Sensitivity and foreground modelling for CMB B-mode polarization satellites

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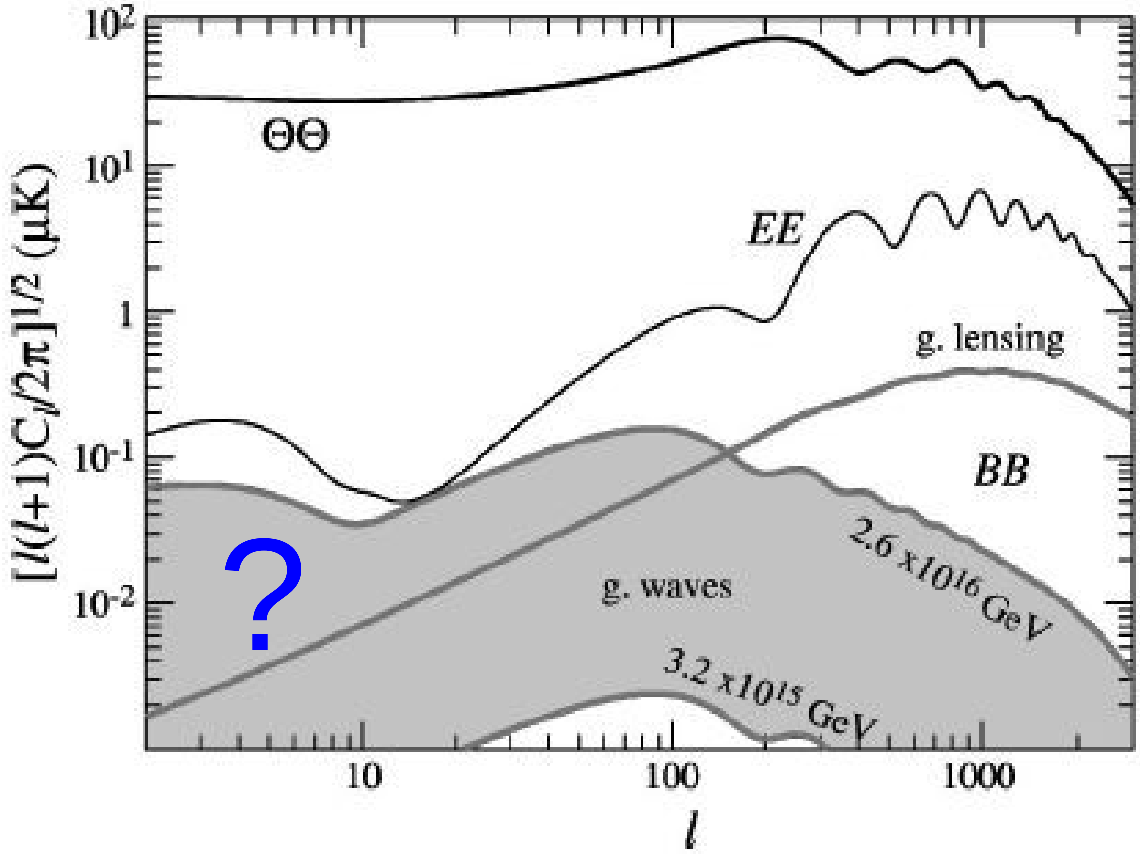
M. Remazeilles, C. Dickinson, H.K. Eriksen, I. Wehus,
"Sensitivity and foreground modelling for CMB B-mode polarization satellite missions", to be submitted soon (2015)

EWASS 2015, 22-26 June

Large-scale CMB B-mode polarization ?



Hu et al., *2003*

- Exclusive signature of gravitational waves / tensor perturbations predicted by Inflation
- Amplitude of CMB B-mode angular power spectrum C_ℓ^{BB} :

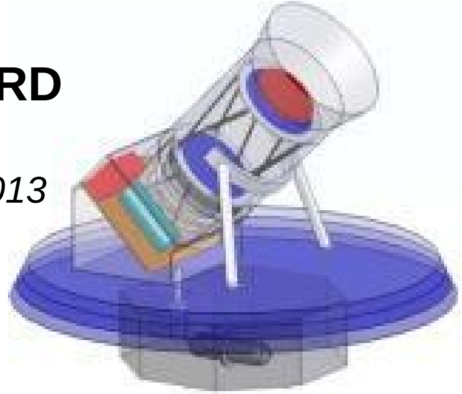
  tensor-to-scalar parameter $r = P_T(k) / P_S(k)$

- Related to the energy scale of Inflation

A next-generation CMB satellite mission ?

