BAYESIAN END-TO-END CMB ANALYSIS FROM LFI TO HFI

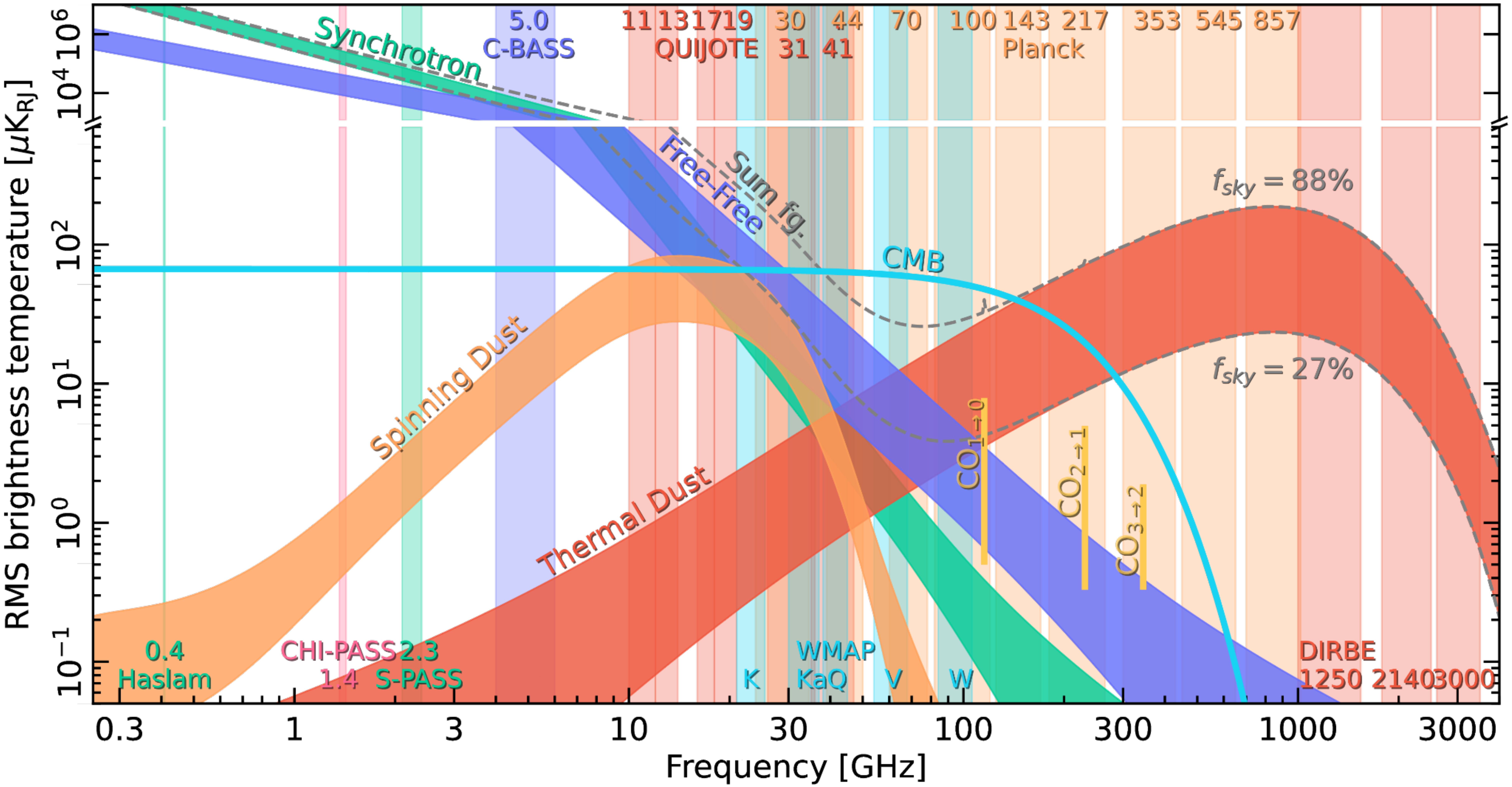
Artem Basyrov, PhD student
Institute of Theoretical Astrophysics, University of Oslo

COLLABORATION

- BeyondPlanck
- Cosmoglobe
- LiteBIRD

IDEA

- Joint analysis of several data sets together to avoid ‘blind spots’ (scanning strategies) and degeneracies (component separation)
- Integrated approach from the properties of the instrument to the sky model (and from the sky model to the instrument uncertainties)
- More technically: creating a modular algorithm suitable to be used for any future experiments
- More technically: a hands free pipeline from the TOD level to the maps and cosmological parameters without preprocessing and human intervention in-between



