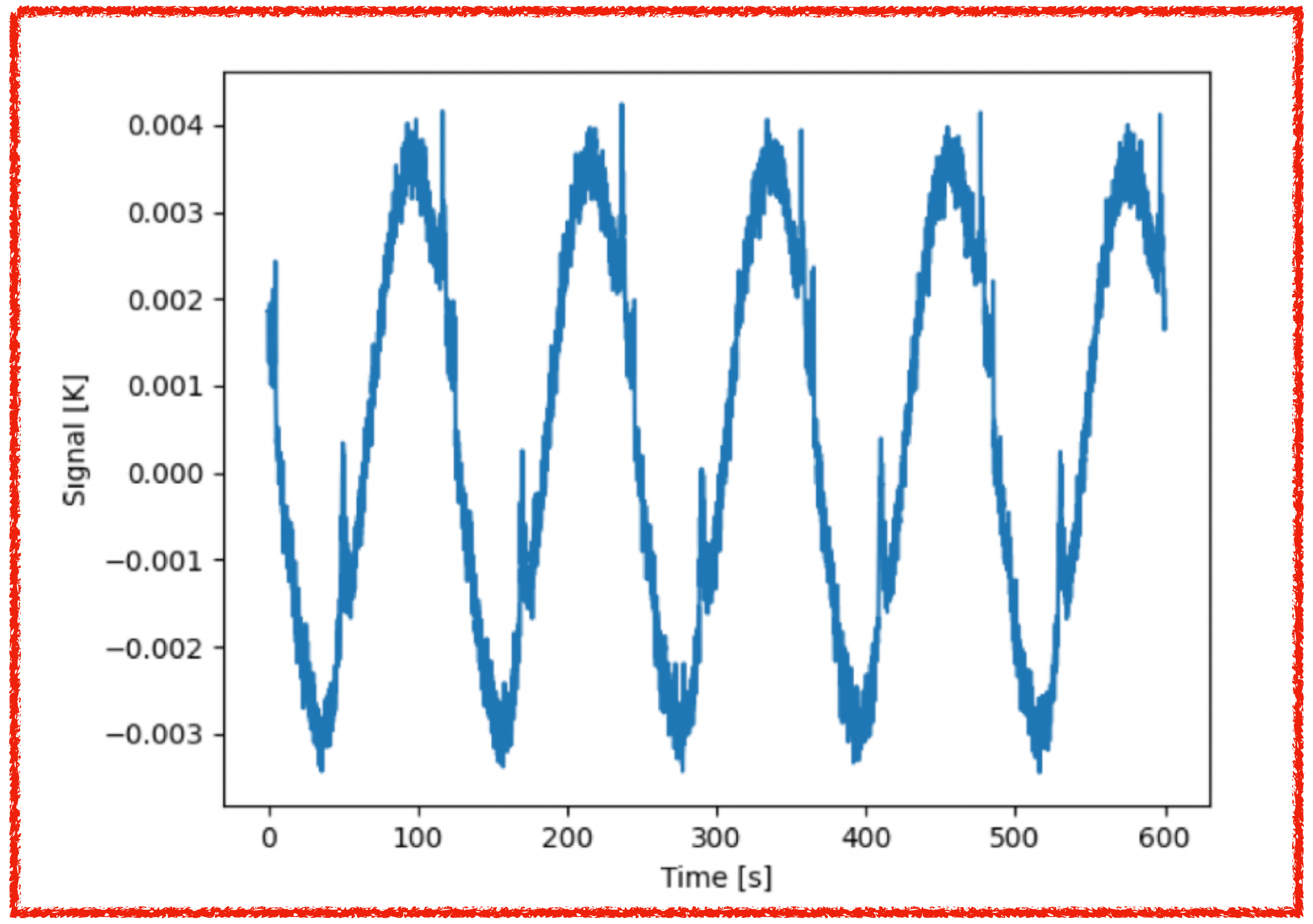
H0 from CMB measurements


Pixar’s The Moon

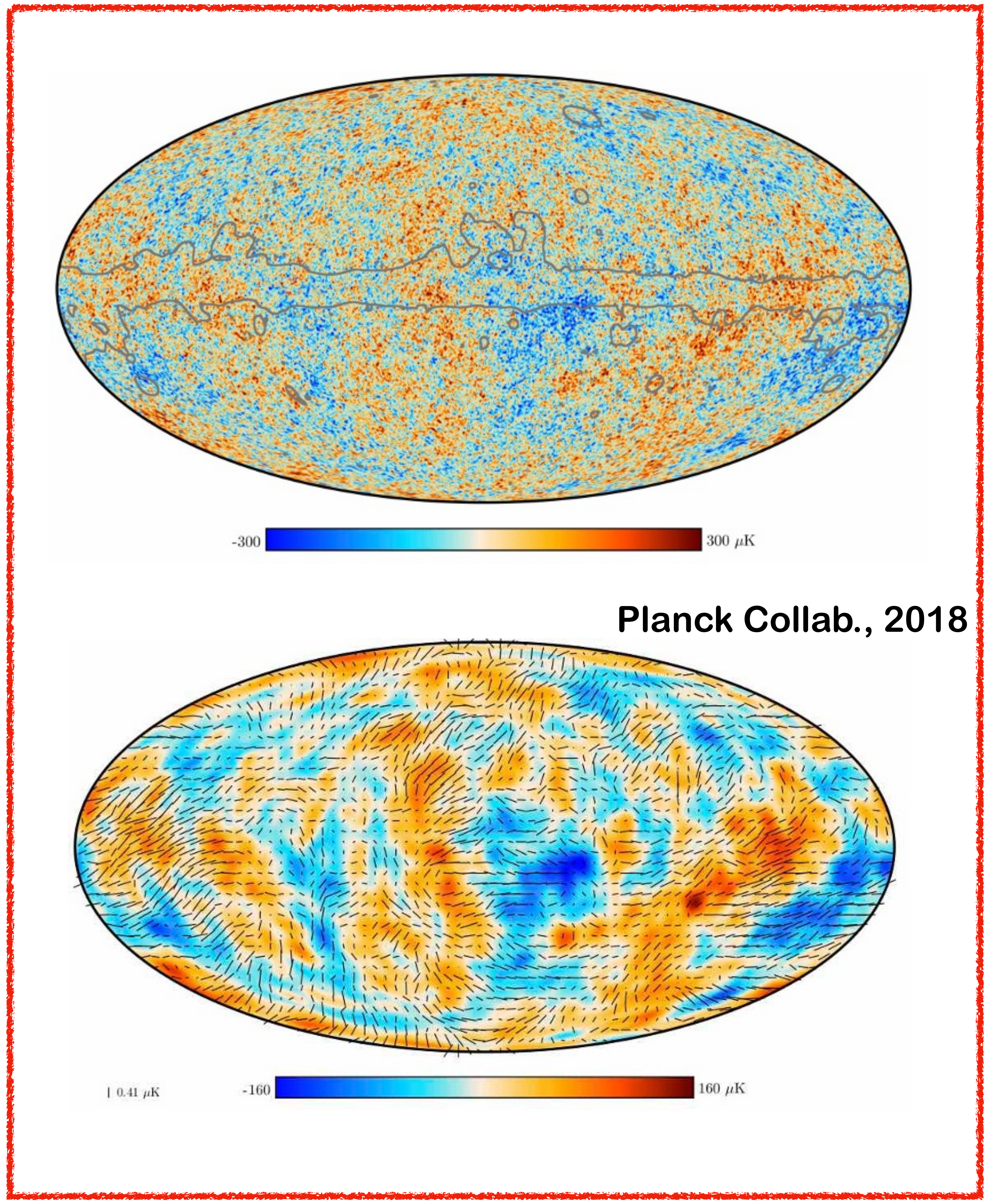
Martina Gerbino (INFN Ferrara)

Dark Energy: from fundamental theories to observations (and back) - LNF, 13 Sep 2023

