前景放射除去アルゴリズム デルタマップ法の紹介と その性能について

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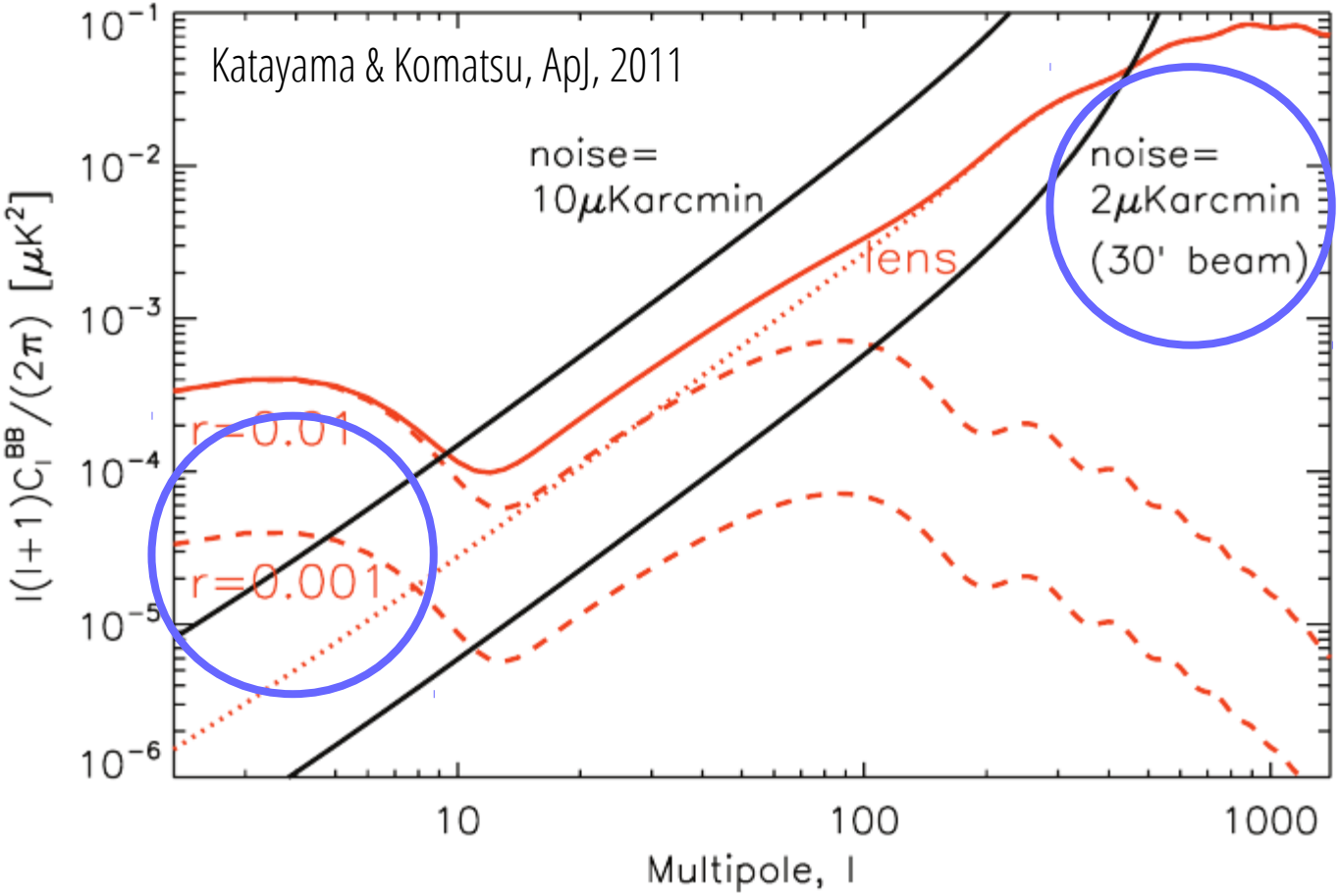
overview

