GNILC

Generalized Needlet Internal Linear Combination

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MANCHESTER 1824

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Remazeilles, Delabrouille, Cardoso, MNRAS 2011
Planck intermediate results. XLVIII, A&A 2016
Planck 2018 results. IV, 1807.06208
Planck 2018 results. XII, 1807.06212

"CMB foregrounds for B-mode studies"
Tenerife, 15-18 October 2018

Overview of GNILC

1. Thermal dust and CIB separation
2. Thermal dust polarization
3. CMB B-modes

Overview of GNILC

1. Thermal dust and CIB separation
2. Thermal dust polarization
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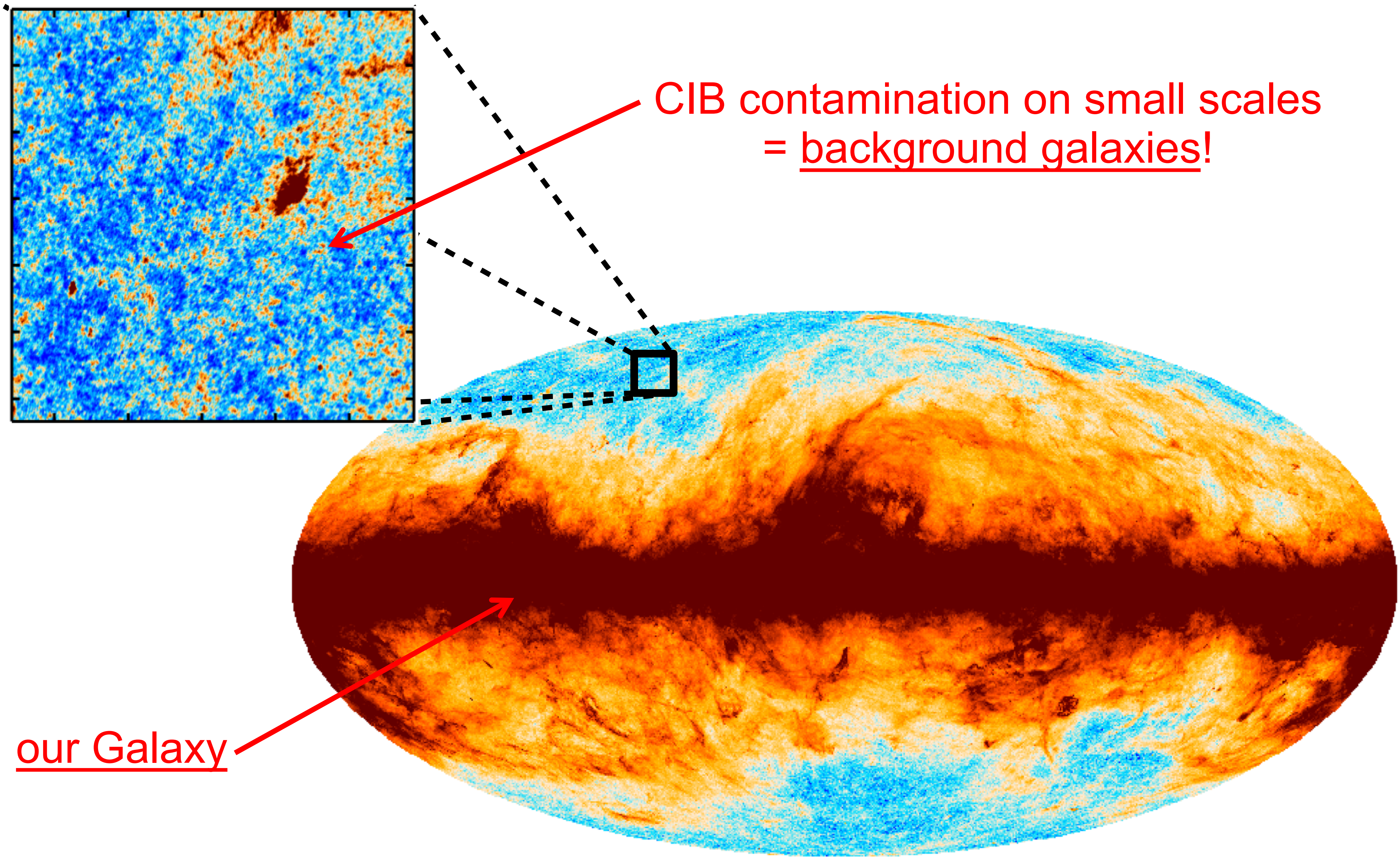
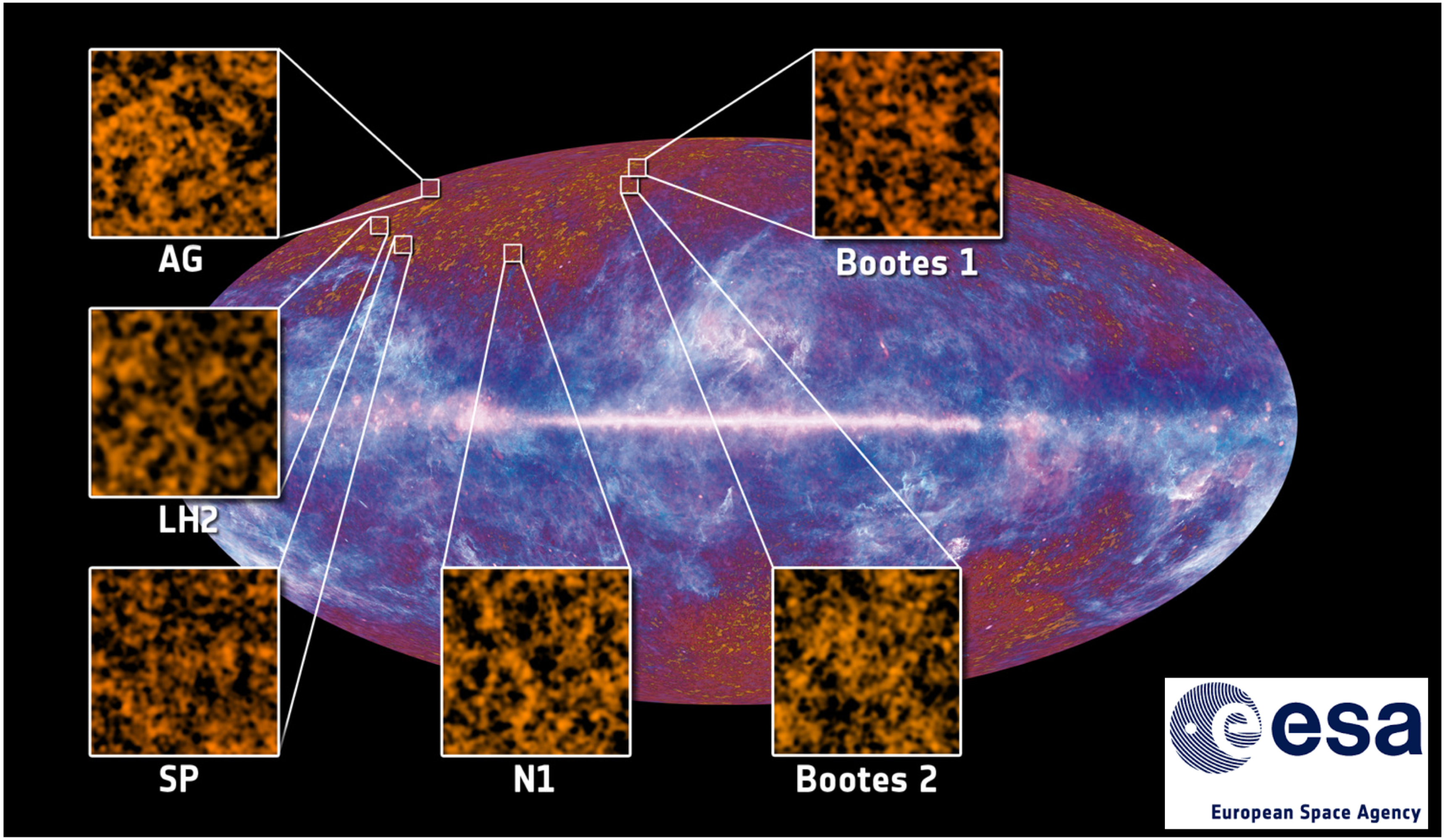
Planck **2013** Galactic dust all-sky map



Planck 2013 results. XI, "All-sky model of thermal dust emission", A&A (2014)

Cosmic infrared background (CIB)

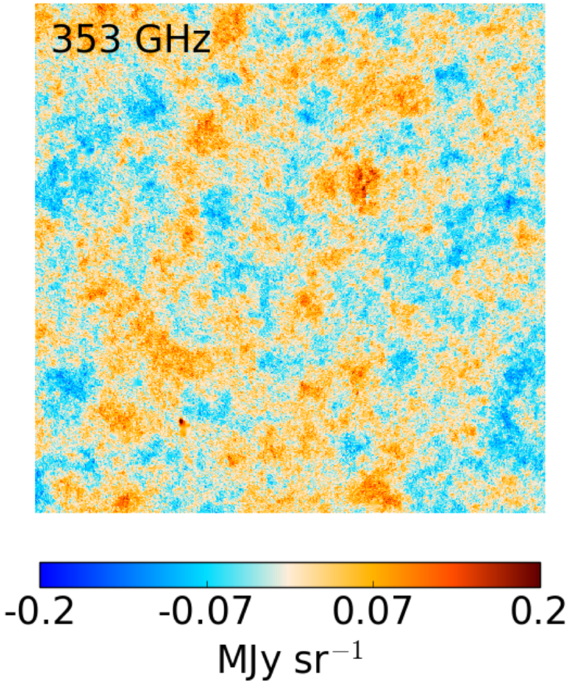
Cumulative diffuse emission from all dusty star-forming galaxies ($1 < z < 3$)
"extragalactic background radiation"



Planck early results. XVIII, A&A 2011
Planck 2013 results. XXX, A&A 2014

How Planck **2013** dust was extracted?

Planck observation map



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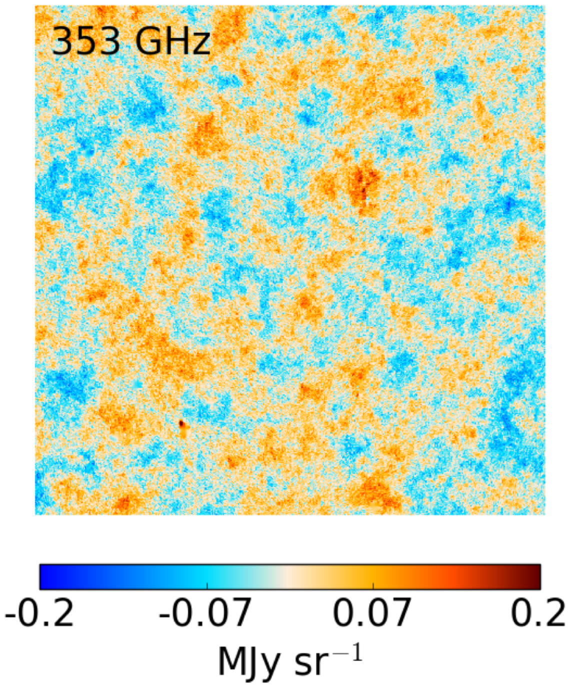
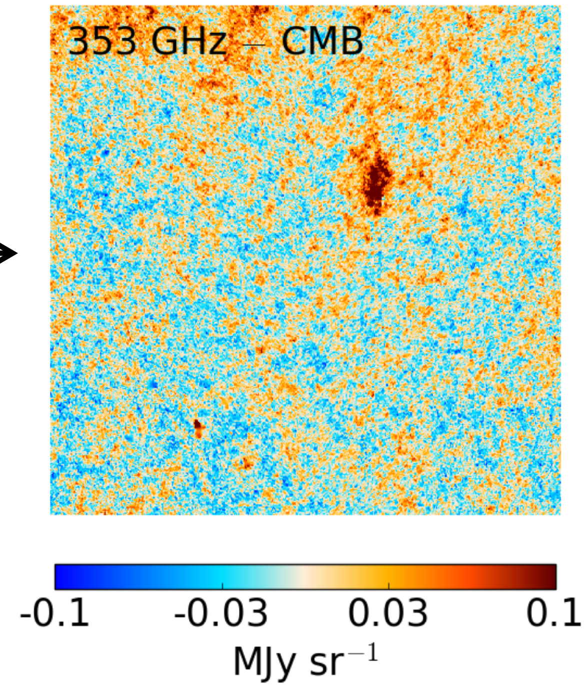


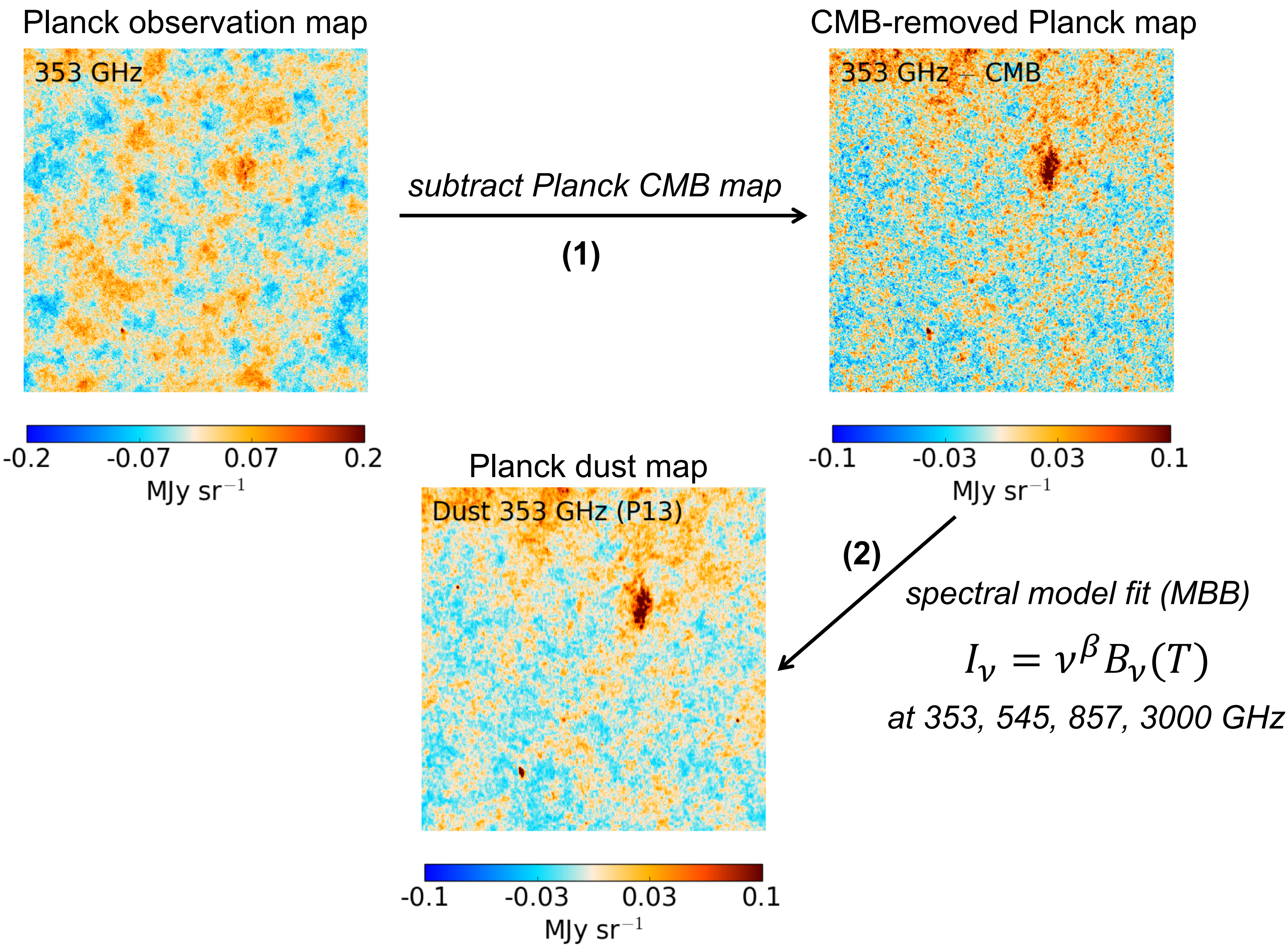
subtract Planck CMB map

(1)

CMB-removed Planck map



How Planck **2013** dust was extracted?

