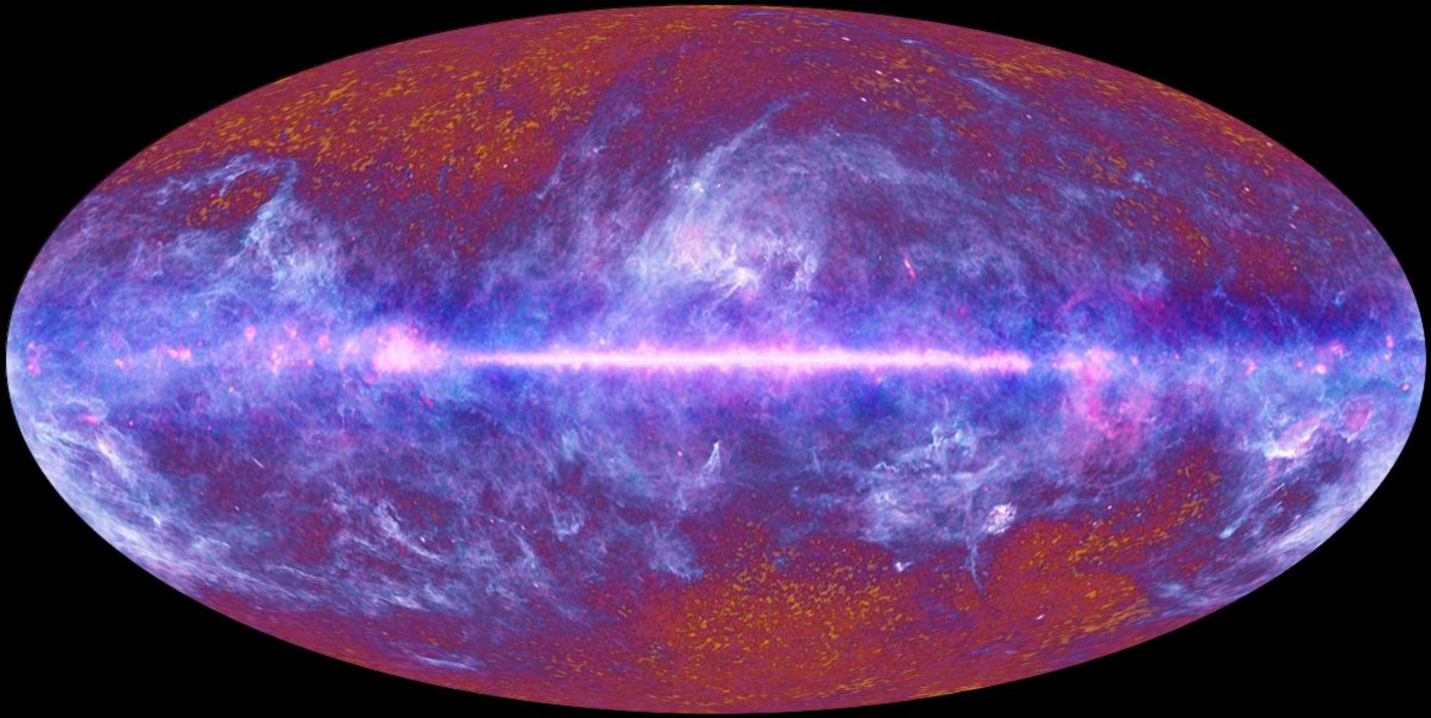
The millimeter and submillimeter sky in the Planck mission era
Paris, 10-14 January 2011

Planck-LFI data and performance



Marco Bersanelli
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On behalf of the Planck-LFI Team

Planck-LFI: the Team

Planck early results: first assessment of LFI in-flight performance

A. Mennella[19,33], M. Bersanelli[19,35], R. C. Butler[34], A. Curto[43], F. Cuttaia[34], R. J. Davis[46], J. Dick[53], M. Frailis[33], S. Galeotta[33], A. Gregorio[20], H. Kurki-Suonio[13,28], C. R. Lawrence[45], S. Leach[53], J. P. Leahy[46], S. Lowe[46], D. Maino[19,35], N. Mandolesi[34], M. Maris[33], E. Martínez-González[43], P. R. Meinhold[16], G. Morgante[34], D. Pearson[45], F. Perrotta[53], G. Polenta[2,32], T. Poutanen[28,13,1], M. Sandri[34], M. D. Seiffert[45,6], A.-S. Suur-Uski[13,28], D. Tavagnacco[33], L. Terenzi[34], M. Tomasi[19,35], J. Valiviita[41], F. Villa[34], R. Watson[46], A. Wilkinson[46], A. Zacchei[33], A. Zonca[16], B. Aja[10], E. Artal[10], C. Baccigalupi[53], A. J. Banday[40,49], R. B. Barreiro[43], J. G. Bartlett[4,45], N. Bartolo[17], P. Battaglia[57], K. Bennett[26], A. Bonaldi[31], L. Bonavera[53,5], J. Borrill
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Planck Early Results: Low Frequency Instrument Data Processing

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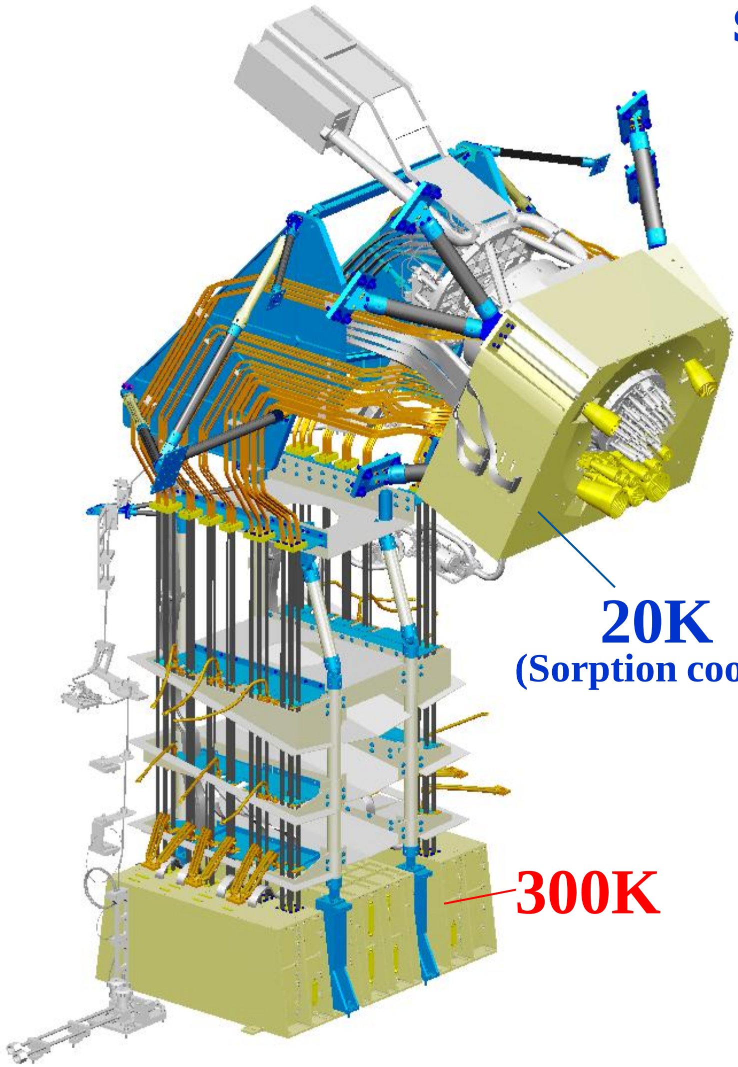
(Affiliations can be found after the references)

(main references for this presentation)

Planck-LFI: the Instrument

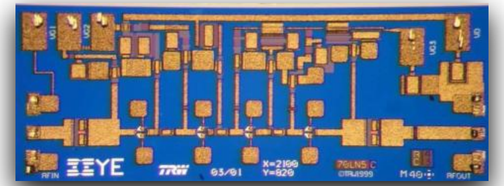
Sensitivity, stability & low systematics



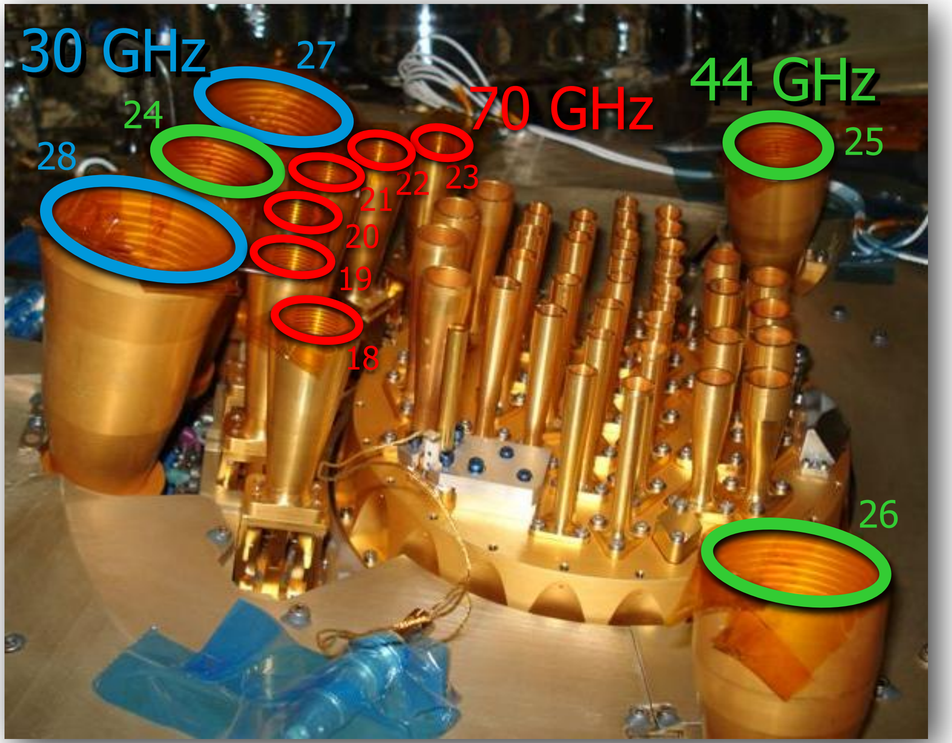
(MB et al 2010, Mandolesi et al 2010)

Sensitivity ($\Delta T/T \sim 3 \times 10^{-6}$/pix)

- State-of-the-art InP LNA technology
- Cryo operation
  20K Sorption Cooler
- 22-element array

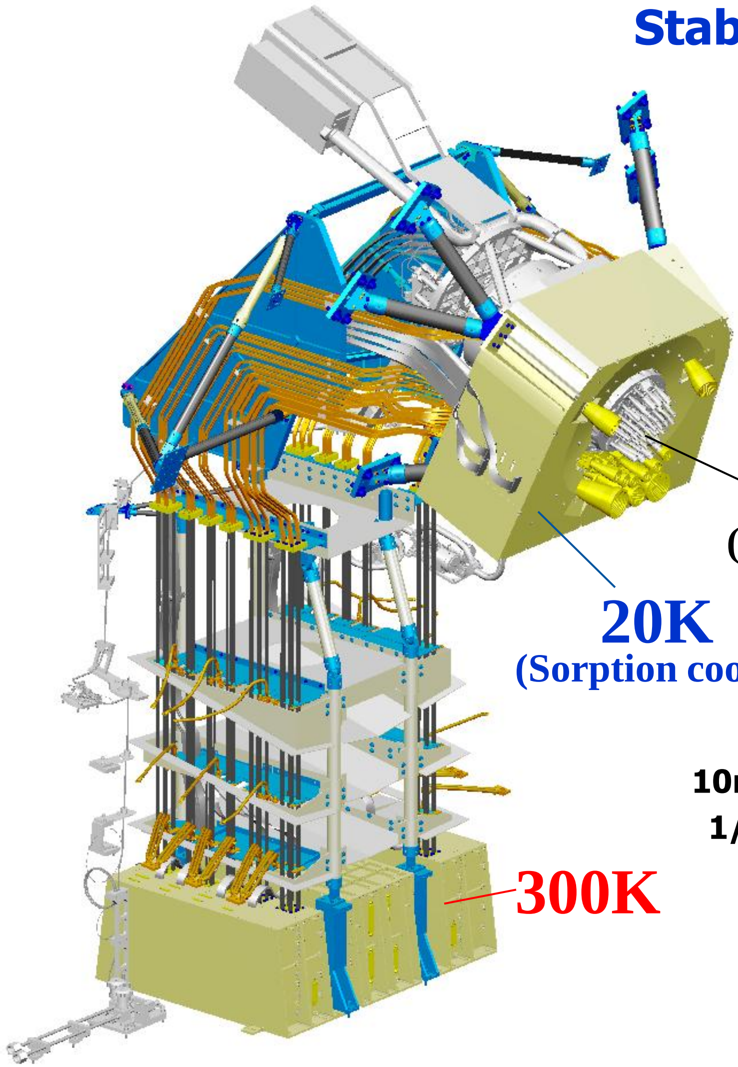


70 GHz MMIC HEMT



Planck-LFI: the Instrument

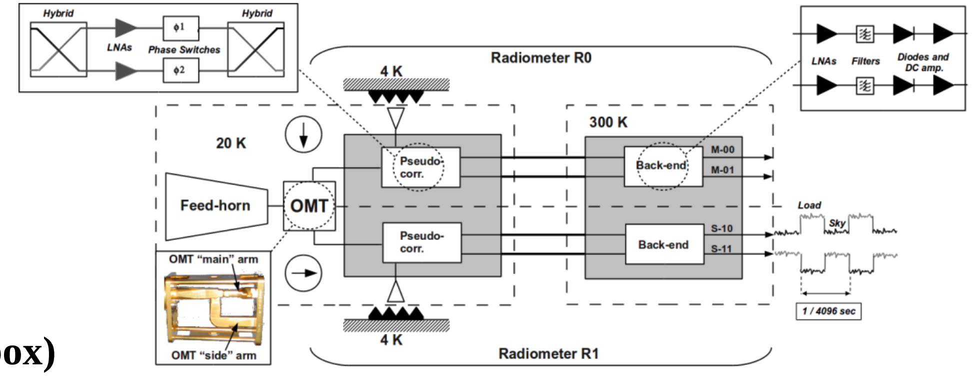
Sensitivity, stability & low systematics



