Planck- The Low Frequency Instrument

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esa

planck

cnes

asi agenzia spaziale italiana

NASA

cnrs

DTU Space National Space Institute

Science & Technology Facilities Council

INAF Istituto Nazionale di Astrofisica

CSIC

National Research Council of Italy

Gobierno de España Ministerio de Ciencia e Innovación

CSA ASC

DLR Deutsches Zentrum für Luft- und Raumfahrt e.V.

UK SPACE AGENCY

Max-Planck-Gesellschaft

HFI PLANCK

PLANCK LFI

IAS orsay

IAP

INAF - IASF BO Istituto Nazionale di Astrofisica

A"

ioa

KICC

University of Cambridge

Cardiff University Prifysgol Caerdydd

irfu cea saclay

CEFCA

CESR

CITA–ICAT

IASF

cnrs INSU

cnrs IN2P3

ipac

Helsinki Institute of Physics

IFCA

Imperial College London

Università degli Studi di Milano

NÉEL Institut

IPAG

iSDC

JPL

LAL

l'Observatoire de Lyon LERMA

LPSC Grenoble

MilliLab

NUI Maynooth

INAF Osservatorio Astronomico di Padova

Sapienza

Rutherford Appleton Laboratory

UBC

UC

UCSB

SISSA

US University of Denver

Haverford

esa

University of Helsinki

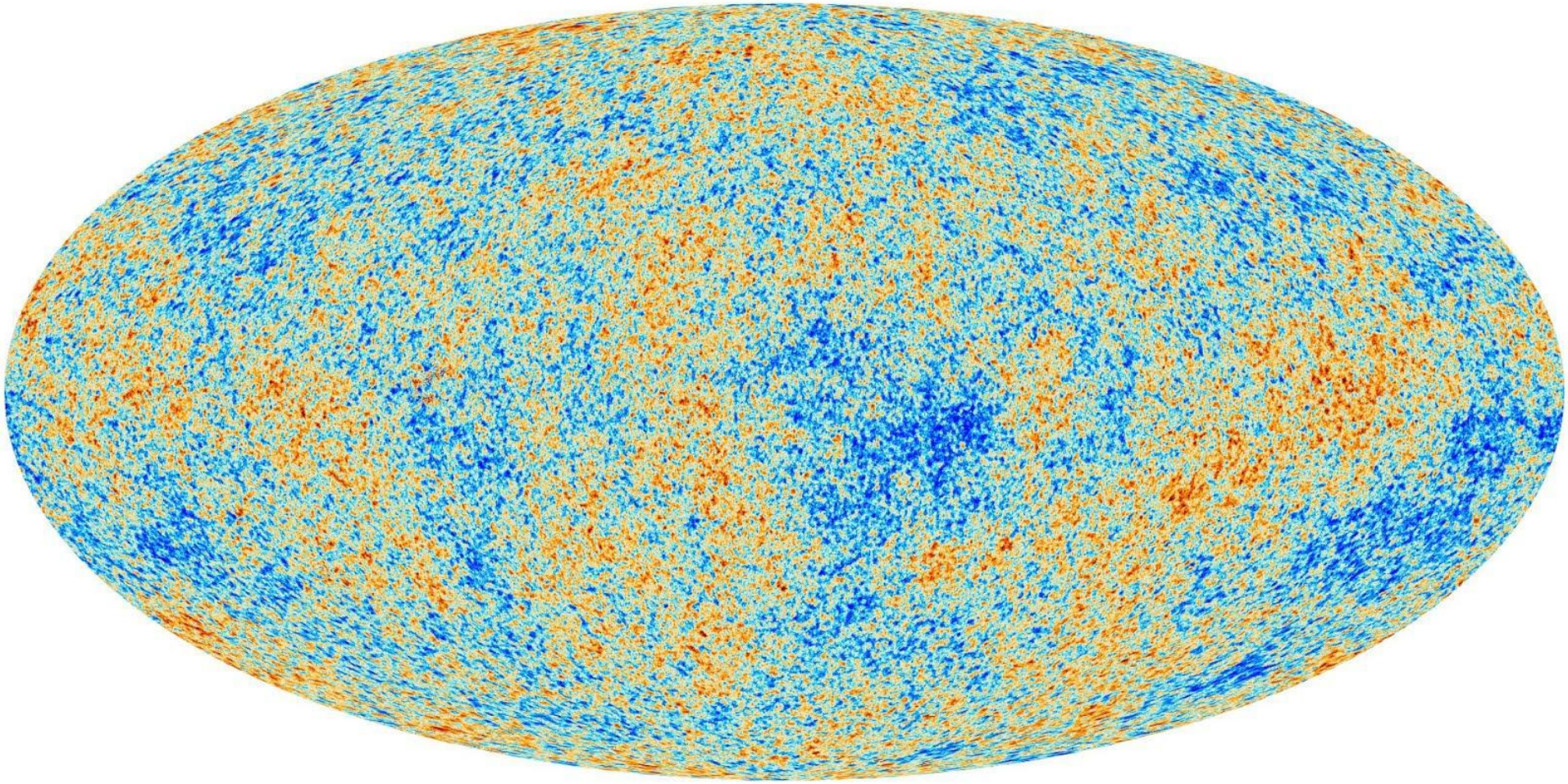
Université de Genève

University of Toronto

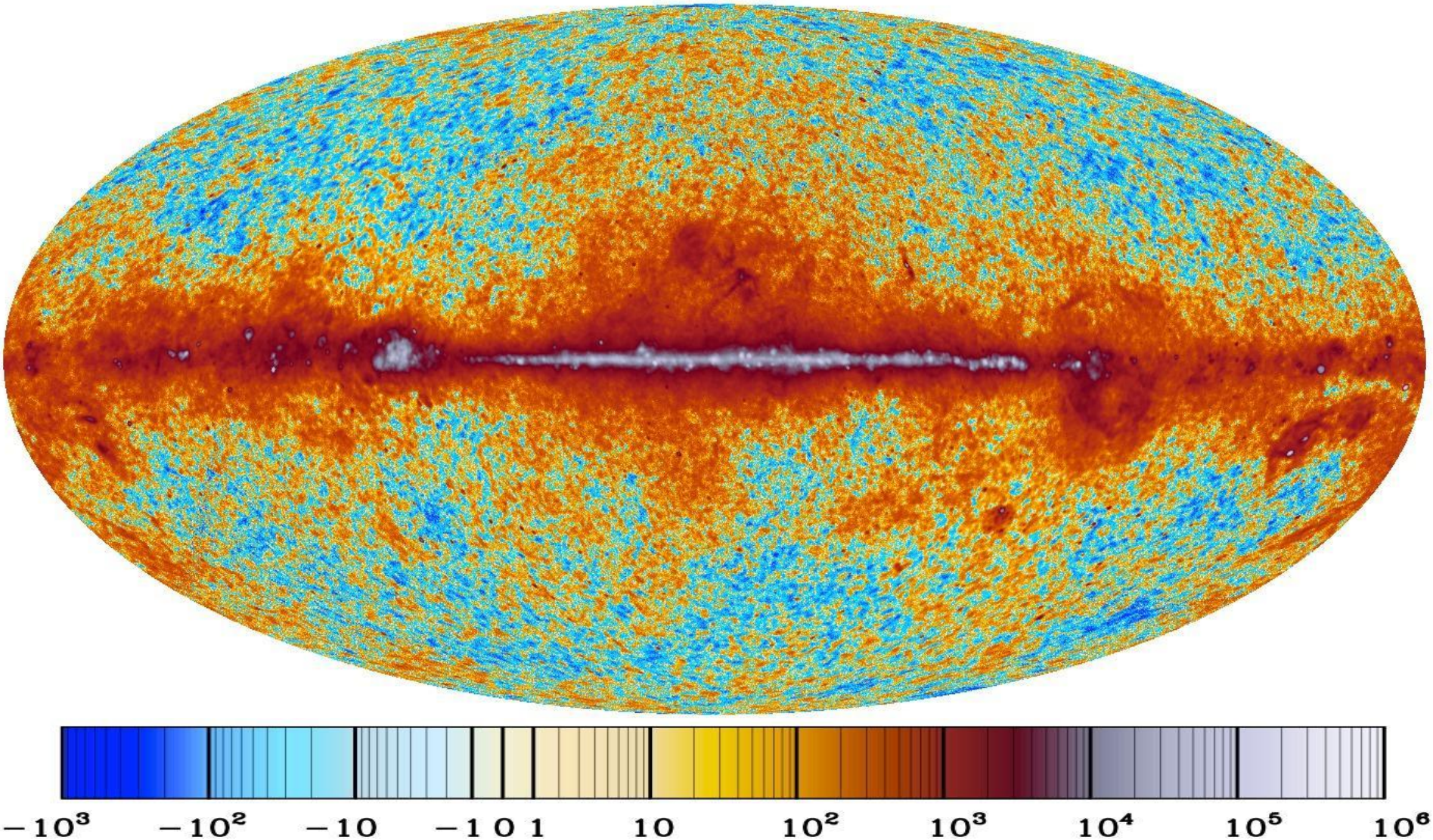
Université de Paris-Sud XI

asdc

Foreground removed CMB



30 GHz


-10^3
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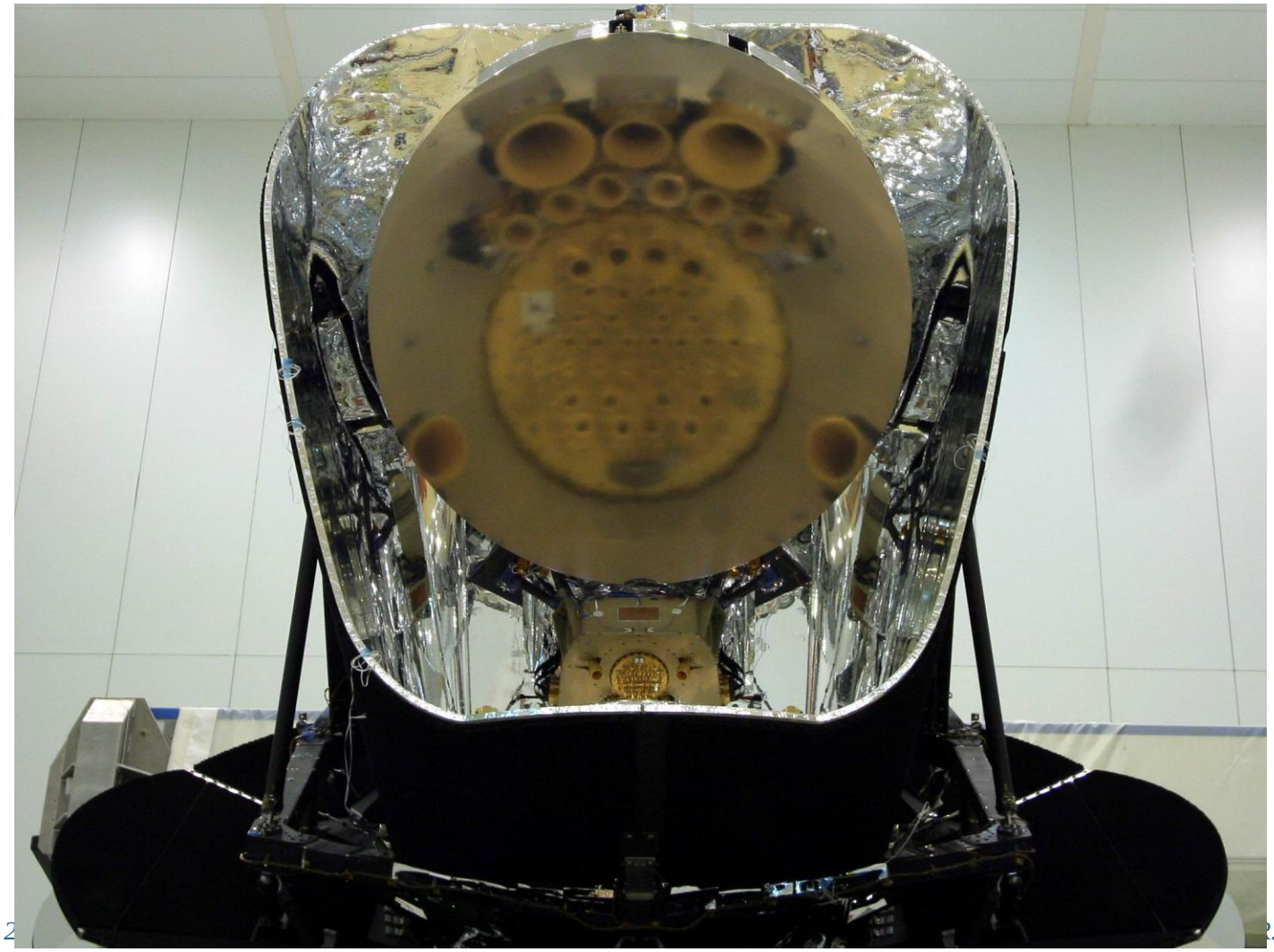
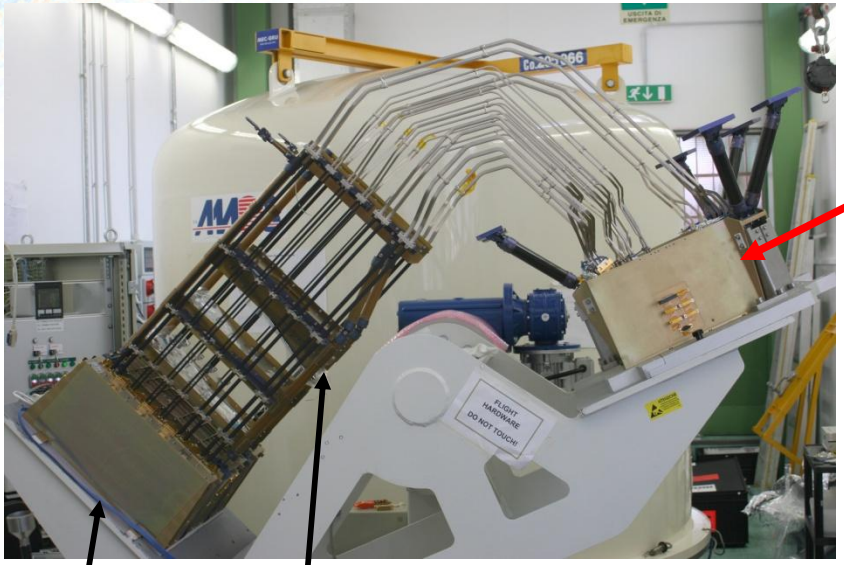
30−353 GHz: δT [μK_{CMB}]; 545 and 857 GHz: surface brightness [kJy/sr]