THE SKY MODEL

Different experiments augment each other

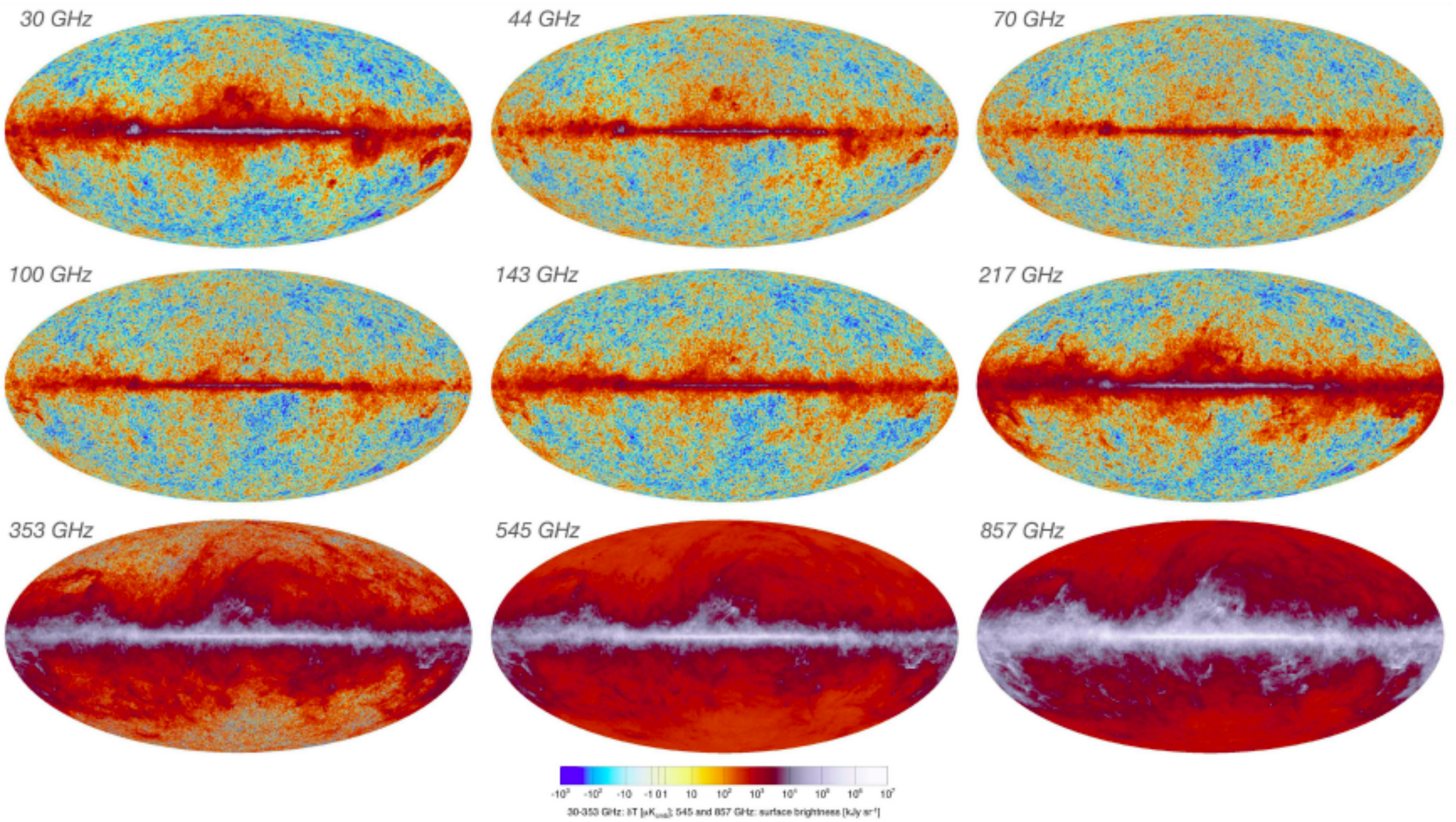
*BeyondPlanck sky model

THE SKY MODEL*

$$
\begin{aligned}
s = {} & a_{\mathrm{CMB}} \frac{x^2 e^x}{(e^x - 1)^2} \qquad x = h\nu / kT_0 \\
& + a_{\mathrm{s}} \left(\frac{\nu}{\nu_{0,\mathrm{s}}} \right)^{\beta_{\mathrm{s}}} \\
& + a_{\mathrm{ff}} \left(\frac{\nu}{\nu_{0,\mathrm{ff}}} \right)^{-2} \frac{g_{\mathrm{ff}}(\nu; T_{\mathrm{e}})}{g_{\mathrm{ff}}(\nu_{0,\mathrm{ff}}; T_{\mathrm{e}})} \\
& + a_{\mathrm{ame}} \left(\frac{\nu}{\nu_{0,\mathrm{ame}}} \right)^{-2} \frac{f_{\mathrm{ame}}\left(\nu \cdot \frac{30\mathrm{GHz}}{\nu_{\mathrm{p}}}\right)}{f_{\mathrm{ame}}\left(\nu_{0,\mathrm{ame}} \cdot \frac{30\mathrm{GHz}}{\nu_{\mathrm{p}}}\right)} \\
& + a_{\mathrm{d}} \left(\frac{\nu}{\nu_{0,\mathrm{d}}} \right)^{\beta_{\mathrm{d}}+1} \frac{e^{h\nu_{0,\mathrm{d}}/k_{\mathrm{B}}T_{\mathrm{d}}} - 1}{e^{h\nu/k_{\mathrm{B}}T_{\mathrm{d}}} - 1} \\
& + \sum_{j=1}^{N_{\mathrm{src}}} a_{j,\mathrm{src}} \left(\frac{\nu}{\nu_{0,\mathrm{src}}} \right)^{\alpha_{j,\mathrm{src}}-2}
\end{aligned}
$$

- Cosmic Microwave Background
- Synchrotron emission
- Free-free emission
- Anomalous Microwave (spinning dust) emission
- Dust emission
- Point source (stars, galaxies) emission

BeyondPlanck Collaboration: A&A 675, A1 (2023)



We can reconstruct the sky model using the maps from different frequencies

Planck 2018 A&A 641 A1

HOW TO CALCULATE THE RESIDUAL?

- Ideally the residual should be pure normal noise, meaning only the white noise remains in the system

- However, in a system as complex as Planck satellite there are many sources of 'noise'

$$r_j = (d_j - n_j^{\mathrm{corr}} - s_j^{\mathrm{1Hz}})/g_j - s_j^{\mathrm{sky}} - s_j^{\mathrm{orb}} - s_j^{\mathrm{fsl}} - s_j^{\mathrm{leak}}$$

r_j - residual TOD

d_j - raw TOD (actual data)