LiteBIRD

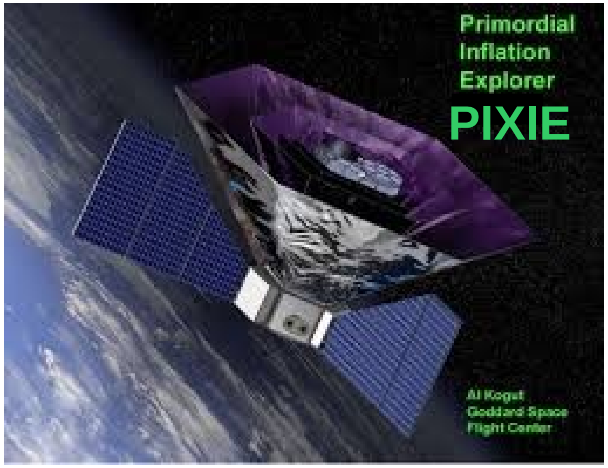
Matsumura et al., 2013

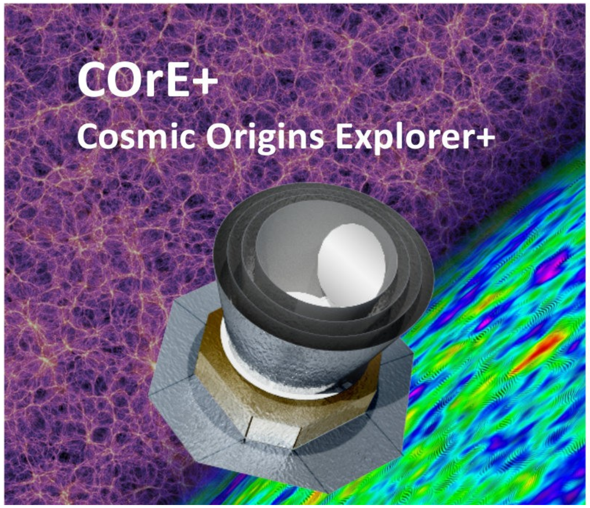


COrE

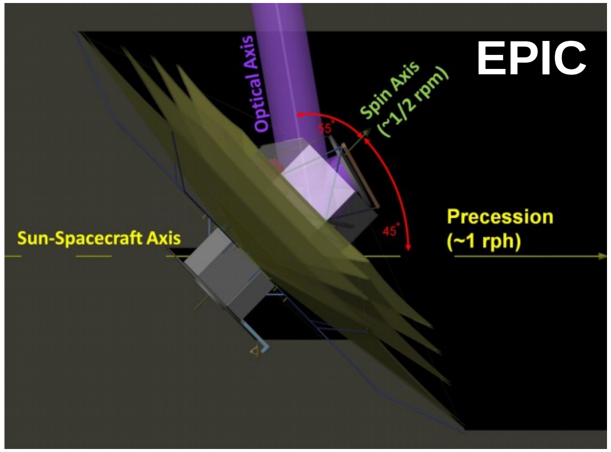
COrE Collaboration et al., 2011

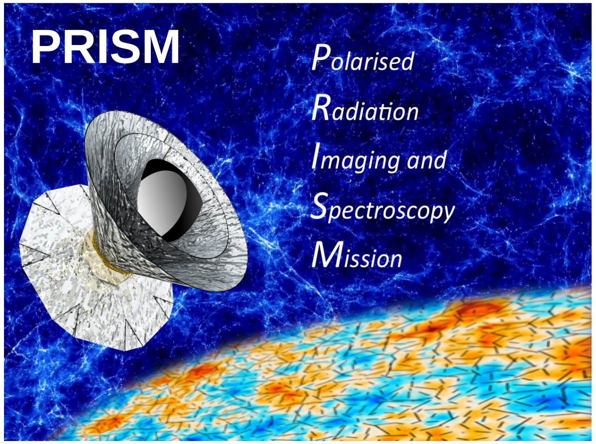
Kogut et al., 2011





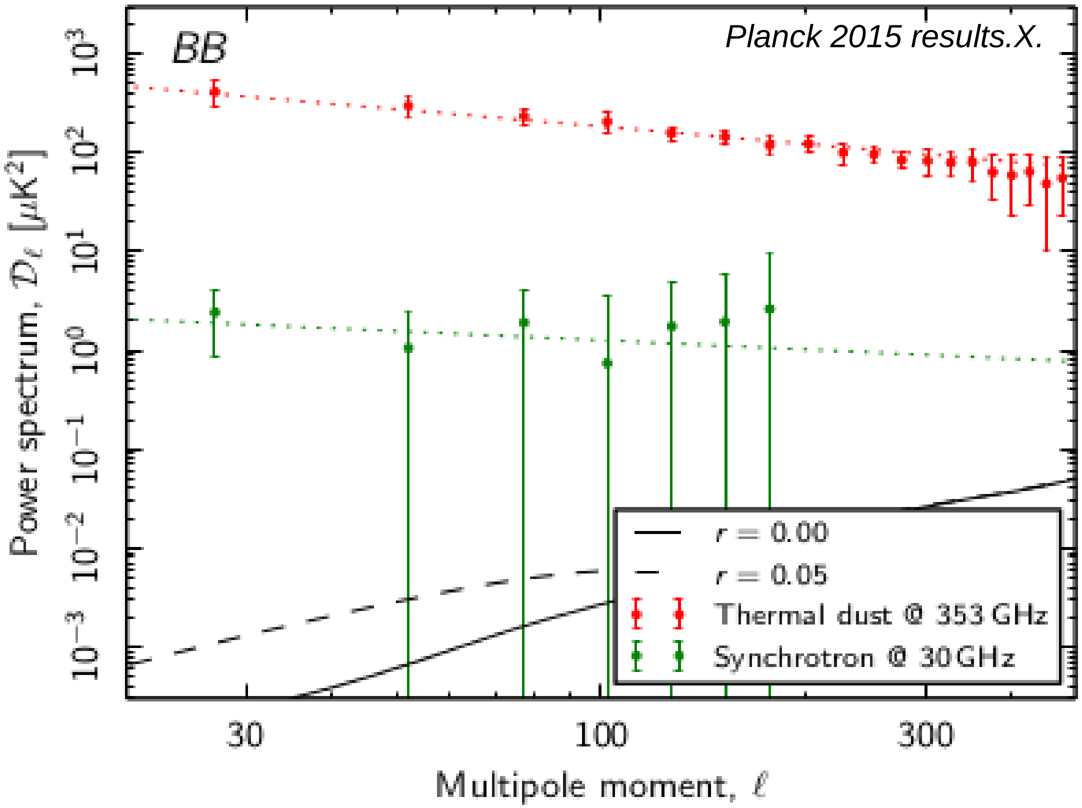
Bock et al., 2008





André et al., 2014

CMB versus Foreground B-modes



Highly polarized Galactic foregrounds

@ any frequency
@ any direction on the sky
@ any angular scale

many orders of magnitude larger than primordial CMB B-modes

- Spectral information on polarized foregrounds ?

  - synchrotron curvature ?
  - thermal dust emissivity / emissivities ?

- How many polarized foregrounds in the sky ?

  - thermal dust
  - synchrotron
  - spinning dust ?
  - … ?

not only depends on physics but also on instrument sensitivity

Bayesian parametric fitting and Gibbs sampling

Eriksen et al. *(2008)*

Model

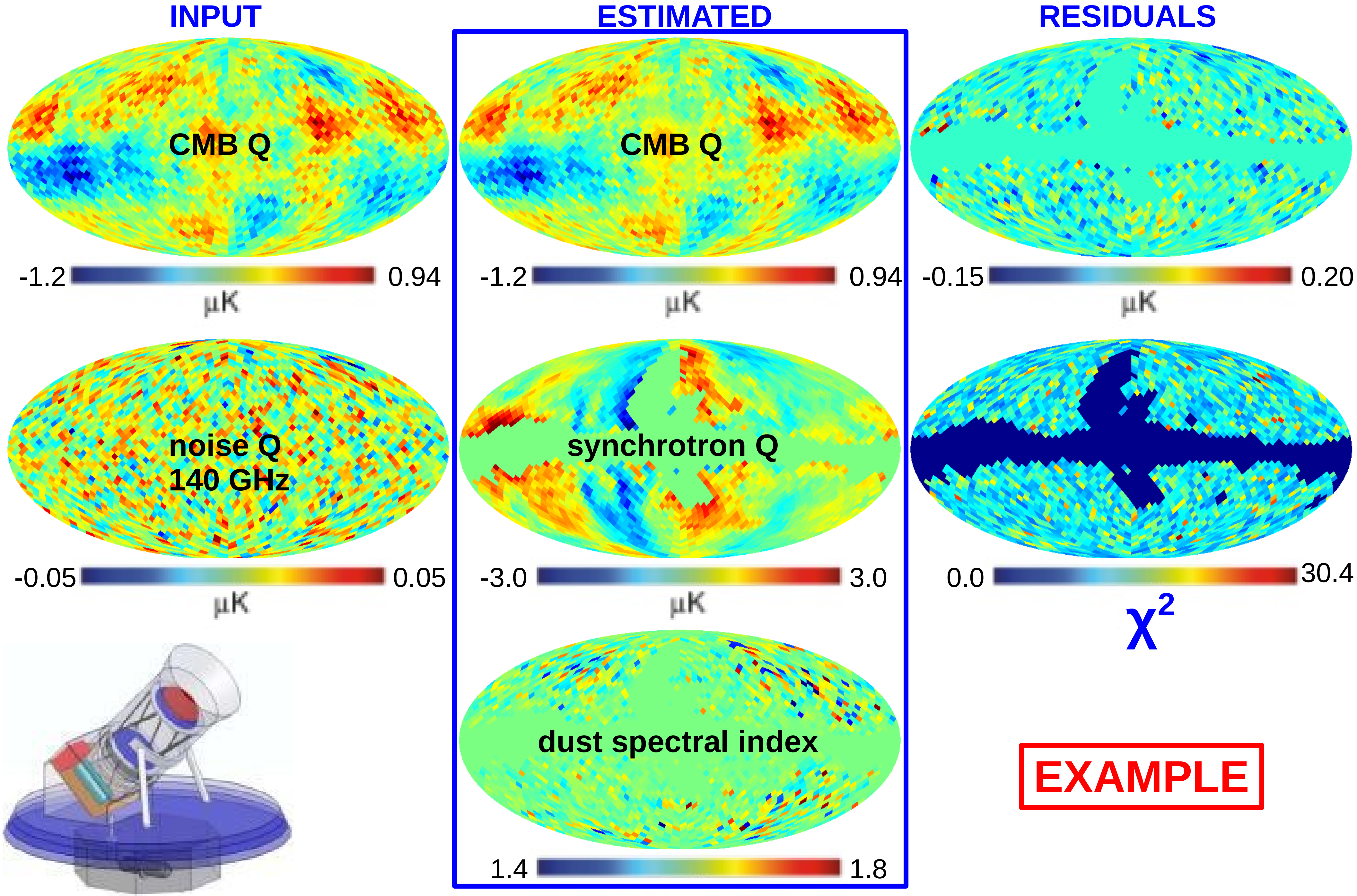
$$
\begin{aligned}
\boldsymbol{m}(p,\nu) &= a(\nu)\,\boldsymbol{s}^{cmb}(p) \\
&+ \left(\frac{\nu}{\nu_0^s}\right)^{\beta_s(p)} \boldsymbol{s}^{sync}(p) \\
&+ \left(\frac{\nu}{\nu_0^d}\right)^{\beta_d(p)} B_\nu\left(T_d(p)\right)\boldsymbol{s}^{dust}(p) \\
&+ \boldsymbol{n}(p,\nu)
\end{aligned}
$$

Gibbs sampling

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

Parameters

$$
\boldsymbol{s} = \left(\boldsymbol{s}^{cmb},\boldsymbol{s}^{dust},\boldsymbol{s}^{sync}\right),\boldsymbol{\beta} = \left(\beta_d,\beta_s,T_d\right),C_\ell = \langle|\boldsymbol{s}_{\ell m}^{cmb}|^2\rangle
$$



EXAMPLE

	institution	frequencies [GHz]	beam FWHM [arcmin]	sensitivities [uK deg]
LiteBIRD	Japan (JAXA)	60,78,100, 140,195,280	75,58,45, 32,24,16	0.172,0.108,0.078, 0.062,0.0517,0.063

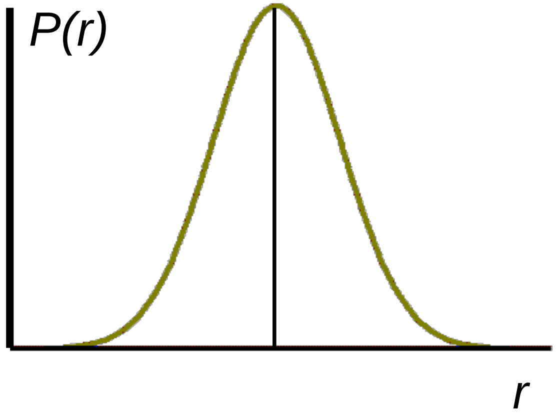
Likelihood distribution of the tensor-to-scalar

After foreground cleaning :

$C^{EE}_{\ell<12} \propto \tau^2$ (optical depth to reionization)

$C^{BB}_{\ell<12} \propto r$ (tensor-to-scalar ratio)

