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Polarized foregrounds and implications for future surveys

Jacques Delabrouille

Centre Pierre Binétruy

CNRS & UC Berkeley, CA, USA

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!! -- WORK IN PROGRESS -- !!

ALL OF THIS IS STILL

PRELIMINARY

The polarized foregrounds problem

- Foregrounds are a key issue for CMB polarization measurements, in particular **polarized synchrotron** and **polarized thermal dust**.

- Existing observations (Planck, WMAP) of polarized foreground emission are *noise-dominated* in clean regions of the sky.

- Sky models used in simulations are uncertain, and vary significantly from model to model (amplitude, complexity). Cannot be trusted to ***predict*** the contamination.

- Additional foreground observations from the ground are potentially costly (trade-off with sensitivity in the main CMB atmospheric windows).

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Can we still try to improve ***predictive***
polarized synchrotron and ***polarized dust*** models...

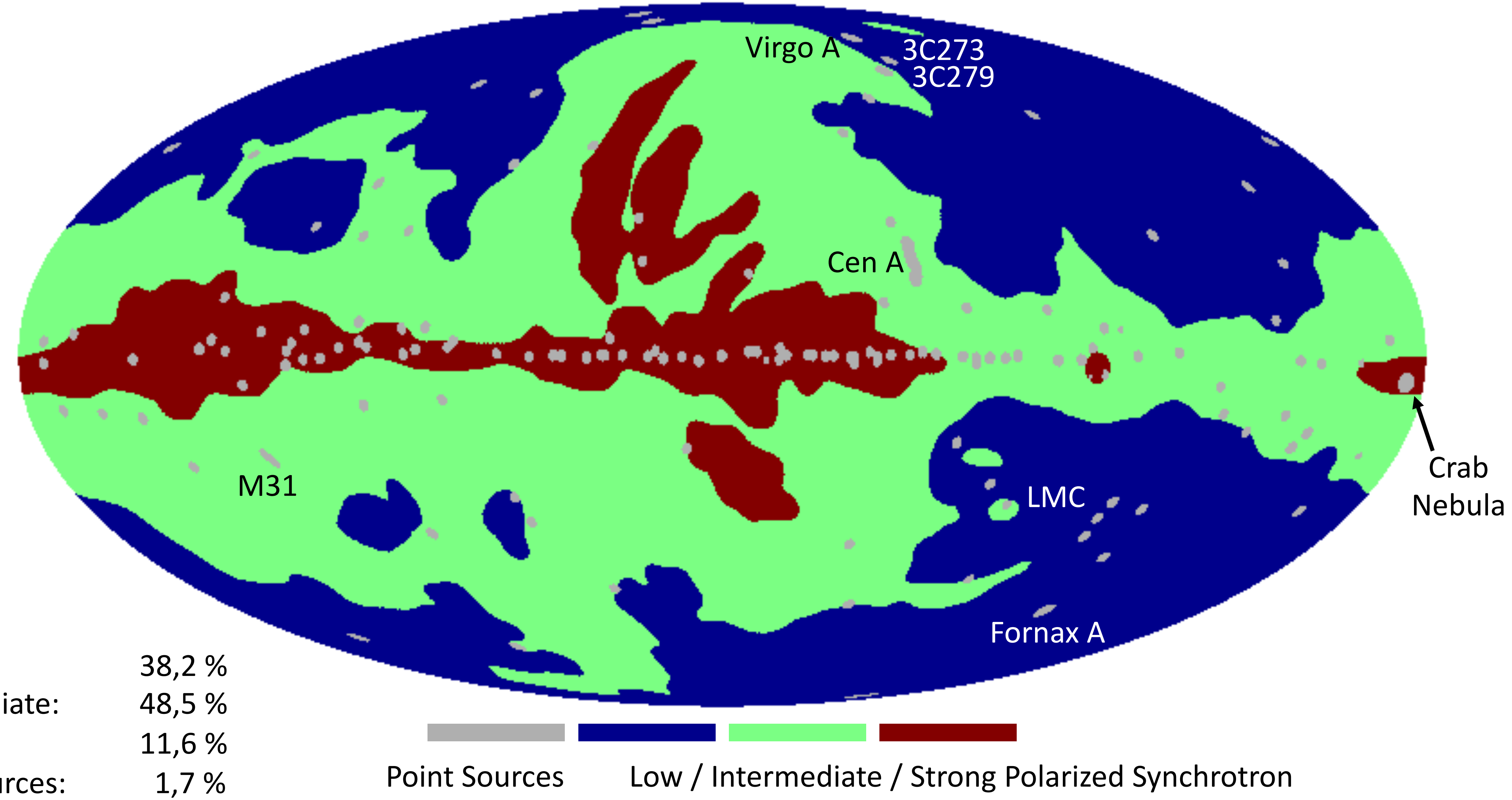
...Using only ***available observations***
(in particular from *WMAP* and *Planck*)...

...and, to be useful for more ***accurate foreground-cleaning***
in future ground-based observations...

...with ***well-characterized uncertainties*** ?

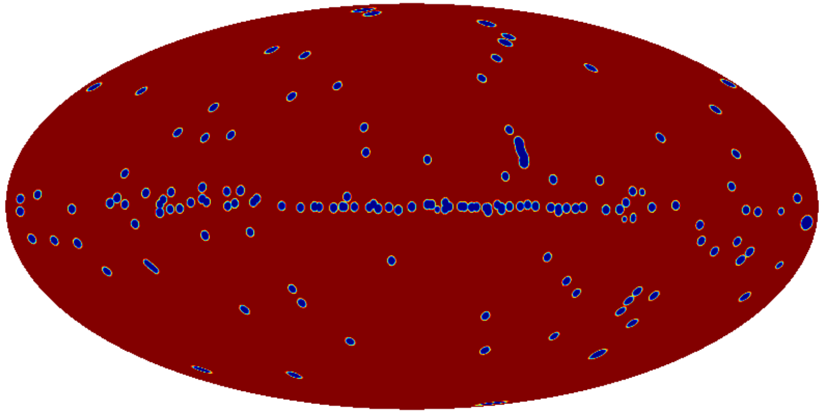
SYNCHROTRON

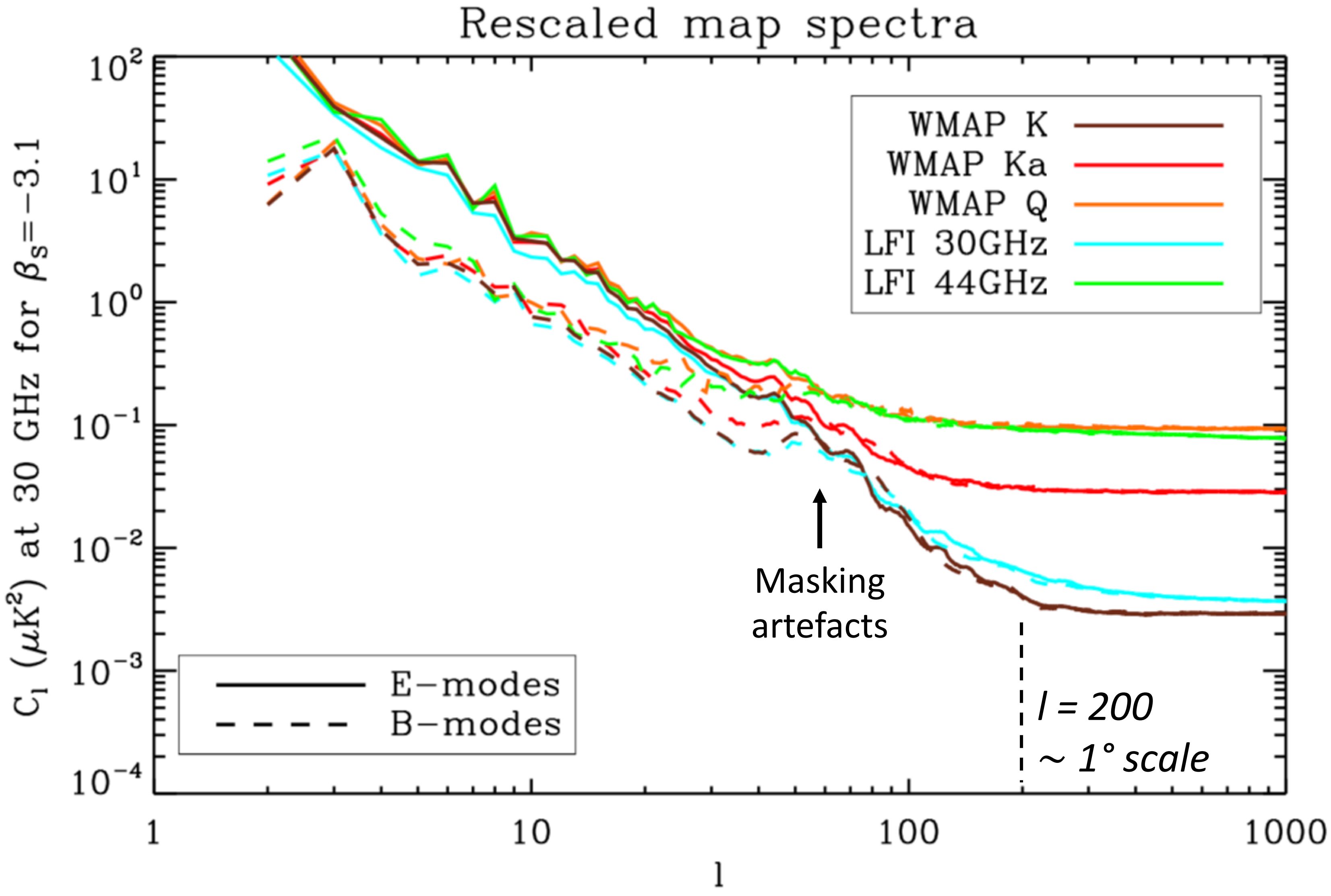
Low-frequency masks (my own)



Low:	38,2 %
Intermediate:	48,5 %
Strong:	11,6 %
Point Sources:	1,7 %

WMAP and LFI map polarization spectra

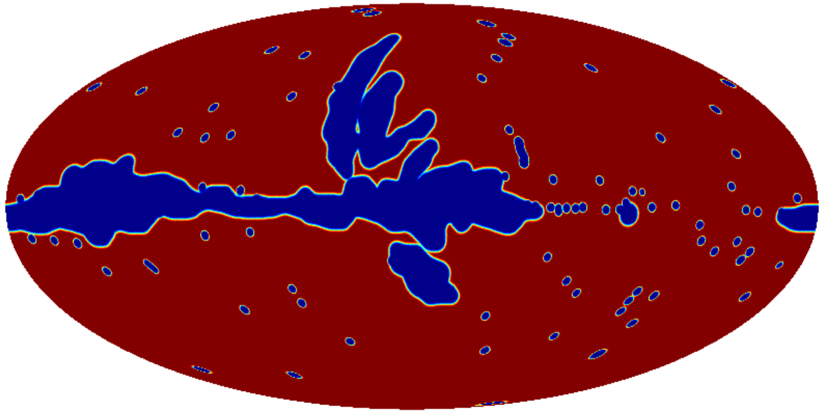




Synchrotron detected with S/N > 1 in all five maps for l < 50 to 200

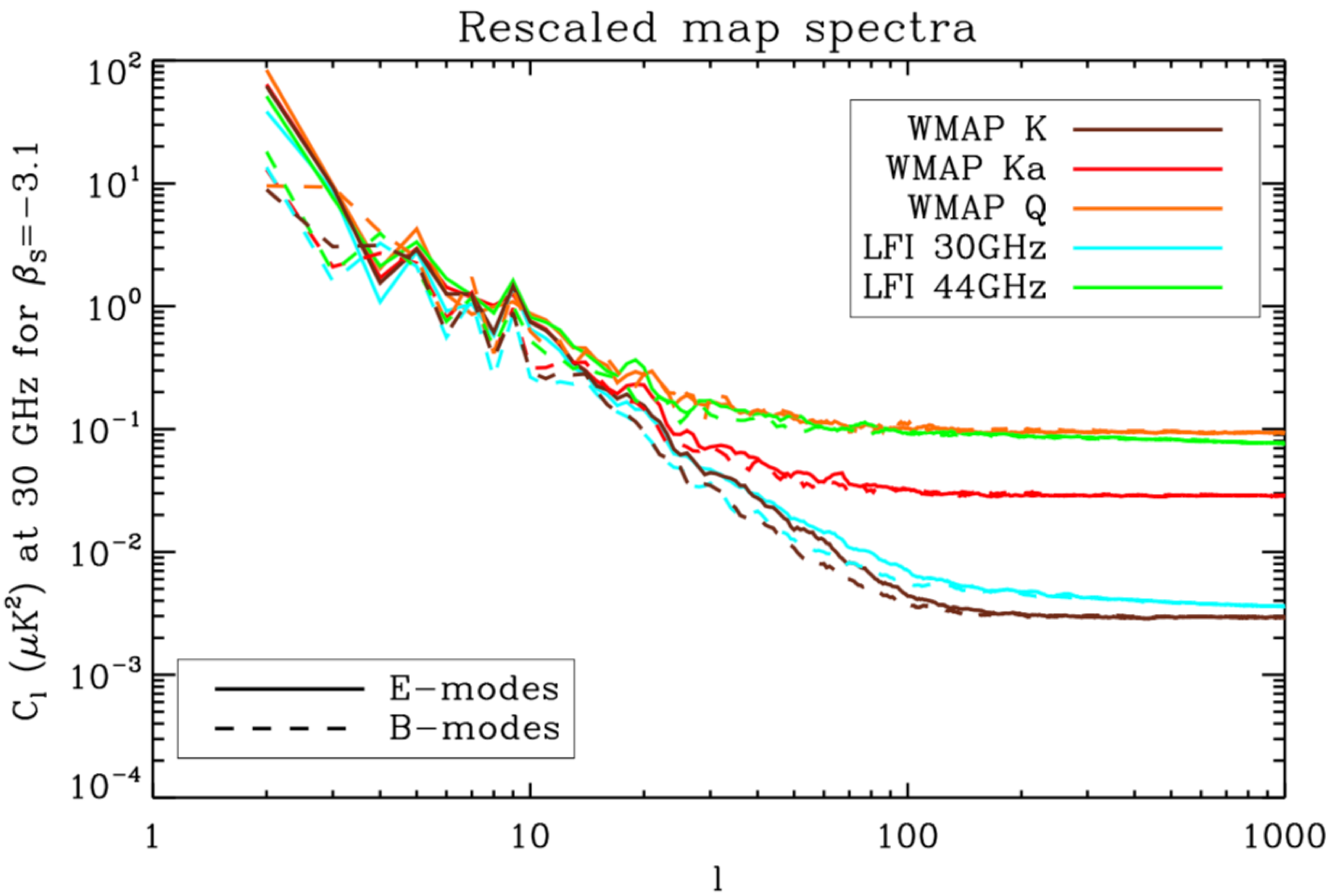
E modes stronger than B modes by a factor 4-5 at low l

WMAP and LFI map polarization spectra

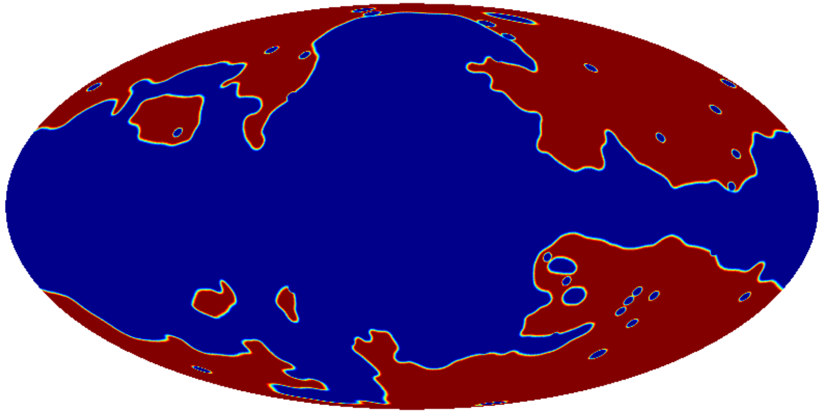


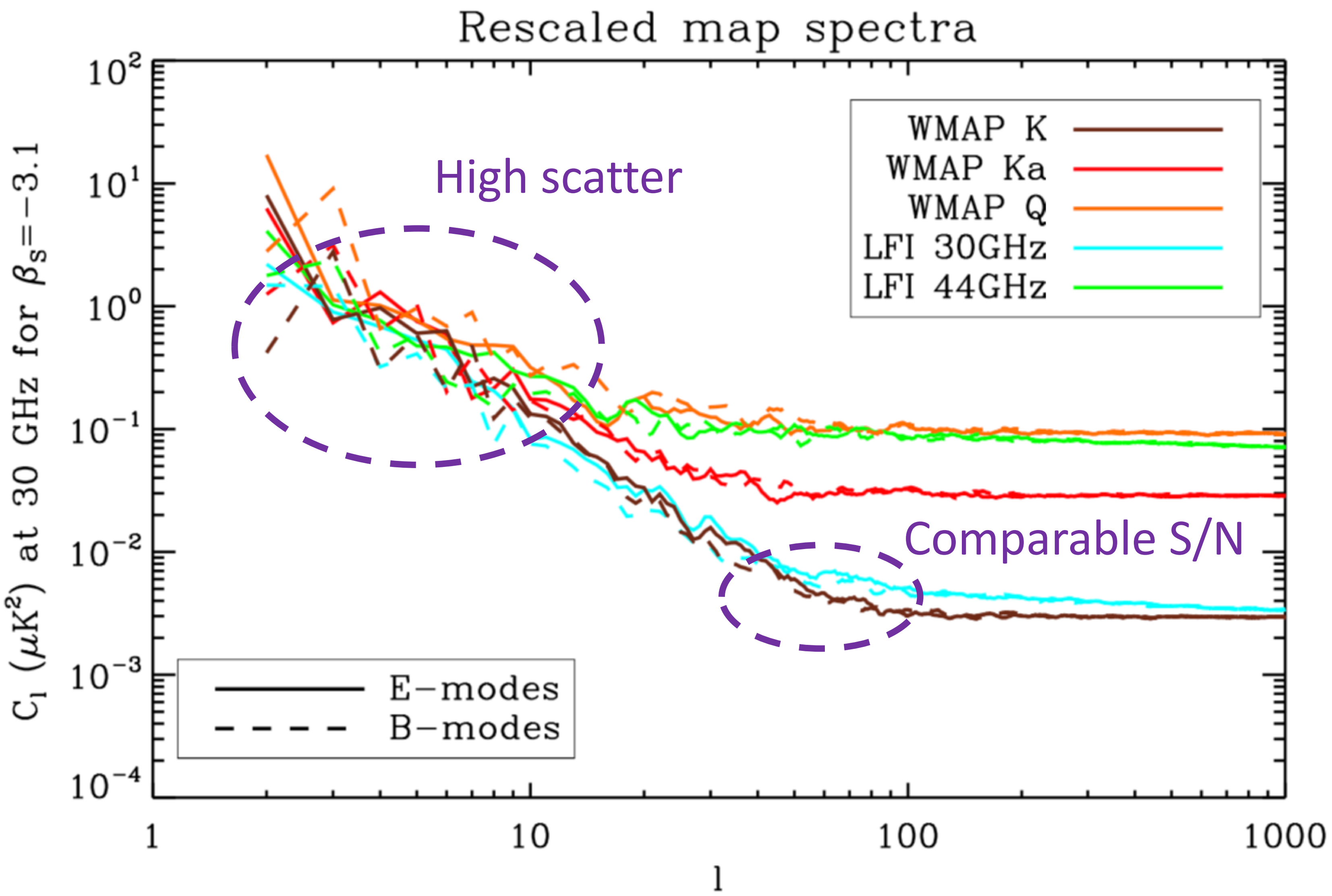
Synchrotron detected with S/N > 1 in all five maps for l < 20 to 100

E modes slightly stronger than B modes (not very obvious)



WMAP and LFI map polarization spectra



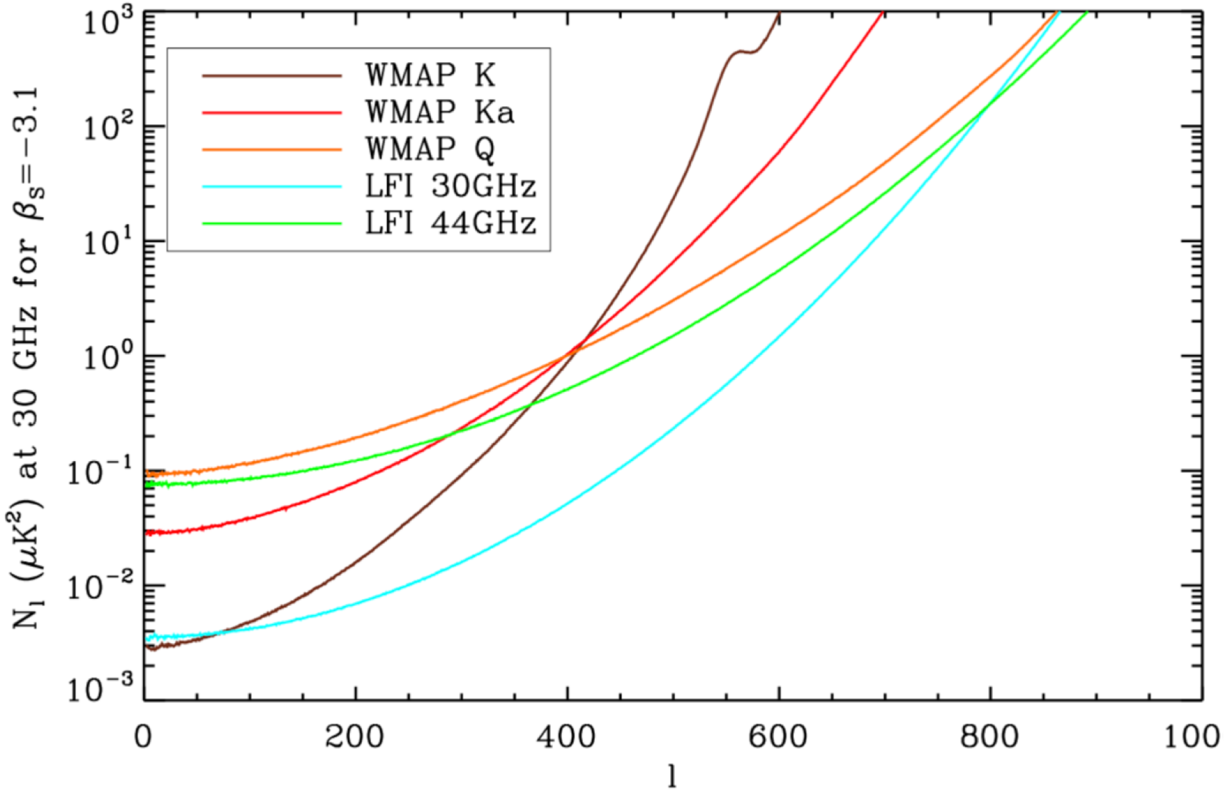


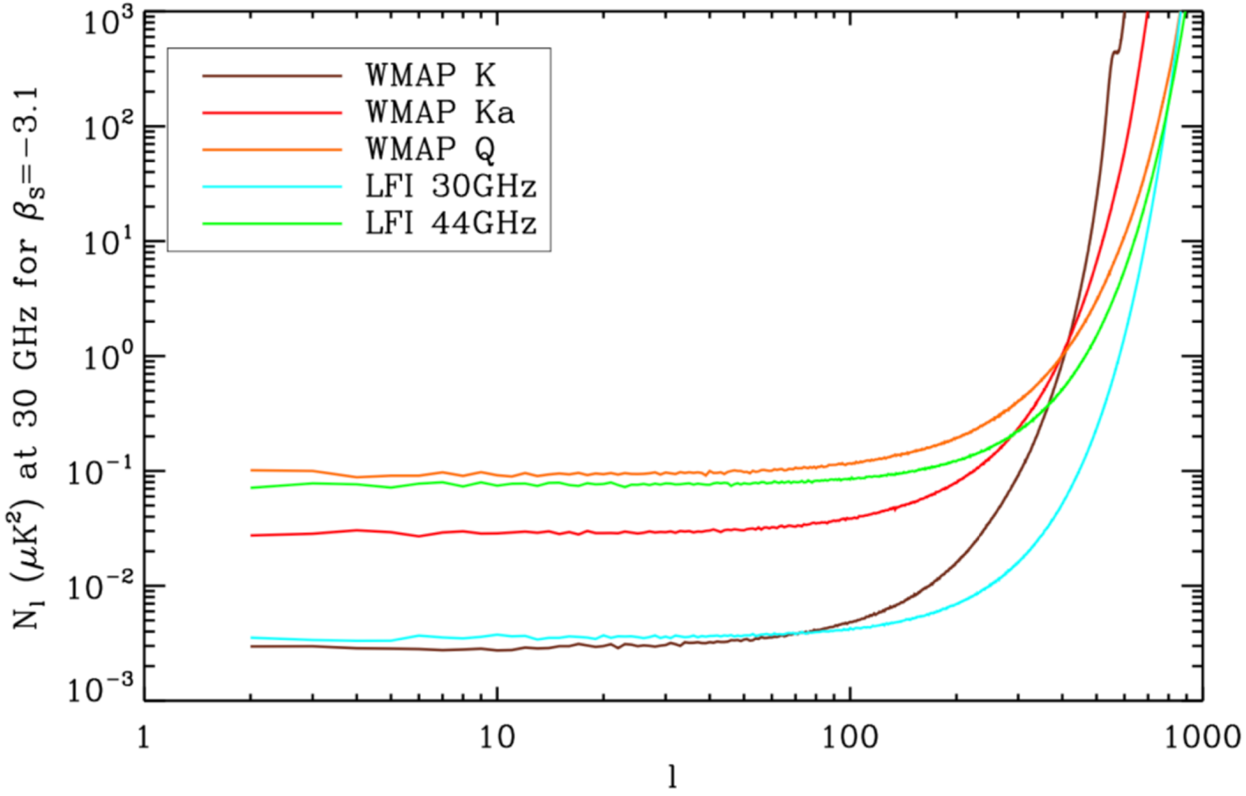
Synchrotron detected with S/N > 1 in all five maps for l < 10 to 50

Scatter can be a sign of systematics, varying β_S or multi-component synchrotron, or all of that

Projected noise spectra (full sky)

Average noise power, scaled to equivalent synchrotron sensitivity at 30 GHz





Noise levels in the various maps

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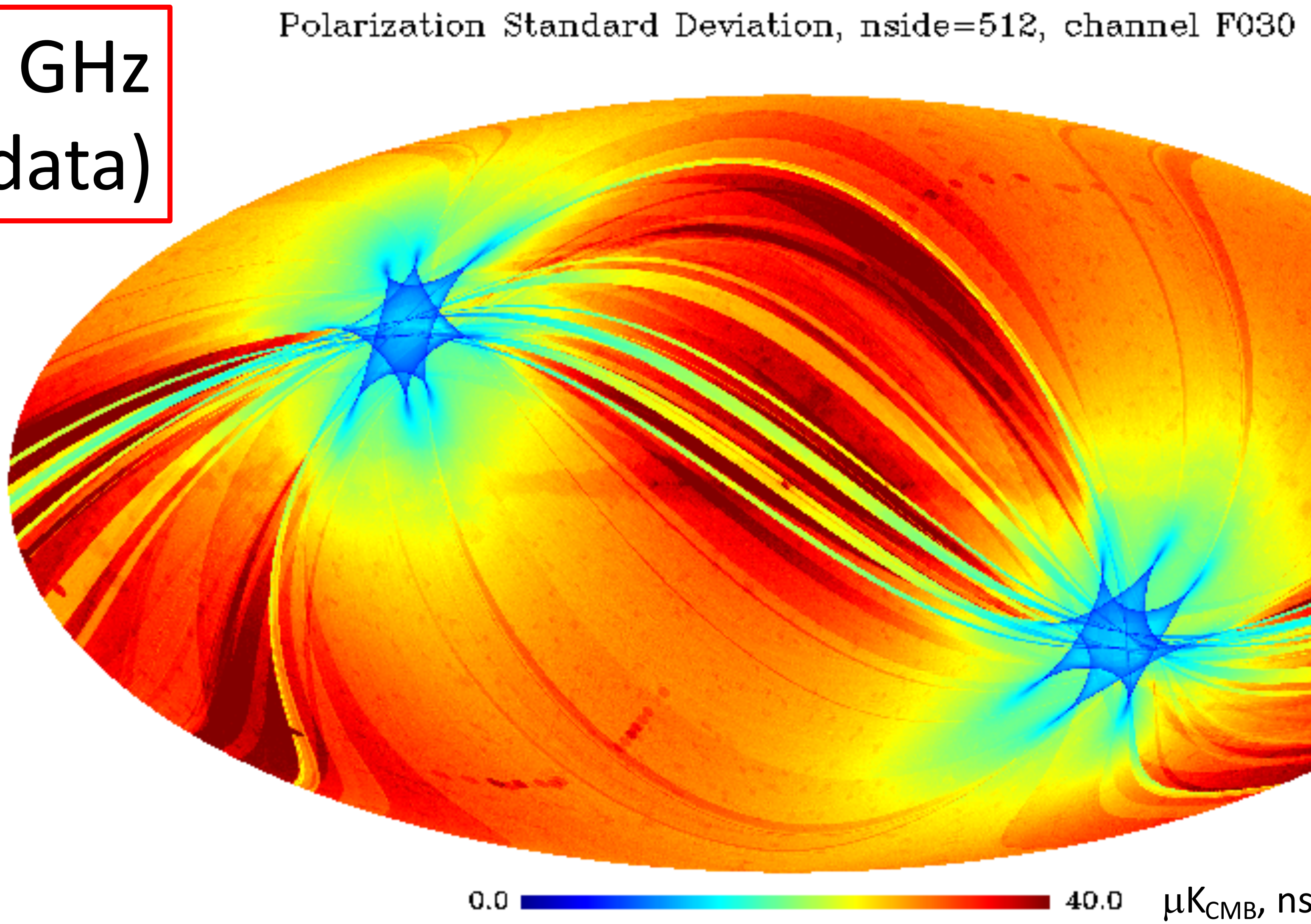
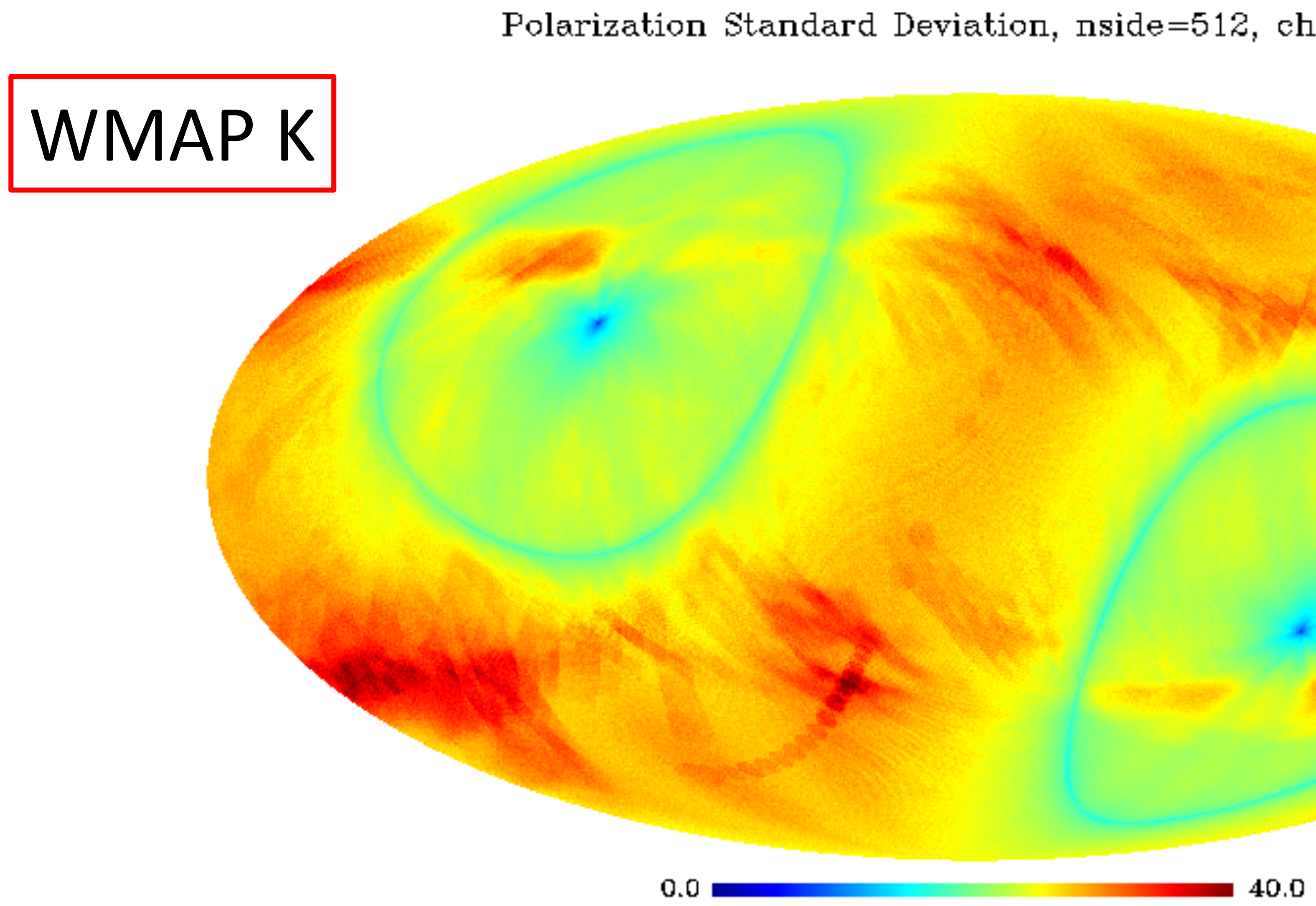
LFI 30 GHz
(DR4 data)



