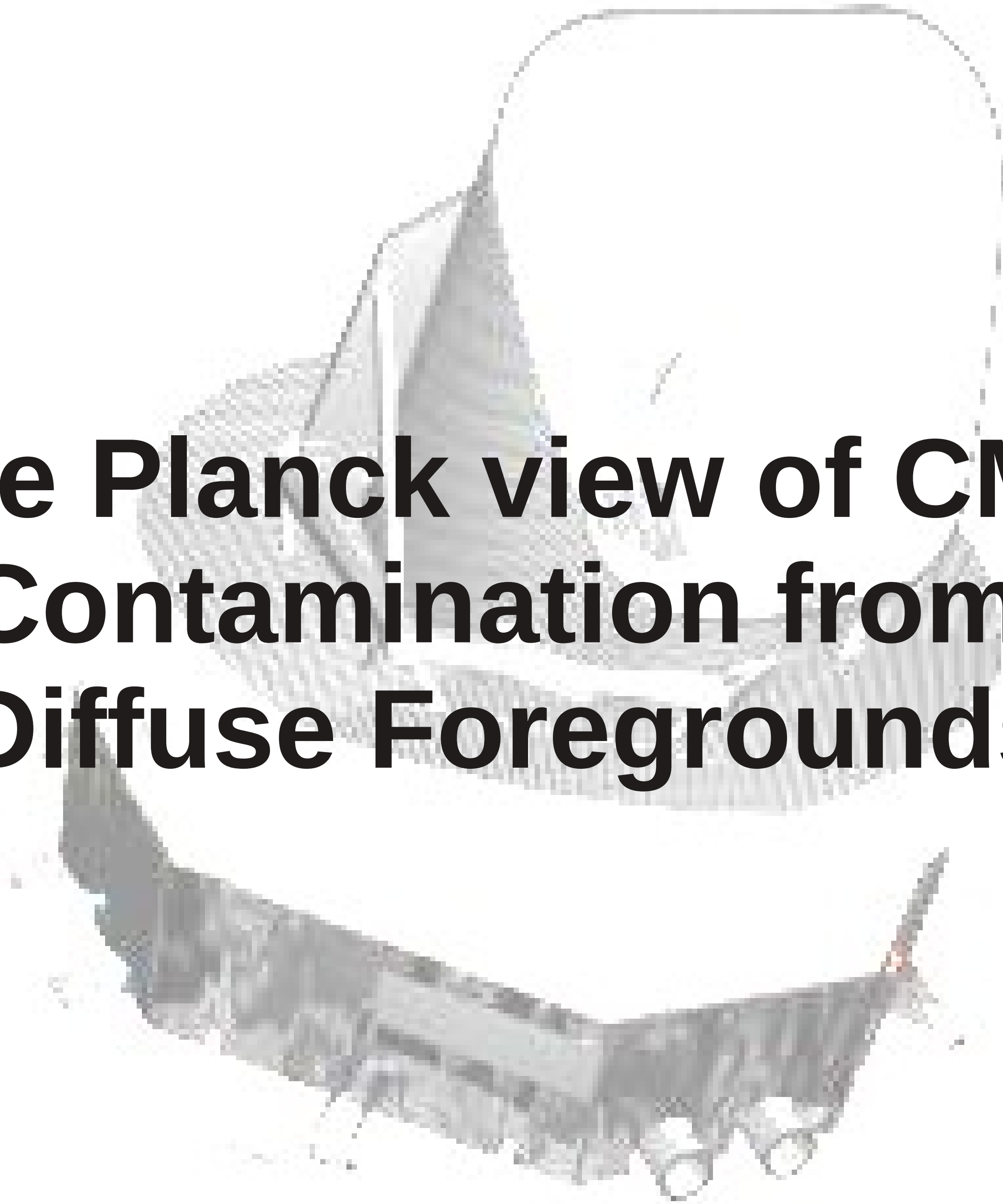
The Planck view of CMB Contamination from Diffuse Foregrounds



Carlo Baccigalupi
On Behalf of the Planck Collaboration
KITP Conference, April 2013

Outline

- Component Separation for Planck
- CMB solutions
- Consistency and Robustness
- Cosmology from Component Separation
- Diffuse Foregrounds
- Conclusions

Outline

- Component Separation for Planck
- CMB solutions
- Consistency and Robustness
- Cosmology from Component Separation
- Diffuse Foregrounds
- Conclusions

Contribution from
Jean-Francois Cardoso

Outline

- Component Separation for Planck
- CMB solutions
- Consistency and Robustness
- Cosmology from Component Separation } See Graca's talk
- Diffuse Foregrounds
- Conclusions

Outline

- Component Separation for Planck
- CMB solutions
- Consistency and Robustness
- Cosmology from Component Separation
- Diffuse Foregrounds } Thanx to Ingunn and the C-R team
- Conclusions

Outline

- Component Separation for Planck
- CMB solutions
- Consistency and Robustness
- Cosmology from Component Separation
- Diffuse Foregrounds
- Conclusions

The Planck Component Separation Group

Component separation for Planck

Component Separation for Planck

$$d = As + n$$

Component Separation for Planck

Your data

The mixing matrix

CMB and foregrounds

$$d = As + n$$

Noise

Component Separation for Planck

$$d = As + n$$

- d: frequencies × resolution elements
- A: frequencies × components
- s: components × resolution elements
- n: frequencies × resolution elements

On foregrounds you...

- Know nothing
- Know something

Thus you...

- Look for minimum variance
- Model and fit

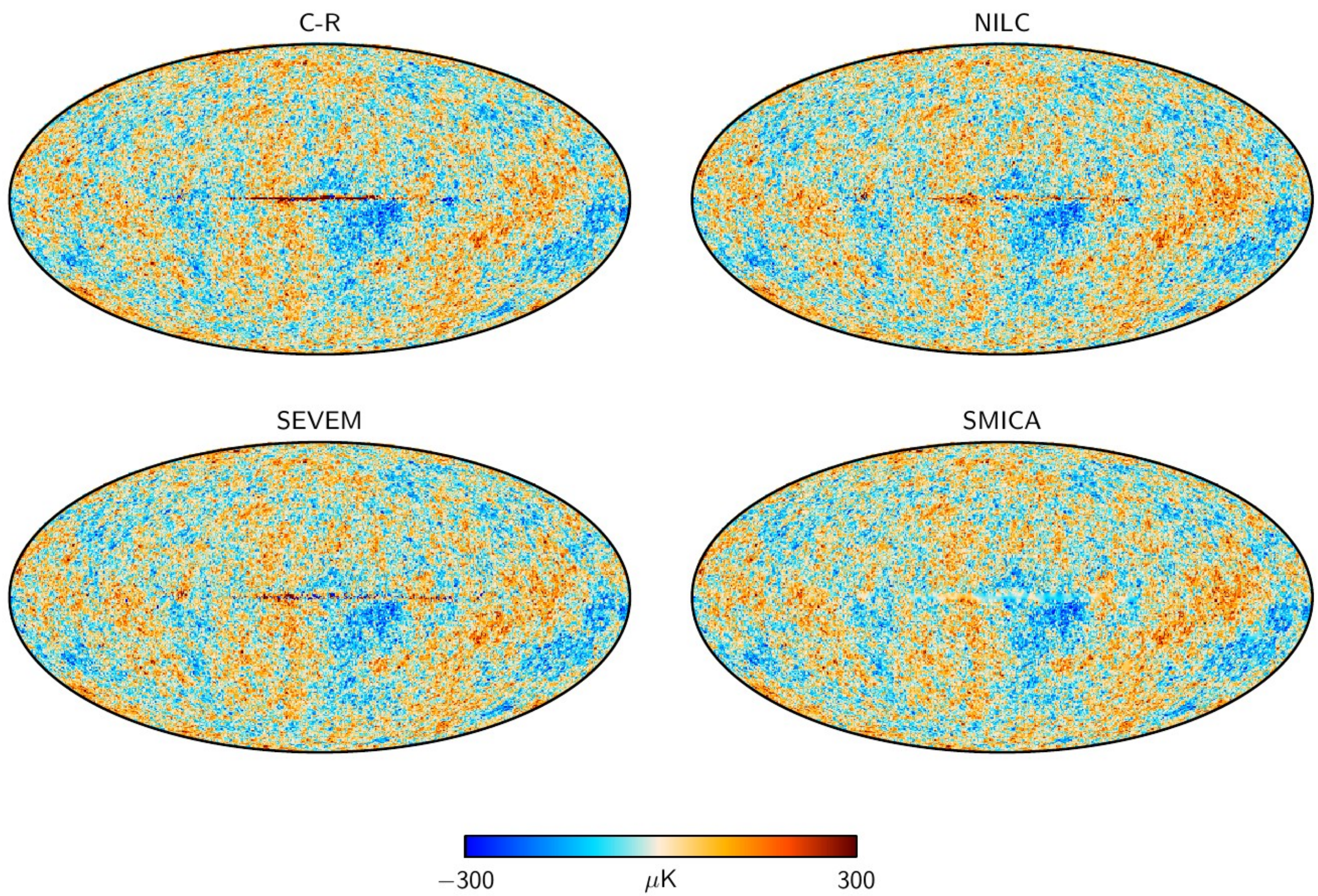
And you...

- Look for minimum variance
  1. in the needlet (spherical wavelet) domain – NILC
  2. in the pixel domain – SEVEM
- Model and fit
  3. semi-parametrically in the harmonic domain – SMICA
  4. physical parameters in the pixel domain – C-R

And you...

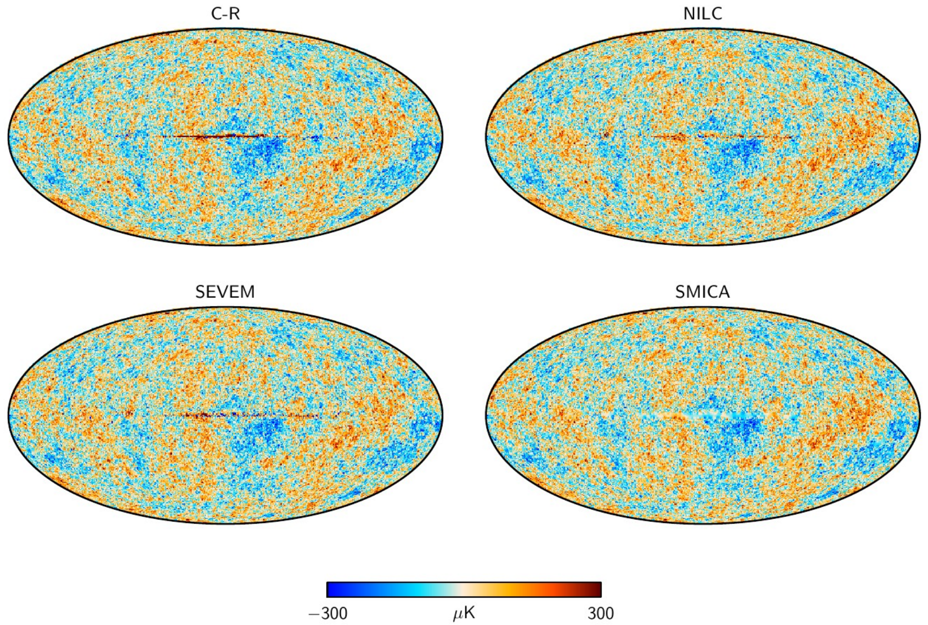
- Look for minimum variance
  1. in the needlet (spherical wavelet) domain
  2. in the pixel domain
- Model and fit
  3. semi-parametrically in the harmonic domain
  4. physical parameters in the pixel domain

