How reliable are neutrino mass limits derived from SN1987A?

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We examine in detail the so-called *model-independent* limits on the electron-neutrino mass which follow from a dispersion analysis of the 2-sec neutrino pulse from SN1987A detected by Kamiokande II (KII). When experimental realities are taken into account, we conclude that no *reliable* constraint better than the current laboratory limits (i.e., better than order 20 eV) can be obtained. In fact, when all 11 events in the 12.4-sec KII pulse and the 8 Irvine-Michigan-Brookhaven events are considered, a 20-eV or so neutrino mass might actually diminish the inferred duration of the burst at the source. In view of all the pitfalls inherent to a model-independent analysis, we conclude that elaborate model testing is necessary to seriously address the question of neutrino mass.

I. INTRODUCTION

The recent supernova in the Large Magellanic Cloud (LMC), denoted SN1987A,[1] was an unexpected gift from the heavens. The wealth of observational data anticipated should greatly advance our understanding of the type-II supernova phenomenon. The observation of a neutrino burst associated with the optical fireworks has verified in a dramatic fashion the basic model of a type-II supernova:[2] collapse of a massive star ($\gtrsim 8-10 M_{\odot}$) to a neutron star (or black hole) with the release of the $\sim 3\times 10^{53}$ ergs of binding energy in neutrinos.

A number of authors have used the observation of the neutrino burst to constrain the properties of neutrinos — masses,[3,4] mixing angles,[5] lifetimes,[5] and magnetic moments.[5] The focus of this paper will be a critical analysis of electron-neutrino mass constraints. In particular, we will carefully examine the mass constraint which can be obtained by analyzing the dispersion of the 2-sec neutrino pulse observed by Kamiokande II. Contrary to the claims of numerous authors,[4] we do not believe that when all the experimental realities are taken into account one can obtain a *reliable limit* which is more stringent than the present 18–30-eV laboratory limit.[6]

All analyses to date are based upon the time dispersion of the emitted pulse of neutrinos caused by a nonzero neutrino mass. The velocity β of a neutrino of mass m_ν and energy $E_\nu \equiv \gamma m_\nu$ is given by

$$\beta=(1-\gamma^{-2})^{1/2}\simeq 1-0.5m_\nu^2/E_\nu^2+O(m_\nu^4/E_\nu^4)\ , \qquad (1)$$

where γ is the usual Lorentz factor. The time interval between emission (t_e) and detection (t_d) of a neutrino which traverses a distance d is

$$t_d-t_e=(d/c)/\beta\simeq(d/c)(1+0.5m_\nu^2/E_\nu^2)\ . \qquad (2)$$

Given the arrival times of the detected neutrinos, one can, for a given assumed neutrino mass, reconstruct the emission times *assuming* one knows the distance of SN1987A and the neutrino energies. Suppressing the constant d/c term one can plot the inferred emission time line as a function of m_ν^2. We have done this in Figs. 1 and 2 for all the candidate neutrino events recorded by Kamiokande II and the Irvine-Michigan-Brookhaven collaboration (IMB). The dispersive effect of a neutrino mass is apparent.

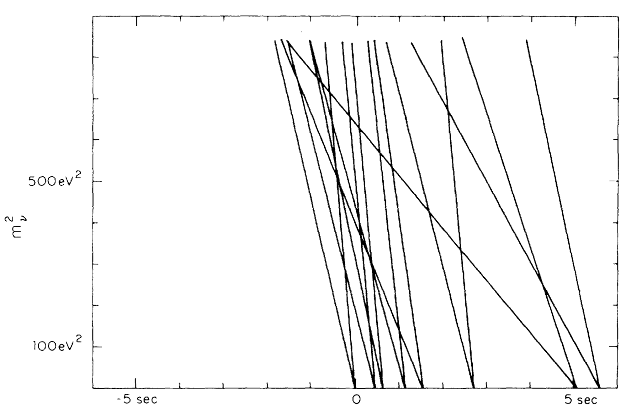

FIG. 1. Inferred neutrino event time line at the source as a function of m_ν^2 for all 8 IMB events, as computed from Eq. (7).

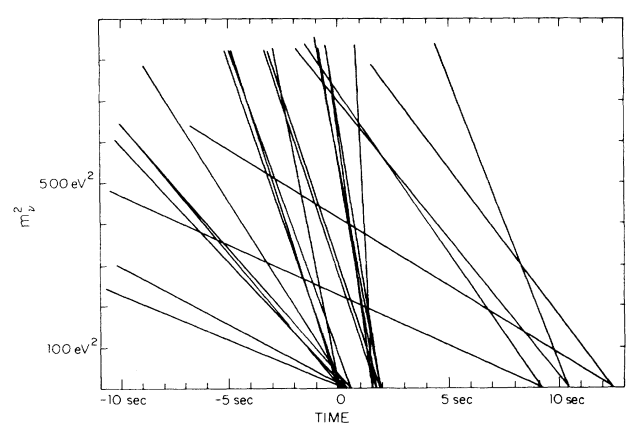

FIG. 2. Same as Fig. 1, but for all 11 KII events.

Deriving a limit on the electron-neutrino mass involves a number of steps, each wrought with uncertainties and subtleties. In order to compute the time delay for a given event one needs the *neutrino* energy (electron or positron energies are the observable) and the distance to the supernova (the distance is probably known to an accuracy of only about 30%). In order to turn the inferred time line of the events at the source into a limit on the neutrino mass one needs to specify how long a neutrino pulse one expects (or is willing to tolerate). We will discuss the process in detail and comment on the issues involved, both experimental and theoretical.

II. THE DATA

Neutrino pulses associated with SN1987A have been reported from four different underground detectors: UNO (Mt. Blanc),[7] Baksan,[8] Kamiokande II,[9] and IMB.[10] Only Kamiokande II (hereafter KII) and IMB have reported full details of their observations, and so we will restrict our discussion and analysis to their data. The 11 KII events and the 8 IMB events are summarized in Tables I and II. Several comments are in order. The energies deposited in the detector are the electron (or positron) energies, and not the neutrino energies. Two qualitatively different kinds of neutrino events expected are $\bar{\nu}_e+p\to n+e^+$ (capture) and $\nu+e^-\to\nu+e^-$ (scattering).

