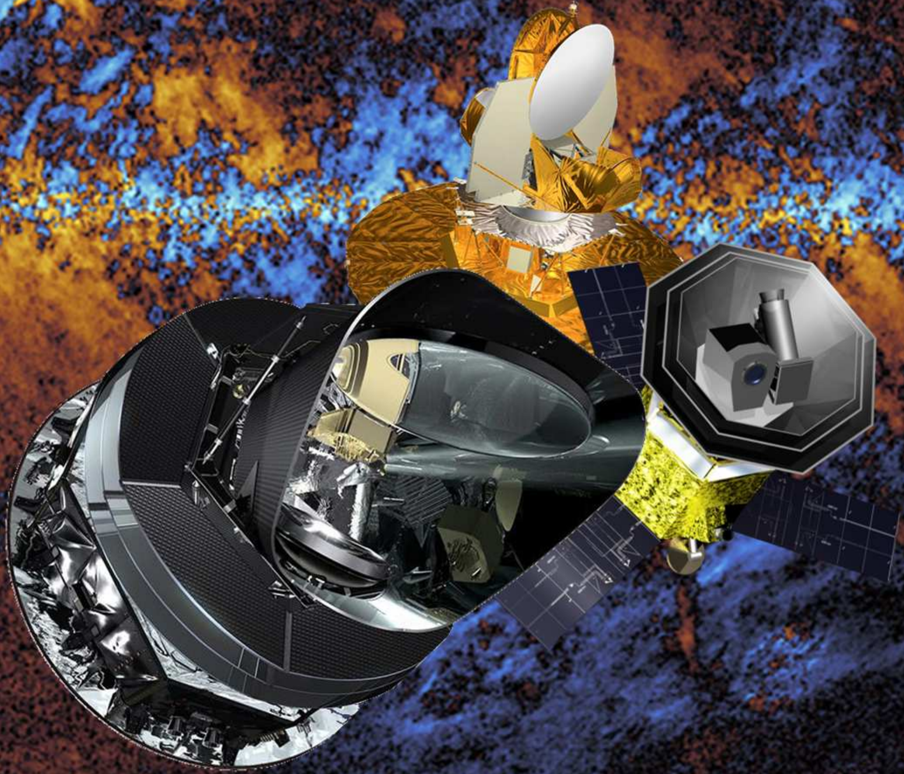
The Planck Low Frequency Instrument

Marco Bersanelli



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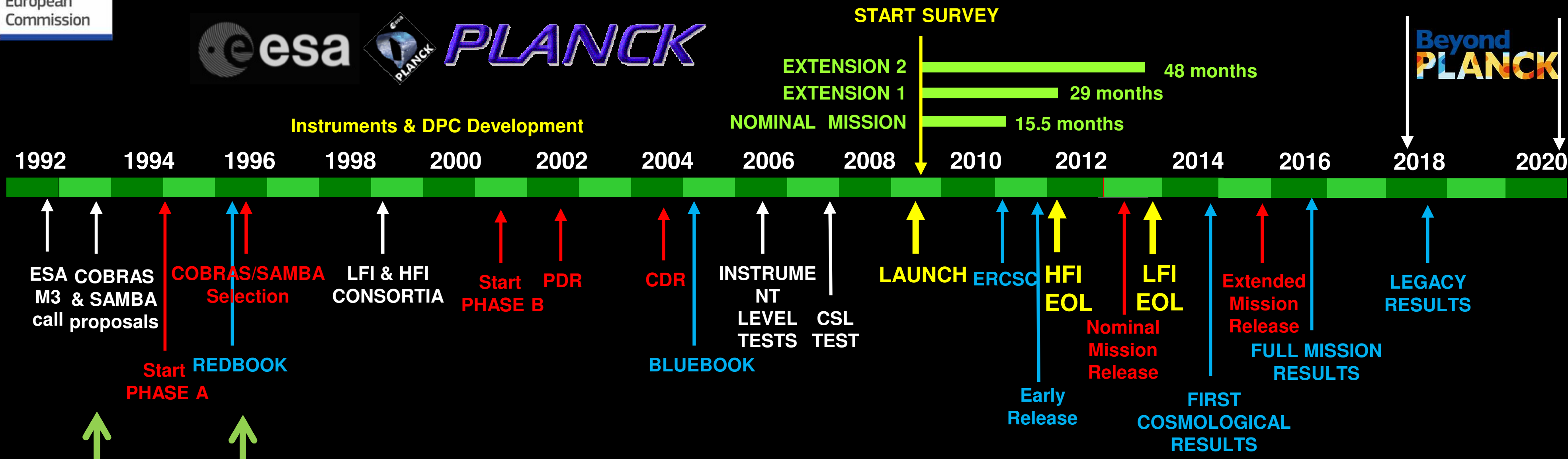

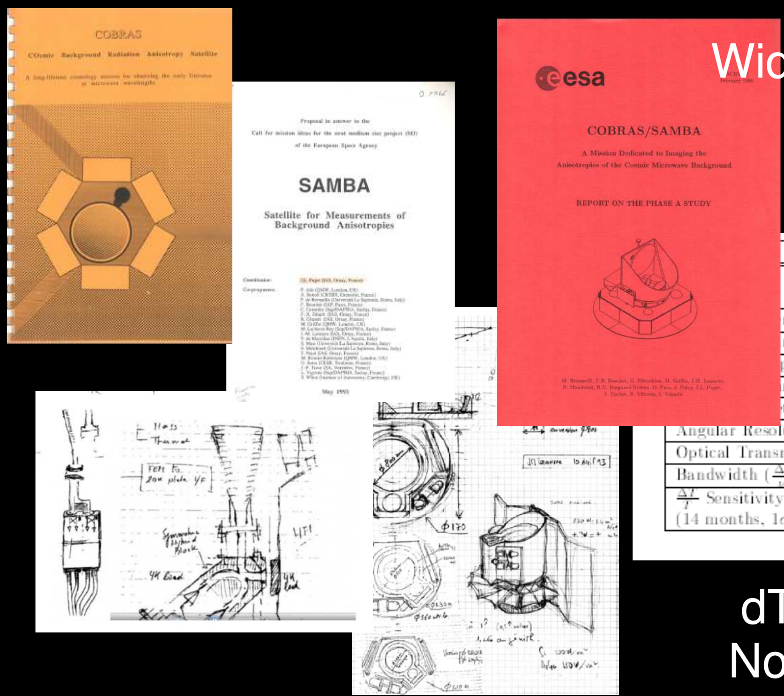

Wide spectral range (30-850 GHz)
Two different technologies
Control of systematics

PAYLOAD									
	1.5 m Diam. Gregorian; shared focal plane; system emissivity 1% Viewing direction offset 70° from spin axis.								
ncy (GHz)	31.5	53	90	125	143	217	353	545	857
nology	HEMT radio receiver arrays				Bolometer arrays				
perature	~100 K				0.1-0.15 K				
rements	Passive				Cryocooler + Dilution system				
tectors	4	14	26	12	8	12	12	12	12
Angular Resolution (arcmin)	30	18	12	12	10.3	7.1	4.4	4.4	4.4
Optical Transmission	1	1	1	1	0.3	0.3	0.3	0.3	0.3
Bandwidth ($\frac{\Delta\nu}{\nu}$)	0.15	0.15	0.15	0.15	0.37	0.37	0.37	0.37	0.37
$\frac{\Delta T}{T}$ Sensitivity per res. element (14 months, 1σ, 10^{-6} units)	7.8	7.5	14.4	35.4	1.2	2.0	12.1	76.6	4166

$dT/T \sim 2 \times 10^{-6}$ $1/\ell \sim 5'–180°$

No requirements on polarisation!

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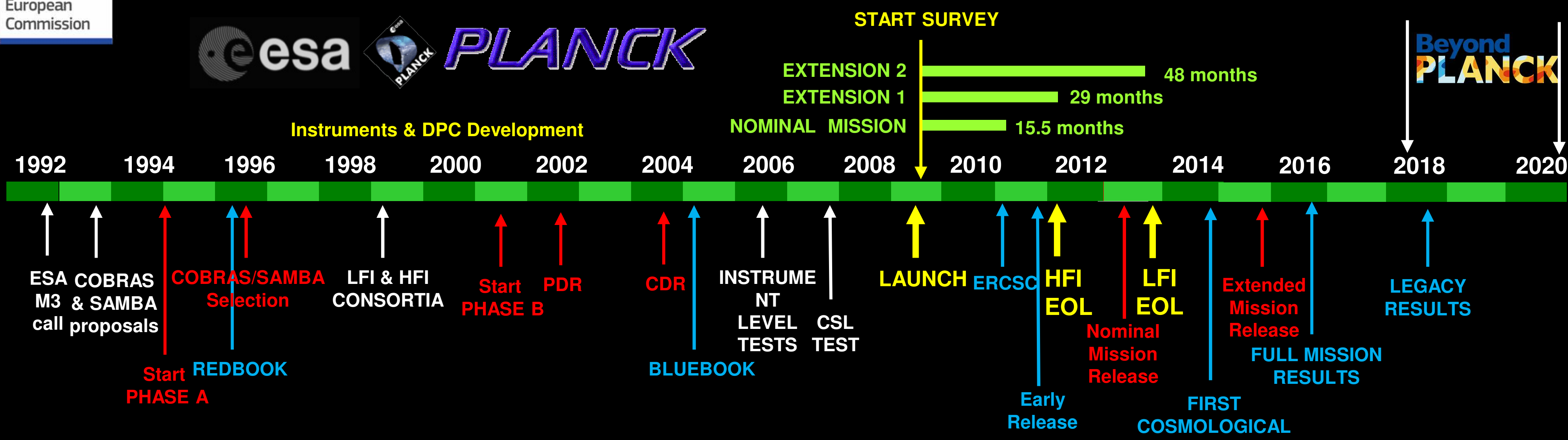

