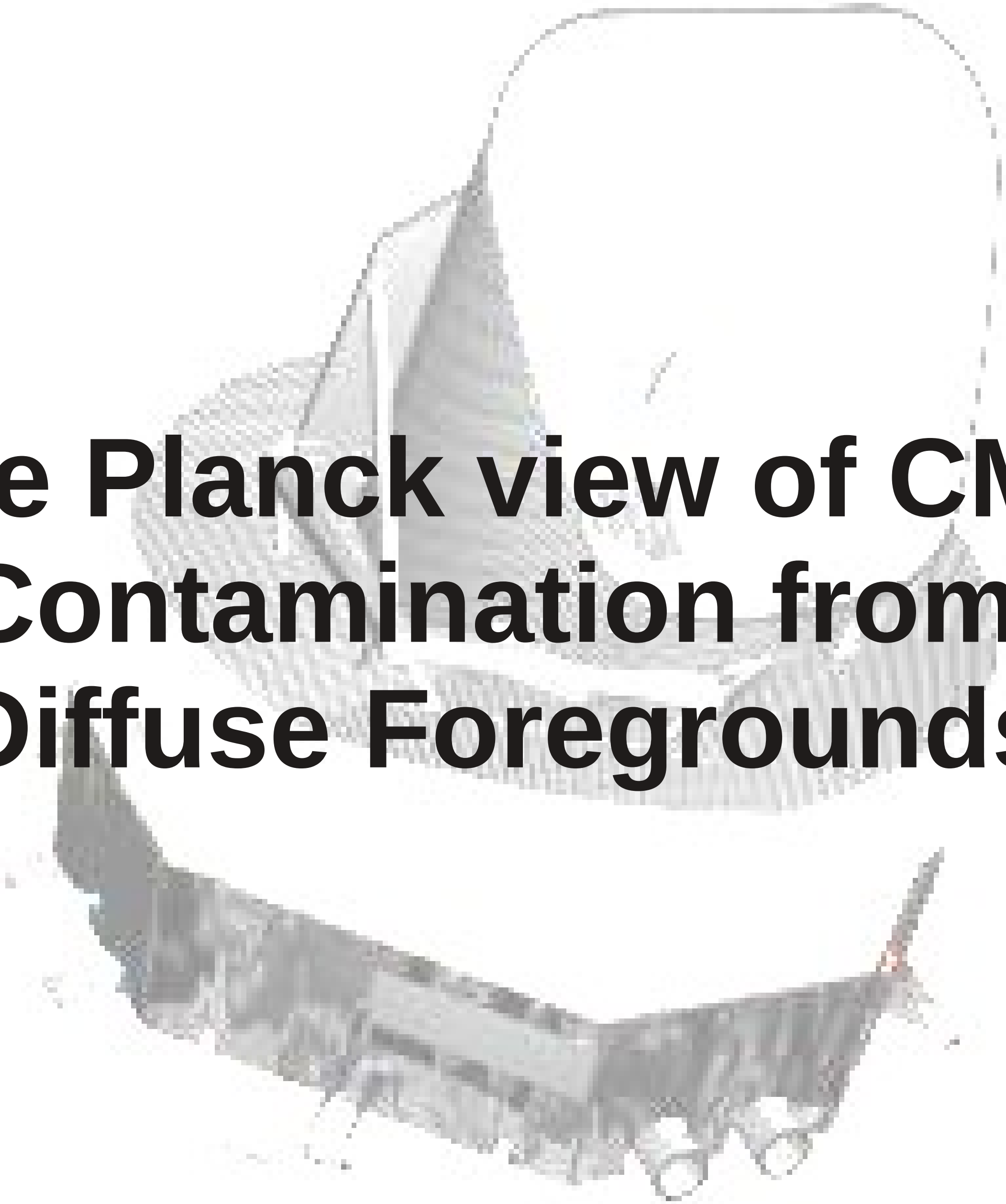

The Planck view of CMB Contamination from Diffuse Foregrounds

Carlo Baccigalupi, SISSA, Trieste
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

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Contribution from
Jean-Francois Cardoso

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- Component Separation for Planck
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- Cosmology from Component Separation } See Graca's talk
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- Conclusions

Outline

- Component Separation for Planck
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- Conclusions

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The Planck Component Separation Group

Component separation for Planck

Component Separation for Planck

$$d = As + n$$

Component Separation for Planck

Your data

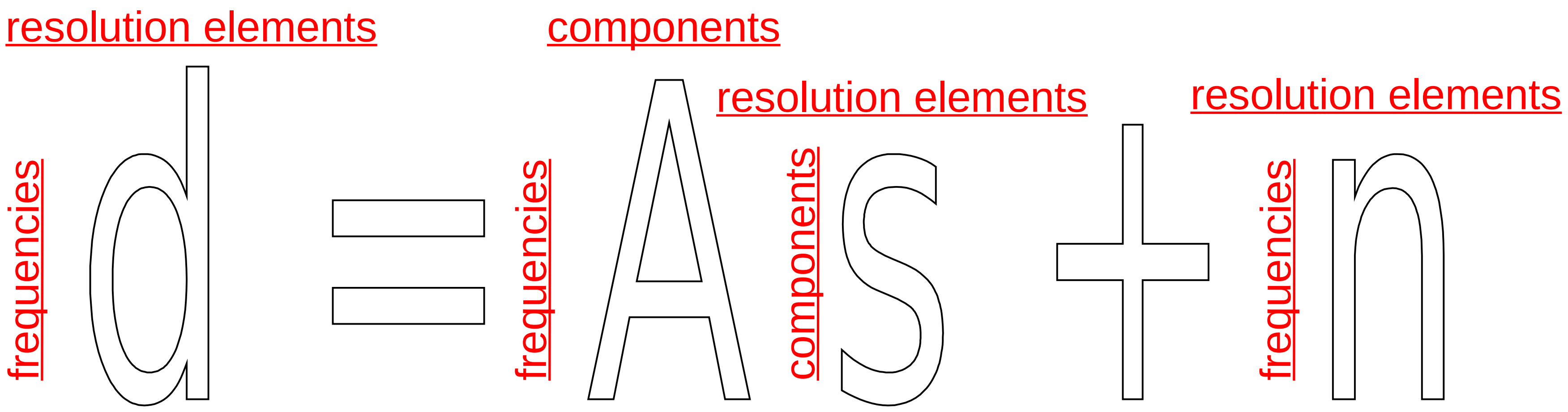
The mixing matrix

CMB and foregrounds

$$d = As + n$$

Noise

Component Separation for Planck



resolution elements

components

resolution elements

resolution elements

frequencies

frequencies

components

frequencies

$$d = As + n$$

On foregrounds you...

- Know nothing
- Know something

Thus you...

- Look for minimum variance
- Model and fit

And you...

- Look for minimum variance
    1. not int the pixel domain
    2. in the pixel domain
- Model and fit
    3. not in the pixel domain
    4. in the pixel domain

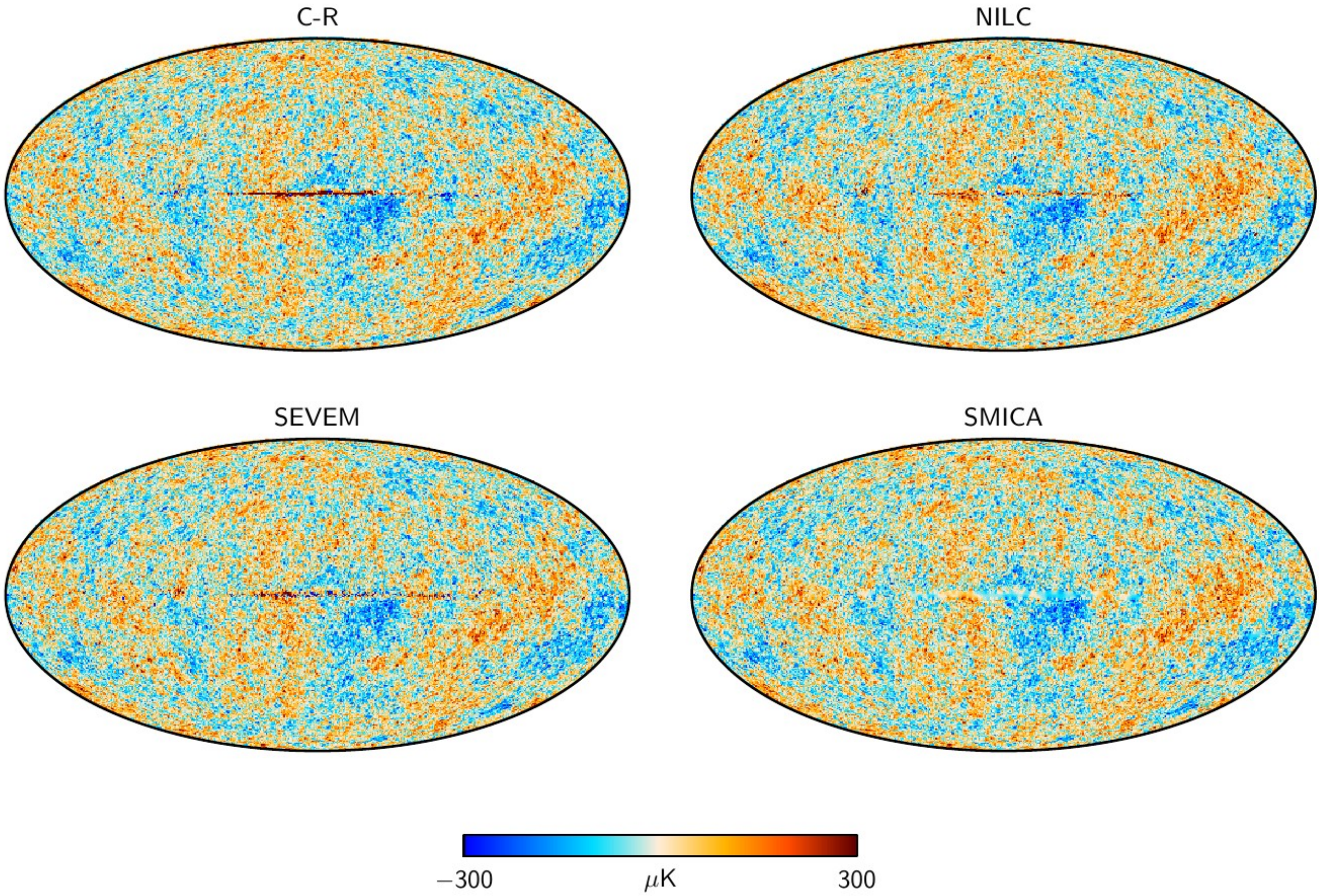
And you...

- 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

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

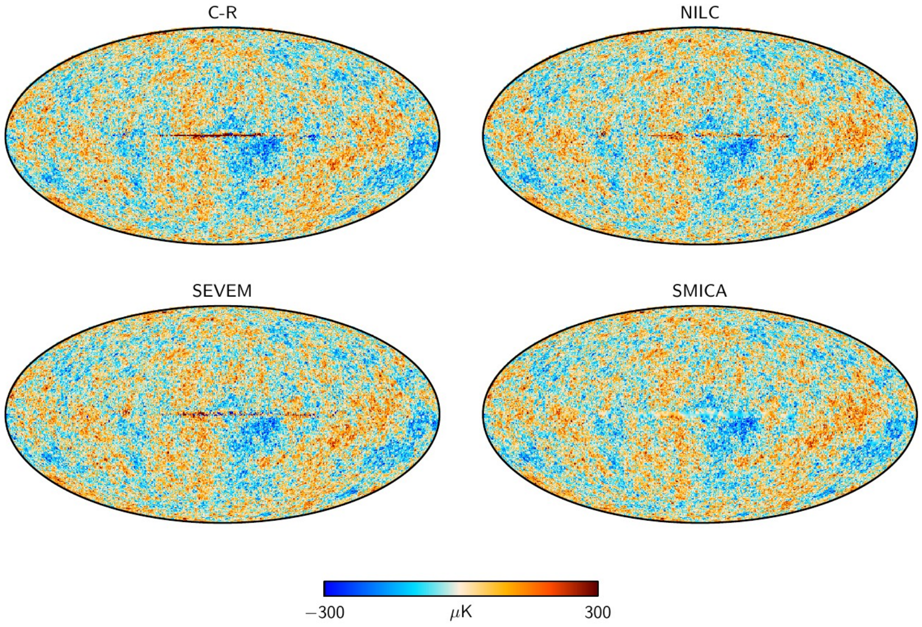
CMB solutions



The Planck Collaboration XII

Characterization of the CMB solutions

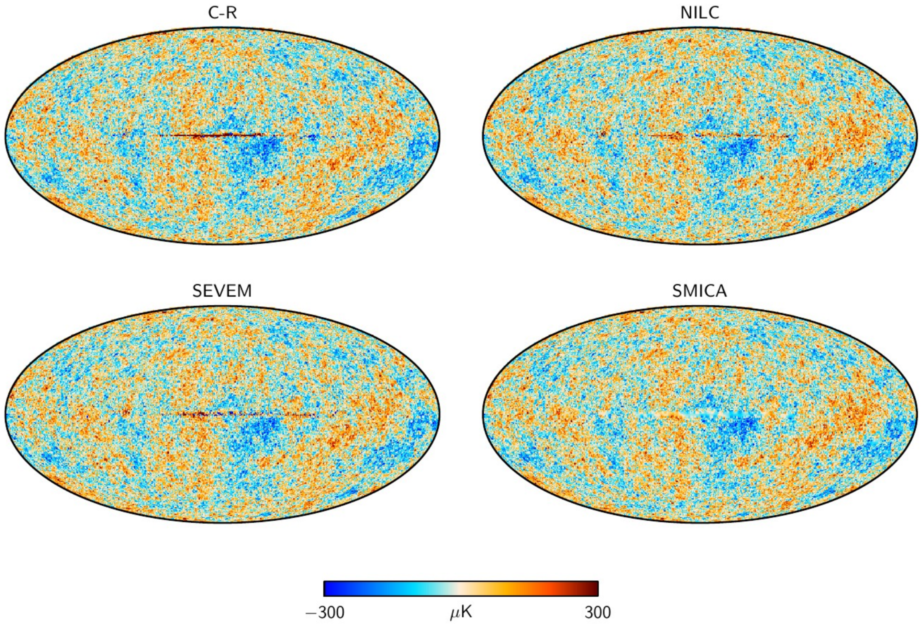
- Parallel runs on data and Full Focal Plane (FFP6) simulations, including the best in flight knowledge of instrumental behavior
- Instrumental error is propagated through noise variance (and covariance at low l for C-R for use in the likelihood) as well as through half-ring differences
- Beam information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



