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A QUICK AND DIRTY EARLY UNIVERSE / COSMOLOGY COURSE

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A Quick And Dirty Early Universe/ Cosmology Course

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This series of lectures is intended to provide an introductory, non-rigorous overview of those aspects of the standard, hot big bang cosmology useful for understanding and appreciating the astroparticle physics-cosmology connection. Following a minimal introduction to the cosmography and dynamics of the Universe, the basic physics underlying the early evolution of the Universe is outlined. The intent of these lectures is pedagogical and no claim of originality is made. If these lectures are sucessful, the previously unitiated might be prepared to proceed from here to an understanding of current literature on the particle physics-cosmology connection.

1. Introduction

Progress in elementary particle physics inexorably points towards "new physics" at ever higher energy scales, stretching the ingenuity and budgets of the high energy physics community. Thus in the last 2-3 decades, attention has increasingly turned to the Ultimate Accelerator - the Early Universe - as a probe of physics at the highest energies. Increasingly, particle physicists are becoming fluent in cosmology and astrophysics (sadly, the reverse is only rarely occurring). In anticipation of the next generation of accelerators (LHC, etc), and in view of the flawless success of the "standard model" of particle physics, the Universe - at present and during its early evolution - is providing an indispensible laboratory for the study of high energy physics. It is the intent of these lectures to provide the vocabulary necessary for at least a superficial understanding and appreciation of this cosmology-particle physics connection. There is no attempt - nor claim of - completeness or rigor in this exposition. The interested reader is encouraged to move on from this pre-introduction to such texts as Zeldovich-Novikov[1] and Kolb Turner[2]; further details and, especially, further references may be found there. The approach to cosmology here is inspired and informed by Weinberg[3]; the reader, however, is encouraged to regard with skepticism any quantitative results in that excellent book as they are likely to have been superceded by more recent observations.

2. Cosmography

X-ray, γ-ray as well as Radio Astronomy data offer strong support for the Optical data which reveals a Universe which - on the very largest scales - is homogeneous and is expanding isotropically. The high isotropy of the cosmic background radiation (CBR)-the 2.7K blackbody radiation - provides the best evidence that the Universe, at present and during most of its history, is isotropic and homogeneous. Such a Universe may be described by a unique metric - the Robertson-Walker metric[3].

$$ds^2 = c^2dt^2 - a^2(t)[(d\Theta)^2 + r^2d\Omega^2] \quad (1)$$

In (1), s is the proper distance, c the speed of light (in most of the following, c $\equiv$ 1), t the time and a(t) is the scale factor which describes the expansion of the Universe. Θ and r are two alternative comoving radial coordinates,

$$d\Theta = \frac{dr}{(1-kr^2)^{1/2}} \quad (2)$$

where k is the 3-space curvature constant. The comoving angular coordinates θ and ϕ (which will not concern us here) are contained in $d\Omega^2$

$$d\Omega^2 \equiv (d\theta)^2 + sin^2\theta(d\phi)^2 \quad (3)$$

To ilustrate the use of (1), consider photons or other particles which move on geodesics (ds=0). The equation of motion, which relates the comoving radial coordinates to the cosmic time, is

$$d\Theta = \frac{dr}{(1-kr^2)^{1/2}} = \pm\frac{cdt}{a(t)} \quad (4)$$

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This leads us naturally to the concept of the (particle) Horizon. Consider a photon emitted at Θ =0 at t=0. At any later time the comoving radial coordinate of this photon will be,

$$\Theta_H(t) = \int_o^t \frac{cdt'}{a(t')} \tag{5}$$

$\Theta_H(t)$ is the furthest - in comoving coordinates - a signal or any causal effect could have traveled up till time t.