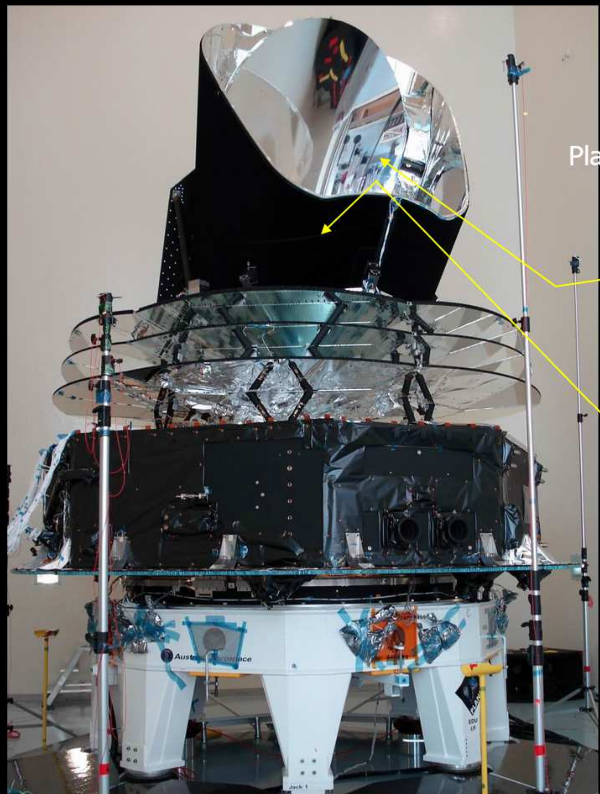

Planck Telescope
1.5x1.9m off-axis Gregorian
T = 50 K

LFI Radiometers
27-77 GHz, T = 20 K

HFI Bolometers
100-850 GHz, T = 0.1 K

asi agenzia spaziale italiana

cnes CENTRE NATIONAL D'ÉTUDES SPATIALES

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European Commission

The Planck Collaboration

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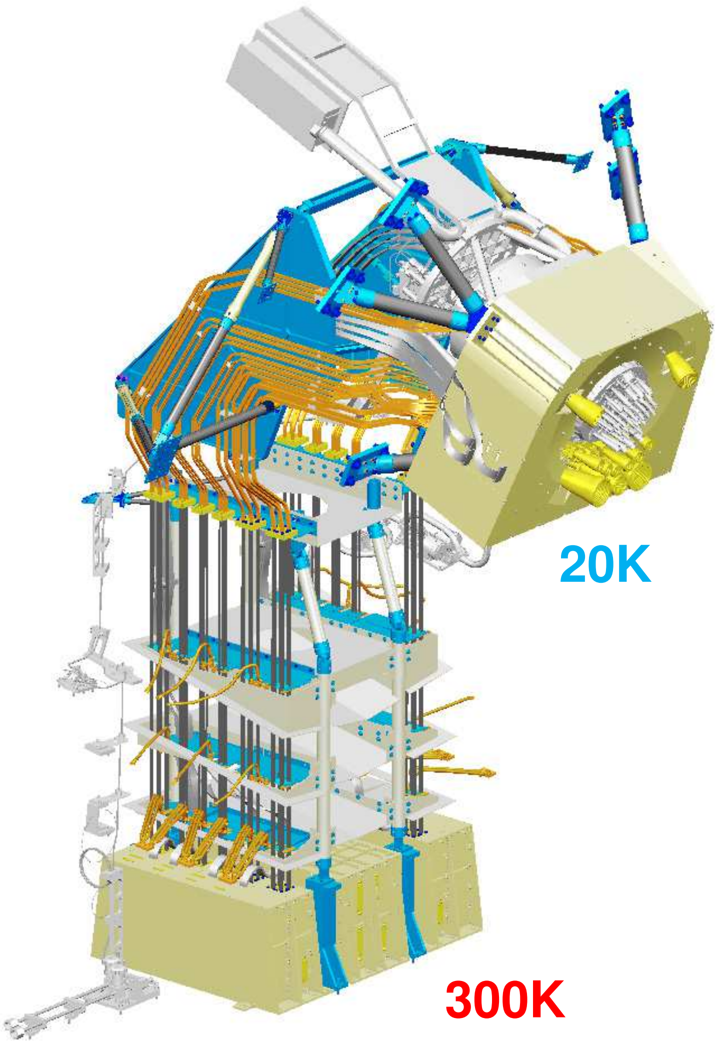
Zorita

Beyond PLANCK

The Low Frequency Instrument

Low frequency side (30, 44, 70 GHz) of Planck observations



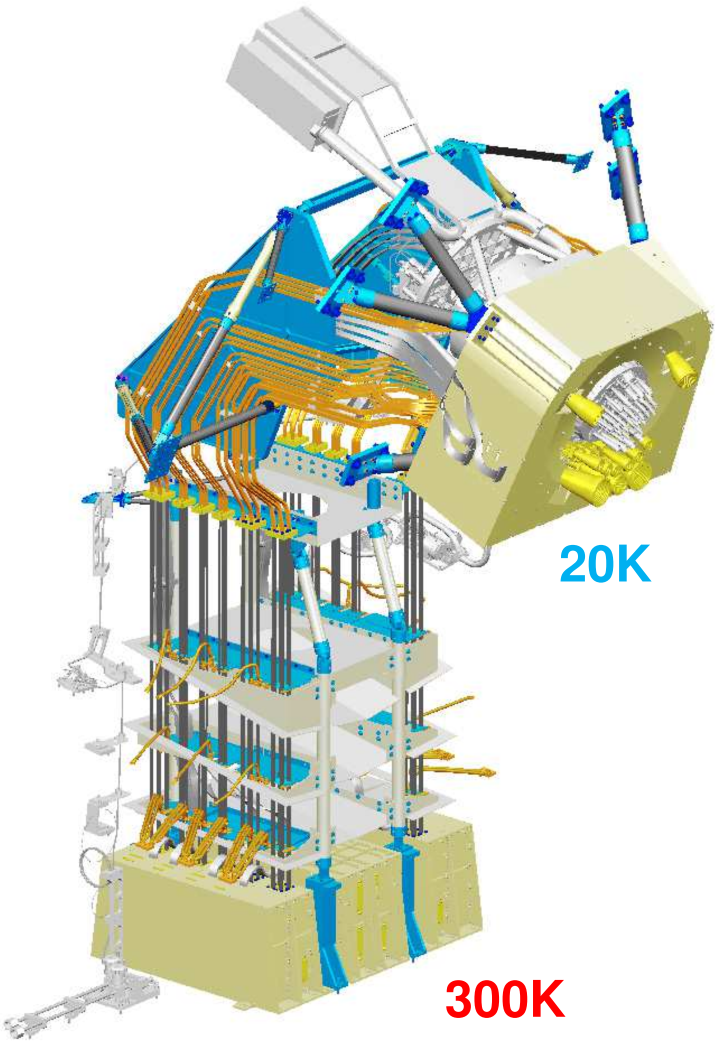
- Based on InP HEMT low noise amplifiers cooled to 20K
- Differential pseudo-correlation receiver, comparing sky signal with internal BB reference load at 4K
- System naturally sensitive to polarization

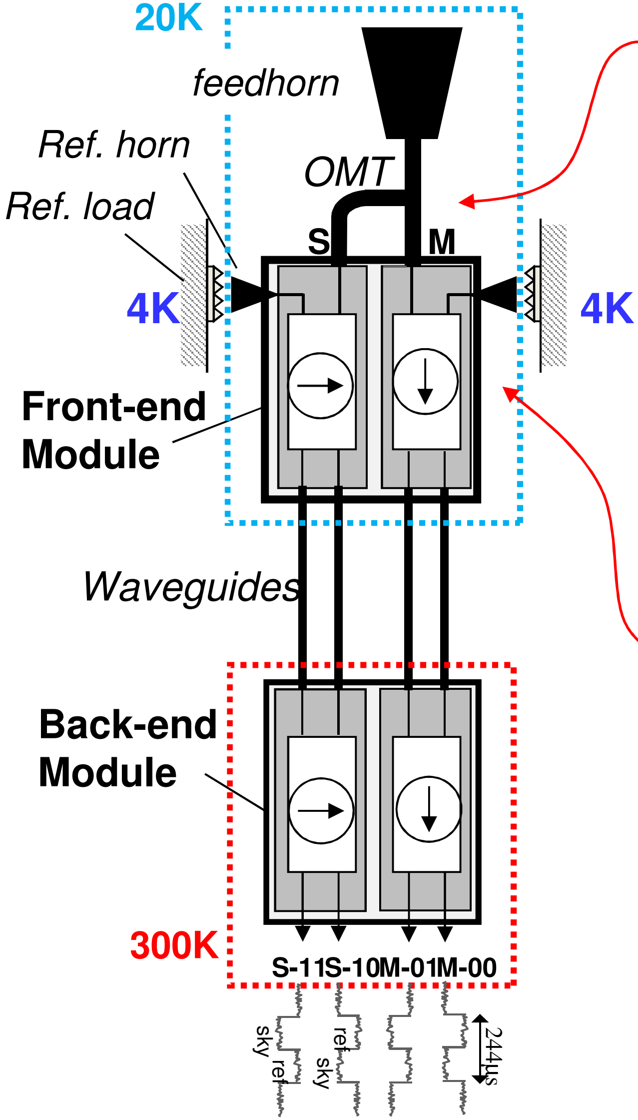
LFI PERFORMANCE GOALS[a]

INSTRUMENT CHARACTERISTIC	CENTER FREQUENCY [GHz] 30	44	70
InP HEMT Detector technology	MIC		MMIC
Detector temperature		20 K	
Cooling system		H_2 Sorption Cooler	
Number of feeds	2	3	6
Angular resolution [arcminutes FWHM]	33	24	14
Effective bandwidth [GHz]	6	8.8	14
Sensitivity [$\mathrm{mK\,Hz^{-1/2}}$]	0.17	0.20	0.27
System temperature [K]	7.5	12	21.5
Noise per 30′ reference pixel [μK]	6	6	6
$\Delta T/T$ Intensity [b] [10^{-6} μK/K]	2.0	2.7	4.7
($\Delta T/T$) Polarisation (Q and U) [b] [μK/K]	2.8	3.9	6.7
Maximum systematic error per pixel [μK]	< 3	< 3	< 3

Planck BlueBook pre-launch (2005)

