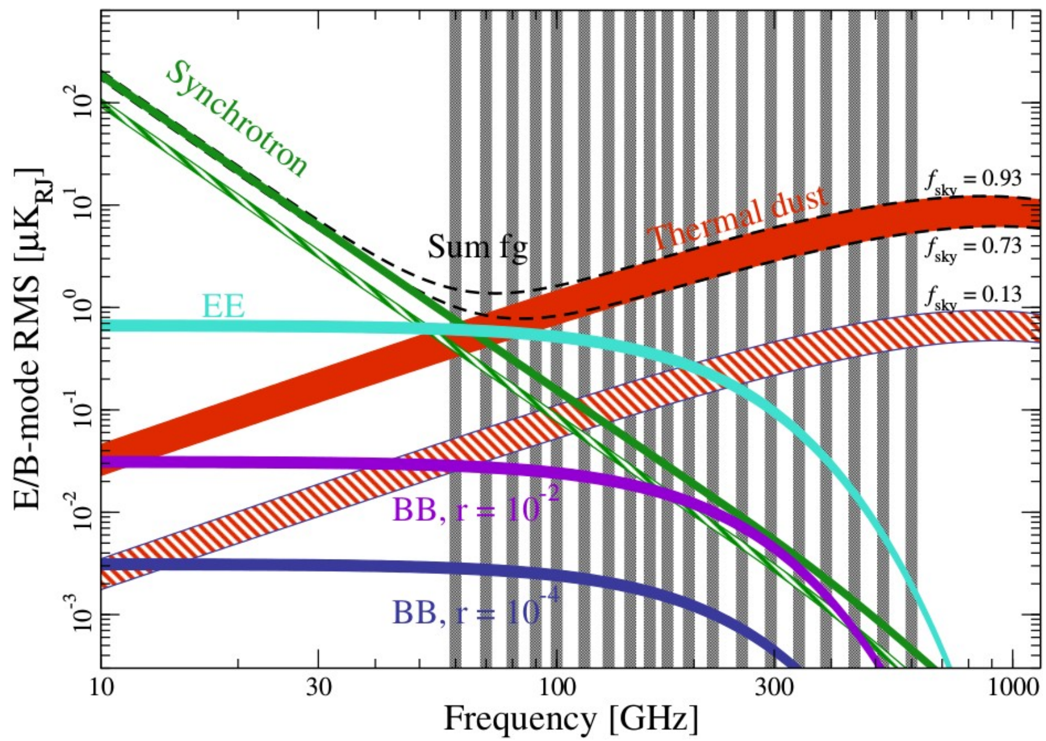
Frequency [GHz]	Beam [arcmin]	Q and U noise RMS [μK.arcmin]
60	17.87	10.6
70	15.39	10.0
80	13.52	9.6
90	12.08	7.3
100	10.92	7.1
115	9.56	7.0
130	8.51	5.5
145	7.68	5.1
160	7.01	5.2
175	6.45	5.1
195	5.84	4.9
220	5.23	5.4
255	4.57	7.9
295	3.99	10.5
340	3.49 (4.0)	15.7
390	3.06 (4.0)	31.1
450	2.65 (4.0)	64.9
520	2.29 (4.0)	164.8
600	1.98 (4.0)	506.7

- **Full-sky**
- **19 frequency bands in range 60 – 600 GHz**
- Aggregate **sensitivity** in polarization ~ **2 μK.arcmin**
- **High resolution** allowing for **60% delensing**

  – Challinor et al 2017, for the CORE collab. –

– Delabrouille et al 2017, for the CORE collaboration –

Primordial B-mode vs foregrounds



Foreground minimum at ~70 GHz on degree scales (but scale-dependent)

- Polarization <u>less complex</u> than intensity (less foreground components) but <u>more difficult</u> (requires higher precision since CMB signal is much weaker)

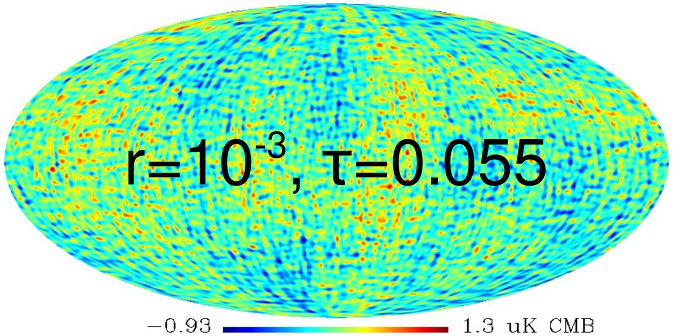
- Foregrounds cannot be avoided by limiting the frequency range of observations to high frequencies :

  → at ~300 GHz, Synchrotron has same amplitude and color than CMB B-modes ($r=10^{-2}$) !

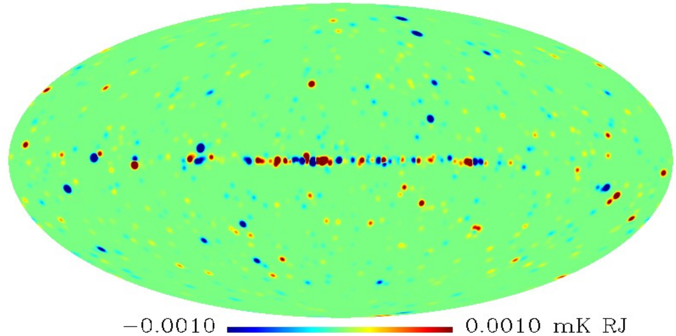
Remazeilles et al 2017, for the CORE collaboration

Sky simulation: Q Stokes polarization maps

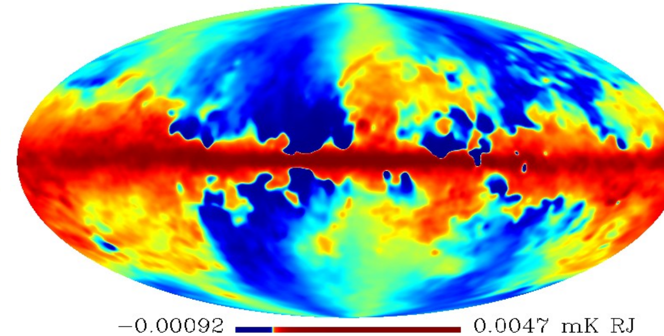
Lensed CMB



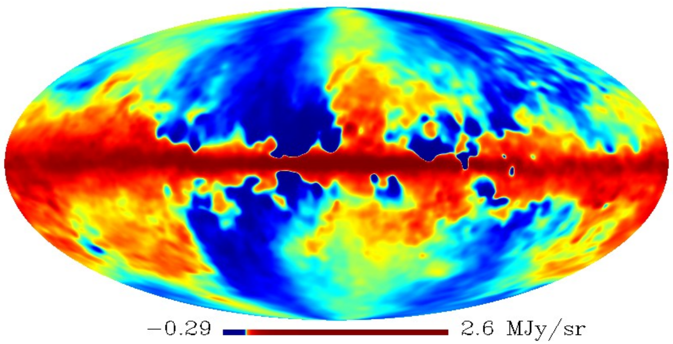
Radio & IR sources



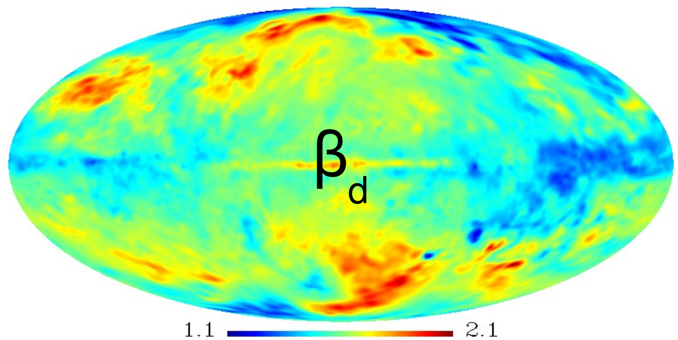
AME (1% polar), 60 GHz



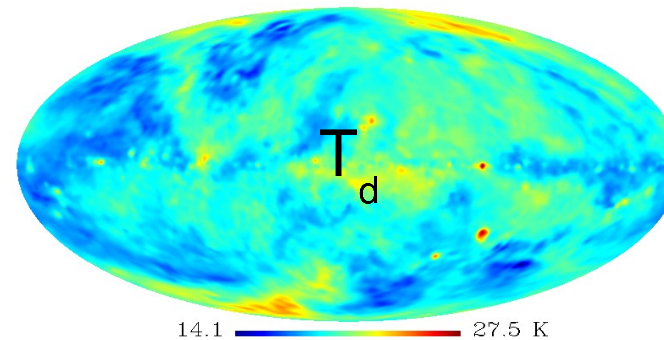
Thermal dust, 353 GHz



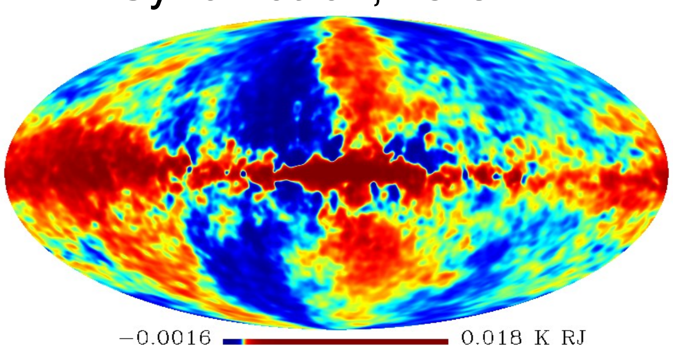
Dust spectral index



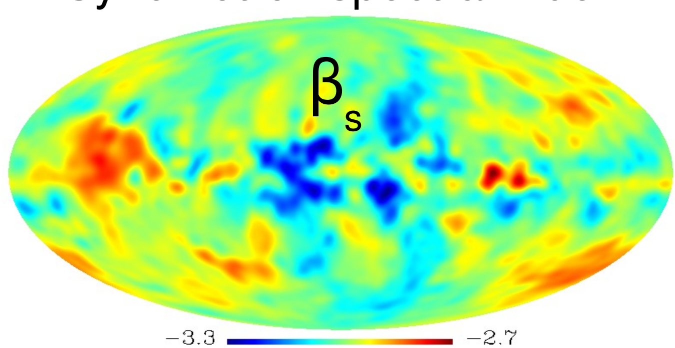
Dust temperature



Synchrotron, 23 GHz



Synchrotron spectral index



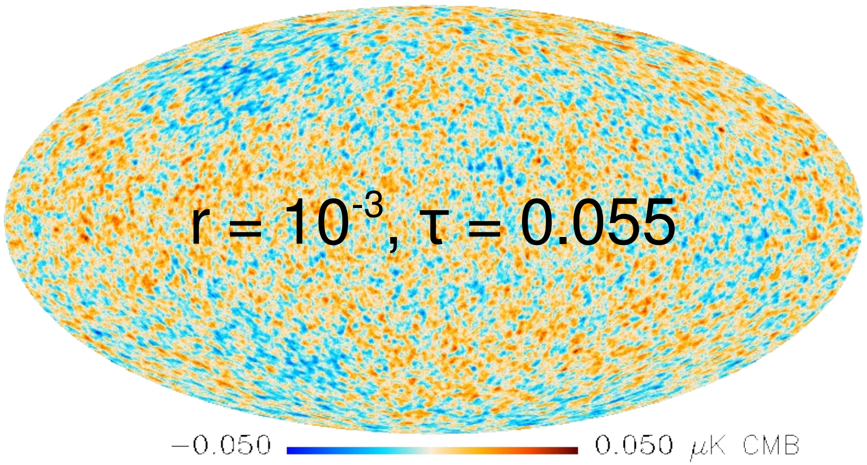
smoothed to 1°
for illustration purposes

