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## CONSTRAINTS ON DIRAC NEUTRINOS FROM SN 1987A

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### Abstract

The Livermore Supernova Explosion Code was used to calculate the effect of a massive Dirac neutrino on neutrino emission from SN 1987A in a fully self-consistent manner. Spin-flip interactions lead to the copious emission of sterile, right-handed neutrinos and cool the core faster than the observed neutrino emission time for Dirac masses exceeding about 3 keV. This limit is relaxed to 7 keV if pion emission processes in the core are neglected. These limits are compared with the previous less stringent limits of Burrows et al.



## Introduction

Many authors [1] noted that spin-flip reactions enable the weakly interacting left-handed components of Dirac neutrinos to change to sterile right-handed neutrinos and thereby free-stream out of the central core of a nascent neutron star. This free streaming, rather than the usual diffusion [2], leads to a rapid cooling of the core and thereby shortens the duration of the neutrino burst. Since the SN1987A neutrino burst was observed by the Kamiokande (KII) [3] and the Irvine-Michigan-Brookhaven (IMB) [4] detectors to last of order 10 sec, the KII and IMB results can be used to constrain Dirac neutrino masses. The production of sterile right-handed neutrinos is proportional to the neutrino mass squared, and so the larger the mass, the more rapid the cooling. Based upon numerical cooling models that incorporated the cooling effects of right-handed neutrinos, Gandhi and Burrows set a mass limit of 28 keV [1]. With the interest generated by the possible existence of a 17 keV neutrino, this limit was re-examined [5]. This re-examination culminated in a calculation that included the neutrino-nucleon spin-flip scattering, nucleon-nucleon bremsstrahlung, and pion emission processes, allowed for the effects of degeneracy, and explored a range of cooling models [6]. The result was a very conservative mass limit of 25 keV and a limit of 15 keV when pions are assumed to be as abundant as nucleons, with an estimated uncertainty of 10 keV.

Given that this limit is indecisively close to 17 keV and, in general, to help clarify the sensitivities to the cooling model, we decided to carry out a similar calculation with the Livermore Supernova Explosion Code [2]. The Livermore Supernova Explosion Code has a somewhat higher central temperature than the models used by Burrows et al. [6]. The Livermore Code follows the pre-collapse evolution of a massive star [7] that fits the characteristics of the progenitor to SN 1987A, which leads to a collapsing core that is on a higher temperature adiabat. In addition, the equations of state used in the Livermore Code are somewhat different from those of Burrows et al. [6], particularly with regard to the treatment of pions. For all these reasons, we felt it important to explore the limits that follow from the Livermore Code. The emphasis of this paper will be those aspects of the calculation that differ from Burrows et al. [6]. While the final fate of the 17 keV neutrino obviously lies in the hands of the experimentalists, it is nonetheless interesting to see what constraints the SN 1987A neutrino observations imply. We note that there are other stringent limits based upon SN 1987A that apply to unstable neutrinos [8,9].

## The Model

The general model of gravitational collapse as it relates to neutrino emission and to SN 1987A is reviewed in Ref. [10]. The Livermore Supernova Explosion Code is described in detail in Refs. [2, 11, 12]. As discussed in Ref. [12], the code has been "tuned" to fit the observed aspects of SN 1987A, including the pre-collapse progenitor, neutrino emission, and the explosion energy. In addition, the present calculations are based upon an improved equation of state, which yields a significantly higher meson density in the

core, but does not otherwise alter the agreement with SN 1987A. The high pion (and Kaon) densities follow from modelling heavy-ion collisions at the Bevalac with a mean-field equation of state of the type used in stellar-collapse calculations [13]. High meson densities are a consequence of finite-density effects on the energy-momentum relation for pions (and Kaons), and receive theoretical support from recent work by Politzer and Wise [14] and others [13, 15], indicating that Kaon-condensates are to be expected in nuclear matter. In addition, the work of McAbee and Wilson [13] indicates that Bevalac heavy-ion experiments support these ideas. While these equation-of-state effects are of small importance to the basic collapse observables, they have a dramatic effect on the production of sterile, right-handed neutrinos due to pion-nucleon scattering production of right-handed neutrinos,

$$\pi + N \rightarrow N + \nu_R \bar{\nu}_R. \quad (1)$$

The rates we have used for right-handed neutrino production are the same as those used by Burrows et al. [6], and all three processes they considered are considered here. Thus, the key difference is the equation of state (and hence the densities of pions and other mesons and the temperatures).

We use the pion mean-field model [13]. This model has the following equations for the energy-momentum dispersion relation:

$$\epsilon^2 = m_\pi^2 + p^2 \left[ \frac{1 + \Lambda^2 \chi}{1 - g' \Lambda^2 \chi} \right]; \quad (2)$$

$$\Lambda^2 \chi = \frac{-4.52 \omega \rho \exp[-(p/7m_\pi)^2]}{m_\pi^2 (\omega^2 - \epsilon^2)}; \quad (3)$$

$$\omega(p) = \sqrt{m_\Delta^2 + p^2} - m_N; \quad (4)$$

where  $m_\pi$ ,  $m_N$ ,  $m_\Delta$  are respectively the pion, nucleon and delta masses,  $g'$  is the Landau-Migdal parameter, and  $\rho$  is the nucleon density. By reproducing the experimental results, both pion numbers and spectra from Bevalac experiments involving La on La collisions at 1.35, 0.74, 0.53 GeV/N [13], McAbee and Wilson determined a fit for the Landau-Migdal parameter,  $g' = 0.50 + 0.06\rho/\rho_n$ , where  $\rho_n$  is nuclear matter density,  $0.16 \text{ fm}^{-3}$ . The same equation of state used in these heavy-ion collision calculations was used in the present supernova calculations. The temperature and densities spanned in the Bevalac experiments are comparable to those encountered in the regions of the proto-neutron star where right-handed neutrino production is the largest.