- イントロ
  - B-mode, 前景放射, 先行研究からの課題
- デルタマップ法
- 様々な前景放射モデルに適用した結果
- 結論

Target: B-mode

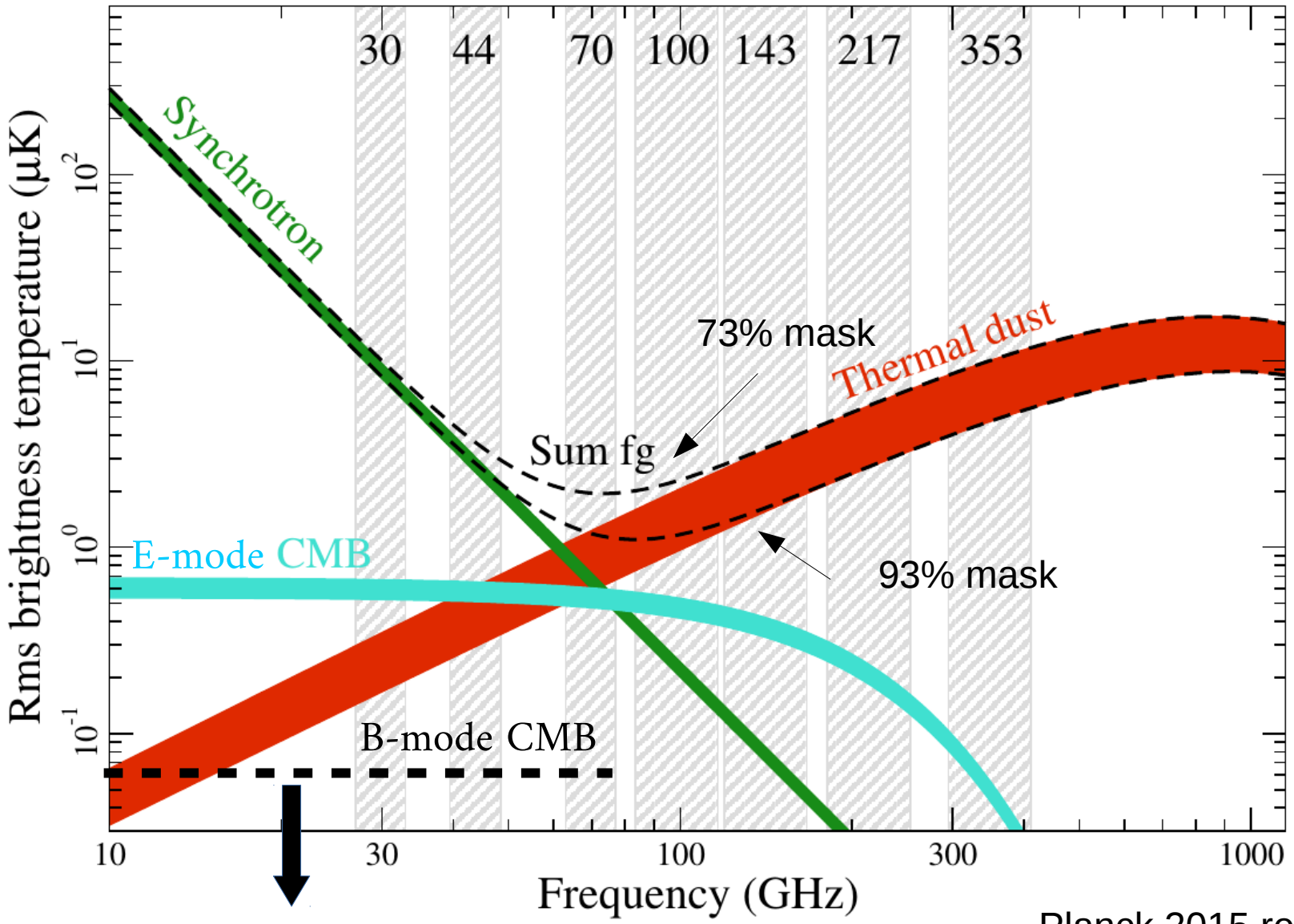


検出器ノイズが
$5\mu\mathrm{K}\ \mathrm{arcmin}$

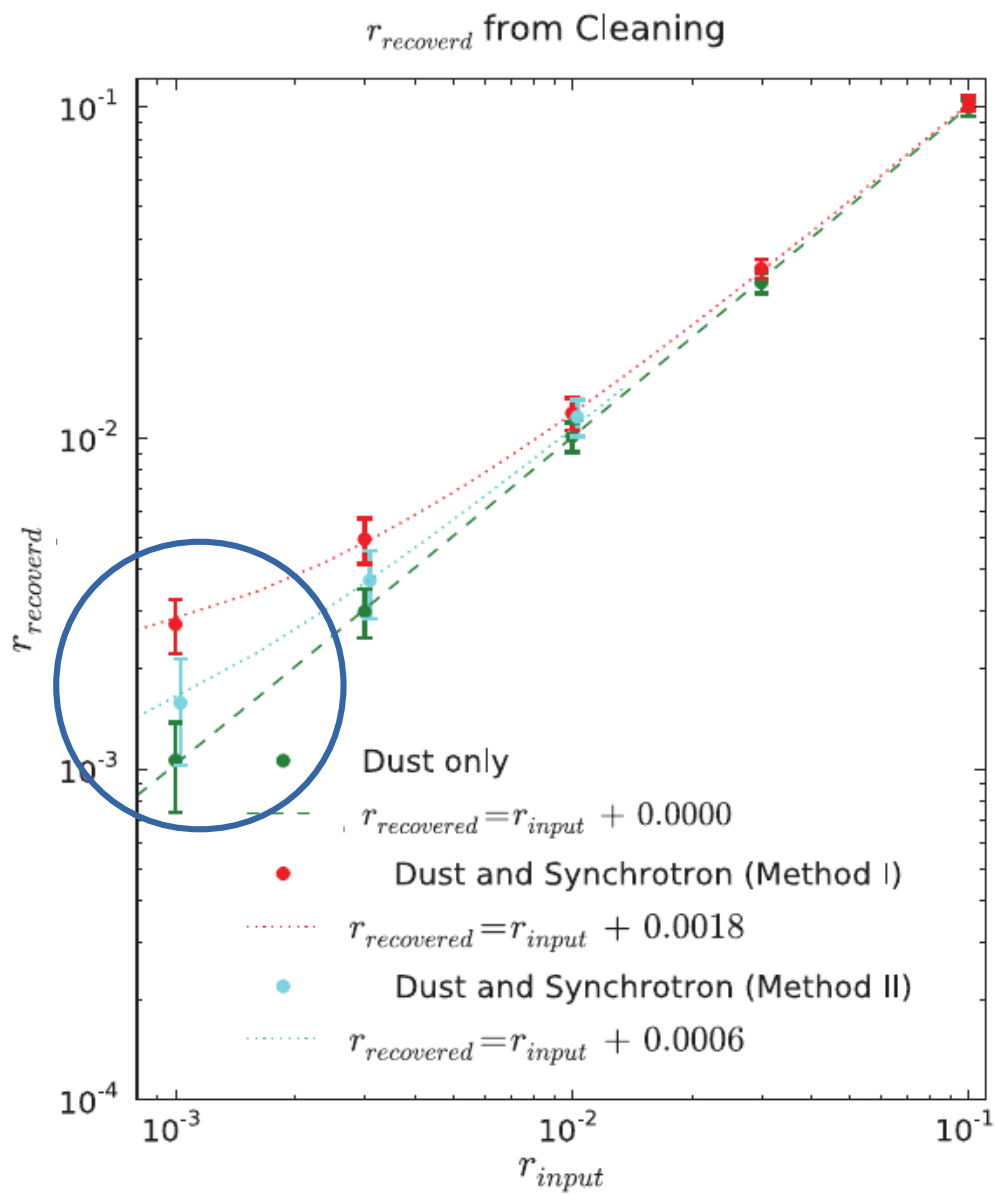
以下なら、
CMB lensingが
原理的なノイズ