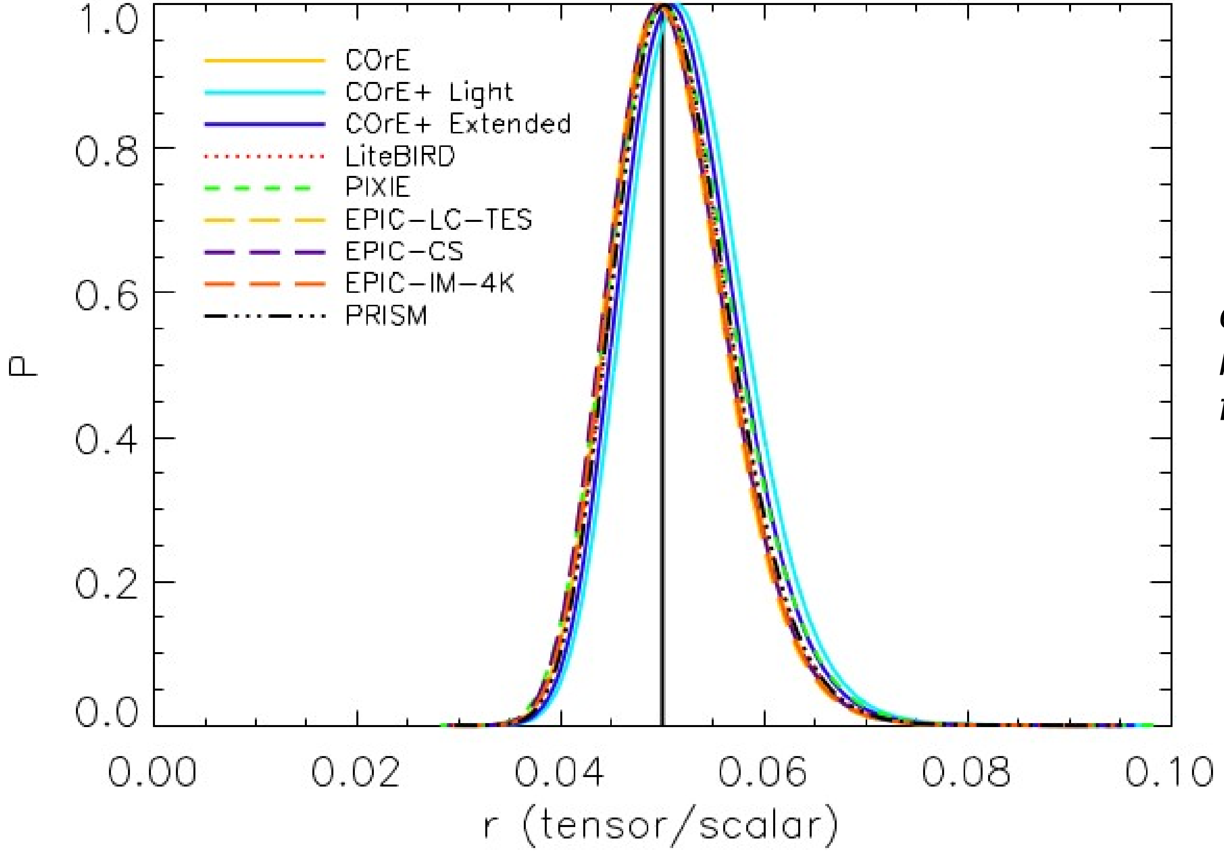
$$\mathcal{L}\left(C_\ell \middle| \tau, r\right) \propto \frac{e^{-\frac{1}{2}\left[C_\ell - C_\ell^{th}(\tau,r)\right]\Sigma^{-1}\left[C_\ell - C_\ell^{th}(\tau,r)\right]}}{\Sigma^{1/2}}$$



No foregrounds : overall sensitivity

0.05276 ± 0.00596
0.05206 ± 0.00585
0.05111 ± 0.00576
0.05137 ± 0.00579
0.05150 ± 0.00617
0.05078 ± 0.00572
0.05091 ± 0.00584
0.05100 ± 0.00573
0.05144 ± 0.00578

r = 0.05



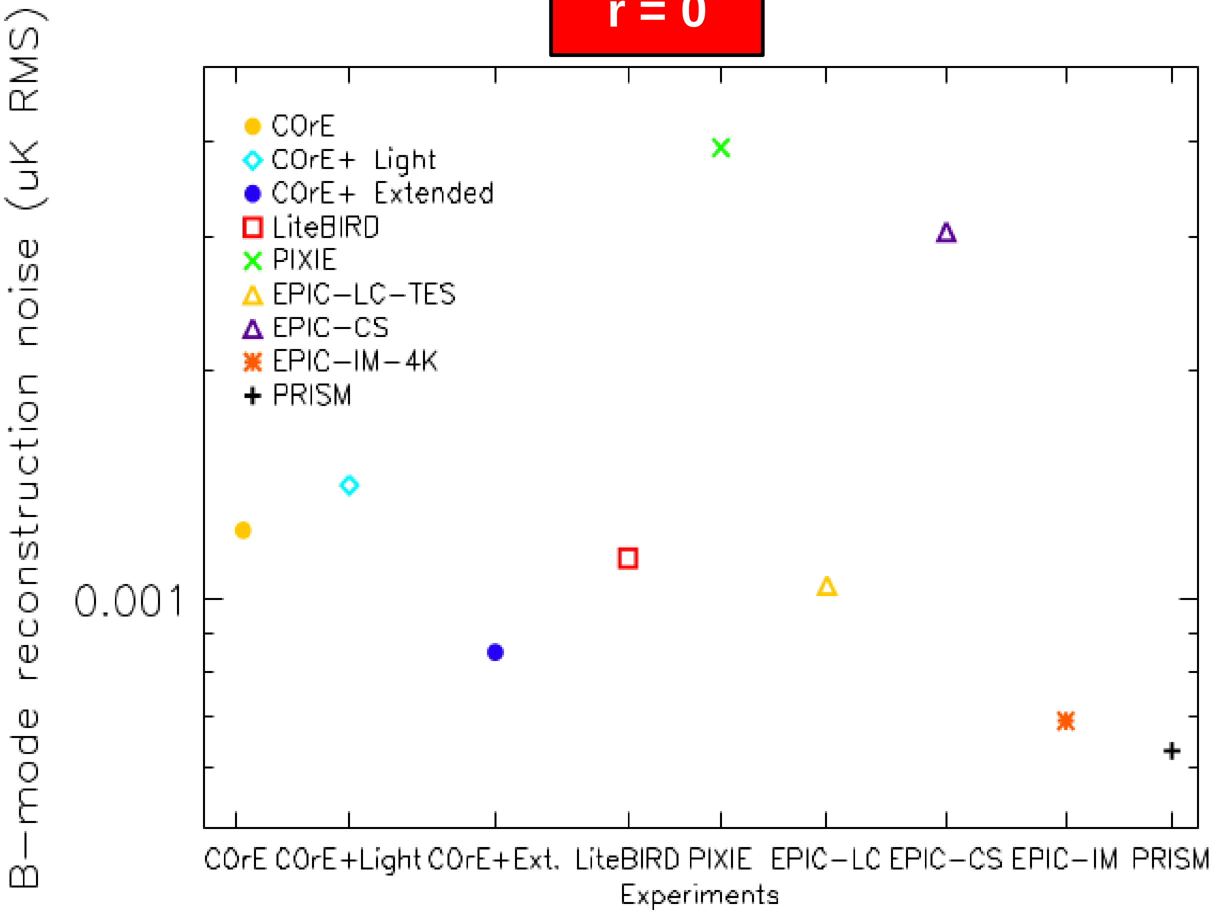
*errors on **r** dominated*
by cosmic variance
for all satellite concepts

$\ell_{max} \sim 12$

***Remazeilles, Dickinson, Eriksen, Wehus,** in prep. (2015)*

No foregrounds : overall sensitivity

r = 0



-PRISM,
-EPIC-IM,
-COrE+ Extended
are the most
sensitive to B-modes

2 degree beam

Remazeilles, Dickinson, Eriksen, Wehus, *in prep. (2015)*

What is the impact on the tensor-to-scalar ratio of incorrect foreground modelling ?

> *“ Because of much higher sensitivity of future CMB space missions,*
> *the estimation of the tensor-to-scalar ratio will be much more sensitive*
> *to any imperfect foreground modelling ”*

M. Remazeilles, C. Dickinson, H.K. Eriksen, I. Wehus,
“Sensitivity and foreground modelling for CMB B-mode polarization satellite missions”,
to be submitted soon (2015)

Exercise : mismatch between the foreground model and the data

$$
\begin{aligned}
\boldsymbol{m}(p,\nu) &= a(\nu)\,\boldsymbol{s}^{cmb}(p) \\
&+ \left(\frac{\nu}{\nu_0^s}\right)^{\beta_s(p)} \boldsymbol{s}^{sync}(p) \\
&+ \left(\frac{\nu}{\nu_0^d}\right)^{\beta_d(p)} B_\nu\left(T_d(p)\right)\,\boldsymbol{s}^{dust}(p) \\
&+ \boldsymbol{n}(p,\nu)
\end{aligned}
$$