Data reduction is model independent

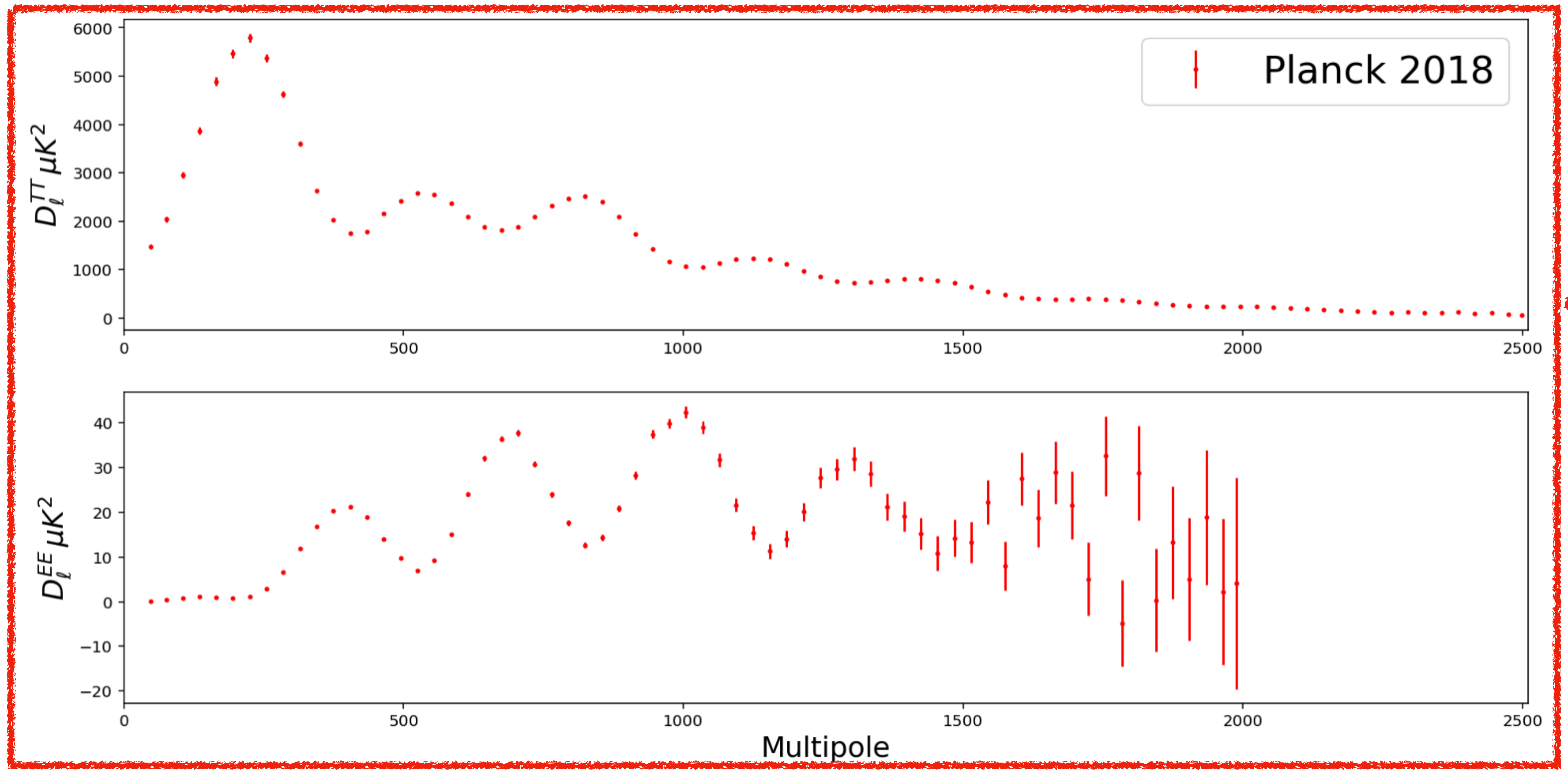


From TOD to maps

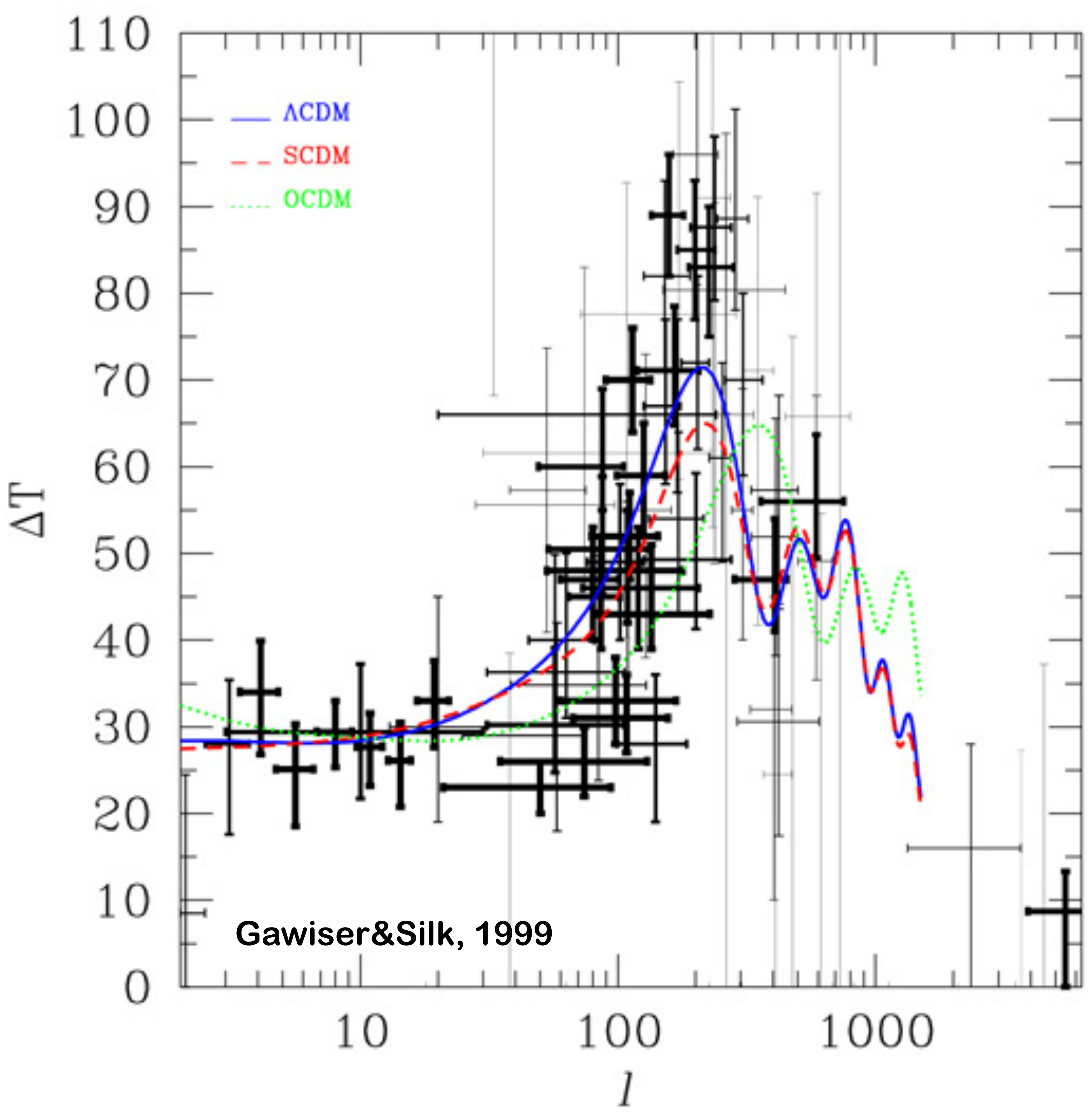


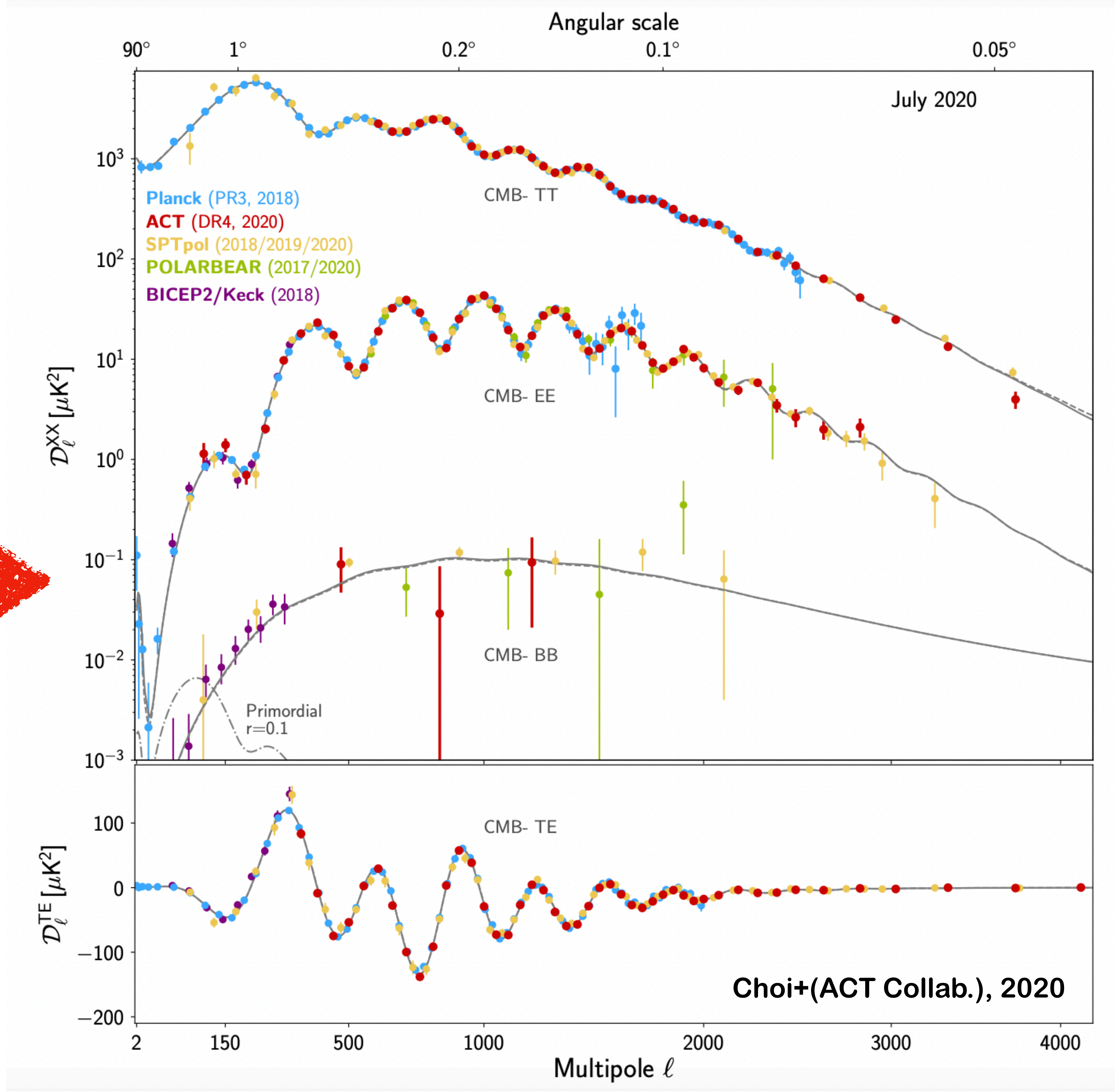
Planck Collab., 2018

From maps to spectra

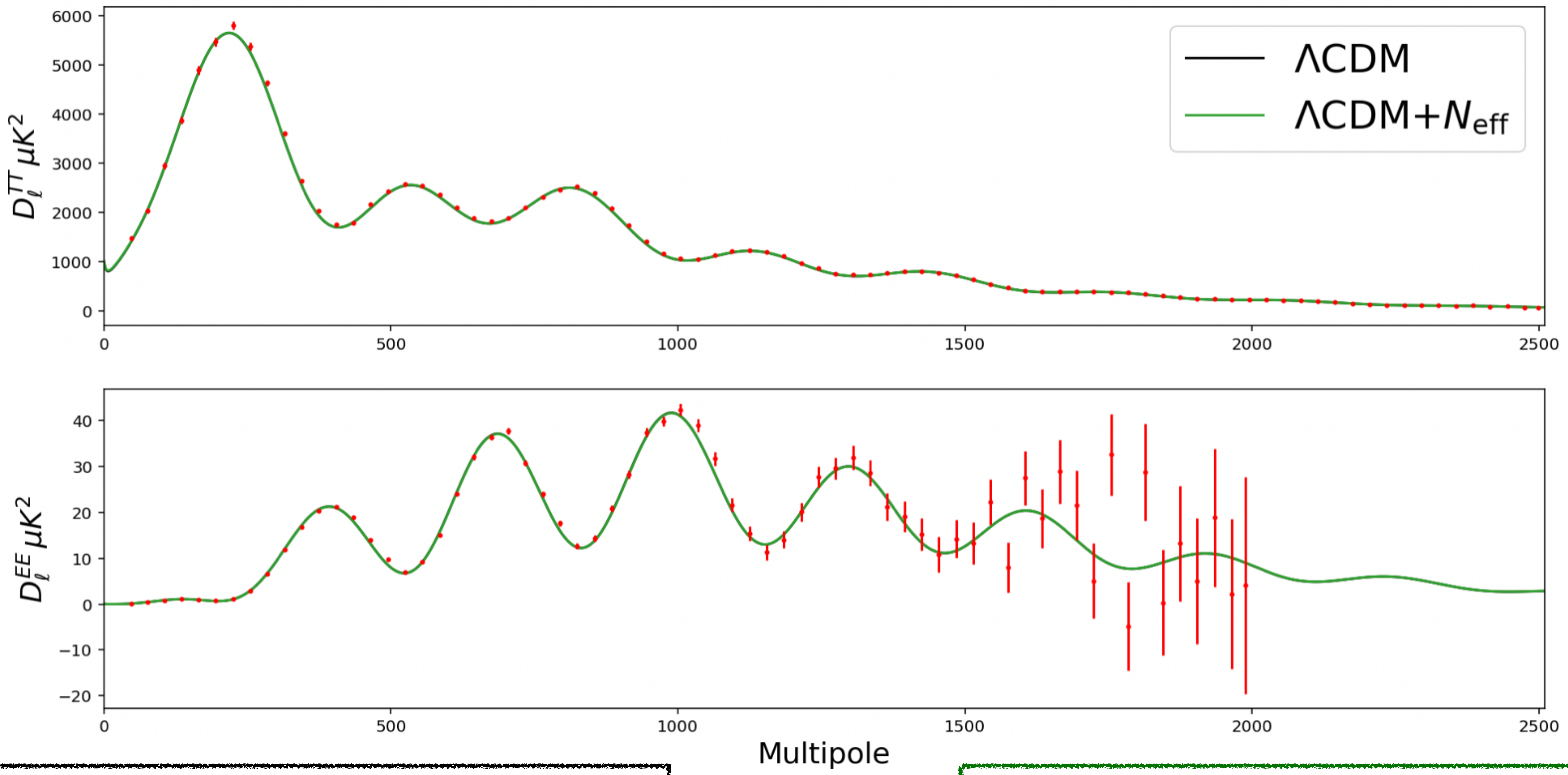


Data reduction is model independent





Data interpretation is model-dependent



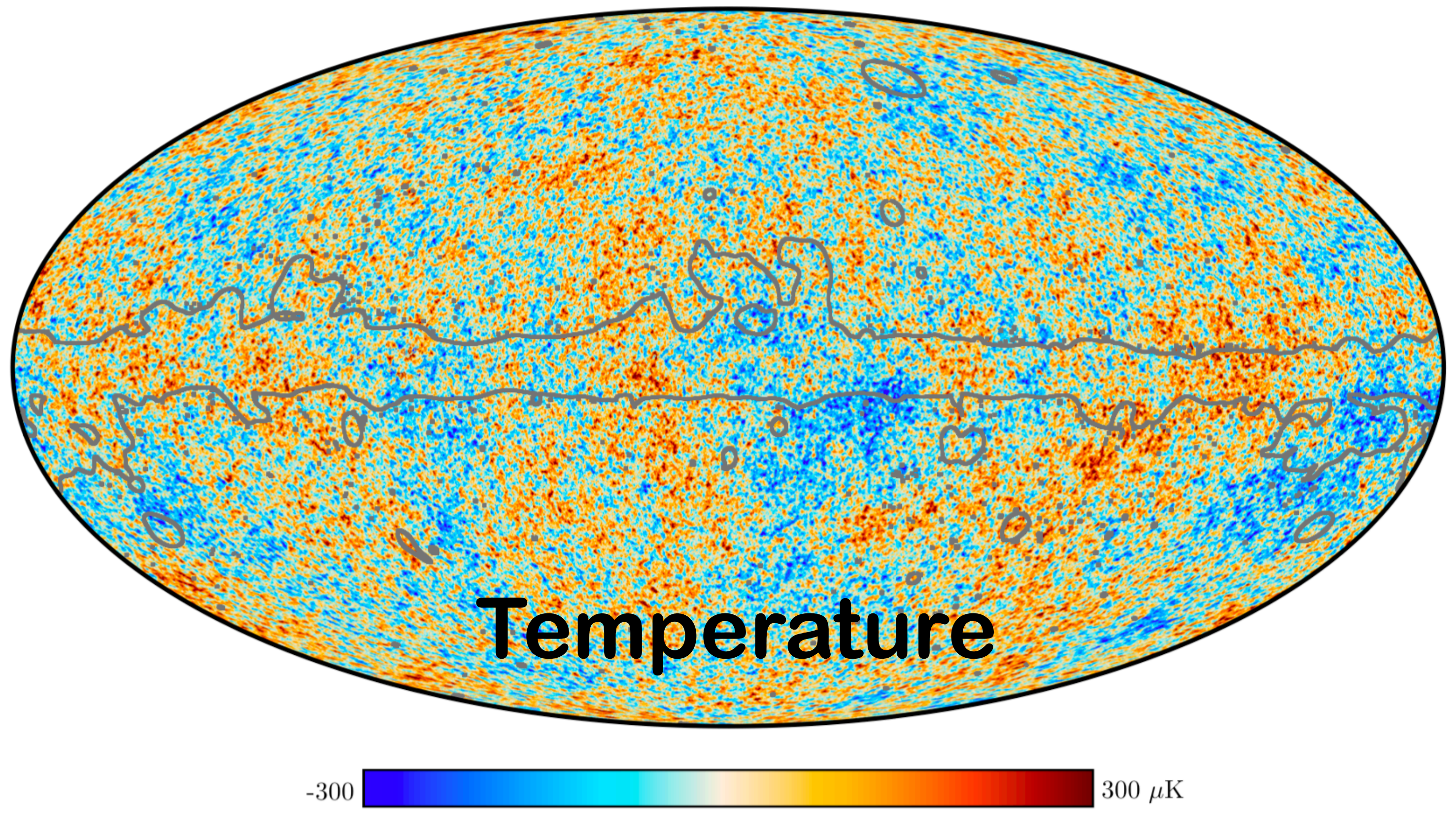
$H_0 = (67.36 \pm 0.54)\,\mathrm{km/s/Mpc}$

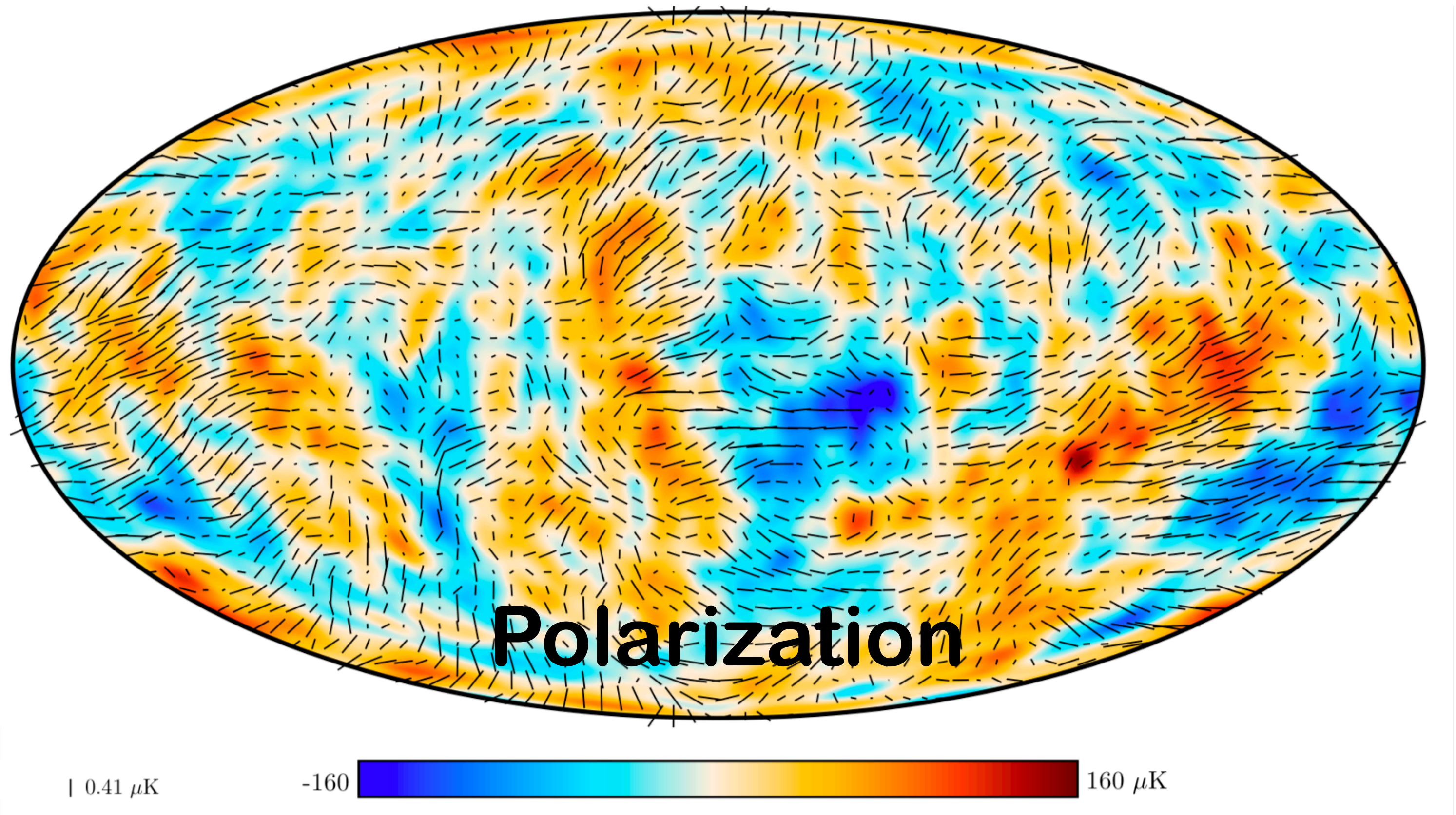
$H_0 = (66.3 \pm 1.4)\,\mathrm{km/s/Mpc}$

From data to parameters

$$\delta^X \sim \Delta^X \delta_{\mathcal{P}}$$

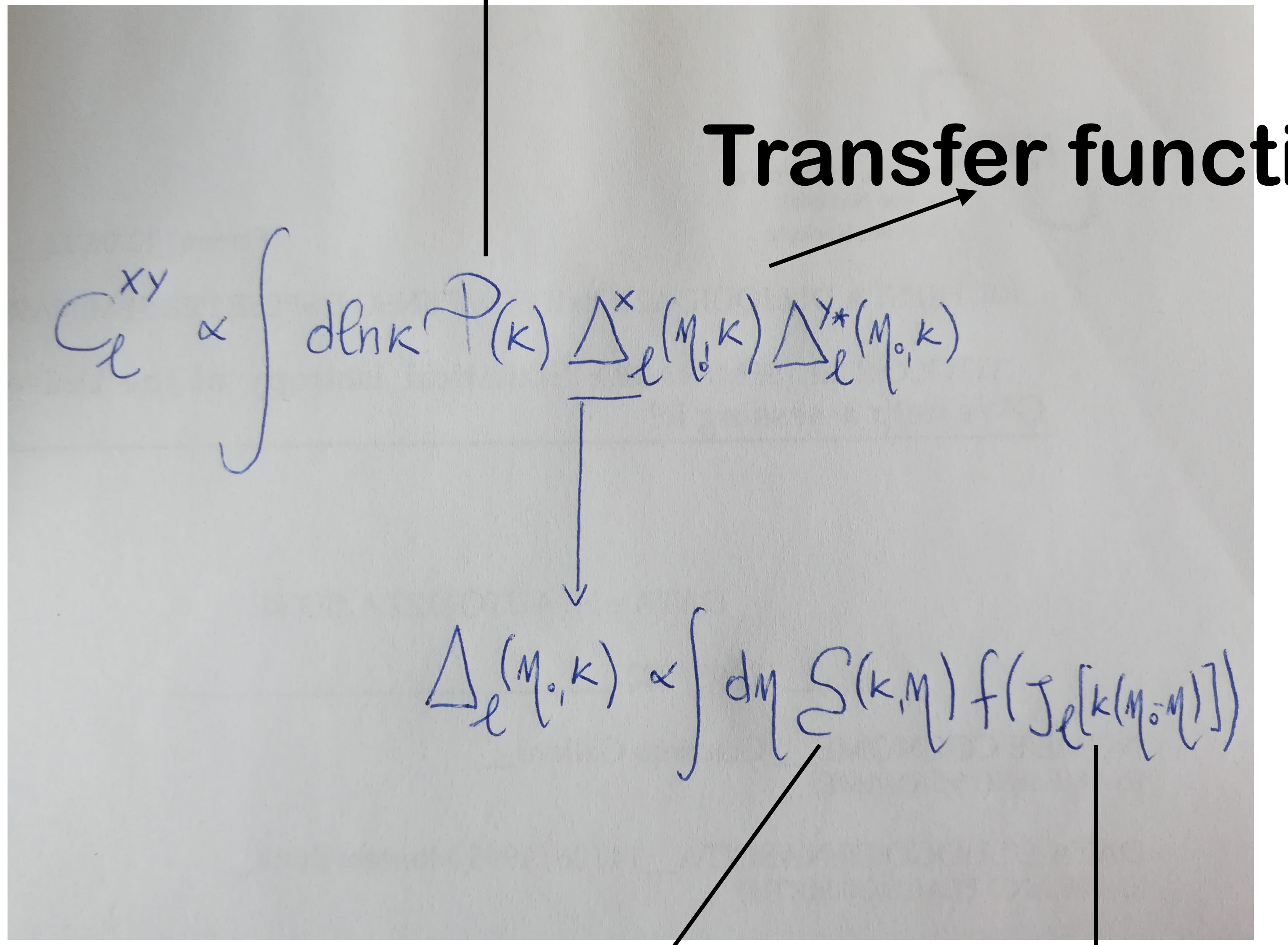
- Δ^X → "Deterministic" evolution
- $\delta_{\mathcal{P}}$ → Stochastic primordial field





Credit: ESA Planck

Primordial perturbations
(ns, As, r, nt, …)



Transfer functions

Source function
(tau, obh2, Neff, …)

