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PRIMORDIAL NUCLEOSYNTHESIS WITH A DECAYING TAU NEUTRINO

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ABSTRACT

A comprehensive study of the effect of an unstable tau neutrino on primordial nucleosynthesis is presented. The standard code for nucleosynthesis is modified to allow for a massive decaying tau neutrino whose daughter products include neutrinos, photons, $e^{\pm}$ pairs, and/or noninteracting (sterile) daughter products. Tau-neutrino decays influence primordial nucleosynthesis in three distinct ways: (i) the energy density of the decaying tau neutrino and its daughter products affect the expansion rate tending to increase ^{4}He, D, and ^{3}He production; (ii) electromagnetic (EM) decay products heat the EM plasma and dilute the baryon-to-photon ratio tending to decrease ^{4}He production and increase D and ^{3}He production; and (iii) electron neutrinos and antineutrinos produced by tau-neutrino decays increase the weak rates that govern the neutron-to-proton ratio, leading to decreased ^{4}He production for short lifetimes ($\lesssim 30\,$sec) and masses less than about 10 MeV and increased ^{4}He production for long lifetimes or large masses. The precise effect of a decaying tau neutrino on the yields of primordial nucleosynthesis and the mass-lifetime limits that follow depend crucially upon decay mode. We identify four generic decay modes that serve to bracket the wider range of possibilities: tau neutrino decays to (1) sterile daughter products (e.g., $\nu_\tau \rightarrow \nu_\mu + \phi$;

1 Introduction

Primordial nucleosynthesis is one of the cornerstones of the hot big-bang cosmology. The agreement between the predictions for the abundances of D, ^{3}He, ^{4}He and ^{7}Li and their inferred primordial abundances provides the big-bang cosmology's earliest, and perhaps most, stringent test. Further, big-bang nucleosynthesis has been used to provide the best determination of the baryon density [1, 2] and to provide crucial tests of particle-physics theories, e.g., the stringent bound to the number of light neutrino species [3, 4].

Over the years various aspects of the effect of a decaying tau neutrino on primordial nucleosynthesis have been considered [5, 6, 7, 8, 9, 10, 11, 12]. Each previous study focused on a specific decay mode and incorporated different microphysics. To be sure, no one study was complete or exhaustive. Our purpose here is to consider all the effects of a decaying tau neutrino on nucleosynthesis in an comprehensive and coherent manner. In particular, for the first time interactions of decay-produced electron neutrinos and antineutrinos, which can be important for lifetimes shorter than 100 sec or so, are taken into account.

The nucleosynthesis limits to the mass of an unstable tau neutrino are currently of great interest as the best laboratory upper mass limits [13], 31 MeV by the ARGUS Collaboration and 32.6 MeV by the CLEO Collaboration,[1] are tantalizingly close to the mass range excluded by nucleosynthesis, approximately 0.4 MeV to 30 MeV for lifetimes greater than about 300 sec. If the upper range of the cosmologically excluded band can be convincingly shown to be greater than the upper bound to the mass from laboratory experiments, the two bounds together imply that a long-lived tau-neutrino must be less massive than about 0.4 MeV. This was the major motivation for our study.

The effects of a massive, decaying tau neutrino on primordial nucleosynthesis fall into three broad categories: (i) the energy density of the tau neutrino and its daughter product(s) increase the expansion rate, tending to increase ^{4}He, D, and ^{3}He production; (ii) the electromagnetic (EM) plasma is heated by the daughter product(s) that interact electromagnetically (photons and $e^\pm$ pairs), diluting the baryon-to-photon ratio and decreasing ^{4}He production and increasing D and ^{3}He production; and (iii) electron neutrino

[1] Both are 95% C.L. mass limits based upon end-point analyses of tau decays to final states containing five pions. The CLEO data set contains 113 such decays and the ARGUS data set contains 20 such decays [13].

While these four generic decay modes serve to bracket the possibilities, the situation is actually somewhat more complicated. Muon neutrinos are not completely sterile, as they are strongly coupled to the electromagnetic plasma down to temperatures of order a few MeV (times of order a fraction of a second), and thus can transfer energy to the electromagnetic plasma. However, for lifetimes longer than a few seconds, their interactions with the electromagnetic plasma are not very significant (see Ref. [15]), and so to a reasonable approximation muon-neutrino daughter products can be considered sterile. Precisely how much electromagnetic entropy is produced and the effect of high-energy neutrinos on the proton-neutron interconversion rates depend upon the energy distribution of the daughter products and their interactions with the ambient plasma (photons, $e^{\pm}$ pairs, and neutrinos), which in turn depends upon the number of daughter products and the decay matrix element.

Without going to extremes, one can easily identify more than ten possible decay modes. However, we believe the four generic decay modes serve well to illustrate how the nucleosynthesis mass-lifetime limits depend upon the decay mode and provide reasonable estimates thereof. In that regard, input assumptions, e.g., the acceptable range for the primordial abundances and the relic neutrino abundance[2] probably lead to comparable, if not greater, uncertainties in the precise limits.

Finally, a brief summary of our treatment of the microphysics: (1) The relic abundance of the tau neutrino is determined by standard electroweak annihilations and is assumed to be frozen out at its asymptotic value during the epoch of nucleosynthesis, thereafter decreasing due to decays only. Because we assume that the relic abundance of the tau neutrino has frozen out we cannot accurately treat the case of short lifetimes, $\tau_\nu \lesssim (m_\nu/\,\mathrm{MeV})^{-2}$ sec, where inverse decays can significantly affect the tau-neutrino abundance and that of its daughter products [16].[3] (2) Sterile daughter products, other than neutrinos, are assumed to have a negligible pre-decay abundance (if this is not true, the nucleosynthesis limits become even more stringent). (3) The electromagnetic energy produced by tau-neutrino decays is assumed to

[2]The variation between different calculations of the tau-neutrino abundance are of the order of 10% to 20%; they arise to different treatments of thermal averaging, particle statistics, and so on. Since we use the asymptotic value of the tau-neutrino abundance our abundances are in general smaller, making our limits more conservative.

[3]For generic decay mode (1) the effect of inverse decays for short lifetimes was considered in Ref. [12]; it leads to additional mass constraints for short lifetimes.

scale factor). They are: ρ_{ν_τ}, ρ_ϕ (where ϕ is any sterile, relativistic decay product), T_γ, and Δ_e and Δ_μ, the perturbations to the electron-neutrino and mu-neutrino phase-space distributions.