Model

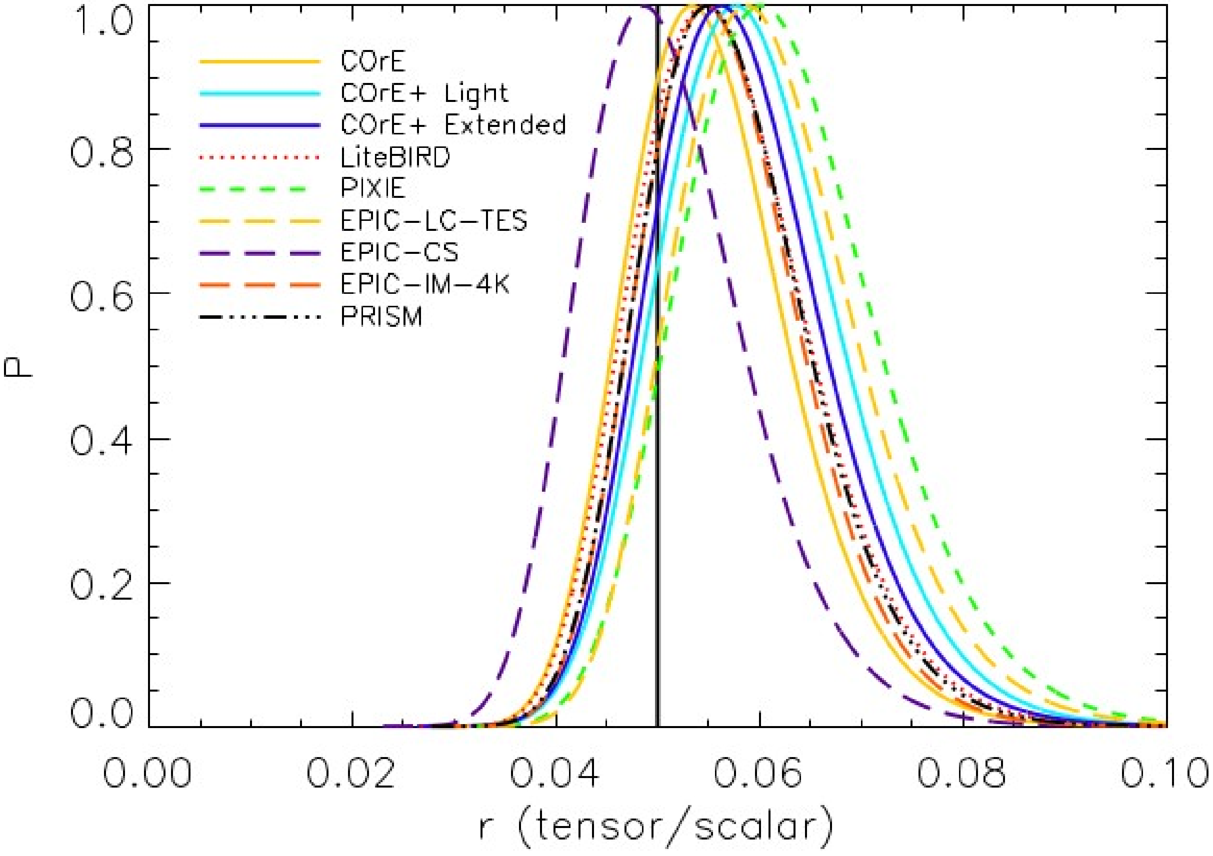
$$
\begin{aligned}
\boldsymbol{d}(p,\nu) &= a(\nu)\,\boldsymbol{s}^{cmb}(p) \\
&+ \left(\frac{\nu}{\nu_0^s}\right)^{\beta_s(p)\boxed{+C\ln(\nu/\nu_0^s)}} \boldsymbol{s}^{sync}(p) \quad \text{curvature} \\
&+ \left[f_1\left(\frac{\nu}{\nu_0^d}\right)^{\beta_1(p)} B_\nu\left(T_1(p)\right) \boxed{+f_2\left(\frac{\nu}{\nu_0^d}\right)^{\beta_2(p)} B_\nu\left(T_2(p)\right)}\right] \boldsymbol{s}^{dust}(p) \\
&\qquad \text{cold dust MBB} \\
&+ \boxed{\epsilon(\nu)\,\boldsymbol{s}^{spinning\ dust}(p)} \\
&\qquad \text{spinning dust} \\
&+ \boldsymbol{n}(p,\nu)
\end{aligned}
$$

Data

M. Remazeilles, C. Dickinson, H.K. Eriksen, I. Wehus,
“Sensitivity and foreground modelling for CMB B-mode polarization satellite missions”,
to be submitted soon (2015)

Correct foreground modelling

0.05971 ± 0.00908
0.05840 ± 0.00875
0.05548 ± 0.00815
0.05688 ± 0.00873
0.06262 ± 0.00978
0.06144 ± 0.00925
0.05113 ± 0.00830
0.05676 ± 0.00806
0.05714 ± 0.00838



r = 0.05

*Galactic foregrounds inflate the error on **r** but there is no bias*

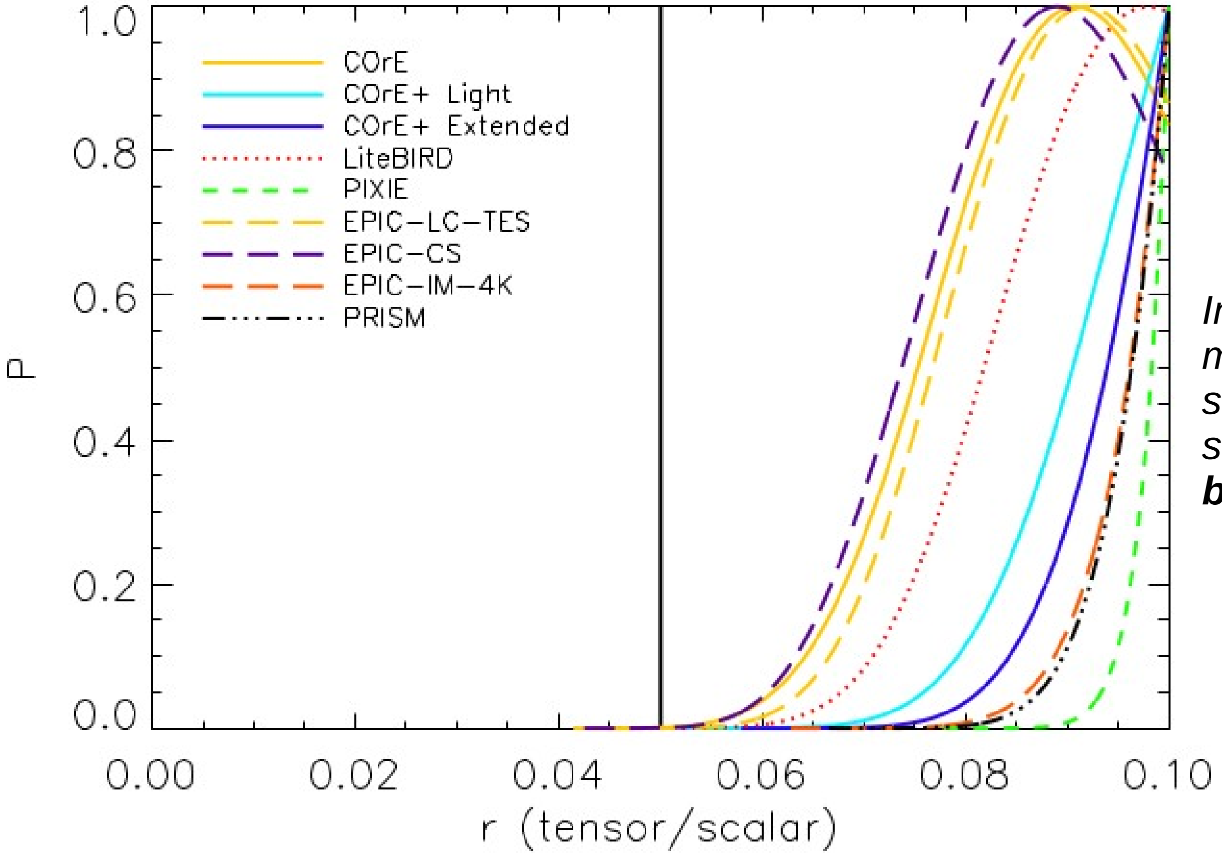
$\ell_{max} \sim 12$

***Remazeilles, Dickinson, Eriksen, Wehus,** in prep. (2015)*

Incorrect spectral modelling : one MBB dust instead of two MBB dust

0.09225 ± 0.00617
0.09404 ± 0.00500
0.08596 ± 0.00908
0.08907 ± 0.00770
0.09785 ± 0.00202
0.08690 ± 0.00849
0.08522 ± 0.00921
0.09555 ± 0.00398
0.09594 ± 0.00359

r = 0.05



Incorrect spectral modelling of thermal dust strongly bias the most sensitive experiments ***by more than 5σ***

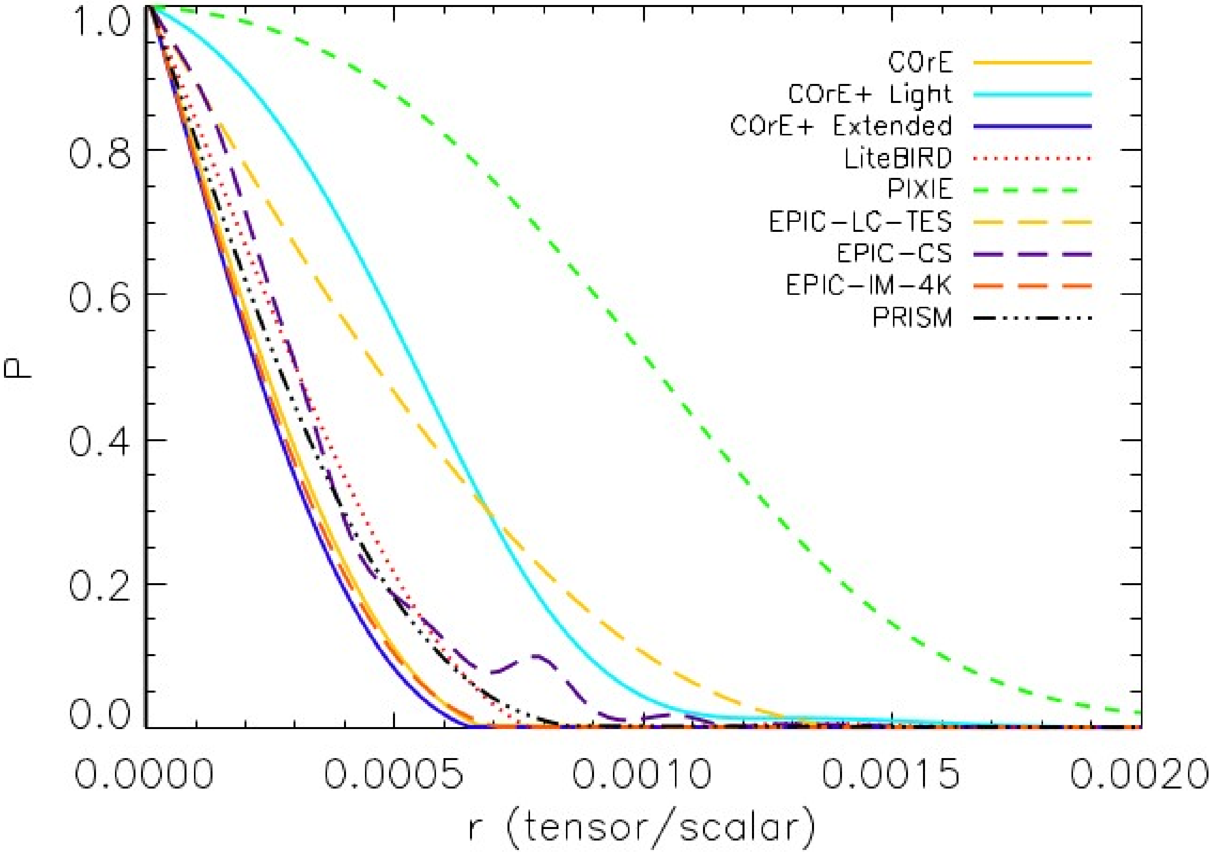
$\ell_{max} \sim 12$

Remazeilles, Dickinson, Eriksen, Wehus, in prep. *(2015)*

Correct foreground modelling

r = 0

0.00035 ± 0.00027
0.00017 ± 0.00013
0.00019 ± 0.00014
0.00023 ± 0.00019
0.00063 ± 0.00047
0.00037 ± 0.00029
0.00025 ± 0.00022
0.00018 ± 0.00014
0.00022 ± 0.00017



