PLANCK AND COSMIC TENSIONS

19th November 2021
Cosmology Intertwined Mini-Workshop

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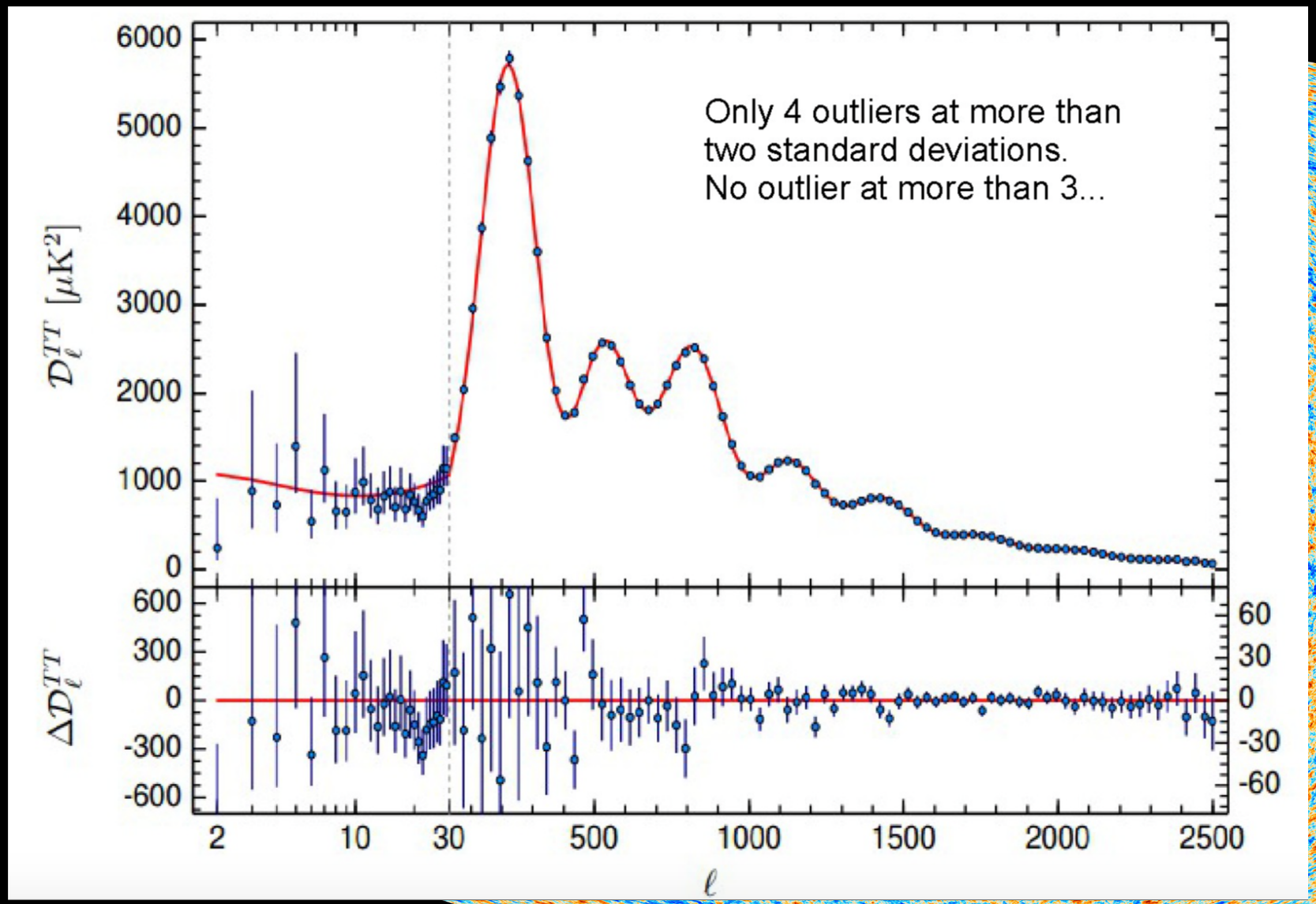
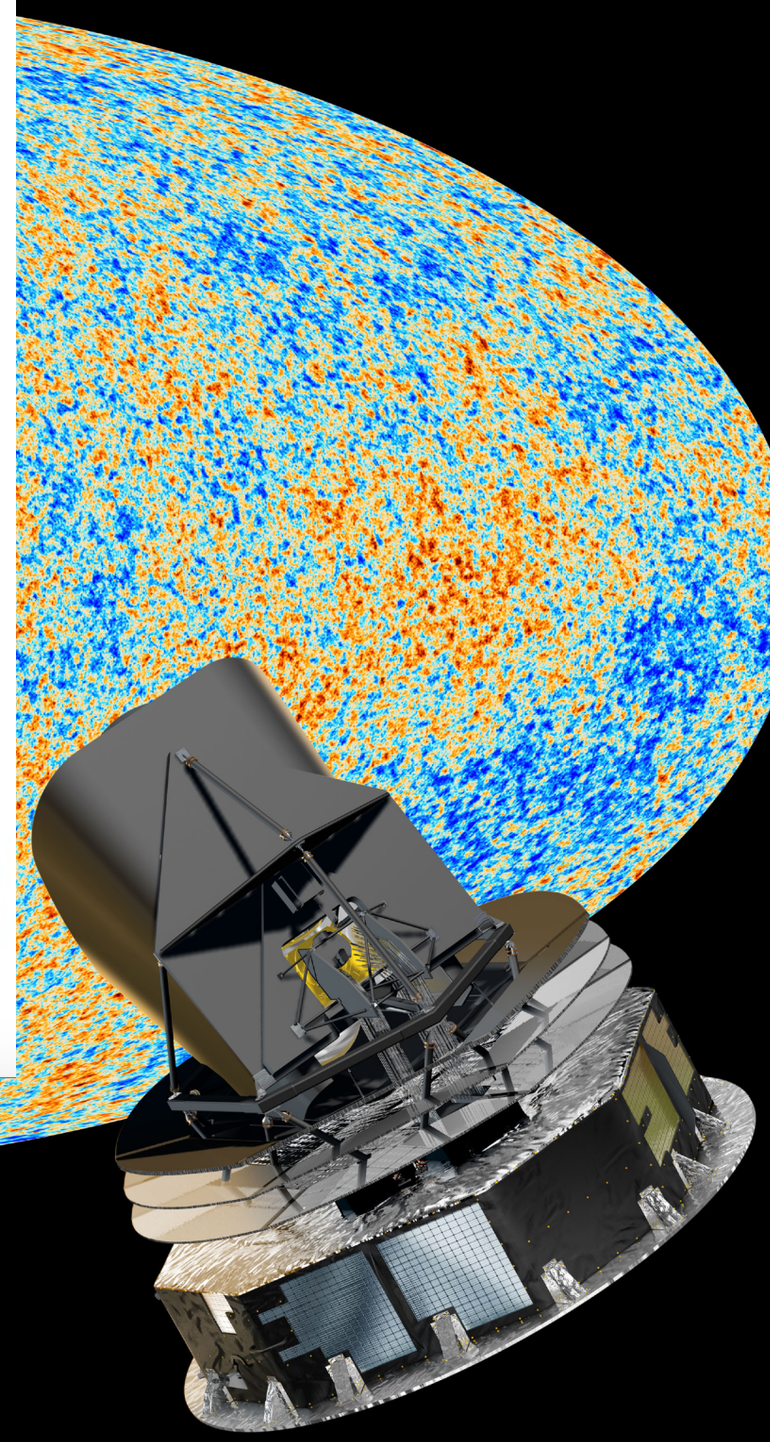
A PERFECT (LCDM) UNIVERSE ?





The recent CMB measurements made by the Planck satellite are in excellent agreement with the expectations of the LCDM model.

