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HIT Fitting

Hybrid Internal combination with Template Fitting

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CMB Foregrounds for B-mode studies
La Laguna, October 2018

Motivation and concerns

- Methods based on a linear combination of maps are a simple, faster and practical methodology to recover the CMB signal.
- Internal Linear Combination (ILC) is the simplest approach. However, in real space, it is biased (cross-correlation).
- The Internal Template Fitting is expected to have a lower bias than the ILC. This method is a useful tool in CMB recovering (e. g. SEVEM).
- In real/pixel space, can we construct a new approach that considers the ILC with a methodology to reduce the bias and/or with lower foreground residuals (such as the ITF)?

New approach: HIT Fitting

Hybrid Internal linear combination with Template fitting

$$\hat{T}_{\mathrm{HIT}} = \boxed{\boxed{\sum_{i=1}^{n\alpha} \alpha_i\, T_i} - \sum_{j=1}^{n\beta} \beta_j T_j}$$

ILC performance

ITF performance

- We combine two methodologies:
  Internal Linear Combination
  Internal Template Fitting
- Here, we consider the implementation in the pixel space.

Internal Linear Combination (ILC)

- Focused on CMB.
- No prior information about foregrounds.
- **A CMB map** is obtained from a linear combination.

$$T_i \equiv \text{Map at freq. } i := \nu$$

$$T_{\mathrm{CMB,ILC}} = \sum_{j=1}^{n\omega} \boxed{\omega_j} \boxed{T_j}$$

Maps in a common beam resolution

Coefficients of the linear combination

$$\sum_{j=1}^{n\omega} \omega_j = 1$$

Condition that ensures an unbiased measurement of the studied component

The coefficients are estimated by minimizing the variance of the CMB map estimator ($T_{\mathrm{CMB,ILC}}$).

(see e.g. Tegmark+1998, Bennett+2003, Eriksen+2004, Remazeilles+2011)

Internal Linear Combination (ILC)

➢ Using Lagrange multipliers:

$$\boxed{\omega_j = \frac{\sum_{i=1}^{n\omega} C_{i,j}^{-1}}{\sum_{j,i=1}^{n\omega} C_{i,j}^{-1}}}$$

$$C_{i,j} = \langle T_i \, T_j \rangle \; - \; \langle T_i \rangle \, \langle T_j \rangle$$

Covariance matrix of data

- Maps must be smoothed at the same beam resolution.
- We expect a bias from cross-correlation between CMB and foregrounds (e.g. *Efstathiou+2009, Hinshaw+2007*).

$$\boxed{\sigma_{\mathrm{ILC}}^2 = \sigma_c^2 - \sigma_{cf}^2/\sigma_f^2}$$

Internal Template Fitting (ITF)

- Focused on CMB.
- No prior information about foregrounds.
- **A map is cleaned**, and foregrounds could be subtracted from a linear combination of templates.

$$T_i \equiv \text{Map at freq. } i := \nu$$

$$T_{\mathrm{CMB,TF}} = T_{\nu_c} - \sum_{k=1}^{nt} \boxed{\alpha_k} \boxed{T_k}$$

- Templates contain only the foregrounds contribution.
- They can be constructed from external or internal data.

Map to be cleaned

Coefficients of the linear combination

The coefficients are estimated by minimizing the variance of the $T_{\mathrm{CMB,ITF}}$ map.

(see e.g. Martínez-González+2003, Leach+2008, Fernández-Cobos+2012)

Internal Template Fitting (ITF)

Goal : α ⇨ $\min\Big(Var(T_{\mathrm{CMB,TF}})\Big)$

$$\boxed{\mathrm{Var}(T_{\mathrm{CMB,TF}}(p)) \;=\; \langle T_{\mathrm{CMB,TF}}(p)^2\rangle - \langle T_{\mathrm{CMB,TF}}(p)\rangle^2}$$

⇩

$$\alpha = \mathbf{C}^{-1}\mathbf{B}$$

It depends on the considered region.

$$C_{kj} = \langle \mathcal{T}_k\, \mathcal{T}_j\rangle \;-\; \langle \mathcal{T}_k\rangle\, \langle \mathcal{T}_j\rangle$$

Covariance matrix of templates

$$B_k = \langle T_{\nu_c}\, \mathcal{T}_k\rangle$$

Correlation between templates and map to be cleaned

➢ **Internal** templates: $\mathcal{T}_k = T_i - T_{i+1} = F_i - F_{i+1} + N_i - N_{i+1}$

New approach: HIT Fitting

- Focused on CMB.
- No prior information about foregrounds.
- **A CMB map** is obtained from a linear combination of maps with a foreground cleaning.

$$\hat{T}_{\mathrm{HIT}} = \sum_{i=1}^{n\alpha} \alpha_i T_i - \sum_{j=1}^{n\beta} \beta_j T_j$$

“ILC coefficients”

“ITF coefficients”

$$\sum_{i=1}^{n\alpha} \alpha_i = 1$$

Condition that ensures an unbiased measurement of the CMB component.

