Point source extraction

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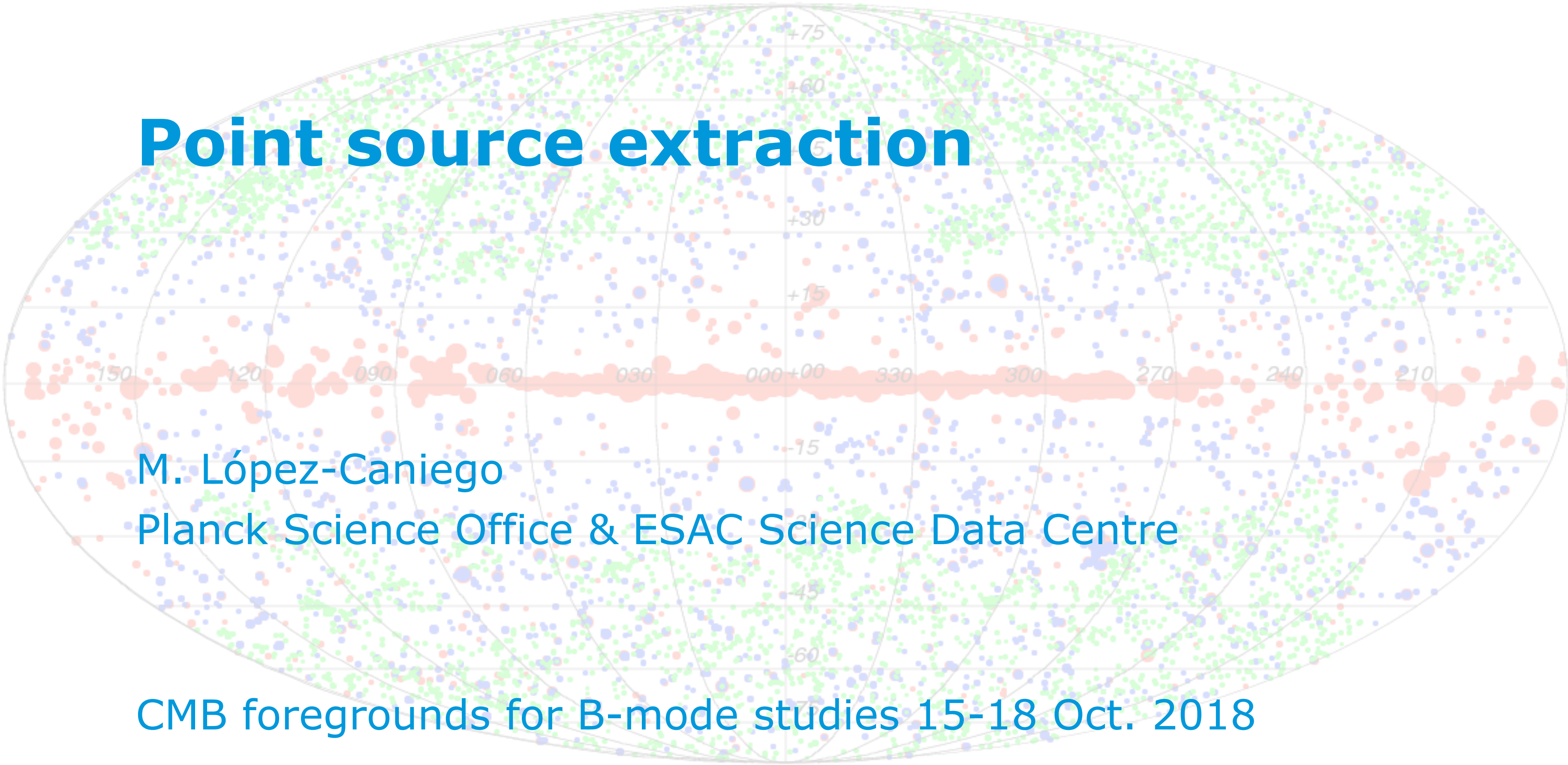
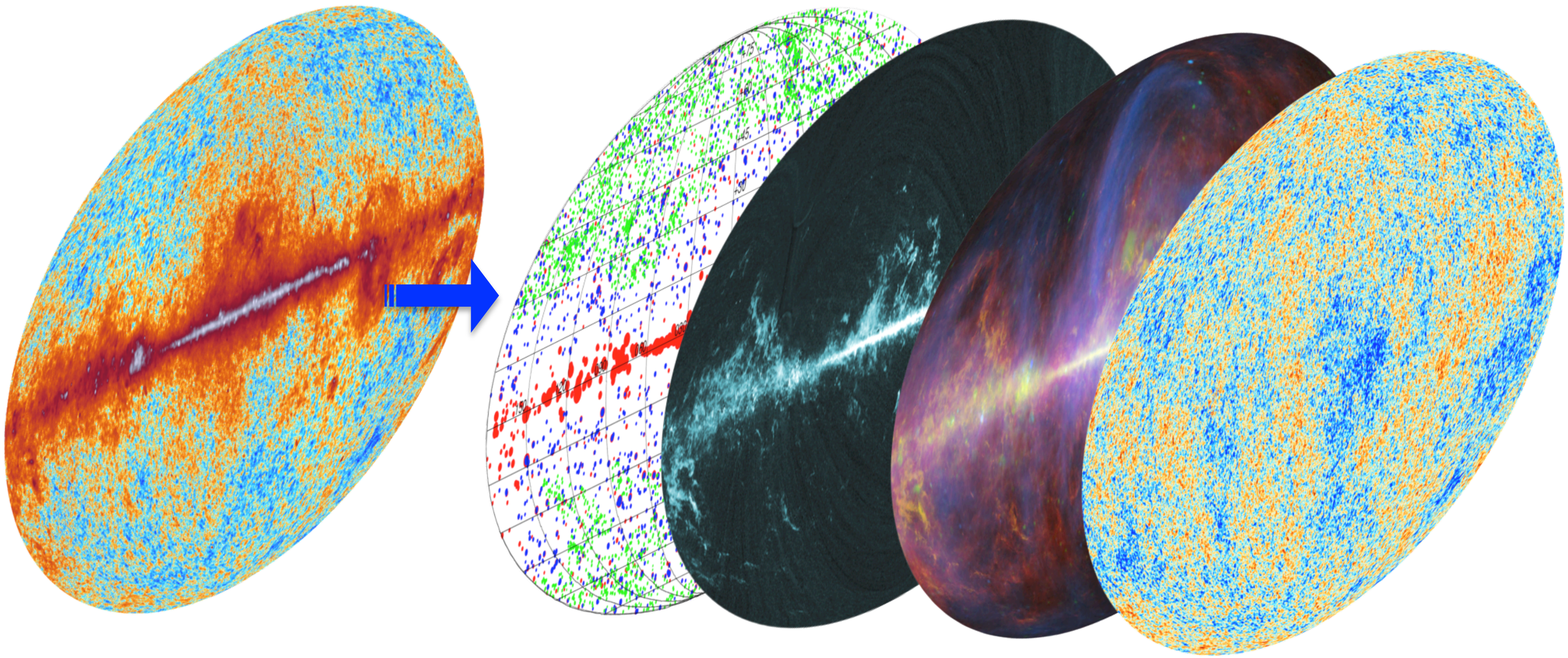
CMB foregrounds for B-mode studies 15-18 Oct. 2018



Introduction

- **CMB experiments have to deal with not only the diffuse galactic foregrounds but also compact source emission from our galaxy and from distant galaxies and clusters of galaxies.**



- **The goal is to separate these components in order to do cosmology with the CMB and galactic and extragalactic science with the diffuse and compact emissions.**

Introduction

- Different approaches have been proposed to detect and characterize compact sources in maps of the microwave sky in intensity and polarization.

- In some cases there is a clear distinction between the detection of a source and its characterization, in some other cases they are part of the same process.

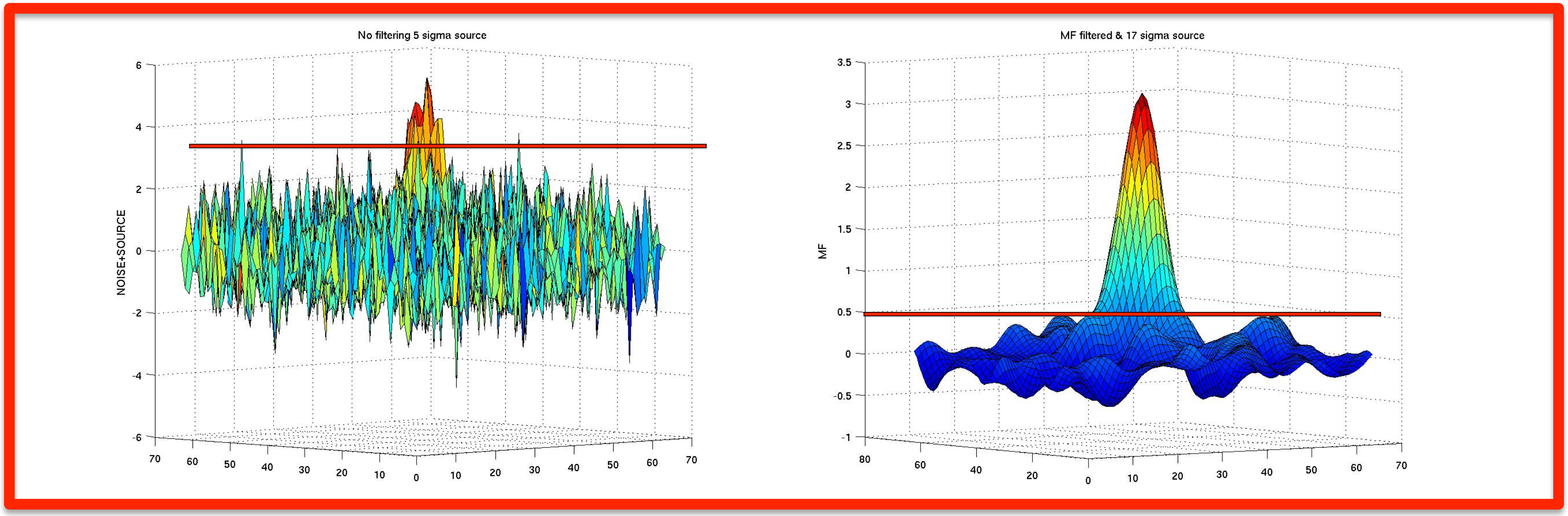
- Using one technique or another depends on the complexity of the problem, complexity of the implementation, or personal taste.

- One tool fits all does not apply here: difficult to find a technique equally effective detecting and characterizing point sources in very clean regions of the sky at low and extended non-circular sources in the vicinity of galactic plane in a high-frequency high-resolution map where the dust emission dominates at many different scales including that of the compact sources.

Detection

- **In terms of detection, we typically speak of:**
  - **Blind detection**
  - **Non-blind (detection?)**

- **Both the blind and non-blind detection can be generally improved pre-processing the data.**
- **One approach is to filter out the large scale diffuse structures, and, to some extent, the small-scale noise, one frequency at the time.**



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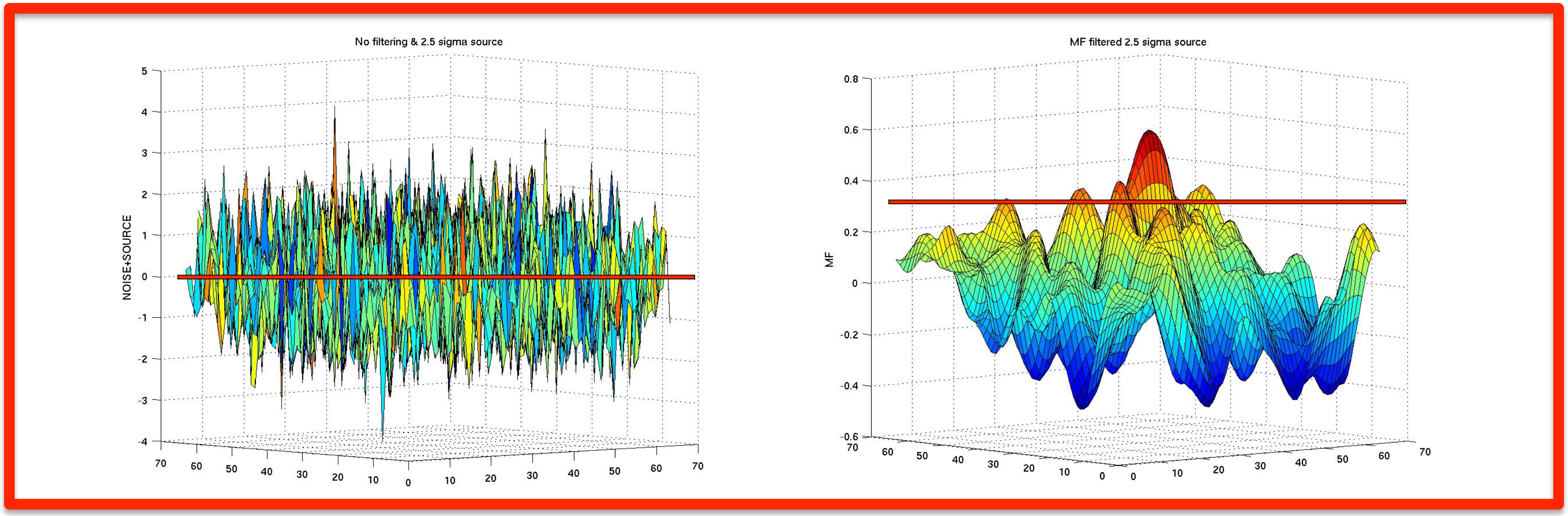
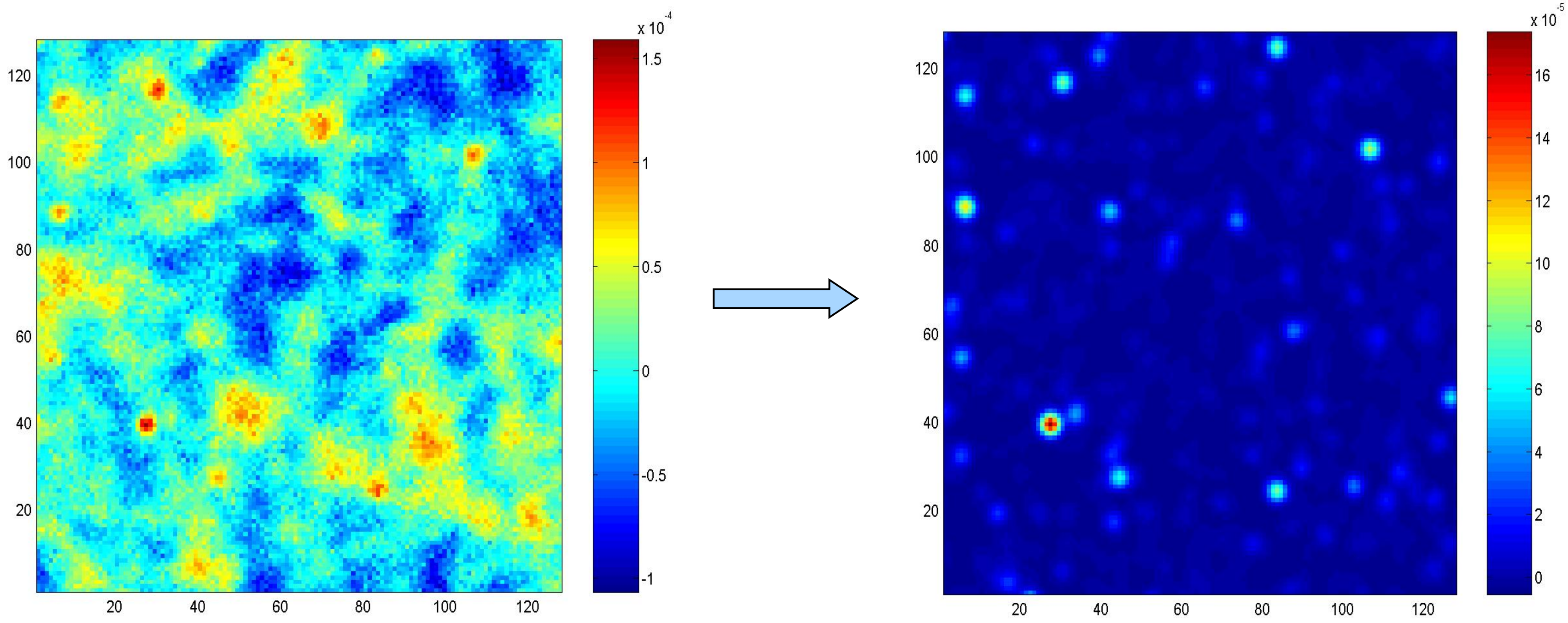