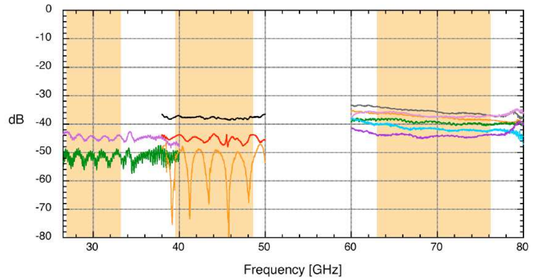
The Low Frequency Instrument





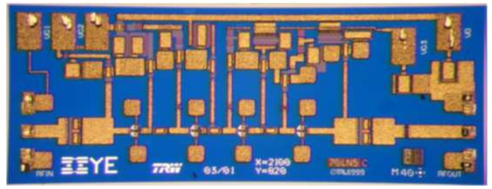
High polarization purity

OMT: Isolation < -35 dB

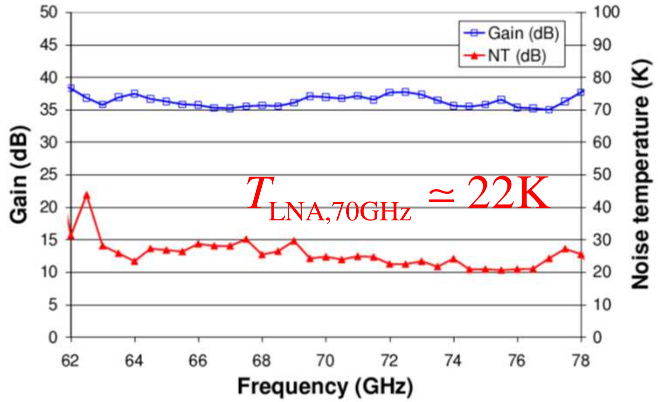


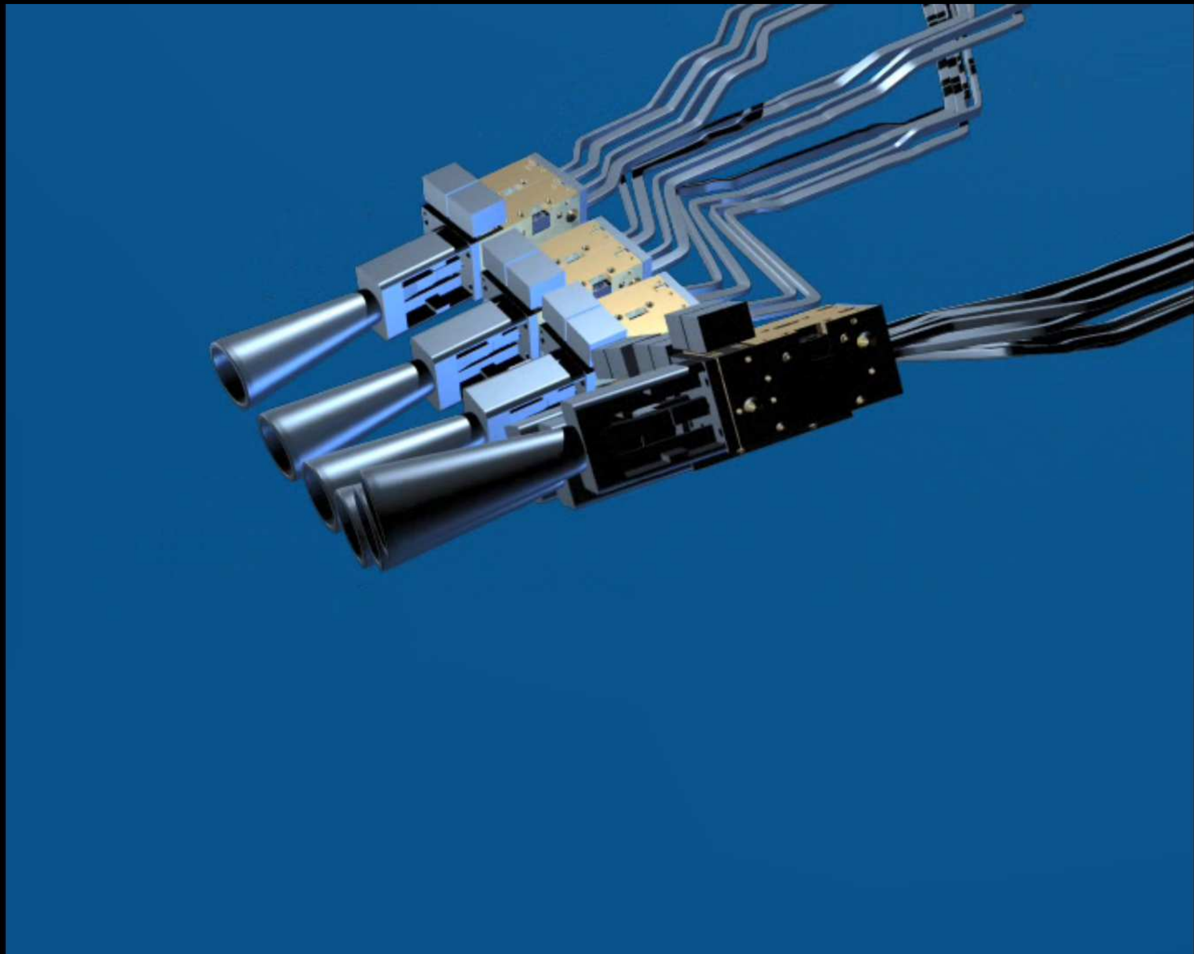
Low noise

2.1 mm x 0.8 mm



TRW MMIC 4-stage InP cryo HEMT Low Noise Amps





VTT – Finland – LFI 70GHz

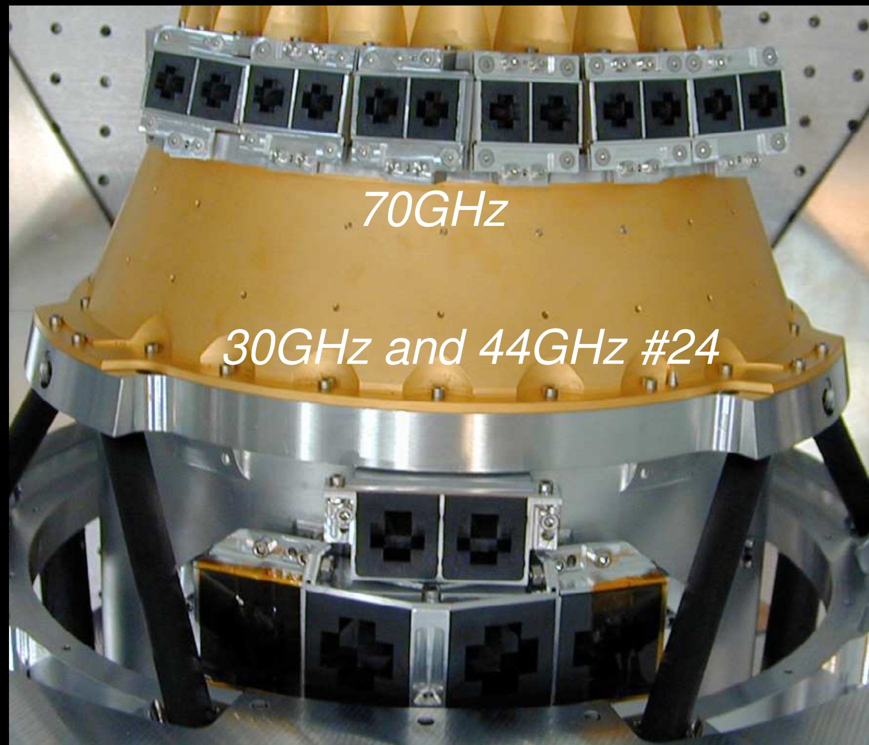
LFI

30 GHz

44 GHz

70 GHz

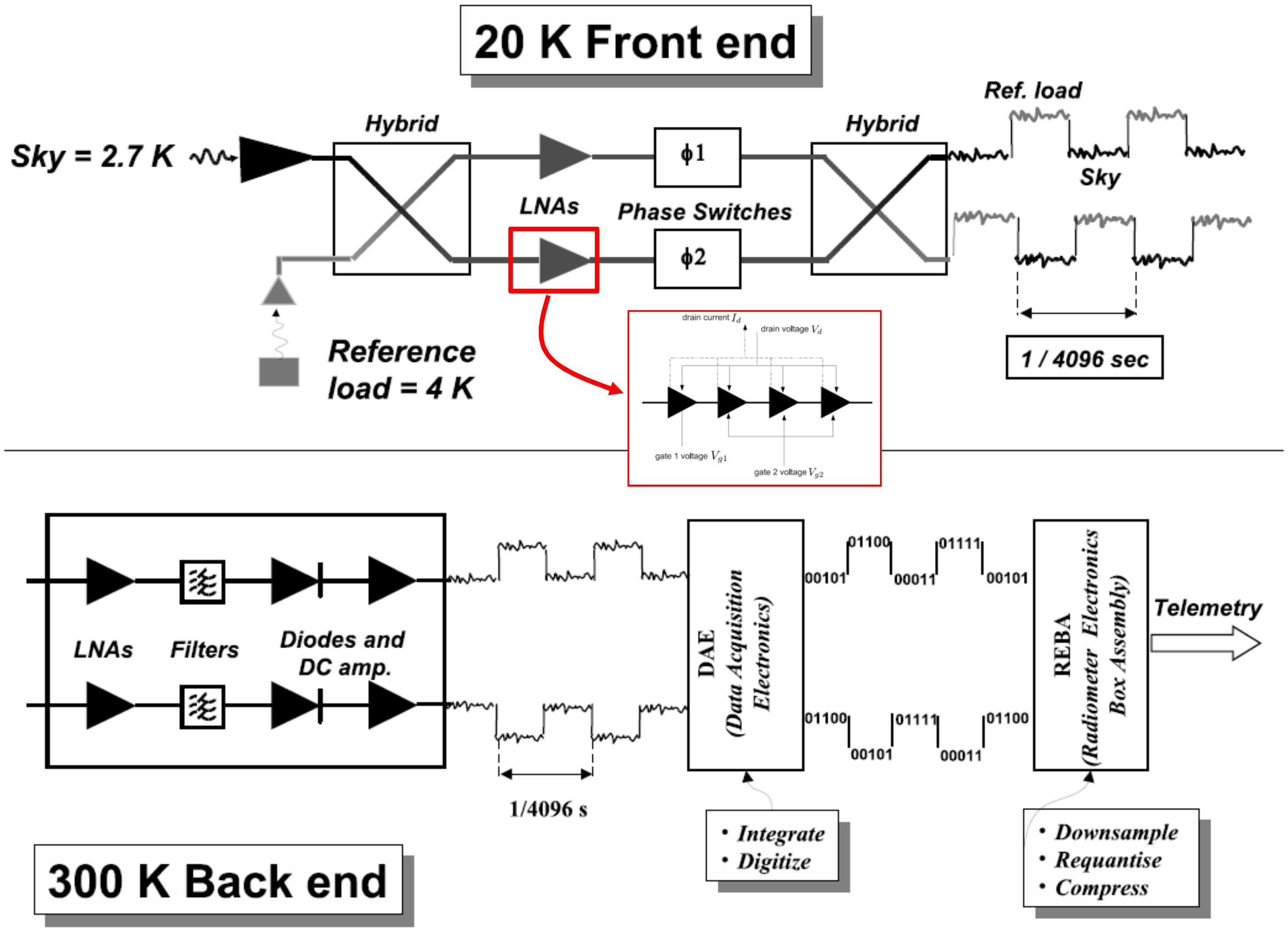
LFI 4K reference loads



HFI 4K box

Endoscope picture
Ref. horn – 4K load
1.5-mm thermal
gap (44GHz)

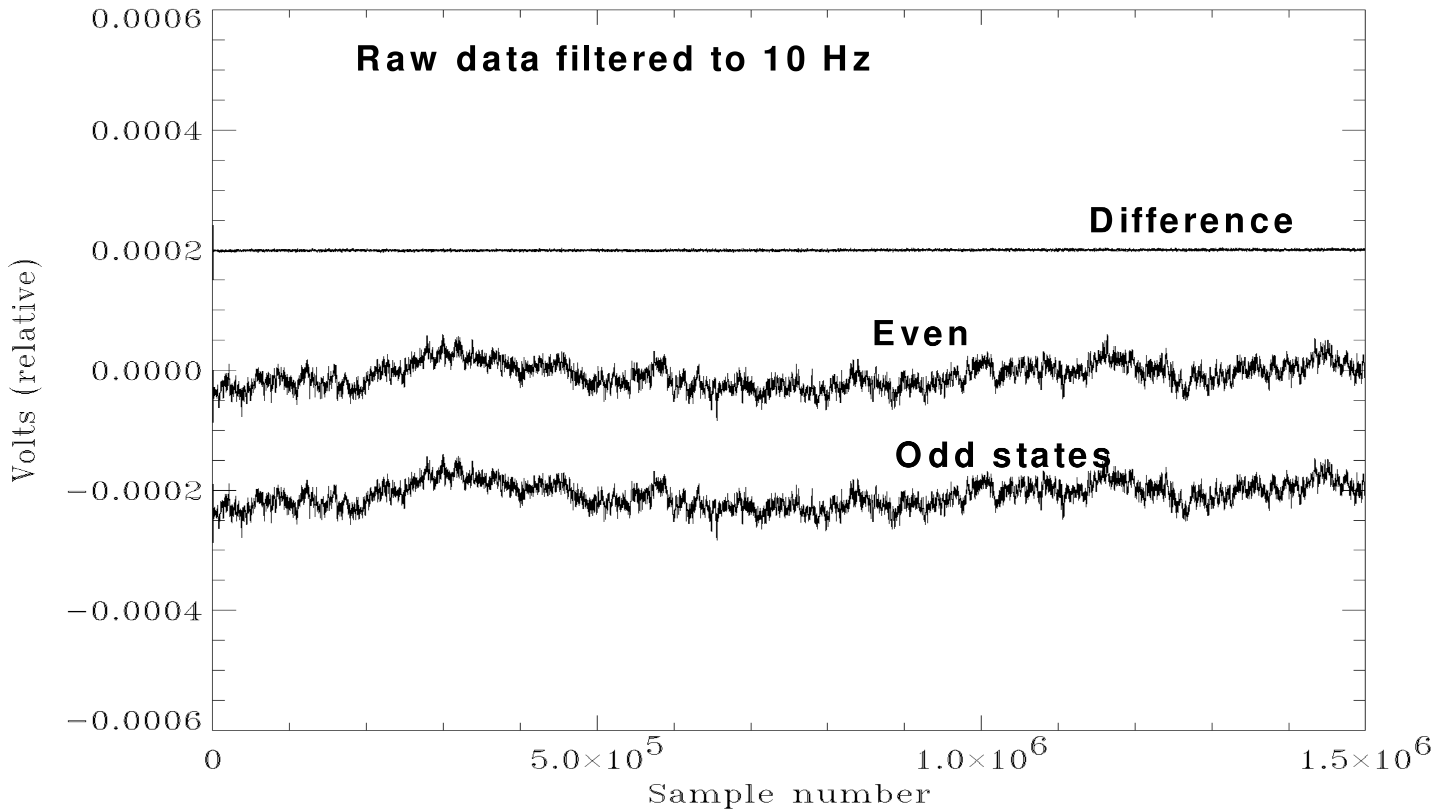
LFI pseudo-correlation receiver concept



- In each radiometer leg, booth sky and reference signals undergo the same 1/f fluctuations (f_k reduced by factor 10^4)
- Phase switch (4kHz) further suppresses fluctuations (e.g. from Back end)