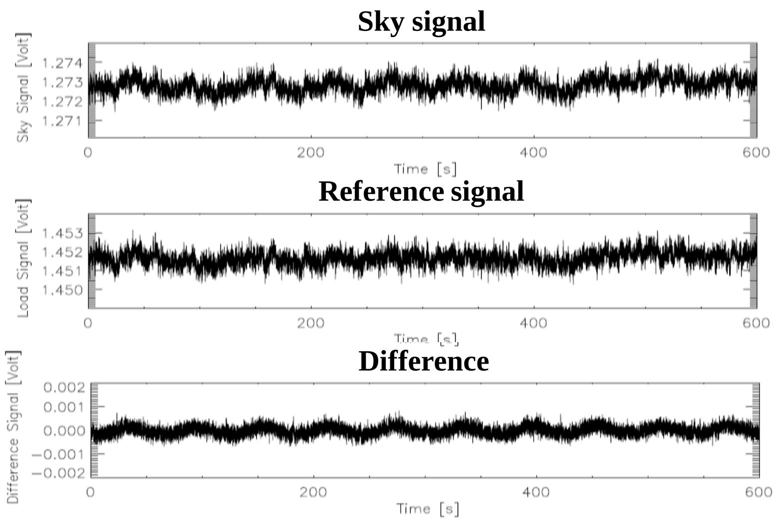
(MB et al 2010, Mandolesi et al 2010)

Stability (f_K < 50 mHz) & Low systematics (~1μK)

- Pseudo-correlation radiometer design
- Refs cooled to 4K

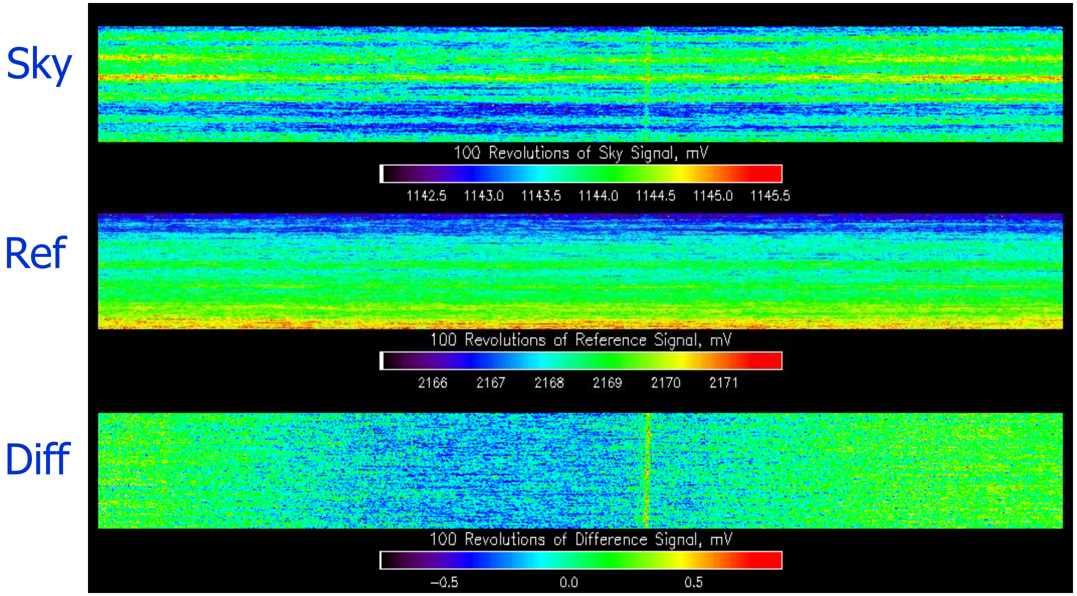


10min of flight data
1/44 LFI detectors
(LFI27S-11)

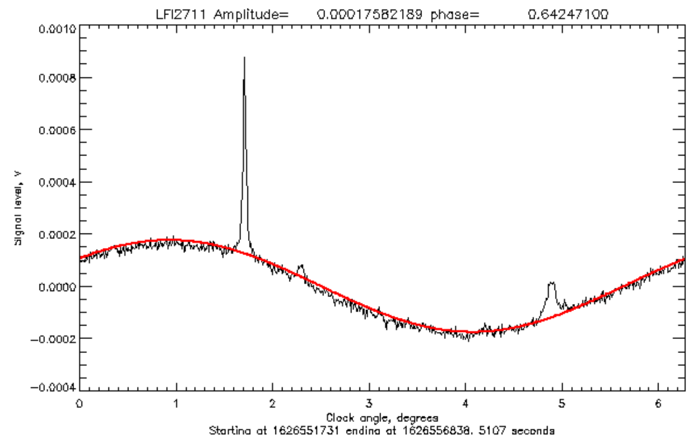


"First light"

Data from 14 Jun 09 (2 months before start of survey, NO tuning)



- Preliminary Dipole Calibration



In-flight tuning

(Jun-Jul 09)

(Cuttaia et al 2009, Gregorio et al 2011)

- Functionality tests …

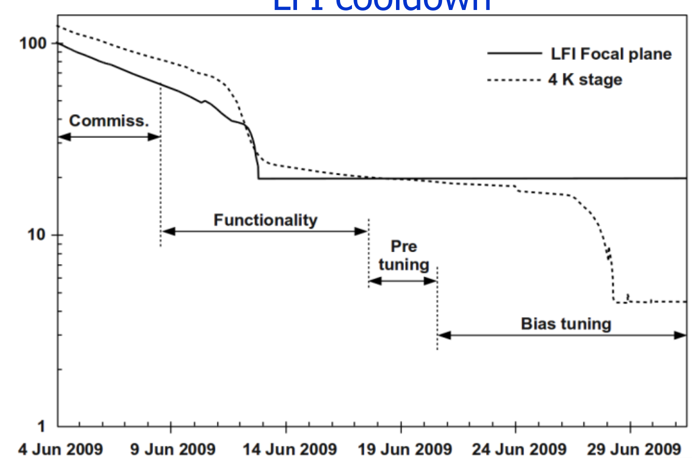
  → all 44 LFI detectors OK!

- Optimisation of bias for LNAs, Phase switches

  Exploit cool-down of HFI 4K stage (LFI loads)

- Tuning of electronics and compression parameters

LFI cooldown



Planck-LFI: Data Processing

(Zacchei, Maino, et al. 2011)

- Beginning of Nominal Survey: 13/08/2009
- Till now, LFI acquired about 500 days of data

11 Jan 2011 release based on OD's 91-389

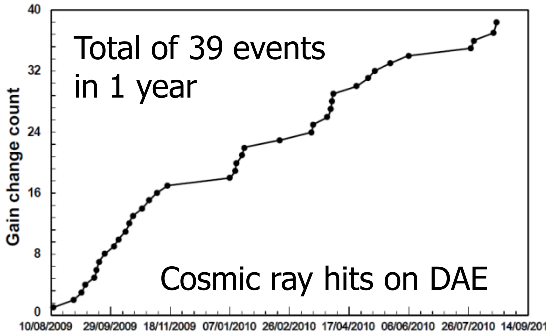
- No significant problems detected, no missed OD's

Percentage of missed data

		30 GHz	44 GHz	70 GHz
Missing	[%]	0.00016	0.00027	0.00039
Anomalies	[%]	0.41412	0.69726	0.41025
Maneuvers	[%]	8.29798	8.29798	8.29798
Usable	[%]	91.28774	91.0049	91.29138

Real gaps

Data flagged as not suitable for science
- Occasional Idrain steps
- DAE gain changes

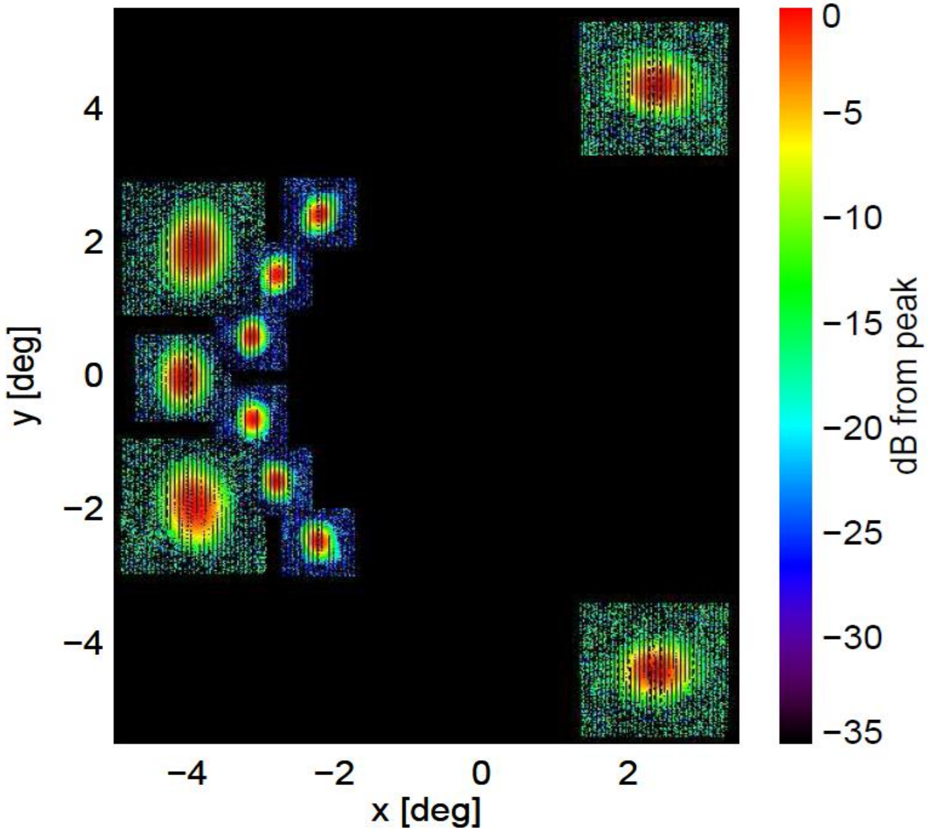


Science data acquired during re-pointing
- Currently not usable by pipeline
- In principle recoverable with full pointing information

- The stability of the pipeline contributed to the creation of ERCSC (first public product from Planck) with high quality

LFI Beams

(Sandri, Villa et al. 2010, 2011)



- Jupiter is by far best beam calibrator for LFI
  (in LFI beams: 24 Oct – 1 Nov, 2009)
- Use calibrated, differenced TOD's
  → Measure M and S radiometers independently
- 1/f fluctuations removed by destriping (Madam)

Beam ID	FWHM	FWHM Uncertainty
	70 GHz	
	Ave FWHM: 13.′01; ave e: 1.27	
LFI18	13.′39	0.170′
LFI19	13.′01	0.174′
LFI20	12.′75	0.170′
LFI21	12.′74	0.156′
LFI22	12.′87	0.164′
LFI23	13.′27	0.171′
	44 GH	
	Ave FWHM: 27.′92	ave e: 1.26
LFI24	22.′98	0.652′
LFI25	30.′46	1.075′
LFI26	30.′31	1.131′
	30 GHz	
	Ave FWHM: 32.′65	ave$e$: 1.38
LFI27	32.′65	1.266′
LFI28	32.′66	1.287′

- χ2 fit of beam model (bivariate Gaussian)
  (Burigana et al. 2001)

  - Uncertainty on FWHM ~0.1′-1.3′

  - Ellipticity ~1.3, as expected

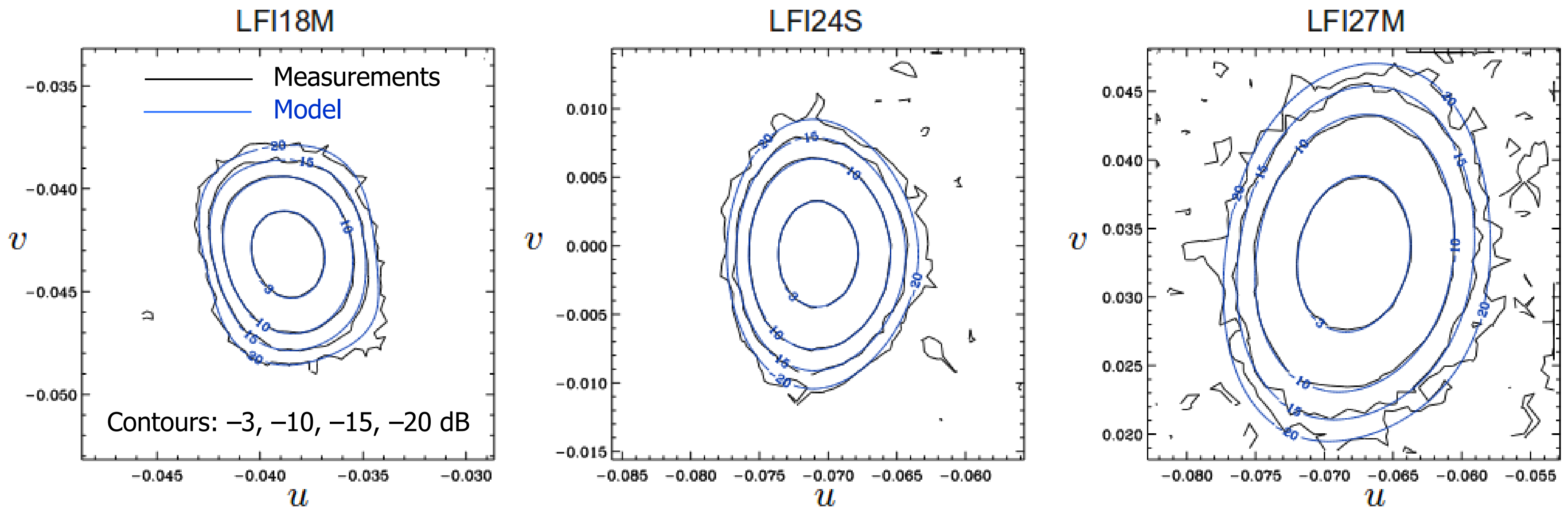
Good match with model predictions…

LFI Beams

(Sandri, Villa et al. 2010, 2011)

