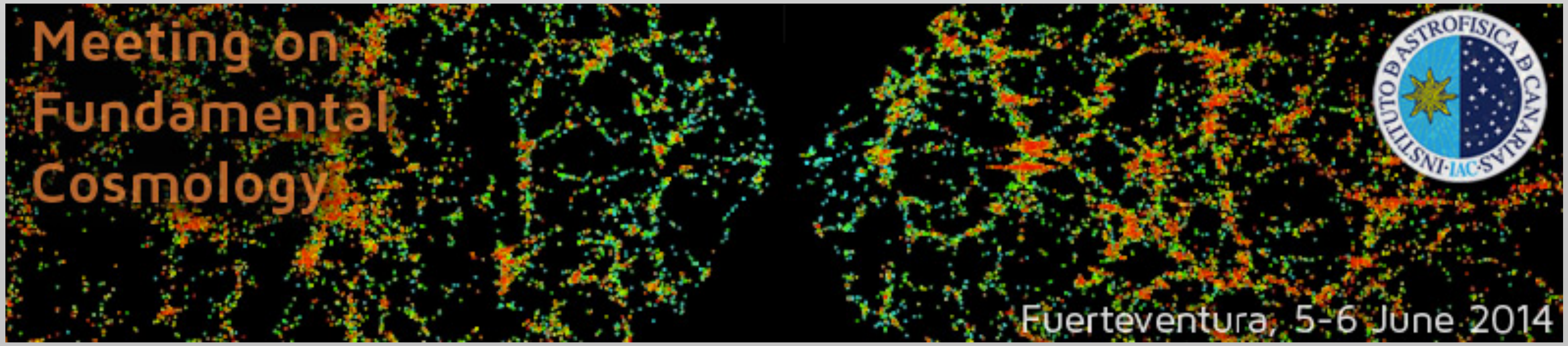
CMB polarization
Review of current and future experiments

Ricardo Génova Santos (IAC)



Inflation

✤ Epoch of exponential expansion of the Universe with nearly constant energy density. Between 10^{-36} and 10^{-32} s after the BB the size of the Universe increased a factor $\sim 10^{26}$

✤ Proposed in the 80s (Starobinsky 1980, Guth 1981, Linde 1982, Albretch & Steinhardt 1982), it solves several problems of standard Big Bang cosmology:

- Horizon problem
- Flatness problem
- Absence of unwanted relics (magnetic monopoles)

✤ Consequences of inflation:

- Density perturbations ⇒ seeds for the Universe's structure ➞ **scalar perturbations**
- Creates **gravitational waves** (ripples in the space-time metric) ➞ **tensor perturbations**

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- Flat geometry (by construction) ✓
- Nearly scale-invariant perturbations (with n_{es} <1 but close to unity) ✓
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- Gravitational waves, with nearly scale-invariant spectrum for the simplest models ⟶ Detection by BICEP2

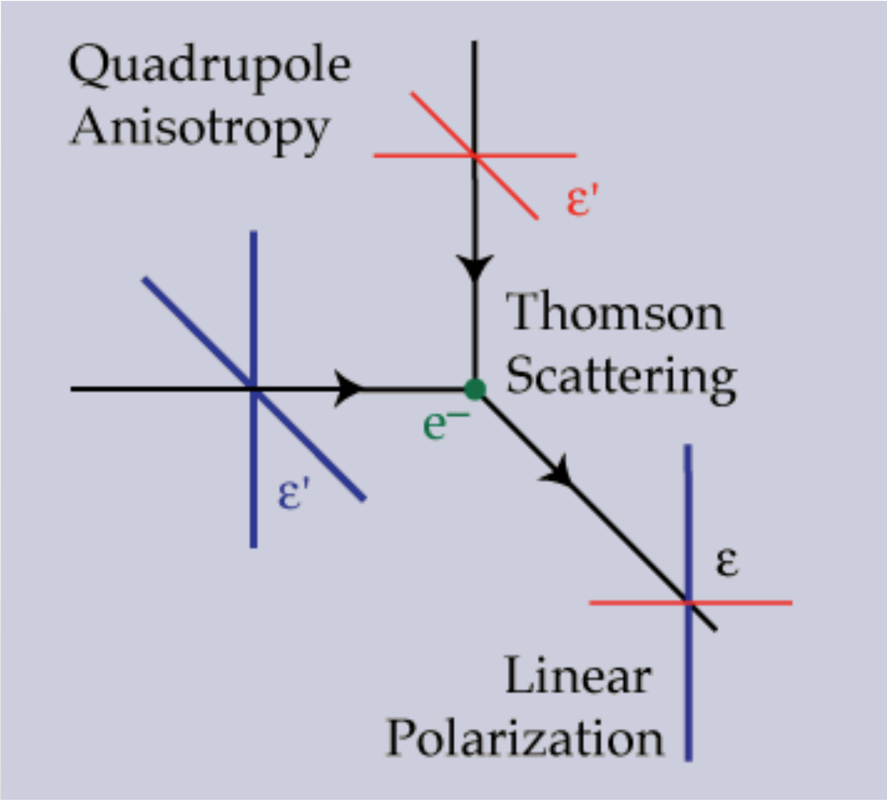
} CMB polarization

CMB polarization

✤ The CMB anisotropies are intrinsically polarized due to Thomson scattering during recombination

✤ A net polarization is generated during recombination in the presence of a quadrupole in the incident radiation field

✤ The resulting polarization is linear, i.e. the CMB will have non-zero Stokes parameters Q and U, but V=0



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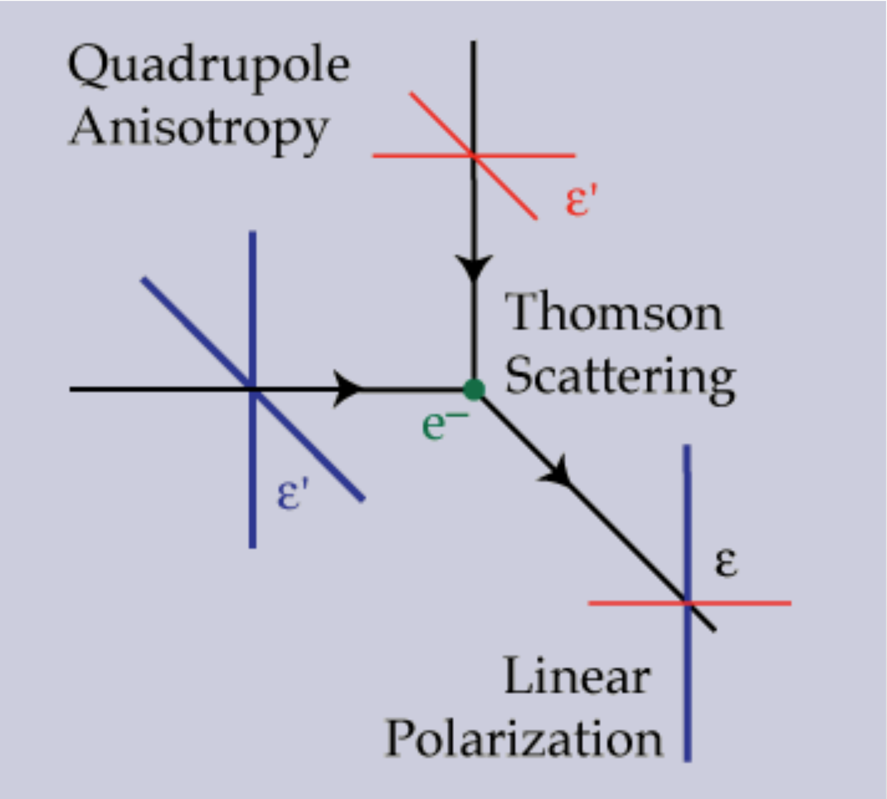

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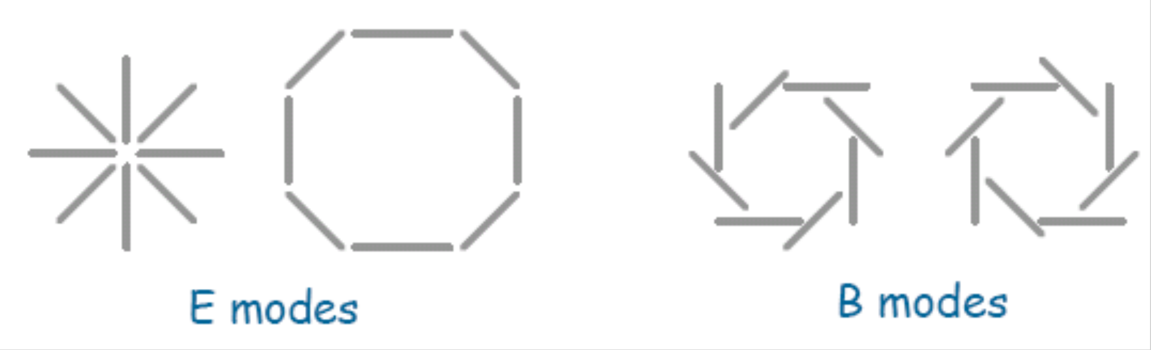
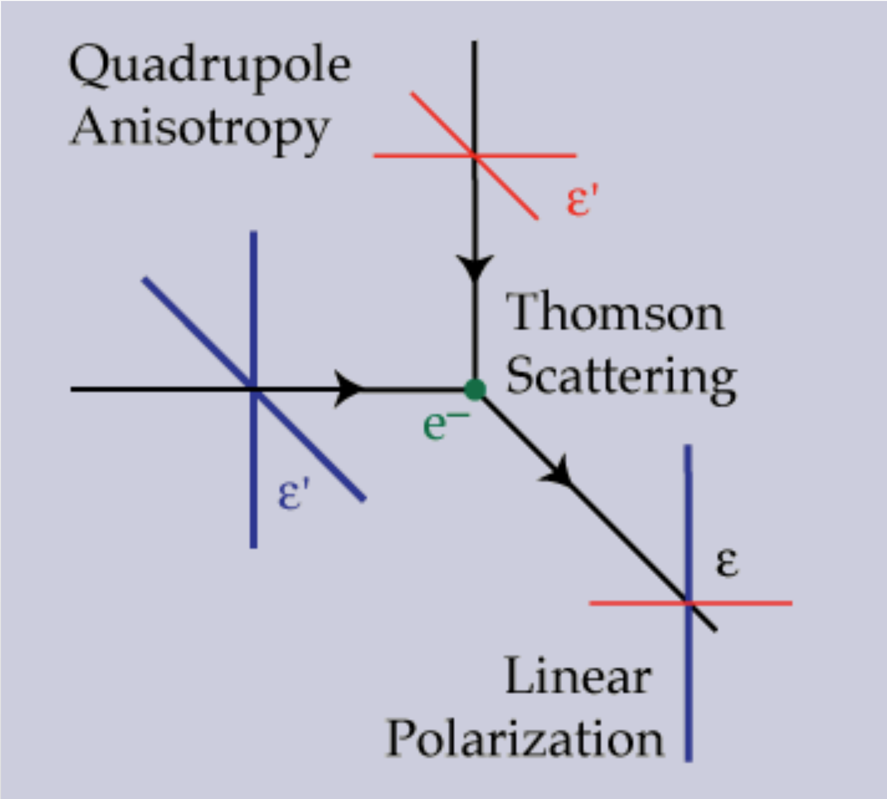
✤ Polarization maps can usually be decomposed into:

- **E-modes** (analog to gradient component)
- **B-modes** (analog to curl component)

Kamionkowski et al. 1997; Seljak & Zaldarriaga 1997



CMB polarization



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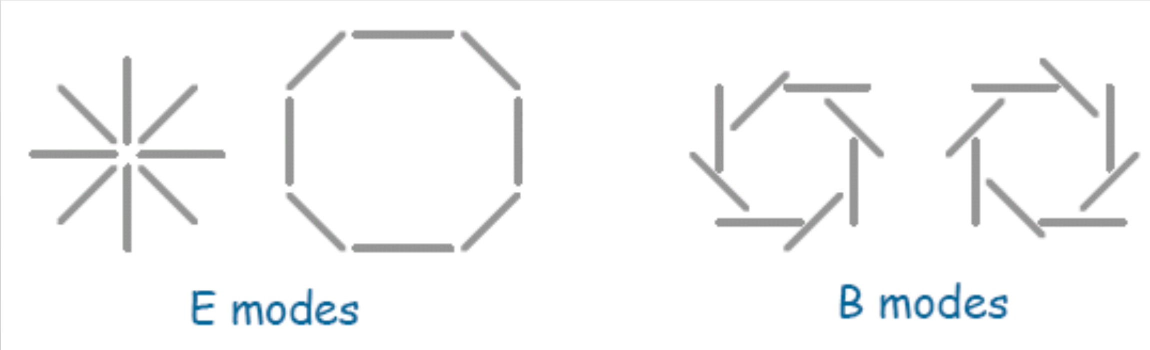
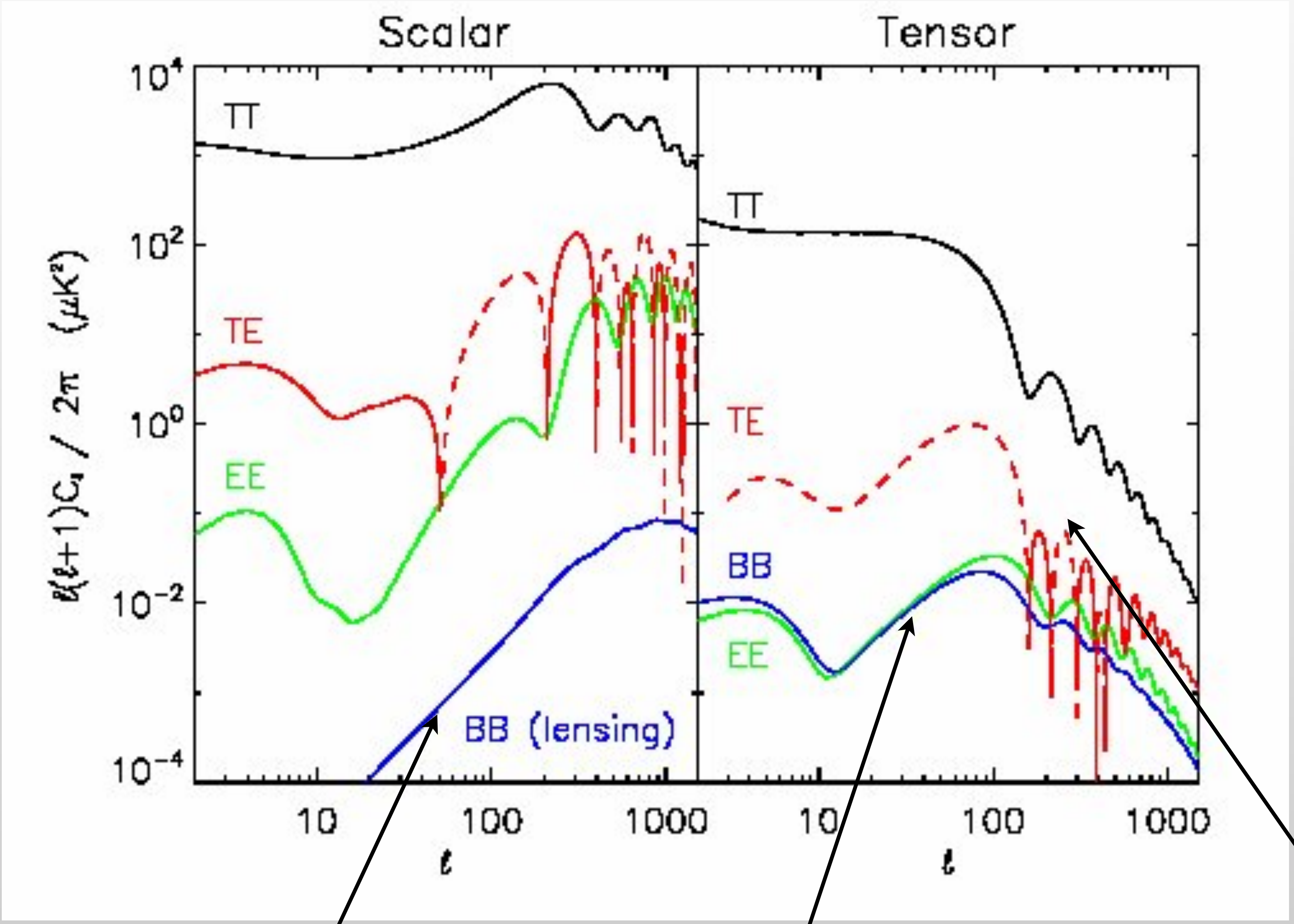


✤ Different types of anisotropies in the primordial universe create different types of modes

	E-modes	B-modes
Scalar (density perturbations)	✓	X
Tensor (gravitational waves)	✓	✓

✤ Power spectra of scalar (density) and tensor (GW) perturbations:



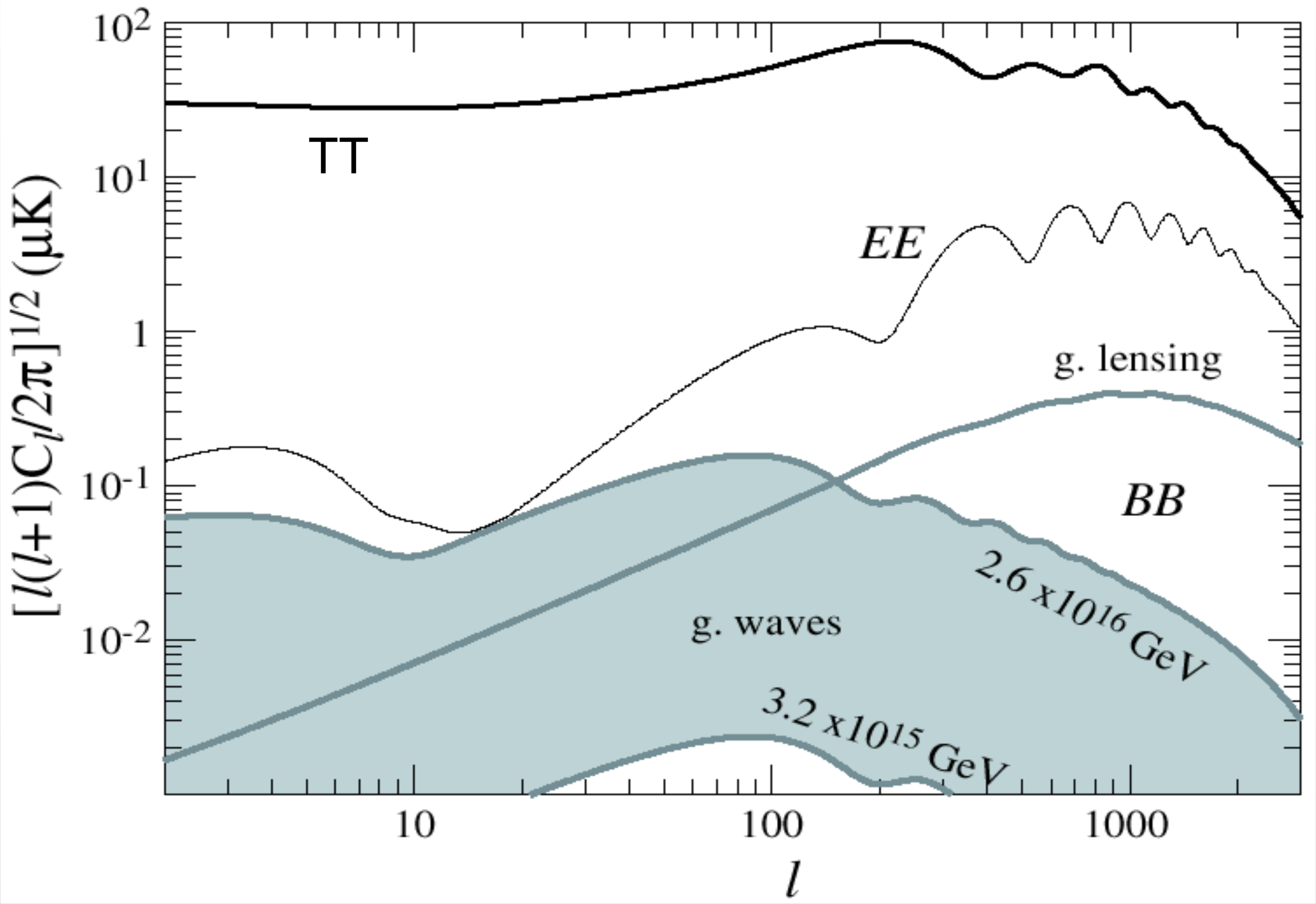
Lensing B-mode (not primordial)

Primordial B-modes from GW

Effects only on large scales because gravitation waves damp inside horizon

✤ Amplitude of the B-mode power spectrum:

(From http://cosmology.berkeley.edu/~yuki/CMBpol/CMBpol.htm)



- Tensor-to-scalar ratio: $r \equiv \frac{P_{tensor}(k_0)}{P_{scalar}(k_0)} = 0.008\left(\frac{E_{\inf}}{10^{16}GeV}\right)^4$

- $E_{inf}=2.6\times10^{16}$ GeV corresponds to r=0.37, and $E_{inf}=3.2\times10^{15}$ GeV to $r=8.4\times10^{-5}$

- r=0.01 corresponds to the GUT scale (~10^{16} GeV)

Observability of B-modes

✤ Signals are extremely small!!

- r=0.2 corresponds to an RMS B-mode anisotropy < 200 nK

➡ Extremely high sensitivities are required ⇒ large number of very-sensitive detectors with large bandwidths needed

$$\Delta T_{\rm RMS} = \frac{T_{\rm sys}}{\sqrt{\Delta\nu\ t\ N_{\rm chan}}}\sqrt{\frac{\Omega_{\rm sky}}{\Omega_{\rm beam}}}$$

(Final map sensitivity)

Experiment	Final map sensitivity (μK/degree)
COBE	~190
WMAP @ 94 GHz (DR5)	4.3
Planck @ 143 GHz (DR1)	0.46
BICEP2 @ 150 GHz	0.087

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➡ Accurate control of **systematics** is mandatory

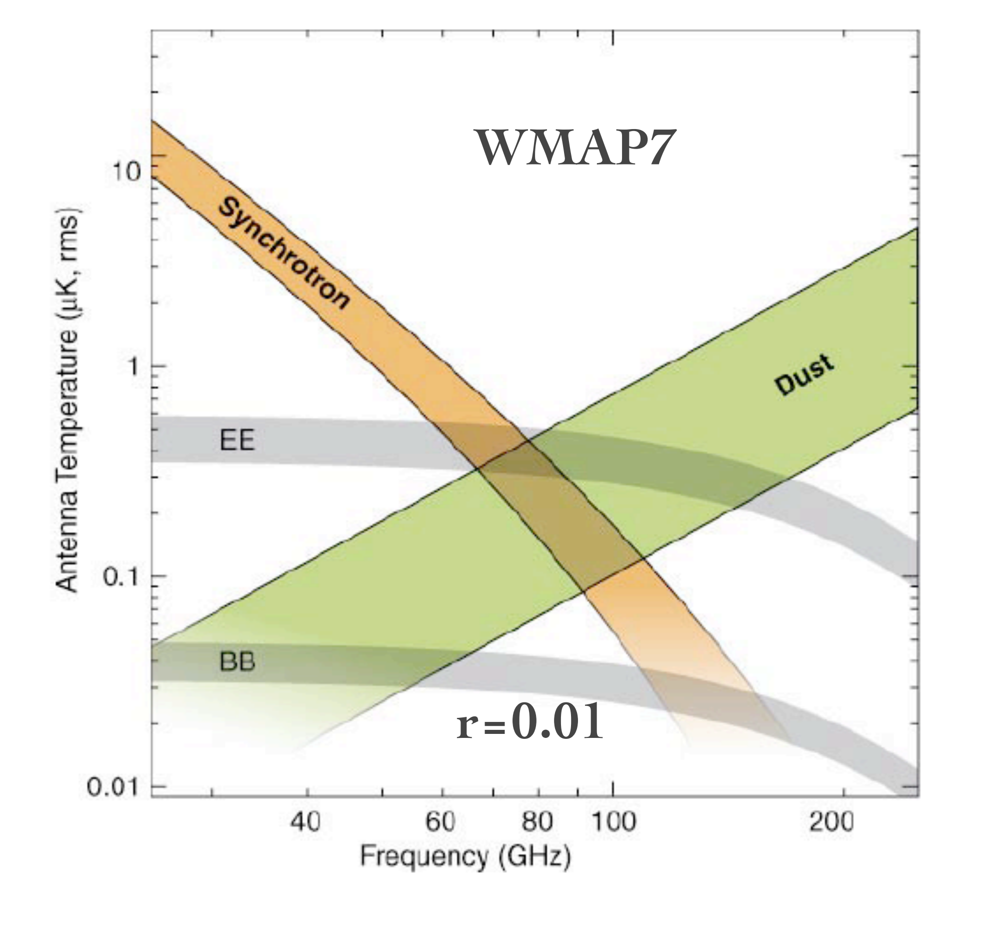
- Beam (cross-polar, asymmetries, sidelobes)
- Instrumental polarization
- Pointing accuracy
- Relative calibration (spectral responses)
- RFI

All these effects can lead to T→B or E→B leakage

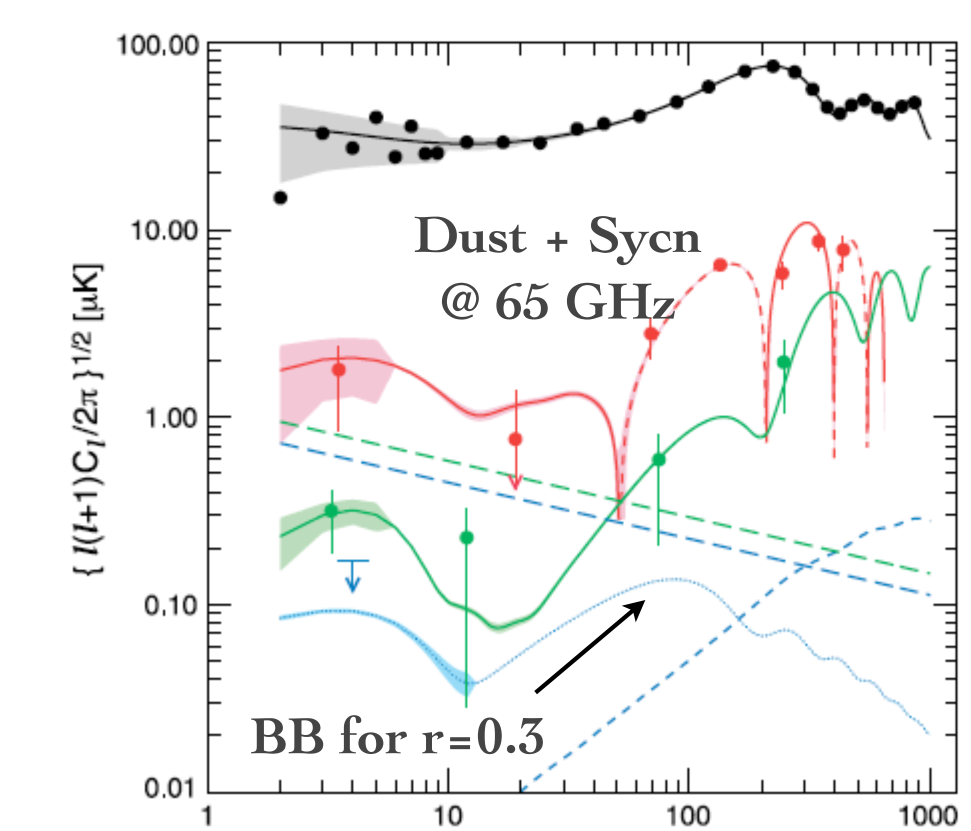
Observability of B-modes

➡ **Foregrounds**. B-mode signal is subdominant over Galactic foregrounds

- Free-free, low-freq, not polarized
- Synchrotron, low-freq, pol ~10%
- Thermal dust, high-freq, pol ~10%
- Anomalous emission, 20-60 GHz, <1% (?)
- Point sources, low-freq, pol ~5-10%



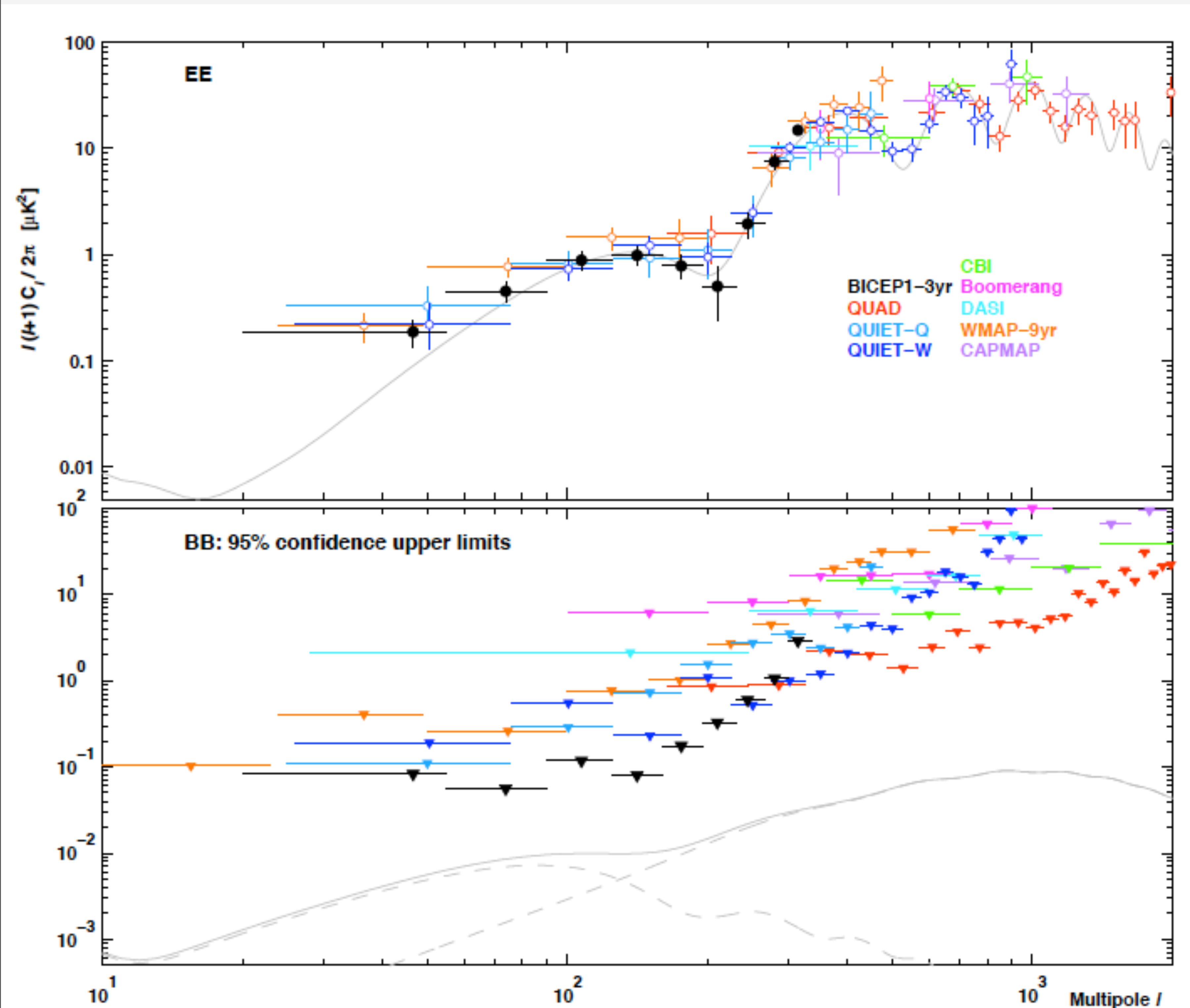
➡ Systematic program to study polarized astrophysical foreground signals is needed (see NASA-NSF report "Task Force on CMB research" and ESA-ESO report on "Fundamental cosmology")



Page et al. 2007

pre-BICEP2 status

(Before March 17)



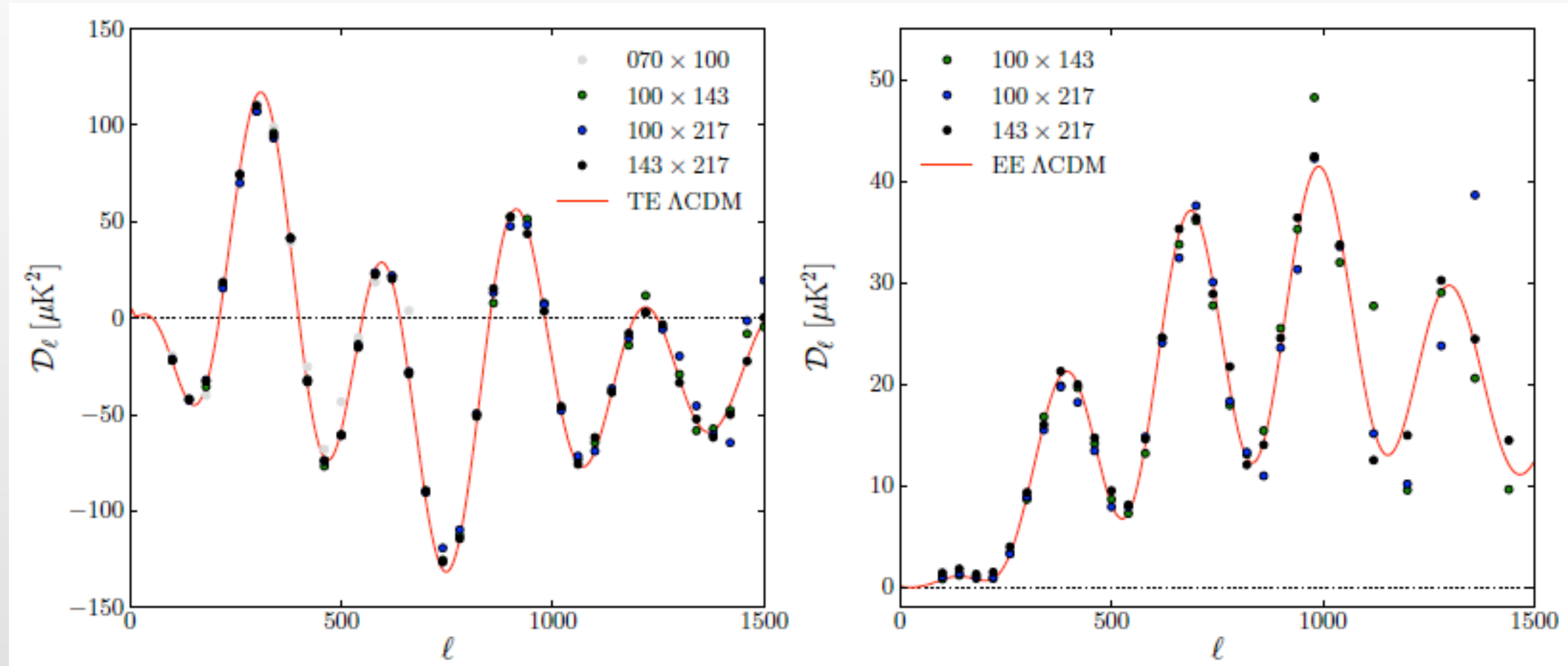
(Barkats et al. 2013, arXiv:1310.1422)