Galactic foregrounds inflate the error on ***r*** *but there is no bias*

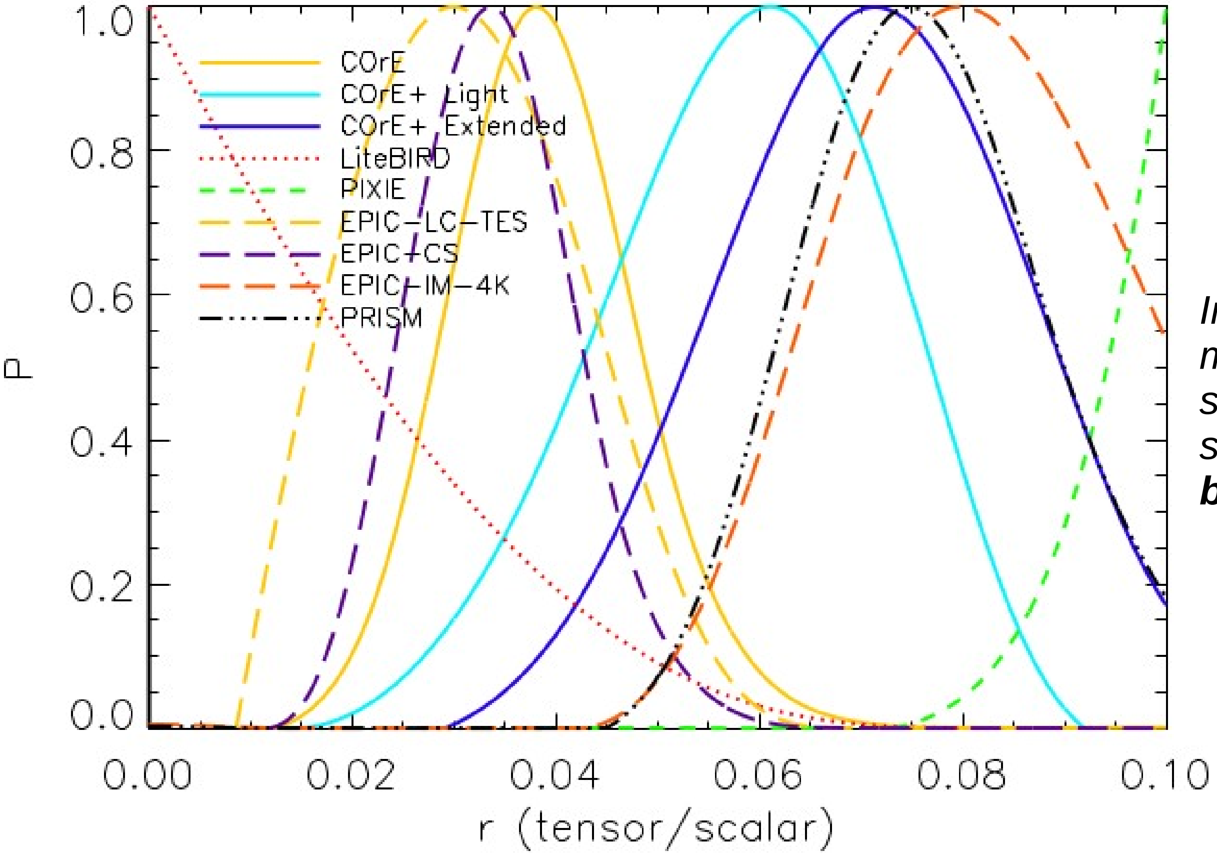
$\ell_{max} \sim 12$

Remazeilles, Dickinson, Eriksen, Wehus, *in prep. (2015)*

Incorrect spectral modelling : one MBB dust instead of two MBB dust

r = 0

0.05851 ± 0.01357
0.07038 ± 0.01398
0.03897 ± 0.00920
0.01803 ± 0.01410
0.09391 ± 0.00522
0.03146 ± 0.01057
0.03402 ± 0.00795
0.07877 ± 0.01204
0.07550 ± 0.01114



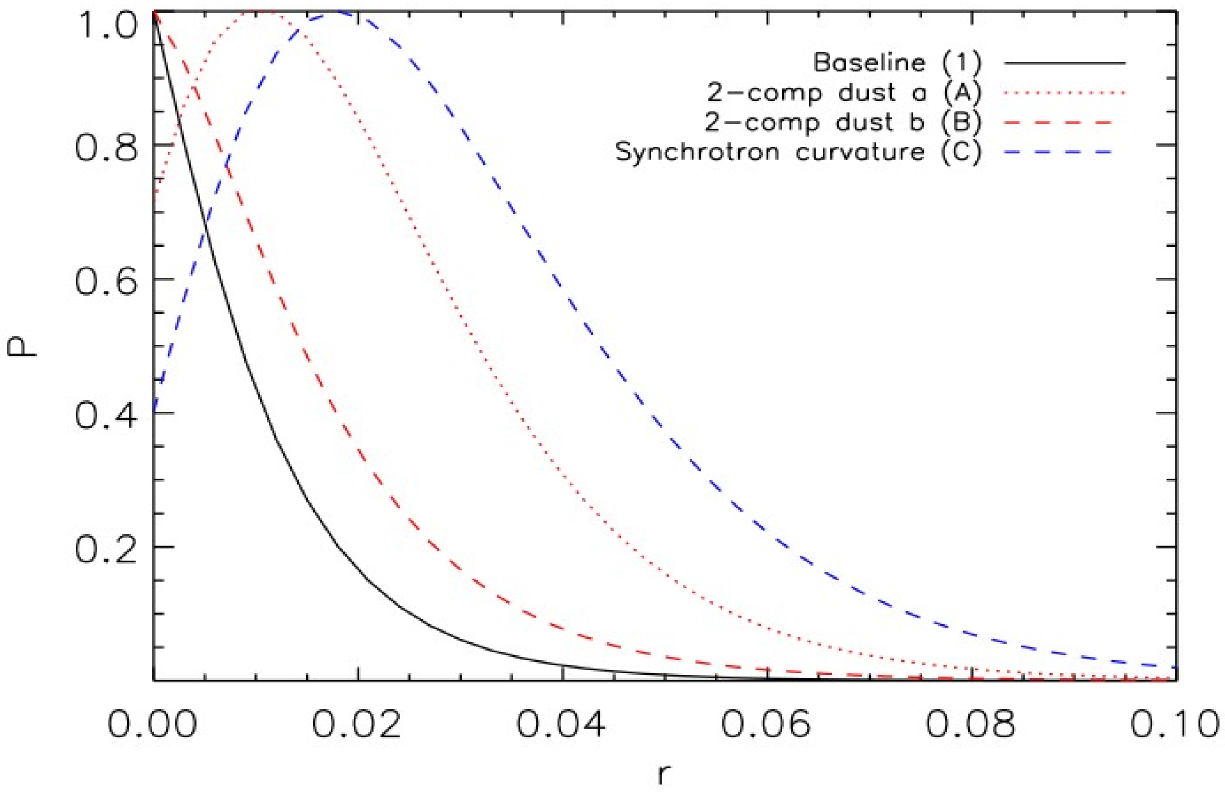
Incorrect spectral modelling of thermal dust strongly bias the most sensitive experiments ***by more than 5σ***

