Planck review and lessons learned

LFI systematic effects / calibration challenge

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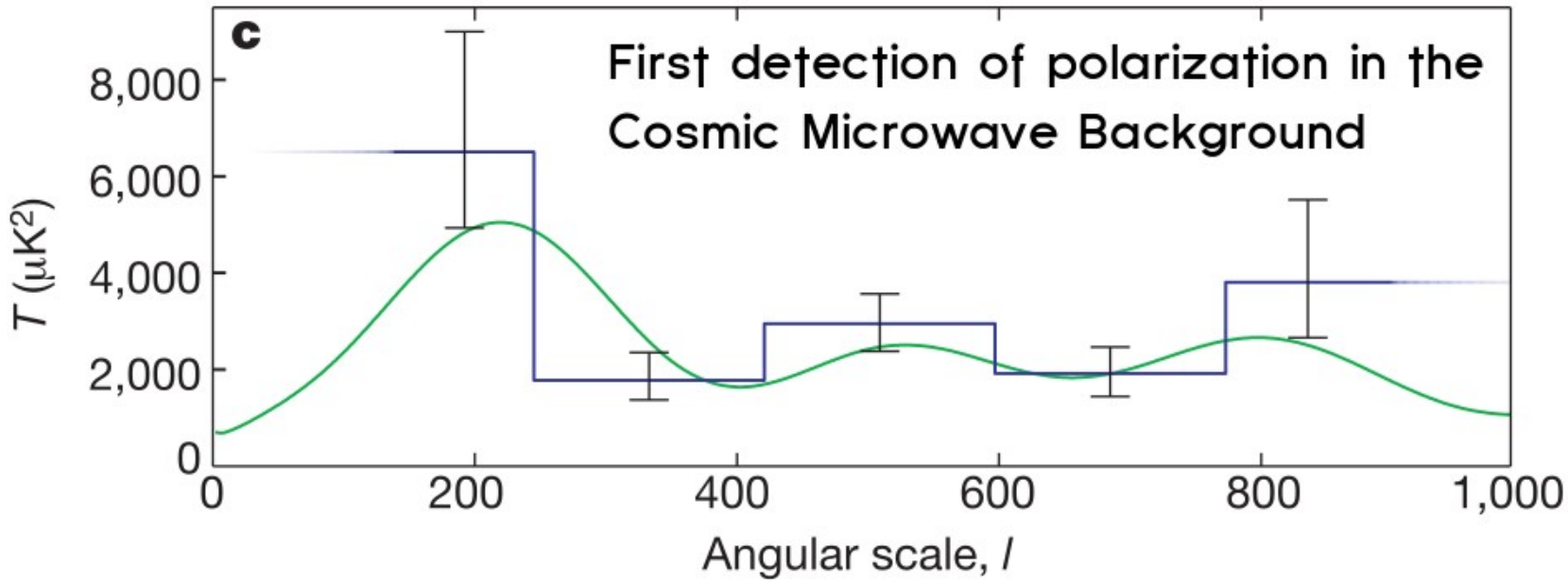
It seems yesterday

Detection of polarization in the cosmic microwave background using DASI

J. M. Kovac*†‡, E. M. Leitch§†‡, C. Pryke§†‡||, J. E. Carlstrom§*†‡||, N. W. Halverson¶† & W. L. Holzapfel¶†

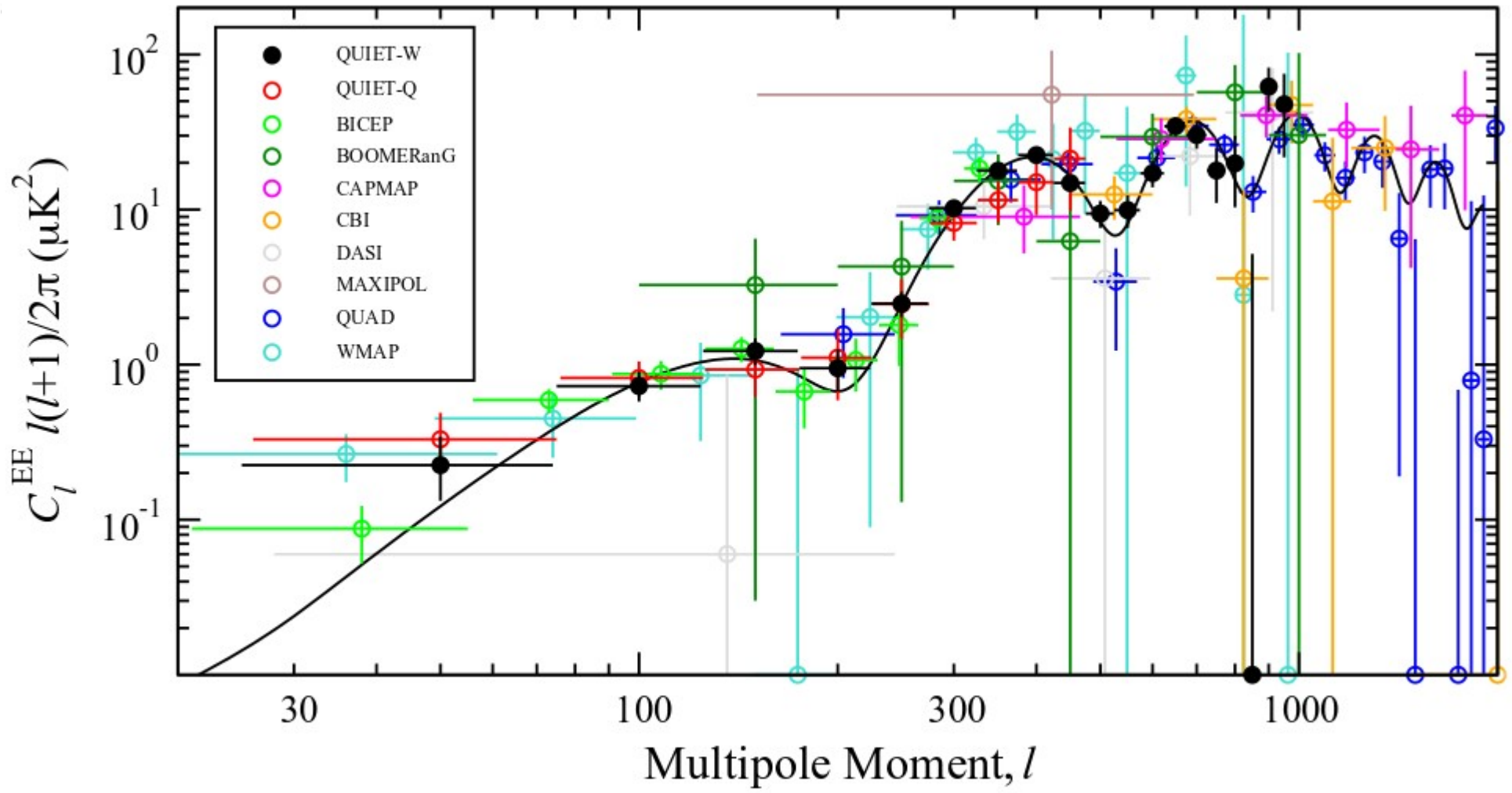
NATURE | VOL 420 | 19/26 DECEMBER 2002 | www.nature.com/nature



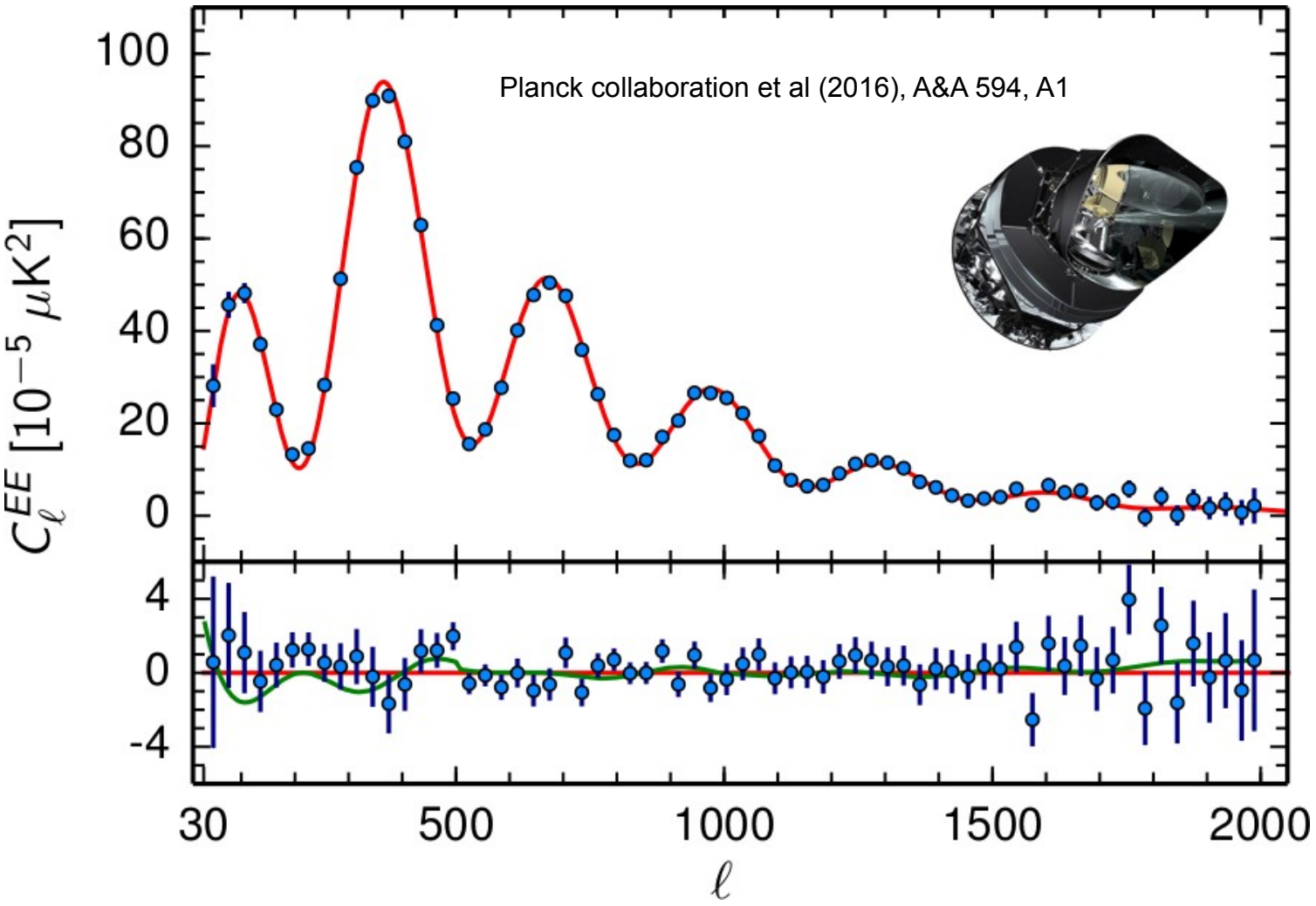
Ten years later

The Astrophysical Journal, 760:145 (10pp), 2012 December 1

QUIET Collabor



Yesterday..... and today



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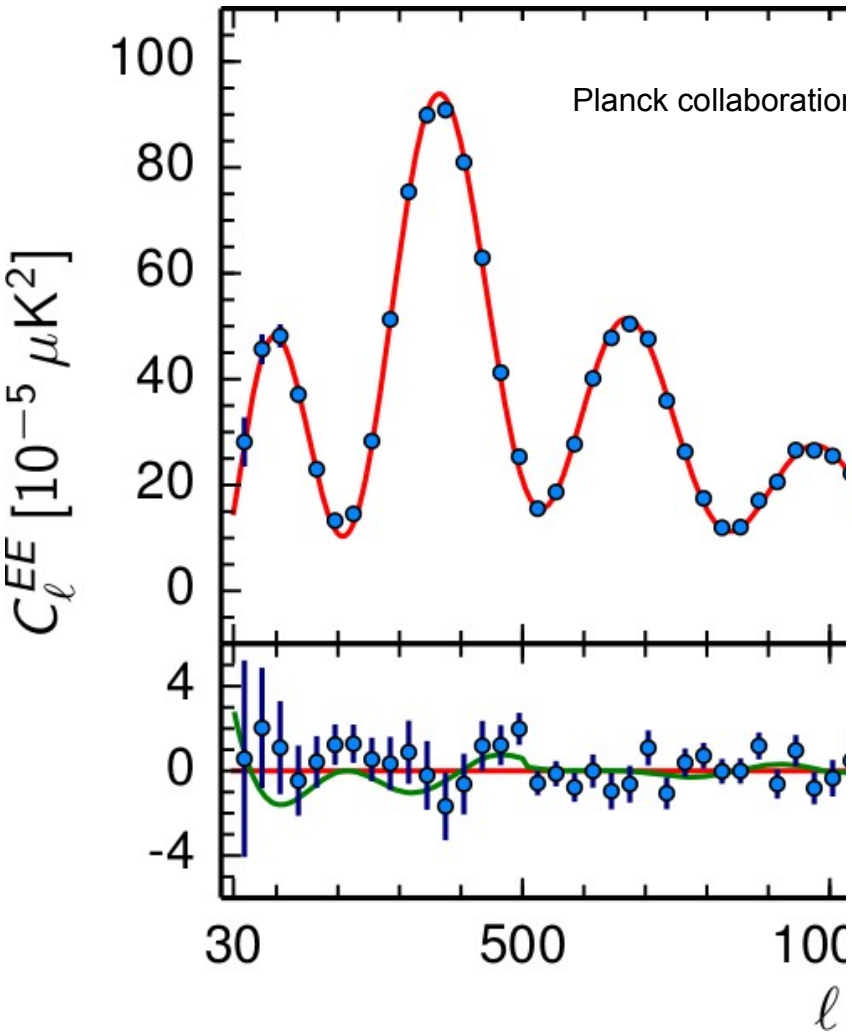

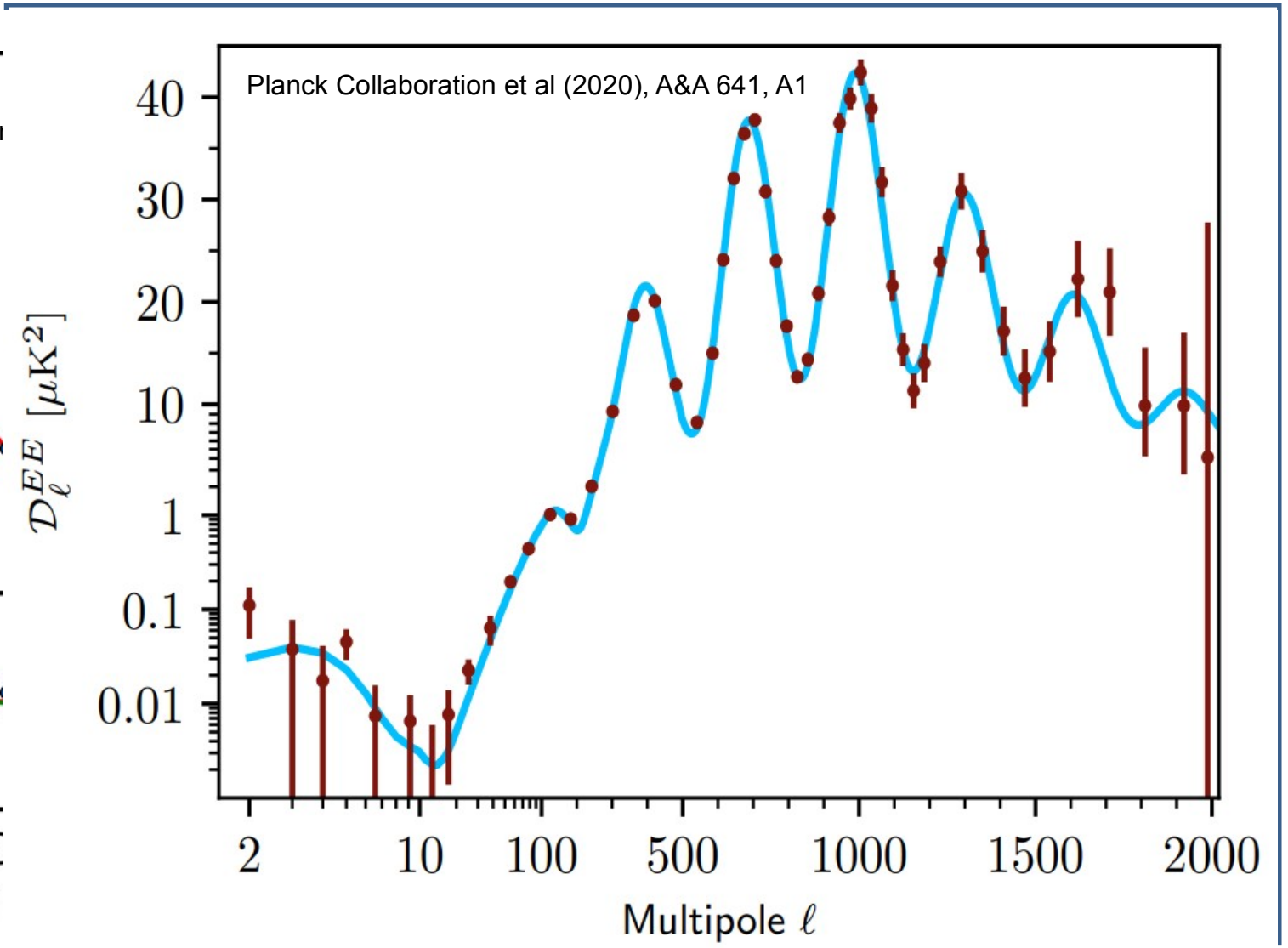

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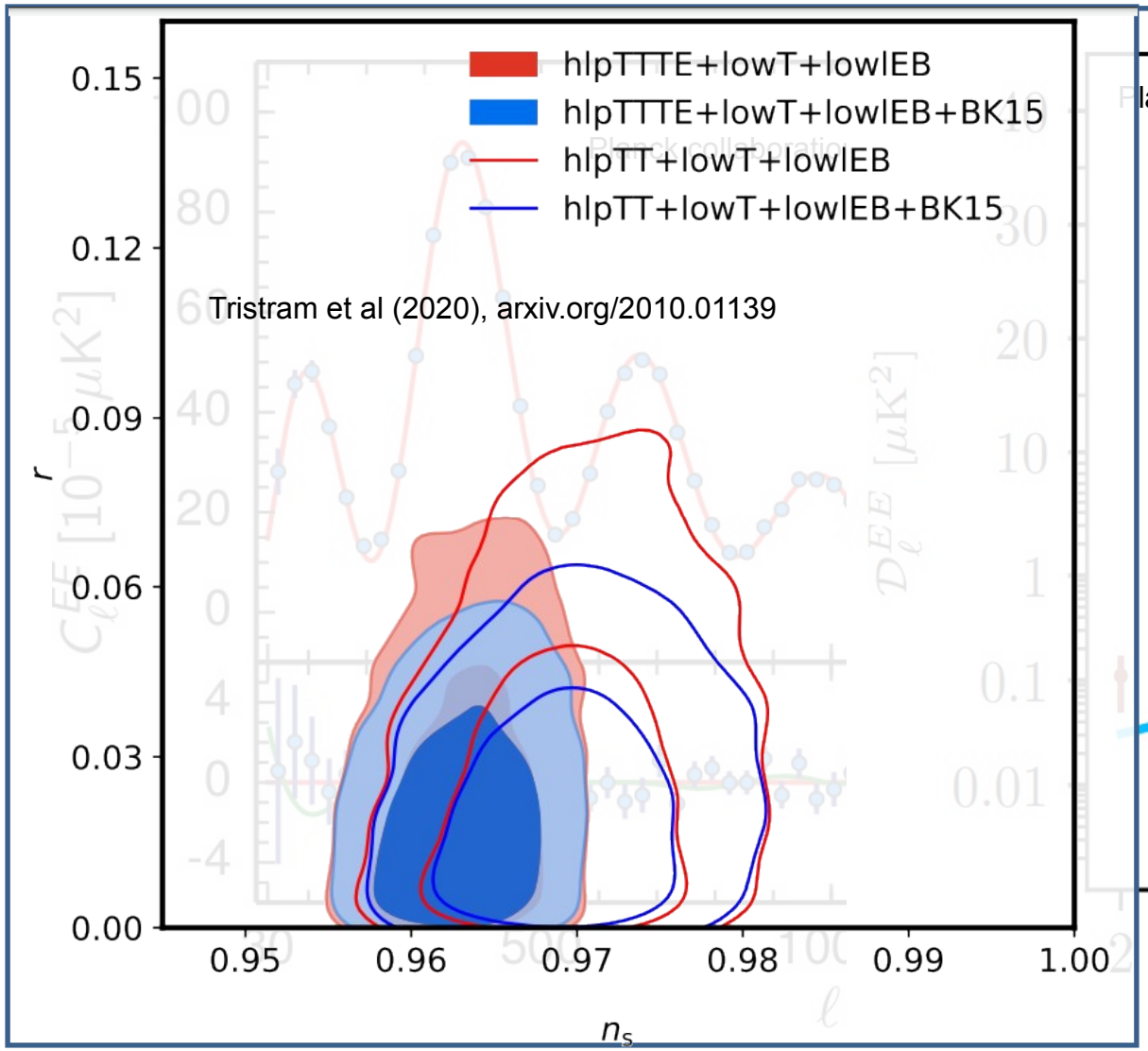
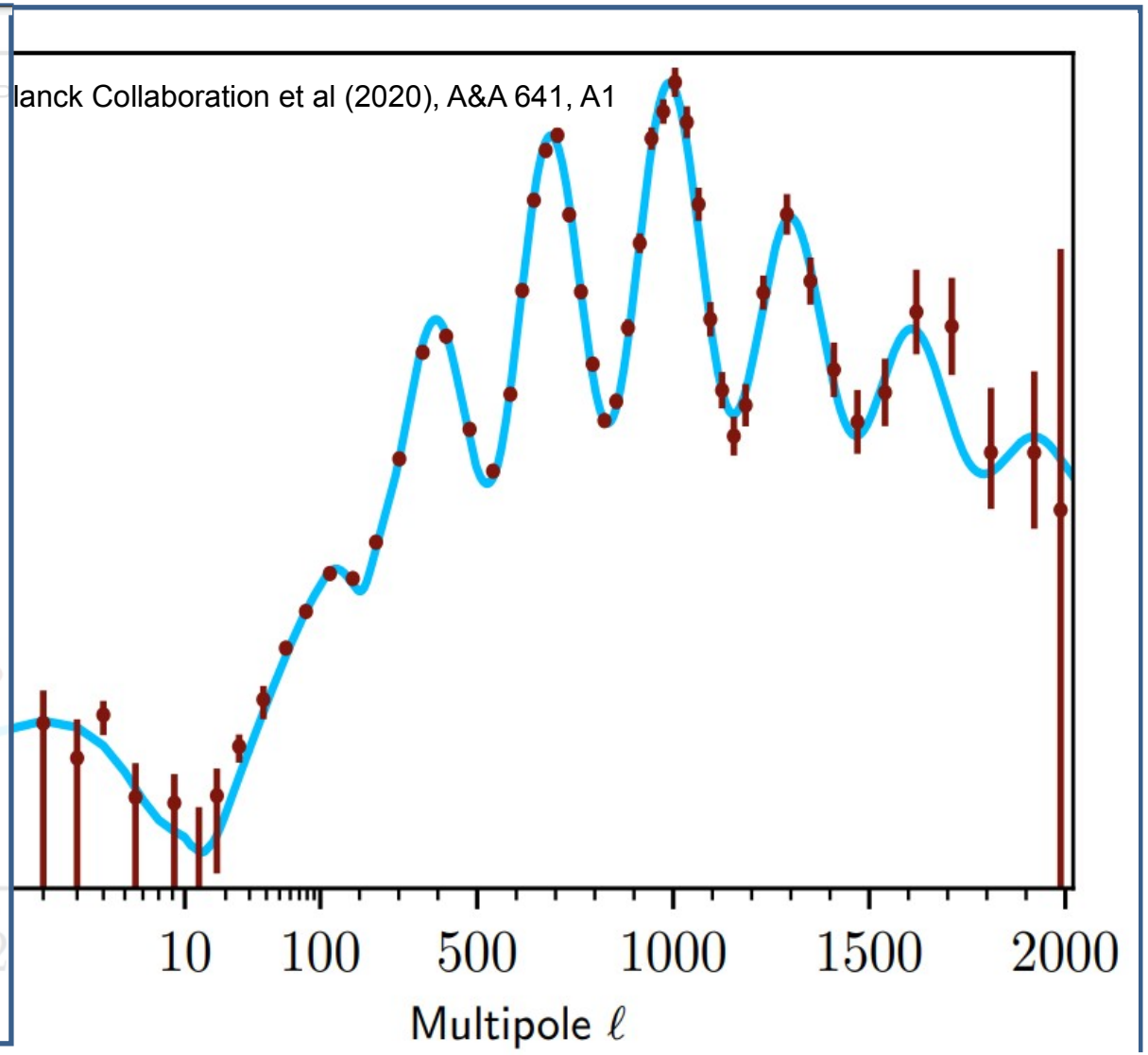
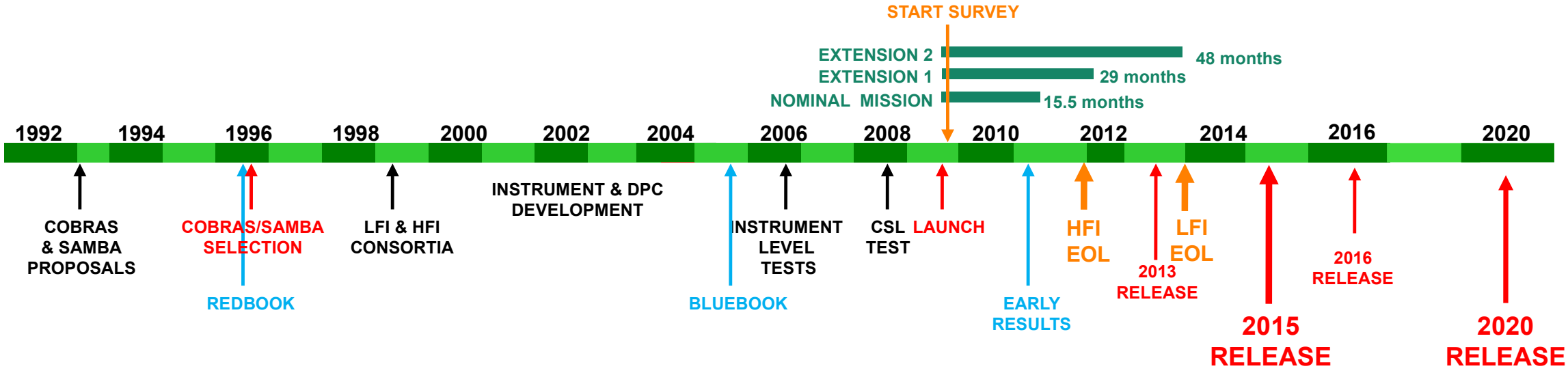




