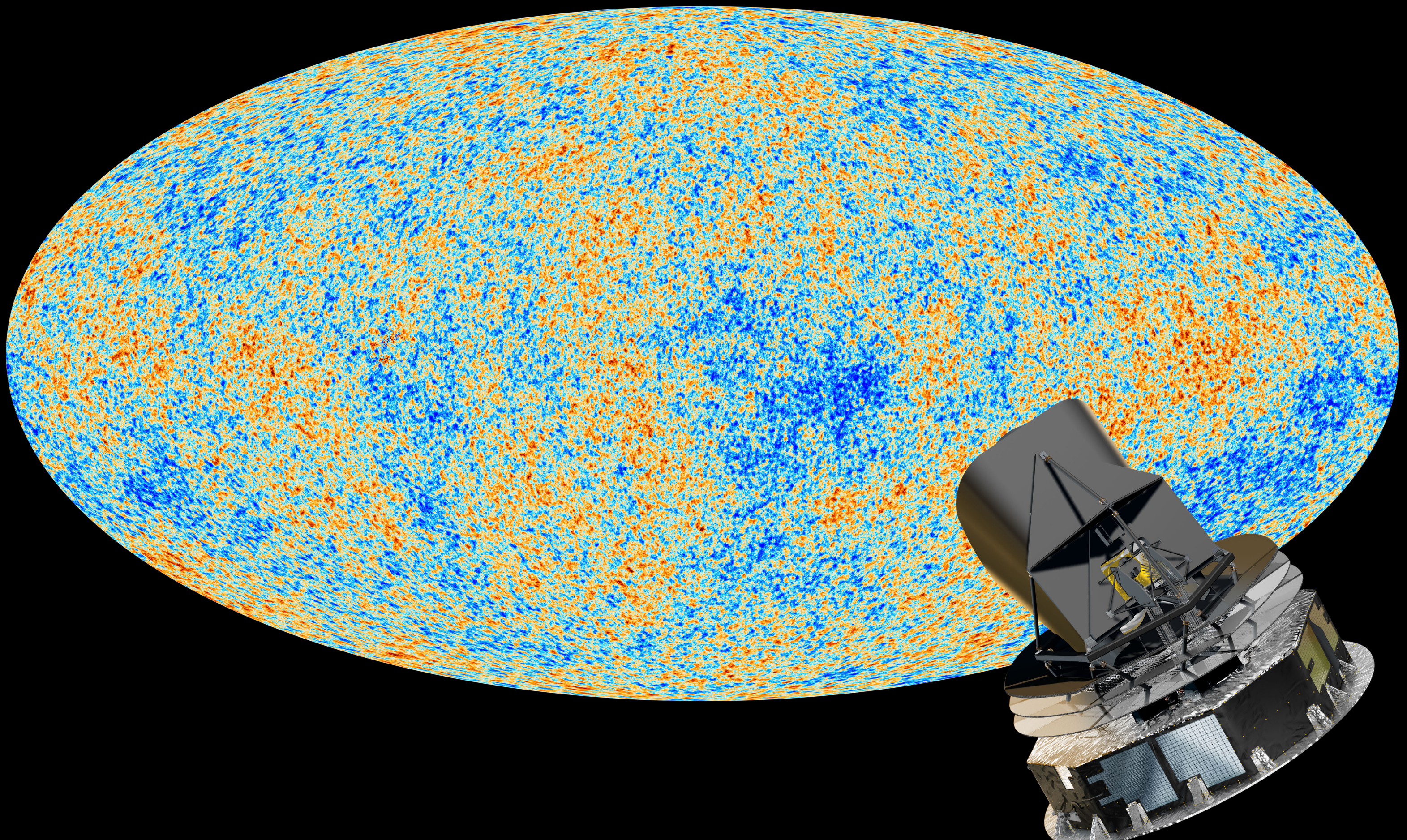
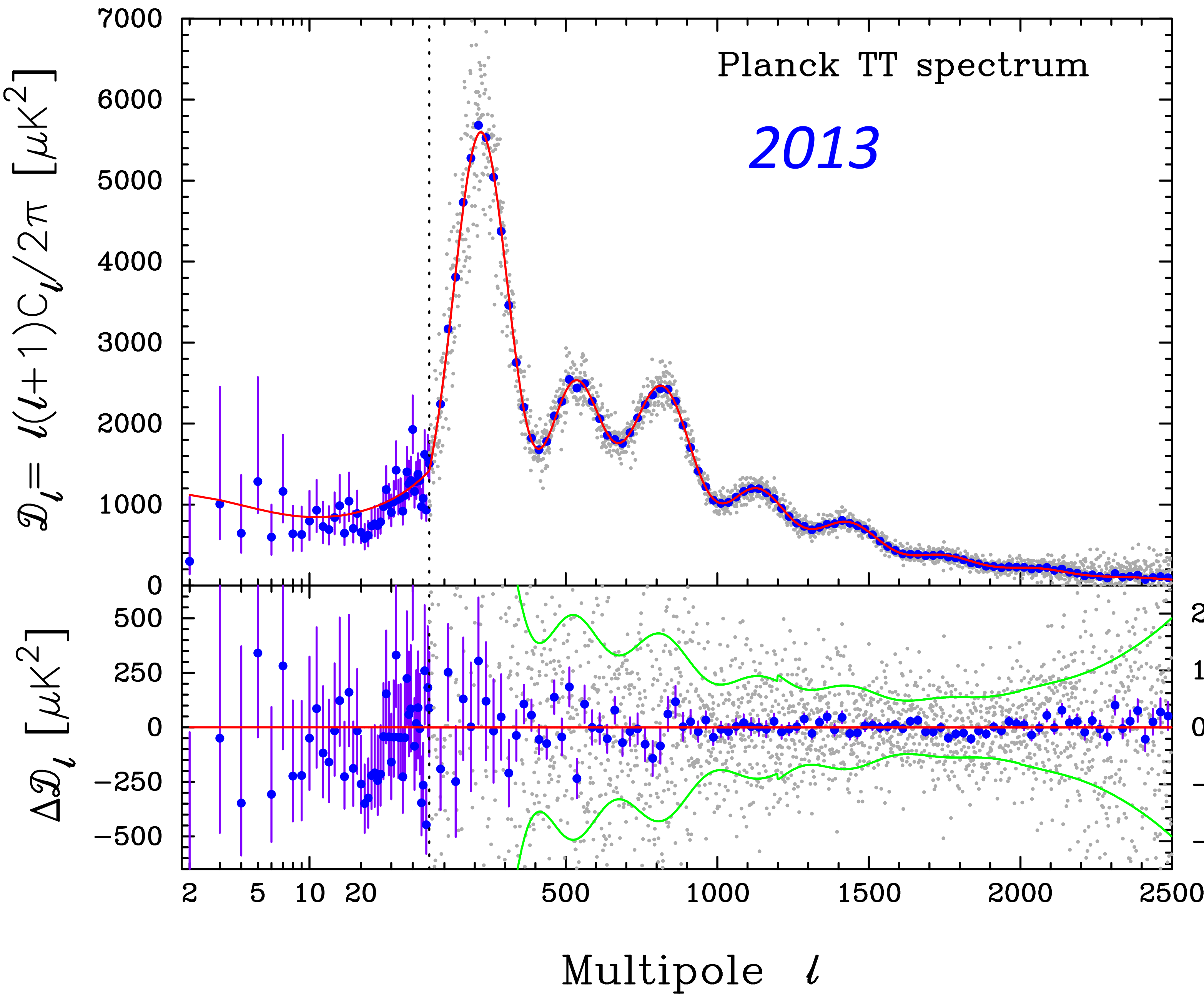
Planck, ΛCDM & H_0

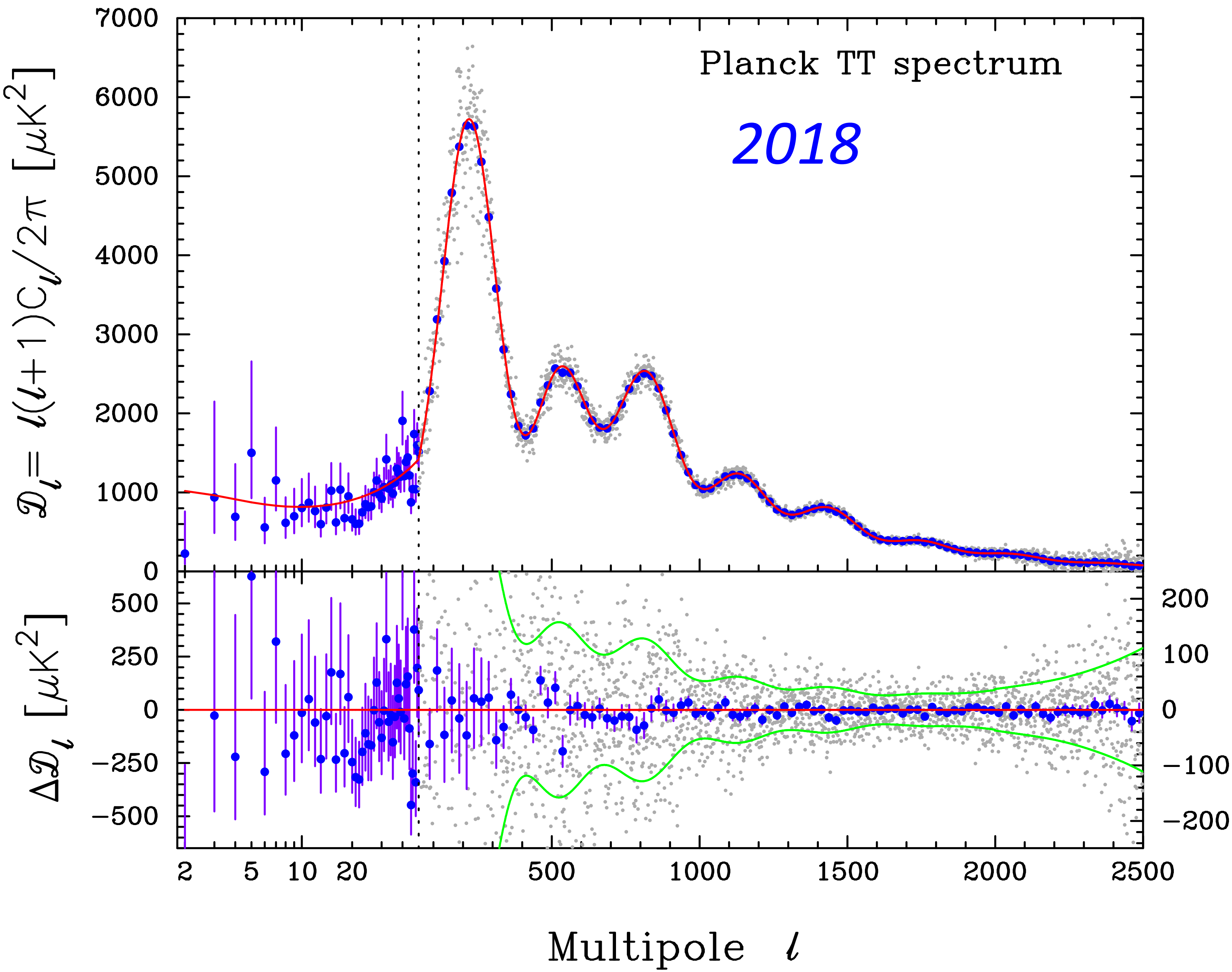
George Efstathiou KICC



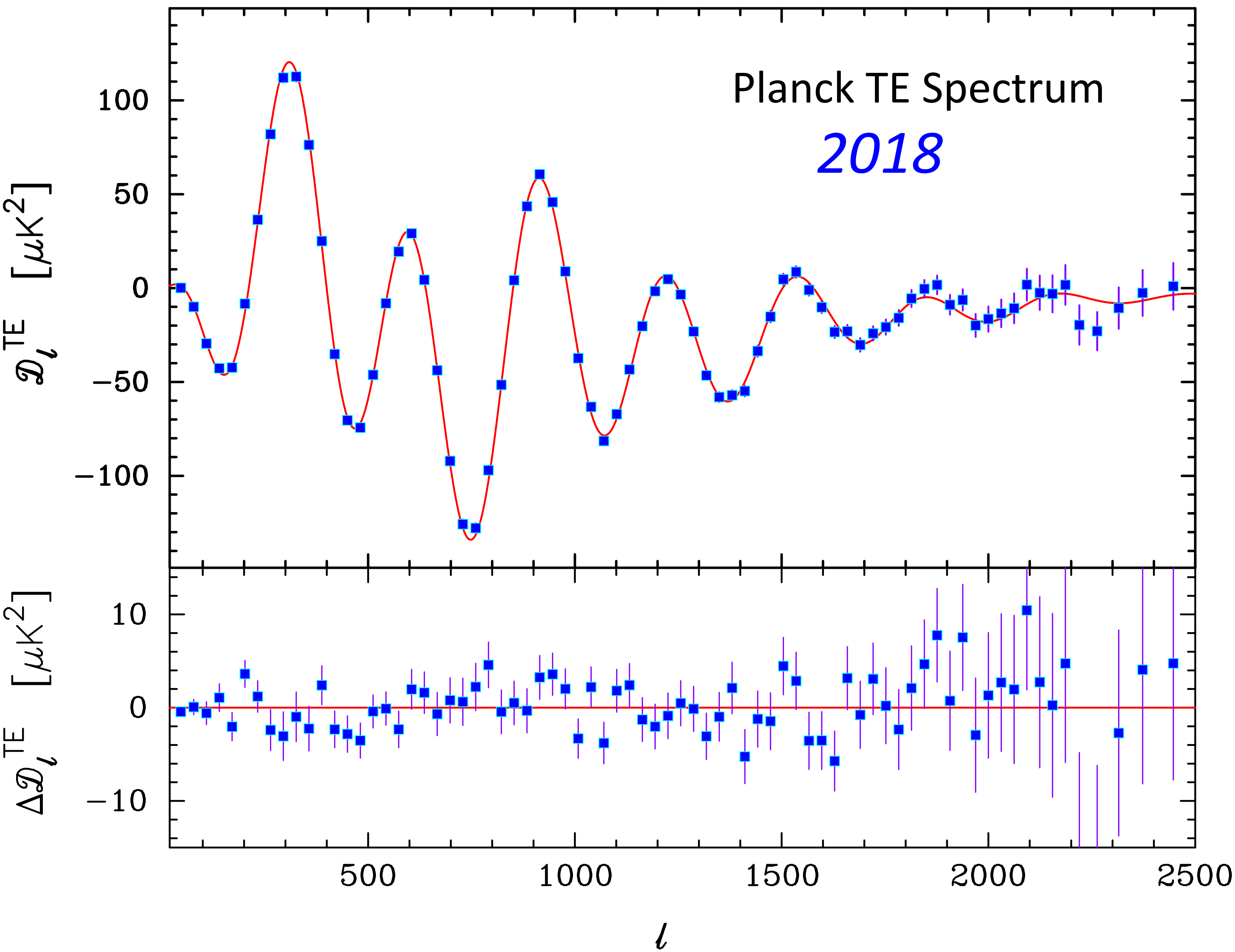
30th March 2021



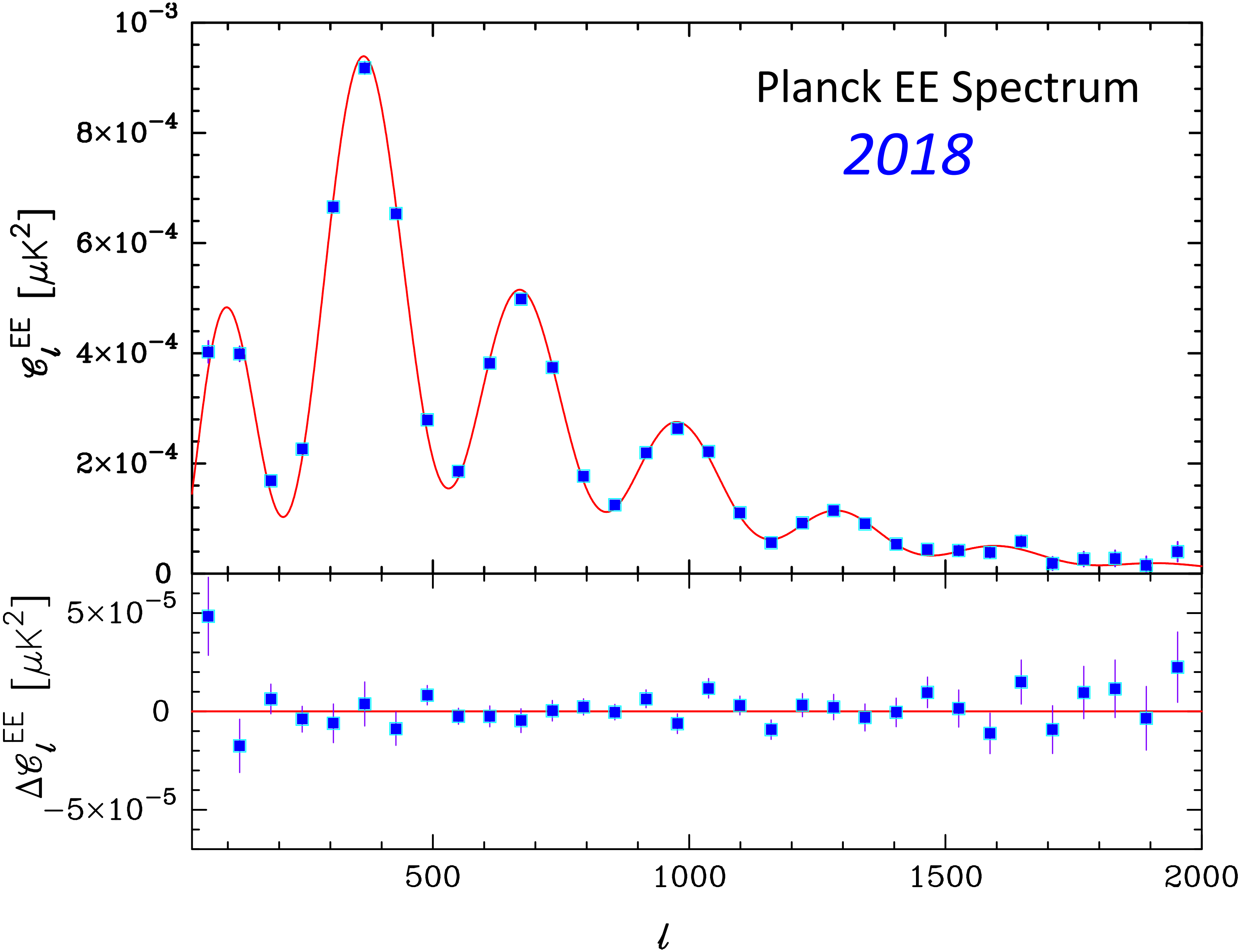
Planck TT spectrum
2013
$\mathcal{D}_\ell = \ell(\ell+1)C_\ell/2\pi\ [\mu K^2]$
$\Delta\mathcal{D}_\ell\ [\mu K^2]$
Multipole ℓ
7000
6000
5000
4000
3000
2000
1000
0
500
250
0
−250
−500
200
100
0
−100
−200
2
5
10
20
500
1000
1500
2000
2500



