The PLANCK 2018 CMB Maps

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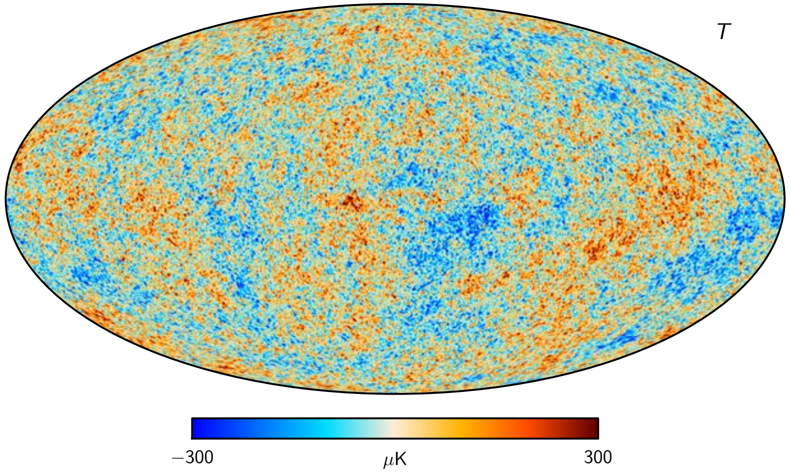
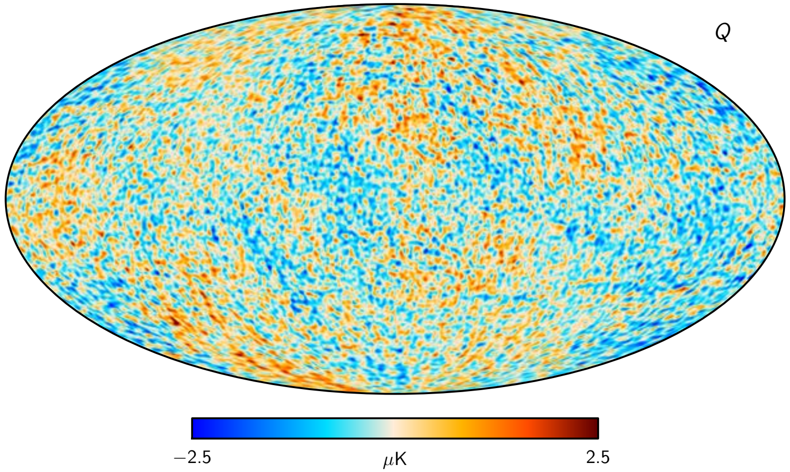
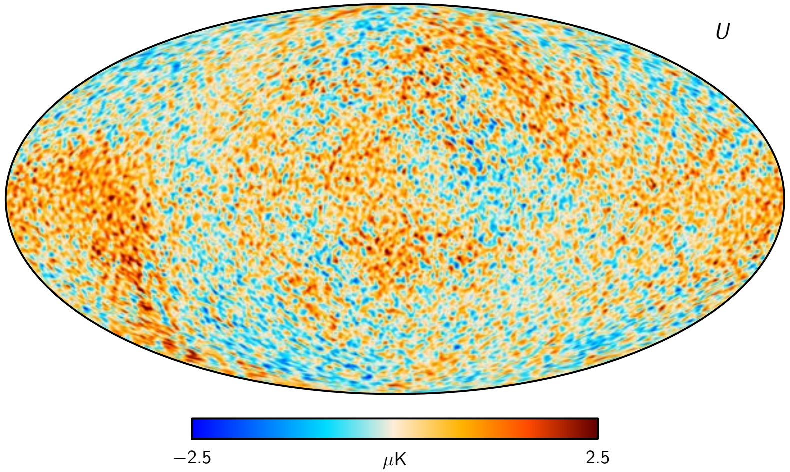
on behalf of the Planck Collaboration

Planck 2018 CMB maps (inpainted)



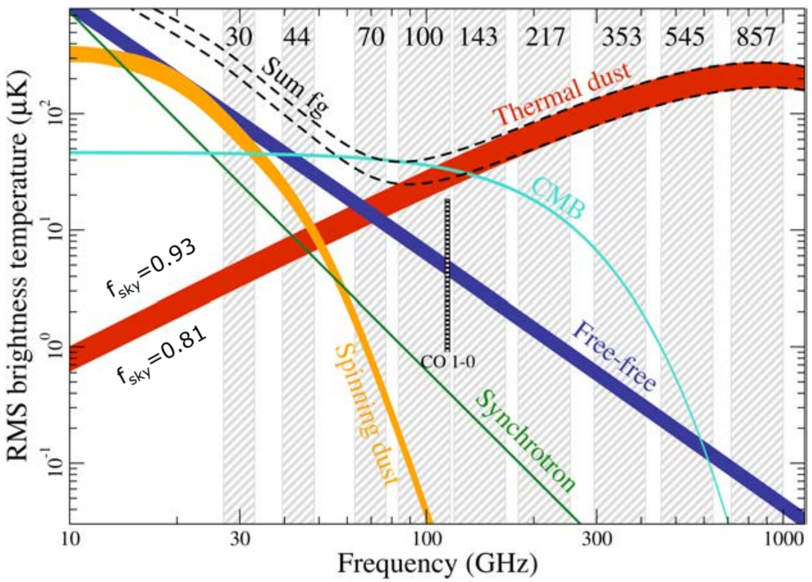




Planck 2018 results IV. Diffuse component separation

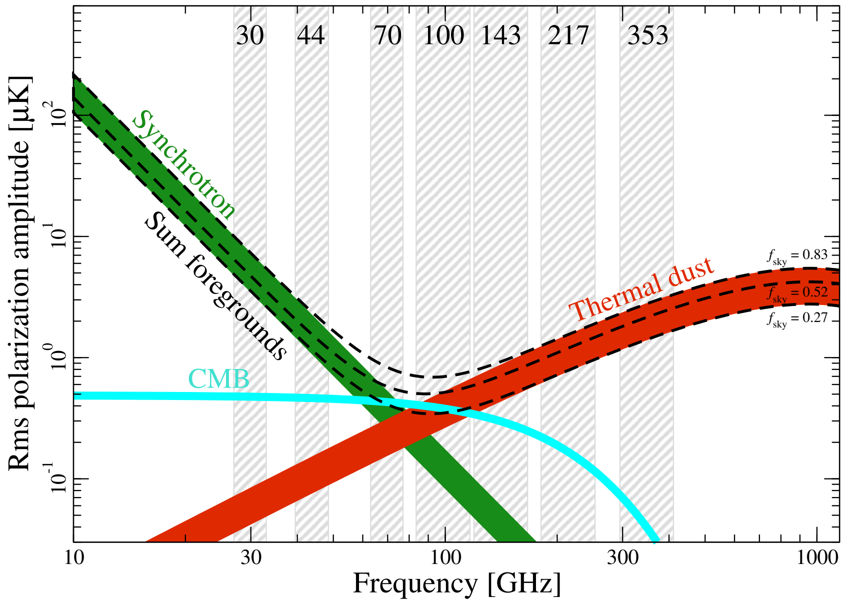
Component separation problem

- The observed microwave sky is a combination of the CMB signal plus different astrophysical emissions (foregrounds), instrumental noise and systematics
- Component separation methods exploit the fact that CMB and foregrounds have different frequency dependence



Intensity

[Planck 2015 Results. X]



Polarization

[Planck 2018 Results. L04]

Component separation methods

Four different CMB maps have been constructed using four independent component separation pipelines

- Commander: Bayesian parametric method
  - It implements a standard Bayesian fitting procedure, in which an explicit parametric model including cosmological, astrophysical and instrumental parameters are fitted to the observations through the posterior distribution.
  - It recovers the CMB as well as the foreground components in intensity and polarization