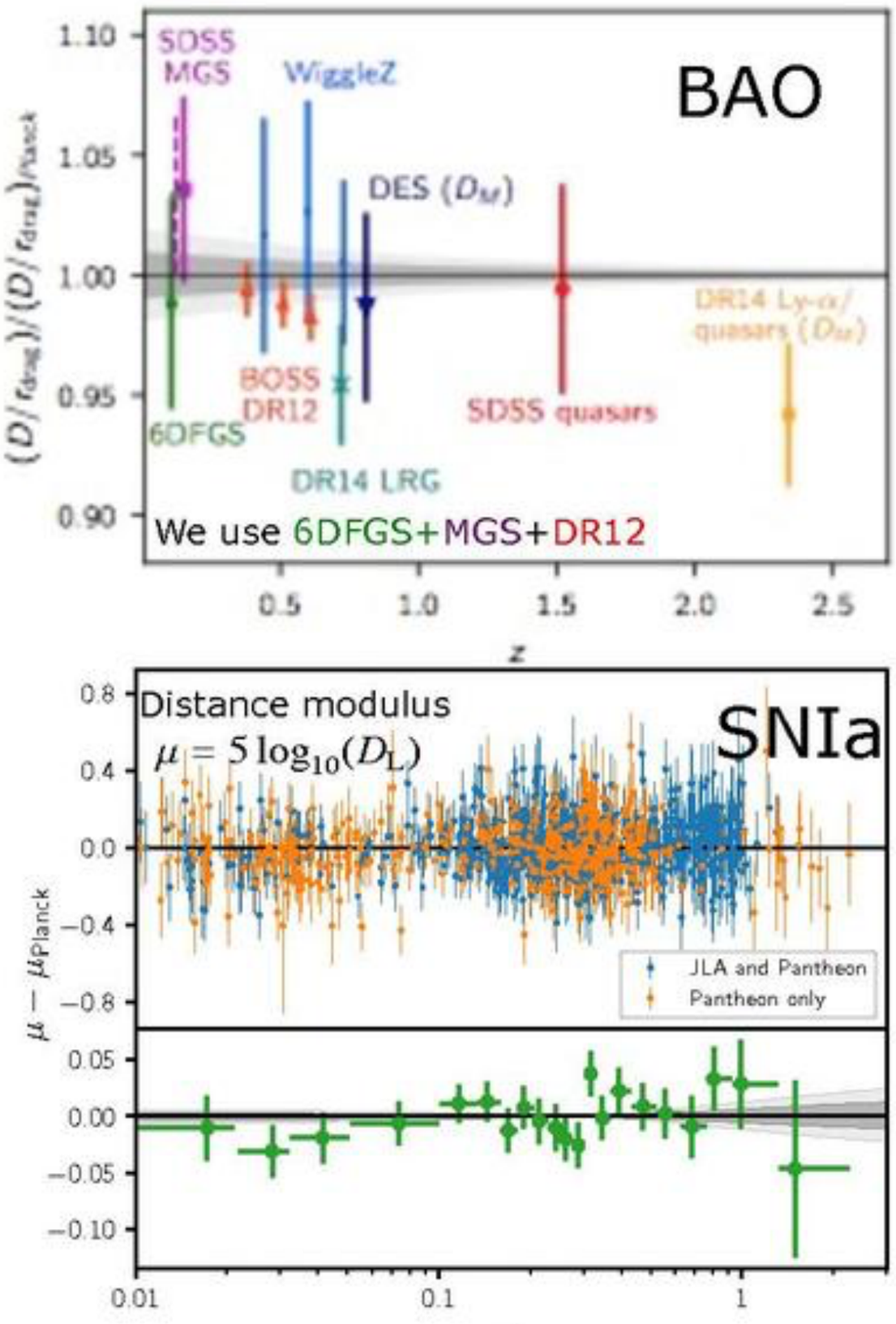
Planck collaboration, arXiv:1502.01589

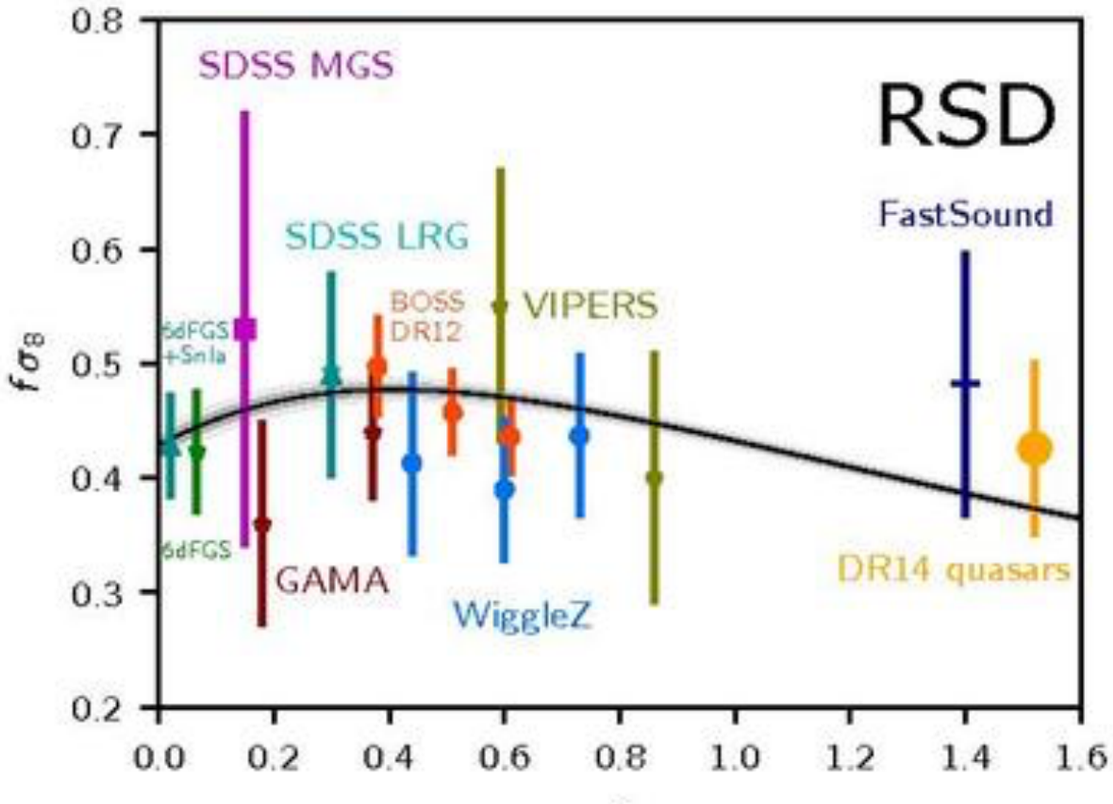
Cosmological Parameters from Planck 2018

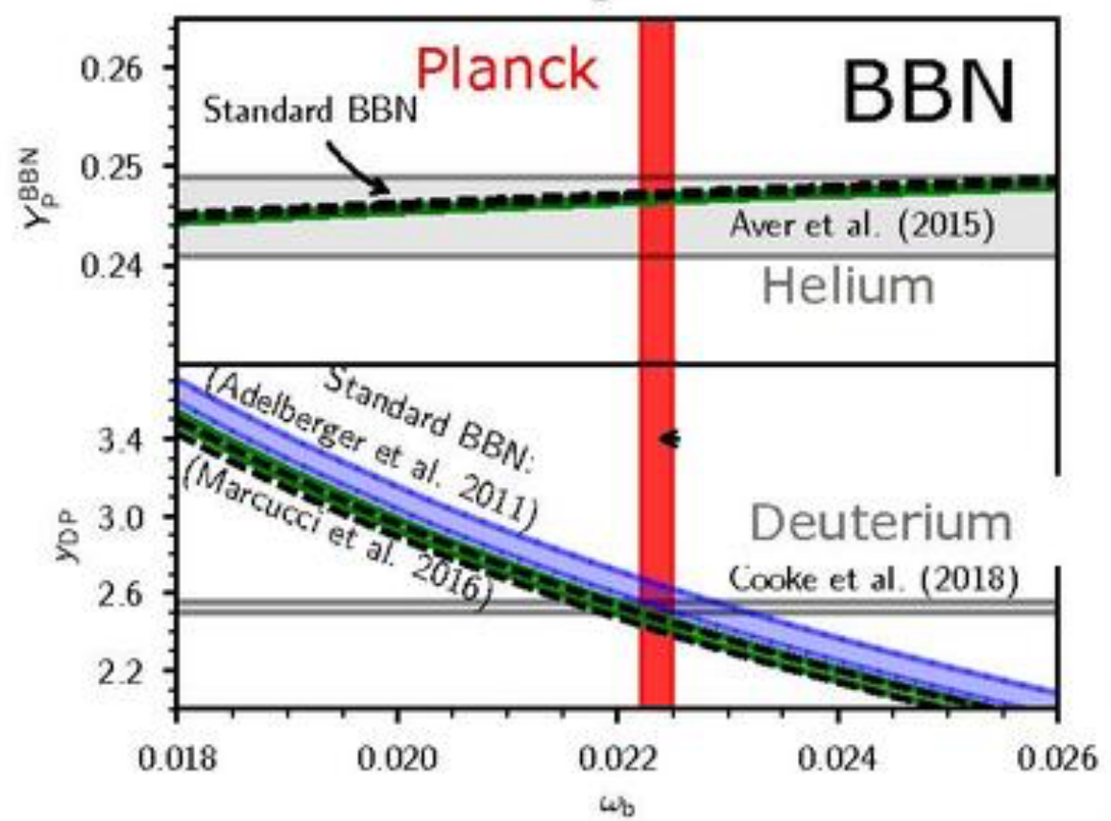
Parameter	Plik best fit	Plik [1]	CamSpec [2]	([2] − [1])/σ_1	Combined
$\Omega_b h^2$	0.022383	0.02237 ± 0.00015	0.02229 ± 0.00015	−0.5	0.02233 ± 0.00015
$\Omega_c h^2$	0.12011	0.1200 ± 0.0012	0.1197 ± 0.0012	−0.3	0.1198 ± 0.0012
$100\theta_{MC}$	1.040909	1.04092 ± 0.00031	1.04087 ± 0.00031	−0.2	1.04089 ± 0.00031
τ	0.0543	0.0544 ± 0.0073	$0.0536^{+0.0069}_{-0.0077}$	−0.1	0.0540 ± 0.0074
$\ln(10^{10} A_s)$	3.0448	3.044 ± 0.014	3.041 ± 0.015	−0.3	3.043 ± 0.014
n_s	0.96605	0.9649 ± 0.0042	0.9656 ± 0.0042	+0.2	0.9652 ± 0.0042
$\Omega_m h^2$	0.14314	0.1430 ± 0.0011	0.1426 ± 0.0011	−0.3	0.1428 ± 0.0011
H_0 [km s^{-1}Mpc^{-1}]	67.32	67.36 ± 0.54	67.39 ± 0.54	+0.1	67.37 ± 0.54
Ω_m	0.3158	0.3153 ± 0.0073	0.3142 ± 0.0074	−0.2	0.3147 ± 0.0074
Age [Gyr]	13.7971	13.797 ± 0.023	13.805 ± 0.023	+0.4	13.801 ± 0.024
σ_8	0.8120	0.8111 ± 0.0060	0.8091 ± 0.0060	−0.3	0.8101 ± 0.0061
$S_8 \equiv \sigma_8(\Omega_m/0.3)^{0.5}$	0.8331	0.832 ± 0.013	0.828 ± 0.013	−0.3	0.830 ± 0.013
z_{re}	7.68	7.67 ± 0.73	7.61 ± 0.75	−0.1	7.64 ± 0.74
$100\theta_*$	1.041085	1.04110 ± 0.00031	1.04106 ± 0.00031	−0.1	1.04108 ± 0.00031
r_{drag} [Mpc]	147.049	147.09 ± 0.26	147.26 ± 0.28	+0.6	147.18 ± 0.29

The 6 parameters of the LCDM model are measured with incredible precision. From these parameters we can also derive precise constraints on more parameters (like the age of the universe) that are not directly measured by the CMB.

Good consistency with BAO, RSD, SnIa, BBN





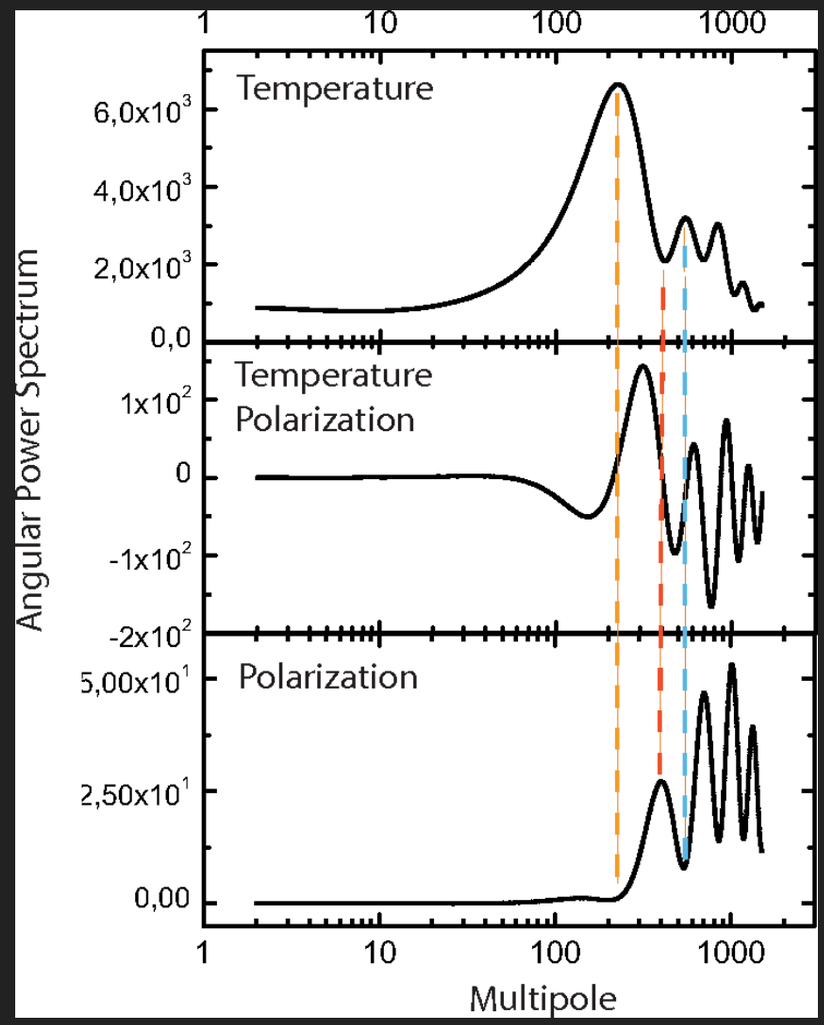


ARE MODELS BEYOND LCDM RULED OUT?

