The status of CMB and the cosmological model

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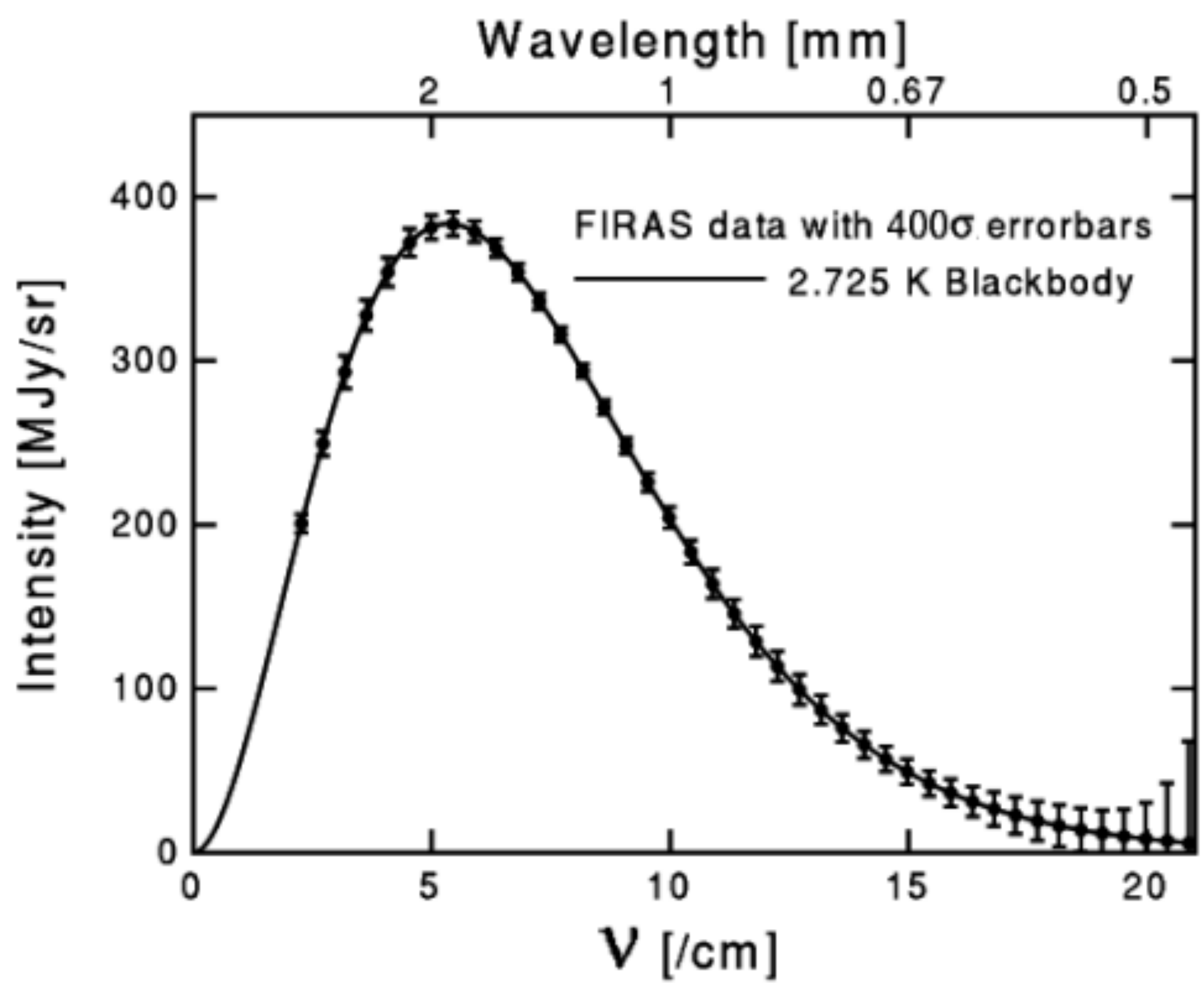
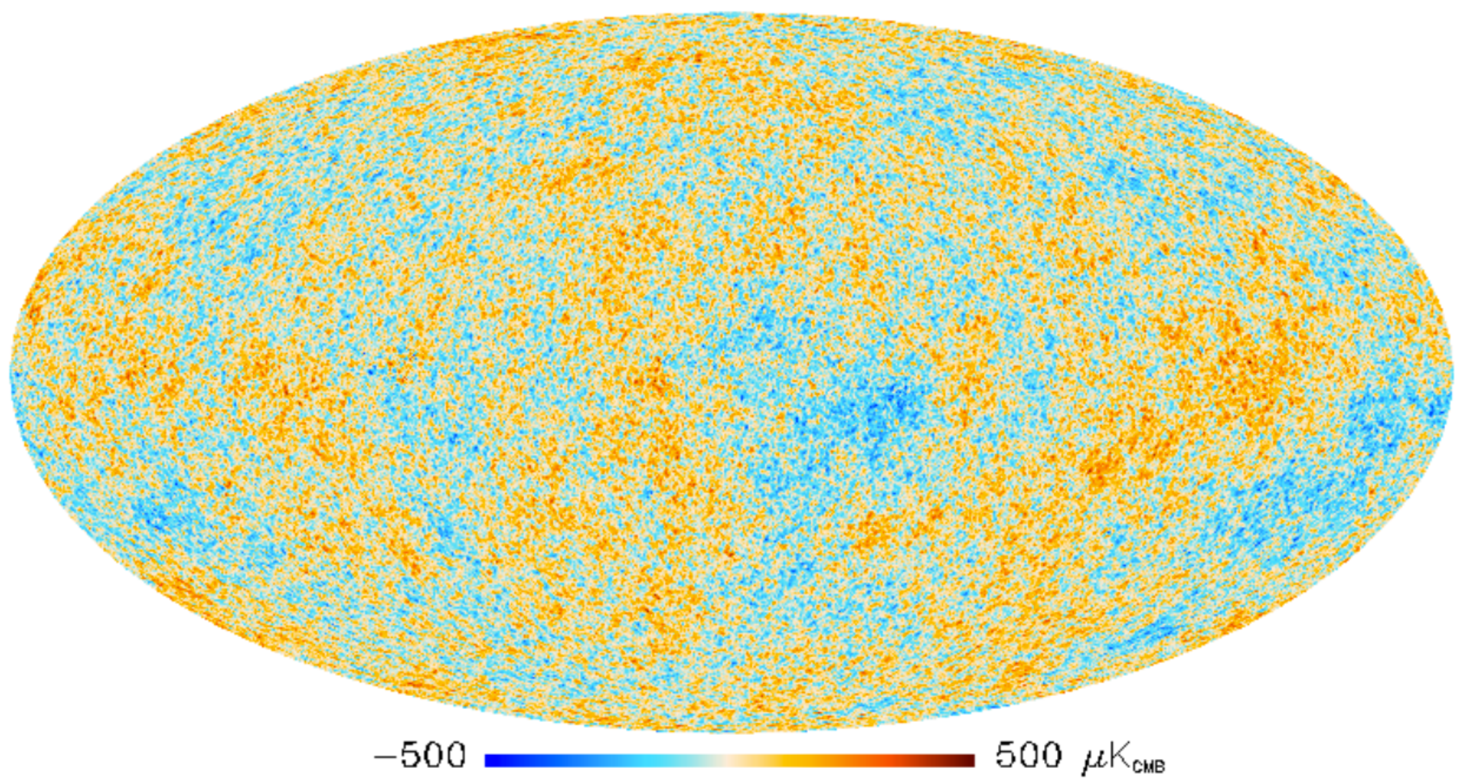
- 1963: “There are only two and a half facts in cosmology” (P. Scheuer)

- 1964/5: Penzias & Wilson discover the CMB

- 1992: COBE finds CMB anisotropies + measures black body spectrum



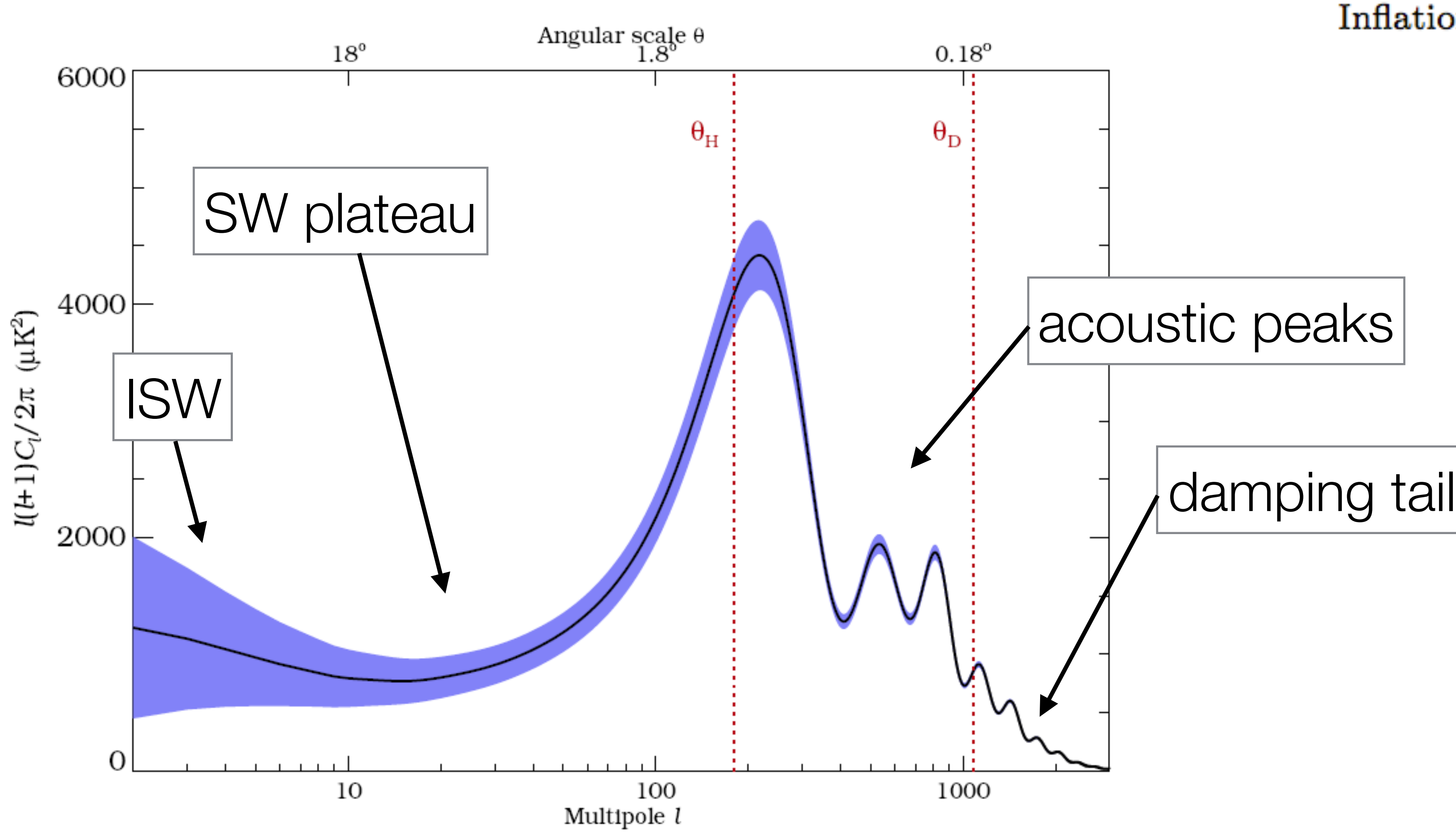


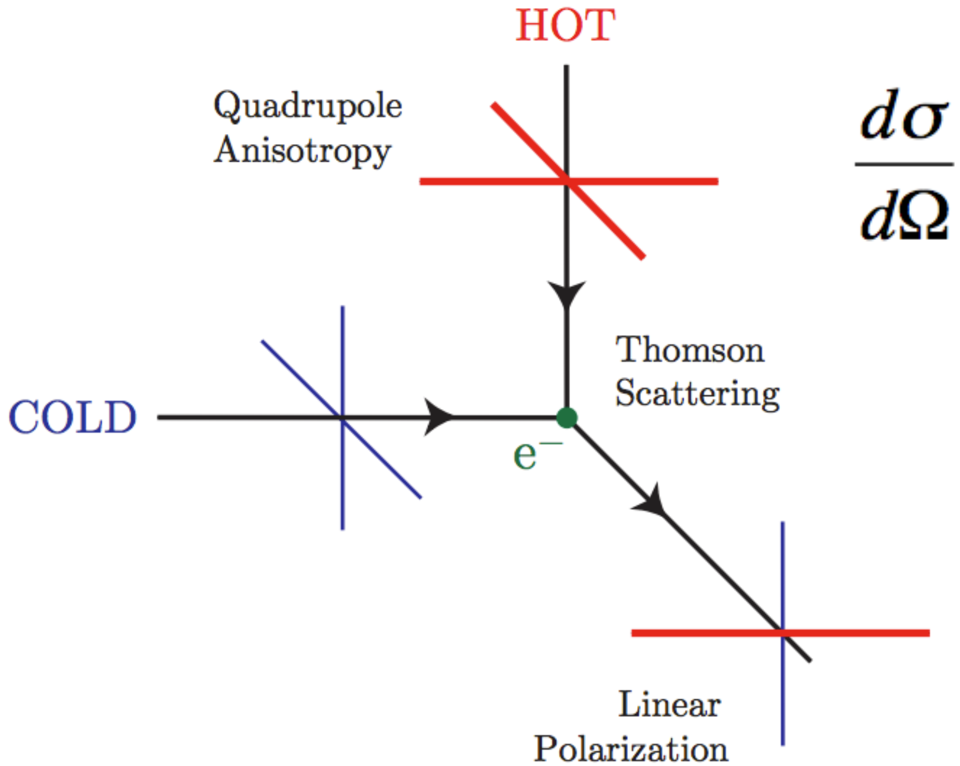
primordial fluctuations evolve **linearly** and are imprinted on the CMB at recombination (t≈380 000 y)

$$\frac{\Delta T(\hat{n})}{T_0} = \sum_{\ell m} a_{\ell m} Y_{\ell m}(\hat{n})$$

$$C_\ell^{TT} = \frac{1}{2\ell+1} \sum_m \langle a_{\ell m}^* a_{\ell m} \rangle$$

$$C_\ell^{TT} = \frac{2}{\pi} \int k^2 \mathrm{d}k \underbrace{P_{\mathcal{R}}(k)}_{\text{Inflation}} \underbrace{\Delta_{T\ell}(k)\Delta_{T\ell}(k)}_{\text{Anisotropies}}$$





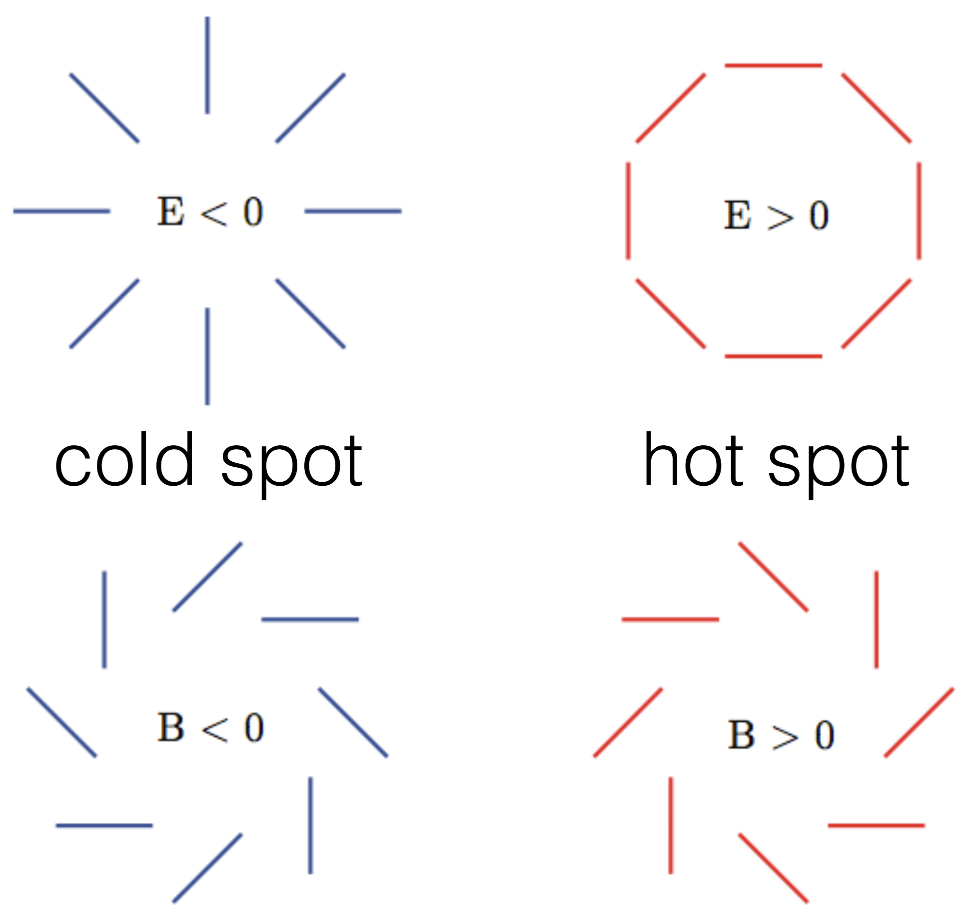
$$\frac{d\sigma}{d\Omega} = \frac{3}{8\pi}\left|\hat{\varepsilon}' \cdot \hat{\varepsilon}\right|^2 \sigma_T$$

linear polarization is produced if quadrupole anisotropy is present at last scattering

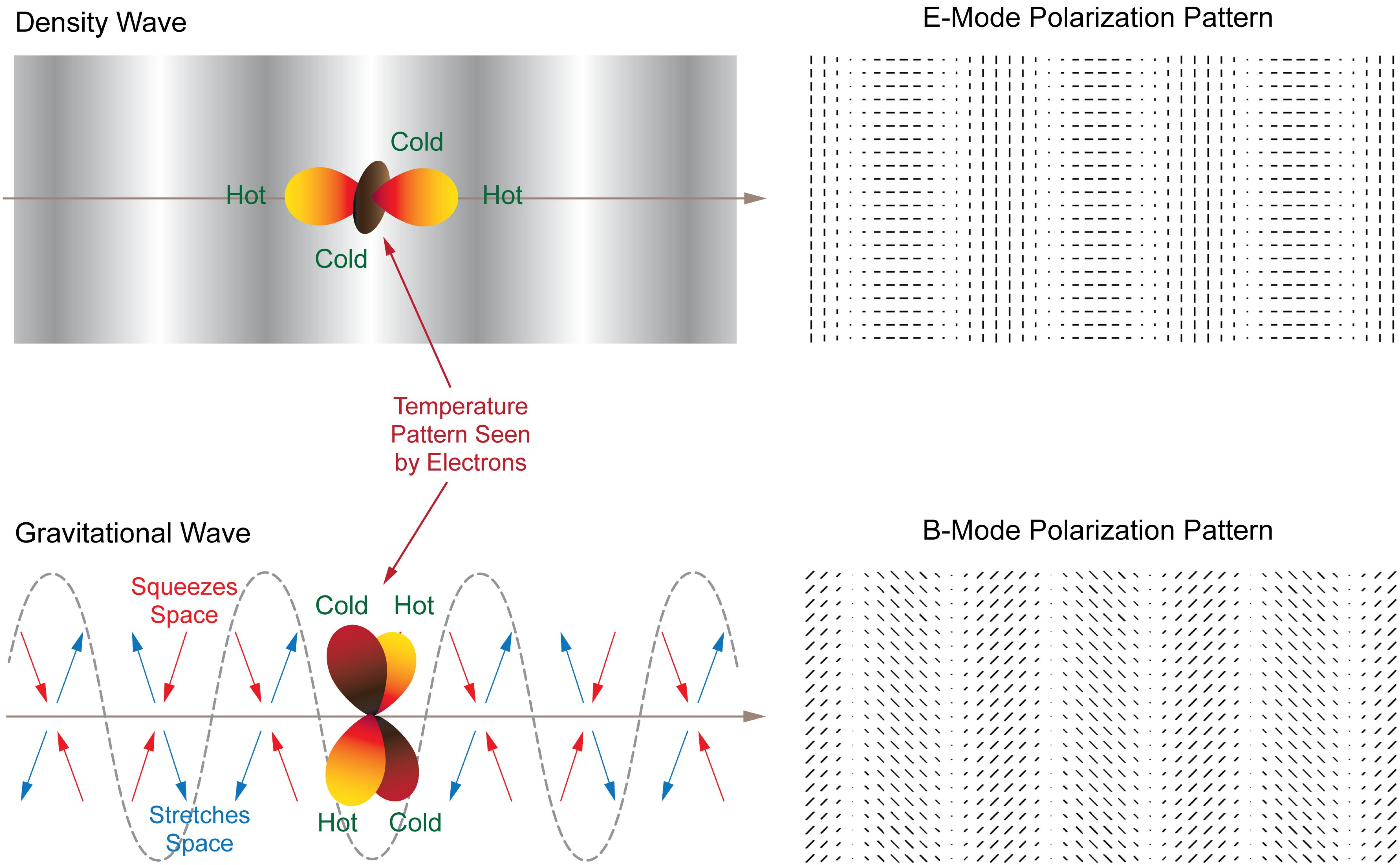
(this means the expected polarization signal is a small fraction of the total intensity)

