How Much Can We Learn from SN1987A Events?

Or More Modestly: An Improved Analysis of SN1987A $\bar{\nu}_e$ Events

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We analyze the data of Kamiokande-II, IMB, Baksan using a parameterized description of the antineutrino emission, that includes an initial phase of intense antineutrino luminosity. The luminosity curve, the average energy of $\bar{\nu}_e$ and the astrophysical parameters of the model, derived by fitting the observed events (energies, times and angles) are in reasonable agreement with the generic expectations of the Bethe and Wilson scenario for the explosion.

Based on Pagliaroli, Vissani, Costantini, Ianni, LNGS/TH-01/08, submitted for publication.

Rapid Historical Excursus, A.D. 2008

Colgate & White '66 propose the paradigm of core collapse supernovae, where neutrinos are the key agents.

Bethe & Wilson '85 suggest that energy deposition on a scale of half a second can re-energize the stalled shock wave.

Kamiokande-II, IMB, Baksan and LSD '87 observe several events in correlation with SN1987A.

Several authors (e.g., ***Bahcall '89***) remark that non-LSD data generically meet the expectations. Then the main interest shifts on oscillations.

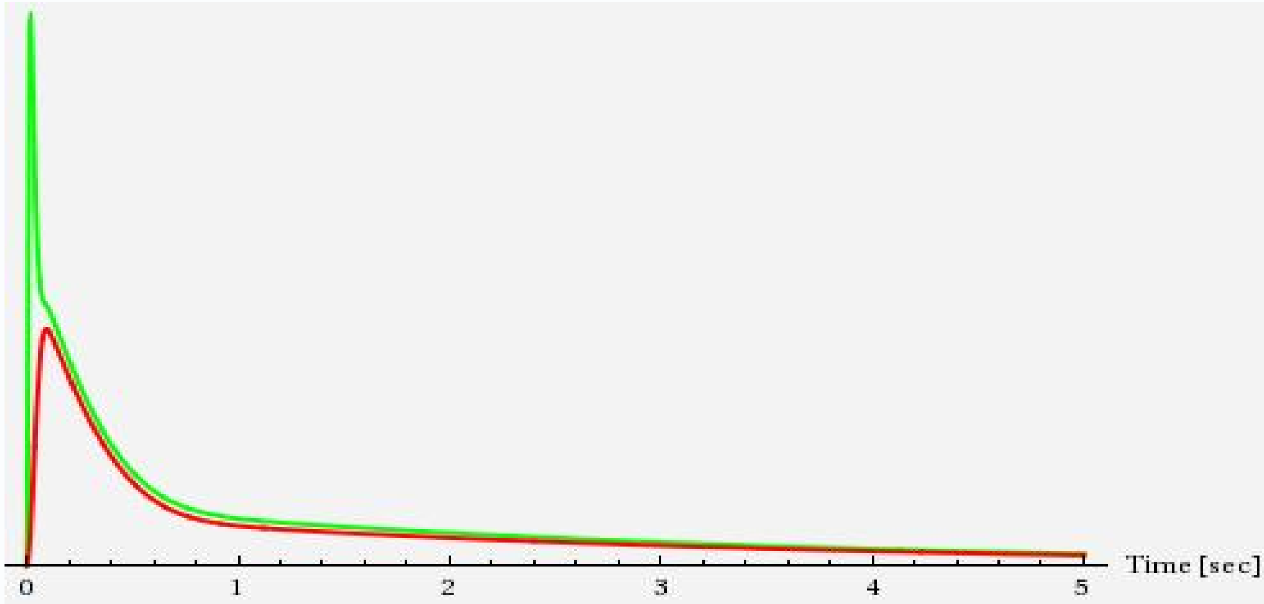
Lamb & Loredo '01 discuss whether SN1987A data indicate specific imprints of the Bethe & Wilson scenario.

