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GRAVITINOS AS THE COLD DARK MATTER IN AN $\Omega = 1$ UNIVERSE

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ABSTRACT

In attempts to simultaneously have galaxy formation with adiabatic fluctuations, dark galactic halos and a critical $\Omega = 1$, recent models have been proposed with a heavy (cold) species which decays and a lighter (hot or warm) one which is stable. Surprisingly enough, these models are very constraining. Independent of the particle physics model, the decay width of the heavy particle must be $O(10^{-40})$GeV. Such a scale is only natural in theories involving gravity where one expects $\Gamma \sim M_H^3/M_p^2$, where M_H is the mass of the heavy particle and M_p is the planck mass. In this paper, we suggest that the heavy particle might be the gravitino which is present in all supergravity theories. This model would then require that the gravitino decay products not include photons, indicating that the lightest supersymmetric particle (LSP) must be something other than the photino. An acceptable candidate for the LSP might be the axino, the supersymmetric partner of the axion.

Inflationary models[1] imply that we live in an $\Omega = 1$ Universe. ($\Omega = \rho/\rho_{crit}$, where ρ is the cosmological density and ρ_{crit} is the critical density.) Observational determinations of Ω indicate that the luminous parts of spiral galaxies contribute only a fraction[2] $\Omega = (2-6) \times 10^{-3}$. On larger scales, those of binaries and small groups of galaxies (which would include galactic halos), one finds[2] $\Omega = 0.05$ to 0.15. Even on the largest scales where determinations of Ω have been made one finds[2],[3] that Ω is probably no larger than a few tenths. In short, this represents a hierarchy of missing mass problems. If Ω is actually one, then a large fraction of the mass of the Universe is either totally or as yet unclustered.

In addition, the observation of quasars at redshift $z \gtrsim 3$ indicate condensed objects have formed by that epoch and yet the limits on the isotropy of the microwave background show that temperature variations $\delta T/T$ at decoupling ($z \sim 1000$) were[4] $\sim 6 \times 10^{-5}$. Assuming baryons are produced by Grand Unified interactions in the early Universe, then only adiabatic primordial density fluctuations are reasonable.[5] Therefore baryon density fluctuations are limited to be small at decoupling and only nonbaryonic matter with $\Omega \sim 1$ can have fluctuations grow rapidly enough.[6] (For $\Omega < 1$ density fluctuations stop growing at $z \sim 1/\Omega$.)

In the past, three types of scenarios have been proposed to attempt to solve the dark matter problems in galaxy formation.[7] They are the hot, warm and cold matter scenarios. Examples of hot particles are neutrinos[8] or very light photinos/Higgsinos[9]-[11] with $\lesssim 100$ eV masses. Warm particles are heavier and might have masses up to ~ 1 keV. Warm particle candidates might be superweakly interacting right-handed neutrinos.[12] Cold particles are those which have become non-relativistic before their relevance for galaxy formation. Any heavy particle such as a heavy neutrino[13] ($m \sim O(10)$ GeV) or massive photino/Higgsino,[14),11] sneutrinos[15] (i.e. a LSP with $m \gtrsim 1$ GeV) or axions[16], which are light but slow, are prime candidates. We will not here review these models but instead refer the reader to recent articles (ref. 17) which point out the deficiencies of each of the scenarios when taken alone. The hot enables large scale filaments, voids and $\Omega = 1$ but doesn't enable galaxy formation to occur rapidly enough, nor does it provide dark halos for low mass objects. The cold enables rapid galaxy formation and provides dark halos even for dwarf spheroidal galaxies but it puts all the dark matter on small scales where Ω is observed to be $\lesssim 0.3$.[3] Thus it does not allow $\Omega \sim 1$.

Indeed, if $\Omega \simeq 0.2$ for the Universe (as it might very well be) then the cold matter scenario almost works,[17] except for difficulties in perturbation growth.[6] However, if $\Omega = 1$, one faces the problem of how to uncluster material which is extremely good at clustering. A possible non-particle physics solution to this problem is to have the light not trace the mass and have light emission only occur in rare (3σ) events.[18] Models of this type might, in different ways, help either the hot or cold scenarios. The physics of these models however is very uncertain and implies the near irrelevance of observational astronomy.