Our calculations were done with two separate codes. The first code tracks ρ_{ν_τ}, ρ_ϕ, T_γ, Δ_e, and Δ_μ as a function of T, for simplicity, using Boltzmann statistics. These five quantities were then converted to functions of the photon temperature using the $T(T_\gamma)$ relationship calculated, and their values were then passed to the second code, a modified version of the standard nucleosynthesis code [17].[4] We now discuss in more detail the four modifications.

2.1 Energy density

There are four contributions to the energy density: massive tau neutrinos, sterile decay products, two massless neutrino species, and the EM plasma. Let us consider each in turn.

As mentioned earlier, we fix the relic abundance of tau neutrinos assuming that freeze out occurs before nucleosynthesis commences ($t \ll 1\,\text{sec}$). We follow Ref. [10] in writing

$$\rho_{\nu_\tau} = r\left[\frac{\sqrt{(3.151T)^2 + m_\nu{}^2}}{3.151T}\right]\rho_\nu(m_\nu = 0)\,\exp(-t/\tau_\nu), \tag{1}$$

where r is the ratio of the number density of massive neutrinos to a massless neutrino species, the $(3.151T)^2$ term takes account of the kinetic energy of the neutrino, and the exponential factor takes account of decays. The relic abundance is taken from Ref. [10]; for a Dirac neutrino it is assumed that all four degrees are freedom are populated for masses greater than $0.3\,\text{MeV}$ (see Ref. [10] for further discussion).

Note that for temperatures much less than the mass of the tau neutrino, $\rho_{\nu_\tau}/\rho_\nu(m_\nu = 0) = rm_\nu e^{-t/\tau_\nu}/3.151T$, which increases as the scale factor until the tau neutrinos decay; further, rm_ν determines the energy density contributed by massive tau neutrinos and hence essentially all of their effects on nucleosynthesis. The relic neutrino abundance times mass (rm_ν) is shown in Fig. 1.

[4]The correct statistics for all species are of course used in the nucleosynthesis code; the five quantities are passed as fractional changes (to the energy density, temperature and rates) to minimize the error made by using Boltzmann statistics in the first code.

where in our case $\rho_{\rm TOT} = \rho_{\rm EM} + \rho_{\nu 0} + \delta\rho_\nu + \rho_\phi + \rho_{\nu_\tau}$, $p_{\rm TOT} = p_{EM} + p_{\nu 0} + \delta p_\nu + p_\phi + p_{\nu_\tau}$, $\delta p_\nu = \delta\rho_\nu/3$, $p_\phi = \rho_\phi/3$, and

$$p_{\rm EM} = \frac{2T_\gamma^4}{\pi^2} + \frac{2m_e^2T_\gamma^2}{\pi^2}\, K_2(m_e/T_\gamma). \tag{7}$$

Eq. (6) can be rewritten in a more useful form,

$$\frac{dT_\gamma}{dt} = \frac{-3H\left(\rho_{\rm TOT} + p_{\rm TOT} - 4\rho_{\nu 0}/3\right) - d(\delta\rho_\nu + \rho_\phi + \rho_{\nu_\tau})/dt}{d\rho_{\rm EM}/dT_\gamma}. \tag{8}$$

The quantity $d\rho_{\rm EM}/dT_\gamma$ is easily calculated, and the time derivatives of the densities can either be solved for analytically, or taken from the previous time step.

2.3 Neutrino phase-space distribution functions

The Boltzmann equations governing the neutrino phase-space distribution functions in the standard case were derived and solved in Ref. [15]. We briefly summarize that treatment here, focusing on the modifications required to include massive tau-neutrino decays.

We start with the Boltzmann equation for the phase-space distribution of neutrino species a in the absence of decays:

$$\begin{aligned}\frac{\partial f_a}{\partial t} - \frac{H|p|^2}{E_a}\frac{\partial f_a}{\partial E} &= -\frac{1}{2E_a}\sum_{\rm processes}\int d\Pi_1 d\Pi_2 d\Pi_3 (2\pi)^4\delta^4(p_a + p_1 - p_2 - p_3)\\ &\times\ |\mathcal{M}_{a+1\leftrightarrow 2+3}|^2[f_a f_1 - f_2 f_3],\end{aligned} \tag{9}$$

where the processes summed over include all the standard electroweak $2 \leftrightarrow 2$ interactions of neutrinos with themselves and the electromagnetic plasma, and Boltzmann statistics have been used throughout.

We write the distribution functions for the electron and muon neutrinos as an unperturbed part plus a small perturbation:

$$f_i(p,t) = \exp(-p/T) + \Delta_i(p,t), \tag{10}$$

where we have assumed that both species are effectively massless. During nucleosynthesis the photon temperature begins to deviate from the neutrino temperature T, and we define

$$\delta(t) = T_\gamma/T - 1.$$

conversion (per nucleon) are respectively

$$\delta\lambda_{pn} = \frac{1}{\lambda_0\tau_n}\int_{m_e}^{\infty} EdE(E^2-m_e^2)^{1/2}(E+Q)^2\Delta_e(E+Q), \tag{14}$$

$$\delta\lambda_{np} = \frac{1}{\lambda_0\tau_n}\int_{m_e}^{\infty} EdE(E^2-m_e^2)^{1/2}(E-Q)^2\Delta_e(E-Q), \tag{15}$$

where Boltzmann statistics have been used for all species, τ_n is the neutron mean lifetime, $Q = 1.293\,\mathrm{MeV}$ is the neutron-proton mass difference, and

$$\lambda_0 \equiv \int_{m_e}^{Q} EdE(E^2-m_e^2)^{1/2}(E-Q)^2.$$

The perturbations to the weak rates are computed in the first code and passed to the nucleosynthesis code by means of a look-up table. The unperturbed part of the weak rates are computed by numerical integration in the nucleosynthesis code; for all calculations we took the neutron mean lifetime to be 889 sec.

3 Results

In this section we present our results for the four generic decay modes. Mode by mode we discuss how the light-element abundances depend upon the mass and lifetime of the tau neutrino and derive mass/lifetime limits. We exclude a mass and lifetime if, for no value of the baryon-to-photon ratio, the light-element abundances can satisfy:

$$Y_P \le 0.24; \tag{16}$$

$$\mathrm{D/H} \ge 10^{-5}; \tag{17}$$

$$(\mathrm{D} + {}^3\mathrm{He})/\mathrm{H} \le 10^{-4}; \tag{18}$$

$$\mathrm{Li/H} \le 1.4\times 10^{-10}. \tag{19}$$

For further discussion of this choice of constraints to the light-element abundances we refer the reader to Ref. [2].