LFI pseudo-correlation receiver concept

Diode difference



$$\langle p \rangle \cong T_{A,sky} - rT_{A,load}$$

Gain modulation factor (applied in s/w)

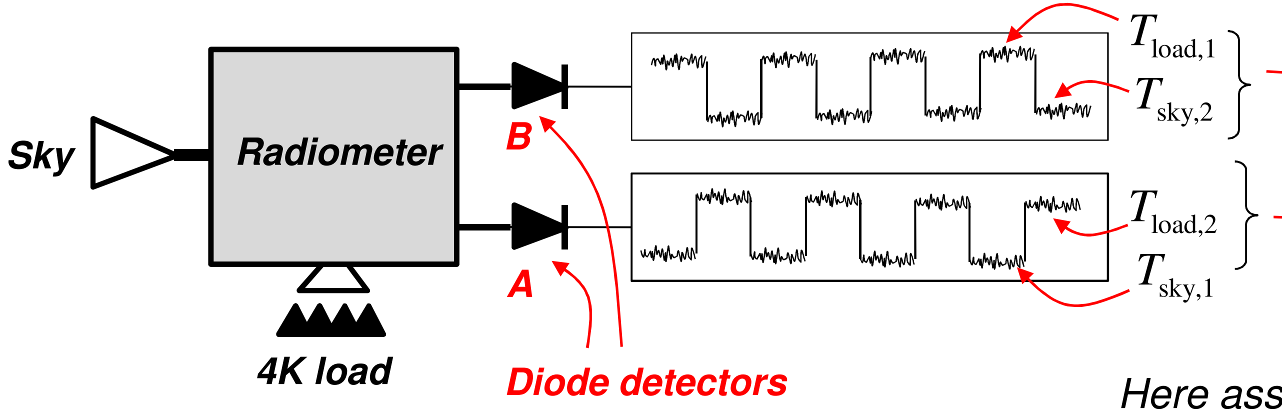
$$r = \frac{T_{sky} + T_{noise}}{T_{load} + T_{noise}} \simeq \frac{V_{sky}}{V_{load}}$$

- *r-factor optimized to null radiometer output*
- *Further reduction in 1/f knee frequency*

LFI pseudo-correlation receiver concept

Radiometer difference

- Further stabilization is obtained by differencing the two diode of each radiometer
  - *Phase switch non-idealities are removed to first order*
  - *Improvement in knee frequency demonstrated in EBB tests*



Sky-load difference

Here assume
$r_1 = r_2 = 1$

$$\Delta T_B = (T_{\text{sky},1} - T_{\text{load},2})$$

$$\Delta T_A = (T_{\text{load},1} - T_{\text{sky},2})$$

$$T_{\text{sky/load},i} = T_{\text{sky/load}} + \delta T_i$$

Diode (B-A) difference

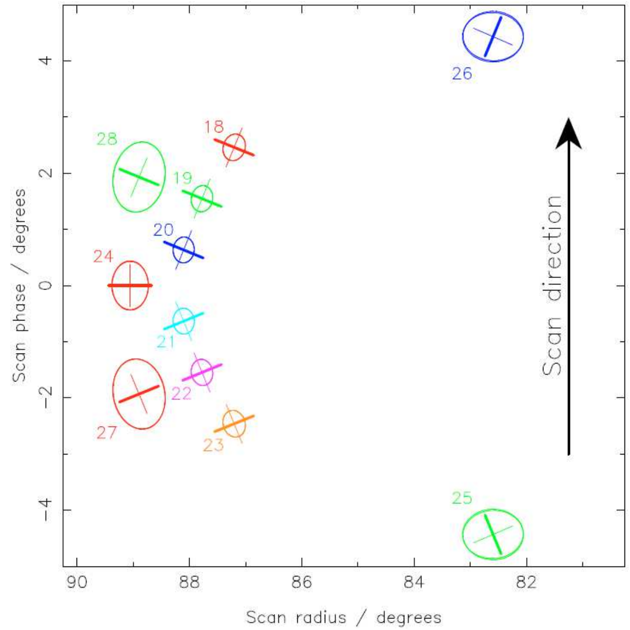
We apply inverse-noise weights when averaging

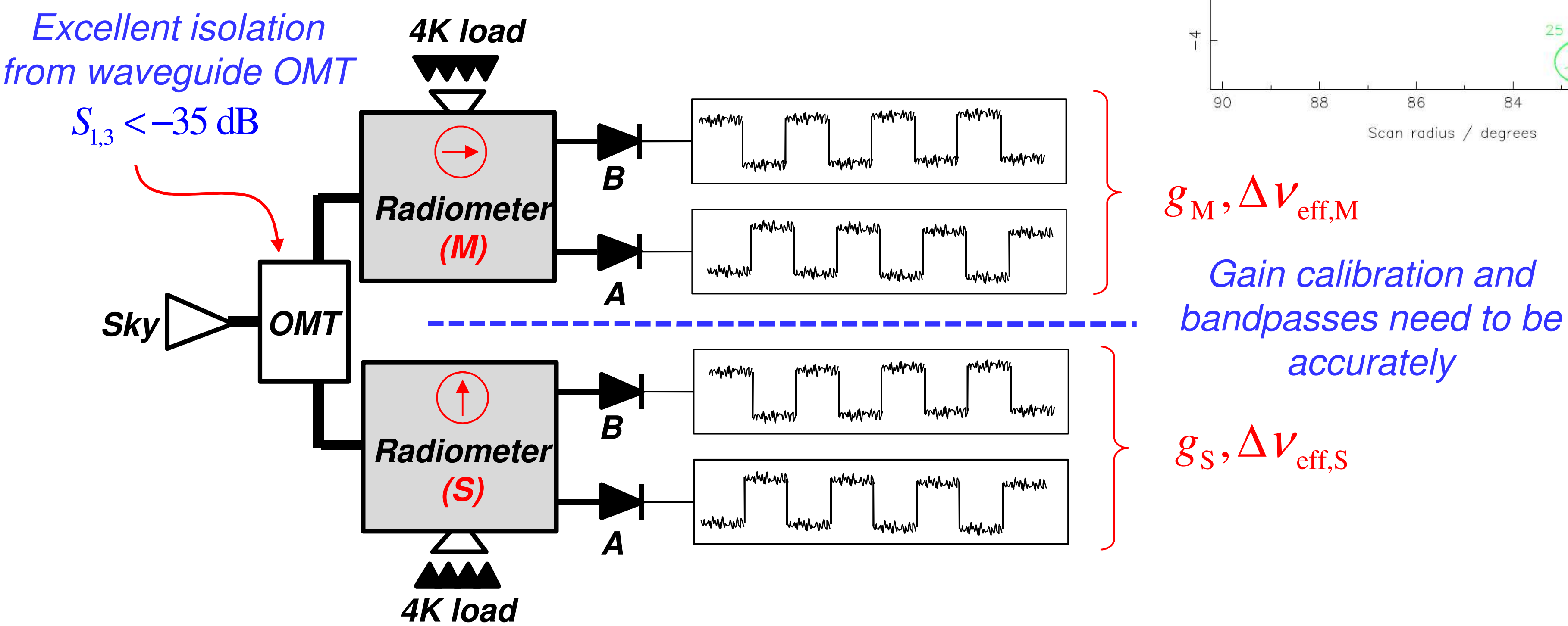
$$\begin{aligned}\Delta T_{\text{B}} - \Delta T_{\text{A}} &= (T_{\text{sky},1} - T_{\text{load},2}) - (T_{\text{load},1} - T_{\text{sky},2}) = \\ &= (T_{\text{sky}} + \delta T_1 - T_{\text{load}} - \delta T_2) - (T_{\text{load}} + \delta T_1 - T_{\text{sky}} - \delta T_2) \\ &= 2(T_{\text{sky}} - T_{\text{load}})\end{aligned}$$

Planck scanning strategy: 40-60 spins are fully overlapping
Redundancy and crossing in polar regions

LFI as a polarimeter

- Projected angles in the sky optimized to extract Q and U Stokes parameters
- Require differencing between M and S in horn-coupled and combination of paired horns
- Paired radiometers downstream the OMT are RF-independent

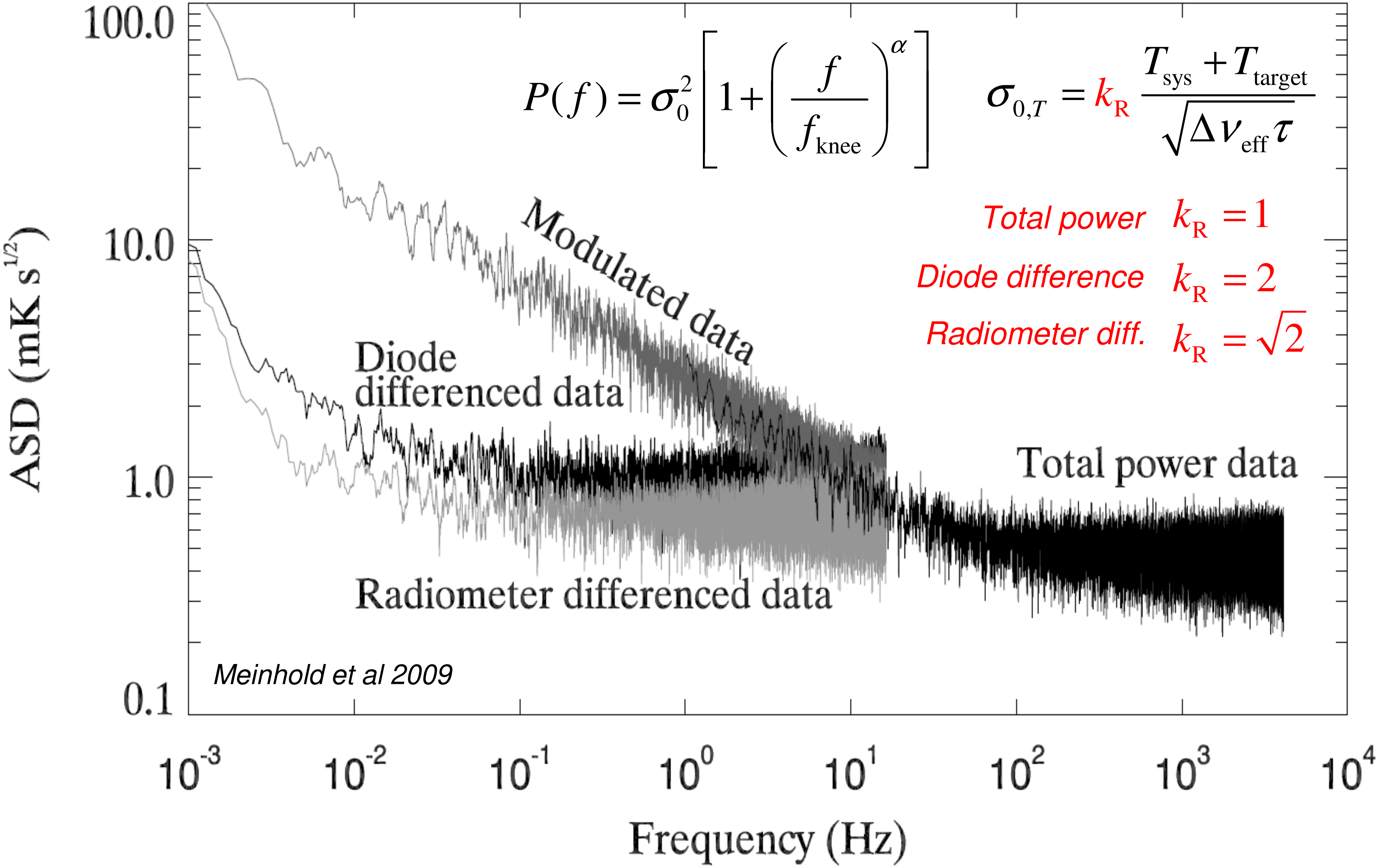




- Calibration or bandpass errors at ~few 0.01% level introduce significant T to P leakage for EE polarization