On the particle physics side, another type of solution has emerged.[19)-21] There are two different guises for this approach. Both involve two species of dark matter, in which the heavier one is unstable. (The simple two component picture with one stable hot and one stable cold particle doesn't seem to work since the streaming of the hot particle damps the growth of the cold particle's density fluctuations[22].) In the first model proposed by Turner, Steigman and Krauss[19] and Gelmini, Schramm and Valle[20], the Universe is today dominated by the radiation produced by the decay. In this case, the Universe is somewhat too young ($t_u \sim 10^{10}$ yrs for a hubble constant $h_o = 0.5$) and there is no further growth of structure since the decay. The second model[21] by Olive, Seckel and Vishniac, is a modification of the first in which the Universe returns to a matter dominated epoch at a redshift of about 3. In this case, the Universe is slightly older ($t_u = 1.2 \times 10^{10}$ yrs for $h_o = 0.5$) and there is growth of structure on very large scales today. Although in refs. 19 and 20, the model was not constructed to be a cold matter scenario, it can easily be adapted to one as we will see below.

In this paper we will describe a supersymmetric model which fits these scenarios. We will in particular discuss the scenario of ref. 21. We will then show that by relaxing certain conditions we arrive at the scenario described in refs. 19 and 20. Finally we will note that this model actually relaxes certain constraints on the reheating of inflationary models.

As we have indicated, the model will consist of (at least) two particle species, H and L. H is unstable and decays into lighter particles, excluding photons, which we take to include L. There will thus be two seas of L particles: the primordial ones and those produced by the decays of H. The mass density of primordial L's will be

$$\rho_L = (3/4)M_L\, n_\gamma(T_L/T_o)^3(g_L/2) \tag{1}$$

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[23], and g_L is the number of degrees of freedom for L. The fraction of critical density $\rho_c = 1.88 \times 10^{-29}\ h_o^2$ g cm^{-3} contributed by primordial L's is

$$\Omega_L = \rho_L/\rho_c \simeq 0.1(g_L/2)M_L(\mathrm{eV})h_o^{-2}(T_o/2.7)^3/N(T^*) \tag{2}$$

where $N(T^*) = 3.9(T_o/T_L)^3$ is the number of interacting degrees of freedom at T^*.

The fraction of Ω which is made up of the decay products of H is similarly expressed as

$$\Omega_D = \rho_D/\rho_c \simeq M_H n_\gamma Y(T_o/T_D)/\rho_c \tag{3}$$

where Y is the abundance of H's relative to photons before their decay at T_D. If H were a heavy neutrino (as in refs. 19 and 20), then Y would be known: $Y = (3/4)(T_\nu/T_o)^3 = 3/11$; ($N(T_\nu^*) = 10.7$). However, since we have in mind that H is the gravitino, it will have decoupled at the planck epoch, i.e. before inflation. The number density of gravitinos would then be drastically reduced during inflation and their final abundance would be determined by the temperature to which the Universe reheated,[24),25),11),29] T_R. We will return to this point later, but keep in mind that $Y \ll 1$ is certainly possible. We can rewrite eq. 3 as

$$\Omega_D \simeq 8 \times 10^{-6} \, (M_H Y/T_D) h_o^{-2} (T_o/2.7)^4 \tag{4}$$

In addition to the heavy and light particles we must include the contributions coming from baryons. From Big Bang Nucleosynthesis we have that[26)]

$$0.01 \lesssim \Omega_b h_o^2 \lesssim 0.05 \tag{5}$$

If we neglect the contribution from relativistic particles other than decay products (i.e. photons and massless neutrinos)

$$\Omega = \Omega_D + \Omega_L + \Omega_b + \Omega_o = 1 \tag{6}$$

where Ω_o contains any other non-relativistic species present (i.e. massive neutrinos). We will refer to $\Omega_{NR} = \Omega_L + \Omega_b + \Omega_o$ as the total non-relativistic contributions. The first model[21)] we will look at will have $\Omega_D = 0.2$ and $\Omega_{NR} = 0.8$. The radiation dominated model[19),20)] will have $\Omega_D = 0.8$ and $\Omega_{NR} = 0.2$.