$\ell_{max} \sim 12$

Remazeilles, Dickinson, Eriksen, Wehus, *in prep. (2015)*

Incorrect spectral modelling : minor impact on Planck

Armitage-Caplan et al., *MNRAS 2012*



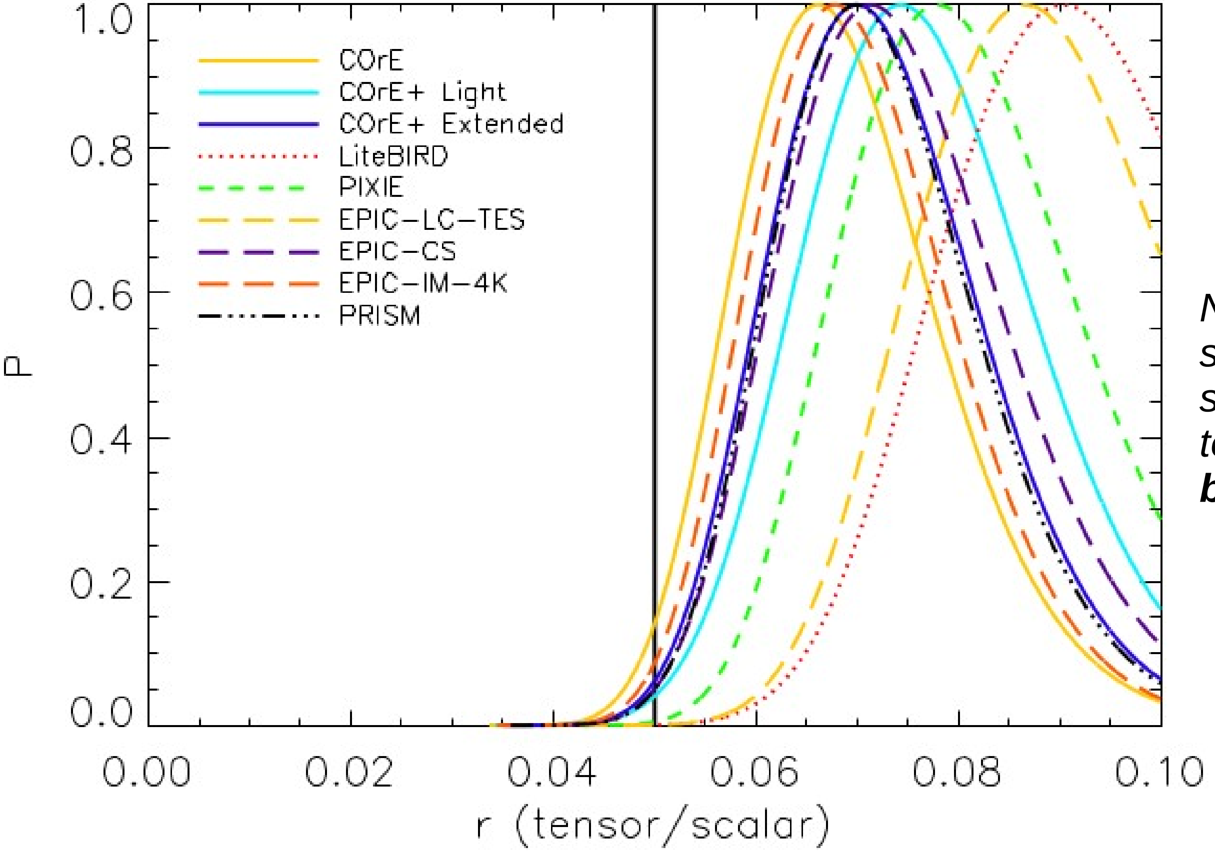
$\ell_{max} \sim 12$

- *Because of lower sensitivity, <u>Planck is less impacted</u> by incorrect spectral assumptions on the Galactic foregrounds*

Incorrect spectral modelling : neglected synchrotron curvature

0.07582 ± 0.01058
0.07228 ± 0.01018
0.06887 ± 0.01009
0.08602 ± 0.00891
0.07928 ± 0.01002
0.08459 ± 0.00913
0.07381 ± 0.01052
0.07029 ± 0.00992
0.07226 ± 0.00995

r = 0.05



Neglecting the curvature of synchrotron spectral index significantly bias the tensor-to-scalar ratio ***by at least 2σ***

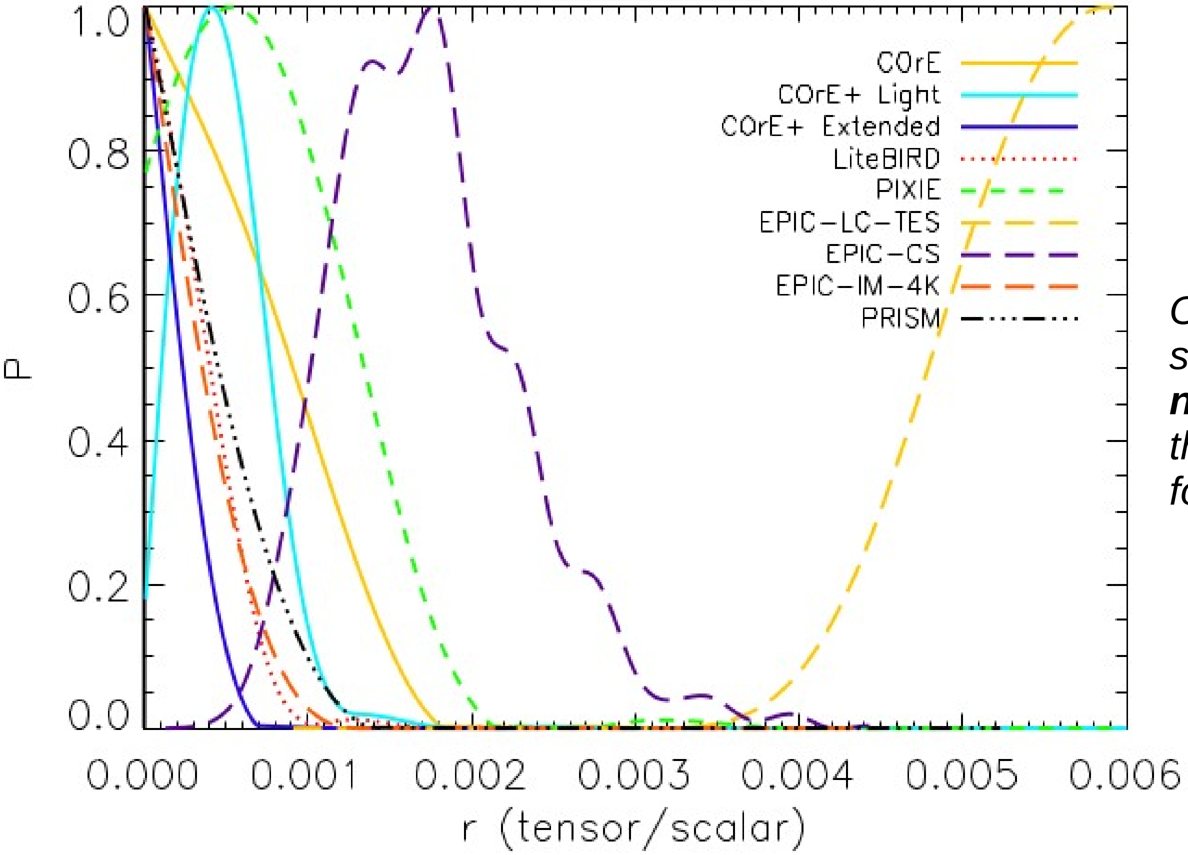
$\ell_{max} \sim 12$

Remazeilles, Dickinson, Eriksen, Wehus, *in prep. (2015)*

Missing polarized foreground : spinning dust

r = 0

0.00049 ± 0.00028
0.00019 ± 0.00014
0.00057 ± 0.00041
0.00029 ± 0.00025
0.00076 ± 0.00050
0.00647 ± 0.00135
0.00173 ± 0.00058
0.00029 ± 0.00023
0.00036 ± 0.00028



Omitting the 1% polarized spinning dust makes a ***non-negligible bias*** *on the tensor-to-scalar ratio for some experiments*

$\ell_{max} \sim 12$

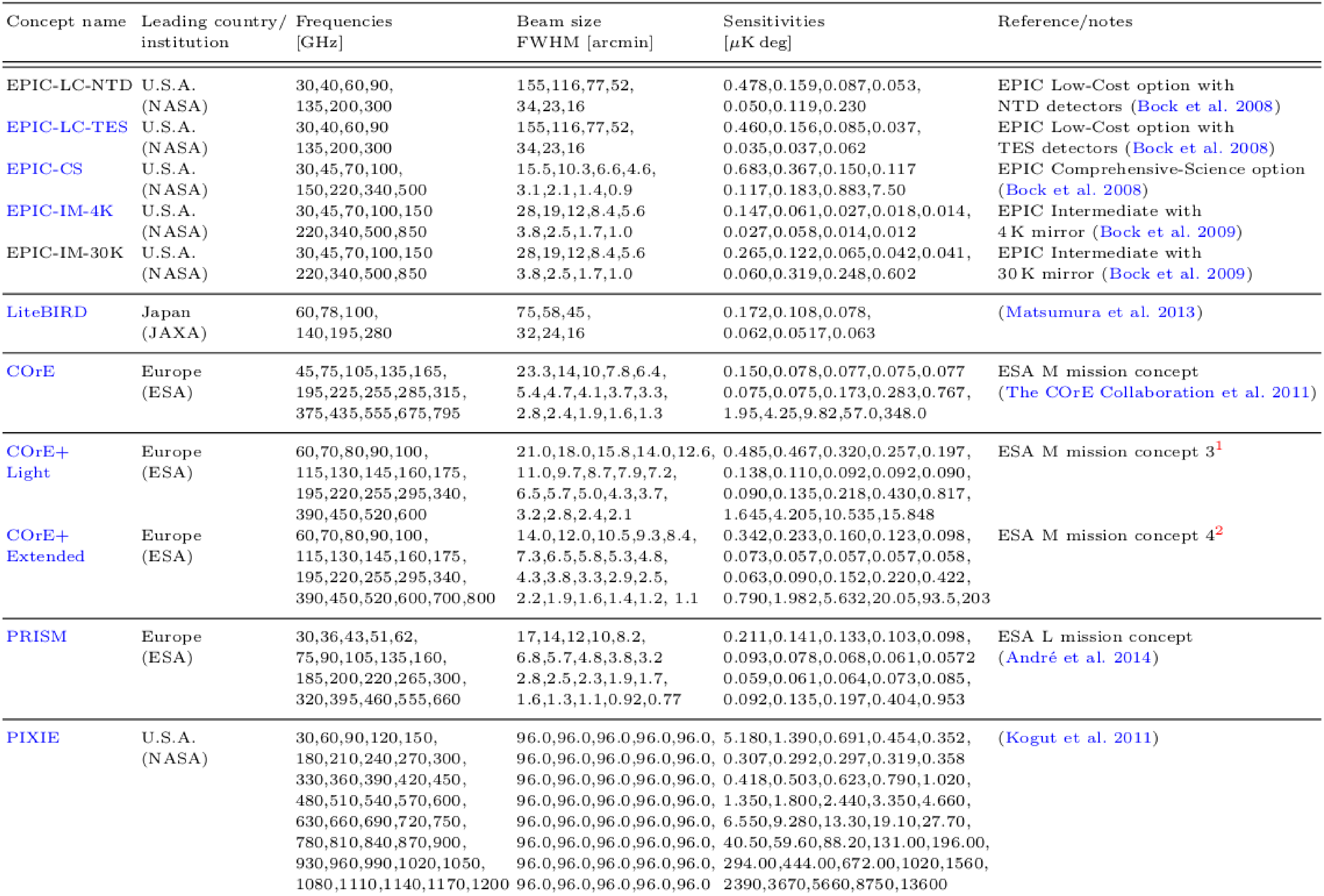
Remazeilles, Dickinson, Eriksen, Wehus, *in prep. (2015)*