Planck Collaboration, A&A 643, id.A42 (2020)

μK_{CMB}, nside=512, scaled to 30 GHz

Noise levels in the various maps



μK_{CMB}, nside=512, scaled to 30 GHz

Noise levels in the various maps

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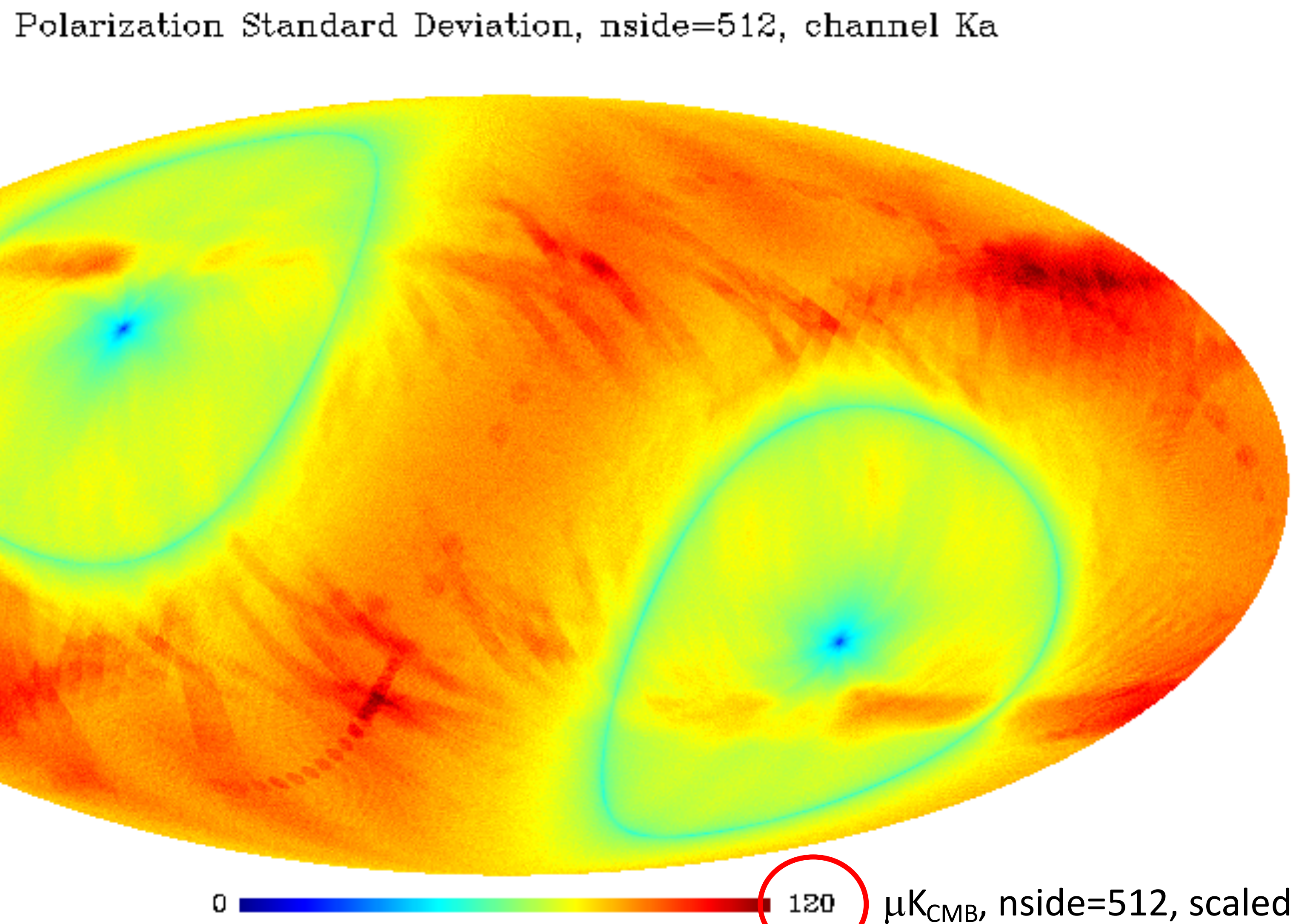
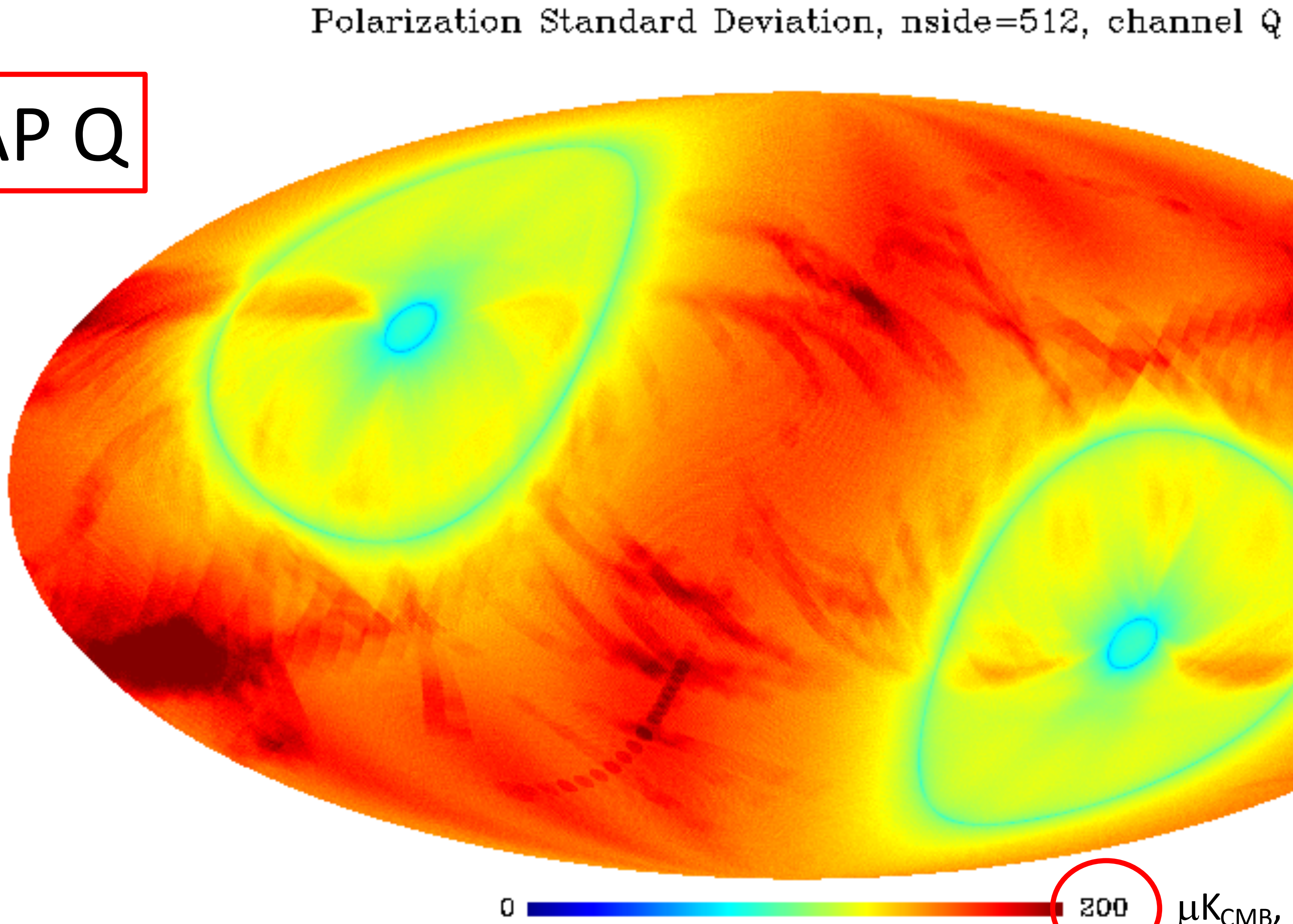
WMAP Ka



μK_{CMB}, nside=512, scaled to 30 GHz

Noise levels in the various maps

WMAP Q



μK_{CMB}, nside=512, scaled to 30 GHz

Noise levels in the various maps

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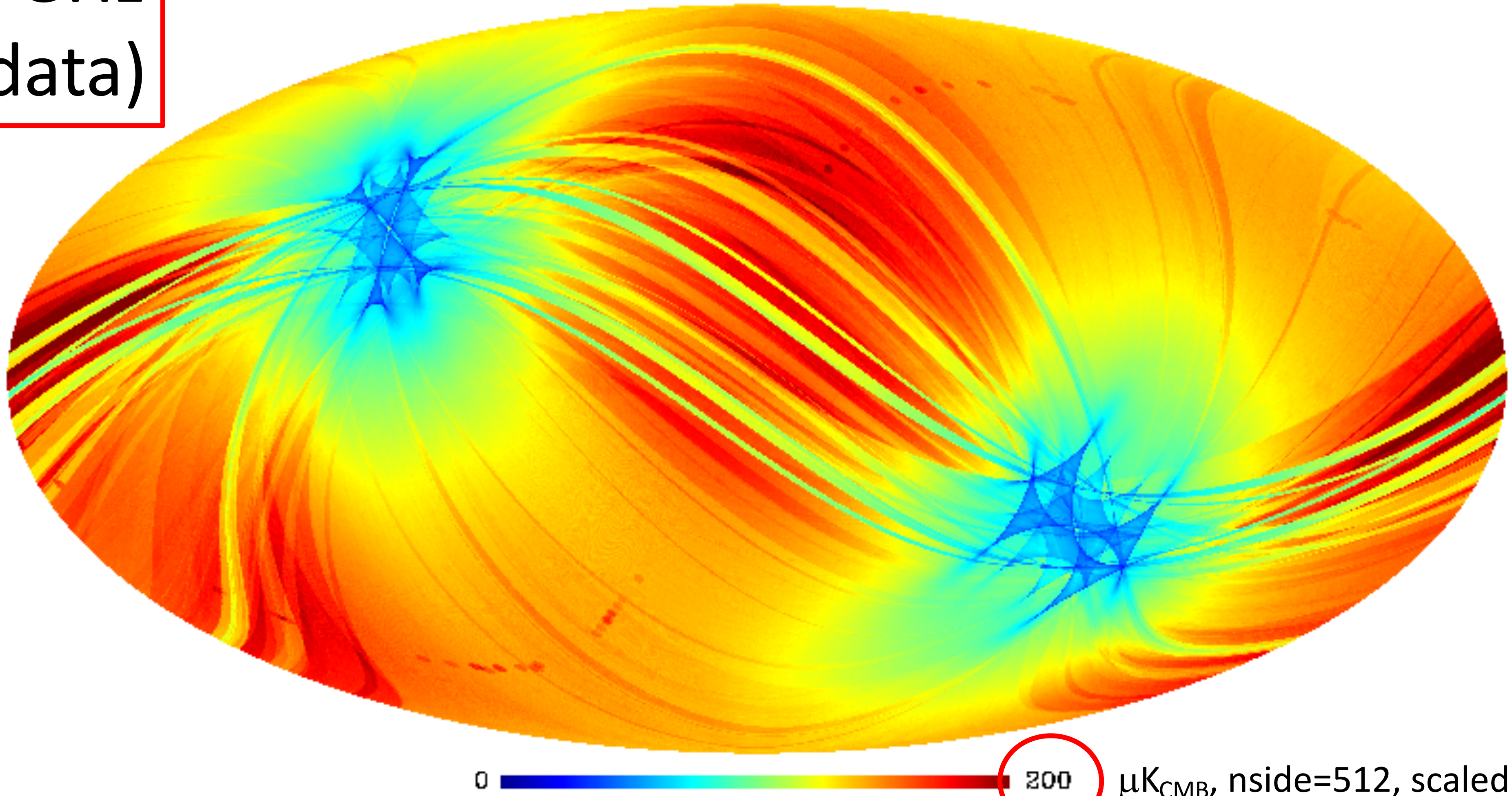
LFI 44 GHz (DR4 data)

Polarization Standard Deviation, nside=512, channel F044



μK_{CMB}, nside=512, scaled to 30 GHz

State of the art: SMICA and Commander

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- Official Polarized Synchrotron Planck products: **Commander** and **SMICA** maps at 30GHz from Planck 2018

- Main path for improvement:

  - **Synchrotron maps are obtained solely from Planck data, so they can be improved by including WMAP observations (at comparable sensitivity)**

  - **Improve the characterization: noise properties, beam, error budget**

Plan for a better synchrotron template

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- We will use WMAP **K**, **Ka** and **Q** maps, and LFI **30 GHz** and **44 GHz** maps
- We will work in **needlet space** to take into account variability of weights both in pixel space and in harmonic space.
- We will assume that **we know the CMB** power spectra C_l^{EE} and C_l^{BB} (Planck best fit with r=0)
- We will assume that polarized dust below 50 GHz is negligible and hence WMAP K, Ka and Q, and LFI 30GHz and 44 GHz see only synchrotron, some CMB, and instrumental noise.
- We assume a **synchrotron spectral index of β_S = -3.1**
- We combine the 5 channels with **weights that minimize the noise**.

Pipeline

1. Polarization is the focus
2. Put all maps at the same angular resolution (40' or 60'), same pixelisation (nside=512)
3. Subtract a Wiener-filtered version of the SMICA CMB (full sky)
4. Put all maps in synchrotron units (in μK_{CMB} at 30 GHz)
5. Do a special needlet transform with 20 bands for $0 < l < 1000$
   (special transform using Q,U needlets instead of E,B needlets)
6. Compute the noise level of each channel in needlet space
7. Co-add maps with inverse noise variance in needlet space
8. Recombine needlets into synchrotron Q,U maps and E,B maps

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A Wiener-filtered CMB map

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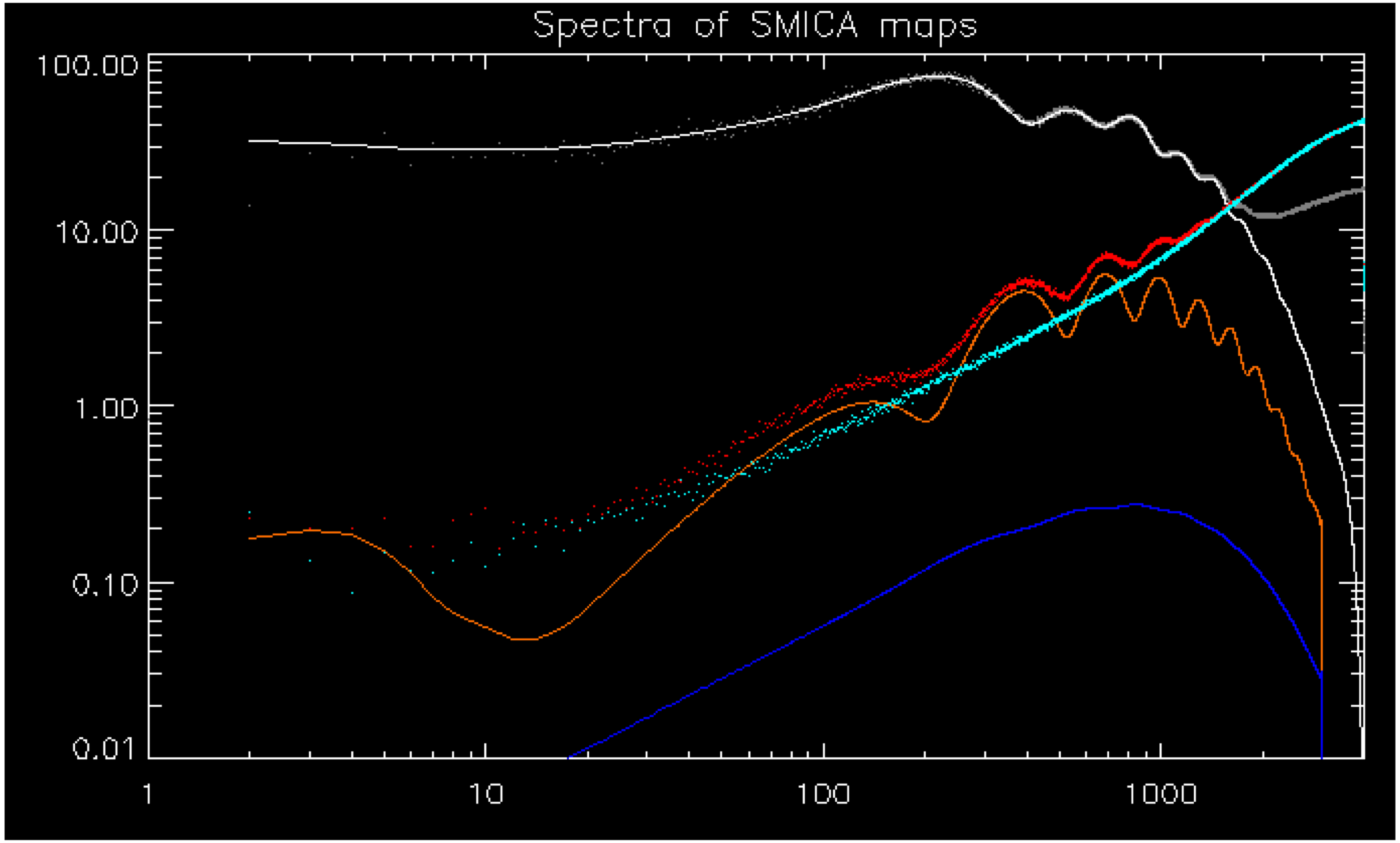
- CMB polarization is sub-dominant in WMAP K, Ka and Q, as well as in LFI 30 and 44 GHz channels, but is not completely negligible.

- We can subtract a best-estimate of CMB polarization with a multi-field Wiener filter that uses the prior knowledge of C_l^{TT}, C_l^{TE}, C_l^{EE}, C_l^{BB}.

- As most of the CMB sensitivity comes from 100,150 and 220 GHz, the noise in this map is essentially uncorrelated from the noise in low frequency channels

A Wiener-filtered CMB map

Start from SMICA maps
T,Q and U

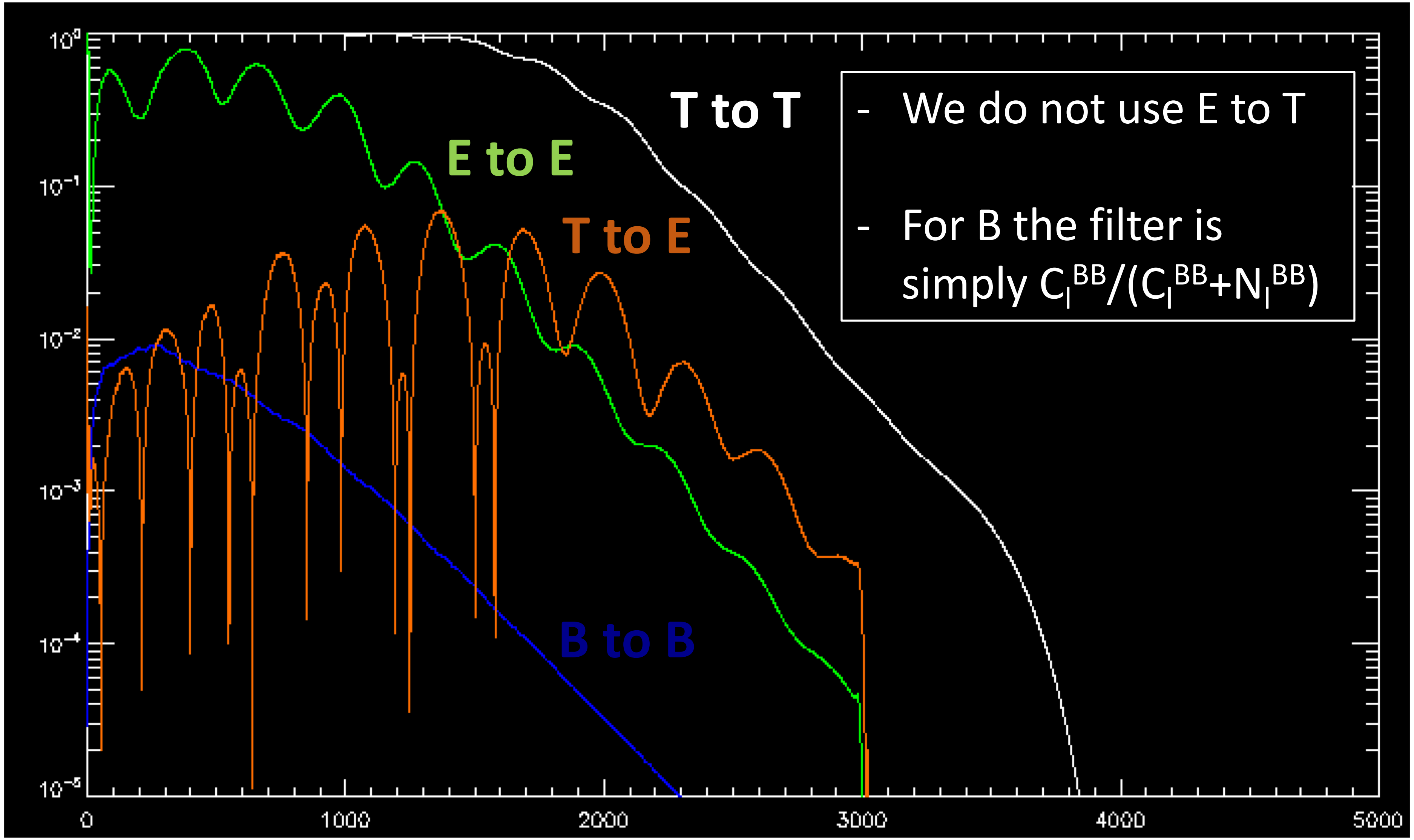


Wiener filter: $w = C\,[C+N]^{-1}\,x$,

where C *is the CMB multivariate model spectrum,*

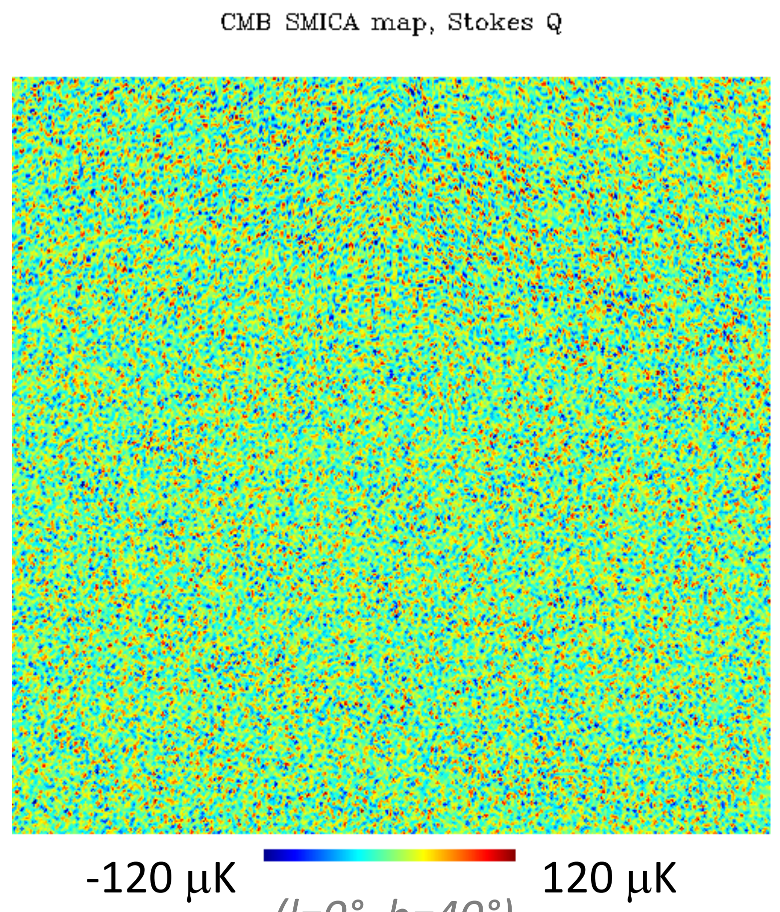
and [C+N] *the CMB+noise (= observed) multivariate spectrum*

Wiener weights



- We do not use E to T
- For B the filter is simply $C_l^{BB}/(C_l^{BB}+N_l^{BB})$

Visualisation of SMICA CMB Stokes Q map



(l=0°, b=40°)

The original Planck CMB polarization maps are noise dominated, as seen on this panel showing the DR3 SMICA Q map at 5' around (l=0°, b=40°).

About half of the noise in Q and U comes from B-modes, where the signal is very faint!

E-mode polarization is signal dominated in some ranges of scales.

Wiener-filtered SMICA CMB Stokes Q map

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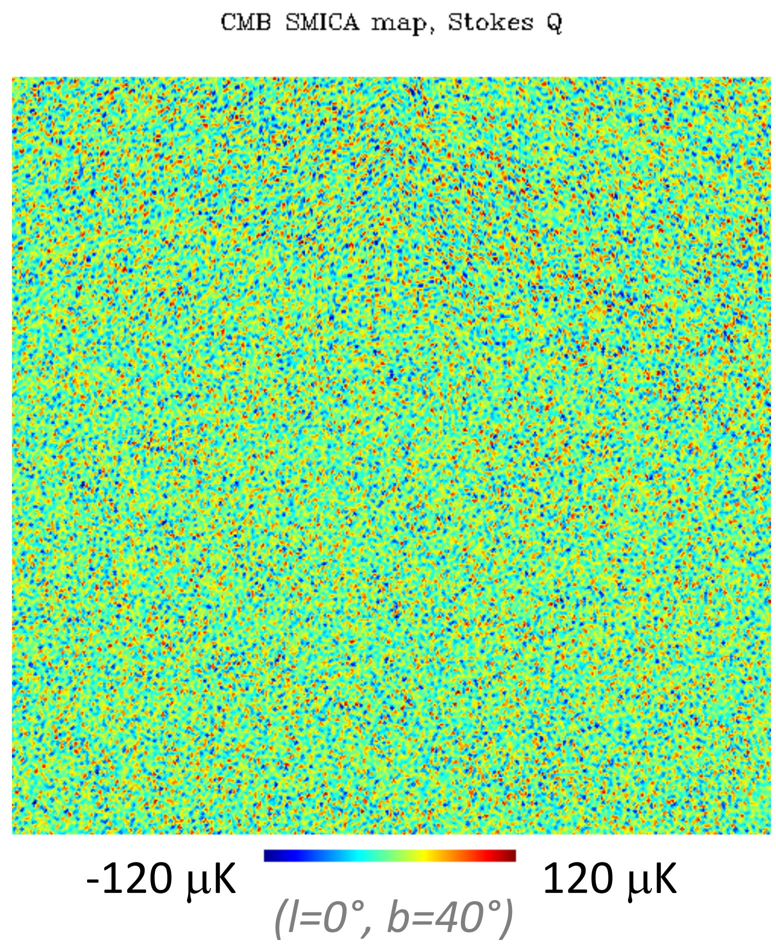
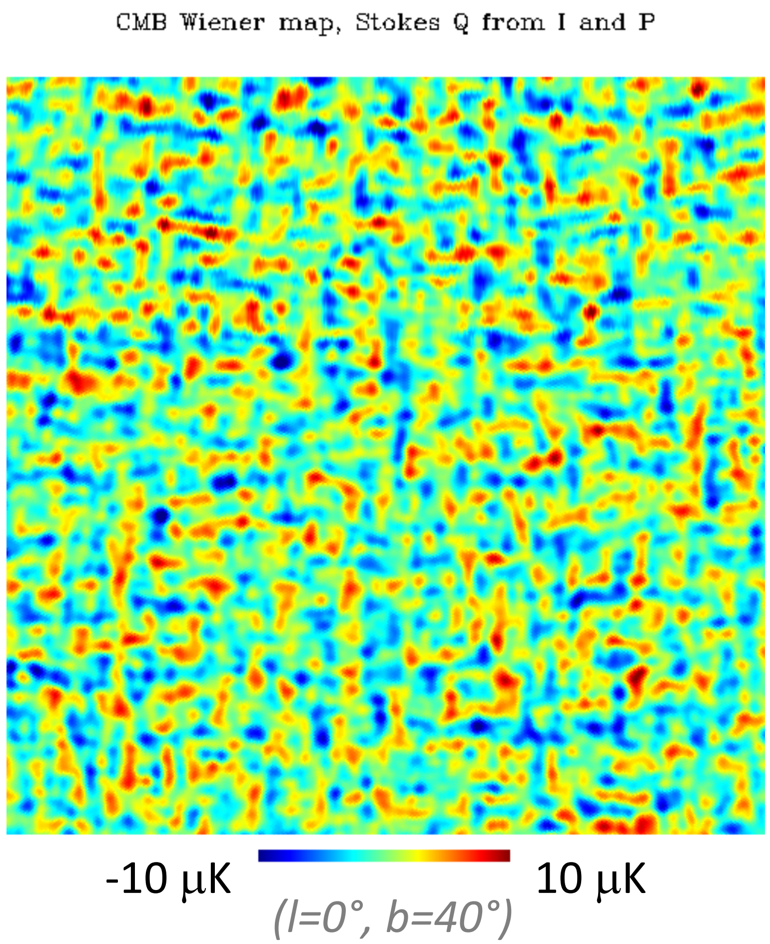
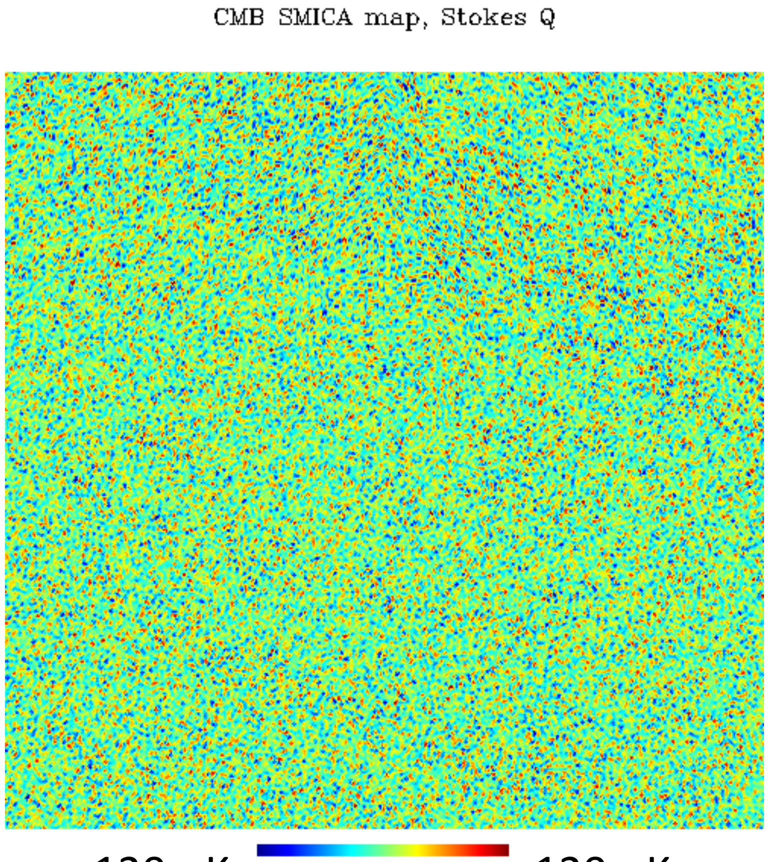