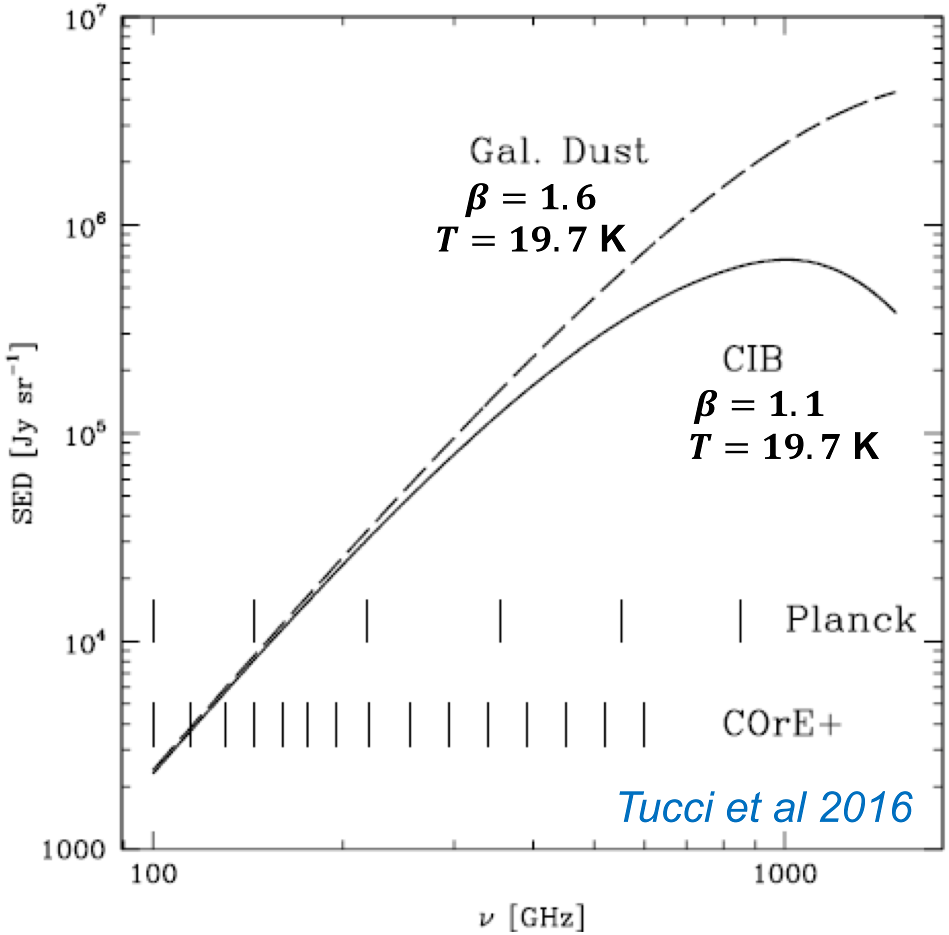


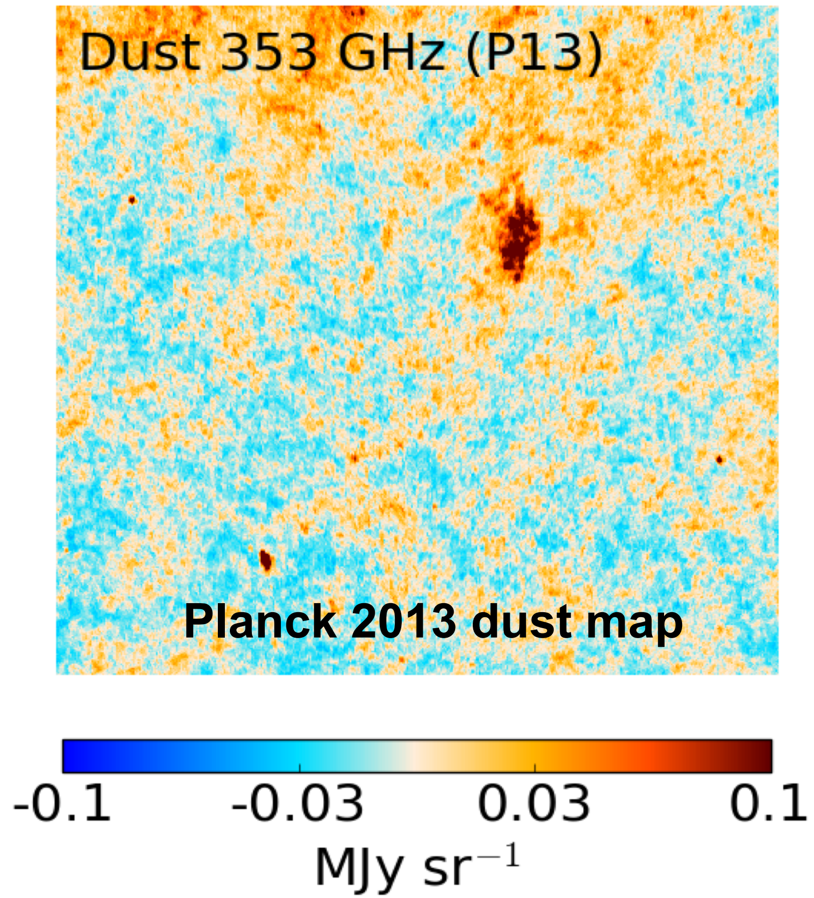
Why CIB leaks into Planck **2013** dust map?

Spectral degeneracy between Galactic dust and CIB:

$\Longrightarrow$

As a result of MBB fit, CIB leaks into Galactic dust:





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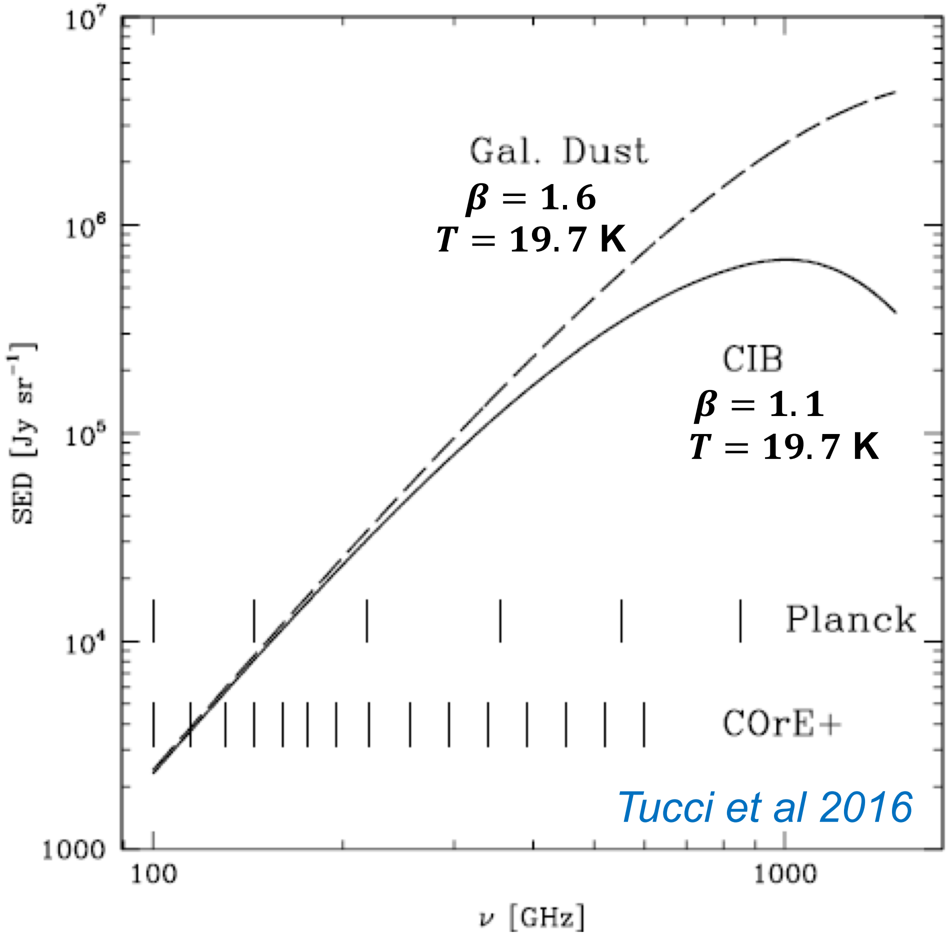
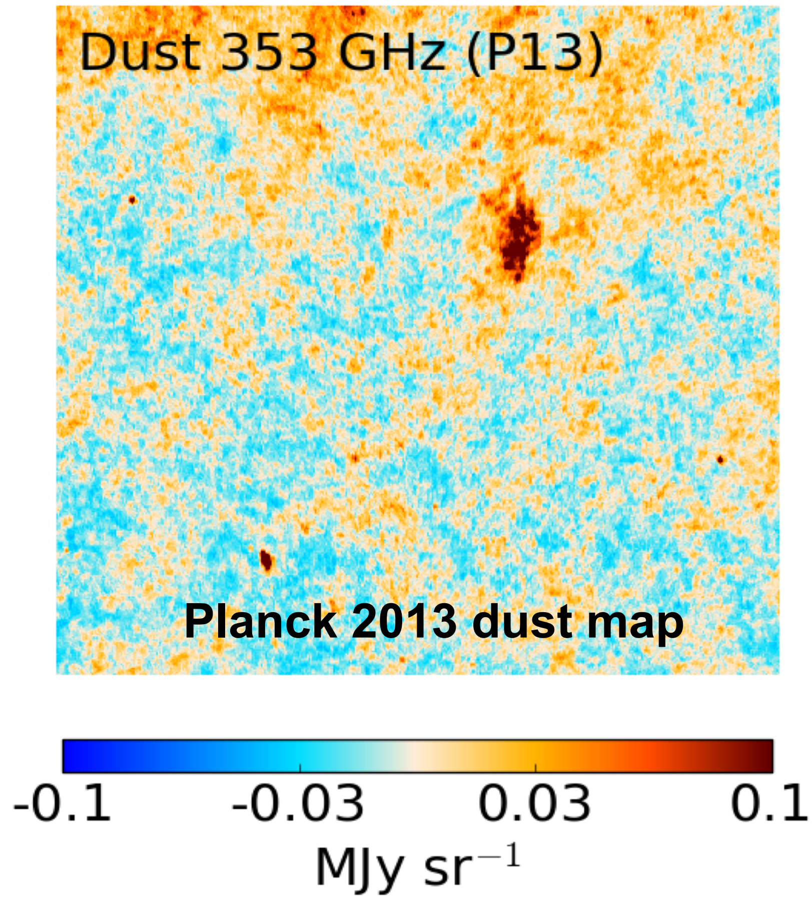




In order to disentangle Galactic dust and extragalactic CIB emissions, an extra discriminating statistical information is needed!

GNILC

Remazeilles, Delabrouille, Cardoso, MNRAS 2011

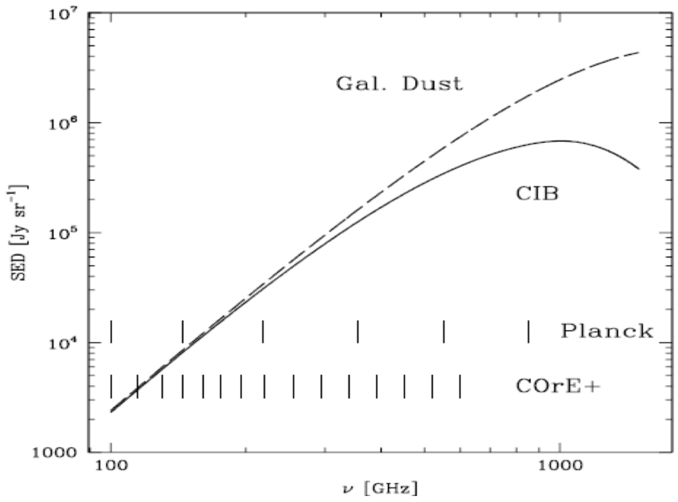
Basic idea:

Use not only **spectral information** but also **spatial information** (angular power spectrum) to discriminate between Galactic dust and CIB anisotropies

Properties:

- ✓ **Blind method:**
  - No assumption on Galactic foreground properties / astrophysics
  - Sole prior information: angular power spectra of CIB, CMB, noise
- ✓ **Wavelet-based**:
  - Adjust component separation to the local conditions of contamination both over the sky and over the scales

Spectral information



Dust and CIB suffer from spectral degeneracy

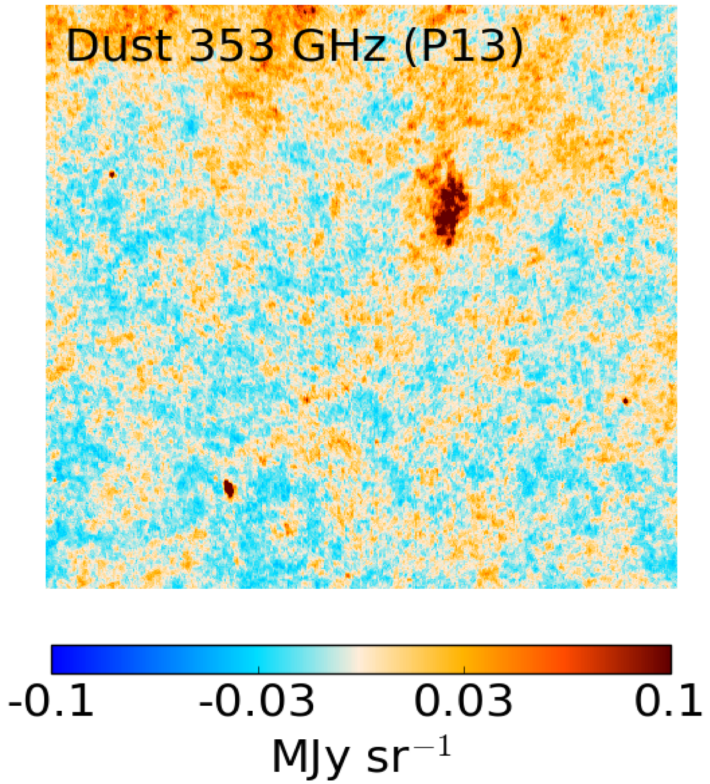
spectral fit (MBB)