In our somewhat oversimplified view of the Universe we imagine a class of particles (e.g., galaxies) which expand with the average expansion of the Universe. These "comoving particles" remain at fixed values of the comoving coordinates; i.e., Θ_g is independent of time ("g" stands for "galaxy"). Now, if light is emitted by a galaxy at Θ_g at t_e, it will be observed at $\Theta = 0$ at a later time t_o where,

$$\Theta_g = \int_{t_e}^{t_o} \frac{cdt}{a(t)} \tag{6}$$

Since Θ_g is constant,

$$\frac{d\Theta_g}{dt_o} = \frac{c}{a_o} - \frac{c}{a_e}\frac{dt_e}{dt_o} = 0 \tag{7}$$

so that time intervals at emission and observation scale with the scale factor.

$$dt_o/dt_e = a_o/a_e \tag{8}$$

Wavelengths and frequencies of light may be related to the time intervals to reveal that photons emitted with frequency (wavelength) $\nu_e(\lambda_e)$ will be observed at a shifted frequency (wavelength) $\nu_o(\lambda_o)$ where

$$a_o/a_e = \lambda_o/\lambda_e = \nu_e/\nu_o \tag{9}$$

That is, as the Universe expands ($a_o > a_e$) all wavelengths are stretched ($\lambda_o > \lambda_e$). The "redshift" z is defined by $z \equiv (\lambda_o - \lambda_e)/\lambda_e$ so that $1 + z = a_o/a_e$

Since 3-space is, in general, curved ($k \neq 0$) and expanding ($a(t)$) there are many different, operationally defined, distances. Here we restrict attention to the "proper distance" along a radius. Although artificial, it may be related to observationally defined measures (see[1–3]). Suppose time were stopped ($dt = 0$) and distance was measured along a radius ($d\theta = d\phi = 0$). Then we would find

$$R(t) = a(t)\Theta = a(t)\int \frac{dr}{(1-kr^2)^{1/2}} \tag{10}$$

For example, the proper radial distance to the horizon is,

$$R_H(t) = a(t)\Theta_H(t) = a(t)\int_o^t \frac{cdt'}{a(t')} \tag{11}$$

The proper volume at time t, out to comoving radial coordinate Θ, is

$$V(\Theta, t) = 4\pi a^3(t)\int_o^{r(\Theta)} \frac{r^2dr}{(1-kr^2)^{1/2}} \tag{12}$$

Note that for the special, "flat" 3-space case ($k = 0$), $\Theta = r$ and $V = \frac{4\pi}{3}R^3$.

3. Dynamics

To proceed further we must describe the evolution of the Universe; we must determine the time dependence of the scale factor. The Hubble parameter is a measure of the expansion rate of the Universe.

$$H(t) = \frac{1}{a}\frac{da}{dt} \tag{13}$$

The present value of the Hubble parameter, $H_o \equiv H(t_o)$, is often called the Hubble "constant". Since H_o has dimensions of velocity/length, it is conventional in astronomy to measure H_o in units of $kms^{-1}Mpc^{-1}$ where $1Mpc \approx 3 \times 10^{24}$ cm. The inverse of the Hubble parameter is a timescale - it provides a measure of the age of the Universe. Thus we may write

$$H_o = 100h\ kms^{-1}Mpc^{-1} \tag{14}$$

$$H_o^{-1} = 9.8h^{-1}Gyr$$

h in (14) is introduced to account for the present observational uncertainty in H_o; it is likely that

0.4 - 0.5 $\leq h \leq$ 0.9 -1.0. The equations describing the dynamics of the evolution of the Universe are found by substituting the Robertson-Walker metric (eq. 1) into the Einstein equations[1, 3]. The Friedman-Lemaitre equation relates the expansion rate (H) and the density (ρ).

$$H^2 = \frac{8\pi}{3}G\rho - \frac{kc^2}{a^2} \tag{15}$$

In (15) G is Newton's gravitational constant, ρ the (total) universal mass (energy) density, k is the 3-space curvature constant and c the speed of light. If there is a non-zero cosmological constant Λ, then $\Lambda/3$ should be added to the right hand side of eq.15. Eq. 15 may be rewritten in a suggestive form,

$$\frac{1}{2}(\frac{da}{dt})^2 - \frac{GM}{a} = -kc^2 \tag{16}$$

where $M \equiv \frac{4\pi}{3}a^3\rho$. From (16) it is clear that the geometry (k) and dynamics are related; for $k \leq 0$ unlimited expansion is possible; for $k > 0$ the Universe expands to a maximum and then recollapses.

