Radiation Driving

Enhancing oscillations

\( \Phi \)

\( \sigma_\gamma \)

\( \frac{1}{4} \delta_\gamma + \Phi \)

\( k r_s / \pi \)
Figure 9. The angular variations of the CMB power spectrum are consequence of the dynamics of sound waves in the photon-baryon fluid. On large scales (region I), the fluctuations are frozen and we directly see the spectrum of the initial conditions. At intermediate scales (region II), we observe the oscillations of the fluid as captured at the moment of last-scattering. Finally, on small scales (region III), fluctuations are damped because their wavelengths are smaller than the mean free path of the photons.
Contribution to $\Delta N_{\text{eff}}$

Different types of new light particle
$N_{\text{eff}}$ and the CMB

**Figure 12.** Variation of the CMB spectrum $C_l \equiv l(l+1)C_l$ as a function of $N_{\text{eff}}$ for fixed $\theta_*$.

**Figure 13.** Variation of the undamped power spectra, $K_l = D_l^{-1}C_l$, as a function of $N_{\text{eff}}$. The physical baryon density $\omega_b$, the matter-to-radiation ratio $\rho_m/\rho_r$, and the angular size of the sound horizon $\theta_*$ are held fixed in all panels. The dominant effect in the first panel is the variation of the damping scale $\theta_D$. In the second panel, we fixed $\theta_D$ by adjusting the Helium fraction $Y_P$. The dominant variation is now the amplitude perturbation $\delta A$. In the third panel, the spectra are normalized at the fourth peak. The remaining variation is the phase shift $\varphi$ (see the zoom-in in the fourth panel).
Planned Experimental Efforts

This looks outdated?

Figure 14. Evolution of the sensitivity of past and future CMB experiments (figure adapted from [19]).
Constraints on the axion decay constant

Photon coupling: Some require axion DM

\[ \Delta N_{\text{eff}} \geq 0.027 \]
Constraints on the axion decay constant

Gluon coupling: Some require DM

\[ \Delta N_{\text{eff}} \geq 0.027 \]
Other relativistic hypotheticals are left as an exercise for the student...