CIB leakage in thermal dust map

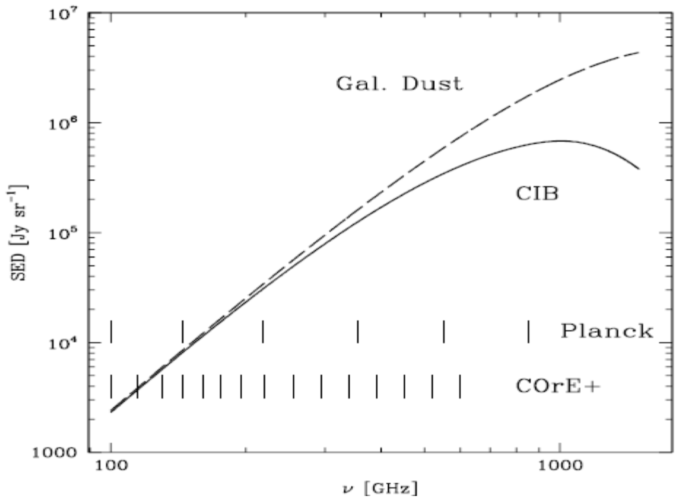
Spectral fit:

- *Planck 2013 Results. XI, A&A 2014*
- *Planck 2015 Results. X, A&A 2016*

Planck 2013 dust map is contaminated by CIB



Spectral information



Dust and CIB suffer from spectral degeneracy

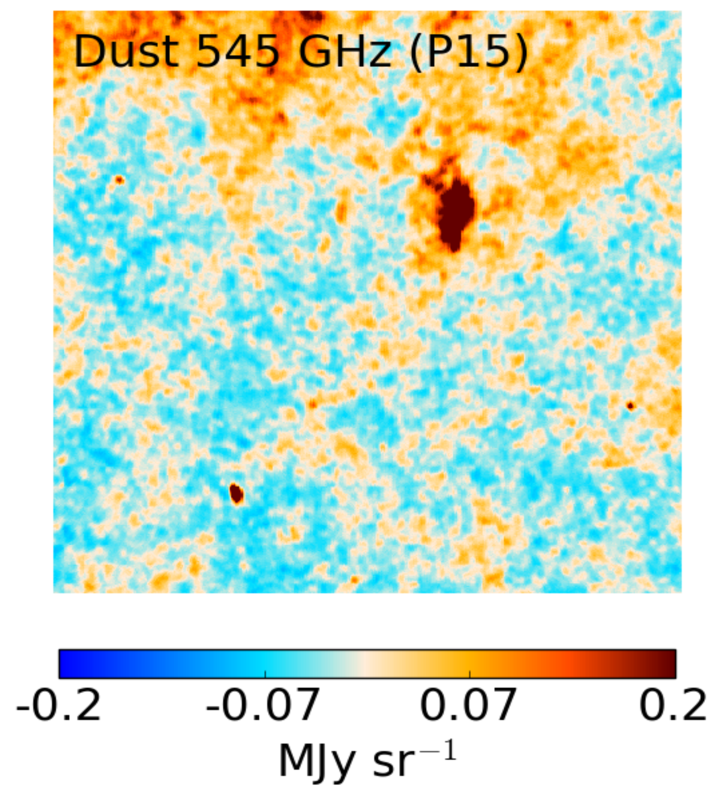
↓ spectral fit (MBB)

CIB leakage in thermal dust map

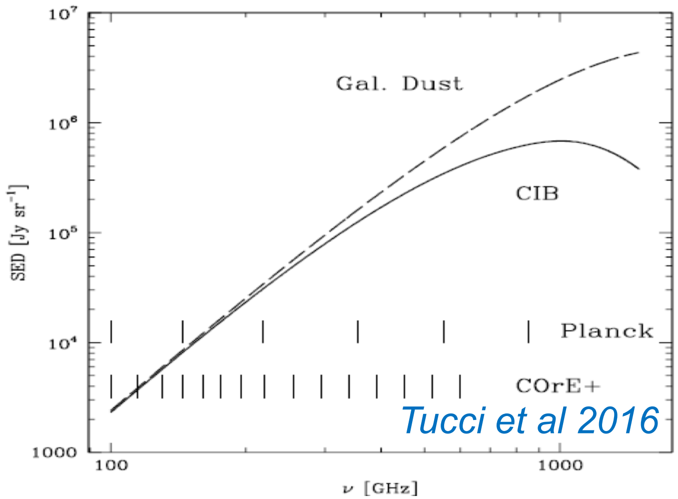
Spectral fit:

- *Planck 2013 Results. XI, A&A 2014*
- *Planck 2015 Results. X, A&A 2016*

Planck 2015 Commander dust map is <u>also</u> contaminated by CIB



Spectral information



Dust and CIB suffer from spectral degeneracy

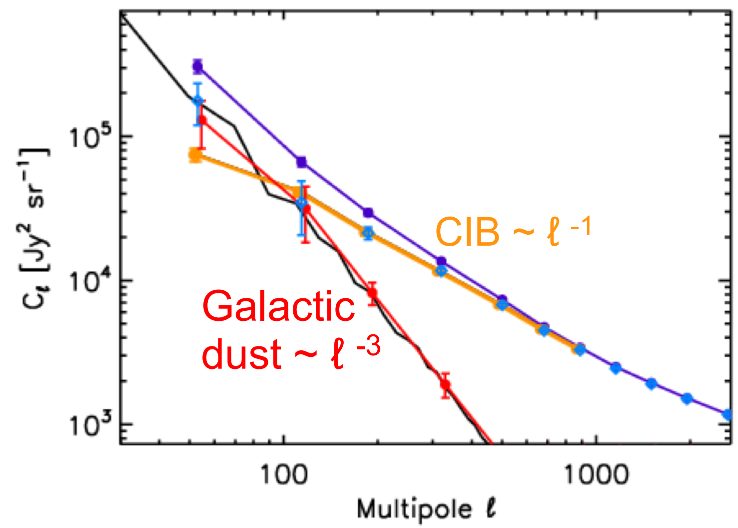
↓ spectral fit (MBB)

CIB leakage in thermal dust map

Spectral fit:

- *Planck 2013 Results. XI, A&A 2014*
- *Planck 2015 Results. X, A&A 2016*

Spatial information



Dust and CIB have distinct angular power spectra

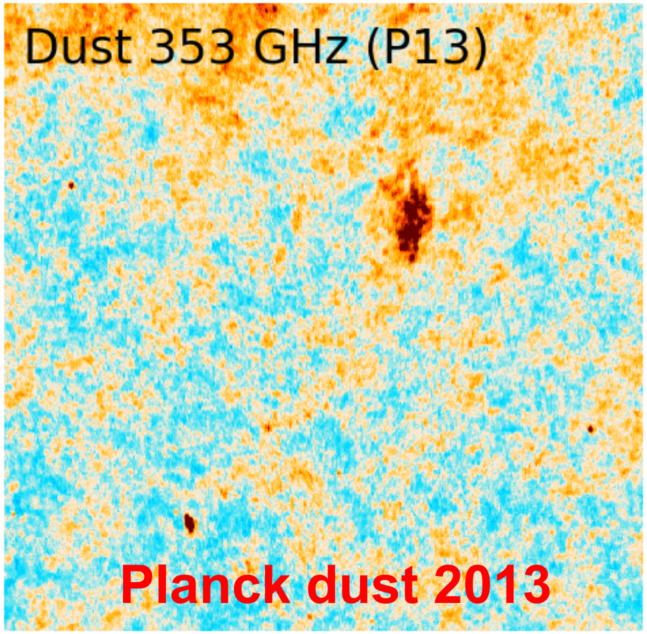
↓ GNILC

disentangle thermal dust and CIB

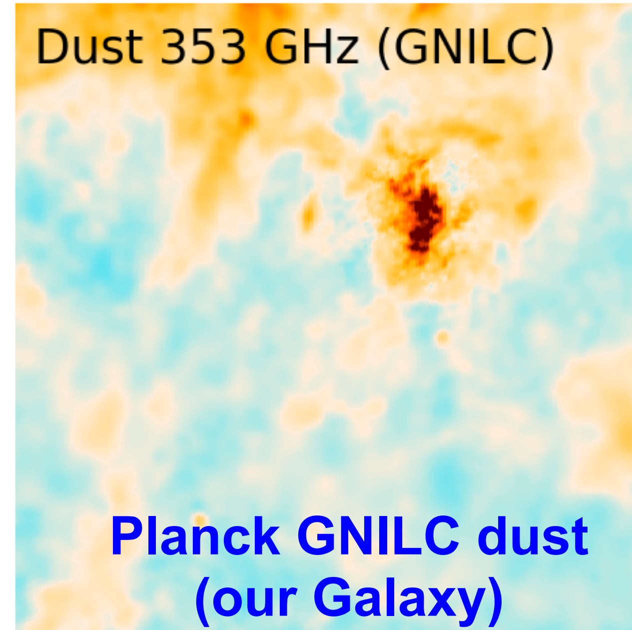
GNILC:

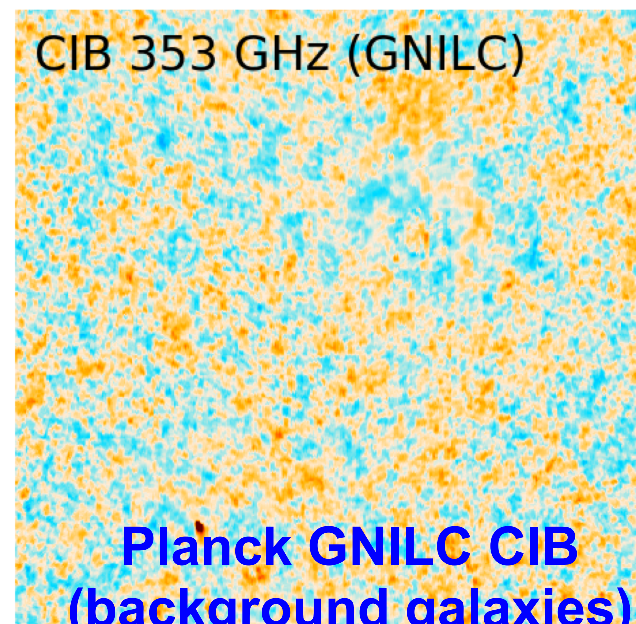
- *Remazeilles et al MNRAS 2011*
- *Planck intermediate results. XLVIII, A&A 2016*
- *Planck 2018 results. IV, arXiv:1807.06208*
- *Planck 2018 results. XII, arXiv:1807.06212*

Separate Galactic dust and CIB in Planck data



GNILC



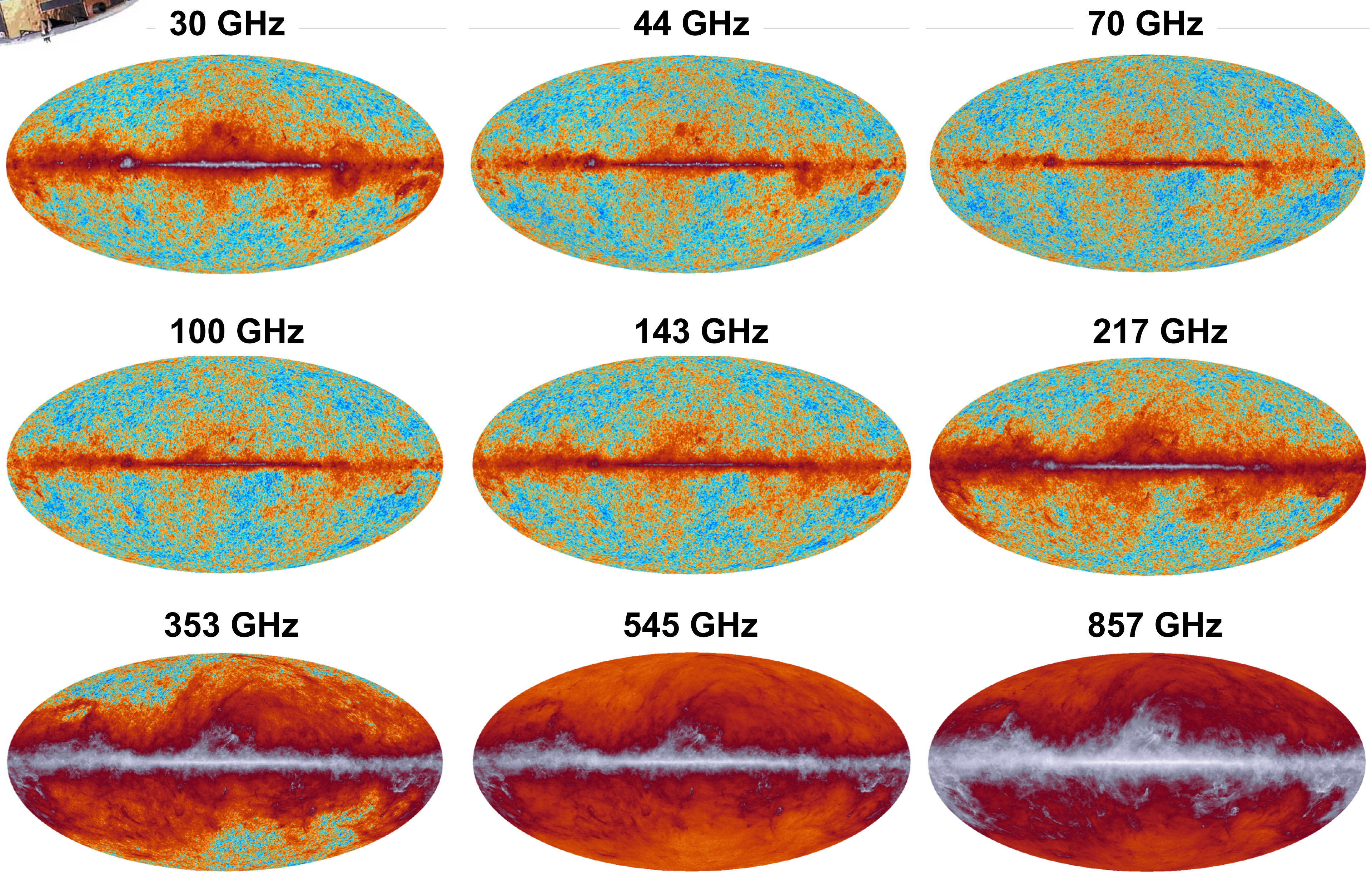


Planck intermediate results. XLVIII, A&A 2016

Remazeilles, Delabrouille, Cardoso, MNRAS 2011

GNILC method in 5 steps

Planck sky observations



Complex mixture of various emission processes!