New approach: HIT Fitting

$$\boxed{\langle \hat{T}^2_{\mathrm{HIT}} \rangle - \langle \hat{T}_{\mathrm{HIT}} \rangle^2 = \alpha^T A \alpha + \beta^T B \beta - 2\alpha^T C \beta}$$

Using Lagrange multipliers:

$$\alpha_i = \frac{\sum_{m=1}^{n\alpha} G^{-1}_{m,i}}{\sum_{m,i=1}^{ni} G^{-1}_{m,i}}$$

$$\beta_j = \frac{\sum_{m=1}^{n\beta} H^{-1}_{m,j}}{\sum_{m,j=1}^{nt} G^{-1}_{m,j}}$$

$$\begin{aligned} G^{-1} &= \left(A - CB^{-1}C^T\right)^{-1} \\ H^{-1} &= B^{-1}C^T G^{-1} \end{aligned}$$

$$\begin{aligned} A_{i,l} &= \langle T_i \, T_l \rangle - \langle T_i \rangle \, \langle T_l \rangle, \\ B_{j,k} &= \langle T_j \, T_k \rangle - \langle T_j \rangle \, \langle T_k \rangle, \\ C_{i,j} &= \langle T_i \, T_j \rangle - \langle T_i \rangle \, \langle T_j \rangle \end{aligned}$$

- The T_i maps must be smoothed to a common beam resolution.
- Templates do not contain information of the CMB signal.
- We expect a bias lower than the ILC performance.

Foreground and Noise residual map

Foreground residual

$$\boxed{F_{\mathrm{HIT}} = \sum_{i=1}^{n\alpha} \alpha_i \, F_i \; - \; \sum_{j=1}^{n\beta} \beta_j \, \mathcal{F}_j}$$

$$\boxed{\begin{aligned} \mathcal{F}_1 &= F_{20} - F_{30}, & \mathcal{F}_5 &= F_{220} - F_{150} \\ \mathcal{F}_2 &= F_{30} - F_{40}, & \mathcal{F}_6 &= F_{270} - F_{220}. \end{aligned}}$$

- We compute the foregrounds map using all coefficients.
- For Noise, we follow the propagation methodology.
- This procedure is analogue for the ILC, ITF and HIT Fitting.

Bias of the residual map

$$R_{\mathrm{HIT}} = T_{\mathrm{HIT,CMB}} - T_{\mathrm{CMB}}$$

$$\Delta_{\mathrm{ITF}} = C_\ell(R_{\mathrm{HIT}}) \; - \; C_\ell(F_{\mathrm{HIT}}) \; - \; C_\ell(N_{\mathrm{HIT}})$$

These are tests to compare the ILC, ITF and HITF performance.

Microwave sky simulations

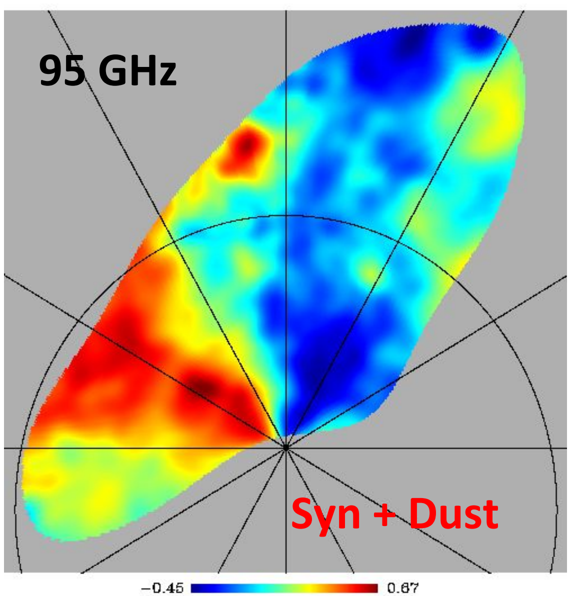
Proposed experiment (inspired by SO)

- 7 bands from 20-270 GHz and Sky fraction 5%.
- Synchrotron (no curvat.) and thermal dust (one comp.).
- Noise (Gaussian white) and CMB (**r = 0**).
- Maps smoothed to a common resolution (130 arcmin).