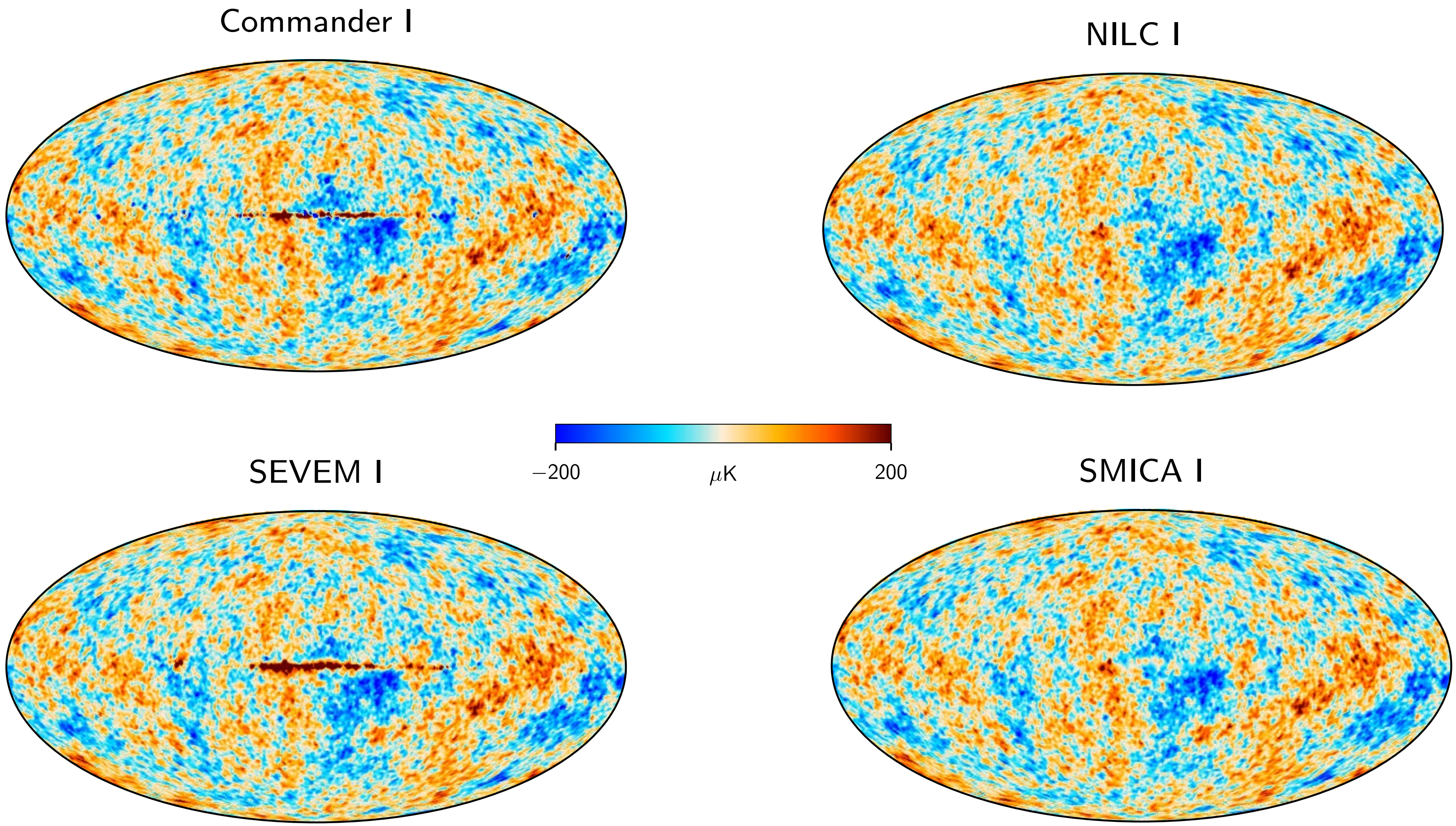
- NILC: Needlet internal linear combination
  - The CMB is constructed as a linear combination of the data such that minimises the variance in a particular wavelet base (needlets)

Component separation methods

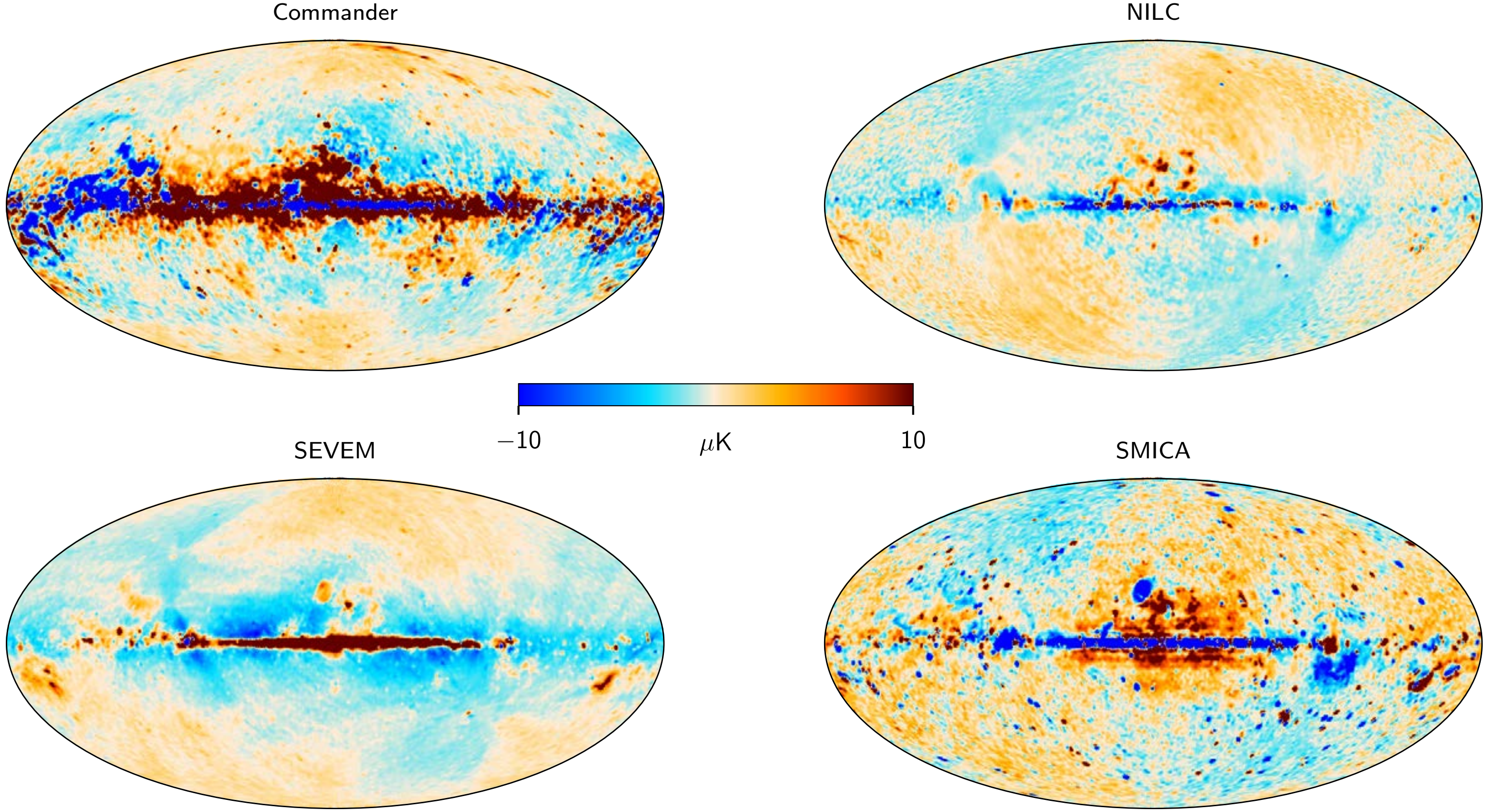
- SEVEM: Internal template fitting
  - It produces cleaned CMB maps at individual frequencies by subtracting a linear combination of templates. The templates are constructed from the Planck data
  - A number of these cleaned maps are then combined into a final CMB map

- SMICA: Spectral Matching Independent Component Analysis
  - It performs an internal linear combination in harmonic space. The weights are calculated taking into account an estimation of the involved spectral covariance matrices (by minimising the spectral matching criterion)
  - It also produces foreground components in polarization

