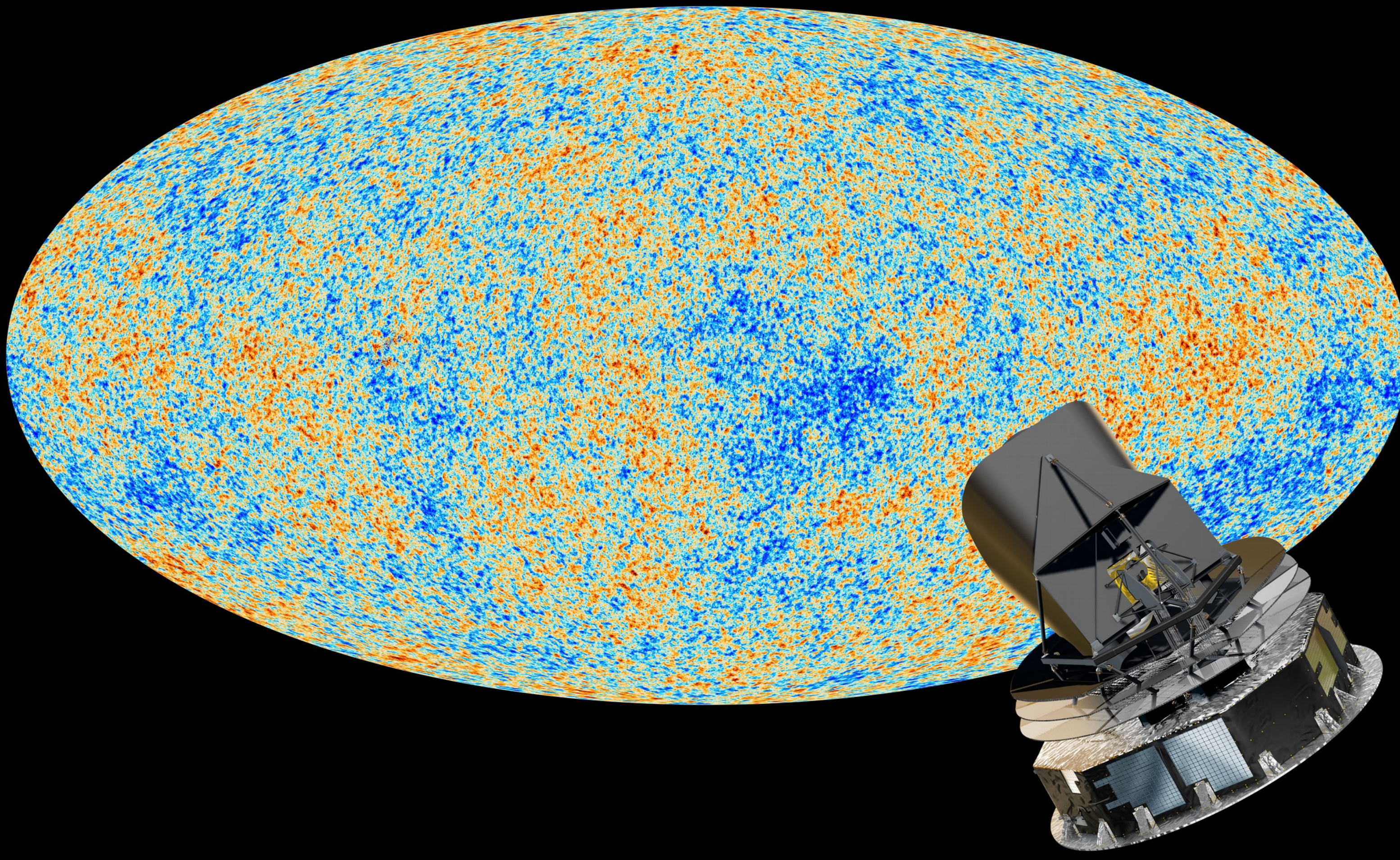
The Planck view of ΛCDM

George Efstathiou KICC

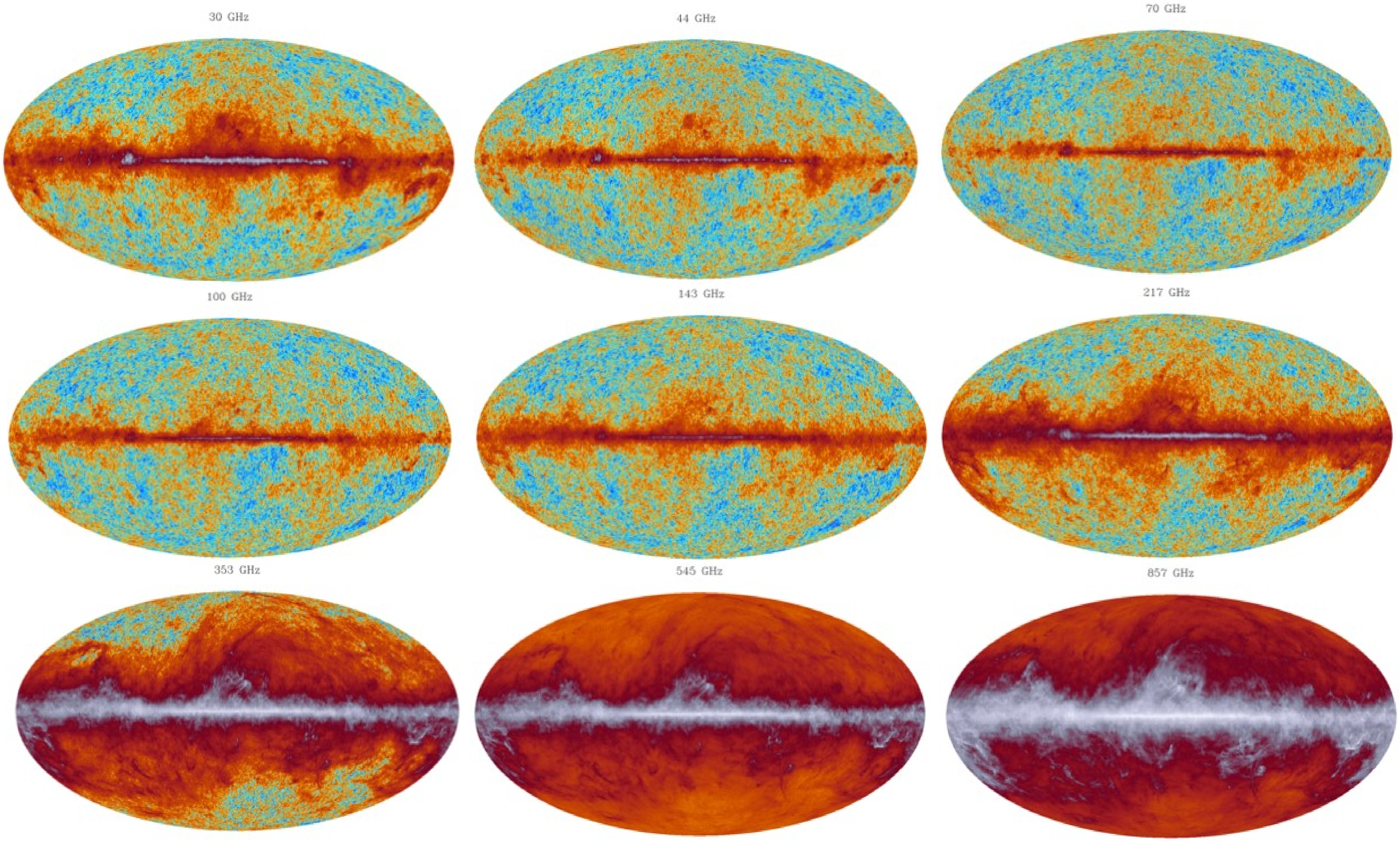


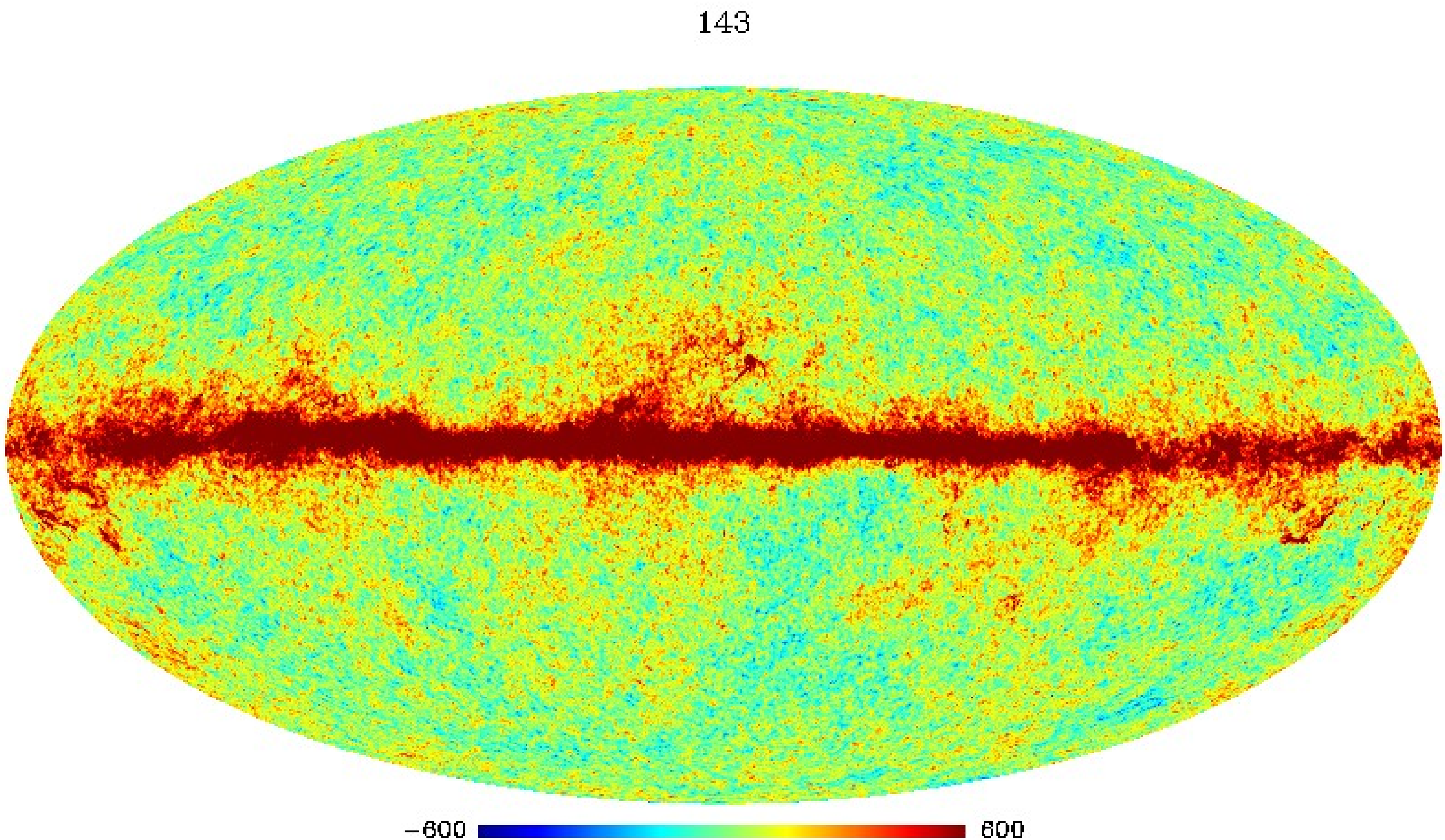

ΛCDM?
That’s Fake News!!!
23 hours ago

The Assertions:

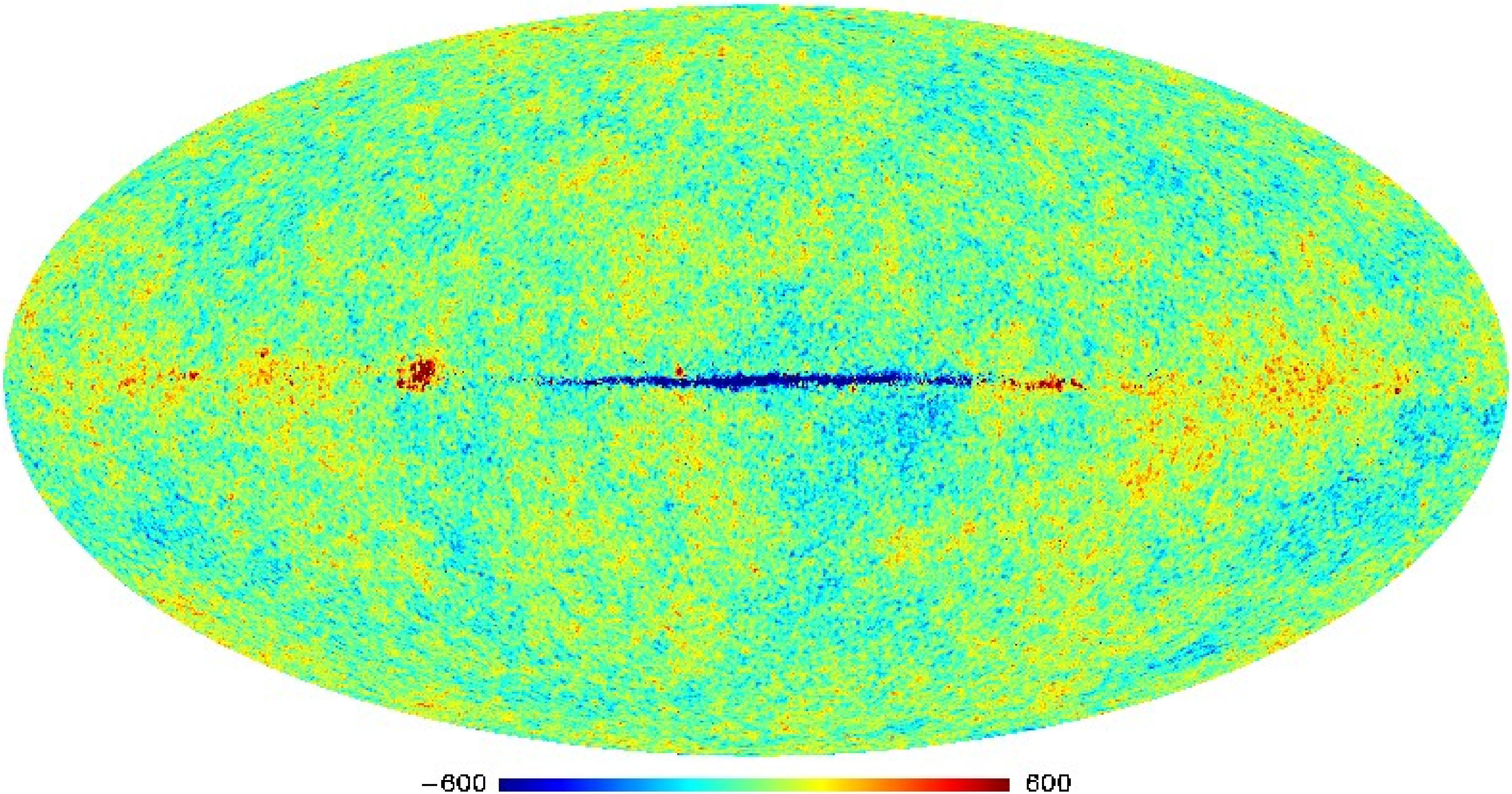
- There are no internal inconsistencies in the Planck data
- Planck polarization tells the same story as Planck temperature
- Temperature and polarization restricted to l < 800 gives same ΛCDM parameters as full Planck.
- If your experiment (CMB, LSS, H_0 ………) disagrees with Planck, then either you are wrong, or there is new physics beyond ΛCDM.