Imshennik & Ryazhskaya '04, suggest a 2 stage scenario with essential role of rotation and possible explanation of LSD.

Today: proof of Bethe-Wilson scenario missing; wait for a new supernova.

Generic Expectations for Bethe-Wilson Scenario

Figure 1: *A sketch of* ν_e *and* $\bar{\nu}_e$ *luminosity curves.*



80-90% of energy radiated in NS cooling, the last stage; note the 3 phases (2 phases) emission for ν_e (for $\bar{\nu}_e$).

Main reactions in the beginning: $e^- p \to n \nu_e$ ***and*** $e^+ n \to p \bar{\nu}_e$.

Conventional Model for $\bar{\nu}_e$ Emission (=Exponential Cooling)

The thermal emission–cooling of NS–is parameterized by a black body model with a steadily decreasing temperature:

$$\begin{cases} \dfrac{dN_c}{dt\, dE} = \dfrac{R_c^2}{2\pi} \cdot \dfrac{E^2}{1+\exp[E/T_c(t)]} \\ \textbf{\textit{with}}\ T_c(t) = T_c \cdot \exp[-t/(4\tau_c)] \end{cases}$$

Its 3 parameters are needed to describe:

1. **The intensity of the emission: R_c, the neutrinosphere radius;**
2. **The average energy of $\bar{\nu}_e$: T_c, the initial temperature;**
3. **The duration of the process: τ_c, the luminosity time scale.**

An isotropic emission from $D = 50$ kpc is assumed.

Procedure of Analysis

Use only the relative times of the events ($t_1 = 0$).

Consider Kamiokande-II, IMB, Baksan data in 30 s.

Account for measured background dead-times angular-bias.

Bin-sample in energy, time, angle. In the i-th bin:

$$P_i = \begin{cases} e^{-\mu_i} \ \texttt{if} \ n_i = 0 \\ \mu_i \ e^{-\mu_i} \ \texttt{if} \ n_i = 1 \end{cases} \quad \Rightarrow \quad \mathcal{L} = e^{-\sum_j \mu_j} \prod_{i\,:\,n_i=1} \mu_i$$

Account for error in energy measurement.

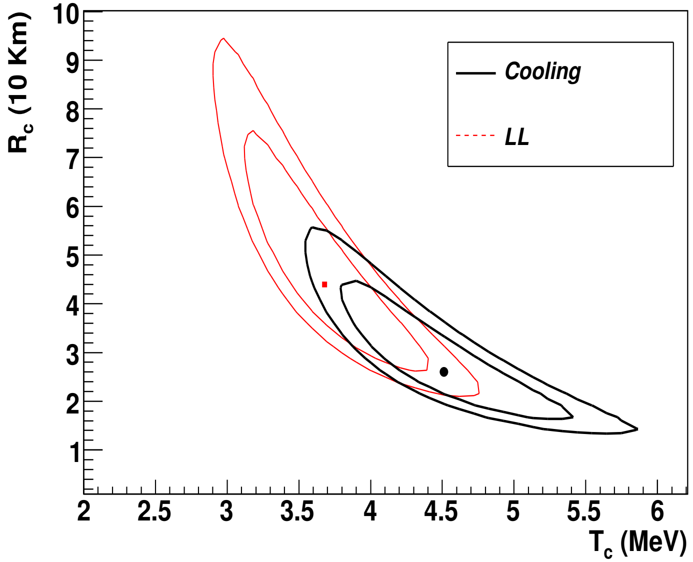
Expected number of signal events $\mu_i \ll 1$ ***obtained from***

$$\frac{dN}{dt dE_e d\cos\theta} = N_p \frac{d\sigma_{\bar\nu_e p}}{d\cos\theta}(E_\nu, \cos\theta)\Phi_{\bar\nu_e}(t, E_\nu)\xi_d(\cos\theta)\eta_d(E_e)\frac{dE_\nu}{dE_e},$$

i.e., protons, xsec, flux, angular bias, efficiency & jacobian.

