CERN-TH.4701/87
UMN-TH-605/87

CONSTRAINTS ON LIGHT PARTICLES FROM SUPERNOVA SN 1987a

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A B S T R A C T

We show how the recent observations of neutrinos from SN 1987a can be used to constrain the properties of light particles, including the number of neutrino species N_ν and the coupling strength of a light pseudoscalar boson such as the axion. First we demonstrate the consistency of Kamiokande II and IMB III data with each other and with the standard theory of neutrino emission from a supernova core of radius $R \sim 20$ km and effective temperature $T \sim 5$ to 6 MeV. The total amount of energy emission by neutrinos is compatible with the binding energy of a neutron star only if $N_\nu \leq 6$. The upper limit on the difference between the binding energy and the energy lost via $N_\nu = 3$ neutrino species excludes light pseudoscalar bosons with couplings to electrons in the range $10^{-27} < \alpha_e < 10^{-24}$, which enables one to extend astrophysical bounds on the axion decay constant to $f_a > 4 \times 10^9$ GeV.

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April 1987

The observation¹⁾⁻³⁾ of neutrinos from the supernova SN 1987a is not only a historic event for astrophysics, but is also of interest for particle physics. According to the standard theory of supernova collapse⁴⁾, the core becomes a plasma with a temperature of several MeV. This is the highest temperature known to appear anywhere in the Universe since before primordial nucleosynthesis. Measurements of the collapse offer particle physicists a unique opportunity to probe the thermodynamics of matter at temperatures higher than those available naturally elsewhere. Such measurements are possible via observations of neutrinos, and in principle other neutral weakly interacting particles weighing $\lesssim 10$ MeV, emitted from the supernova core. The two sets of neutrino observations with the highest levels of statistical significance are those of Kamiokande II¹⁾ and IMB III²⁾. Many authors, and many more non-authors, have discussed how their observations can be used to place an upper limit on $m_{\bar{\nu}_e}$ of order 10 eV. To make this bound precise, one should run a Monte Carlo program which treats carefully the errors in the measurements of the neutrino energies as well as the detector thresholds, and compare a representative selection of models for supernova collapse with the observations, assuming different values of the neutrino mass. Such a Monte Carlo analysis could also be used to make precise the order-of-magnitude statement that $\gamma\tau_{\bar{\nu}_e} \gtrsim 10^5$ y on the basis of the supernova neutrino data.

The Kamiokande II and IMB III data can also be used to constrain the total number of light electroweakly interacting particle species and their couplings. The basic idea is that the supernova can radiate energy not only via the known neutrinos, but also via other particles weighing $\lesssim 10$ MeV. If their mean free paths inside the core are short compared with its radius, but they can escape freely from its surface, the radiation of such particles will be essentially thermal⁴⁾. In this case the energy output in the form of $\bar{\nu}_e$ inferred from the Kamiokande II and IMB III events should be scaled by the total number of such light particle species to infer the total energy released. However, the total energy released must be less than the binding energy of a neutron star, which we take to be $E_{\text{tot}} \leq 4 \times 10^{53}$ ergs. Dividing this figure by an estimate of the total energy emitted in the form of $\bar{\nu}_e$ therefore gives an upper bound on the total number of such light particle species with mean free paths smaller than the core radius. Light particles with even weaker interactions whose mean free path is large compared with the core radius could be emitted from the interior of the core, and the neutron star binding energy less the energy radiated via three neutrino species provides a non-trivial upper limit on the coupling of such an

ultraweakly interacting particle, e.g., an "invisible" axion⁵⁾. As in the case of the neutrino mass, a precise evaluation of these limits on light particles would require a Monte Carlo analysis comparing the data with a selection of different models for supernova collapse including additional light particles. It is not obvious that the limits obtained in this way would be very interesting and so worth the effort of a detailed Monte Carlo study. In this paper we report a first exploration of this idea which suggests that interesting bounds could be obtained which would justify such an effort.