If the event was due to $\bar{\nu}_e+p\to n+e^+$, then the neutrino energy is related to the deposited energy by

$$E_\nu=\frac{E_e+\Delta+(\Delta^2-m_e{}^2)/2m_p}{1-(E_e-p_e\cos\theta_{\rm LMC})/m_p}\ , \tag{3}$$

where $\Delta=m_n-m_p=1.293$ MeV, E_e (p_e) is the energy (momentum) of the positron, and $\theta_{\rm LMC}$ is the angle between the positron and the incoming neutrino. Equation (3) takes into account the neutron-proton mass difference and the recoil energy of the neutron [which is a small correction: $E_{\rm rec}\lesssim 0.02E_\nu(E_\nu/10\ \text{MeV})$].[11] The process $\bar{\nu}_e+p\to n+e^+$ is to a reasonable approximation isotropic; neglecting terms of $O(E_e/m_p)$,

$$\frac{d\sigma}{d\cos\theta_{\rm LMC}}=\frac{G_F{}^2}{\pi}p_eE_e[(1+g_A{}^2)+0.5(g_A{}^2-1)(1-p_e\cos\theta_{\rm LMC}/E_e)]\propto[1.0+0.11(1-\cos\theta_{\rm LMC})]\ ,$$

where $g_A\simeq 1.26$ is the axial-vector coupling of the nucleon. The differential cross section is about 22% larger in the backward direction than in the forward direction. [For $E_e=10$ MeV, including the $O(E_e/m_p)$ terms reduces 0.11 to 0.09.]

If the event was due to ν-e^- scattering the situation is more complicated. First consider the process $\nu_e+e^-\to\nu_e+e^-$. The $y(\equiv E_e/E_\nu)$ distribution for ν_e-e^- scattering is very flat $(d\sigma/dy=\sigma_0[2.11+0.2(1-y)^2]$, where $\sigma_0=G_F{}^2m_eE_\nu/2\pi\simeq 4.29\times 10^{-44}\ \text{cm}^2\ (E_\nu/10\ \text{MeV}))$, so that the energy of the incoming neutrino is not well determined. The angle $\theta_{\rm LMC}$ between the recoil electron and the incident neutrino and y are related by

$$\cos\theta_{\rm LMC}=[(y-\epsilon)/(y+\epsilon)]^{1/2}(1+\epsilon)\ , \tag{4}$$

where $\epsilon=m_e/E_\nu$, and the kinematic limits are $\arcsin\epsilon\le\theta_{\rm LMC}\le\pi/2$ and $\epsilon\le y\le 1$. Equation (4) is plotted in Fig. 3(a). For the neutrino energies of interest, the scattering angle of the electron is peaked in the forward direction.

For a type-II supernova, the fluxes of neutrinos and antineutrinos of all types (i.e., flavors and helicities) are expected to be comparable, with the flux of electron neutrinos perhaps a factor of 2 higher. The average neutrino energies are expected to be of order 15 MeV.[12] The expected ratio of ν_e-e^- scattering events to capture is

$$R=\phi_{\nu_e}n_e\sigma(\nu_e-e^-)/\phi_{\bar{\nu}_e}n_p\sigma(\bar{\nu}_e-p)\ ,$$

where ϕ is the integrated flux of ν_e's (or $\bar{\nu}_e$'s), n_e is the number density of electrons, and n_p is the number density of free protons.

The ratio of electrons to free protons in water is 5, and

TABLE I. The 8 IMB events. In computing E_ν all the events were assumed to be $\bar{\nu}_e+p\to n+e^+$, and E_ν is related to E_e by Eq. (3) (Ref. 11). Uncertainty in E_ν is calculated using the standard formulas for propagation of error.

Event	Time (sec)	PMT's	E_e (MeV)	E_ν (MeV)	$\theta_{\rm LMC}$ (deg)
33162	0	47	38 ± 9.5	40.5 ± 10.1	74 ± 15
33164	0.42	61	37 ± 9.3	38.9 ± 9.6	52 ± 15
33167	0.65	49	40 ± 10	42.1 ± 10.4	56 ± 15
33168	1.15	60	35 ± 8.8	37.0 ± 9.2	63 ± 15
33170	1.57	52	29 ± 7.3	30.5 ± 7.4	40 ± 15
33173	2.69	61	37 ± 9.3	38.9 ± 9.6	52 ± 15
33179	5.01	44	20 ± 5	21.4 ± 5.1	39 ± 15
33184	5.59	45	24 ± 6	26.1 ± 6.4	102 ± 15

TABLE II. Same as Table I, except for the 11 KII events. Event 6 which did not satisfy their criterion $N_{\rm hit}>20$ was included only for completeness.

Event	Time (sec)	$N_{\rm hit}$	E_e (MeV)	E_ν (MeV)	$\theta_{\rm LMC}$ (deg)
1	0	58	20.0 ± 2.9	21.3 ± 2.9	18 ± 18
2	0.107	36	13.5 ± 3.2	14.8 ± 3.2	15 ± 27
3	0.303	25	7.5 ± 2.0	8.9 ± 2.05	108 ± 32
4	0.324	26	9.2 ± 2.7	10.6 ± 2.75	70 ± 30
5	0.507	39	12.8 ± 2.9	14.4 ± 3.05	135 ± 23
(6	0.686	16	6.3 ± 1.7	7.6 ± 1.7	68 ± 77)
7	1.541	83	35.4 ± 8.0	36.9 ± 8.1	32 ± 16
8	1.728	54	21.0 ± 4.2	22.4 ± 4.25	30 ± 18
9	1.915	51	19.8 ± 3.2	21.2 ± 3.25	38 ± 22
10	9.219	21	8.6 ± 2.7	10.0 ± 2.8	122 ± 30
11	10.433	37	13.0 ± 2.6	14.4 ± 2.65	49 ± 26
12	12.439	24	8.9 ± 1.9	10.3 ± 1.95	91 ± 39

the relevant cross sections are[13]

$$\sigma(\nu_e\text{-}e^-)=0.94\times10^{-43}\,\mathrm{cm}^2(E_\nu/10\ \mathrm{MeV})\ , \tag{5a}$$

$$\sigma(\bar{\nu}_e\text{-}p)=0.89\times10^{-41}\,\mathrm{cm}^2(E_e/10\ \mathrm{MeV})^2\ . \tag{5b}$$

The expected ratio of events is in the range of $R \simeq 0.06-0.12(10\ \mathrm{MeV}/E_\nu)$.