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

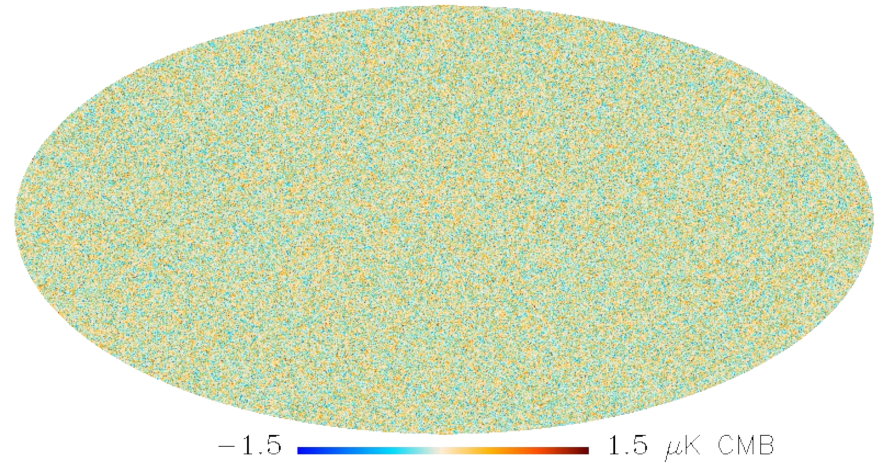
Remazeilles et al 2017,
for the CORE collaboration

Sky simulation: B-mode polarization maps

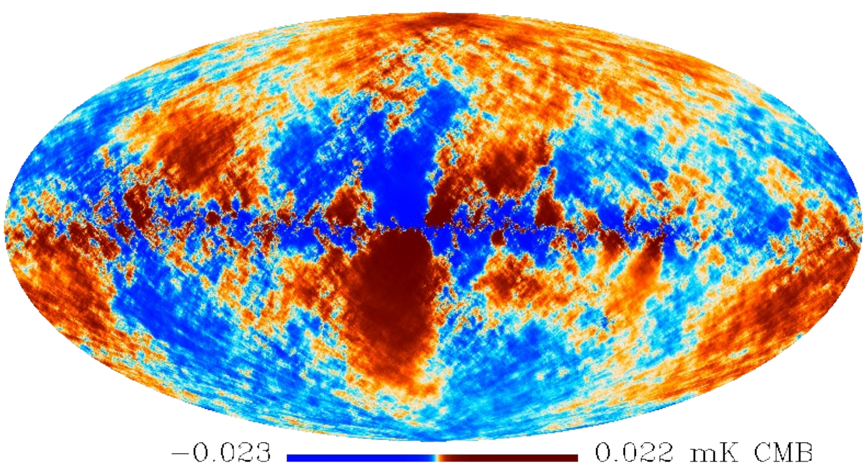
Primordial CMB B-modes



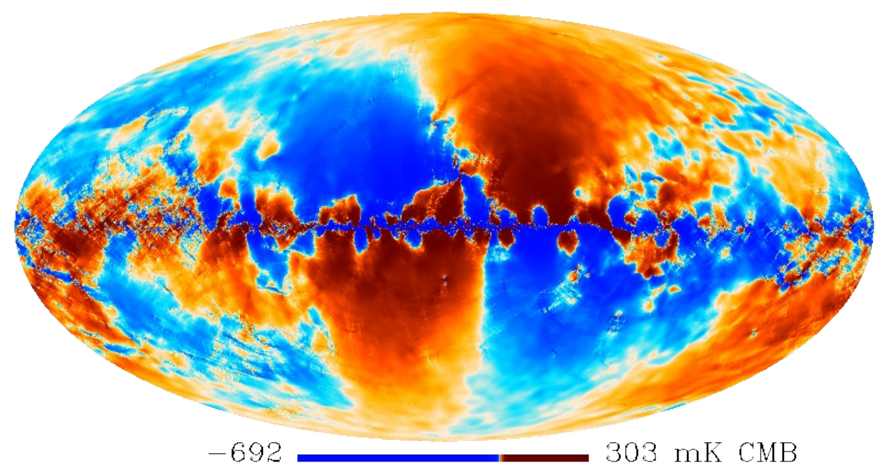
Lensed CMB B-modes



Synchrotron B-modes



Dust B-modes



Remazeilles et al 2017,
for the CORE collaboration

Component separation methods

Three independent methods, either blind or parametric:

- `Commander` – *Eriksen et al 2004, 2008 ; Remazeilles et al 2016*

  Bayesian parametric fitting with MCMC Gibbs sampling

  Spectral fitting in pixel space

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

  Spectral Matching Independent Component Analysis

  Power spectrum fitting in harmonic space

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

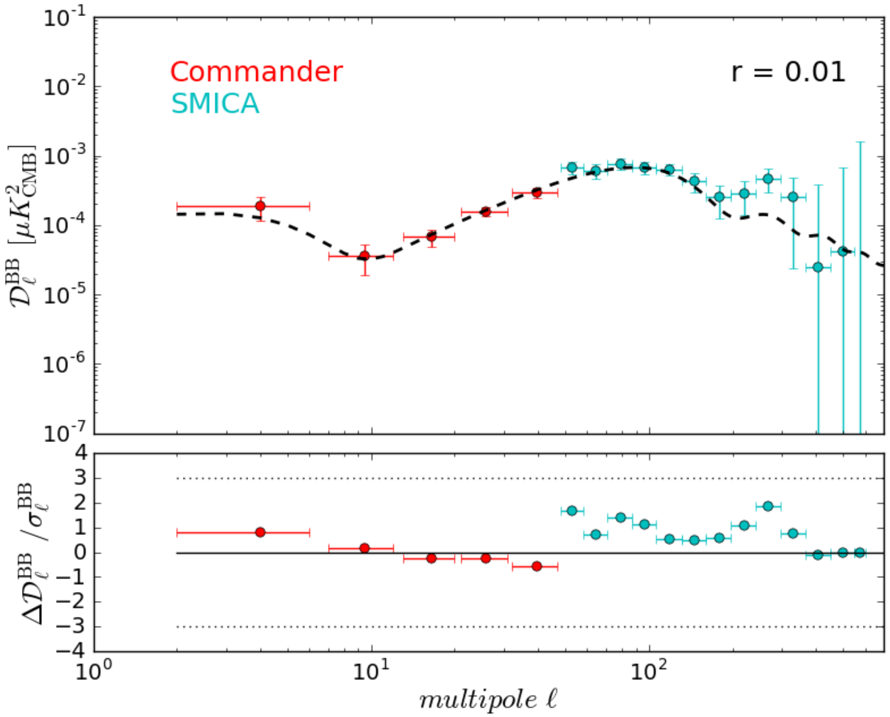
  Needlet Internal Linear Combination

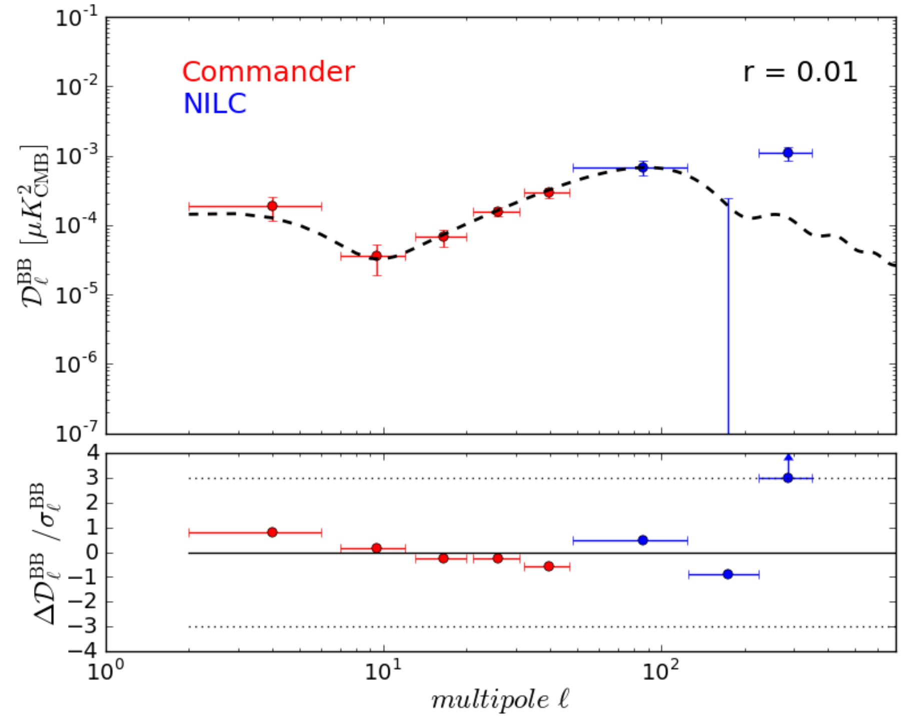
  Constrained variance minimization in wavelet space

These algorithms have been thoroughly and successfully used on Planck data!

