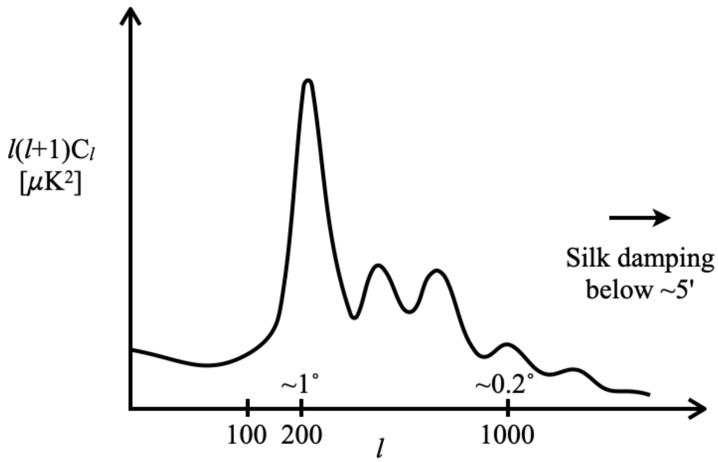
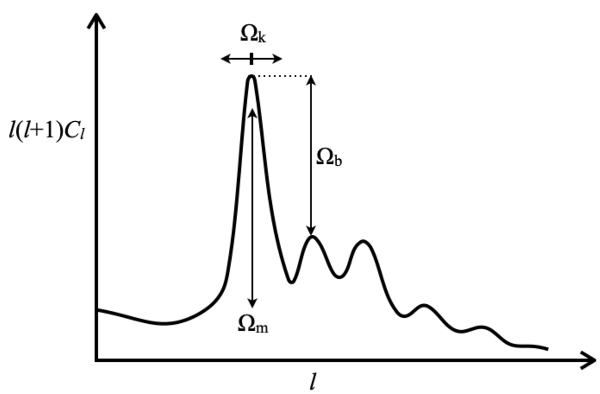


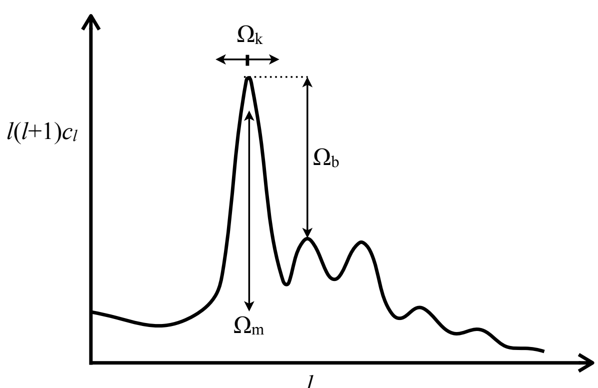
1.C Cosmology with the CMB

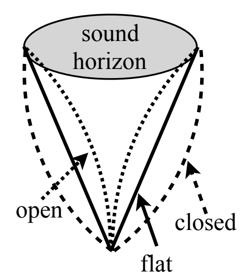


We can derive the cosmological parameters Ω_k, Ω_m, and Ω_b from the first and second peaks of the power spectrum.

- Derive Ω_k f
  The actual
  scale/angul

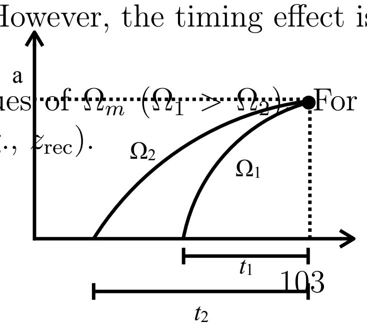
  In an open
  will appear
  In a closed
  for the first





- Derive Ω_m from the first peak:
  A naive assumption might lead us to believe that more matter means more gravity and so bigger peaks. However, the timing effect is more important!