Other types of ν-e^- scattering events are also possible: $\nu_i+e^- \rightarrow \nu_i+e^-$ $(i=\mu,\tau)$; $\bar{\nu}_i+e^- \rightarrow \bar{\nu}_i+e^-$ $(i=e,\mu,\tau)$. The cross sections[13] for these interactions are smaller:

$$\sigma(\bar{\nu}_e\text{-}e^-)=3.9\times10^{-44}\,\mathrm{cm}^2(E_\nu/10\ \mathrm{MeV})(d\sigma/dy=\sigma_0[2.11(1-y)^2+0.2])\ ,$$

$$\sigma(\bar{\nu}_{\mu,\tau}\text{-}e^-)=1.3\times10^{-44}\,\mathrm{cm}^2(E_\nu/10\ \mathrm{MeV})(d\sigma/dy=\sigma_0[0.3(1-y)^2+0.2])\ ,$$

$$\sigma(\nu_{\mu,\tau}\text{-}e^-)=1.6\times10^{-44}\,\mathrm{cm}^2(E_\nu/10\ \mathrm{MeV})(d\sigma/dy=\sigma_0[0.2(1-y)^2+0.3])\ .$$

The y distributions for these processes are not as flat as that for ν_e-e^- scattering [see Fig. 3(b)]; however, because of kinematics [see Fig. 3(a)] these elastic processes should still be peaked in the forward direction. Taking the integrated ν_e flux to be twice that of the other flavors, the expected ratio of ν_e-e^- scattering events to all other ν-e^- scattering events is about 2.0.

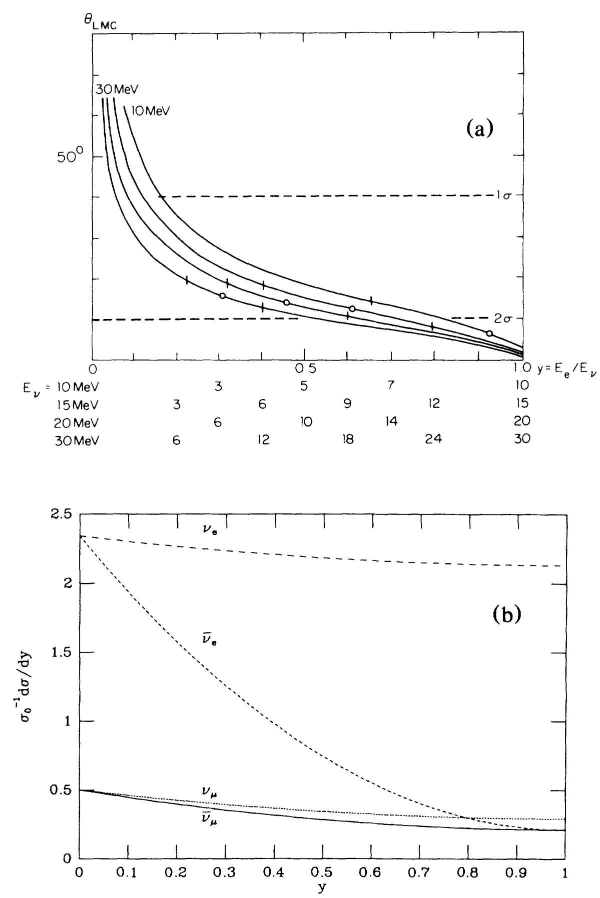

FIG. 3. (a) Scattering angle as a function of y for ν-e^- scattering, for incident neutrino energies of $E_\nu=10$, 15, 20, 30 MeV. Open circles and vertical ticks (1σ energy error flags) on the curves refer to candidate ν-e^- scattering event 4. (b) The y distribution, $\sigma_0{}^{-1}d\sigma/dy$ as a function of y for the different ν-e^- scattering processes: $\sigma_0=G_F{}^2m_eE_\nu/2\pi$.

Comparing the ratio of the total ν-e^- scattering cross sections to the total capture cross section to estimate the relative numbers of $\bar{\nu}_e$-p and ν-e^- events expected can be misleading, and probably overestimates the expected number of ν-e^- scattering events. For capture events the e^+ carries off all but ~1.3 MeV of the incident neutrino's energy, while for the ν-e^- scattering events the e^- carries off only a fraction y of the neutrino's energy. Because of detector thresholds, only ν-e^- scatterings with $y \gtrsim E_{\mathrm{threshold}}/E_\nu$ can be detected. To illustrate the significance of the detector threshold, note that

$$\int_{1/3}^{1}(d\sigma/dy)dy \Big/ \int_{\epsilon}^{1}(d\sigma/dy)dy = 0.66(\nu_e\text{-}e^-)$$
$$=0.38(\bar{\nu}_e\text{-}e^-)$$
$$=0.60(\nu_{\mu,\tau}\text{-}e^-)$$
$$=0.54(\bar{\nu}_{\mu,\tau}\text{-}e^-)\ .$$

To properly address the question of the relative numbers of capture versus scattering events will necessarily require more elaborate model testing.

Only neutrino interactions which deposit energy $\gtrsim 5-10$ MeV can be detected, so that processes like $\nu+p \rightarrow \nu+p$ are not detectable. At the relevant energies, the cross sections for $\nu_e+{}^{16}\mathrm{O} \rightarrow e^-+{}^{16}\mathrm{F}$ and $\bar{\nu}_e+{}^{16}\mathrm{O} \rightarrow e^++{}^{16}\mathrm{N}$ are far below those for the two processes discussed above, and can be ignored.

