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GALAXY FORMATION WITH DECAYING COLD DARK MATTER

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ABSTRACT

Galaxy formation with cold dark matter is very efficient in producing small scale (galactic) structure. In addition to inflation, the growth of density perturbations seems to require $\Omega \simeq 1$. However on small scales Ω is observed to be $\lesssim 0.3$. A possible solution to this problem is decaying cold matter. The very long lifetime needed for decay seems to imply a gravitational decay indicating a possible solution in the context of N=1 supergravity.

In this conference, we have heard much of the current status of galaxy formation. In particular, we have seen that of the three types of dark matter candidates[1] none seem to be really compatible with our observed structure. The three types of candidates that I am referring to are of course hot, warm and cold matter. They are distinguished by their effective temperature at the time they decoupled from the thermal background. Examples of hot particles are neutrinos[2] or very light photinos/Higgsinos[3,4] with $\lesssim$ 100eV masses. These particles decouple at $T_d \sim$ 1MeV and are thus still relativistic at T_d. Warm particles decouple earlier and have higher masses (up to $\simeq$ 1keV). Any superweakly interacting neutral particle is a warm candidate such as a right handed neutrino.[5] Cold particles are non-relativistic at temperatures relevant for galaxy formation and have masses $\gtrsim$ 1GeV. Examples of these include heavy neutrinos,[6] photinos/Higgsinos,[7,4] sneutrinos[8] and axions.[9]

Problems arise when any of these candidates are taken alone to resolve the dark matter problem. Part of the difficulty is that the amount of dark matter needed varies with length or mass scales. Hence there are several dark matter problems.[10] On the one hand, inflation[11] tells us that the density parameter $\Omega = \rho/\rho_{crit} = 1$ ($\rho_{crit} = 1.88\times10^{-29}\ h_o^2$ gcm^{-3}, $h_o = H_o/100$ km Mpc^{-1} s^{-1} is the Hubble parameter). Observational determinations of Ω indicate that the luminous parts of spiral galaxies contribute only a fraction[12] $\Omega = (2-6)\times10^{-3}$. On larger scales, those of binaries and small groups of galaxies (which would include galactic halos), one finds[12] $\Omega = 0.05$ to 0.15. Even on the largest scales where determinations of Ω have been made one finds[12,13] that Ω is probably no larger than a few tenths. In short, this represents a hierarchy of missing mass problems.

Hot particles are very good at producing large scale structure such as filaments and voids.[2] The problem is that this scale is too large to be compatible with observations.[14] Galaxies tend to form too late and on too large of a scale. The clustering scale is determined by the Jeans mass[15]

$$M_J \approx 3 \times 10^{18} \, M_\odot/m_\nu^2(\mathrm{ev}) \qquad (1)$$

which for $m_\nu < 100\mathrm{eV} \rightarrow M_J > 3 \times 10^{14} M_\odot >> M_G \sim 10^{11} - 10^{12} M_\odot$. Because of their larger mass, one might think that warm particles could correct this.[5,16] However if dwarf galaxies also contain large amounts of dark matter[17] then it remains a problem to get clustering down to these scales $M_D \sim 10^6 - 10^7 M_\odot$.

Cold dark matter is clearly the best choice for obtaining the small scale structure.[18] Cold matter, however is too good at clustering and if $\Omega = 1$, would contribute too much mass on small scales. On the other hand, if $\Omega = 0.2$, perturbations which stop growing at a redshift $z \sim \Omega^{-1}$[19] have little chance to become non-linear. Recently models have been proposed in which light is no longer a tracer of mass and luminous objects are in fact rare (3σ) events[20] or hydrodynamics prevent pancakes from becoming observable.[21]

In this contribution, I would like to discuss another alternative to make dark matter more compatible with galaxy formation, that is the case of decaying dark matter.[22] Recently, there have been two approaches to this problem. The first in which the Universe becomes and remains radiation dominated[23,24,25] and the second in which the Universe passes through a brief radiation period but then becomes matter dominated again.[25,26] In refs. 23,24, the idea was that a neutrino (presumably the μ or τ-neutrino) decays to a lighter one non-radiatively through the exchange of majorons or familons. These are basically hot scenarios and are subject to the same problems of forming galaxies through fragmentation. In addition, from limits on the anisotropy of the microwave background radiation it appears that the redshift of decay is highly constrained.[27]

