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CMB Component Separation

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on behalf of the Planck Collaboration

Paper: Planck 2013 results. XII. Component separation

The scientific results 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

Inputs to component separation

- Data from LFI and HFI
  - Frequency channel maps
  - Half-ring maps
  - Beam transfer functions
  - Bandpasses
  - Source catalogues and masks
- Full focal plane simulations (FFP6)
  - Use pointing, data flags, and measured beams and bandpasses
  - Input sky generated using Planck sky model (PSM)
  - Frequency maps generated by simulating timestreams and making maps
  - Outputs
    - “Observed” frequency maps and half-ring maps
    - Maps of individual input components
    - 1000 Monte Carlo realizations of the CMB
    - 1000 Monte Carlo realizations of instrumental noise

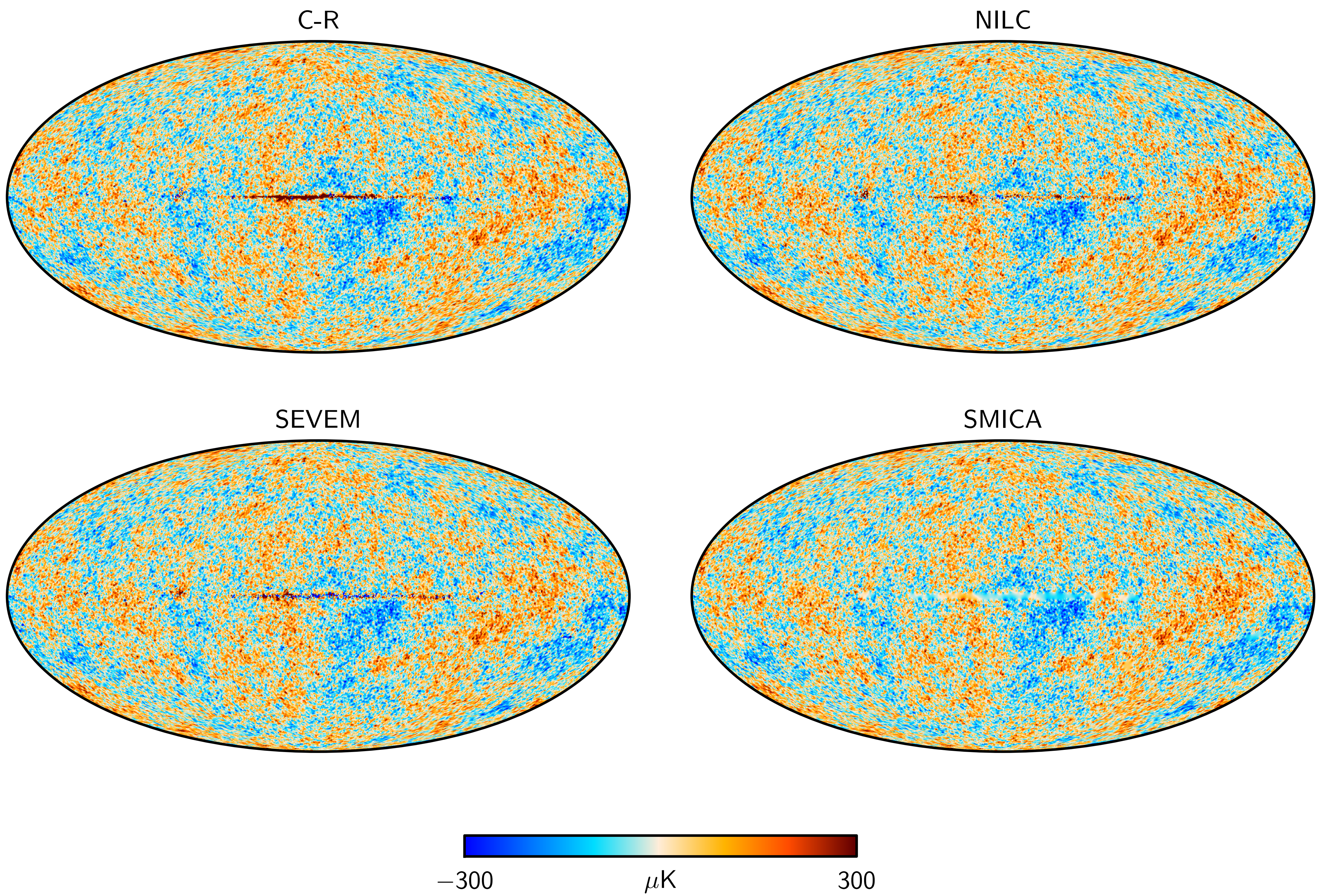
Algorithms

- Two algorithms based on model fitting
- Bayesian parameter fitting (Commander-Ruler, C-R)
  - Works in pixel domain
  - Fits parametrized model of the CMB and foregrounds to the data
  - Commander: MCMC sampling of amplitudes and spectral parameters at low resolution (40’)
  - Ruler: solves for high-resolution amplitudes using Commander spectral parameters
  - 30 - 353 GHz channels
  - ~7.4’ resolution
- Spectral matching (SMICA)
  - Work in harmonic domain
  - Fits model of CMB, generalized correlated foregrounds, and noise to the auto- and cross-spectra of the maps, then solves for amplitudes of CMB map
  - 30 - 857 GHz channels
  - 5’ resolution, $l_{max} = 4000$
  - Version of CMB map filled with constrained realization in processing mask (3% of the sky)