r= $\dfrac{\text{重力波のパワー}}{\text{密度揺らぎのパワー}}$ **=0.001 のB-mode は** $\ell \lesssim 10$ でのみ観測

前景放射



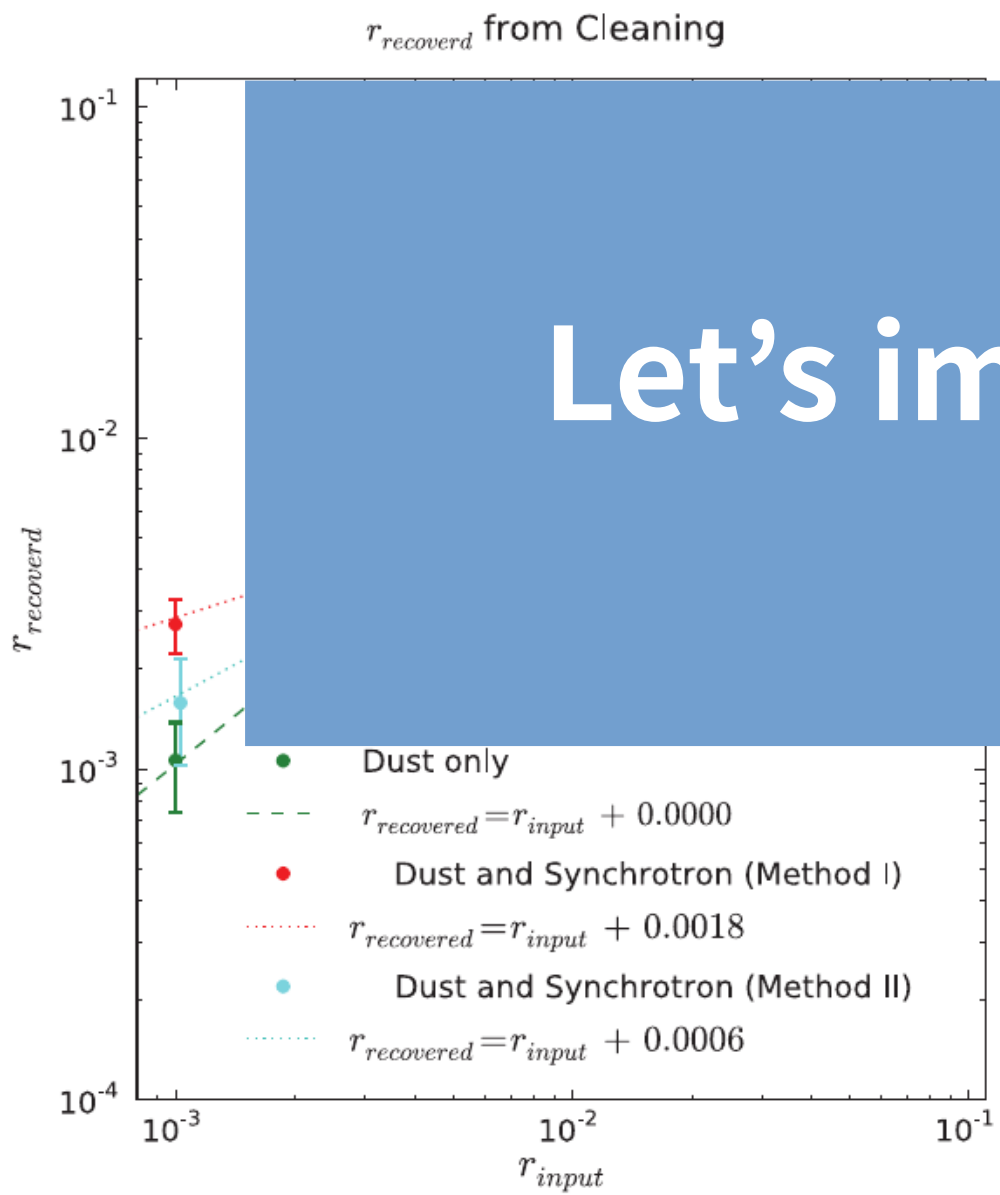
Planck 2015 results. X



Katayama & Komatsu, ApJ, 2011

先行研究からの課題:

前景放射のスペクトルが空の方向によって異なる場合、考慮しなければ **r** の推定がバイアスする



Let’s improve this!

