CMB-CAL @ BICOCCA

Requirements on systematic effects calibration with component separation

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CMB CAL 2024, Milano Bicocca, Nov. 4-8th

Simulation set-up

CMB lensing
+Galactic foregrounds `d0s0`
+White noise

Simulate the effect of an imperfect gain calibration <u>into a single-frequency channel</u>:

$$g_\nu = 1 + \mathcal{N}(0, \Delta g_\nu)$$

Goal : Set requirement on the gain calibration accuracy, therefore, on the amplitude of Δg_ν for each frequency channel.

2 sets of maps, with and without gain calibration uncertainties,

$m(\Delta g_\nu \neq 0)$ **and** $m(\Delta g_\nu = 0)$

with the <u>same CMB and noise realisation</u>.

Component separation

Apply component separation on both $m(\Delta g_\nu \neq 0)$ and $m(\Delta g_\nu = 0)$

Minimum-variance

ILC, HILC, NILC, MC-NILC…

Minimum variance solution from the linear combination of multi-frequency observations

$$\tilde{X}_{\mathrm{CMB}} = \sum_{\nu=1}^{N_\nu} \omega_\nu X^\nu = \sum_{\nu=1}^{N_\nu} \omega_\nu (a^\nu_{\mathrm{CMB}} X_{\mathrm{CMB}} + X^\nu_{\mathrm{fg}} + X^\nu_{\mathrm{n}})$$

$$\sum_{\nu=1}^{N_\nu} \omega_\nu a^\nu_{\mathrm{CMB}} X_{\mathrm{CMB}} = X_{\mathrm{CMB}}$$

Sensitive to CMB frequency scaling

Parametric-fitting

FG Buster, Commander, B-SECRET…

Marginalisation over the spectral parameters of Galactic foreground: β^{dust}, β^{synch}

$$-2\ln\mathcal{L}_{data}(s, \beta_d, \beta_s) = C + (d - As)^T N^{-1} (d - As)$$

$$-2\ln\mathcal{L}_{spec}(\beta_d, \beta_s) = C - (A^T N^{-1} d)^T (A^T N^{-1} A)^{-1} (A^T N^{-1} d)$$

Sensitive to Galactic foregrounds frequency scaling

Requirement on Δg_ν

Infer the tensor-to-scalar ratio from the two compsep. outcomes and compute,

$$\delta_r = r(\Delta g_\nu \neq 0) - r(\Delta g_\nu = 0)$$

for different values of Δg_ν and for each, consider <u>many CMB and noise realisations</u>

↓

δr-distribution for each value of Δg_ν

The requirement on Δg_ν is the value for which, $\Delta = [\mu(\delta r)^2 + \sigma(\delta r)^2]^{1/2}$, RMS of δr-distribution, is equal to the δr threshold

Repeat the full procedure for all frequency channels!

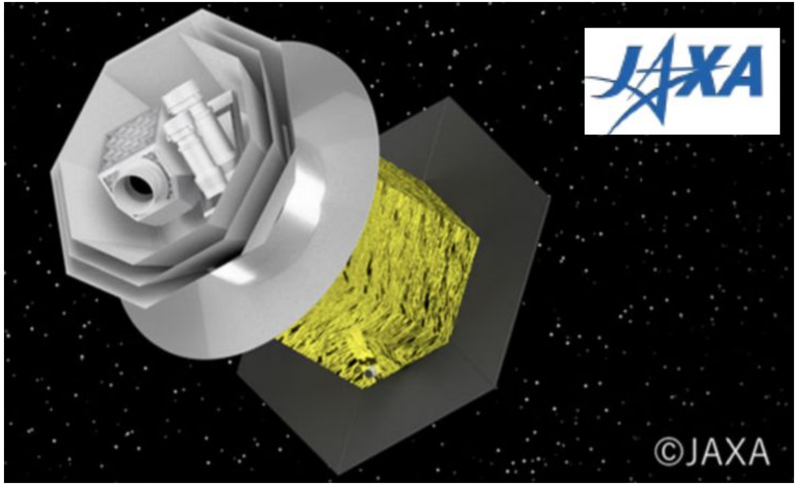
↓

$\Delta g_{req}(\nu)$

Application to *LiteBIRD* experiment

Lite (Light) satellite for the study of *B*-mode polarization and Inflation from cosmic background Radiation Detection