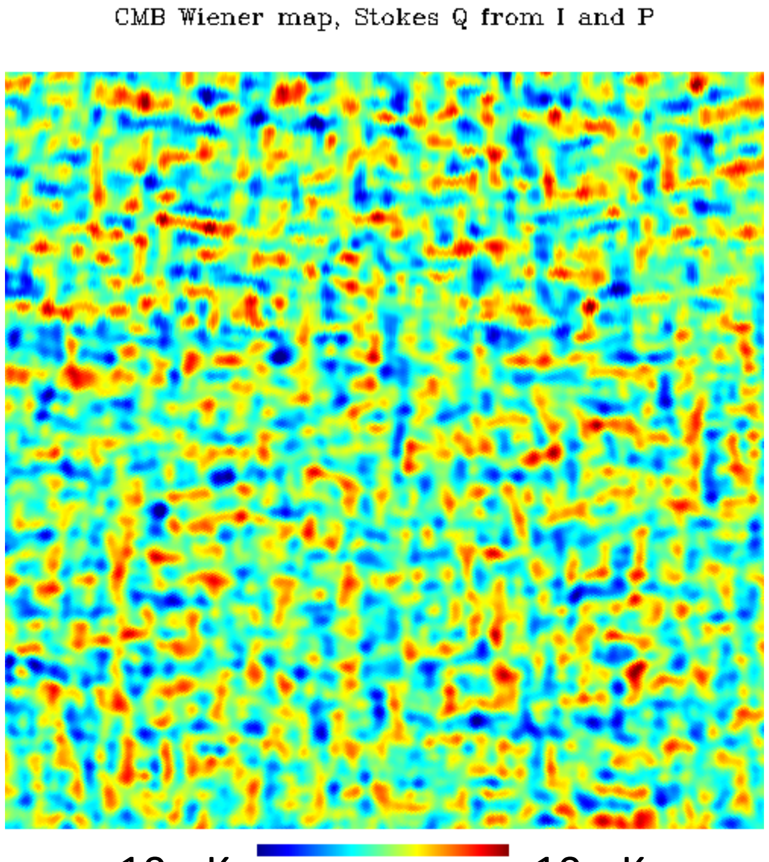


These CMB features are mostly real

Wiener-filtered SMICA CMB Stokes Q map

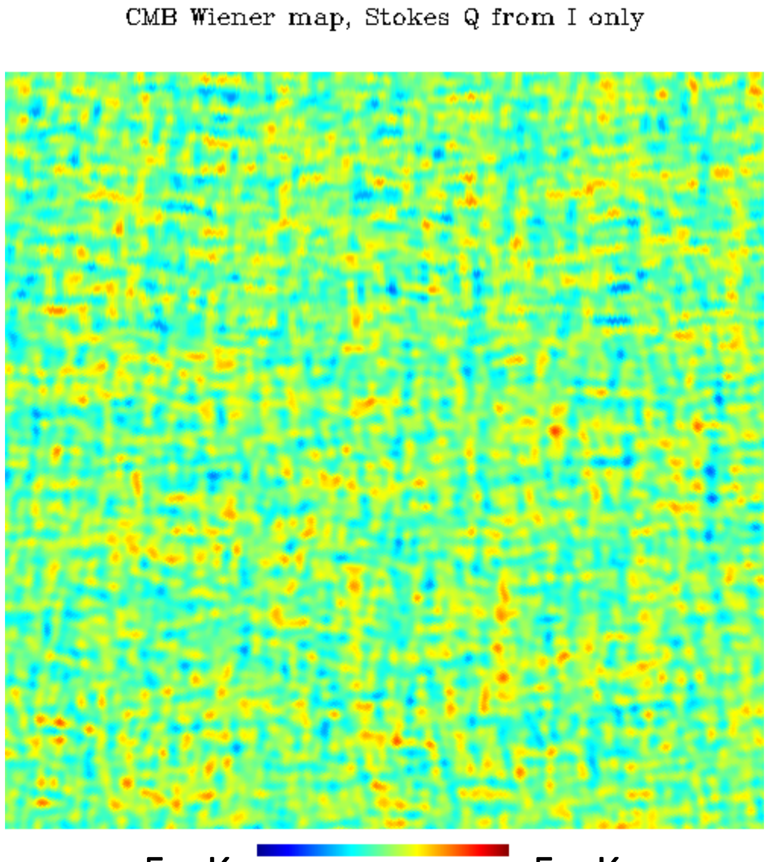


-120 μK 120 μK
(l=0°, b=40°)



-10 μK 10 μK
(l=0°, b=40°)

STANDARD DEVIATION: 2.7 μK



-5 μK 5 μK
(l=0°, b=40°)

STANDARD DEVIATION: 0.7 μK

Wiener-filtered SMICA CMB Stokes Q map

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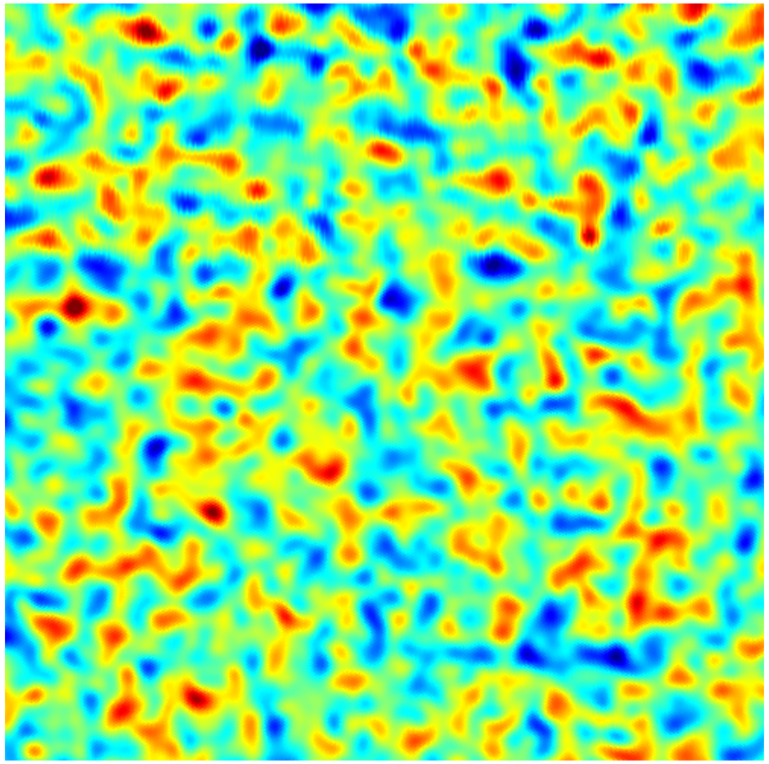
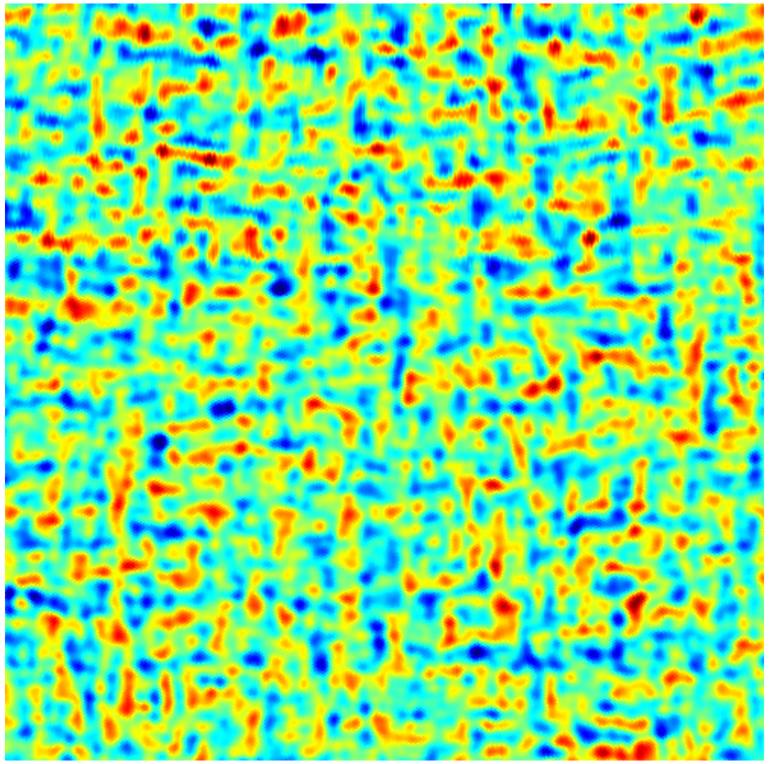
CMB SMICA map, Stokes Q, 20 arcmin



-10 μK 10 μK
(l=0°, b=40°)

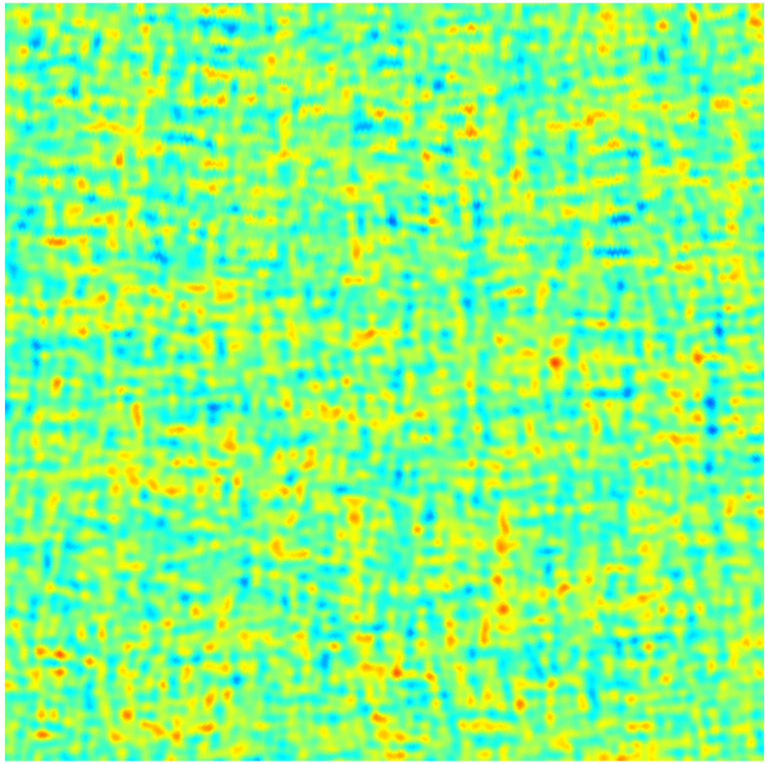
CMB Wiener map, Stokes Q from I and P



-10 μK 10 μK
(l=0°, b=40°)

STANDARD DEVIATION: 2.7 μK

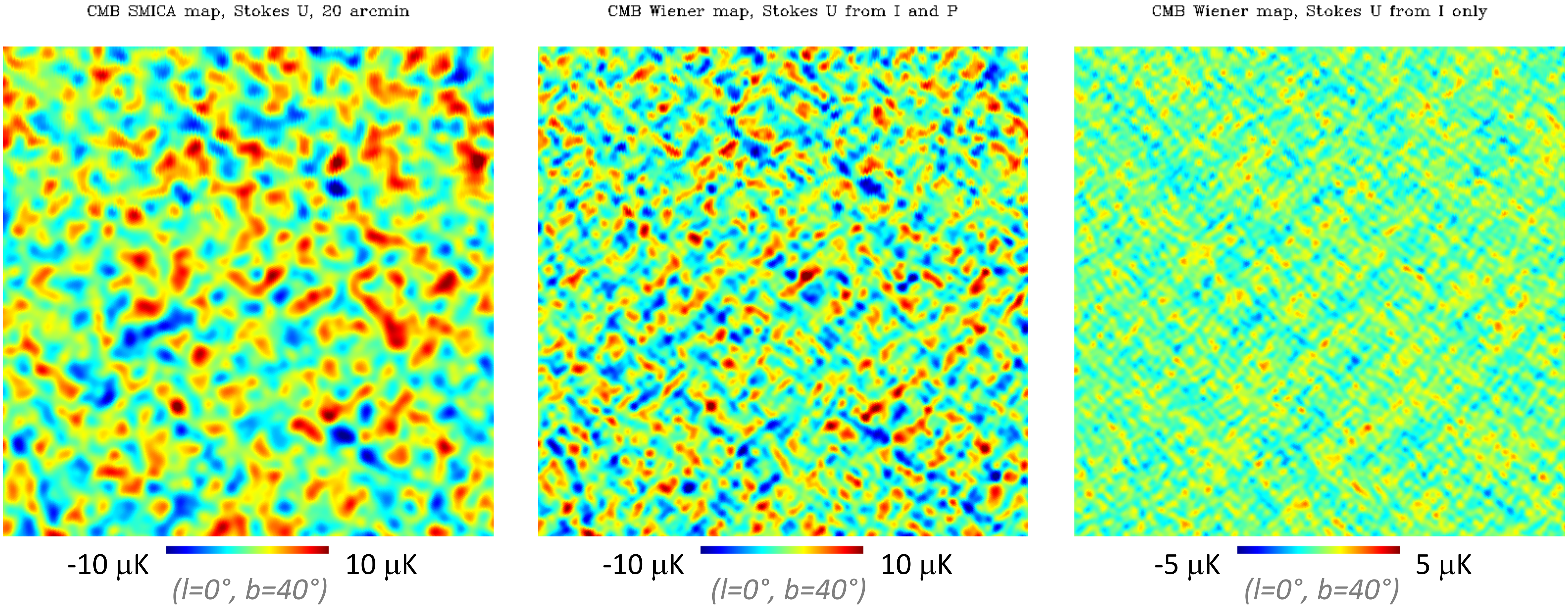
CMB Wiener map, Stokes Q from I only



-5 μK 5 μK
(l=0°, b=40°)

STANDARD DEVIATION: 0.7 μK

Wiener-filtered SMICA CMB Stokes U map



STANDARD DEVIATION: 2.7 mK

STANDARD DEVIATION: 0.7 mK

Parenthesis: Use of Wiener-filtered E-mode map

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Towards ending the partial sky E-B ambiguity in CMB observations

Shamik Ghosh,[a,b,1] Jacques Delabrouille,[c,d,e] Wen Zhao,[a,b] and Larissa Santos[f]

Abstract. A crucial problem for partial sky analysis of CMB polarization is the E-B leakage problem. Such leakage arises from the presence of 'ambiguous' modes that satisfy properties of both E and B modes. Solving this problem is critical for primordial polarization B mode detection in partial sky CMB polarization experiments. In this work we introduce a new method for reducing the leakage. We demonstrate that if we complement the E-mode information outside the observation patch with ancillary data from full-sky CMB observations, we can reduce and even effectively remove the E-to-B leakage. For this objective, we produce E-mode Stokes QU maps from Wiener filtered full-sky intensity and polarization CMB observations. We use these maps to fill the sky region that is not observed by the ground-based experiment of interest, and thus complement the partial sky Stokes QU maps. Since the E-mode information is now available on the full sky we see a significant reduction in the E-to-B leakage. We evaluate on simulated data sets the performance of our method for a 'shallow' $f_{\rm sky} = 8\%$, and a 'deep' $f_{\rm sky} = 2\%$ northern hemisphere sky patch, with AliCPT-like properties, and a LSPE-like $f_{\rm sky} = 30\%$ sky patch, by combining those observations with Planck-like full sky polarization maps. We find that our method outperforms the standard and the pure-B method pseudo-C_ℓ estimators for all of our simulations. Our new method gives unbiased estimates of the B-mode power spectrum through-out the entire multipole range with near-optimal pseudo-C_ℓ errors for $\ell > 20$. We also study the application of our method to the CMB-S4 experiment combined with LiteBIRD-like full sky data, and show that using signal-dominated full sky E-mode data we can eliminate the E-to-B leakage problem.

Shamik Ghosh

Shamik Ghosh et al.,
JCAP Issue 02, article id. 036 (2021).

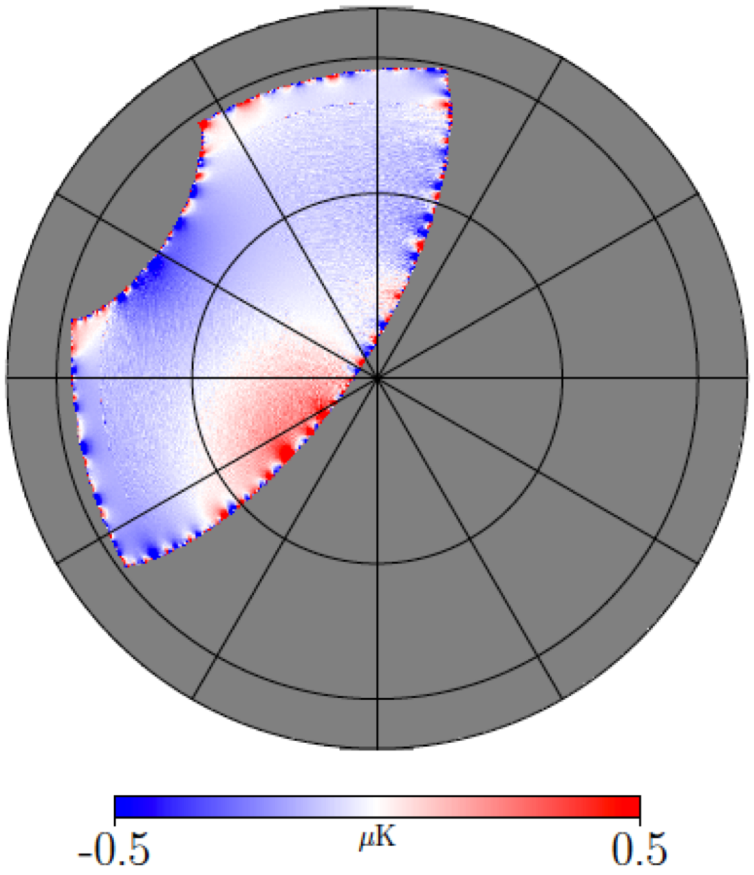

Figure 9: *E-to-B leakage for the three sky patches considered here. Left: north sky patch 1; Center: north sky patch 2, Right: south sky CMB-S4 patch.*

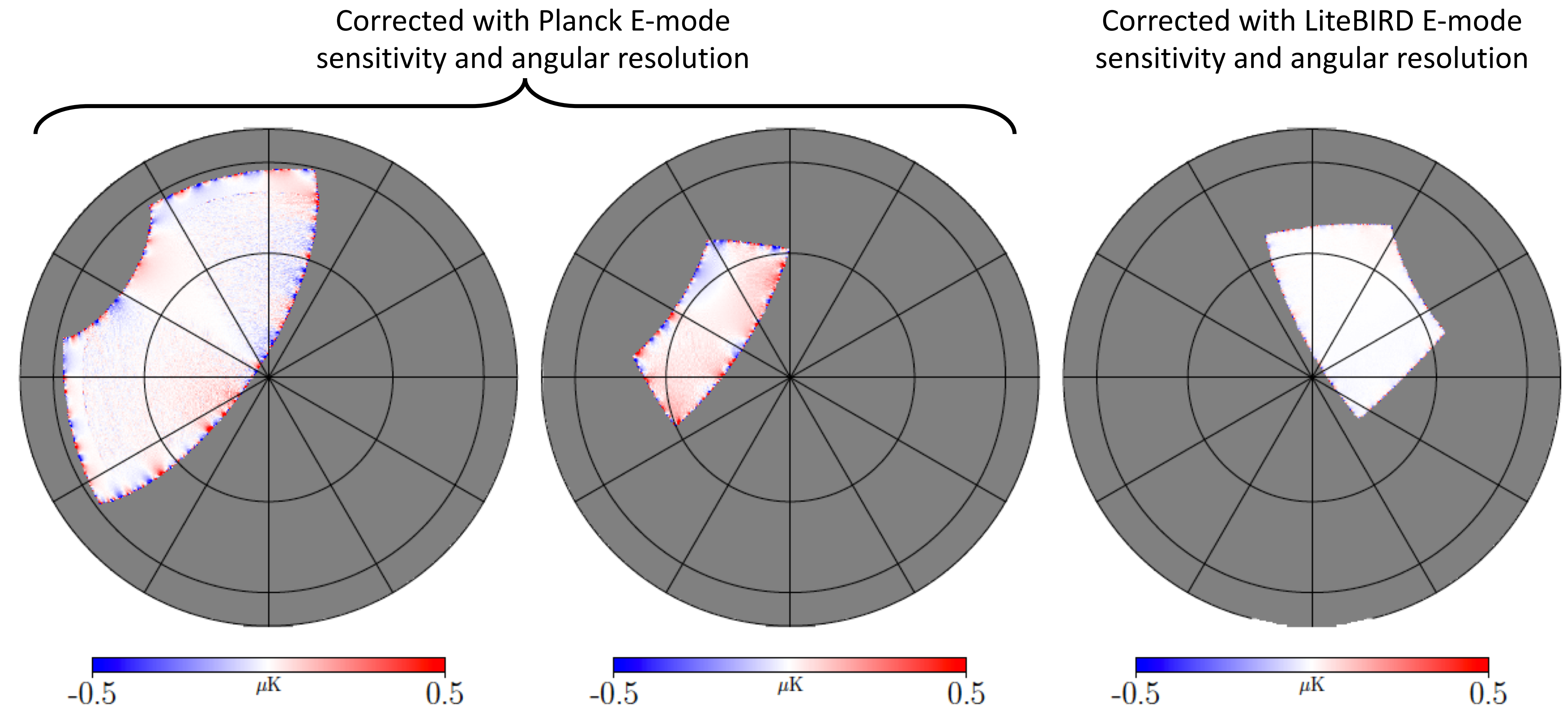

Figure 12: *E-B leakage with E-mode combination, for the three sky patches considered here. Left: north sky patch 1 with* $\mathbf{d}_{patch1}$ - $\widehat{\mathbf{d}}_{Planck1}$ *combination; Center: north sky patch 2 with* $\mathbf{d}_{patch2}$ - $\widehat{\mathbf{d}}_{Planck1}$ *combination, Right: south sky CMB-S4 patch with* $\mathbf{d}_{CMB\text{-}S4}$ - $\widehat{\mathbf{d}}_{LiteBIRD}$ *combination. The leakage is mostly concentrated at the edge of the patch.*

Pipeline

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Synchrotron mixing column

β_s	-2.9	-3.0	-3.1	-3.2	-3.3
2.3 GHz	1700	2200	2850	3690	4770
WMAP K	2.22	2.28	2.34	2.42	2.49
LFI 30 GHz	1.20	1.21	1.22	1.23	1.24
30 GHz	1.00	1.00	1.00	1.00	1.00
WMAP Ka	0.77	0.76	0.75	0.75	0.74
WMAP Q	0.42	0.41	0.40	0.39	0.37
LFI 44 GHz	0.34	0.33	0.32	0.31	0.29
95 GHz	0.043	0.039	0.034	0.031	0.027
150 GHz	0.016	0.014	0.012	0.010	0.008

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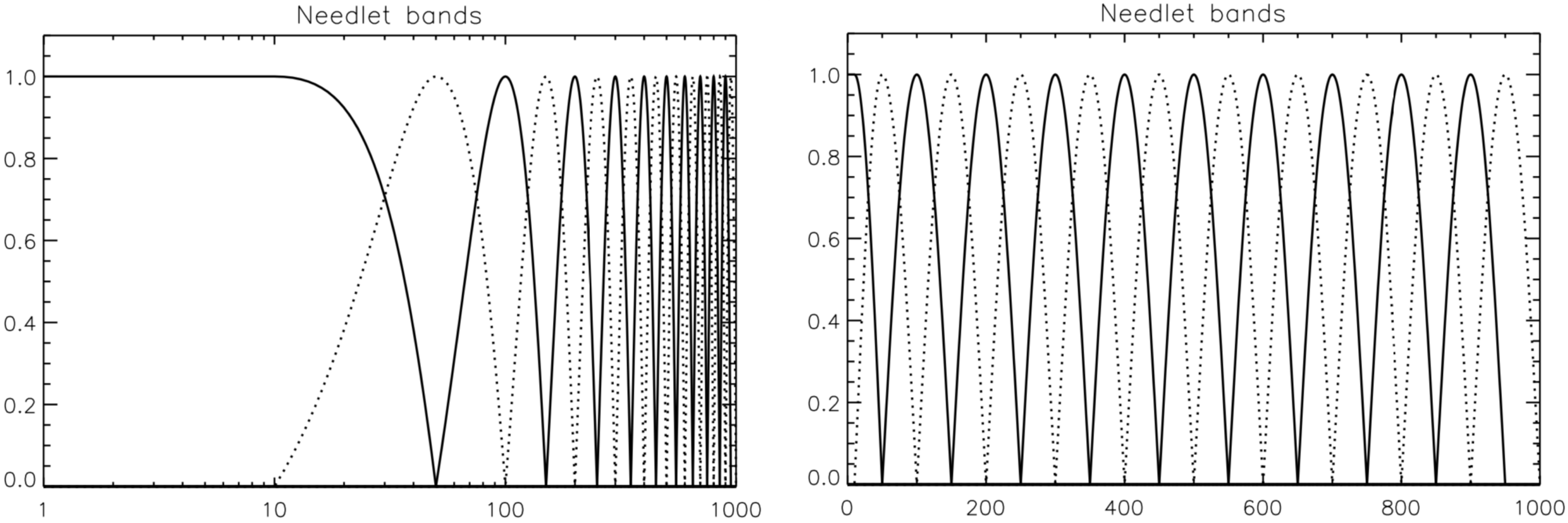
Needlet bands



20 needlet bands $h_b(l)$ ranging from 0 to 1000, and such that $\sum_b h_b(l)^2$ = 1 (except for the second half of the last band)

Special needlet transform

- Start from sky maps (preprocessed as described above)
- Transform to a_{lm}^E and a_{lm}^B
- Filter a_{lm}^E and a_{lm}^B using the bands shown above
- Transform back to Q and U (and not to E and B)
- We get "special" needlet maps !

Pipeline

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Weights in needlet space (Stokes Q)

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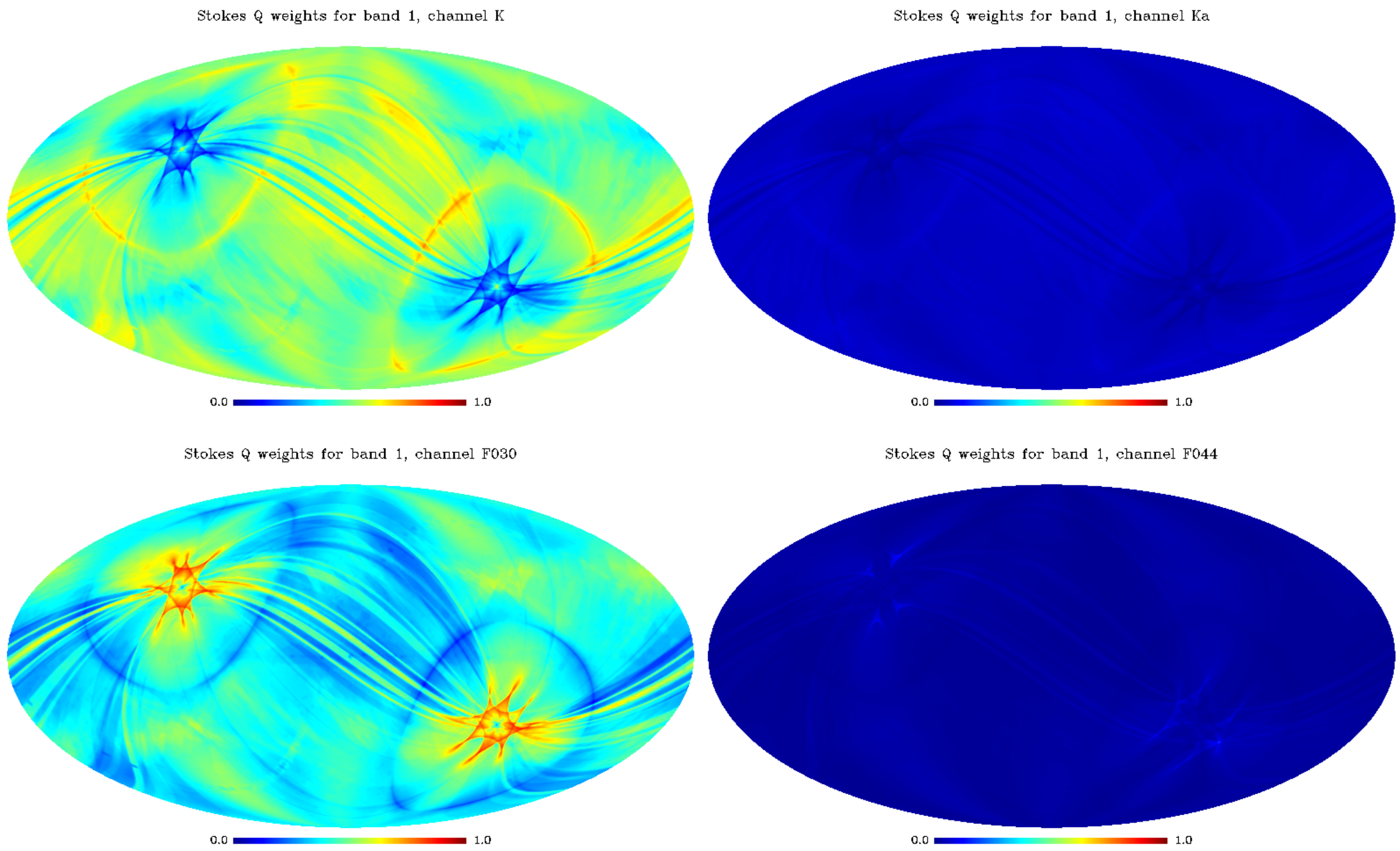
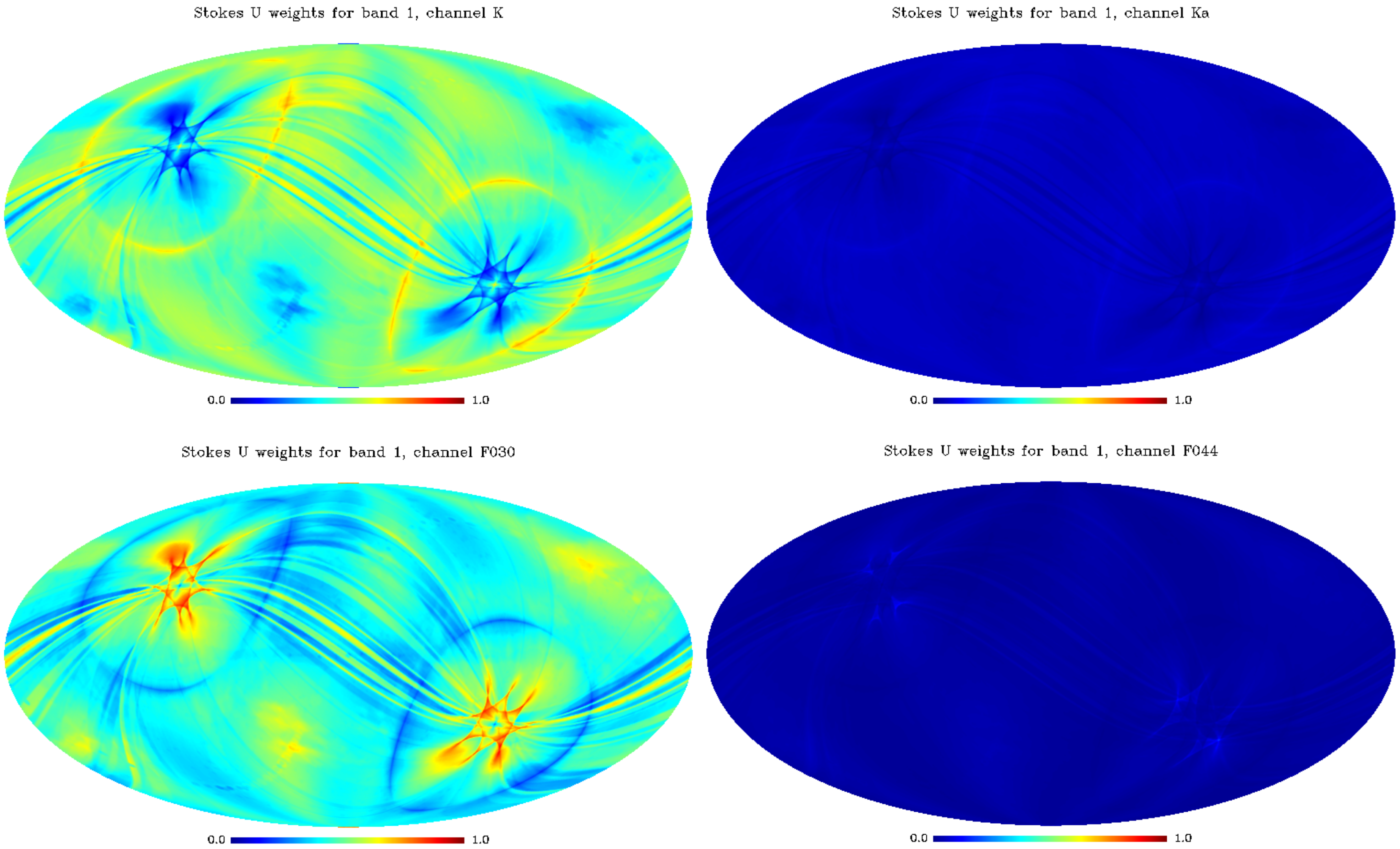


Band 1 (l < 50)

Map at 40' resolution

Weights dominated by K and F030.
Weights adapt to local variance...

