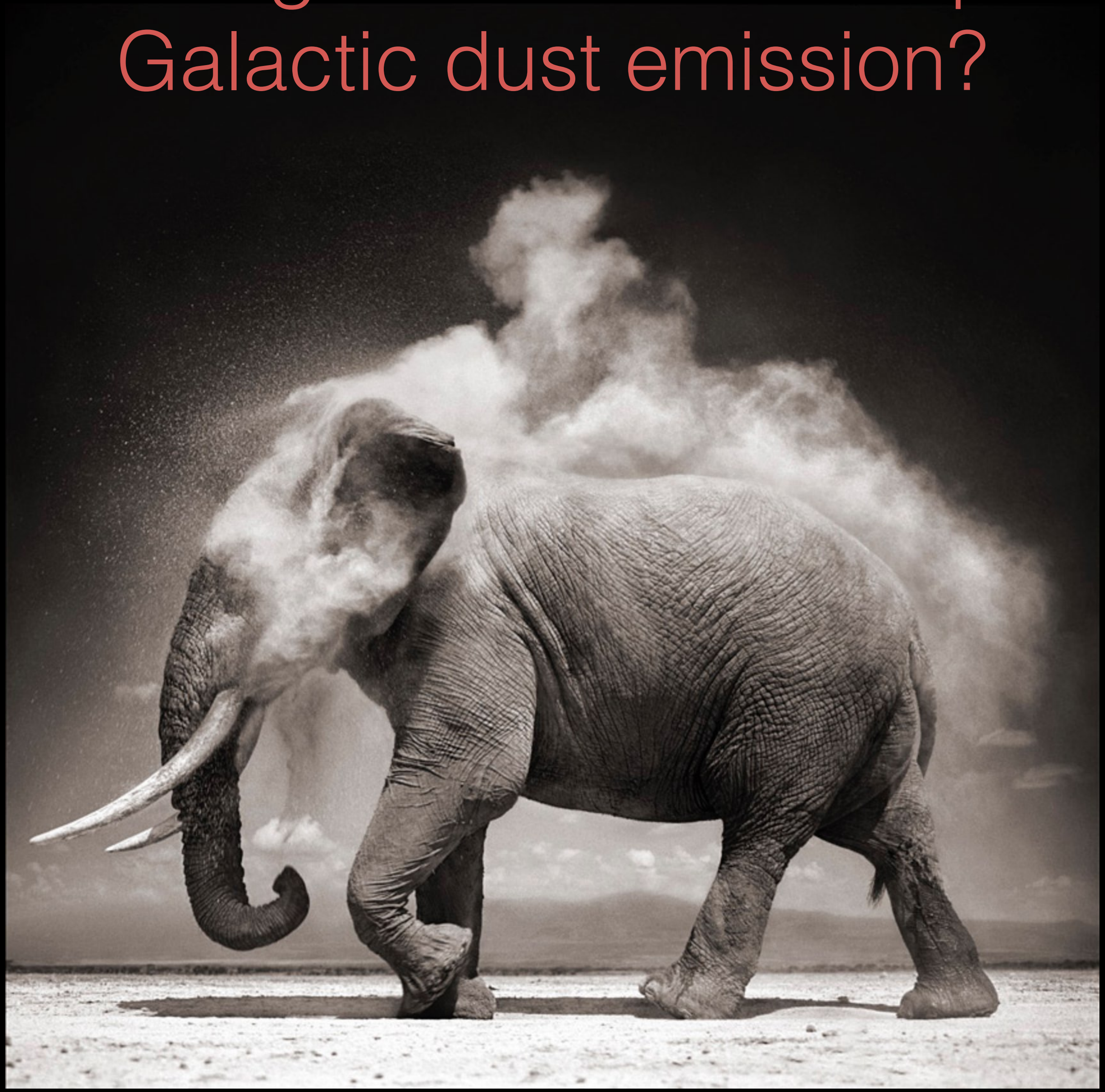
Can we detect the CMB B modes without taking into account the polarized Galactic dust emission?



Jonathan Aumont

(IAS Orsay)

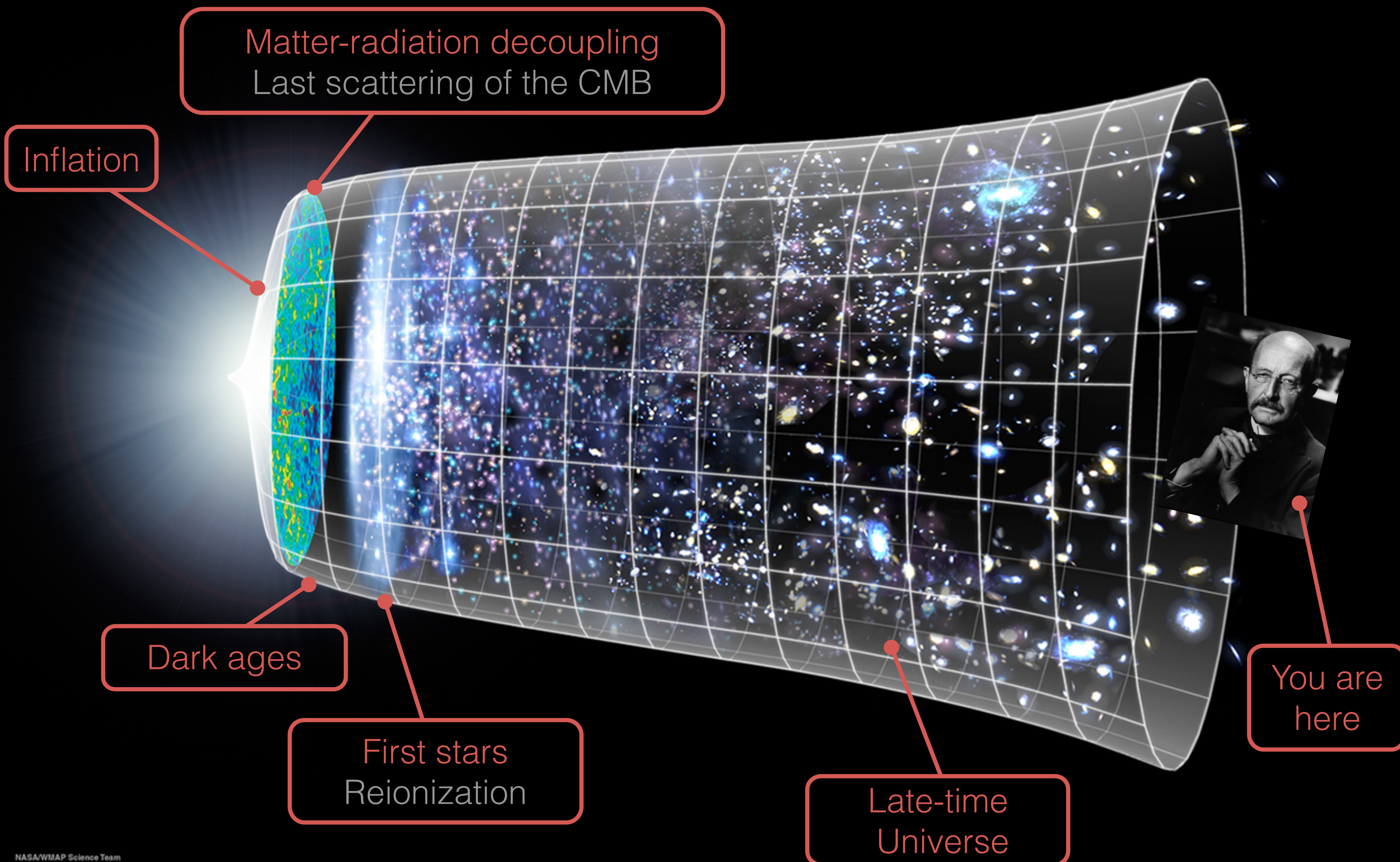
Séminaire de l'APC

Tuesday, January 27th 2015

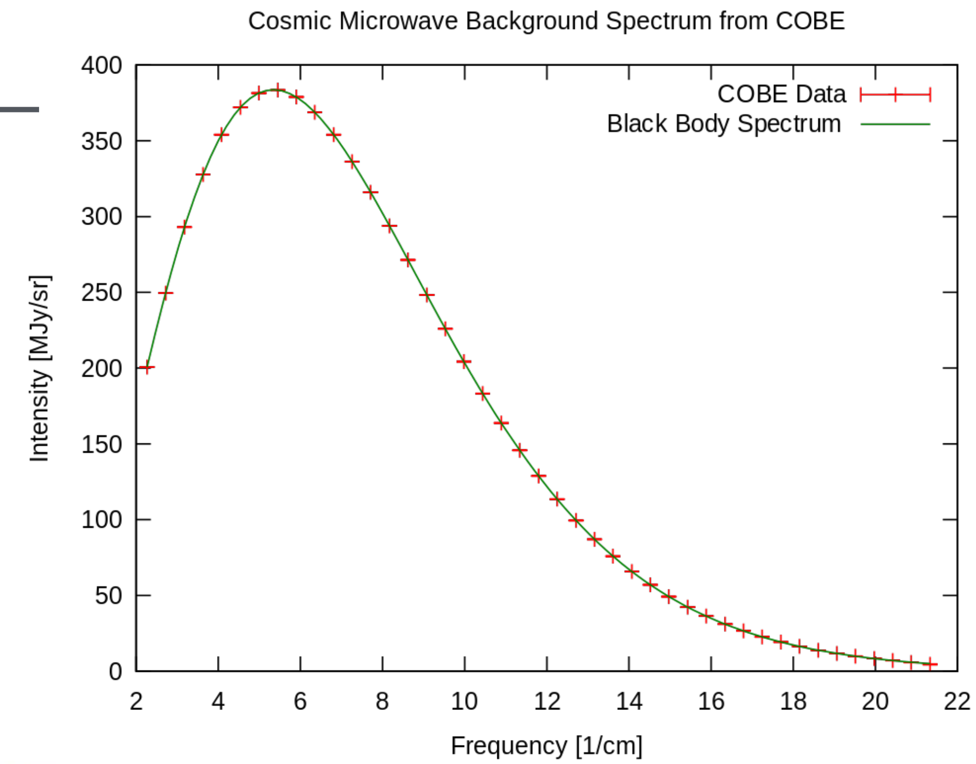
Outline

1. The polarization of the Cosmic Microwave Background
2. Statistical measurement of the Galactic dust polarized emission with Planck
3. Implications for the BICEP2 experiment measurements

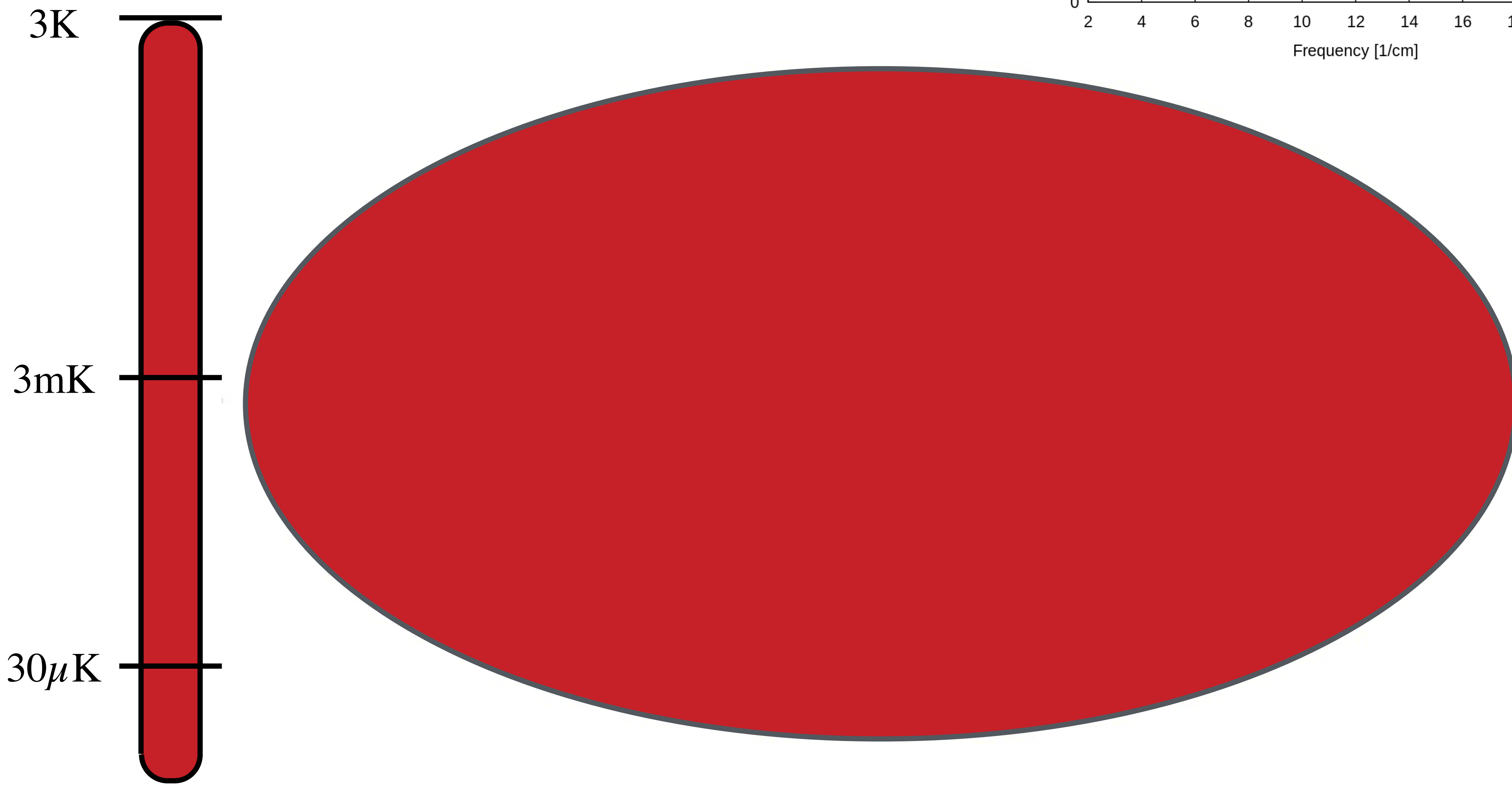
The "Standard Model" of cosmology



The Cosmic Microwave Background



- ★ Radiation discovered by [Penzias et Wilson 1965]
- ★ In first approximation isotropic and homogeneous with T = 2.725 ± 0.001 K



The Cosmic Microwave Background

- ★ Radiation discovered by [Penzias et Wilson 1965]
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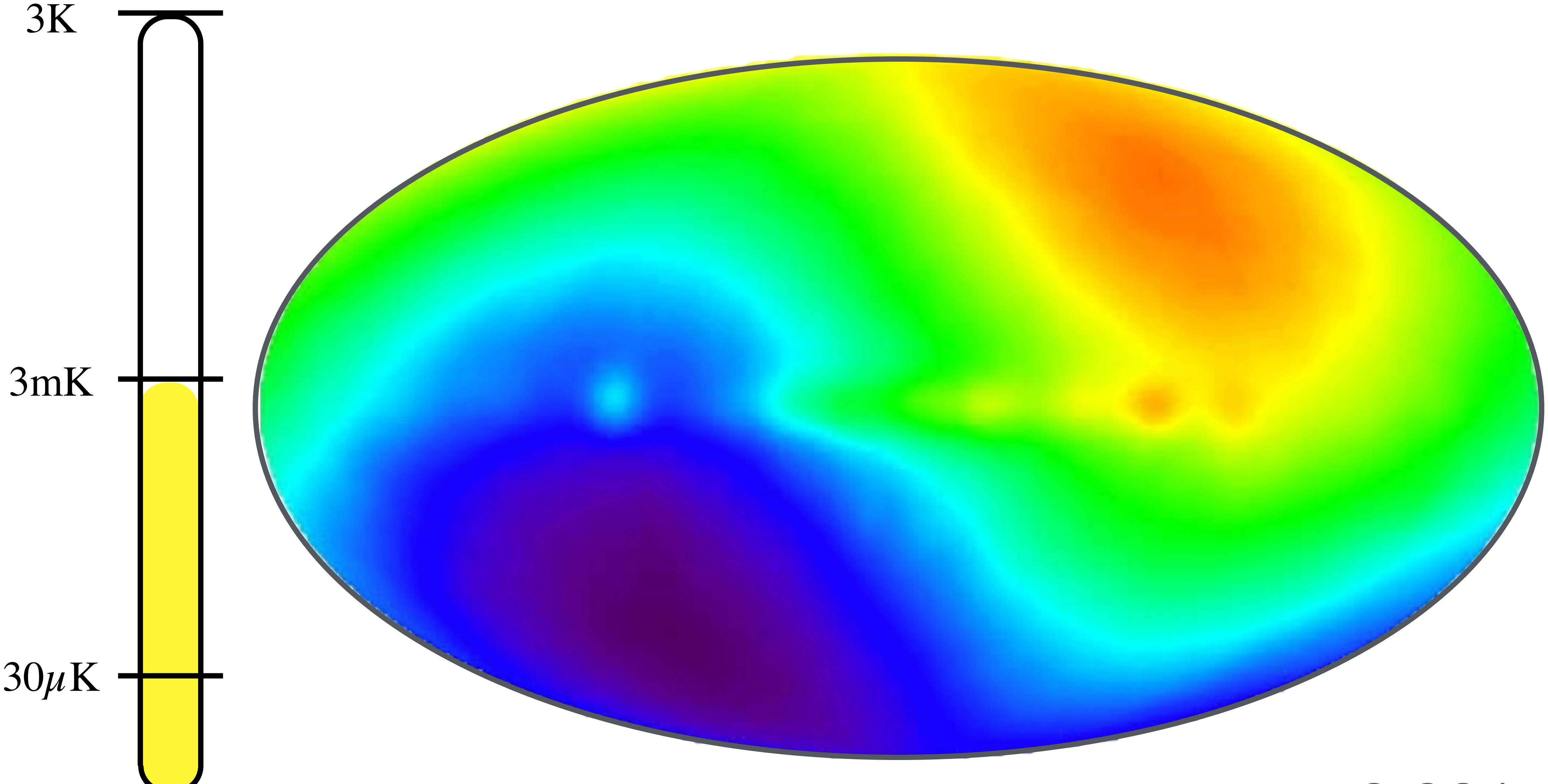
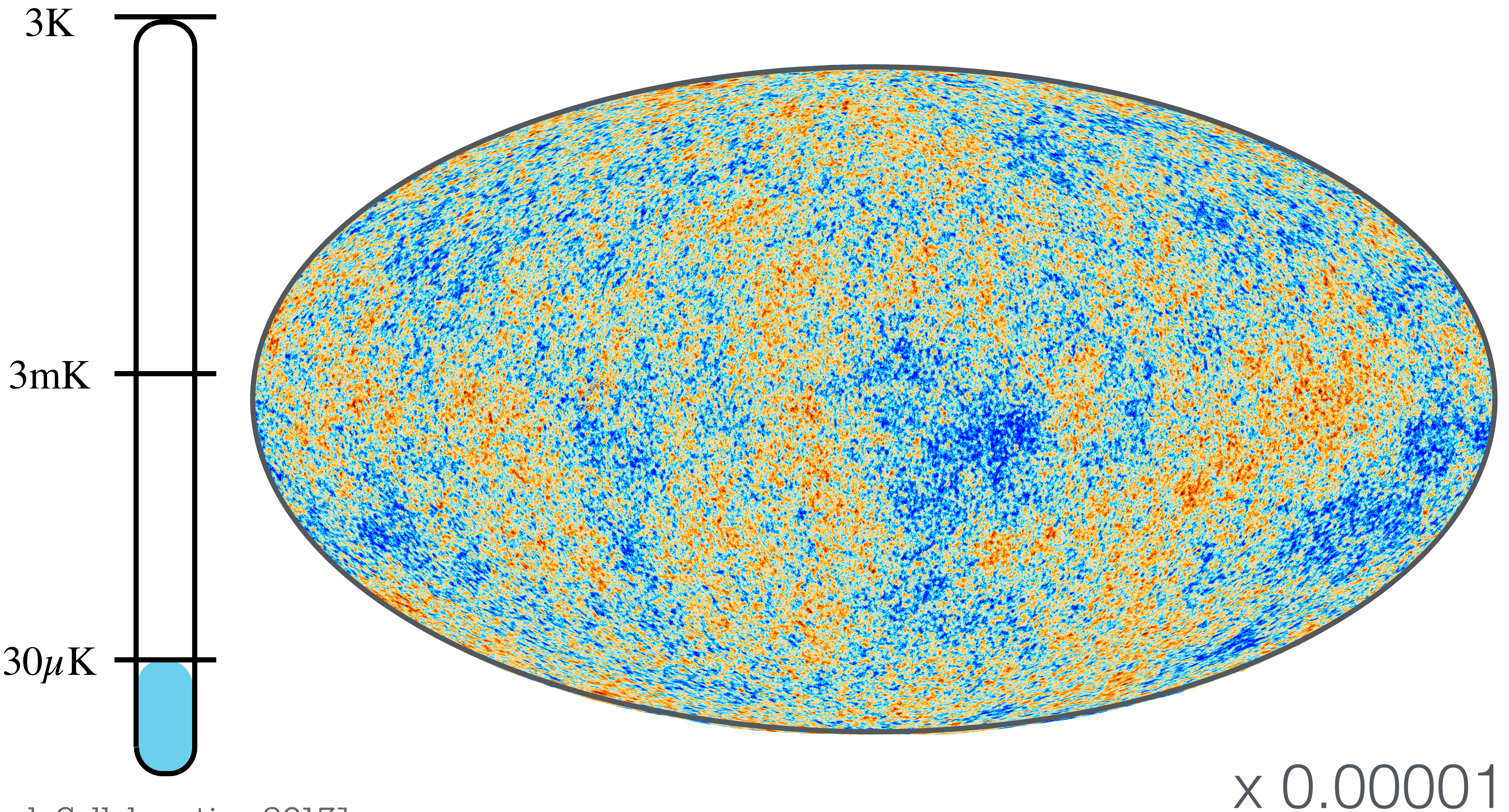


x 0.001

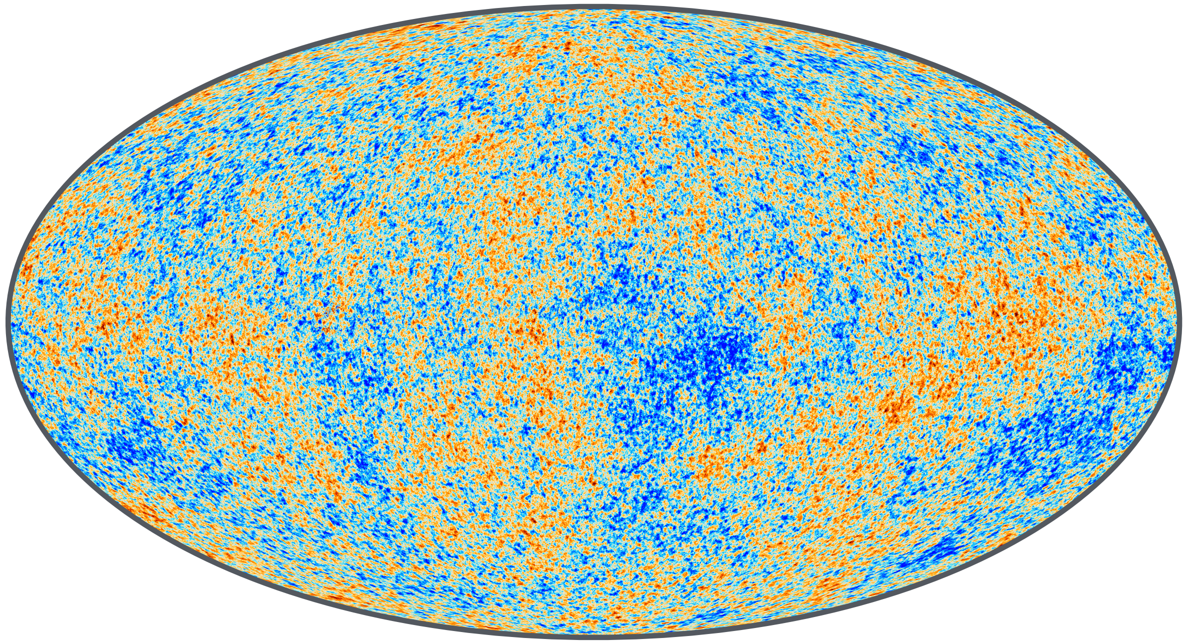
The Cosmic Microwave Background

- ★ Radiation discovered by [Penzias et Wilson 1965]
- ★ In first approximation isotropic and homogeneous with $T = 2.725 \pm 0.001$ K
- ★ … but has some anisotropies which are the imprints of the primordial density fluctuations



[Planck Collaboration 2013]

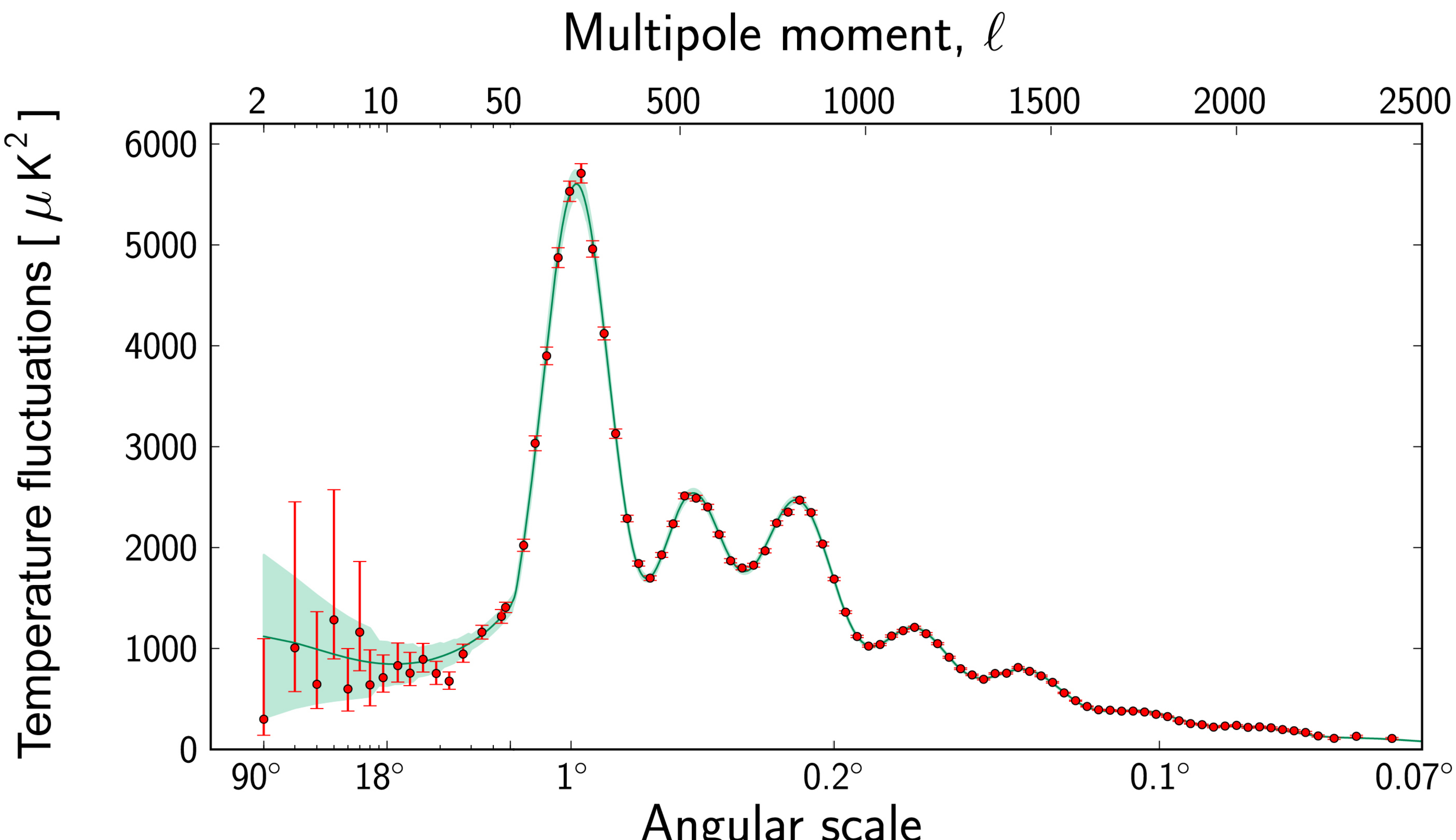
The Cosmic Microwave Background



$$\frac{\Delta T(\mathbf{n})}{T_0} = \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} a^T_{\ell m} Y_{\ell m}(\mathbf{n})$$

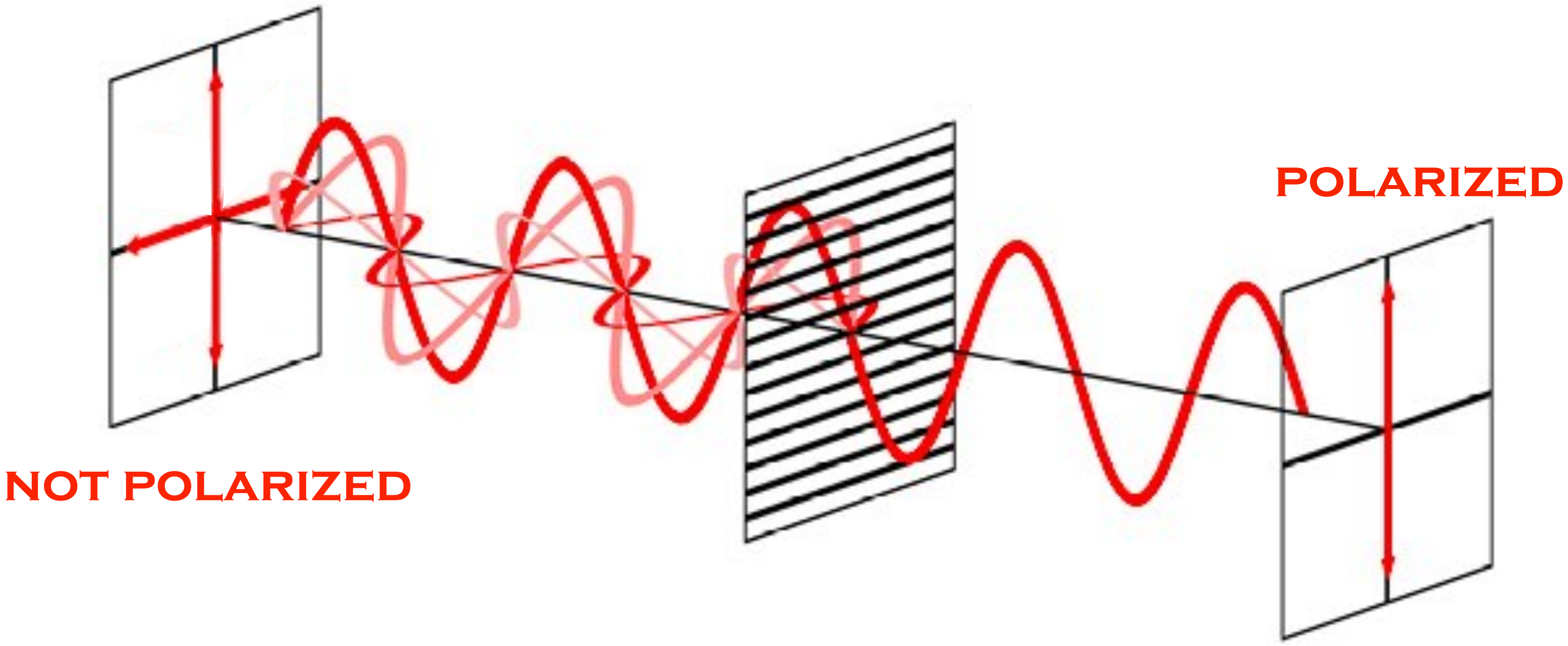
$$C^{TT}_{\ell} = \langle a^T_{\ell m} a^{T\star}_{\ell m} \rangle$$