- First E-mode detection by DASI experiment (Kovac et al. 2002)
- Characterization of the EE and TE power spectra provided by many other experiments: CAPMAP, QUaD, Boomerang, WMAP, BICEP, QUIET,...
- BB constraints coming from BICEP: r<0.72 (Chiang et al. 2010), **r<0.70** (Barkats et al. 2013) at 95% CL
- QUIET results: r<2.7 (QUIET collaboration 2012)
- WMAP7 gives r<0.93 at 95% CL using TE/EE/BB, and r<2.1 with BB alone

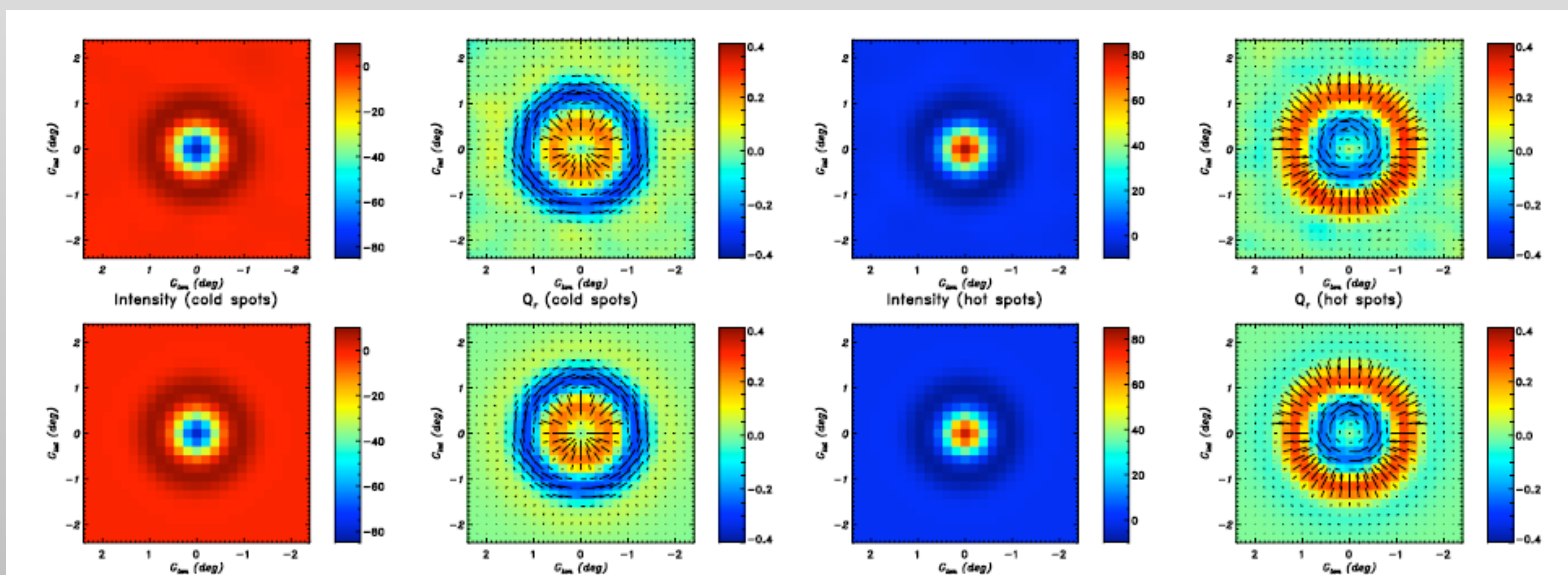
Planck results

TE and EE power spectra

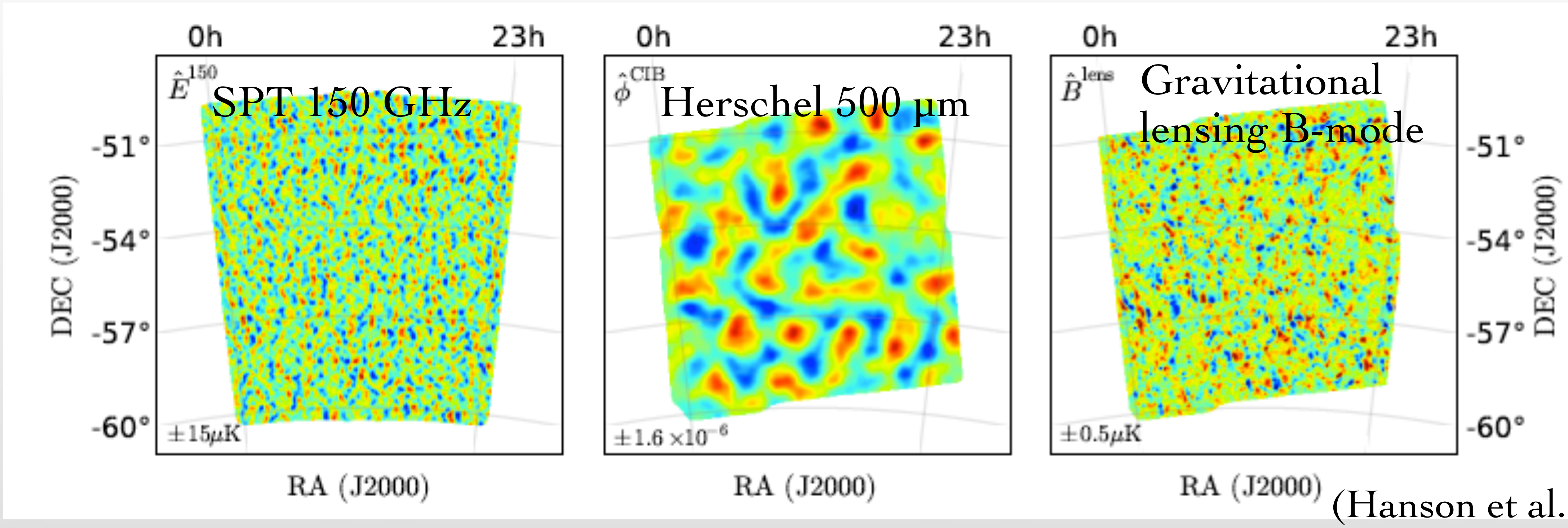
(CPP15, arXiv:1303.5075)



Stacked I and Q maps around hot and cold spots. Detection of the signal from adiabatic scalar fluctuations from inflation (CPP1, arXiv:1303.5062):

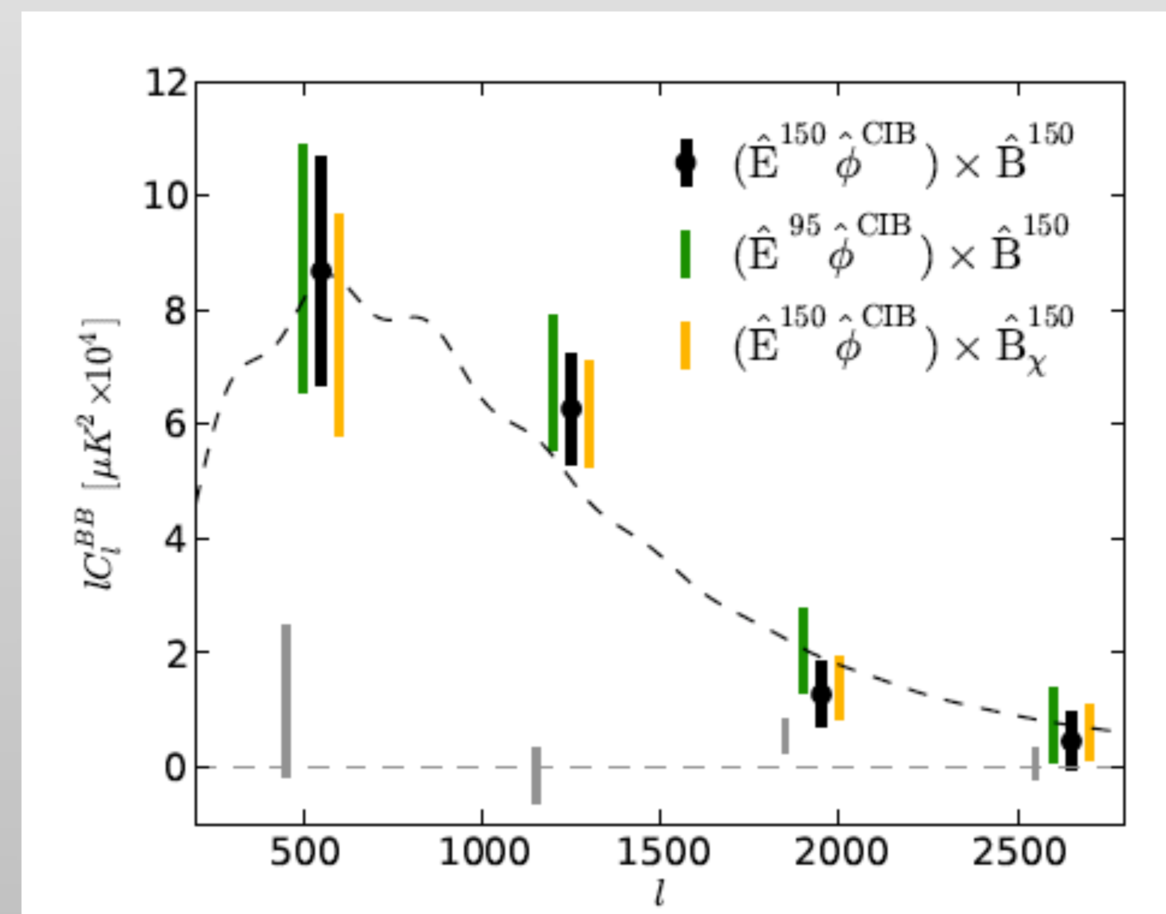


SPTpol results



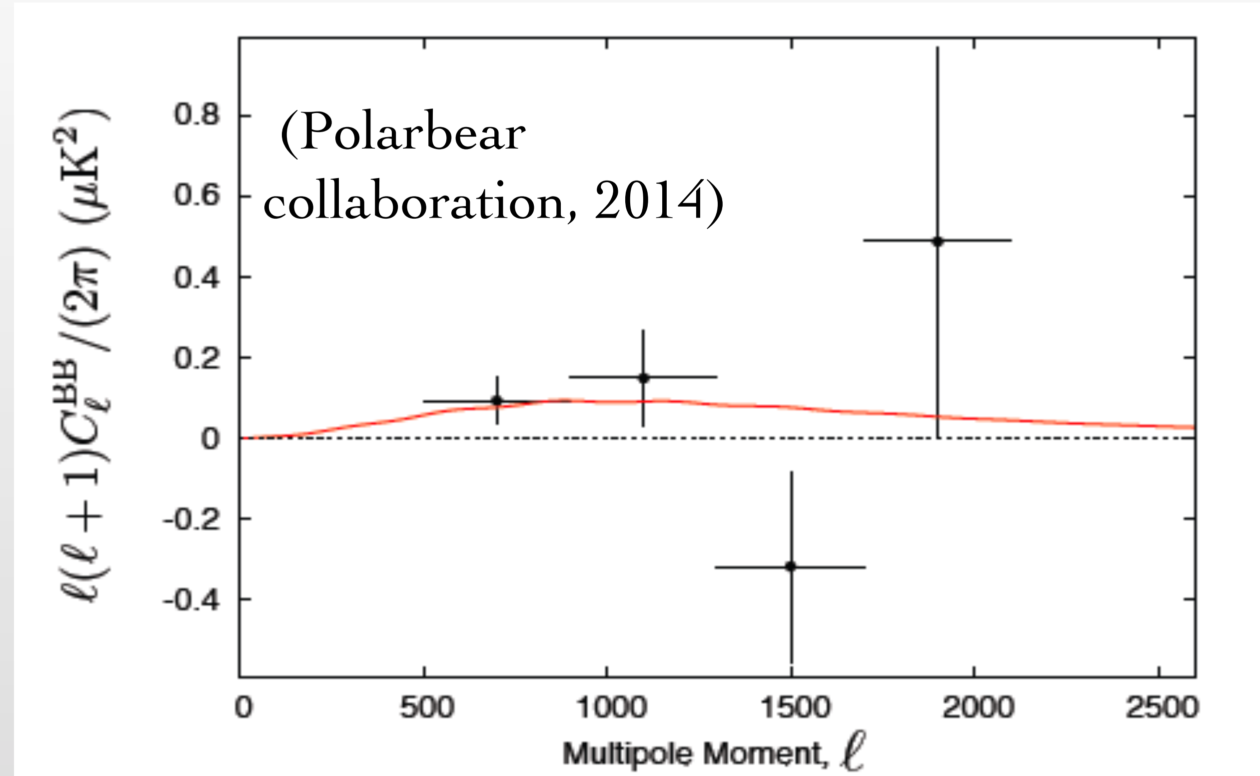
(Hanson et al. 2013)

- First (indirect) detection of **BB signal from lensing!** (Hanson et al. 2013, arXiv: 1307.5830). 22 July 2013
- 95 and 150 GHz observations over 100 deg^2
- Indirect detection by cross-correlating SPTpol maps of the B-mode signal with templates tracing the lensing potential built from the E-mode signal measured by SPT pol and maps of the CIB from Herschel
- This gives a *7.7σ* correlation



Polarbear results

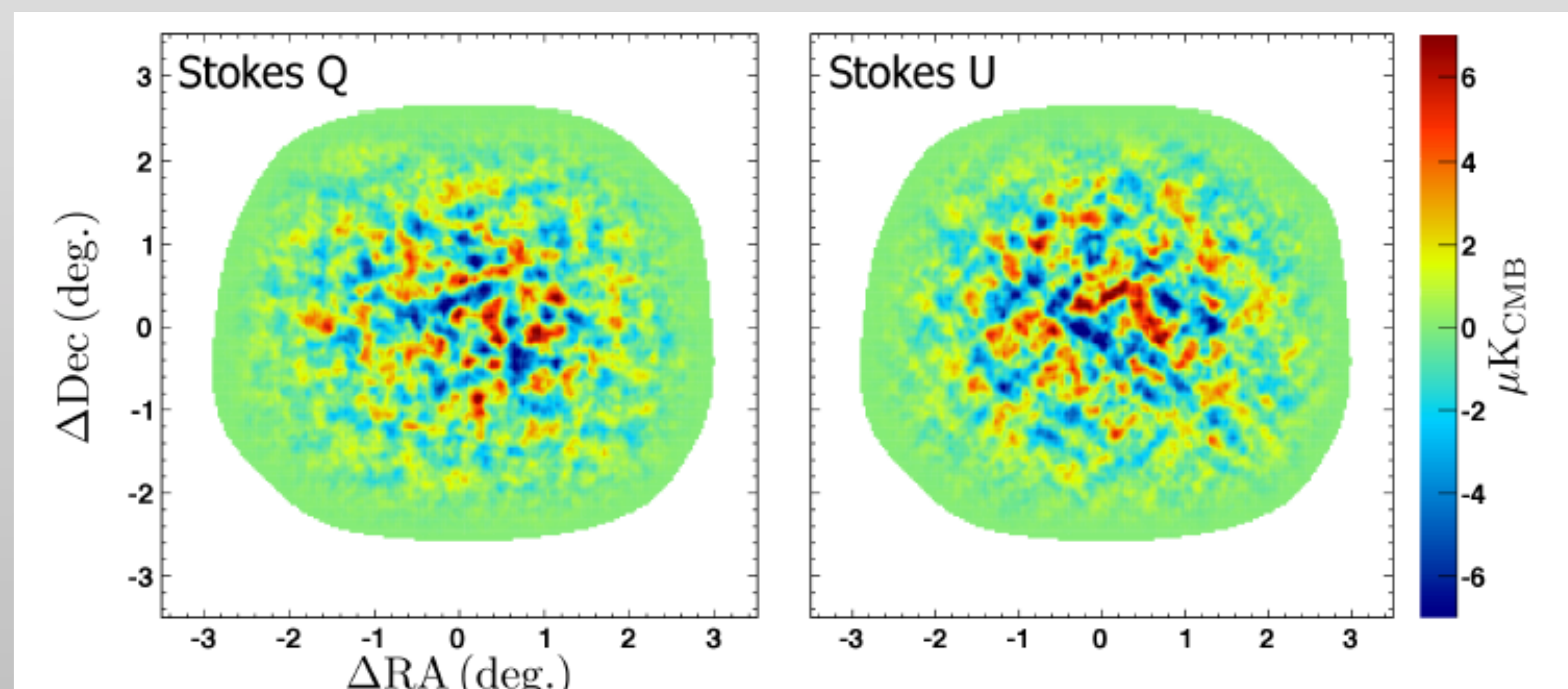
A_{BB}= 1.12±0.61 (1.8σ detection)



- Detection of CMB polarization lensing through correlation with CIB, at 2.3σ (arxiv:1312.6645). 23 December 2013

- First direct detection of BB signal from lensing! (Polarbear collaboration 2014, arXiv: 1403.2369). 10 March 2013

- Results based on observations of 30 deg^2 at 150 GHz with 3.5' angular resolution