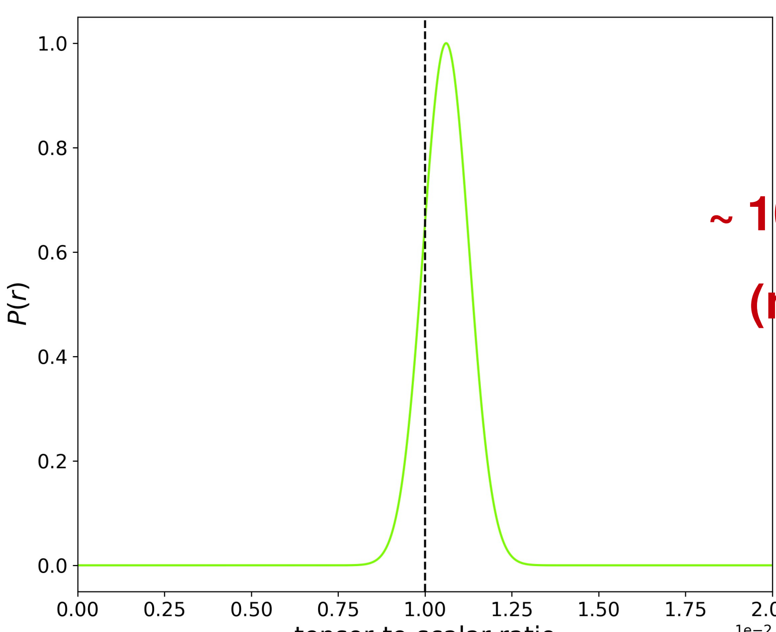
– Planck 2015 results. IX., A&A 2016

CORE reconstruction of the primordial B-mode



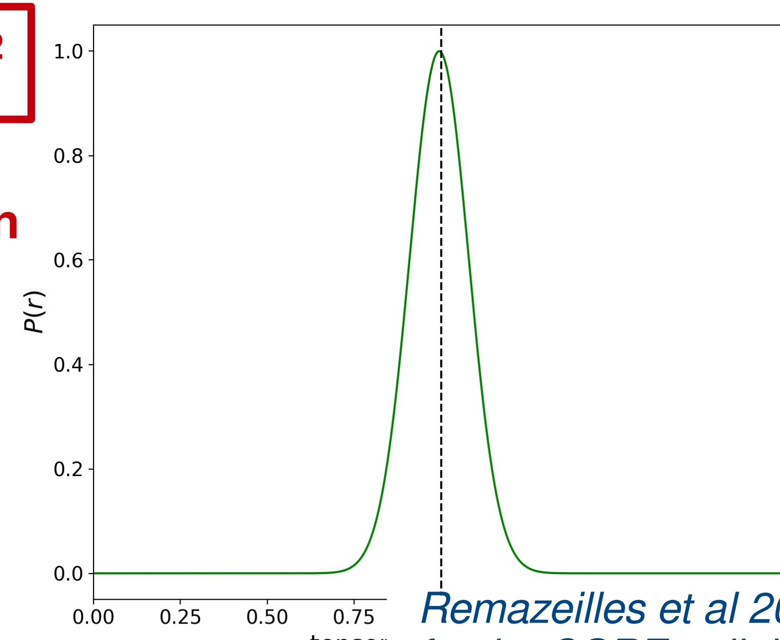


$r = 10^{-2}$



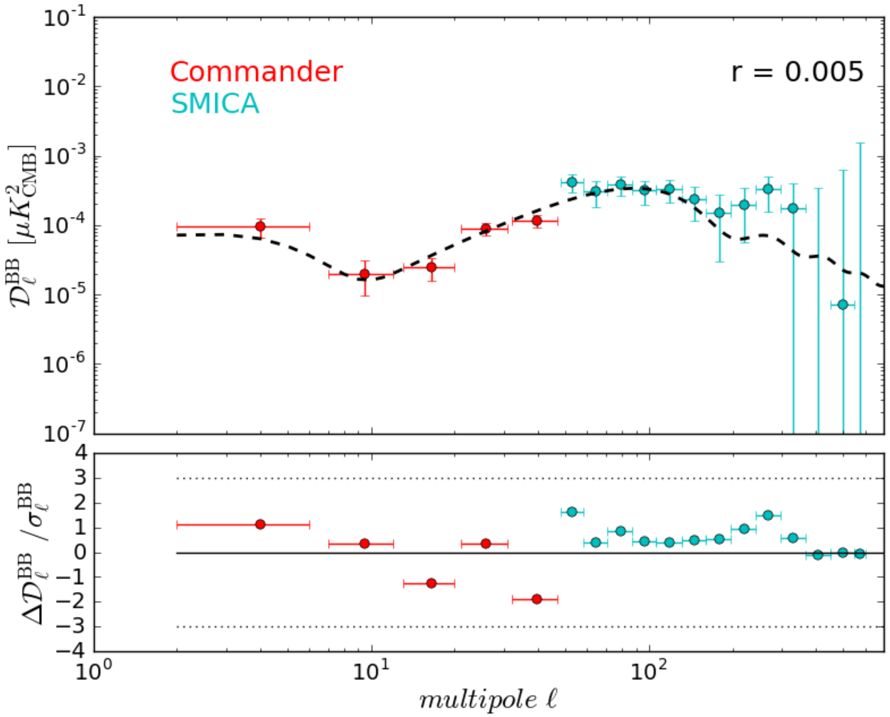
~ 10σ detection

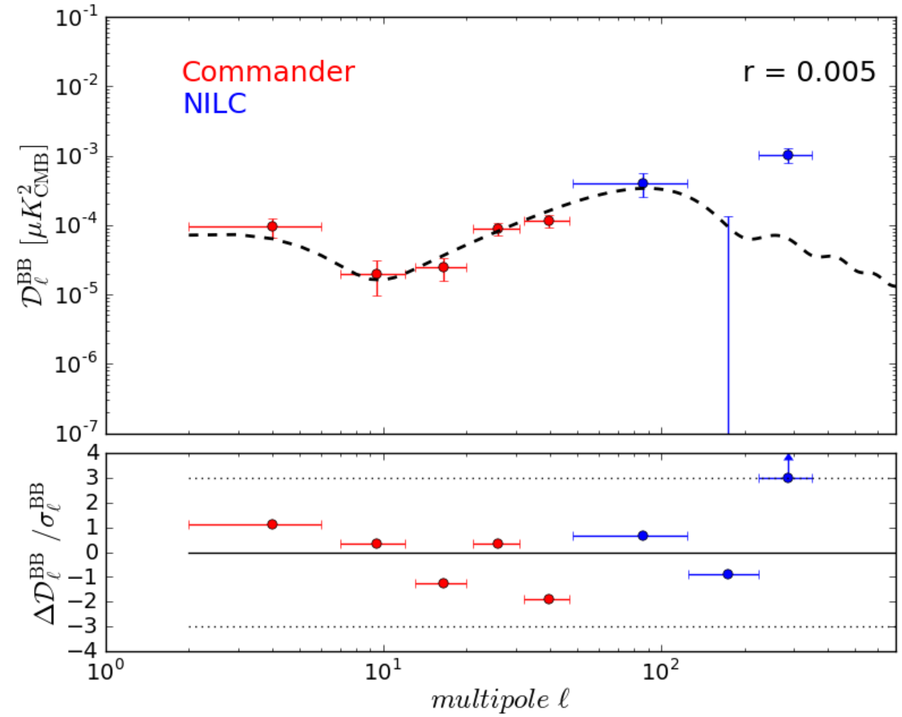
(no lensing)



Remazeilles et al 2017, for the CORE collaboration

CORE reconstruction of the primordial B-mode

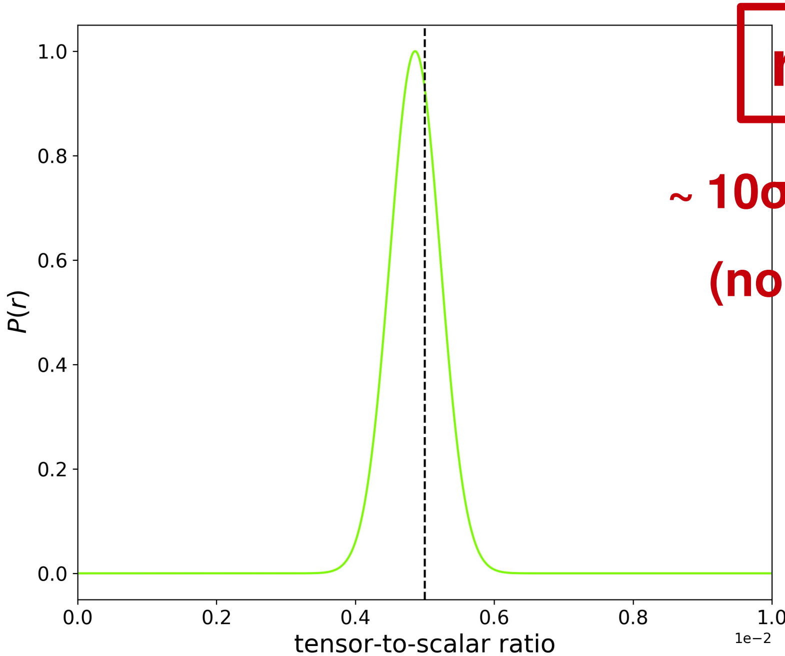


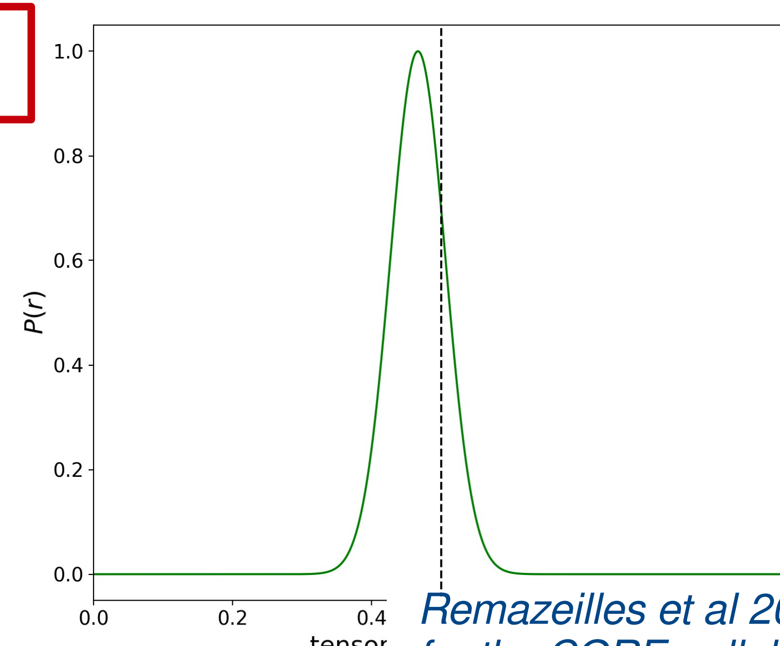


r = 5x10^{-3}

~ 10σ detection

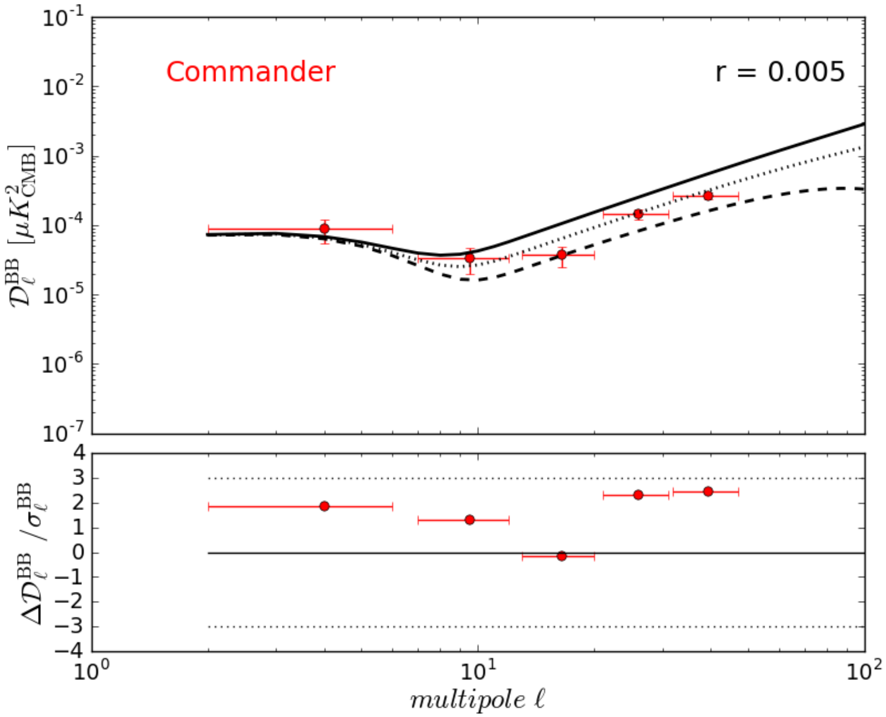
(no lensing)