n_j^{corr} - correlated noise

s_j^{1Hz} - electronic 1Hz spike correction

g_j - instrumental gain

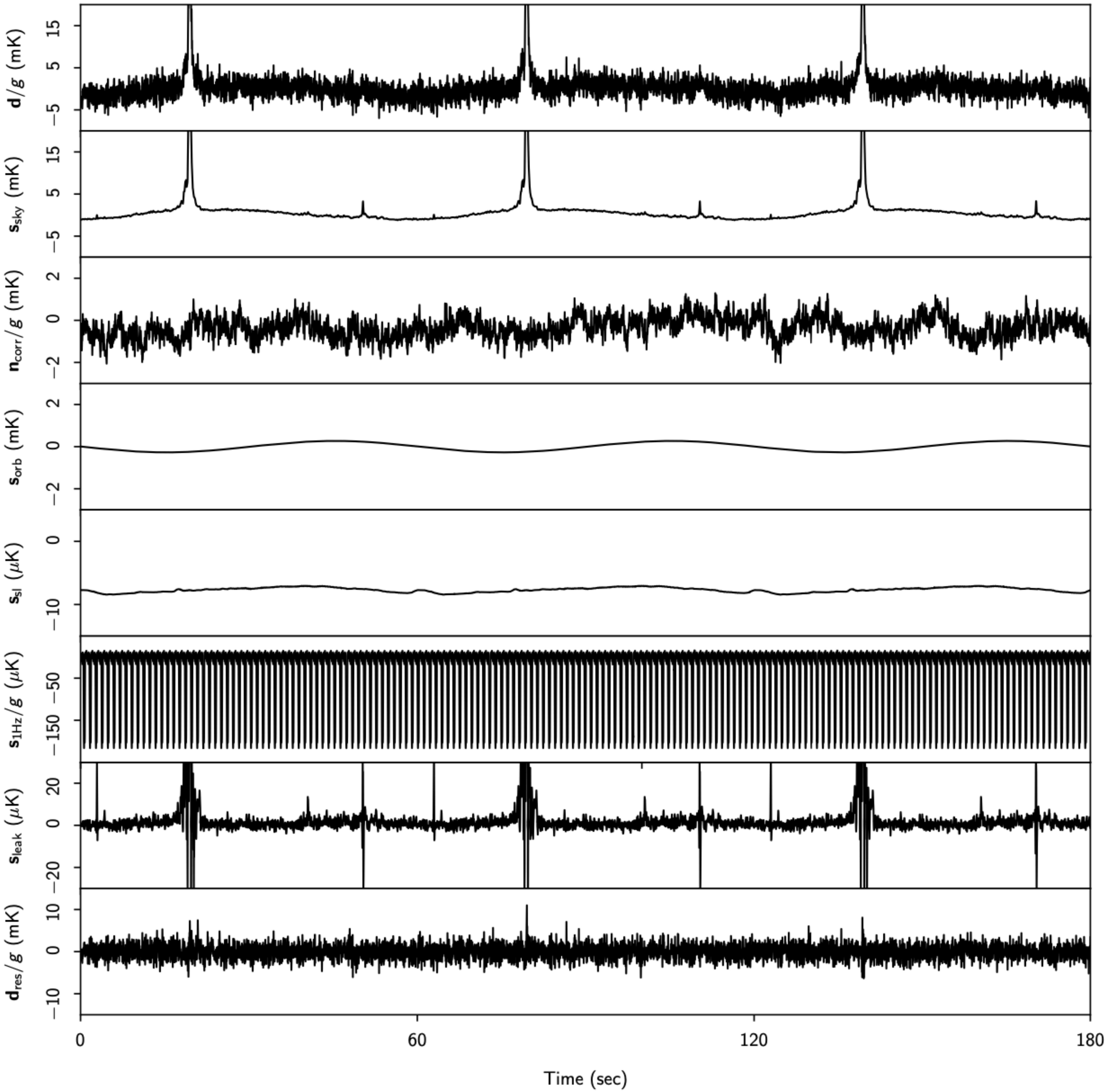
s_j^{sky} - sky signal

s_j^{orb} - orbital CMB dipole signal

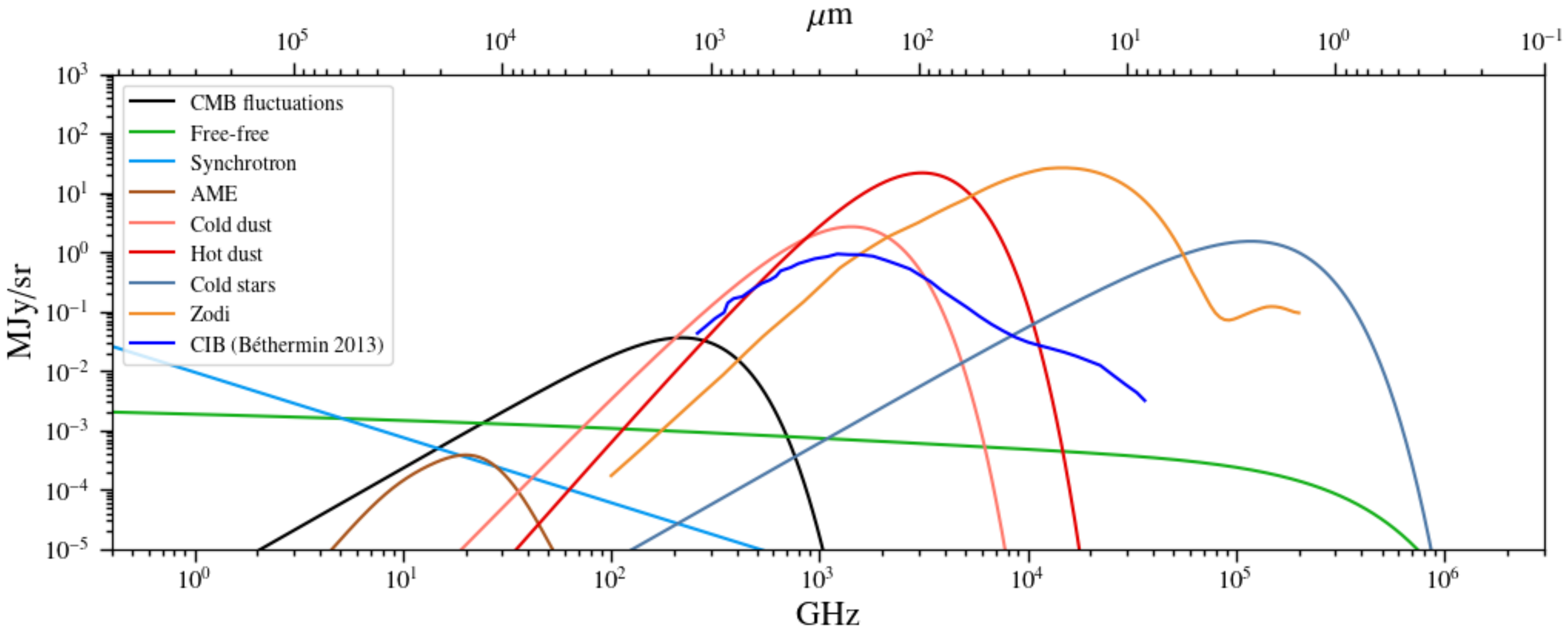
s_j^{fsl} - far sidelobes correction

s_j^{leak} - bandpass and beam leakage correction

Basyrov, A., et al.: A&A 675, A10 (2023)



Basyrov, A., et al.: A&A 675, A10 (2023)



ADDING MORE COMPONENTS!

Interesting side-project going on is adding DIRBE, FIRAS, IRIS and other high frequency maps, which allows to solve the degeneracies

PLANCK HFI

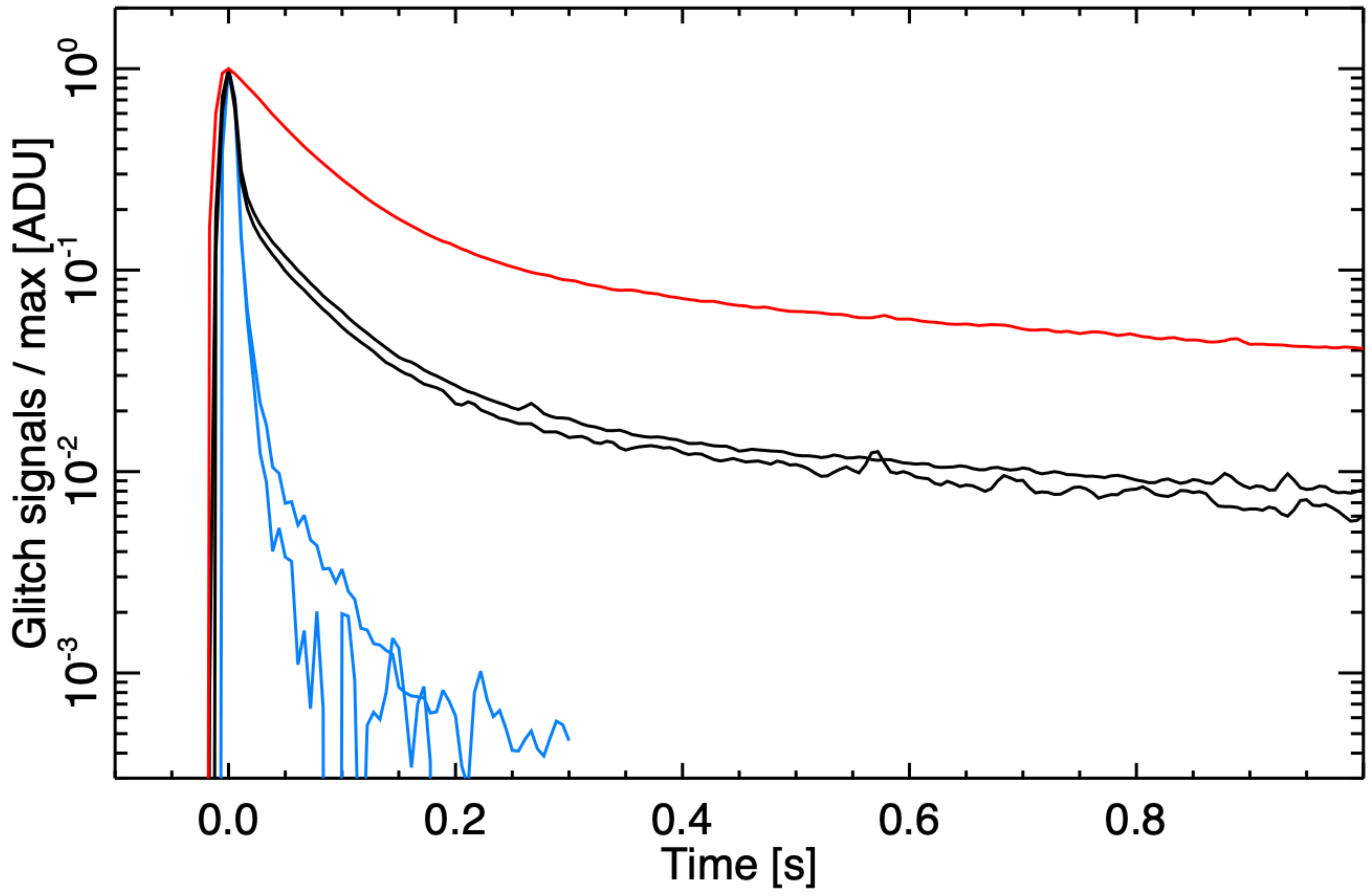
- The **analogue-to-digital conversion (ADC)** in the HFI was drifting with time, and has both linear (similar to LFI) and non-linear effects, which require correction
- HFI cooler was actively trying to compensate **temperature variations** through out the whole mission (unlike passive cooler for LFI), which creates extra source of instrumental noise.
- **Cosmic rays** created extra signal depending on which part of the detector they would hit
- Since HFI was using a different detector technology (radiometers on LFI vs bolometers on HFI), and required higher angular sensitivity while measuring higher frequencies compared to LFI, the **bolometer transfer function** plays an important role in the deconvolution of data

COSMIC RAY

- **The blue line** shows an example for short glitches due to a direct impact on a thermometer

- **The black line** - for long glitches due to an impact on the support structure of a bolometer's absorber

- **The red line** - for slow glitches, the origin of which is a mystery not known to humankind



Planck Collaboration: Planck 2013 results. X.

TRANSFER FUNCTION

- Describes a reaction of a bolometer to measuring a signal through the series of filters