The "$\cos\theta$" histogram for KII's events is nearly isotropic, with an excess of 2–4 events in the bins nearest to the direction of the LMC, suggesting that a few of their events are due to ν-e^- scattering. Based upon our previous discussion, this is about what one would expect on theoretical grounds. Using the Kolmogorov-Smirnov statistic we have tested models for the angular distribution of the KII events which allow for both capture and scattering events, and take into account the Gaussian angular uncertainties in the direction of the positron (or electron). We find that for between 2 and 8 ν-e^- scattering events the Kolmogorov-Smirnov significance level is greater than 0.3, while for zero scattering events the significance level is only 0.08. We hasten to add that since the angular distribution for $\bar{\nu}_e+p \rightarrow n+e^+$ is nearly isotropic and the angular uncertainty is large (of the order of 30°), one cannot identify which events are ν-e^- scattering events, except in a statistical sense.

Since the energies of the IMB events are higher and there are fewer events, one would expect less than 1 ν-e^-

scattering event. In any case, because of detector malfunction [due to the failure of a high-voltage power supply, 25% of their photomultiplier tubes (PMT's) were not functional[10]], their $\cos\theta$ histogram is of dubious value (it is not flat, and is peaked in a direction of 20°–40° away from the LMC). Indeed, similar model testing shows a level of significance of less than 0.20 for *any* number of assumed ν-e^- scattering events (for zero scattering events the level of significance is 0.02).

In Tables I and II the uncertainties in the energy of the electron (positron) and its direction (relative to a vector from the LMC to the detector) are also listed. For IMB the uncertainties in energy and angle are *estimated* uncertainties, and there may be additional systematic uncertainties due to the detector malfunction. For KII the quoted uncertainties for both energy and angle are stated to be Gaussian, 1σ values. [Presumably the stated uncertainty in energy for a given event is the variance of the spread in *detected* energies for incident electrons (or positrons) of the *stated* energy.] A note of caution here too. Determining the probability distribution of *inferred* electron (or positron) energies for a *given* observed energy requires knowledge of the energy distribution of incident neutrinos as well as knowledge of the detector response, and is thus *model dependent.*

If we allow ourselves to make assumptions about the incident neutrino spectrum, then we may calculate the probability distribution of the *actual* electron (or positron) energies for each event. Bayes's theorem tells us that the probability distribution for electron (or positron) energies ($\equiv E_e$) for a *given* observed energy ($\equiv E_{\rm obs}$) is

$$p(E_e\,|\,E_{\rm obs})dE_e=\frac{p(E_{\rm obs}\,|\,E_e)dE_{\rm obs}p(E_e)dE_e}{p(E_{\rm obs})dE_{\rm obs}}, \quad (6)$$

where we have used the standard notation for conditional probabilities. The denominator is independent of E_e and only serves to normalize the distribution. The conditional distribution $p(E_{\rm obs}\,|\,E_e)$ gives the spread in measured energies for a given actual energy, and depends only on the detector response. The distribution $p(E_e)$ is the expected distribution of energies of detected electrons (or positrons) and is given by

$$p(E_e)\propto\phi_{\bar\nu_e}(E_e+\Delta)\sigma_{\bar\nu_e p}(E_e)\epsilon(E_e),$$

where $\epsilon(E_e)$ is the detection efficiency for positrons of energy E_e and the normalization constant is independent of E_e. For simplicity we have restricted ourseleves to the capture process only.

The distribution of *actual* positron energies for a given *measured* energy will be "approximately" the same as the distribution of *measured* energies for a given *actual* energy if $p(E_e)$ is "roughly constant," where $p(E_{\rm obs}\,|\,E_e)$ is "large," i.e., if either the measurement errors are small or if $p(E_e)$ is approximately independent of energy. If this were the case then the quoted energies and errors (in Tables I and II) would be good indicators of the actual positron energies and uncertainties.

Unfortunately, the measurement errors are not small and the expected energy distribution of detected positrons is not particularly flat. For a thermal flux of $\bar\nu_e$'s $\phi_{\bar\nu_e}\propto E_\nu{}^2/[\exp(E_\nu/T)+1]$, and $p(E_e)\propto E_e{}^2(E_e+\Delta)^2\times\epsilon(E_e)/[\exp(E_e/T+\Delta/T)+1]$. Thus the expected energy distribution is not even approximately constant, but is sharply peaked around $E_e\sim 4T$ with a variance that is comparable to the measurement uncertainties. The median and variance of the distribution for the inferred positron energy, given the measured energy, will not be similar to that for the distribution of measured energies for incident positrons of a given energy. Using the published detector efficiencies and taking $p(E_{\rm obs}\,|\,E_e)$ to be a Gaussian of the stated variance, we have computed the *model-dependent* positron energy distributions for both the IMB and KII events, with assumed $\bar\nu_e$ temperatures of 3, 4, and 5 MeV. The median energies and effective standard deviations are given in Tables III and IV.

The differences between the median positron energy and the measured energy are striking; for the low-energy events the most likely energies are upgraded and for the high-energy events the energies are reduced. In short, because of the strong energy dependence of the positron energy distribution $p(E_e)$, the most likely positron energies regress to the mean. That this should occur is easy to understand. Because the flux of high-energy $\bar\nu_e$'s falls exponentially with energy, it is more likely that an event with a large measured energy (e.g., KII event 7) actually originated from a lower-energy positron which deposited more energy than usual, than it is that the positron actually had the measured energy. For KII event 7 and an as-

TABLE III. The median of the expected positron energy distribution and effective standard deviation for the 8 IMB events, assuming that they were due to $\bar\nu_e+p\to n+e^+$, and that the $\bar\nu_e$'s are characterized by a temperature of 3, 4, or 5 MeV.