LFI noise spectrum

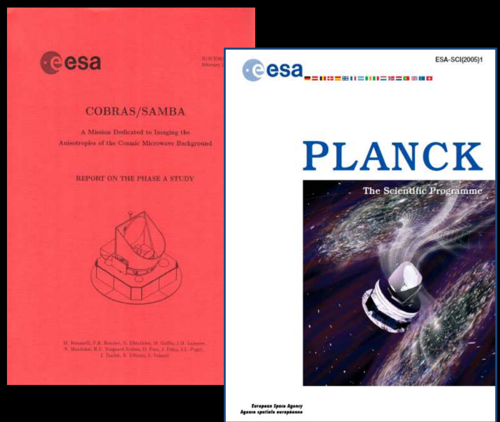
LFI pre-launch test data



LFI sensitivity

Noise ***measured in-flight****, full mission (CMB channels)*

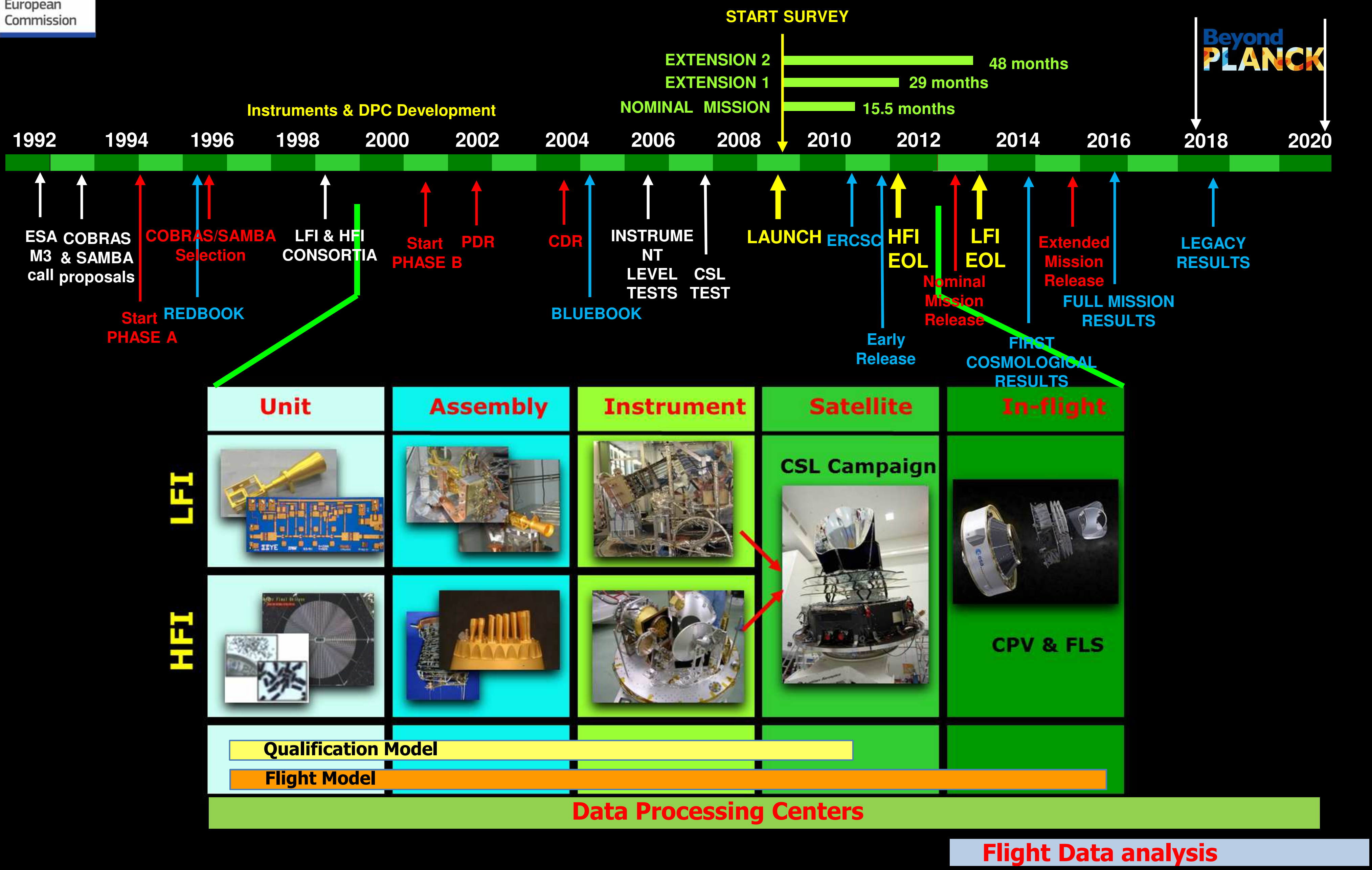
	30GHz	44GHz	70GHz	100GHz	143GHz	217GHz	353GHz
Angular resolution [arcmin]	33.2	28.1	13.1	9.7	7.3	5.0	4.9
Noise sensitivity [μK_{CMB} $s^{1/2}$]	148.5	173.2	151.9	41.3	17.4	23.8	78.8
NOISE/PIXEL							
From detector sensitivity [μK_{CMB}]	9.2	12.7	23.9	9.6	5.4	10.7	36.5
Measured from maps [μK_{CMB}]	9.2	12.5	23.2	11.2	6.6	12.0	43.2
Extended mission [months]	*48*	*48*	*48*	*29*	*29*	*29*	*29*
End-of-missioni [μK_{CMB}]	5.2	7.1	13.2	8.2	4.8	8.8	31.6
Measured End-of-Mission [ΔT/T, μK/K]	**1.9**	**2.6**	**4.8**	**3.0**	**1.8**	**3.2**	**11.6**
2005: Blue book GOAL [ΔT/T, μK/K]	**2.0**	**2.7**	**4.7**	**2.5**	**2.2**	**4.8**	**14.7**
1996: Red book GOAL [ΔT/T, μK/K]	**~ 2**						



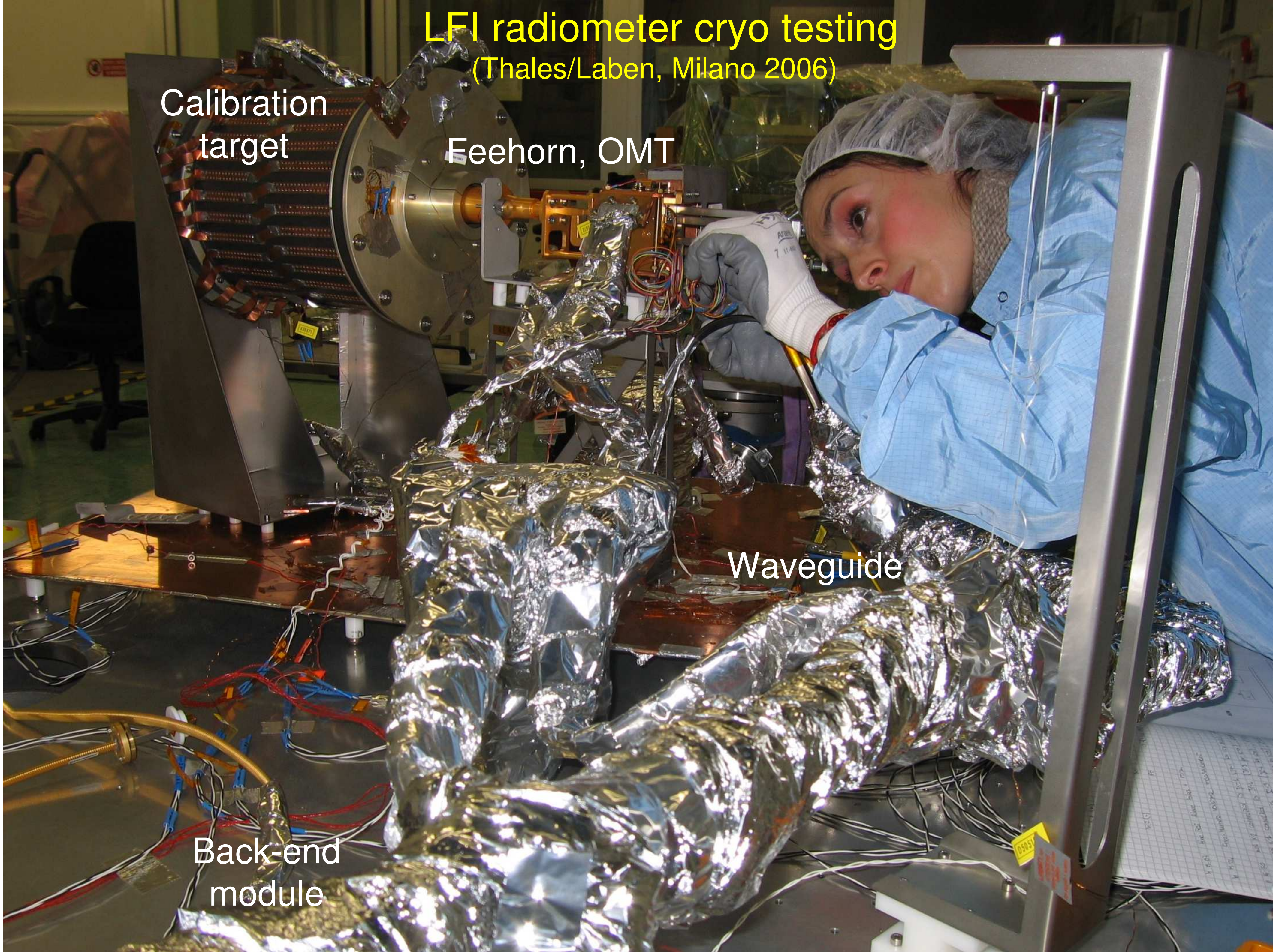
At end of mission Planck fulfills completely the sensitivity goals proposed in the design phase many years in advance

But this is not enough!