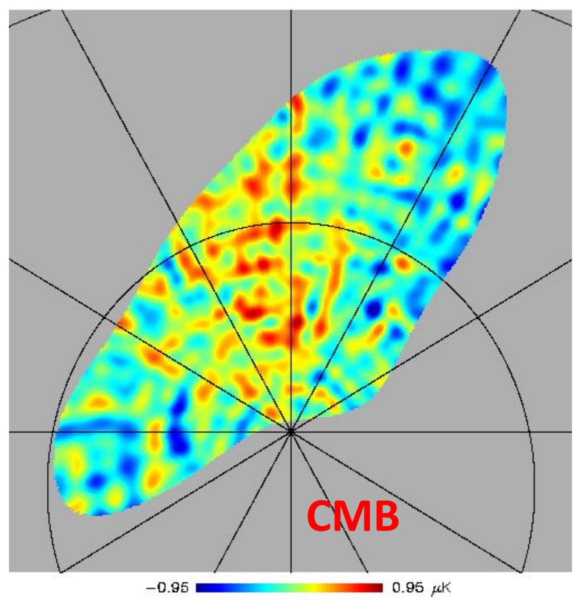
Freq GHz	FWHM arcmin	Sensitivity μK-arcmin
21	120	6.4
29	91	4.6
40	66	2.9
95	28	1.6
150	18	1.8
220	12	5.7
270	10	8.2

Stokes Q

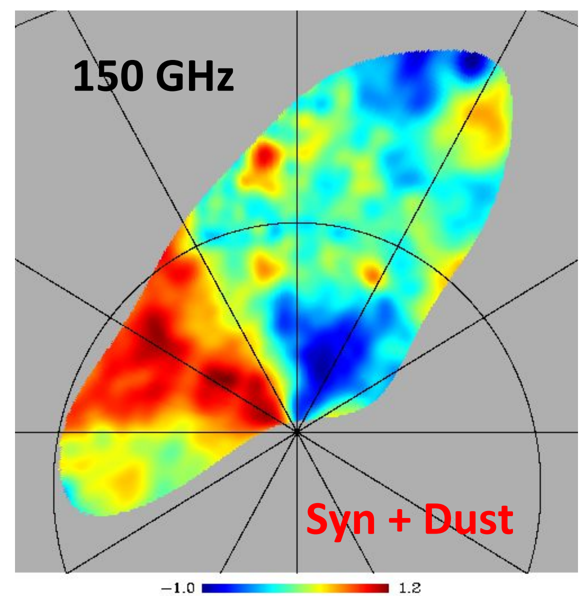
$$T_i(p) = T_{cmb}(p) + N_i(p) + F_i(p)$$



-0.45 to 0.07 μK



-0.95 to 0.95 μK



-1.0 to 1.2 μK

Microwave sky simulations

➢ We construct templates as:

$$T_i(p) = T_{cmb}(p) + N_i(p) + F_i(p)$$

$$\mathcal{T}_1 = T_i - T_j = N_i - N_j + F_i - F_j$$

We need several templates for complex foregrounds

$$\begin{aligned}
\mathcal{T}_1 &= T_{20} - T_{30} \\
\mathcal{T}_2 &= T_{30} - T_{40} \\
\mathcal{T}_3 &= T_{40} - T_{95} \\
\mathcal{T}_4 &= T_{150} - T_{95} \\
\mathcal{T}_5 &= T_{220} - T_{150} \\
\mathcal{T}_6 &= T_{270} - T_{220}
\end{aligned}$$

➢ **ILC and ITF** implementation:

- For ILC, we used all bands.
- For ITF, we have many configurations, depending on the templates and maps to be cleaned (95 and 150 GHz).