One Phase Emission: Results

Figure 2: *2D marginal distributions. Red, 68% and 90% C.L. contours following Lamb & Loredo (LL). Black, our result for one component cooling model.*



Difference mostly due to treatment of efficiency–not of background, inclusion of angles, or better xsec. LL include efficiency in the exponential of $e^{-\sum \mu_j(\text{with})} \prod \mu_i(\text{w/o})$, we use the traditional procedure instead and include it in both.

Our best fit very close to the value in Bahcall book.

Should We Stop Here?

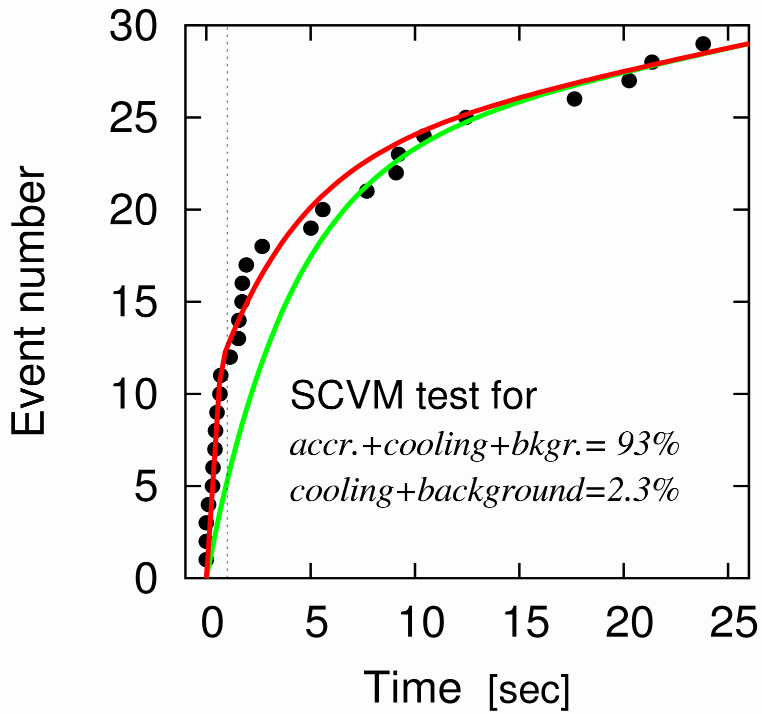
One could presume that Bahcall would have answered "yes".

In his book, the analysis of SN1987A data is introduced by the statement:
Unfortunately, a "minimum" model has proven adequate to describe the sparse amount of data;
the study of the 'exponential cooling' model is then commented with the sentence:
The success of this simplified "standard" model suggests that it will be difficult to use the neutrino events observed from SN1987A to establish more detailed models.

I wish to note that "difficult" does not mean "impossible" and, remaining aware of this authoritative opinion, I would like to continue the discussion begun by Lamb & Loredo: *whether it is worthwhile to go beyond the exponential cooling model.*

