Enhanced foreground mitigation in thermal SZ Compton-y maps via polarization-aided cleaning and CIB deprojection

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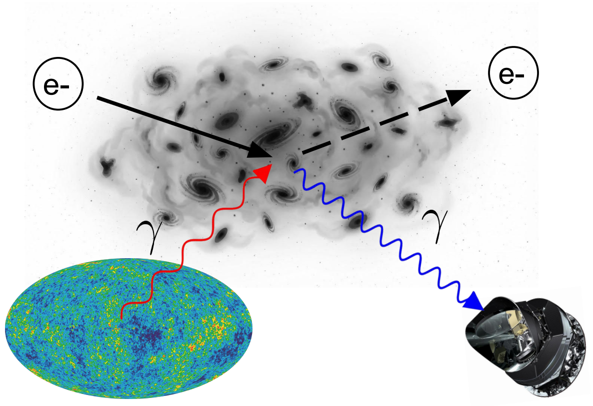
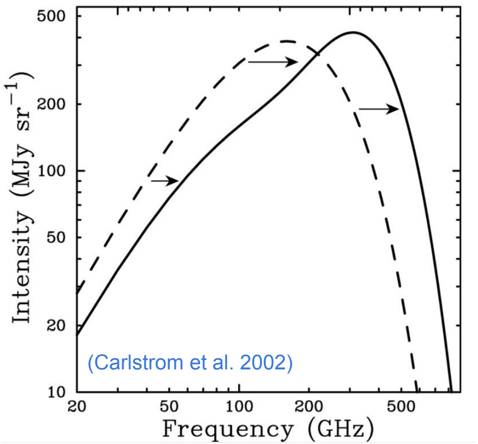
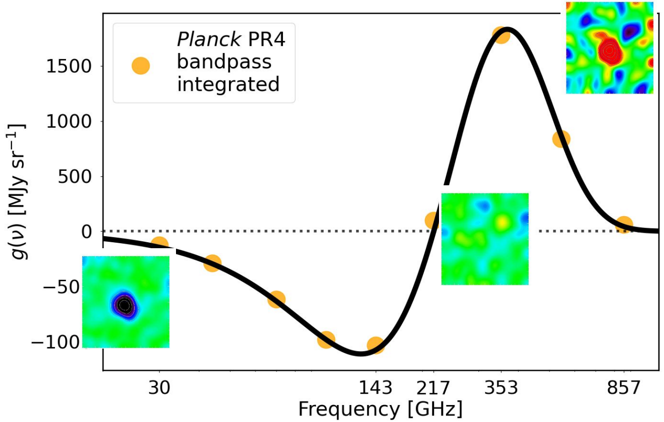
Thermal Sunyaev-Zeldovich (tSZ) Effect







Compton scattering of CMB photons by hot e^- gas in galaxy clusters and IGM (traced by **Compton *y*-parameter**)

Average shift to higher frequencies causes a **spectral distortion of CMB blackbody spectrum**

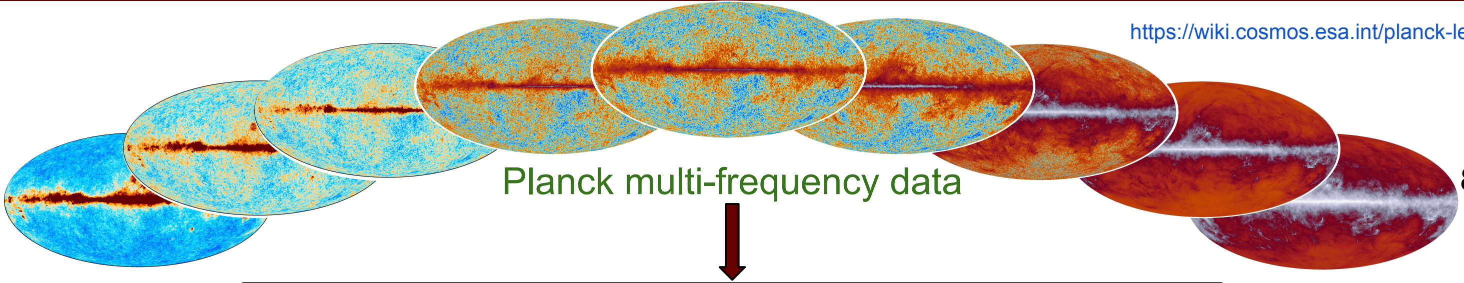
Planck frequencies have been designed to trace **frequency dependence** of tSZ

$$\frac{\Delta T_{tSZ}}{T_{CMB}} = g(\nu)y(\hat{\mathbf{n}}) = \left[x(\nu)\coth\frac{x(\nu)}{2} - 4\right] \cdot \frac{\sigma_T}{m_e c^2}\int_{los} n_e k T_e(\hat{\mathbf{n}})dl$$

Reconstruction of Compton *y*-map with Needlet ILC

https://wiki.cosmos.esa.int/planck-legacy-archive

30 GHz



857 GHz

Planck multi-frequency data

$$\boxed{x(\nu, \hat{\mathbf{n}}) = g(\nu)y(\hat{\mathbf{n}}) + n(\nu, \hat{\mathbf{n}})}$$

Unparameterized contaminants

$$w_j^\nu = \frac{\sum_{\nu'} g_{\nu'}[C_j^{-1}(\hat{\mathbf{n}})]^{\nu\nu'}}{\sum_{\nu,\nu'} g_{\nu'}[C_j^{-1}(\hat{\mathbf{n}})]^{\nu\nu'} g_\nu}$$

$$\boxed{\hat{y}(\hat{\mathbf{n}}) \longleftarrow \hat{y}_j(\hat{\mathbf{n}}) = \sum_\nu w_j^\nu \gamma_j^\nu(\hat{\mathbf{n}})}$$

j: needlet band index
γ: needlet coefficient map

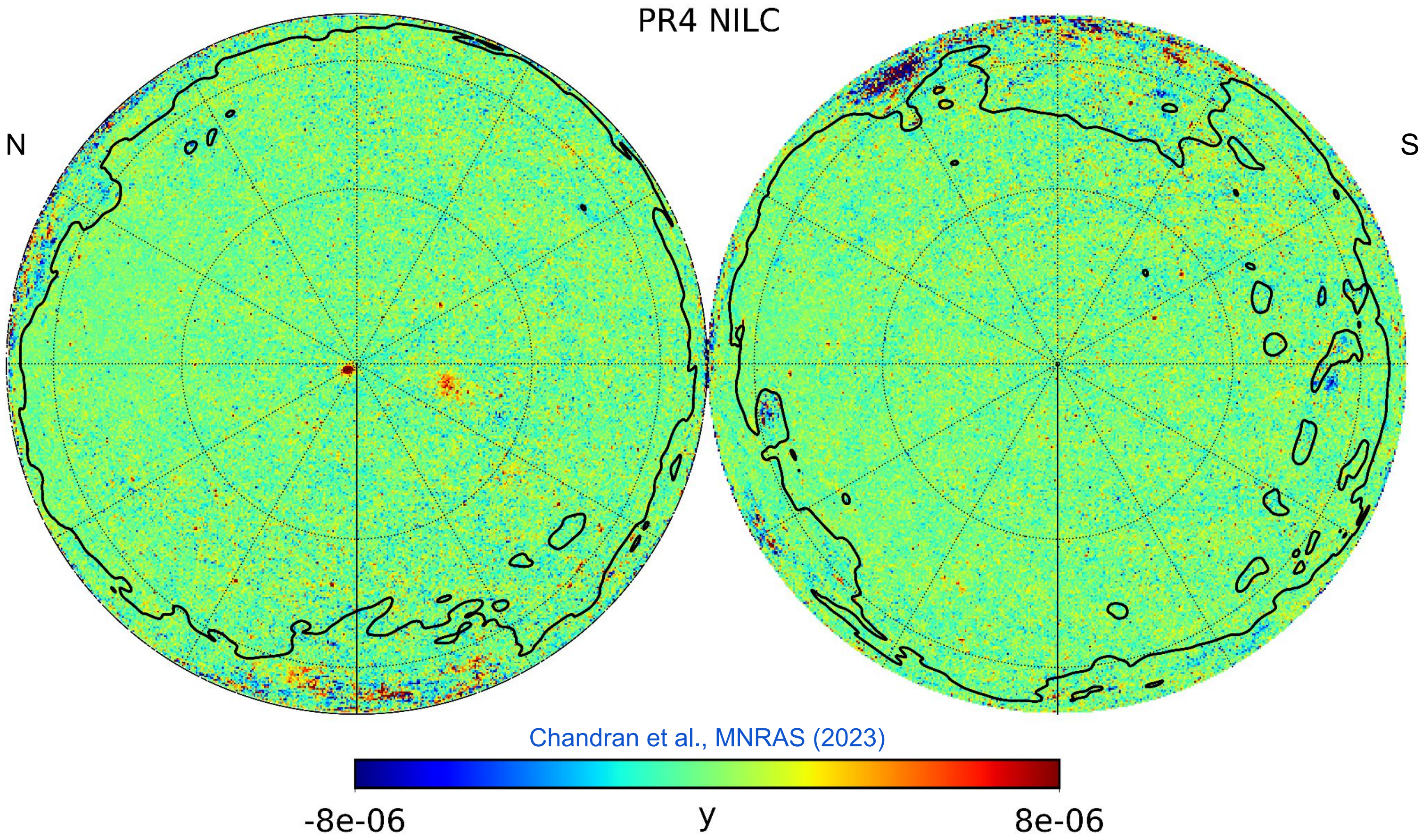
Inversion

Needlet ILC (NILC) [Delabrouille et al. 2009, Remazeilles et al. 2011, 2013]