PLANCK FREQUENCYMAPS

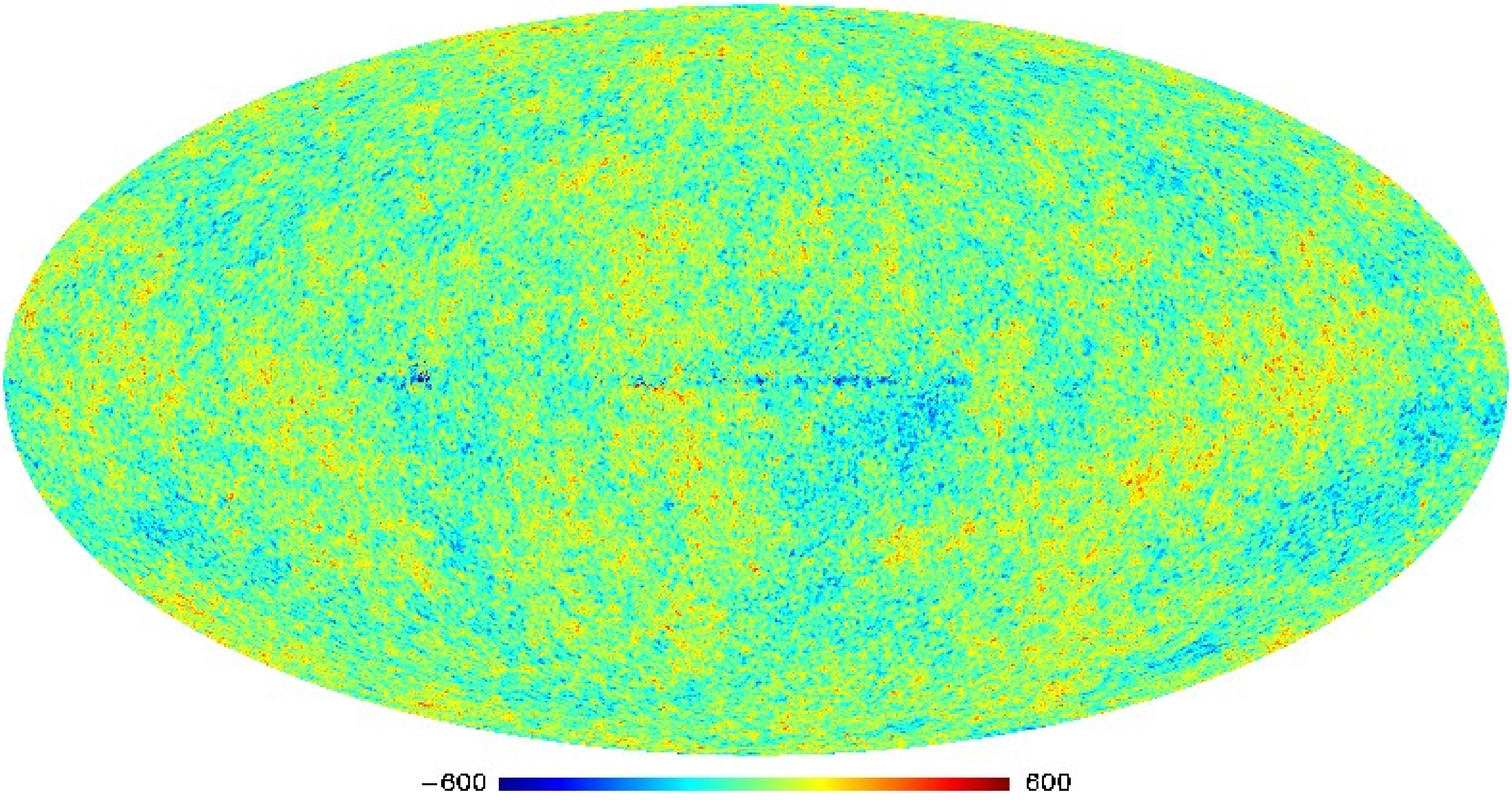


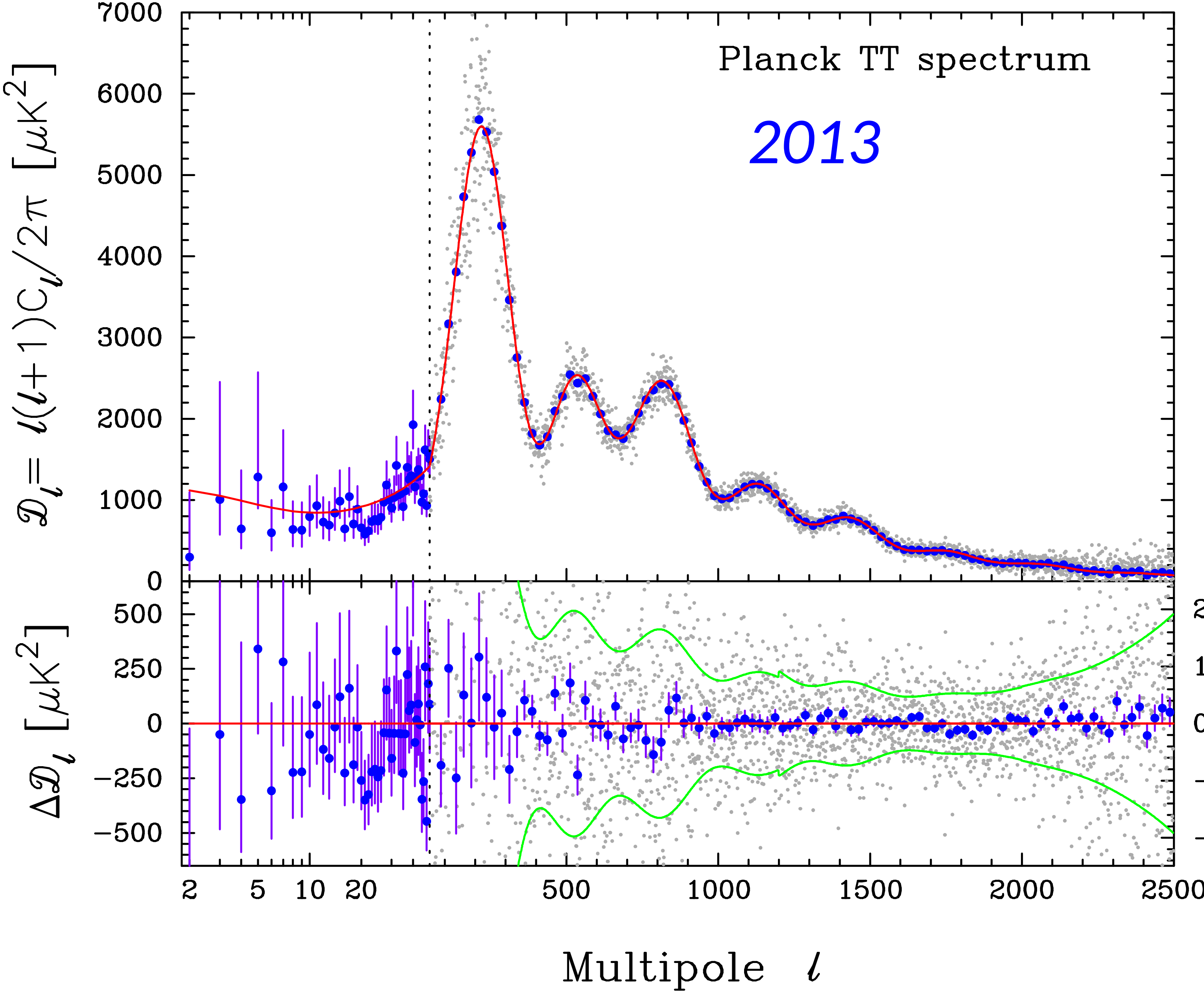

143
−600
600

143 cleaned with 545

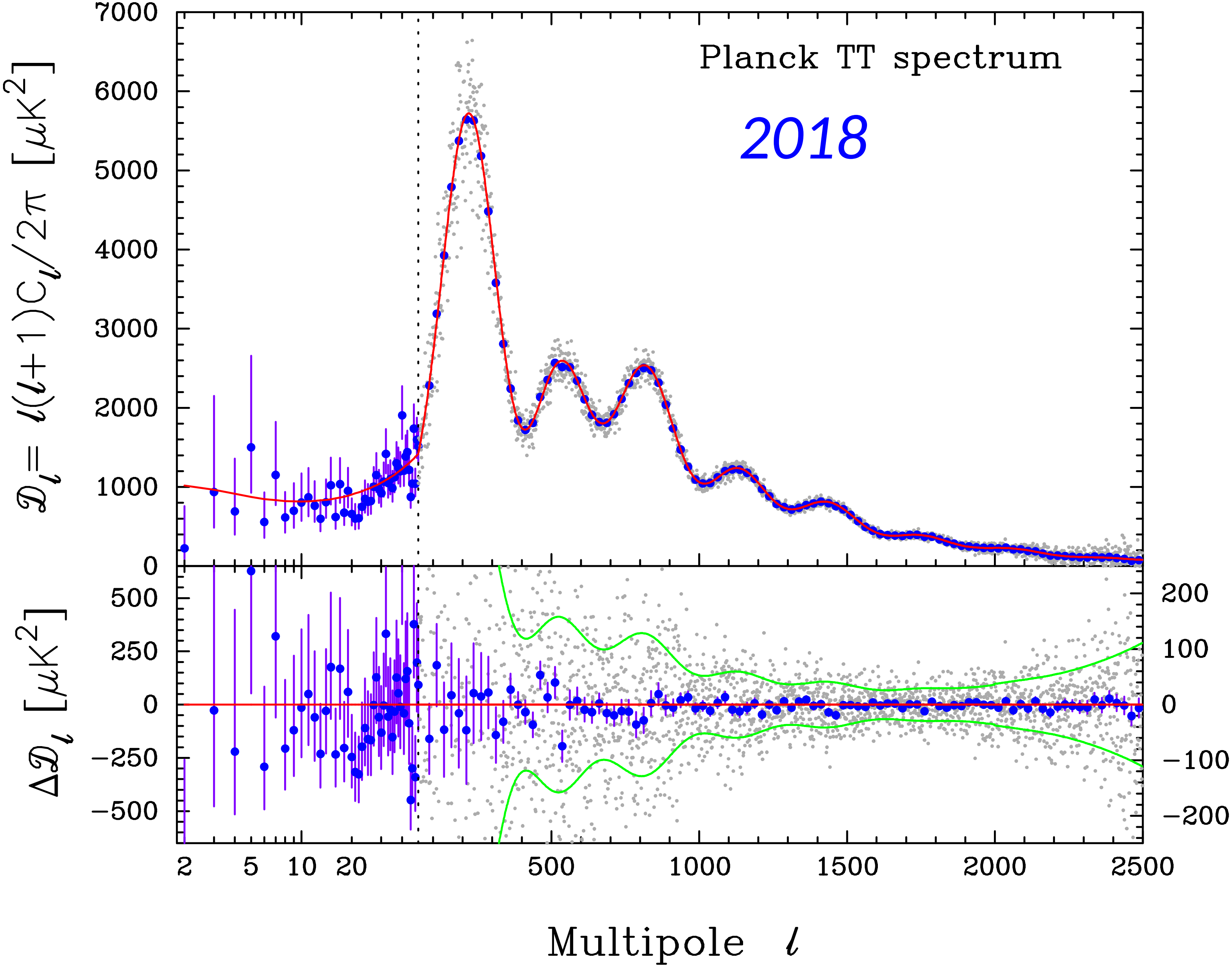


SMICA

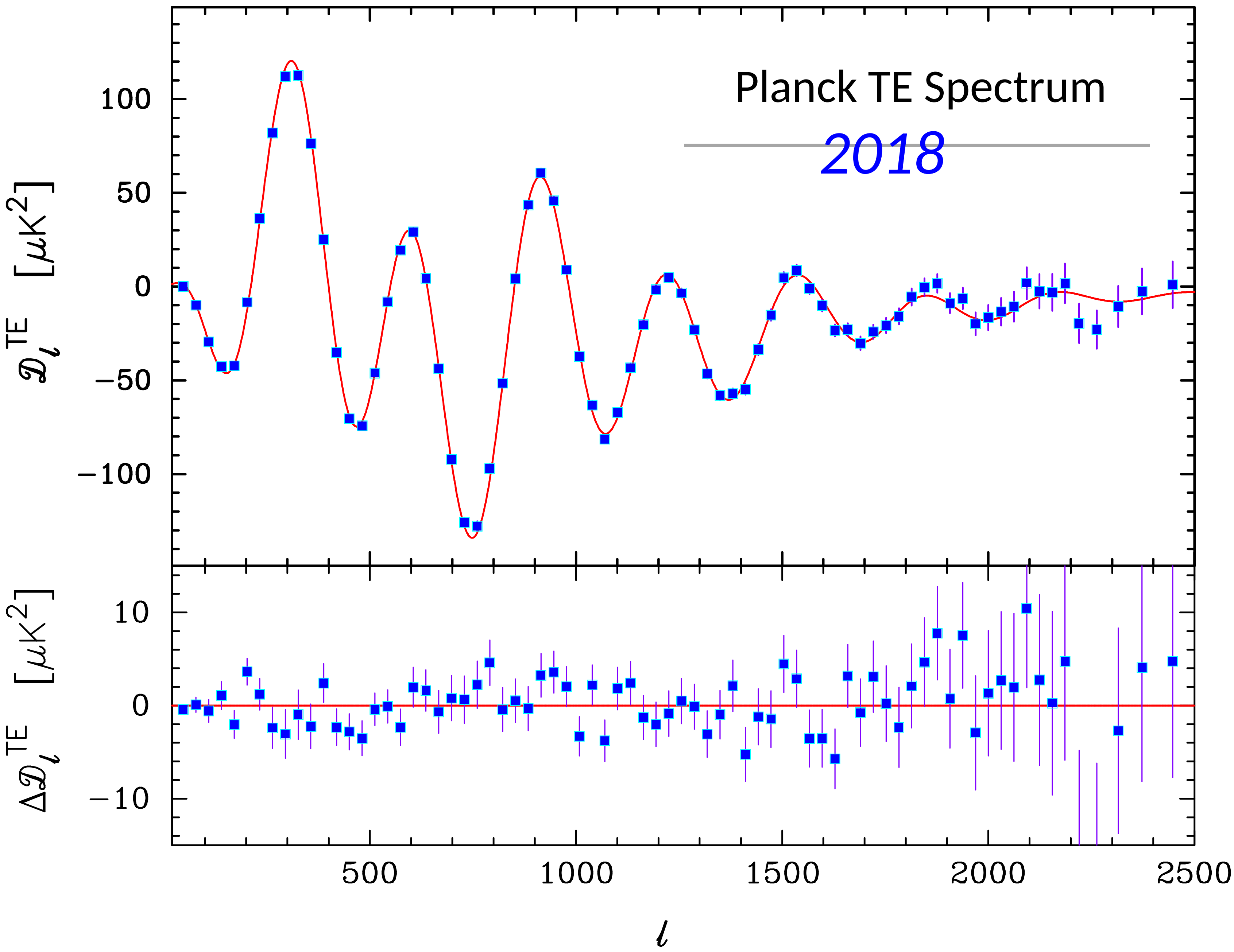




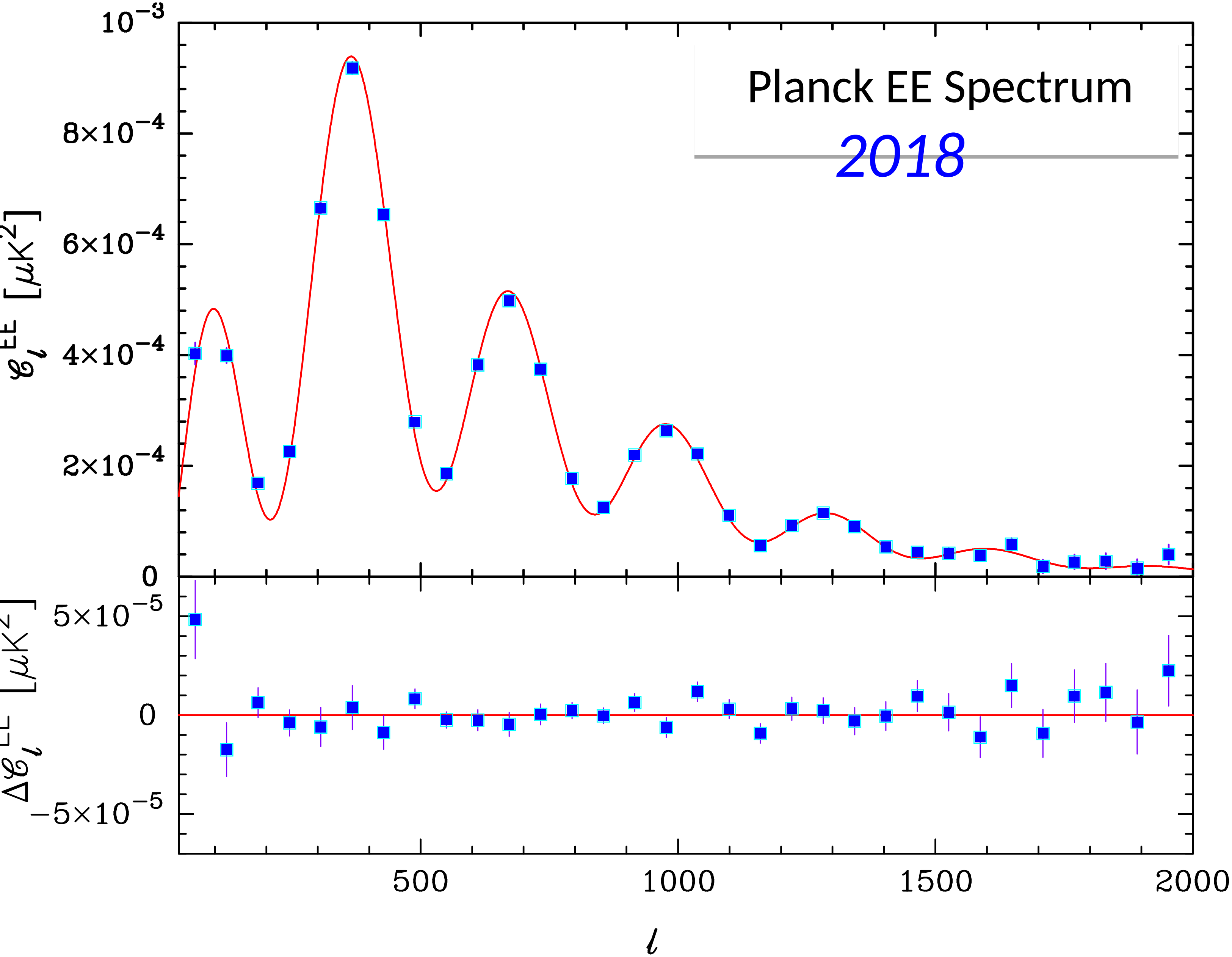
Planck TT spectrum
2013
$\mathcal{D}_\ell = \ell(\ell+1)C_\ell/2\pi\ [\mu K^2]$
$\Delta\mathcal{D}_\ell\ [\mu K^2]$
Multipole ℓ
7000
6000
5000
4000
3000
2000
1000
0
500
250
0
−250
−500
200
100
0
−100
−200
2
5
10
20
500
1000
1500
2000
2500