We check for mutual consistency between the Kamiokande II data¹⁾, the IMB III data²⁾, and the standard theory of supernova collapse⁴⁾. We find consistency if we assume a pulse duration of 2s, and the emitting region has a radius $\sim 20 \text{ km}$ ⁶⁾ and a temperature T between 5 and 6 MeV, in which case the energy emitted by neutrinos is $(1.8 \text{ to } 2.6) \times 10^{53} \times (N_\nu/3)$ ergs. Theory and experiment are not so consistent if we assume a pulse duration of 10s: in this case a temperature $T \lesssim 5 \text{ MeV}$ and the emission of about $4 \times 10^{53} \times (N_\nu/3)$ ergs would be preferred. Since the binding energy of a neutron star is expected to be $\lesssim 4 \times 10^{53}$ ergs, we use the former, more consistent, case to give a conservative bound on the energy emission by additional light particles beyond the canonical three neutrino species: $\Delta E \lesssim 2.2 \times 10^{53}$ ergs in 2s. We find:

- (1) that the total number of neutrino species $N_\nu \leq 6$;
- (2) that any light pseudoscalar boson ϕ must have an electron coupling strength $\alpha_e \equiv g_{ee\phi}^2/4\pi \lesssim 10^{-27}$. This corresponds in the case of an "invisible" axion to a decay constant $f_a \gtrsim 4 \times 10^9 \text{ GeV}$, which improves slightly the previous astrophysical limits^{7),8)}.

We first analyze the consistency of the Kamiokande II and IMB III data sets with each other and with a simple approximate model of thermal neutrino emission: Since at low energies $\sigma(\bar{\nu}_e p \rightarrow e^+ n) \approx 7.5 \times 10^{-41} (E/\text{MeV})^2 \text{ cm}^2$ is much larger than low-energy ν_e , ν_μ , $\bar{\nu}_\mu$, ν_τ and $\bar{\nu}_\tau$ scattering cross-sections, it is expected that (almost) all the events seen are due to this reaction, and we will assume this henceforth. The total energy emitted in the form of $\bar{\nu}_e$ can therefore be estimated as

$$E_{\bar{\nu}_e} = \frac{\bar{E}}{\bar{\sigma}} \frac{4\pi D^2}{V_n} \frac{2}{18} N_{ev} \quad (1)$$

where $\bar{E}$ is the average energy of the events seen, $D \sim 50 \text{ kpc}$ is the distance to the Larger Magellanic Cloud, $\bar{\sigma}$ is $\sigma(\bar{\nu}_e p \rightarrow e^+ n)$ at the energy $\bar{E}$, V is the volume of

the H₂O detector, $n = 6 \times 10^{23}$ is Avogadro's number, and N_{ev} is the number of events which would have been observed in a perfect detector. Numerically, Eq. (1) may be evaluated to yield

$$E_{\bar{\nu}_e} = 9.5 \times 10^{51} \left(\frac{1 \text{ kton}}{m} \right) \left(\frac{10 \text{ MeV}}{E} \right) \left(\frac{D}{50 \text{ kpc}} \right)^2 N_{ev} \text{ ergs} \quad (2)$$

To obtain the total energy emitted in the form of neutrinos, we must multiply $E_{\bar{\nu}_e}$ (2) by a factor which is approximately $2N_v$. To estimate N_{ev} from the data, we must correct for the threshold inefficiencies $\chi(E)$ of the detectors:

$$N_{ev} = N_{obs} \times \frac{\int_0^\infty E^2 dE / (e^{E/T} + 1)}{\int_0^\infty E^2 \chi(E) dE / (e^{E/T} + 1)} \quad (3)$$

We see from (3) that the estimates of N_{ev} and hence of $E_{\bar{\nu}_e}$ (1,2) for the two detectors depend on the temperature T of the emitting region which is assumed. In using (3) to correct the two sets of data, we have actually replaced the integrations in the denominators by sums over energy bins of width 2 MeV in regions where $\chi(E)$ is changing appreciably, and an integral with $\chi(E) = 0.9$ for $E > 14$ MeV (30 MeV) for the Kamiokande II (IMB III) data. Numerical values of $\chi(E)$ for the two detectors are given in Refs. 9) and 10). An ambiguity in calculating N_{ev} is whether one should include all the neutrino events which were seen in the pulses, which have lengths of 13s(6s) for Kamiokande II (IMB III), or only use the events in the first subpulses, which have lengths 2.0(2.7)s for the first 8(6) events of Kamiokande II (IMB III). We will present results for both cases.

Figure 1a shows our estimates of $E_{\bar{\nu}_e}$ (assuming $N_v = 3$) for the complete neutrino pulses of Kamiokande II and IMB III, as functions of the temperature T assumed for the emitting region. We assign arbitrarily possible scale errors of $2^{\pm 1/2}$ to these estimates. We see that the two estimates of $E_{\bar{\nu}_e}$ are consistent if $T > 5.0$ MeV. Figure 1b shows the corresponding estimates of $E_{\bar{\nu}_e}$ for the initial subpulses consisting of 8(6) events for Kamiokande II (IMB III), including similar scale errors of $2^{\pm 1/2}$. We see that in this case the two estimates of $E_{\bar{\nu}_e}$ are consistent if $T > 5.1$ MeV.

