Extracting anisotropic $\mu$-type spectral distortions

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Remazeilles & Chluba
arXiv:1802.10101

“Probing fundamental physics with CMB spectral distortions”
CERN TH Institute, 12-16 Mar 2018
µ-type CMB spectral distortions

At redshifts $10^4 < z < 2 \times 10^6$ (pre-recombination), energy injections into primordial plasma prevent brehmsstrahlung and double Compton scattering to create photons to maintain Planck's equilibrium, leading to Bose-Einstein equilibrium:

$$n_{BE} \approx n_{PI} + \mu \frac{e^x}{(e^x - 1)^2} \left( \frac{x}{2.19} - 1 \right)$$

$x \equiv h \nu / k T_{CMB}$

Caused by exciting physics processes occurring at redshifts $z > 10^4$:

$\rightarrow$ dissipation of small-scale acoustic modes $-$ Silk 1968

$\rightarrow$ annihilation/decay of relic particles $-$ Hu & Silk 1993

$\rightarrow$ evaporation of primordial black holes $-$ Carr et al 2010

LCDM predicts: $|\mu| = 2.3 \times 10^{-8} \rightarrow$ very faint signal! $-$ Chluba 2016

COBE/FIRAS constraint: $|\mu| < 9 \times 10^{-5}$ $-$ Fixsen et al 1996
Anisotropic \( \mu \)-type distortions

Aside from CMB monopole distortions...

Primordial non-Gaussianity in the ultra-squeezed limit predicts:

- **Anisotropies of \( \mu \)-type distortions** (*spectral-spatial distortions*):

  \[
  C_{\ell}^{\mu \times \mu} = 144 \ C_{\ell}^{TT, SW} \ f_{NL}^2 \ <\mu>^2.
  \]

- **\( \mu \)-T correlations** between CMB temperature and \( \mu \)-distortion anisotropies:

  \[
  C_{\ell}^{\mu \times T} = 12 \ C_{\ell}^{TT, SW} \ \rho(\ell) \ f_{NL} \ <\mu>.
  \]

- **Scale-dependent** \( f_{NL}(k) = f_{NL}(k_0)(k/k_0)^{n_{NL^{-1}}} \) with running index of \( n_{NL} \leq 1.6 \) would allow for:

  \[
  f_{NL}(k_0 = 0.05 \text{ Mpc}^{-1}) \approx 5 \quad \leftarrow \text{CMB temperature anisotropies}
  \]

  \[
  f_{NL}(k = 740 \text{ Mpc}^{-1}) \approx 4500 \quad \leftarrow \text{\( \mu \)-type distortion anisotropies}
  \]

\( k_s \sim 10^2 - 10^4 \text{ Mpc}^{-1} \)

\( k_L \sim 10^{-3} \text{ Mpc}^{-1} \)
Questions

- Can we detect the $\mu$-$T$ correlated signal with future CMB satellites?

- What limit on $f_{NL} (k=740 \text{ Mpc}^{-1})$ can be achieved in the presence of foregrounds?
Spectral signature of distortions

Distinct spectral signatures!

Multi-frequency observations allow (in principle) to disentangle those signals
**CMB satellite concepts**

- **LiteBIRD (JAXA)**
  - Matsumura et al., 2013
  - 40 – 402 GHz; 2.5 μK.arcmin

- **PIXIE (NASA?)**
  - Kogut et al., 2011
  - 30 – 6000 GHz; 6.6 μK.arcmin (Δν=30 GHz)

- **CORE (ESA? ISRO?)**
  - Delabrouille et al., 2017
  - 60 – 600 GHz; 1.7 μK.arcmin

- **PICO (NASA?)**
  - S. Hannany, priv. comm.
  - 21 – 800 GHz; 1.1 μK.arcmin
Anisotropic primordial spectral distortions

Similar dynamic range between signal and foregrounds than primordial B-modes at $r \sim 10^{-3}$