Compare data with predictiond from "Model Design":

- Ideal properties of: Reflectors surface, alignment, feeds beam pattern
- Smearing effect due to satellite rotation (~2% effect)



Model computation: GRASP9, PO/PTD on primary and sub-reflector

Excellent agreement down to –20 dB

→ Optical performance of LFI optical system (telescope & feeds) is as expected

→ No measurable deviations from elliptical fit down to –10dB

Reconstruction of focal plane geometry

- In-flight position of beams measured with *few arcsec* accuracy

Calibration

$$V \cong G(T_{\mathrm{Sky}} - rT_{\mathrm{Ref}}) + wn$$

Measure $G = G(t)$ [V/K]

For each of the 44 LFI detectors

- Main LFI calibrator: CMB Dipole
- For each pointing period (~45min): $\Delta V_k \cong G_k(\Delta T_{\mathrm{Sky}} + wn) + b_k$

CMB dipole — Orbital dipole

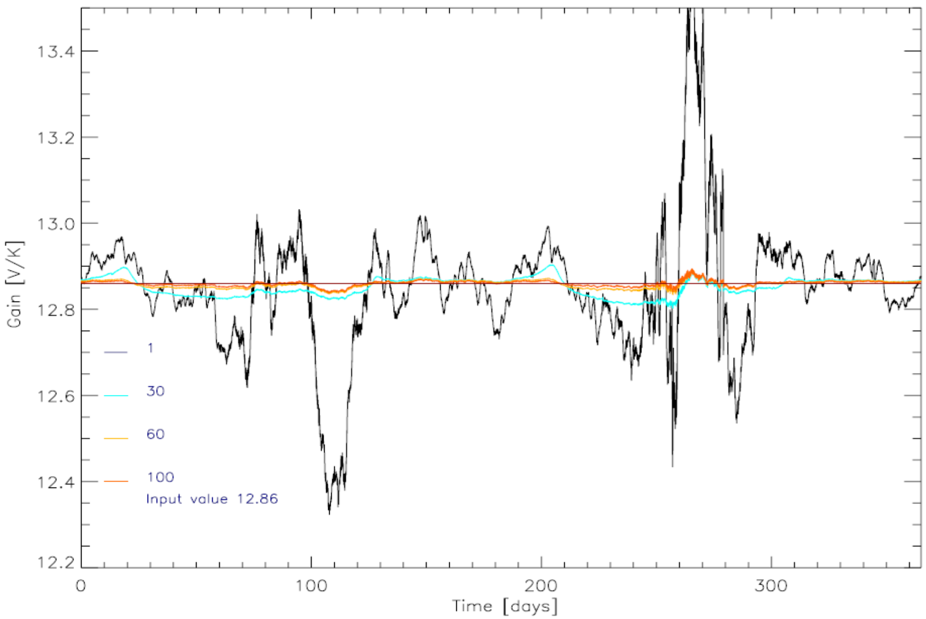
$$\chi^2 = \sum_{i \in k} \frac{[\Delta V(t_i) - G_k(\Delta T_{\mathrm{D}} + \Delta T_{\mathrm{v}}) - b_k]^2}{\sigma_i^2} \rightarrow G_k, b_k$$

$$\Delta V^{(n+1)} = \Delta V^{(n)} - G_k^{(n)} \Delta T^{(n)}_{\mathrm{CMB+foreg}}$$

Main limitation: "contamination" from CMB anisotropy, foregrounds

→ Mask Galactic plane and bright sources (82% of the sky preserved)

→ Iterative algorithm

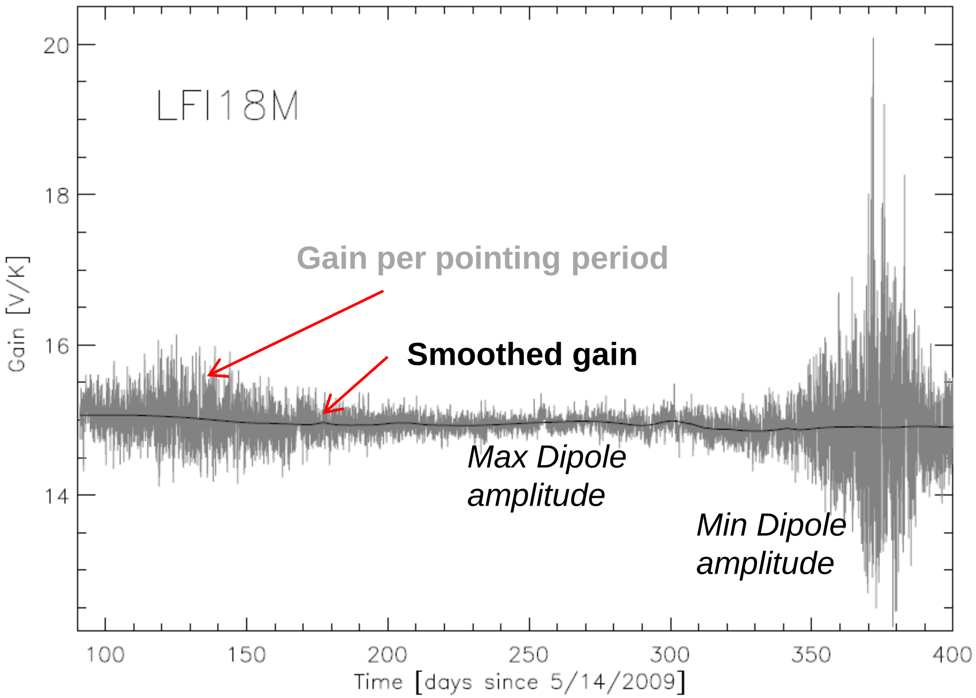


Simulated iterative procedure
LFI30GHz (worst case)

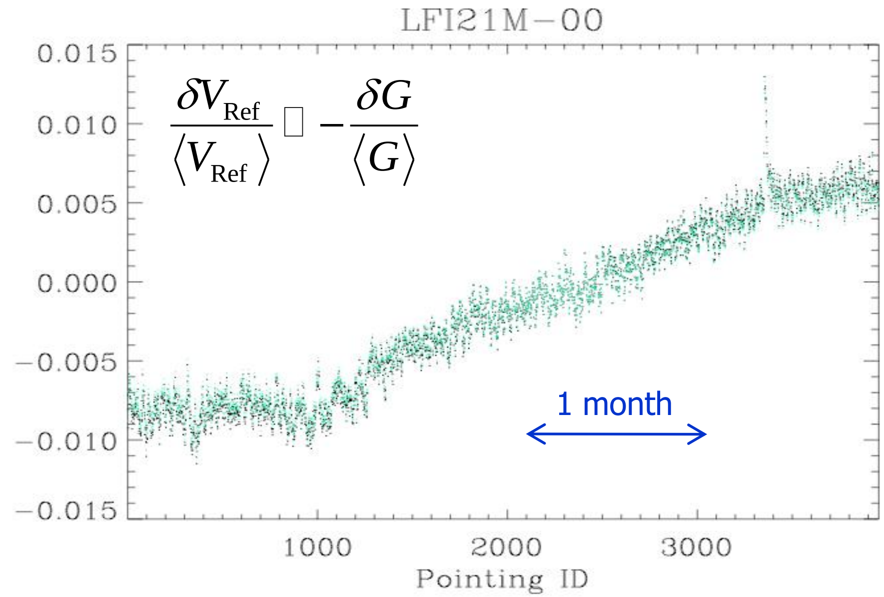
- Convergence reached typically after ~50 iterations
- Local deviations <0.6%

Zacchei, Maino et al. (2011)
Cappellini et al. (2003)

Calibration
Current model (1% accuracy)



Instrument stable <0.5% in several weeks!



→ Running average (5 to 30 OD's)
→ Further smoothing (wavelets)

Calibration Accuracy

Absolute calibration

per frequency map: ~1% (conservative)

Relative calibration

per radiometer: ~0.3 −0.4% (typical)
per frequency map:
30 GHz: ~0.05%
44 GHz: ~0.07%
70 GHz: ~0.12%

Calibration

The next step: 0.1% accuracy

$$G(t) = G_0\left(1 + \frac{\delta G(t)}{G_0}\right)$$

Absolute calibration

Relative calibration

Absolute calibration

$$\frac{\sigma_{G_0}}{G_0} = \frac{1}{<\Delta T_D + \Delta T_v>}\sqrt{\sigma^2_{\Delta T_D} + \sigma^2_{\Delta T_v} + (G_0\sigma_{\Delta V})^2} \rightarrow \sigma_{\Delta T_v} << \sigma_{\Delta T_D} = 0.4\%$$

(FIRAS)

Use only orbital component

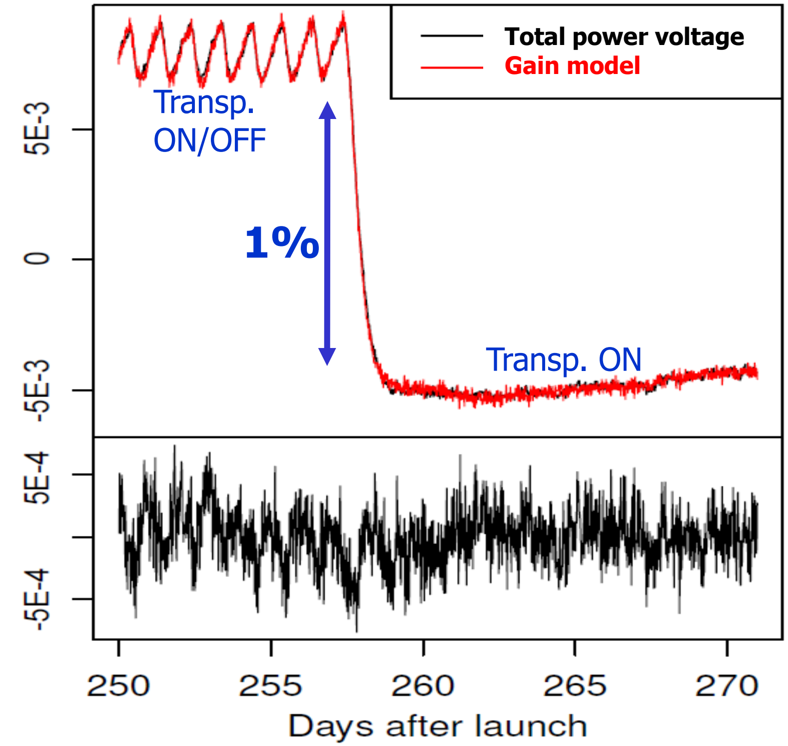
Relative calibration

1. Total power voltage (ref load)

$$\frac{\delta V_{\mathrm{Ref}}}{\langle V_{\mathrm{Ref}}\rangle} = \sqrt{\left(\frac{\delta(1/G)}{\langle 1/G\rangle}\right)^2 + \left(\frac{\delta T_{\mathrm{Ref}}}{\langle T_{\mathrm{Ref}} + T_{\mathrm{Noise}}\rangle}\right)^2 + \left(\frac{\delta T_{\mathrm{Noise}}}{\langle T_{\mathrm{Ref}} + T_{\mathrm{Noise}}\rangle}\right)^2}$$

$< 2\times10^{-4}$ Worst case 44GHz

$< 10^{-3}$ Thermal



2. Gain model $\frac{\delta G}{\langle G\rangle} = \eta_{BE}\delta T_{BE}(t) + \eta_{FE}\delta T_{FE}(t) + \ldots$

3. White noise $\frac{\delta G}{\langle G\rangle} = \frac{\delta(wn)}{\langle wn\rangle}$

4. Multiple component model

→ **Optimise for polarisation analysis**

Noise properties

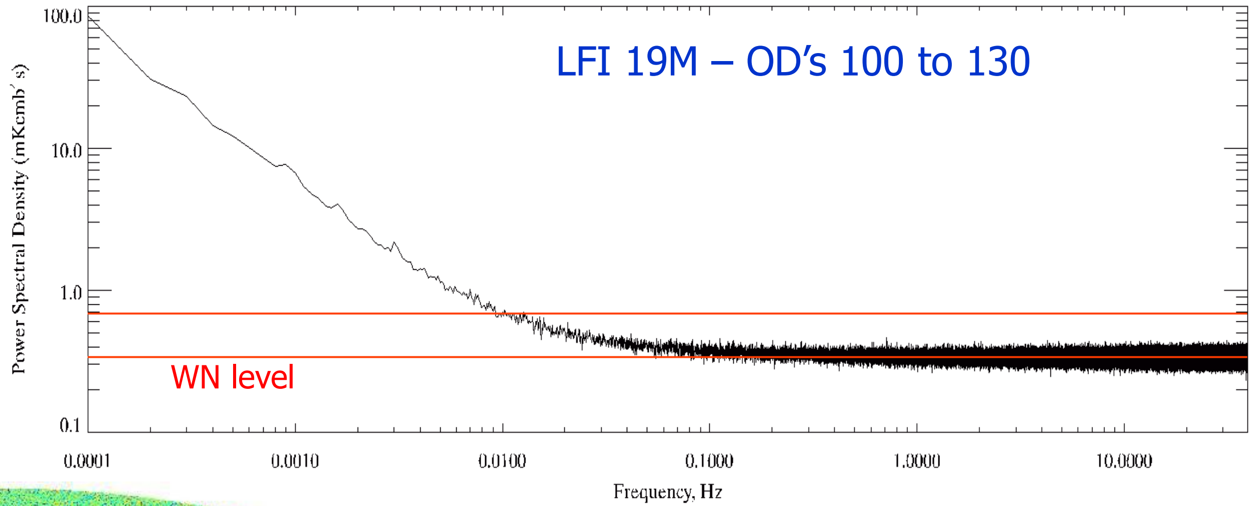
• Noise spectra well described by 2-component (3-parameter) model (of all 22 LFI radiometers)