Observations Offer Some Motivation to Proceed

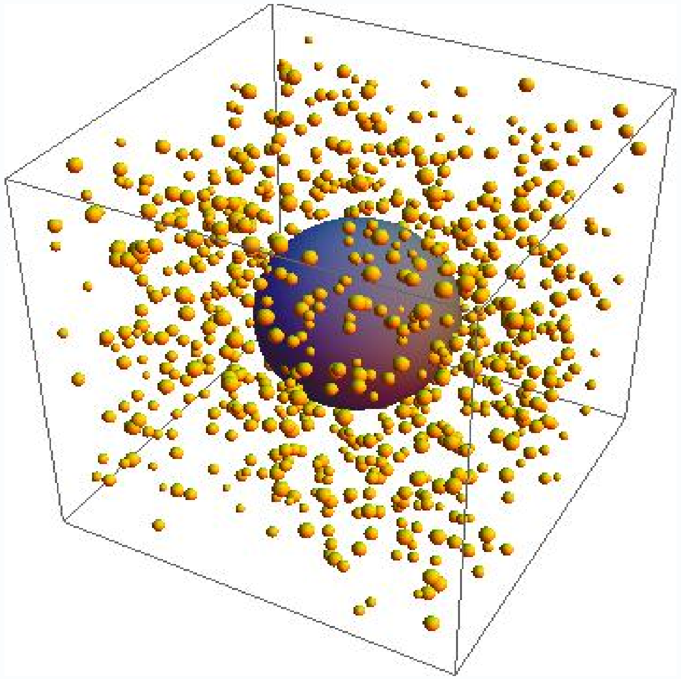
Figure 3: *Temporal distribution of the events. Two time distributions, comprising 7 background events, are given. In the green one, the 22 signal events belong to cooling. In the red one, only 13 signal events belong to cooling; the remaining 9 belong to accretion phase. Also indicated their GOF.*



There is a hint of an increased luminosity in the 1st second.

How to Describe the Initial Emission (=Accretion)

Figure 4: *The yellow centers surrounding the NS (in gray) represent pictorially the individual reactions $e^- p \to n\nu_e$ and $e^+ n \to p\bar{\nu}_e$ occurring during accretion.*



Thermal e^+'s react on target neutrons

$$N_n(t) = \frac{Y_n \; M_a(t)}{m_n}$$

yielding many $\bar{\nu}_e$'s.

The initial emission is dominated by the quasi-transparent accreting region: on top of the previous black body emission, we simply need to model the radiation of $\bar{\nu}_e$ from $e^+ n \to p\bar{\nu}_e$.

The $\bar{\nu}_e$ Flux During Accretion

Quite directly, we use $$\frac{dN_a}{dtdE} = \frac{1}{\pi^2} N_n(t)\sigma_{e+n}(E_\nu)\frac{E_e^2}{1+\exp[E_e/T_a]}$$

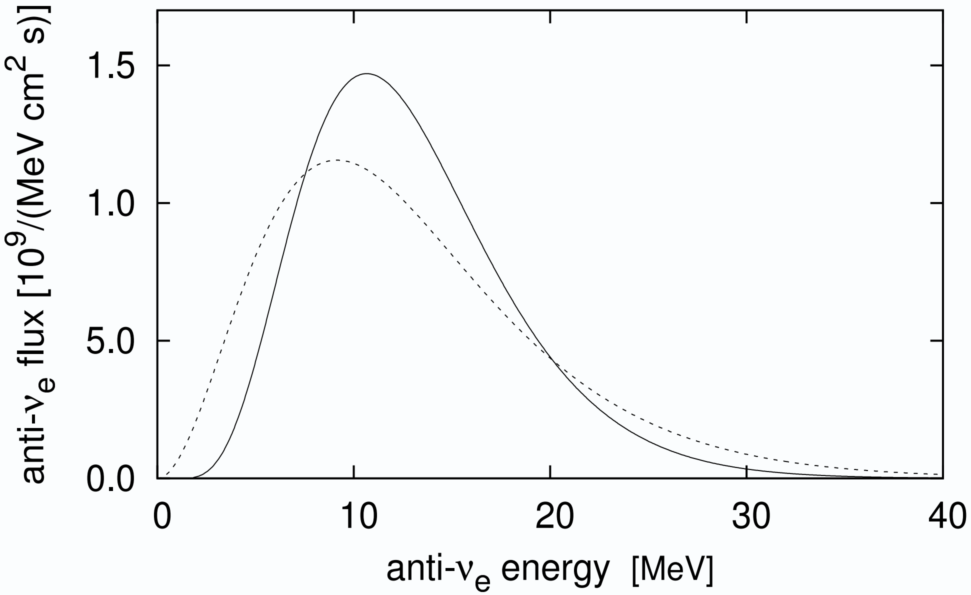


Figure 5: *Continuous curve: $\bar{\nu}_e$ flux for $M_a = 0.15\ M_\odot$ and $T_a = 2.5$ MeV. Dotted curve: black body distribution with the same luminosity (1.1×10^{53} erg/s) and average energy (13 MeV), namely, with parameters $R_c = 82$ km and $T_c = 4.1$ MeV. (The pinching is an output, not an input; pinching factor ~ 4).*