pure E

pure B



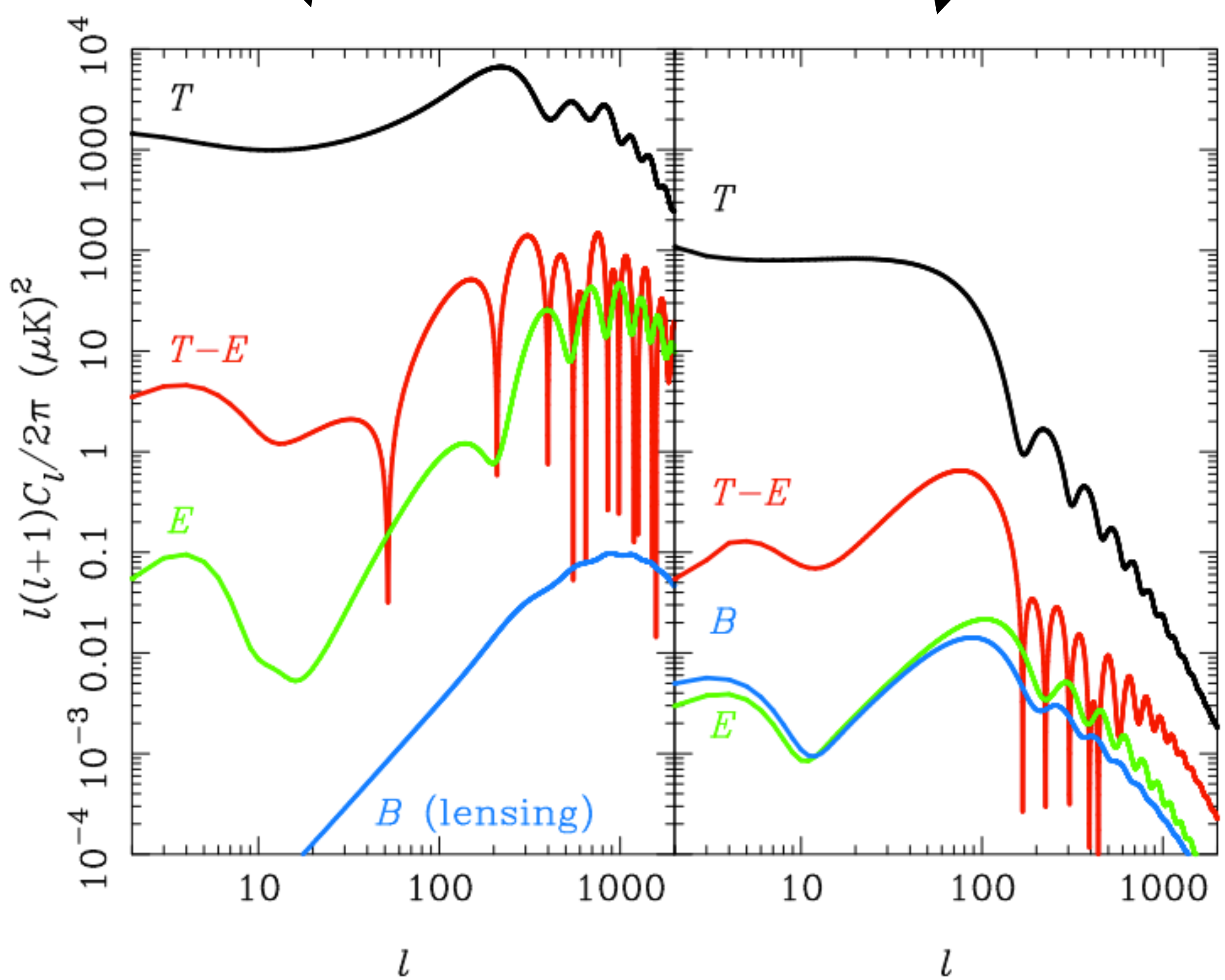
different symmetry under parity



Density Wave
Cold
Hot
Hot
Cold
E-Mode Polarization Pattern
Temperature
Pattern Seen
by Electrons
Gravitational Wave
Squeezes
Space
Cold
Hot
Stretches
Space
Hot
Cold
B-Mode Polarization Pattern

scalar perturbations
do not produce B-polarization (but there is an effect from gravitational lensing)

tensor perturbations
contribute to both temperature and polarization

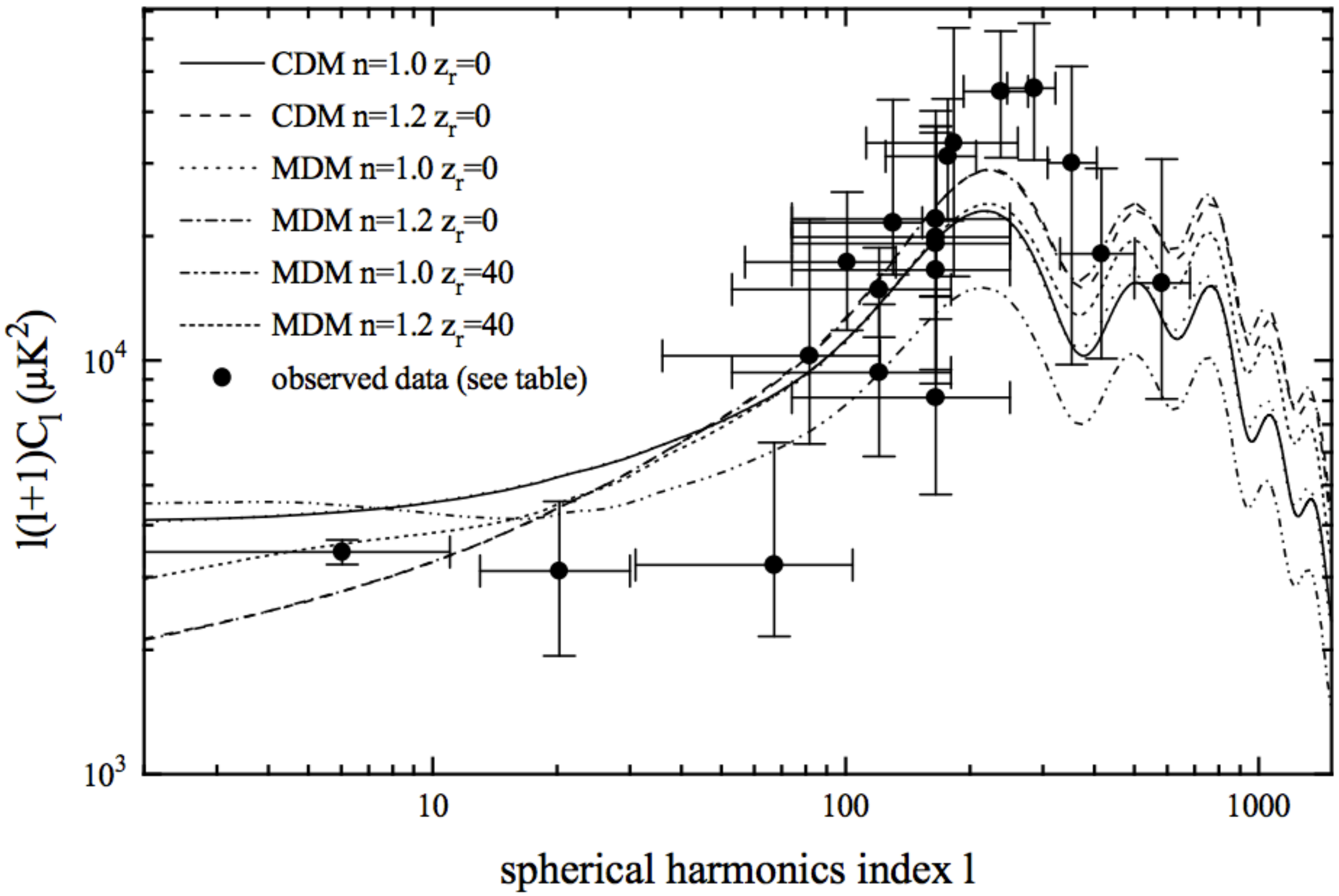


B-polarization is a unique signature of tensor perturbations (gravitational waves) and of inflation

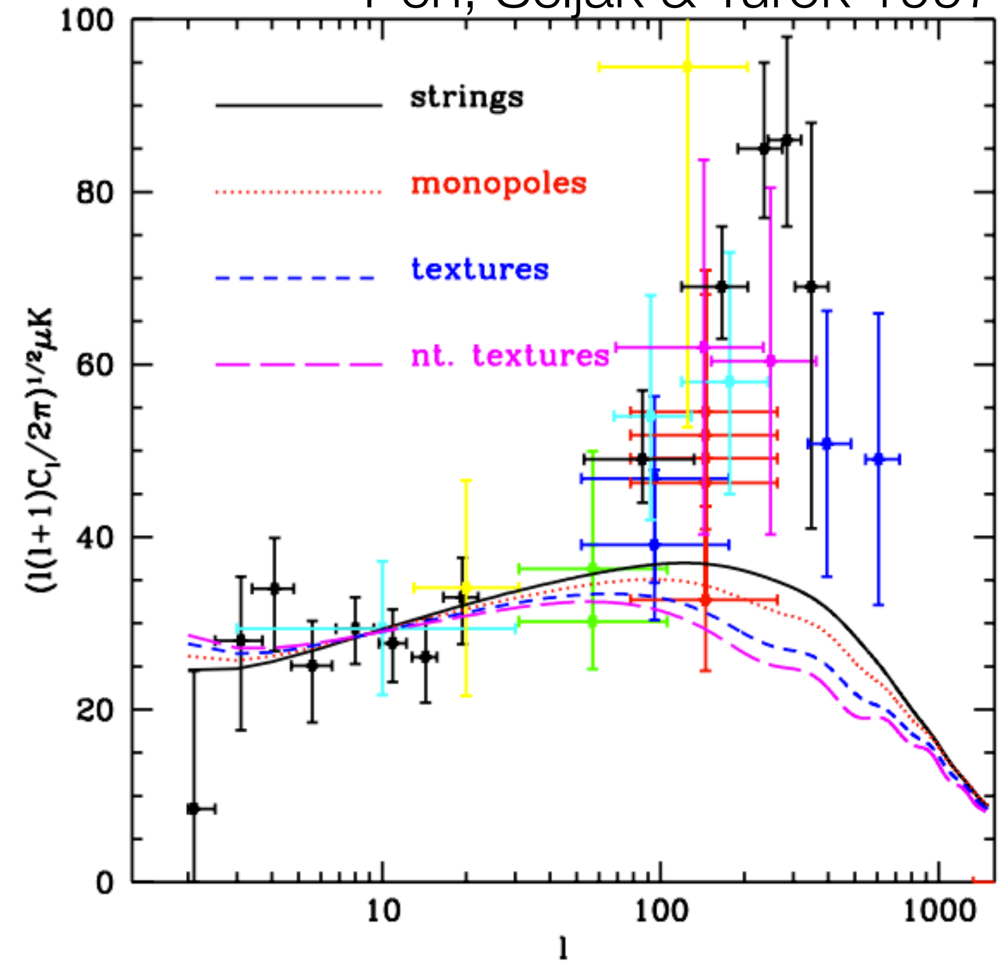
looking back
~20 years ago

(this was the published article
from my “laurea” thesis)

de Bernardis et al 1996



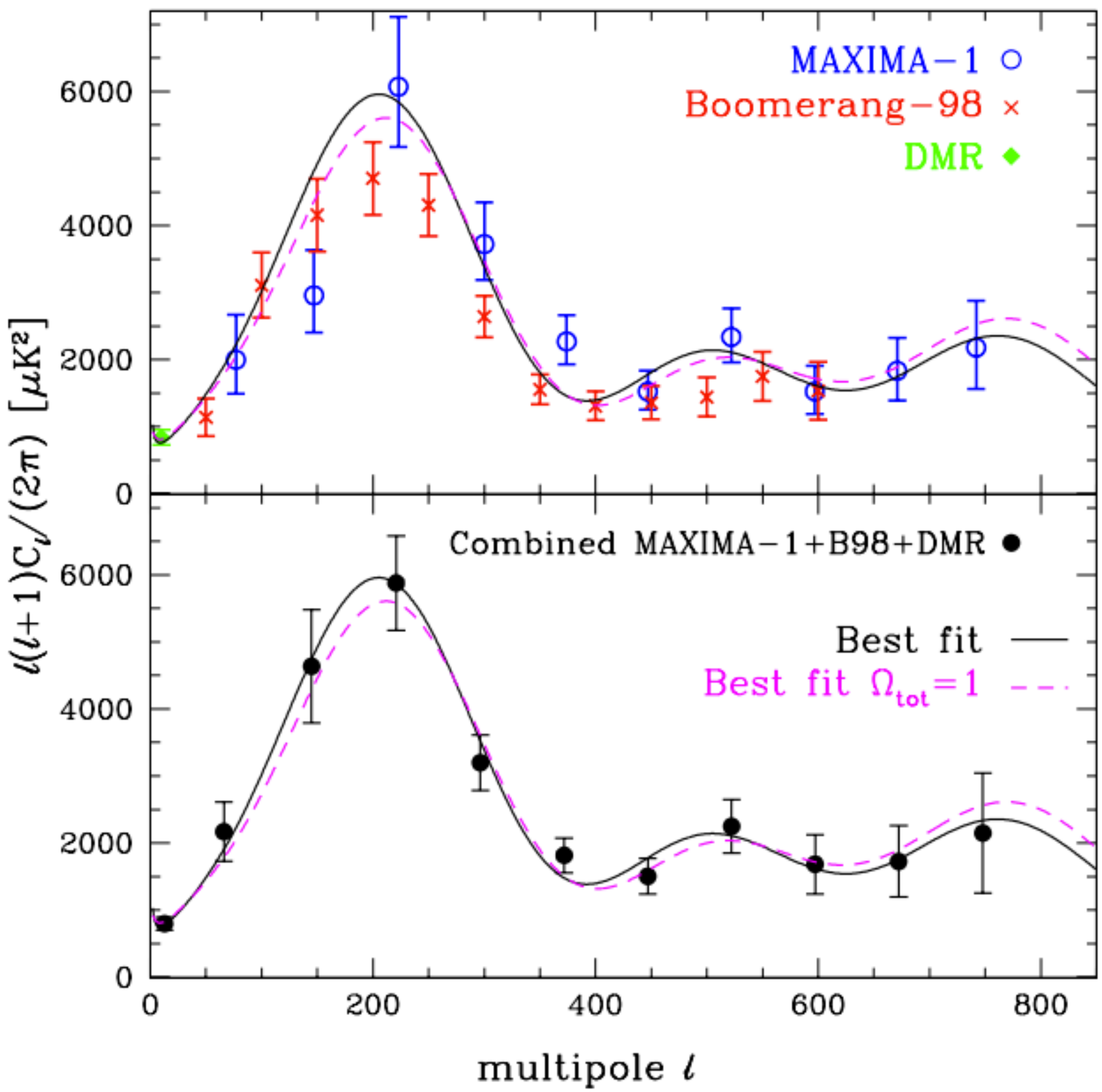
Pen, Seljak & Turok 1997

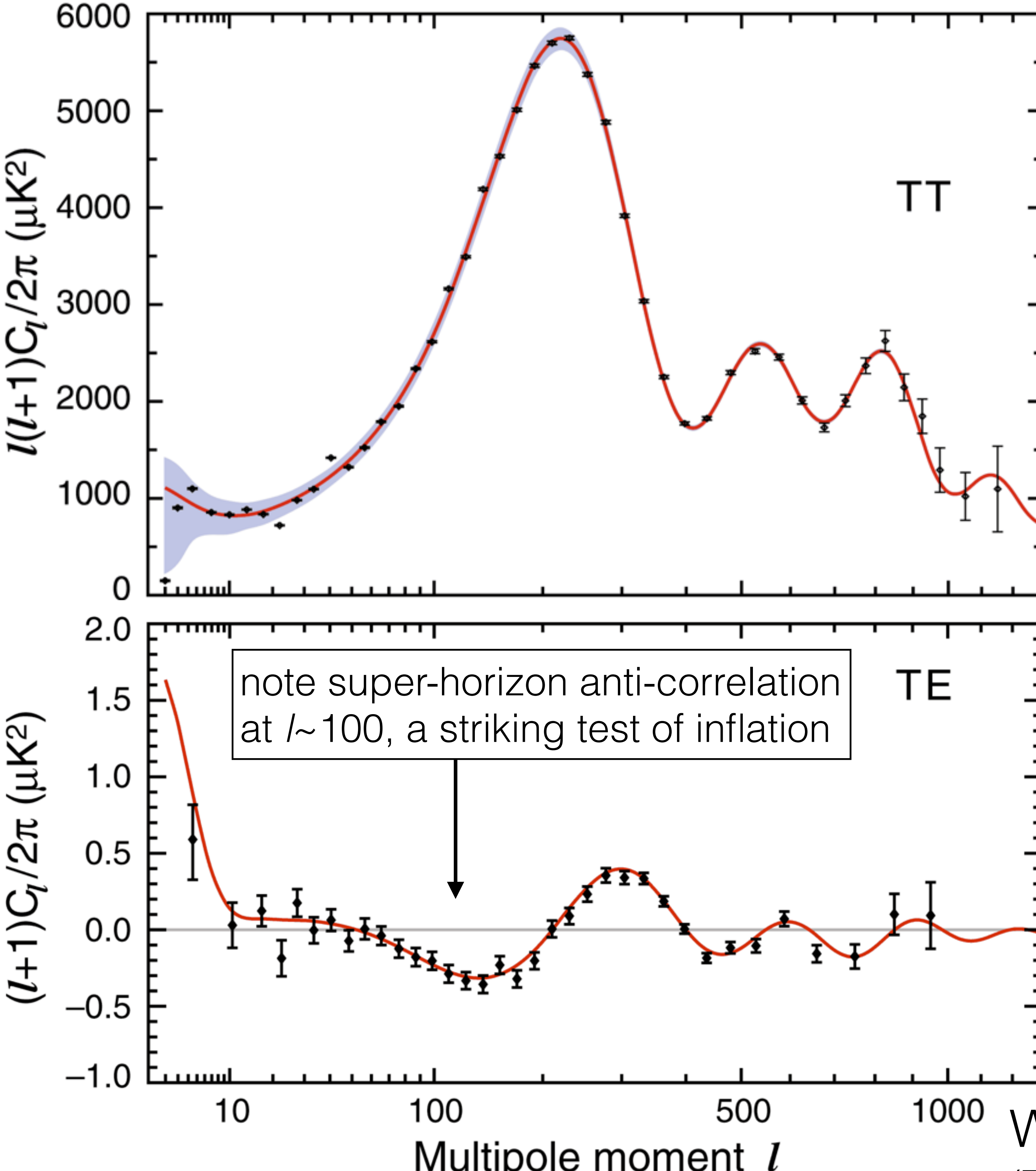


looking back
~15 years ago

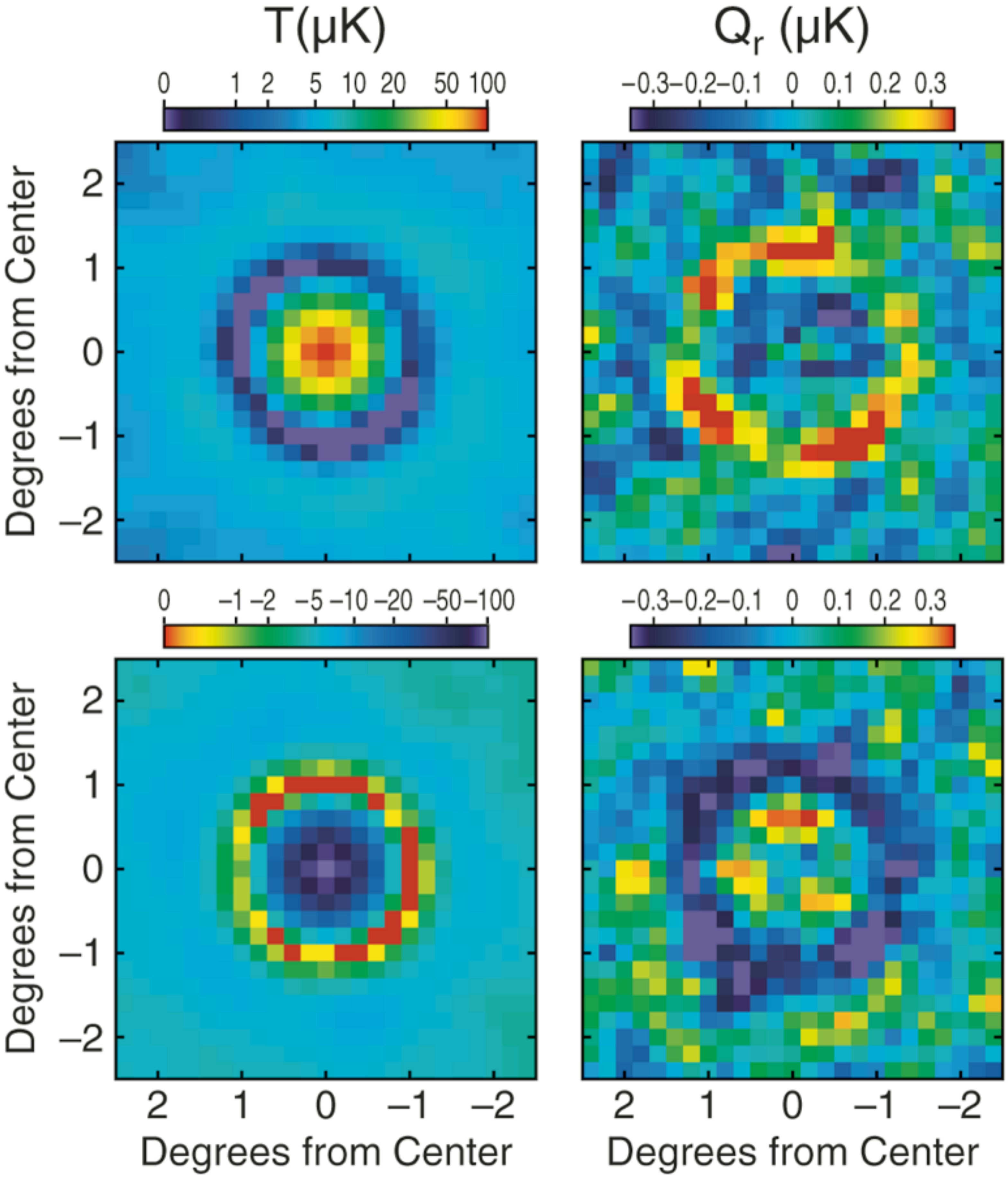
(and here is my phd thesis)