The Planck collaboration



Outstanding questions

- Why is polarization so interesting?
- Why is it so hard to measure?
- What did we learn from Planck?

From Planck we learned...

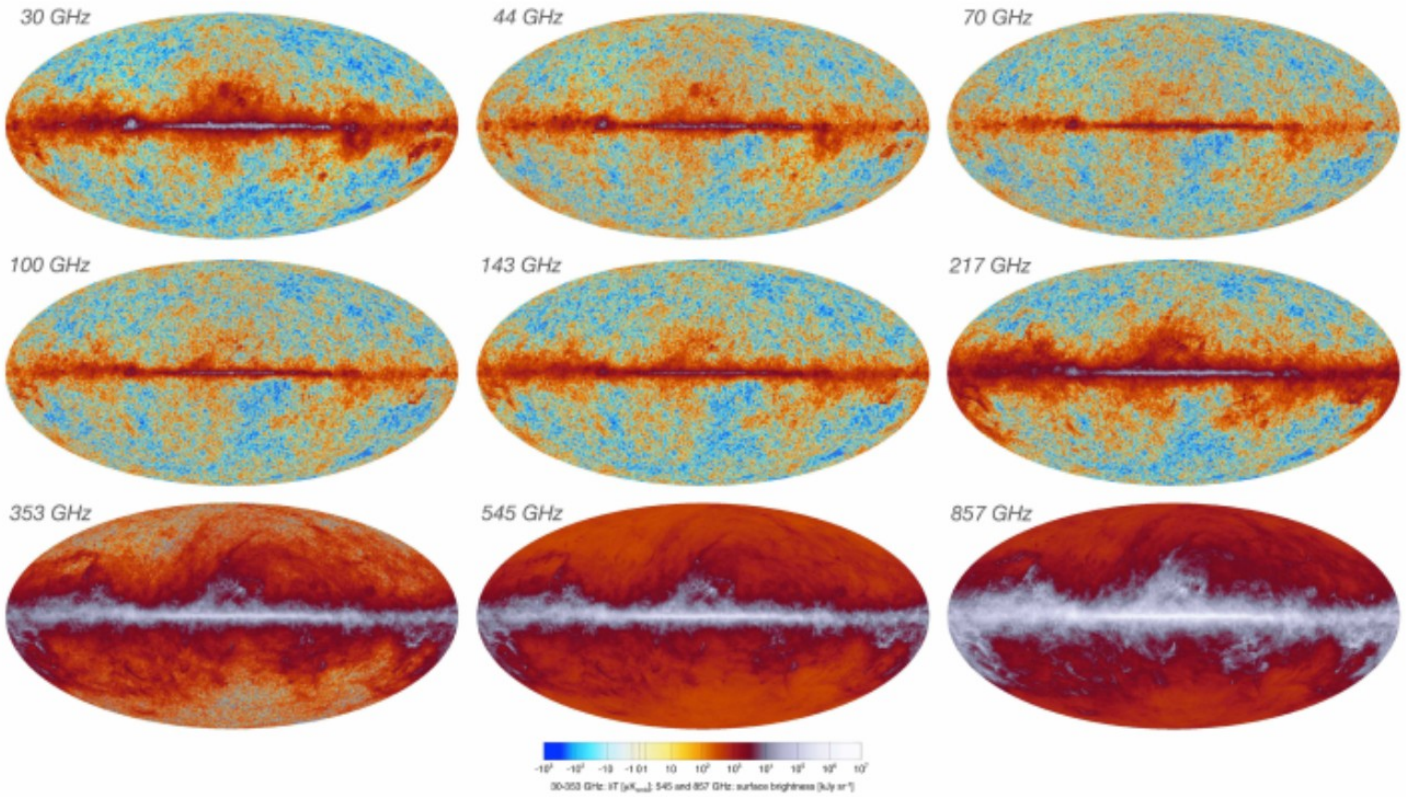
Know your instrument

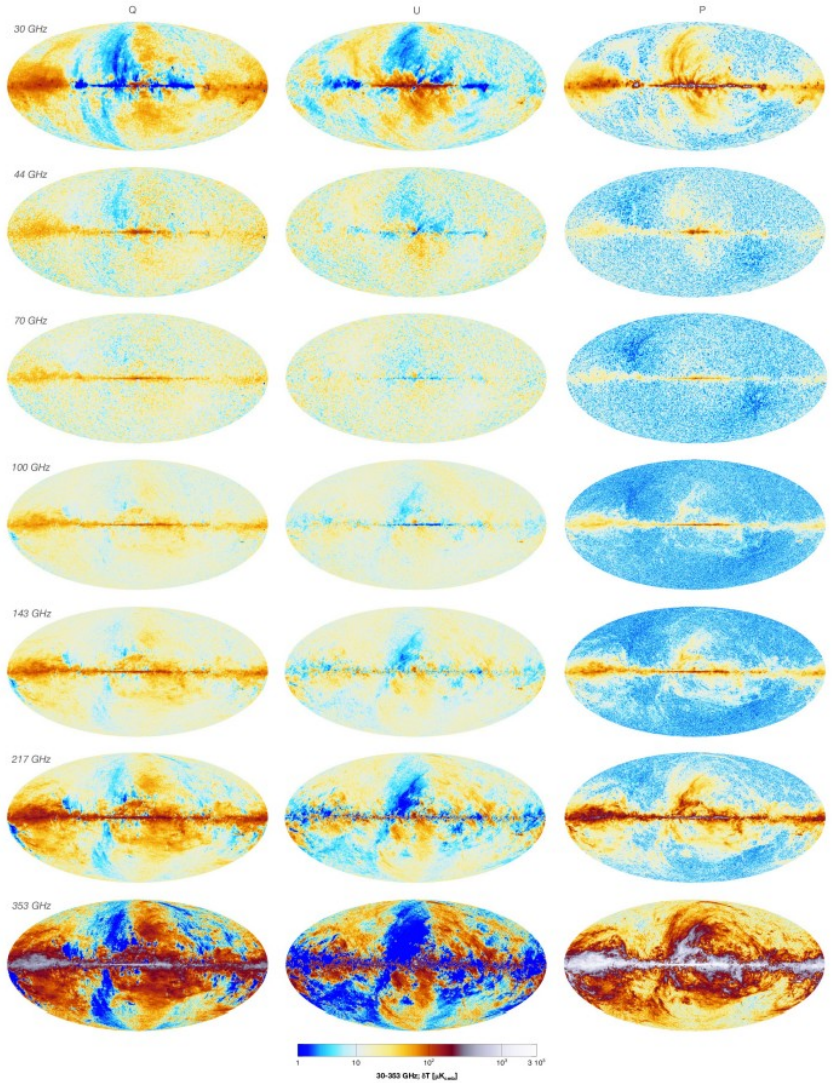
and

know your sky

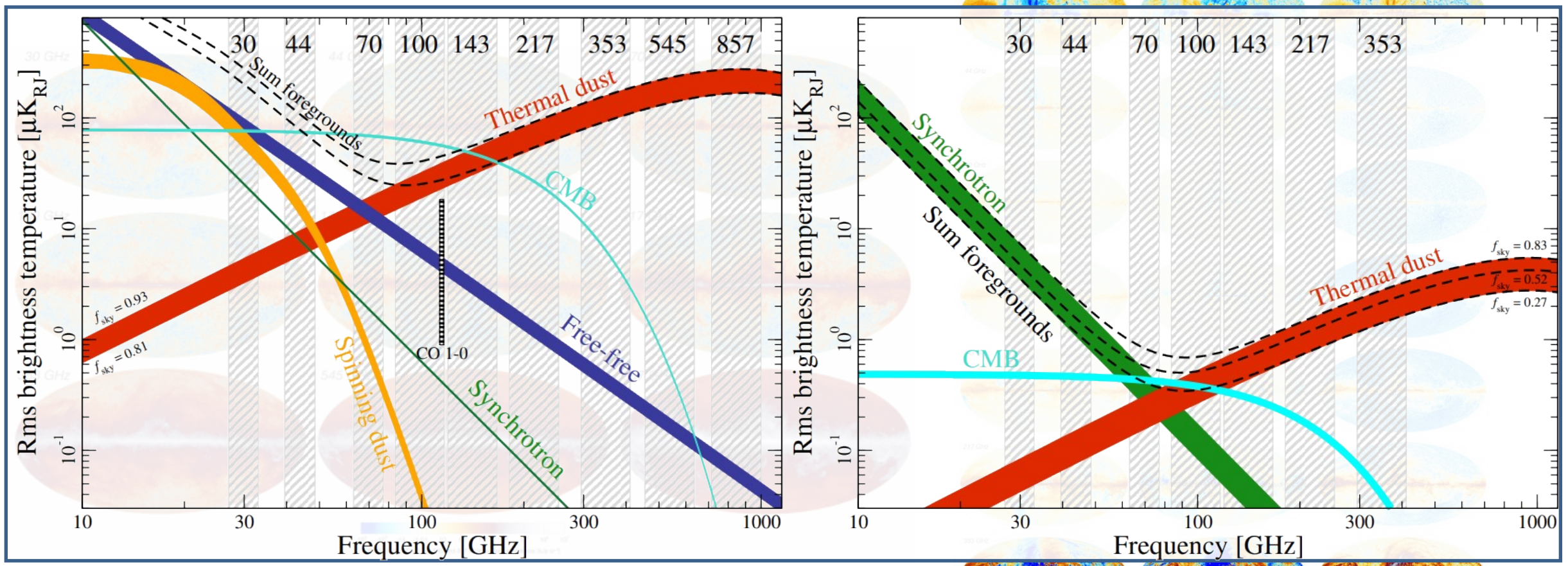
(Sensitivity) power is nothing without (systematics and foregrounds) control

Know your sky



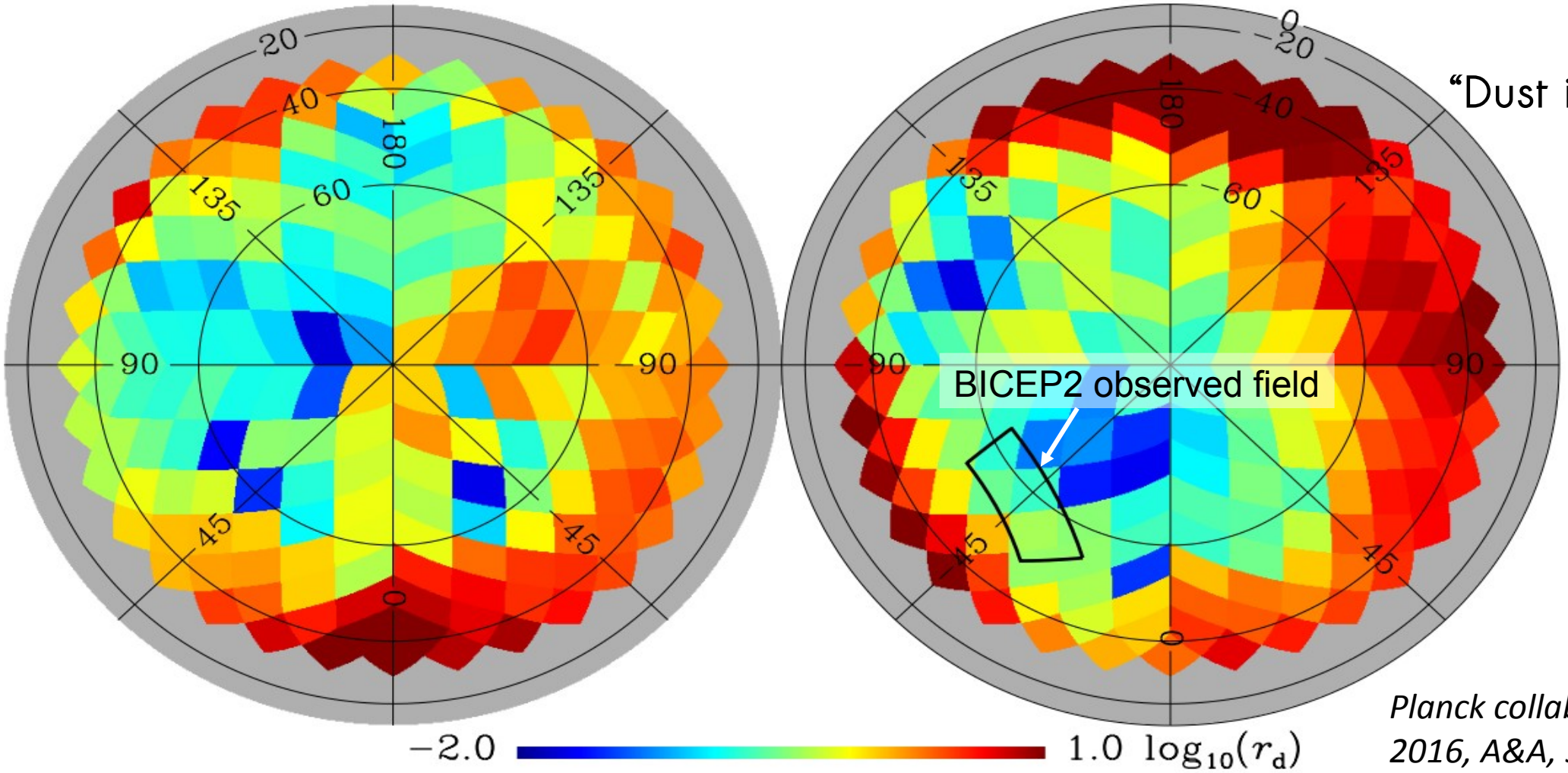


Know your sky



Know your sky - dust contamination

Contribution to r at 150 GHz and ℓ=80 due to dust, extrapolated from Planck 353 GHz data



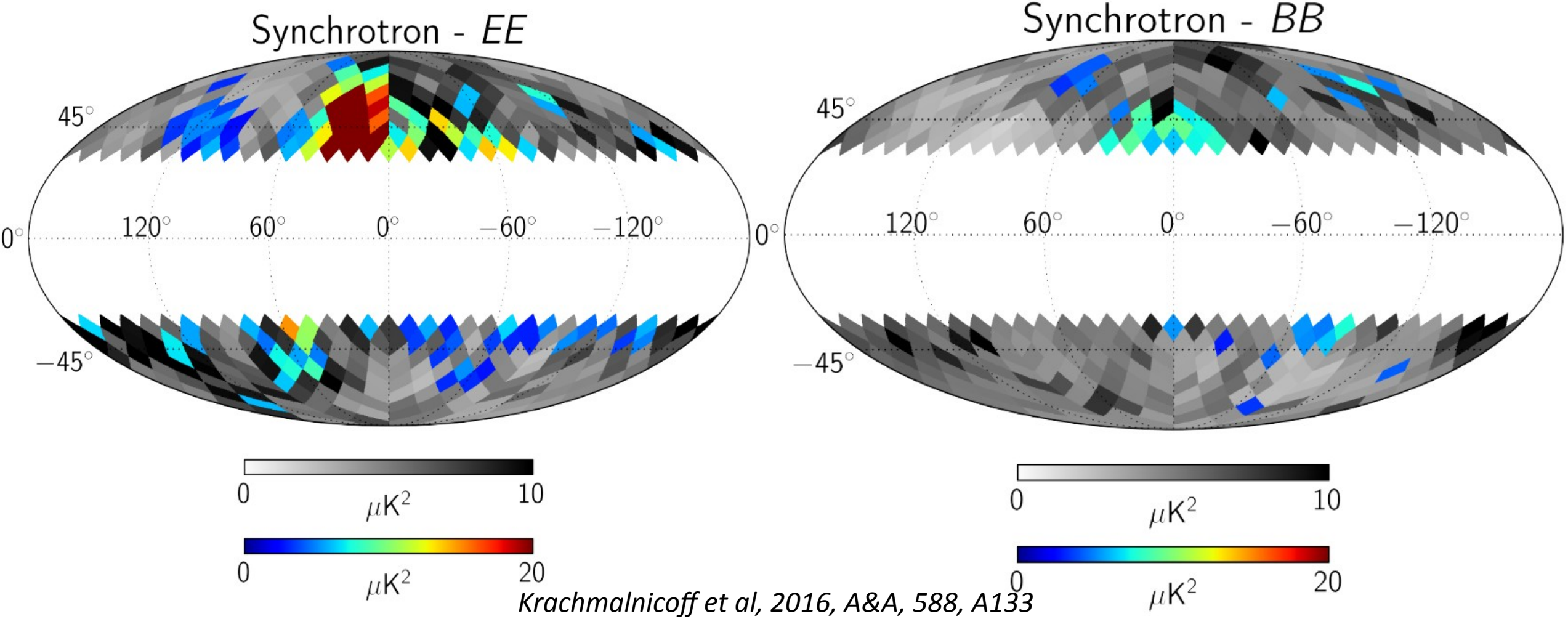
"Dust is everywhere"