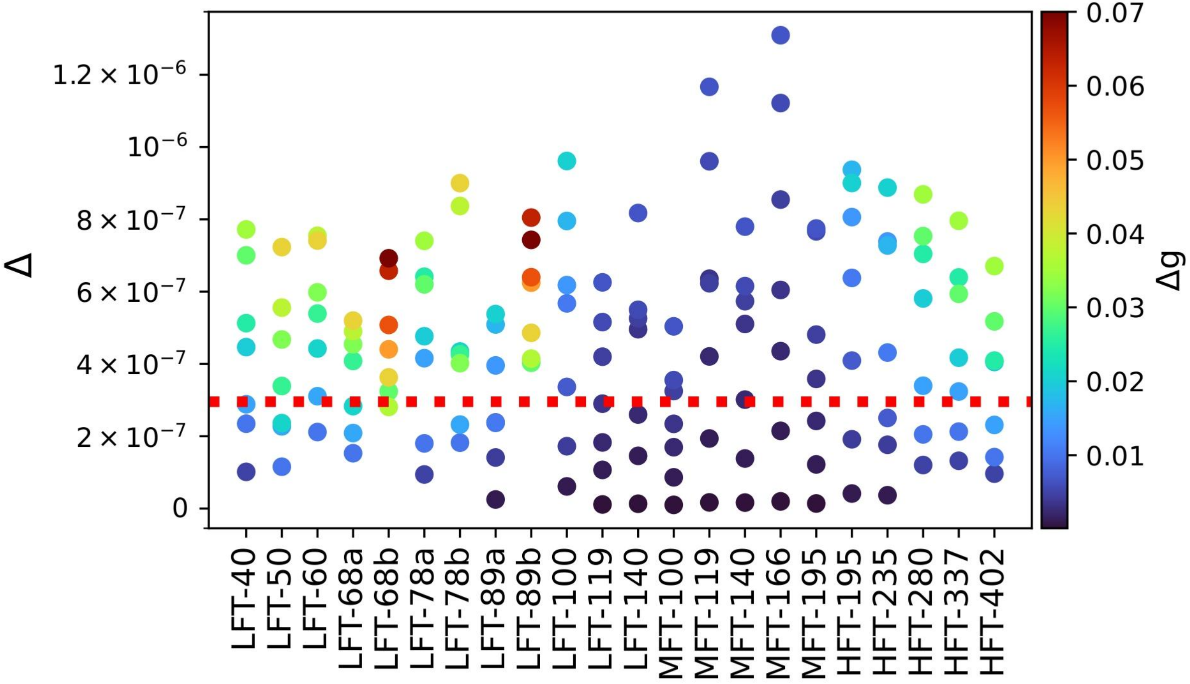
- Measurement of both recombination and reionisation bumps of the CMB B-modes (low multipoles)
- All-sky 3-year survey
- Large frequency coverage (**40–402 GHz**, 15 bands) to characterize Galactic emissions and CMB signal



Gain calibration requirements for *LiteBIRD*

Analysis done for constant spectral indices for dust and synchrotron (`d0s0` models in PySM) with Needlet Internal Linear Combination (NILC) component separation.