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



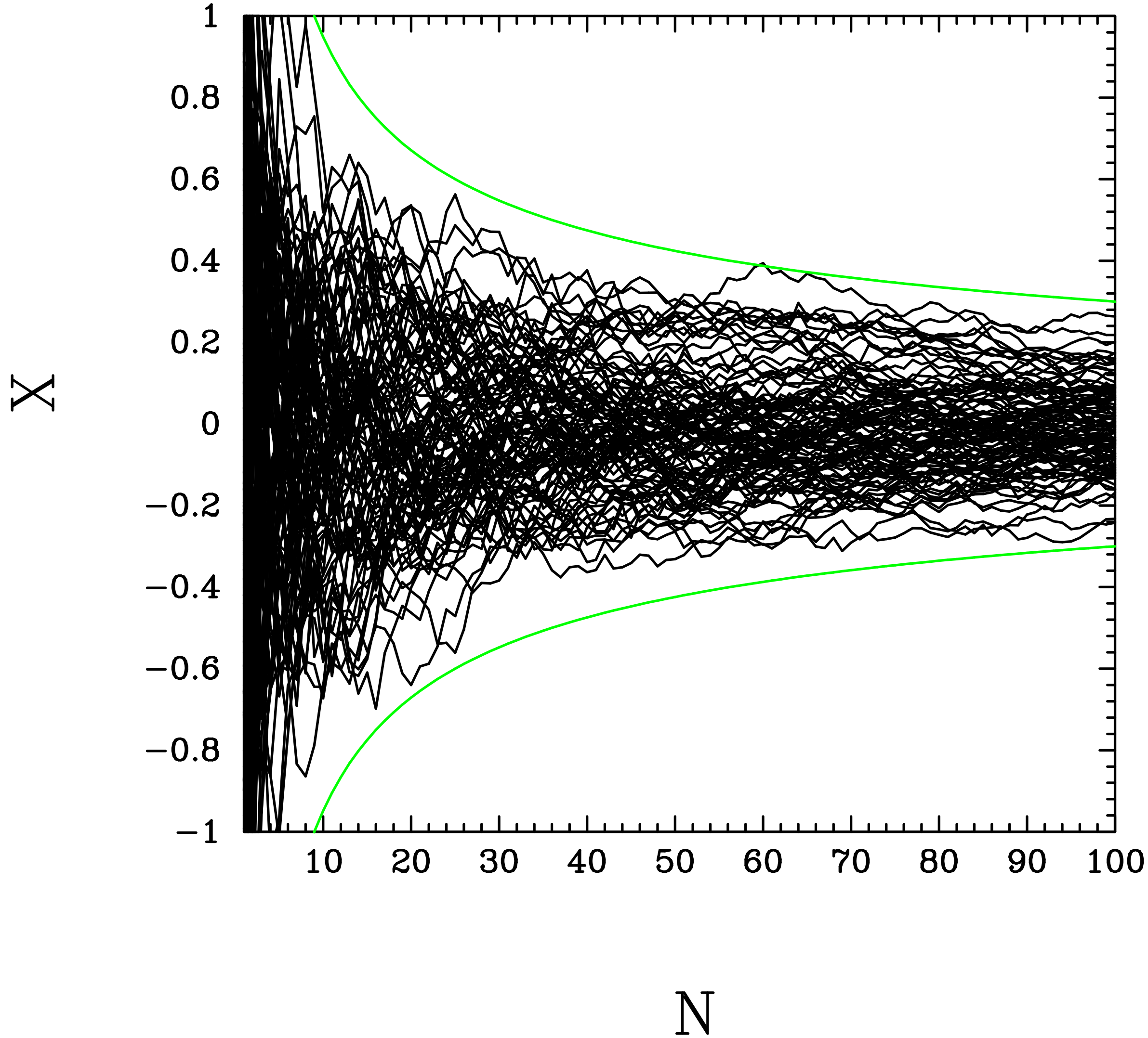
Planck EE Spectrum
2018
10^{-3}
8×10^{-4}
6×10^{-4}
4×10^{-4}
2×10^{-4}
0
$\mathscr{C}_\ell^{EE}\ [\mu K^2]$
5×10^{-5}
0
-5×10^{-5}
$\Delta\mathscr{C}_\ell^{EE}\ [\mu K^2]$
500
1000
1500
2000
ℓ

'Odd' aspects of Planck spectra?

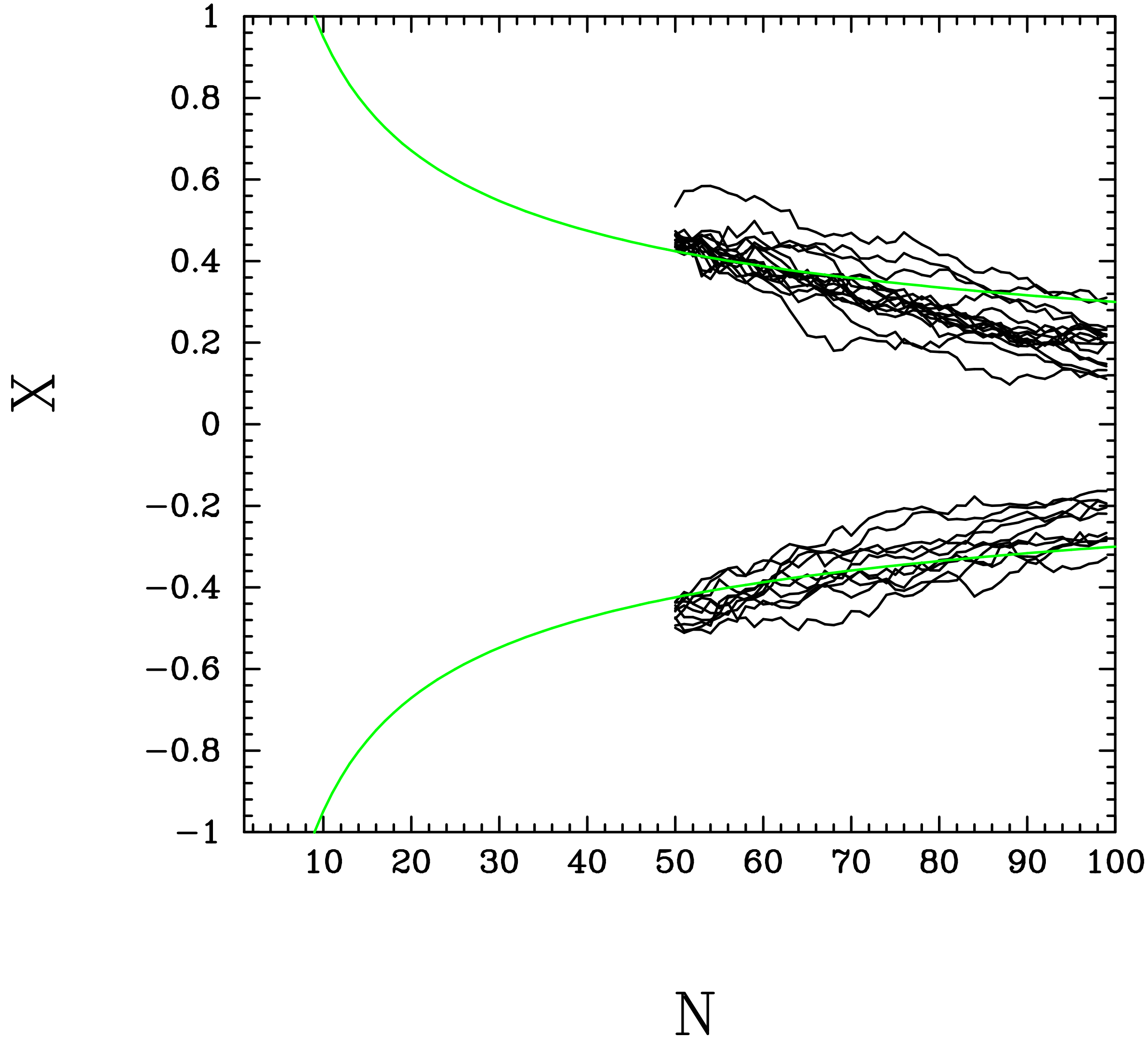
- Planck temperature spectra want more lensing (A_L >1) .
- Planck data favour closed universes.
- High multipoles (ℓ > 800) give different parameters to lower multipoles (e.g. Addison etal 2016, ApJ, 818, 132).
- Outliers in TT spectrum and in TE spectrum (e.g. ℓ ~ 165 in TE , Obied etal 2017, PRD,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

