Foreground subtraction & B-mode reconstruction with PICO

Mathieu Remazeilles

PICO Collaboration Science Meeting
Minneapolis, USA, 1-3 May 2018
Sky simulations 1: PSM

"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.

Sensitive to:
- Synchrotron curvature $C_s = 0.3$
- Dust spectral index $\beta_d$
- Dust temperature $T_d$
- Synchrotron spectral index $\beta_s$

CMB:
- $r = 10^{-3}$, $\tau = 0.06$ + lensing

Thermal dust @353 GHz:
- $T_d$, $\beta_d$
- 2.6 MJy/sr

Synchrotron @23 GHz:
- $\beta_s$
- 0.018 K RJ
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

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### PICO v3.0
**21- 800 GHz**

**Increased sensitivities!**

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Component separation methods

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

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

\[
\hat{S}_i(x) = d_i(x) - \sum_{i=1}^{N_v} \alpha_i t_i(x)
\]

- 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 \( \alpha_i \) are obtained by minimizing the variance of the cleaned map outside a given mask
- Fast \( \Rightarrow \) it can work at high resolution
- Robust \( \Rightarrow \) 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
SEVEM: example of cleaned 110 GHz channel (Q)

- Simulations from M. Remazeilles ($N_{side}=16$)
- 12 templates (constructed from 21-52, 270-800 GHz)
- Preliminary results
SEVEM: example of cleaned 110 GHz channel (U)

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

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

\[
 s^{(i+1)} \leftarrow P \left( s | C^{(i)}_\ell, \beta^{(i)}, d \right),
\]

\[
 C^{(i+1)}_\ell \leftarrow P \left( C_\ell | s^{(i+1)} \right),
\]

\[
 \beta^{(i+1)} \leftarrow P \left( \beta | s^{(i+1)}, d \right),
\]

amplitudes (CMB, foregrounds)

power spectrum (CMB)

spectral indices (foregrounds)

2. Likelihood estimation of \( r \) and \( A_{\text{Lens}} \):

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

\[
 C^{\text{th}}_\ell = r C^{\text{tensor}}_\ell (r = 1) + A_{\text{Lens}} C^{\text{lensing}}_\ell (r = 0).
\]

3. Blackwell-Rao posterior:

\[
 \mathcal{P} (r, A_{\text{Lens}}) \approx \frac{1}{N} \sum_{i=1}^{N} \mathcal{L} \left[ \hat{C}_\ell^{i} | C^{\text{th}}_\ell (r, A_{\text{Lens}}) \right]
\]

The Commander algorithm has strong heritage from real Planck data analysis
Commander reconstruction of CMB E-modes
21 – 800 GHz

\[ \tau = 0.0607 \pm 0.0023 \]

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

Foregrounds:

- Synchrotron power-law with curvature: \( \beta_s, C_s \)
- Thermal dust MBB: \( \beta_d, T_d \)

M. Remazeilles
Commander reconstruction of CMB B-modes
21 – 800 GHz

\[ r = 10^{-3} + \text{lensing}, f_{\text{sky}} = 50\% \]

\[ r = (0.30 \pm 0.41) \times 10^{-3} \]

**Foregrounds:**

- Synchrotron power-law with curvature: \( \beta_s, C_s \)
- Thermal dust
  MBB: \( \beta_d, T_d \)
  \( \beta_d, T_d, \beta_s \) locally fitted in each pixel
  \( C_s \) globally fitted

2 \leq \ell \leq 50

\[ f(\ell \mid l_{\text{max}}, g_{\text{energy}} \mu K^2) \]

\[ P(r) \]
Commander reconstruction of CMB B-modes
21 – 800 GHz

Foregrounds:
- Synchrotron power-law with curvature: $\beta_s$, $C_s$
- Thermal dust MBB: $\beta_d$, $T_d$

$\beta_d$, $T_d$, $\beta_s$ locally fitted in each pixel
$C_s$ globally fitted

Increased sensitivity reduces $\sigma(r)$ by 10% only

$2 \leq \ell \leq 50$

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

$r = (0.51 \pm 0.36) \times 10^{-3}$
Thanks to the broad frequency range of PICO, dust and synchrotron spectral parameters are all accurately recovered.
Commander results on foregrounds
PICO v3.0