Weights in needlet space (Stokes U)

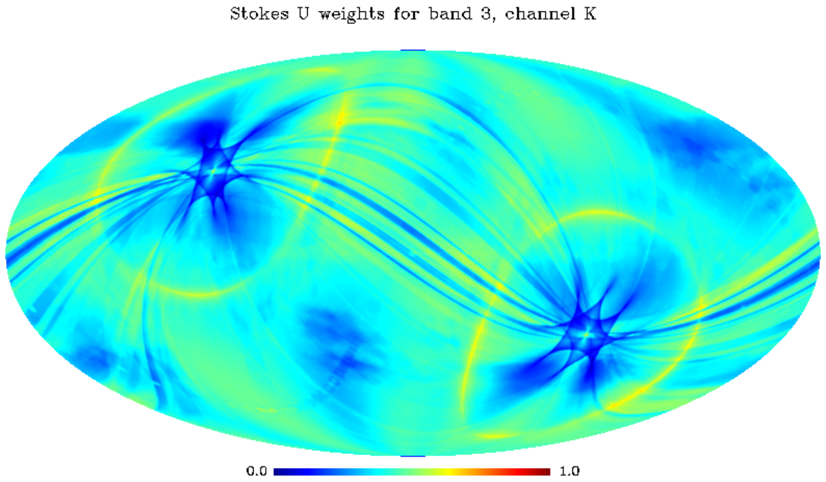


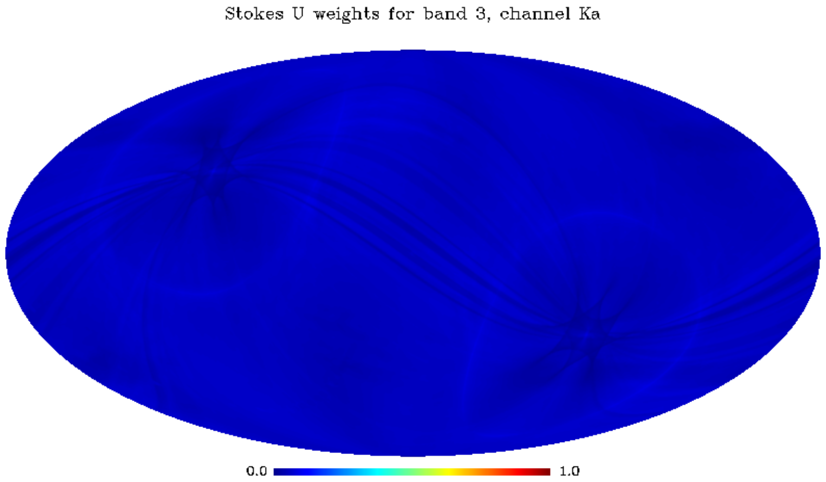
Band 1 (l < 50)

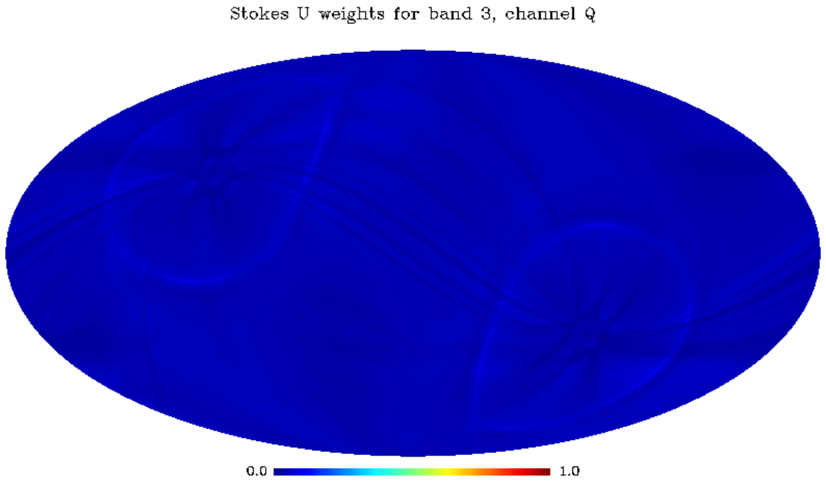
Map at 40' resolution

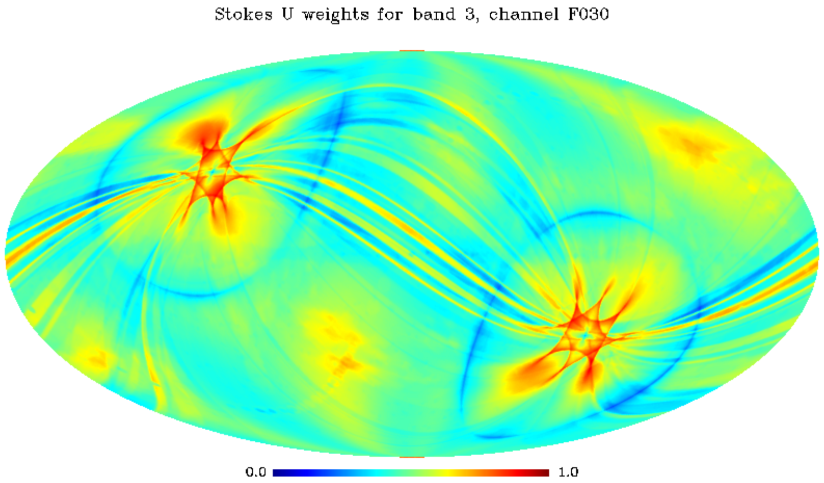
U weights different from Q weights

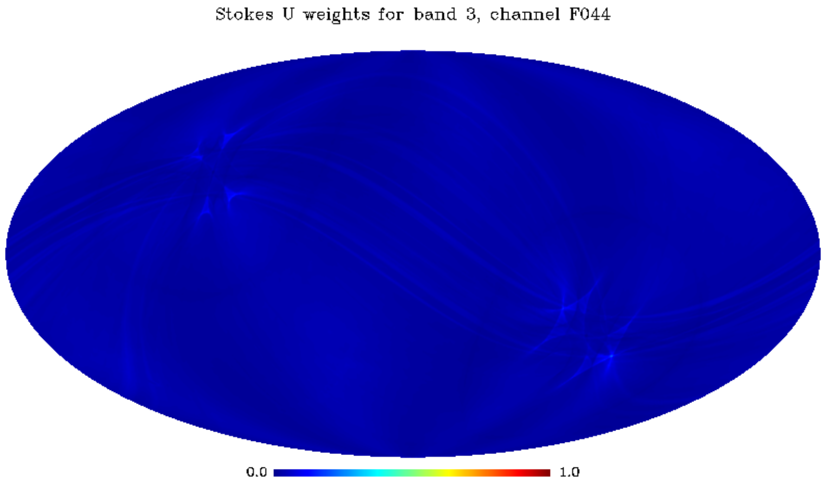
Weights in needlet space (Stokes U)







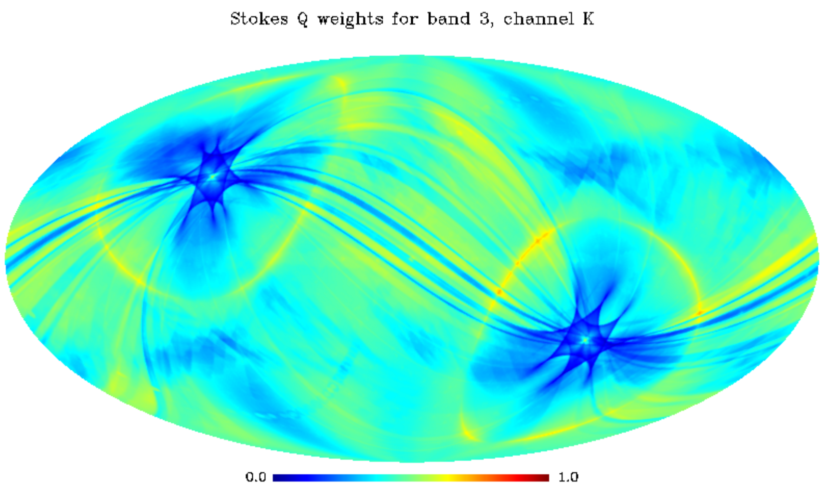


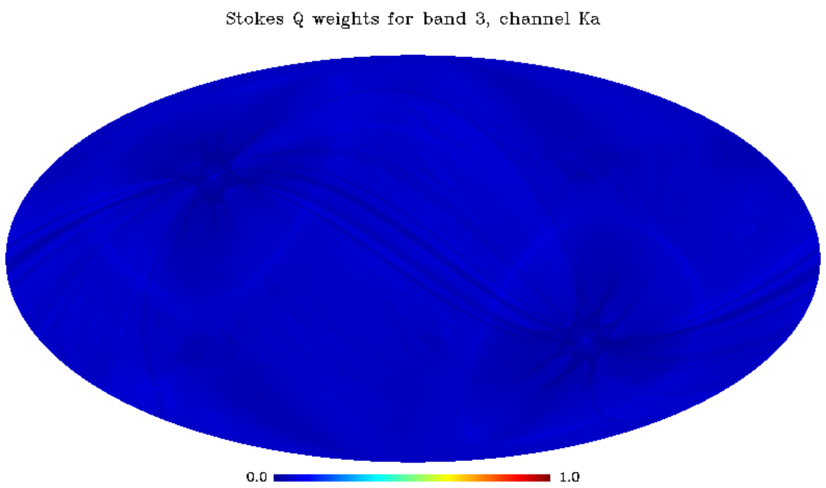


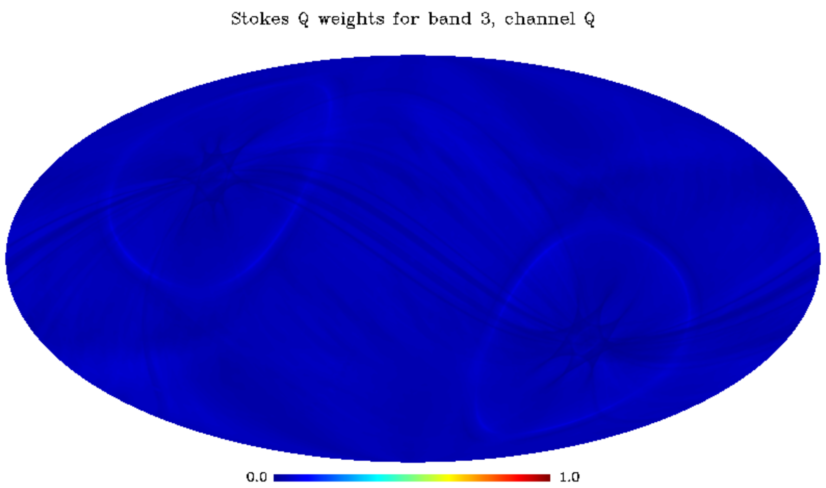
Band 3 (50 < l < 150)

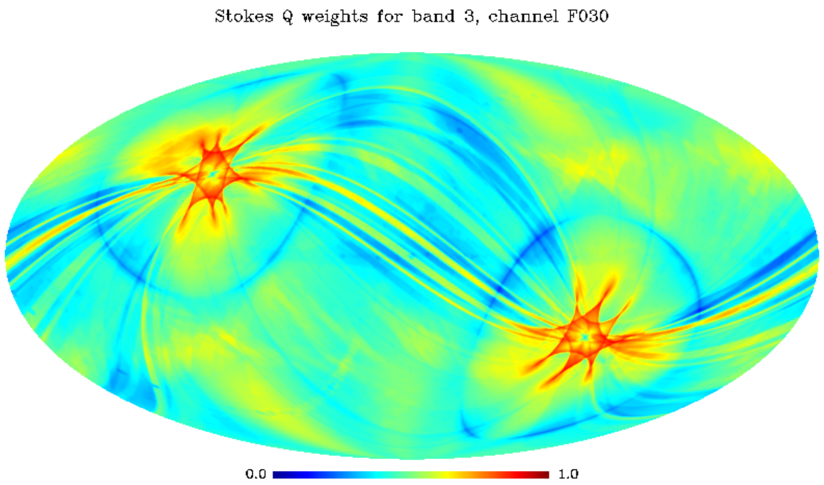
Map at 40' resolution

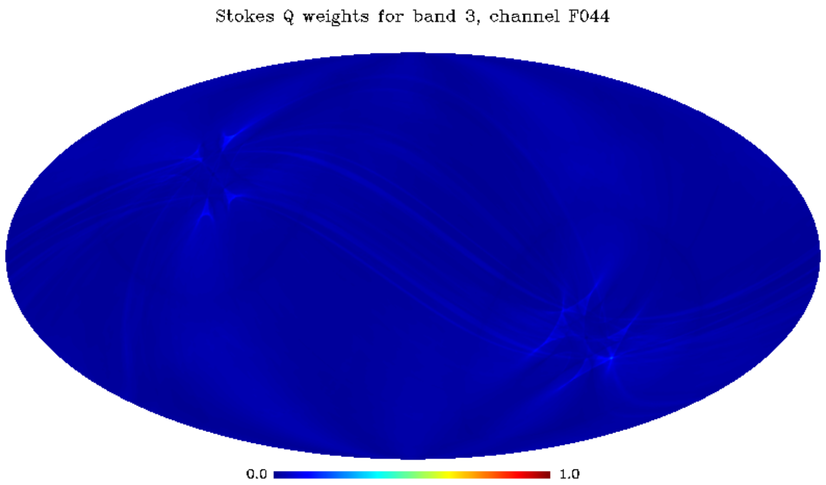
Weights in needlet space (Stokes Q)











Band 3 (50 < l < 150)

Map at 40' resolution

Weights in needlet space (Stokes Q)

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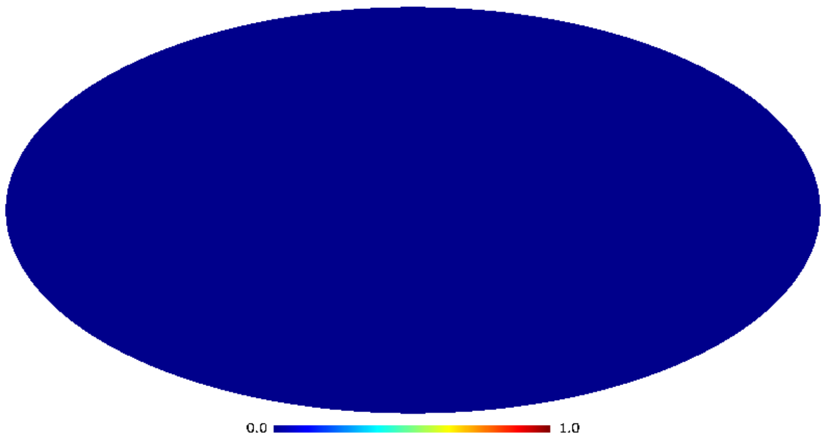
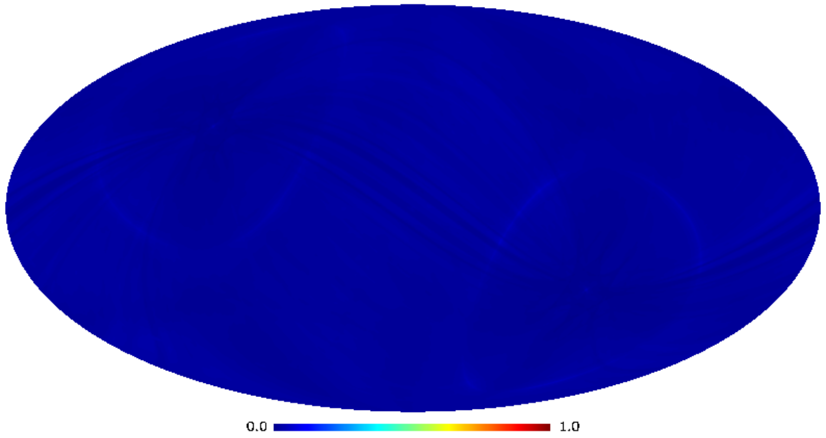
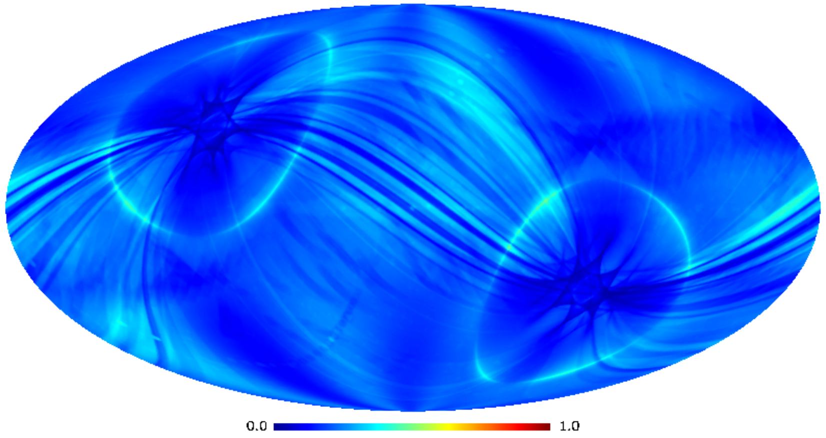
Stokes Q weights for band 13, channel K



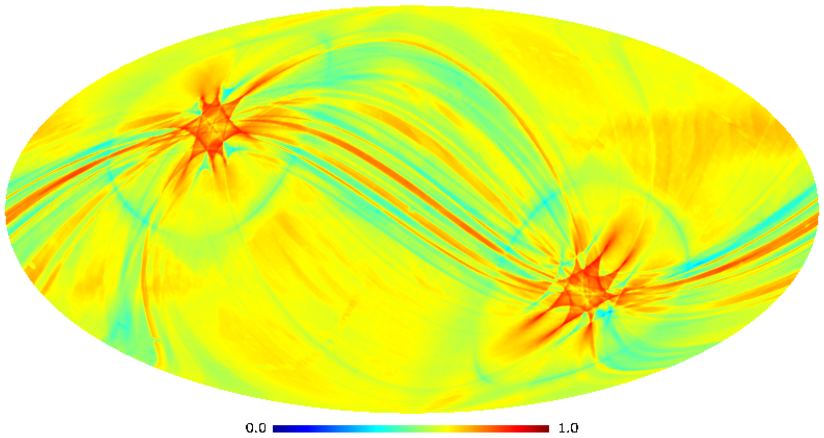
Stokes Q weights for band 13, channel Ka



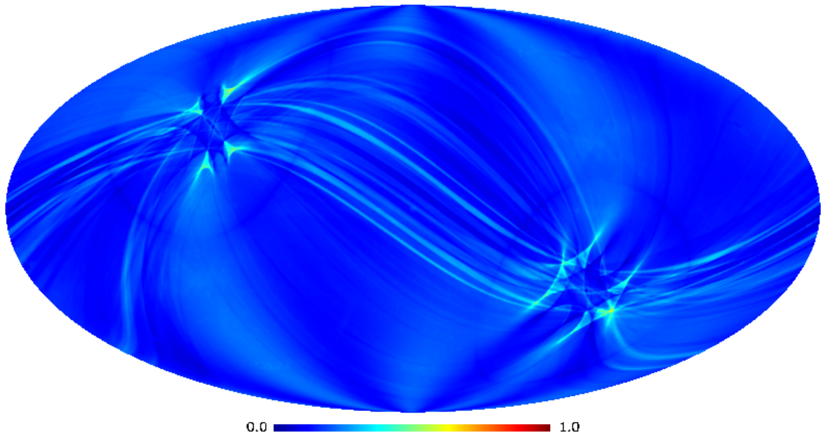
Stokes Q weights for band 13, channel Q



Stokes Q weights for band 13, channel F030



Stokes Q weights for band 13, channel F044



<u>Band 13 (550 < l < 650)</u>

Map at 40' resolution

Pipeline

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1. Polarization is the focus
2. Put all maps at the same angular resolution (40' or 60'), same pixelisation (nside=512)
3. Subtract a Wiener-filtered version of the SMICA CMB (full sky)
4. Put all maps in synchrotron units (in μK_{CMB} at 30 GHz)
5. Do a special needlet transform with 20 bands for $0 < l < 1000$
   (special transform using Q,U needlets instead of E,B needlets)
6. Compute the noise level of each channel in needlet space
7. Co-add maps with inverse noise variance in needlet space
8. Recombine needlets into synchrotron Q,U maps and E,B maps

map comparisons

Composite Synchrotron Q at 60' resolution

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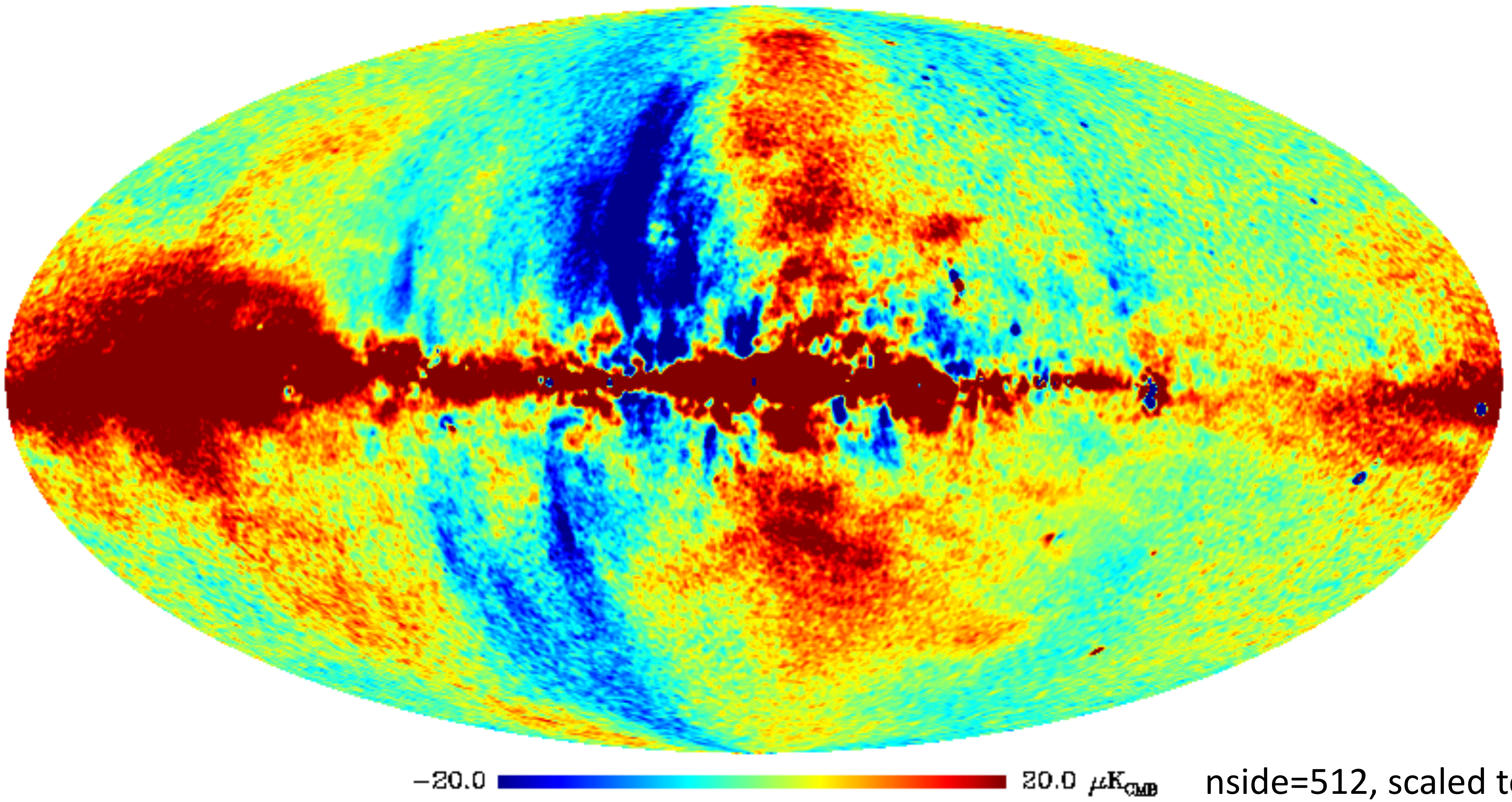
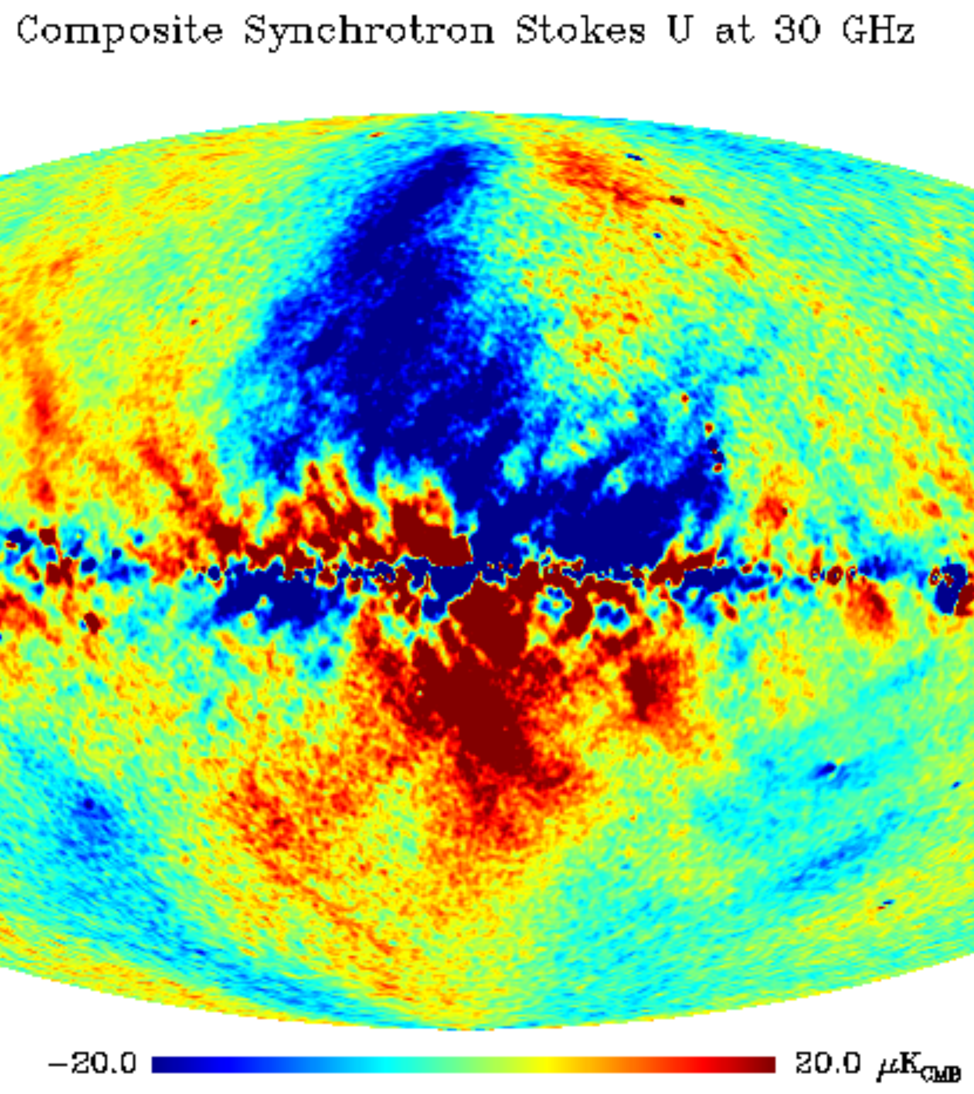
Composite Synchrotron Stokes Q at 30 GHz



nside=512, scaled to 30 GHz

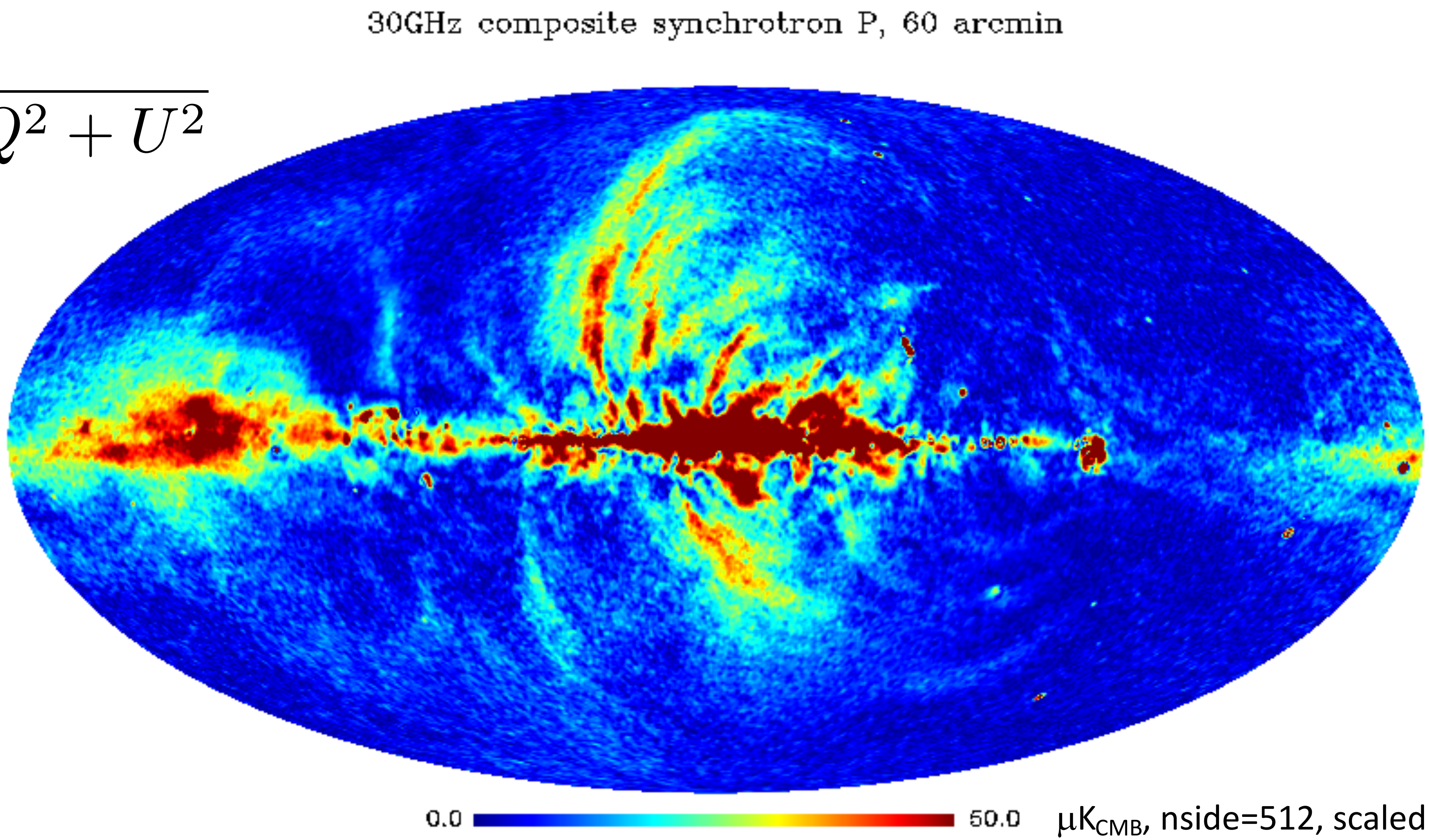
Composite Synchrotron U at 60' resolution



nside=512, scaled to 30 GHz

Composite Synchrotron P at 60' resolution

$$P = \sqrt{Q^2 + U^2}$$



μK_{CMB}, nside=512, scaled to 30 GHz

Synchrotron P from SMICA

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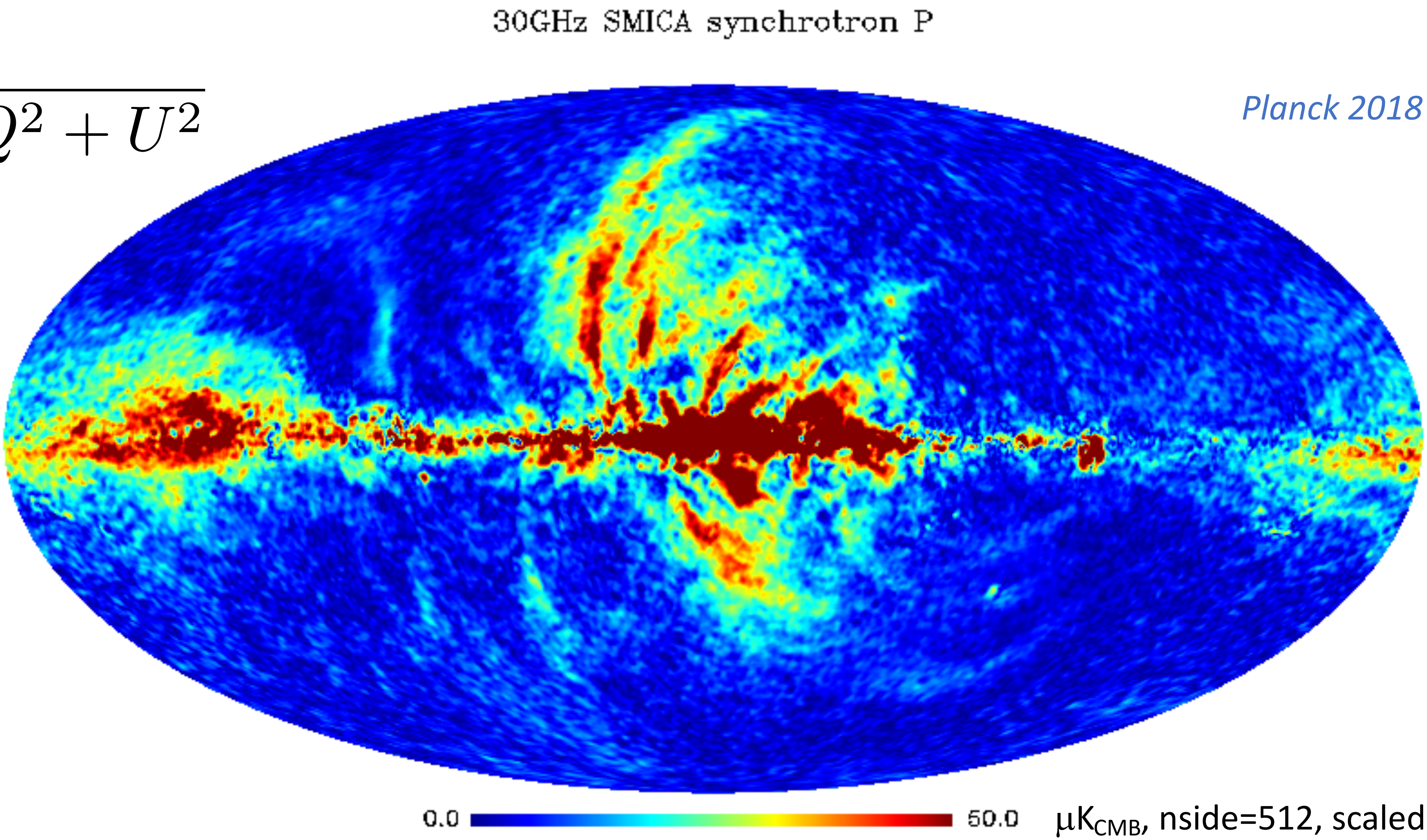
$$P = \sqrt{Q^2 + U^2}$$