Algorithms

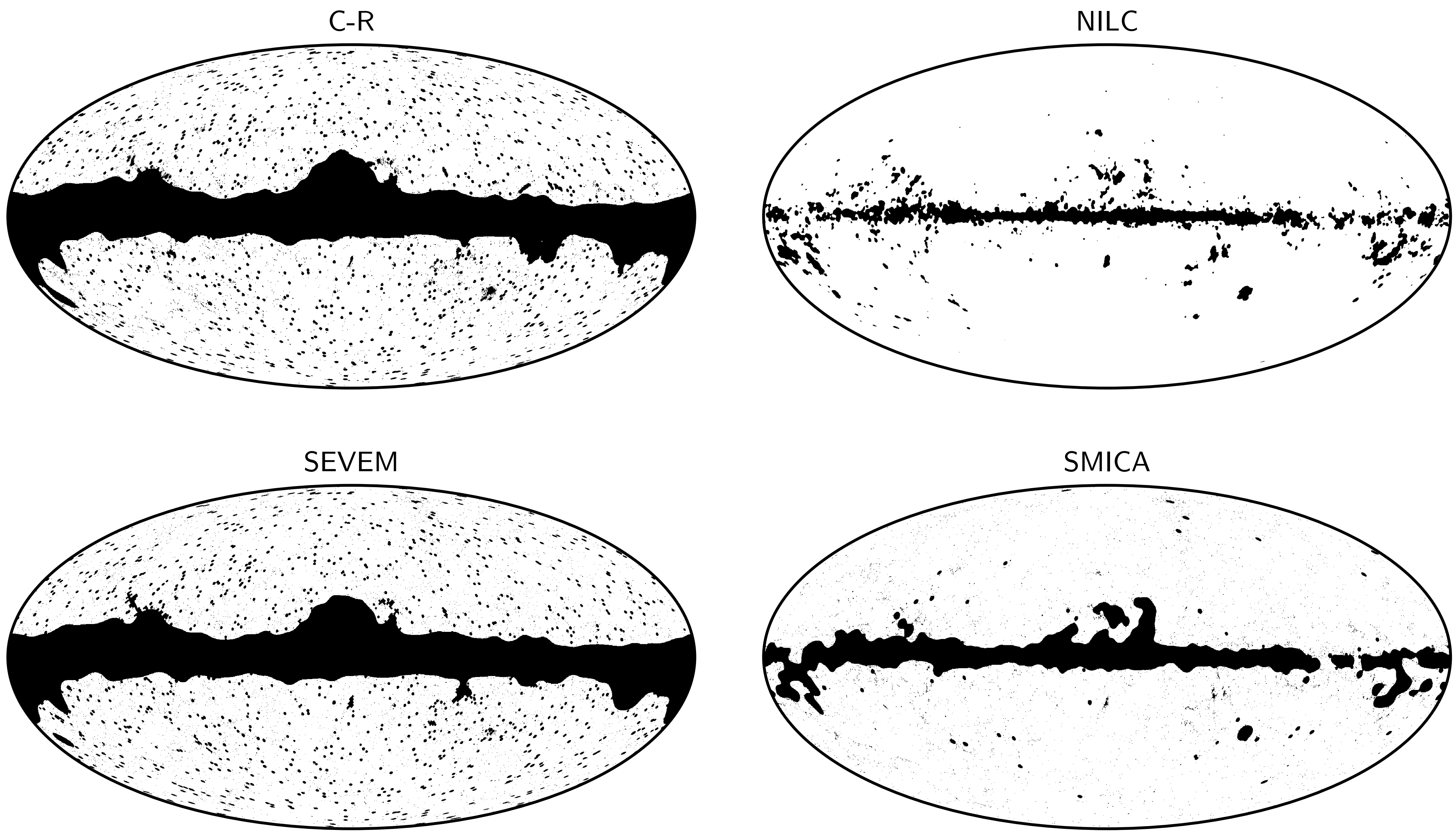
- Two algorithms based on minimising the variance of CMB component
- Internal linear combination (NILC)
  - Works in needlet (wavelet) domain
  - Makes ILC at each needlet scale independently
  - 44 - 857 GHz channels
  - 5' resolution, $l_{max} = 3200$
- Template fitting (SEVEM)
  - Works in pixel domain
  - Uses internal templates produced by subtracting frequency channels after smoothing to common resolution: (30 - 44), (44 - 70), (857 - 535), (545 - 353)
  - Templates are used to clean 143 and 217 GHz maps
  - Combines maps afterwards in harmonic space to produce single CMB map
  - 5' resolution, $l_{max} = 3100$

Foreground-cleaned CMB maps



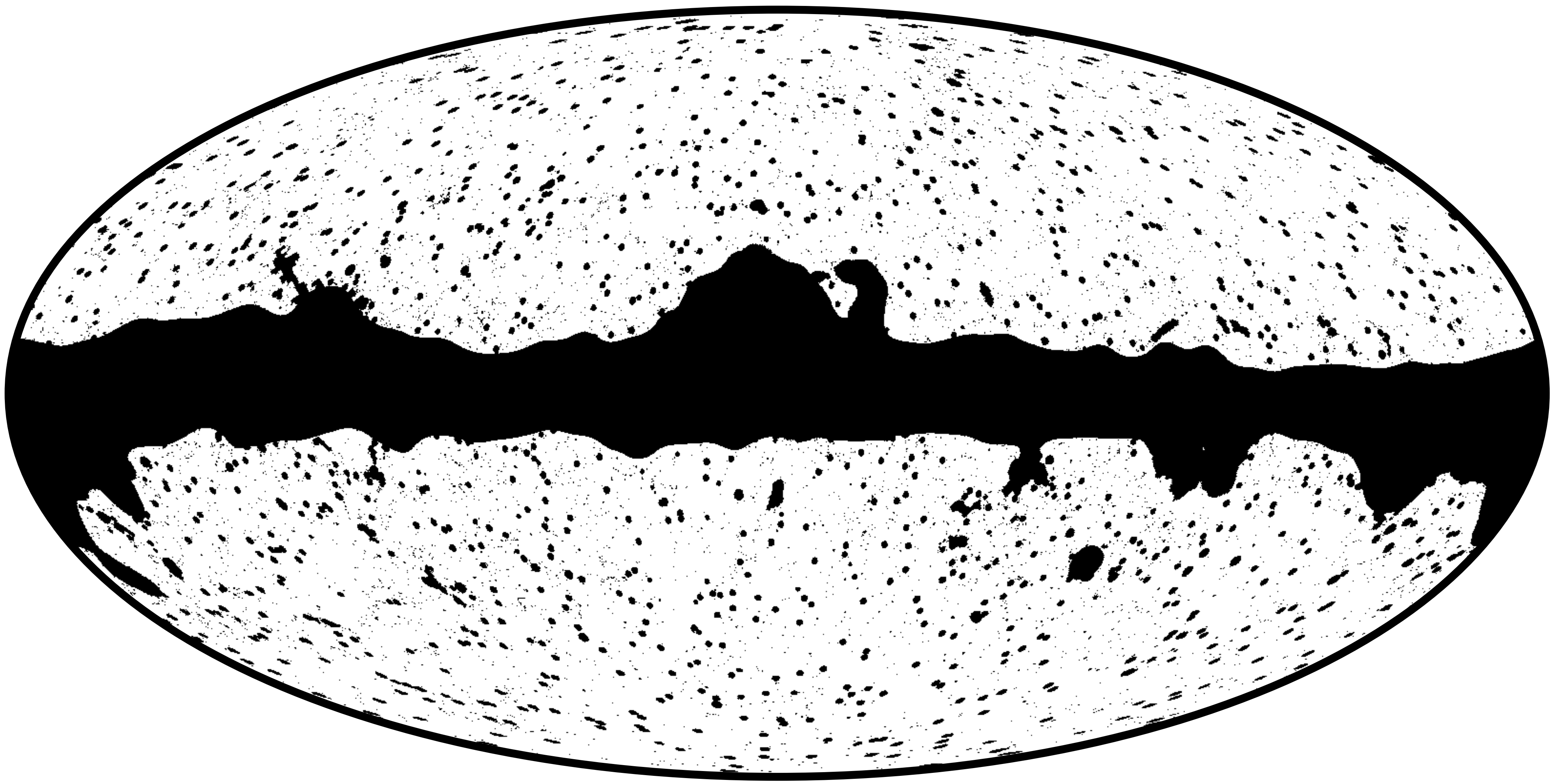
SMICA works in harmonic space; it uses a 3% processing mask to prevent foreground leakage from low to high Galactic latitudes, hence the smooth appearance in the Galactic plane