Carralot, Carones, Krachmalnicoff and LiteBIRD collaboration (2024)



$$\Delta = \sqrt{\mu(\delta_r)^2 + \sigma(\delta_r)^2}$$

bias *extra-variance*

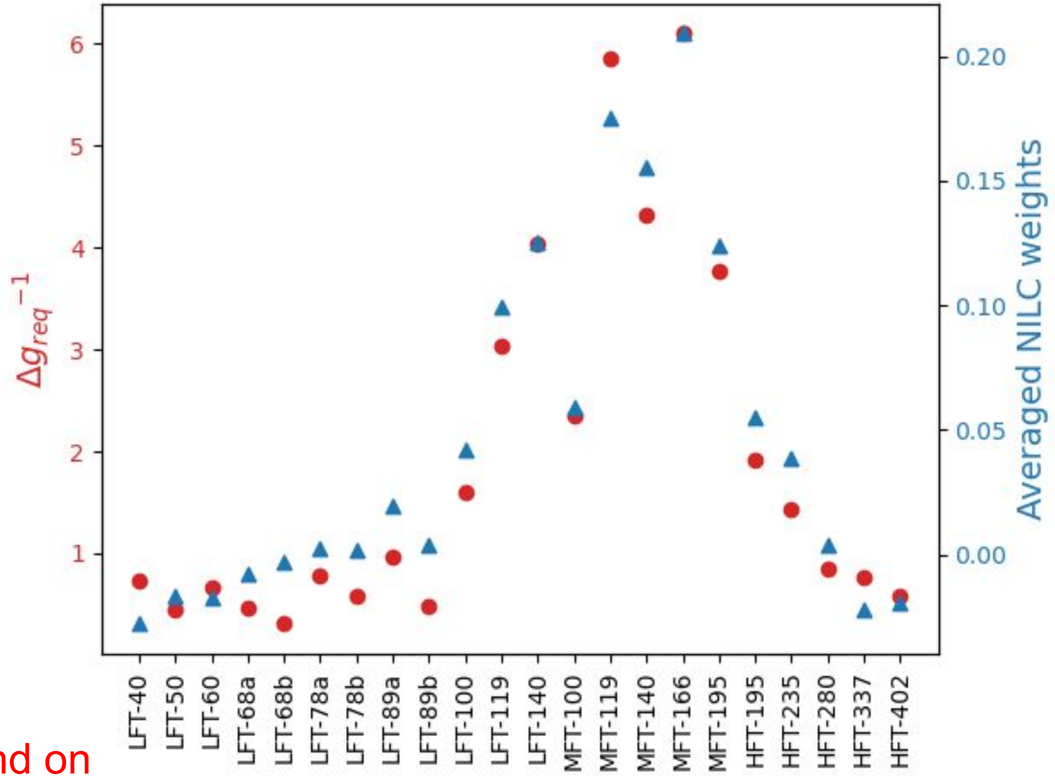
The **most sensitive channels** corresponds to the central frequencies, **where the CMB is relatively brighter.** While being at foreground-dominated frequencies with `FG Buster` Ghigna et al. (2020)

Gain calibration requirements for *LiteBIRD*

Requirements on the gain calibration accuracy range from **$1.6.10^{-3}$** to **$3.2.10^{-2}$**

→ Less stringent than those obtained with a parametric component separation approach Ghigna et al. (2020)

Especially, in low S/N regimes
Dick, Remazeilles, Delabrouille (2009)



The constraints on the gain calibration depend on the component separation approach we consider.