Katayama & Komatsu, ApJ, 2011

デルタマップ法 (1)

- **前景放射モデル:**

$$Q(\nu,\hat{n}) = \mathrm{CMB}(\hat{n}) + g_\nu \left(\frac{\nu}{\nu_*}\right)^{\beta(\hat{n})} Q^{\mathrm{dust}}(\nu_*,\hat{n}) + \mathrm{noise}$$

⬇ 線形化

$$\beta(\hat{n}) \equiv \bar{\beta} + \delta\beta(\hat{n})$$

$$Q(\nu,\hat{n}) \approx \mathrm{CMB}(\hat{n}) + g_\nu \left(\frac{\nu}{\nu_*}\right)^{\bar{\beta}} \left[1 + \ln\left(\frac{\nu}{\nu_*}\right)\delta\beta(\hat{n})\right] Q^{\mathrm{dust}}(\nu_*,\hat{n}) + \mathrm{noise}$$

Let us estimate $\delta\beta(\hat{n})Q^{\mathrm{dust}}(\nu_*,\hat{n})$ **and subtract it !**

デルタマップ法 (2)

- **2 bands** (280, 337GHz) 使用して線形和 '**delta map**' を計算して**CMB band** (140GHz)に足す

$$Q(\nu_0) + \boxed{\alpha_1 Q(\nu_1) + \alpha_2 Q(\nu_2)} = (1 + \alpha_1 + \alpha_2)\mathrm{CMB}$$
$$+ f(\alpha_1, \alpha_2, \bar{\beta}) Q^{\mathrm{dust}}(\nu_*)$$
$$+ g(\alpha_1, \alpha_2, \bar{\beta}) \delta\beta Q^{\mathrm{dust}}(\nu_*)$$

- $f = 0$, $g = 0$ となるようにα_1, α_2を$\bar{\beta}$の関数として解く

Likelihood解析 … 前景放射が引けていれば、ガウシアンシグナルのはず

- **high angular resolution not necessary**
  - **use the full likelihood in pixel space**

$$\mathcal{L}(r, \bar{\beta}_{\rm sync}, \bar{\beta}_{\rm dust}) \propto \frac{\exp\left[-\frac{1}{2}[Q,U]_i^T C_{ij}^{-1}[Q,U]_j\right]}{\sqrt{|C_{ij}|}}$$

- **Model:**

$$C_{ij}(r, \bar{\beta}_{\rm sync}, \bar{\beta}_{\rm dust}) = C_{ij}^{\rm tens}(r) + C_{ij}^{\rm scal}$$

$$+\underline{N_{ij}(\bar{\beta}_{\rm sync}, \bar{\beta}_{\rm dust})} + n\delta_{ij}$$

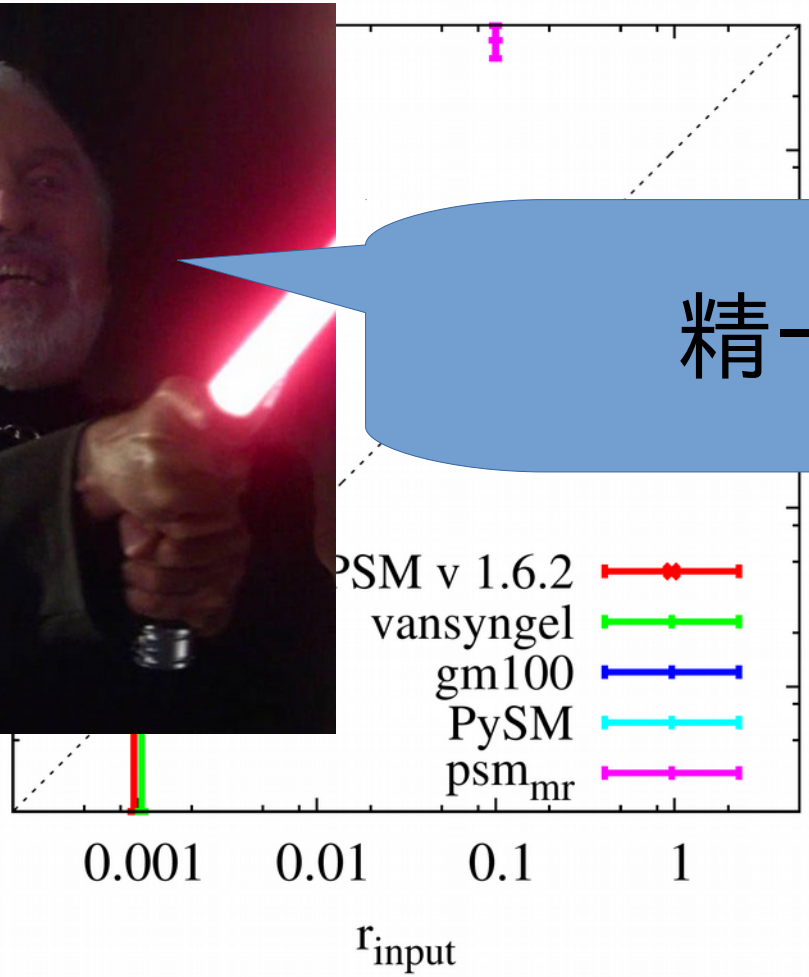
Noise covariances depend on foreground parameter:
Depending on how large portion of CMB component is subtracted by the linear combination of the maps.