Planck 2018 - IV



μK_{CMB}, nside=512, scaled to 30 GHz

Synchrotron P from Commander

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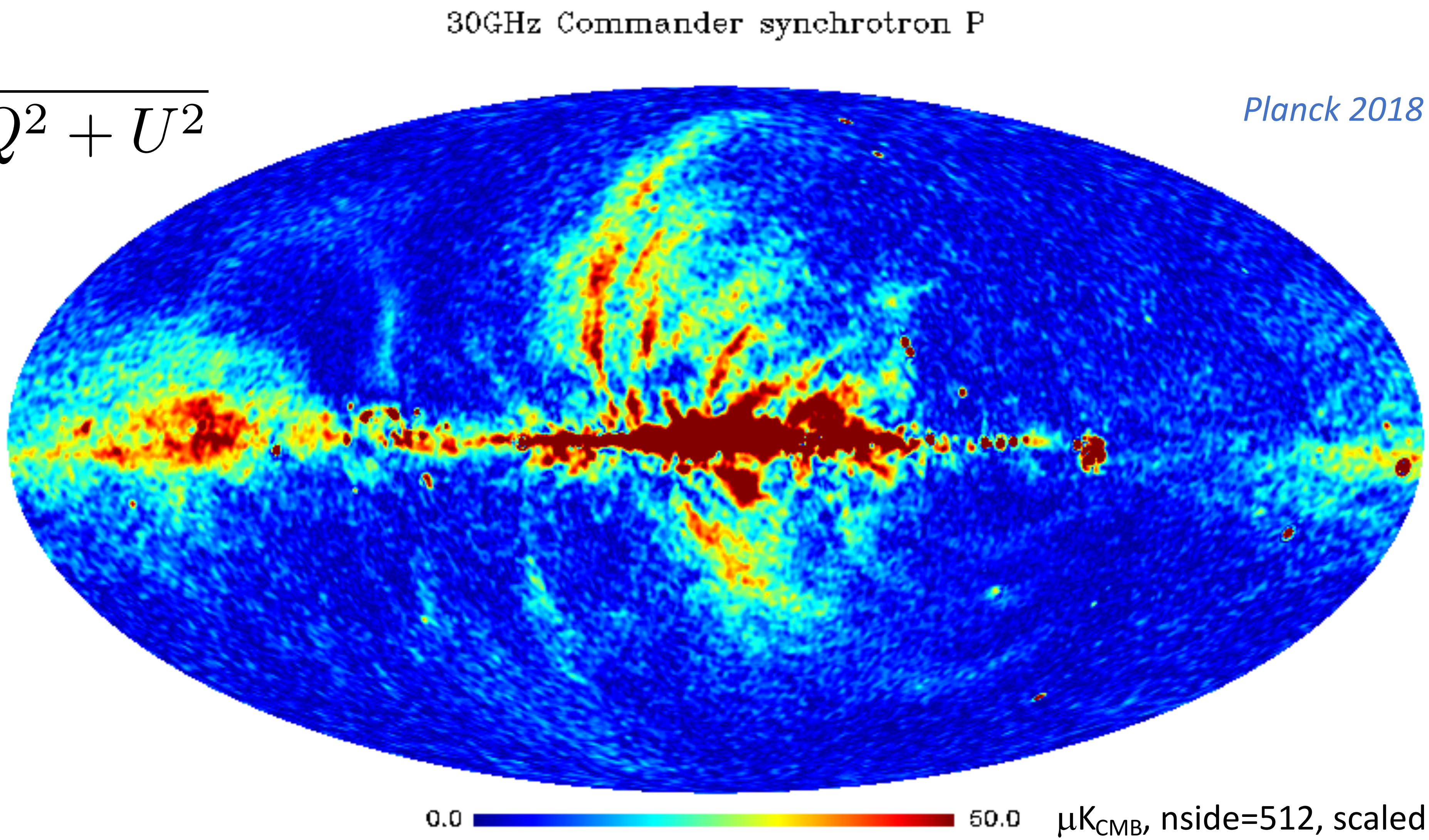
Centre Pierre Binétruy

$$P = \sqrt{Q^2 + U^2}$$

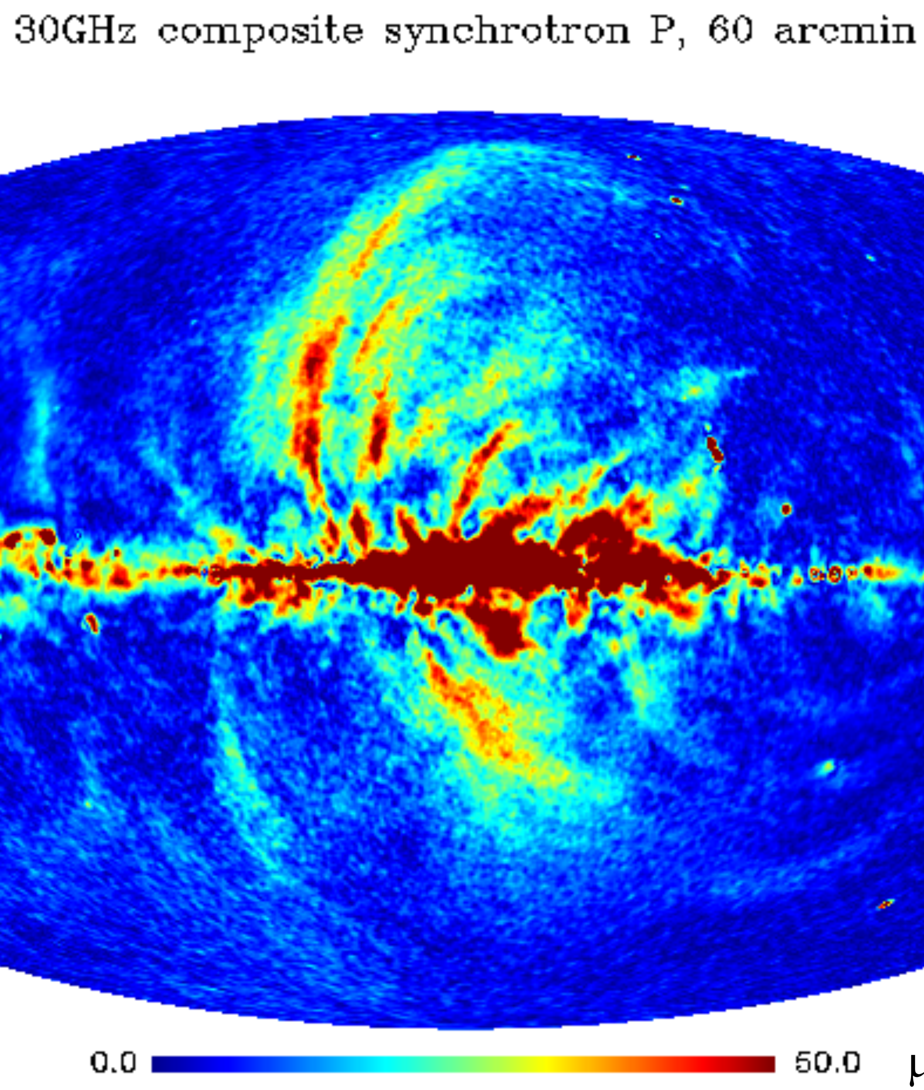
Planck 2018 - IV



μK_{CMB}, nside=512, scaled to 30 GHz

Composite Synchrotron P at 60' resolution

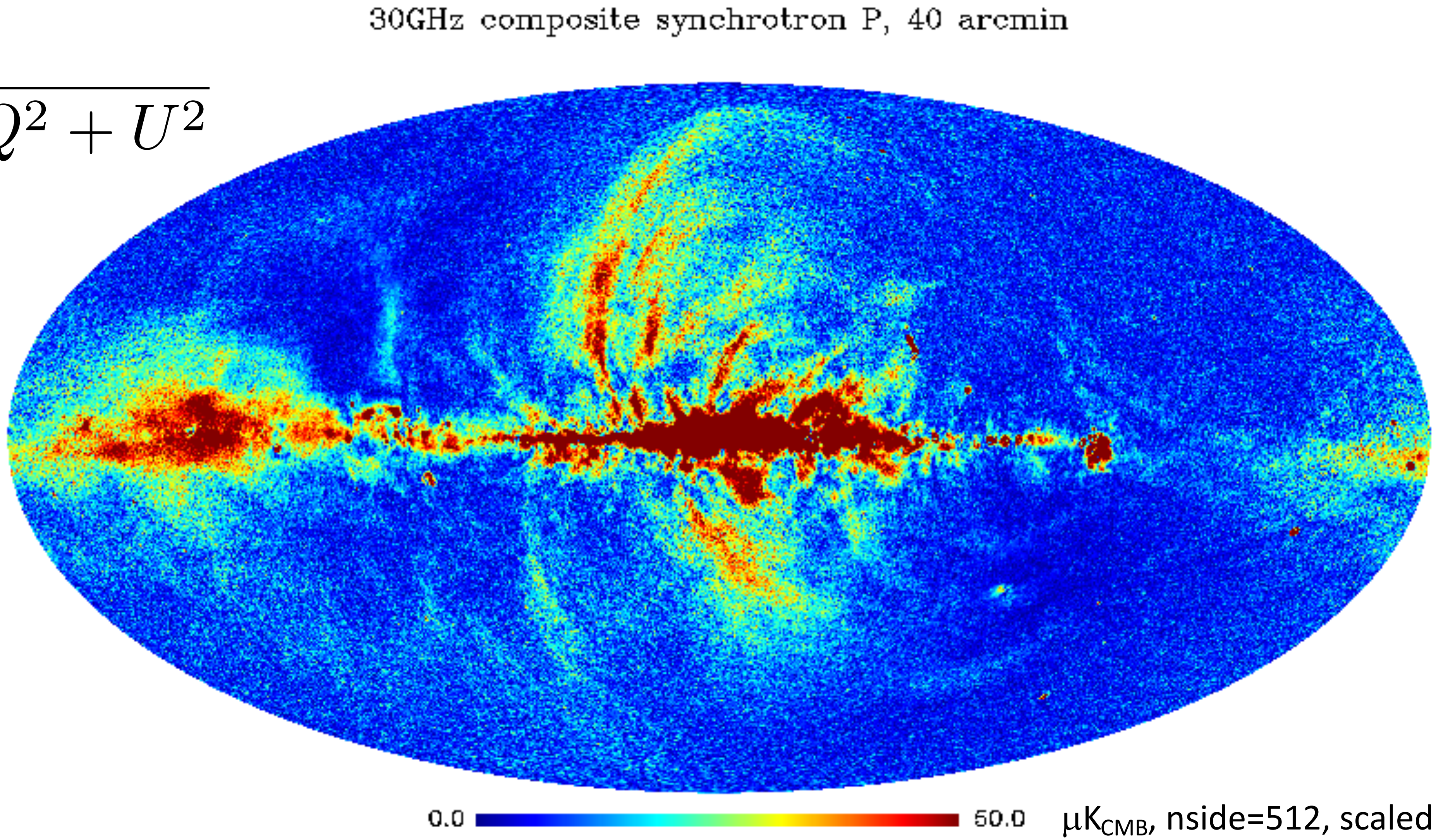
$$P = \sqrt{Q^2 + U^2}$$



μK_{CMB}, nside=512, scaled to 30 GHz

Composite Synchrotron P at 40' resolution

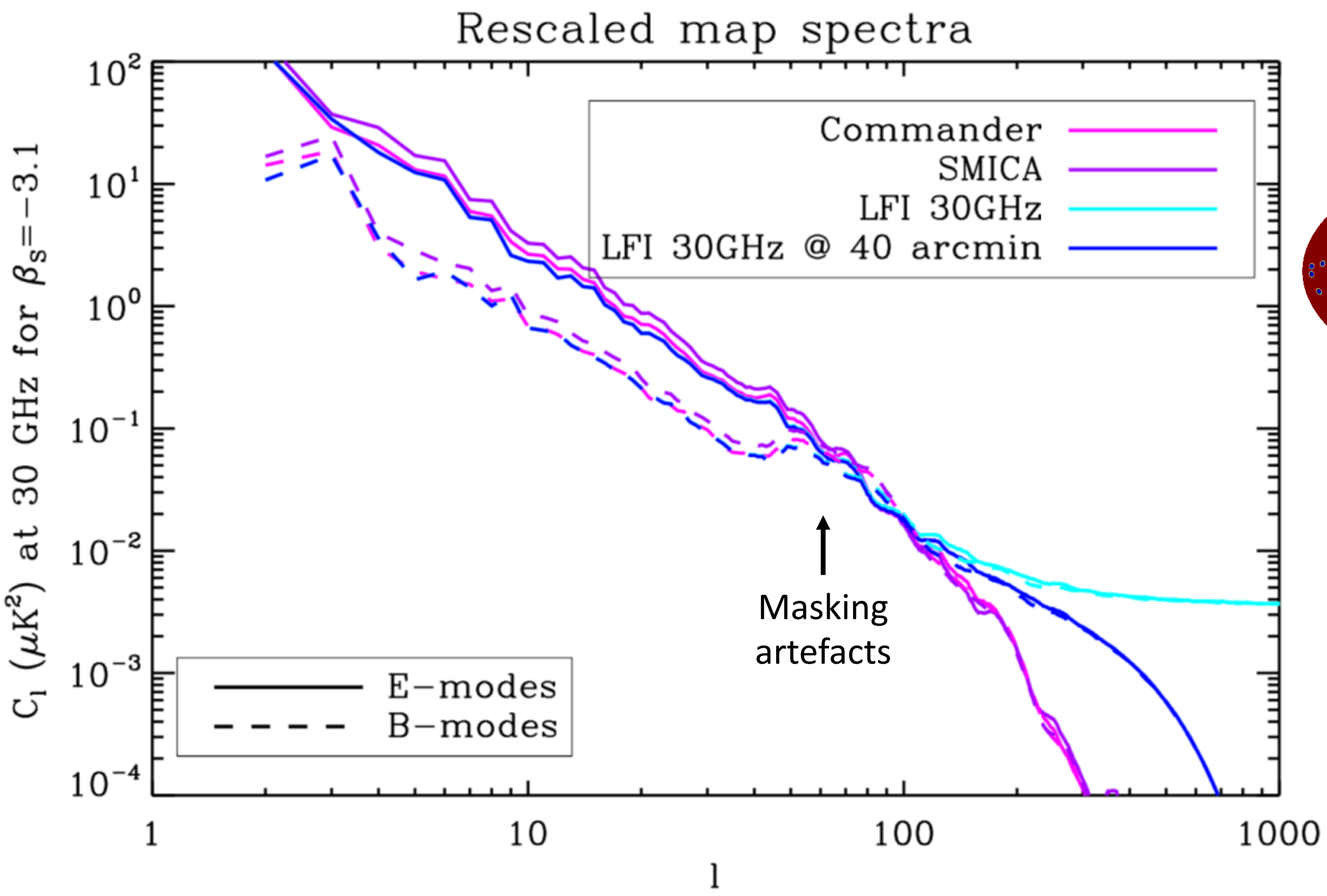
$$P = \sqrt{Q^2 + U^2}$$



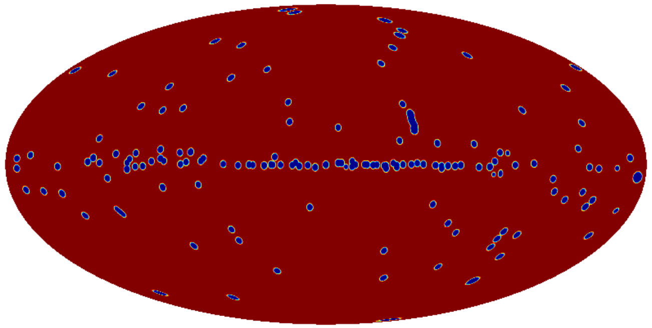
μK_{CMB}, nside=512, scaled to 30 GHz

spectra comparisons

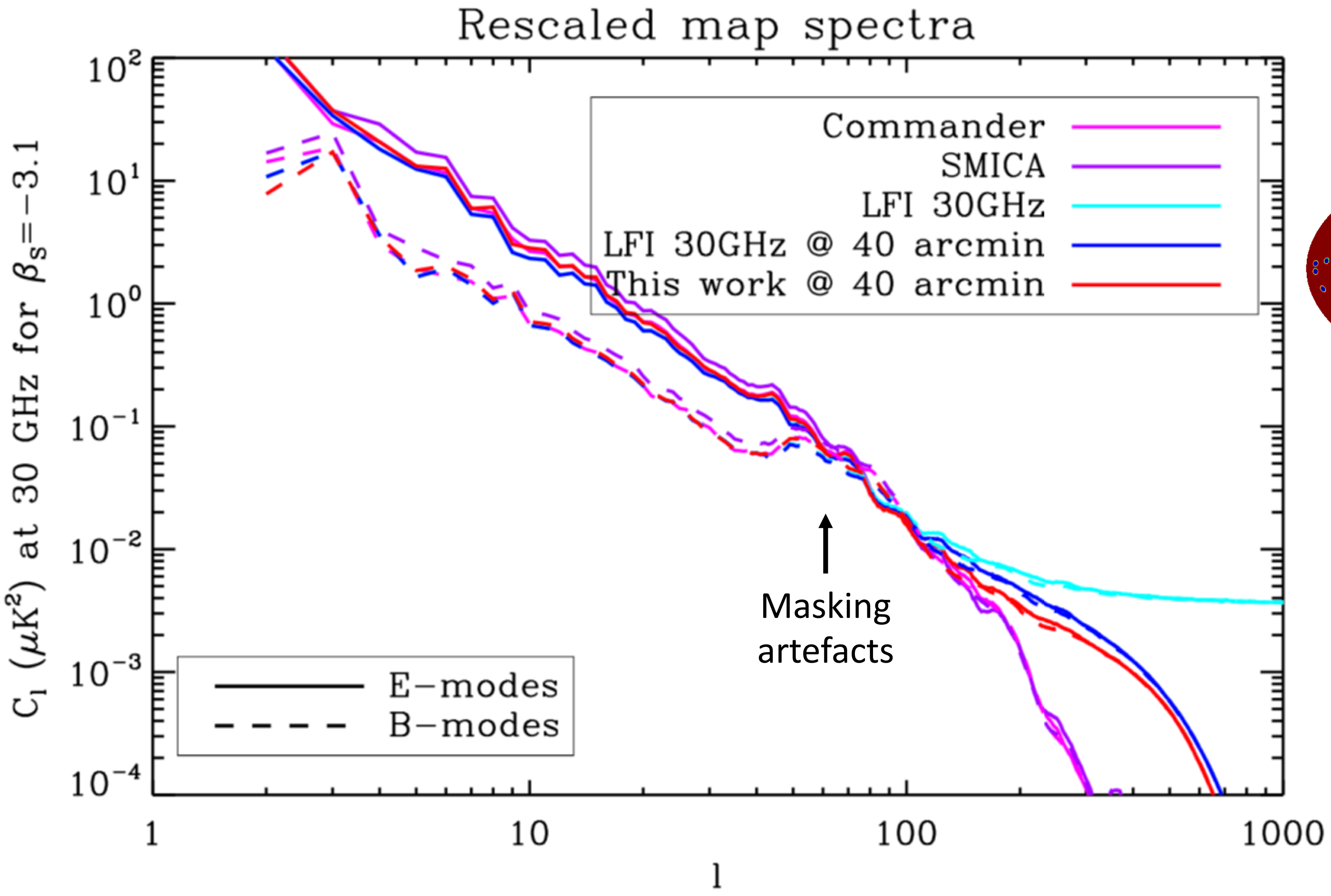
SMICA and Commander synchrotron spectra



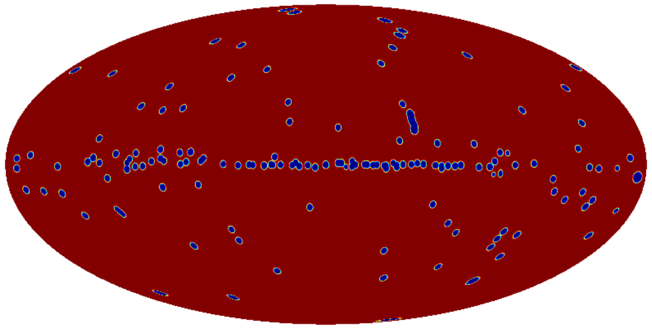
Point source mask



With composite synchrotron



Point source mask



Comparison for the PS mask

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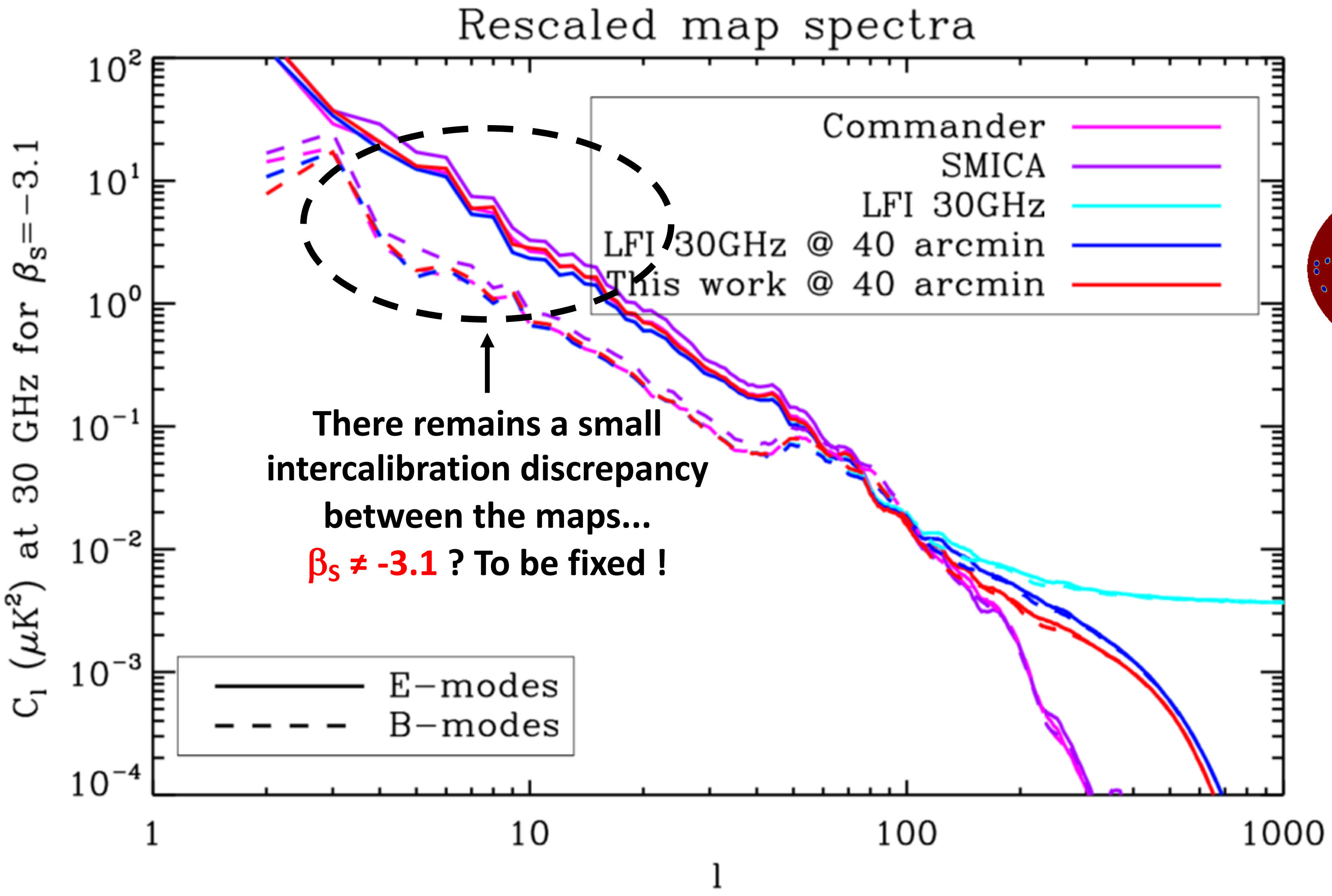
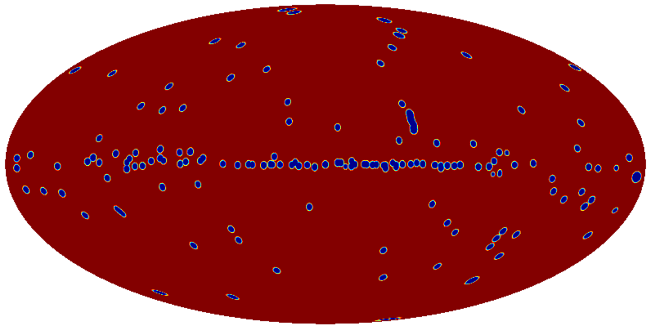
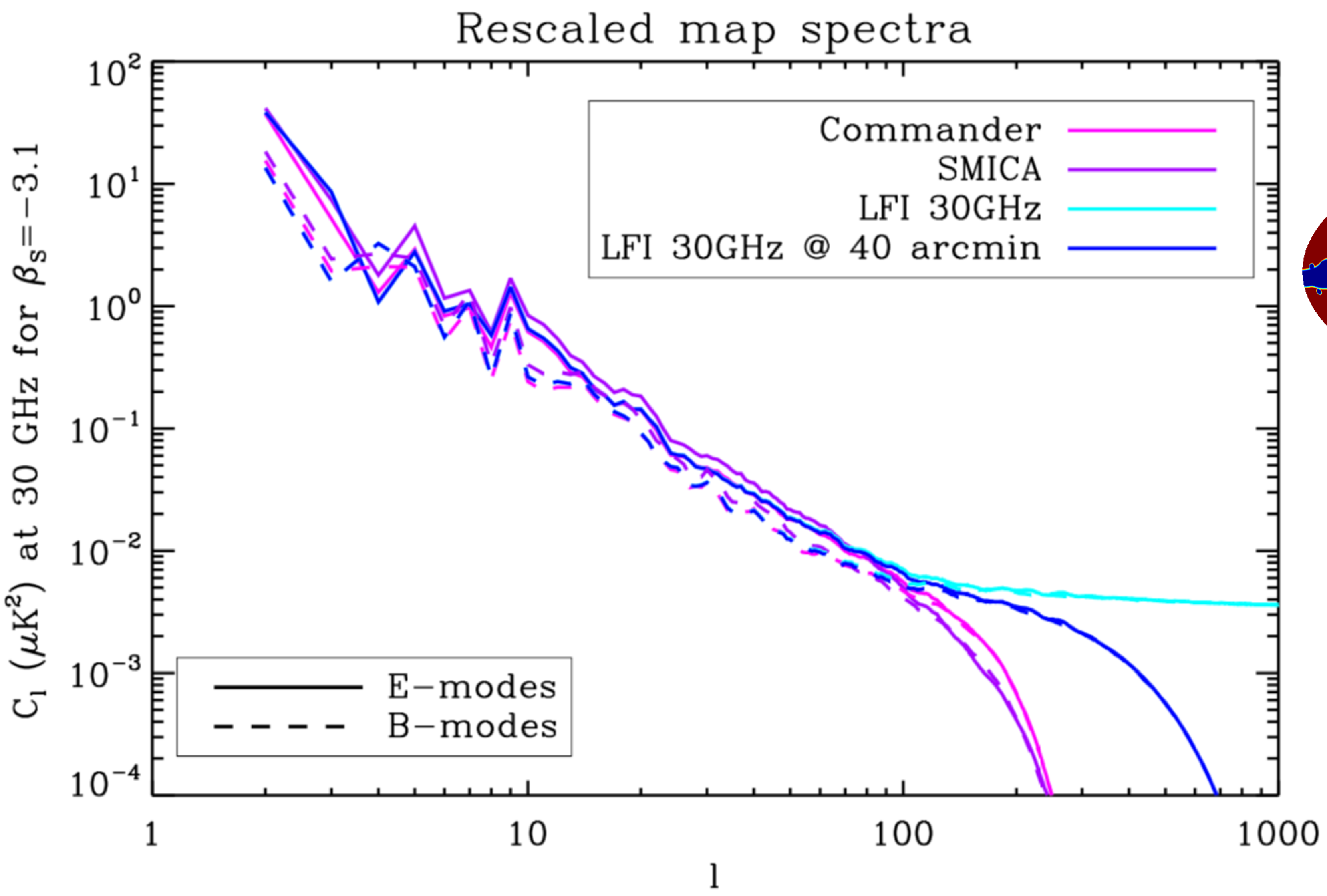