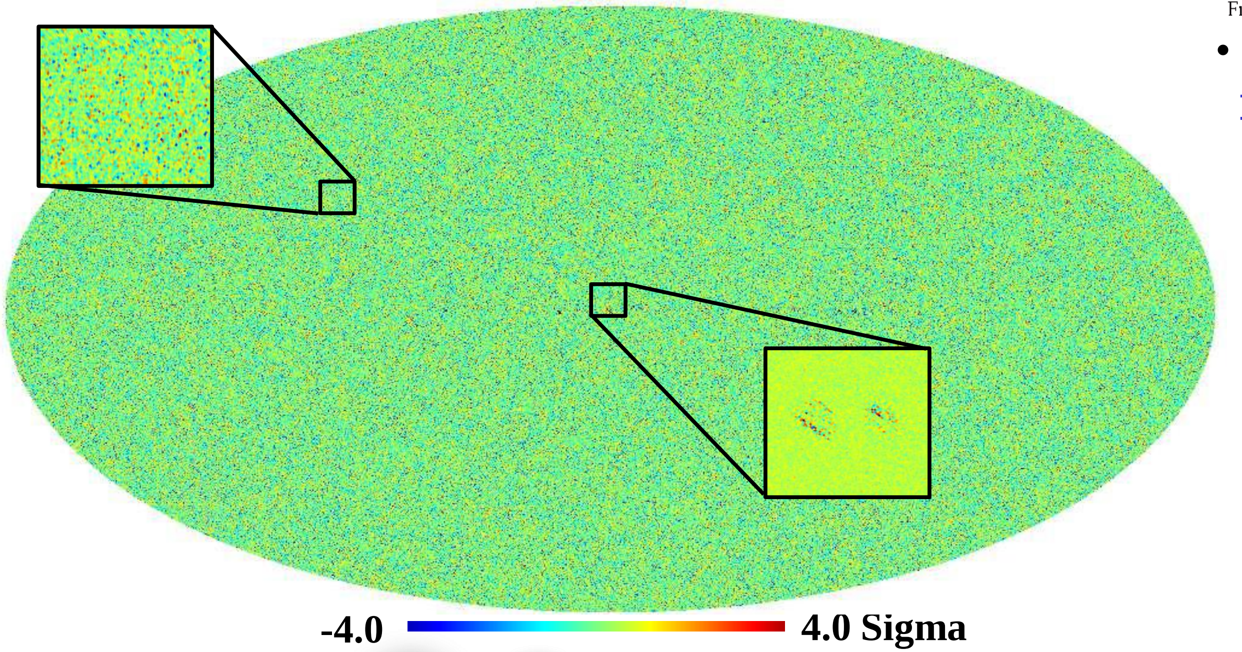
$$P(f) = \sigma_{\mathrm{WN}}^2 \left[1 + \left(\frac{f}{f_{\mathrm{knee}}} \right)^{\alpha} \right]$$

with slope: $\alpha \approx -1$

• Fit to noise power spectra

(Natoli et al. 2001)
(de Gasperis et al. 2005)





• Map from Jack-knife timelines:

1st – 2nd half of each pointing period

- Structure-less map
- Small residuals on galactic plane due to beam ellipticity

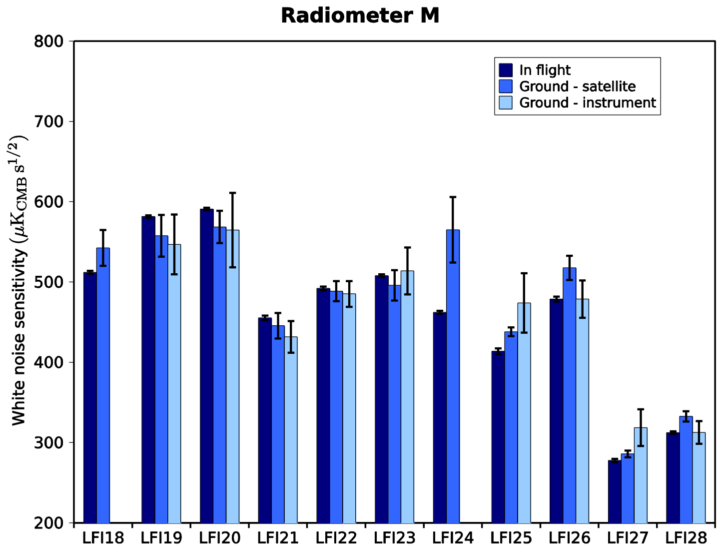
Contribution of residual 1/f to white noise:

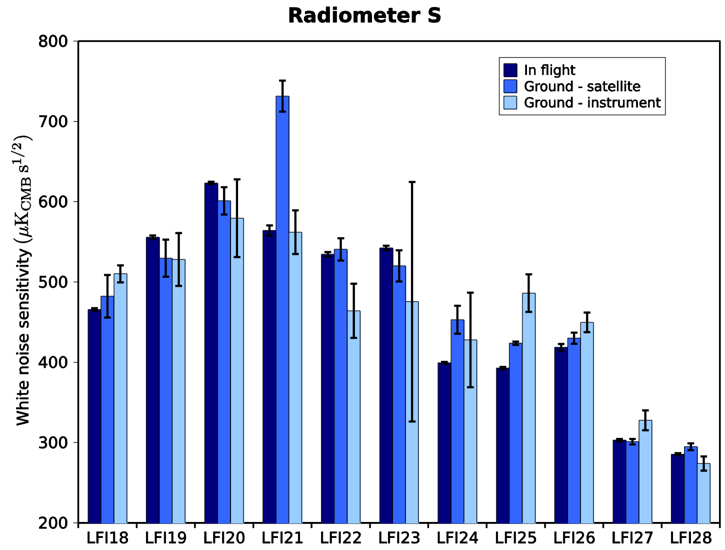
4.0% at 30 GHz
1.6% at 44 GHz
0.2% at 70 GHz

Requirement: < 12%

Noise properties: wn component

Calibrated WN from flight data, compared to ground tests

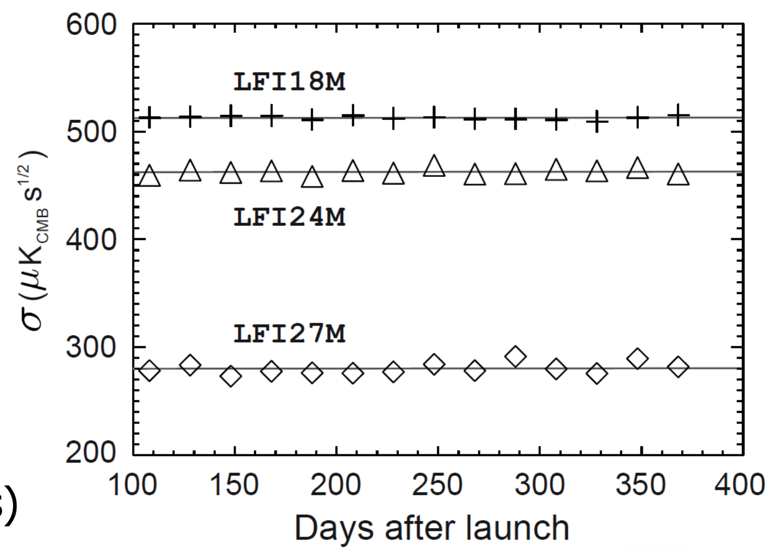




- Good agreement with ground tests
- In-flight tuning → significant improvement for a few radiometers
- Noise ~25% above req (118 $\mu K\, s^{1/2}$), more than compensated by extended mission

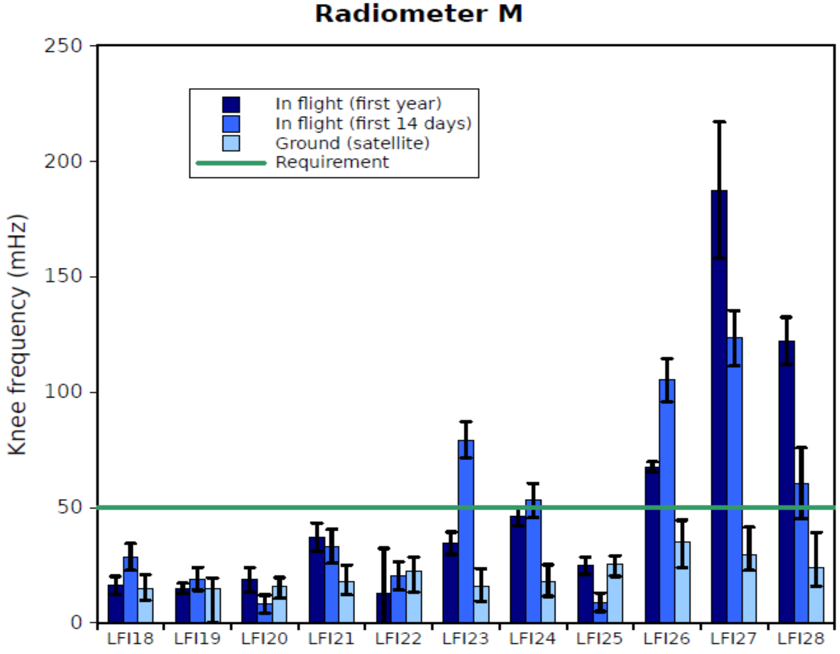
30 GHz...... 143 $\mu K\, s^{1/2}$
44 GHz...... 164 $\mu K\, s^{1/2}$
70 GHz...... 134 $\mu K\, s^{1/2}$

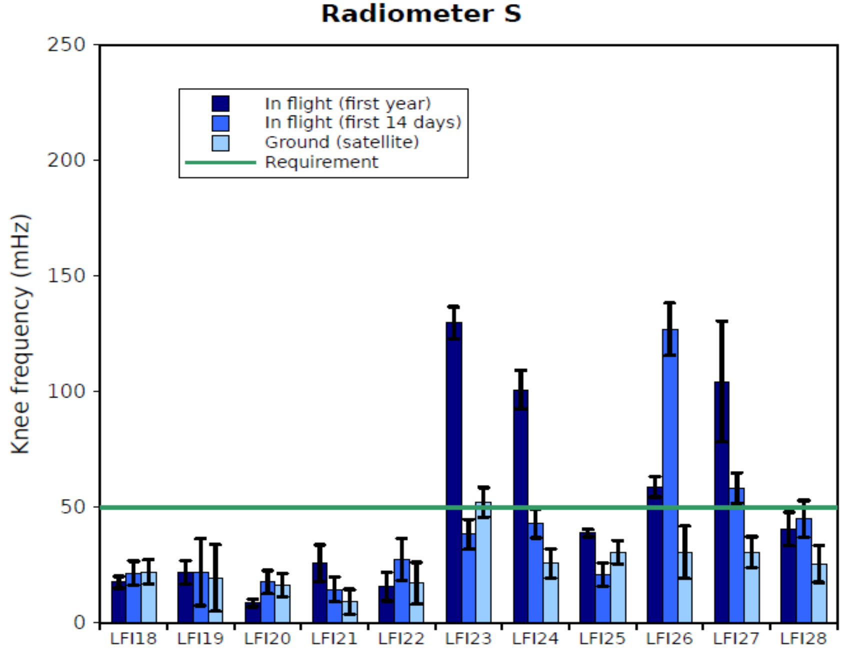
- Good stability through 1st year survey (all parameters)



Noise properties: 1/f component

In-flight measured knee frequency, compared to ground tests





Knee frequency:

- Typically $f_{\text{knee}} < 50$ mHz
  within requirements
- Few exceptions (30GHz)
  effectively removed by destriping
- Accuracy ~15-20%

Slope:

- Typically $\alpha \sim -1$
  (–0.83 to –1.04)
- Accuracy ~10%, stable

Systematic effects

Planck design driver: minimise systematic errors

Objective: reduce systematic errors well below instrument white noise.