LCDM

LCDM model implies

acoustic oscillations…

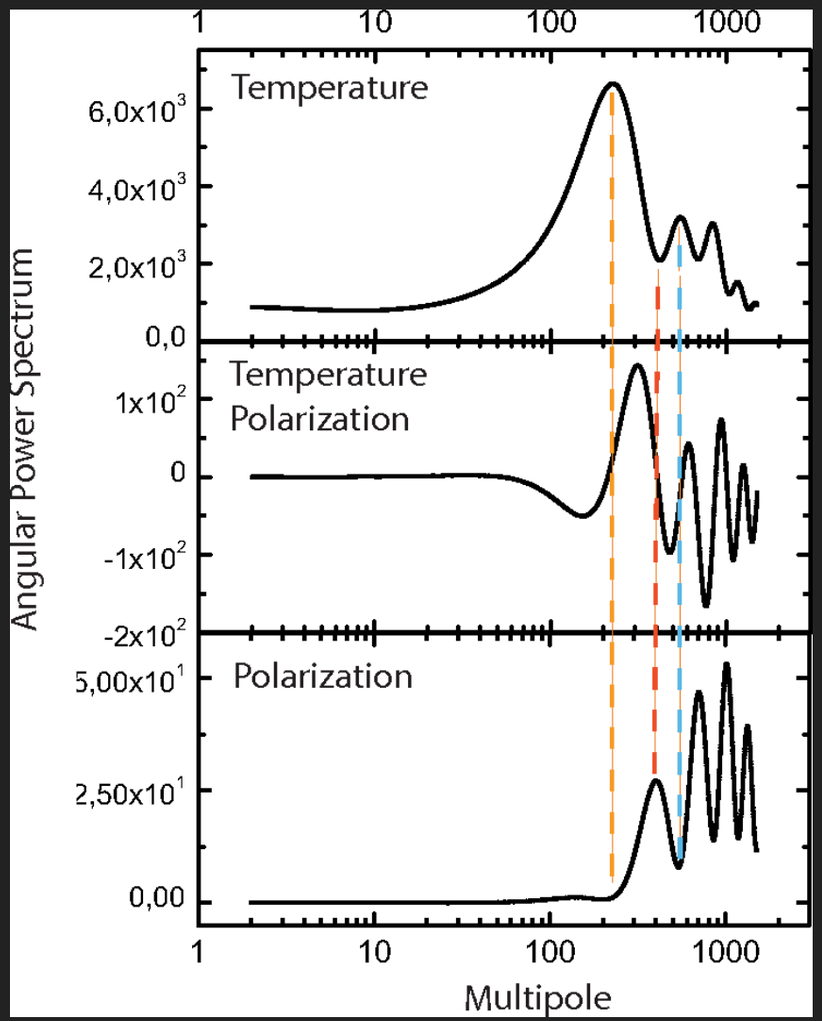


ARE MODELS BEYOND LCDM RULED OUT?

LCDM

…but acoustic oscillations DO NOT imply LCDM !!!!

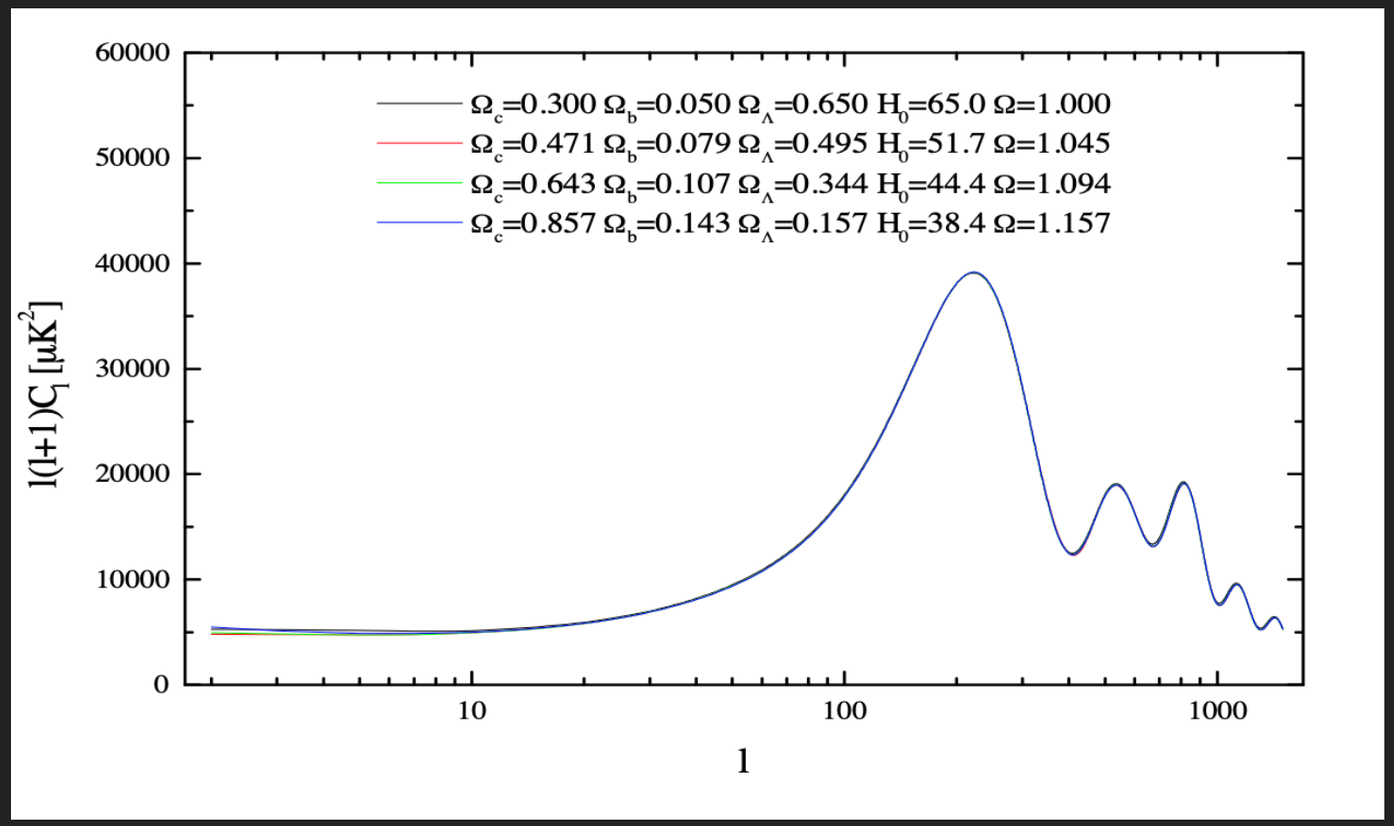
LCDM provides an excellent fit to Planck…but the same statement is valid for several other scenarios!



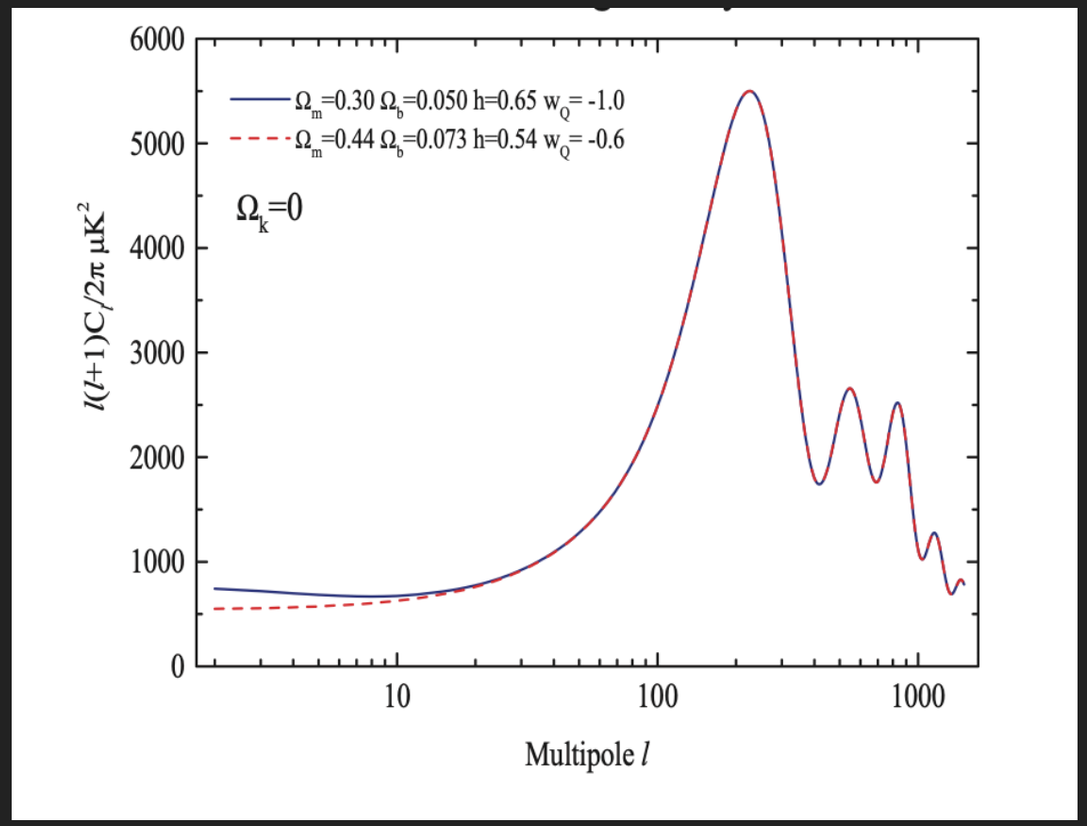
COSMIC CONFUSION

Efstathiou & Bond MNRAS, 1999 (just primary anisotropies)