Instrument development
Ground & in-flight calibration

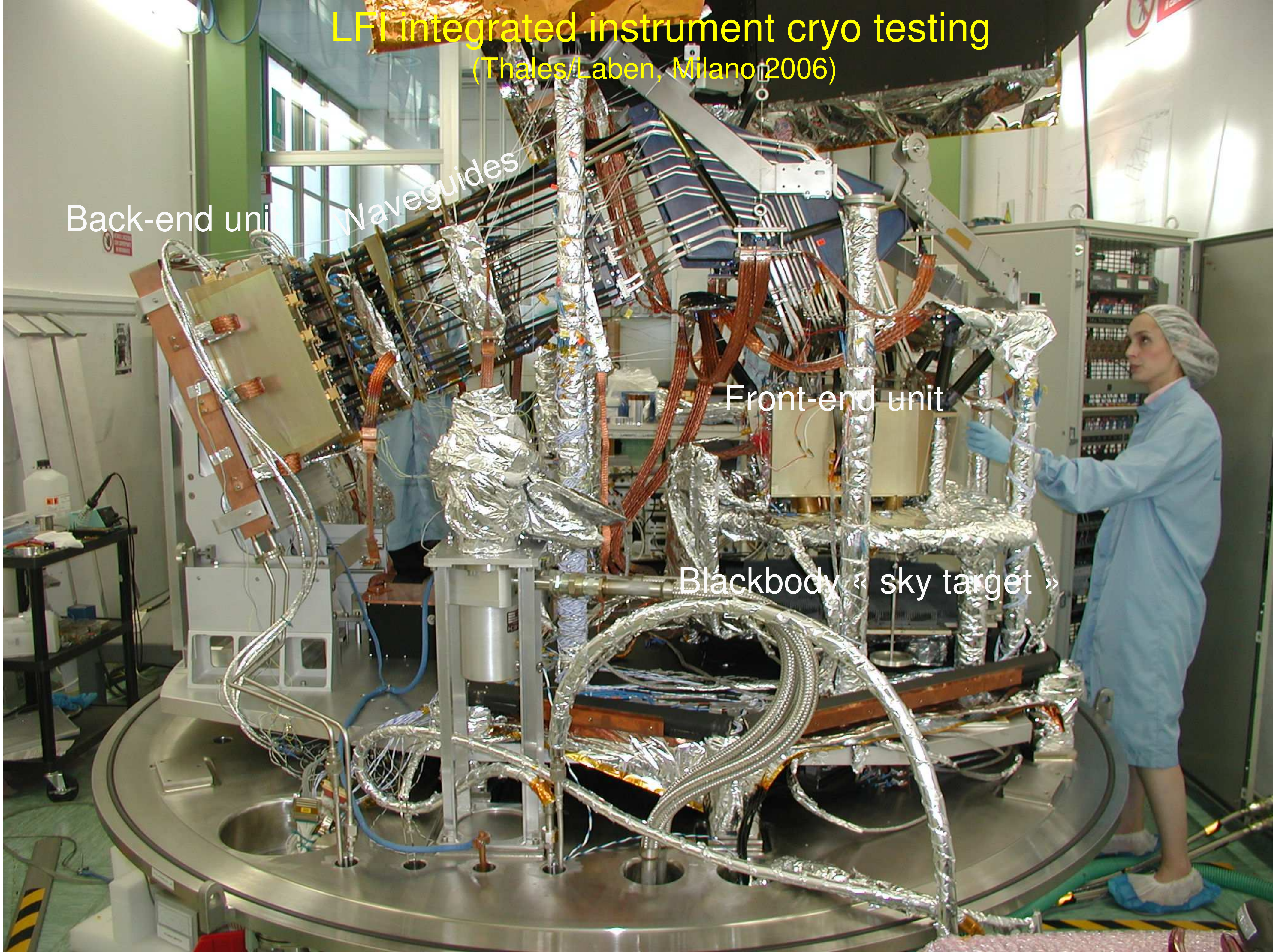


Lesson learned: Do not underestimate ground calibration!


LFI radiometer cryo testing
(Thales/Laben, Milano 2006)
Calibration target
Feehorn, OMT
Waveguide
Back-end module

LFI integrated instrument cryo testing

(Thales/Laben, Milano 2006)



Satellite-level cryo testing
(CSL, Liege 2007)


Maurizio celebrates
Celebrating
Enrico
LFI Telegraph Editor
Stefania
Dave keeping cool
"What is it?"
Christian
SCOS is fun!!
"Hi Chris"
Andrea
"It happened tomorrow"
The Matrix: Paola
Rodrigo gets a LIFE
More celebrations
Peter at work
Orfeto
Fabrizio has a rest
Luis
Marco
Sleeping beauty
Francesco hard at work
"Tell it to me"
How many baguettes?
Leticia
Matrix Tuning: Neo
Daily dinner
Happy SCOS operators
Enthralled by data
The end of CRYO-01

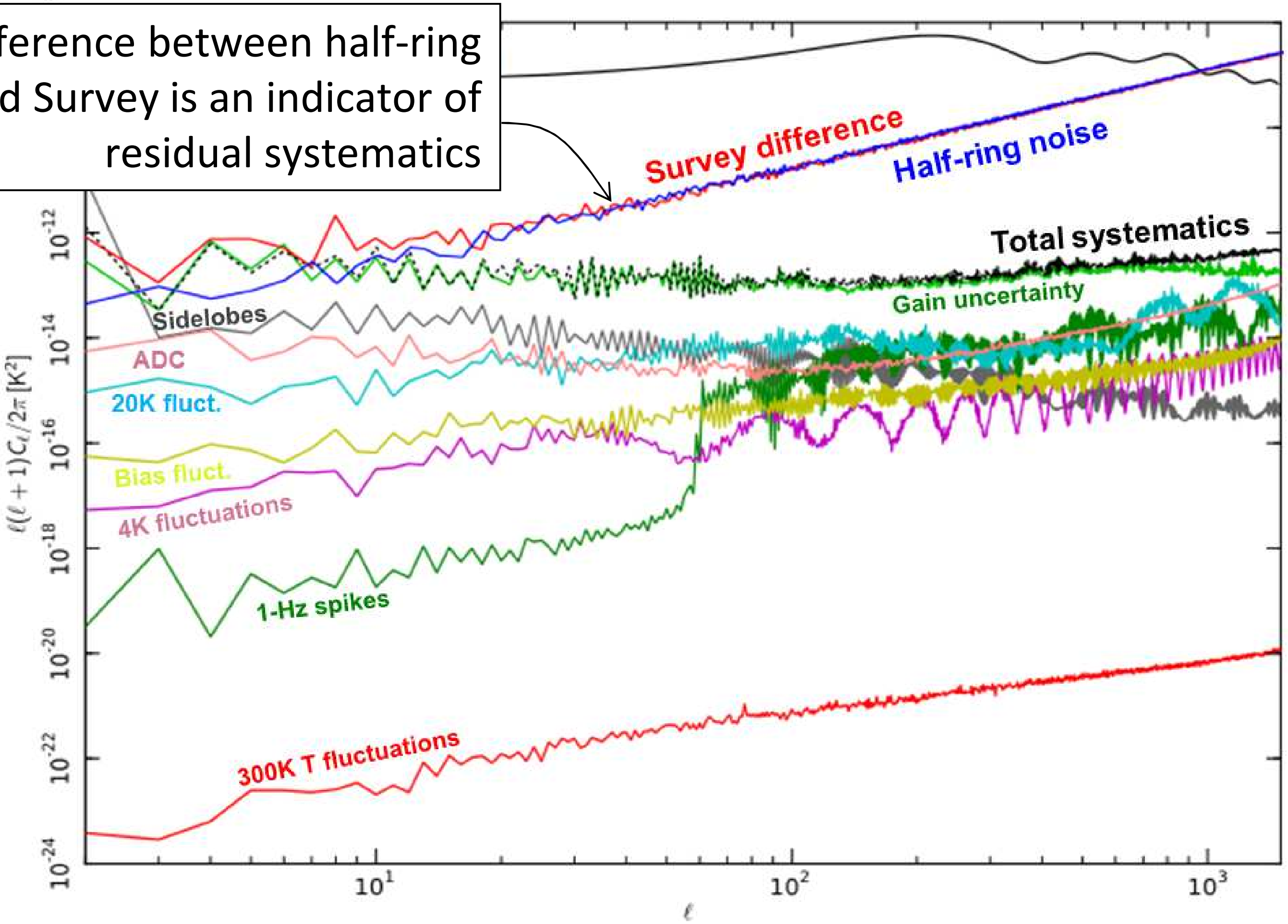
Main challenge: systematic effetcs

European Commission

LFI systematics summary – Temperature

Weighted average of each effect over the 30, 44 and 70GHz channels

Difference between half-ring and Survey is an indicator of residual systematics



[Planck Collaboration III. LFI Systematics, 2013]

Planck Collaboration,
2020, A&A, 641, A2
2016, A&A, 594, A2+A3
2014, A&A 571, A2+A3
Mennella et al 2011 A&A 536, A3

- Detailed models & simulations for each foreseeable effect
- Based on testing from unit-level to system-level
- Systematics well under control for TT

Beyond PLANCK

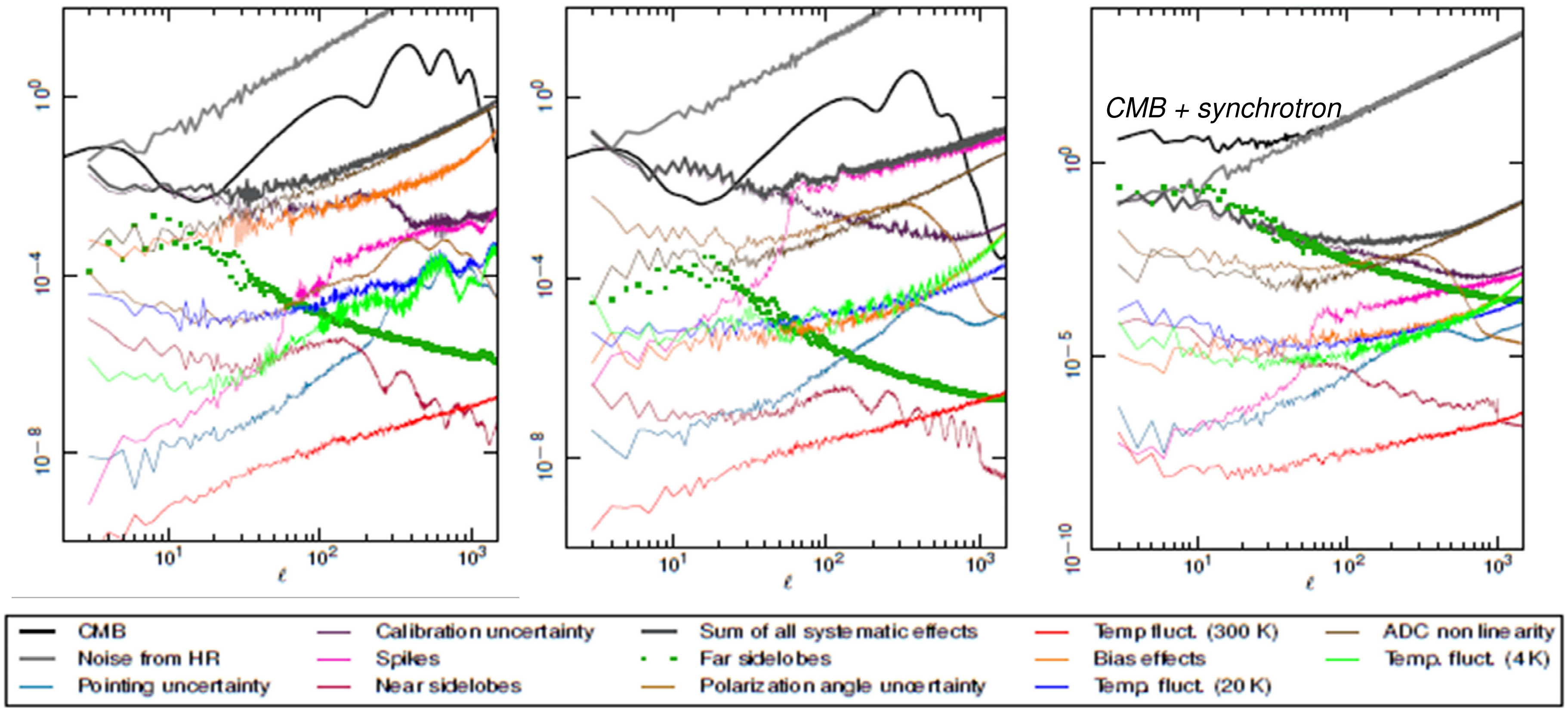
LFI systematic effects

European Commission

LFI systematics summary – EE polarization

Independent analysis for the 30, 44 and 70GHz channels

70 GHz 44 GHz 30 GHz



Planck Collaboration,
2020, A&A, 641, A2
2016, A&A, 594, A2+A3
2014, A&A 571, A2+A3
Mennella et al 2011 A&A 536, A3