- Instruments & S/C design
- Orbit & scanning strategy
- Planck SEWG **(J.-M. Lamarre & M.B. 2000)**

LFI goal: Overall systematics ~1μK

(LFI Scientific Requirements, 1999)
(Mennella et al 2003)
(M.B. et al 2010)

- Receiver differential scheme
- Reference loads cooled to 4K
- Gain modulation factor
- Diode averaging
- Stringent thermal stability requirements

LFI systematic error budget

Source	Random Fraction of $\delta T_{1-\text{sec}}$	Spin synch μK	Periodic μK
External Straylight	N/A	1	N/A
Internal Straylight	0.045	1	0.9
4K load	0.026	1	0.6
LFI thermal fluctuations	0.031	0.8	1.1
Front end 1/f	0.217	N/A	N/A
Back end 1/f	0.453	N/A	N/A
DC electronics	0.04	N/A	N/A
Quantisation	0.01	N/A	N/A
Total	0.507	1.9	1.5
Noise increase	0.121		

First in-flight assessment

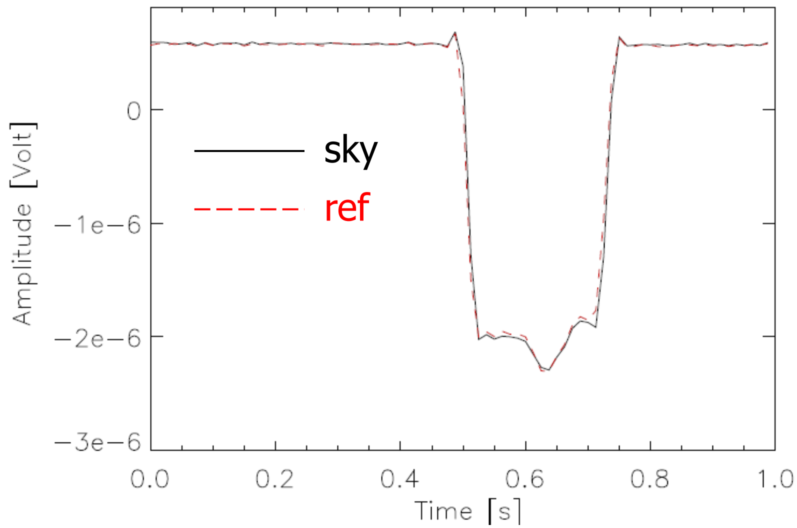
(Mennella et al. 2011)

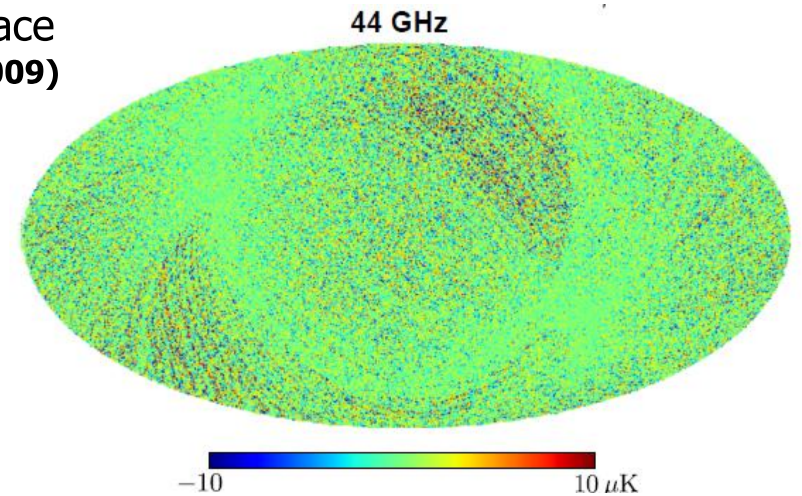
- Quantify all effects relevant at current stage of analysis:
  - **1-Hz frequency spikes**
  - **Thermal fluctuations: at 300K, 20K, and 4K (ref. loads)**

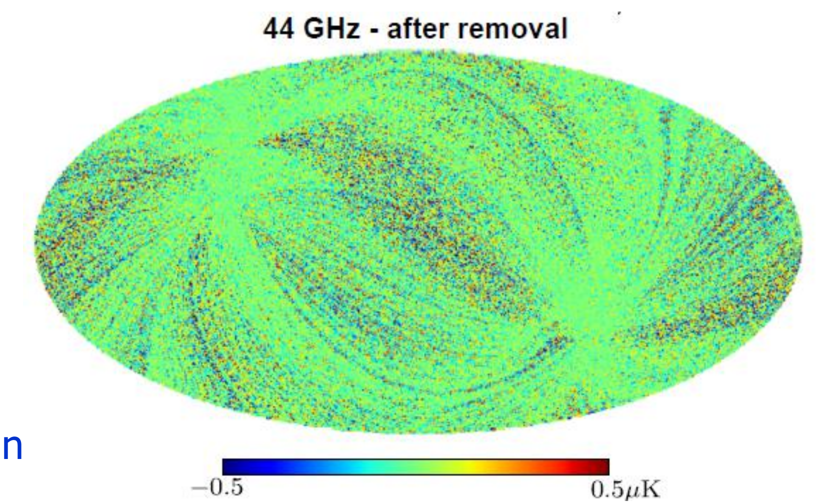
Systematic effects

"1-Hz frequency spikes"

- Identified and extensively tested in ground campaign
  - → Due to coupling with 1-second H/K electronics circuit
- Detailed simulations, removal algorithms already in place **(Meinhold et al 2009)**
- Signature is nearly identical in sky and ref signals
  - → Differencing greatly suppresses effect







- Effect modeled and projected through scanning strategy
  - → 30 & 70 GHz: δT_{rms} < 0.4 μK
  - → 44 GHz more sensitive (low Vout, high DAE gain Reduced to δT_{rms} ~ 0.2 μK after removal

Systematic effects

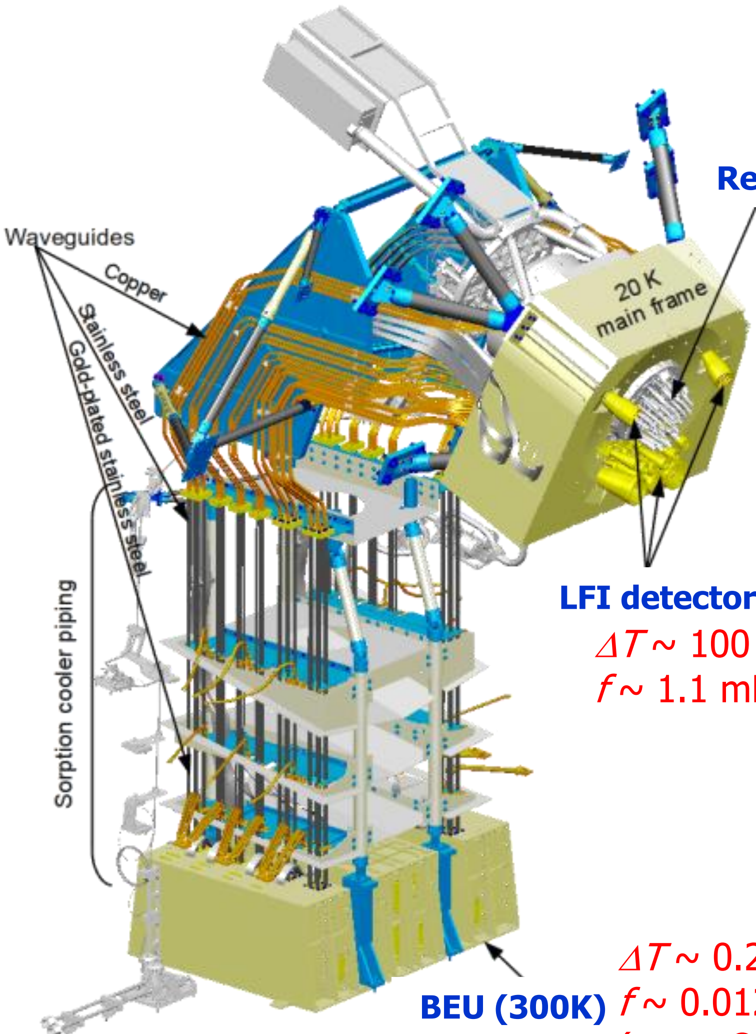
Thermal effects

(Terenzi et al. 2009, Morgante et al. 2009, Tomasi et al 2009)

Temperature changes are "slow" compared to spin rate: $f_{\text{Thermal}} << f_{\text{Spin}} \approx 16$ mHz

→ Efficiently removed by destriping (Madam)

→ Fast variations damped by thermal mass



Ref Loads (4K)

$\Delta T \sim$ 0.9 mK

$f \sim$ 1.1 mHz (15min)

$f \sim$ 0.2 mHz (90min)

LFI detectors (20K)

$\Delta T \sim$ 100 mK

$f \sim$ 1.1 mHz (15min)

BEU (300K)

$\Delta T \sim$ 0.2 K

$f \sim$ 0.012 mHz (24h) (up to OD 258)

Except for 4K loads, fluctuations are common mode

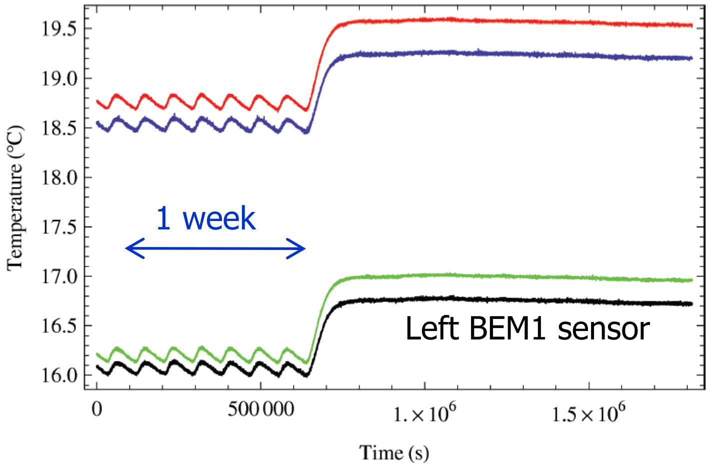
→ Differencing drastically reduces impact

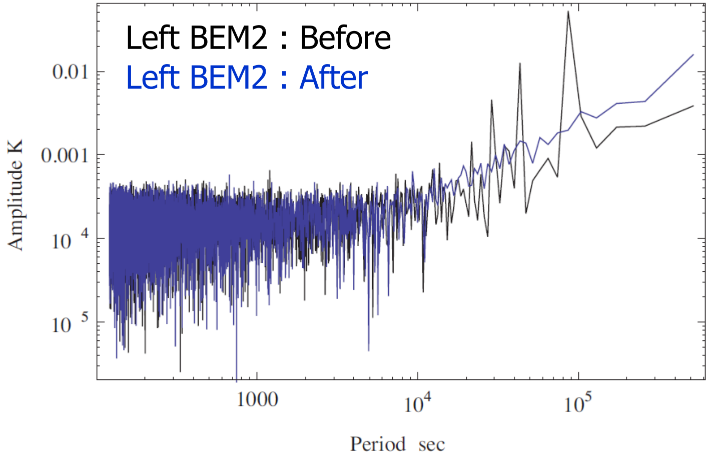
How can we quantify the effect?

- Start with representative Temperature Sensor(s) data streams
- Apply thermal transfer functions (get physical temperature at sensitive component)
- Apply radiometric transfer function (get fluctuation in antenna temperature)
- Re-sample and build differenced time ordered data
- Build destriped maps (with *Madam*)

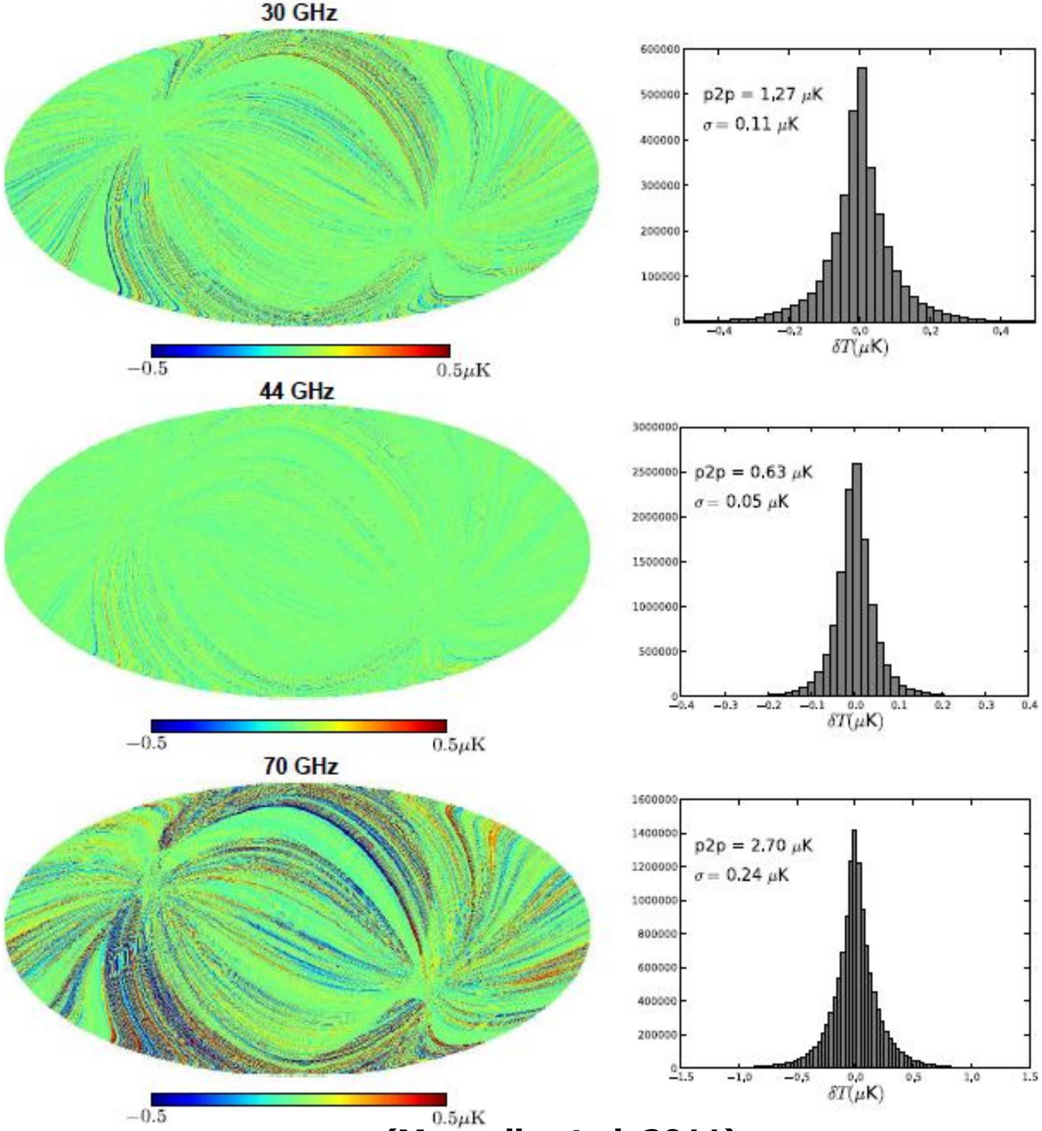
Thermal systematic effects
Back-end fluctuations (300K)