based on work done with Steven Gratton

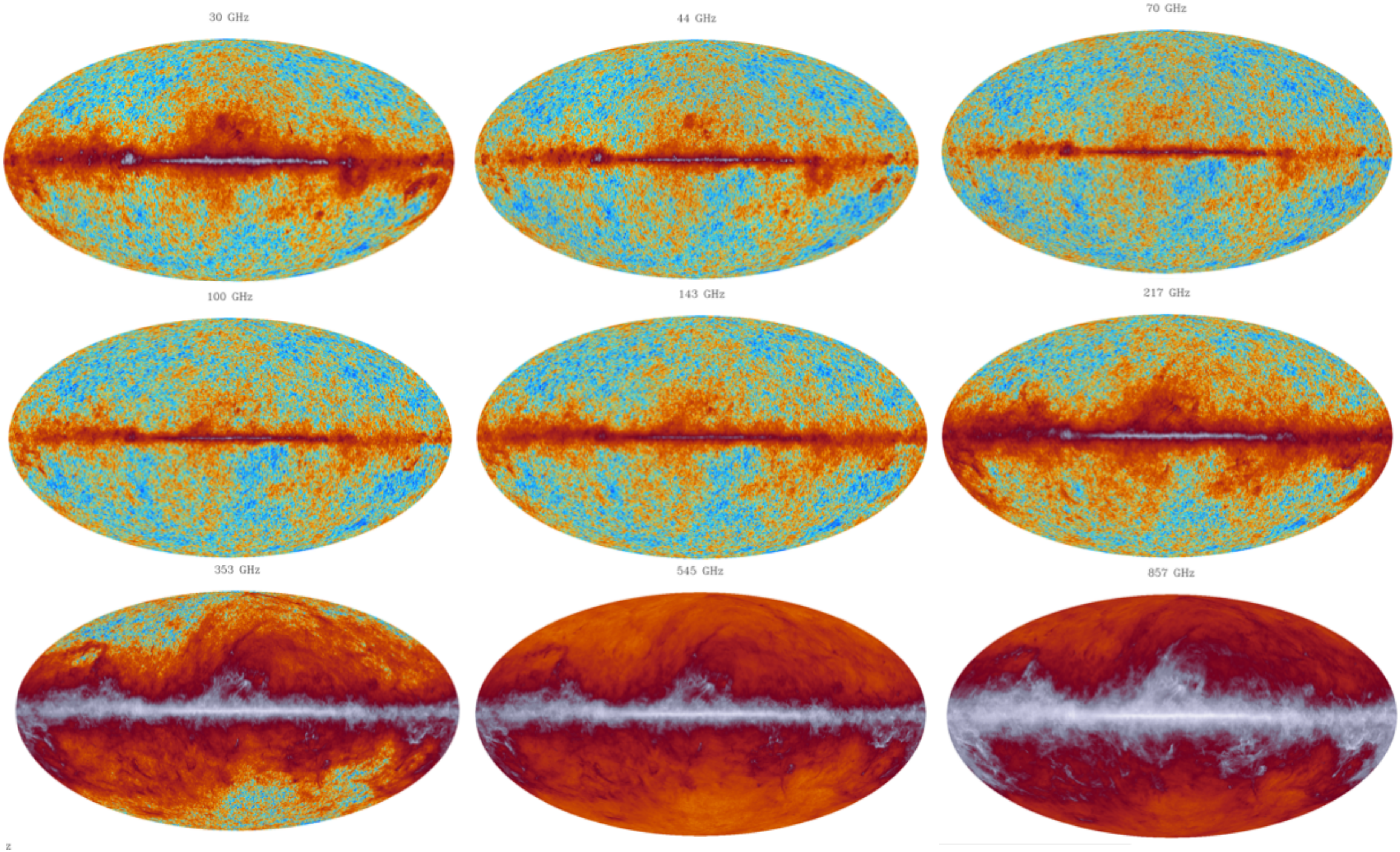
$$X = \frac{1}{N} \sum_{i=1}^{N} x_i$$

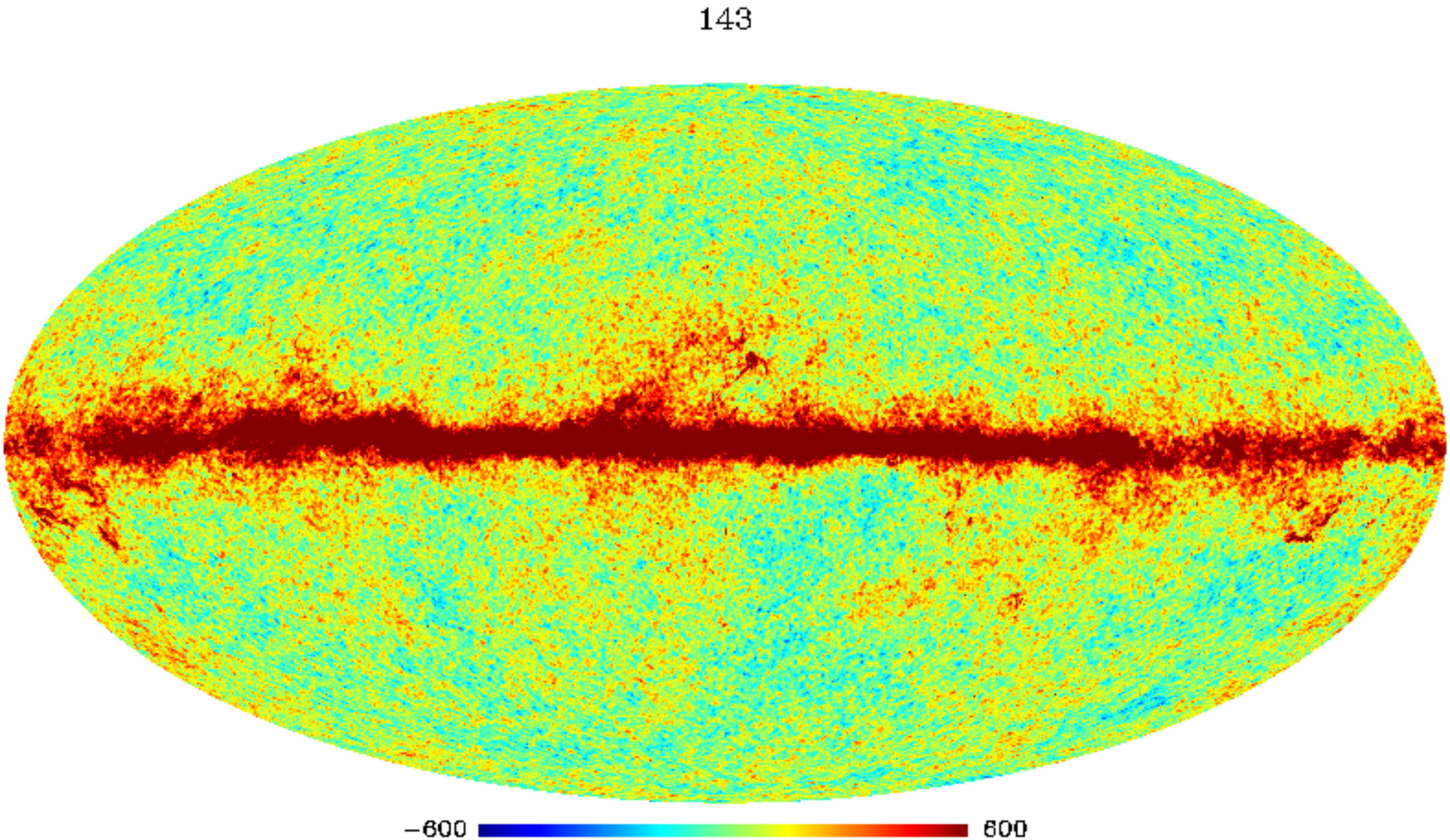


$$X = \frac{1}{N}\sum_{i=1}^{N} x_i$$

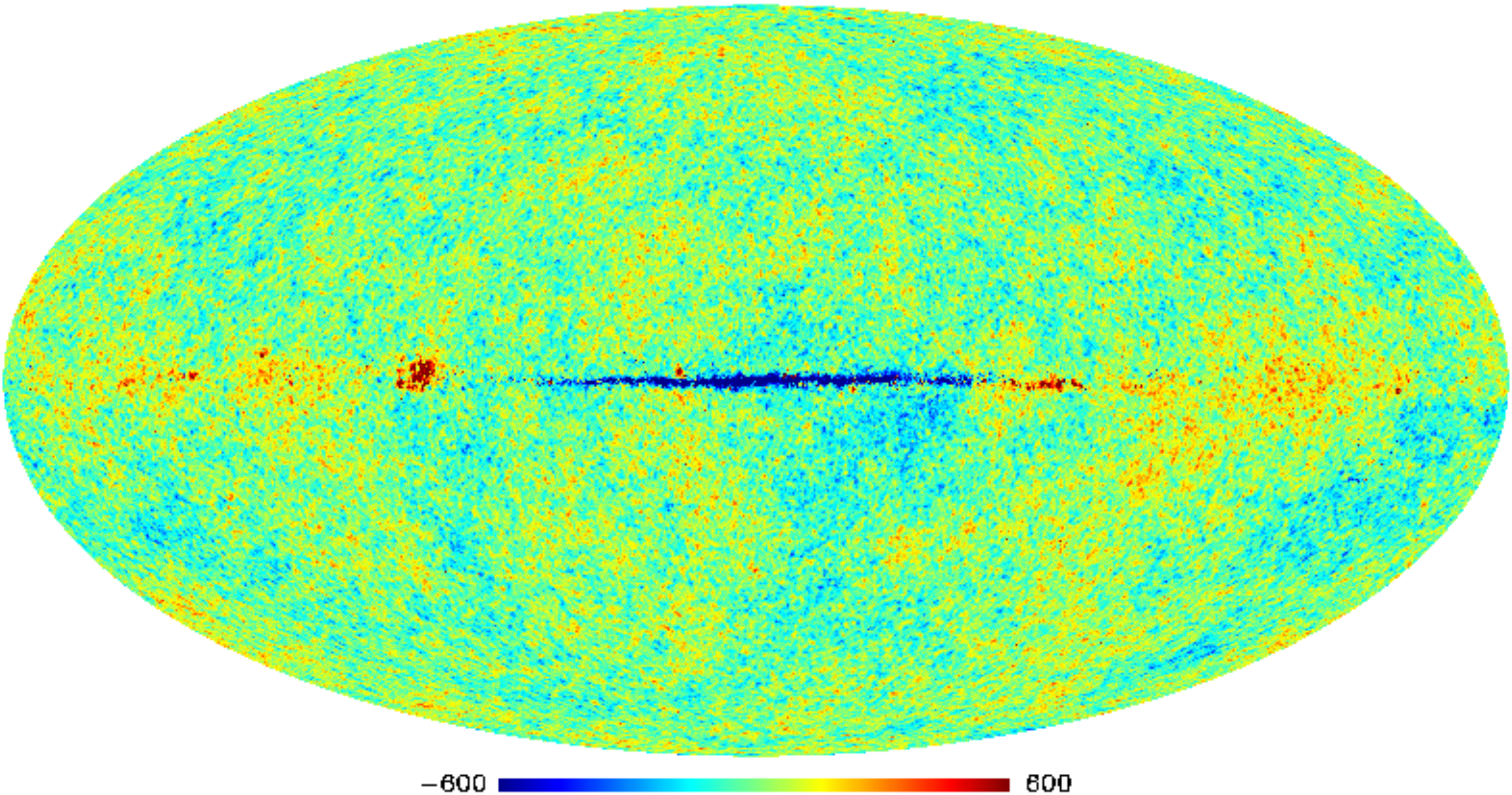


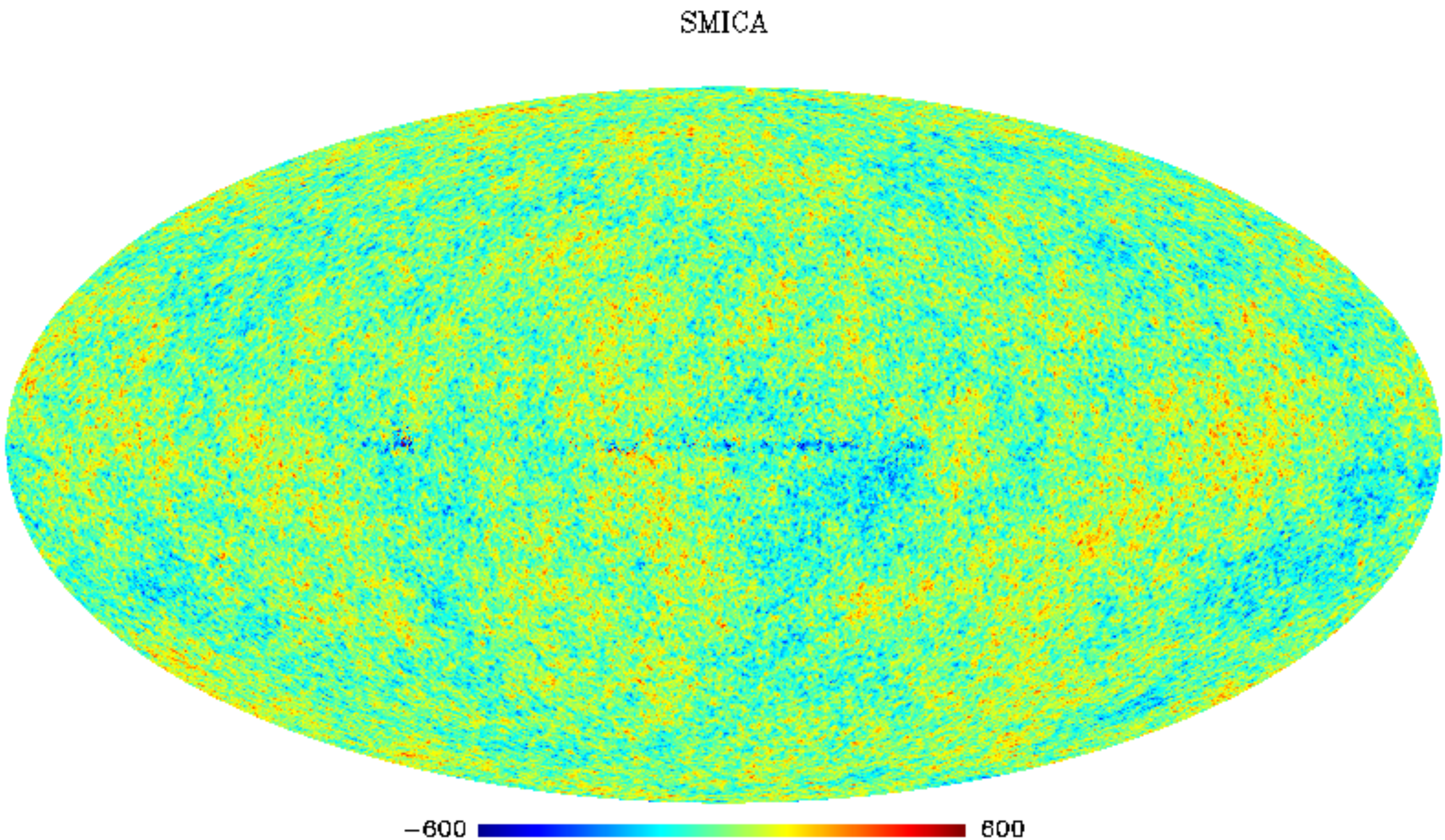
PLANCK FREQUENCYMAPS

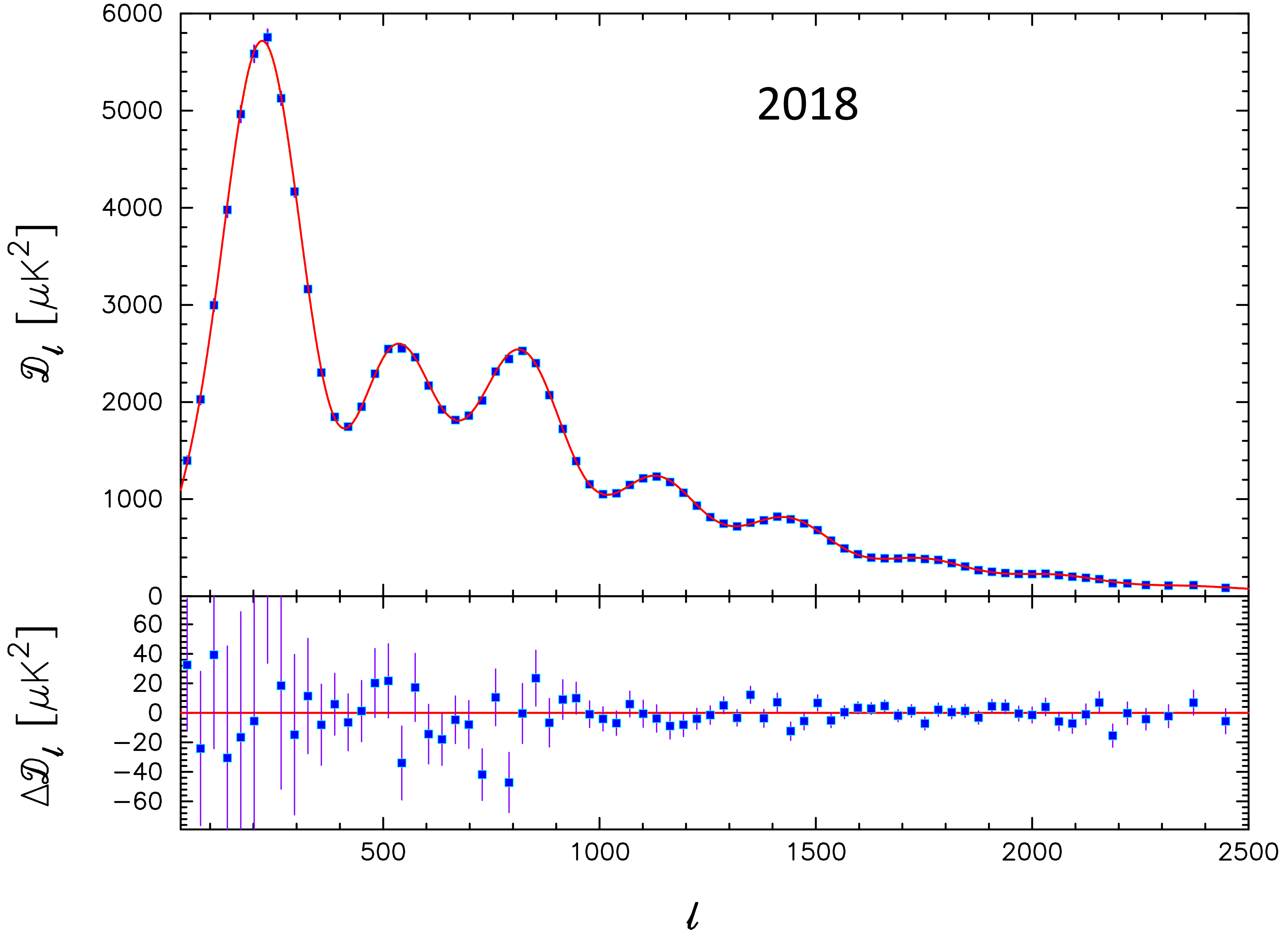



143
−600
600

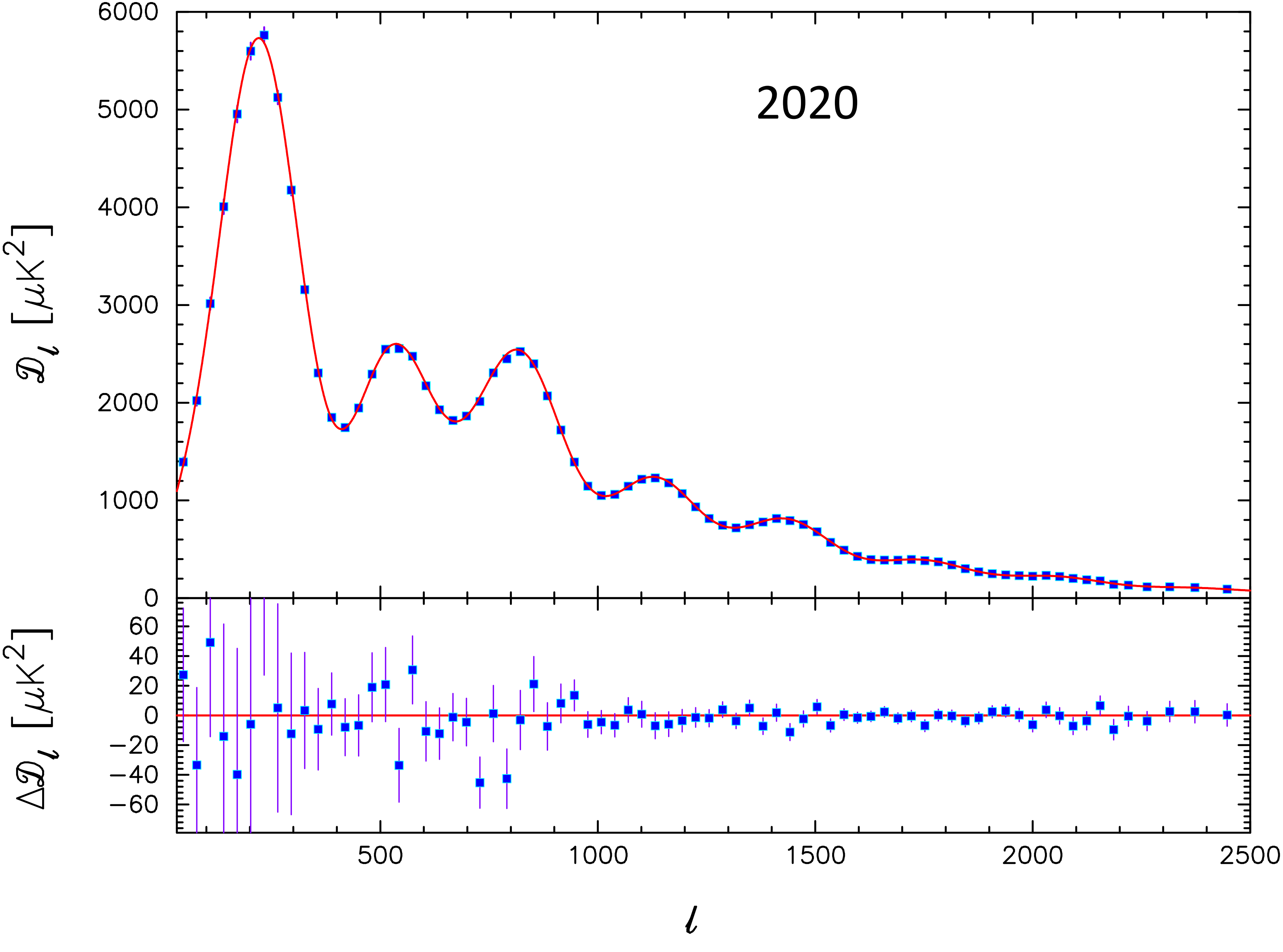
143 cleaned with 545



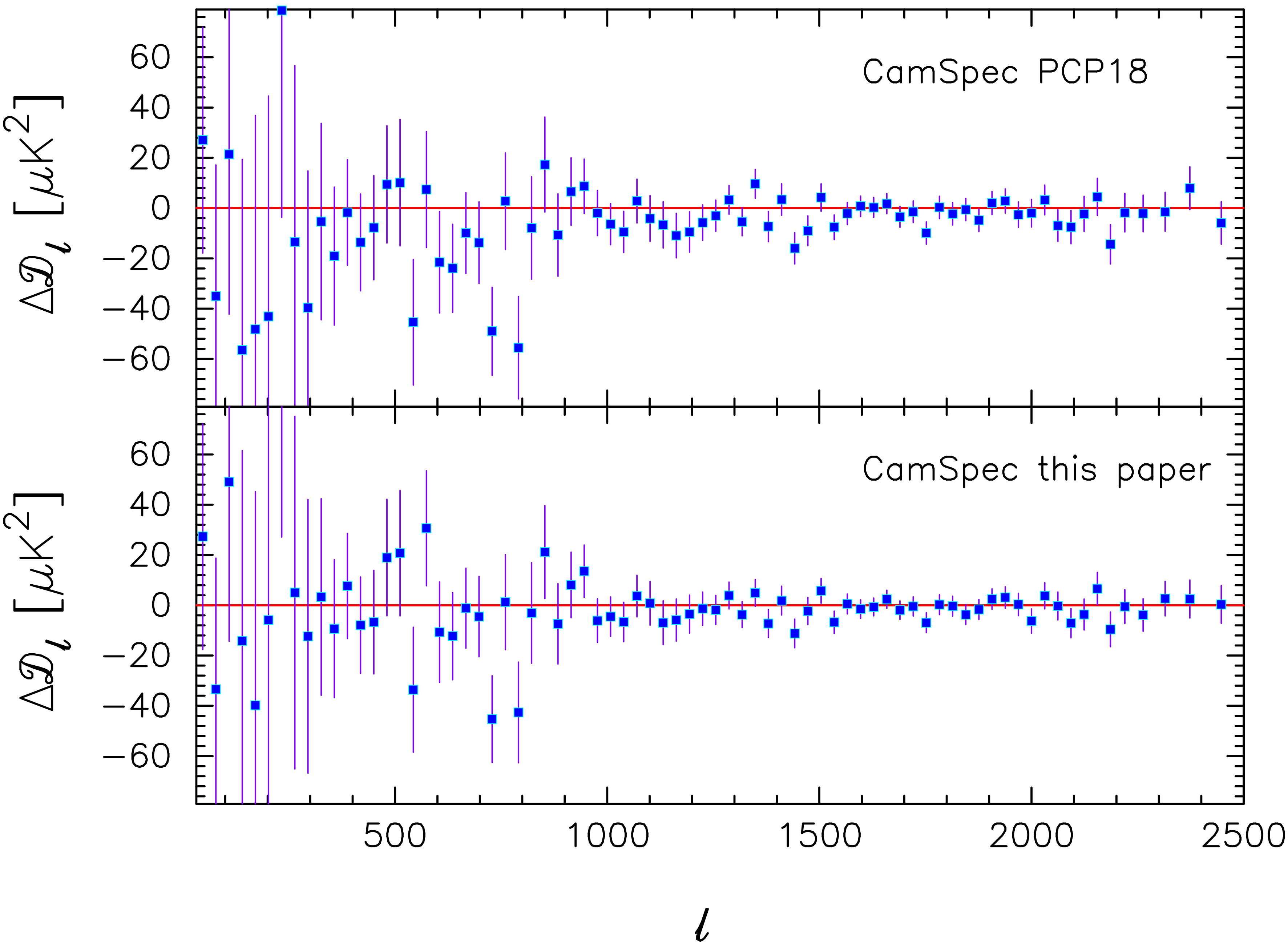

SMICA
−600
600

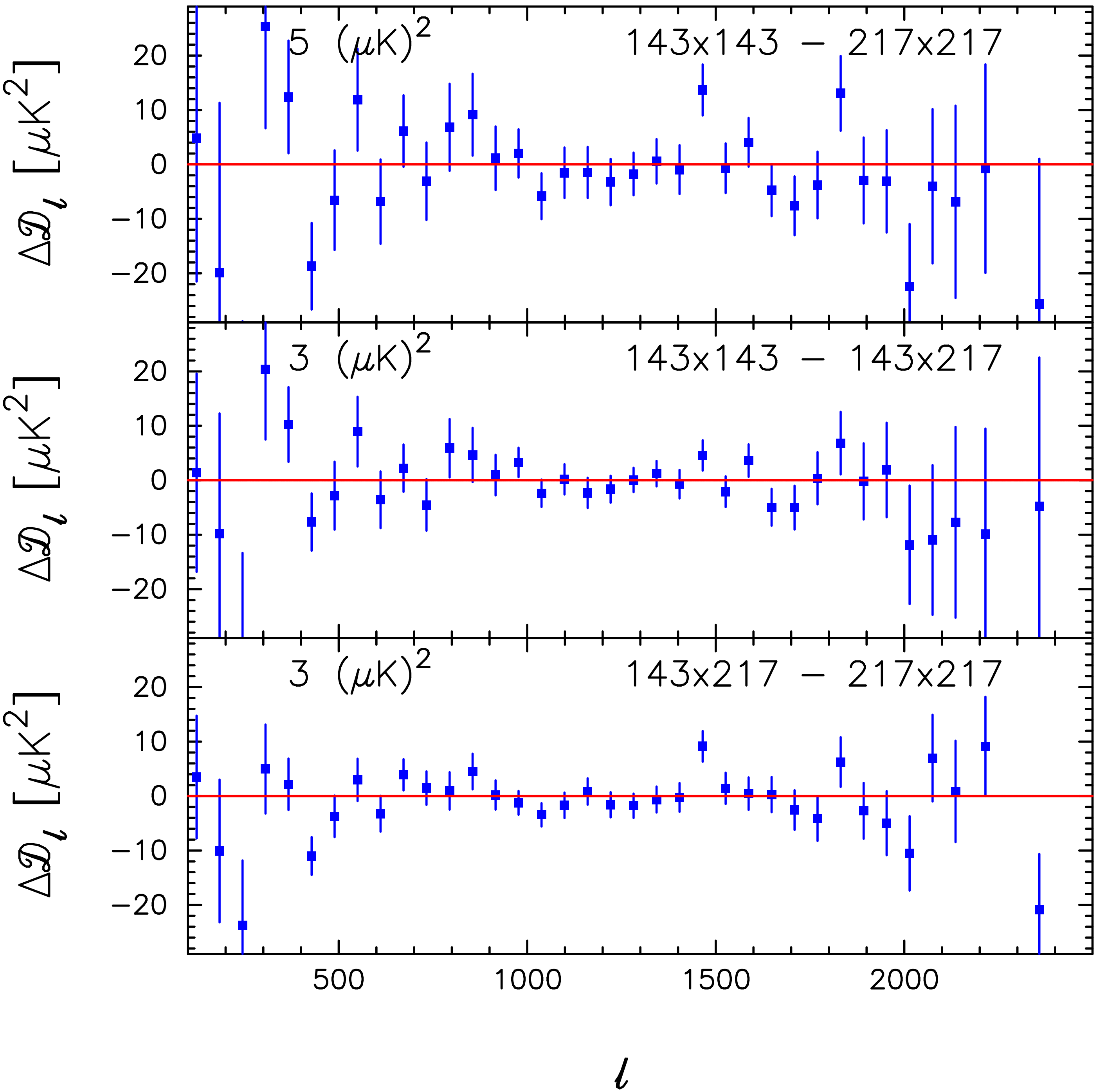