There are two unknown functions of time $a(t)$ and $\rho(t)$ in eq. 16. Thus, another equation is required; it has a form suggestive of entropy conservation ($dU + pdV = 0$).

$$d\rho + 3(\rho + p)da/a = 0 \tag{17}$$

In (17), p is the (isotropic) pressure. Thus, to solve for the evolution of the Universe, the equation of state: $p = p(\rho)$, must be specified. Two limiting cases suffice to describe most epochs in the evolution of the Universe. If the density is dominated by pressureless (non-relativistic) matter, e.g., "ordinary" baryonic matter, the Universe is called "Matter Dominated" (MD). In this case ρa^3 = constant and (15) may be solved for any choice of k. Note that for a(t) $\ll a_o$ and/or k=0, eq. 15 simplifies and, for a MD Universe, $a \sim t^{2/3}$ and $H(t)t = 2/3$. If, in contrast, the universal density is dominated by relativistic matter ("radiation") for which $p = 1/3\rho c^2$ (we are being careless about $c = 1$), the Universe is called "Radiation Dominated" (RD). In this case ρa^4 = constant and, again, (15) may be solved for any choice of k. Again, for early evolution ($a \rightarrow 0$ and/or $k = 0$), eq. 15 simplifies and, for a RD Universe, a $\sim t^{1/2}$ and H(t)t=1/2. Note that for the early ($a \rightarrow 0$) evolution of the Universe and/or $k = 0, \rho(t) \sim t^{-2}$. For thermal radiation, $\rho \sim T^4$ so that the temperature and scale factor vary inversely with each other,

$$T/T' = a'/a = (1 + z)/(1 + z') \tag{18}$$

For the early, RD Universe, $T \sim t^{-1/2}$.

It is interesting to compare the universal "potential energy", $GM/a \equiv \frac{4\pi G}{3}\rho\, a^2$, to the universal "kinetic energy", $1/2(da/dt)^2$,

$$\Omega = \Omega(t) \equiv \frac{PE}{KE} \equiv \frac{8\pi\, G\rho}{3H^2} \equiv \frac{\rho}{\rho_c} \tag{19}$$

In (19), the critical density is $\rho_c \equiv 3H^2/8\pi G$. Comparing (15) and (19) reveals the deep connection between Dynamics and Geometry.

$$kc^2 = (aH)^2(\Omega - 1) \tag{20}$$

In general Ω is time-dependent. For $k > 0, \Omega > 1$ and, as the Universe expands, $\Omega \rightarrow \infty$. For $k < 0, \Omega < 1$ and, as the universe expands, $\Omega \rightarrow 0$. Thus, for $k \neq 0, \Omega$ may be anywhere in the range $0 < \Omega < \infty$. Further, at the earliest epochs $(a \rightarrow 0), \Omega \rightarrow 1$. So, as the Universe evolves, Ω should depart from unity and, much later, should either be very small or very large. However, at present, some 10-20 Gyr after the Big Bang, Ω is apparently within an order of magnitude of unity. It is this "coincidence"that led Dicke & Peebles[4] to propose that k=0; in this case, Ω = 1 for all times (see eq. 20). The inflationary paradigm[5] proposes a physical mechanism for driving $kc^2/a^2 \rightarrow 0$.