CMB solutions



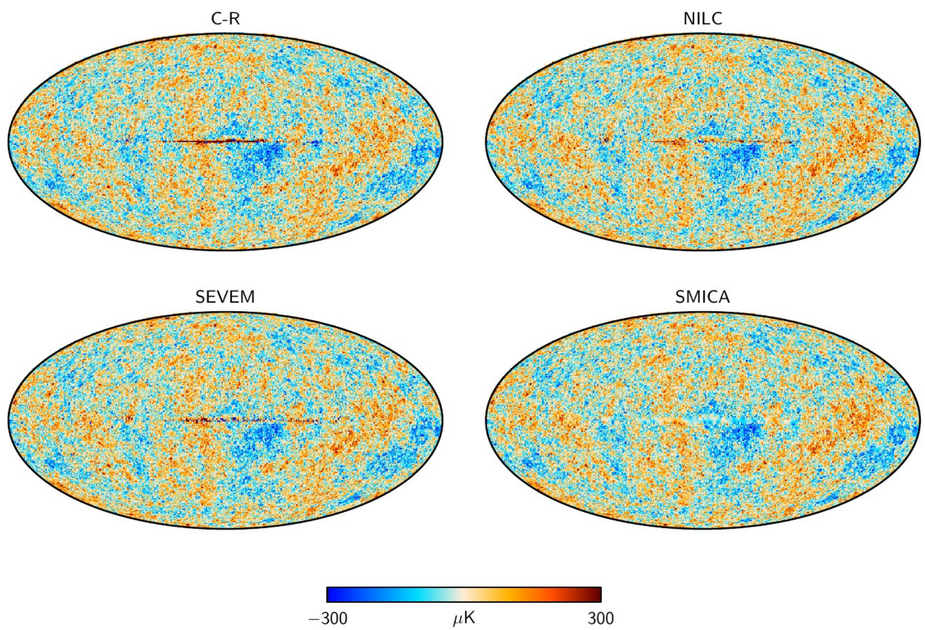
Characterization of the CMB solutions

- Parallel runs on data and Full Focal Plane (FFP6) simulations, including the best in flight knowledge of instrumental behavior
- Instrumental error is propagated through noise variance (and covariance at low l for C-R for use in the likelihood) as well as through half-ring differences
- The beam is evaluated through ...
- Quantitative claims on:
  - auto-spectra, cosmological parameter estimation
  - Primordial Non-Gaussianity
  - Lensing



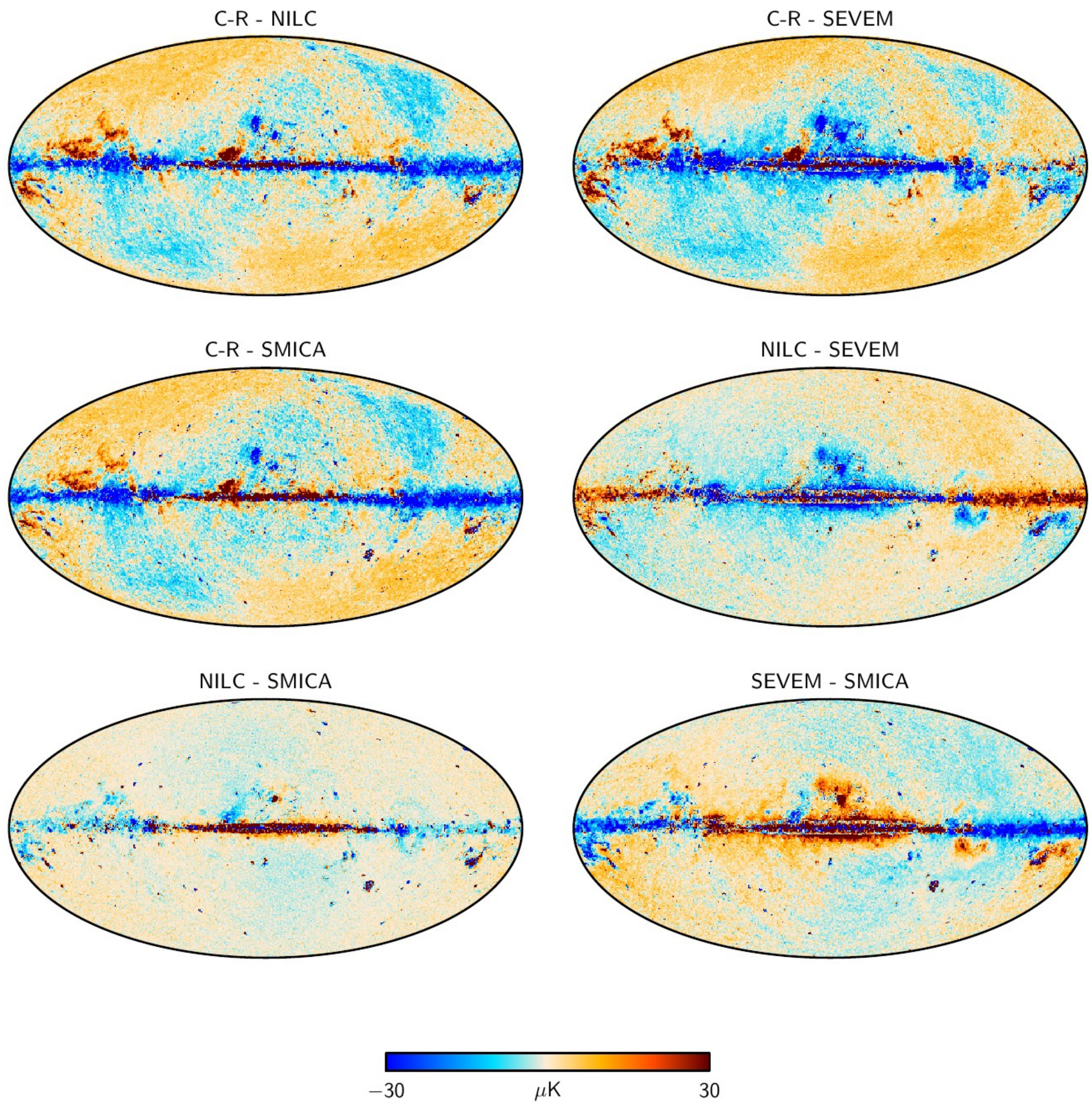
CMB solutions and Planck papers

- 2013 paper where component separation products were used for quantitative statements:
  - Planck 2013, I, overview
  - Planck 2013, XI, consistency
  - Planck 2013 XIII, CO
  - Planck 2013 XV, likelihood
  - Planck 2013 XVI, cosmological parameters
  - Planck 2013 XVII, lensing
  - Planck 2013 XIX, ISW
  - Planck 2013 XXIII, Isotropy
  - Planck 2013 XXIV, non-Gaussianity
  - Planck 2013 XXV, cosmic strings
  - Planck 2013 XXVI, topology
  - ...

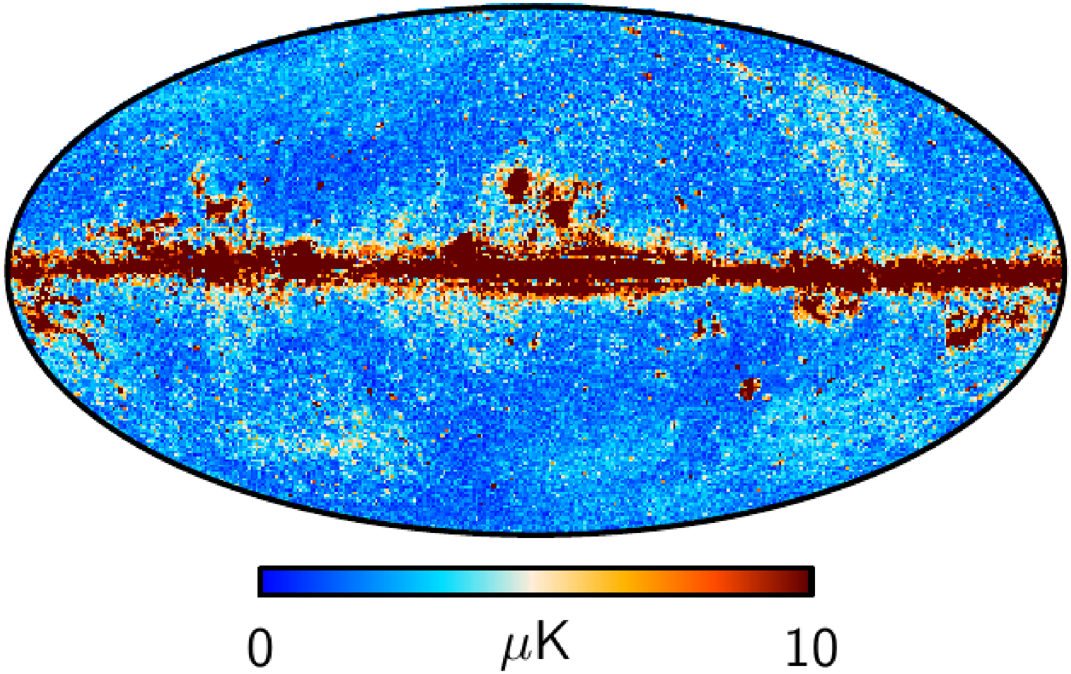


The Planck Collaboration XII

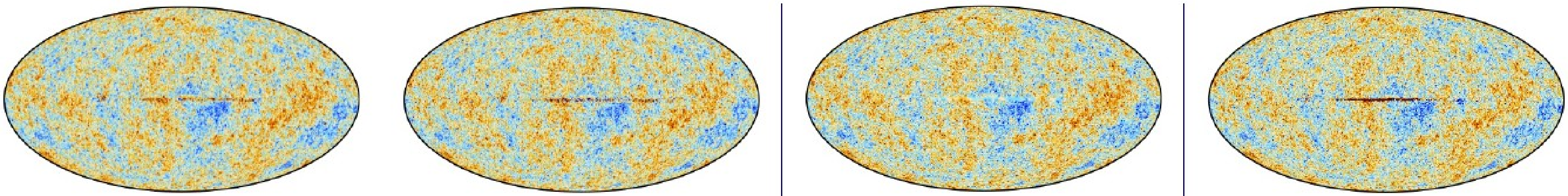
CMB solutions differences



CMB standard deviation evaluated over methodology



Four CMB anisotropy maps delivered on March 21st to the Planck Legacy Archive



NILC	SEVEM	SMICA	C-R
$\ell_{\rm max} = 3200$	$\ell_{\rm max} = 3100$	$\ell_{\rm max} = 4000$	Pixel-based
5 arc-min	5 arc-min	5 arc-min	$\sim$ 7 arc-min
$\ell_{\rm SNR=1} = 1790$	$\ell_{\rm SNR=1} = 1790$	$\ell_{\rm SNR=1} = 1790$	$\ell_{\rm SNR=1} = 1550$
non-parametric	non-parametric	semi-parametric	parametric