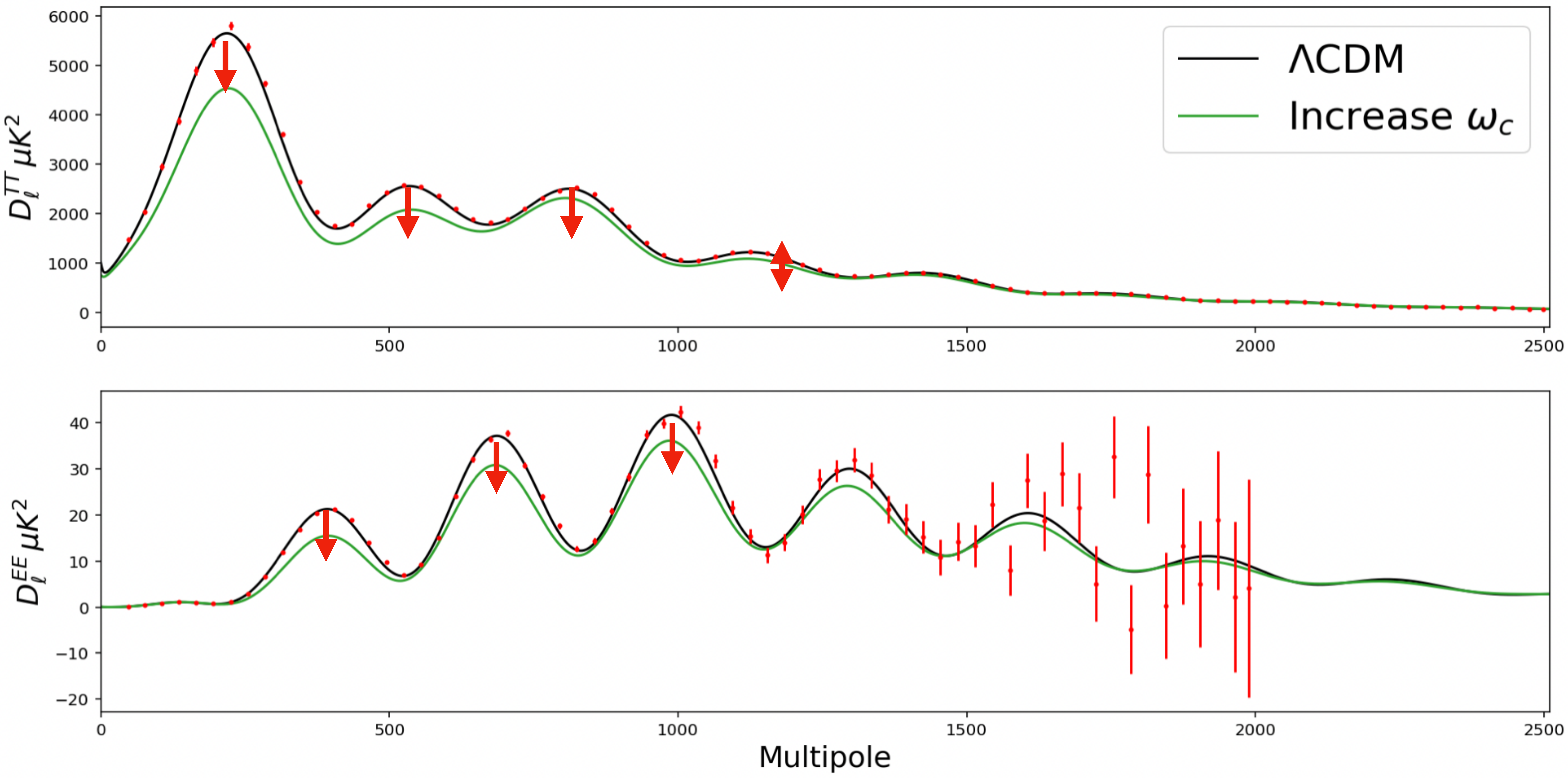
Projection
(theta, och2, oL, …)

+late-time effects due to interaction with LSS
(gravitational lensing)

Dependence on primordial parameters

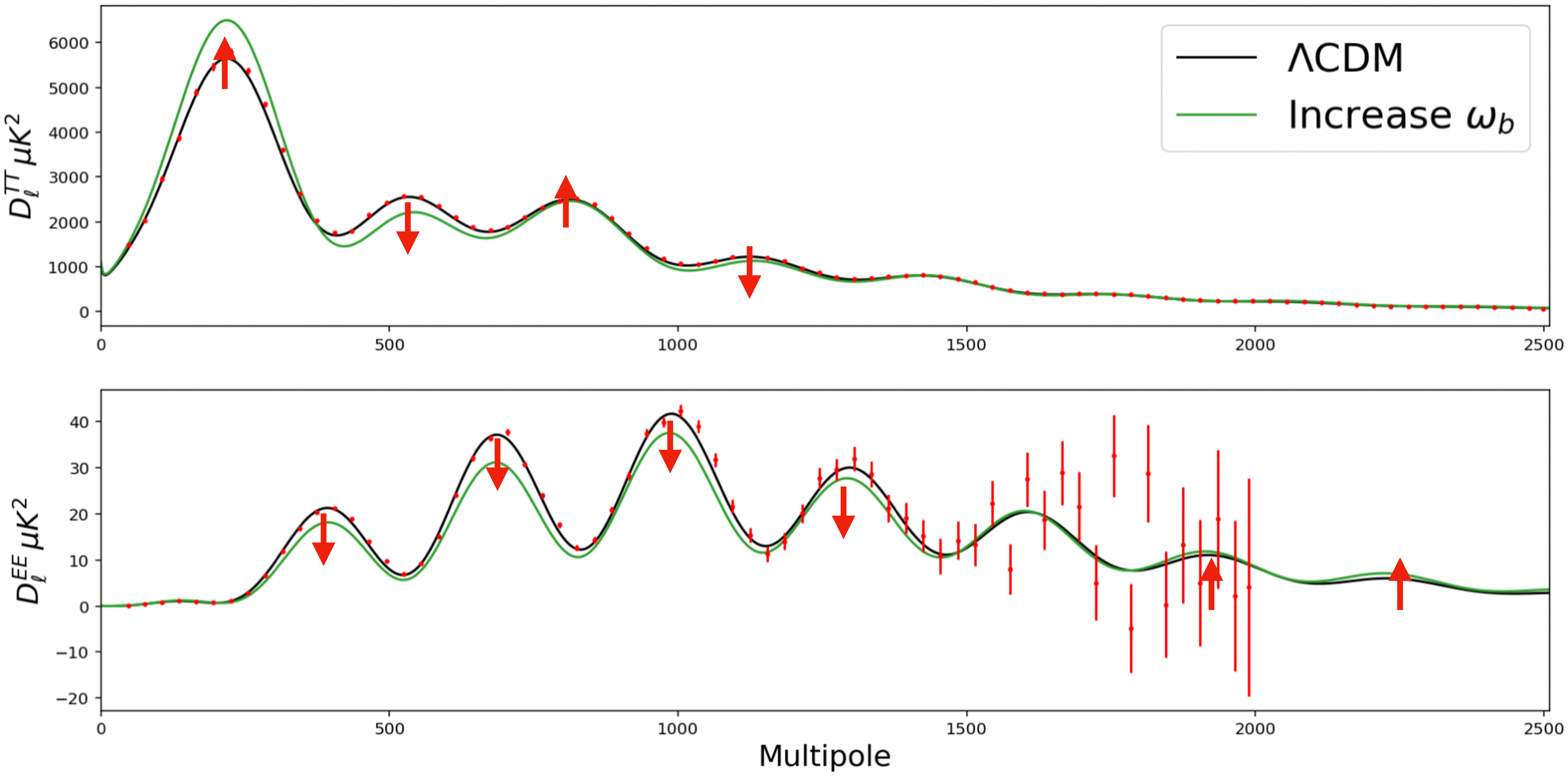
Primordial amplitude -> overall rescaling
Spectral index -> overall tilt

Dependence on (CDM) matter density



Change in gravity balance -> peak amplitude is modified
Change in matter-radiation equality -> Early ISW (amplitude of first peak in TT)
Change in lensing contribution -> smearing of acoustic peaks modified

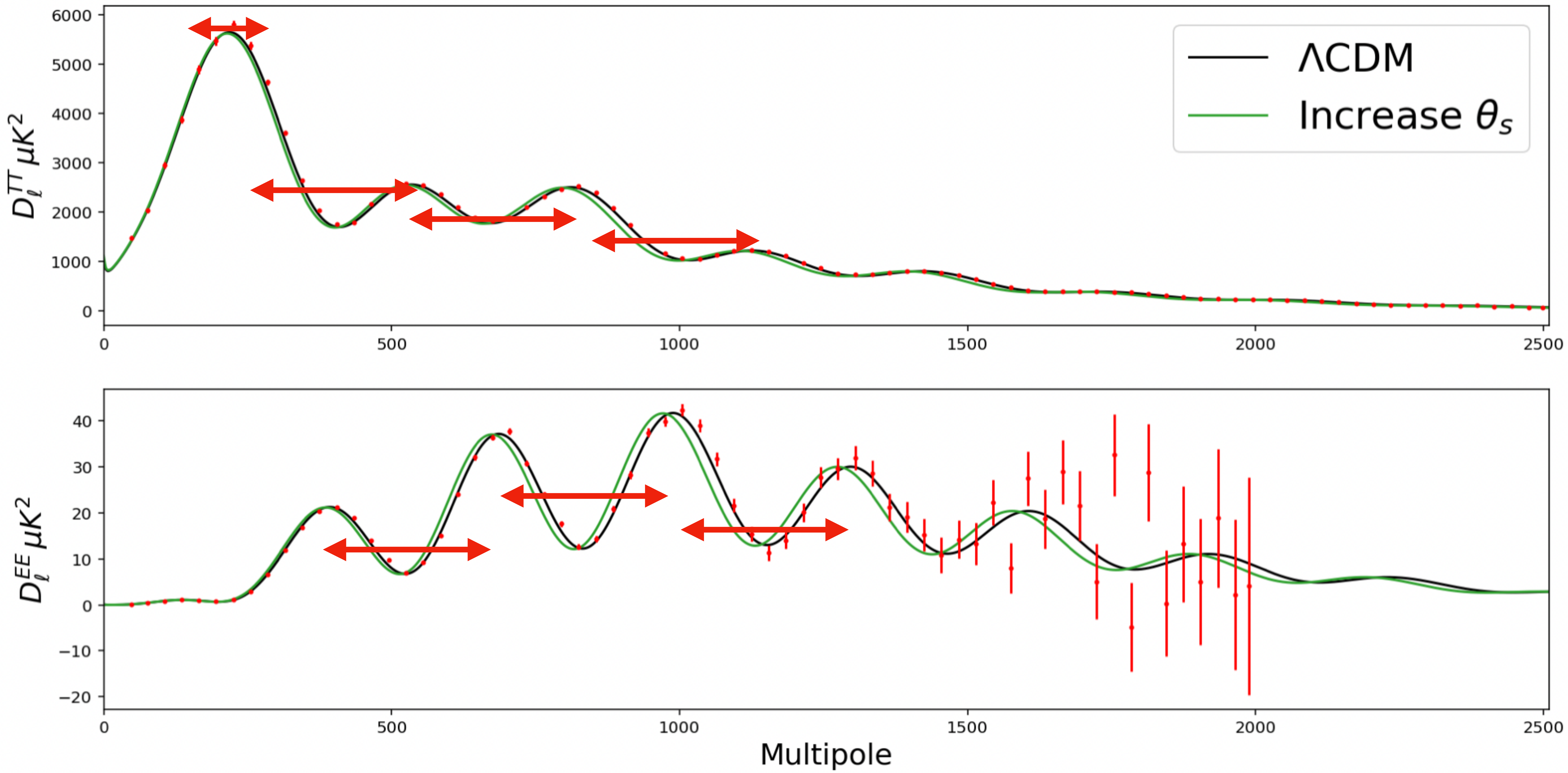
Dependence on (baryonic) matter



Density and velocity fields modified -> change in relative amplitude of temperature odd/even peaks, change in amplitude of polarisation peaks

Change in photon mean free path -> angular scale of diffusion damping modified

Dependence on sound horizon scale



$$\theta_* = \frac{r_s(z_*)}{D_A(z)*}$$

Comoving sound horizon

$$r_s(z_*) = \int_{z_*}^{\infty} c_s \frac{dz}{H(z)}$$

Comoving angular diameter distance

$$D_A(z_*) = \int_0^{z_*} c \frac{dz}{H(z)}$$

Spacing between acoustic peaks and, <u>up to a phase</u>, first peak position

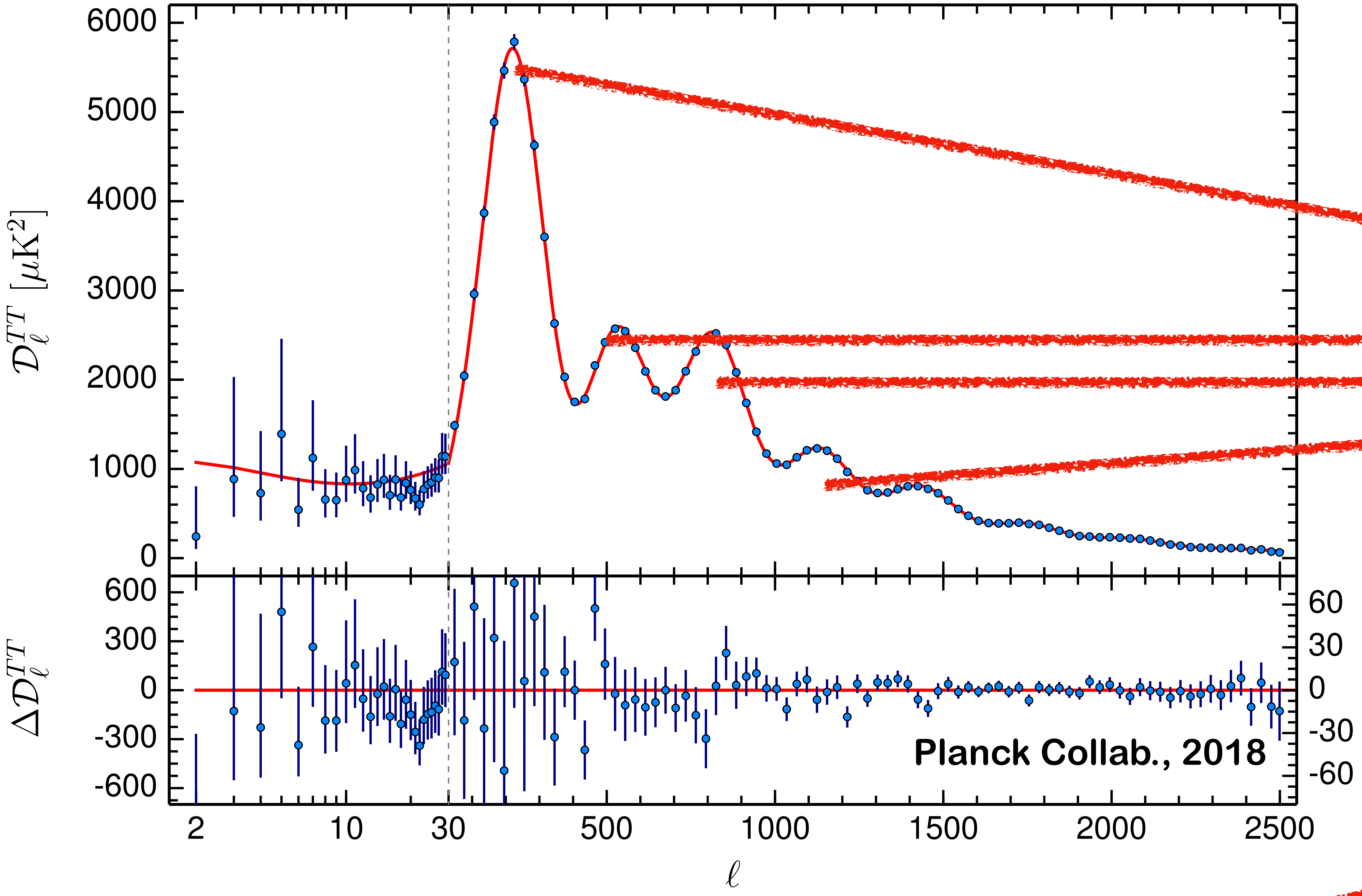
Dependence on sound horizon scale

Parameter(s)	$\Omega_b h^2$	$\Omega_c h^2$	$100\theta_{MC}$	H_0	n_s	$\ln(10^{10}A_s)$
Base ΛCDM	0.02237 ± 0.00015	0.1200 ± 0.0012	1.04092 ± 0.00031	67.36 ± 0.54	0.9649 ± 0.0042	3.044 ± 0.014
r	0.02237 ± 0.00014	0.1199 ± 0.0012	1.04092 ± 0.00031	67.40 ± 0.54	0.9659 ± 0.0041	3.044 ± 0.014
$dn_s/d\ln k$	0.02240 ± 0.00015	0.1200 ± 0.0012	1.04092 ± 0.00031	67.36 ± 0.53	0.9641 ± 0.0044	3.047 ± 0.015
$dn_s/d\ln k, r$	0.02243 ± 0.00015	0.1199 ± 0.0012	1.04093 ± 0.00030	67.44 ± 0.54	0.9647 ± 0.0044	3.049 ± 0.015
$d^2n_s/d\ln k^2, dn_s/d\ln k$.	0.02237 ± 0.00016	0.1202 ± 0.0012	1.04090 ± 0.00030	67.28 ± 0.56	0.9625 ± 0.0048	3.049 ± 0.015
N_{eff}	0.02224 ± 0.00022	0.1179 ± 0.0028	1.04116 ± 0.00043	66.3 ± 1.4	0.9589 ± 0.0084	3.036 ± 0.017
$N_{eff}, dn_s/d\ln k$	0.02216 ± 0.00022	0.1157 ± 0.0032	1.04144 ± 0.00048	65.2 ± 1.6	0.950 ± 0.011	3.034 ± 0.017
Σm_ν	0.02236 ± 0.00015	0.1201 ± 0.0013	1.04088 ± 0.00032	$67.1^{+1.2}_{-0.67}$	0.9647 ± 0.0043	3.046 ± 0.015
$\Sigma m_\nu, N_{eff}$	0.02223 ± 0.00023	0.1180 ± 0.0029	1.04113 ± 0.00044	$66.0^{+1.8}_{-1.6}$	0.9587 ± 0.0086	3.038 ± 0.017
$m^{eff}_{\nu,\,sterile}, N_{eff}$	$0.02242^{+0.00014}_{-0.00016}$	$0.1200^{+0.0032}_{-0.0020}$	$1.04074^{+0.00033}_{-0.00029}$	$67.11^{+0.63}_{-0.79}$	$0.9652^{+0.0045}_{-0.0056}$	$3.050^{+0.014}_{-0.016}$
α_{-1}	0.02238 ± 0.00015	0.1201 ± 0.0015	1.04087 ± 0.00043	67.30 ± 0.67	0.9645 ± 0.0061	3.045 ± 0.014
w_0	0.02243 ± 0.00015	0.1193 ± 0.0012	1.04099 ± 0.00031	...	0.9666 ± 0.0041	3.038 ± 0.014
Ω_K	0.02249 ± 0.00016	0.1185 ± 0.0015	1.04107 ± 0.00032	$63.6^{+2.1}_{-2.3}$	0.9688 ± 0.0047	$3.030^{+0.017}_{-0.015}$
Y_P	0.02230 ± 0.00020	0.1201 ± 0.0012	1.04067 ± 0.00055	67.19 ± 0.63	0.9621 ± 0.0070	3.042 ± 0.016
Y_P, N_{eff}	0.02224 ± 0.00022	$0.1171^{+0.0042}_{-0.0049}$	1.0415 ± 0.0012	$66.0^{+1.7}_{-1.9}$	0.9589 ± 0.0085	3.036 ± 0.018
A_L	0.02251 ± 0.00017	0.1182 ± 0.0015	1.04110 ± 0.00032	68.16 ± 0.70	0.9696 ± 0.0048	$3.029^{+0.018}_{-0.016}$