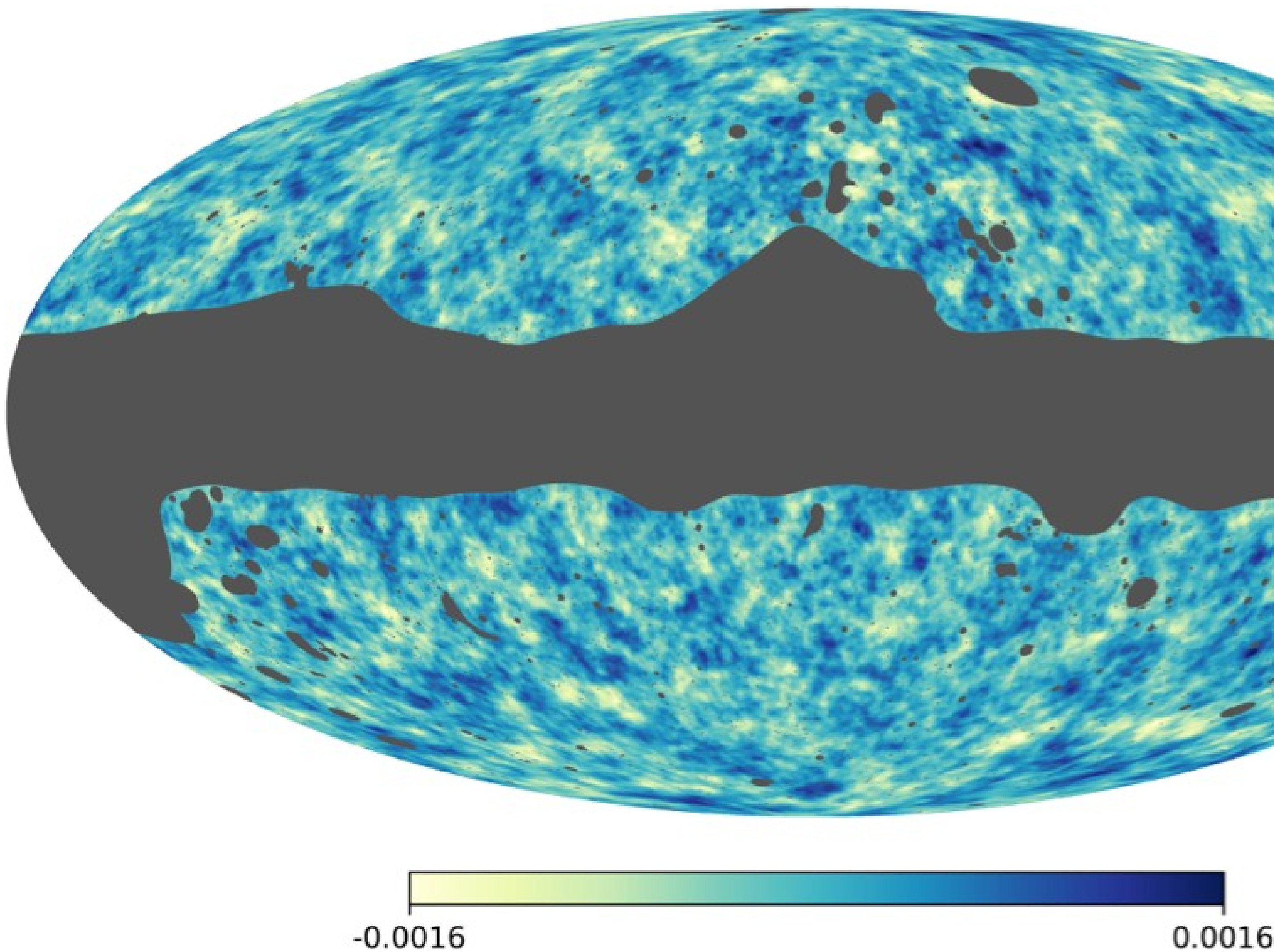
Planck TT spectrum
2018
$\mathcal{D}_\ell = \ell(\ell+1)C_\ell/2\pi\ [\mu K^2]$
$\Delta\mathcal{D}_\ell\ [\mu K^2]$
Multipole ℓ
7000
6000
5000
4000
3000
2000
1000
0
500
250
0
−250
−500
200
100
0
−100
−200
2
5
10
20
500
1000
1500
2000
2500

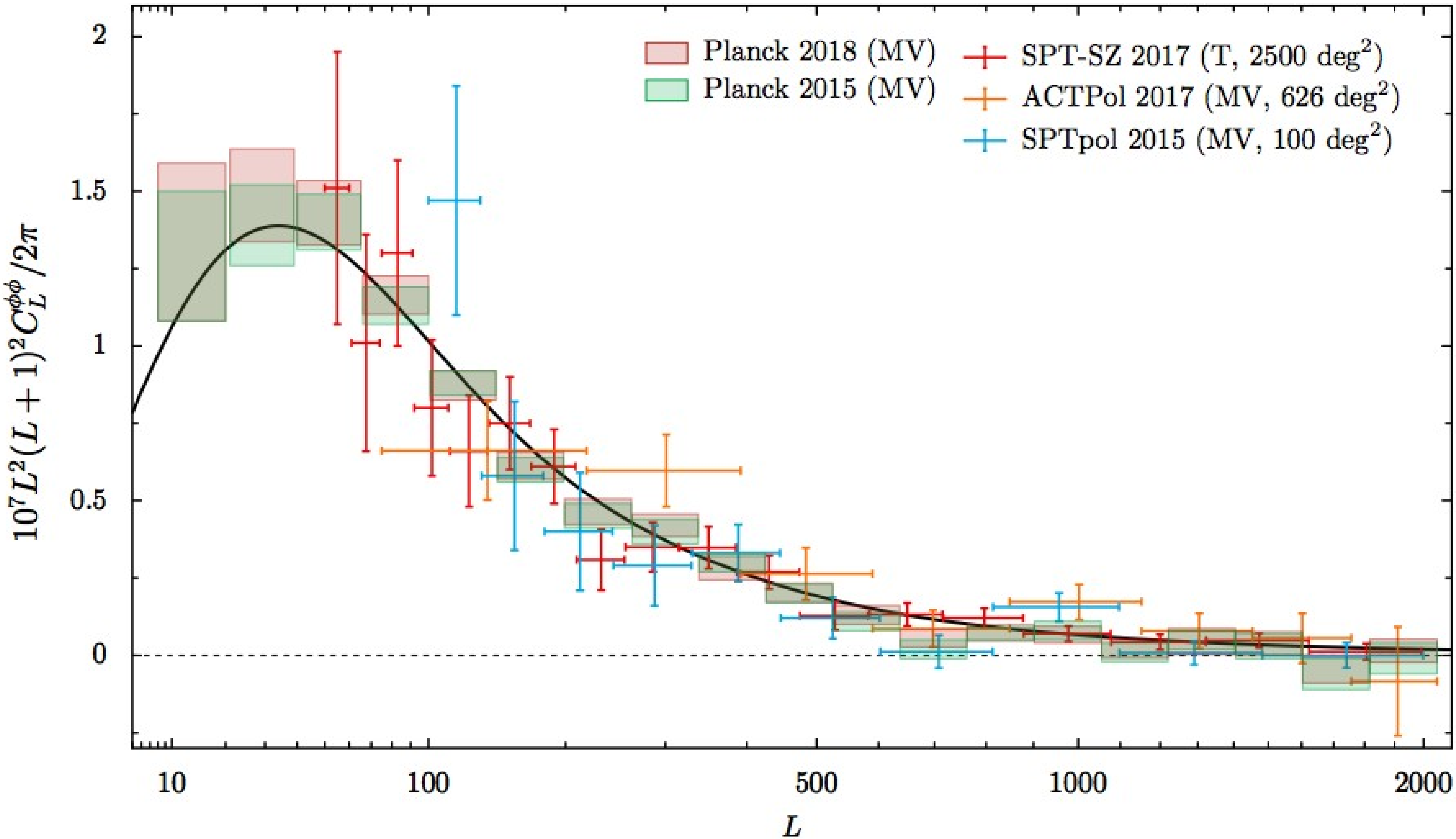


Planck TE Spectrum
2018
100
50
0
−50
−100
$\mathcal{D}_\ell^{TE}$ [μK^2]
10
0
−10
$\Delta\mathcal{D}_\ell^{TE}$ [μK^2]
500
1000
1500
2000
2500
ℓ

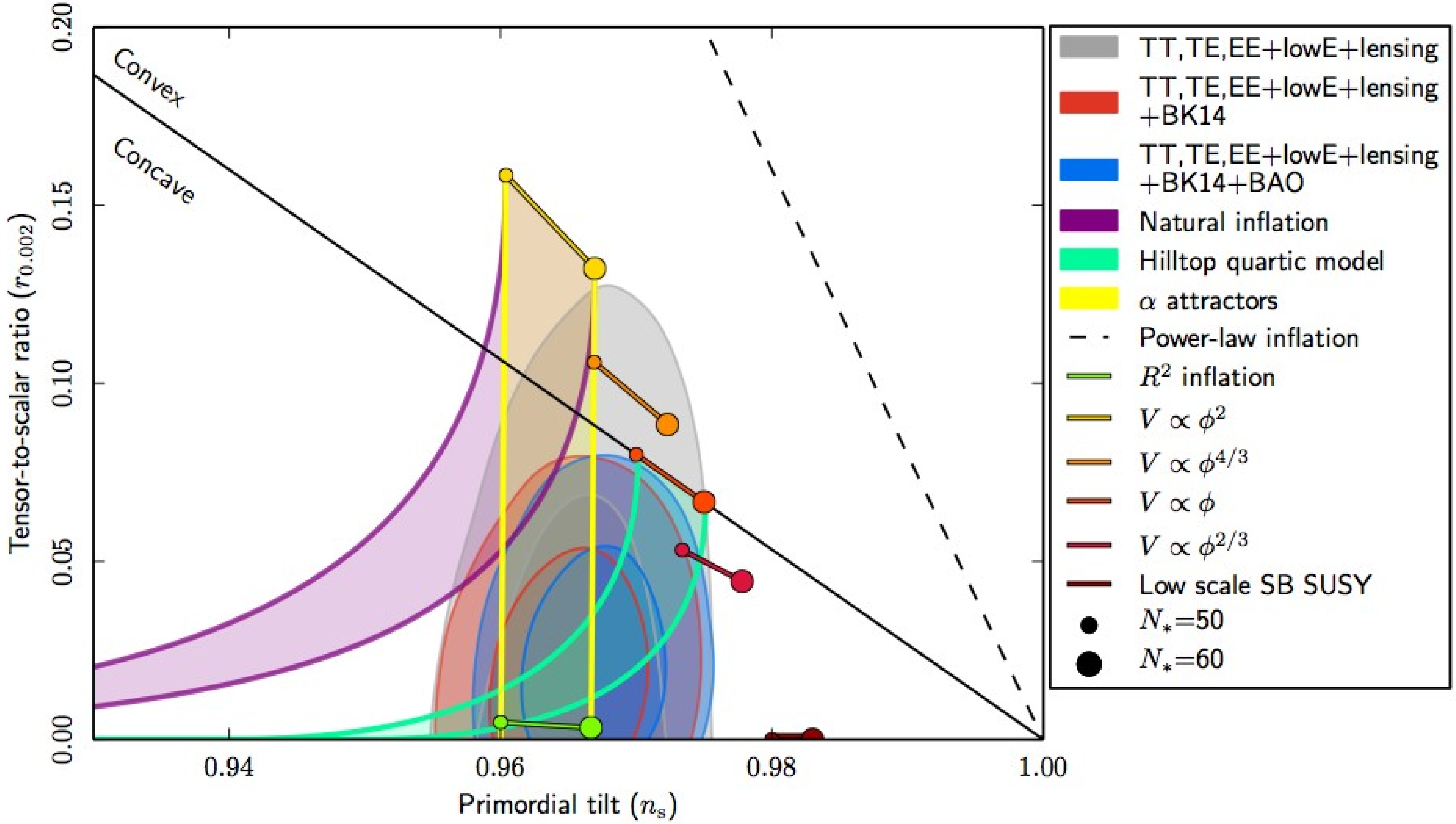


Planck EE Spectrum
2018
10^{-3}
8×10^{-4}
6×10^{-4}
4×10^{-4}
2×10^{-4}
0
$\mathscr{C}_\ell^{EE}$ [μK^2]
5×10^{-5}
0
-5×10^{-5}
$\Delta\mathscr{C}_\ell^{EE}$ [μK^2]
500
1000
1500
2000
ℓ


-0.0016
0.0016



Planck 2018 (MV)
Planck 2015 (MV)
SPT-SZ 2017 (T, 2500 deg^2)
ACTPol 2017 (MV, 626 deg^2)
SPTpol 2015 (MV, 100 deg^2)
$10^7 L^2(L+1)^2 C_L^{\phi\phi}/2\pi$
L
2
1.5
1
0.5
0
10
100
500
1000
2000



Convex
Concave
Tensor-to-scalar ratio ($r_{0.002}$)
Primordial tilt (n_s)
0.00
0.05
0.10
0.15
0.20
0.94
0.96
0.98
1.00
TT,TE,EE+lowE+lensing
TT,TE,EE+lowE+lensing +BK14
TT,TE,EE+lowE+lensing +BK14+BAO
Natural inflation
Hilltop quartic model
α attractors
Power-law inflation
R^2 inflation
$V \propto \phi^2$
$V \propto \phi^{4/3}$
$V \propto \phi$
$V \propto \phi^{2/3}$
Low scale SB SUSY
N_*=50
N_*=60

Slow roll parameters

$$\epsilon = \frac{m_{\rm pl}^2}{16\pi}\left(\frac{V'}{V}\right)^2, \quad \eta = \frac{m_{\rm pl}^2}{8\pi}\left(\frac{V''}{V}\right)$$

$$n_s = 1 - 6\epsilon + 2\eta, \quad r = 16\epsilon, \quad n_t = -2\epsilon/N$$

If $V(\phi) = \lambda\phi^\alpha$ then

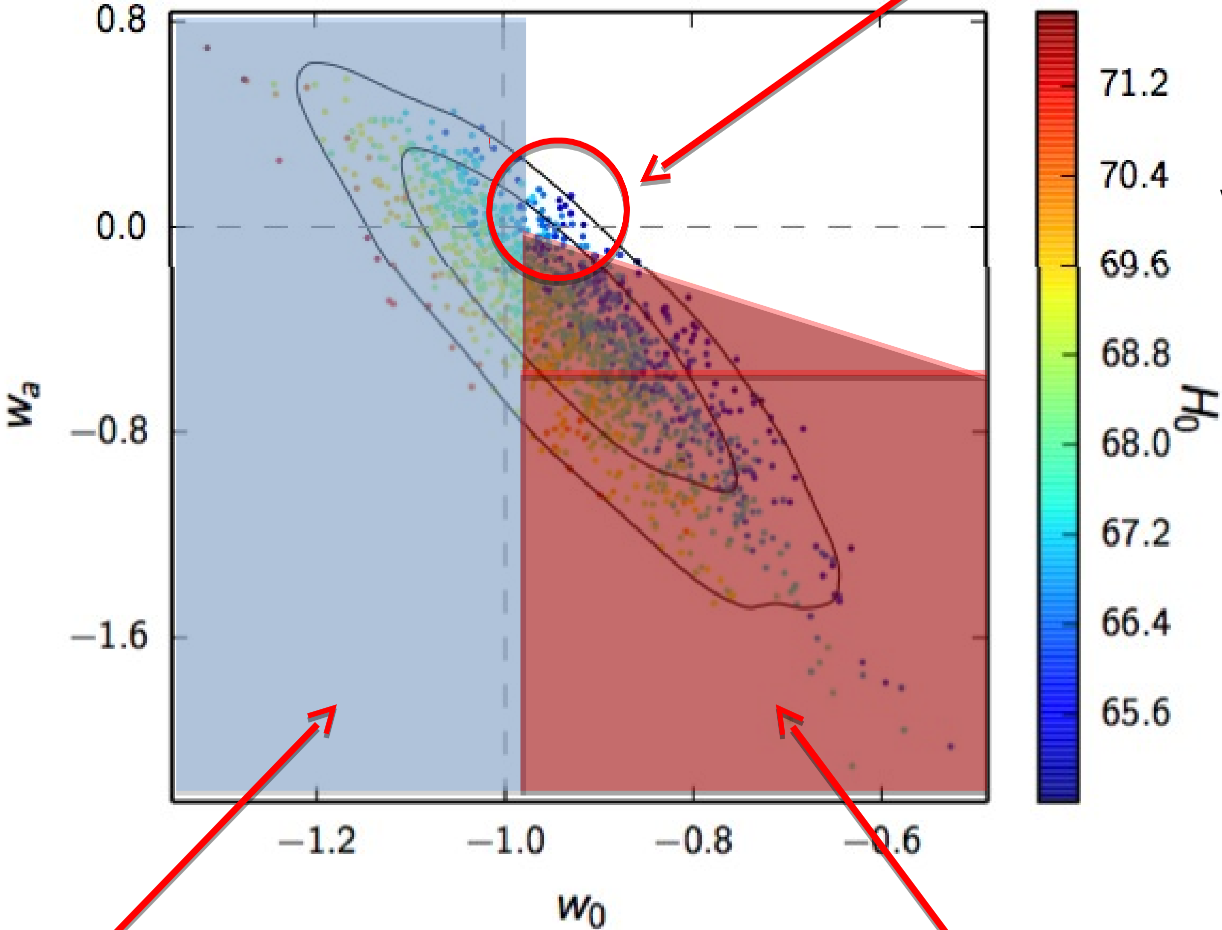
$$1 - n_s = (\alpha + 2)/N, \qquad r = 4\alpha/N,$$

For $n_s = 0.965$, $N \approx 60$, $\alpha \approx 2.2$, $r \approx 0.15$.

so we have a hierarchy, ε << η.