C. Lawrence, ca 2009

Planck collaboration et al, 2016, A&A, 586, A133

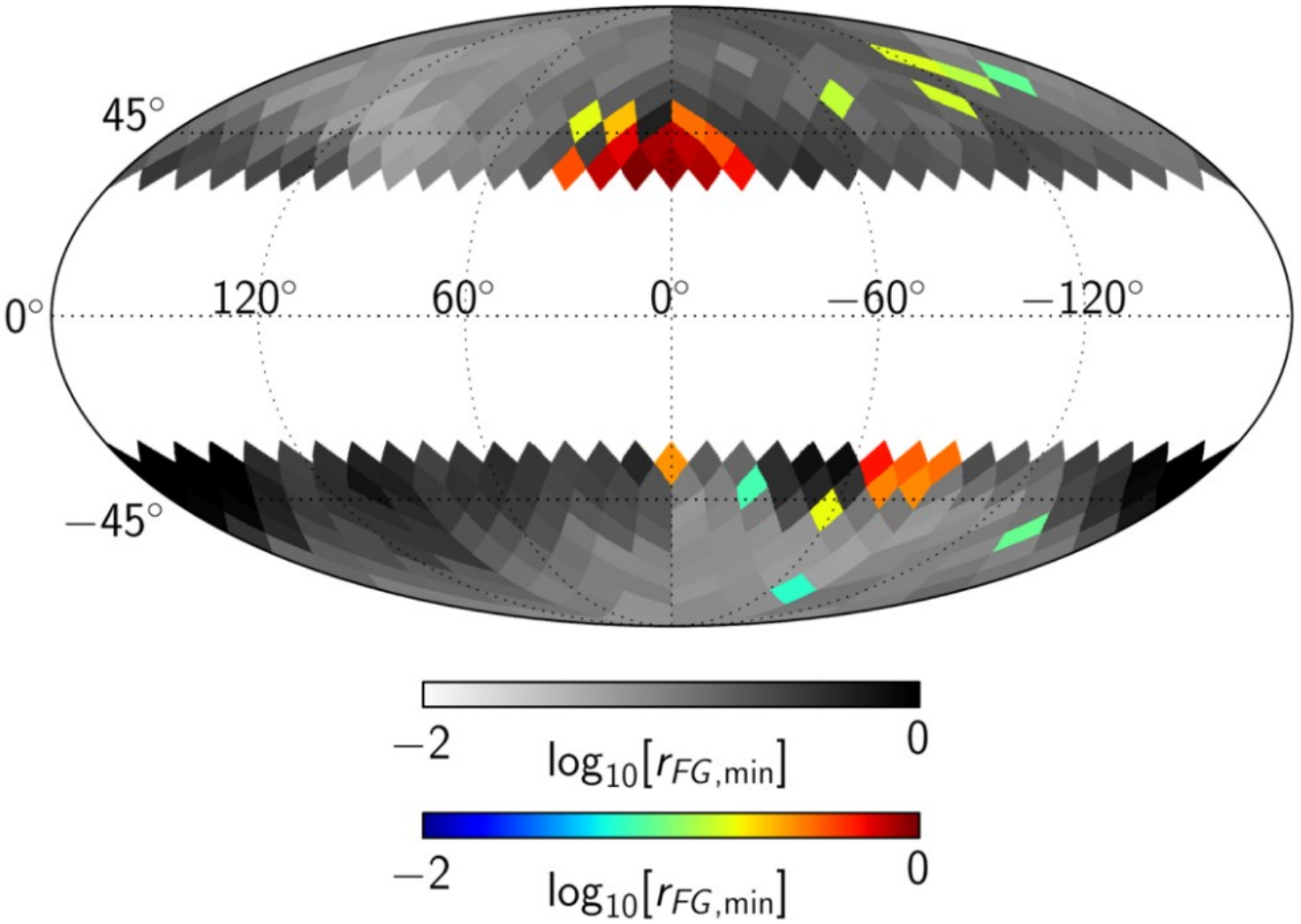
Know your sky - synchrotron is everywhere, too

Synchrotron polarization power spectrum at ℓ=80 (cross-correlation LFI30 and WMAP-K)



Krachmalnicoff et al, 2016, A&A, 588, A133

Know your sky - synchrotron + dust contamination

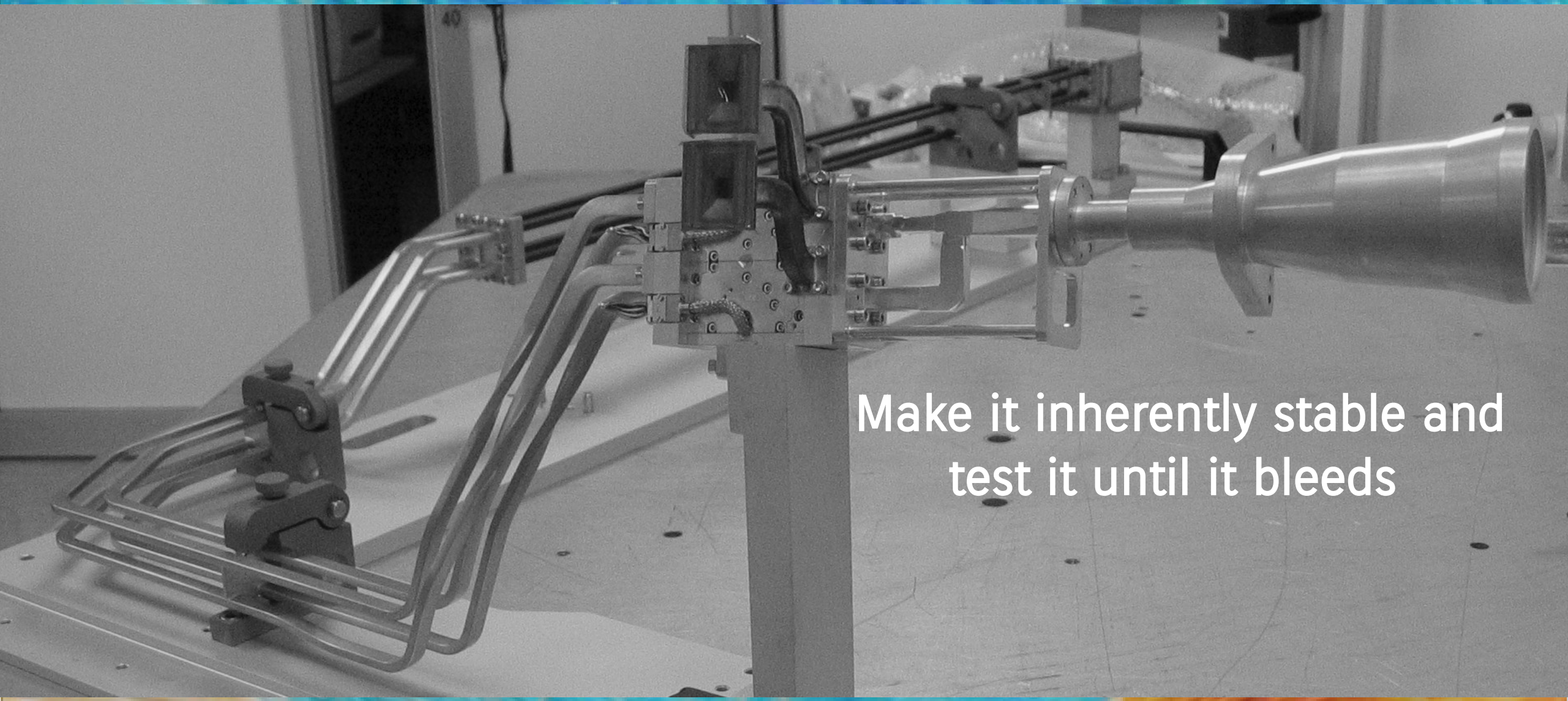


Limit on r detection at the frequency where dust + synchrotron is minimum

- No region of the sky can be considered clean if we aim at B-modes detection of $r \lesssim 0.01$
- Controlling foregrounds implies to characterize emissions over a large frequency interval with narrow bandwidths

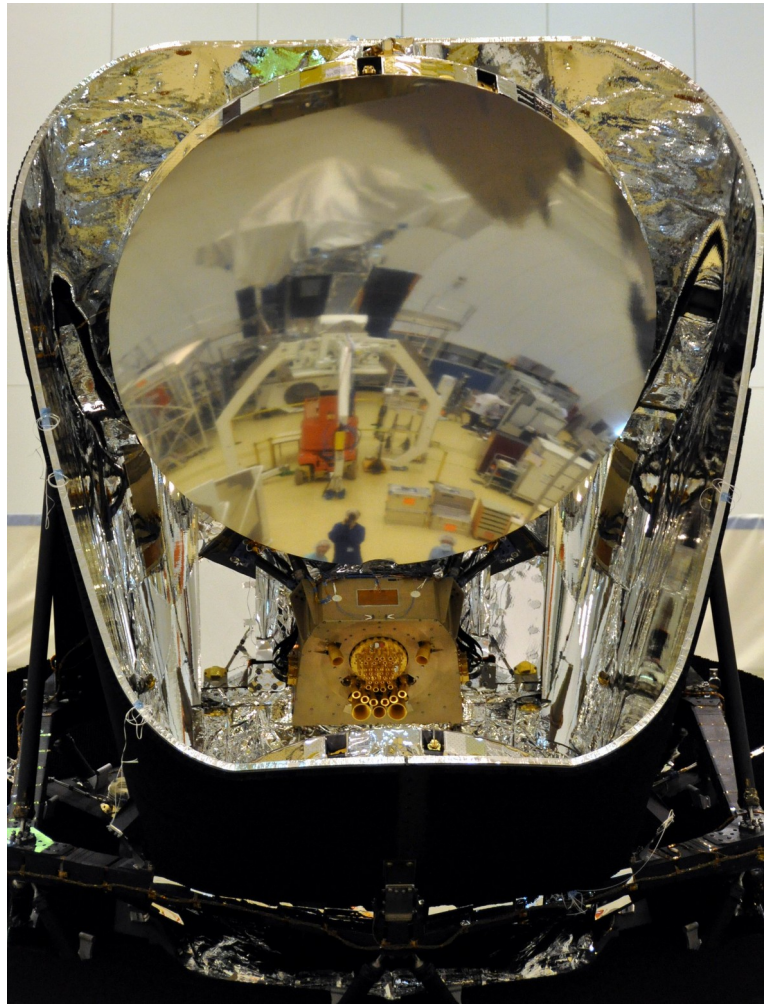
Krachmalnicoff et al, 2016, A&A, 588, A133

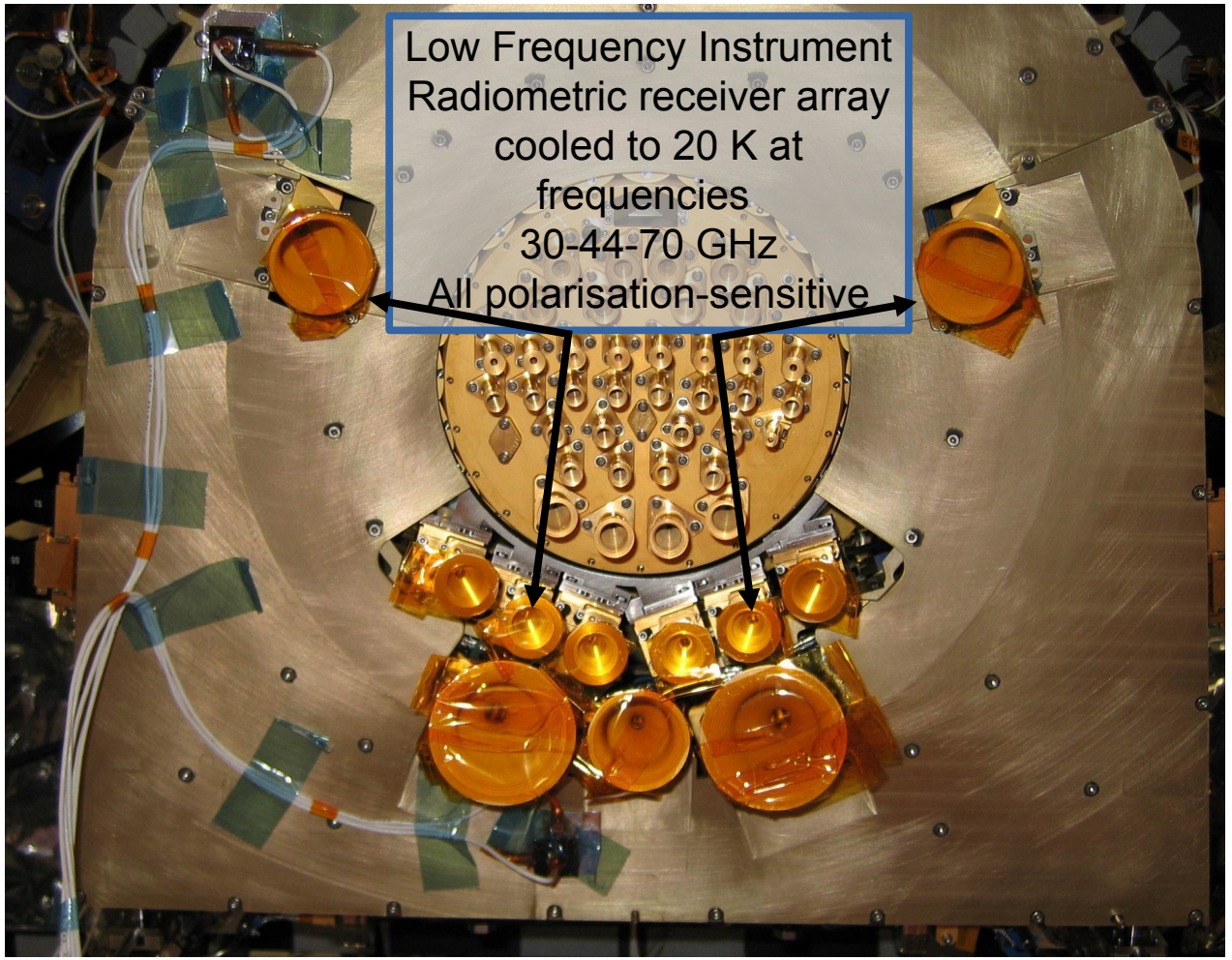
Know your instrument



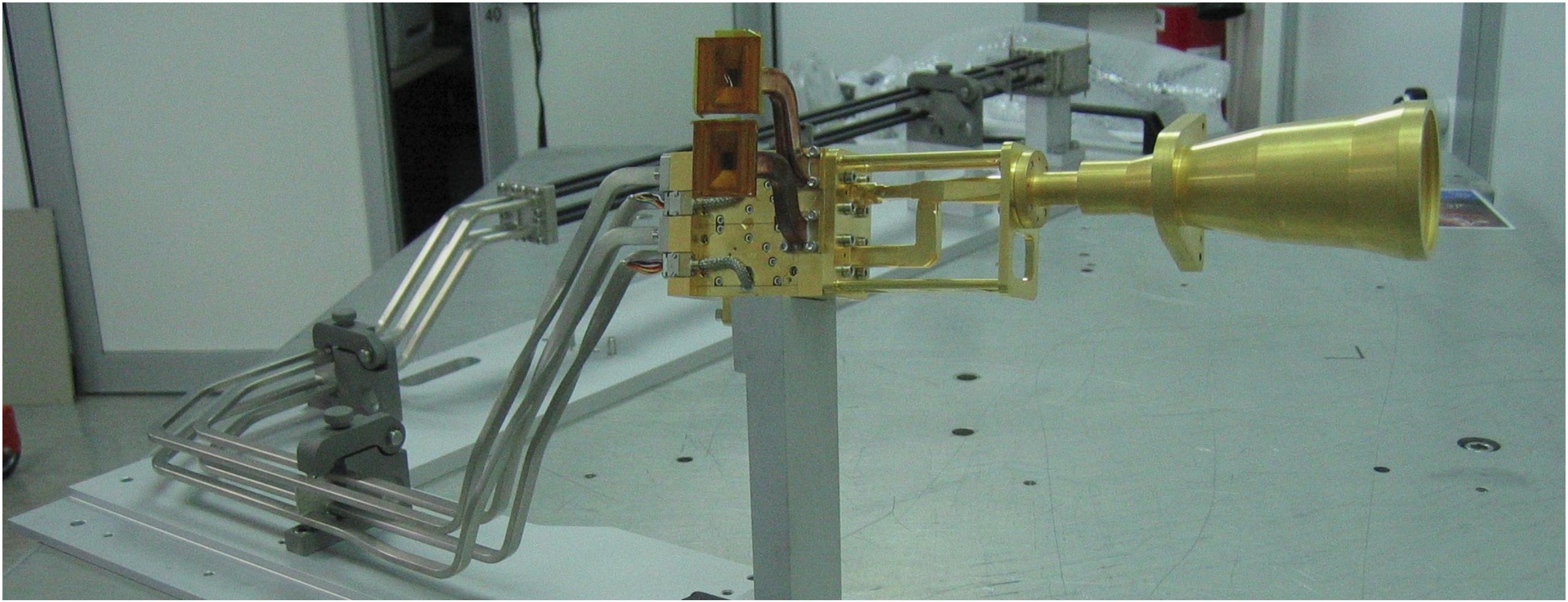
Make it inherently stable and test it until it bleeds

Know your instrument - The Planck machine





Know your instrument - The LFI radiometers



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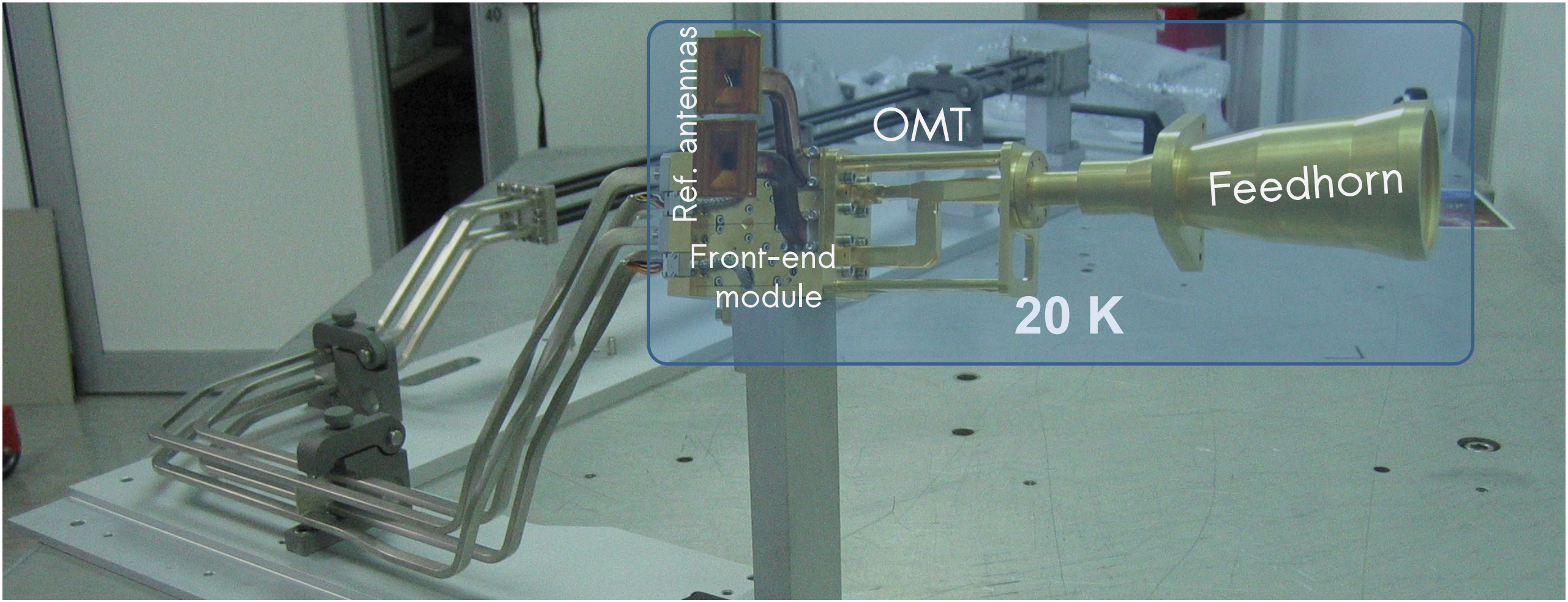

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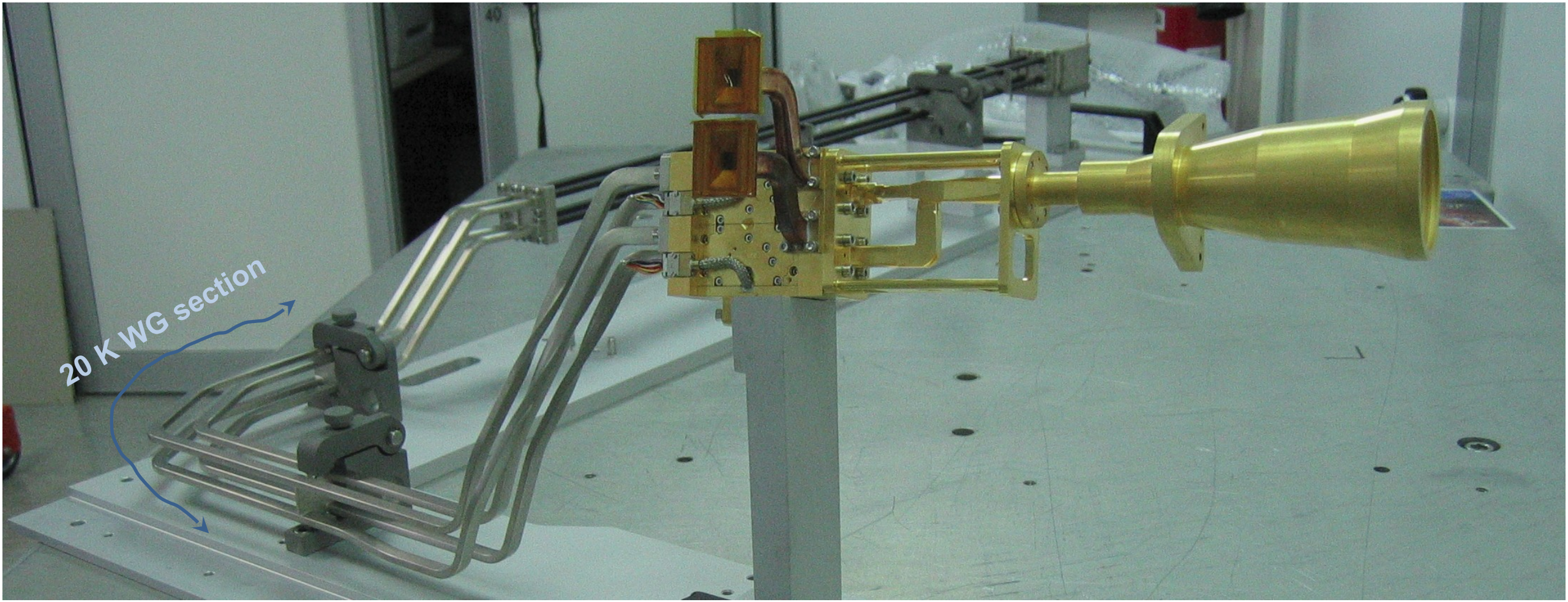