Component separation

Planck frequency maps

$$d_\nu(p) = x_\nu^{dust}(p) + \overbrace{x_\nu^{CIB}(p) + x^{CMB}(p) + x_\nu^{noise}(p)}^{\text{“nuisance”}}$$

signal of interest

ν: frequency

p: pixel (position in the sky)

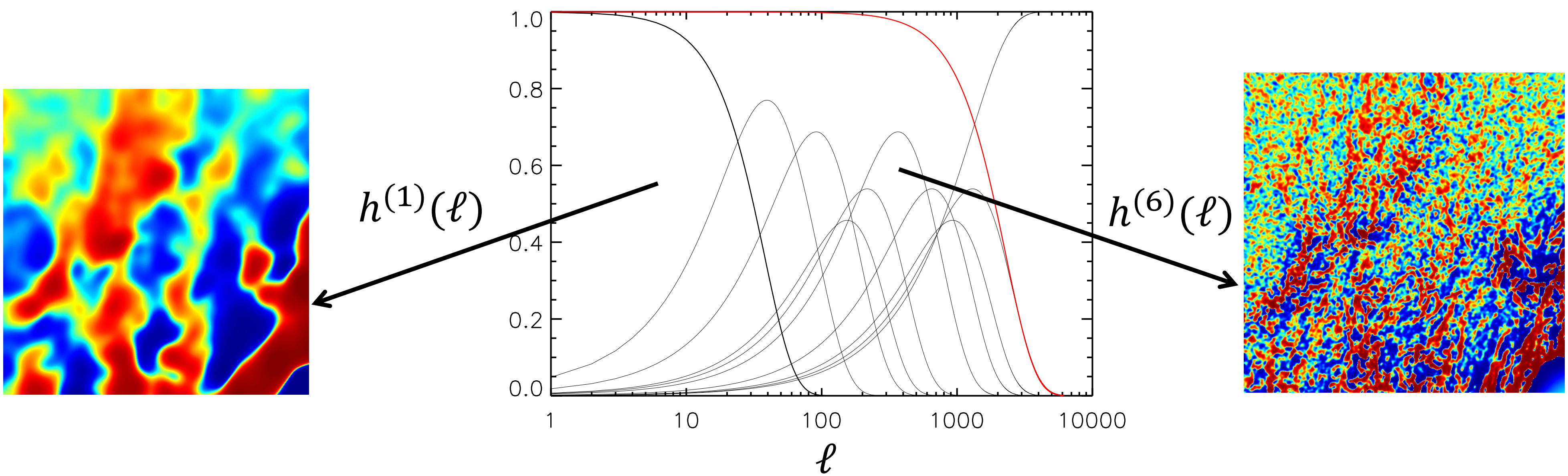
GNILC

Remazeilles et al MNRAS 2011

1. Needlet (spherical wavelet) decomposition of the Planck sky maps

$$d_\nu(p) \xrightarrow{SHT} d_\nu(\ell, m) \xrightarrow{\times h^{(j)}(\ell)} d_\nu(\ell, m) \times h^{(j)}(\ell) \xrightarrow{SHT^{-1}} d_\nu^{(j)}(p)$$

"bandpass filtering in harmonic space through needlet windows"



The data analysis is thus local both over the sky and over the scales

GNILC

Remazeilles et al MNRAS 2011

2. For each needlet scale (j), compute the data covariance matrix in each pixel p of a pair of frequencies a, b

$$R_{ab}^{(j)}(p) = \sum_{p' \in \mathfrak{D}(p)} d_a^{(j)}(p')\, d_b^{(j)}(p')$$

At each pixel p *and each scale* (j), $R^{(j)}(p)$ *is a* 9×9 *matrix*

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Remazeilles et al MNRAS 2011

3. Use priors on CIB + CMB + noise power spectra to model the covariance matrix of the "nuisance" contribution

- Use *Planck* best-fit $\boldsymbol{C_\ell^{CMB}}$, $\boldsymbol{C_\ell^{CIB}}(\boldsymbol{\nu_1}, \boldsymbol{\nu_2})$, $\boldsymbol{C_\ell^{noise}}(\boldsymbol{\nu})$ to simulate Gaussian realisations of the "nuisance" emission:

$$n_\nu(p) \equiv \hat{x}^{CMB}(p) + \hat{x}_\nu^{CIB}(p) + \hat{x}_\nu^{noise}(\mathrm{p})$$

- Perform needlet decomposition of the "nuisance" maps: $n_\nu(\mathrm{p}) \rightarrow n_\nu^{(j)}(\mathrm{p})$

- For each needlet scale (j), compute the *prior* covariance matrix of the "nuisance":

$$N_{ab}^{(j)}(p) = \sum_{p\prime \in \mathfrak{D}(p)} n_a^{(j)}(p')\, n_b^{(j)}(p')$$

GNILC

Remazeilles et al MNRAS 2011

4. Perform a PCA of the "whitened" data covariance matrix:

$$N^{-1/2} R N^{-1/2} = U D U^t$$

$$N^{-1/2} R N^{-1/2} \simeq (U_s | U_N) \left(\begin{array}{ccc|ccc} 1+\mu_1 & & & & & \\ & \ddots & & & & \\ & & 1+\mu_m & & & \\ \hline & & & 1 & & \\ & & & & \ddots & \\ & & & & & 1 \end{array} \right) \left(\frac{U_S^t}{U_N^t} \right)$$

GNILC

Remazeilles et al MNRAS 2011

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Those eigenvalues do not contain any power from Galactic dust. The signal is consistent with CIB, CMB, noise.

GNILC

Remazeilles et al MNRAS 2011

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Those eigenvectors form a basis of <u>independent</u> ”nuisance” modes

Those eigenvalues do not contain any power from Galactic dust. The signal is consistent with **CIB, CMB, noise.**

GNILC

Remazeilles et al MNRAS 2011

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Those eigenvalues contain power from **Galactic dust.**

GNILC

Remazeilles et al MNRAS 2011

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Those eigenvectors form an orthogonal basis of <u>independent</u> dust modes: "Galactic dust subspace"

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GNILC

Remazeilles et al MNRAS 2011

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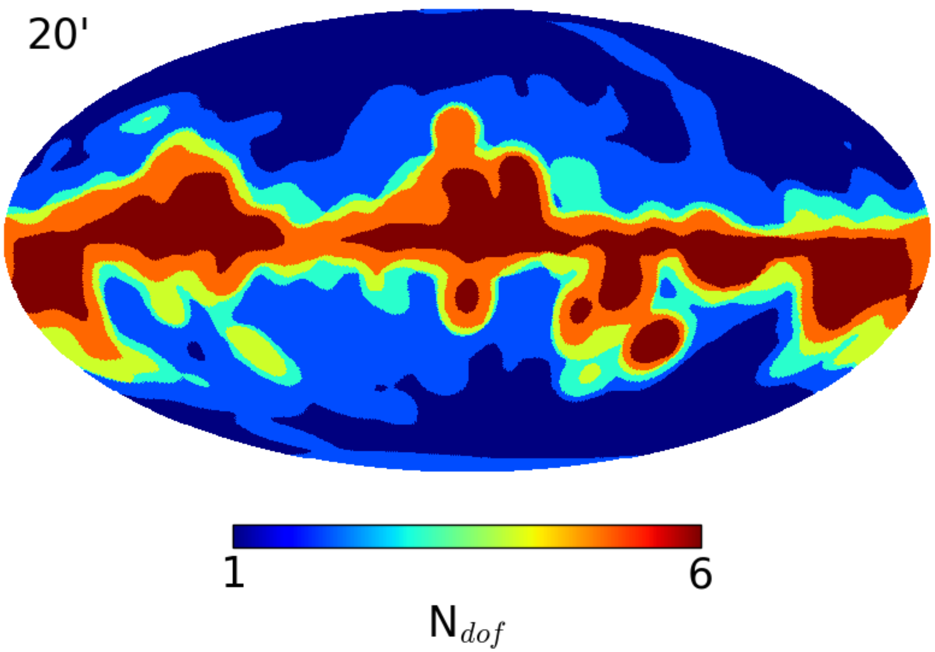
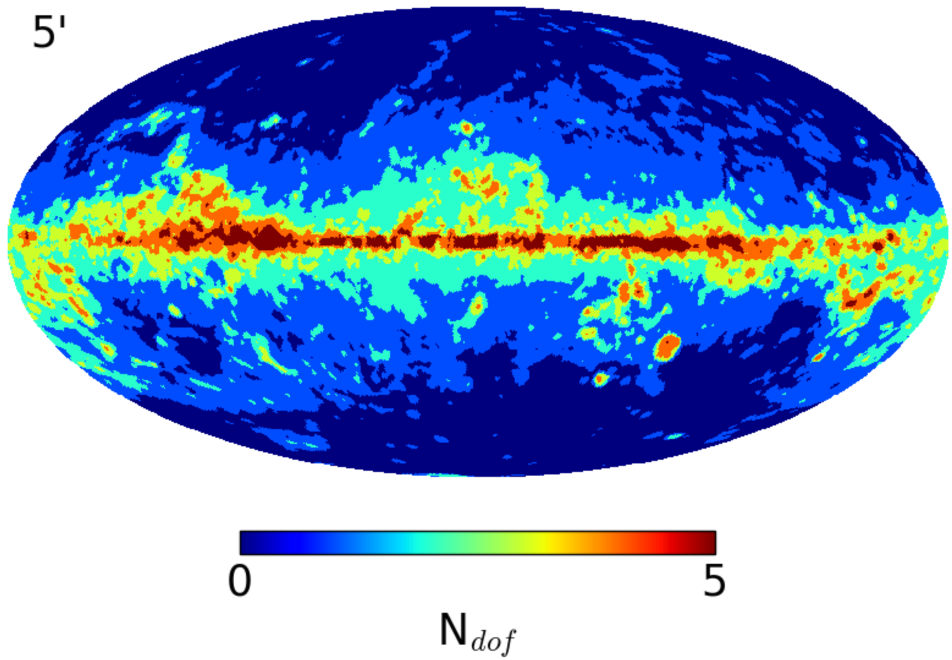
Those eigenvalues contain power from **Galactic dust.**

As a correlated component of emission, Galactic dust can thus be decomposed on a subset of m <u>independent</u> (not physical) templates

Dimension of the dust foregrounds

- In the same spirit of the "moment expansion" (*Chluba et al 2017*), **GNILC** gives you the **number of <u>independent</u>** (not physical) **dust degrees of freedom:**





- *The number of independent modes is not determined "ad-hoc" from the PCA, but through statistical model selection with the Akaike Information Criterion (AIC)*
- *The AIC penalty prevents from overfitting the dimension of the "Galactic dust subspace"*

GNILC

Remazeilles et al MNRAS 2011

5. Perform a m-dimensional ILC in the "Galactic dust subspace"

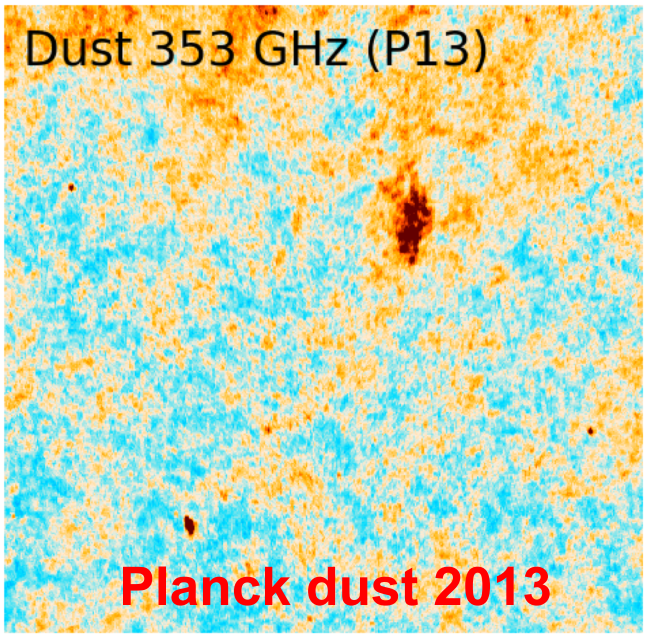
(data compression)

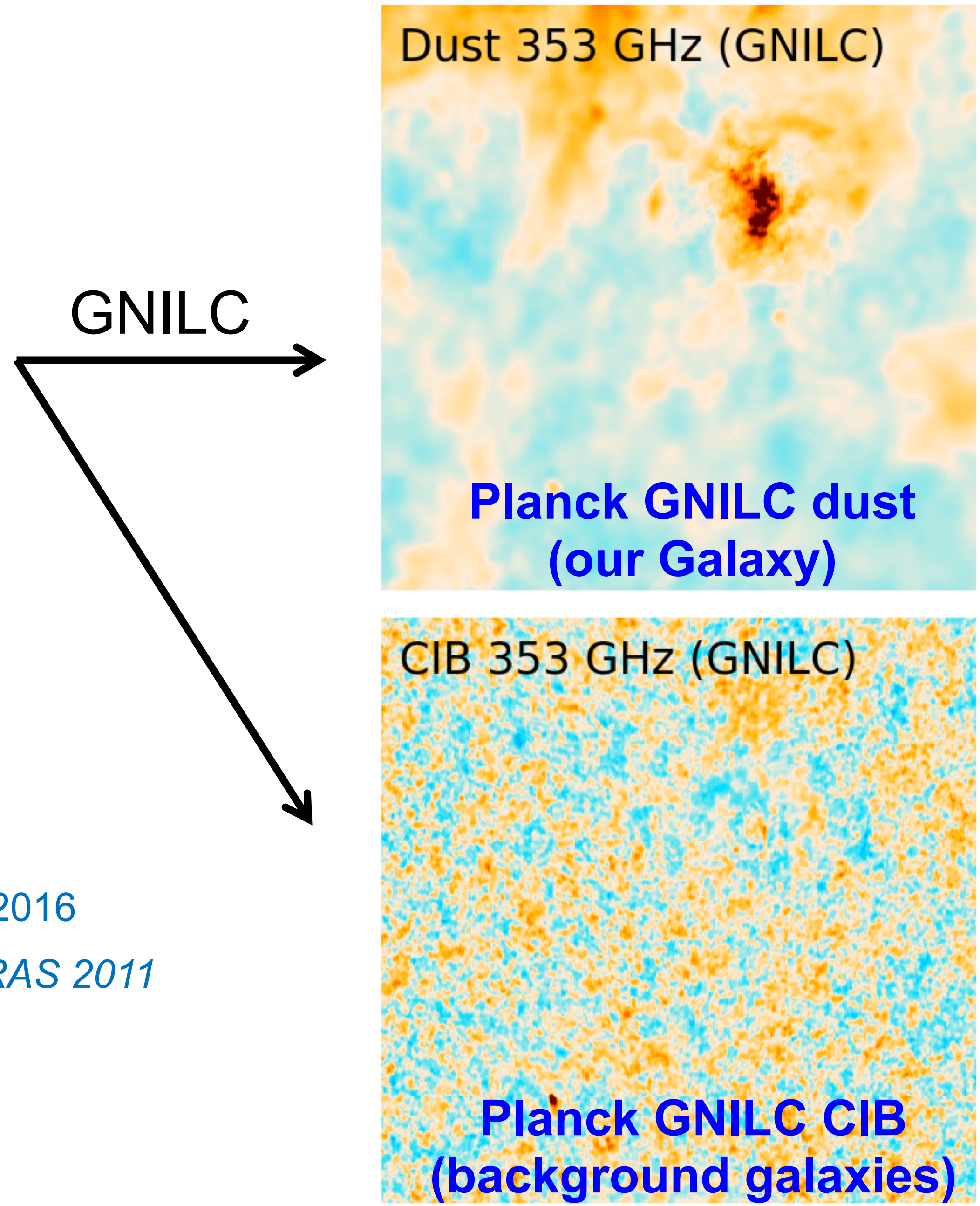
$$\hat{\boldsymbol{s}}_{\boldsymbol{\nu}}{}^{\boldsymbol{dust}}(\boldsymbol{p}) = \sum_{\boldsymbol{\nu}'} \boldsymbol{W}(\boldsymbol{\nu}, \boldsymbol{\nu}')\, \boldsymbol{d}_{\boldsymbol{\nu}'}(\boldsymbol{p})$$

where $\boldsymbol{W} = \boldsymbol{F}(\boldsymbol{F}^{t}\boldsymbol{R}^{-1}\boldsymbol{F})^{-1}\boldsymbol{F}^{t}\boldsymbol{R}^{-1}$ and $\boldsymbol{F} \equiv \boldsymbol{N}^{1/2}\ \boldsymbol{U}_{\boldsymbol{s}}$

CIB-free, CMB-free, noise-free estimate of the Galactic dust !