The last thing a CMB photon sees when it reaches Planck



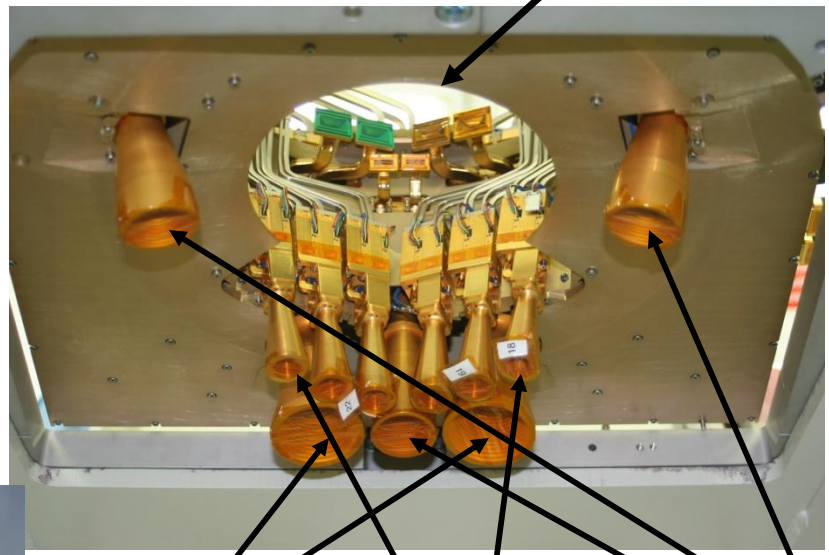
LFI:1/2



Front End Unit (cooled to 20 Kelvin)

Back End Unit (300 Kelvin)

Waveguide supports (flight)

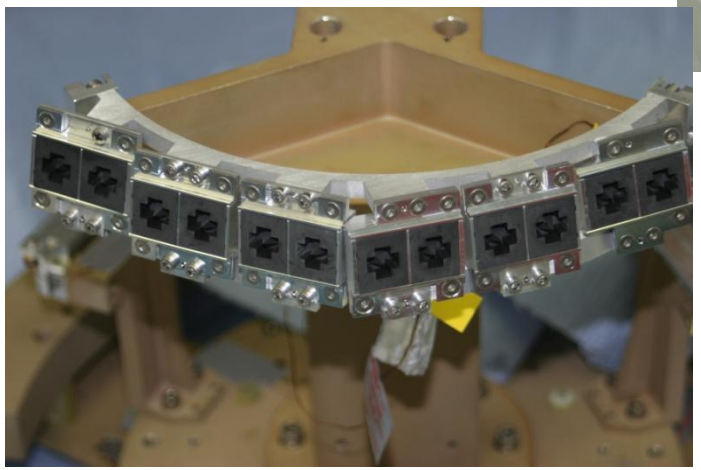


HFI goes here

30 GHz

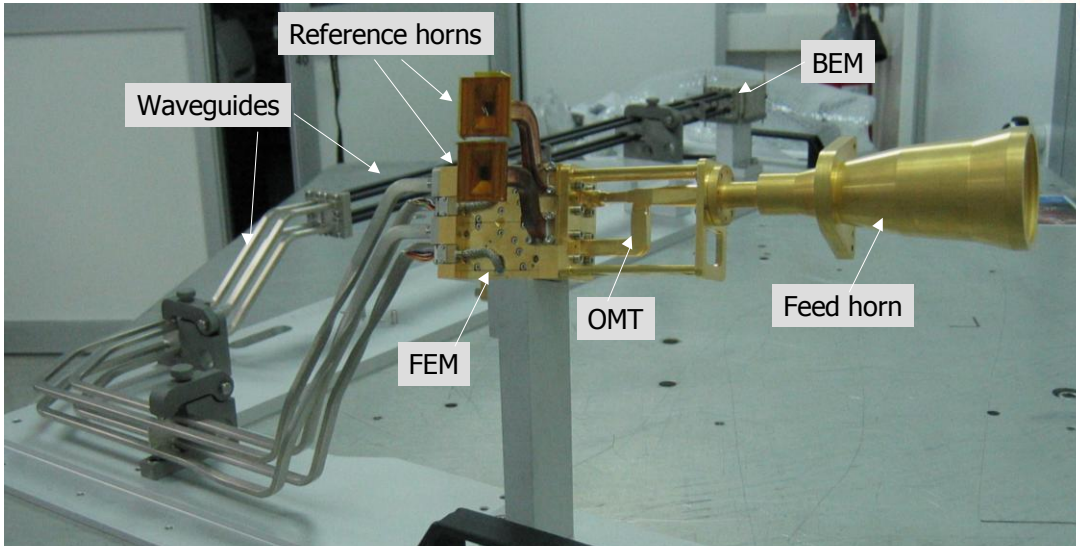
70 GHz

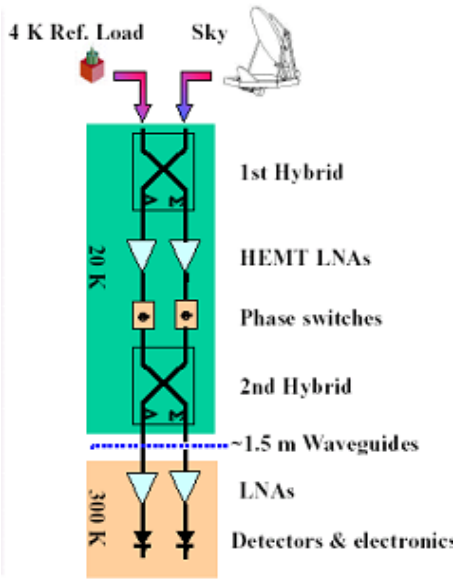
44 GHz



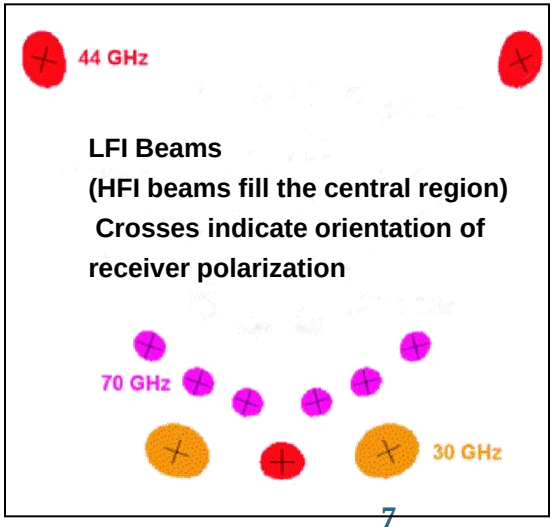
70 GHz reference loads, one per horn per polarization (mounted to HFI mockup)

LFI: 2/2





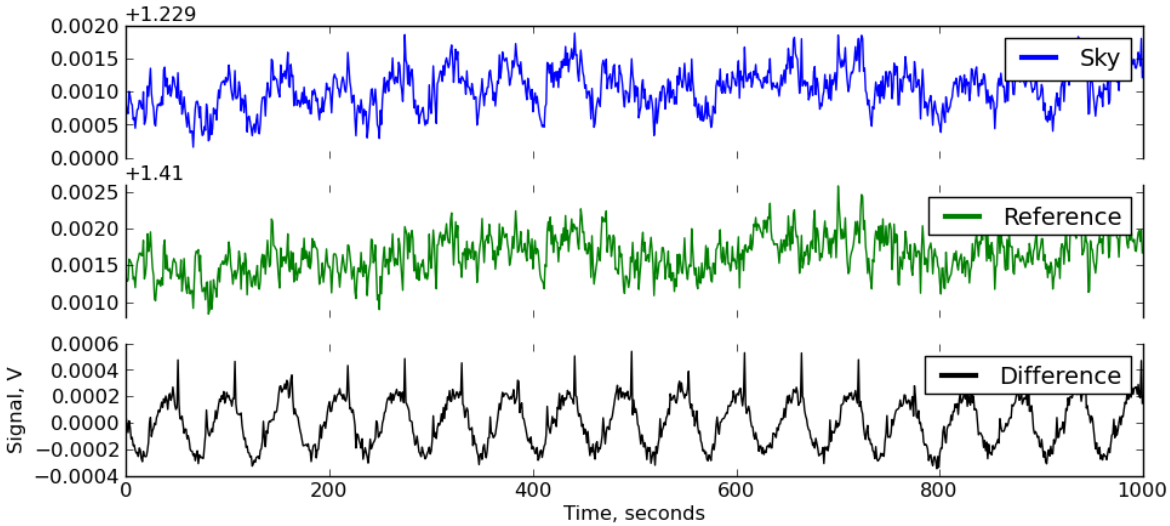
LFI "Continuous Comparison" Pseudo-correlation receiver. One phase switch switches at 8192 Hz, providing alternately 'Sky' and 4 K 'Reference' outputs at each diode. Differencing these states effectively removes 1/f noise from the data.



Main LFI Parameters

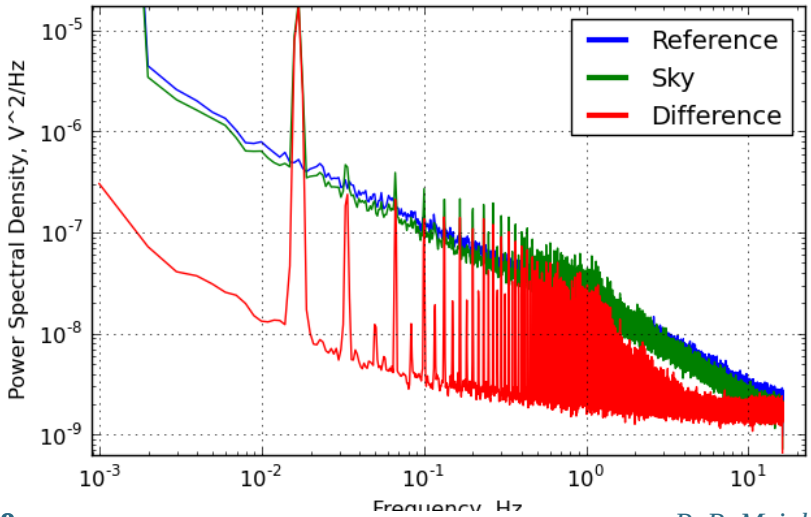
Center Frequency (GHz)	30	44	70
Number of Feeds	2	3	6
Number of detectors	8	12	24
Angular Resolution (arcmin)	32	28	13
Effective Bandwidth (GHz)	6	8.8	14
Sensitivity (microK/√Hz)	148	173	152
Median Noise per º pixel (mK)	9	12	23
1/f knee frequency (mHz)	114	46	20
Systematic uncertainty (mK)	21	6	8
FEM power dissipation (mW)	27	34	24

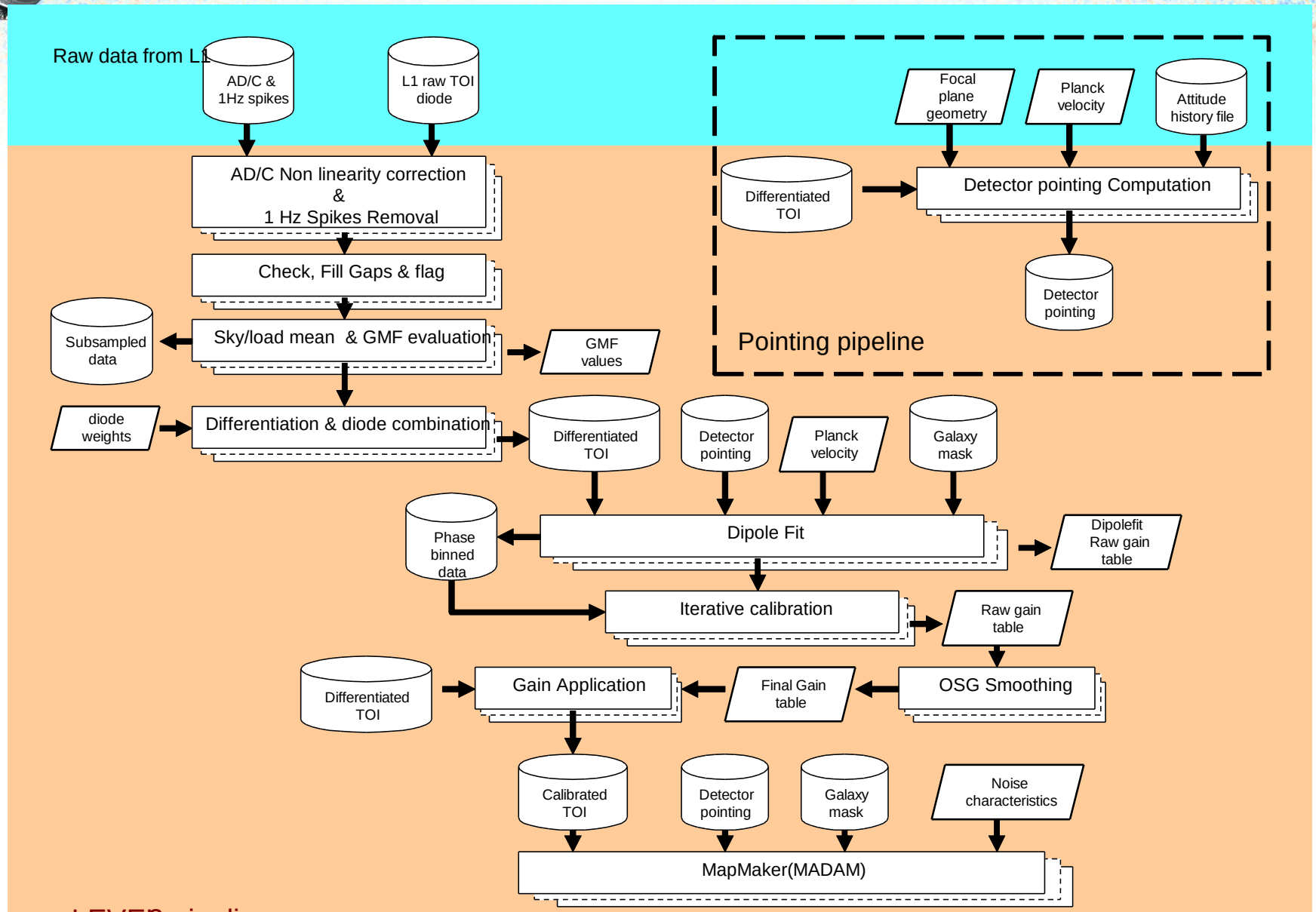
Sample of how LFI pseudocorrelation reduces 1/f



We bring down both Sky and Reference voltages, to allow optimizing the 'Gain modulation factor' for 1/f in the difference data. F_{knee} is reduced by 3 orders of magnitude.