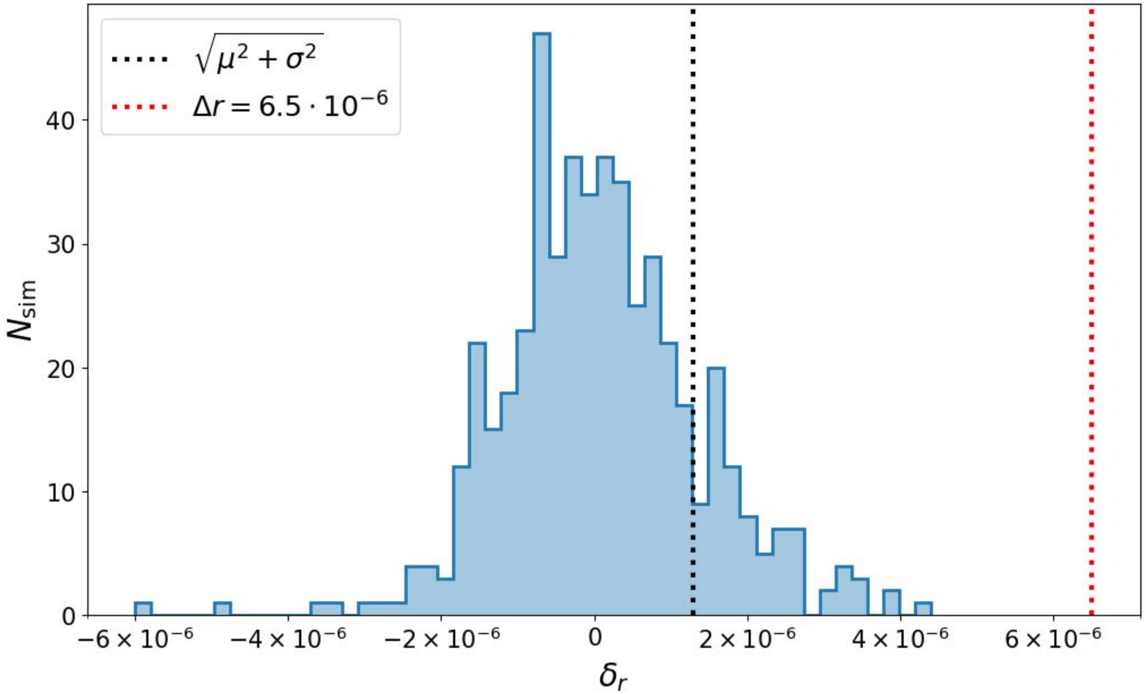
Overall impact of gain calibration uncertainties on *r*

All channels perturbed simultaneously :

$$g_{\nu_i} = 1 + \mathcal{N}(0, \Delta g_{\mathrm{req}}(\nu_i))$$

With $\Delta g_{\mathrm{req}}(\nu_i)$

requirement on the gain calibration for i$^{\mathrm{th}}$ frequency channel.



The contributions in δr from single channel perturbation do not add up linearly if the same gain calibration uncertainties are propagated through all channels simultaneously = **correlations induced by the NILC weights readjustment.**

Extension to more complex sky models

The requirements on the gain calibration are derived assuming a sky model with constant spectral indices for the foreground emission, which however, is not realistic.

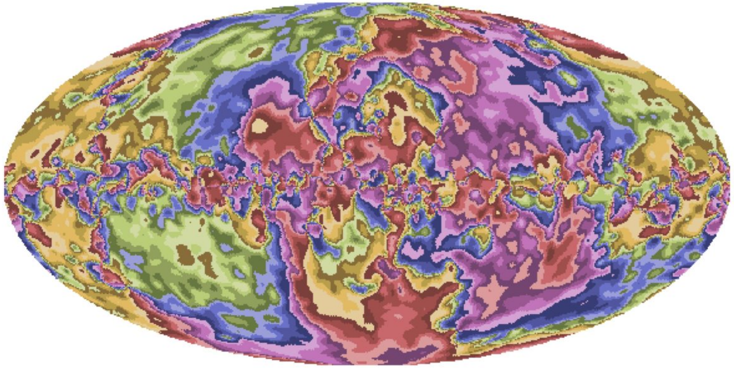
→ What is the overall impact on r if the requirements are propagated through all channels for which are assumed intermediate and high complexity sky models?