Planck Collab. VI, 2018

0.05% measurement of the angular scale of sound horizon
Robust determination with respect to the cosmological model

Getting H0 in LCDM



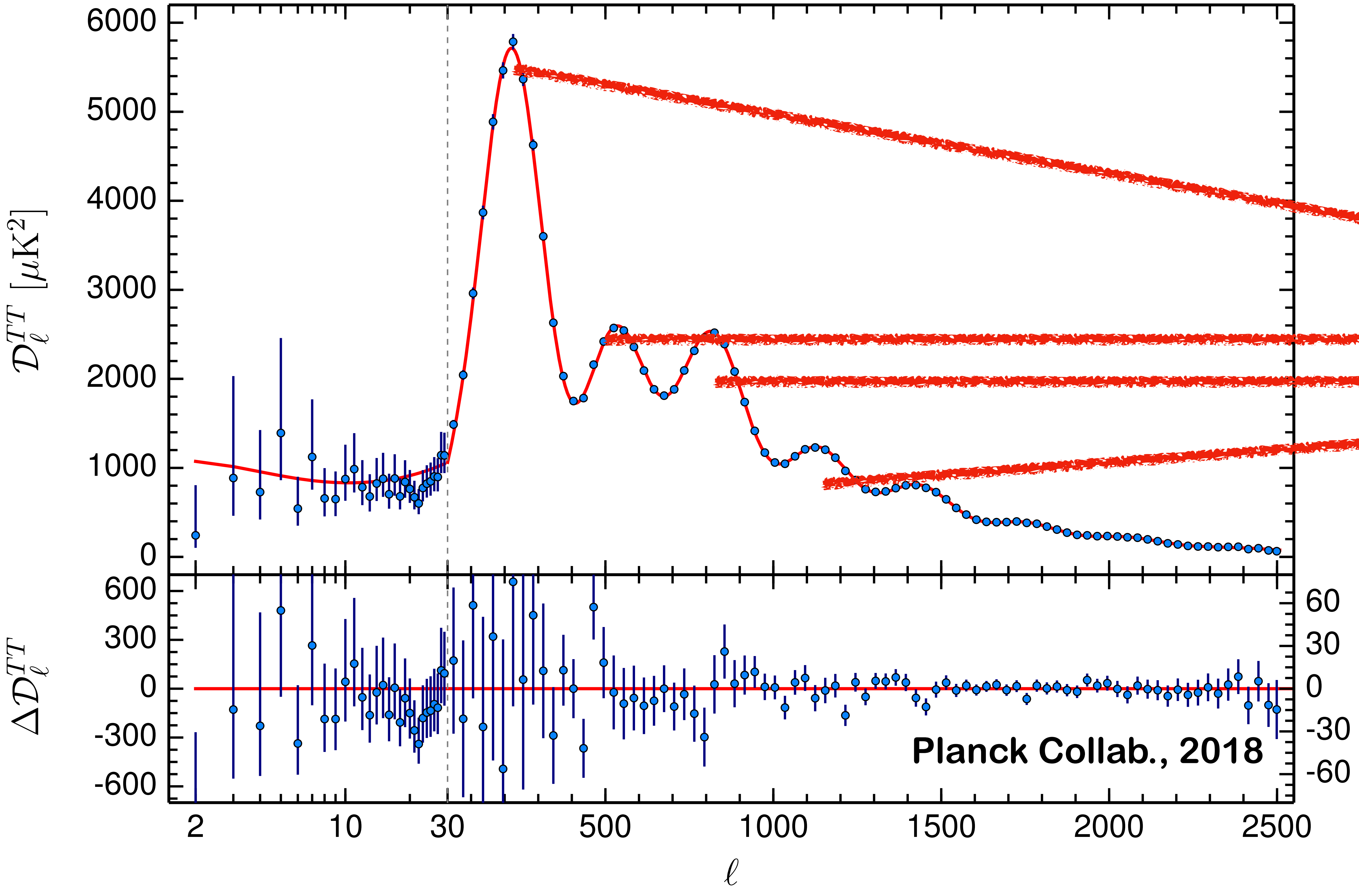
$$\theta_* = \frac{r_s(z_*)}{D_A(z)_*}$$

Directly measured From T_{CMB}

$$\frac{r_*}{3000\,\mathrm{Mpc}} = \int_{z_*}^{\infty} \frac{c_s dz}{\left[\Omega_\gamma h^2 \left(1 + \frac{7}{8}\left(\frac{4}{11}\right)^{\frac{4}{3}} N_{\mathrm{eff}}\right)(1+z)^4 + \Omega_m h^2 (1+z)^3\right]^{1/2}}$$

$$\frac{d_A}{3000\,\mathrm{Mpc}} = \int_0^{z_*} \frac{dz}{\left[\Omega_m h^2 (1+z)^3 + \Omega_\Lambda h^2\right]^{1/2}}$$

Getting H0 in LCDM



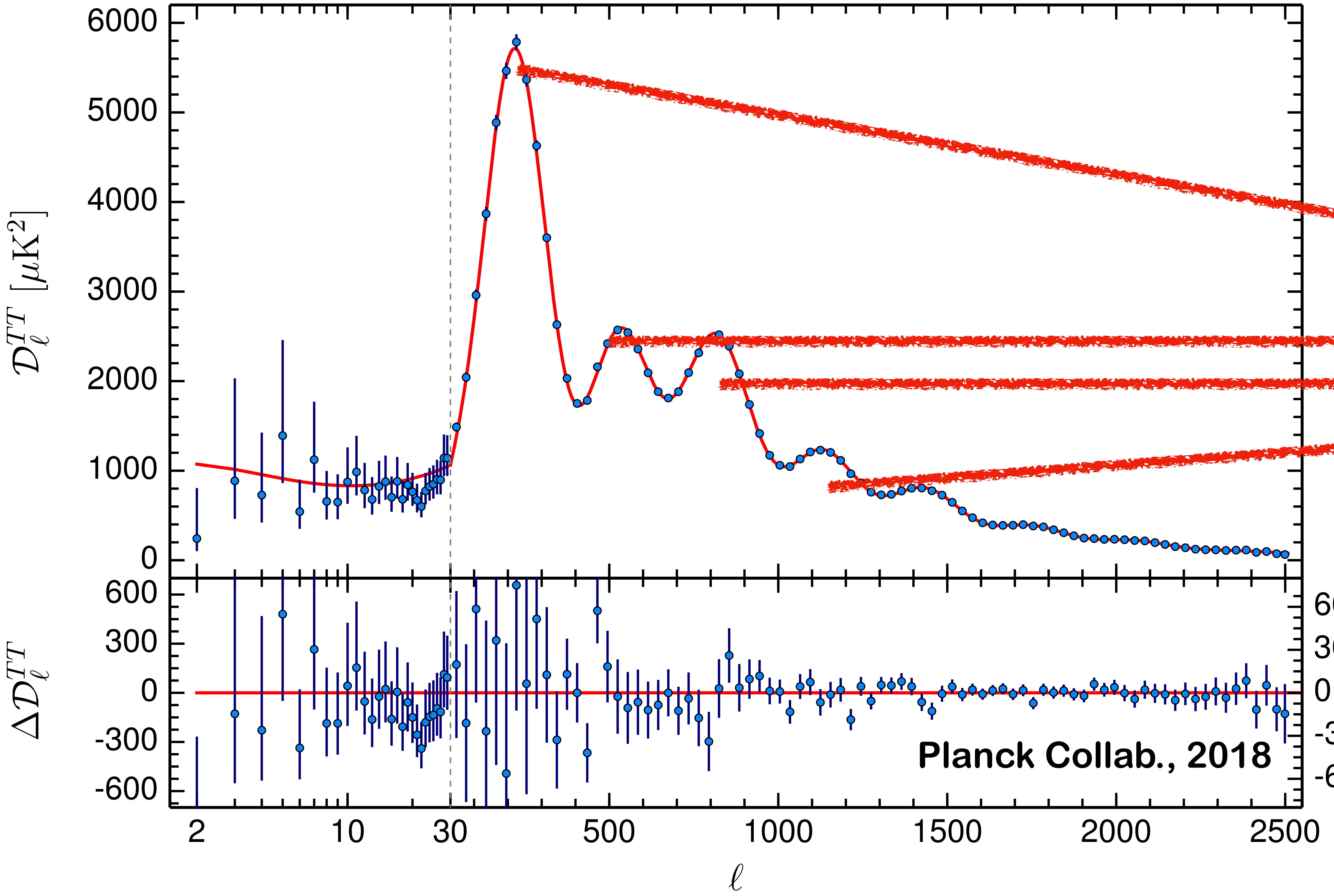
$$\theta_* = \frac{r_s(z_*)}{D_A(z)_*}$$

$N_{\rm eff} = 3.044$
In standard cosmology

$$\frac{r_*}{3000\,\mathrm{Mpc}} = \int_{z_*}^{\infty} \frac{c_s dz}{\left[\Omega_\gamma h^2 \left(1 + \frac{7}{8}\left(\frac{4}{11}\right)^{\frac{4}{3}} N_{\rm eff}\right)(1+z)^4 + \Omega_m h^2 (1+z)^3\right]^{1/2}}$$

$$\frac{d_A}{3000\,\mathrm{Mpc}} = \int_0^{z_*} \frac{dz}{\left[\Omega_m h^2 (1+z)^3 + \Omega_\Lambda h^2\right]^{1/2}}$$

Getting H0 in LCDM



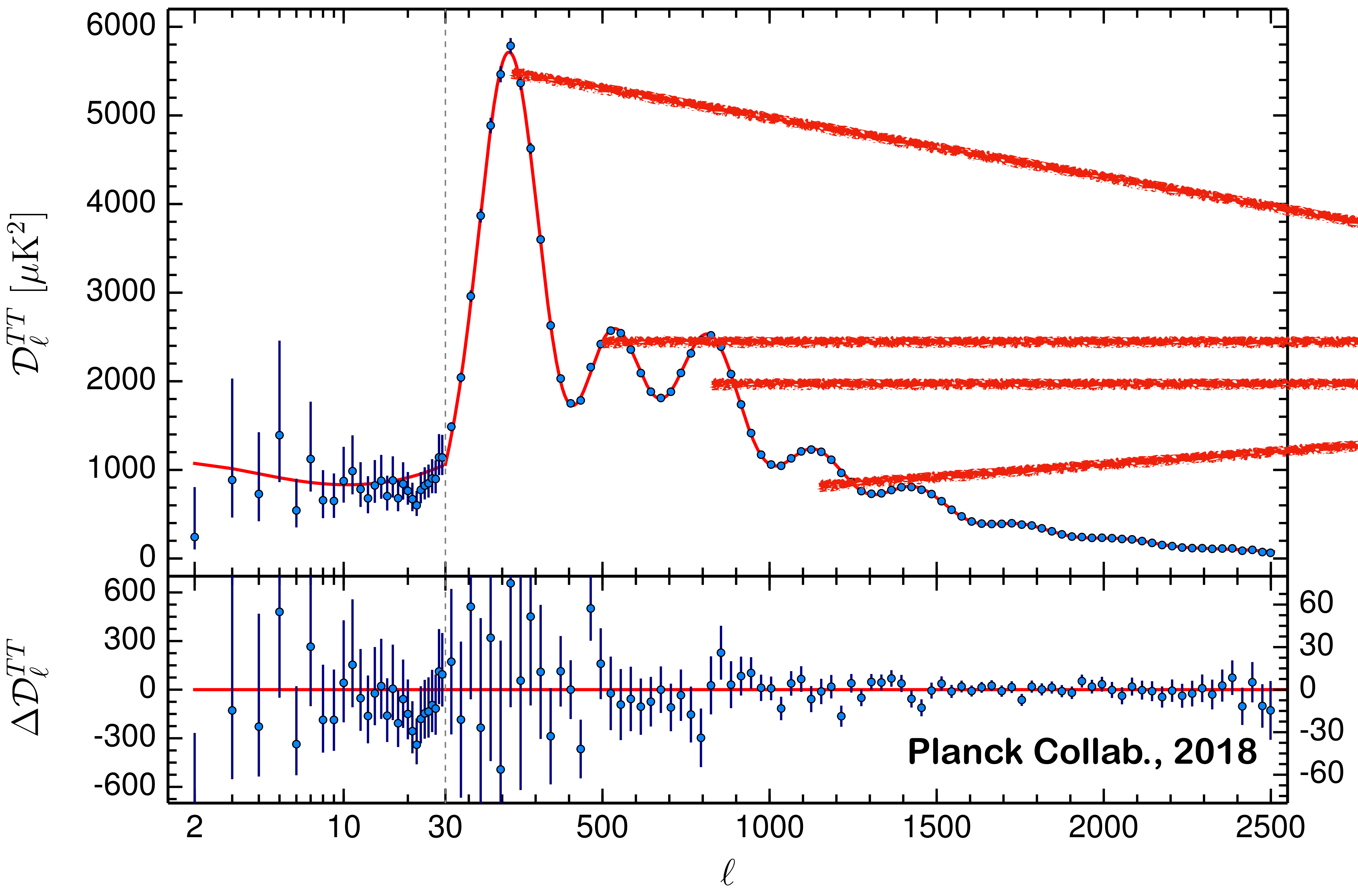
$$\theta_* = \frac{r_s(z_*)}{D_A(z)_*}$$

Depends on ω_b which is fixed by relative height of peaks and damping tail

$$\frac{r_*}{3000\,\mathrm{Mpc}} = \int_{z_*}^{\infty} \frac{c_s dz}{\left[\Omega_\gamma h^2 \left(1 + \frac{7}{8}\left(\frac{4}{11}\right)^{\frac{4}{3}} N_{\rm eff}\right)(1+z)^4 + \Omega_m h^2 (1+z)^3\right]^{1/2}}$$

$$\frac{d_A}{3000\,\mathrm{Mpc}} = \int_0^{z_*} \frac{dz}{\left[\Omega_m h^2 (1+z)^3 + \Omega_\Lambda h^2\right]^{1/2}}$$

Getting H0 in LCDM



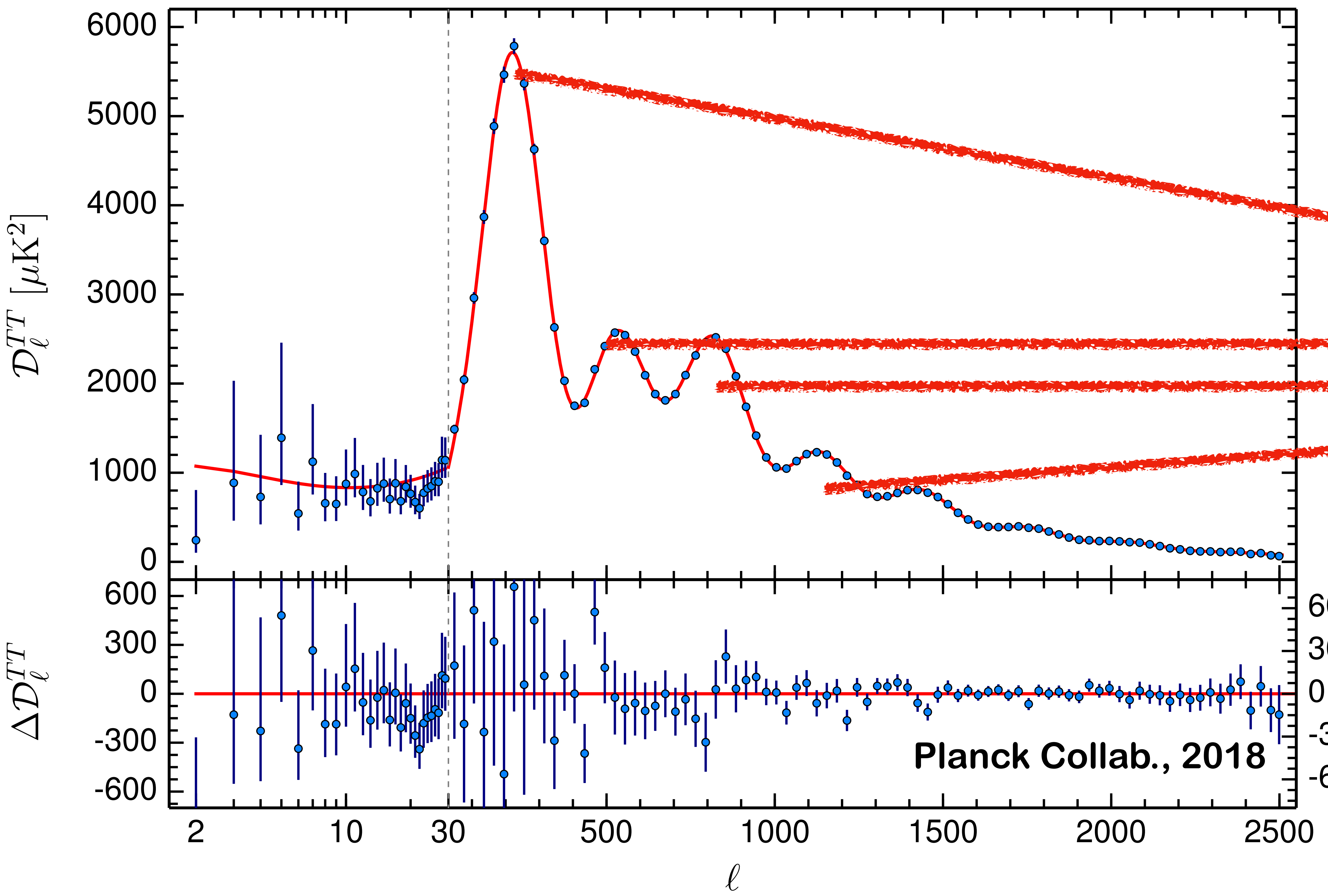
$$\theta_* = \frac{r_s(z_*)}{D_A(z)_*}$$