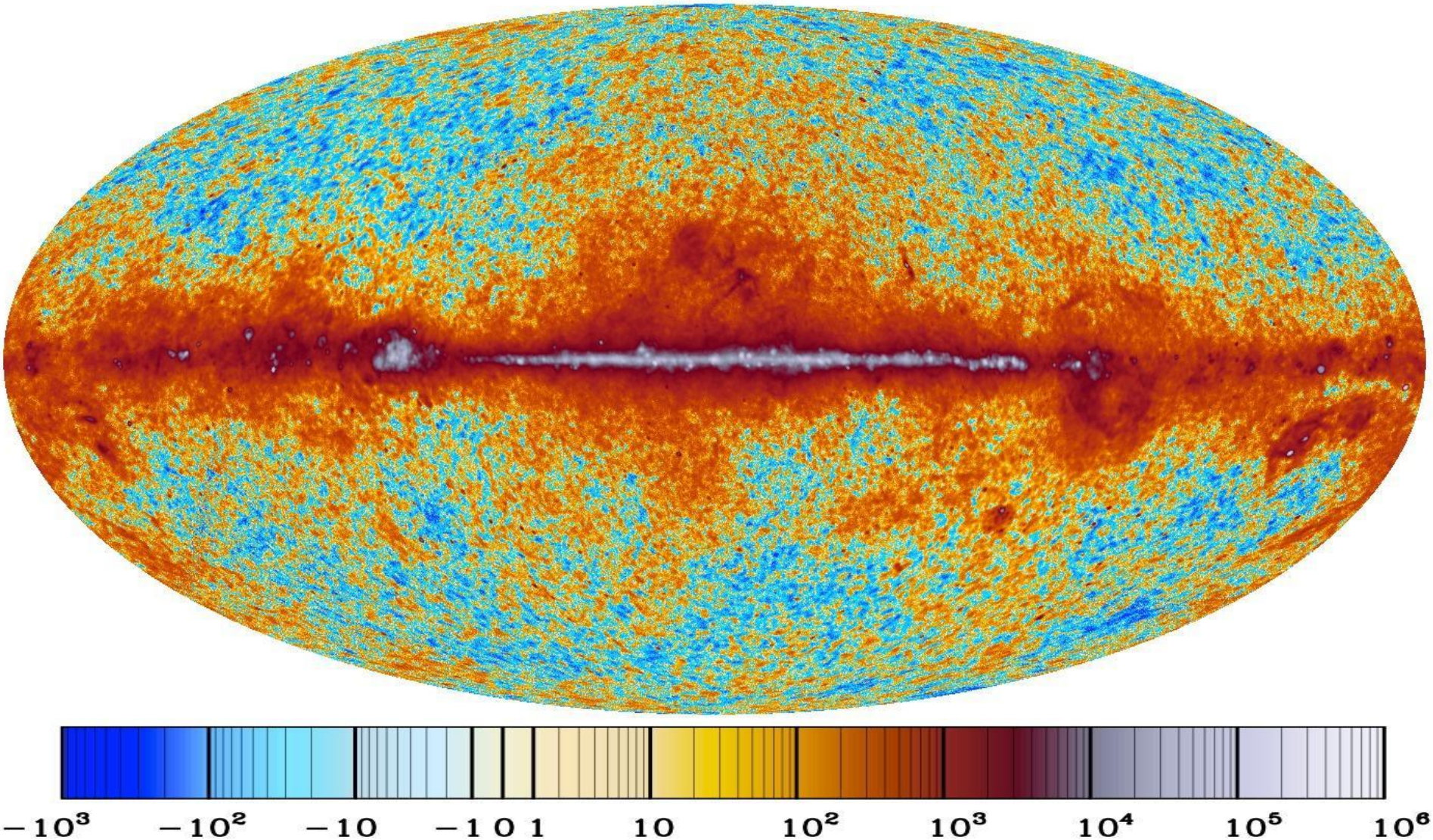
These 'DC' values are also very useful for radiometer diagnostics and for calibration.





LEVEL2 pipeline

30 GHz


-10^3
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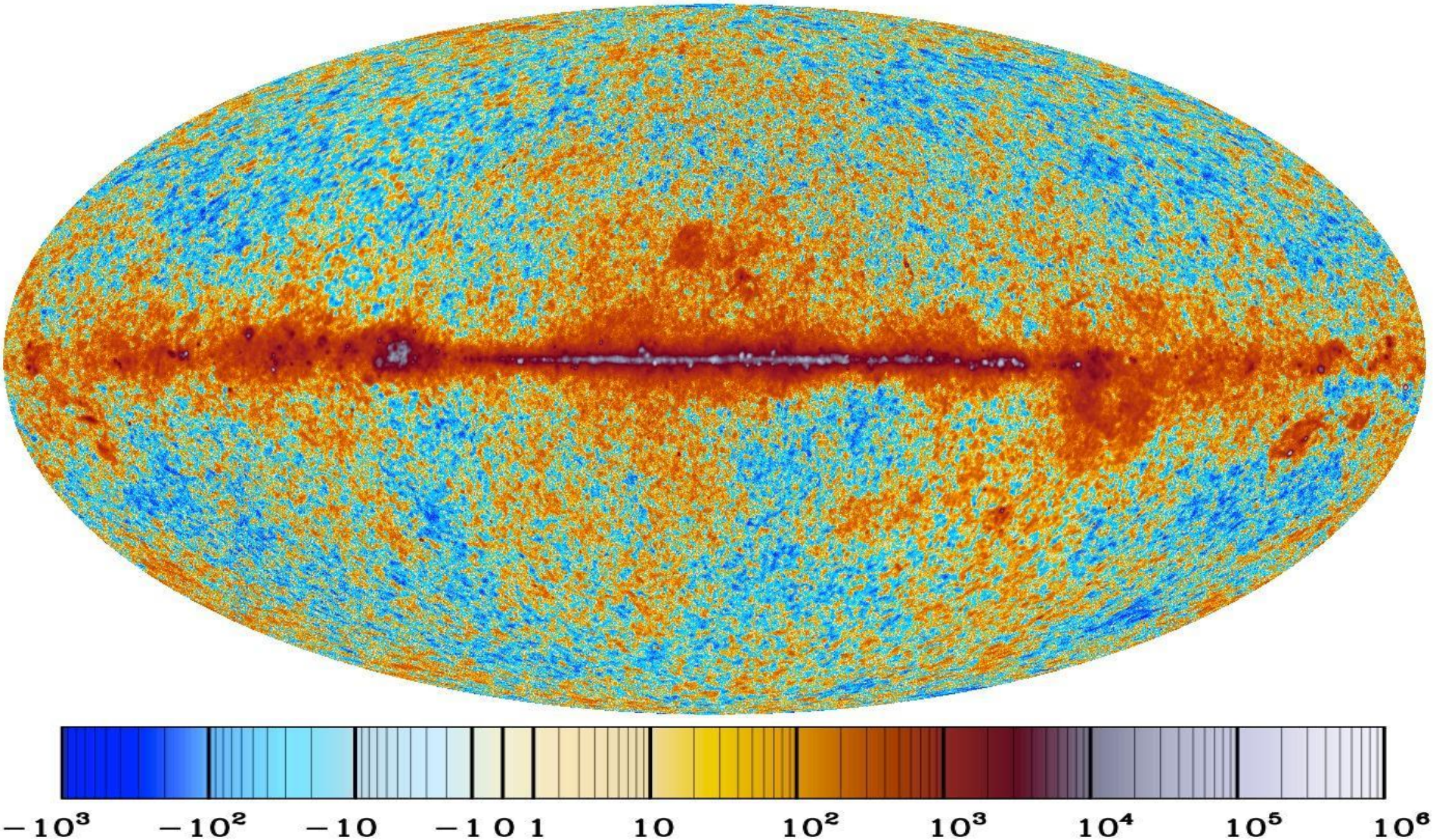
10^6
30−353 GHz: δT [μK_{CMB}]; 545 and 857 GHz: surface brightness [kJy/sr]

44 GHz


-10^3
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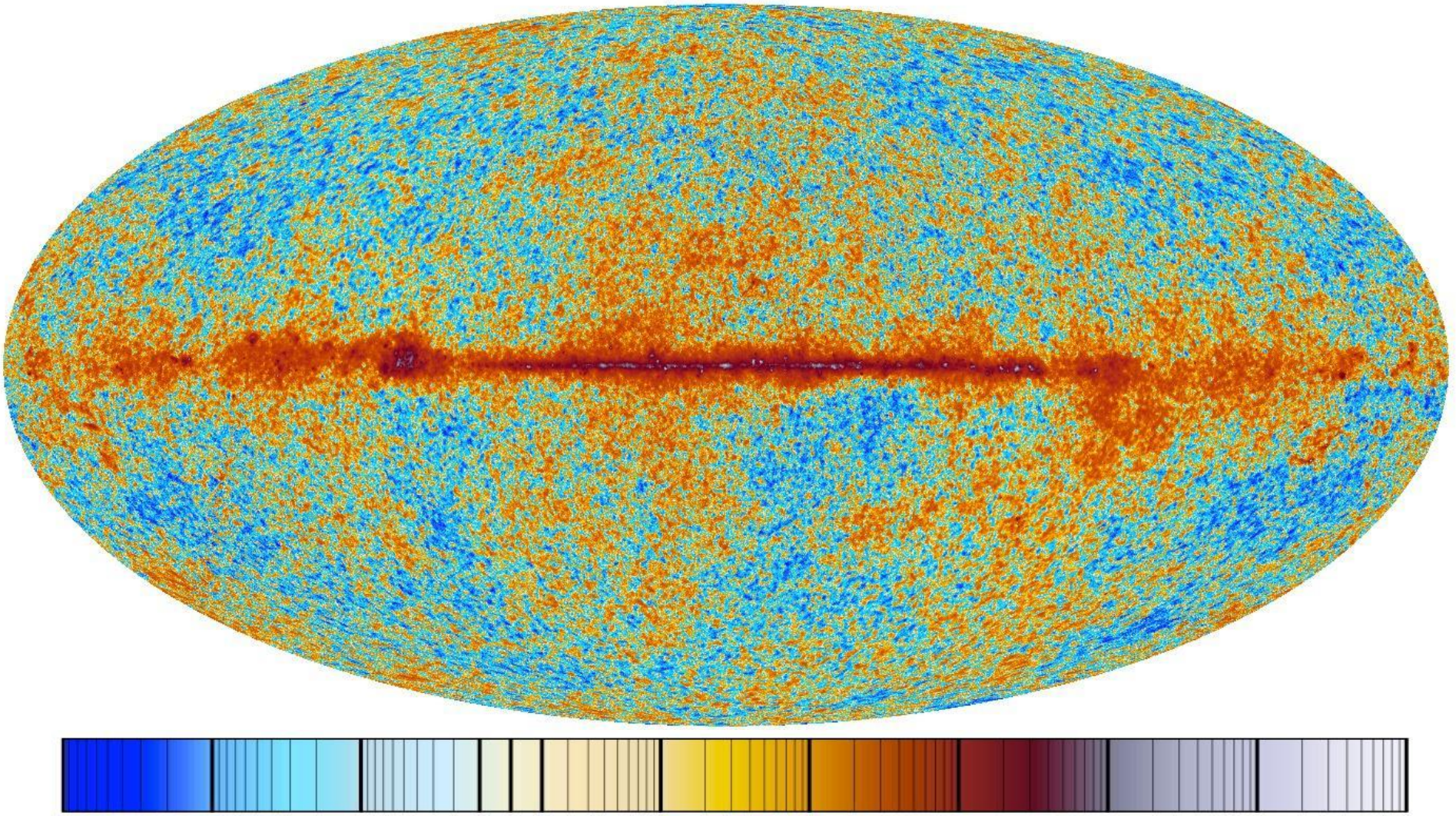
30−353 GHz: δT [μK_{CMB}]; 545 and 857 GHz: surface brightness [kJy/sr]

70 GHz


-10^3
-10^2
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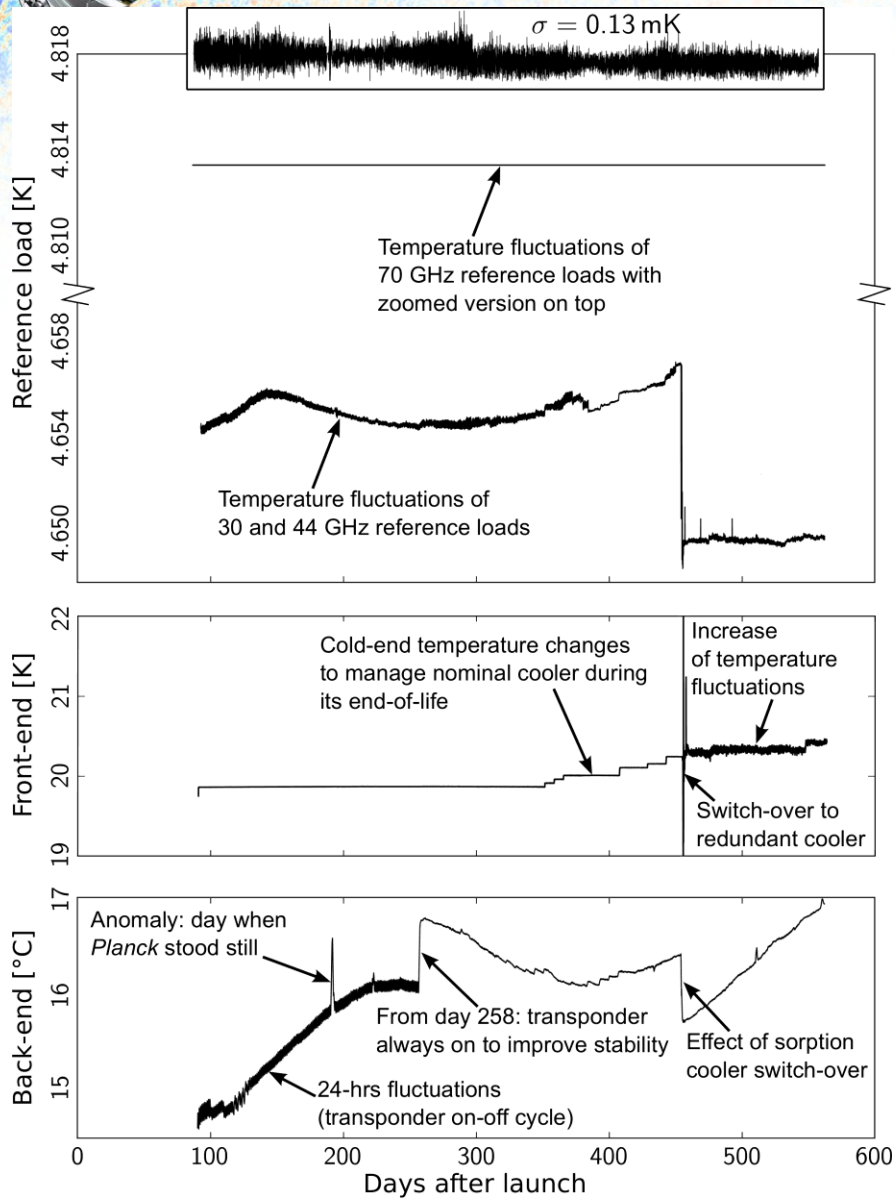
-1 0 1
10
10^2
10^3
10^4
10^5
10^6
30−353 GHz: δT [μK_{CMB}]; 545 and 857 GHz: surface brightness [kJy/sr]