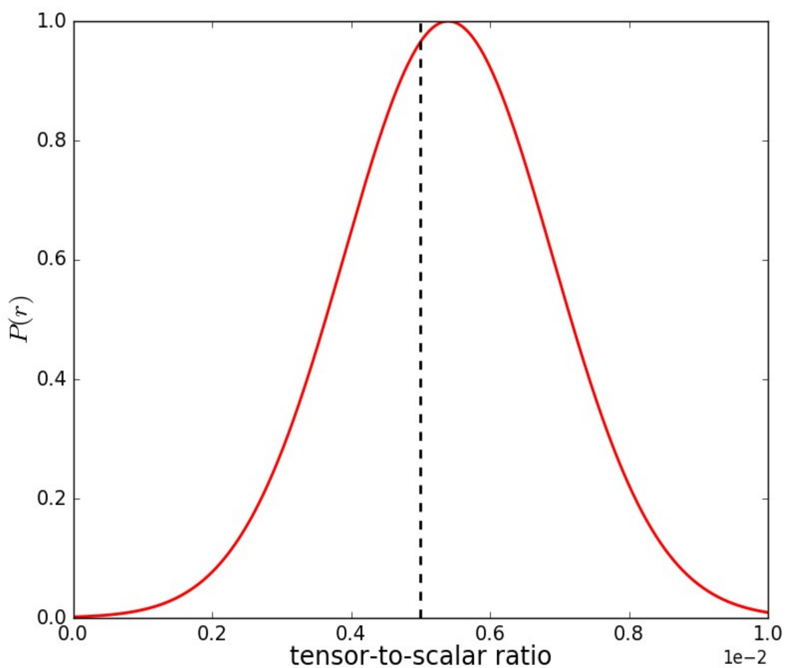




Remazeilles et al 2017,
for the CORE collaboration

CORE reconstruction of the primordial B-mode





After foregrounds cleaning

and 60% delensing:

$r = (5.4 \pm 1.5) \times 10^{-3}$

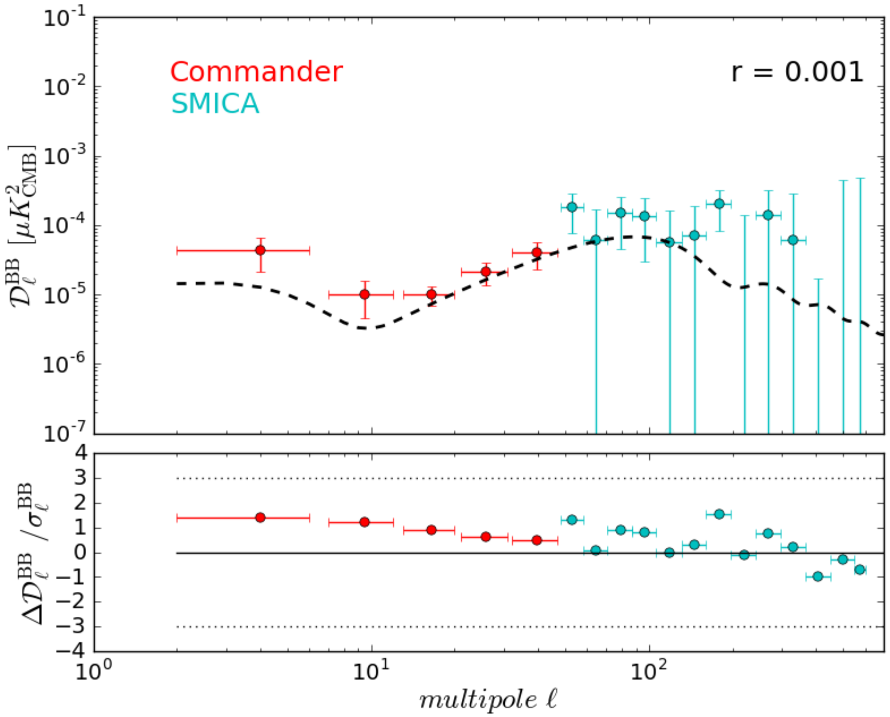
$\boxed{r = 5\times10^{-3}}$

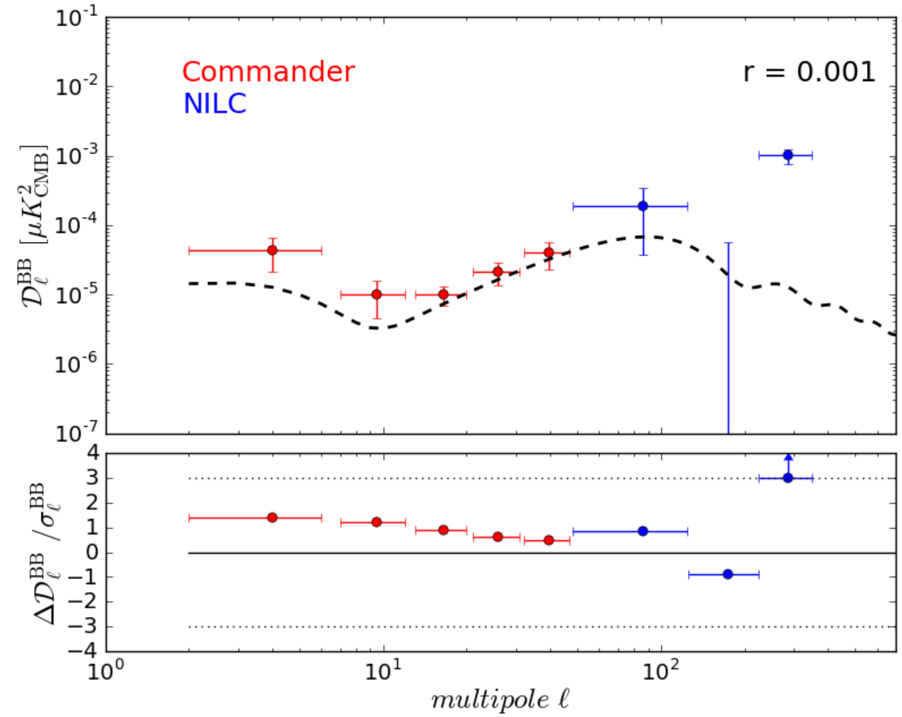
~ 4σ detection

(with lensing)

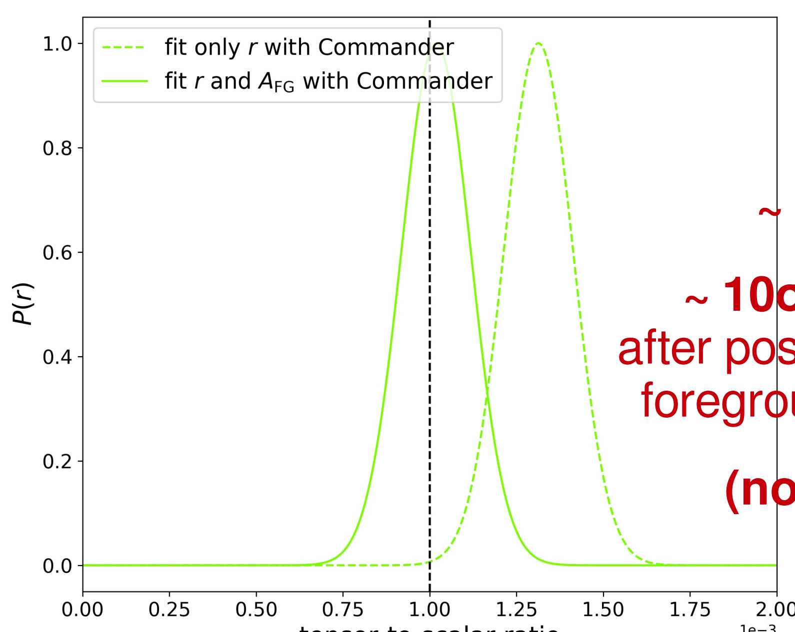
Remazeilles et al 2017,
for the CORE collaboration

CORE reconstruction of the primordial B-mode





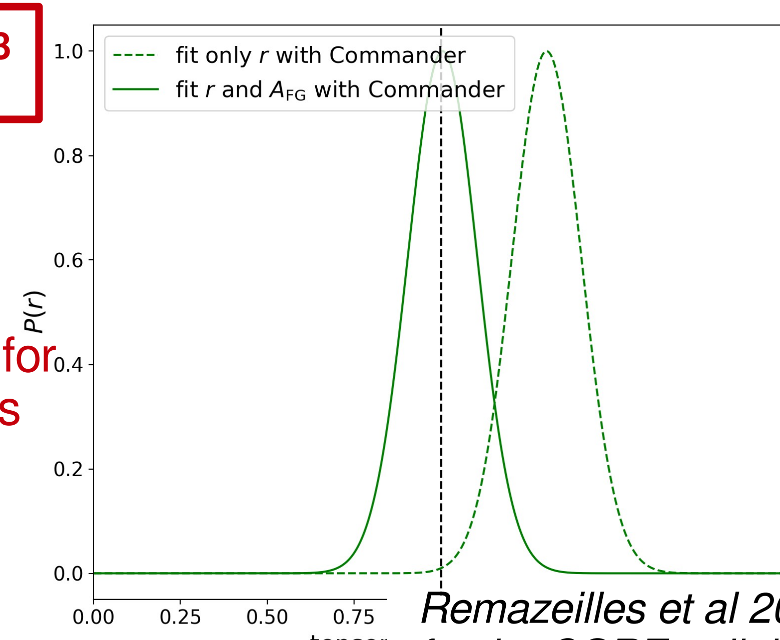
r = 10^{-3}



~ 3σ bias

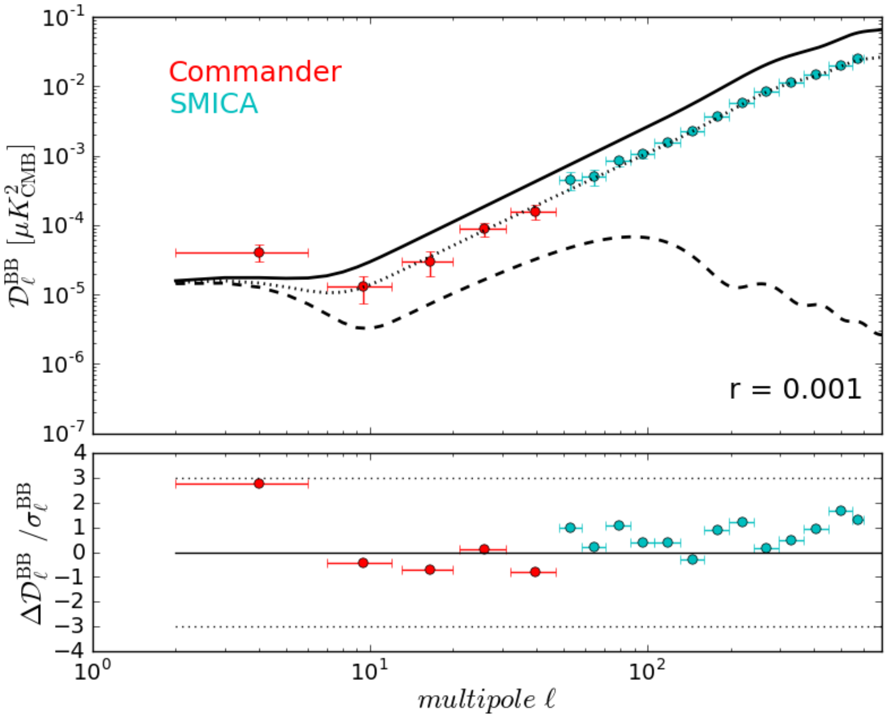
~ 10σ detection
after post-correction for foreground residuals