- ★ Two point angular correlation function
- ➔ Angular power spectrum



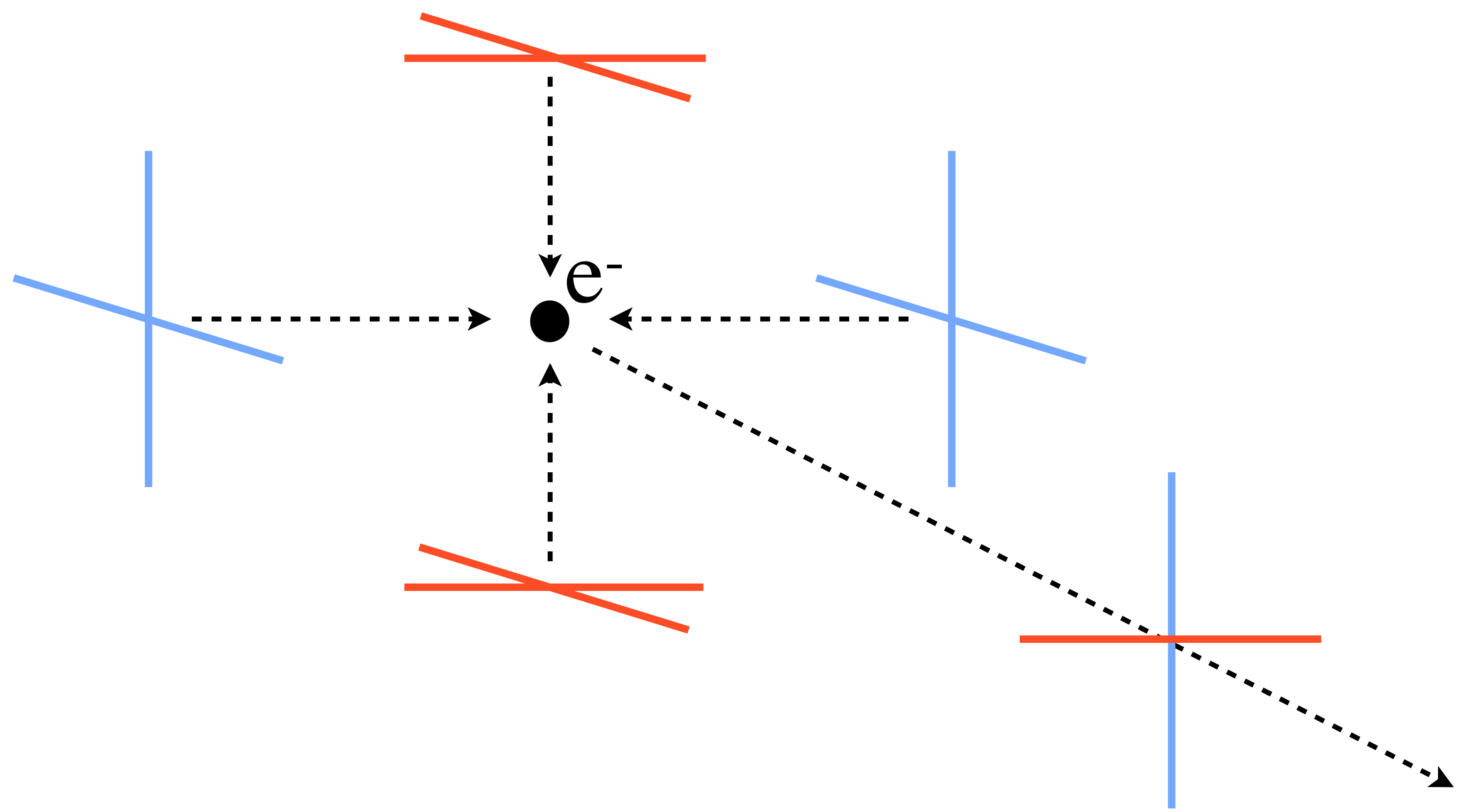
[Planck Collaboration 2013]

The CMB polarization

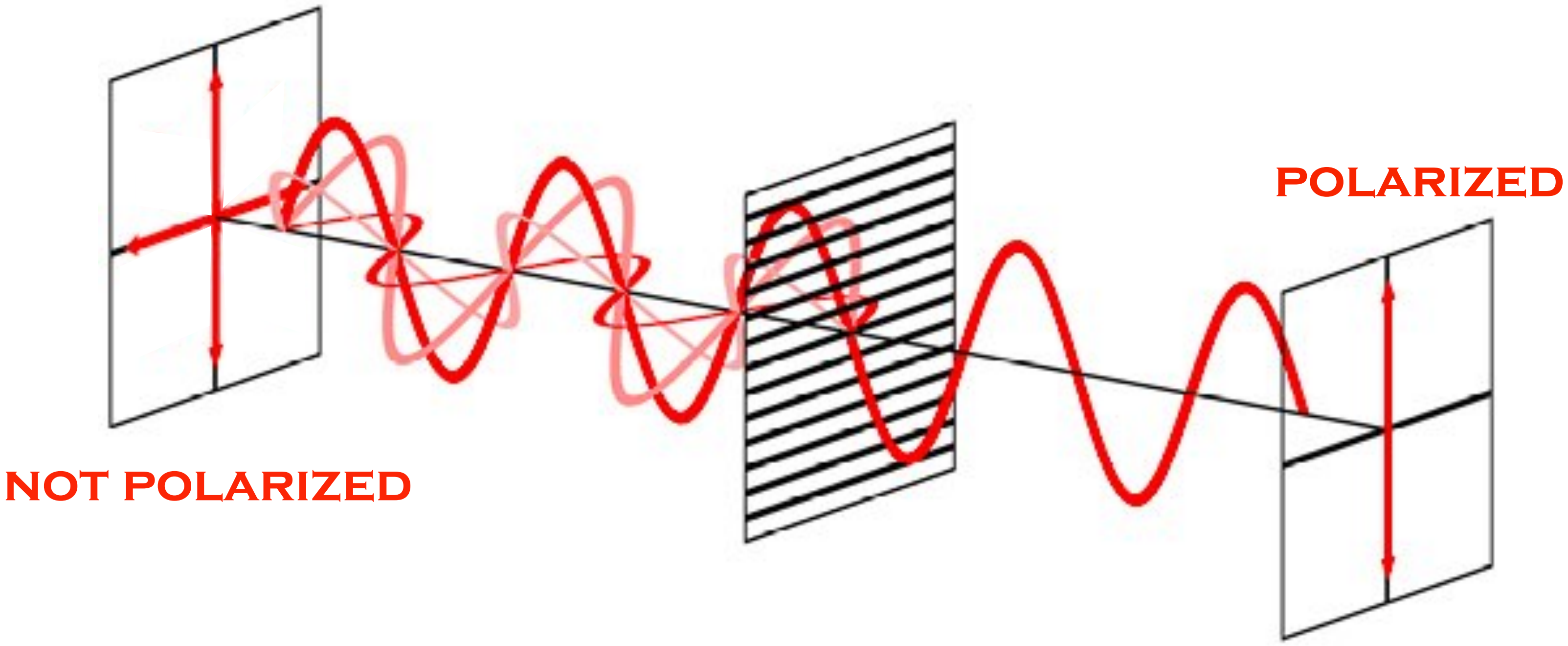


★ The CMB is a polarized radiation

★ The CMB polarization has been produced by the quadrupolar anisotropies at the moment of decoupling



The CMB polarization



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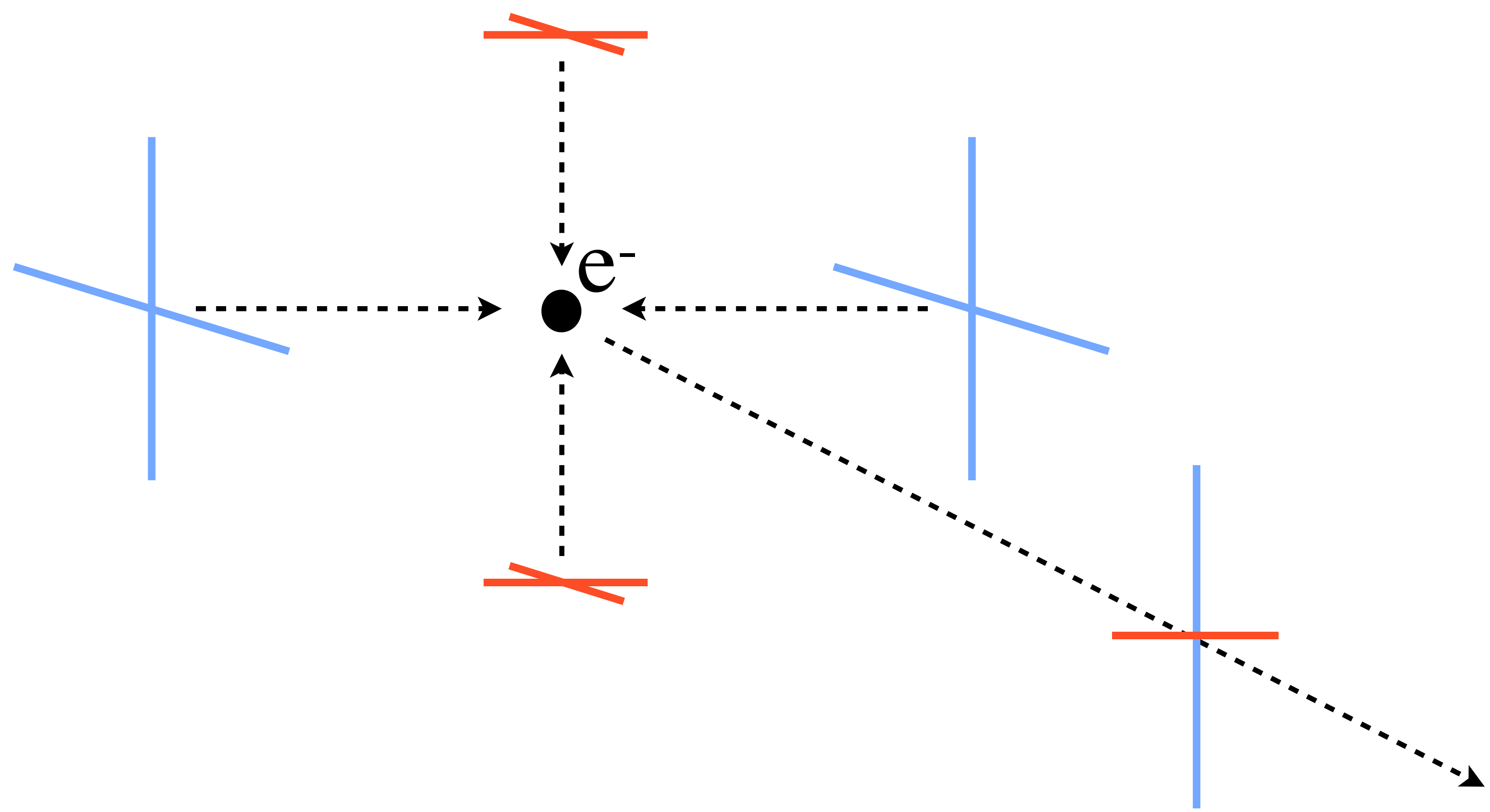
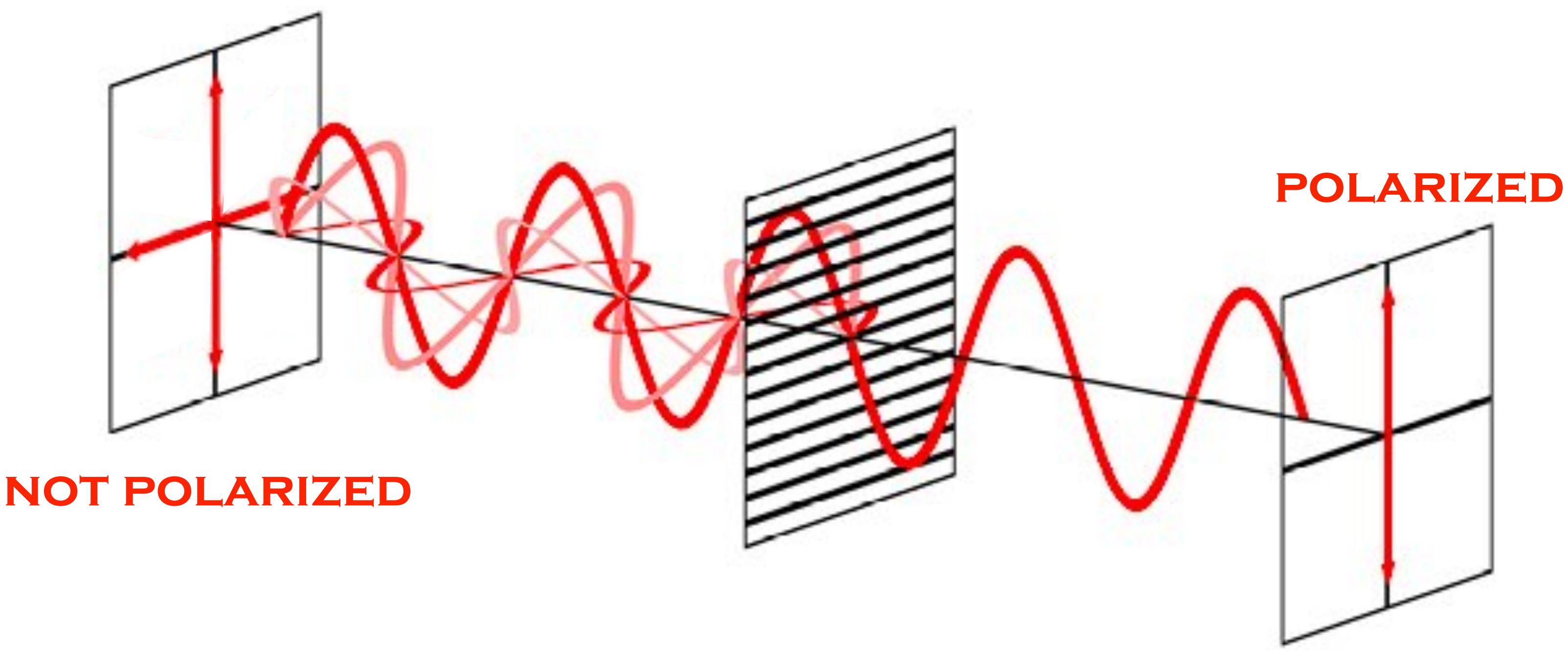
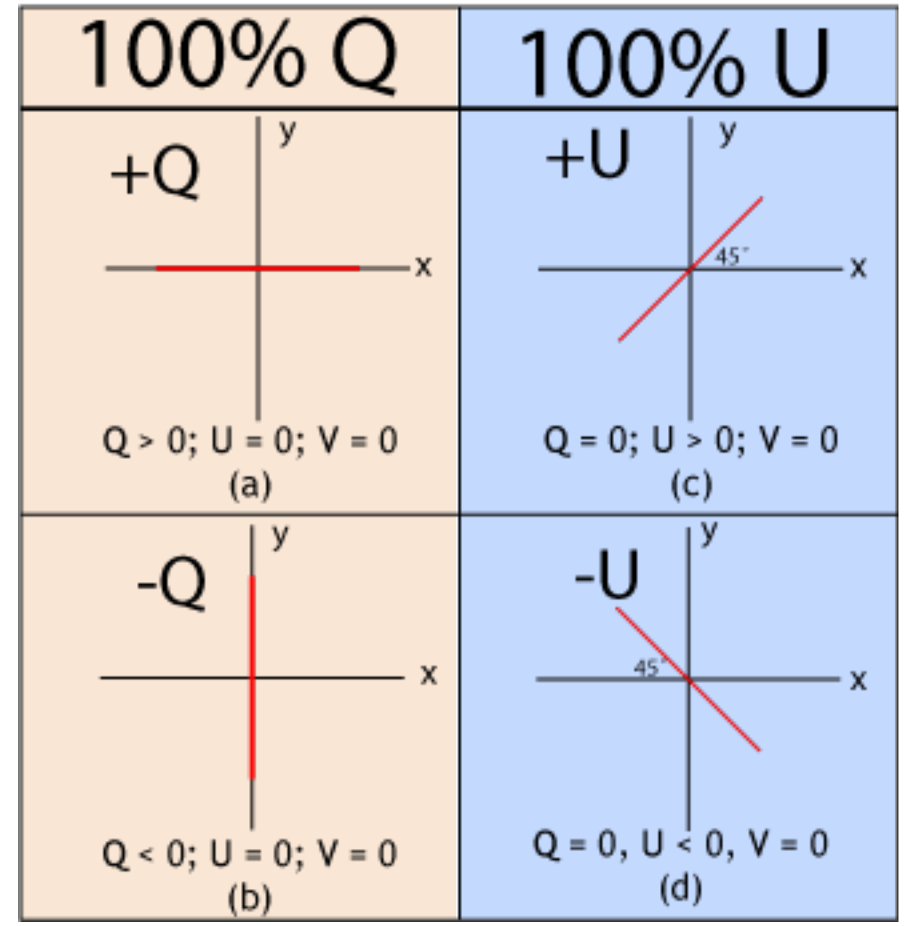


The CMB polarization





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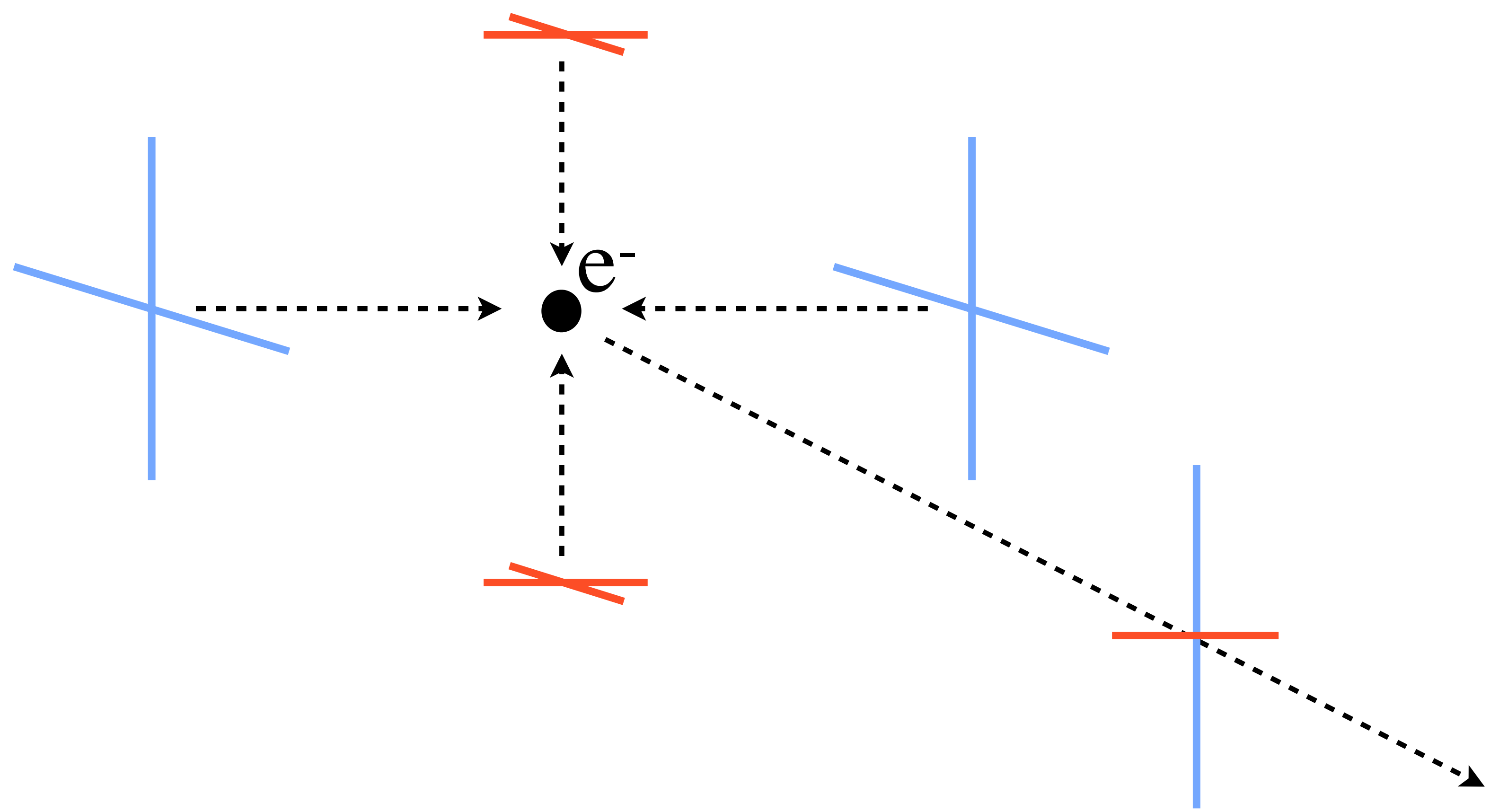