Detection

30 GHz Planck simulation before and after filtering with MHW at the scale of the sources



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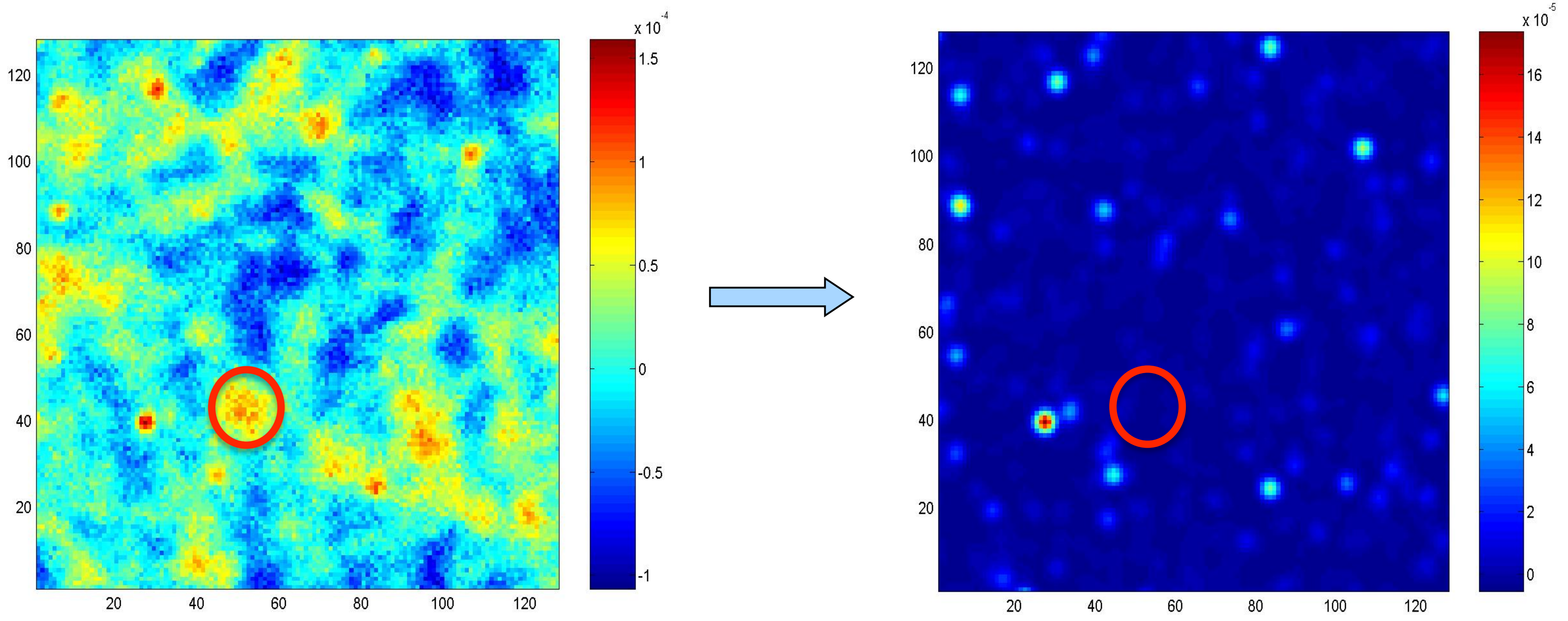
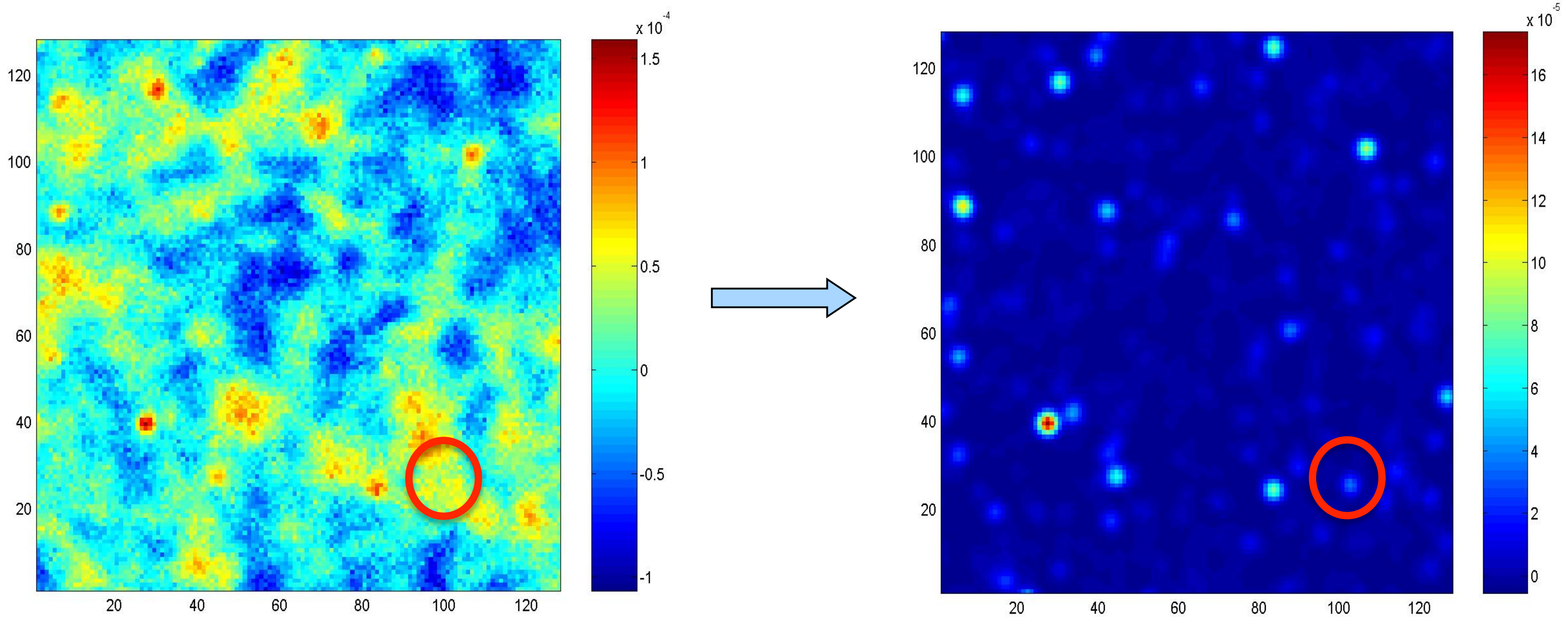


By filtering at this particular scale you remove structures with other angular scales
and at the same time increasing the signal to noise of the sources, improving completeness.

Detection

30 GHz Planck simulation before and after filtering with MHW at the scale of the sources



By doing this we also increase the SNR of structures with angular scales similar to that of the sources, and there is a trade off between completeness and reliability

Detection

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  - **Blind detection**
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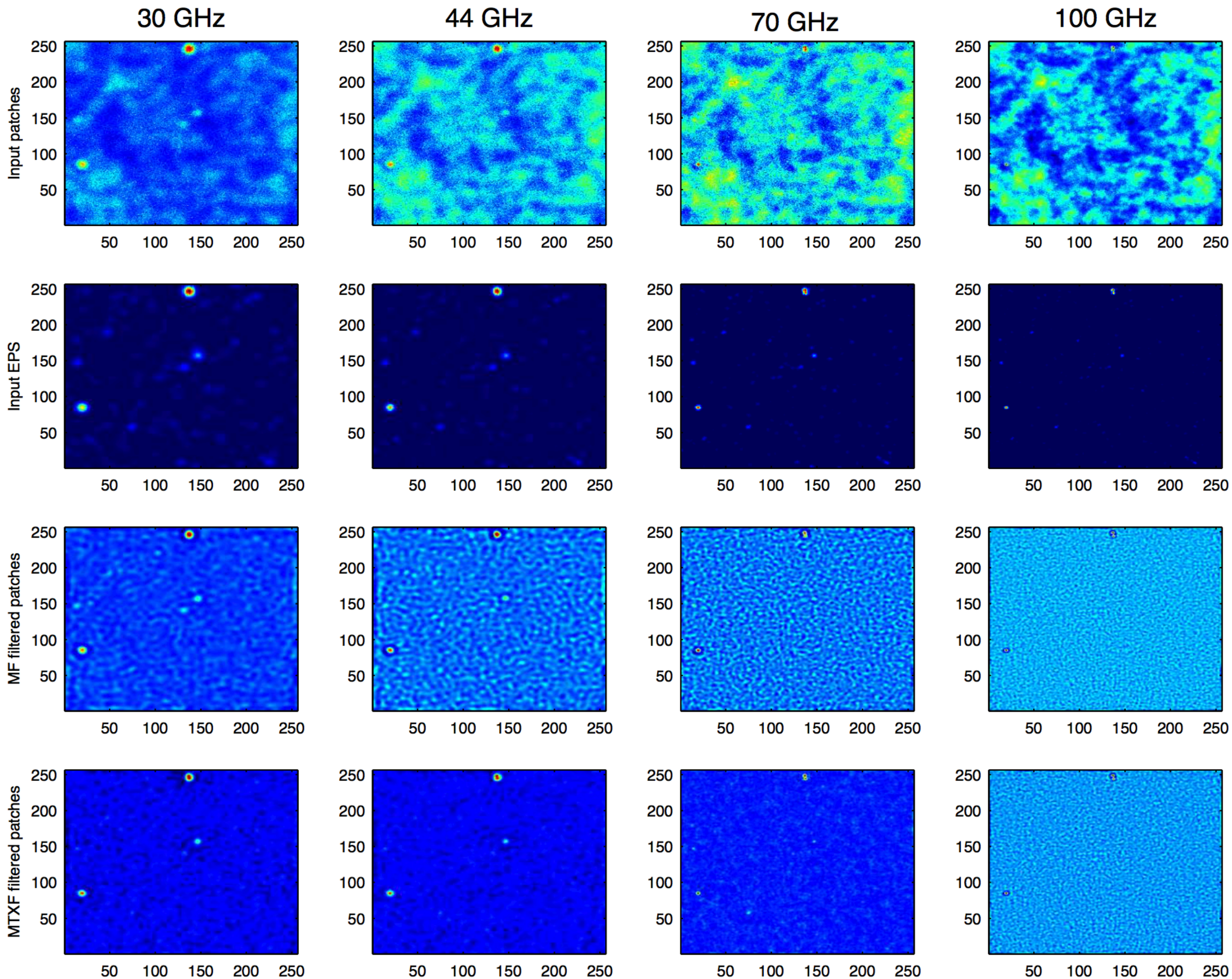
- **Both the blind and non-blind detection can be generally improved pre-processing the data.**

- **One approach is to filter out the large scale diffuse structures and to some extent the small-scale noise, one frequency at the time.**

- **Another approach is to combine multiple frequencies into a new combined map “optimal” for detection.**

- **This multi-frequency approach has been very successfully applied to the detection of SZ clusters using the Matched Multi Filter (MMF) from Herranz et al. 2002, to PS (MMF-PS, Lanz et al. 2014).**

- **The matrix filters (MTXF, Herranz et al. 2009) recently used in PIP LIV, Multifrequency catalogue of non-thermal sources, A&A, 2018, forthcoming.**



MTXF, Herranz et al 2009   This image: Herranz, Argüeso and Carvalho, 2012, AdAst. 22H

Detection: techniques

- **There are many types of filters, operating on the sphere and on flat patches, some examples:**

  - **Matched-filter or matched-filter-like filters**

$$\tilde{\Psi}_{MF} \propto \frac{\tau(q)}{P(q)}$$

For a Gaussian profile and a Scale-free Power Spectrum P(q) prop. $q^{-\gamma}$, the MF is

$$\tilde{\Psi}_{MF} \propto x^{\gamma} e^{-\frac{1}{2}x^2}$$

MF in CMB: Tegmark & Oliveira-Costa, 1998;
MF in CMB: WMAP Point source catalogue
SAF for PS: Sanz et al 2001, Herranz et al. 2002;
MMF for SZ: Herranz et al 2002;
Other imp. of MMF: Schaefer et al 2005, Melin et al. 2006

MTF for PS: L-C et al 2004;
BSAF for PS: L-C et al. 2005;
MMF for PS: Lanz et al. 2010
FF for PS in P: Argüeso et al. 2010

  - **Bayesian methods**

    - Using a Bayesian formalism, these methods look for maxima in the posterior and decided if these maxima correspond to a real object performing a Bayesian model selection. As Spiderman would say: "With great **power** comes great **responsibility".**

MCCLEAN: Hobson and McLachlan 2003. Powelsnakes I: Carvalho et al. 2009. Powelsankes II: Carvalho 2012
BeeP: Carvalho, L-C and Tauber PCCS2 annex in preparation.

Detection: techniques

- **The Mexican Hat Wavelet (MHW) used as a filter**

In 2D: $$\psi_{MH}(x) \propto \left(1-\frac{x^2}{2}\right)e^{-\frac{1}{2}x^2},\ x \equiv |\vec{x}|$$ Vielva et al. 2001, Cayón et al. 2003

Detection: techniques

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- **The Mexican Hat Wavelet Family**
  - MHW1 and MHW2 (1st a nd 2nd order Laplacian of the Gaussian)
  - CMHW (perfect reconstruction of a function at any scale).

$$\begin{aligned}
\varphi(x) &= \frac{1}{2\pi}e^{-\frac{x^2}{2}}, & \varphi(q) &= e^{-\frac{q^2}{2}},\\
\psi_{vh}(x) &= \frac{1}{2\pi}\left(1-\frac{x^2}{2}\right)e^{-\frac{x^2}{2}}, & \psi_{vh}(q) &= \frac{q^2}{2}e^{-\frac{q^2}{2}},\\
\psi_d(x) &= \frac{1}{2\pi}\left(1-\frac{x^2}{2}+\frac{x^4}{8}\right)e^{-\frac{x^2}{2}}, & \psi_d(q) &= \frac{q^4}{8}e^{-\frac{q^2}{2}},\\
\psi_c(x) &= \delta(\vec{x})-\frac{1}{2\pi}\left(3-\frac{3x^2}{2}+\frac{x^4}{8}\right)e^{-\frac{x^2}{2}} & \psi_c(q) &= 1-\left(1+\frac{q^2}{2}+\frac{q^4}{8}\right)e^{-\frac{q^2}{2}}
\end{aligned}$$

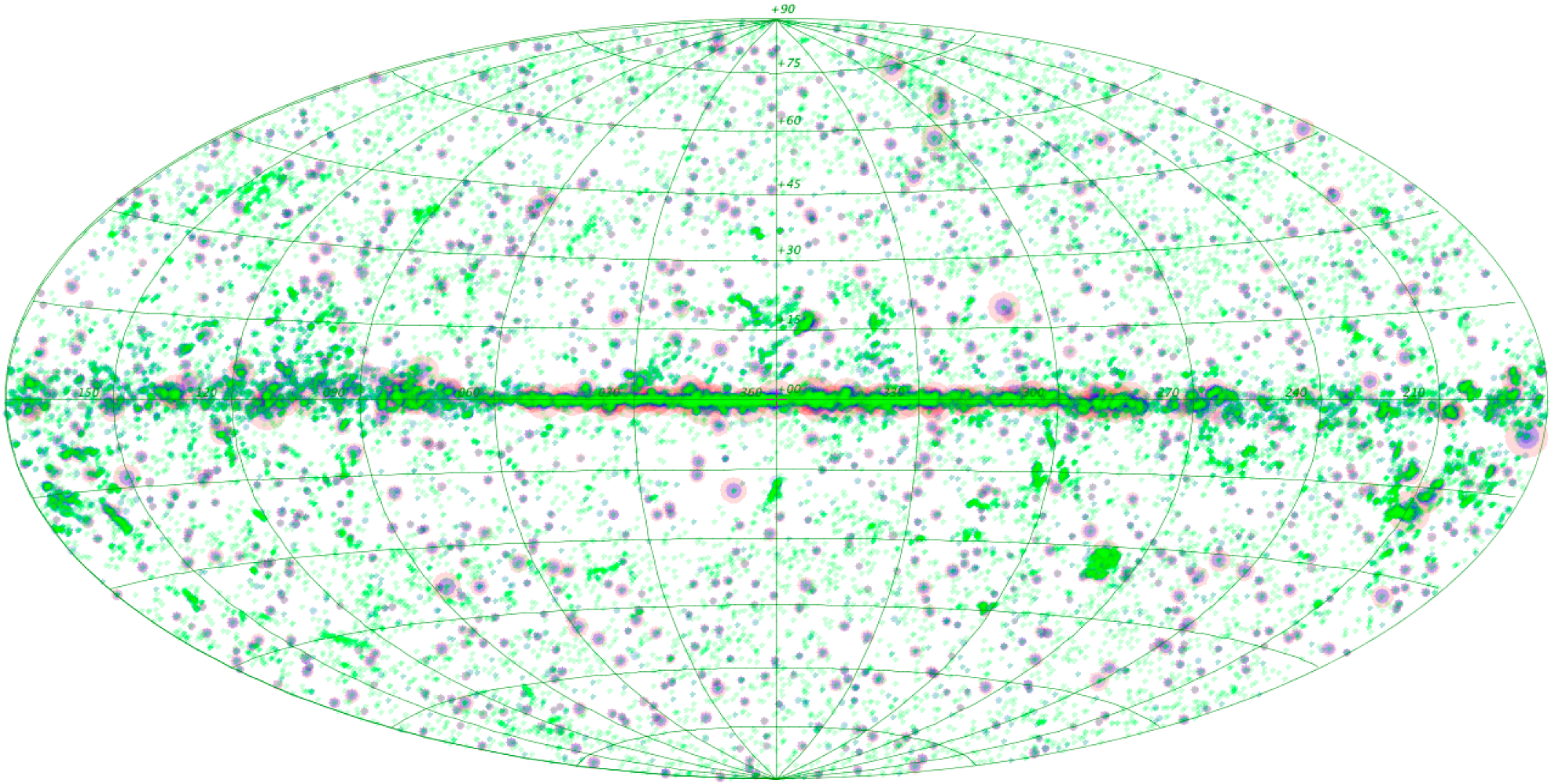
MHWF: González-Nuevo et al. 2006, MNRAS 369, 1603.