The ^{4}He and D + ^{3}He abundances play the most important role in determining the excluded regions. The mass/lifetime limits that follow necessarily depend upon the range of acceptable primordial abundances that one adopts, a fact that should be kept in mind when comparing the work of different authors and assessing confidence levels. Further, the relic abundances used by the massive tau neutrino exceeds that of a massless neutrino species before it decays, in spite of its smaller abundance (i.e., $r \ll 1$). The higher energy density increases the expansion rate and ultimately ^{4}He production because it causes the neutron-to-proton ratio to freeze out earlier and at a higher value and because fewer neutrons decay before nucleosynthesis begins. Since the neutron-to-proton ratio freezes out around 1 sec and nucleosynthesis occurs at around a few hundred seconds, the ^{4}He abundance is only sensitive to the expansion rate between one and a few hundred seconds.

In Fig. 2 we see that for short lifetimes ($\tau_\nu \ll 1\,\mathrm{sec}$) the ^{4}He mass fraction approaches that for two massless neutrinos (tau neutrinos decay before their energy density becomes significant). As expected, the ^{4}He mass fraction increases with lifetime leveling off at a few hundred seconds at a value that is significantly greater than that for three massless neutrino species.

The yields of D and ^{3}He depend upon how much of these isotopes are not burnt to ^{4}He. This in turn depends upon competition between the expansion rate and nuclear reaction rates: Faster expansion results in more unburnt D and ^{3}He. Thus the yields of D and ^{3}He increase with tau-neutrino lifetime, and begin to level off for lifetimes of a few hundred seconds as this is when nucleosynthesis is taking place (see Fig. 3).

The effect on the yield of ^{7}Li is a bit more complicated. Lithium production decreases with increasing η for $\eta \lesssim 3\times10^{-10}$ because the final abundance is determined by competition between the expansion rate and nuclear processes that destroy ^{7}Li, and increases with increasing η for $\eta \gtrsim 3\times10^{-10}$ because the final abundance is determined by competition between the expansion rate and nuclear processes that produce ^{7}Li. Thus, an increase in expansion rate leads to increased ^{7}Li production for $\eta \lesssim 3\times10^{-10}$ and decreased ^{7}Li production for $\eta \gtrsim 3\times10^{-10}$; this is shown in Fig. 4. Put another way the valley in the ^{7}Li production curve shifts to larger η with increasing tau-neutrino lifetime.

We show in Figs. 5 and 6 the excluded region of the mass/lifetime plane for a Dirac and Majorana tau neutrino respectively. As expected, the excluded mass range grows with lifetime, asymptotically approaching 0.3 MeV to 33 MeV (Dirac) and 0.4 MeV to 30 MeV (Majorana). We note the significant dependence of the excluded region on lifetime; our results are in good agreement with the one other work where comparison is straightforward [10], and in general agreement with Refs. [7, 12].

Fig. 7. As can be seen in the figure or from Eq. (20), entropy production becomes significant for lifetimes longer than about 100 sec.

3.3 $\nu_\tau \to \nu_e$ + sterile daughter products

Once again, by our definition of sterility this includes decay modes such as $\nu_\tau \to \nu_e + \phi$ or $\nu_\tau \to \nu_e + \nu_\mu \bar{\nu}_\mu$. Here, we specifically considered the two-body decay mode $\nu_\tau \to \nu_e + \phi$, though the results for the three-body mode are very similar.

Two effects come into play: the energy density of the massive tau neutrino and its daughter products and the interaction of daughter electron neutrinos with the nucleons and the ambient plasma. The first effect has been discussed previously. The second effect leads to some interesting new effects.

Electron neutrinos and antineutrinos produced by tau-neutrino decays increase the weak rates that govern the neutron-to-proton ratio. For short lifetimes ($\lesssim 30$ sec) and masses less than about 10 MeV the main effect is to delay slightly the "freeze out" of the neutron-to-proton ratio, thereby decreasing the neutron fraction at the time of nucleosynthesis and ultimately ^{4}He production. For long lifetimes, or short lifetimes and large masses, the perturbations to the $n \to p$ and $p \to n$ rates (per nucleon) are comparable; since after freeze out of the neutron-to-proton ratio there are about six times as many protons as neutrons, this has the effect of increasing the neutron fraction and ^{4}He production. This is illustrated in Fig. 8. The slight shift in the neutron fraction does not affect the other light-element abundances significantly.

The excluded portion of the mass/lifetime plane is shown in Figs. 5 and 6. It agrees qualitatively with the results of Ref. [8].[6] Comparing the limits for this decay mode with the all-sterile mode, the effects of electron-neutrino daughter products are clear: for long lifetimes much higher mass tau neutrinos are excluded and for short lifetimes low-mass tau neutrinos are allowed.

[6]The authors of Ref. [8] use a less stringent constraint to ^{4}He production, $Y_P \leq 0.26$; in spite of this, in some regions of the $m_\nu - \tau_\nu$ plane their bounds are as, or even more, stringent. This is presumably due to the neglect of electron-neutrino interactions with the ambient plasma.

for lifetimes greater than about 100 sec the limit to rm should be relatively insensitive to particle mass.

We show in Fig. 11 the excluded regions of the rm-τ plane for a 20 MeV decaying particle. In deriving these limits we used the same criteria for acceptable light-element abundances and assumed three massless neutrino species. The limits to rm for decay modes without electron-neutrino daughter products are strictly independent of mass; the two other should be relatively insensitive to the particle mass for $\tau \gtrsim 100$ sec (and the actual limits are more stringent for $m > 20$ MeV).

4 Laboratory and Other Limits

There are a host of other constraints to the mass and lifetime of the tau neutrino [20]. As a general rule, cosmological arguments, such as the one presented above, pose *upper* limits to the tau-neutrino lifetime for a given mass: cosmology has nothing to say about a particle that decays very early since it would not have affected the "known cosmological history." Laboratory experiments on the other hand pose *lower* limits to the lifetime because nothing happens inside a detector if the lifetime of the decaying particle is too long. Finally, astrophysical considerations generally rule out bands of lifetime since "signals" can only be detected if (a) the tau neutrinos escape the object of interest before decaying and (b) decay before they pass by earthly detectors.

4.1 Laboratory

The most important limits of course are the direct limits to the tau-neutrino mass. These have come down steadily over the past few years. The current upper limits are 31 MeV and 32.6 MeV [13].

