中山大學
SUN YAT-SEN UNIVERSITY

Removal of point source leakage from time-order data filtering

Speaker: ZHANG Zhaoxuan (SYSU)
Supervisors: LIU Hao (AHU)
ZHANG Le (SYSU)
Collaborators: HUANG Lu (SYSU)
LIU Yang (IHEP)
LI Siyu (IHEP)

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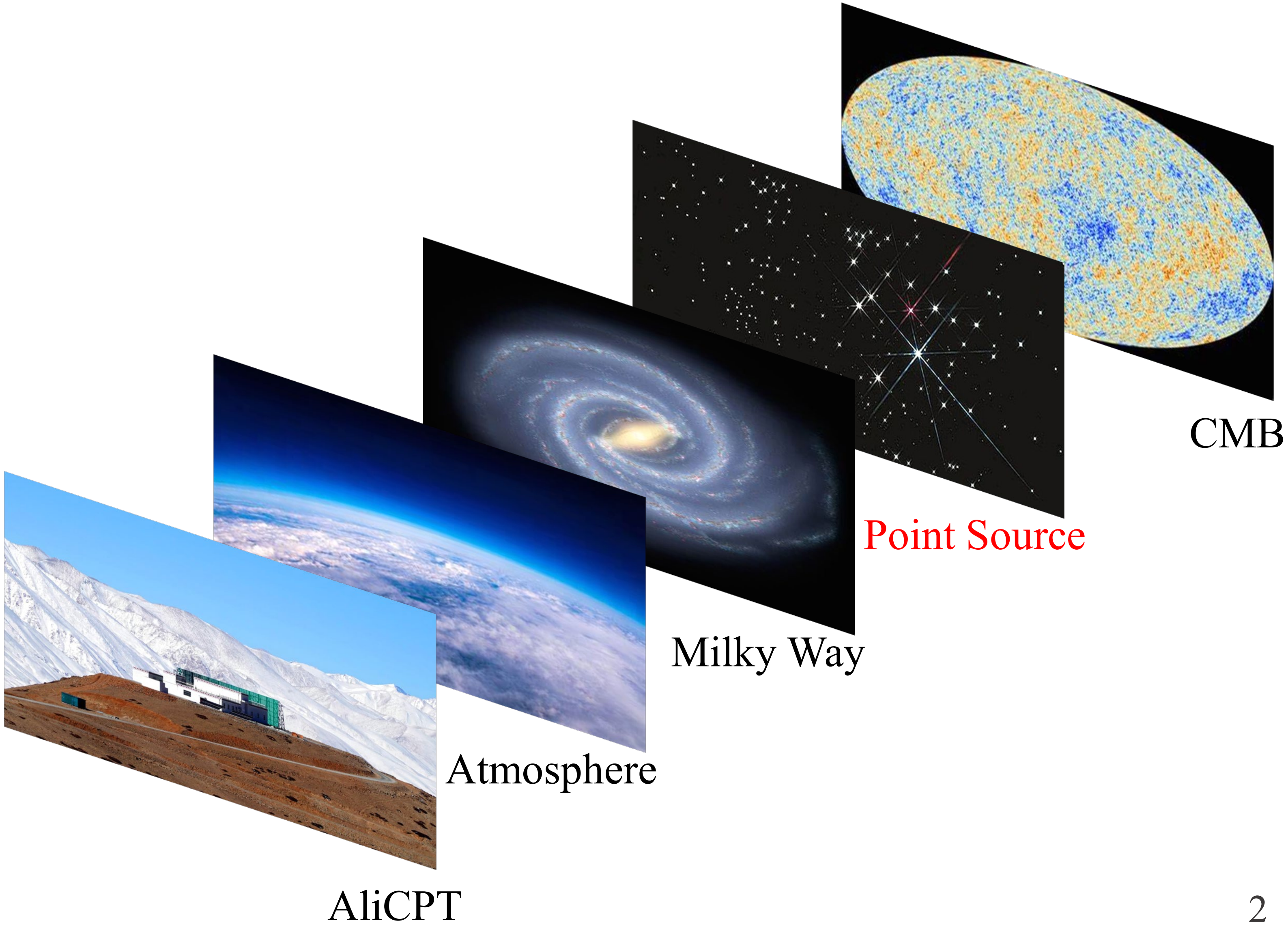


Background

Time-ordered data (TOD)

Data analysis pipeline:
Data splitting and cutting,
Pointing and polarization orientation reconstruction,
Time domain filtering,
The final time-to-pixel domain map making.