To incorporate the pions into the supernova calculations, we determine the pion abundances,  $n_{\pi^+}$ ,  $n_{\pi^-}$ , and  $n_{\pi^0}$ , by requiring chemical equilibrium,  $\mu_{\pi^-} = -\mu_{\pi^+} = (\mu_n - \mu_p)$ , and charge balance,  $n_{e^+} + n_p + n_{\pi^+} - n_{\pi^-} - n_{e^-} = 0$ . In addition,  $\beta$ -equilibrium implies that  $\mu_e - \mu_{\nu_e} = \mu_n - \mu_p$ . The high electron chemical potential encountered in the central

regions of the core of a proto-neutron star without pions is greatly reduced by the presence of negative pions, and the “degeneracy energy” released increases the temperature considerably (see Fig. 1).

In our calculations, right-handed neutrino losses are implemented as follows. Energy loss due to neutrino-nucleon spin-flip scattering ( $\nu_L + N \rightarrow \nu_R + N$ ) is given by:

$$\dot{\epsilon}_{SF} = \frac{\mu_{\nu_e} G_F^2 m_\nu^2 (m_N T)^{3/2}}{2^{9/2} \pi^5} [1.2 I_s(r_p) + 1.4 I_s(r_n)]; \quad (5)$$

where the approximation for  $I_s$  used is given by

$$I_s(r)^{-1} = \frac{2e^{-r}}{\sqrt{\pi}} + \frac{1}{\sqrt{1+|r|}} - \frac{1}{8(1+|r|)^{3/2}}; \quad (6)$$

where  $r_{p,n} = (\mu_{p,n} - m_N)/T$ . This energy loss, is apportioned to the matter energy and the neutrino energy in the ratio of 2:1. Thus, every third spin flip caused a loss in lepton number.

Energy loss due to nucleon-nucleon bremsstrahlung processes ( $N + N \rightarrow N + N + \nu_L \bar{\nu}_L$ ) is given by:

$$\begin{aligned} \dot{\epsilon}_{BR} &= \frac{160 f^4 g_A^2 G_F^2 m_\nu^2 m_N^{9/2} T^{13/2}}{15 \pi^2 m_\pi^4} [0.5(I_b(r_p, r_p) + I_b(r_n, r_n)) + 3I_b(r_p, r_n)]; \\ I_b(r_1, r_2) &= 2.39 \times 10^5 [e^{-r_1 - r_2} + 0.25(e^{-r_1} + e^{-r_2})] + \\ &\left\{ \frac{1.73 \times 10^4}{(1 + |\frac{r_1 + r_2}{2}|)^{1/2}} + \frac{6.92 \times 10^4}{(1 + |\frac{r_1 + r_2}{2}|)^{3/2}} + \frac{1.73 \times 10^4}{(1 + |\frac{r_1 + r_2}{2}|)^{5/2}} \right\}; \end{aligned} \quad (7)$$

where  $f \sim 1$  is the pion-nucleon coupling and  $g_A \sim 1.25$  is the axial-vector coupling.

Energy loss due to pion processes ( $\pi + N \rightarrow N + \nu_L \bar{\nu}_L$ ) is given by:

$$\dot{\epsilon}_\pi = \frac{2^{10} g_A^2 f^2 G_F^2 m_\nu^2}{105 \pi^{7/2} m_\pi^2} T^3 n_N n_\pi; \quad (8)$$

with  $n_\pi = n_{\pi^-} + n_{\pi^+} + n_{\pi^0}$ . The losses from bremsstrahlung and pion processes are taken out of the matter energy only. In all our calculations we take the tau neutrino to be the massive neutrino (so far as supernova physics goes, it could just as well be the muon neutrino as the tau and mu neutrinos are treated identically). We also assume that all three neutrino species are in chemical equilibrium with  $\mu_\nu = \mu_e$ . The rates used here are described in detail in Ref. [17].

In the present calculations we have ignored the presence of Kaons. If we apply the Kaon mass reduction formula of Refs. [14, 15, 18] to the conditions in the central part of the proto-neutron star at the time of large right-handed neutrino losses, the presence of Kaons would lead to the additional release of electron-degeneracy energy, about 20 to 30 MeV per nucleon. This energy release would further increase the temperature. We have

not included the Kaons in our calculations for energy loss because the parameters involved are not well established at present, and thus we are probably underestimating right-handed neutrino losses since they increase rapidly with temperature.

In general, our high pion densities yield higher core temperatures which leads to less degenerate conditions, thereby exaggerating the differences between Burrows' treatment and the Livermore Code. Since the Bevalac data implies a high pion density [13], and since the Livermore Code's initial conditions are well fit to initial models of the SN 1987A progenitor [7], we feel that the more stringent constraints we obtain here should be taken seriously. We also note that merely adding pions, as was done in Ref. [6], cannot mimic all the pion effects we have found here, because the presence of pions also leads to higher core temperatures.

We note, in passing, that high pion/Kaon densities should also affect axion production. Since these pion/Kaon effects were not included in previous SN 1987A axion mass limits [16], we intend to explore the high pion/Kaon density effects on axion constraints in a subsequent paper. A preliminary estimate suggests that the mass limit of  $10^{-3}$ eV may improve to  $10^{-4}$ eV [17].

Because of the immense time it takes to run models where the feedback of right-handed neutrino emission on the cooling of the core is taken into account, we carried out some calculations without full feedback to explore sensitivity to parameter choices. These runs also serve to illustrate how important feedback is in determining constraints. Since much discussion in the literature has focused on the effect of electron, neutrino, and nucleon degeneracy on right-handed neutrino emission [5,6], it is worth noting that in our models all degeneracy effects are properly taken into account. Moreover, temperatures are sufficiently high that all species are non-degenerate to a good approximation, making the point moot.