2018
6000
5000
4000
3000
2000
1000
0
$\mathcal{D}_\ell$ [μK^2]
60
40
20
0
−20
−40
−60
$\Delta\mathcal{D}_\ell$ [μK^2]
500
1000
1500
2000
2500
ℓ

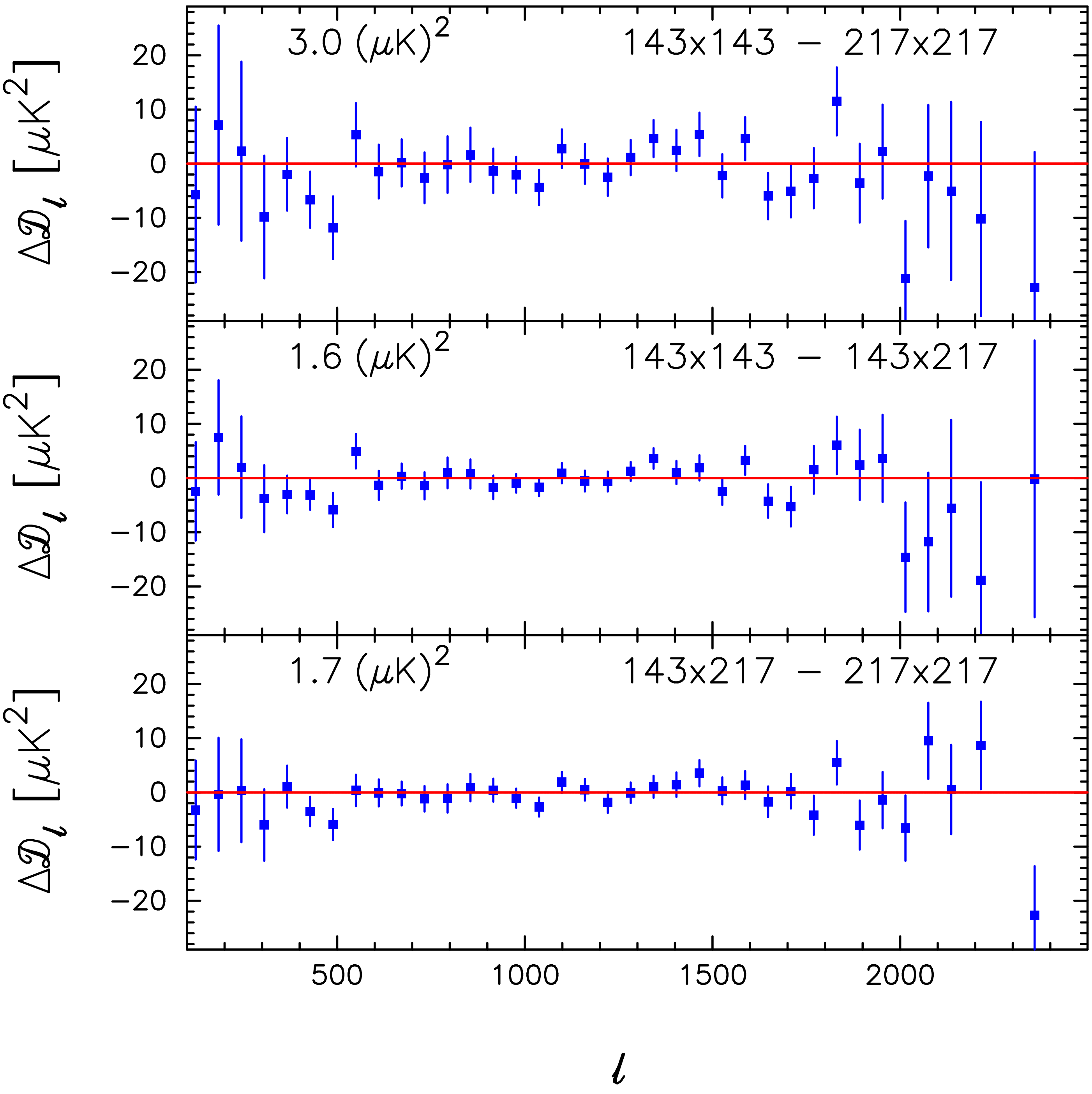


2020
6000
5000
4000
3000
2000
1000
0
60
40
20
0
−20
−40
−60
500
1000
1500
2000
2500
$\mathcal{D}_\ell$ $[\mu K^2]$
$\Delta\mathcal{D}_\ell$ $[\mu K^2]$
ℓ

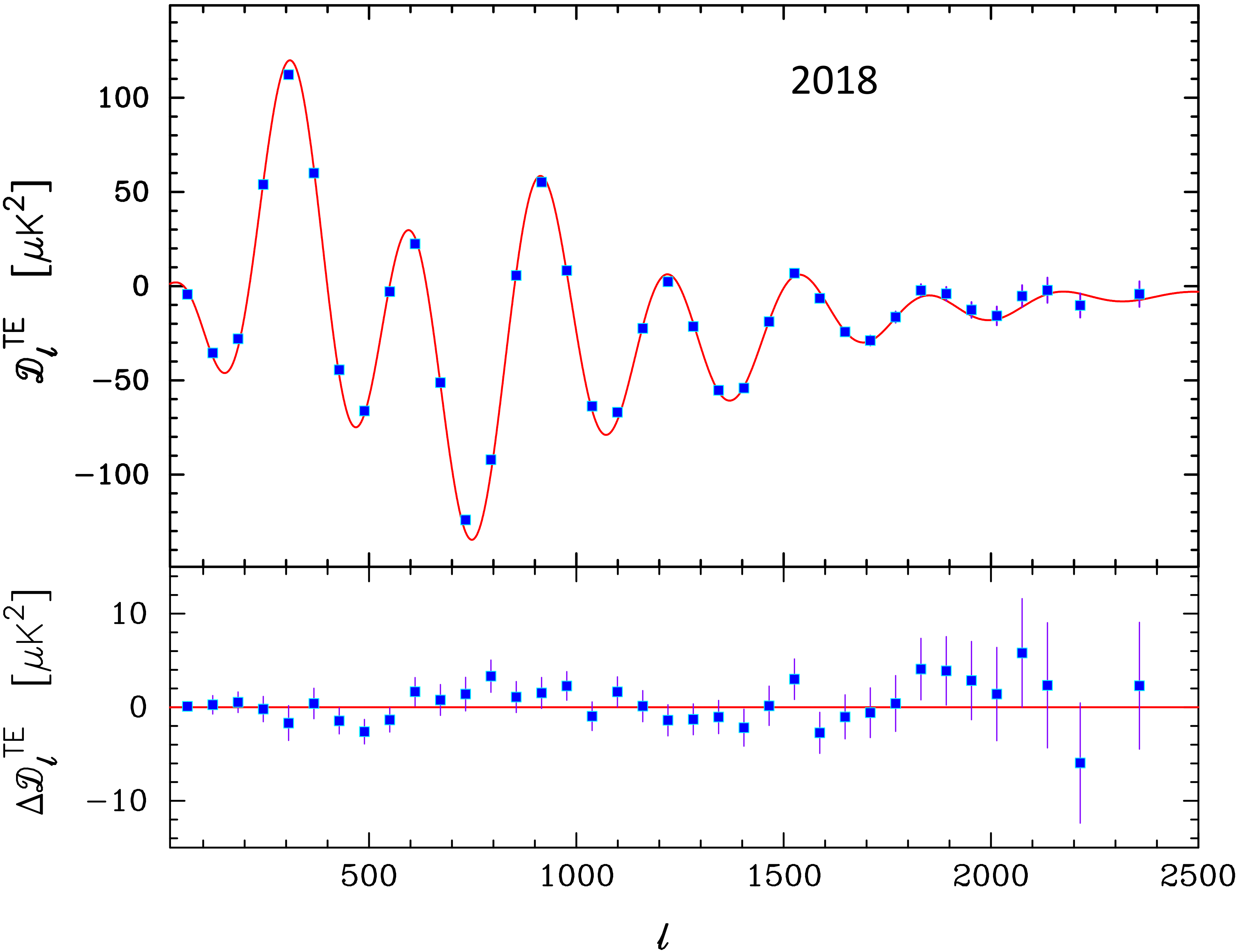

CamSpec PCP18
CamSpec this paper
$\Delta\mathcal{D}_\ell$ [μK^2]
$\Delta\mathcal{D}_\ell$ [μK^2]
60
40
20
0
−20
−40
−60
500
1000
1500
2000
2500
ℓ