The CMB polarization

Stokes parameters

Intensity

$$I = T$$

Linear polarization

$$Q$$

$$U$$

"Physical" parameters

Polarized intensity

$$P = \sqrt{Q^2 + U^2}$$

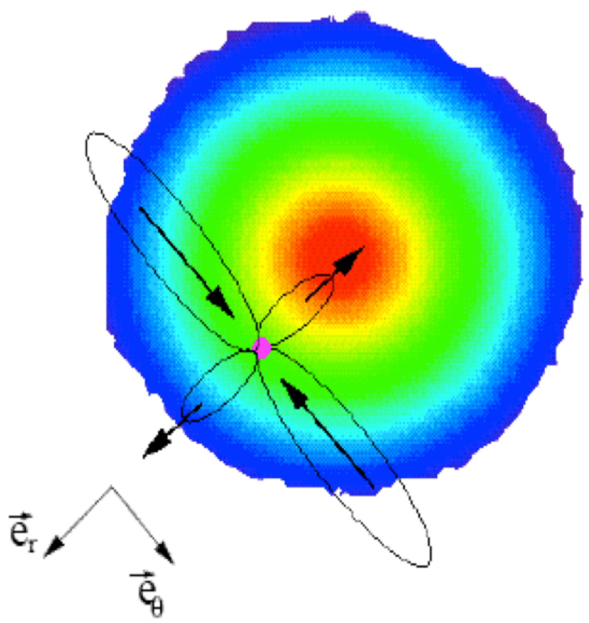
Polarization fraction

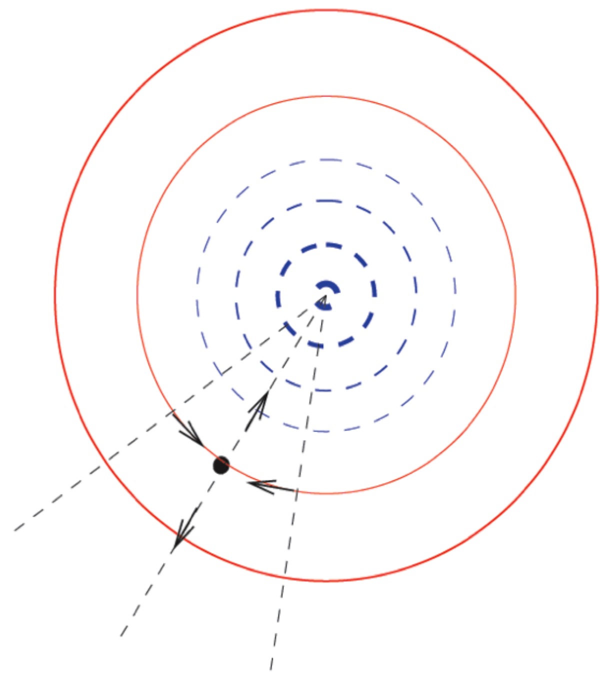
$$p = \frac{P}{I}$$

Polarization angle

$$\gamma = \frac{1}{2}\arctan\left(\frac{U}{Q}\right)$$

The CMB polarization

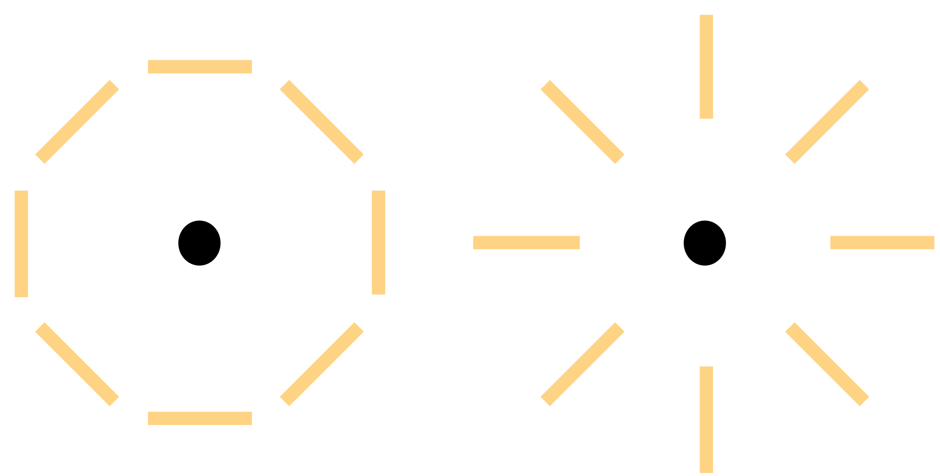




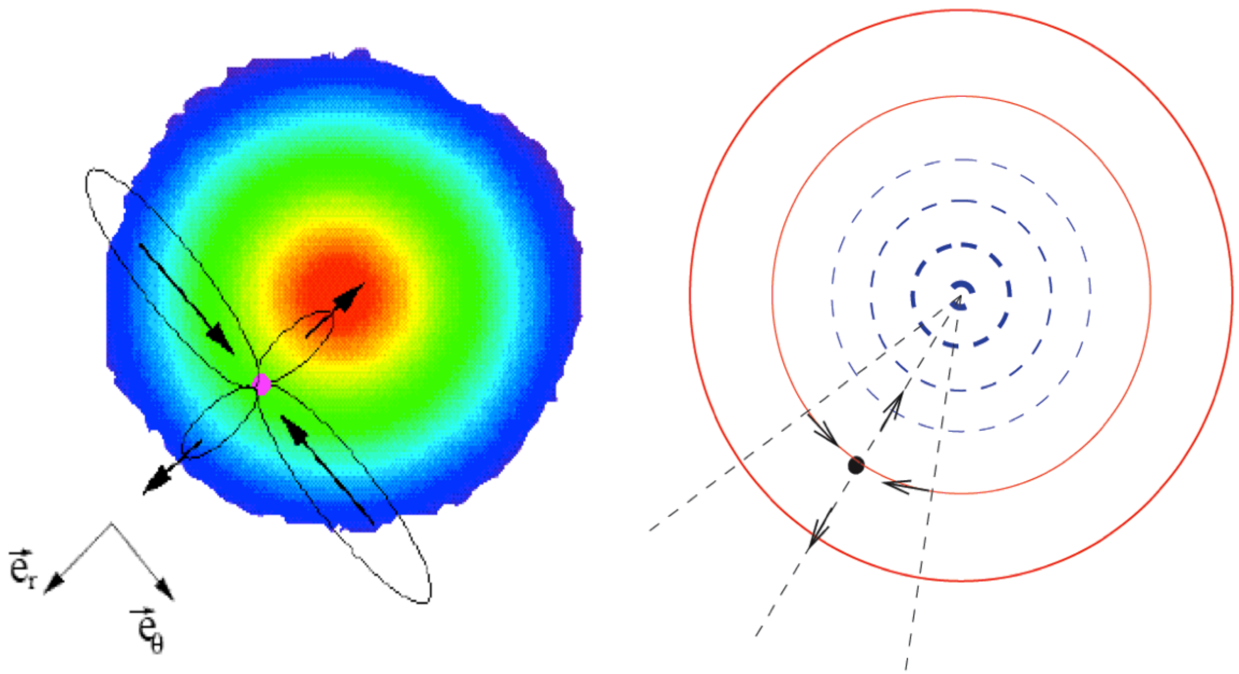
Scalar perturbations

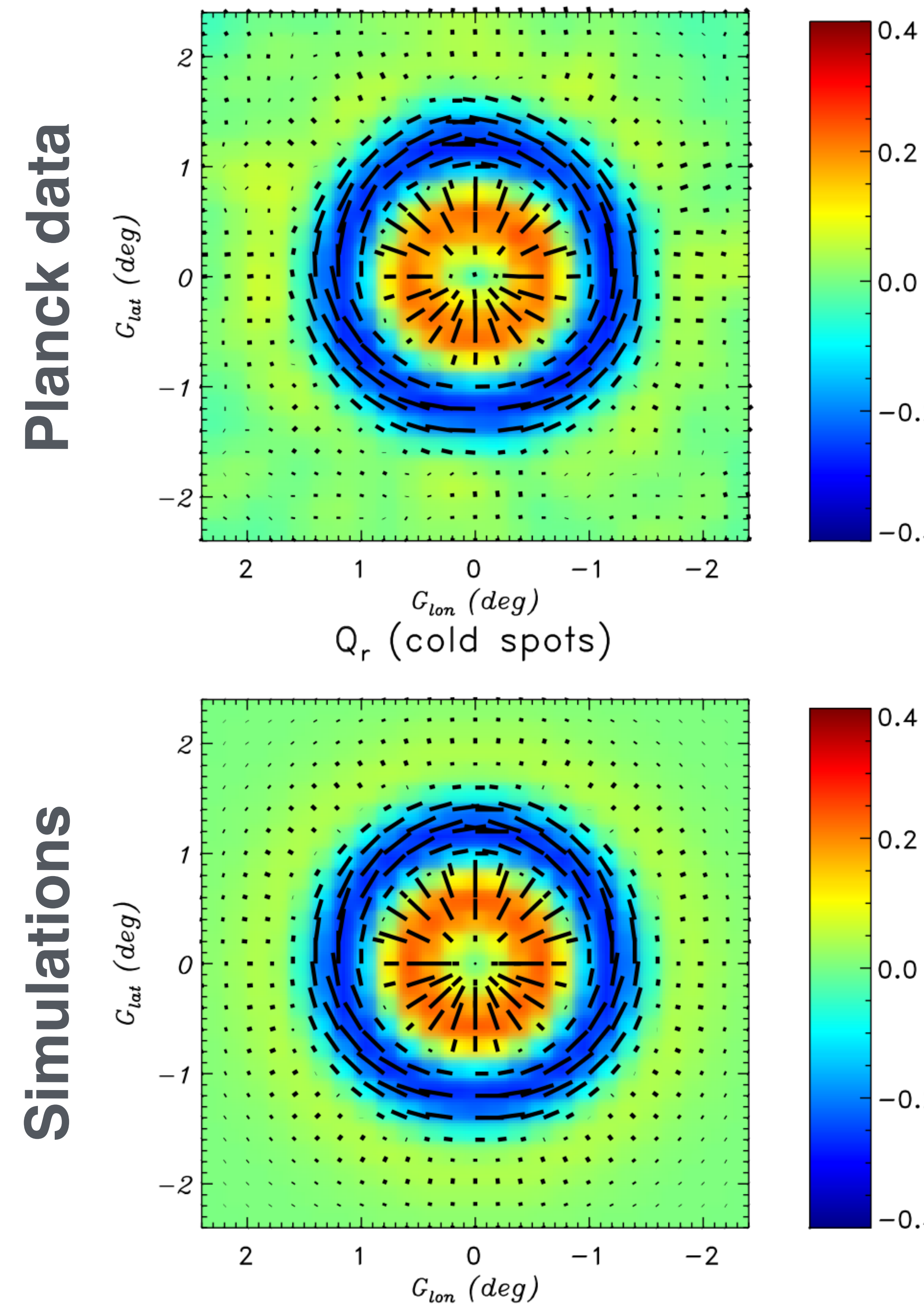
Density perturbations

Generate Q_r polarization

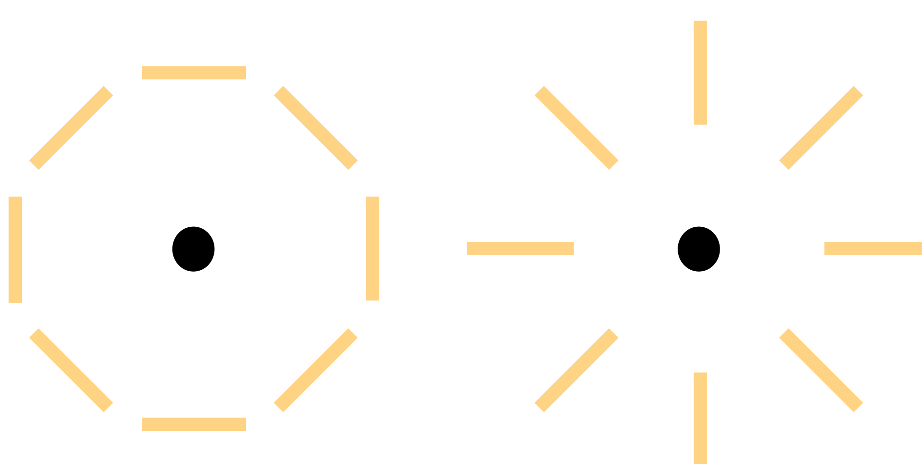


The CMB polarization



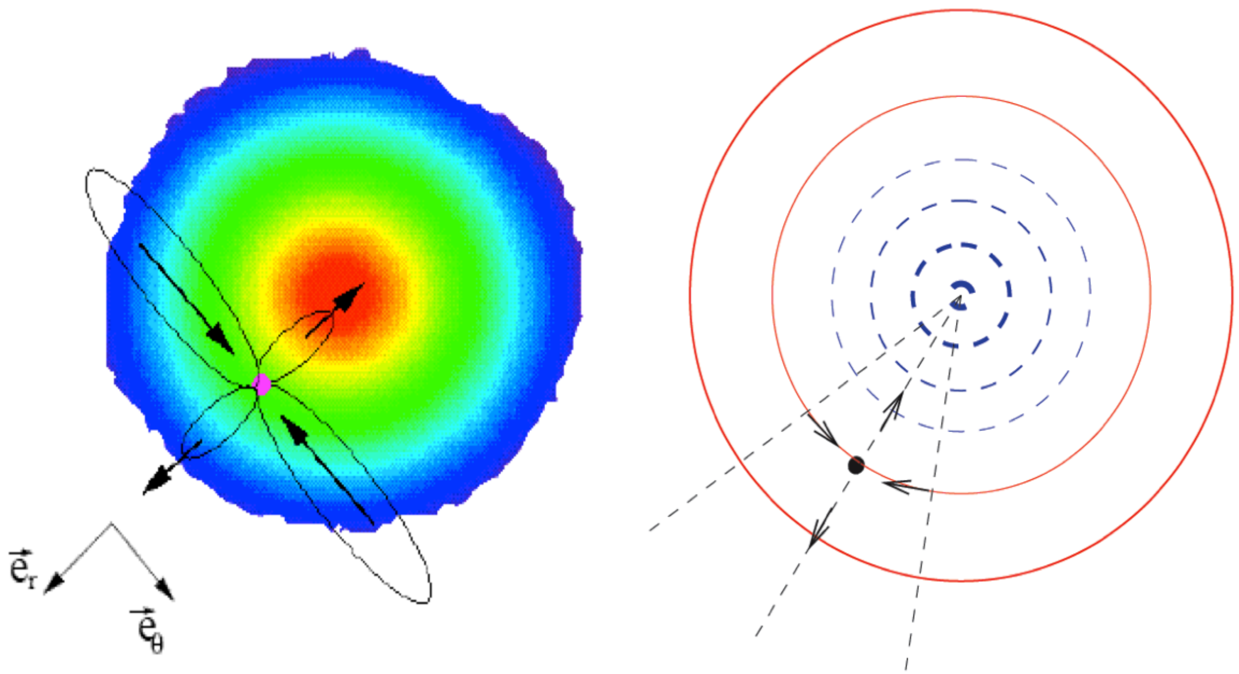


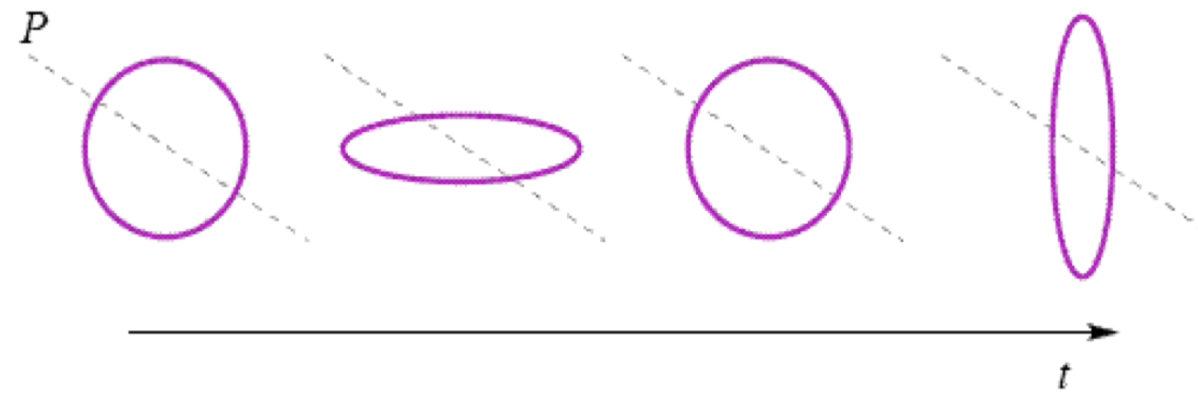
Scalar perturbations
Density perturbations
Generate Q_r polarization



[Planck Collaboration 2013]

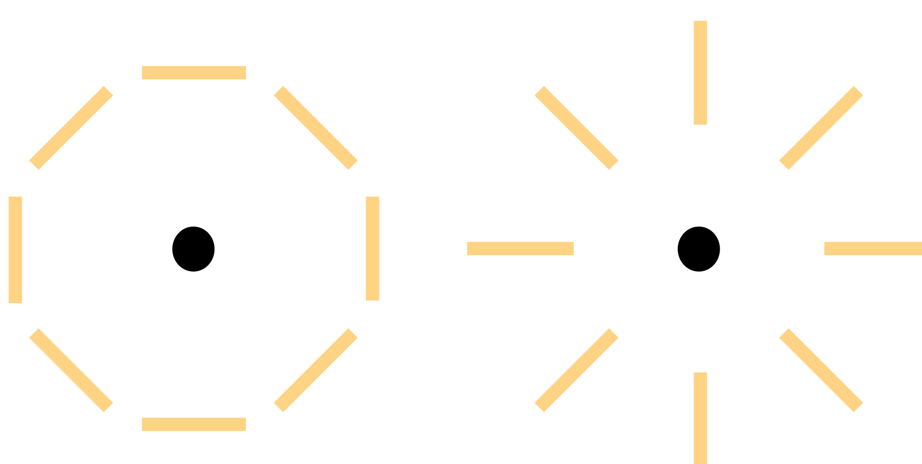
The CMB polarization

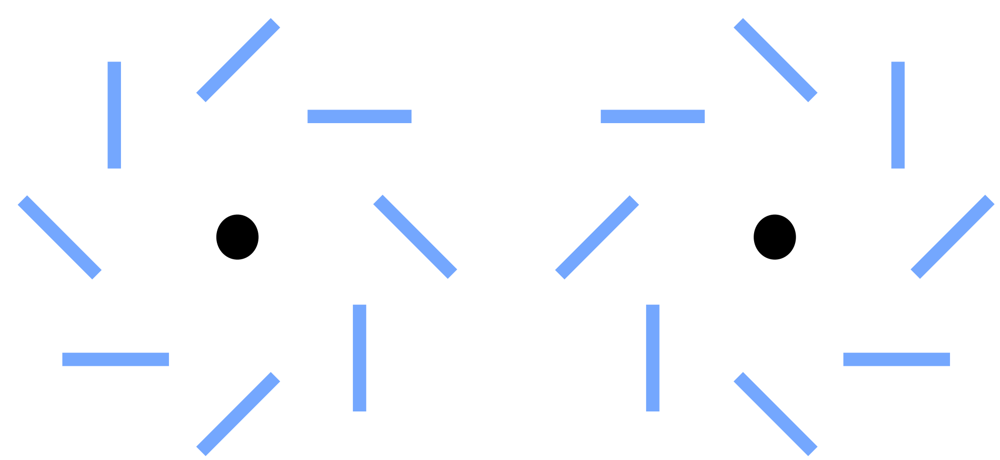




Scalar perturbations
Density perturbations
Generate Q_r polarization

Tensor perturbations
Primordial gravitational waves
Generate Q_r and U_r polarization





The CMB polarization

★ Intensity: projection into spherical harmonics

$$\frac{\Delta T(\mathbf{n})}{T_0} = \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} a^T_{\ell m} Y_{\ell m}(\mathbf{n})$$

★ Polarization: projection into spinned spherical harmonics

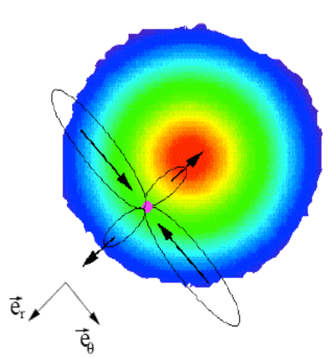
$$(Q \pm iU)(\mathbf{n}) = \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} a_{\pm 2 \ell m} \cdot {}_{\pm 2}Y_{\ell m}(\mathbf{n})$$

$$a^E_{\ell m} = -\frac{a_{2\ell m} + a_{-2\ell m}}{2}$$

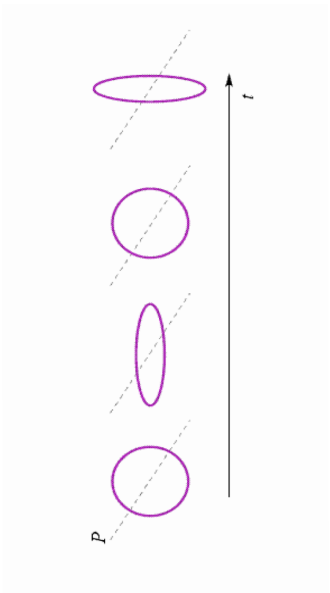
$$E(\mathbf{n}) \equiv \sum_{\ell,m} a^E_{\ell m} Y_{\ell m} = \int w(\mathbf{n} - \mathbf{n}') Q_r(\mathbf{n}') d\mathbf{n}'$$

$$a^B_{\ell m} = i\frac{a_{2\ell m} - a_{-2\ell m}}{2}$$

$$B(\mathbf{n}) \equiv \sum_{\ell,m} a^B_{\ell m} Y_{\ell m} = \int w(\mathbf{n} - \mathbf{n}') U_r(\mathbf{n}') d\mathbf{n}'$$

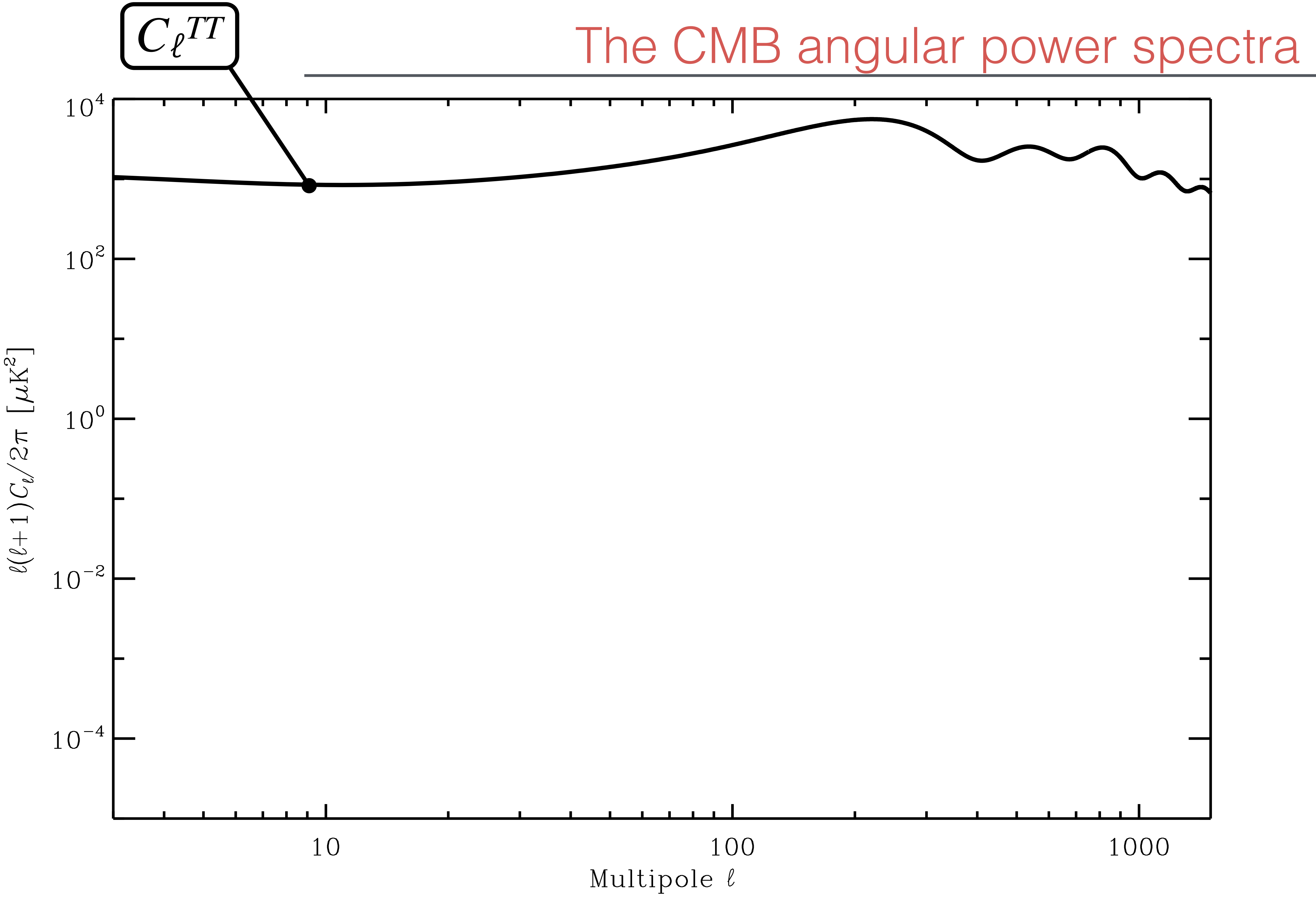


Scalar perturbations
Generate Q_r,
thus E

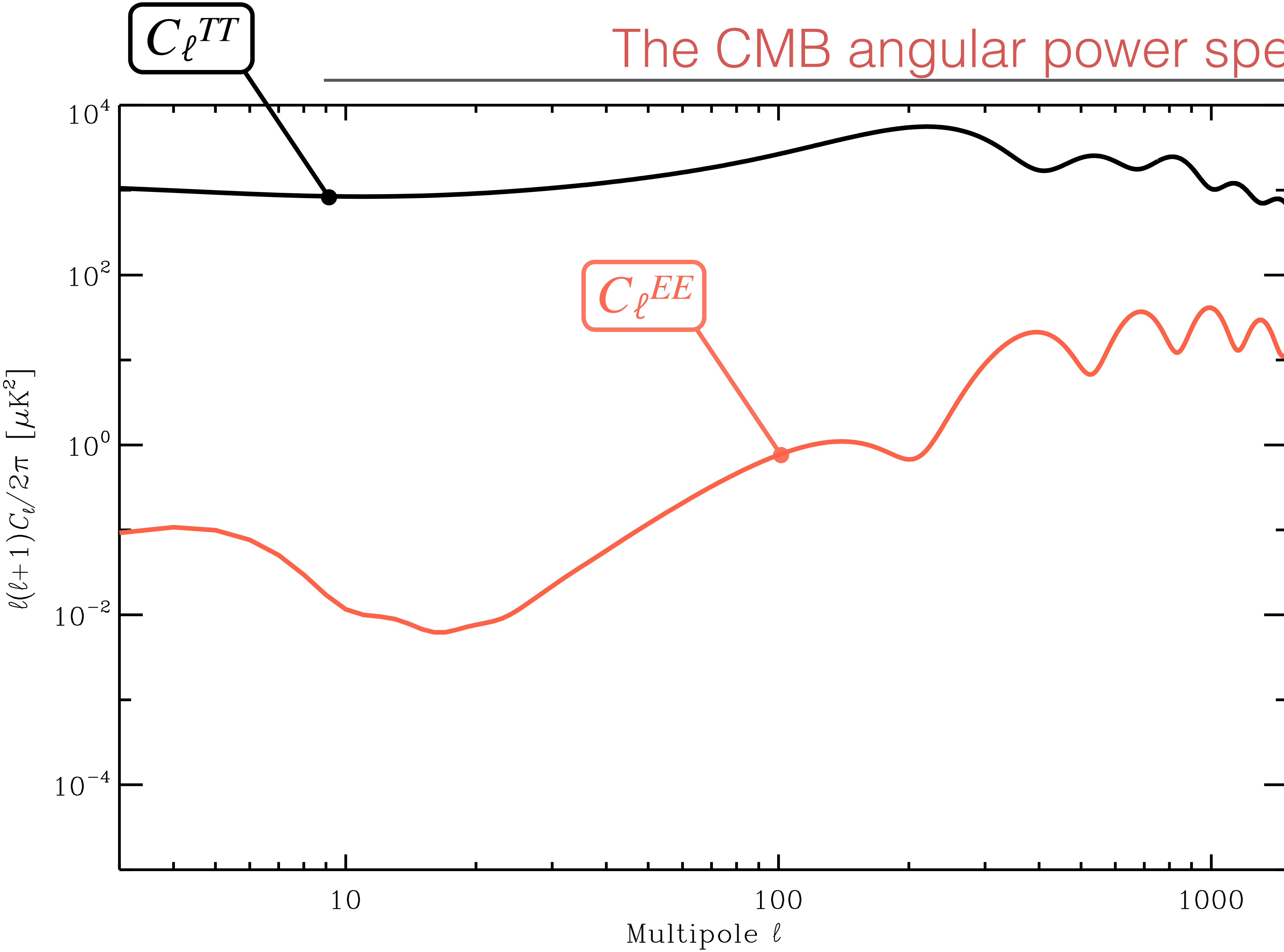


Tensor perturbations
Generate Q_r and U_r,
thus E and B

The CMB angular power spectra



The CMB angular power spectra



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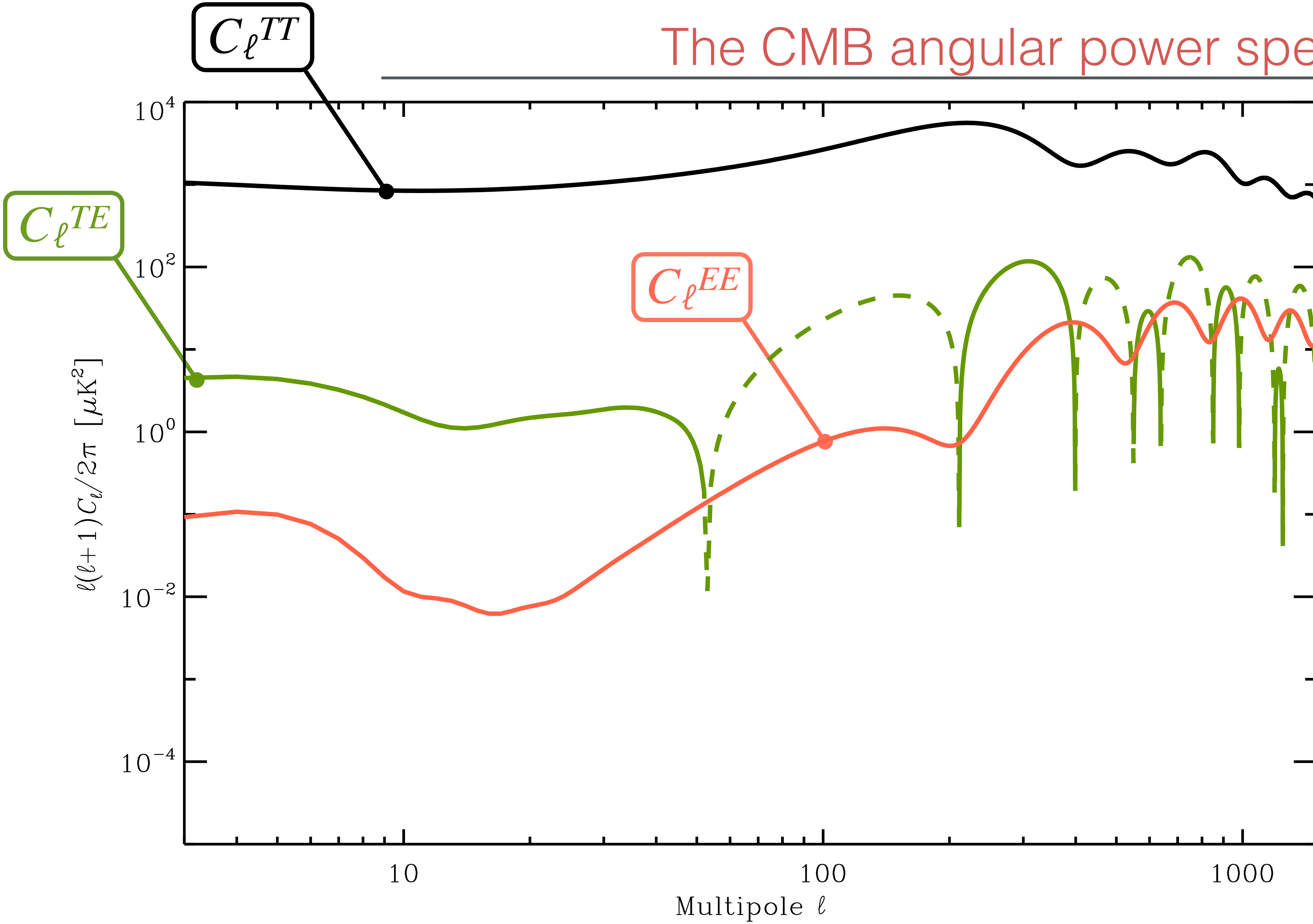
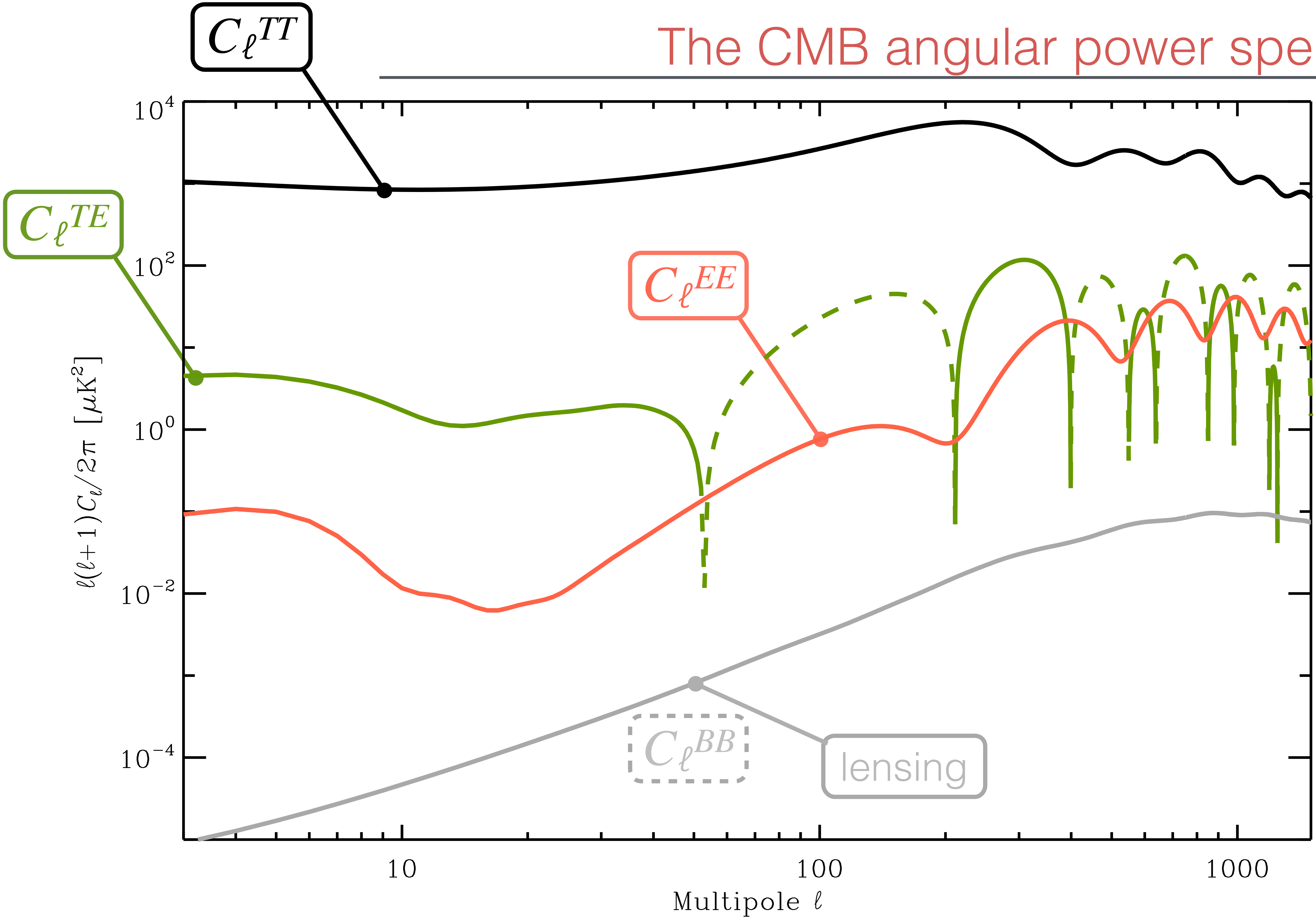
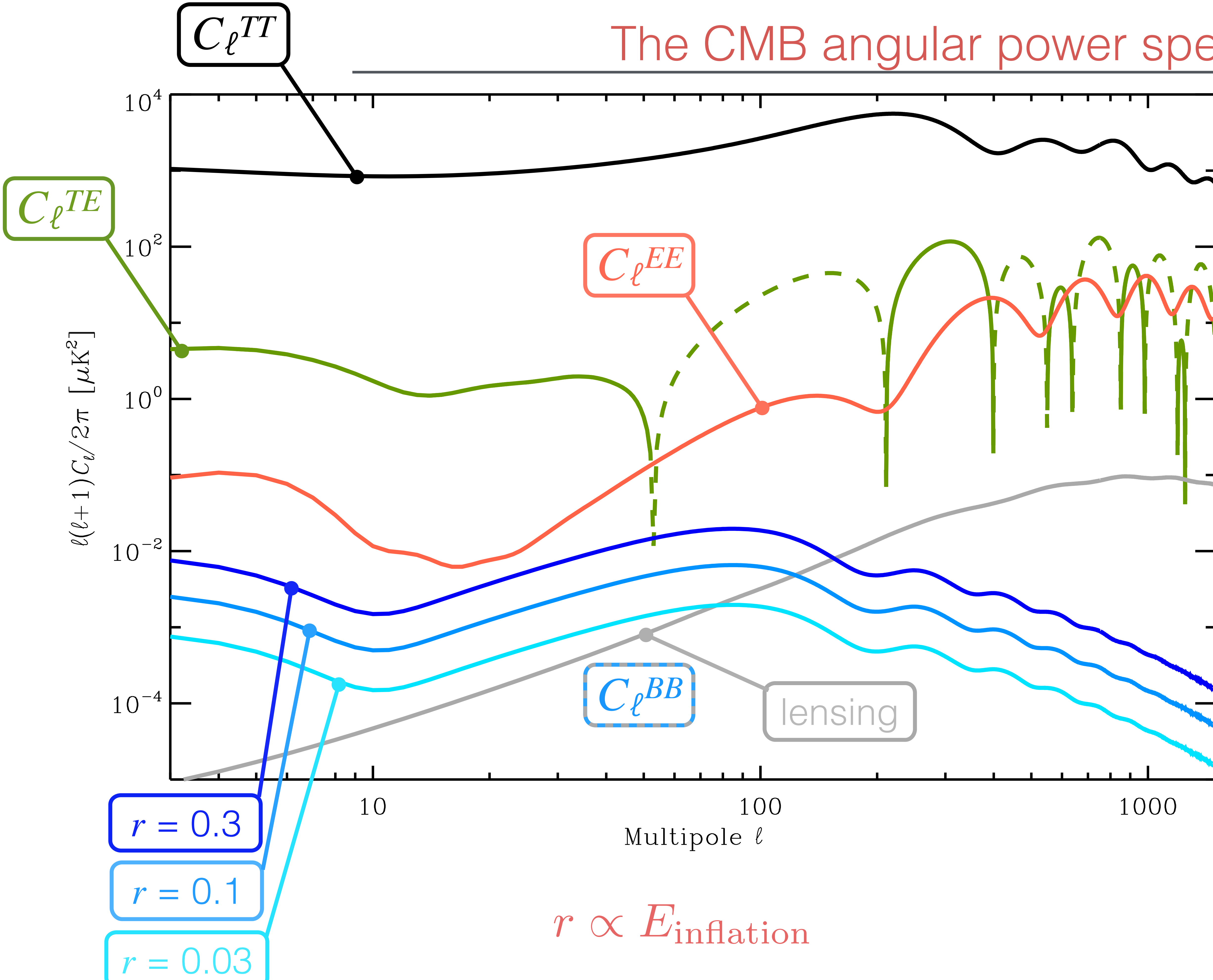