Curvature

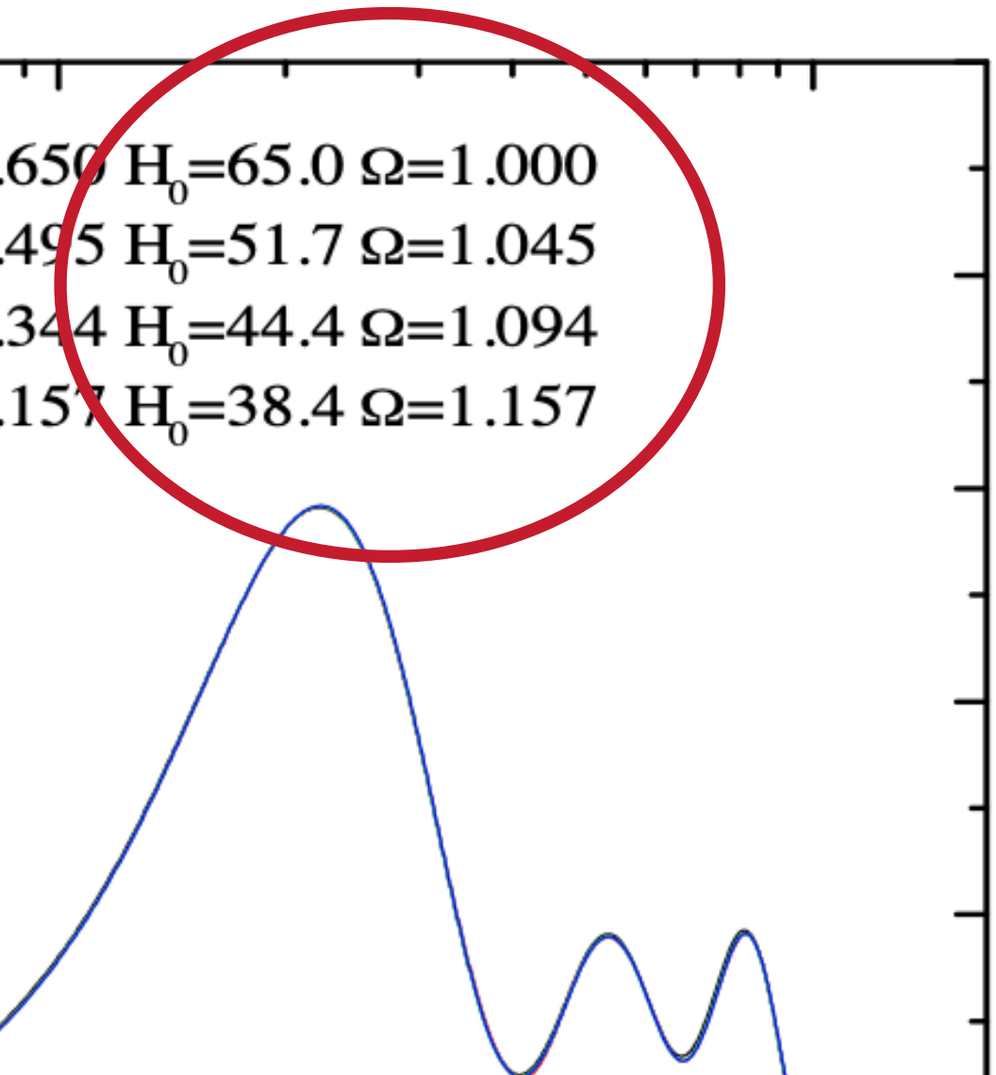


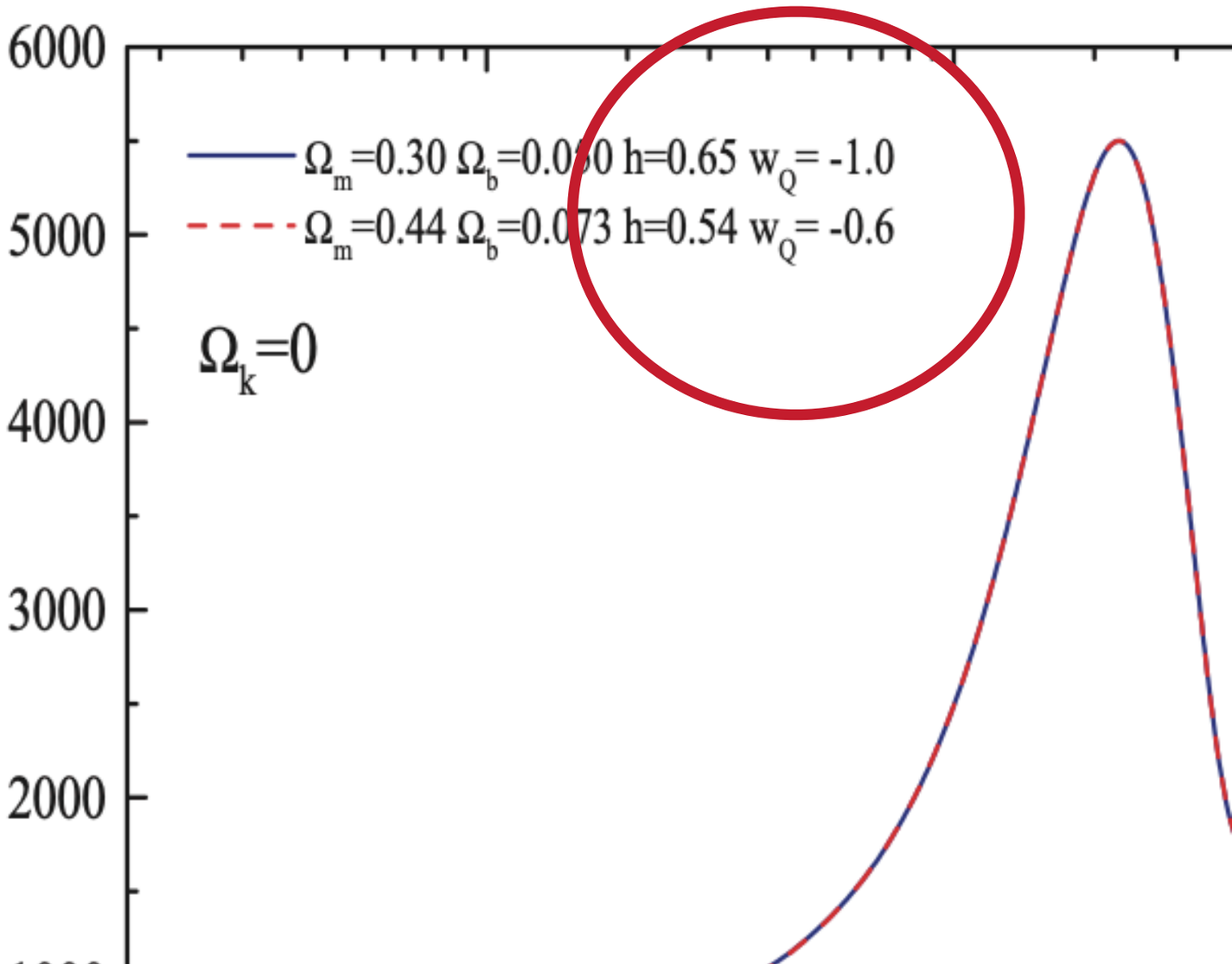
Dark Energy



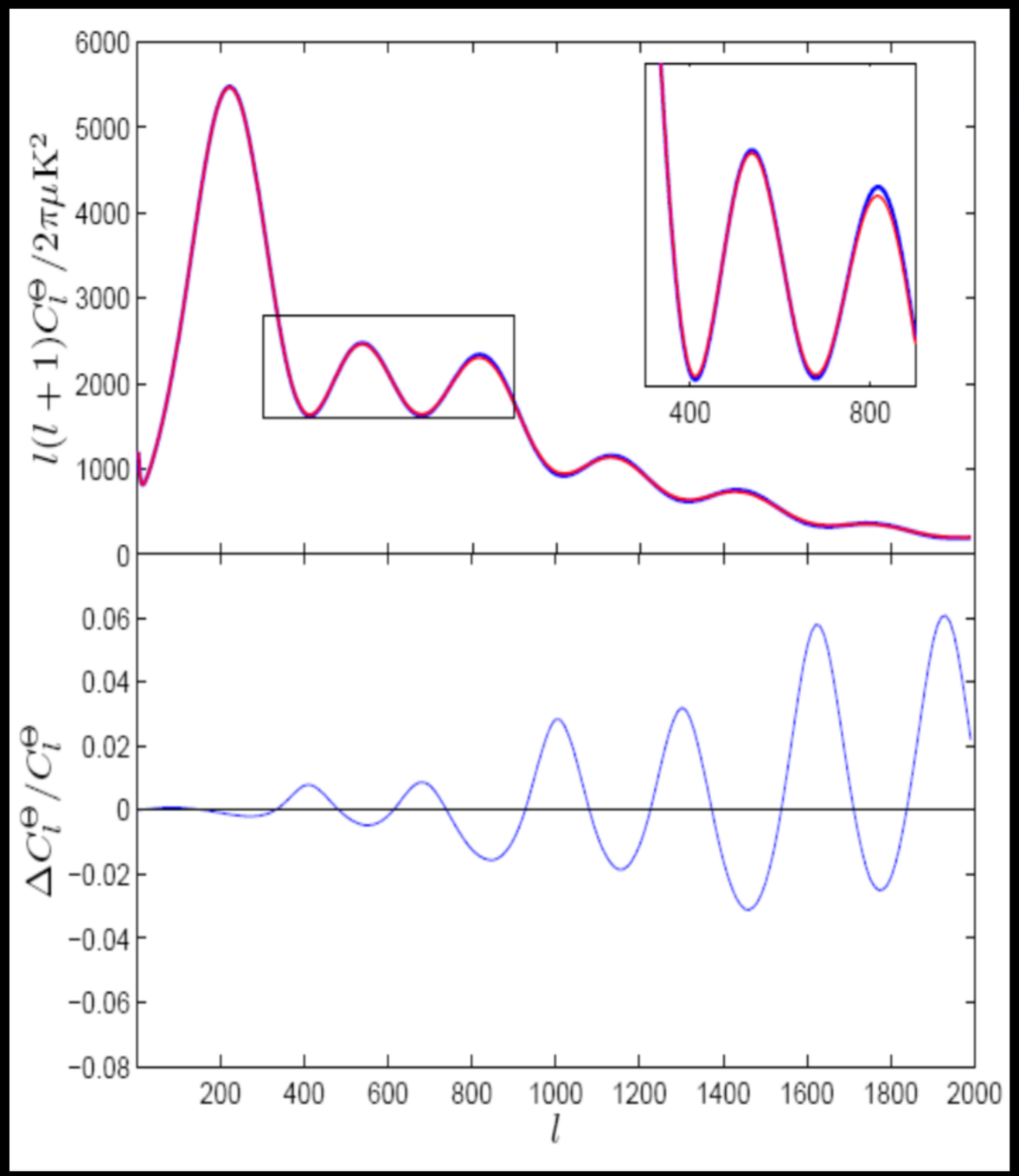
After fixing the acoustic horizon scale at LSS (fix matter and baryon physical densities) you can have nearly identical CMB angular spectra assuming the same angular distance at recombination. Curvature and/or dark energy equation of state can be significantly different from what expected in LCDM without altering the CMB peaks structure !!!!