Systematic Errors

- ADC nonlinearity –
  - Effect visible in a few channels, in the DC radiometer levels. Mapped using flight data and corrected. Does not affect science
- Additive instrumental effects
  - Thermal signatures
  - Electronics noise
- Calibration
  - Time variability and mis-estimation
- Optics
  - Beam asymmetry
  - Sidelobes
  - Beam efficiency
- Bandpass asymmetry correction
  - Challenges from limitations in the ground data.
  - Important for foregrounds, pretty well in hand- continuous improvement

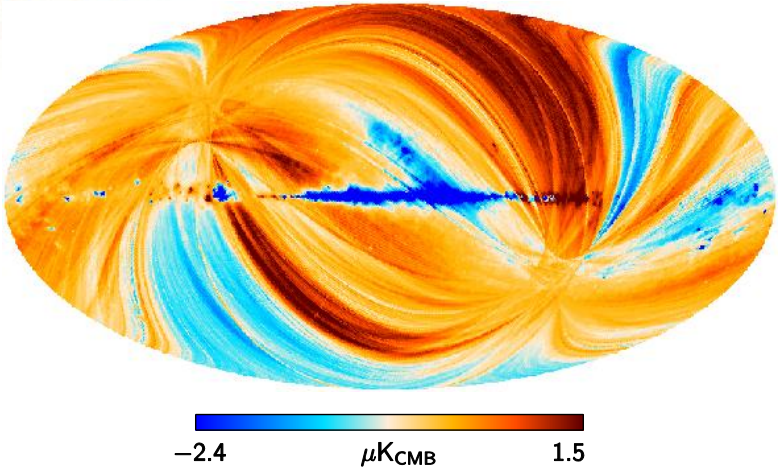


The Thermal environment for LFI is not perfectly benign:

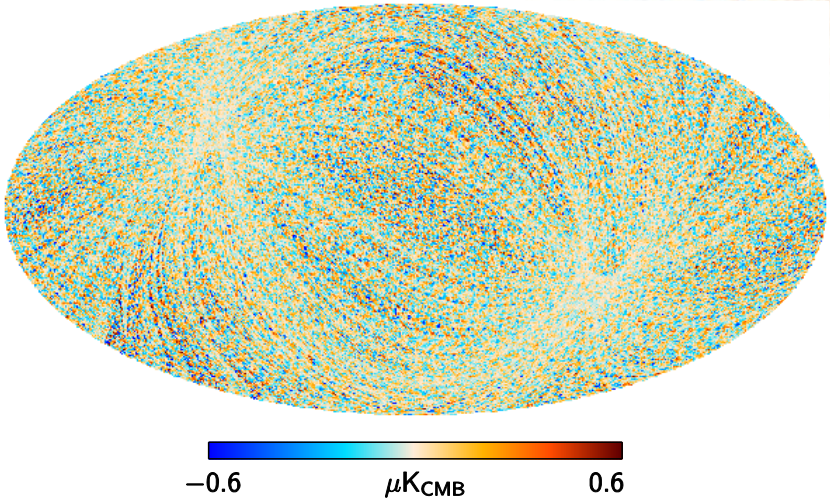
- Very stable on short (<60 Sec= 1 revolution) timescales, particularly 4K loads
- Significant variability on longer times:
  - Diurnal variations first survey
  - Sorption cooler updates
  - S/C switchover
- Effects at all stages:
  - Focal plane (offsets and gain)
  - Back End (same)
  - 4K loads (offsets)
- Slowly changing offsets are effectively removed via destriping.
- Gain effects are our primary headache.

Sample systematic effects maps (30 GHz)

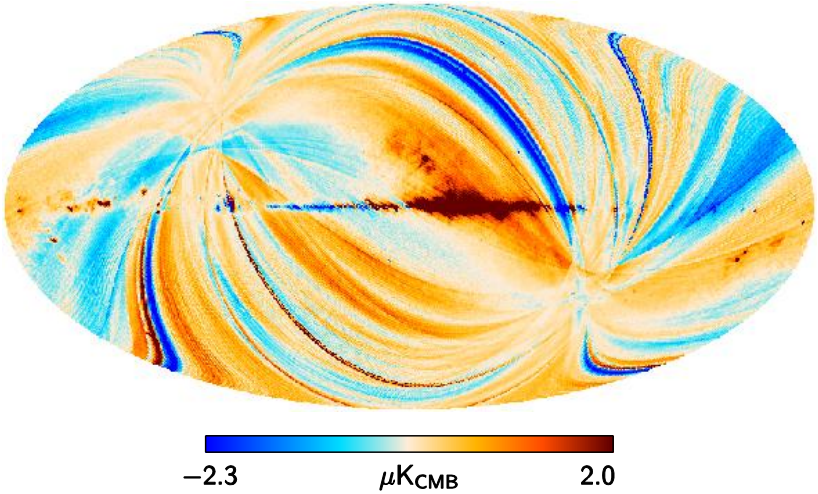
ADC correction



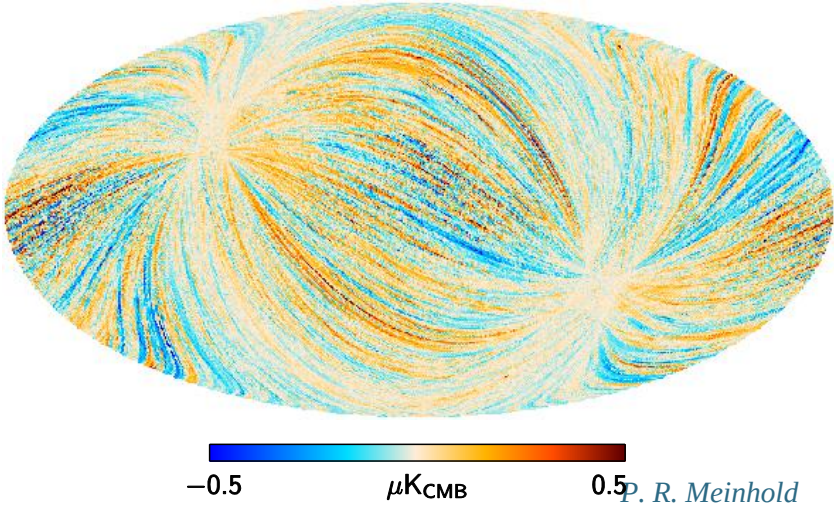
Electronics ‘spikes’