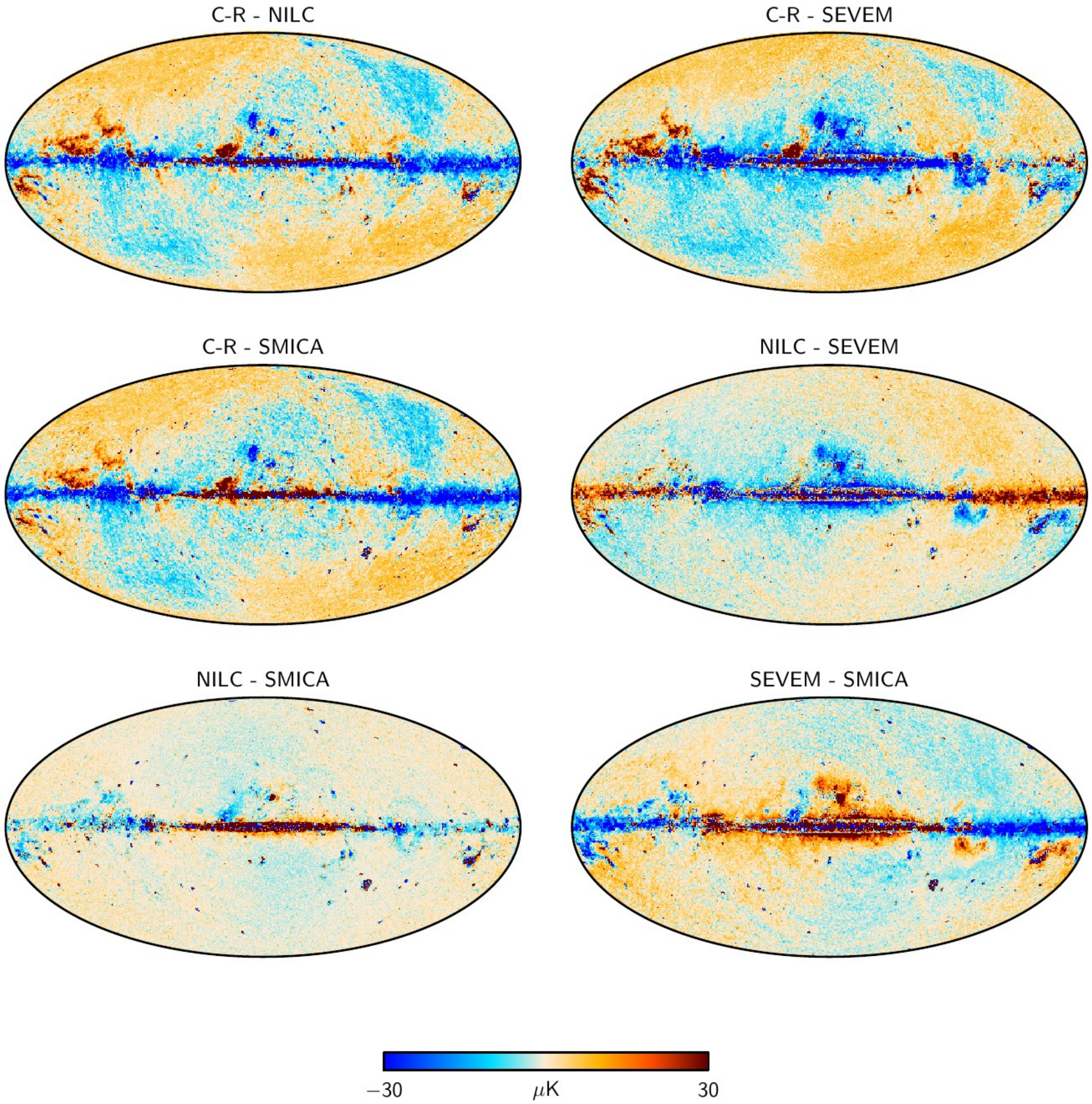
The Planck Collaboration XII

CMB solutions and Planck papers

- 2013 papers where component separation products were used for quantitative analyses:
  - 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
  - ...

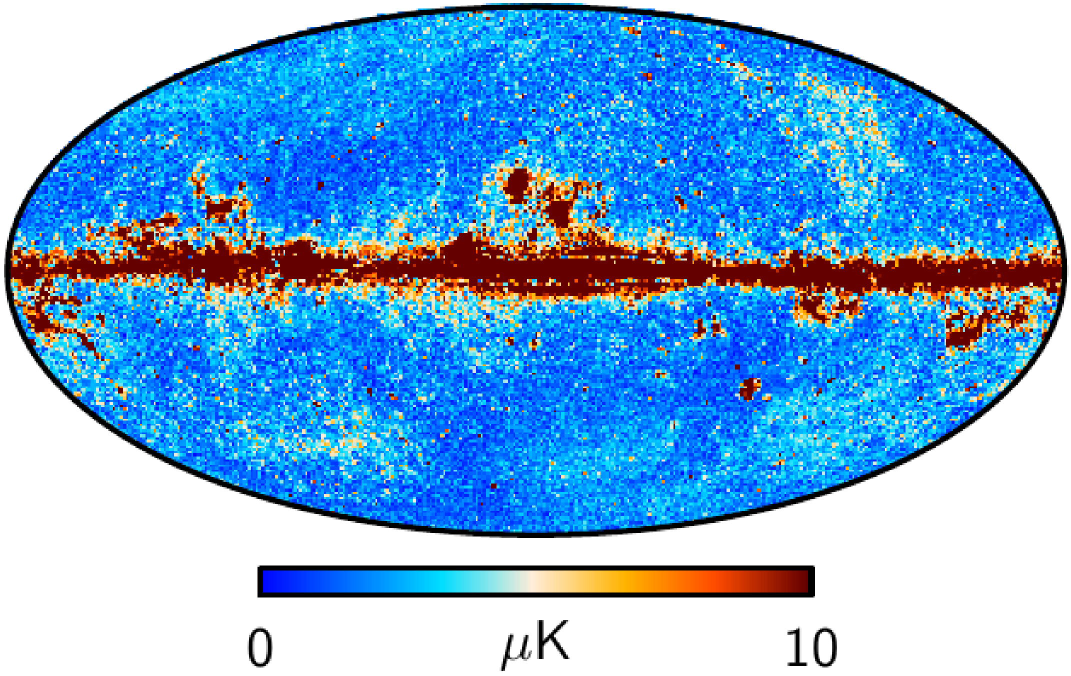


CMB solutions differences



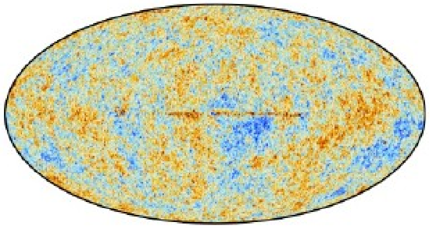
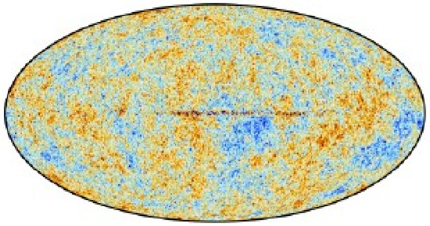
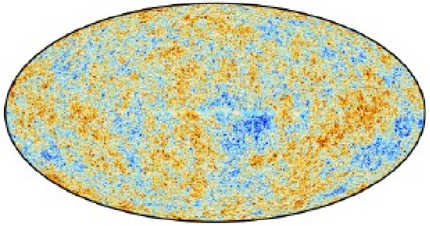
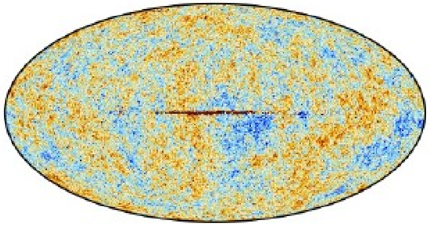
The Planck Collaboration XII

CMB standard deviation evaluated over methodology



The Planck Collaboration XII

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

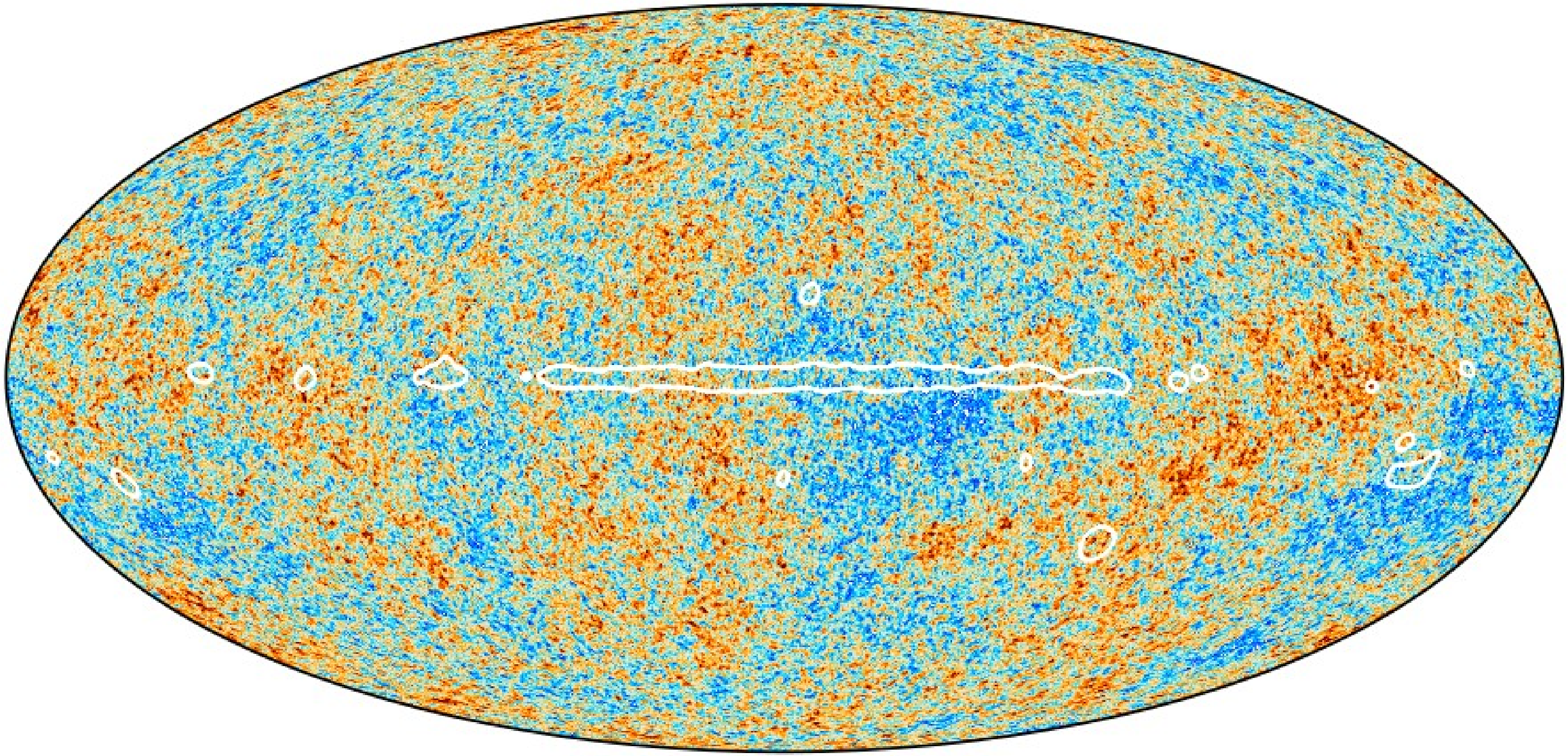
			
NILC	SEVEM	SMICA	C-R
$\ell_{\mathrm{max}} = 3200$	$\ell_{\mathrm{max}} = 3100$	$\ell_{\mathrm{max}} = 4000$	Pixel-based
5 arc-min	5 arc-min	5 arc-min	$\sim$ 7 arc-min
$\ell_{\mathrm{SNR=1}} = 1790$	$\ell_{\mathrm{SNR=1}} = 1790$	$\ell_{\mathrm{SNR=1}} = 1790$	$\ell_{\mathrm{SNR=1}} = 1550$
non-parametric	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; slide from Jean-Francois Cardoso @ ESLAB