[T, Q, U] maps

TOD filtering will cause leakages from point sources to the pixel domain:

Filtering matrix ($\boldsymbol{F}$) Point source ($\boldsymbol{d_p}$)

$$\begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & F_{11} & F_{12} & F_{13} & 0 \\ 0 & F_{21} & F_{22} & F_{23} & 0 \\ 0 & F_{31} & F_{32} & F_{33} & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ d \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} 0 \\ F_{12} \cdot d \\ F_{22} \cdot d \\ F_{32} \cdot d \\ 0 \end{bmatrix}$$

Background

- Although TOD filtering can efficiently remove the atmosphere/ground emissions, it will also remove part of the CMB signal and cause leakages from point sources to the pixel domain regions around them.

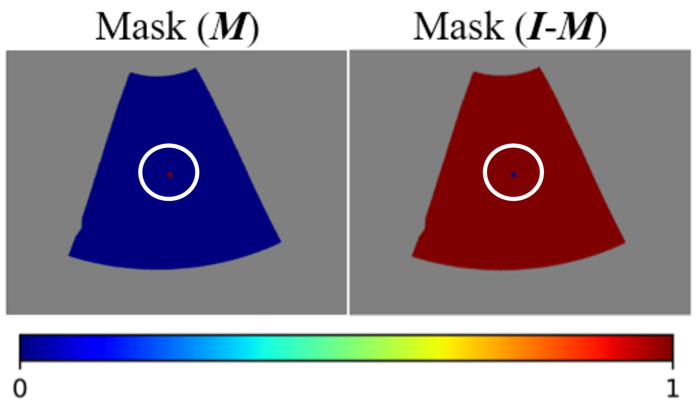
- Point source leakage usually has no preference for the *E*- and *B*-modes: when the point source is strong, it can significantly contaminate the weak primordial *B*-mode signal in a large pixel domain region.

We introduce a new "template-fitting" method to remove the point source leakage due to the filtering of TOD.

Methods

Data: D → Filter(F) → Mask(I-M) → D' ($D = d + d_p$)

Ideal template: d_p → Filter(F) → Mask(I-M) → $\mathcal{T}_0$



$\mathcal{T}_0$ is the theoretical true leakage of point source, and it has a better performance but requires complete knowledge of the beam profile, which is unavailable.

Realistic template: d_p → Mask(M) → Filter(F) → Mask(M) → Filter(F) → Mask(I-M) → $\mathcal{T}_1$

$\mathcal{T}_1$ is an available approximation of the unavailable true point source leakage, which is constructed directly from the product of the pipeline, and its error is acceptable.

Other signals: d → Filter(F) → Mask(I-M) → d' ($d = d_c + d_f + n$)

(CMB, Foreground, Noise)

Results

- Fitting parameters: k_ξ (known polarization direction) and k_ξ^Q, k_ξ^U (unknown polarization direction)
- The polarization sky map of two types of templates and residuals
- The power spectra of CMB, residuals and true leakage

Known polarization direction:

$$\begin{cases} \left(\sigma_\xi^Q\right)^2 = \frac{1}{n}\left[\sum_{i=1}^{n}\left(\boldsymbol{D}' - \sum_j k_{\xi j}\boldsymbol{\mathcal{T}}_{\xi j}\right)_i^2\right]_Q \\ \left(\sigma_\xi^U\right)^2 = \frac{1}{n}\left[\sum_{i=1}^{n}\left(\boldsymbol{D}' - \sum_j k_{\xi j}\boldsymbol{\mathcal{T}}_{\xi j}\right)_i^2\right]_U \\ \sigma_\xi^2 = \left(\sigma_\xi^Q\right)^2 + \left(\sigma_\xi^U\right)^2 \end{cases}$$