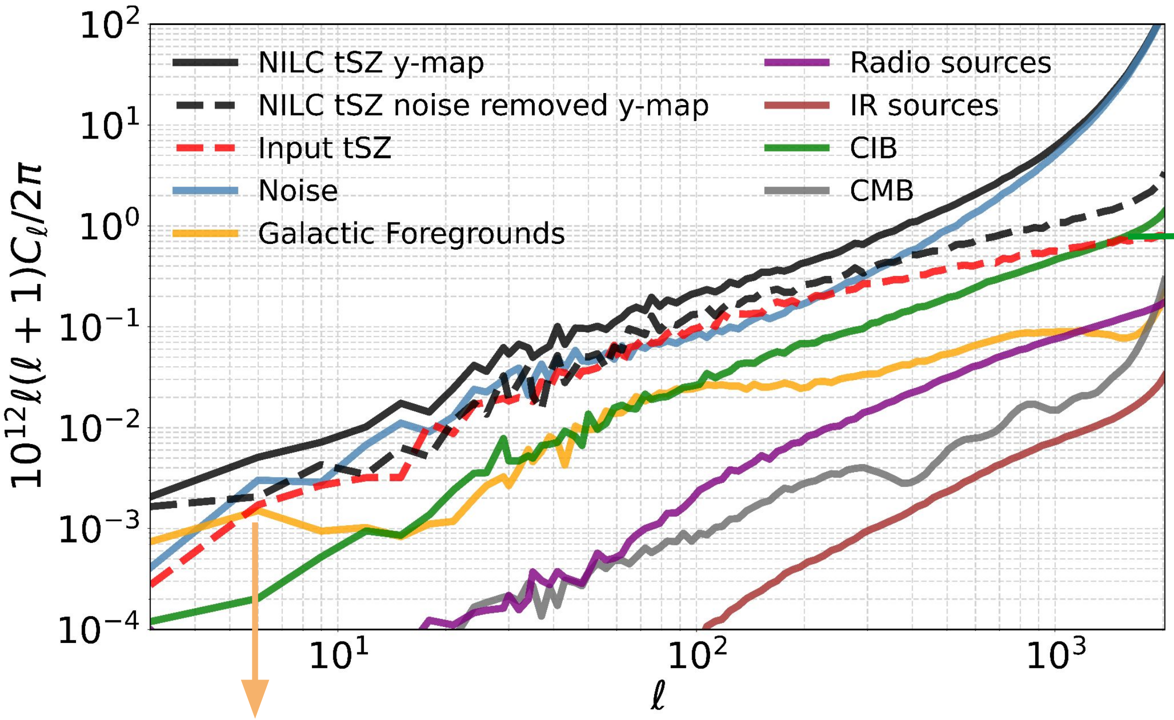
- Simultaneous localization in spatial (pixel) and spectral (harmonic) domains
- Not dependent on knowledge of contaminants (blind)

Planck thermal SZ NILC y-map

Planck PR4 NILC *y*-map (Chandran+2023 — our starting point)



NILC *y*-map and contaminants from *Planck* simulations



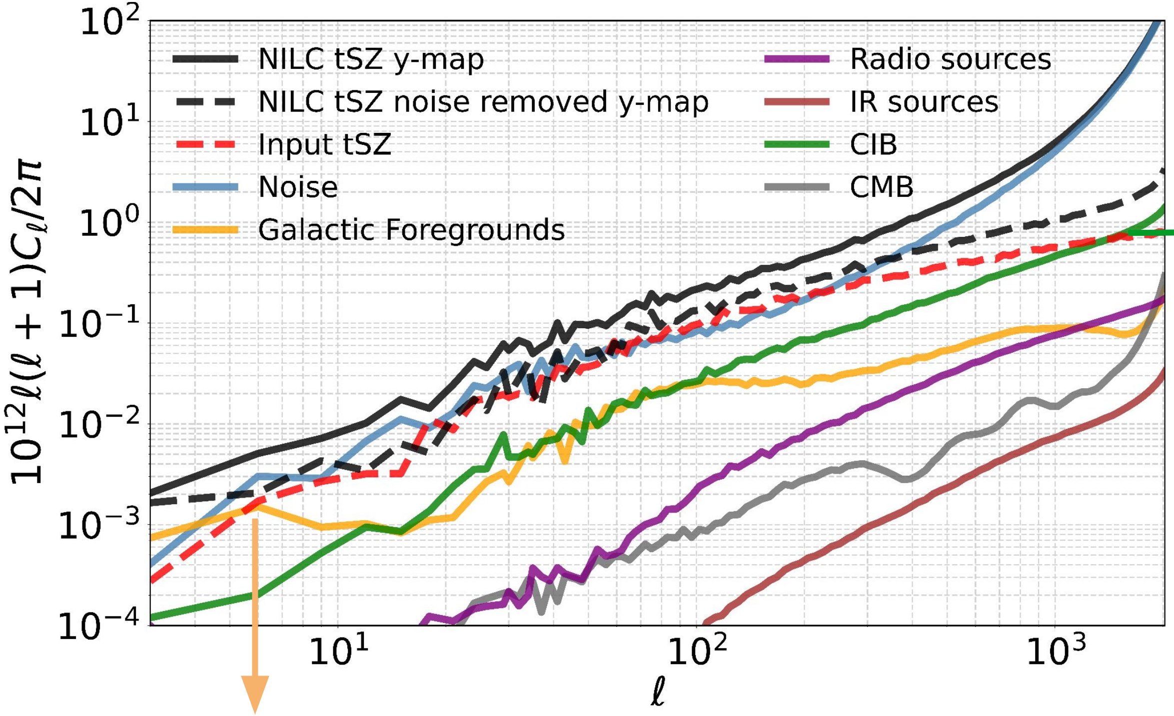
Small scales:

CIB

Large scales:

Galactic foregrounds

NILC *y*-map and contaminants from *Planck* simulations



Small scales:

CIB

Large scales:

Galactic foregrounds

Hybrid NILC + **Moment deprojection**

Multi-stokes Hybrid NILC

Idea: tSZ signal ⇒ *unpolarized*, Galactic dust and synchrotron ⇒ *strongly polarized* and show correlated structures in temperature and Q/U. Use this correlation to enhance cleaning of the Galactic contamination in y-map.

- Estimate: $$\hat{y}(p) = (\mathbf{w}_T^t \ \mathbf{w}_E^t) \begin{pmatrix} \mathbf{t}(p) \\ \mathbf{e}(p) \end{pmatrix}$$

Could use E, B, Q, U or P

- Variance: $$\langle \hat{y}^2(p) \rangle = (\mathbf{w}_T^t \ \mathbf{w}_E^t) \begin{pmatrix} \mathbf{C}^{TT} & \mathbf{C}^{TE} \\ \mathbf{C}^{ET} & \mathbf{C}^{EE} \end{pmatrix} (p) \begin{pmatrix} \mathbf{w}_T \\ \mathbf{w}_E \end{pmatrix}$$

- Constraint: $$\mathbf{w}^t \mathbf{a}_{\mathrm{tSZ}} = (\mathbf{w}_T^t \ \mathbf{w}_E^t) \begin{pmatrix} \mathbf{g} \\ \mathbf{0} \end{pmatrix} = 1$$

g is the tSZ SED; 9T + 7Pol

Temperature - Polarization Correlation

$$\mathrm{P} = \left(\mathrm{C}^{TT}\right)^{-1}\mathrm{C}^{TE}\left(\mathrm{C}^{EE}\right)^{-1}\mathrm{C}^{ET}$$

$$\mathbf{w}_T = \frac{(\mathrm{I}-\mathrm{P})^{-1}\left(\mathrm{C}^{TT}\right)^{-1}\mathbf{g}}{\mathbf{g}^t(\mathrm{I}-\mathrm{P})^{-1}\left(\mathrm{C}^{TT}\right)^{-1}\mathbf{g}}$$

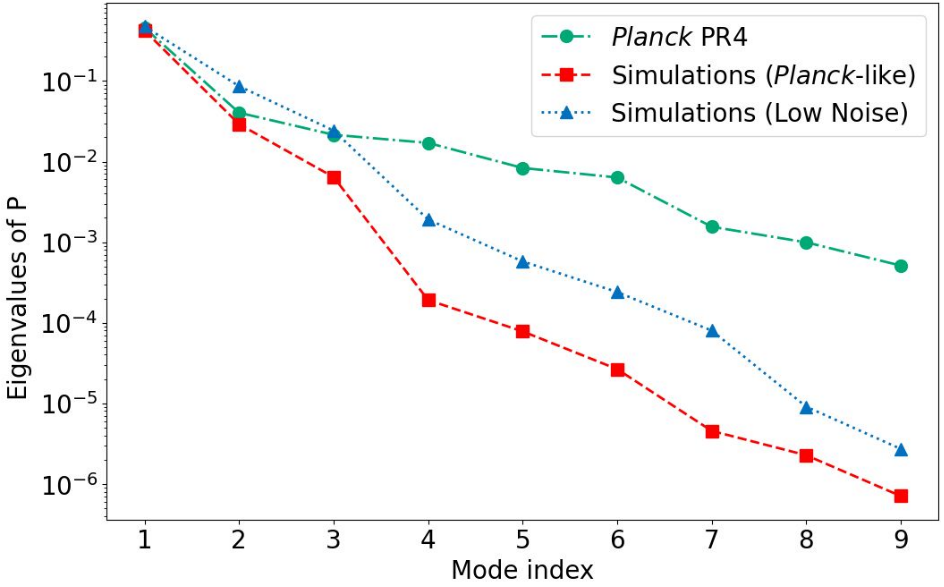
$$\mathbf{w}_E = -\left(\mathrm{C}^{EE}\right)^{-1}\mathrm{C}^{ET}\,\mathbf{w}_T$$

$$\frac{\langle\hat{y}^2\rangle}{\langle\hat{y}^2_{\mathrm{std}}\rangle} = \frac{\mathbf{g}^t\left(\mathrm{C}^{TT}\right)^{-1}\mathbf{g}}{\mathbf{g}^t(\mathrm{I}-\mathrm{P})^{-1}\left(\mathrm{C}^{TT}\right)^{-1}\mathbf{g}} < 1$$

The variance ratio of the hybrid vs standard NILC *y*-maps < 1 shows that adding polarization reduces foreground variance while preserving the tSZ signal.