Planck TT+BAO+JLA

Standard dark energy!



$$w(a) = w_0 + w_a(1\text{-}a)$$

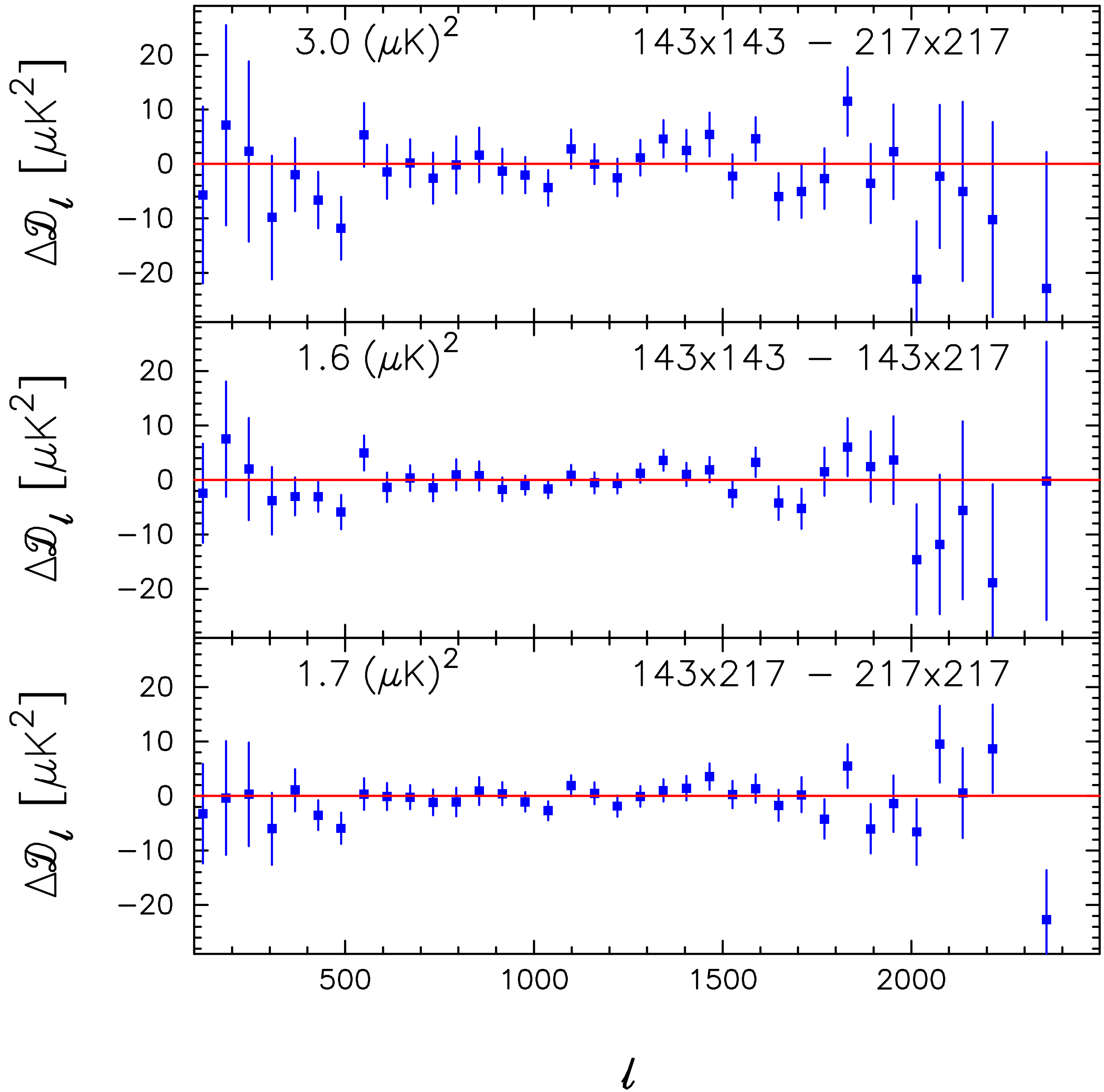
phantom at z=0

phantom in past

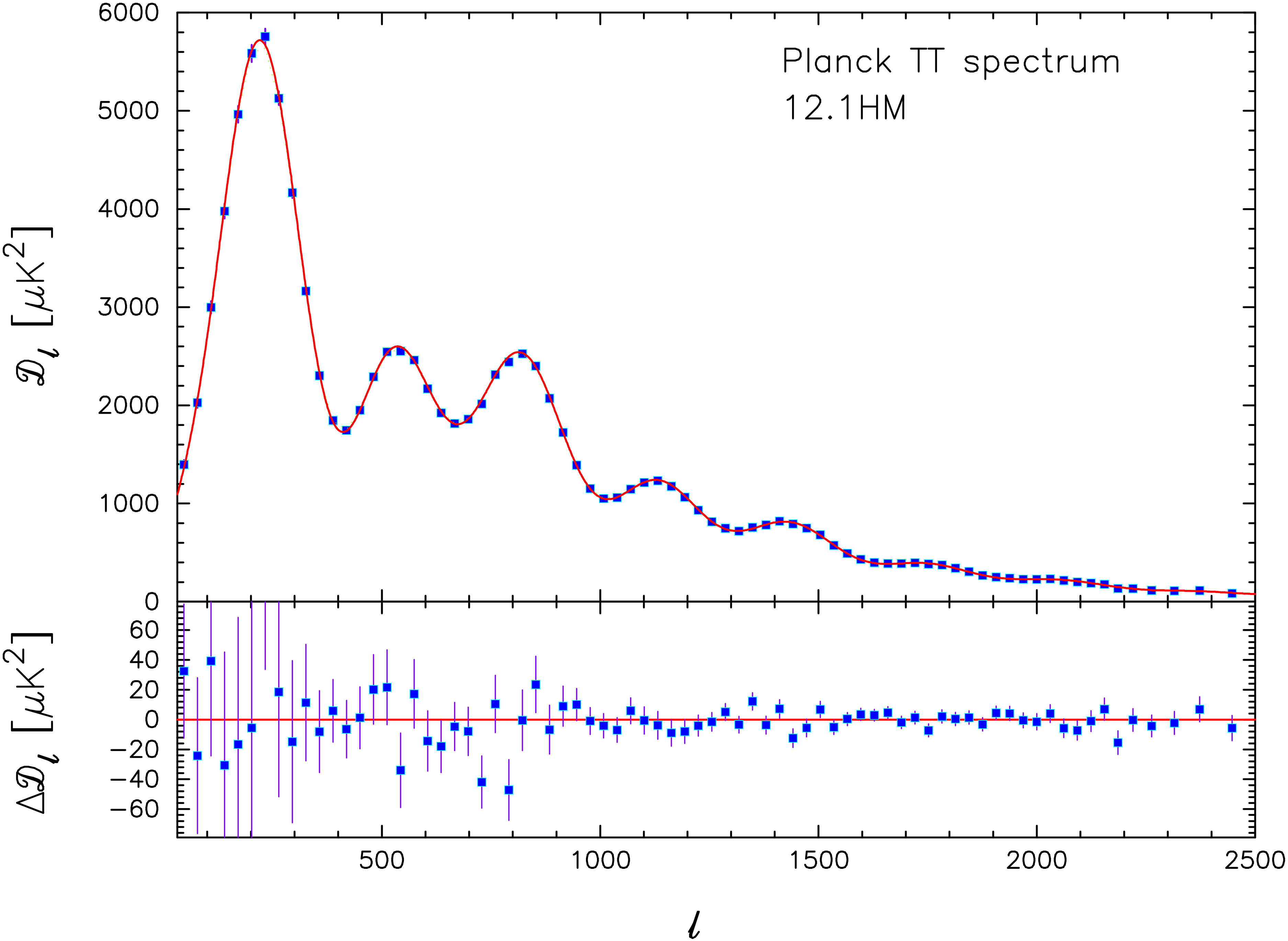
‘Odd’ aspects of Planck spectra?

- Planck temperature spectra want more lensing (A_L >1) .
- Planck data favour closed universes.
- High multipoles (l > 800) give different parameters to lower multipoles (e.g. Addison etal 2016, ApJ, 818, 132).
- Outliers in TT spectrum and in TE spectrum (e.g. l > 165 in TE , Obied etal 2017, PRD, 083526).

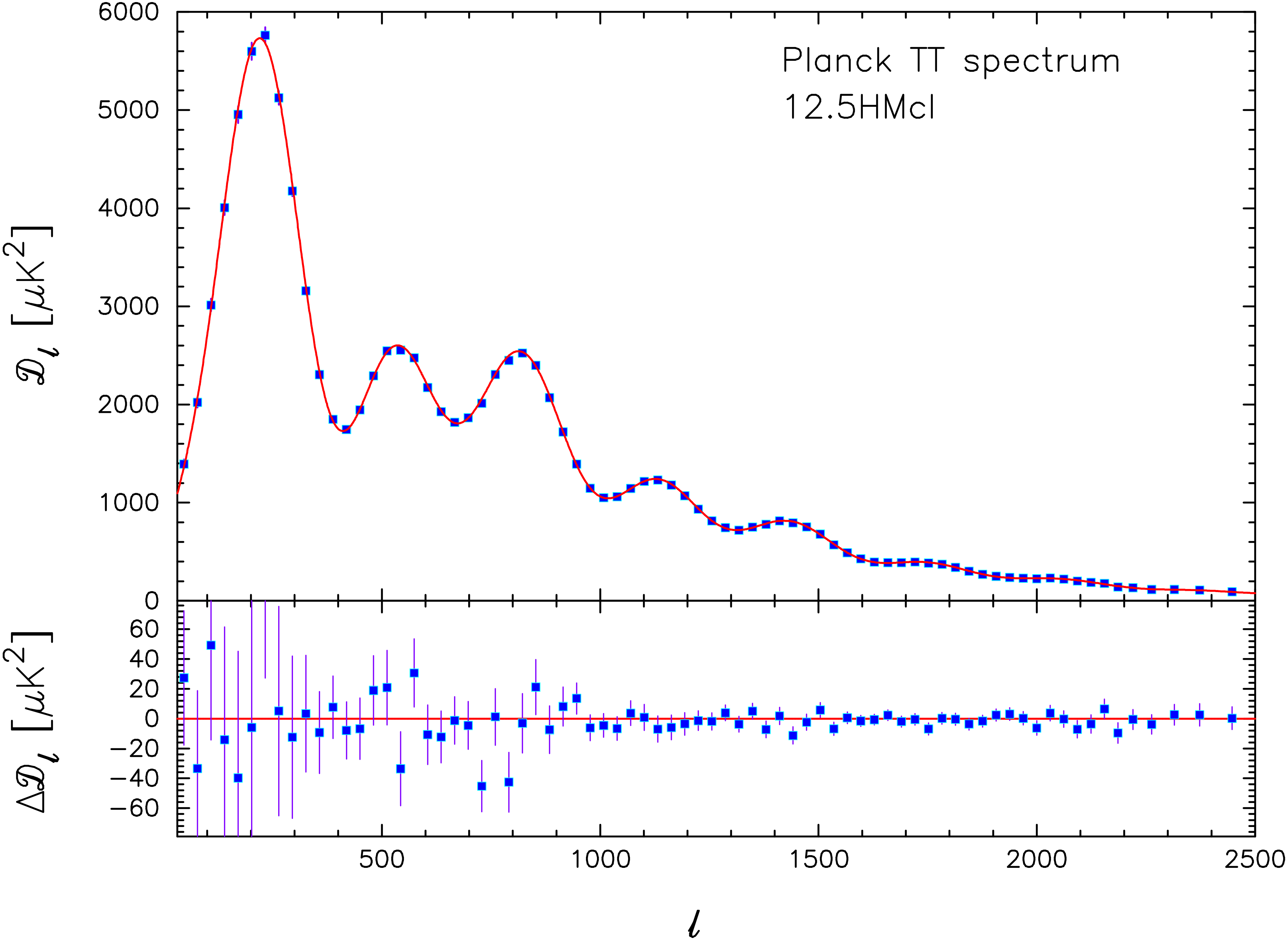
based on work done with Steven Gratton



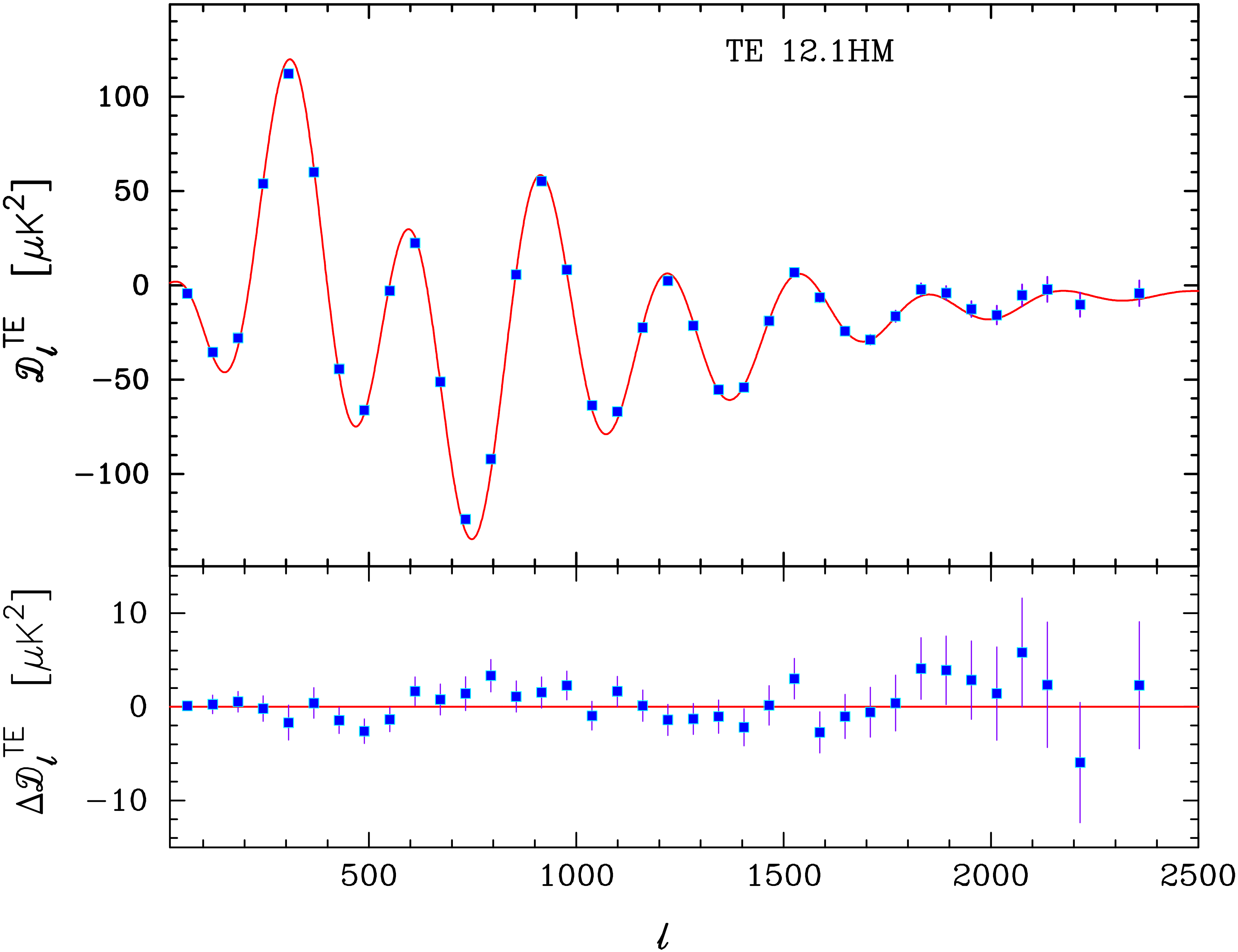
3.0 (μK)^2
143x143 − 217x217
1.6 (μK)^2
143x143 − 143x217
1.7 (μK)^2
143x217 − 217x217
$\Delta\mathcal{D}_\ell$ [μK^2]
20
10
0
−10
−20
500
1000
1500
2000
ℓ