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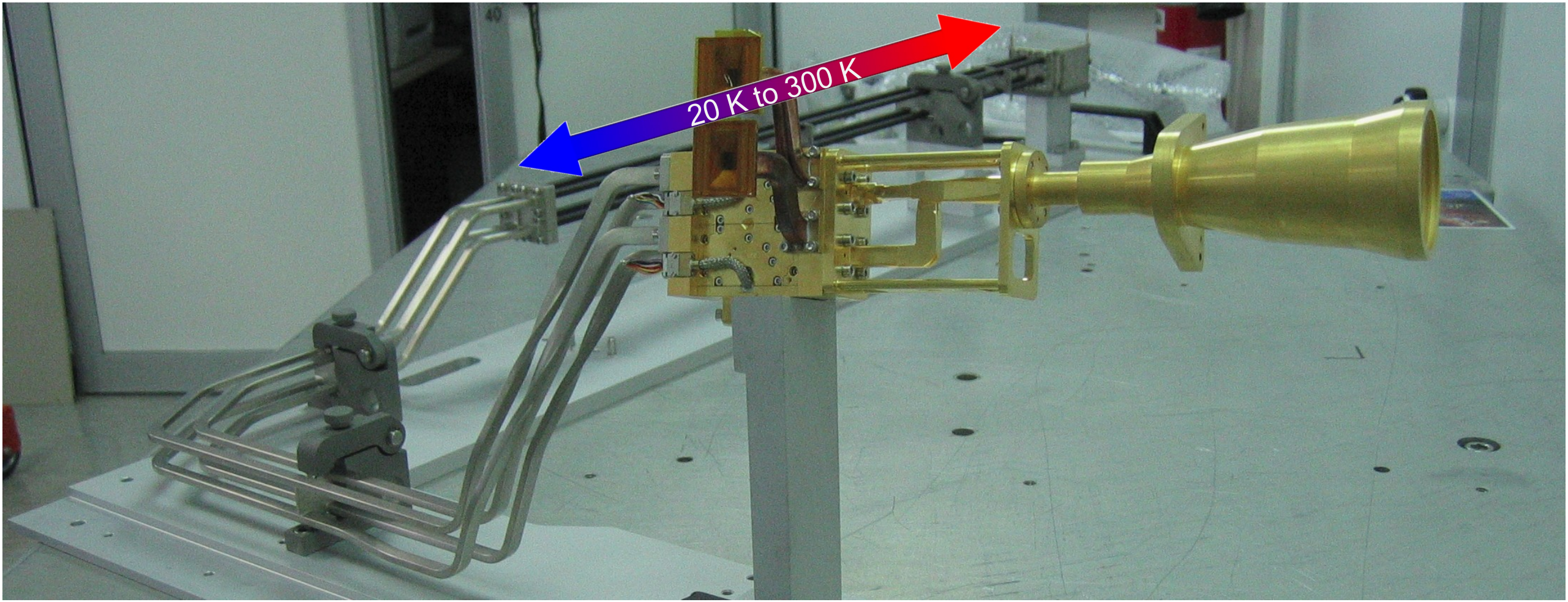

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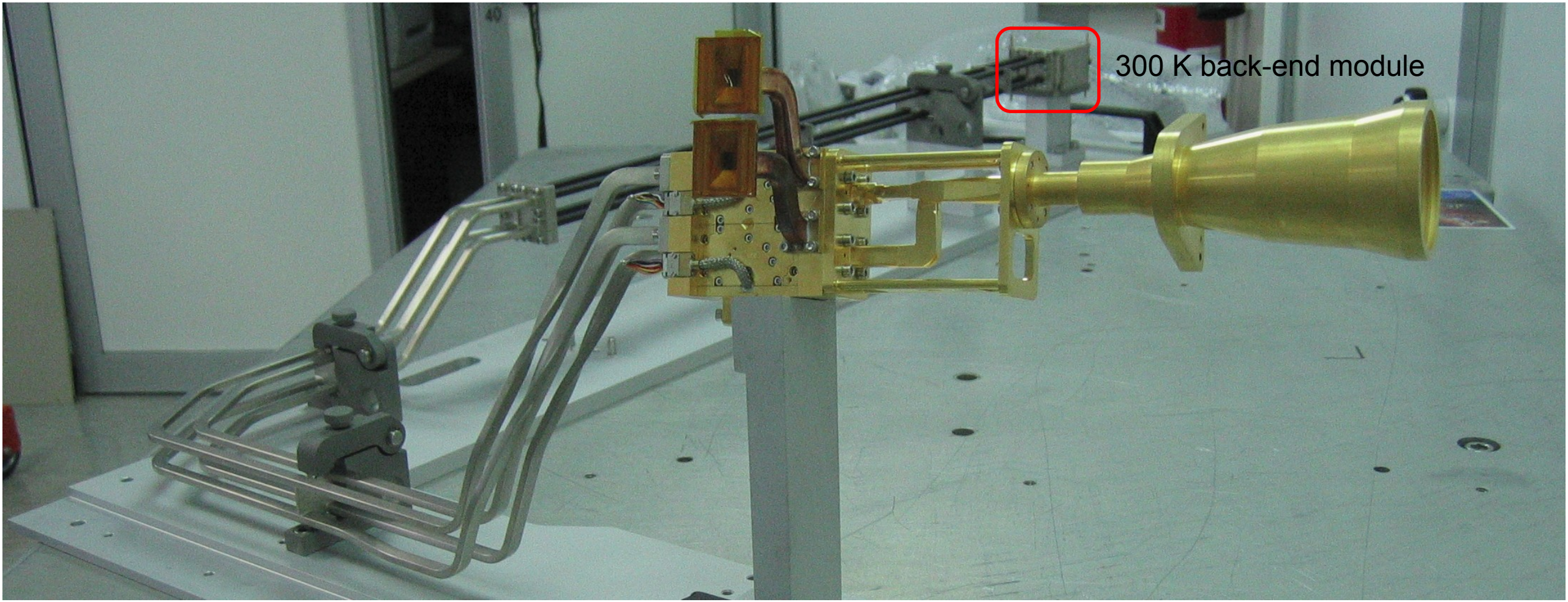
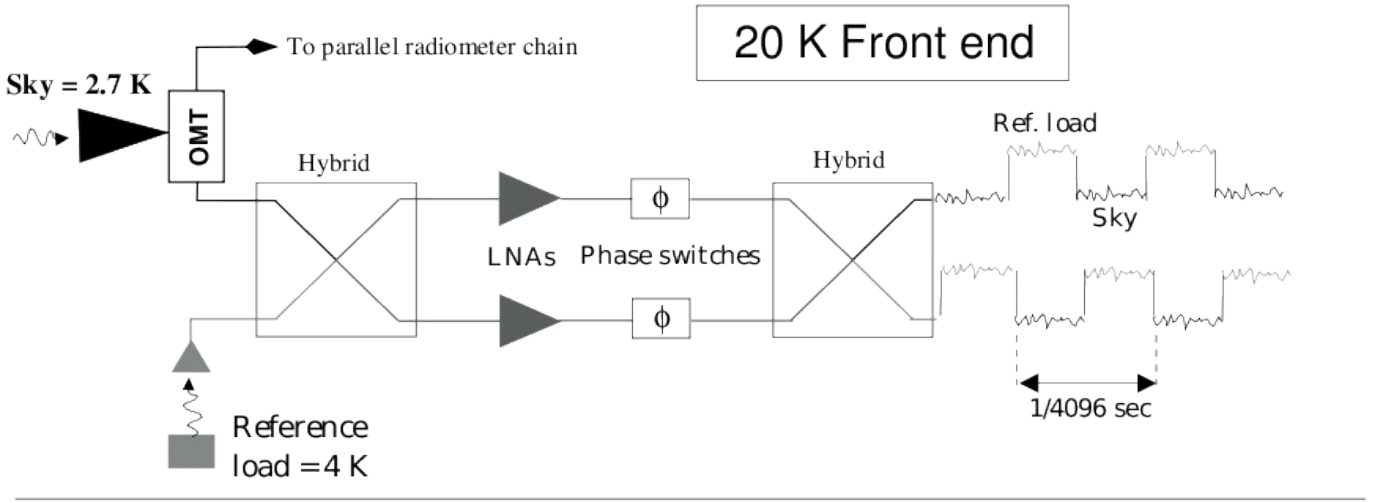


Differential design - inherent stability



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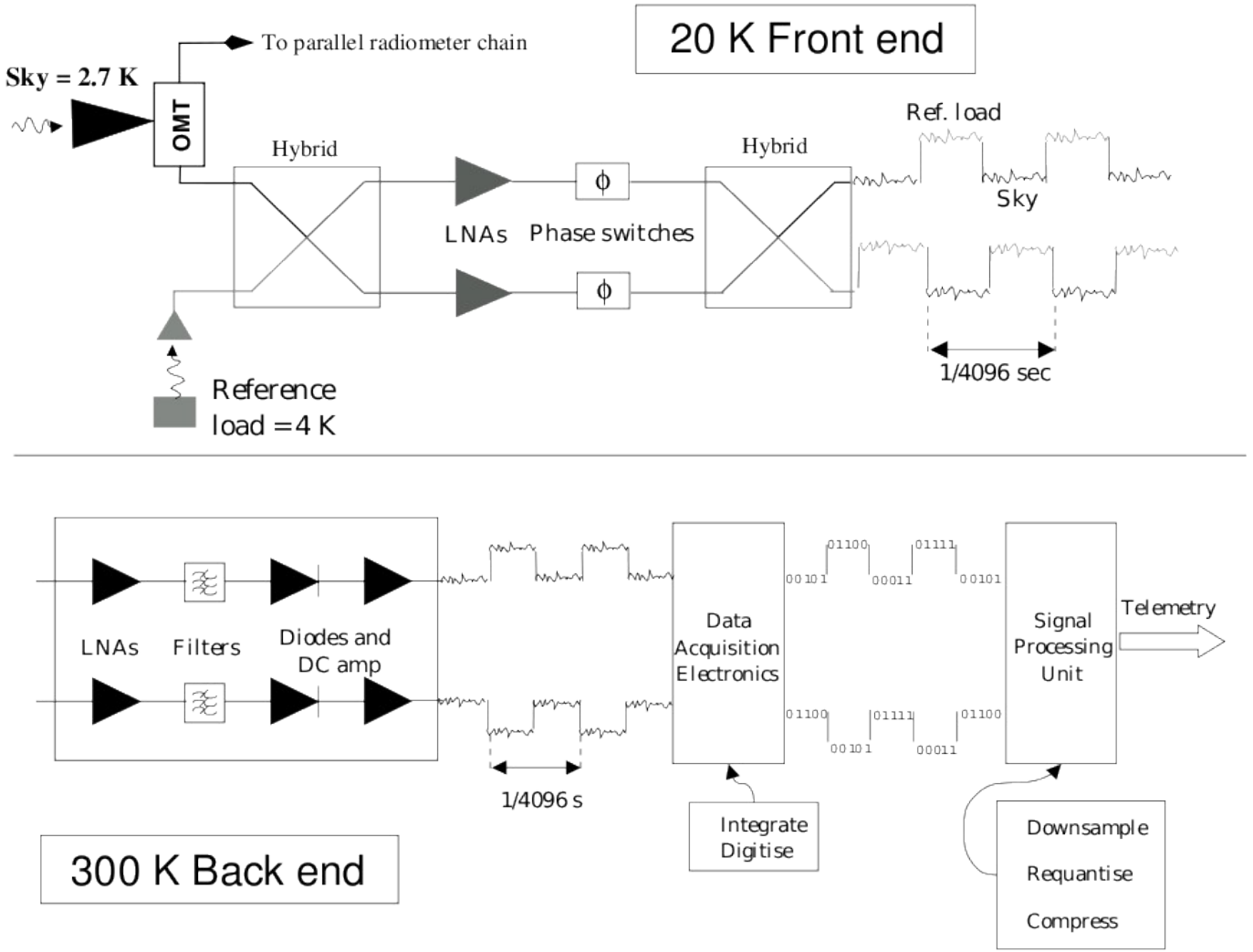

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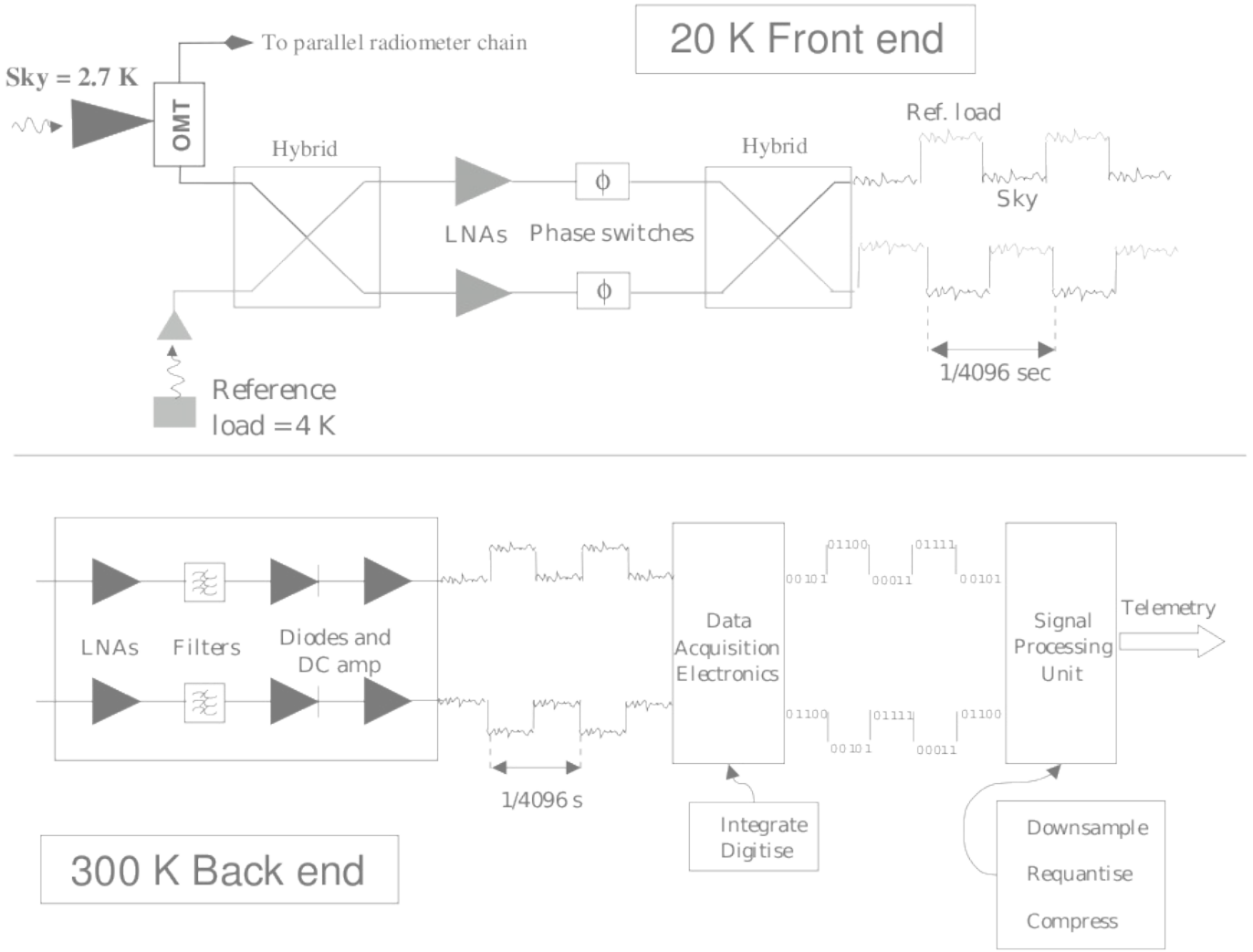
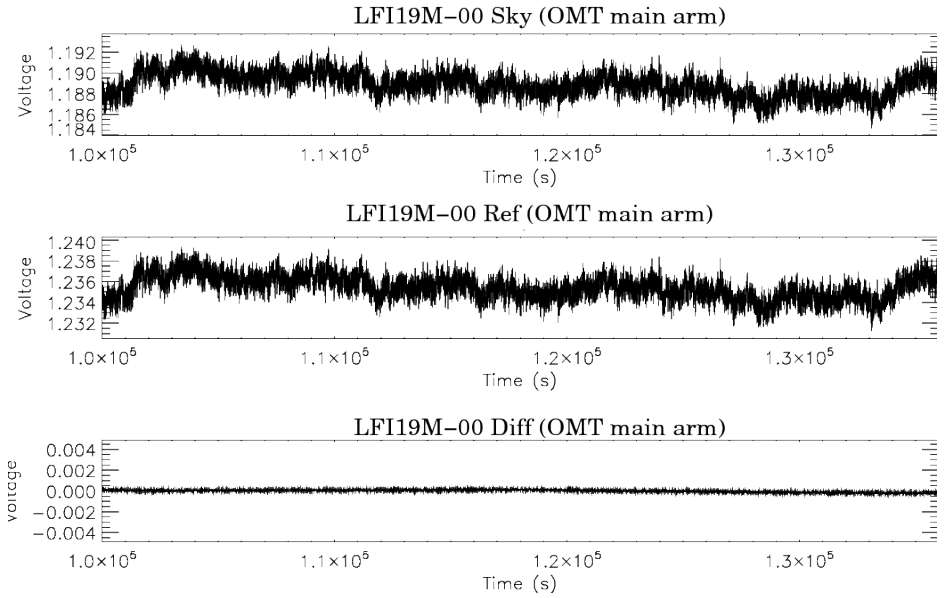


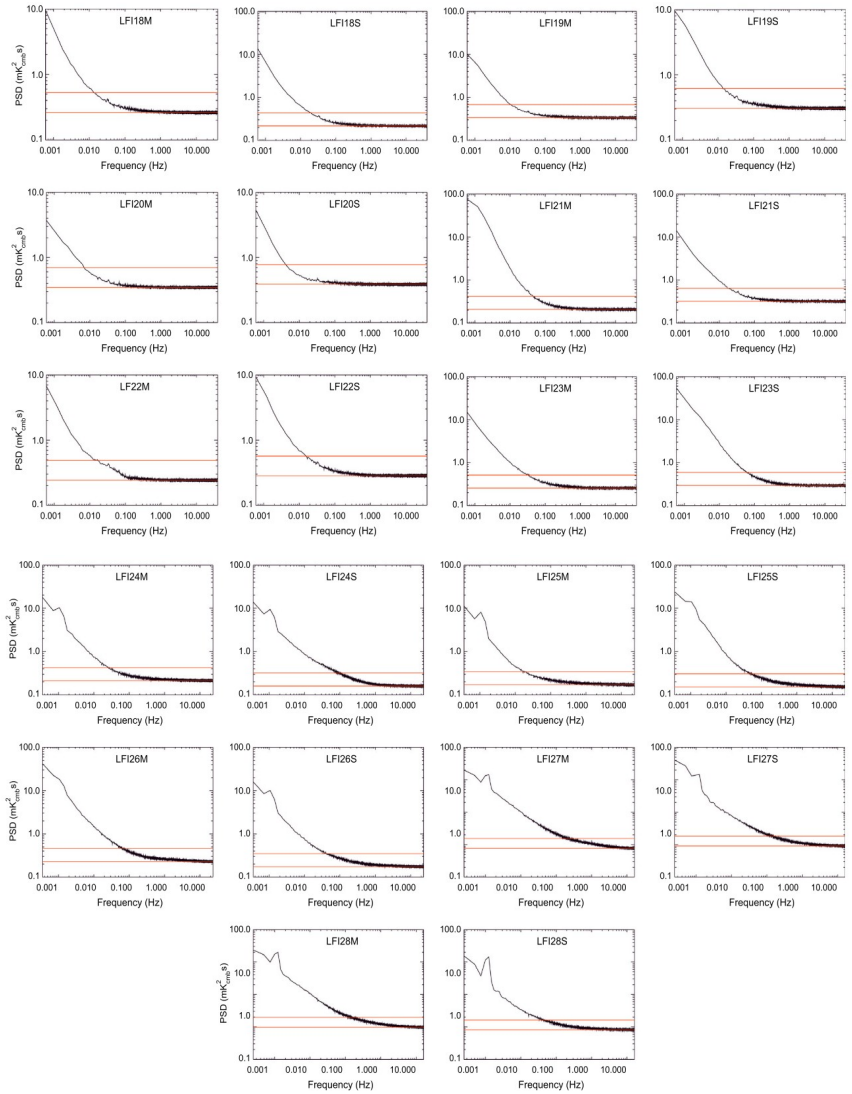
$$P_{\text{out}} = Gk\Delta\nu\,[T_{\text{sky}} + T_{\text{noise}} - r \times (T_{\text{ref}} + T_{\text{noise}})]$$

$$r = \frac{T_{\text{sky}} + T_{\text{noise}}}{T_{\text{ref}} + T_{\text{noise}}}$$



Spectra and ring-based null tests

Mennella et al (2011), A&A 536, A3



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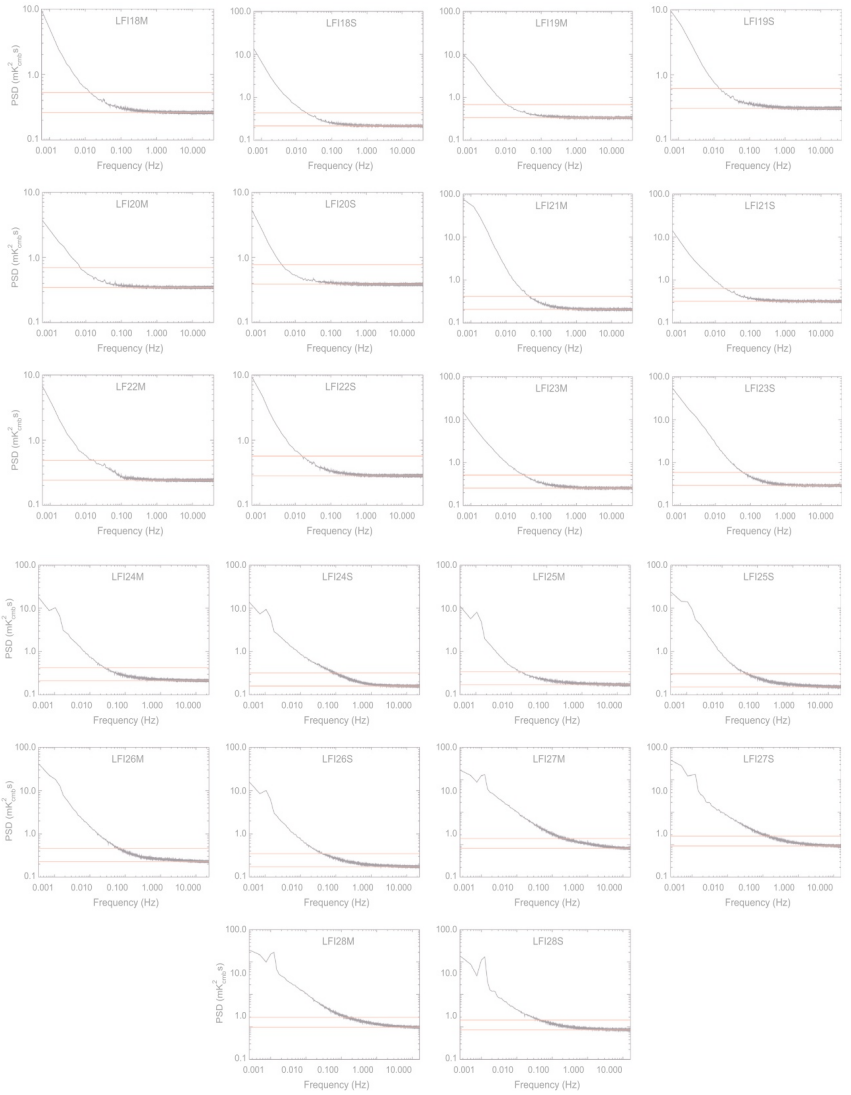