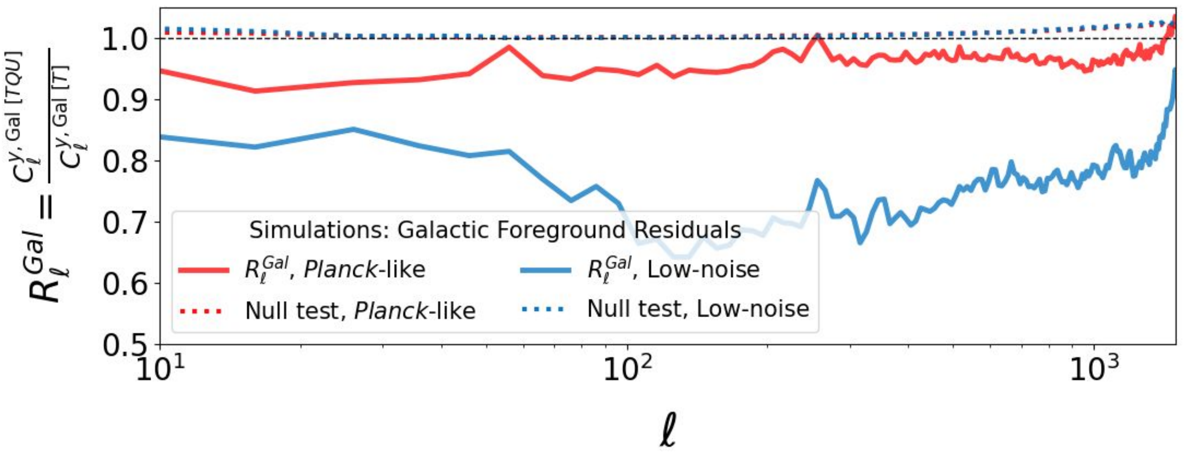
Temperature - Polarization Correlation

$$\mathrm{P} = \left(\mathrm{C}^{TT}\right)^{-1}\mathrm{C}^{TE}\left(\mathrm{C}^{EE}\right)^{-1}\mathrm{C}^{ET}$$



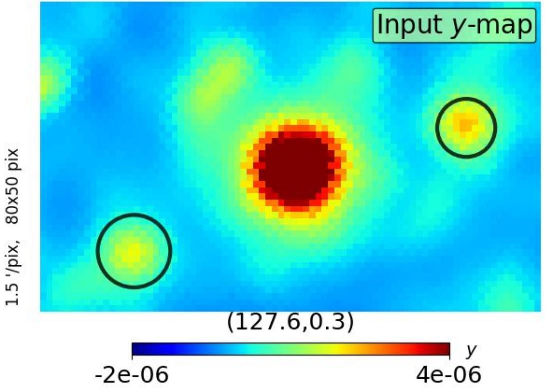
Larger eigenvalues of P ⇒ stronger Galactic T–P correlation ⇒ stronger foreground suppression by the Hybrid NILC.

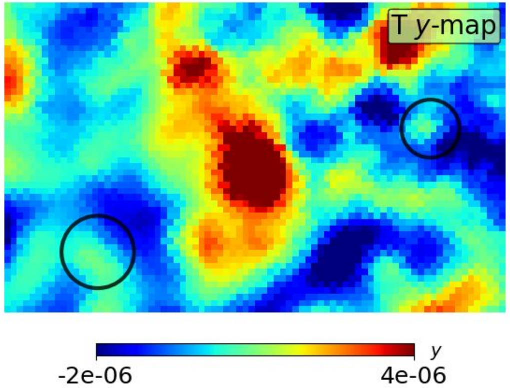
Simulations: Improvement from T to TQU *y*-map (Galactic FG residuals)

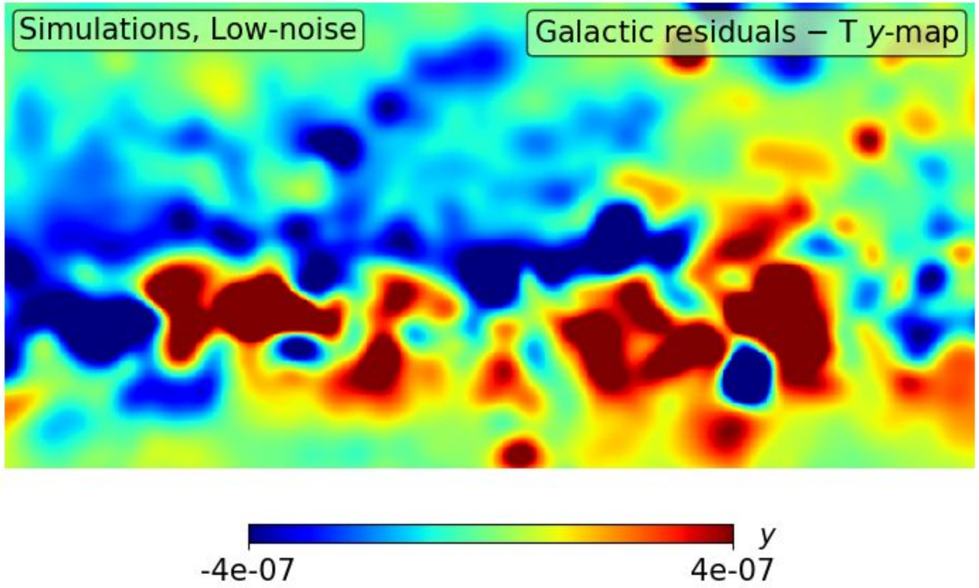


- Planck-like simulation: TQU *y*-map has lower Galactic-residual power across multipoles w.r.t the T *y*-map.
- Low-noise simulation (sensitivity x 25): reduction further improves by ≈ 25% in Galactic residual power across relevant multipoles.