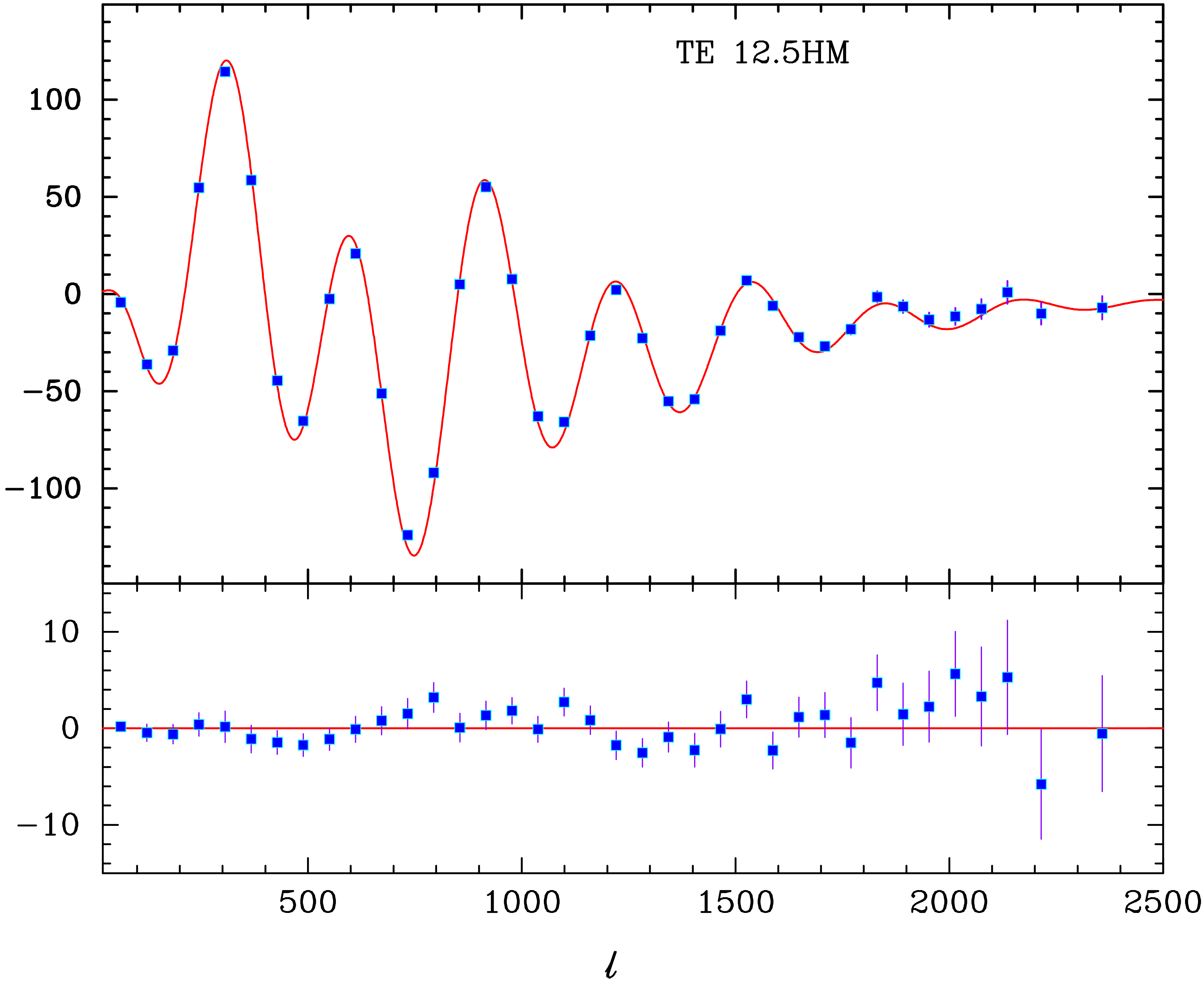


Planck TT spectrum
12.1HM
$\mathcal{D}_\ell$ [μK^2]
$\Delta\mathcal{D}_\ell$ [μK^2]
ℓ
0
1000
2000
3000
4000
5000
6000
60
40
20
0
−20
−40
−60
500
1000
1500
2000
2500

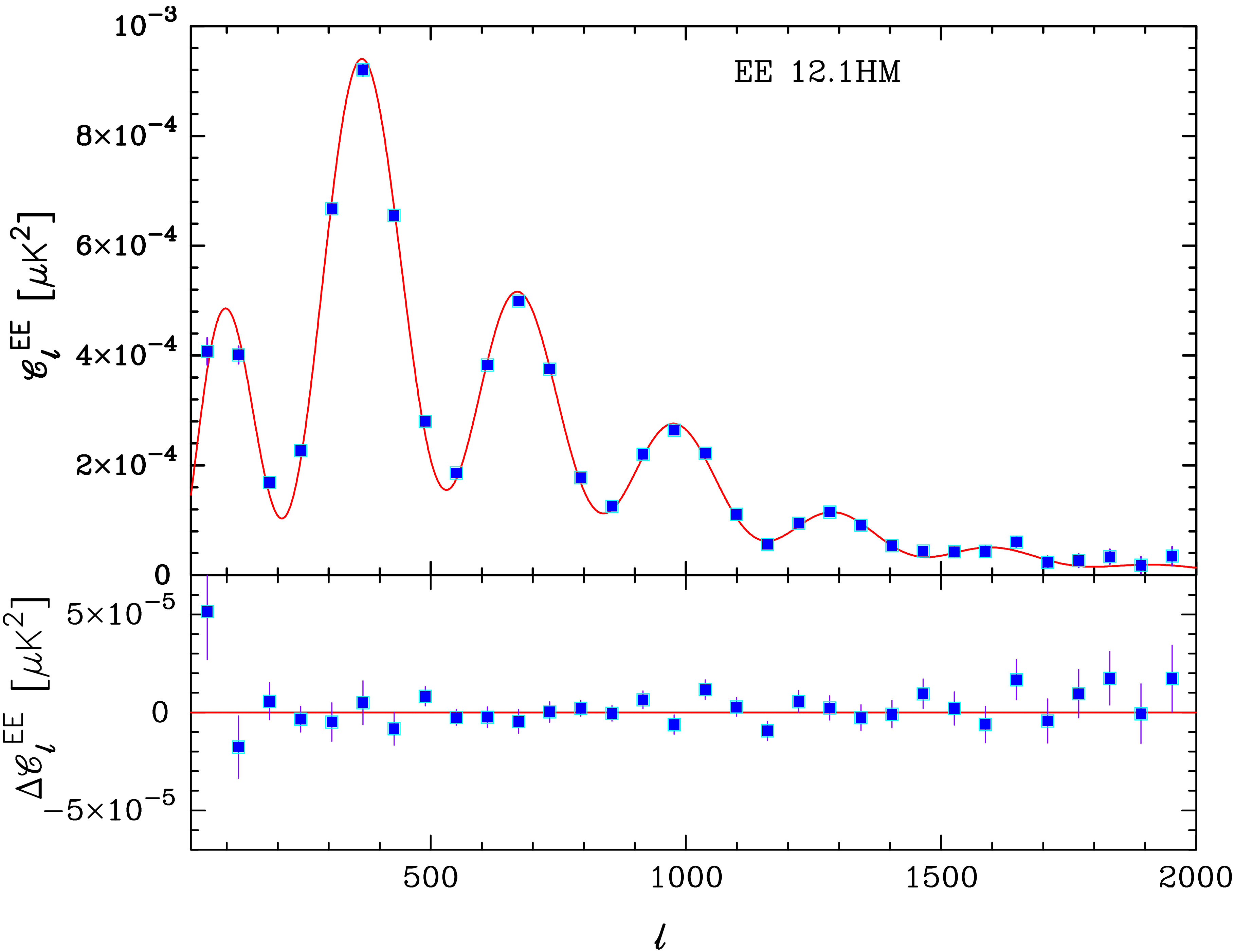


Planck TT spectrum
12.5HMcl
$\mathcal{D}_\ell\ [\mu K^2]$
$\Delta\mathcal{D}_\ell\ [\mu K^2]$
ℓ
0
1000
2000
3000
4000
5000
6000
60
40
20
0
−20
−40
−60
500
1000
1500
2000
2500

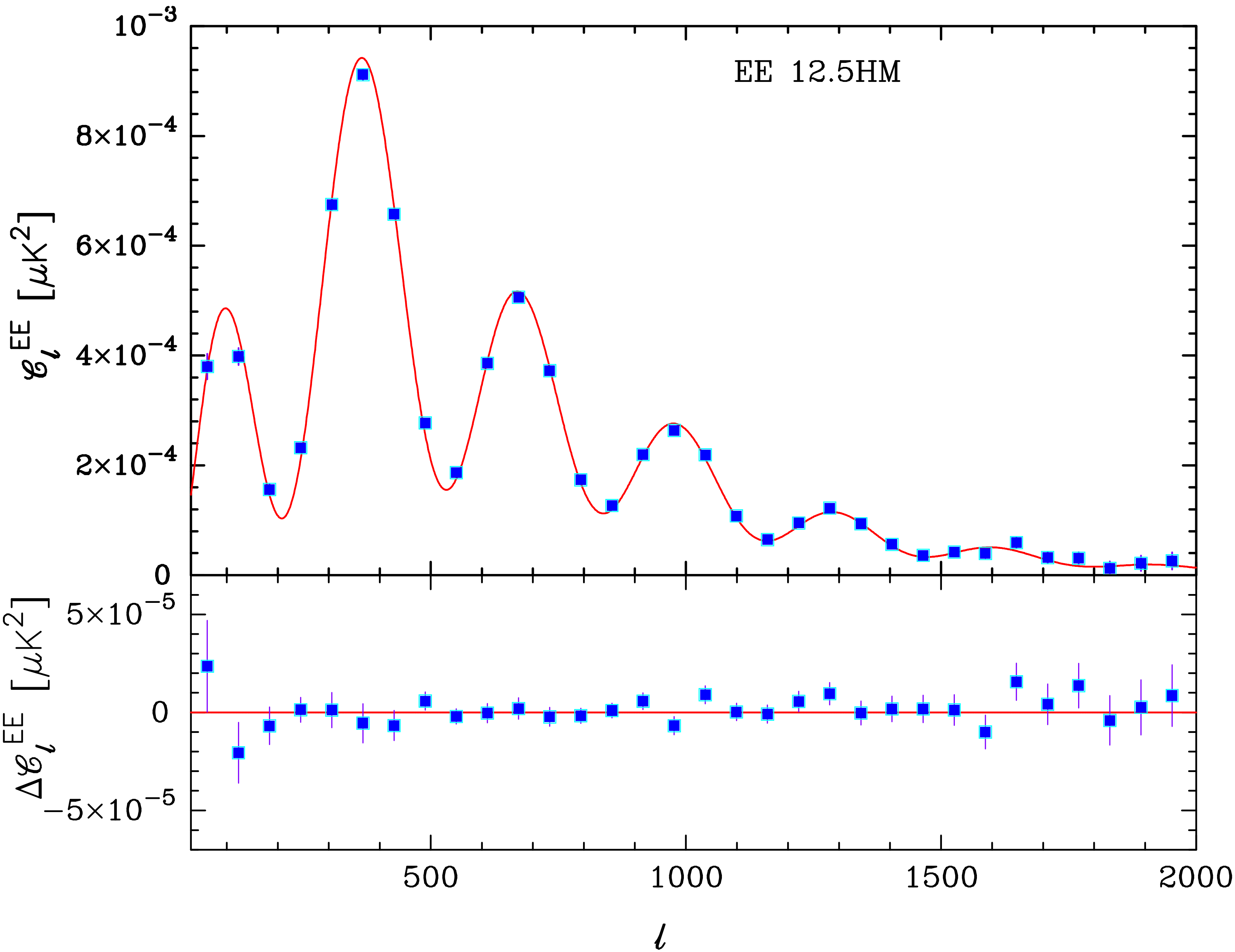

TE 12.1HM
$\mathcal{D}_\ell^{TE}$ [μK^2]
$\Delta\mathcal{D}_\ell^{TE}$ [μK^2]
100
50
0
−50
−100
10
0
−10
500
1000
1500
2000
2500
ℓ



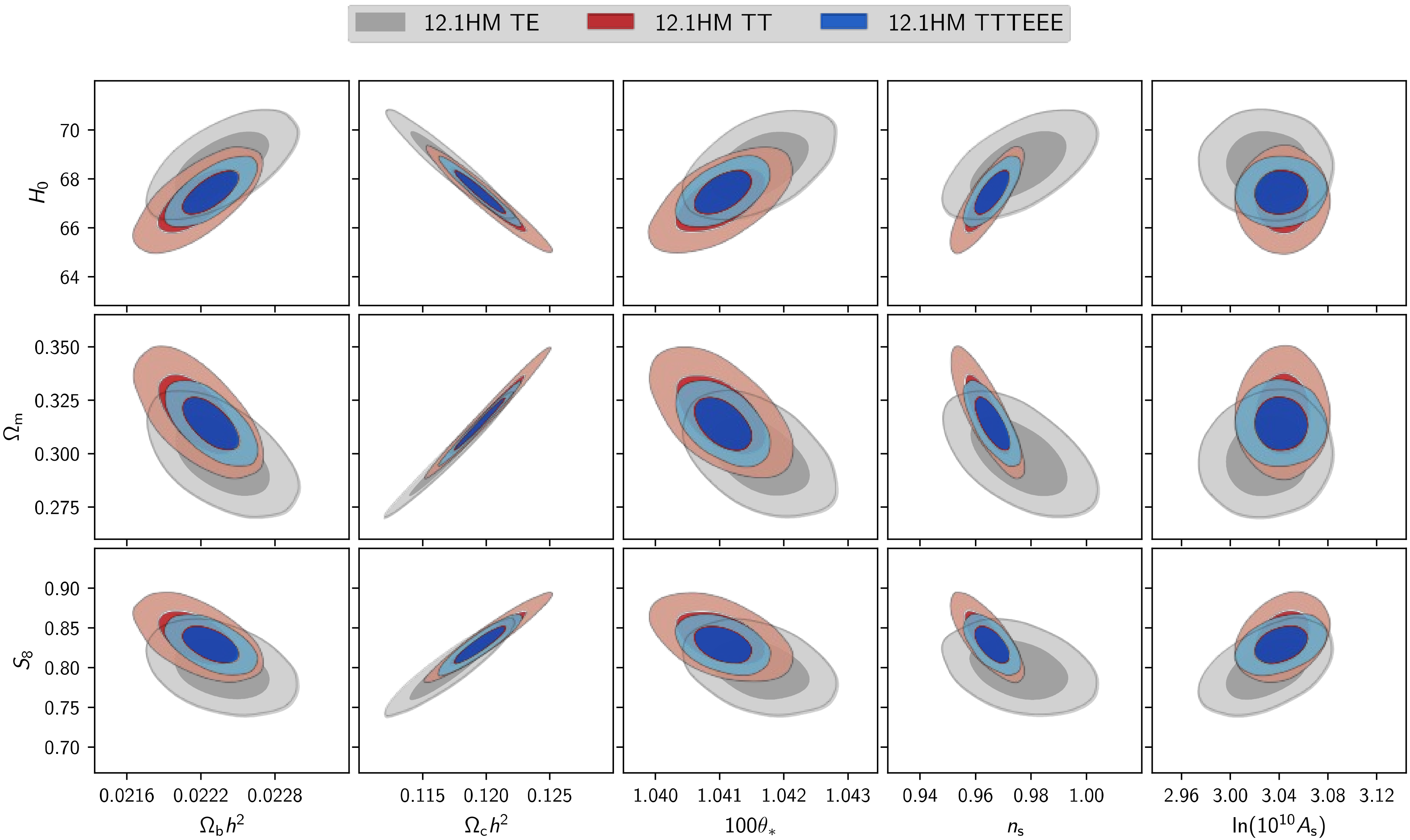
TE 12.5HM
$\mathcal{D}_\ell^{TE}$ [μK^2]
$\Delta\mathcal{D}_\ell^{TE}$ [μK^2]
100
50
0
−50
−100
10
0
−10
500
1000
1500
2000
2500
ℓ