→ to be definitely considered by future CMB satellites...
Anisotropic primordial spectral distortions

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

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

$\to$ to be definitely considered by future CMB satellites...
Cosmic history of CMB spectral distortions
The problem of foregrounds

\[ z > 10^4 \]

Chluba 2014

\( \mu \)-type spectral distortions open a new window to probe physics occurring behind the last-scattering surface, where the universe is invisible!
The problem of foregrounds

$z \approx 10^3$

CMB last-scattering surface (foreground)

$0 < z < 10^3$

SZ clusters (foreground)

$z > 10^4$

cosmological signal

$\mu$-type spectral distortions open a new window to probe physics occurring behind the last-scattering surface, where the universe is invisible!
The problem of foregrounds

Chluba 2014

$z \approx 10^3$

CMB last-scattering surface (foreground)

$0 < z < 10^3$

SZ clusters (foreground)

$z = 0$

Galactic foregrounds

$\mu$-type spectral distortions open a new window to probe physics occurring behind the last-scattering surface, where the universe is invisible!
Component separation: the problem

\(\mu\)-distortion anisotropies

Angular power spectrum

\(\ell, \ell'\) - multipole

\(\mu K_{\text{CMB}}\)
Component separation: the problem

$\mu$-distortion + CMB temperature anisotropies

Angular power spectrum

$\ell \langle l+1 \rangle C_\ell \propto 2\pi$

CMB
Component separation: the problem

\( \mu \text{-distortion + CMB + SZ} \)
Component separation: the problem

\( \mu \)-distortion + CMB + SZ + Galactic

Angular power spectrum

\[ \ell (\ell + 1) C_\ell / 2\pi \]

Multipole \( \ell \)

- CMB
- SZ
- Galactic
Component separation: the problem

$\mu$-distortion + CMB + SZ + Galactic + noise

Angular power spectrum

$\ell$-dependence of the power spectrum

- CMB
- SZ
- Galaxy
- Noise
Sky observation at frequency $\nu$ and pixel $n$:

$$X_\nu(n) = a_\nu S_{\text{CMB}}(n) + b_\nu S_{\text{SZ}}(n) + N_\nu(n)$$

Minimum-variance weighted linear combination of the frequency maps:

$$\hat{S}_{\text{CMB}}(n) = \sum w_\nu X_\nu(n)$$

where

- variance $<\hat{s}^2>$ minimum
- $\sum w_\nu a_\nu = 1$

**Standard ILC**

$$W = \frac{a^t C^{-1}}{a^t C^{-1} a}$$

*Benett et al, 2003*

*Tegmark et al, 2003*

*Eriksen et al, 2004*

*Delabrouille et al, 2009*
Standard ILC

Sky observation at frequency $\nu$ and pixel $n$

$$X_{\nu}(n) = a_{\nu} S_{\text{CMB}}(n) + b_{\nu} S_{\text{SZ}}(n) + N_{\nu}(n)$$

“foregrounds + noise”

Minimum-variance weighted linear combination of the frequency maps:

$$\hat{S}_{\text{SZ}}(n) = \sum w_{\nu} X_{\nu}(n)$$

where

$$\sum w_{\nu} b_{\nu} = 1$$

$$\text{variance } <\hat{s}^2> \text{ minimum}$$

Standard ILC

$$W = \frac{b^t C^{-1}}{b^t C^{-1} b}$$

Benett et al, 2003
Tegmark et al, 2003
Eriksen et al, 2004
Delabrouille et al, 2009
Constrained ILC

Sky observation at frequency $\nu$ and pixel $n$

$$X_\nu(n) = a_\nu S_{\text{CMB}}(n) + b_\nu S_{\text{SZ}}(n) + N_\nu(n)$$

where

$$\hat{S}_{\text{CMB}}(n) = \sum w_\nu X_\nu(n)$$

with orthogonality constraint to kill SZ contamination

$\sum w_\nu a_\nu = 1$

$\sum w_\nu b_\nu = 0$

Constrained ILC

$$W = \frac{(b^t C^{-1} b) a^t C^{-1} - (a^t C^{-1} a) b^t C^{-1}}{(a^t C^{-1} a) (b^t C^{-1} b) - (a^t C^{-1} b)^2}$$