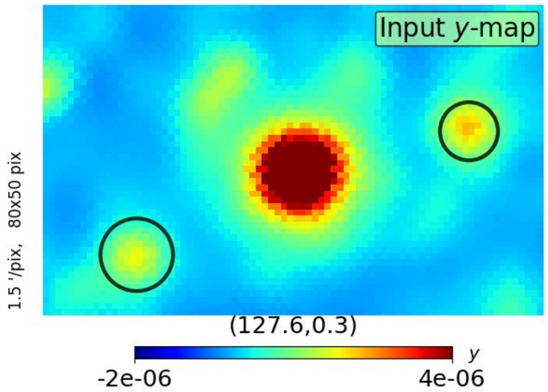
Simulations (low-noise): T y-map

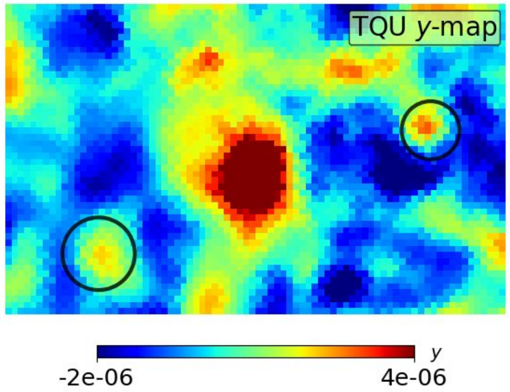


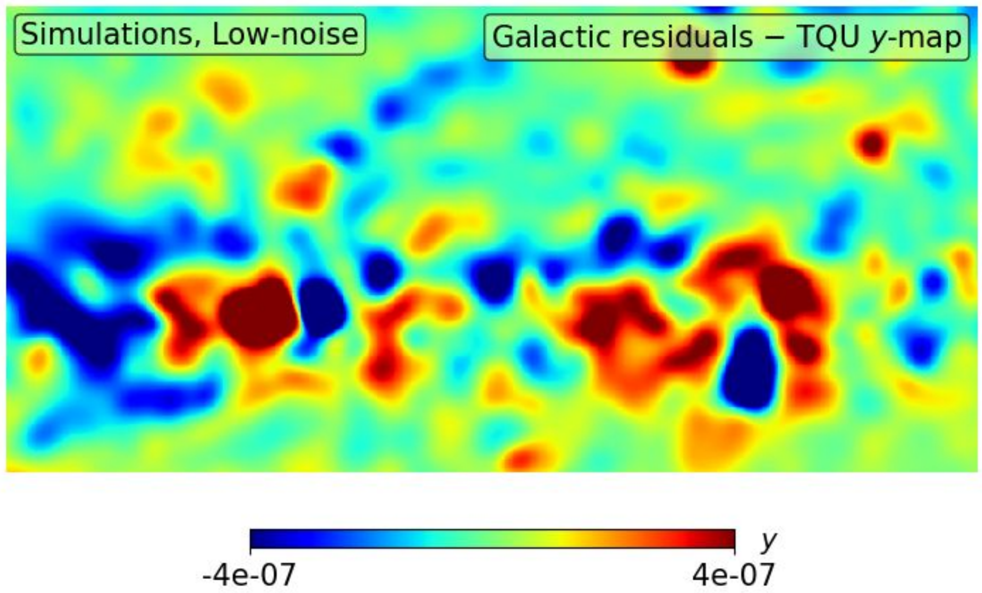




Simulations (low-noise): TQU y-map

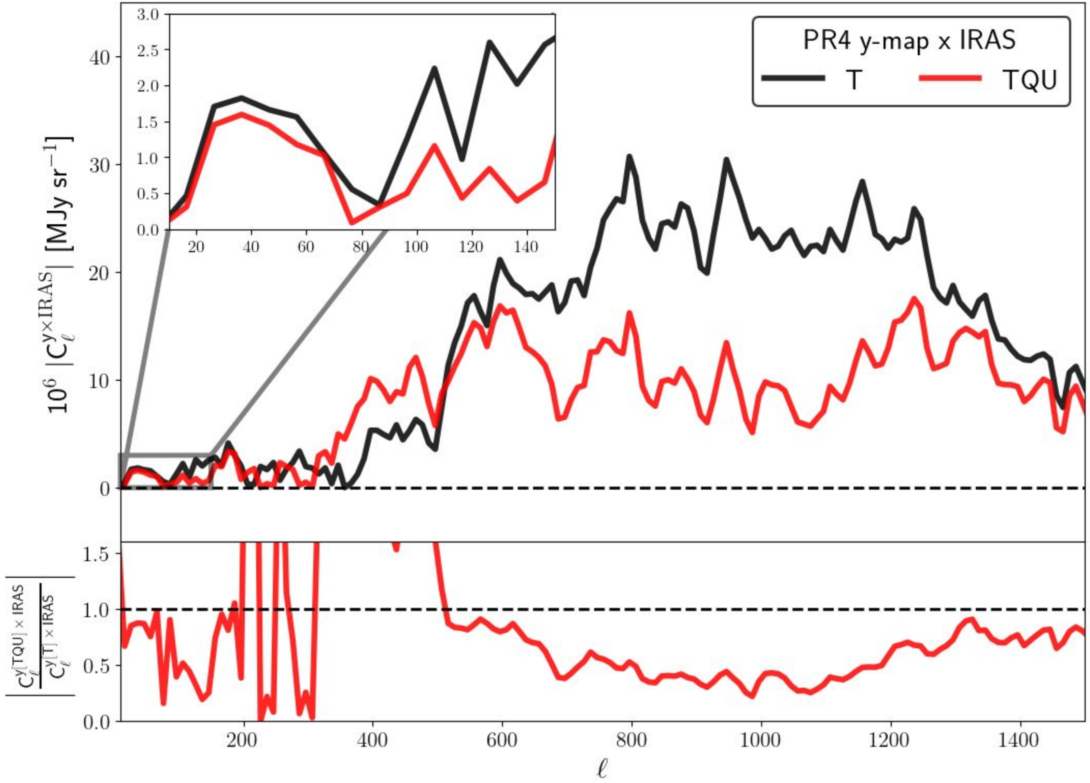






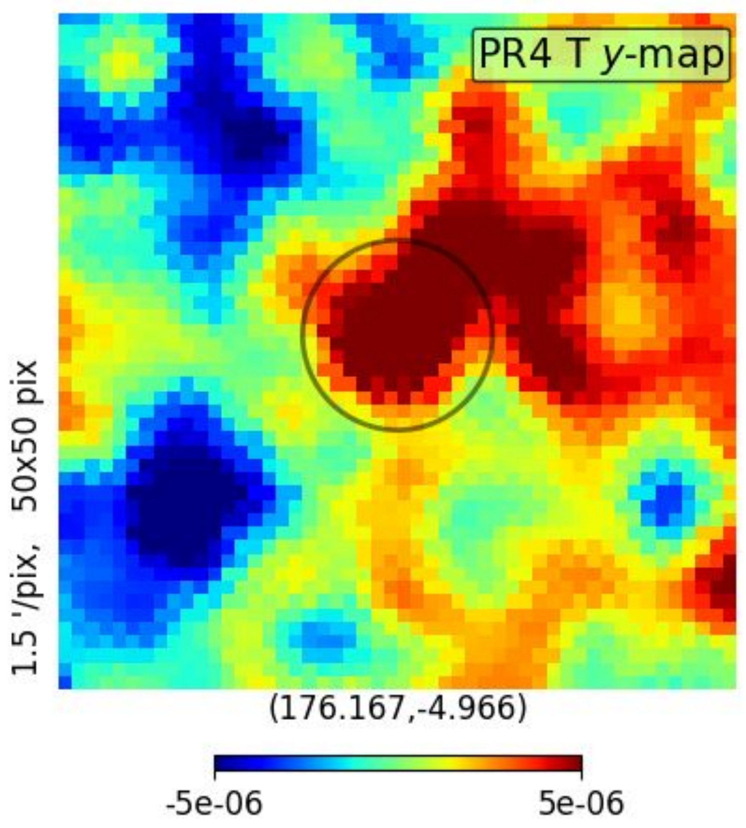
Lower galactic residuals ⇒ better cluster detection & fsky

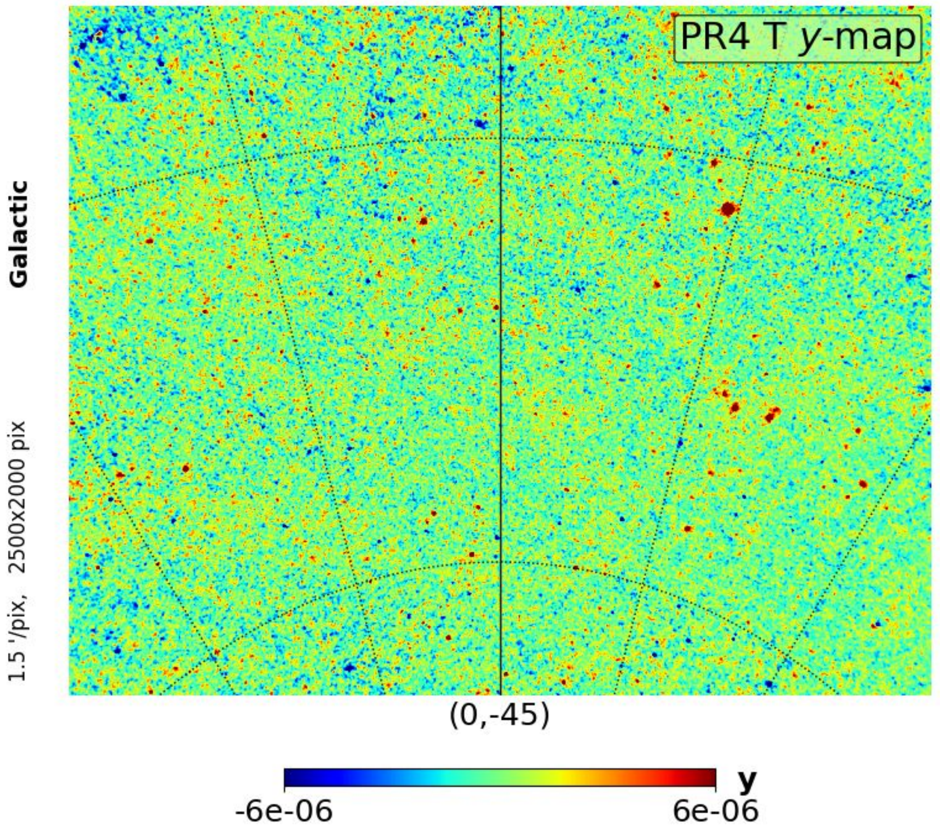
Planck PR4 data: Improvement from T to TQU y-map



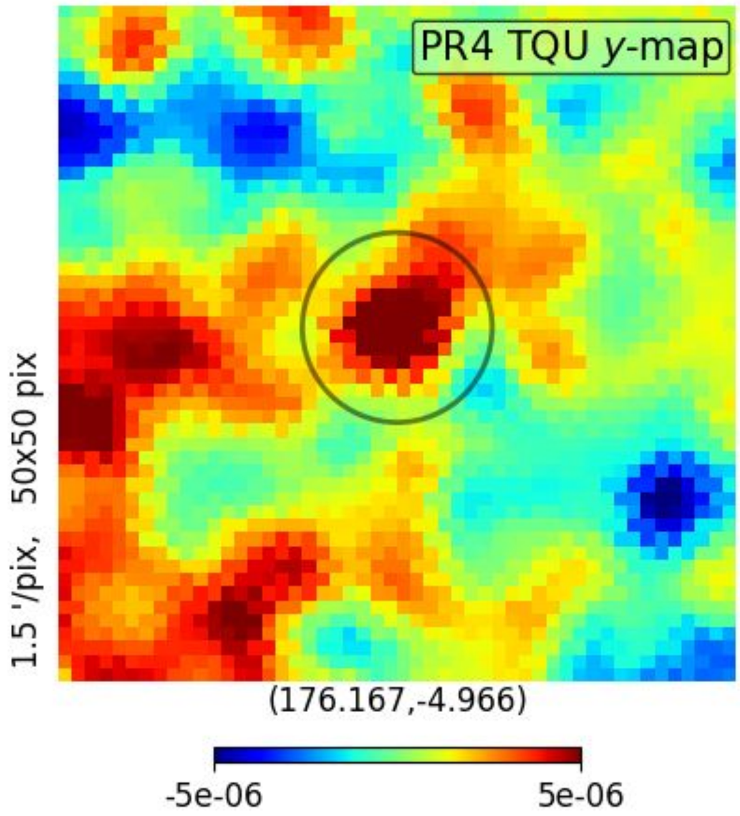
Cross-spectra with IRAS 100 µm over fsky ≃ 0.98 indicate a ≈ 40% decrease in residual dust contamination for TQU y-map compared to the T y-map.

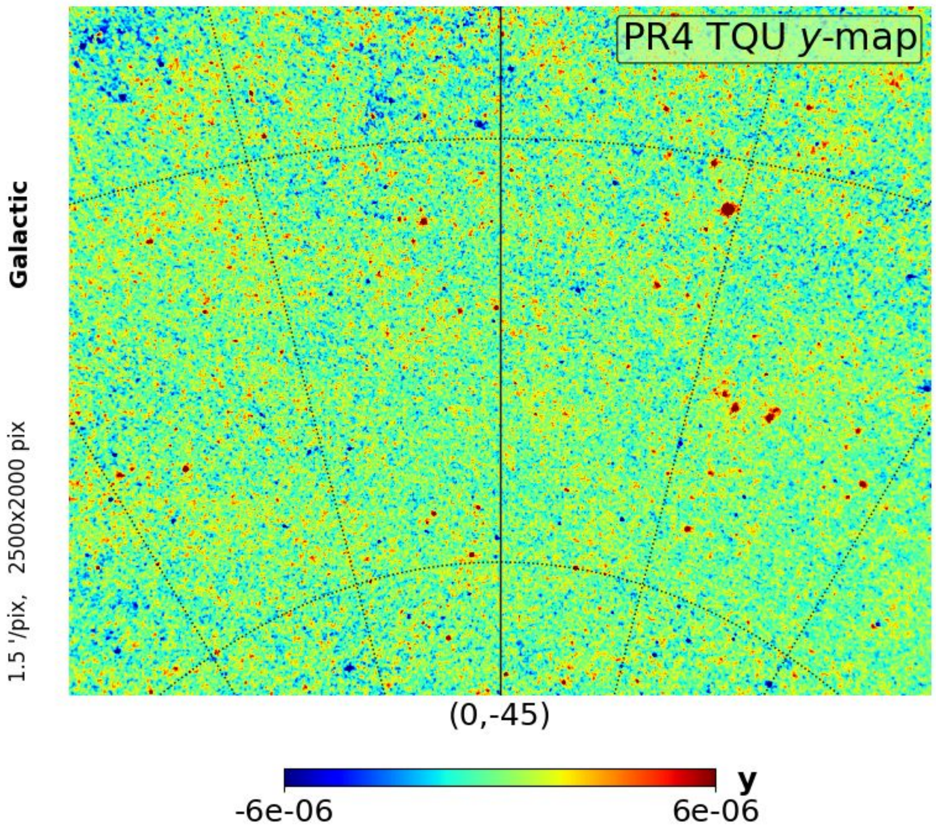
Planck PR4 data: T y-map





Planck PR4 data: TQU y-map





Selective CIB Moment Deprojection

Idea: Selective, scale-dependent CIB moment deprojection targets the moments and multipoles, avoiding the large noise penalty of blindly deprojecting all moments.