CMB Maps, full mission: Intensity

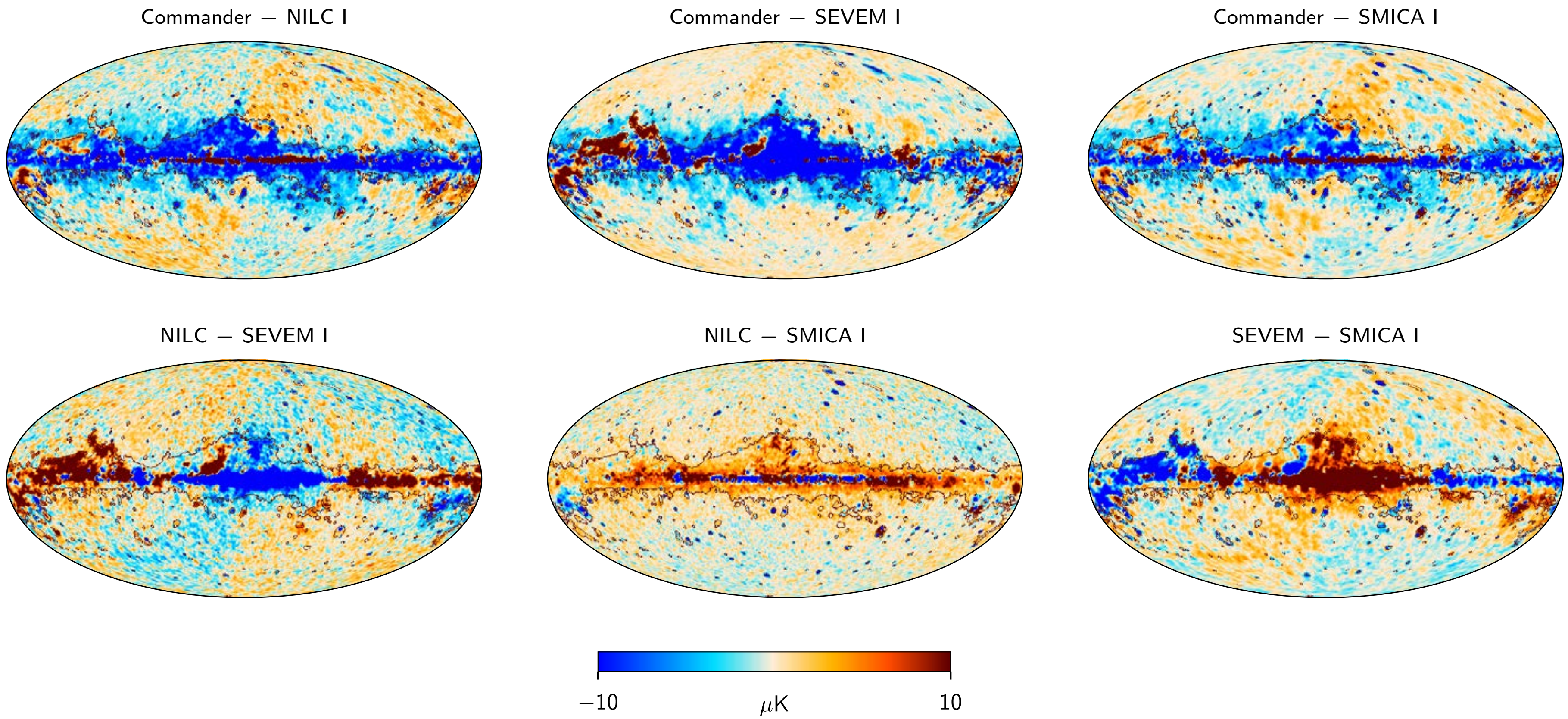


Differences with 2015 results



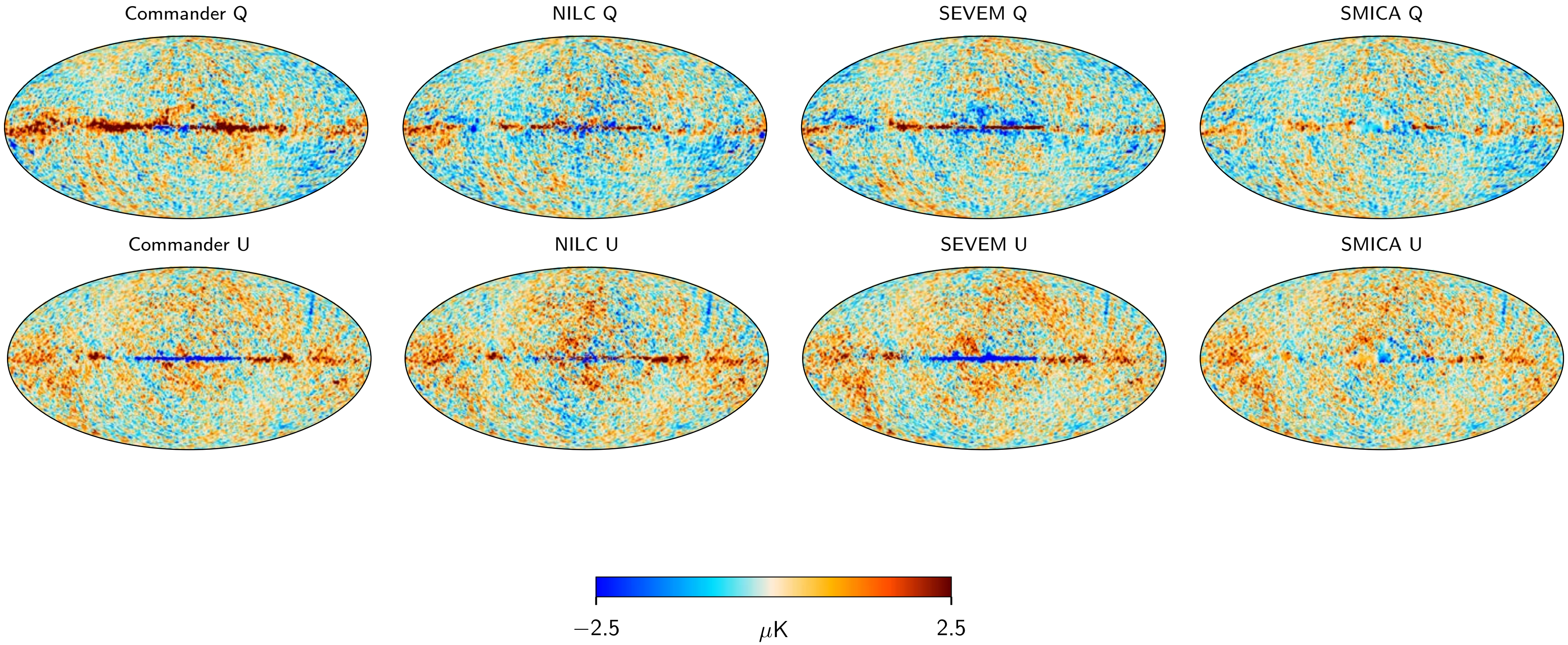
Main differences due to changes in component separation pipelines rather than in the different data processing