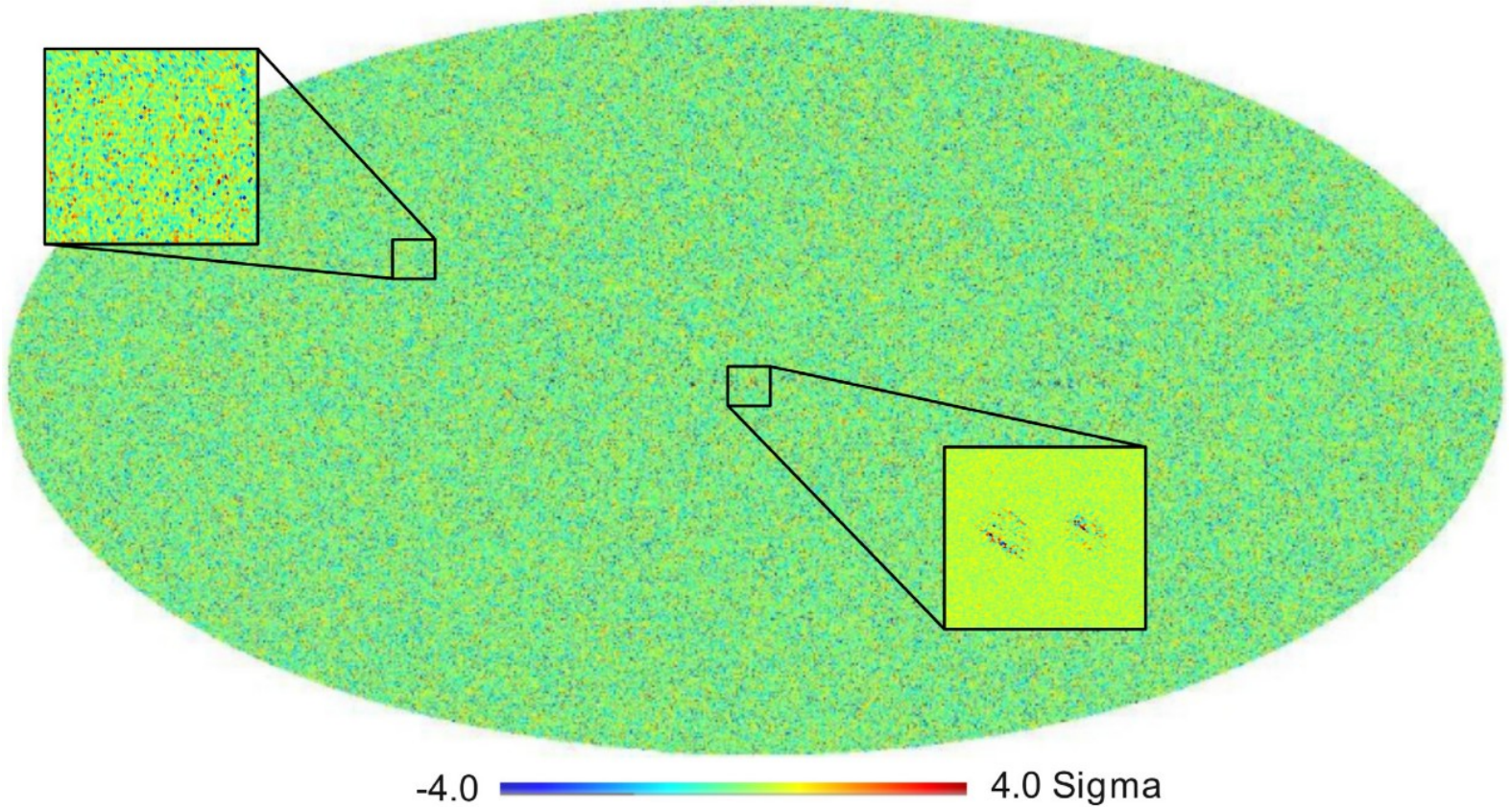
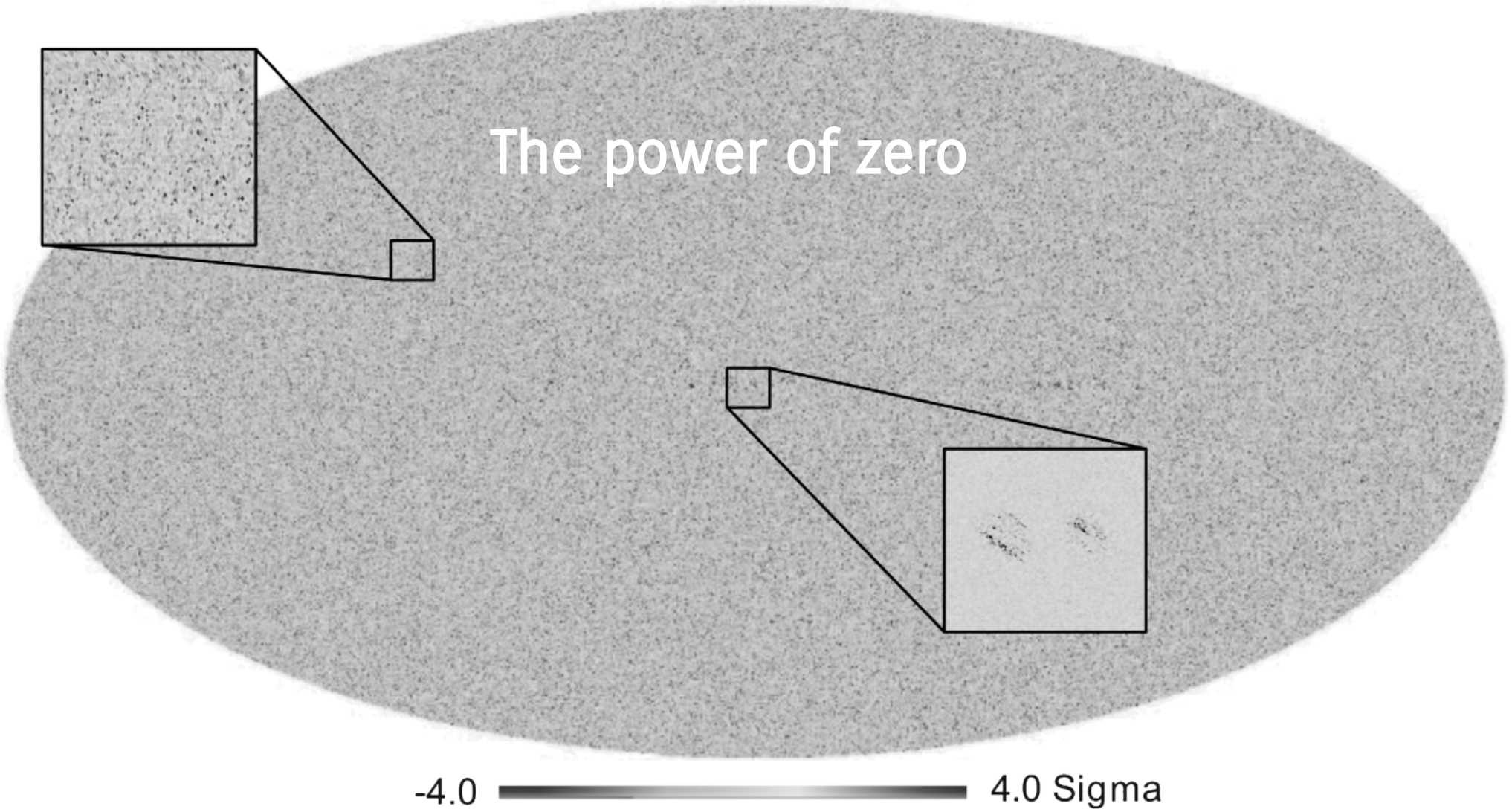


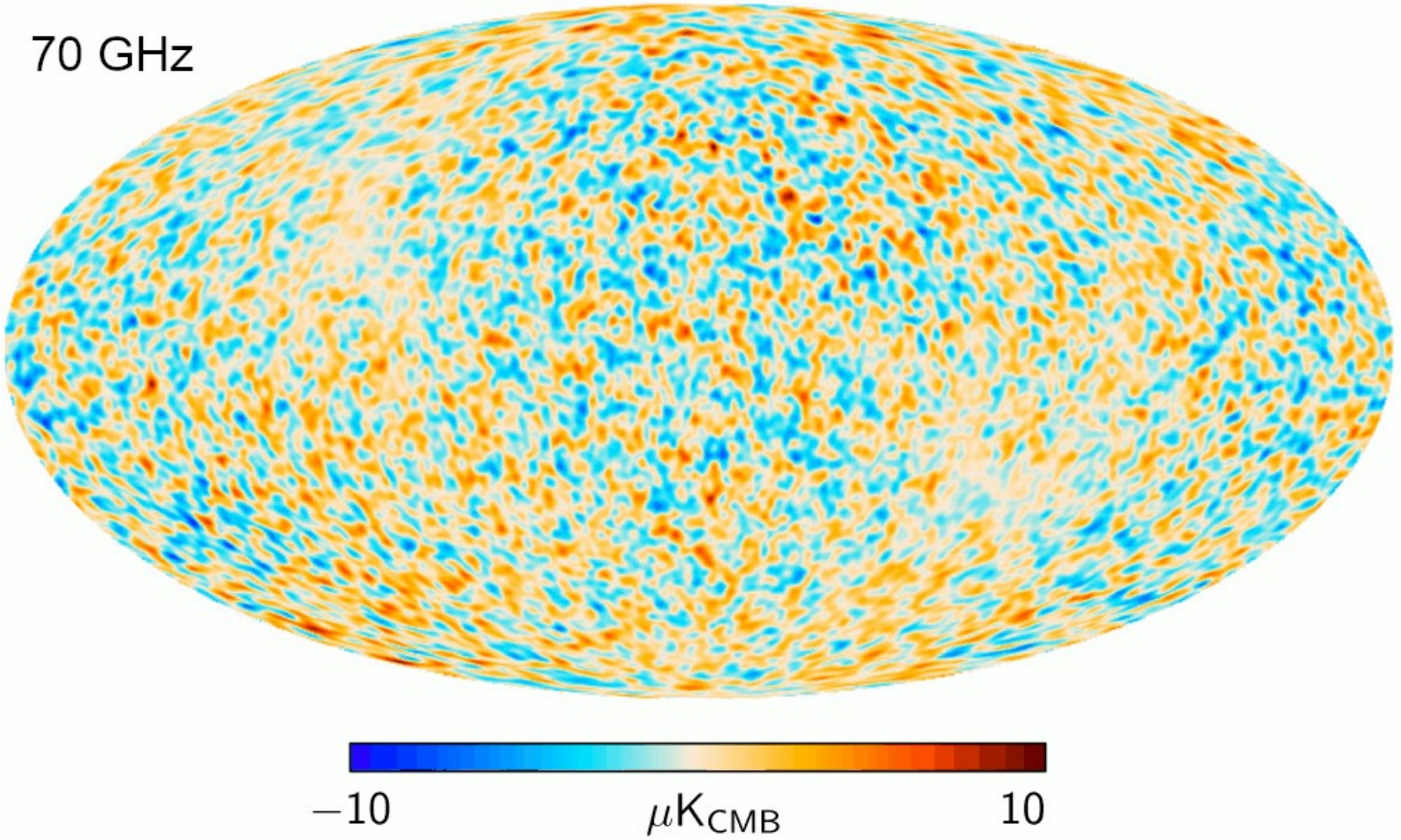
Table 12. Standard deviation of normalised noise maps.

	30 GHz	44 GHz	70 GHz
Standard deviation	1.039	1.016	1.002

Know your instrument



Ring-based null maps

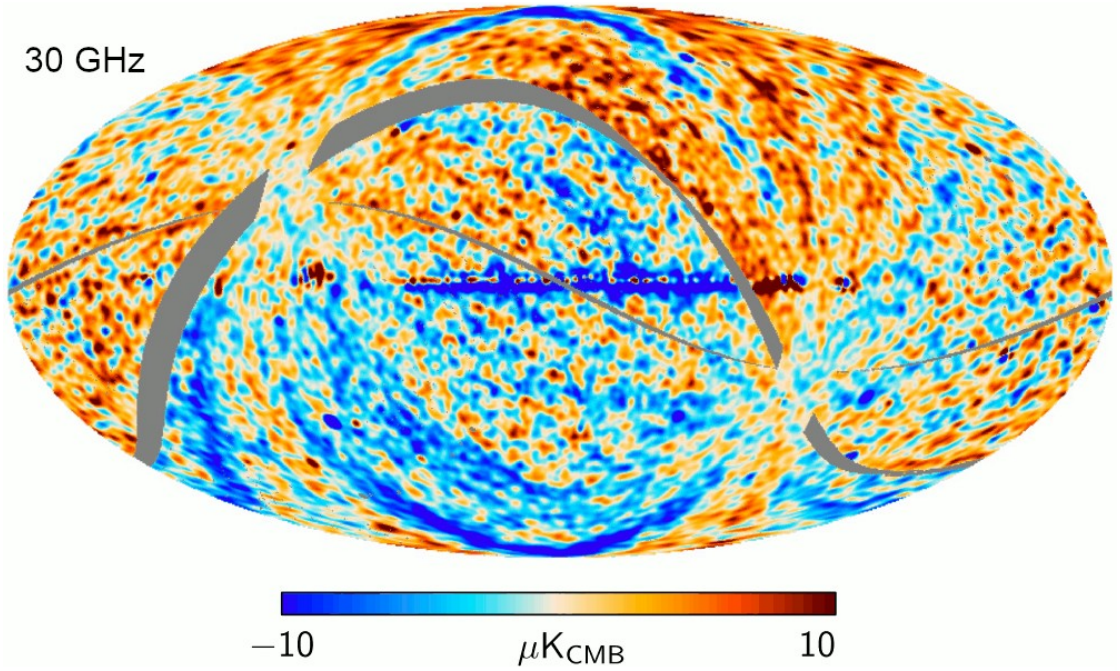


Planck Collaboration (2014), A&A 571, A3

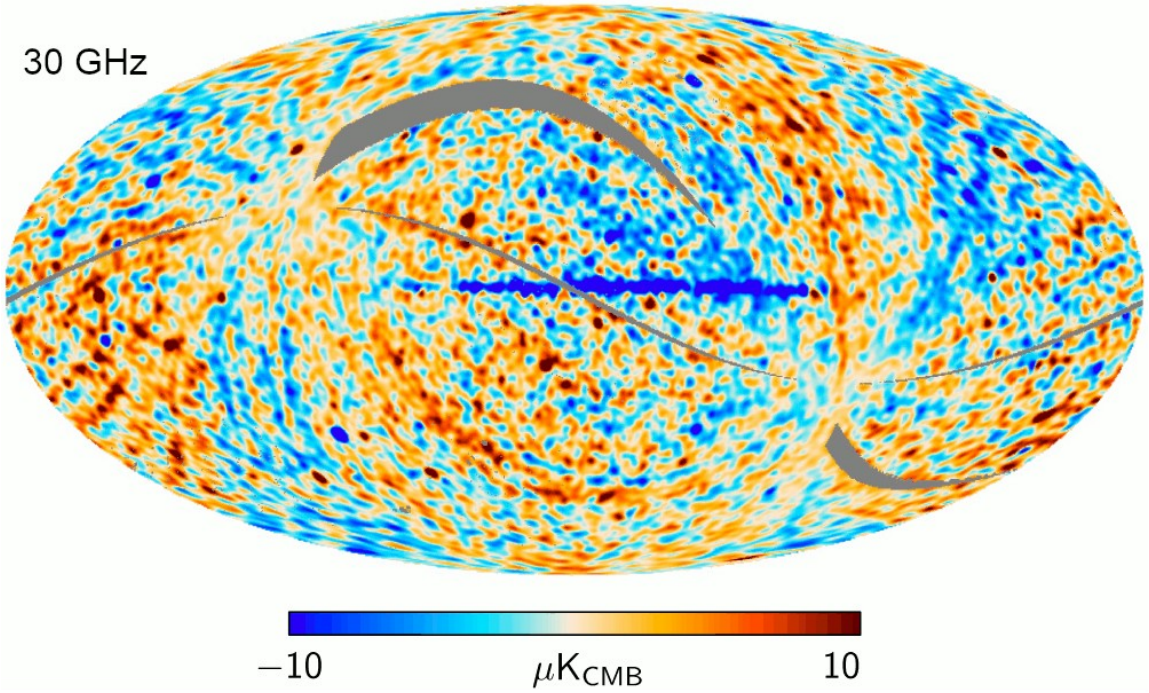
Survey-based null maps

Planck Collaboration (2014), A&A 571, A3

Survey 1 - Survey 2

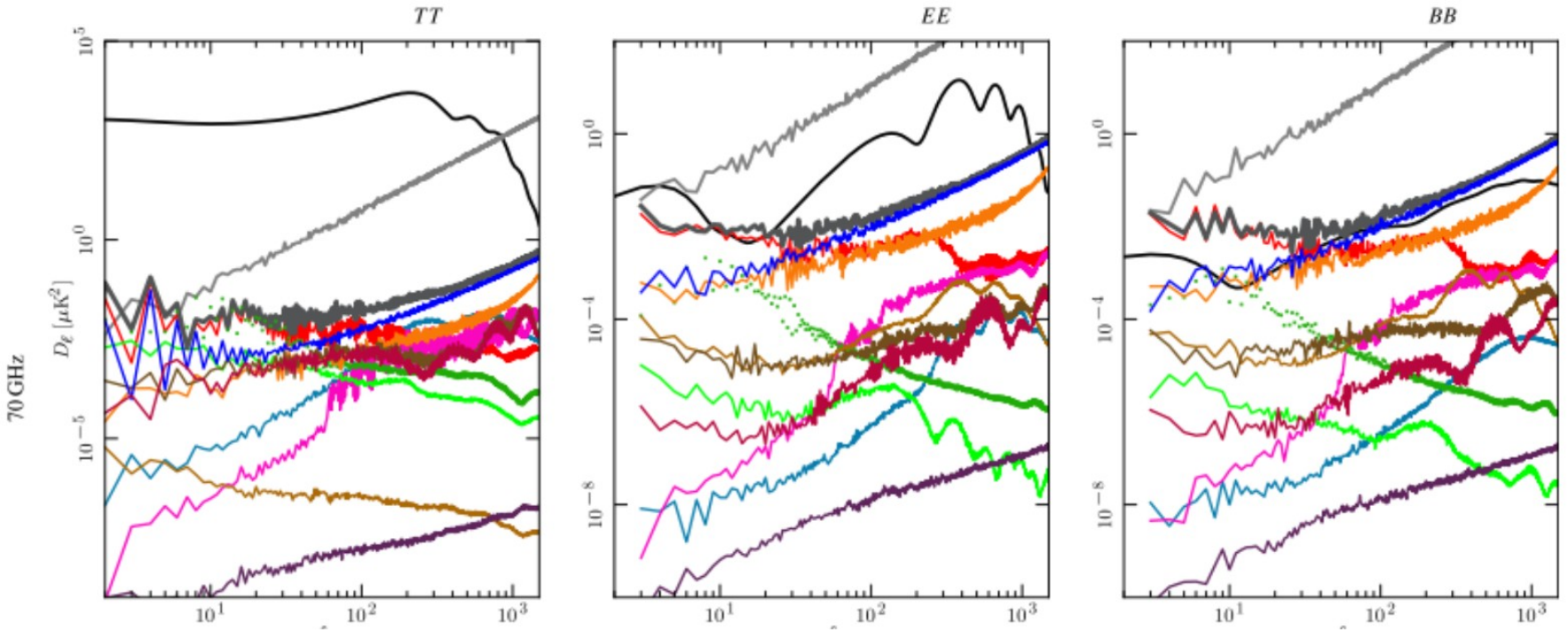


Survey 1 - Survey 3



Know your instrument

Model the residuals



The full-glory of LFI systematic effects

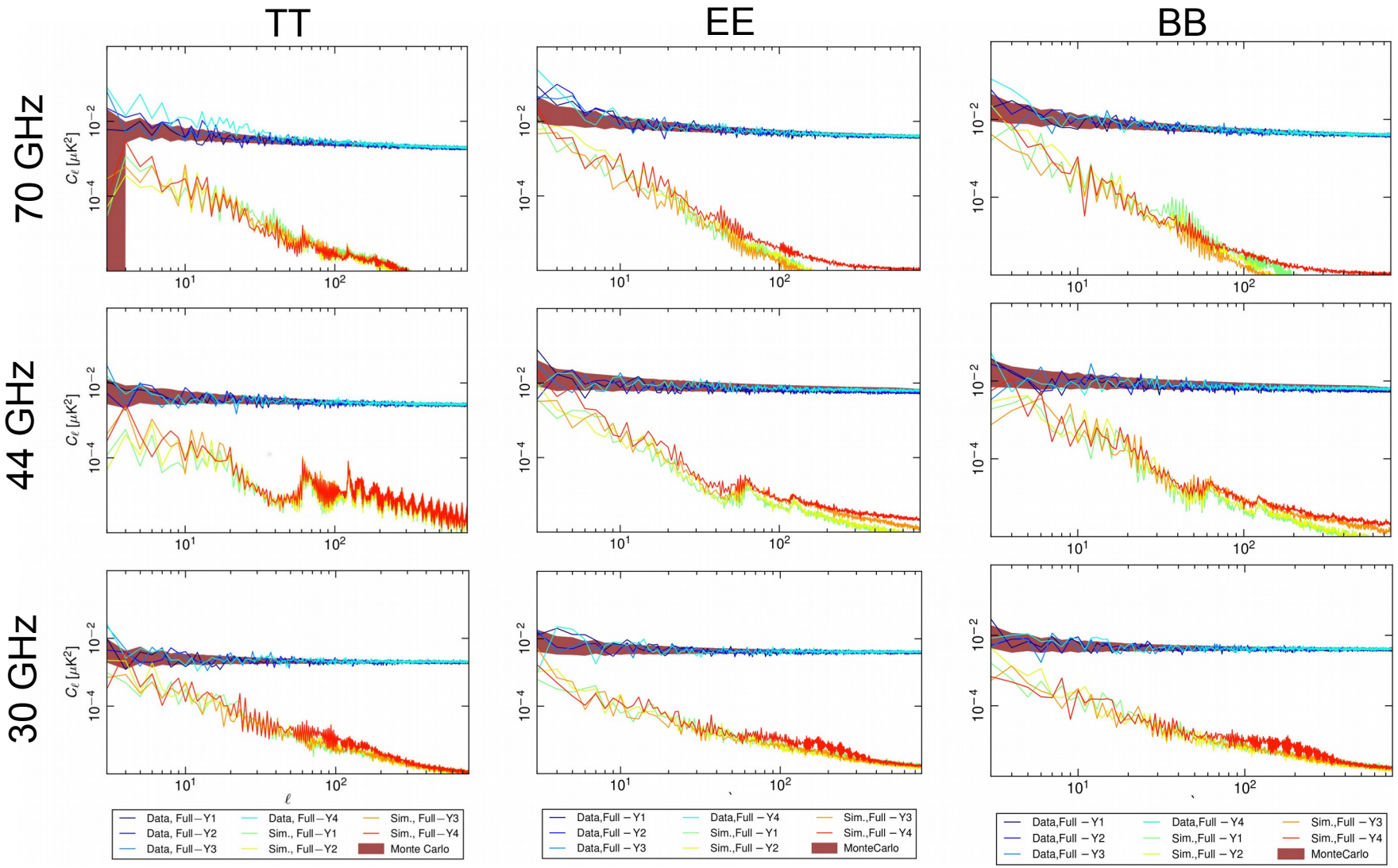
Planck Collaboration (2016), A&A 594, A3