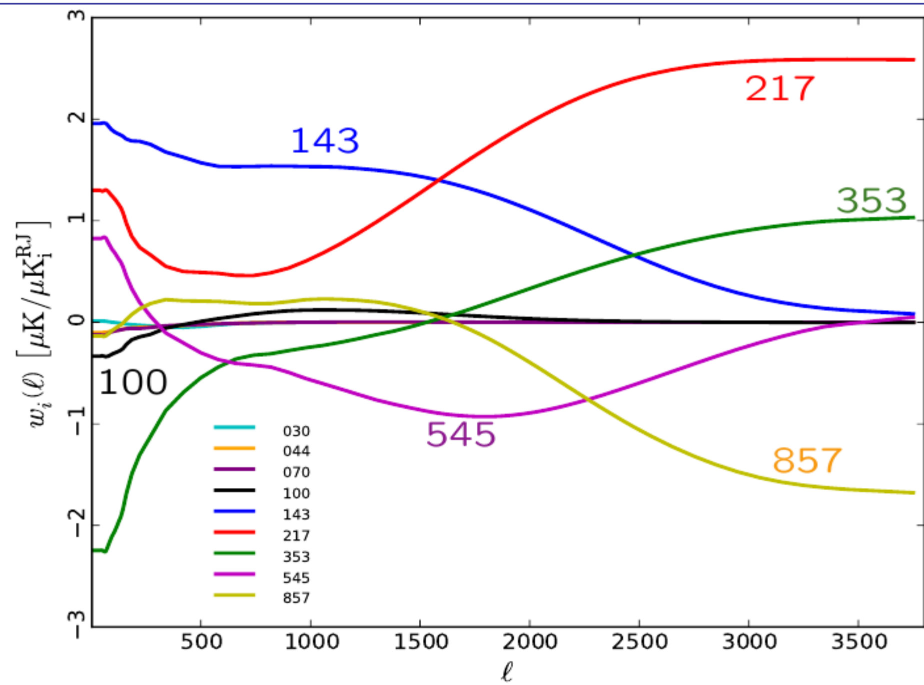
The SMICA product selected as the 'Main product' for CMB map. What it does:

- Combines Planck channels with ℓ-dependent weights
- Optimal weights determined from a Maximum Likelihood fit. . .
- . . . of a "semi-parametric" model.

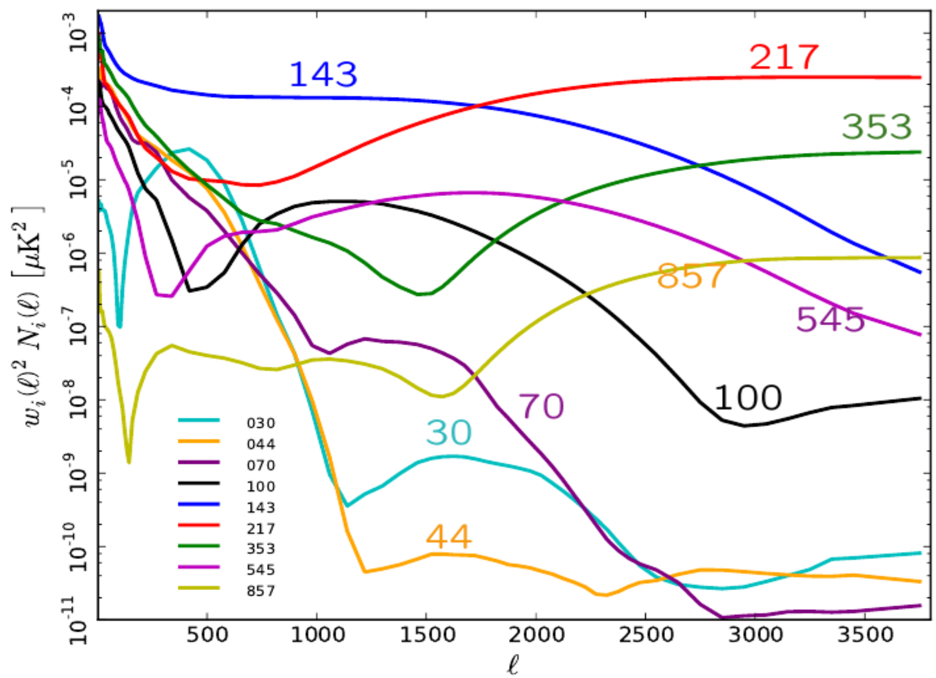
The Planck Collaboration XII; Courtesy of Jean-Francois Cardoso

Highlights on Component Separation: Spectral Matching

What SMICA does to signal... and to noise



SMICA channel weighting vs multipole



Noise contribution from each channel

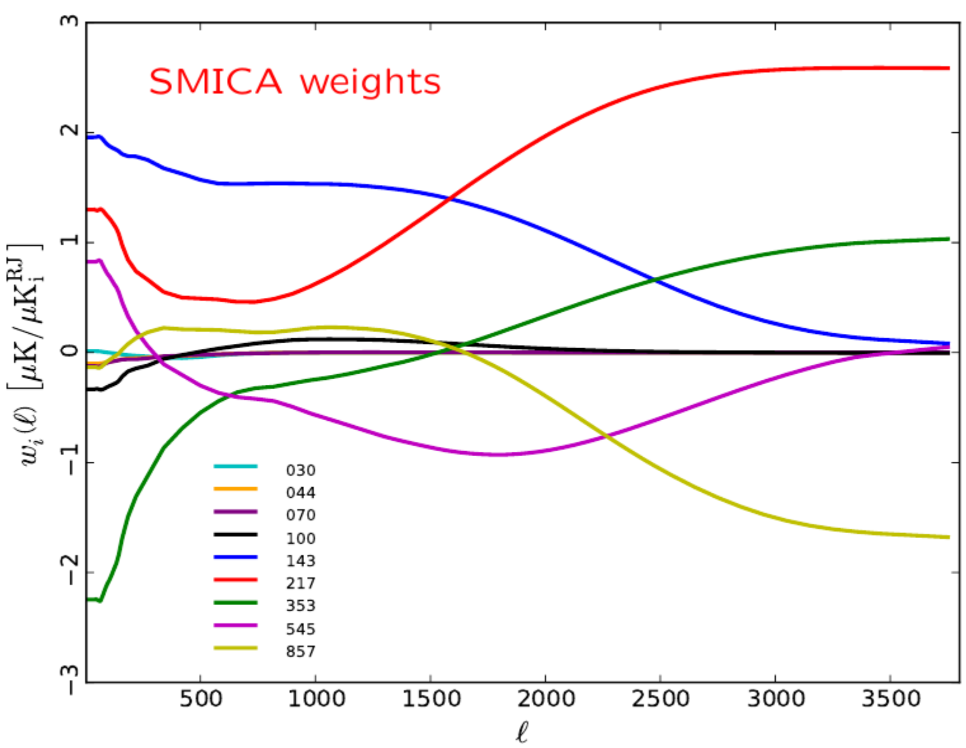
The data (and common sense) are telling us to let the weights depend on angular frequency.

They do not strongly advise us to let them vary with position (See NILC performance).

The Planck Collaboration XII; Courtesy of Jean-Francois Cardoso

Highlights on Component Separation: Spectral Matching

SMICA filtering (where do those weights come from?)



Combine channels in harmonic space:

$$\widehat{s}_{\ell m} = \mathbf{w}_\ell^\dagger \mathbf{d}_{\ell m}$$

Assume coherent CMB:

$$\mathbf{d}_{\ell m} = \mathbf{a}\, s_{\ell m} + \text{contamination}_{\ell m},$$

Best weights for known $\mathbf{C}_\ell = \mathrm{Cov}(\mathbf{d}_{\ell m})$:

$$\mathbf{w}_\ell = \frac{\mathbf{C}_\ell^{-1}\mathbf{a}}{\mathbf{a}^\dagger \mathbf{C}_\ell^{-1}\mathbf{a}}$$

- But spectral matrix $\mathbf{C}_\ell$ is unknown. . .

$\longrightarrow$ At high ℓ, fear not and take

$$\widehat{\mathbf{C}}_\ell = \frac{1}{2\ell+1}\sum_m \mathbf{d}_{\ell m}\mathbf{d}_{\ell m}^\dagger$$

$\longrightarrow$ At low ℓ, model $\mathbf{C}_\ell(\theta)$ and fit

$$\mathbf{C}_\ell(\widehat{\theta}) = \max_\theta P(\widehat{\mathbf{C}}_\ell | \mathbf{C}_\ell(\theta))$$

The Planck Collaboration XII; Courtesy of Jean-Francois Cardoso

Highlights on Component Separation: Spectral Matching

SMICA semi-parametric model

- SMICA models the 9 Planck channels as noisy linear mixtures of CMB and 6 "foregrounds":

$$\begin{bmatrix} d_1 \\ d_2 \\ \vdots \\ \vdots \\ d_9 \end{bmatrix} = \begin{bmatrix} a_1 & F_{11} & \dots & F_{16} \\ a_2 & F_{21} & \dots & F_{26} \\ \vdots & \vdots & \dots & \vdots \\ \vdots & \vdots & \dots & \vdots \\ a_9 & F_{91} & \dots & F_{96} \end{bmatrix} \times \begin{bmatrix} s \\ f_1 \\ \vdots \\ f_6 \end{bmatrix} + \begin{bmatrix} n_1 \\ n_2 \\ \vdots \\ \vdots \\ n_9 \end{bmatrix} \quad \text{or} \quad \mathbf{d}_{\ell m} = [\,\mathbf{a} \mid \mathbf{F}\,] \begin{bmatrix} s_{\ell m} \\ \mathbf{f}_{\ell m} \end{bmatrix} + \mathbf{n}_{\ell m}$$

- SMICA only uses the decorrelation between foregrounds and CMB.

The foregrounds must have 6 dimensions but are otherwise completely unconstrained: they may have any spectrum, any color, any correlation...

So the data model is very blind: all non-zero parameters are free!

$$\mathrm{Cov}(\mathbf{d}_{\ell m}) = [\,\mathbf{a} \mid \mathbf{F}\,] \begin{bmatrix} C_\ell^{\mathrm{cmb}} & 0 \\ 0 & \mathbf{P}_\ell \end{bmatrix} [\,\mathbf{a} \mid \mathbf{F}\,]^\dagger + \begin{bmatrix} \sigma_{1\ell}^2 & \dots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \dots & \sigma_{9\ell}^2 \end{bmatrix} = \mathbf{C}_\ell(\mathbf{a}, C_\ell^{\mathrm{cmb}}, \mathbf{F}, \mathbf{P}_\ell, \sigma_{i\ell}^2).$$

- Blind identifiability: can it be done? Maths say: yes!

If no foreground combination can mimick the CMB angular spectrum, then the semi-parametric elements $\mathbf{a}\, s_{\ell m}$ and $\mathbf{F}\ \mathbf{f}_{\ell m}$ are uniquely fitted.