BICEP2 I: DETECTION OF *B*-mode POLARIZATION AT DEGREE ANGULAR SCALES

BICEP2 COLLABORATION - P. A. R. ADE[1], R. W. AIKIN[2], D. BARKATS[3], S. J. BENTON[4], C. A. BISCHOFF[5], J. J. BOCK[2,6], J. A. BREVIK[2], I. BUDER[5], E. BULLOCK[7], C. D. DOWELL[6], L. DUBAND[8], J. P. FILIPPINI[2], S. FLIESCHER[9], S. R. GOLWALA[2], M. HALPERN[10], M. HASSELFIELD[10], S. R. HILDEBRANDT[2,6], G. C. HILTON[11], V. V. HRISTOV[2], K. D. IRWIN[12,13,11], K. S. KARKARE[5], J. P. KAUFMAN[14], B. G. KEATING[14], S. A. KERNASOVSKIY[12], J. M. KOVAC[5,16], C. L. KUO[12,13], E. M. LEITCH[15], M. LUEKER[2], P. MASON[2], C. B. NETTERFIELD[4], H. T. NGUYEN[6], R. O'BRIENT[6], R. W. OGBURN IV[12,13], A. ORLANDO[14], C. PRYKE[9,7,16], C. D. REINTSEMA[11], S. RICHTER[5], R. SCHWARZ[9], C. D. SHEEHY[9,15], Z. K. STANISZEWSKI[2,6], R. V. SUDIWALA[1], G. P. TEPLY[2], J. E. TOLAN[12], A. D. TURNER[6], A. G. VIEREGG[5,15], C. L. WONG[5], AND K. W. YOON[12,13]

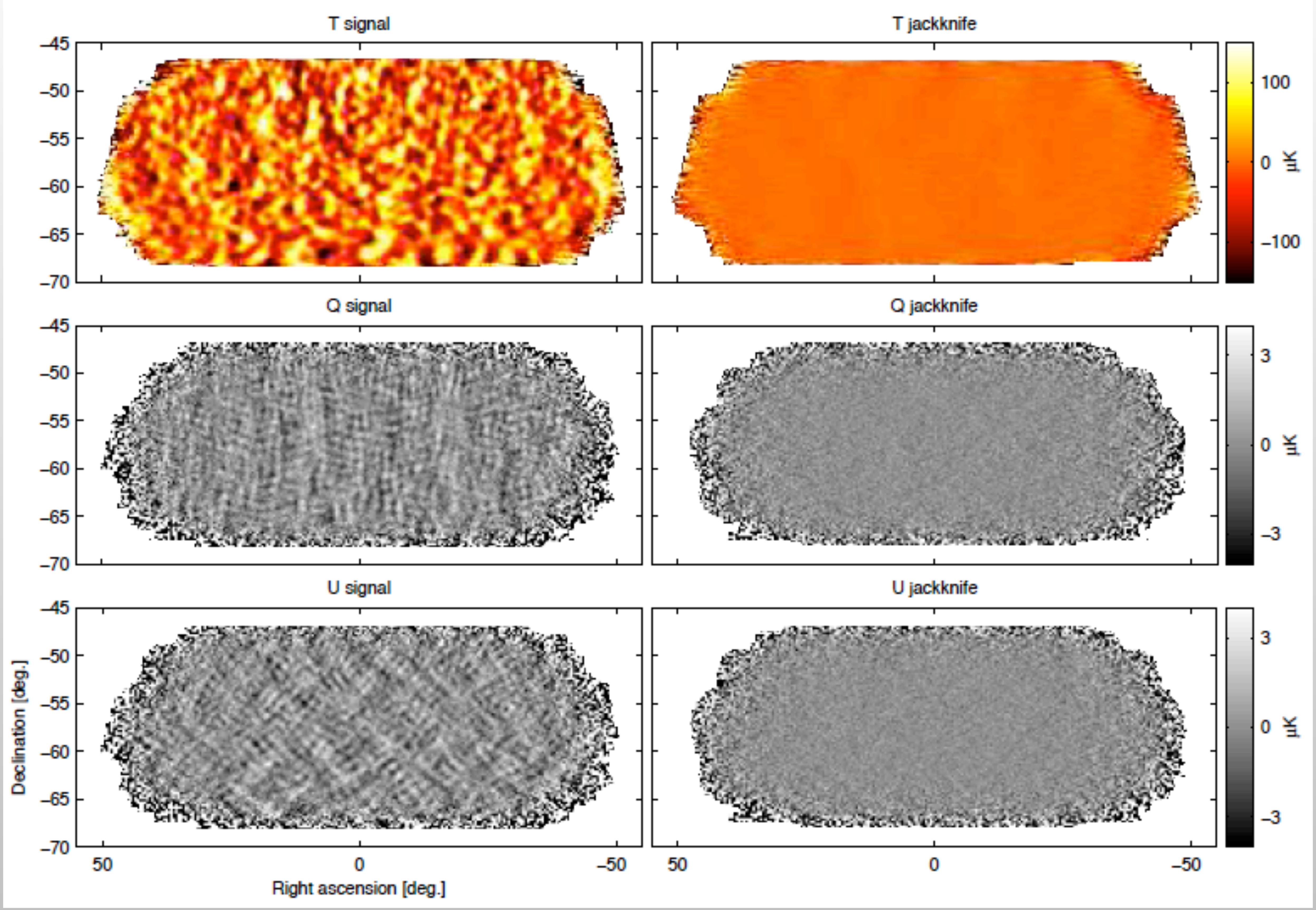
$$r = 0.20^{+0.07}_{-0.05}$$

Announced March 17

"BICEP2 I: Detection of B-mode polarization at degree angular scales", arXiv:1403.3985

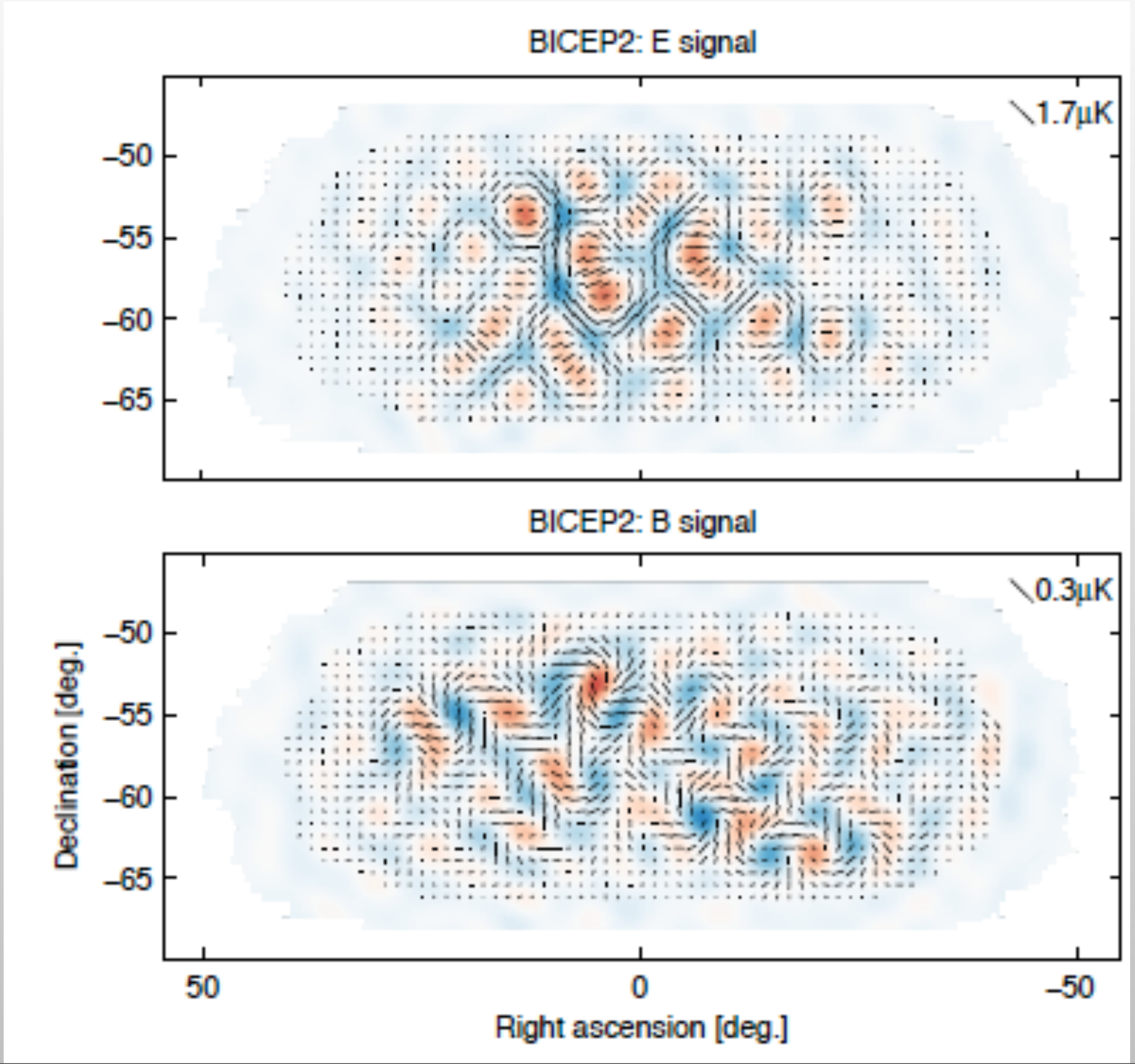
"BICEP2 II: Experiment and three-year data set", arXiv:1403.4302

TQU maps

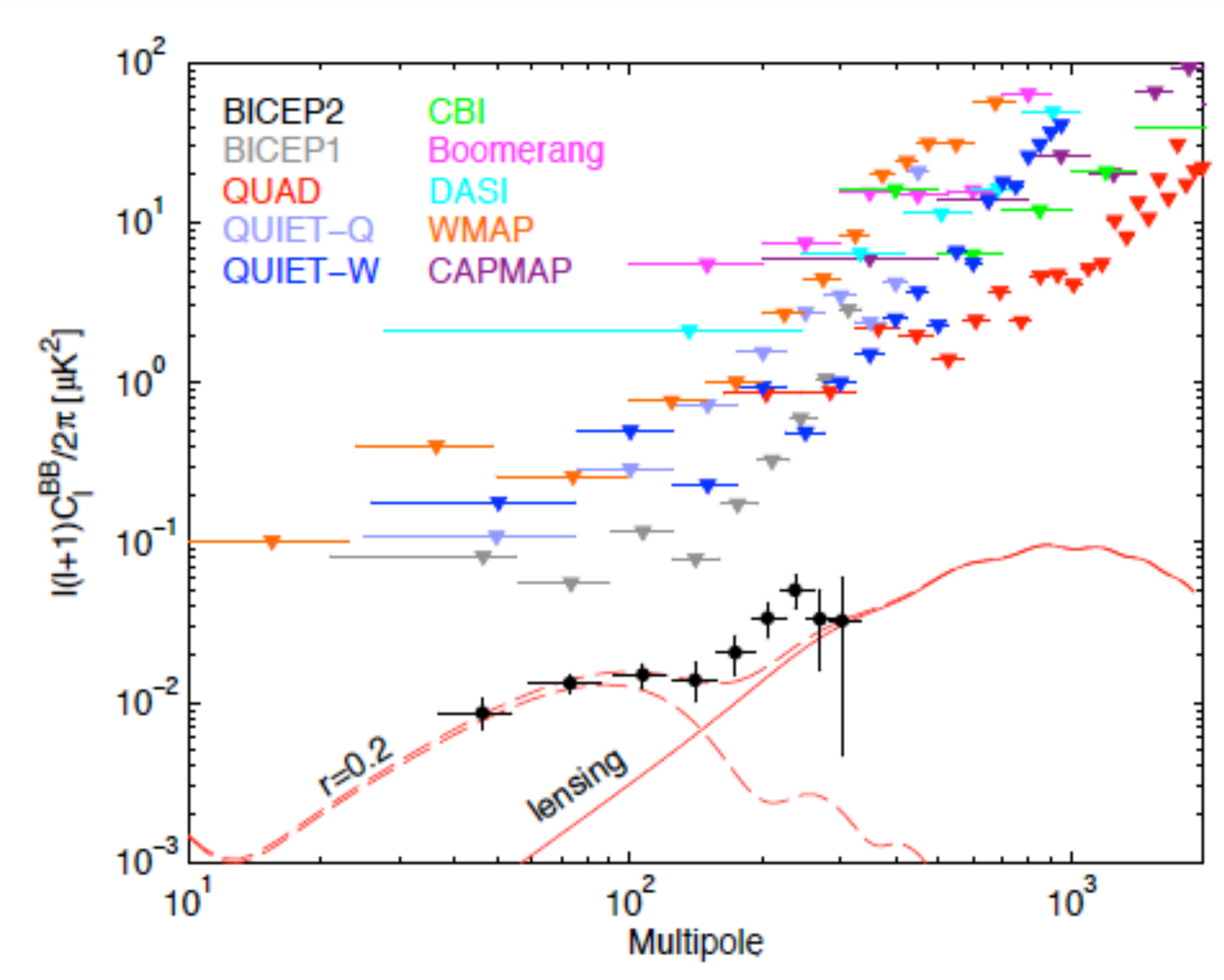


T signal
T jackknife
Q signal
Q jackknife
U signal
U jackknife
Declination [deg.]
Right ascension [deg.]
μK
100
0
−100
3
−3
−45
−50
−55
−60
−65
−70
50
−50

E and B maps


BICEP2: E signal
1.7μK
−50
−55
−60
−65
BICEP2: B signal
0.3μK
Declination [deg.]
50
0
−50
Right ascension [deg.]

Final BB power spectrum



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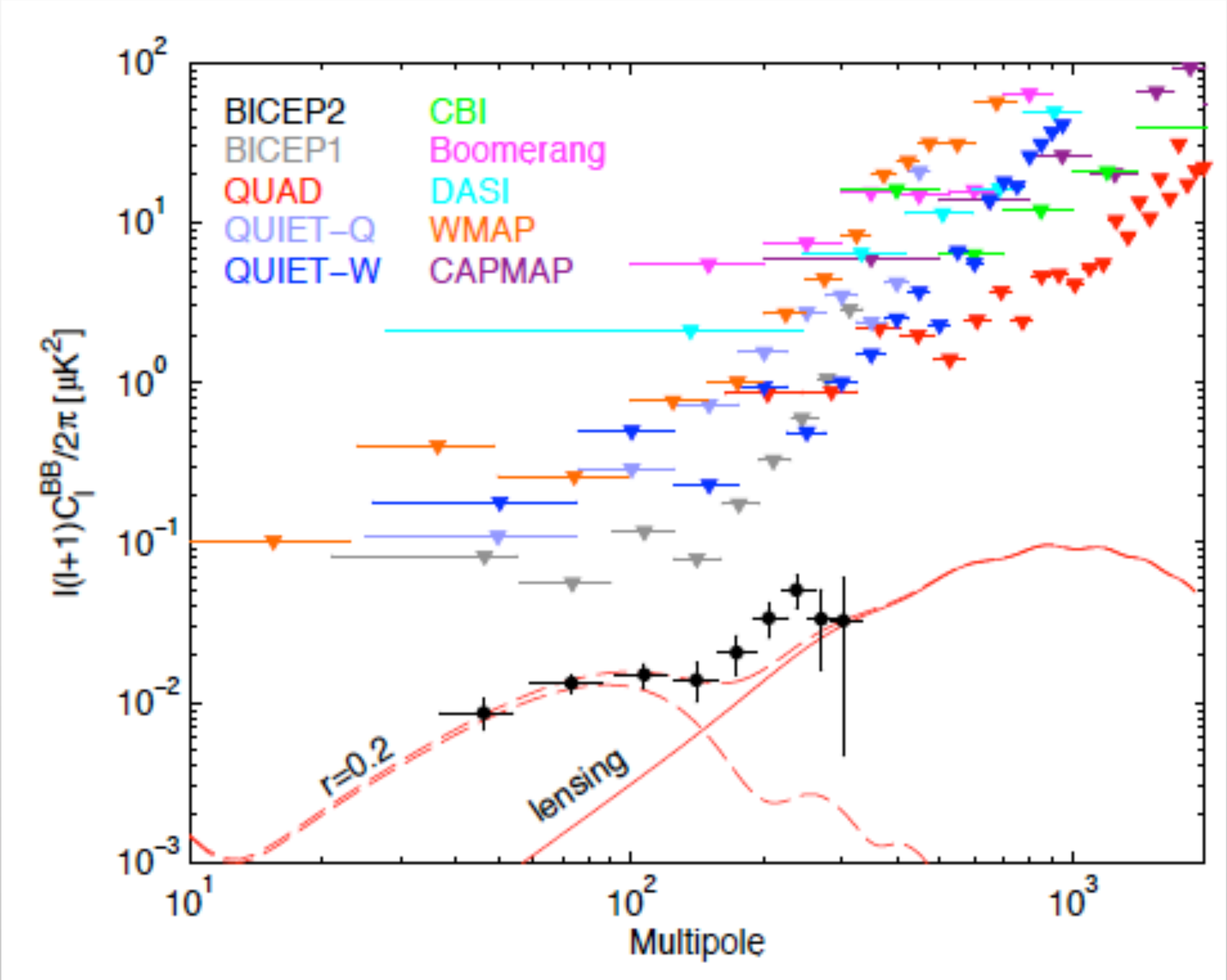


