Measuring the polarization of the CMB

What we learned from Planck

Aniello Mennella

University of Milan - Dept. of Physics

on behalf of the Planck collaboration

EWASS Conference, Tenerife

23 June 2015

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

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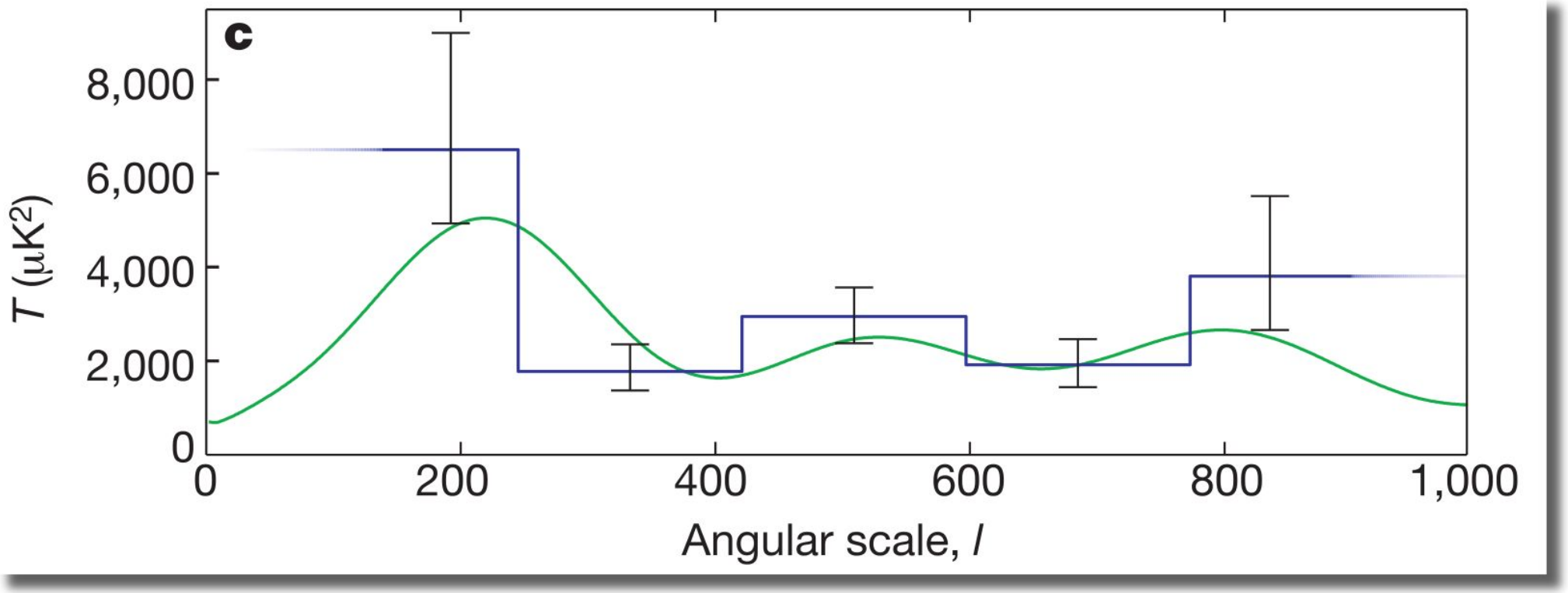

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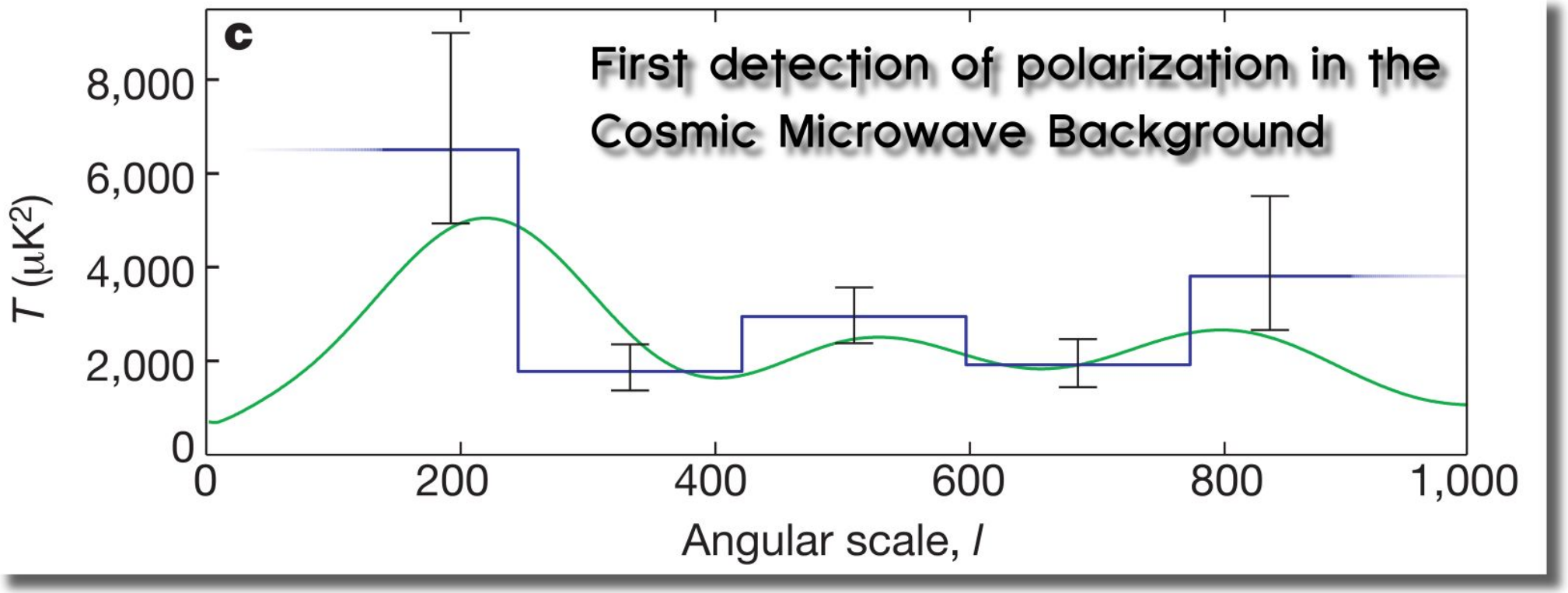
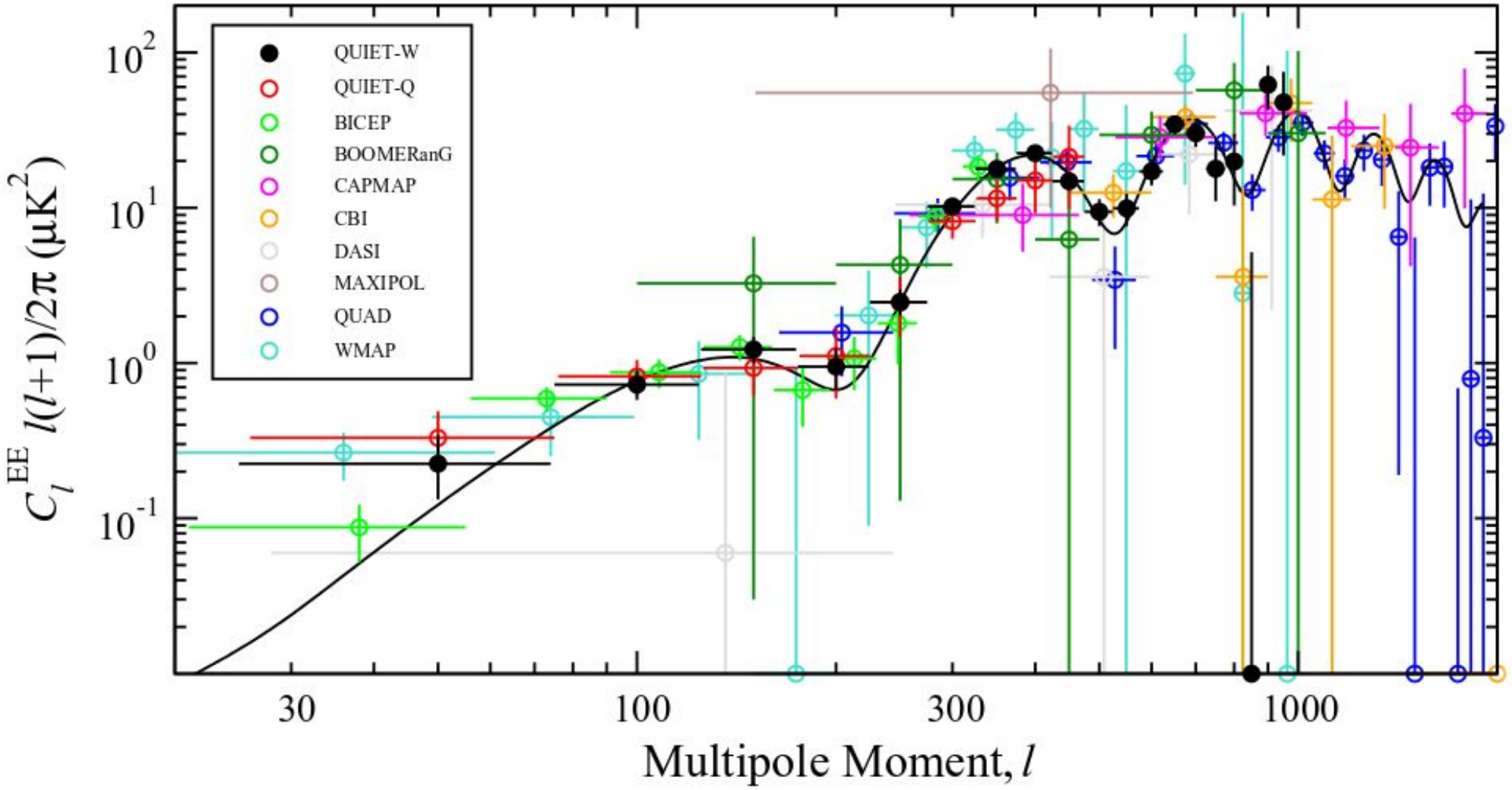


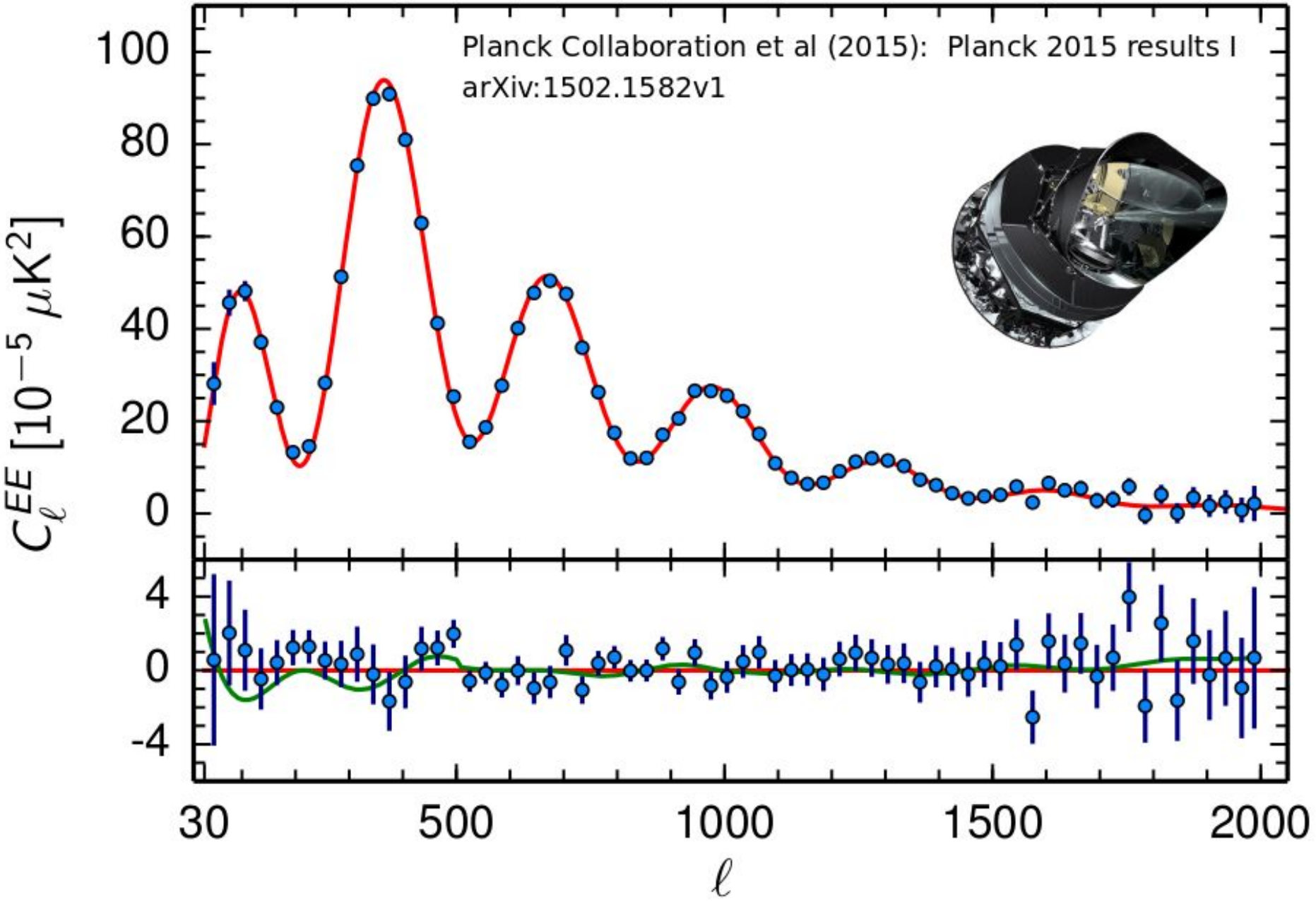
Ten years later

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

QUIET Collaboration et al.



Today


Planck Collaboration et al (2015): Planck 2015 results I
arXiv:1502.1582v1
C_ℓ^{EE} [10^{-5} μK^2]
100
80
60
40
20
0
4
0
-4
30
500
1000
1500
2000
ℓ

Main questions

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

It's interesting because...

It encodes unique information about the history of the universe

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- Reionization history

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- Reionization history
- Primordial gravitational waves (inflation)

It's difficult because...

Polarization is a tiny fraction of a tiny signal

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- We need sensitivity

It's difficult because...

Polarization is a tiny fraction of a tiny signal

- We need sensitivity
- Systematic effects and foregrounds can be killers

From Planck we learned...

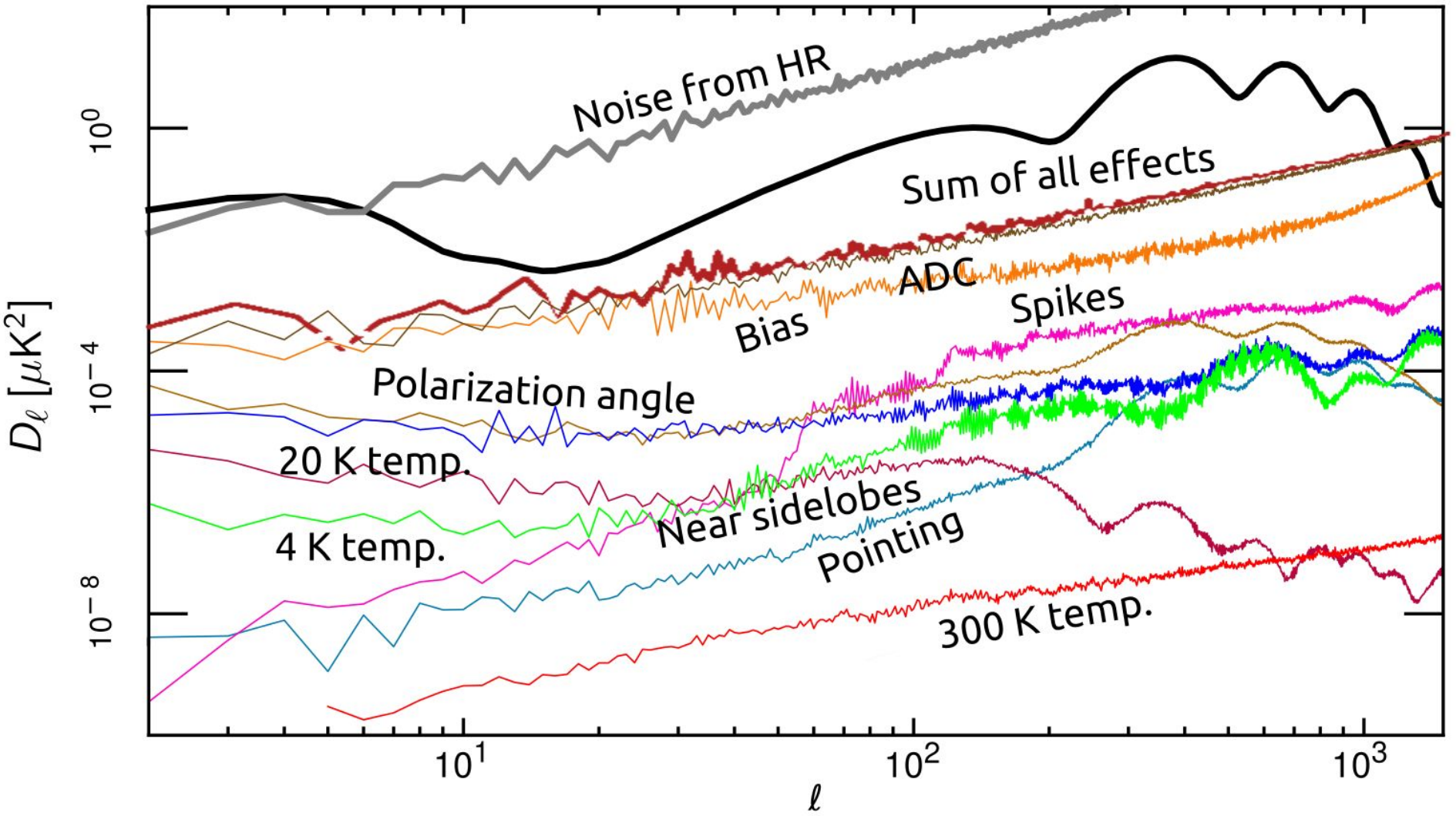
Know your instrument

and

know your sky

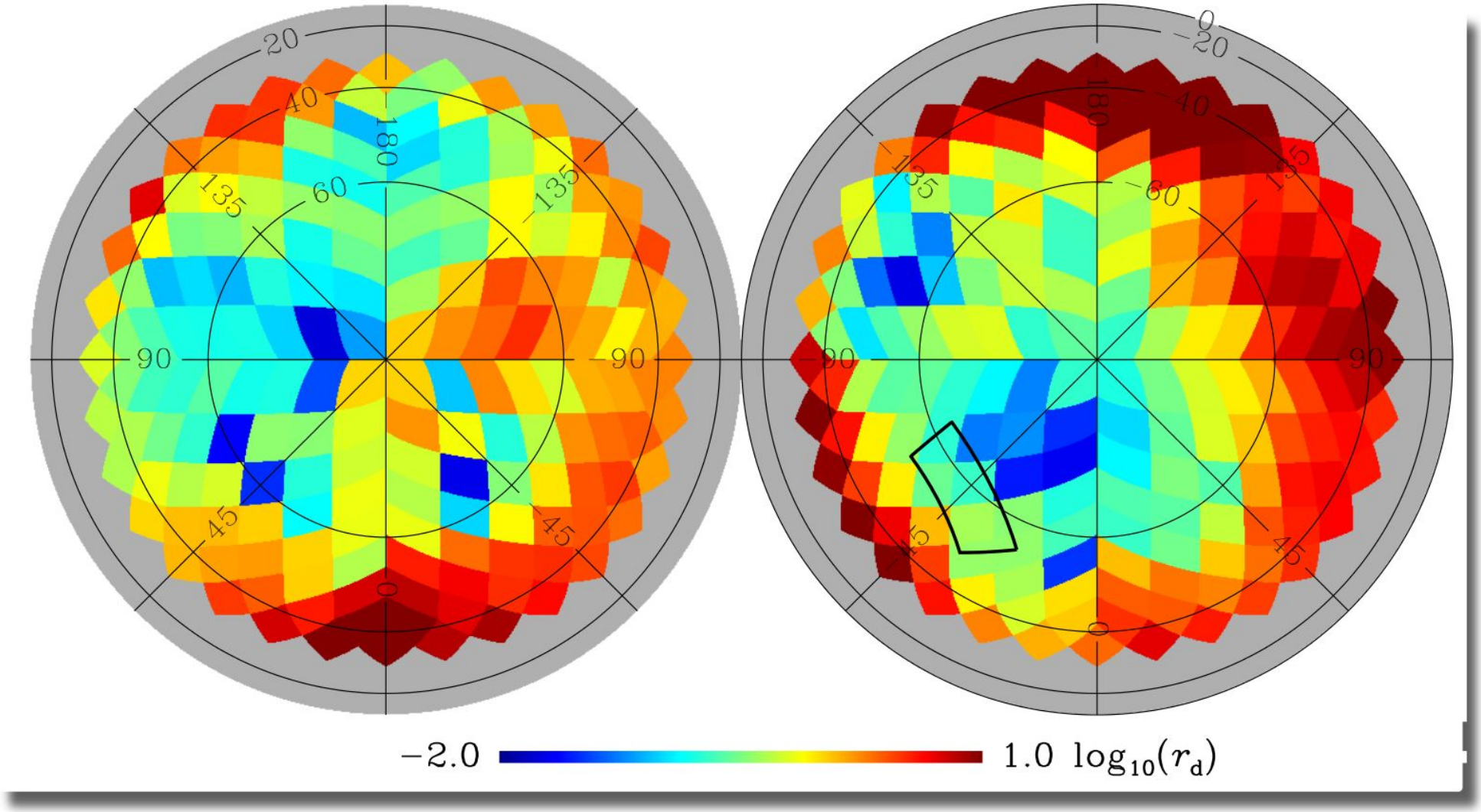
Know your instrument

Planck 70 GHz systematic effects



Know your sky

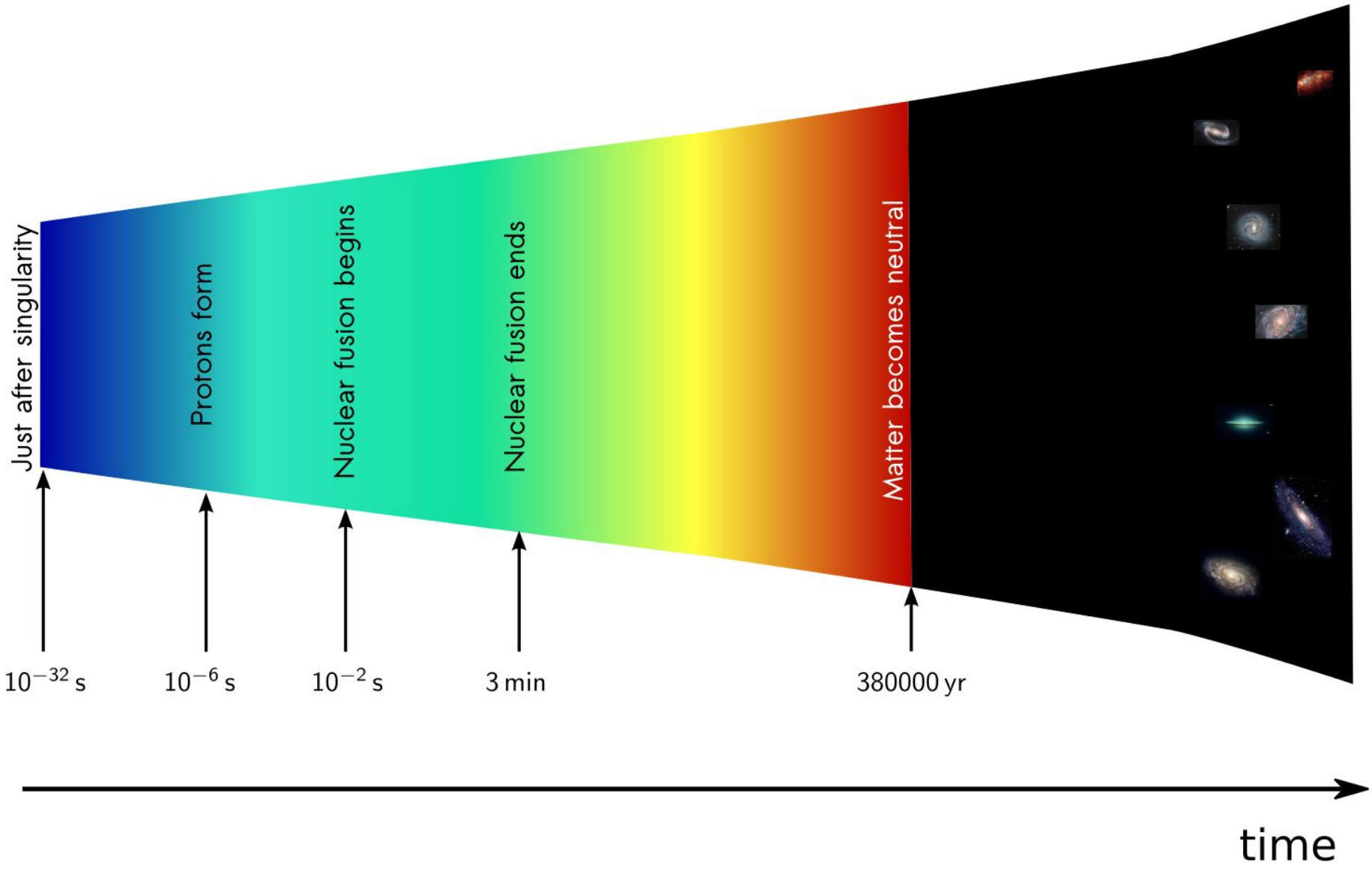
Dust polarization contamination at 150 GHz estimated from Planck 353 GHz data



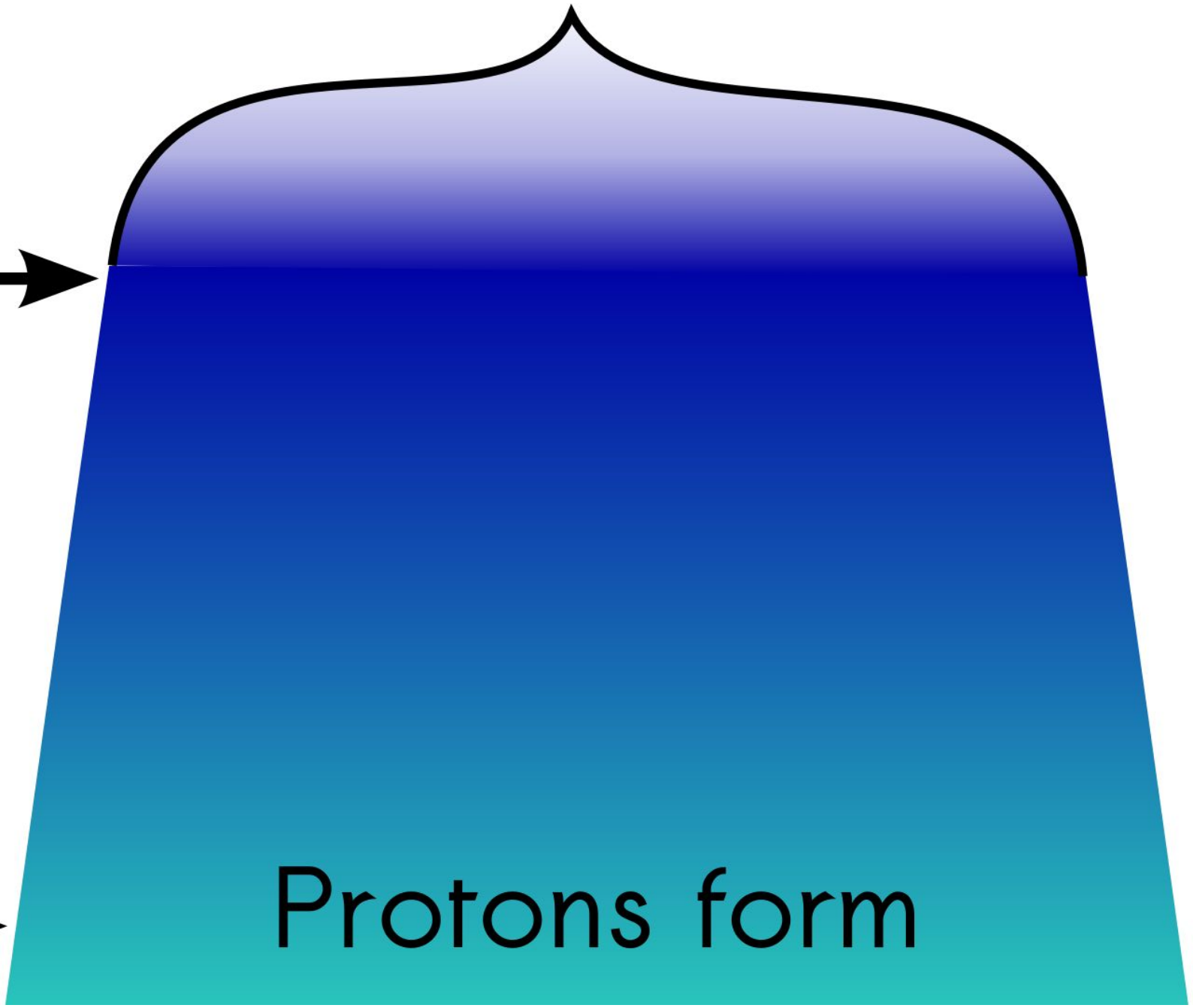
For the next 20 minutes...