Tested foreground models

	synchrotron	Thermal dust	Spin dust	Point source	FF	decorrelation
PSM v 1.6.2	power law varying β	power law varying β	-	-	-	-
gm100	power law varying β	2 components modified BB varying T	-	-	-	on
PySM 1608.02841	power law varying β	modified BB varying T&β	unpol	-	unpol	-
psm_mr	power law varying β	modified BB varying T&β	CNM 1% pol	4 types 1% pol	-	-
vansyngel	power law fixed β	modified BB fixed β	-	-	-	-

結果：デルタマップ法の性能

精一杯か？



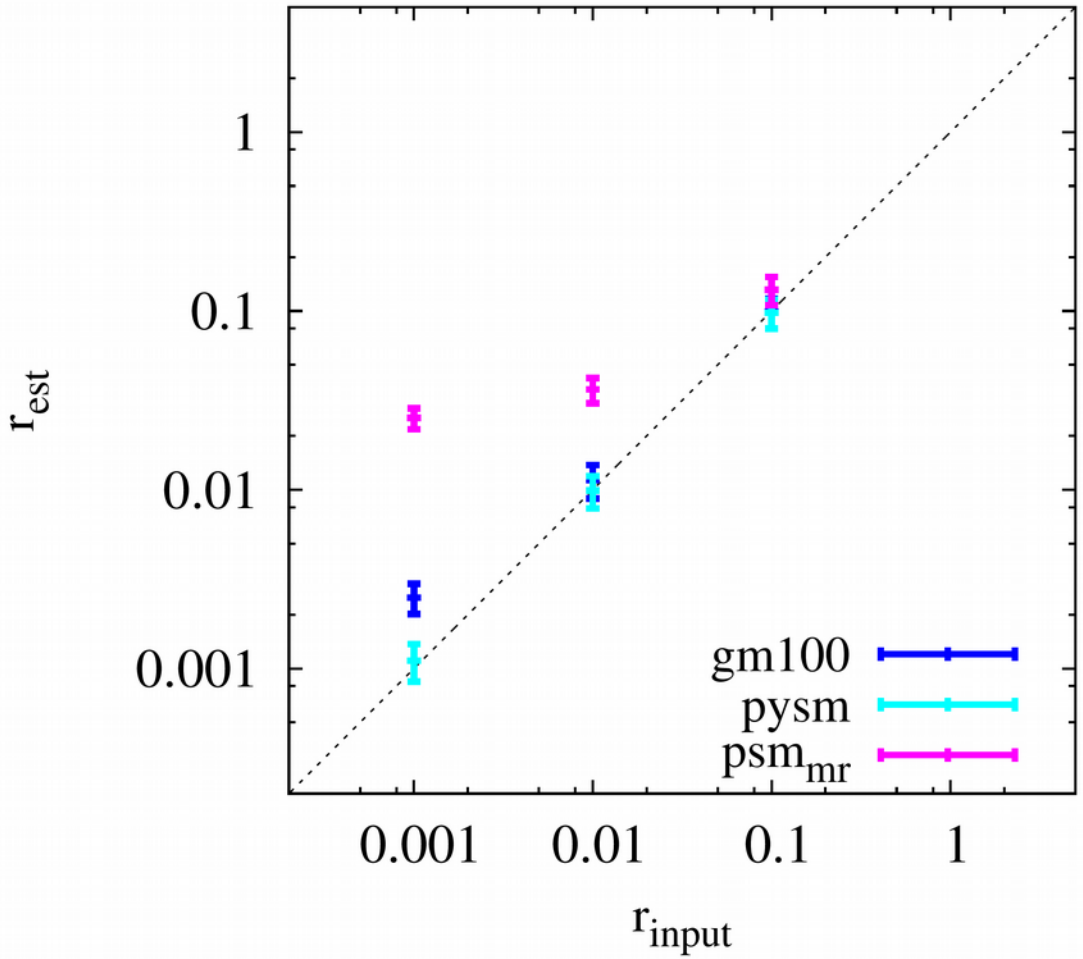
デルタマップ法（＋）

- **The sky model is modified to:**

$$Q(\nu,\hat{n}) \approx \mathrm{CMB}(\hat{n})$$
$$+g_\nu \left(\frac{\nu}{\nu_*}\right)^{\bar{\beta}_\mathrm{d}} \frac{1}{e^x-1}\left[1+\ln\left(\frac{\nu}{\nu_*}\right)\delta\beta(\hat{n}) + \frac{xe^x}{e^x-1}\frac{\delta T(\hat{n})}{\bar{T}}\right] Q^\mathrm{d}(\nu_*,\hat{n})$$
$$+\mathrm{noise} \qquad (x = h\nu/k\bar{T})$$

Again estimate $\delta\beta(\hat{n})Q^\mathrm{d}(\nu_*,\hat{n})$ **and** $\delta T(\hat{n})Q^\mathrm{d}(\nu_*,\hat{n})$ **and subtract them ! (We now need four bands)**

デルタマップ法（＋）の性能



注）これはノイズレスシミュレーション

Result summary

	bias	Error (95%)	bias(デルタマップ(+))
	r=0.001	r=0	
PSM v 1.6.2	$\delta r \sim 0.7 \times 10^{-3}$	$r \lesssim 3.8 \times 10^{-3}$	Not tested
gm100 (金井氏トーク)	$\delta r \sim 25 \times 10^{-3}$	$0.017 < r < 0.032$	$\delta r \sim 1.5 \times 10^{-3}$
PySM (1608.02841)	$\delta r \sim 62 \times 10^{-3}$	$0.043 < r < 0.081$	$\delta r \sim 0.1 \times 10^{-3}$
psm_mr	$\delta r \sim 3.9$	Not tested	$\delta r \sim 24 \times 10^{-3}$
Vansyngel (1611.02577)	$\delta r \sim 0.2 \times 10^{-3}$	$r \lesssim 2.6 \times 10^{-3}$	Not tested