Confidence masks



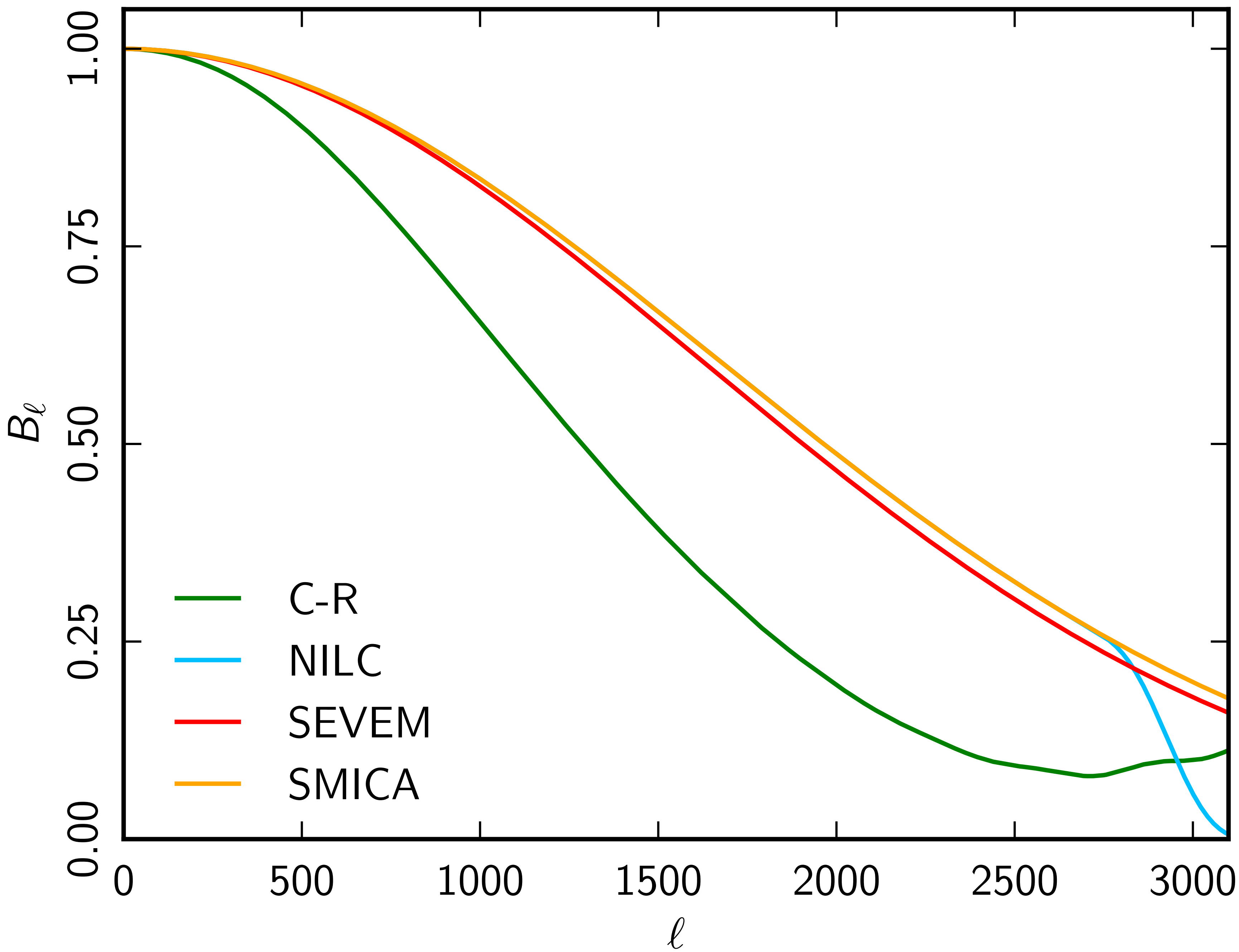
Confidence masks define region of the sky in which the solutions are considered to be statistically robust

Union mask



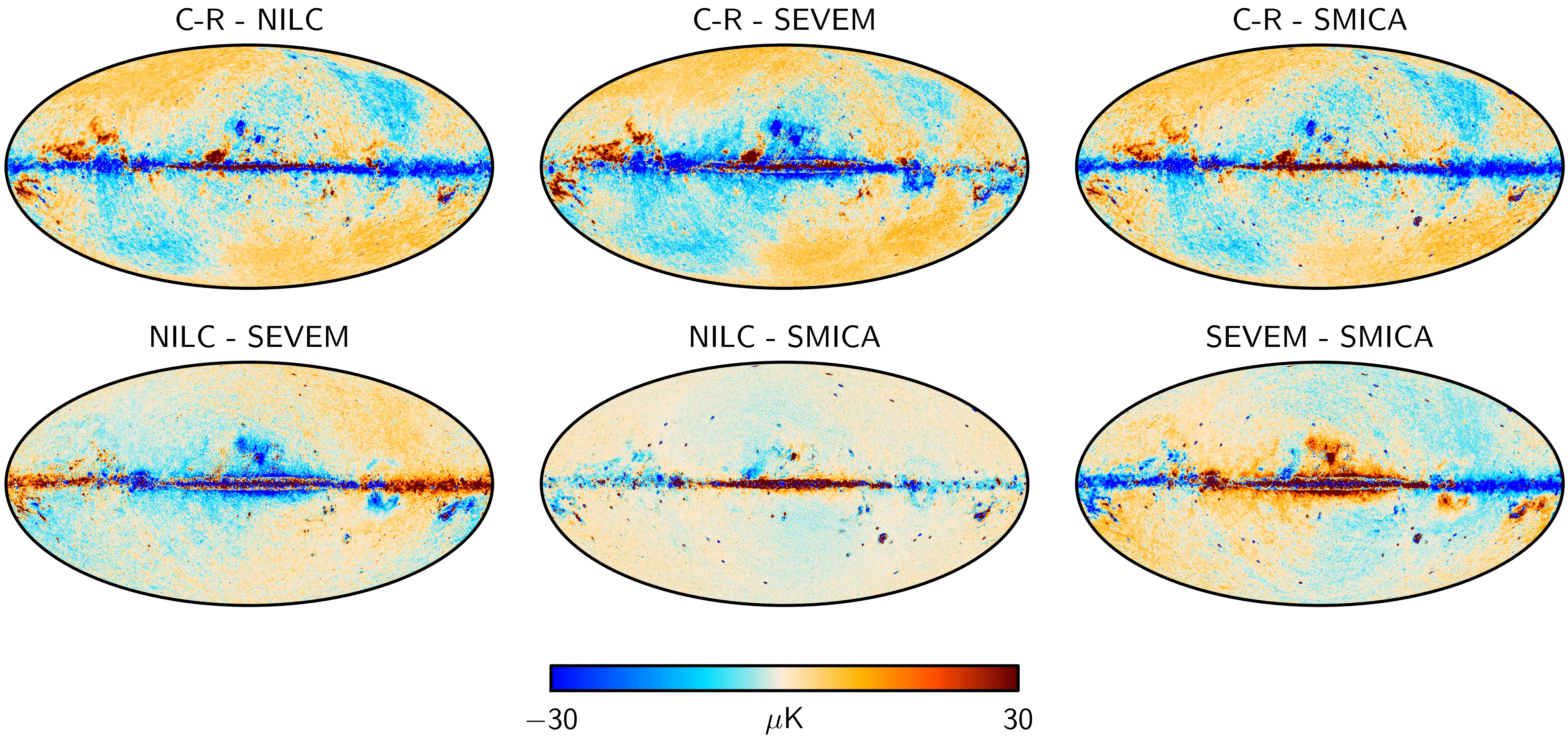
Union of the confidence masks (U73), leaving 73% of the sky