		Positron energy distribution (MeV)		
Event	Energy deposited (MeV)	$T=3$ MeV	$T=4$ MeV	$T=5$ MeV
33 162	38 ± 9.5	$28.8^{6.4}_{-5.6}$	$32.1^{+7.2}_{-6.2}$	$34.5^{+7.7}_{-6.7}$
33 164	37 ± 9.3	$28.5^{+6.3}_{-5.5}$	$31.7^{+7.1}_{-6.1}$	$34.0^{+7.5}_{-6.5}$
33 167	40 ± 10	$29.2^{+6.7}_{-5.8}$	$32.8^{+7.6}_{-6.5}$	$35.5^{+8.0}_{-7.1}$
33 168	35 ± 8.8	$28^{+6.0}_{-5.3}$	$30.9^{+6.7}_{-5.8}$	$33.0^{+7.0}_{-6.2}$
33 170	29 ± 7.3	$26.1^{+5.1}_{-4.6}$	$28.2^{+5.5}_{-5.0}$	$29.6^{+5.7}_{-5.1}$
33 173	37 ± 9.3	$28.5^{+6.3}_{-5.5}$	$31.7^{+7.1}_{-6.1}$	$34.0^{+7.5}_{-6.5}$
33 179	20 ± 5	$21.8^{+3.6}_{-3.2}$	$22.8^{+3.8}_{-3.4}$	$23.5^{+3.9}_{-3.5}$
33 184	24 ± 6	$23.9^{+4.4}_{-3.9}$	$25.4^{+4.6}_{-4.1}$	$26.4^{+4.7}_{-4.3}$

TABLE IV. Same as Table III, except for the 11 KII events.

Event	Energy deposited (MeV)	Positron energy distribution (MeV) $T=3$ MeV	$T=4$ MeV	$T=5$ MeV
1	20 ± 2.9	$19.0^{+2.8}_{-2.6}$	19.7 ± 2.7	$20.0^{+2.8}_{-2.7}$
2	13.5 ± 3.2	$13.9^{+2.7}_{-2.6}$	$14.5^{+2.8}_{-2.6}$	$14.9^{+2.8}_{-2.7}$
3	7.5 ± 2.0	$8.9^{+1.7}_{-1.5}$	$9.2^{+1.7}_{-1.6}$	$9.3^{+1.8}_{-1.6}$
4	9.2 ± 2.7	$10.7^{+2.3}_{-2.1}$	11.2 ± 2.2	$11.4^{+2.3}_{-2.2}$
5	12.8 ± 2.9	$13.3^{+2.5}_{-2.4}$	$13.8^{+2.6}_{-2.4}$	14.2 ± 2.5
7	35.4 ± 8.0	$24.9^{+6.7}_{-6.2}$	$28.6^{+7.1}_{-6.7}$	$31.0^{+7.2}_{-6.8}$
8	$21.0+4.2$	$19.1^{+3.7}_{-3.6}$	$20.2^{+3.9}_{-3.6}$	$21.0^{+3.8}_{-3.7}$
9	19.8 ± 3.2	$18.7^{+3.0}_{-2.9}$	$19.4^{+3.0}_{-2.9}$	$19.9^{+3.0}_{-2.9}$
10	8.6 ± 2.7	$10.3^{+2.3}_{-2.0}$	10.8 ± 2.2	$11.0^{+2.3}_{-2.1}$
11	13.0 ± 2.6	13.4 ± 2.3	$13.8^{+2.3}_{-2.2}$	14.1 ± 2.3
12	8.9 ± 1.9	$9.8^{+1.8}_{-1.6}$	10.1 ± 1.7	10.3 ± 1.7

sumed $\bar{\nu}_e$ temperature of 4 MeV, the median of the positron energy distribution corresponds to a 1σ downward fluctuation from the measured energy.

Our purpose here is not to do the definitive analysis of the most probable positron energies—that will best be done by the experimenters themselves—but rather to illustrate the difficulty of a "model-independent" analysis: Not even the most likely positron energies and uncertainties can be assigned in a model-independent way.

Another experimental reality which must be kept in mind is the background count rate. (For our purposes background refers to any event not associated with the supernova; e.g., detector noise, radioactivity, etc.) For KII the background count rate per 10-sec interval for events with $N_{\rm hit}\geq 20,25,30$ is $\bar{n}(N_{\rm hit}\geq 20)=0.219$, $\bar{n}(N_{\rm hit}\geq 25)\simeq 0.1$, $\bar{n}(N_{\rm hit}\geq 30)=0.0121$ ($N_{\rm hit}$ is the number of PMT's which "fire"). The background rates for $N_{\rm hit}\geq 20,30$ are well measured and are Poisson distributed;[9] the rate for $N_{\rm hit}\geq 25$ is estimated.[14] The importance of these rates is the fact that some of the "events," especially the events with $N_{\rm hit}\lesssim 25$, have a reasonable probability of being random background events not associated with the supernova. The background rate for the trigger used at IMB was 0.77 per 10-sec interval, and it too is well described by a Poisson distribution.[10] For the IMB data, there is a probability of $1-\exp(-0.77)\simeq 0.54$ to have at least 1 background event during a 10-sec interval.

III. THE SUPERNOVA

As mentioned earlier, in order to use the neutrino-pulse dispersion technique to constrain the electron-neutrino mass one must have some knowledge about the supernova itself. From Eq. (1) it is clear that one needs to know its distance from the detector. One of the most unsettled and controversial issues in astronomy today is the distance scale. (For recent reviews of the current state of affairs, see Refs. 15–17.) Remarkably, distances within our own Galaxy are only known to an accuracy of about 10%. The distances to members of our local group (of which the LMC is a member) have been and still are a lively topic of investigation. The distance to the LMC has been determined using Cepheid variables, RR Lyrae stars, Novae, and other techniques. In Rowan-Robinson's recent review[15] he obtains a weighted average of 54.9 kpc ($=1.70\times10^{23}$ cm), with an estimated error of 7% (internal) and 5% (external). (Remarkably, both Sandage and Tammann and de Vaucouleurs obtain very similar distances to the LMC, 52.2 and 45.9 kpc, respectively.[15]) These errors *do not* reflect any of the uncertainties associated with the "lower rungs" of the distance ladder (e.g., the distance to the Hyades cluster, galactic extinction corrections, etc.) needed to get out to the LMC. When all of those uncertainties are taken into account, Huchra[17] estimates a total uncertainty in the distance to the LMC of about 29%. In addition, the diameter of the LMC is of the order of 10 kpc, and the depth of SN1987A within the LMC is not known at present. A reasonable estimate of the distance to SN1987A is probably $d\simeq 55\pm 15$ kpc. In fact, the distance to the LMC and SN1987A may best be measured by studying the supernova itself.[18]