The CMB angular power spectra



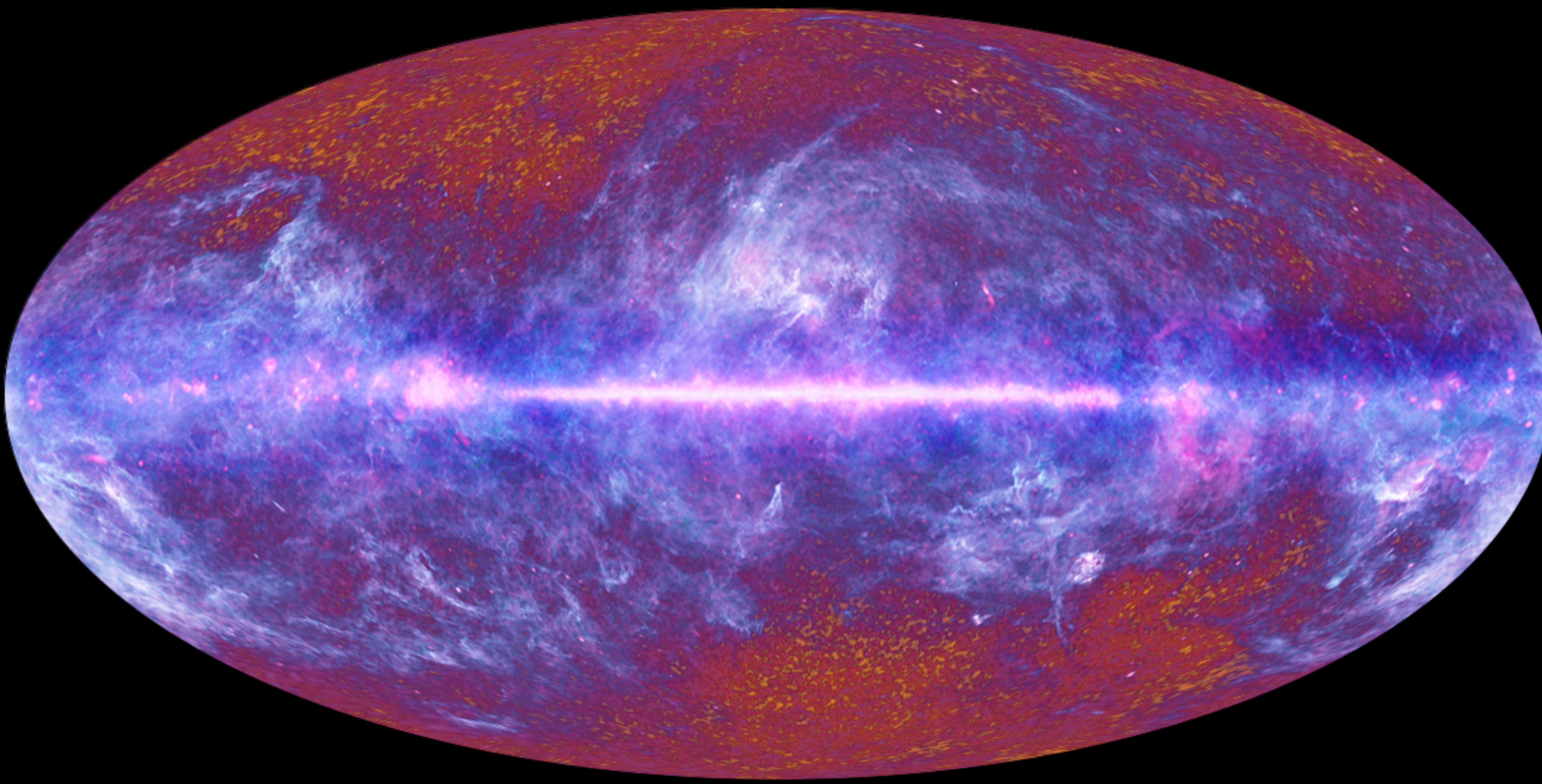
The CMB angular power spectra



$r \propto E_{\text{inflation}}$

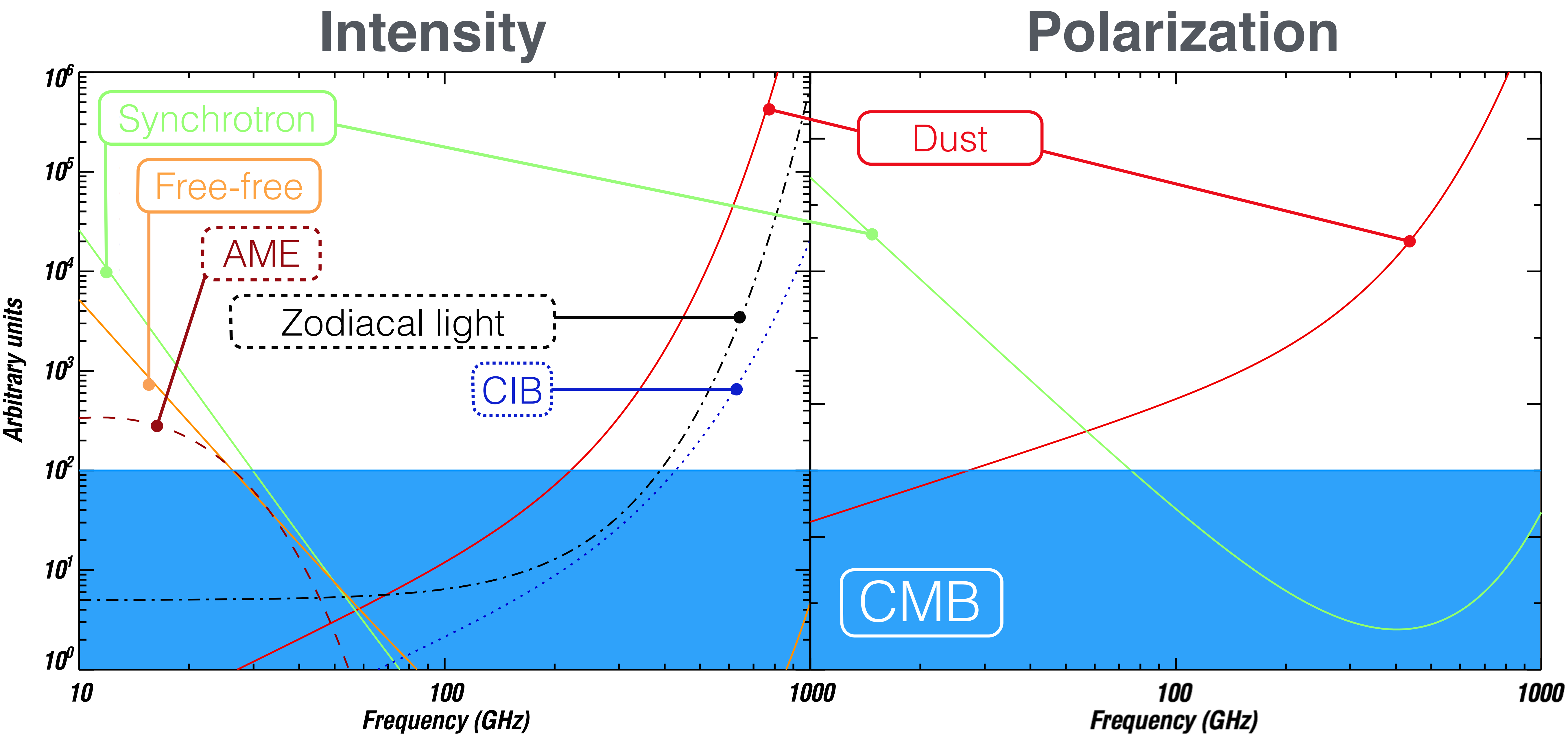
The CMB foreground emissions

30 GHz 40 GHz 70 GHz 100 GHz 143 GHz 217 GHz 353 GHz 545 GHz 857 GHz



[Planck Collaboration 2011]

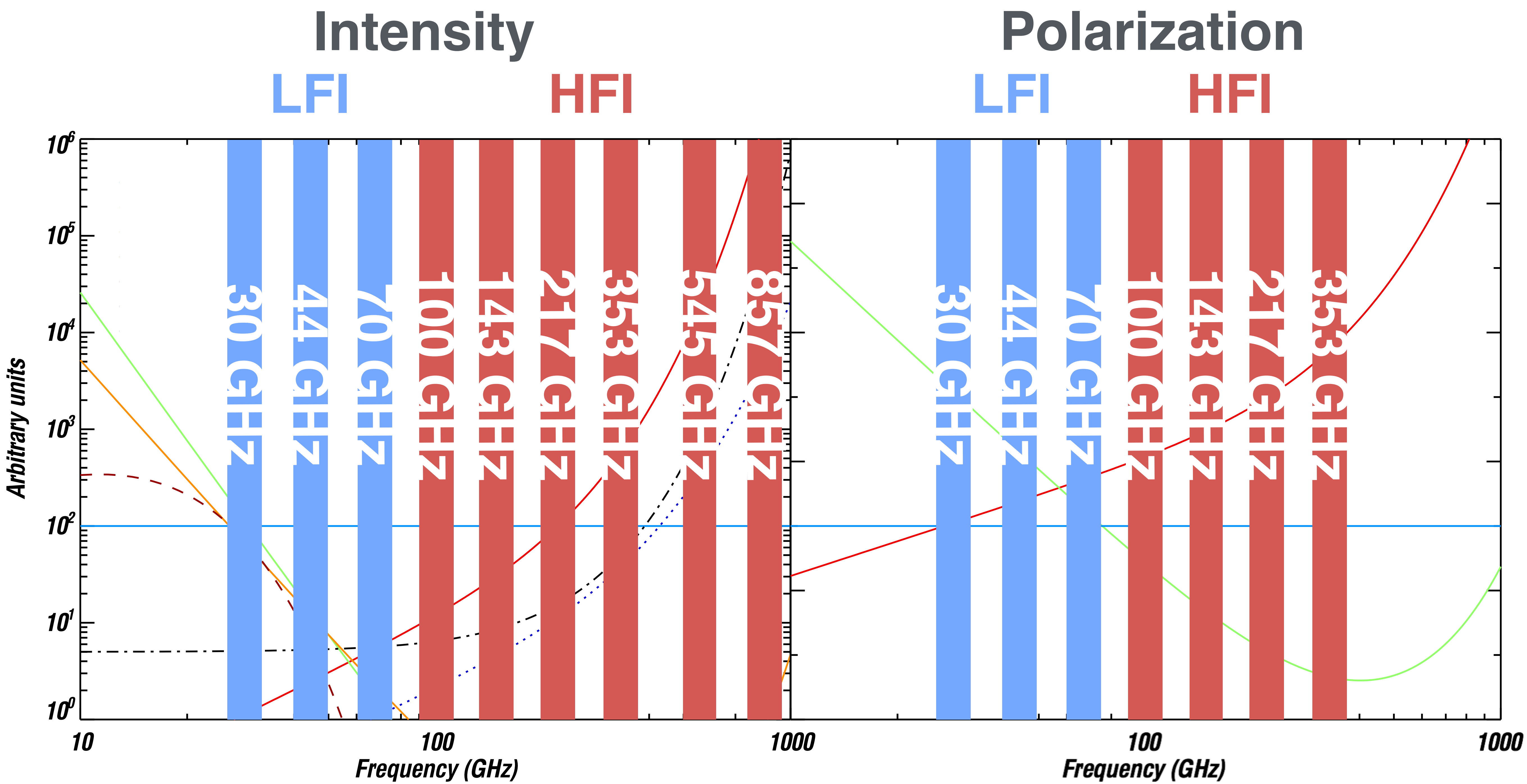
The CMB foreground emissions



★ The polarized sky is more "simple" than the intensity one

★ The CMB is less polarized than its foregrounds

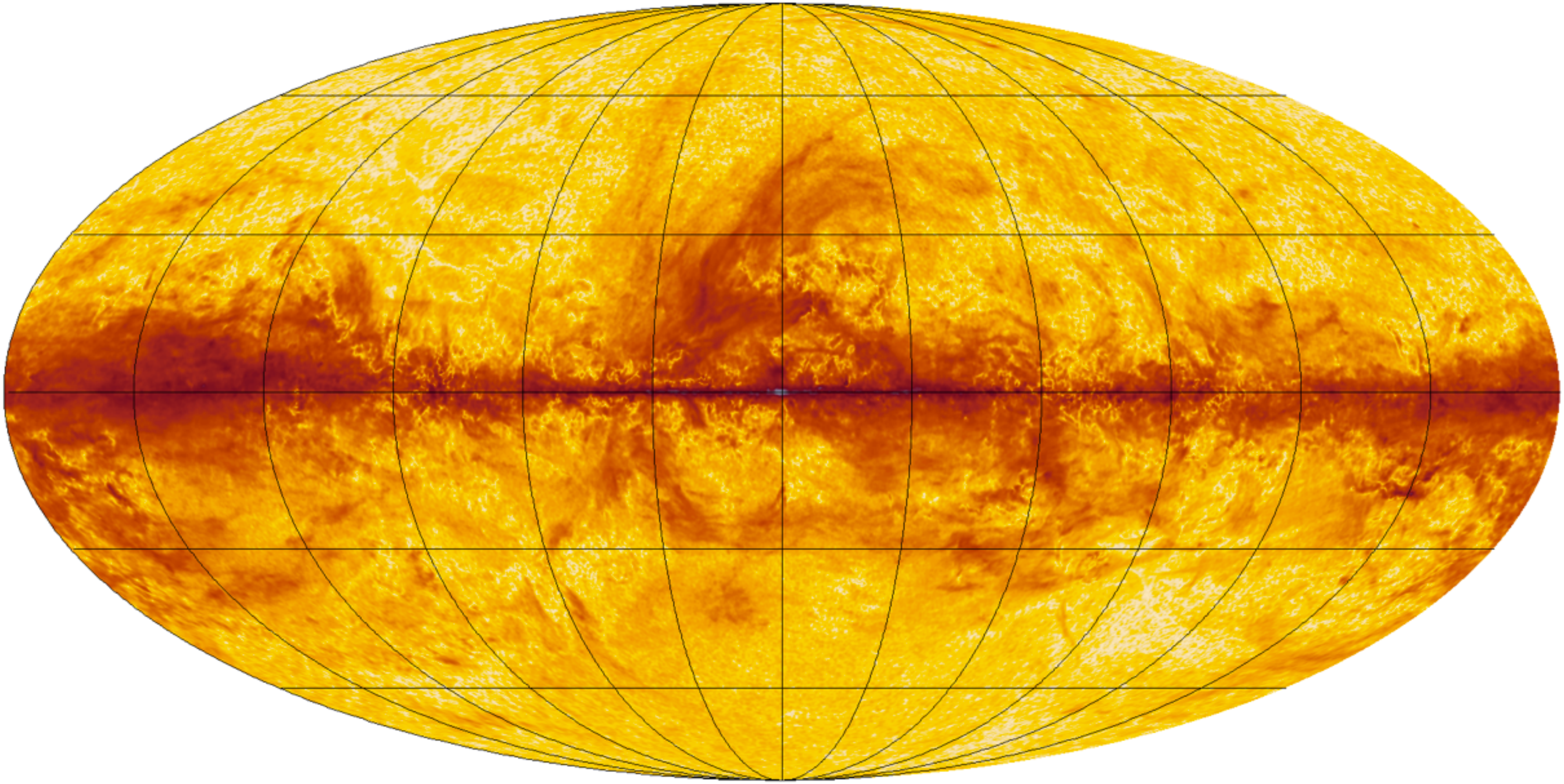
The CMB foreground emissions



- ★ The polarized sky is more "simple" than the intensity one
- ★ The CMB is less polarized than its foregrounds

The polarized emission of dust

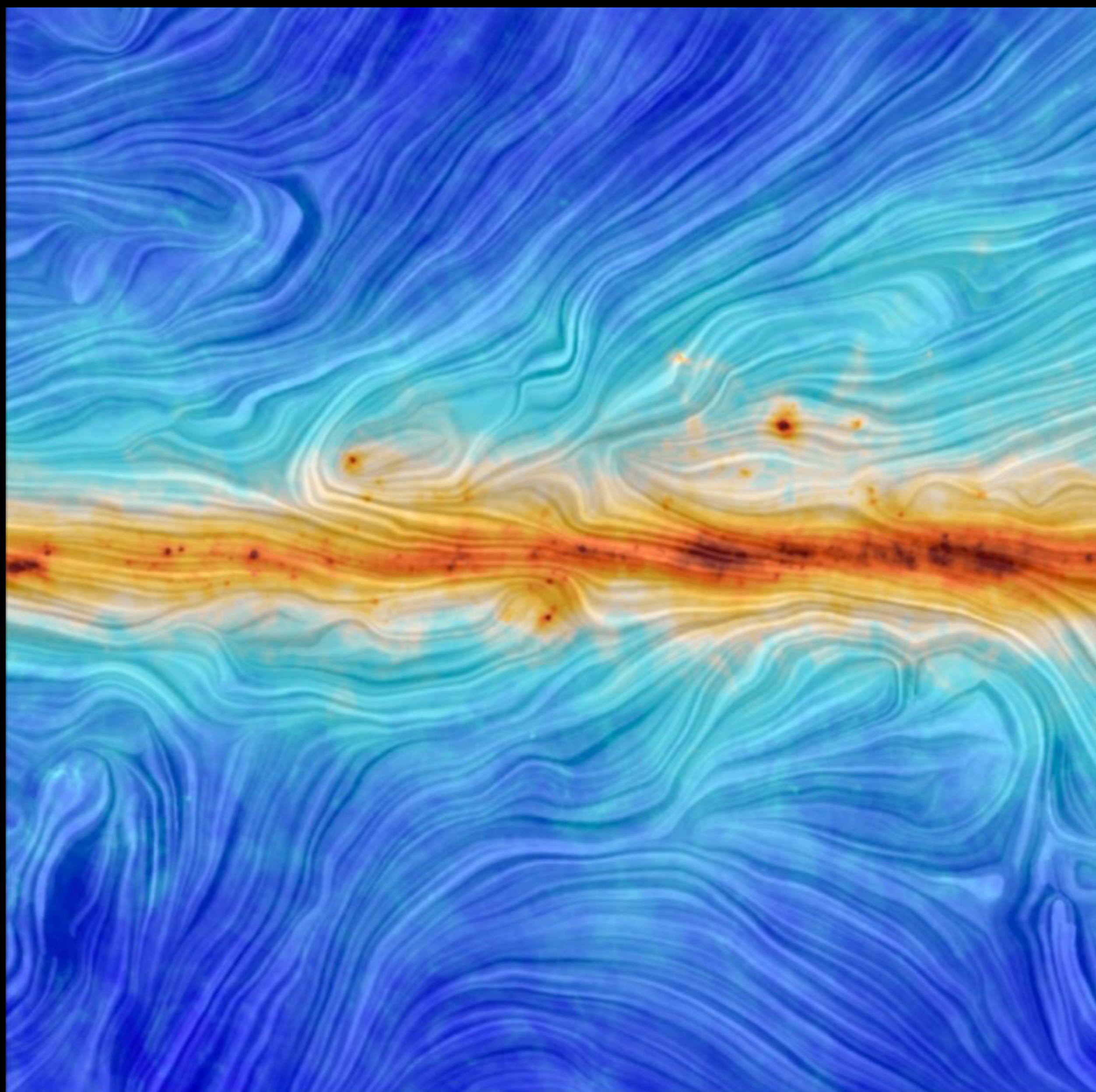
P 353 GHz



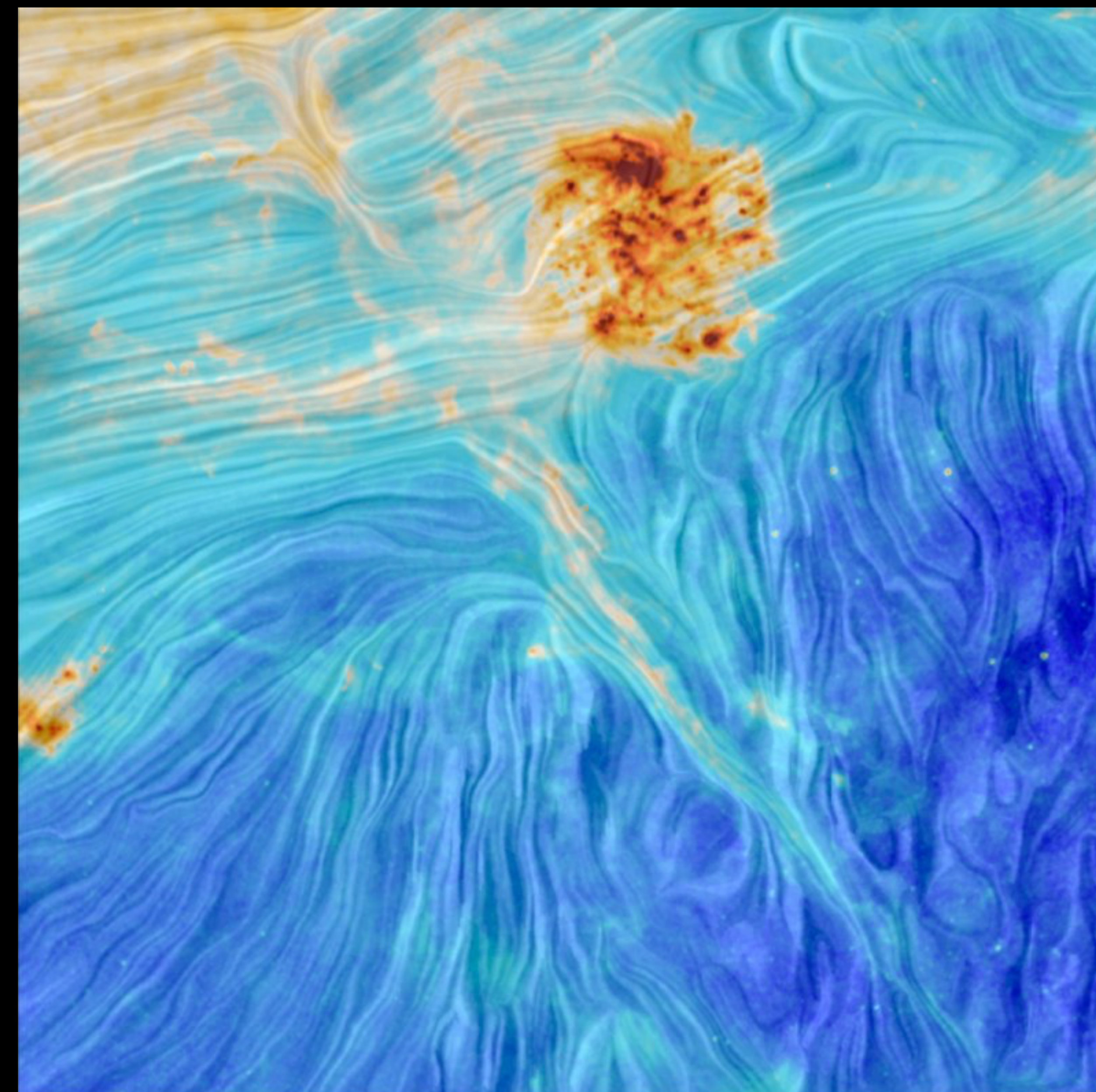
★Planck unveils a "new" sky!

[Planck Collaboration 2014]

The polarized emission of dust



[G_{lon} = 35°, G_{lat} = 0°]



[G_{lon} = 282°, G_{lat} = -42°]

★ The polarized emission of dust is due to the interplay of the Galactic magnetic field and the interstellar matter

[Planck Collaboration 2014]

Outline

1. The polarization of the Cosmic Microwave Background
2. Statistical measurement of the Galactic dust polarized emission with Planck
3. Implications for the BICEP2 experiment measurements

Motivation of this work

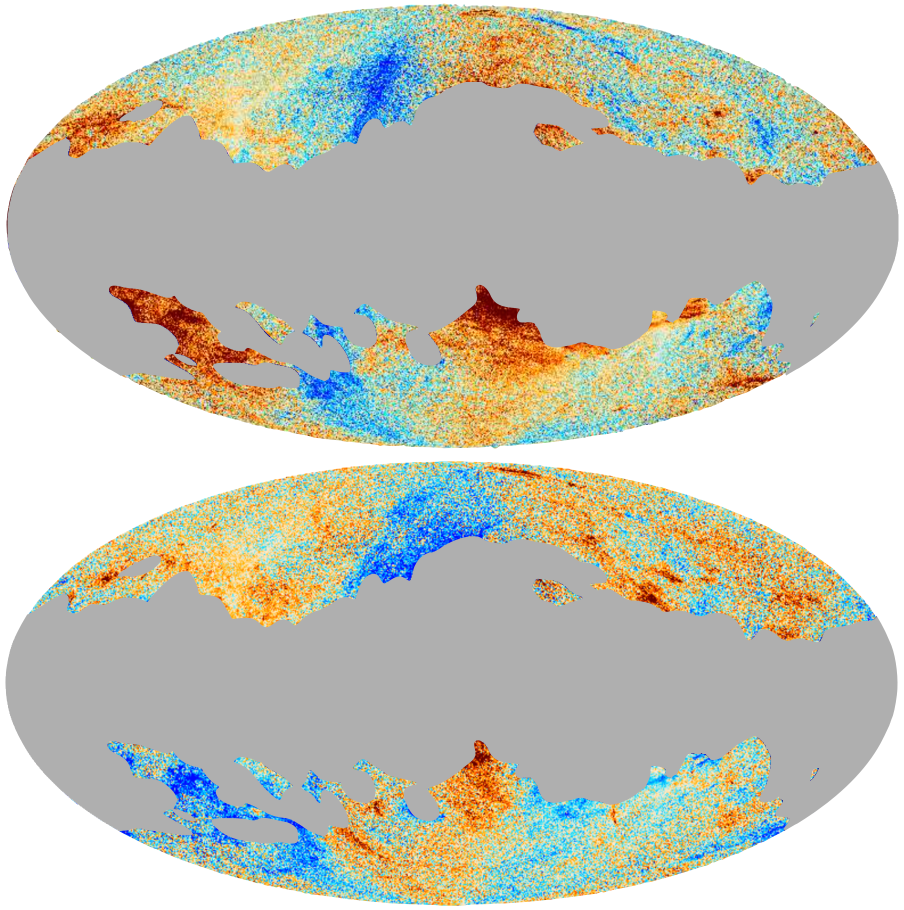
★ Study statistically the polarized emission from interstellar dust, in the formalism used to study the CMB, using the angular power spectra

1. Draw some general properties that can be used for the cosmological analysis or for component separation

2. Quantify the contamination of CMB measurements by polarized dust

3. Give constraints for Galactic magnetic field and Galactic dust models

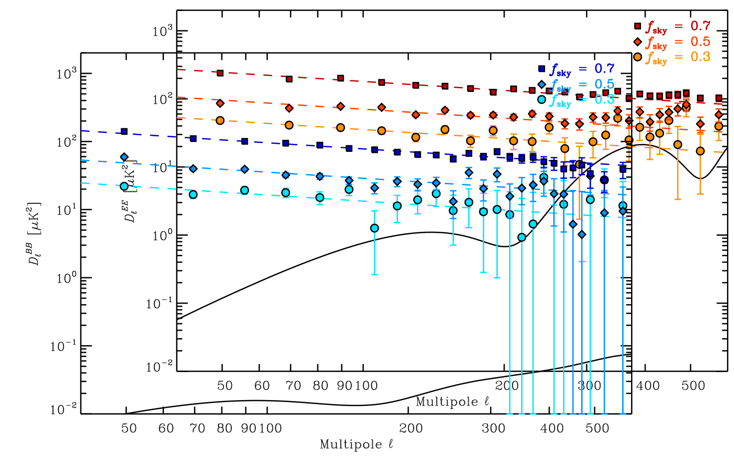
General methodology



PLANCK
Q and U maps at 353 GHz

XPOL
pseudo-C_ℓ estimator
based on **XSPECT**
[Tristram et al. 2005]