If the tau neutrino has a mass greater than $2m_e = 1.02$ MeV, then the decay $\nu_\tau \to \nu_e + e^\pm$ takes place through ordinary electroweak interactions at a rate

$$\Gamma = \frac{G_F^2 m_\nu^5}{192\pi^3}|U_{e\tau}|^2|U_{ee}|^2 \simeq \frac{(m_\nu/\,\mathrm{MeV})^5|U_{e\tau}|^2}{2.9\times10^4\ \mathrm{sec}}, \qquad (21)$$

where $U_{e\tau}$ and U_{ee} are elements of the unitary matrix that relates mass eigenstates to weak eigenstates, the leptonic equivalent of the Cabbibo-Kobayashi-Maskawa matrix. We note that the rate could be larger (or even perhaps the mass regime of interest there are two ways out of this constraint: The lifetime can be so long that the arrival time was more than ten seconds after the electron antineutrinos arrived, or the lifetime can be so short that the daughter photons were produced inside the progenitor. We can take account of both of these possibilities in the following formula for the expected fluence of γ rays:

$$f_{\gamma,10} = f_{\nu 0} W_\gamma B_\gamma \langle F_1 F_2 \rangle \tag{24}$$

where the subscript 10 reminds us that we are only interested in the first ten seconds, $f_{\nu 0} \simeq 1.4 \times 10^{10}$ cm^{-2} is the fluence of a massless neutrino species, $W_\gamma \sim 1/4$ is the fraction of decay photons produced with energies between 4.1 MeV and 6.4 MeV, F_1 is the fraction of tau neutrinos that decay outside the progenitor, and F_2 is the fraction of these that decay early enough so that the decay products were delayed by less than ten seconds. The quantity B_γ is the branching ratio to a decay mode that includes a photon. For $m_\nu \gtrsim 1$ MeV one expects the $\nu_e + e^\pm$ mode to be dominant; however, ordinary radiative corrections should lead to $B_\gamma \simeq 10^{-3}$ [29]. Finally angular brackets denote an average over the Fermi-Dirac distribution of neutrino momenta,

$$\langle A \rangle \equiv \frac{1}{1.5\zeta(3)T^3} \int_0^\infty \frac{A\, dp\, p^2}{e^{E/T}+1}, \tag{25}$$

where $T \simeq 4$ MeV is the temperature of the neutrinosphere and $E = (p^2 + m_\nu^2)^{1/2}$.

To evaluate the fluence of gamma rays we need to know F_1 and F_2. The fraction F_1 that decay outside the progenitor is simply e^{-t_1/τ_L} where $t_1 = R/v = RE/p$ and the "lab" lifetime $\tau_L = \tau E/m_\nu$. Of these, the fraction whose decay products arrive *after* ten seconds is $e^{-t_2/\tau_L}/e^{-t_1/\tau_L}$ where $t_2 = 10\,\mathrm{sec}/(1 - v/c)$; thus, $F_2 = 1 - e^{(t_1 - t_2)/\tau_L}$. Figure 12 shows this constraint assuming a branching ratio $B_\gamma = 10^{-3}$.

The second constraint comes from observing that if tau neutrinos decayed within the progenitor supergiant, the energy deposited (up to about 10^{53} erg) would have "heated up" the progenitor so much as to conflict with the observed optical luminosity of SN 1987A (and other type II supernovae) [29, 30]. We require

$$E_{\mathrm{input}} = \langle (1 - F_1) \rangle E_\nu \lesssim 10^{47}\,\mathrm{erg}, \tag{26}$$

where $E_\nu \sim 10^{53}$ erg is the energy carried off by a massless neutrino species, and $1 - F_1$ is the fraction of tau neutrinos that decay within the progenitor.

5 Summary and Discussion

We have presented a comprehensive study of the effect of an unstable tau neutrino on primordial nucleosynthesis. The effects on the primordial abundances and the mass/lifetime limits that follow depend crucially upon the decay mode. In the context of primordial nucleosynthesis we have identified four generic decay modes that bracket the larger range of possibilities: (1) all-sterile daughter products; (2) sterile daughter product(s) + EM daughter product(s); (3) ν_e + sterile daughter product(s); and (4) ν_e + EM daughter product(s). The excluded regions of the tau-neutrino mass/lifetime plane for these four decay modes are shown in Figs. 5 (Dirac) and 6 (Majorana).

In the limit of long lifetime ($\tau_\nu \gg 100\,\text{sec}$), the excluded mass range is: $0.3\,\text{MeV} - 33\,\text{MeV}$ (Dirac) and $0.4\,\text{MeV} - 30\,\text{MeV}$ (Majorana). Together with current laboratory upper mass limits, 31 MeV (ARGUS) and 32.6 MeV (CLEO), our results very nearly exclude a long-lived, tau neutrino more massive than about 0.4 MeV. Moreover, other astrophysical and laboratory data exclude a tau-neutrino in the $0.3\,\text{MeV} - 50\,\text{MeV}$ mass range if its decay product(s) include a photon or $e^\pm$ pair. Thus, if the mass of the tau neutrino is the range 0.4 MeV to 30 MeV, then its decay products cannot include a photon or an $e^\pm$ pair and its lifetime must be shorter than a few hundred seconds.

We note that the results of Ref. [12] for the all-sterile decay mode are more restrictive than ours, excluding masses from about 0.1 MeV to about 50 MeV for $\tau_\nu \gg 100\,\text{sec}$. This traces in almost equal parts to (i) small ($\Delta Y \simeq +0.003$), but significant, corrections to the ^{4}He mass fraction and (ii) slightly larger relic neutrino abundance. With regard to the first difference, this illustrates the sensitivity to the third significant figure of the ^{4}He mass fraction. With regard to the second difference, it is probably correct that within the assumptions made the tau-neutrino abundance during nucleosynthesis is larger than what we used. However, other effects that have been neglected probably lead to differences in the tau-neutrino abundance of the same magnitude. For example, for tau-neutrino masses around the upper range of excluded masses, $50\,\text{MeV} - 100\,\text{MeV}$, finite-temperature corrections, hadronic final states (e.g., a single pion), and tau-neutrino mixing have not been included in the annihilation cross section and are likely to be important at the 10% level.