Update: inpainted CMB maps delivered for SMICA and NILC (end of March)



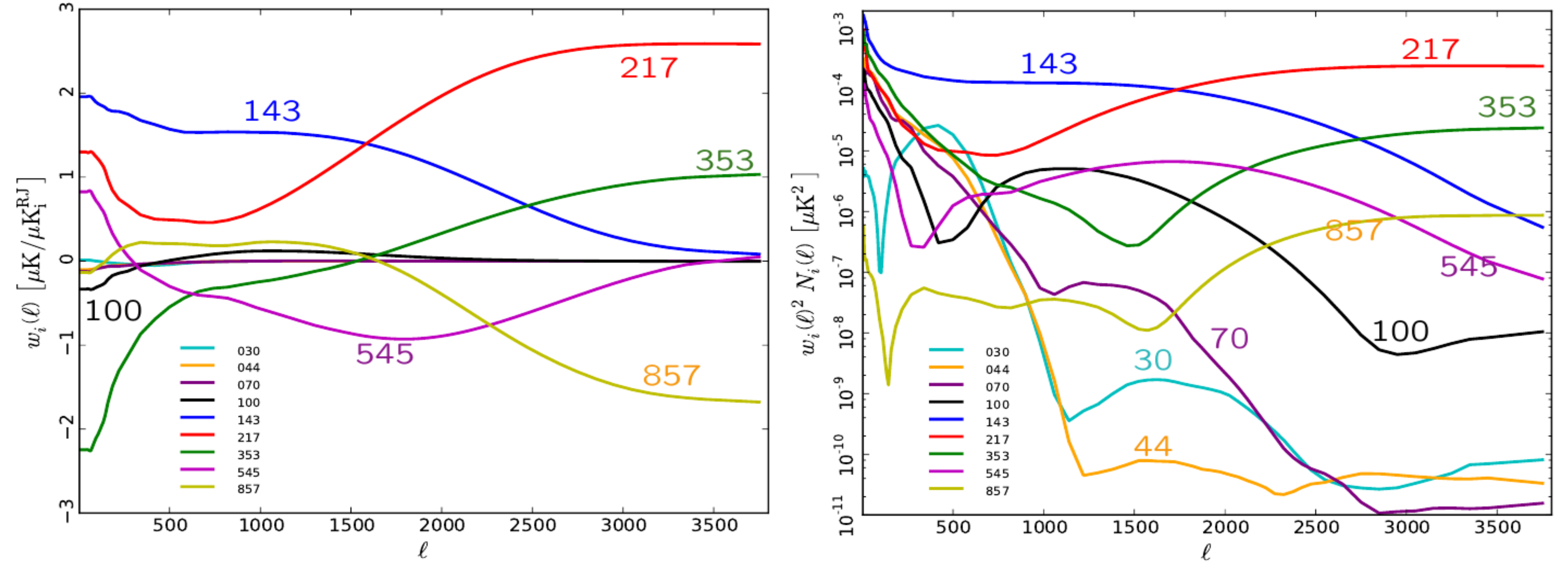
Inpainting of 3% of the sky: ‘large’ bright regions (shown here) plus the masked point sources.

The inpainted SMICA map was used for PR. Good scientific value too.

The Planck Collaboration XII; slide from Jean-Francois Cardoso @ ESLAB

Highlights on Component Separation: Spectral Matching

What SMICA does to signal... and to noise



SMICA channel weighting vs multipole

Noise contribution from each channel

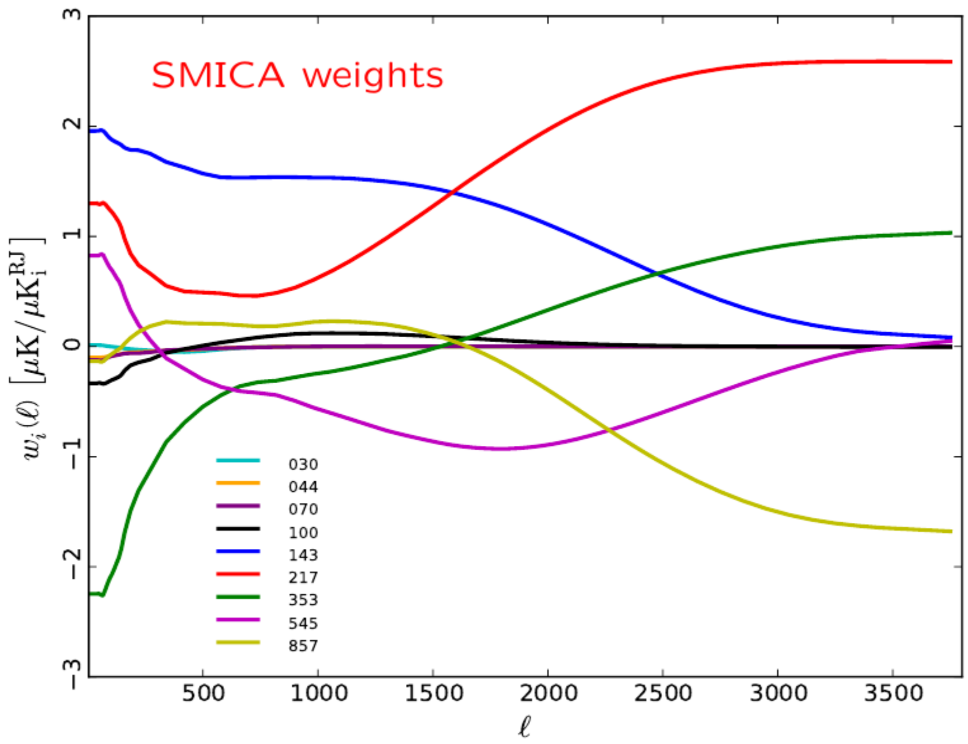
The data (and common sense) are telling us to let the weights depend on angular frequency.

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

The Planck Collaboration XII; appendix D; slide from Jean-Francois Cardoso @ ESLAB

Highlights on Component Separation: Spectral Matching

SMICA filtering (where do those weights come from?)



Combine channels in harmonic space:

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

Assume coherent CMB:

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

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

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

- 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;appendix D; slide from Jean-Francois Cardoso @ ESLAB

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!

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

- 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; appendix D; slide from Jean-Francois Cardoso @ ESLAB

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

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

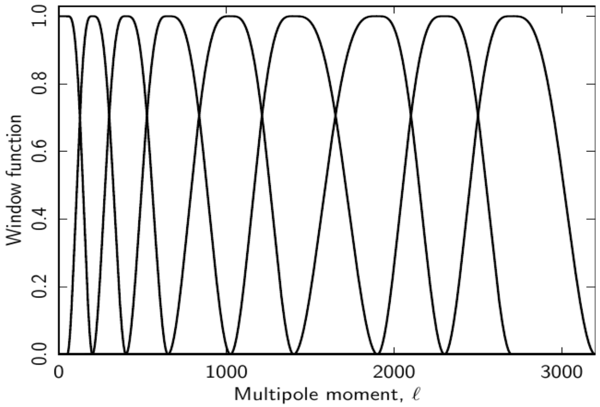
    For instance, a sky-varying low-frequency emission $\mathbf{a}_{\text{LF}}(\theta_{\text{pix}})$ could be approximatively represented by two fixed columns over the whole sky: $[\ \mathbf{a}_{\text{LF}}(\langle\theta\rangle),\ d\mathbf{a}_{\text{LF}}/d\theta(\langle\theta\rangle)\ ]$

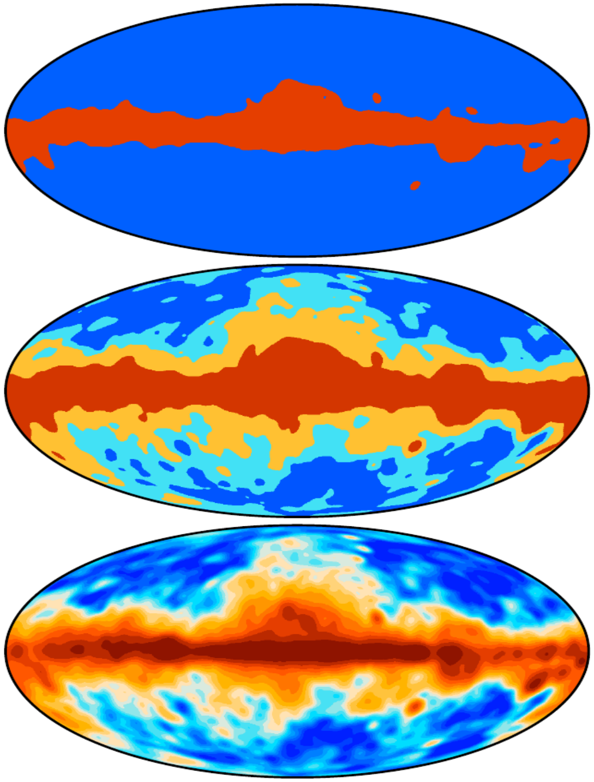
    What SMICA does: use more columns in $\mathbf{A}$ than physical foregrounds.

The Planck Collaboration XII; appendix D; slide from Jean-Francois Cardoso @ ESLAB

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; appendix B

Highlights on Component Separation: Physical Parametrization

Probability(s,parameters|d)=Likelihood(s,parameters) priors

- Direct physical parametrization in the pixel domain
- MCMCs with Gibbs sampling at intermediate resolution (n_{side}=256) targeting spectral parameters, likelihood analysis for cosmology (Commander), see the Planck Collaboration XV
- High resolution inversion through generalized least square based on low resolution, adopting diagonal covariance matrices (Ruler)

The Planck Collaboration XII; appendix A

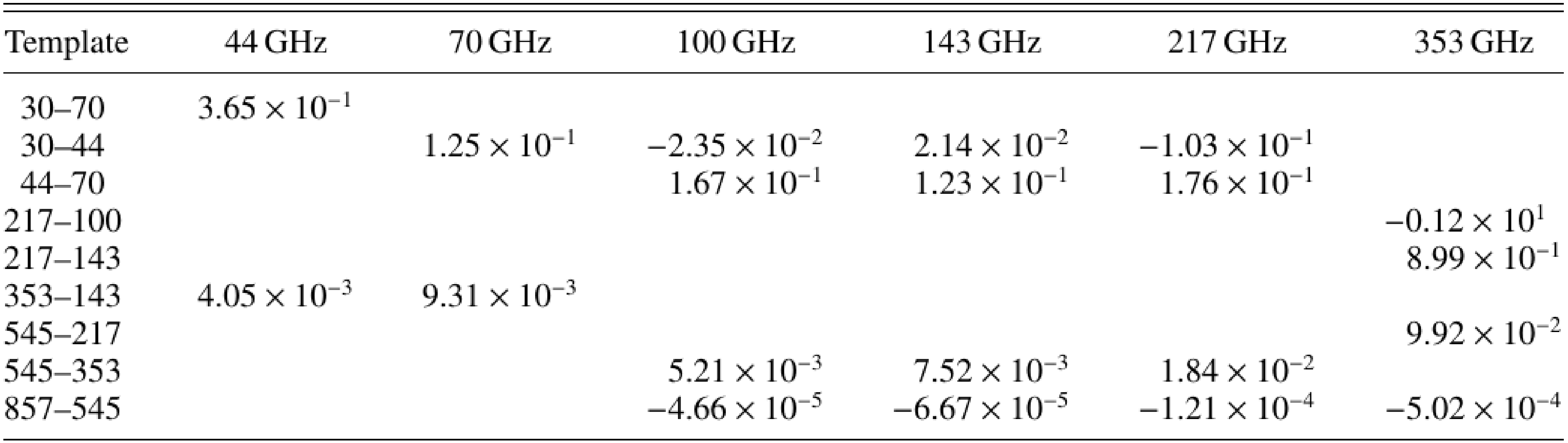
Highlights on Component Separation: Template Fitting

$$s = d - \Sigma_{\text{frequencies}} \text{ coefficients frequencies}$$

- Foregrounds are estimated through differenciation of data at Planck frequencies
- Cleaning is achieved by looking for minimum variance combination in CMB dominated channels, at 100, 143, 217 GHz