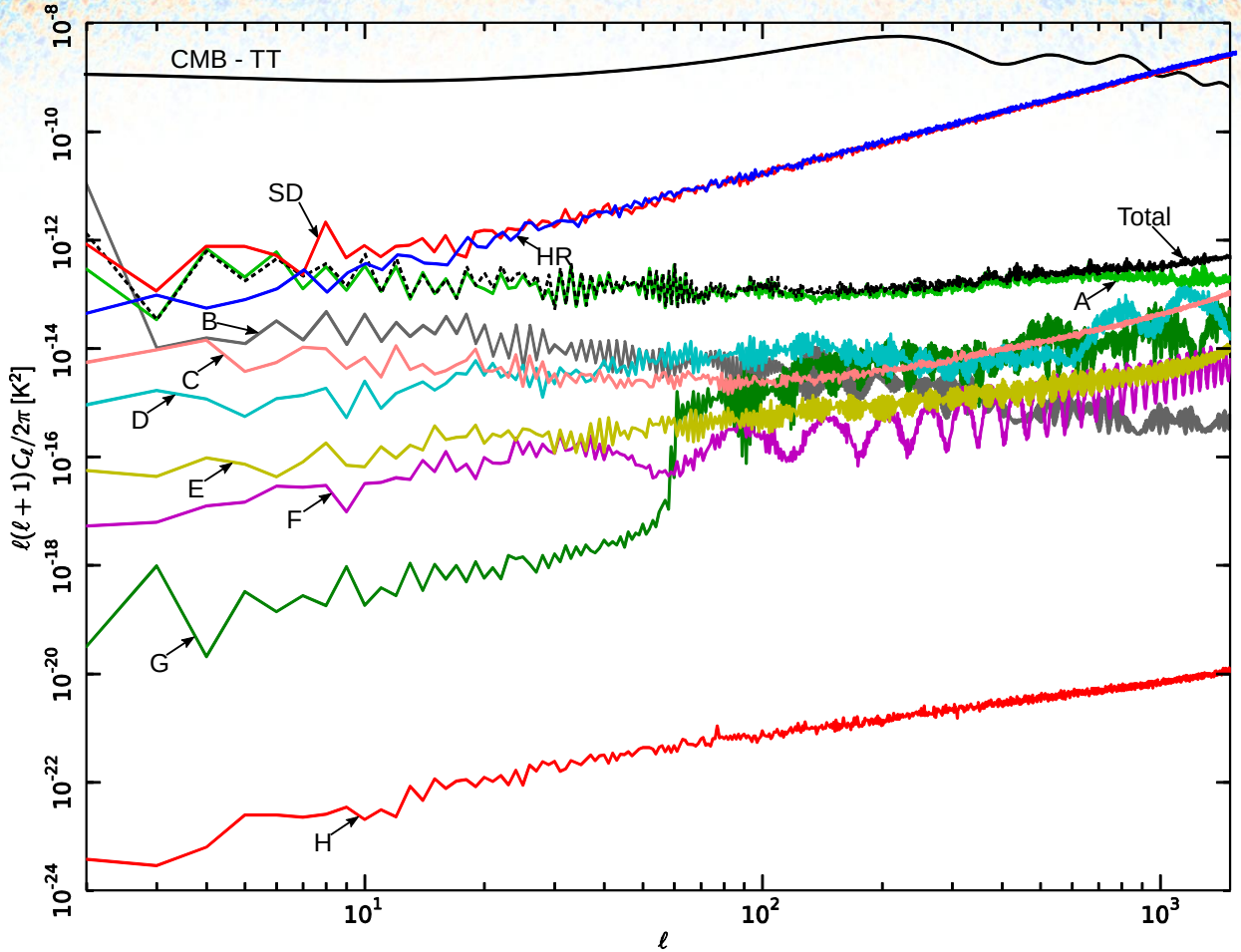


Gain mis-estimation *



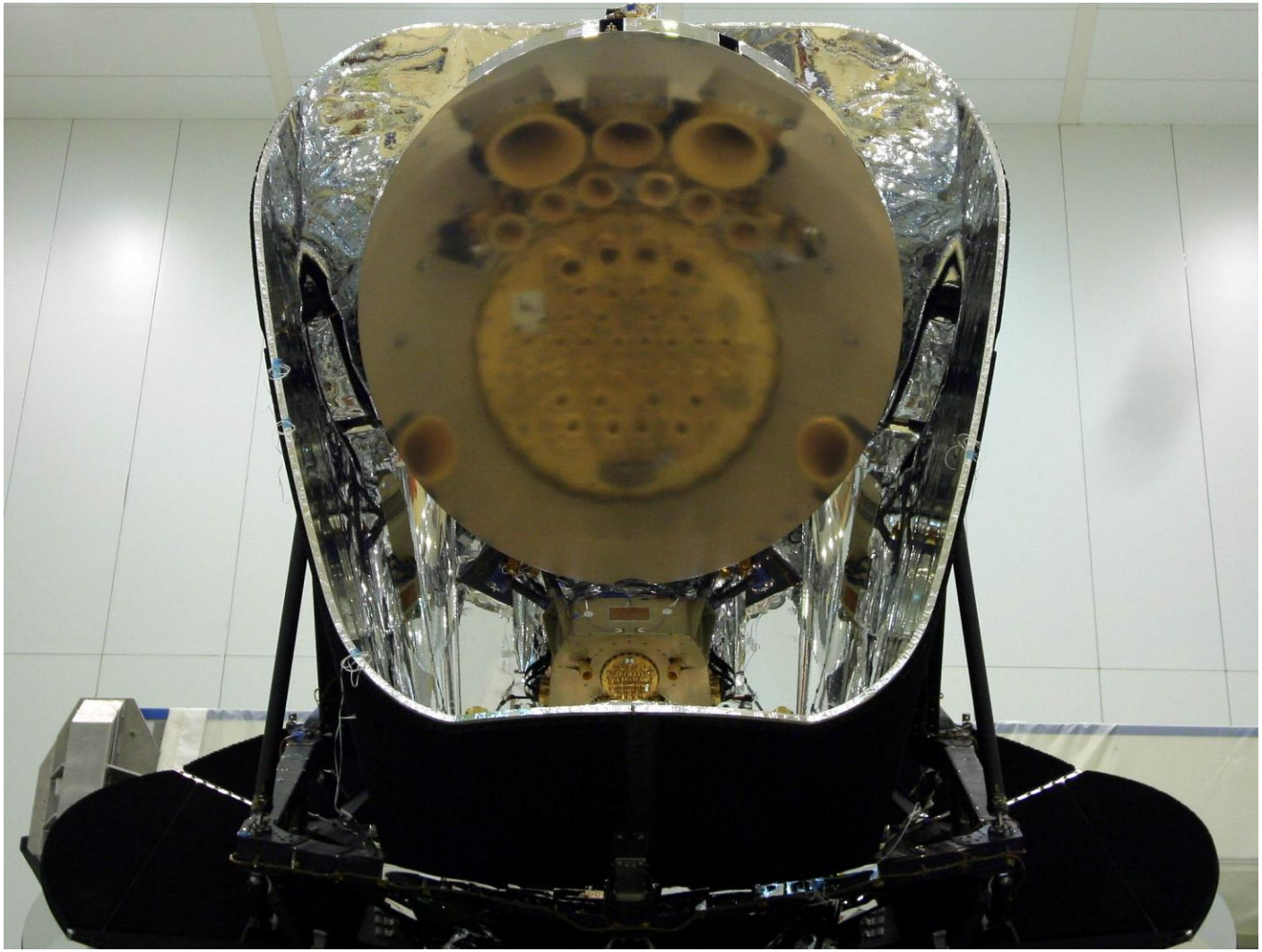
Combined Thermal



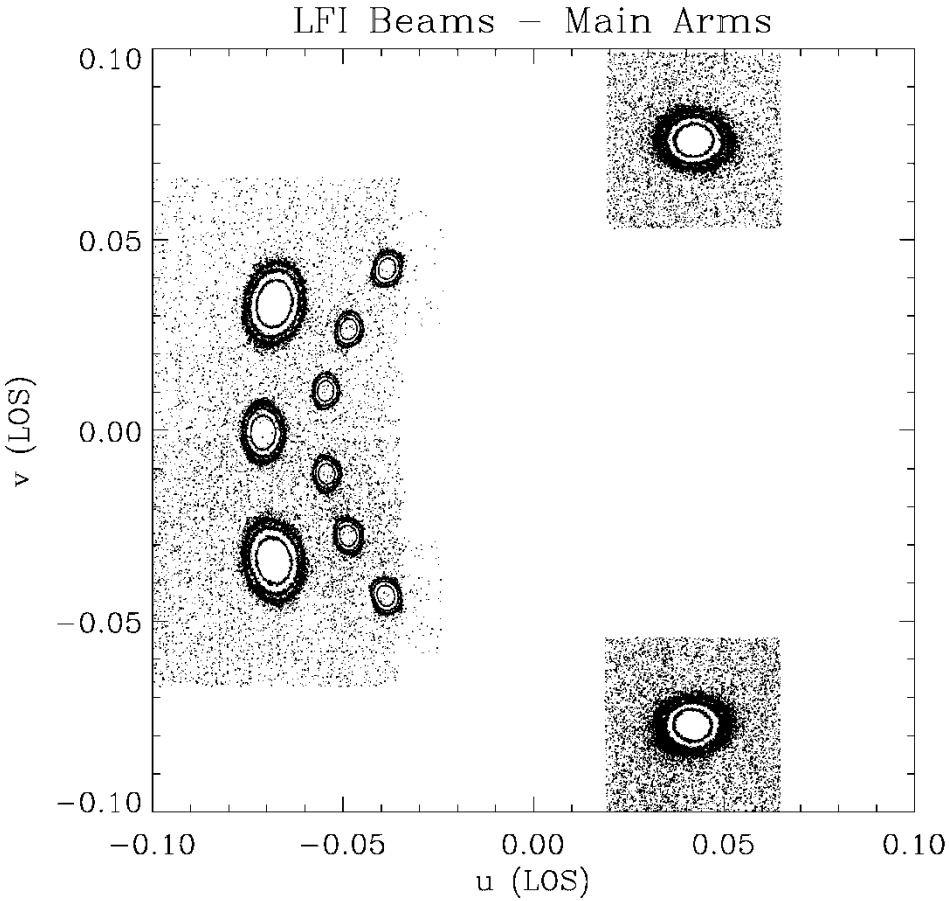


CMB - TT	(E) Bias uct.	
(A) Gain uncertainty	(F) Temp. uct. (4 K)	(SD) Survey di erence
(B) Far sidelobes	(G) 1-Hz spikes	(HR) Half-ring noise
(C) ADC	(H) Temp. uct. (300 K)	
(D) Temp. uct. (20 K)	Total	

What's not to like here?



Reconstructed focal plane

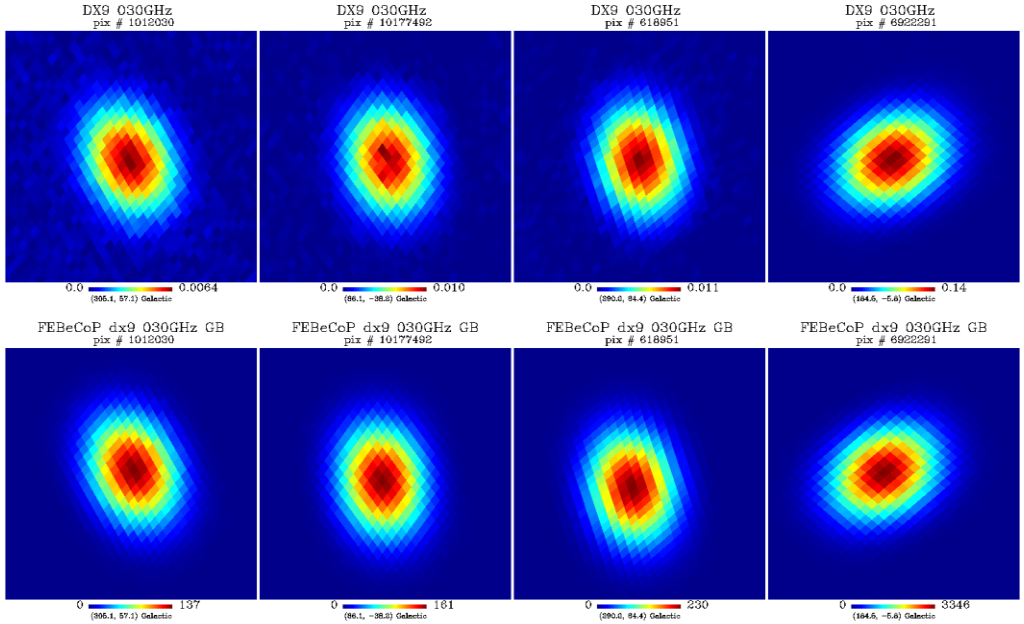


The positions of the LFI beams are found using the planet scans. The detailed shape of the main beams for use in later analysis is determined by referencing the GRASP MrGTD optics model to the Jupiter scans.

Effective Beams

Sources

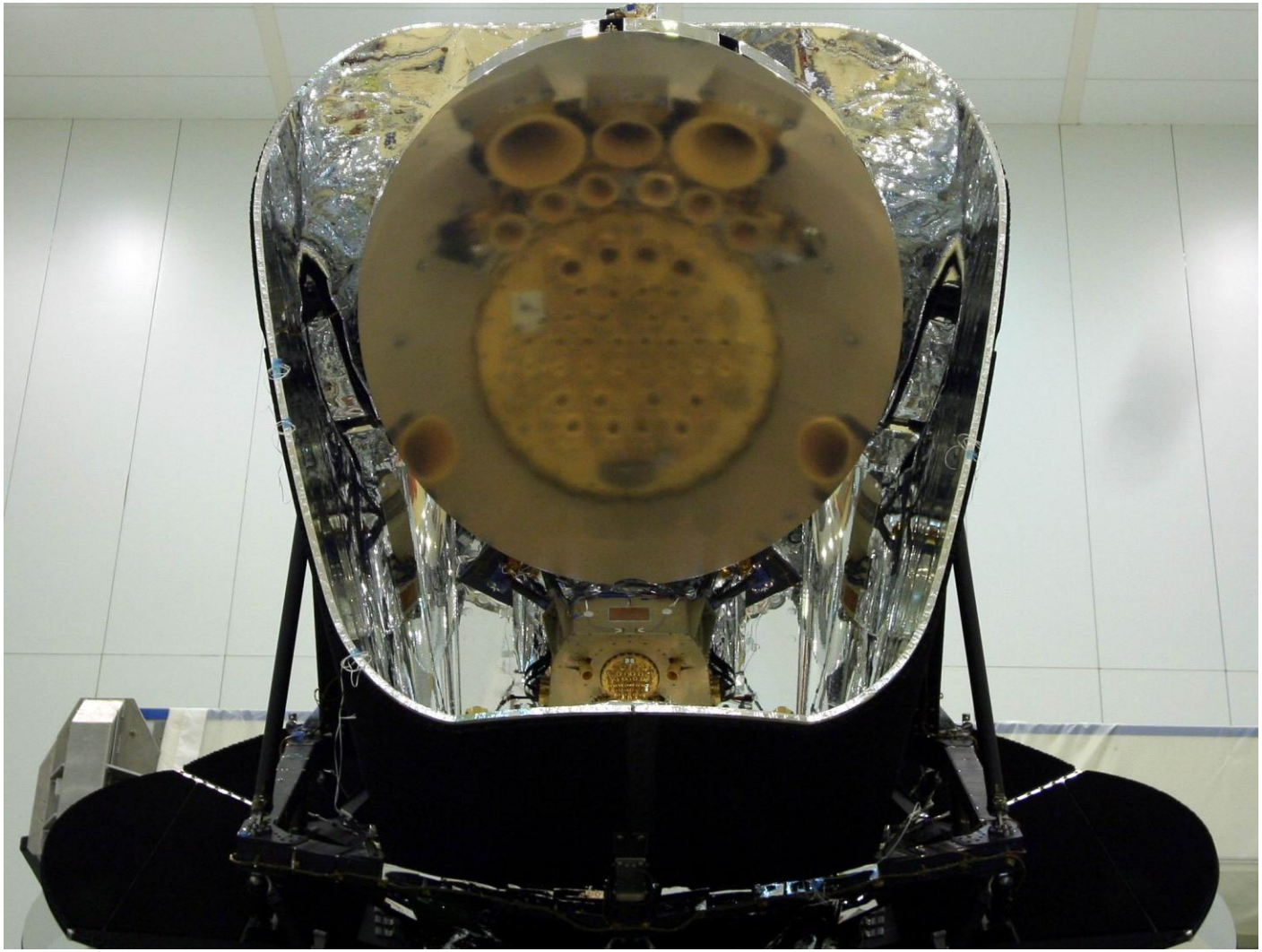
Effective beams



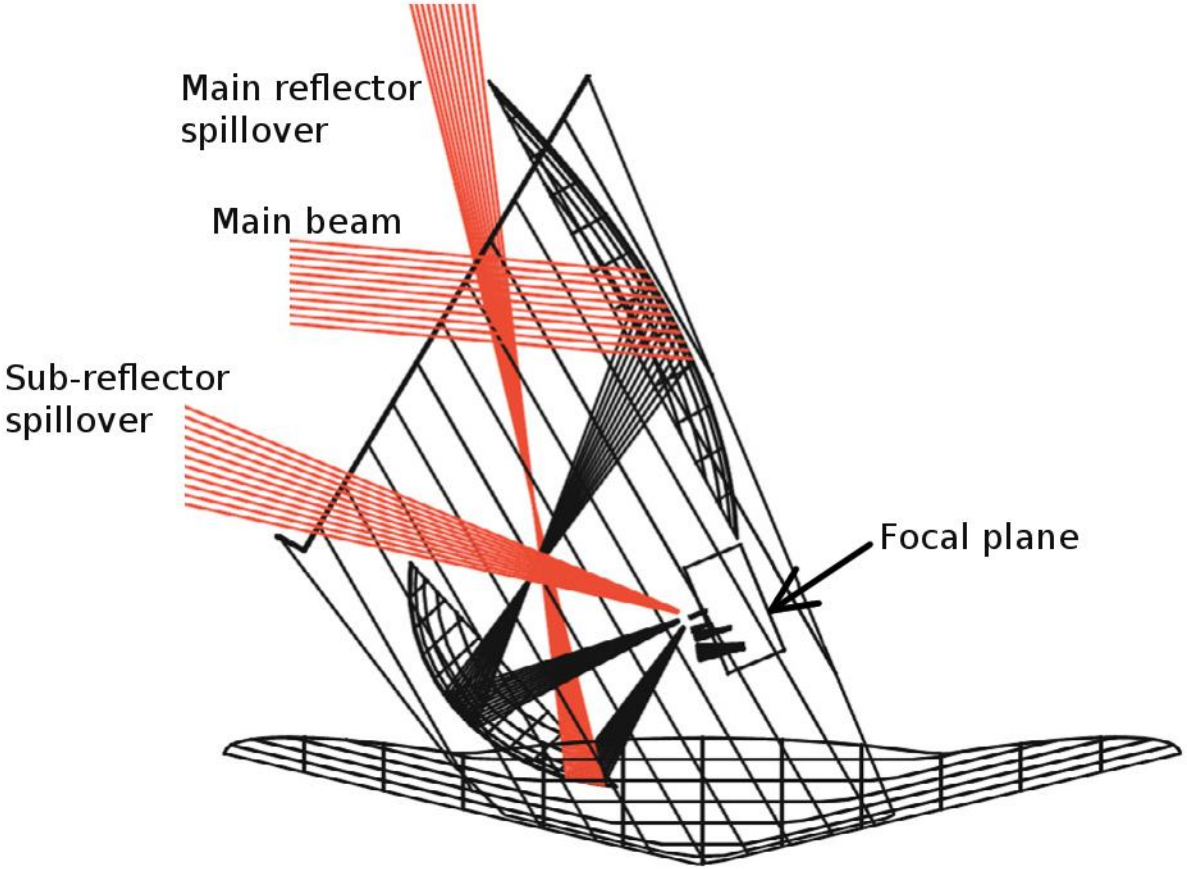
As Planck scans the sky, the elliptical beams sample different regions at different angles. Combing surveys and different horns requires careful accounting of the weighting of the observations. FEBECOP is the main Planck tool for doing this, producing ‘effective beams’. For LFI, optical inputs to FEBECOP come from GRASP simulations

Its critical to use the proper window function based on these effective beams to analyze the maps.

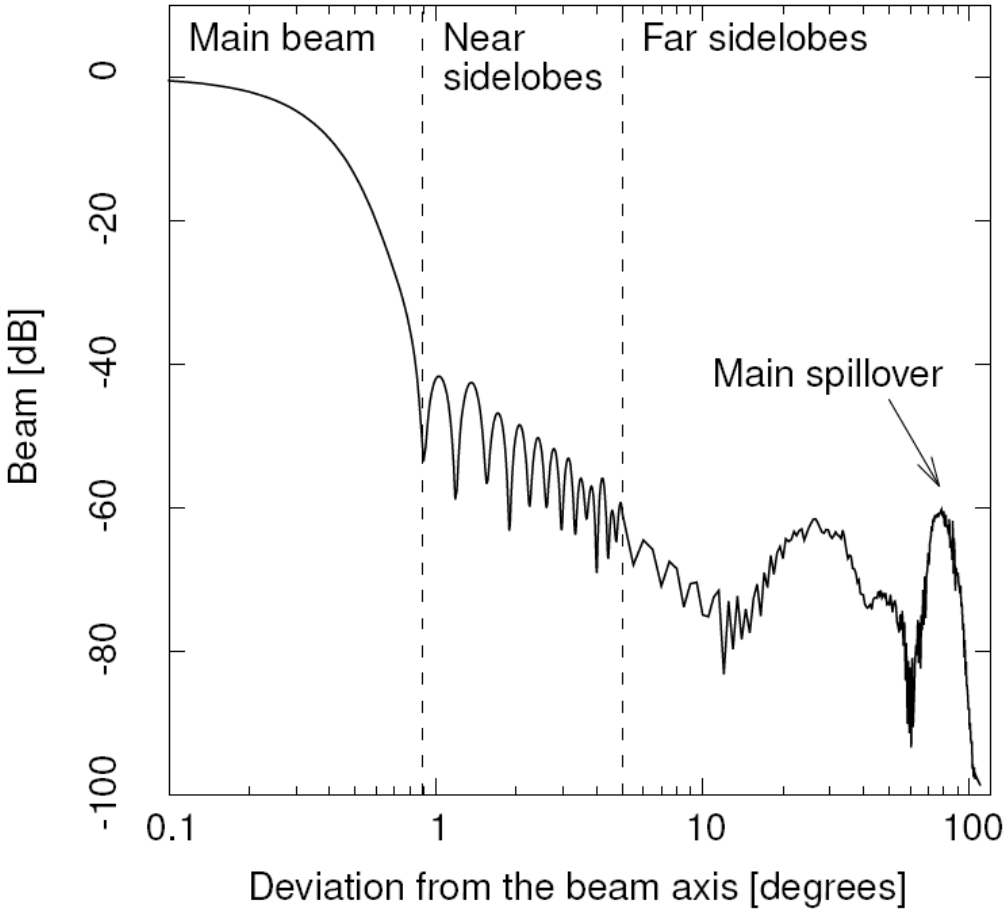
What else is not to like?