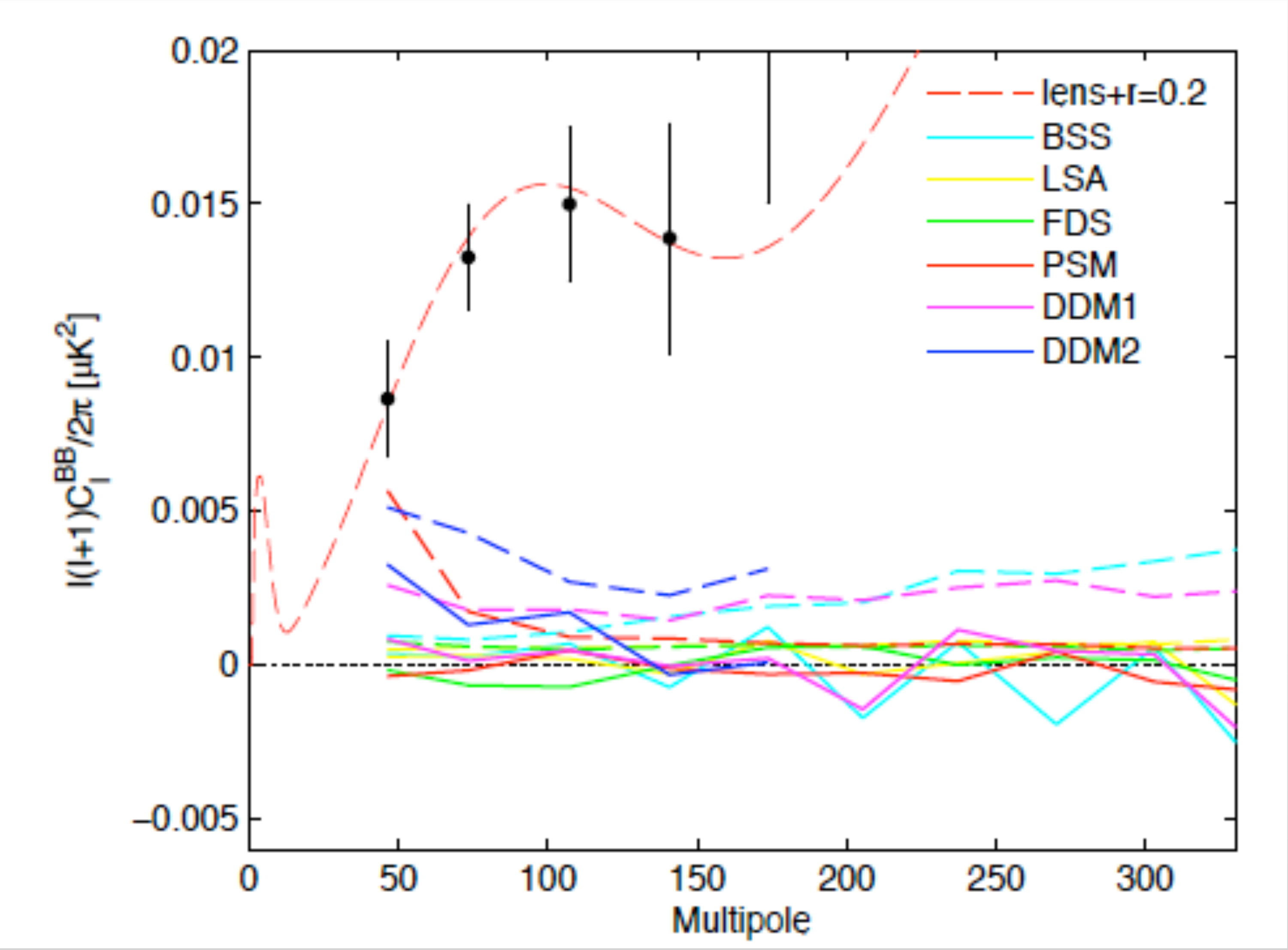
$$r = 0.20^{+0.07}_{-0.05}$$

Assessment of foreground contamination

✤ Thermal dust:

- Use various models:
    - BSS, LSA - Two models of the Galactic magnetic field (O'Dea et al. 2012)
    - FDS, assuming P/I=5%, and Q=U
    - PSM with P/I=15%
    - DDM1, with P/I=5%, and DDM2 using a digitized map of P/I and ψ from a Planck talk

Claim: residuals at $r = 0.02$



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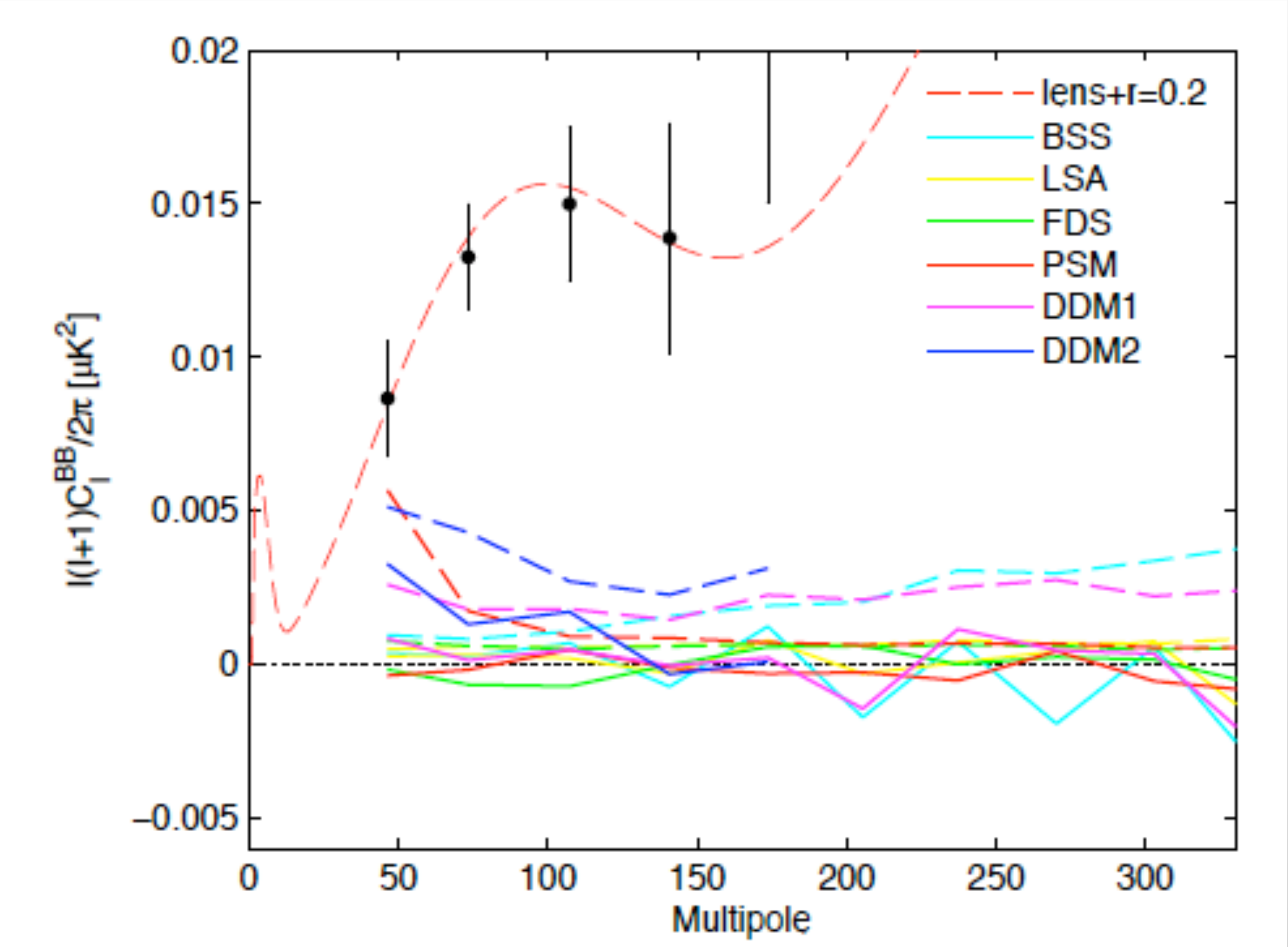


✤ Synchrotron:

- Extrapolate from WMAP 23 GHz assuming β=-3.3
- Below r = 0.003

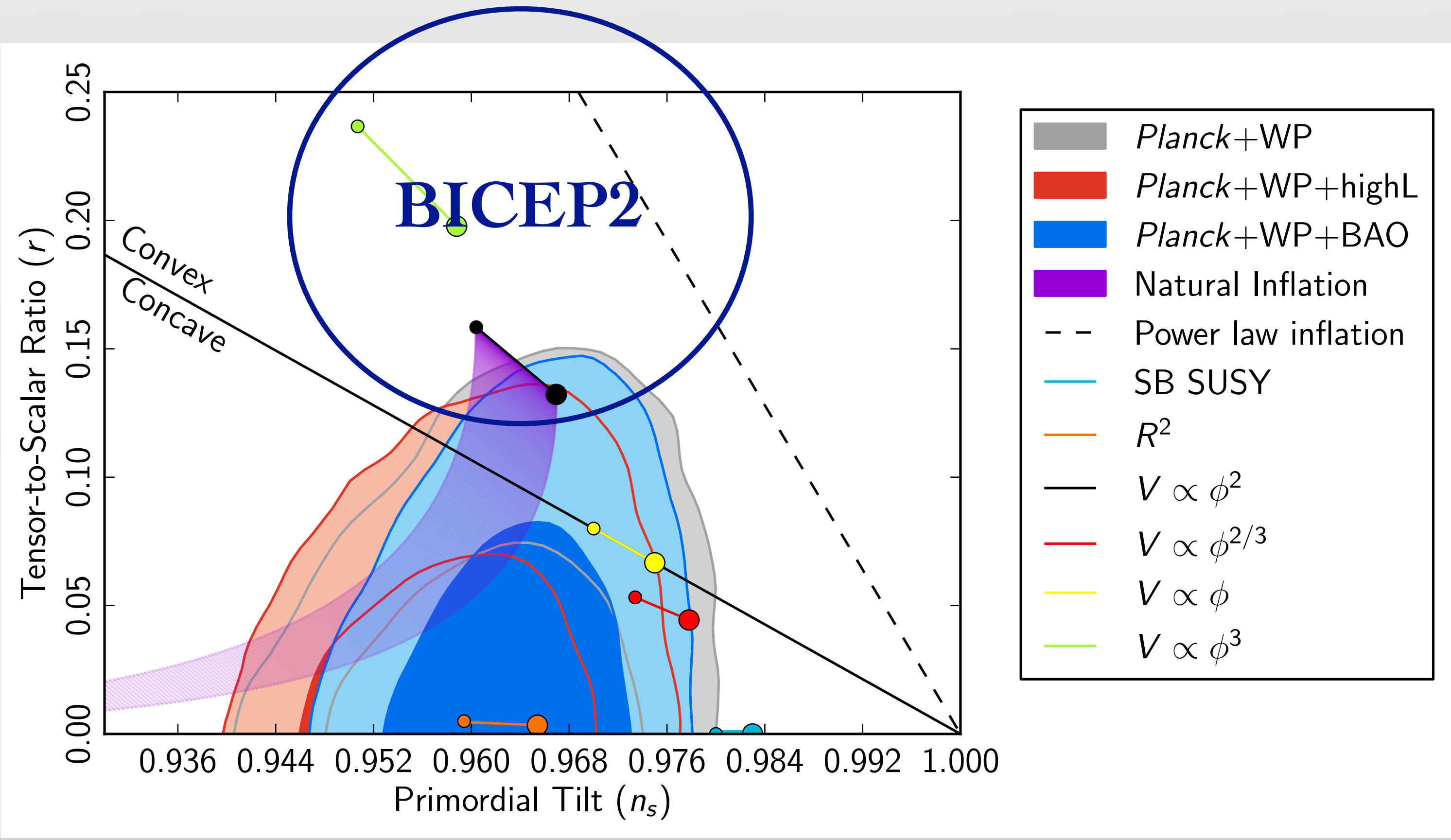
✤ Point sources:

- 143 GHz fluxes from the Planck catalogue together with polarization information from ATCA
- Contribution of $r \approx 0.001$

Implications

✤ The value r=0.20 implies an energy scale for inflation higher than 10^{16} GeV. This is comparable to GUT scale

✤ However, there is some tension between BICEP2 and previous constraints from Planck TT, $r < 0.11$ (95% CL, Planck collaboration XVI (2013)



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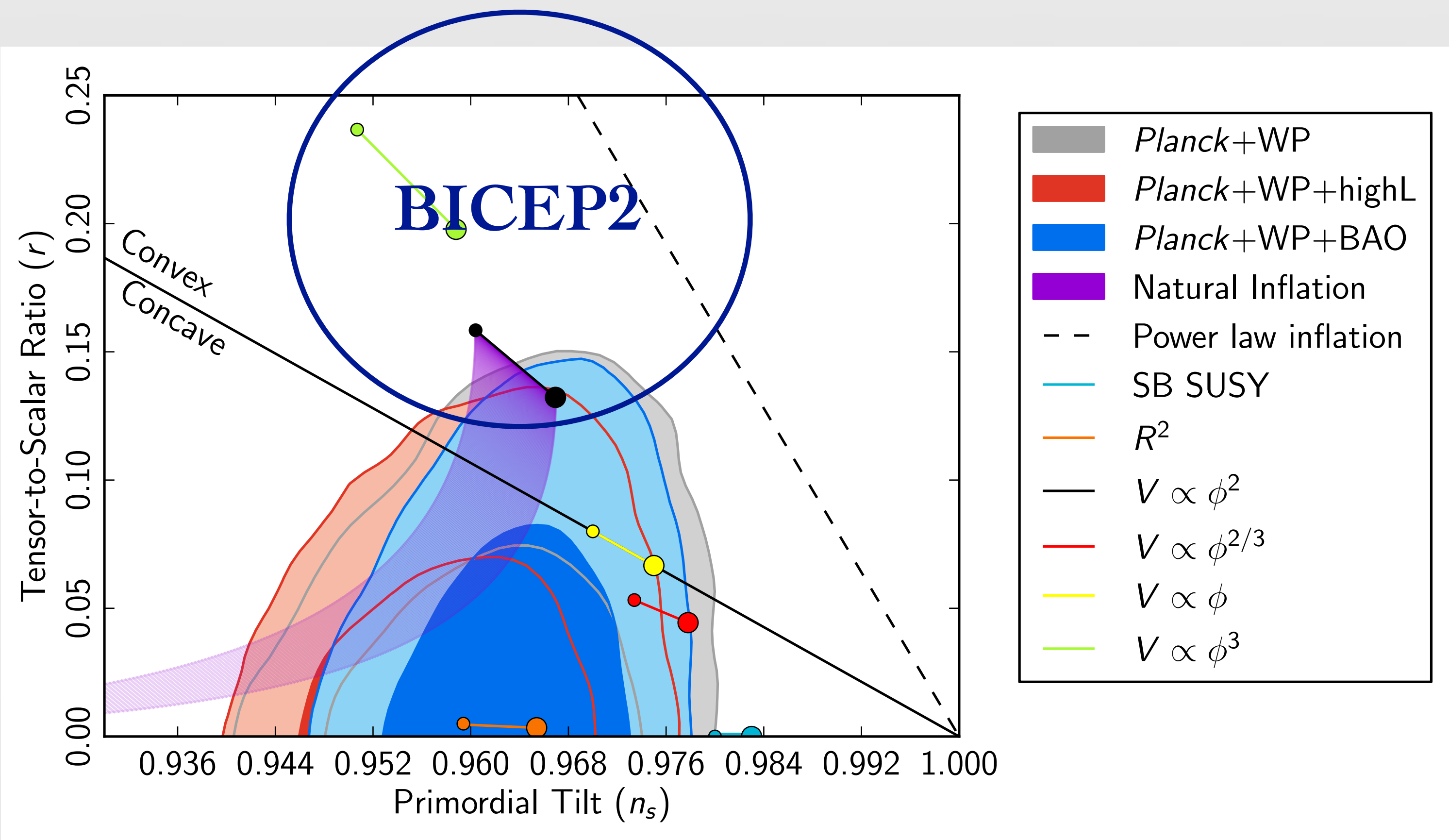

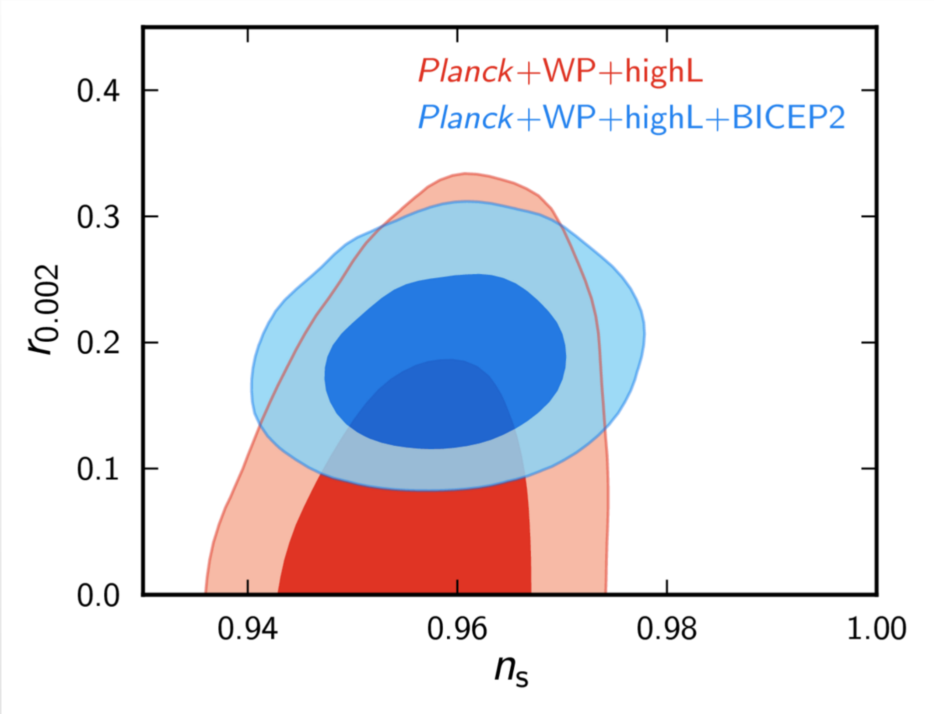

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✤ A running of the spectral index relaxes the constraints from Planck ($r<0.26$ - Planck collaboration XVI)

✤ Other possibilities:

- Blue tilt of the tensor spectrum ($n_t>0$, Cheng et al. 2014)
- Extra sterile neutrino species (Zhang et al. 2014, Dvorkin et al. 2014)
- Primordial magnetic fields (Bonvin et al. 2014)
- r spatial modulation (Chluba et al. 2014)

Skepticism...