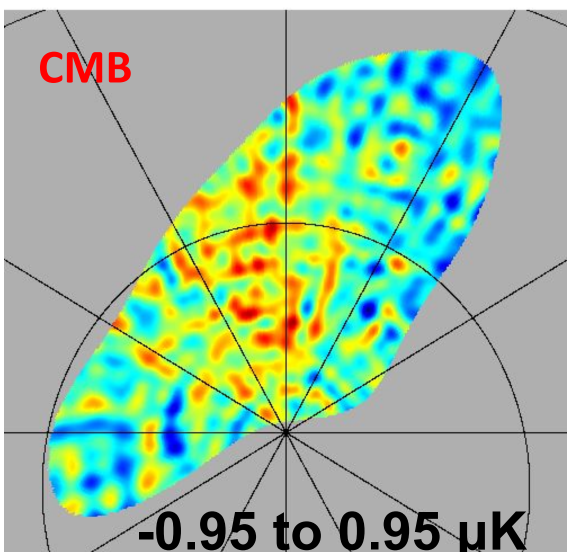
$$\begin{aligned}
T_{\nu_c} &= T_{150} \\
T_{\nu_c} &= T_{95}
\end{aligned}$$

T_{95} with $\mathcal{T}_1, \mathcal{T}_2, \mathcal{T}_5$ and $\mathcal{T}_6$

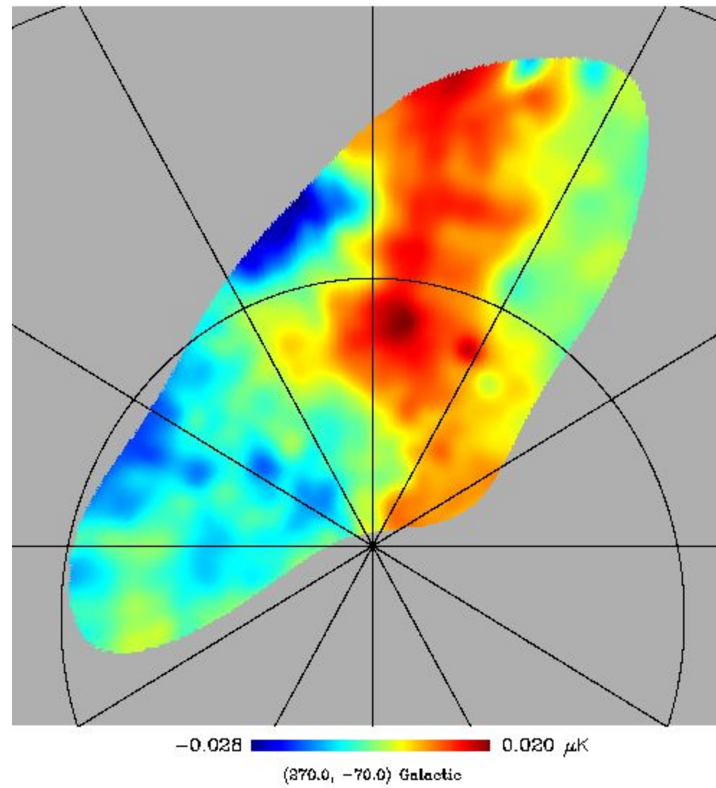
Results from ILC, ITF and HIT fitting:

Best performance

- ILC part: 20, 95 and 270 GHz.
- We considered:
  Template 2 (40-30 GHz)
  Template 6 (220-150 GHz).
- The performance is compatible with the ITF (foreground residuals).



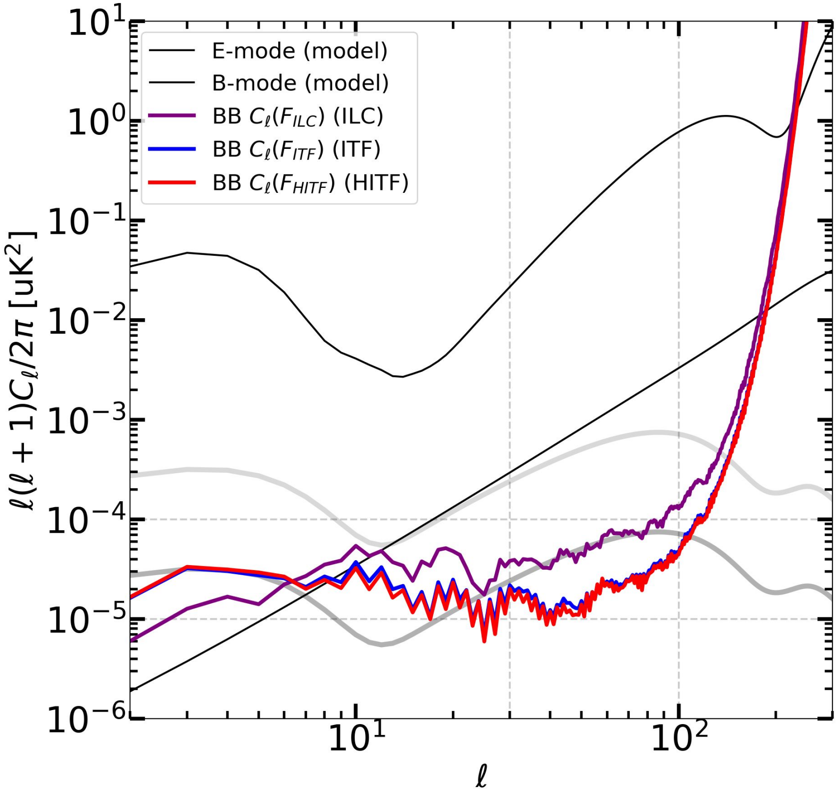
Foreground residual map (Stokes Q)