The Planck Collaboration XII; Courtesy of Jean-Francois Cardoso

Highlights on Component Separation: Spectral Matching

Foregrounds, physical components and the mixing matrix

- Mixing matrix. The 9 Planck channels as noisy linear mixtures of components:

  $$\mathbf{d} = \mathbf{A}(\theta)\ \mathbf{s}\ +\ \mathbf{n}$$

- Some models for the mixing matrix $\mathbf{A} = \mathbf{A}(\theta)$:

Type	Mixing matrix	parameters θ	dim(θ)
physical, fixed	$\mathbf{A} = [\mathbf{a}_{\mathrm{cmb}}\ \mathbf{a}_{\mathrm{dust}}\ \mathbf{a}_{\mathrm{CO}}\ \mathbf{a}_{\mathrm{LF}}]$	$\theta = [\,]$	0
physical, parametric	$\mathbf{A} = [\mathbf{a}_{\mathrm{cmb}}\ \mathbf{a}_{\mathrm{dust}}(T)\ \mathbf{a}_{\mathrm{CO}}\ \mathbf{a}_{\mathrm{LF}}(\beta)\ ]$	$\theta = (T, \beta)$	2
equivalent to ILC	$\mathbf{A} = [\mathbf{a}_{\mathrm{cmb}}\ \mathbf{B}]$ (a square matrix)	$\theta = \mathbf{B}$	$N_{\mathrm{chan}} \times (N_{\mathrm{chan}} - 1)$
semi-parametric, SMICA	$\mathbf{A} = \mathbf{A}$ (any tall matrix)	$\theta = \mathbf{A}$	$N_{\mathrm{chan}} \times N_{\mathrm{comp}}$

- Note: Sky-varying emission spectra can be accounted for:
  - locally by letting $\mathbf{A}$ depend on the pixel: $\mathbf{A}(\theta_{\mathrm{pix}})$ (Commander), or
  - globally by adding columns to $\mathbf{A}$.

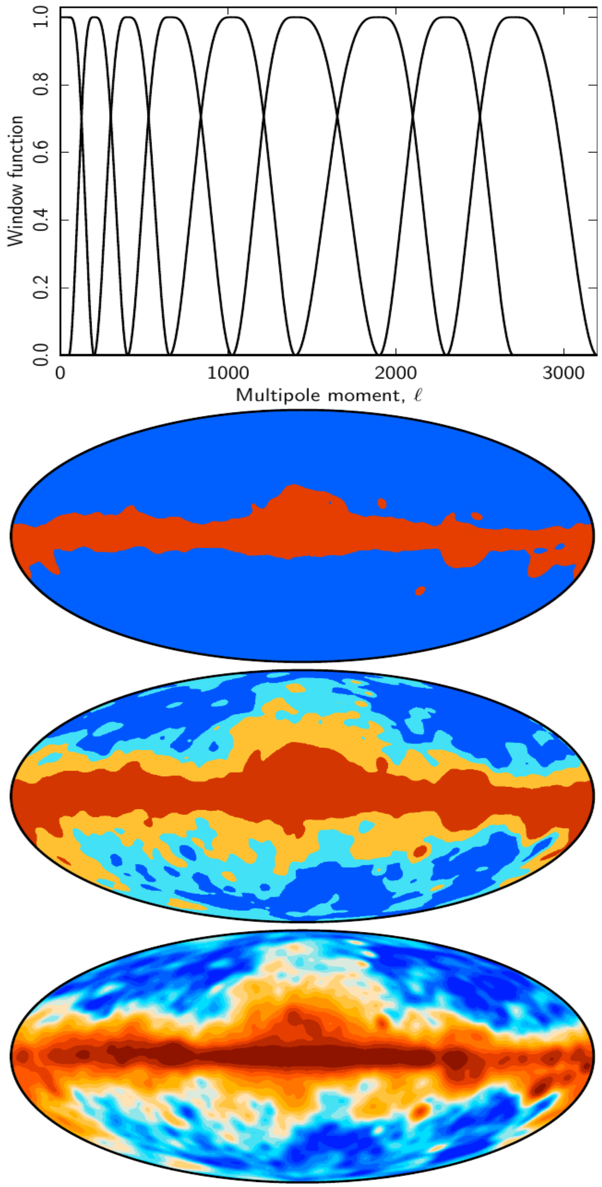
    For instance, a sky-varying low-frequency emission $\mathbf{a}_{\mathrm{LF}}(\theta_{\mathrm{pix}})$ could be approximatively represented by two fixed columns over the whole sky: $[\ \mathbf{a}_{\mathrm{LF}}(\langle\theta\rangle),\ d\mathbf{a}_{\mathrm{LF}}/d\theta(\langle\theta\rangle)\ ]$

    What SMICA does: use more columns in $\mathbf{A}$ than physical foregrounds.

The Planck Collaboration XII; Courtesy of Jean-Francois Cardoso

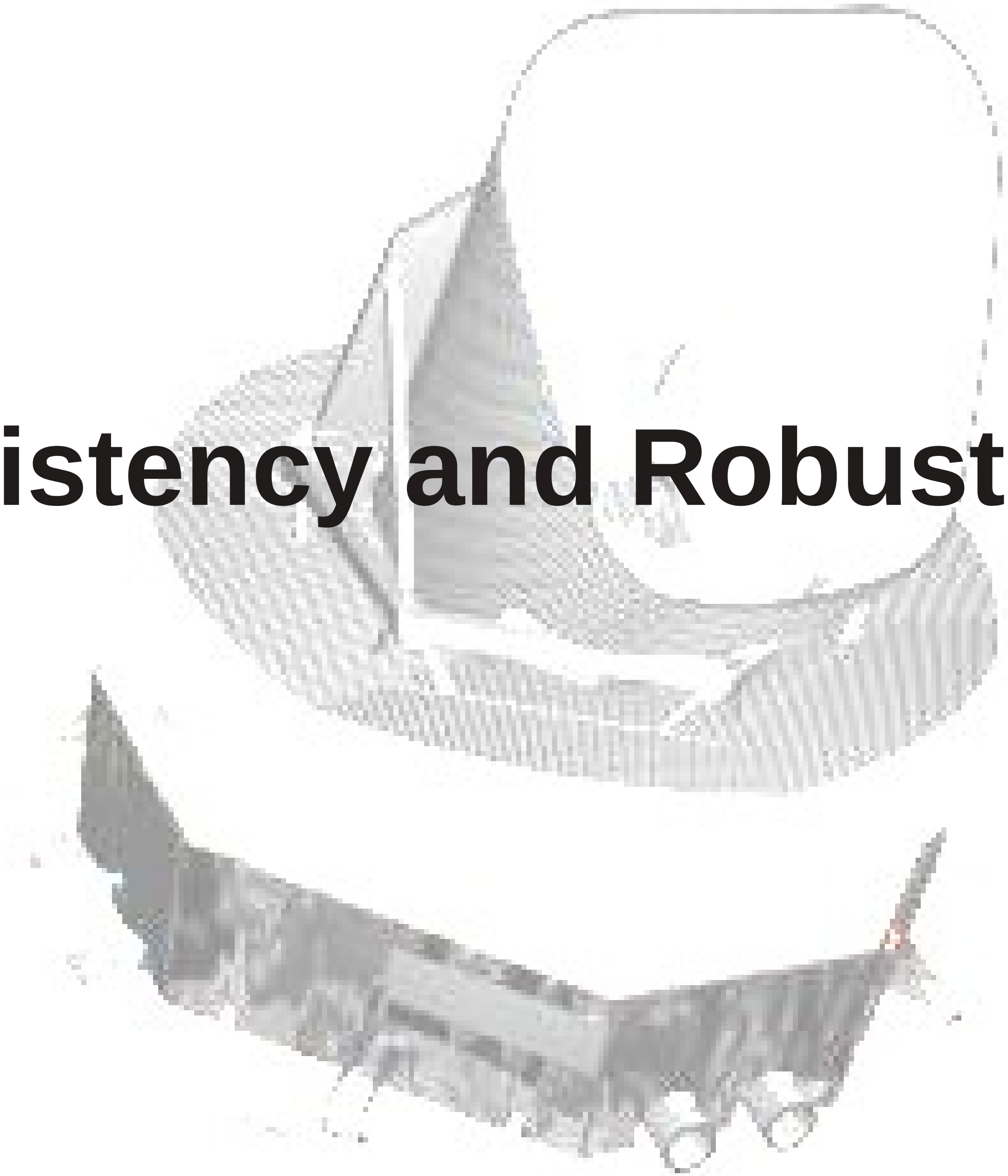
Highlights on Component Separation: Spatial and Spectral Localization

- Localization in the pixel and harmonic domain (needlets) allows to treat foregrounds differently depending on their intensity in different regions of the sky and the angular domain
- Reducing to channel coaddition when they are absent, typically at small angular scales

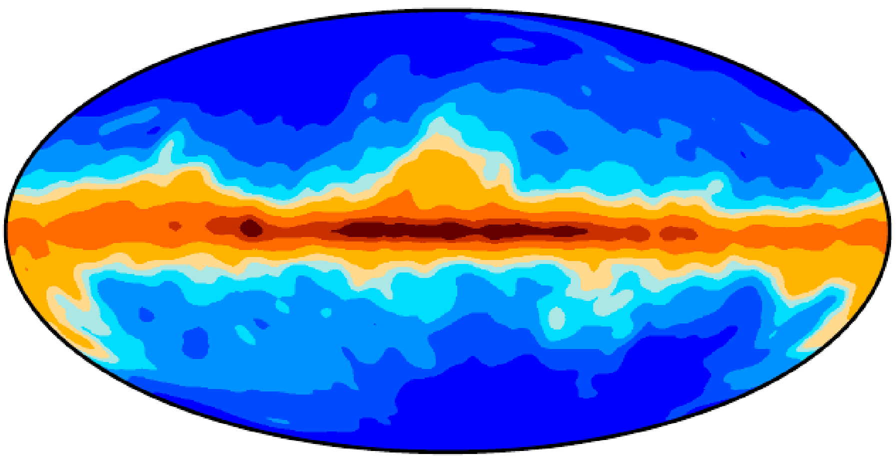


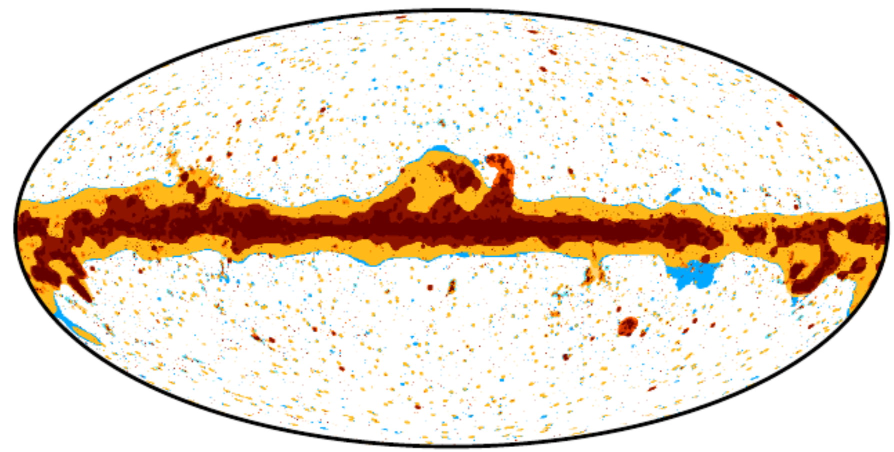
The Planck Collaboration XII; Courtesy of Jean-Francois Cardoso