So is a tau neutrino with lifetime greater than a few hundred seconds and mass greater than a fraction of an MeV ruled out or not? Unlike a limit based

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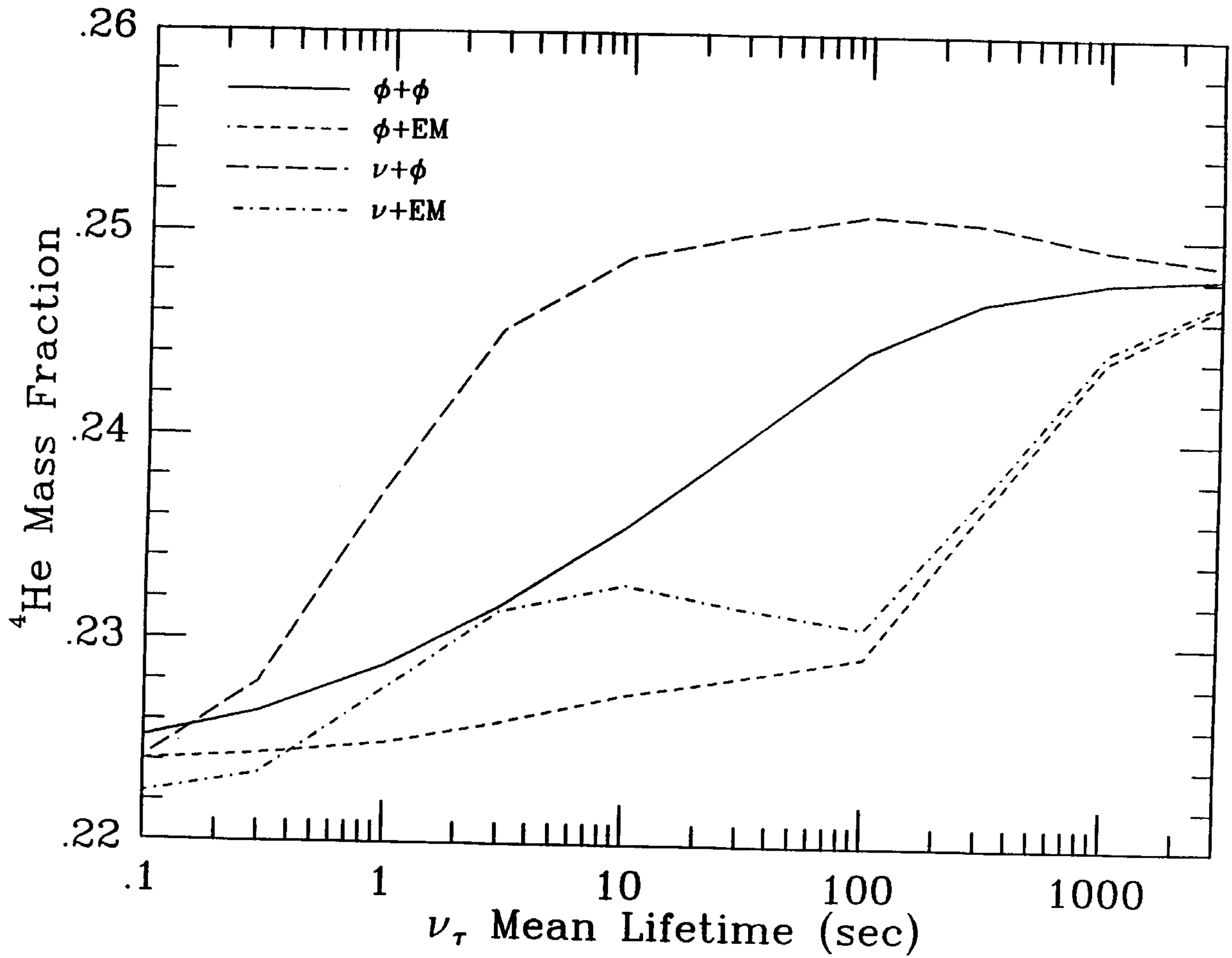
For reference, the ^{4}He yield in the absence of a decaying tau neutrino is $Y_P = 0.2228$ (2 massless neutrinos) and 0.2371 (3 massless neutrinos).

Figure 9: ^{4}He yield as a function of tau-neutrino lifetime for the $\nu_\tau \to \nu_e$ + EM decay mode, $\eta_0 = 3 \times 10^{-10}$, and Dirac masses of 1, 5, 10, 20 MeV. For reference, the ^{4}He yield in the absence of a decaying tau neutrino is $Y_P = 0.2228$ (2 massless neutrinos) and 0.2371 (3 massless neutrinos).

Figure 10: ^{4}He yield as a function of lifetime for the $\nu_e + \phi$ decay mode, $\eta_0 = 3 \times 10^{-10}$, $rm = 3.5$, and masses of 5, 10, 20, 30 MeV. For reference, the ^{4}He yield in the absence of a decaying tau neutrino is $Y_P = 0.2228$ (2 massless neutrinos) and 0.2371 (3 massless neutrinos).

Figure 11: Excluded regions of the $rm - \tau$ plane for the four different decay modes and a 20 MeV mass particle. The limits for the first two decay modes are strictly independent of mass; for the last two decay modes they should be relatively insensitive to mass for $\tau \gtrsim 100$ sec (and actually more stringent than those shown here for $m > 20$ MeV). Excluded regions are above the curves.

Figure 12: Regions of the tau-neutrino mass-lifetime plane excluded by laboratory experiments and astrophysical arguments. The excluded regions are to the side of the curve on which the label appears. The dashed curve summarizes a host of different laboratory limits to $|U_{e\tau}|^2$, translated to a model-dependent bound to $\tau_\nu(\nu_\tau \to \nu_e e^\pm)$, cf. Eq. (21). SNL denotes the supernova-light constraint which extends to lifetimes shorter than those shown here.



.26
.25
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^{4}He Mass Fraction
$\phi+\phi$
ϕ+EM
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ν+EM
.1
1
10
100
1000
ν_τ Mean Lifetime (sec)