Standard ILC

input thermal SZ

input kinetic SZ

input CMB

\[ w = \frac{a^t C^{-1}}{a^t C^{-1} a} \]

Standard ILC

Input thermal SZ

Input kinetic SZ

Input CMB

Error: ILC - CMB

Thermal SZ residuals!
(clusters in the CMB)

\[ w = \frac{a^t C^{-1}}{a^t C^{-1} a} \]

Constrained ILC

input thermal SZ

input kinetic SZ

input CMB

error: Constrained ILC - CMB

\[ w = \frac{(b^\dagger C^{-1} b) a^\dagger C^{-1} - (a^\dagger C^{-1} a) b^\dagger C^{-1}}{(a^\dagger C^{-1} a) (b^\dagger C^{-1} b) - (a^\dagger C^{-1} b)^2} \]

Extracting foreground-obscured \( \mu \)-anisotropies

\[
data(\nu;n) = \mu + T + \text{(foregrounds+noise)}
\]

- \( \text{CMB } T \) anisotropies is a significant foreground to \( \mu \)-distortion anisotropies
- \textbf{Most sneaky, the CMB } T \text{ foreground is also correlated with the } \mu \text{ signal!}
- \textbf{If residual } T \text{ anisotropies are left in the reconstructed } \mu \text{-distortion signal after component separation}

\[
\hat{\mu} = \mu + \varepsilon_1 T + \varepsilon_2 \text{(foregrounds+noise)}
\]

then the \( \mu \)-\( T \) \textit{correlation signal} will be biased by \textit{spurious } TT \textit{ correlations}:

\[
\hat{\mu} \times \hat{T} = \mu \times T + \varepsilon_1 TT + \ldots
\]

\textit{Remazeilles & Chluba (2018) }\rightarrow \textit{our solution: use the “Constrained ILC” approach}
CMB-free $\mu$-distortion reconstruction

$$X(\nu;n) = a_\mu(\nu) \mu(n) + a_T(\nu) T(n) + N(\nu;n)$$

**Constrained ILC estimate:**

$$\hat{\mu}(n) = \sum_\nu w(\nu) X(\nu;n)$$

such that

$$\begin{cases} \text{variance } \langle \mu^2 \rangle \text{ minimum} & (1) \\ \sum_\nu w_\nu a_\mu(\nu) = 1 & (2) \\ \sum_\nu w_\nu a_T(\nu) = 0 & (3) \end{cases}$$

orthogonality constraint to kill CMB $T$ contamination
CMB-free $\mu$-distortion reconstruction

$$X(\nu; n) = a_{\mu}(\nu) \mu(n) + a_{T}(\nu) T(n) + N(\nu; n)$$

sky observation at frequency $\nu$ and pixel $n$

$\mu$ SED $\mu$-distortion anisotropies CMB SED CMB temperature anisotropies foregrounds + noise

Constrained ILC estimate:

$$\hat{\mu}(n) = \sum_{\nu} w(\nu) X(\nu; n)$$

such that

\[
\begin{cases}
\text{variance } <\mu^2> \text{ minimum} & (1) \\
\sum_{\nu} w_{\nu} a_{\mu}(\nu) = 1 & (2) \\
\sum_{\nu} w_{\nu} a_{T}(\nu) = 0 & (3)
\end{cases}
\]

orthogonality constraint to kill CMB $T$ contamination

$$\hat{\mu}(n) = \left( \sum_{\nu} w_{\nu} a_{\mu}(\nu) \right) \mu + \left( \sum_{\nu} w_{\nu} a_{T}(\nu) \right) T + \sum_{\nu} w_{\nu} N_{\nu}$$