Beam transfer functions



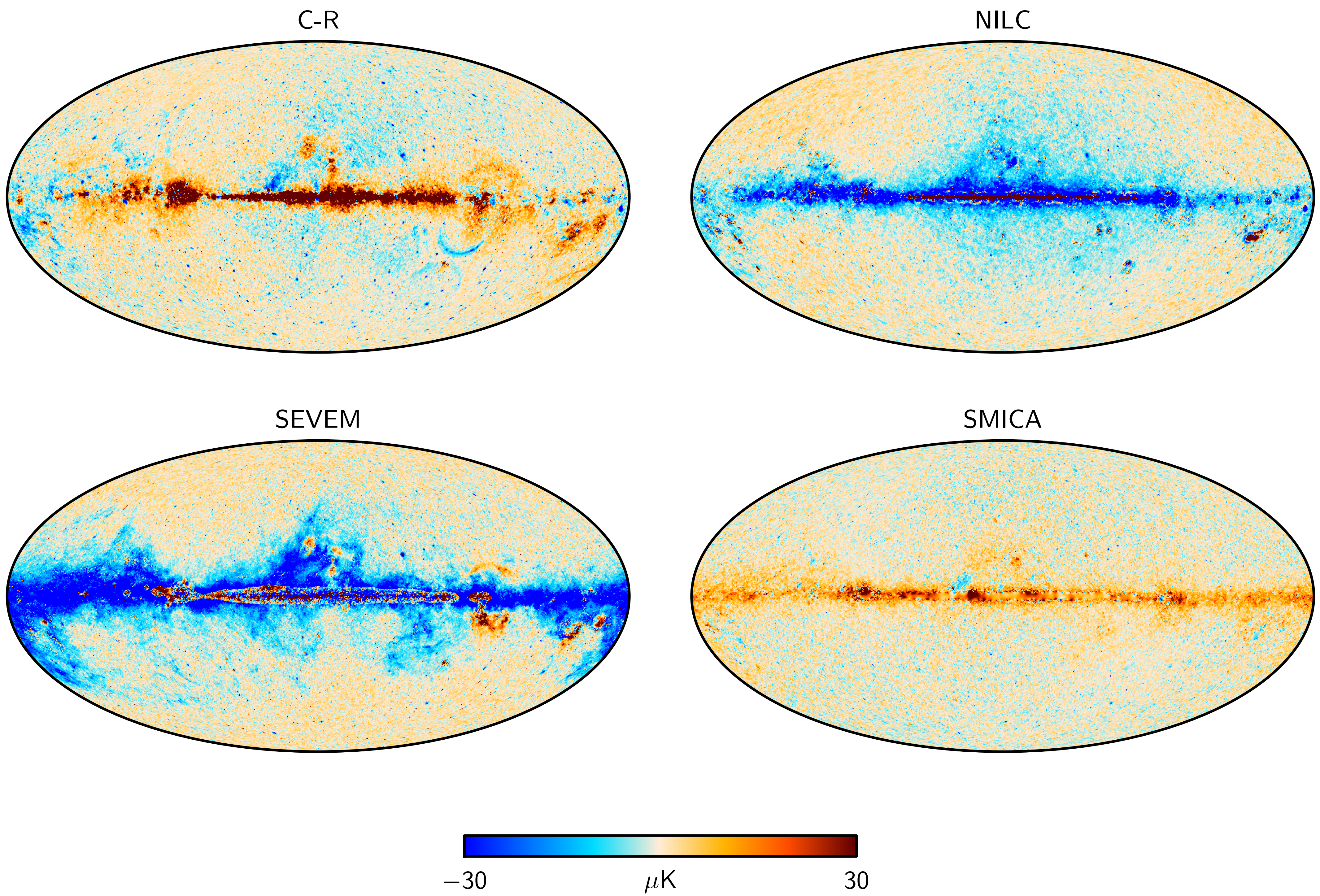
- NILC, SEVEM and SMICA have 5' resolution, but they differ in their treatment of the pixel window function
- NILC beam falls faster at high l due to last needlet window
- Commander-Ruler works entirely in pixel space so it has a lower resolution of around 7.4'