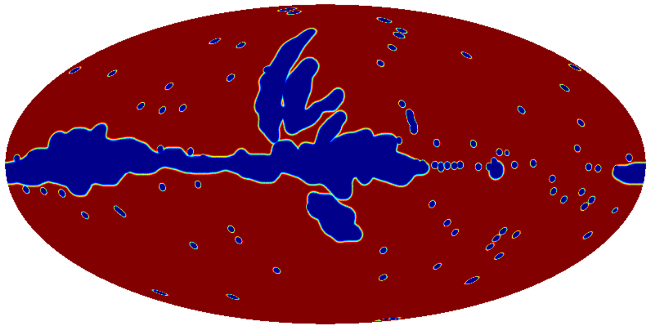
Point source mask



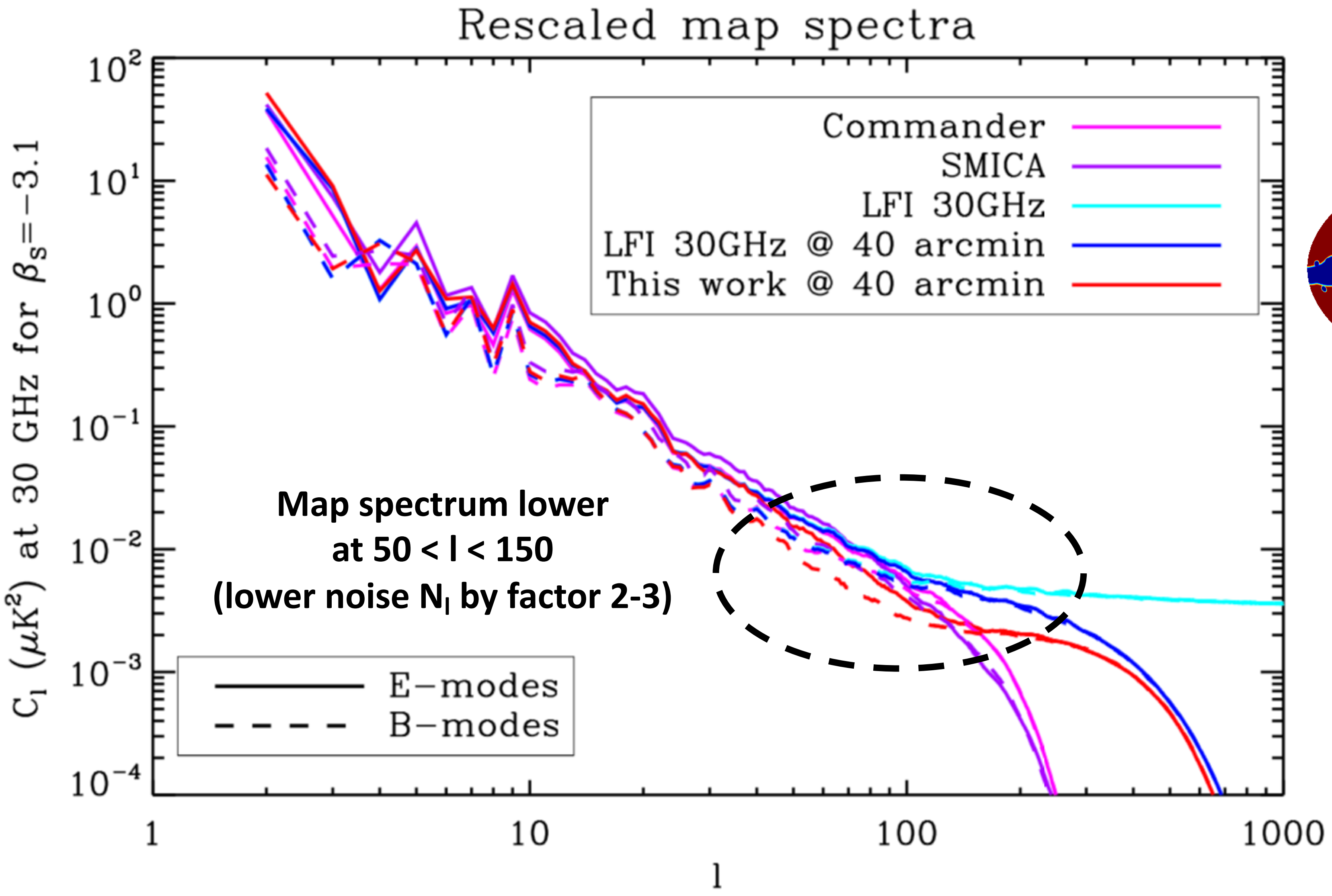
SMICA and Commander synchrotron spectra



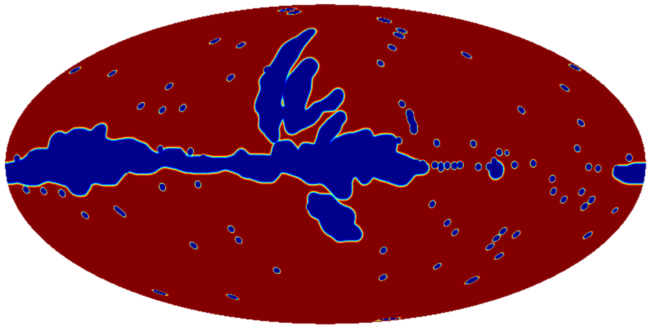
Small mask



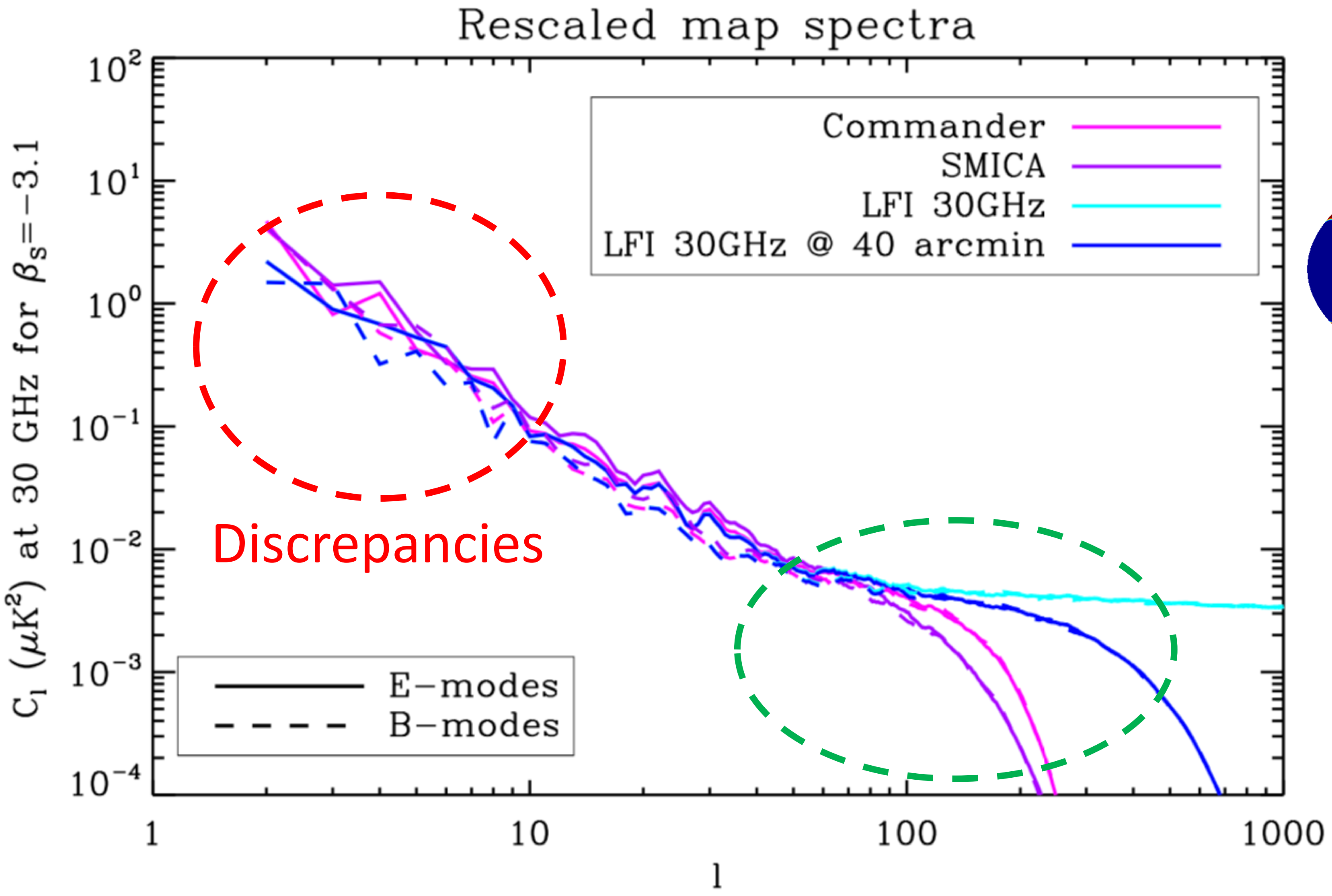
With composite synchrotron



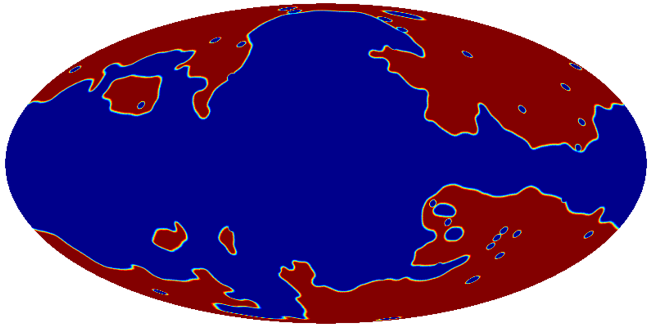
Small mask



SMICA and Commander synchrotron spectra



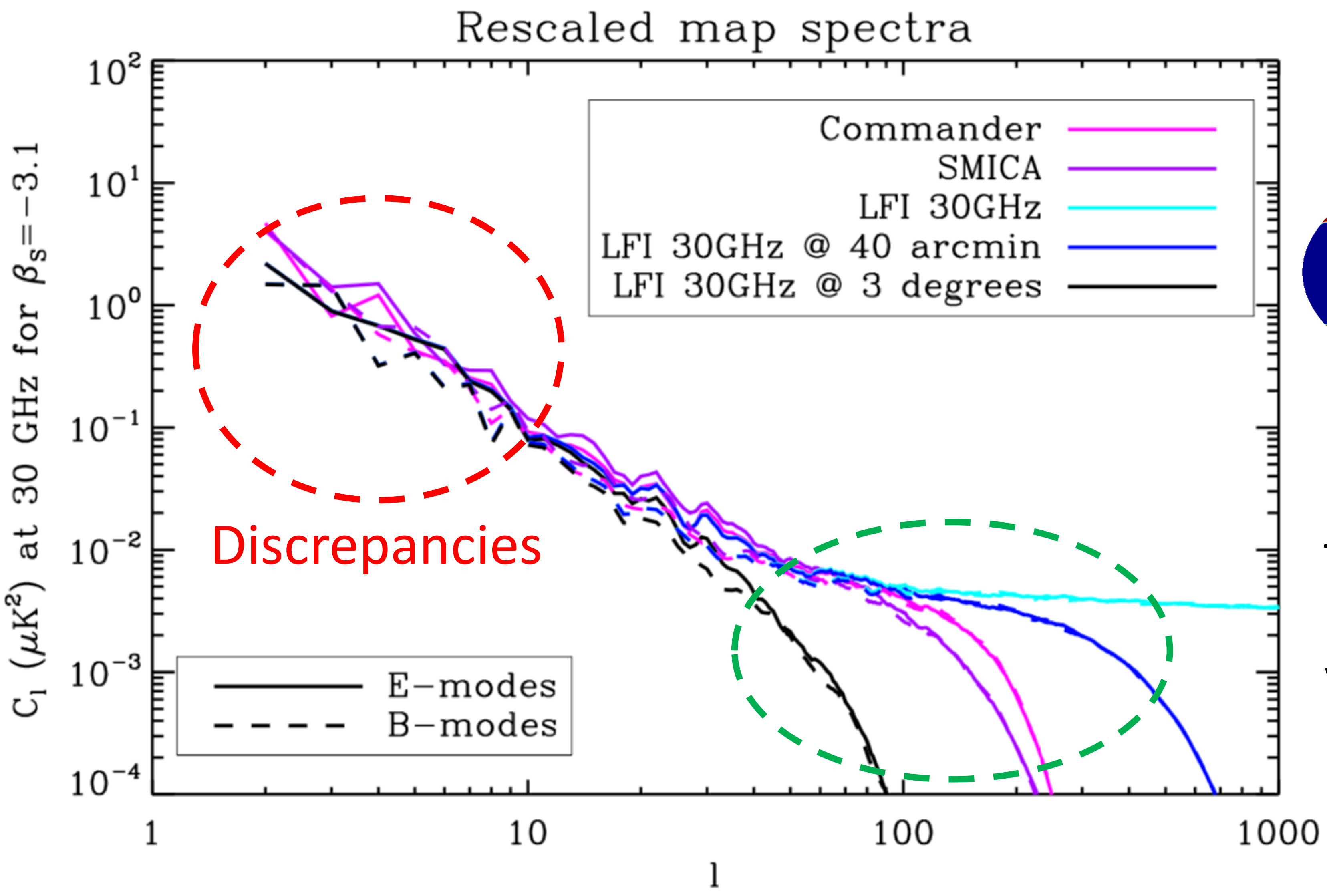
Large mask



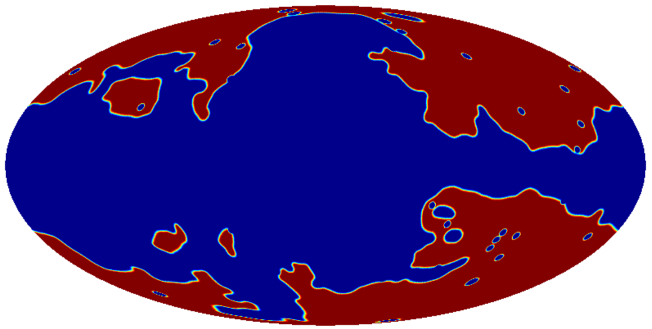
The effective beam is not 40 arcminutes.

Commander seems to be more noisy.

SMICA and Commander synchrotron spectra

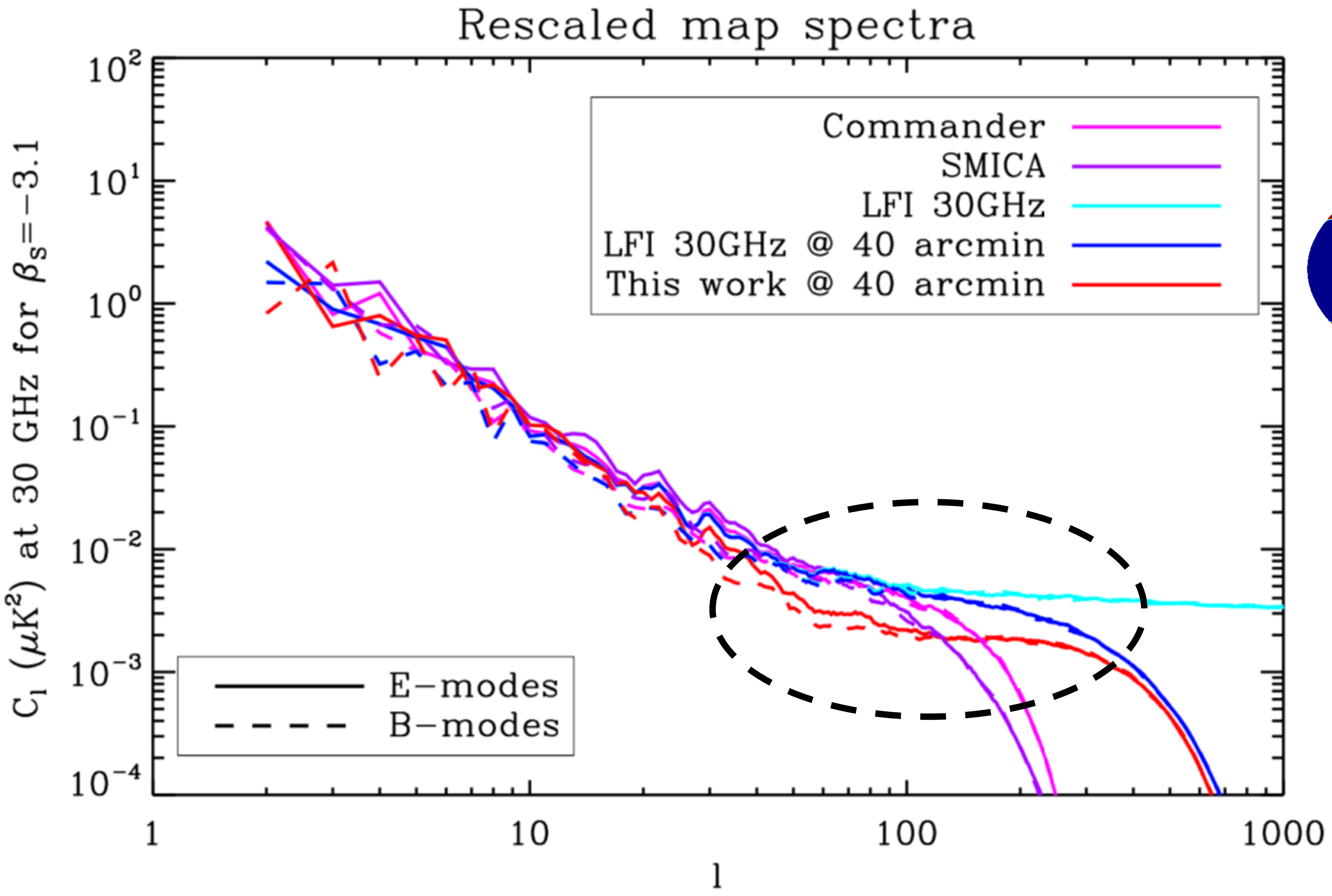


Large mask

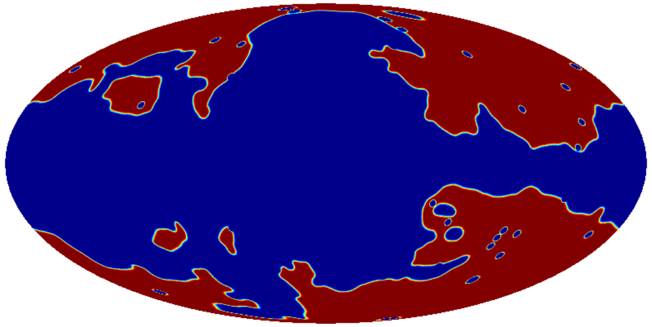


The effective beam
is not 3 degrees either...
Wiener filtered 40' ?

With composite synchrotron



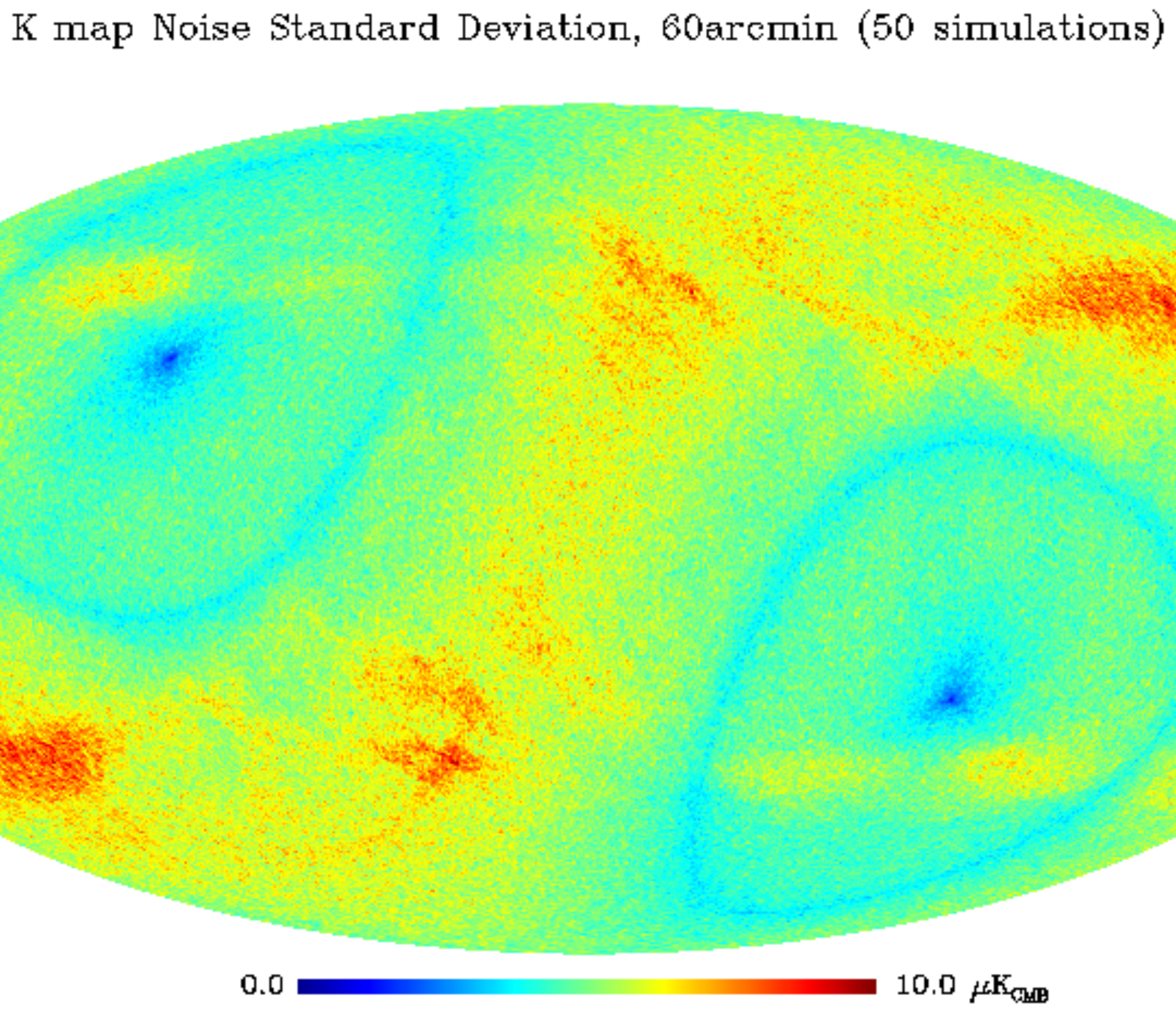
Large mask



noise comparisons

Noise: WMAP K, 60', rescaled to 30GHz with β_S=-3.1

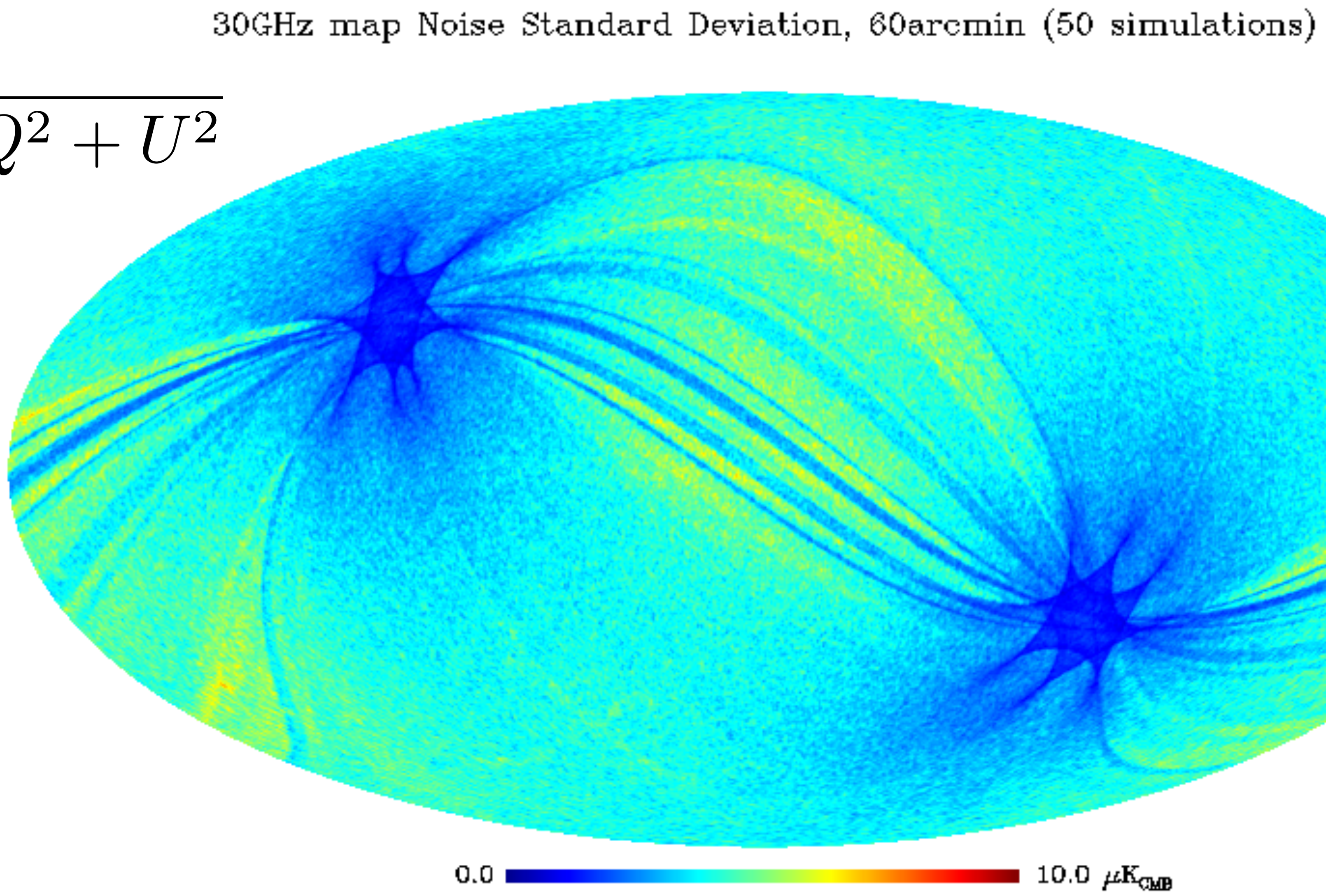
$$P = \sqrt{Q^2 + U^2}$$



mean = 5.32 μK_{CMB}

Noise: LFI 30GHz, 60', rescaled to 30GHz with β_S=-3.1

$$P = \sqrt{Q^2 + U^2}$$



mean = 3.76 μK_{CMB}

Noise: Map from this work, 60', 30GHz with β_S=-3.1

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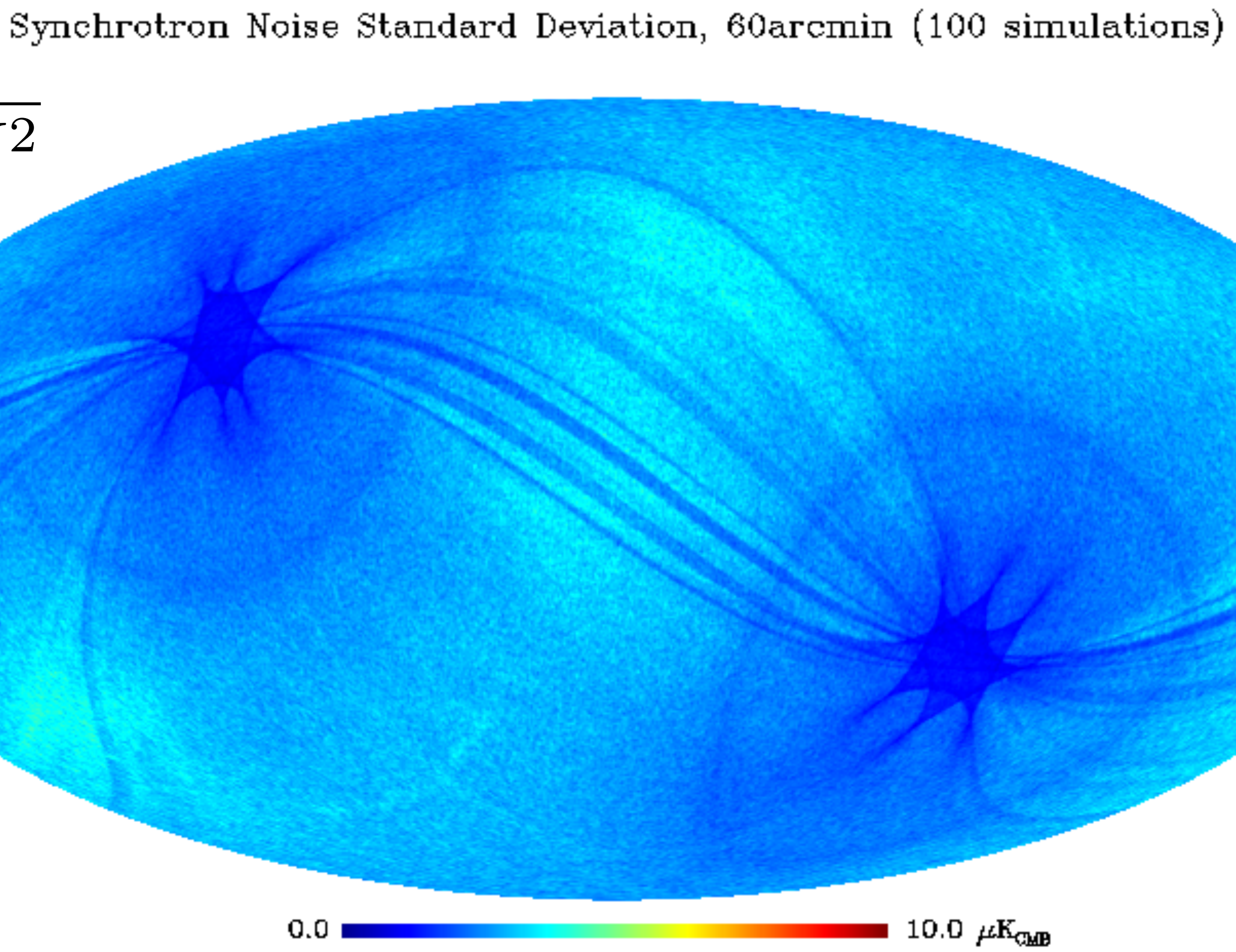
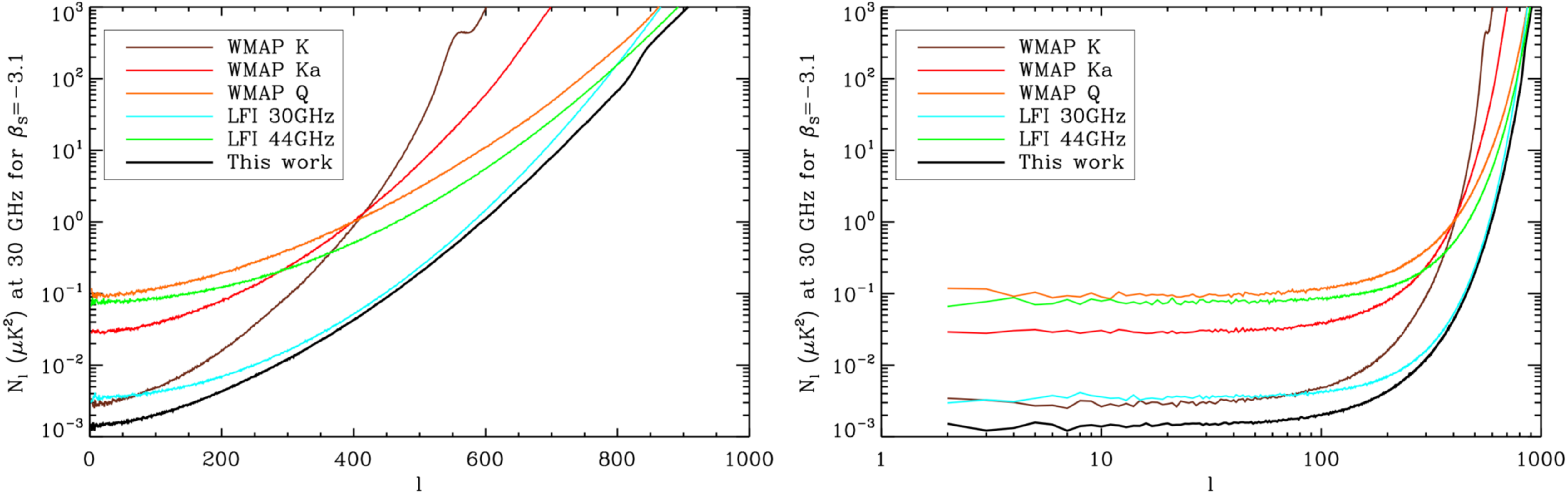
$$P = \sqrt{Q^2 + U^2}$$



mean = 2.79 μK_{CMB}
19.2 μK_{CMB}.arcmin

Projected noise spectra (full sky)

Noise scaled to equivalent synchrotron sensitivity at 30 GHz



Projected noise spectra (full sky)

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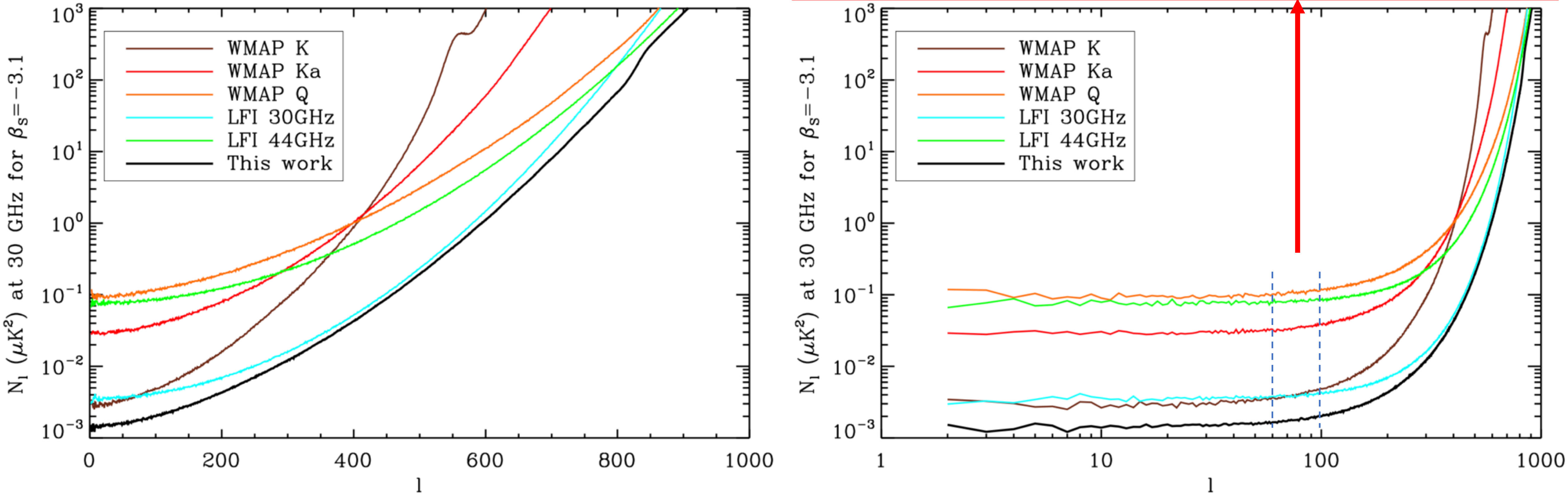
Noise scaled to equivalent synchrotron sensitivity at 30 GHz

Average N_l for $50 < l < 100$:	WMAP K:	4.01×10^{-3}
	LFI 30GHz:	3.92×10^{-3}
	Combined:	1.79×10^{-3}



$N_l = 1.79 \times 10^{-3}$ corresponds to (for $\beta_S = -3.1$)

σ = 145 μK.arcmin at 30 GHz
σ = 5.0 μK.arcmin at 95 GHz
σ = 1.7 μK.arcmin at 150 GHz

discussion

Is this synchrotron map good enough?