Summary

- These results are preliminary !
- Bayesian framework useful
  - to propagate foreground modelling errors towards ***r***
  - to re-adjust Galactic foreground models
- Because of unprecedented sensitivity,
  next-generation CMB satellites also more sensitive
  to incorrect assumptions on Galactic foregrounds
  - Assuming one MBB versus two MBB dust → ***r*** biased by more than 5σ
  - Neglecting synchrotron curvature (C=0.3) → ***r*** biased by at least 2σ
  - Neglecting 1% spinning dust polarization → ***r*** non-negligible bias
- Given the expected sensitivity to B-modes :
  How accurately should we know the spectral properties of foregrounds ?

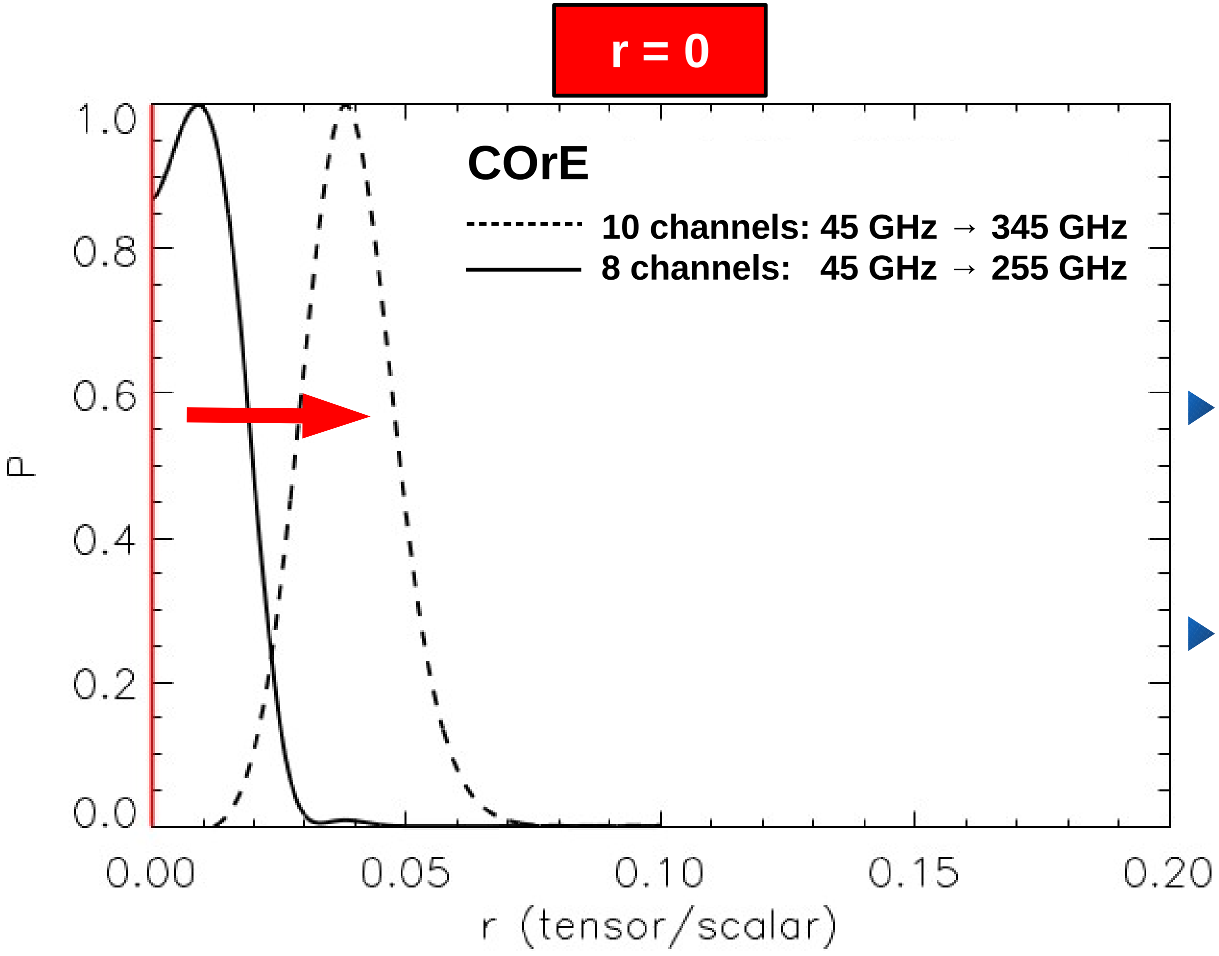
Backup slides

CMB B-mode polarization satellite concepts



Concept name	Leading country/ institution	Frequencies [GHz]	Beam size FWHM [arcmin]	Sensitivities [μK deg]	Reference/notes
EPIC-LC-NTD	U.S.A. (NASA)	30,40,60,90, 135,200,300	155,116,77,52, 34,23,16	0.478,0.159,0.087,0.053, 0.050,0.119,0.230	EPIC Low-Cost option with NTD detectors (Bock et al. 2008)
EPIC-LC-TES	U.S.A. (NASA)	30,40,60,90 135,200,300	155,116,77,52, 34,23,16	0.460,0.156,0.085,0.037, 0.035,0.037,0.062	EPIC Low-Cost option with TES detectors (Bock et al. 2008)
EPIC-CS	U.S.A. (NASA)	30,45,70,100, 150,220,340,500	15.5,10.3,6.6,4.6, 3.1,2.1,1.4,0.9	0.683,0.367,0.150,0.117 0.117,0.183,0.883,7.50	EPIC Comprehensive-Science option (Bock et al. 2008)
EPIC-IM-4K	U.S.A. (NASA)	30,45,70,100,150 220,340,500,850	28,19,12,8.4,5.6 3.8,2.5,1.7,1.0	0.147,0.061,0.027,0.018,0.014, 0.027,0.058,0.014,0.012	EPIC Intermediate with 4 K mirror (Bock et al. 2009)
EPIC-IM-30K	U.S.A. (NASA)	30,45,70,100,150 220,340,500,850	28,19,12,8.4,5.6 3.8,2.5,1.7,1.0	0.265,0.122,0.065,0.042,0.041, 0.060,0.319,0.248,0.602	EPIC Intermediate with 30 K mirror (Bock et al. 2009)
LiteBIRD	Japan (JAXA)	60,78,100, 140,195,280	75,58,45, 32,24,16	0.172,0.108,0.078, 0.062,0.0517,0.063	(Matsumura et al. 2013)
COrE	Europe (ESA)	45,75,105,135,165, 195,225,255,285,315, 375,435,555,675,795	23.3,14,10,7.8,6.4, 5.4,4.7,4.1,3.7,3.3, 2.8,2.4,1.9,1.6,1.3	0.150,0.078,0.077,0.075,0.077 0.075,0.075,0.173,0.283,0.767, 1.95,4.25,9.82,57.0,348.0	ESA M mission concept (The COrE Collaboration et al. 2011)
COrE+ Light	Europe (ESA)	60,70,80,90,100, 115,130,145,160,175, 195,220,255,295,340, 390,450,520,600	21.0,18.0,15.8,14.0,12.6, 11.0,9.7,8.7,7.9,7.2, 6.5,5.7,5.0,4.3,3.7, 3.2,2.8,2.4,2.1	0.485,0.467,0.320,0.257,0.197, 0.138,0.110,0.092,0.092,0.090, 0.090,0.135,0.218,0.430,0.817, 1.645,4.205,10.535,15.848	ESA M mission concept 3[1]
COrE+ Extended	Europe (ESA)	60,70,80,90,100, 115,130,145,160,175, 195,220,255,295,340, 390,450,520,600,700,800	14.0,12.0,10.5,9.3,8.4, 7.3,6.5,5.8,5.3,4.8, 4.3,3.8,3.3,2.9,2.5, 2.2,1.9,1.6,1.4,1.2, 1.1	0.342,0.233,0.160,0.123,0.098, 0.073,0.057,0.057,0.057,0.058, 0.063,0.090,0.152,0.220,0.422, 0.790,1.982,5.632,20.05,93.5,203	ESA M mission concept 4[2]
PRISM	Europe (ESA)	30,36,43,51,62, 75,90,105,135,160, 185,200,220,265,300, 320,395,460,555,660	17,14,12,10,8.2, 6.8,5.7,4.8,3.8,3.2 2.8,2.5,2.3,1.9,1.7, 1.6,1.3,1.1,0.92,0.77	0.211,0.141,0.133,0.103,0.098, 0.093,0.078,0.068,0.061,0.0572 0.059,0.061,0.064,0.073,0.085, 0.092,0.135,0.197,0.404,0.953	ESA L mission concept (André et al. 2014)
PIXIE	U.S.A. (NASA)	30,60,90,120,150, 180,210,240,270,300, 330,360,390,420,450, 480,510,540,570,600, 630,660,690,720,750, 780,810,840,870,900, 930,960,990,1020,1050, 1080,1110,1140,1170,1200	96.0,96.0,96.0,96.0,96.0, 96.0,96.0,96.0,96.0,96.0, 96.0,96.0,96.0,96.0,96.0, 96.0,96.0,96.0,96.0,96.0, 96.0,96.0,96.0,96.0,96.0, 96.0,96.0,96.0,96.0,96.0, 96.0,96.0,96.0,96.0,96.0, 96.0,96.0,96.0,96.0,96.0	5.180,1.390,0.691,0.454,0.352, 0.307,0.292,0.297,0.319,0.358 0.418,0.503,0.623,0.790,1.020, 1.350,1.800,2.440,3.350,4.660, 6.550,9.280,13.30,19.10,27.70, 40.50,59.60,88.20,131.00,196.00, 294.00,444.00,672.00,1020,1560, 2390,3670,5660,8750,13600	(Kogut et al. 2011)