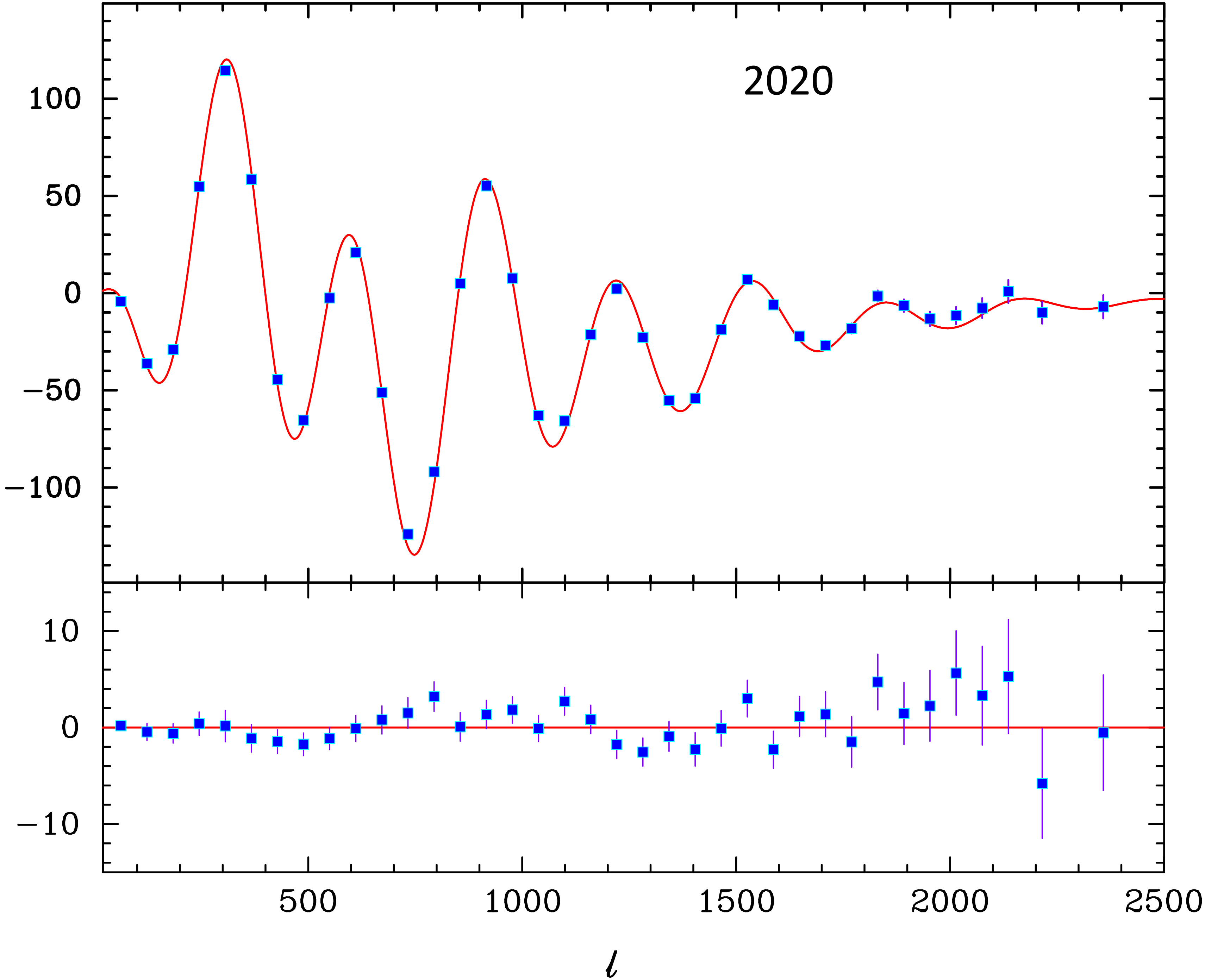
5 $(\mu K)^2$
143x143 − 217x217
3 $(\mu K)^2$
143x143 − 143x217
3 $(\mu K)^2$
143x217 − 217x217
$\Delta\mathcal{D}_\ell$ [μK^2]
ℓ

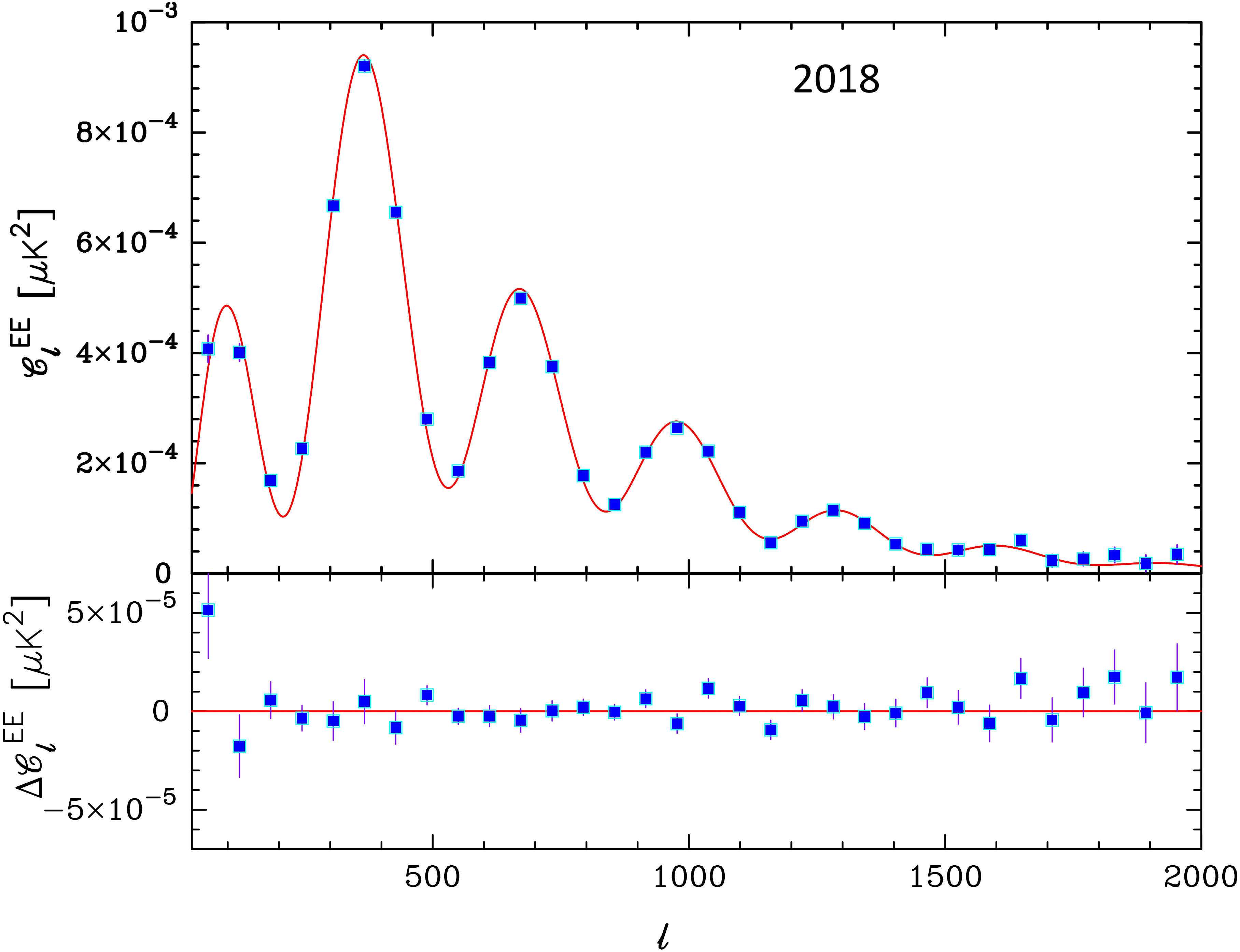


3.0 (μK)^2
143x143 − 217x217
1.6 (μK)^2
143x143 − 143x217
1.7 (μK)^2
143x217 − 217x217
ΔD_ℓ [μK^2]
20
10
0
−10
−20
500
1000
1500
2000
ℓ

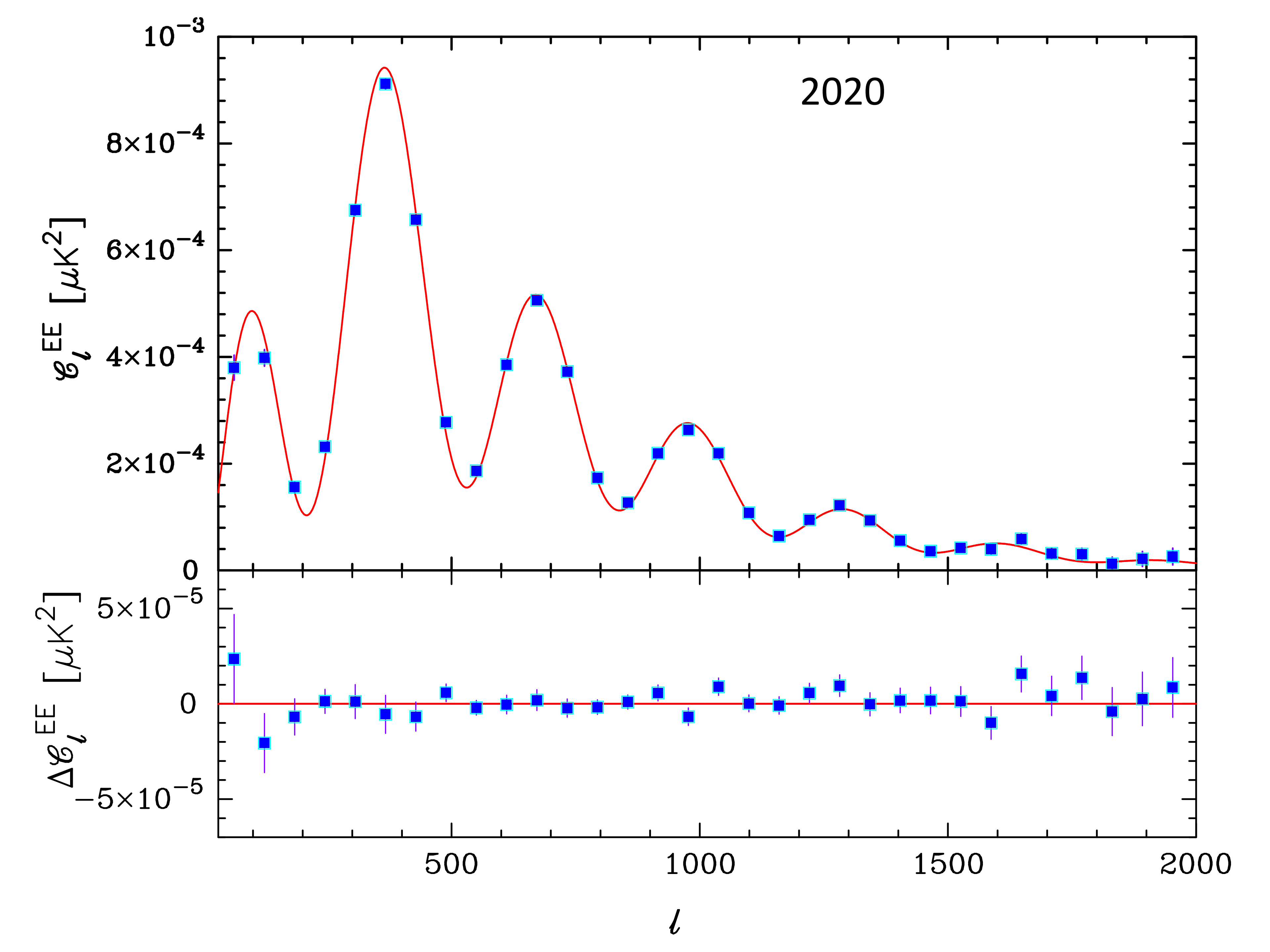


2018
100
50
0
−50
−100
$\mathcal{D}_\ell^{TE}$ [μK^2]
10
0
−10
$\Delta\mathcal{D}_\ell^{TE}$ [μK^2]
500
1000
1500
2000
2500
ℓ

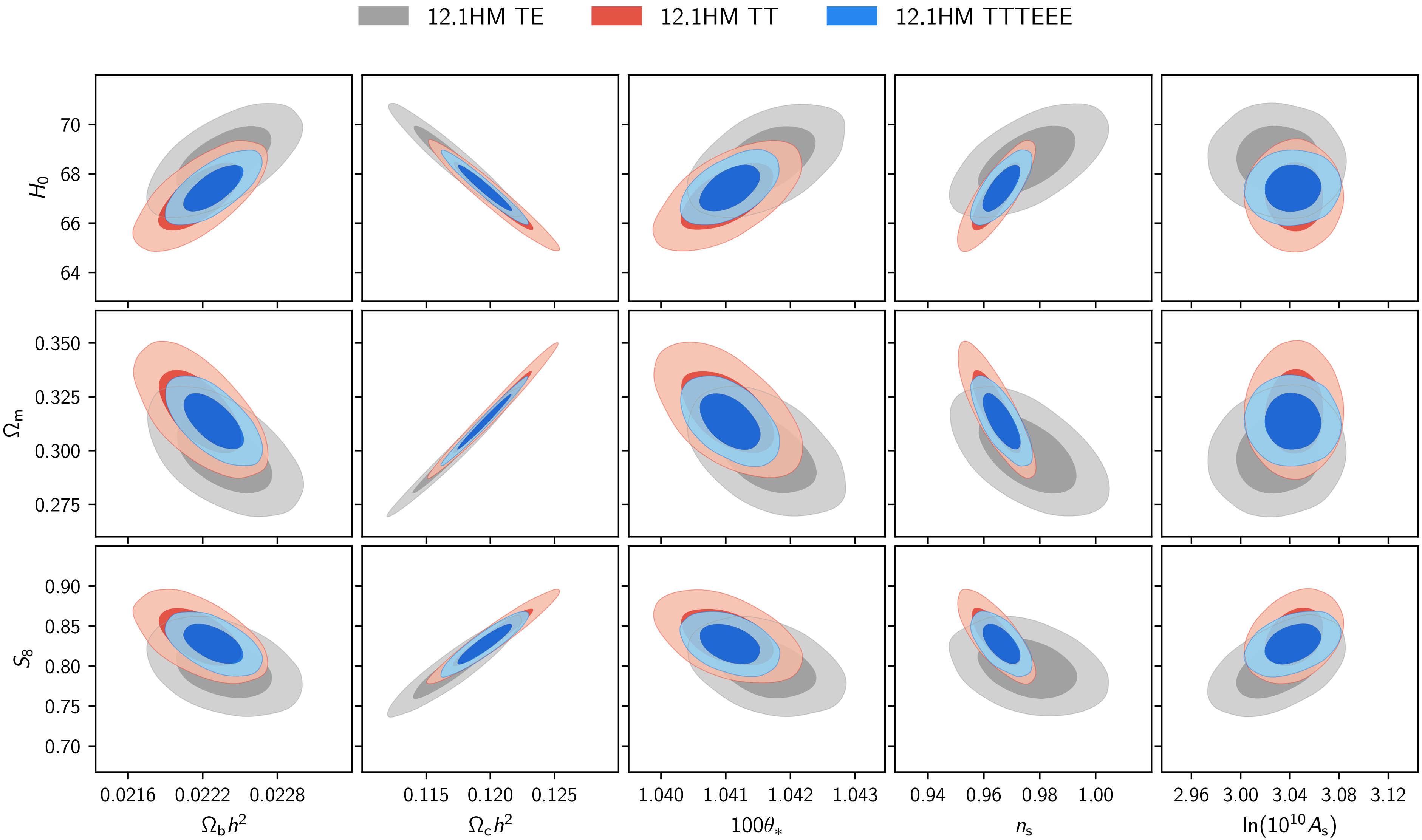

2020
100
50
0
−50
−100
$\mathcal{D}_\ell^{TE}$ [μK^2]
10
0
−10
$\Delta\mathcal{D}_\ell^{TE}$ [μK^2]
500
1000
1500
2000
2500
ℓ

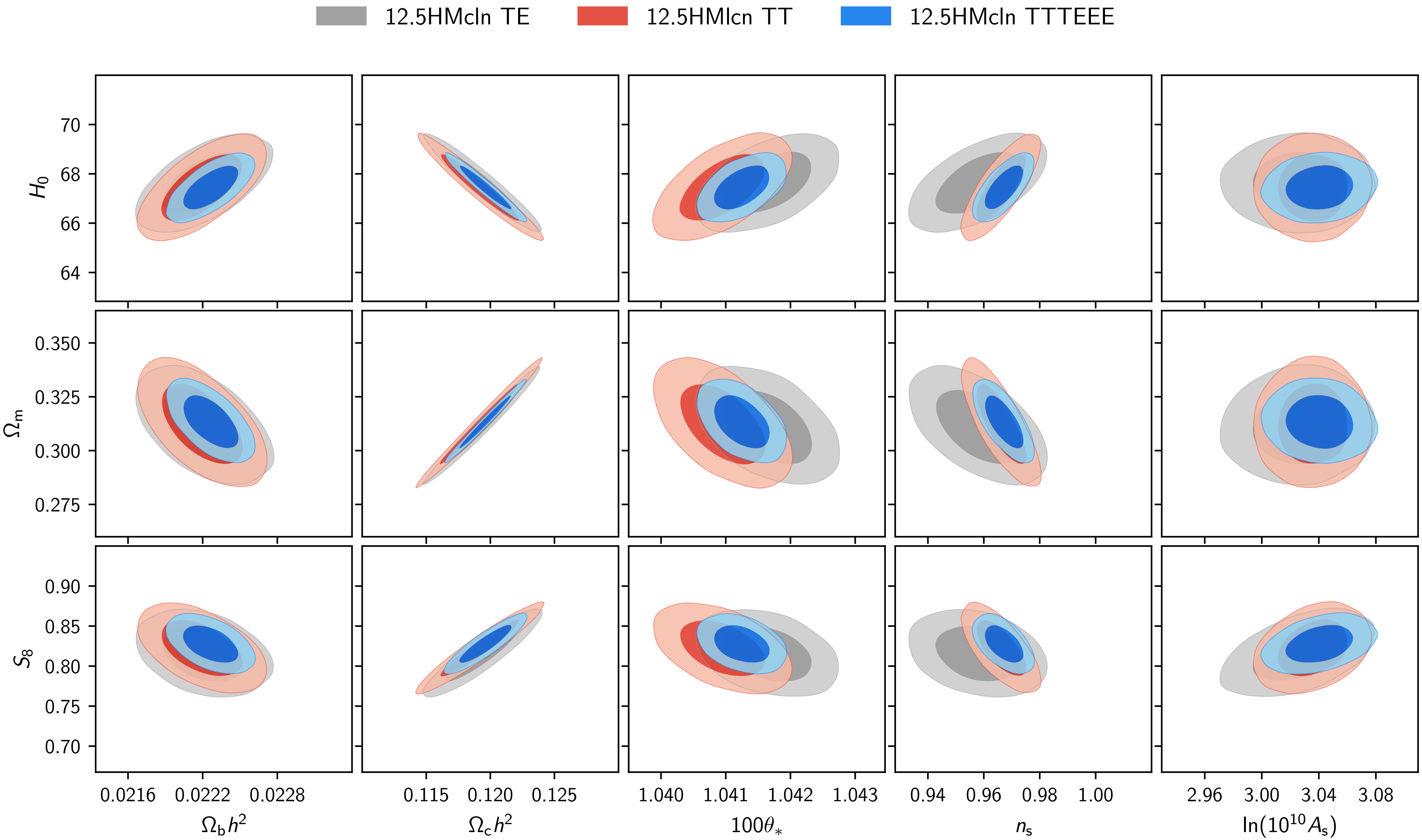


2018
$\mathscr{C}_\ell^{EE}$ [μK^2]
$\Delta\mathscr{C}_\ell^{EE}$ [μK^2]
10^{-3}
8×10^{-4}
6×10^{-4}
4×10^{-4}
2×10^{-4}
0
5×10^{-5}
0
-5×10^{-5}
500
1000
1500
2000
ℓ