-0.028 to 0.020 μK

Results from ILC, ITF and HIT fitting:

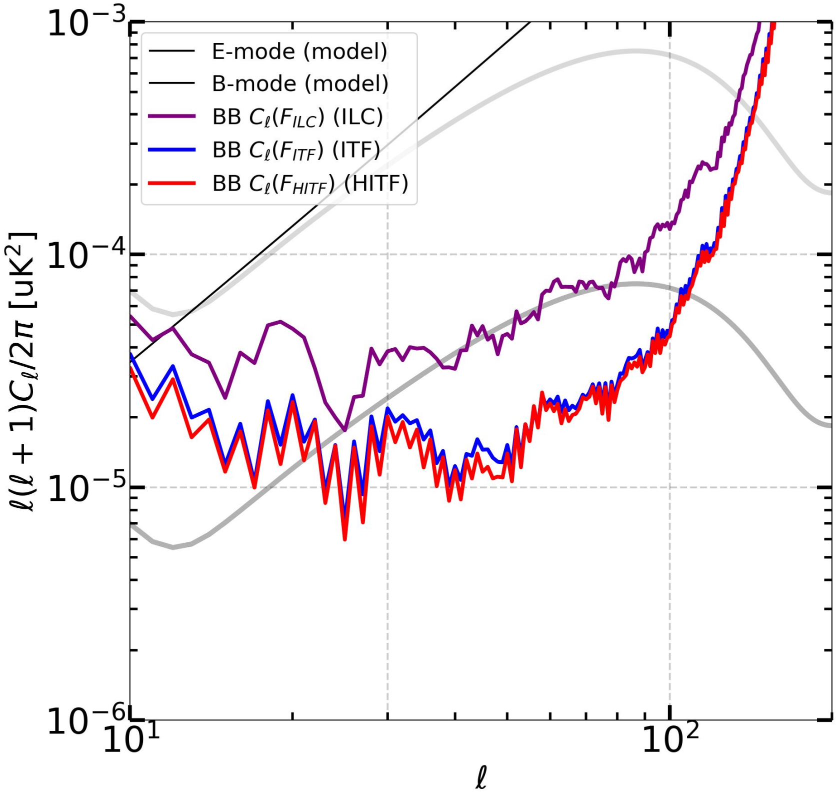
PW of Foreground residual map



- ILC shows residuals compatible with the BB (r = 10^{-3}).
- HITF and ITF have similar foreground residuals level in several multipoles.
- The foreground residuals are lower than primordial BB (r = 10^{-3}).
- HITF appears to be a better performance than ITF.

Results from ILC, ITF and HIT fitting:

PW of Foreground residual map



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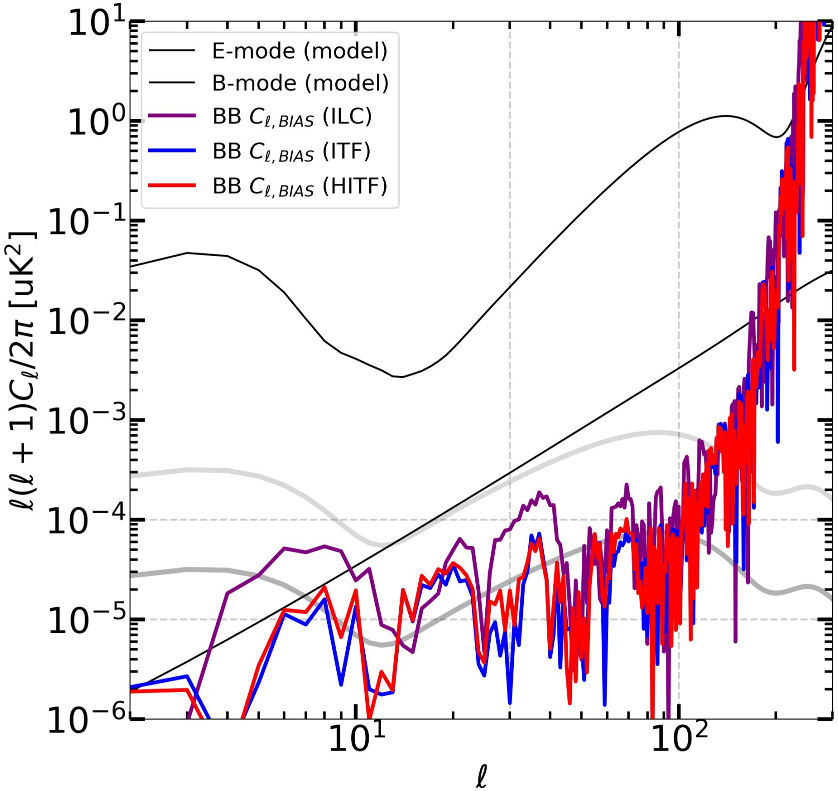
Results from ILC, ITF and HIT fitting:

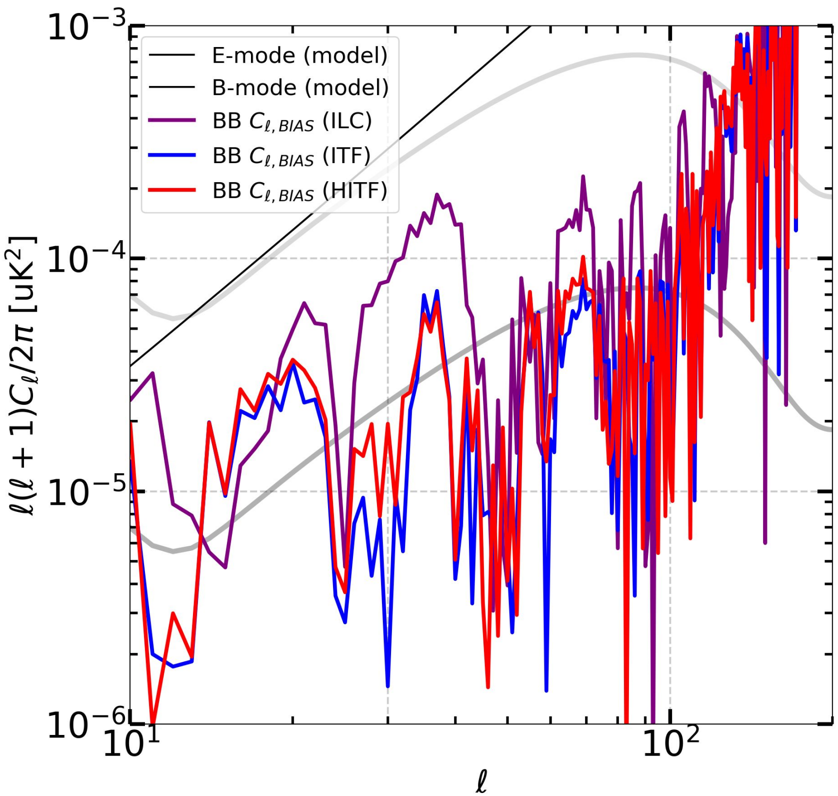
Bias contribution



- The bias estimator is noisy and we need more simulations.
- ILC bias is stronger than the bias from ITF and HITF.
- HITF and ITF have the same levels of bias.
- We will carry out more tests to establish the HITF performance.

Results from ILC, ITF and HIT fitting:

Bias contribution



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- HITF and ITF have the same levels of bias.
- We will carry out more tests to establish the HITF performance.

Summary, conclusions and prospective

- The HIT Fitting is a new approach to recover the CMB signal using a linear combination.
- HITF and ITF have similar foreground residual level and bias level (in several multipoles). However, we cannot confirm which of them has better performance.
- We expect to apply the HIT Fitting in multifrequency experiments such as liteBIRD, PICO and CORE, and in joint analysis (e.g. groundBIRD-QUIJOTE-Planck).
- Some other tests must be carried out (effect of gain, etc.).
- We expect to implement a Needlet and Two Spin approaches.

Thank you!