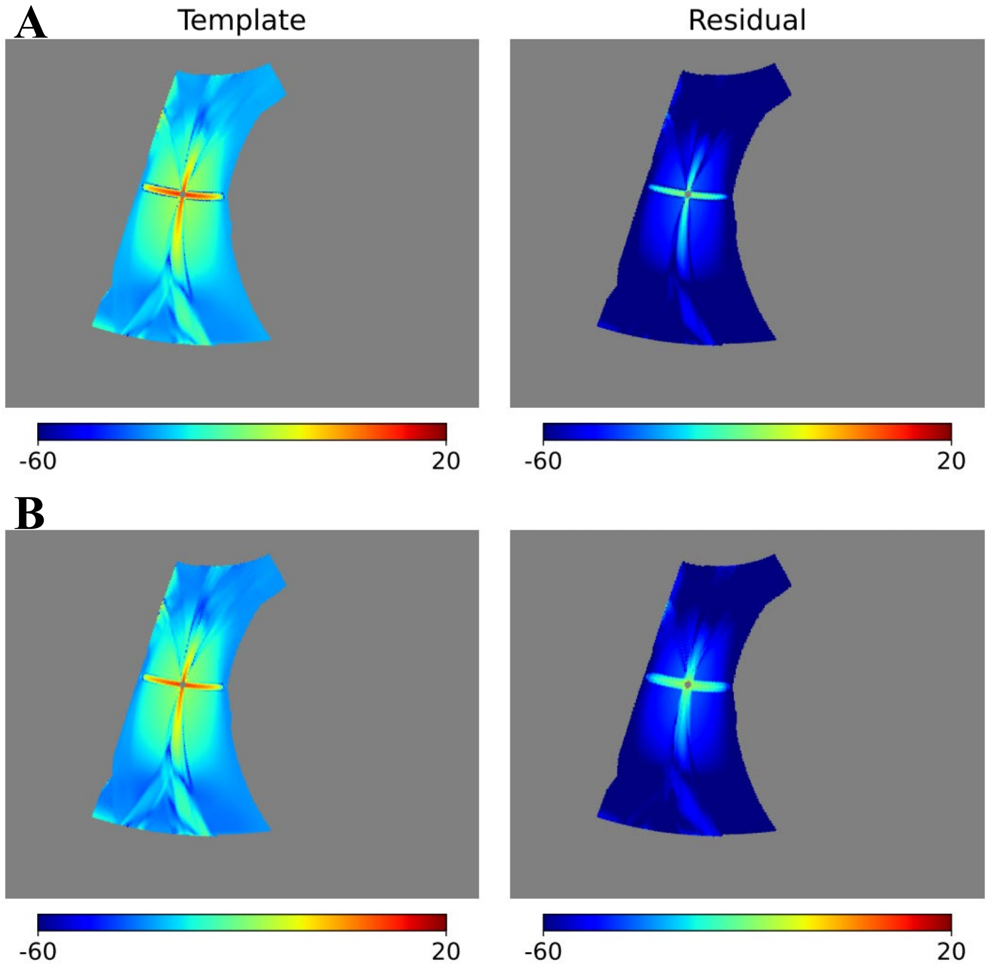
Residual: $\boldsymbol{\delta}_\xi = \left(\boldsymbol{D}' - \sum_j k_{\xi j}\boldsymbol{\mathcal{T}}_{\xi j}\right) - \boldsymbol{d}'$

Unknown polarization direction: ($\xi = 0, 1$)

$$\begin{cases} \left(\sigma_\xi^Q\right)^2 = \frac{1}{n}\left[\sum_{i=1}^{n}\left(\boldsymbol{D}' - \sum_j k_{\xi j}^Q\boldsymbol{\mathcal{T}}_{\xi j}^Q - \sum_j k_{\xi j}^U\boldsymbol{\mathcal{T}}_{\xi j}^U\right)_i^2\right]_Q \\ \left(\sigma_\xi^U\right)^2 = \frac{1}{n}\left[\sum_{i=1}^{n}\left(\boldsymbol{D}' - \sum_j k_{\xi j}^Q\boldsymbol{\mathcal{T}}_{\xi j}^Q - \sum_j k_{\xi j}^U\boldsymbol{\mathcal{T}}_{\xi j}^U\right)_i^2\right]_U \\ \sigma_\xi^2 = \left(\sigma_\xi^Q\right)^2 + \left(\sigma_\xi^U\right)^2 \end{cases}$$