The basic scenario is then as follows. The Universe becomes matter dominated at T_{MD} by the heavy particles. It remains matter dominated until T_D, the temperature at which they decay. The ratio T_{MD}/T_D is basically determined by $\Omega_D h_o^2$,

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

where $N(T_{MD}) = 2 - 3.4$ is the number of degrees of freedom at T_{MD} and depends on the number of massless neutrinos. For no massless neutrinos $N(T_{MD}) = 2$ while for 3 massless neutrinos $N(T_{MD}) = 3.4$.

During this first matter dominated epoch, i.e. between T_{MD} and T_D, density perturbations begin to grow linearly. From the constraints coming from the quadropole moment on the isotropy of the microwave background radiation[4] $\delta T/T < 6 \times 10^{-5}$ implies that the initial magnitude of density perturbations must be[21] $\delta\rho/\rho \lesssim 1.2 \times 10^{-4}$.† The only structures to survive after T_D will be those on scales which have gone non-linear ($\delta\rho/\rho \gtrsim 1$) before decay. The largest scale to have gone non-linear before T_D was found to be[21]

$$\lambda_{NL} = B\ \lambda_{MD} \tag{8a}$$

$$\lambda_{MD} \simeq 7.5(T_o/T_D)[N(T_{MD})]^{1/2}(T_o/2.7)^2/\Omega_D h_o^2 \text{ Mpc} \tag{8b}$$

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. 21). λ_{NL} must be set to agree with determinations from the two-point galaxy correlation function,[27] λ_{NL} = 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

$$M_{NL} = \Omega_{NR}\rho_c\lambda_{NL}^3 = 3.3 \times 10^{13}\Omega_{NR}/h_o \ \ M_\odot \tag{9}$$

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

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†The models discussed here are only consistent if $\delta\rho/\rho > 2.5 \times 10^{-5}$.

The decay of the heavy particles will temporarily inhibit any further growth of structure. In addition, it will disperse a large fraction of the lighter particles which had clustered on scales below λ_{NL}. The baryons will not be dispersed as they will have already begun dissipative processes leading to disk and star formation. The fraction of light material to be left behind is approximately[21] between $(T_E/(T_E + 1.1\ T_D))^2$ and $2\Omega_B$ where T_E is the temperature at which the Universe is once again matter dominated,

$$\left(\frac{T_E}{T_o}\right) = \frac{\Omega_{NR}}{\Omega_D} \tag{10}$$

That part which is left behind can make the dark halos of galaxies.

Between T_D and T_E the Universe is radiation dominated and large scale perturbations are damped by the free streaming light particles released by the decay. For $T < T_E$, perturbations will begin to grow again. The next scale to go non-linear, will be the free-streaming scale λ_{fs} of the lighter particles and[21]

$$\lambda_{fs} \sim O(1)\lambda_{MD} \tag{11}$$

Today the perturbations on that scale will be $\delta\rho/\rho \sim (1/2)(1+T_E/T_o)$. Evidence for clustering on such large scales may be present in the cluster-cluster correlation functions[28] and in the largest superclusters and supervoids.

Once we require that $\lambda_{NL} > 10$ Mpc (or any other suitable value), the model will be determined by the choice of $\Omega_{NR}(\Omega_D)$. In Figure 1, we plot the results for T_D as a function of Ω_{NR} with $h_o = 0.5$ and

λ_{NL} = 10 Mpc. The cosmological scenarios are very different along the curve, with the most obvious difference being the change from a radiation to a matter dominated Universe today.