✤ Specially after the Planck collaboration put in the arXiv four PIPs describing the polarized dust properties (in regions not covering BICEP2 footprint), rumors have spread (blogs, facebook thread, newscientist, science,...) about a potentially significant polarized dust contamination affecting the BICEP2 measurement

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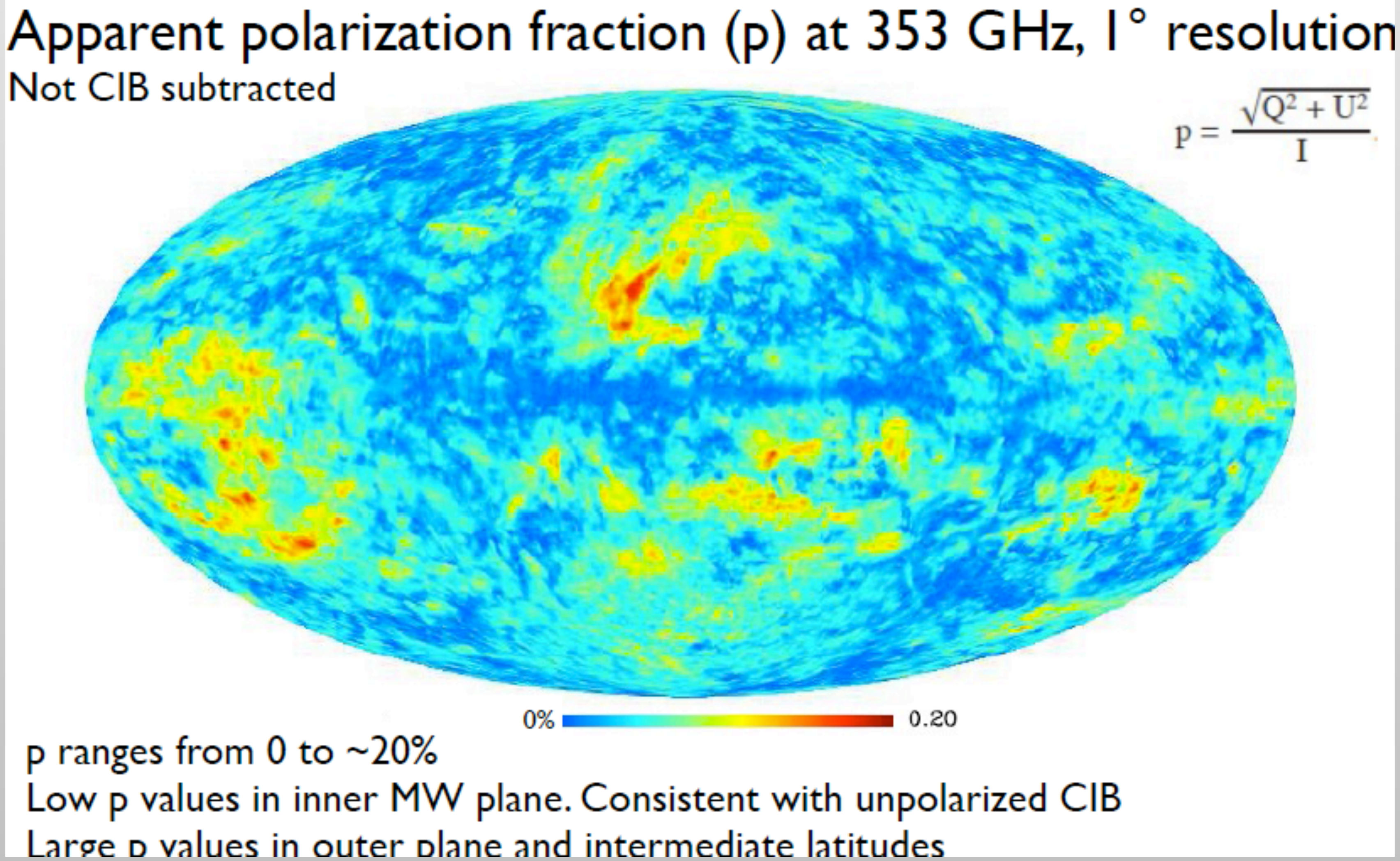
✤ Strong criticism about the use by the BICEP2 team of an apparently digitized image of a Planck map of the dust polarization at 353 GHz, taken from a slide from the ESLAB conference (J,-Ph. Bernard's talk)

✤ Also, they seem to have ignored the non-subtraction of the CIB in this map



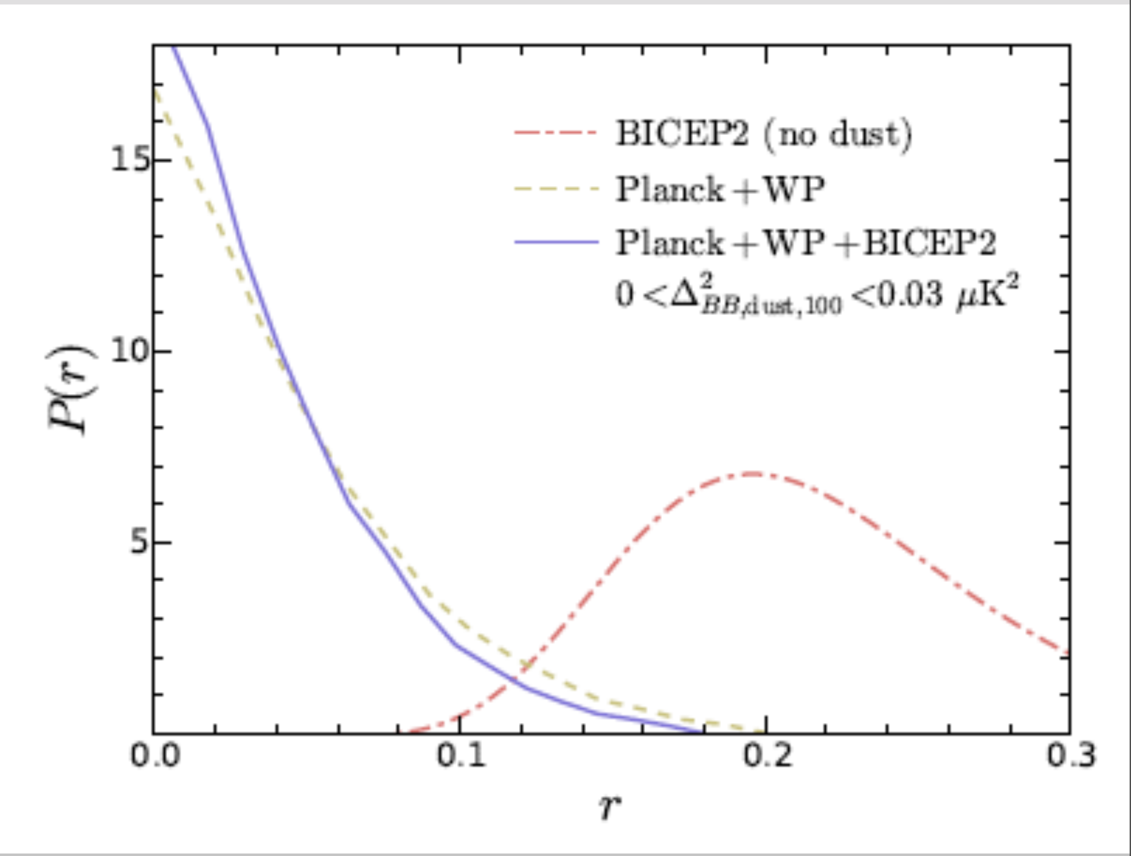
Skepticism...

- Mortonson & Seljak, arXiv:1405.5857 (22 May)

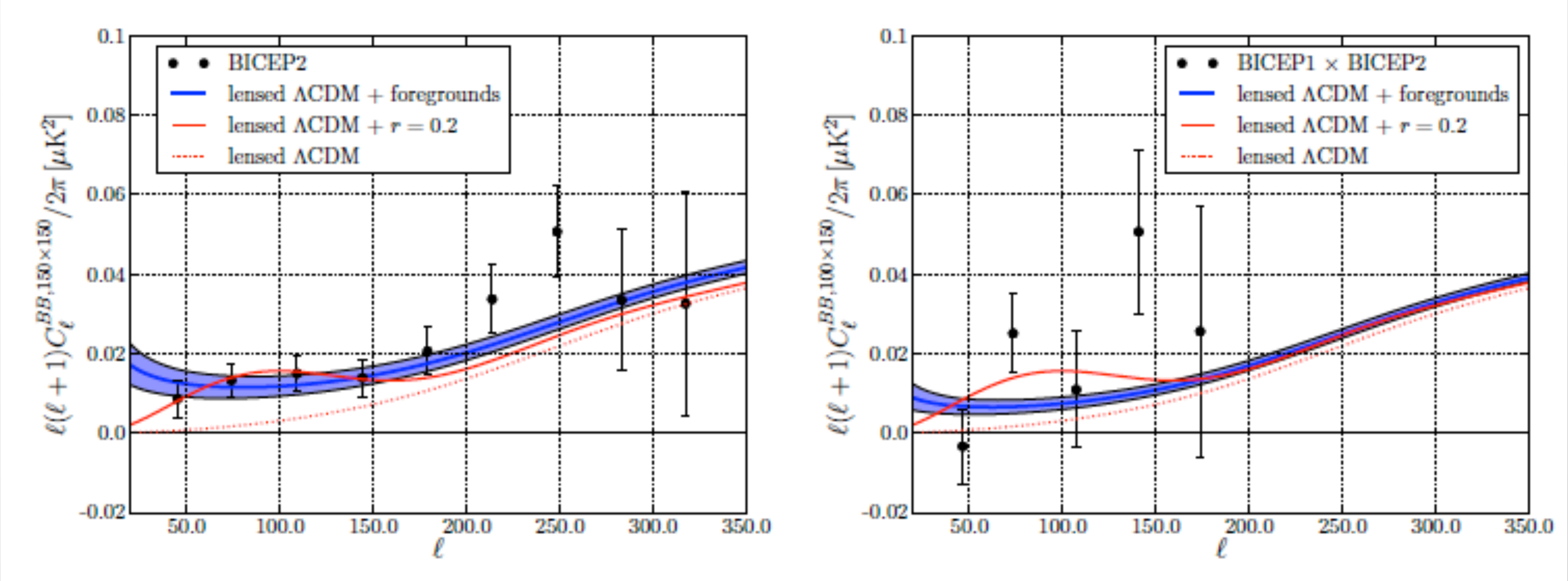
  - Planck + BICEP2 analysis including a polarized dust component, with free amplitude and a fixed power-low power spectrum ($C_l^{dust} \propto l^{-2.3}$)

  - The resulting joint BICEP2+Planck analysis slightly favours solutions without gravitational waves (only dust and B-mode lensing), with r<0.11

- "This result does not automatically mean that BICEP2 has no evidence for primordial gravitational waves. It does, however, mean that the case strongly relies on understanding the actual dust polarization contribution in the BICEP2 field, which at the moment is unavailable and possibly higher than the various estimates presented by the BICEP2 team. It is thus too early to celebrate the BICEP2 results as a definitive proof of inflation"



- Flauger, Hill & Spergel, arXiv:1405.7351 (28 May)
  - Used more refined dust models than BICEP2, and re-analized the 100×150 GHz and the 150×150 GHz correlations
  - Reached similar conclusions to Mortonson & Seljak (2014): BICEP2 data consistent with a cosmology with r=0.2 and negligible foregrounds, but also with r=0 and significant dust polarization signal
  - The expected amplitude of dust polarization remains uncertain by a factor of three



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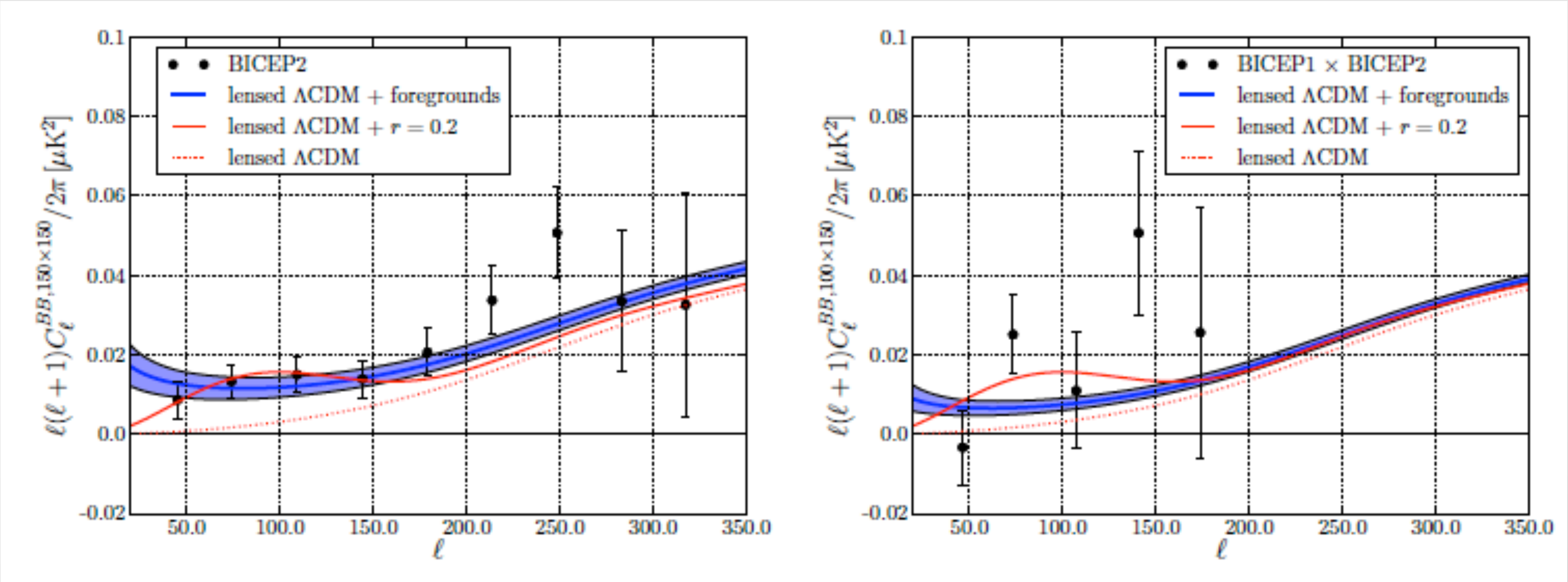

Definitely **need to wait for Planck polarization data** (october 2014) to determine the true level of dust polarization at 150 GHz, and for results of **independent B-mode experiments**

CMB polarization experiments

Name	Platform	Area [deg^2]	FWHM	Freq [GHz]	Detectors	r_{lim}	Starts
BICEP	Ground	800	~1°	100,150	PSB bolom.	0.1	2010
QUIET-II	Ground	1600	4'-30'	40, 90	MMIC HEMT	0.01	2010
QUIJOTE	Ground	5000	~1°	10-40	MMIC HEMT	0.05	2012
PolarBear	Ground	1200	3'-7'	90,150, 220	TES bolom	0.01	2012
QUBIC	Ground	800	~1°	90,150,220	Bol interf	0.01	2014
ACTPol	Ground	4000	~1'	150,218,277	Bolometer	0.03?	2013
SPTPol	Ground	500	1'-1.6'	100,150,220	TES Bolom.	0.03	2013
EBEX	Balloon	350	8'	150,250,350,450	TES bolom	0.03	2012
SPIDER	Balloon	24000	17'-50'	90,145,280	TES bolom	0.03	2013
LSPE	Balloon	9500	30'	40-250GHz	Bolo+HEMTs	0.03	2015
Planck	Satellite	Full sky	5'-33'	30-353	MMIC/Bol	0.05	2009
LiteBIRD	Satellite	Full sky	30'	50-270	TES bol	0.001	2020
PIXIE	Satellite	Full sky	1.6°	30-6000	Bolometers	0.001	2018 ?
PRISM	Satellite	Full sky	17'-5"	30-6000	Bolometers	0.0005	2028 ?
EPIC/ CMBPol	Satellite	Full sky	~10'	30-300	Bolometers	0.001	2025 ?