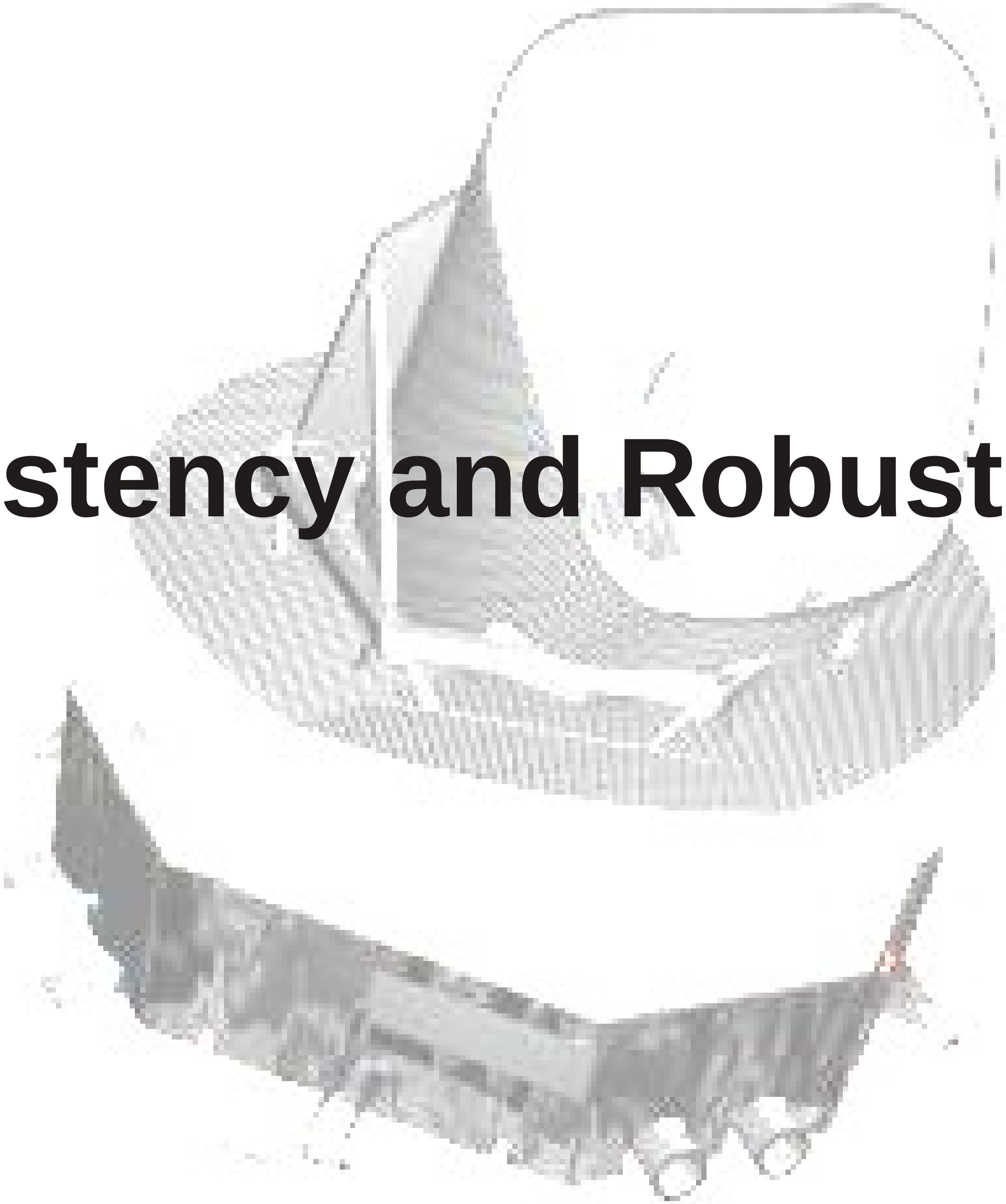
The Planck Collaboration XII; appendix C

Highlights on Component Separation: Template Fitting Coefficients



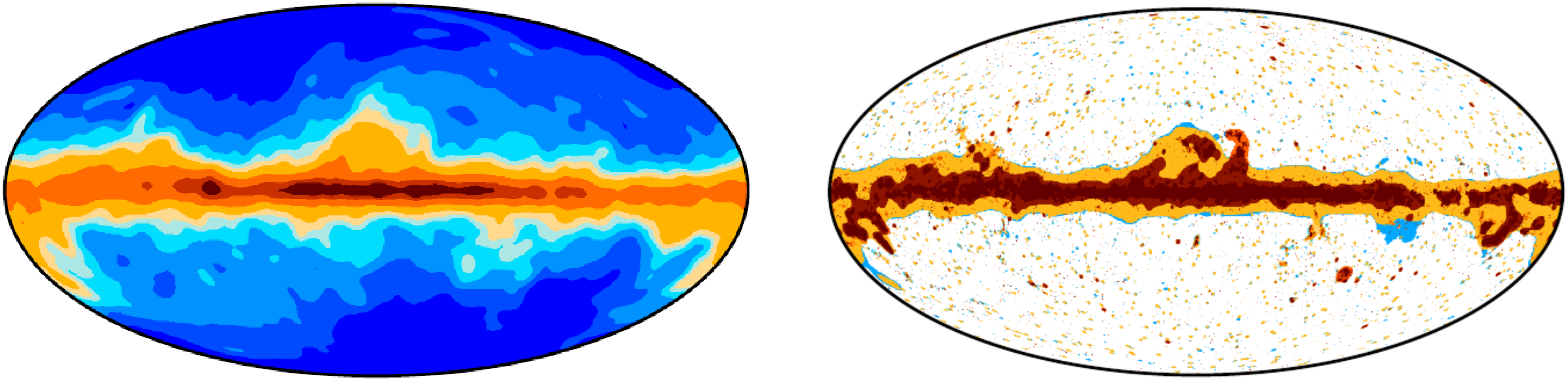
Template	44 GHz	70 GHz	100 GHz	143 GHz	217 GHz	353 GHz
30–70	3.65×10^{-1}					
30–44		1.25×10^{-1}	-2.35×10^{-2}	2.14×10^{-2}	-1.03×10^{-1}	
44–70			1.67×10^{-1}	1.23×10^{-1}	1.76×10^{-1}	
217–100						-0.12×10^{1}
217–143						8.99×10^{-1}
353–143	4.05×10^{-3}	9.31×10^{-3}				
545–217						9.92×10^{-2}
545–353			5.21×10^{-3}	7.52×10^{-3}	1.84×10^{-2}	
857–545			-4.66×10^{-5}	-6.67×10^{-5}	-1.21×10^{-4}	-5.02×10^{-4}

The Planck Collaboration XII; appendix C

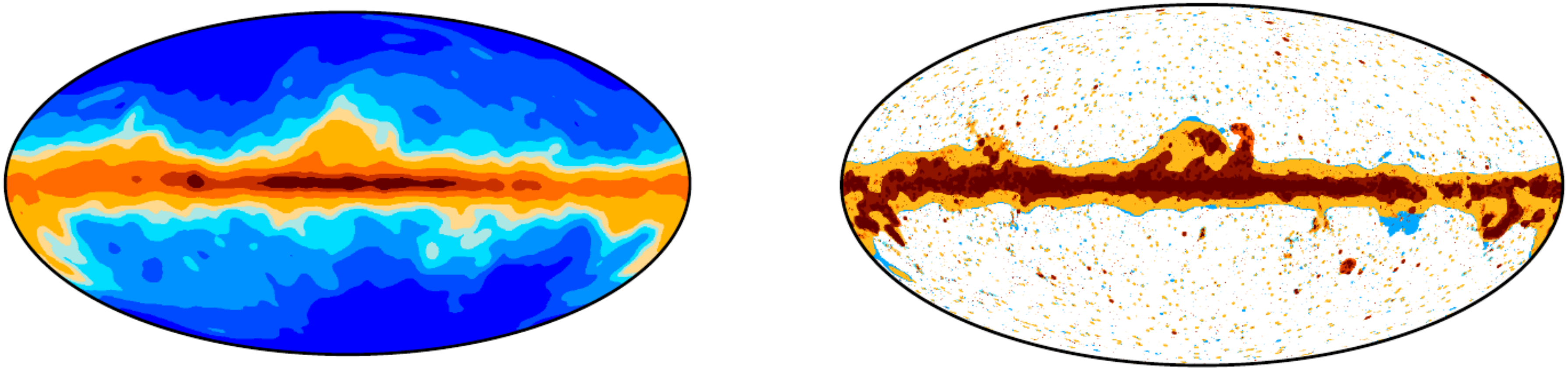


Consistency and Robustness

Sky masks

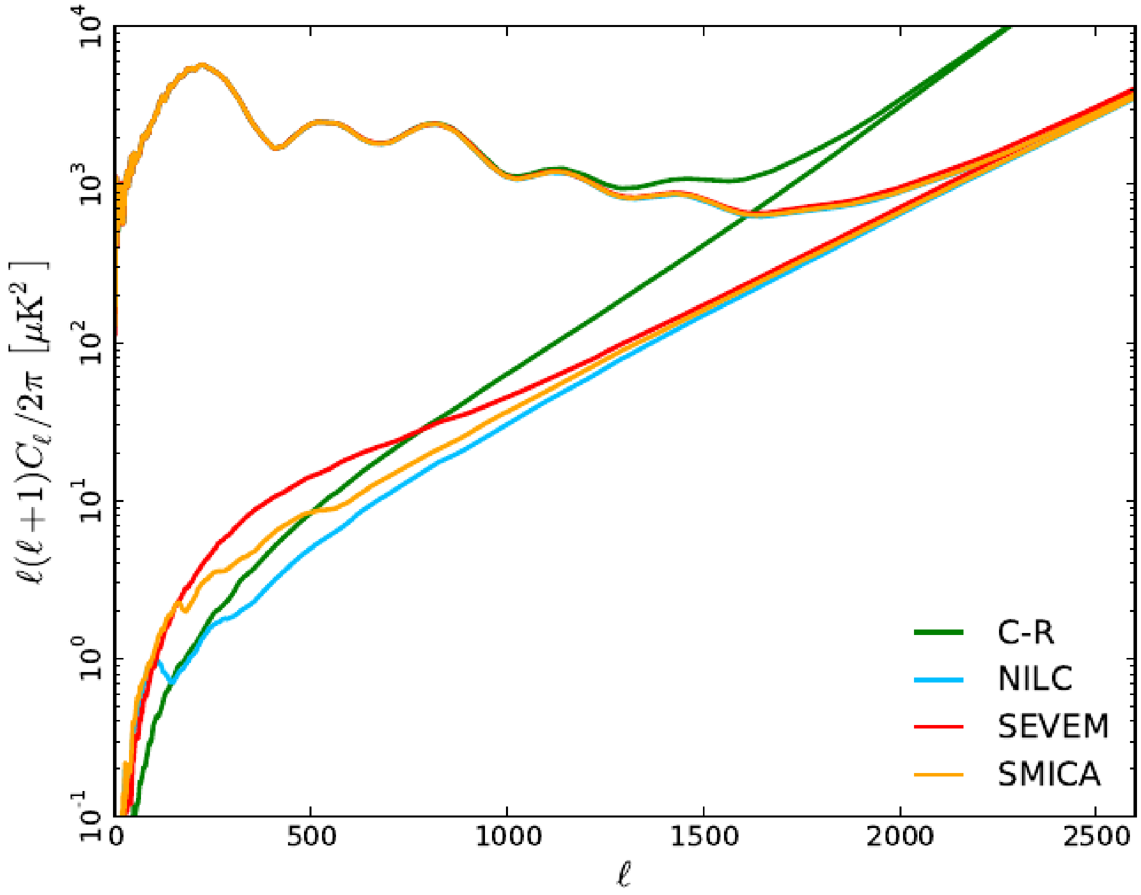


Sky masks

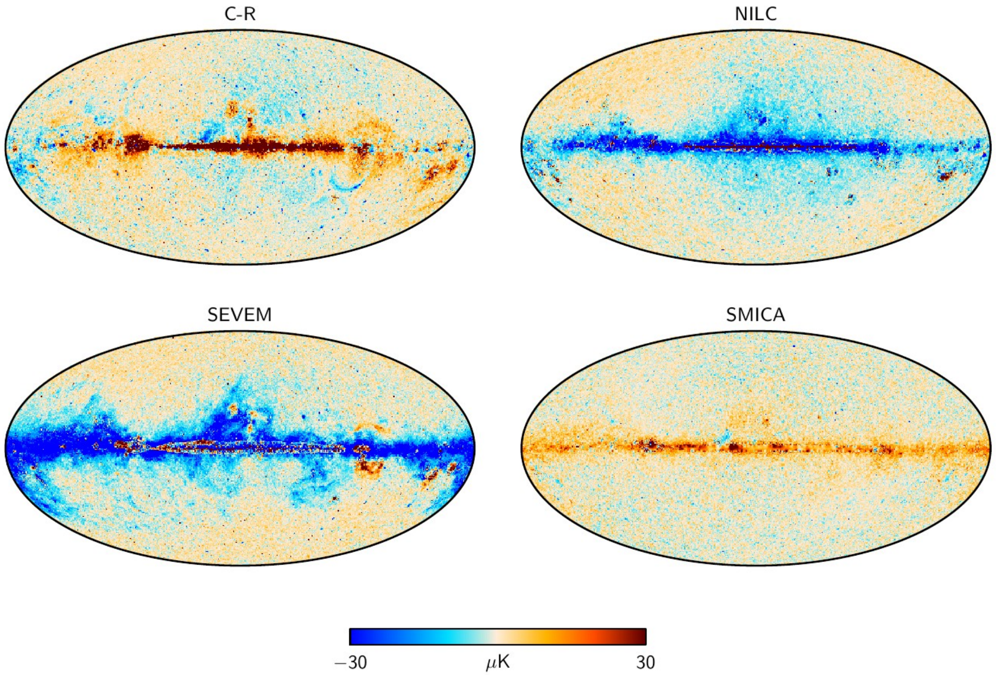


- Threshold maskings is made by combining 30 and 353 Ghz flux thresholding for achieving a given sky fraction
- Confidence masks are method dependent:
  - C-R: 87% from fitting efficiency
  - NILC: 97% thresholding mask
  - SEVEM: 97% thresholding mask
  - SMICA: 97% thresholding mask
  - For quantitiative analysis, point source and 80% sky masking (CG80) are superimposed to confidence masks, see Graca's talk

