Question 1 - CMB Power Spectrum

Use CAMB to generate the CMB C_ℓ's. Make plots of C_ℓ versus ℓ, changing the cosmological parameters one at a time, and explain the effects you see on the spectrum. Vary the following parameters:

Ω_m: matter density
T_γ: photon temperature (or similarly its density Ω_γ)
Ω_b: baryon density
Ω_{DE}: dark energy density
Ω_k: curvature density
w: dark energy equation of state
h: Hubble constant
N_{eff}: effective number of massless neutrino species
A_s: spectral amplitude of primordial scalar perturbations
n_s: spectral index of primordial scalar perturbations
τ: optical depth

Table 1: Standard cosmology values (without units of measure).

Parameter	Value
$\Omega_b h^2$	0.022
$\Omega_c h^2$	0.12
h	0.67
n_s	0.965
A_s	$2.1 \cdot 10^{-9}$
τ	0.06
Ω_k	0.0
w	-1
N_{eff}	3.046
T_{CMB}	2.7255

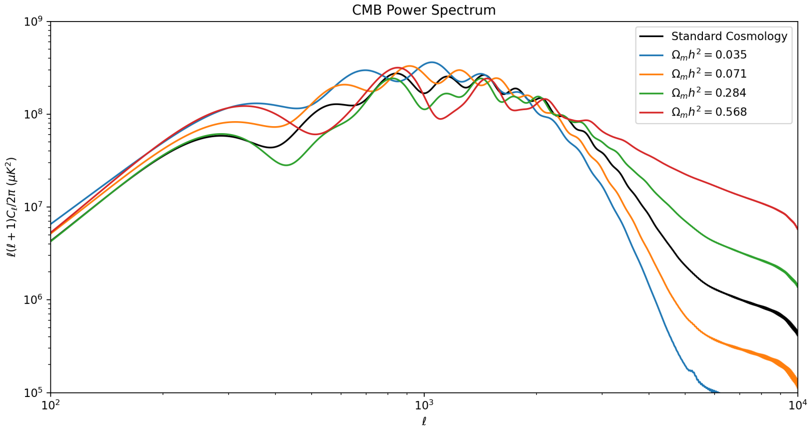

Figure 1: Changes in C_ℓ when $\Omega_m h^2$ varies.

In a flat universe, inhomogenities on scales k appear at $\ell = k\eta_0$, so the peaks are going to show up at $\ell_p \approx k_p\eta_0 \approx n\pi\eta_0/r_s(\eta_*)$. The changes in the matter density are very sensitive to the C_ℓ, and as Ω_m goes down, the space between peaks increases.

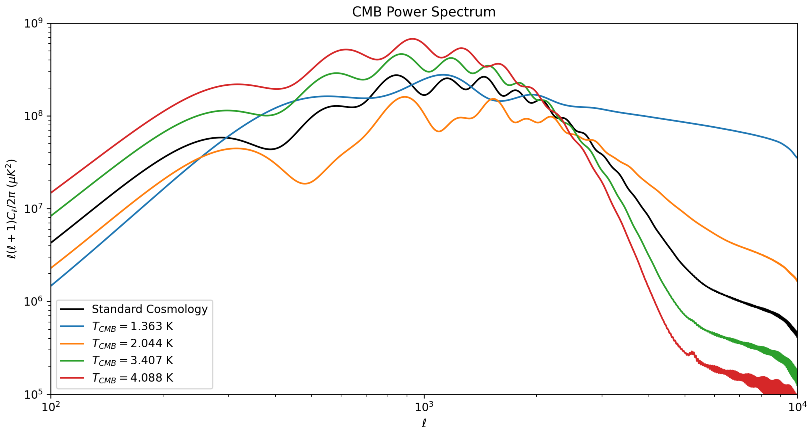

Figure 2: Changes in C_ℓ when T_{CMB} varies.

In Figure 2, we can see an similar behavior to that of Figure 1, this happens because the CMB temperature is in essence an function of Ω_m.