- As expected, DPC analysis showed significant contamination at 44GHz (and 30GHz) for large scale polarization
- 44GHz channel not used for cosmological analysis

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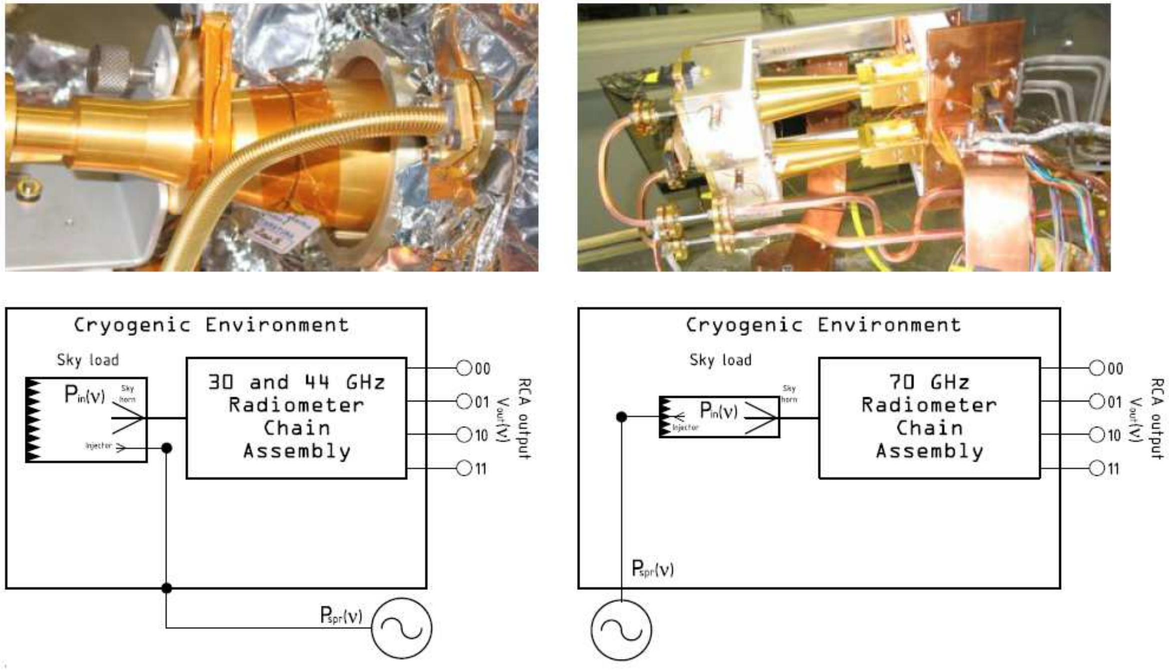
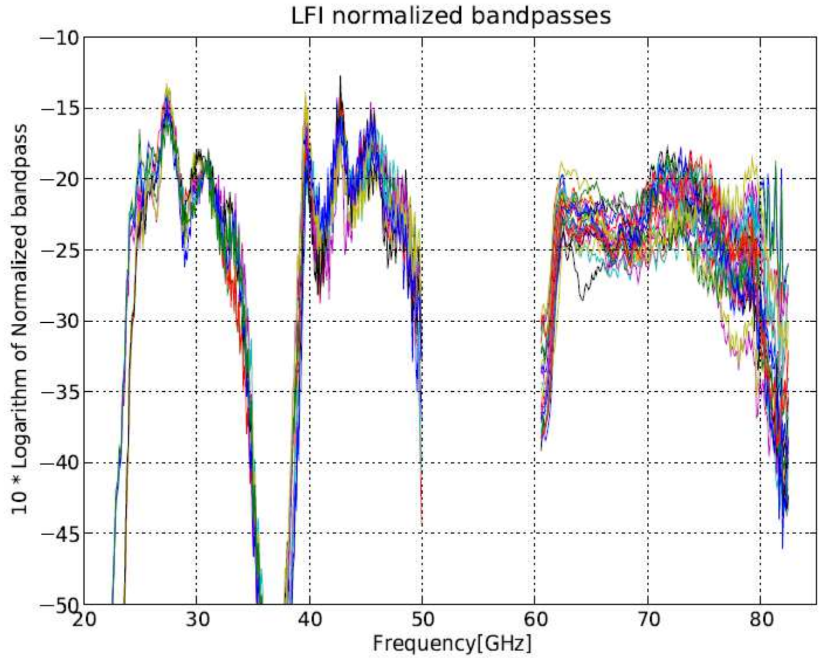
Limiting factors of LFI Characterization

Bandpass measurements



Villa et al 2010



Zonca et al 2009

- Coupling foregrond emission with instrument systematics
- Intensity to Polarization leakage

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Limiting factors of LFI characterization

Assumption of stationary noise

3-parameter noise model: $$P(f) = \sigma_0^2 \left[1 + \left(\frac{f}{f_{\mathrm{knee}}} \right)^{\alpha} \right]$$

	Knee Frequency f_{knee} [mHz]		Slope β	
	Radiometer M	Radiometer S	Radiometer M	Radiometer S
70 GHz				
LFI-18	14.8 ± 2.5	17.8 ± 1.5	-1.06 ± 0.10	-1.18 ± 0.13
LFI-19	11.7 ± 1.2	13.7 ± 1.3	-1.21 ± 0.26	-1.11 ± 0.14
LFI-20	8.0 ± 1.9	5.7 ± 1.5	-1.20 ± 0.36	-1.30 ± 0.41
LFI-21	37.9 ± 5.2	13.3 ± 1.5	-1.25 ± 0.09	-1.21 ± 0.09
LFI-22	9.7 ± 2.3	14.8 ± 6.7	-1.42 ± 0.23	-1.24 ± 0.30
LFI-23	29.7 ± 1.1	59.0 ± 1.4	-1.07 ± 0.03	-1.21 ± 0.02
44 GHz				
LFI-24	26.8 ± 1.3	88.3 ± 8.9	-0.94 ± 0.01	-0.91 ± 0.01
LFI-25	20.1 ± 0.7	46.4 ± 1.8	-0.85 ± 0.01	-0.90 ± 0.01
LFI-26	64.4 ± 1.9	68.2 ± 9.5	-0.92 ± 0.01	-0.76 ± 0.07
30 GHz				
LFI-27	174.5 ± 2.9	108.8 ± 2.5	-0.93 ± 0.01	-0.91 ± 0.01
LFI-28	130.1 ± 4.4	43.1 ± 2.4	-0.93 ± 0.01	-0.90 ± 0.02

Planck 2015, A03

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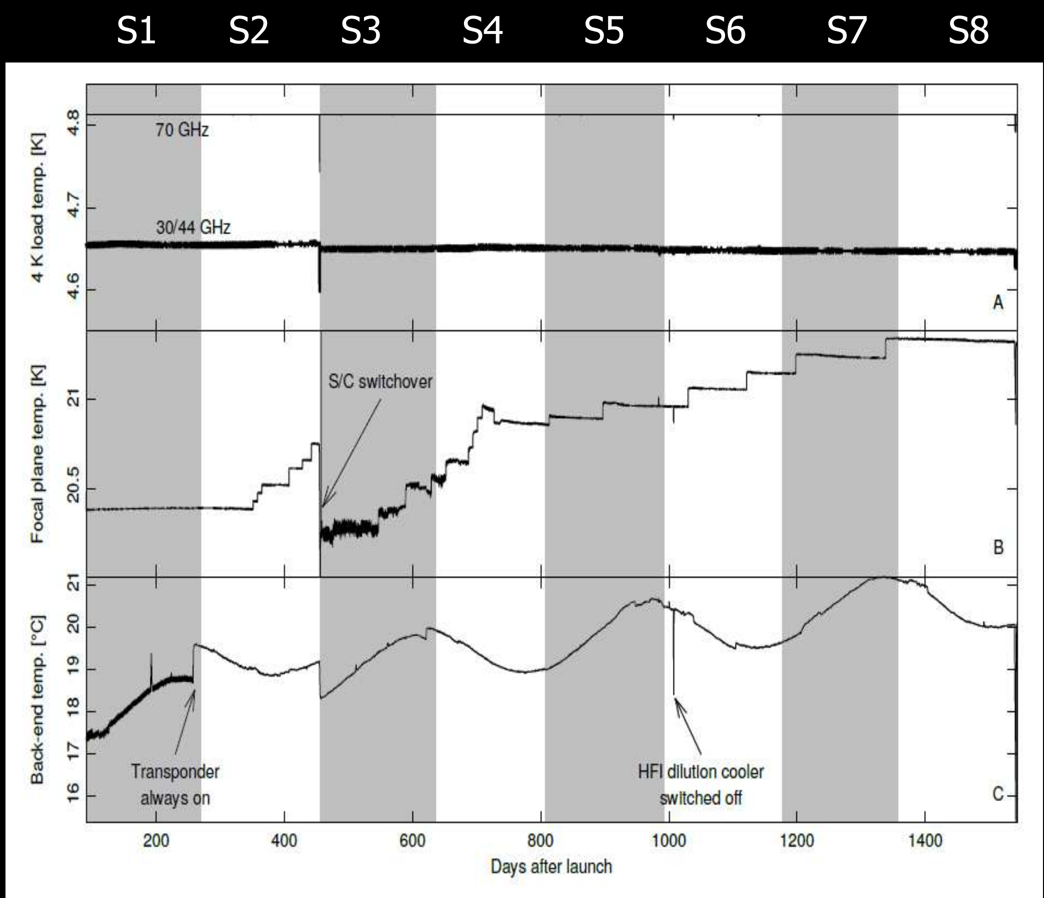
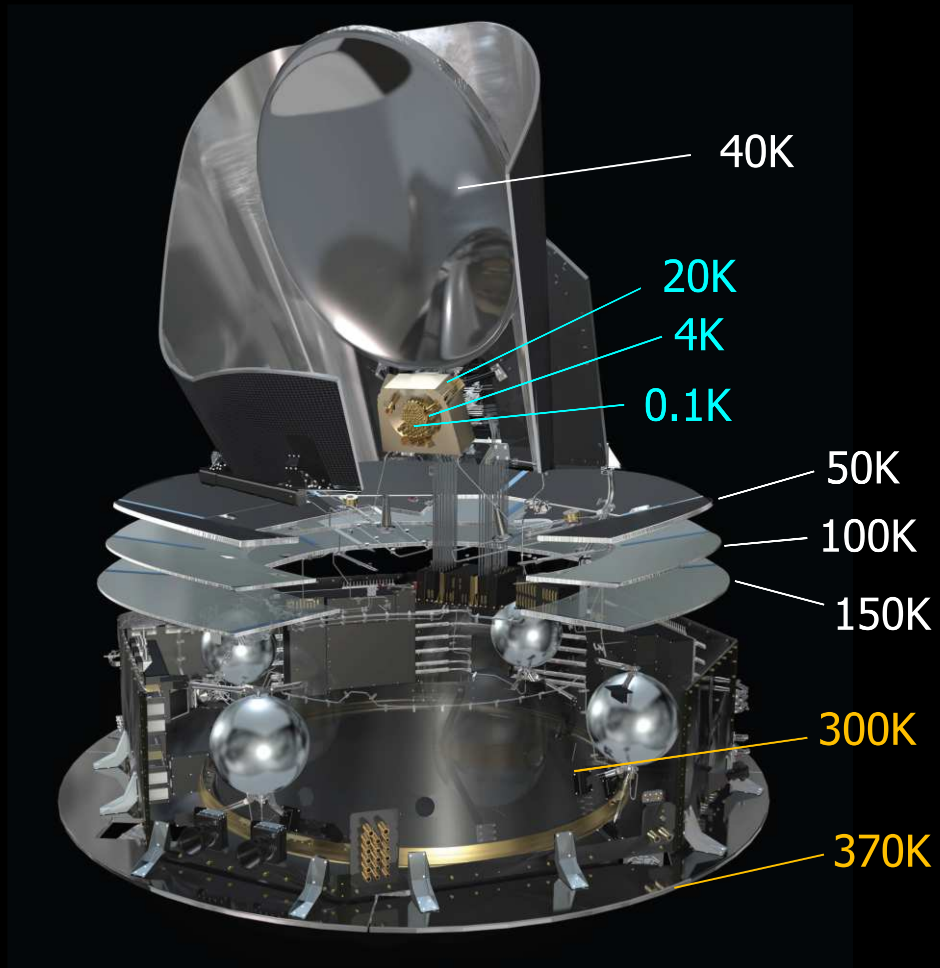
Planck in-flight thermal stability