Two Phases Emission: Lamb & Loredo Model

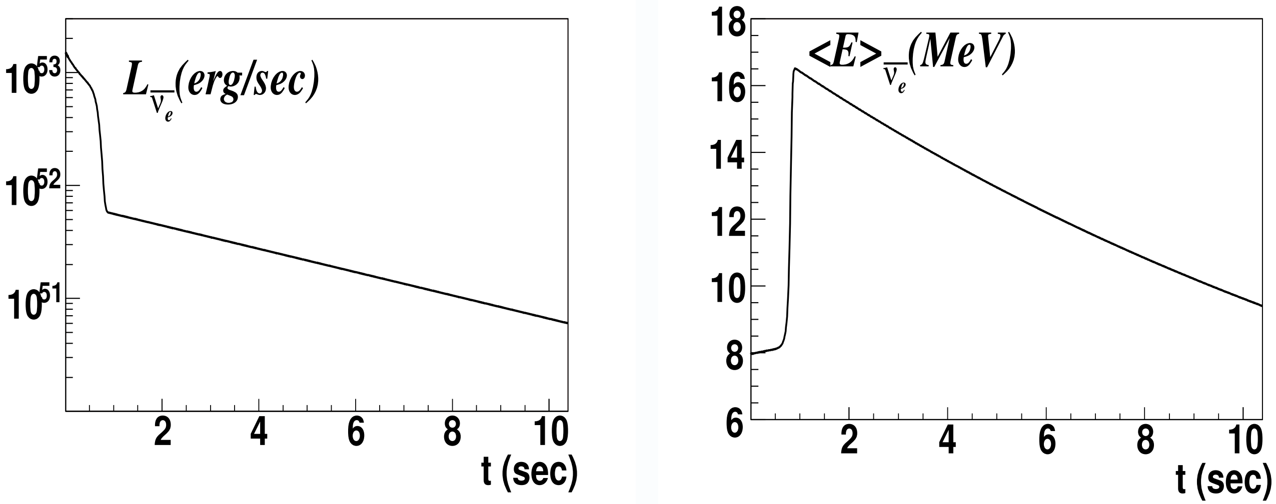
The best fit point is:

$$R_c = 12\ \boldsymbol{km}, \quad T_c = 5.5\ \boldsymbol{MeV}, \quad \tau_c = 4.3\ \boldsymbol{s},$$

$$M_a = 5.5\ M_\odot, \quad T_a = 1.5\ \boldsymbol{MeV}, \quad \tau_a = 0.7\ \boldsymbol{s}.$$

Big M_a and small T_a, dictated by KII early events.

Figure 6: *The antineutrino luminosity and average energy in the best fit point.*



Not a very appealing result, especially the second plot!