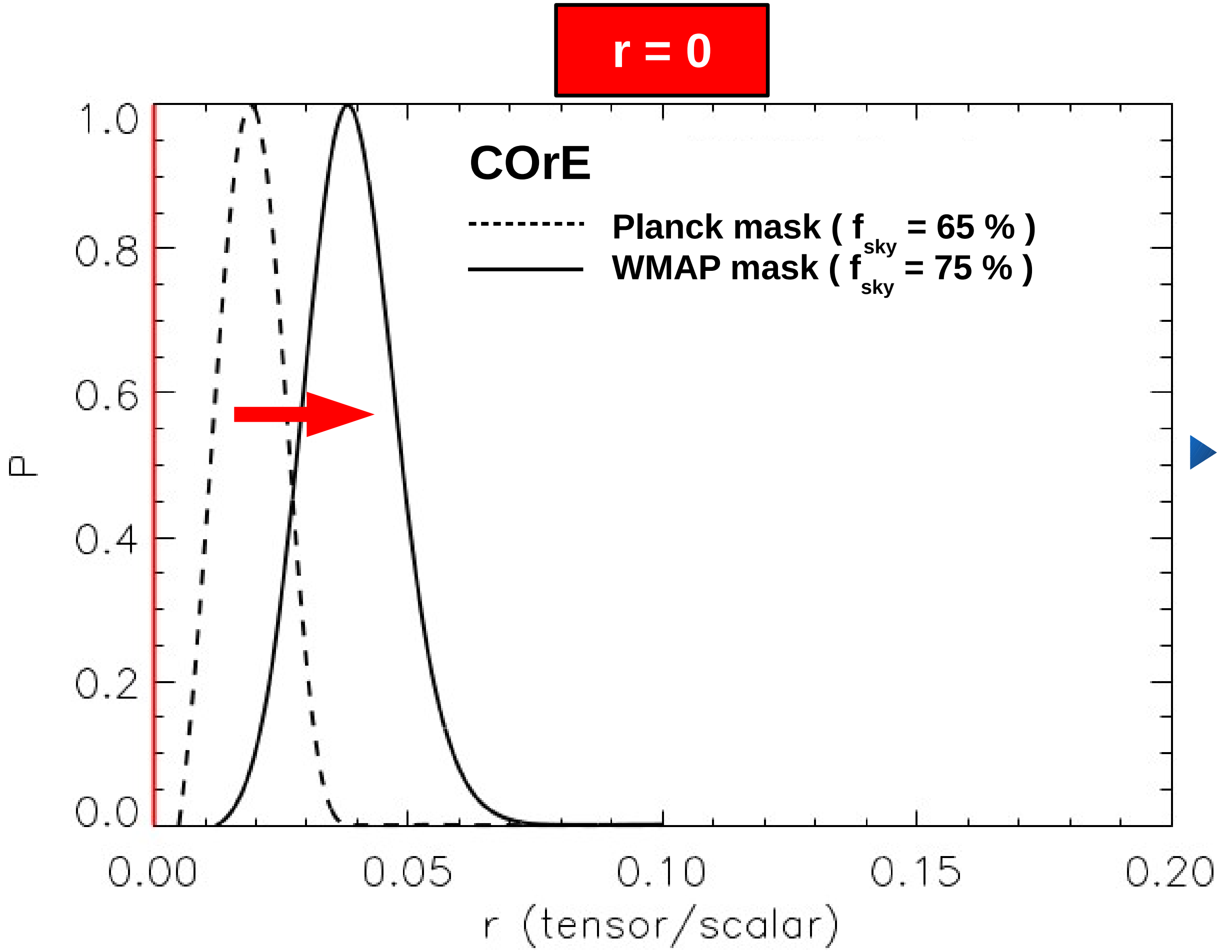
Incorrect dust modelling : impact of high frequency channels



- *High-frequency channels useful to highlight any failure in the model of polarized dust*
- *Instability of P(r) distribution with respect to frequencies highlights spurious detection of dust B-modes*

Remazeilles, Dickinson, Eriksen, Wehus, *in prep. (2015)*

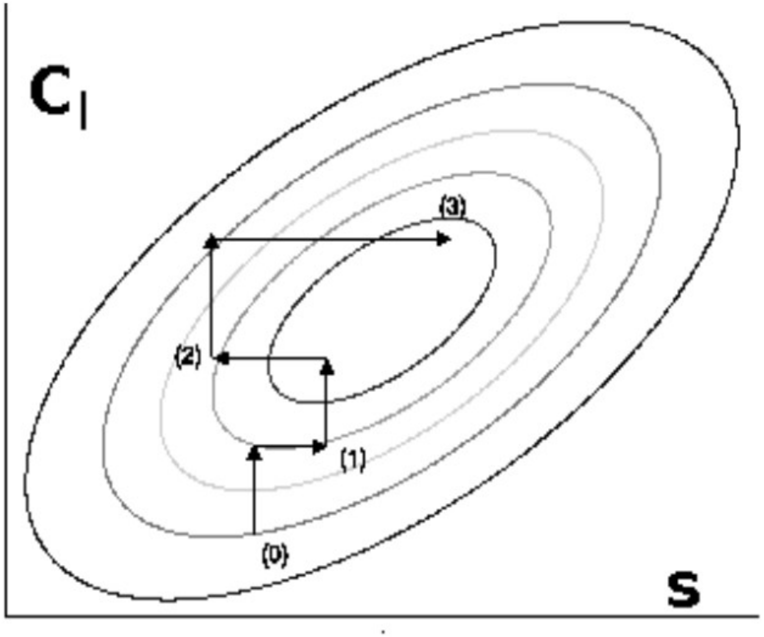
Incorrect dust modelling : impact of Galactic masking



- *Instability of P(r) distribution with respect to the size of the mask highlights spurious detection of dust B-modes*

***Remazeilles, Dickinson, Eriksen, Wehus,** in prep. (2015)*

MCMC Gibbs sampling



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

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

C_ℓ sampling

$$P\left(C_\ell \middle| \boldsymbol{s}, \boldsymbol{d}\right) = P\left(C_\ell \middle| \boldsymbol{s}\right) \propto \frac{e^{-\frac{(2\ell+1)}{2C_\ell}\left(\frac{1}{2l+1}\sum_{m=-\ell}^{\ell}|\boldsymbol{s}_{\ell m}|^2\right)}}{C_\ell^{(2\ell+1)/2}}$$

- Inverse-Gamma distribution
- Simple textbook sampling algorithm → $C_\ell^{(i+1)}$

Amplitude sampling

$$
\begin{aligned}
P\left(\boldsymbol{s}\middle|C_\ell, \boldsymbol{d}\right) &\propto P\left(\boldsymbol{d}\middle|\boldsymbol{s}, C_\ell\right) P\left(\boldsymbol{s}\middle|C_\ell\right) \\
&\propto e^{(-1/2)(\boldsymbol{d}-\boldsymbol{s})^T \boldsymbol{N}^{-1}(\boldsymbol{d}-\boldsymbol{s})} e^{(-1/2)\boldsymbol{s}^T \boldsymbol{S}^{-1}\boldsymbol{s}} \\
&\propto e^{(-1/2)(\boldsymbol{s}-\widehat{\boldsymbol{s}})^T \left(\boldsymbol{S}^{-1}+\boldsymbol{N}^{-1}\right)(\boldsymbol{s}-\widehat{\boldsymbol{s}})}
\end{aligned}
$$

- Gaussian distribution where $\widehat{\boldsymbol{s}} = \left(\boldsymbol{S}^{-1} + \boldsymbol{N}^{-1}\right)^{-1} \boldsymbol{N}^{-1}\boldsymbol{d}$ is the Wiener

- $\boldsymbol{s}^{(i+1)}$ is solution (conjugate gradients) of

$$\left(\boldsymbol{S}^{-1} + \boldsymbol{N}^{-1}\right)\boldsymbol{s} = \boldsymbol{N}^{-1}\boldsymbol{d} + \boldsymbol{S}^{-1/2} w_0 + \boldsymbol{N}^{-1/2} w_1$$

where $w_0, w_1 \sim \mathcal{N}(0, 1)$