Consistency and Robustness

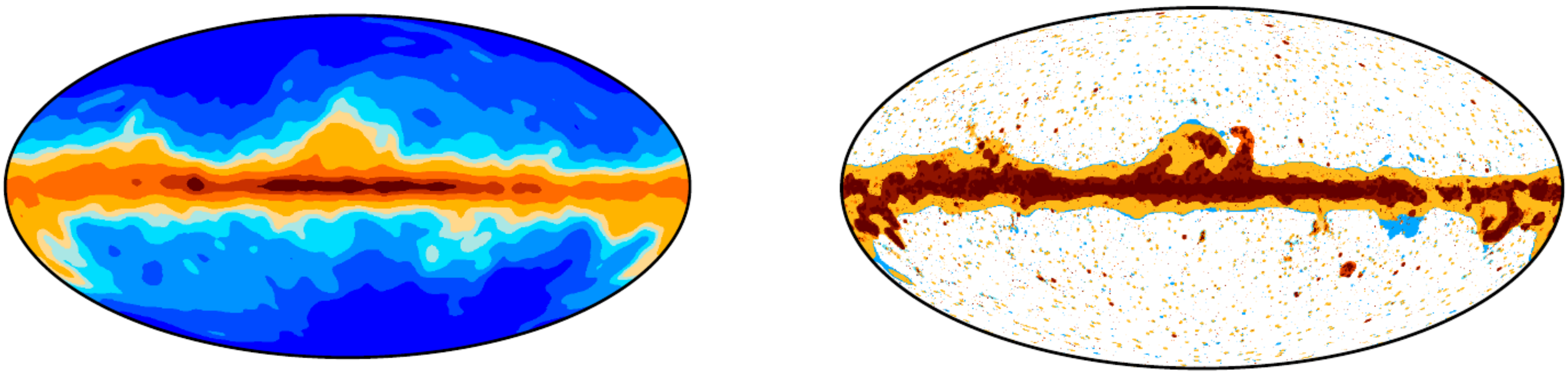


Sky masks



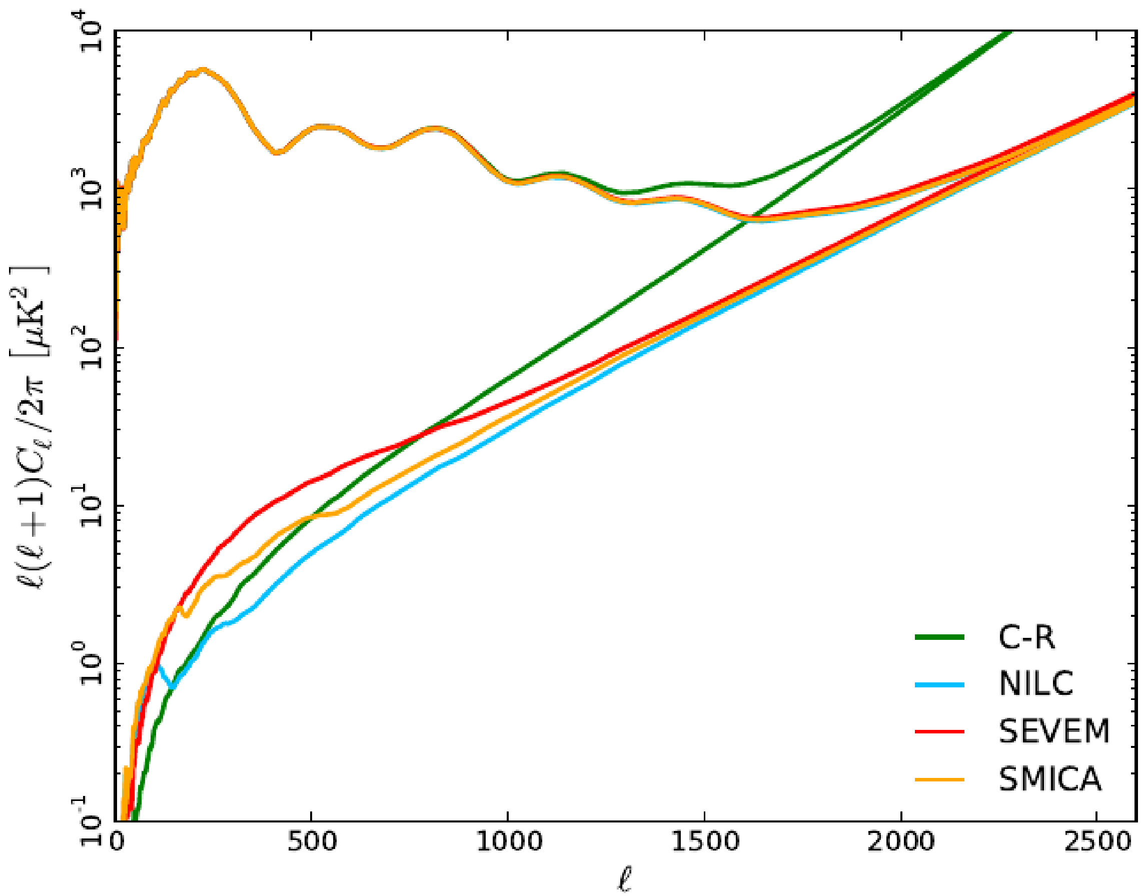


Sky masks



- Threshold maskings is made by combining 30 and 353 Ghz flux thresholding for achieving a given sky fraction
- Confidence masks are method dependent:
  - C-R
  - NILC
  - SEVEM
  - SMICA

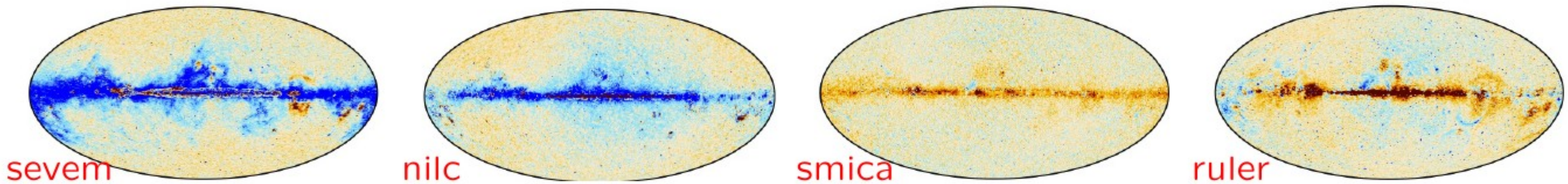
Pseudo-spectra



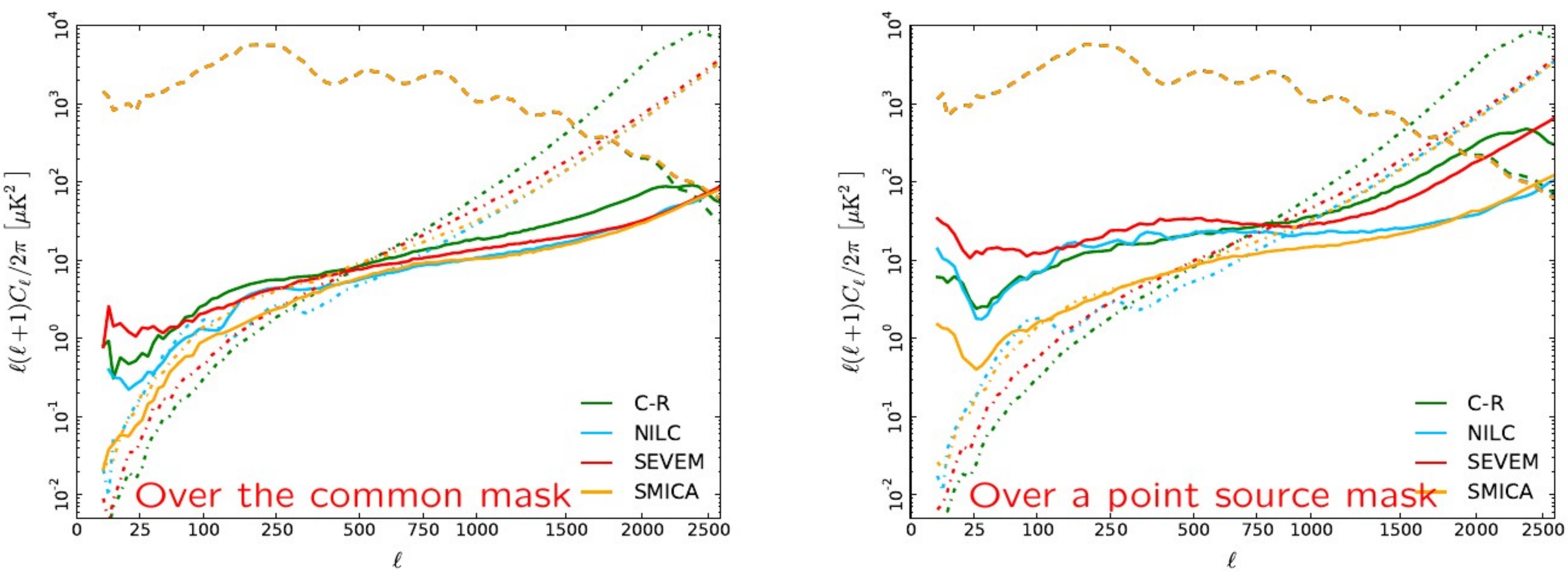
Pseudo-spectra

Comparison on the FFP6 simulations

- Large scale residuals ($N_{\text{side}} = 128$. Color scale: $\pm 30\mu K$).

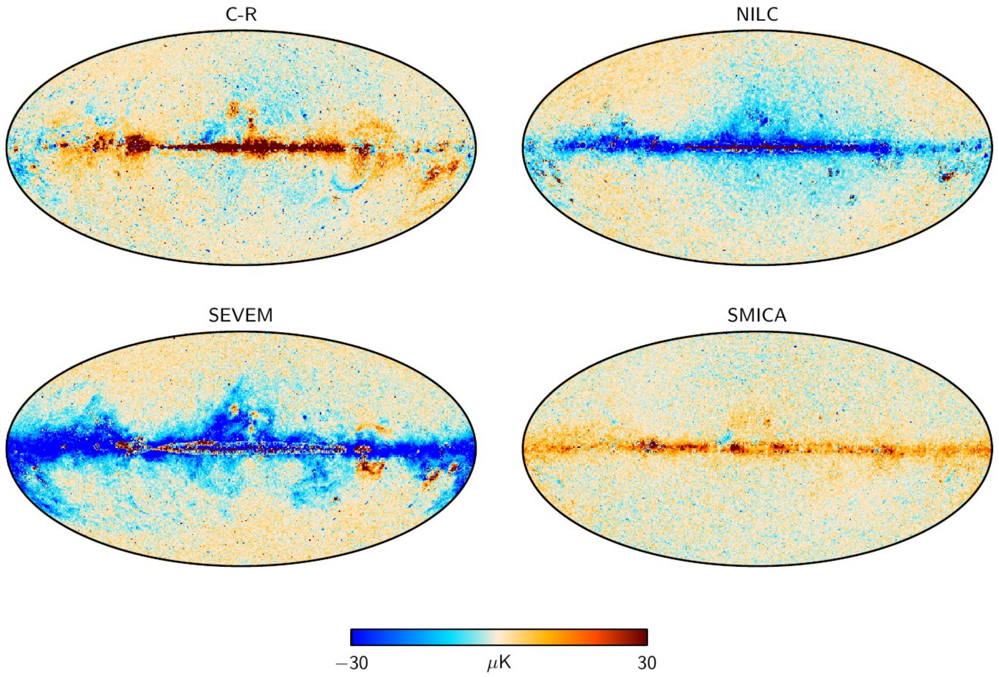


- Propagation of CMB, foregrounds, noise through each pipeline.