Let's roll back and tell the story behind these lessons

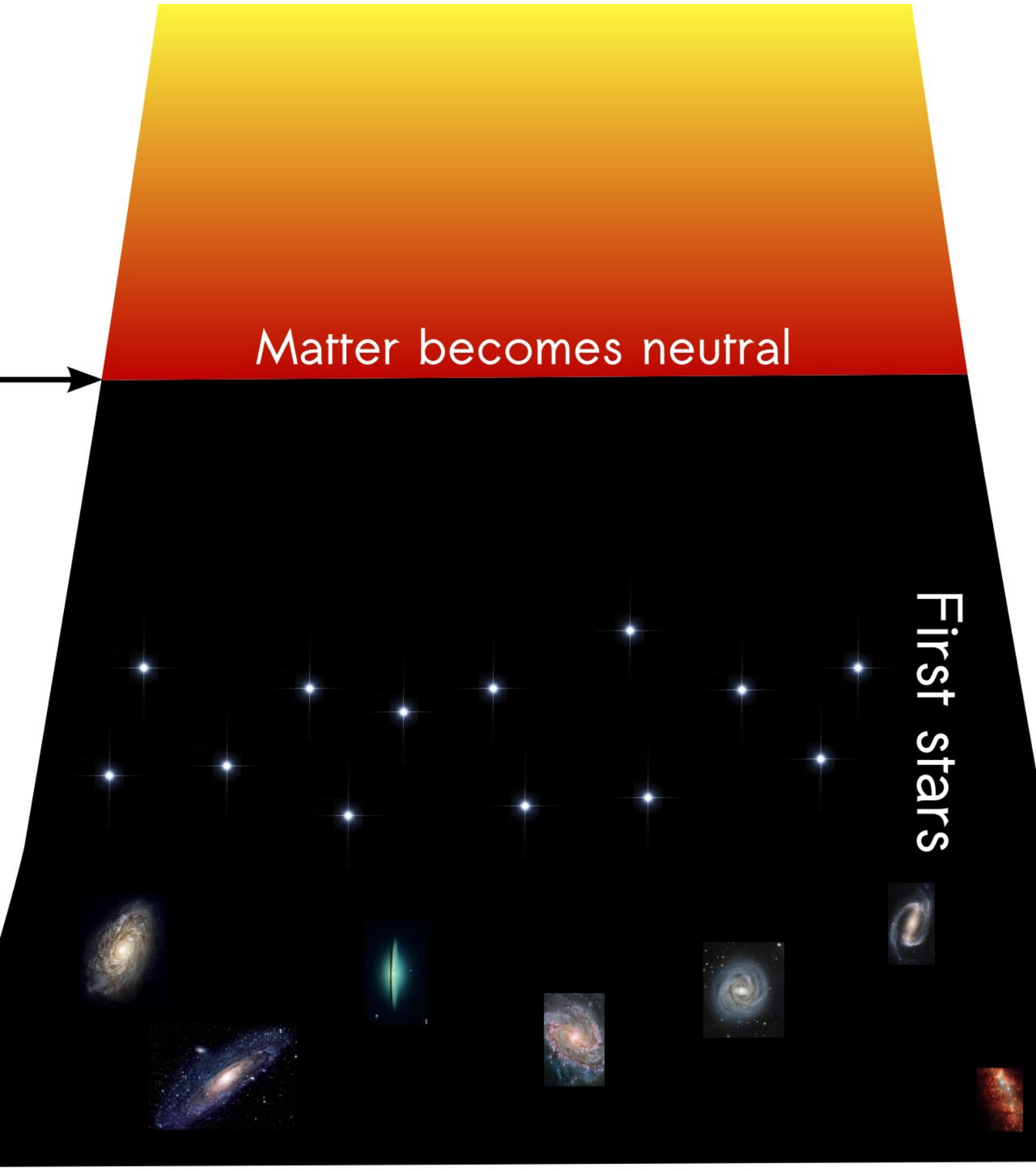
Two big questions

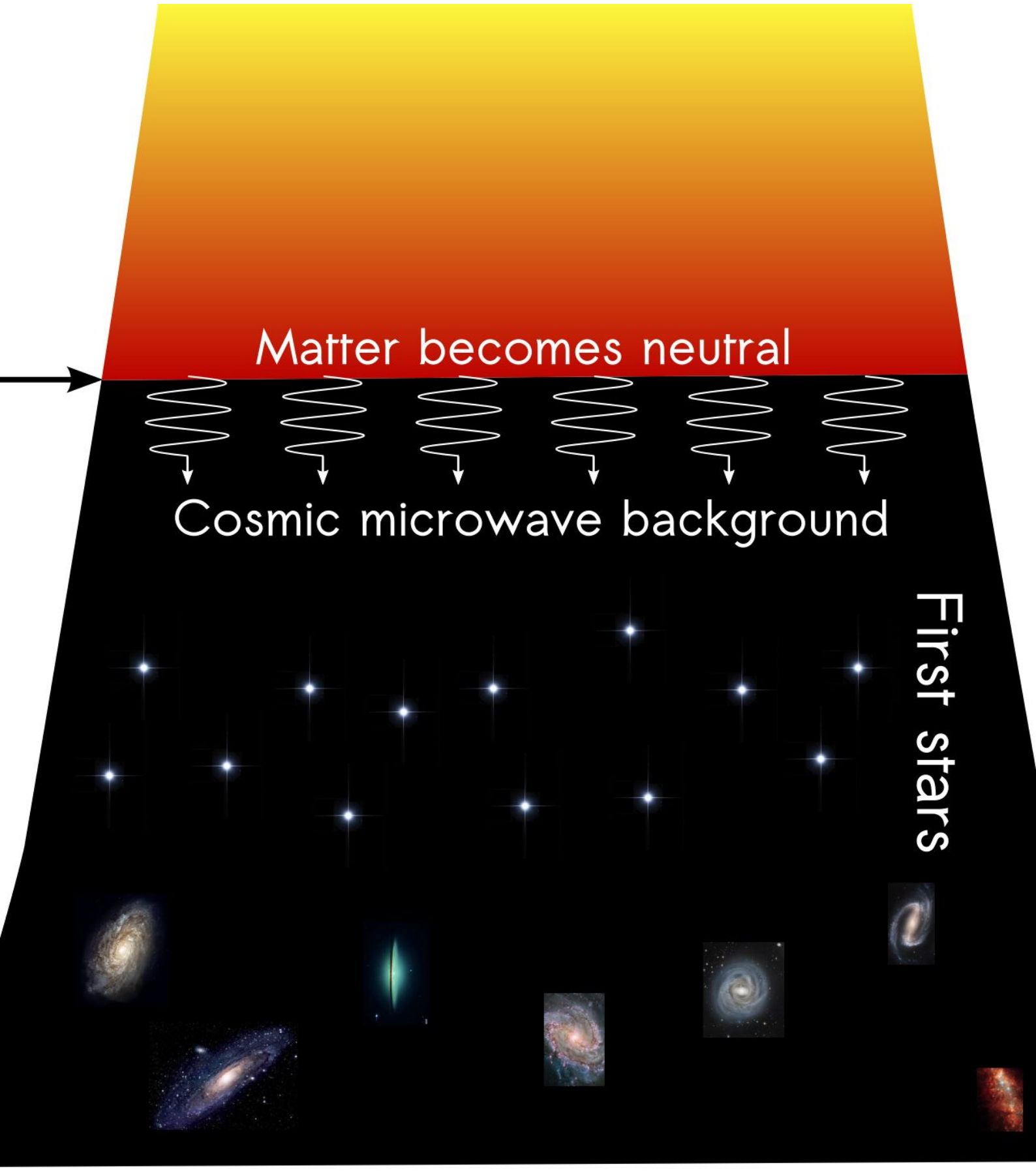


SINGULARITY

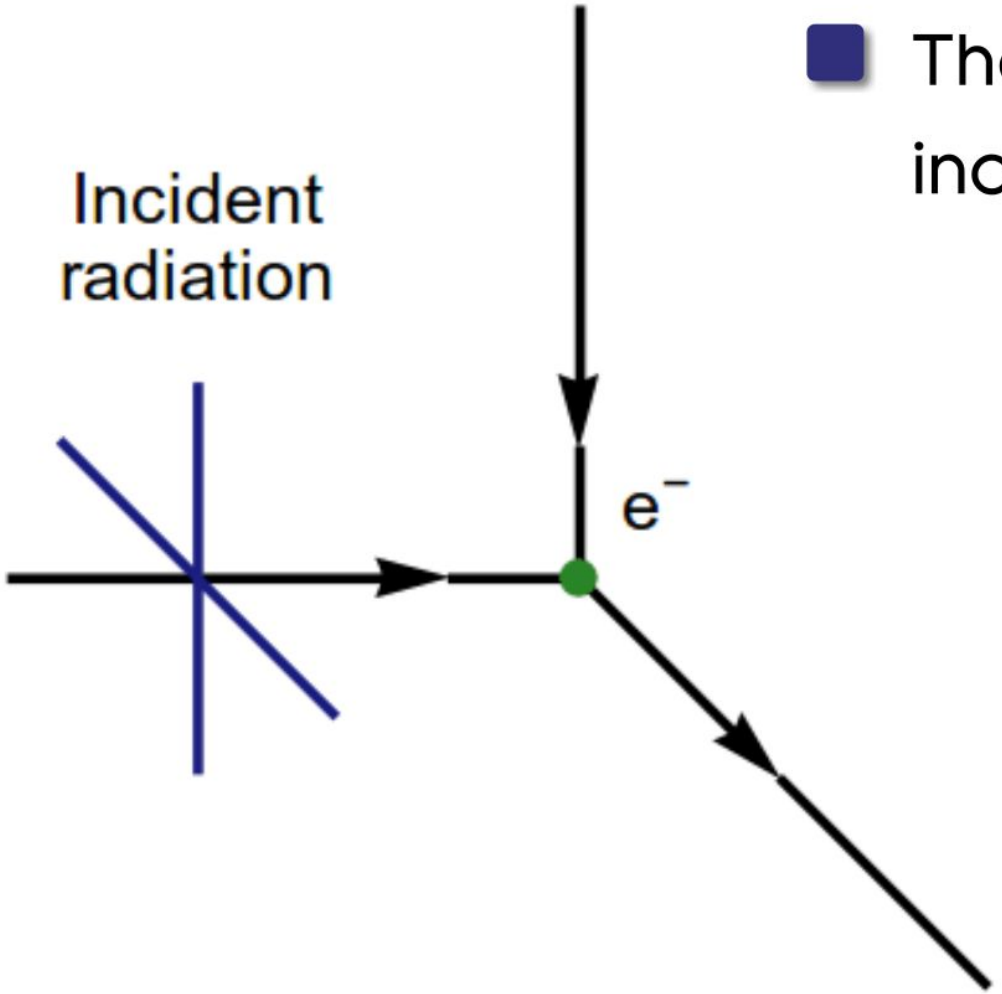


Protons form


Matter becomes neutral
First stars

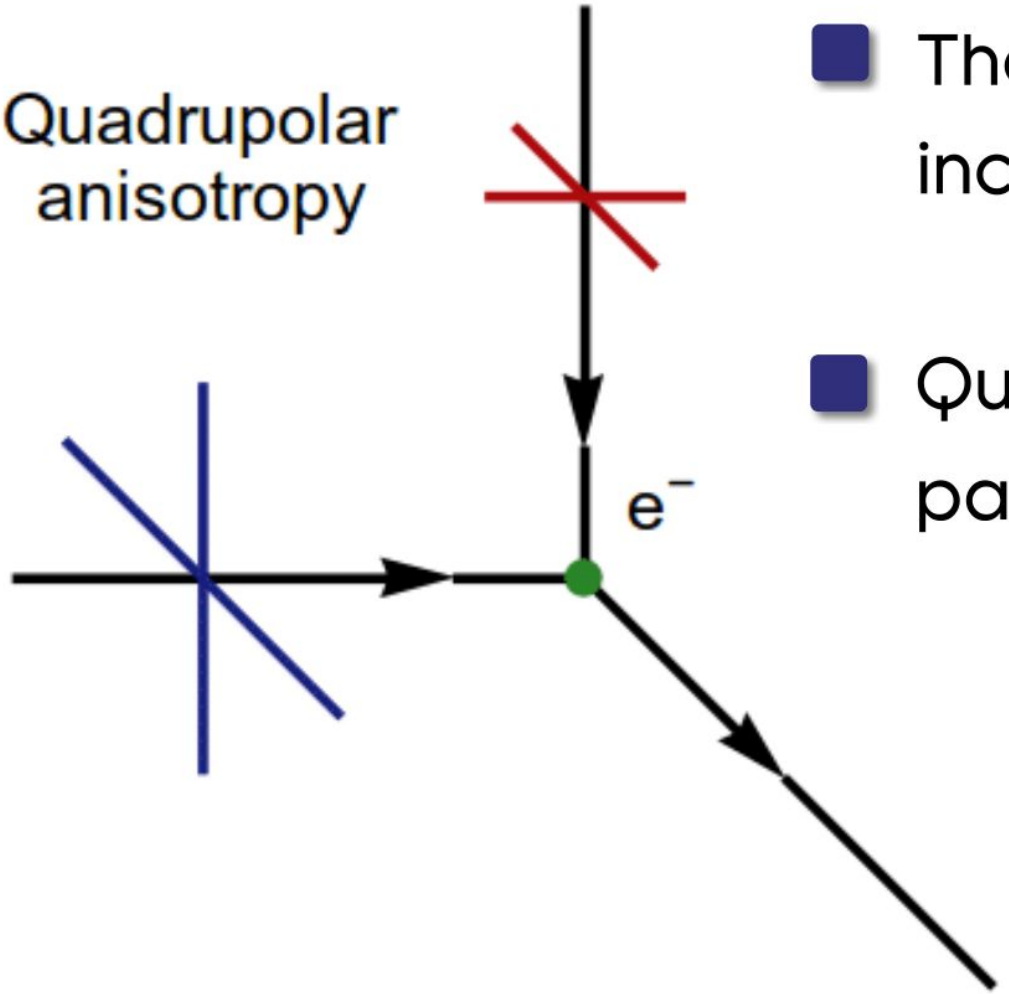

Matter becomes neutral
Cosmic microwave background
First stars

Quadrupolar anisotropy



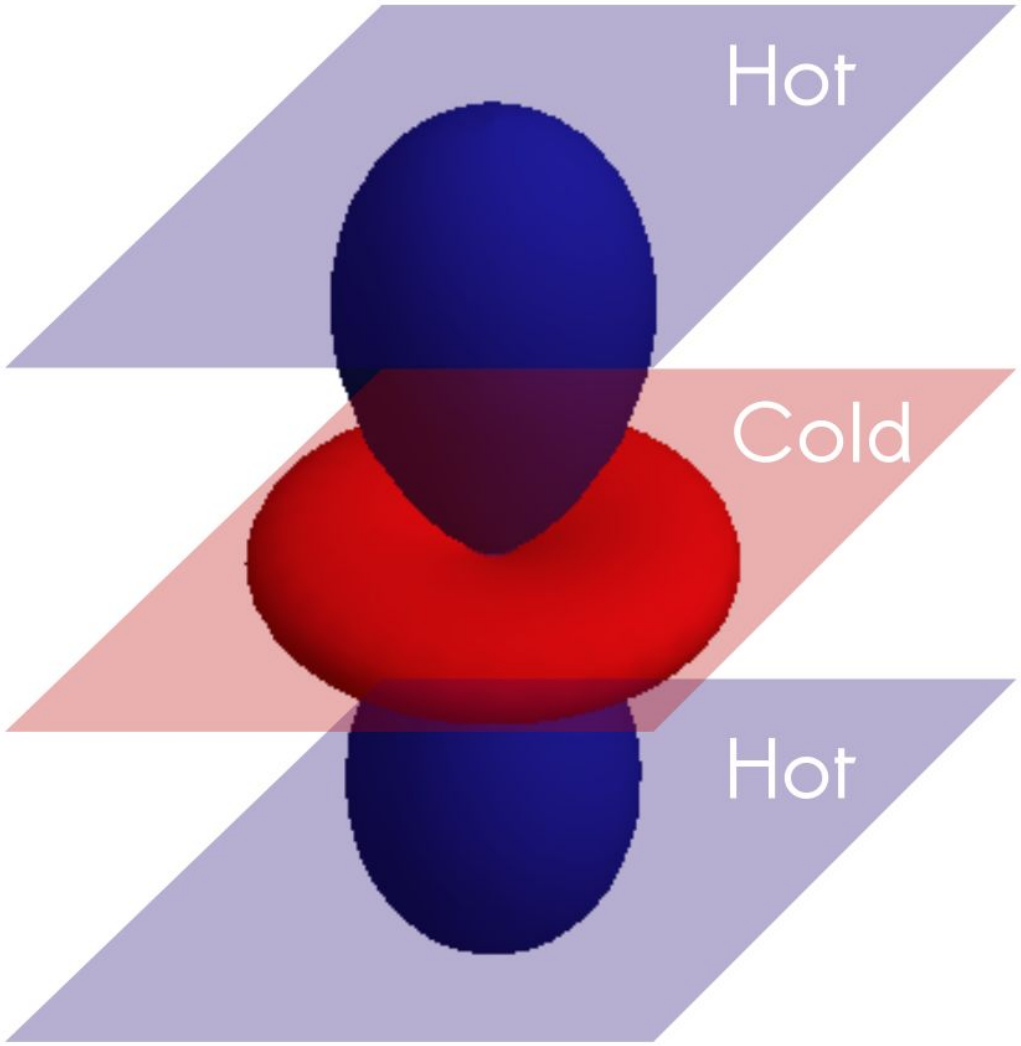
- Thomson scattering polarizes incident radiation

Quadrupolar anisotropy



- Thomson scattering polarizes incident radiation
- Quadrupolar anisotropy ⇔ partial polarization in CMB