A similar decaying scenario[25,26] with cold dark matter is the possibility I would like to discuss here. In particular, what is found in all of these models is that the dark matter must be very long lived and decay only recently. The lifetime is generally about 10^8 yrs or equivalently the particle decay rate is $\Gamma \sim 2\times10^{-40}$ GeV. Such a small decay rate is not typical of known particle interactions. It is however, typical of what one would expect from a gravitational decay rate

$$\Gamma \sim G_N m^3 \sim m^3/M_p^2 \sim 6 \times 10^{-39} m^3(\mathrm{GeV}) \ \mathrm{GeV} \qquad (2)$$

so that a particle with a mass of a few hundred MeV with a pure gravitational decay would fit the bill. This makes the gravitino an interesting candidate for the dark matter. The gravitino is the spin 3/2 supersymmetric partner of the graviton in N=1 supergravity theories and naturally has a decay rate of the form of eq. 2.

In the discussion that follows, the Universe may end up either as a radiation or matter dominated Universe. The matter dominated Universe being preferred because it allows one a slightly older Universe (t_u = 1.2×10^{10} yrs for h_o = 1/2), the age of the Universe being problematic in all of these scenarios. The fate of the Universe is determined by the ratio Ω_{NR}/Ω_D where Ω_{NR} is that part of Ω which is non-relativistic. (I will assume throughout that Ω_{total} = 1), Ω_D is the relativistic component of Ω which is due to the decay of the gravitino or to be more general the heavy particle H. In this scenario we assume therefore that H will decay non-radiatively (no photons) into lighter particles L. The L particles therefore are present today in two components, a relativistic component due to the decay and a primordial non-relativistic component left over in the thermal background (just as if neutrinos had some mass). Thus we can divide Ω_{NR} into its constituents

$$\Omega_{NR} = \Omega_L + \Omega_B + \Omega_o \tag{3}$$

where Ω_B is that part of Ω in baryons, (which we will take to be about 0.05) Ω_o is any other non-relativistic component and Ω_L represents the primordial L particles.

We can write Ω_L and Ω_D in terms of the masses of L and H and the temperature of H decay, T_D,

$$\begin{aligned}\Omega_L = \rho_L/\rho_c &= (3/4)M_L\ n_\gamma\ (T_L/T_o)^3\ g_L/2\rho_c \\ &\simeq 0.1\ (g_L/2)M_L(\mathrm{eV})h_o^{-2}(T_o/2.7)^3/N(T^*)\end{aligned} \tag{4}$$

where n_γ is the number density of photons today with blackbody temperature T_o, T_L is the temperature of the L's and depends on the temperature T^* at which the L's decoupled from the thermal background,[28] g_L is the number of degrees of freedom for L and $N(T^*) = 3.9(T_o/T_L)^3$ is the number of interacting degrees of freedom at T^*. Similarly we have

$$\begin{aligned}\Omega_D = \rho_D/\rho_c &= M_H n_\gamma Y(T_o/T_D)/\rho_c \\ &\simeq 8 \times 10^{-6}(M_H Y/T_D)h_o^{-2}(T_o/2.7)^4\end{aligned} \tag{5}$$

where Y is the abundance of H's relative to photons before their decay at T_D. If H were a neutrino, then $Y = (3/4)(T_\nu/T_\gamma)^3 = 3/11$. For H a gravitino, Y is expected to be much smaller because having decoupled at the Planck time its number density was greatly reduced by inflation. The residual Y in eq. (5) was produced by the reheating period after inflation. Thus Y can lie anywhere in the range 10^{-14} to 10^{-4} depending on the details of inflation.