$$I_\nu^{\mathrm{CIB}}(p) \propto I_\nu(\bar{z}, \bar{\beta}, \bar{T}) + \left\langle \beta - \bar{\beta} \right\rangle_z \frac{\partial I_\nu}{\partial \bar{\beta}} + \left\langle T - \bar{T} \right\rangle_z \frac{\partial I_\nu}{\partial \bar{T}} \qquad \bar{z} \simeq 0.2, \bar{\beta} = 1.75, \bar{T} = 21.71\,K$$

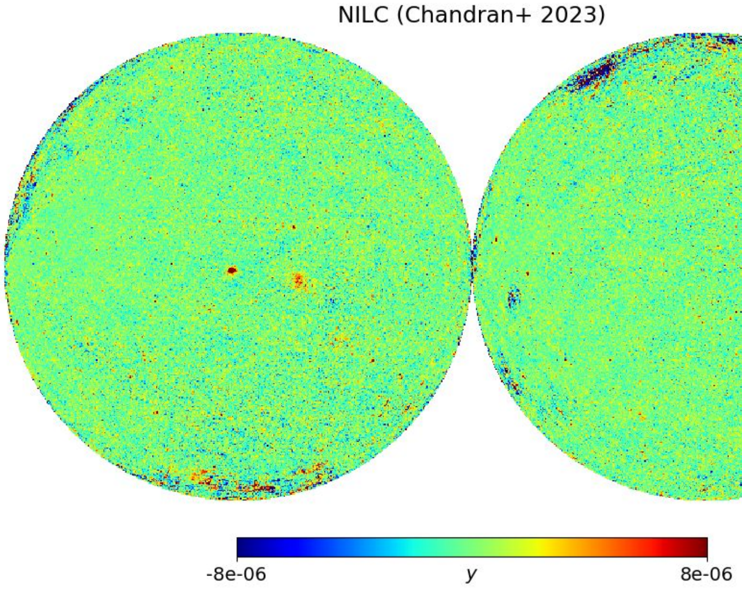
$$\mathbf{w}^t = \mathbf{e}^t \left(\mathrm{A}^t \mathrm{C}^{-1} \mathrm{A}\right)^{-1} \mathrm{A}^t \mathrm{C}^{-1}$$

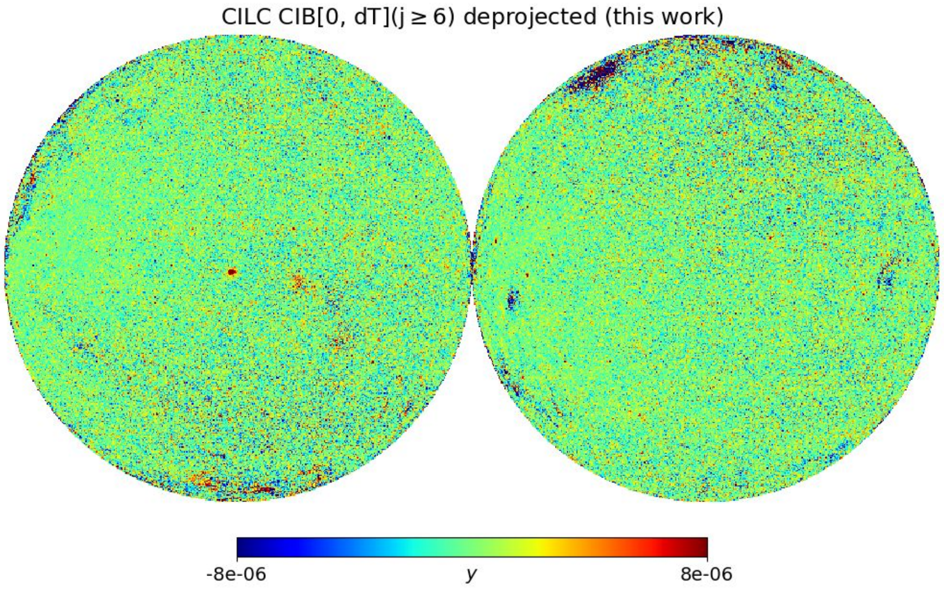
$$\boxed{\sum_\nu w_\nu \frac{\partial^k I_\nu}{\partial \bar{T}^k} = 0}$$

$$\mathrm{A} = \left(\mathbf{g} \quad \partial^k \boldsymbol{I} / \partial \bar{T}^k\right)$$

Method name	Associated SEDs
CILC CIB$[0]$	I_ν
CILC CIB$[0, d\beta]$	$I_\nu, \frac{\partial I_\nu}{\partial \beta}$
CILC CIB$[0, d\beta, dT]$	$I_\nu, \frac{\partial I_\nu}{\partial \beta}, \frac{\partial I_\nu}{\partial T}$
CILC CIB$[0, dT]$	$I_\nu, \frac{\partial I_\nu}{\partial T}$
CILC CIB$[0, dT]\,(j \geq 6)$	I_ν for $j \geq 6$, $\frac{\partial I_\nu}{\partial T}$ for $j \geq 6$
CILC CIB$[0, d\beta(j < 6), dT(j \geq 6)]$	$I_\nu, \frac{\partial I_\nu}{\partial \beta}$ for $j < 6$, $\frac{\partial I_\nu}{\partial T}$ for $j \geq 6$

Selective CIB Moment Deprojection

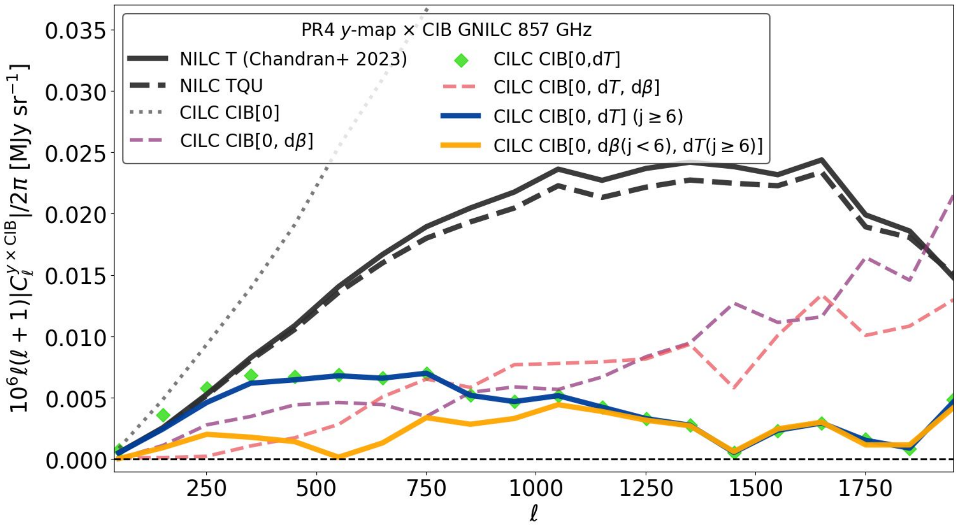




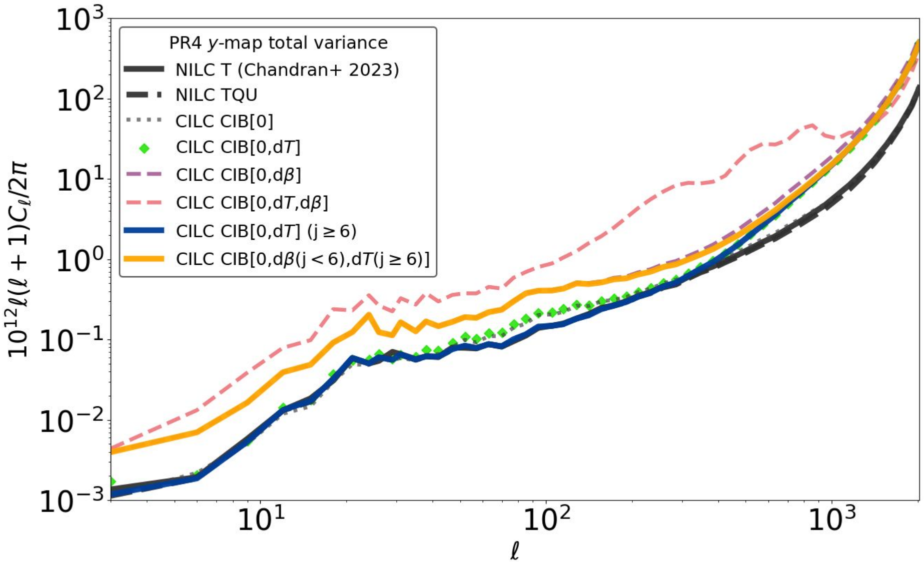
CIB deprojection with optimal CIB suppression vs total-variance trade-off

Planck PR4 data: Selective CIB Moment Deprojection

Residual CIB contamination (y x CIB)



Total-variance



- **CILC CIB[0, dT] (j≥6)**: Near-NILC variance while substantially reducing the CIB contamination on small scales.
- CILC CIB[0, dβ (j<6), dT (j≥6)]: Lowest CIB residual but higher total variance.