Residual: $\boldsymbol{\delta}_\xi = \left(\boldsymbol{D}' - \sum_j k_{\xi j}^Q\boldsymbol{\mathcal{T}}_{\xi j}^Q - \sum_j k_{\xi j}^U\boldsymbol{\mathcal{T}}_{\xi j}^U\right) - \boldsymbol{d}'$

Single point source (known polarization direction)



Comparison of results for r = 0.023, obtained using the ideal template (A) and the realistic template (B), where the polarization values of the templates (left) and the residuals (right).

Fitting parameters and RMS of residuals:

k_0	$\sigma_0/10^{-3}$ μK	k_1	$\sigma_1/10^{-3}$ μK
1.004	1.339	1.205	2.115

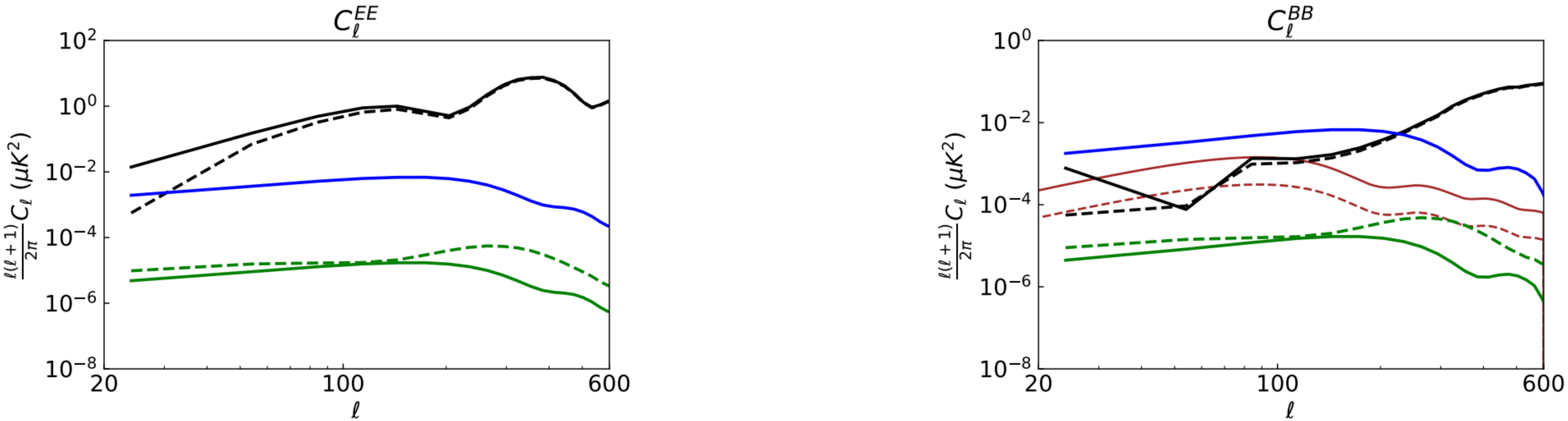
RMS of other signals (μK):

$\sigma_{d'_c}$	$\sigma_{d'_f}$	$\sigma_{n'}$
0.334	0.027	0.121

Conclusion:

- For ideal template, the fitting parameter is close to 1. For realistic template, it is a little greater than 1.
- The leakage of point source has a diffused star-like structure, and the residual is much weaker.