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

\[ \beta_{\text{synch}} \]

\[ \beta_{\text{dust}} \]

\[ T_{\text{dust}} \]

M. Remazeilles
Commander reconstruction of CMB B-modes
No foregrounds, 50% mask

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

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

That's the minimal uncertainty that can be achieved from $2 \leq \ell \leq 50$ in the absence of foregrounds on 50% of the sky
How \( \sigma(r) \) 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:

\[
C_\ell^{BB}(\text{CMB}) = C_\ell^{BB}(\text{tensor}) + 0.40 \times C_\ell^{BB}(\text{lensing})
\]

2. Foreground cleaning is then performed on the “modified” sky simulations
Commander reconstruction of CMB B-modes
no delensing

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

Foregrounds:
- Synchrotron power-law with curvature: \( \beta_s, C_s \)
- Thermal dust MBB: \( \beta_d, T_d \)

\[ 2 \leq \ell \leq 50 \]
Commander reconstruction of CMB B-modes
60% delensing

**Foregrounds:**

- **Synchrotron**
  power-law with curvature: $\beta_s, C_s$

- **Thermal dust**
  MBB: $\beta_d, T_d$

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

\( 2 \leq \ell \leq 50 \)
Discarding PICO frequencies?
Commander reconstruction of CMB B-modes
21 – 800 GHz

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

after foreground cleaning

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

M. Remazeilles
Commander reconstruction of CMB B-modes
43 – 462 GHz

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

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

Input Commander

M. Remazeilles
COMMANDER results on foregrounds
PICO 21 – 800 GHz

$\beta_{\text{synch}}$

$\beta_{\text{dust}}$

$T_{\text{dust}}$

M. Remazeilles
COMMANDER results on foregrounds

PICO 43 – 462 GHz

**$\beta_{\text{synch}}$**

Lack of frequency range / high frequencies

Lack of precision/constraint on $T_{\text{dust}}$

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

**$\beta_{\text{dust}}$**

**$T_{\text{dust}}$**

M. Remazeilles
PICO
21 – 800 GHz

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

(75% increase)

PICO
43 – 462 GHz

\[ \sigma(r=10^{-3}) = 0.7 \times 10^{-3} \]
$\beta_{\text{synch}}$

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

(25% increase)

$\beta_{\text{dust}}$

$T_{\text{dust}}$

PICO
21 – 800 GHz

PICO
43 – 800 GHz
### Summary for PICO

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<th>$\sigma(r=10^{-3})$ [$\times 10^{-3}$]</th>
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<td><strong>21 – 800 GHz, with foregrounds, 50% mask</strong></td>
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<tr>
<td>PICO v2-1.4</td>
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<td>PICO v3.0</td>
<td>0.51</td>
<td>0.36</td>
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<tr>
<td>PICO v3.0 + 60% delensing</td>
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<td><strong>43 – 800 GHz, with foregrounds, 50% mask</strong></td>
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<td><strong>43 – 462 GHz, with foregrounds, 50% mask</strong></td>
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<td>0.7</td>
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</table>

These results are for $2 \leq \ell \leq 50$.

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

M. Remazeilles
Path forward with foregrounds

- 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 $N_{\text{side}} = 16$ 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 $\mu$-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:

The Sneaky Point:

CMB experiments with narrow frequency range $< 400$ GHz show no evidence ($\chi^2 \sim 1$) 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 \( \ell \gtrsim 50 \)*

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Curto et al 2013
#3. What about magnetic dust (MD)?

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

Ferromagnetic lattice with spins aligned.
Thermal fluctuations will move them away, producing magnetic dipole radiation

Draine & Hensley 2013
#4. Averaging effects

The actual foreground SED on the maps differs from the real SED in the sky!

Chluba, Hill, Abitbol, 2017

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 $\mu$-type distortions at $z > 10^4$

$\mu$-$T$ correlation signal between CMB temperature and $\mu$-distortion anisotropies

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

$\rightarrow$ to be definitely considered by future CMB satellites!