Fixed by height of peaks

$$\frac{r_*}{3000\,\mathrm{Mpc}} = \int_{z_*}^{\infty} \frac{c_s dz}{\left[\Omega_\gamma h^2 \left(1 + \frac{7}{8}\left(\frac{4}{11}\right)^{\frac{4}{3}} N_{\mathrm{eff}}\right)(1+z)^4 + \Omega_m h^2 (1+z)^3\right]^{1/2}}$$

$$\frac{d_A}{3000\,\mathrm{Mpc}} = \int_0^{z_*} \frac{dz}{\left[\Omega_m h^2 (1+z)^3 + \Omega_\Lambda h^2\right]^{1/2}}$$

Getting H0 in LCDM



$$\theta_* = \frac{r_s(z_*)}{D_A(z)_*}$$

$$\Omega_\Lambda h^2 = h^2 - \omega_m$$

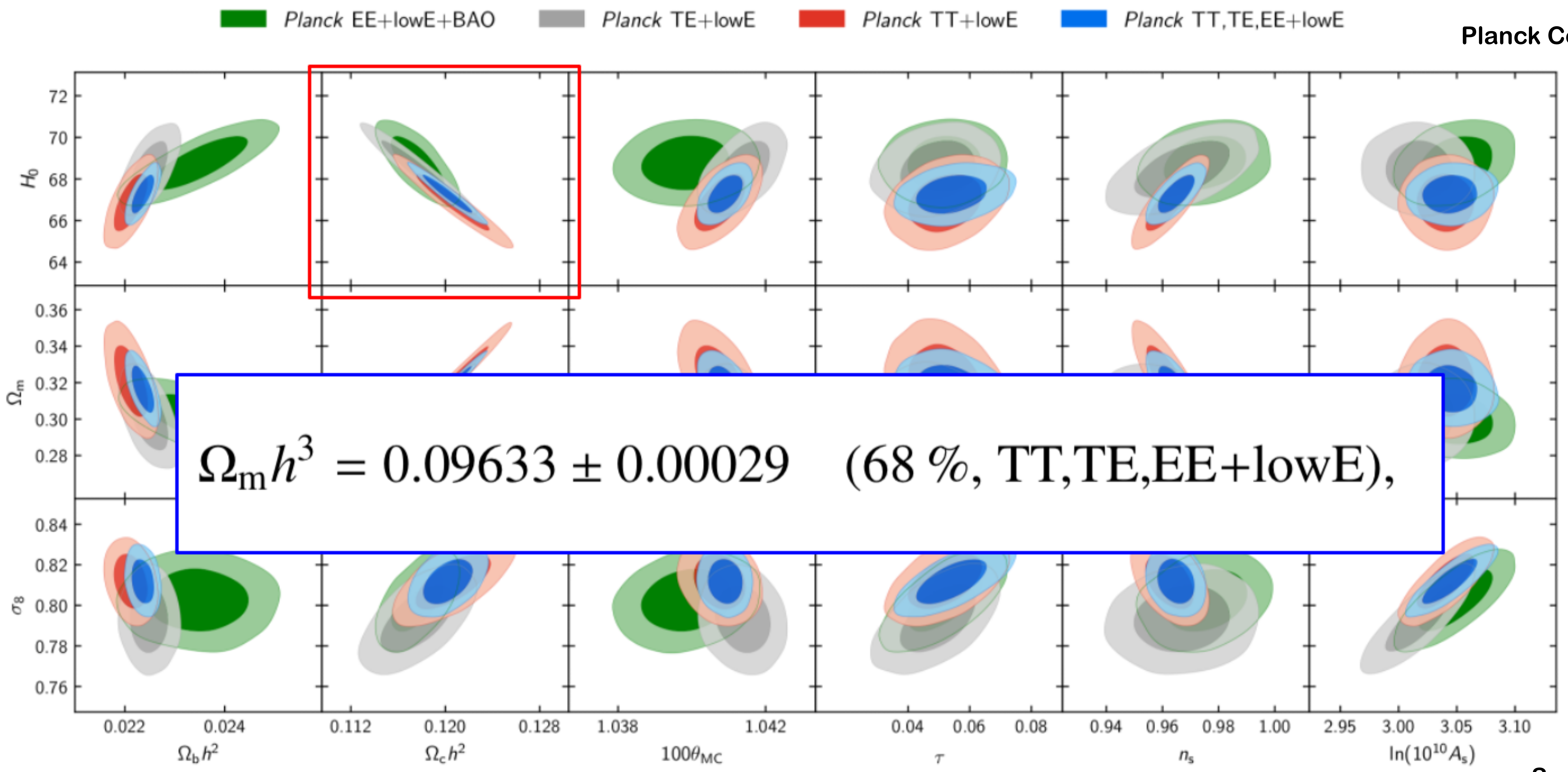
In LCDM

$$\frac{r_*}{3000\,\mathrm{Mpc}} = \int_{z_*}^{\infty} \frac{c_s dz}{\left[\Omega_\gamma h^2 \left(1 + \frac{7}{8}\left(\frac{4}{11}\right)^{\frac{4}{3}} N_{\rm eff}\right)(1+z)^4 + \Omega_m h^2 (1+z)^3\right]^{1/2}}$$

$$\frac{d_A}{3000\,\mathrm{Mpc}} = \int_0^{z_*} \frac{dz}{\left[\Omega_m h^2 (1+z)^3 + \Omega_\Lambda h^2\right]^{1/2}}$$

Getting H0 in LCDM

Planck Collab. VI, 2018



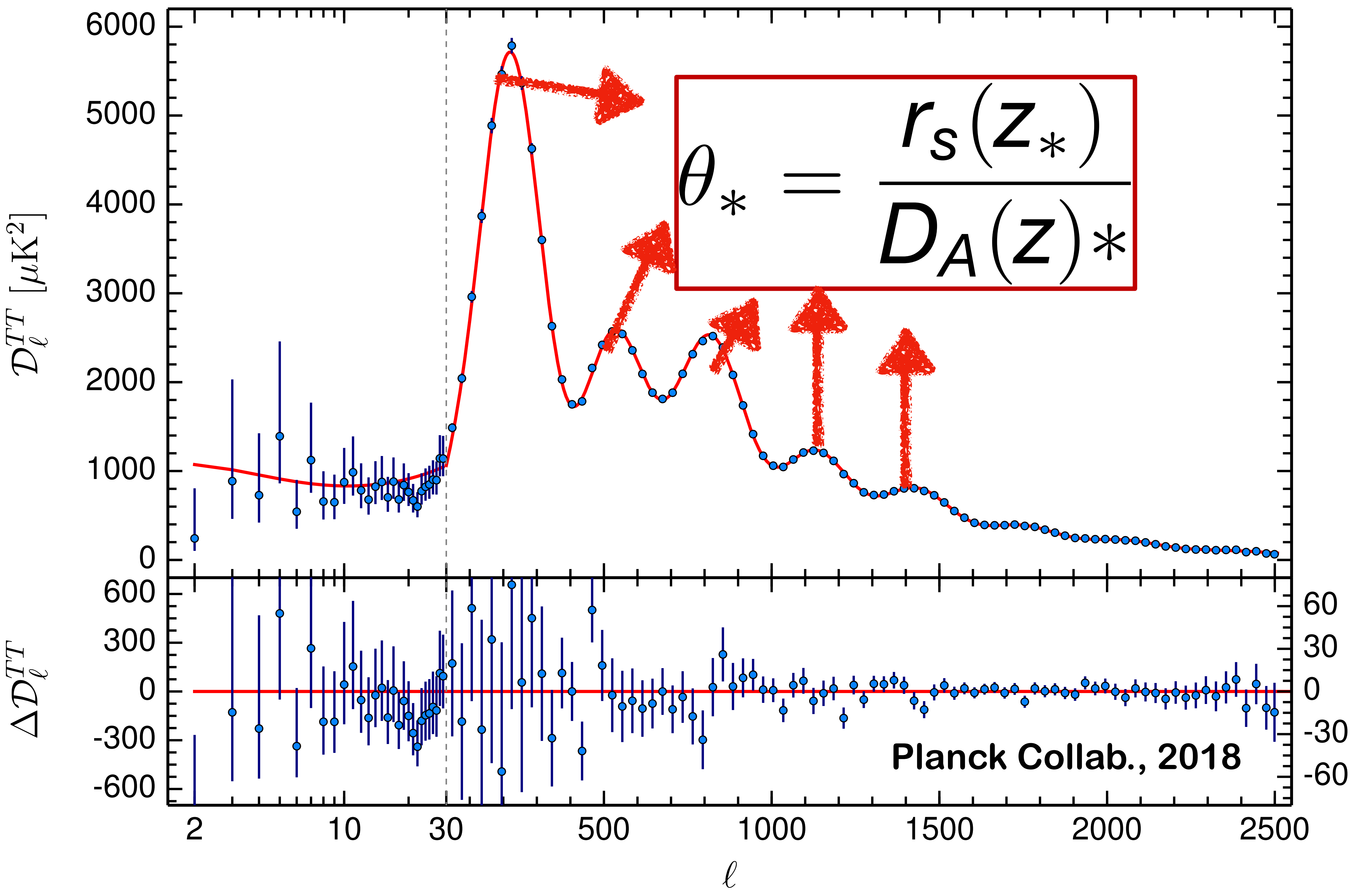
$$\Omega_m h^3 = 0.09633 \pm 0.00029 \quad (68\,\%,\ \mathrm{TT,TE,EE{+}lowE}),$$

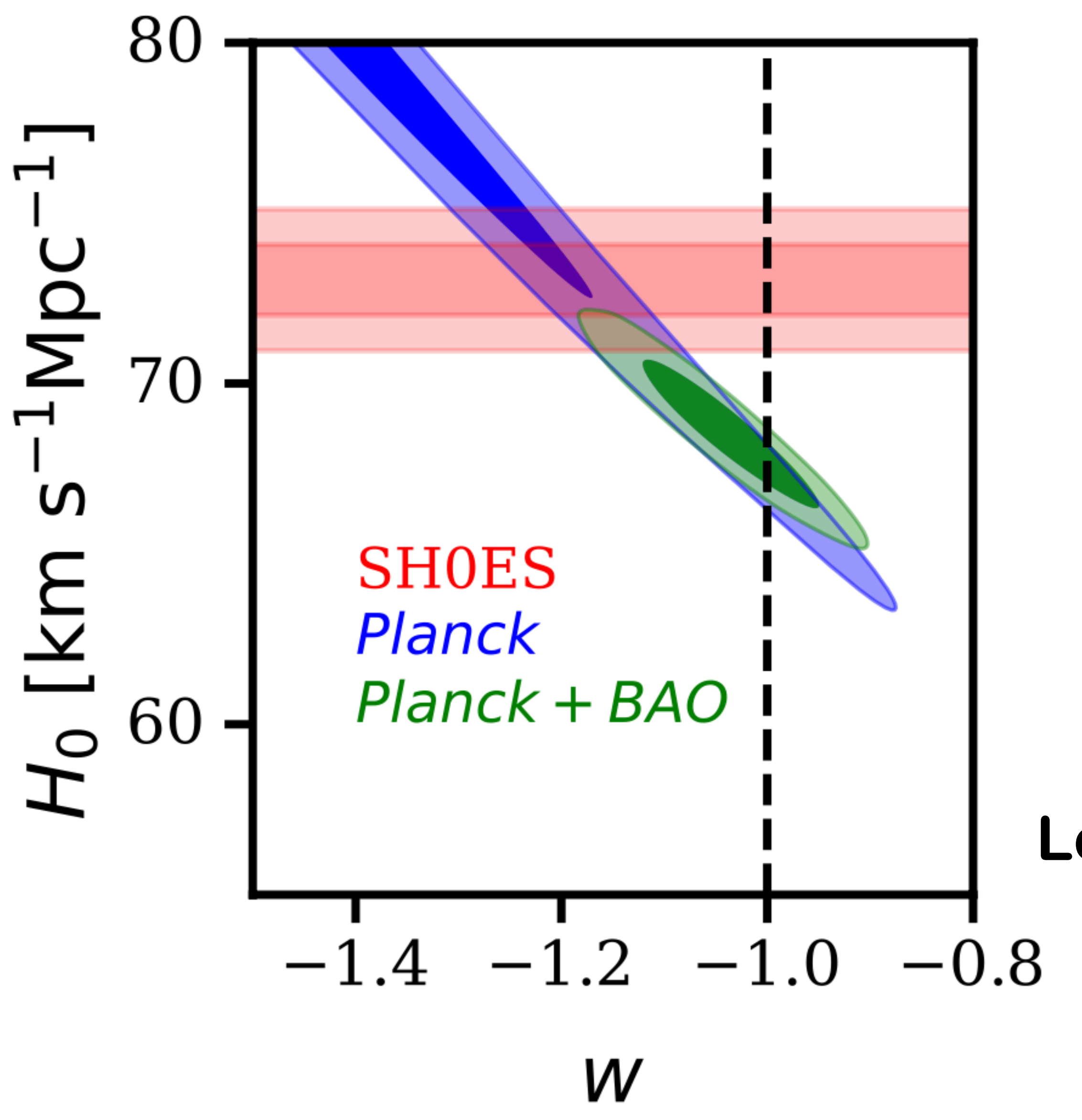
See Percival+, 2002

Getting H0 in beyond LCDM

0.05% measurement (in LCDM) of the angular scale of sound horizon
Robust determination with respect to the cosmological model
H0 estimates do change if we allow for more freedom in the model

Getting H0 in beyond LCDM - late times





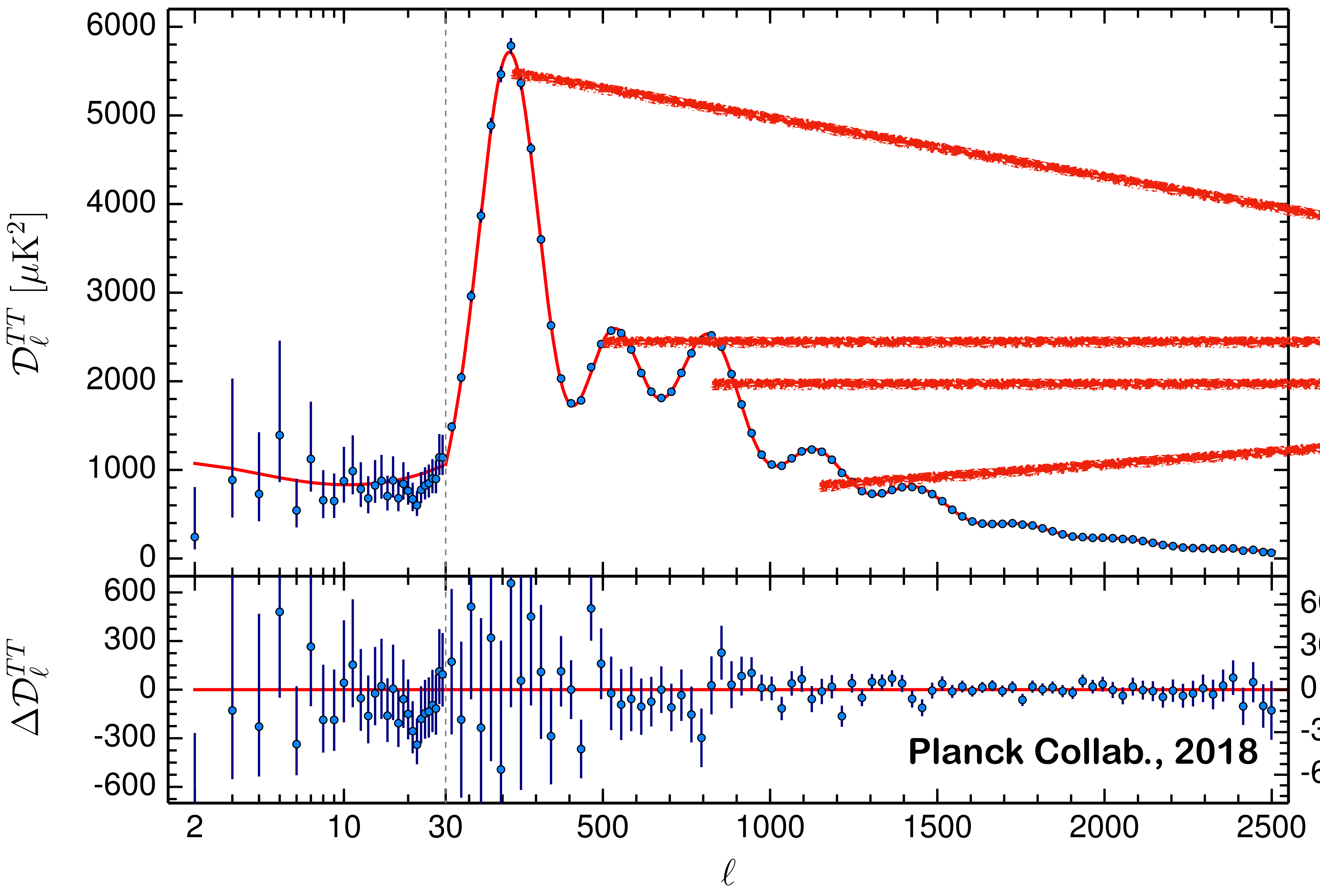
Lemos&Shah,2023

More freedom in estimate of h when allowing for dynamical dark energy, and/or non-flat Universe, …

$$\frac{r_*}{3000\,\mathrm{Mpc}} = \int_{z_*}^{\infty} \frac{c_s dz}{\left[\Omega_\gamma h^2 \left(1 + \frac{7}{8}\left(\frac{4}{11}\right)^{\frac{4}{3}} N_{\mathrm{eff}}\right)(1+z)^4 + \Omega_m h^2 (1+z)^3\right]^{1/2}}$$

$$\frac{d_A}{3000\,\mathrm{Mpc}} = \int_0^{z_*} \frac{dz}{\left[\Omega_m h^2 (1+z)^3 + \Omega_\Lambda h^2\right]^{1/2}}$$