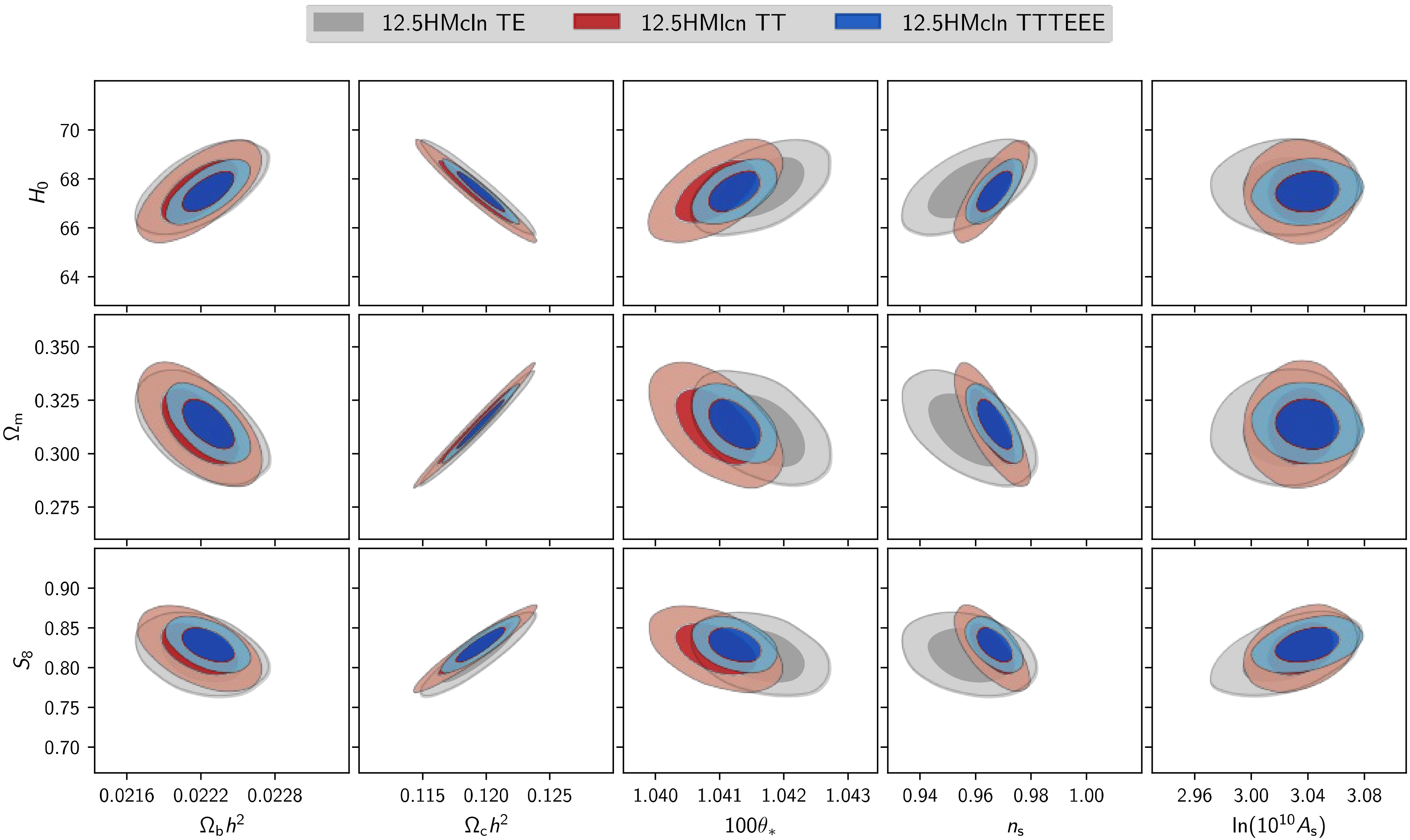
EE 12.1HM
10^{-3}
8×10^{-4}
6×10^{-4}
4×10^{-4}
2×10^{-4}
0
$\mathcal{C}_\ell^{EE}$ [μK^2]
5×10^{-5}
0
-5×10^{-5}
$\Delta\mathcal{C}_\ell^{EE}$ [μK^2]
500
1000
1500
2000
ℓ



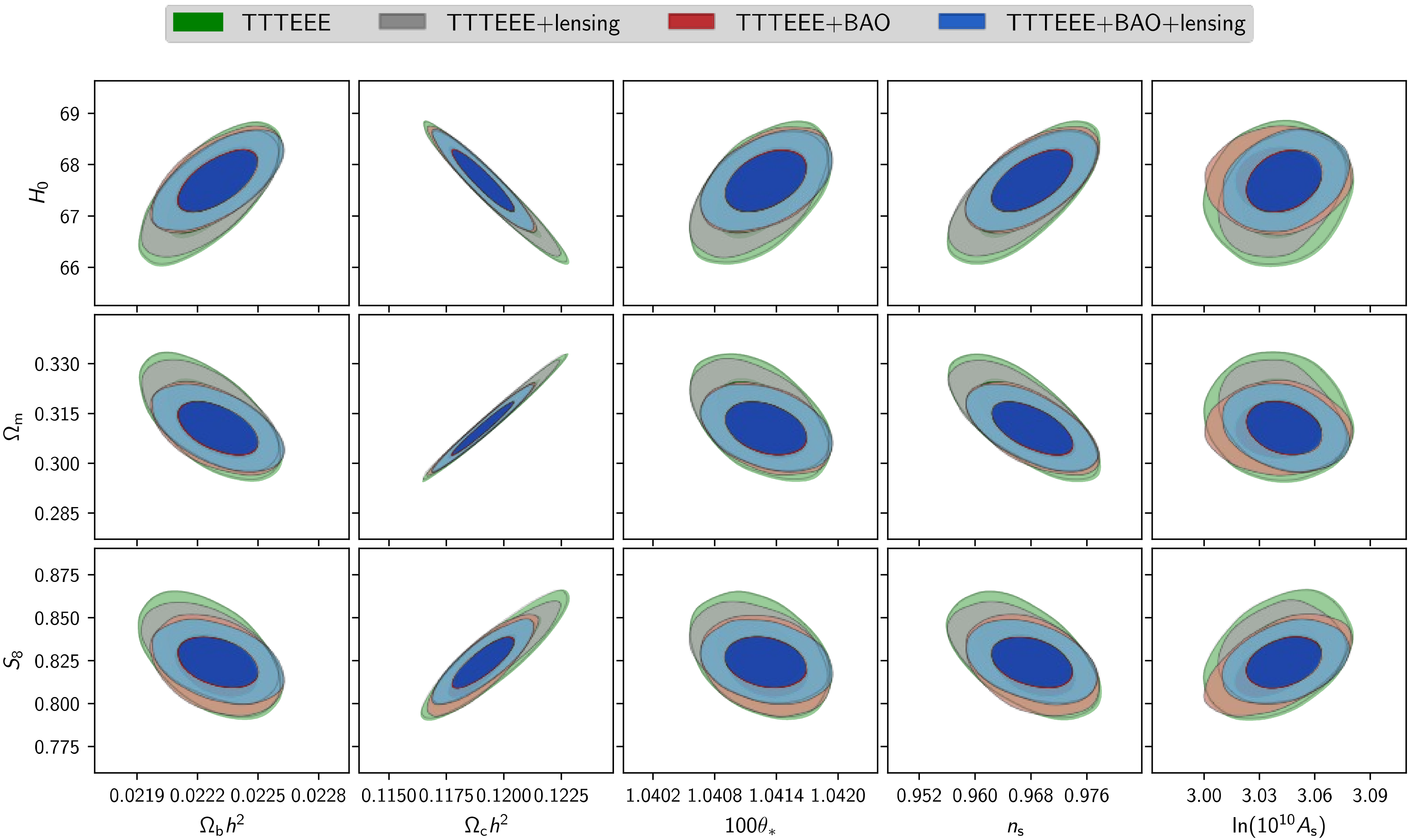
EE 12.5HM
10^{-3}
8×10^{-4}
6×10^{-4}
4×10^{-4}
2×10^{-4}
0
$\mathscr{C}_\ell^{EE}$ [μK^2]
5×10^{-5}
0
-5×10^{-5}
$\Delta\mathscr{C}_\ell^{EE}$ [μK^2]
500
1000
1500
2000
ℓ



12.1HM TE
12.1HM TT
12.1HM TTTEEE
H_0
Ω_m
S_8
$\Omega_\mathrm{b}h^2$
$\Omega_\mathrm{c}h^2$
$100\theta_*$
n_s
$\ln(10^{10}A_\mathrm{s})$

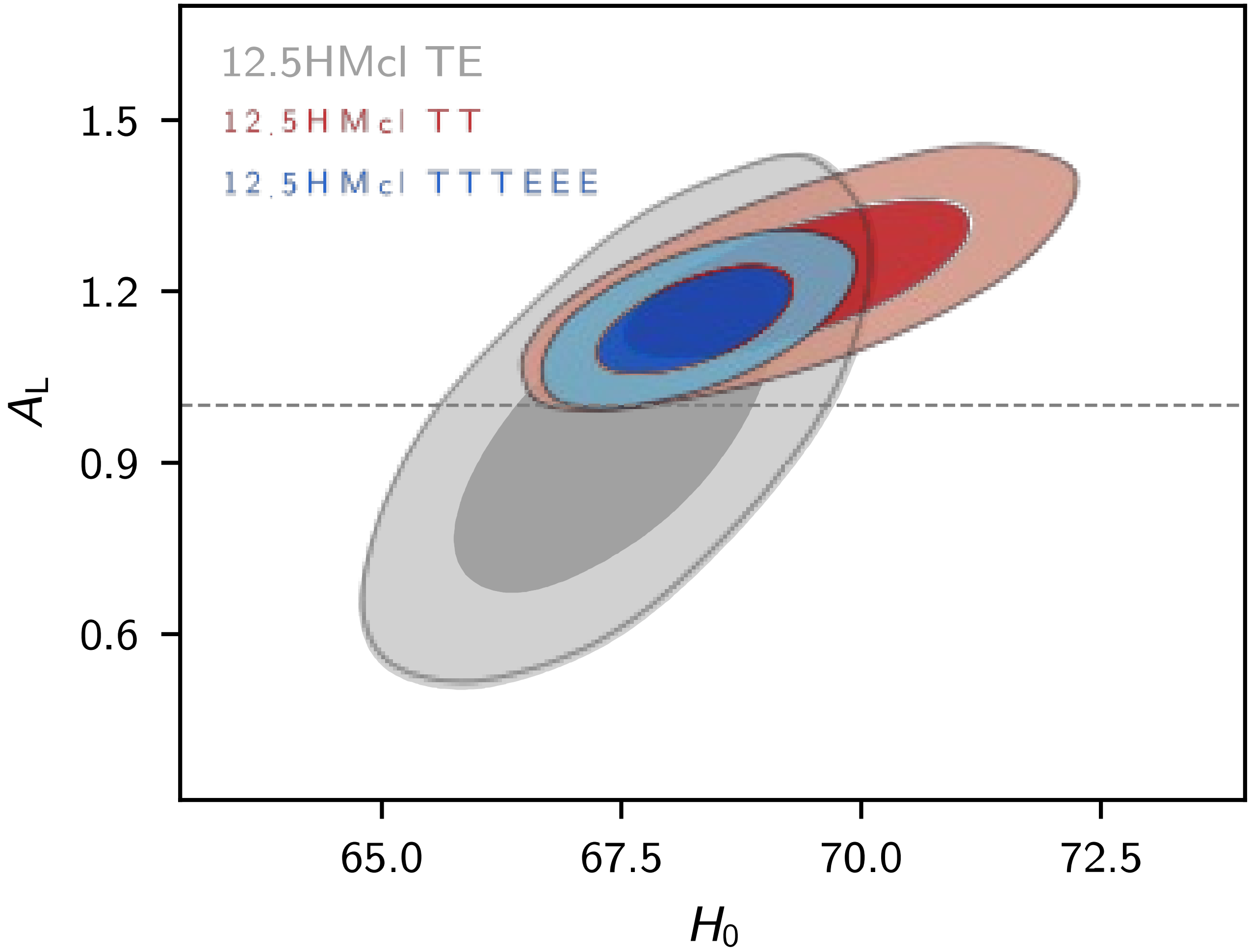


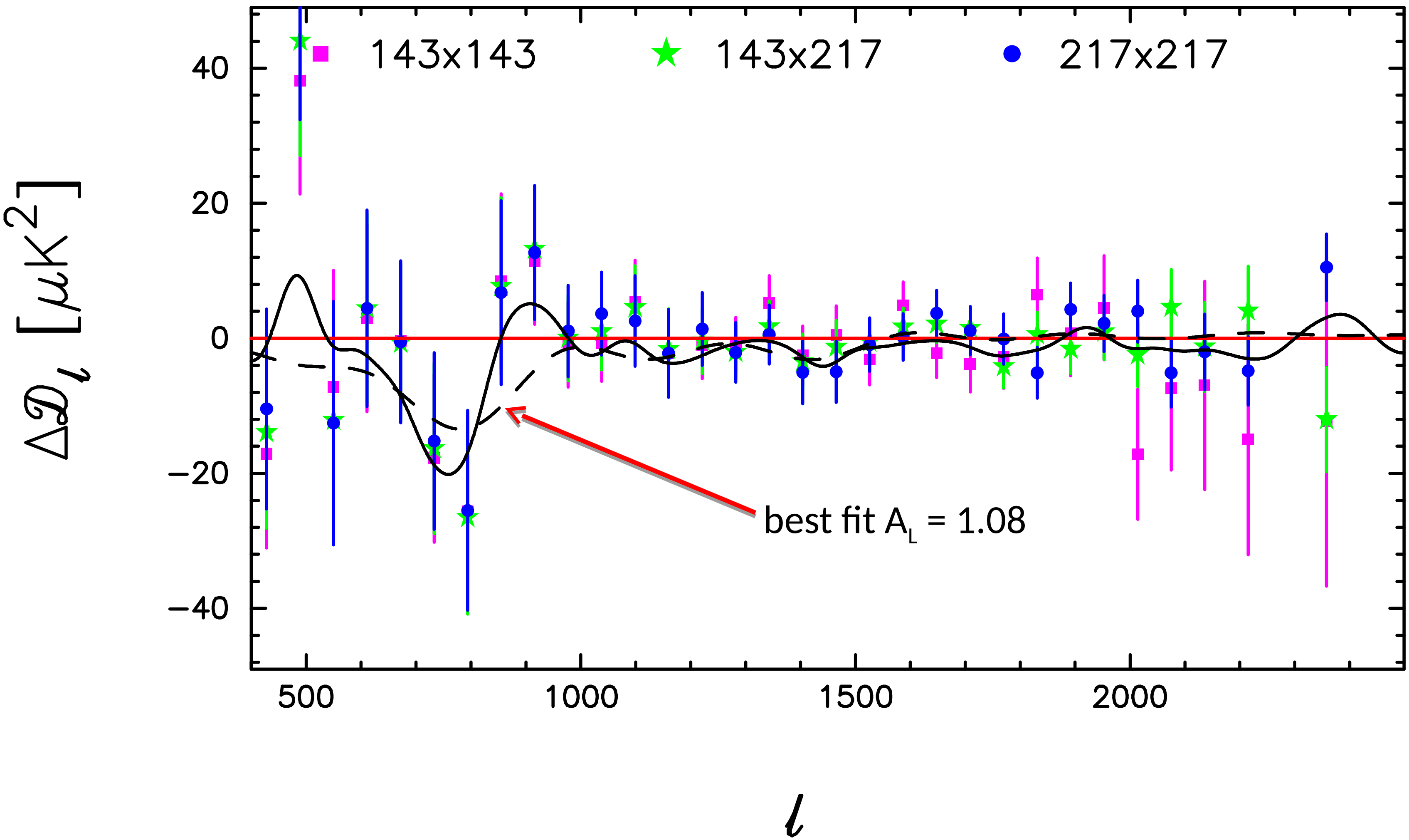
12.5HMcln TE
12.5HMlcn TT
12.5HMcln TTTEEE
H_0
Ω_m
S_8
$\Omega_b h^2$
$\Omega_c h^2$
$100\theta_*$
n_s
$\ln(10^{10} A_s)$



TTTEEE
TTTEEE+lensing
TTTEEE+BAO
TTTEEE+BAO+lensing
H_0
Ω_m
S_8
$\Omega_b h^2$
$\Omega_c h^2$
$100\theta_*$
n_s
$\ln(10^{10} A_s)$