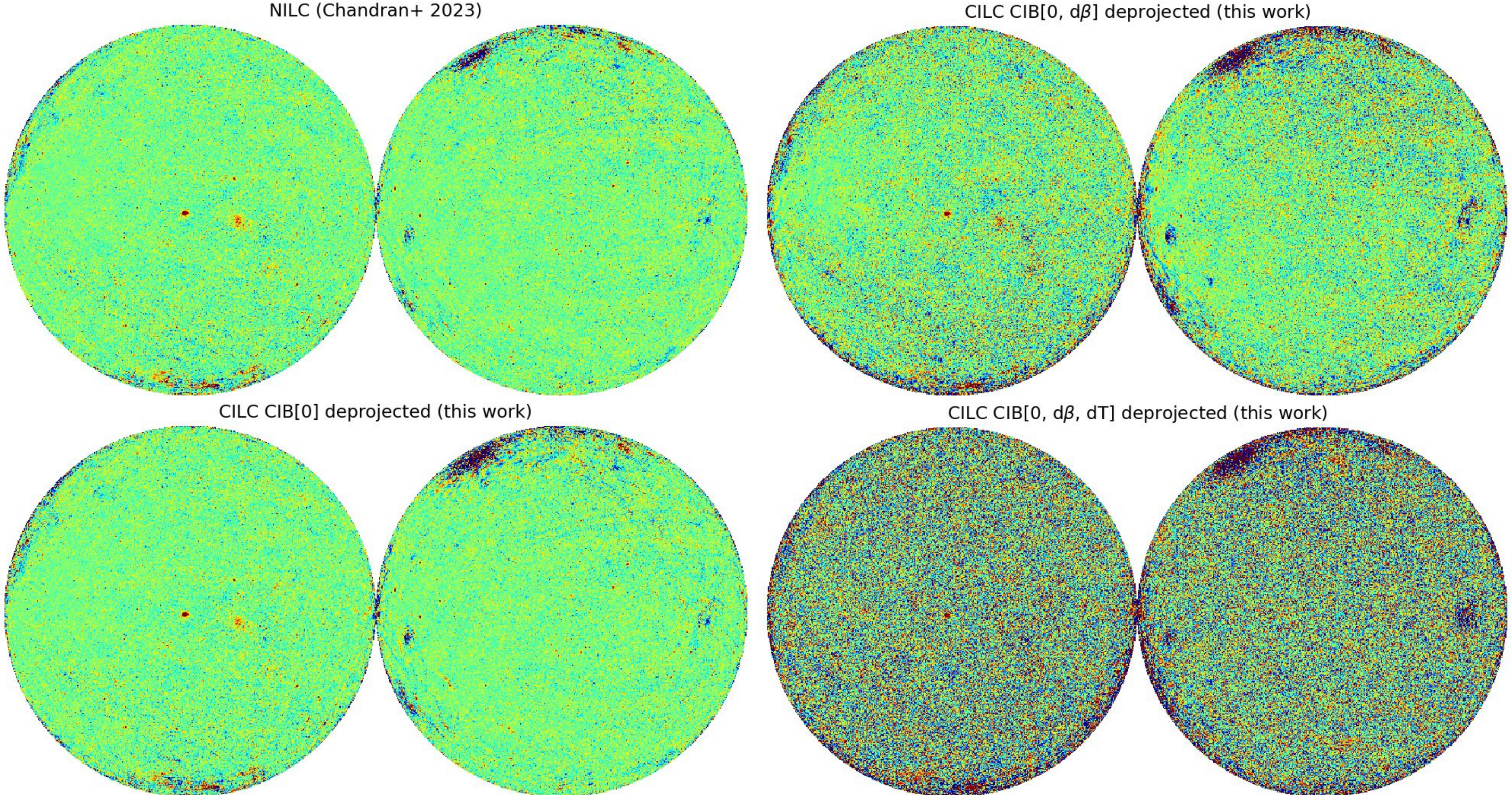
Summary

- Multi-Stokes Hybrid NILC exploits the intrinsic temperature–polarization correlation of Galactic foreground components to suppress their variance while preserving the unpolarized tSZ signal.
- This method is especially useful for future high-sensitivity surveys like LiteBIRD.
- Can be extended to separate spectrally degenerate signals (where polarization can add discriminating power) such as thermal dust and CIB, or CMB and kinetic SZ effect.
- The Planck PR4 TQU CILC y-map (with selective CIB moment deprojection) available at https://doi.org/10.5281/zenodo.18876142 for community use.

PhD expected Spring 2027, IFCA. Looking for postdocs in signal extraction from multi-frequency surveys — CMB and adjacent (spectral distortions, LIM) — and ML for source detection. chandran@ifca.es

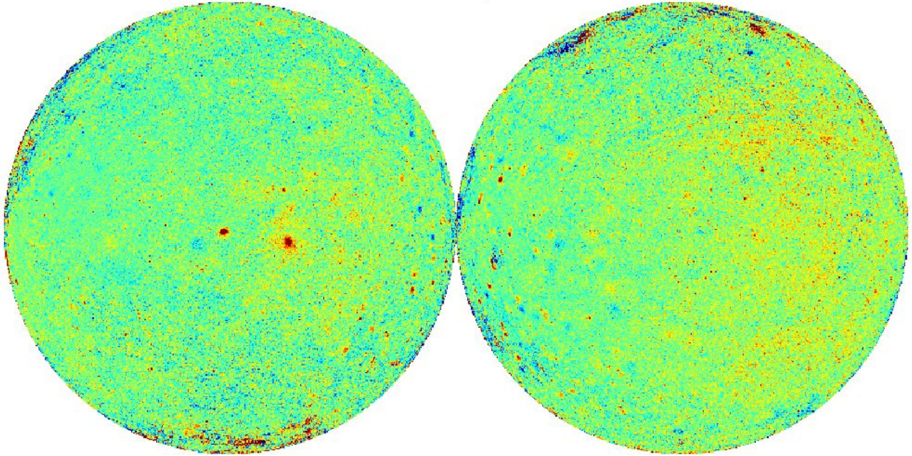
BACKUP

Selective CIB Moment Deprojection comparison (maps)

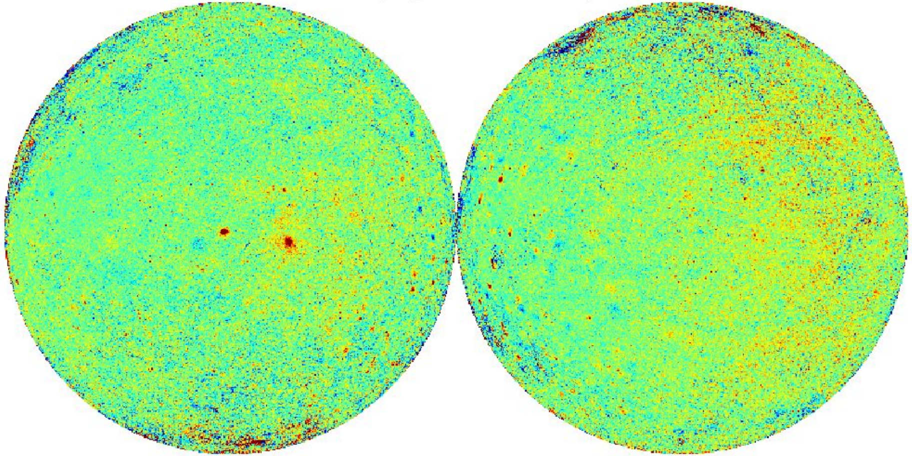


Selective CIB Moment Deprojection comparison (maps)

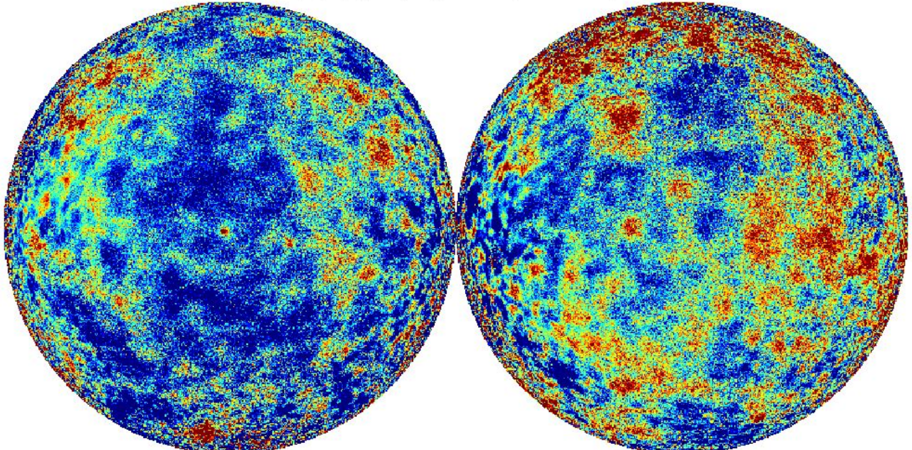
NILC (McCarthy+ 2024)



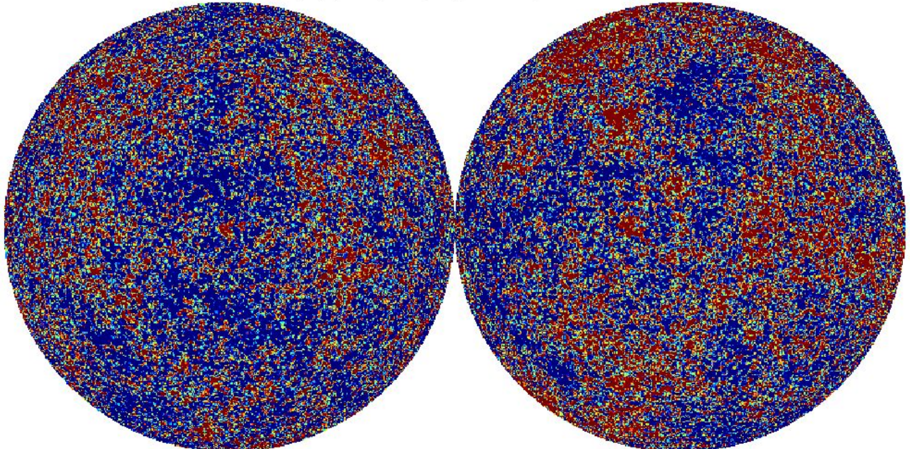
CILC CIB[0] deprojected (McCarthy+ 2024)