Full LFI mission (8 sureys)





L2 is an extremely stable environment

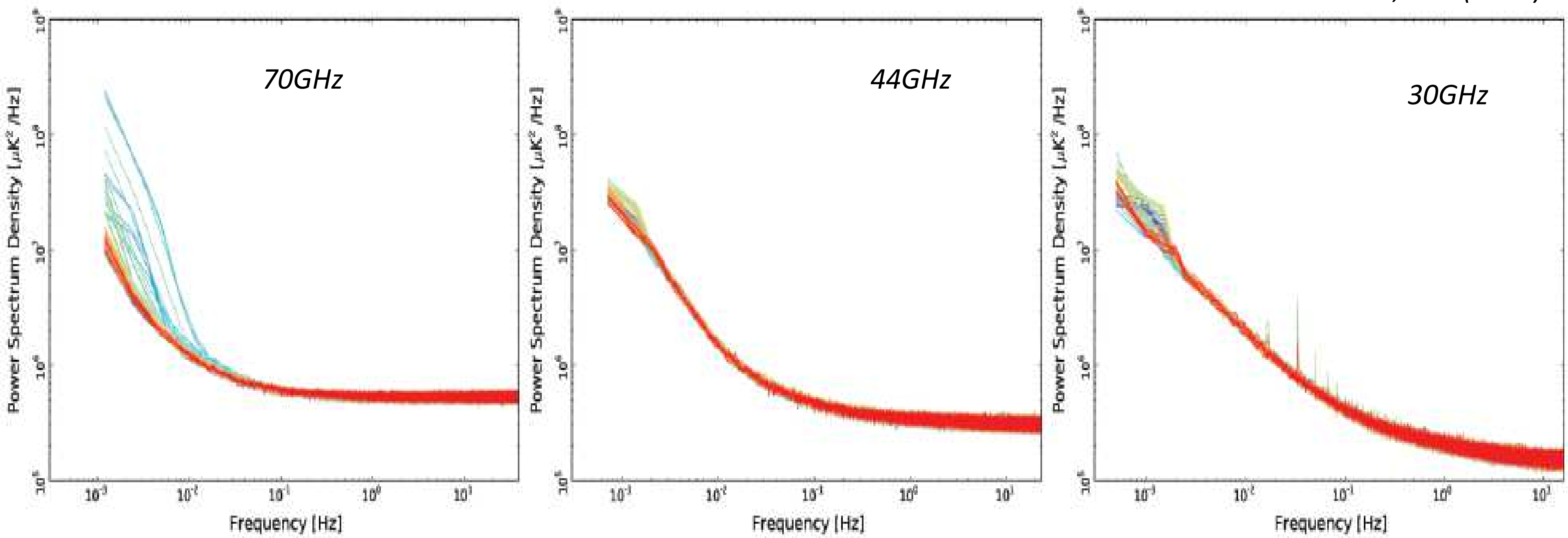
Thermal changes related to operations during mission lifetime

Moderate impact on LFI noise properties

Limiting factors of LFI characterization

Assumption of stationary noise

Planck 2018 release
A&A, A02 (2020)



- *Noise model assumed average values of* $\sigma_0, f_{\mathrm{knee}}, \alpha$
- *Variations of noise properties were observed, but not studied in detail in previous analyses*

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Håvard Tveit Ihle's presentation

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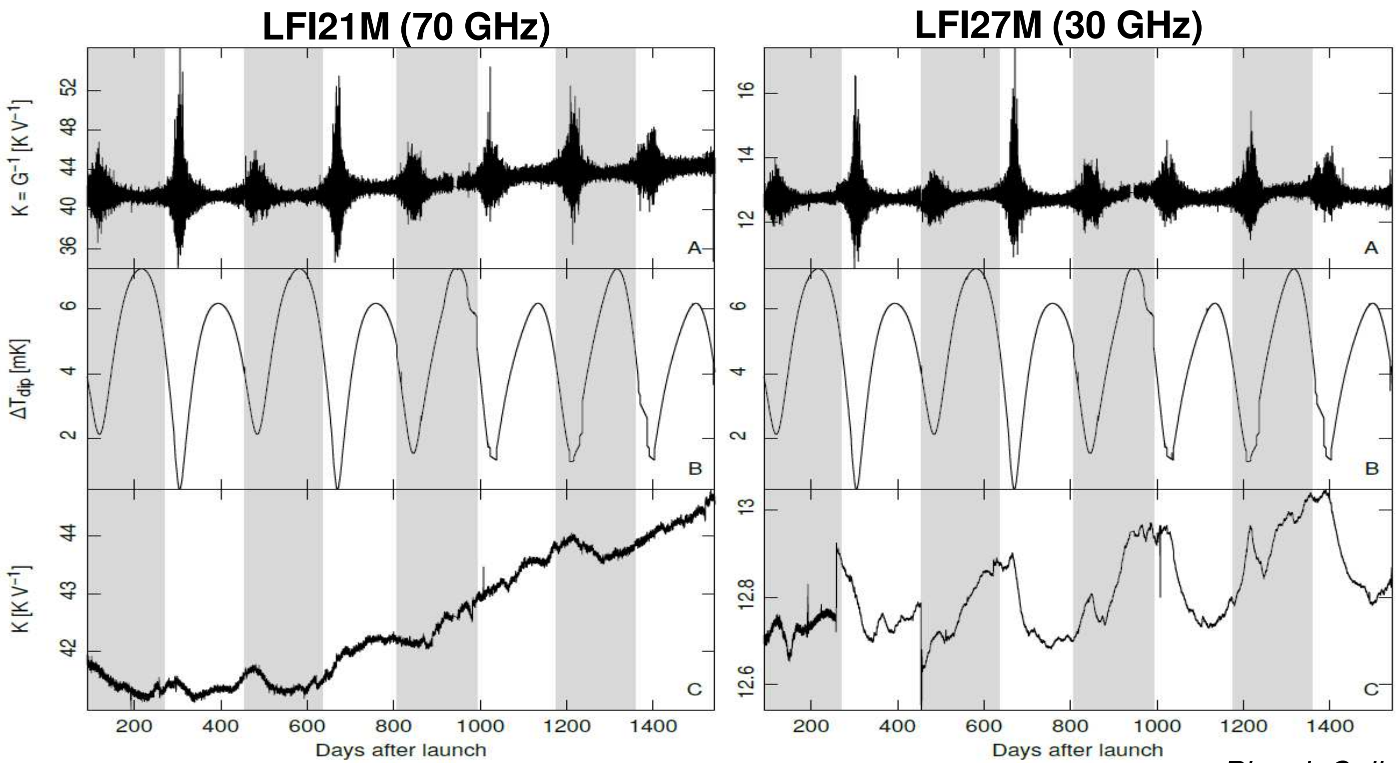
Limiting factors of LFI characterization

Gain reconstruction



Gain

Dipole amplitude

Smoothed gain

Planck Collaboration 2016, A&A, 594, A5

- Large uncertainties in periods of dipole minima
- Foreground emission contaminating gain reconstruction

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Eirik Gjerløw's presentation

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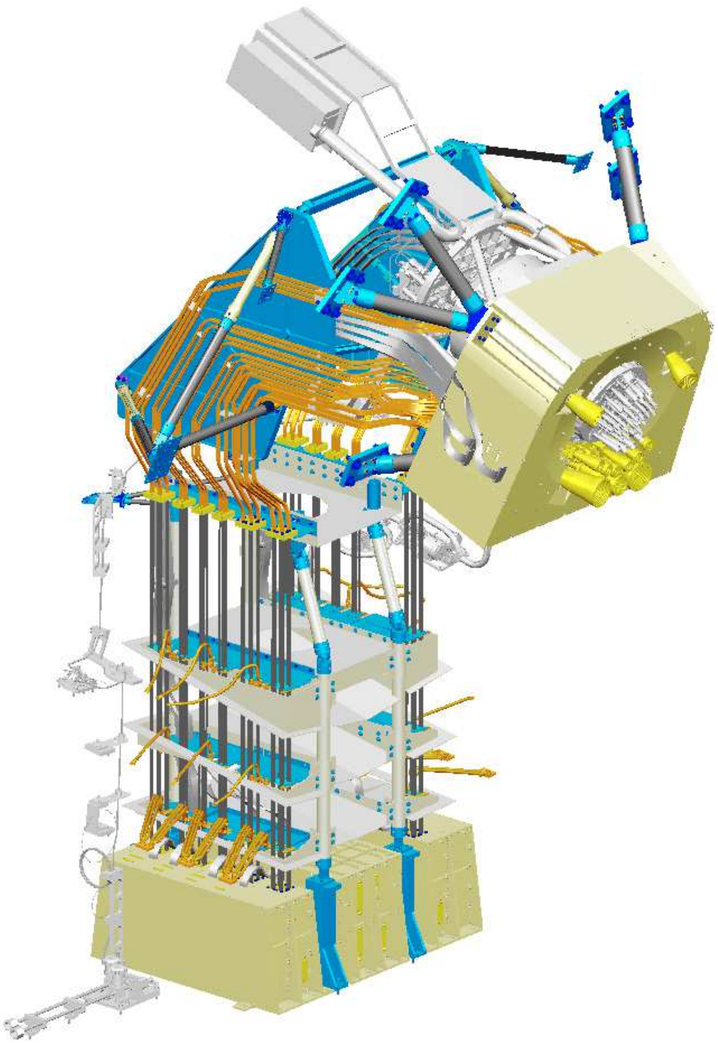
Conclusions



- The LFI differential scheme strongly suppresses 1/f noise and other instabilities, leading (*to first order*) to a simple 3-parameters noise model
- In-flight, LFI was fully functional (*22 radiometers out of 22*) and reached its sensitivity goal at end-mission
- Systematic effects are fully under control for Temperature. For Polarization gain calibration and bandpass uncertainties are a challenge at the largest angular scale scales
- The main criticality is the combination of foregrounds with instrumental systematics: This is at the heart of the BeyondPlanck approach
- BeyondPlanck features:
  - *fully-iterative calibration*
  - *parametrisation of bandpasses*
  - *non-stationary noise*

  provide a novel opportunity for data analysis of Planck and of other CMB experiments

Beyond PLANCK

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  - COMPET-4 program
  - PI: Hans Kristian Eriksen
  - Grant no.: 776282
  - Period: Mar 2018 to Nov 2020

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- "*bits2cosmology*"
  - ERC Consolidator Grant
  - PI: Hans Kristian Eriksen
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- "*Cosmoglobe*"
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  - PI: Ingunn Wehus
  - Grant no: 819 478
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