## Results

Figure 1 shows the core temperature 0.5 seconds after core bounce. As discussed above, the equation of state with high pion density results in significantly higher core temperatures than that without low pion density. As time goes on, the peak temperature (at  $\sim 0.5M_{\odot}$  in Fig. 1) moves inward. It is worth noting that the density and absolute value of the neutrino chemical potential is also higher in the central core when pions are included, but  $\mu_{\nu}/T$  is lower.

Figure 2 shows the time evolution of the radius of the neutrino "photosphere" for a 10 keV Dirac neutrino compared with a zero mass neutrino. Time is measured from core bounce. Only at late times is the difference significant.

Figure 3 shows the average energy of the proper-helicity anti-electron neutrinos (the neutrinos responsible for the KII and IMB events) versus time for zero mass and a mass of 10 keV; as expected, this energy is insensitive to the Dirac neutrino mass.

Figure 4a shows the luminosity in 10 keV right-handed neutrinos for all three emission

processes in a calculation with full feedback. Note that for a 10 keV neutrino, the neutrino-nucleon spin-flip process is large and cools the inner core so fast that the pion processes are barely dominant, and then only at late times. Thus, even without the pion processes, a 10 keV mass Dirac neutrino would lead to unacceptably rapid cooling. Figure 4b is the same as 4a but for a mass of 3.16 keV. Here the pion processes are more significant. Figure 4c shows the right-handed neutrino luminosities for a 1 keV Dirac neutrino with no feedback. Note that the pion processes are about 100 times larger than the other two. Since the right-handed neutrino emission rates vary as  $m_\nu^2$ , it is clear that pion processes would dominate and rapidly cool the core for masses as small as a fraction of a keV when feedback is neglected, and hence a reliable estimate of the mass limit requires taking feedback into account.

Figure 5 shows a comparison of the proper-helicity anti-electron neutrino luminosity in full feedback models with pion processes for  $m_\nu = 0, 3.16$  and 10 keV. For a mass greater than 3 keV or so, the duration of the  $\bar{\nu}_e$  burst is significantly shortened, and thus a Dirac neutrino mass larger than this can be excluded by the KII and IMB results.

## Conclusions

In summary, based upon our calculations employing full feedback and the Livermore Gravitational Supernova Explosion Code, and incorporating an equation of state that reproduces the Bevalac heavy-ion experiments, we use the duration of the neutrino bursts observed by KII and IMB to exclude a Dirac neutrino mass greater than about 3 keV. Including the presence of Kaons in the post-collapse core would only strengthen our limit. Even if pion emission processes are ignored, it still appears difficult to accommodate a mass greater than 10 keV with the Livermore Code. The difference between the Burrows et al. [6] “very conservative” limit of 25 keV and the 10 keV limit obtained (here ignoring the pion processes) traces to the higher core temperatures in our models. Further, the present results indicate that the Burrows et al. limits were, as stated, very conservative, and suggest that the KII and IMB data very probably exclude a 17 keV neutrino.

## Acknowledgements

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## References

- [1] R. Gandhi and A. Burrows, Phys. Lett. B **246**, 19 (1990); *ibid* **261**, 519 (1991); G.G. Raffelt and D. Seckel, Phys. Rev. Lett. **60**, 1793 (1988); K. Gaemers et al., Phys. Rev. D **40**, 309 (1989); J.A. Grifols and E. Masso, Nucl. Phys. B **331**, 244 (1990); *ibid.* Phys. Lett. B **242**, 77 (1990); A. Perez and R. Gandhi, Phys. Rev. D **41**, 2374 (1990).
- [2] See e.g., R. Mayle, J.R. Wilson, and D.N. Schramm, ApJ **318**, 288 (1987).
- [3] K. Hirata et al., Phys. Rev. Lett. **58**, 1490 (1987).
- [4] R.M. Bionta et al., Phys. Rev. Lett. **58**, 1494 (1987).
- [5] M.S. Turner, Phys. Rev. D **45**, 1066 (1992); R. Gandhi and A. Burrows, Phys. Lett. B **261**, 519 (1991); G.G. Raffelt and D. Seckel, unpublished (1992).
- [6] A. Burrows, R. Gandhi, and M.S. Turner, Phys. Rev. Lett. **68**, 3834 (1992); the cooling models used in these calculations are discussed by A. Burrows and J. Lattimer, ApJ **309**, 178 (1986) and A. Burrows, ApJ **334**, 891 (1988).
- [7] S. Woosley and T. Weaver, Phys. Rep. **163**, 79 (1988).
- [8] S. Dodelson, J.A. Frieman, and M.S. Turner, Phys. Rev. Lett. **68**, 2572 (1992).
- [9] E.W. Kolb and M.S. Turner, Phys. Rev. Lett. **62**, 509 (1989).
- [10] D.N. Schramm and J.W. Truran, Phys. Rep. **189**, 89 (1990).
- [11] R. Mayle, Ph.D. Thesis, University of California (1987).
- [12] R. Mayle and J.R. Wilson, Livermore Report UCRL-97355 (1987).
- [13] T. McAbee and J.R. Wilson, Livermore preprint (1992); R. Mayle, M. Tavani, and J.R. Wilson, Livermore preprint (1992).
- [14] H.D. Politzer and M. Wise, Phys. Lett. B **273**, 156 (1991); D. Montano, H.D. Politzer, and M. Wise, Nucl. Phys. B **375**, 507 (1992).
- [15] G.E. Brown, K. Kubodeva, and M. Rho, K.K. & G.E.B. preprint #6, Stony Brook (1992).
- [16] see e.g., M. Burrows, M.S. Turner, and R.P. Brinkman, Phys. Rev. D **39**, 1020 (1989); R. Mayle, J.R. Wilson, J. Ellis, K. Olive, D.N. Schramm, and G. Steigman, Phys. Lett. B **219**, 515 (1989).
- [17] M.S. Turner, Phys. Rev. D **45**, 1066 (1992).
- [18] B. Friedman, V.R. Panharipande, and Q.N. Usmani, Nucl. Phys. A **372**, 483 (1981).