3.1. Age of the Universe

For the "Open" Universe model, $k < 0$, as the Universe continues to expand, $\rho \rightarrow 0$. In this case, $Ht \rightarrow 1$. If $\Omega_o \ll 1$, then this model would be a good approximation to the present Universe and $t_o \approx H_o^{-1} \approx 9.8h^{-1}$ Gyr. In any realistic model, however, $\rho > 0$ and this has the effect of slowing the expansion (the scale factor is a concave function of time). As a result, the

Universe is always younger than H^{-1} : $t_o < H_o^{-1}$. That is, $t_o = H_o^{-1}\ f(\Omega_o)$ where $f \leq 1$. For the MD Universe,

$$f_{MD}(\Omega_o) = \int_o^1 \frac{x^{1/2}dx}{(\Omega_o + (1-\Omega_o)x)^{1/2}} \qquad (21)$$

Note that $f_{MD}(0) = 1$ and $f_{MD}(1) = 2/3$. For the RD Universe,

$$f_{RD}(\Omega_o) = \int_o^1 \frac{xdx}{(\Omega_o + (1-\Omega_o)x^2)^{1/2}} = \frac{1}{1+\Omega_0^{1/2}} \qquad (22)$$

3.2. The early (RD) Universe

Recall that for non-relativistic (pressureless) matter $\rho_{NR} \sim a^{-3}$, while for extremely relativistic (radiation) matter $\rho_{ER} \sim a^{-4}$, so that as the Universe expands it evolves from an early RD epoch to the present MD epoch ($\rho_{ER}/\rho_{NR} \sim a^{-1}$). Further, if we concentrate on the early evolution of the Universe, any curvature may be neglected (*i.e.*, $kc^2/a^2 \ll 8\pi\ G\rho/3$). Thus, for the early Universe, (15) & (17) reduce to

$$\frac{32\pi}{3}G\rho\ t^2 = 1 \qquad (23)$$

It is conventional to write the total density in terms of the photon density, introducing an "effective" number of degrees of freedom

$$\rho \equiv \frac{g_{eff}}{2}\rho_\gamma \qquad (24)$$

Since $\rho_\gamma \sim T^4$, $g_{eff}T^4\ t^2$ = constant, so the expansion rate, $t^{-1} \sim g_{eff}^{1/2}T^2$, increases with g_{eff}. For an early, RD Universe,

$$t(sec) = 2.4 g_{eff}^{-1/2} T_{MeV}^{-2} \qquad (25)$$

If g_{eff} increases - due, for example, to the presence of "new" (ER) particles - then at fixed T, the Universe is expanding faster and is therefore younger (compared to the "standard" case).

Knowing the time-temperature relation is key to probing the physics of the early Universe. Primordial nucleosynthesis in particular provides a unique window to the early Universe. Any new physics which modifies the time-temperature relation at the epoch of nucleosynthesis may be revealed in the abundances of the light elements D, ^3He ^4He and ^7Li[6]. Thus, the remainder of these lectures concentrates on the thermodynamics of the early universe and illustrates the results with several examples. For further details, see[1–3, 7].

4. The Thermal History of the Early Universe

In equilibrium at (photon) temperature T, the number density of (blackbody) photons is

$$n_\gamma = \frac{2\zeta(3)}{\pi^2}(\frac{kT}{\hbar\ c})^3 \approx 400(\frac{T}{2.7K})^3\ cm^{-3} \qquad (26)$$

The energy density in CBR photons is

$$\rho_\gamma = \frac{6\zeta(4)}{\pi^2}kT(\frac{kT}{\hbar\ c})^3 \approx \frac{1}{4}(\frac{T}{2.7\ K})^4 eVcm^{-3} \qquad (27)$$

It is convenient to relate the number/energy densities of other particles to that of photons. For extremely relativistic bosons (e.g., pions when $T > m_\pi$),

$$n_B/n_\gamma = (g_B/2)(T_B/T_\gamma)^3 \qquad (28)$$

$$\rho_B/\rho_\gamma = (g_B/2)(T_B/T_\gamma)^4$$

In (28), g_B is the number of helicity states and T_B the temperature of each boson. The difference between Fermi-Dirac and Bose-Einstein statistics leads to similar but slightly different results for ER fermions.