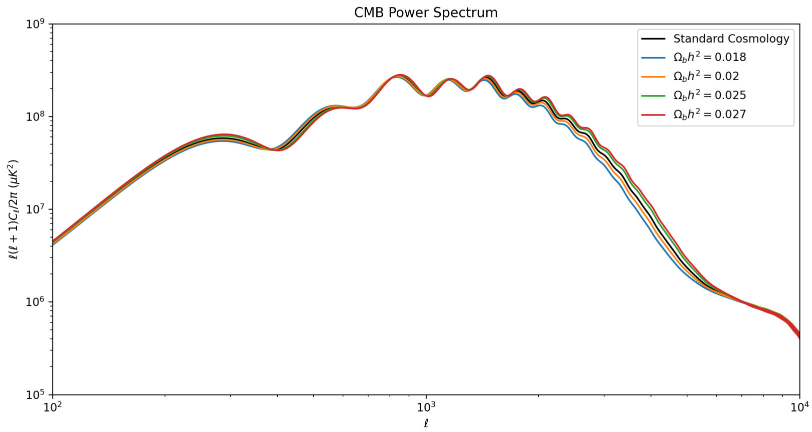

Figure 3: Changes in C_ℓ when $\Omega_b h^2$ varies.

We can see in Figure 3 that the C_ℓ is not very sensitive to $\Omega_b h^2$ variations, this happens because the comparative value of Ω_b in the matter component is far less predominant than Ω_c. Also, the shift and height changes in peaks are due to the change in the sound horizon $r_s(\eta_*)$.

Increasing $\Omega_b h^2$ also leads to increased k_D, so the anisotropy spectrum for scales bigger than $\ell = 1000$ are larger as well.

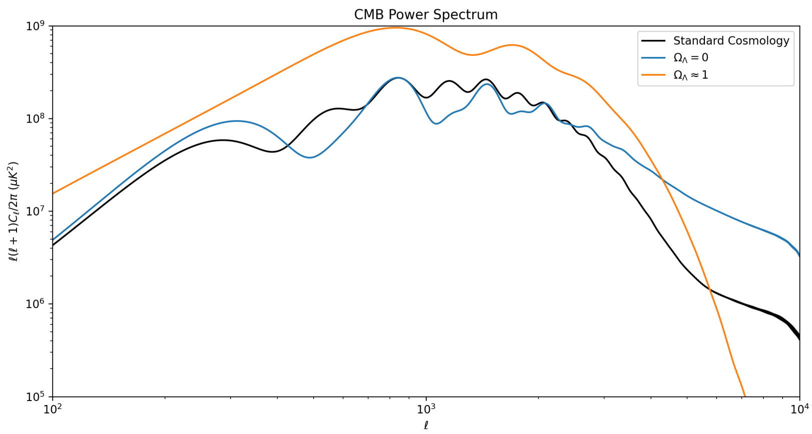

Figure 4: Changes in C_ℓ when Ω_Λ varies.

In Figure 4, we can see a notable increase in the C_ℓ for $\Omega_\Lambda \approx 1$ due to the late-time ISW effect, which is less prominent in the blue curve ($\Omega_\Lambda = 0$).

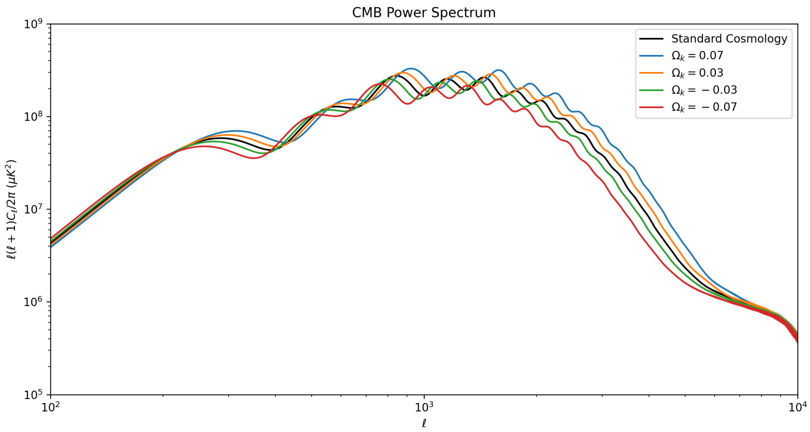

Figure 5: Changes in C_ℓ when Ω_k varies.

For an open universe, we can see in Figure 5 the peaks shifting to higher ℓs because fixed physical scales are projected onto much smaller angular scales. And as expected, we can see the oposite happening for an closed universe.