Balbi et al 2000
Jaffe et al 2001





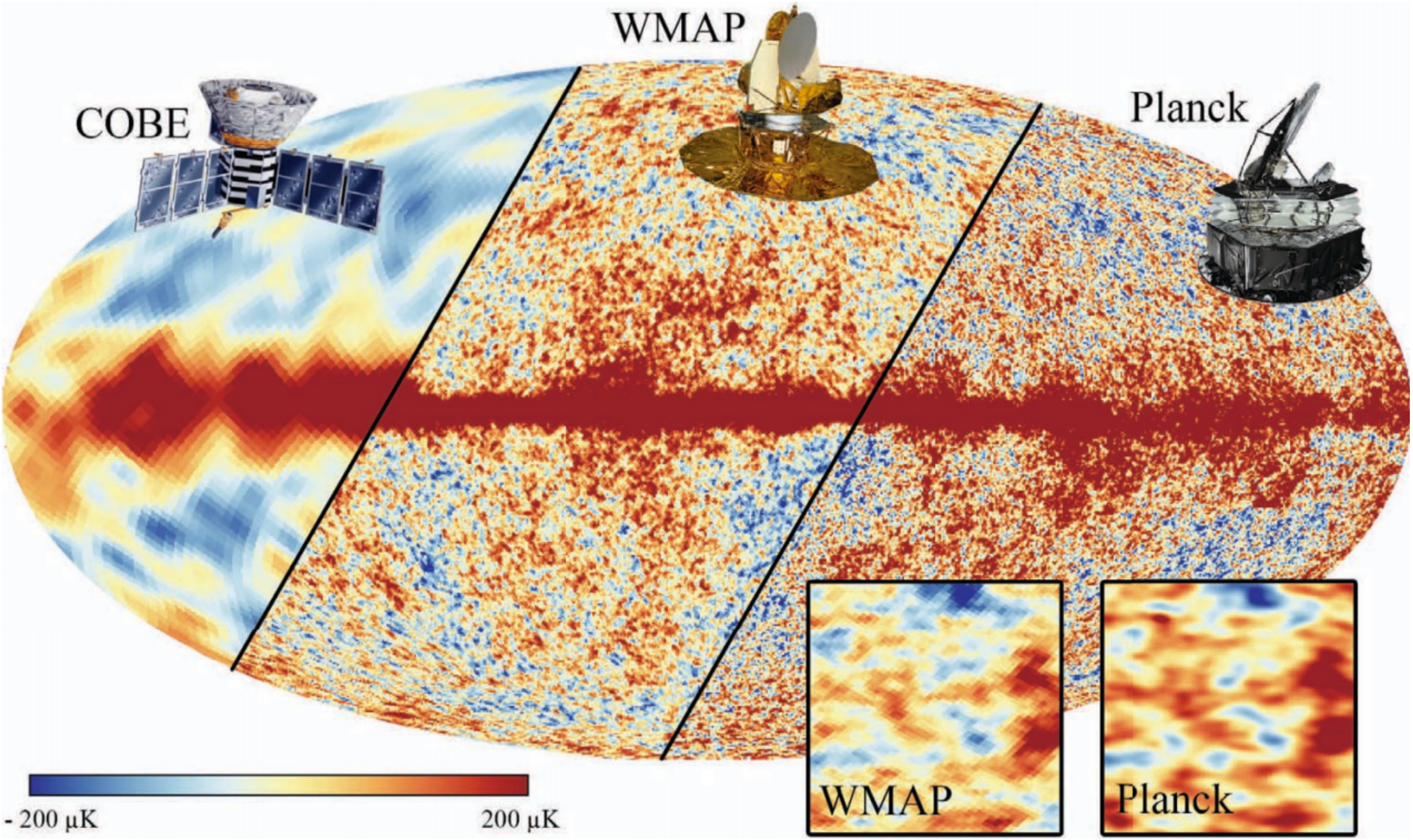
WMAP final results
(Bennett et al 2013)



radial correlation to hot spots

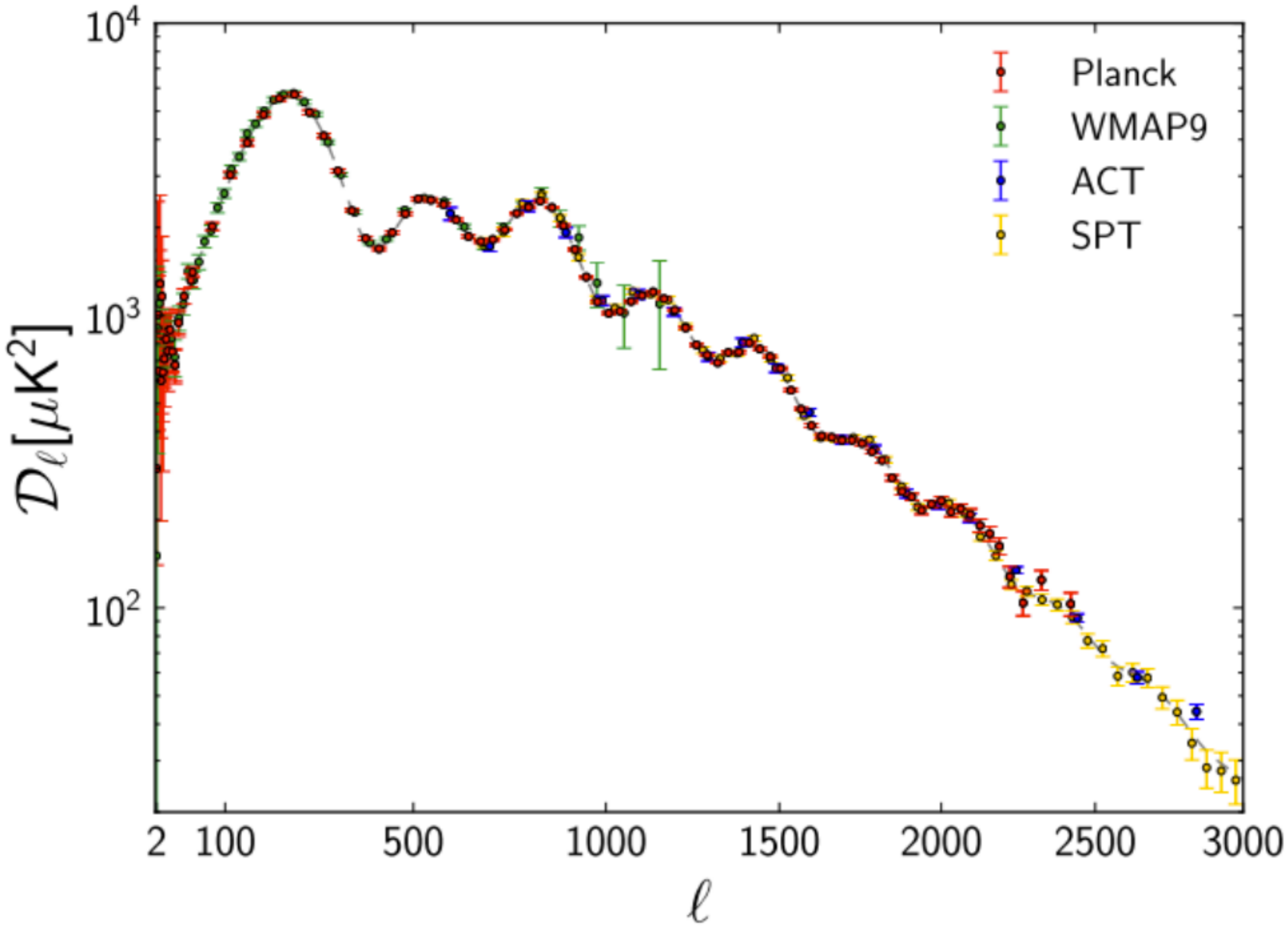
tangential correlation to cold spots

(Hinshaw et al 2013)


COBE
WMAP
Planck
- 200 μK
200 μK
WMAP
Planck

spectacular agreement with 6-parameter ΛCDM model

(fixing $\Omega = 1$, $dn/d \ln k = 0$, $r = 0$, and $w = -1$)



basic parameters:

$\ln(10^{10}A) = 3.09 \pm 0.03$

$n = 0.958 \pm 0.007$

$\Omega_b h^2 = 0.0221 \pm 0.0003$

$\Omega_c h^2 = 0.120 \pm 0.003$;

$100\ \theta_* = 1.0415 \pm 0.0006$

$\tau = 0.091 \pm 0.014$

derived parameters:

$h = 0.673 \pm 0.012$

$\Omega_\Lambda\ (= 1 - \Omega_m) = 0.685 \pm 0.016$

$\sigma_8 = 0.828 \pm 0.012$

$t_0 = 13.813 \pm 0.058$

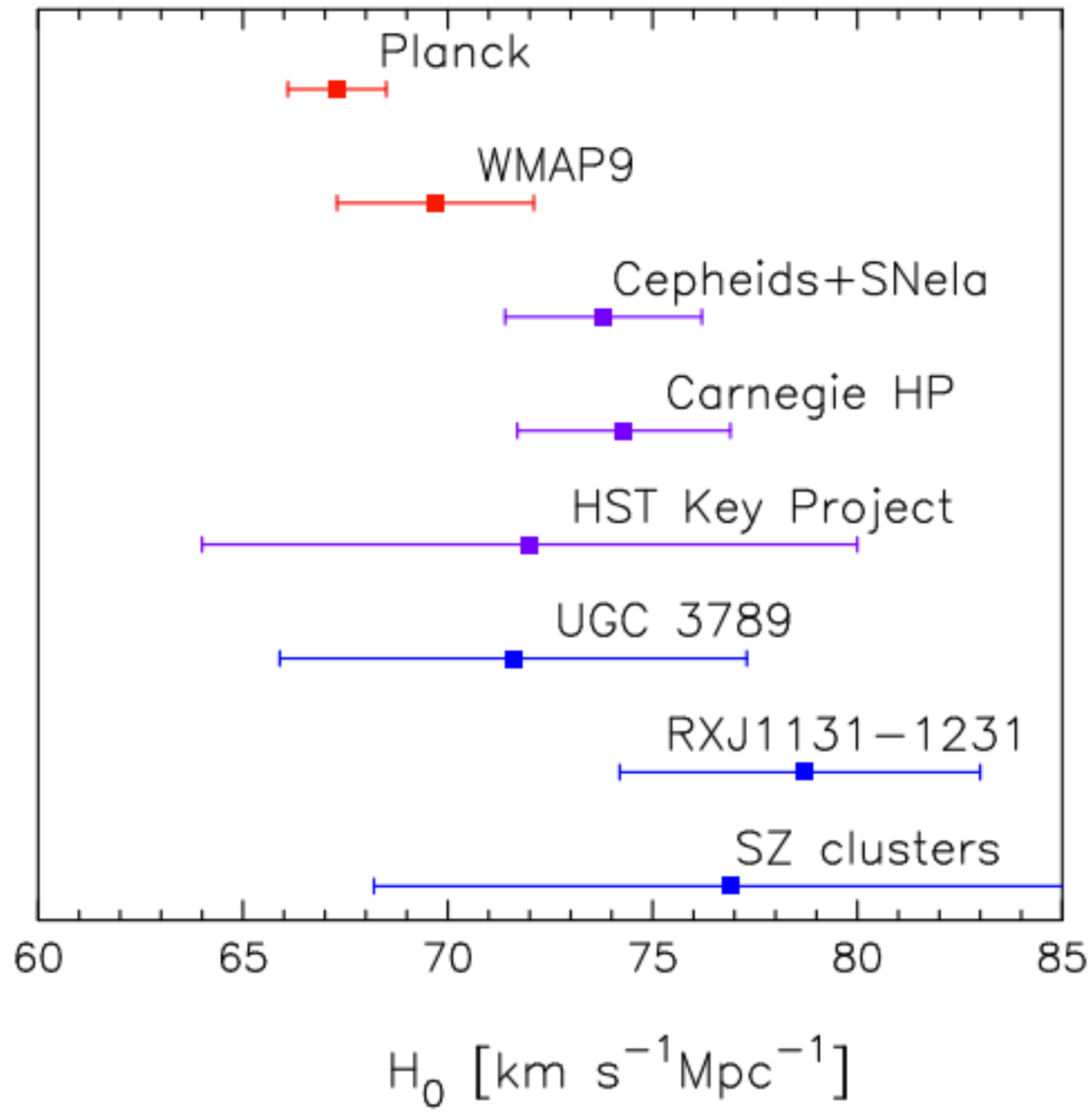
no compelling evidence for extending the basic ΛCDM model with the inclusion of extra parameters

	Planck+WP		*Planck*+WP+BAO		*Planck*+WP+highL		*Planck*+WP+highL+BAO	
Parameter	Best fit	95% limits	Best fit	95% limits	Best fit	95% limits	Best fit	95% limits
Ω_K	-0.0326	$-0.037^{+0.043}_{-0.049}$	0.0006	$0.0000^{+0.0066}_{-0.0067}$	-0.0389	$-0.042^{+0.043}_{-0.048}$	-0.0003	$-0.0005^{+0.0065}_{-0.0066}$
Σm_ν [eV]	0.002	< 0.933	0.000	< 0.247	0.000	< 0.663	0.001	< 0.230
$N_{\rm eff}$	3.25	$3.51^{+0.80}_{-0.74}$	3.32	$3.40^{+0.59}_{-0.57}$	3.38	$3.36^{+0.68}_{-0.64}$	3.33	$3.30^{+0.54}_{-0.51}$
$Y_{\rm P}$	0.2896	$0.283^{+0.045}_{-0.048}$	0.2889	$0.283^{+0.043}_{-0.045}$	0.2652	$0.266^{+0.040}_{-0.042}$	0.2701	$0.267^{+0.038}_{-0.040}$
$dn_{\rm s}/d\ln k$	-0.0125	$-0.013^{+0.018}_{-0.018}$	-0.0097	$-0.013^{+0.018}_{-0.018}$	-0.0146	$-0.015^{+0.017}_{-0.017}$	-0.0143	$-0.014^{+0.016}_{-0.017}$
$r_{0.002}$	0.000	< 0.120	0.000	< 0.122	0.000	< 0.108	0.000	< 0.111
w	-1.94	$-1.49^{+0.65}_{-0.57}$	-1.106	$-1.13^{+0.24}_{-0.25}$	-1.94	$-1.51^{+0.62}_{-0.53}$	-1.113	$-1.13^{+0.23}_{-0.25}$

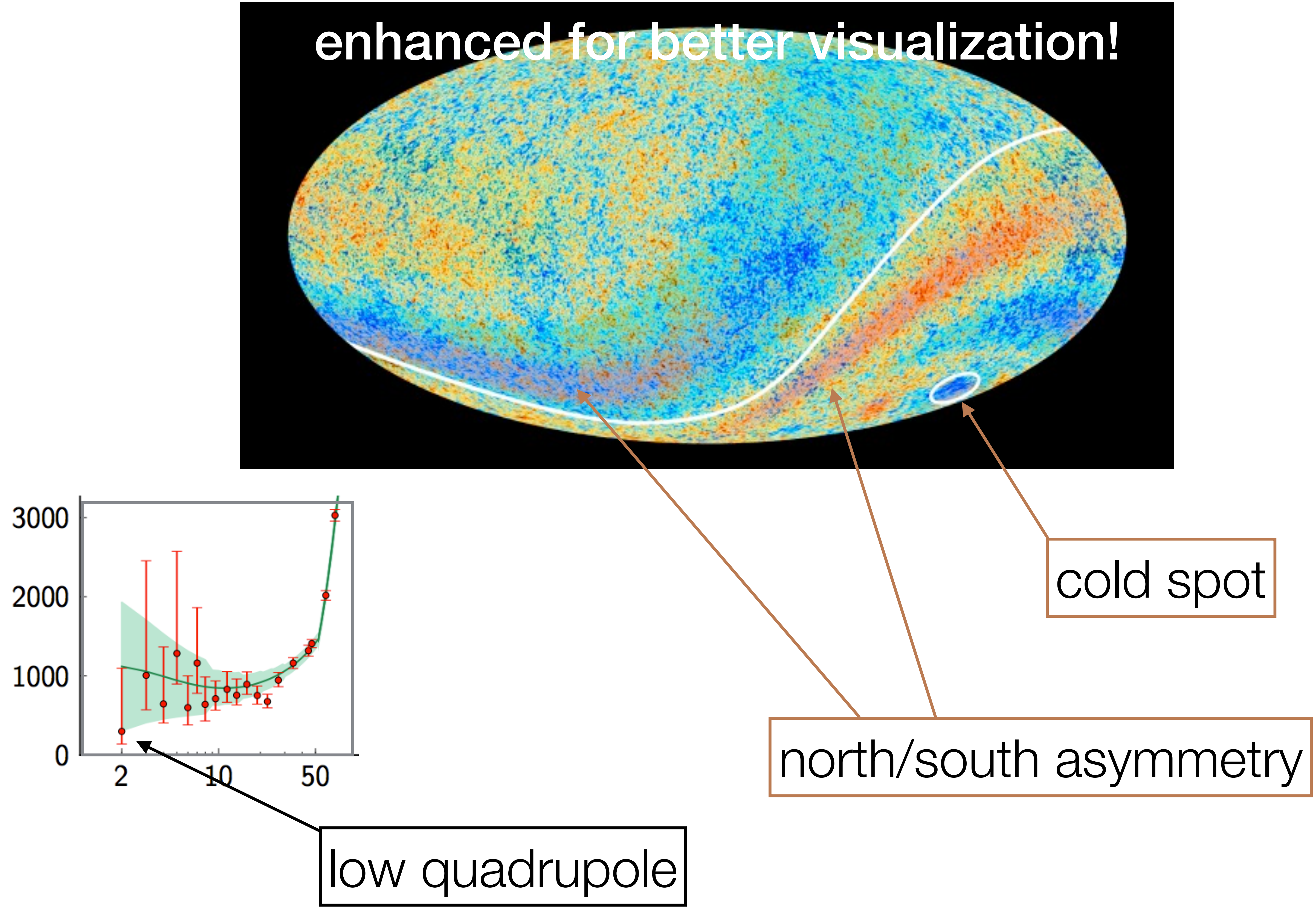
(Planck collaboration XVI 2013)

mild tension between the Hubble constant value estimated from the CMB and from local (distance ladder) measurements

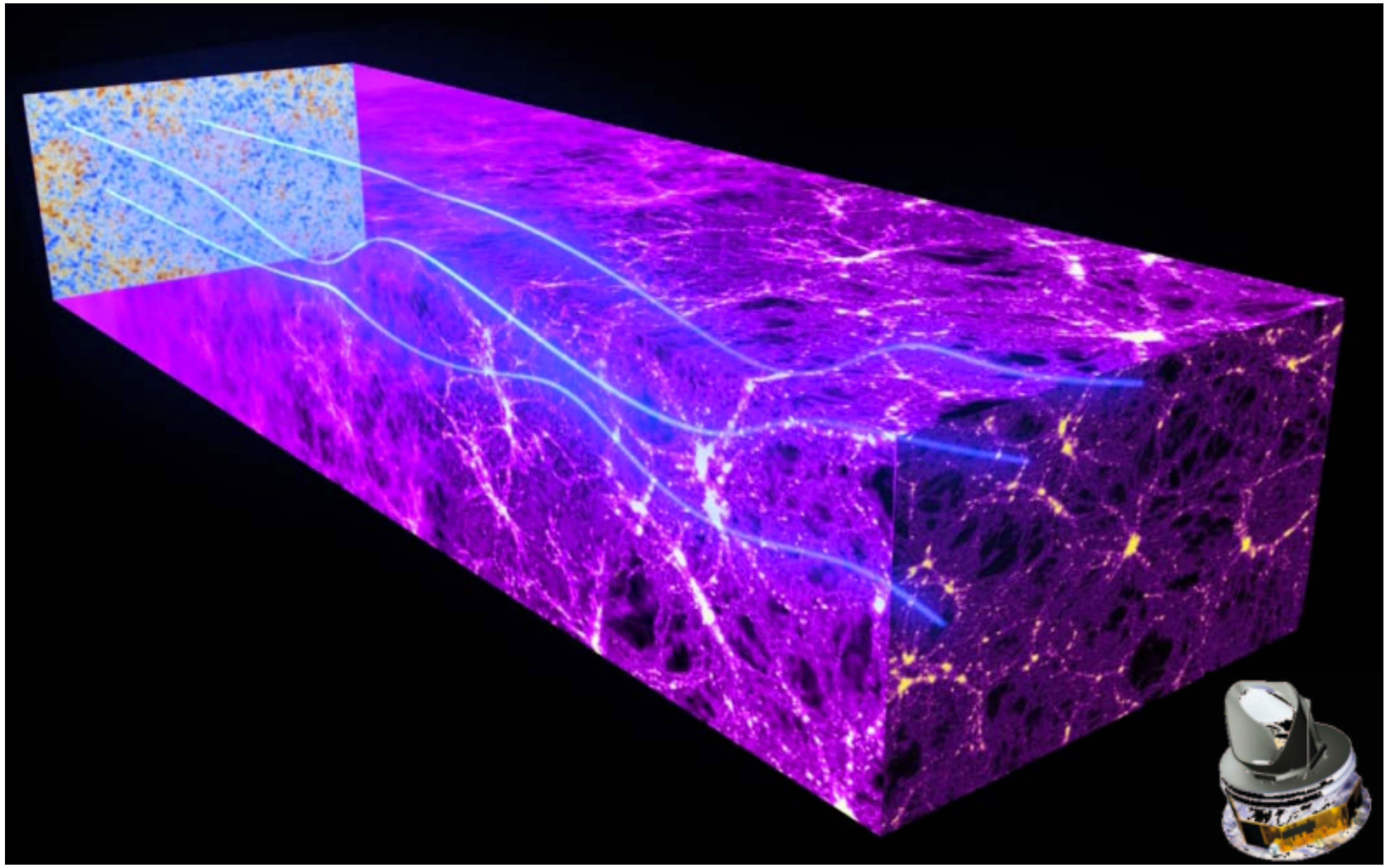
(Planck collaboration XVI 2013)