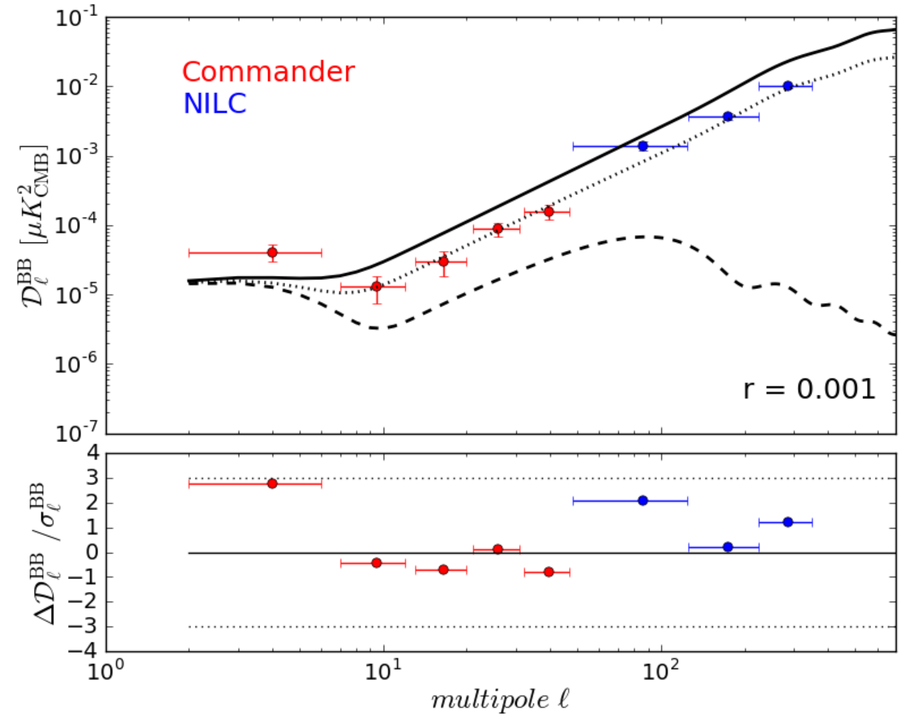
(no lensing)



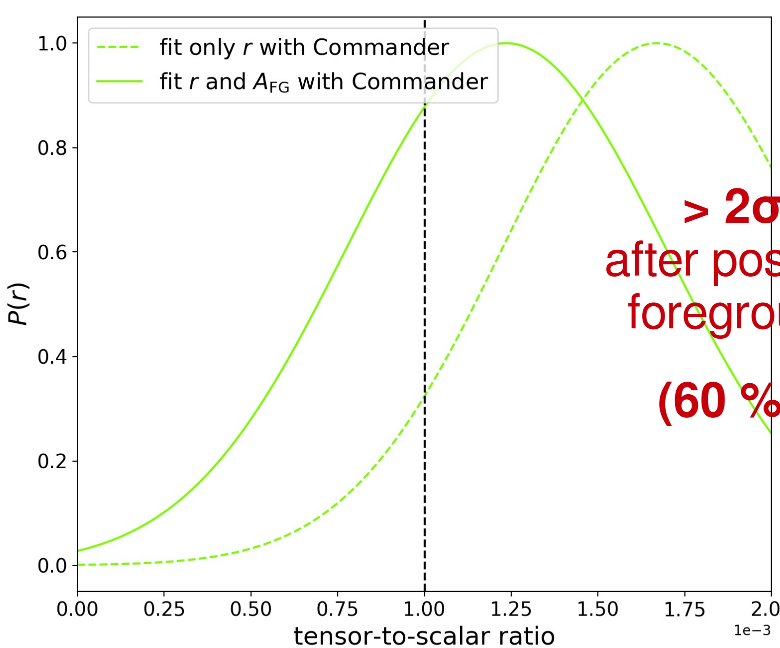
Remazeilles et al 2017, for the CORE collaboration

CORE reconstruction of the primordial B-mode



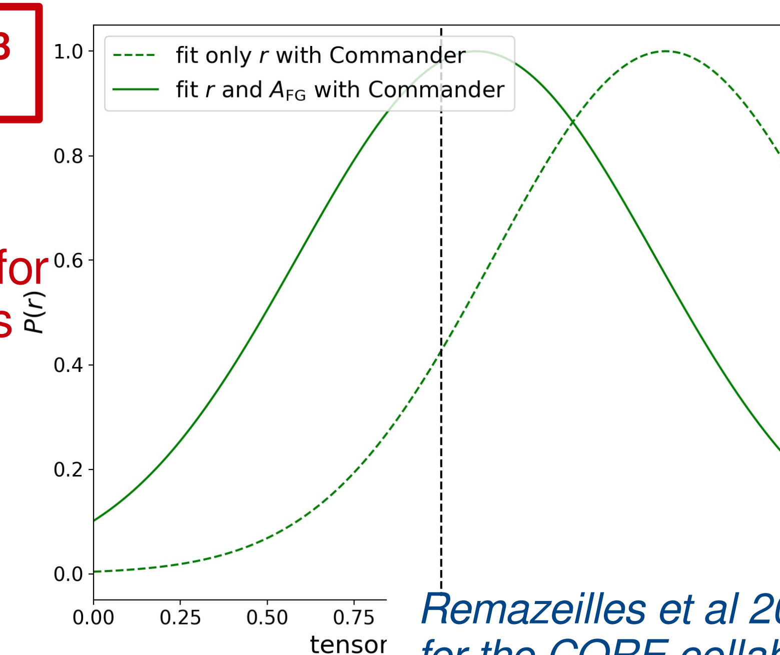


$r = 10^{-3}$



> 2σ detection
after post-correction for foreground residuals

(60 % delensing)

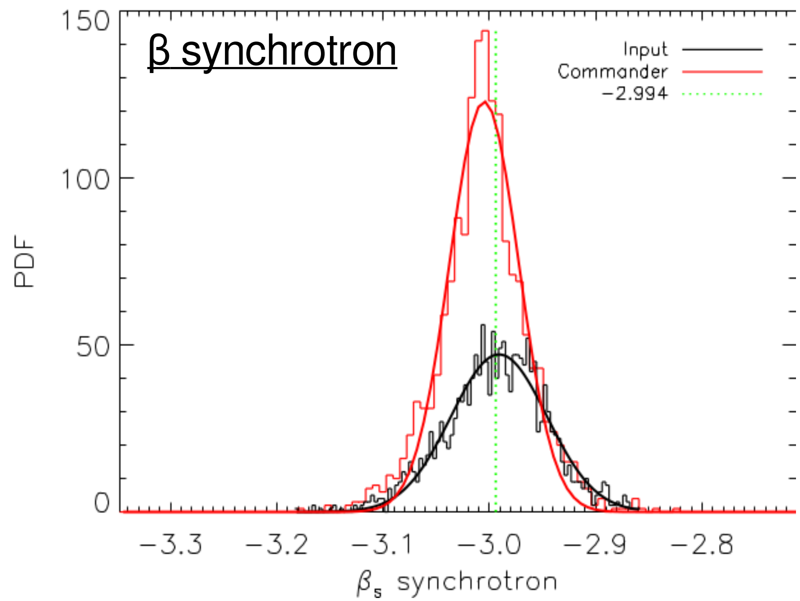


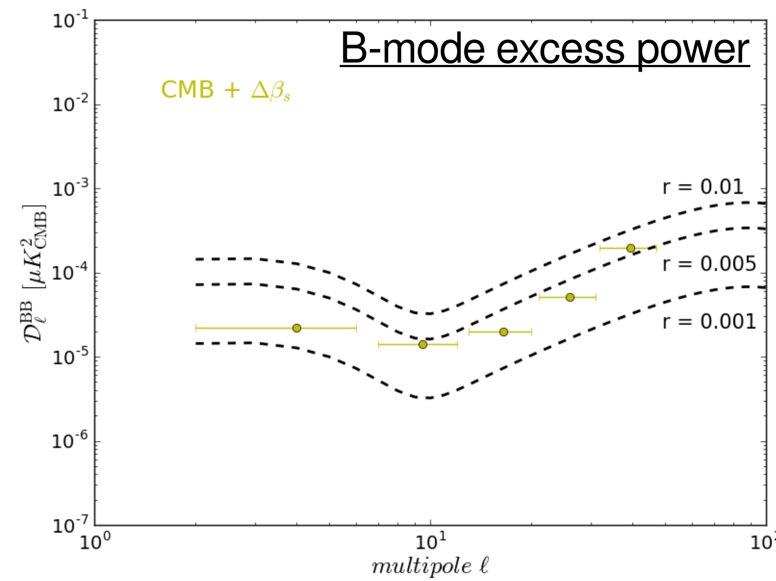
Remazeilles et al 2017, for the CORE collaboration

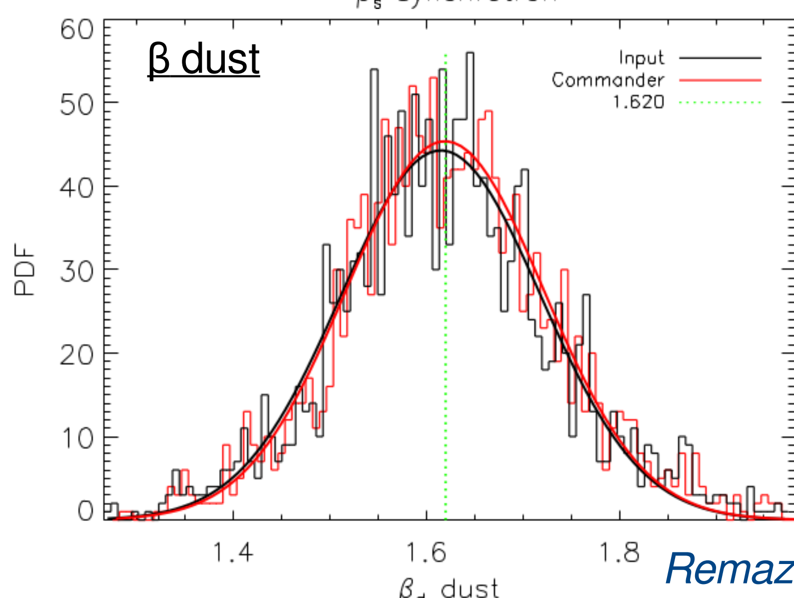
Issue #1: Required precision on synchrotron?