The QUIJOTE collaboration

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★ IDOM

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★ **Goals:**

- To obtain six polarization maps in the frequency range **10-40 GHz** with sufficient sensitivity to correct **foreground emission** (synchrotron and AME) and constrain the imprint of **B-modes down to r=0.05**

★ **Site:** Teide Observatory (altitude: 2400 m, latitude: 28º), Spain

★ **Observability:** -32º<Dec.<88º (f_{sky} ~0.65)

★ **Frequencies:** **11,13, 17, 19, 30** and **40 GHz**

★ **Angular resolution:** 1 degree (52 arcmin @ 11 GHz)

★ **Telescope and instruments:**

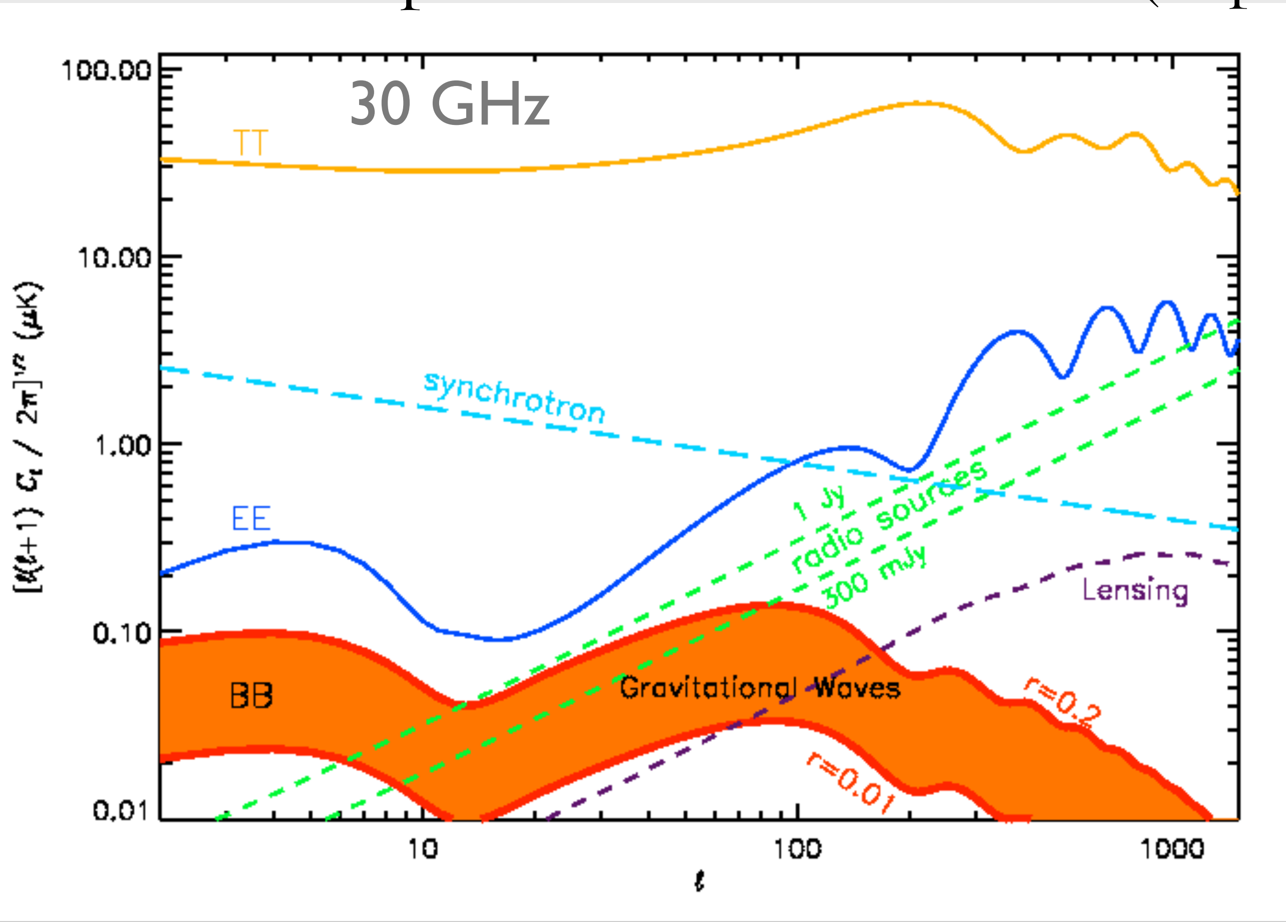
- **Phase I**:
  - First Telescope (**QT1**)
  - Equipped with a Multifrequency Instrument (**MFI**) with 4 polarimeters @ **10-20 GHz**. Started operations Nov. 2012
  - Second Instrument (**TGI**) with 31 polarimeters @ **30 GHz**. Funded; to start operations by the end of 2014
  - Polarized Source Subtractor
- **Phase II**:
  - Second Telescope (**QT2**). Under construction (mid of 2014)
  - **FGI** with 40 polarimeters @ **40 GHz**. Funded (2015)

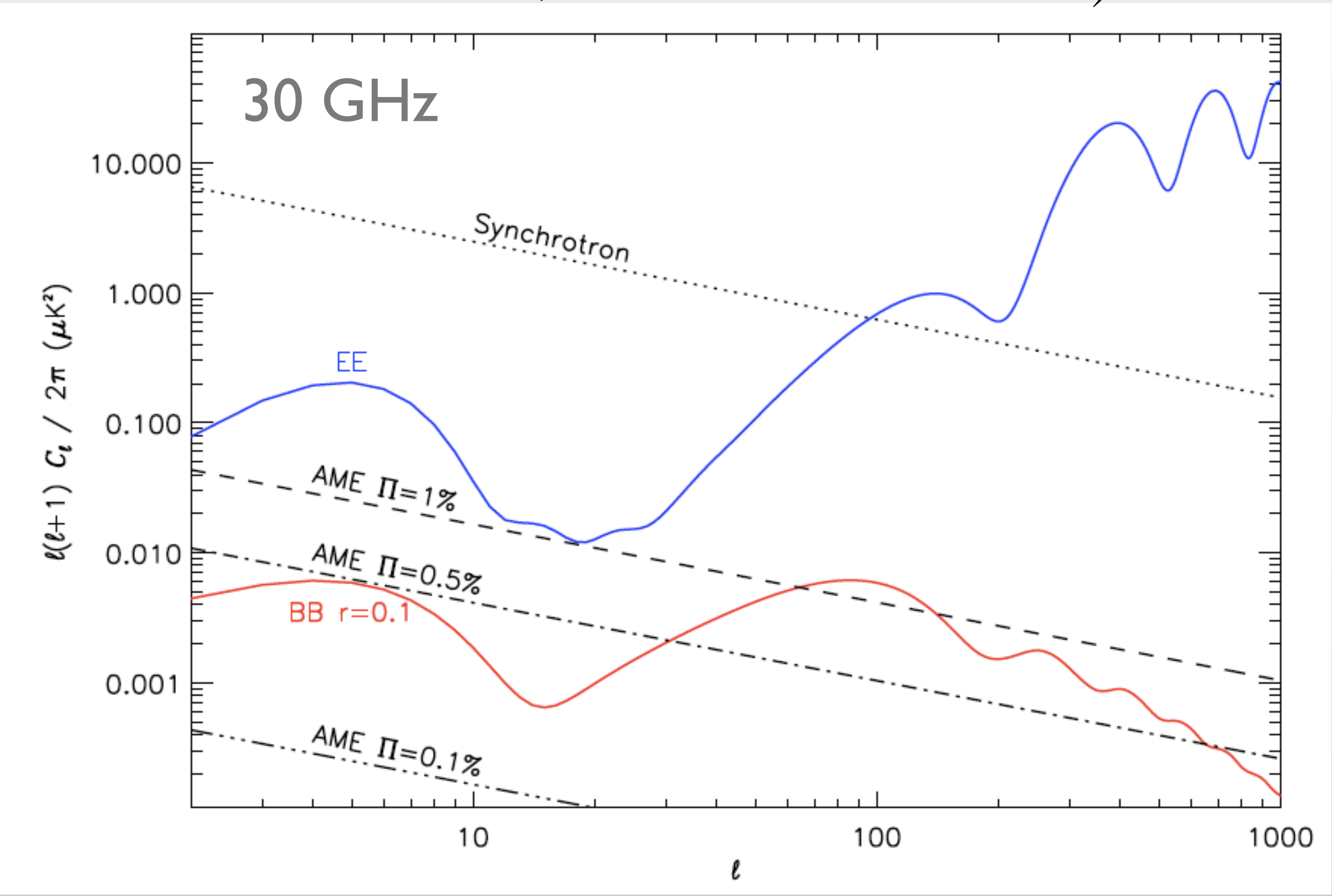
★ **Scientific operation plan:** 2012-2020

Science with the MFI

★ These maps will provide valuable information about the polarization properties of:

- Synchrotron emission: should dominate the emission at the MFI frequencies. WMAP 23 GHz shows it to be polarized at ~5-15%, depending on the Galactic latitude
- Anomalous microwave emission: little known about its polarization. Best upper limits on the polarization fraction: <1% (López-Caraballo et al. 2011, Dickinson et al. 2011)

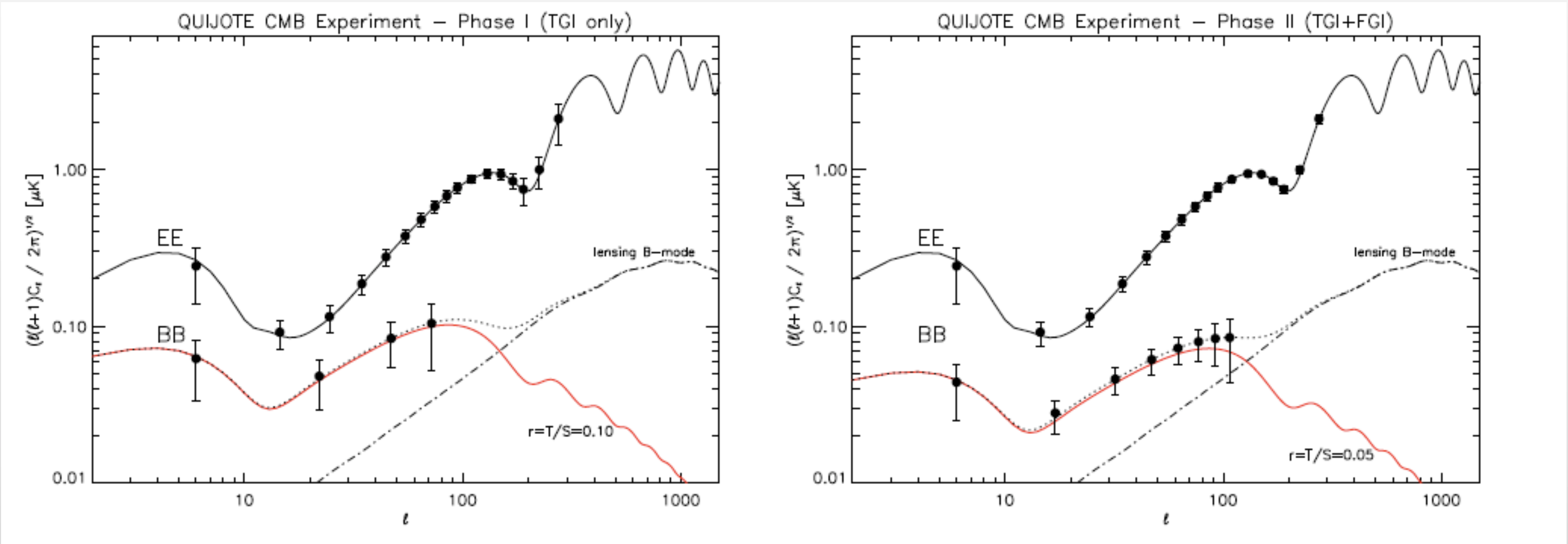




★ MFI maps will be used to clean the 30 GHz and 40 GHz maps of the second (TGI) and third (FGI) QUIJOTE instruments

★ Excellent complement of Planck at low frequencies. Planck will provide information about the polarization of the thermal dust emission at high frequencies (October 2014)

Science with the TGI and FGI



★ **Left**: example of the QUIJOTE-CMB scientific goal after the Phase I. It is shown the case for 1 year (effective) observing time with the TGI, and a sky coverage of 3,000 deg^2. The red line corresponds to the primordial B-mode contribution in the case of **r = 0.1**

★ **Right**: QUIJOTE-CMB Phase II. Here we consider 3 years of effective operations with the TGI, and that during the last 2 years, the FGI will be also operative. The red line now corresponds to **r = 0.05**

MFI observations status

Commissioning phase
(November 2012 – March 2013)

- Calibrators (>100 hrs observing CRAB, CASS-A, Moon, Jupiter)
- Polarization tests
- Local interference map (~10 hrs)
- Tsys calibration (~10hrs)
- Science demonstration cases:
    - Cygnus loop (~1hr)
    - Fan region (> 135 hrs)
    - Perseus molecular cloud (>125hrs)

Science phase
(April 2013 - now)

- Wide survey (3000h; will repeat this)
- Cosmological fields (1400h)
- Daily calibrators (Crab, Cas A, Jupiter, sky dips)
- 3C58 in the Fan region (25h)
- Galactic Haze (200h)
- Perseus molecular cloud
- Some faint point sources (3C273, NGC7027,..)

Observing efficiency **~ 70%** (including bad weather & technical problems).

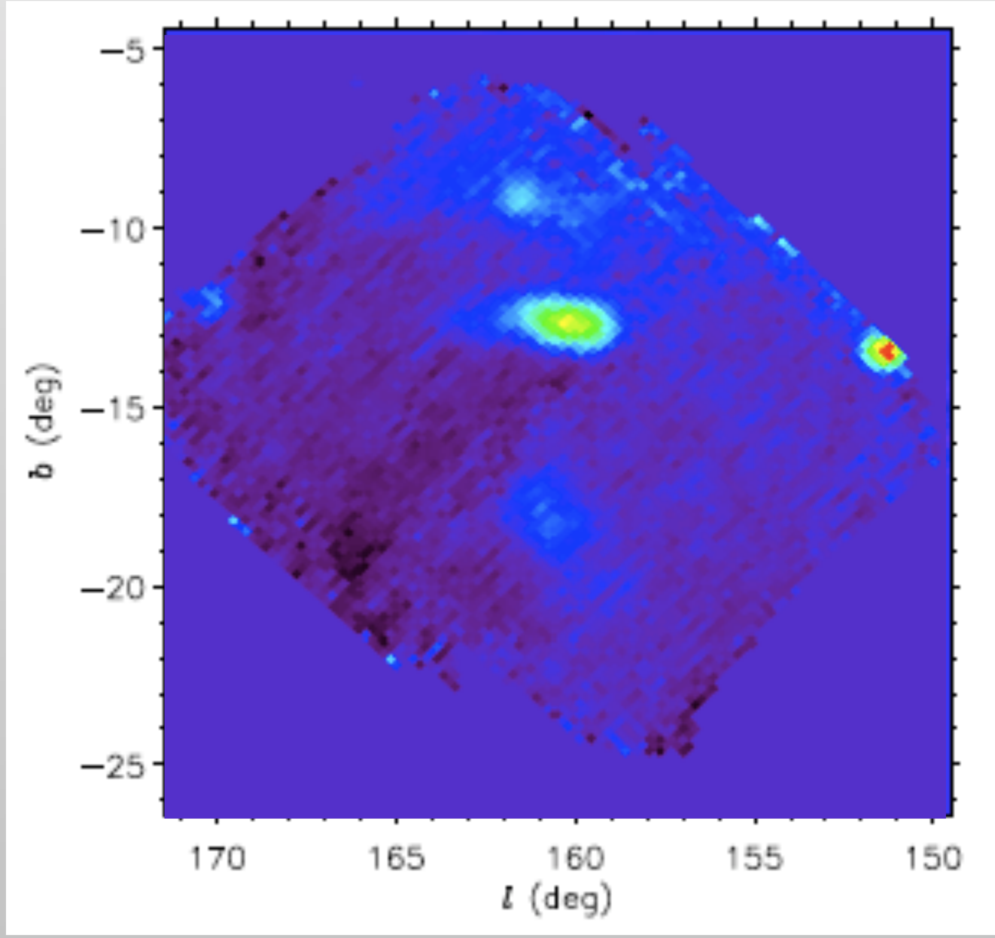
Perseus molecular complex

★ Large observation program (~132 hours, 12/2012 to 04/2013), on an area covering ~200 deg^2 around the Perseus molecular complex. One of the brightest AME regions on the sky (Watson et al. 2005, Planck collaboration 2011)

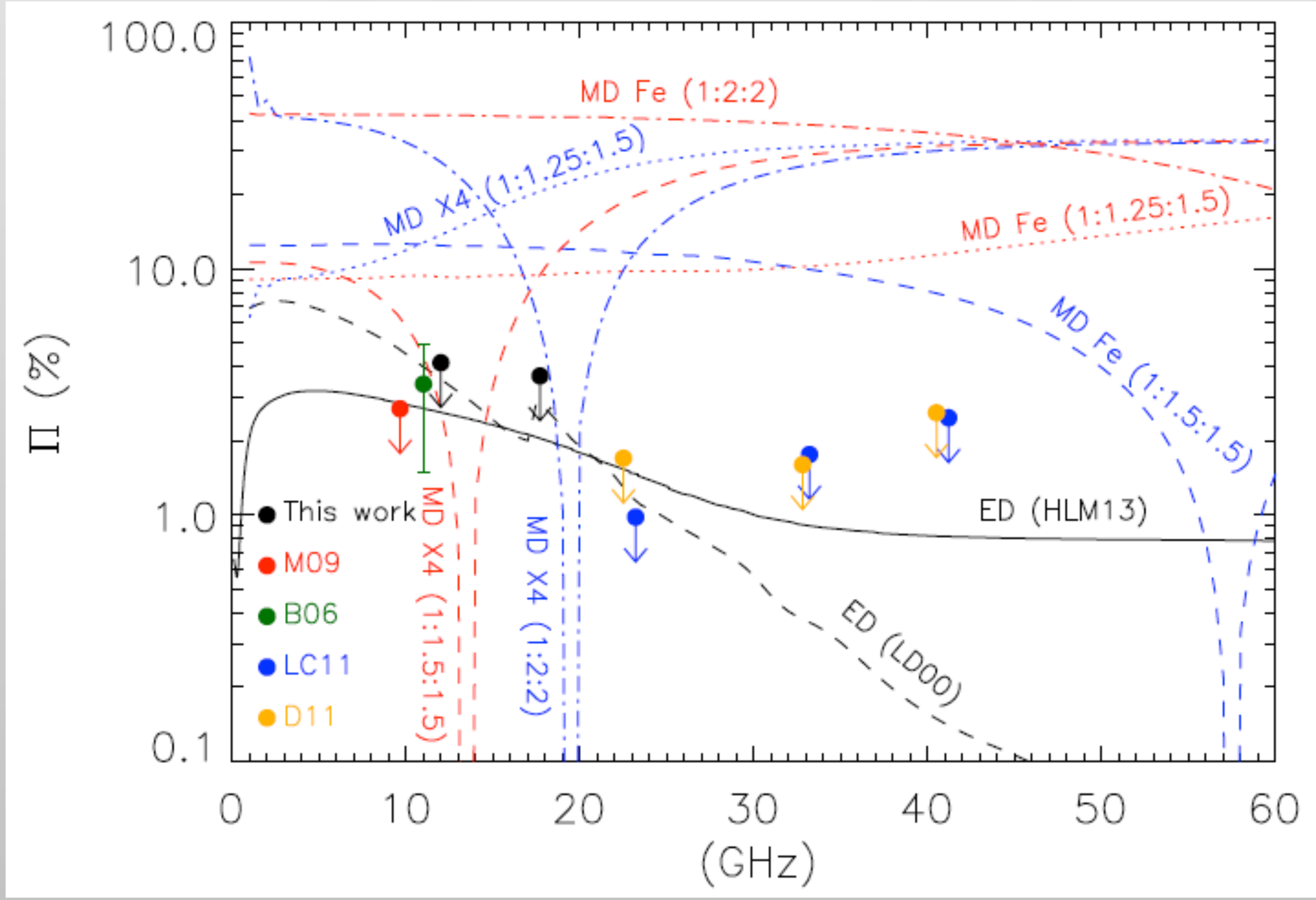
★ Also covering the California nebula (HII region - null polarization control region)