Comparison between CMB maps: intensity



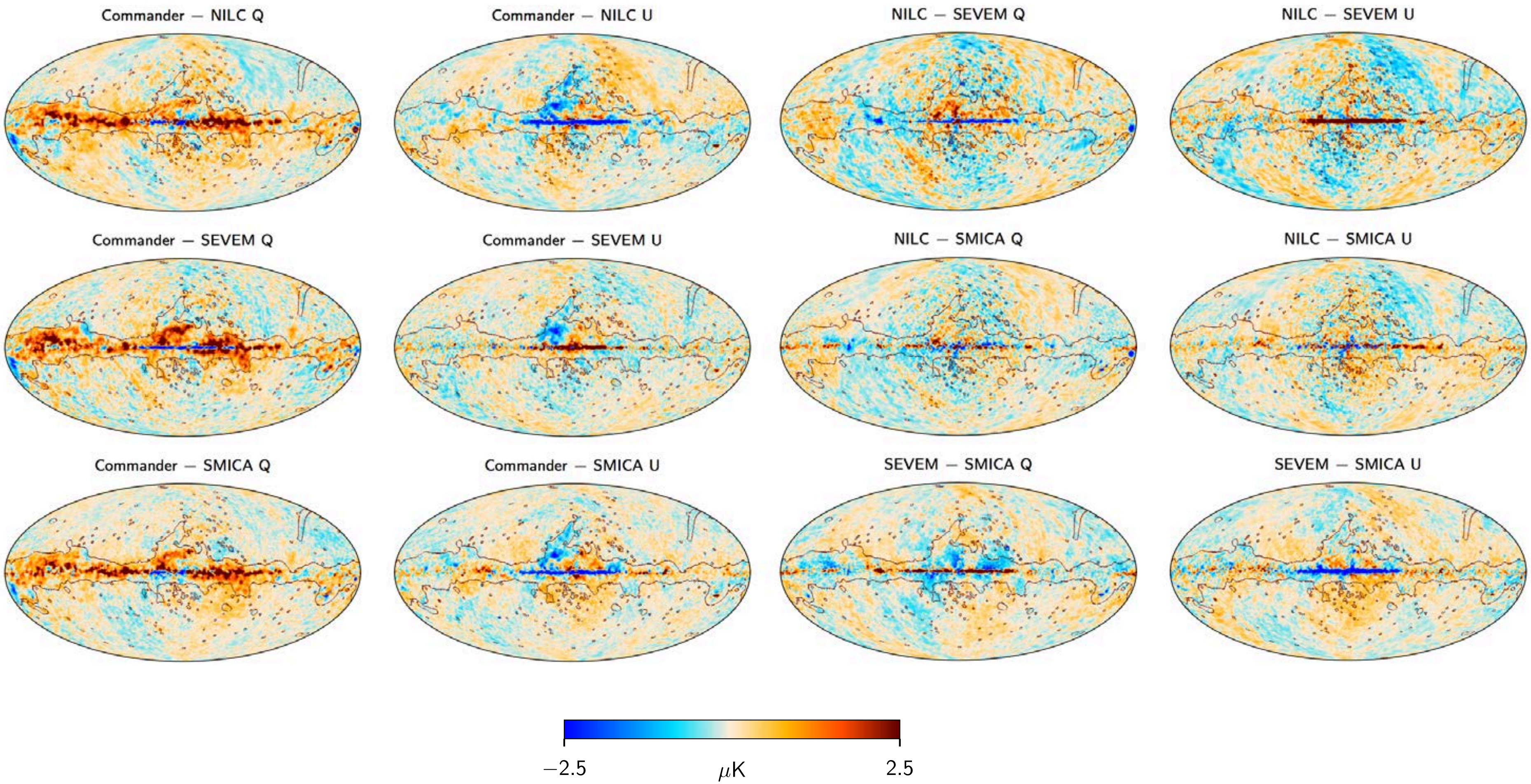
Confidence mask is overlaid

CMB maps, full mission: polarization

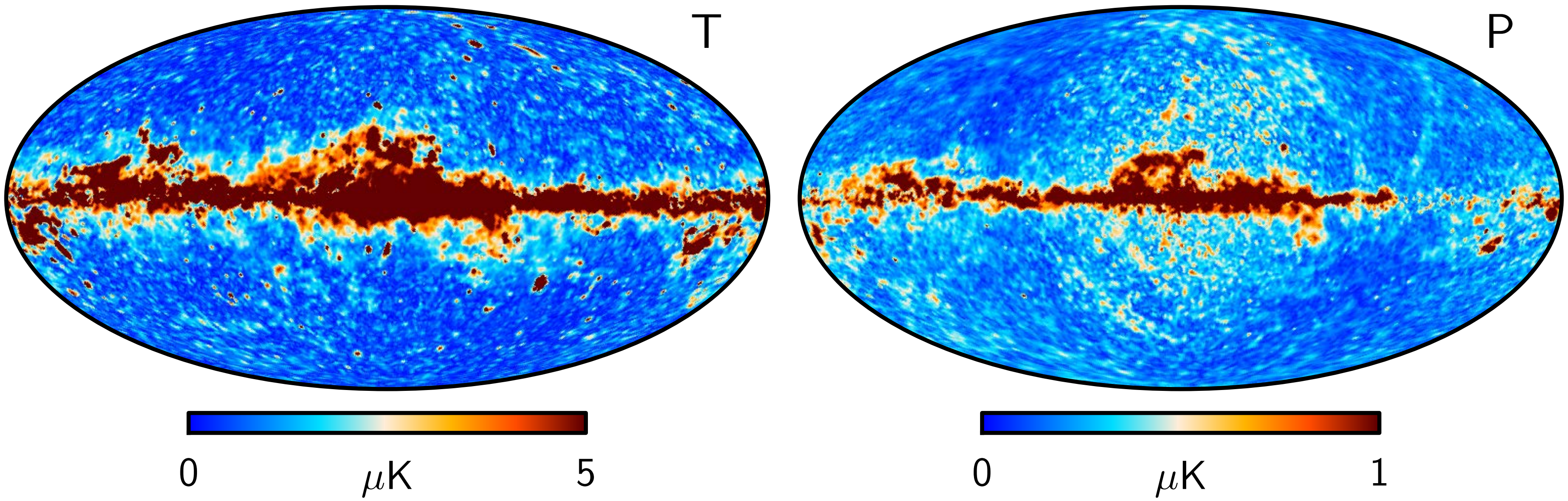


Significantly lower large-scale systematics → all scales kept in CMB maps (2015 CMB maps were high-passed filtered)

Comparison between CMB maps: polarization

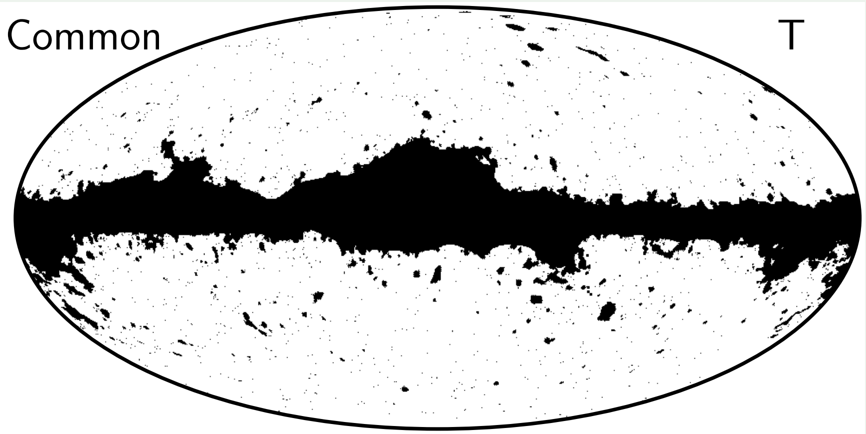


Comparison between CMB maps



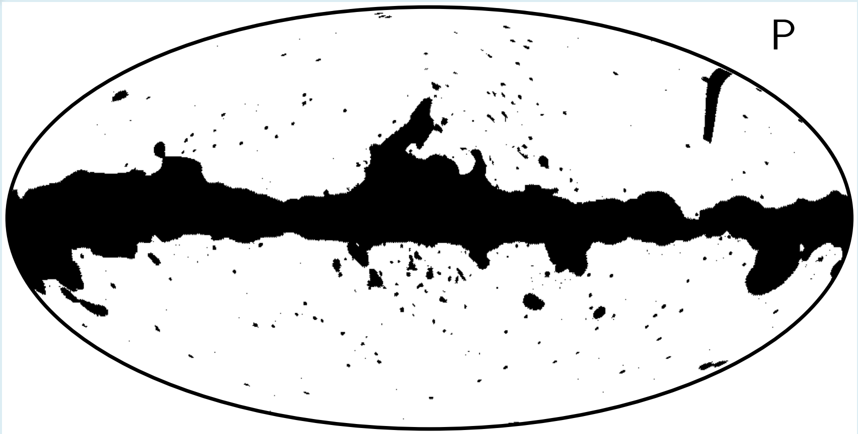
Standard deviation of the CMB maps between the four component-separation methods, at 80′ resolution. The polarization standard deviation is defined as sqrt(var(Q) + var(U)).