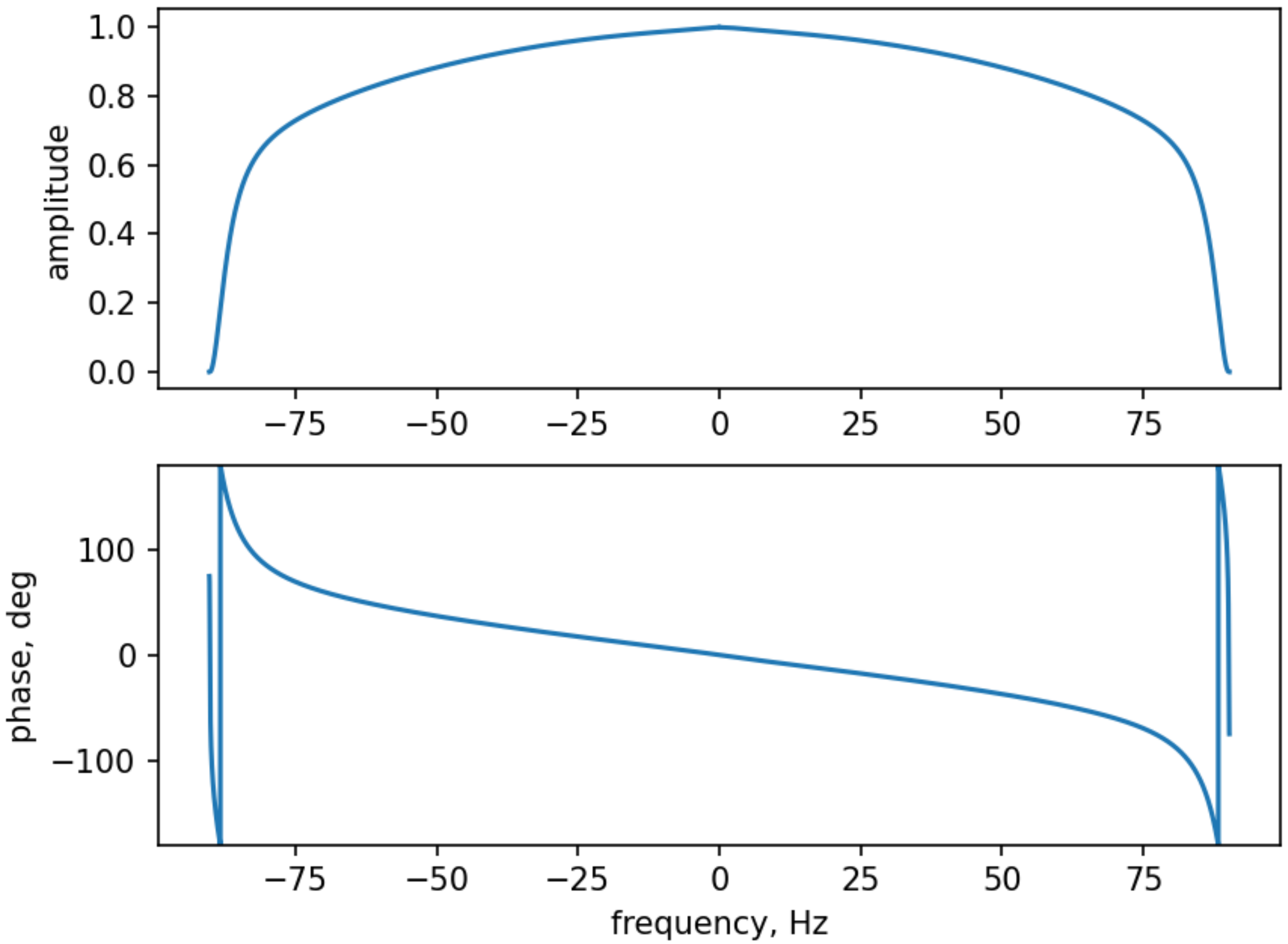
$$f_{\text{tran}}(\omega) = F(\omega)H'(\omega)$$

$$F(\omega) = \sum_{i=1,4} \frac{a_i}{1 + i\omega\tau_i}$$

single pole low pass filters (bolometer transfer function)

$$H(\omega) = \prod_{i=1,5} h_i$$

effective electronics transfer function



Planck Collaboration: Planck 2013 results. VII.

TRANSFER FUNCTION

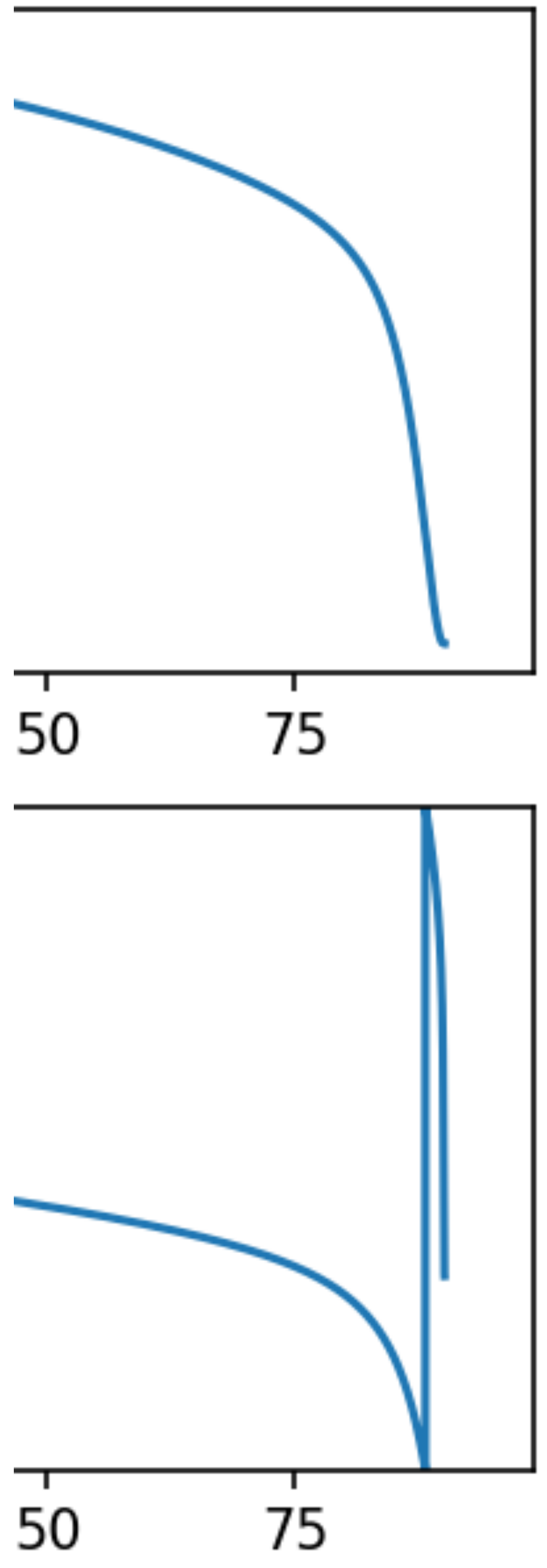
• Descri
measu
filters

$f_{\mathrm{tran}}(\omega)$:

$F(\omega) =$

$H(\omega) =$

Filter	Description	Parameters	Function
0	Stray capacitance low pass filter	$\tau_{\mathrm{stray}} = R_{\mathrm{bolo}} C_{\mathrm{stray}}$	$h_0 = \dfrac{1}{1.0 + \tau_{\mathrm{stray}} s}$
1	Low pass filter	$R_1 = 1\,\mathrm{k}\Omega$ $C_1 = 100\,\mathrm{nF}$	$h_1 = \dfrac{2 + R_1 C_1 s}{2(1 + R_1 C_1 s)}$
2	Sallen Key high pass filter	$R_2 = 51\,\mathrm{k}\Omega$ $C_2 = 1\,\mu\mathrm{F}$	$h_2 = \dfrac{(R_2 C_2 s)^2}{(1 + R_2 C_2 s)^2}$
3	Sign reverse with gain	...	$h_3 = -5.1$
4	Single pole low pass filter with gain	$R_4 = 10\,\mathrm{k}\Omega$ $C_4 = 10\,\mathrm{nF}$	$h_4 = \dfrac{1.5}{1 + R_4 C_4 s}$
5	Single pole high pass filter coupled to a Sallen Key low pass filter	$R_9 = 18.7\,\mathrm{k}\Omega$ $R_{12} = 37.4\,\mathrm{k}\Omega$ $C = 10.0\,\mathrm{nF}$ $R_{78} = 510\,\mathrm{k}\Omega$ $C_{18} = 1.0\,\mu\mathrm{F}$ $K_3 = R_9^2 R_{78} R_{12}^2 C^2 C_{18}$ $K_2 = R_9 R_{12}^2 R_{78} C^2 + R_9^2 R_{12}^2 C^2 + R_9 R_{12}^2 R_{78} C_{18} C$ $K_1 = R_9 R_{12}^2 C + R_{12} R_{78} R_9 C_{18}$	$h_5 = \dfrac{2\ R_{12} R_9 R_{78} C_{18} s}{s^3 K_3 + s^2 K_2 + s K_1 + R_{12} R_9}$



Planck Collaboration: Planck 2013 results. VII.