d1s1 d10s5

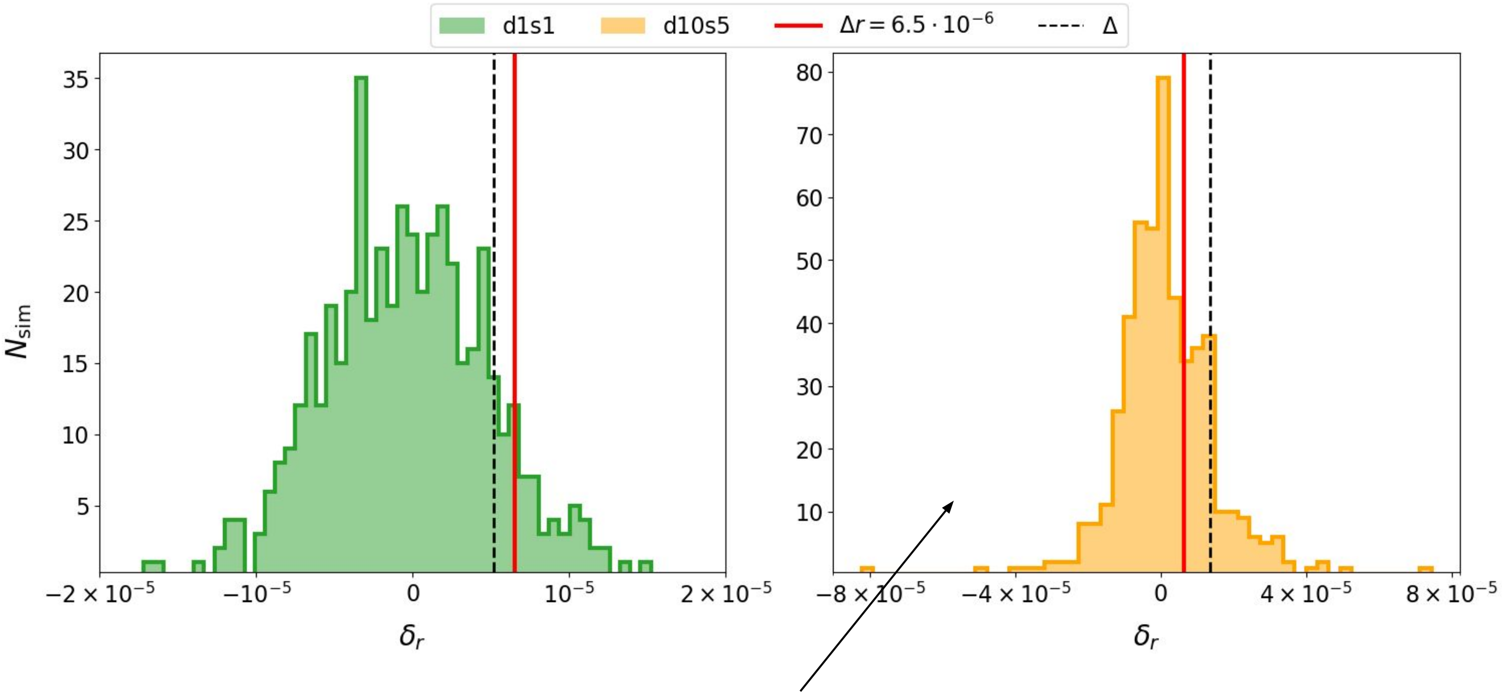
Multi-Clustering Needlet ILC

Carones et al. (2023)

The variance minimisation is independently performed within sky patches, to trace local spectral variations of the foreground emission.



Realistic MC-NILC : the spectral tracer is derived from foreground templates derived by applying GNILC pipeline to multi-frequency sky maps. (+ marginalisation over fg residuals)



For the most realistic scenario, the requirements on the gain calibration accuracy should be tighten by a factor 1.8 to match the allocated budget to gain systematics.