Let us now see what values we get for the parameters for the choices Ω_D = 0.2 and Ω_{NR} = 0.8. From eq. 4, we see that independent of the particle physics, the quantity $M_H Y/T_D$ is fixed,

$$M_H Y/T_D \simeq 6 \times 10^3 \tag{12}$$

For these parameters and $N(T_{MD})$ = 3.36, we have[21] $B \simeq 0.5$

$$\lambda_{NL} \simeq 140(T_o/T_D)\ \mathrm{Mpc} \tag{13}$$

and requiring $\lambda_{NL} > 10$ Mpc implies that

$$(T_D/T_o) < 14 \tag{14}$$

This corresponds to a structure with baryonic mass

$$M_b = (\Omega_b/\Omega_{NR})M_{NL} \gtrsim 3 \times 10^{12}\ M_\odot \tag{15}$$

for Ω_b = .05 and is certainly large enough to encompass small groups of galaxies.

By fixing T_D, the correlation function has thus also fixed the decay rate Γ_D for the heavy particle. Since the Universe is matter dominated at T_D, Γ_D is given by (for $T_D = 14T_o$)

$$\Gamma_D = (3/2)H \simeq 2.5(M_H Y T_D^3/M_p^2)^{1/2} \lesssim 1.8 \times 10^{-40}\,\mathrm{GeV} \qquad (16)$$

and the combination

$$M_H Y \lesssim 2 \times 10^{-8}\,\mathrm{GeV} \qquad (17)$$

The chronology of the model is now complete. At $T_{MD} \sim 6$ eV the Universe becomes matter dominated and the primary growth of perturbations occur. The heavy particles decay at $T_D \simeq 3.3 \times 10^{-3}$ eV and the Universe is briefly radiation dominated until $T_E \simeq 10^{-3}$ eV. Because of the decay most of the clustered material begins to free stream leaving only a fraction, 15%, of the non-baryonic, non-relativistic material behind or a contribution $\Omega \sim 0.1$ (in addition to $\Omega_b = 0.05$) to form galactic halos. The remaining light matter free streams out to a distance λ_{fs} where structure again is beginning to form. Note that on this scale we would expect that $\Omega = 0.8$. This prediction is in contrast to the model making galaxies from 3σ fluctuations.[18)]

The very small decay rate of the heavy particles given in eq. (16) suggests that it is unstable only due to gravitational effects. A perfect candidate is the spin 3/2 massive gravitino of N = 1 supergravity, which decays to lighter particles at a rate[29)]

$$\Gamma_{3/2} \simeq \frac{m_{3/2}^3}{2\pi M^2} \qquad (18)$$

assuming that there is only one channel for the decay; $m_{3/2}$ is the gravitino mass and $M = 1/\sqrt{8\pi G_{NEWTON}} = 2.4 \times 10^{18}\,\mathrm{GeV}$. Models of particle physics invoking N = 1 supergravity are currently popular.[30] In these models, weak interaction symmetry breaking is triggered by gravitational effects, and the W and Z boson masses (as well as those of the as yet unobserved superpartners of ordinary particles) come out to be of the same order as the gravitino mass. Thus we expect $m_{3/2}$ to be a few tens of GeV. This cannot be taken too seriously, however. The gravitino mass and the superpartner masses are subject to different, cutoff dependent, gravitational radiative corrections.[31] Different values of the cutoff could significantly alter the tree level mass relationships among the gravitinos and the other superpartners. Furthermore, models have been proposed[32] in which even the tree level connection is absent. For similar reasons, we cannot trust the tree level relation of eq. (18); instead we will write

$$\Gamma_{3/2} = \frac{\alpha m_{3/2}^{3}}{M^{2}} \tag{19}$$

and treat α as a free parameter.

The gravitino can decay into any pair of superpartners, unless the decay is kinematically forbidden. For our purposes, we want one of the decay products to have a mass of order ~eV to ~100 eV, and the other to be massless, or at least have a mass much less than a few eV. No photons should be produced. The only plausible candidate for such a superpartner pair are a Goldstone boson and its fermion partner. For concreteness, we will take the decay products to be the axion, axino pair. The mass of the axino will be determined (astrophysically) by eq. 2 and the masses of any other light particles such as neutrinos. This appears to fit a (theoretically) estimated range of 3 - 300 eV for the axino mass.[33]

If we now use the form eq. (19) for the decay rate of the gravitino, we find a relation between α and $m_{3/2}$,

$$\alpha\, m^3_{3/2} = 1.1 \times 10^{-3}\ \mathrm{GeV}^3. \tag{20}$$

Thus for the tree level choice $\alpha = 1/2\pi$, $m_{3/2} \simeq 200$ MeV which is somewhat low. On the other hand, $m_{3/2} \simeq 20$ GeV require $\alpha \simeq 1.5 \times 10^{-7}$. Figure 2 shows the possible choices for α and $m_{3/2}$. Again, we emphasize that the tree level values cannot be trusted due to possibly large gravitational radiative corrections.