$$\left\{ \begin{array}{c}
= 1 \\
= 0 \\
\text{minimized}
\end{array} \right\}$$

Remazeilles & Chluba (2018)
CMB-free $\mu$-distortion reconstruction

$$X(\nu;n) = a_\mu(\nu) \mu(n) + a_T(\nu) T(n) + N(\nu;n)$$

- Sky observation at frequency $\nu$ and pixel $n$
- $\mu$ SED
- $\mu$-distortion anisotropies
- CMB SED
- CMB temperature anisotropies
- Foregrounds + noise

**Constrained ILC estimate:**

$$\hat{\mu}(n) = \sum_\nu w(\nu) X(\nu;n)$$

such that

$$\begin{cases} 
\text{variance } <\mu^2> \text{ minimum} & (1) \\
\sum_\nu w(\nu) a_\mu(\nu) = 1 & (2) \\
\sum_\nu w(\nu) a_T(\nu) = 0 & (3) 
\end{cases}$$

Orthogonality constraint to kill CMB $T$ contamination

$$\hat{\mu}(n) = (\sum_\nu w(\nu) a_\mu(\nu)) \mu + (\sum_\nu w(\nu) a_T(\nu)) T + \sum_\nu w(\nu) N_\nu$$

- $= 1$ (2)
- $= 0$ (3)
- Minimized (1)

Remazeilles & Chluba (2018)
CMB-free $\mu$-distortion reconstruction

$$X(\nu;n) = a_\mu(\nu)\mu(n) + a_T(\nu)T(n) + N(\nu;n)$$

**Sky observation at frequency $\nu$ and pixel $n$**

- $\mu$ SED
- $\mu$-distortion anisotropies
- CMB SED
- CMB temperature anisotropies
- Foregrounds + noise

**Constrained ILC estimate:**

$$\hat{\mu}(n) = \sum_{\nu} w(\nu) X(\nu;n)$$

such that

1. Variance $\langle \mu^2 \rangle$ minimum
2. $\sum_{\nu} w(\nu) a_\mu(\nu) = 1$
3. $\sum_{\nu} w(\nu) a_T(\nu) = 0$ (orthogonality constraint to kill CMB $T$ contamination)

$$\rightarrow \hat{\mu} \times \hat{T} = \mu \times T + \varepsilon_1 T T + \ldots$$

Remazeilles & Chluba (2018)
CMB-free $\mu$-distortion reconstruction

$$X(\nu;n) = a_\mu(\nu) \mu(n) + a_T(\nu) T(n) + N(\nu;n)$$

- sky observation at frequency $\nu$ and pixel $n$
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$$\hat{\mu}(n) = \sum_\nu w(\nu) X(\nu;n)$$

such that

1. variance $\langle \mu^2 \rangle$ minimum
2. $\sum w_\nu a_\mu(\nu) = 1$
3. $\sum w_\nu a_T(\nu) = 0$

**Solution:**

$$W = \frac{(a_T^t C^{-1} a_\mu^t) a_\mu^t C^{-1} - (a_T^t C^{-1} a_\mu^t) a_T^t C^{-1}}{(a_\mu^t C^{-1} a_\mu^t)(a_T^t C^{-1} a_T) - (a_\mu^t C^{-1} a_T)^2}$$

Remazeilles & Chluba (2018)
Simulation of correlated μ and T fields

\[ C_{\ell}^{TT} \]

6 orders of magnitude!

\[ C_{\ell}^{\mu \times T} \]

\[ f_{\text{NL}} = 4500, \langle \mu \rangle = 2 \times 10^{-8} \]

Ravenni et al (2017)
Simulation of correlated $\mu$ and $T$ fields

Remazeilles & Chluba (2018)
Our sky simulations (e.g. LiteBIRD)

\[ \langle \mu \rangle = 2 \times 10^{-8} \]
\[ f_{NL} = 4500 \]