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Not quite, but we are close !

Simons observatory (from arXiv:1808.07445v2, table 1):

	SATs ($f_{\rm sky} = 0.1$)		
Freq. [GHz]	FWHM (′)	Noise (baseline) [μK-arcmin]	Noise (goal) [μK-arcmin]
27	91	35	25
39	63	21	17
93	30	2.6	1.9
145	17	3.3	2.1
225	11	6.3	4.2
280	9	16	10

Original table gives Temperature sensitivity, polarization is $\sqrt{2}$ higher

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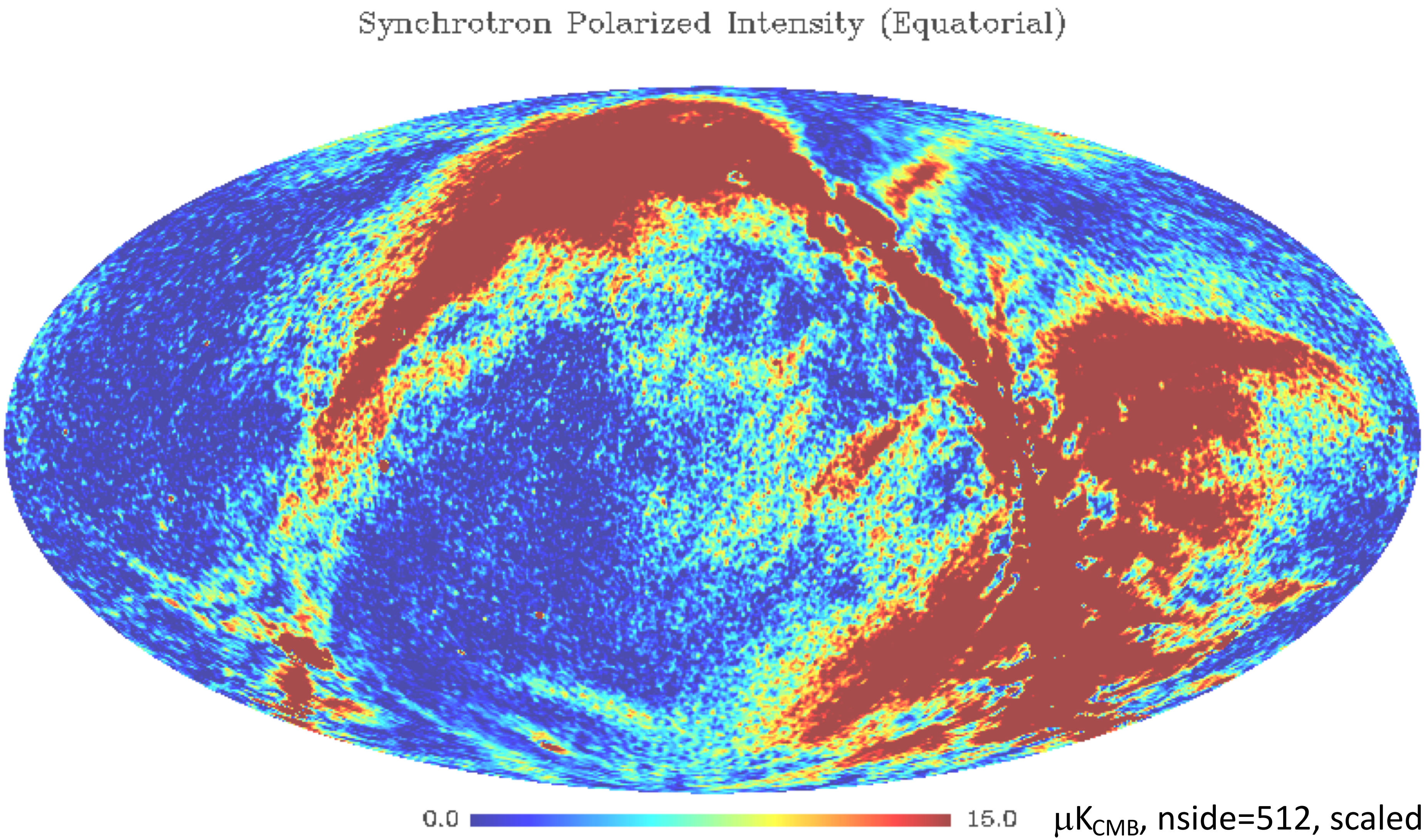
Freq. [GHz]	FWHM (′)	Noise (baseline) [μK-arcmin]	Noise (goal) [μK-arcmin]
27	91	35 **49**	25
39	63	21	17
93	30	2.6 **3.7**	1.9
145	17	3.3 **4.7**	2.1
225	11	6.3	4.2
280	9	16	10

Original table gives Temperature sensitivity, Polarization is $\sqrt{2}$ higher

Composite Synchrotron (f_{sky}=1)	
FWHM	μK.arcmin
60'	**104**
60'	**5.0**
60'	**1.7**

Equivalent noise for 50 < l < 100 (at 60' resolution)

Synchrotron in CMB-S4 fields of view



μK_{CMB}, nside=512, scaled to 30 GHz

Synchrotron in CMB-S4 fields of view

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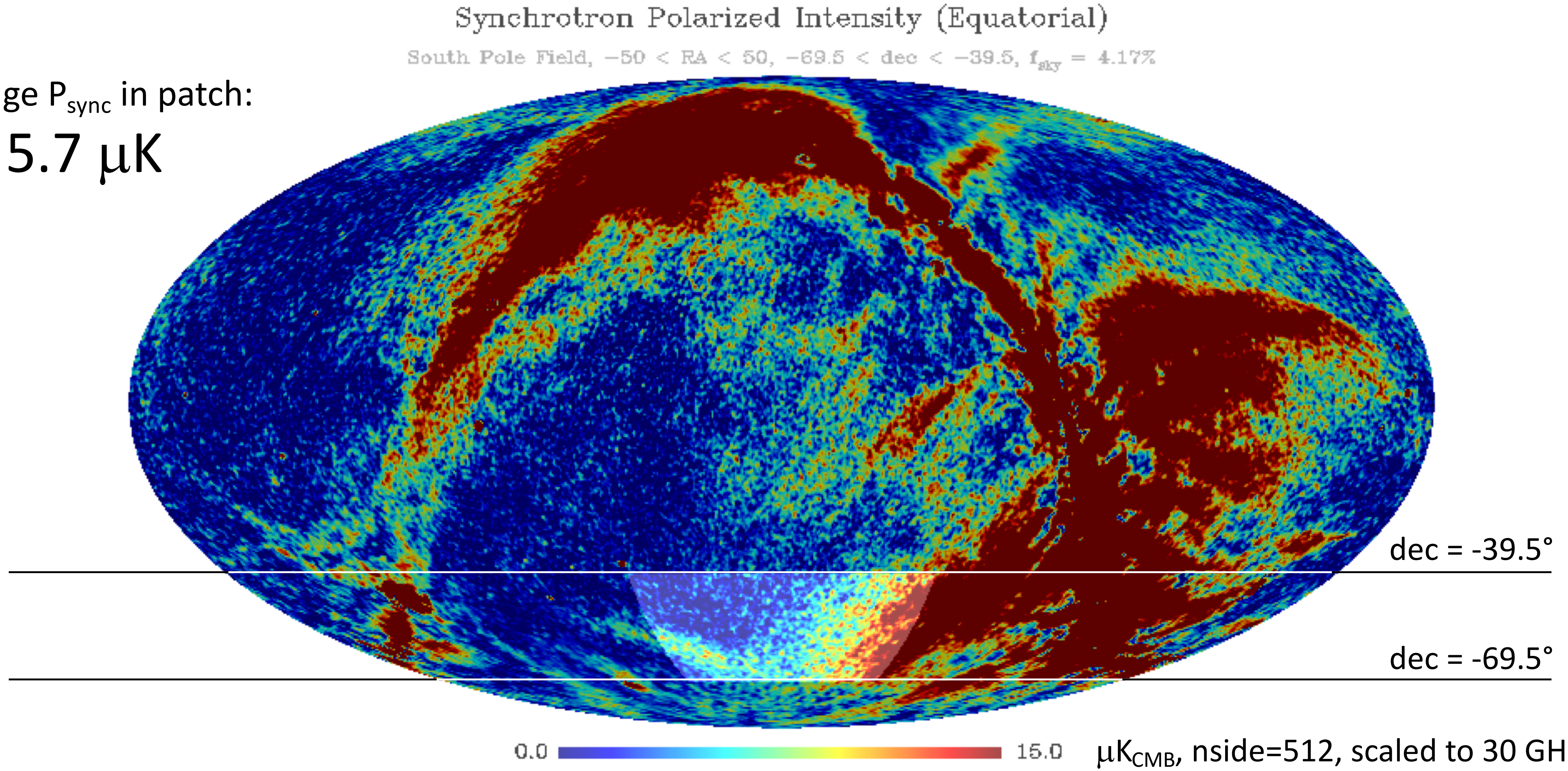
Average P_{sync} in patch:

5.7 μK

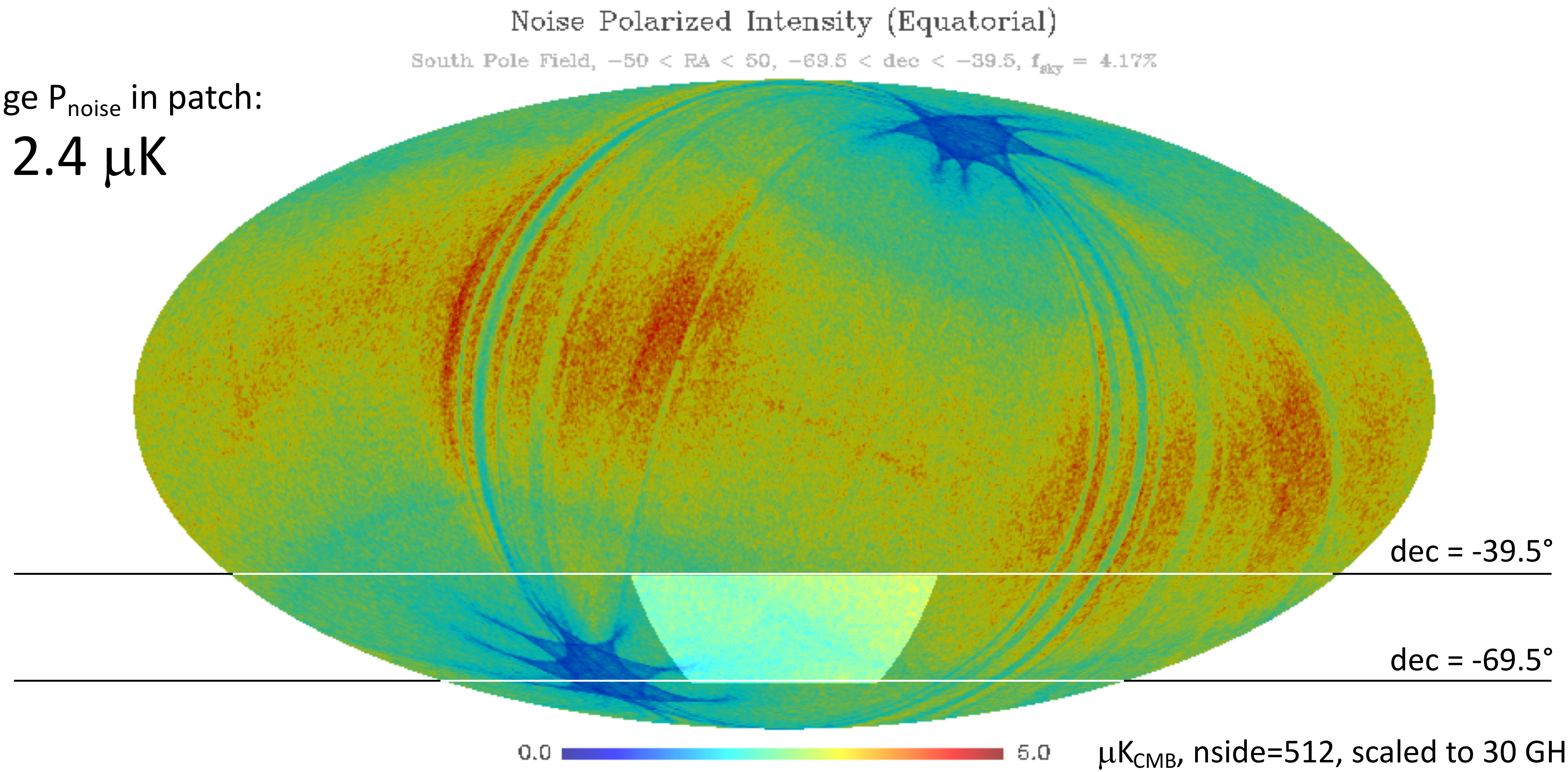


μK_{CMB}, nside=512, scaled to 30 GHz

Noise in CMB-S4 fields of view

Average P_{noise} in patch:

2.4 μK



μK_{CMB}, nside=512, scaled to 30 GHz

Synchrotron in CMB-S4 fields of view

CNRS • Berkeley
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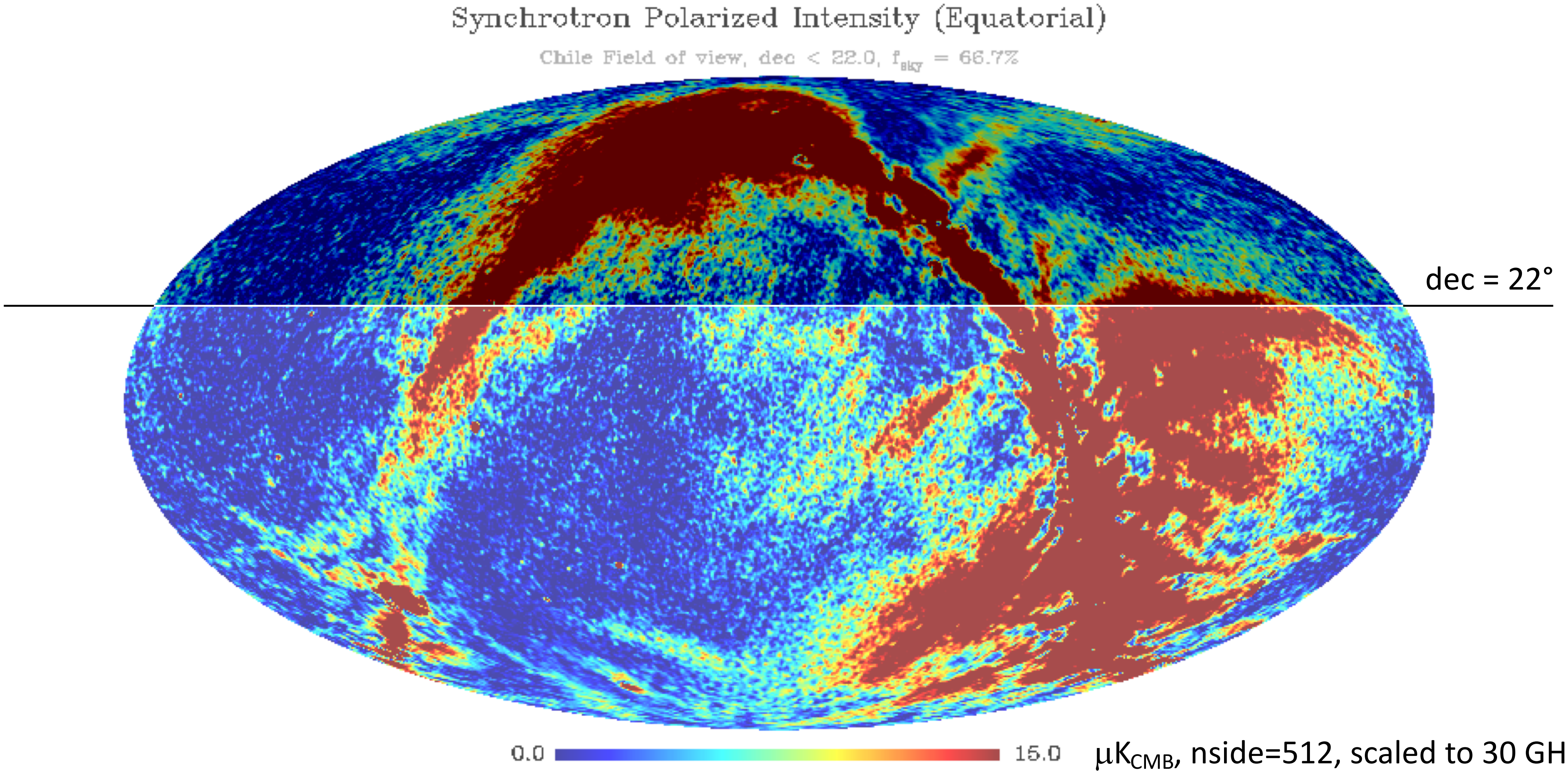

μK_{CMB}, nside=512, scaled to 30 GHz

Noise in CMB-S4 fields of view

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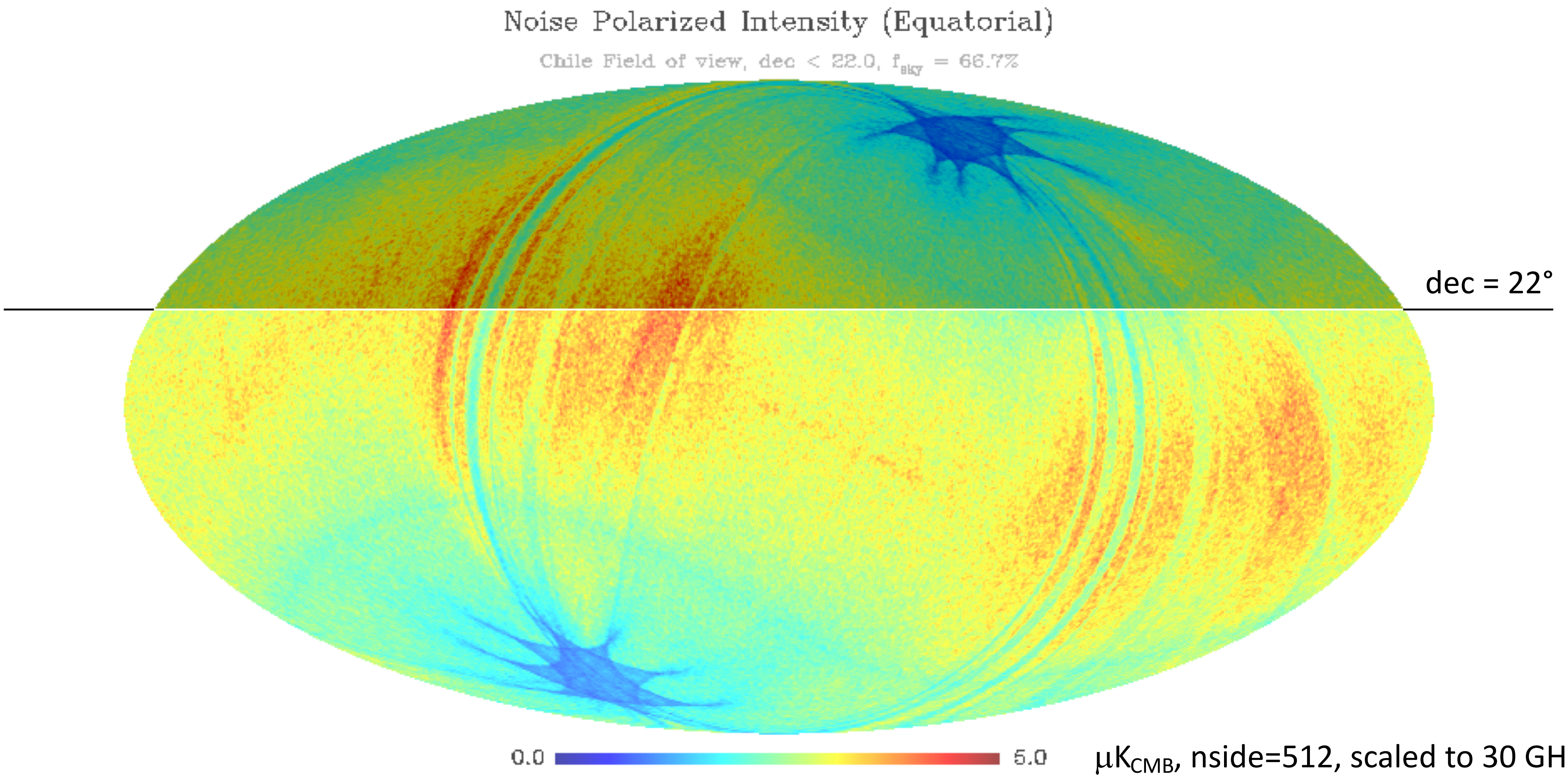

μK_{CMB}, nside=512, scaled to 30 GHz

Characterization of uncertainties

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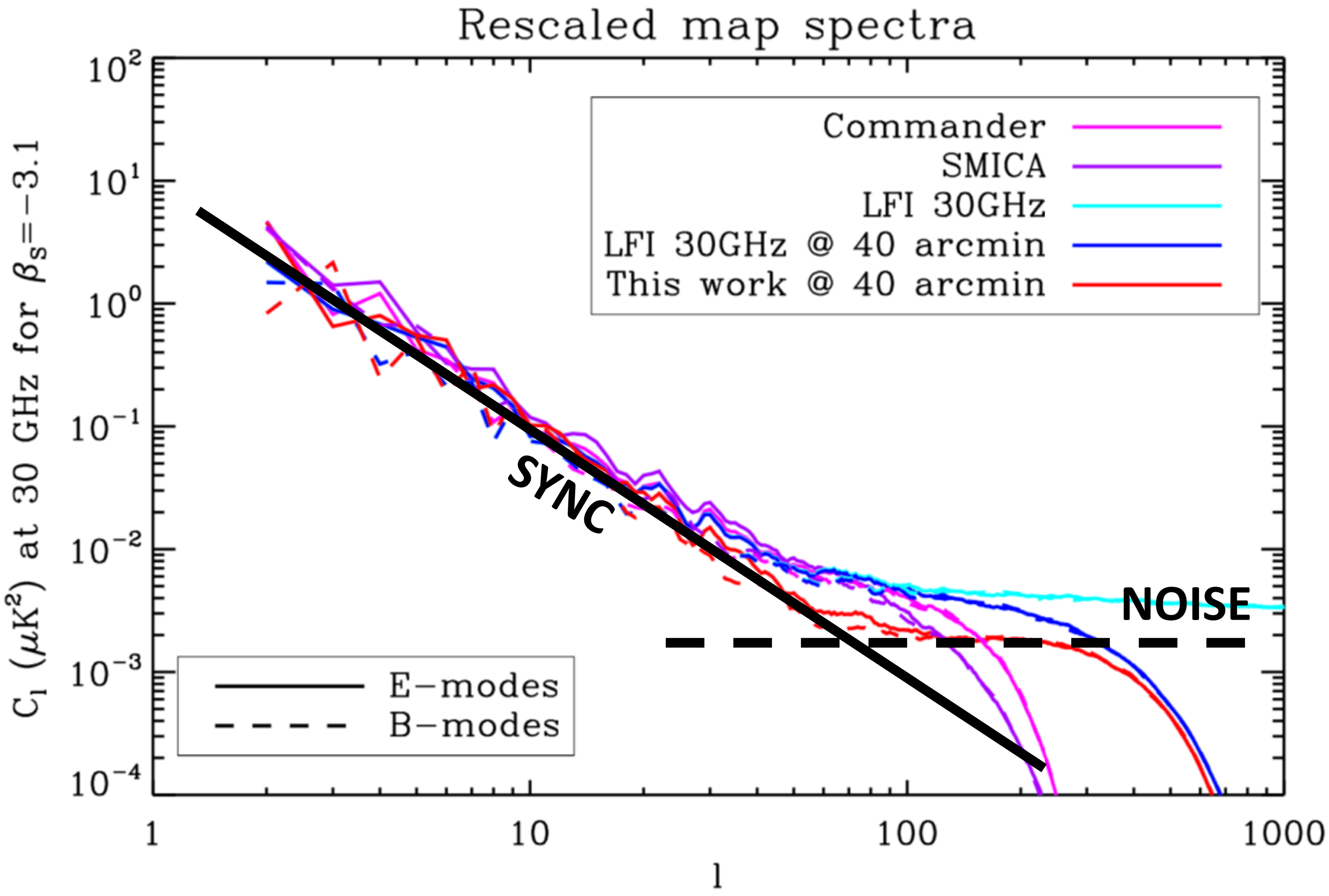
- Full propagation of noise simulations (WMAP and Planck) through the analysis pipeline: Statistical uncertainties

- Note: Statistical uncertainties from noise (additive errors) are dominant for clean sky regions around l=80

- **<u>To be done:</u>** Synchrotron scaling uncertainty (multiplicative errors) will be estimated by repeating the pipeline with various values of β_S (and perhaps with maps of varying β_S)

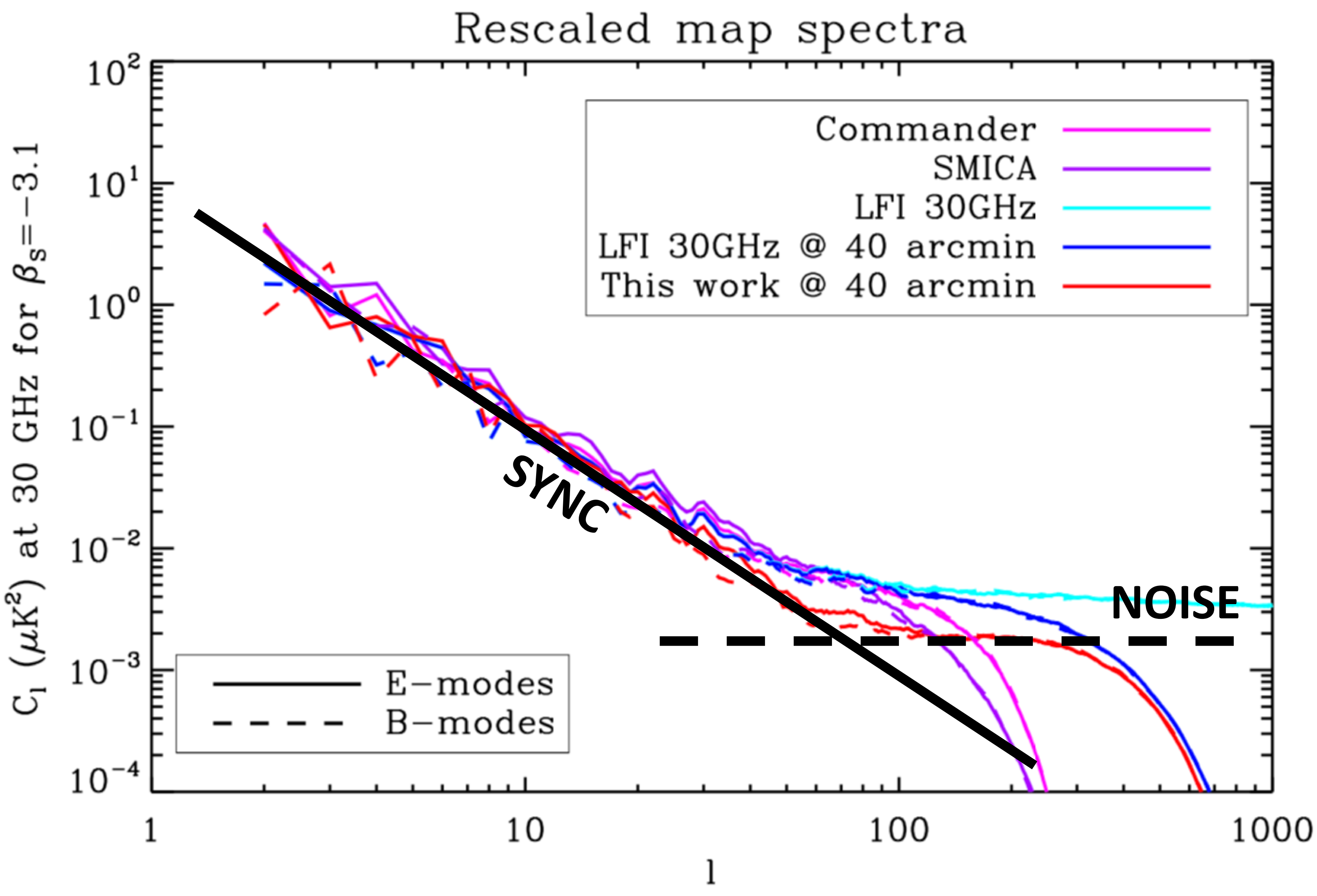
Paths for improvement 1: predict synchrotron power



$$\Delta C_\ell \simeq \frac{N_\ell + C_\ell}{\sqrt{(2\ell+1)f_{\rm sky}}}$$

Works better for larger f_{sky}

Paths for improvement 1: predict synchrotron power



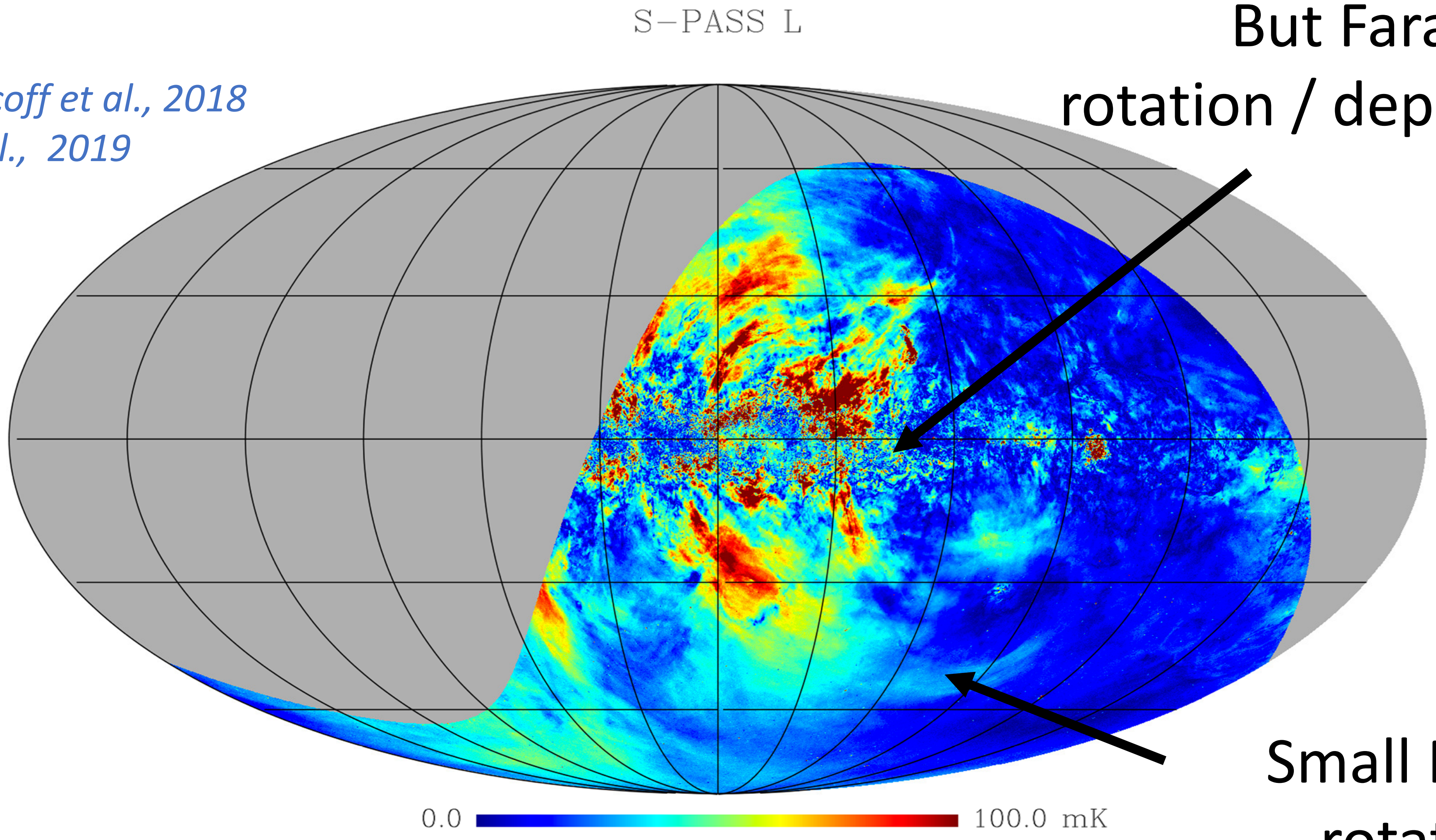
With a model of C_l

$$\Delta C_\ell \simeq \frac{\cancel{N_\ell} + C_\ell}{\sqrt{(2\ell+1)f_{\rm sky}}}$$

Works better for larger f_{sky}

Paths for improvement 2: merge also 2.3 GHz S-PASS data ?

