

# Cosmology 1

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## Proposed problem, lecture 20

Topic: thermal history.

Consider a thermal soup made of photons, electron-positron pairs, muon-antimuon pairs and three families of neutrino-antineutrino pairs (present only in one helicity state). Compute the values of the  $g^*$  and  $\tilde{g}$  statistical weights in the time intervals delimited by these events:

- (1) The starting moment is the annihilation of mesons at  $T = 130$  MeV.
- (2) At  $T \simeq 100$  MeV muons annihilate, disappearing from the thermal soup.
- (3) At  $T \simeq 900$  keV neutrinos decouple.
- (4) At  $T \simeq 500$  keV electrons and positrons annihilate.
- (5) At  $T = 2.73$  K we observe the Universe.

Using the relation

$$t = \sqrt{\frac{3}{32\pi G\rho}}$$

where  $\rho = u/c^2$ , compute the time at which the first three events have taken place; use the value of  $g_*$  just before the event.