Effect	Source	Control/Removal	Reference
	Effects independent of the sky signal (temperature and polarization)		
White noise correlation	Phase switch imbalance	Diode weighting	Planck Collaboration III (2014)
$1/f$ noise	RF amplifiers	Pseudo-correlation and destriping	Planck Collaboration III (2014)
Bias fluctuations	RF amplifiers, back-end electronics	Pseudo-correlation and destriping	Sect. 3.2.5
Thermal fluctuations	4-K, 20-K and 300-K thermal stages	Calibration, destriping	Sect. 3.2.4
1-Hz spikes	Back-end electronics	Template fitting and removal	Sect. 3.2.6
	Effects dependent on the sky signal (temperature and polarization)		
Main beam ellipticity	Main beams	Accounted for in window function	Planck Collaboration III (2016)
Near sidelobe pickup	Optical response at angles <5° from the main beam	Masking of Galaxy and point sources	Planck Collaboration II (2016), Sects. 2.1.2, 3.2.1
Far sidelobe pickup	Main and sub-reflector spillover	Model sidelobes removed from timelines	Sects. 2.1.1, 3.2.1
Analogue-to-digital converter nonlinearity	Back-end analogue-to-digital converter	Template fitting and removal	Sect. 3.2.3
Imperfect photometric calibration	Sidelobe pickup, radiometer noise temperature changes, and other non-idealities	Adaptive smoothing algorithm using 4π beam, 4-K reference load voltage output, temperature sensor data	Planck Collaboration II (2016), Sects. 2.2, 3.2.2
Pointing	Uncertainties in pointing reconstruction, thermal changes affecting focal plane geometry	Negligible impact on anisotropy measurements	Sects. 2.1, 3.2.1
	Effects specifically impacting polarization		
Bandpass asymmetries	Differential orthomode transducer and receiver bandpass response	Spurious polarization removal	Sect. 2.3
Polarization angle uncertainty	Uncertainty in the polarization angle in-flight measurement	Negligible impact	Sects. 2.1.3, 3.2.1
Orthomode transducer cross-polarization	Imperfect polarization separation	Negligible impact	Leahy et al. (2010)

- Simulation pipeline dedicated to systematic effects
- Using data and information from flight operations and ground calibrations
- Allowed us to simulate timelines, maps and power spectra for each systematic effect

Null tests from data and simulations

Planck Collaboration (2016), A&A 594, A3



Null tests from data and simulations

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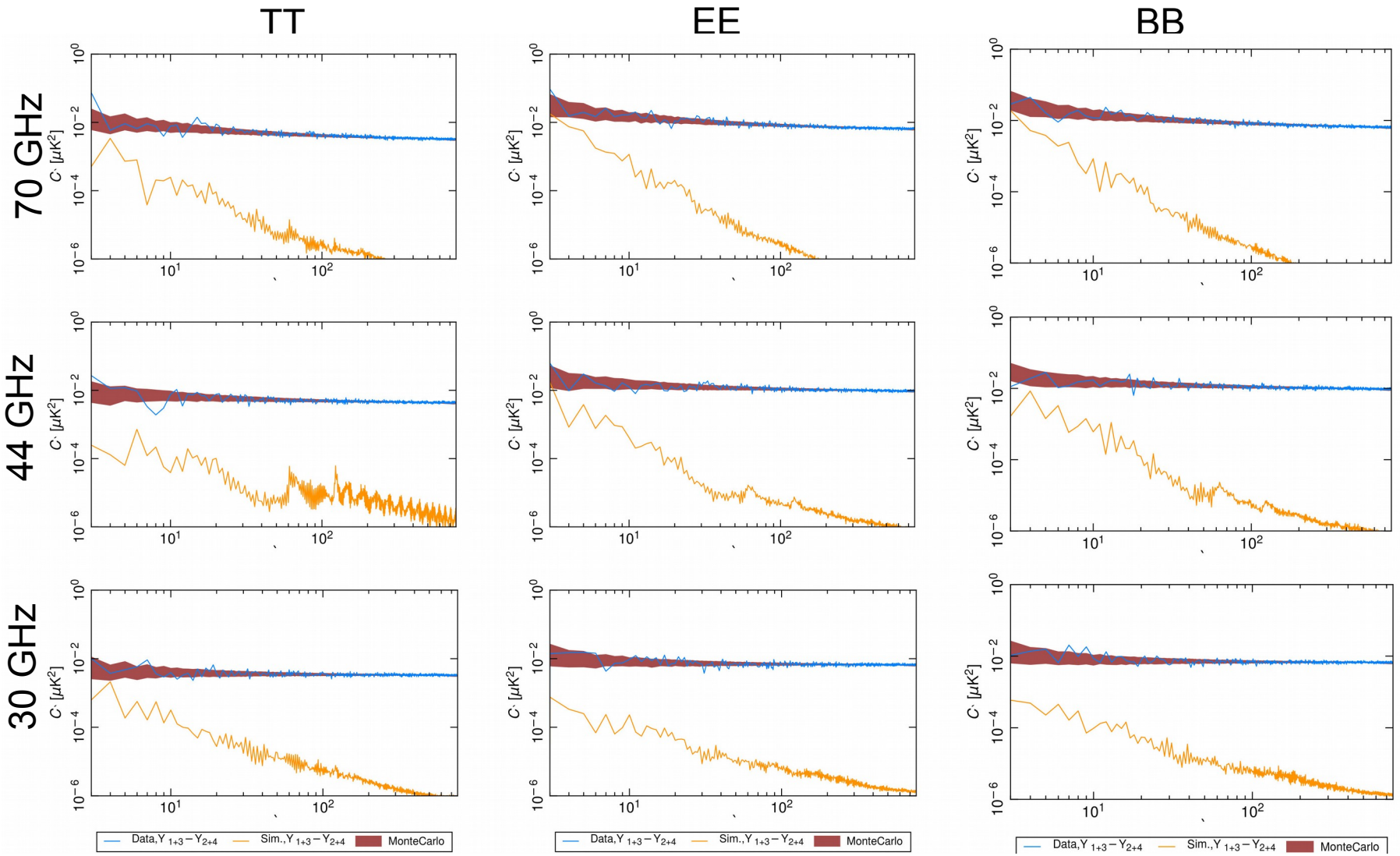
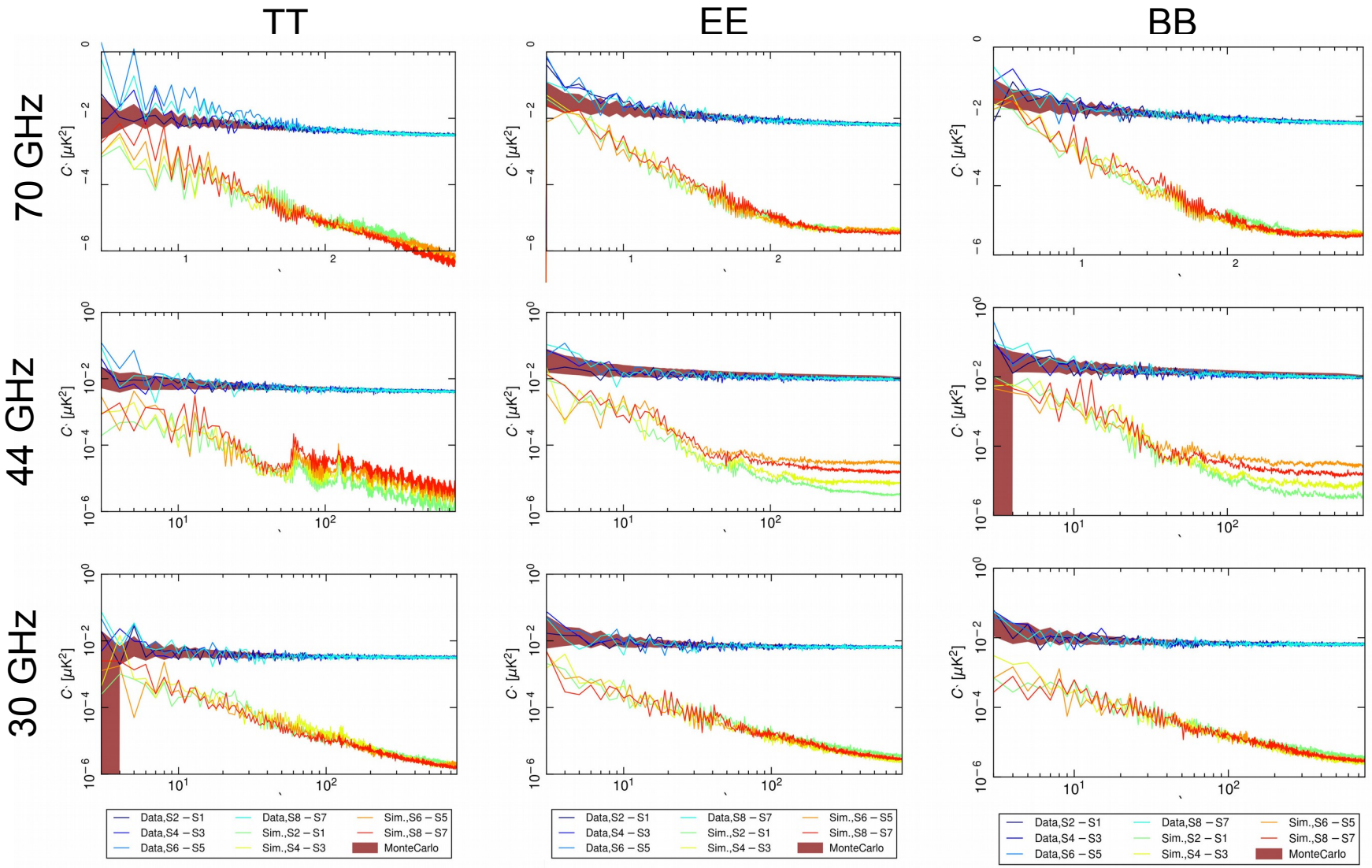


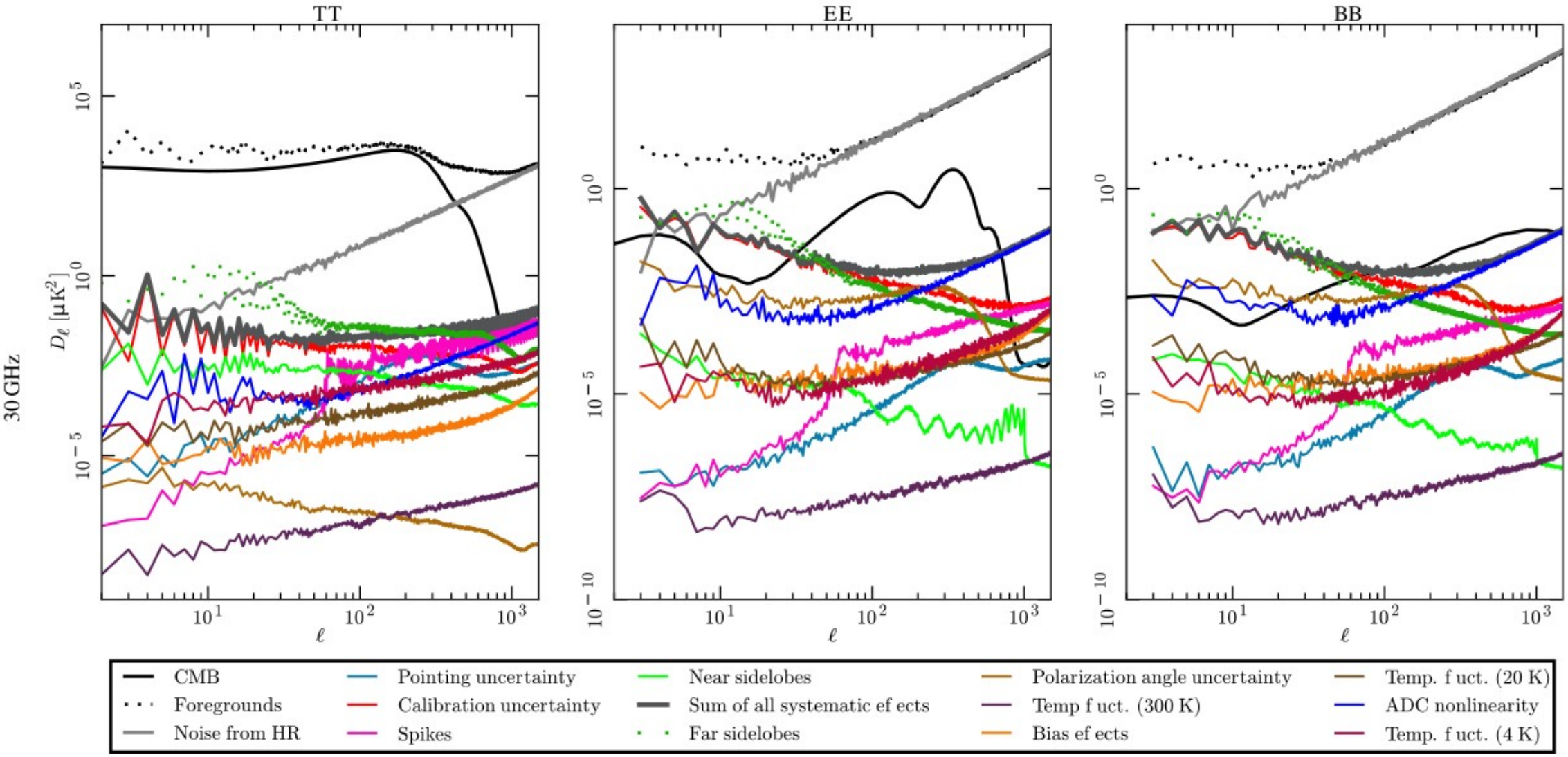
Null tests from data and simulations

Planck Collaboration (2016), A&A 594, A3



The LFI systematic effects dictionary - 30 GHz

Planck Collaboration (2016), A&A 594, A3



The LFI systematic effects dictionary - 30 GHz

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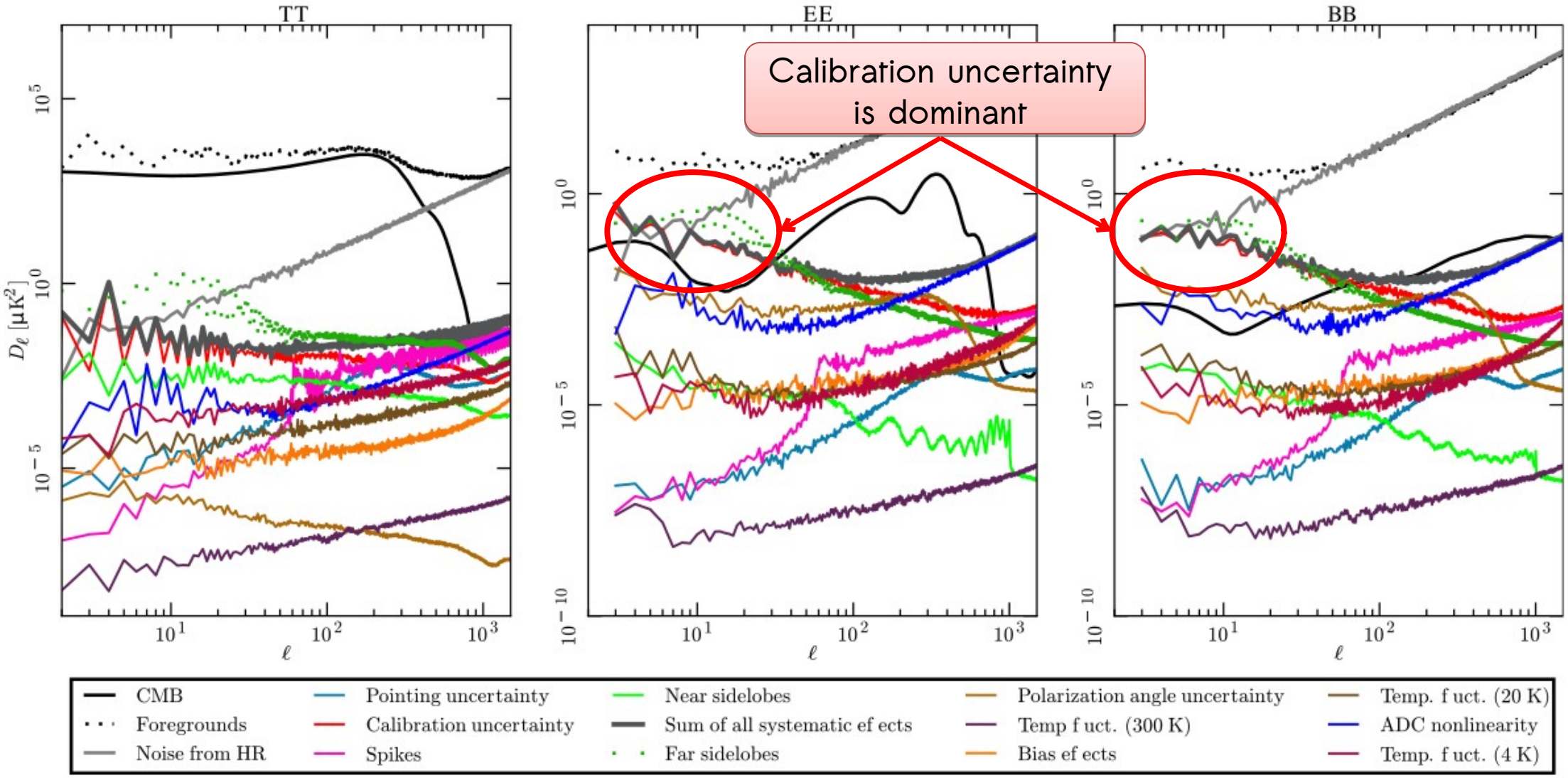
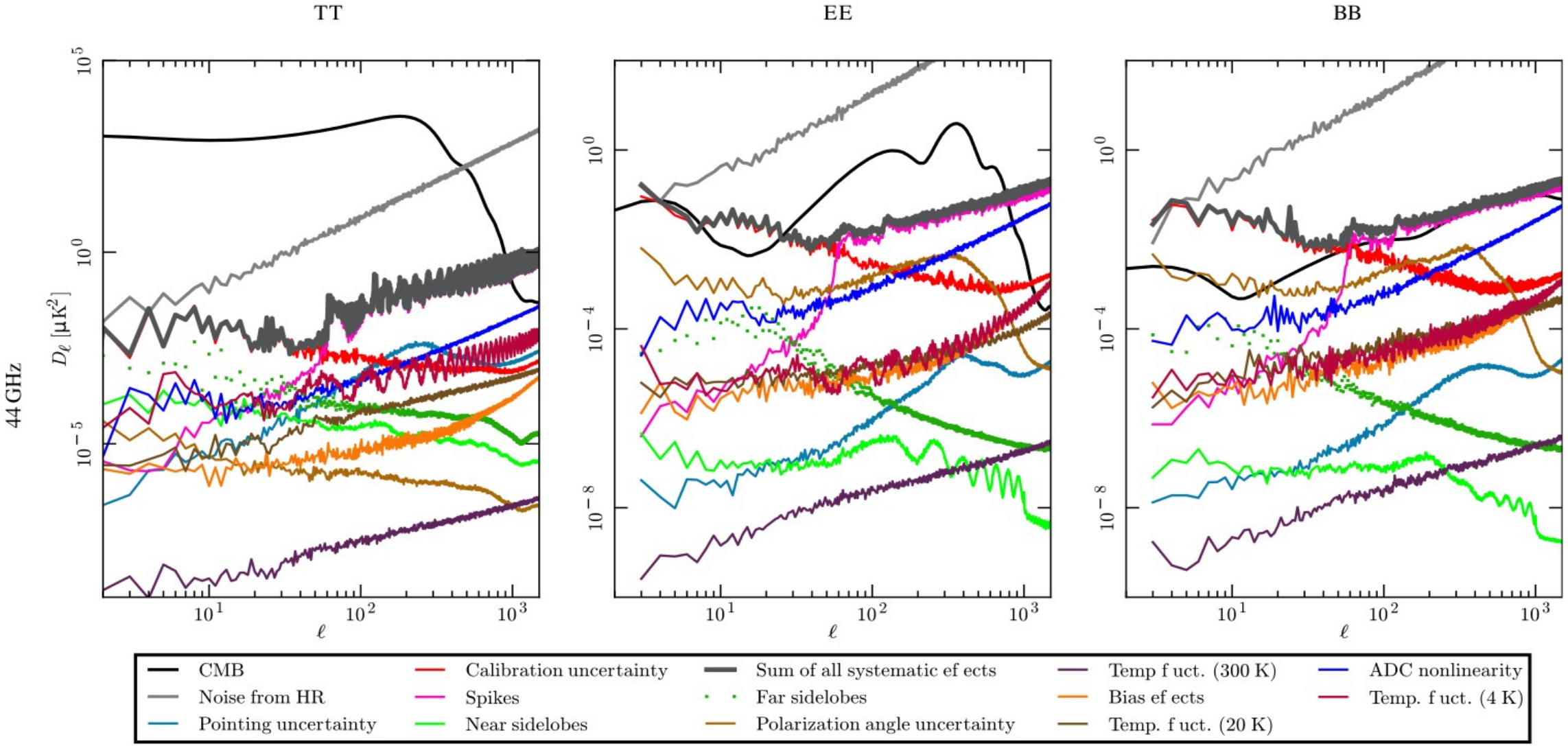