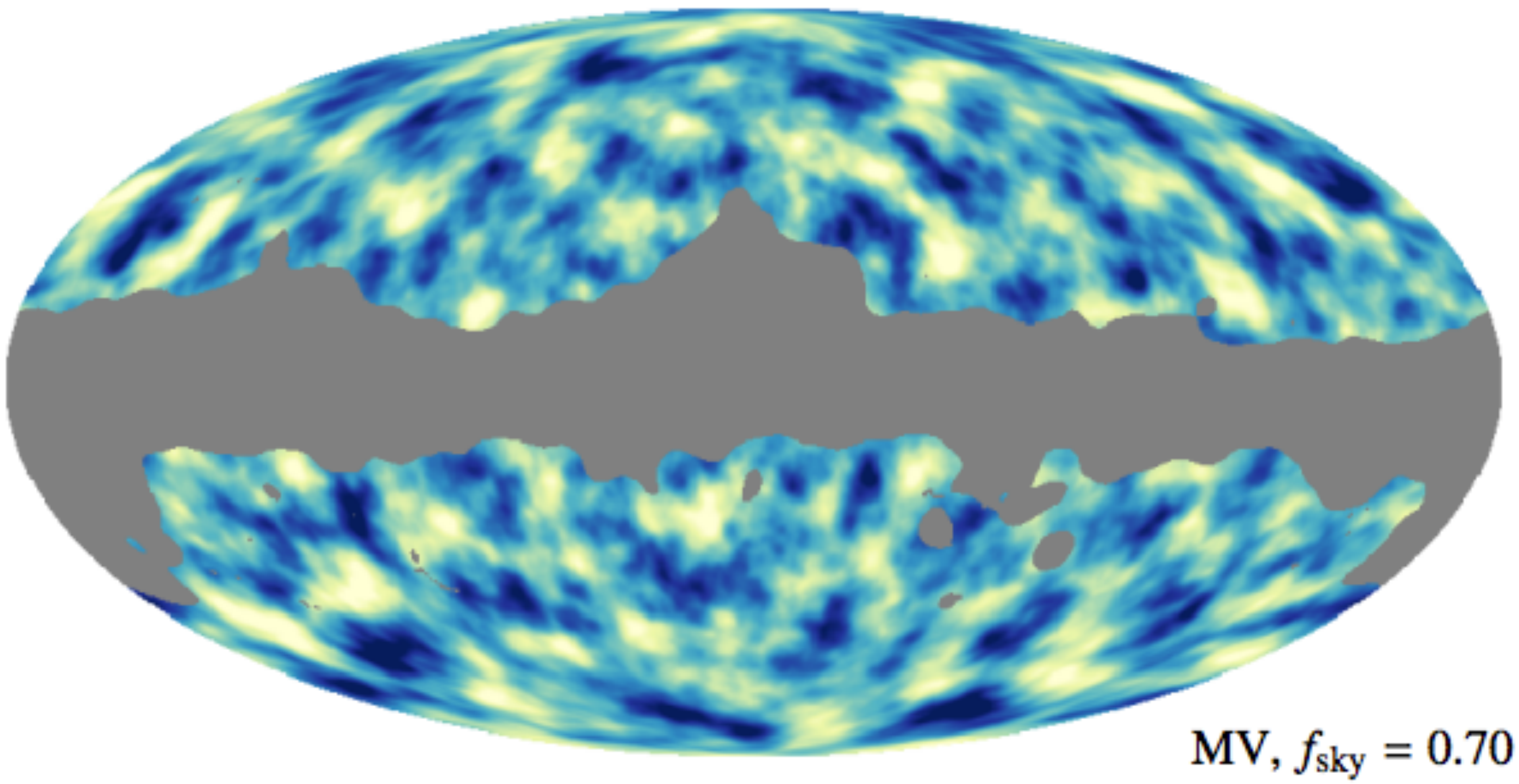
anomalies (of low statistical significance) at large scales (where cosmic variance dominates)



lensing of the CMB by large-scale structure

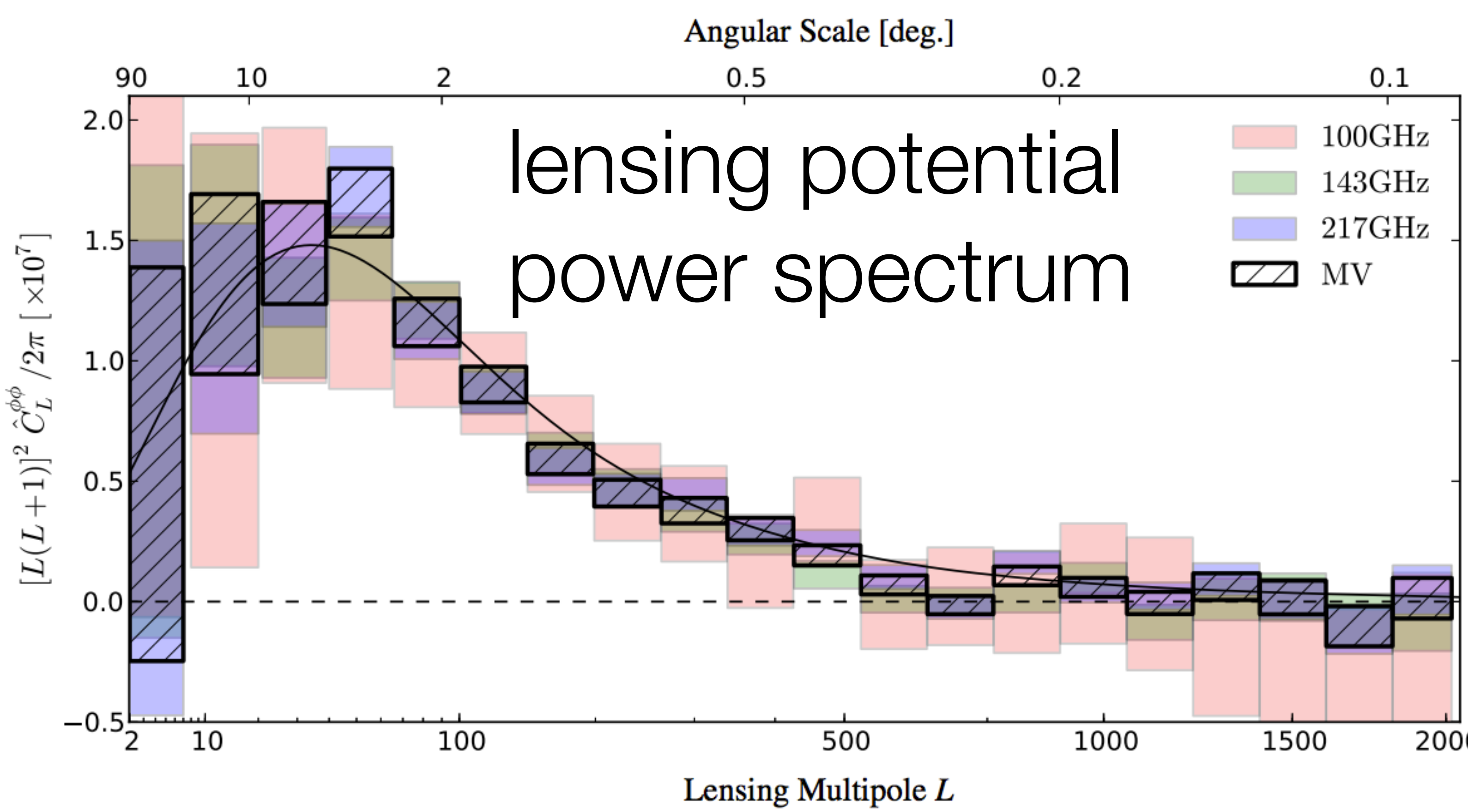


- results in a gentle smoothing of acoustic features at high multipoles (l~1000), helps reducing parameter degeneracies
- gaussian source at well known redshift (z~1100) + linear physics
- but: observationally very challenging (requires high S/N at small angular scales)



lensing potential map

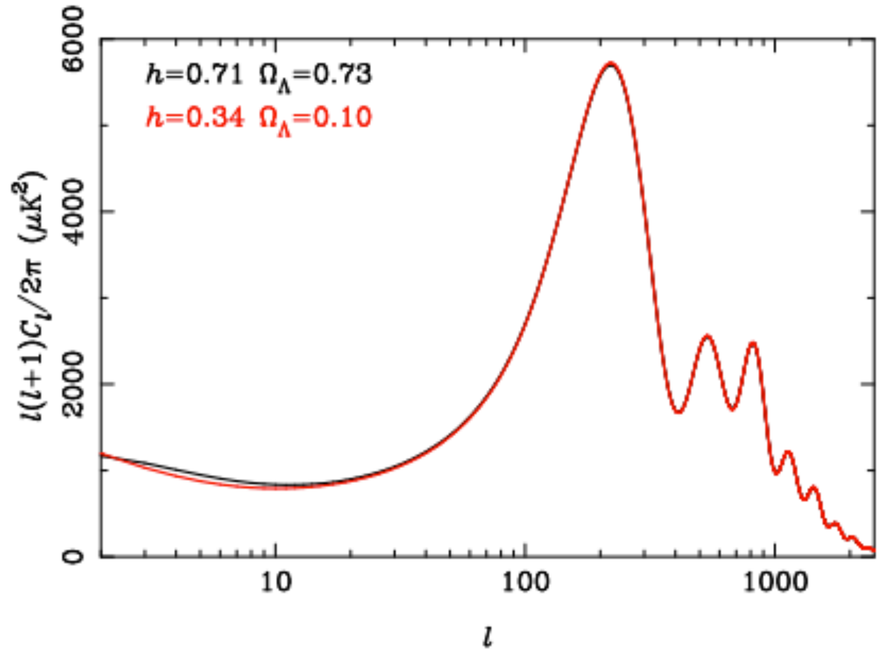
~25σ detection

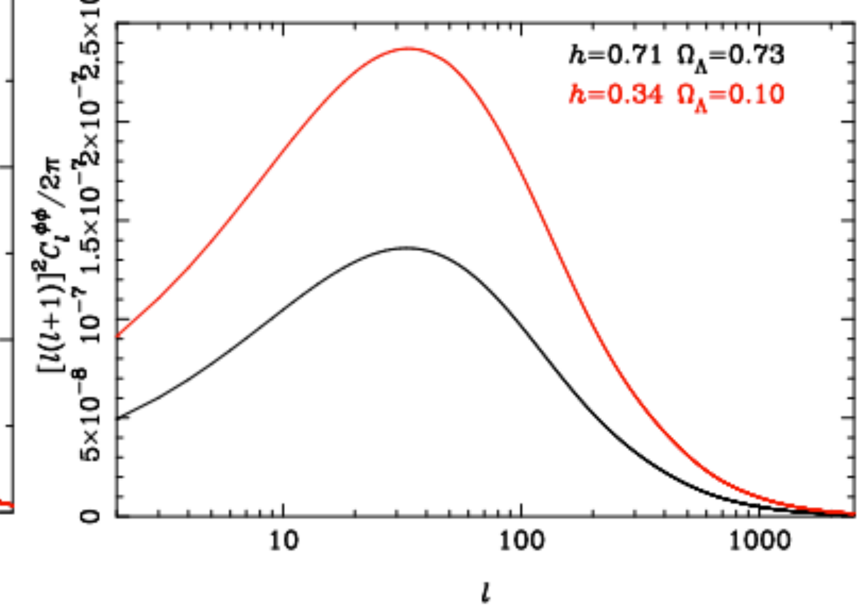


Planck Collaboration XVII (2013)

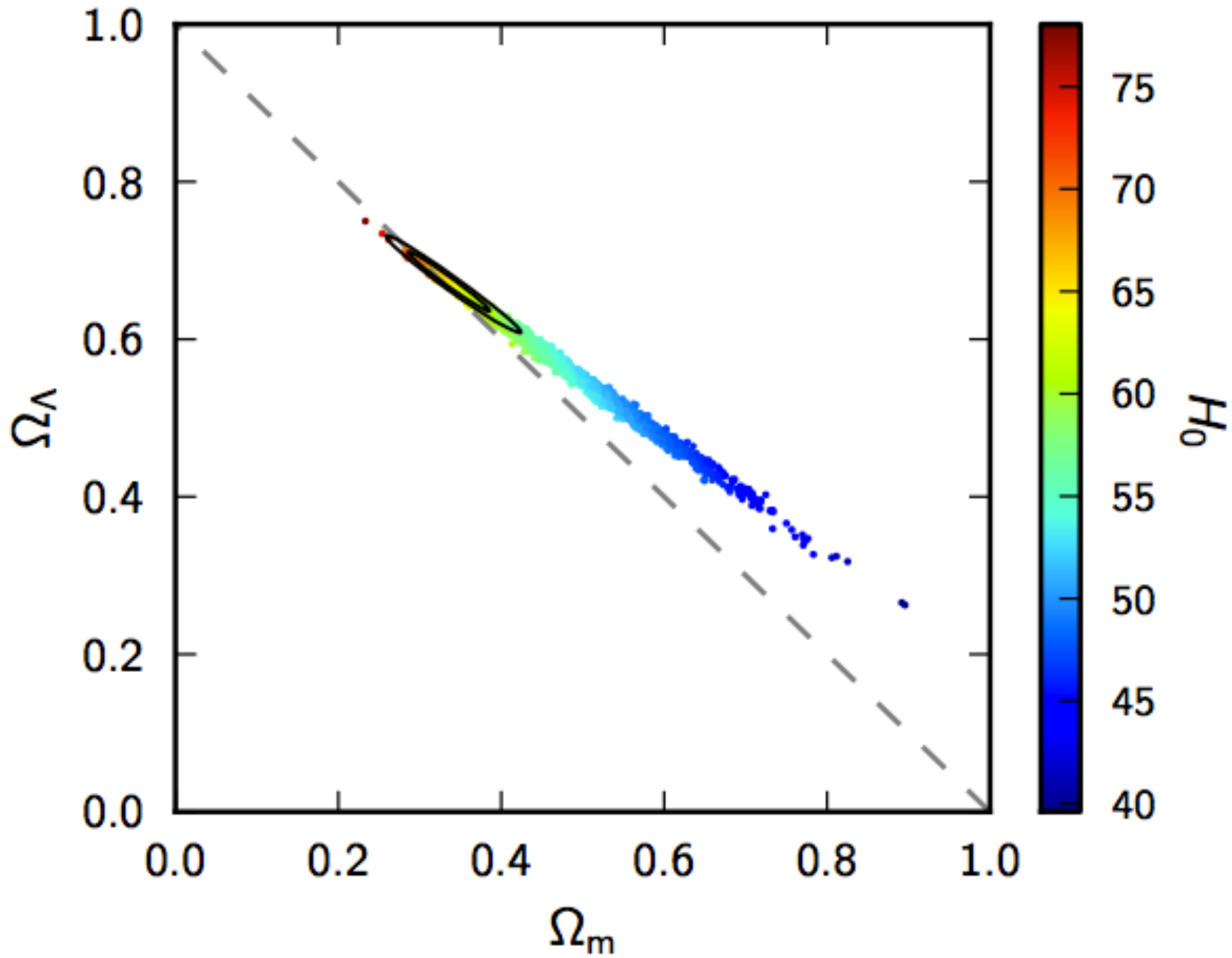
the inclusion of lensing breaks the geometrical degeneracy, improving the constraints on curvature

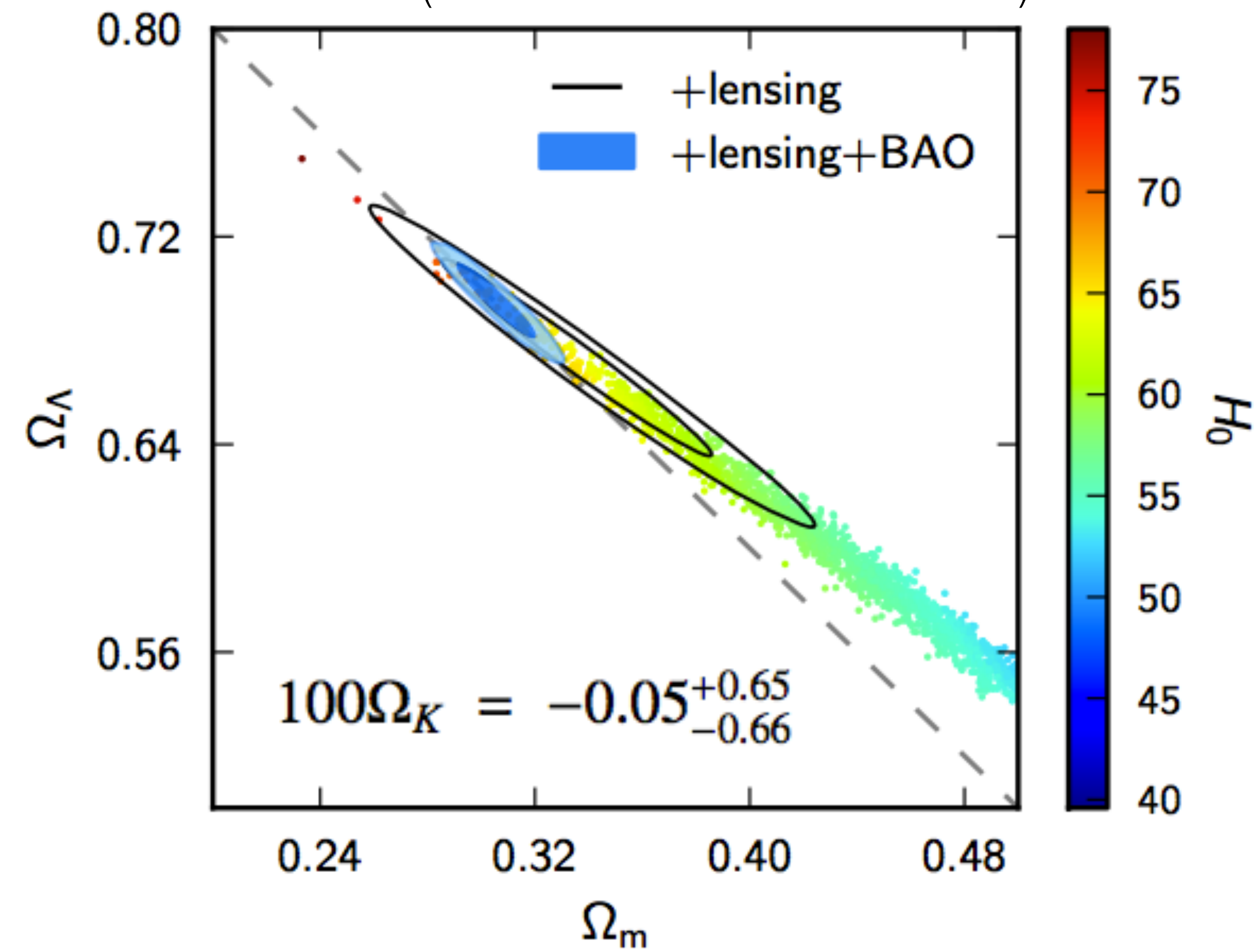
Challinor 2012





(Planck collaboration XVI 2013)

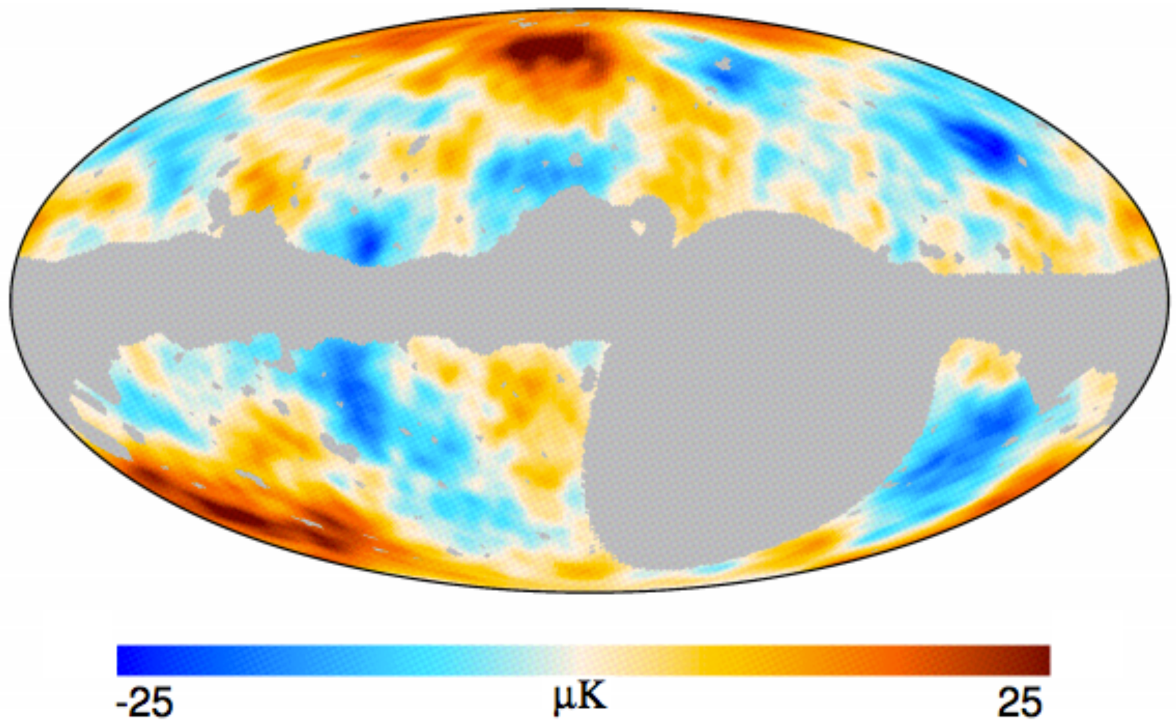




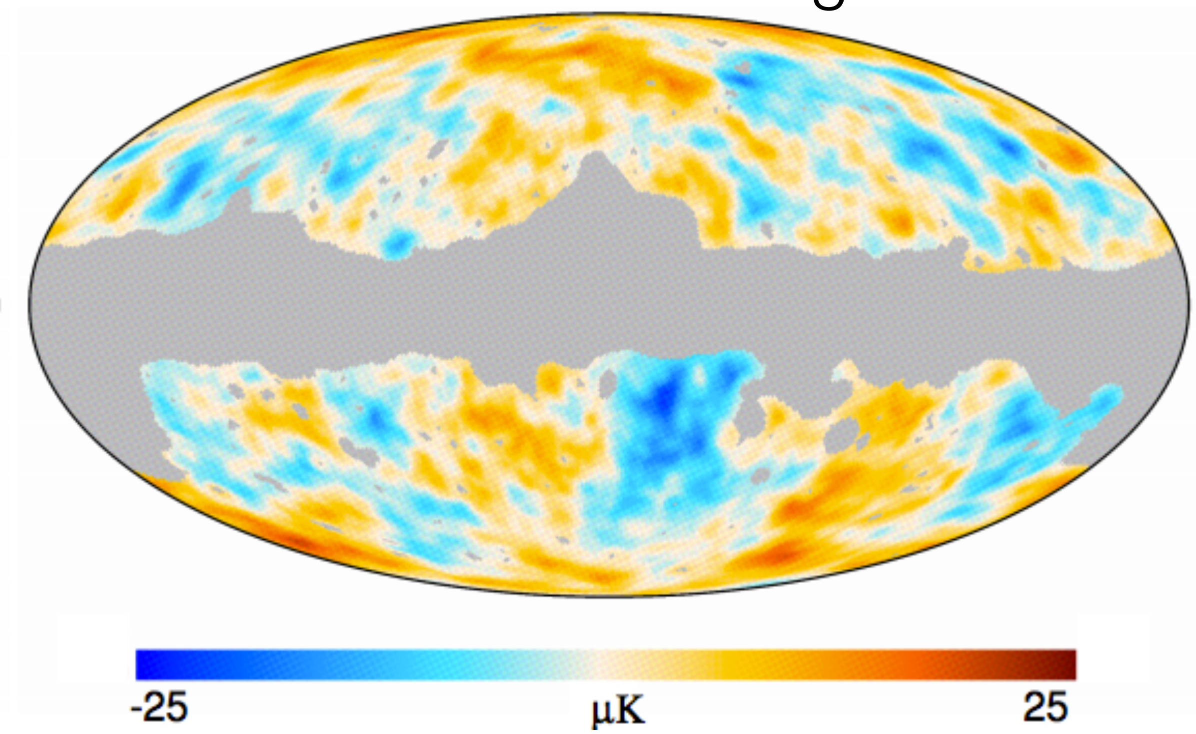
ISW signal $$\frac{\Delta T}{T} = 2\int_{\eta_\star}^{\eta_0} d\eta \frac{\partial \phi(\eta)}{\partial \eta}$$

subdominant contribution at large angular scales, detected via cross-correlation with LSS tracers