Also shown in Figs. 1a,b are the energy outputs which would be predicted if the core behaved as a spherical black body of radius R and temperature T for a period Δt :

$$E_{\nu}^{th} = Q \Delta t : Q = \frac{7\pi^3}{120} T^4 R^2 N_{\nu} \quad (4)$$

which may be evaluated to yield

$$E_{\nu}^{th} = 1.3 \times 10^{50} \left(\frac{T}{\text{MeV}} \right)^4 \left(\frac{R}{20 \text{ km}} \right)^2 \left(\frac{N_{\nu}}{3} \right) \left(\frac{\Delta t}{1 \text{ s}} \right) \text{ ergs} \quad (5)$$

We have plotted in Fig. 1a the prediction E_{ν}^{th} as a function of T for the preferred cases $R = 20 \text{ km}$ and $N_{\nu} = 3$, and taking $\Delta t = 10 \text{ s}$. An arbitrary scale error of $2^{\pm 1/2}$ is again included. We see that this estimate agrees within a factor of 2 with the Kamiokande II estimate of E_{ν} if $3.6 \text{ MeV} < T < 4.6 \text{ MeV}$, and with the IMB III estimate of E_{ν} if $4.3 \text{ MeV} < T < 5.2 \text{ MeV}$. The corresponding prediction E_{ν}^{th} for $\Delta t = 2 \text{ s}$ is shown in Fig. 1b, where it can be compared with the estimates of E_{ν} based on the initial subpulses of Kamiokande II and IMB III. We see that E_{ν}^{th} is compatible within a factor of 2 with Kamiokande II if $4.5 \text{ MeV} < T < 5.9 \text{ MeV}$, and with IMB III if $5.1 \text{ MeV} < T < 6.2 \text{ MeV}$.

The overall level of consistency of the data sets with each other and with approximate theory (4) is quite remarkable. The regions of overlap are in ranges of the temperature T which agree with estimates⁴⁾ made before the supernova was observed. As shown in Fig. 1a, the (arbitrary) error margins on the theory and the full neutrino pulses in the two experiments do not all overlap simultaneously, but a fair fit would be

$$T \sim 4.8 \text{ MeV} , E_{\nu} \sim 4 \times 10^{53} \text{ ergs} \quad (6)$$

If we restrict ourselves to the initial subpulses of 8 events for Kamiokande II and 6 events for IMB III, we see in Fig. 1b that there is complete consistency between all three estimates of E_{ν} in the cross-hatched region where

$$T = (5.1 \text{ to } 5.9) \text{ MeV} , E_{\nu} = (1.8 \text{ to } 2.6) \times 10^{53} \text{ ergs} \quad (7)$$

In most models⁴⁾ of supernova collapse, the binding energy available to be emitted in the form of neutrinos and other light particles is $< 4 \times 10^{53} \text{ ergs}$. The best fit (6) of Fig. 1a is marginally consistent with this upper bound on E_{ν} , whilst the region (7) of consistency in Fig. 1b is comfortably compatible with this upper bound. If we had used a larger value of R , the consistency of astrophysical data

with the theory would have been worse, and the best estimates of the total neutrino energy released would have been larger.

It may seem strange that we are estimating the core temperature and the total neutrino energy emission without using the experimental measurements of the event energies. However, we are implicitly using information on the neutrino energy spectra by incorporating the correct experimental thresholds to estimate N_{ev} on the basis of N_{obs} . Our point of view is that the most reliable pieces of information from the two experiments are the zeroth energy moments of the data, i.e., the total numbers of events. One can then check a posteriori the consistency of our analysis with other, higher energy moments of the data, such as the first energy moment $\bar{E}$. We exhibit in the Table the predicted values of $\bar{E}$ for the Kamiokande II and IMB III experiments, for a thermal distribution with a temperature T convoluted with the E^2 energy-dependence of $\sigma(\bar{\nu}_e p \rightarrow e^+ n)$ and the two different experimental threshold efficiency factors. These are compared with the observed values of $\bar{E}$, which would have errors of order 7(10)% for Kamiokande II (IMB III) if all the energy measurements were independent, which is probably an underestimate of the overall error. The range $T \sim 5$ to 6 MeV favoured in Fig. 1b is clearly compatible with the average energy $\bar{E}$ observed in the IMB III experiment. Taken by itself, the Kamiokande II data would seem to prefer a lower temperature. Consistency with the theory could then be maintained by increasing R , increasing our estimate of the total ν energy output by $\sim 50\%$. Since this would correspond to a less conservative bound of the properties of light particles, we prefer to retain our previous estimate. We consider that it would be unreasonable to analyze higher energy moments of the data, particularly since the thermal model is likely to weak down for the tails of the distributions.