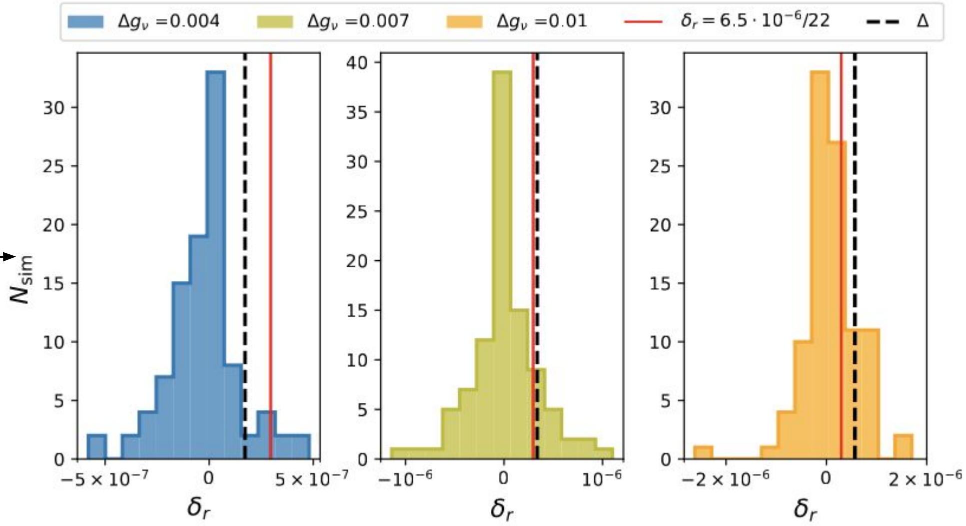
Take home messages

- The proposed procedure can be applied to any kind of systematic effect : currently tested on beam far-side lobes with NILC following Leloup et al. (2023) procedure.
- The minimum-variance NILC technique is less sensitive to gain calibration uncertainties than `FG Buster`, requiring a marginalisation over gain calibration errors.
- The most sensitive channels, with NILC, are at CMB frequencies where the weights are larger.
- Given the future refinements on the component separation techniques and sky models, we are not able yet to set definitive gain calibration requirements for *LiteBIRD*.
- The proposed strategy is : derive requirements for the **simplest sky model** constituting an **optimistic bound** for the requirements. The **pessimistic bound** is set by **rescaling** the latter set of requirements in order to fulfill the budget when the high complexity sky model is assumed.