Separate Galactic dust and CIB in Planck data

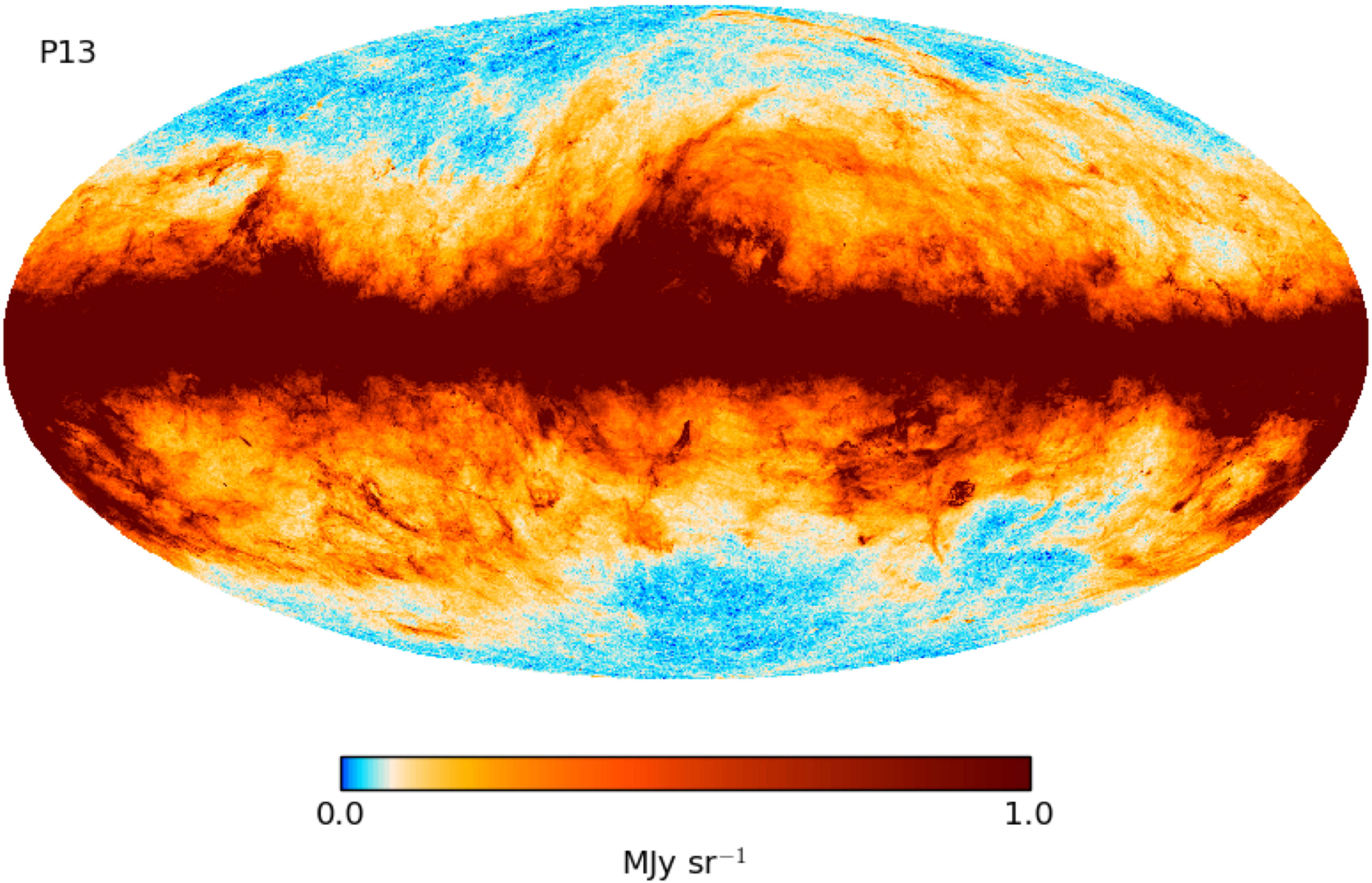




Planck intermediate results. XLVIII, A&A 2016

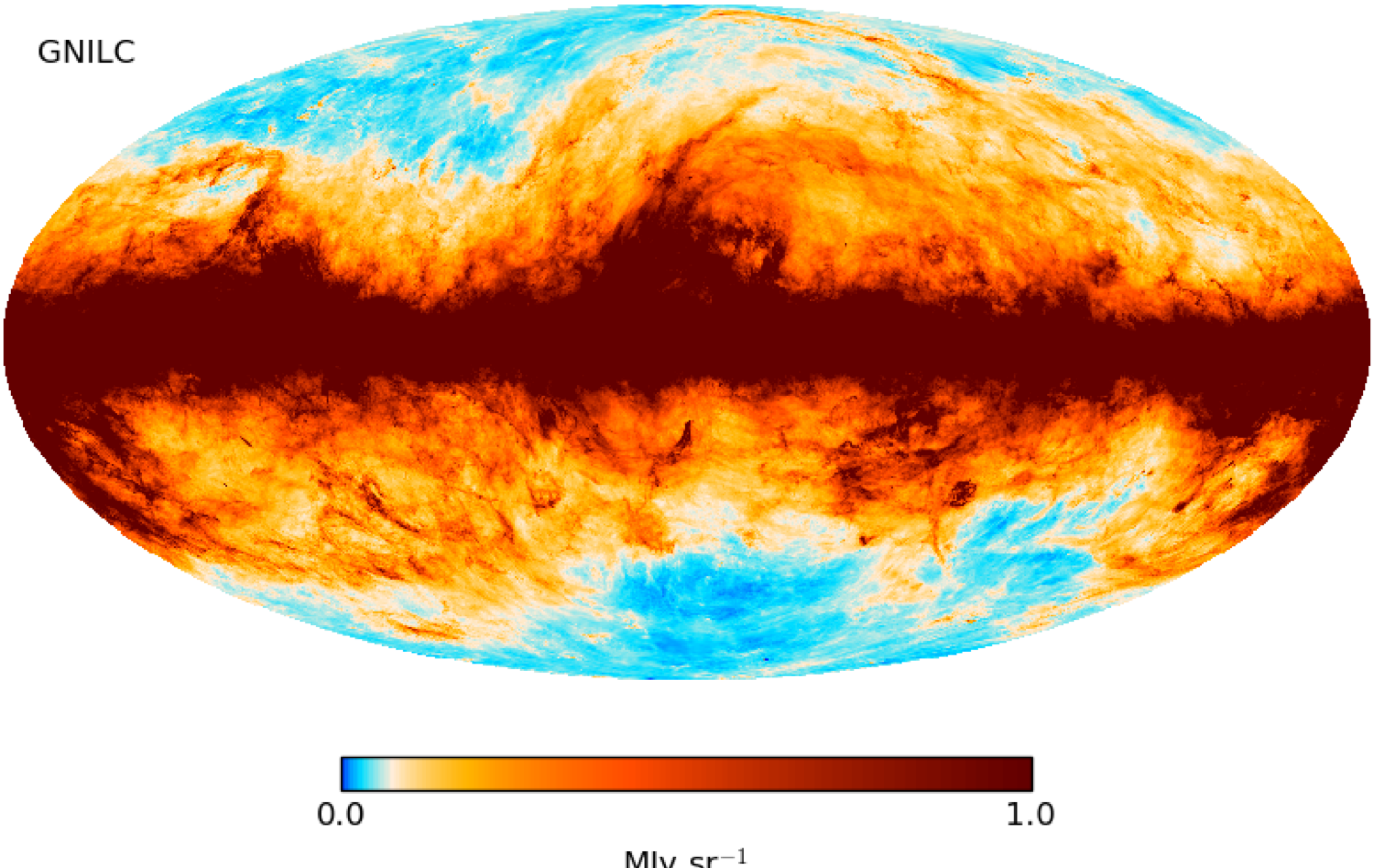
Remazeilles, Delabrouille, Cardoso, MNRAS 2011

Planck **2013** dust map



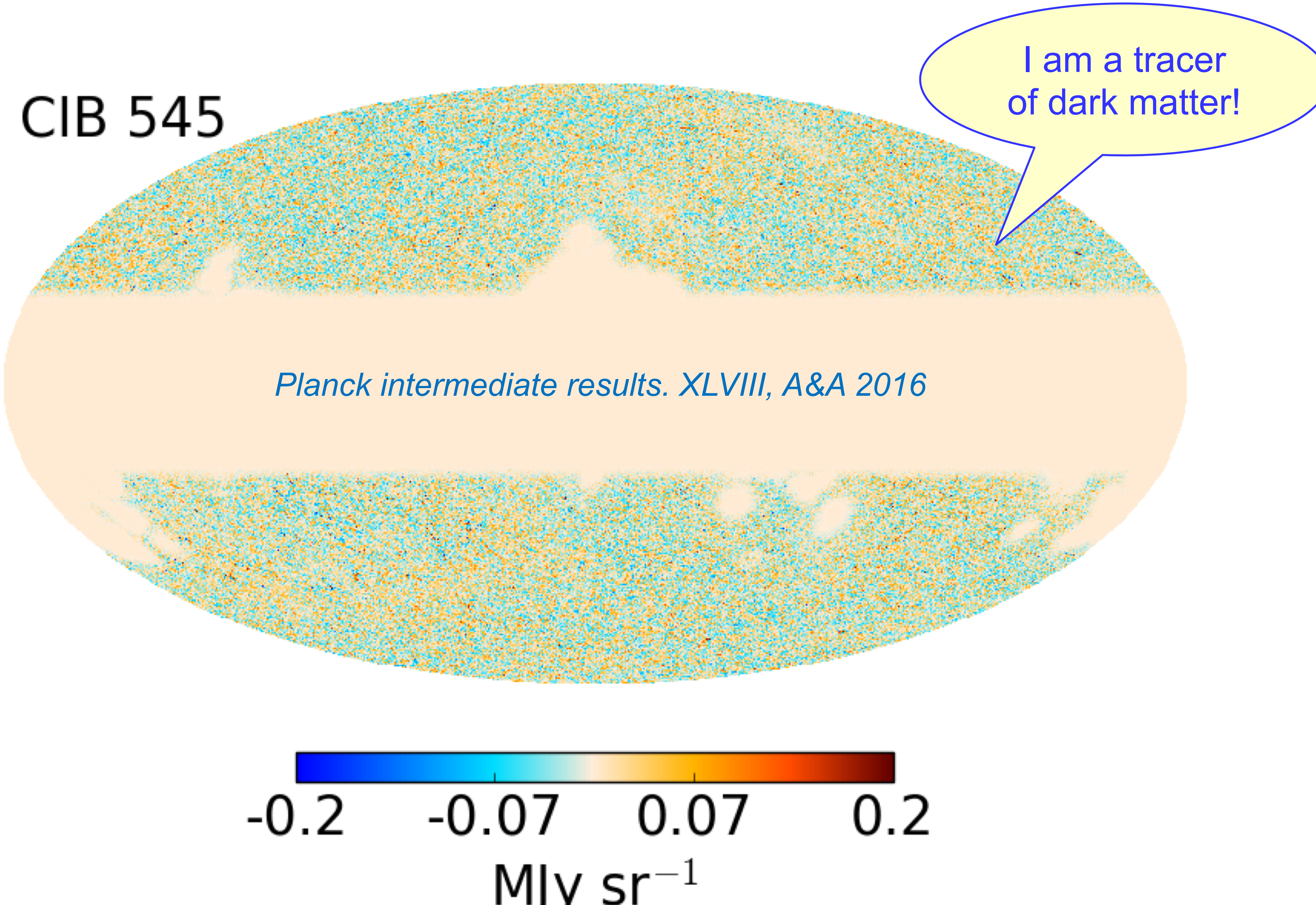
Planck 2013 results. XI, A&A 2014

Planck **GNILC** dust map



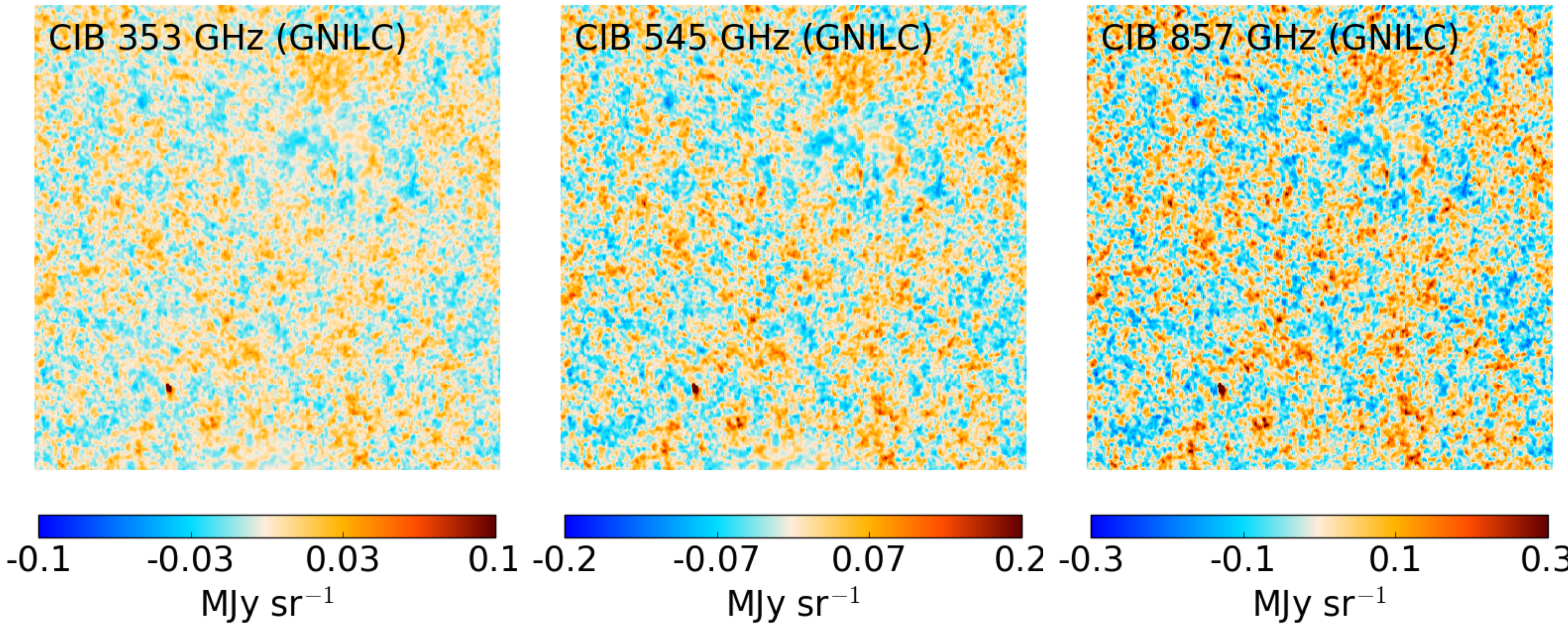
Planck intermediate results. XLVIII, A&A 2016