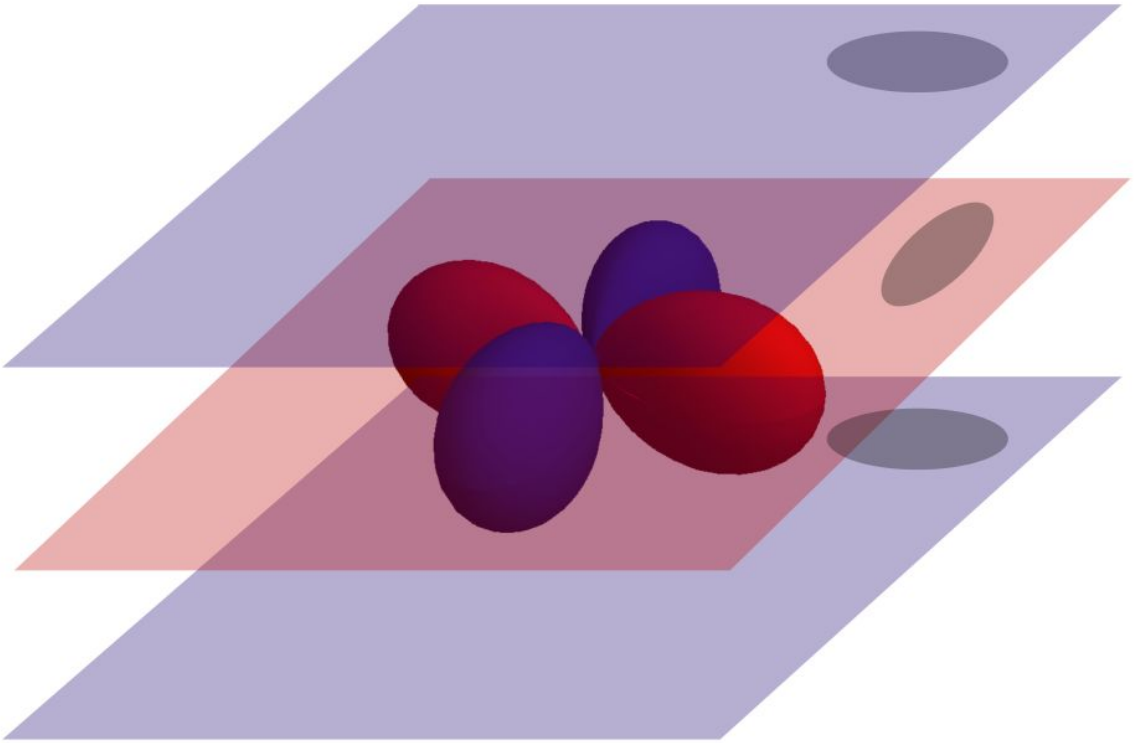
Scalar and tensor perturbations



Scalar perturbations

- Generated by variations in the plasma density
- Symmetric photon anisotropy

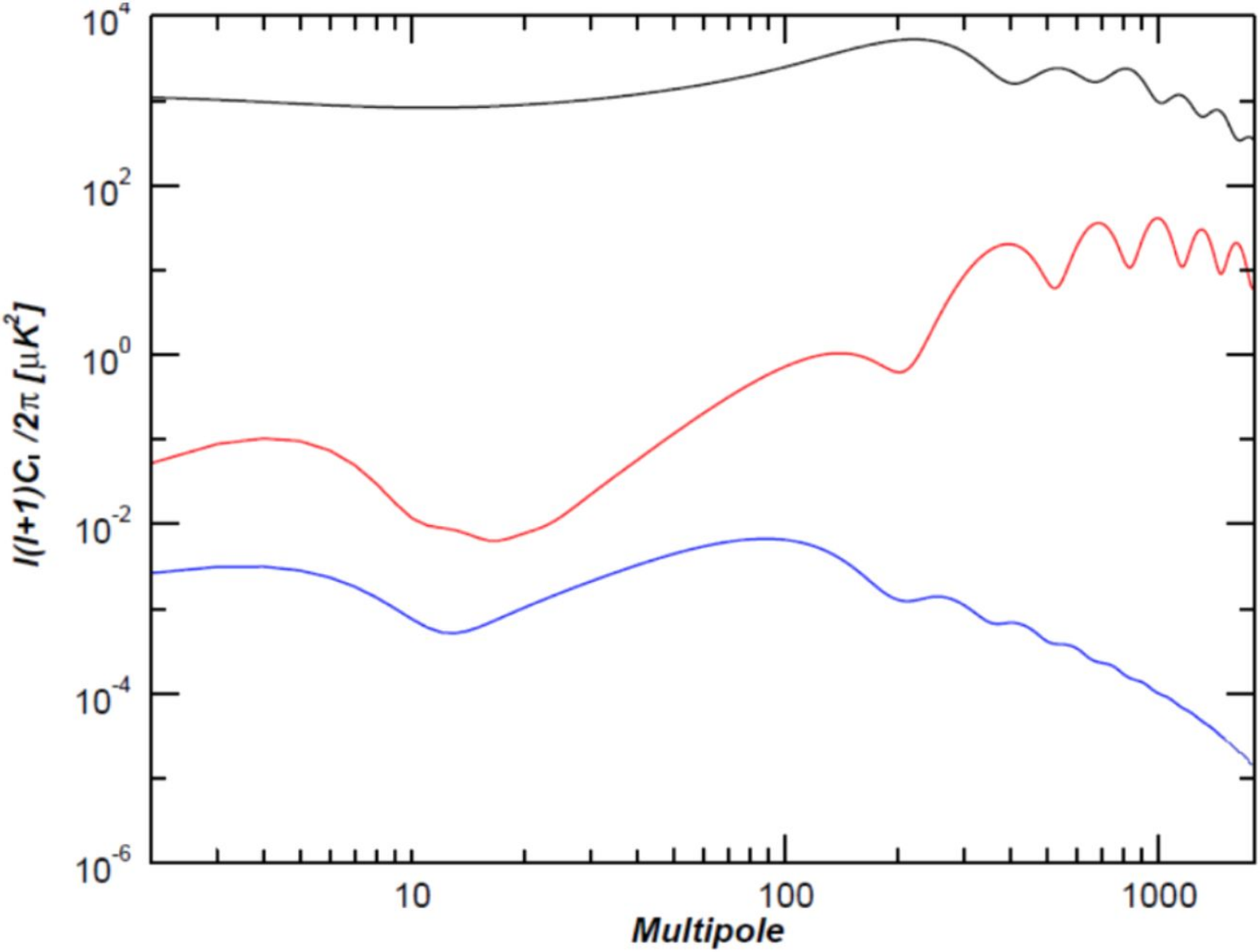
Scalar and tensor perturbations



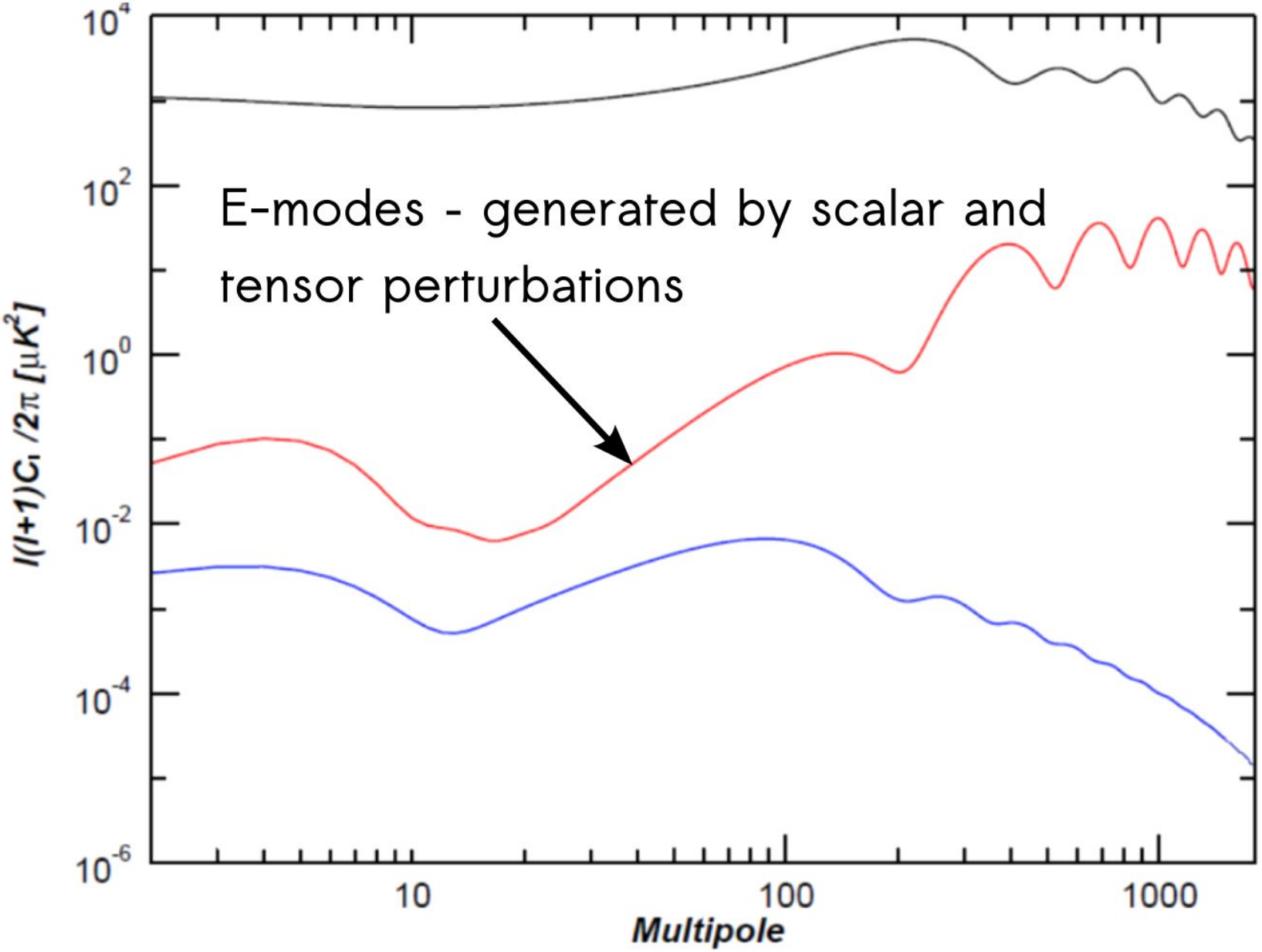
Tensor perturbations

- Generated by gravitational waves stretching space-time

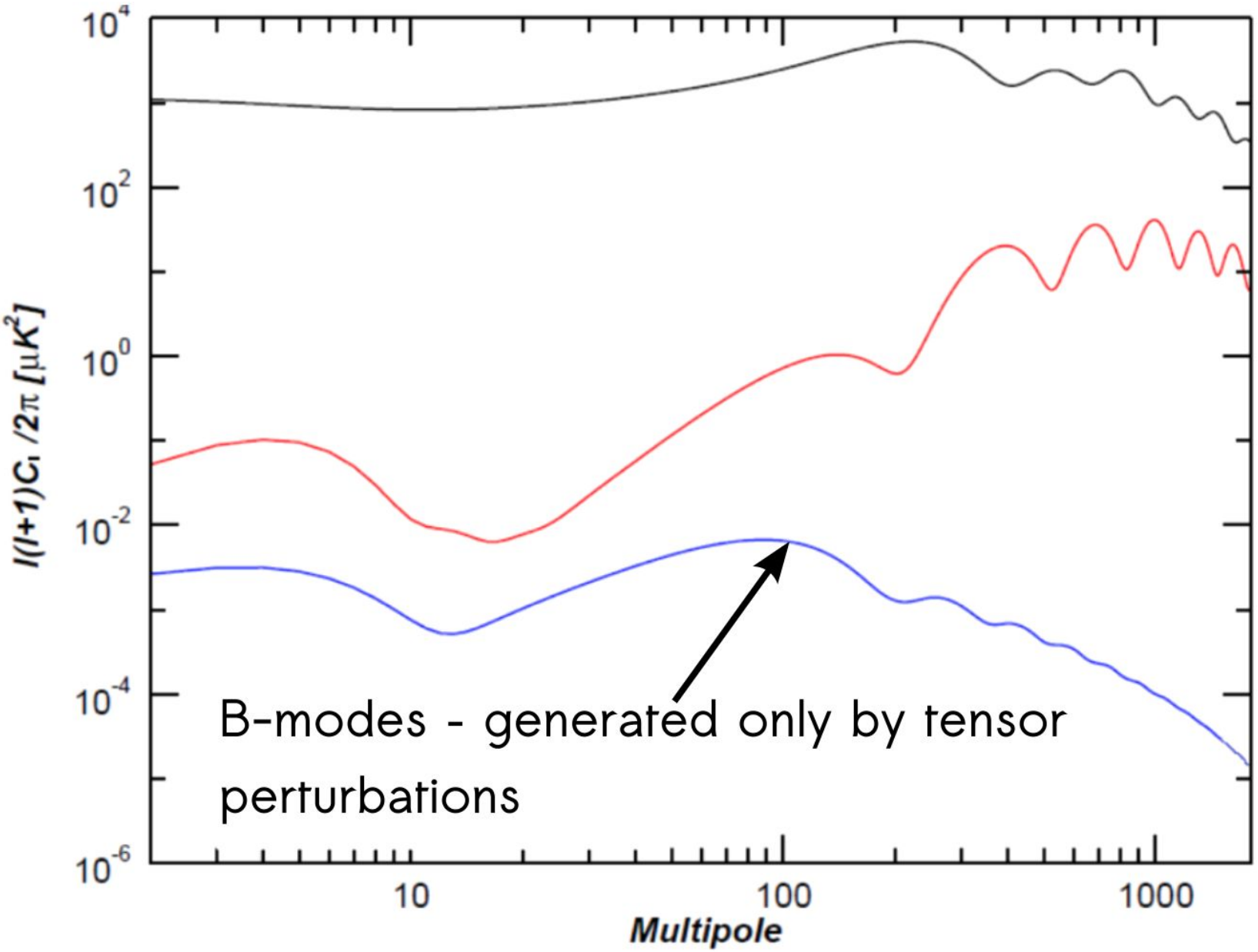
E and B modes power spectra

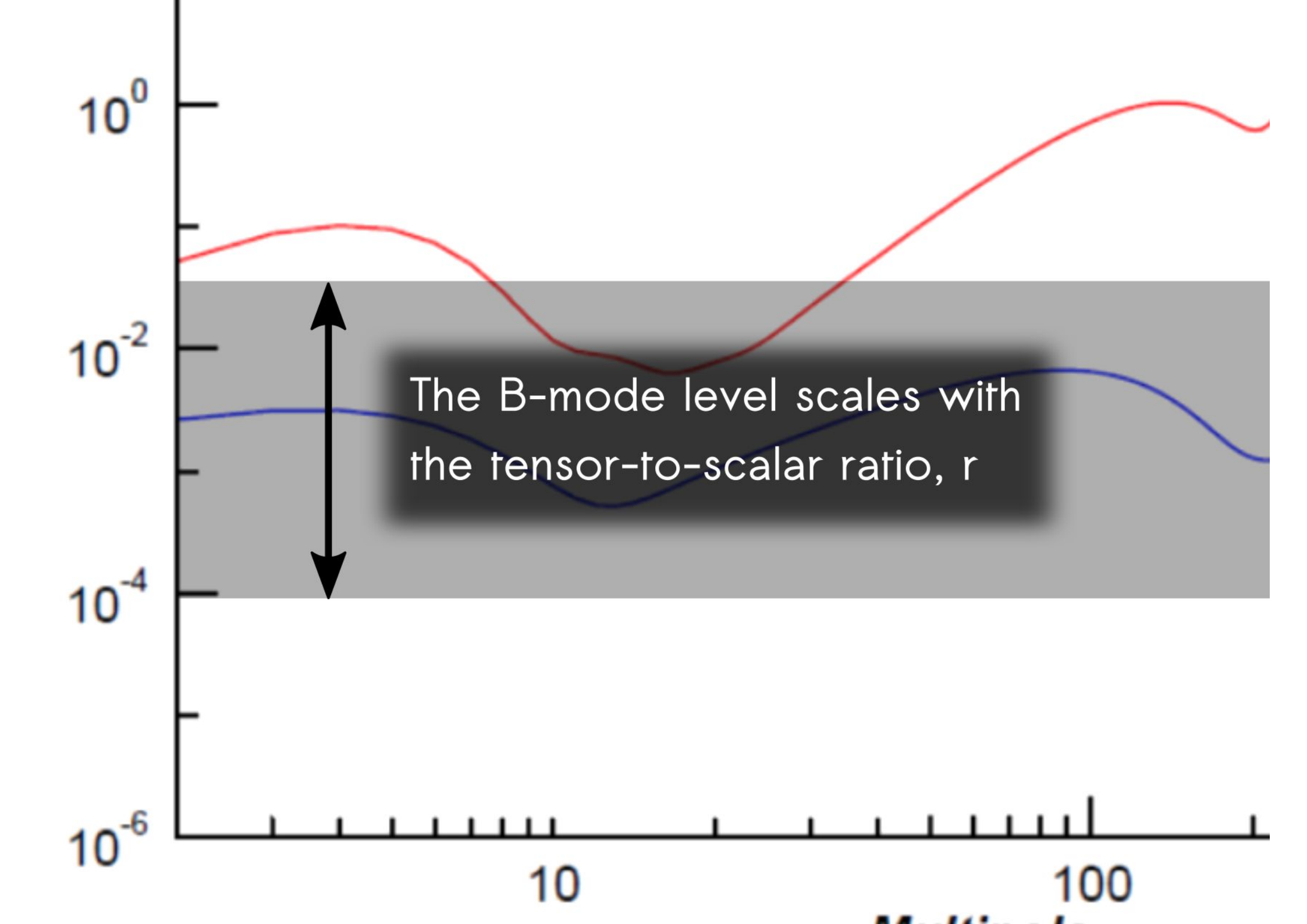


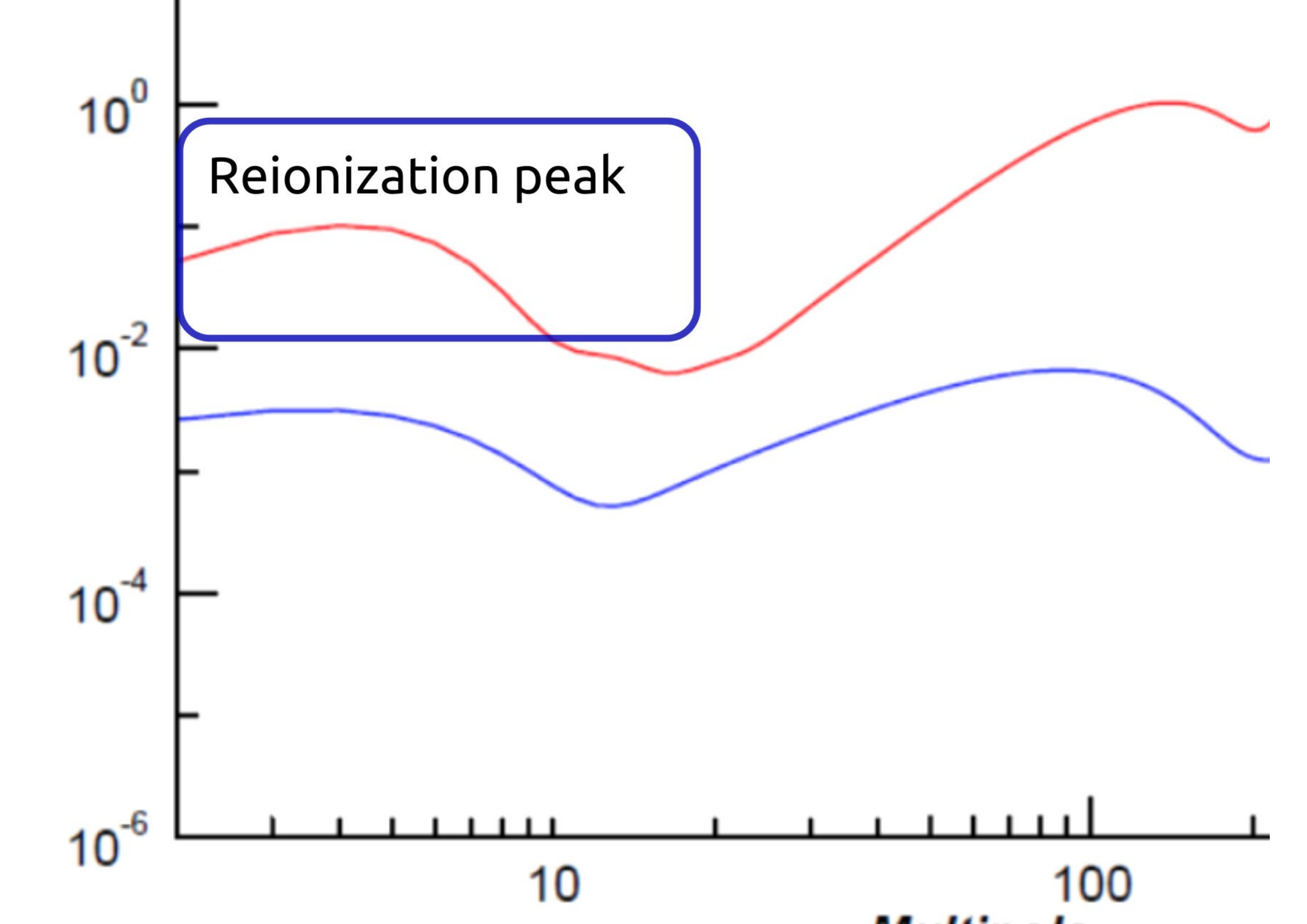
E and B modes power spectra



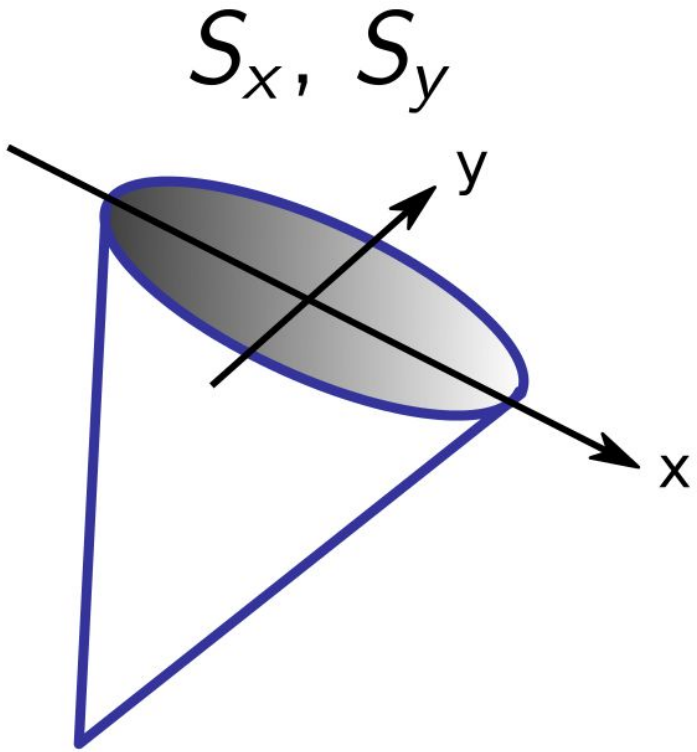
E and B modes power spectra



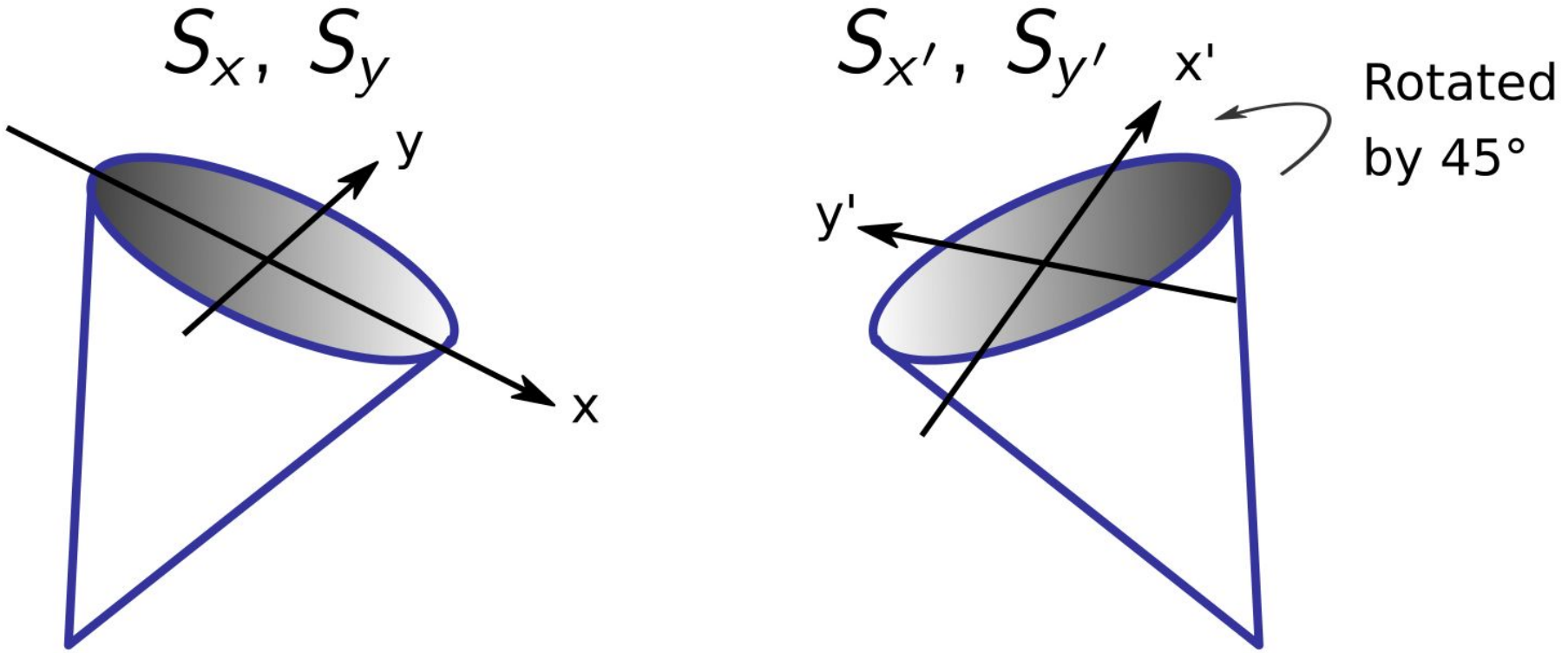

10^{0}
10^{-2}
10^{-4}
10^{-6}
10
100
The B-mode level scales with
the tensor-to-scalar ratio, r


Reionization peak
10^{0}
10^{-2}
10^{-4}
10^{-6}
10
100

How Planck measures polarization



How Planck measures polarization



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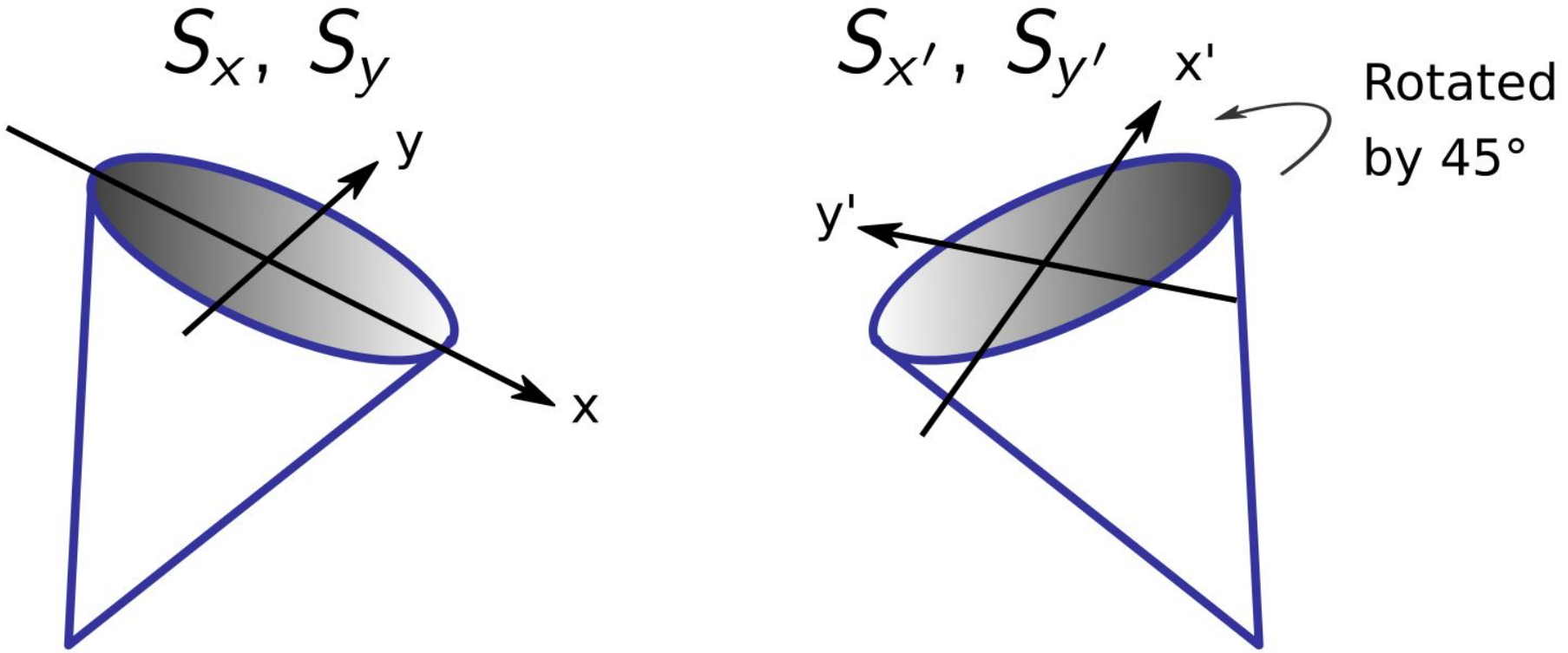


$$I = I' = S_x + S_y = S_{x'} + S_{y'}$$

$$U = Q' = S_{x'} - S_{y'}$$

$$U' = -Q = S_y - S_x$$

Systematic effects

Optical	*Beam ellipticity / cross polarization* *Sidelobes (Earth, Sky pickup)*
Polarization	*I → Q/U leakage* *Q → U leakage*
Noise and stability	*1/f noise* *Thermal stability* *Cosmic ray hits* *Time constants*
Pointing	*Pointing uncertainties*
Electronics	*ADC non linearities* *DC spurious signals*

Systematic effects - HFI

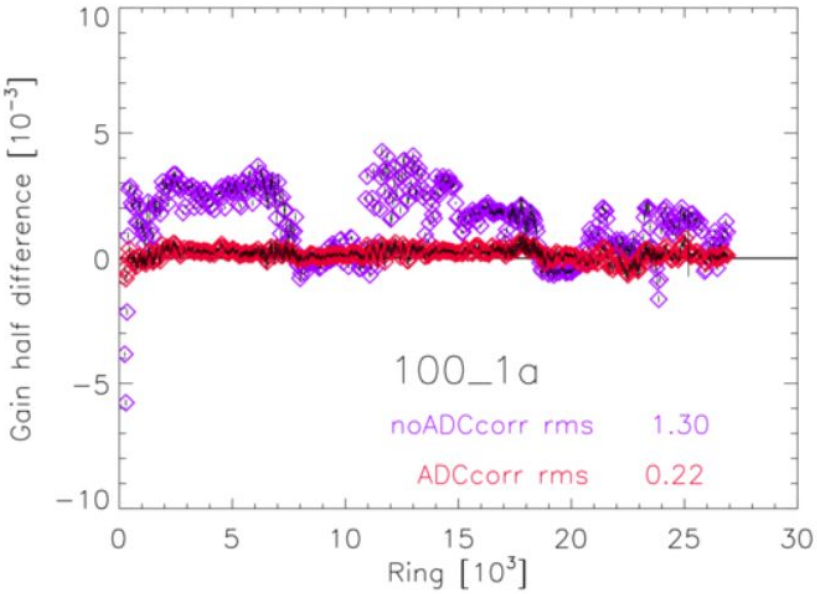
HFI known effects corrected in data processing