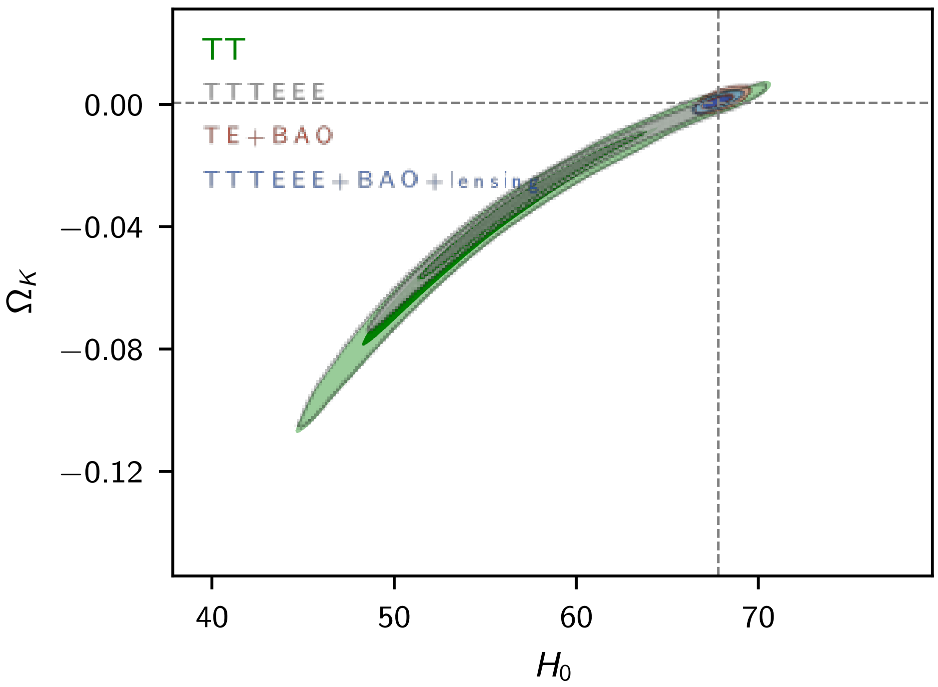
Lensing amplitude



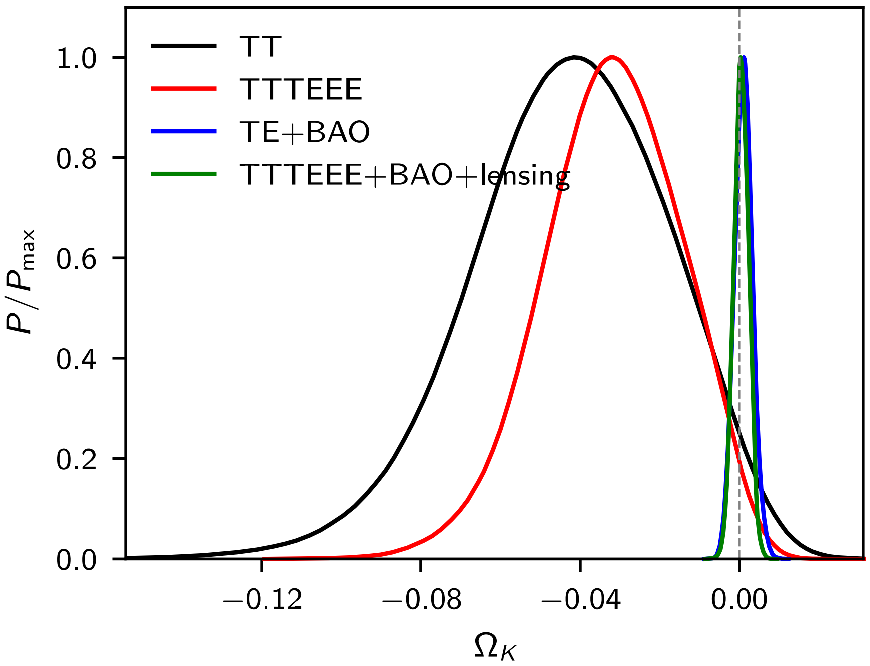


143x143
143x217
217x217
40
20
0
−20
−40
500
1000
1500
2000
$\Delta\mathcal{D}_\ell$ [μK^2]
ℓ
best fit A_L = 1.08

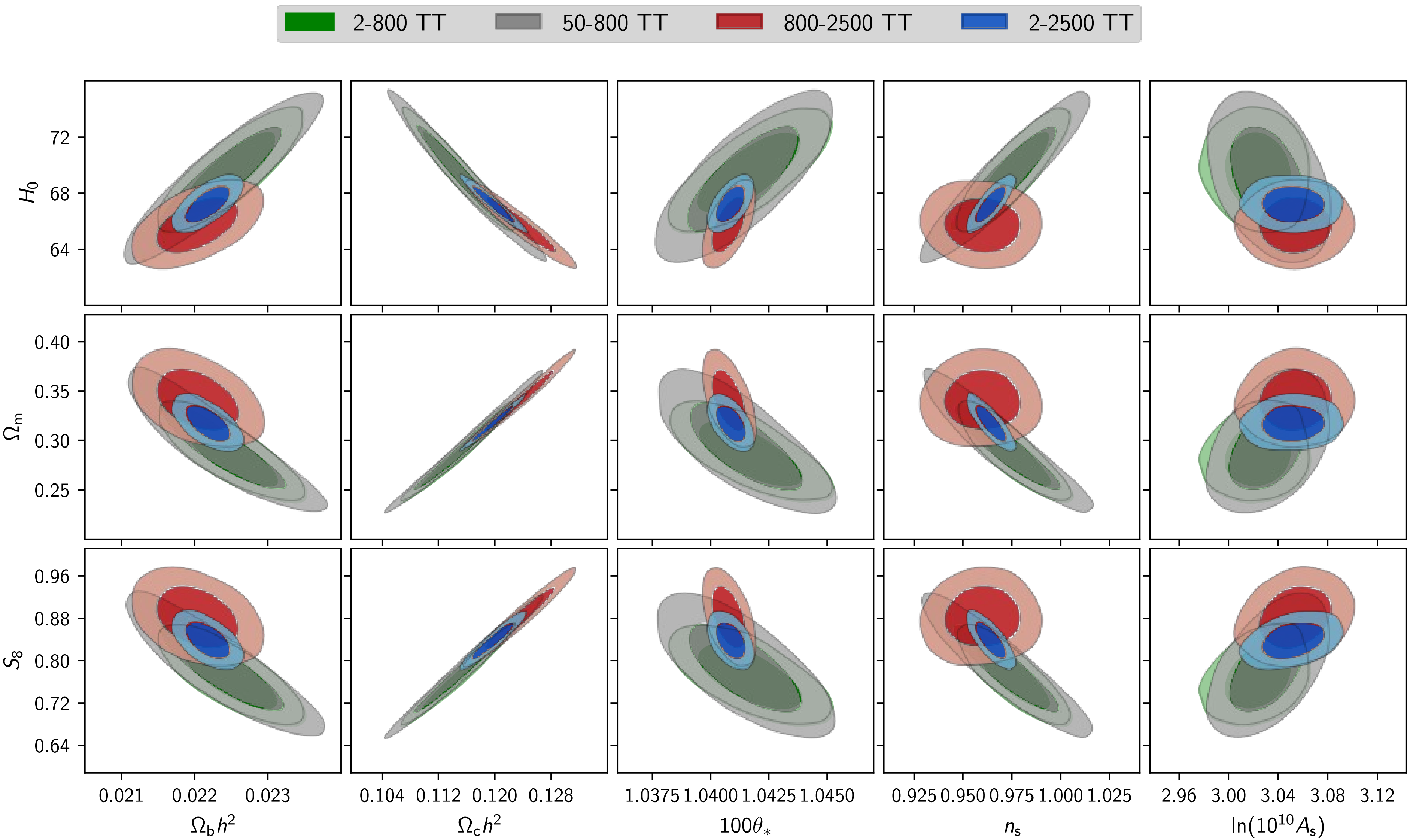
Curvature

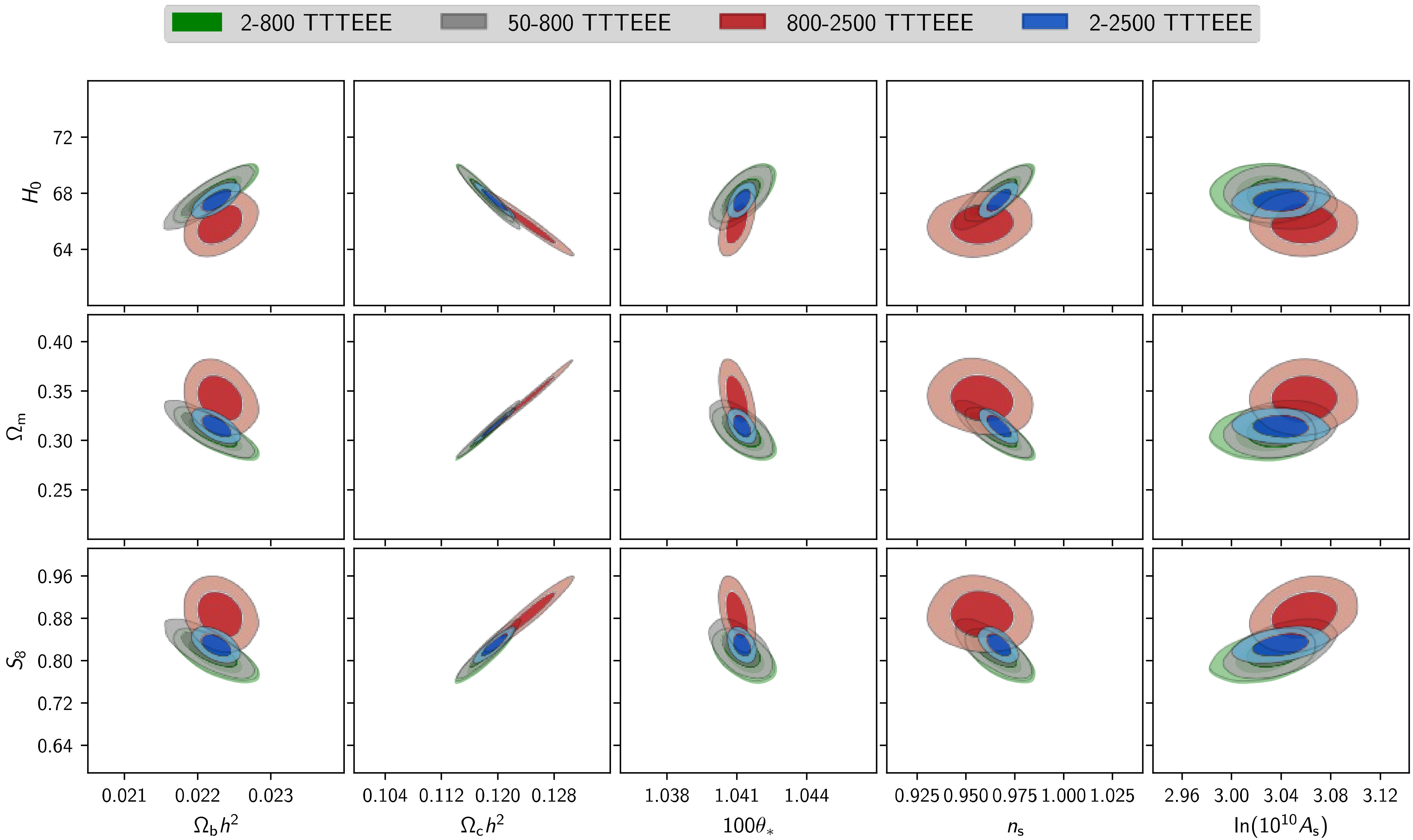


TT
TTTEEE
TE+BAO
TTTEEE+BAO+lensing
0.00
−0.04
−0.08
−0.12
40
50
60
70
H_0
Ω_K

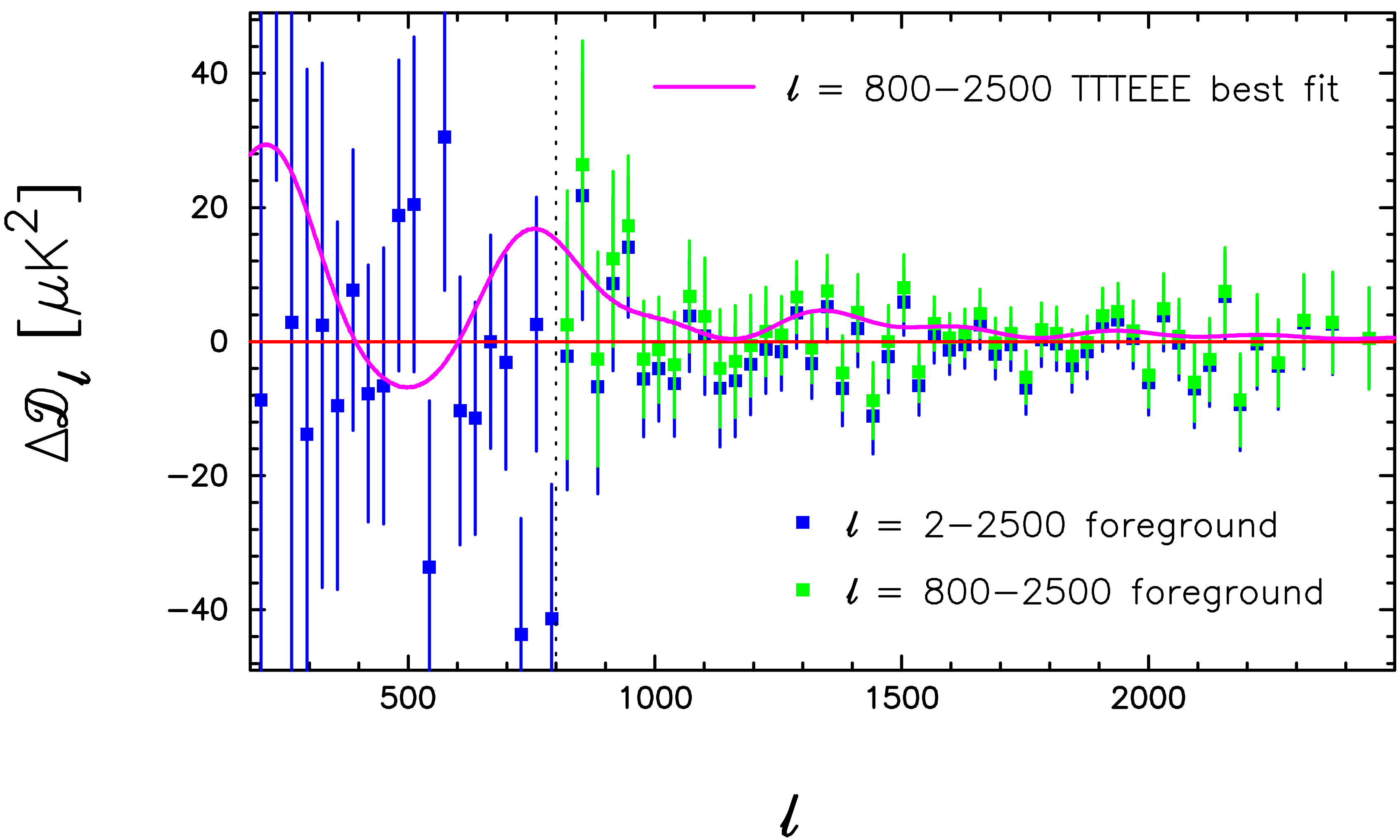


TT
TTTEEE
TE+BAO
TTTEEE+BAO+lensing
1.0
0.8
0.6
0.4
0.2
0.0
−0.12
−0.08
−0.04
0.00
$P/P_{\max}$
Ω_K