Let us now see what happens to all of these parameters when we relax the model to that of the scenario in refs. 19 and 20. Recall in that scenario the Universe today is radiation dominated and there is no large scale growth occurring today. If we now choose $\Omega_D = 0.8$ and $\Omega_{NR} = 0.2$, we have

$$M_H Y/T_D \simeq 2.5 \times 10^4. \tag{21}$$

In this case the largest scale to go non-linear is somewhat different ($B \simeq 1.5$)

$$\lambda_{NL} \approx 100\ (T_o/T_D)\ \mathrm{Mpc} \tag{22}$$

and by requiring $\lambda_{NL} > 10$ Mpc we have

$$(T_D/T_o) \lesssim 10\ . \tag{23}$$

The decay rate is now found to be identical to (16)

$$\Gamma_D \lesssim 1.8 \times 10^{-40} \text{ GeV} \tag{24}$$

and

$$M_H Y \lesssim 5.8 \times 10^{-8} \text{ GeV} \tag{25}$$

In refs. 19 and 20, H was taken to be a neutrino, hence $Y = 3/11$ and the required mass $M_H \sim 200$ eV. For H a gravitino, we have the same relation between α and $m_{3/2}$ (eq. 20).

As we said earlier, this scenario also removes the constraints on the reheating temperature in inflationary models. Without inflation, the abundance of gravitinos today would be

$$Y_{3/2} = 3.9/N(T^{*}_{3/2}) \sim 10^{-2} \tag{26}$$

in which case their decay would create too large an energy density (if $Y_{3/2} \gtrsim 10^{-8}$).[34),25),24),11),29)] It was also recently pointed out that radiative decays would destroy too much deuterium and spoil the agreement between observations and Big Bang Nucleosynthesis calculations (if $Y > 10^{-11}$).[35)]

However, a period of inflation could remedy this situation.[24)] In inflationary models, the abundance of gravitinos is driven very low and Y is determined by the temperature which the Universe reheates to,[25),24),11),29)]

$$Y \approx 10^{-1}\ T_R/M_p. \tag{27}$$

Thus, the above constraints on Y translate in to upper limits on the reheating temperature after inflation. For example, the constraint from the deuterium abundance[35)] implies that $T_R \lesssim 2 \times 10^{+9}$GeV. We note, however, that in some models of inflation in N = 1 supergravity, T_R is naturally low $T_R \sim 10^6 - 10^{10}$ GeV.[36)]

In the present model, all of these constraints on T_R disappear. If the photino is heavier than the gravitino, there are no photons produced in the decay, and the deuterium limit goes away. The other limits go away as well if the LSP is light (i.e. the axino). In this case, the limit on T_R is eased. However, it is not arbitrary in this model but rather is determined by eqs. 17 and 19. Hence we have a relation between $Y(T_R)$ and α

$$Y \lesssim 2 \times 10^{-7}\ \alpha^{1/3} \tag{28}$$

or

$$T_R \lesssim 2 \times 10^{13}\ \alpha^{1/3}\text{GeV}. \tag{29}$$

Finally, we would like to point out that gravitinos are not the unique candidate for H in supersymmetric theories. For example any particle which is only gravitationally coupled to ordinary matter is a possibility. In particular, theories in which a hidden sector breaks supersymmetry involve scalar fields which could fit the description of the H particle. We stress again that the very small decay rate needed in these scenarios naturally picks out gravitational interactions and hence supersymmetry becomes a prime candidate for helping explain the dark matter problems on all scales.