Since the time delay is proportional to $dm_\nu{}^2$, an error of 30% in the distance translates to an error of about 15% in any neutrino mass limit. To be conservative we take 40 kpc as a reasonable lower bound to the distance to the supernova, Eq. (1) becomes

$$t_d-t_e\simeq 4.1\times10^{12}\,\text{sec}+2.1\,\text{sec}(m_{10}{}^2/E_{10}{}^2)\ , \qquad (7)$$

where $m_{10}=m_\nu/10$ eV and $E_{10}=E_\nu/$ 10 MeV. The numerical coefficient in our Eq. (7) differs from other authors,[4] many of whom have used about 2.6 sec, and reflects our realism with regard to present knowledge of the distance to the supernova. [Note: Our mass limits can be rescaled to a different assumed distance for the LMC by $m_\nu\rightarrow(40\ \text{kpc}/d)^{1/2}m_\nu$.]

Now that we have dealt with the easy matter of the distance to the object, on to the less certain matter of the theoretical expectations for the characteristics of the neutrino pulse itself. Since the seminal work of Colgate and White,[2] essentially all theorists agree that the bulk of the binding energy of the neutron star which is formed is released in neutrinos. Most of the recent calculations for the expected neutrino fluxes agree that[12] (1) the total energy ($\sim 3\times10^{53}$ ergs) is shared about equally between all six neutrino flavors (perhaps the total energy in electron neutrinos is a factor of 1.5–2 larger); (2) the spectrum of emitted neutrinos is nearly thermal (Fermi-Dirac distribution), with a temperature of the order of 5 MeV (which might vary during the burst) [a preliminary maximum-likelihood determination of the inferred temperature based on the combined KII and IMB data gives $T \simeq 4$ MeV (Ref. 19)]; and (3) the bulk of the energy should be released in a time period of the order of a few sec (perhaps as long as 10 sec), with the most detailed models giving burst durations of about 1–3 sec. For purposes of a "model-independent" model, these three features have become "theoretical facts."

IV. PULSE-DISPERSION MASS CONSTRAINTS

A quick glance at Eq. (7) suggests that one should plot the inferred time line at the source versus neutrino mass squared to see the dispersive effect for different neutrino masses.[3] (Ideally, one would start with a model for neutrino emission at the source and then evolve the expected pulse at the detector. Since we are trying to address the issue of *model-independent* bounds we cannot do this.) Shortening of the inferred pulse at the source for some value of m_ν^2 might suggest evidence for a nonzero electron-neutrino mass. Significant lengthening of the pulse, relative to the pulse observed at the detector, would seem to provide evidence against a neutrino mass of the value indicated, or for a "conspiracy of sorts," e.g., lower-energy neutrinos being emitted earlier than higher-energy neutrinos (interestingly, there is such an indication in the models of Mayle and co-workers[12]).

Pulse-dispersion plots are shown in Figs. 1 and 2 for all the IMB and KII events. For these plots all the events are assumed to be due to the process $\bar{\nu}_e + p \to n + e^+$, and for each event, a 1σ cone is drawn. That is, the energy is interpreted to be the energy computed in Eq. (3) $\pm$ the stated 1σ uncertainty (see Tables I and II). (Because of the ± 1 min absolute timing uncertainty of the KII events the two data sets cannot be combined.)

From Fig. 1 it is clear that the IMB data not show significantly greater dispersion at the source than at the detector for neutrino masses less than about 30 eV. In fact, a neutrino mass of the order of 20–30 eV could significantly reduce the inferred pulse width at the source. (Recall too that there is a probability of 0.54 of having at least 1 background event during a 10-sec interval so that one of the 8 events may not be associated with the supernova at all.) Indeed, none of the authors[4] have used the IMB data to obtain a mass constraint.

When all 11 KII events are displayed (Fig. 2), one has a pulse at the detector of about 12.4-sec duration, longer than the theoretical expectations, suggesting that if theory and observation are to be reconciled, either a nonzero neutrino mass is required or some of the events have to be ignored (ignoring 10, 11, and 12 narrows the pulse width to about 2 sec). A quick visual scan of Fig. 2 suggests that a 20-eV neutrino mass might ("if the 1σ's break the right way") improve the agreement between the KII data and theoretical expectations. Without performing an elaborate Monte Carlo simulation to test the various theoretical models, we believe that this is about all one can say about the constraints that the *entire* data set provide.

Many authors[4] go on and for one reason or another argue that events 10–12 should be ignored (or just ignore them). Can they be so easily dismissed? The probability of having 3 or more background events with $N_{\rm hit} \geq 20$ in a 10-sec interval is

$$p_{\geq 3} = 1 - \exp(-\bar{n})(1 + \bar{n} + \bar{n}^2/2!) \simeq 1.5 \times 10^{-3}$$

(where $\bar{n} = 0.219$). The probability of having 2 or more background events with $N_{\rm hit} \geq 25$ in a 10-sec interval is (estimating $\bar{n} \simeq 0.1$)

$$p_{\geq 2} = 1 - \exp(-\bar{n})(1 + \bar{n}) \simeq 4.7 \times 10^{-3} \ .$$

The probability of having 1 or more background events with $N_{\rm hit} \geq 30$ is only

$$p_{\geq 1} = 1 - \exp(-\bar{n}) \simeq 1.2 \times 10^{-2}$$

[where $\bar{n} = 0.121$; presumably $\bar{n}(N_{\rm hit} \geq 37) \ll \bar{n}(N_{\rm hit} \geq 30)$, so that the probability of a background event as energetic as event 11 is much, much less than 10^{-2}]. We conclude that it is very unlikely that all of the final 3 events are random background events. The more than 7-sec gap between events 9 and 10 is very puzzling. Poisson fluctuations are of no assistance in explaining them away. Based upon a constant count rate of 11 events in 12.4 sec, the probability that a 7-sec interval would have zero events is

$$p_0 = \exp(-6.2) \simeq 2.0 \times 10^{-3} \ .$$

There is no indication that the detector was not operative during this gap.[20] One should keep in mind that the expected neutrino flux decays with time, and perhaps the neutrino flux and average neutrino energy dropped off significantly after the first 2 sec so that the typical incident neutrinos are near threshold, thereby giving rise to only a few events (with large fluctuations) in the last 10 sec.