The LFI systematic effects dictionary - 44 GHz

Planck Collaboration (2016), A&A 594, A3



The LFI systematic effects dictionary - 44 GHz

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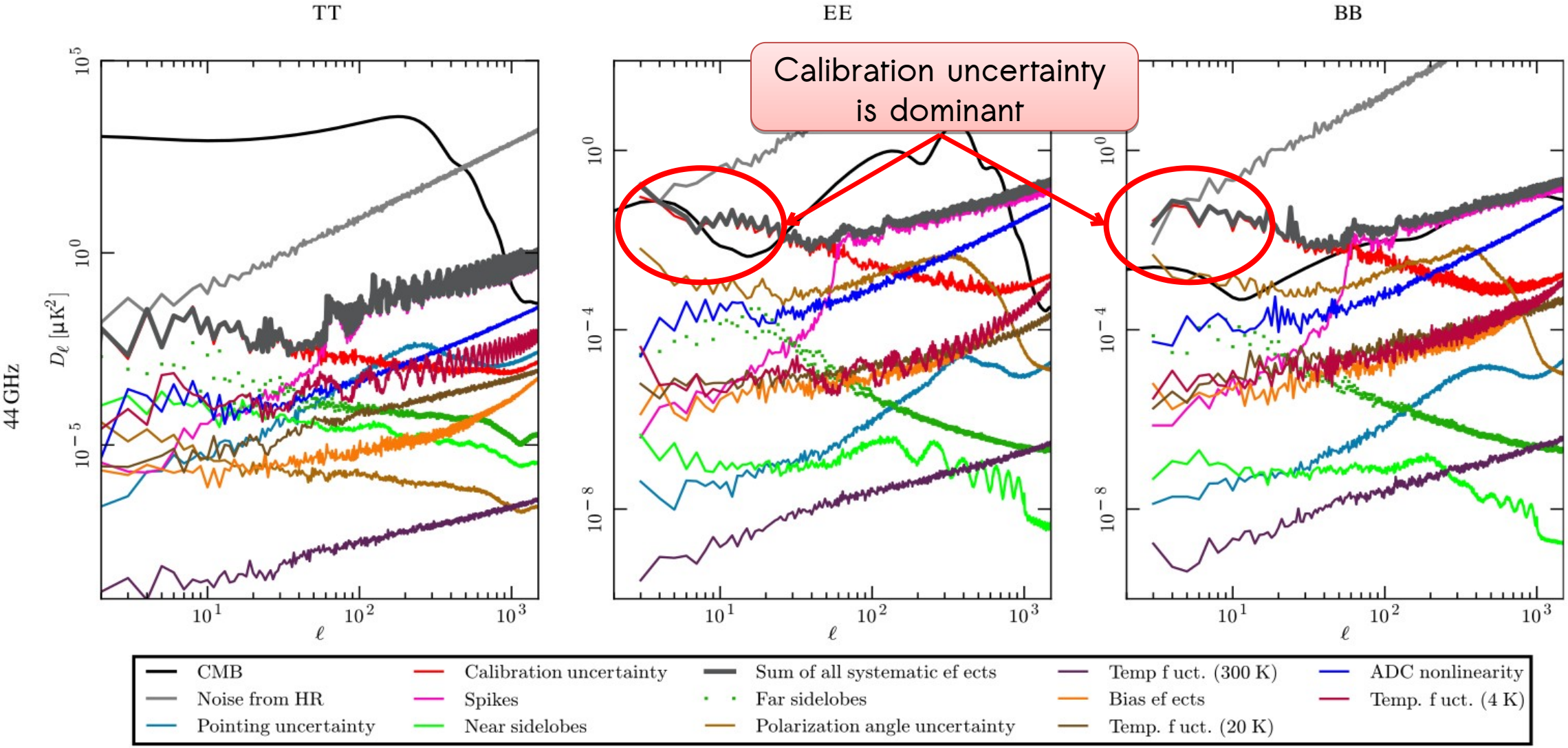
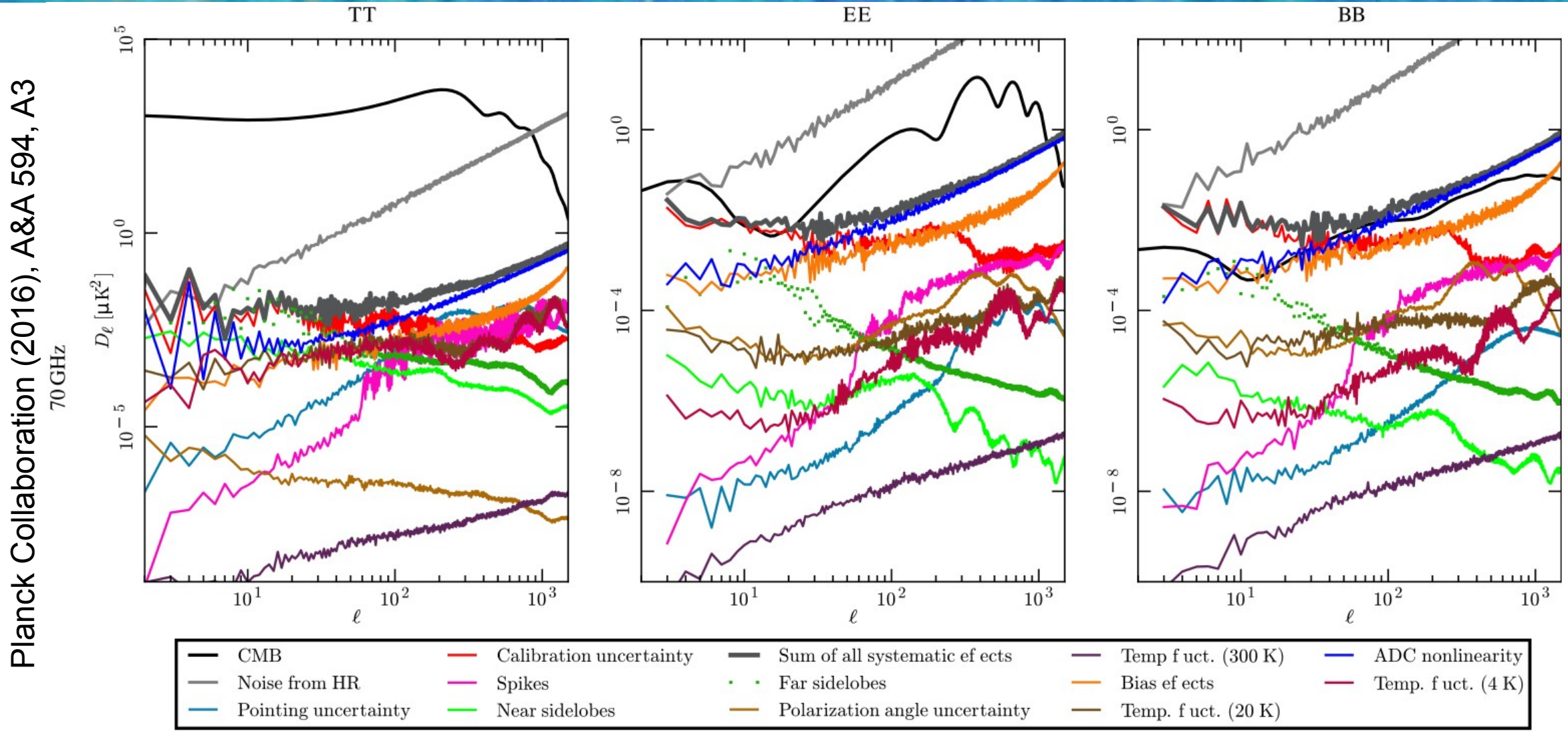


The LFI systematic effects dictionary - 70 GHz

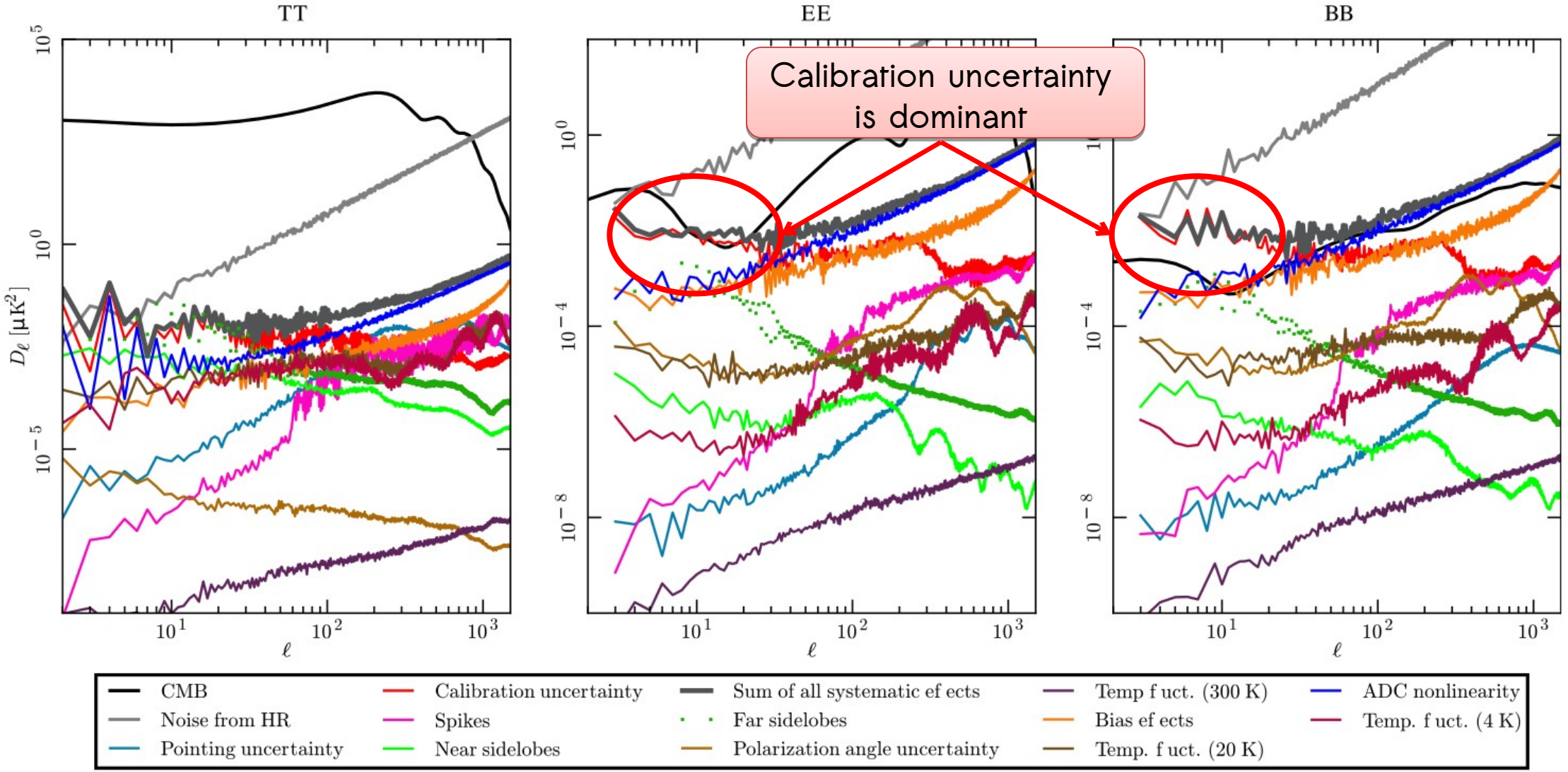


Planck Collaboration (2016), A&A 594, A3

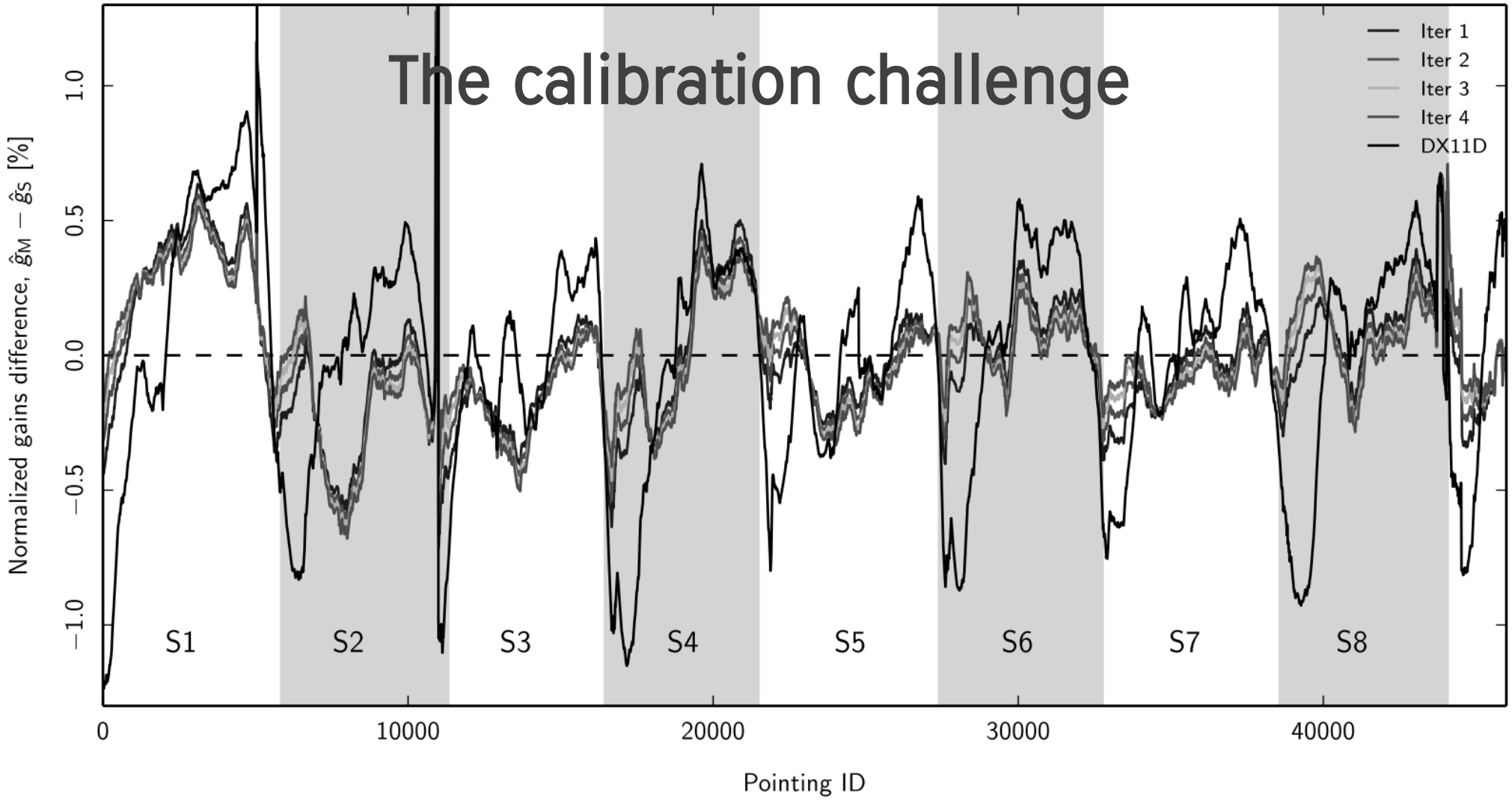
The LFI systematic effects dictionary - 70 GHz

Planck Collaboration (2016), A&A 594, A3

70 GHz



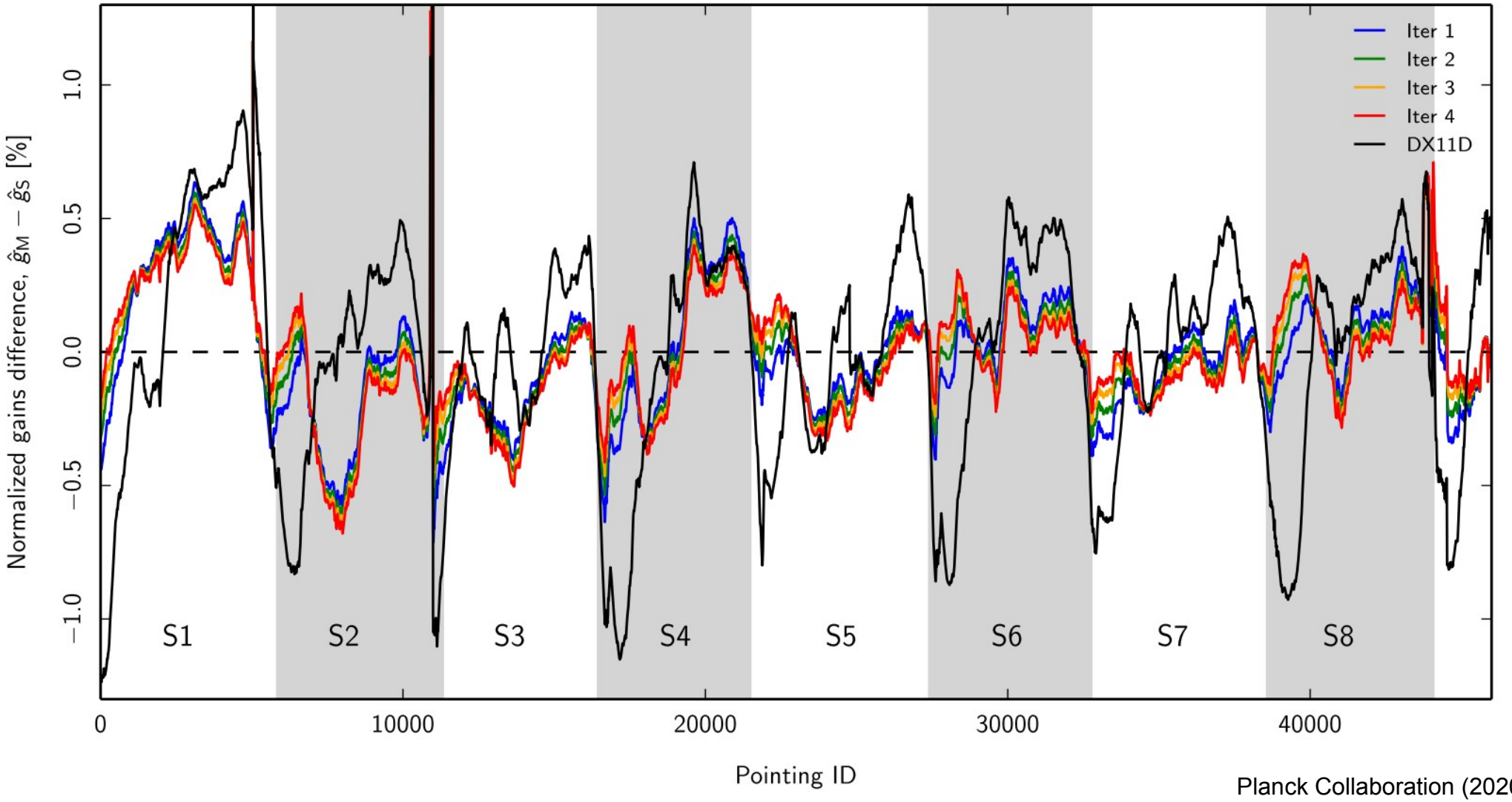
Know your instrument



Calibration uncertainties

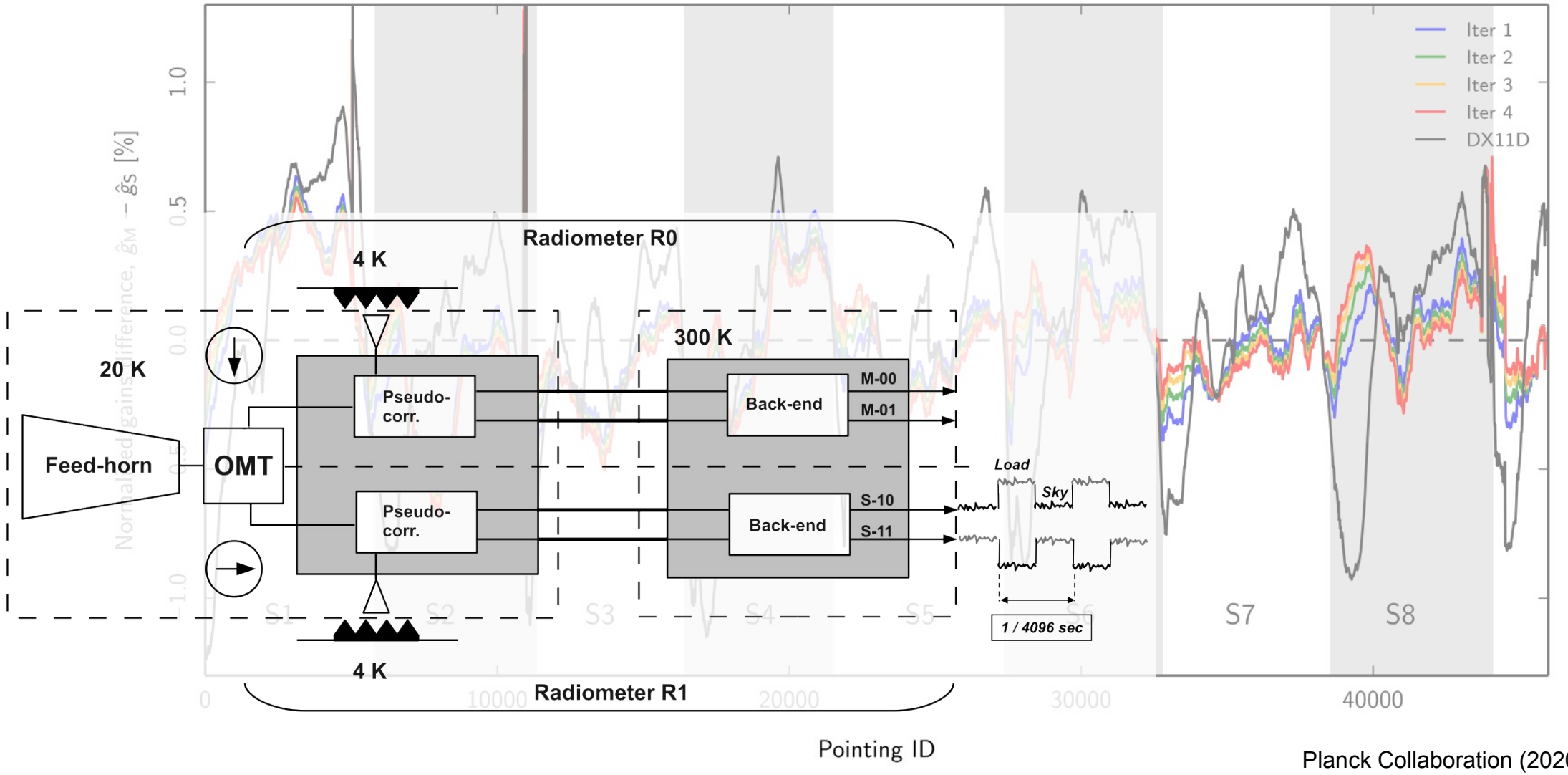
- The uncertainty in the calibration constant turned out to drive the final uncertainty
- The calibration process couples with all the instrument systematic effects
- Optical effects (sidelobes) are of particular relevance, in particular for polarization