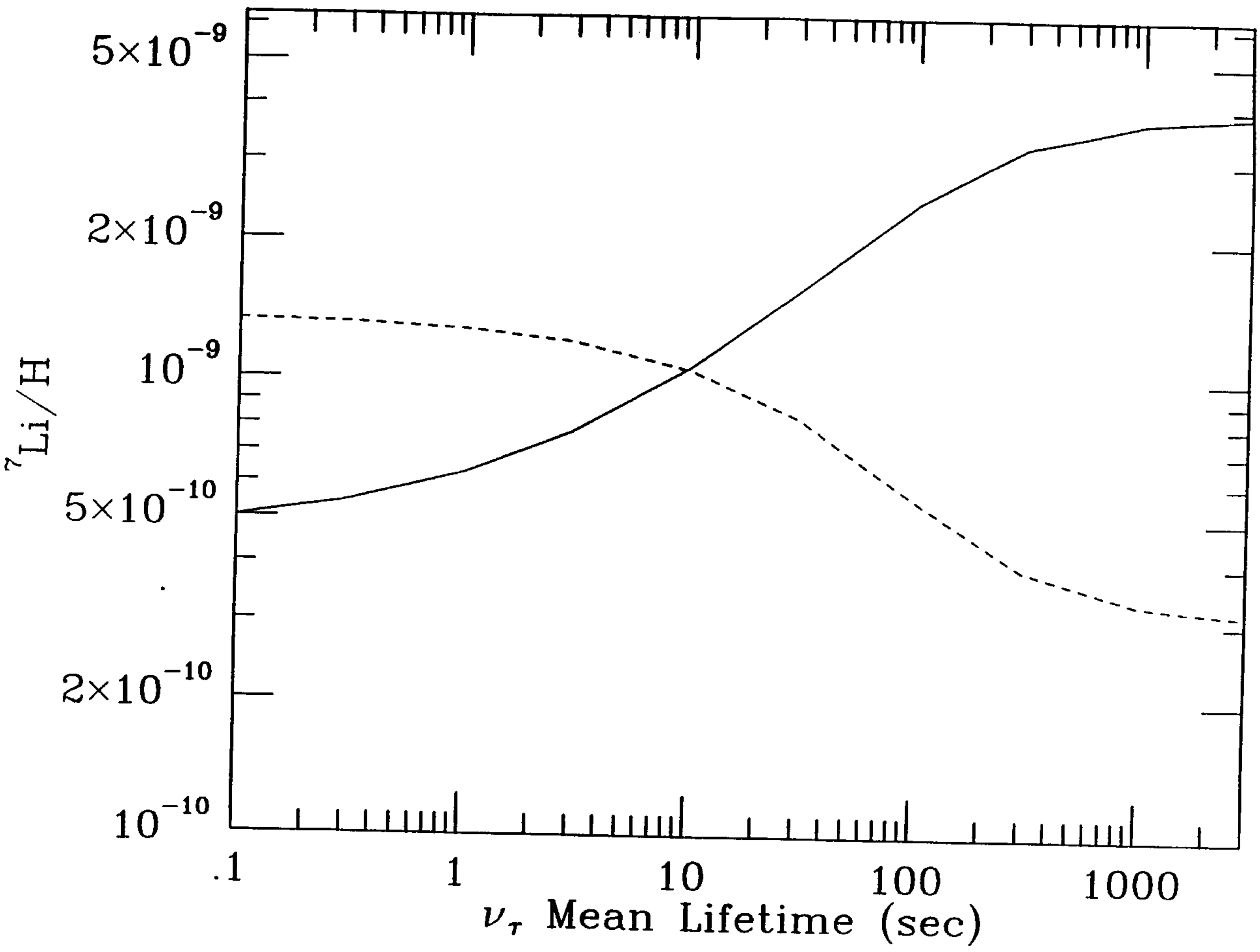

5×10^{-9}
2×10^{-9}
10^{-9}
5×10^{-10}
2×10^{-10}
10^{-10}
^{7}Li/H
.1
1
10
100
1000
ν_τ Mean Lifetime (sec)