Comparison between MHW1, MHW2 and MF for Planck sims: L-C et al. 2006, MNRAS, 370, 2047

MHW2 used to extract PS in WMAP, Planck and QUIJOTE. In Planck: PCCS and PCCS2 and SEVEM PS masks.

Detection on Planck: PCCS (nominal mission)

2013 PCCS: 30 (red), 143 (blue) and 857 (green) GHz



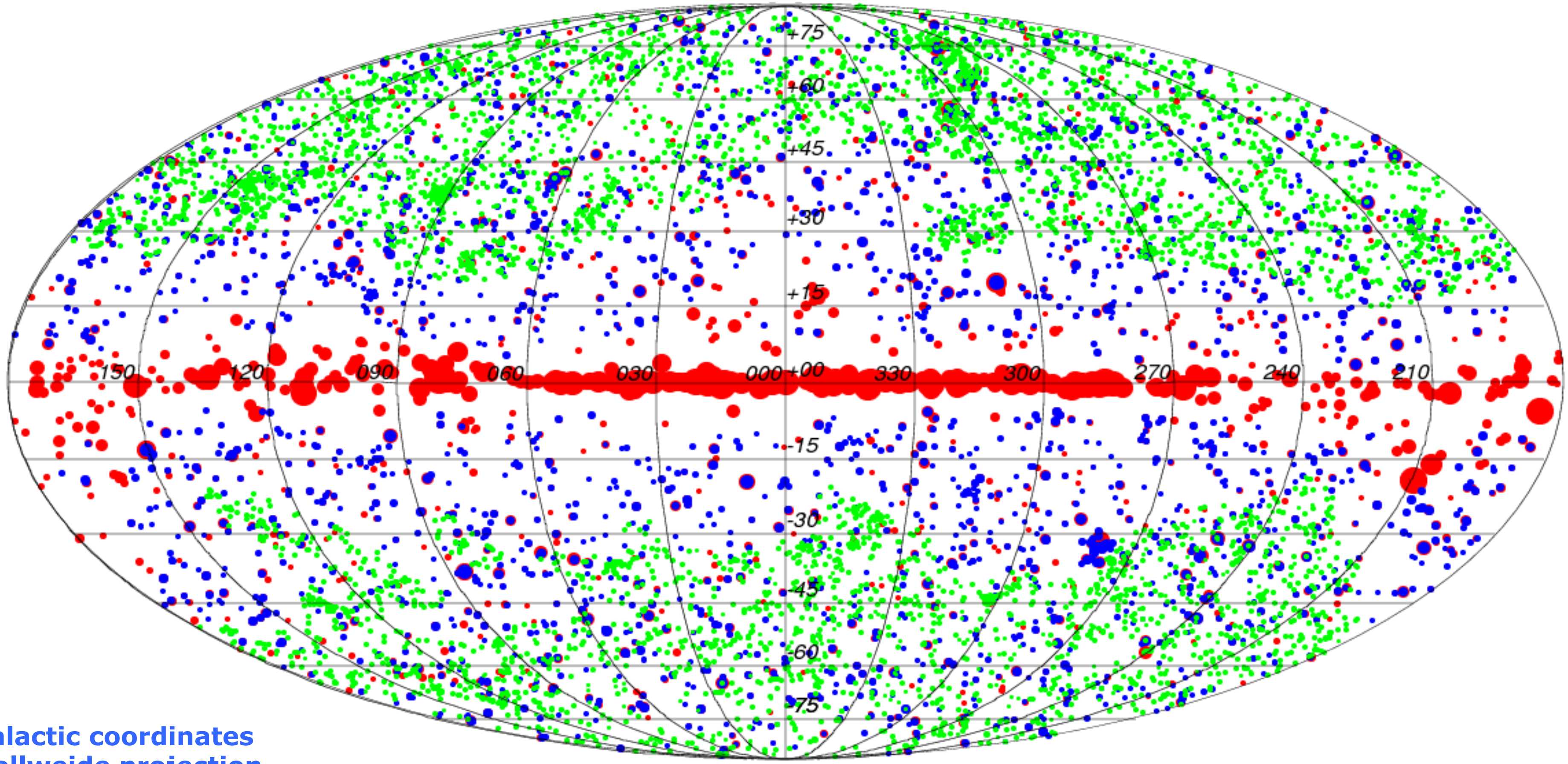
Detection on Planck: PCCS (nominal mission)

Table 1. PCCS characteristics.

	Channel								
	30	44	70	100	143	217	353	545	857
Frequency [GHz]	28.4	44.1	70.4	100.0	143.0	217.0	353.0	545.0	857.0
Wavelength, λ [μm]	10 561	6807	4260	3000	2098	1382	850	550	350
Beam *FWHM*[a] [arcmin]	32.38	27.10	13.30	9.65	7.25	4.99	4.82	4.68	4.33
Pixel size [arcmin]	3.44	3.44	3.44	1.72	1.72	1.72	1.72	1.72	1.72
S/N thresholds:									
Full sky	4.0	4.0	4.0	4.6	4.7	4.8	...	...	...
Extragalactic zone[b]	...	...	...	...	...	...	4.9	4.7	4.9
Galactic zone[b]	...	...	...	...	...	...	6.0	7.0	7.0
Number of sources:									
Full sky	1256	731	939	3850	5675	16 070	13 613	16 933	24 381
$\|b\| > 30°$	572	258	332	845	1051	1901	1862	3738	7536
$N(>S)$[c]:									
Full sky	934	535	689	3425	5229	15 107	13 184	15 781	23 561
$\|b\| > 30°$	373	151	191	629	857	1409	1491	2769	6773
$\|b\| \leq 30°$	561	384	498	2796	4422	13 698	11 693	13 012	16 788
Flux densities:									
Minimum[d] [mJy]	461	825	566	266	169	149	289	457	658
90% completeness [mJy]	575	1047	776	300	190	180	330	570	680
Uncertainty [mJy]	109	198	149	61	38	35	69	118	166
Position uncertainty[e] [arcmin]	1.8	2.1	1.4	1.0	0.7	0.7	0.8	0.5	0.4

Detection on Planck: PCCS2 (full mission)

2015 PCCS2: 3 lists of sources 30-70 GHz & 6 lists of sources 100-857 GHz.

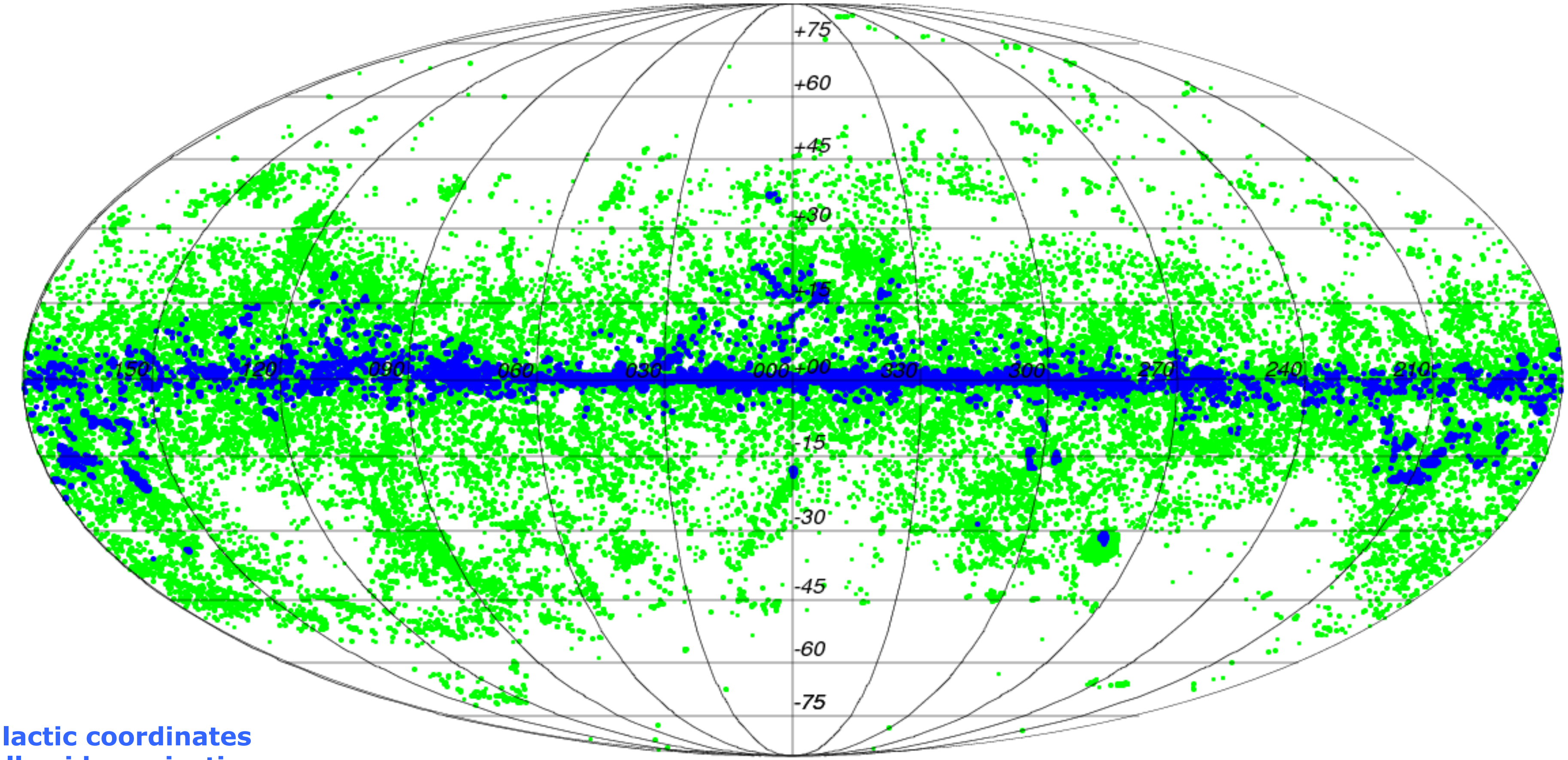


Galactic coordinates
Mollweide projection

PCCS2 T 30, 143 and 857 GHz

Detection on Planck: PCCS2/PCCS2E full mission

2015 PCCS2E: 6 lists of sources 100-857 GHz, 45.000 sources



Galactic coordinates
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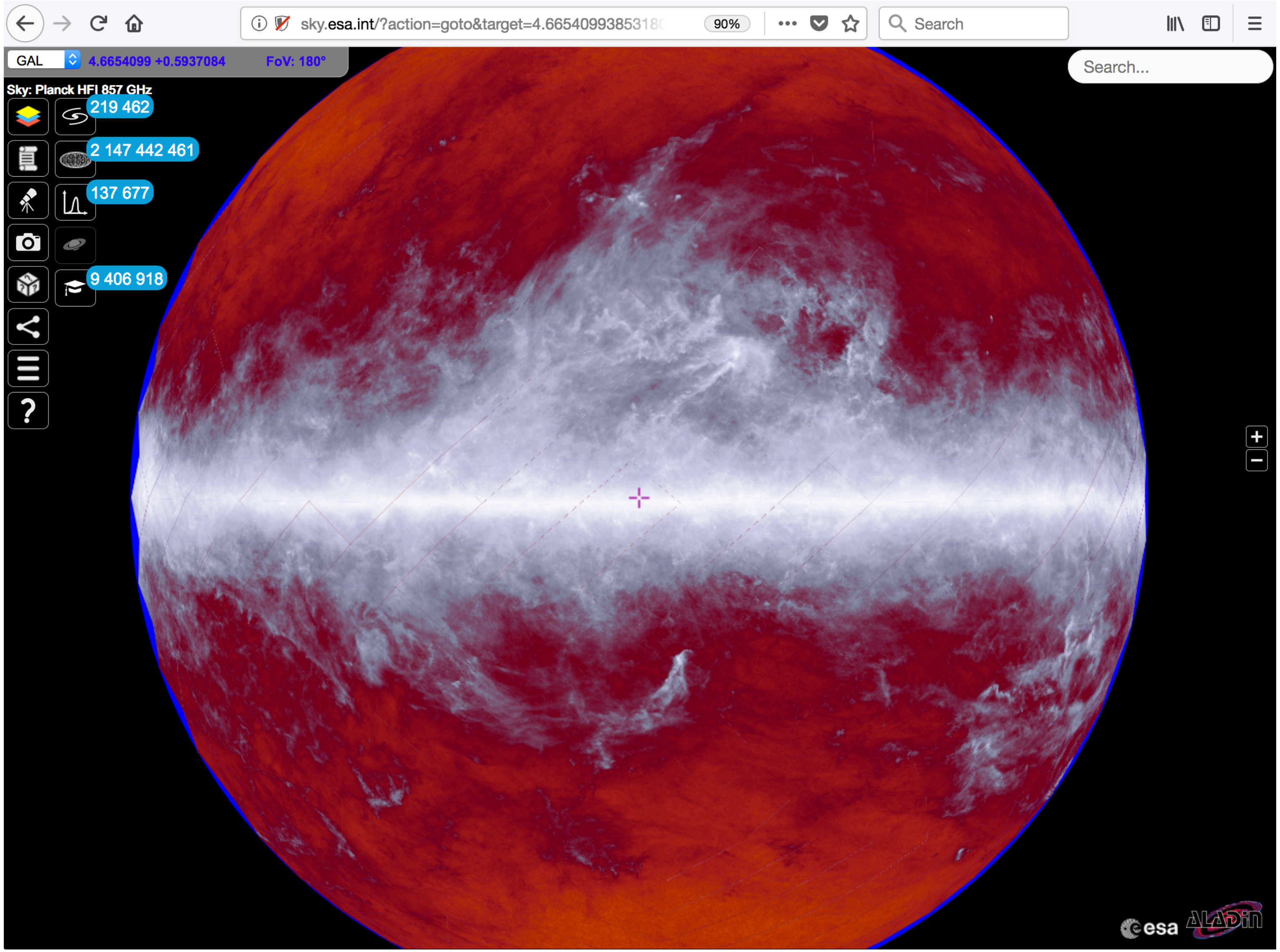
PCCS2E T 143 & 857 GHz

Detection on Planck: PCCS2/PCCS2E full mission

Summary Total Intensity

Channel	30	44	70	100	143	217	353	545	857
Freq [GHz]	28.4	44.1	70.4	100.0	143.0	217.0	353.0	545.0	857.0
λ [μm]	10561	6807	4260	3000	2098	1382	850	550	350
Number of sources									
PCCS2	1560	934	1296	1742	2160	2135	1344	1694	4891
PCCS2E	...	...	...	2487	4139	16842	22665	31068	43290
Union PCCS2+PCCS2E	...	...	...	4229	6299	18977	24009	32762	48181
PCCS[a]	1256	731	939	3850	5675	16070	13613	16933	24381

Detection on Planck: PCCS2/PCCS2E full mission



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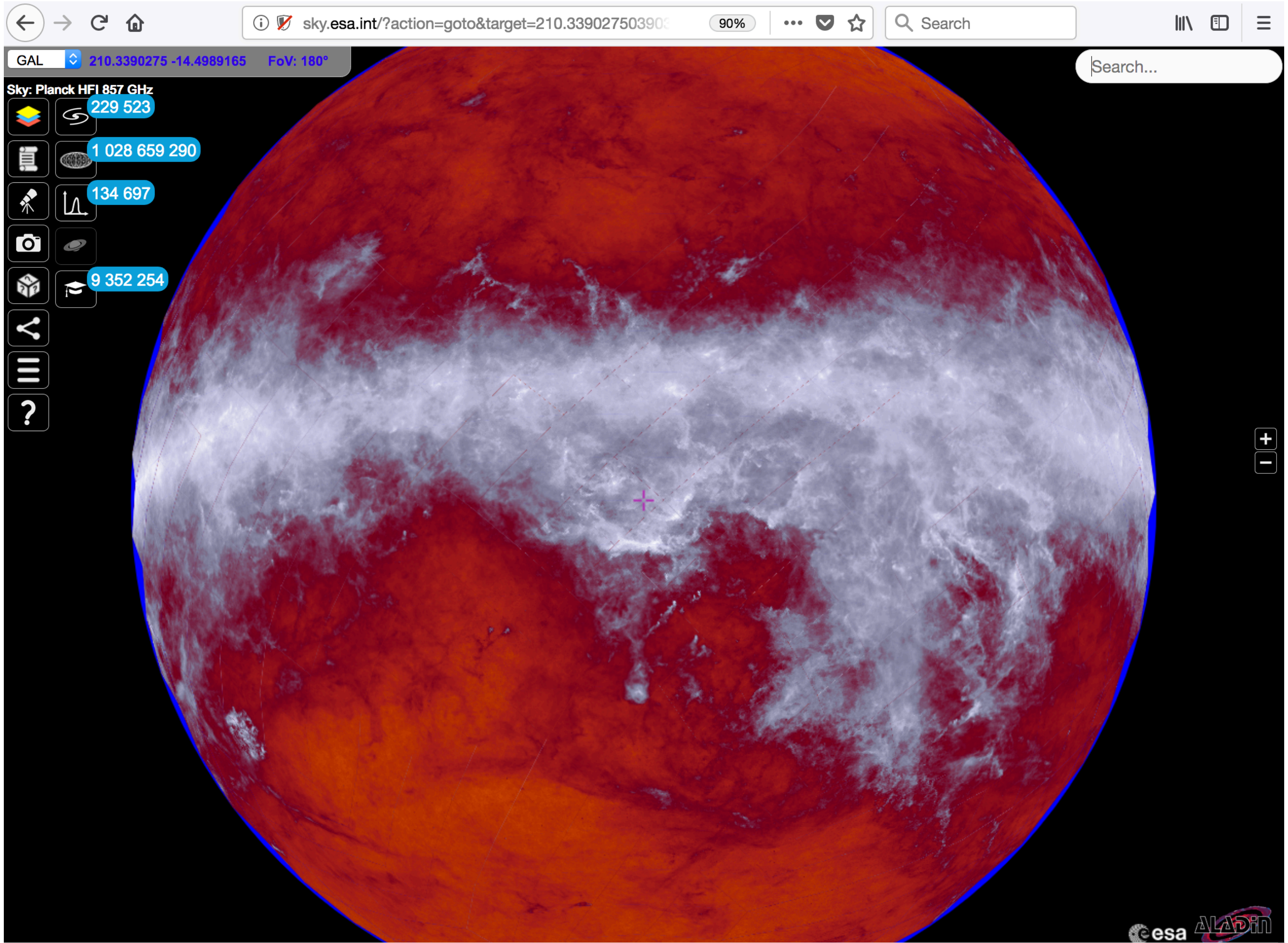