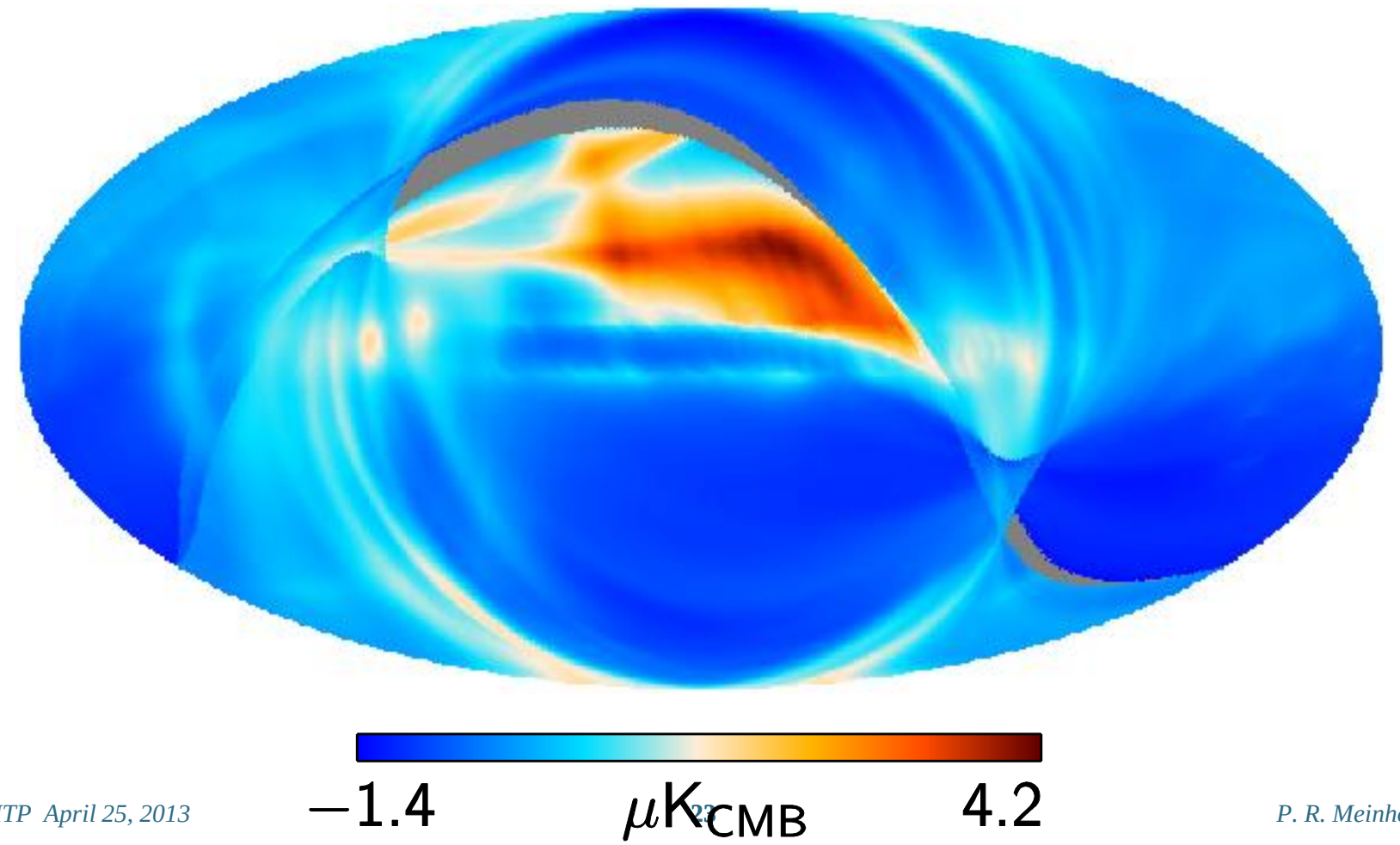
Routes for off axis response on the Planck telescope



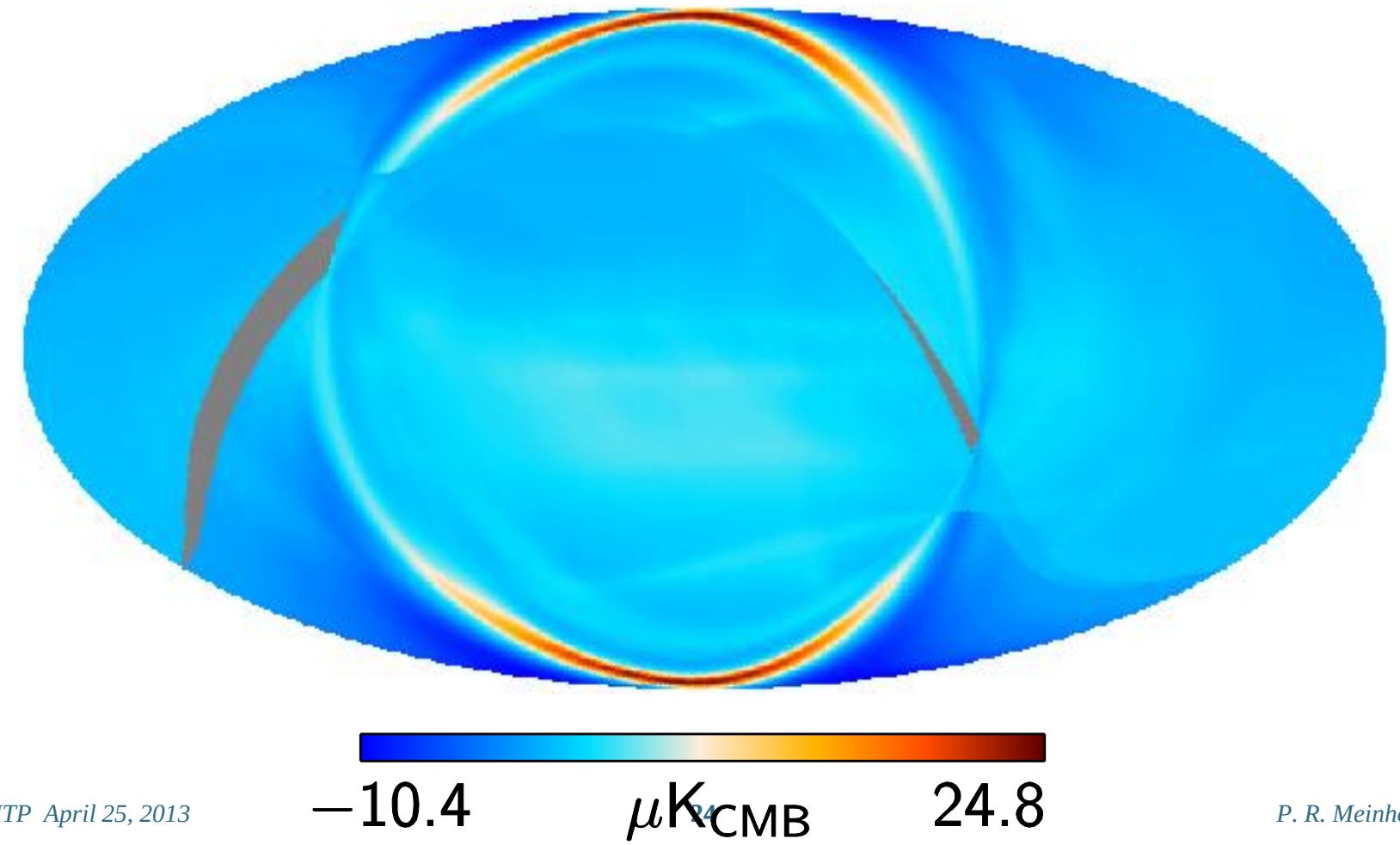
GRASP simulated beam profile (representative cut, 30 GHz)



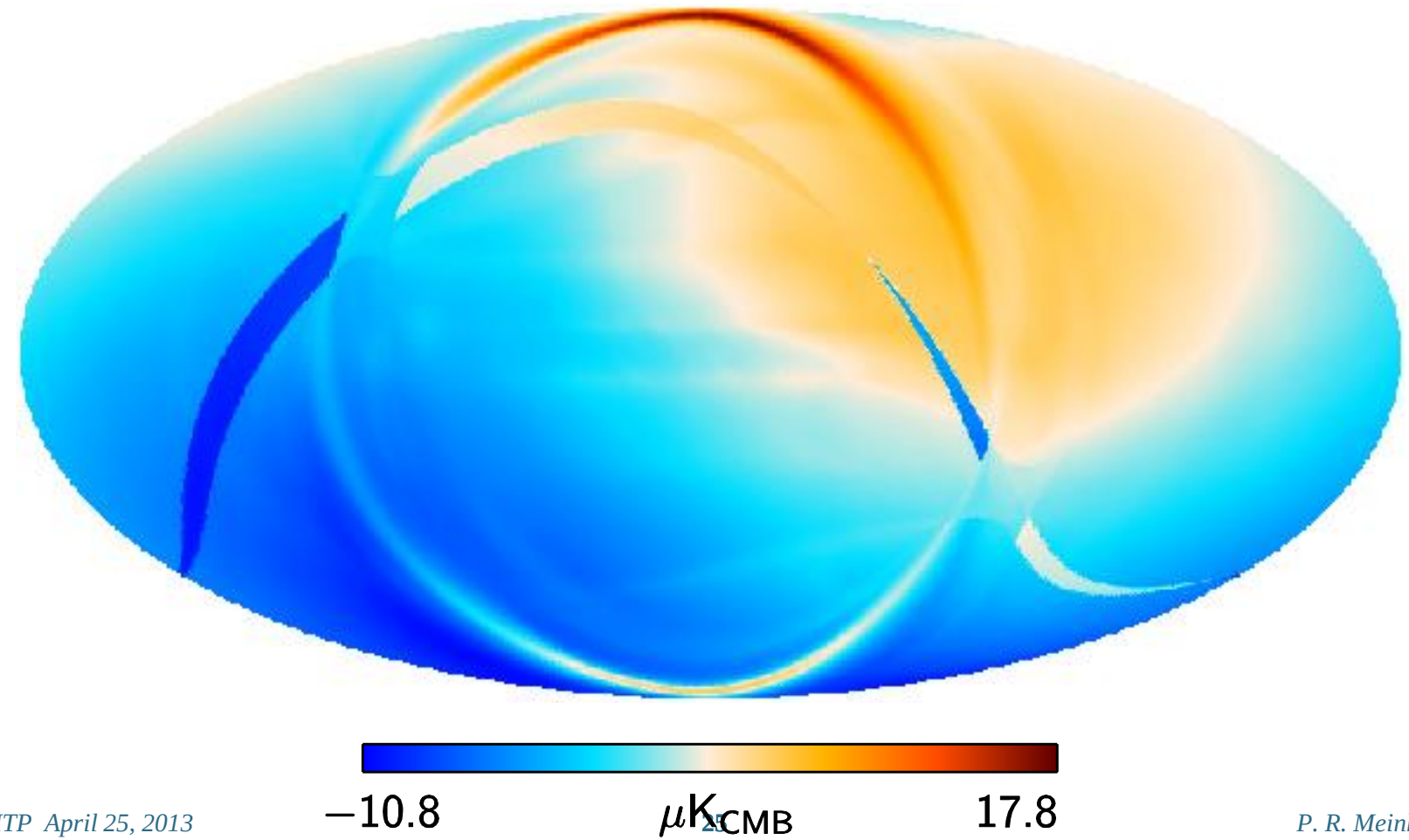
30 GHz: galaxy as seen through sidelobes, survey 1 (frequency dependent 'band-weighted' grasp model)