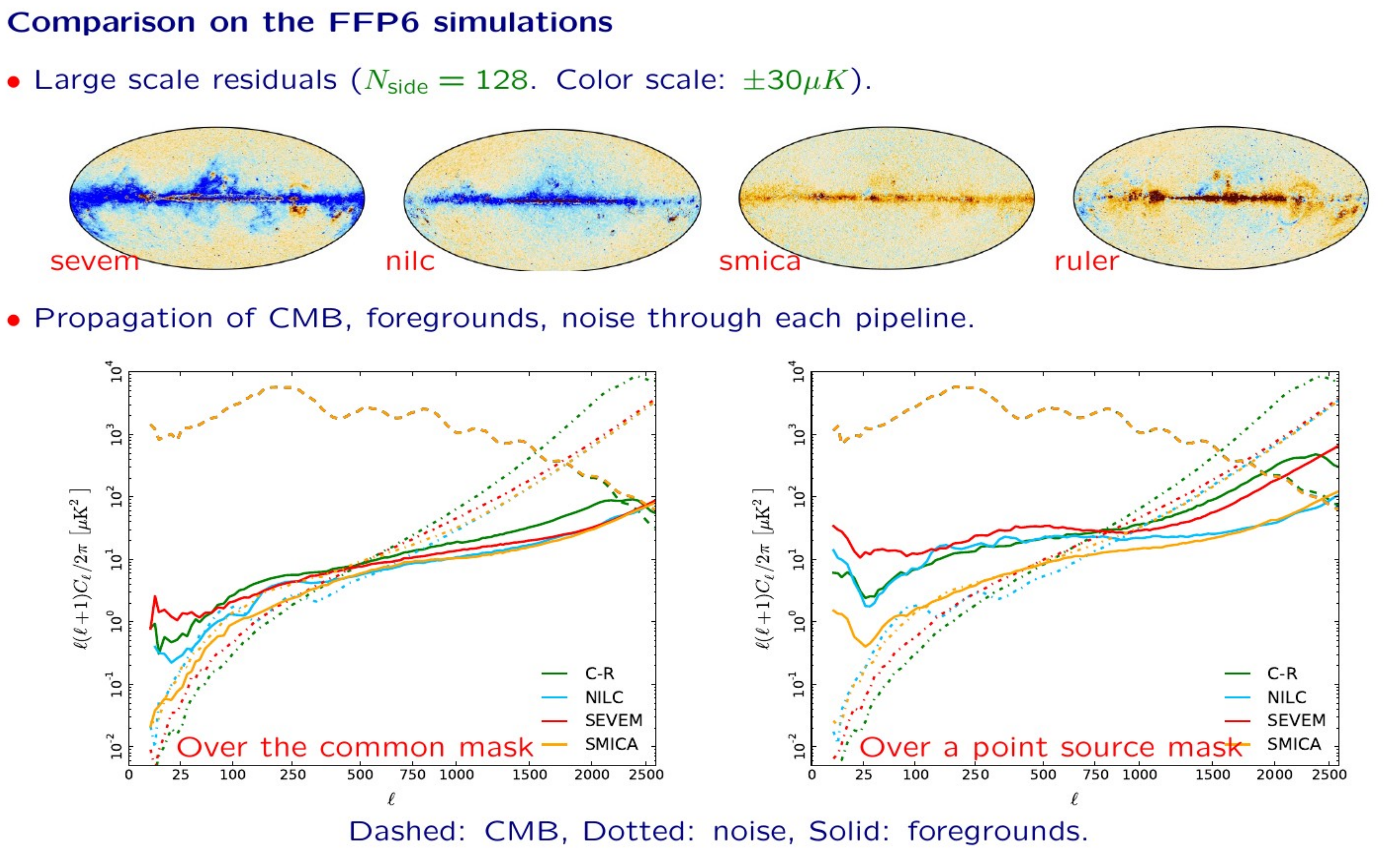
Pseudo-spectra



Null tests on FFP6: foreground residuals



Null tests on FFP6: Pseudo-spectra for foreground residuals



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.

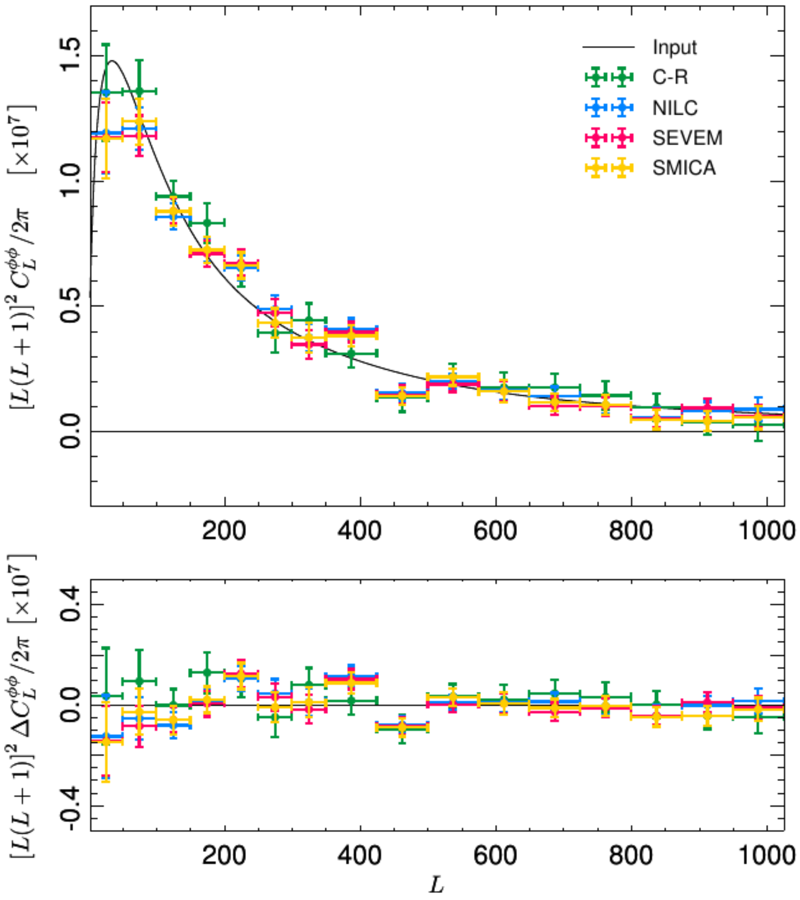
Dashed: CMB, Dotted: noise, Solid: foregrounds.

The Planck Collaboration XII; slide from Jean-Francois Cardoso @ ESLAB

Null tests on FFP6:
primordial non-Gaussianity

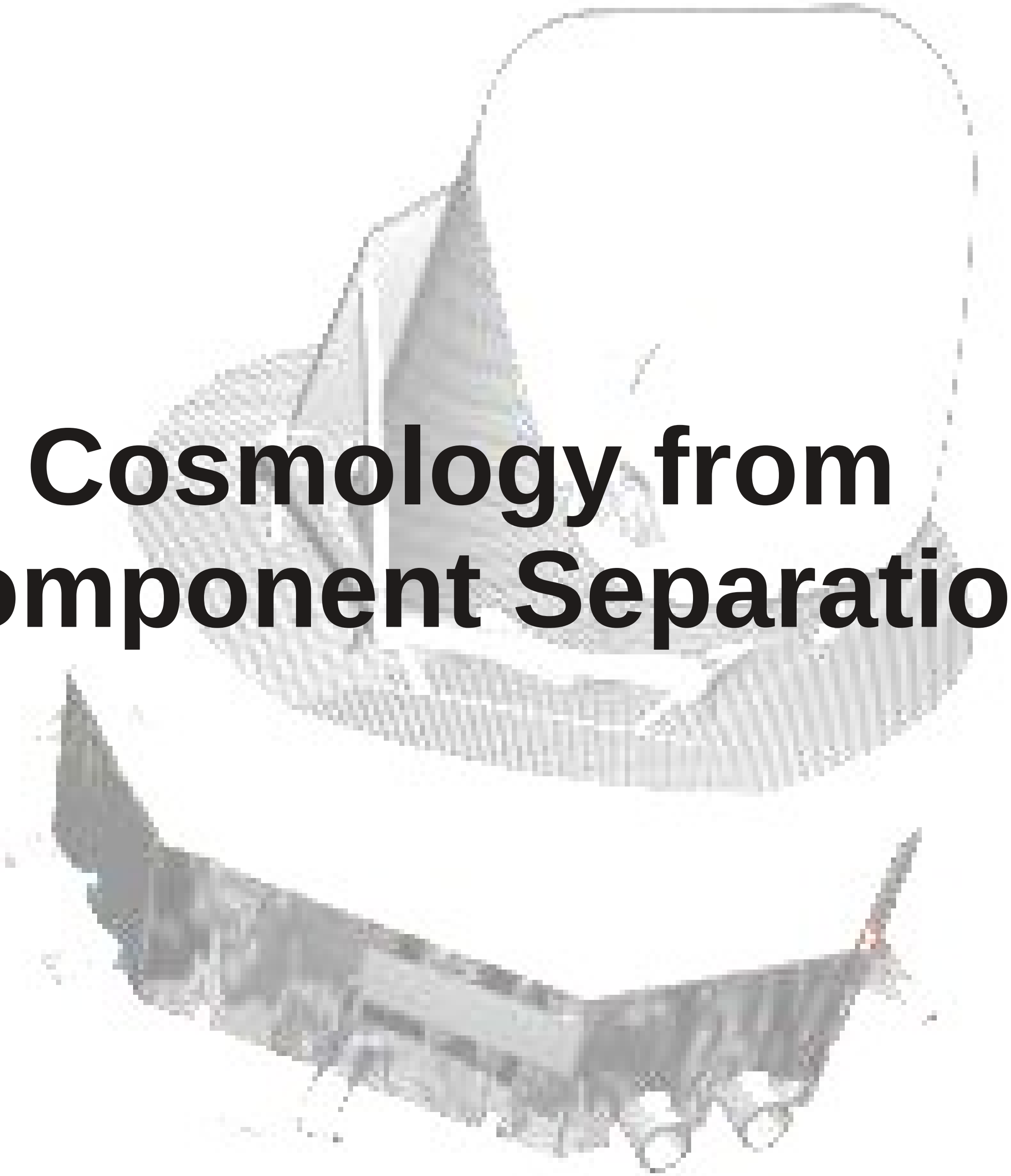
- Two FFP tests were conducted on simulated observations containing on-Gaussian distortion with non-zero and detectable f_{NL} (about 20)
- Tests were conducted blindly
- All four methodologies reported positive detection at 2σ