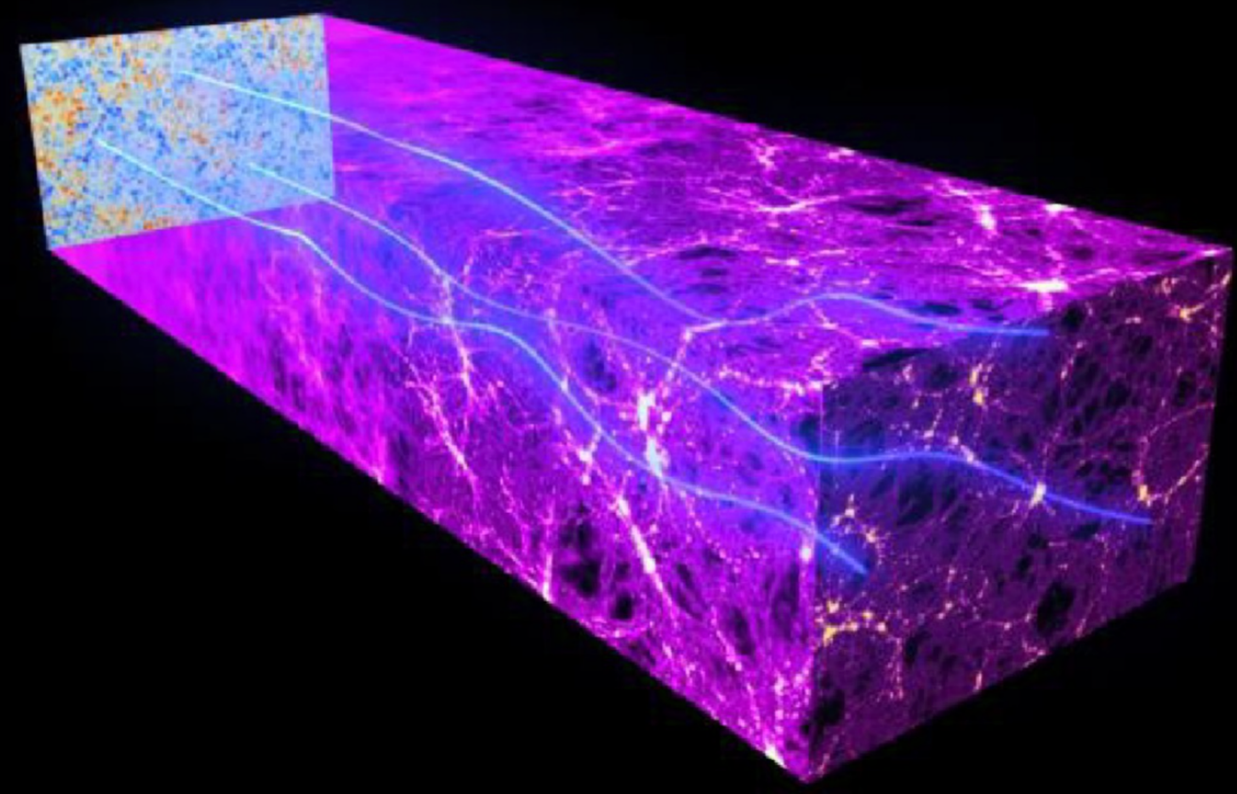
WITHOUT ASSUMING LCDM, YOU DON'T MEASURE H0 FROM CMB PRIMARY ANISOTROPIES ALONE!





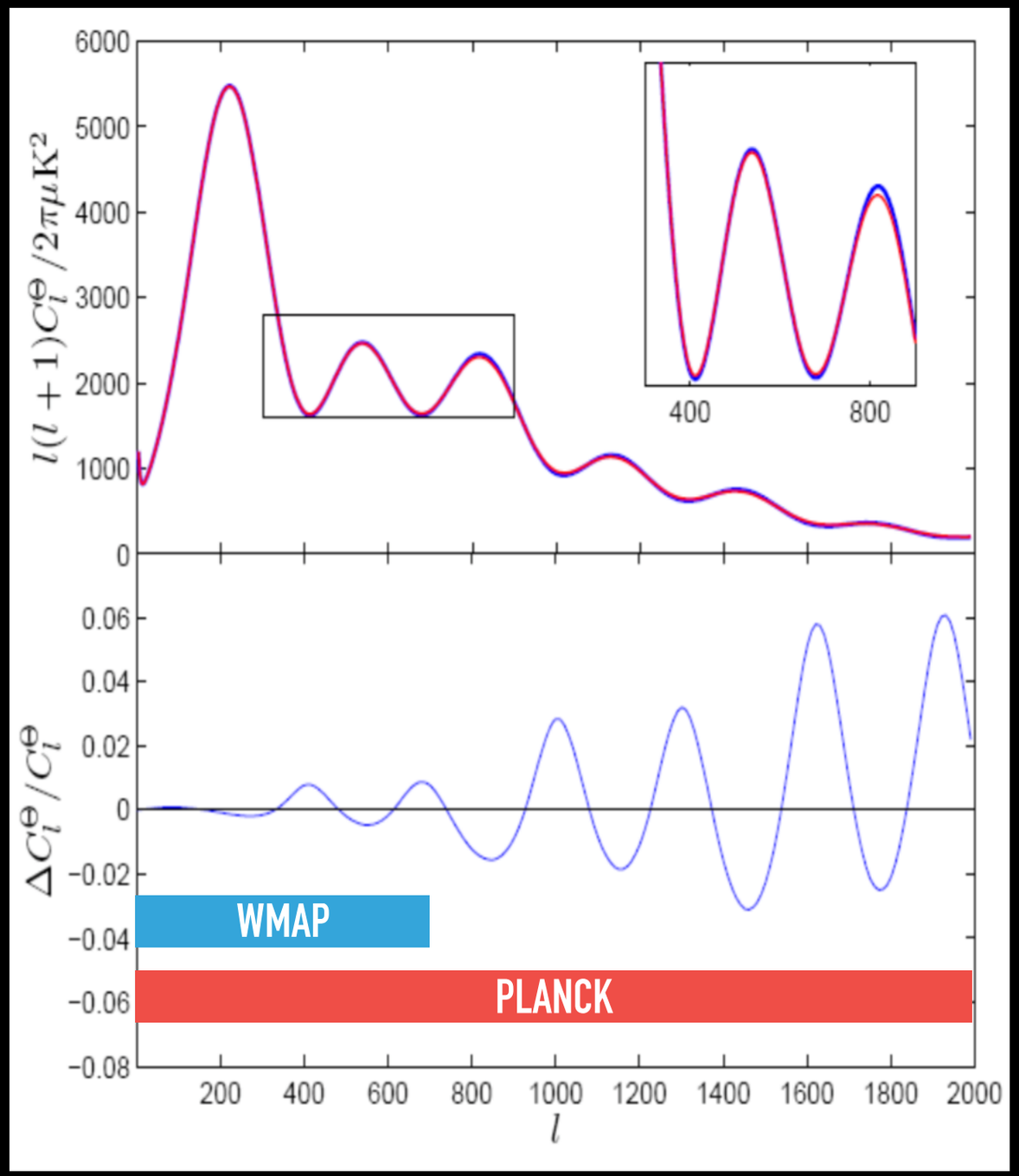
CMB LENSING





CMB photons emitted at z=1100 are deflected by the gravitational lensing effect of massive cosmic structures. This affects the CMB anisotropy angular spectrum by smearing the high l peaks.

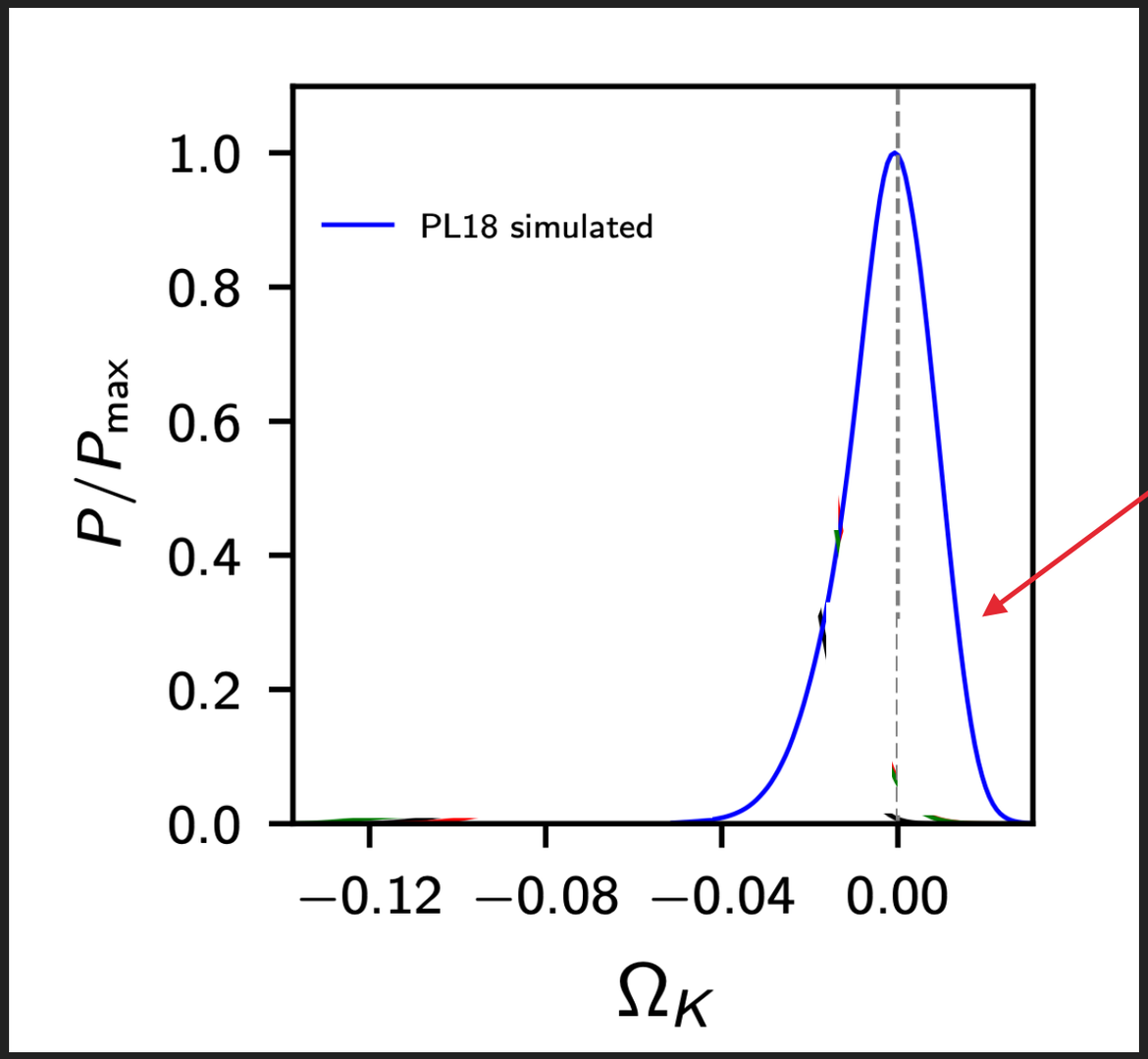
CMB LENSING



Lensing signal depends on dark matter density. By measuring it you can break cosmic degeneracy!