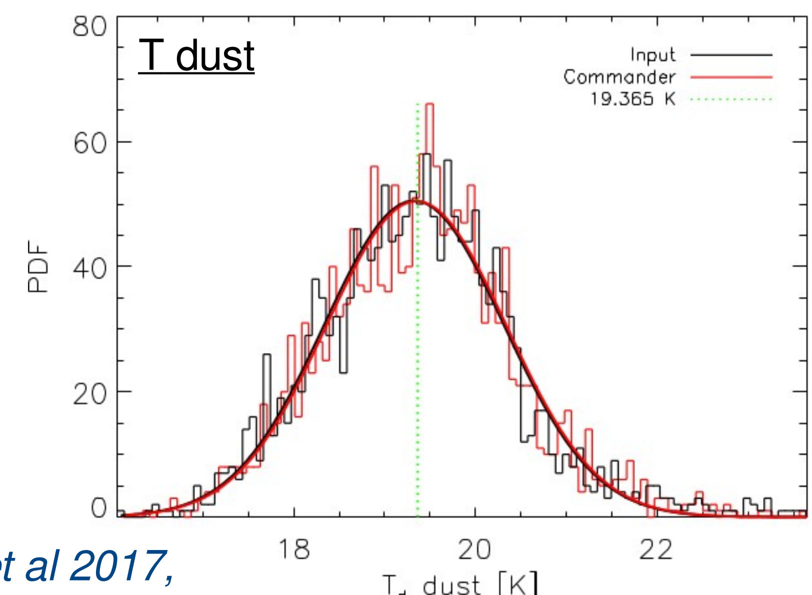
- Is the frequency range [60 – 600 GHz] sufficient to fit for synchrotron at the <u>required precision</u>?

Errors $\Delta\beta_{synchrotron}$ ~ 0.02 $\Rightarrow$ Error Δr ~ 10^{-3} !





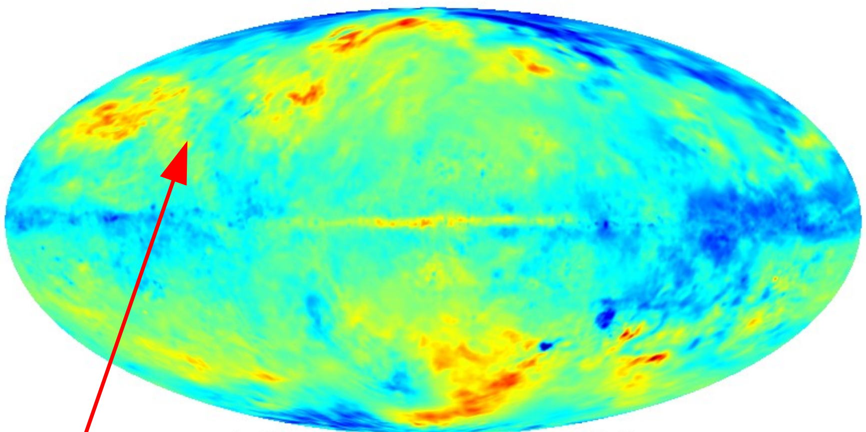




Remazeilles et al 2017,
for the CORE collaboration

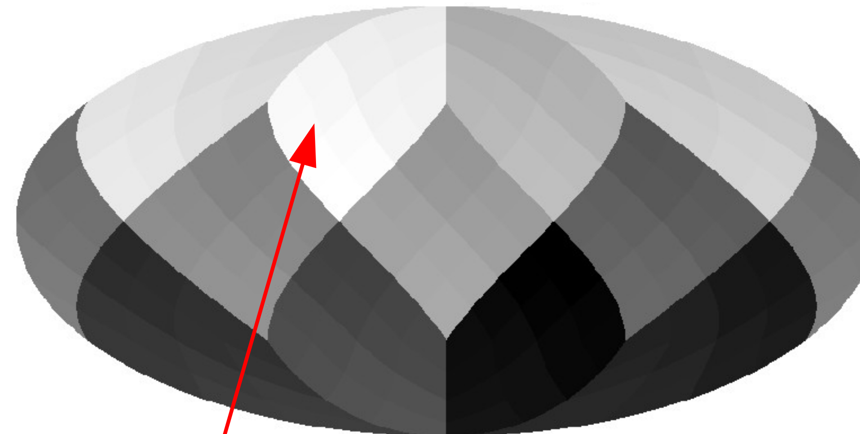
Issue #2: Averaging of dust spectral indices within pixels / beams

Dust spectral indices in the sky



one β_{dust} value per line-of-sight

Map pixelization



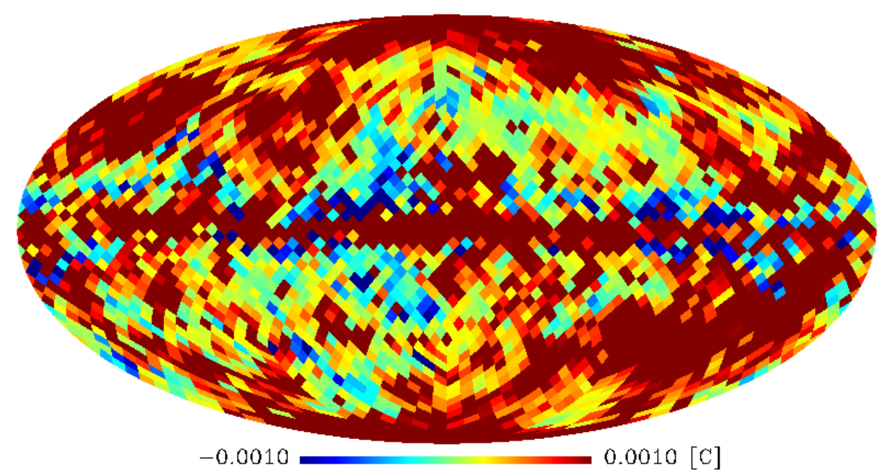
many β_{dust} values per pixel

<u>Effect of averaged power-law indices within pixels / beams</u>:

spurious curvature $C \neq 0$ in the foreground spectral distribution!

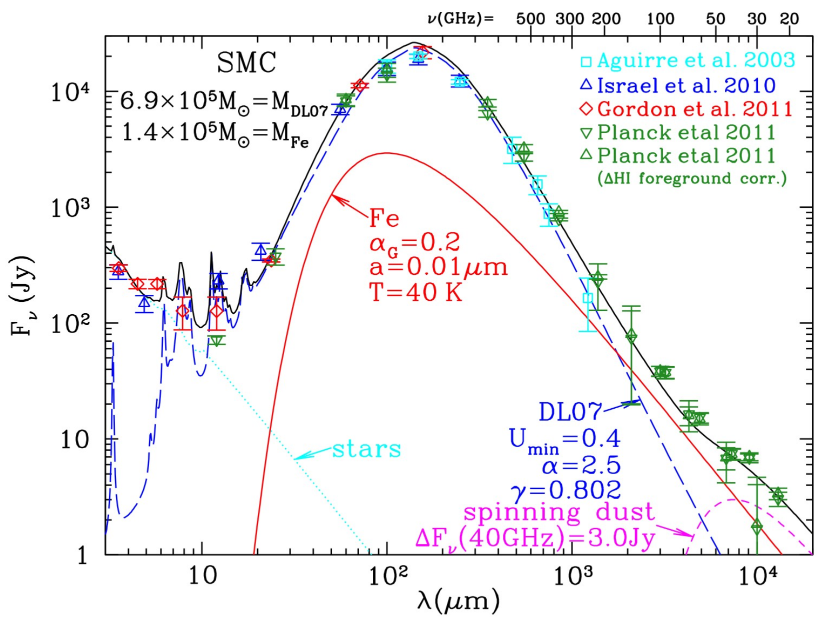
– Chluba et al 2017 –

– Remazeilles et al 2017, for the CORE collaboration –

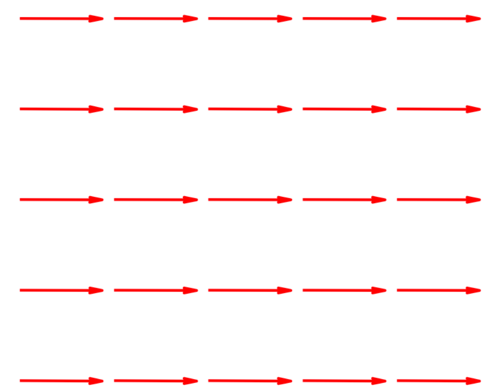


Result of fitting $\nu^{\beta + C^{*}\log(\nu)}$ when $C = 0$ on degraded pixelization

Issue #3: What about magnetic dust?



Draine & Hensley 2013



Ferromagnetic lattice with spins aligned.

Thermal fluctuations will move them away, producing magnetic dipole radiation

- Diffuse magnetic dust (MD) not yet observed (we need observations!)
- Theoretically, MD is <u>highly polarized</u> ~35%
- In SMC, MD shows <u>spectral degeneracy</u> with CMB around 100 GHz !
- We may need component-separation methods that use both spectral and spatial correlations

  e.g. a la `GNILC` – *Remazeilles et al 2011 ; Planck intermediate result XLVIII*

Conclusions

<u>After foregrounds cleaning and 60% delensing,</u>

- CORE enables to measure the primordial CMB B-mode power spectrum at both <u>reionization</u> and <u>recombination</u> peaks without bias.

- CORE enables to measure $r = 5 \times 10^{-3}$ at 4σ significance without bias.

  CORE allows to constrain the Starobinsky's R^2 inflation model.

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

  - Foreground mismodelling : omitting curvature, AME, dust components
  - Lack of frequency range / sensitivity to $\beta_{synchrotron}$ and T_{dust}
  - Averaging effects of spectral indices by pixelization / beam convolution
  - Spectral degeneracies, e.g. CMB and magnetic dust?