FIG 4

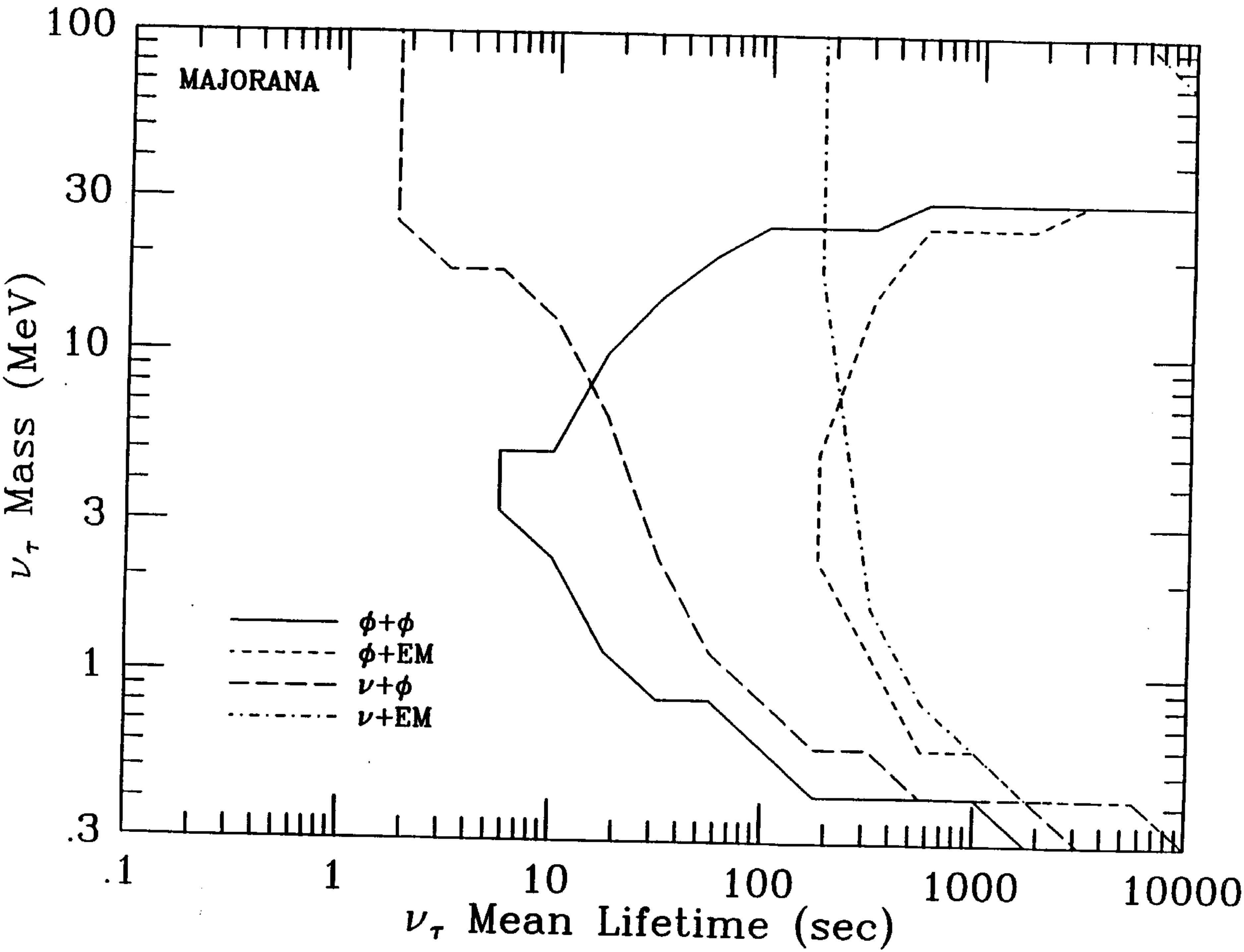
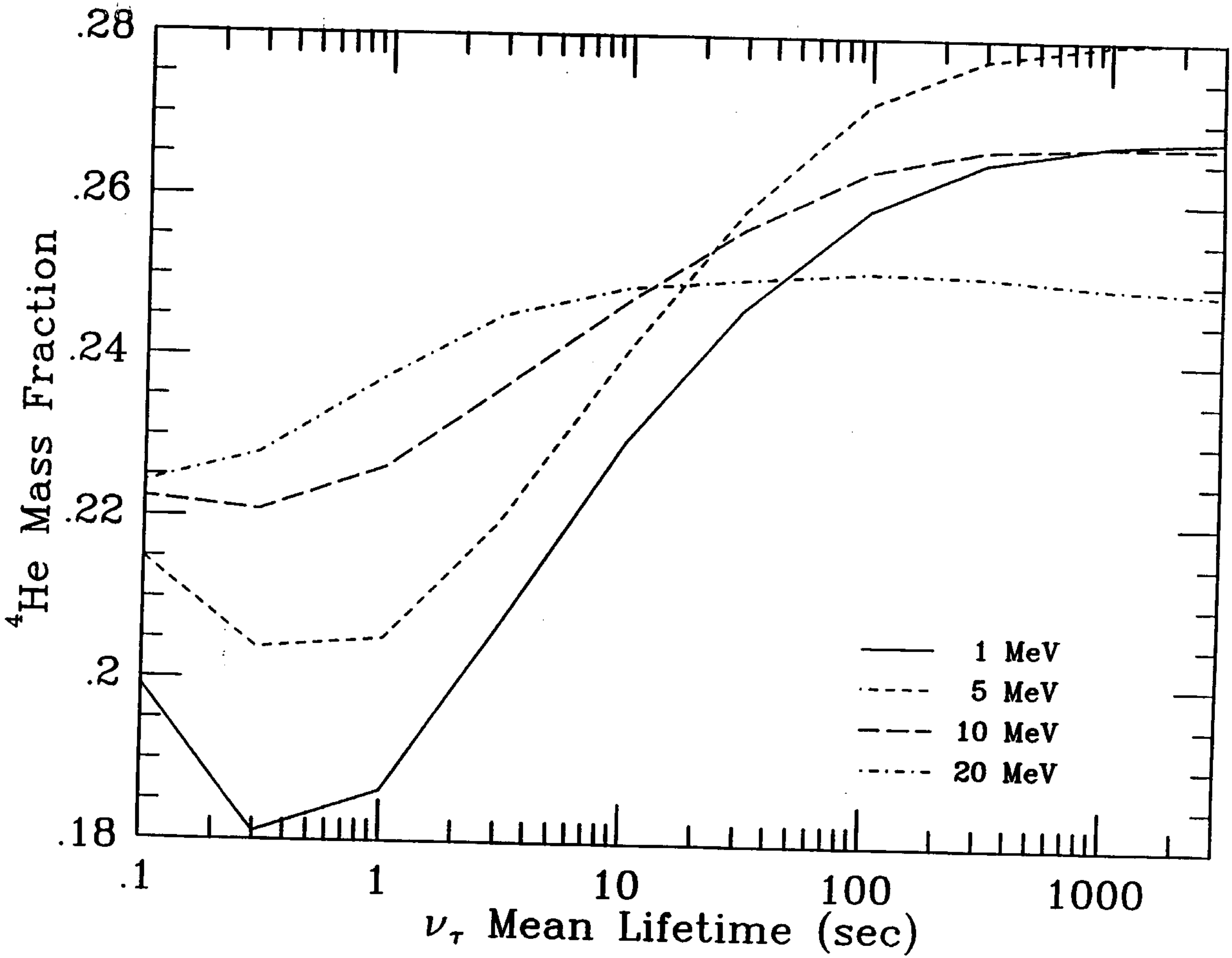
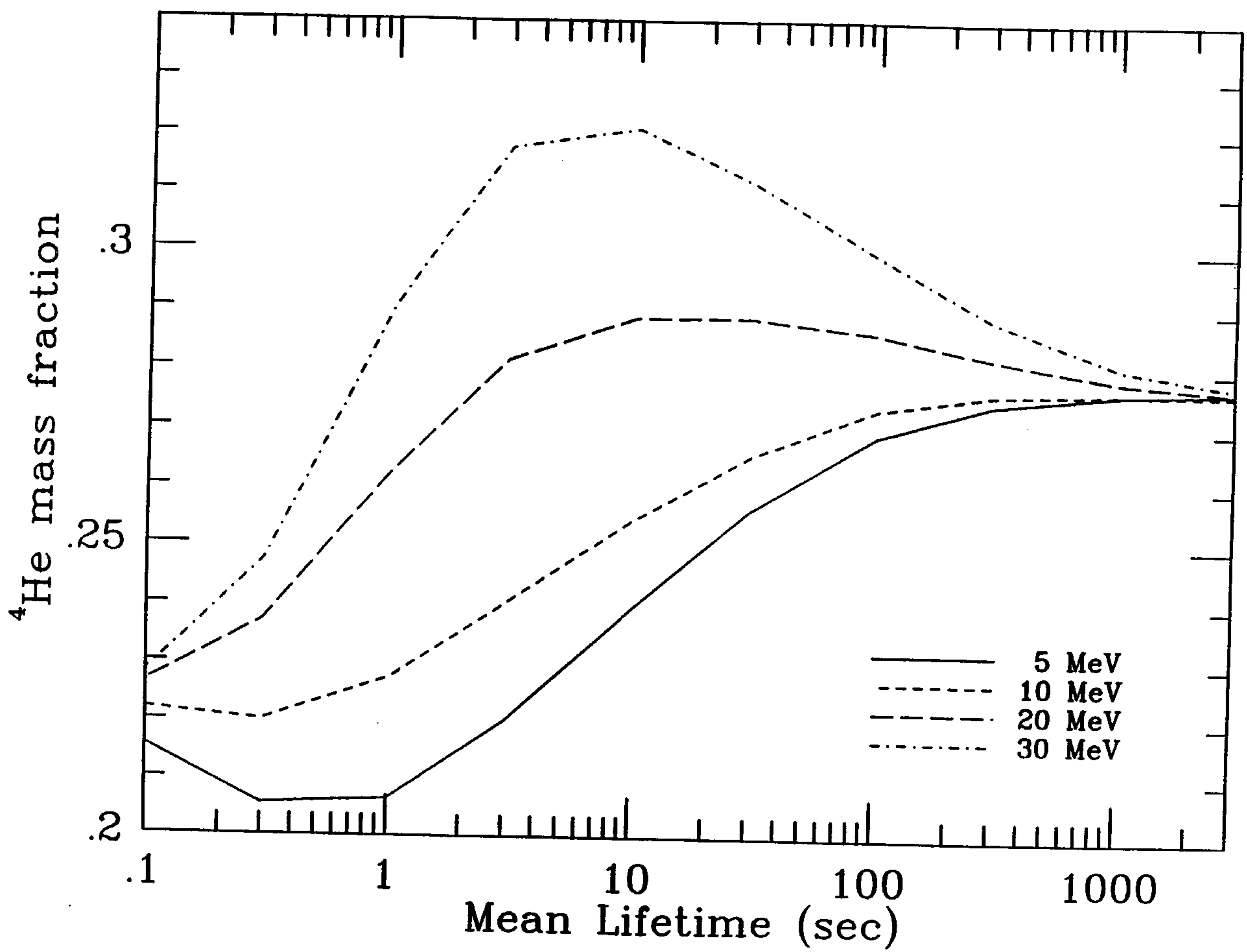