\( \mu_{\text{CMB}} \)
Constrained ILC $\mu$-map reconstruction (LiteBIRD)

Remazeilles & Chluba (2018)
Constrained ILC $\mu$-map reconstruction (LiteBIRD)

Remazeilles & Chluba (2018)

significant foreground contamination
Constrained ILC \( \mu \)-map reconstruction (LiteBIRD)

\( f_{NL} = 10^4 \)

\( f_{NL} = 10^5 \)

\( f_{NL} = 10^6 \)

significant foreground contamination

Remazeilles & Chluba (2018)
Constrained ILC $\mu$-map reconstruction (LiteBIRD)

This is actually $\mu\mu$. What about $\mu \times T$?

Remazeilles & Chluba (2018)
$C_\ell^{\mu-x_T}$ reconstruction: $f_{NL} = 4500$ (w/o foregrounds)

Remazeilles & Chluba (2018)
$C_\ell^\mu T$ reconstruction: $f_{\text{NL}} = 4500$ (with foregrounds)

Remazeilles & Chluba (2018)
$C_\ell^\mu T$ reconstruction: $f_{NL} = 4500$ (with foregrounds)

Remazeilles & Chluba (2018)
$C_{\ell}^{\mu \times T}$ reconstruction: $f_{NL} = 10^4$ (with foregrounds)

Remazeilles & Chluba (2018)
$C_\ell^\mu \times T$ reconstruction: $f_{NL} = 10^5$ (with foregrounds)
Standard ILC vs Constrained ILC

In light of these considerations, the constraints on $\mu T$ from Planck data (Khatri & Sunyaev 2015) should be taken cautiously.
Forecasts on primordial non-Gaussianity

Table 5. Detection forecasts on $f_{\text{NL}}(k \approx 740 \text{ Mpc}^{-1})$ after component separation, based on multipoles $2 \leq \ell \leq 200$.

<table>
<thead>
<tr>
<th>$f_{\text{NL}}$ (fiducial)</th>
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<td><strong>PIXIE</strong></td>
<td>$(1.11 \pm 0.40) \times 10^5$</td>
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<td>$(1.5 \pm 3.9) \times 10^4$</td>
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Remazeilles & Chluba (2018)
Forecasts on primordial non-Gaussianity

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*PICO is in the best position to detect the $\mu$-$T$ correlation signal at $f_{NL}(k=740 \text{ Mpc}^{-1}) \lesssim 4500$ in the presence of foregrounds*
Despite a very broad frequency coverage, PIXIE results on anisotropic $\mu$ are of poorer quality than those from PICO, CORE, LiteBIRD

**Why?! → because of lower sensitivity and lower spatial resolution**

- We find that increasing PIXIE resolution from 96' to 40', while keeping the baseline sensitivity, would improve $\sigma(f_{NL})$ by 50%

  → high-resolution channels enable using more spatially correlated information to improve foreground cleaning

- If the foreground complexity can be captured by, say, 10 degrees of freedom, then 15-20 frequency bands are enough to remove the foregrounds

  → *In this case, the most sensitive experiments will make a difference in the ILC trade-off of minimizing the balance between foreground and noise contamination*

- If the foreground complexity relies on more than 20 degrees of freedom, then the broad frequency range of PIXIE will make a difference with respect to imagers
In the absence of μ-distortion anisotropies, the reconstruction by Constrained ILC is consistent with $f_{NL} = 0$.\)

$\mu$-T reconstruction for $f_{NL} = 0$

$\mu = 2 \times 10^{-8}$

Remazeilles & Chluba (2018)
Table 6. Detection limits for PICO on $f_{NL}(k \approx 740 \text{ Mpc}^{-1})$ after component separation, based on the multipole range $2 \leq \ell \leq 500$ using the model of Ravenni et al. (2017) to describe the $\mu - T$ cross-correlation. Foregrounds are included in all cases and the fiducial $f_{NL}$ parameter was varied.