Null tests on FFP6: lensing



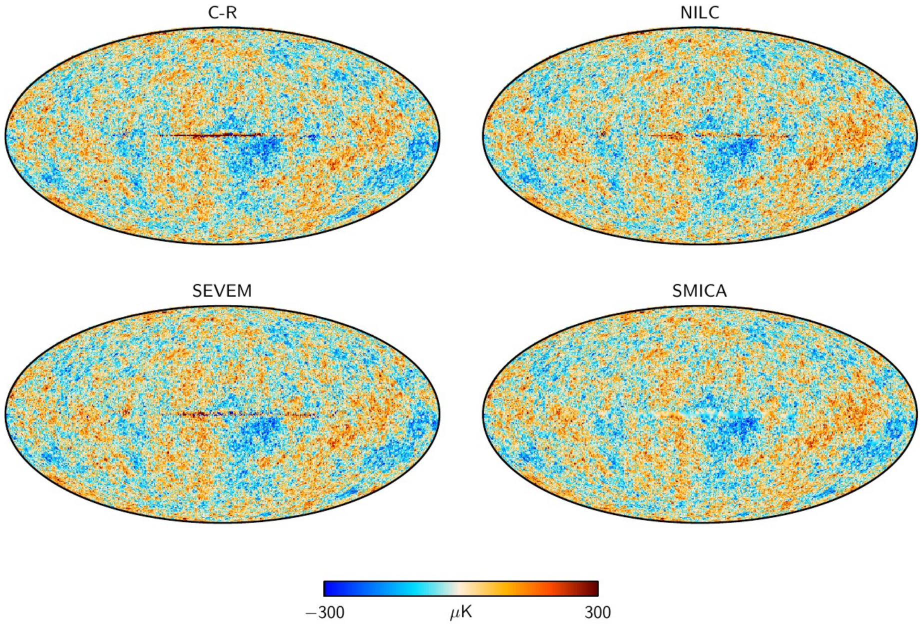
The Planck Collaboration XII

Cosmology from Component Separation



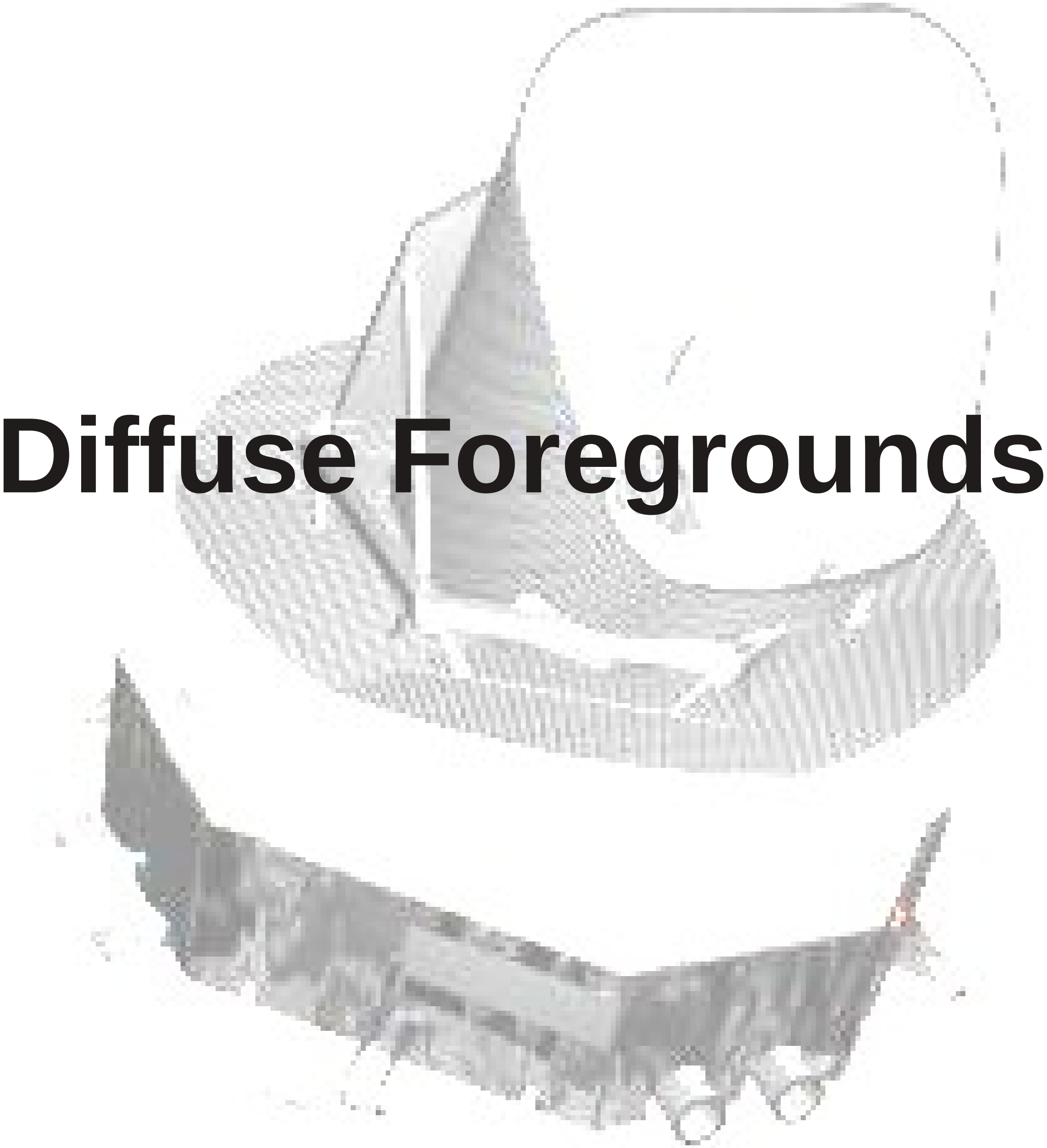
Cosmology with Component Separation

- 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



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 due to (invincible?) Galactic complexity
- Simulations enable us to isolate the SMICA solution as the one with the lowest expected residual contamination from diffuse foregrounds



Diffuse Foregrounds

Fitting 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, Gibbs sampling
- 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

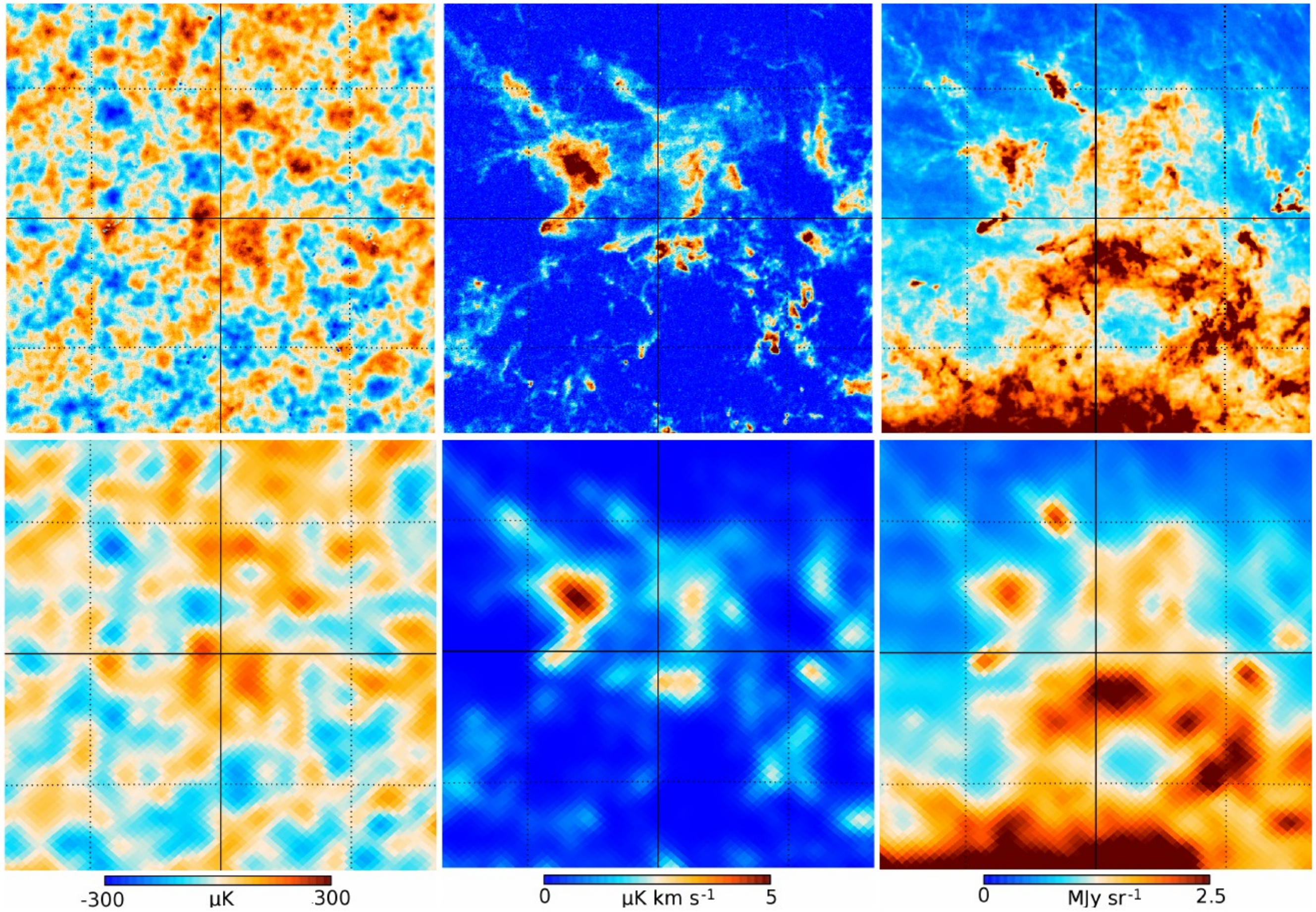
Studying diffuse foregrounds with Planck

- Results for diffuse foregrounds in the Planck XII paper, although outstanding, are not representative of the full use that we can do with Planck concerning diffuse foregrounds
- Foreground oriented component separation studies using ancillary data are in progress
- Foreground analyses on targeted emissions/sky regions were and are being published in specific papers:
  - Planck 2013 paper, XIII: CO
  - Planck 2013 paper, XIV: Zodiacal Light Emission
  - Planck 2013 paper, in preparation: Dust Opacity
  - Planck 2013 intermediate paper, XII: the Gould Belt Region
  - Planck 2013 intermediate paper, IX: the Galactic haze
  - Planck 2012 early papers, XVII: the anomalous dust emission
  - Planck 2012 early paper, XIX, XXI, XXIV, XXV: interstellar dust
  - Planck 2012 early paper, XX: the anomalous dust emission
  - Planck 2012 early papers, XXII-XXII
  - ...l

Foreground model

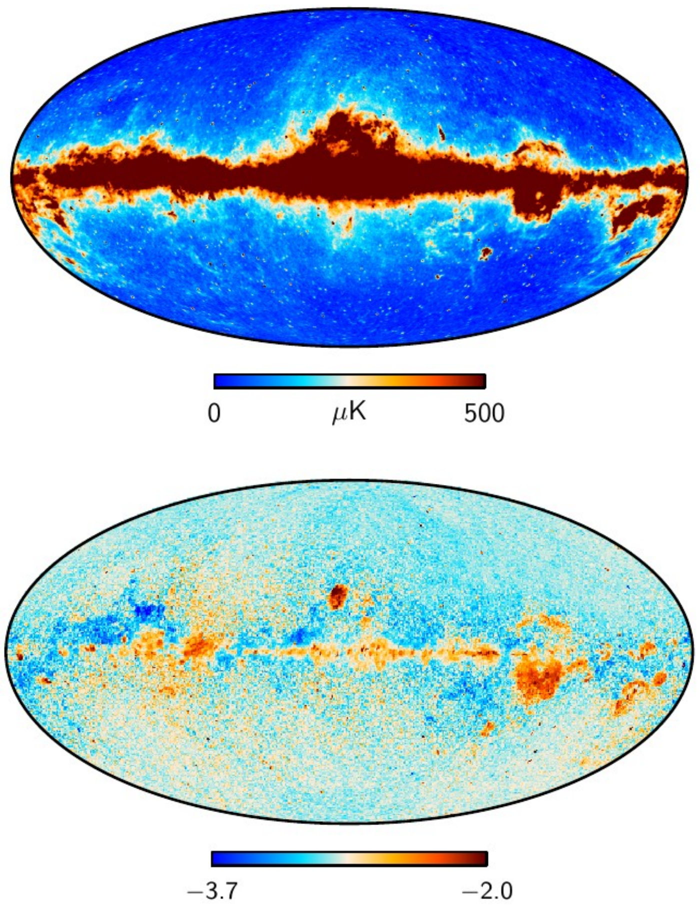
- Low frequency amplitude at 30 GHz and spectral index, effectively describing a mixture of various astrophysical effects, as Brehmsstrahlung (free-free), Anomalous Dust Emission (AME), Synchrotron
- CO amplitude at 100 GHz
- Thermal Dust amplitude at 353 GHz and grey body temperature and emissivity
- All parameters estimated at low resolution ($n_{side} = 256$), estimated mixing matrix applied to the data to gain high resolution results