We will not enter here into the vexed question whether the later events in the Kamiokande II and IMB III pulses should be interpreted as part of the signal of neutrinos from SN 1987a. Instead, we just note that to establish a conservative upper bound on the amount of energy that could have been emitted by other light particle species, one should use the lower estimate (7) of the energy emitted by the canonical 3 neutrino species. This is indeed conservative because the effective temperatures of the ν_μ , ν_τ , $\bar{\nu}_\mu$ and $\bar{\nu}_\tau$ are expected to be higher than for the $\bar{\nu}_e$, and because the initial neutronization of the core emits additional ν_e . We also note that it was conservative to assume that all the events observed were induced by $\bar{\nu}_e$, since the ν_e , ν_μ , ν_τ , $\bar{\nu}_\mu$ and $\bar{\nu}_\tau$ cross-sections are all

smaller, so that events induced by them would correspond [cf. Eq. (11)] to much more energy being emitted by those species.

After this lengthy foreplay, we are now ready for some action. It is trivial to use (7) to give an upper limit on the number of neutrino species:

$$N_\nu < \frac{4}{1.8} \times 3 = 6.7 \quad (8)$$

Since somewhat more energy is expected¹¹⁾ to be radiated by ν_e than by other species, the upper bound (8) is probably overstated by $\Delta N_\nu \sim \frac{1}{2}$. In any case, the largest integer number of neutrino species permitted is $N_\nu = 6$.

More generally, we can subtract the energy loss due to 3 neutrinos in the allowed region of Fig. 1b from 4×10^{53} ergs, and divide by the relevant $\Delta t = 2s$ to get an upper bound on the rate Q of energy loss by any other light particle:

$$Q \lesssim \begin{cases} 7.5 \times 10^{52} \text{ erg s}^{-1} & \text{if } T = 5.1 \text{ MeV} \\ 1.1 \times 10^{53} \text{ erg s}^{-1} & \text{if } T = 5.6 \text{ MeV} \end{cases} \quad (9a)$$

$$(9b)$$

In particular, we can use (9) to bound the couplings of any light pseudoscalar boson ϕ , for which (9a) provides the most conservative bound. Three cases must be distinguished, depending on the ratio of the mean free path L to the radius R of the emission region:

$$\left(\frac{L}{R}\right) = 1.1 \times 10^{-20} \left(\frac{\rho}{10^{12} \text{ g cm}^{-3}}\right)^{1/3} \left(\frac{1 \text{ MeV}}{T}\right)^7 \frac{1}{\alpha_\phi} \quad (10)$$

(A) $L/R \gtrsim 1$: the bosons ϕ stream freely out of the core and emit energy at a rate¹²⁾

$$Q_\phi = Q_\phi^0 : Q_\phi^0 = \frac{4.1 \times 10^{37}}{(\rho/10^{12} \text{ g cm}^{-3})} \left(\frac{1}{T \text{ MeV}}\right)^{11} \alpha_\phi \text{ erg g}^{-1} \text{ s}^{-1} \quad (11)$$

(B) $L/R \lesssim 1$: the bosons ϕ diffuse out of the core and emit energy at a rate:

$$Q_\phi = \left(\frac{L}{R}\right)^2 Q_\phi^0 \quad (12)$$

(C) $L/R \ll 1$: the bosons ϕ are completely thermalized and emit energy at about 4/7 the rate of a single neutrino species.