Thanks to its improved sensitivity to smaller angular scales PLANCK is the first satellite experiment that can do this !

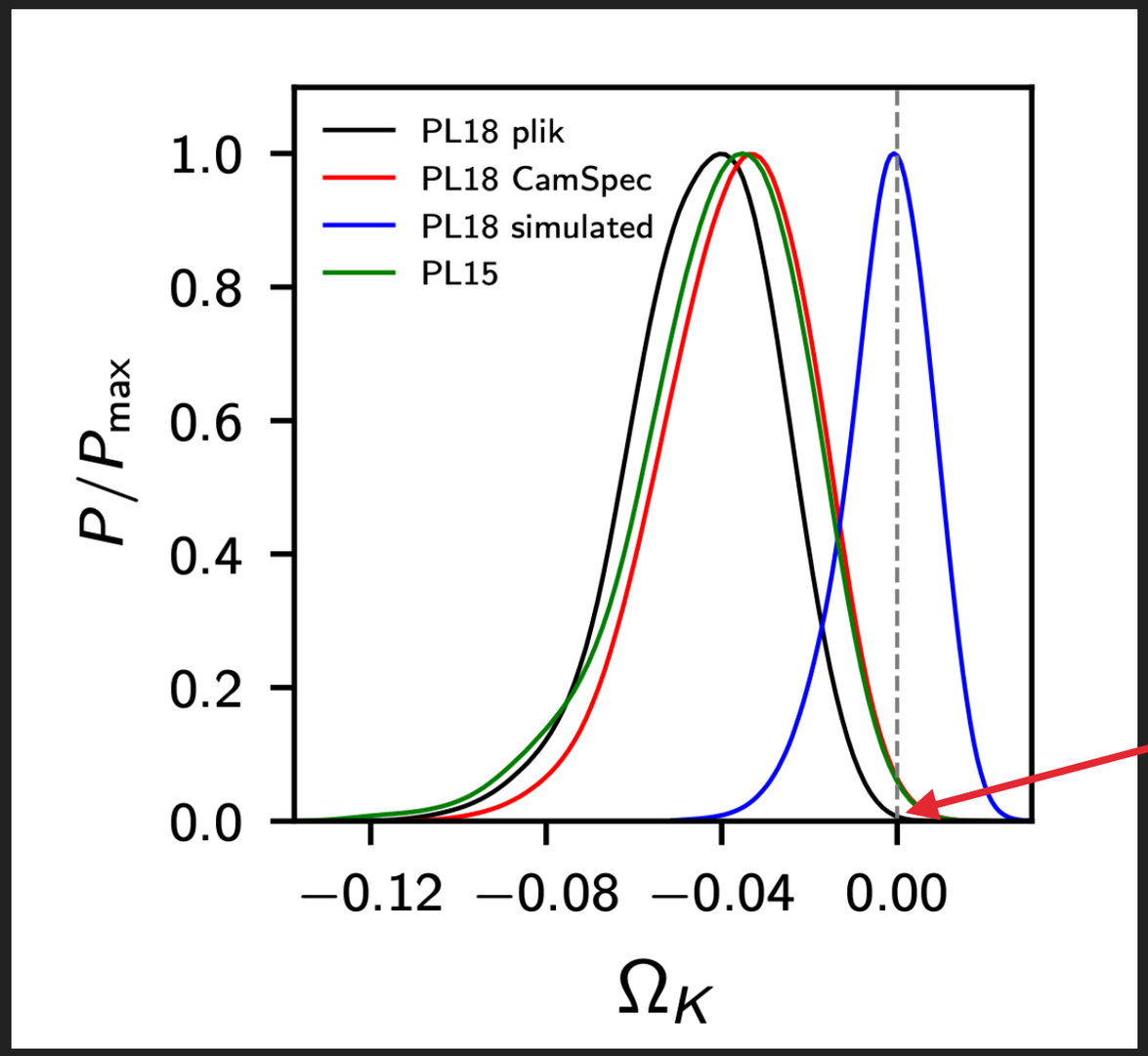
PLANCK ALONE HAS THE POTENTIAL TO CONSTRAIN CURVATURE AT FEW PERCENT (1.5%) ACCURACY



Simulated constraints on curvature from Planck (assuming a flat Universe)

Di Valentino, Melchiorri, Silk, Nature Astronomy 2020

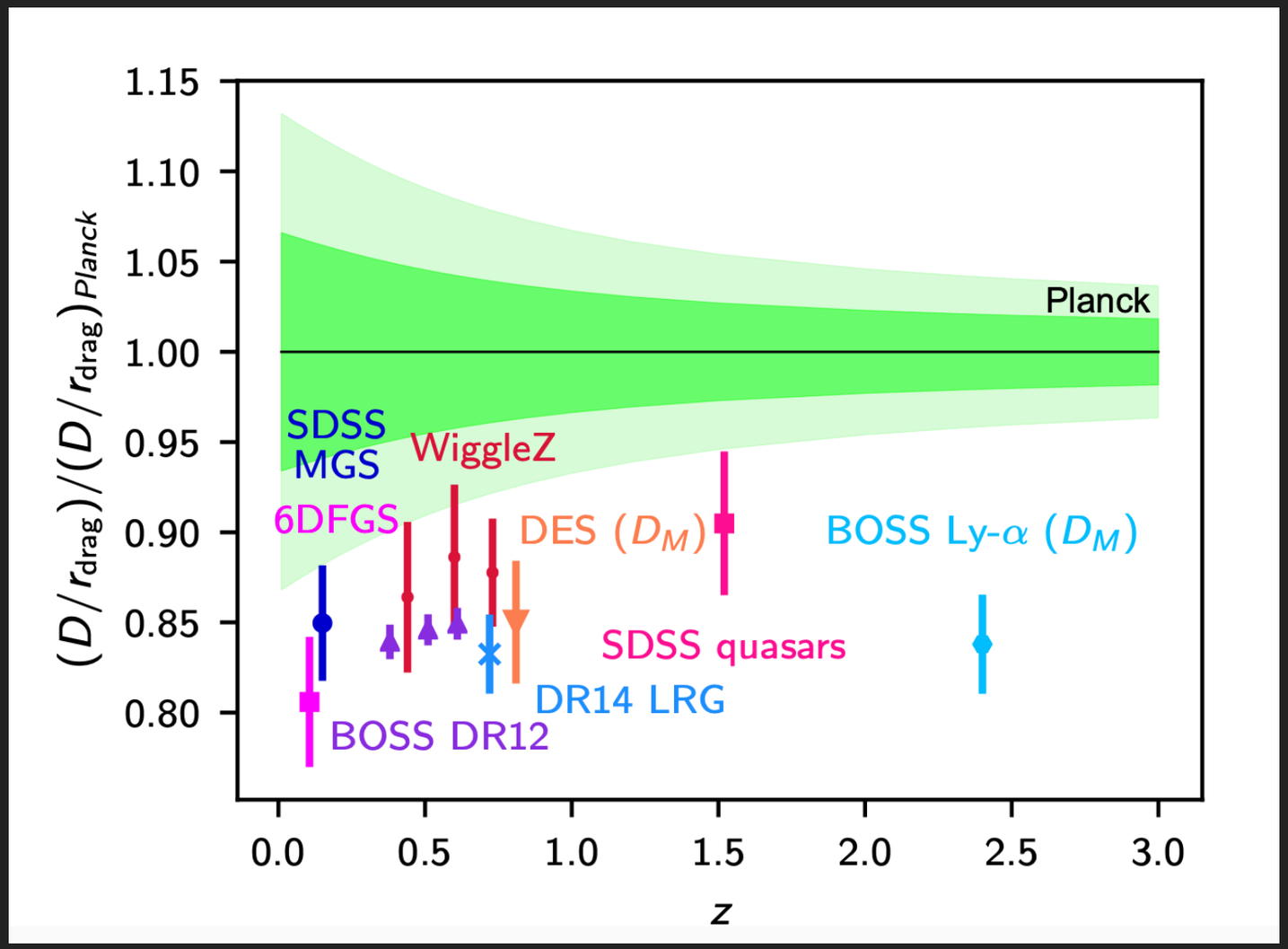
NOT SO FLAT . . .



Planck 2018 data do break cosmic degeneracy but…prefer a closed universe at more than 3 standard deviations !!!

Planck Alone	Best fit	95% C.L.
H_0	54.1	54^{+8}_{-7}

BUT A CLOSED UNIVERSE IS A CATASTROPHE!



If we let curvature to vary Planck is not anymore in agreement with other late universe observables as BAO or SN-Ia or etc etc!

The current agreement between Planck and BAO depends on the assumption of LCDM!

So long, concordance cosmology...

TWO VERY DIFFERENT PATHS…YOU DECIDE!

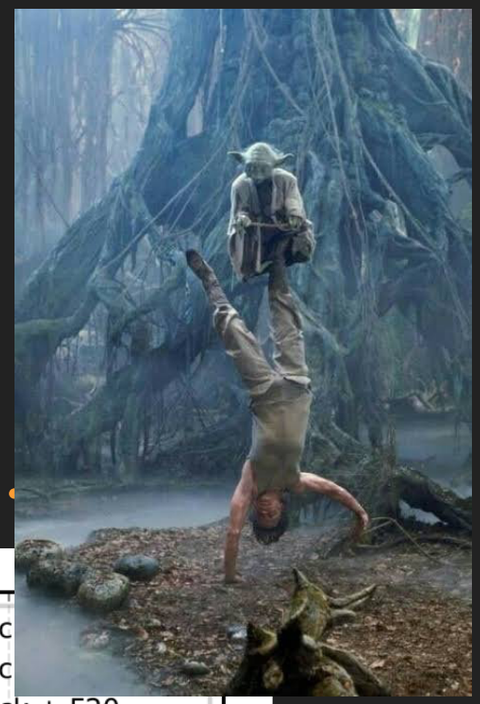
Jedi (Rebels):

- My ally is the Planck data and a powerful ally it is. Try to include extra physics to accommodate a closed Universe with late universe observations.