LFI back-end
Temperature Sensors
(around OD258)





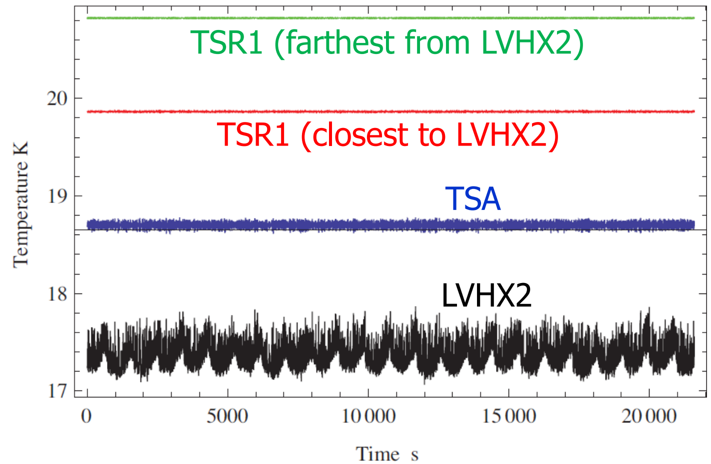
(Planck Collaboration 2011)

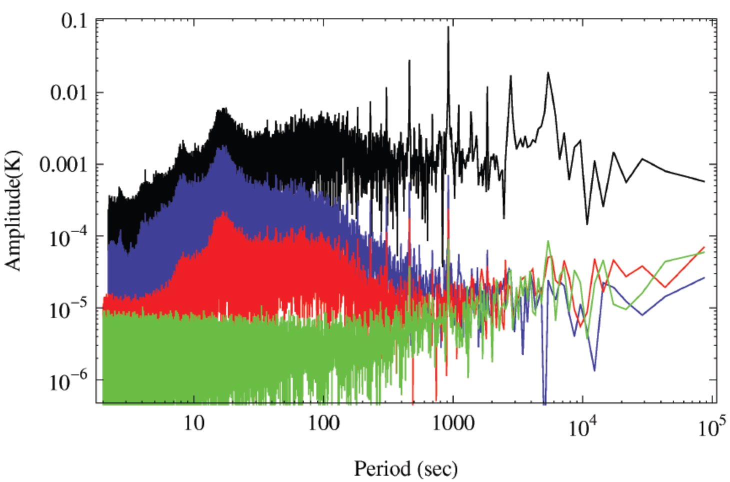


(Mennella et al. 2011)

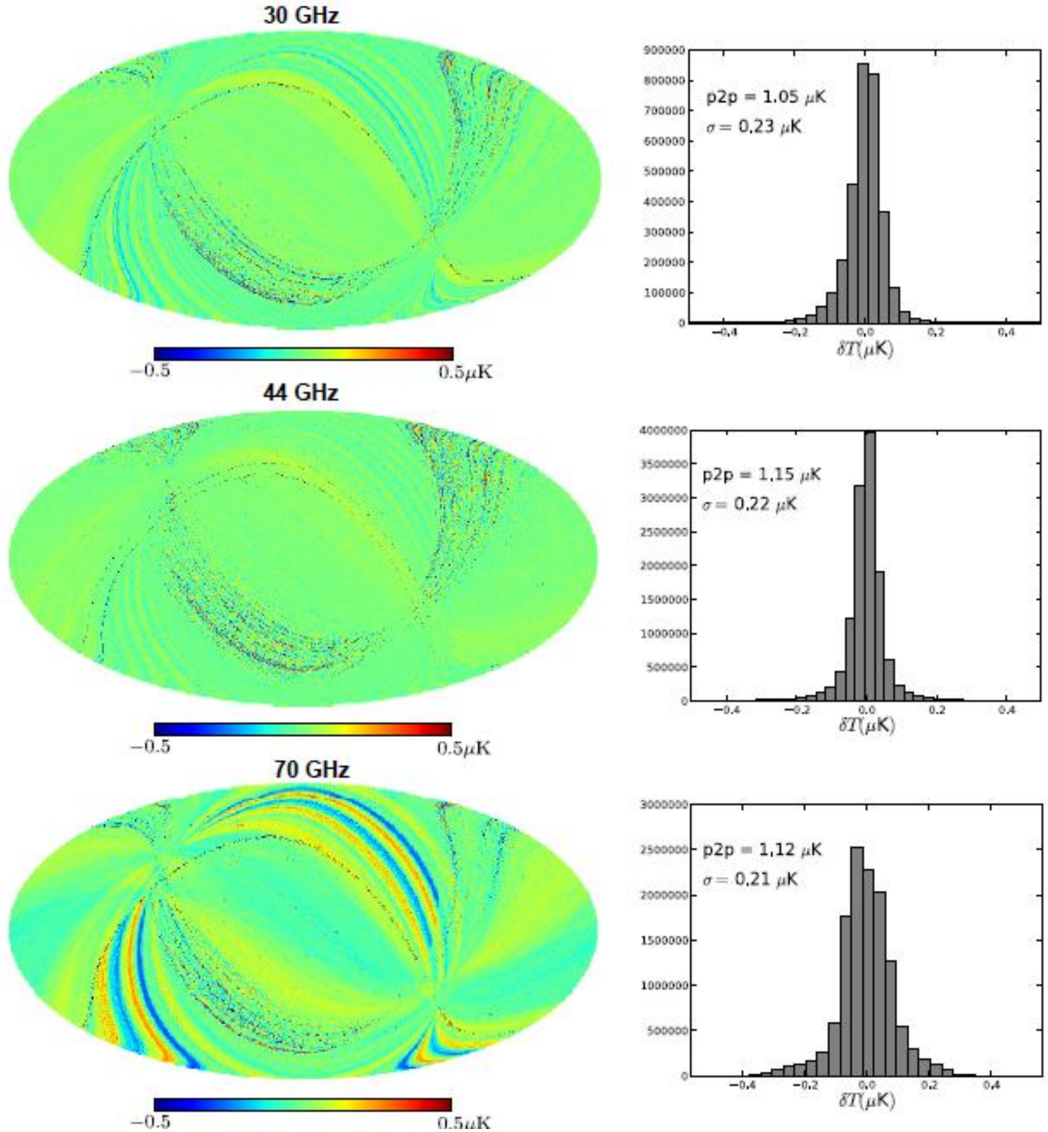
Thermal systematic effects
Front-end fluctuations (20K)

LFI focal plane
Temperature Sensors
(24h, Oct 09)





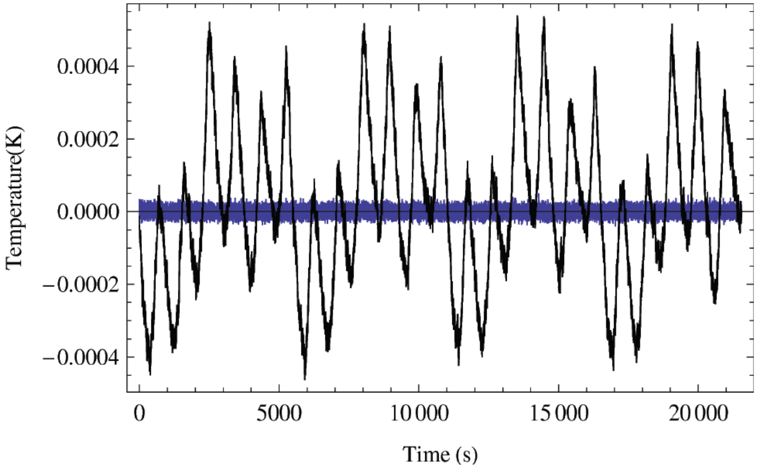
(Planck Collaboration 2011)

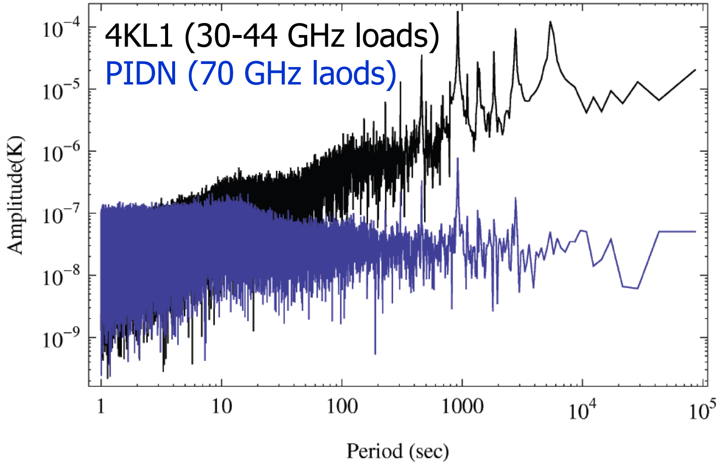


(Mennella et al. 2011)

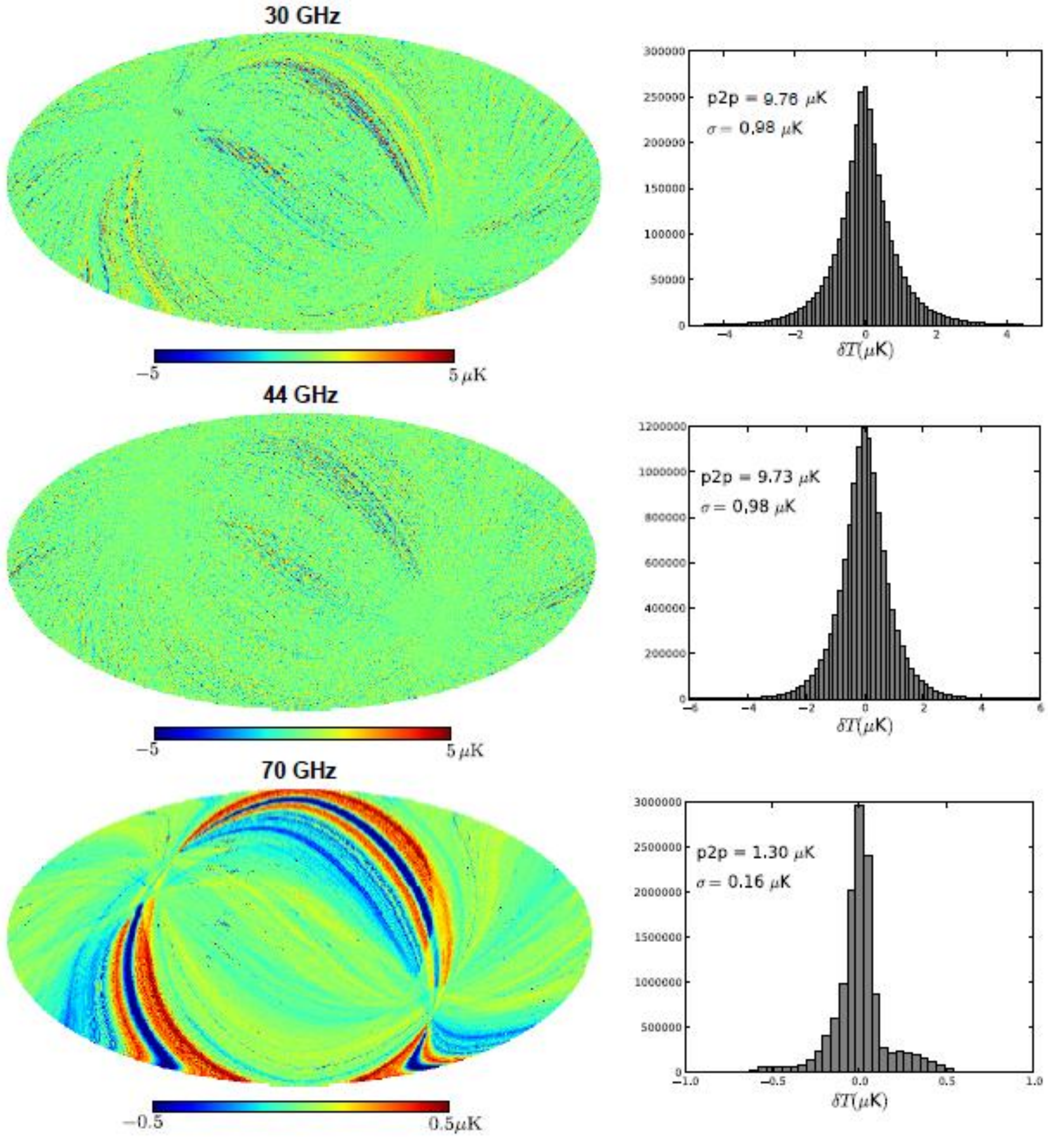
Thermal systematic effects
Reference Loads fluctuations (4K)

HFI outer shield
Temperature Sensors
(24h, Oct 09)