$$n_F/n_\gamma = 3/4(g_F/2)(T_F/T_\gamma)^3 \qquad (29)$$

$$\rho_F/\rho_\gamma = 7/8(g_F/2)(T_F/T_\gamma)^4$$

Comparing (24) with (28) and (29), we may write for g_{eff}

$$g_{eff} = \sum_B g_B(\frac{T_B}{T\gamma})^4 + \frac{7}{8}\sum_F g_F(\frac{T_F}{T_\gamma})^4 \qquad (30)$$

To illustrate the above, consider as an example the epoch when the temperature is in the range $\sim 1-100\ MeV$. During this epoch the only contributors - in the standard model - to the total energy density are ER photons, $e^\pm$ pairs, ν_e, ν_μ, ν_τ.

Also, during this epoch all particles are in thermal equilibrium so that $T_\gamma = T_e = T_\nu$. Thus, in this epoch,

$$g_{eff} = 2 + 7/8(4 + 3 \times 2) = 43/4 \quad (31)$$

and

$$t(sec) \approx 0.74\, T_{MeV}^{-2} \quad (32)$$

As another example, consider the epoch when $T \ll m_e$, so that the $e\pm$ pairs have annihilated away (but, the Universe is still radiation dominated). Now the only ER particles present are $\gamma, \nu_e, \nu_\mu, \nu_\tau$. As we will see shortly, the photons have been "heated" relative to the decoupled neutrinos by the annihilating electrons, so that $T_\gamma = (11/4)^{1/3} T_\nu$. Therefore, in this case

$$g_{eff} = 2 + (7/8) \times 3 \times 2(4/11)^{4/3} = 3.36 \quad (33)$$

and

$$t(sec) \approx 1.3\, T_{MeV}^{-2} \quad (34)$$

It is important to note that in some variations on the standard model (e.g., a massive tau-neutrino with $m_{\nu\tau}$ a few to a few tens of MeV), even the early energy density need not be RD. Nonetheless, we may still define g_{eff} through eq.24: $g_{eff}/2 = \rho_{TOT}/\rho_\gamma$. However, eq. (30) only applies when ρ_{TOT} is dominated by the contribution from ER particles.

4.1. Entropy Conservation: T_X vs. T_γ

As the Universe expands and cools, particles will envolve from ER to NR and, when $T \leq m$, they will begin to annihilate and/or decay. Although these massive particles may cease to contribute to ρ_{TOT}, their annihilation/decay "heats" the remaining interacting ER particles. However, at any epoch, ρ_{TOT} may consist of contributions from interacting (coupled) particles as well as from non-interacting (decoupled) particles. An example is the Universe after $e^\pm$ annihilation, dominated by interacting photons and decoupled neutrinos. In order to evaluate the contribution of a decoupled particle - call it X - to g_{eff}, we must know the ratio T_X/T_γ. Entropy conservation[1–3, 7] permits us to find this ratio.

Consider the entropy in a comoving volume of the expanding Universe,

$$S \sim a^3(p + \rho)/T \sim a^3(\rho/T) \quad (35)$$

We may relate ρ to ρ_γ and ρ_γ/T to n_γ in such a way that we may define,

$$S = g(T)N_\gamma(T) \quad (36)$$

where $N_\gamma(T)$ is the number of CBR photons in our comoving volume at temperature T. Except during phase transitions, as the Universe evolves S is conserved. Now, since our particle X is decoupled, S_X itself is conserved and $N_X(T)$, the number of Xs in a comoving volume is unchanged (no production/annihilation; X is assumed to be stable). As long as X decoupled when extremely relativistic, $N_X \sim a^3 T_X^3 \sim V T_X^3$. Thus, T_X provides a measure of the evolution of our comoving volume. That is, we may specify the size of our comoving volume by specifying N_X. As a result, $aT_X =$ constant. Now, since S and S_X are conserved, so too is $S_I = S - S_X$. That is, the entropy carried by the interacting particles is separately conserved.

$$S_I = g_I(T)N_\gamma(T) \quad (37)$$

Note that $S_I \sim g_I a^3 T_\gamma^3 \sim g_I(T_\gamma/T_X)^3$ remains constant as the Universe evolves. This is the relation we have been searching for; as g_I decreases when particles annihilate/decay, the ratio T_γ/T_X increases.