Pairwise difference between CMB maps



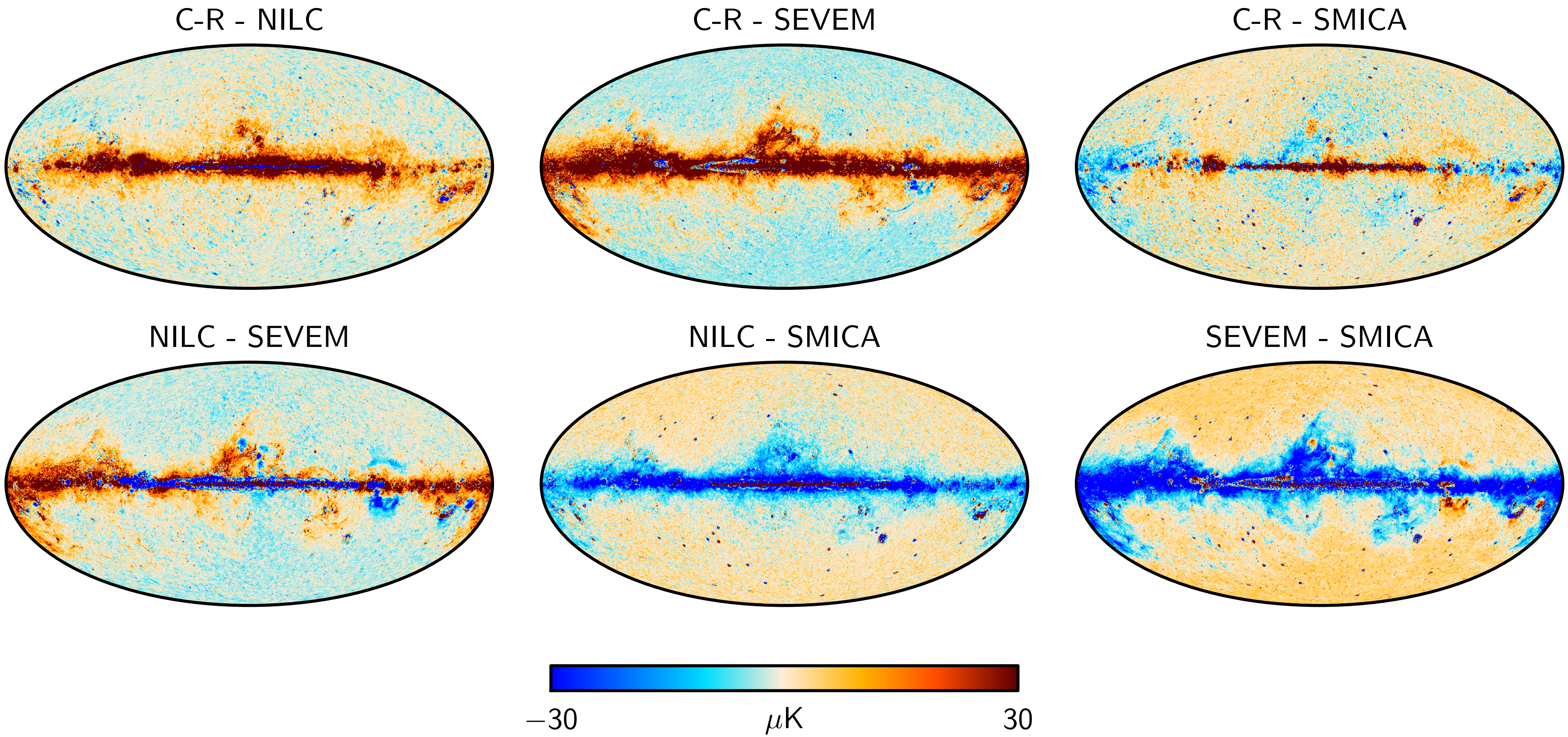
- Maps have been downgraded to N_{side} = 128 to show large scale features
- Large-scale features could be due to zodiacal light emission at high-frequencies
- Residuals at typically less than 5 μK at high Galactic latitude
- Discontinuity in SEVEM differences is due to two regions being used in the solution

Residuals from FFP6 simulations



- Use FFP6 to illustrate the level of residuals expected from the component separation
- Maps have been downgraded to $N_{side} = 128$ to show large scale features
- SMICA has lowest foreground residuals at large angular scales

Pairwise difference from FFP6 simulations

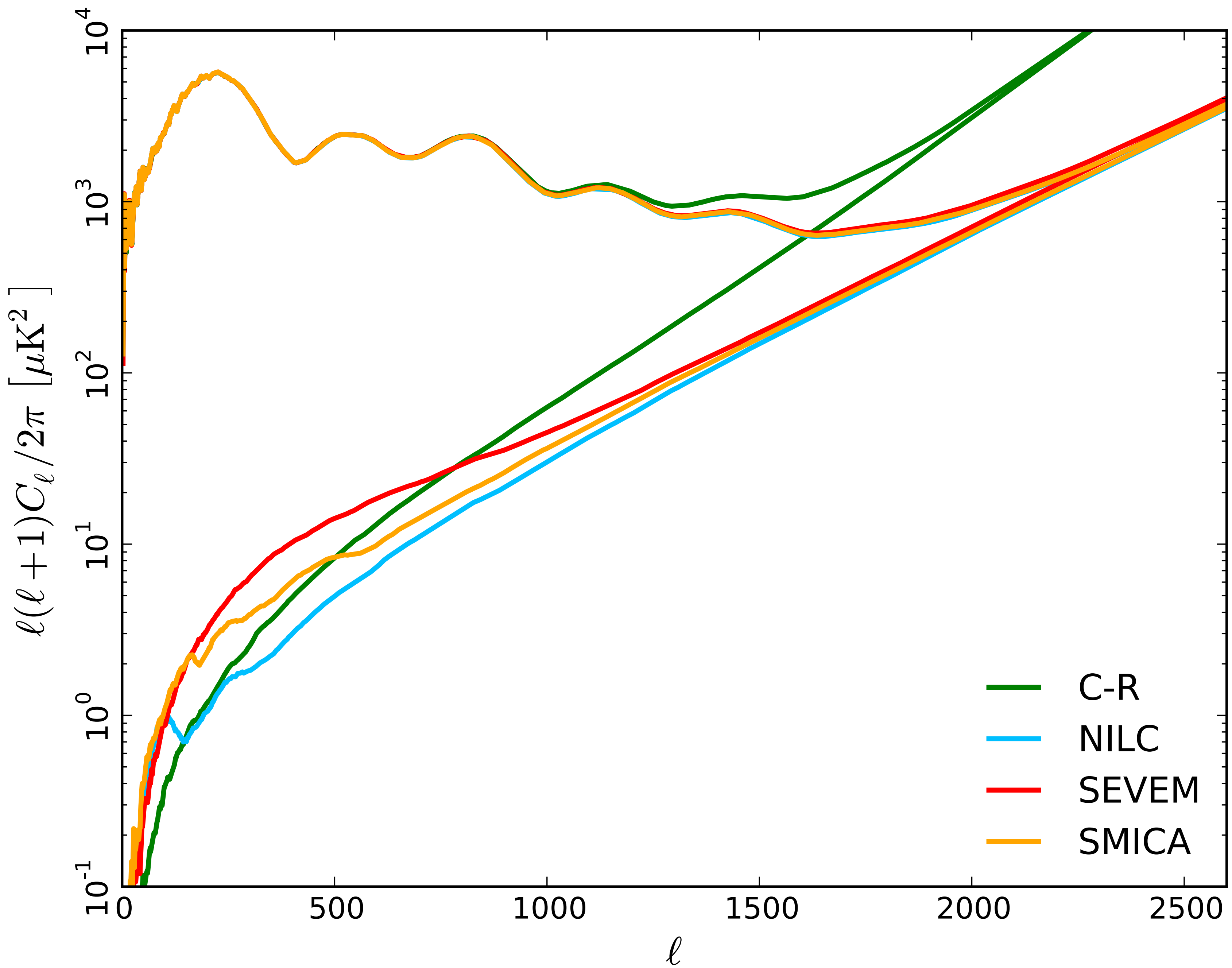


- Maps have been downgraded to N_{side} = 128 to show large scale features
- In the Galactic plane, residuals are larger than in the data
- FFP6 gives conservative estimate of residuals