- デルタマップで除去可
  - PSMv1.6.2, vansyngel (power-law models)
- デルタマップ(＋)であれば除去可
  - PySM,(gm100)
- 空を分割すれば、更に**bias**を減らすことは可能
- psm_mrが引けない原因は究明中

CONCLUSION

Tested foreground models

	synchrotron	Thermal dust	Spin dust	Point source	FF	decorrelation
PSM v 1.6.2	power law varying β	power law varying β	-	-	-	-
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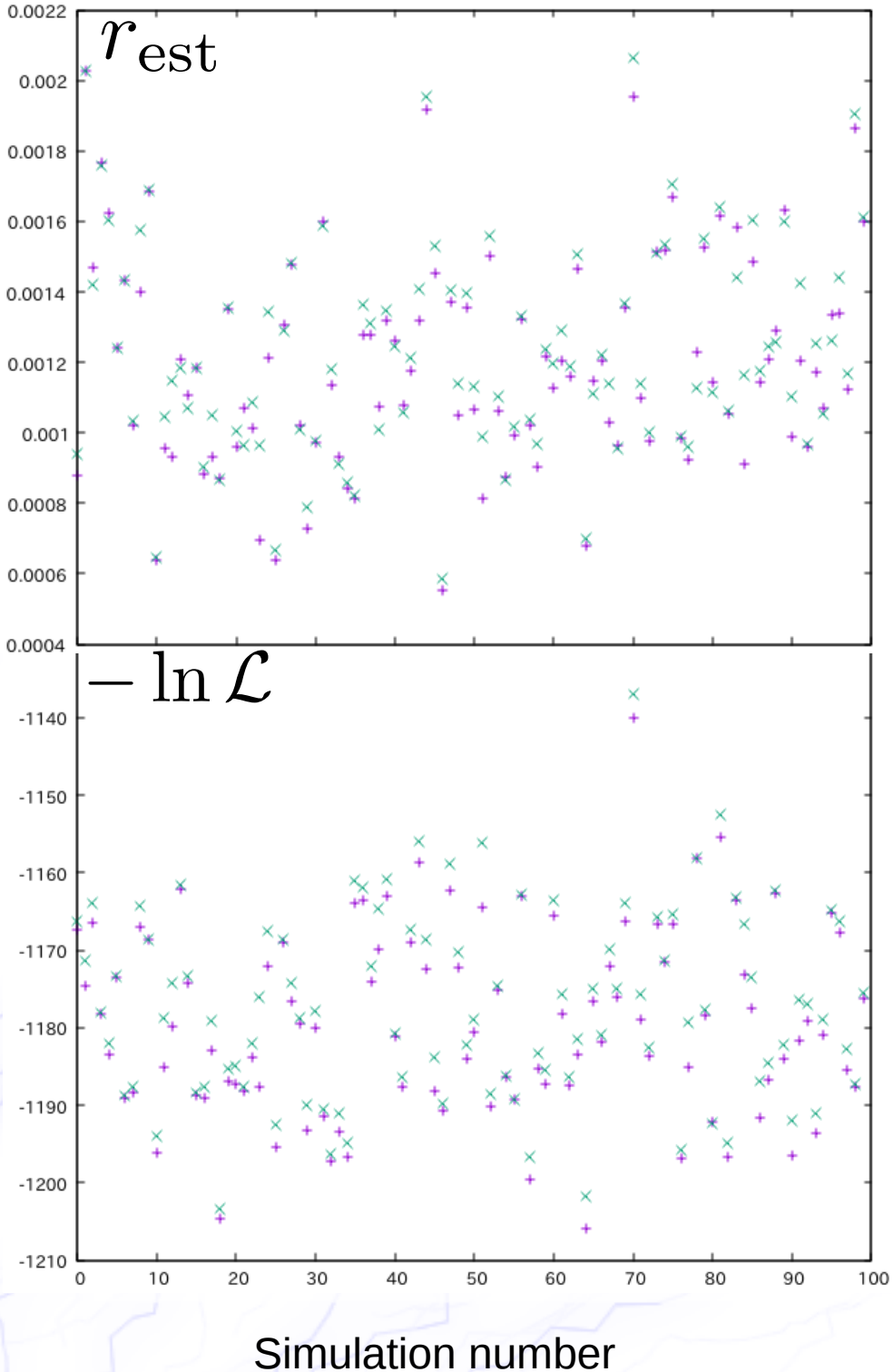