To illustrate the application of (37), consider the ordinary neutrinos which decouple at temperatures of a few MeV. Somewhat later, when the temperature falls below $\sim 1/2 MeV$, $e^\pm$ pairs annihilate heating the CBR photons. If "before" indicates prior to $e^\pm$ annihilation but after ν - decoupling, then

$$Before : g_I = 2 + (7/8) \times 4 = 11/2 \quad (38)$$

If "after" denotes after $e^\pm$ annihilation is complete,

$$After : g_I = 2 \quad (39)$$

Comparing (38), (39) and (37), we find that

$$N_\gamma^{After} = (11/4)N_\gamma^{Before} \quad (40)$$

and, $(T_\gamma/T_X)_{After} = (11/4)^{1/3}$.

Thus, in our same comoving volume (containing N_X X - particles which, in this case, might be the decoupled neutrinos), there are more photons after $e^\pm$ annihilation and, they are hotter than they would have been had the $e^\pm$ not annihilated.

Since below m_e there are no further ER particles, the "After" quantities in (40) are those we would observe today.

$$N_{\gamma o} = (11/4)N_\gamma(T \geq m_e) \tag{41}$$
$$(T_\gamma/T_\nu)_o = (11/4)^{1/3}$$

We are often interested in physics at scales higher than the few MeV decoupling scale of neutrinos. To apply our results to higher temperatures - when the neutrinos were still coupled/interacting - we must relate N_γ above a few MeV to N_γ below m_e. For $T \geq$ few MeV (the scale at which the neutrinos decouple),

$$g_I(T)N_\gamma(T) = (\frac{43}{4})N_\gamma(few\ MeV) = (\frac{43}{11})N_{\gamma_o} \tag{42}$$

In (42), g_I (few MeV) $= 2 + 7/8(4 + 3 \times\ 2) = 43/4$. As an example, consider a particle X which decouples at T_{dX} where: $m_\mu < T_{dX} < m_\pi (105 < T_{dX} < 135 MeV)$. Then, $g_I(T_{dX}) = 43/4 + 7/8 \times 4 = 57/4$ (the ER muon contributes the extra degrees of freedom), so that $t(sec) \approx\ 0.64\ T_{MeV}^{-2}$ and,

$$N_{\gamma o} = \frac{11}{43} \times \frac{57}{4} N_\gamma(T_{dX}) \tag{43}$$
$$(T_X/T_\gamma)_o = [\frac{43/11}{g_I(T_{dX})}]^{1/3} = 0.65$$

4.2. The Epoch of Nucleosynthesis

Many of the early Universe constraints on particle physics beyond the standard model follow from comparison of the predictions of big bang nucleosynthesis (BBN) with the observed abundances of the light elements[6] . The neutrinos decouple shortly before the epoch of nucleosynthesis so that, from BBN to the present, the ratio T_X/T_ν is preserved. For $T \geq\ m_e, T_\nu = T_\gamma$ and $g_I = 43/4$ so that,

$$(\frac{T_X}{T_\nu})NUC = [\frac{43/4}{g_I(T_{dX})}]^{1/3} = (\frac{T_X}{T_\nu})o \tag{44}$$

Suppose, for illustration, that the X particle in the previous example ($m_\mu < T_{dX} < m_\pi$) is a "new" (more weakly coupled) light neutrino (fermion; $g_X = 2$). Then, $(T_X/T_\nu)_{NUC} = (43/57)^{1/3} = 0.91$ and the effective number of degrees of freedom at BBN increases to

$$g_{eff}^{NUC} = \frac{43}{4} + \frac{7}{8} \times\ 2(\frac{T_X}{T_\nu})^4_{NUC} = \frac{47.8}{4} \tag{45}$$