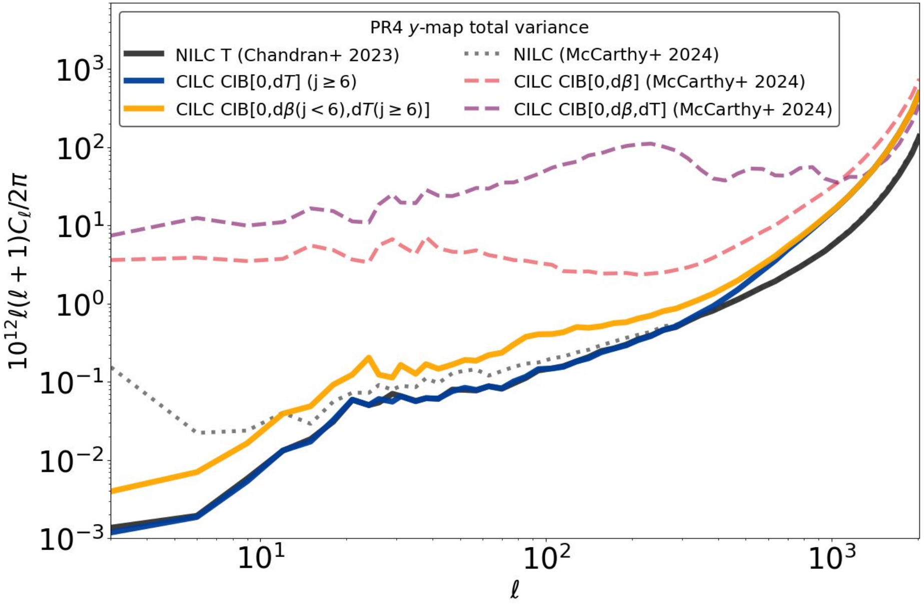
CILC CIB[0, dβ] deprojected (McCarthy+ 2024)

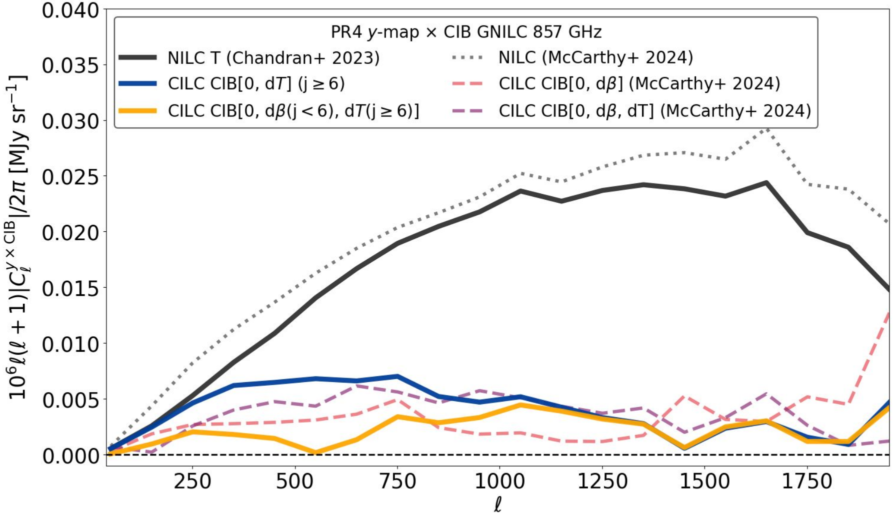


CILC CIB[0, dβ, dT] deprojected (McCarthy+ 2024)



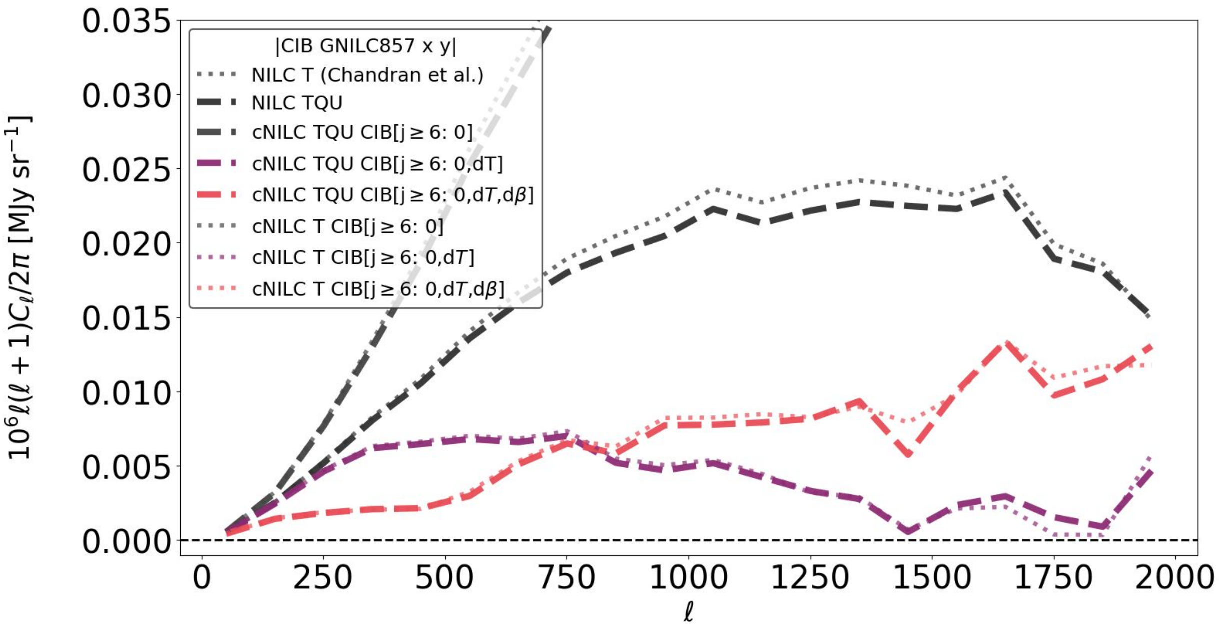
Selective CIB Moment Deprojection comparison (power spectra)





Our best cases of CIB deprojected y-maps have comparable level of CIB residuals to other contemporary maps in the relevant multipoles. But have lower total variance, especially in large scales.

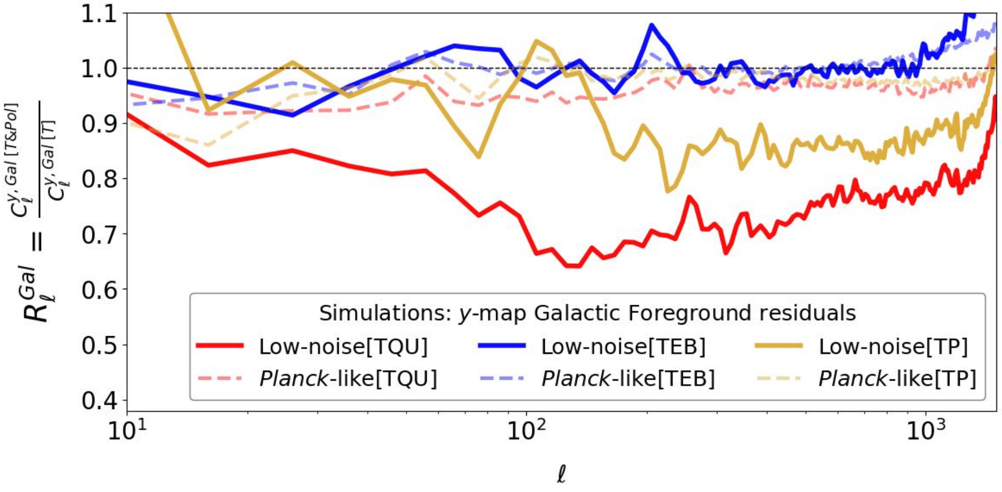
Selective CIB Moment Deprojection (maps, T vs TQU)

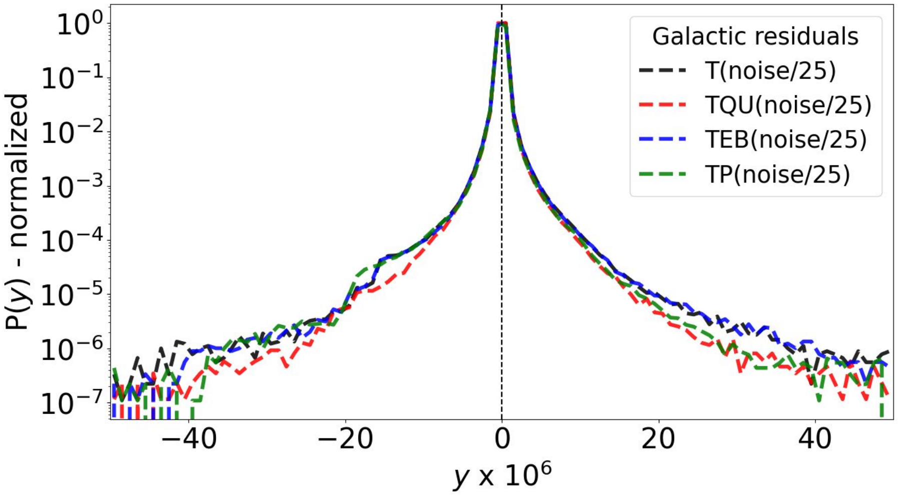


A representative set of CIB deprojection cases for temperature only case (T) and temperature plus polarization case (TQU).