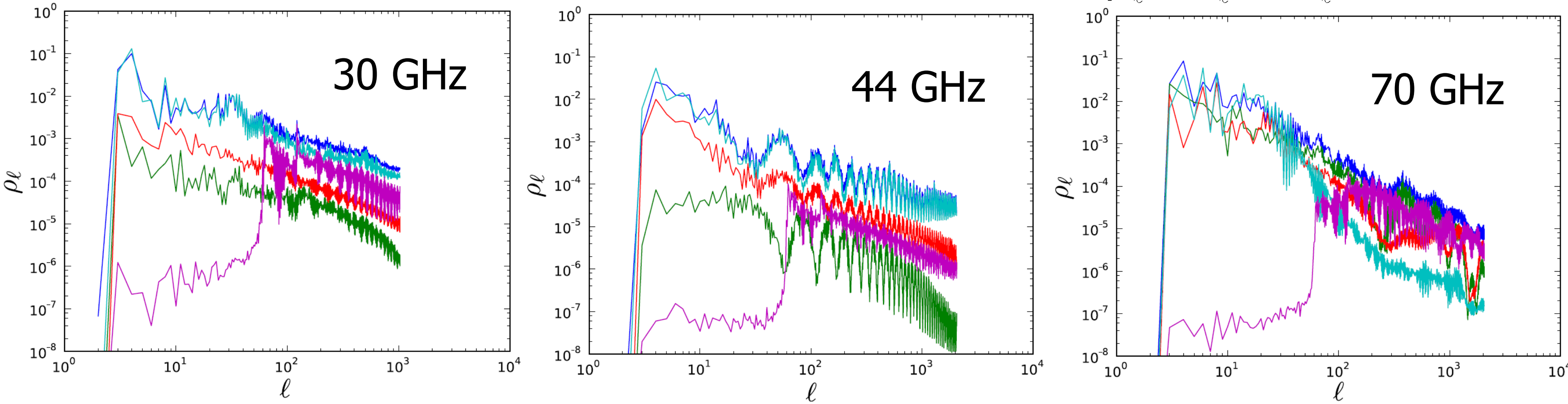
(Planck Collaboration 2011)

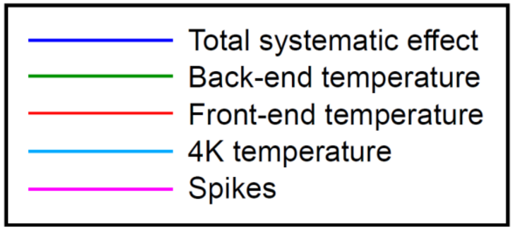


(Mennella et al. 2011)

Systematic effects
Summary

Contribution of LFI systematics to WN power spectrum: $\rho_\ell \equiv C_\ell^{\rm syst} / C_\ell^{\rm noise}$





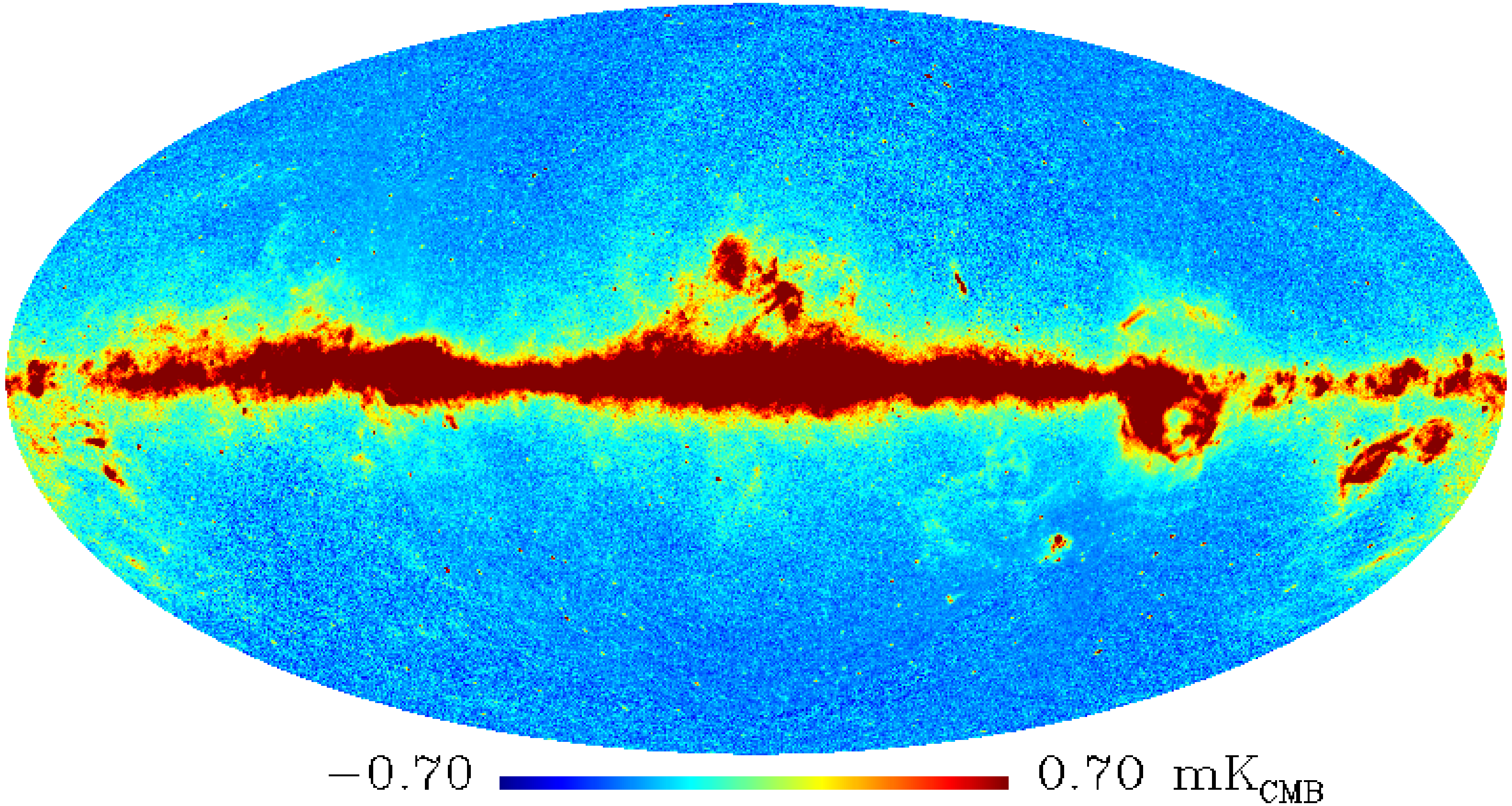
	30 GHz		44 GHz		70 GHz	
	p-p	r.m.s.	p-p	r.m.s.	p-p	r.m.s.
1-Hz spikes	4.00	0.45	1.51	0.15	2.56	0.30
BEM T fluct.	1.27	0.11	0.63	0.05	2.70	0.24
FEM T fluct.	1.05	0.23	1.15	0.22	1.12	0.21
4 K T fluct.	9.76	0.98	9.73	0.98	1.30	0.16
Total	10.92	1.10	9.73	0.98	4.28	0.45

NB: per sample (worst case)

- Impact in power spectrum is 1–3 orders of magnitude below WN level (of order ~1μK)
- Only removal in pipeline (to date): 1-Hz spikes at 44GHz
- Dominant effects:
  - → **30 and 44 GHz**: 4K loads fluctuations
  - → **70 GHz**: back-end fluctuations (large scale); frequency spikes (small scales)

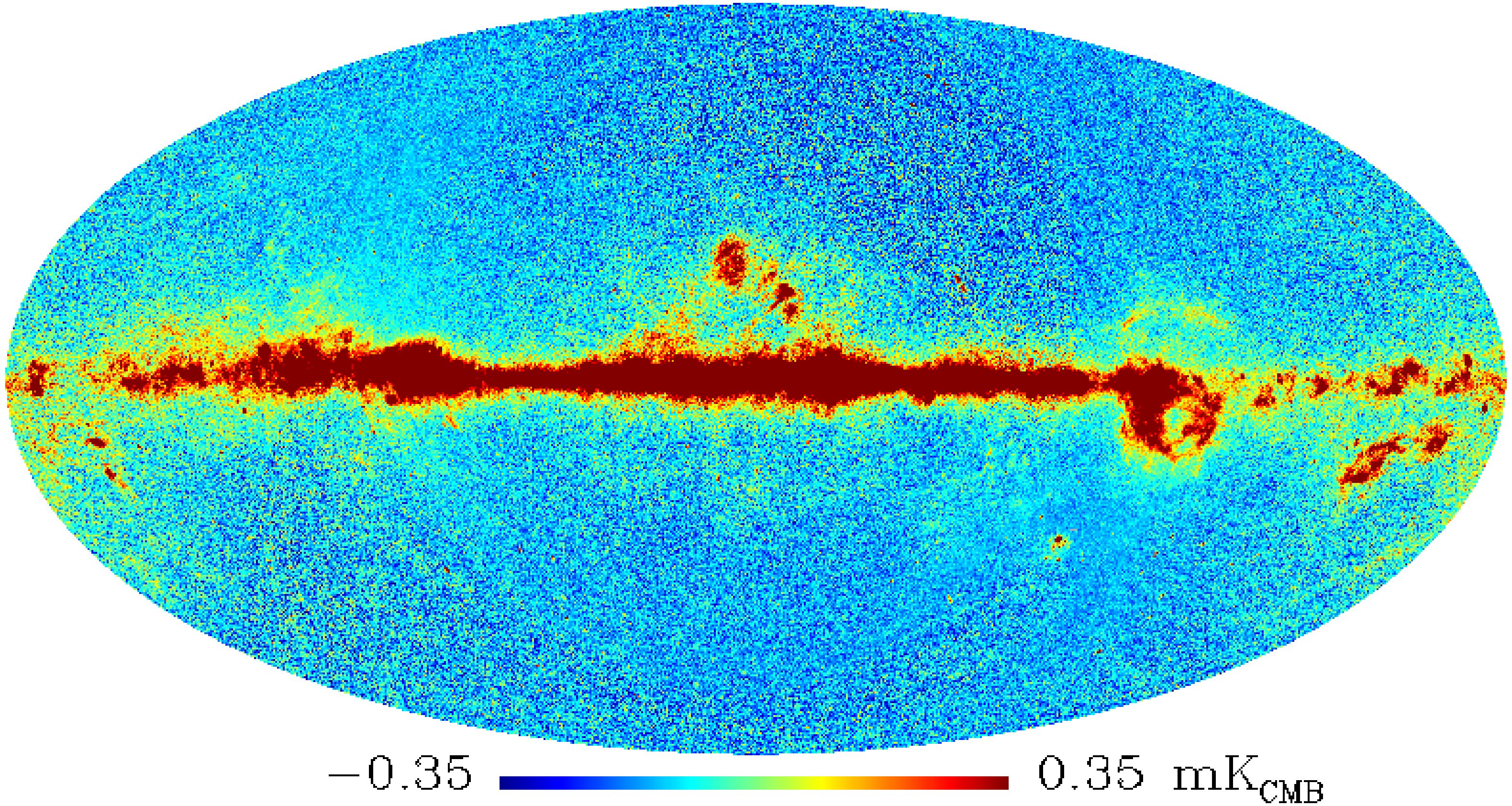
Planck-LFI – 30 GHz Channel

Full sky maps of foreground emission after 1 year



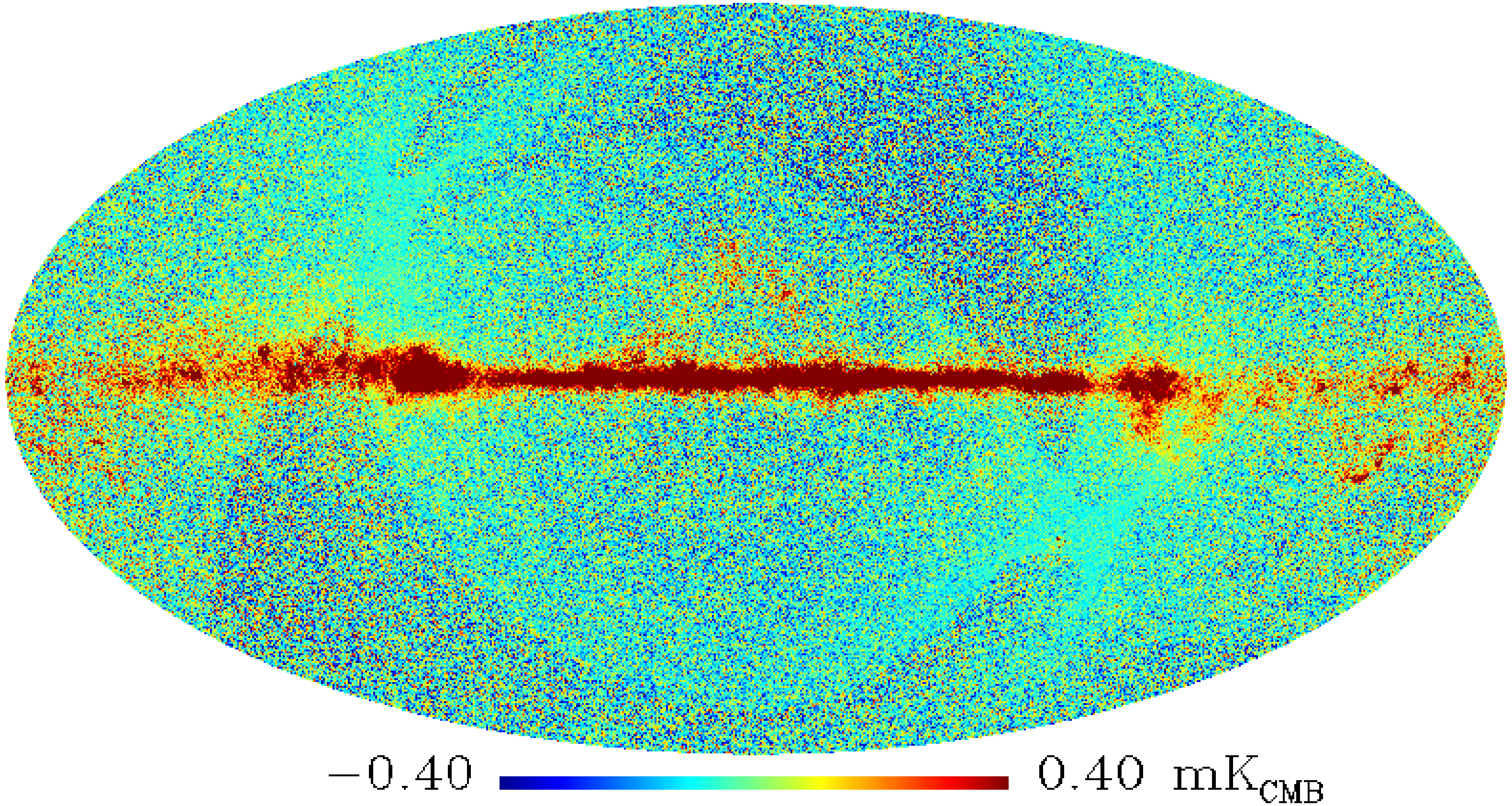
Planck-LFI – 44 GHz Channel

Full sky maps of foreground emission after 1 year



Planck-LFI – 70 GHz Channel

Full sky maps of foreground emission after 1 year



Conclusions

In-flight measured performance in excellent agreement with pre-launch expectations