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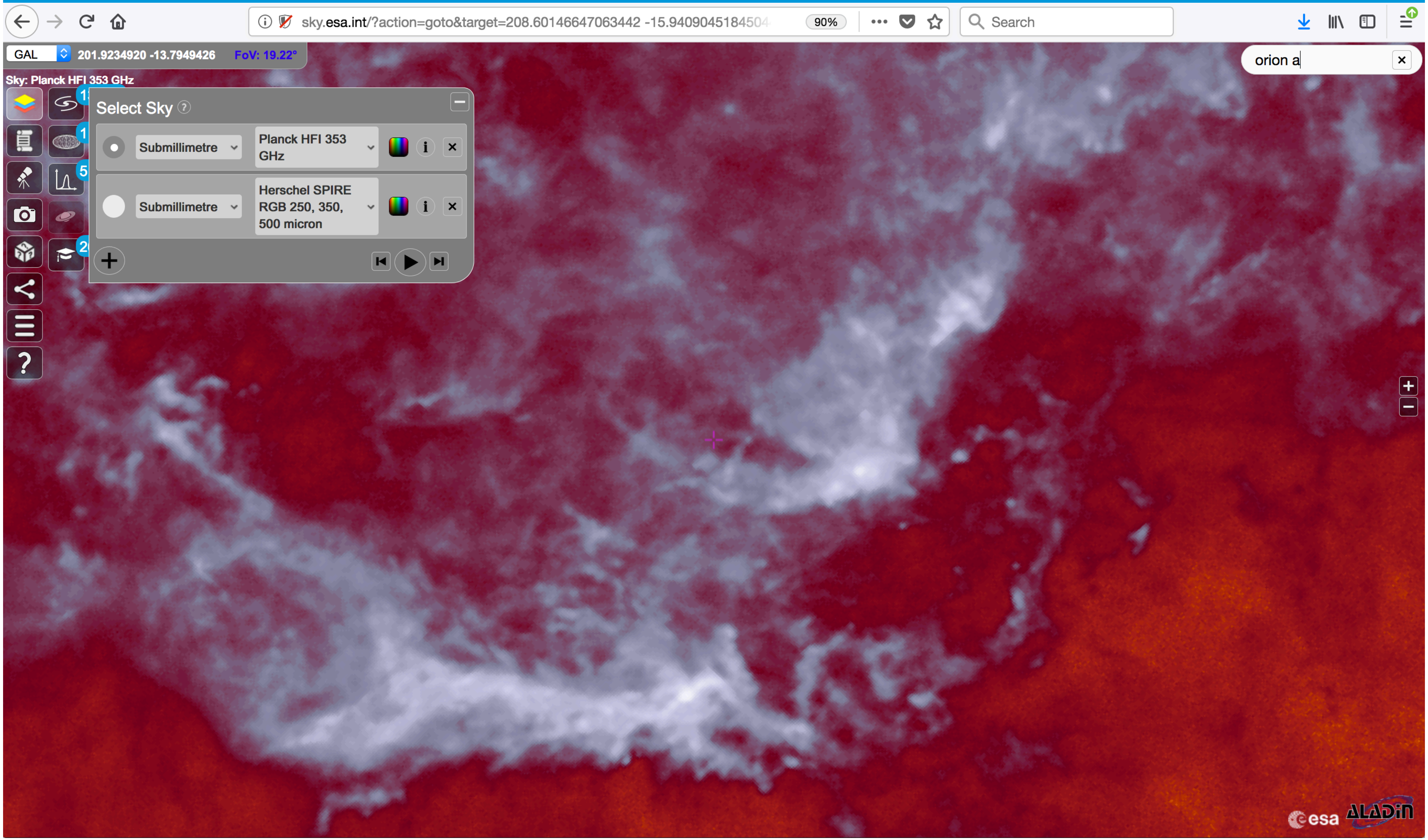

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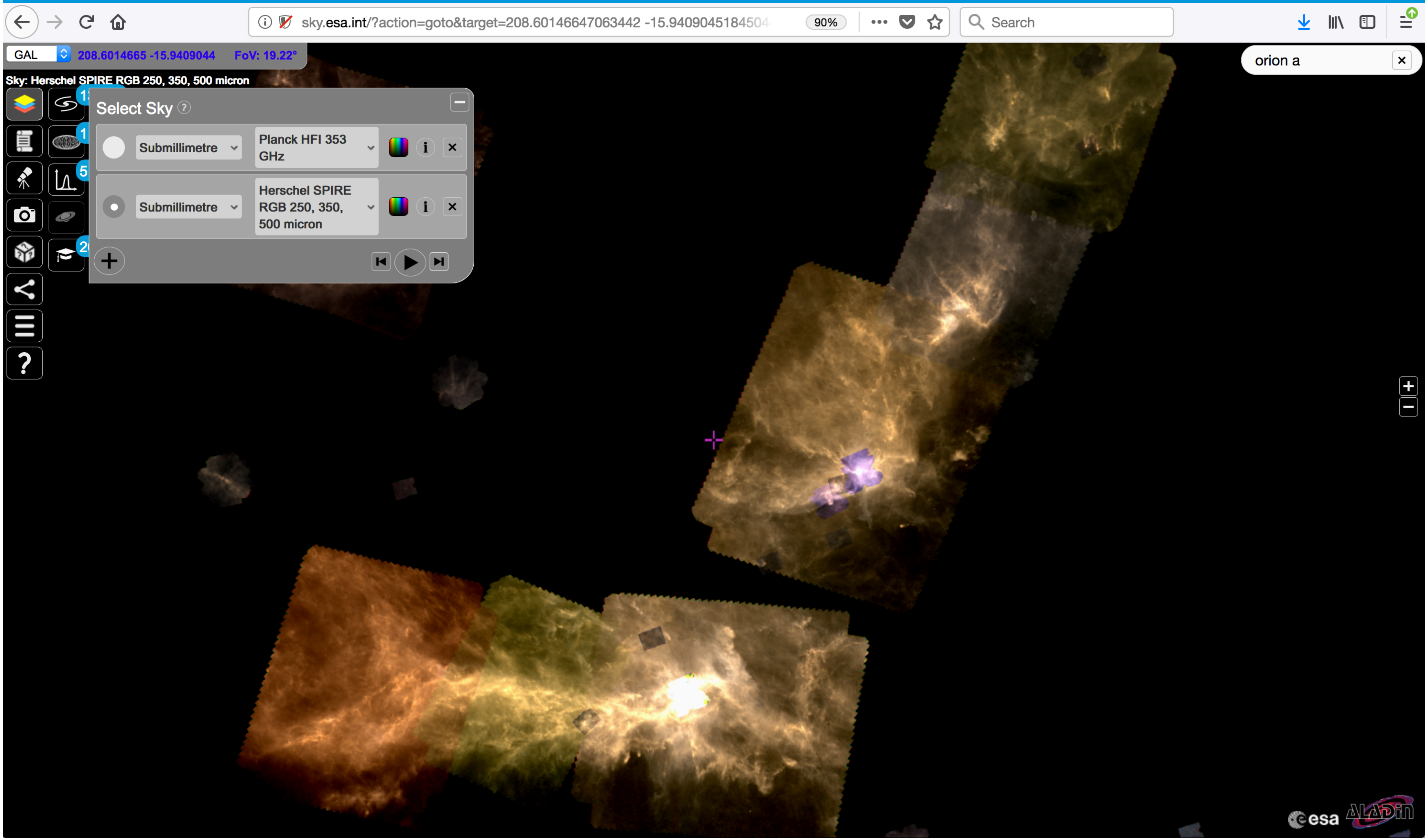

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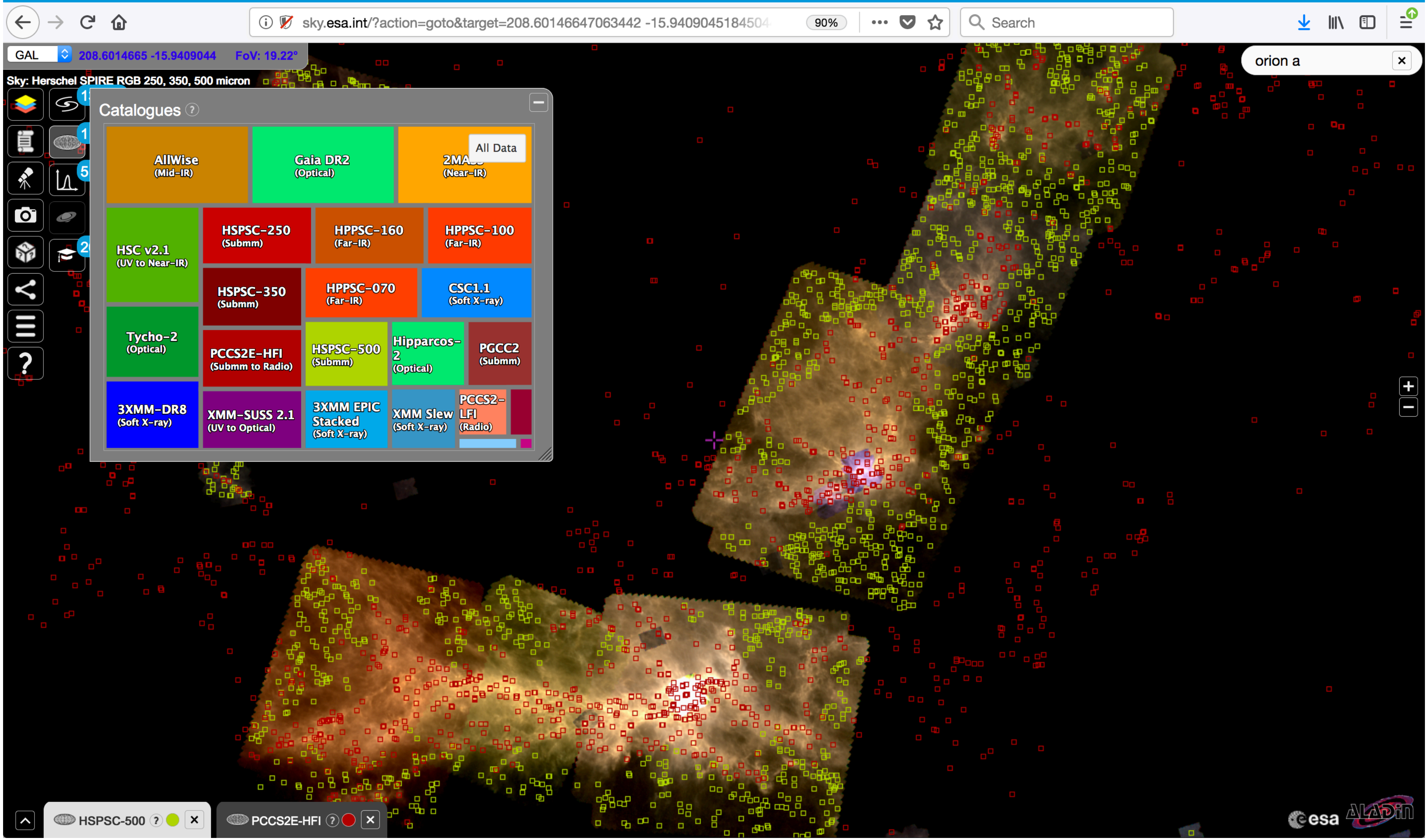

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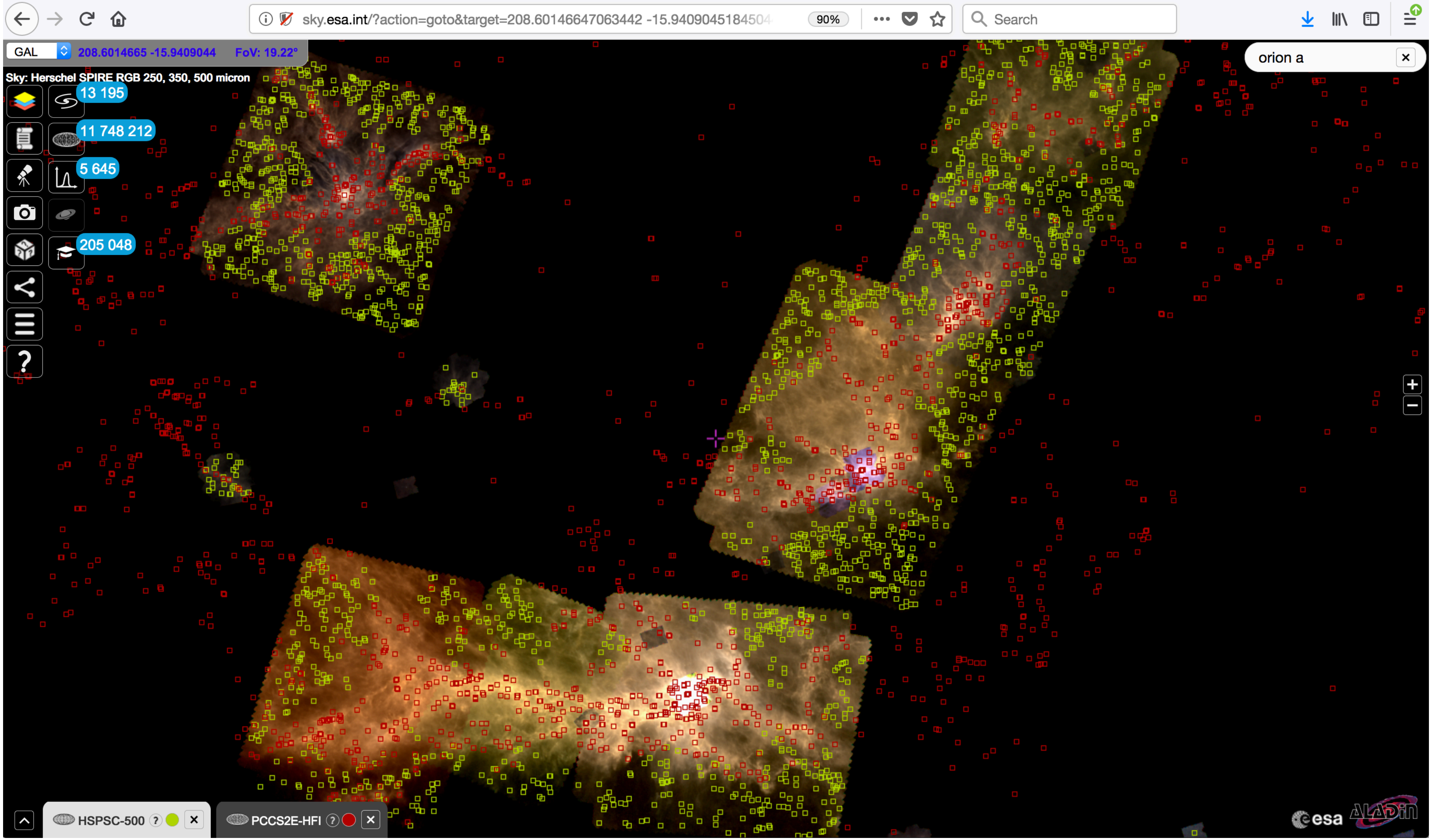
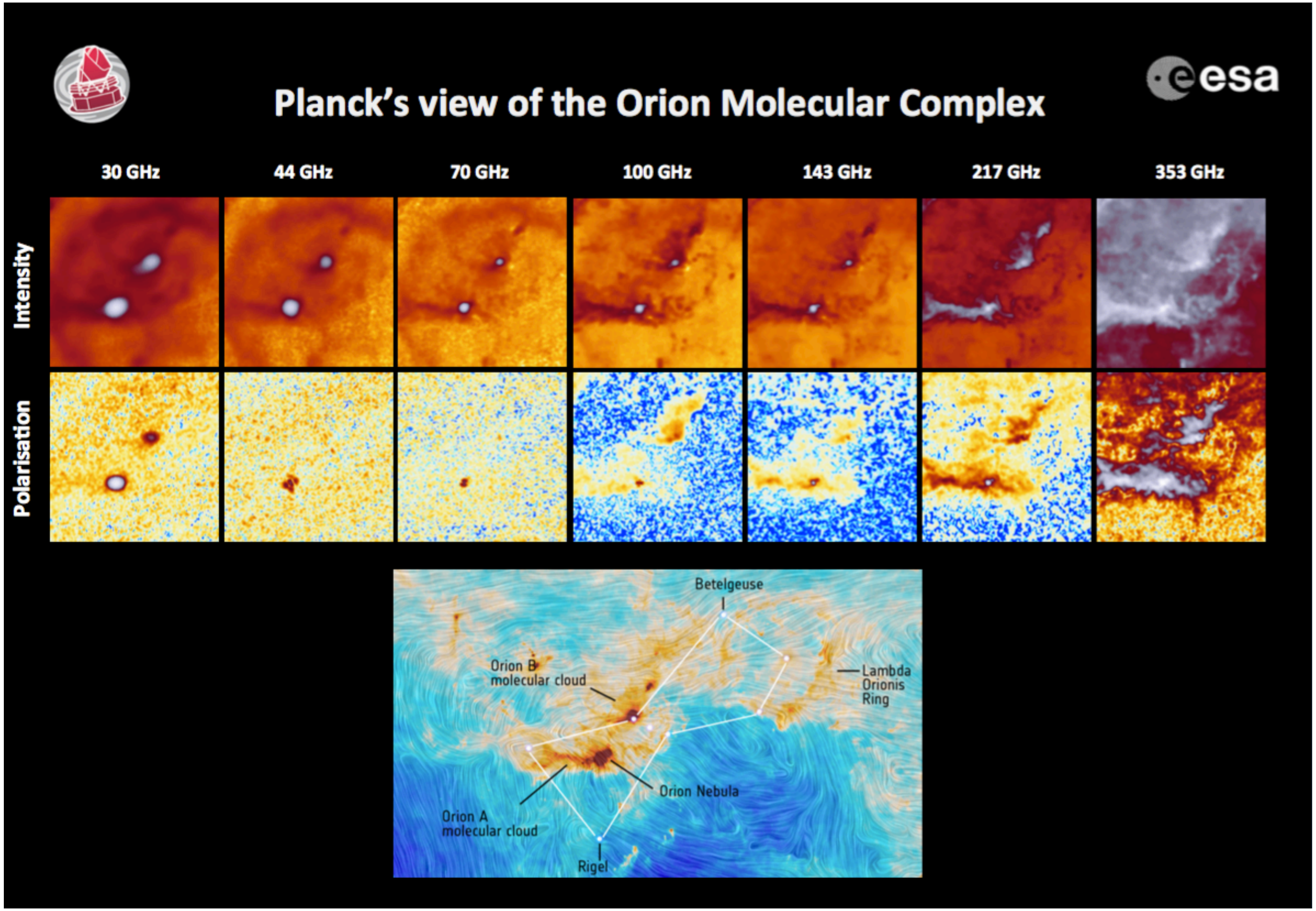