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Figure Captions

Figure 1: The decay temperature as a function of Ω_{NR} for λ_{NL} = 10 Mpc. The cross represents the maximum value of Ω_{NR} with $T_E < T_D$.

Figure 2: Possible values for α and $m_{3/2}$.

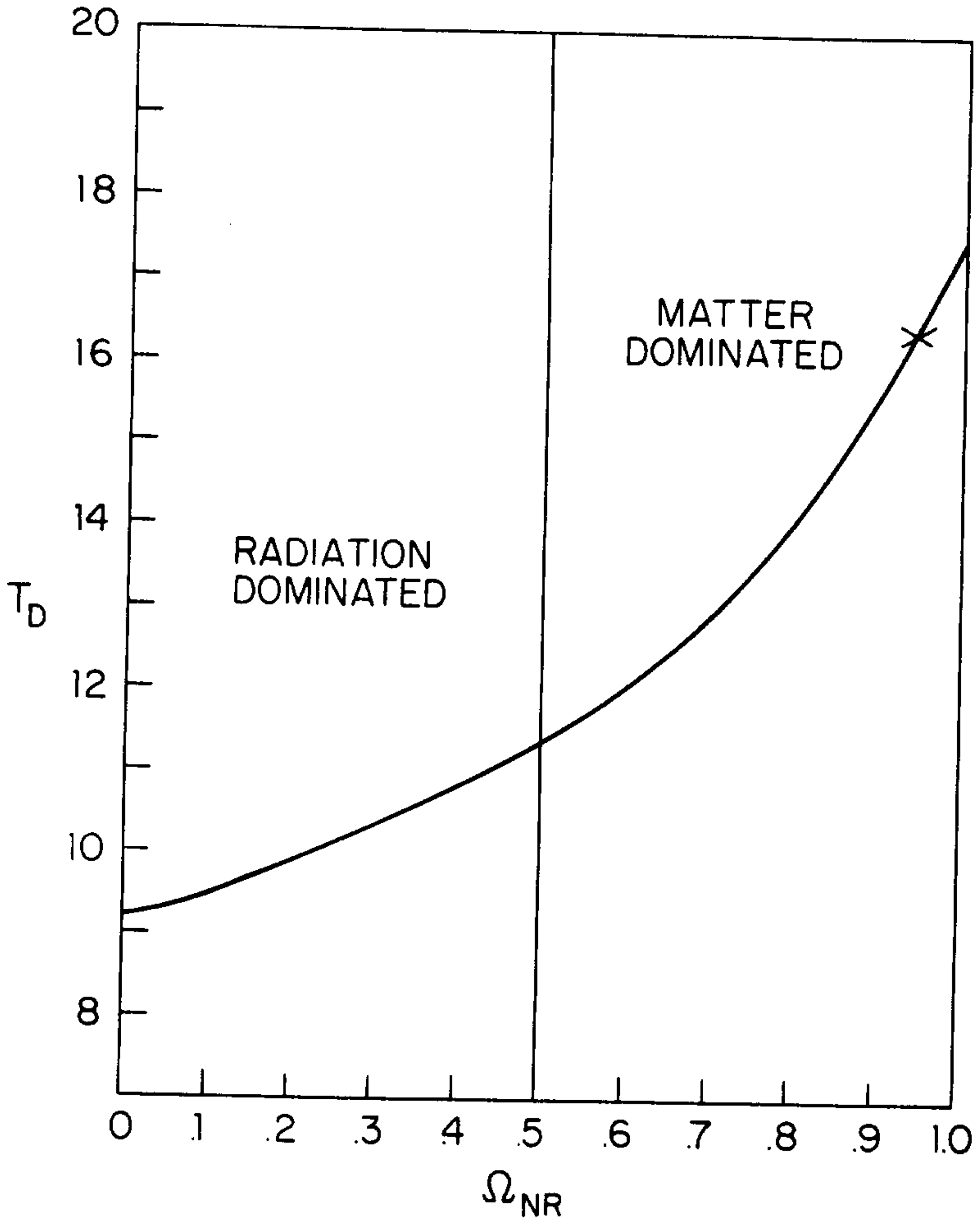
20
18
16
14
12
10
8
T_D
RADIATION DOMINATED
MATTER DOMINATED
0
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
Ω_{NR}