There also appears to be substructure within the 2-sec KII pulse—a gap of 1.034 sec between events 5 and 7 (or 0.855 sec between events 6 and 7). This gap is statistically less significant, however. Assuming that the event rate during the 2-sec pulse is a constant 4 sec^{-1}, there is a probability of 1.6% (3.3%) for having a gap of 1.034 sec (0.855 sec), based again on Poisson statistics.

Without ignoring events 10–12 one cannot place an interesting constraint on the mass of the electron neutrino; indeed, by careful model testing one may be able to conclude that the best agreement between theoretical models and the data *requires* a neutrino mass of order 20 eV. That remains to be seen. As others have done, let us ignore events 10–12, and see what neutrino mass limits follow from the KII data. [Before going on, we mention a very novel scenario which could justify ignoring events 10–12. Dismiss the two softest events, 10 and 12 ($N_{\rm hit} = 21, 24$), as background events, and identify event 11 as a $\nu_{\mu,\tau}$-e^- or $\bar{\nu}_{\mu,\tau}$-e^- scattering event. The 7-sec gap can then be explained by a mass of order 30 eV for either the μ or τ neutrino.]

Figure 4 is an inferred time line at the source versus neutrino mass squared plot with an expanded time scale

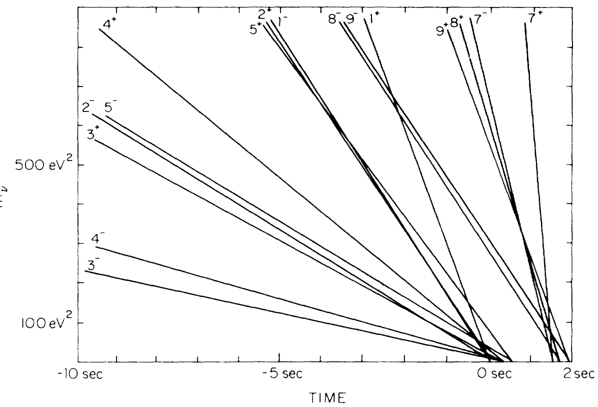

FIG. 4. Same as Fig. 1, but for the 8 KII events in the first 2 sec.

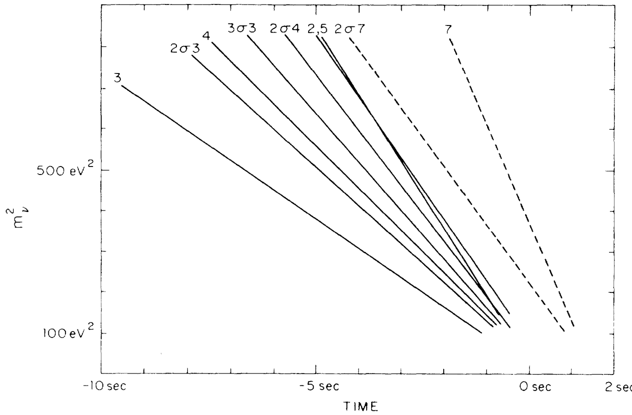

FIG. 6. Same as Fig. 5, except using the median positron energies and effective standard deviations, assuming a 4-MeV temperature for the emitted $\bar{\nu}_e$'s (see Table IV).

and without events 10–12. It is clear from this plot that the inferred "pulse envelope" diverges rapidly for $m_\nu{}^2 \gtrsim 100$ eV^2. The expanding envelope is defined on the right by the very stiff event 7 (36.9 $\pm$8.0 MeV) and on the left by the two very soft events 3 and 4 (8.9$\pm$2.0 MeV and 10.6$\pm$2.7 MeV, respectively). That the envelope should be defined by the stiffest and two of the softest events is not surprising. For future reference we mention that if event 7 should become suspect, the right side is buttressed by almost identical events 8 and 9, and on the left, should events 3 and 4 be suspect, events 2 and 5 become the buttress. The envelopes defined by events 3, 4, 2–5, 7, and 8 and 9 are shown in Fig. 5. For comparison and to illustrate the difficulty of "model-independent" analysis, we show in Fig. 6 the analogous envelopes using the median positron energies and effective standard deviations from Table IV for an assumed $\bar{\nu}_e$ temperature of 4 MeV. The differences between the two figures are striking; since the most likely energies are lower than the measured energies for the higher-energy events and higher than the measured energies for the lower-energy events, the inferred pulse envelope is narrower.

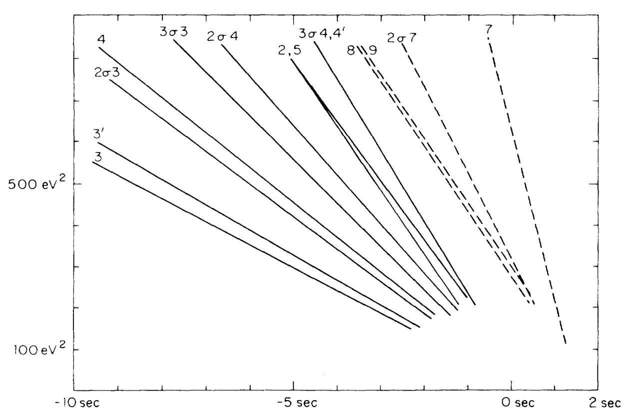

FIG. 5. Neutrino pulse-dispersion envelope for the 8 KII events in the first 2 sec. The inferred pulse width at the source is defined by choosing a dashed line and solid line. Event 3′ is a 1σ interpretation of event 3 with an additional 0.511 MeV added to the energy in Table II (see Ref. 11). Event 4′ is a 1σ interpretation of event 4 as ν_e-e^- scattering with $y=0.6$.