TF… ON

Bolometer	a_1	τ_1 [ms]	a_2	τ_2 [ms]	a_3	τ_3 [ms]	a_4	τ_4 [ms]	$\tau_{\rm stray}$ [ms]	$S_{\rm phase}$
100-1a ……	0.392	10.0	0.534	20.9	0.0656	51.3	0.00833	572	1.59	0.00139
100-1b ……	0.484	10.3	0.463	19.2	0.0451	71.4	0.00808	594	1.49	0.00139
100-2a ……	0.474	6.84	0.421	13.6	0.0942	37.6	0.0106	346	1.32	0.00125
100-2b ……	0.126	5.84	0.717	15.1	0.142	35.1	0.0145	293	1.38	0.00125
100-3a ……	0.744	5.39	0.223	14.7	0.0262	58.6	0.00636	907	1.42	0.00125
100-3b ……	0.608	5.48	0.352	15.5	0.0321	63.6	0.00821	504	1.66	0.00125
100-4a ……	0.411	8.2	0.514	17.8	0.0581	57.9	0.0168	370	1.25	0.00125
100-4b ……	0.687	11.3	0.282	24.3	0.0218	62.0	0.00875	431	1.38	0.00139
143-1a ……	0.817	4.47	0.144	12.1	0.0293	38.7	0.0101	472	1.42	0.00125
143-1b ……	0.49	4.72	0.333	15.6	0.134	48.1	0.0435	270	1.49	0.00125
143-2a ……	0.909	4.7	0.076	17.0	0.00634	100	0.00871	363	1.48	0.00125
143-2b ……	0.912	5.24	0.051	16.7	0.0244	26.5	0.0123	295	1.46	0.00125
143-3a ……	0.681	4.19	0.273	9.56	0.0345	34.8	0.0115	317	1.45	0.00125
143-3b ……	0.82	4.48	0.131	13.2	0.0354	35.1	0.0133	283	1.61	0.00083
143-4a ……	0.914	5.69	0.072	18.9	0.00602	48.2	0.00756	225	1.59	0.00125
143-4b ……	0.428	6.06	0.508	6.06	0.0554	22.7	0.00882	84	1.82	0.00125
143-5 ……	0.491	6.64	0.397	6.64	0.0962	26.4	0.0156	336	2.02	0.00139
143-6 ……	0.518	5.51	0.409	5.51	0.0614	26.6	0.0116	314	1.53	0.00111
143-7 ……	0.414	5.43	0.562	5.43	0.0185	44.9	0.00545	314	1.86	0.00139
217-5a ……	0.905	6.69	0.080	21.6	0.00585	65.8	0.00986	342	1.57	0.00111
217-5b ……	0.925	5.76	0.061	18.0	0.00513	65.6	0.0094	287	1.87	0.00125
217-6a ……	0.844	6.45	0.068	19.7	0.0737	31.6	0.0147	297	1.54	0.00125
217-6b ……	0.284	6.23	0.666	6.23	0.0384	24	0.0117	150	1.46	0.00111
217-7a ……	0.343	5.48	0.574	5.48	0.0717	23	0.0107	320	1.52	0.00139
217-7b ……	0.846	5.07	0.127	14.40	0.0131	47.9	0.0133	311	1.51	0.00139
217-8a ……	0.496	7.22	0.439	7.22	0.0521	32.5	0.0128	382	1.79	0.00111
217-8b ……	0.512	7.03	0.41	7.03	0.0639	27.2	0.0139	232	1.73	0.00125
217-1 ……	0.014	3.46	0.956	3.46	0.0271	23.3	0.00359	1980	1.59	0.00111
217-2 ……	0.978	3.52	0.014	26.1	0.00614	42	0.00194	686	1.6	0.00125
217-3 ……	0.932	3.55	0.034	3.55	0.0292	32.4	0.00491	279	1.74	0.00125
217-4 ……	0.658	1.35	0.32	5.55	0.0174	26.8	0.00424	473	1.71	0.00111
353-3a ……	0.554	7.04	0.36	7.04	0.0699	30.5	0.0163	344	1.7	0.00125
353-3b ……	0.219	2.68	0.671	6.95	0.0977	23.8	0.0119	289	1.57	0.00111
353-4a ……	0.768	4.73	0.198	9.93	0.0283	50.5	0.00628	536	1.81	0.00125
353-4b ……	0.684	4.54	0.224	10.8	0.0774	80	0.0149	267	1.66	0.00111
353-5a ……	0.767	5.96	0.159	12.4	0.0628	30.3	0.0109	357	1.56	0.00111
353-5b ……	0.832	6.19	0.126	11.1	0.0324	35	0.0096	397	1.66	0.00111
353-6a ……	0.049	1.76	0.855	6.0	0.0856	21.6	0.0105	222	1.99	0.00125
353-6b ……	0.829	5.61	0.127	5.61	0.0373	25.2	0.00696	360	2.28	0.00111
353-1 ……	0.41	0.74	0.502	4.22	0.0811	17.7	0.0063	329	1.32	0.00097
353-2 ……	0.747	3.09	0.225	7.26	0.0252	44.7	0.00267	513	1.54	0.00097
353-7 ……	0.448	0.9	0.537	4.1	0.0122	27.3	0.00346	433	1.78	0.00125
353-8 ……	0.718	2.23	0.261	6.08	0.0165	38	0.00408	268	1.77	0.00111
545-1 ……	0.991	2.93	0.007	26.0	0.00139	2600	…	…	2.16	0.00111
545-2 ……	0.985	2.77	0.013	24.0	0.00246	2800	…	…	1.87	0.00097
545-4 ……	0.972	3.0	0.028	25.0	0.00078	2500	…	…	2.22	0.00111
857-1 ……	0.974	3.38	0.023	25.0	0.00349	2200	…	…	1.76	0.00111
857-2 ……	0.84	1.48	0.158	6.56	0.00249	3200	…	…	2.2	0.00125
857-3 ……	0.36	0.04	0.627	2.4	0.0111	17	0.002	1900	1.52	0.00126
857-4 ……	0.278	0.4	0.719	3.92	0.00162	90	0.00152	800	1.49	0.00056

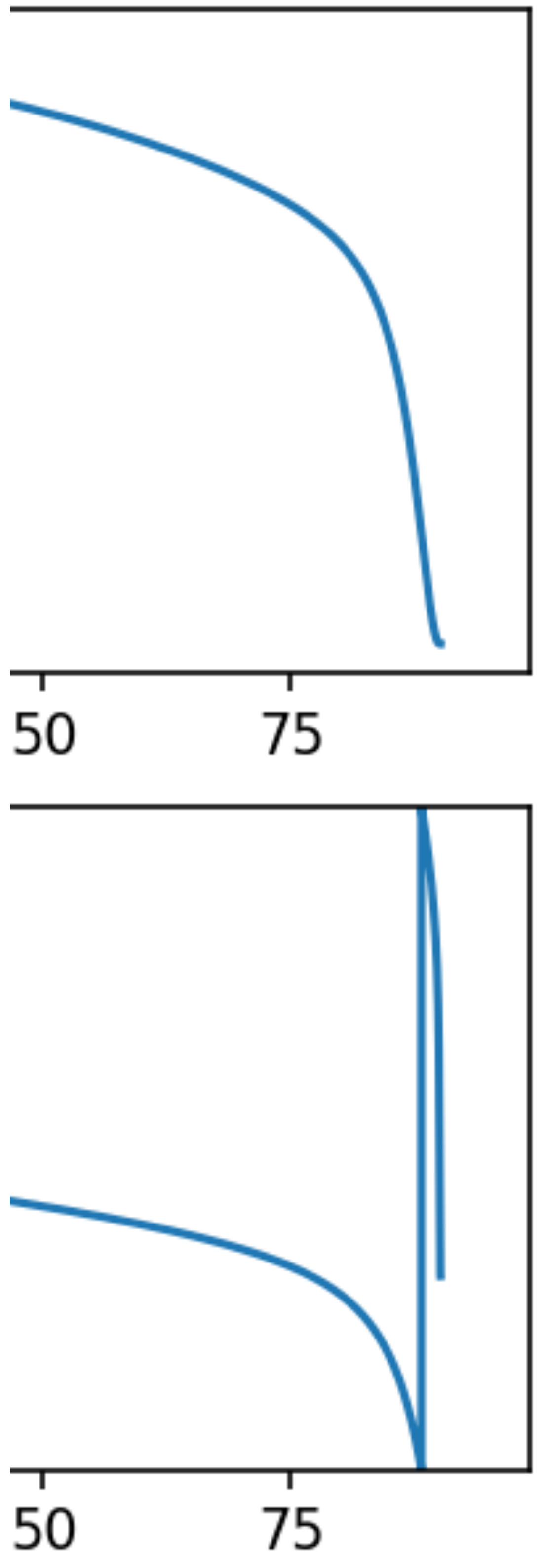
Filter	Desc…	Function
0	Stray capacitance l…	$= \dfrac{1}{1.0 + \tau_{\rm stray} s}$
1	Low pass filter	$= \dfrac{2 + R_1C_1 s}{2(1 + R_1C_1 s)}$
2	Sallen Key high pa…	$= \dfrac{(R_2C_2 s)^2}{(1 + R_2C_2 s)^2}$
3	Sign reverse with g…	$= -5.1$
4	Single pole low pa…	$= \dfrac{1.5}{1 + R_4C_4 s}$
5	Single pole high p… Sallen Key low …	$= \dfrac{2\ R_{12}R_9R_{78}C_{18} s}{s^3K_3 + s^2K_2 + sK_1 + R_{12}R_9}$