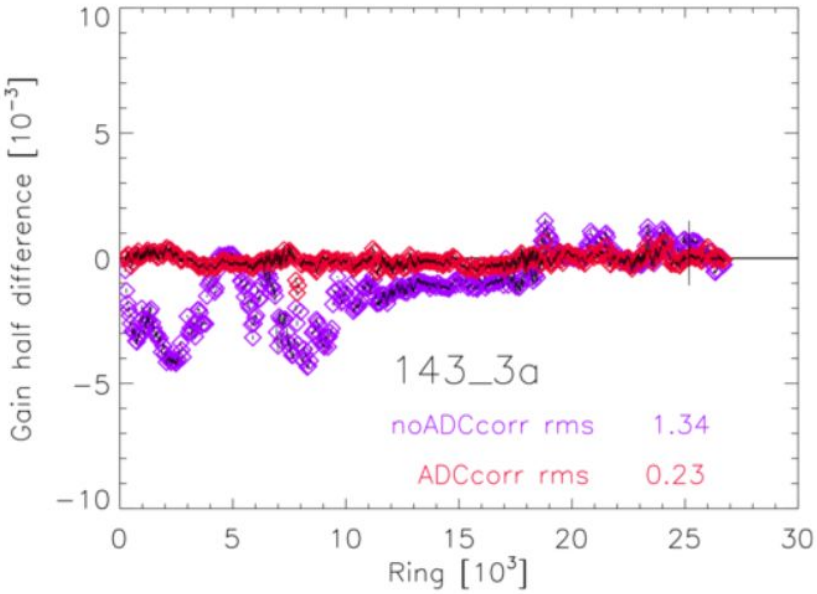
Systematic effects - HFI

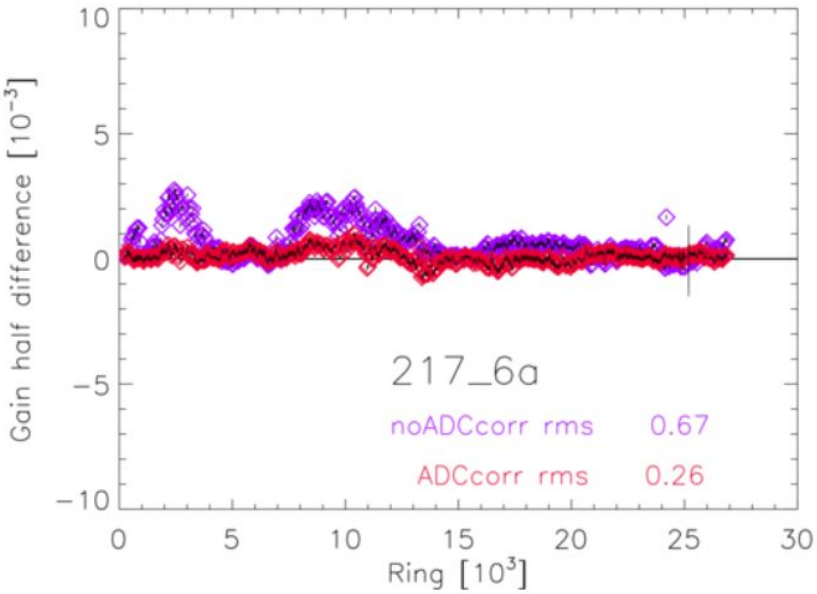
HFI known effects corrected in data processing

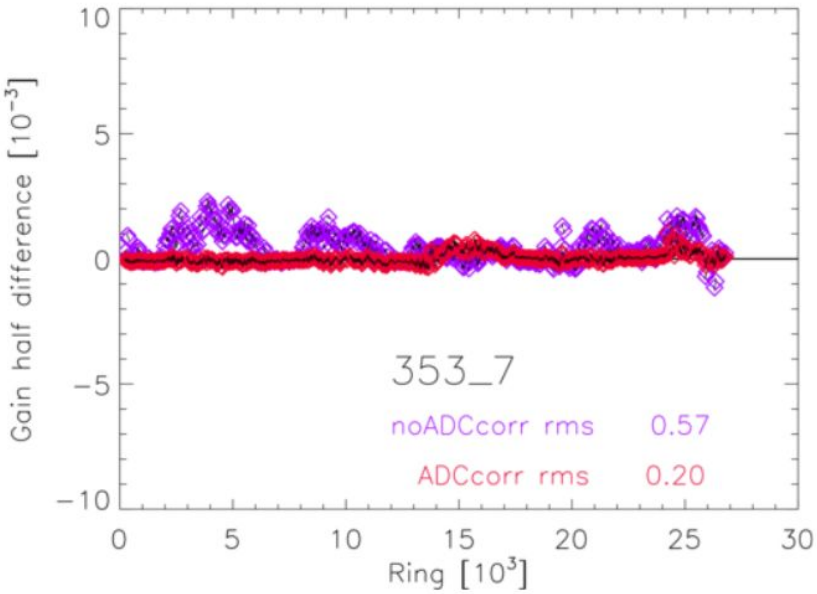
- ADC non linearity
- 4 K cooler electronics
- Cosmic ray glitches (removal improved by the better understanding of the long time constants)
- Near and far sidelobes

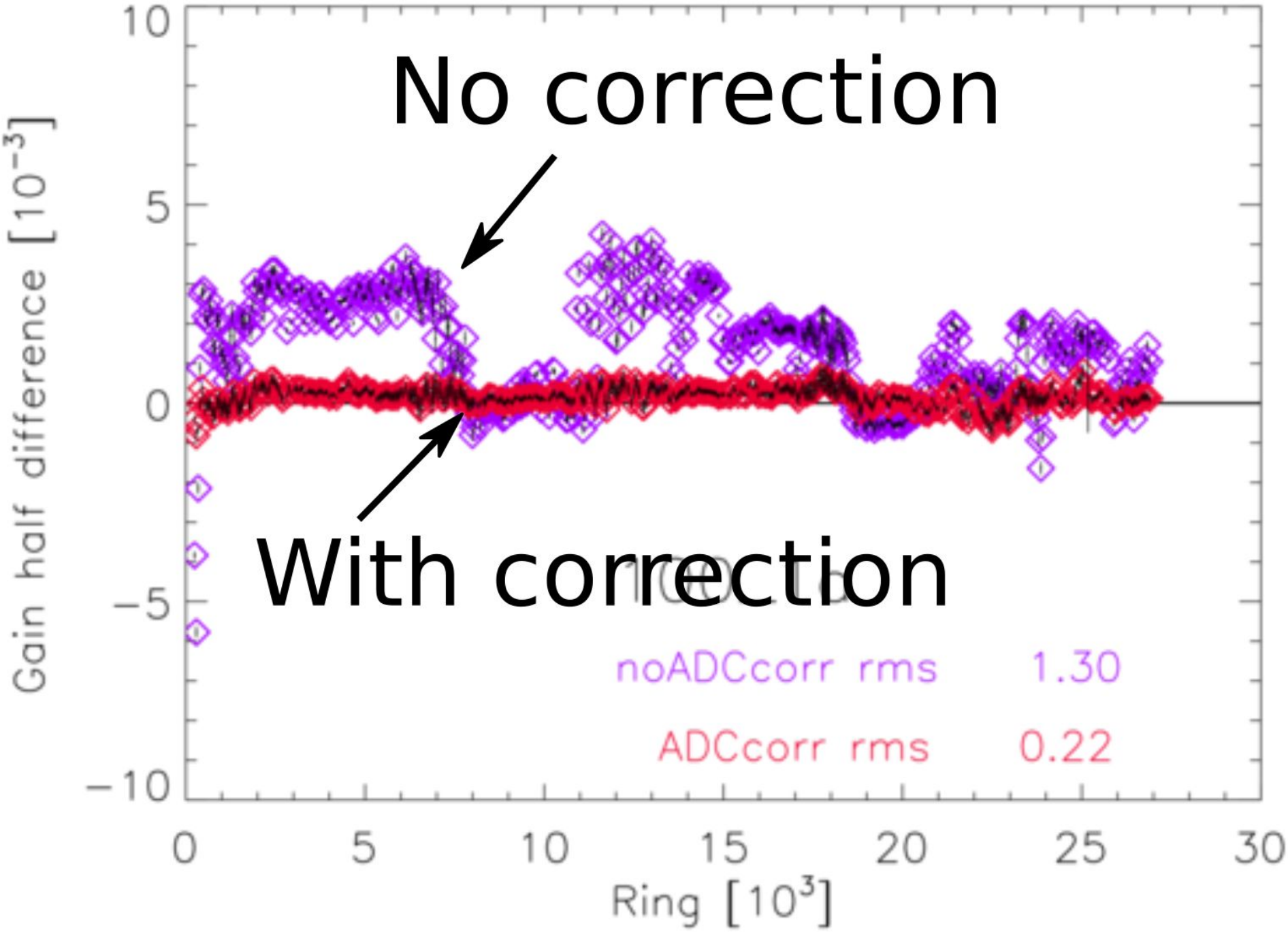
ADC correction

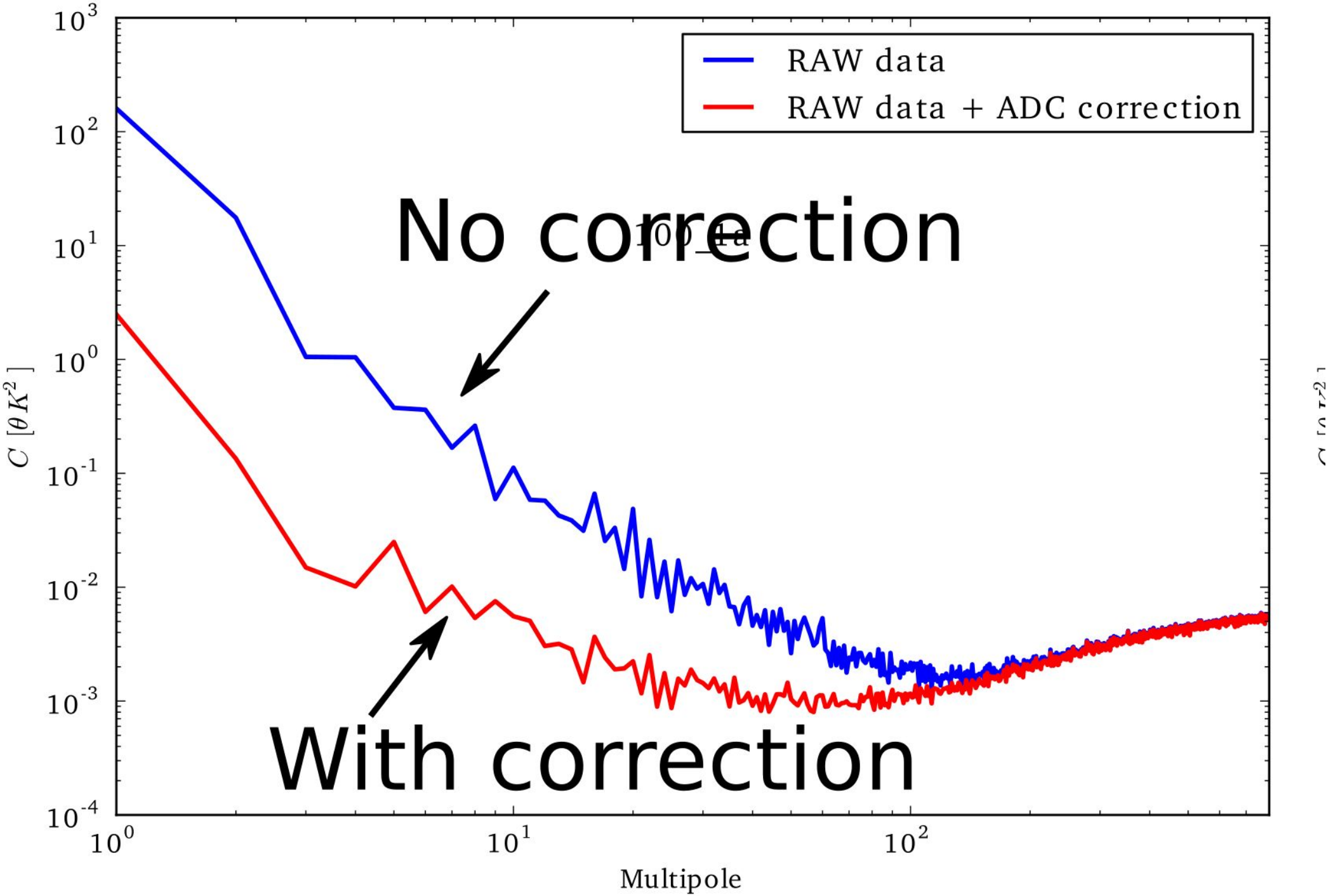




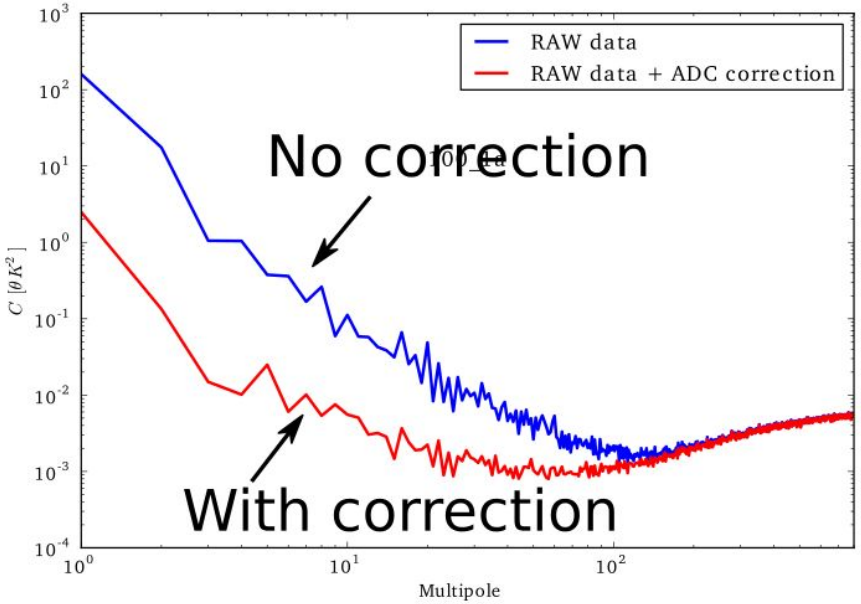


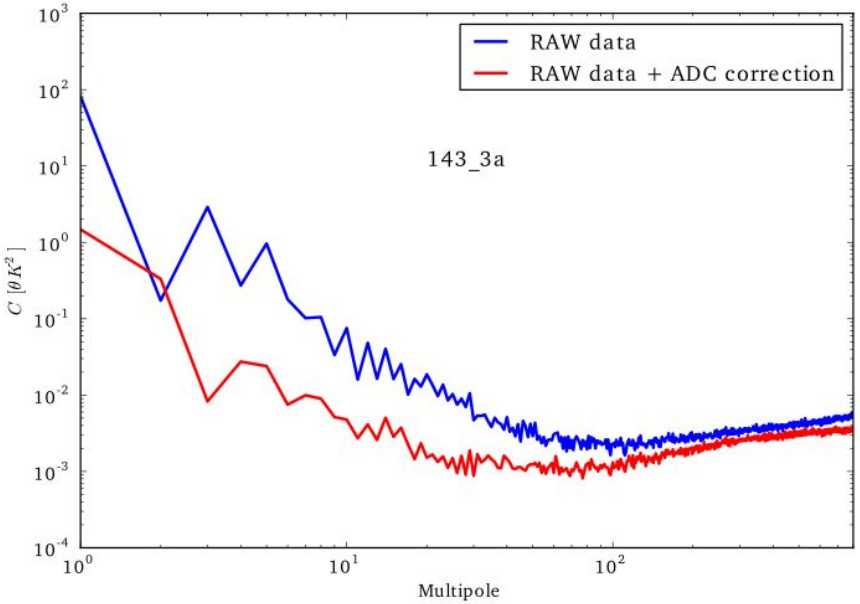


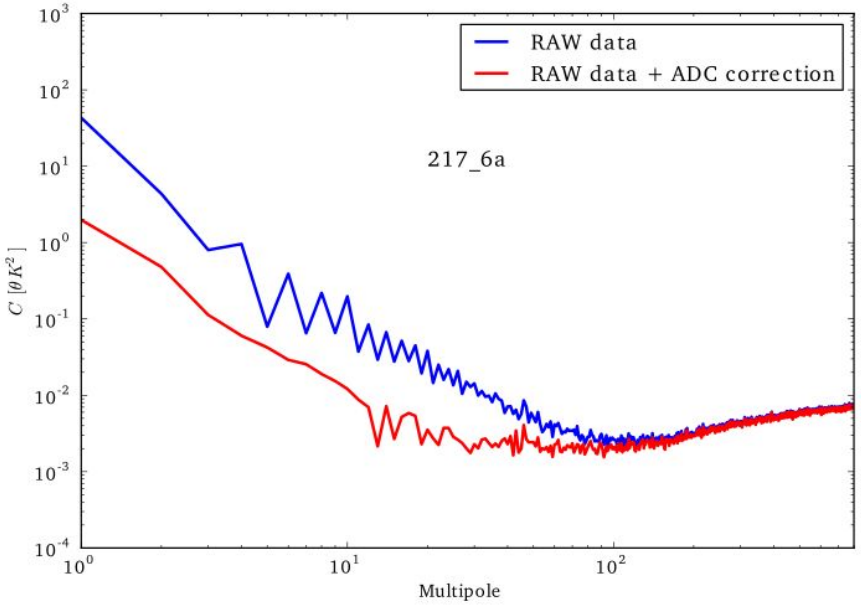

No correction
With correction
noADCcorr rms 1.30
ADCcorr rms 0.22
Gain half difference [10⁻³]
Ring [10³]
10
5
0
−5
−10
0
5
10
15
20
25
30

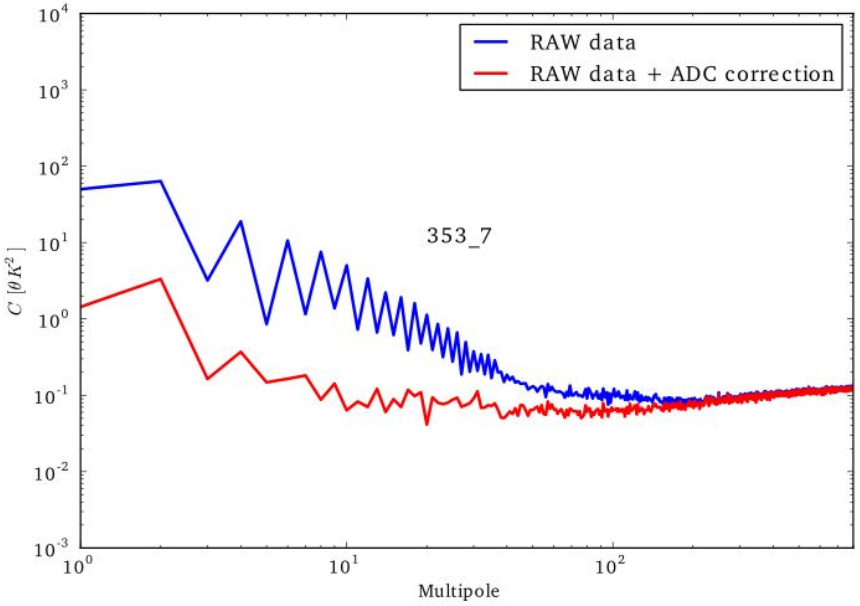

RAW data
RAW data + ADC correction
No correction
With correction
$C\ [\theta K^2]$
Multipole
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^0
10^1
10^2

ADC correction



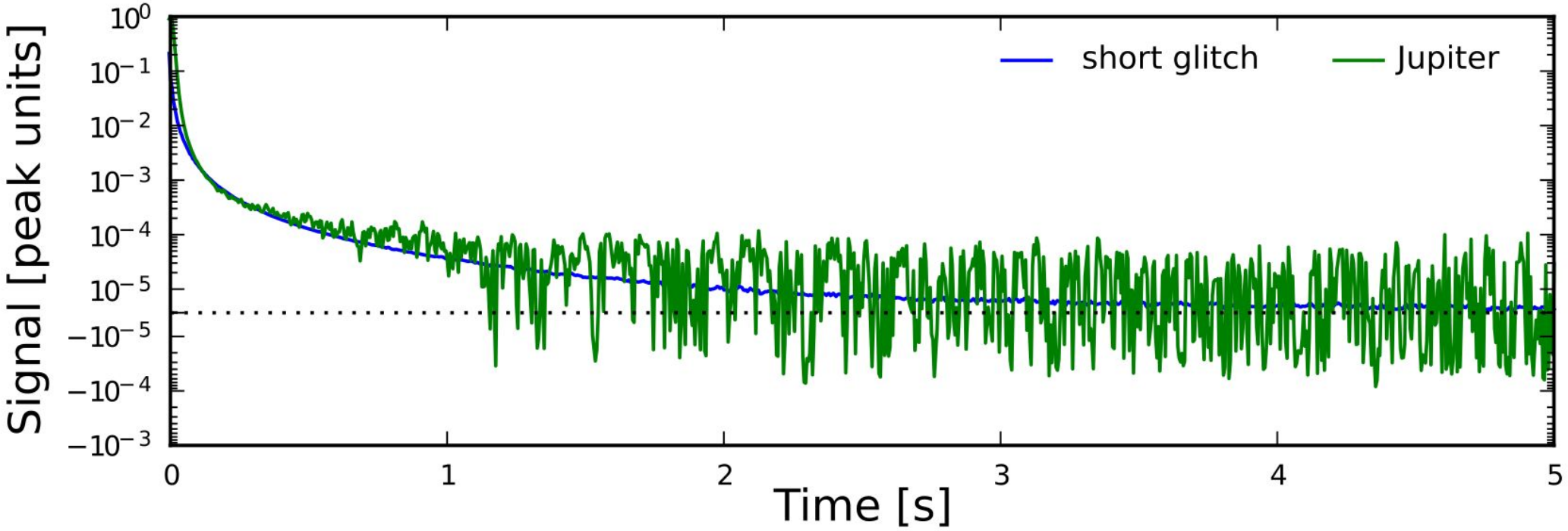






Time constants

- Short glitches effective to characterize bolometer time constants to a level better than 10^{-4}
- Glitch removal improved from much better knowledge of bolometer time constants



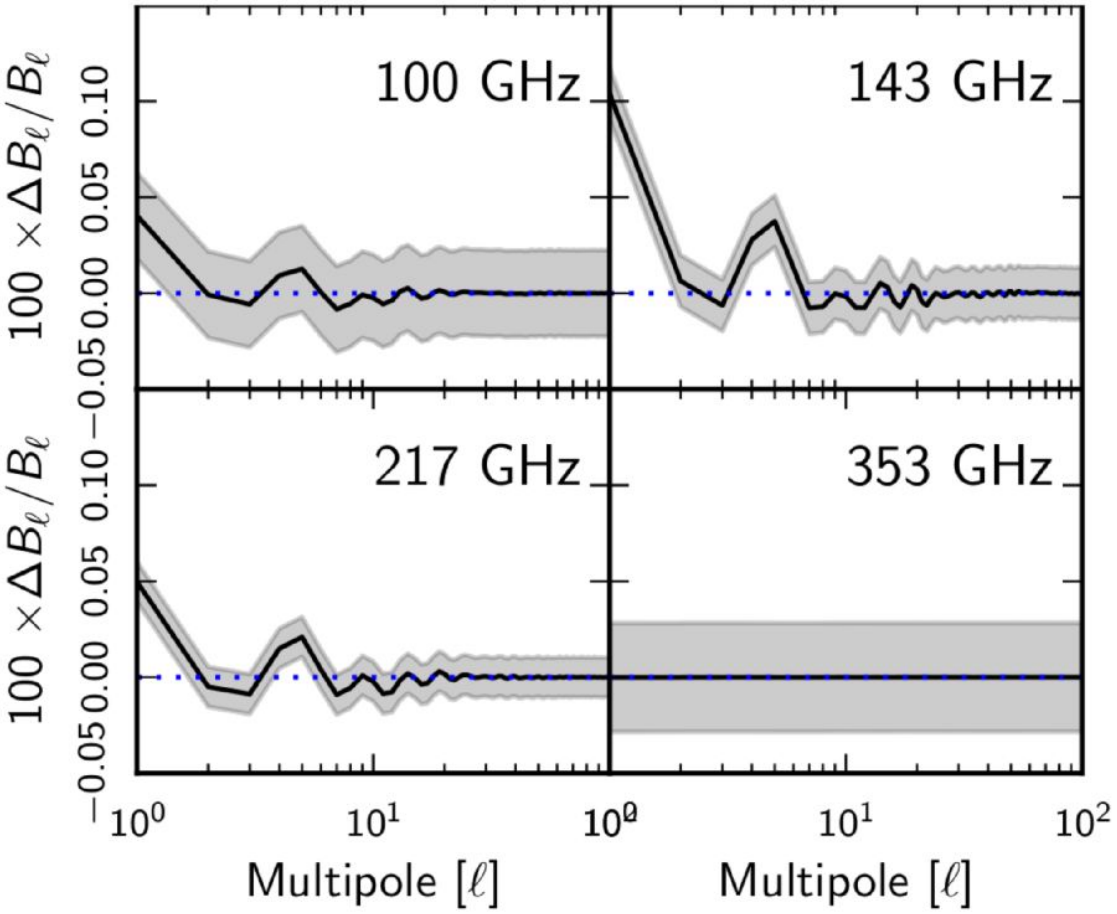
Beams

- Main beam reconstruction extended from 40' to 100' to account for fraction of near sidelobes

Beams

- Main beam reconstruction extended from 40' to 100' to account for fraction of near sidelobes
- Far sidelobes simulated with GRASP and estimated effect on window function

window function

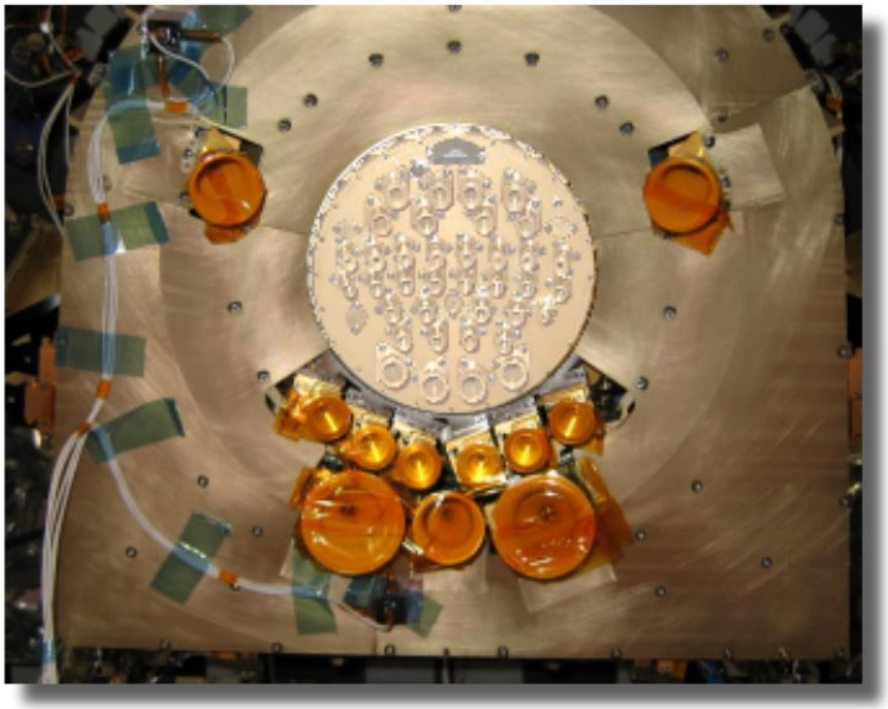


The uncetainties are larger than the correction except at large angular scales.