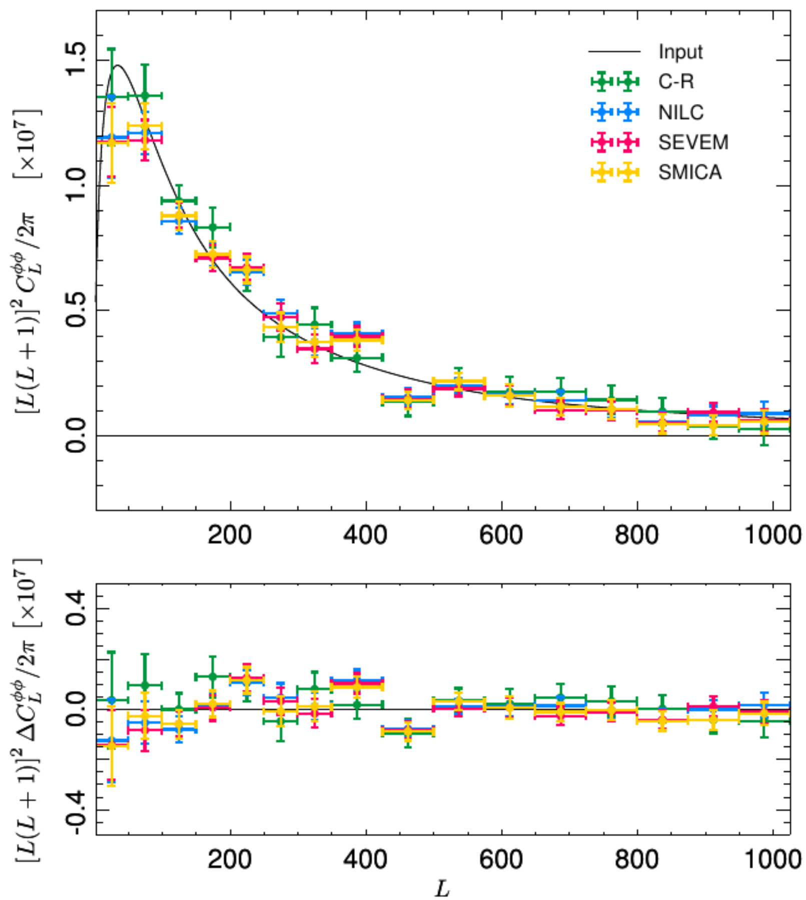


Dashed: CMB, Dotted: noise, Solid: foregrounds.

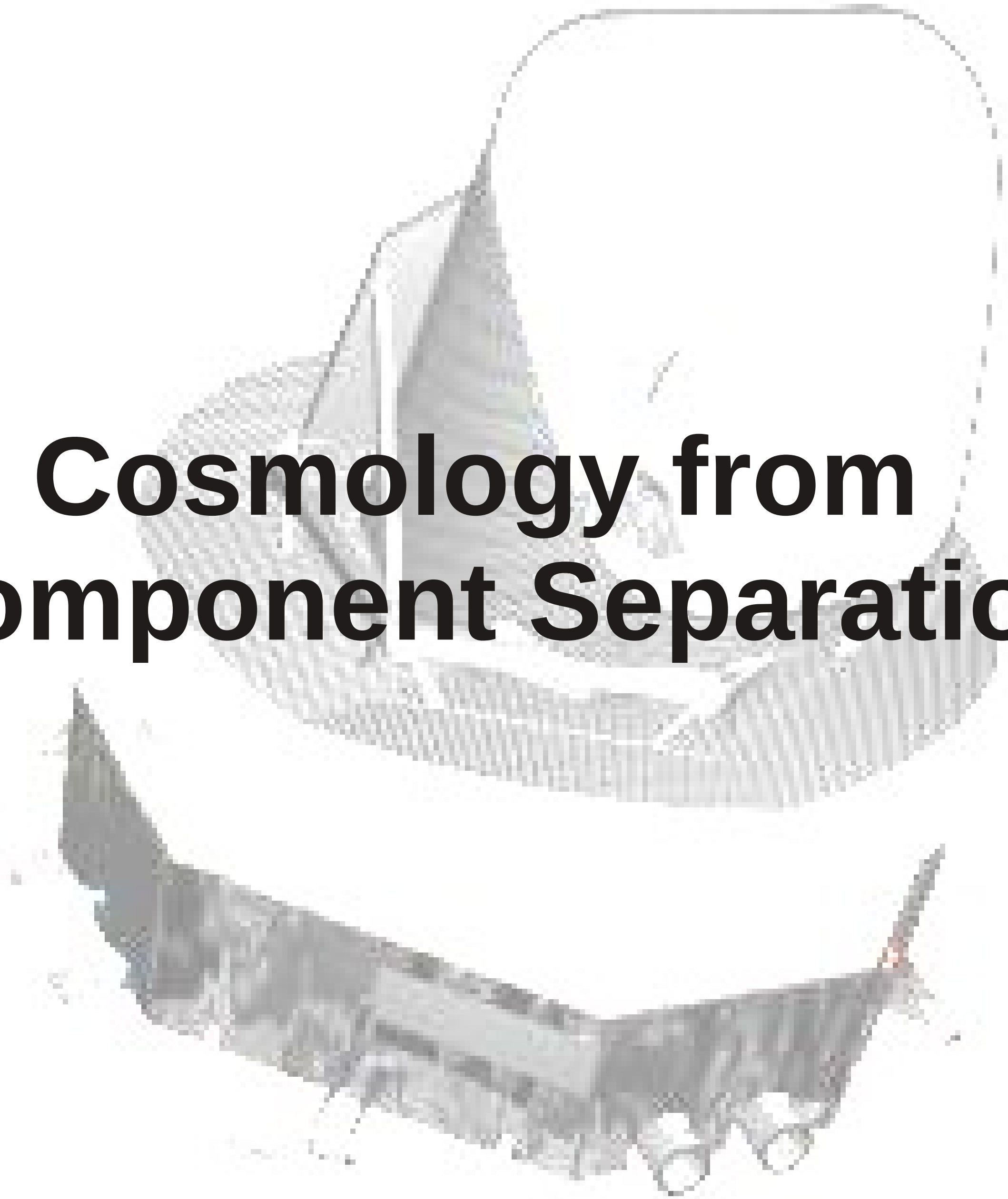
Null tests on FFP6: foreground residuals



Null tests on FFP6: lensing



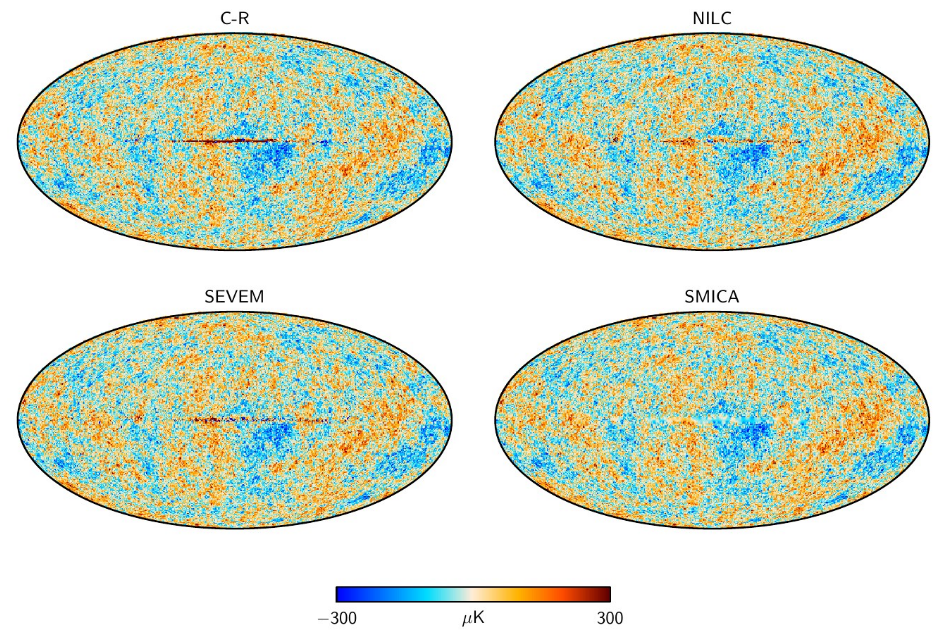
The Planck Collaboration XII



Cosmology from Component Separation

Cosmology with Component Separation

- See forthcoming Graca's talk on power spectra and cosmological parameter estimation
- Paul and Ben's talks on primordial non-Gaussianity
- Duncan's talk on lensing extraction
- Full list:
  - Planck 2013 XV, likelihood
  - Planck 2013 XVI, cosmological parameters
  - Planck 2013 XVII, lensing
  - Planck 2013 XIX, ISW
  - Planck 2013 XXIII, Isotropy
  - Planck 2013 XXIV, non-Gaussianity
  - Planck 2013 XXV, cosmic strings
  - Planck 2013 XXVI, topology



The Planck Collaboration XII

Conclusions: CMB

- A leap forward for Component Separation in Planck
- Likely to split from now on into specialized foreground cleaning for CMB extraction, and foreground reconstruction for astrophysical studies
- CMB solutions from a complete set of approaches are consistent on a large sky fraction, at the level of the two and three point statistics
- Cosmological parameters from auto-spectra are consistent with the cross-spectra likelihood (see Graca's talk)
- Primordial non-Gaussianity and lensing results are consistent (see Paul's, Ben's and Duncan's talks monday)
- At low latitudes, relevant differences persist
- Simulations enable us to isolate the solution with the lowest residual contamination from diffuse foregrounds

Diffuse Foregrounds

Recovery of diffuse foregrounds with Planck

- Planck adopts a pixel based parametric approach for separating diffuse foregrounds
- Parameters in the pixel domain: spatially varying spectral indices and amplitudes of foreground components
- Fitting procedure: Markov Chains Monte Carlo over the multi-frequency datasets
- Main references: Brandt et al. 1994 (main idea), Eriksen et al. 2006 (efficient fitting through Gibbs sampling), Eriksen et al. 2008 (Jeffrey's prior is introduced), Stompor et al. 2009 (high resolution fitting on the basis of chains conducted at low resolution)
- Implementation in the Commander-Ruler code which was used for all results presented in the Planck XII paper

