Absolute calibration of future CMB *B*-mode experiments using the CRAB NEBULA

Image Credit: NASA, ESA, J. Hester, A. Loll (ASU)

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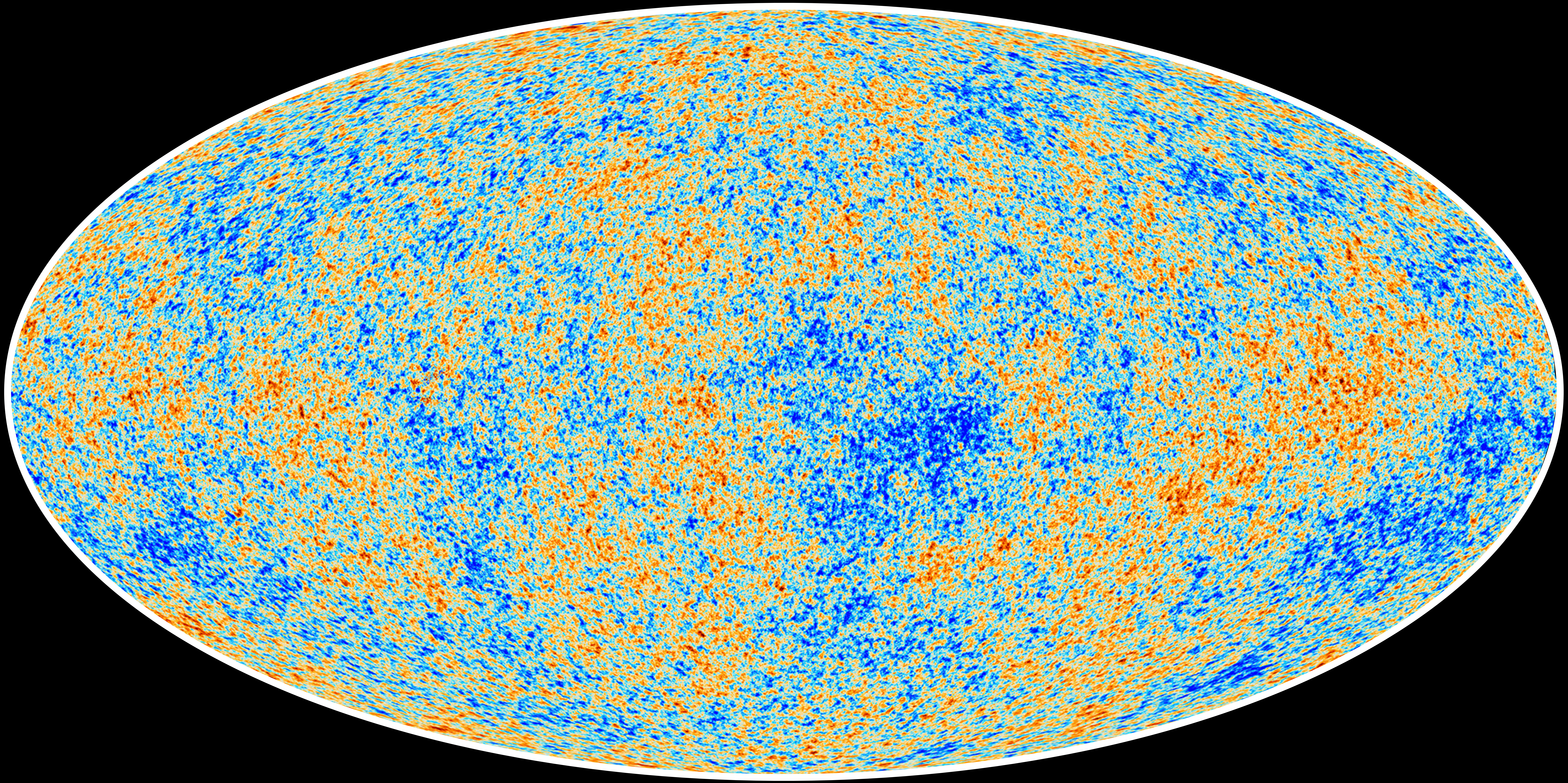
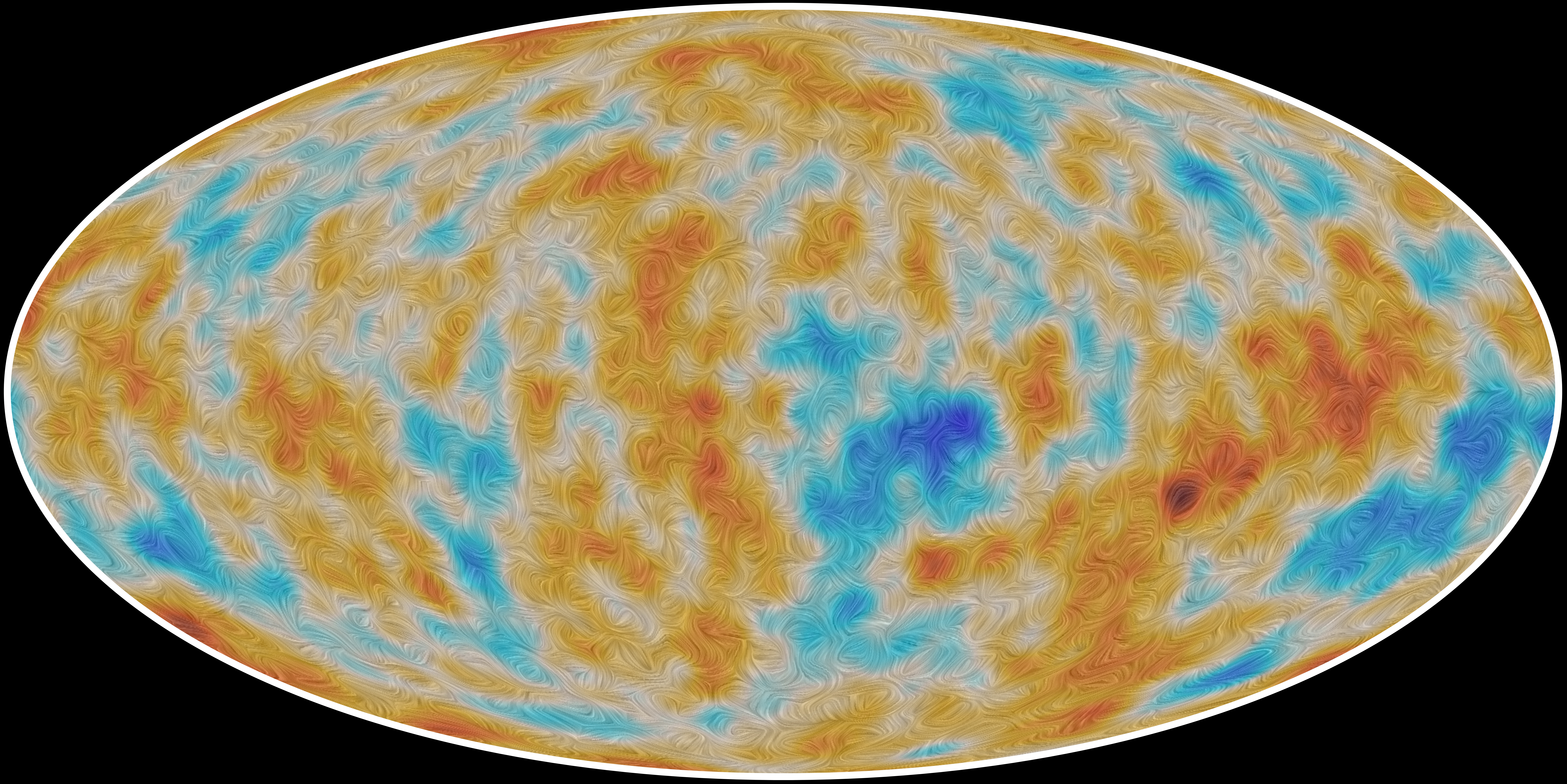
mm Universe @ NIKA2 — Grenoble — June 5th 2019