In the decaying matter scenarios the Universe becomes matter dominated at a temperature $T_{MD} > T_D$ when the energy density in matter ($\rho_H + \rho_L + \rho_B$) becomes equal to that in radiation (photons and neutrinos)

$$T_{MD} \simeq (3/4)M_H Y/N_{MD} \tag{6}$$

where N_{MD} = 2 - 3.4 is the number of degrees of freedom at T_{MD}. (The range depends on the number of massless neutrinos.) The ratio T_{MD}/T_D it turns out is independent of the particle physics

$$T_{MD}/T_D \simeq 10^5\Omega_D h_o^2(2.7/T_o)^4/N_{MD} \tag{7}$$

At T_D the Universe becomes radiation dominated again by the relativistic decay products of H. If the ratio $\Omega_{NR}/\Omega_D > 1$ the Universe will become matter dominated again at

$$T_E/T_o = \Omega_{NR}/\Omega_D \tag{8}$$

A more important distinction made by the ratio Ω_{NR}/Ω_D is on the spectrum of density perturbations and the large scale structure which I will now discuss.

The primary growth of density perturbation occurs between T_{MD} and T_D. We will take[28] an initial value $(\delta\rho/\rho)|_i \lesssim 1.2 \times 10^{-4}$ in accordance to the limits on quadropole anisotropy of the microwave background radiation.[29] Because of the decay, the only structures to survive after T_D will be those scales which have gone non-linear $(\delta\rho/\rho \geq 1)$ before decay. The largest scale to have gone non-linear before T_D was found to be[26]

$$\lambda_{NL} = B\ \lambda_{MD} \tag{9}$$

$$\lambda_{MD} = 7.5(T_o/T_D)[N(T_{MD})]^{1/2}(T_o/2.7)^2/\Omega_D h_o^2 \text{ Mpc} \tag{10}$$

where λ_{MD} is the horizon scale at matter dominance and B is a function of $(\delta\rho/\rho)$, T_D and T_{MD} (see Ref. 26). λ_{NL} must set to agreement with determinations from the two-point galaxy correlation function,[30] $\lambda_{NL} \approx$ 10 - 20 Mpc. This must also correspond to mass scales large enough to encompass galaxies and small groups of galaxies. Once λ_{NL} is set, to say 10 Mpc, the largest mass scale to go non-linear is given by

$$M_{NL} = \Omega_{NR}\rho_c\lambda_{NL}^3 \approx 3.3 \times 10^{13}\Omega_{NR}/h_o\ M_\odot \tag{11}$$

That part of M_{NL} in baryons is just $M_{NL}^{(b)} = (\Omega_b/\Omega_{NR})M_{NL}$.

Further growth of structure will be halted due to the free streaming of the decay products.[22] In addition the sudden loss of mass from the objects which have just formed will also cause a large fraction of the primordial L's to begin free streaming out. The baryons, we expect to remain behind as they will have already begun dissipative processes. Those L's left behind[26] (about $2\Omega_B$) will serve as the dark matter for halos of galaxies and small groups. Now for $\Omega_{NR}/\Omega_D<1$, there will be little or no structure on scales $\lambda>\lambda_{NL}$. For $\Omega_{NR}/\Omega_D>1$, density perturbations will again begin to grow as the Universe becomes matter dominated at T_E.

In the latter case, as was just pointed out, the free streaming of the escaping L's wipe out perturbations on scales less than λ_{fs}, the scale to which the free streaming occurs. For $\lambda>\lambda_{fs}$ structure is forming again. λ_{fs} is determined by the time at which the hubble flow catches up to the free streaming particles. It has been estimated that[26] $\lambda_{fs} \sim O(1)\lambda_{MD}$. Evidence for structure on these scales may be present in the cluster-cluster correlation functions.[31]

Let us now look at two specific cases 1) $\Omega_{NR}/\Omega_D = 1/4$ and 2) $\Omega_{NR}/\Omega_D \approx 4$. In the former case the Universe is radiation dominated today. Specifically let us take Ω_D=0.8 and Ω_L=0.15 so that Ω_{NR}=0.2. From eq. (5) we see that the combination $M_H Y/T_d \approx 2.5\times10^4$ is fixed. The largest scale to go non-linear λ_{NL}, in this case (B ≈ 1.5) is

$$\lambda_{NL} \approx 100(T_o/T_D) \text{ Mpc.} \tag{12}$$

If we require that $\lambda_{NL} > 10$ Mpc we have $(T_D/T_o) \lesssim 10$ or a redshift of decay $z_D \lesssim 9$. The decay rate required to give this redshift of decay is