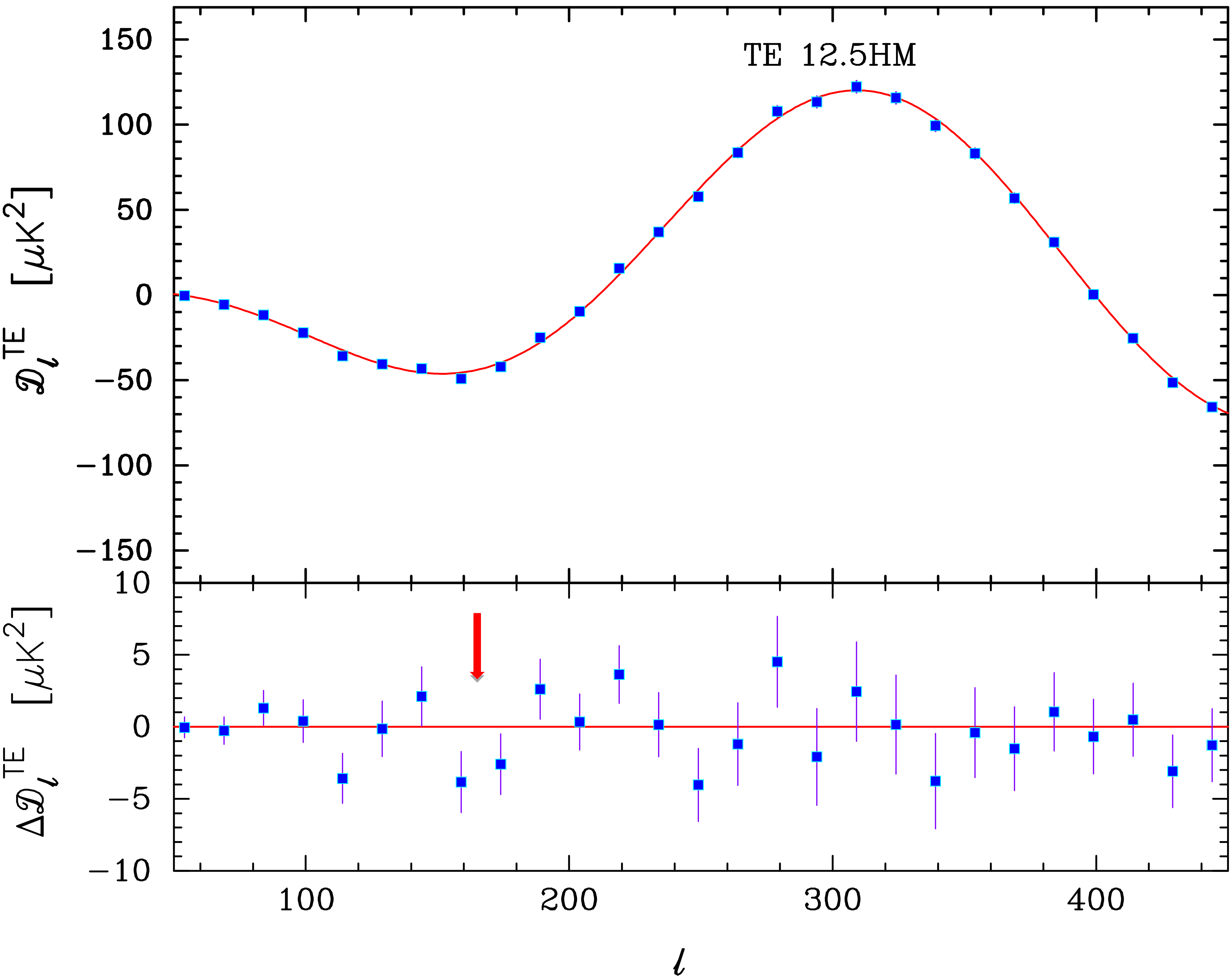

2-800 TT
50-800 TT
800-2500 TT
2-2500 TT
H_0
Ω_m
S_8
$\Omega_b h^2$
$\Omega_c h^2$
$100\theta_*$
n_s
$\ln(10^{10}A_s)$



2-800 TTTEEE
50-800 TTTEEE
800-2500 TTTEEE
2-2500 TTTEEE
H_0
Ω_m
S_8
$\Omega_b h^2$
$\Omega_c h^2$
$100\theta_*$
n_s
$\ln(10^{10} A_s)$

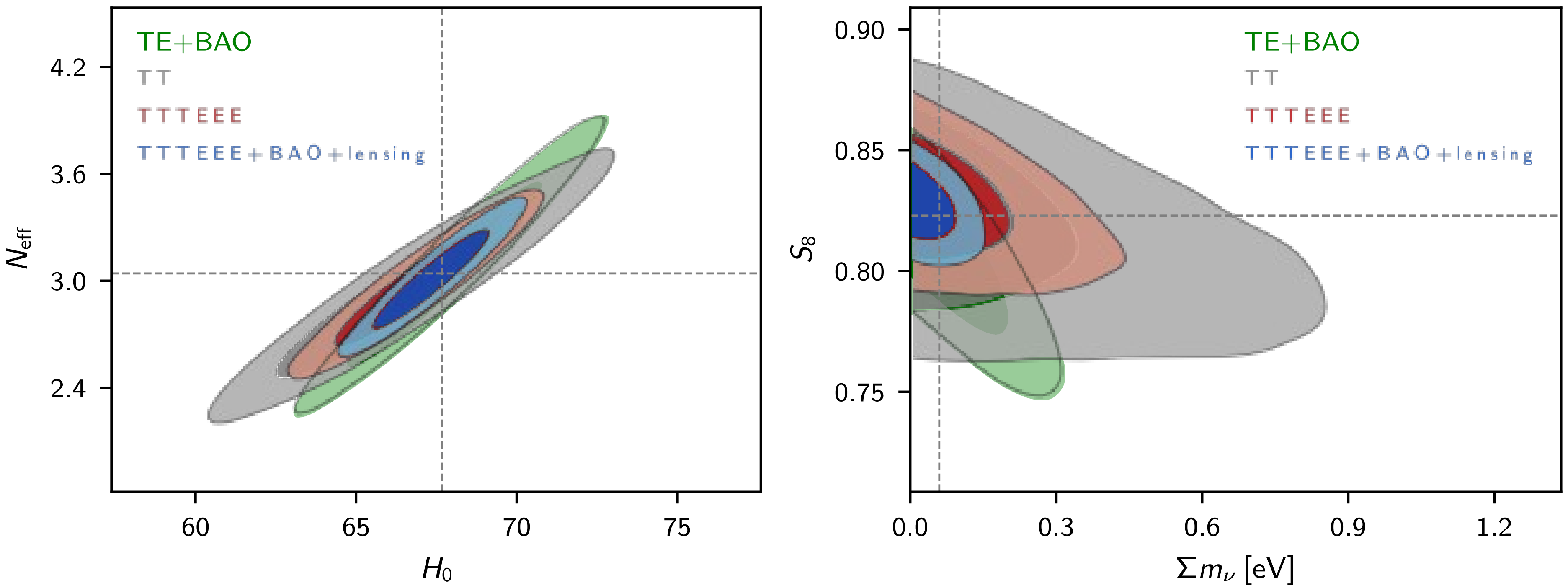


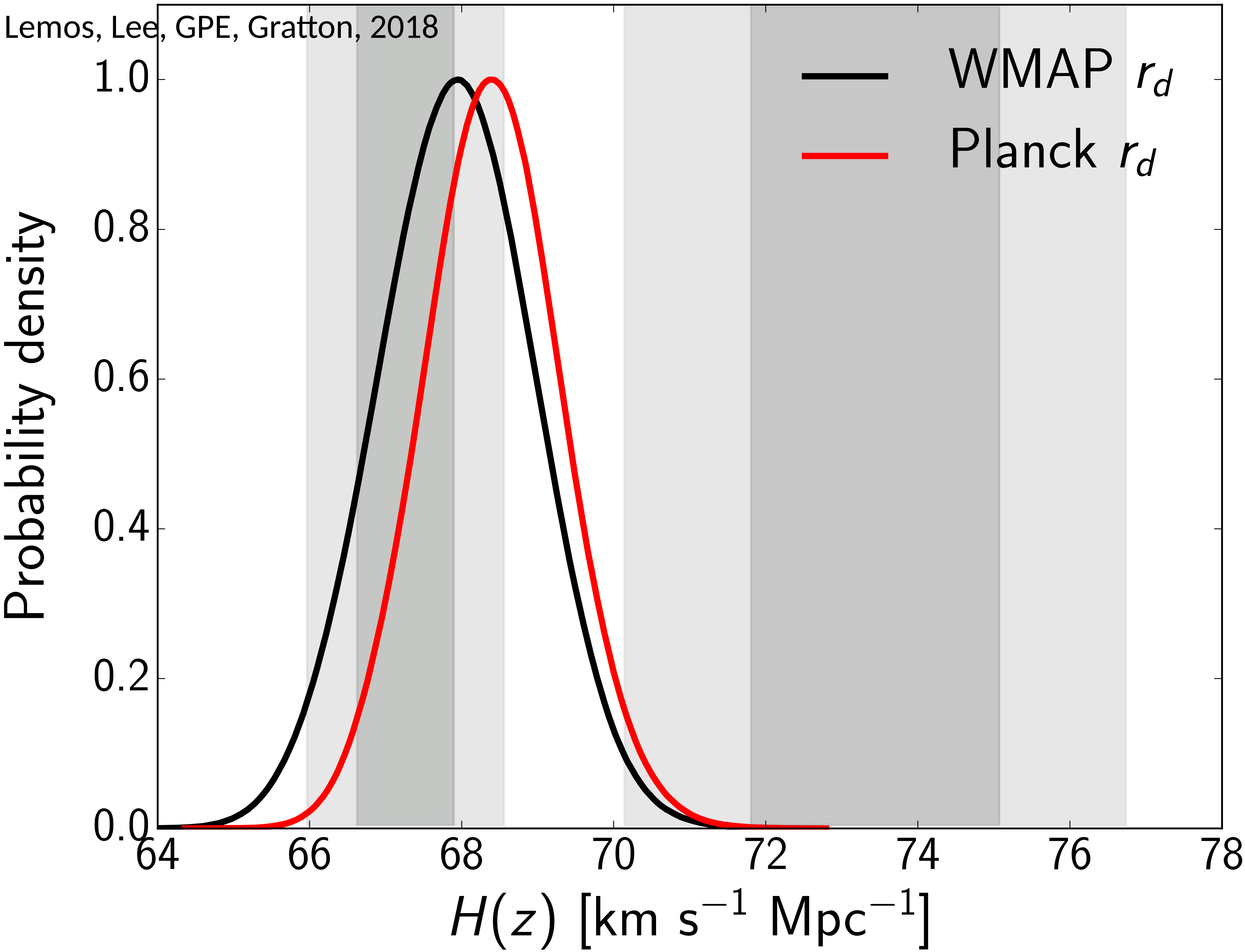
ℓ = 800–2500 TTTEEE best fit
ℓ = 2–2500 foreground
ℓ = 800–2500 foreground
$\Delta\mathcal{D}_\ell$ [μK^2]
40
20
0
−20
−40
500
1000
1500
2000
ℓ



TE 12.5HM
$\mathcal{D}_\ell^{TE}$ $[\mu K^2]$
$\Delta\mathcal{D}_\ell^{TE}$ $[\mu K^2]$
ℓ
150
100
50
0
−50
−100
−150
10
5
0
−5
−10
100
200
300
400

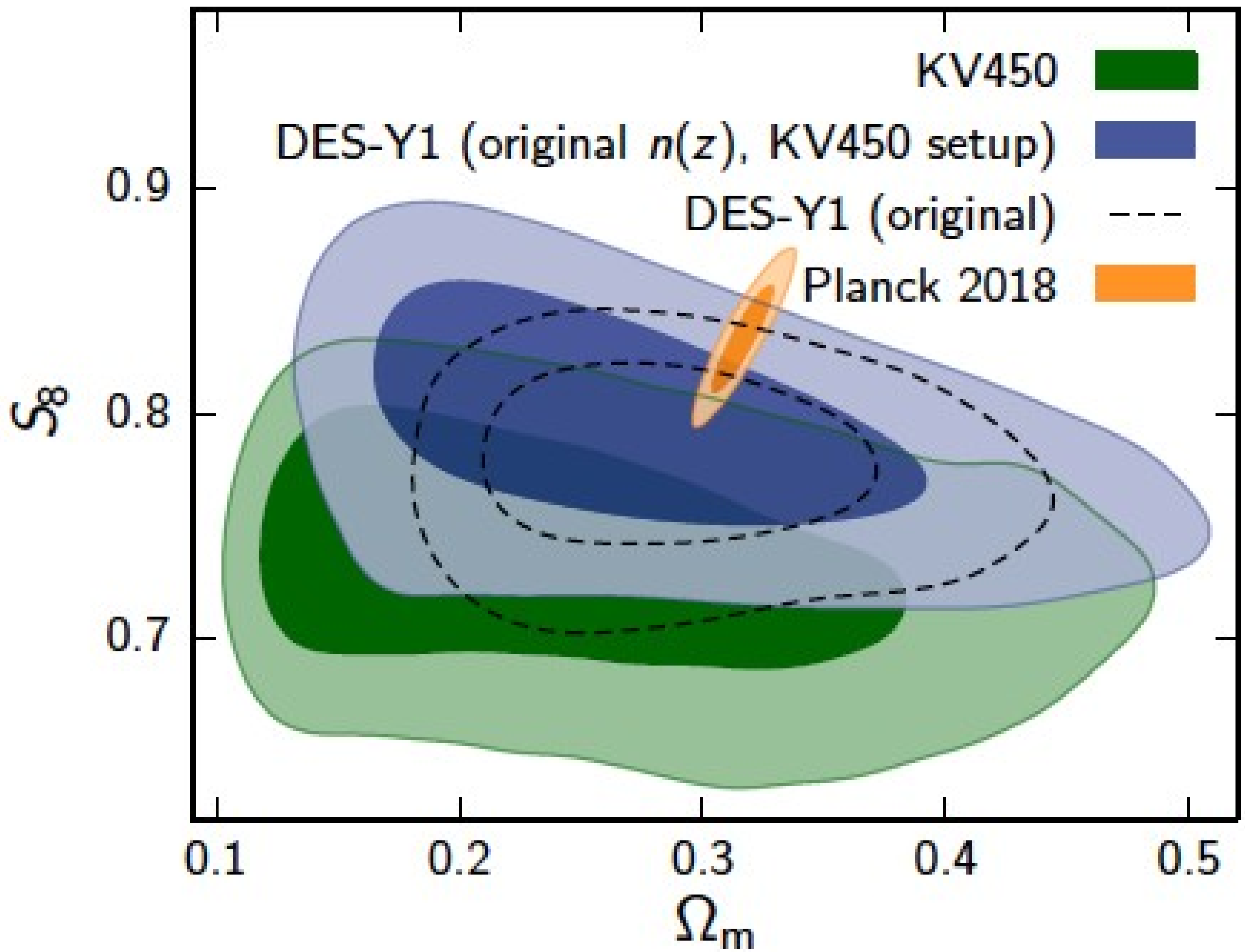
$S_8 = \sigma_8\ (\Omega_m/0.3)^{0.5}$





Lemos, Lee, GPE, Gratton, 2018
WMAP r_d
Planck r_d
Probability density
0.0
0.2
0.4
0.6
0.8
1.0
64
66
68
70
72
74
76
78
$H(z)$ [km s^{-1} Mpc^{-1}]

Galaxy Lensing: Joudaki et al arXiv:1906.09262

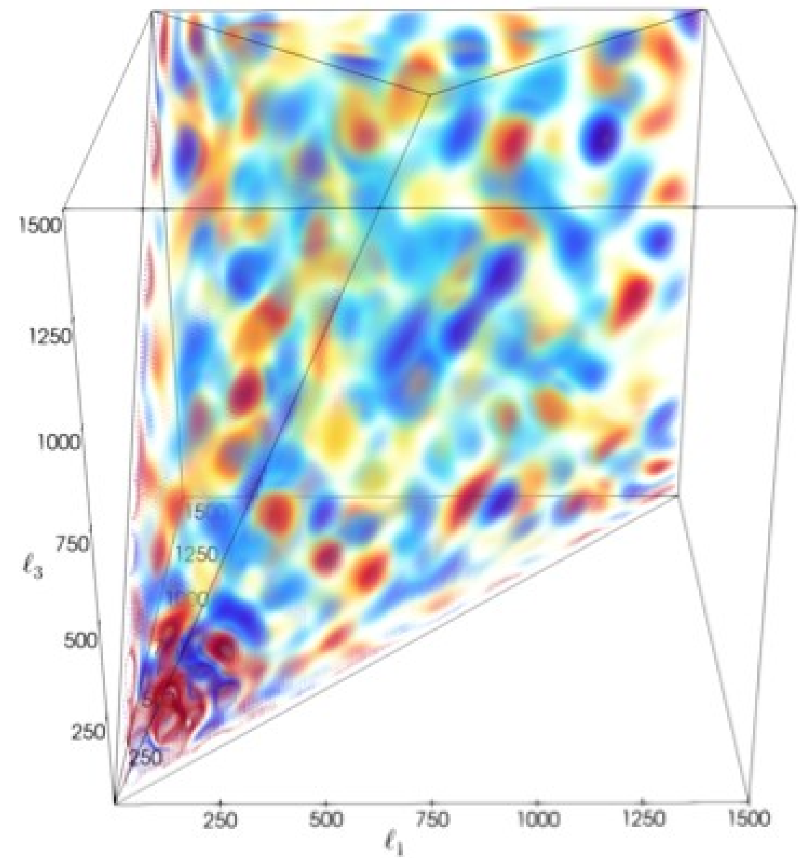


The Conclusions:

- ΛCDM fits the Planck data perfectly within acceptable statistical errors
- If your experiment (CMB, LSS, H_0 ………) disagrees with Planck, then either you are wrong, or there is new physics beyond ΛCDM.
- Any new physics must produce temperature and polarization spectra that are degenerate with base ΛCDM over the multipole range $2 \leq l \leq 2500$. Any such evidence is strongly dependent on the fidelity of other data.

Non-Gaussianity

$$f_{NL}^{\text{local}} = -0.9 \pm 5$$
$$f_{NL}^{\text{equil}} = -26 \pm 47$$
$$f_{NL}^{\text{orth}} = -34 \pm 24$$



Lemos, Lee, GPE, Gratton, 2018

$H_0 = 74.03 \pm 1.403$ km/s/Mpc (Riess etal)

$H_0 = 67.44 \pm 0.58$ km/s/Mpc (Planck)

$$H^2(z) = H^2_f\,[\,A(1+z)^3 + B + Cz + D(1+z)^{\varepsilon}\,]$$