From Commander to Ruler



The Planck low frequency foregrounds

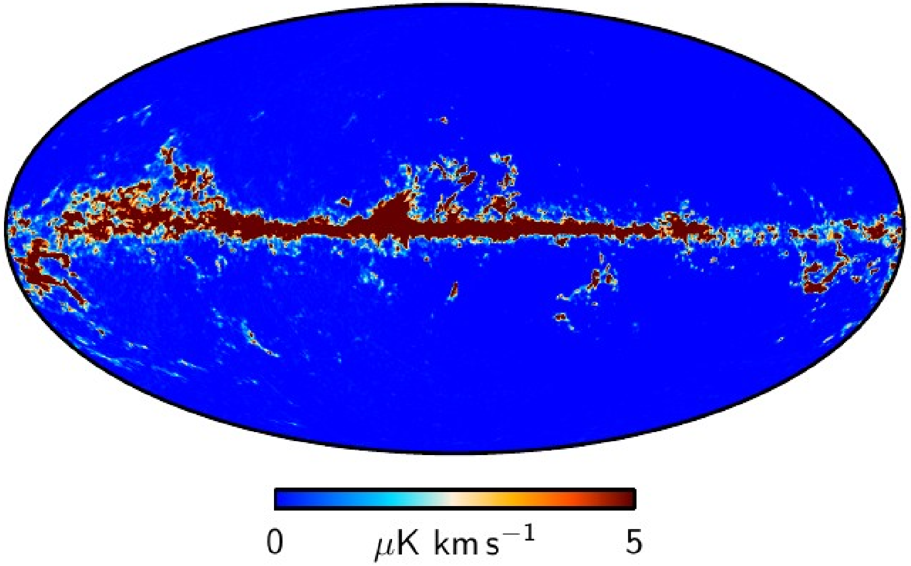
- Amplitude and spectral index of the low frequency component as seen by Planck
- Different emission mechanisms, such as Brehmsstralung, synchrotron and low frequency dust emission are reflected in the sky distribution of the spectral index



The Planck Collaboration XII

CO emission as seen by Planck

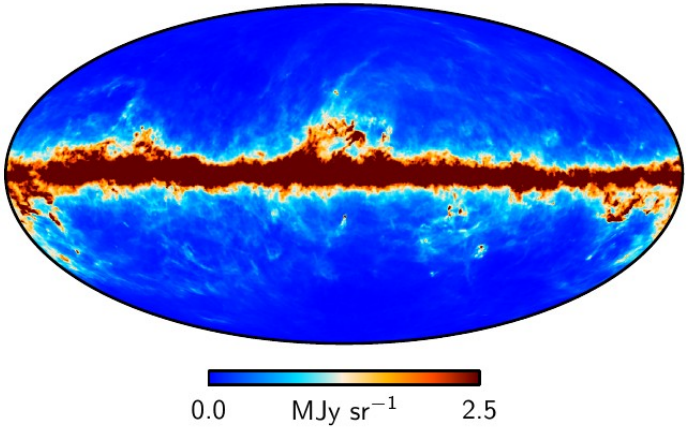
- Planck is sensitive to 9 CO transition lines in its frequency range
- A single amplitude is adopted for isolating intense CO emission regions and provide guidance to follow-up observations

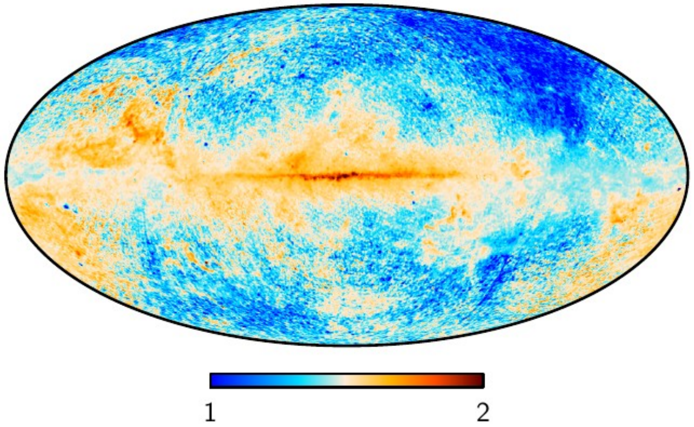


The Planck Collaboration XII

The Planck view of thermal dust

- Planck provides an exquisite high sensitivity and resolution mapping of the Galactic thermal dust over hundreds of Ghz
- Planck resolves the sky pattern of dust emissivity, reflecting different phases in the interstellar gas
- Separate and independent reconstructions in the main component separation paper (XII) and Dust Opacity reconstruction (in progress) considering highest frequency channels





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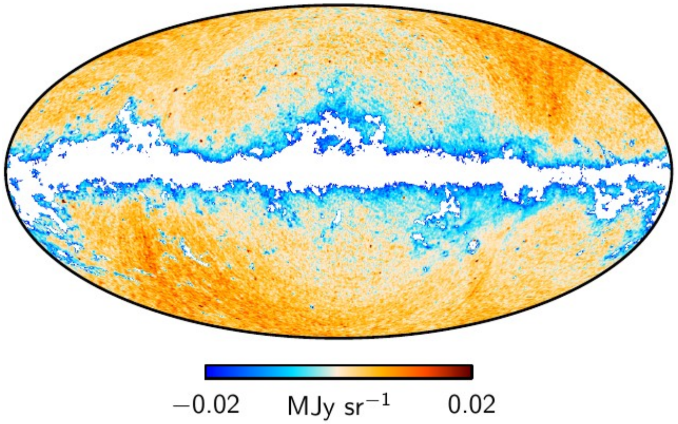
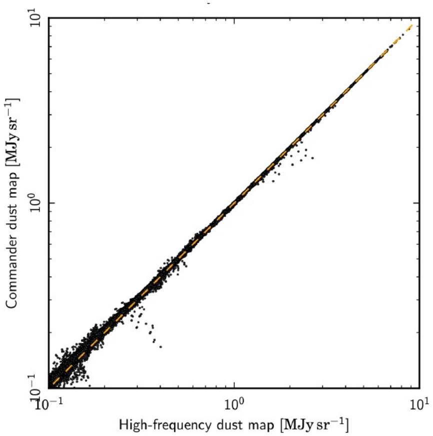
The Planck view of thermal dust

- 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





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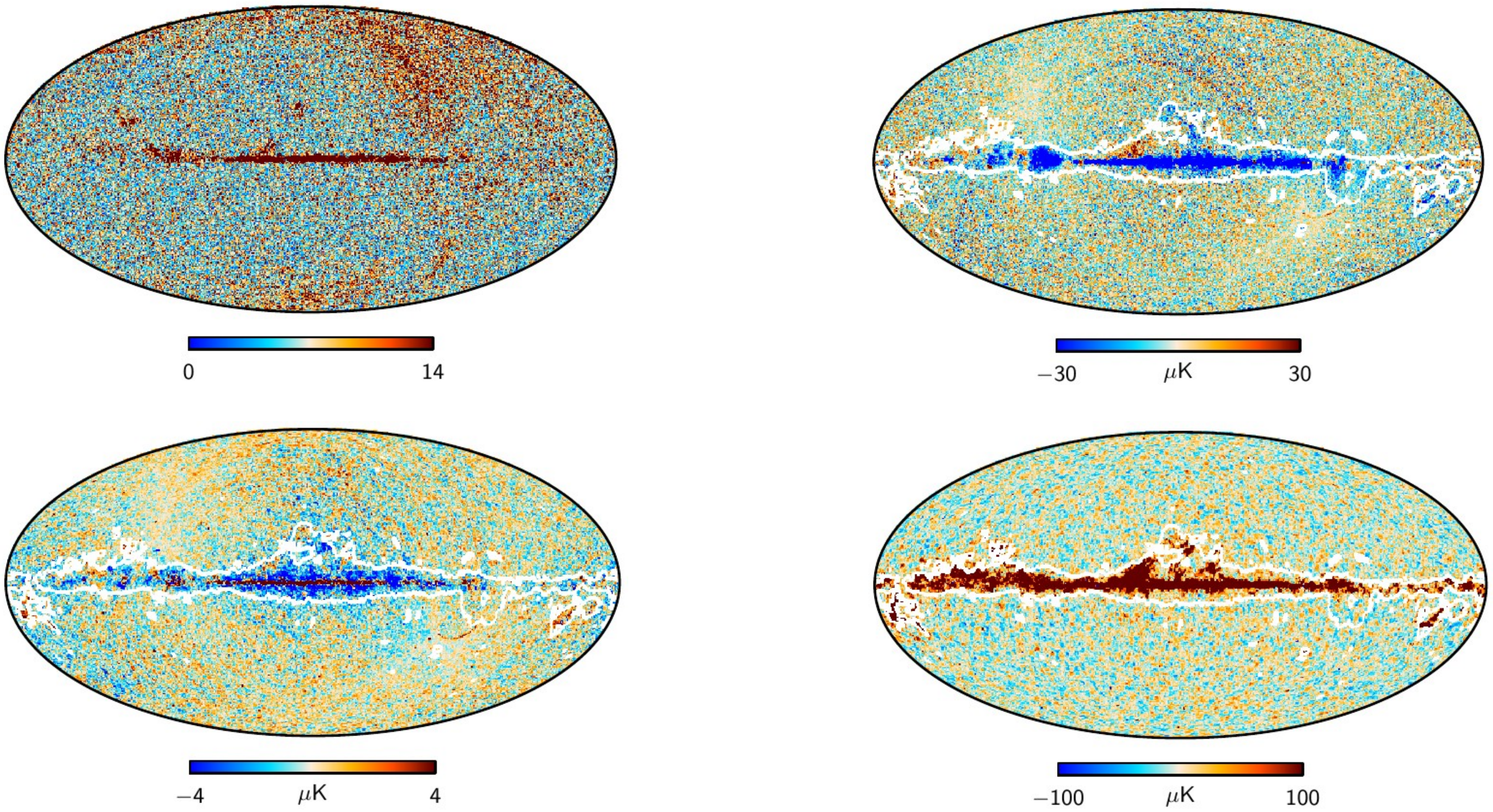
Validating on FFP6...



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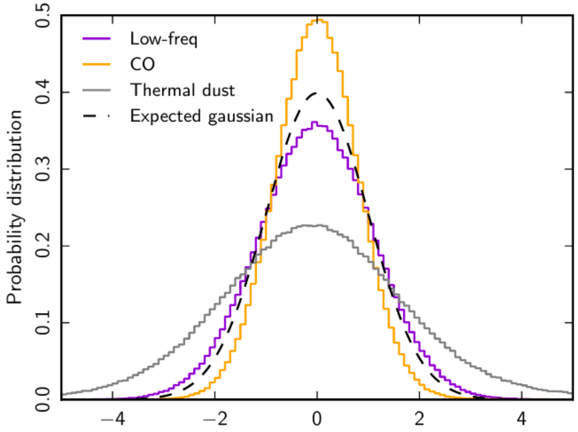
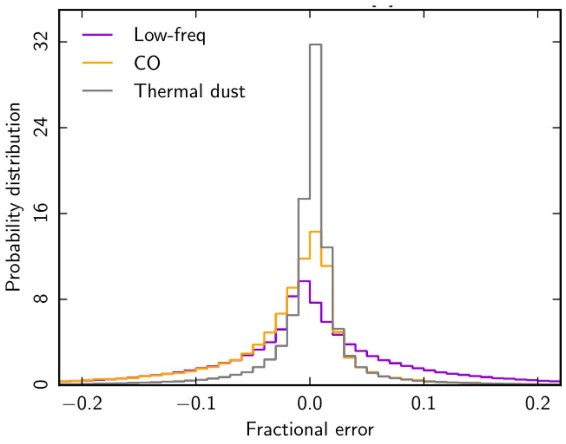
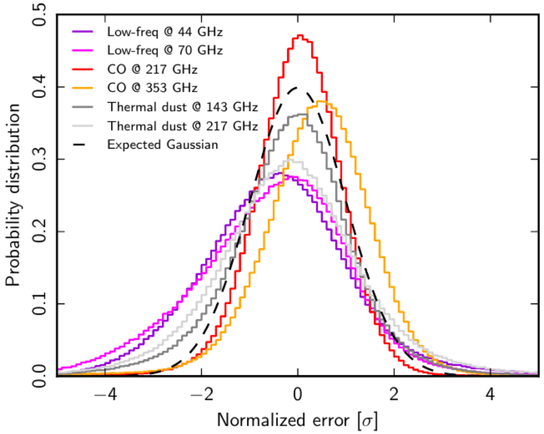
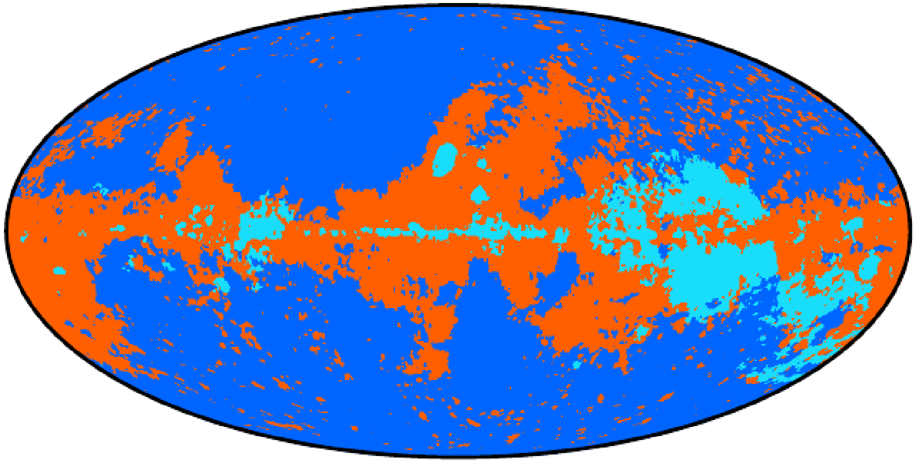
Validating on FFP6...