CMB – Temperature anisotropies



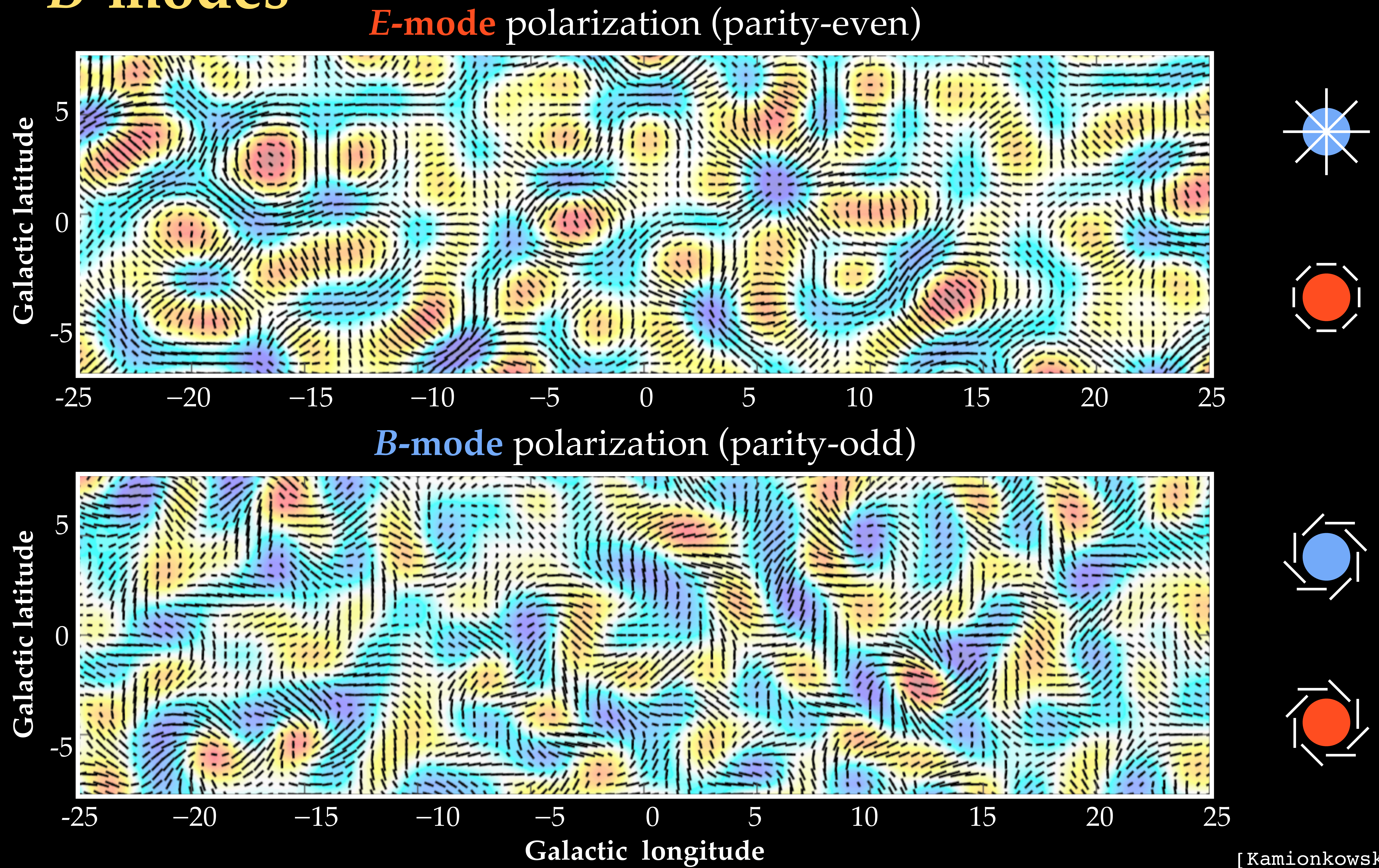
[Planck 2015 I]

CMB – Polarization



[Planck 2015 I]

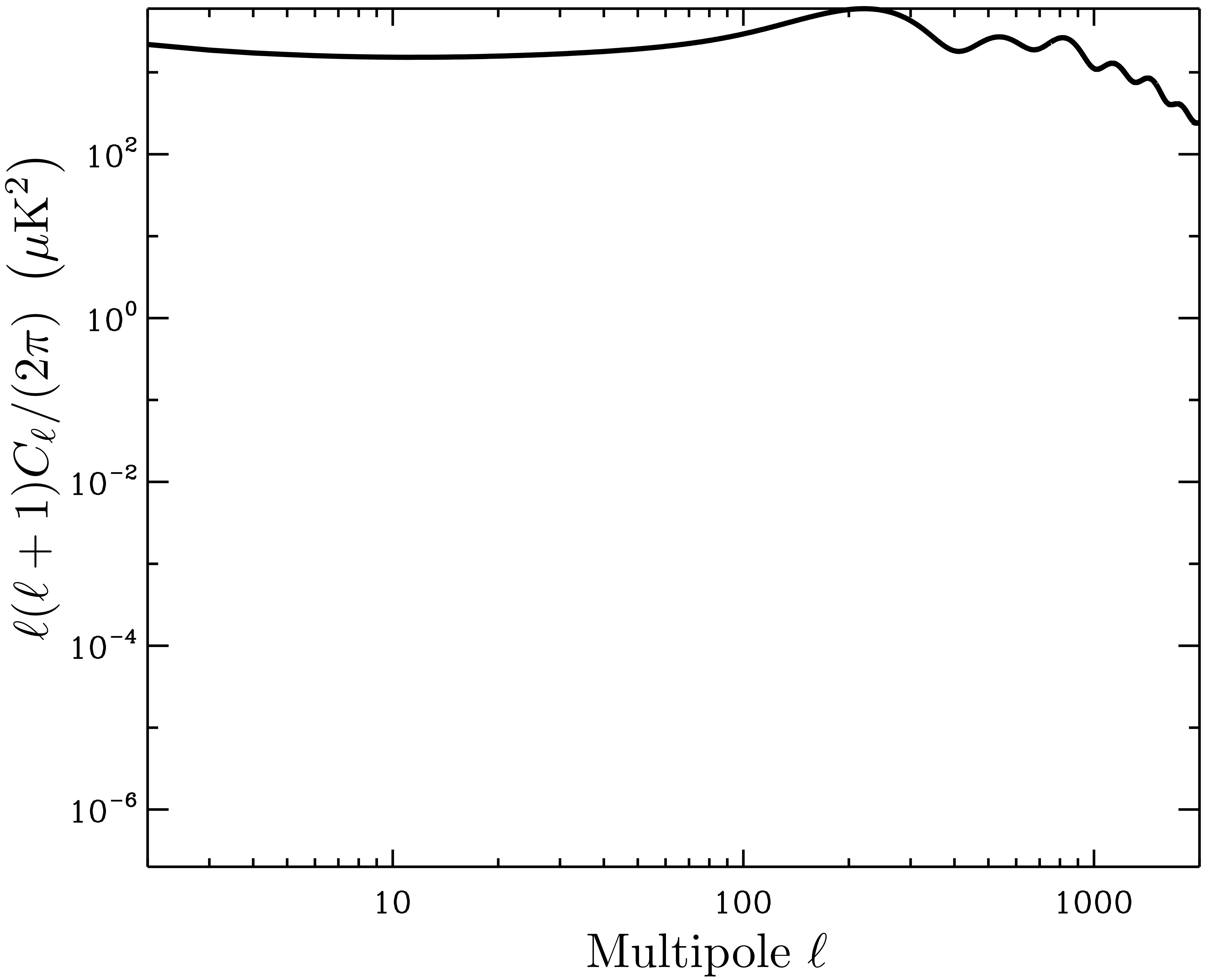
CMB – *B*-modes



[Kamionkowski+16]

CMB – *B*-modes

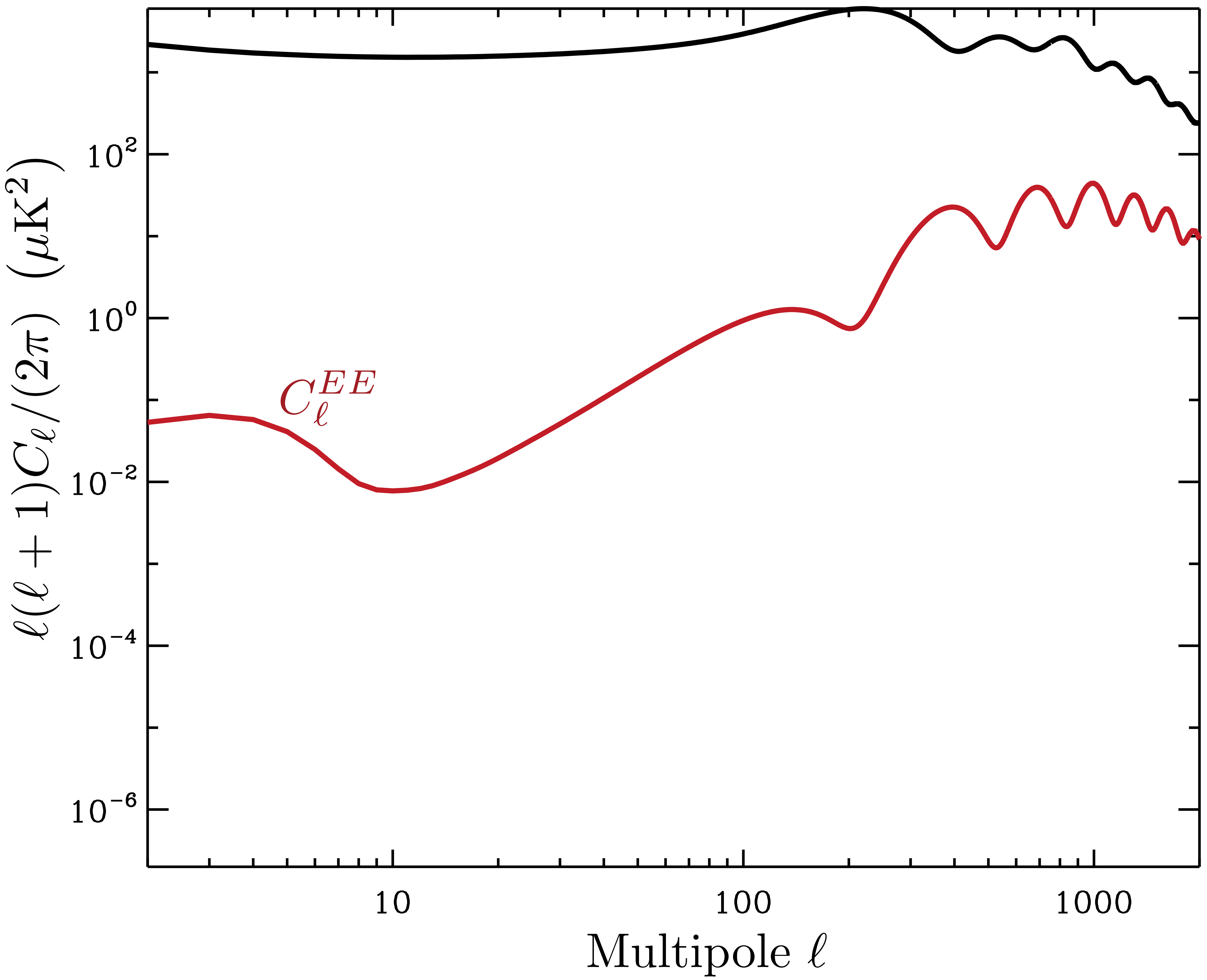
★ *TT* spectrum: cosmological parameters from density perturbations