Single point source (known polarization direction)

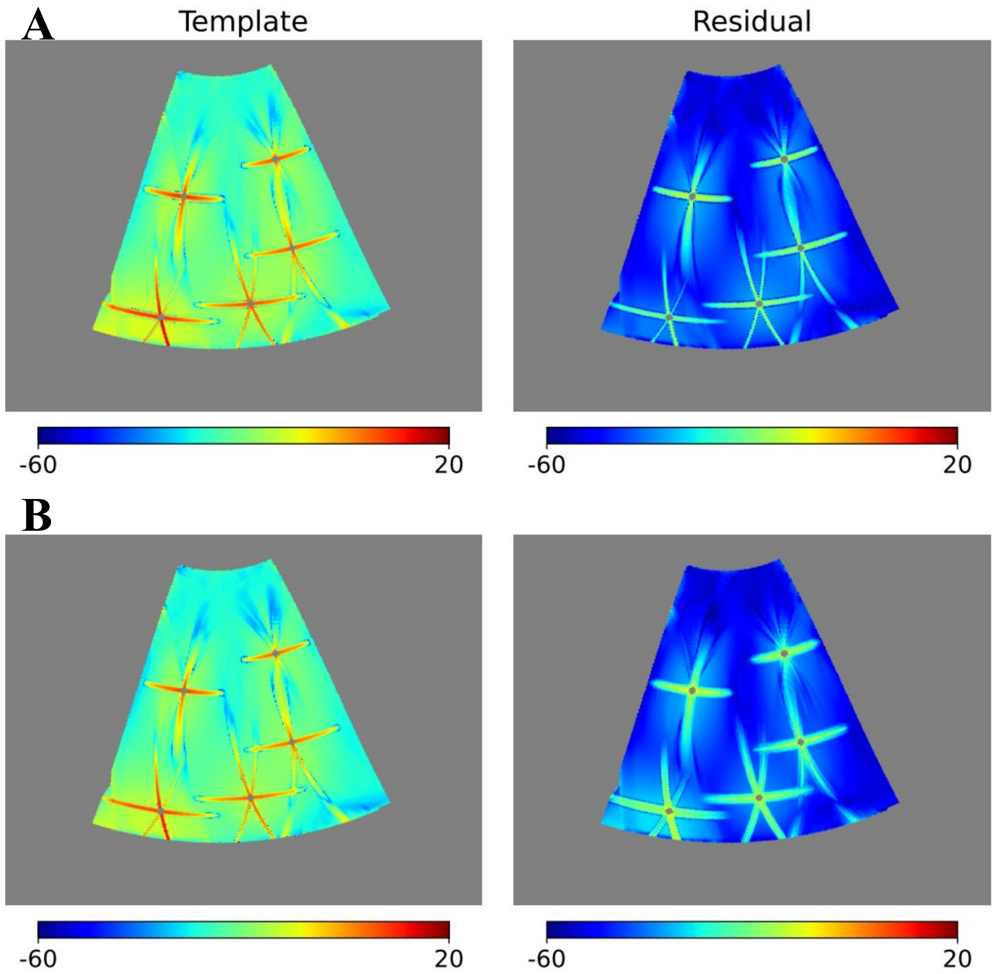


The *EE* and *BB* power spectra (r = 0.023) including: input and filtered CMB (black solid/dashed respectively), residuals after the leakage removal with the ideal and realistic templates (green solid/dashed respectively), the true leakage (blue), and unlensed CMB *BB* spectra with r = 0.023 (red solid) and r = 0.005 (red dashed) as references.