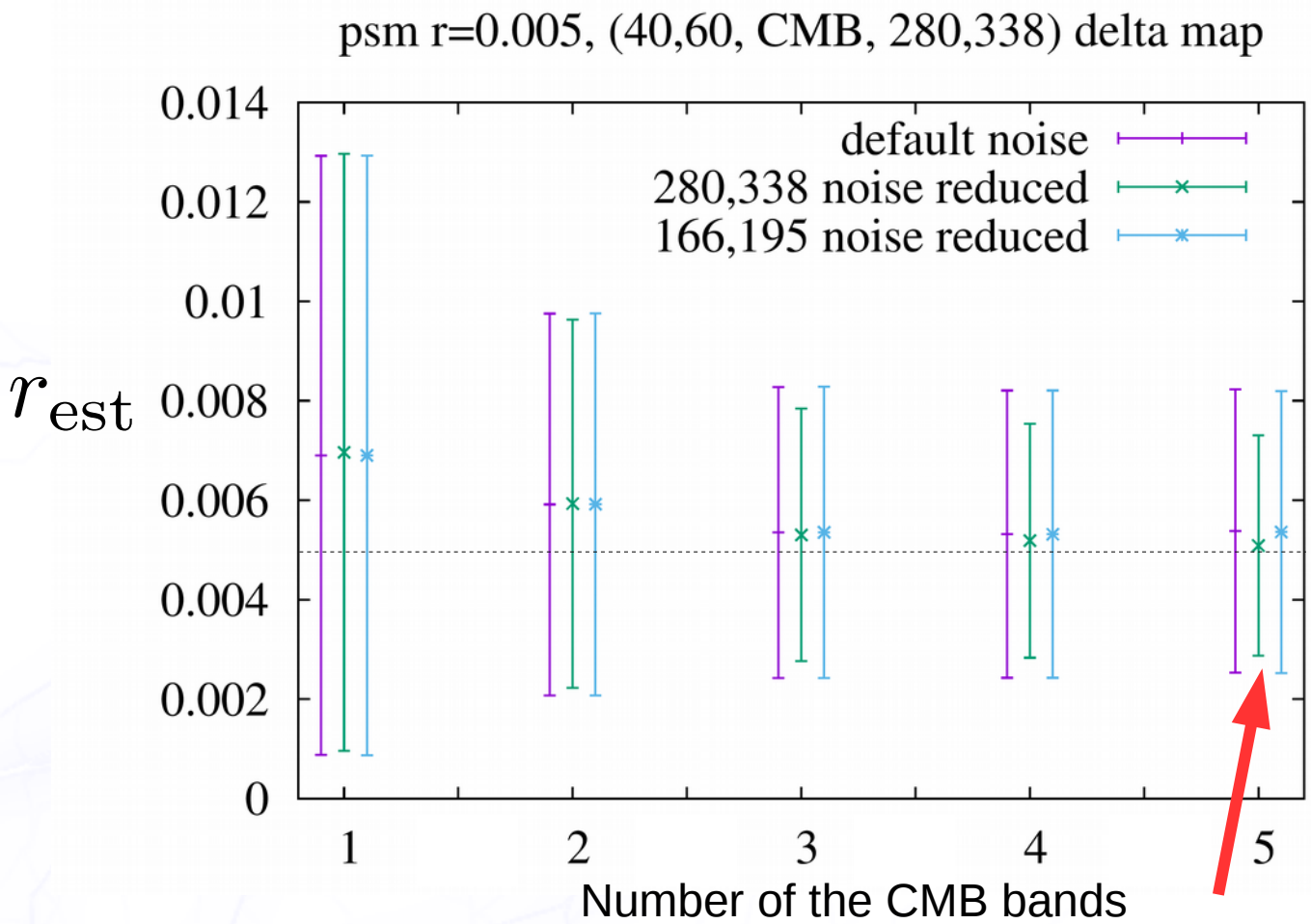
Depolarization effect is small?

Cyan: $\beta_{\rm s}, \beta_{\rm d}, T_{\rm d}$ **(common)**

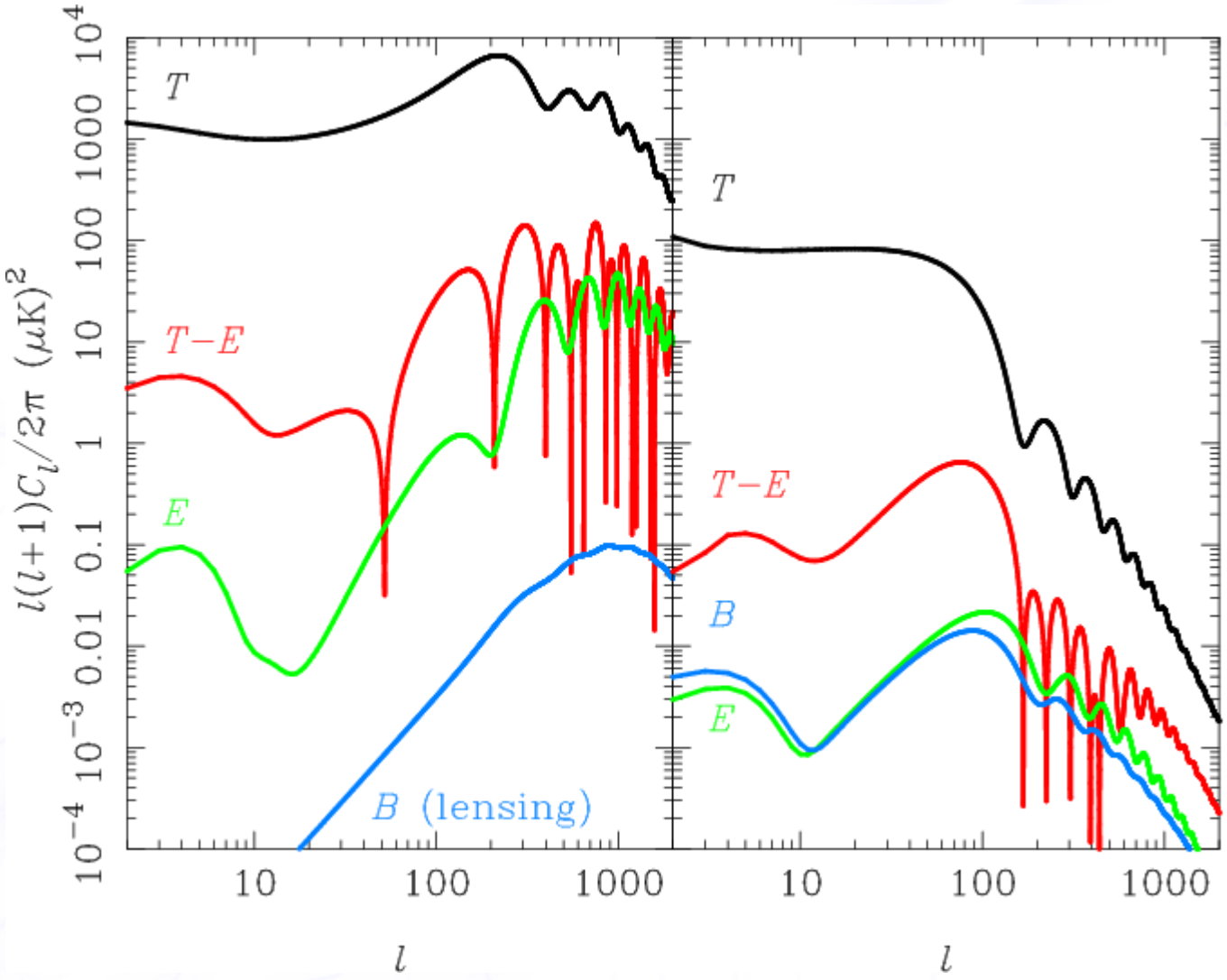
Purple: $\beta_{\rm s}^{Q}, \beta_{\rm d}^{Q}, T_{\rm d}^{Q}$