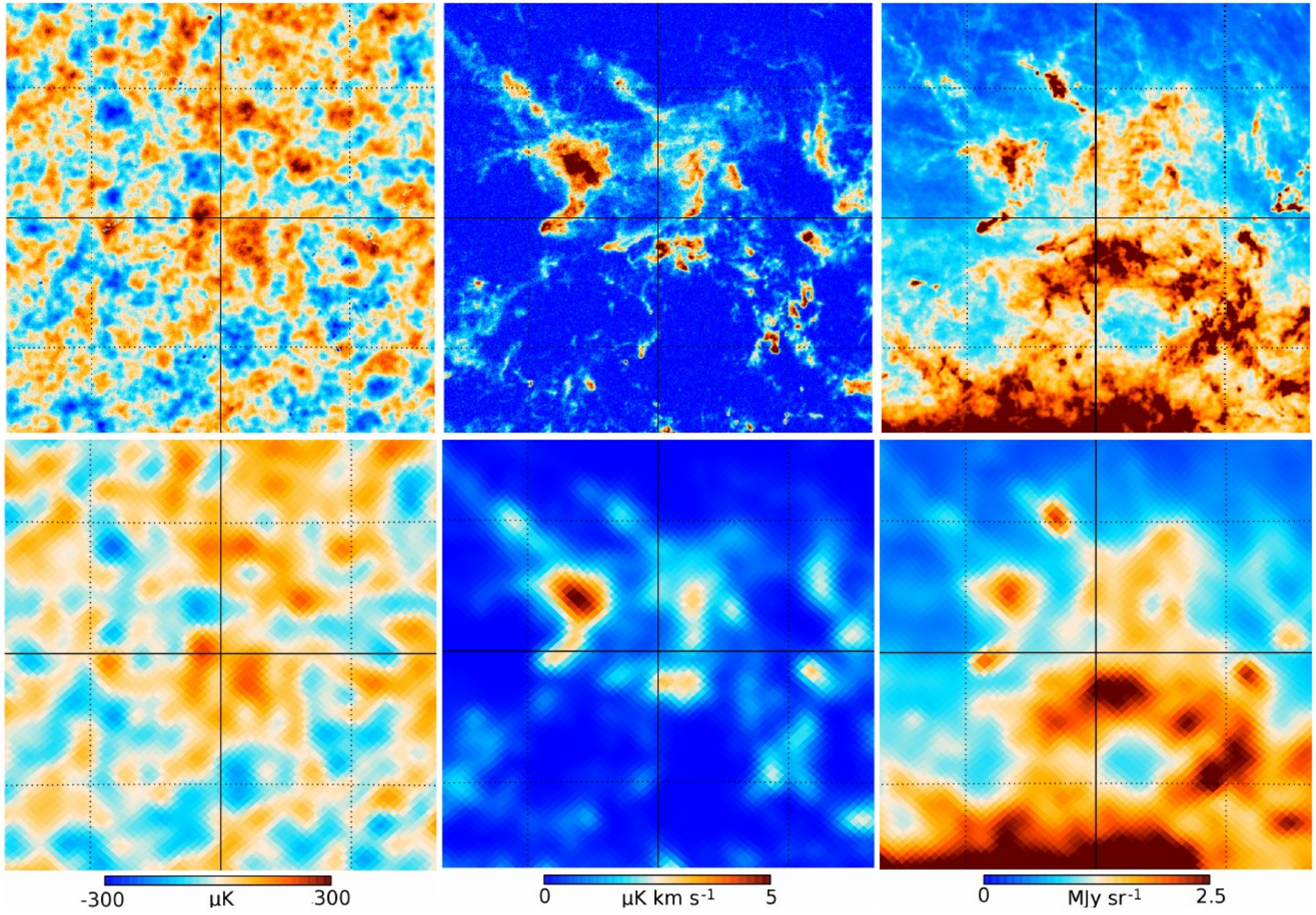
Foreground model

- Low frequency amplitude at 30 GHz and spectral index, effectively describing a mixture of various astrophysical effects, as Brehmsstrahlung (free-free), Anomalous Dust Emission (AME), Synchrotron
- CO amplitude at 100 GHz
- Thermal Dust amplitude at 353 GHz and grey body temperature and emissivity
- Monopoles and dipoles over the frequency channels which are considered for separation, to be estimated separately, at low resolution (Wehus et al. 2013)

Methodology

- Inputs: Planck sky maps, 30-353 GHz, total and half-ring datasets along with their characterization
- Spectral indices estimation at low resolution takes as inputs the maps are smoothed to 40 arcminutes common resolution, re-pixelized at Nside=256
- Mixing matrices are applied to the Ruler resolution dataset corresponding to 7.1 arcminutes

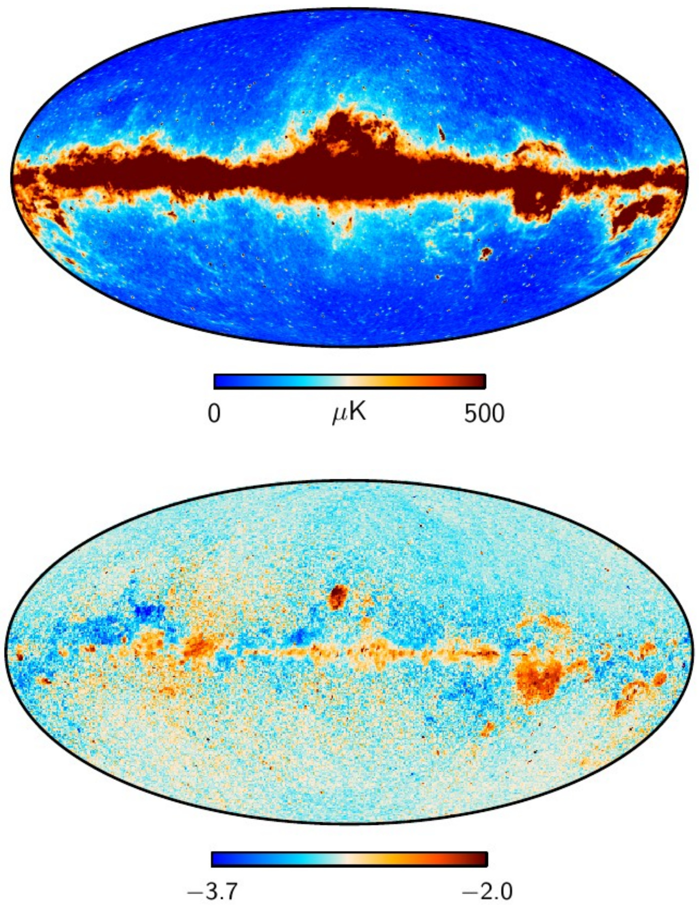
From Commander to Ruler



The Planck Collaboration XII

The Planck low frequency foregrounds

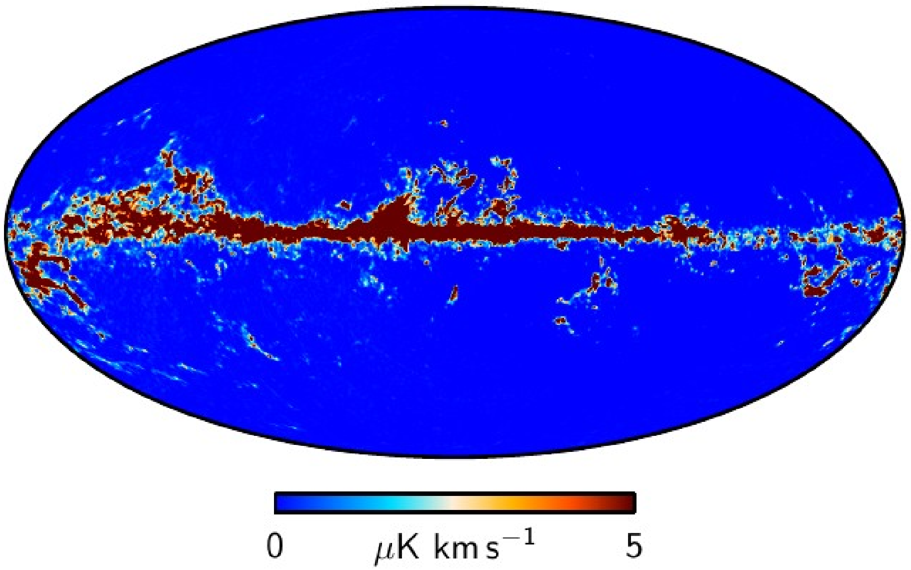
- Amplitude and spectral index of the low frequency component as seen by Planck
- Different emission mechanism, such as Brehmstraalung, synchrotron and low frequency dust emission are reflected in the sky distribution of the spectral index



The Planck Collaboration XII

CO emission as seen by Planck

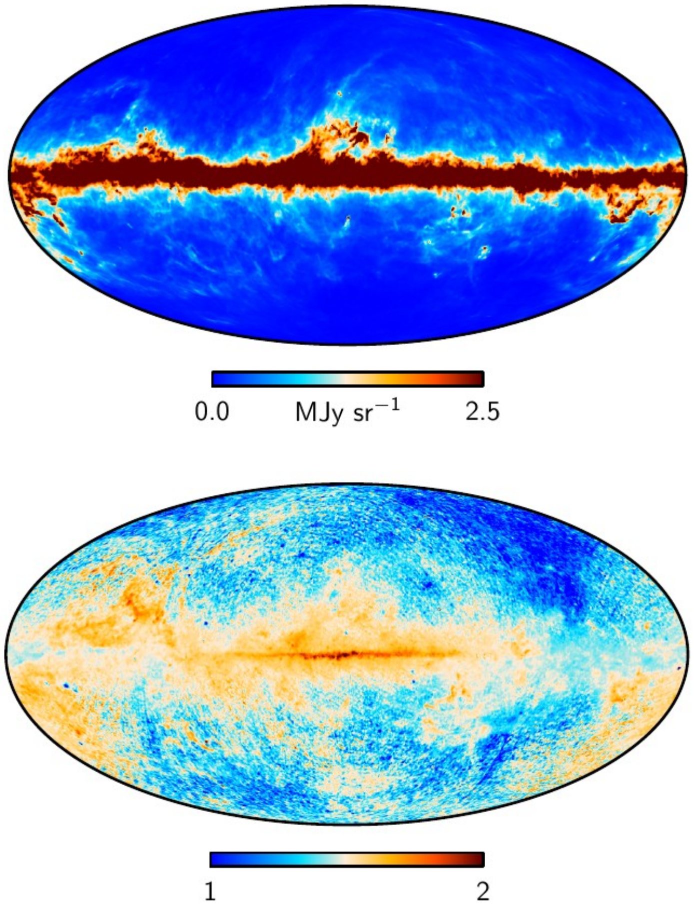
- Planck is sensitive to 9 CO transition lines in its frequency range
- Fit is done by modeling the emission is modelled as a constant line ratio over the full sky for increasing signal to noise ratio, isolate regions heavily affected by this emission



The Planck Collaboration XII

The Planck view of thermal dust

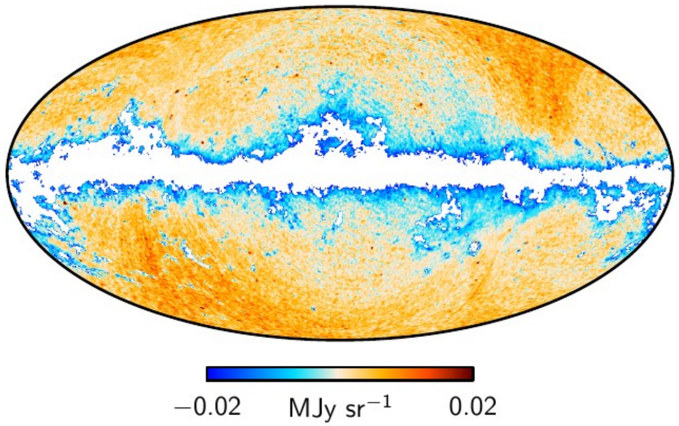
- Planck provides an exquisite mapping of the Galactic thermal from 100 to 857 Ghz
- Planck resolves the sky pattern of dust emissivity, reflecting different phases in the interstellar gas