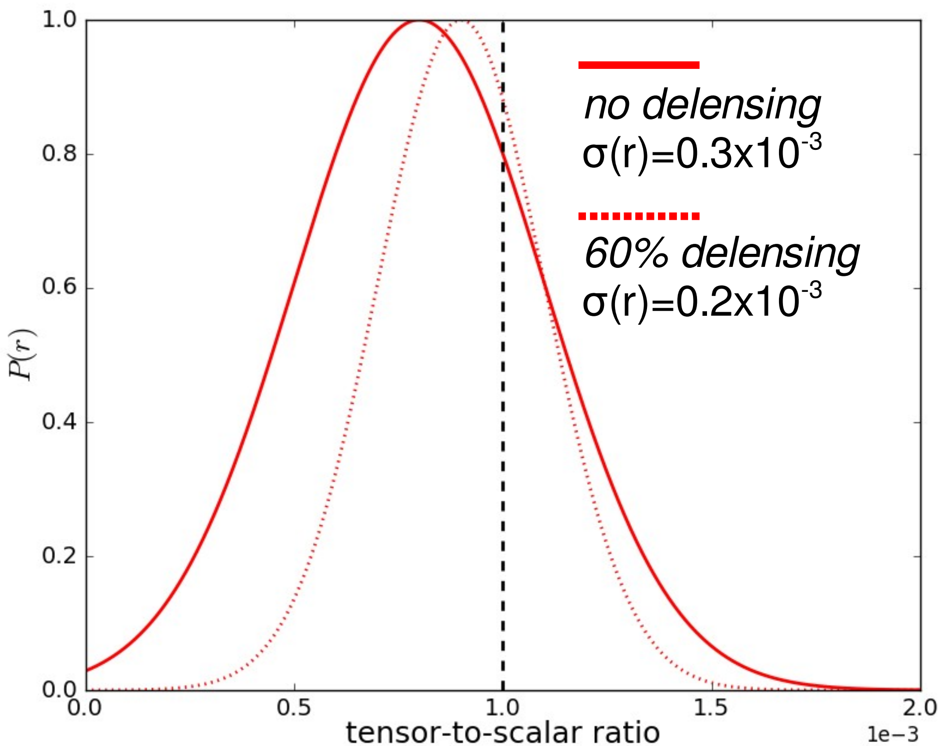
Thank you !

Backup slides

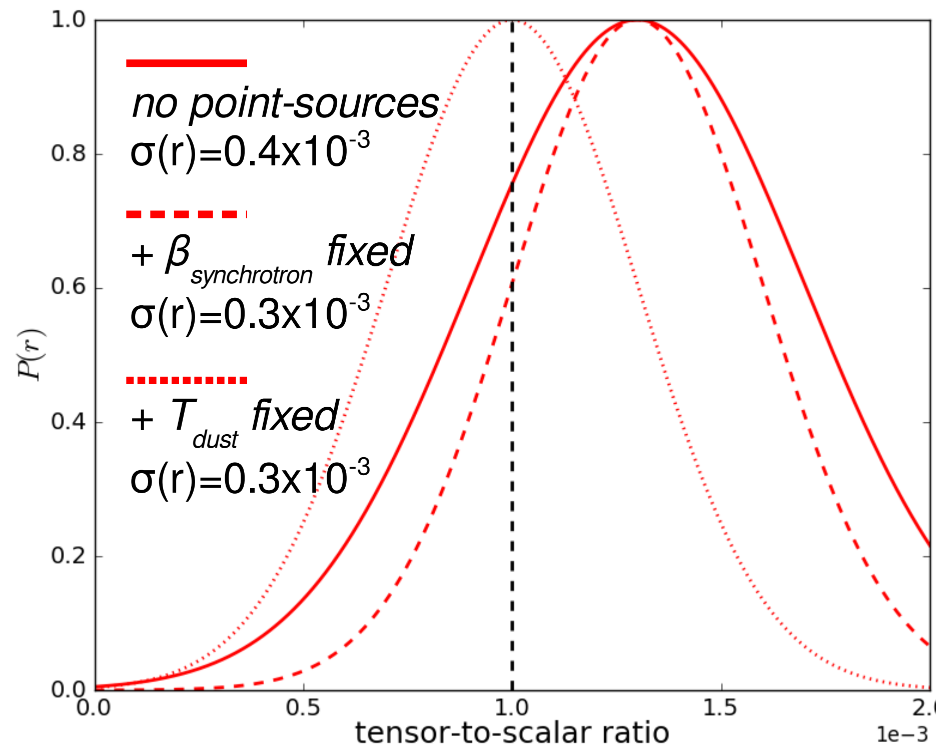
Further improvements for $r = 10^{-3}$

- Aggregating CORE 60 – 600 GHz observations with external foreground data (e.g. C-BASS 5 GHz, future catalogues of polarized sources) can help in reducing the bias and uncertainty on $r = 10^{-3}$

Without foregrounds



With foregrounds & 60% delensing



Using multipoles $2 \leq \ell \leq 50$

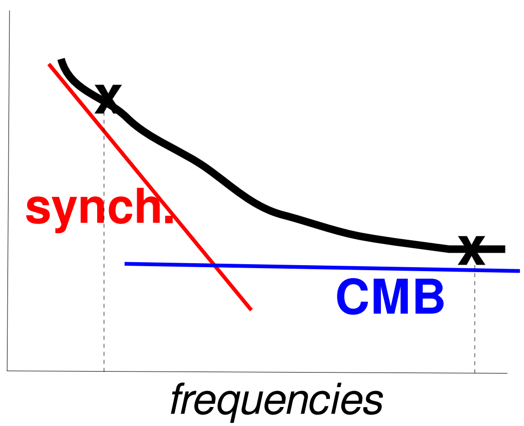
Remazeilles et al 2017, for the CORE collaboration

What frequencies ?

- How many frequency bands ?
- What frequency range ?

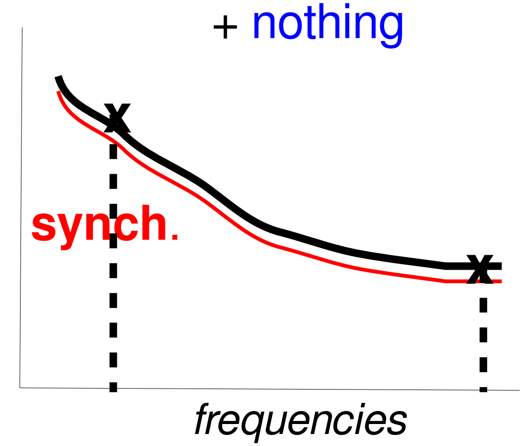
1. Biases may occur from a lack of frequency bands:

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

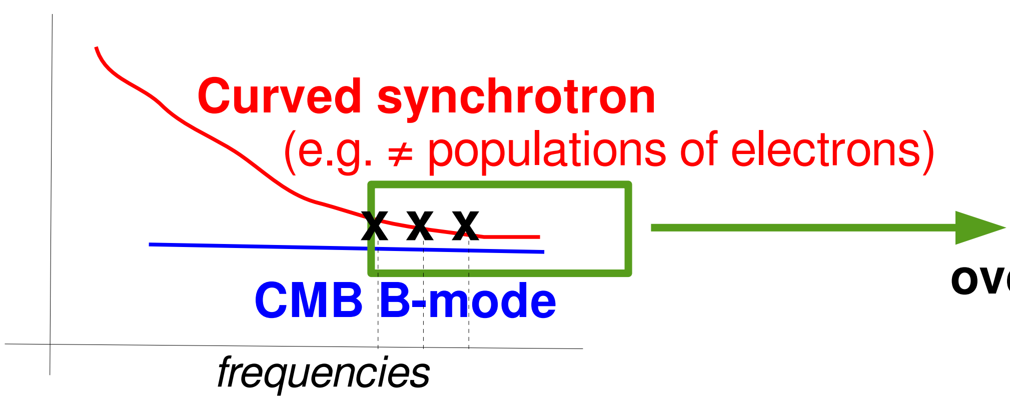


Same chi-square goodness-of-fit!

(b) Total sky = curved synchrotron + nothing

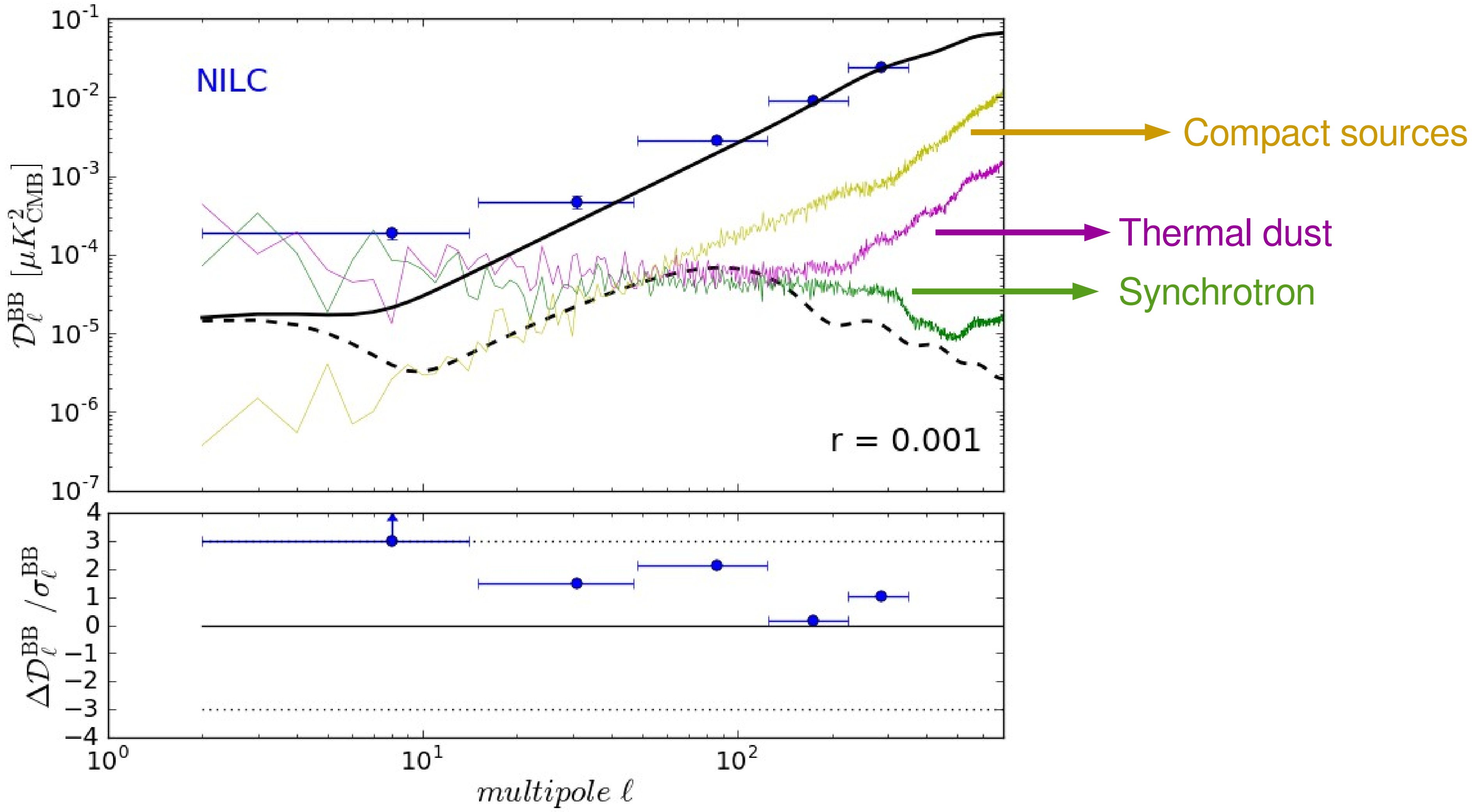


2. Biases may occur from a limited frequency range:



Spectral degeneracy over a limited frequency range!