## Figure Captions

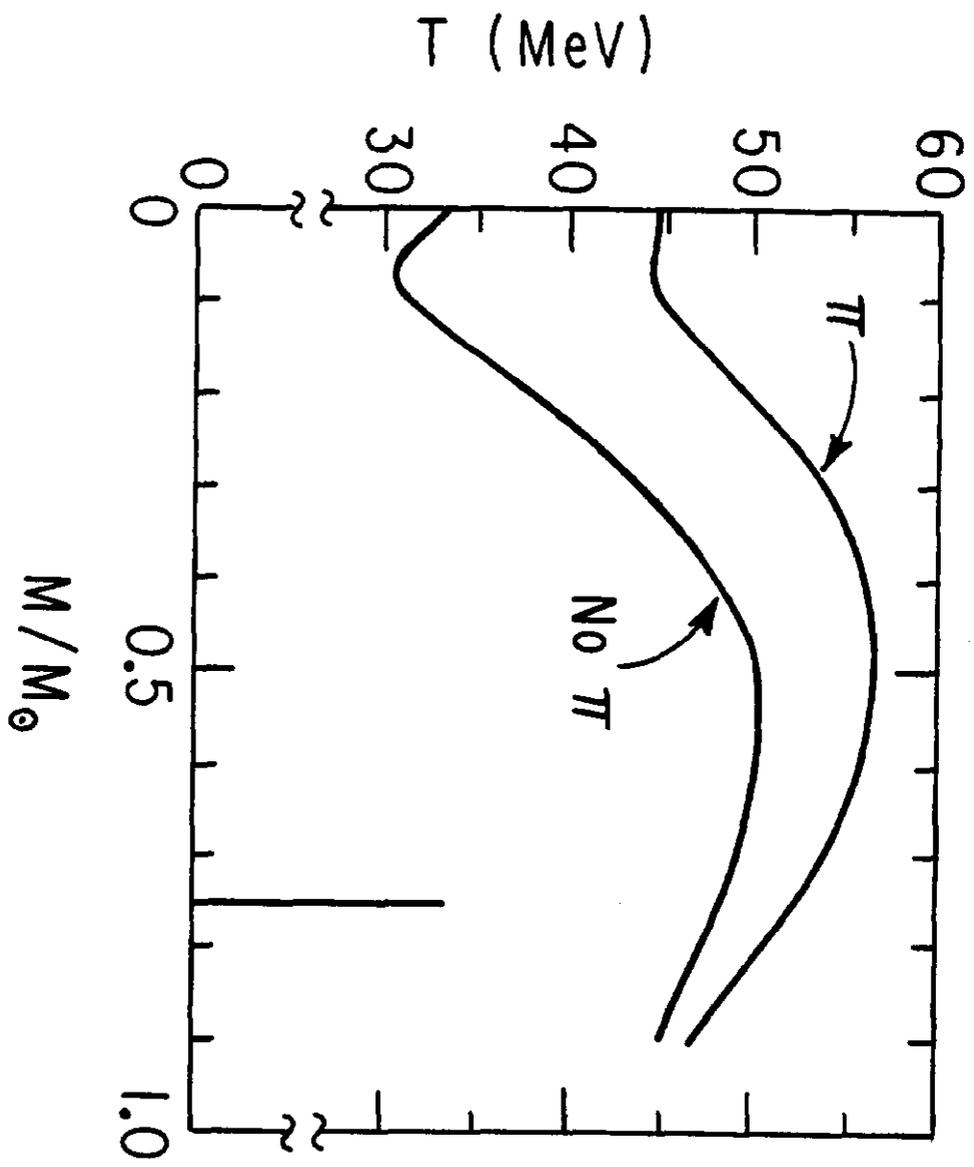
Fig. 1. The core temperature as a function of interior mass 0.5 seconds after core bounce. Note the large effect that the high density of pions has on the core temperature.

Fig. 2. The time evolution of the radius of the neutrino “photosphere” for Dirac masses of 0 and 10 keV.