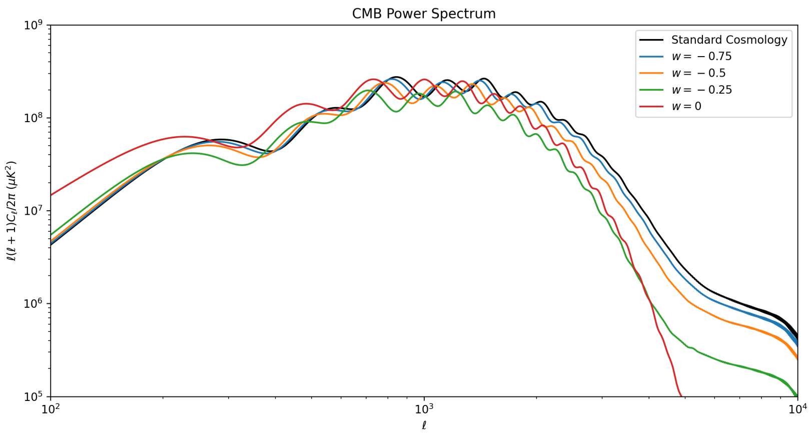

Figure 6: Changes in C_ℓ when w varies.

In Figure 6, we can see that as w increases, the peaks shift to larger angular scales and the power on smaller scales decreases, indicating that for higher values of w, dark energy can have stronger impacts in the universe expansion, with the fluctuations clustering at smaller scales.

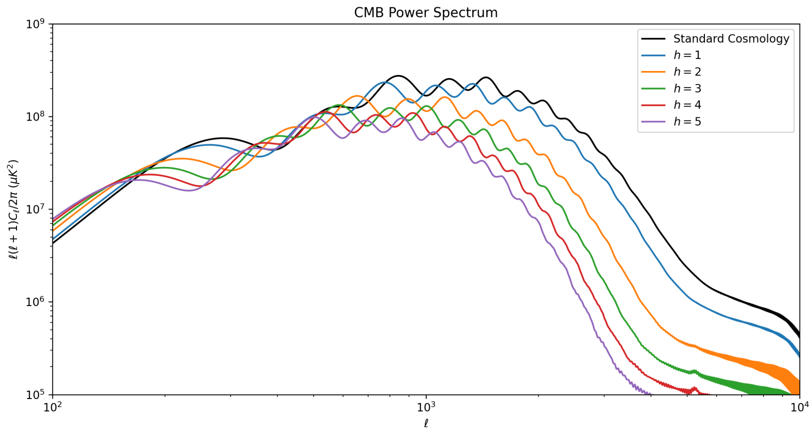

Figure 7: Changes in C_ℓ when h varies.

Increasing h means that the universe is expanding faster, so in Figure 7, we can see that the C_ℓ curves go earlier down for higher h.

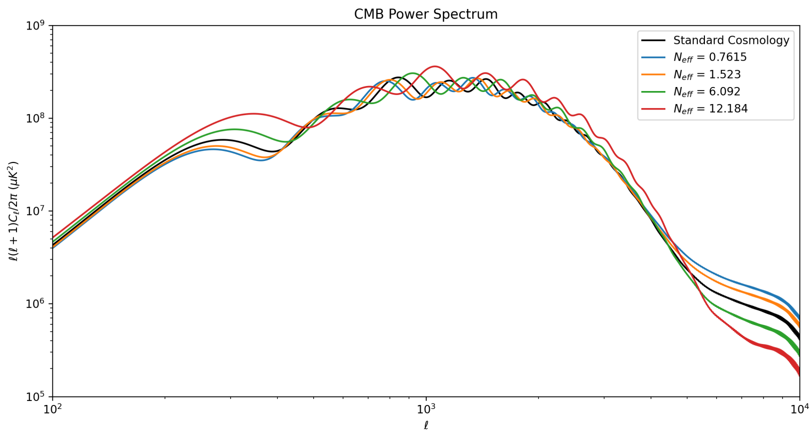

Figure 8: Changes in C_ℓ when N_{eff} varies.

Higher values of N_{eff} (Figure 8) lead to shifts of the acoustic peaks to larger angular scales and slightly higher amplitudes, which can reflect an universe with more relativistic particles in the early universe. This probably leads to an faster expansion of the universe.

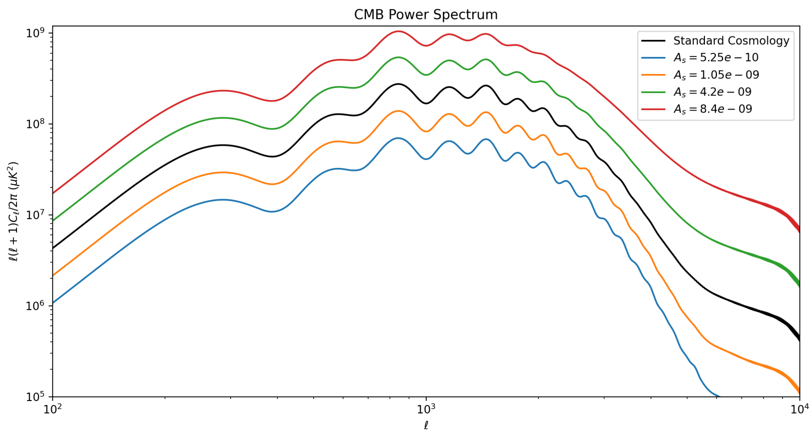

Figure 9: Changes in C_ℓ when A_s varies.