Far sidelobes considered only in calibration at large scales

Systematic effects - LFI

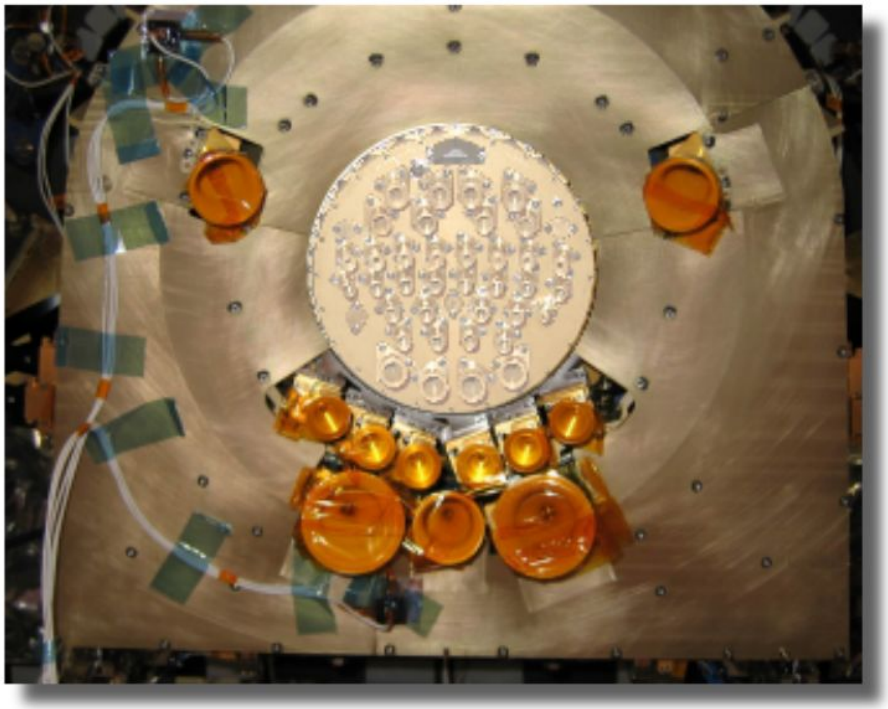
LFI known effects



Effect	Source	Control/Removal
	Effects independent of sky signal (T and P)	
White noise correlation	Phase switch imbalance	Diode weighting
$1/f$ noise	RF amplifiers	Pseudo-correlation and destriping
Bias fluctuations	RF amplifiers, back-end electronics	Pseudo-correlation and destriping
Thermal fluctuations	4 K, 20 K and 300 K thermal stages	Calibration, destriping
1 Hz spikes	Back-end electronics	Template fitting and removal
	Effects dependent on the sky signal (T and P)	
Main beam ellipticity	Main beams	Accounted for in window function
Near sidelobes pickup	Optical response at angles $< 5°$ from the main beam	Masking of Galaxy and point sources
Far sidelobes pickup	Main and sub-reflector spillovers	Model sidelobes removed from timelines
Analogue-to-digital converter non linearity	Back-end analogue-to-digital converter	Template fitting and removal
Imperfect photometric calibration	Sidelobe pickup, radiometer noise temperature changes and other non-idealities	Calibration using the 4 K reference load voltage output
Pointing	Uncertainties in pointing reconstruction, thermal changes affecting focal plane geometry	Negligible impact anisotropy measurements
	Effects specifically impacting polarization	
Bandpass asymmetries	Differential orthomode transducer and receiver bandpass response	Spurious polarisation removal
Polarization angle uncertainty	Uncertainty in the polarization angle in-flight measurement	Negligible impact
Orthomode transducer cross-polarization	Imperfect polarization separation	Negligible impact

Systematic effects - LFI

LFI known effects



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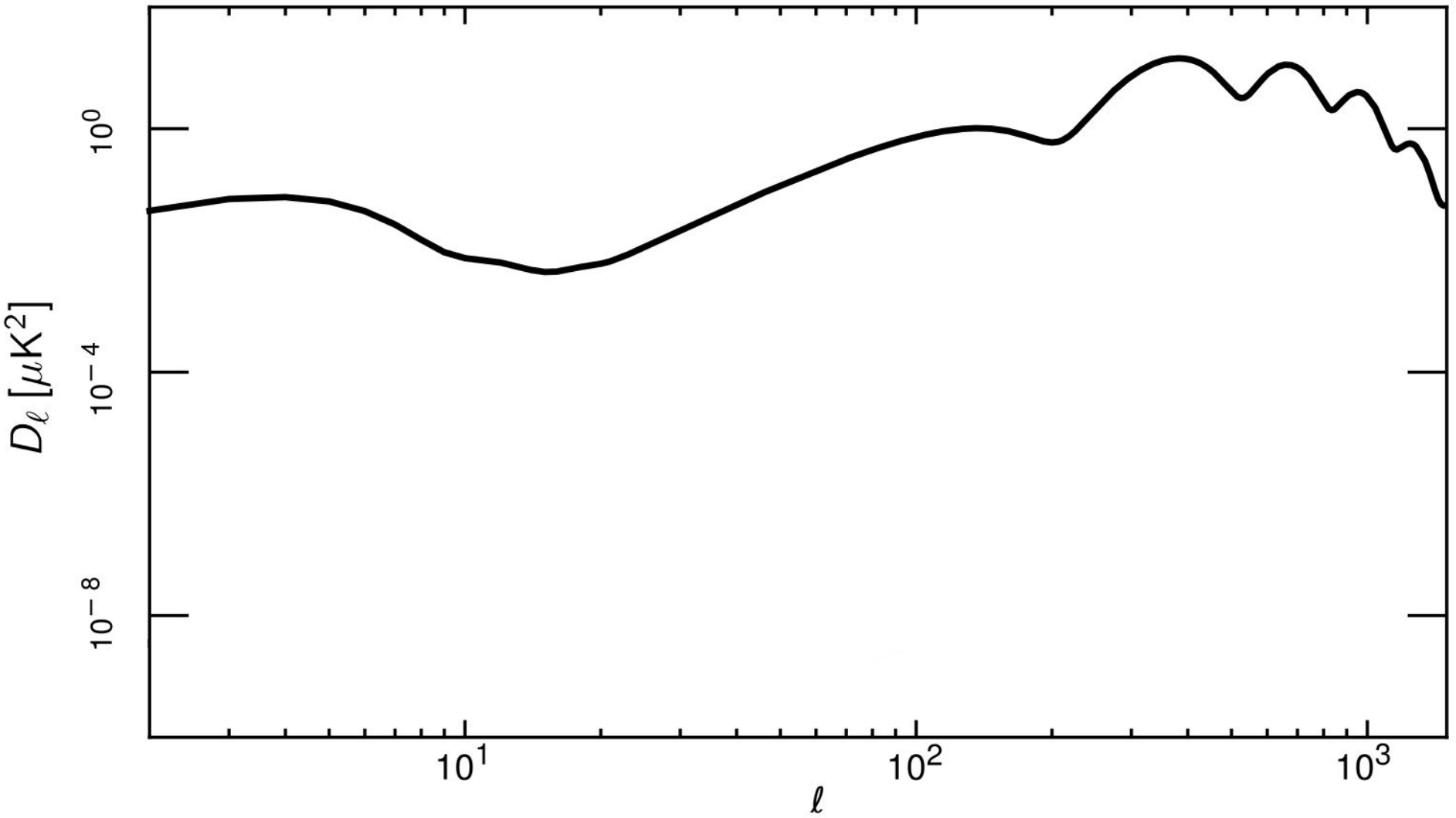
Results not public yet

Systematic effects - LFI

Planck 70 GHz systematic effects



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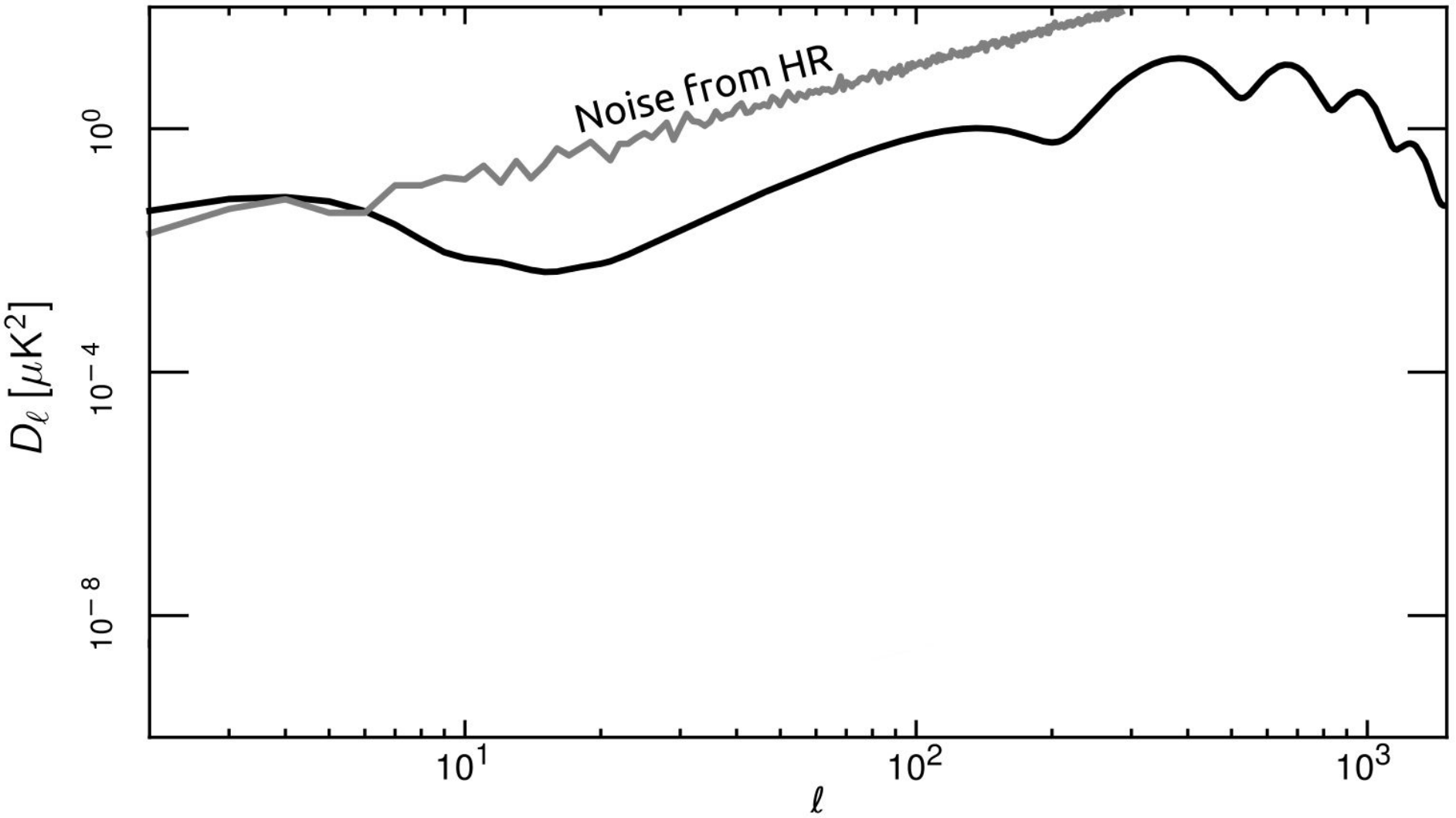

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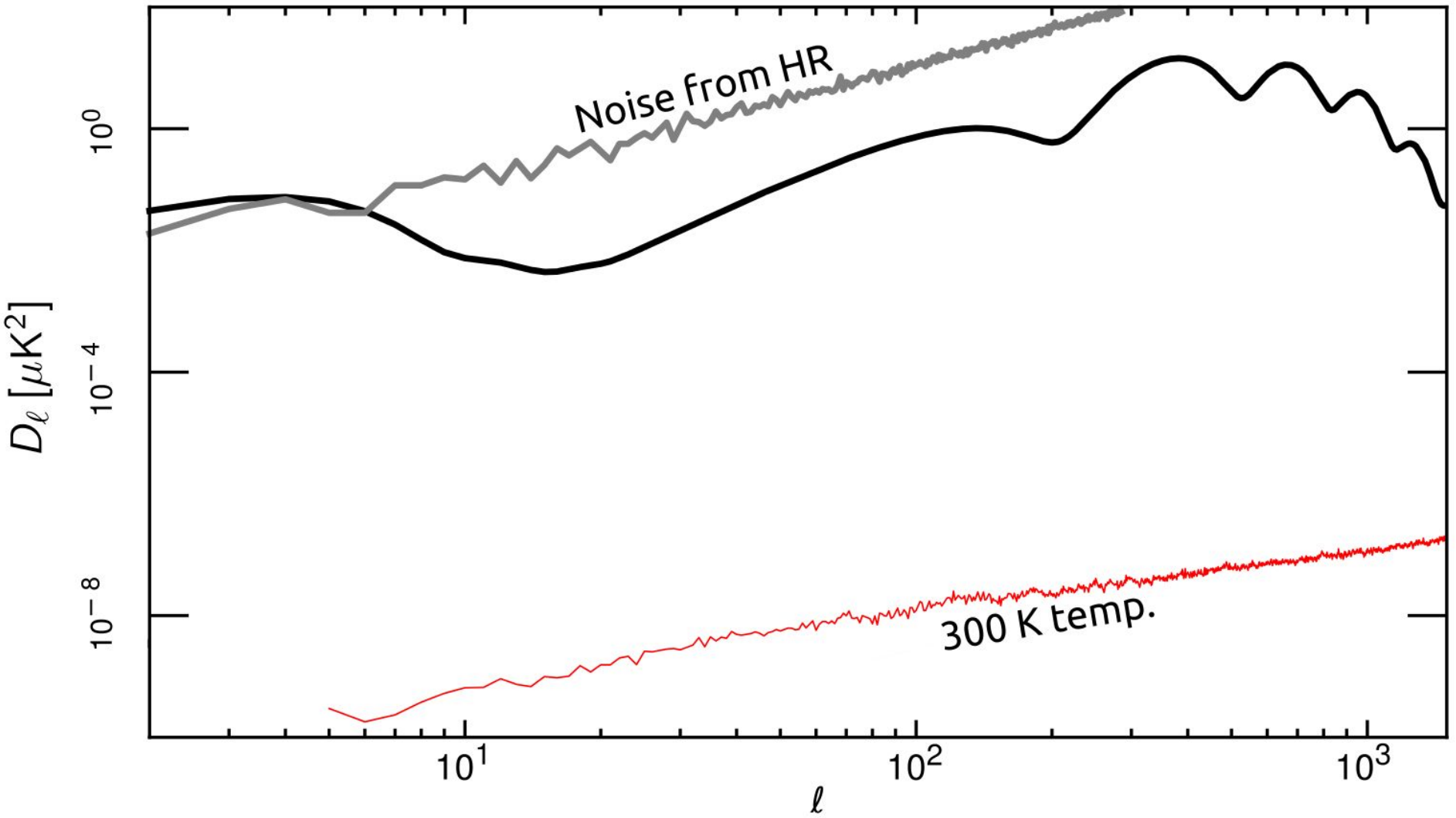

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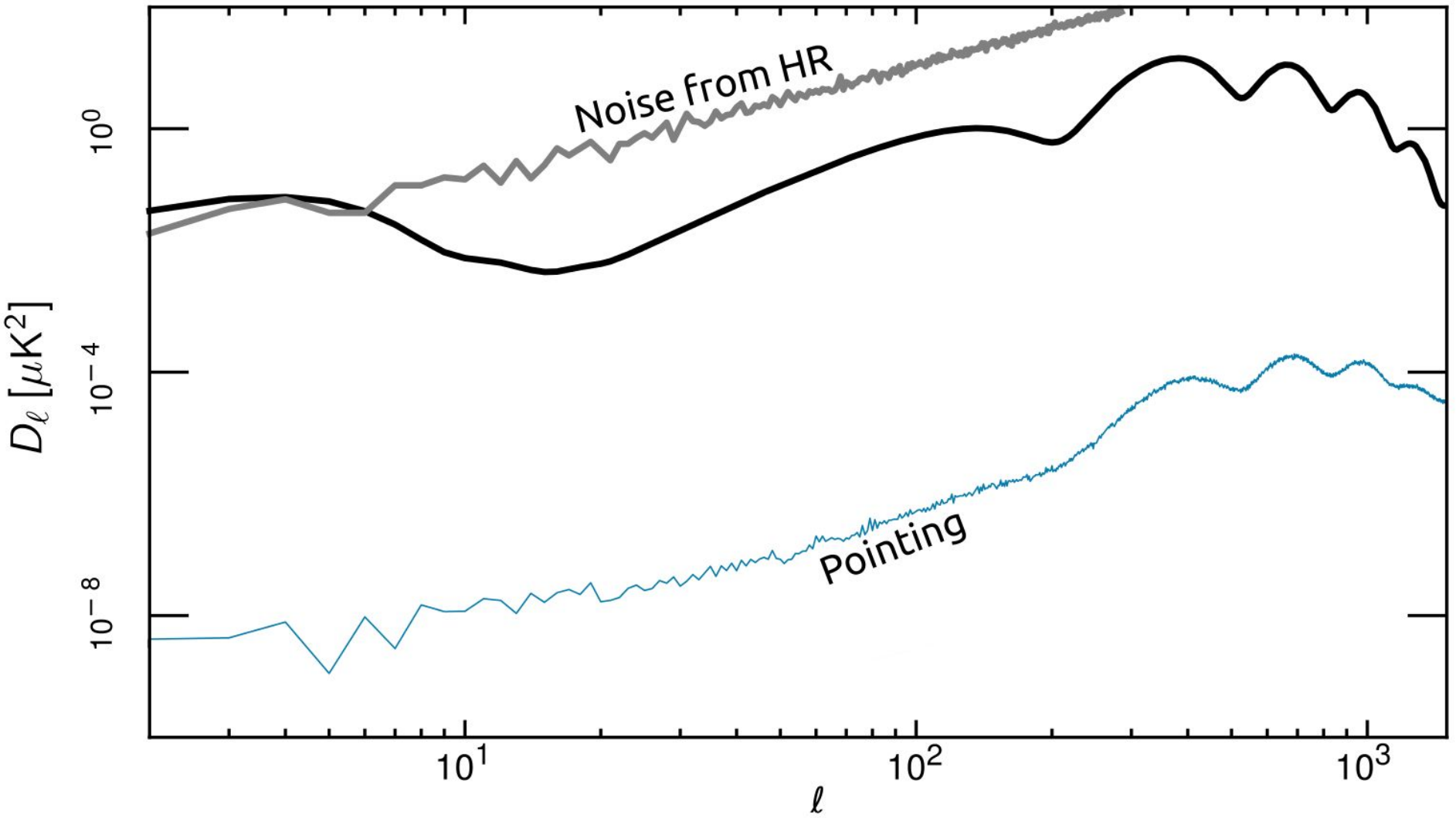
Planck 70 GHz systematic effects



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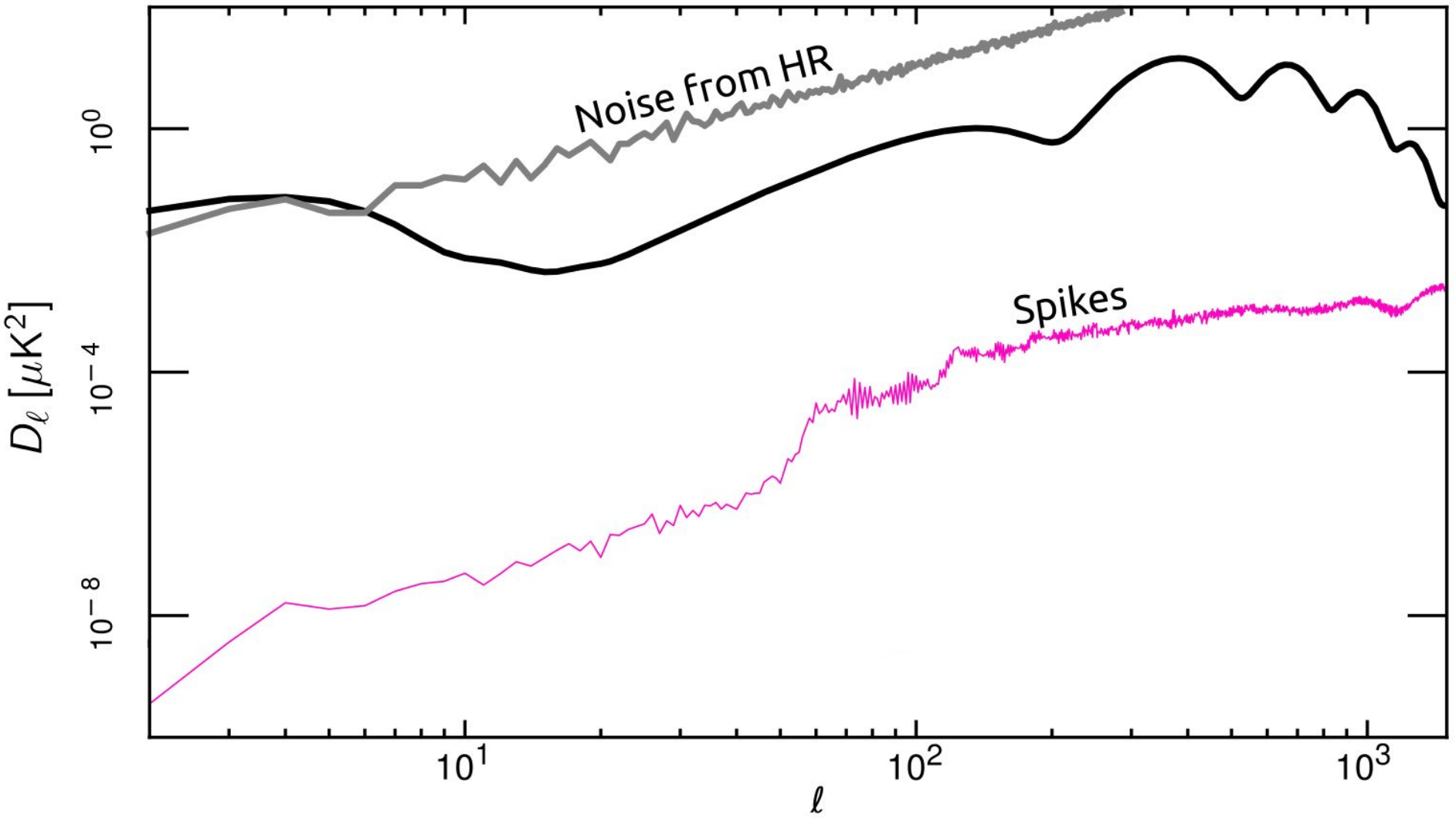

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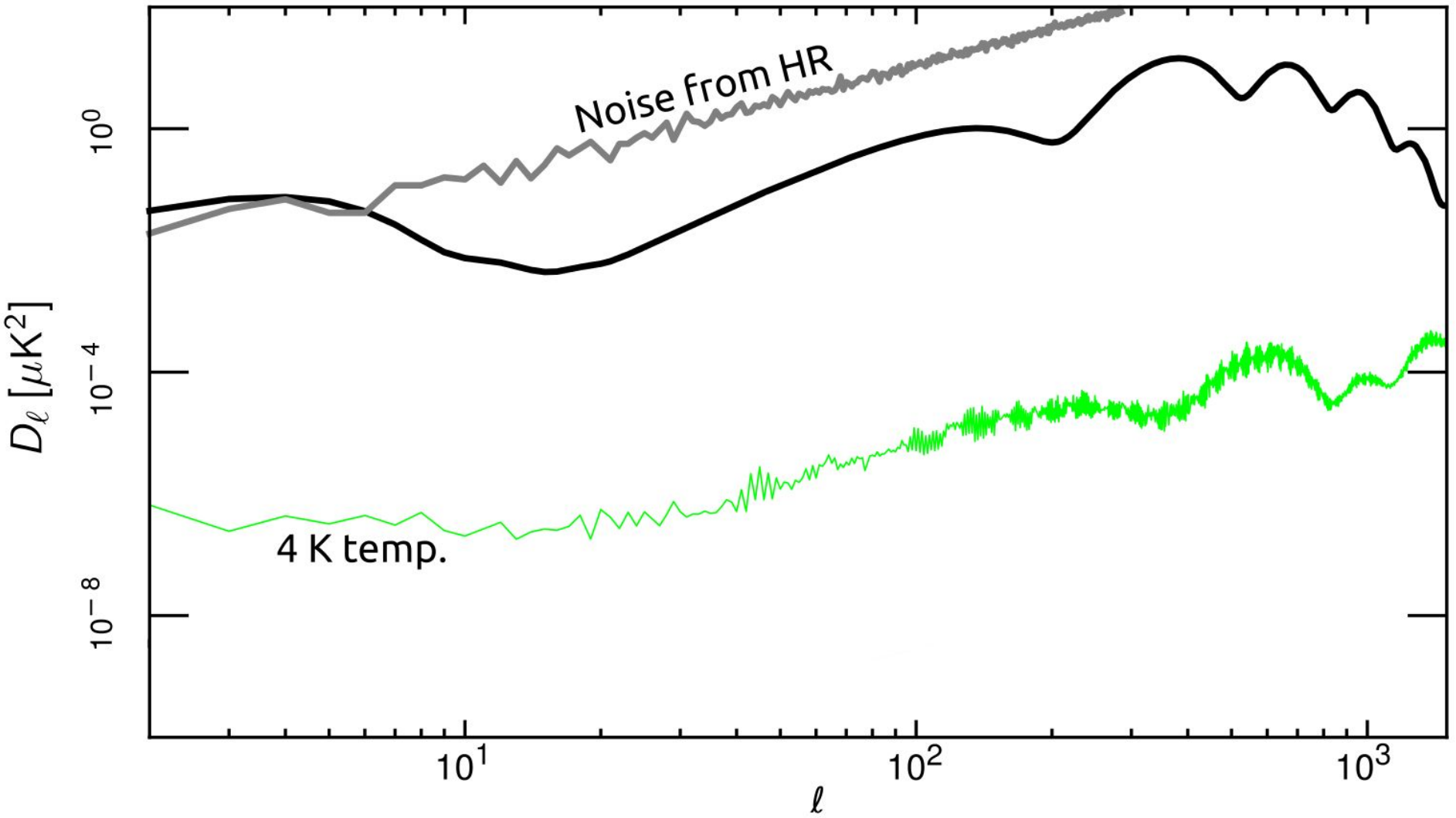

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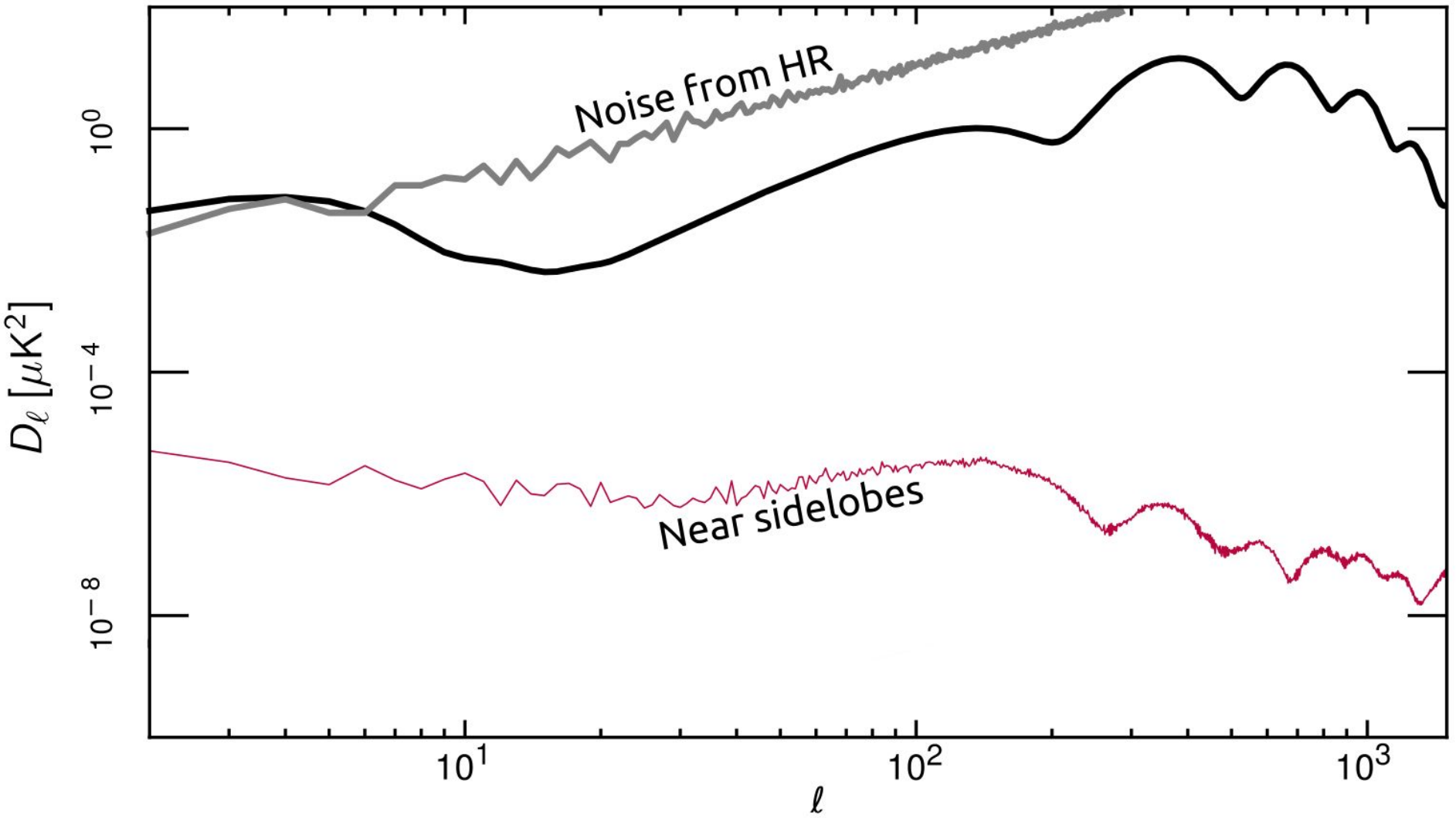
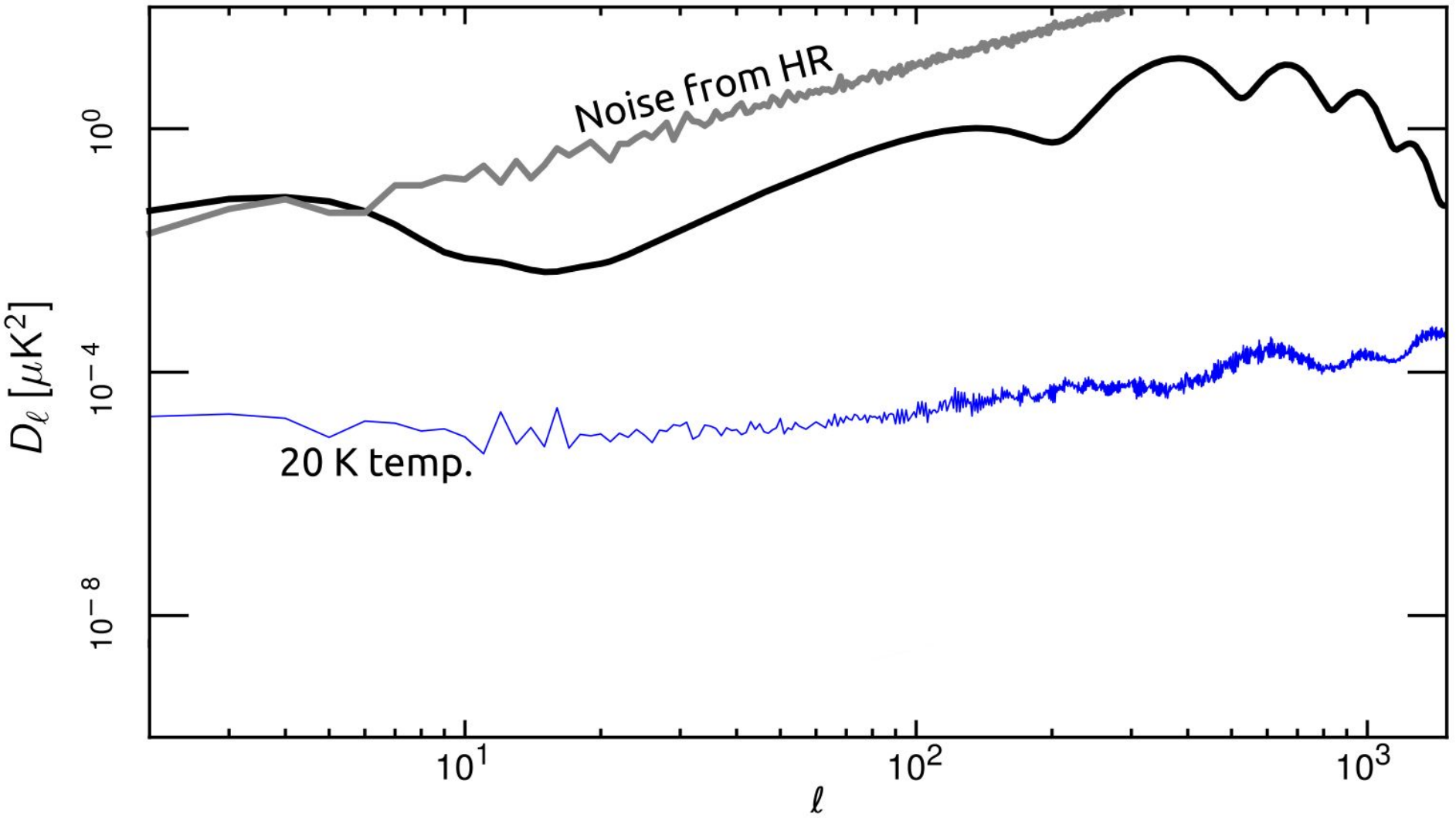


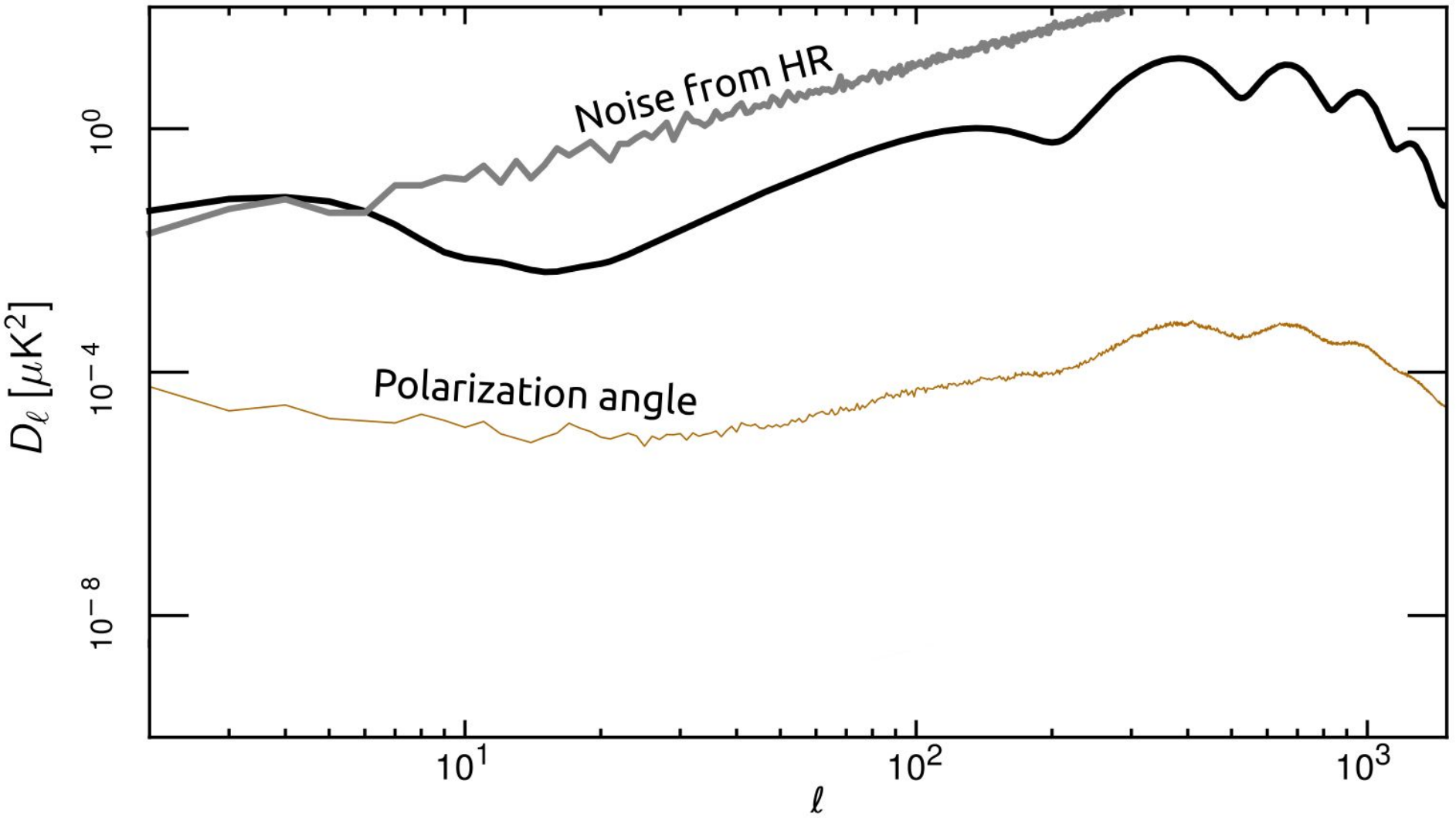
Systematic effects - LFI

Planck 70 GHz systematic effects



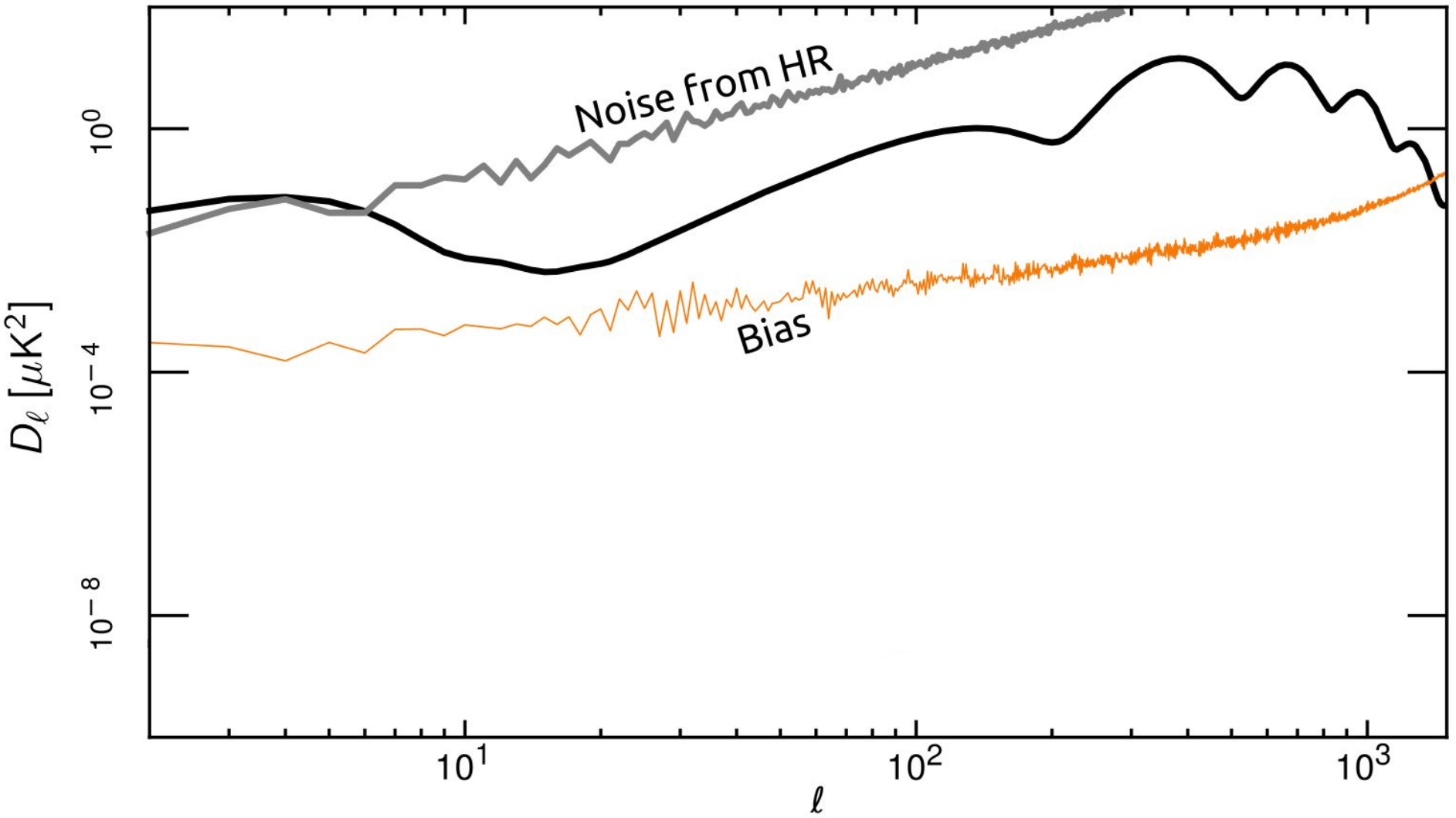
Systematic effects - LFI

Planck 70 GHz systematic effects



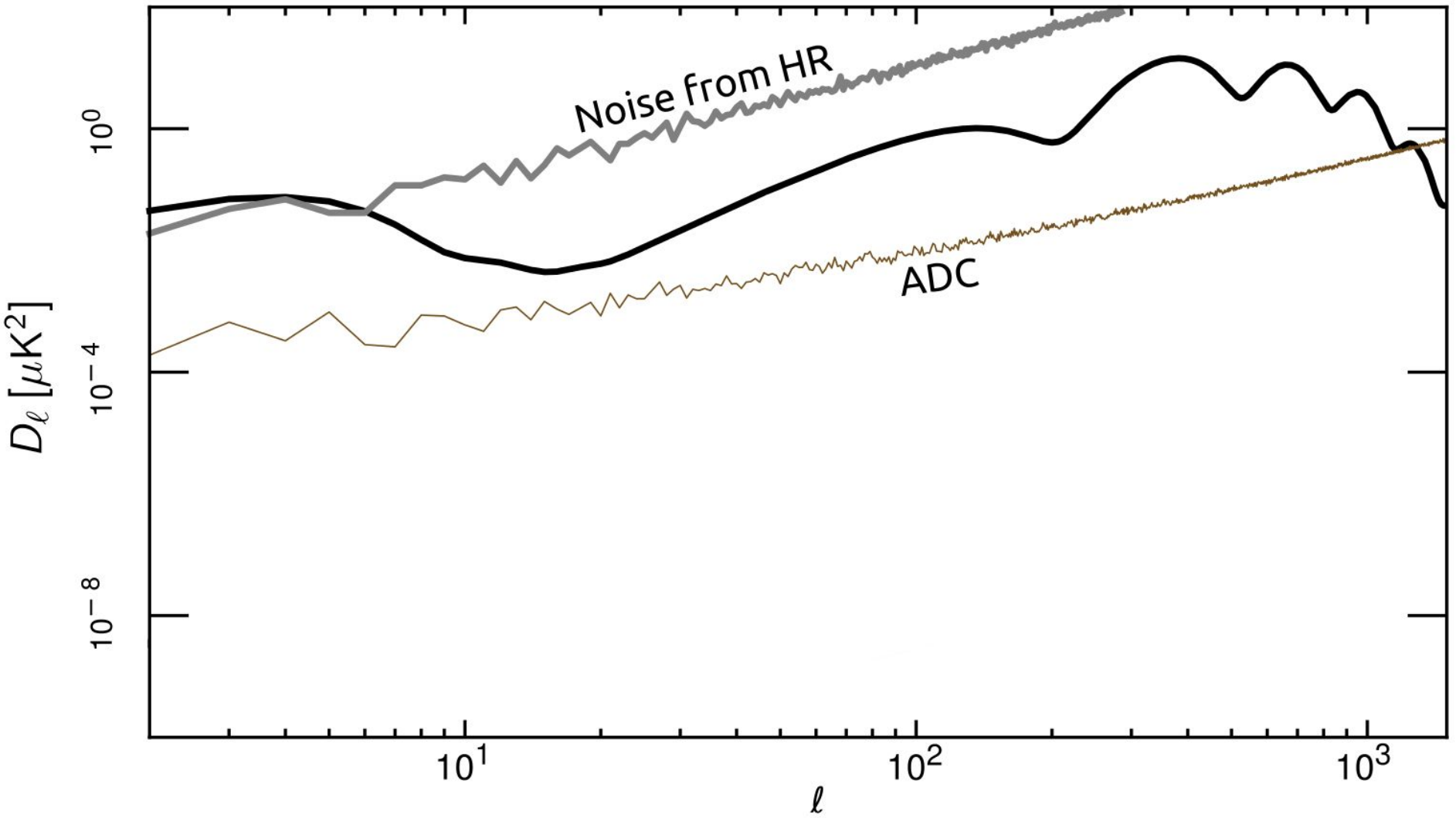
Systematic effects - LFI

Planck 70 GHz systematic effects



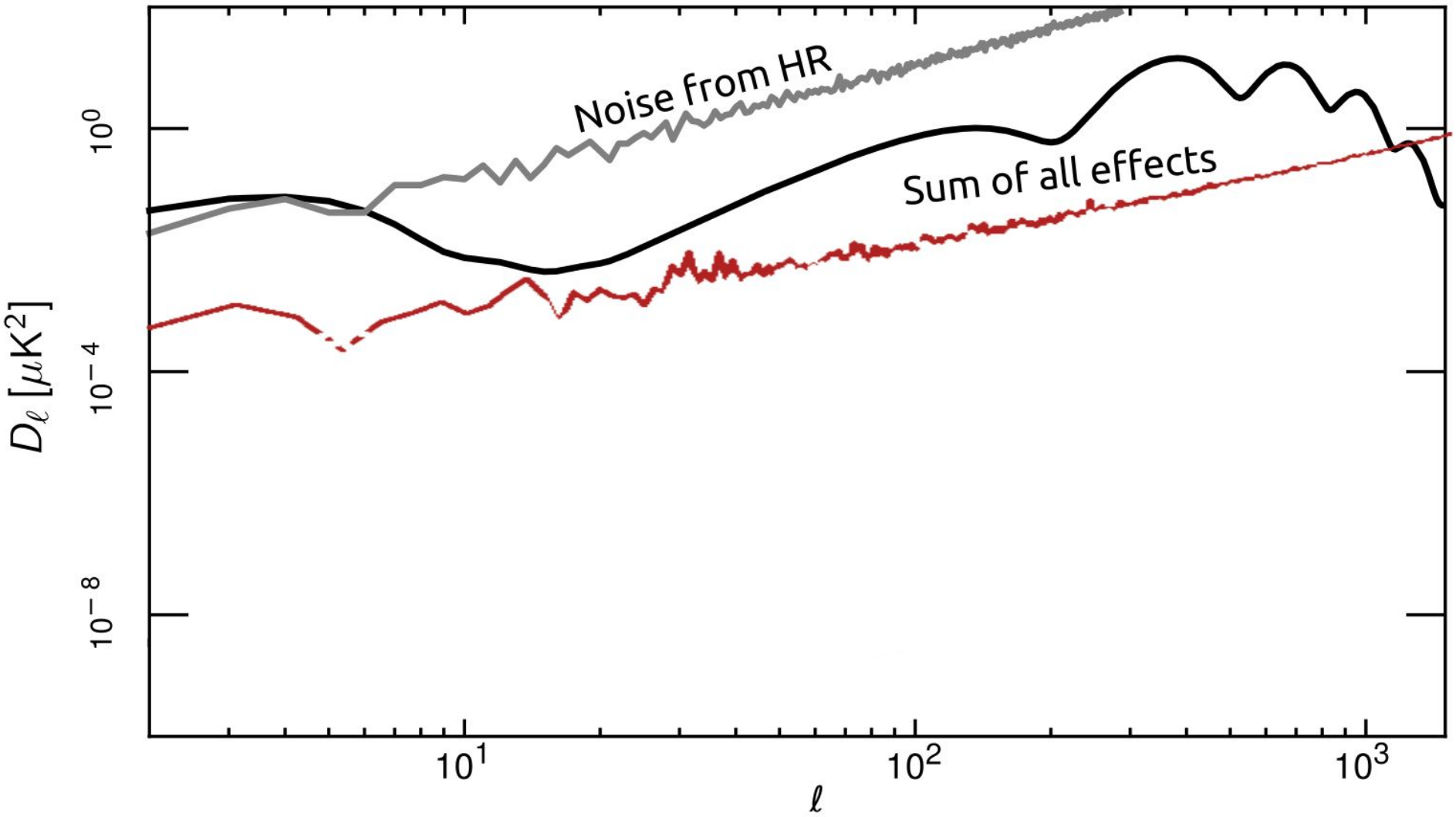
Systematic effects - LFI

Planck 70 GHz systematic effects



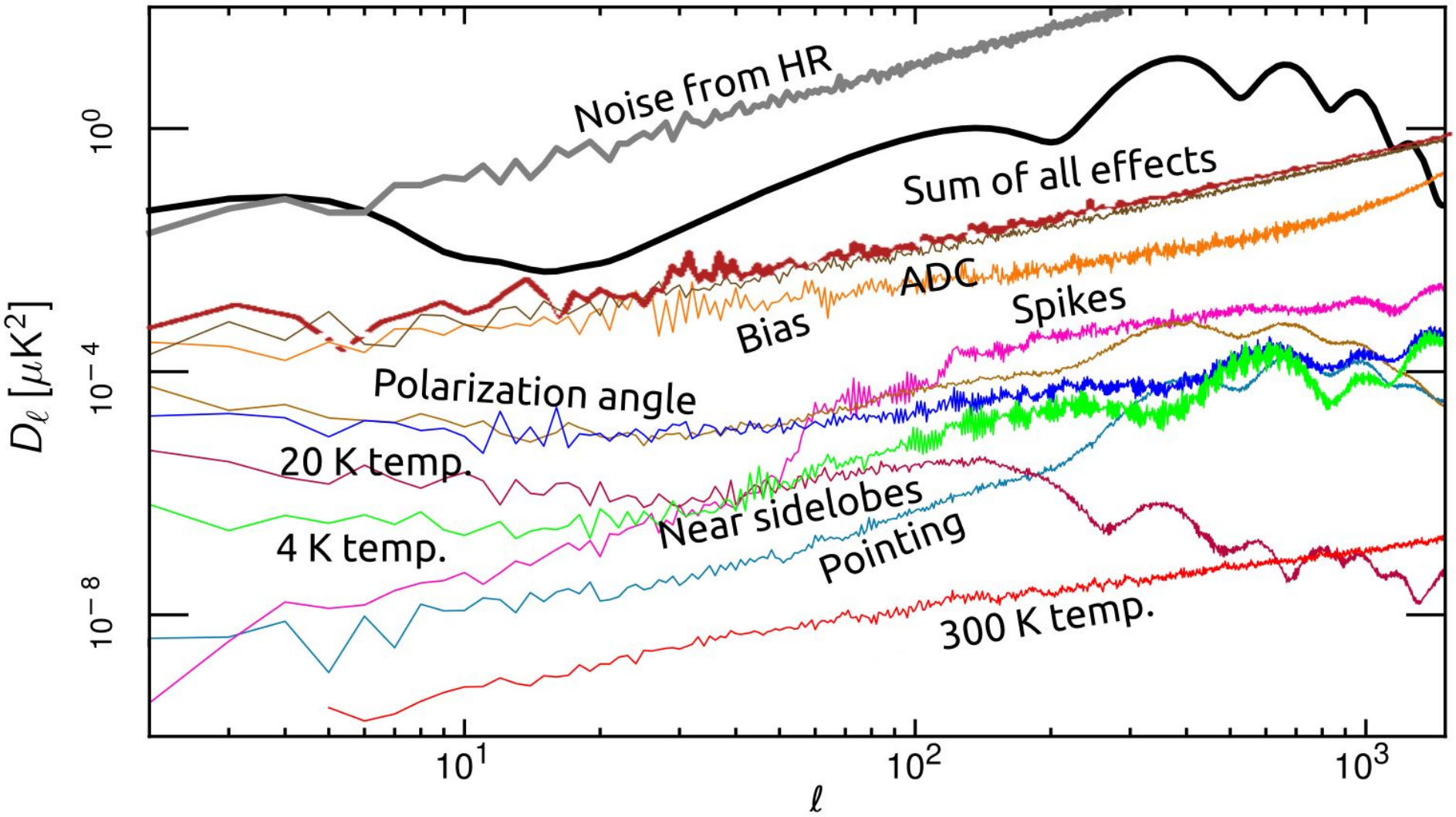
Systematic effects - LFI

Planck 70 GHz systematic effects



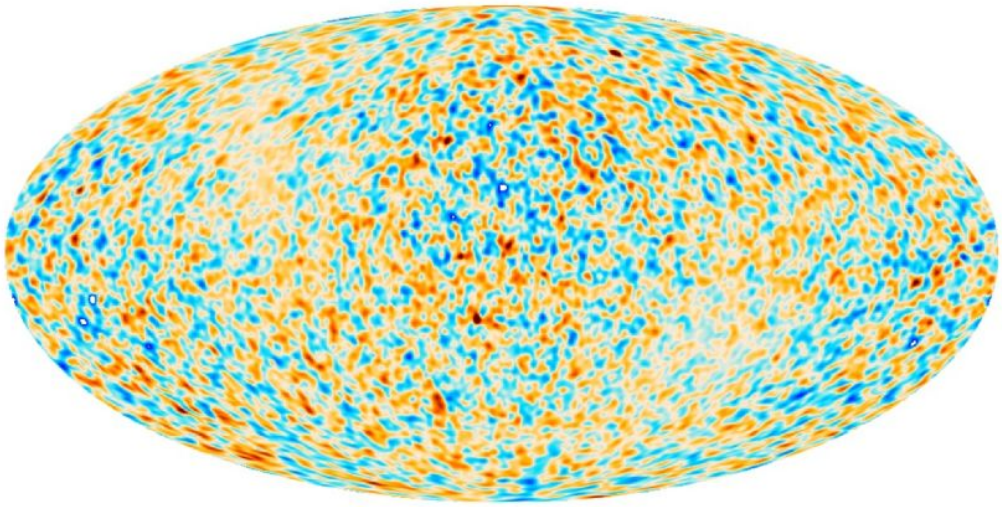
Systematic effects - LFI

Planck 70 GHz systematic effects



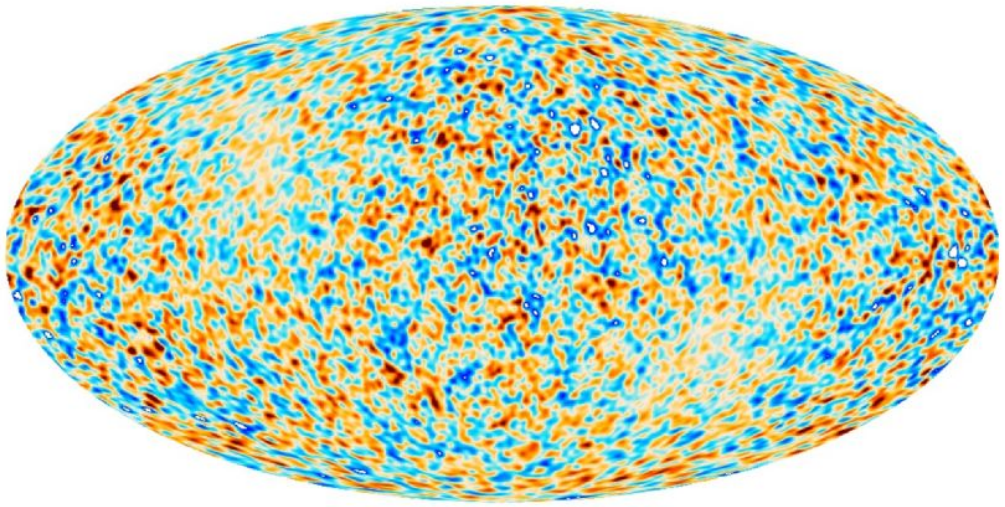
70 GHz odd – even year maps

I



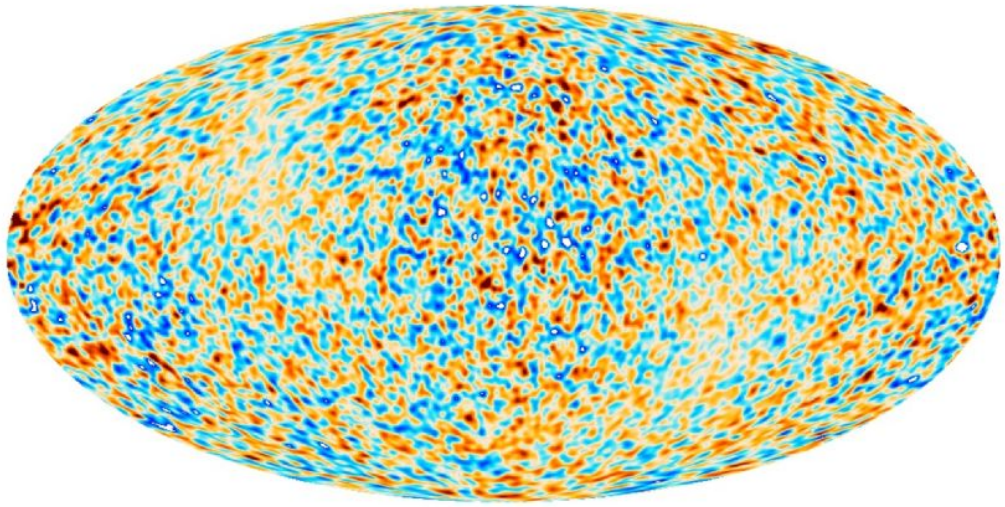
−5.00 μK 5.00 μK

Q



−5.00 μK 5.00 μK

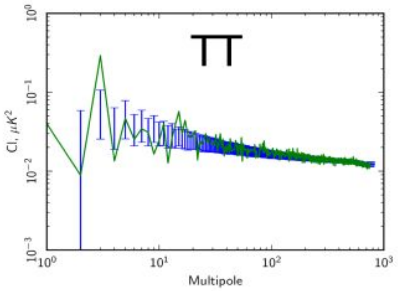
U

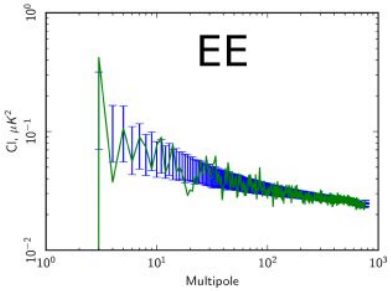


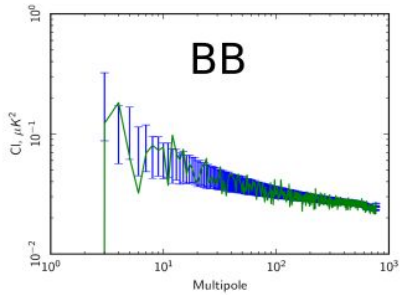
−5.00 μK 5.00 μK

Odd – even year spectra

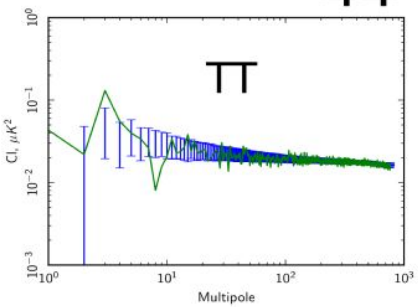
30 GHz

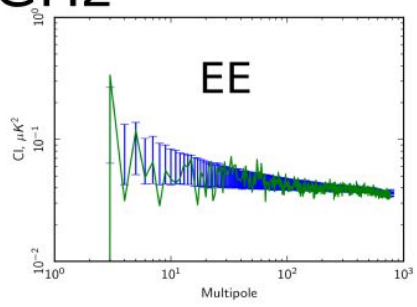


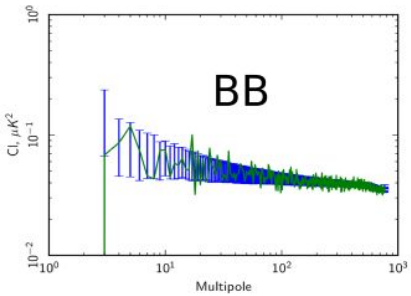




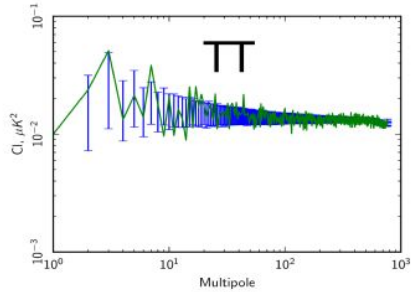
44 GHz

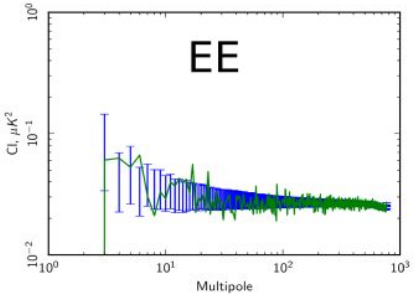


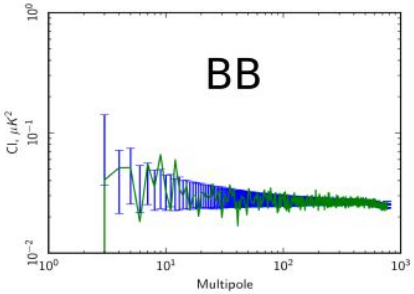




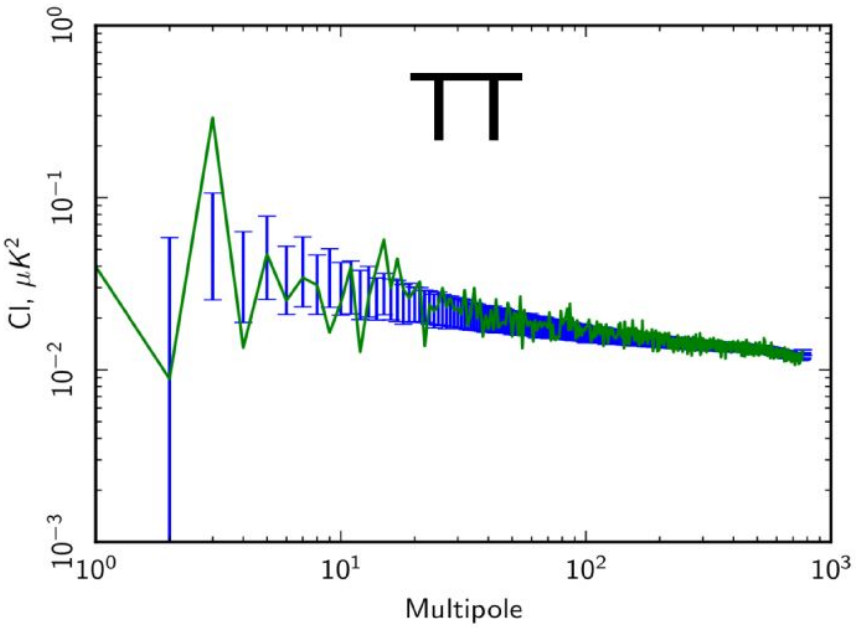
70 GHz

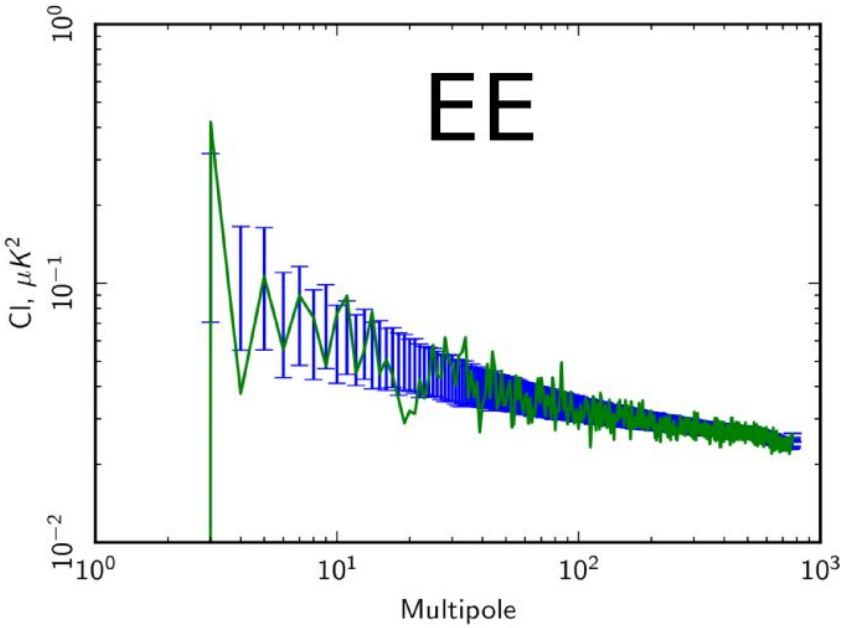


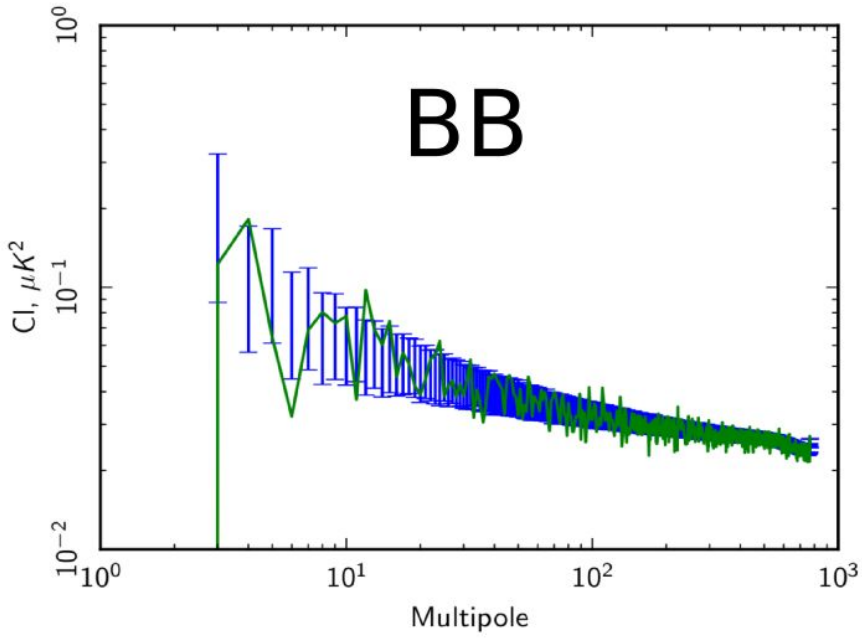




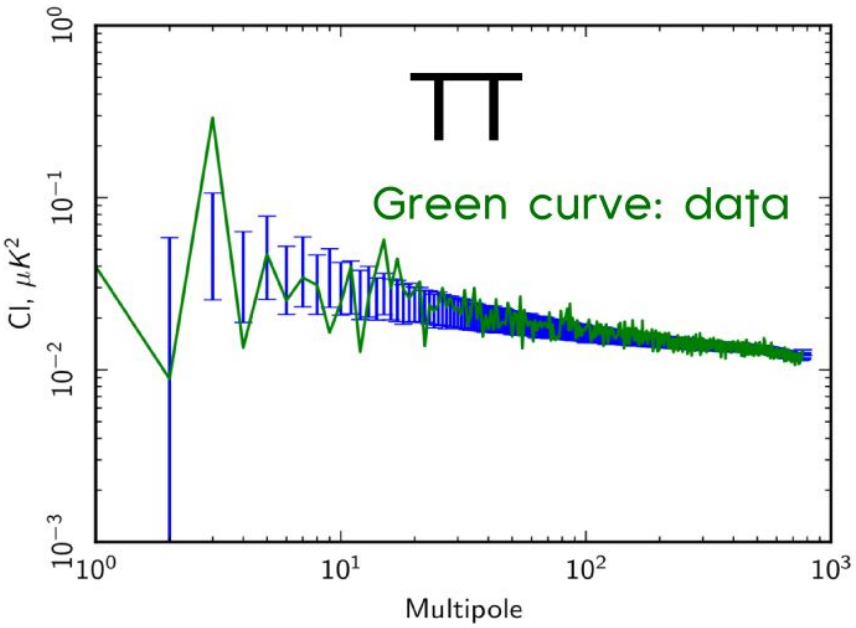
30 GHz

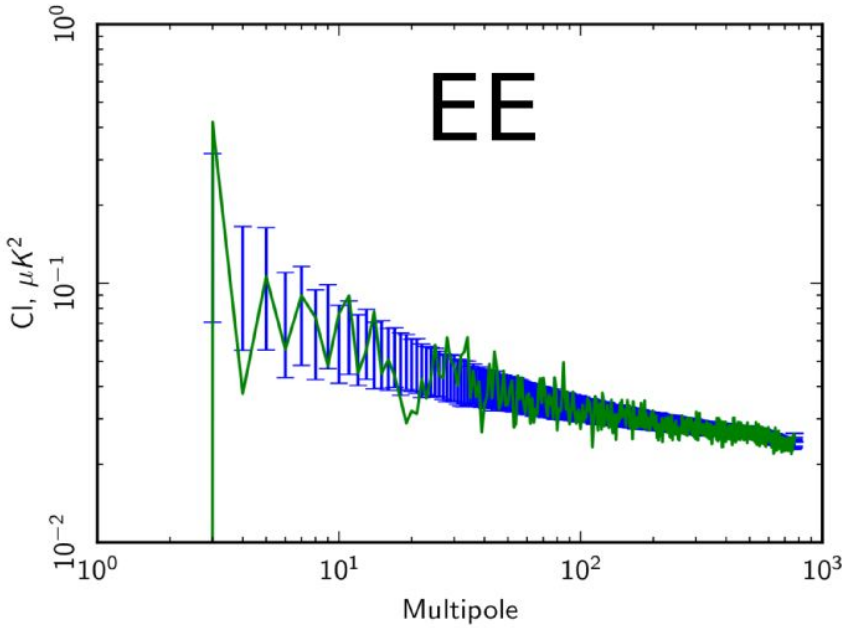

TT
Cl, μK^2
Multipole

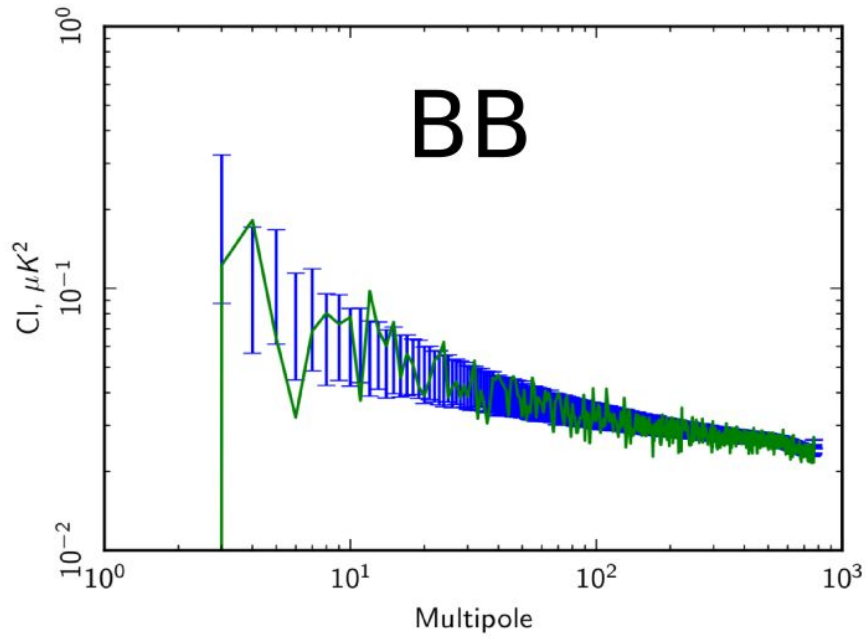

EE
Cl, μK^2
Multipole


BB
Cl, μK^2
Multipole

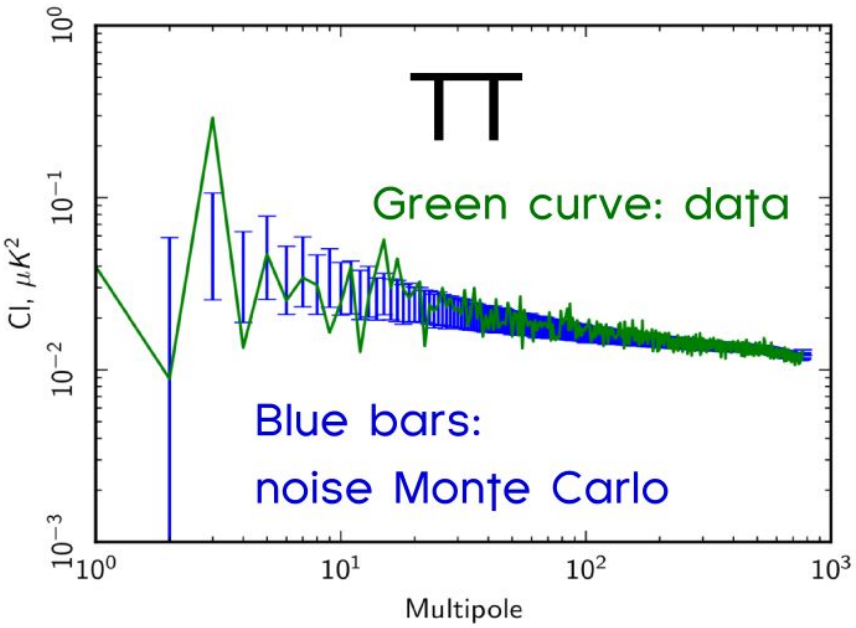
30 GHz

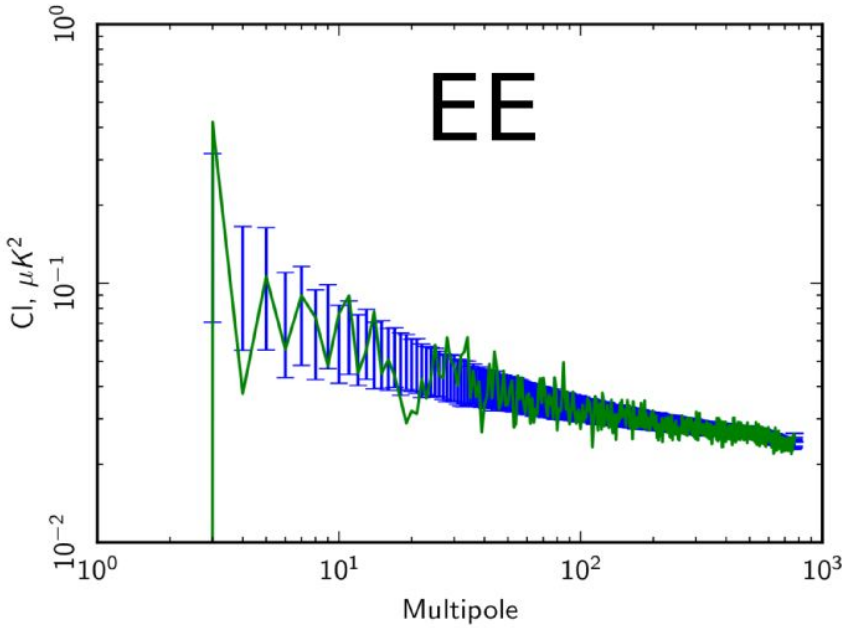

TT
Green curve: data
Cl, μK^2
Multipole

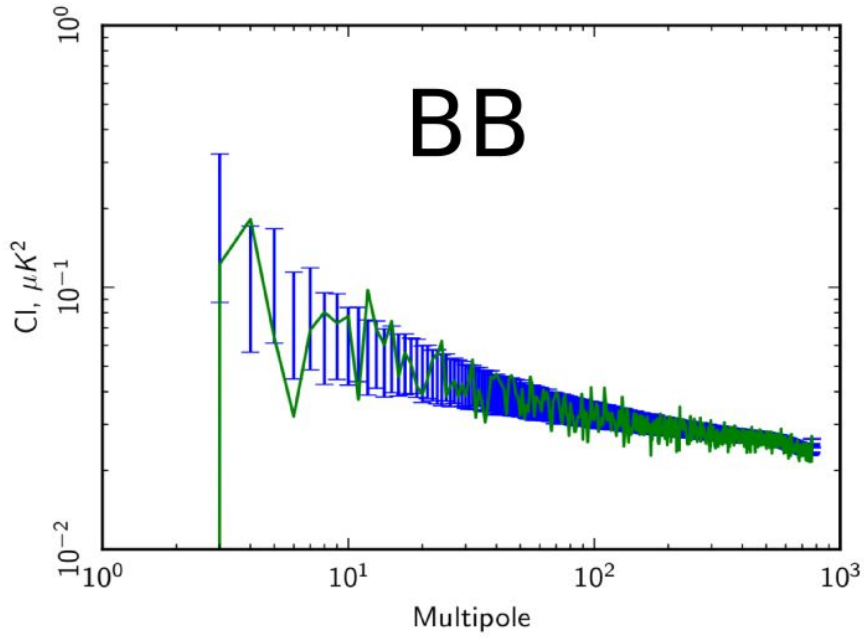

EE
Cl, μK^2
Multipole


BB
Cl, μK^2
Multipole

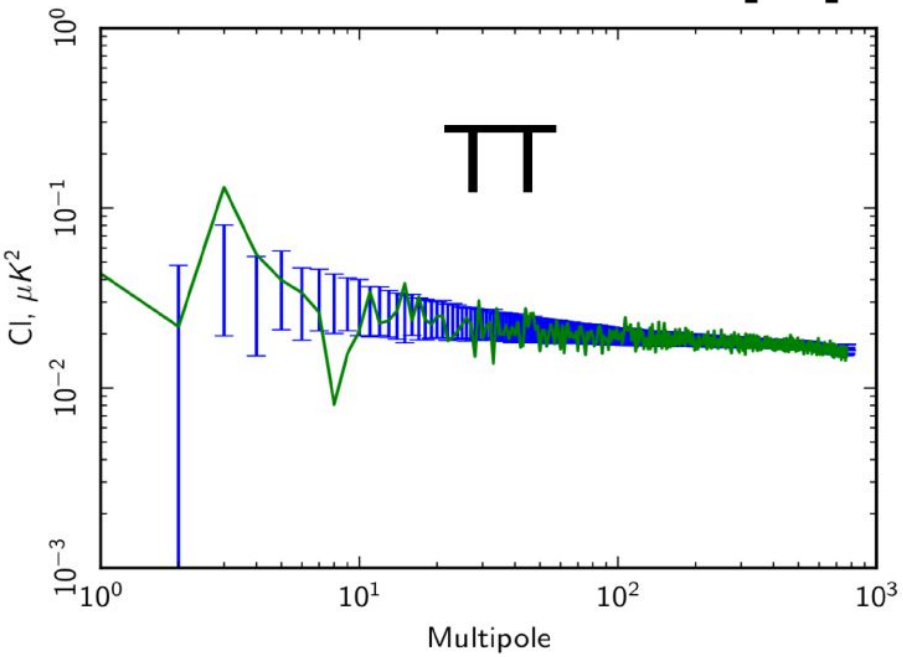