Polarized foregrounds and calibration



Planck Collaboration (2020), A&A 641, A2

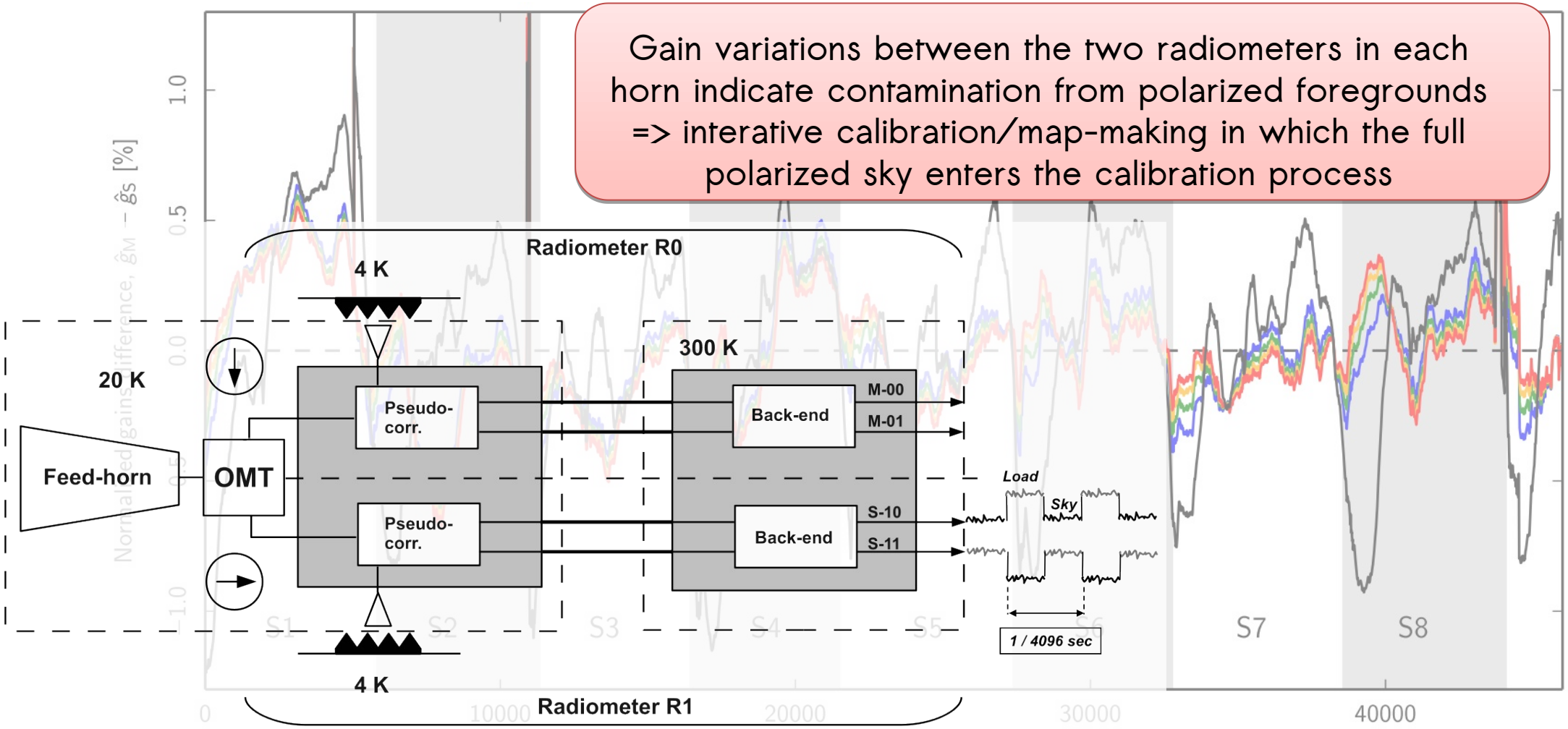
Polarized foregrounds and calibration



Planck Collaboration (2020), A&A 641, A2

Polarized foregrounds and calibration

Gain variations between the two radiometers in each horn indicate contamination from polarized foregrounds => interative calibration/map-making in which the full polarized sky enters the calibration process



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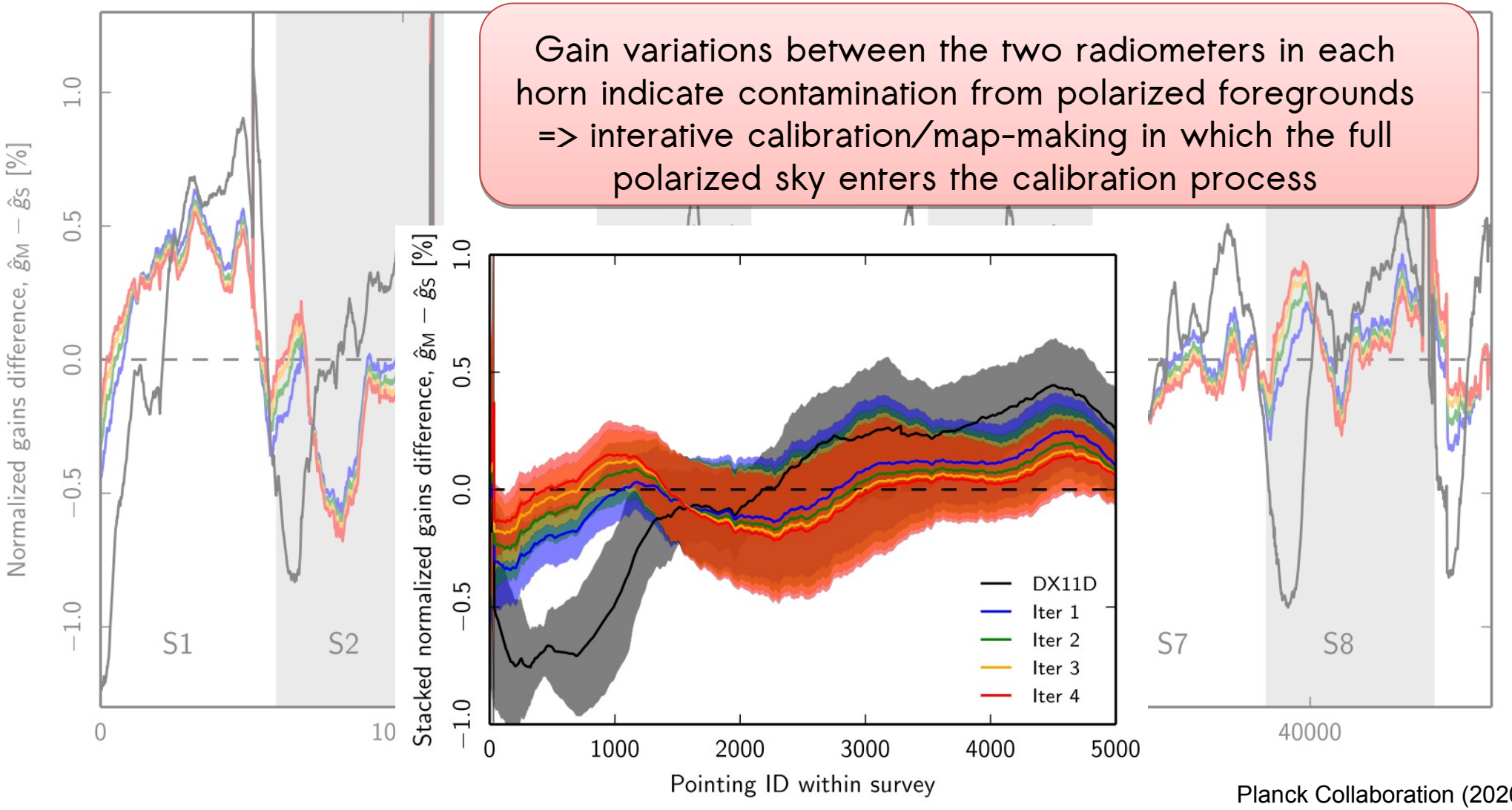
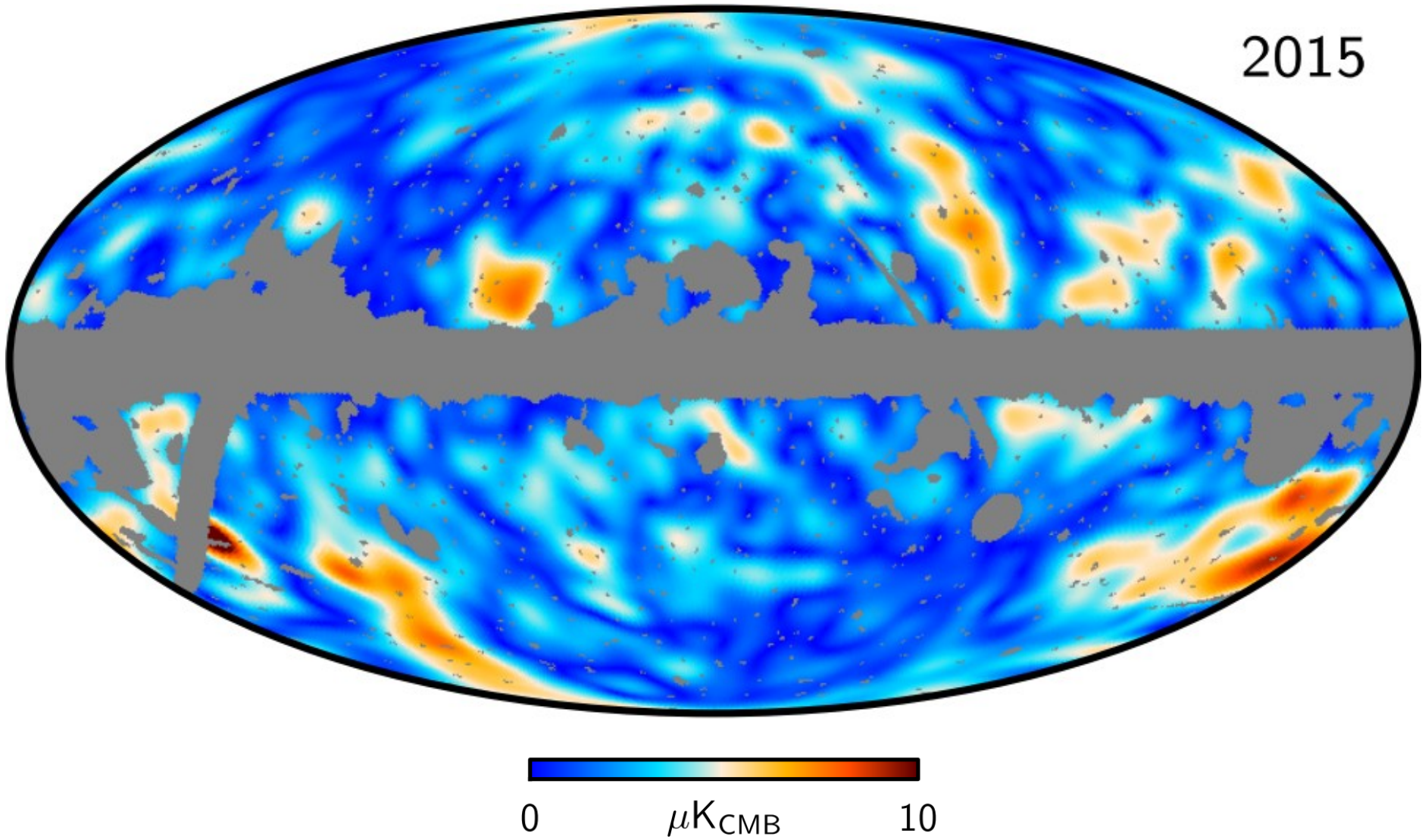
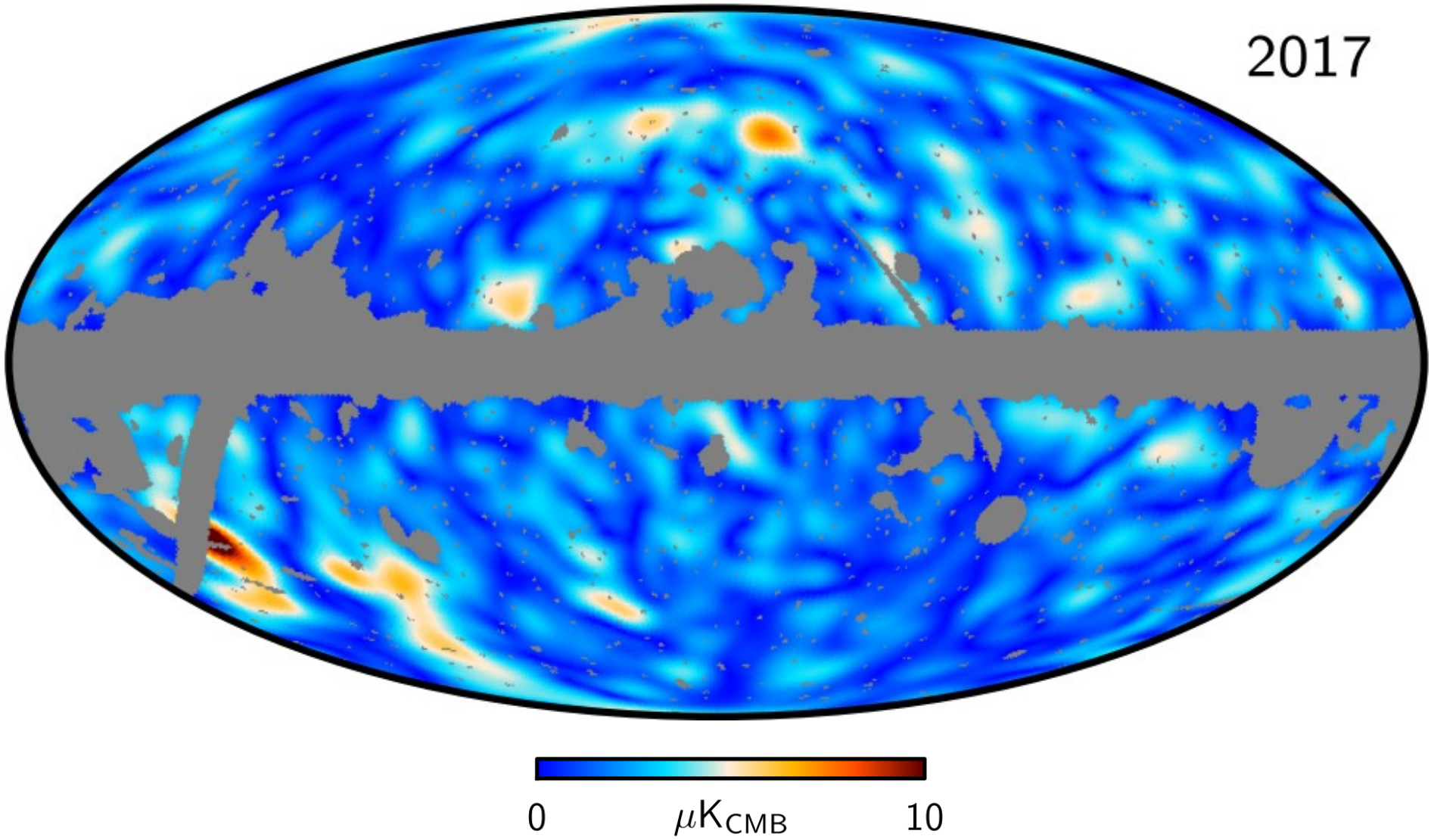


Planck Collaboration (2020), A&A 641, A2

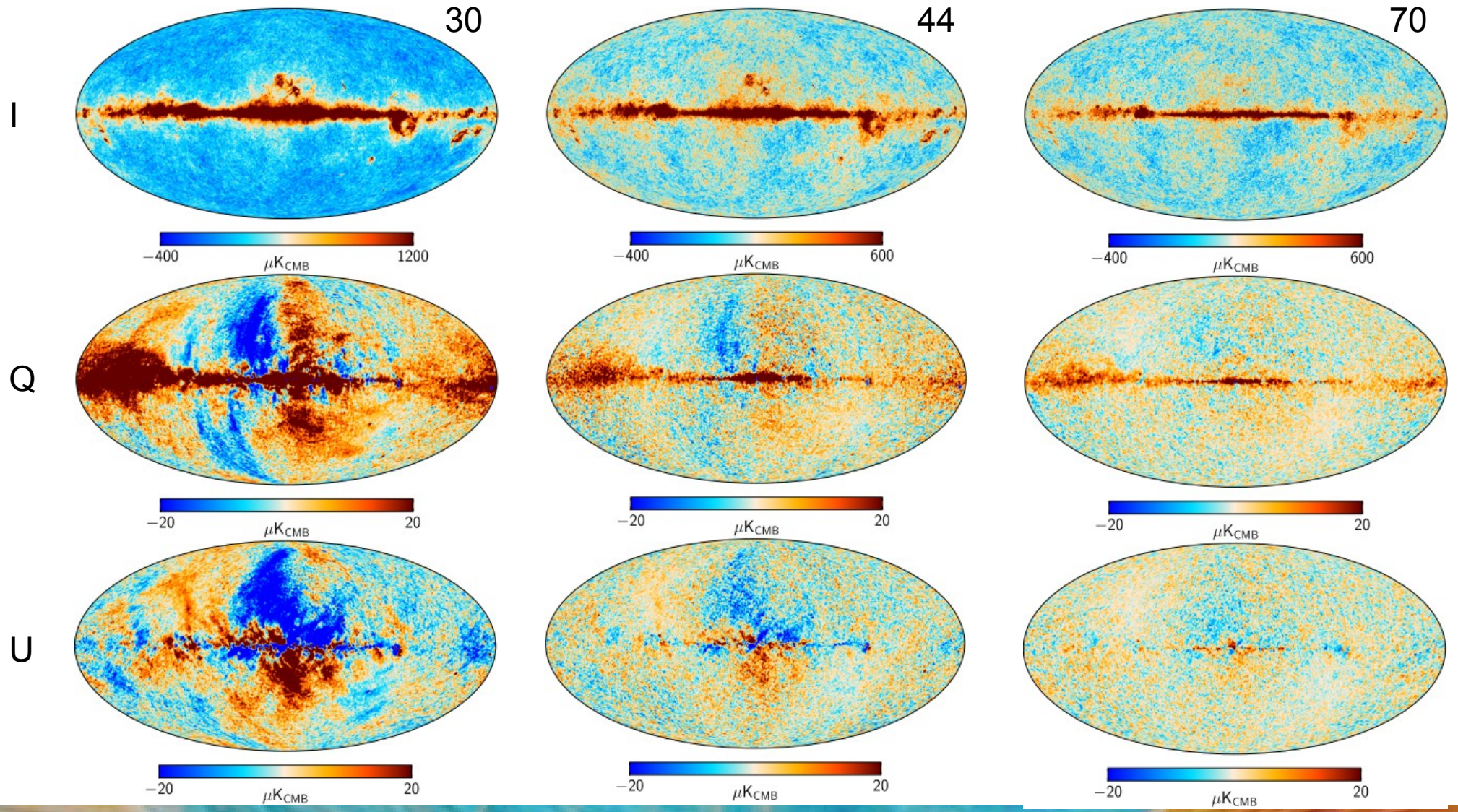
Improvement in survey null tests (30 GHz)



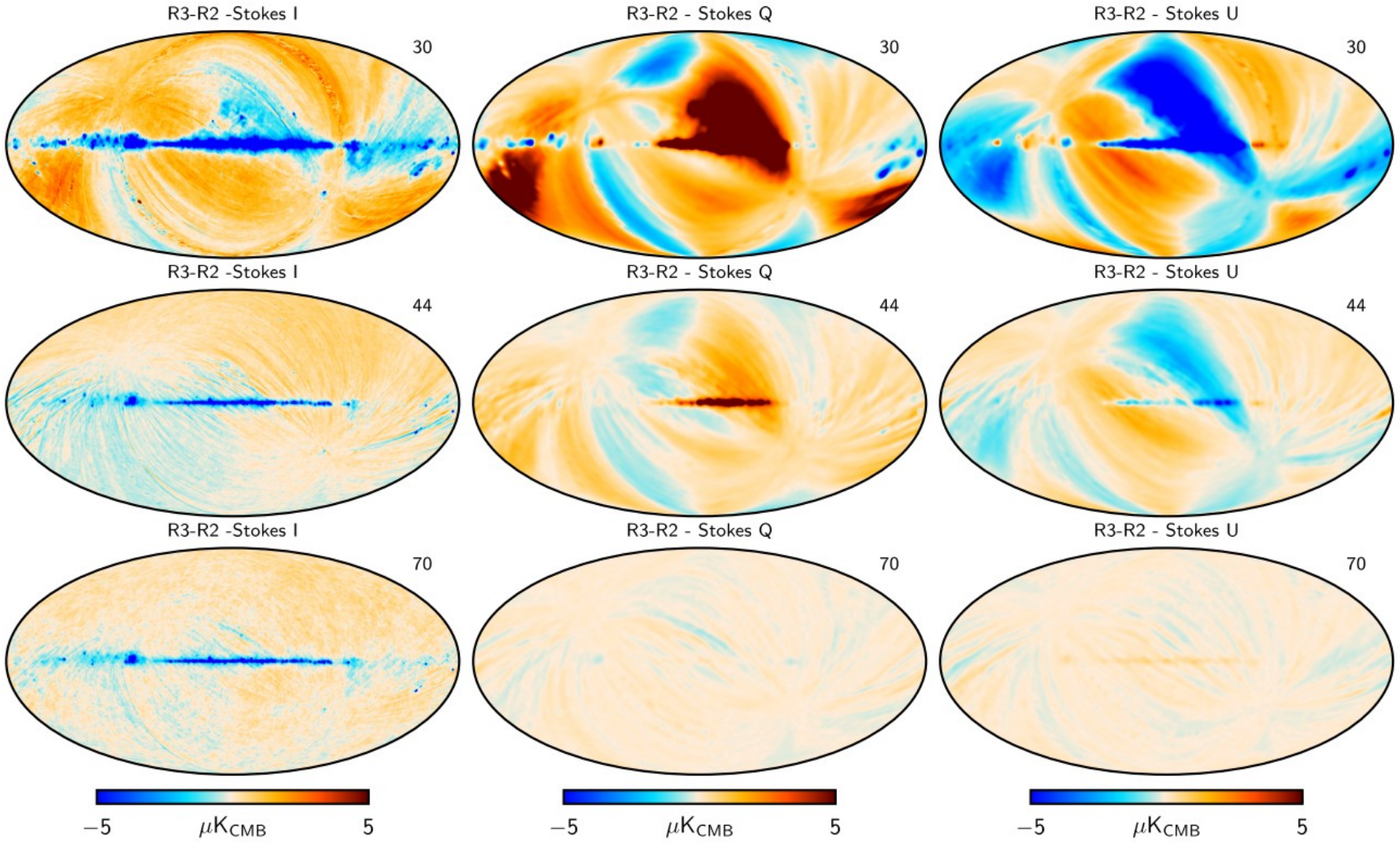
Improvement in survey null tests (30 GHz)



Final Planck-LFI release



Difference with 2015 release



Conclusions and perspectives

- Controlling instrumental effects in CMB B-modes experiments is an extraordinary challenge
- In-hardware stability must be the leading way in hardware development
- Testing, testing, testing, and surely it won't be enough
- Null-tests and systematic effects simulations are complementary handles to control uncertainties in real-data
- Iterative data analysis pipelines (à la BeyondPlanck) can be a way to further improve the control of systematic effects