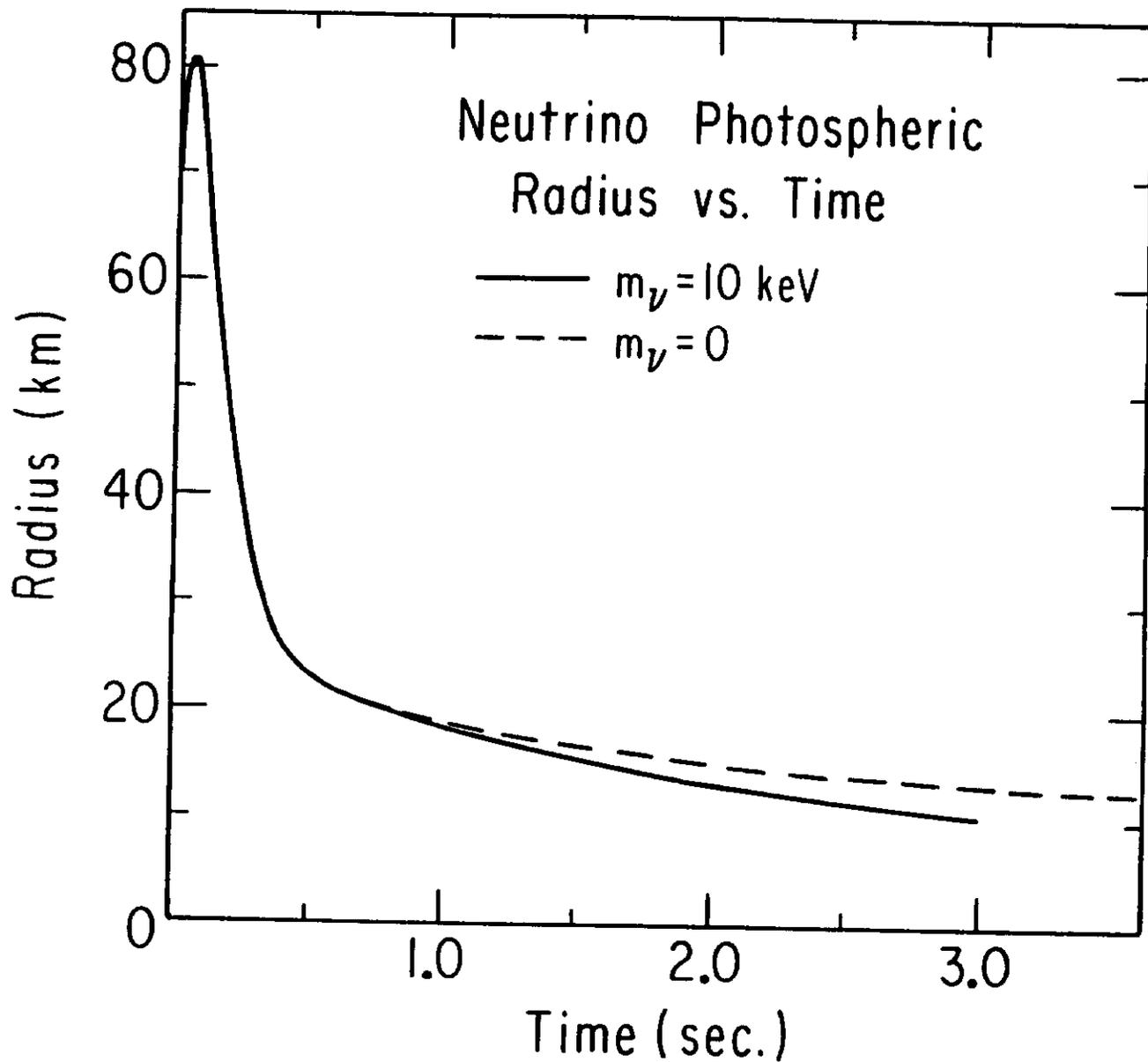
Fig. 3. The average energy of the proper-helicity  $\bar{\nu}_e$ 's as a function of time after core bounce for Dirac masses of 0 and 10 keV.

Fig. 4. The energy loss rates in right-handed neutrinos as a function of time after core bounce for the three emission processes: (a)  $m_\nu = 10$  keV with feedback; (b)  $m_\nu = 3.16$  keV with feedback; (c)  $m_\nu = 1$  keV with no feedback.

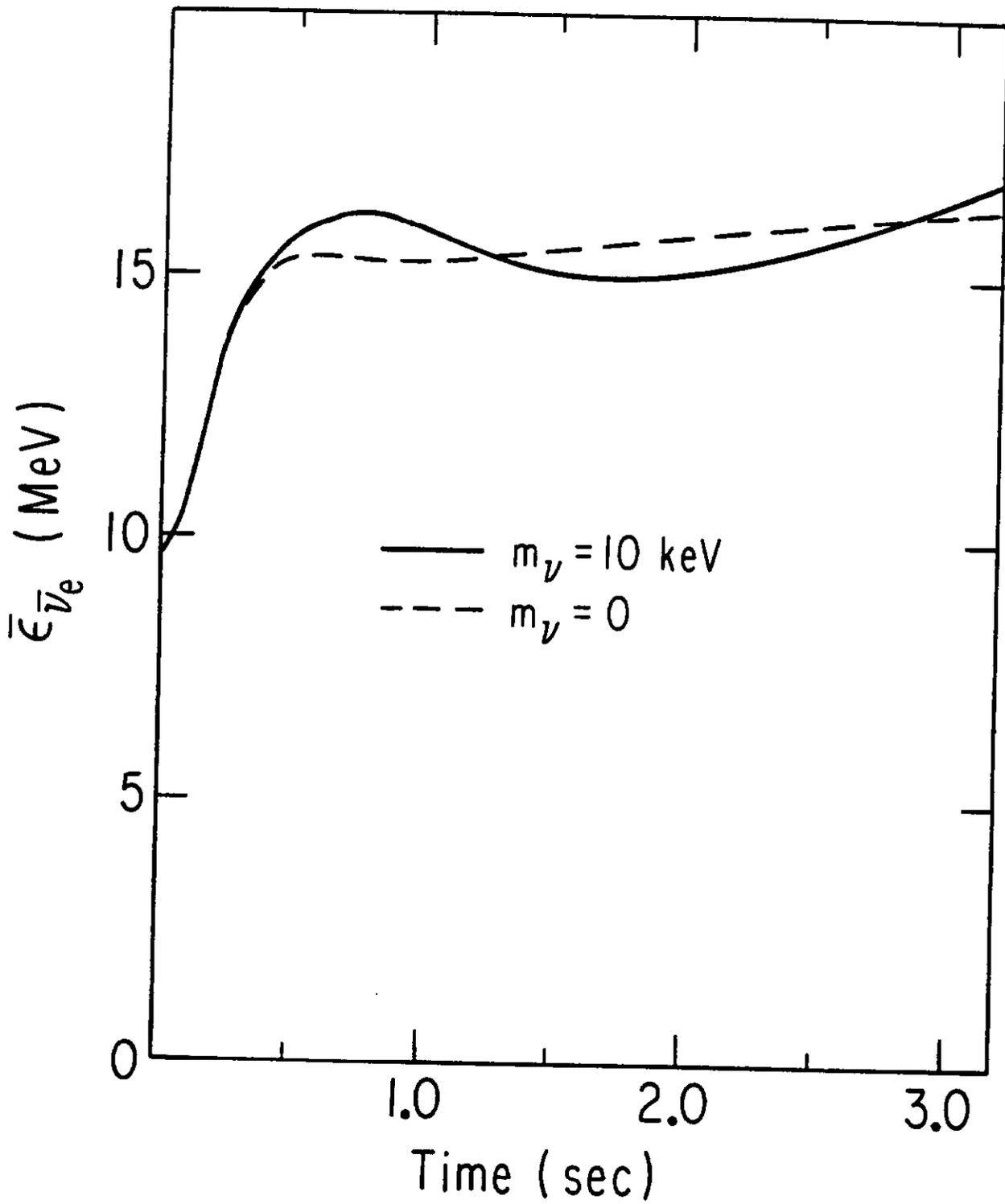
Fig. 5. The luminosity in proper-helicity  $\bar{\nu}_e$ s for  $m_\nu = 0, 3.16, 10$  keV with full feedback and pion processes included. Note that for  $m_\nu \gtrsim \mathcal{O}(3 \text{ keV})$  the duration of the neutrino burst is significantly shortened, and thus a Dirac mass this large can be excluded by the KII and IMB data.