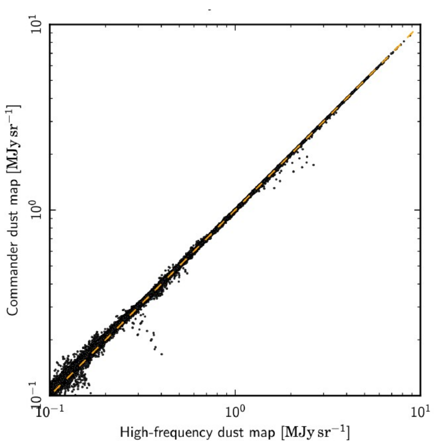


The Planck Collaboration XII

The Planck view of thermal dust

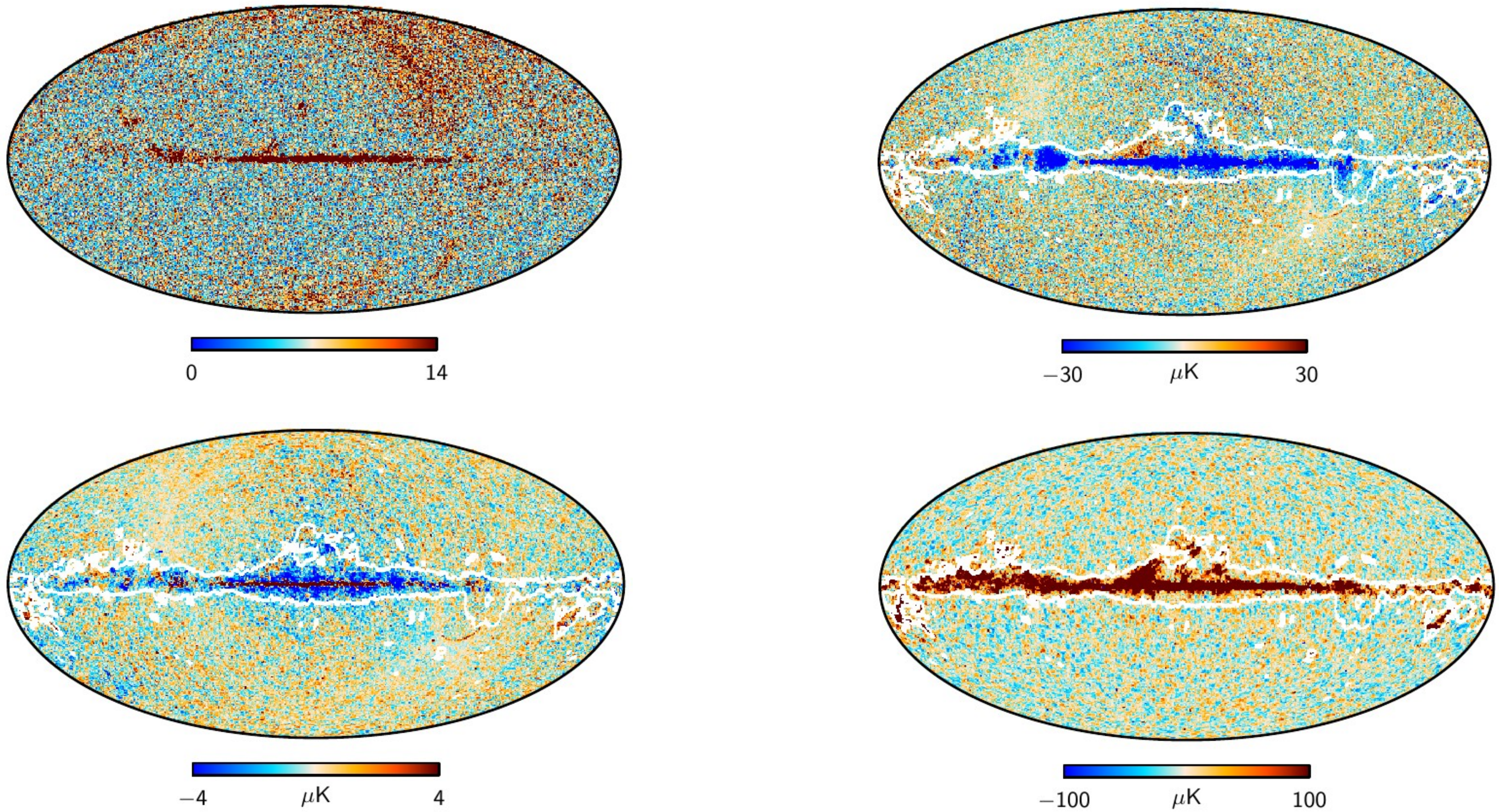
- A comparison is made between the dust solution in the frequency interval where the fit is done and the dust dominated channels at 545, 857 Ghz
- A scatter plot reveals substantial agreement in the common 353 Ghz channel



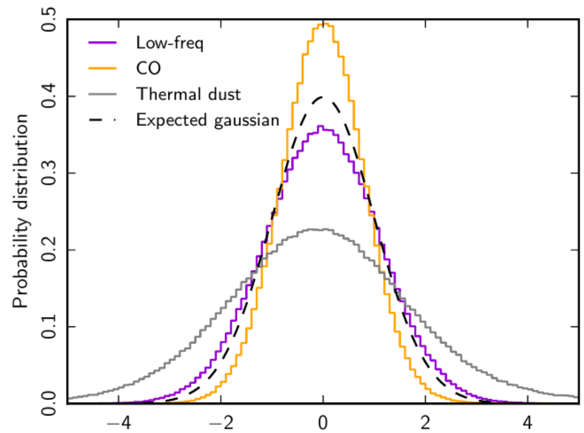


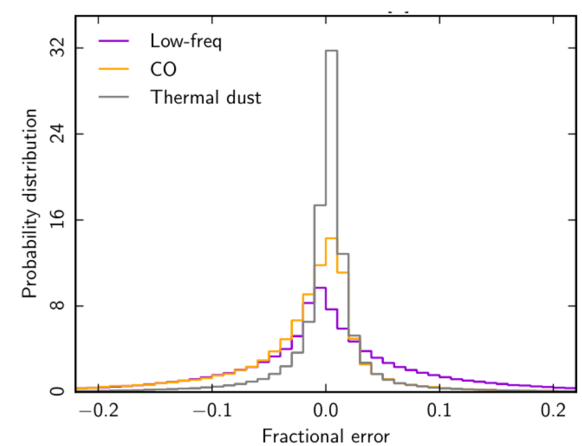
The Planck Collaboration XII

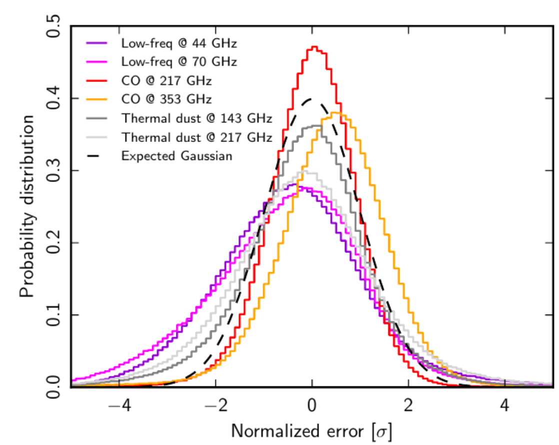
Validating on FFP6...



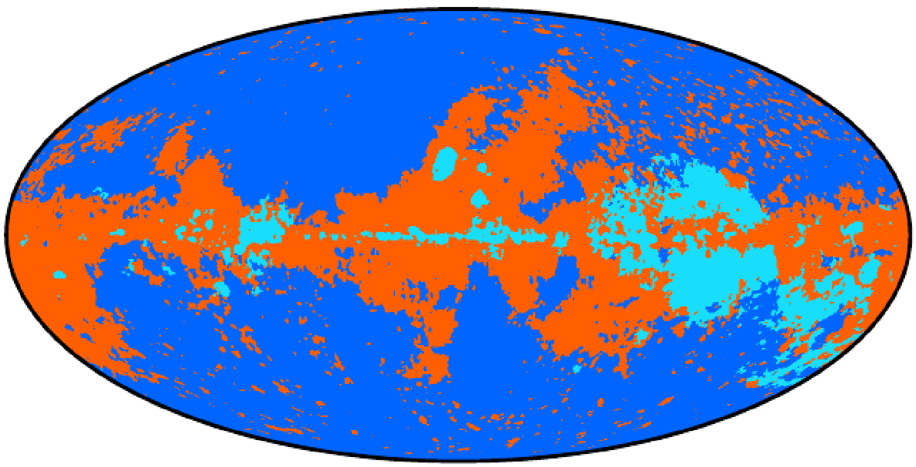
Validating on FFP6...

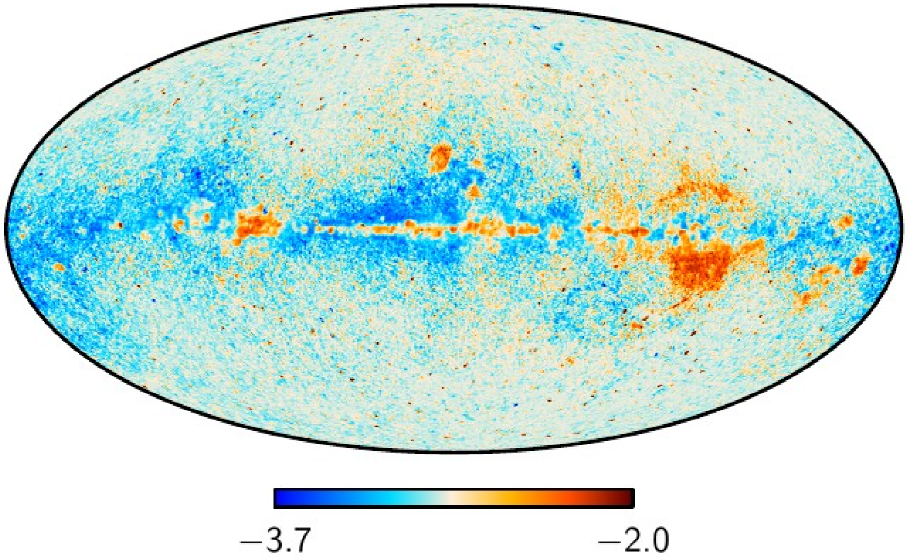






Validating on FFP6...





Conclusions: foregrounds

- Planck is able to separate diffuse Galactic foregrounds on 87% of the sky, quantifying uncertainties from the separation procedure as well as instrumental noise
- Planck resolves a single low frequency component amplitude and effective spectral index, CO line ratio, and a thermal dust amplitude and emissivity
- An extensive study involving other datasets is necessary for fully exploit the Planck capability of studying the astrophysical properties of foregrounds, in particular at low frequencies

What's next

- Over the next year we plan to...
- Say goodbye to Component Separation doing everything, welcome specialization for CMB extraction and foreground recovery
- Extracting Foregrounds using Ancillary Datasets
- Use more data, 2.5 years versus 1
- Continuing to study systematics, beam effect at arcminute resolution in particular
- Polarization...
- ...

Beams

- Beams transfer functions are provided
- NILC, SEVEM, SMICA adopt a Gaussian representation of the beam with 5 arcminutes FWHM
- C-R esimates the beam transfer function though FFP6 Mcs adopting in flight main beam measurements