CMB – *B*-modes

★ *TT* spectrum: cosmological parameters from density perturbations

★ *EE* spectrum: model coherence, leaves degeneracies (τ, n_s, …)

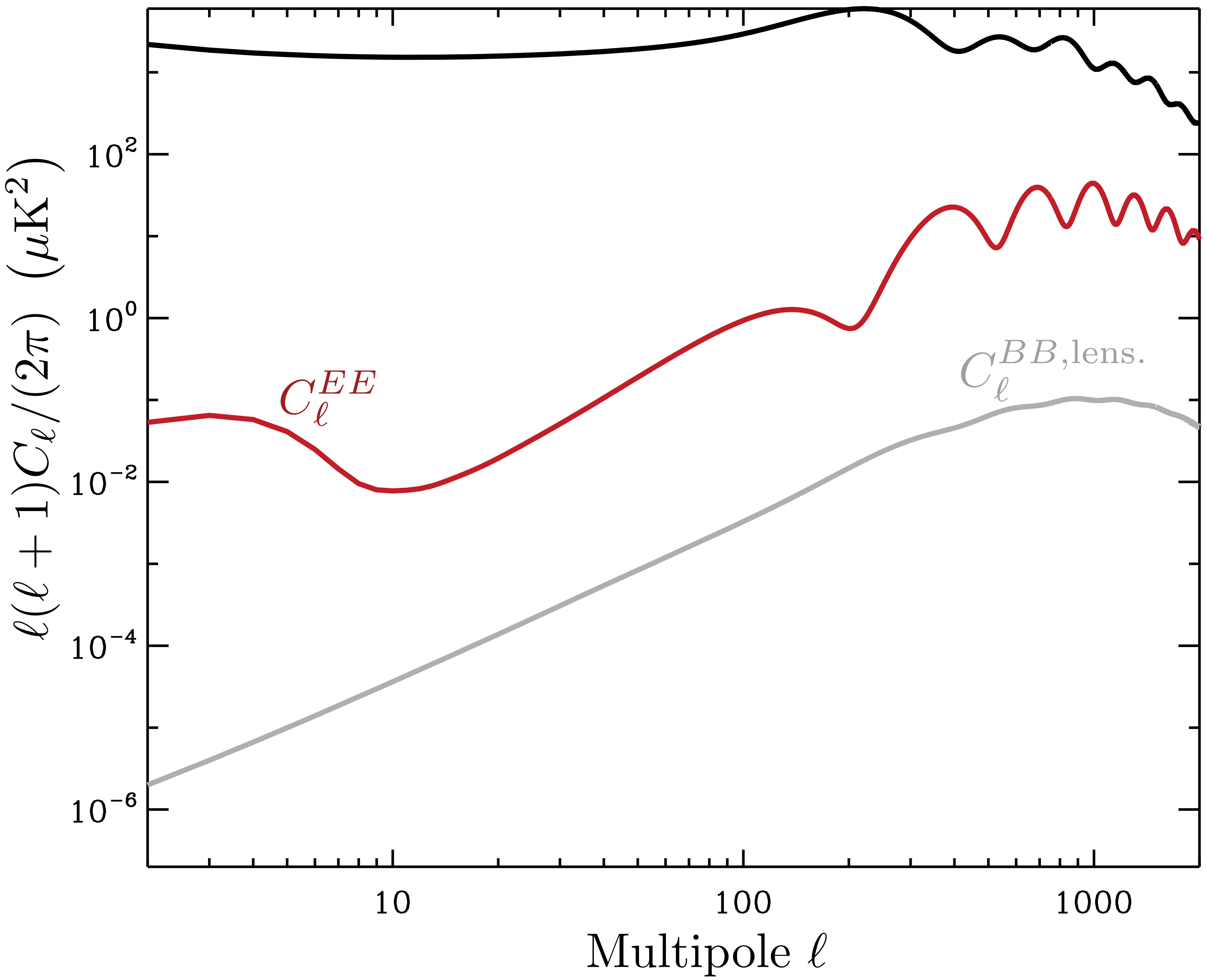


CMB – *B*-modes

★ *TT* spectrum: cosmological parameters from density perturbations

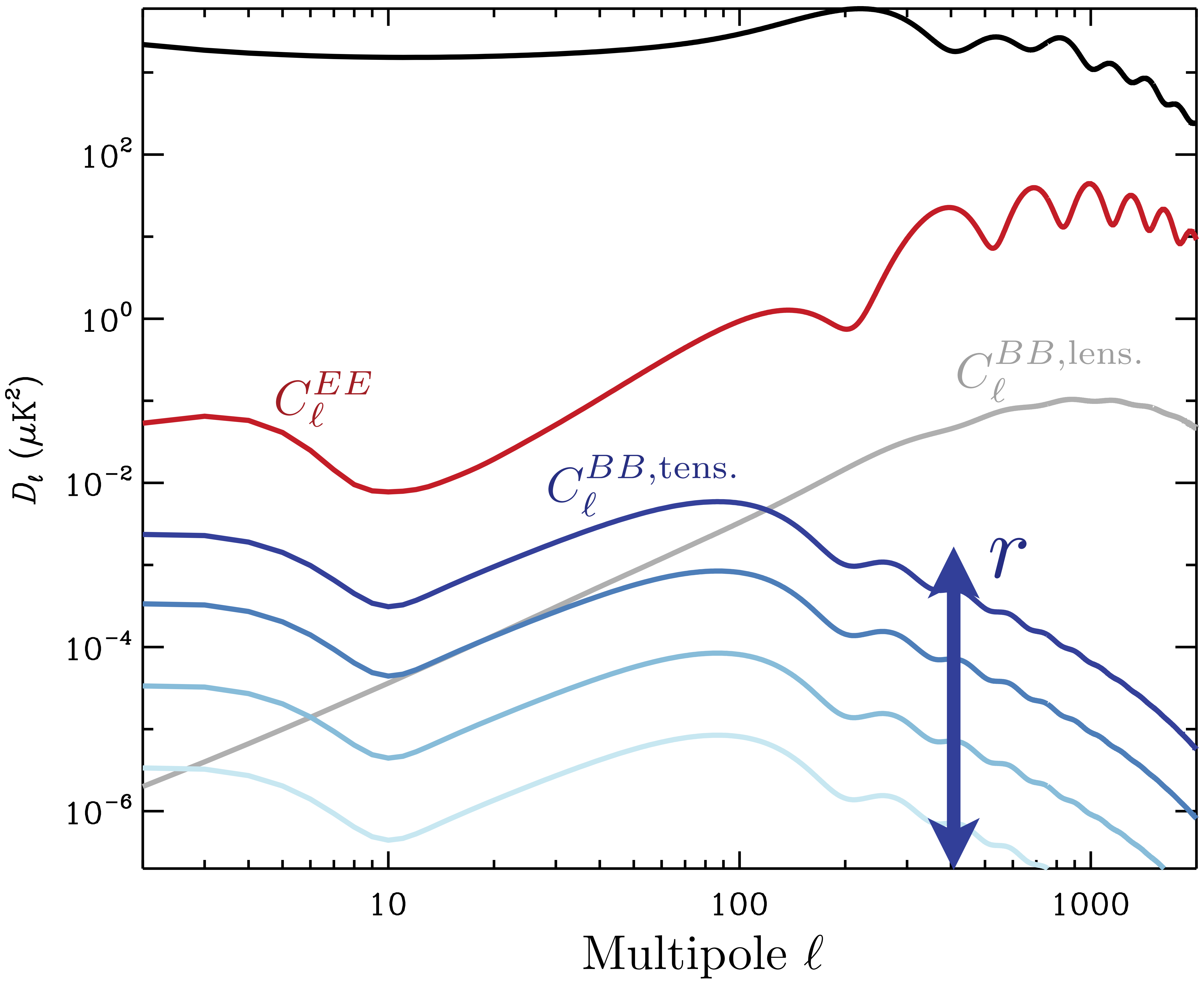
★ *EE* spectrum: model coherence, leaves degeneracies (τ, n_s, …)

★ *BB* lensing spectrum: gravitational lensing of *EE* modes, large-scale structures



CMB – *B*-modes

- ★ *TT* spectrum: cosmological parameters from density perturbations
- ★ *EE* spectrum: model coherence, leaves degeneracies (τ, n_s, …)
- ★ *BB* lensing spectrum: gravitational lensing of *EE* modes, large-scale structures
- ★ *BB* primordial spectrum: tensor perturbations from primordial gravitational wave background, linearly scaled by tensor to scalar ratio *r*, linked to the energy scale of inflation