Detection on Planck: Polarization



Detection on Planck: Polarization

- "Detecting" and characterizing polarized sources in Planck was really hard, not many sources, low SNR, systematics, etc.

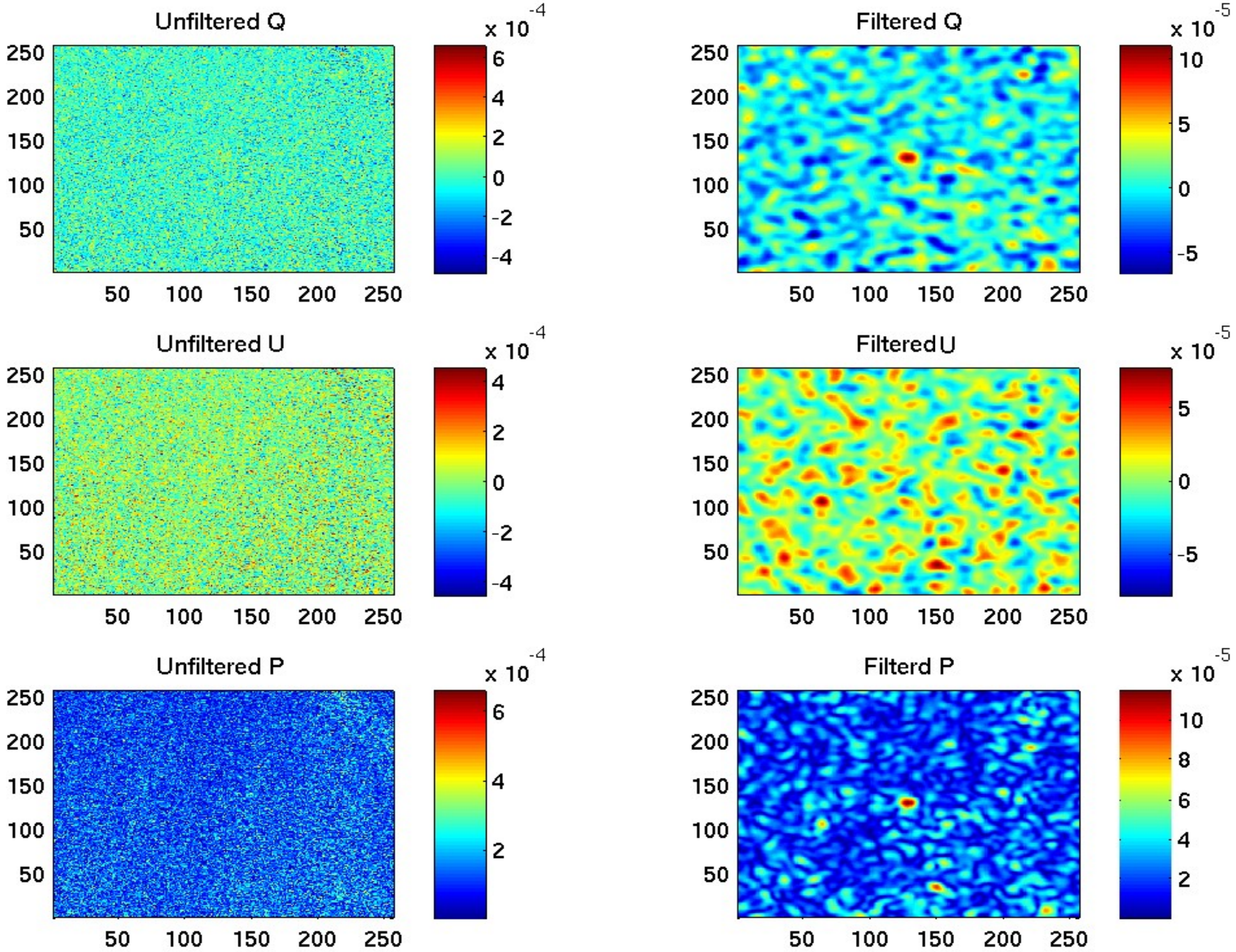
- To prepare for Planck we used simulations from the Planck Sky Model and the filtered fusion method from Argüeso et al. 2010 we built IFCAPOL. The trick here is applying MF's on the Q and U maps before building P, reducing the biases to a level below our own uncertainties in the flux density determination down to low flux densities

IFCAPol (Filtered Fusion) technique to assess the significance of the detection and estimate the flux density of sources embedded in early LFI polarization maps:

Source 2: Pictor A

The source is in the center of the patch and in many cases it is hardly visible in the unfiltered maps.

We have applied The FF technique to WMAP5yr maps and to Planck simulations and data maps, recovering unbiased fluxes down to 300 mJy for the 30 GHz case.



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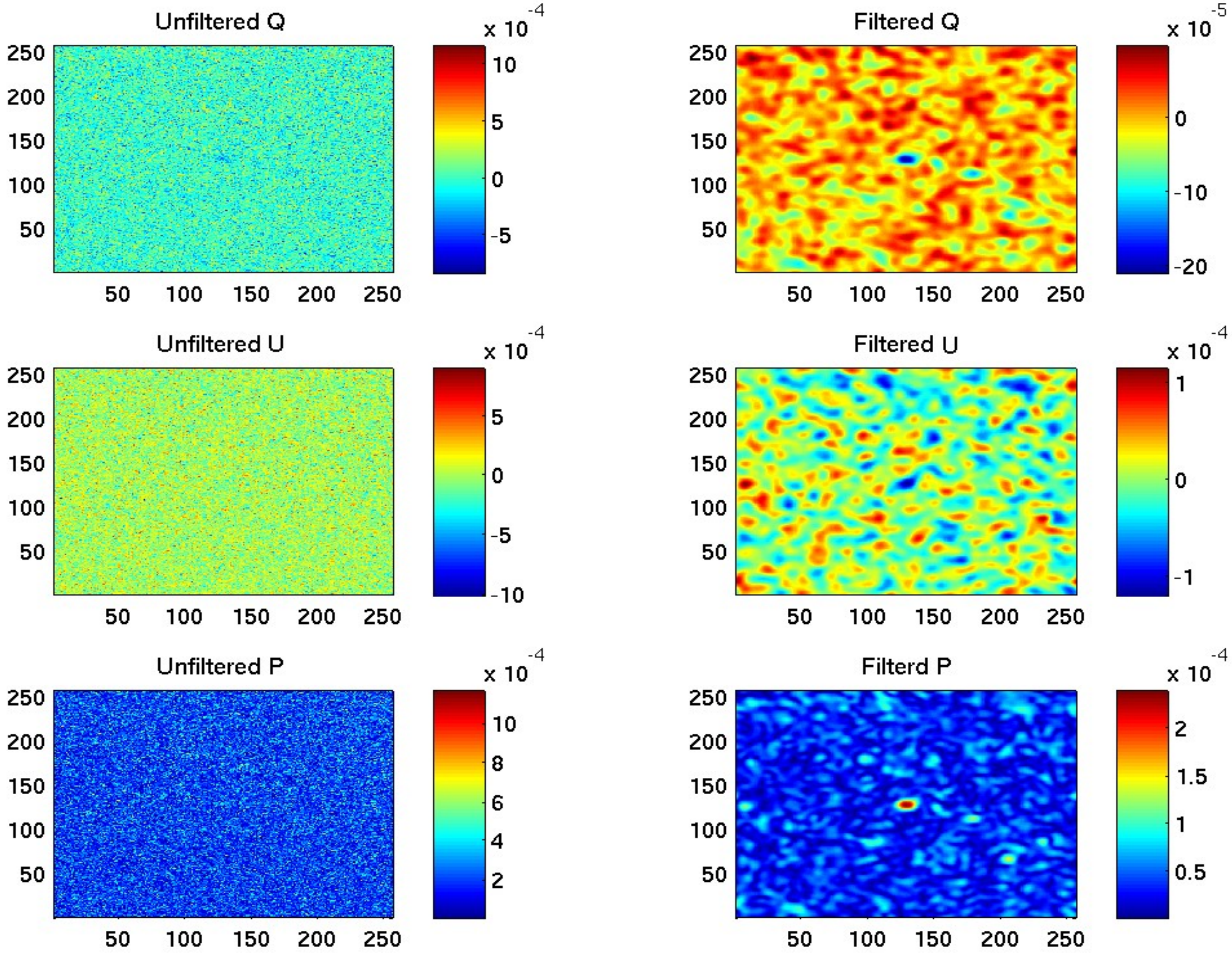
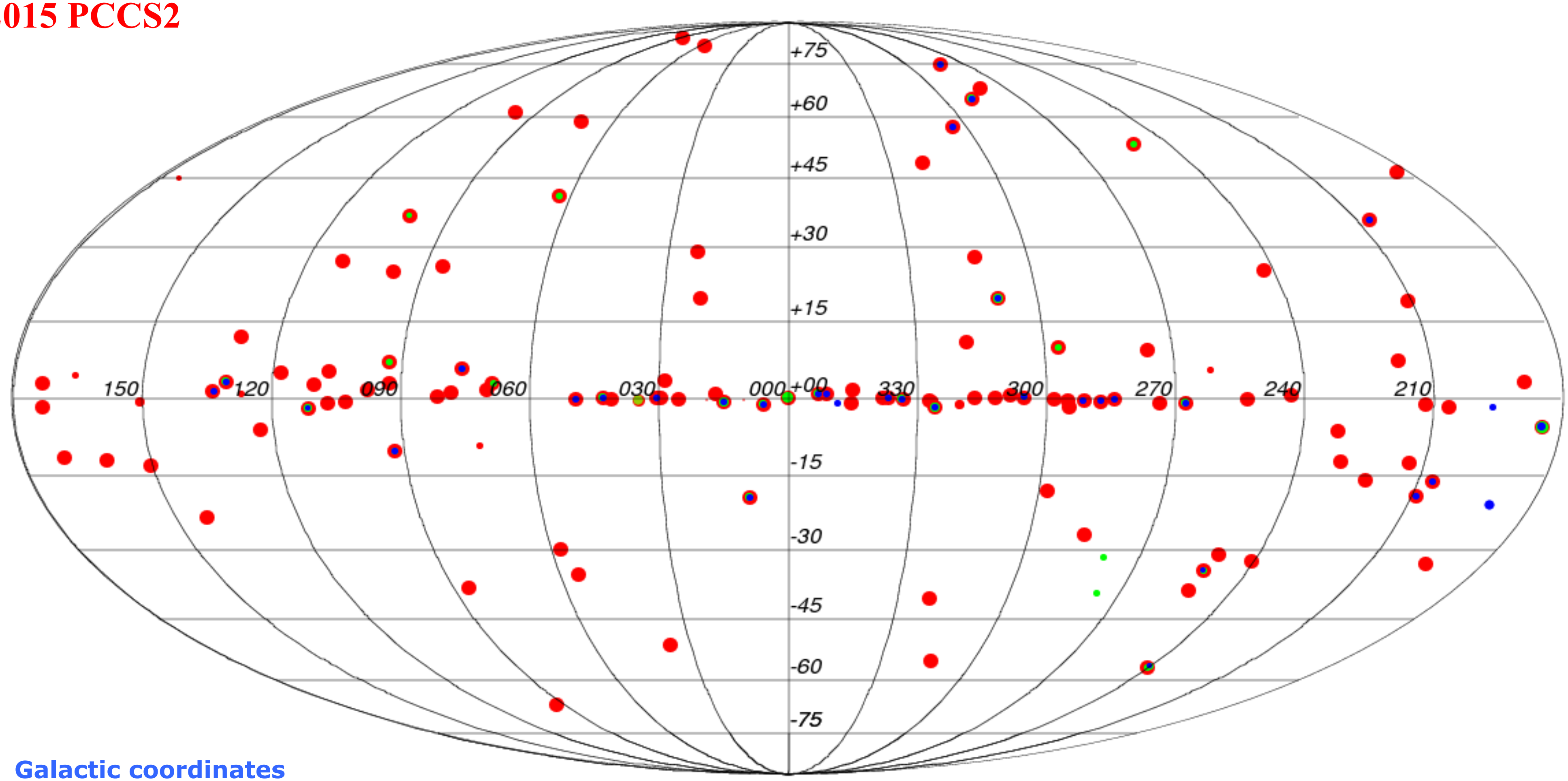


Detection on Planck: Non-blind analysis in Polarization

2015 PCCS2



Galactic coordinates
Mollweide projection

PCCS2 in Polarization 30, 44 and 70 GHz

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- This was very successfully applied to WMAP (L-C et al. 2009) and later to Planck PCCS2 an now to QUIJOTE data (see D. Herranz and J. González-Nuevo talks).

- In all cases it is a non-blind analysis at the positions of the sources detected in intensity, where we assess the significance level of the “detections” and stay above 99.90%.

- In Planck we also modified the Powelsnakes code turning off all the Bayesian machinery and keeping the MF part to have a second independent analysis.