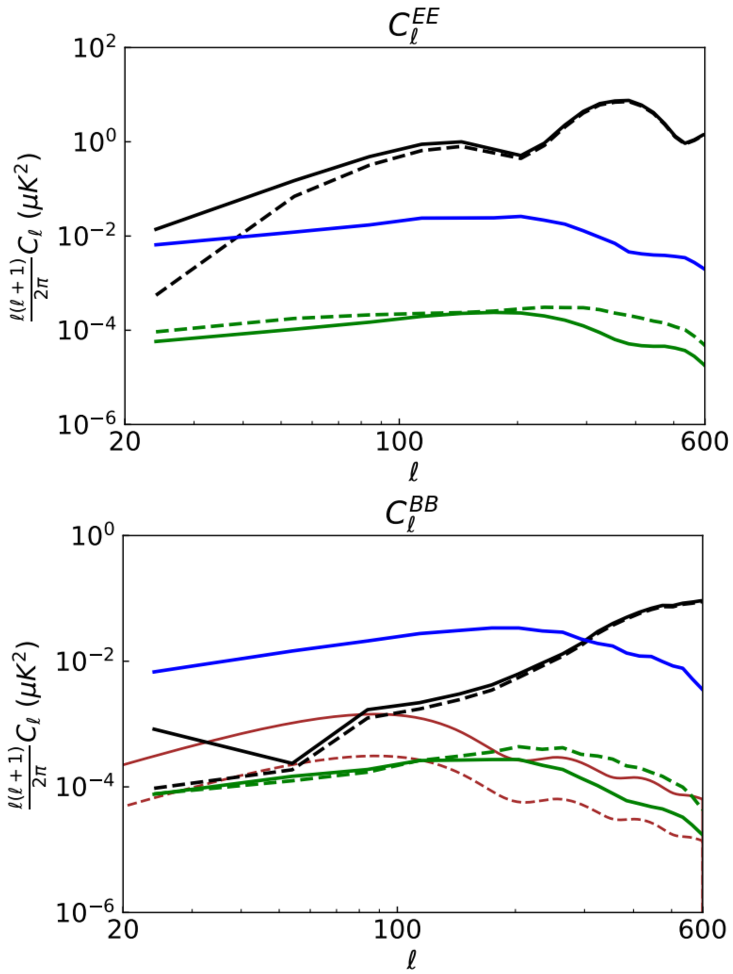
Conclusion:

- The residual spectra are 2 or 3 orders of magnitudes lower than that of the true leakage.
- The residual spectra are much smaller than both of the lensed and unlensed CMB spectra.

Multiple point sources (unknown polarization direction)