FIGURE 1

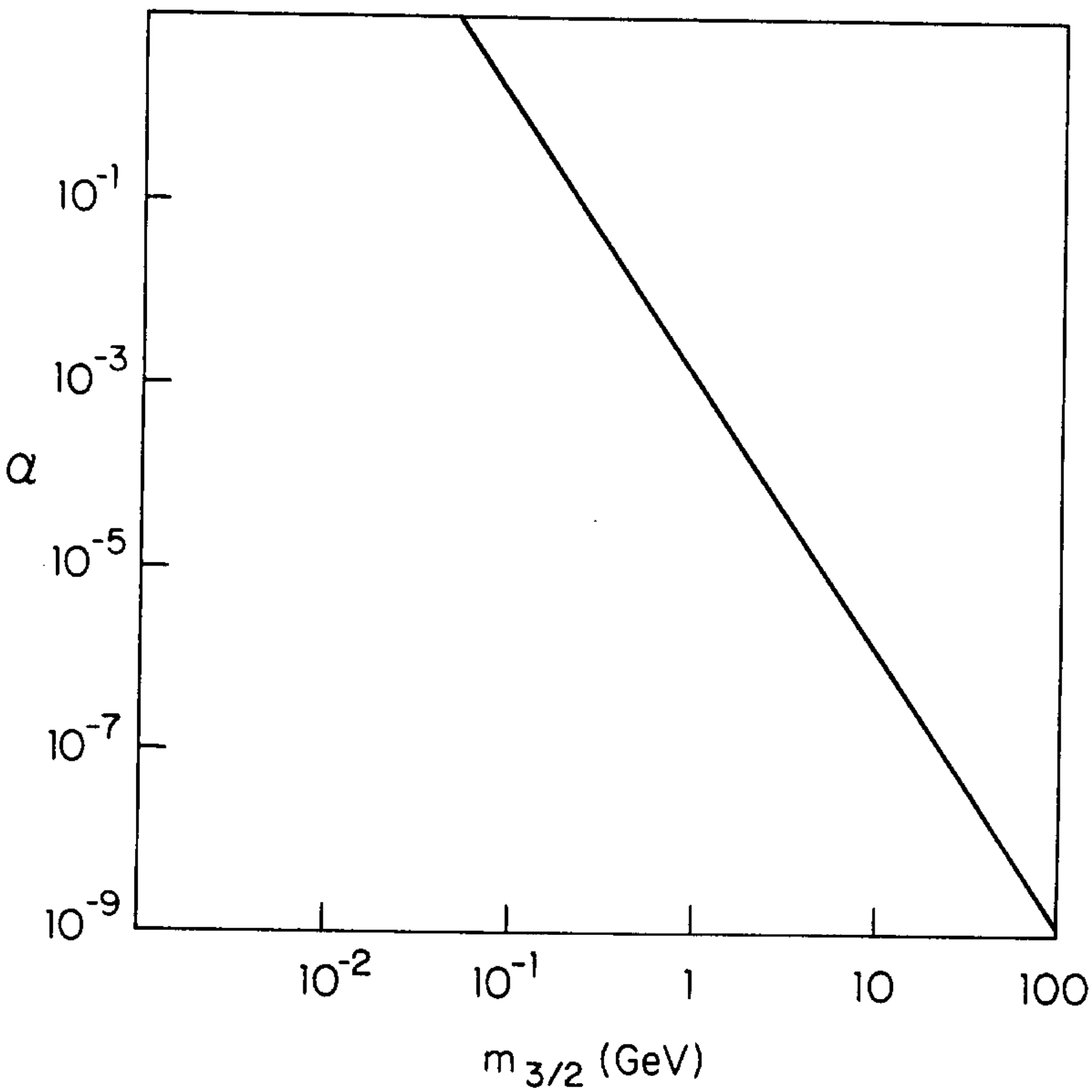

FIGURE 2