Confidence masks



Intensity mask constructed from:

- Map of standard deviation of pipelines
- Pipeline specific masks (Comm. and Sevem)
- Inpainting point sources from Sevem and Smica

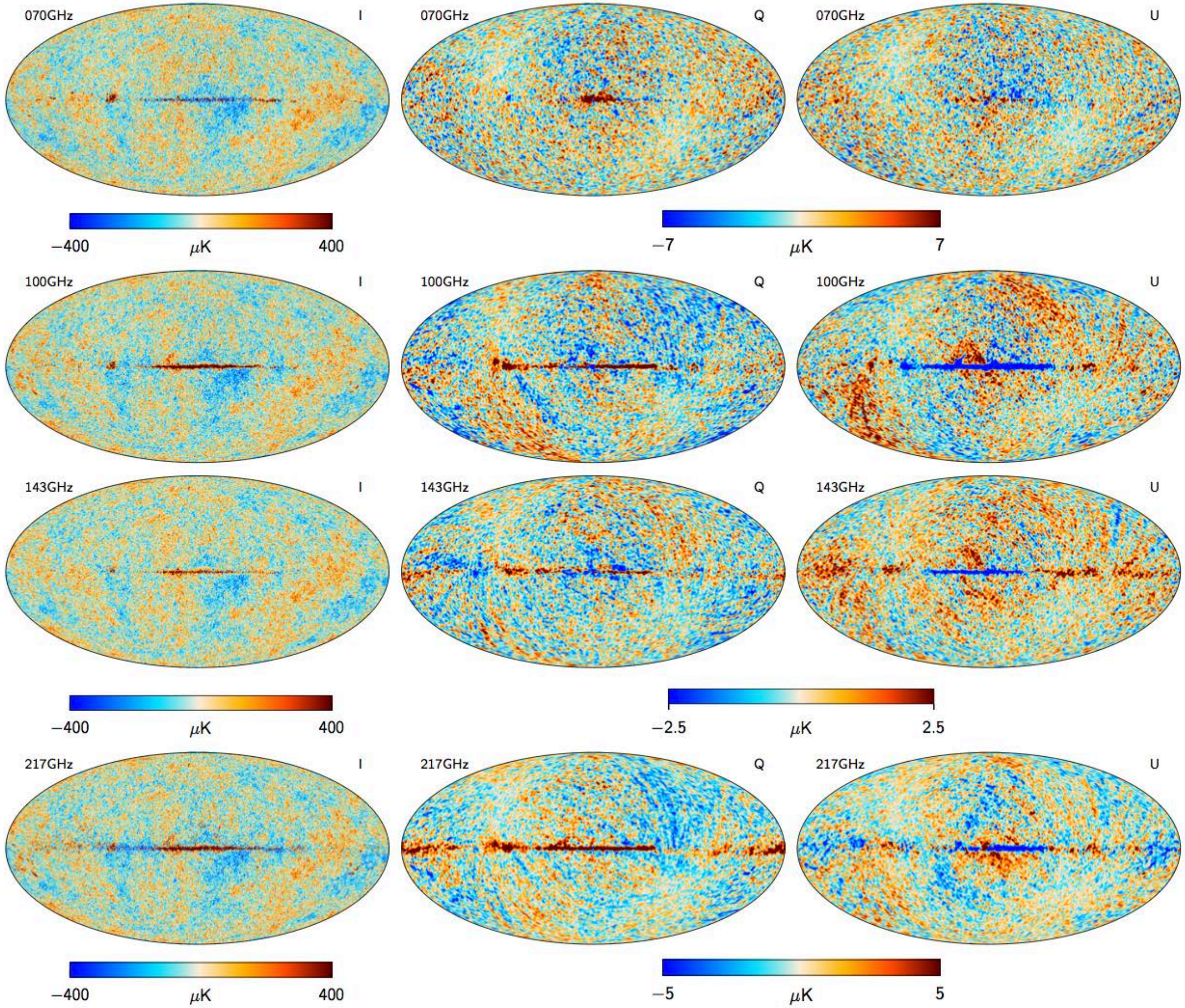


Polarization mask constructed from:

- Map of standard deviation of pipelines
- Pipeline specific masks (Comm. and Sevem)
- Inpainting point sources from Sevem and Smica
- Cosmic rays contaminated region
- CO emission regions

Sky fraction available ~0.78

SEVEM CMB frequency maps



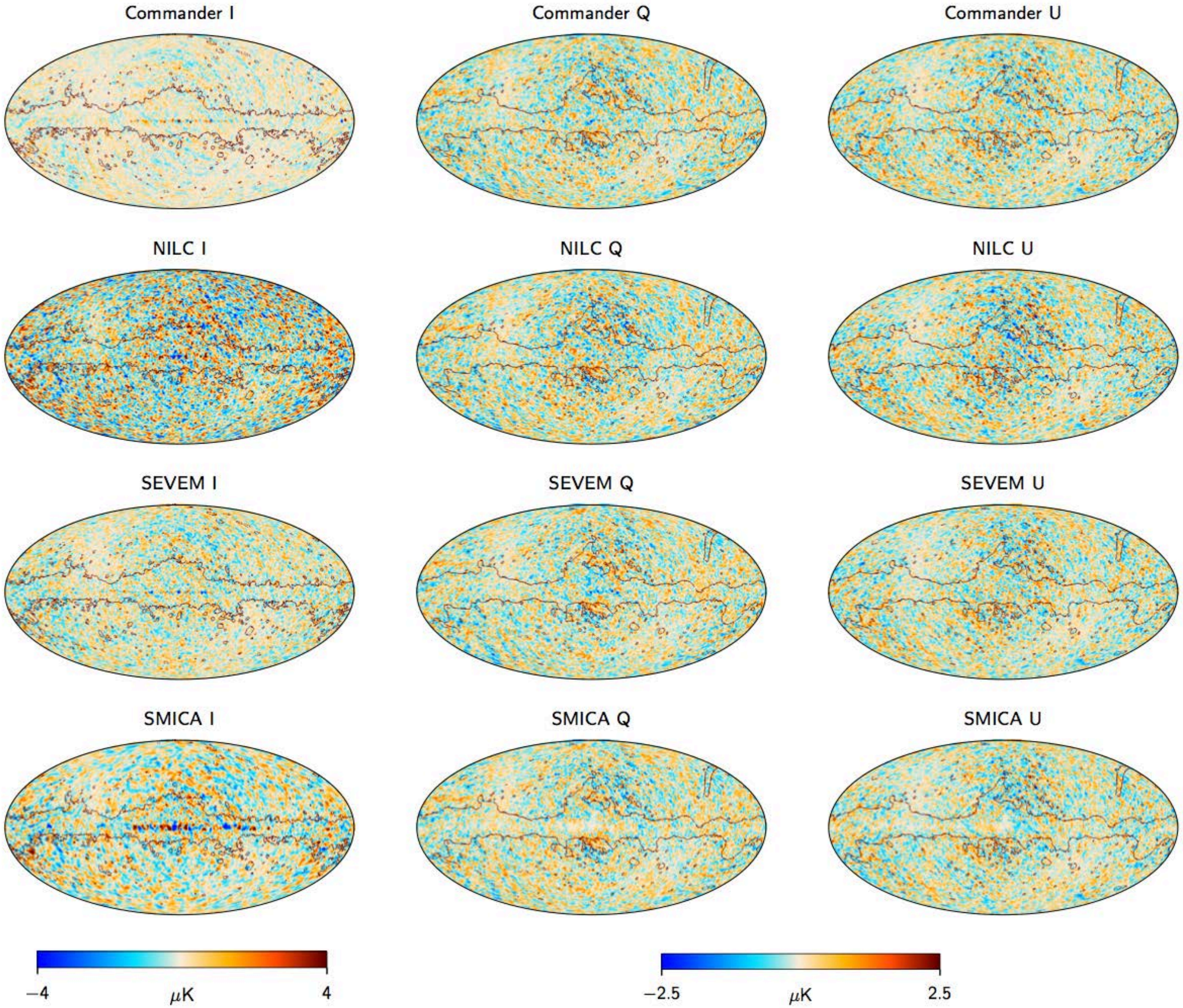
Statistical characterization of the noise

The instrumental noise characteristics of the *Planck* observations are complex, and a simple white-noise approximation is inadequate for high-precision analyses