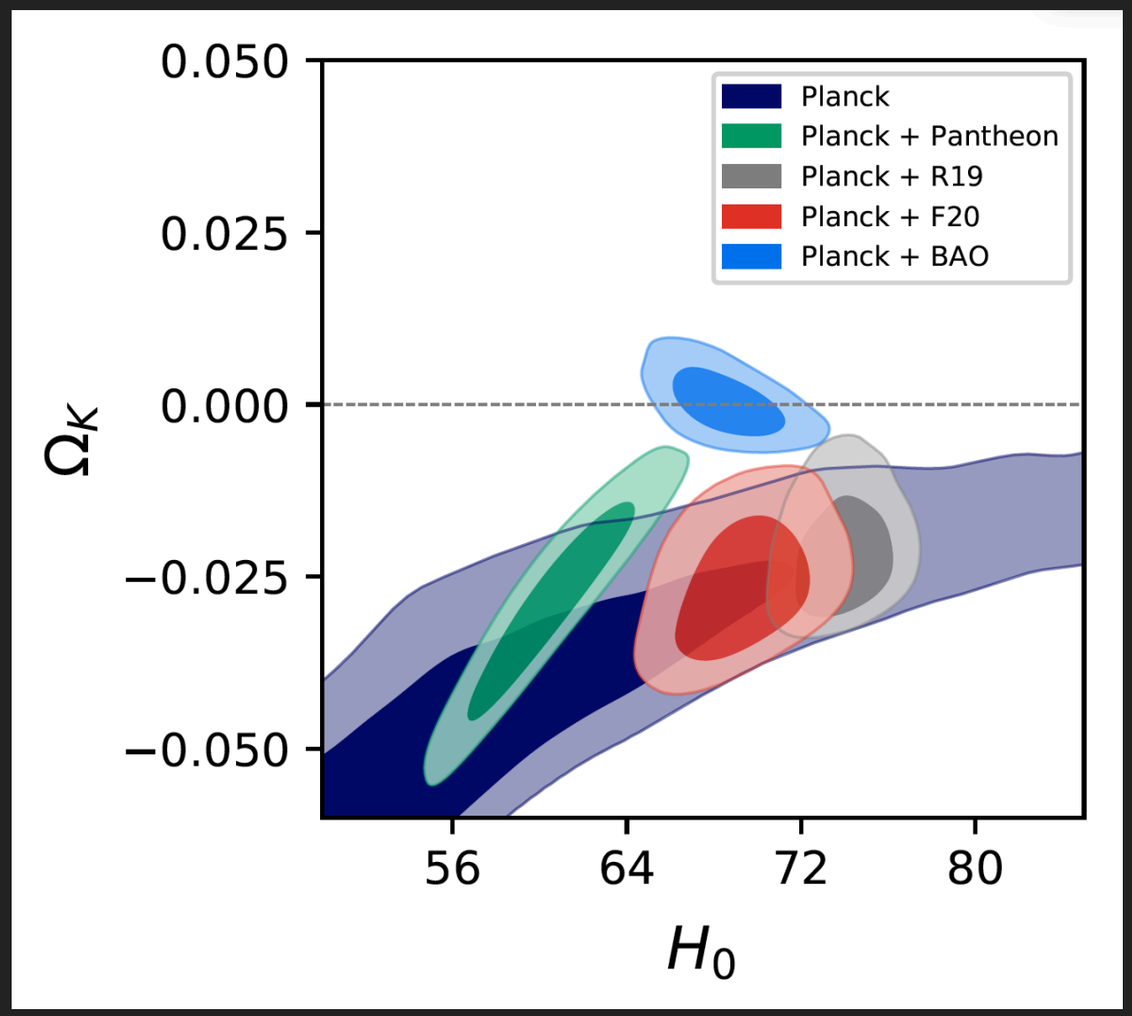
Sith (LCDM Empire):

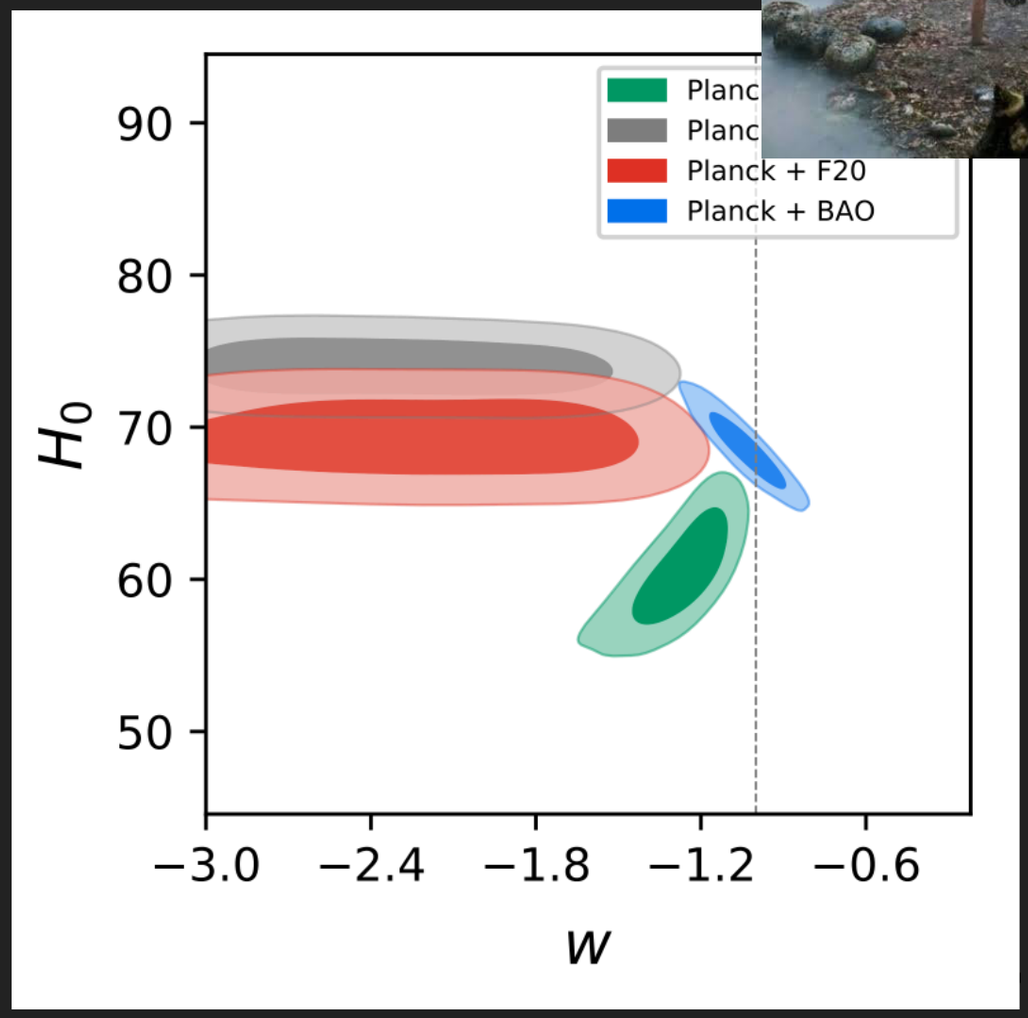
- Do not underestimate the power of inflation. Keep on assuming a flat universe and check for systematics in Planck data.

JEDI PATH: CONCORDANCE IN A CURVED UNIVERSE (TRICKY)



Let's vary w, curvature, neutrino mass, running at the same time…





Planck closed model is in perfect agreement with ANY luminosity distance data when w is let to vary. However we have discordances between Planck+Pantheon and Planck+SHOES (Di Valentino, Melchiorri, Silk, ApJ letters 2021).

SITH PATH: ASSUME A FLAT UNIVERSE AND VARY LENSING BY HAND

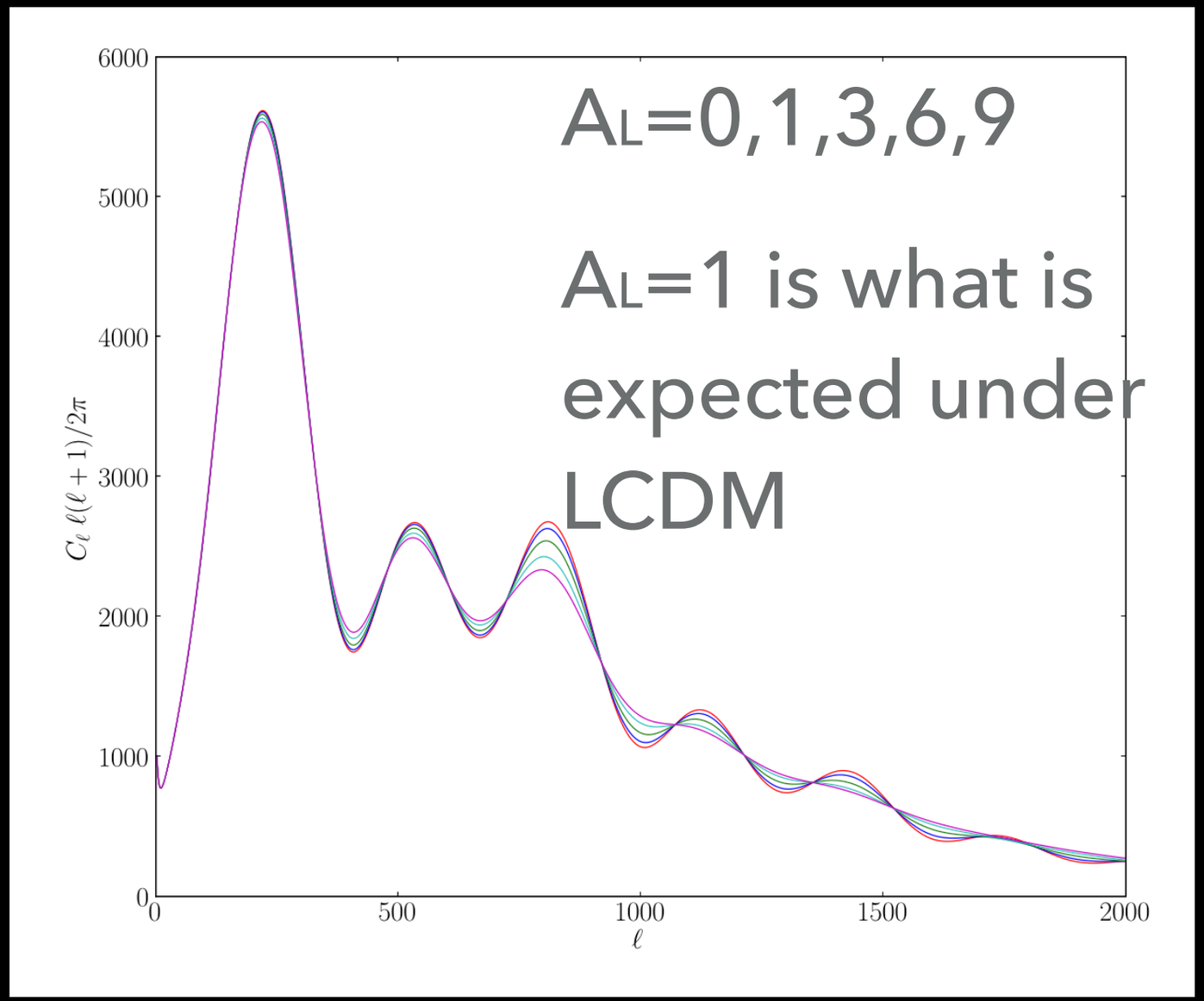
We can parametrize the lensing amplitude by an effective (unphysical) rescaling parameter A_L (Calabrese, Slosar, Melchiorri, Smoot, Zahn, 2008).