★ Final integration time of ~ 3300 s/beam, yielding a sensitivity of ~ 30 mJy/beam in Q and U

Quijote 11 GHz



AME constraints (preliminary)

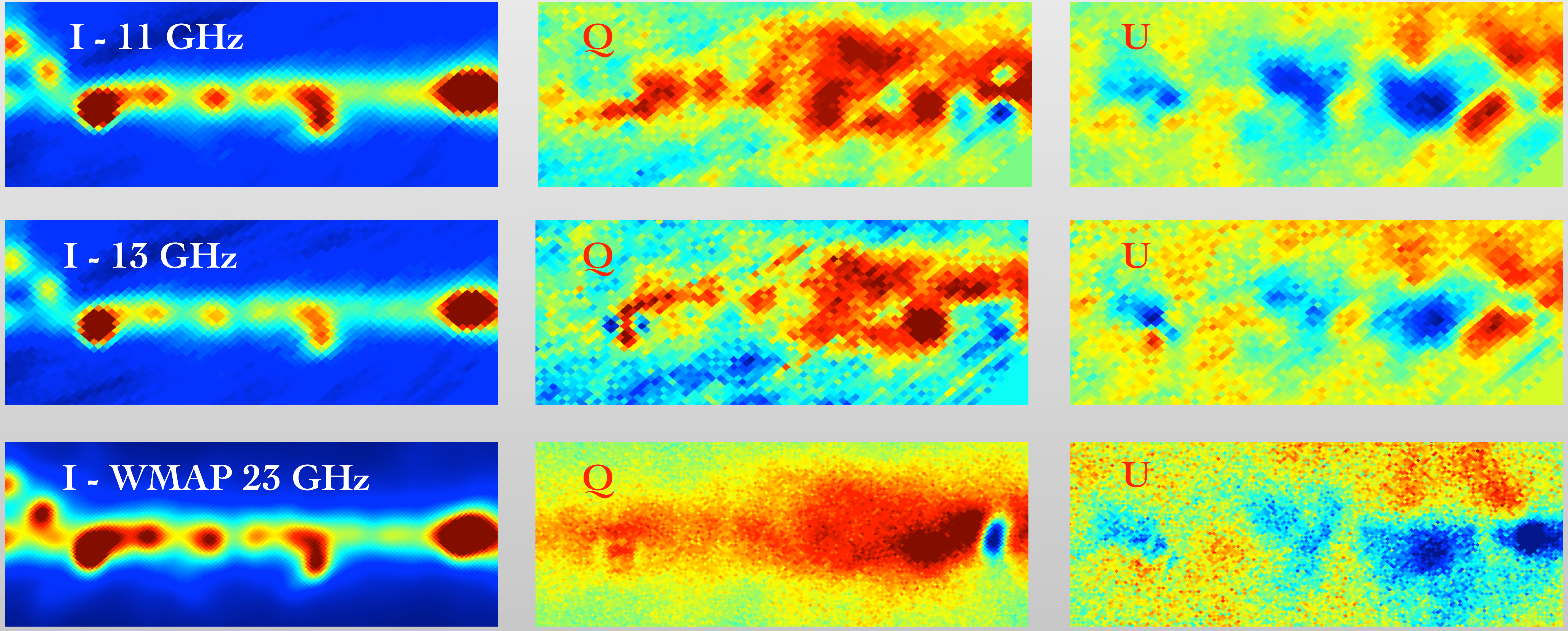


Galactic Haze

★ Large observation program still ongoing (~200 hours, from June until now), on an area covering ~1000 deg^2 around the Galactic centre

★ The goal is to study the polarization of the Galactic Haze emission

★ Preliminary 11 and 13 GHz maps (20×6 deg^2) of the Galactic plane around the Galactic centre, in comparison with WMAP 23 GHz



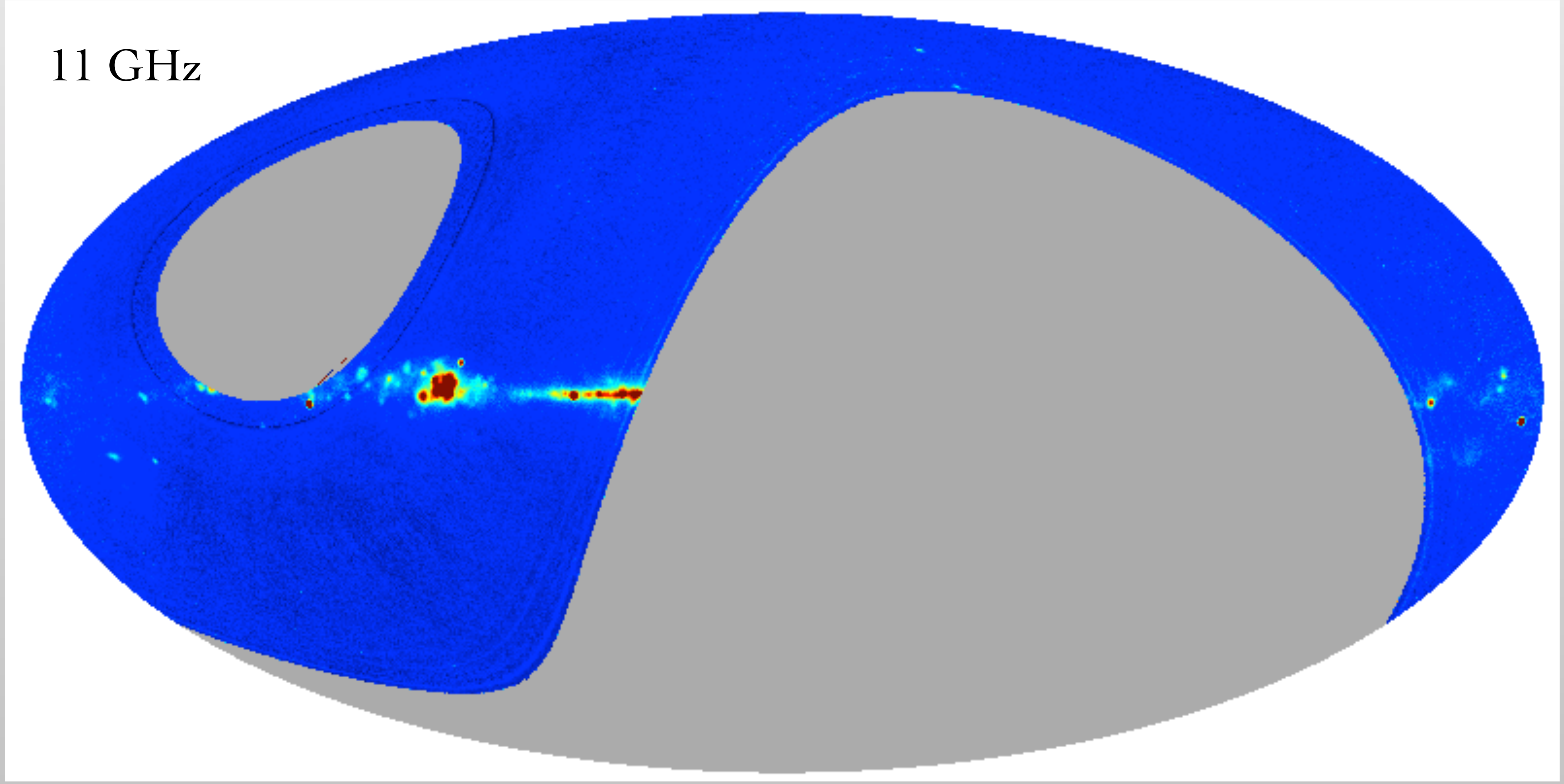
★ Quijote maps trace the large-scale polarized emission, but fails to detect polarized emission from Sgr-A (possible Faraday depolarization?)

Wide survey

★ 3000h of a large region of ~20,000 deg^2 of the north sky to study diffuse foreground emission

★ Conducted between April and June 2013 and 2014 (64 days of continuous observations each year). Will repeat the same survey, starting next month

★ Resulting map from 700 hours:



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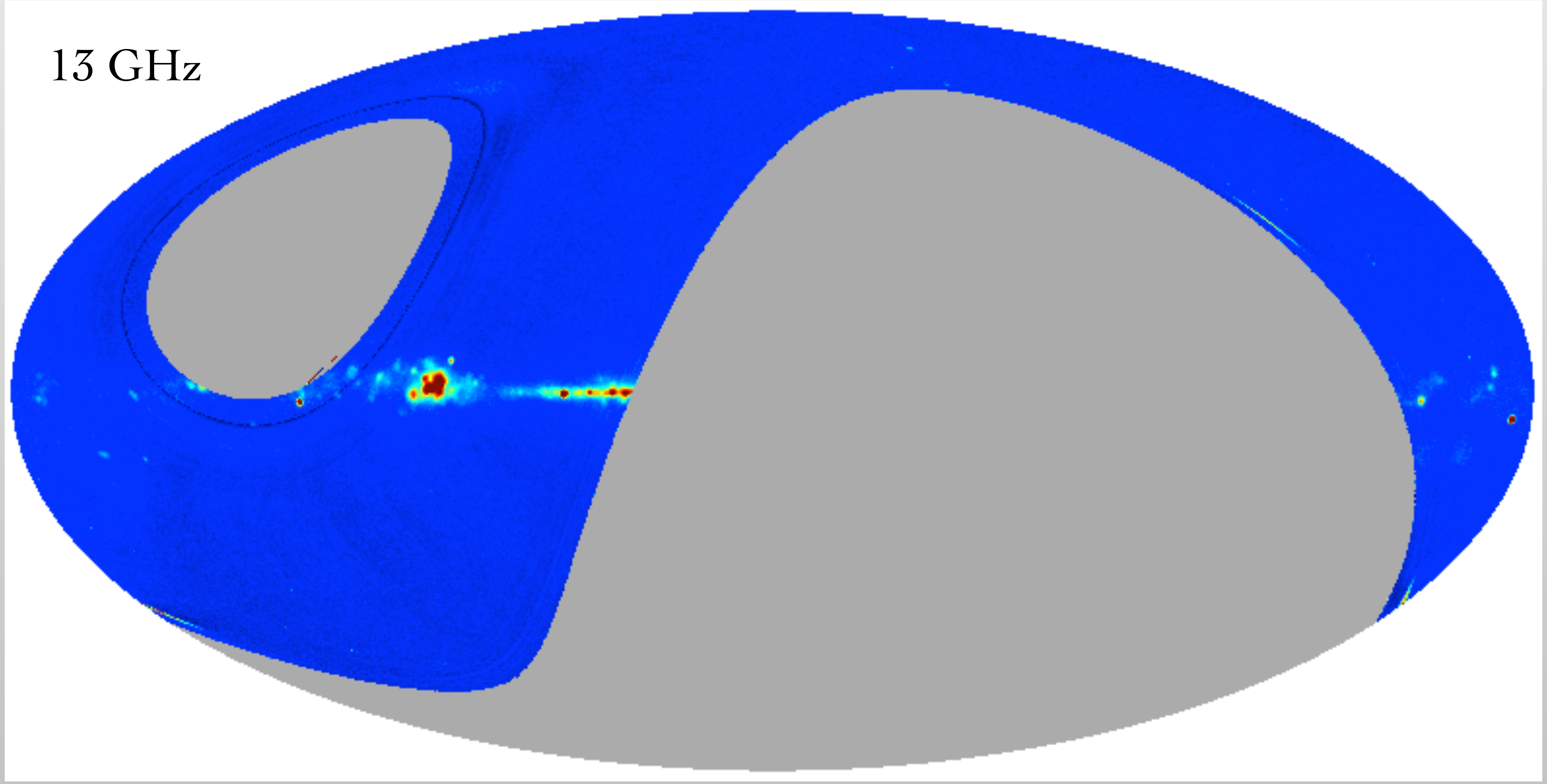
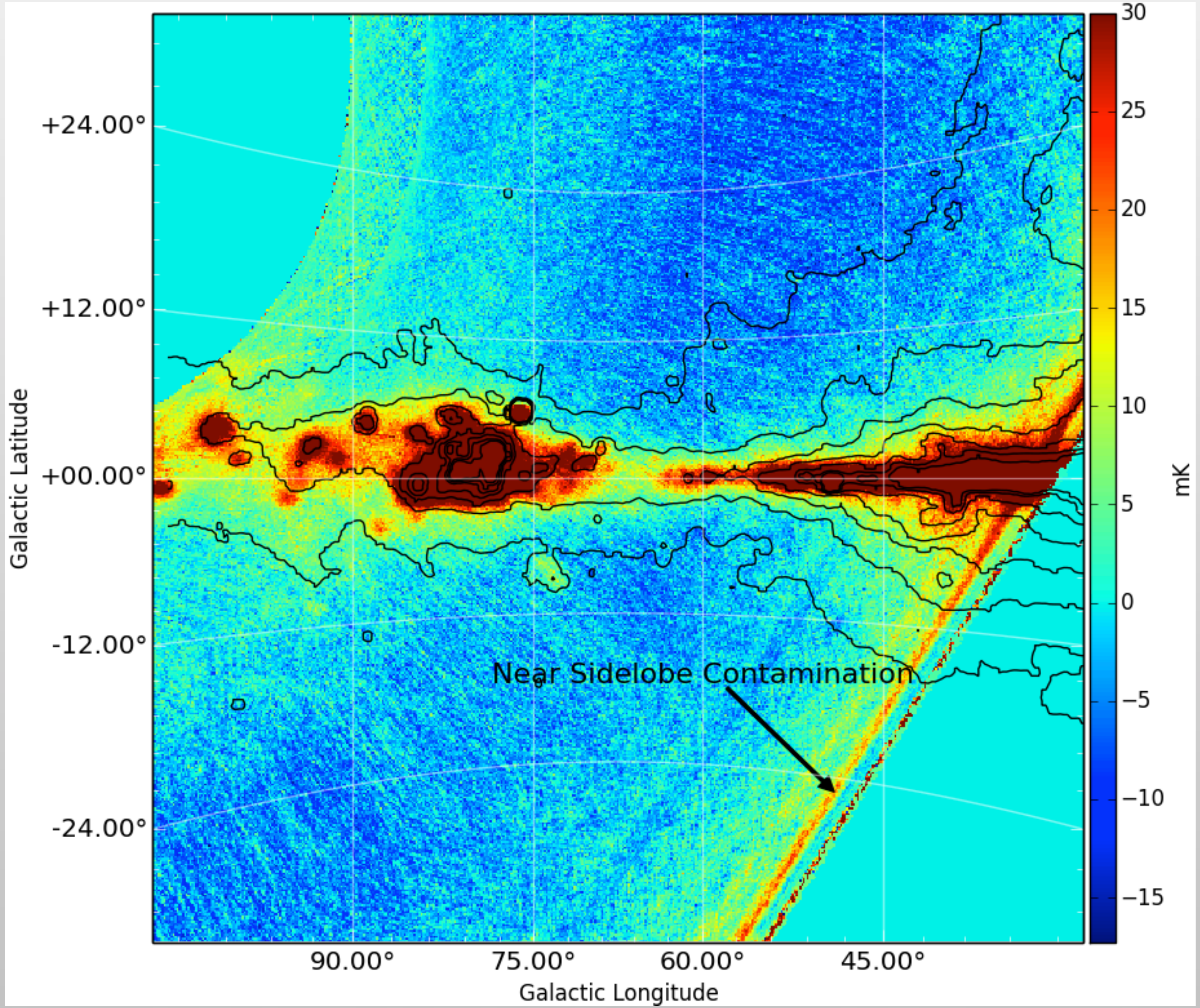


Wide survey

★ Blow-up of the Galactic plane:



✤ The study of the polarization of the CMB opens a new window to study tensor (gravitational waves) perturbations from the inflationary epoch only 10^{-36}s after the Big Bang

✤ BICEP2 have recently claimed a detection of primordial B-modes in the polarization pattern of the CMB, which would have been imprinted by the Gravitational Wave Background

✤ The inferred value of the tensor-to-scalar ratio, $r=0.20$, is in tension with previous measurements from Planck ($r<0.11$). This tension can however be relieved by the inclusion of extra parameters, which are not always compatible with standard inflationary models

✤ Some skepticism has recently spread about the possible dust contamination in this measurement. It seems that the confirmation of this signal needs to wait until a better characterization of the dust polarization is provided by Planck

✤ Equally important is to get data from independent experiments at different frequencies and, if possible, at more than one individual frequency. This is likely to be the only way to disentangle the cosmological and the foreground signal

✤ QUIJOTE will provide this (and is the only current experiment capable to measure the synchrotron polarization), at a completely different frequency range. One year of observations with the TGI should allow to reach a sensitivity $r=0.1$