CMB – *B*-modes

★ *TT* spectrum: cosmological parameters from density perturbations

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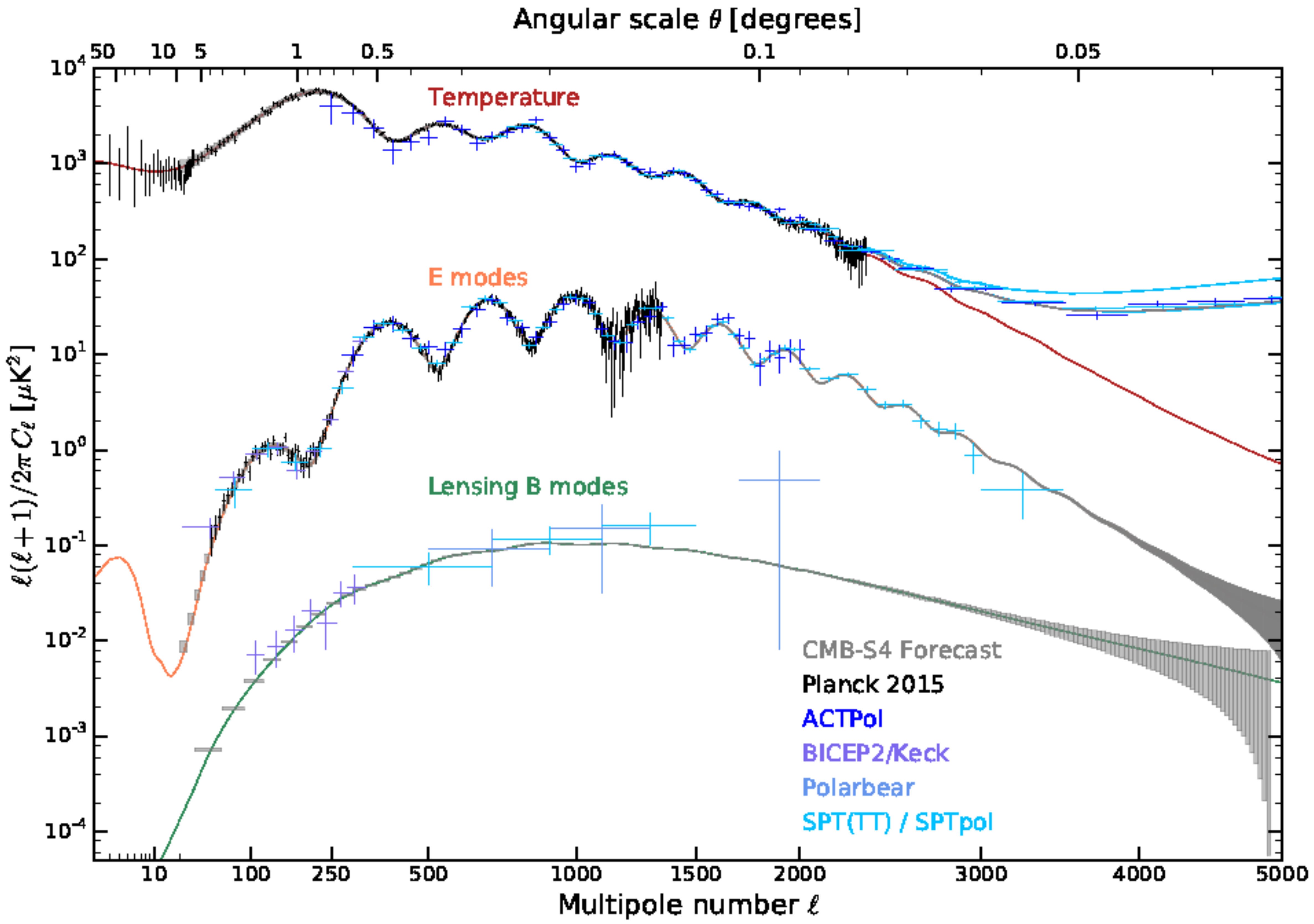
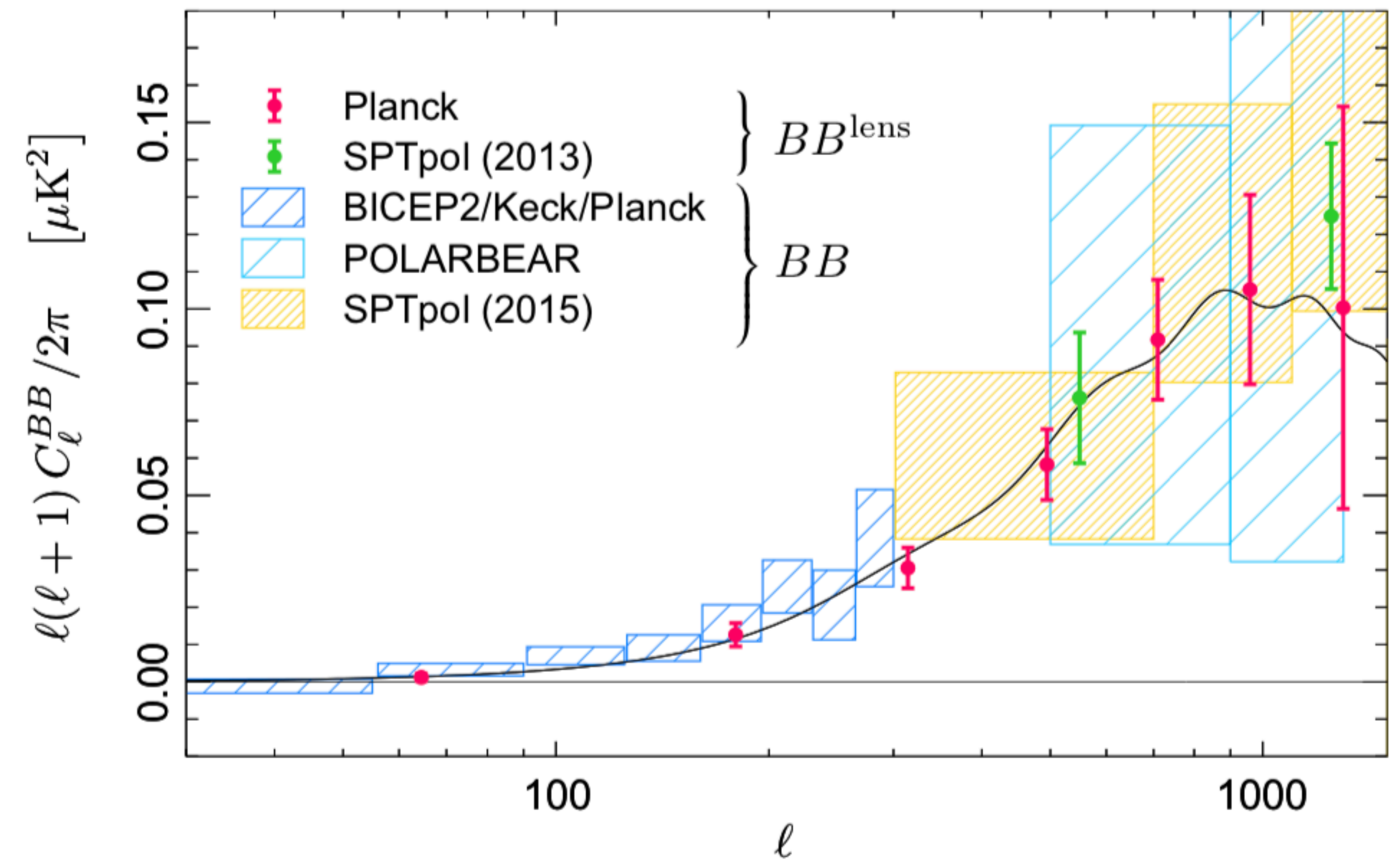


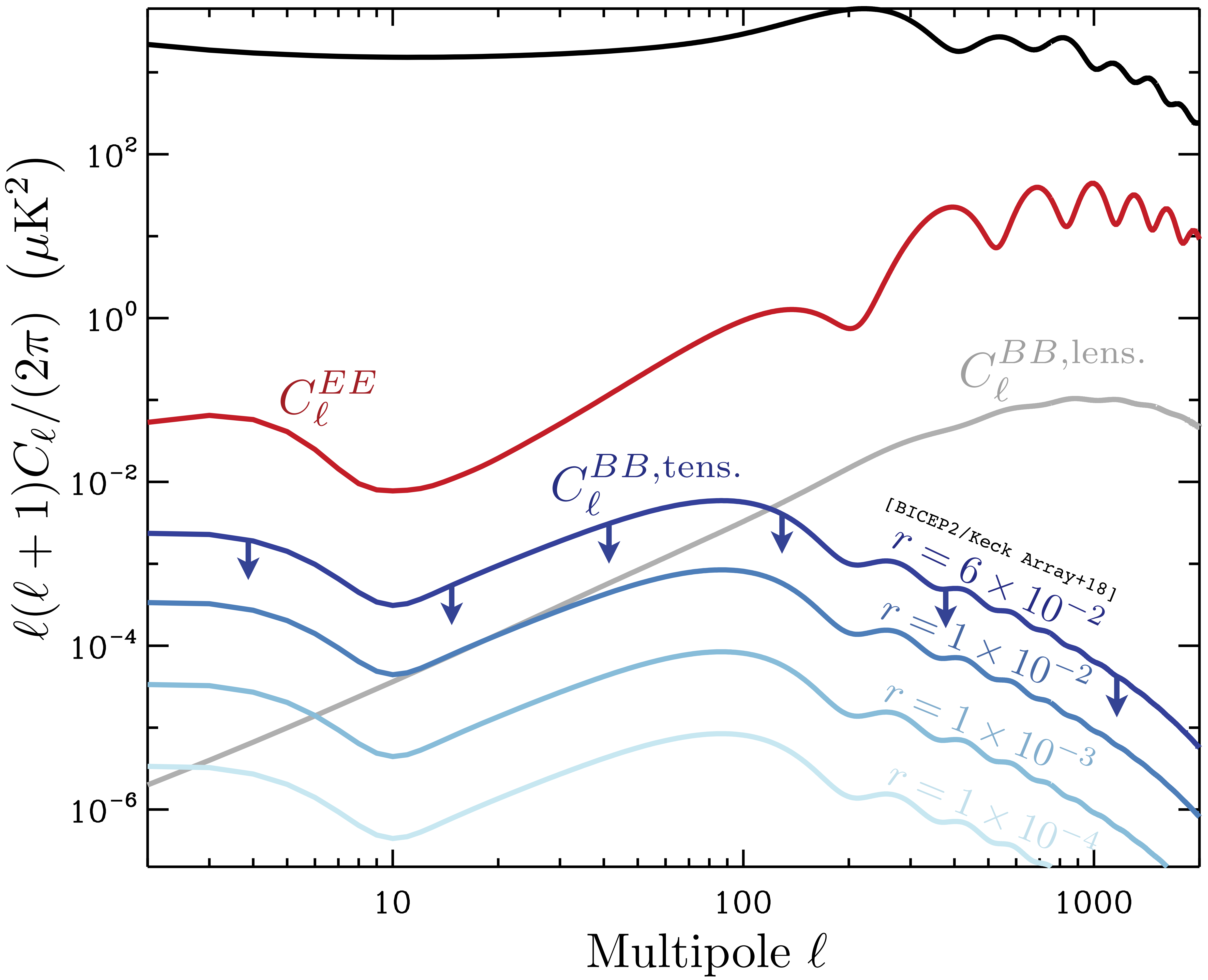
[CMB-S4+16]



[Planck Int. XLI]

CMB – *B*-modes

- ★ *TT* spectrum: cosmological parameters from density perturbations
- ★ *EE* spectrum: model coherence, leaves degeneracies (τ, n_s, …)
- ★ *BB* lensing spectrum: gravitational lensing of *EE* modes, large-scale structures
- ★ *BB* primordial spectrum: tensor perturbations from primordial gravitational wave background, linearly scaled by tensor to scalar ratio r, linked to the energy scale of inflation
- ★ Unknown amplitude, best upper limit is $r < 0.06$ `[BICEP2/Keck Array+18]` (see D. Barkats' talk)
- ★ Experiments are designed and build that target $r = 10^{-3}$



CMB – Beyond the B-modes

★ "Standard" cosmology does not produce *TB* and *EB* spectra (parity conserving physics)

★ Cosmological birefringence is a rotation of the polarization plane that changes *E* modes into *B* modes and thus produces non zero *TB* and *EB* spectra

➡ May reveal parity violation in either the electromagnetic (e.g. cosmological pseudo-scalar field `[e.g. Carroll99]`) or gravitational sectors (e.g. chiral gravitational waves `[e.g. Lue+99]`) of the fundamental interactions

➡ May reveal primordial magnetic fields through Faraday rotation (frequency dependent, **B** < 4.4 nG `[Planck 2015 XIX]`)

★ No evidence for cosmological *TB* and *EB* spectra yet

★ Foregrounds (interstellar dust and synchrotron) produce frequency dependent non zero *TB* and *EB* spectra (*TB* already measured `[Planck Int. XXX]`)

CMB – Absolute angle calibration

★ Timestream of data for a single polarization sensitive detector:

$$d_i(t) = g_i \left[T(\mathbf{n}) + \frac{1-\varepsilon_i}{1+\varepsilon_i} \left(Q(\mathbf{n}) \cos 2\psi_i + U(\mathbf{n}) \sin 2\psi_i \right) \right]$$

With:

$$\psi_i = \psi_i^{\text{design}} + \Delta\psi$$

- ψ_i: Detector's polarization angle projected onto the sky
- ψ_i^{design}: Intended orientation of the detector onto the sky
- $\Delta\psi$: Miscalibration (or birefringence)

CMB – Absolute angle (mis-)calibration

$$\psi_i = \psi_i^{\text{design}} + \Delta\psi$$

↓

★ Behaviour of the Stokes parameters under a miscalibration of the polarization angle:

$$\tilde{Q}(\mathbf{n}) \pm i\tilde{U}(\mathbf{n}) = e^{\pm 2i\Delta\psi}\left(Q(\mathbf{n}) \pm iU(\mathbf{n})\right)$$

★ Behaviour of the polarized angular power spectra:

$$\tilde{C}_\ell^{EE} = \sin^2(2\Delta\psi)C_\ell^{BB} + \cos^2(2\Delta\psi)C_\ell^{EE} - \sin(4\Delta\psi)C_\ell^{EB}$$

$$\tilde{C}_\ell^{BB} = \cos^2(2\Delta\psi)C_\ell^{BB} + \sin^2(2\Delta\psi)C_\ell^{EE} + \sin(4\Delta\psi)C_\ell^{EB}$$

$$\tilde{C}_\ell^{TE} = \cos(2\Delta\psi)C_\ell^{TE} - \sin(2\Delta\psi)C_\ell^{TB}$$

$$\tilde{C}_\ell^{TB} = \sin(2\Delta\psi)C_\ell^{TE} + \cos(2\Delta\psi)C_\ell^{TB}$$

$$\tilde{C}_\ell^{EB} = \frac{1}{2}\sin(4\Delta\psi)(C_\ell^{EE} - C_\ell^{BB}) + \left(\cos^2(2\Delta\psi) - \sin^2(2\Delta\psi)\right)C_\ell^{EB}$$

[see e.g. Pagano+09]

CMB – Absolute angle (mis-)calibration

$$\psi_i = \psi_i^{\rm design} + \Delta\psi$$

⬇

★ Behaviour of the Stokes parameters under a miscalibration of the polarization angle:

$$\tilde{Q}(\mathbf{n}) \pm i\tilde{U}(\mathbf{n}) = e^{\pm 2i\Delta\psi}\left(Q(\mathbf{n}) \pm iU(\mathbf{n})\right)$$

★ Behaviour of the polarized angular power spectra:

$$\text{For } \Delta\psi \ll 1,\ C_\ell^{BB} \ll C_\ell^{EE},\ C_\ell^{TB} \ll C_\ell^{TE} \text{ and } C_\ell^{EB} \ll C_\ell^{EE}:$$

$$C_\ell^{BB} \simeq 4\Delta\psi^2 C_\ell^{EE}$$
$$C_\ell^{TB} \simeq 2\Delta\psi C_\ell^{TE}$$
$$C_\ell^{EB} \simeq 2\Delta\psi C_\ell^{EE}$$

★ Need for a exquisite calibration of the absolute polarization angle to be able to constrain primordial *BB*, *TB* or *EB* signals!

CMB – Angle calibration state-of-the-art

$\Delta\psi$?

1 GROUND CALIBRATION

- ➡ Depends a lot on the design
- ➡ Mechanical alignment of the system orientation is in principle very good
- ➡ Need anyway to be validated during operations because of thermal effects and environment change

2 EXTERNAL CALIBRATION SOURCE

- ➡ On a satellite (e.g. Calsat [Johnson+15]), a balloon (e.g. POLOCALC [Nati+17]), etc…
- ➡ Potential good accuracy, probes system during operations
- ➡ Never done

3 SELF-CALIBRATION

- ➡ assumes *TB* and *EB* are only instrumental
- ➡ Good accuracy, probes system during operations
- ➡ Loose constraining power on fundamental phenomena
- ➡ Problem of foregrounds

4 SKY CALIBRATION

- ➡ Probes system during operations, no science loss
- ➡ Frequency dependence, time variability, extended sources
- ➡ Best option is Crab Nebula (Tau A)

