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Silk Damping and Suppression of CMB Power at Small Scales:

So far we have assumed a perfect fluid consisting of baryons and photons, which are coupled through electromagnetic interactions. As a result, overdensity of baryons gives rise to overdensity of photons (compressed fluid) and underdensity of baryons leads to underdensity of photons (rarefied fluid). Dragging of photons by baryons results in pressure, and hence oscillations, in the fluid. This oscillatory pattern leads to acoustic peaks as observed in the CMB power spectrum.

However, it is important to note that the baryon-photon coupling happens because of electron-photon scattering (Thomson scattering). Therefore, photons are free particles at length scales below their mean free path. Between any two successive scatterings, photons move as free particles.

At small scales, the motion of a photon is just like a random walk in three dimensions. The photon mean free path is given by:

$$\boxed{\lambda_{\gamma(t)} \sim (X_e n_e \sigma_T)^{-1} \sim 2.5 \times 10^{27} X_{e(t)}^{-1} a_{(t)}^{3}}$$

X_e is the fractional ionizations (which obeys the Saha ionization equation, as we discussed earlier) and $a_{(t)}$ is the scale factor of the universe.

The r.m.s distance travelled by a photon in time Δt follows:

$$\boxed{\Delta r^2 \simeq \frac{\Delta t}{\lambda_{\gamma(t)}} \underbrace{\frac{\lambda_\gamma^2(t)}{a^2_{(t)}}}_{\text{redshift}}}$$

The Silk length is given by the following expression:

$$\lambda_s^2 = \int_0^{t_{dec}} d_t \frac{\lambda_\gamma(t)}{a^2_{(t)}} \Rightarrow \boxed{\lambda_s^2 = \frac{3}{5} \frac{t_{dec} \lambda_\gamma(t_{dec})}{a^2_{dec}}}$$

Up to a factor of $\frac{3}{5}$, this is the same as λ_γ at $t = t_{dec}$ (recall that $t_{dec} \sim 500{,}000$ yr). This implies that the main contribution to λ_S comes from random walk of photon at $t \sim t_{dec}$. This can be intuitively understood: at later times $n_e X_e$ is smaller, hence photon mean free path is larger.

The photon baryon coupling breaks down at length scales smaller than λ_γ. Also, the coupling is not perfect at length scales below λ_S. We therefore expect suppression of the CMB power spectrum at wavelength less than λ_S. (Silk damping) We see that:

$$\boxed{\lambda_S \sim \lambda_\gamma(t_{dec}) \sim 1\,\text{Mpc}}$$ (Comoving length)

In the ℓ-space, this corresponds to $\underline{\underline{\ell > O(200)}}$. As we discussed in the previous lecture, the power spectrum rises at large "l" in the presence of dark matter. However, the "Silk damping" (also called collisional damping) compensates for this. The net effect is suppression of the CMB power at small scales.