Corrects for incomplete sky coverage, pixel and beam window functions



Angular power spectra
C_ℓ^{EE} and C_ℓ^{BB}

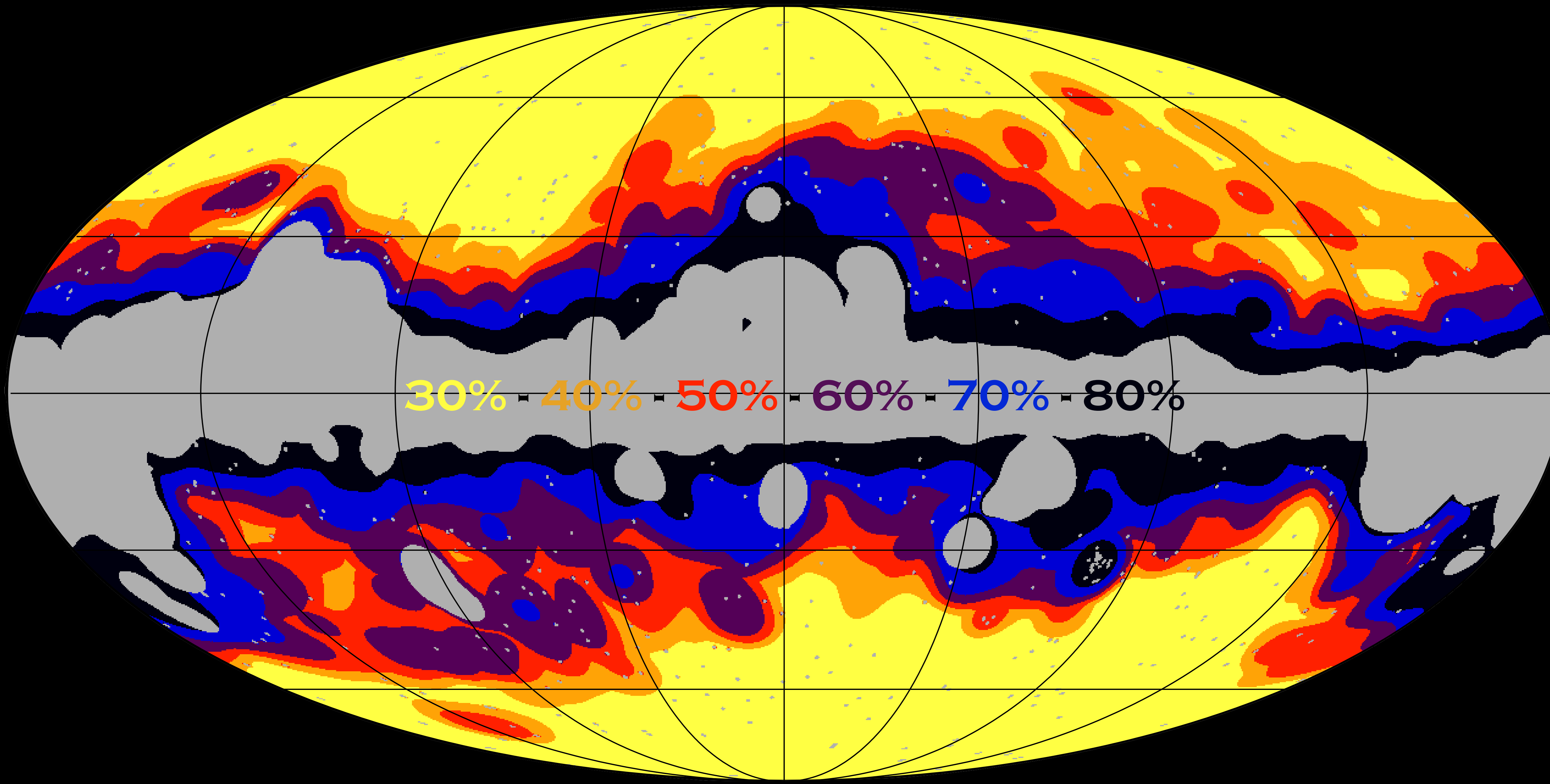
Spectra are computed from the two noise-independent Detector Set maps

$$C_\ell(\nu \times \nu) \equiv C_\ell(D^1_\nu \times D^2_\nu)$$

The CMB C_ℓ^{EE} best fit model is removed
[Planck Collaboration XIV 2014]

Large sky fraction regions

Masks: built from the smoothed (10 degrees) dust intensity map at 857 GHz



+ CO + radio point sources mask + apodization (5 degrees)

[Planck Intermediate XXX 2014, arXiv 1409.5738]

Results

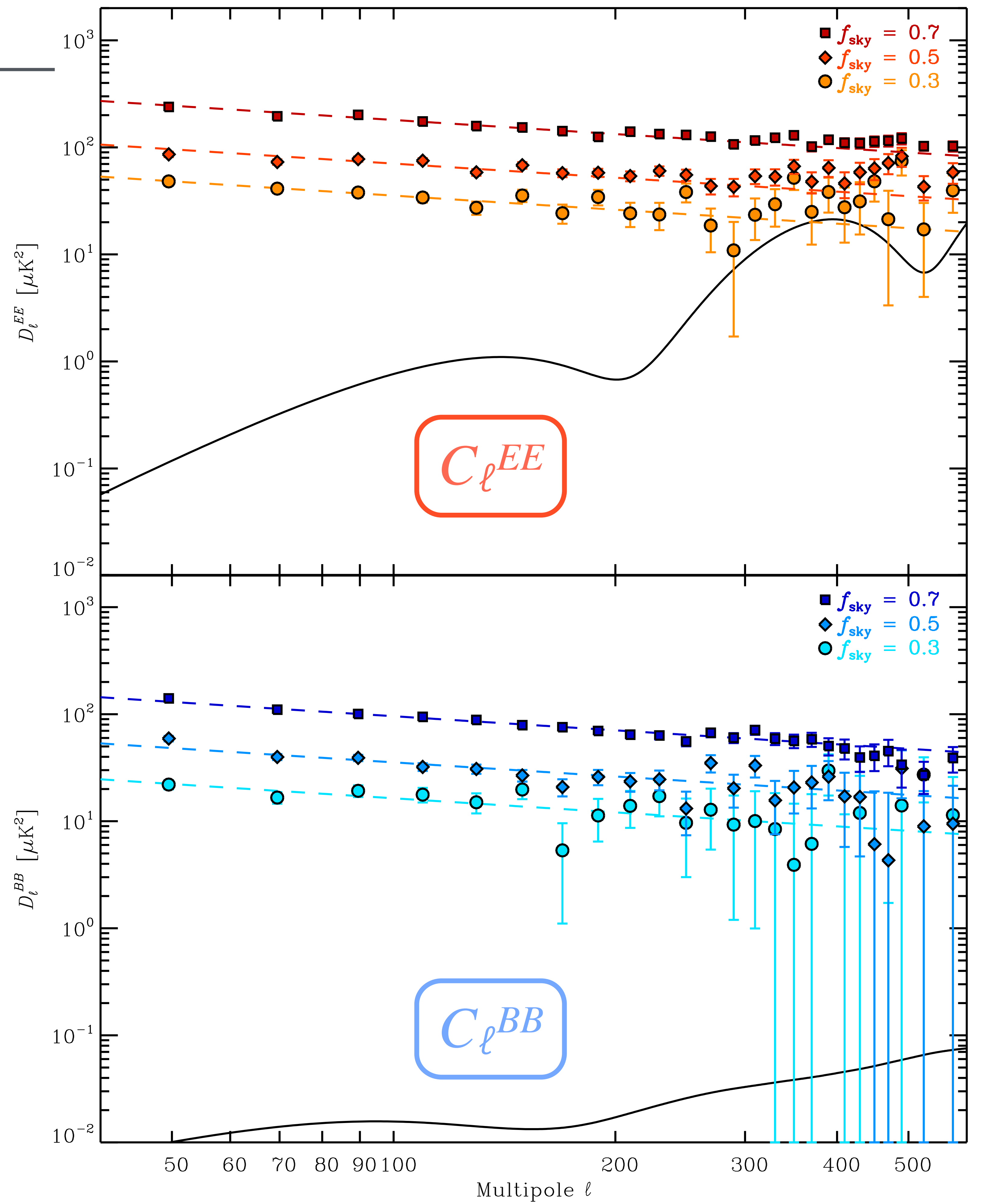
★ 353 GHz *EE* and *BB* angular power spectra

★ First detection of the dust polarized angular power spectra at ℓ>10

★ Even on 30% of the sky, the dust polarized emission dominates the CMB, at all scales

1. Shape of the spectra?
2. Variation of their amplitudes with respect to the mask?
3. *BB*/*EE* ratio?
4. Amplitudes at other frequencies?

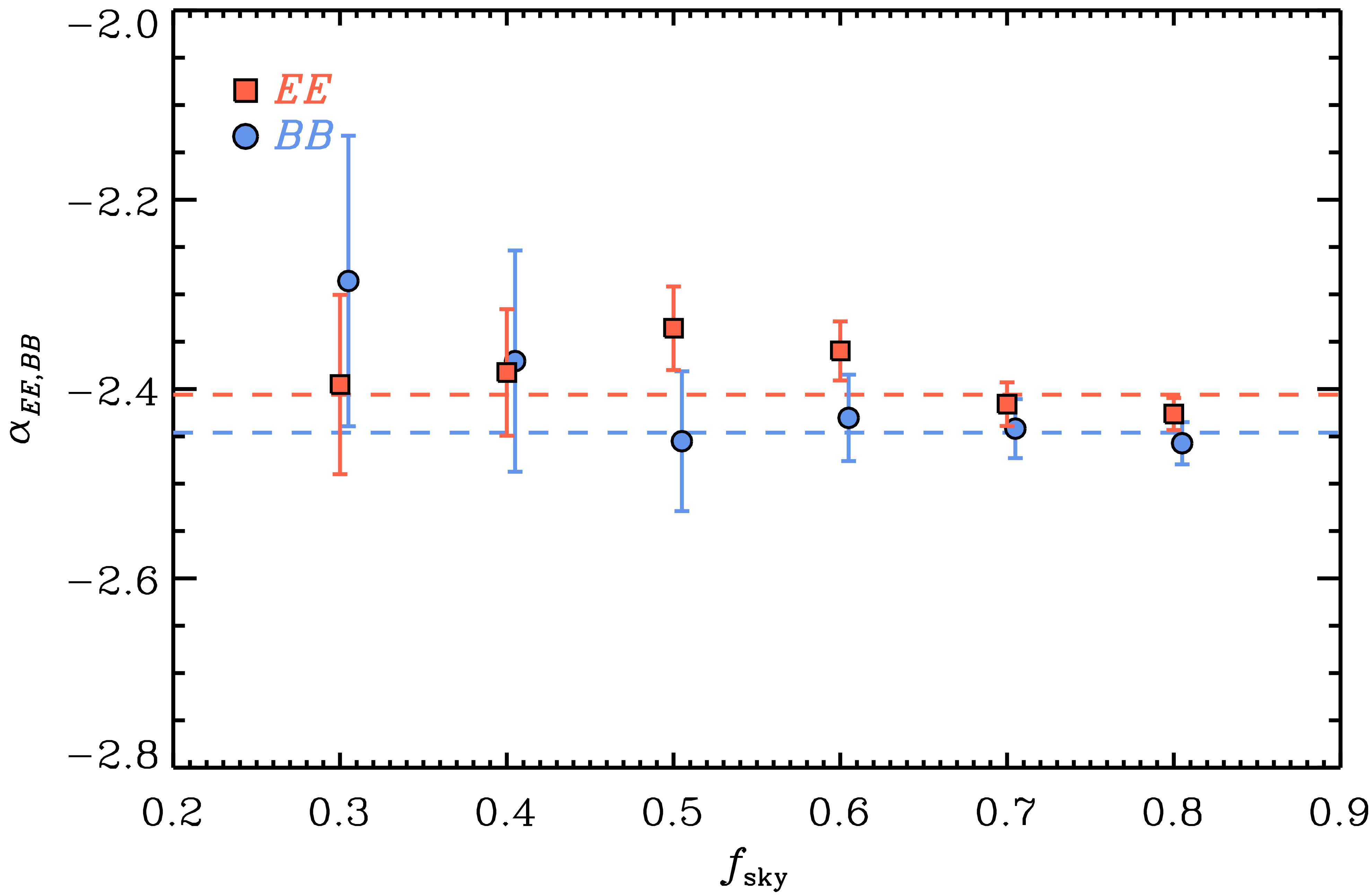
[Planck Intermediate XXX 2014, arXiv 1409.5738]



Shape of the spectra?

Power-law: $C_\ell^{EE,BB} \equiv A^{EE,BB} \ell^{\alpha_{EE,BB}}$

[Planck Intermediate XXX 2014, arXiv 1409.5738]



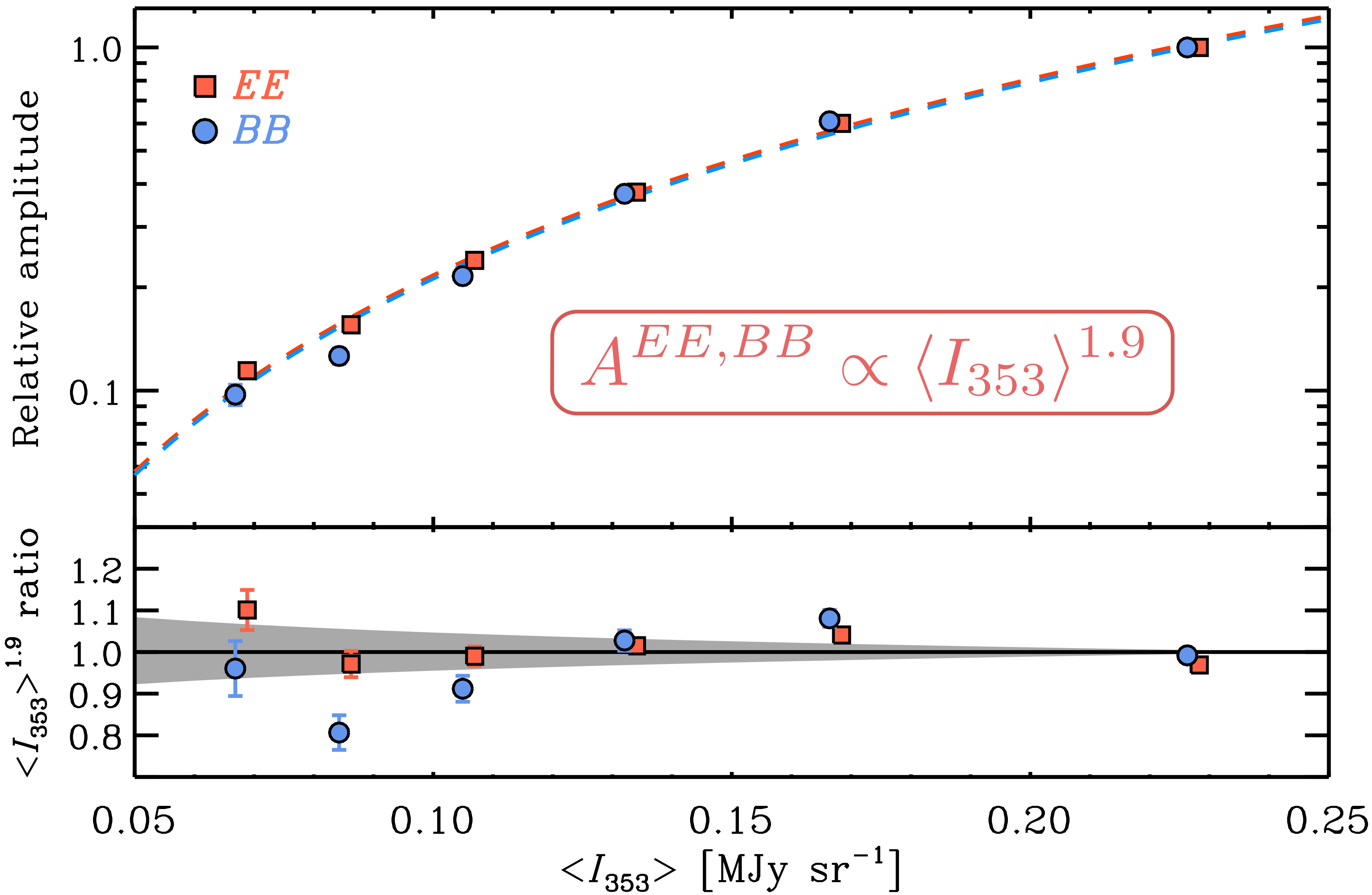
★ The spectra are compatible with power-laws with a -2.42 slope

★ No significant difference between *EE* and *BB*

Amplitude as a function of the mask

$$C_\ell^{EE,BB} \equiv A^{EE,BB} \ell^{-2.42}$$

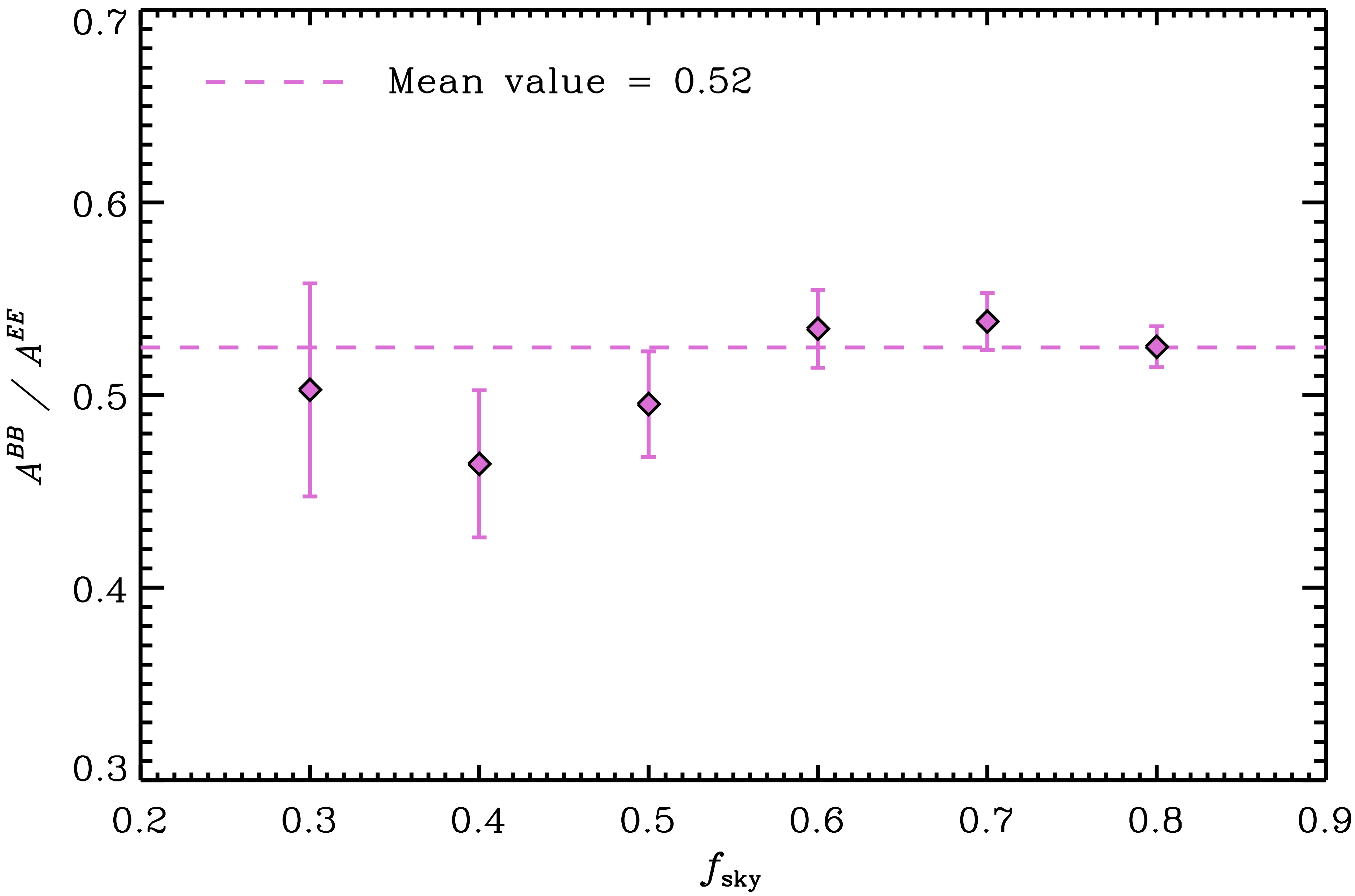
[Planck Intermediate XXX 2014, arXiv 1409.5738]



★ There is an empirical relation between the amplitude and the mean dust intensity on the considered region

BB/*EE* ratio?

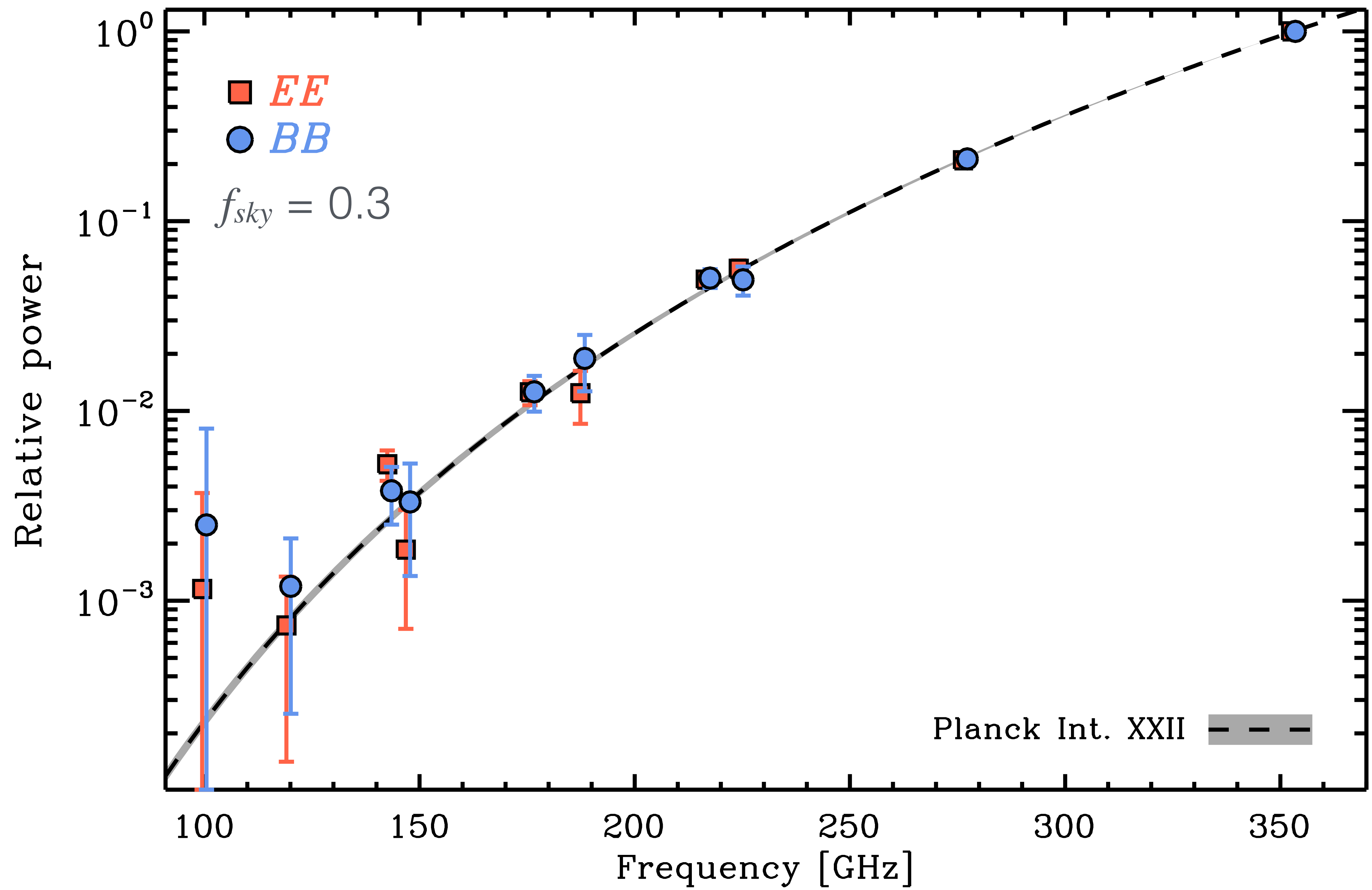
[Planck Intermediate XXX 2014, arXiv 1409.5738]



★ The dust polarized emission produces twice as much *EE* than *BB*
★ The existing dust models give *BB*/*EE*~1

Amplitude as a function of the observing frequency?

[Planck Intermediate XXX 2014, arXiv 1409.5738]
[Planck Intermediate XXII 2014, arXiv 1405.0874]

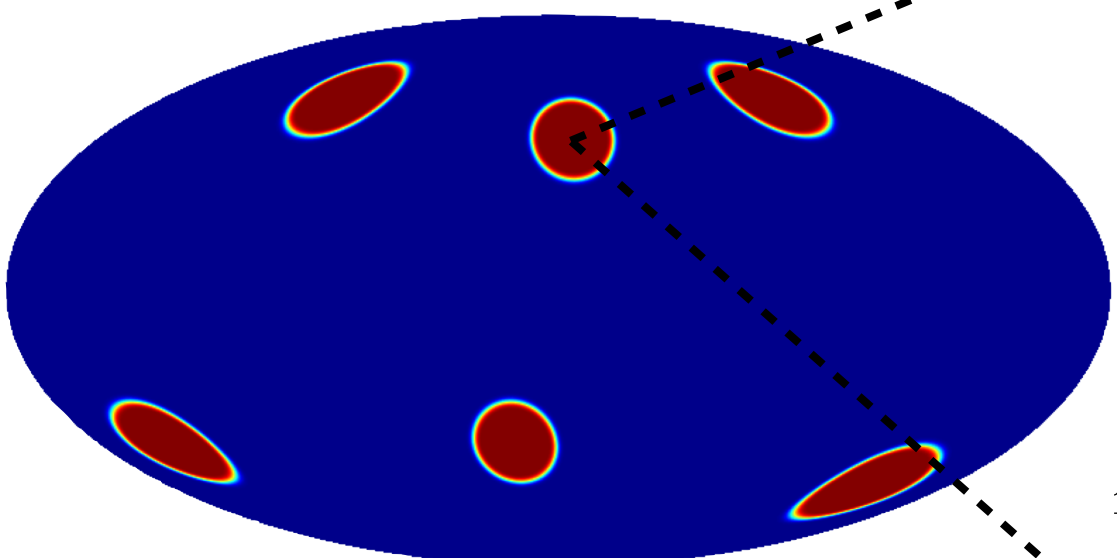


★ The spectra amplitudes follow the frequency dependence of the dust polarization for both *EE* and *BB*

Statistics on 400 deg²

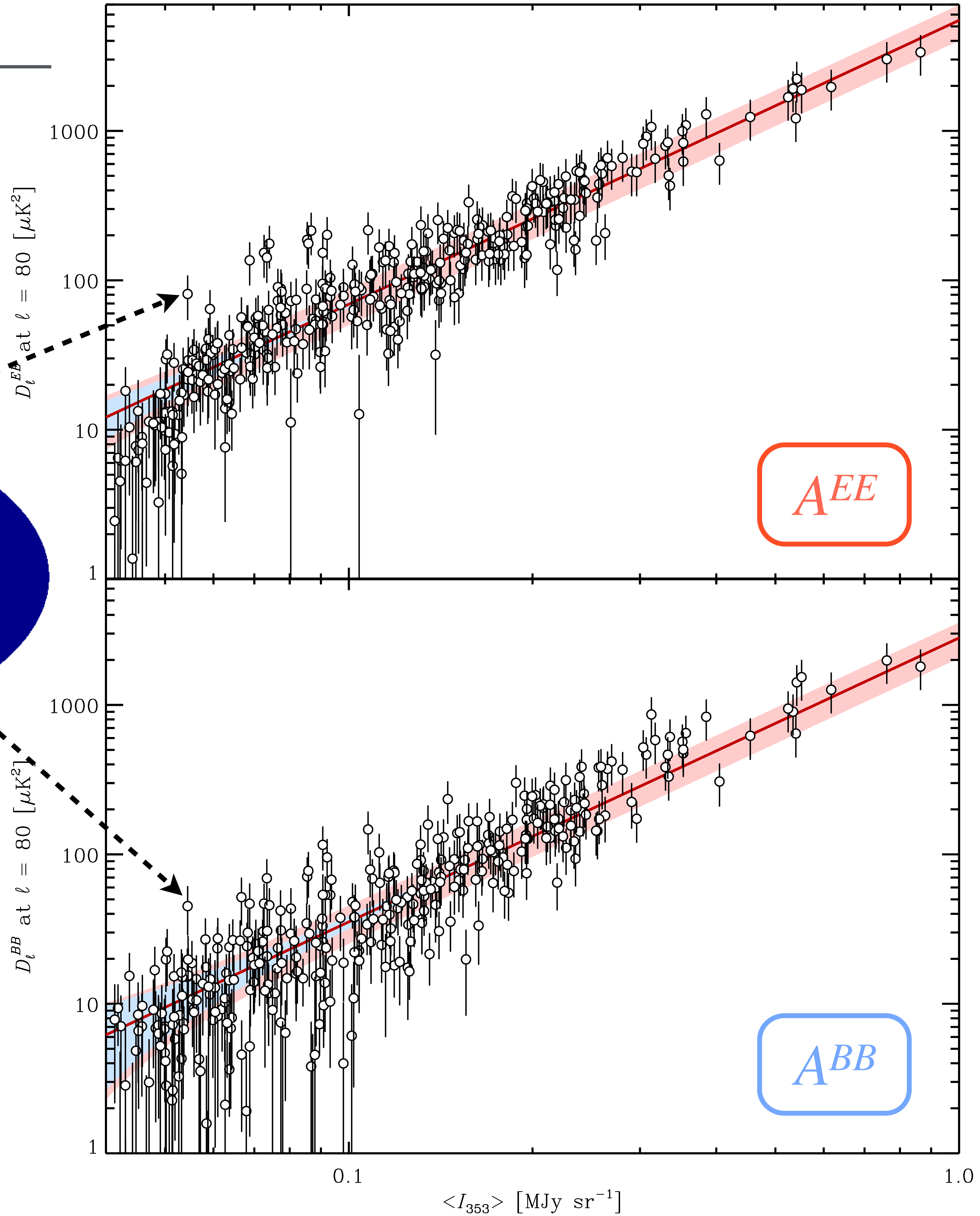
[Planck Intermediate XXX 2014, arXiv 1409.5738]

★ 352 patches with $|b|>35°$



★ Empirical law as a function of the mean dust intensity is also derived for theses patches