Planck gives $A_L>1$ at almost 3 sigmas.

A_L	$= 1.243 \pm 0.096$	(68 %, *Planck* TT+lowE),
A_L	$= 1.180 \pm 0.065$	(68 %, *Planck* TT,TE,EE+lowE)

Exactly 3 sigmas with Planck+BAO!

A_L	1.185	$1.18^{+0.12}_{-0.12}$



A_L IS THE KEY ?

Perfectly consistent with BAO

Suggested by Planck+BAO at 3 σ

Lowers S_8 by 3.5%

Increases H_0 by 1.5%

3.6 base_Alens_plikHM_TTTEEE_lowl_lowE_post_BAO

Parameter	Best fit	95% limits	Parameter	Best fit	95% limits	Parameter	Best fit	95% limits
$\Omega_b h^2$	0.022617	$0.02258^{+0.00030}_{-0.00029}$	σ_8	0.8011	$0.800^{+0.015}$	$D_M(0.15)$	635.1	$635.9^{+8.3}_{-8.2}$
$\Omega_c h^2$	0.11802	$0.1182^{+0.0021}_{-0.0021}$	S_8	0.8	$0.805^{+0.028}_{-0.028}$	$H(0.38)$	83.49	$83.43^{+0.64}_{-0.62}$
$100\theta_{MC}$	1.04115	$1.04113^{+0.00058}_{-0.00057}$	$\sigma_8\Omega_m^{0.5}$	0.4		$D_M(0.38)$	1516.7	1518^{+17}_{-17}
τ	0.0507	$0.049^{+0.017}_{-0.017}$	$\sigma_8\Omega_m^{0.25}$	0.5942	$0.594^{+0.015}_{-0.016}$	$H(0.51)$	90.13	$90.07^{+0.52}_{-0.49}$
A_L	1.185	$1.18^{+0.12}_{-0.12}$	$\sigma_8/h^{0.5}$	0.9691	$0.969^{+0.022}_{-0.024}$	$D_M(0.51)$	1966.2	1968^{+20}_{-20}
$\ln(10^{10}A_s)$	3.0325	$3.029^{+0.035}_{-0.036}$	$r_{drag}h$	100.68	$100.5^{+1.7}_{-1.7}$	$H(0.61)$	95.682	$95.64^{+0.43}_{-0.40}$
n_s	0.9722	$0.9705^{+0.0078}_{-0.0077}$	$\langle d^2\rangle^{1/2}$	2.607	$2.60^{+0.11}_{-0.12}$	$D_M(0.61)$	2289.1	2291^{+21}_{-21}
y_{cal}	0.99994	$1.0000^{+0.0048}_{-0.0047}$	z_{re}	7.23	$7.0^{+1.7}_{-1.9}$	$H(2.33)$	235.52	$235.6^{+1.3}_{-1.3}$
A_{217}^{CIB}	42.4	45^{+10}_{-10}	10^9A_s	2.075	$2.068^{+0.069}_{-0.079}$	$D_M(2.33)$	5745.5	5748^{+19}_{-20}
$\xi^{tSZ\times CIB}$	0.997	—	$10^9A_se^{-2\tau}$	1.8747	$1.875^{+0.021}_{-0.021}$	$f\sigma_8(0.15)$	0.4459	$0.446^{+0.014}_{-0.015}$
A_{143}^{tSZ}	6.86	$5.8^{+3.6}_{-3.5}$	D_{40}	1214.3	1217^{+24}_{-23}	$\sigma_8(0.15)$	0.7412	$0.740^{+0.014}_{-0.014}$
A_{100}^{PS}	238	249^{+60}_{-50}	D_{220}	5737	5738^{+74}_{-74}	$f\sigma_8(0.38)$	0.4660	$0.466^{+0.012}_{-0.013}$
A_{143}^{PS}	49.8	42^{+10}_{-20}	D_{810}	2533.0	2531^{+26}_{-26}	$\sigma_8(0.38)$	0.6580	$0.657^{+0.012}_{-0.012}$
$A_{143\times217}^{PS}$	57.6	42^{+20}_{-20}	D_{1420}	816.8	$815.5^{+9.3}_{-9.0}$	$f\sigma_8(0.51)$	0.4657	$0.465^{+0.011}_{-0.012}$
A_{217}^{PS}	124.3	116^{+20}_{-20}	D_{2000}	232.76	$232.2^{+3.0}_{-3.0}$	$\sigma_8(0.51)$	0.6161	$0.615^{+0.011}_{-0.012}$
A^{kSZ}	0.00	< 6.73	$n_{s,0.002}$	0.9722	$0.9705^{+0.0078}_{-0.0077}$	$f\sigma_8(0.61)$	0.4615	$0.461^{+0.010}_{-0.011}$
A_{100}^{dustTT}	8.76	$8.8^{+3.5}_{-3.6}$	Y_P	0.245486	$0.24547^{+0.00012}_{-0.00011}$	$\sigma_8(0.61)$	0.5865	$0.585^{+0.011}_{-0.011}$
A_{143}^{dustTT}	10.62	$10.6^{+3.5}_{-3.5}$	Y_P^{BBN}	0.246813	$0.24680^{+0.00012}_{-0.00011}$	$f\sigma_8(2.33)$	0.2961	$0.2955^{+0.0053}_{-0.0054}$
$A_{143\times217}^{dustTT}$	19.7	$18.1^{+6.3}_{-6.3}$	10^5D/H	2.541	$2.548^{+0.053}_{-0.053}$	$\sigma_8(2.33)$	0.3056	$0.3050^{+0.0055}_{-0.0056}$
A_{217}^{dustTT}	95.4	94^{+10}_{-10}	Age/Gyr	13.7574	$13.763^{+0.043}_{-0.044}$	f_{2000}^{143}	25.8	27^{+5}_{-6}
A_{100}^{dustTE}	0.115	$0.114^{+0.077}_{-0.077}$	z_*	1089.441	$1089.50^{+0.48}_{-0.48}$	$f_{2000}^{143\times217}$	29.74	30^{+4}_{-4}
$A_{100\times143}^{dustTE}$	0.134	$0.135^{+0.057}_{-0.059}$	r_*	144.755	$144.74^{+0.47}_{-0.48}$	f_{2000}^{217}	104.44	$105.1^{+3.6}_{-3.6}$
$A_{100\times217}^{dustTE}$	0.480	$0.48^{+0.17}_{-0.17}$	$100\theta_*$	1.04130	$1.04129^{+0.00057}_{-0.00056}$	χ^2_{small}	395.67	396.9 (ν: 1.4)
A_{143}^{dustTE}	0.220	$0.22^{+0.11}_{-0.11}$	$D_M(z_*)$/Gpc	13.9013	$13.900^{+0.045}_{-0.045}$	χ^2_{lowl}	22.06	22.34 (ν: 0.3)
$A_{143\times217}^{dustTE}$	0.659	$0.66^{+0.15}_{-0.16}$	z_{drag}	1060.35	$1060.29^{+0.60}_{-0.58}$	χ^2_{plik}	2337.1	2353.2 (ν: 15.5)
A_{217}^{dustTE}	2.05	$2.06^{+0.54}_{-0.54}$	r_{drag}	147.342	$147.34^{+0.48}_{-0.48}$	χ^2_{6DF}	0.002	0.030 (ν: 0.0)
c_{100}	0.99975	$0.9997^{+0.0012}_{-0.0012}$	k_D	0.14079	$0.14076^{+0.00059}_{-0.00058}$	χ^2_{MGS}	1.82	1.79 (ν: 0.1)
c_{217}	0.99814	$0.9981^{+0.0012}$		0.160519	$0.16056^{+0.00035}_{-0.00036}$	$\chi^2_{DR12BAO}$	3.43	3.95 (ν: 0.3)
H_0	68.33	$68.23^{+0.99}_{-0.97}$		3360.8	3364^{+48}_{-47}	χ^2_{prior}	1.3	11.3 (ν: 9.7)
Ω_Λ	0.6974	$^{-0.013}$	z_{eq}	0.010258	$0.01027^{+0.00015}_{-0.00014}$	χ^2_{BAO}	5.25	5.77 (ν: 0.3)
Ω_m	0.3026	$0.304^{+0.013}_{-0.012}$	$100\theta_{eq}$	0.8216	$0.8209^{+0.0092}_{-0.0091}$	χ^2_{CMB}	2754.9	2772.4 (ν: 17.0)
$\Omega_m h^2$	0.14128	$0.1414^{+0.0020}_{-0.0020}$	$100\theta_{s,eq}$	0.45355	$0.4532^{+0.0047}_{-0.0047}$			
$\Omega_m h^3$	0.09654	$0.09649^{+0.00061}_{-0.00057}$	$H(0.15)$	73.52	$73.44^{+0.86}_{-0.84}$			

Best-fit $\chi^2_{eff} = 2761.40$; $\Delta\chi^2_{eff} = -10.51$; $\bar{\chi}^2_{eff} = 2789.54$; $\Delta\bar{\chi}^2_{eff} = -8.37$; $R - 1 = 0.01310$

χ^2_{eff}: BAO - 6DF: 0.00 (Δ -0.03) MGS: 1.82 (Δ 0.60) DR12BAO: 3.43 (Δ -0.99) CMB - simall_100x143_offlike5_EE_Aplanck_B: 395.67 (Δ -0.54) commander_dx12_v3_2_29: 22.06 (Δ -0.81) plik_rd12_HM_v22b_TTTEEE: 2337.12 (Δ -8.38)

Planck+BAO data indicate Al>1 at 3 sigmas. Introduce AL does not solve completely current H0 and S8 tensions but IT GOES IN THE RIGHT DIRECTION.

Maybe AL is not the correct parametrisation.

CONCLUSIONS

- Planck is consistent with LCDM also with trillions of models. Moreover, anomalies and tensions with LCDM are now clearly present at 3 sigmas level.
- If we consider curvature all current tensions increase in statistical significance (and curvature is preferred). We need extra parameters to accommodate late universe observations. Tricky but this could hint to the fact that we may really need to change completely our current theoretical scenario (as often happened in the past).
- Introducing an unphysical Al lensing parameter helps in restoring concordance. But what is its nature? systematics or new physics?