CRAB – SED

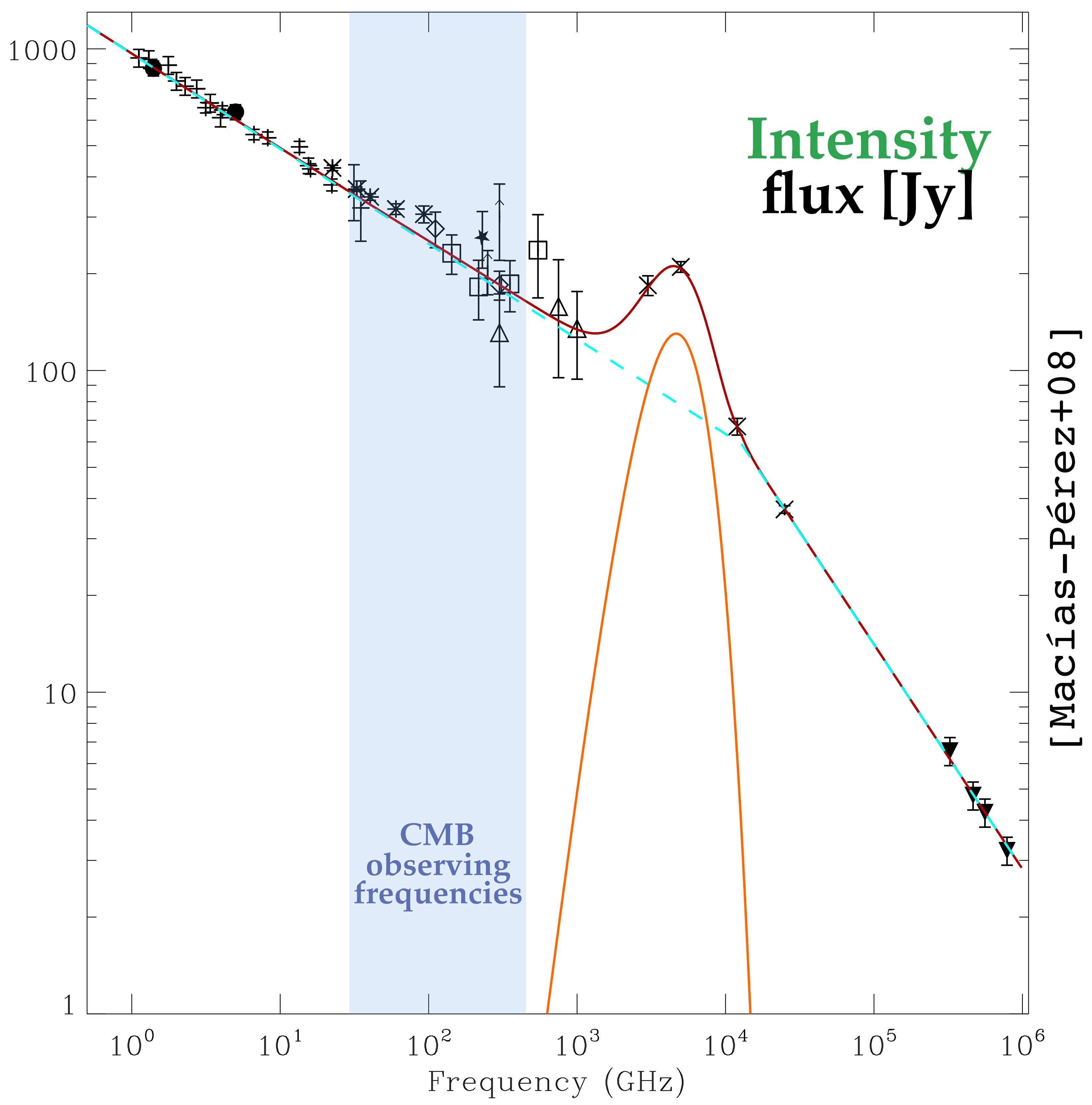
(see A. Ritacco's talk)

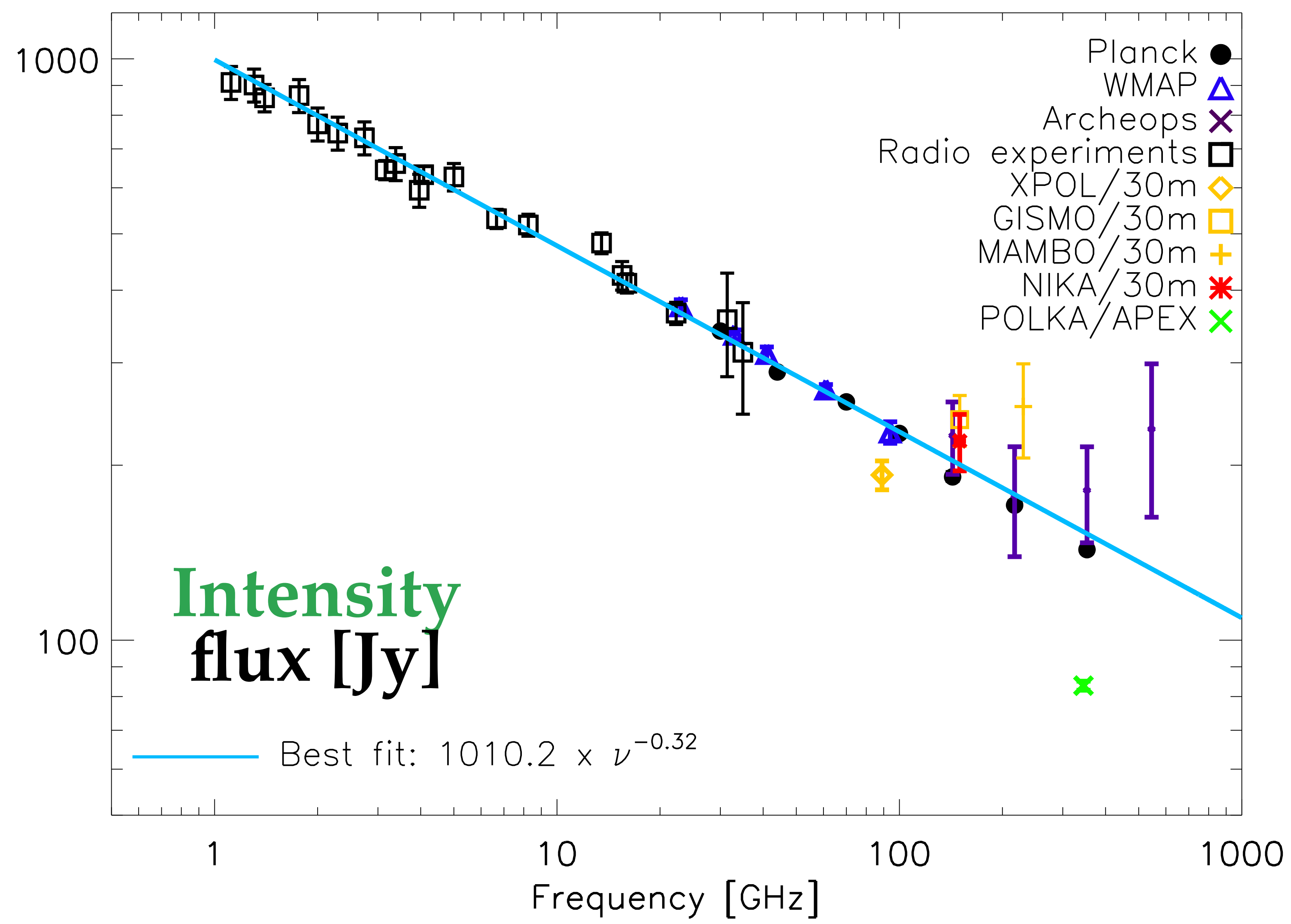
★ The Crab Nebula (Tau A) is a plerion-type supernova remnant, observed from radio to X-rays

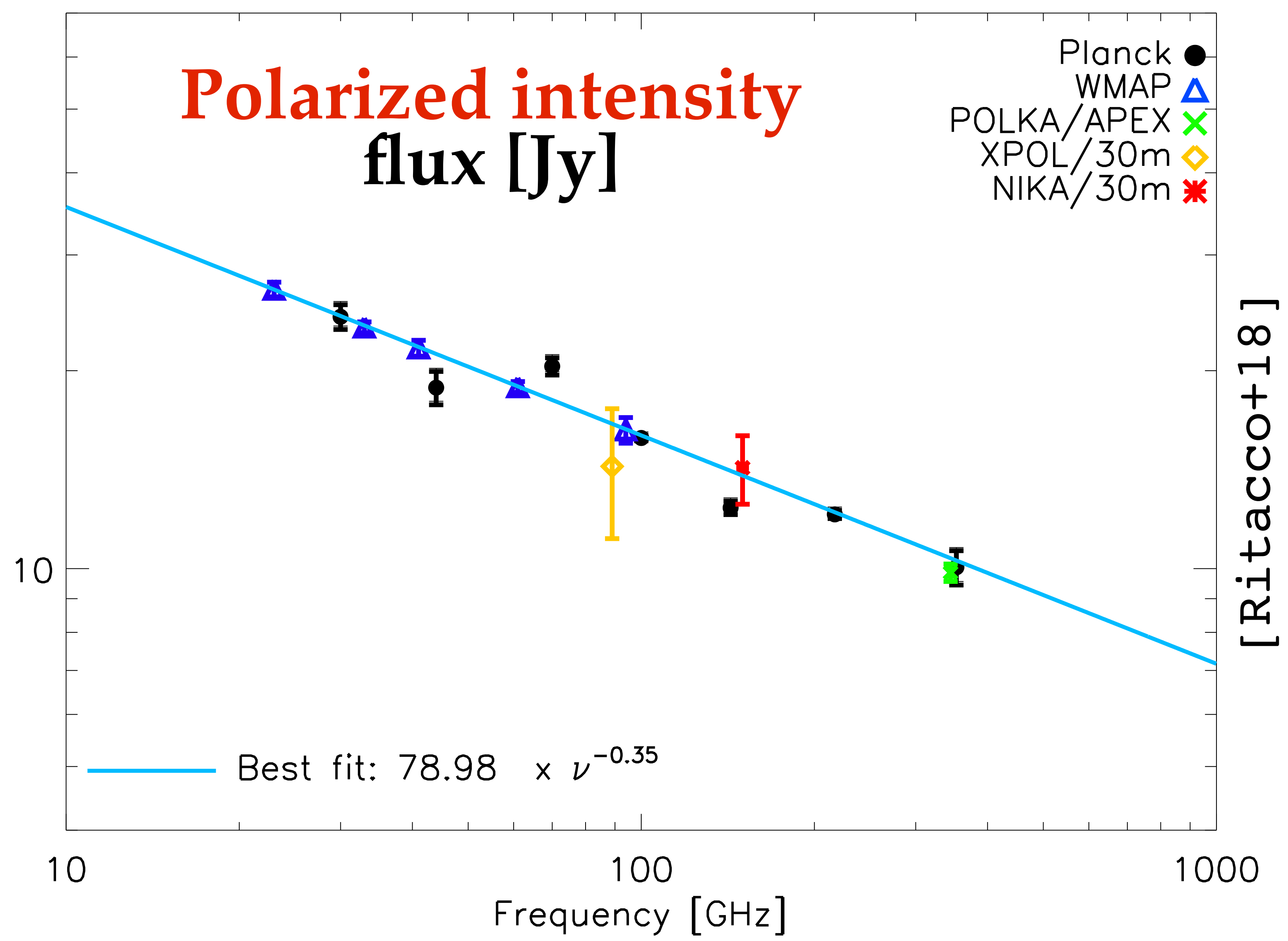
★ Synchrotron emission from radio to mm wavelengths is well characterised by a single power law, both in temperature and polarisation [Ritacco+18]

➡ single population of relativistic electrons responsible for the emission of the nebula.