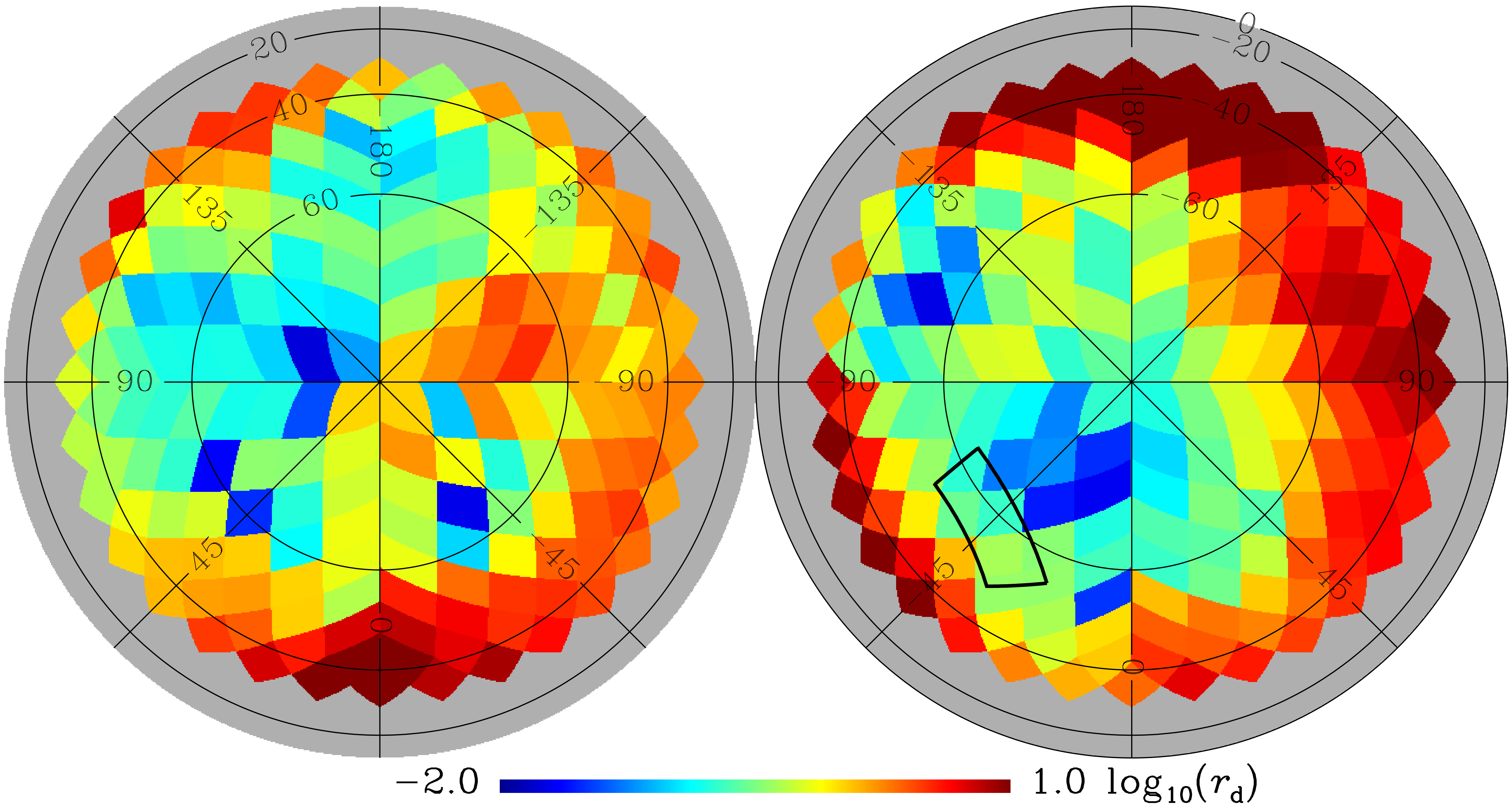
★ The dispersion is higher than it would be expected for a Gaussian process



Statistics on 400 deg²

- ★ Extrapolation of the *BB* amplitudes at 150 GHz
- ★ Amplitudes expressed in units of r_d (*e.g.* r_d = 0.2 means that the dust has the same level as the CMB r = 0.2 à ℓ=80)

[Planck Intermediate XXX 2014, arXiv 1409.5738]



- ★ The cleanest regions of the sky have r_d~0.01±0.06
- ★ In no region the dust polarization can be neglected if one wants to measure the CMB primordial *B*-modes

Outline

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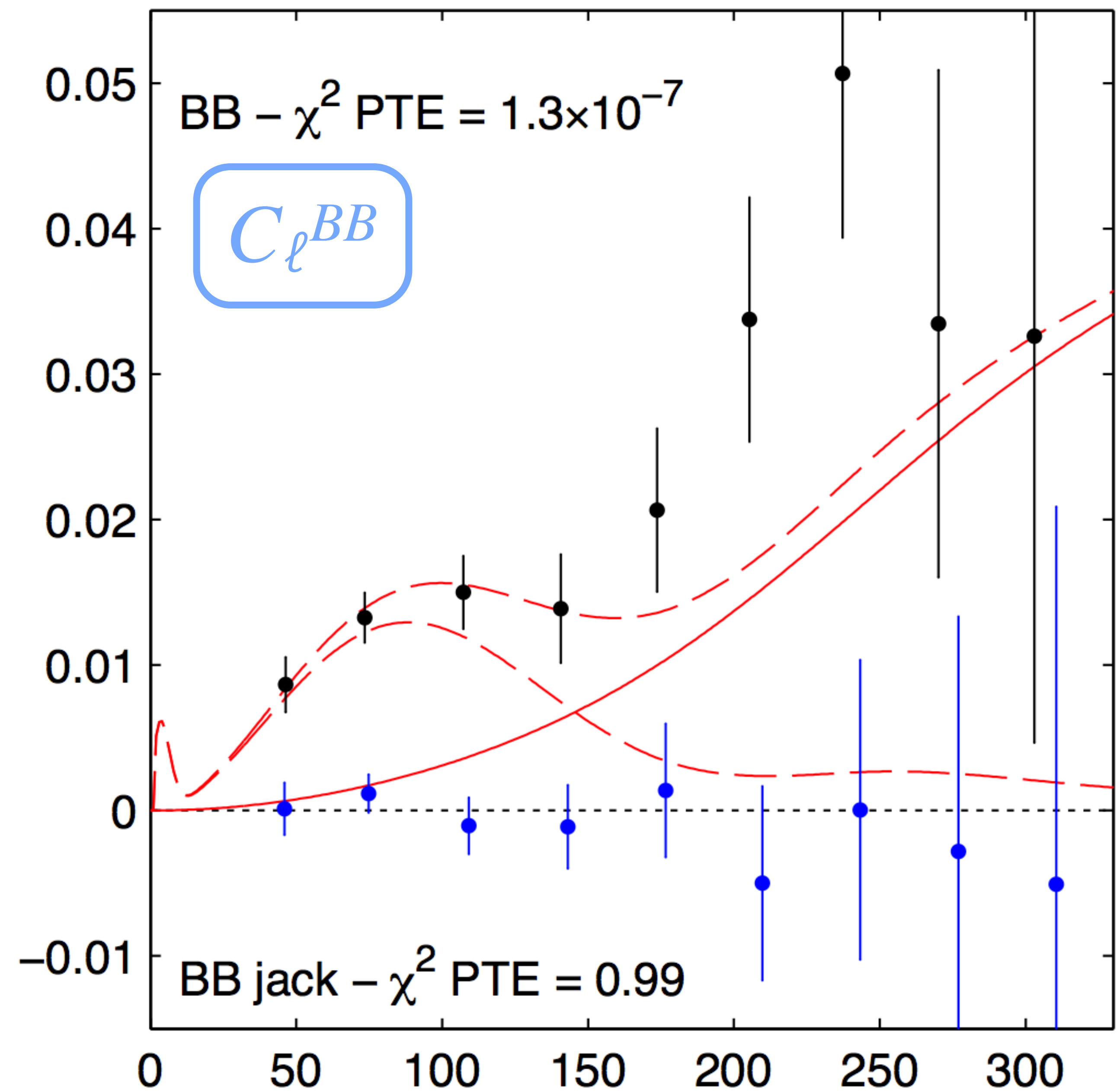
3. Implications for the BICEP2 experiment measurements

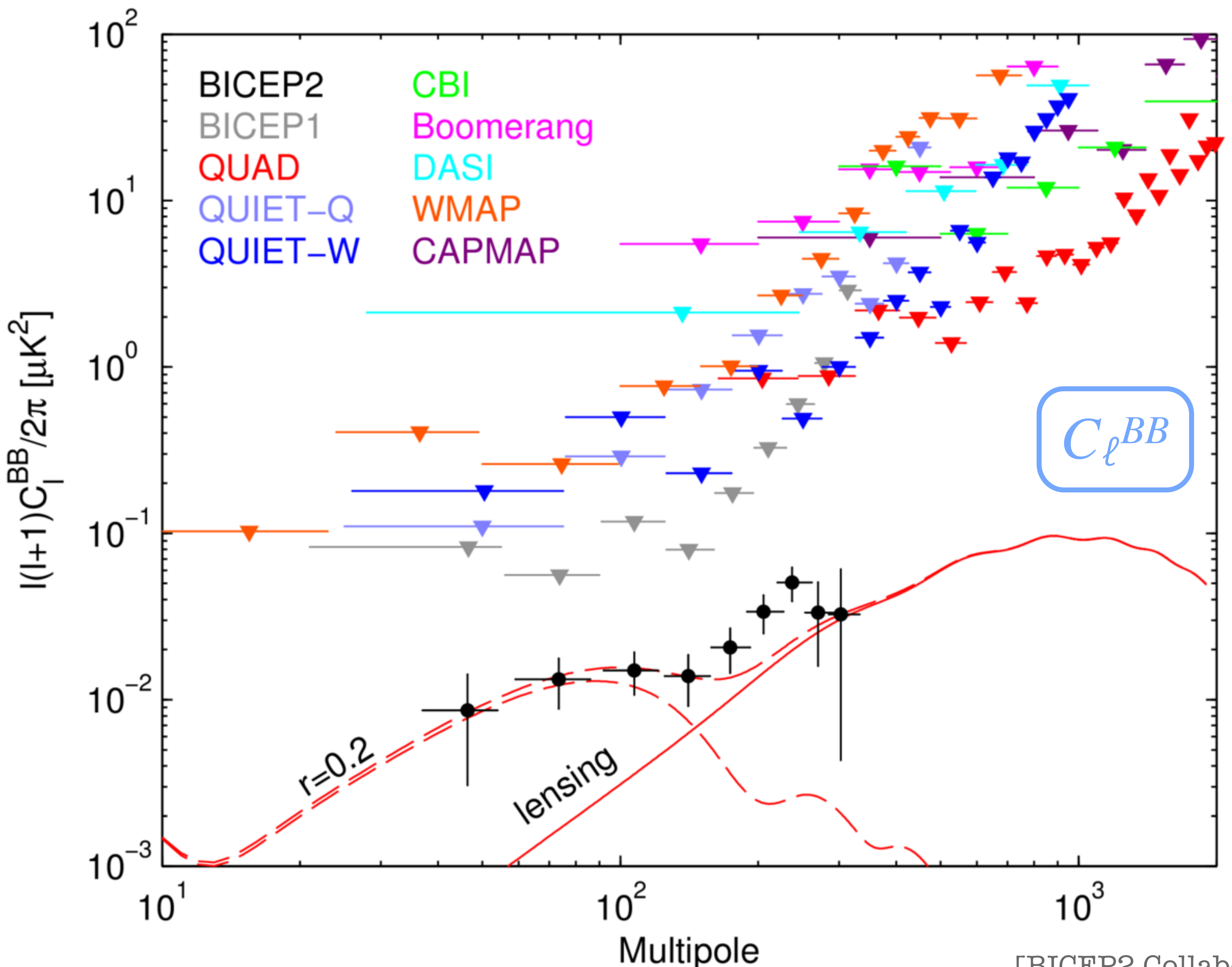
The BICEP2 measurements

- ★ Observed ~5% of the sky from South Pole (~1% used for the analysis)
- ★ 512 TES detectors at 150 GHz
- ★ 30’ resolution
- ★ Integrated sensitivity of 87 nK·arcmin
- ★ Measurement of an significant excess at $40<\ell<150$ with respect to no-tensor B-modes



[BICEP2 Collaboration 2014]

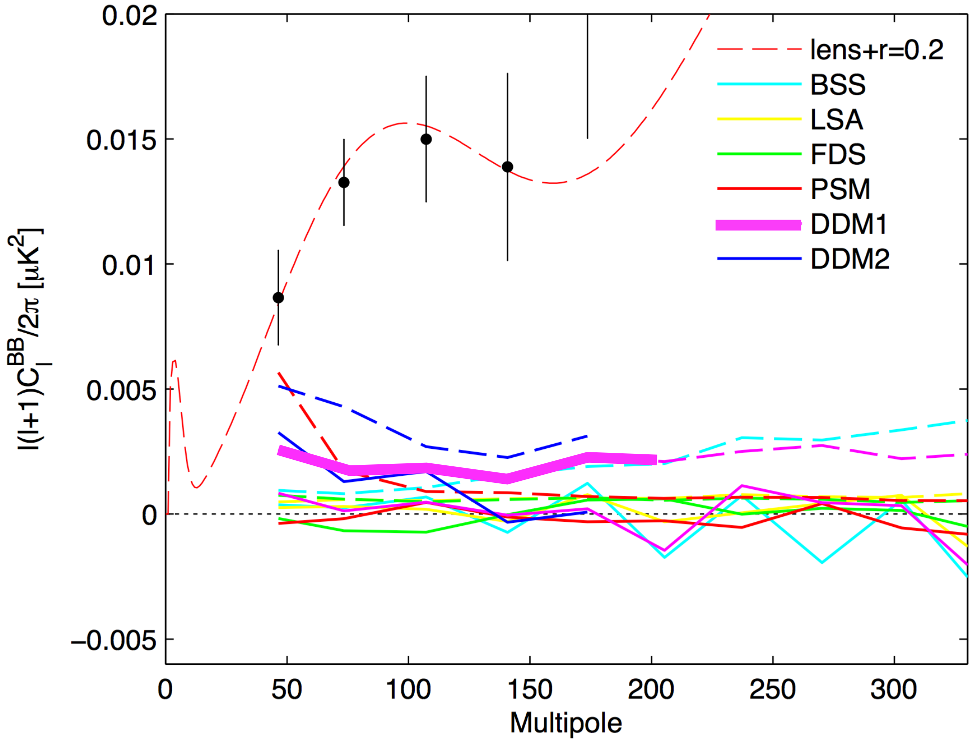
The BICEP2 measurements

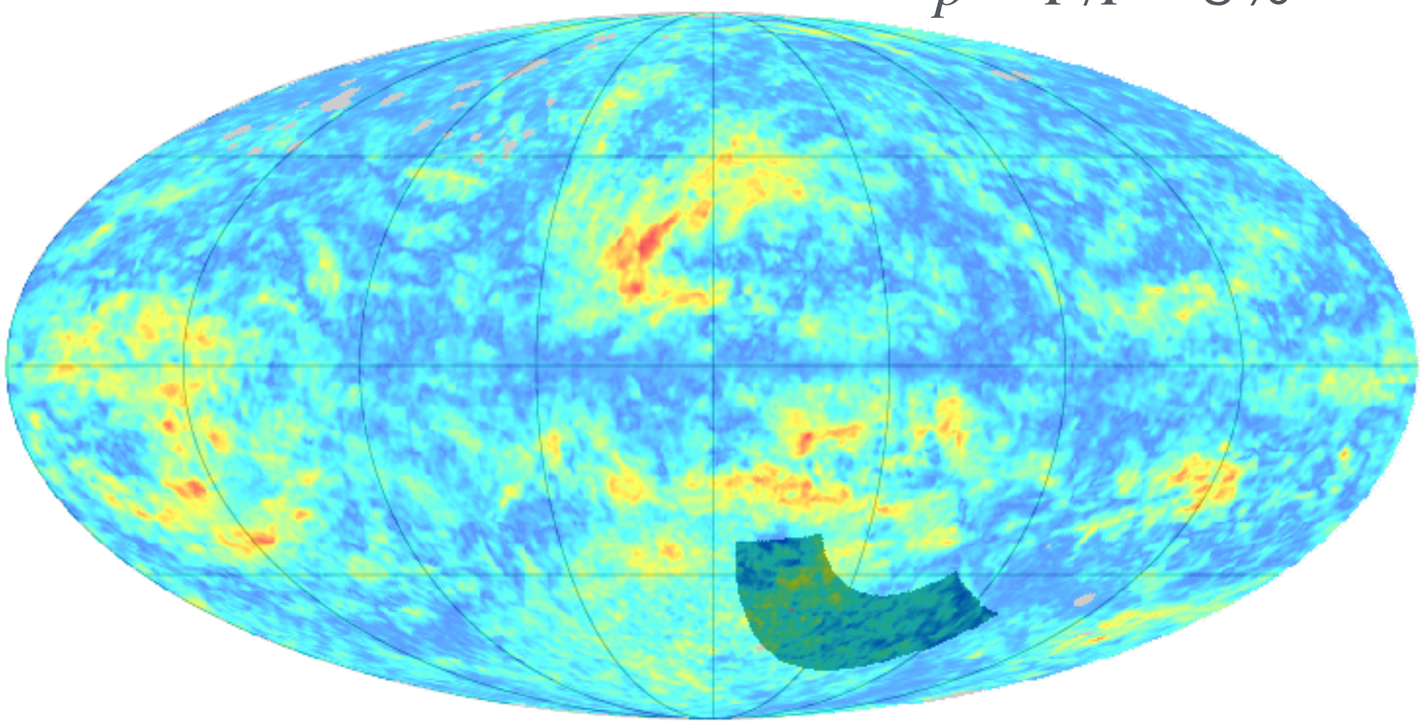


[BICEP2 Collaboration 2014]

Was there some dust in BICEP2 measurements?

CIB zero level not subtracted, $p = P/I \sim 5\%$





[BICEP2 Collaboration 2014]

[Planck Collaboration 2013]

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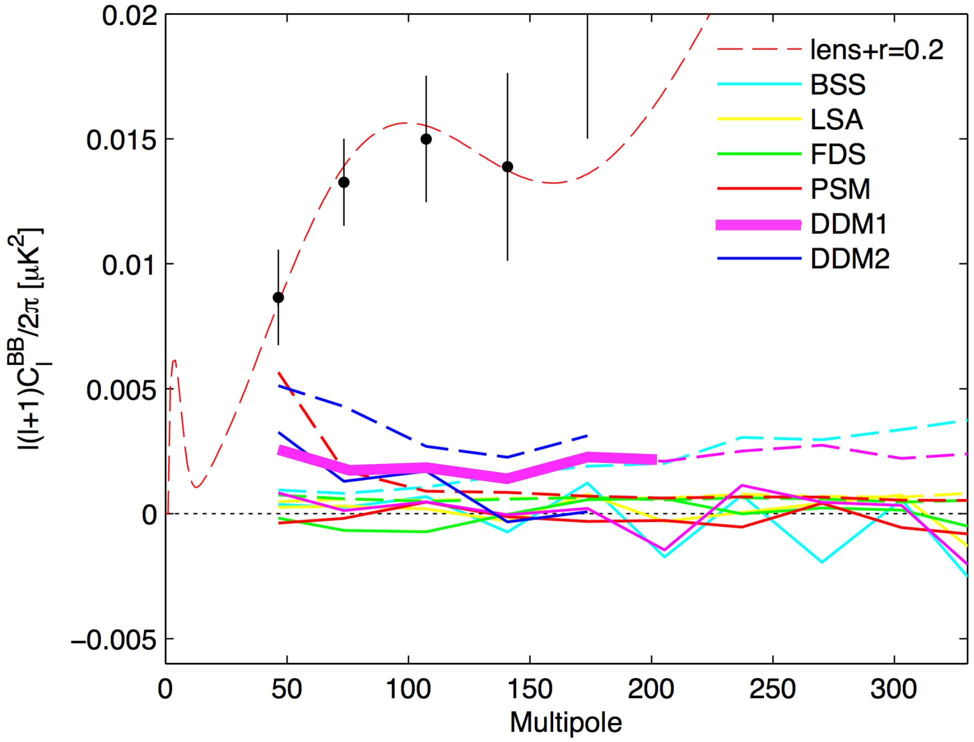
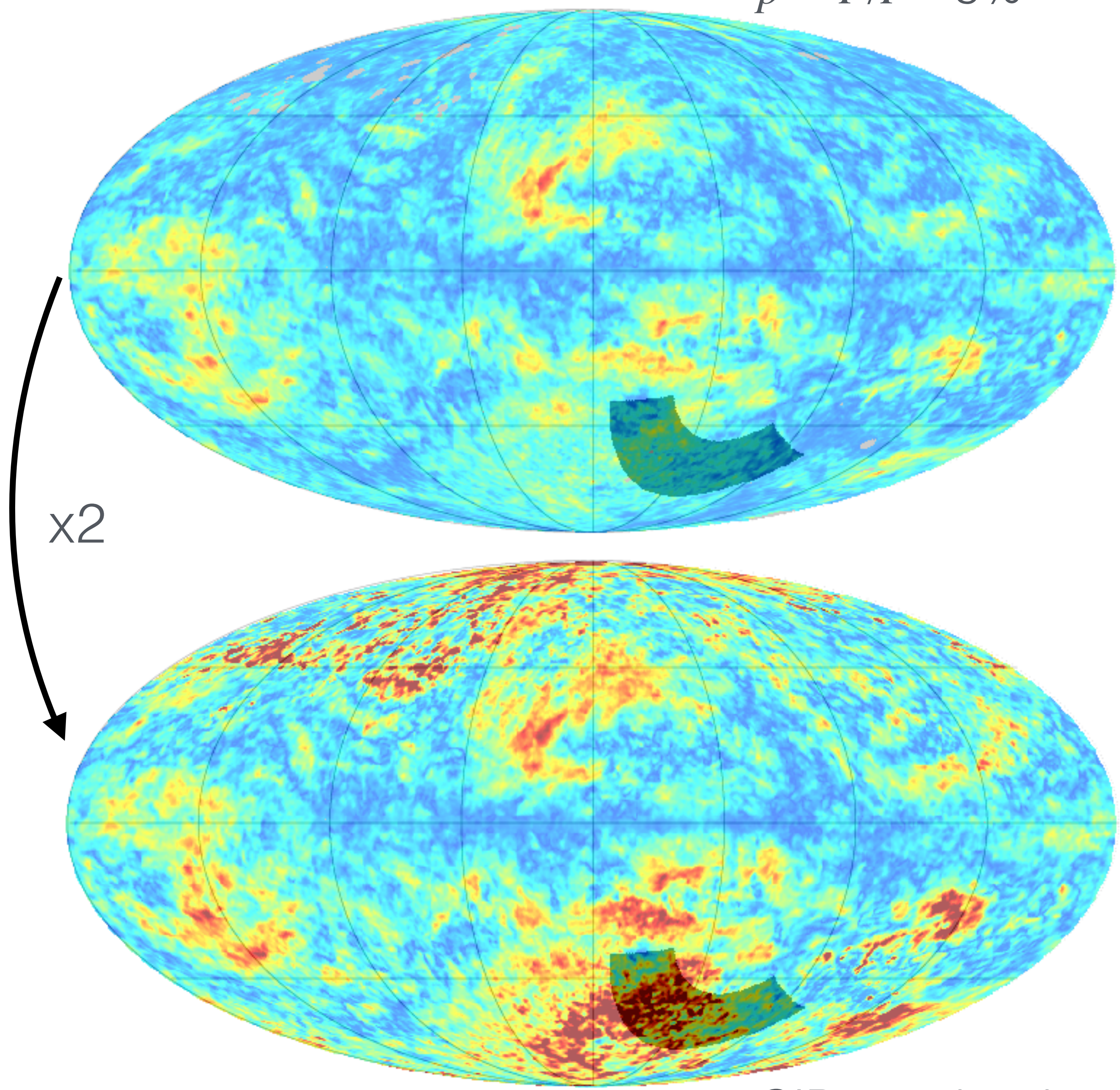


[BICEP2 Collaboration 2014]

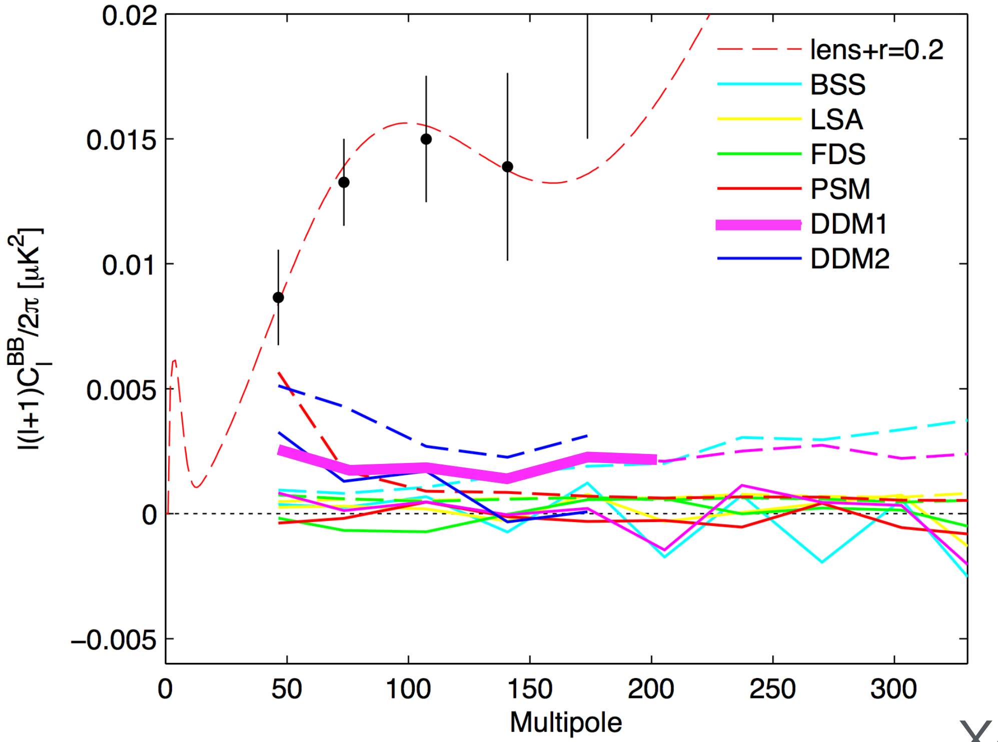
CIB zero level not subtracted, $p = P/I \sim 5\%$



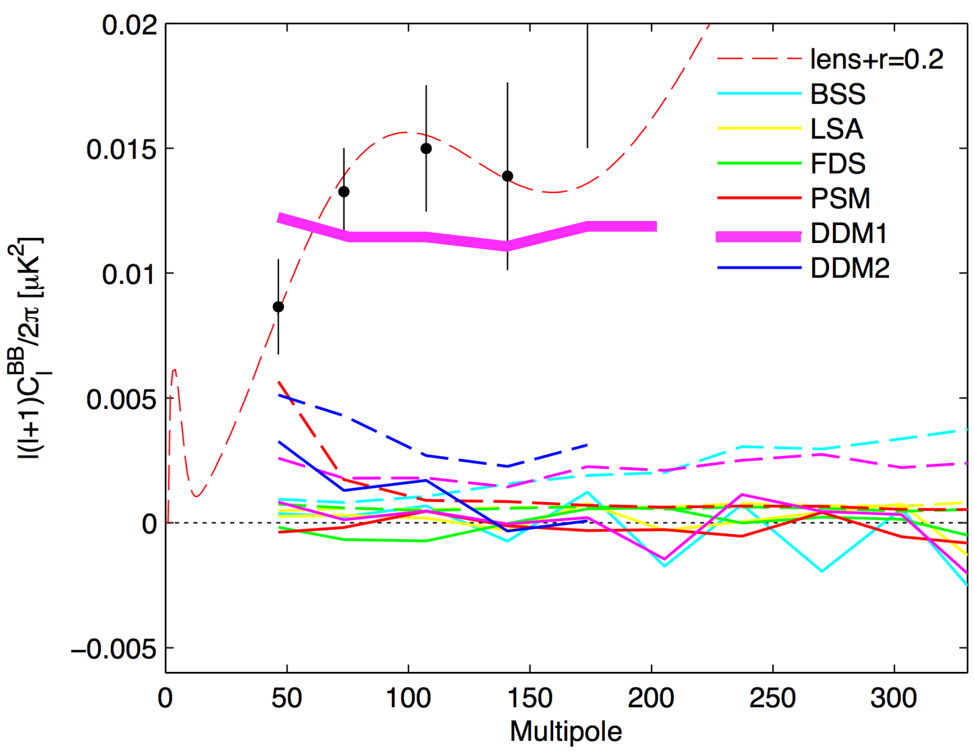
CIB zero level subtracted, $p = P/I \sim 11\%$

[Planck Collaboration 2013]

Was there some dust in BICEP2 measurements?