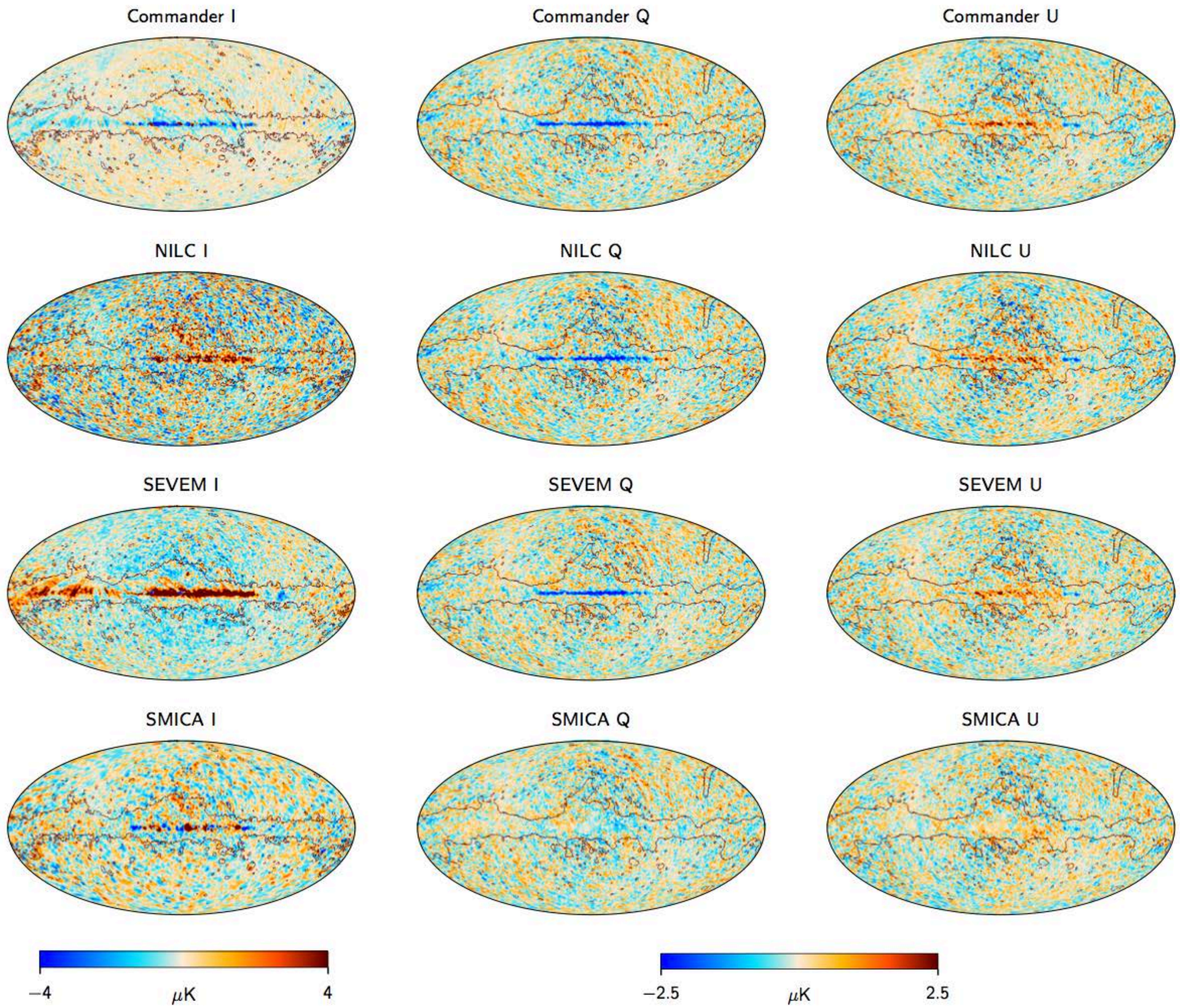
We consider three different measures to characterise the noise

- Odd/even rings half difference maps (OEHD)
  - The time-ordered data is divided according to odd and even ring numbers (HFI) or half-rings (LFI)
  - Systematic effects tend to cancel out in the difference → best instrumental (white and correlated) noise tracer.
- Half-mission half difference maps (HMHD)
  - The time-ordered data are split according to long time periods, defined by years
  - More sensitive to systematic effects that vary on long time scales (e.g. gain variations or sidelobe contamination) → preferred estimate for the combined impact of instrumental noise and systematic effects.
- Full end-to-end (E2E) simulations including noise and systematics
  - Generated as raw time-ordered data, and processed through each step of the analysis pipeline, including map making and component separation
  - 300 realizations available for the full mission and each of the splits

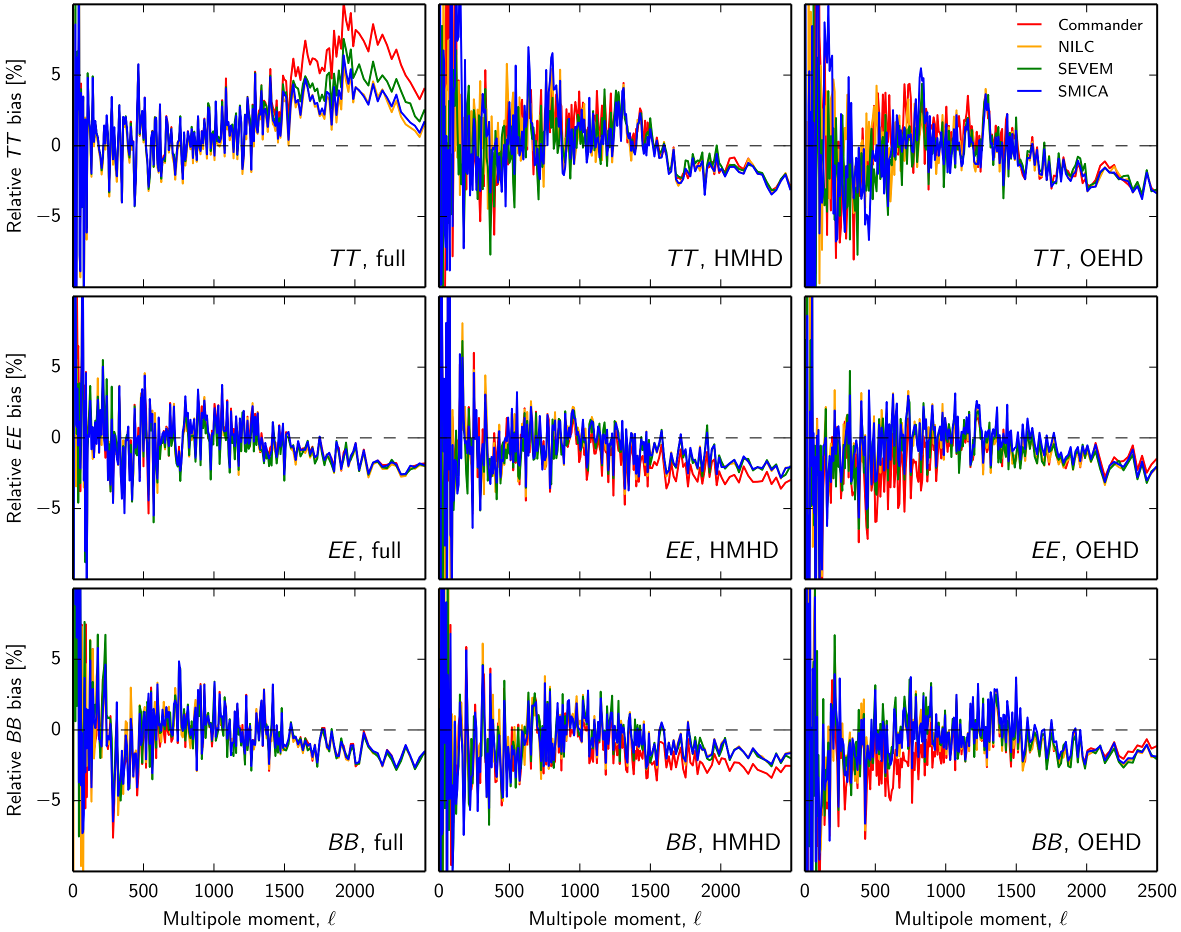
Odd/even rings half difference (80 arcmin)



Half mission half difference
(80 arcmin)



E2E Simulations



- The E2E simulations exhibit power biases of several per cent with respect to the true observations on intermediate and small scales, while reasonable agreement is observed on large angular scales.

- When employing these simulations for scientific analysis, it is important to verify that the statistic of choice is not sensitive to such percentage-level differences.