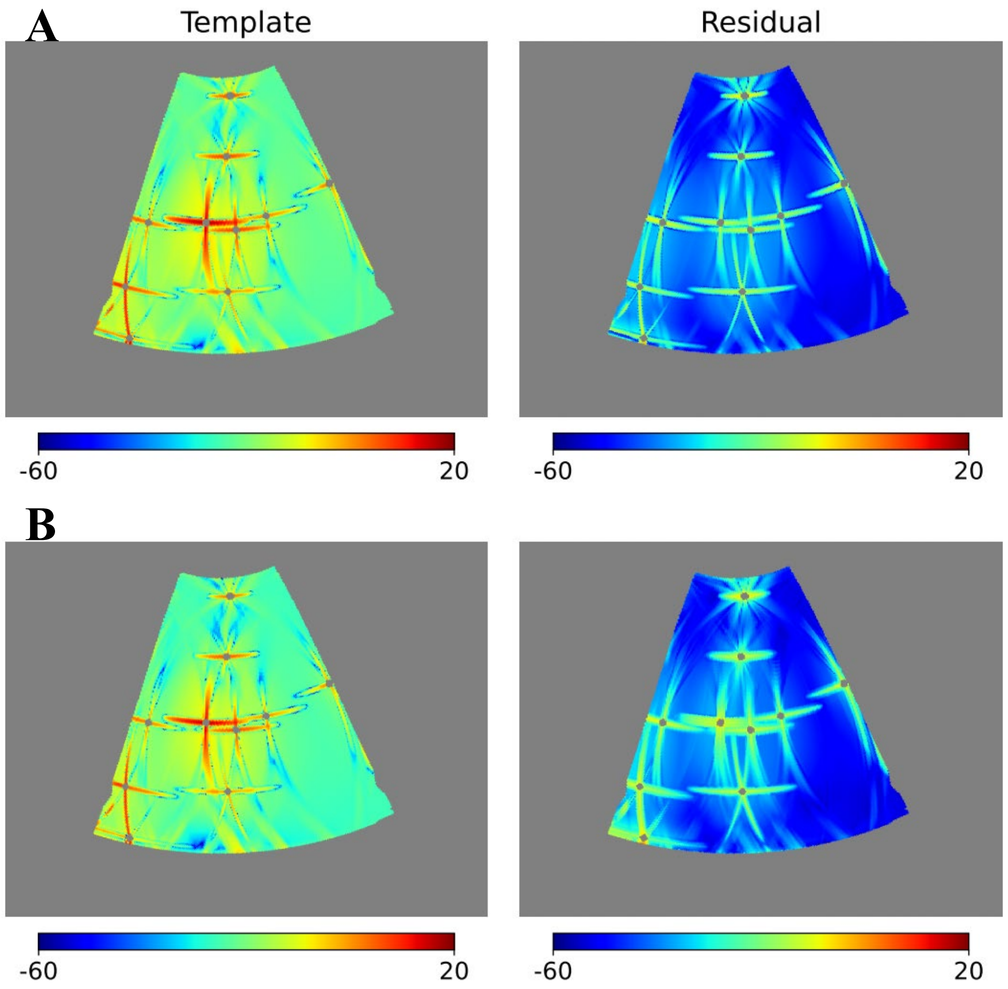


Comparison of results for r = 0.023, obtained using the ideal template (A) and the realistic template (B), where the polarization values of the templates (left) and the residuals (right).

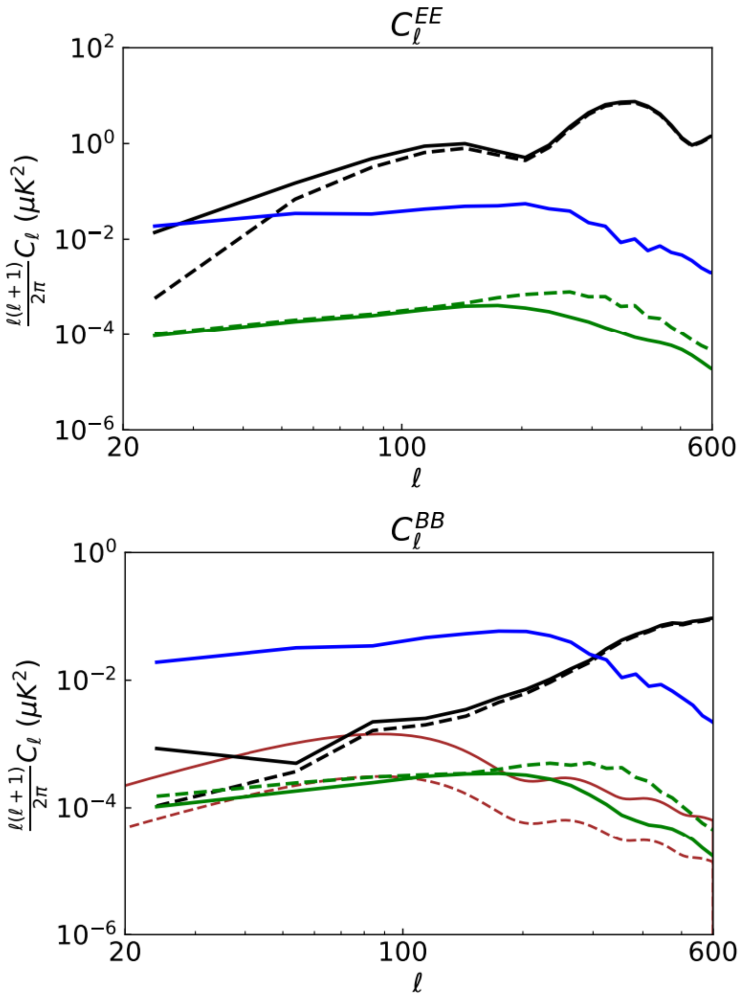


The *EE* and *BB* power spectra for the case of multiple point sources with unknown polarization direction.

Actual point sources (unknown polarization direction)



Comparison of results for r = 0.023, obtained using the ideal template (A) and the realistic template (B), where the polarization values of the templates (left) and the residuals (right).



The *EE* and *BB* power spectra for the case of actual point sources with unknown polarization direction.

Conclusion

- The point source leakage is typically star-like, and it produces certain contamination to the detection of CMB.

- A novel “template-fitting” method is introduced for removing the point source leakage due to time-order data filtering.

- The leakage after “template fitting” can be reduced by 1-2 orders of magnitude in the pixel domain, and by 3-4 orders of magnitude in angular power spectrum.

- The residual *BB* spectrum is about 2 orders of magnitudes lower than the theoretical prediction for the primordial gravitational waves with $r \sim 10^{-2}$ (lensed). And by comparing with the unlensed spectrum with $r = 0.005$, we can see that our method can at least work with $r = 0.005$.