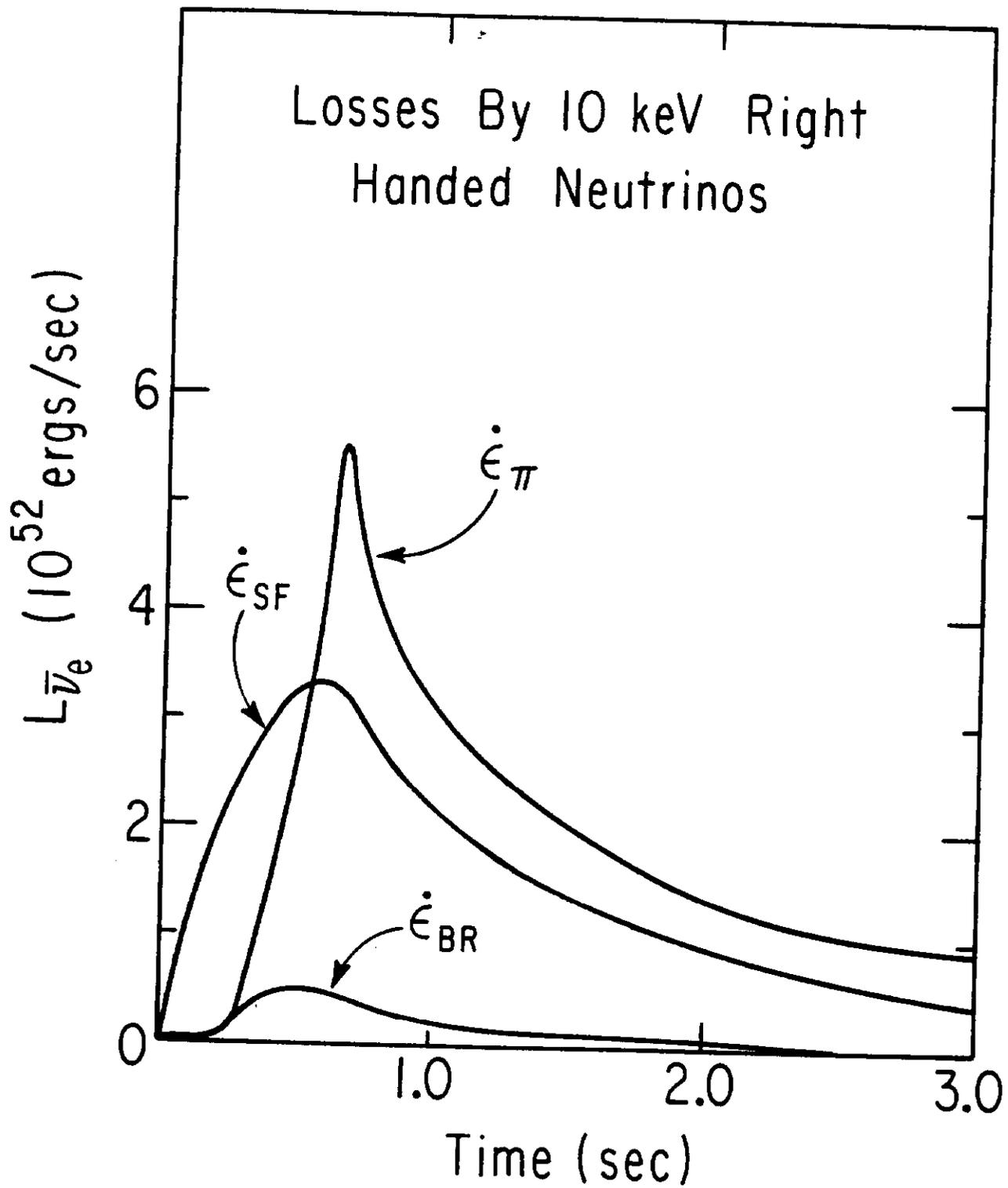
- FIG 1 -



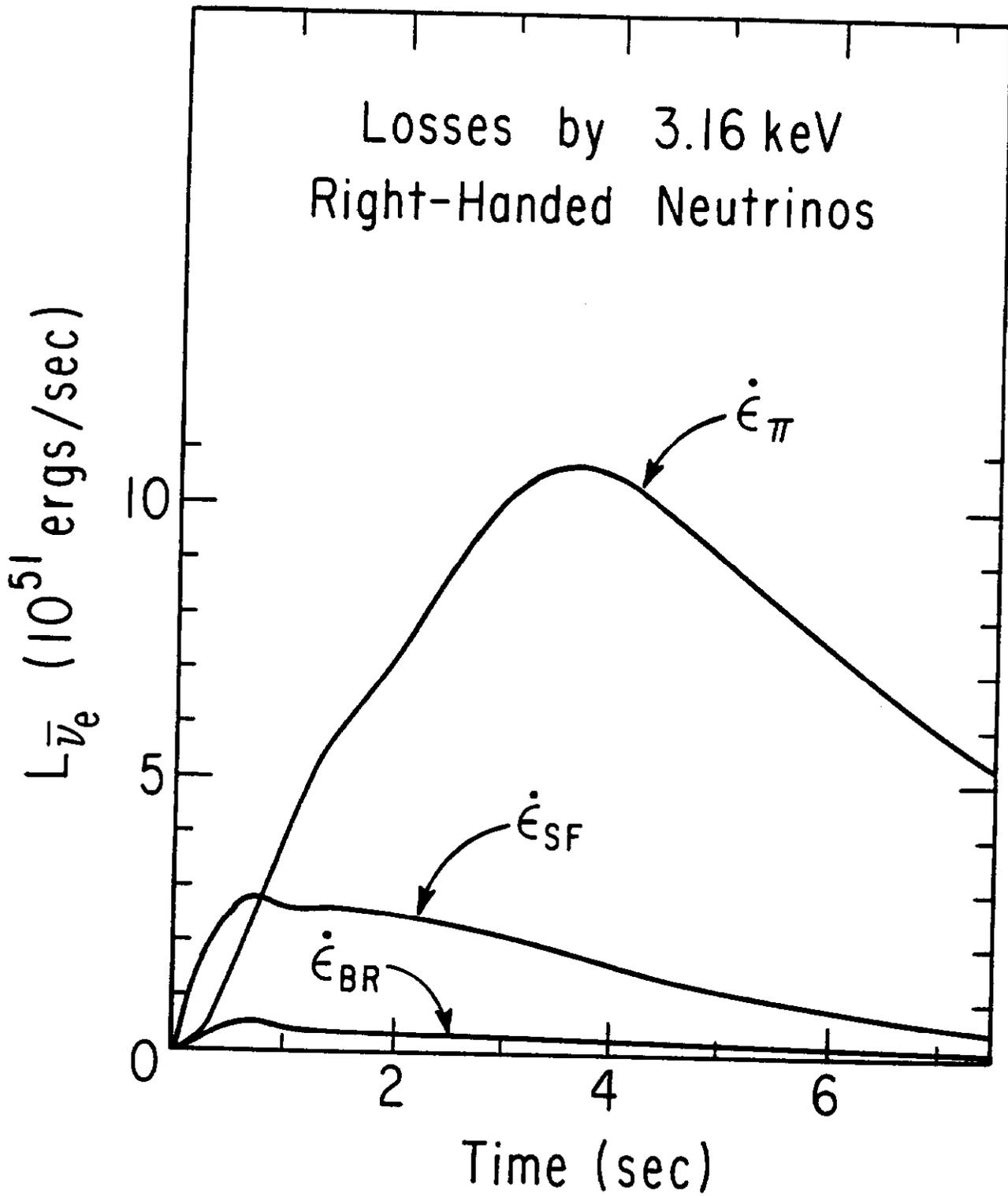