Getting H0 in beyond LCDM - early times



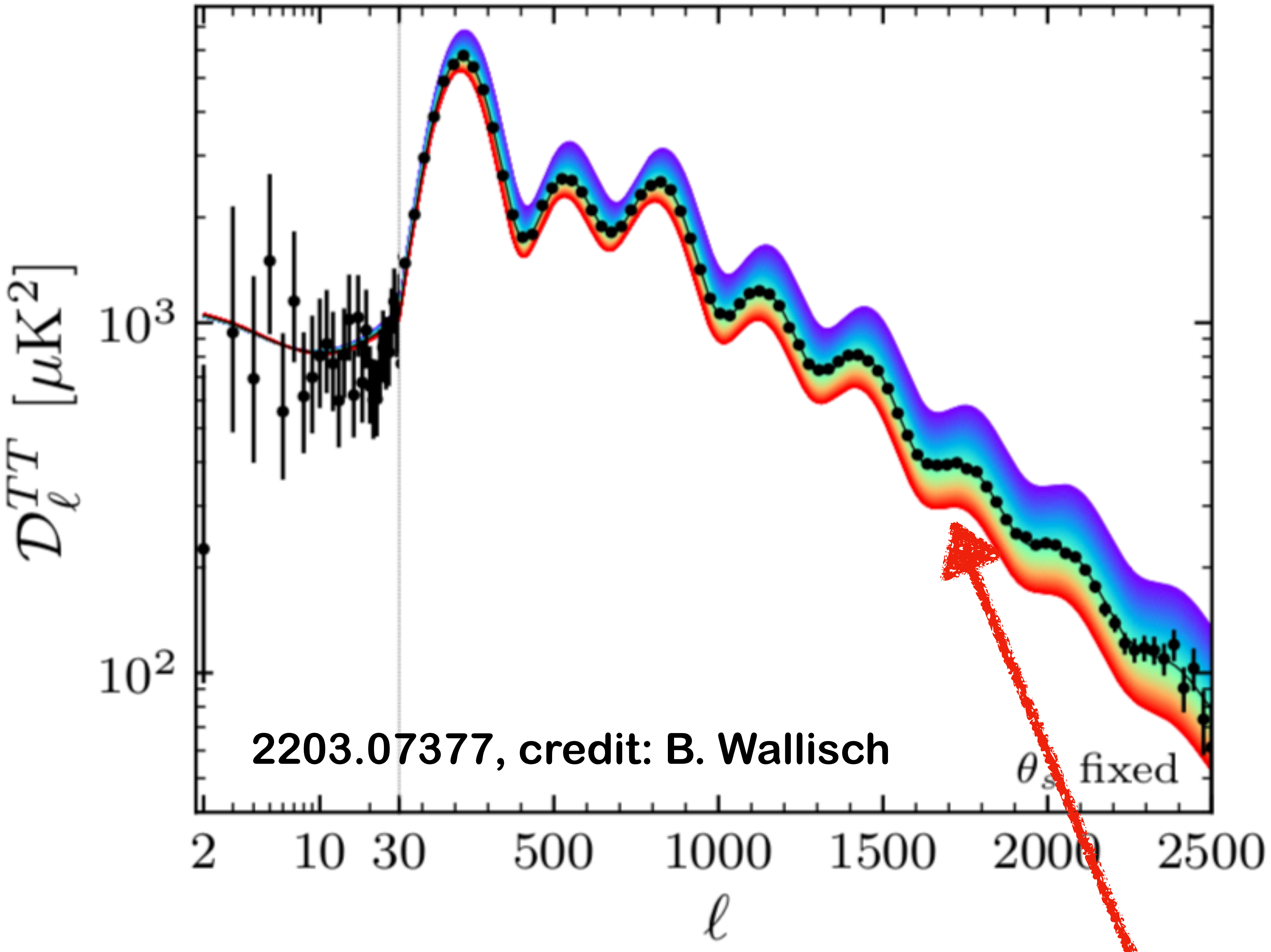
$$\theta_* = \frac{r_s(z_*)}{D_A(z)_*}$$

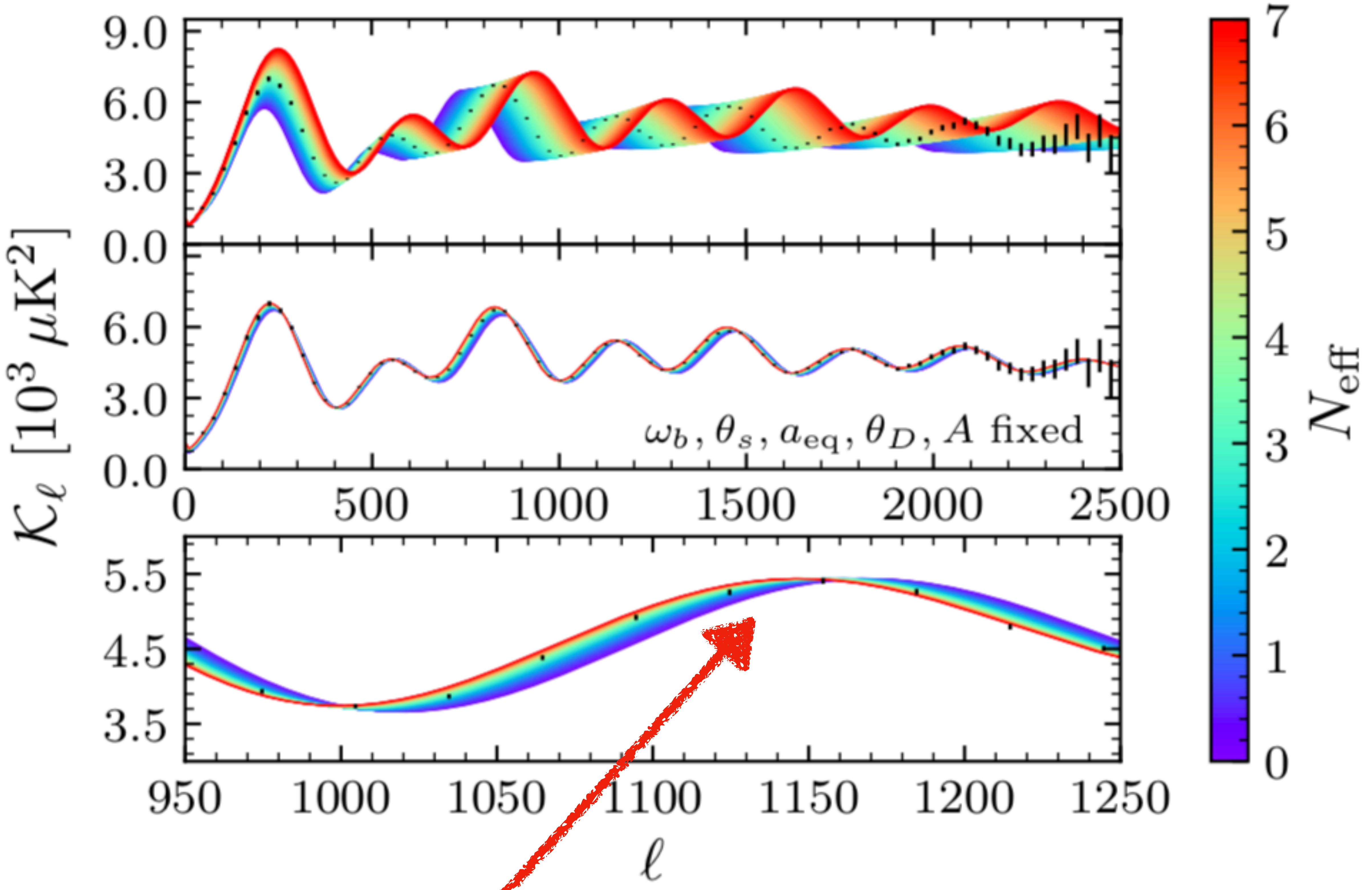
More freedom if allowing for non-standard light relic sector

$$\frac{r_*}{3000\,\mathrm{Mpc}} = \int_{z_*}^{\infty} \frac{c_s dz}{\left[\Omega_\gamma h^2 \left(1 + \frac{7}{8}\left(\frac{4}{11}\right)^{\frac{4}{3}} N_{\rm eff}\right)(1+z)^4 + \Omega_m h^2 (1+z)^3\right]^{1/2}}$$

$$\frac{d_A}{3000\,\mathrm{Mpc}} = \int_0^{z_*} \frac{dz}{\left[\Omega_m h^2 (1+z)^3 + \Omega_\Lambda h^2\right]^{1/2}}$$

Getting H0 in beyond LCDM - early times





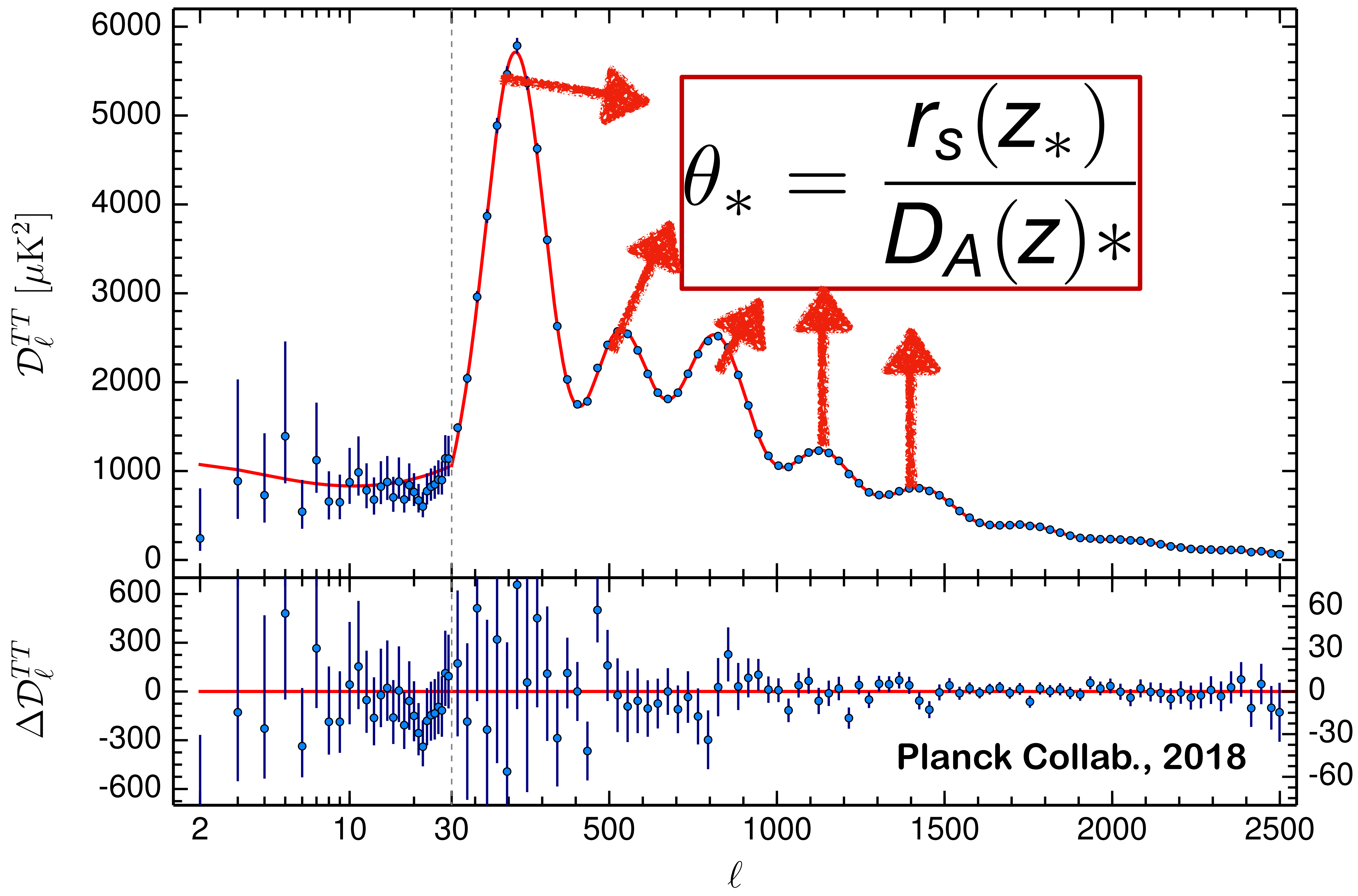
Damping tail suppression:

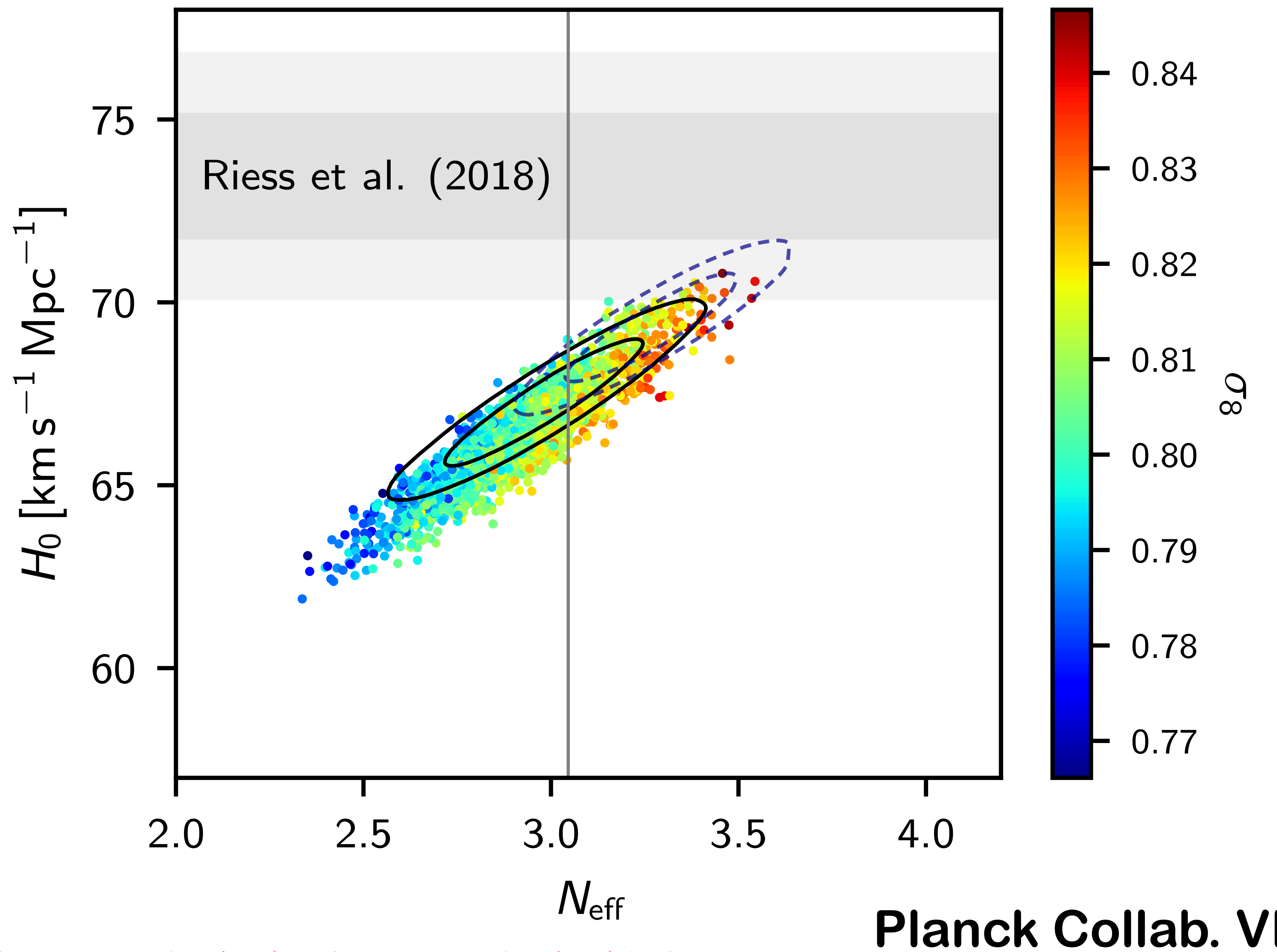
$$\theta_d \sim \sqrt{H(N_{\rm eff})}$$

Shift of acoustic peak position:

$$\ell_p \to 1/\theta_*(n\pi + \phi(N_{\rm eff}^{\rm fs}))$$

Getting H0 in beyond LCDM - early times





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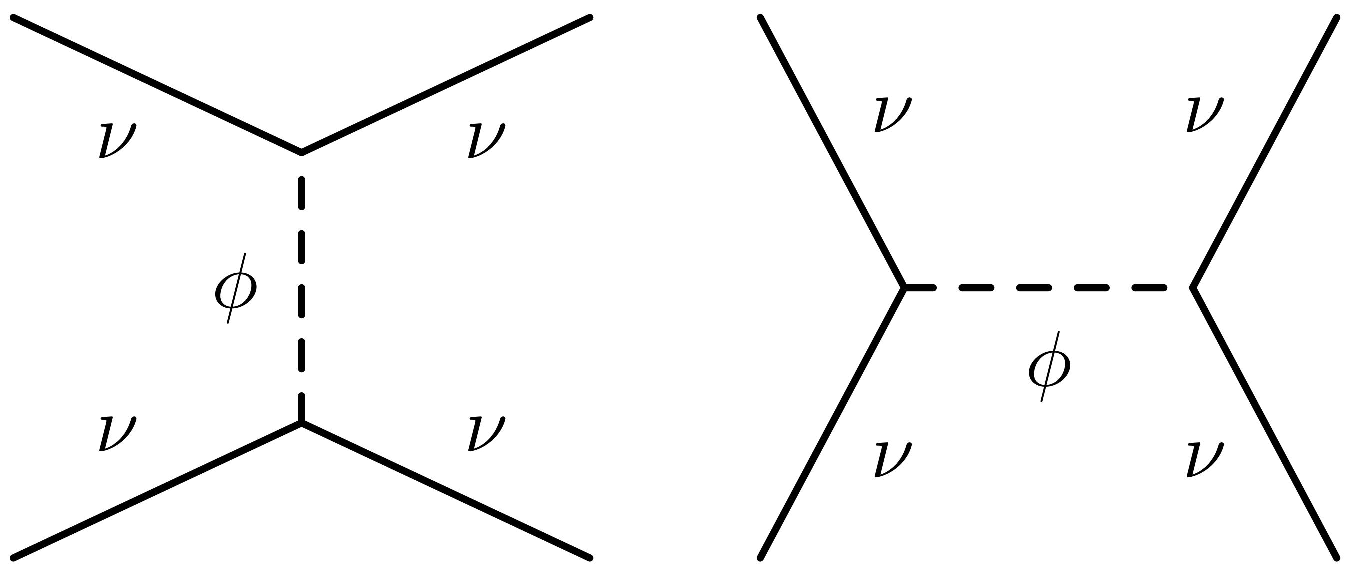
Effects on damping tail and peak position

$$\frac{r_*}{3000\,\mathrm{Mpc}} = \int_{z_*}^{\infty} \frac{c_s dz}{\left[\Omega_\gamma h^2 \left(1 + \frac{7}{8}\left(\frac{4}{11}\right)^{\frac{4}{3}} N_{\rm eff}\right)(1+z)^4 + \Omega_m h^2 (1+z)^3\right]^{1/2}}$$

$$\frac{d_A}{3000\,\mathrm{Mpc}} = \int_0^{z_*} \frac{dz}{\left[\Omega_m h^2 (1+z)^3 + \Omega_\Lambda h^2\right]^{1/2}}$$

Getting H0 in beyond LCDM - early times

$$\mathcal{L} \supset h_{ij}\bar{\nu}_i^c \nu_j \phi + g_{ij}\bar{\nu}_i^c \gamma_5 \nu_j \phi + h.c.$$



Collisional processes suppress stress and affect the perturbation evolution.
Neutrino free-streaming altered non-trivially.