Power spectrum and cosmological parameters

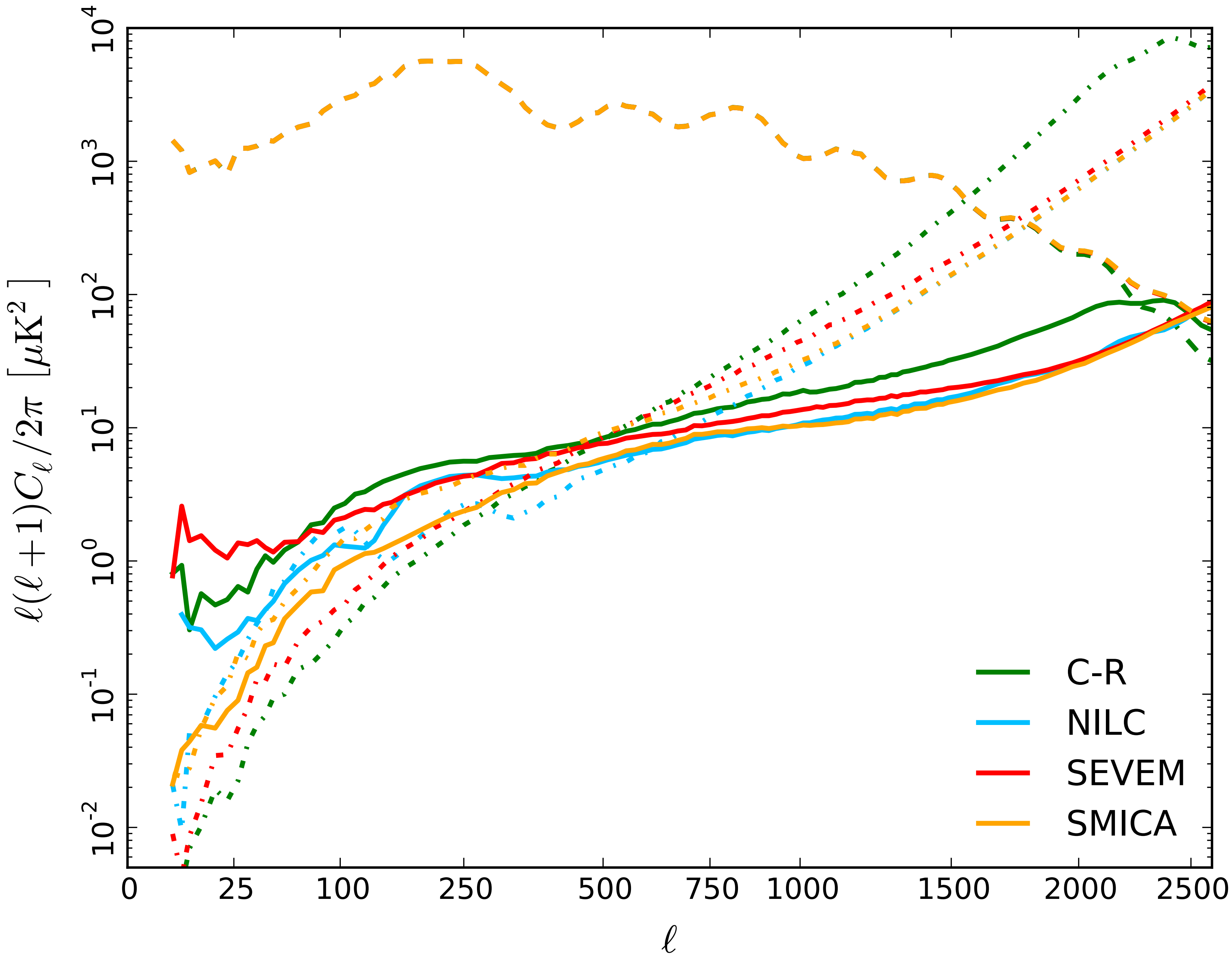
- Objective is to ensure CMB maps are compatible with high-l power spectrum and likelihood analysis which is based on cross-spectra
  - CMB maps are used for higher-order statistics
  - Uses larger sky fraction that the conservative one adopted in the likelihood analysis
- Use XFaster to estimate spectrum and use correlated Gaussian likelihood
  - Half-ring half-difference map is used as estimate of the noise
  - Multipole range $l = 70$ to 2000
  - Gaussian prior, $\tau = 0.0851 \pm 0.014$
  - Residual foregrounds are modelled in the power spectrum with two templates
    - Poisson component C_l = constant
    - Clustered component $D_l = l(l+1)C_l/2\pi \propto l^{0.8}$
- Limitations
  - Some systematic effects are not accounted for in the likelihood
    - Uncertainties in beam transfer functions
    - Uncertainties in inter-calibration between channels
  - Simple foreground model