➡ degree and angle of polarisation of the Crab nebula are expected to be constant across frequencies in this range







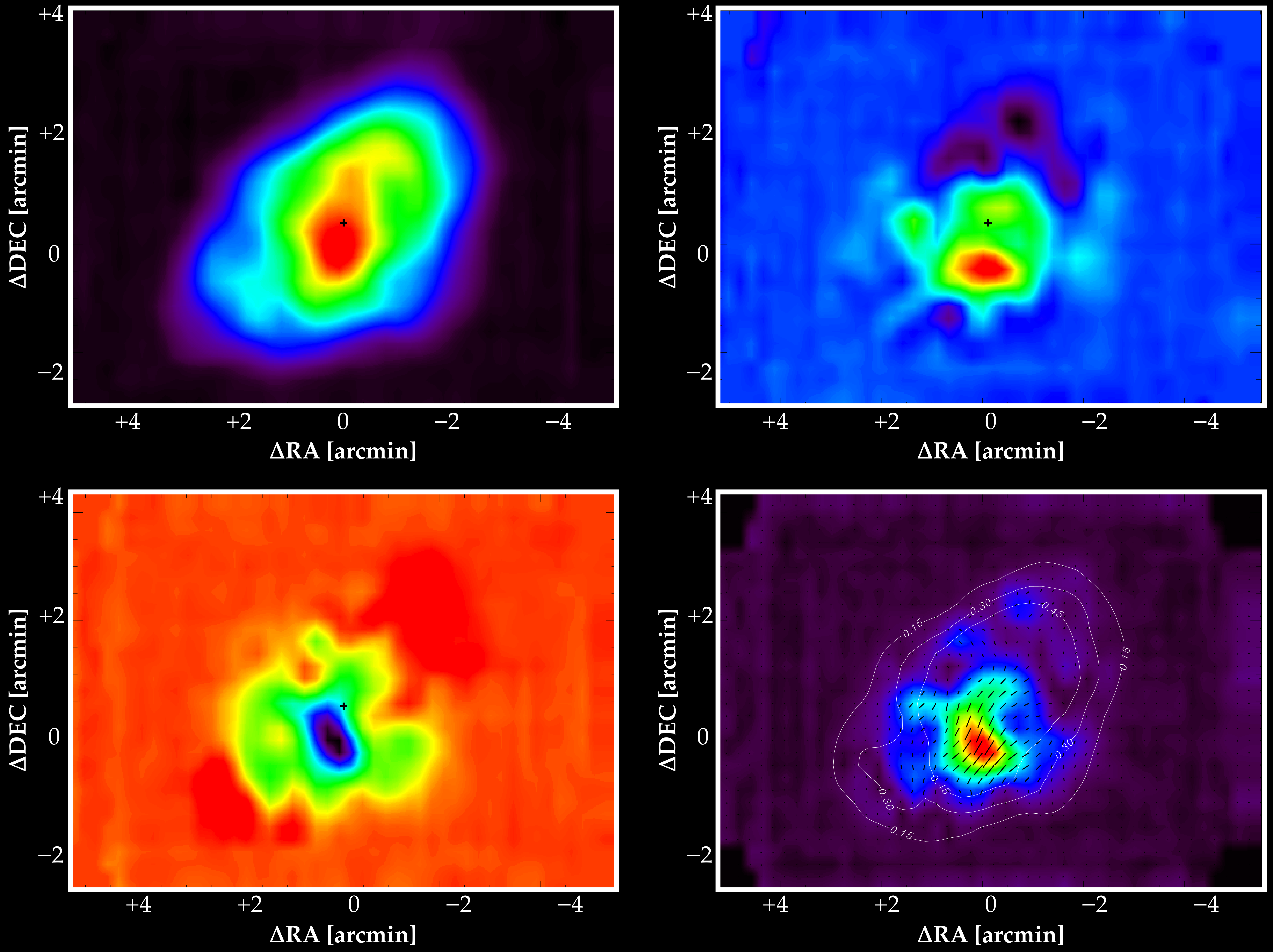
CRAB – Polarized emission

(see A. Ritacco's talk)

★ The Crab nebula microwave emission has an extension of about 5 × 7 arcmin

★ Highly polarized synchrotron emission with a polarization fraction of ~ 20% (~7% convolved by typical CMB experiment beams)

★ Most intense polarized source in the microwave sky, at angular scales of few arc-minutes



IRAM XPOL maps, [Aumont+10]

CRAB – Polarization angle compendium

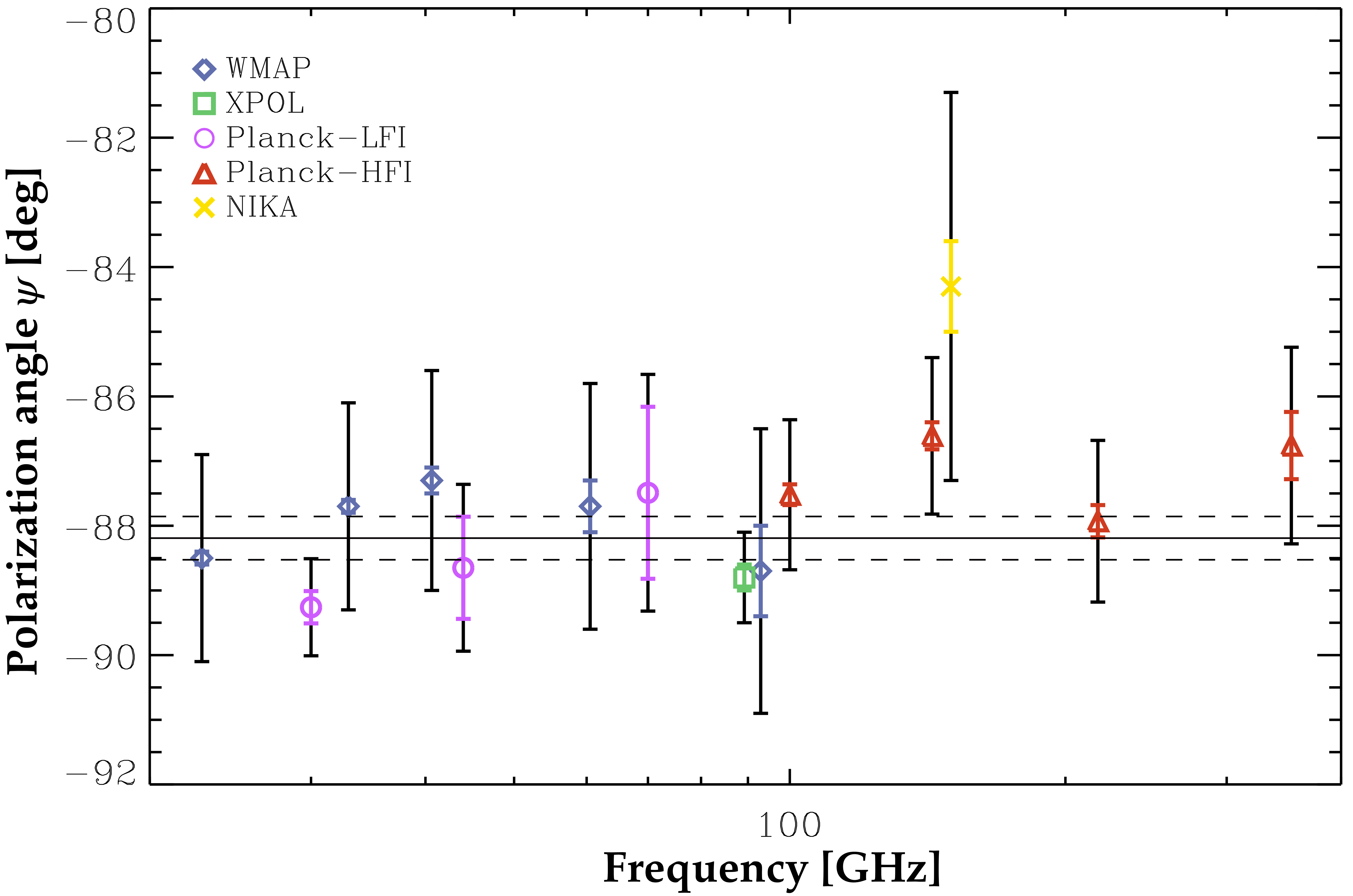
(see A. Ritacco's talk)

★ Compilation of:

- ➡ WMAP [Aumont+10]
- ➡ Planck-LFI [Planck 2015 XXVI], Planck-HFI, re-analyzed in [Ritacco+18])
- ➡ IRAM's XPOL [Aumont+10] and NIKA [Ritacco+18}

★ Polarization angles compatible with a constant angle of:

$$-88.24° \pm ?$$



[Aumont+10,Weiland+11,Planck 2015 XXVI,Ritacco+18]
[Aumont+19]

CRAB – Combining current (and future) measurements

[Aumont+19]