Planck **GNILC** CIB maps



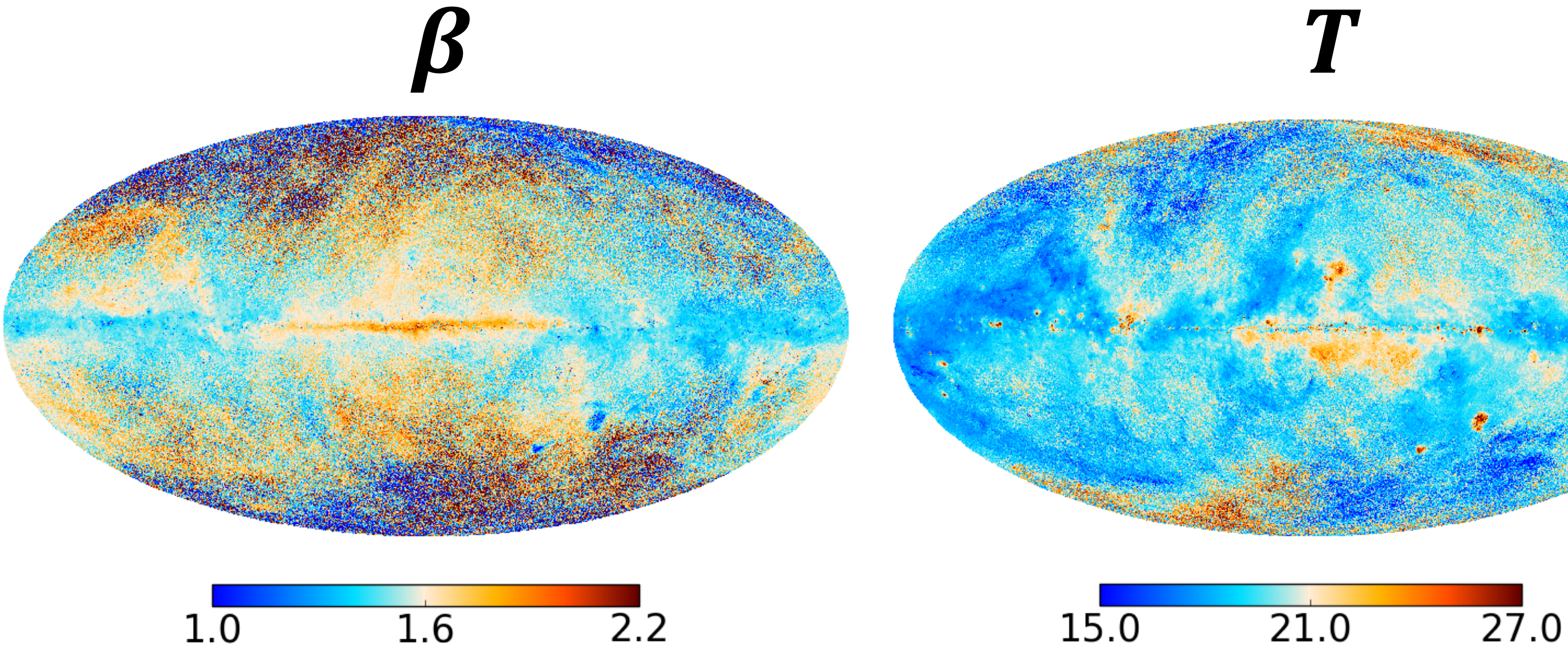
Best template to-date for "delensing", see e.g. Yu, Hill, Sherwin PRD 2017

Planck **GNILC** CIB maps



Planck intermediate results. XLVIII. "Disentangling Galactic dust emission and cosmic infrared background anisotropies", A&A 2016

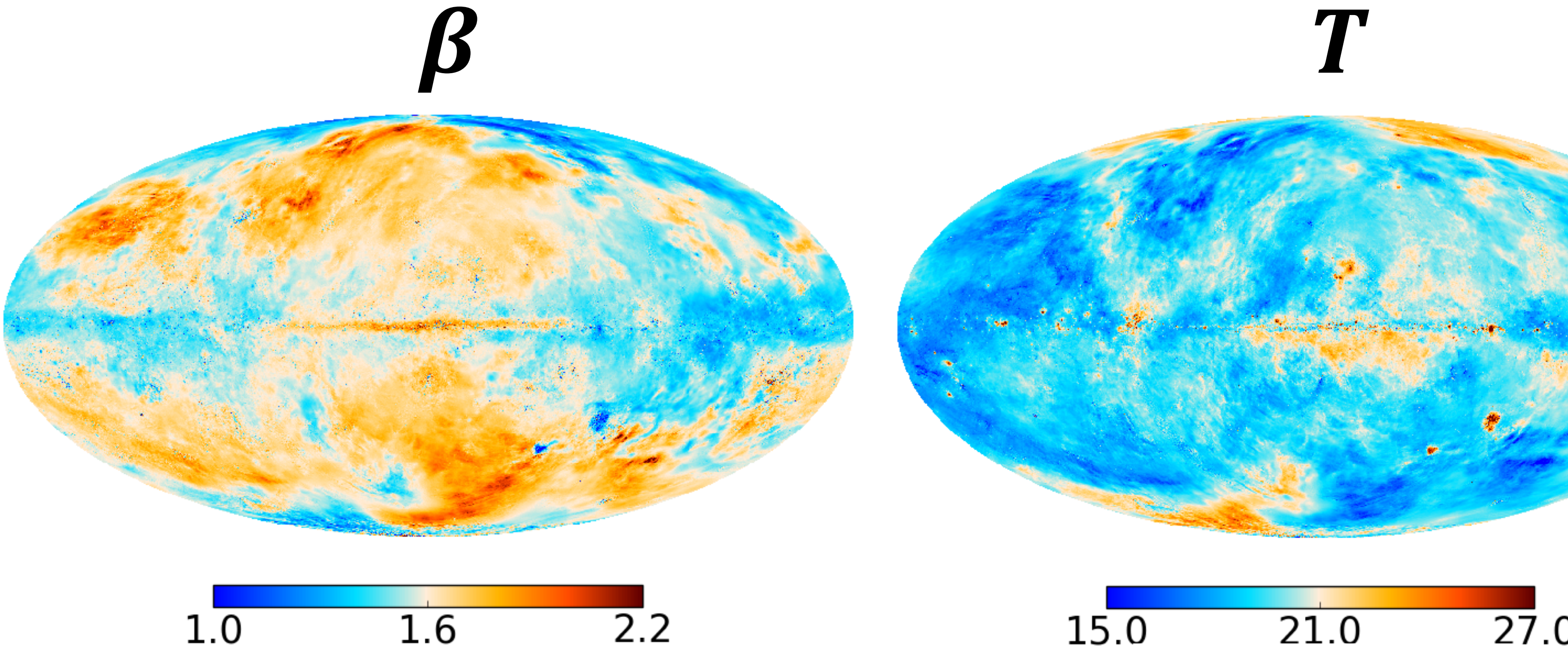
Dust spectral parameters: Planck **2013**



Dispersion at high latitudes due to CIB contamination!

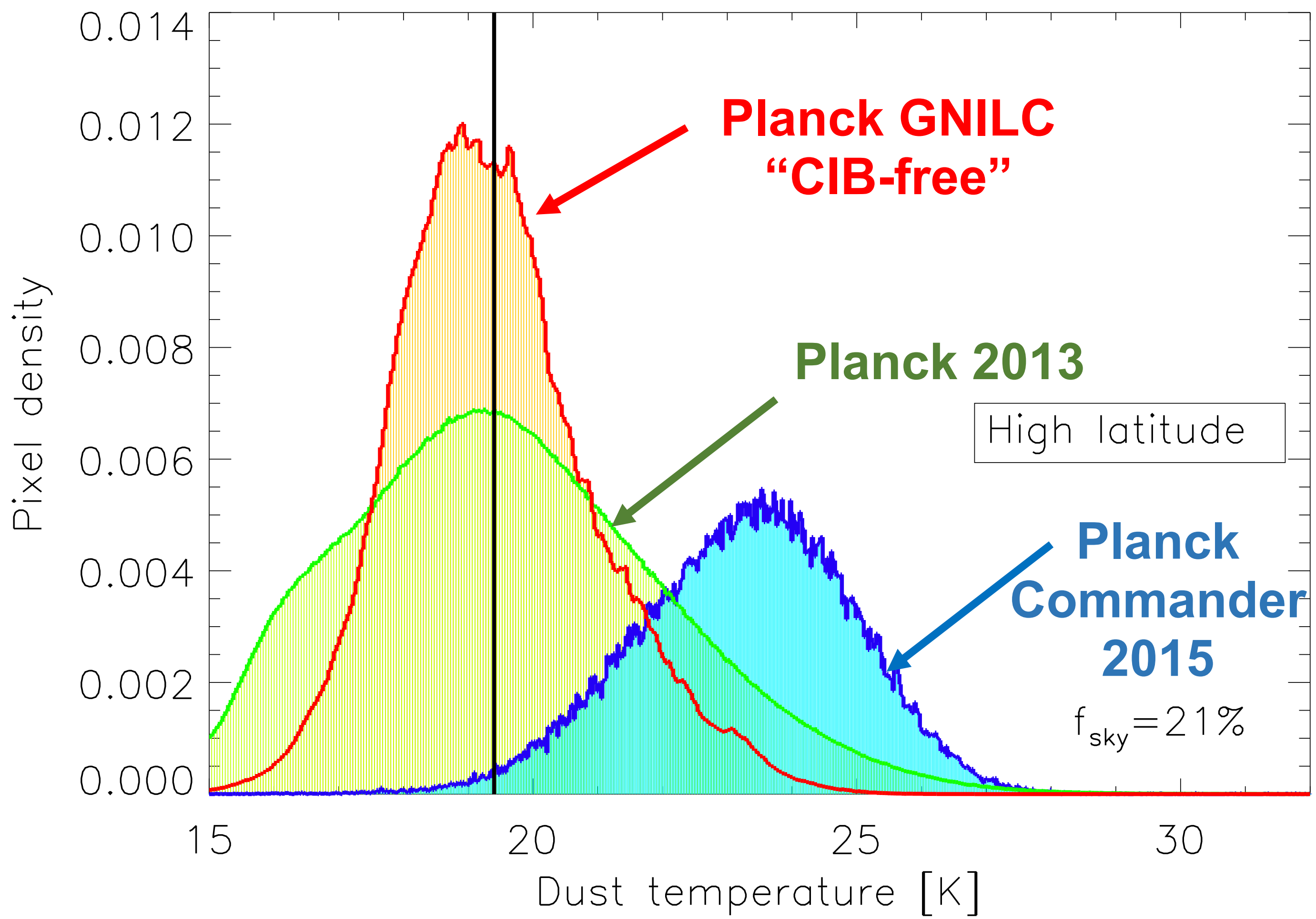
Planck 2013 results. XI, A&A 2014

Dust spectral parameters: Planck **GNILC**



Planck intermediate results. XLVIII, A&A 2016

Dust temperature



Planck intermediate results. XLVIII.
"Disentangling Galactic dust emission and cosmic infrared background anisotropies"
A&A 2016

Overview of GNILC

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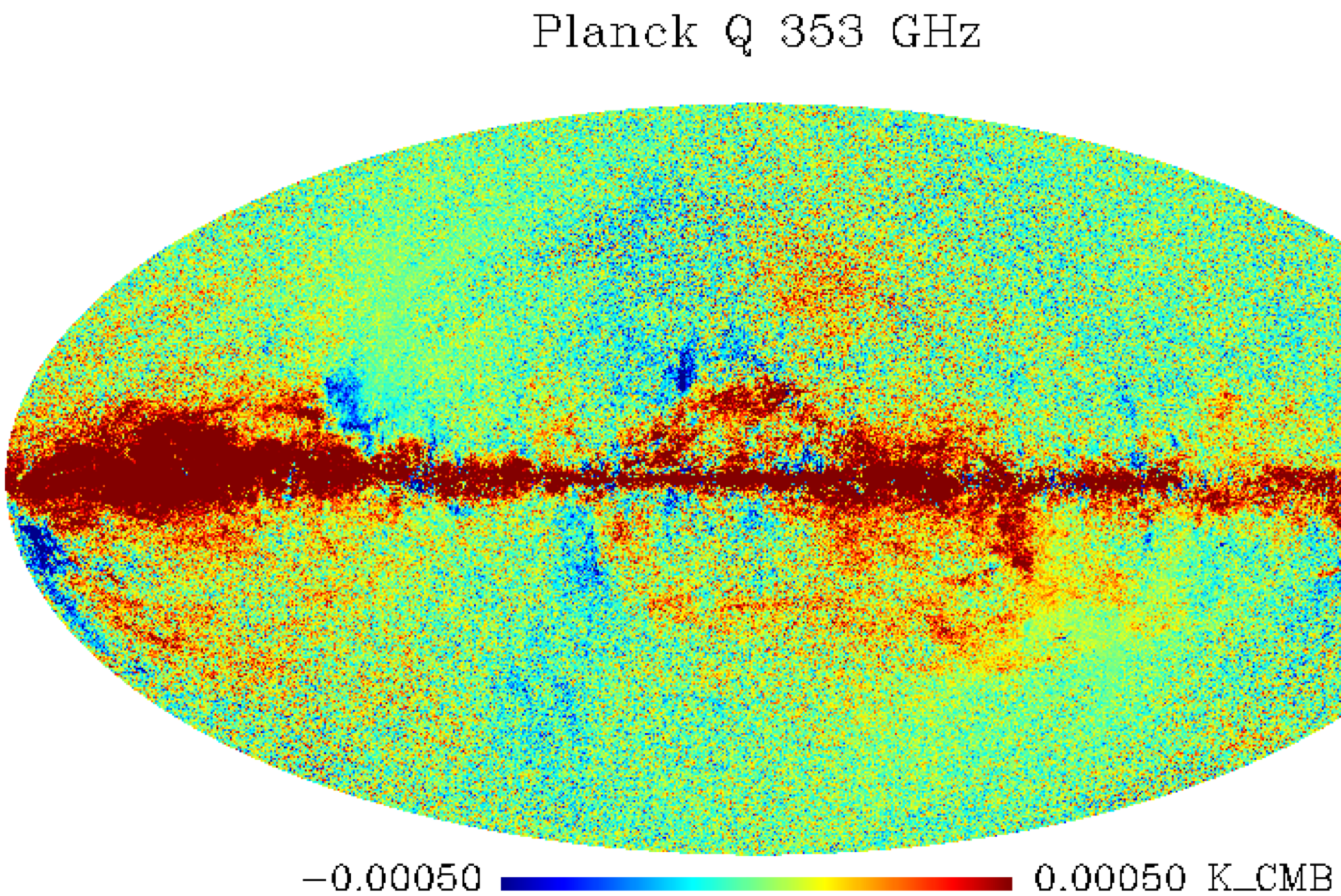
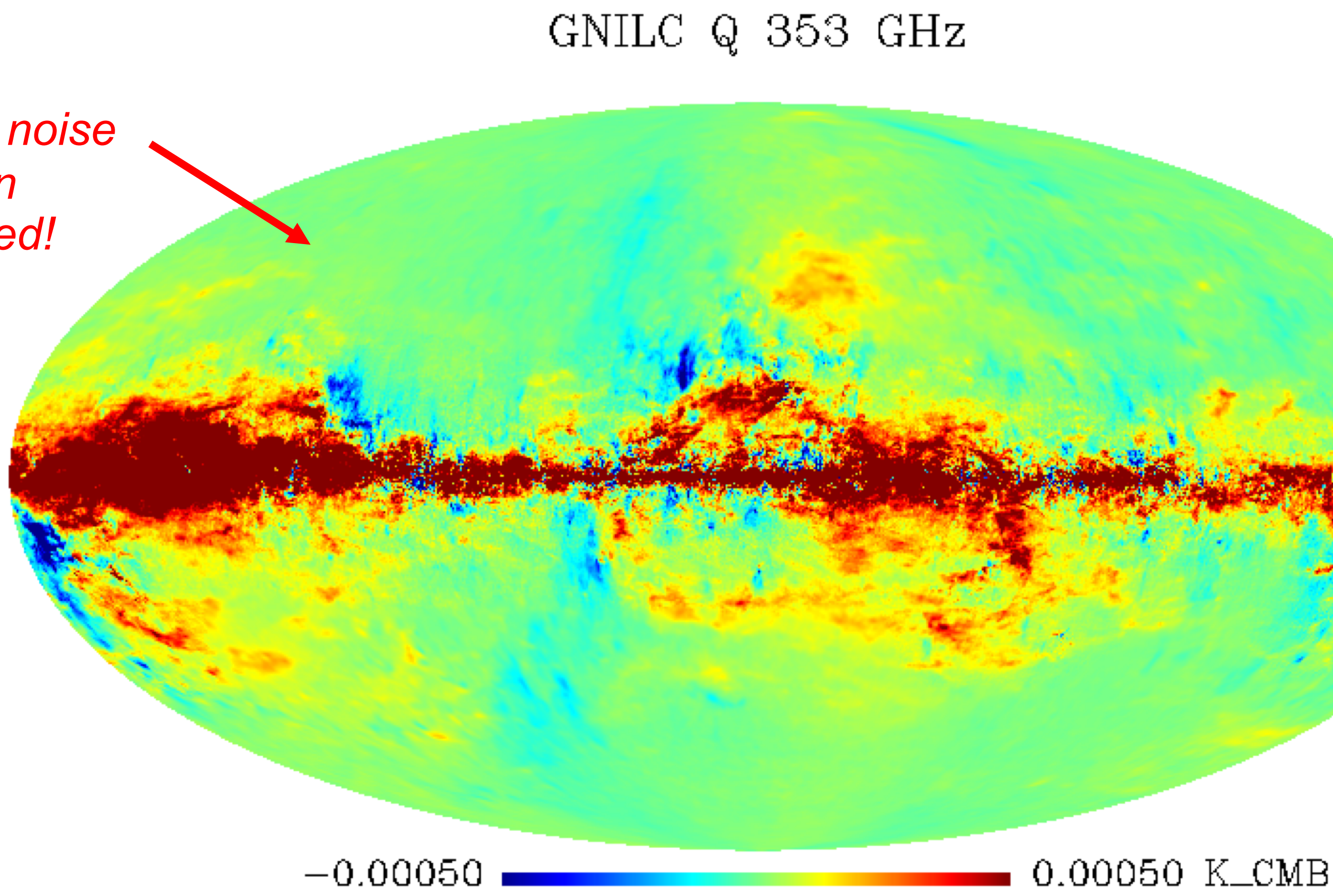
Planck Q map at 353 GHz