30 GHz: galaxy as seen through sidelobes, survey 2 (frequency dependent 'band-weighted' grasp model)

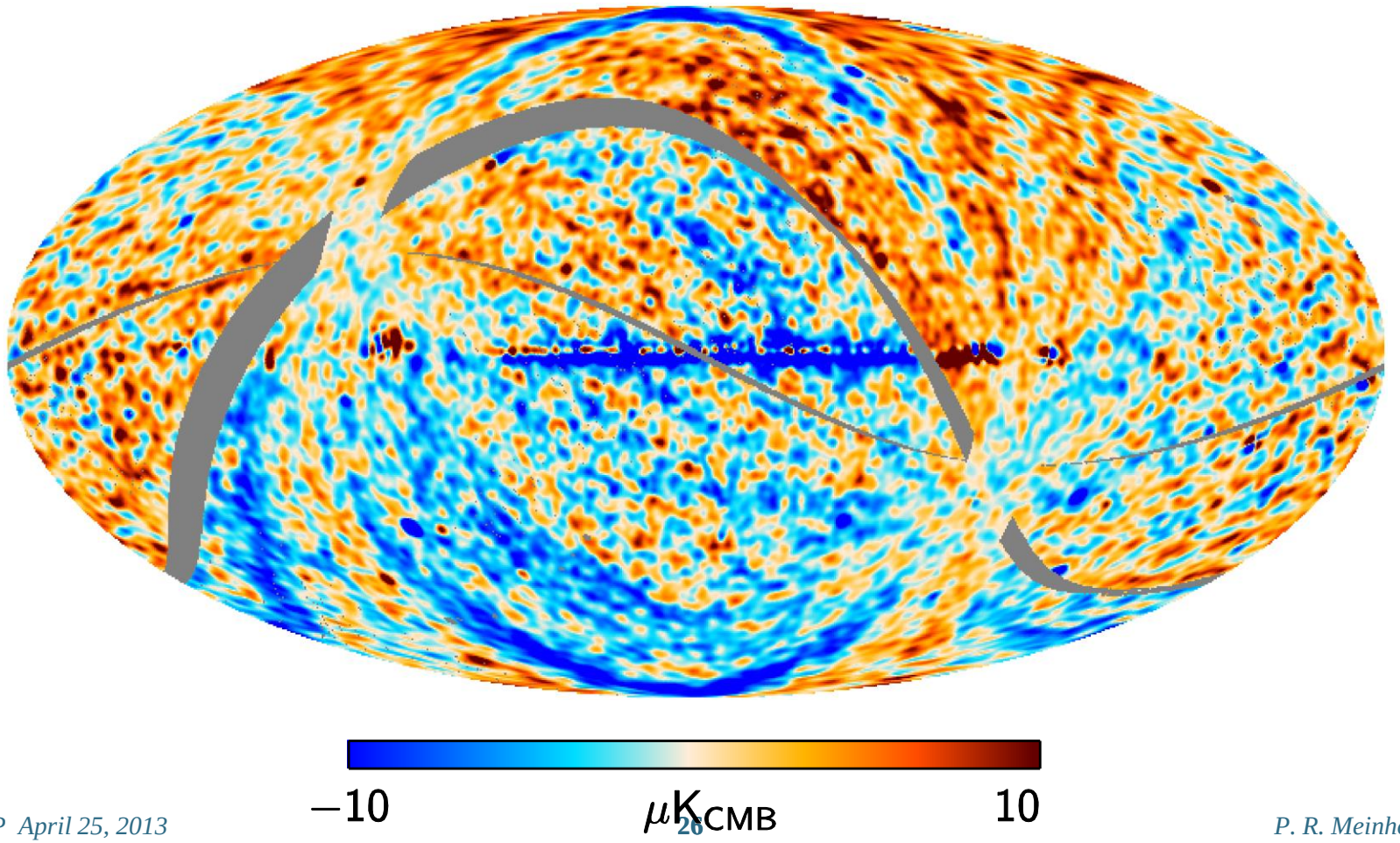


30 GHz: Galaxy + dipole seen through sidelobes, survey 2- survey 1

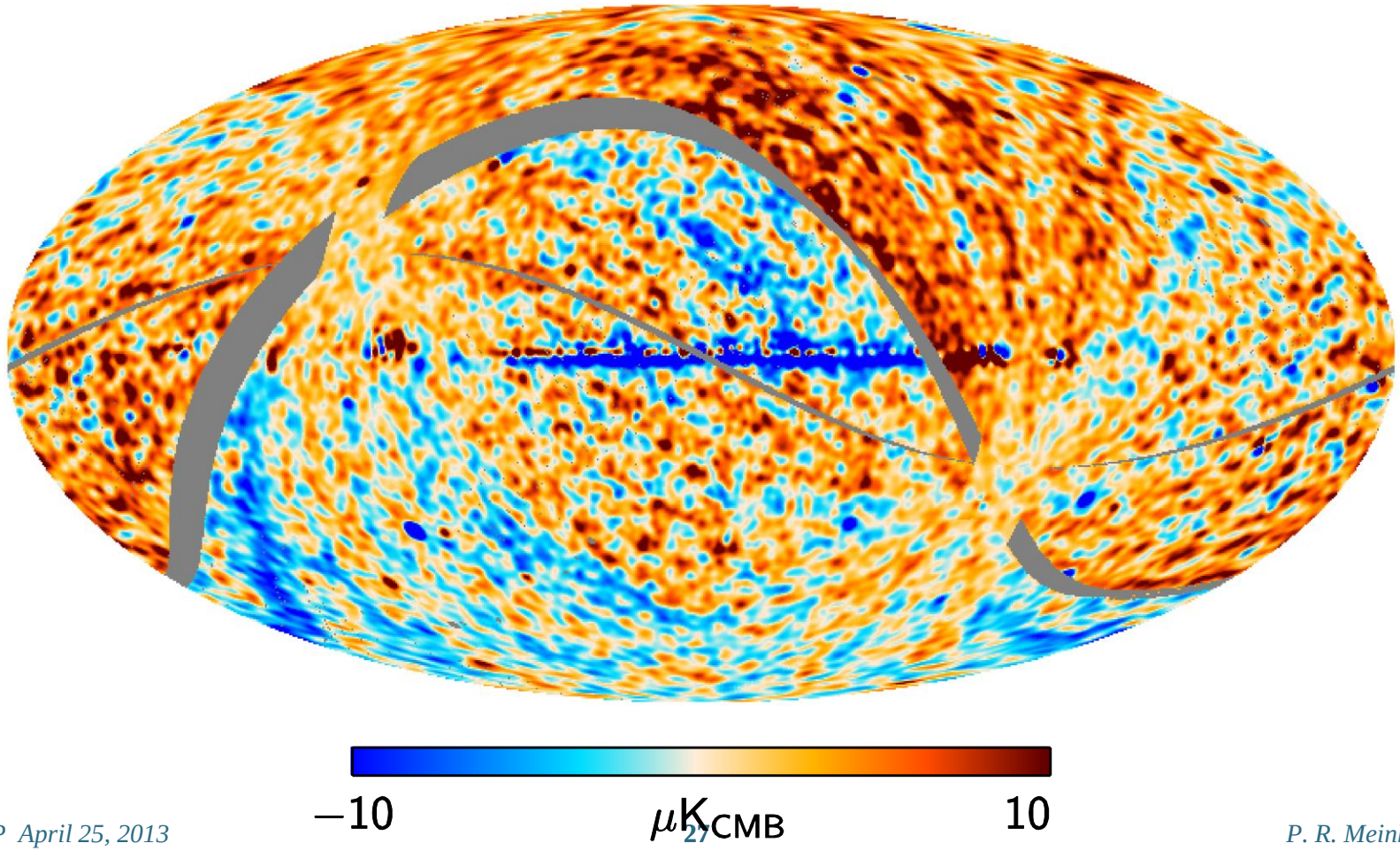


30 GHz Data: Survey 1- survey 2

(sorry, sign is flipped!)



30 GHz Survey1-Survey2 – sidelobe model (dipole+galaxy seen by sidelobes)



Far sidelobe beam fraction, estimated from GRASP

Beam	η (%)	f_{sl} (%)	Ω_{opt} (arcmin^2)	Ω_{sim} (arcmin^2)	Ω_{scn} (arcmin^2)
70 GHz					
18S	99.34	0.66	198.10	203.28	205.81
18M	99.42	0.58	196.89	201.84	203.98
19S	99.29	0.71	188.65	193.34	193.51
19M	99.35	0.65	148.23	191.60	195.04
20S	99.18	0.82	181.21	185.63	185.51
20M	99.21	0.79	180.43	185.20	185.45
21S	99.20	0.80	182.50	186.94	186.63
21M	99.21	0.79	181.26	185.71	183.87
22S	99.27	0.73	188.18	193.07	190.22
22M	99.34	0.66	187.45	192.07	188.24
23S	99.35	0.65	199.95	204.84	200.91
23M	99.43	0.57	198.74	203.72	200.99
44 GHz					
24S	99.84	0.16	576.85	590.99	591.86
24M	99.79	0.21	589.99	602.42	594.76
25S	99.80	0.20	1020.68	1041.63	1040.47
25M	99.79	0.21	967.93	990.28	996.72
26S	99.80	0.20	1006.67	1027.13	1019.03
26M	99.79	0.21	967.93	989.89	993.56
30 GHz					
27S	99.33	0.67	1153.02	1181.94	1184.64
27M	99.30	0.70	1158.00	1186.14	1174.48
28S	99.34	0.66	1153.14	1180.99	1188.41
28M	99.29	0.71	1152.56	1181.98	1179.34

These beam efficiencies **can** affect calibration. Our calibration method automatically corrects for contributions far from the main lobe, which is the bulk of the sidelobe fraction.

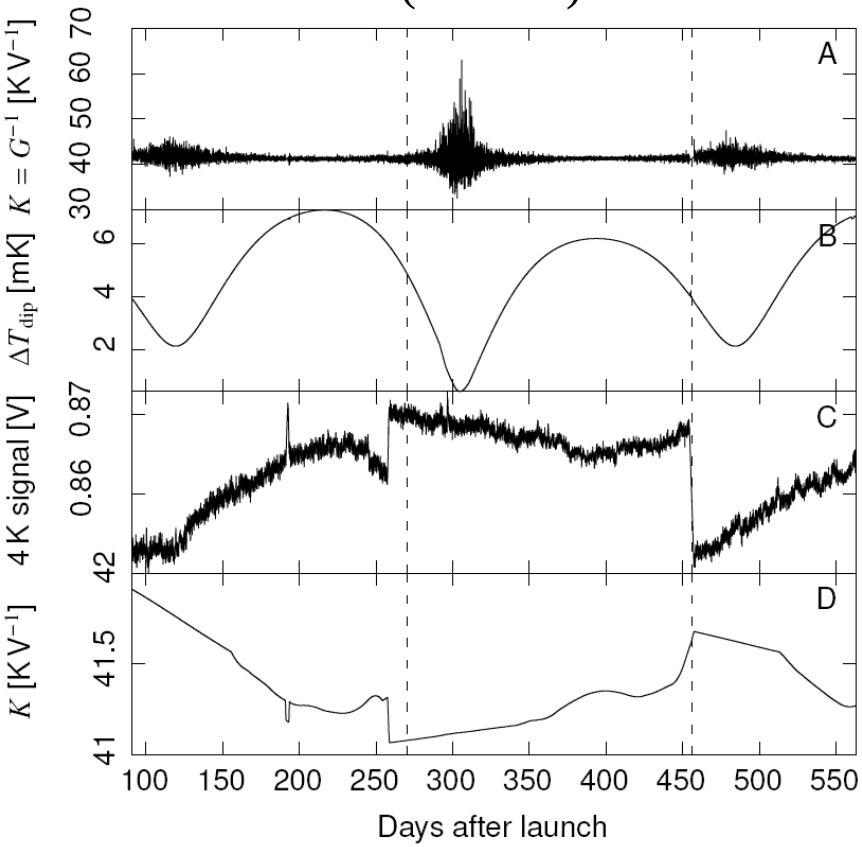
Beam efficiency was carefully considered as a cause of the apparent discrepancy with WMAP.
We extensively compared our methods with HFI and with the published WMAP method : we think we've done this right (and consistently) and residual errors are of order 0.1%

Calibration

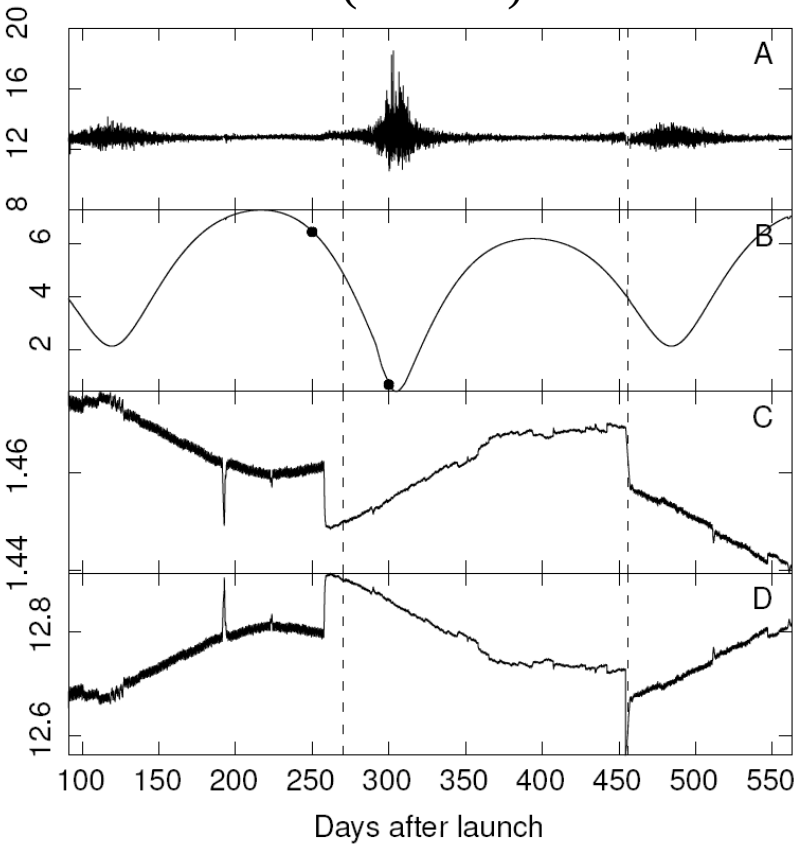
- Multiple methods:
  - Iterative solar dipole calibration
    - The iteration over the mission pulls the calibration to the Orbital dipole
    - S/N is low, and really terrible for some periods of time.
    - At 30 GHz, contamination from far sidelobe pickup of the galaxy is evident
  - Relative calibration from DC radiometer outputs ‘DeltaV ‘ Calibration
    - Highly dependent on ADC linearity and knowledge of the radiometer
- We rely on survey differences to guide our choices, and make extensive internal comparisons among radiometers and on sources and planets.
- For the release:
  - 30 GHz uses ‘Delta V’ calibration, tied to the solar dipole with an overall scaling
  - 44 and 70 GHz use the iterative dipole calibration with smoothing