Having polarization channels affects CIB residual very minimally, especially in the cases with CIB moment deprojection.

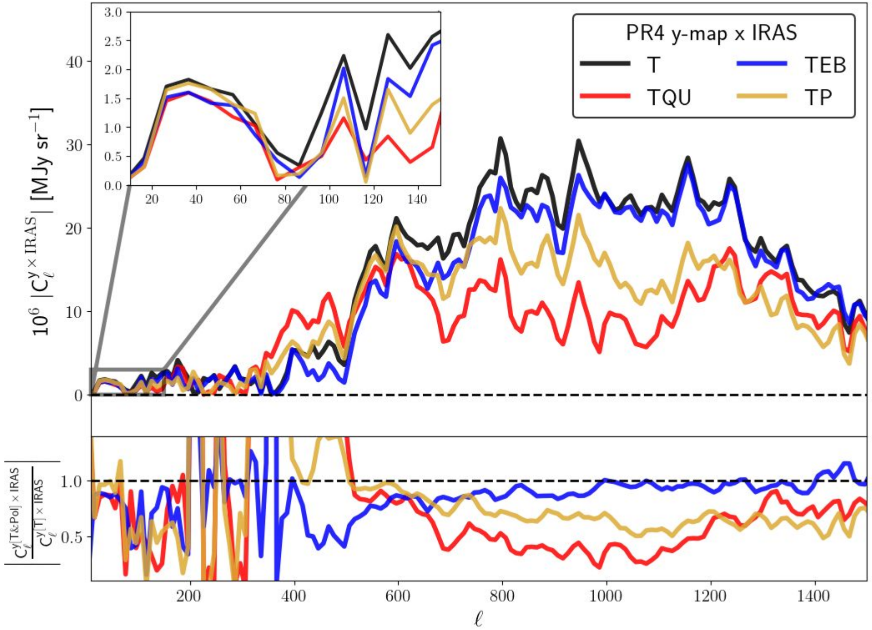
Simulations: T to TQU/TEB/TP y-map

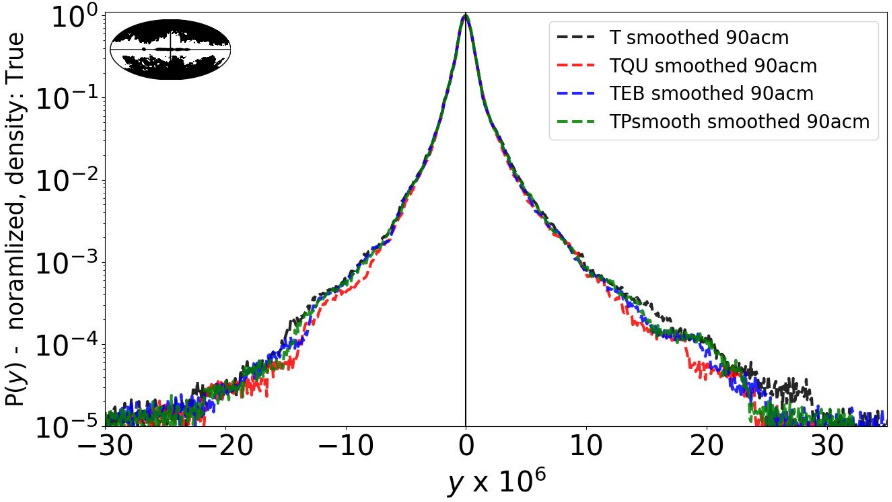




- Both the power spectra ratio as well as the pdf of the Galactic residuals show that using Stokes Q and U channels as auxiliary polarization channels gives the best reduction in Galactic residuals, especially in the low-noise (LiteBIRD like) case.
- Q and U preserves the locality of the correlated morphology of Galactic components
- The non-local transformation to E and B leads to loss of some locality of the relevant components.

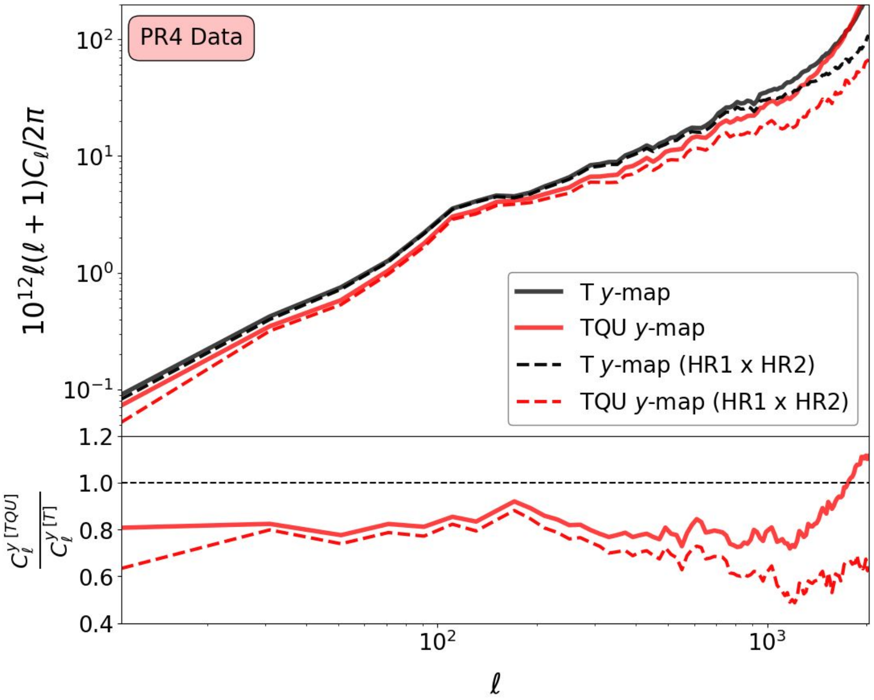
Planck PR4 data: T to TQU/TEB/TP y-map

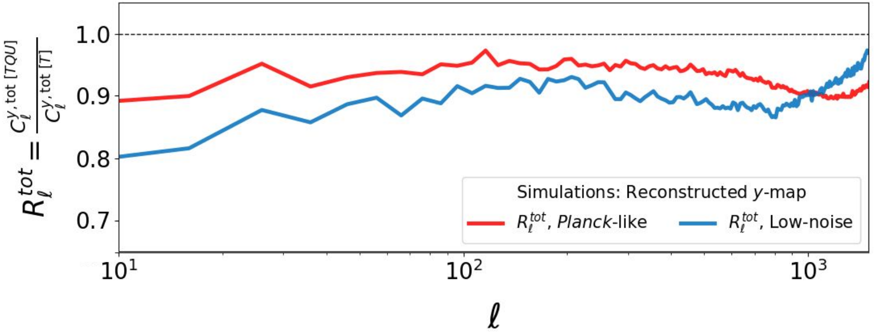




The cross spectra of Planck PR4 y-maps with IRAS 100 microns dust tracer and the PDF of the y-maps in the galactic region confirms that TQU is the better combination in the available ones.

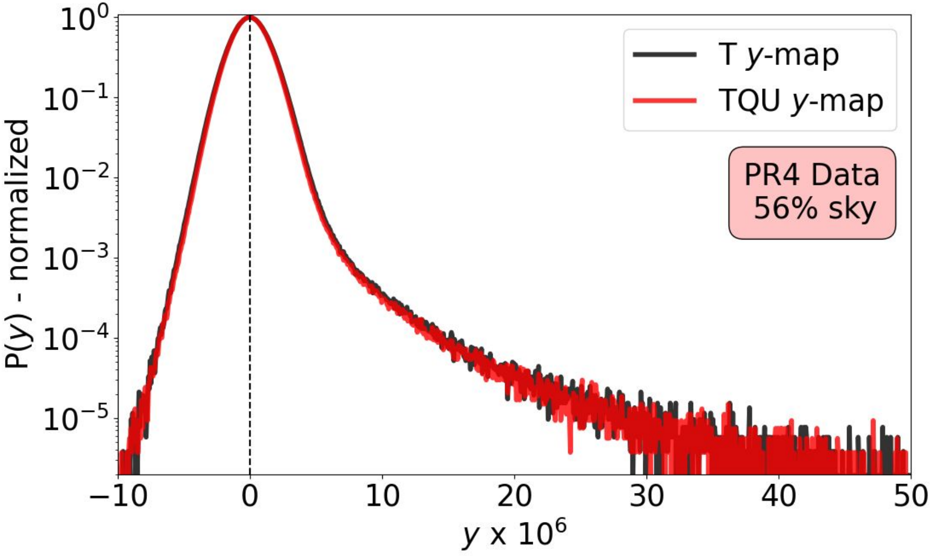
Simulations and PR4: Improvement from T to TQU *y*-map (Total variance)

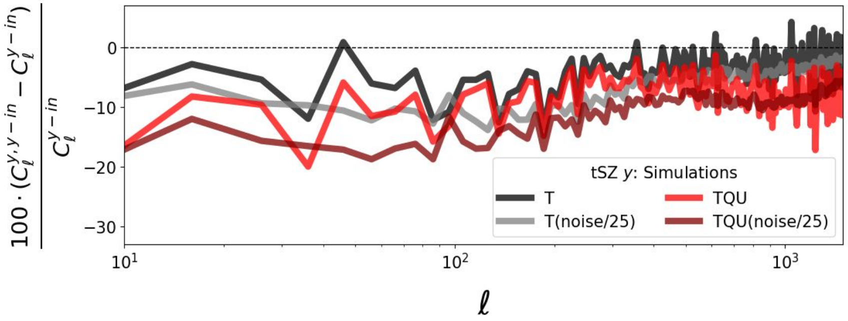




Total variance (power spectra) of T and TQU y-maps for simulations and data. The difference is mostly powered by the reduction of residual Galactic power.

Planck PR4 data: Unbiased tSZ reconstruction check





We have similar reconstruction of the thermal SZ for T and TQU y-maps, evident from the characteristic tSZ tail in the PDF after masking wita large Galactic mask and a point-source mask.

Planck PR4 data: CIB Deprojection (Noise-debiased power spectra)