$\beta_{\rm s}^{U}, \beta_{\rm d}^{U}, T_{\rm d}^{U}$

How to improve the constraint



Reducing noise in the template maps is more effective



A. Challinor, arxiv:1210.6008

Traditional Template Cleaning Method in pixel space

- Pros
  - # of parameters << # of pixels
  - Linear combination of maps .. statistical properties of noise are unaffected
  - simple implementation of foreground masks
    - Free from non-local E&B mixing
- Cons
  - ν dependence is assumed to be independent of position .. large spatial variation of spectral index could possibly bias the power spectrum estimate.

Foregrounds

Table 1: Summary of Galactic emissions

K.Ichiki, PTEP, '14

component	spectrum	polarization
Synchrotron	power law with $\beta \approx -3$; possible curvature by ageing of CRs	$\approx 20\%$, become larger at higher latitudes up to $\approx 40\%$
Spinning dust	$\beta \approx -2.5$ around 20-30 GHz, falls rapidly above 60 GHz [14, 58]	less than 0.5% for $\gtrsim 30$ GHz
Free-free	power-law with $\beta \approx -2.1$	unpolarized; with an upper limit $\lesssim 3.4\%$ [58]
Thermal dust	approximately two temperature components with $\beta_{(1,2)} = (1.67, 2.70)$ [79]	≈ 3.6 % [47]

Foregrounds

Table 1: Summary of Galactic emissions

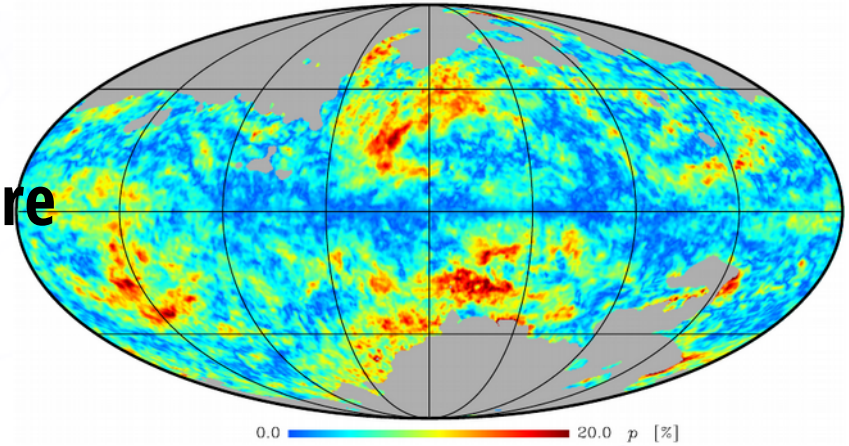
K.Ichiki, PTEP, '14

component	spectrum	polarization
Synchrotron	power law with $\beta \approx -3$; possible curvature by ageing of CRs	$\approx 20\%$, become larger at higher latitudes up to $\approx 40\%$
temperature only		
Thermal dust	approximately two temperature components with $\beta_{(1,2)} = (1.67, 2.70)$ [79]	≈ 3.6 % [47] $\longrightarrow p_{\max} > 20\%$ Planck intermediate results, A&A, '15

Key words

Synch ... lower ν, spatial variation, curvature

Dust ... higher ν, large pol. degree



デルタマップ法 (3)

- Demand that $f = 0,\ g = 0$, and solve $\alpha_1,\ \alpha_2$ as a function of $\bar{\beta}$

$$\boxed{\begin{aligned} \alpha_1 &= -\frac{g_\nu}{g_{\nu_1}} \left(\frac{\nu_0}{\nu_1}\right)^{\bar{\beta}} \frac{\ln\left(\frac{\nu_0}{\nu_2}\right)}{\ln\left(\frac{\nu_1}{\nu_2}\right)} \\ \alpha_2 &= -\frac{g_\nu}{g_{\nu_2}} \left(\frac{\nu_0}{\nu_2}\right)^{\bar{\beta}} \frac{\ln\left(\frac{\nu_0}{\nu_1}\right)}{\ln\left(\frac{\nu_2}{\nu_1}\right)} \end{aligned}}$$

$(\hat{n}, \nu_*)$ **independent**