- Descri… measu… filters

$f_{\rm tran}(\omega) =$ …

$F(\omega) =$ …

$H(\omega) =$ …

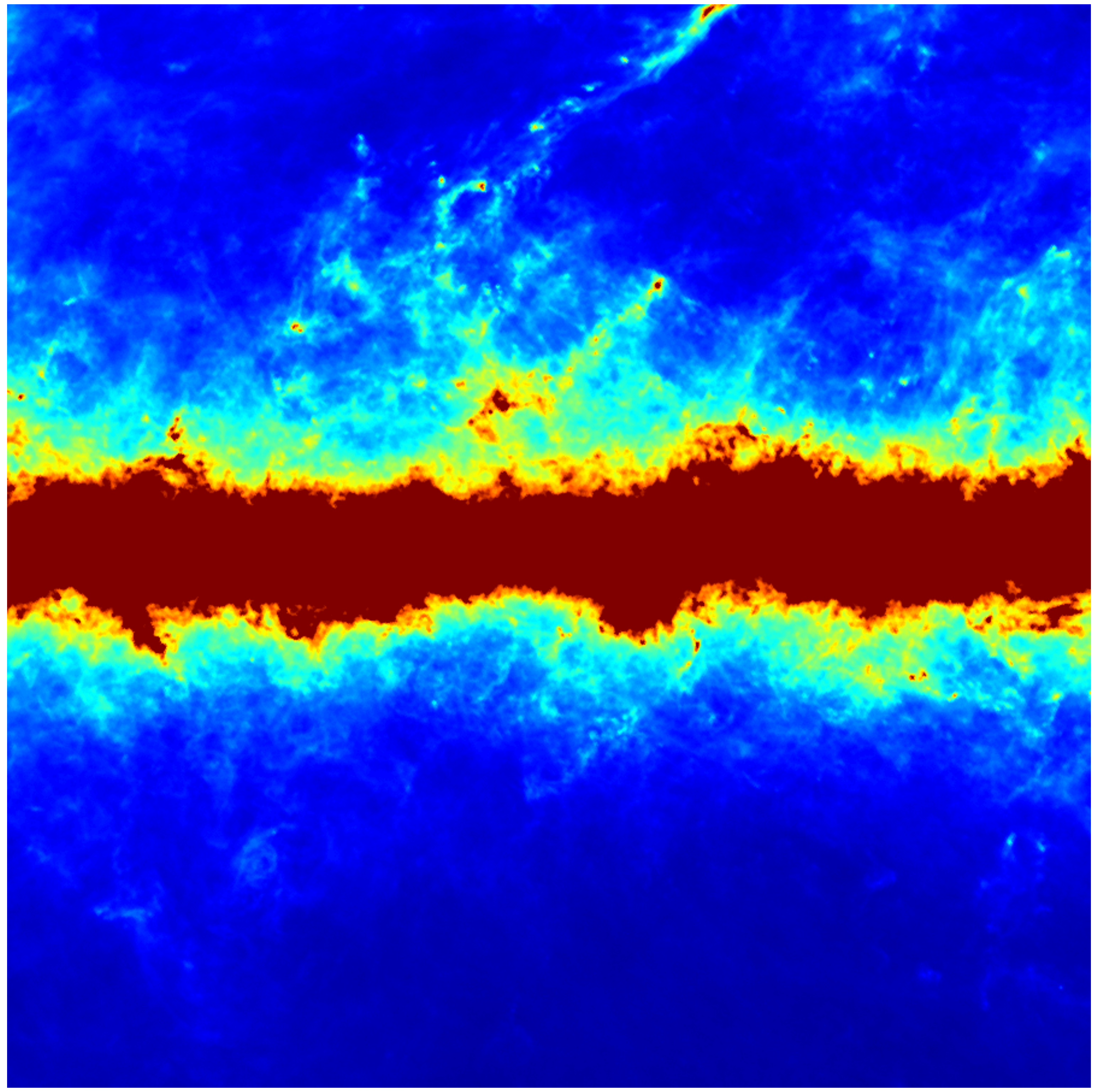


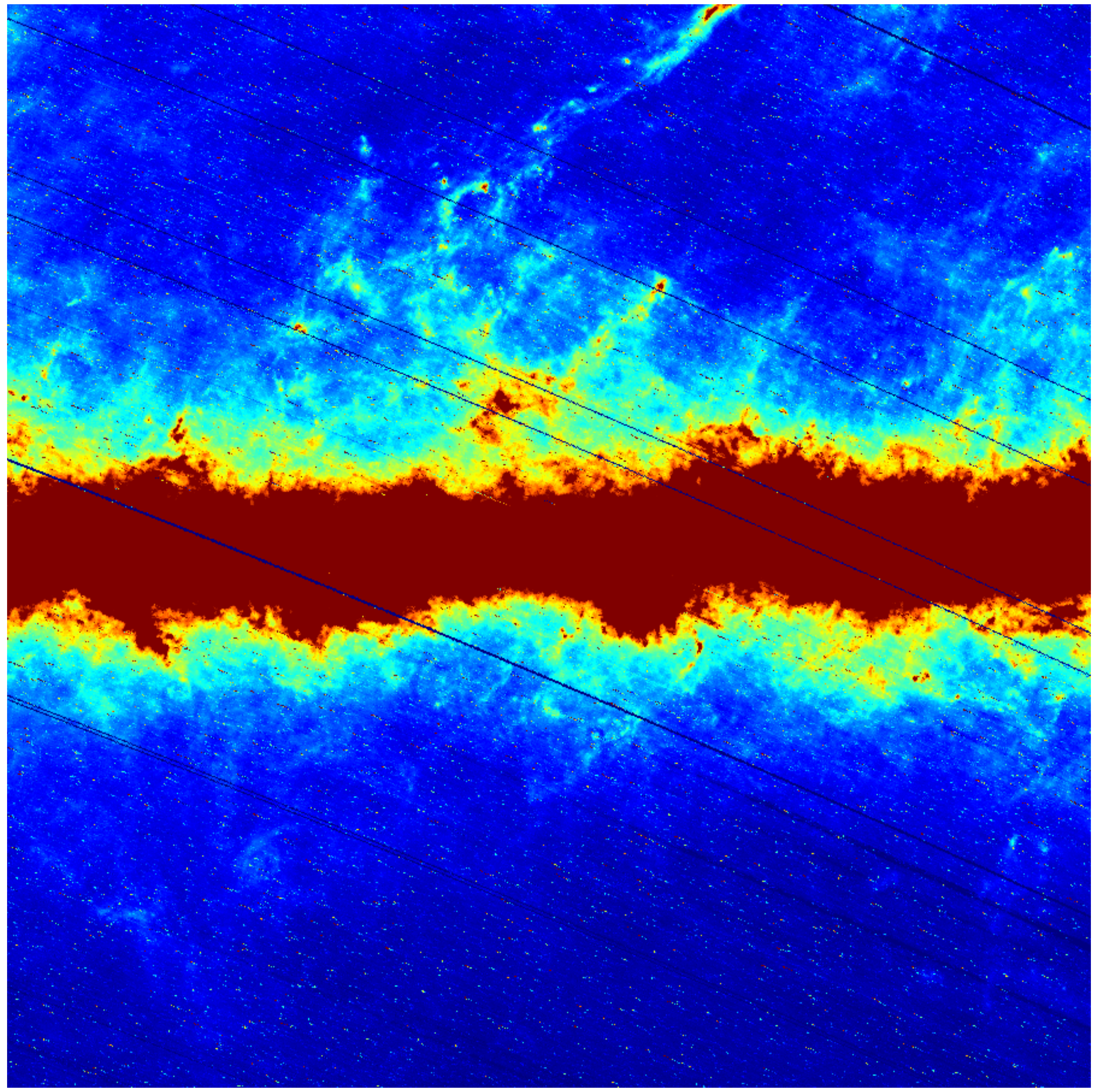
Planck Collaboration: Planck 2013 results. VII.

WHAT'S THE DIFFERENCE?