Power spectra of foreground-cleaned maps



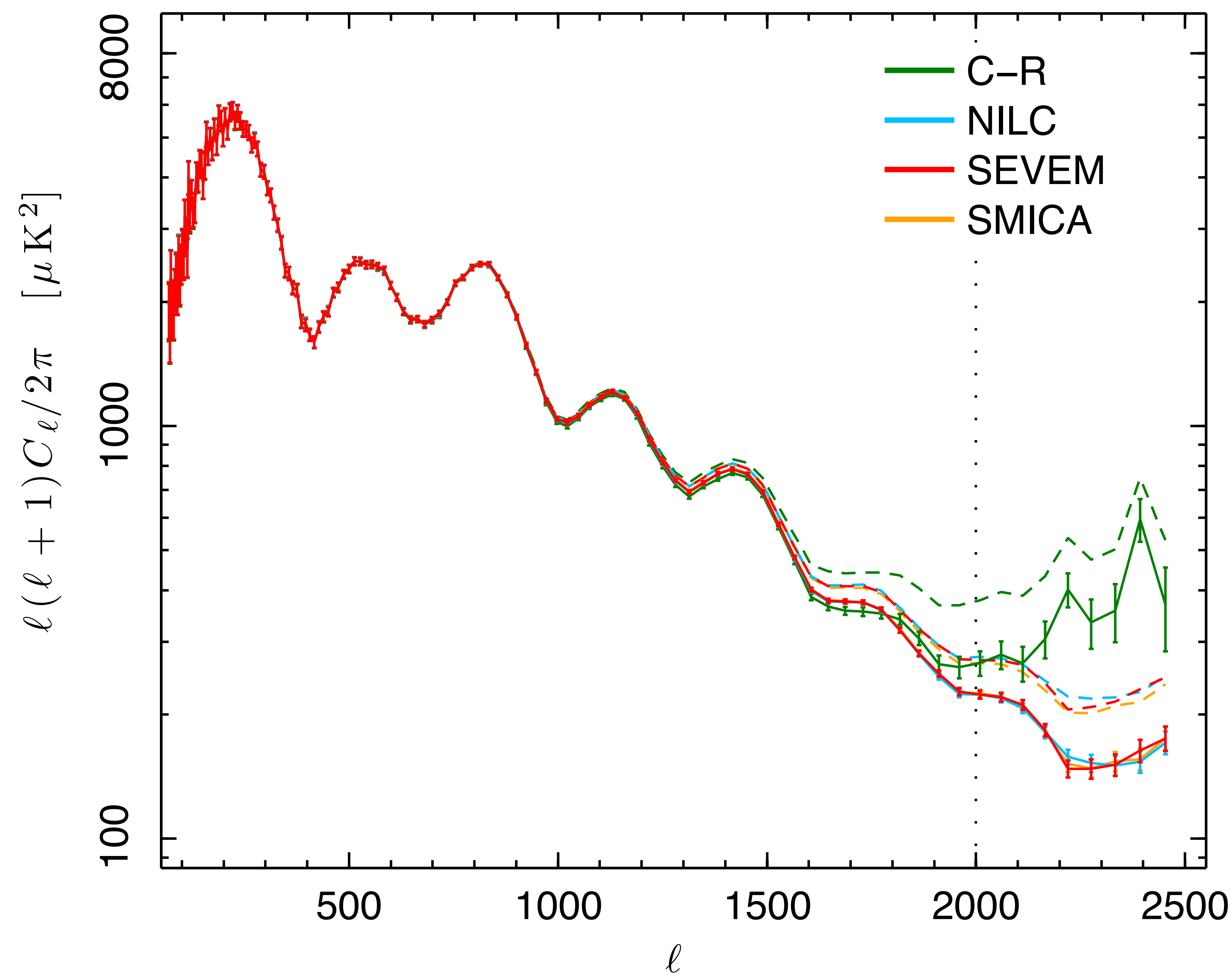
- Power spectra using apodized U73 mask
- Spectra have been corrected for the effect of the mask and beams
- Upper line is spectrum of foreground-cleaned map (CMB, noise, and residual foregrounds)
- Lower line is spectrum of half-ring half-difference (HRHD) map, approximating the noise
- Noise is underestimated by HRHD map, due to correlations in HFI channels induced by glitch removal
- NILC, SEVEM and SMICA have comparable noise at small angular scales

Power spectra of components from FFP6



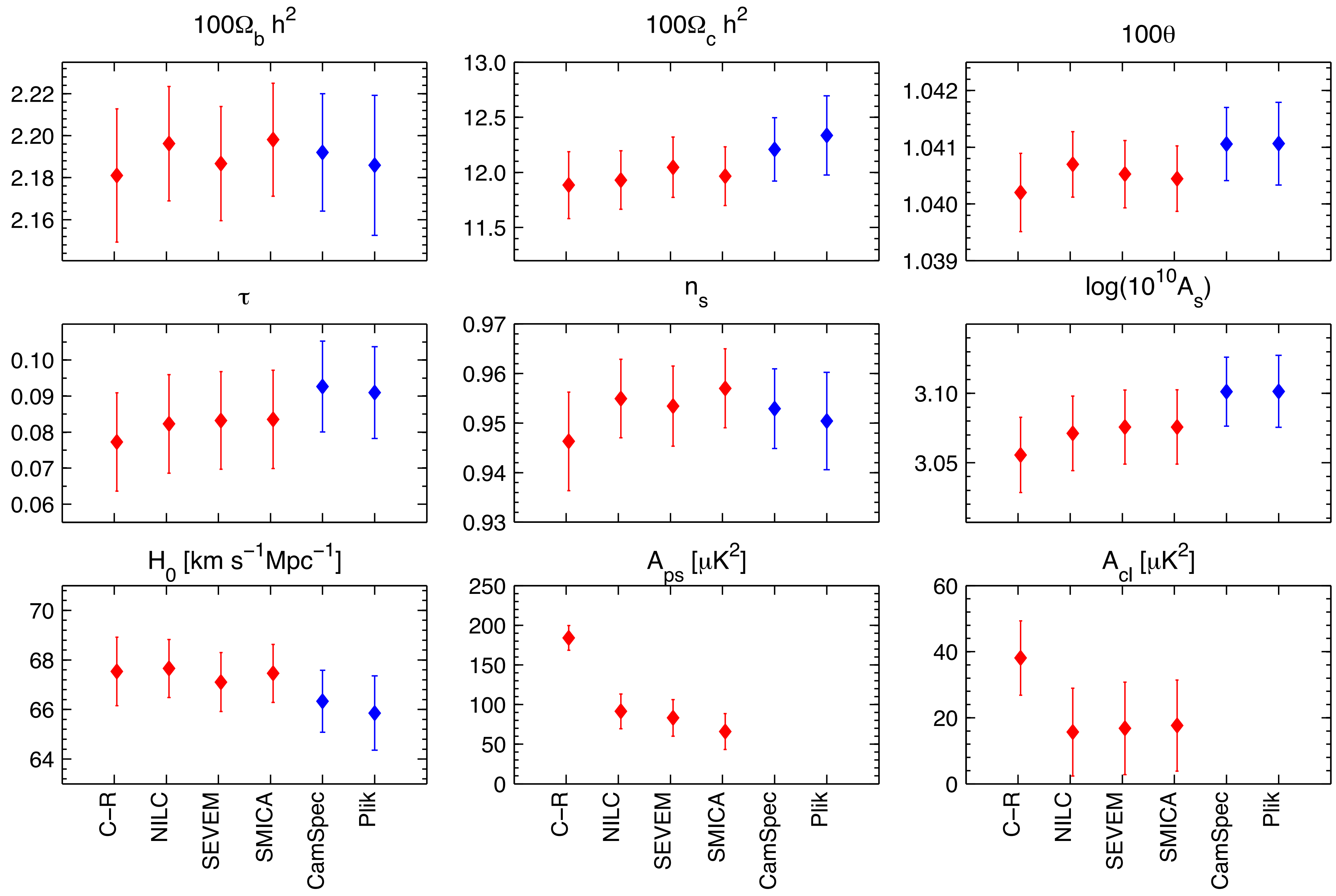
- Power spectra estimated using apodized union mask
- Components: CMB (dashed); noise (dot-dashed); sum of foreground components (solid)
- Non-linear scale is used to enhance the features of the spectrum
- Residual foreground components become comparable to CMB signal at l ≈ 2000
- SMICA has lowest residual foregrounds at large angular scales