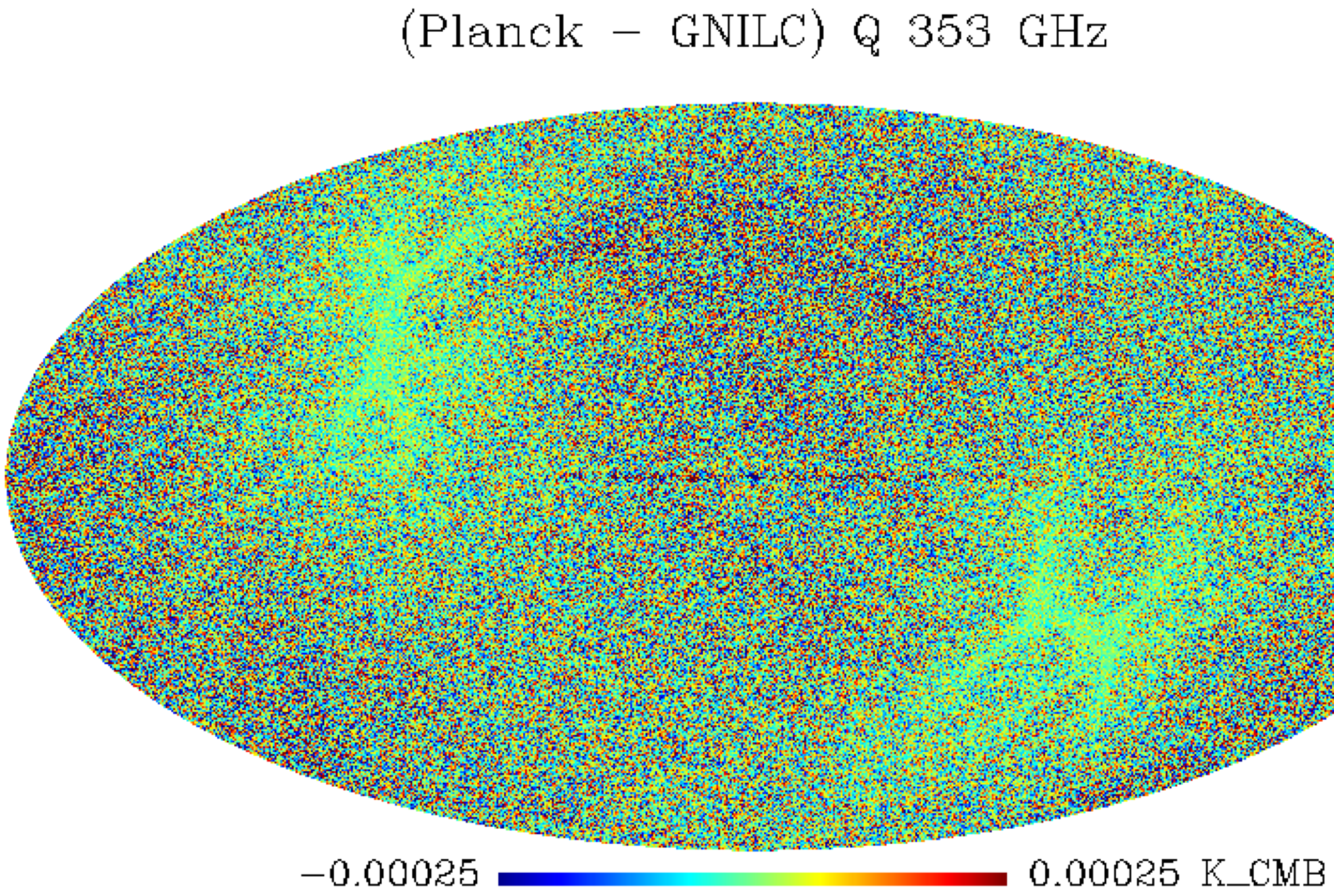
Planck **GNILC** Q map at 353 GHz

CMB and noise have been deprojected!



Planck 2018 results. XII, arXiv:1807.06212
Planck 2018 results. IV, arXiv:1807.06208

Difference (Planck - GNILC)



Planck 2018 GNILC dust polarization map

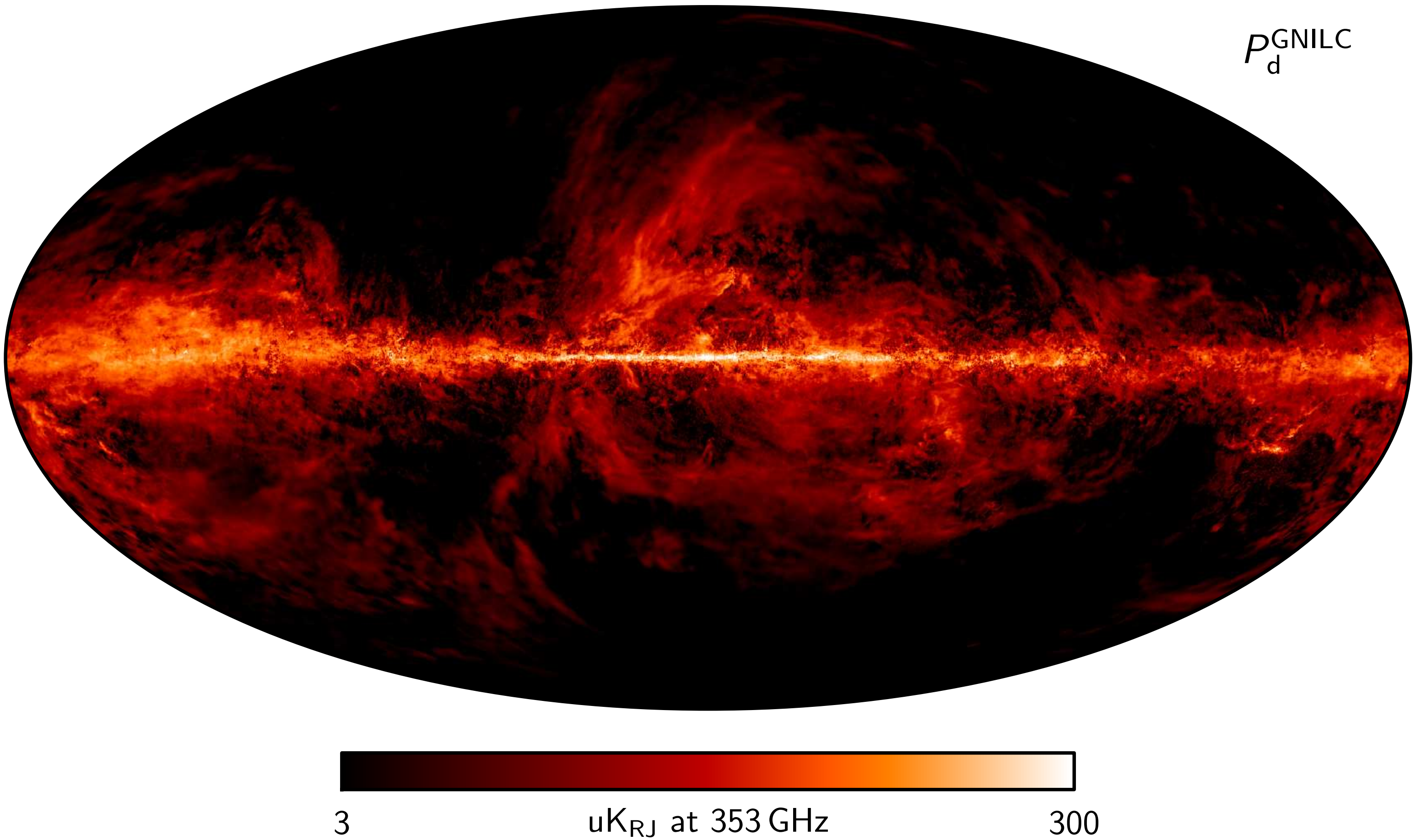
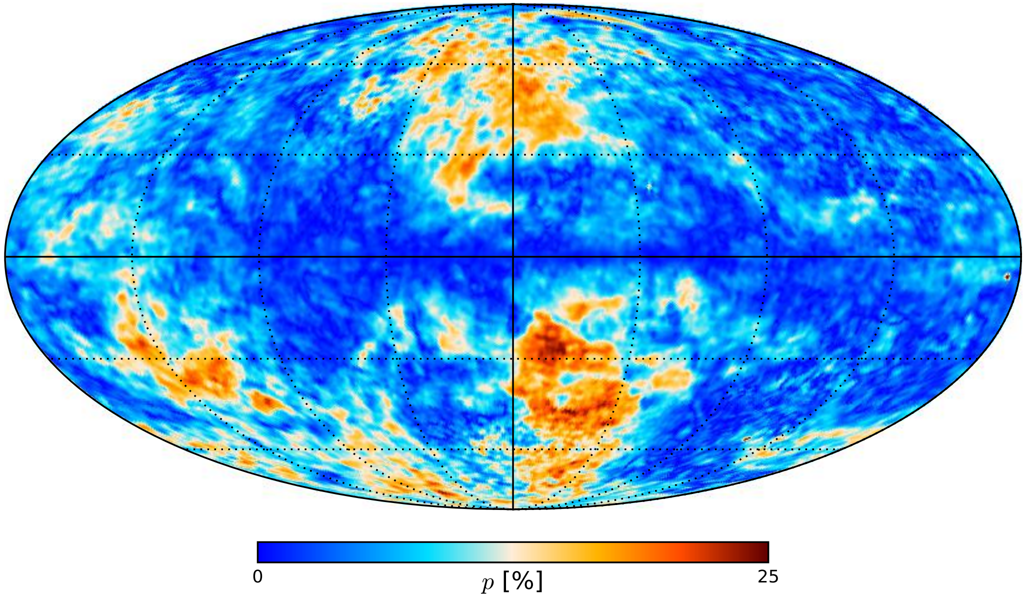
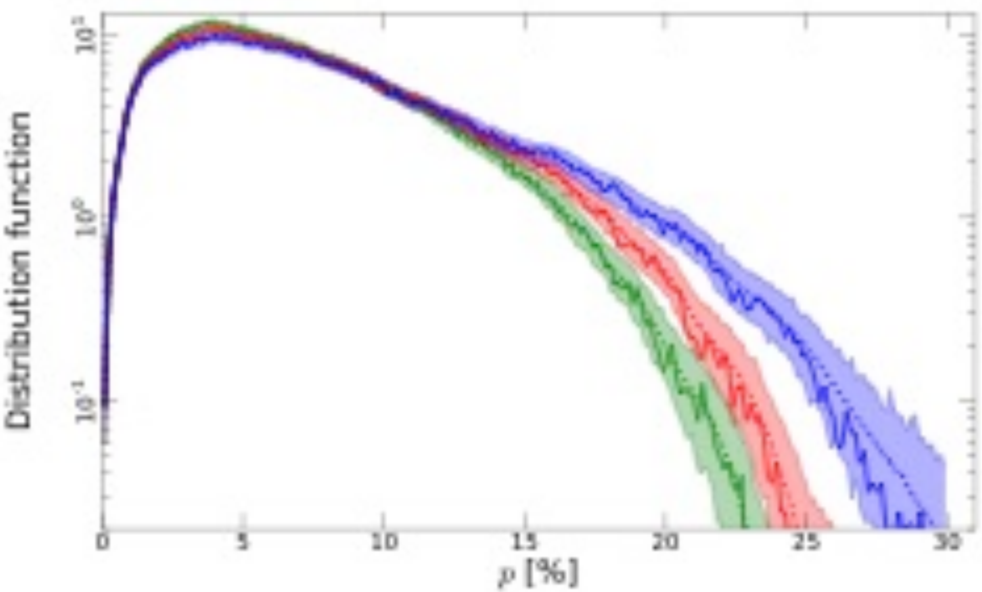


Fig. 26. GNILC 2018 polarized thermal dust amplitude map evaluated at 353 GHz. The angular resolution varies over the sky, as described in Remazeilles et al. (2011b). No colour corrections have been applied to this map.