- Besides from other effects, correction for which has not been implemented yet, the transfer function effect is the most obvious one

- The map looks slightly shifted, which is exactly the transfer function effect





DATA MODEL

$$d = Ts + n$$

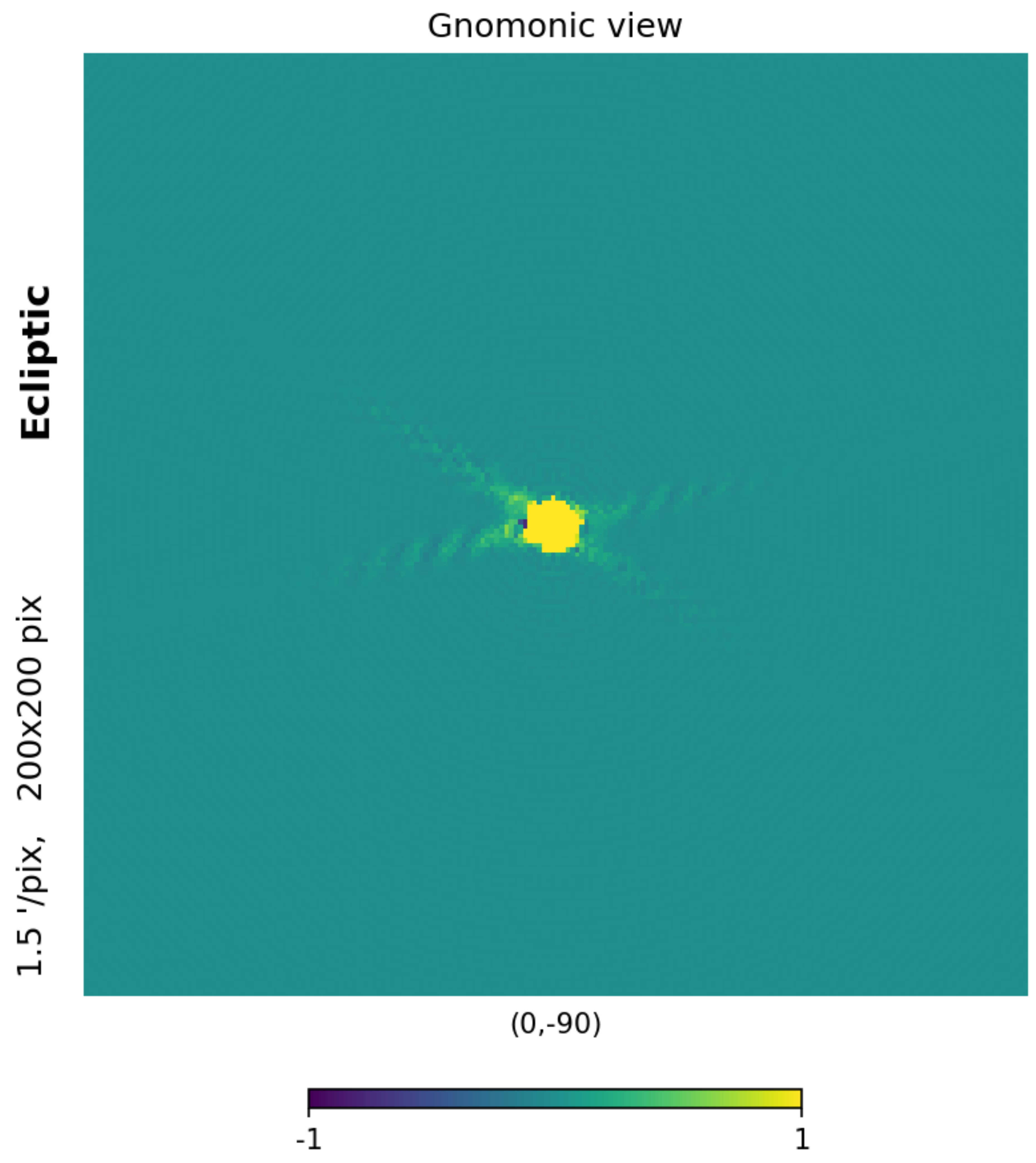
Data recorded from the detector (d) is a sky signal (s) modified with the detector transfer function (T) plus noise (n)

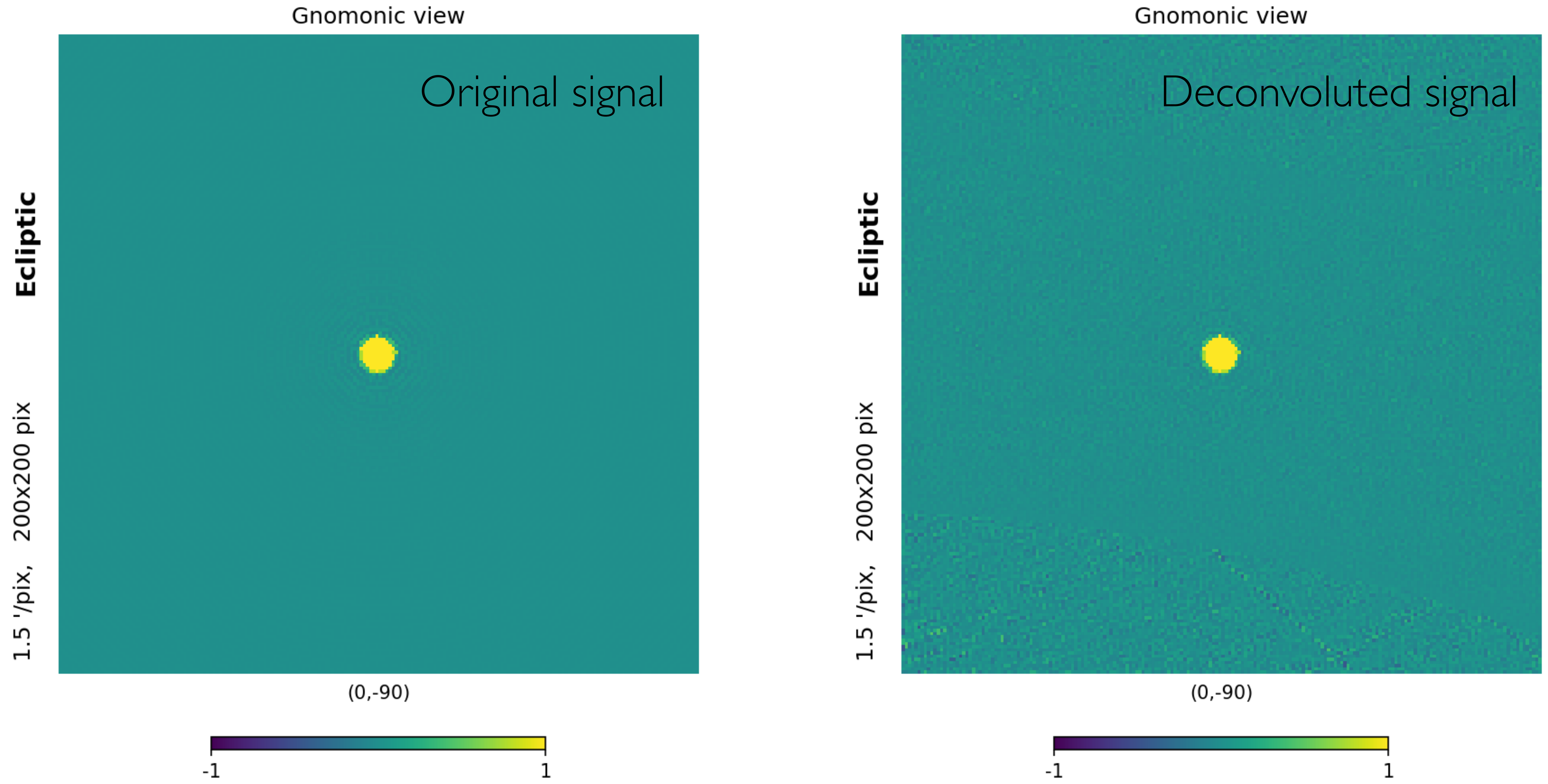
$$T = F^{-1} f_{tran}(\omega) F$$

The operator (T) describing the transfer function effect is a convolution operator in real space or a multiplication operator in Fourier space with transfer function (f) and Fourier transform (F)