  Consider two values of Ω_m ($\Omega_1 > \Omega_2$). For larger Ω_m, the universe is younger for a given redshift (e.g., z_{rec}).



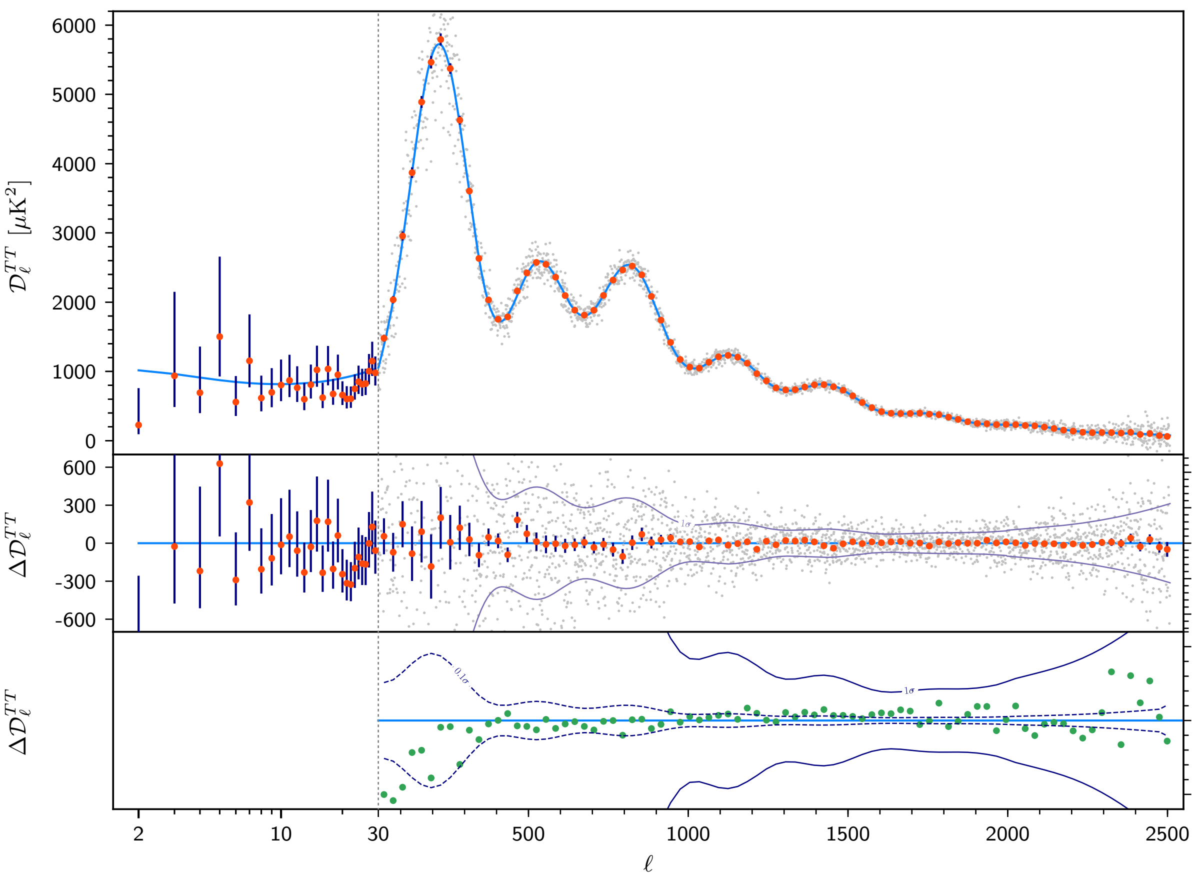
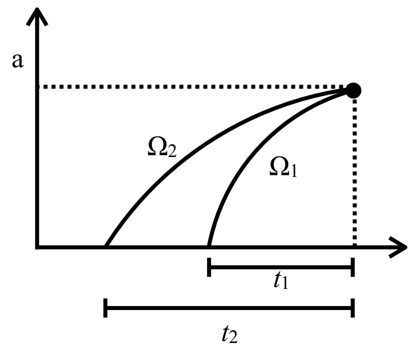