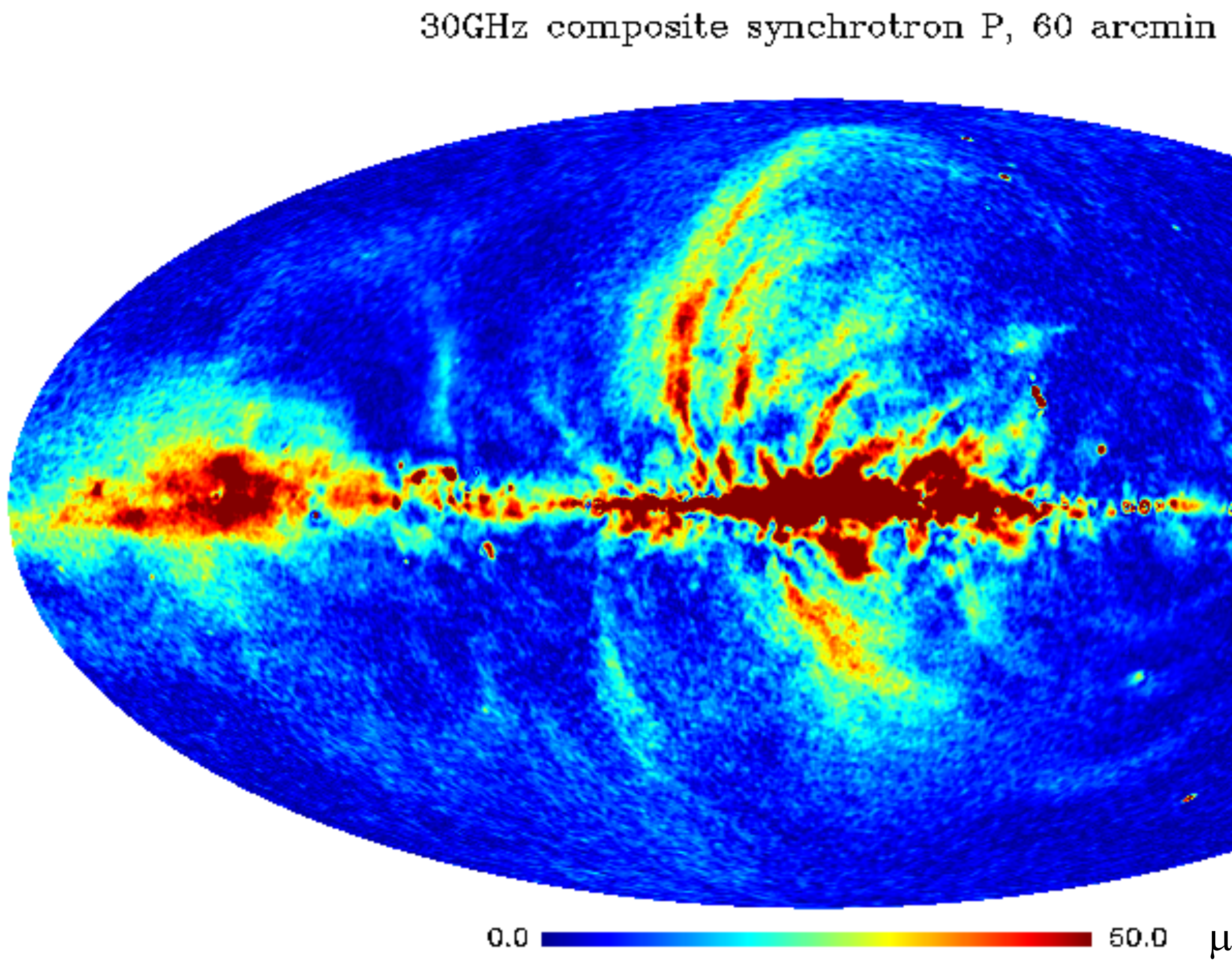
Krachmalnicoff et al., 2018
Carretti et al., 2019



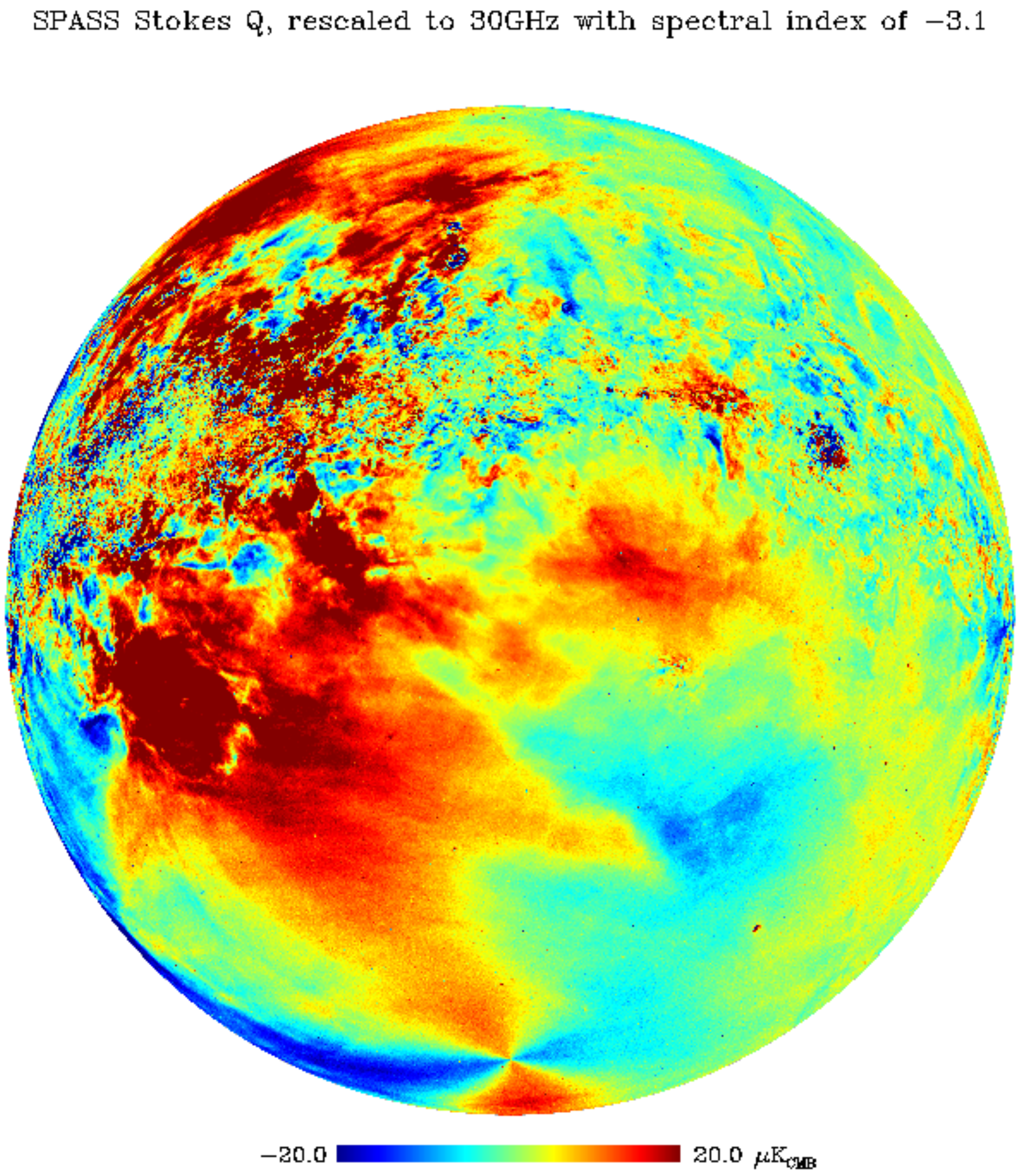
But Faraday rotation / depolarisation

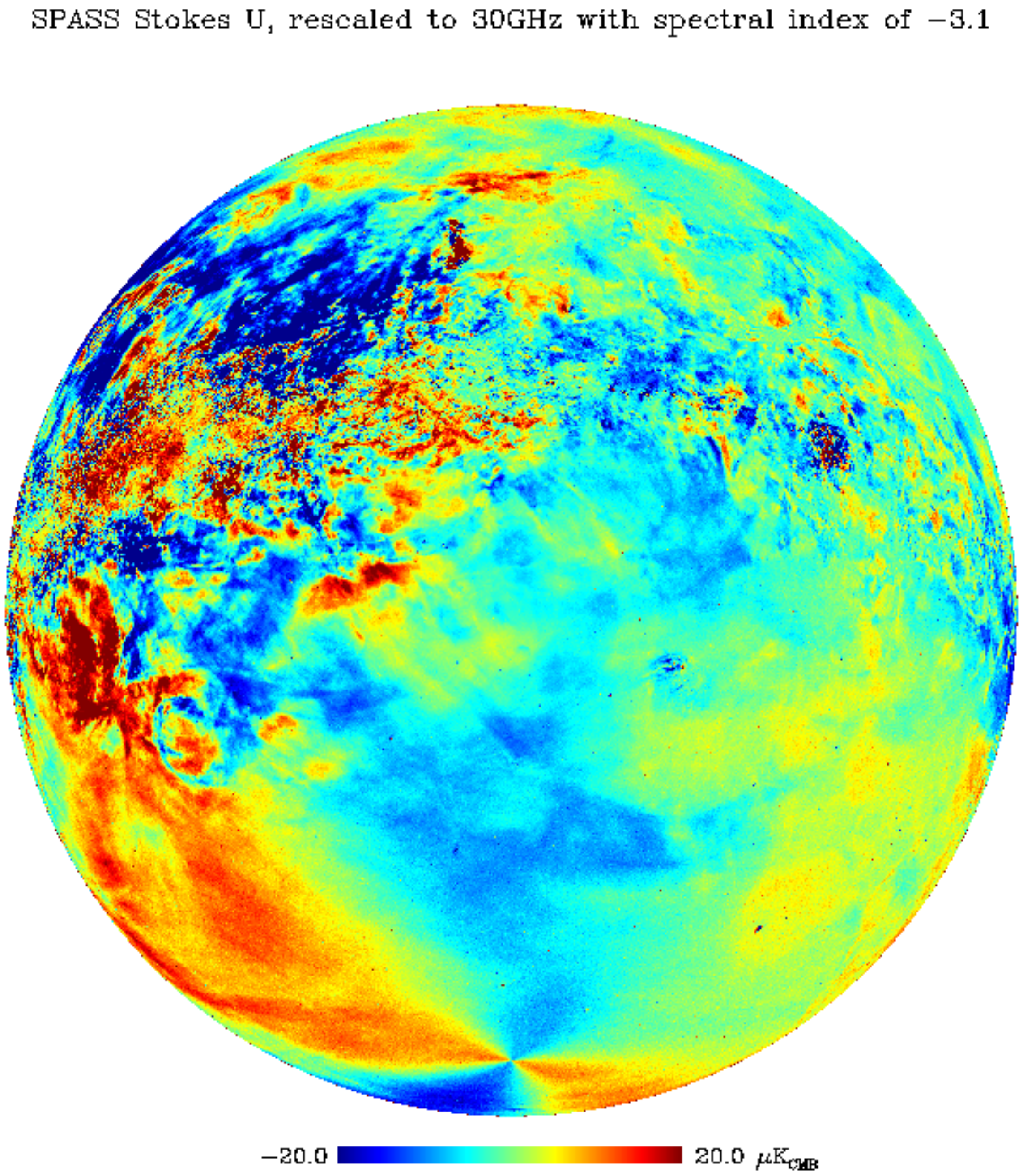
Small Faraday rotation ?

Composite Synchrotron P at 60' resolution

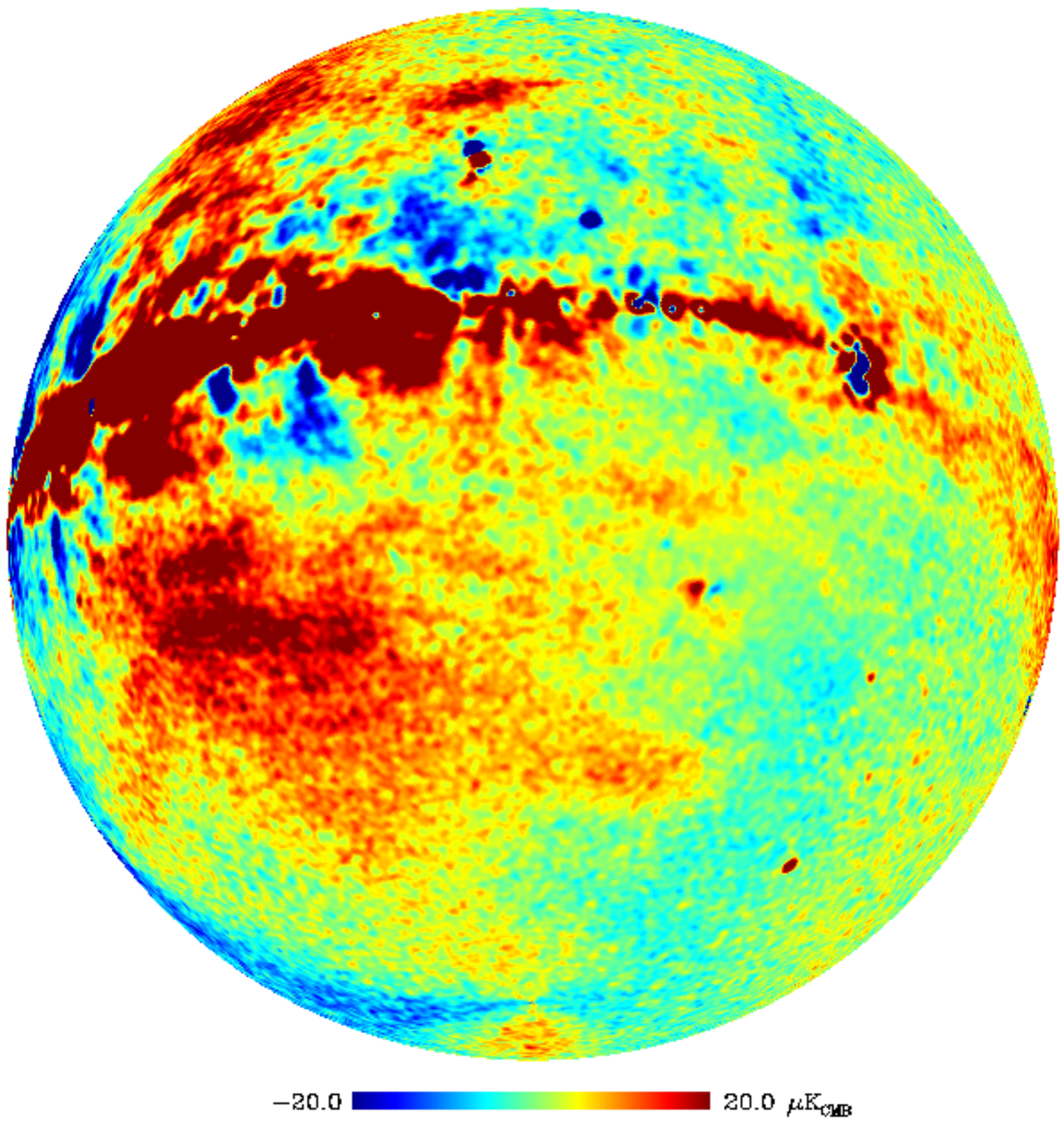


μK_{CMB}, nside=512, scaled to 30 GHz

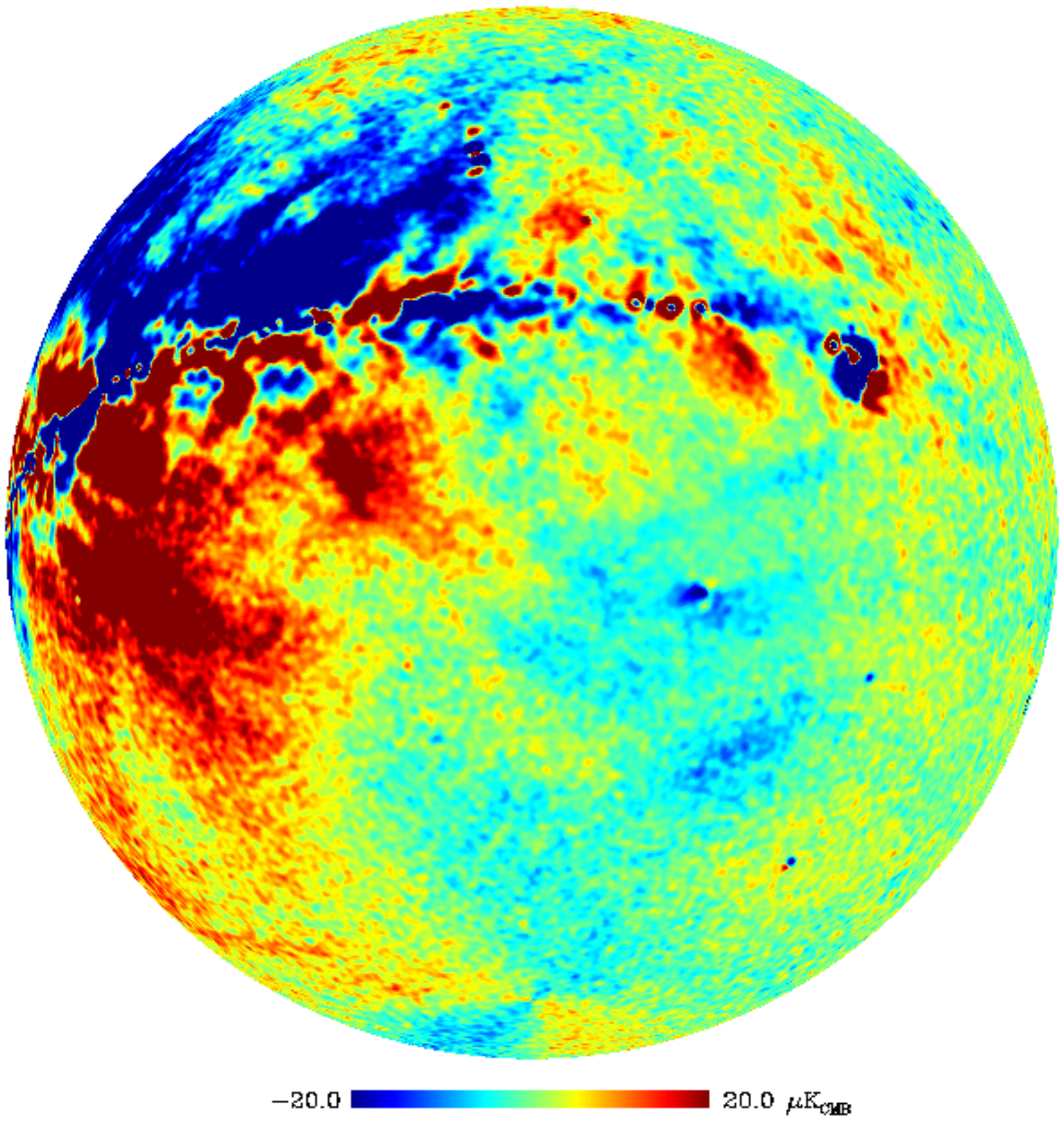

SPASS Stokes Q, rescaled to 30GHz with spectral index of −3.1
−20.0
20.0 μK_CMB

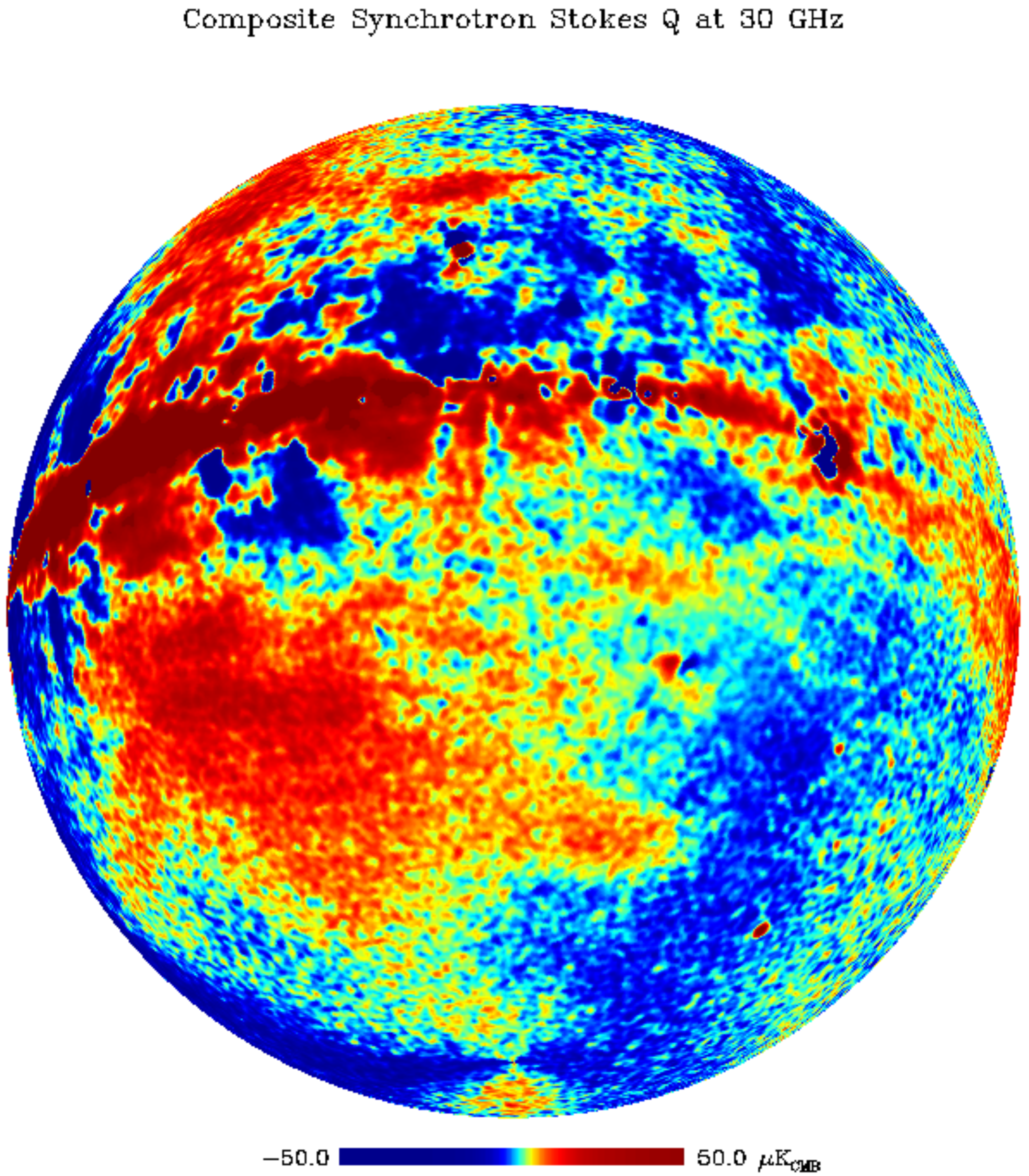

SPASS Stokes U, rescaled to 30GHz with spectral index of −3.1
−20.0
20.0 μK_CMB

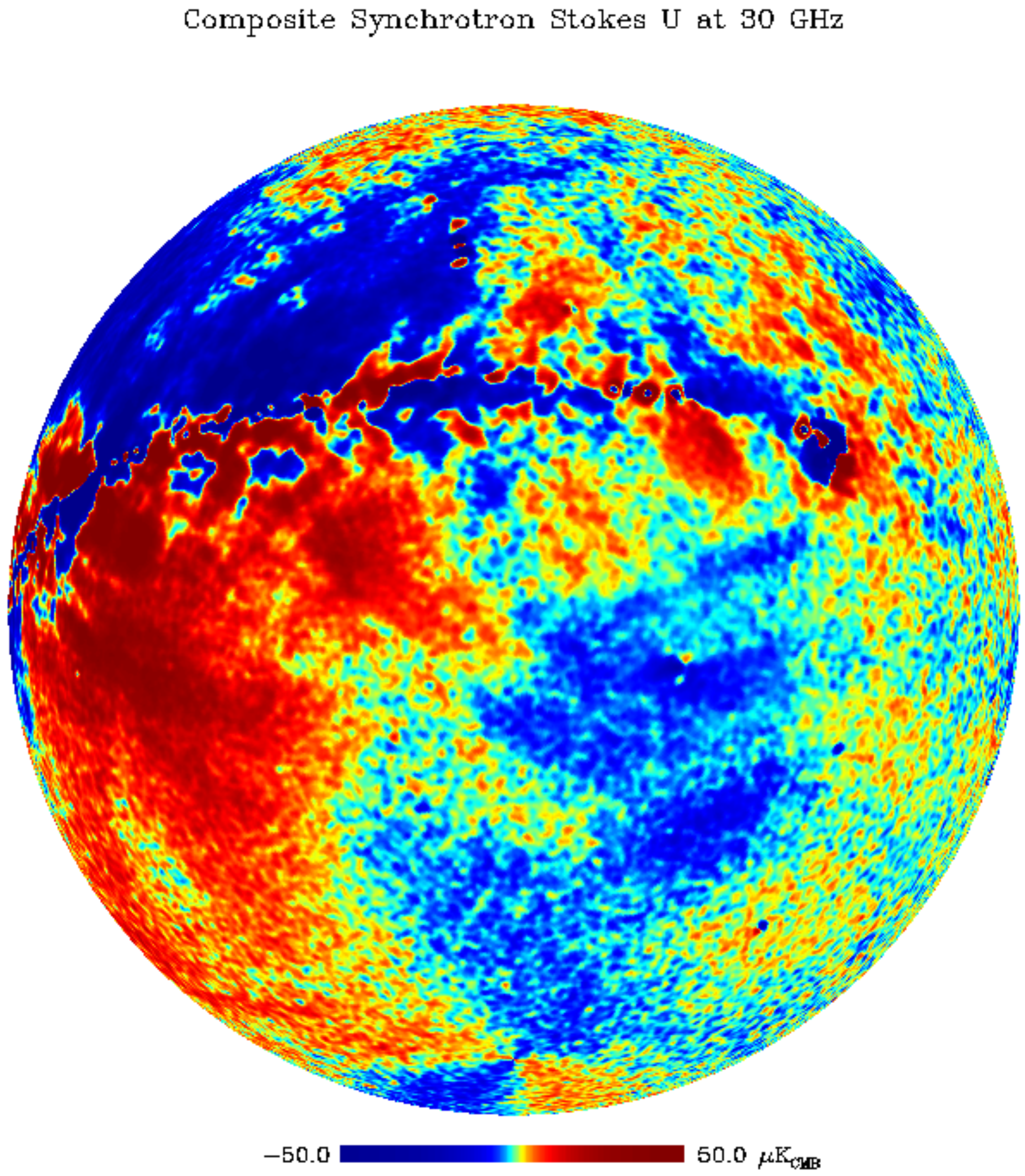
Composite Synchrotron Stokes Q at 30 GHz

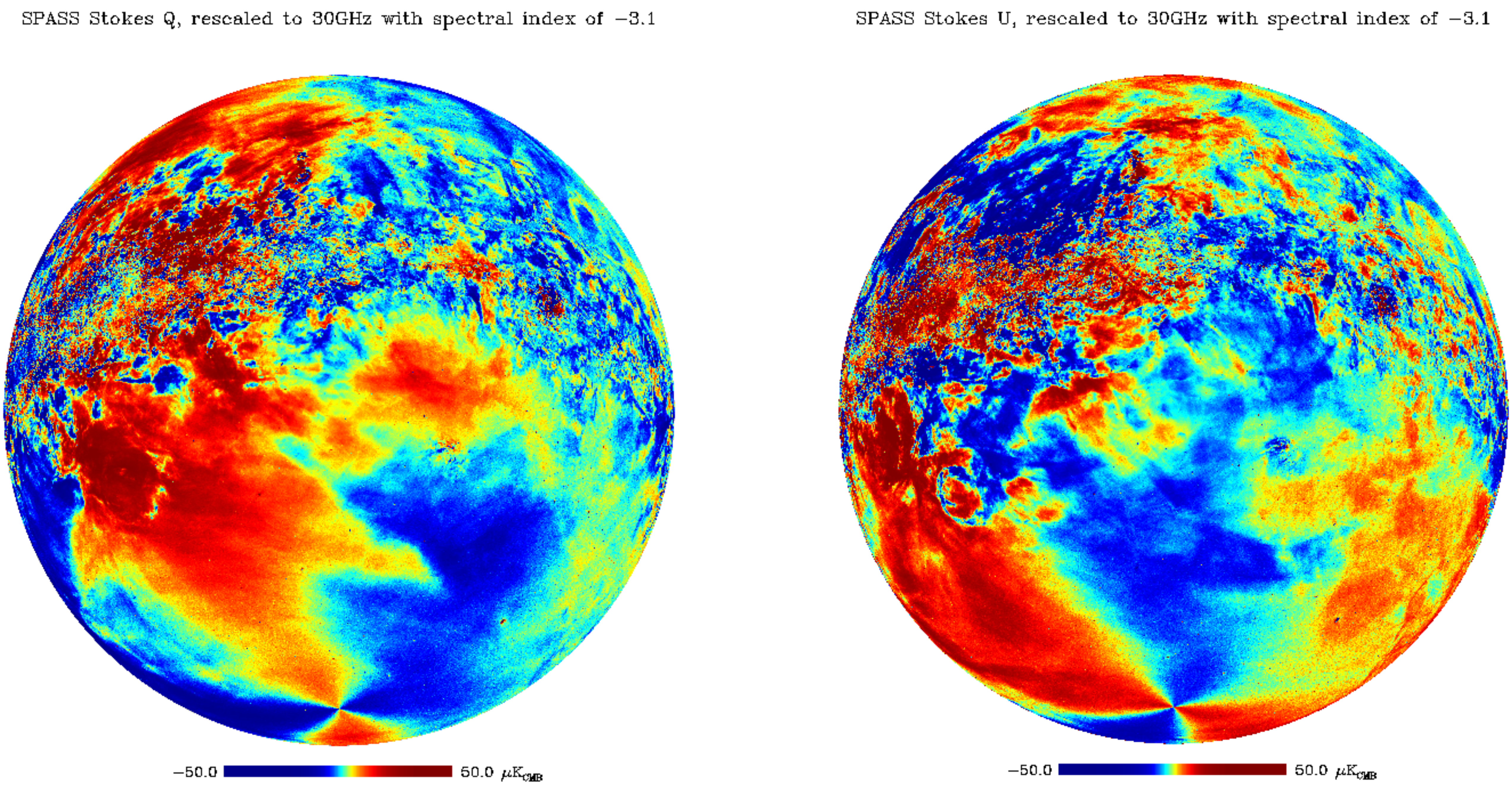


Composite Synchrotron Stokes U at 30 GHz




Composite Synchrotron Stokes Q at 30 GHz
−50.0
50.0 μK_{CMB}


Composite Synchrotron Stokes U at 30 GHz
−50.0
50.0 μK_{CMB}


SPASS Stokes Q, rescaled to 30GHz with spectral index of −3.1
−50.0
50.0 μK_CMB
SPASS Stokes U, rescaled to 30GHz with spectral index of −3.1
−50.0
50.0 μK_CMB

Conclusion on Synchrotron

- The combination of WMAP and Planck provides us with a synchrotron polarization template that is significantly less noisy than DR3 released Planck maps;
- Noise characterization is better, through propagation of noise simulations in the pipeline. The angular resolution is (reasonably) well defined;
- Work still to be done to fully characterize multiplicative errors;
- The maps and spectra obtained in this analysis can be used for better synchrotron cleaning in ongoing and upcoming ground-based CMB experiments;
- There still may be some margin for improvement for the Southern sky by using SPASS data, but the path for characterizing errors will be more complex.

THERMAL DUST

THERMAL DUST

will be for a next CMB-France meeting!

(and refer to Erwan Allys's talk today!)