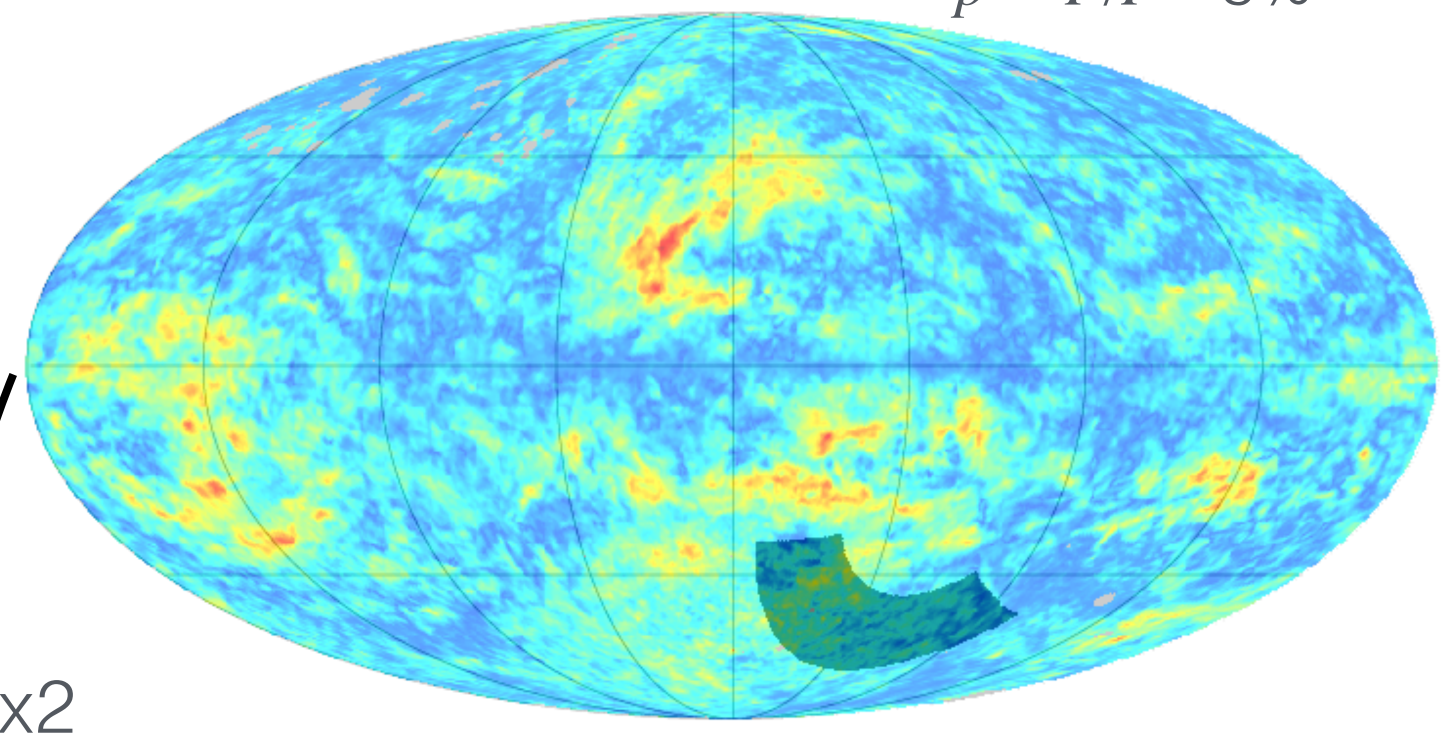


x4

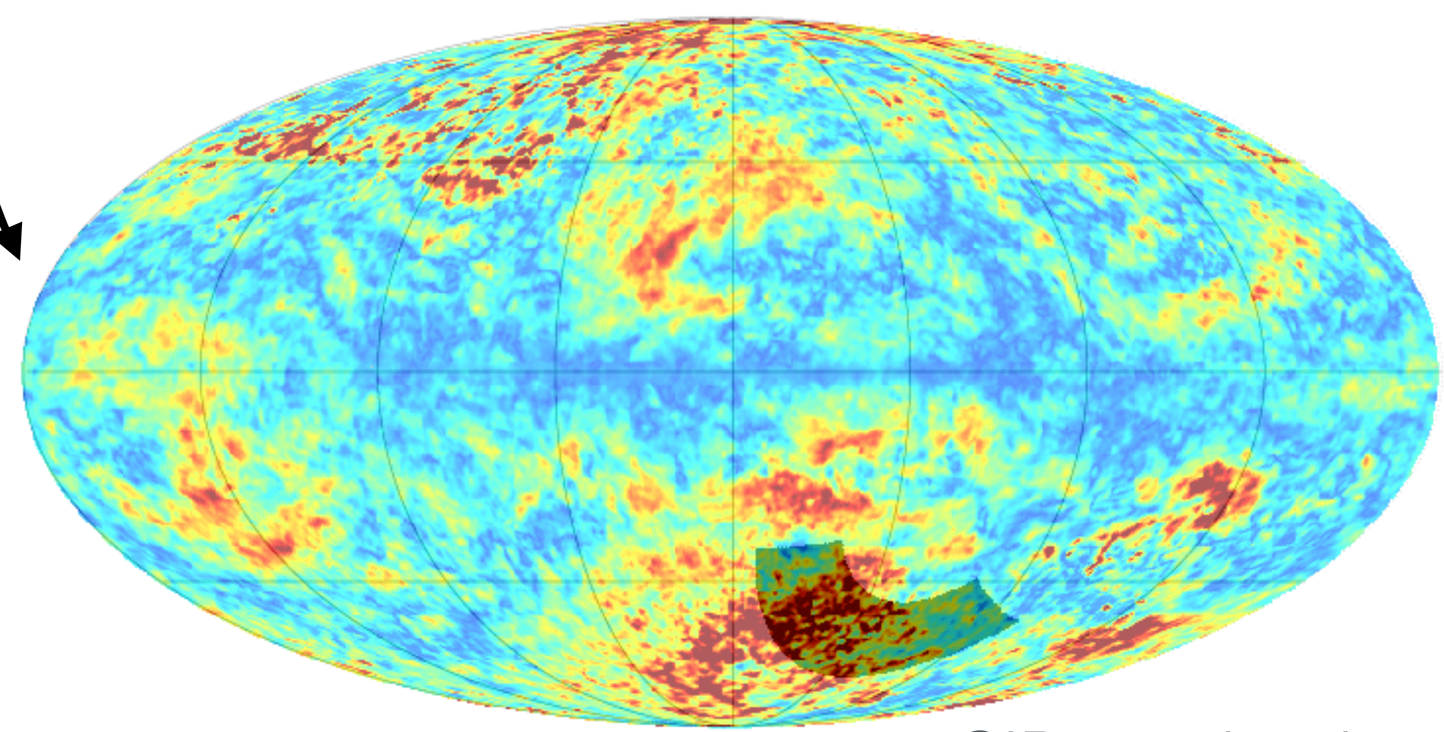


[BICEP2 Collaboration 2014]

CIB zero level not subtracted, $p = P/I \sim 5\%$



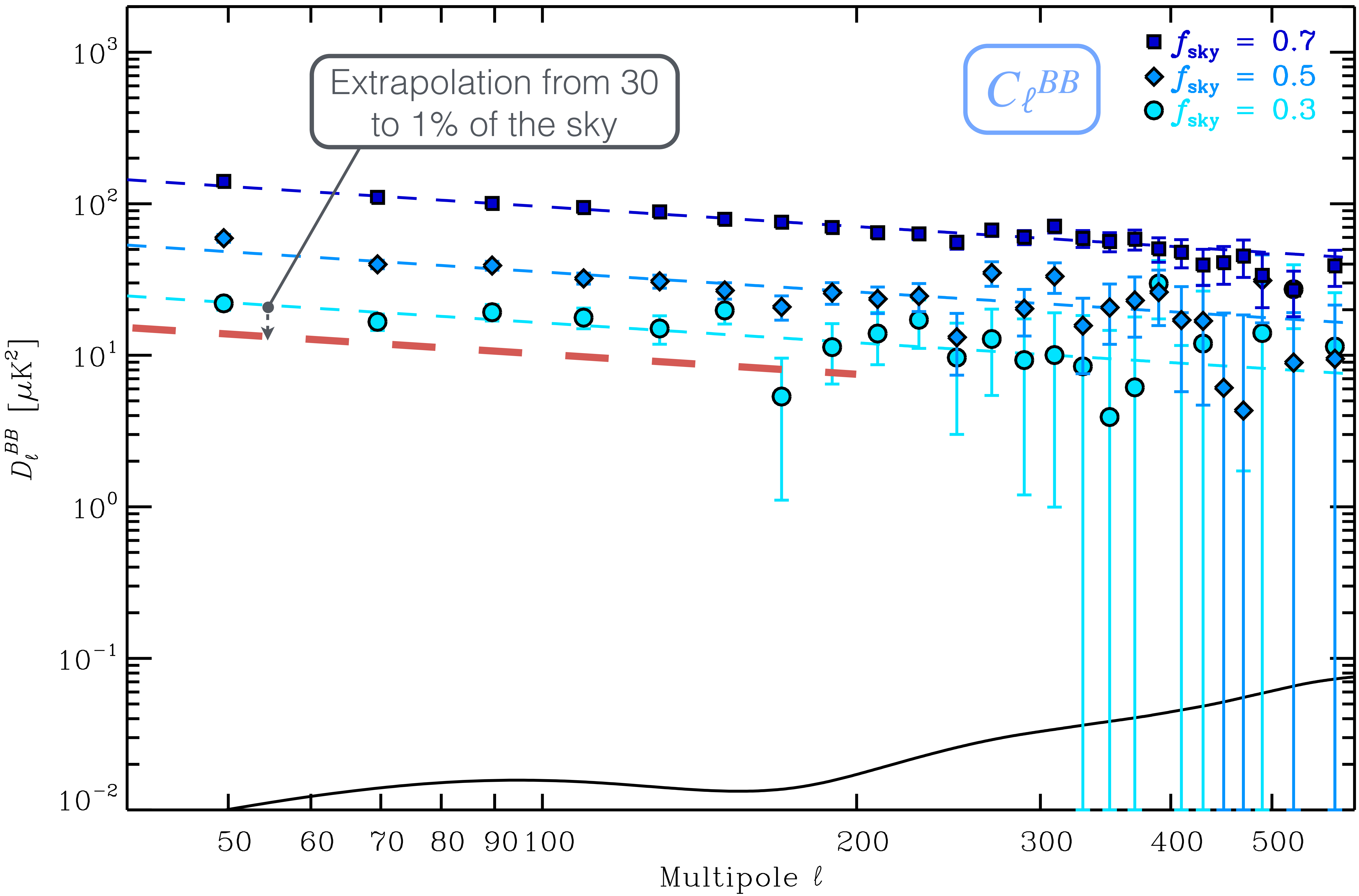
x2



CIB zero level subtracted, $p = P/I \sim 11\%$

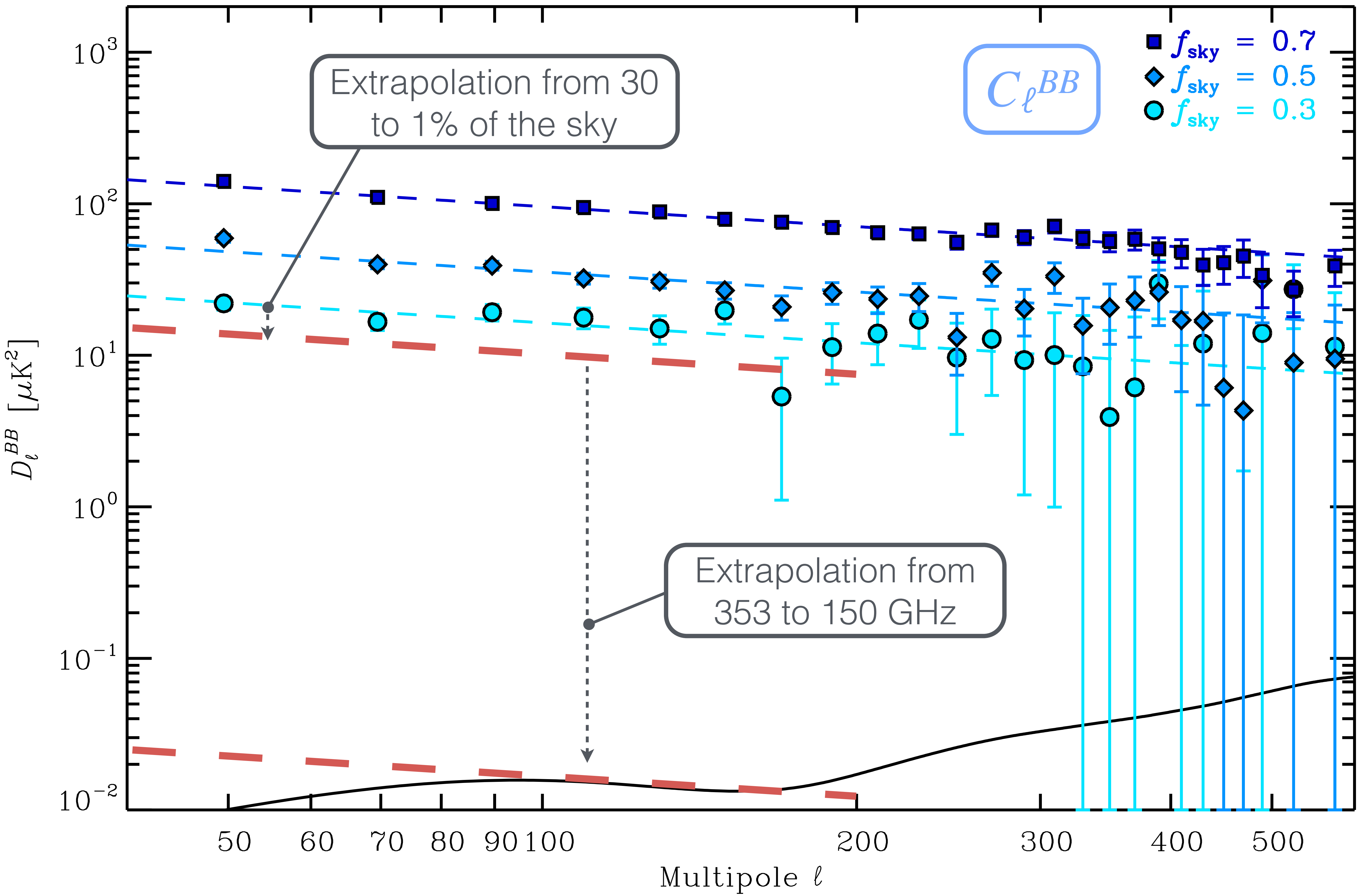
[Planck Collaboration 2013]

Was there some dust in BICEP2 measurements?



[Planck Intermediate XXX 2014, arXiv 1409.5738]

Was there some dust in BICEP2 measurements?

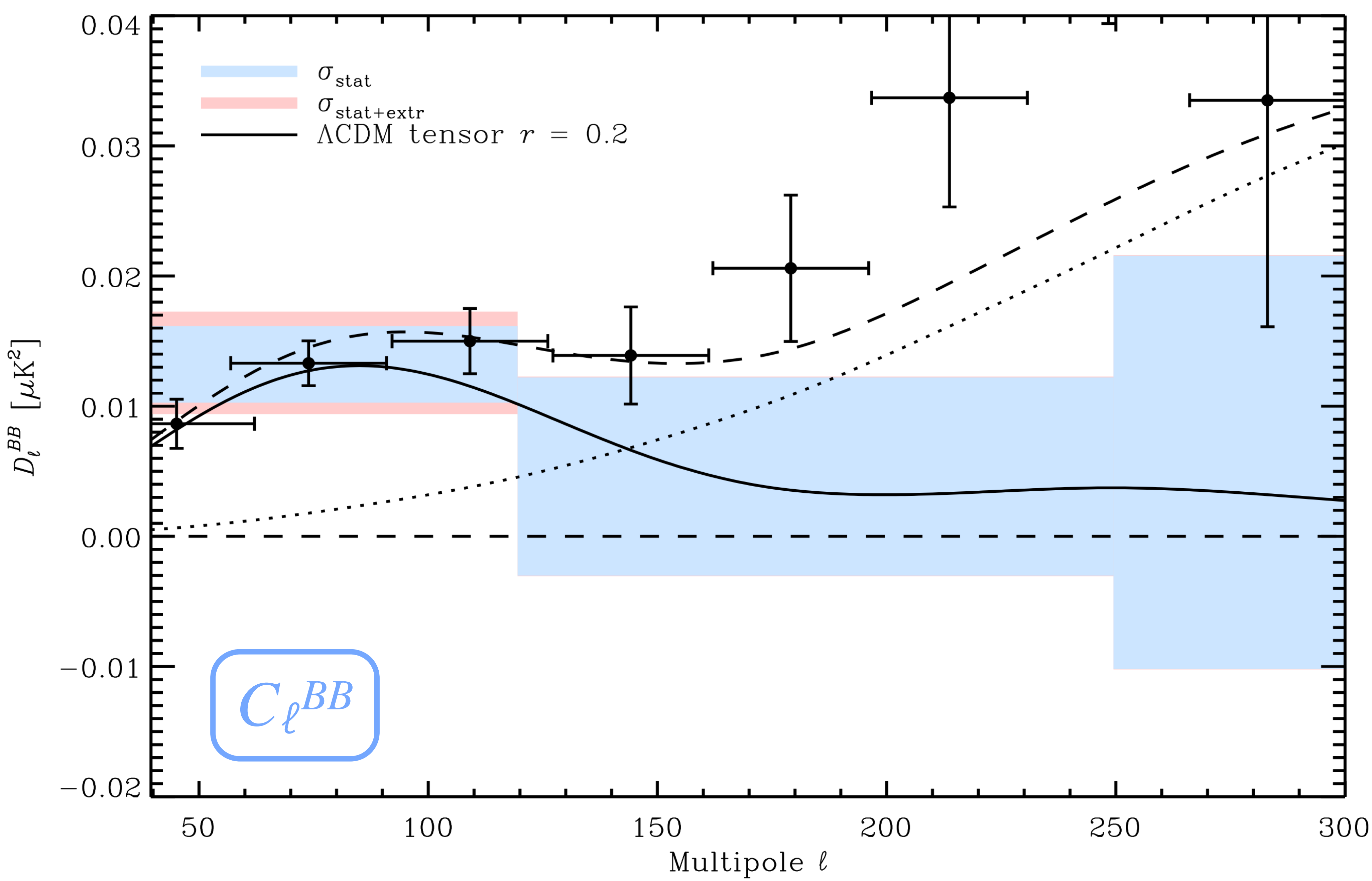


[Planck Intermediate XXX 2014, arXiv 1409.5738]

Measurement of the dust in the BICEP2 field

★ Computation of the *BB* spectrum at 353 GHz in the BICEP2 region
★ Extrapolation to 150 GHz

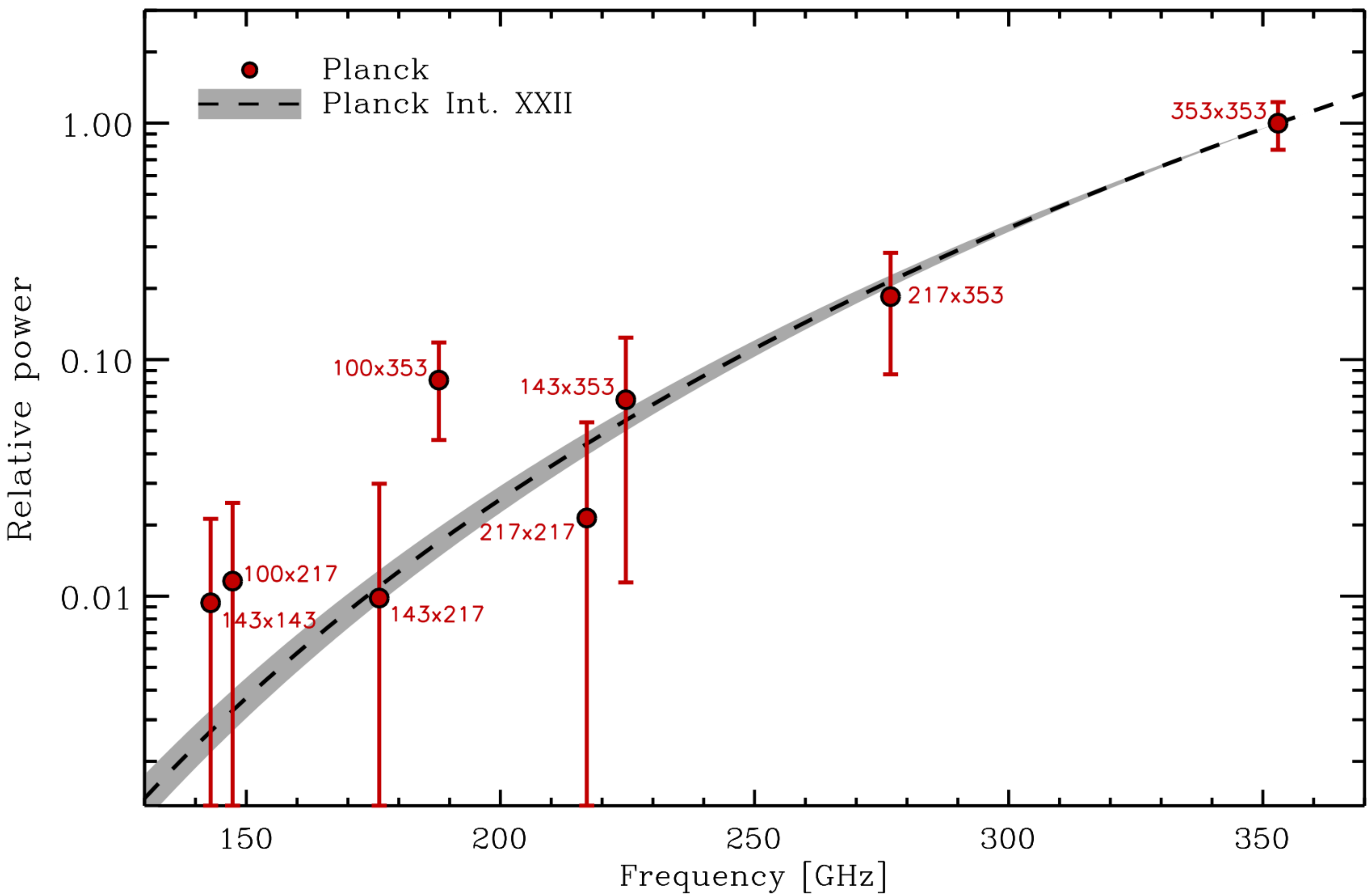
[Planck Intermediate XXX 2014, arXiv 1409.5738]
[BICEP2 Collaboration 2014]



★ 4.5σ detection of the dust at 353 GHz
★ 3.6σ prediction at 150 GHz
★ Prediction of the dust level similar to the *B*-modes measured by BICEP2

Measurement of the dust in the BICEP2 field

[Planck Intermediate XXX 2014, arXiv 1409.5738]
[Planck Intermediate XXII 2014, arXiv 1405.0874]



★ Measurement compatible with polarized dust emission through the Planck-HFI bands

Conclusions…

- ★ Planck allowed to measure for the first time the Galactic dust polarization angular power spectra

- ★ We have shown that these spectra can be described by a simple empirical model
  - ★ C_ℓ have a power-law shape with a slope of -2.42
  - ★ Amplitudes are described by $<I_{353}>^{1.9}$
  - ★ BB/EE ~ 0.5
  - ★ Frequency dependence described by the modified black-body spectrum of [Planck Int. XII]
  - ★ These properties are statistically conserved on 1% of the sky

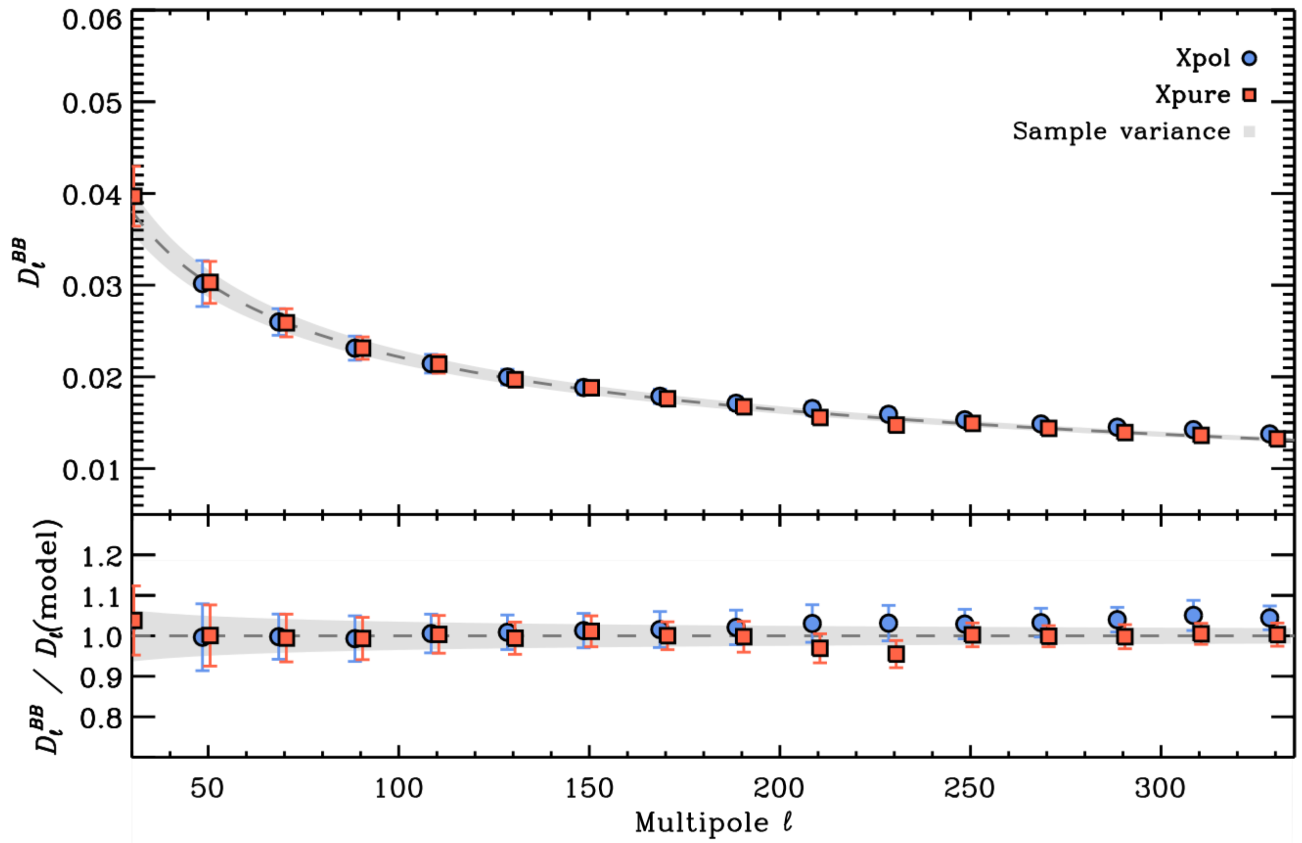
- ★ There are no regions on the sky were the dust polarization B-modes could be neglected (even if some regions are cleaner the the BICEP2 field)

- ★ It is necessary to take into account the dust polarization in the BICEP2 data

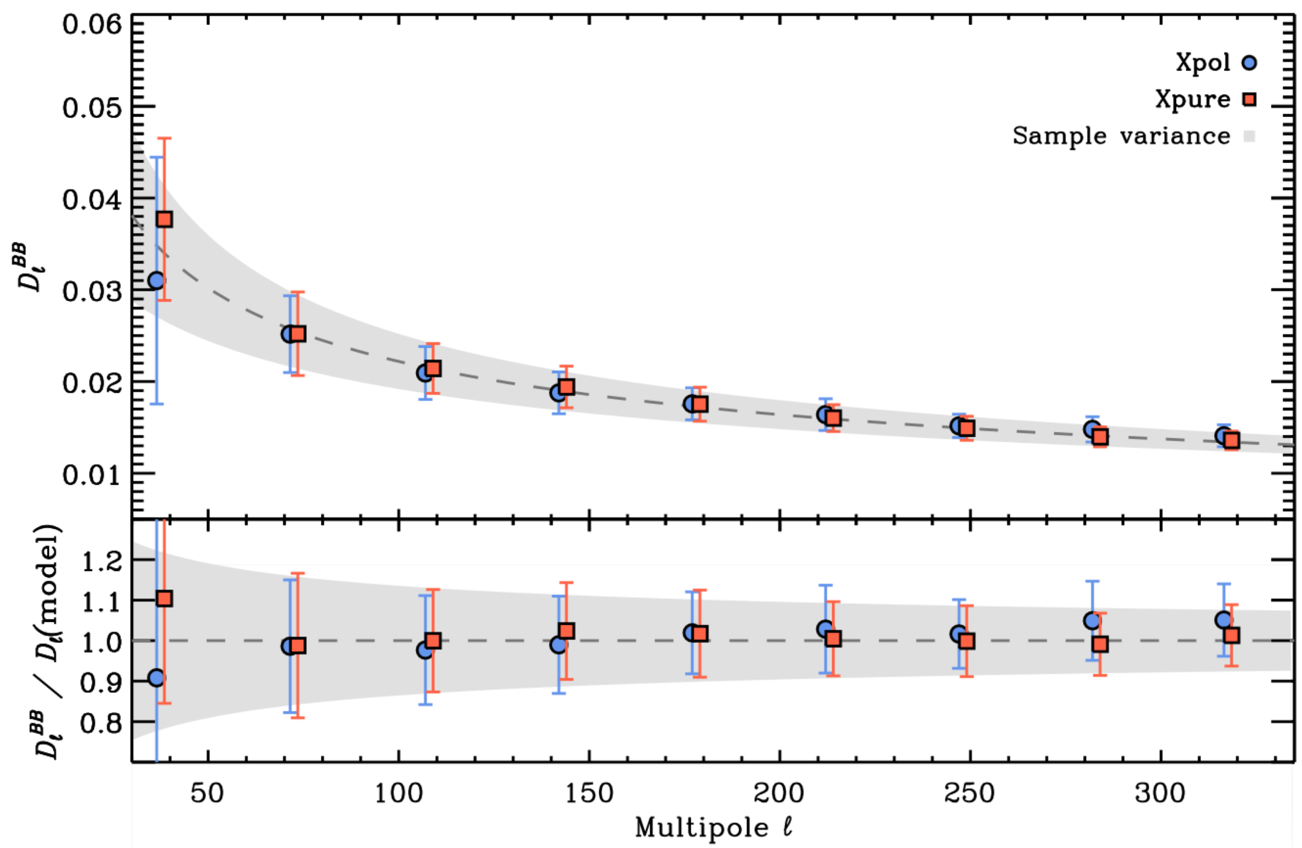
… and perspectives

- ★ All the derived properties will be used as a benchmark for CMB polarization data analysis (likelihood, component separation, …)
- ★ We are currently working at the joint analysis of the Planck and BICEP2 data (MoU between the Planck and BICEP2 collaborations)
- ★ This work is an input for a promising work on the modelization of the polarized dust emission. These models can for the first time rely on all sky data and will have to mimic the properties we have derived