Figure 1: [Fig. 57 of Planck Collaboration V. 2020, A&A, 641, A5] Planck 2018 temperature power spectrum. At multipoles $\ell \geq 30$ we show the frequency-coadded temperature spectrum computed from the `Plik` cross-half-mission likelihood, with foreground and other nuisance parameters fixed to a best fit assuming the base-ΛCDM cosmology. In the multipole range $2 \leq \ell \leq 29$, we plot the power-spectrum estimates from the `Commander` component-separation algorithm, computed over 86% of the sky (see Sect. 2.1.1). The base-ΛCDM theoretical spectrum best fit to the likelihoods is plotted in light blue in the *upper panel*. Residuals with respect to this model are shown in the middle panel. The vertical scale changes at $\ell = 30$, where the horizontal axis switches from logarithmic to linear. The error bars show $\pm 1\sigma$ diagonal uncertainties, including cosmic variance (approximated as Gaussian) and not including uncertainties in the foreground model at $\ell \geq 30$. The 1σ region in the middle panel corresponds to the errors of the unbinned data points (which are in grey). *Bottom panel*: difference between the 2015 and 2018 coadded high-multipole spectra (green points). The 1σ region corresponds to the binned data errors. The vertical scale differs from the one of the middle panel. The trend seen for $\ell < 300$ corresponds to the change in the dust correction model described in Sect. 3.3.2.

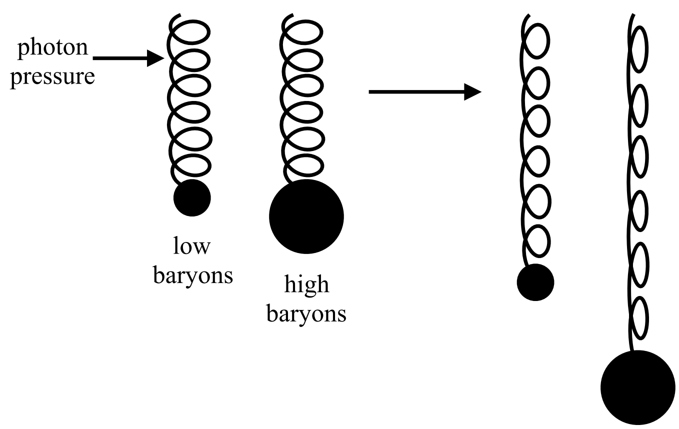


$\Omega_1 > \Omega_2$ leads to $t_1 < t_2$, so there's not as much time to form structures and we get a smaller peak!

Note: based on the first peak, we get Ω_m and Ω_k, so also Ω_Λ (assuming flat universe)!

- Derive Ω_b from the second peak:
  Ω_b is degenerate with Ω_m, so we need the second peak. This can also be derived from Big Bang nucleosynthesis.

  The idea is that a higher baryon mass is like adding mass to a spring ("baryon loading"). More mass causes a deeper fall:



  With more loading, the mass falls deeper but rebounds to the same position. Thus, odd peaks are associated with compression—i.e., how deep the baryons fall into the well. Those peaks get enhanced with more baryons, so the second peak is compressed compared to the first peak. We can therefore constrain Ω_b with the ratio of the two peaks.

2 Thermal history of the Universe

The main idea is that the Universe was very hot in the beginning since $T \propto (1+z)$. For a particle with mass m_x and temperature such that $kT \gtrsim m_x c^2$, we have creation and annihilation reactions. Once T falls low enough, we get *freeze-out* and the reactions stop, freezing the abundance of those particles. (Note: $1\,\text{eV} = 1.1605 \times 10^4\, k_B\text{K} \Rightarrow 1\,\text{eV} \leftrightarrow 10^4\,\text{K}$.)