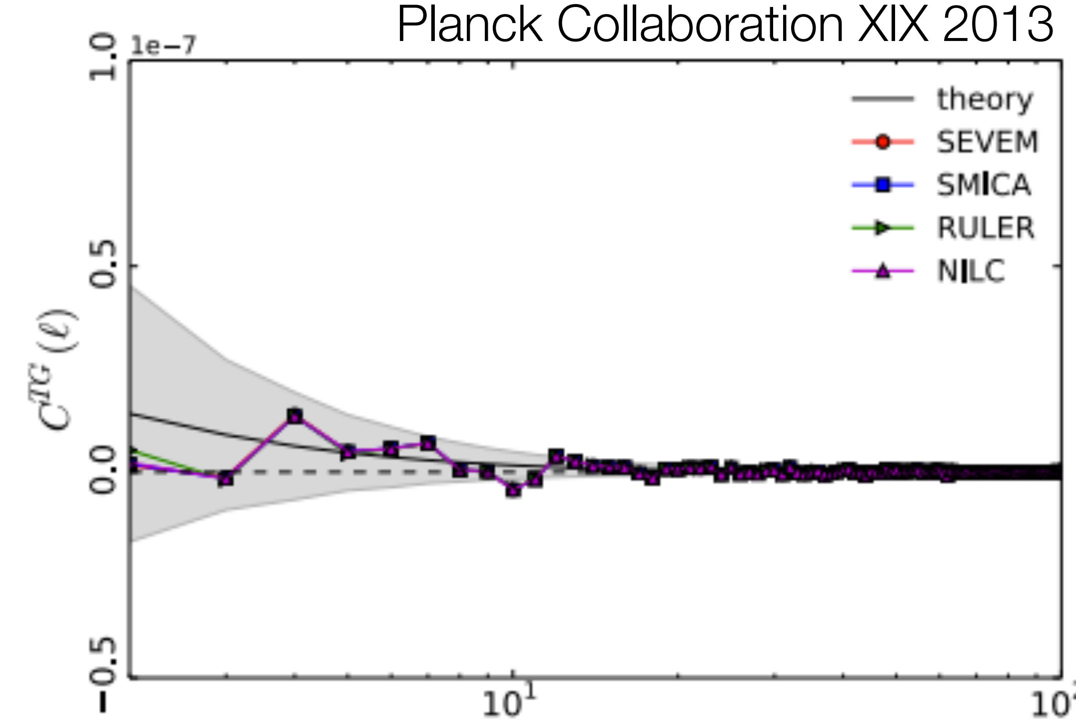
Planck+NVSS



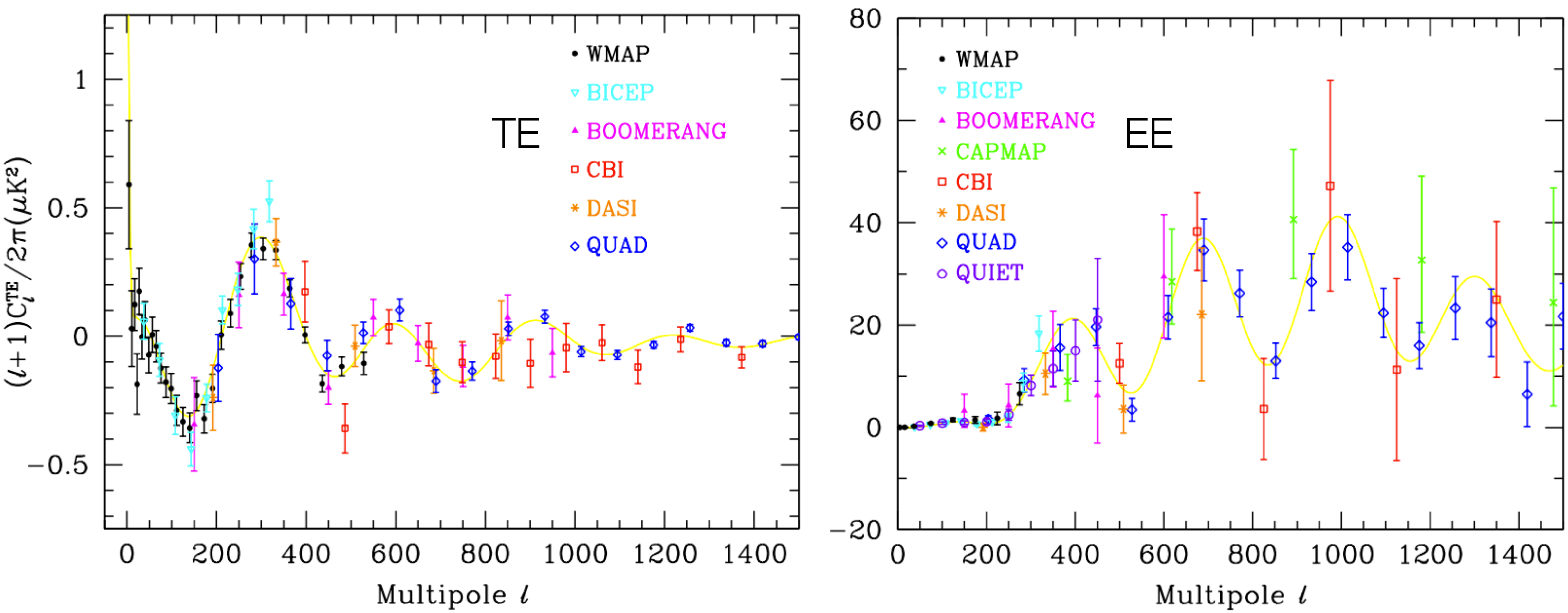
Planck+lensing



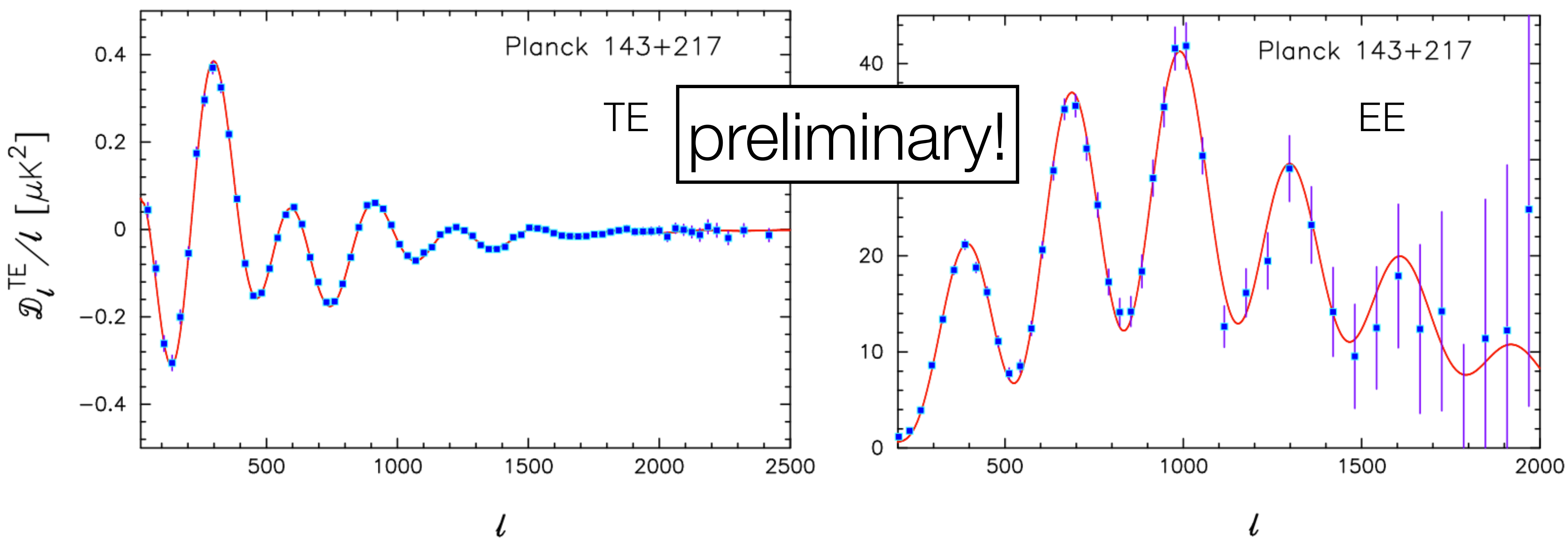
Planck Collaboration XIX 2013



~2-4σ detection

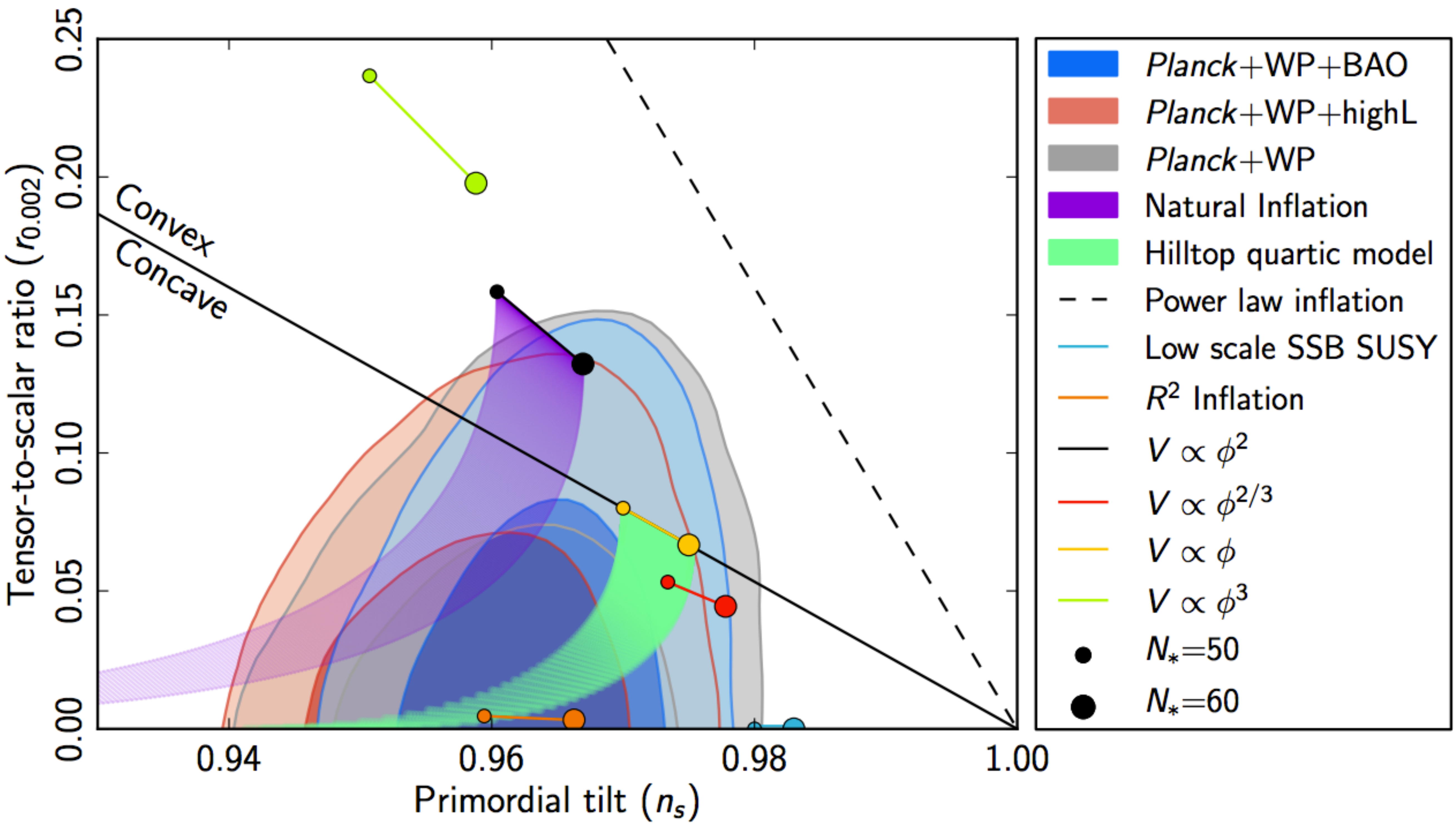


Particle Data Group 2013

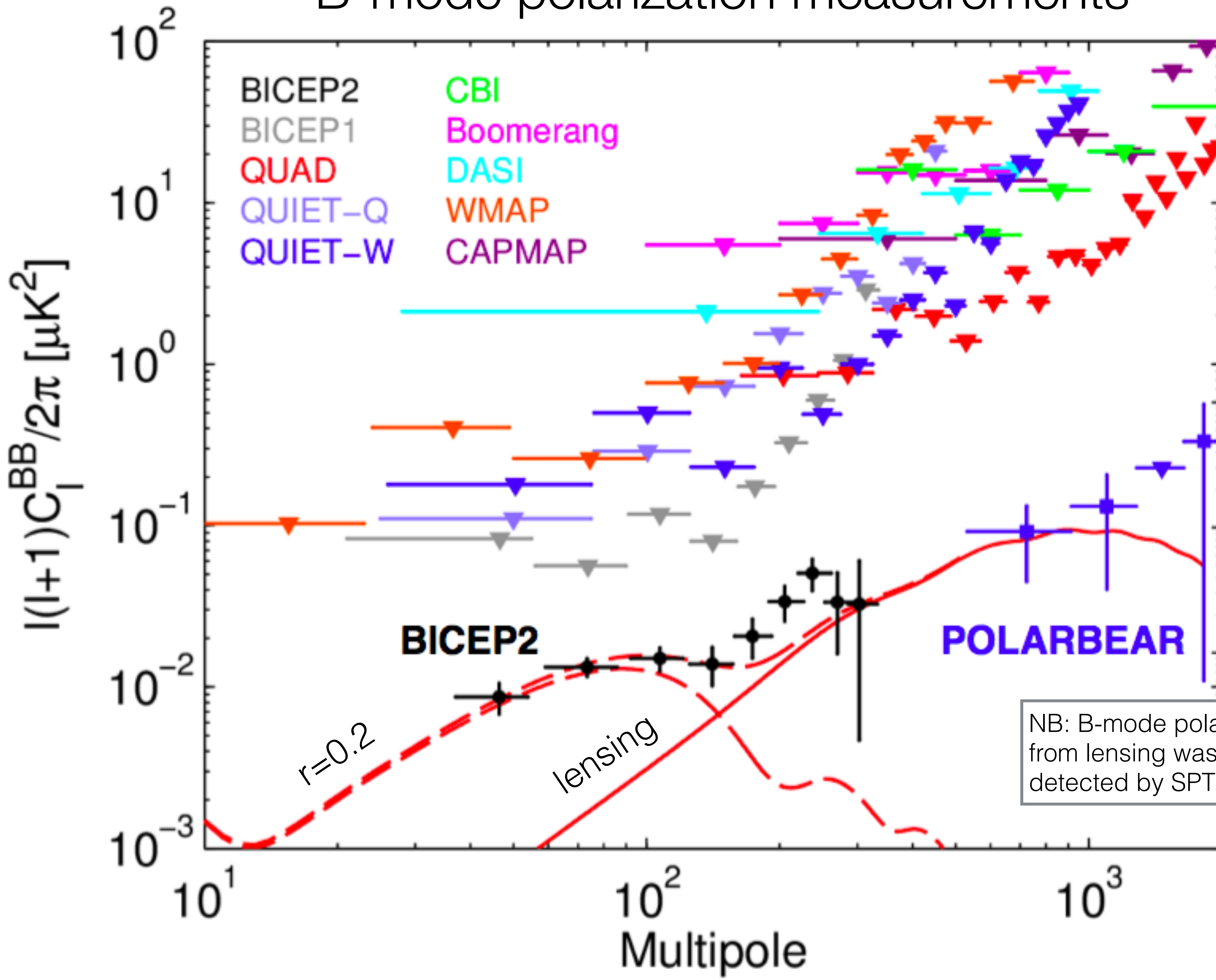


Planck Collaboration XVI 2013

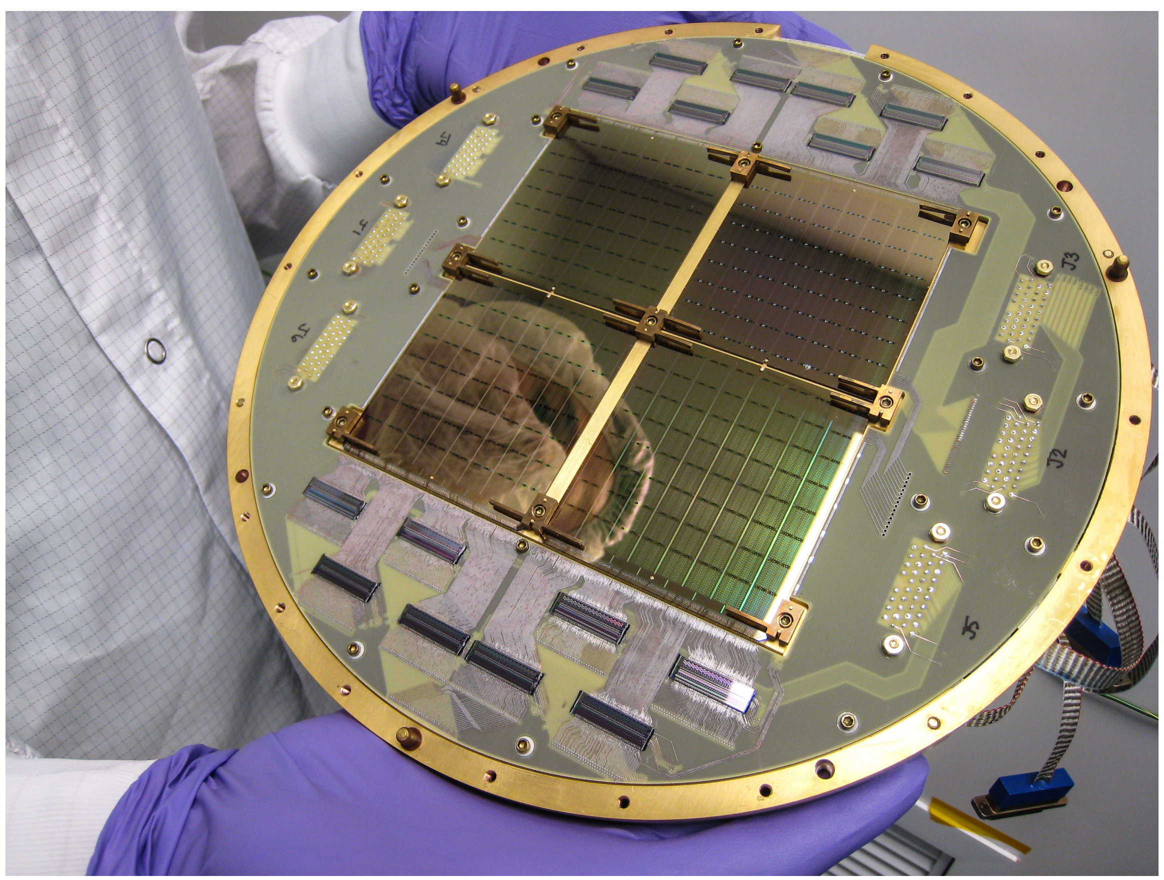
(pre-BICEP2) constraints on inflation



B-mode polarization measurements

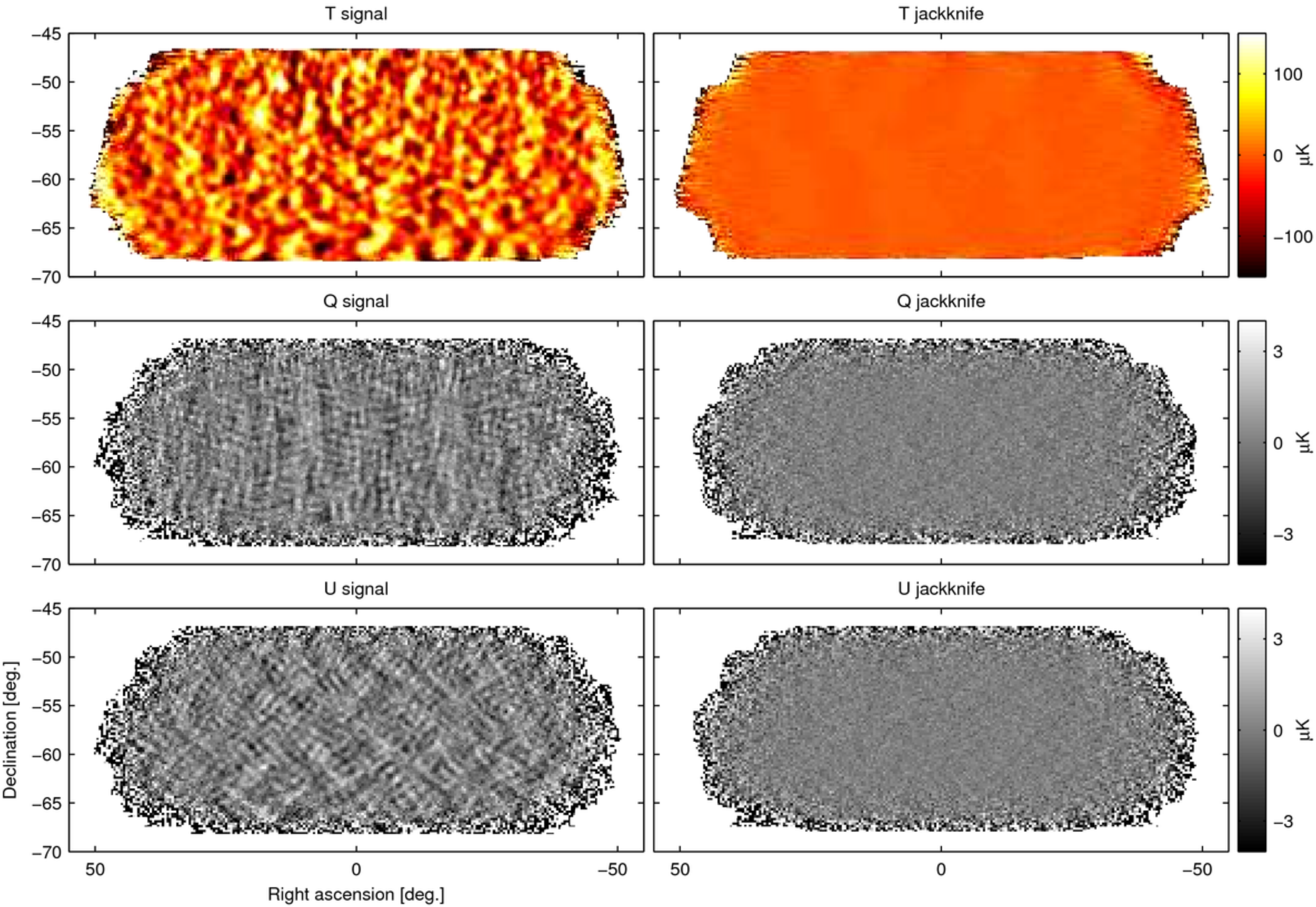


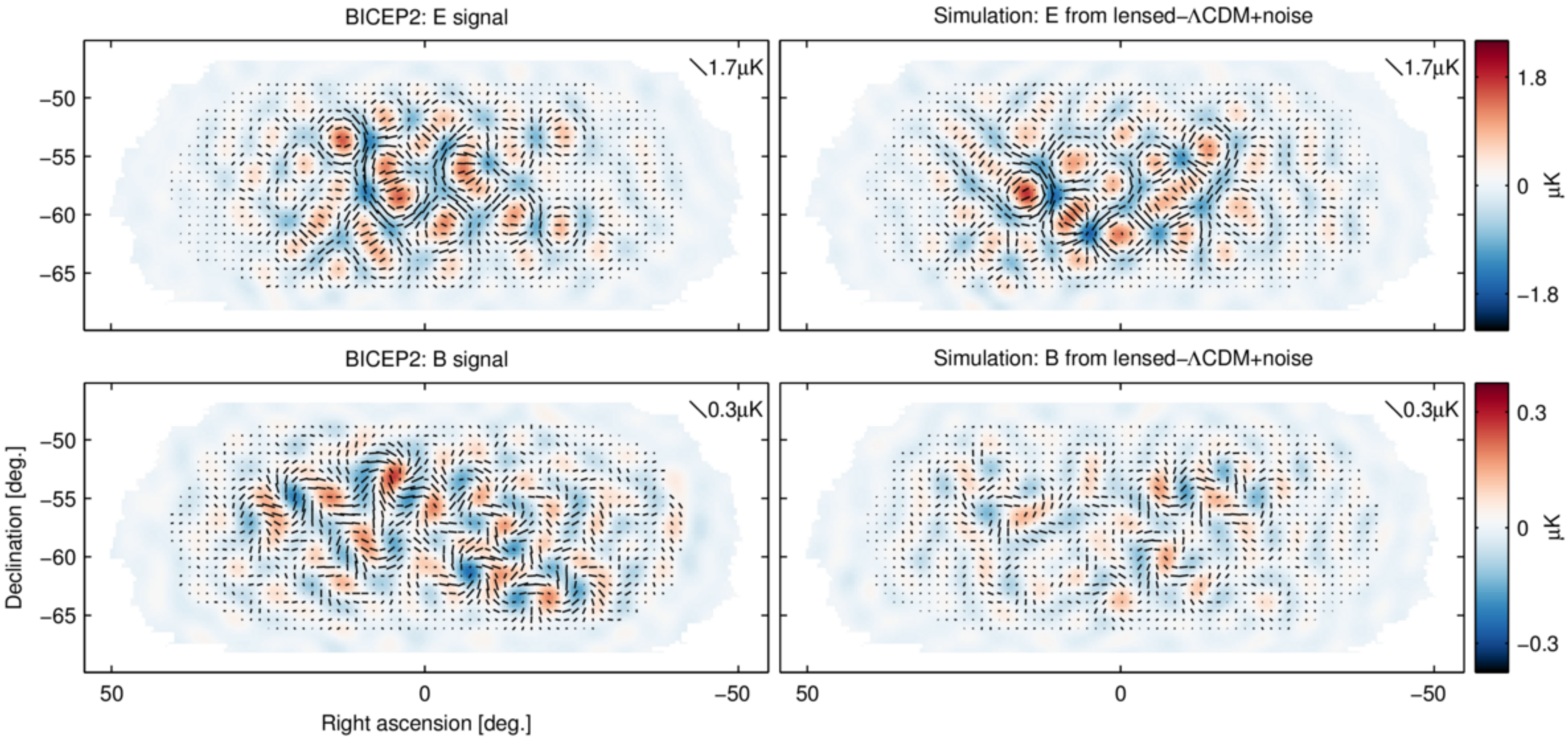
NB: B-mode polarization from lensing was first detected by SPT in 2013