Detection on Planck: Polarization

Summary Total Intensity

Channel	30	44	70	100	143	217	353	545	857
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Number of sources									
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PCCS[a]	1256	731	939	3850	5675	16070	13613	16933	24381

Summary Polarization

Channel	30	44	70	100	143	217	353
Number of significantly polarized sources in PCCS2	122	30	34	20	25	11	1
Minimum polarized flux density[a] [mJy]	117	181	284	138	148	166	453
Polarized flux density uncertainty [mJy]	46	88	91	30	26	30	81
Minimum polarized flux density completeness 90% [mJy]	199	412	397	135	100	136	347
Minimum polarized flux density completeness 95% [mJy]	251	468	454	160	111	153	399
Minimum polarized flux density completeness 100% [mJy]	600	700	700	250	147	257	426
Number of significantly polarized sources in PCCS2E	...	...	...	43	111	325	666
Minimum polarized flux density[a] [mJy]	...	...	...	121	87	114	348
Polarized flux density uncertainty [mJy]	...	...	...	52	44	55	178
Minimum polarized flux density completeness 90% [mJy]	...	...	...	410	613	270	567
Minimum polarized flux density completeness 95% [mJy]	...	...	...	599	893	464	590
Minimum polarized flux density completeness 100% [mJy]	...	...	...	835	893	786	958

Characterization

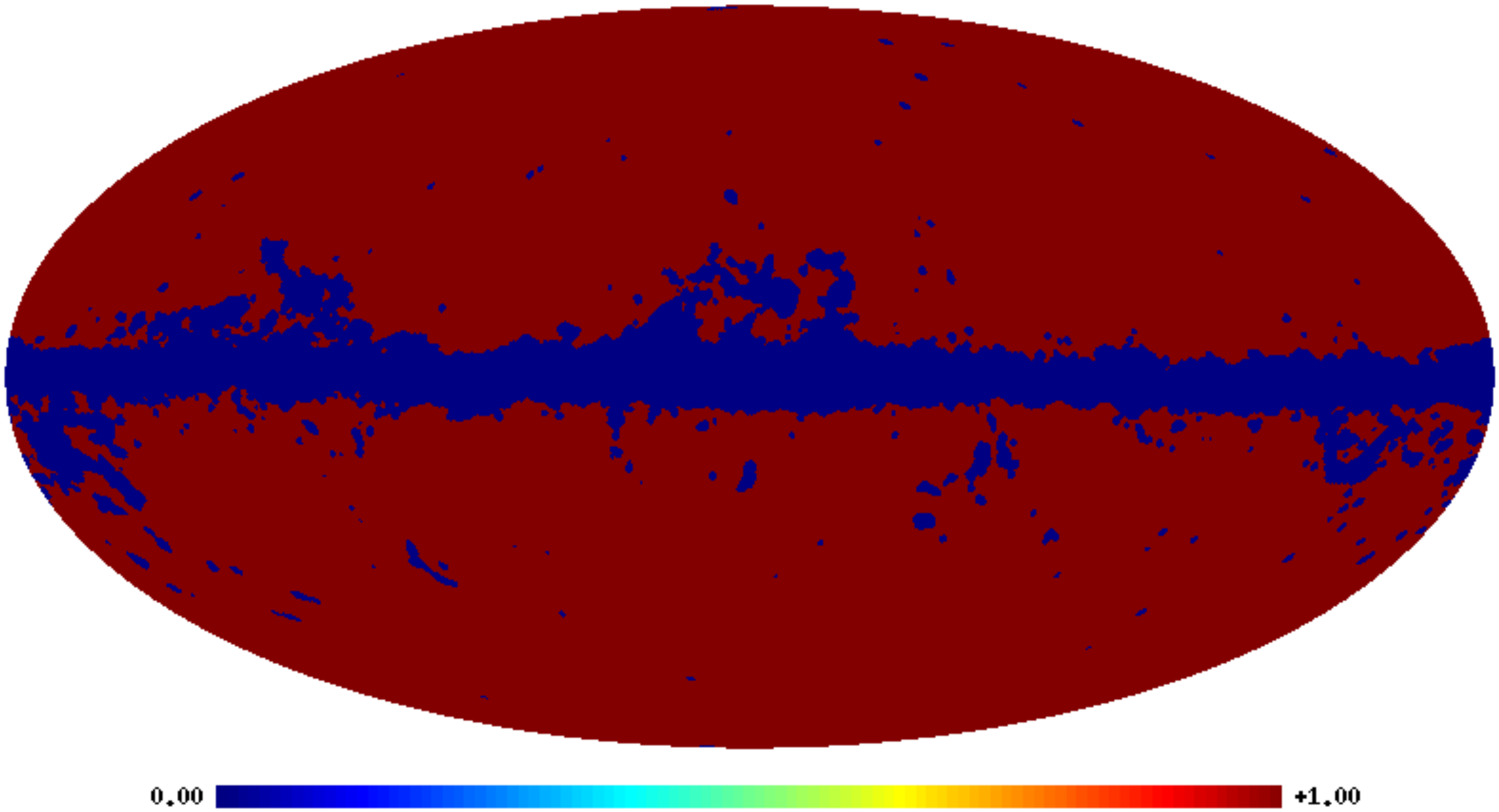
- However, it also common to skip the pre-processing step and perform the characterization of the source, when the position is known, with the most appropriate tool or tools.

- In Planck we see several types of populations of extragalactic radio and infrared galaxies, galactic compact regions, SZ clusters and lots of small scale galactic emission at higher frequencies that looks like a compact source, specially after you filter it with a circularly symmetric filter.

- For example, in the Planck Catalogue of Compact Sources, both the nominal mission PCCS and the full mission PCCS2, one detection method and four different photometries where used in intensity:

    - DETFLUX (MHW2 photometry) coming from the filtered maps
    - APERTURE PHOTOMETRY
    - 2D ELLIPTICAL GAUSSIAN FITTING
    - EFFECTIVE BEAM FITTING

Impact of PS in the CMB angular power spectrum



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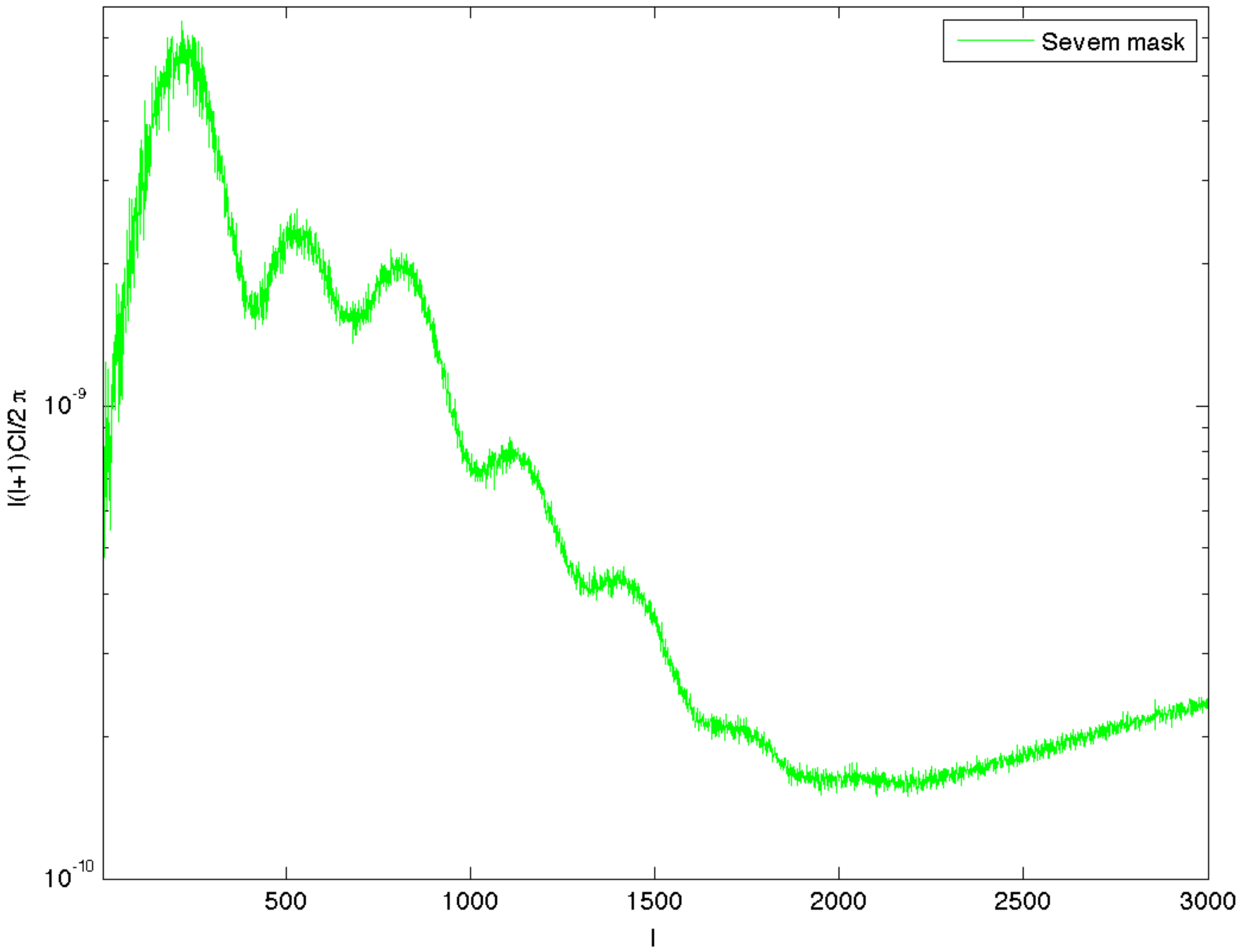

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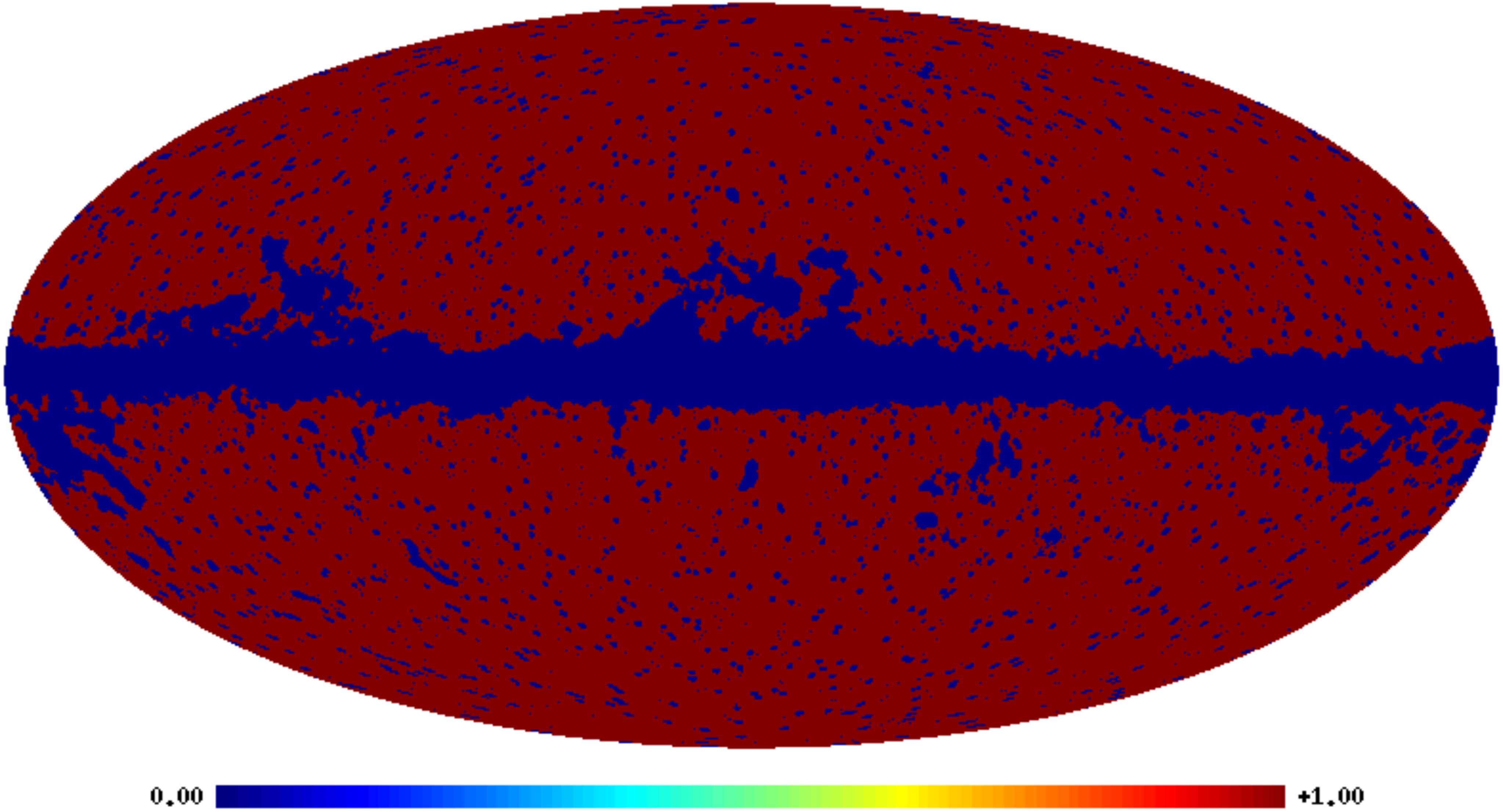

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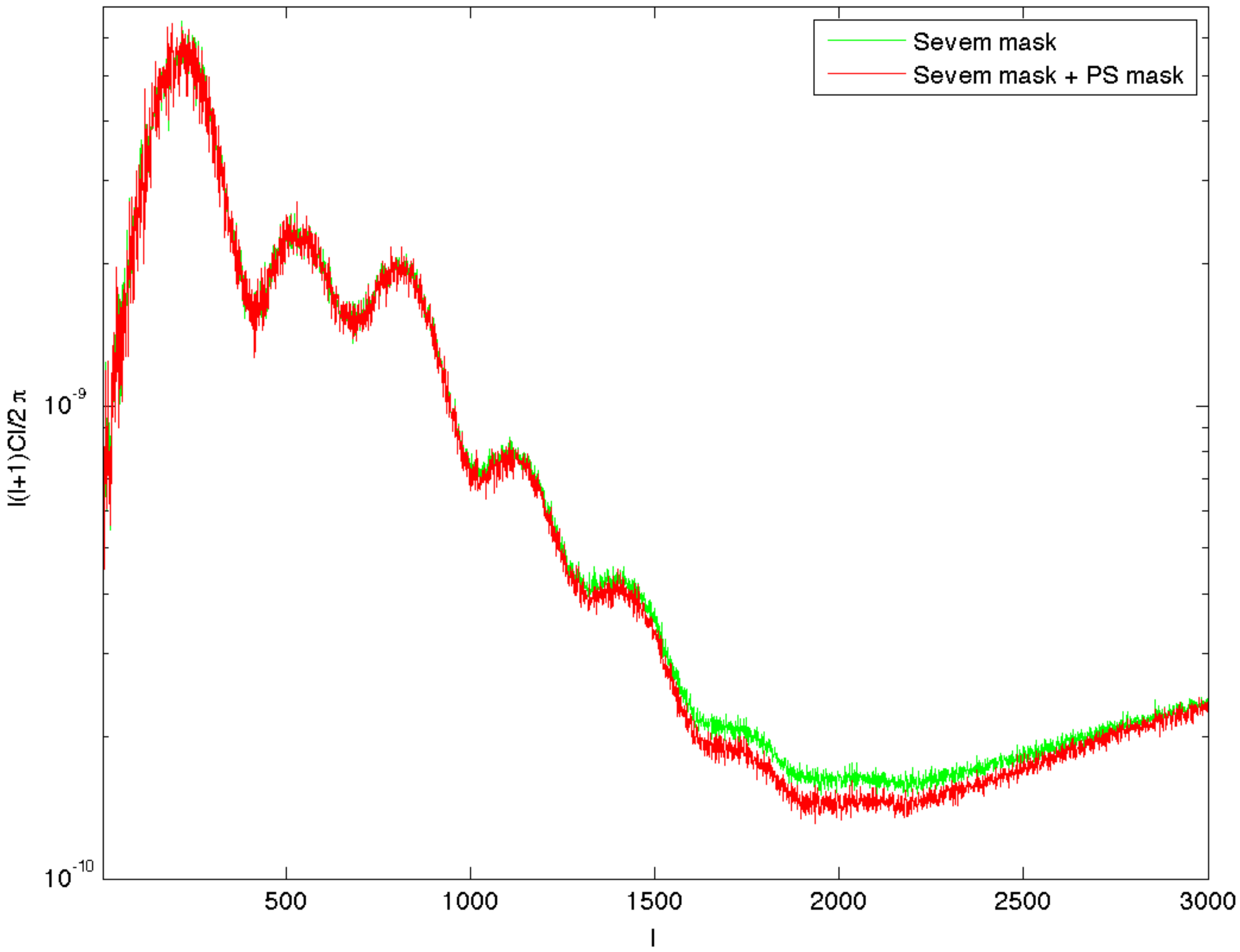