Experiment	ν (GHz)	Beam size	ψ_{Gal}(deg)	Statistical $\Delta\psi^{\mathrm{stat.}}_{\mathrm{Gal}}$(deg)	Systematic $\Delta\psi^{\mathrm{sys.}}_{\mathrm{Gal}}$(deg)		
					Ground	EB	TB
WMAP	23	53′	−88.5	0.1	1.5	–	–
	33	40′	−87.7	0.1	1.5	–	–
	41	31′	−87.3	0.2	1.5	–	–
	61	21′	−87.7	0.4	1.5	–	–
	94	13′	−88.7	0.7	1.5	–	–
XPOL	90	27″	−88.8⋆	0.2	0.5	–	–
PLANCK-LFI	30	33′	−89.26	0.25	0.5	–	–
	44	27′	−88.65	0.79	0.5	–	–
	70	13′	−87.49	1.33	0.5	–	–
PLANCK-HFI	100	10′	−87.52	0.16	1.00	0.63	0.22
	143	7′	−86.61	0.21	1.00	0.42	0.27
	217	5′	−87.93	0.25	1.00	0.51	0.83
	353	5′	−86.76	0.52	1.00	–	–
NIKA	150	18″	−84.3•	0.7	2.3	–	–

[Rosset+10]

[Planck Int. XLVI]

CRAB – Combining current (and future) measurements

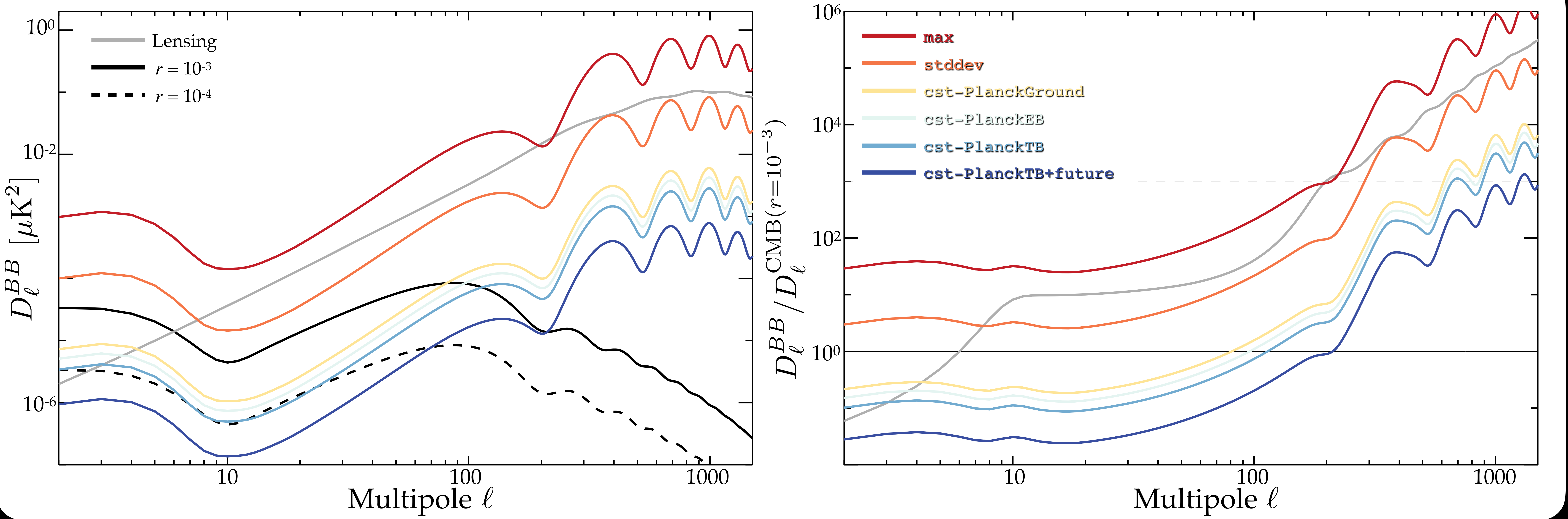
Name	Assumption	Statistical error	Systematic error	Planck Systematics	New experiment	Crab pol. angle uncertainty $\Delta\psi$ (1σ)
`max`	Maximum difference between the mean value and one measurement	✗	✗	✗	✗	3.96°
`stddev`	Standard deviation of the measurements	✗	✗	✗	✗	1.24°
`cst-PlanckGround`	Constant angle	✓	✓	Ground	✗	0.27°
`cst-PlanckEB`	Constant angle	✓	✓	*EB*	✗	0.22°
`cst-PlanckTB`	Constant angle	✓	✓	*TB*	✗	0.17°
`cst-PlanckTB+future`	Constant angle	✓	✓	*TB*	✓	0.11°

2 bands with 0.2° total error

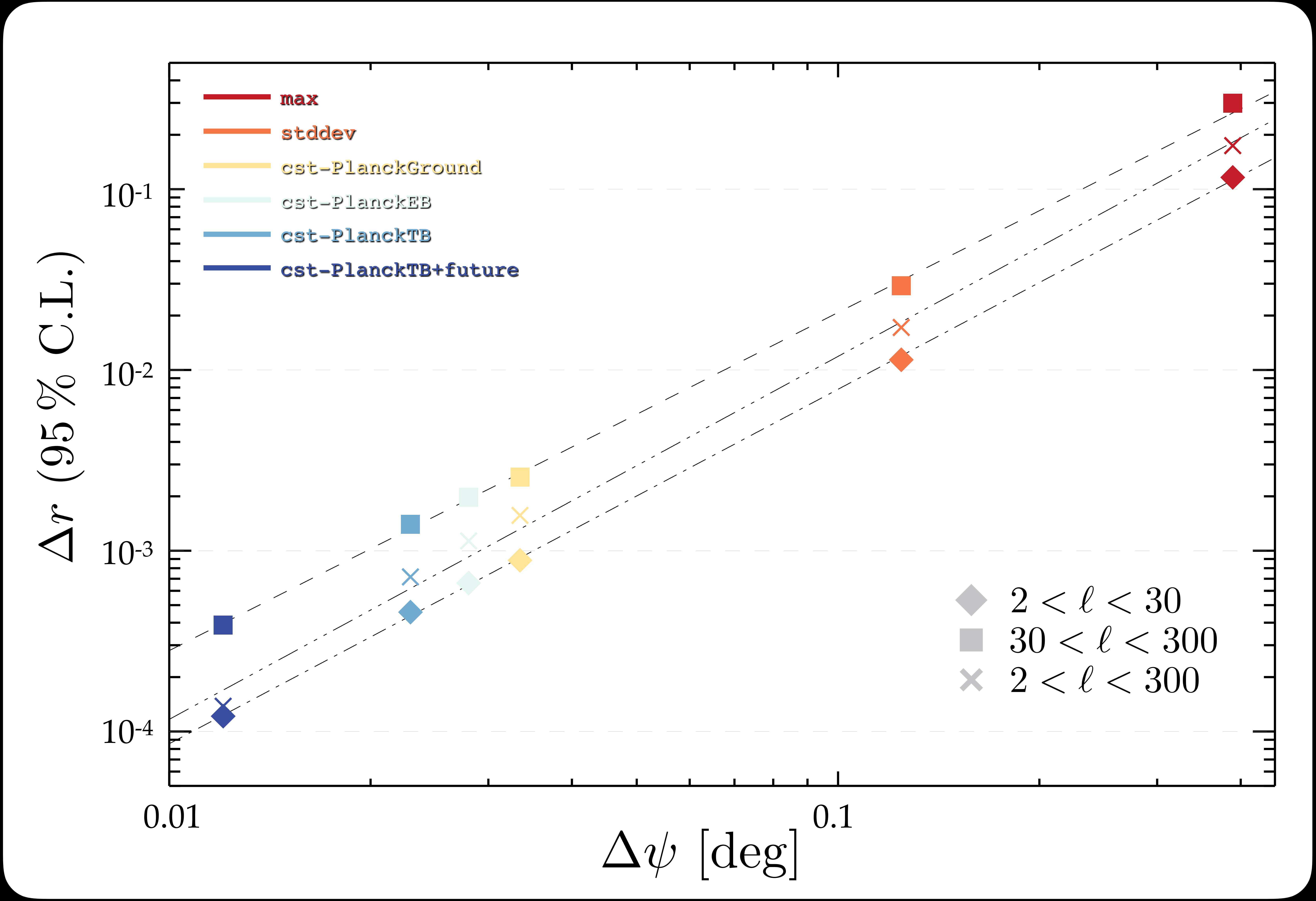
[Aumont+19]

CMB – Miscalibration due to the Crab measurement uncertainty

[Aumont+19]



CMB – Likelihood posterior on *r*



- ★ Likelihood analysis of *r* in presence of a spurious signal due to the absolute polarization angle miscalibration
- ★ Assumption of a constant angle is crucial for next generation experiments
- ★ Current measurements could allow to probe $r = 10^{-2}$
- ★ Future accurate measurements of the Crab are needed to meet the requirements of future CMB experiments to measure $r = 10^{-3}$ (e.g. LiteBIRD, CMB-S4)

[Aumont+19]

SUMMARY

★ Absolute calibration of the polarization angle is crucial for the CMB cosmology

★ Sky calibration of the polarization angle allows to jointly test the system during its operations and to conserve the *TB* and *EB* science

★ Crab Nebula is the best candidate for sky calibration

★ The assumption that the Crab polarization angle is constant has to be made in order to be a competitive calibration source

★ Current measurements could allow to probe $r = 10^{-2}$

★ Future accurate measurements of the Crab are needed to meet the requirements of future CMB experiments to measure $r = 10^{-3}$ (e.g. LiteBIRD, CMB-S4)