- FIG 2 -



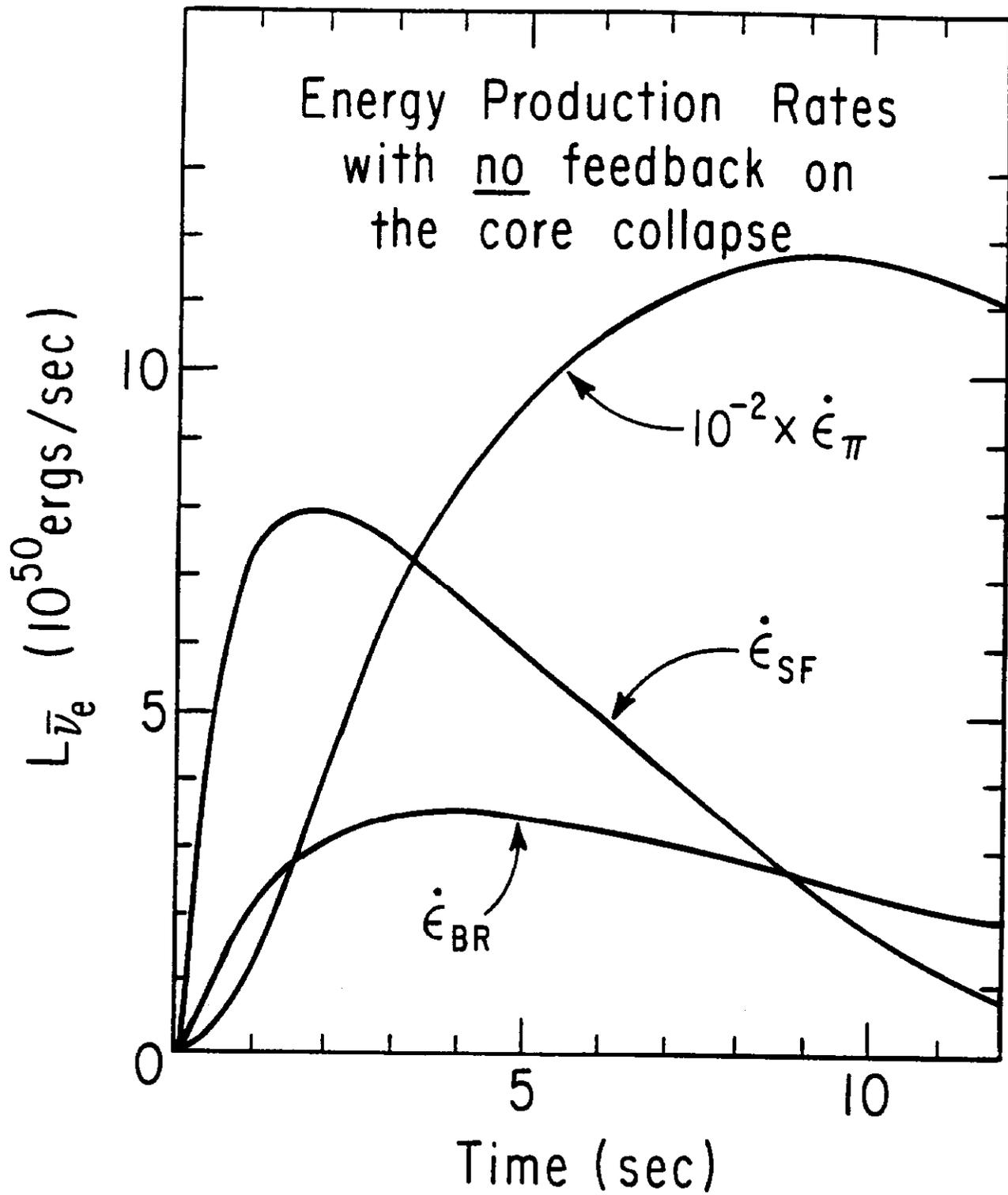
- FIG 3 -