We have evaluated the bounds on α_ϕ obtained from (11) and (12) by assuming that the mass of the core is 1.4 solar masses, implying that for case (A):

$$\alpha_\phi < \begin{matrix} 1.1 \times 10^{-27} \\ (T=5.1 \text{ MeV}) \end{matrix}, \begin{matrix} 5.7 \times 10^{-28} \\ (T=5.6 \text{ MeV}) \end{matrix} \quad (13)$$

for the examples (9a) and (9b) respectively, and for case (B):

$$\alpha_\phi > \begin{matrix} 2.5 \times 10^{-24} \\ (T=5.1 \text{ MeV}) \end{matrix}, \begin{matrix} 1.3 \times 10^{-24} \\ (T=5.6 \text{ MeV}) \end{matrix} \quad (14)$$

We assume for numerical purposes that $\rho = 10^{11} \text{ gm/cm}^3$ and take the less favourable case $T = 5.1 \text{ MeV}$ (9a). The resulting energy emission rate Q_ϕ is shown in Fig. 2: the cases (A), (B) and (C) are indicated, and the maximum allowable loss rate (9a) is also shown. Upper bounds on α_ϕ from the cooling of red giants⁷⁾ and white dwarfs¹³⁾ already exclude the region (14) to the right of the peak in Fig. 2. Therefore we conclude that

$$\alpha_\phi < 1.1 \times 10^{-27} \quad (15)$$

To compare with previous works^{7),13)}, we note that if $g_{ee\phi} = m_e/f_a$ as is generic for an axion¹⁴⁾, then the bound (15) corresponds to $f_a > 4.3 \times 10^9 \text{ GeV}$, while if $g_{ee\phi} = 2m_e/V$, the $V > 8.7 \times 10^9 \text{ GeV}$. In the case of the Majoron¹⁵⁾, where $g_{ee\phi} = 2v_{T_e}m_e/(250 \text{ GeV})^2$, the bound (15) on α_ϕ corresponds to $v_{T_e} < 7.2 \text{ keV}$. These are modest improvements on the previous bounds, but have the merit of being completely independent.

To conclude, we may say that the pioneering data of Kamiokande II and IMB III on neutrino emission from SN 1987a give constraints on the number of light particle species and on their couplings which are comparable with the most stringent obtainable from any other cosmological, astrophysical or particle physics argument. It would clearly be worthwhile to sharpen these bounds by making a more detailed Monte Carlo analysis of the available data in the context of different detailed models for supernova collapse.

ACKNOWLEDGEMENTS

We thank T. Walsh for discussions and also D. Schramm, who tells us that he has obtained similar limits. One of us (J.E.) thanks the Fermilab Astrophysics Group and the University of Minnesota for their kind hospitality during this work. We both thank Northwest Orient Airlines for their hospitality while it was being completed. The work of K.A.O. was supported in part by DOE grant DEE-AC02-83ER-40105.

TABLE - Average neutrino energies

T (MeV)	3	4	5	6	7	8	9
Kamiokande II	16.7	21.2	26.0	30.8	35.7	40.4	44.8
	Observed $\left\{ \begin{array}{l} \bar{E} = 15.4 \text{ MeV for } N_{\text{obs}} = 11 \\ \bar{E} = 17.4 \text{ MeV for } N_{\text{obs}} = 8 \end{array} \right.$						
IMB III	27.4	31.0	34.8	38.8	42.8	46.7	50.3
	Observed $\left\{ \begin{array}{l} \bar{E} = 32.5 \text{ MeV for } N_{\text{obs}} = 8 \\ \bar{E} = 36.0 \text{ MeV for } N_{\text{obs}} = 6 \end{array} \right.$						

The predictions for different values of T are calculated by convoluting a thermal energy distribution with the E^2 dependence of $\sigma(\bar{\nu}_e p \rightarrow e^+ n)$ and the different threshold efficiency factors.

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FIGURE CAPTIONS

Fig. 1 The estimated energy output via three neutrino species for (a) the full pulses of Kamiokande II (labelled K_{11}) and IMB III (labelled I_8) compared with thermal emission over a period $\Delta t = 10s$, and (b) the initial subpulses of Kamiokande II (labelled K_8) and IMB III (labelled I_6) compared with thermal emission over a period $\Delta t = 2s$. Arbitrary errors of $2^{\pm\frac{1}{2}}$ are attached to all estimates. Note the reasonable consistency for $T \sim (4\frac{1}{2} \text{ to } 5) \text{ MeV}$ in (a), and the full consistency for $T \sim (5 \text{ to } 6) \text{ MeV}$ in the cross-hatched region in (b).

Fig. 2 The rate of energy emission Q_ϕ due to a light pseudoscalar boson ϕ , as a function of its coupling strength α_ϕ to electrons. Also shown is the upper limit of $0.75 \times 10^{53} \text{ ergs}^{-1}$ for $T = 5.1 \text{ MeV}$ obtained from Fig. 1b. The aesthetics of this plot are best appreciated by rotating it clockwise through $\pi/2$ radians.

- Figure 1a -

- Figure 1b -

- Figure 2 -