Two Phases Emission: Pagliaroli et al Model

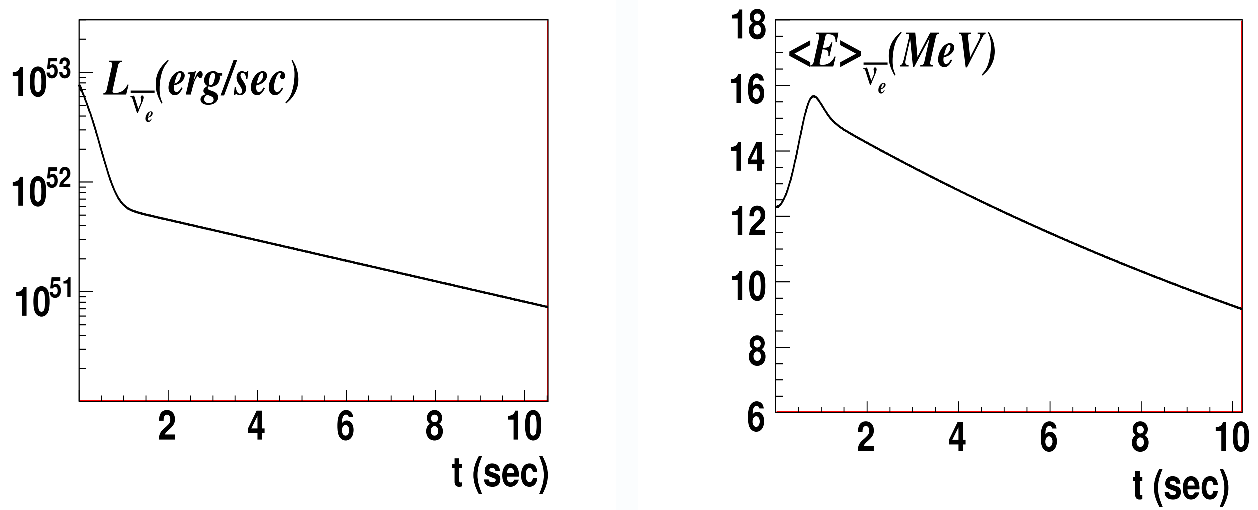
The best fit point is:

$$R_c = 16 \ \boldsymbol{km}, \quad T_c = 4.6 \ \boldsymbol{MeV}, \quad \tau_c = 4.7 \ \boldsymbol{s},$$

$$M_a = 0.2 \ M_\odot, \quad T_a = 2.4 \ \boldsymbol{MeV}, \quad \tau_a = 0.6 \ \boldsymbol{s}.$$

Much smaller M_a and increased T_a.

Figure 7: *The antineutrino luminosity and average energy in the best fit point.*



Regular curves, in much better agreement with simulations.

Why We Get a Different Best Fit Point?

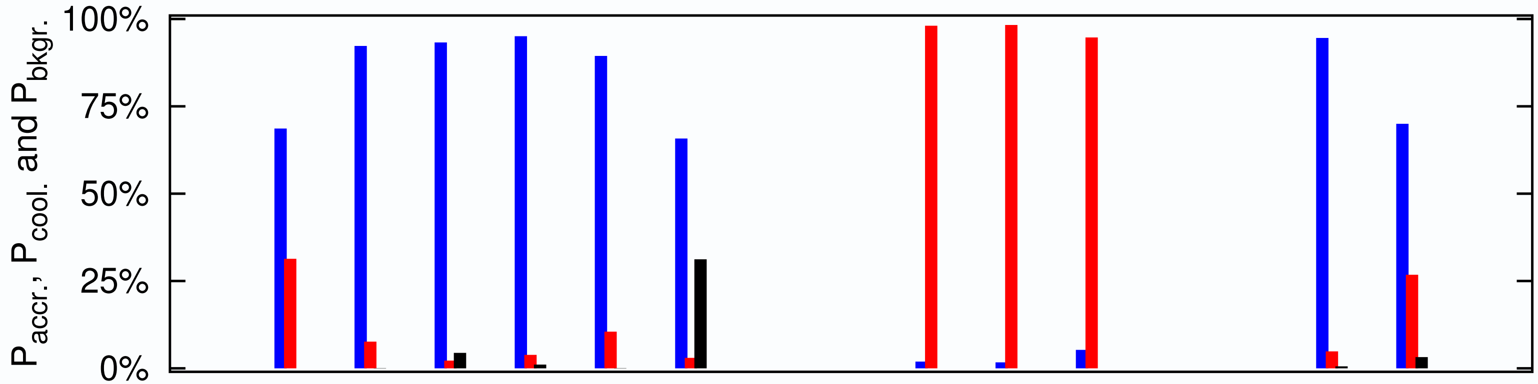
Subsequent improvement	R_c [km]	T_c [MeV]	τ_c [s]	M_a [$M_\odot$]	T_a [MeV]	τ_a [s]	Signif. [%]
technical (≈LL)	12	5.5	4.3	5.6	1.5	0.7	99.8
$T_a(t)$	14	5.0	4.8	0.8	1.8	0.7	98.9
time shift	14	4.9	4.7	0.1	2.4	0.6	98.0
oscillations	16	4.6	4.7	0.2	2.4	0.6	98.0

