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Particle Physics Exp. T2
Fall Semester
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Thermal Equilibrium, Entropy Injection and a Cross-section

1 Decoupled Species Revisited

This part is a rerun of the last bit of Tutorial 1. Please skip this part if you have already finished tutorial 1.

Suppose a massless relativistic particle species V in equilibrium with the cosmological plasma at time t_{fo} suddenly stops interacting at all with itself or anything else. After this happens, the expansion of spacetime will dilute the number density of V particles as a^{-3} energy of each V particle will redshift as a^{-1}.

a) What is the contribution of V to the energy density of the Universe today?

b) Rewrite this result in terms of temperatures and g_{*s} factors assuming entropy conservation after t_{fo}.

c) One can show that the distribution function for V particles tracks the equilibrium form, but with a different effective temperature for the V particles. What is this effective temperature today in terms of the photon temperature and the number of effective degrees of freedom g_*?
Hint: $\rho(T) = \pi^2 g_*(T)\, T^4/30$ *for this distribution function.*

2 Entropy Injection

Consider a Universe consisting of a thermal plasma of light particles together with a heavy particle ψ of mass M and density n_ψ. Suppose ψ is long-lived, and decays instantaneously at time t_ψ when the radiation temperature is $T_\psi \ll M$.

a) Using energy conservation, compute the radiation temperature of the plasma immediately after the decay in terms of T_ψ and $n_\psi(t_\psi)$. You may assume that g_* remains constant.

b) What does this do to the entropy density of the Universe?

c) Suppose we also have a decoupled DM species χ with freeze out temperature T_{fo}, and T_ψ is much smaller than T_{fo} and m_χ, and whose contribution to the energy density is negligible until long after t_ψ. If the temperature of the plasma after the decay is also below T_{fo}, what is the relic density of χ relative to what it would have been if $n_\psi(t_\psi) = 0$? You should assume that no χ particles are produced by the ψ decays.

d) If the temperature after the decay is much larger than T_{fo} and m_χ, what is the χ density today compared to what it would have been with $n_\psi(t_\psi) = 0$?
Hint: if χ thermalizes, any initial relic density reaches the thermal value.

3 A Cross-section

Consider the following interaction lagrangian between dark matter fermion χ, a scalar field ϕ and some other fermion f

$$\mathcal{L} \supset \lambda\, \phi \bar{f} \chi + \text{h.c.}.$$

Assuming that $m_f = 0$ compute the averaged and spin-summed (amplitude)^2 for the following diagram in the limit $m_\phi^2 \gg m_\chi^2$: