PROCEEDINGS OF SCIENCE

Flux of $\bar{\nu}_e$ from SN1987A: analysis and results

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The neutrinos from the core collapse SN1987A are the first extrasolar neutrinos to be ever detected and have been widely studied to infer the thermodynamical and temporal features of a supernova; however their interpretation in terms of the astrophysical properties of the explosion has been giving rise to heated debates since ever. At date, models are still under construction and simulations do not always depict same things, thus the significance of the data at our disposal must be assessed as accurately as possible. By adopting a state-of-the-art parameterized model of electron antineutrino emission, we have made some steps forward in the analysis of the available data from core collapse SN1987A taking into account the times, energies and angles of arrival of all detected events in a reliable framework which includes a finite ramp in the initial stage of the neutrino emission. We determine the parameters of the accretion and cooling emissions and discuss their durations. The results compare well with theoretical expectations and overcome some tensions found in previous similar analyses. We estimate the delay times between the first antineutrino and the first event in the detectors. We test the agreement of the best-fit flux with the empirical temporal, energy and angular distributions, eventually finding a good compatibility with the observed data.

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1. Introduction

Neutrinos play a central role in the dynamics of core-collapse supernovae (SN), being crucial both for energy transport and for the formation of a neutron star. The only direct detection of such neutrinos remains the burst from SN1987A, which exploded in the Large Magellanic Cloud at a distance of $D = 51.4 \pm 1.2$ kpc [1], and was observed by Kamiokande-II, IMB, and Baksan [2–6]. Despite the limited statistics, these events still represent a benchmark for our understanding of SN neutrino emission.

Detailed analyses [7, 8] have suggested the presence of two distinct emission phases in the SN1987A signal. In this work, we revisit the full set of events in a 30 s time window, including time, energy, and angular information, and adopt a statistical framework that incorporates a realistic signal rise time [9], in agreement with SN simulations.

We improve upon previous approaches [7, 8, 10–13], providing updated estimates of the model parameters and their uncertainties. This leads to new constraints on the timing and energy characteristics of the emission, particularly the duration and intensity of the two main phases, as well as the time delay between the start of the emission and the first detected event. We also estimate the accreting mass involved in the early phase, finding values in the range 0.01–0.04 $M_\odot$, in line with theoretical expectations. Finally, we evaluate the goodness-of-fit of the adopted model, supporting its consistency with the observed data.

2. Emission model

We model the antineutrino flux as the sum of an initial accretion component and a subsequent cooling component. The total time- and energy-dependent flux at Earth is given by:

$$\Phi_{\bar{\nu}}(E,t) = \frac{1}{4\pi D^2}\left(\dot{N}_a(E,t) + \dot{N}_c(E,t)\right), \tag{1}$$

where D is the distance to SN1987A and $\dot{N}_a$, $\dot{N}_c$ denote the accretion and cooling spectral rates, respectively.

Accretion Phase The accretion phase is characterized by rapid, non-thermal emission as matter falls onto the proto-neutron star. We parameterize this stage as follow [9]

$$\dot{N}_{\nu,a}(E_\nu,t) = \frac{c}{(hc)^3} \times \xi_n(t) \times \frac{M_\odot}{m_n} \times \sigma_{e^+n}(E_\nu) \times \frac{8\pi E_e^2}{1+\exp(E_e/T_a)}, \tag{2}$$

Where the key parameters are the accretion temperature T_a and the accretion timescale τ_a.

Cooling Phase After the accretion phase, the proto-neutron star cools via thermal neutrino emission. The cooling flux is modeled by a Fermi-Dirac spectrum with temperature T_c and timescale τ_c [9]:

$$\dot{N}_{\nu,c}(E_\nu,t) = \frac{c}{(hc)^3} \times \pi R_{ns}^2 \times \frac{4\pi E_\nu^2}{1+\exp(E_\nu/T_c(t))}, \tag{3}$$

The variation in time of our model is transparently encoded in the time dependence of the parameters T_c and ξ_n, thus allowing for an efficient comparison with the experimental data [9]. The luminosity resulting from our analysis, displaying the various phases of electron antineutrino emission, is presented in figure 1.

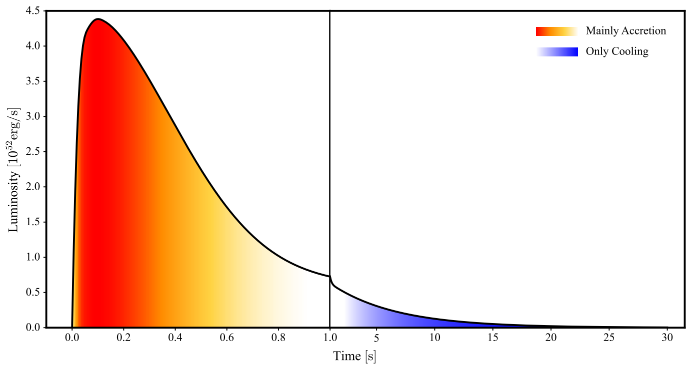

Figure 1: *Antineutrino luminosity obtained by evaluating our model at the best fit points. The color scale is used to discriminate between the phase which is mainly accretion (red-orange) and the subsequent only cooling phase (blue). Note the different time units in the left and right panels. A misprint in the label of the y-axis reported in [14] has been corrected.*

3. Signal and detector response

The dominant detection channel for SN1987A electron antineutrinos is inverse beta decay (IBD),

$$\bar{\nu}_e + p \longrightarrow n + e^+,$$

which reliably accounts for the events in the accretion phase [15, 16]. In an ideal detector with N_p free protons, the triply differential positron rate is

$$S_e(E_e, \cos\theta, t) = N_p\, \Phi_{\bar{\nu}_e}(E_\nu, t)\, \frac{\sigma^{\mathrm{IBD}}}{E_e}(E_\nu, E_e)\, J(E_\nu, \cos\theta),$$

where J is the Jacobian and σ^{IBD} follows the latest calculation [17]. The observed spectrum $S(E_i, \cos\theta, t)$ is obtained by convolving S_e with the detector efficiency $\eta(E_e)$, angular bias $\zeta(\cos\theta)$, and a Gaussian energy resolution $G(E_e - E_i, \sigma(E_e))$ [16, 18]:

$$S(E_i, \cos\theta, t) = \int \zeta(\cos\theta)\, \eta(E_e)\, G(E_e - E_i, \sigma(E_e))\, S_e(E_e, \cos\theta, t)\, E_e.$$

Here $\sigma(E_e)$ is parametrized as

$$\sigma(E_e) = \sigma_{\mathrm{stat}}\sqrt{\frac{E_e}{10\,\mathrm{MeV}}} + \sigma_{\mathrm{syst}}\,\frac{E_e}{10\,\mathrm{MeV}},$$

and the total efficiency above threshold E_{min} reads

$$\varepsilon(E_e, E_{\mathrm{min}}) = \eta(E_e)\,\frac{1 + \mathrm{erf}\big((E_e - E_{\mathrm{min}})/(\sqrt{2}\,\sigma(E_e))\big)}{2}.$$

Values of N_p, E_{min}, $\eta(E_e)$ and $\sigma(E_e)$ for Kamiokande-II, IMB and Baksan are taken from [2, 4, 6, 16].

4. Statistical Analysis

The statistical evaluation of neutrino emission from SN1987A was carried out through two complementary approaches:

1. **Parameter estimation.** Within a family of parameters, we identify the set of values for the parameters that best reproduce the observational data. Specifically, the best-fit values (and their confidence regions) are found by minimizing a χ^2 function, as detailed in Section 4.1.

2. **Goodness-of-fit testing.** After determining the optimal parameter set, we assess the compatibility of the data with the assumed model using standard goodness-of-fit tests.

4.1 Model parameter fitting

We obtain parameter estimates by minimizing the function

$$\chi^2 = -2 \sum_{d\in\{k,i,b\}} \ln \mathcal{L}_d \tag{4}$$

where $\mathcal{L}_d$ is the unbinned Poisson likelihood for detector d (Kamiokande-II, IMB, Baksan):

$$\mathcal{L}_d = \exp\left(-f_{\rm live} N_{\rm tot}\right) \prod_{j=1}^{N_d} \exp\left[S(t_d + \delta t_j + \tfrac{\tau_d}{2})\, \tau_d\right] \times \left[\tfrac{B_j}{2} + S\left(E_j, \cos\theta_j,\, t_d + \delta t_j\right)\right]. \tag{5}$$

Here:

- S denotes the expected signal rate (cf. Section 3), and B_j is the background rate taken from table 1 in [16].

- We define $t = 0$ as the arrival time of the first $\bar{\nu}_e$ on Earth. For each recorded event j,

  $$t_j = t_d + \delta t_j, \quad d \in \{k, i, b\},$$

  where δt_j is the measured time difference relative to the first detection.

- The offsets t_d (one per detector) account for the latency between the neutrino arrival and the first recorded event in each experiment [10].

- For IMB we use $\tau_d = 0.035$ s and $f_{\rm live} = 0.9055$ to model dead-time and muon contamination; for Kamiokande–II and Baksan we set $\tau_d = 0$ and $f_{\rm live} = 1$ [7].

In addition to the three time offsets t_k, t_i, t_b, the model depends on six astrophysical parameters: $t_{\rm max}$, τ_a, τ_c, $R_{\rm ns}$, ξ_{n0}, and T_0. We explored them within the following prior intervals:

$$\begin{aligned}
&1\ \text{km} \le R_{\rm ns} \le 100\ \text{km}, \quad 0 \le \xi_{n0} \le 0.4, \quad 2\ \text{MeV} \le T_0 \le 6\ \text{MeV},\\
&10\ \text{ms} \le t_{\rm max} \le 200\ \text{ms}, \quad 100\ \text{ms} \le \tau_a \le 1\ \text{s}, \quad 1\ \text{s} \le \tau_c \le 10\ \text{s},\\
&0 \le t_d \le 0.5\ \text{s} \quad (d = k, i, b).
\end{aligned}$$

Here $t_{\rm max}$ is the time at which the antineutrino flux peaks, and the time profiles $\xi_n(t)$ and $T_c(t)$ are parameterized via ξ_{n0} and T_0.

To derive confidence intervals, we construct the profile χ^2 for each parameter p, minimizing over the remaining ones, and define

$$\Delta\chi^2(p) = \chi^2(p) - \chi^2_{\rm min}.$$

The best-fit value $p_{\rm best}$ satisfies $\Delta\chi^2 = 0$, while the bounds at 1σ, 2σ, and 3σ correspond to $\Delta\chi^2 = 1, 4, 9$ (for a single parameter) [19].

5. Results

Our analysis, which for the first time incorporates a finite signal rise time and exploits time, energy and angular information for *all* SN1987A events, yields the following key findings [14]:

- We fix the rise-time parameter at $t_{\rm max} = 0.1$ s (data alone cannot constrain it, in agreement with simulations [9, 12]), and determine the delay times between neutrino arrival and the first recorded event:

$$t_k = 0.035^{+0.065}_{-0.024}\ \text{s}, \quad t_i = 0.043^{+0.102}_{-0.029}\ \text{s}, \quad t_b = 0.054^{+0.152}_{-0.041}\ \text{s}.$$