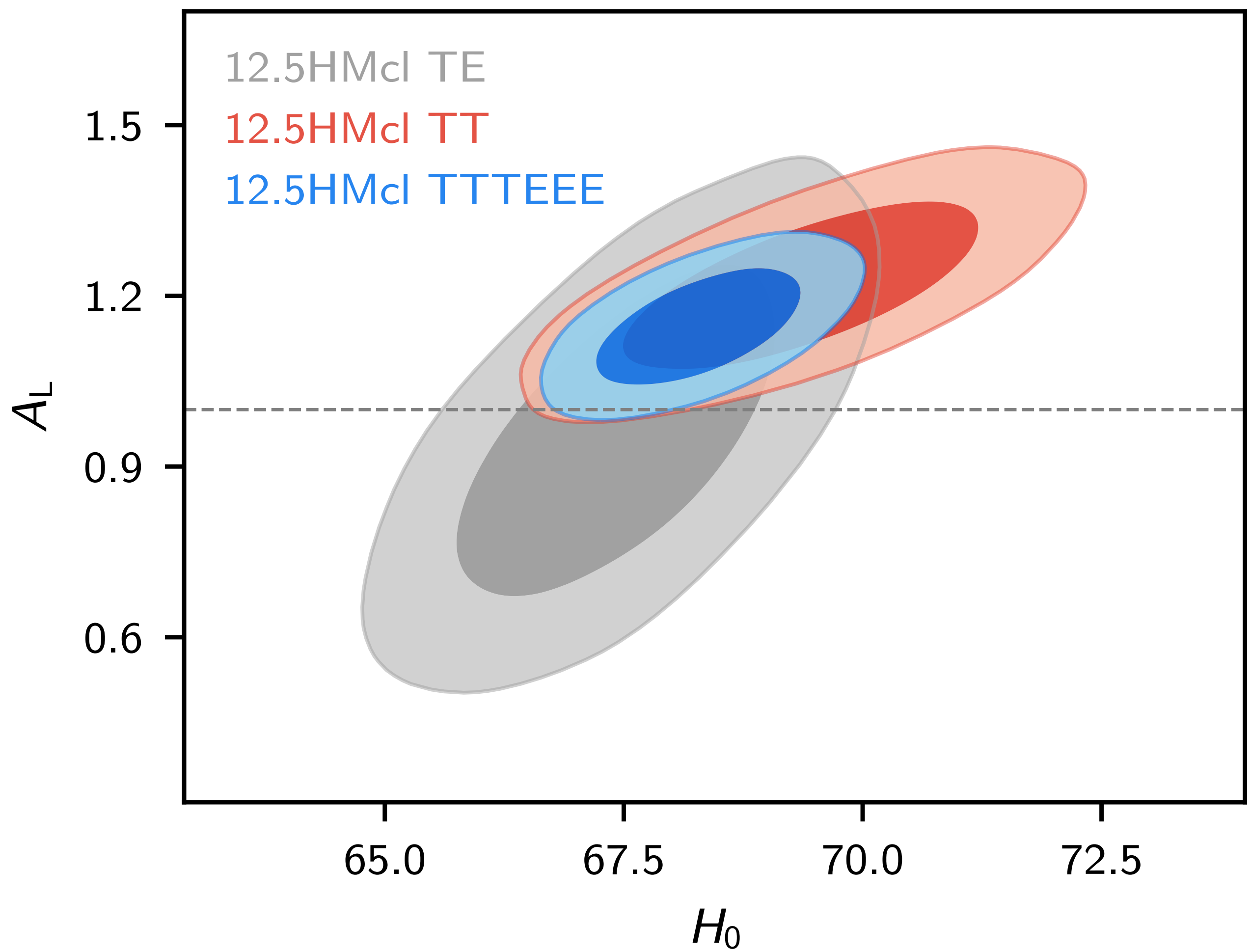
2020
10^{-3}
8×10^{-4}
6×10^{-4}
4×10^{-4}
2×10^{-4}
0
$\mathscr{C}_\ell^{EE}$ [μK^2]
5×10^{-5}
0
-5×10^{-5}
$\Delta\mathscr{C}_\ell^{EE}$ [μK^2]
500
1000
1500
2000
ℓ


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}
$\ln(10^{10} A_{\mathrm{s}})$

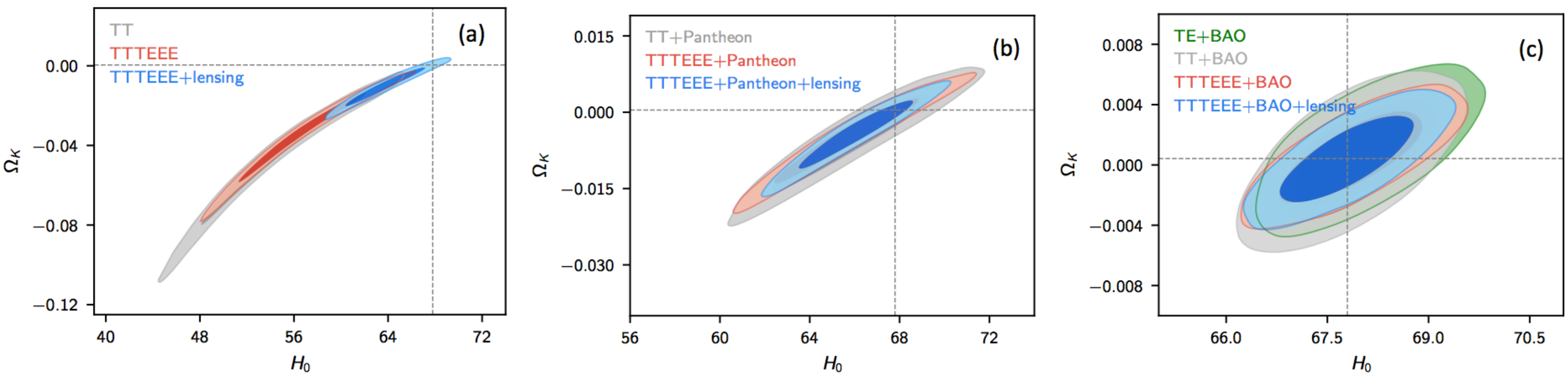


12.5HMcln TE
12.5HMlcn TT
12.5HMcln TTTEEE
H_0
Ω_m
S_8
$\Omega_\mathrm{b} h^2$
$\Omega_\mathrm{c} h^2$
$100\theta_*$
n_s
$\ln(10^{10} A_\mathrm{s})$