→ **Beams** (down to –20dB) and **Focal plane geometry**

- **White noise sensitivity** (for some channels improved after in-flight bias tuning)
- Parameters of **1/*f* noise** in line with ground measurements (typically <50 mHz)

→ Photometric **Calibration** (absolute <1%, relative ~0.1%)

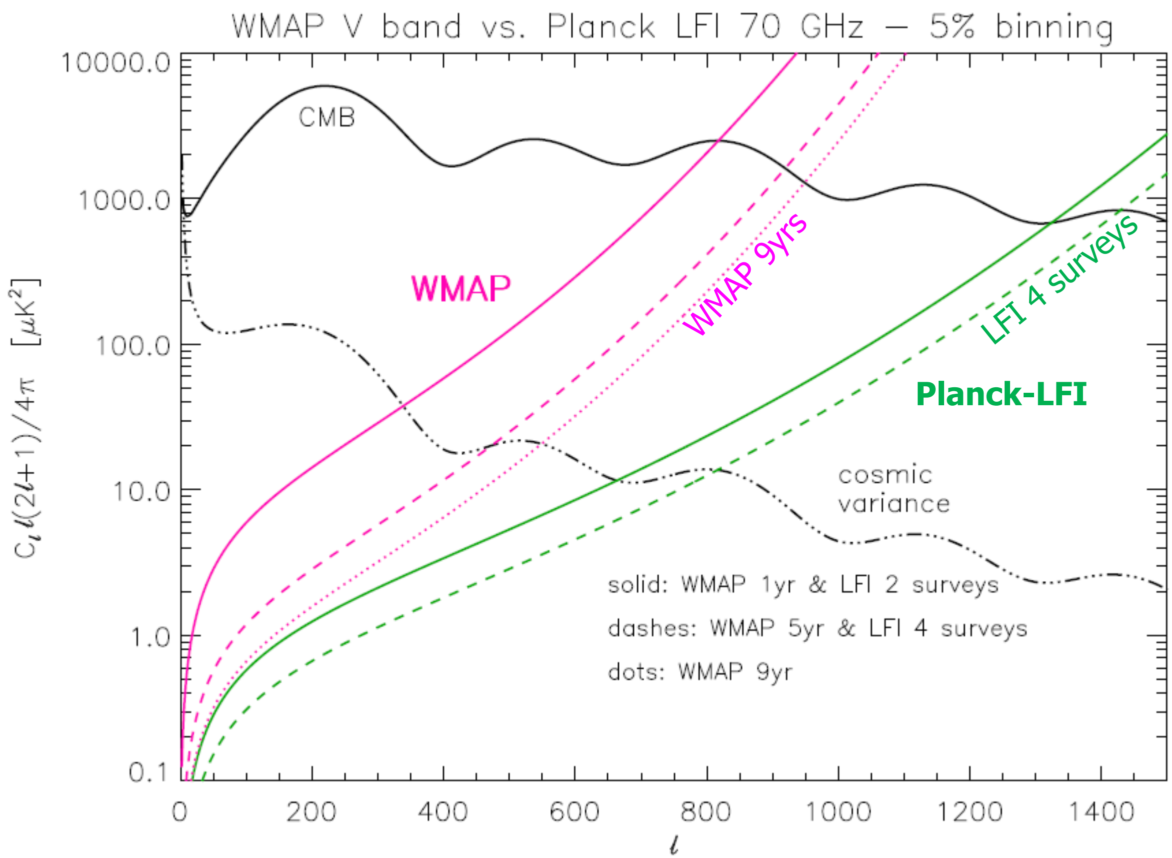
→ Overall **Systematic effects** at ~1μK level

- So far, excellent **Stability** of all performance parameters **(Can be improved)**

Parameter	30 GHz	44 GHz	70 GHz
Centre frequency [GHz]	28.5	44.1	70.3
FWHM [′]	32.65	27.92	13.01
Ellipticity	1.38	1.28	1.26
White noise sensitivity [$\mu K_{CMB}\,s^{1/2}$]	146.8	173.1	152.6
f_{knee} [mHz]	113.7	56.2	29.5
$1/f$ slope	−0.87	−0.89	−1.03
Absolute calibration uncertainty [%]	1	1	1
Relative calibration uncertainty [%]	0.05	0.07	0.12
Systematic effects uncertainty[a] [μK_{CMB}]	1.10	0.98	0.45
$\Delta T/T$ per pixel at EOM (end-2011) including 1/f and systematic effects	2.4×10^{-6}	3.2×10^{-6}	5.9×10^{-6}
$\Delta T/T$ Blue Book goal	2.0×10^{-6}	2.7×10^{-6}	4.7×10^{-6}

(10% better than requirement)

Conclusions

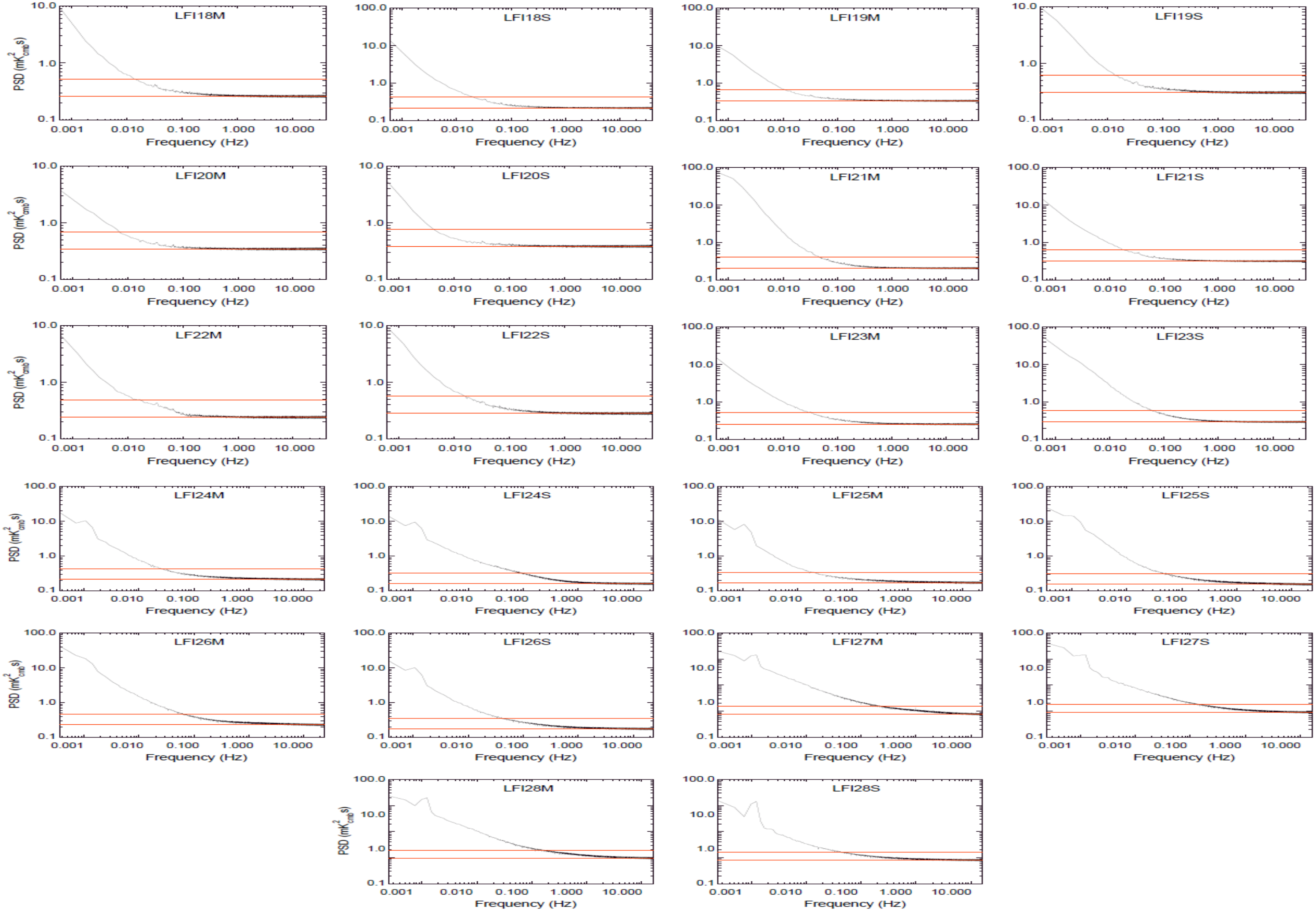


- **Planck-LFI most powerful instrument to date at these frequencies and contributes to make Planck a unique mission**
- **Next challenges:**
  - **(i) Fight systematics**
  - **(ii) Polarisation performance**

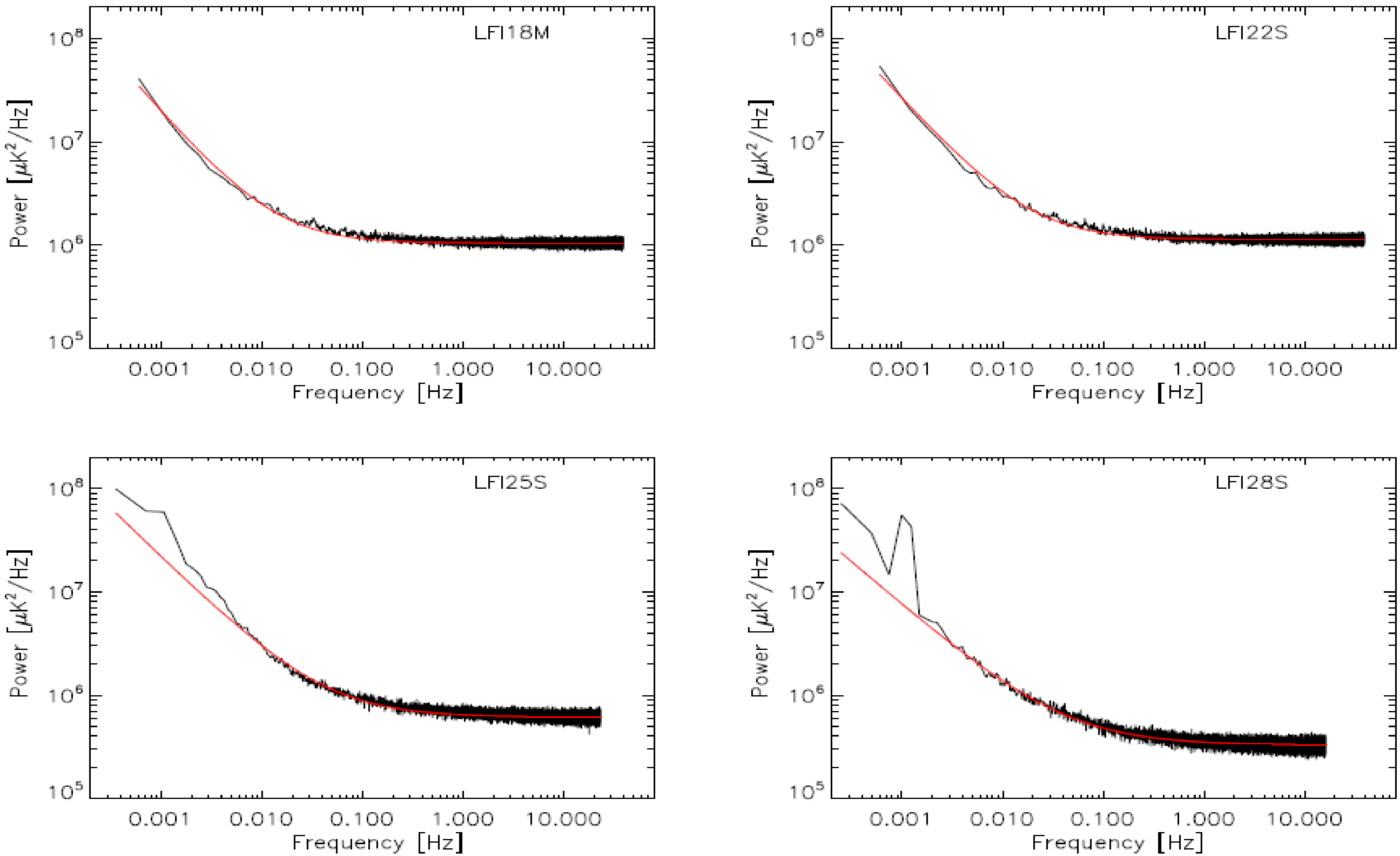
The scientific results that we present today are a product of the Planck Collaboration, including individuals from more than 50 scientific institutes in Europe, the USA and Canada

Planck is a project of the European Space Agency -- ESA -- 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.

Full LFI array – 2-diodes combination per radiometer



Planck-LFI noise power spectra



Hit count maps

Noise maps (from jackknife)

30 GHz

44 GHz

70 GHz