Backup

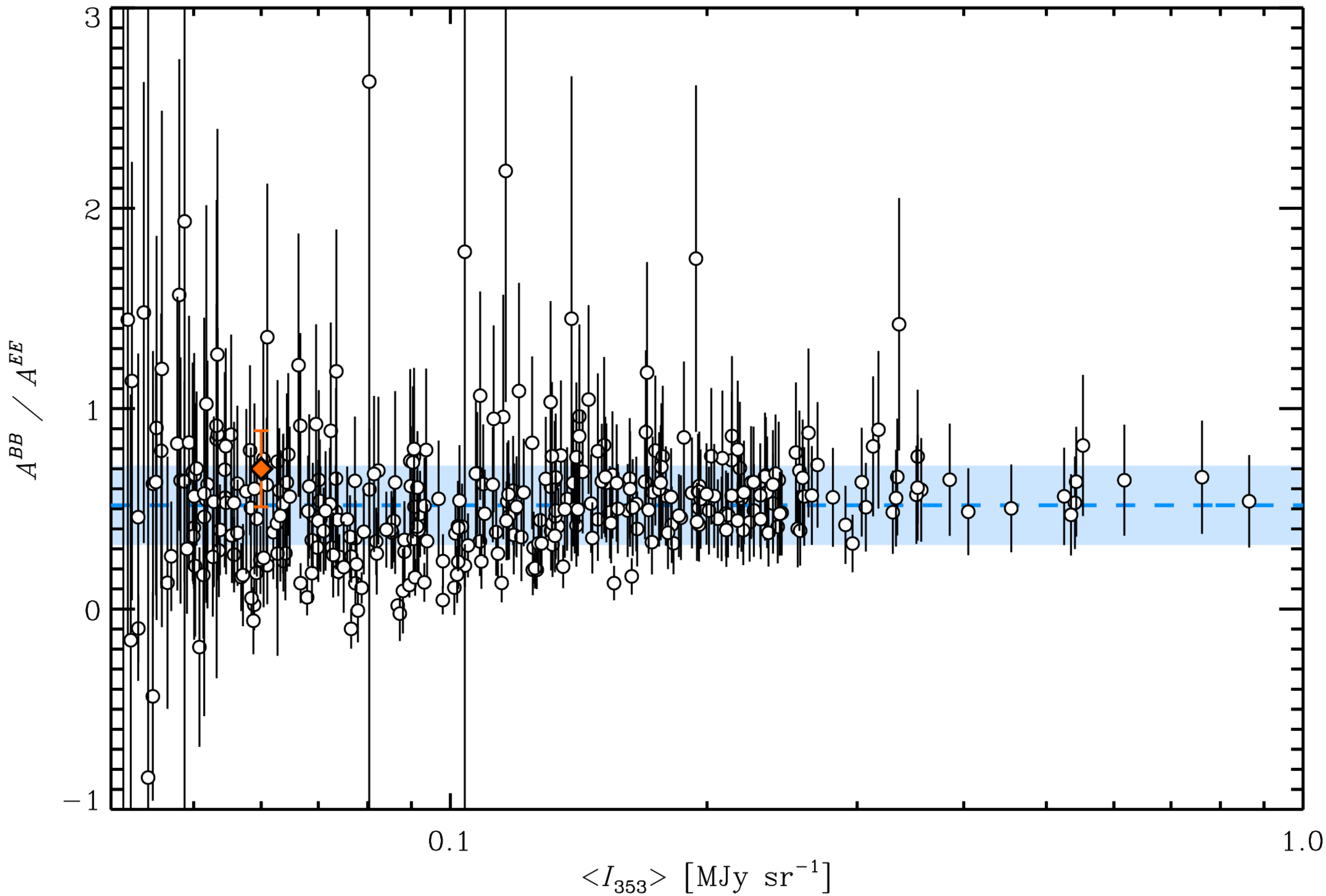


Xpol
Xpure
Sample variance
D_ℓ^{BB}
D_ℓ^{BB} / D_ℓ(model)
Multipole ℓ



Xpol
Xpure
Sample variance
D_ℓ^{BB}
D_ℓ^{BB} / D_ℓ(model)
Multipole ℓ

Backup



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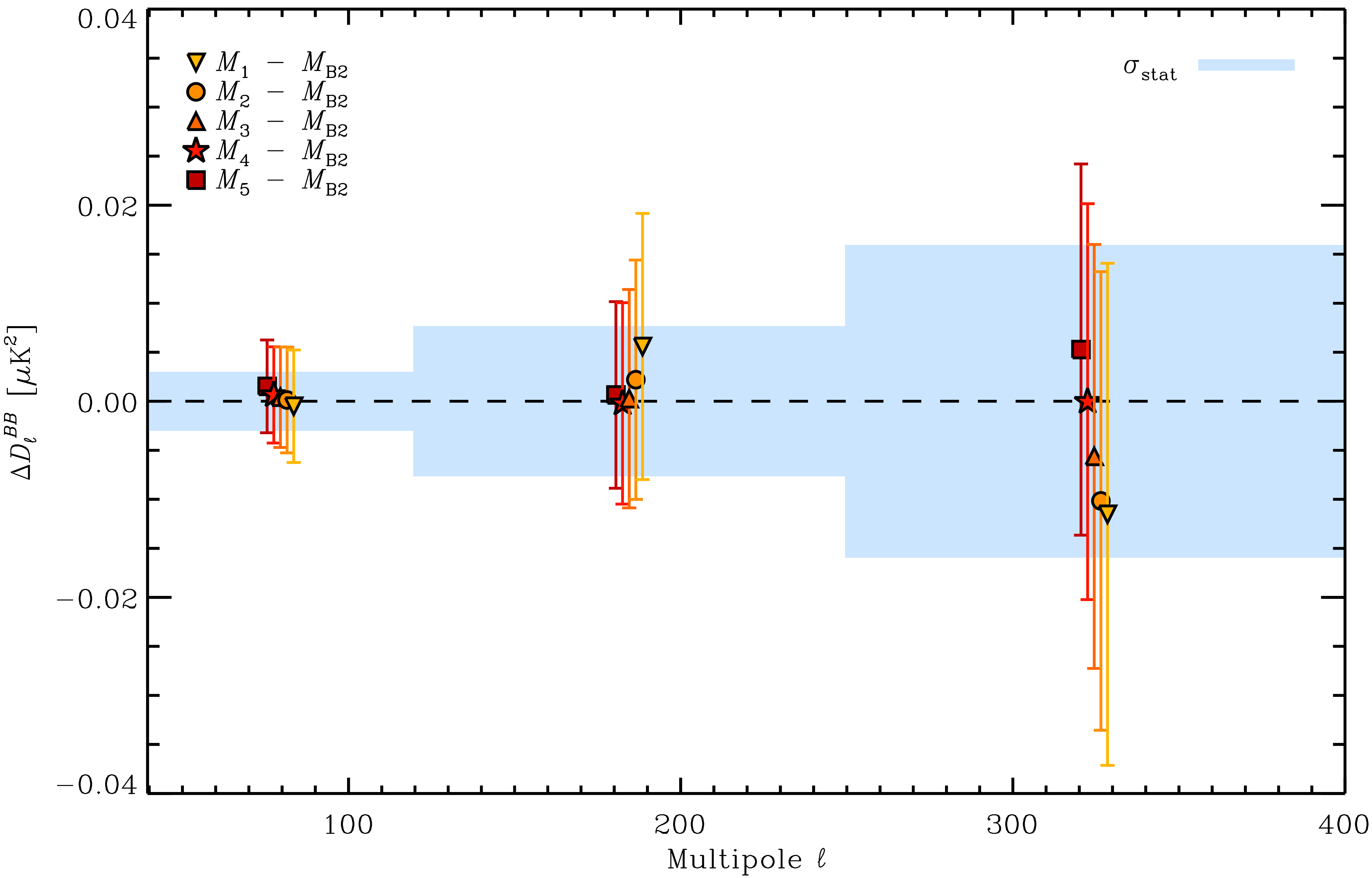
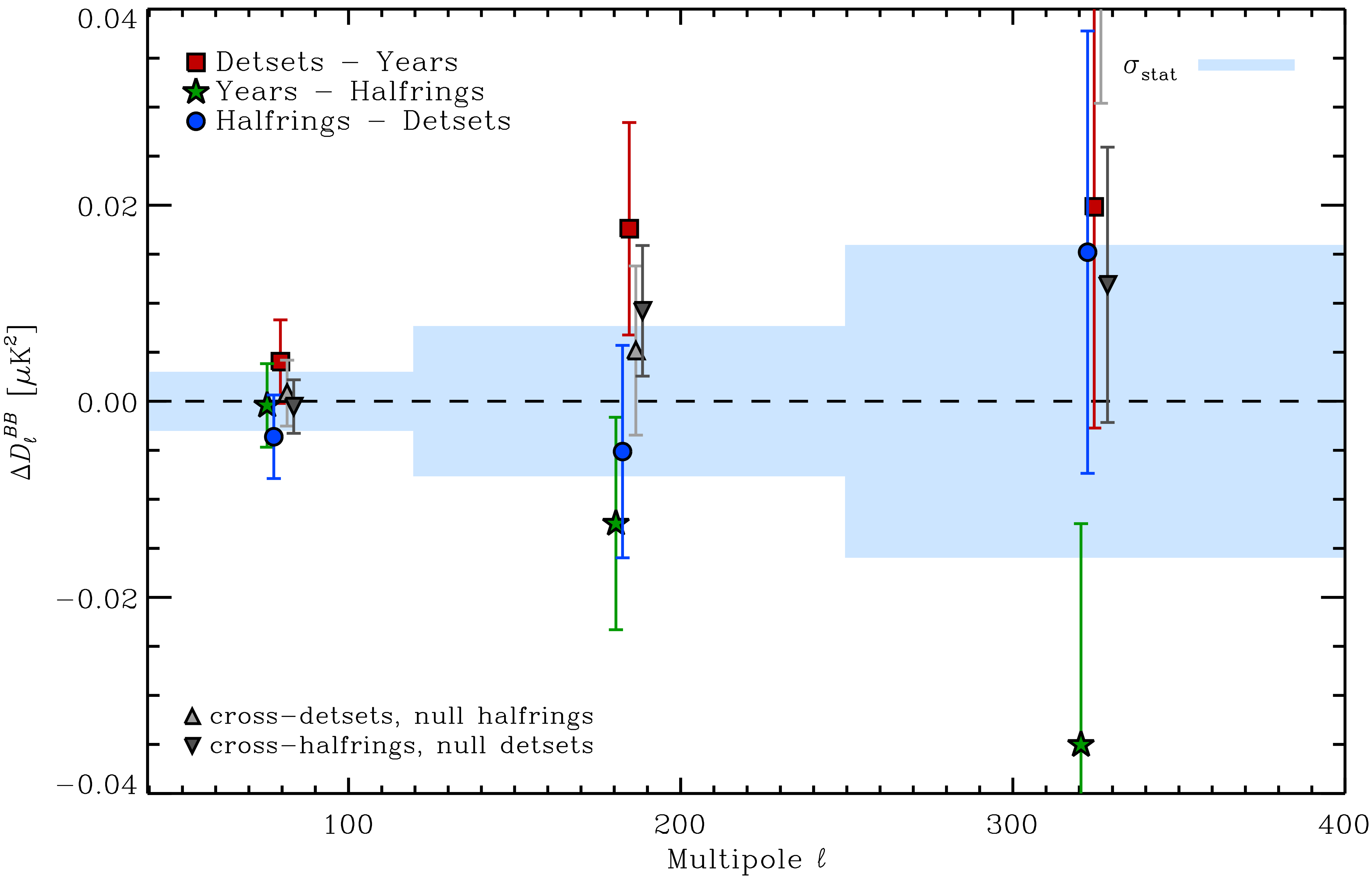


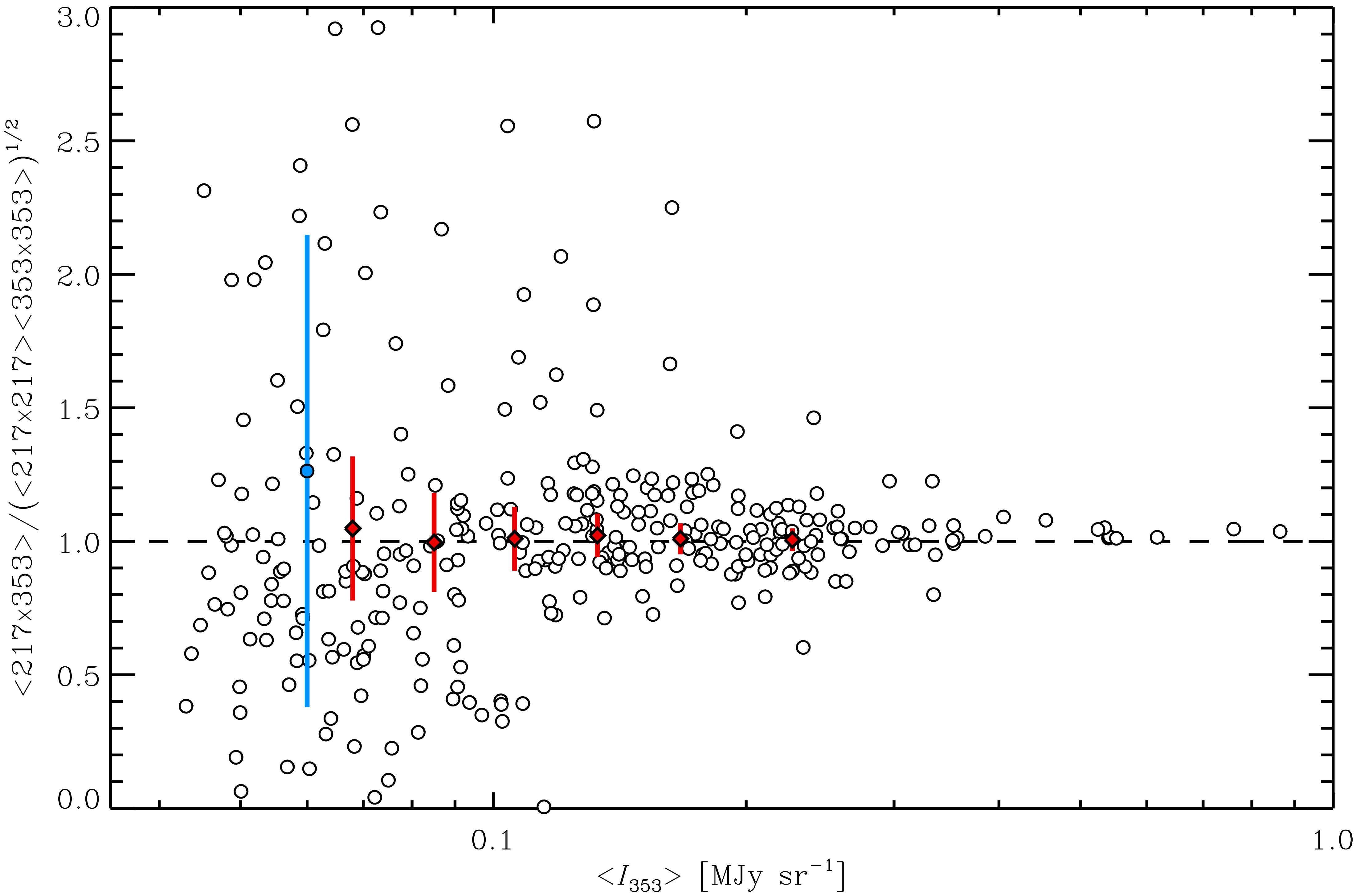
$M_1 - M_{B2}$
$M_2 - M_{B2}$
$M_3 - M_{B2}$
$M_4 - M_{B2}$
$M_5 - M_{B2}$
σ_{stat}
0.04
0.02
0.00
−0.02
−0.04
100
200
300
400
Multipole ℓ
ΔD_ℓ^{BB} [μK^2]

Backup

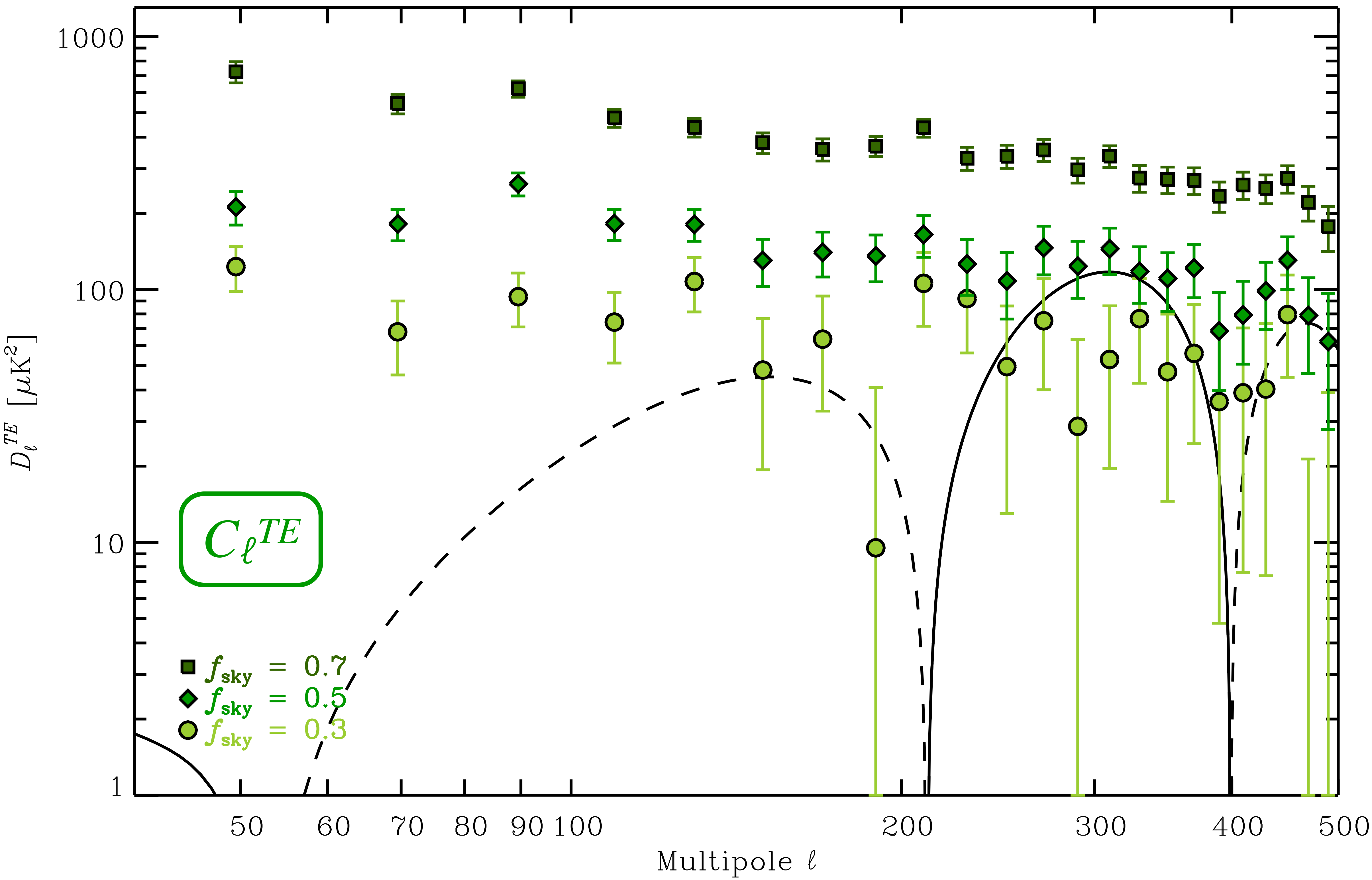


Detsets − Years
Years − Halfrings
Halfrings − Detsets
σ_{stat}
cross−detsets, null halfrings
cross−halfrings, null detsets
0.04
0.02
0.00
−0.02
−0.04
100
200
300
400
Multipole ℓ
ΔD_ℓ^{BB} [μK^2]

Backup

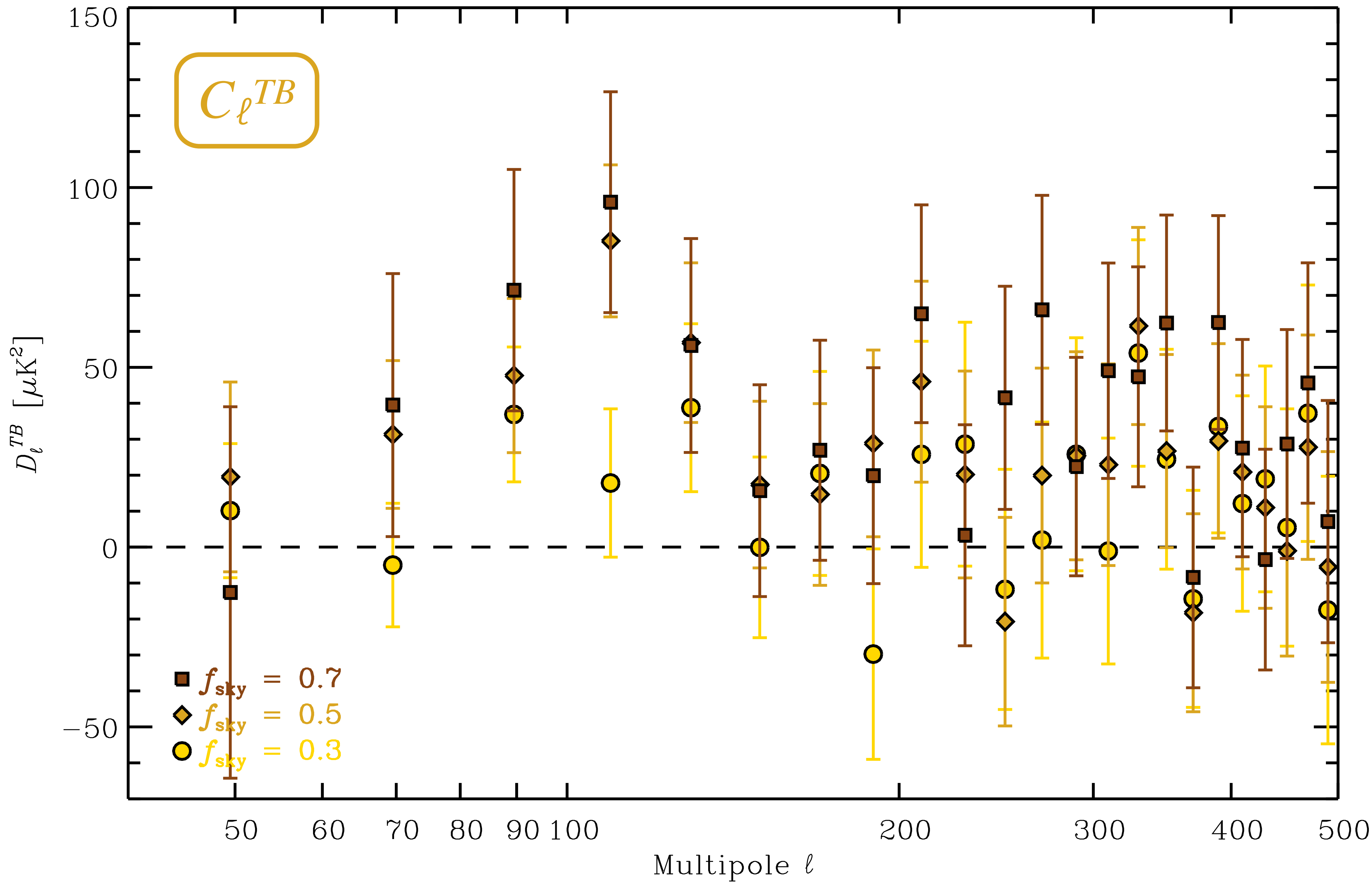


Backup



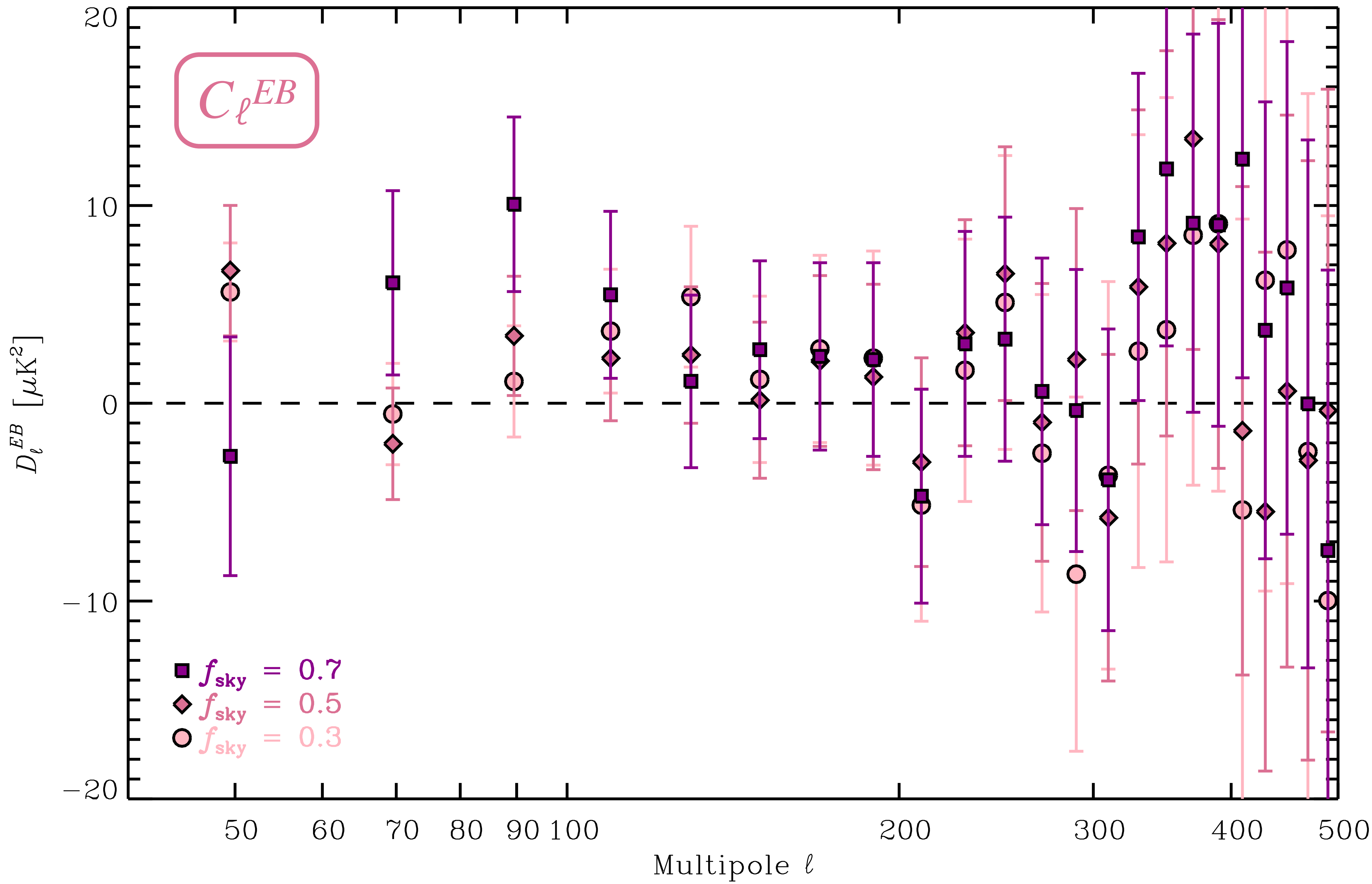
1000
100
10
1
50
60
70
80
90 100
200
300
400
500
Multipole ℓ
D_ℓ^{TE} [μK^2]
C_ℓ^{TE}
f_{sky} = 0.7
f_{sky} = 0.5
f_{sky} = 0.3

Backup



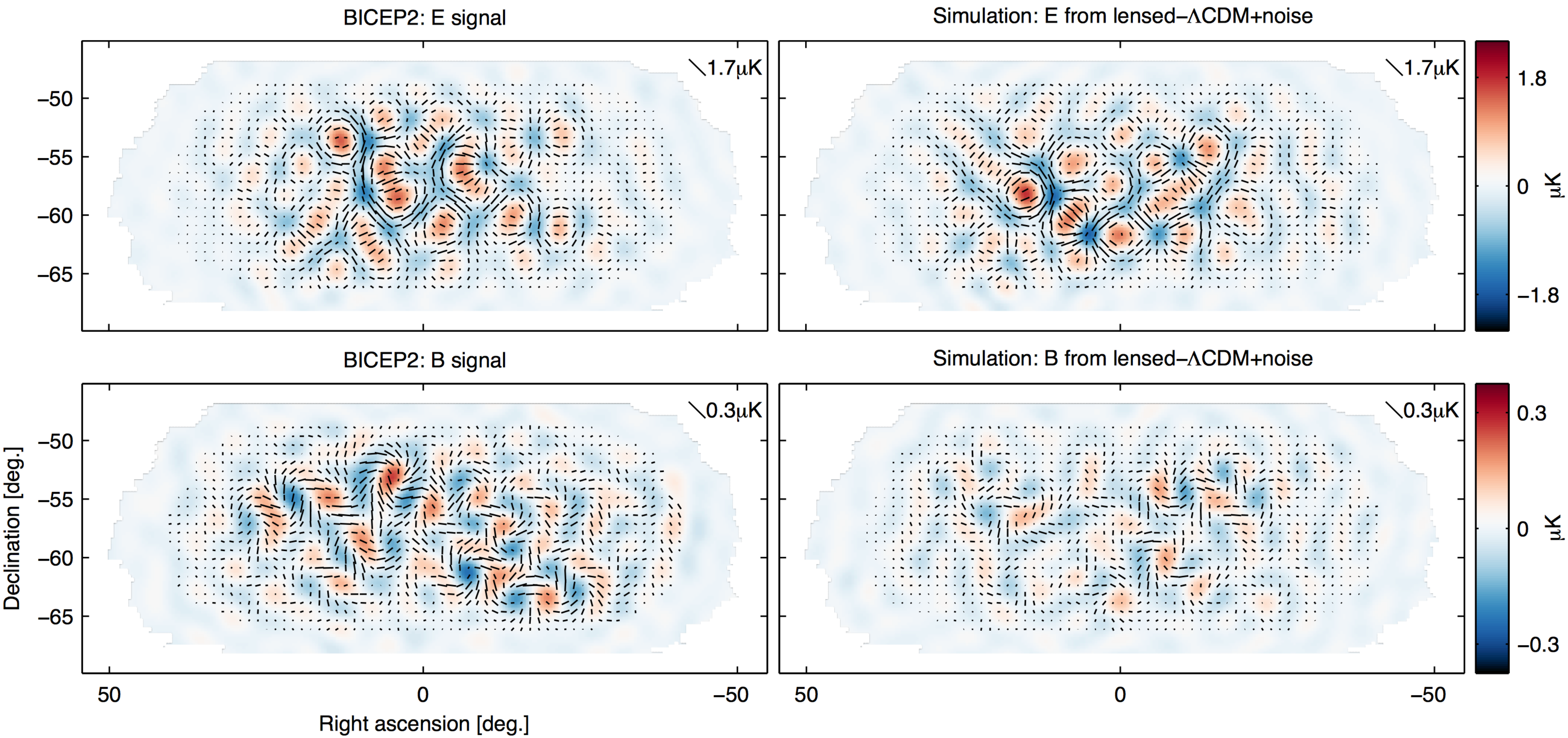
C_ℓ^{TB}
D_ℓ^{TB} [μK^2]
150
100
50
0
−50
50
60
70
80
90
100
200
300
400
500
Multipole ℓ
$f_{\rm sky}$ = 0.7
$f_{\rm sky}$ = 0.5
$f_{\rm sky}$ = 0.3

Backup



C_ℓ^{EB}
20
10
0
−10
−20
D_ℓ^{EB} [μK^2]
50
60
70
80
90
100
200
300
400
500
Multipole ℓ
f_{sky} = 0.7
f_{sky} = 0.5
f_{sky} = 0.3

The BICEP2 measurements



[BICEP2 Collaboration 2014]