BICEP2 specifications

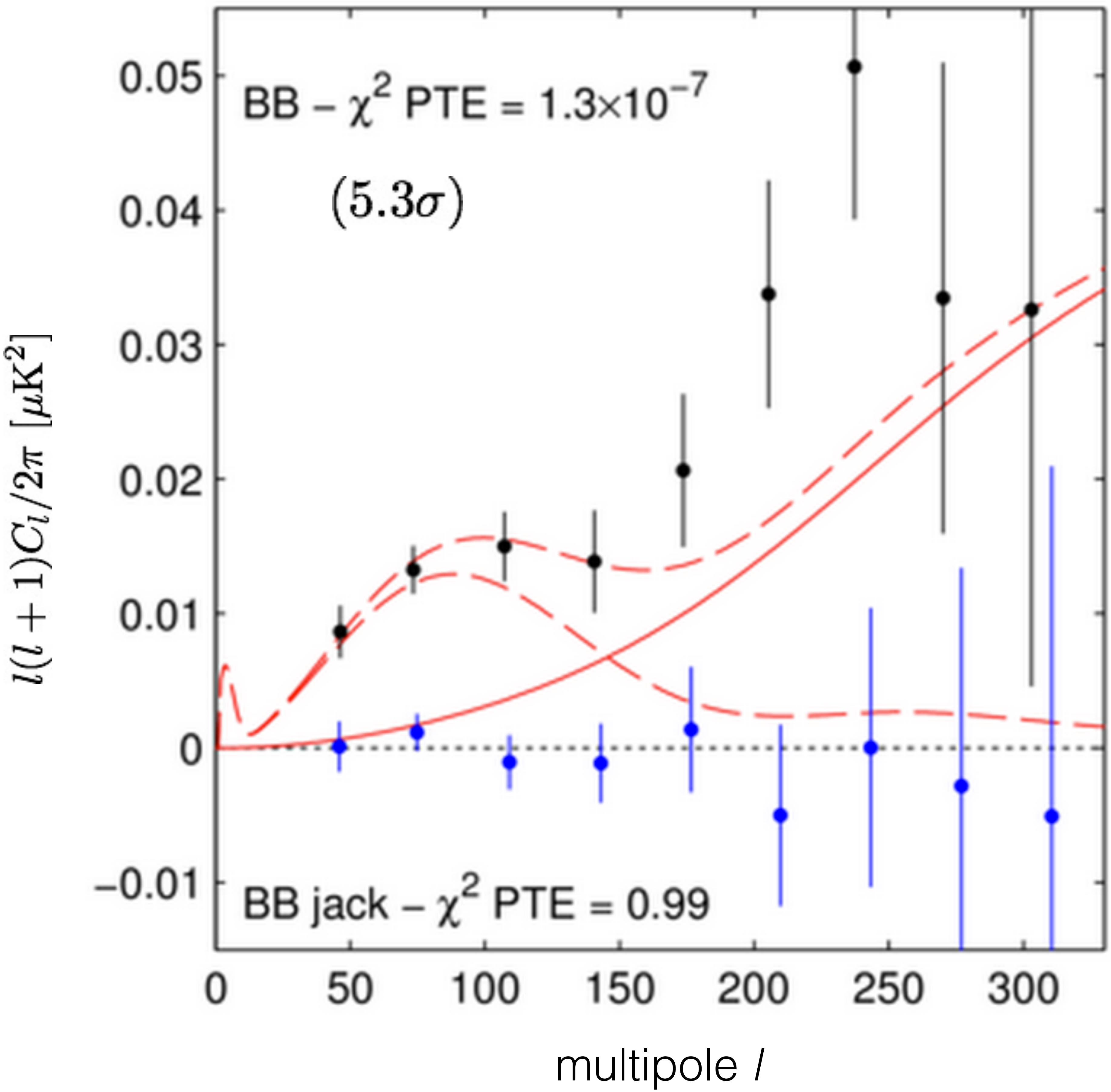
- 26 cm telescope cooled at 4K
- focal plane houses 512 superconducting 150 GHz bolometers cooled at 0.25 K (designed at JPL)
- 380 square degrees in the sky (with 87 nK per degree)

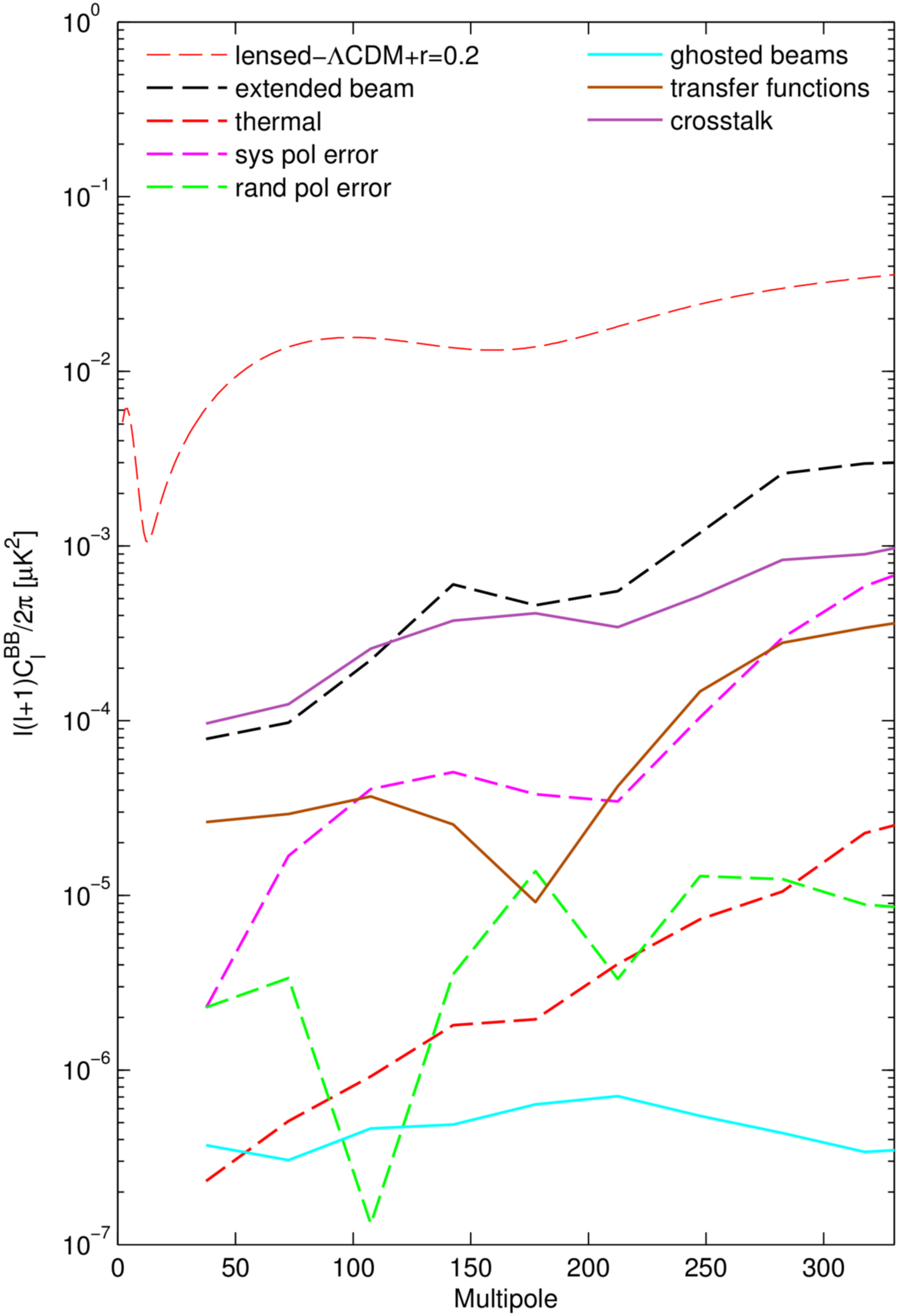

T signal
T jackknife
Q signal
Q jackknife
U signal
U jackknife
−45
−50
−55
−60
−65
−70
50
0
−50
Right ascension [deg.]
Declination [deg.]
100
0
−100
μK
3
0
−3
μK
3
0
−3
μK



no tensors in the simulations!

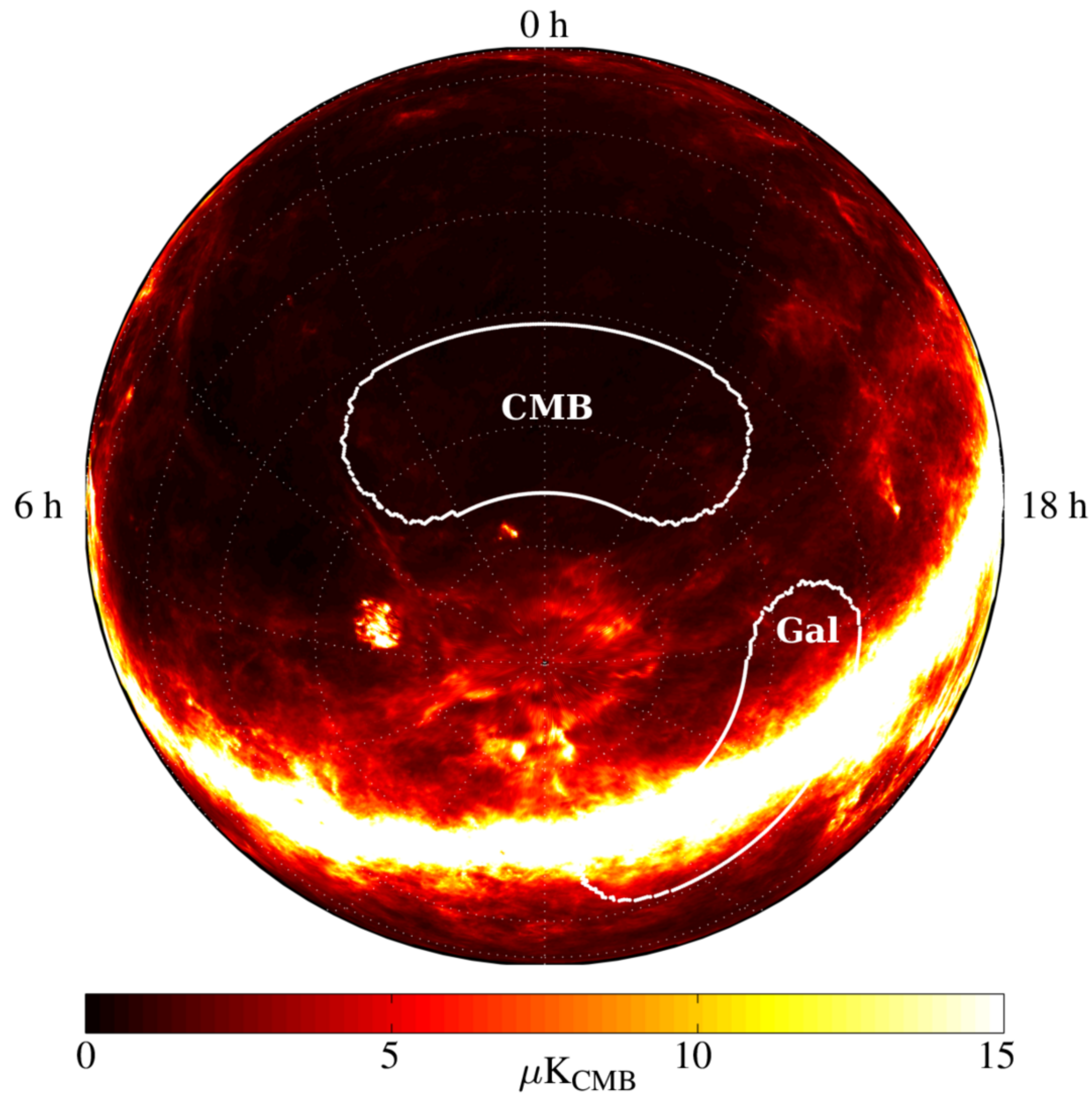
BICEP2 collaboration (2014)