The most stringent constraint on the neutrino mass then relies upon events 3 and 7. How secure are these events? Event 7 is the most energetic event. If it were actually due to ν-e^- scattering, the inferred neutrino energy would be *greater* and any limit would improve. Events 3 and 4 are two of the feeblest events. In particular, using $\bar{n}(N_{\rm hit} \geq 25) \simeq 0.1$, there is a $\sim$12% probability of having at least 1 background event similar to event 3 during the 12.4-sec pulse interval—a 100 times greater probability than events 10–12 (which we just ignored as background) not being associated with the supernova. What about event 4? It too is a very soft event; however, it is not likely that both events 3 and 4 are background events. Event 4 with a measured direction of 70° $\pm$ 30° is at the 1–2σ level a candidate for a ν-e^- scattering event. If it were such an event, the neutrino energy would be something like a factor of 1.2–3 greater than the measured electron energy [see Fig. 3(a)]. In this case, event 4 would be of little or no use in defining the pulse envelope (see Fig. 5).

Armed with this knowledge, how does one go about obtaining a *reliable* constraint to the electron-neutrino mass? In this context, reliable might mean good enough to argue against doing further experiments to search for a neutrino mass in excess of the quoted limit. To preview our conclusion, we do not feel that the neutrino burst data from KII can be used to give a *reliable* (so defined) neutrino mass constraint which is better than current laboratory limits, i.e., better than order 20 eV, or so.

Now for the limits (plural). In Table V we summarize the mass limits which can be obtained by requiring the source pulse to be no longer in duration than the somewhat arbitrary interval of 4 (or 5) sec and using the envelopes defined by events 7 or 8 and 9, and events 3, 4, or 2–5. We will also consider various interpretations of the

TABLE V. Neutrino mass limits. Limits are obtained using the envelopes defined by the events specified using Fig. 5, and assuming that the duration of the neutrino pulse must be less than 4 sec (5 sec), and are given to the nearest 0.5 eV.

Envelope events		≤ 4 sec (eV)	≤ 5 sec (eV)
$1\sigma 7$	$1\sigma 3$	13.5	15.5
	$2\sigma 3$	16.5	19
	$1\sigma 4$	17.5	20
	$3\sigma 3$	19.5	23
	$2\sigma 4$	22	25.5
	$1\sigma 2,5$	25.5	30
$2\sigma 7$	$1\sigma 3$	14.5	17
	$2\sigma 3$	19	22
	$1\sigma 4$	20.5	23.5
	$3\sigma 3$	24	28.5
	$2\sigma 4$	28.5	>30
	$1\sigma 2,5$	>30	>30
$1\sigma 8,9$	$1\sigma 3$	15	17.5
	$2\sigma 3$	20	24
	$1\sigma 4$	22	26

TABLE VI. Neutrino mass limits. Same as Table V, but using the most likely energies and effective standard deviations for $T_{\bar{\nu}_e}=4$ MeV (see Table IV).

Envelope events		≤ 4 sec (eV)	≤ 5 sec (eV)
$1\sigma 7$	$1\sigma 3$	17.0	19.5
	$2\sigma 3$	21.0	24.5
	$1\sigma 4$	23.0	26.5
	$3\sigma 3$	26.0	>30
	$2\sigma 4$	>30	>30
	$1\sigma 2,5$	>30	>30

events, by which we mean considering an energy cone of the stated number of σ. After all, is it reasonable to call a limit based upon a 1σ variation of 1 event reliable? The tightest limit one can obtain is by using the envelope defined by the 1σ interpretation of both events 3 and 7, and tolerating an inferred pulse duration of no longer than 4 sec. The limit is about 13.5 eV. (Here and throughout we will state all "limits" to the nearest 0.5 eV.) Taking a 2σ interpretation of event 3 relaxes the limit to 16.5 eV. Discarding event 3 (or taking a 3σ interpretation of it) results in a 17.5-eV limit based upon a 1σ interpretation of event 4. A 2σ interpretation of event 4 relaxes the limit further to 22 eV. Discarding events 3 and 4 altogether (recall event 3 could be a background event and event 4 a ν-e^- scattering event) and relying upon the 1σ interpretation of events 2 and 5 leads to a limit of 25.5 eV. Relaxing the interpretation of event 7 to 2σ results in the following limits: 14.5 eV (1σ 3), 19 eV (2σ 3), 20.5 eV (1σ 4), 24 eV (3σ 3), 28.5 eV (2σ 4), >30 eV (1σ, 2,5). The corresponding limits imposing a 5-sec duration constraint are enumerated in Table V. In Table VI we list the limits which follow from using the model-dependent most likely positron energies (from Table IV). It is clear from Tables V and VI that the neutrino mass limit one obtains depends on the assumptions one is willing to make about the data, and that the limit cannot be truly model independent.

V. CONCLUDING REMARKS

SN1987A is the brightest supernova seen on our planet since the advent of the telescope. It is a truly remarkable and historic event which will advance our scientific knowledge immeasurably. However, we believe that when the excitement of the moment dies down and *all* the neutrino data from IMB and KII are examined carefully and soberly, this miraculous supernova will not have improved the limit on the mass of the electron neutrino beyond the current laboratory limits in the 18–30-eV range. They will remain the standard. And so it is premature to rule out even an electron-neutrino-dominated Universe yet (recall that the fraction of critical density contributed by a massive neutrino species is $\Omega_\nu = 96h^{-2}$ eV, where the present value of the Hubble parameter is $100h$ km sec^{-1} Mpc^{-1}). That is not to say that theoretical models for the emission of neutrinos from the supernova should not be tested further. They definitely should (and we among others are in the process of doing so). What is clear to us is that it is not possible to address the question of neutrino mass in a "model-independent" way; both the model for supernova neutrino emission and the value of the neutrino mass must necessarily be tested simultaneously. When the *Monte Carlo* simulations are done, and the dice stop rolling, it may very well be that the best agreement between the models and the data will require a nonzero neutrino mass of the order of 20 eV. There are already hints of such in Figs. 1 and 2.

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