Residual foregrounds on NILC CMB B-mode

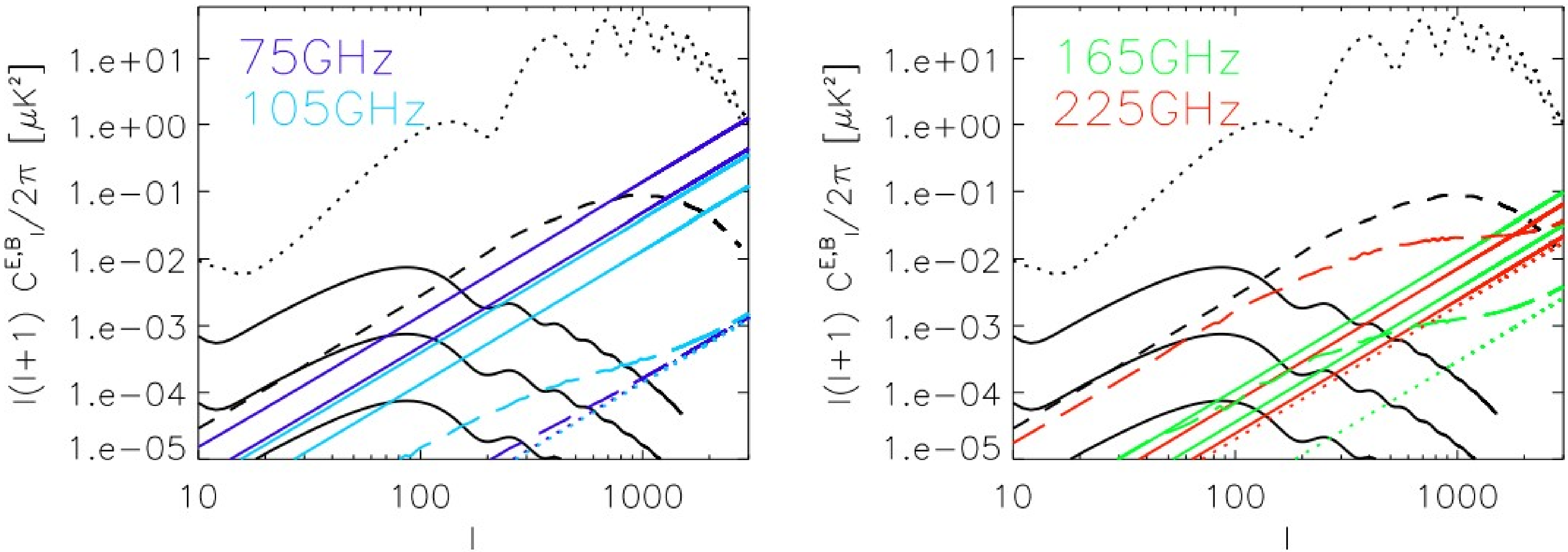


Galactic foregrounds in polarization

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* *- Decorrelation across frequencies*	*~5% - 10%* *(up to ~20+%)*	*Ponthieu et al (2005), Planck intermediate results. XIX (2015), Planck intermediate results. L (2016)*
Magnetic dust?	*- 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)*
Anomalous Microwave Emission (AME)	*- Peaked spectrum ~10-60 GHz*	*<~1%*	*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)*

Extragalactic foregrounds in polarization

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

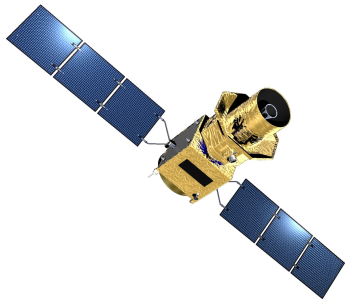


Curto et al 2013

Future CMB satellites aim at detecting **r ~ 10^{-3}**

LiteBIRD

Matsumura et al., 2013

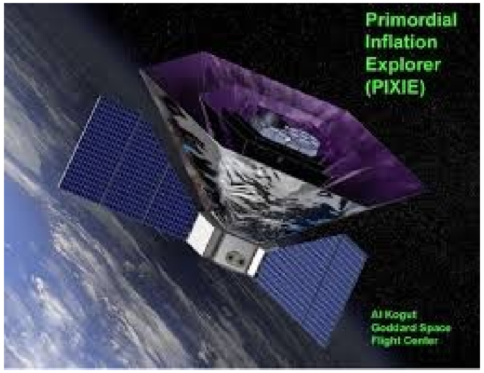


COrE

COrE Collaboration et al., 2011

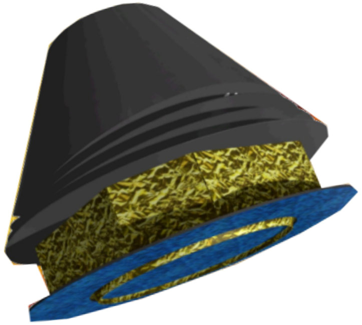
PIXIE

Kogut et al., 2011



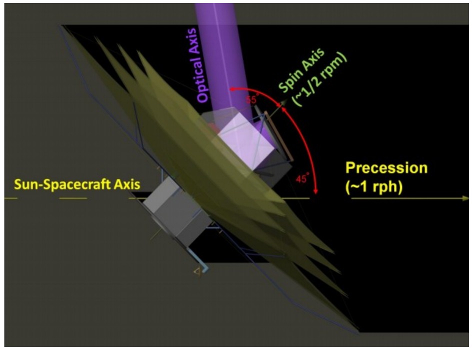
CORE

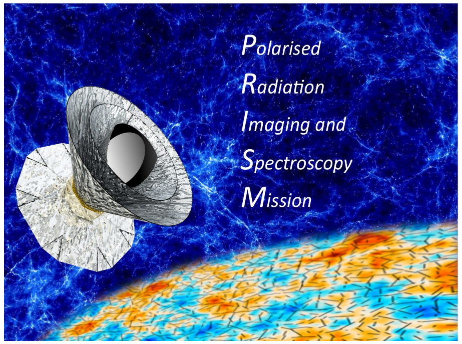
Delabrouille et al., 2017



EPIC

Bock et al., 2008



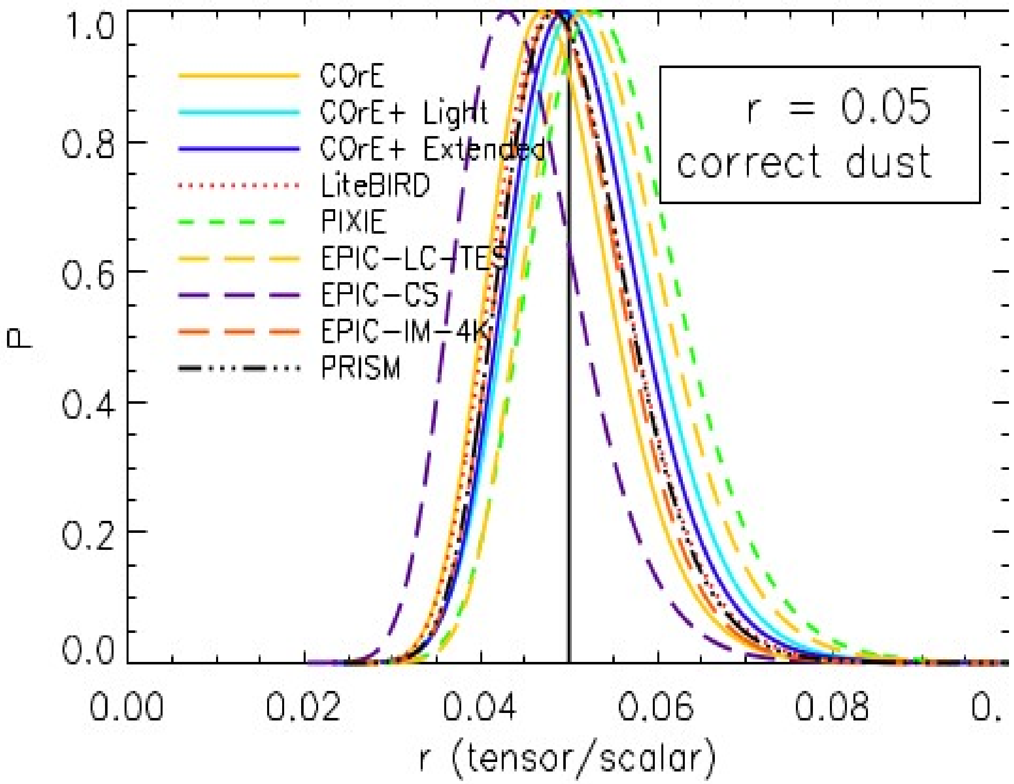


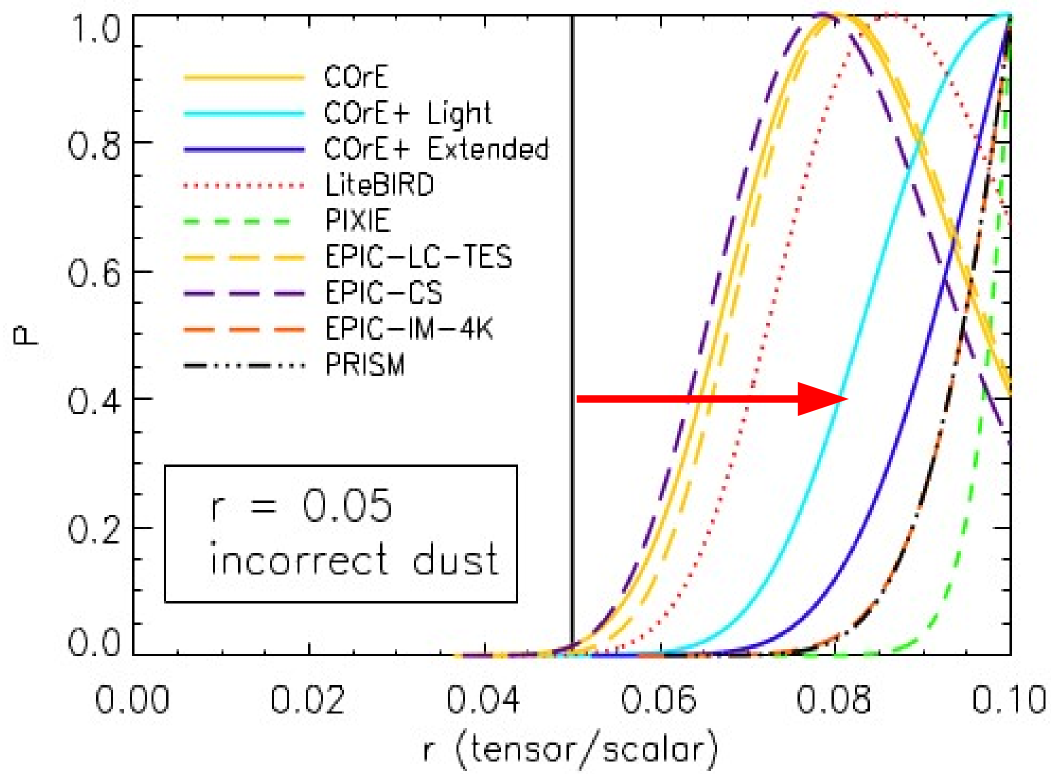
PRISM

André et al., 2014

Impact on r of foreground mismodelling

- Impact on r of mismodelling a two-component dust by a single MBB component:





Remazeilles et al, MNRAS 2016