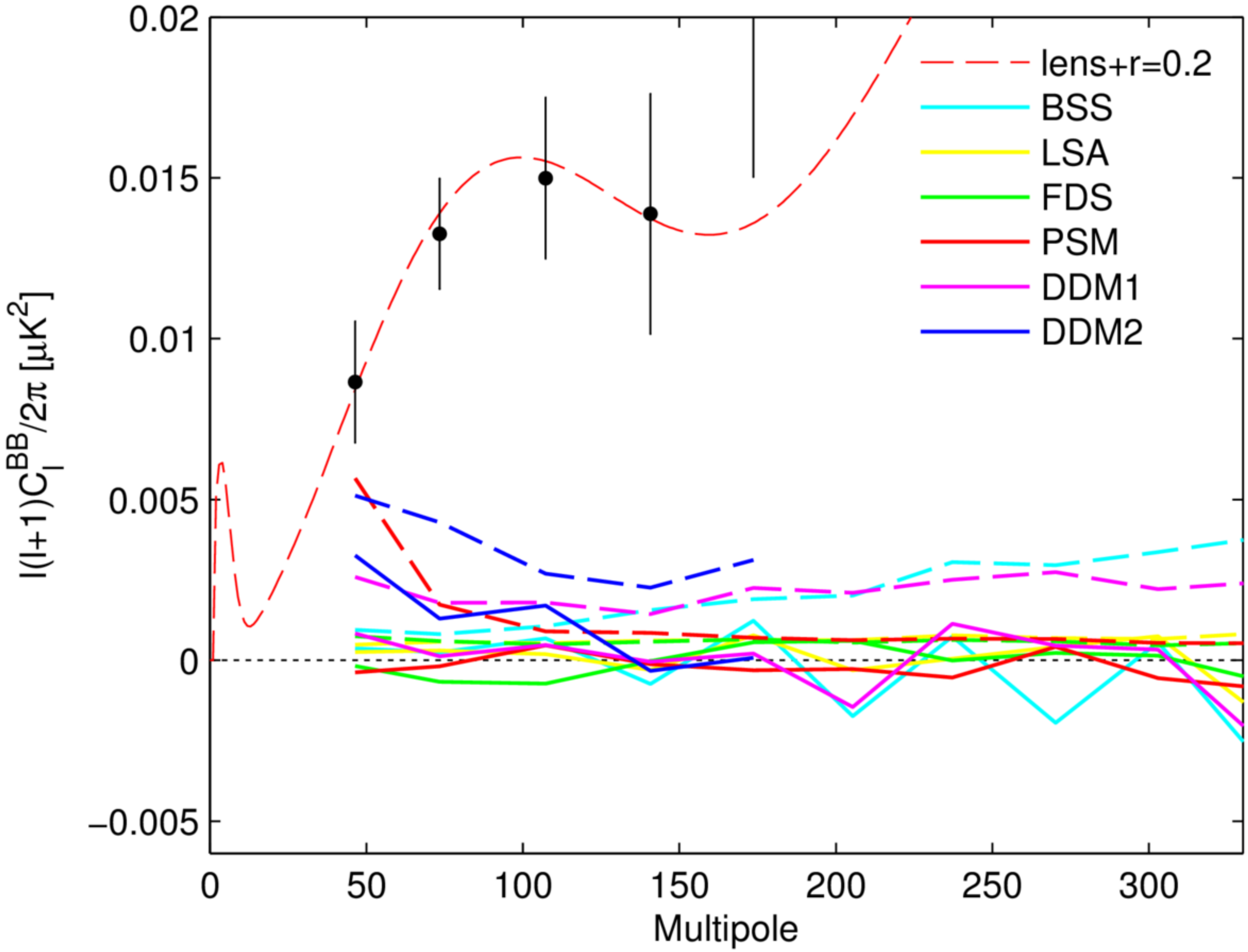


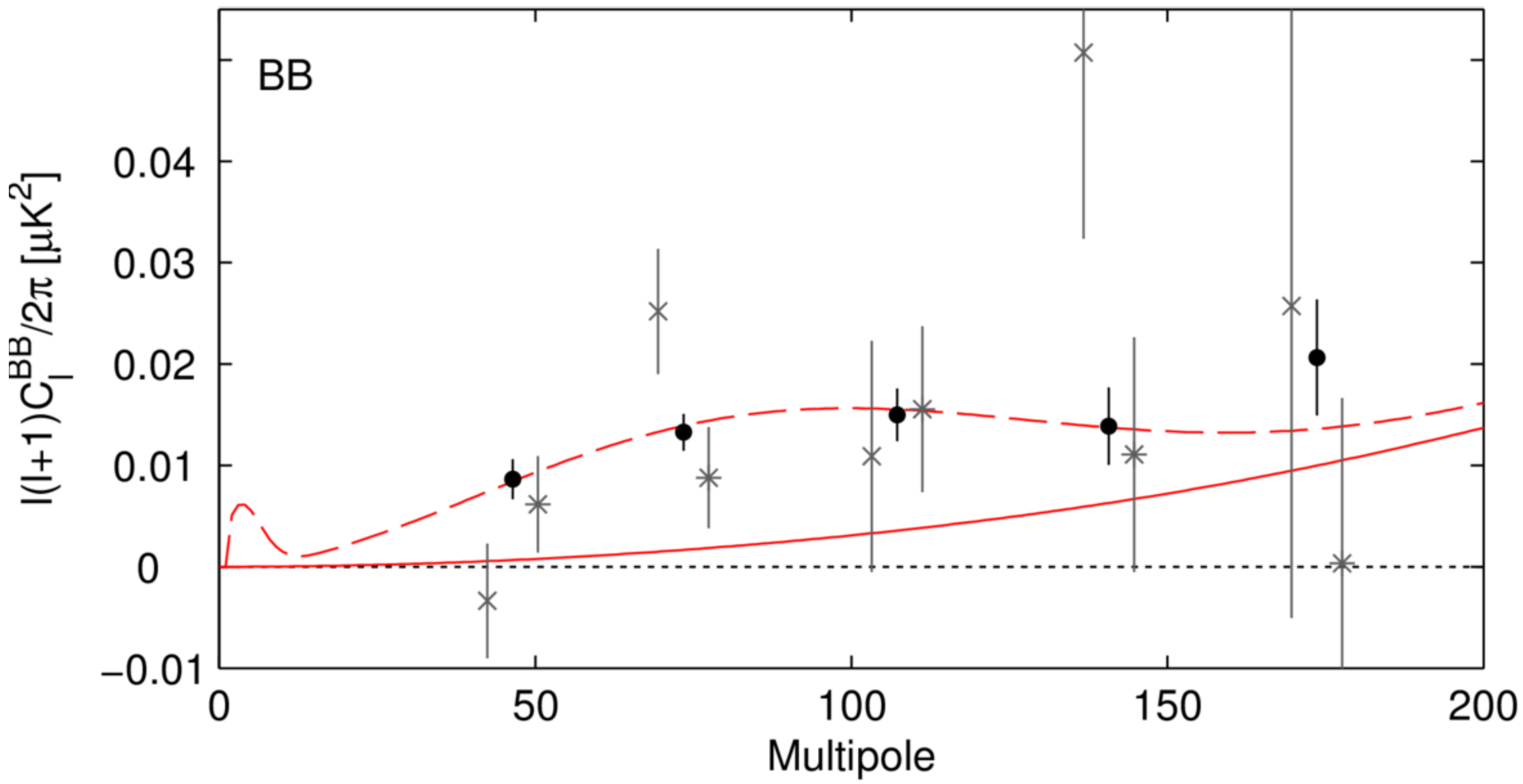
estimates for possible instrumental systematics polarized foregrounds are a source of concern

BICEP2 observes a clean region but at just one frequency (150 GHz, near the peak of CMB emission)

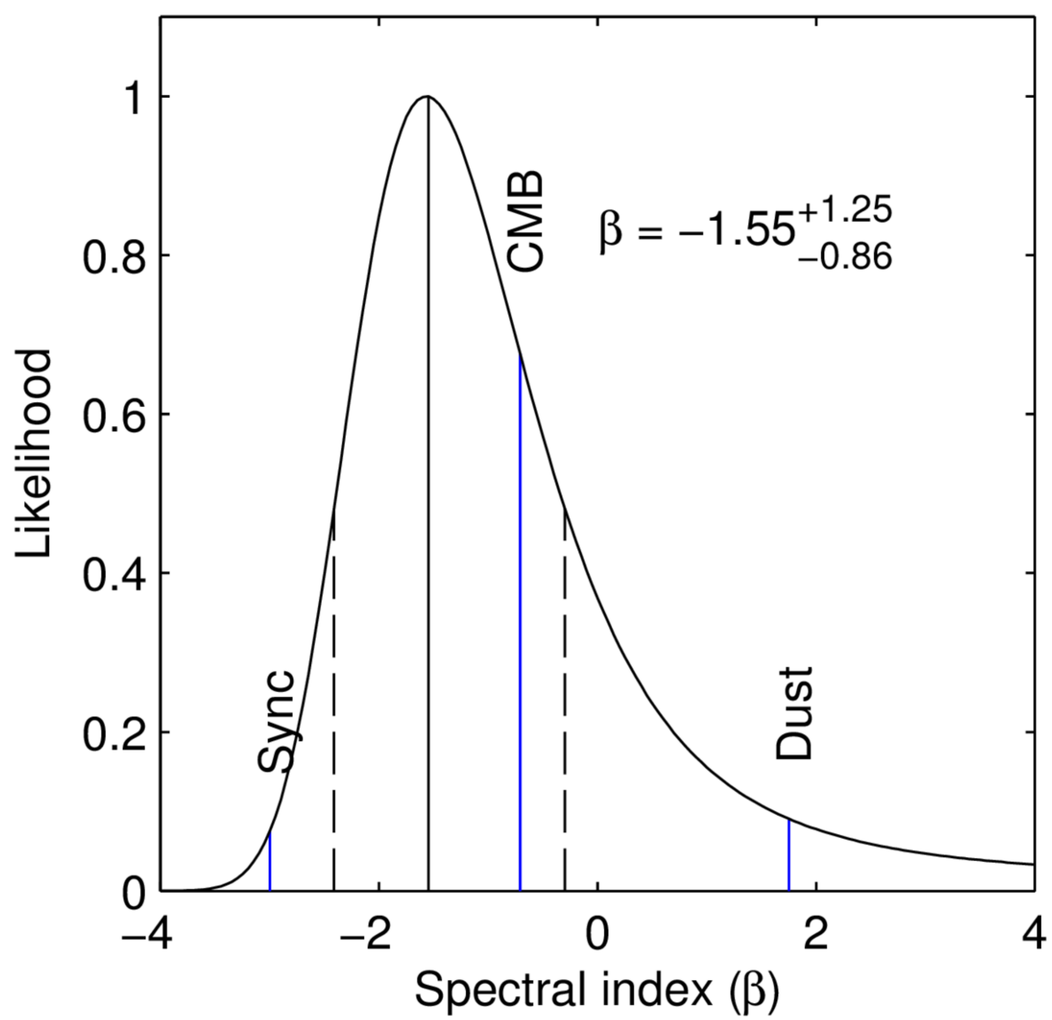


estimated foreground contamination



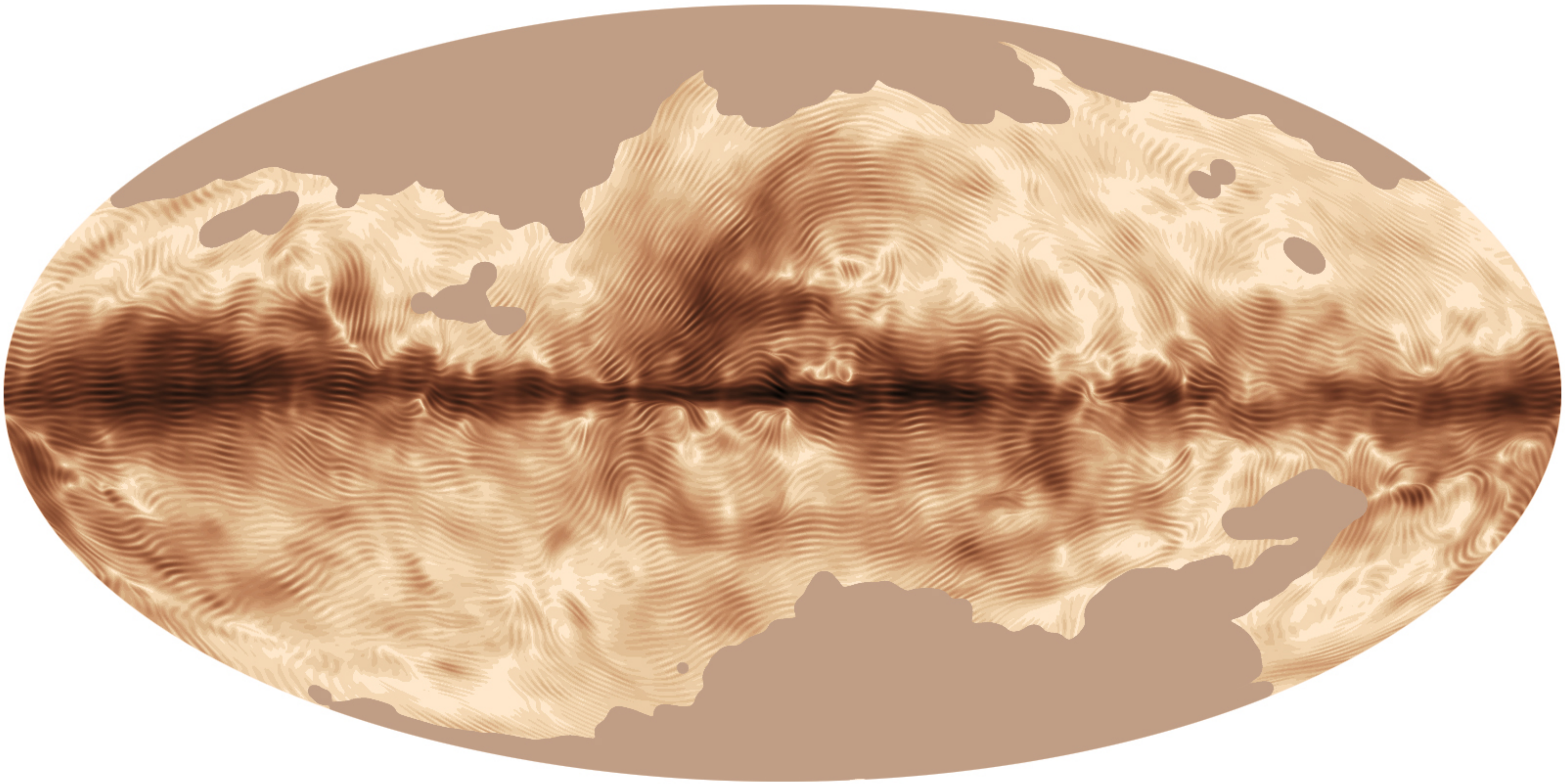


cross correlation
with BICEP1
(100 and 150 GHz)



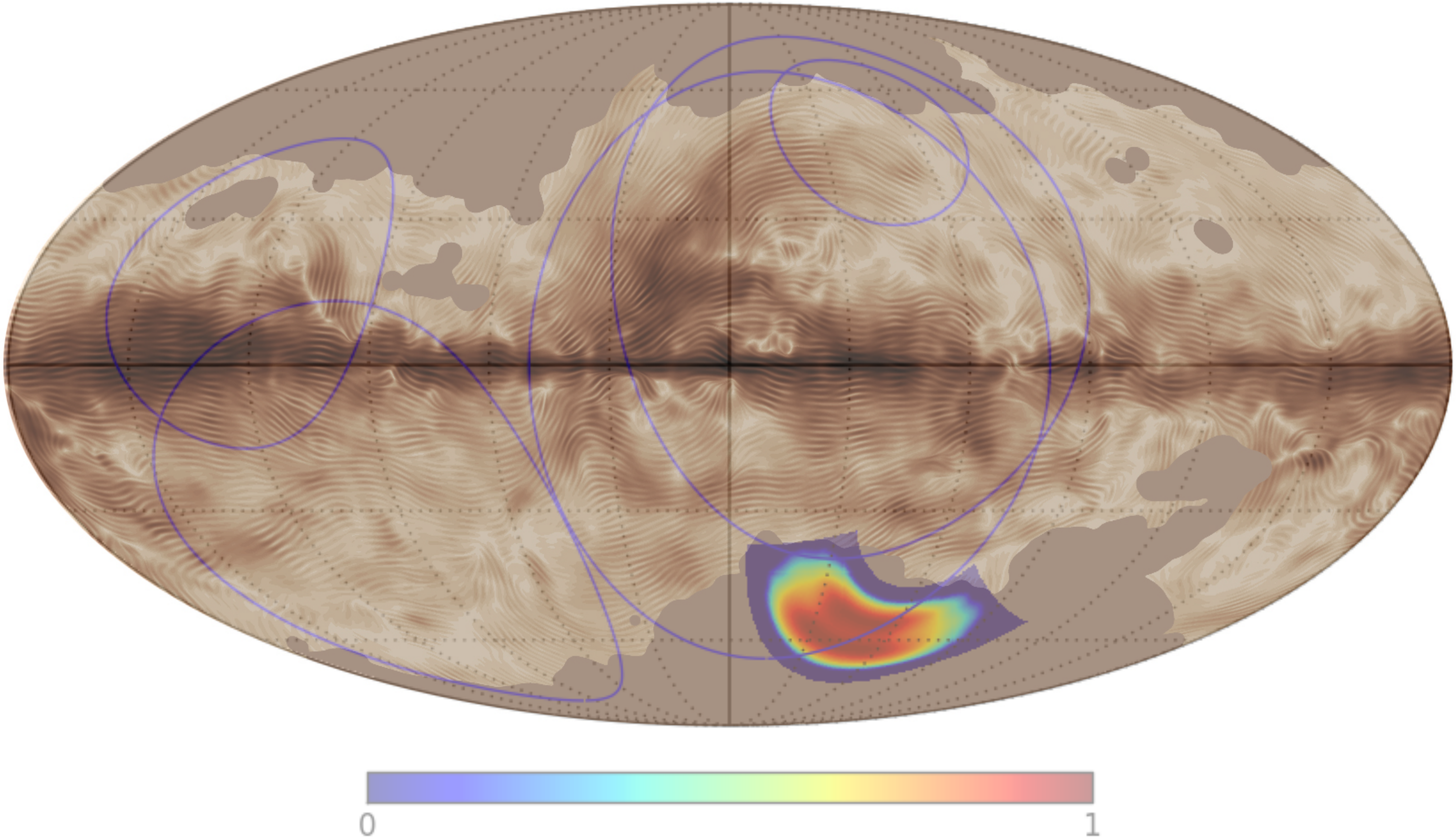
frequency dependence of
various signal components

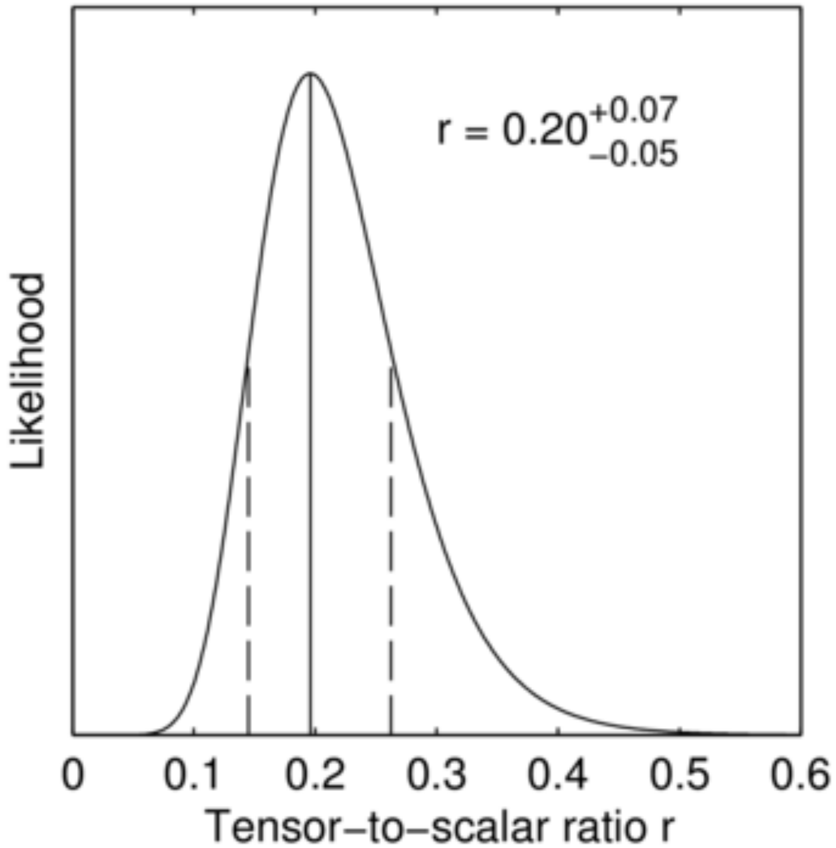
Planck just released a map of the galactic magnetic field estimated from polarized dust emission (through Faraday rotation) at 353GHz

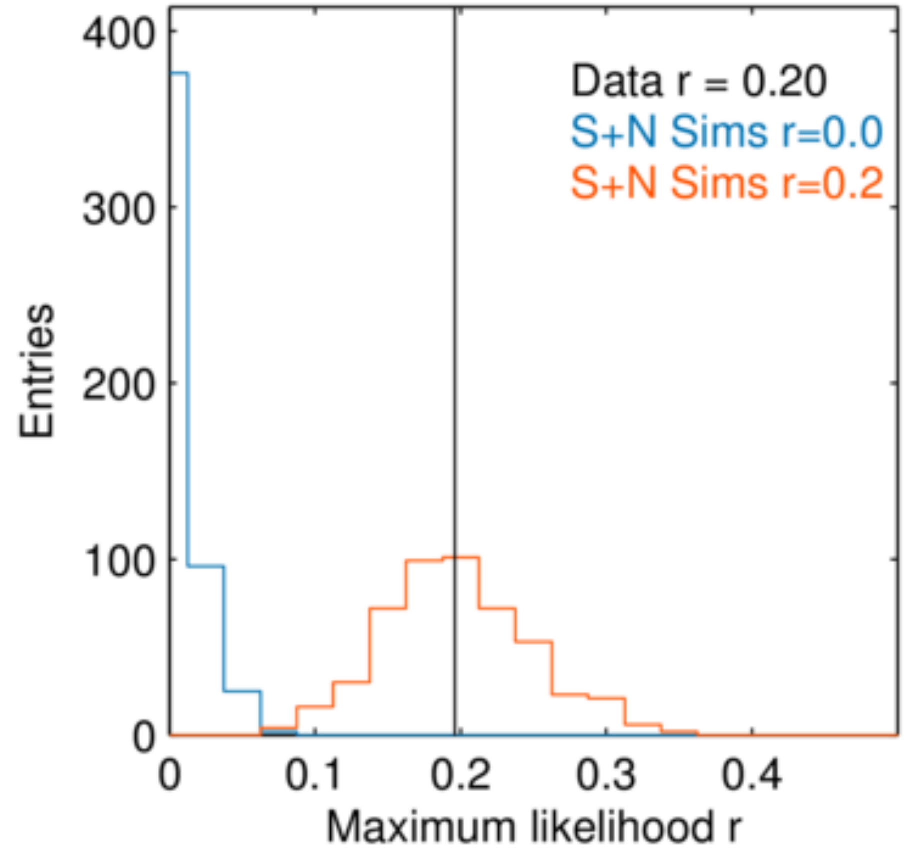


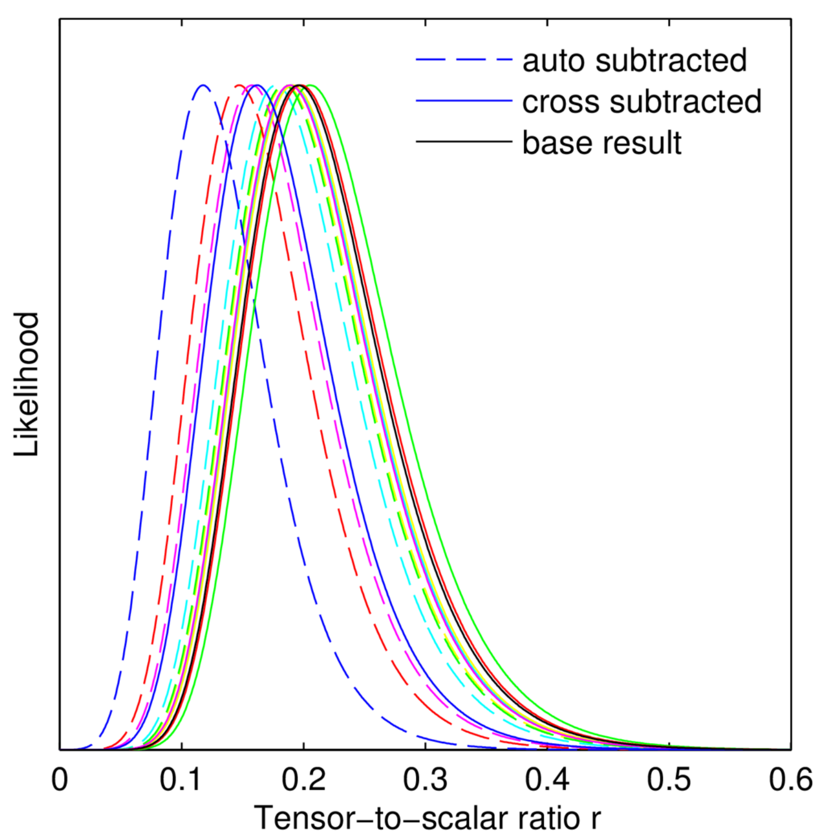
Planck intermediate results XIX (2014)