It is convenient to introduce "the equivalent number of extra neutrinos" $\Delta N_\nu \equiv \Delta\rho_{TOT}/\rho_\nu$. If $\Delta\rho_{TOT}$ is due to new ER particles, it follows from (24) and (30) that

$$\Delta N_\nu = \sum_F{}'(\frac{g_F}{2})(\frac{T_F}{T_\nu})^4_{NUC} + 8/7 \sum_B{}'(\frac{g_B}{2})(\frac{T_B}{T_\nu})^4_{NUC} \tag{46}$$

In (46) the prime on the sums is a reminder that the standard model particles ($\gamma, e^\pm, \nu_e, \nu_\mu, \nu_\tau$) are not included.

Thus, at BBN, we may write

$$g_{eff}^{NUC} = \frac{43}{4} + \frac{7}{4}\Delta N_\nu \tag{47}$$

Recall that, for the early RD Universe, the expansion rate (t^{-1}) varies with $\rho_{TOT}^{1/2}$, so that in the presence of "extra" ER particles the early Universe expands faster by a factor

$$\xi = t/t' = (\rho'_{TOT}/\rho_{TOT})^{1/2} = (1 + \frac{7}{43}\Delta\ N_\nu)^{1/2} \tag{48}$$

For our previous example of a new neutrino which decouples above $m_\mu, \Delta N_\nu = 0.69$ and $\xi = 1.05$. Thus, at a fixed temperature the Universe would be $\sim$ 5% younger; this may affect the predicted relative abundances of the light elements produced during BBN[9].

As another example, consider a new, light, weakly interacting scalar (boson; $g_X = 1$) which decouples above the pion mass but below the temperature of the quark-hadron transition. At T_{dX} the interacting degrees of freedom are: $\gamma, \pi^\pm, \pi^o, e^\pm, \mu^\pm, \nu_e, \nu_\mu, \nu_\tau$, so that

$$g_I(T_{dX}) = 43/4 + (7/8) \times\ 4 + 3 = 69/4 \tag{49}$$

Then, $(T_X/T_\nu)_{NUC} = (43/69)^{1/3} = 0.85$ and

$$\Delta N_\nu = \frac{8}{7}(\frac{1}{2})(\frac{T_X}{T_\nu})^{4/3}_{NUC} = 0.30. \tag{50}$$

In this case $\xi = 1.02$.

As the above examples suggest, BBN can constrain the properties (masses, couplings) of new particles. An upper bound to ΔN_ν will, in general, lead to a lower bound to T_{dX} and an upper bound to the couplings of new particles. For a new "fermion",

$$\Delta N_\nu = \frac{g_F}{2}[\frac{43/4}{g_I(T_{dX})}]^{4/3} \quad (51)$$

If the new particle is a boson,

$$\Delta N_\nu = \frac{4g_B}{7}[\frac{43/4}{g_I(T_{dX})}]^{4/3} \quad (52)$$

A recent reexamination of BBN[9] finds the bound $\Delta N_\nu \leq 0.3$ which, for a new light neutrino requires

$$g_I(T_{dX}) = \frac{43/4}{(\Delta N_\nu)^{3/4}} \geq \frac{106}{4} \quad (53)$$

Such a large value of g_I requires that any new particles must have decoupled above the quark-hadron transition temperature.

5. Summary

The intent of these lectures was pedagogical. It is the hope that student will be prepared - and encouraged - to take the next step. The excellent texts[1–3] and the review articles[6, 7] may help pave the way. It is my firm belief that the symbiotic relationship between astrophysics and high energy physics, which has grown and developed over the last few decades, is an enduring one of great value to cosmology and to particle physics. It is my hope that these notes provide a useful primer to this new and exciting area of research.

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