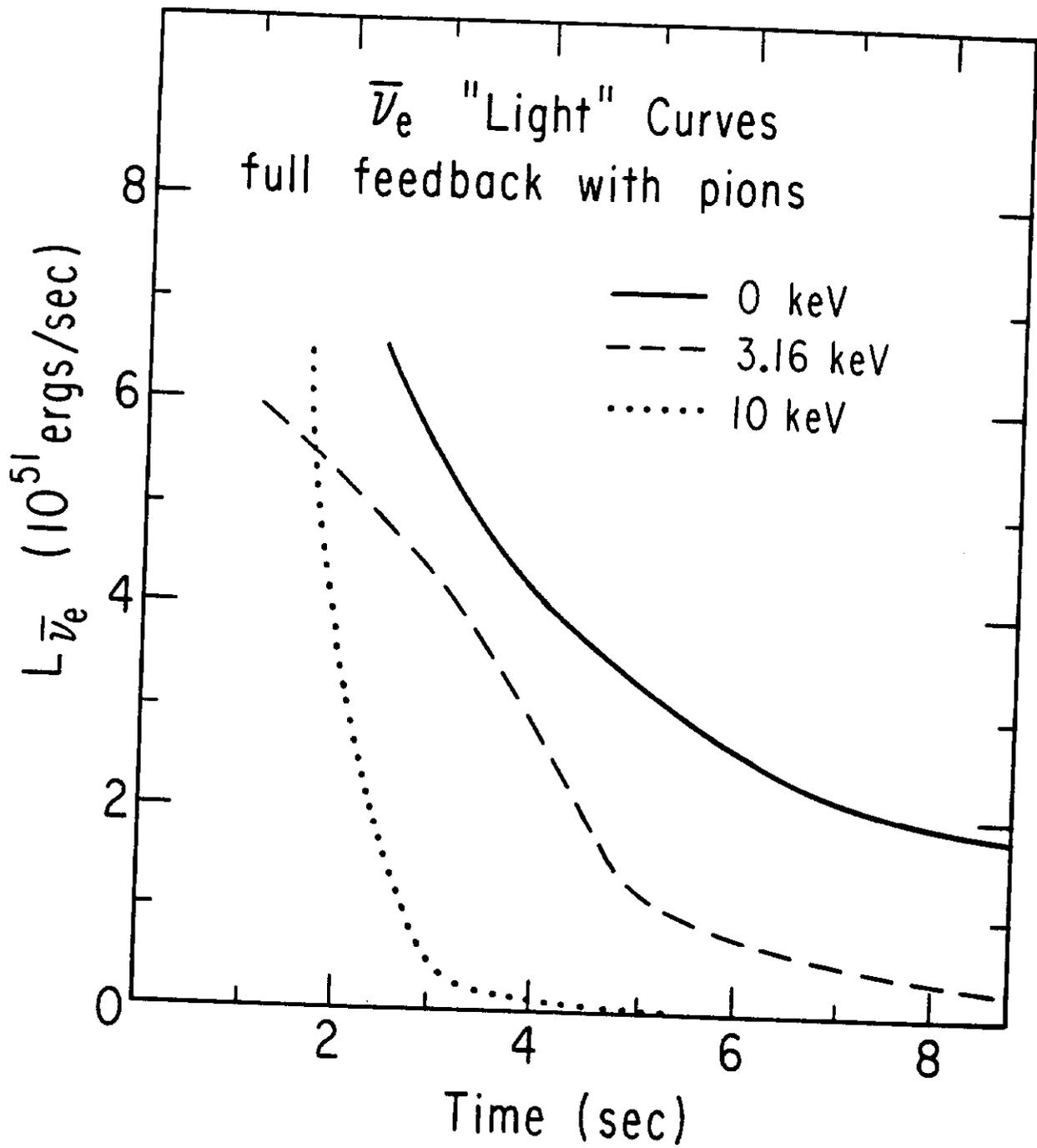
- FIG 4A -



- FIG 4B -



- FIG 4 C -



- FIG 5 -