Representative Calibration plots

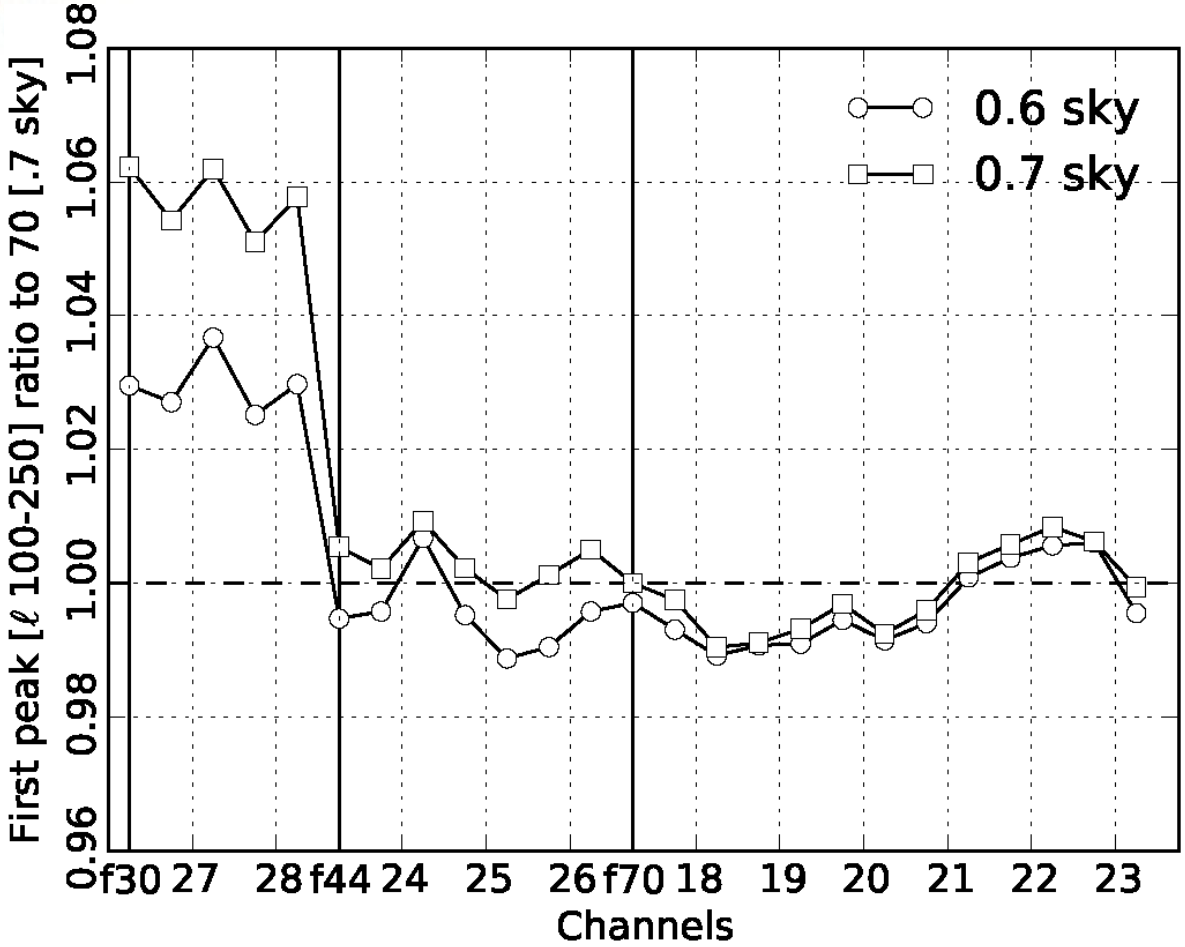
LFI 21M
(70 GHz)



LFI 27M
(30 GHz)

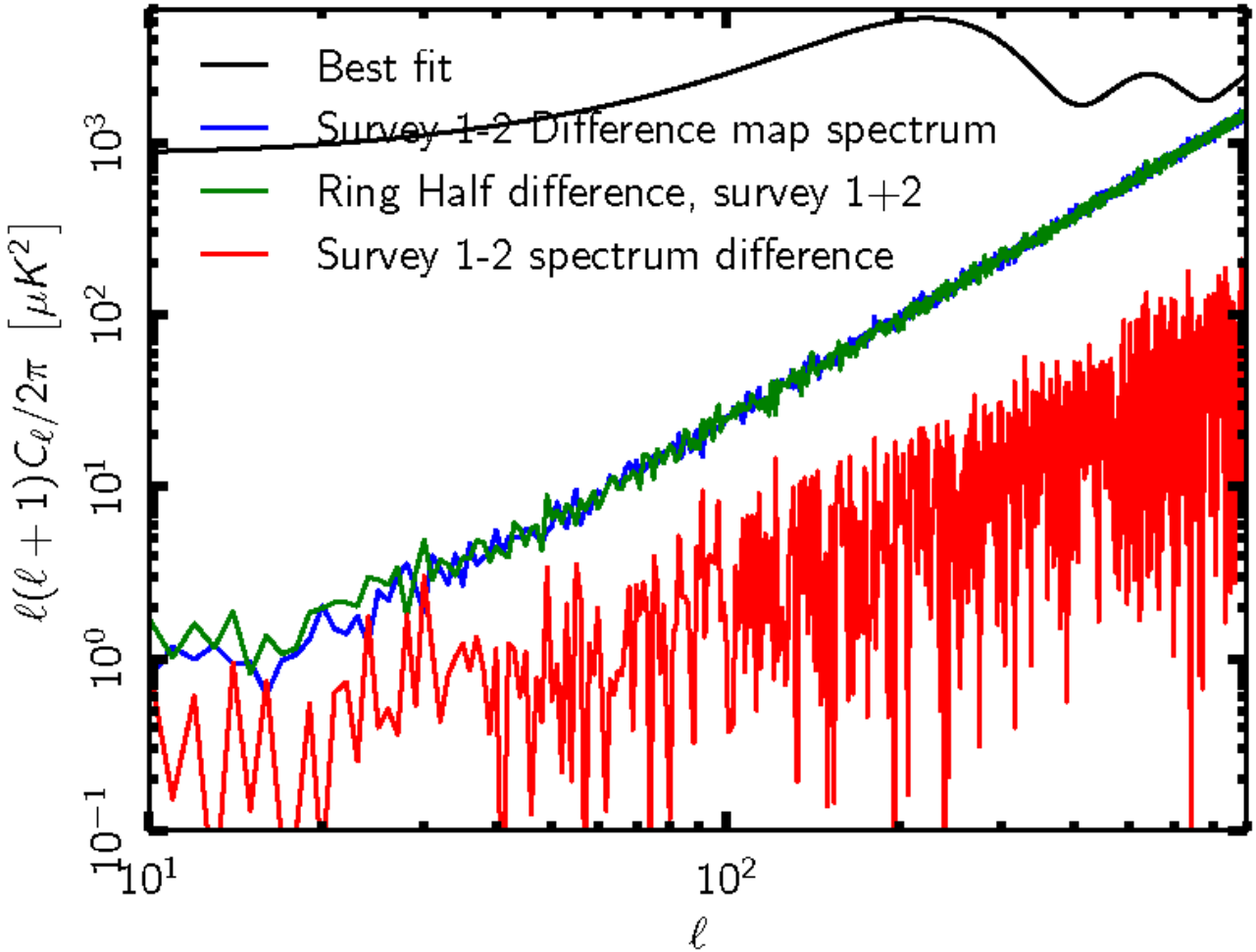


Internal Cal consistency using first acoustic peak (angular power spectra compared over 100 < l < 250)

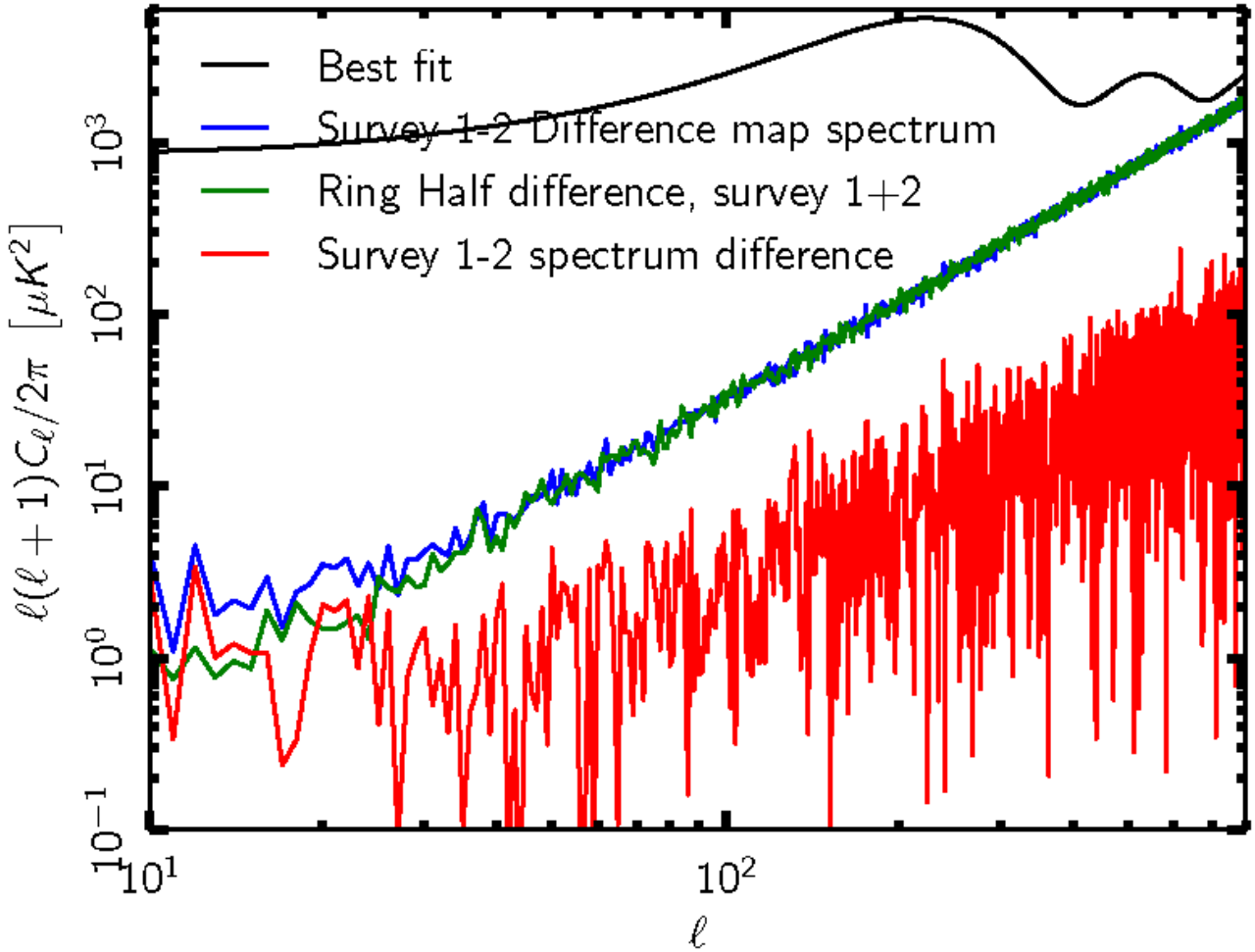


Comparisons include correction via FEBECOP based window function for each receiver, numbers plotted relative to 70 GHz Full frequency band at 0.7 sky fraction

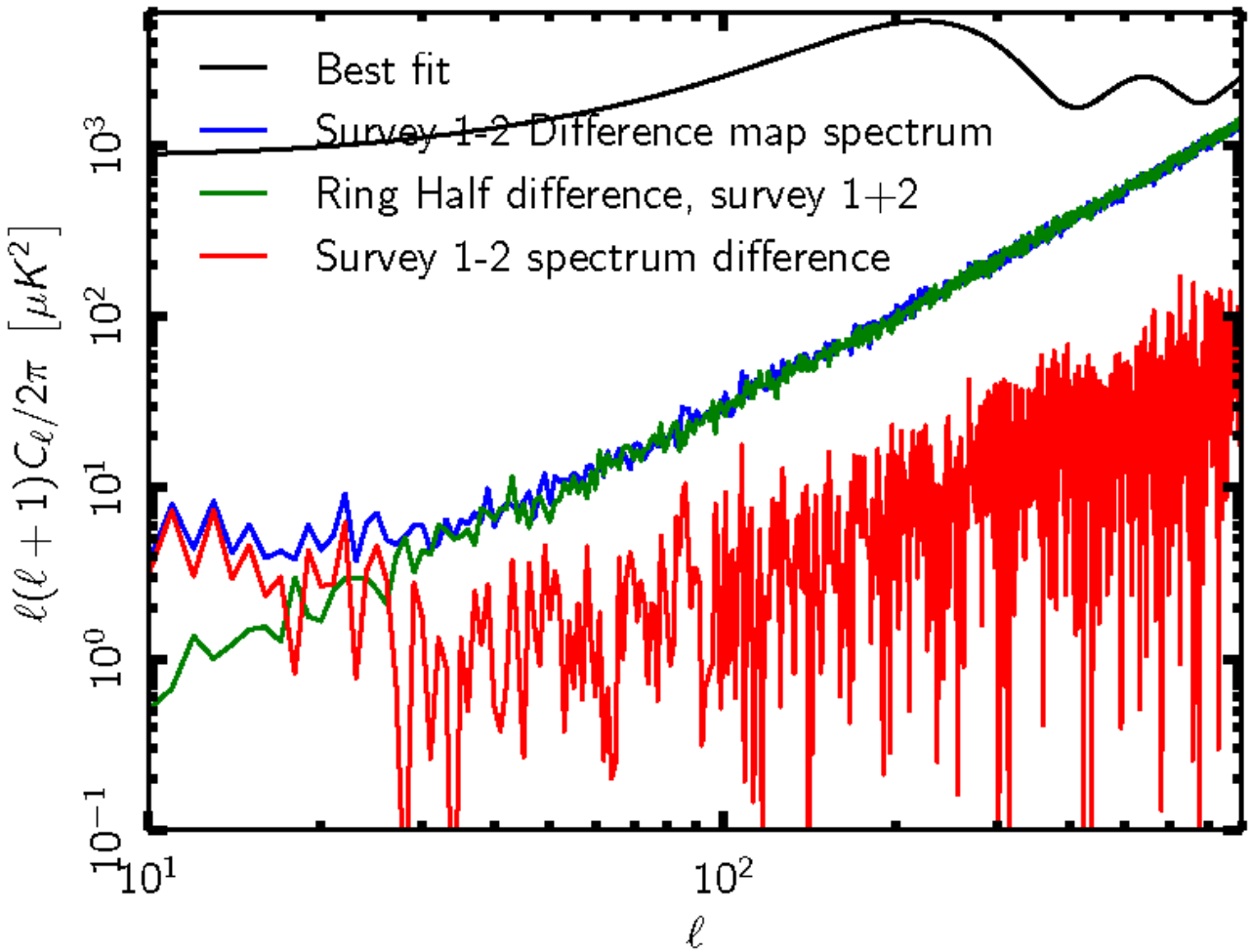
Spectra From null tests (70 GHz)



44 GHz


Best fit
Survey 1-2 Difference map spectrum
Ring Half difference, survey 1+2
Survey 1-2 spectrum difference
$\ell(\ell+1)C_\ell/2\pi\ [\mu K^2]$
10^{-1}
10^0
10^1
10^2
10^3
10^1
10^2
ℓ

30 GHz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Survey 1-2 spectrum difference
$\ell(\ell+1)C_\ell/2\pi\ [\mu K^2]$
10^{-1}
10^0
10^1
10^2
10^3
10^1
10^2
ℓ

What's next

Polarization

- Need to improve low **l** behavior
  - Far sidelobe corrections: GRASP calculations across the bandpass for every receiver
  - Inclusion of FSL response correction in the mapmaking pipeline
  - Alternative calibration schemes
    - Current dipole cal- S/N limited, unconstrained in places. More robust solvers and different constraints.
    - Delta V- needs more instrument effects included, thermal modeling
    - Others under development and test

What's Last

- Current plans are for Planck to be put into a stable Earth-trailing orbit in the early part of October.
- LFI will observe up until the very end
- There may be a sorption cooler regeneration as a test before switching off.