- The best-fit astrophysical parameters are

$$R_{\rm ns} = 17.0^{+0.7}_{-0.5}\ \text{km}, \quad \xi_{n0} = 0.018^{+0.025}_{-0.011}, \quad T_0 = 4.6^{+0.5}_{-0.4}\ \text{MeV},$$

$$\tau_a = 0.52^{+0.24}_{-0.15}\ \text{s}, \quad \tau_c = 5.6^{+1.8}_{-1.3}\ \text{s},$$

  where ξ_{n0} implies an accreting mass $M_a \sim 0.03\, M_\odot$, in much better agreement with theory than earlier estimates [8]. The $\Delta\chi^2$-functions for the parameters with 1σ-confidence intervals (orange bands) are displayed in figure 2

- The two-phase model (accretion + cooling) is strongly favored over cooling only ($\Delta\chi^2 \simeq 8.2$, corresponding to $> 99\%$ significance) [14].

- Goodness-of-fit tests (Cramér–von Mises and Kolmogorov–Smirnov) on time, energy and angle distributions confirm excellent agreement for timing ($p - value \gtrsim 80\%$) and overall signal ($p - value \sim 70\%$), with known mild tension in angular spectra [14].

These results demonstrate that a continuous, finite-rise flux model—together with a consistent treatment of detector response and background—provides a robust and improved description of the SN1987A neutrino signal. We are currently investigating the implications of our findings for SN1987A and for future detections.

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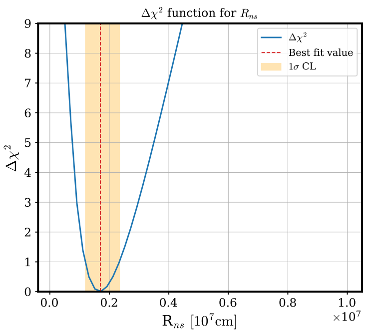
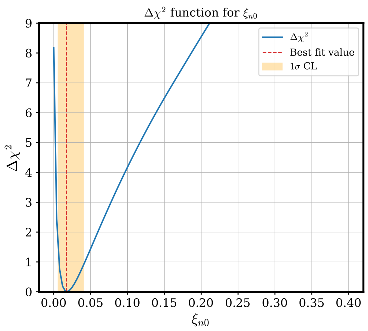
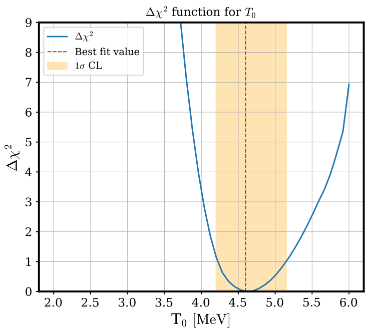


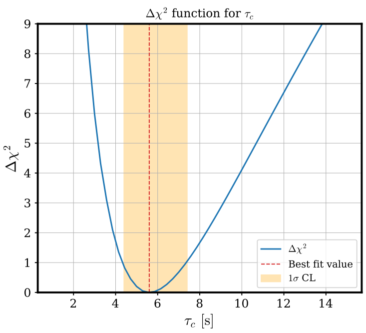
(a) $\Delta\chi^2$*-function of* R_{ns}



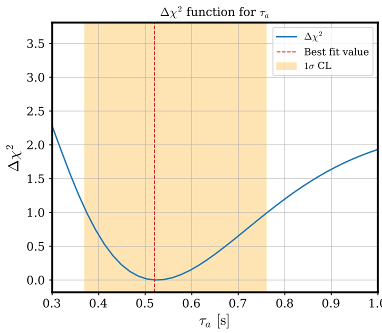
(b) $\Delta\chi^2$*-function of* ξ_{n0}



(c) $\Delta\chi^2$*-function of* T_0



(d) $\Delta\chi^2$*-function of* τ_c



(e) $\Delta\chi^2$*-function of* τ_a

Figure 2: $\Delta\chi^2$*-functions for the astrophysical parameters* τ_a*,* ξ_{n0}*,* T_0*,* τ_c *and* R_{ns}*. The red dashed lines indicate the best fit values. The orange bands show the confidence interval at 1*σ*.*

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