Lensing parameter A_L

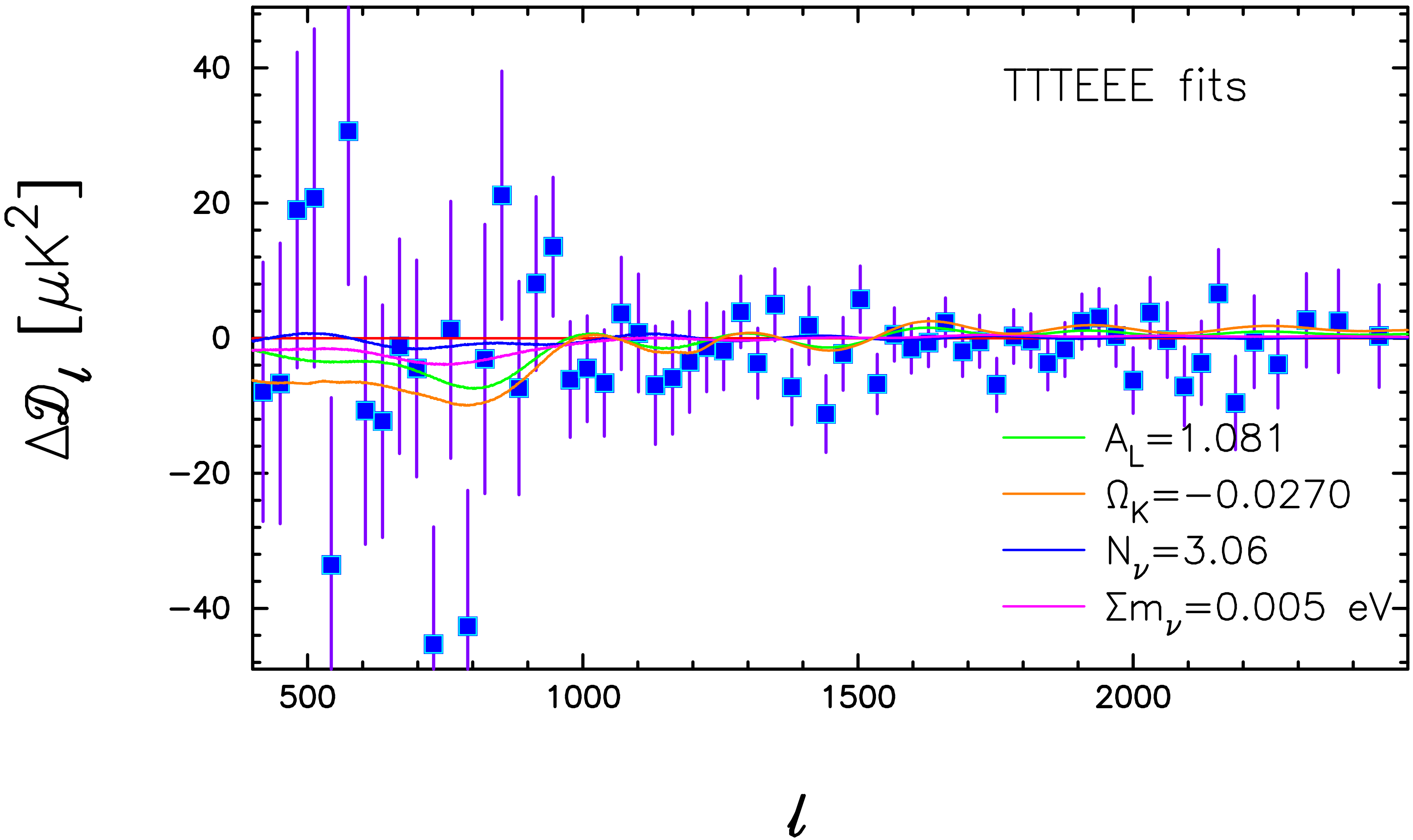


Curvature parameter

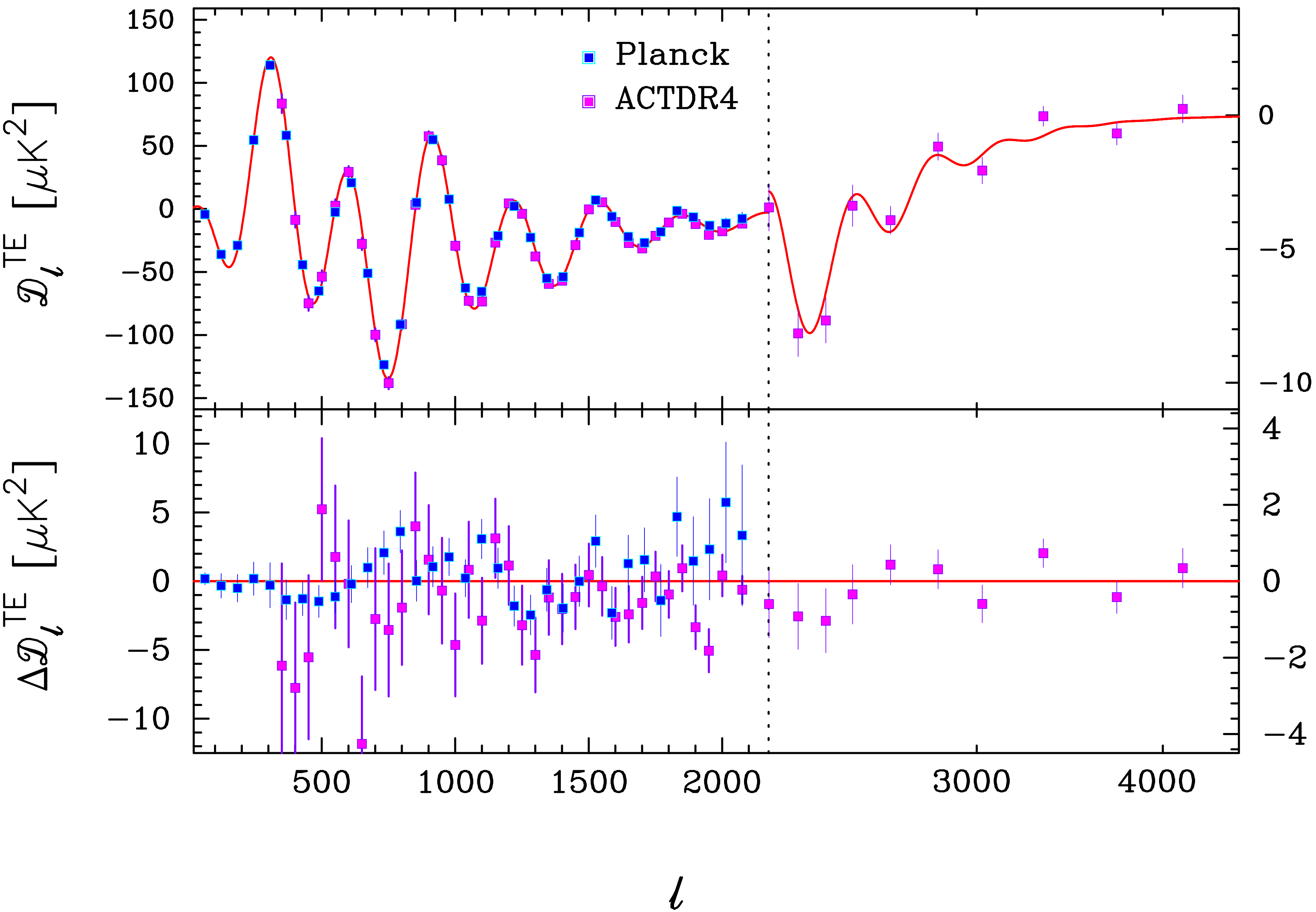


Planck TTTEEE+BAO+pantheon+lensing $\Omega_k = 0.0004 \pm 0.0018$

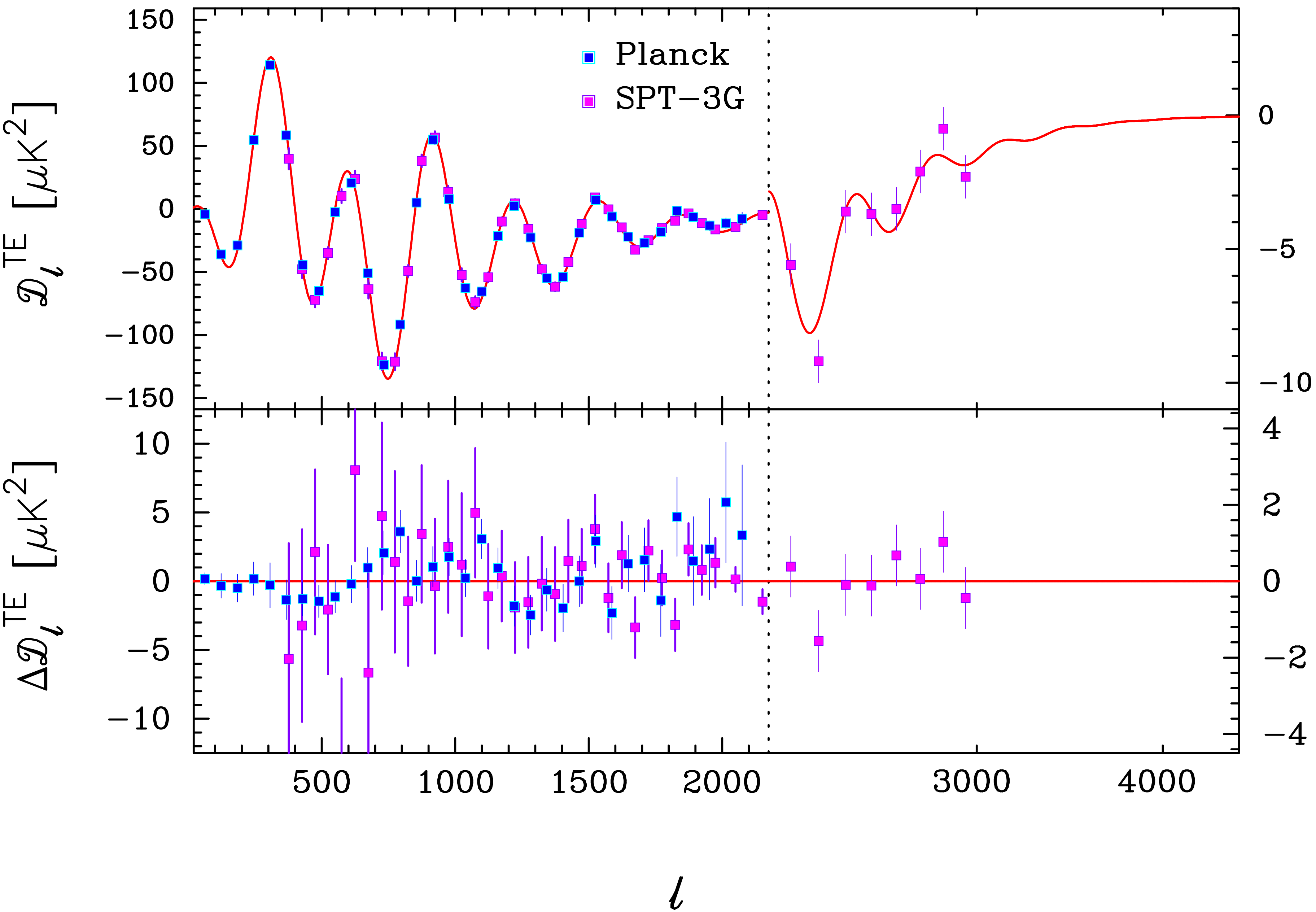
Addition of Ω_k as a parameter improves TTTEEE χ^2 by only -3.02



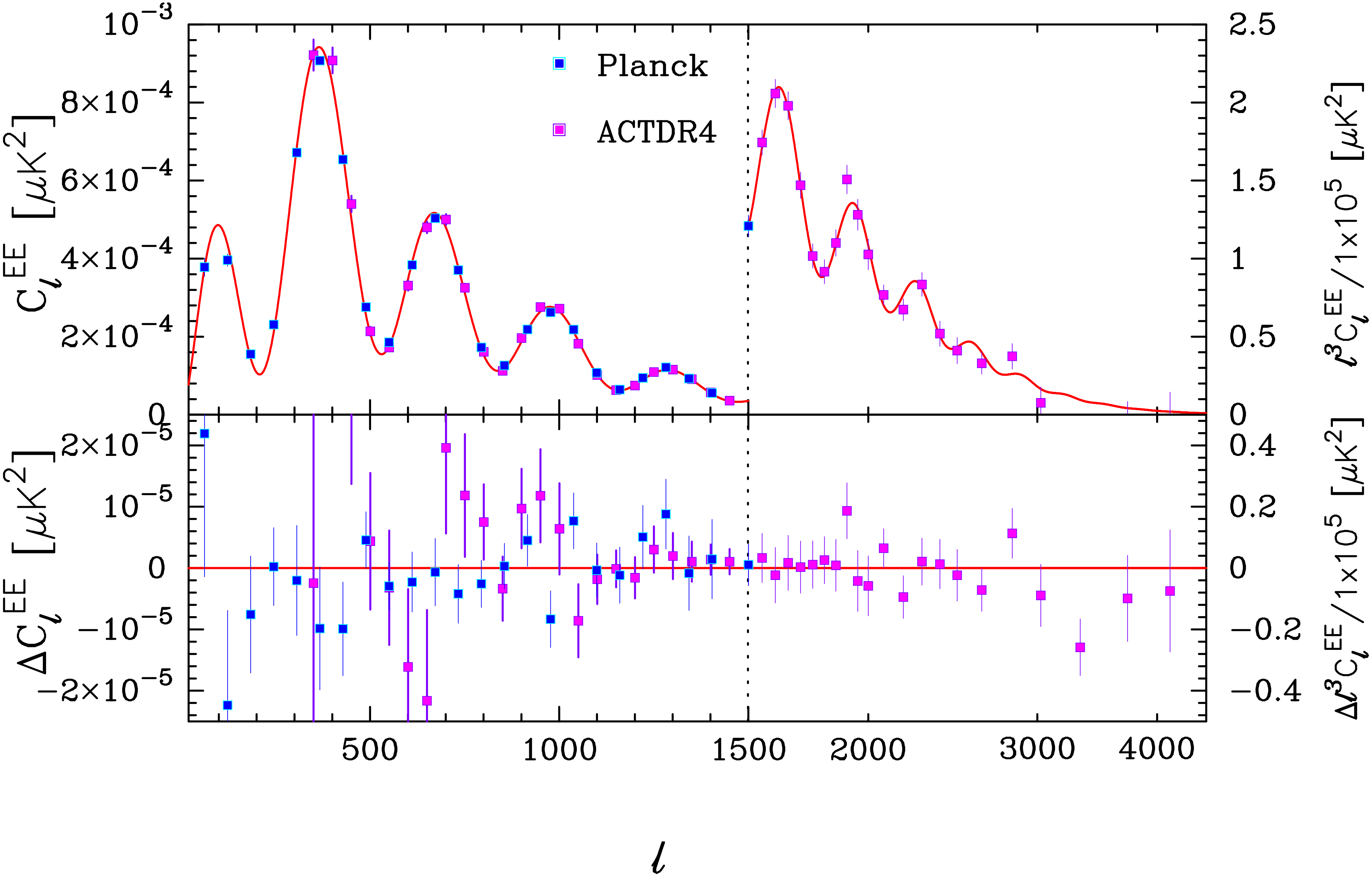
TTTEEE fits
A_L=1.081
Ω_K=−0.0270
N_ν=3.06
Σm_ν=0.005 eV
$\Delta\mathcal{D}_\ell$ [μK^2]
ℓ
40
20
0
−20
−40
500
1000
1500
2000

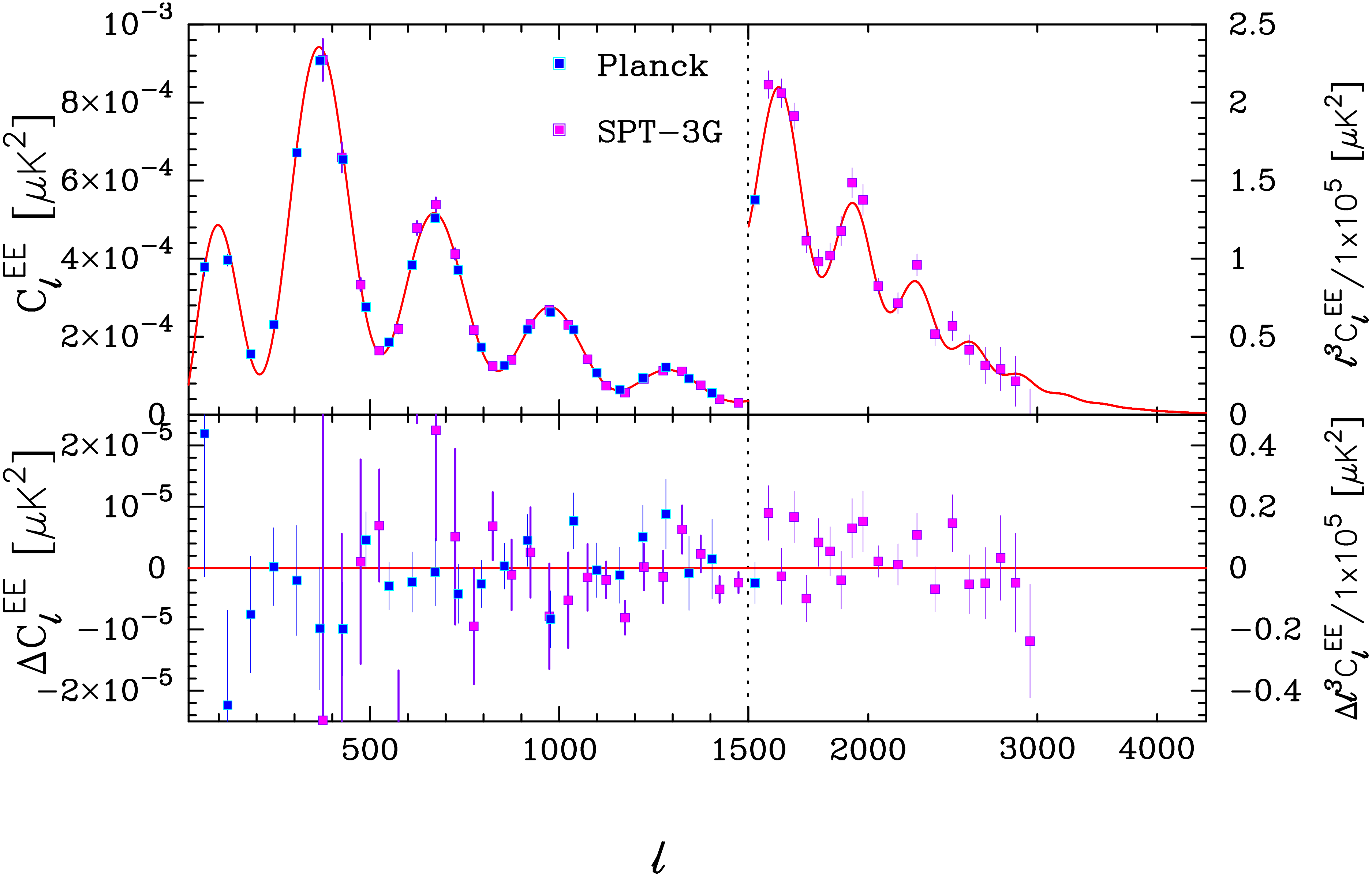


Planck
ACTDR4
$\mathcal{D}_\ell^{TE}$ [μK^2]
$\Delta\mathcal{D}_\ell^{TE}$ [μK^2]
ℓ
150
100
50
0
−50
−100
−150
0
−5
−10
10
5
0
−5
−10
4
2
0
−2
−4
500
1000
1500
2000
3000
4000



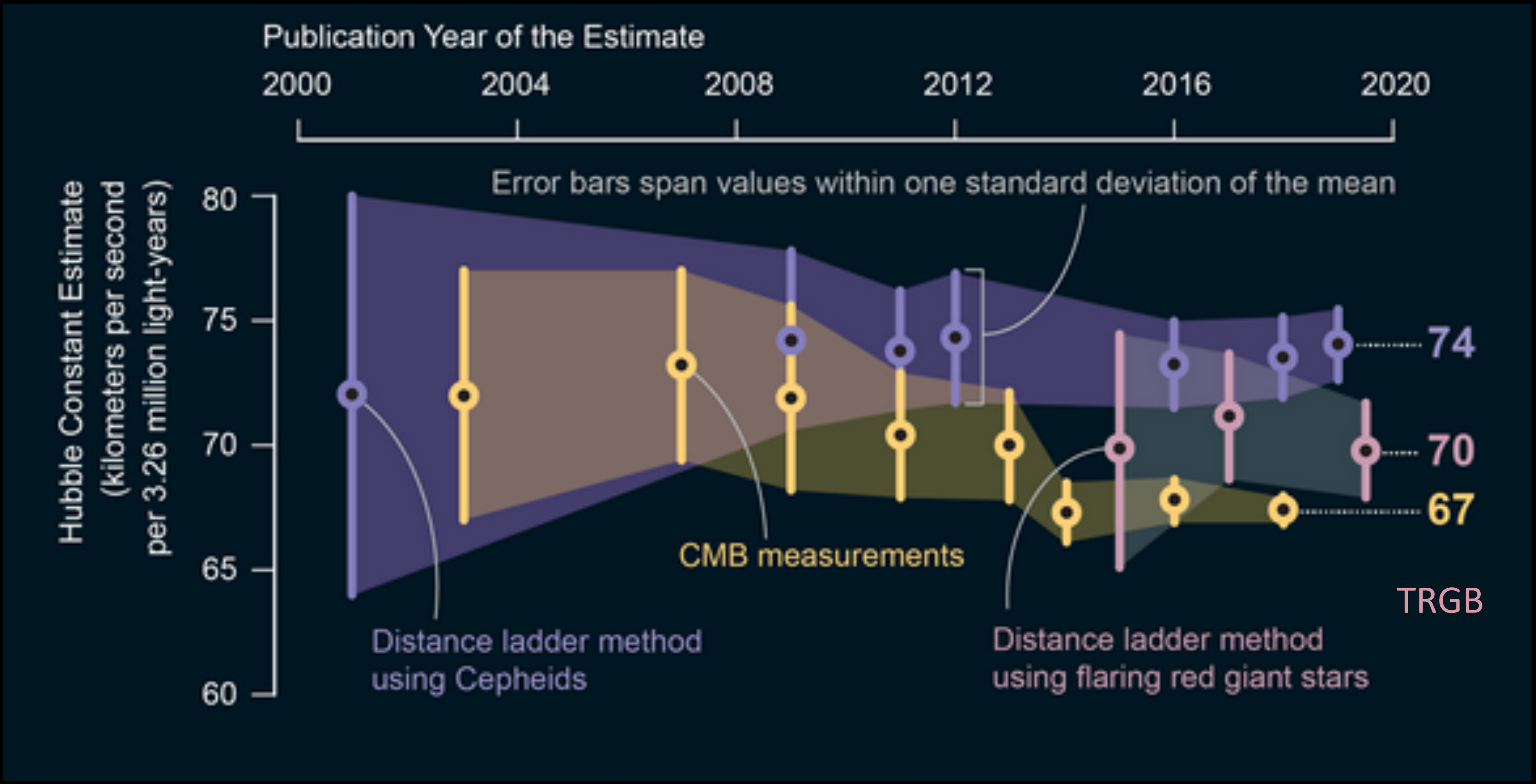
Planck
SPT−3G
$\mathcal{D}_\ell^{TE}$ [μK^2]
$\Delta\mathcal{D}_\ell^{TE}$ [μK^2]
ℓ


Planck
ACTDR4
C_ℓ^{EE} [μK^2]
$\ell^3 C_\ell^{EE}/1\times10^5$ [μK^2]
ΔC_ℓ^{EE} [μK^2]
$\Delta\ell^3 C_\ell^{EE}/1\times10^5$ [μK^2]
ℓ
10^{-3}
8×10^{-4}
6×10^{-4}
4×10^{-4}
2×10^{-4}
0
2.5
2
1.5
1
0.5
0
2×10^{-5}
10^{-5}
0
-10^{-5}
-2×10^{-5}
0.4
0.2
0
−0.2
−0.4
500
1000
1500
2000
3000
4000



Planck
SPT−3G
C_ℓ^{EE} [μK^2]
$\ell^3 C_\ell^{EE}/1\times10^5$ [μK^2]
ΔC_ℓ^{EE} [μK^2]
$\Delta \ell^3 C_\ell^{EE}/1\times10^5$ [μK^2]
ℓ
10^{-3}
8×10^{-4}
6×10^{-4}
4×10^{-4}
2×10^{-4}
0
2×10^{-5}
10^{-5}
-10^{-5}
-2×10^{-5}
2.5
2
1.5
1
0.5
0.4
0.2
−0.2
−0.4
500
1000
1500
2000
3000
4000