Estimates of CMB power spectrum



- Used apodized U73 mask
- Solid line shows power spectrum after subtracting best-fit residual foreground model fitted with l_{max} = 2000
- Dashed line shows spectrum before subtracting residual foreground model
- Error bars show uncertainties from the Fisher matrix

Cosmological parameters

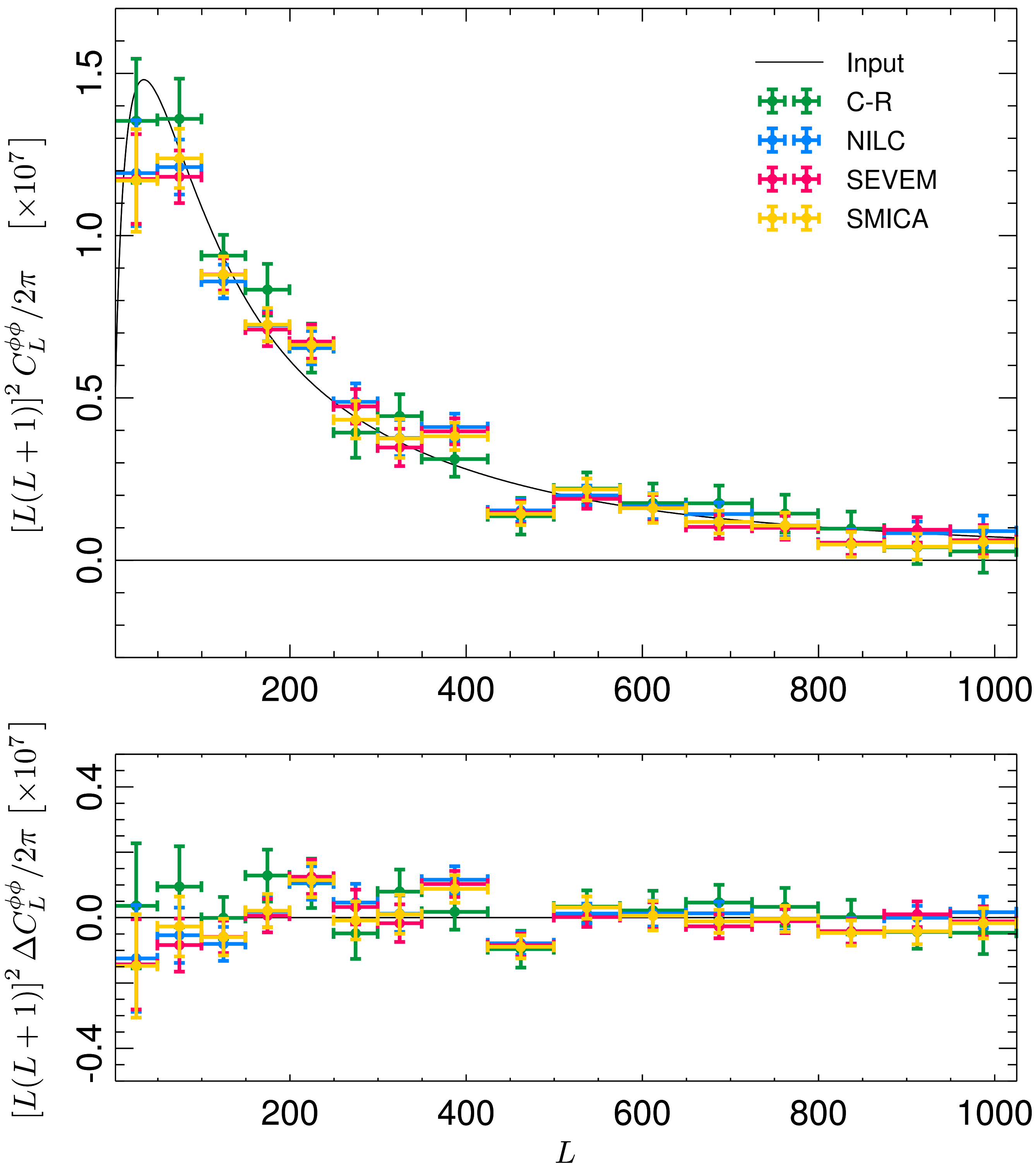


- Parameter estimates are compared to those coming from the cross-spectrum analysis from CamSpec and Plik
- Foreground parameters are not shown for CamSpec and Plik, since they use a different foreground model
- Excess noise is being absorbed into foreground parameters
- The parameters are consistent with the main likelihood analysis using CamSpec

Higher-order statistics

- Tests of higher-order statistics with FFP6
- Non-Gaussianity
  - Recovered values of local f_{NL} from maps with input value of 20.4075
    - C-R $f_{NL} = 8.8 \pm 8.6$
    - NILC $f_{NL} = 19.0 \pm 7.5$
    - SEVEM $f_{NL} = 11.1 \pm 7.6$
    - SMICA $f_{NL} = 19.7 \pm 7.4$
  - NILC and SMICA perform best in this test
- Gravitational lensing by large-scale structure
  - Recovery of lensing potential power spectrum

Lensing potential power spectrum



- Upper panel shown input and recovered lensing potential power spectra for $f_{sky} \approx 0.70$
- Lower panel shows residuals
- Results from all four maps are in good agreement with the input
- C-R uncertainties are larger due to larger beam

Conclusions

- All four algorithms work well on real and simulated data and yield consistent results
- Choose Commander maps for power spectrum likelihood at low-l
    - Diffuse foregrounds dominate at large angular scales, so ability to marginalise over foregrounds in likelihood is essential
- SMICA is the leading method for high-l analyses
    - Performs best on simulations in terms of foreground residuals and preservation of primordial non-Gaussianity
- Use other maps to asses the uncertainties due to choice of methods and their assumptions
- Other talks of interest
    - Planck sky model (J. Delabrouille)
    - Full focal plane simulations (J. Borrill)
    - Non-parametric approaches to CMB cleaning (J.-F. Cardoso)
    - Component separation with Commander (I. Wehus)

SMICA foreground-cleaned CMB map

3% processing mask has been filled with a constrained realization