$$\Gamma_D = 1.8 \times 10^{-40}\ \mathrm{GeV} \tag{13}$$

If H were a neutrino[23,21] then Y=3/11 implies a neutrino mass $m_\nu \simeq 200$ eV. The characteristic mass scale to form is then a few × $10^{13}M_\odot$, with smaller scales wiped out by neutrino free streaming and larger scales having never gone non-linear. In this case one is left with the problem of fragmenting galaxies and the lack of structure on very large scales. An additional problem arises when one takes into account limits from the microwave background anisotropy.[27] Namely $z_D \lesssim 4$ or $m_\nu \lesssim 85$ eV and some of the benefits of a decaying particle begin to disappear.

If instead, H were a massive particle[25] (e.g. a very heavy neutrino or a gravitino) with Y very small then we have essentially a cold matter scenario with structure going all the way down to small scales ($10^6M_\odot$). Again the largest structure formed is few × $10^{13}M_\odot$ so there is again an absence of the very large structure.[31] In this case the limits from the microwave anisotropy are relaxed,[32] the upper limit on z_D increasing with M_H.

In our second example,[26] we will take, $\Omega_D = 0.2$ and $\Omega_L = 0.75$ so that $\Omega_{NR} = 0.8$. In this case, eq. (5) fixes $M_HY/T_D \simeq 6 \times 10^3$ and (B = 0.5)

$$\lambda_{NL} \simeq 140(T_o/T_D)\ \mathrm{Mpc} \tag{14}$$

so that $\lambda_{NL} > 10$ Mpc implies that $(T_D/T_o) < 14$. The decay rate is again given by eq. (13). The scenario here is somewhat different. For M_H large we again have structure on small scales up to few × $10^{13}M_\odot$ (the largest baryonic mass is $(\Omega_B/\Omega_{NR})M_{NL} \sim 3 \times 10^{12}M_\odot$). Because of the free streaming of the L particles, there is no structure between λ_{NL} and λ_{fs} where growth occurs between T_E and the present.

Problems which may arise in this scenario are related to the largest scale structure. On the scale λ_{fs}, it would be expected that $\Omega \approx 0.8$. Thus λ_{fs} must be large enough as there is as yet no evidence for such a large Ω on any intermediate scales.[13] In addition $(\delta\rho/\rho)$ on the scale λ_{fs} must be just going non-linear so that structure on that scale is not yet too well defined.[31]

To conclude this discussion let us return to the idea that H is a gravitino. Gravitinos will decay if there exist any other supersymmetric particles with mass less than the gravitino mass $m_{3/2}$. As we have said earlier, the decay must not involve photons. A possible candidate for the L particle might be the axino, the supersymmetric partner of the axion. Its estimated[33] mass of 3-300eV fits the value O(100eV) required by eq. (4). We can write the decay rate for the gravitino as

$$\Gamma_D = \alpha\, m_{3/2}^3/M_p^2 \tag{15}$$

where α is some coupling constant. At the tree level, we expect[7] $\alpha = 4$, so that $m_{3/2} \sim 200$ MeV is required to give the decay rate in eq. (13). This is somewhat low since we expect that $m_{3/2} \sim m_W \sim 100$ GeV. However, gravitational radiative corrections[34] can change both the tree level values of α and $m_{3/2}$. Indeed small values of $m_{3/2}$

have been employed in certain no-scale models of supergravity.[35] To satisfy eq. (13) we have therefore the following relation between α and $m_{3/2}$ [25]

$$\alpha\, m^3_{3/2} = 2.7 \times 10^{-2} \tag{16}$$

required for this type of decaying cold matter scenario.

To summarize, we have the benefits and deficiencies of decaying dark matter scenarios. Possibilities include both hot and cold scenarios with a radiation or matter dominated Universe today. Radiation dominated models make it difficult to produce very large scale structure and hot scenarios of this type begin to run into conflict with microwave background anisotropies.[27] Cold matter dominated models face a potential difficulty with too much mass on very large scale. Finally, although there is no convincing candidate for the decaying particle, its very long lifetime indicates a gravitational decay making the gravitino an interesting choice.

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