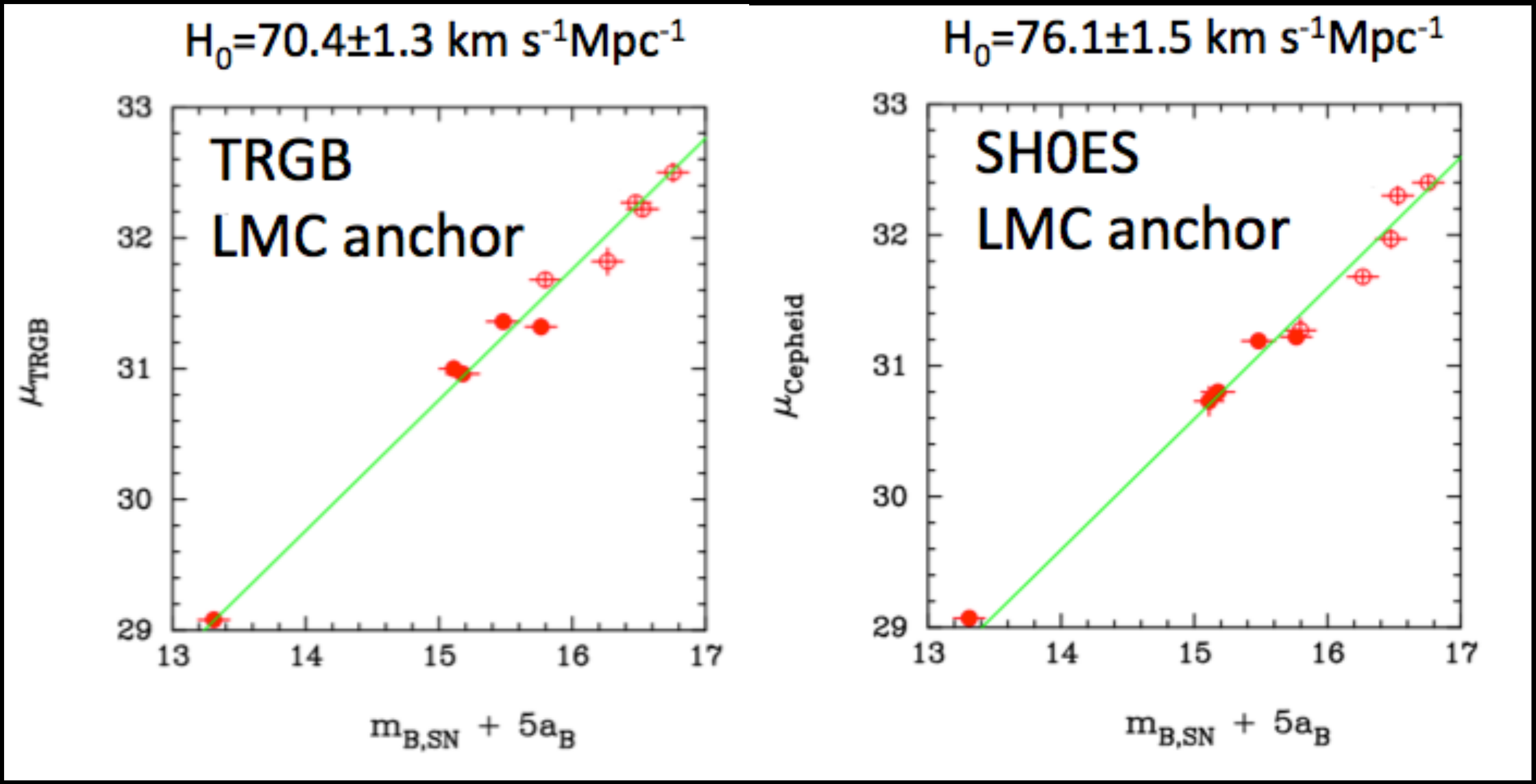
Three things that you may not know about the Hubble tension



Discrepancy of 6.4 km s^{-1} Mpc $^{-1}$ -- a magnitude error of 0.1 mag gives a shift in H_0 of 3.2 km s^{-1} Mpc^{-1}

Point 1 TRGB and Cepheid distance scales are highly discrepant.

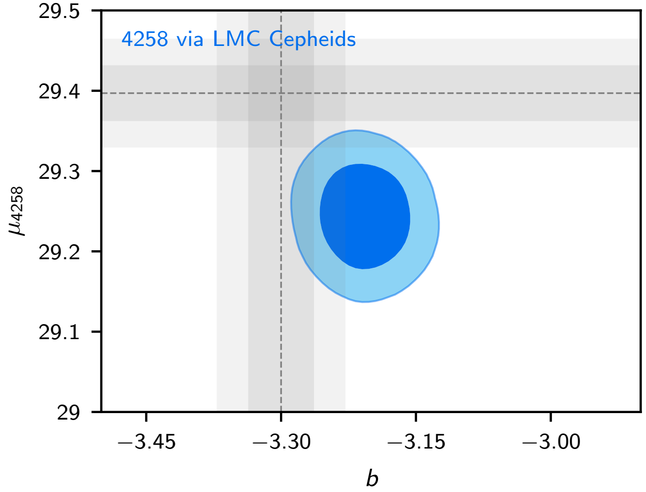
For 10 galaxies in common using the same anchor and Pantheon SN magnitudes:



$\mu_{TRGB} - \mu_{Cepheid} = 0.14 \pm 0.02$

Point 2 The SH0ES analysis is not internally consistent

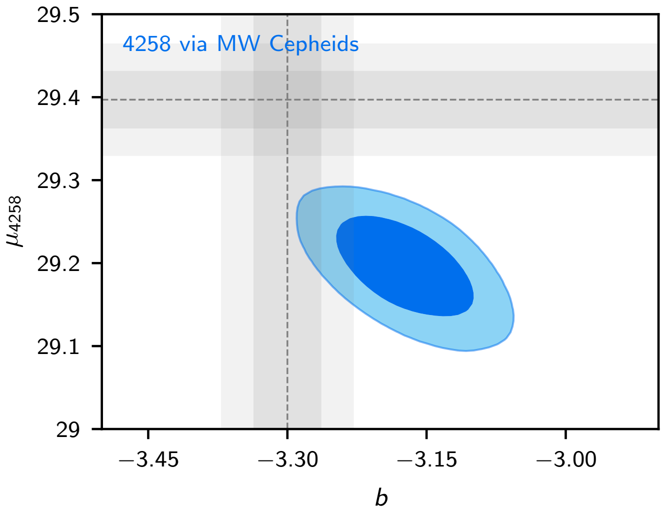
$$m = a + b \log_{10} P + Z \log_{10} (O/H)$$



μ_{N4258} = 29.397 ± 0.033 mag VLBI maser (Reid etal 2019)

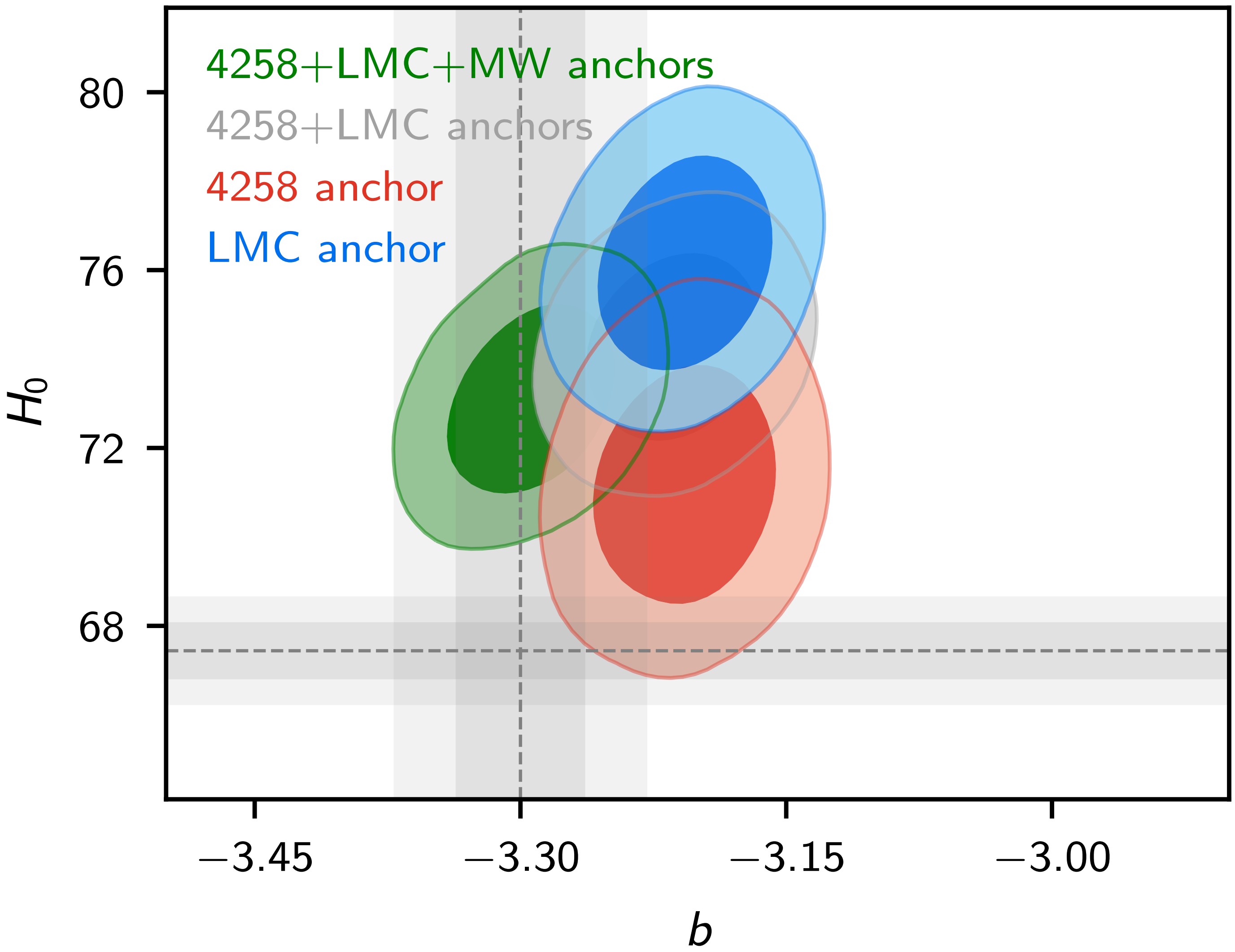
μ_{LMC} = 18.477 ± 0.026 mag Detached eclipsing binaries (Pietrzynski et al 2019)

via SH0ES Cepheids μ_{N4258} = 29.220 ± 0.029 mag



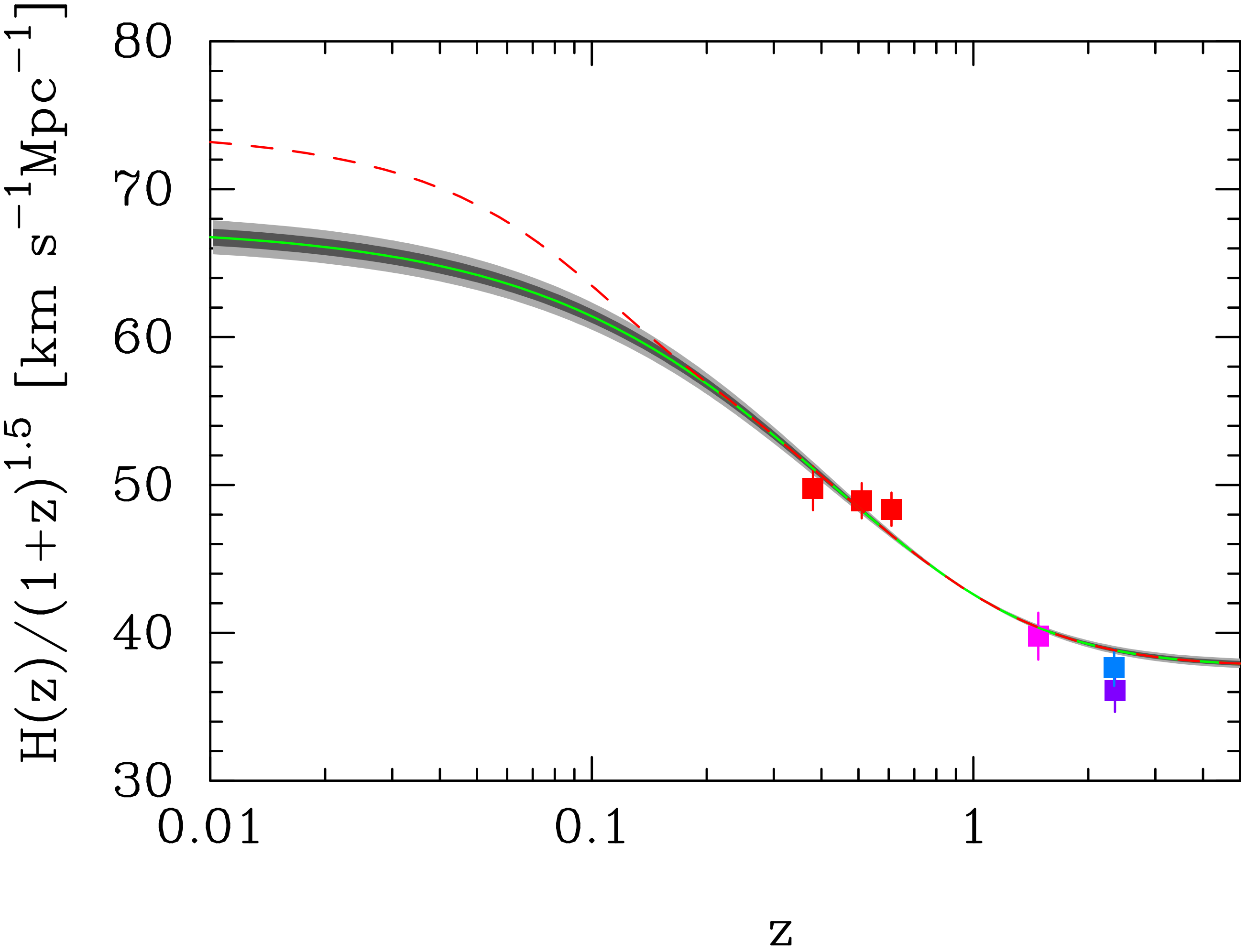
with GAIA DR3 parallaxes and SH0ES Cepheids

μ_{N4258} = 29.211 ± 0.038 mag (3.7σ discrepancy) so beware of



4258+LMC+MW anchors
4258+LMC anchors
4258 anchor
LMC anchor
80
76
72
68
H_0
−3.45
−3.30
−3.15
−3.00
b

Point 3: You cannot solve the Hubble tension by modifying late time physics (arXiv:2103.08723)

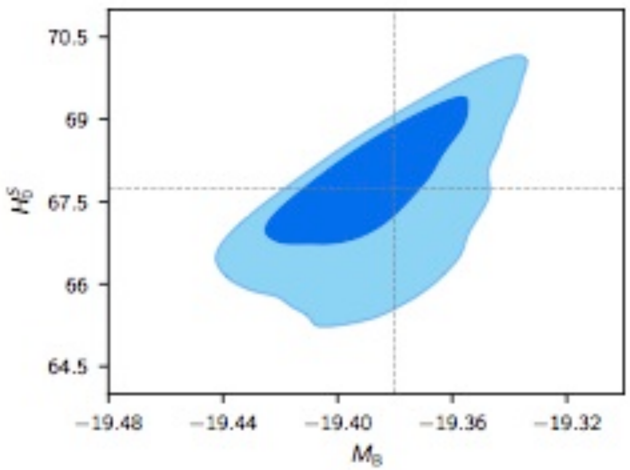


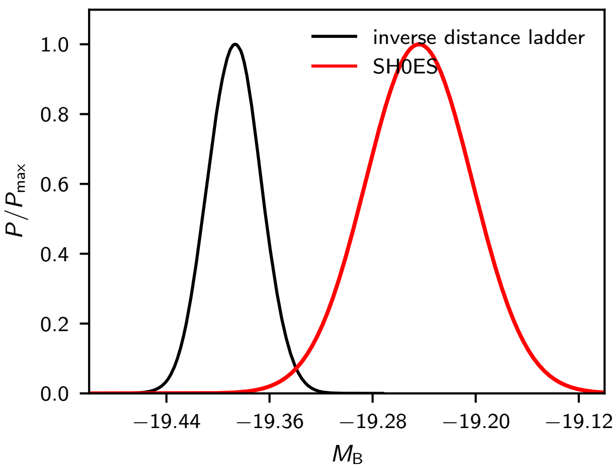
$$H(z) = H_0^f[\Omega_m(1+z)^3 + (1-\Omega_m)(1+\Delta\exp(-(z/z_c)^\beta)]^{1/2}$$

$$\begin{aligned} m &= M + 25 + 5\log_{10} D_L(z), \\ &= -5a + 5\log_{10} c\hat{d}_L(z) \end{aligned}$$

$$a_B = \left(\sum_{ij} C_{ij}^{-1}(\log_{10}\hat{d}_L(z) - 0.2m_B(i))\right) / \sum_{ij} C_{ij}^{-1}$$

$$H_0^S = 10^{0.2(M_B + 5a_B + 25)}$$





Inverse distance ladder tightly constrains the form of H(z) independent of dynamics. No late time solution can work – no phantom DE, interacting DE/DM ……….

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 $2 \leq \ell \leq 2500$. Any such evidence is strongly dependent on the fidelity of other data.