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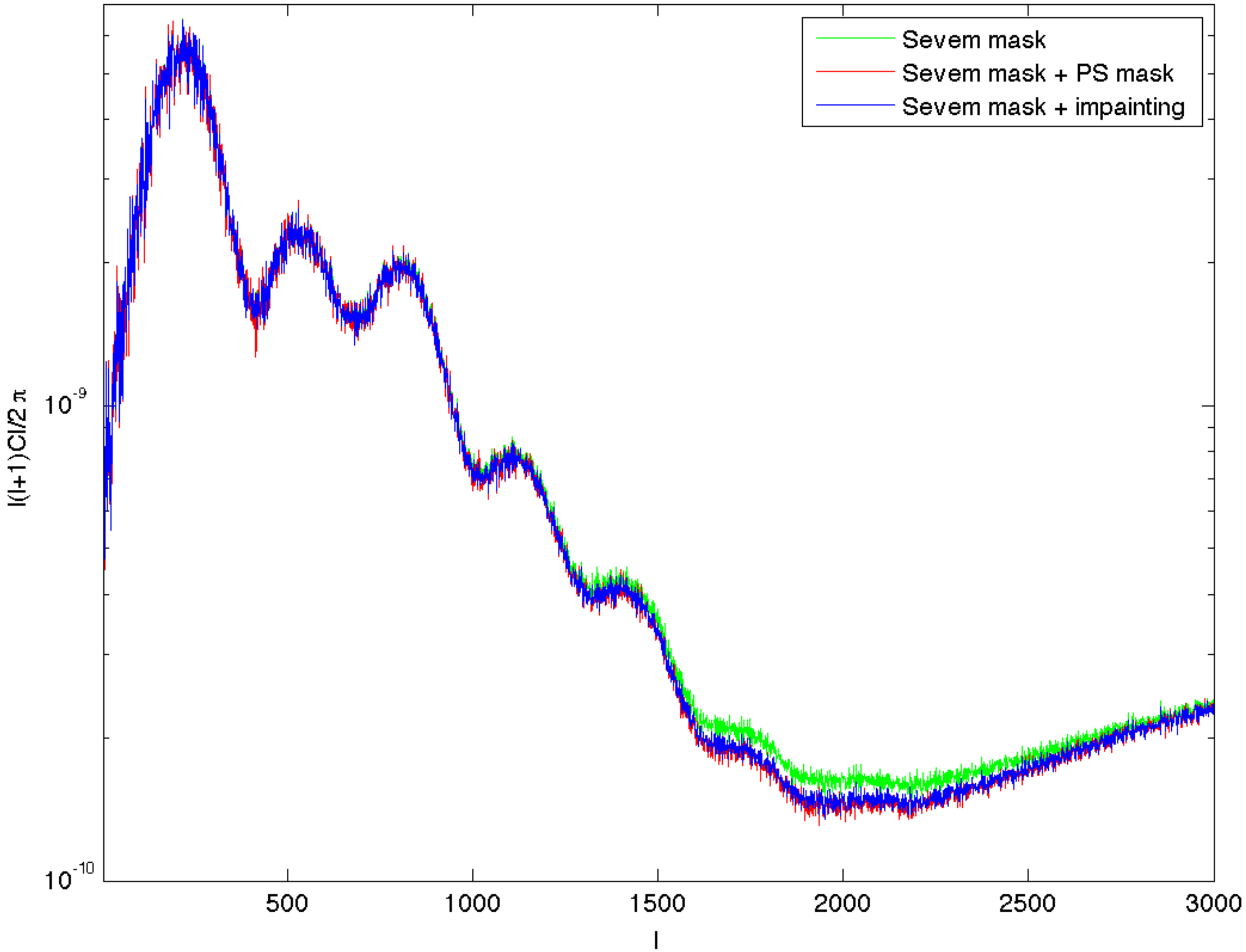
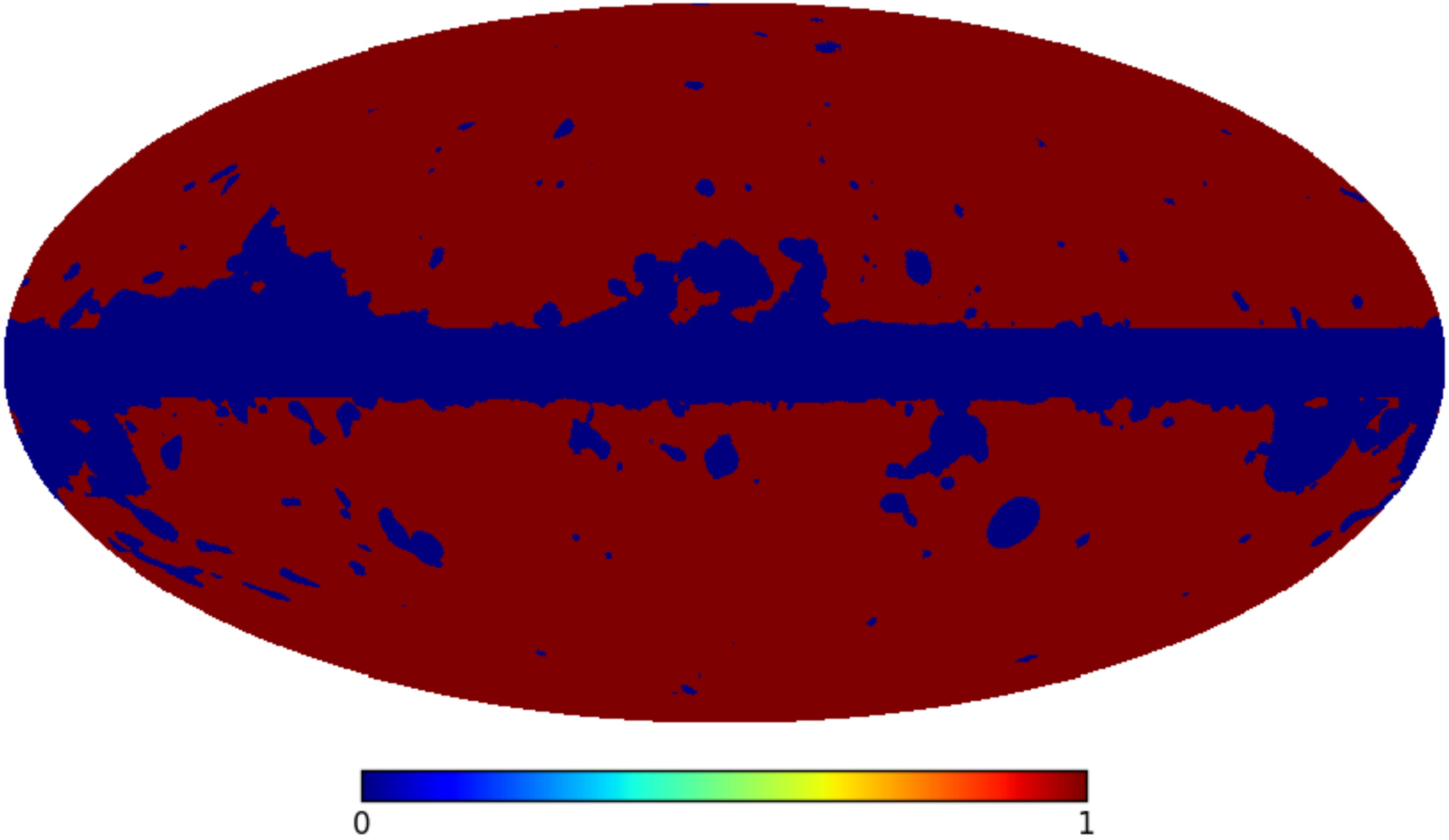


Impact of PS on higher order moments used in NG



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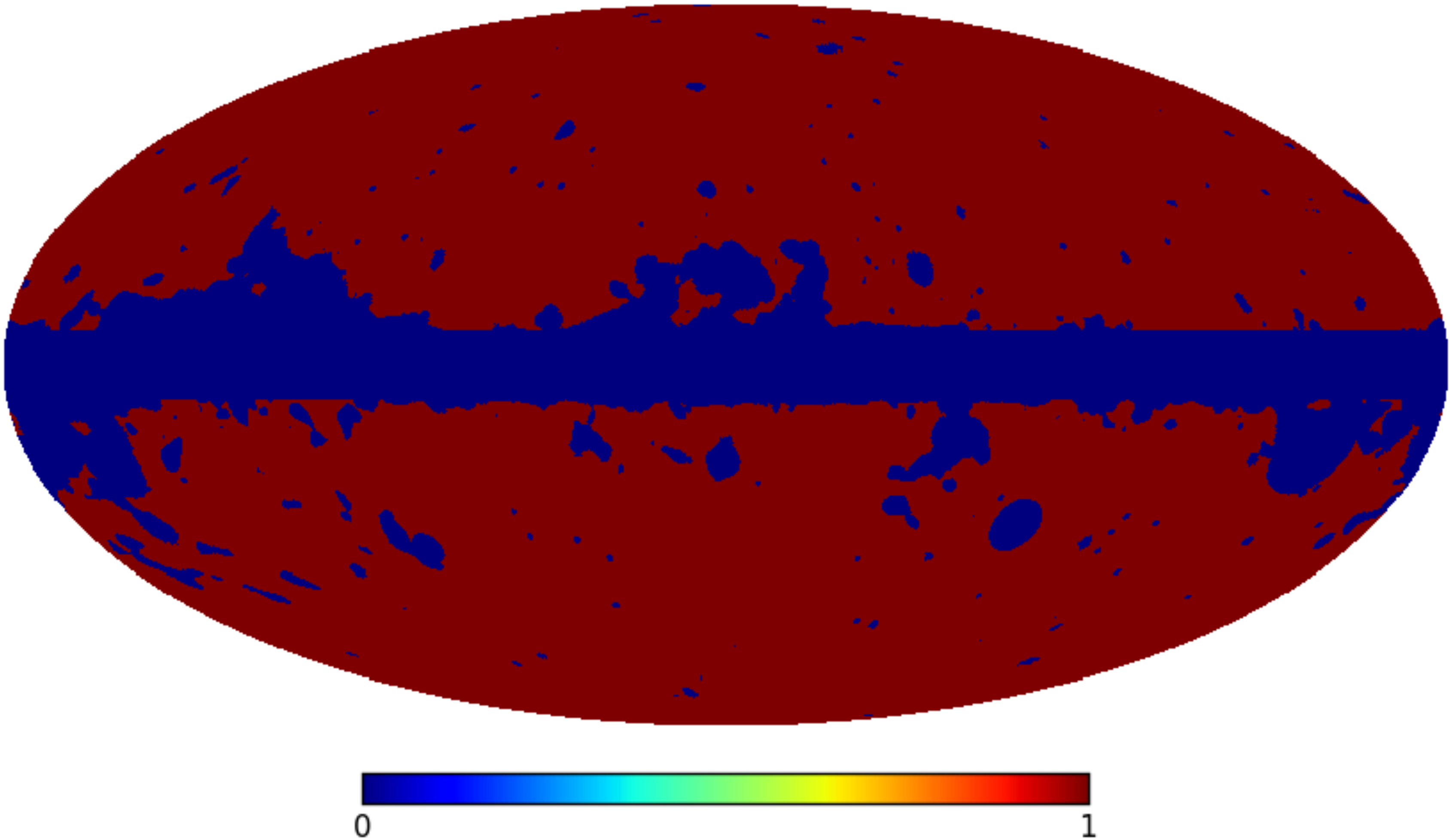

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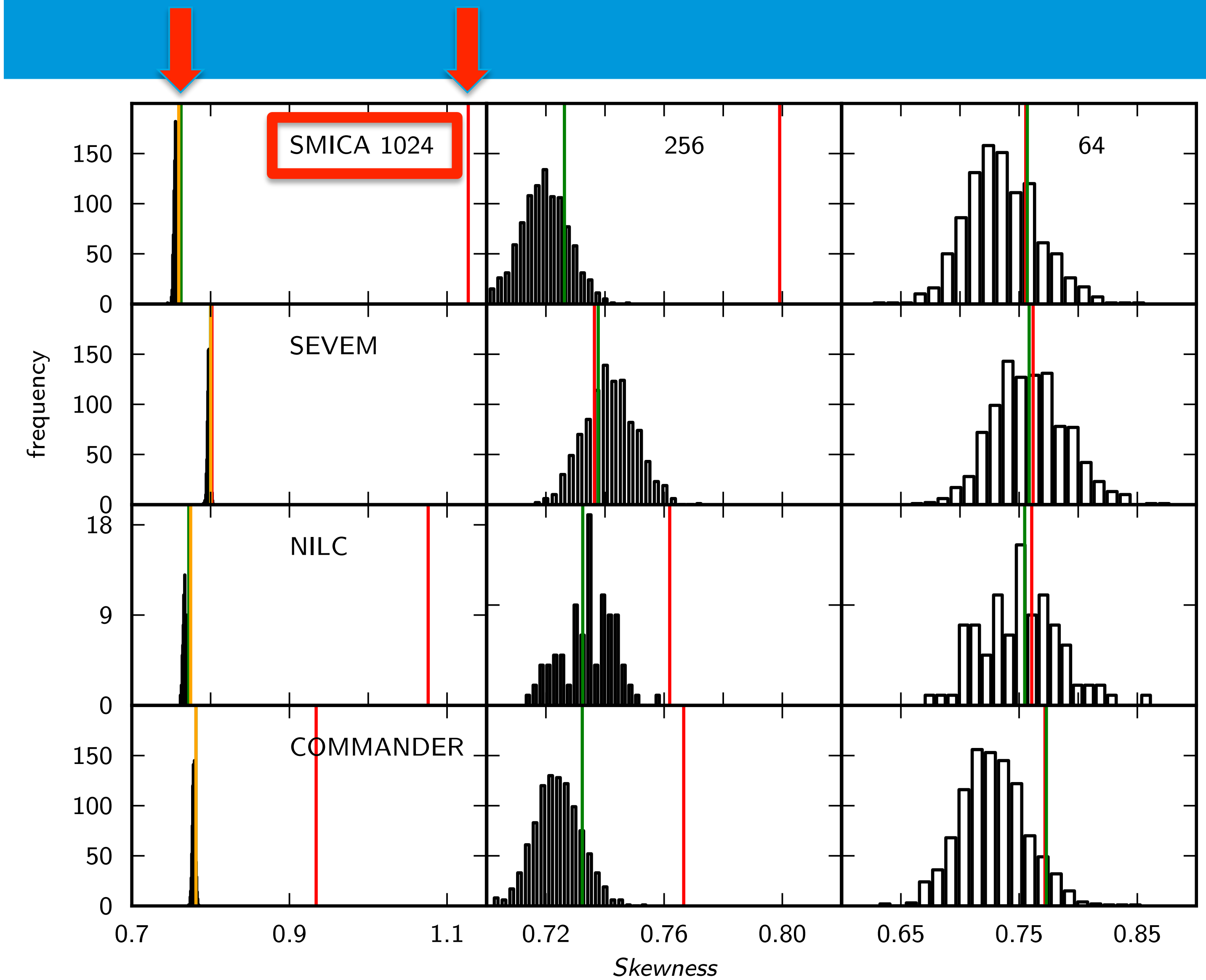


Planck 2015 Component Separation

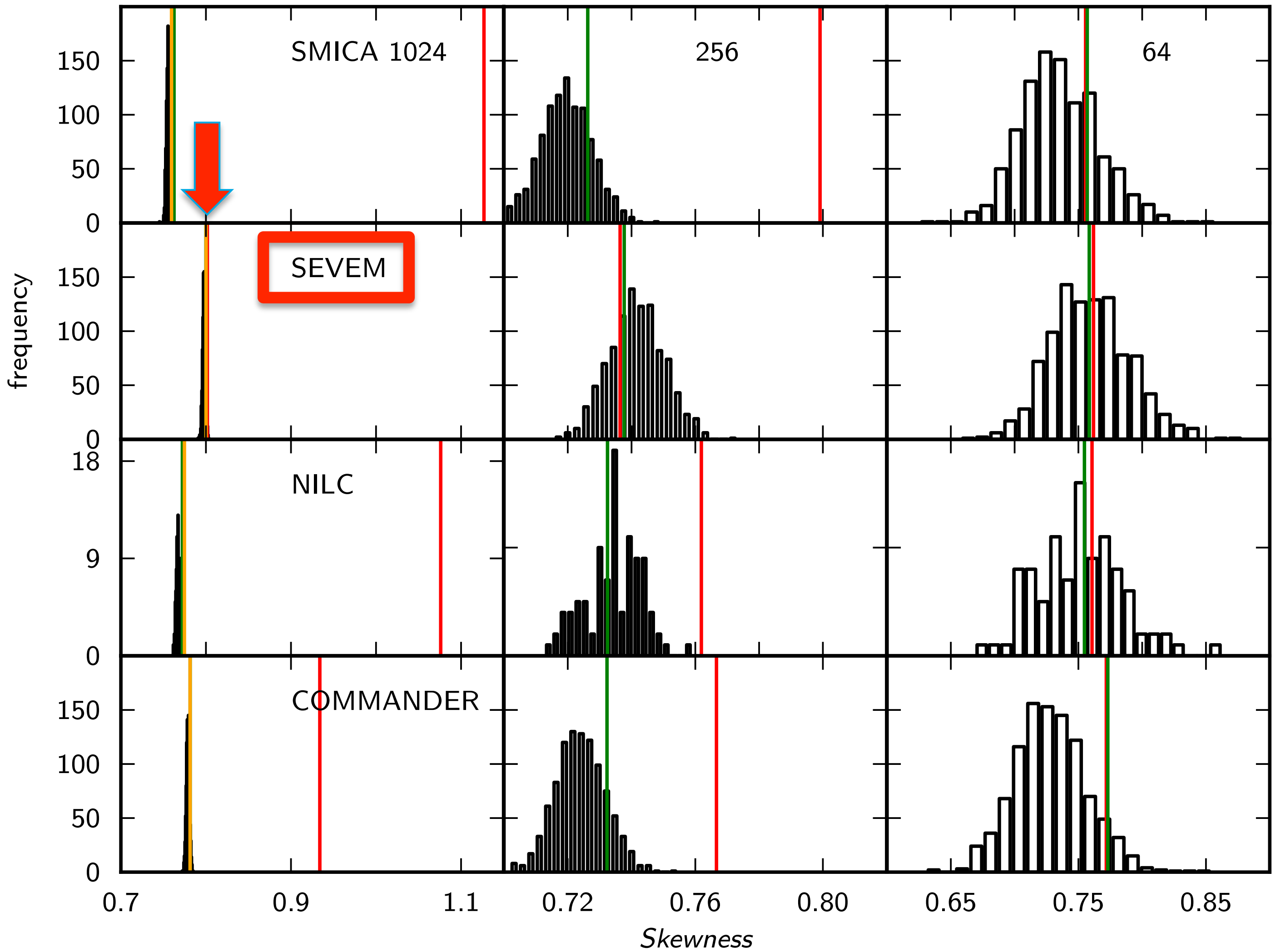
Polarised intensity skewness evaluated from Planck simulations (histograms) and the fiducial map at Nside 1024, 256 and 64 outside the mask.