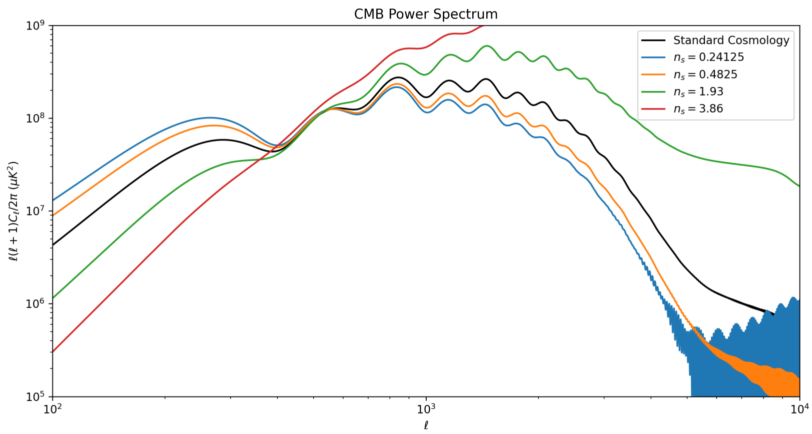

Figure 10: Changes in C_ℓ when n_s varies.

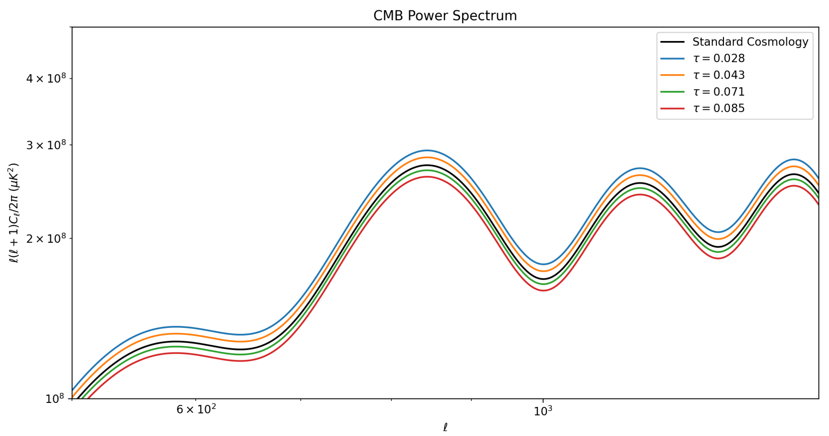

Figure 11: Changes in C_ℓ when τ varies.

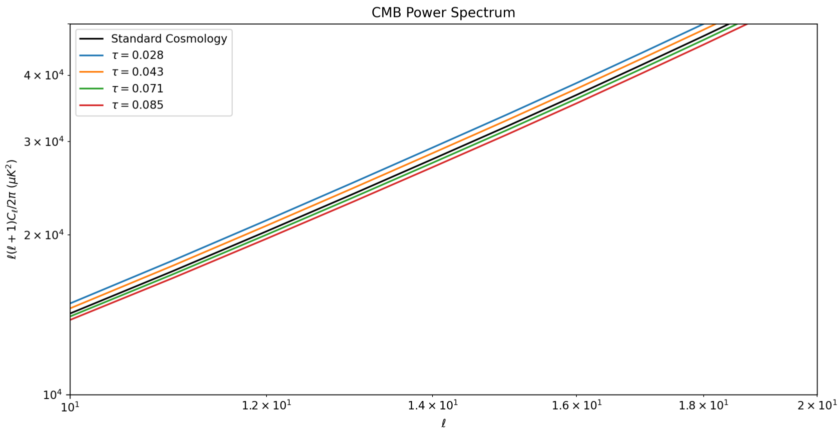

Figure 12: Changes in C_ℓ when τ varies (zoomed in $\ell < 100$).

In Figures 11 and 12, we can see that increasing τ suppresses the anisotropies on small scales due to the scattering effect of photons. For $\ell < 100$ (Figure 12), the anisotropies are almost equal with each other.

This effect can also be seen amplified when changing A_s and n_s (Figures 9 and 10, respectively).