Planck 2018 results. IV, arXiv:1807.06208

Planck GNILC dust polarization fractions



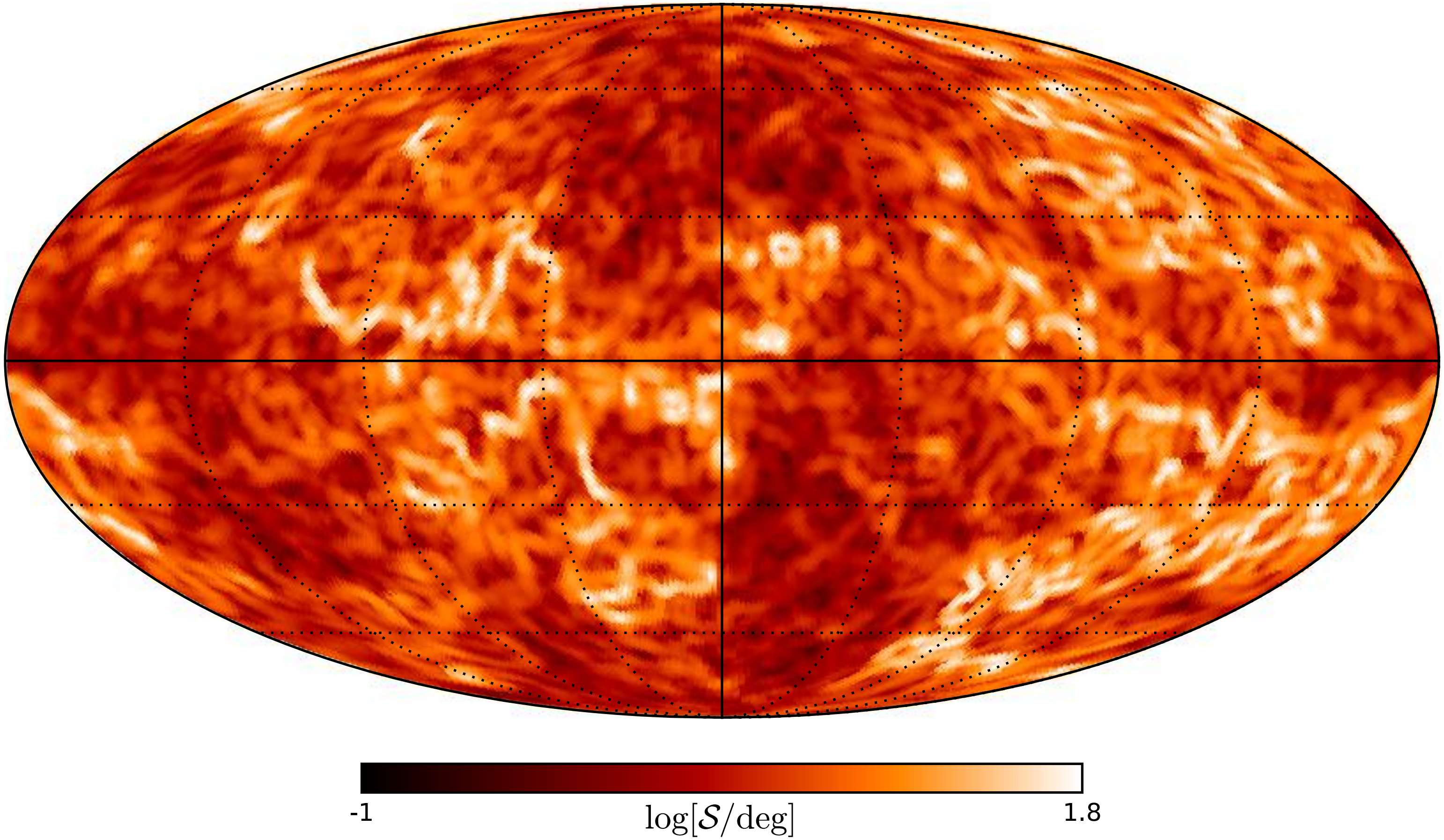


Planck 2018 results. XII, arXiv:1807.06212

[See F. Boulanger's talk](#)

GNILC dust polarization angle dispersion

Used to constrain models of magnetic field turbulence



Planck 2018 results. XII, arXiv:1807.06212

See F. Boulanger's talk

Overview of GNILC

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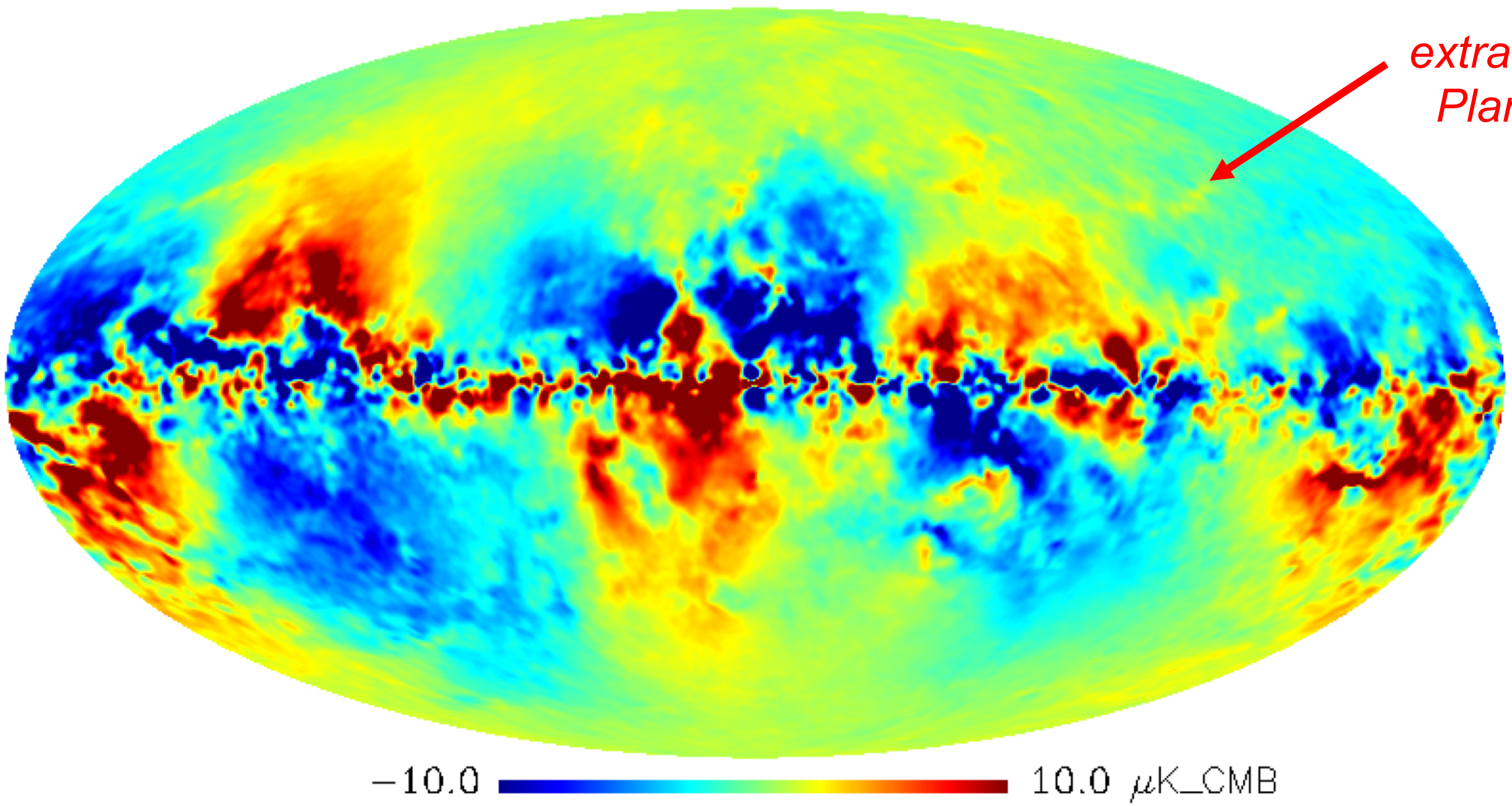
Actual foreground B-modes at 143 GHz

GNILC provides B-mode maps of total foreground contamination directly at CMB frequencies **without extrapolation** from high / low frequencies templates

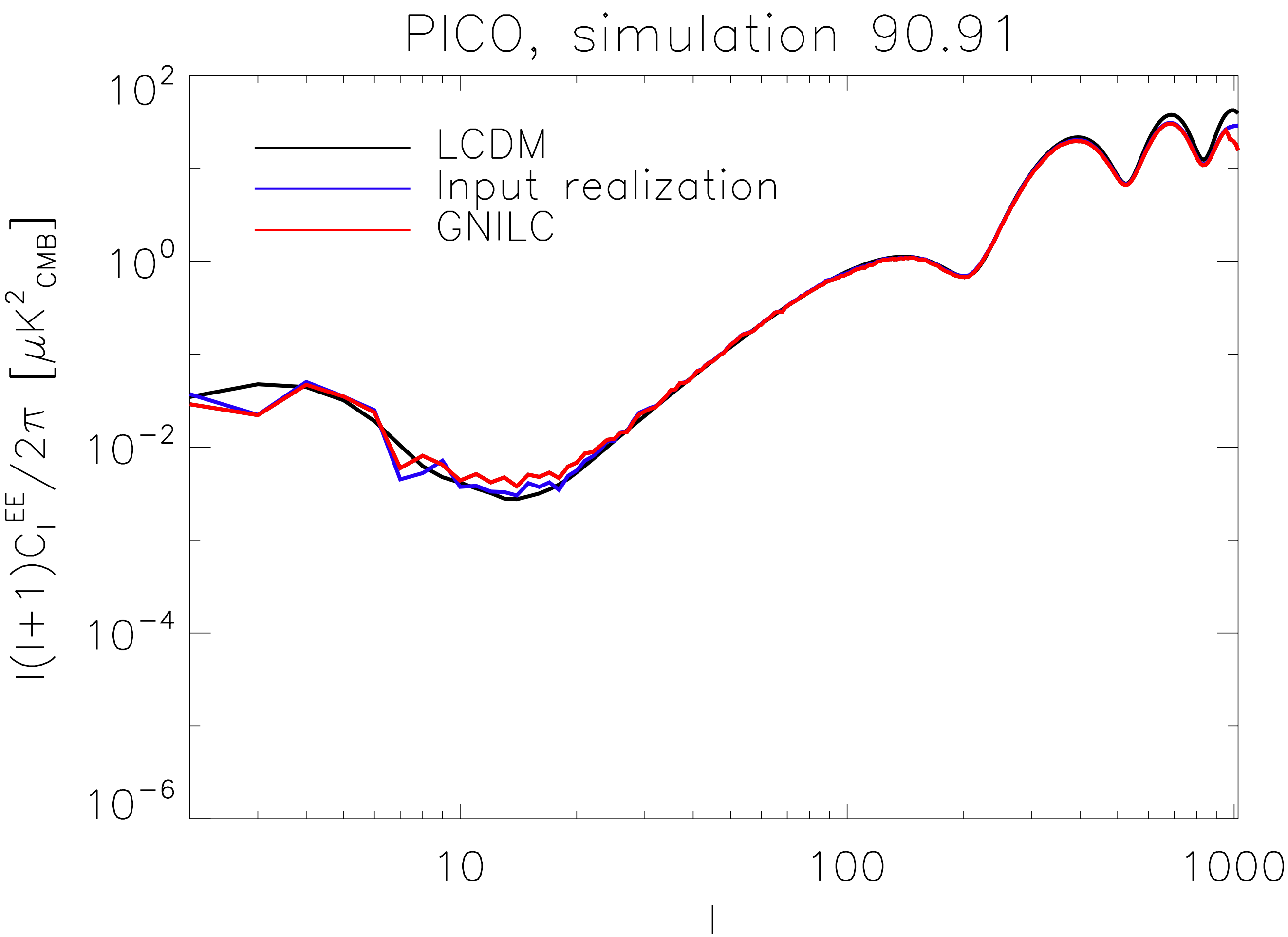
Very relevant in the context of dust decorrelation and B-modes (Tassis et al 2015)

GNILC foreground B-modes at 143 GHz:



extracted from Planck data

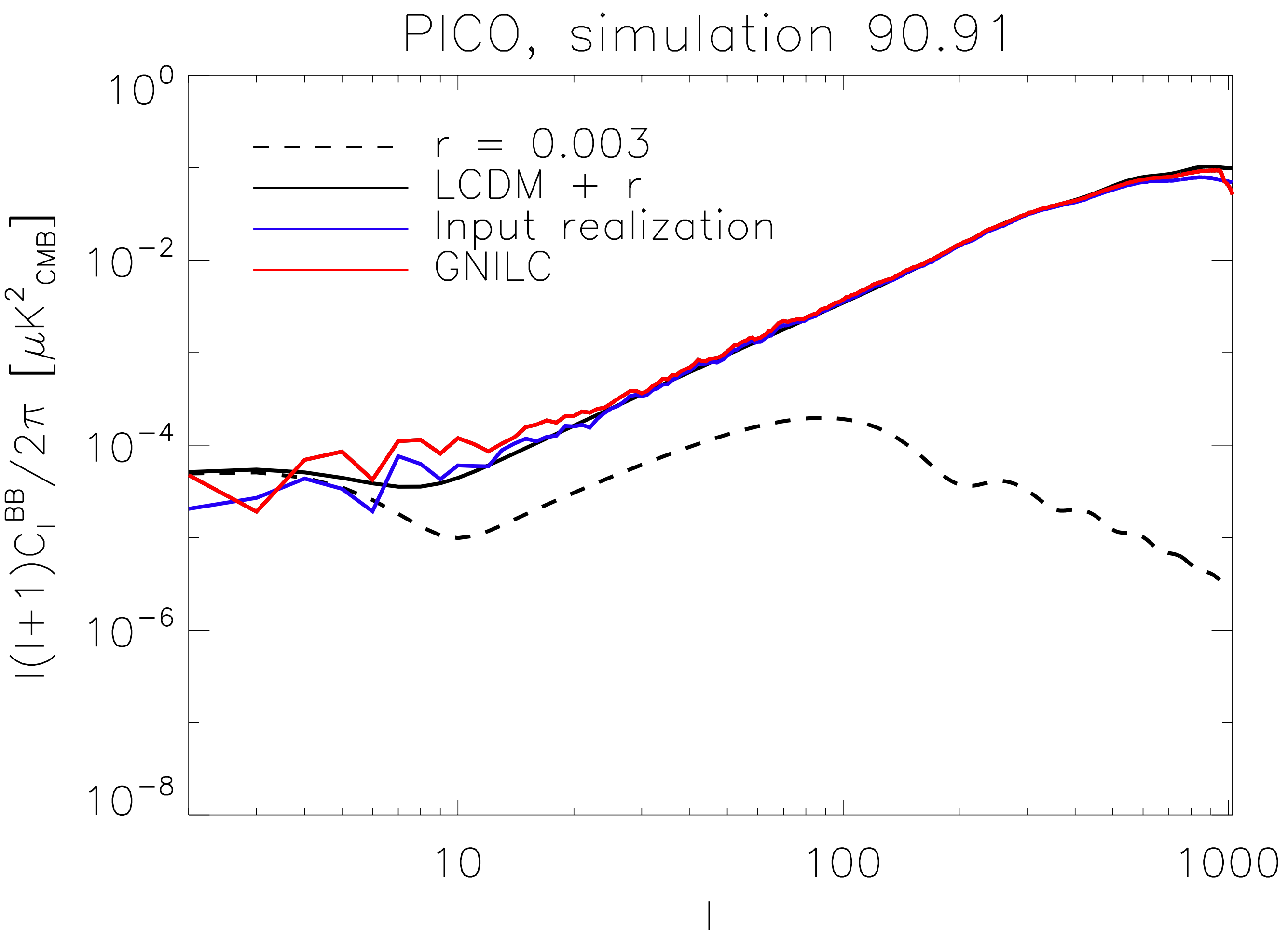
GNILC EE reconstruction with PICO (90.91)



GNILC focuses ILC variance minimization into foreground subspaces instead of minimizing the variance of foregrounds + noise

M. Remazeilles

GNILC BB reconstruction with PICO (90.91)



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Summary

- **GNILC** is a **versatile** and **model-independent** component separation method: *Galactic foregrounds, CIB, CMB, 21-cm signal*

- ***GNILC dust and CIB maps*** *are now at the* ***heart of several Planck papers:***
  Planck intermediate results XLVIII 2016
  Planck 2018 results IV. Diffuse component separation
  Planck 2018 results VIII. Gravitational lensing
  Planck 2018 results XII. Galactic astrophysics using polarized dust emission

- **GNILC property of using both spectral and spatial information is essential to break numerous degeneracies**

- **GNILC is blind, so fairly insensitive to decorrelation / averaging effects**

- **GNILC shows already promising results for CMB B-modes**

Thanks for your attention!