Coloured vertical lines correspond to:

- Before using Pol PS
- Masking Pol PS

D. Molinari
Planck Component Separation WG

Impact of PS on higher order moments used in NG



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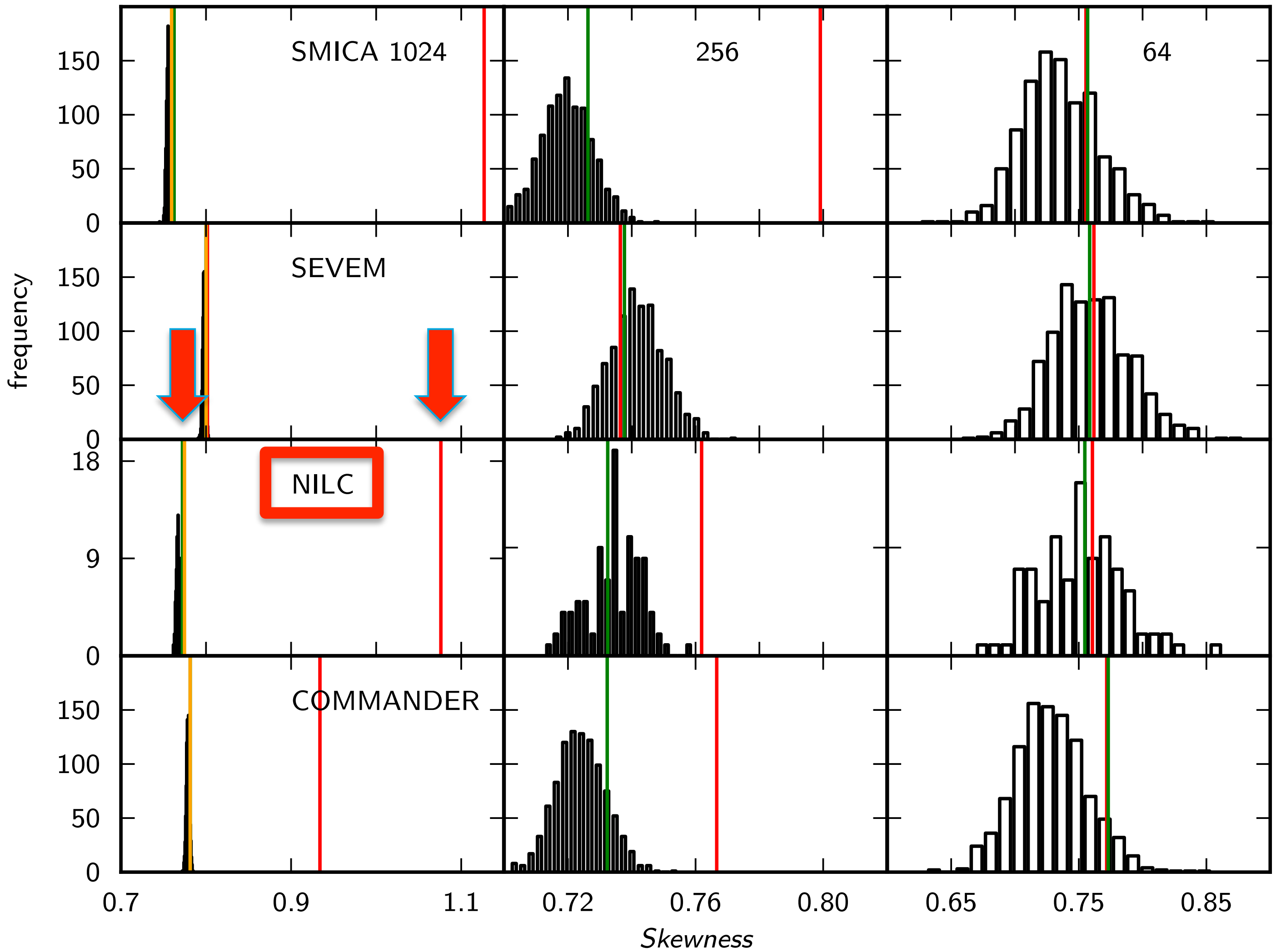

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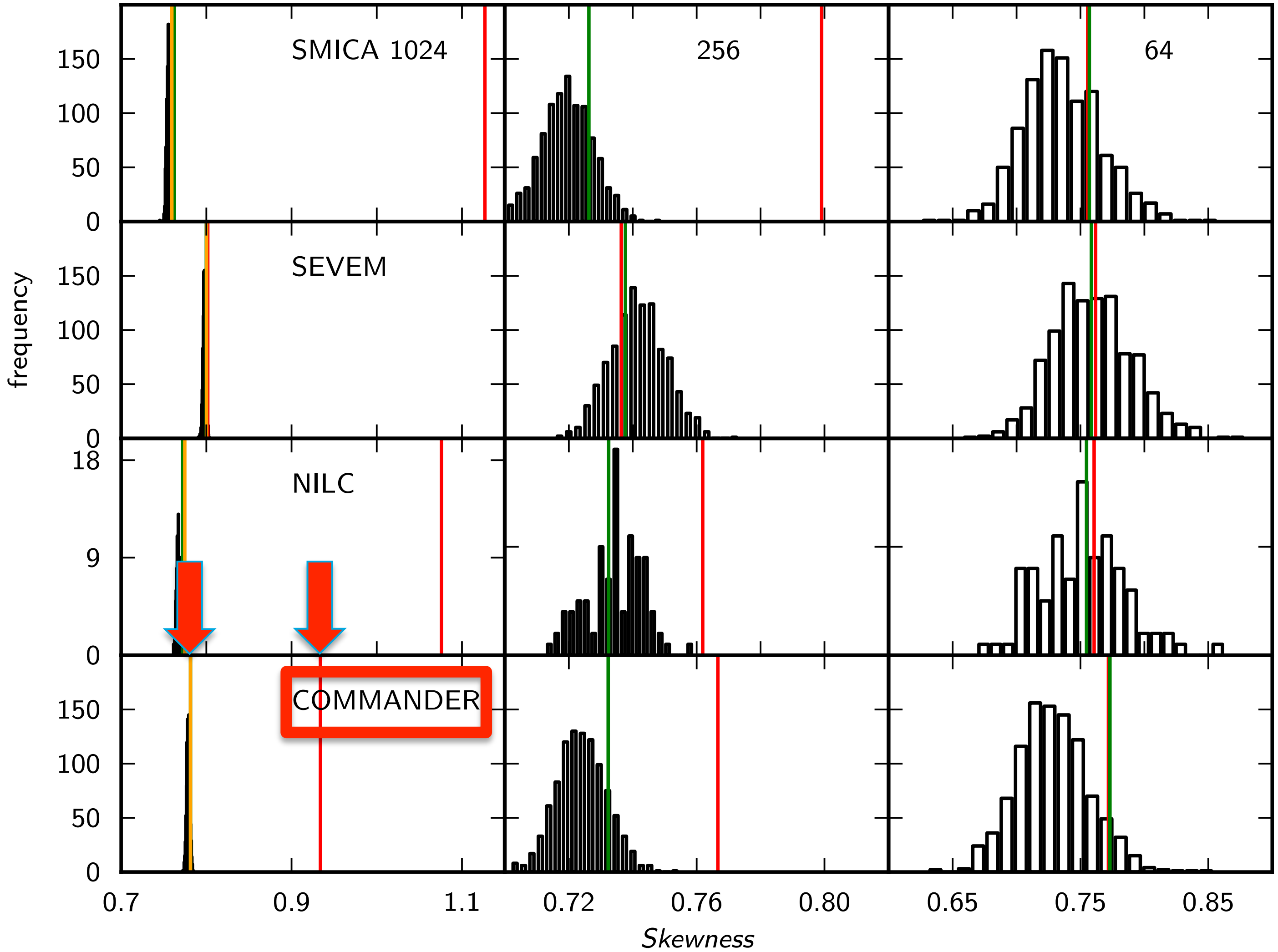
Impact of PS on higher order moments used in NG



Planck 2015 Component Separation

Polarised intensity skewness evaluated from Planck simulations (histograms) and the fiducial map at Nside 1024, 256 and 64 outside the mask.

Coloured vertical lines correspond to:

- Before using Pol PS
- Masking Pol PS

D. Molinari
Planck Component Separation WG

CMB separation: joint Diffuse and Compact analysis

SEVEM 2018

Iterative SEVEM template fitting + MHW2 PS detection and masking

Map	30 GHz	44 GHz	70 GHz	100 GHz	143 GHz	217 GHz	353 GHz	545 GHz	857 GHz
Raw									
T (full-sky)	1593	923	1307	2162	3479	4955	5794	8145	11876
T ($\|b\| > 20°$)	977	470	648	809	1093	1289	1588	2898	6117
P (full-sky)	195	64	74	237	349	632	1075		
P ($\|b\| > 20°$)	65	19	15	56	63	87	134		
Cleaned									
T (full-sky)	...	...	420	1475	2117	3675	...	...	...
T ($\|b\| > 20°$)	...	...	37	93	230	553	...	...	...
P (full-sky)	...	...	10	48	73	199	...	...	...
P ($\|b\| > 20°$)	...	...	1	1	4	16	...	...	...

COMMANDER 2018

Starting from a long list of sources compiled at low frequency, source by source fit the Planck effective beam at that frequency at the position in the sky to the data. If the low frequency source is not visible anymore, this results in a bad fit, if there is something there, this results in a fit with it associated uncertainties in the fitted parameters.

Conclusions

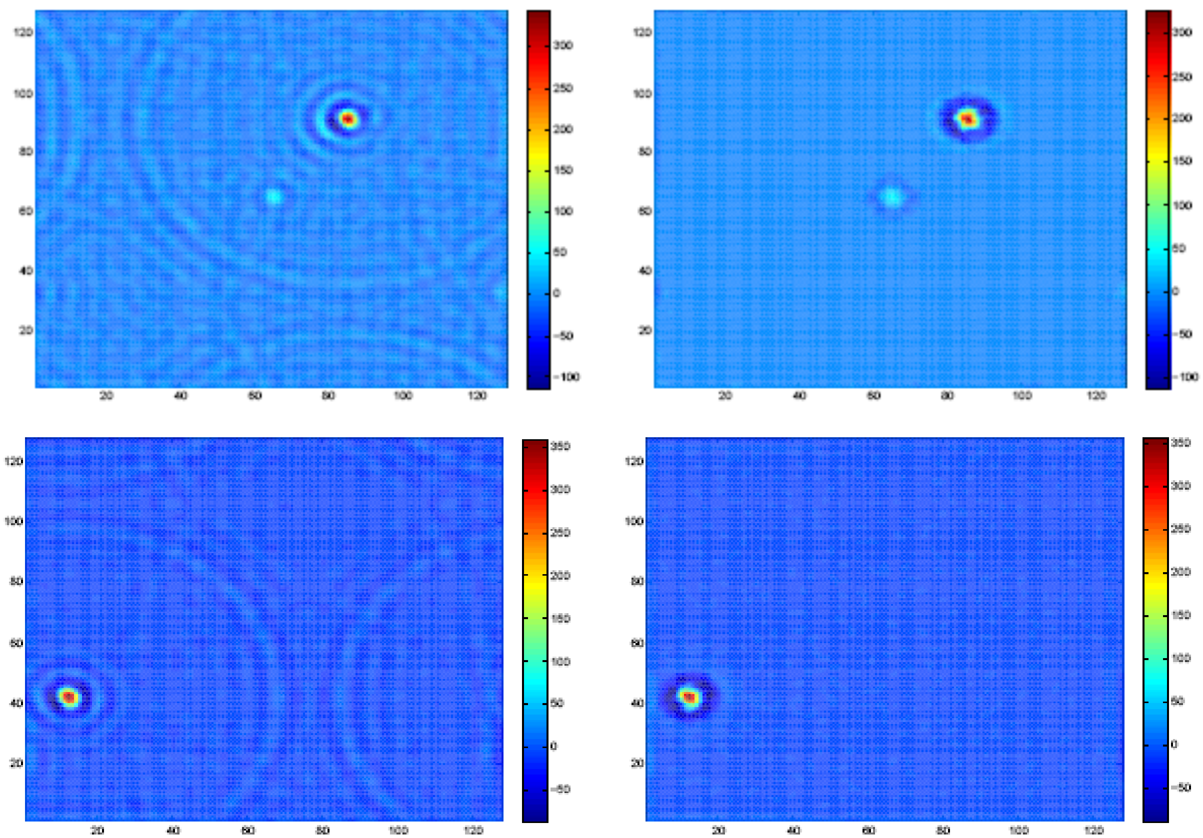
- **The compact sources are a very important source of contamination in CMB analyses and their detection and proper characterization in intensity and polarization is necessary.**
- **These analyses allow us to minimize the residual PS contamination in the CMB map reconstruction, reduce its impact in CMB angular power spectrum, reduce the uncertainties in the determination of cosmological parameters and in NG analyses.**
- **Residual compact source emission is the only foreground at the level of the lensing B-modes, and uncertainties in the level of compact source residual can impact delensing of primordial B-modes.**
- **The times of simple detection techniques are now gone. For the next generation of experiments we need to use all the artillery available: multifrequency information, Bayesian techniques, joint diffuse and compact foreground separation, and any othertool that allow us to understand the objects we are looking, like ESASky.**
- **As a by product, these catalogues are used for compact source science.**

Filters: Matched Filter vs. MHW2

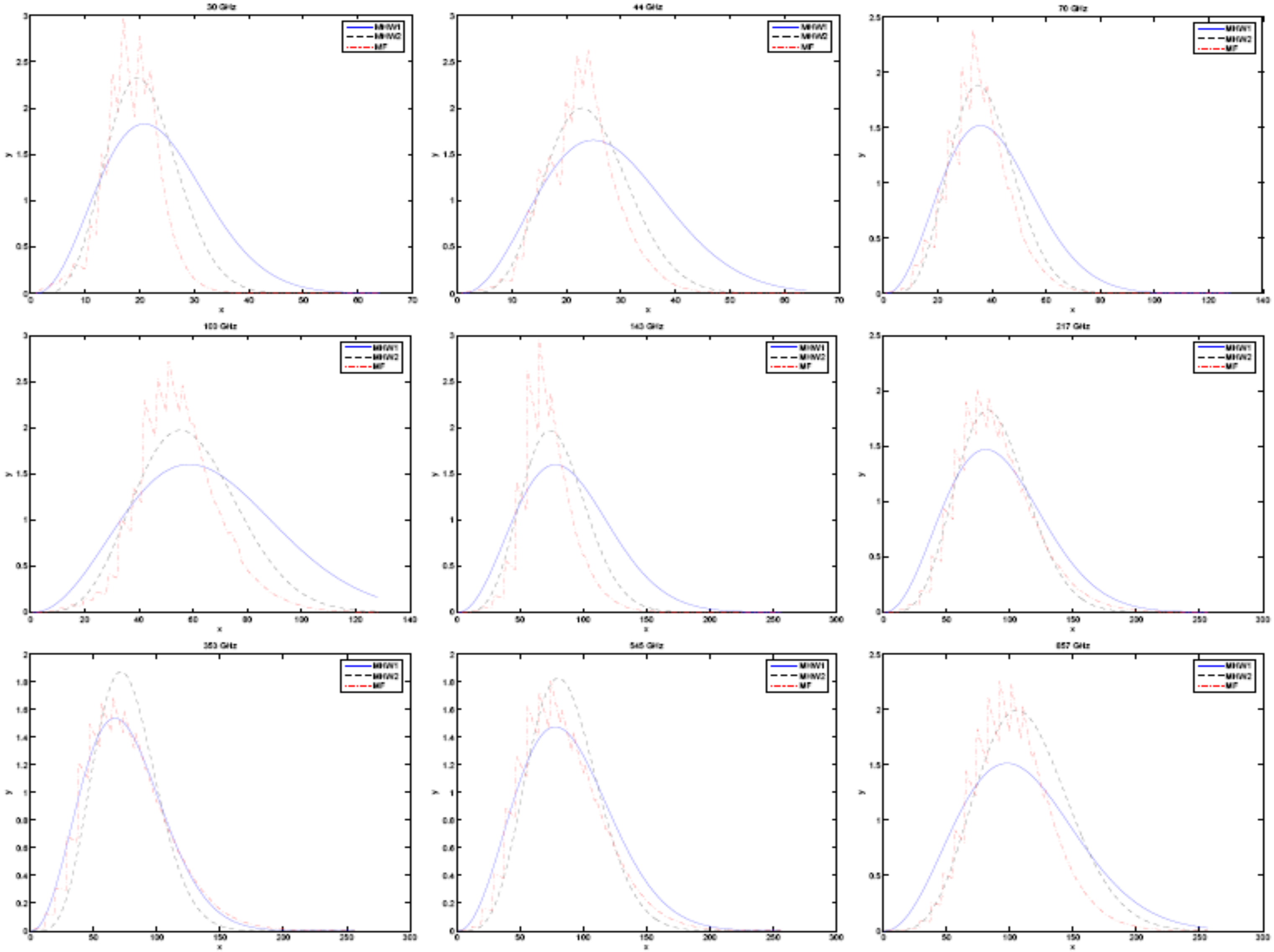
esa

- Theoretically the matched filter is optimal (among the class of linear filters) in the sense of signal-to-noise ratio amplification
- In practice, implementation issues could degrade the performance and some precautions need to be taken into account

MF MHW2



Filters: Comparison of the MHW1 and MHW2 with the MF



Filters: Comparison of the MHW1 and MHW2 with the MF