Fractional difference between the angular power spectrum computed from the observed data and the mean of the simulations

Assessing the impact of simulation noise bias

If the statistics of choice is sensitive…

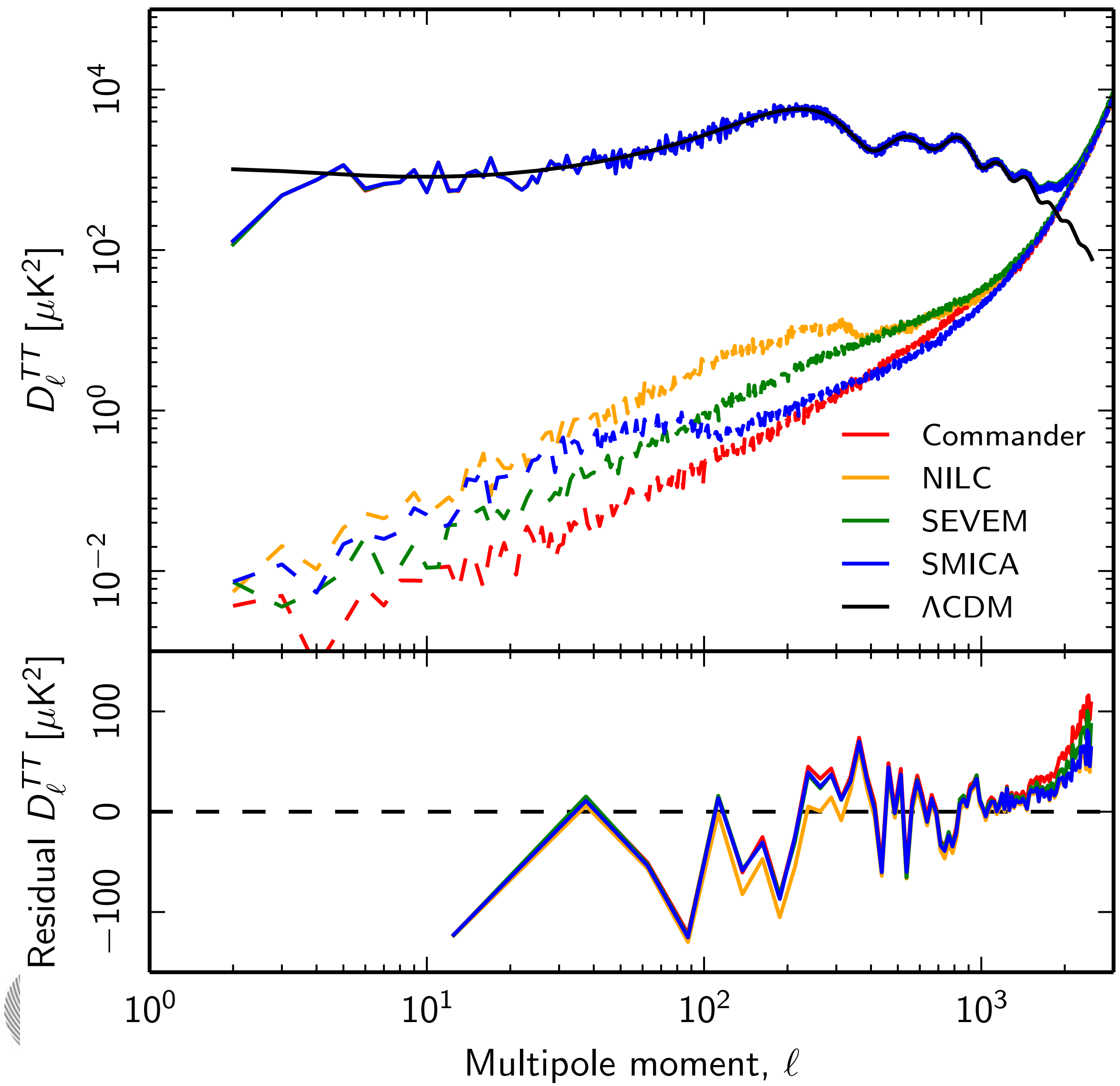
1. …only to large angular scales (ℓ<50) → simulations likely to be adequate
2. …to signal-plus-noise (rather than noise alone) –> simulations likely to be adequate for ℓ<1500 for T and ℓ<250 for polarization
3. … to <5% errors in the noise model → apply the analysis to simulations for which the noise contribution is artificially re-scaled by 5% and check if the results change

No general prescription can be given for all analyses, so one should make the appropriate tests when using the E2E simulations

In any case, they provide the most complete description of the uncertainties in the data set and should be adequate for many applications

See I&S talk for further analyses of the data using the E2E simulations

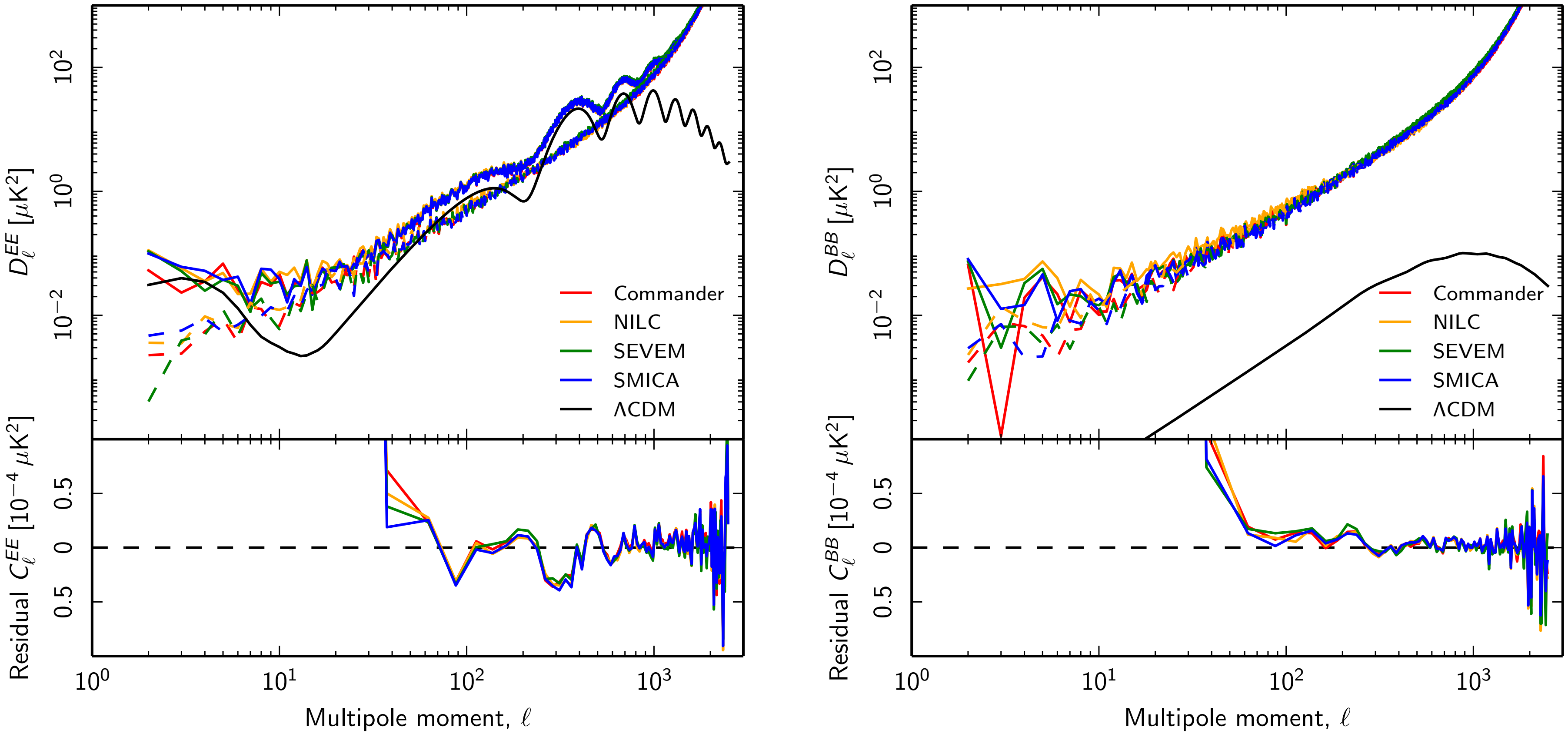
CMB Power spectrum: intensity



Top panel: HMHS (solid lines), HMHD (dashed lines)

Bottom panel: HMHS – HMHD – best-fit Planck 2018 ΛCDM (binned $\Delta\ell$=25)