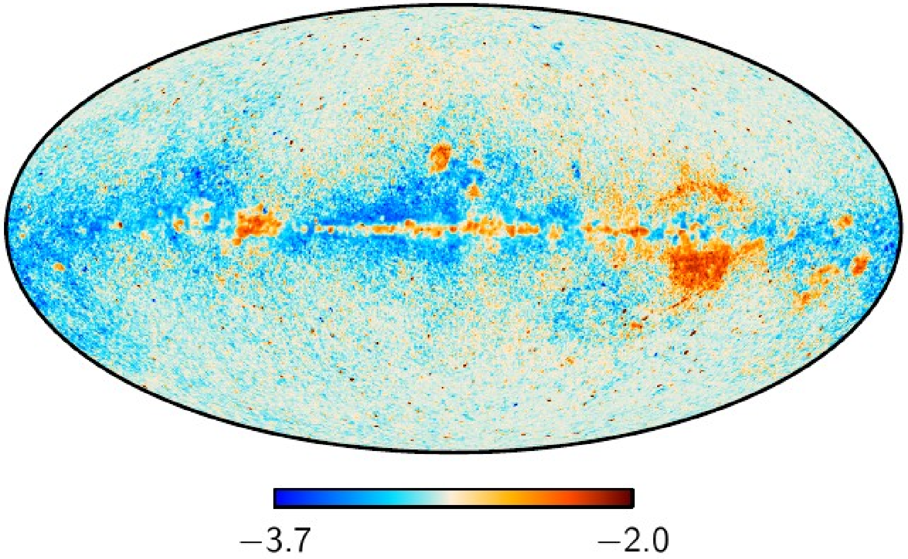






Validating on FFP6...





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 low frequency components parametrized as amplitude and spectral index, CO emission, 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
- Studies targeting specific emissions/sky regions have and are being worked out for achieving the full Planck capability as a diffuse foreground observatory

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...
- ...

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National Space Institute

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INAF ISTITUTO NAZIONALE DI ASTROFISICA

CSIC
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DLR Deutsches Zentrum für Luft- und Raumfahrt e.V.

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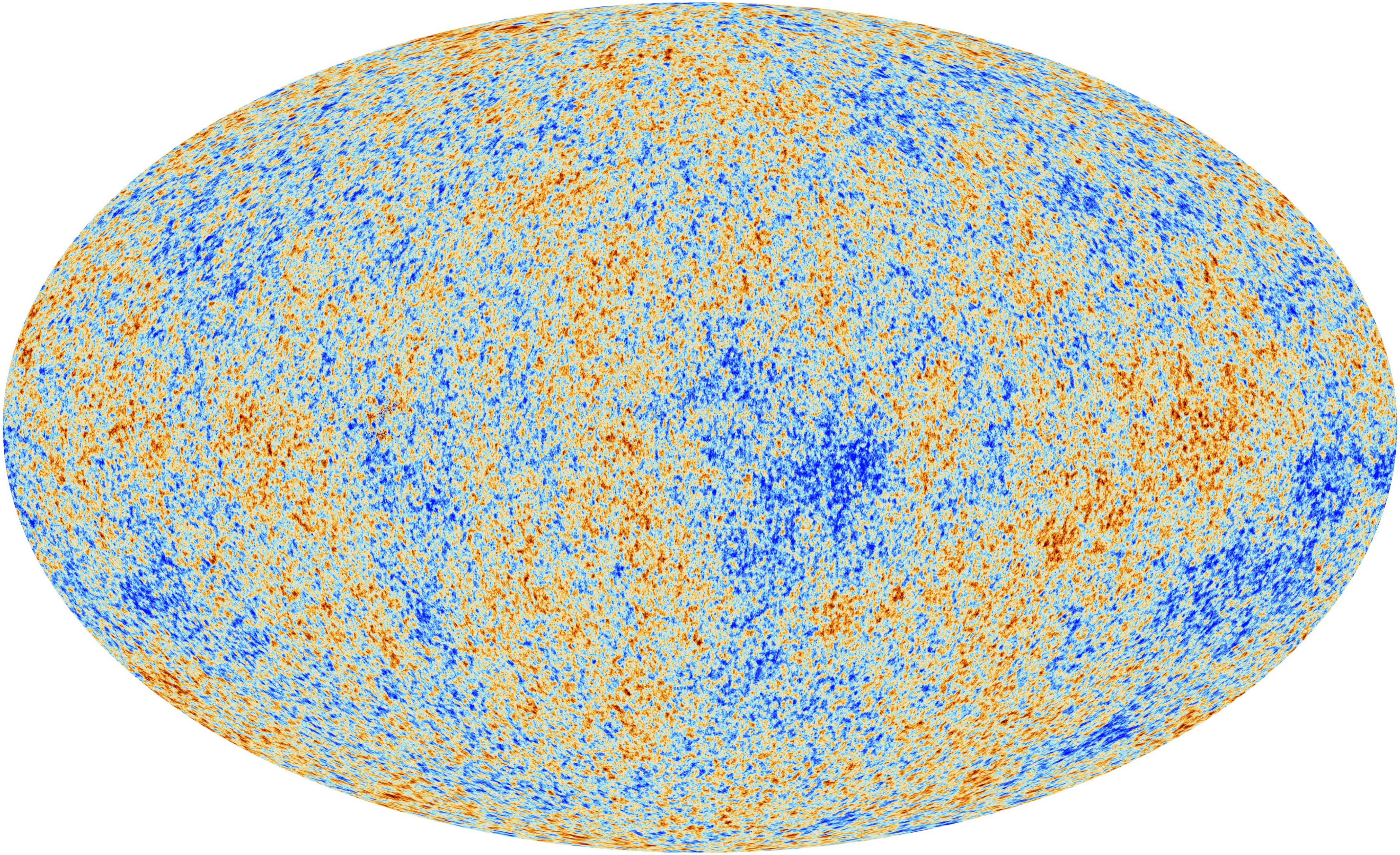

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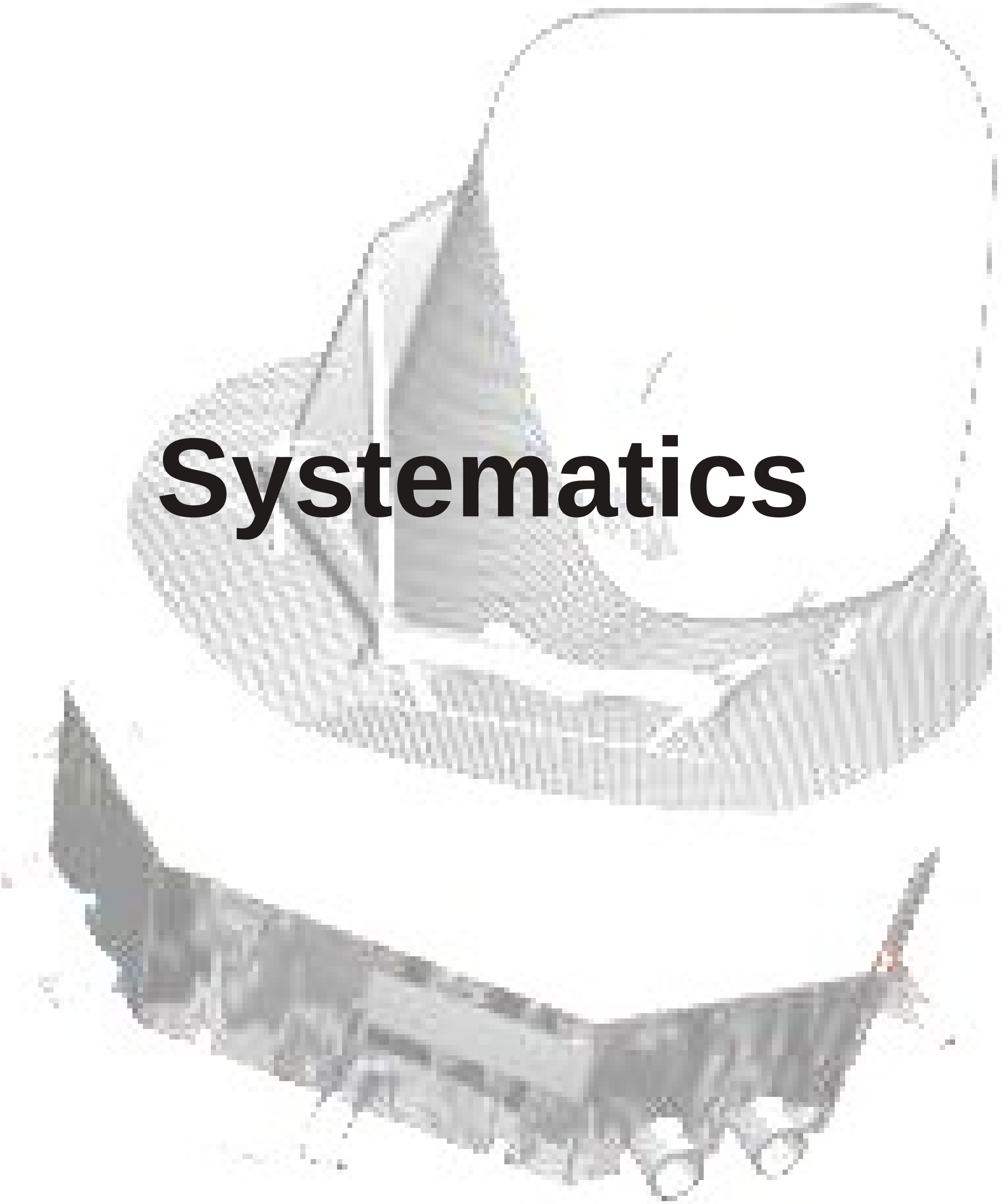
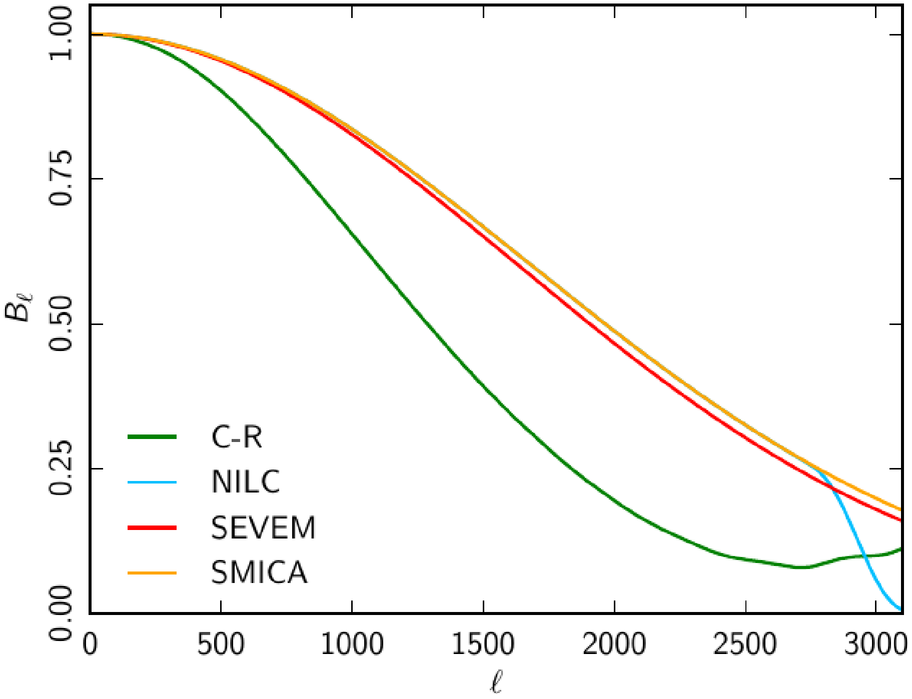


Systematics

Beams

- Effective beam transfer functions are provided, based on in-flight main beam measurements for each input channel
- NILC, SEVEM, SMICA produce maps with an effective Gaussian beam of 5 arcminutes FWHM, by design
- C-R estimates a sky-averaged effective beam through FFP6 MC runs



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