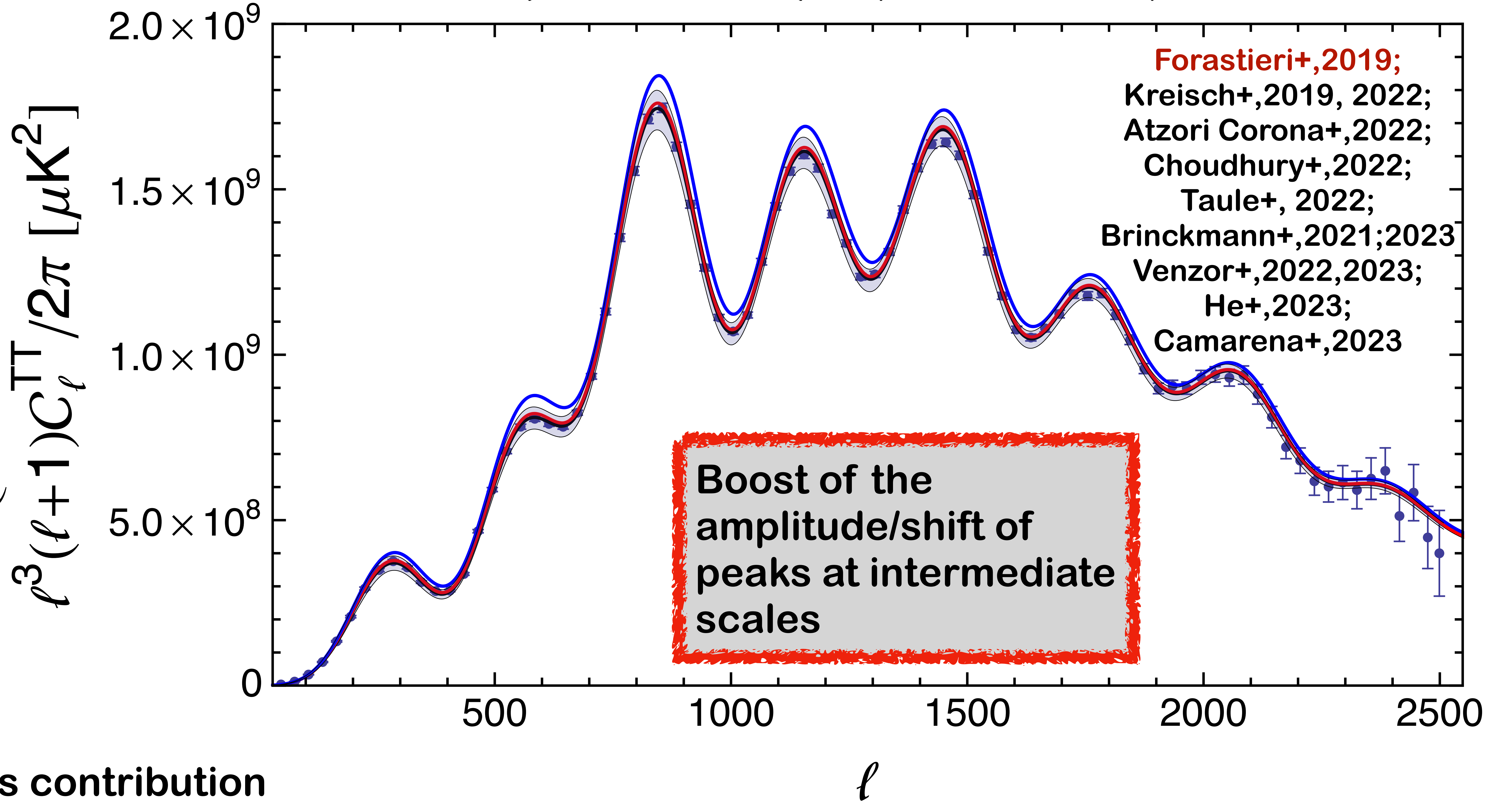
In the massive mediator limit:

$$\Gamma_{\rm NSI} = G_{\rm eff}^2 T^5$$

$$\log_{10}(G_{\rm eff}\,{\rm MeV}^2) = -1.277 \pm 0.090 \quad {\rm SI}\nu$$

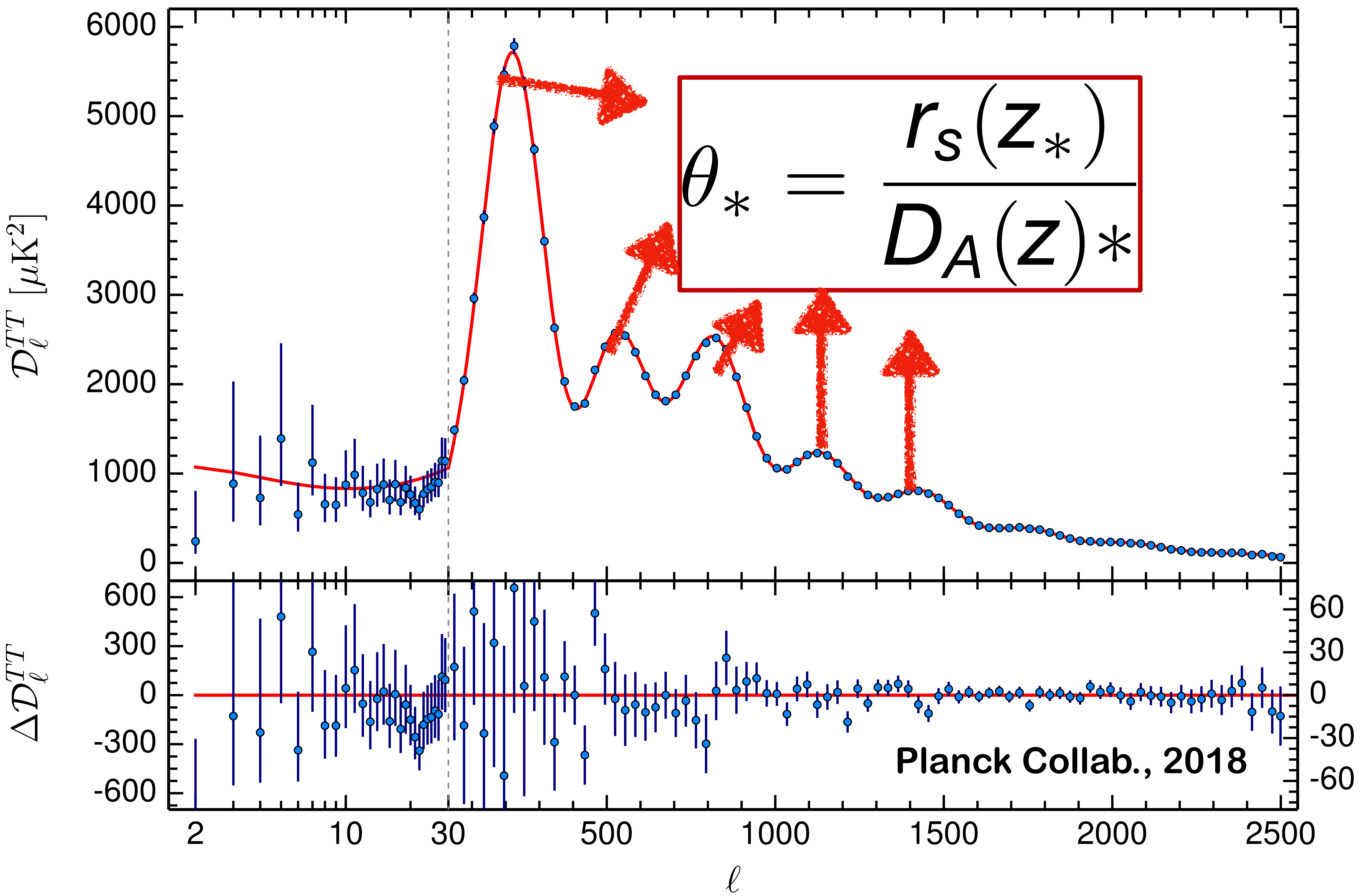
$$H_0 = (69.3 \pm 1.1)\,{\rm km/s/Mpc}$$

ACT+WMAP, Kreisch+(ACT Collab.), 2022

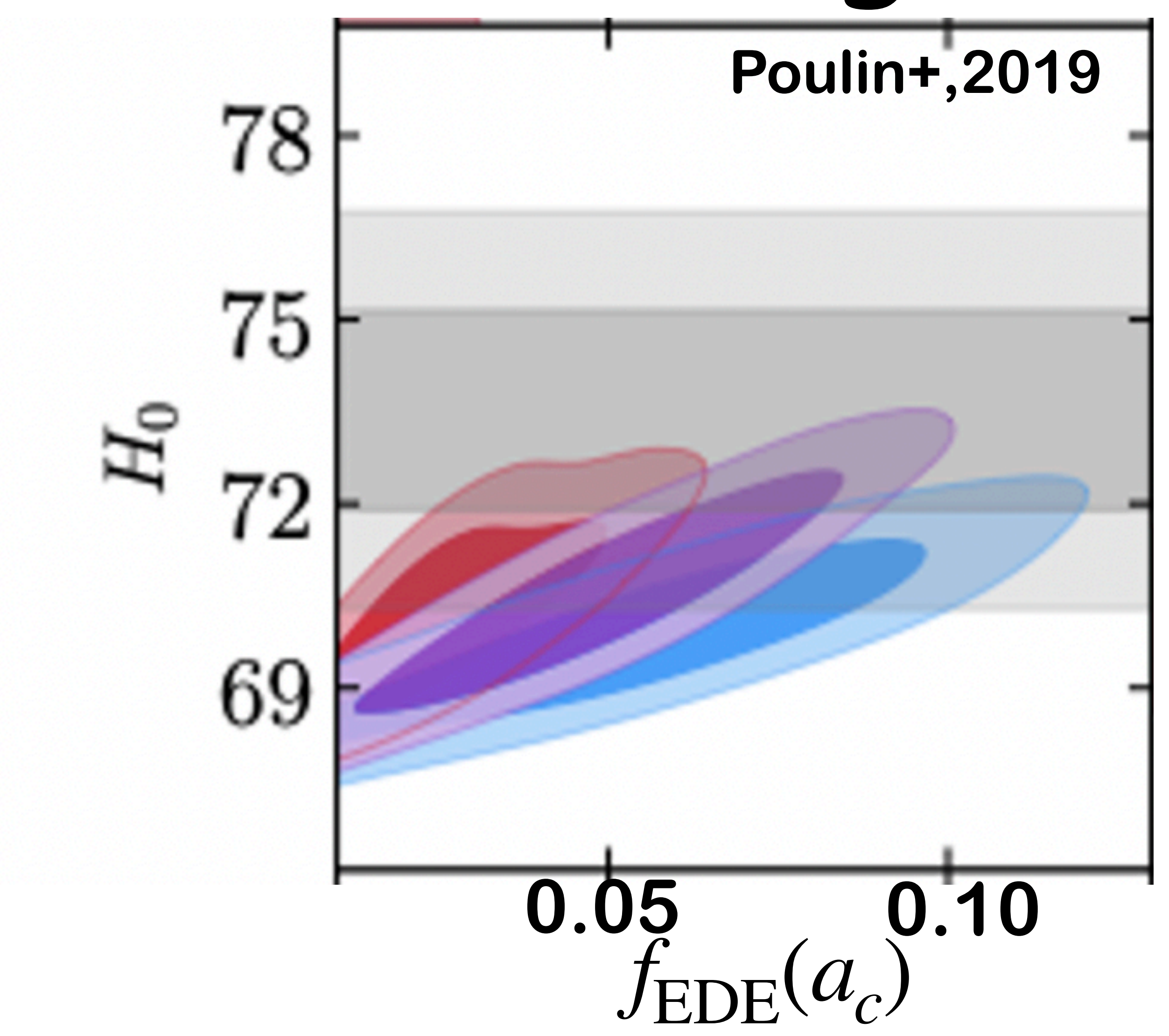


See also Berryman+(incl.MG) 2023, Snowmass contribution

Getting H0 in beyond LCDM - early times



$$\theta_* = \frac{r_s(z_*)}{D_A(z)*}$$

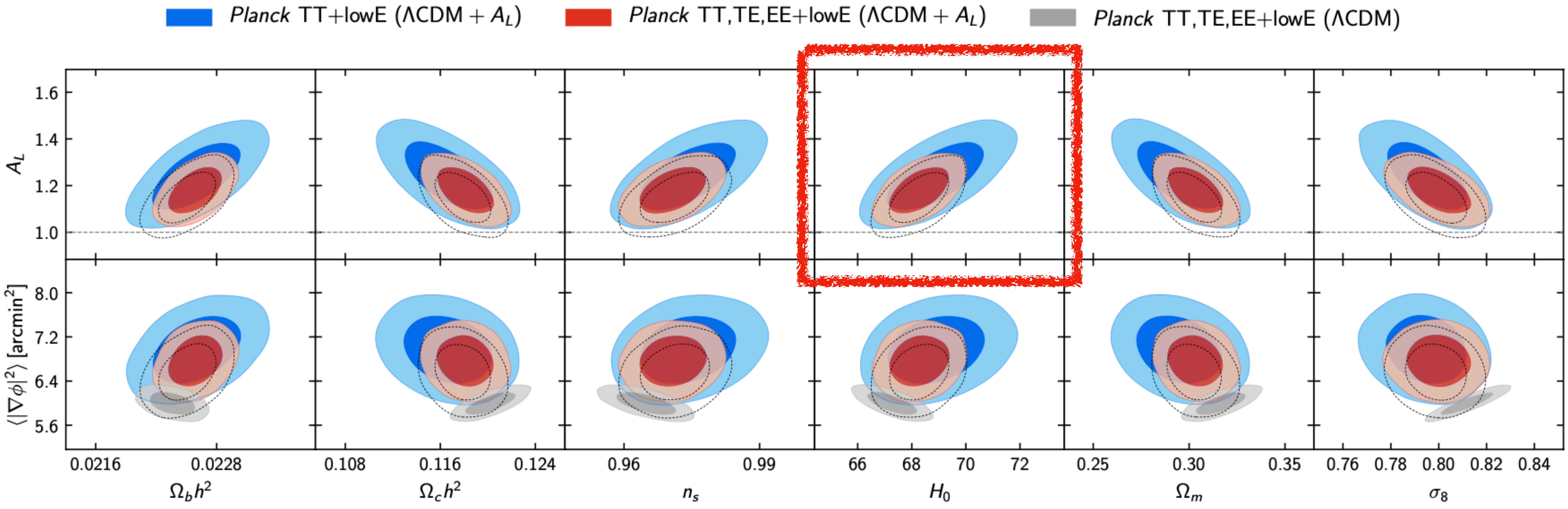


Exotic fluid contributing ~10% around recombination and decaying faster than radiation

$$\frac{r_*}{3000\,\mathrm{Mpc}} = \int_{z_*}^{\infty} \frac{c_s\,dz}{[\Omega_\gamma h^2(1+\frac{7}{8}(\frac{4}{11})^{\frac{4}{3}}N_{\rm eff}(1+z)^4) + \Omega_m h^2(1+z)^3 + \frac{\rho_{\rm EDE}(z)}{\rho_{\rm crit}}h^2]}$$

$$\frac{d_A}{3000\,\mathrm{Mpc}} = \int_0^{z_*} \frac{dz}{[\Omega_m h^2(1+z)^3 + \Omega_\Lambda h^2]^{1/2}}$$