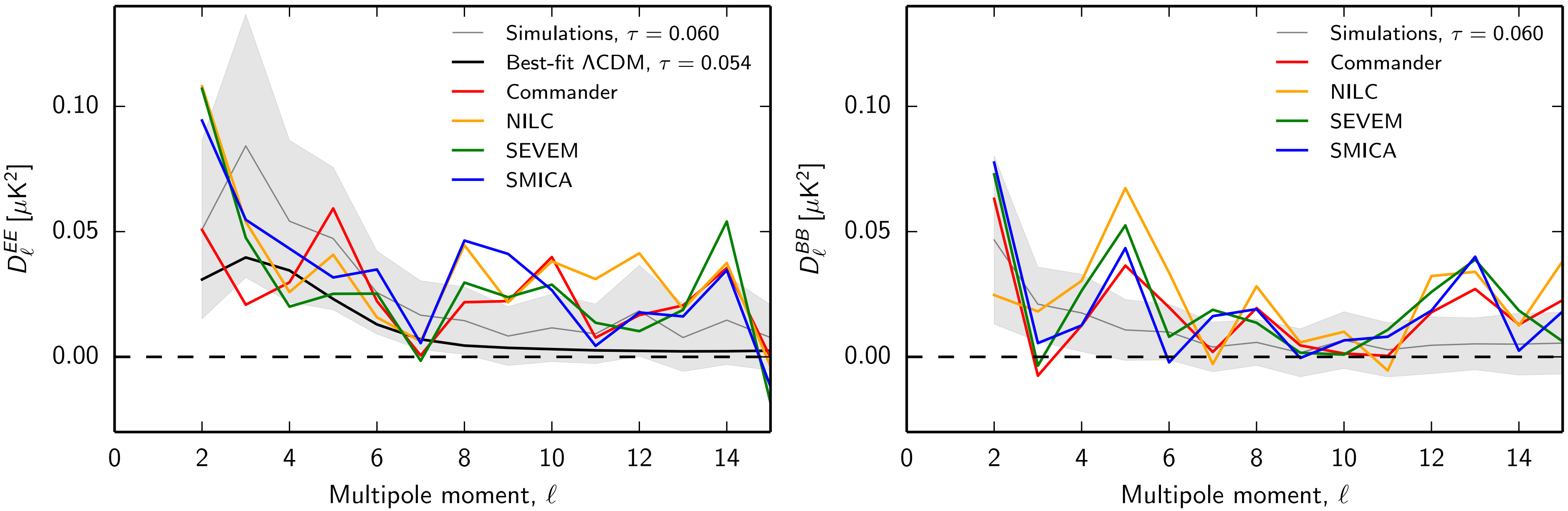
CMB power spectrum: polarization



Top panels: HMHS (solid lines), HMHD (dashed lines)

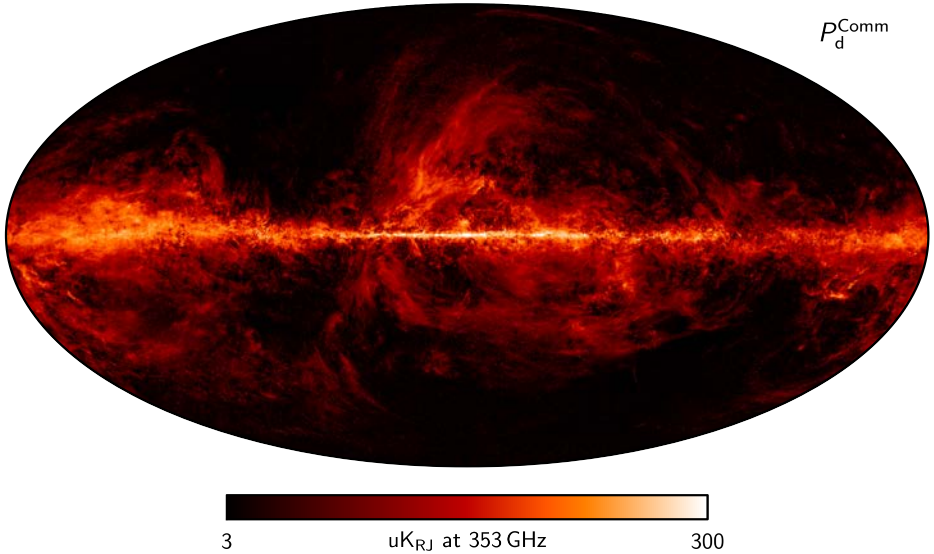
Bottom panels: HMHS – HMHD – Planck best fit 2018

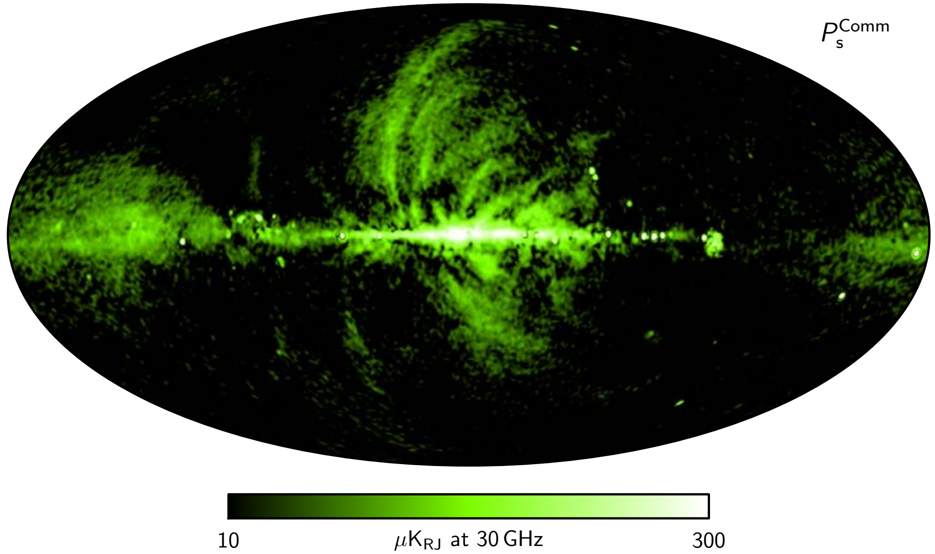
CMB power spectrum: polarization, low multipoles



- Spectrum computed as HMHS – HMHD
- Grey bands show 1σ confidence regions for 300 simulations processed through Commander
- Note the non-zero mean of the simulations for BB → it is crucial to compare with the E2E simulations in any analysis

Foreground maps for polarization





Mean spectral index for polarized dust β_d=1.55±0.05

Mean spectral index for polarized synchrotron β_s=-3.1±0.1

The optimization of the data processing for polarization implied that single detector maps are not available in 2018 → this affects the ability of Commander to resolve individual foregrounds. Therefore, intensity foreground products do not supersede the 2015 results and have not been released for this method

CMB products overview

- CMB maps, full mission
  - I, Q, U maps
  - Resolution: Gaussian beam with FWHM=5′ (N_{side}=2048)
  - Four different pipelines (Commander, NILC, Sevem, SMICA)
- CMB maps, splits
  - Even/odd ring maps
  - Half-mission maps
- Confidence masks
  - Intensity and polarization
  - Masked regions for splits (due to missing pixels)
  - Specific masks per method (point sources, inpainting, etc.)
- End-to-end simulations (also available propagated through each of the pipelines)
  - 999 CMB (including effects of satellite scanning and asymmetric beams)
  - 300 noise + systematics (full-mission)
  - 300 noise + systematics (for each split)

CMB products overview

- Other CMB products
  - CMB single-frequency maps: 70-217 GHz (Sevem)
  - CMB map without SZ signal (Smica)
- Foreground maps in polarization
  - Q, U synchrotron maps @ 30 GHz (full-mission and splits)

    From Commander and Smica
  - Q, U dust maps @ 353 GHz (full mission and splits)

    From Commander, Smica and GNILC (GNILC also provides intensity maps)

All these products (and more) are available at the Planck Legacy Archive at http://pla.esac.esa.int/pla

Summary

- Planck is delivering intensity and polarization CMB maps with unprecedented frequency range, sensitivity and sky coverage
- Significant reduction of the instrumental systematics in Planck 2018 → CMB polarization maps provided at all scales
- Four different sets of CMB maps (Commander, NILC, Sevem, Smica) are provided for robustness
- The noise properties of the Planck products are complicated and use of E2E simulations is essential
- The E2E simulations are accurate at a few per cent level, so results should be tested against this bias when performing quantitative scientific analysis
- Data splits are also provided to characterise further the statistical properties of the noise
- Polarization maps are also provided for synchrotron and thermal dust from different pipelines.
- Planck 2018 CMB maps provide a new state of the art of the field also in terms of polarization

The scientific results that we present today are a product of the Planck Collaboration, including individuals from more than 100 scientific institutes in Europe, the USA and Canada

Planck is a project of the European Space Agency, with instruments provided by two scientific Consortia funded by ESA member states (in particular the lead countries: France and Italy) with contributions from NASA (USA), and telescope reflectors provided in a collaboration between ESA and a scientific Consortium led and funded by Denmark.