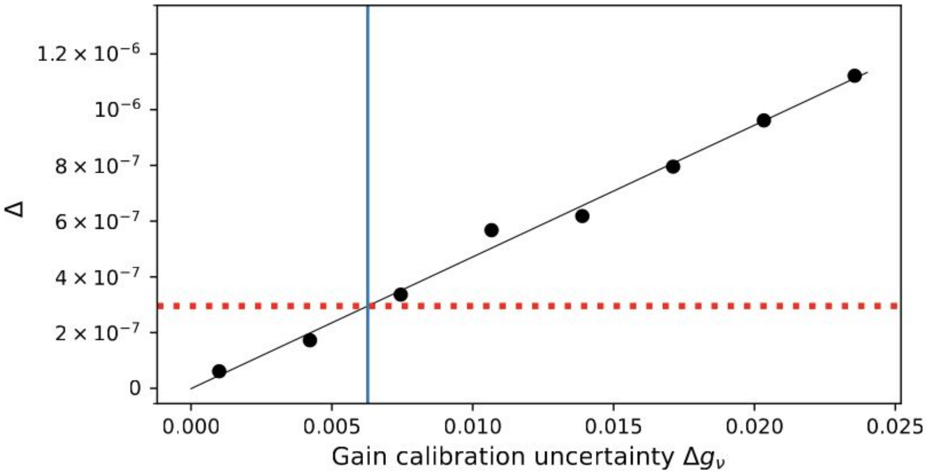
Back up slides

Example for LFT 100 GHz

δr-distribution for different gain uncertainties

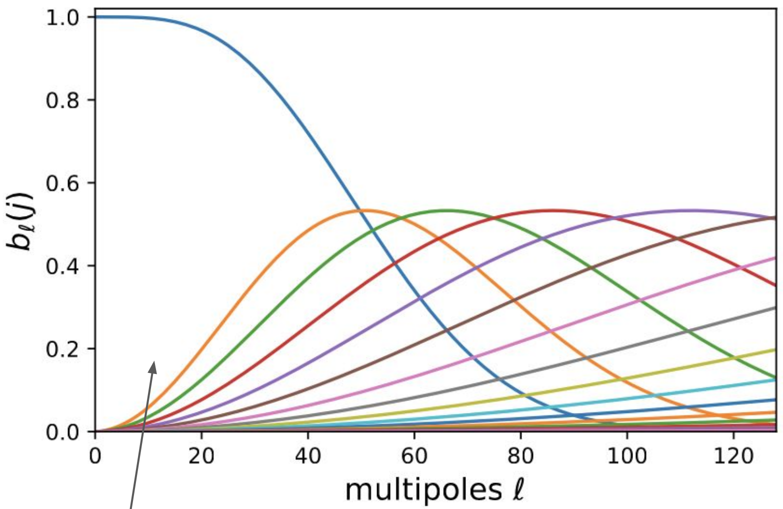


Δ vs gain calibration uncertainty



NILC

- ❖ Needlet : Localisation in both pixels and multipole domains
- ❖ Variance minimisation is performed separately for each needlet scale
- ❖ Inverse needlet transform + sum of all maps gives one CMB solution in pixel space.



The needlet configuration adopted allows to sample more modes at large angular scales where the Galactic emissions are dominant

Tensor-to-scalar ratio estimation

$$-\ln\mathcal{L}({C_\ell}^{\mathrm{obs}}|r) = \sum_\ell \frac{2\ell+1}{2} f_{\mathrm{sky}} \left[\frac{{C_\ell}^{\mathrm{obs}}}{{C_\ell}^{\mathrm{th}}(r)} + \ln({C_\ell}^{\mathrm{th}}(r)) - \frac{2\ell-1}{2\ell+1} \ln({C_\ell}^{\mathrm{obs}}) \right]$$

With: ${C_\ell}^{\mathrm{obs}} = {C_\ell}^{\mathrm{res}} + {C_\ell}^{\mathrm{lensing}}$ and ${C_\ell}^{\mathrm{th}}(r) = r{C_\ell}^{\mathrm{GW},r=1} + {C_\ell}^{\mathrm{lensing}} + {C_\ell}^{\mathrm{res,eff}}$

Residual power spectrum for a single realisation:
foreground + noise residuals + CMB distortion term

foreground + noise residuals template in
the case of an ideal calibration

MC-NILC

To construct the patches you need:

- ➢ a foreground B-mode map at high frequency (337GHz)
- ➢ a foreground B-mode map at central frequency (119 GHz)

$$\frac{B^{hf}_{fgds}}{B^{119}_{fgds}} = \frac{B^{hf}_{dust} + B^{hf}_{synch}}{B^{119}_{dust} + B^{119}_{synch}} = \frac{B^{hf}_{dust}}{B^{119}_{dust}} \cdot \frac{1 + \frac{B^{hf}_{synch}}{B^{hf}_{dust}}}{1 + \frac{B^{119}_{synch}}{B^{119}_{dust}}} \simeq \frac{B^{hf}_{dust}}{B^{119}_{dust}} \cdot \frac{1}{1 + \frac{B^{119}_{synch}}{B^{119}_{dust}}}$$

Carones et al. (2023)

Ideal MC-NILC : Foreground templates at 337 and 119 GHz are obtained by simulation

Realistic MC-NILC : Foreground template at 337 and 119 GHz are derived from total multi-frequency maps (CMB+fg+noise) through GNILC pipeline