Getting H0 in beyond LCDM

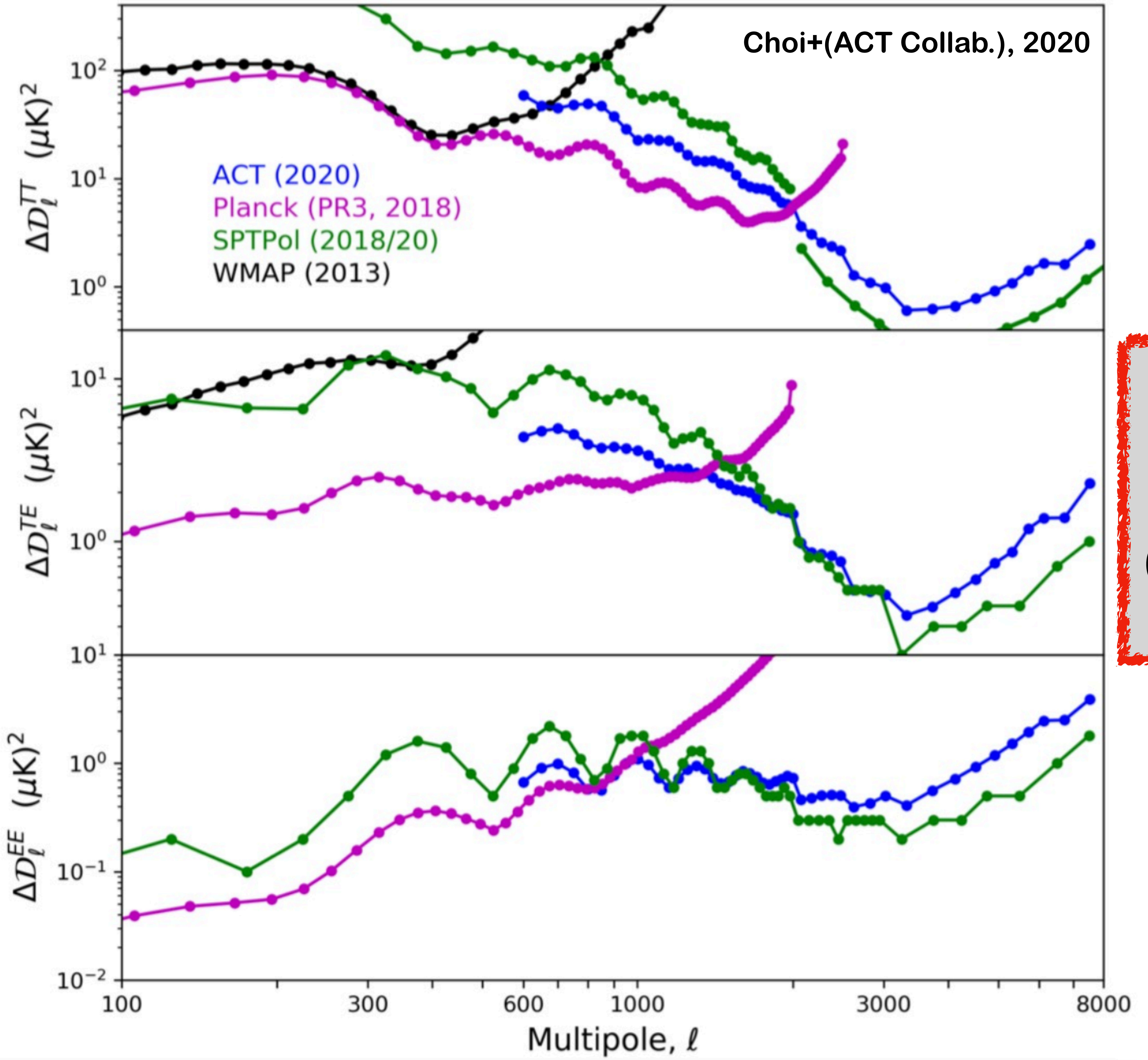


Planck Collab. VI, 2018

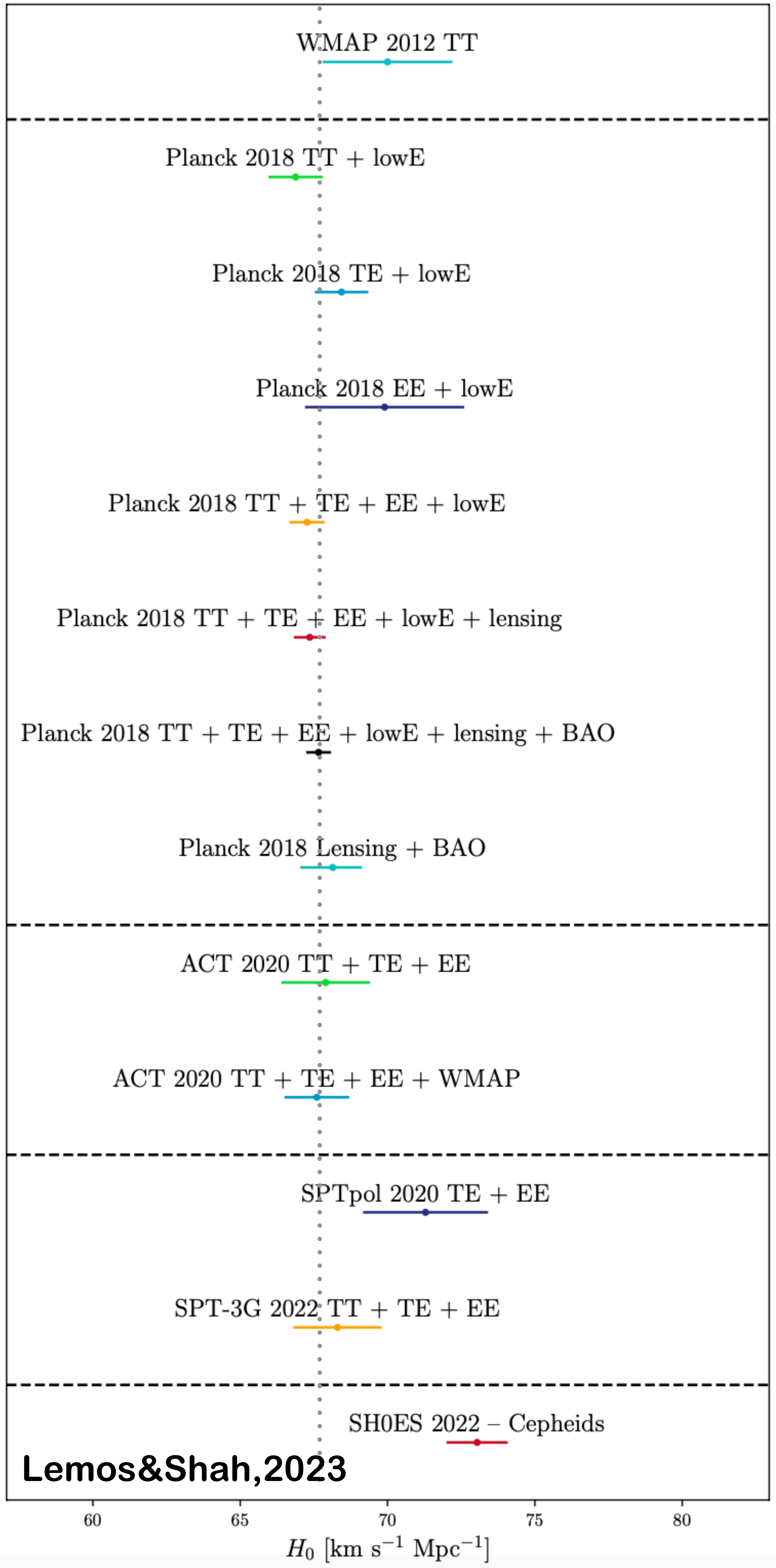
Alens anomaly:

- Allowing for Alens freedom reduce (though does not solve) the tension
- Removing large scales ($\ell < 30$) from analysis removes preference for high Alens
- No evidence for Alens != 1 from other CMB experiments

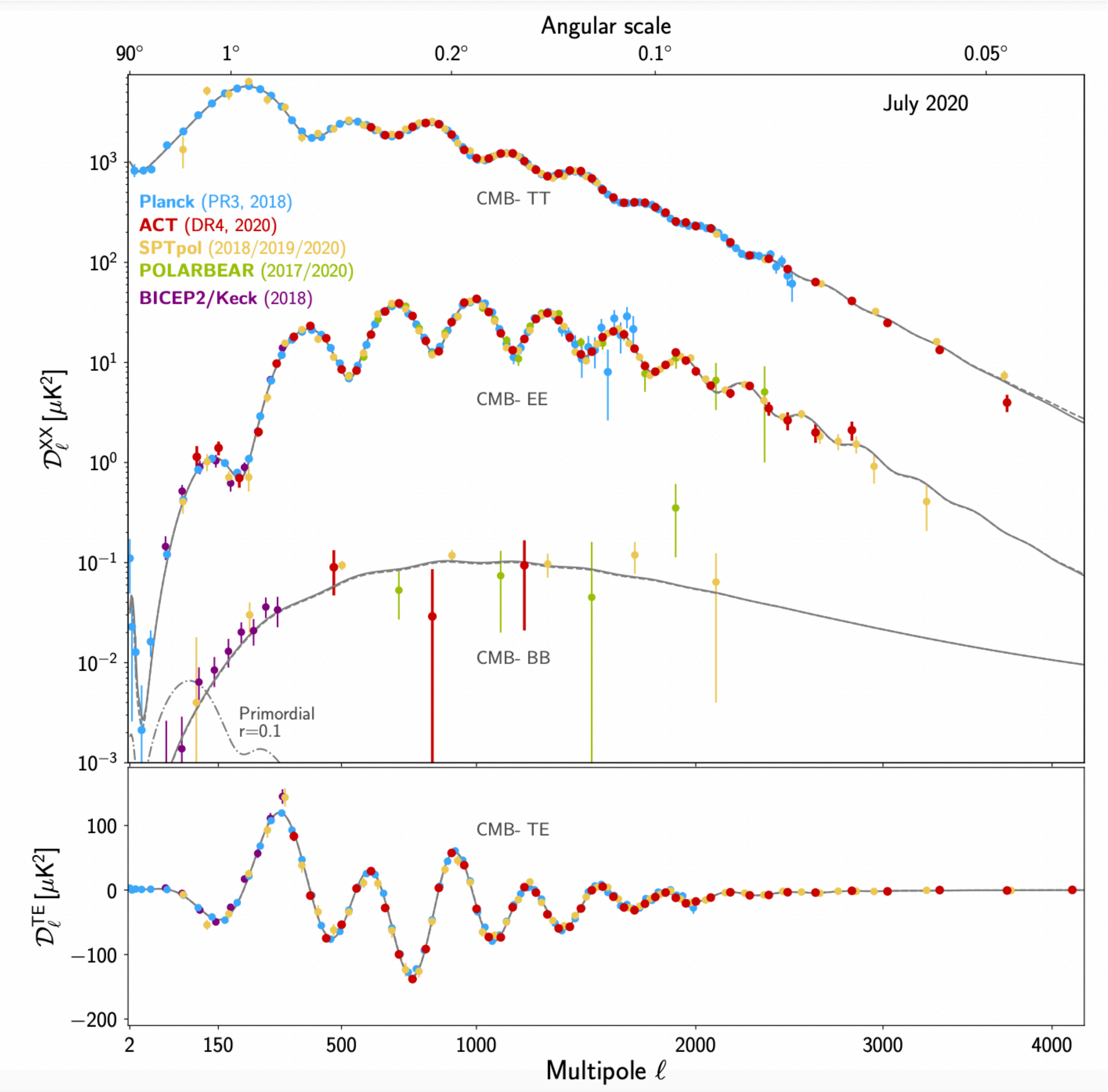
Comparison of CMB analyses



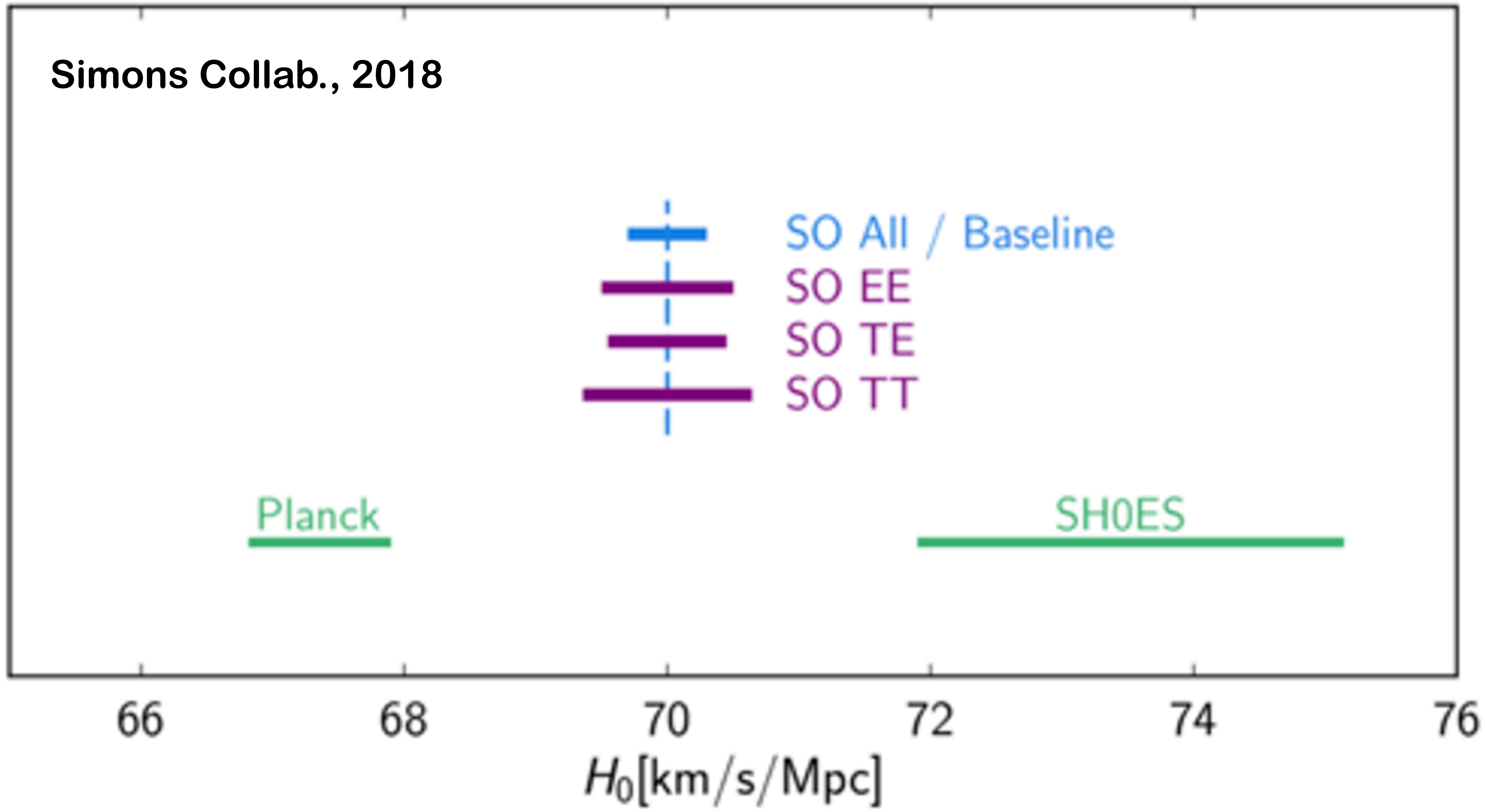
Remarkable agreement between different (and independent) CMB analyses

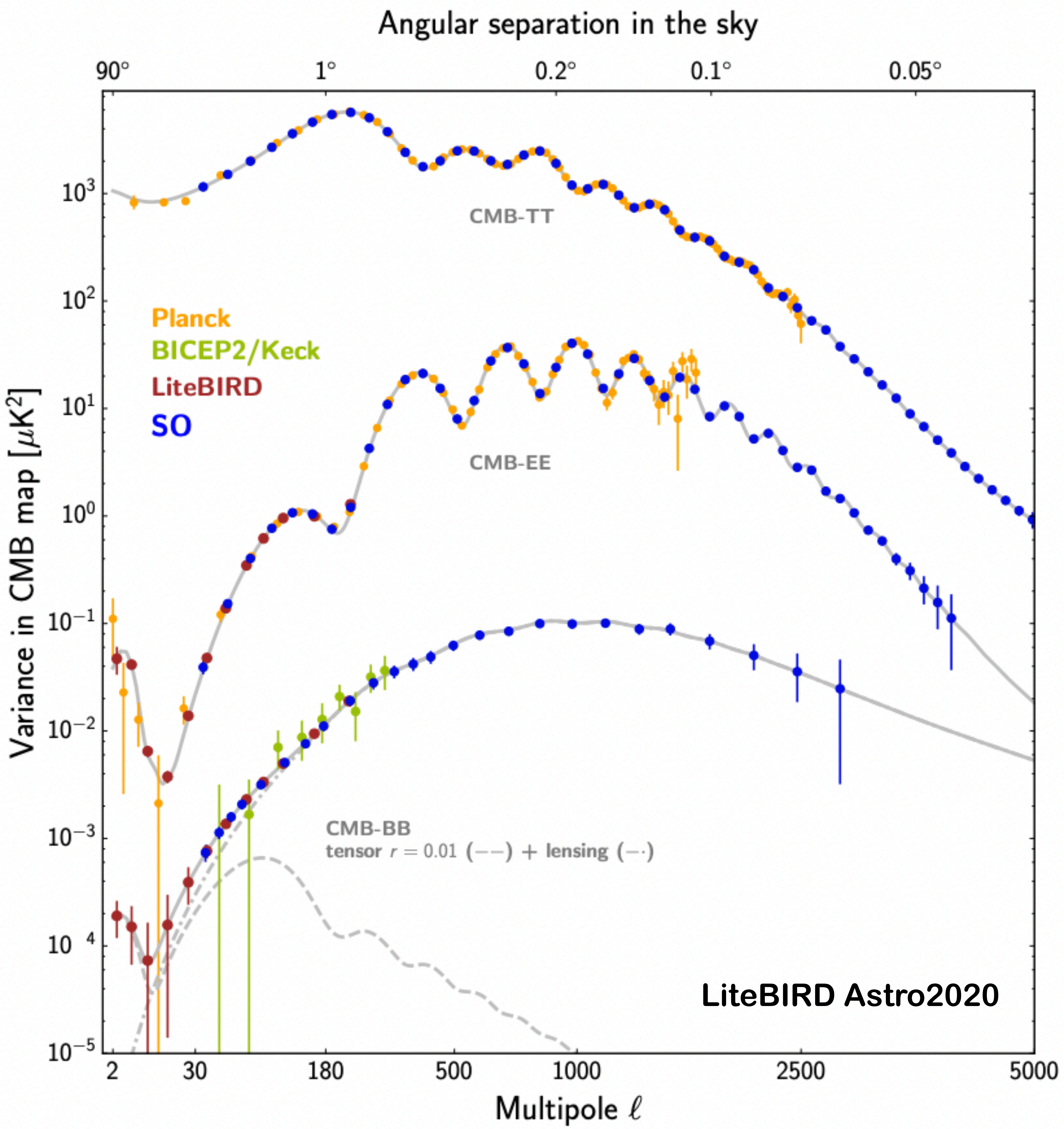


Getting H0 with future CMB surveys



Getting H0 with future CMB surveys





Conclusions

CMB measurements provide estimate of H0
which depends on the underlying cosmological model

Multiple CMB experiments agree on the estimate of H0

Constraints on H0 broadened (and, in some cases, shifted) in extended/exotic models

Tension with “direct” measurements remains

No real satisfying solutions from “high-z” theory modifications;
instrumental systematics less and less plausible