30 GHz

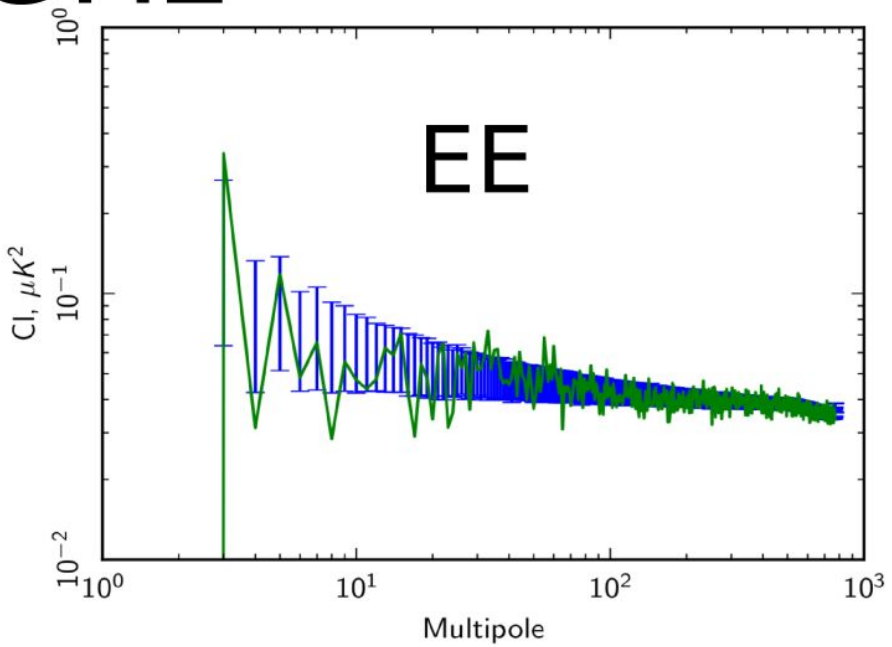

TT
Green curve: data
Blue bars:
noise Monte Carlo
Cl, μK^2
Multipole

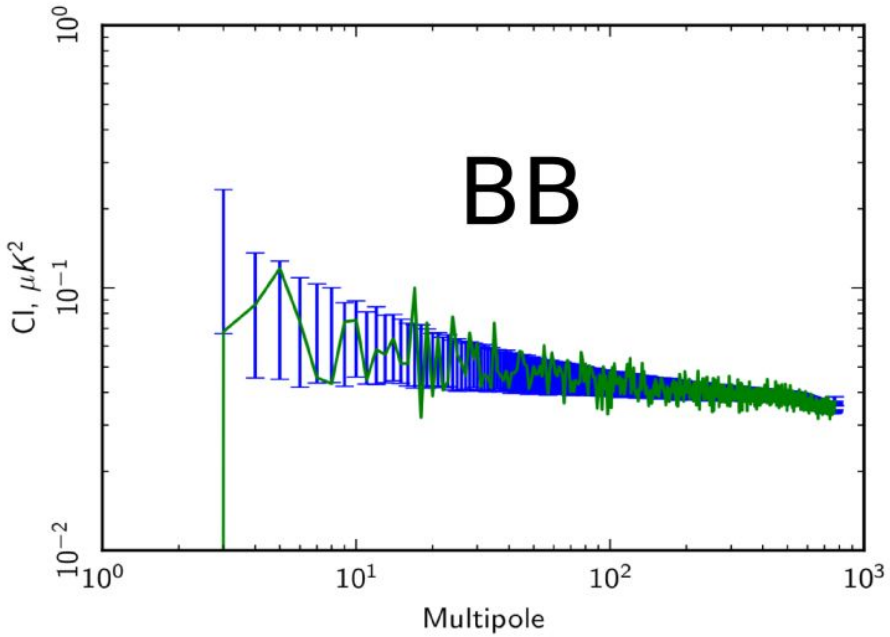

EE
Cl, μK^2
Multipole


BB
Cl, μK^2
Multipole

44 GHz

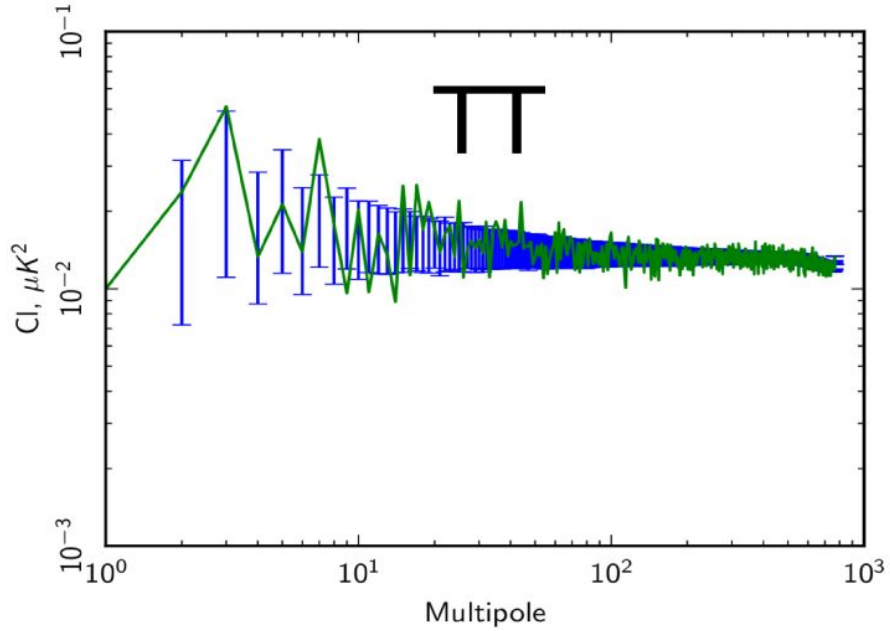

TT
Cl, μK^2
Multipole

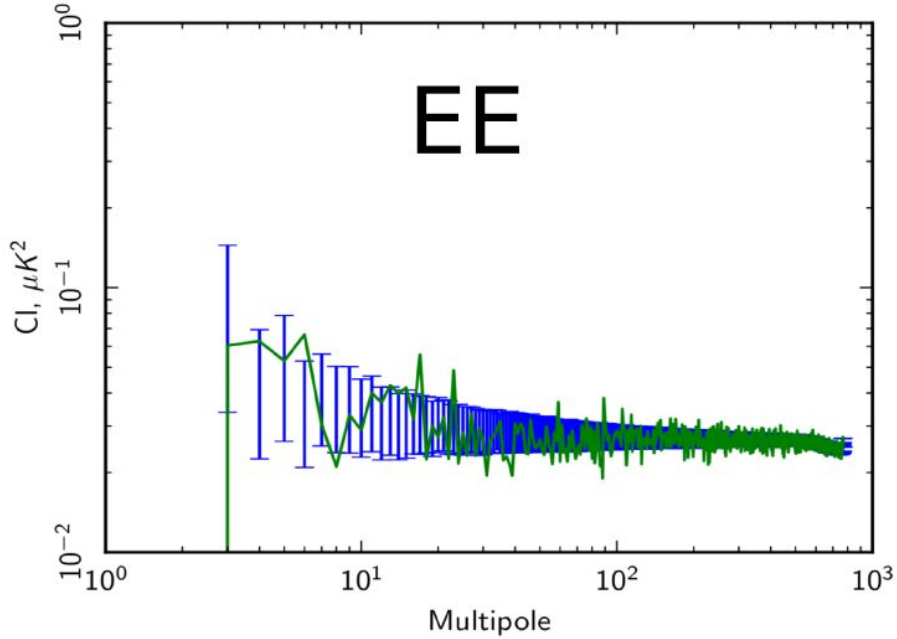

EE
Cl, μK^2
Multipole

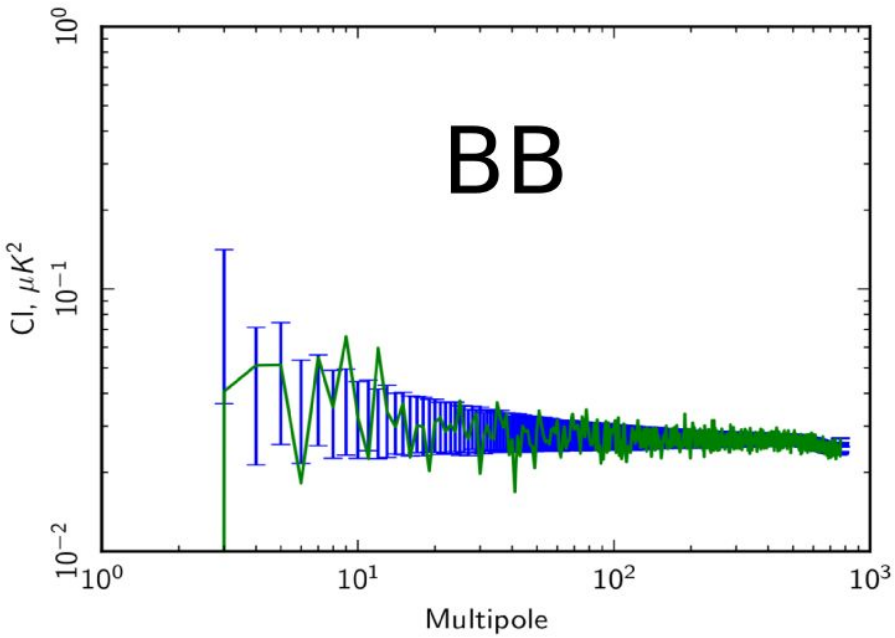

BB
Cl, μK^2
Multipole

GHz

70 GHz

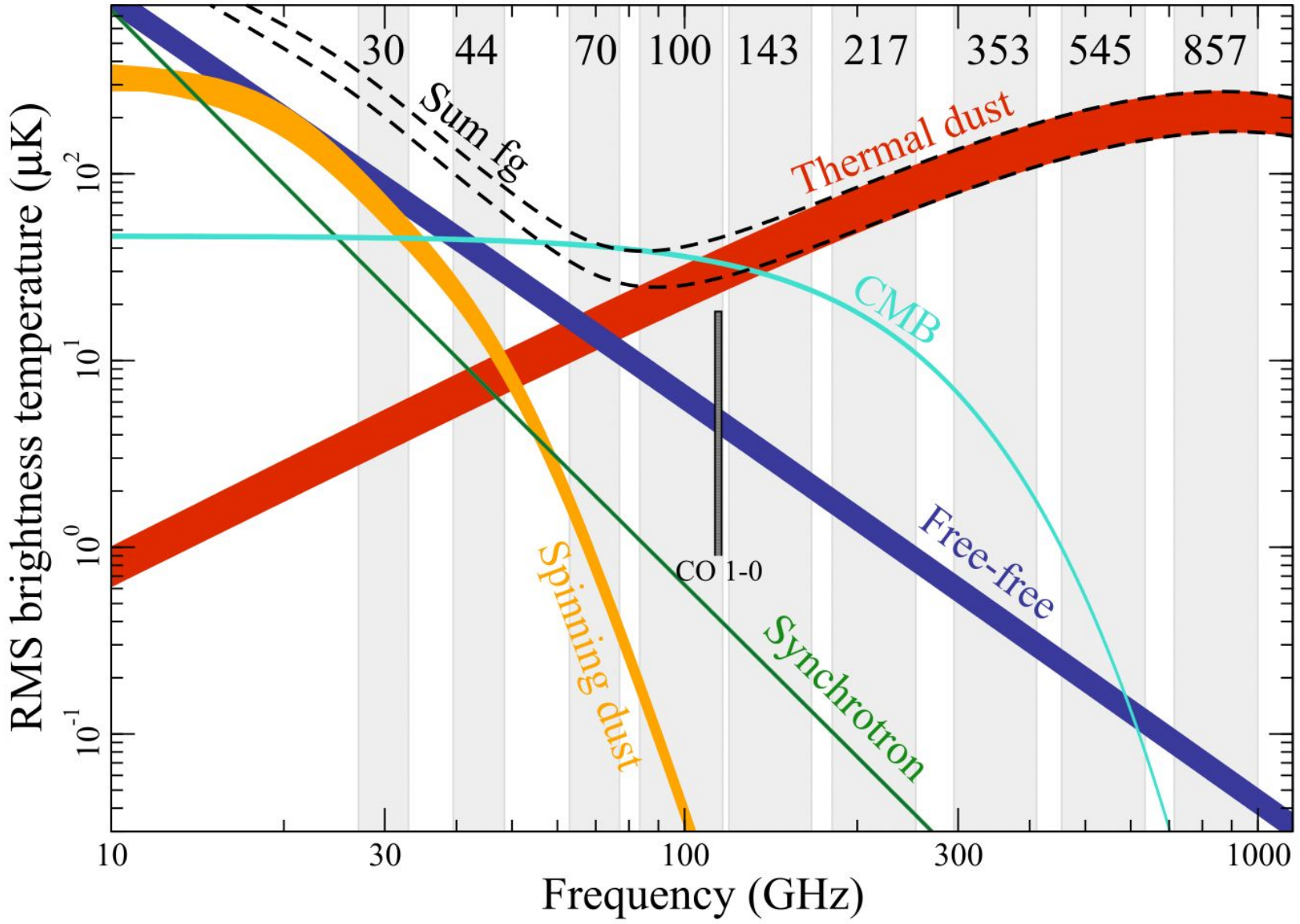

TT
Cl, μK^2
Multipole


EE
Cl, μK^2
Multipole


BB
Cl, μK^2
Multipole

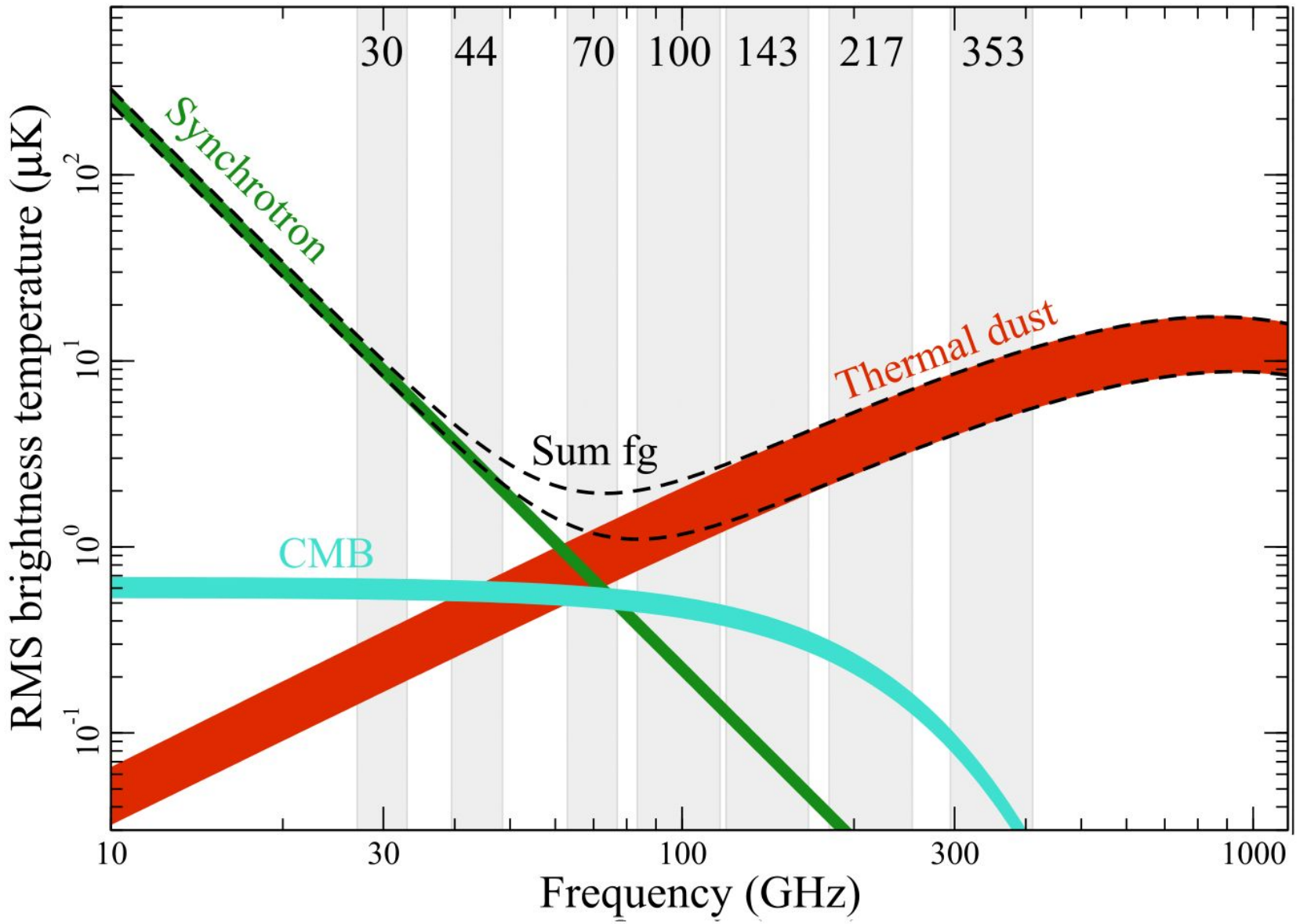
Foregrounds

In temperature



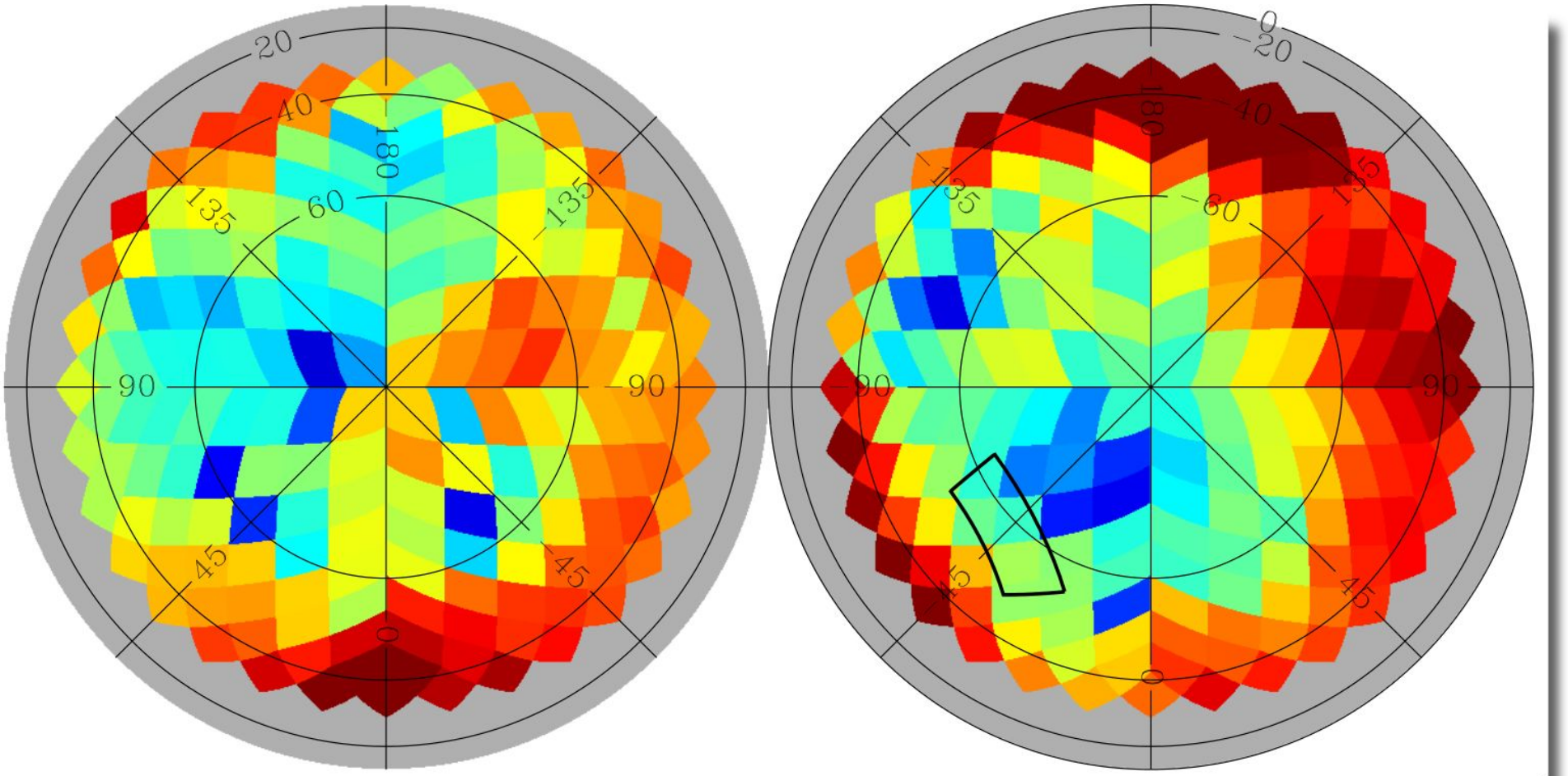
Foregrounds

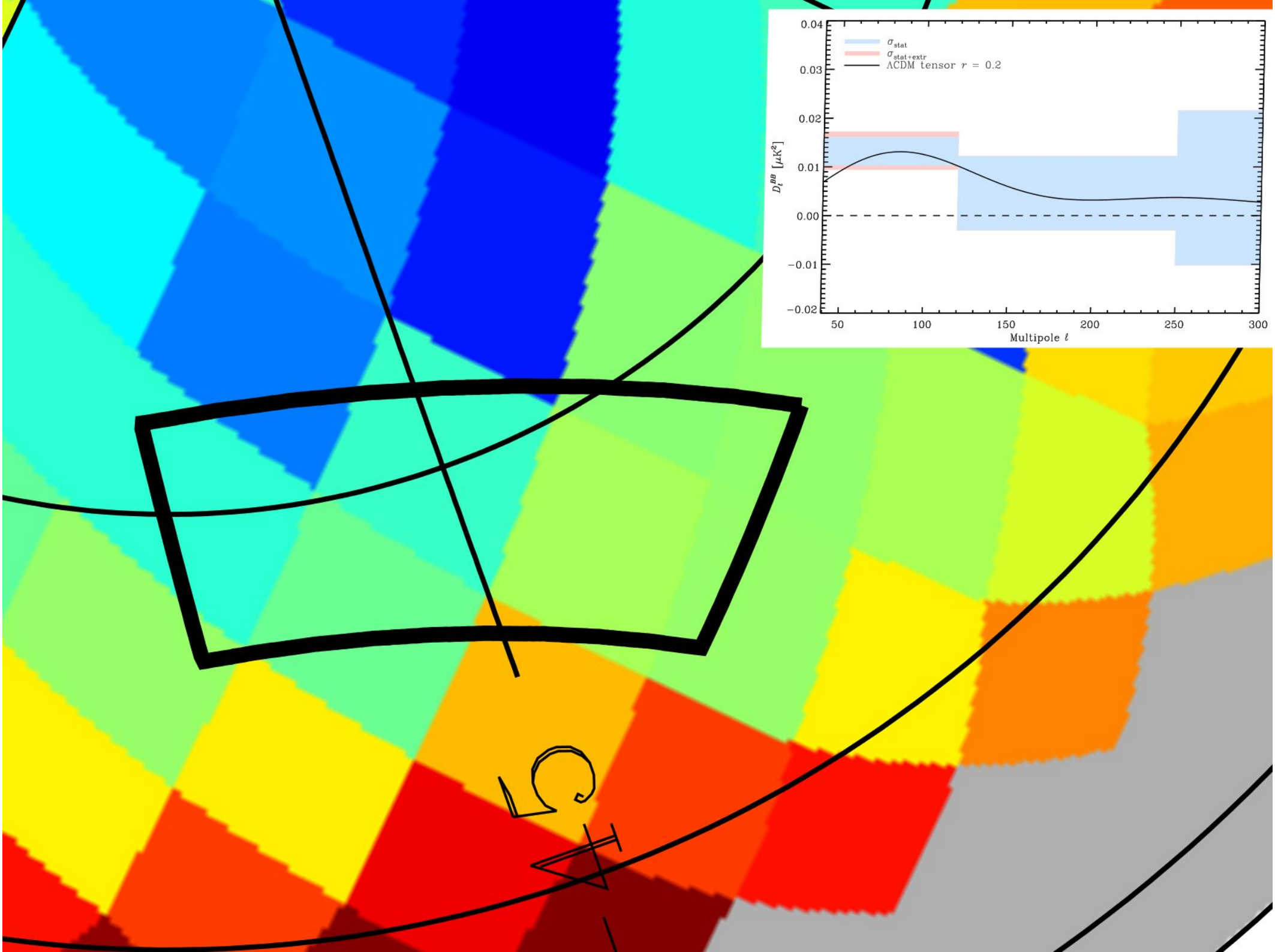
In polarization



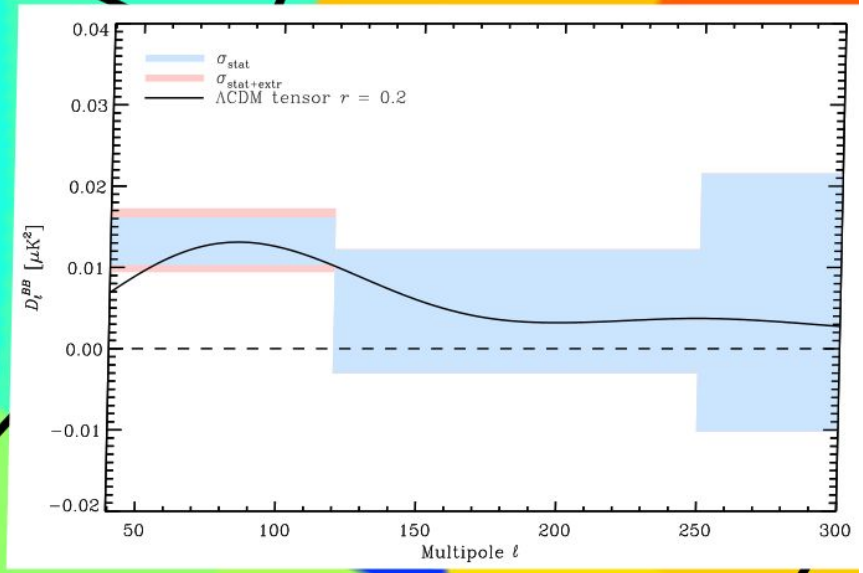
Polarized dust

Dust polarization contamination at 150 GHz estimated from Planck 353 GHz data




0.04
0.03
0.02
0.01
0.00
−0.01
−0.02
D_ℓ^{BB} [μK^2]
$\sigma_{\rm stat}$
$\sigma_{\rm stat+extr}$
ΛCDM tensor r = 0.2
50
100
150
200
250
300
Multipole ℓ

High frequency measurements key to disentangle dust from CMB polarization



In summary

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- Planck has provided us the most sensitive full sky measurements of the polarized sky
- Systematic effects must be avoided *in hardware* as much as possible
- Future instruments must have built-in systematic effects control (e.g. the QUBIC interferometer)
- Polarized foregrounds are probably the most difficult challenge for the future especially at large scales
- Wide-band, multi-frequency observations will be the key to large-scale, **accurate** polarization measurements

In simple words...

Know your instrument

and

know your sky

The Planck collaboration

Planck is a project of the European Space Agency, 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.