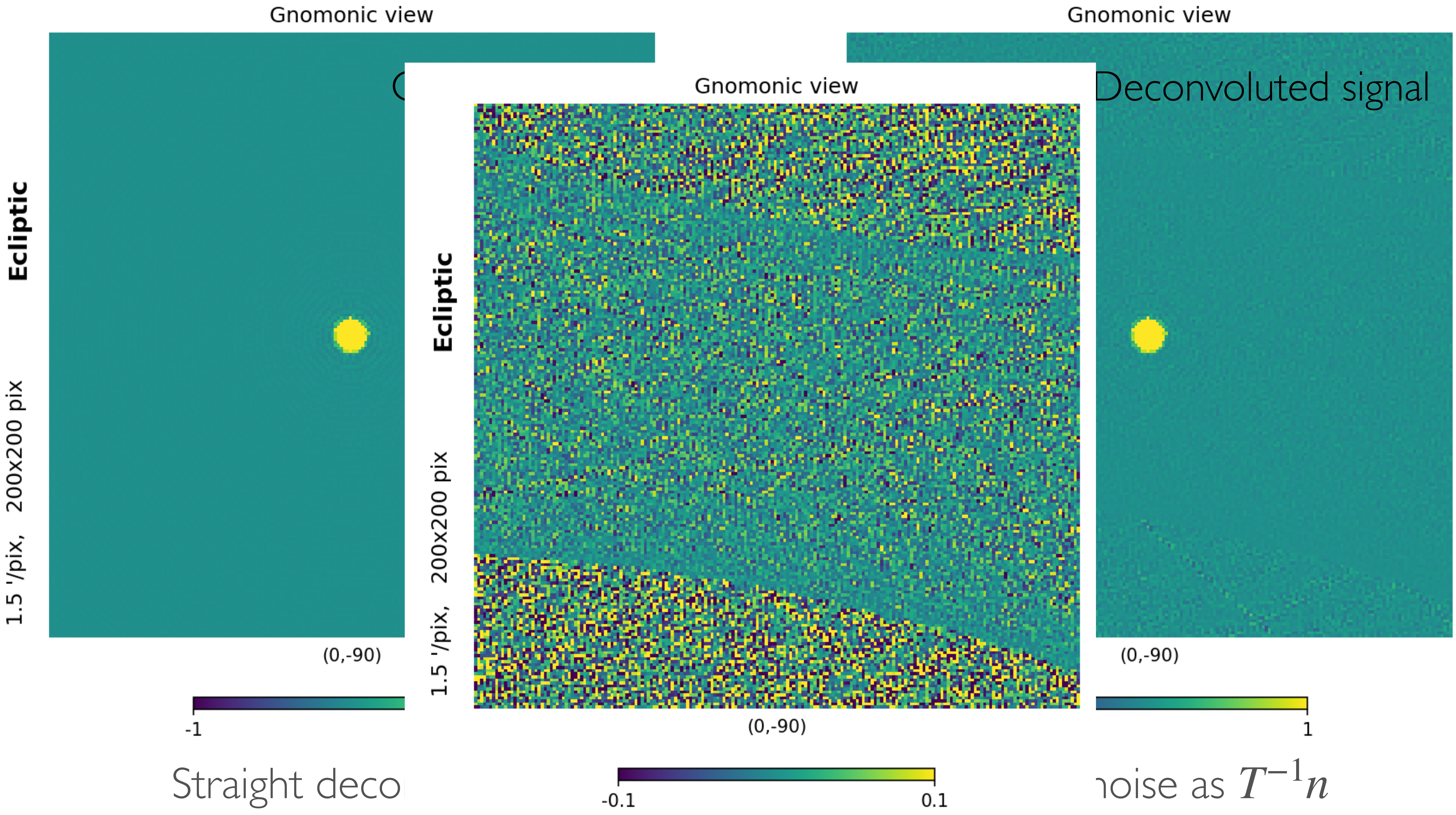
EXPERIMENT

- Let's take the Planck HFI pointing
- Generate a bright beam at one of the often passed points (pole) (s)
- Apply a transfer function T
- Add normal noise n to data d





Straight deconvolution (applying T^{-1} to d) amplifies noise as $T^{-1}n$

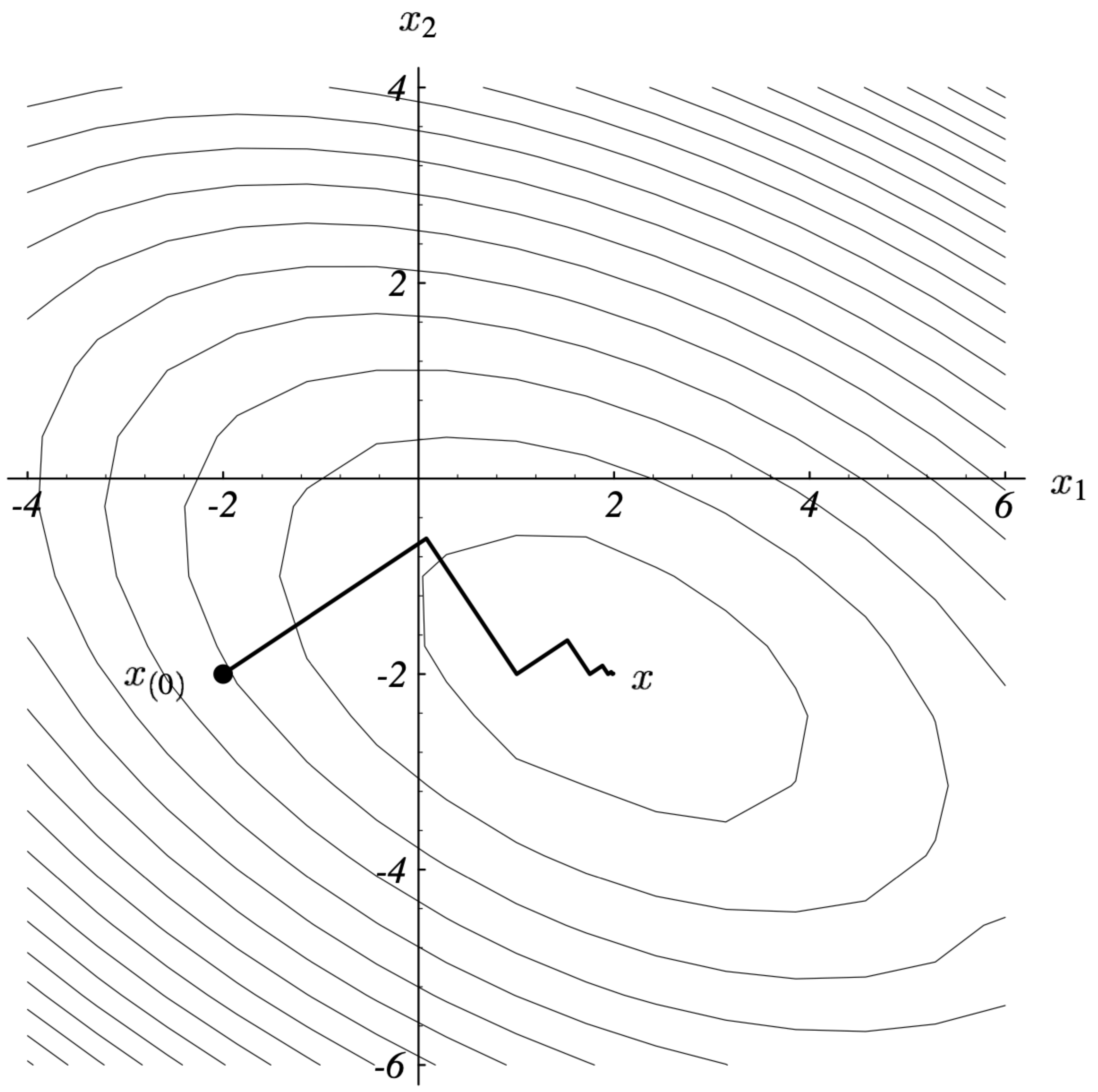

Gnomonic view
Ecliptic
1.5 '/pix, 200x200 pix
(0,-90)
-1
Gnomonic view
Ecliptic
1.5 '/pix, 200x200 pix
(0,-90)
-0.1
0.1
Gnomonic view
Deconvoluted signal
(0,-90)
1
Straight deco
noise as $T^{-1}n$

DEALING WITH TRANSFER FUNCTION AT MAPMAKING LEVEL

- Instead of applying T^{-1} to the data d, as was done by Planck HFI, we can include the operator T into the mapmaking equation $(P^T T^T N^{-1} T P) m = (P^T T^T N^{-1}) d$
- Instead of applying the inverse, we are applying the transpose, which is identical to shifting the data forward in time
- We are stacking the data and applying T along the pointing direction, decreasing white noise

THE COST?

- Extremely computationally heavy, since we are dealing with NTOD = $7 \cdot 10^{11}$, and NSIDE = 2048, corresponding to NPIX = 10^7
- For example, the pointing matrix $P = (\text{NPIX}, \text{NTOD})$
- However, it's still **possible** to solve for m using conjugate gradient method
- The basic mapmaking equation for LFI was $(P^T N^{-1} P)m = P^T N^{-1} d$



Thank you for your attention!