BICEP2 variance-weight map









r=0 ruled out at 7 sigma

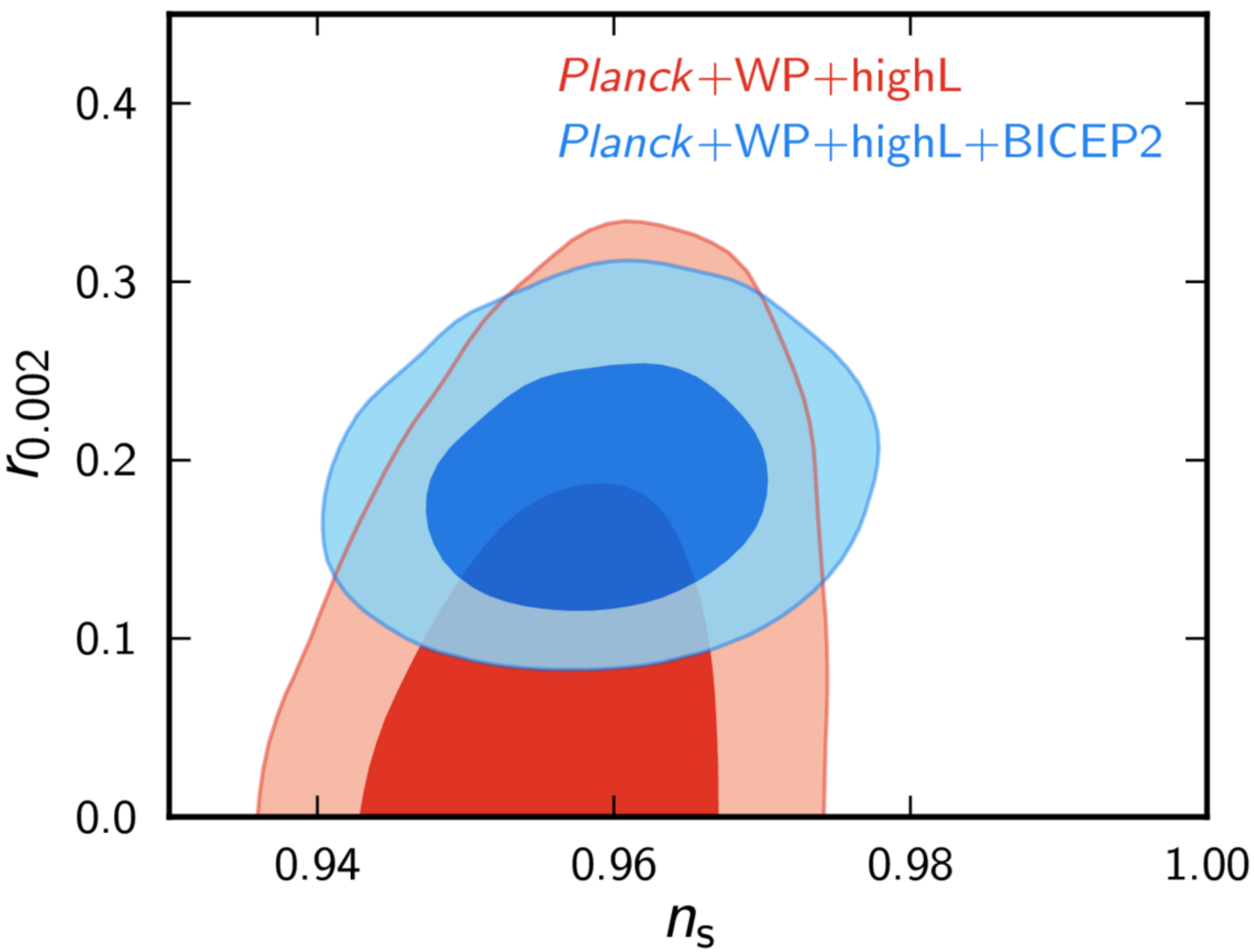
when including foreground projections

$\Rightarrow$ $r = 0.16^{+0.06}_{-0.05}$

(r=0 ruled out at 5.9 sigma)

until now, constraints on r were only *indirect*, i.e. they were derived from the (subdominant) tensor contribution to temperature fluctuations

they gave r<0.11, in tension with BICEP2 estimates, but:



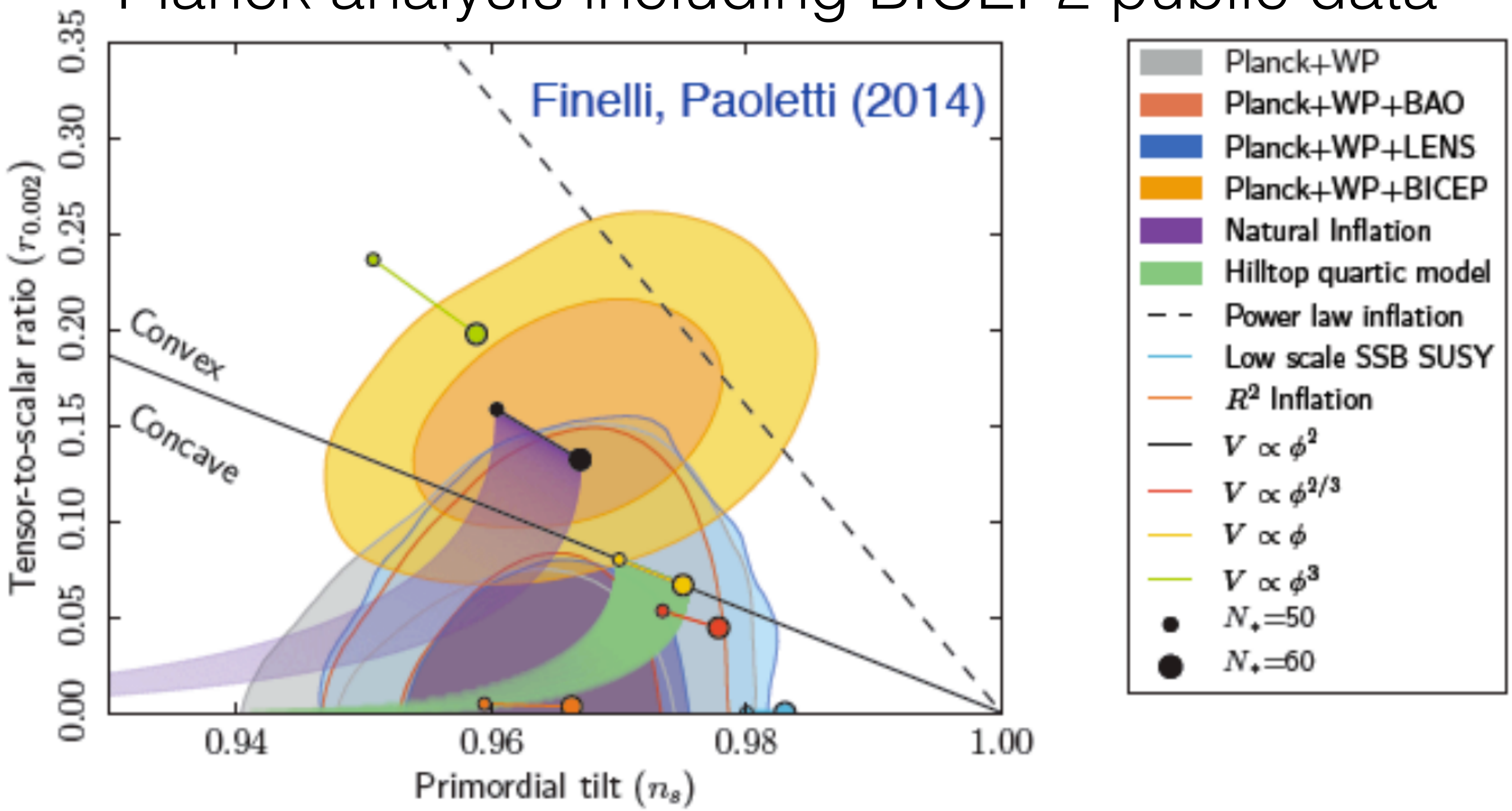
a simple solution: k dependence ("running") of the scalar spectral index:

$$\Delta_s^2(k) = A_s(k_\star)\left(\frac{k}{k_\star}\right)^{n_s(k_\star)-1+\frac{1}{2}\alpha_s(k_\star)\ln(k/k_\star)}$$

but large running not easy to obtain in simple inflationary models

other possibilities can be explored (scalar/tensor anti correlation, sterile neutrinos, etc)

Planck analysis including BICEP2 public data



$$V^{1/4} \simeq 2.25 \cdot 10^{16}\,\mathrm{GeV} \left(\frac{r}{0.2}\right)^{1/4}$$

- if BICEP2 results are confirmed, low energy small field inflation is ruled out
- support for large field, e.g. chaotic inflation with massive scalar potential

(e.g., simple Higgs inflation, which predicts r≈0.0036, is ruled out - Cook et al, 2014) if BICEP2 results are confirmed:

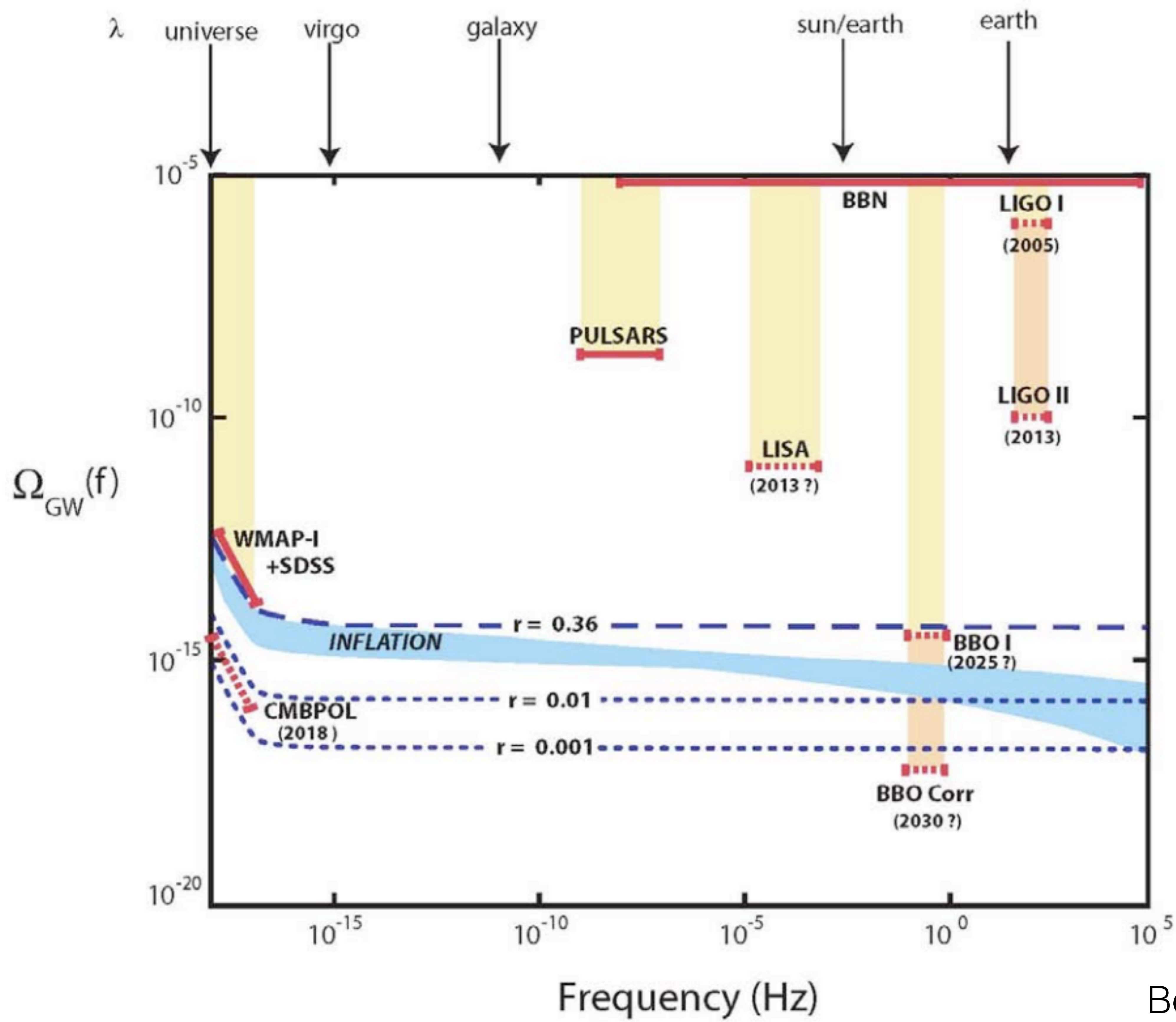
- decisive support for inflation (no serious alternative model - e.g Steinhardt & Turok “ekpyrotic” model - stands up)
- direct measurement of inflation energy scale (~10^{16} GeV)
- many specific inflationary potentials are ruled out
- consequences for fundamental physics (inflaton connection to standard model, hints on quantization of gravity, support for chaotic eternal inflation (+ string theory landscape?), etc)

(near) future prospects:

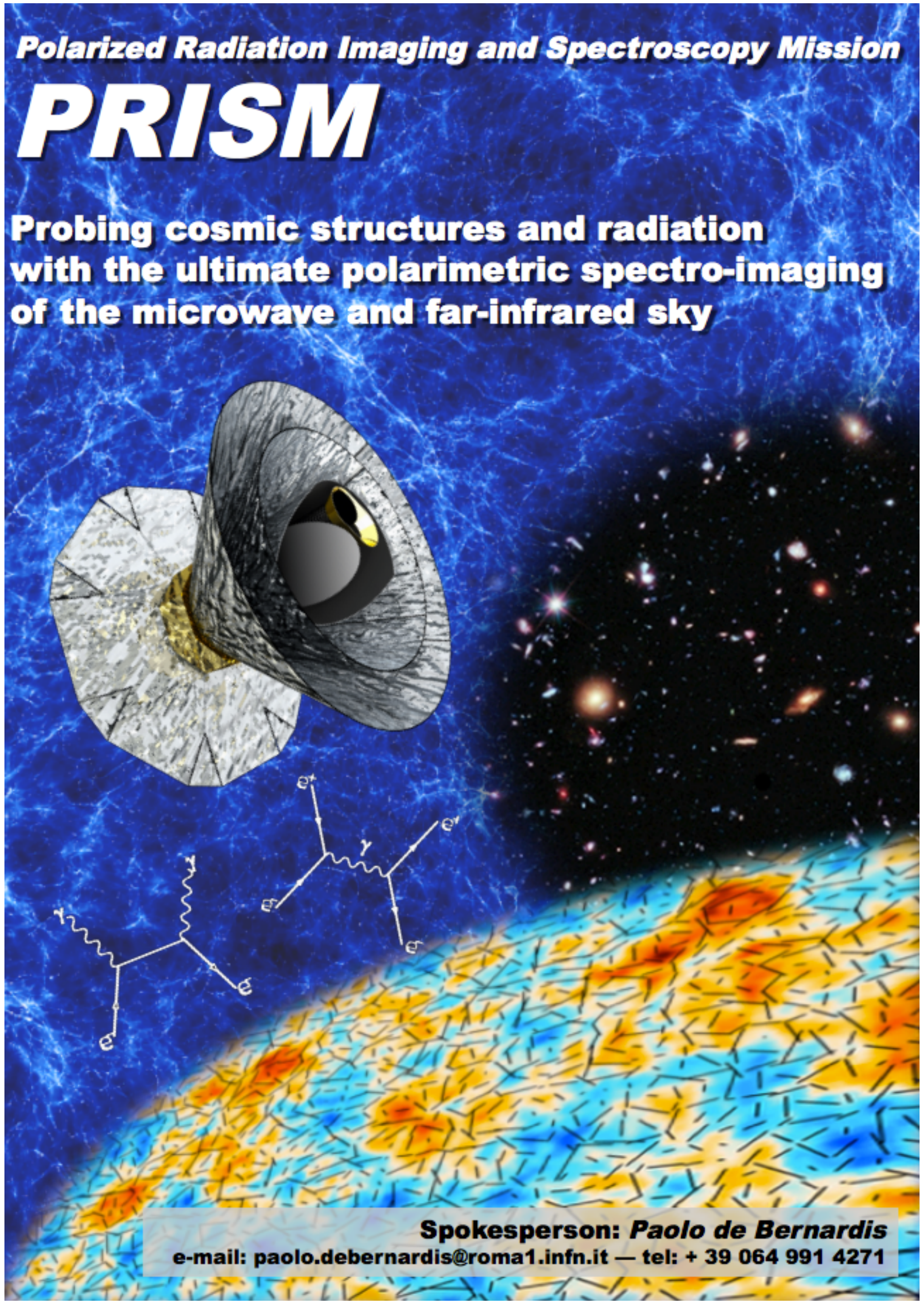
many CMB experiments underway with B-modes capabilities
(ACT, KECK, CLASS, EBEX, PIPER, PIXIE, POLARBEAR, SPTpol, SPIDER, LSPE, …)

Planck polarization results should be released by the end of this year

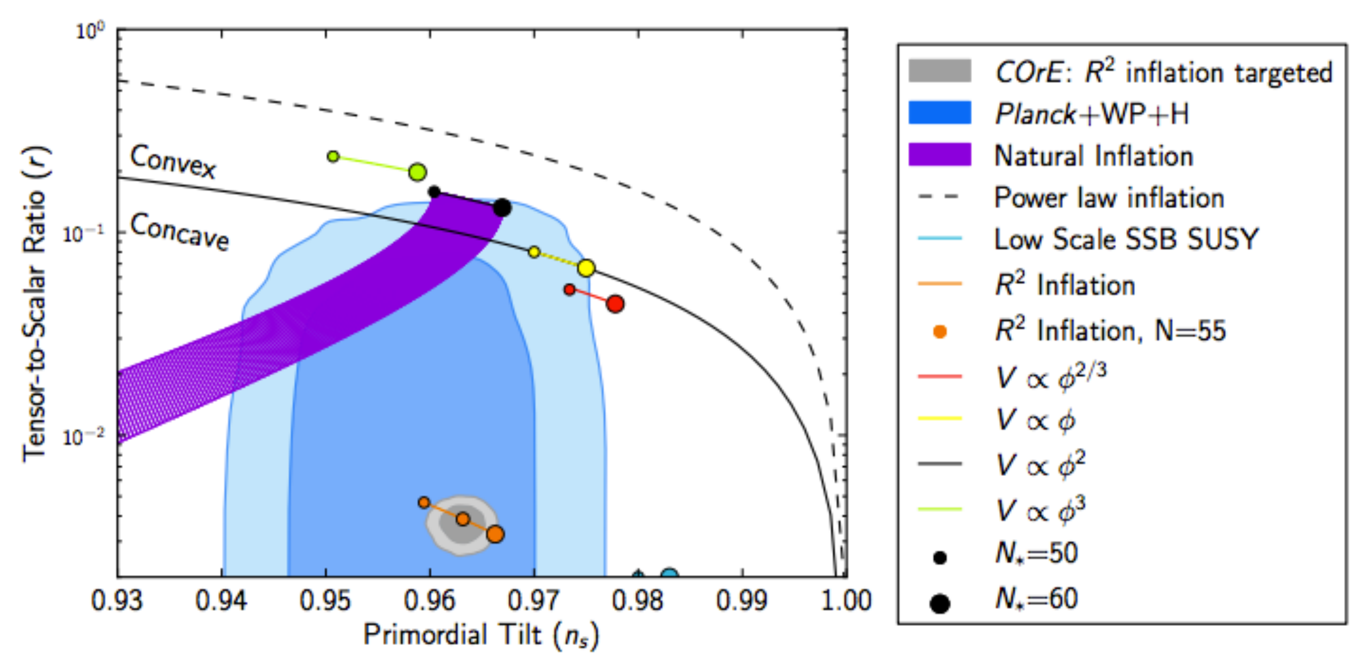
(far) future: direct detection



Bock et al 2006



opportunity for ESA M4
satellite mission



summing up:

- we have exquisitely precise measurements of CMB temperature anisotropies up (and beyond) the damping scale
- we have started to collect high-quality data on the polarized component as well
- a basic ΛCDM model with 6 free parameters is an excellent fit to all existing cosmological data
- the generic predictions of inflation (flatness of the universe, adiabaticity and gaussianity of primordial fluctuations) have passed the test
- mild tensions with other astrophysical data need further investigations
- anomalies in the statistics of the CMB, though of low significance, are suggestive and need to be understood
- the possible detection of primordial gravitational waves from BICEP2 would be a smoking gun for inflation but needs independent confirmation