MAJORANA
100
30
10
3
1
.3
ν_τ Mass (MeV)
.1
1
10
100
1000
10000
ν_τ Mean Lifetime (sec)
$\phi+\phi$
ϕ+EM
$\nu+\phi$
ν+EM

Fig. 1

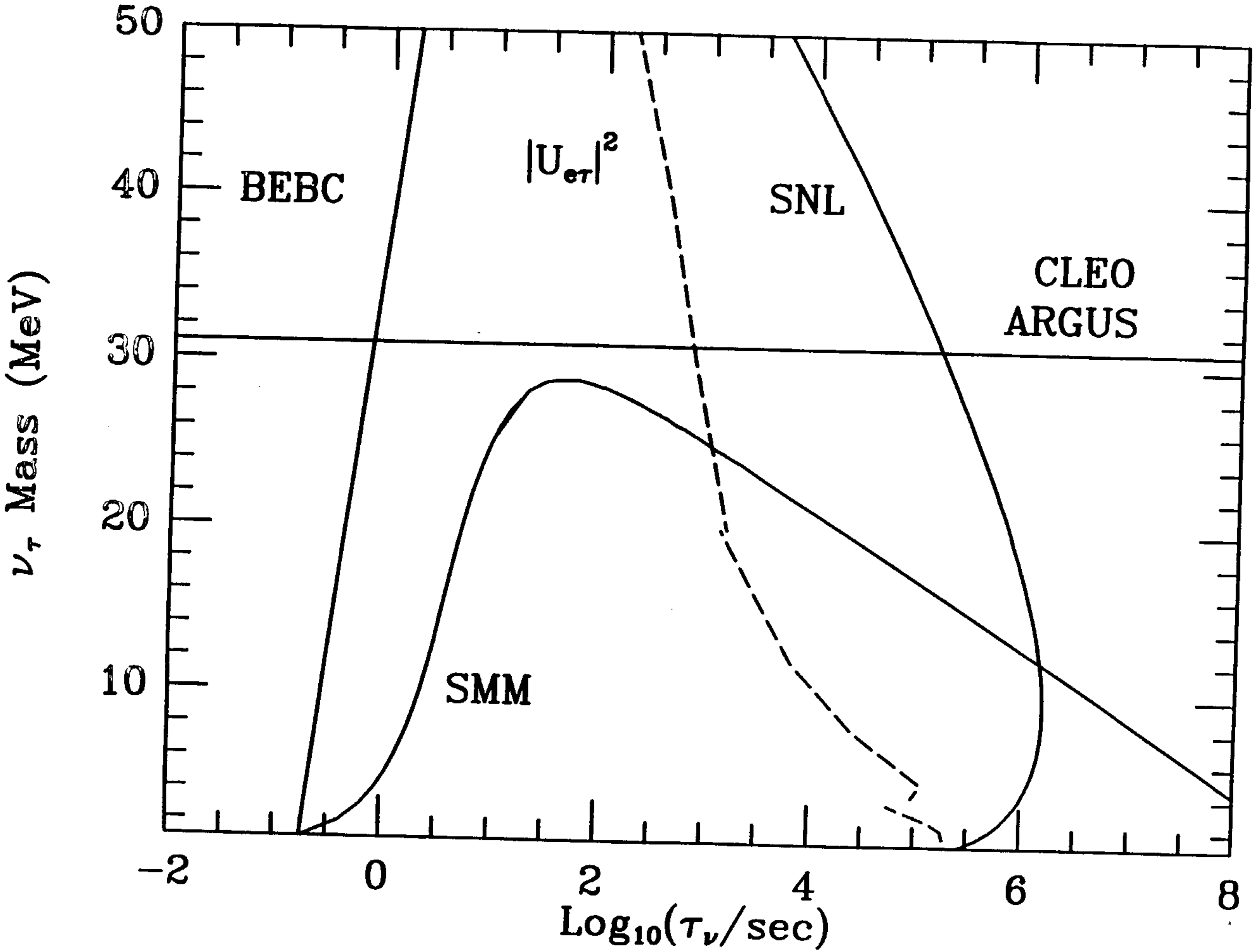


.28
.26
.24
.22
.2
.18
^{4}He Mass Fraction
.1
1
10
100
1000
ν_τ Mean Lifetime (sec)
1 MeV
5 MeV
10 MeV
20 MeV

FIG 8



^{4}He mass fraction
.3
.25
.2
.1
1
10
100
1000
Mean Lifetime (sec)
5 MeV
10 MeV
20 MeV
30 MeV



BEBC
$|U_{e\tau}|^2$
SNL
CLEO
ARGUS
SMM
ν_τ Mass (MeV)
50
40
30
20
10
−2
0
2
4
6
8
$\mathrm{Log_{10}}(\tau_\nu/\mathrm{sec})$