<table>
<thead>
<tr>
<th>$f_{NL}$ (fiducial)</th>
<th>$-4500$</th>
<th>$0$</th>
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<tr>
<td>PICO</td>
<td>$-2996 \pm 2112$</td>
<td>$1325 \pm 2114$</td>
<td>$5698 \pm 2121$</td>
</tr>
<tr>
<td>$2\sigma$</td>
<td>$-\quad$</td>
<td>$2\sigma$</td>
<td>$\quad$</td>
</tr>
</tbody>
</table>

Minimum detection limit by PICO in the presence of foregrounds:

$$|f_{NL}| \leq 2114$$

Remazeilles & Chluba (2018)
More detectors or more frequencies?

“Super-LiteBIRD” with 100 x more detectors
40 – 400 GHz, 0.2 µK.arcmin

PICO baseline
20 – 800 GHz, 0.8 µK.arcmin

Extended frequency coverage at frequencies ν ≤ 40 GHz and ν ≥ 400 GHz provides more leverage than increased channel sensitivity

Remazeilles & Chluba (2018)
What part of the frequency range matters?

- Discarding PICO frequencies above $\nu > 400$ GHz degrades our component separation results by $\sim 7\%$

- Discarding PICO frequencies below $\nu < 40$ GHz degrades our component separation results by $\sim 30\%$

\textit{Low-frequencies $\nu \leq 40$ GHz have more constraining power for $\mu$-distortion anisotropies than high-frequencies above $\nu \geq 400$ GHz}

\textit{Remazeilles & Chluba (2018)}

$\rightarrow$ consistent with the conclusions of \textit{Abitbol et al (2017)} for monopole distortions
Impact of inter-calibration errors

“Calibration errors can screw up the ILC in the high signal-to-noise regimes, through partial cancellation of the variance of the CMB temperature map”

The allowed inter-channel calibration uncertainty for PICO is 0.01 %
(The promise of CORE is to achieve such calibration accuracy)
Averaging effects

Because of averaging different line-of-sight SEDs within a pixel/beam, the actual SED of foregrounds in the maps will differ from the physical SED in the sky — Chluba et al 2017

Spurious SED curvatures created by pixel averaging effects, if ignored in the parametric fit, have been shown to bias primordial B-modes at the level of $\Delta r \sim 10^{-3}$ — Remazeilles et al 2017, for the CORE collaboration

The “Constrained ILC” is blind (no parametrization / assumption on foregrounds), so fairly insensitive to averaging effects
Conclusions

We have computed the first forecasts on the detection of the \(\mu\)-\(T\) correlation signal and \(f_{\text{NL}}(k\approx740 \text{ Mpc}^{-1})\) in the presence of foregrounds with future CMB satellites.

We have proposed a tricky component separation approach (Constrained ILC) to null the CMB contamination in \(\mu\), which otherwise biases the \(\mu\)-\(T\) correlation signal.

Among the CMB satellite concepts, PICO is in the best position to control foregrounds and detect anisotropic \(\mu\)-type distortions with \(f_{\text{NL}}(740 \text{ Mpc}^{-1}) \lesssim 2100\).

Optimization: more detectors or more frequencies?

Extended frequency coverage at frequencies \(v \leq 40 \text{ GHz}\) and \(v \geq 400 \text{ GHz}\) provides more leverage than increased channel sensitivity.

Low-frequencies \(v \leq 40 \text{ GHz}\) have more constraining power on anisotropic \(\mu\)-distortions than high-frequencies \(v \geq 400 \text{ GHz}\).

Absolute calibration / FTS like PIXIE still needed for \(\mu\)-distortion anisotropies to break the \(f_{\text{NL}}\times\langle\mu\rangle\) degeneracy.

Thank you for your attention!