Table 1: *Best-fit values of astrophysical parameters for 2-components model neutrino emission. Each line of this table is an incremental step toward the final improved parameterization. The last column shows the significance of the model in comparison with the 1-component model (likelihood-ratio test, +3 d.o.f.).*

LL-model seems to describe better the data, but *deviates more strongly from the expectations* than our model.

Meaning of the Individual Events

A Posteriori Information on the Events of the First Second: Lamb & Loredo Model



A Posteriori Information on the Events of the First Second: Pagliaroli et al. Model

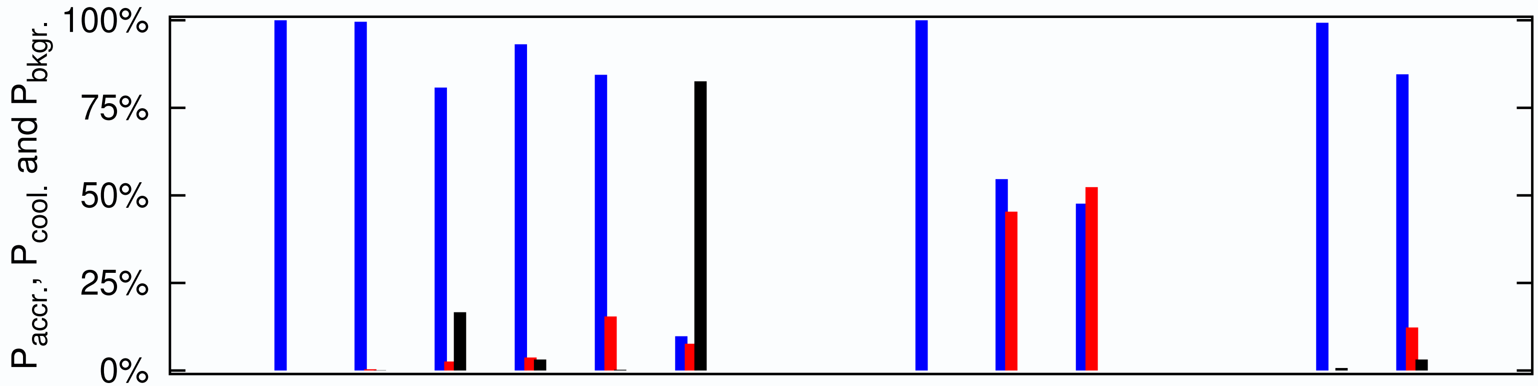
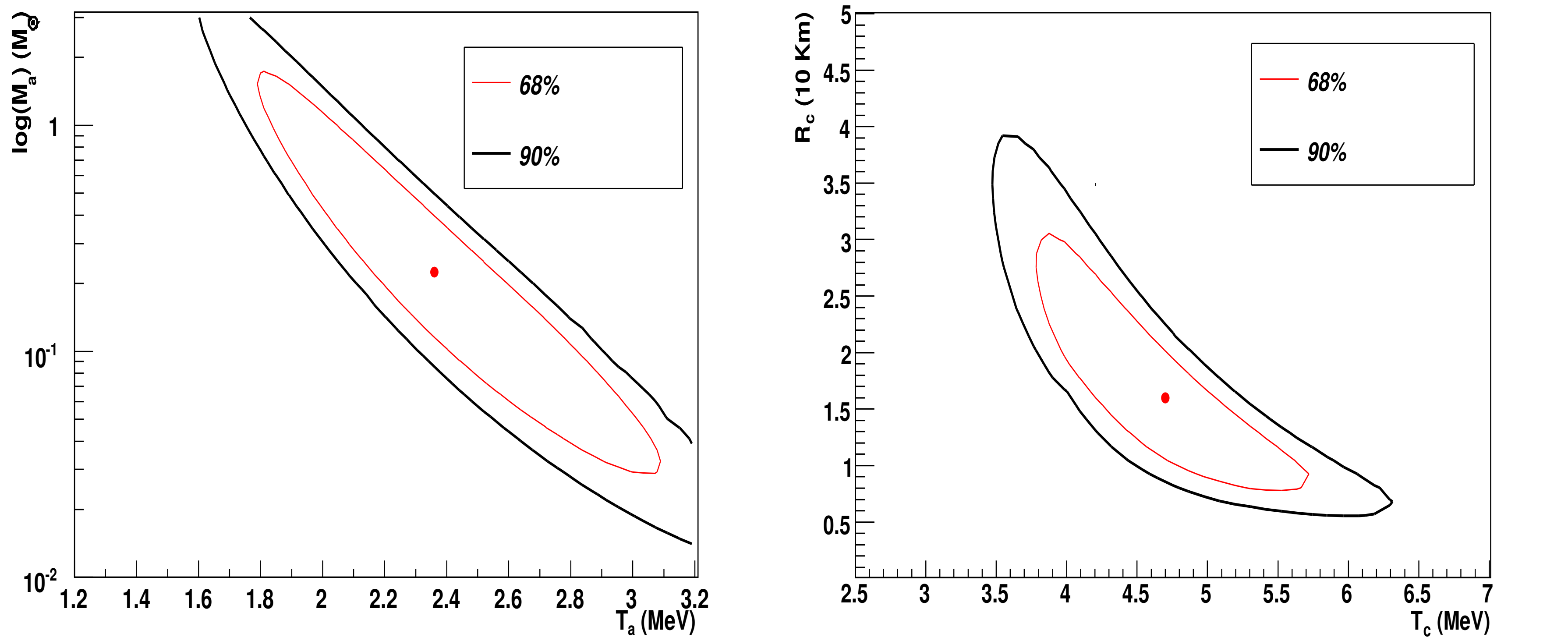


Figure 8: *Events in the first second: 6 in KII, 3 in IMB, 2 in Baksan. blue, accretion probability; red, cooling probability; black, background probability.*

Errors in the Pagliaroli et al Model [1/2]

Figure 9: *Marginal distributions for accretion parameters M_a and T_a of $\bar{\nu}_e$ and for cooling parameters R_c and T_c of $\bar{\nu}_e$ with the complete emission model.*



Other solutions exist at $M_a \sim M_\odot$, here discarded.

Errors in the Pagliaroli et al Model [2/2]

Astrophysical parameters:

$$R_c = 16^{+9}_{-5}\ \text{km}, \qquad M_a = 0.22^{+0.68}_{-0.15}\ M_\odot,$$
$$T_c = 4.6^{+0.7}_{-0.6}\ \text{MeV}, \quad T_a = 2.4^{+0.6}_{-0.4}\ \text{MeV},$$
$$\tau_c = 4.7^{+1.7}_{-1.2}\ \text{s}, \qquad \tau_a = 0.55^{+0.58}_{-0.17}\ \text{s}.$$

Offset times:

$$t^{off}_{KII} = 0.^{+0.07}\ \text{s},\ \ \text{t}^{off}_{IMB} = 0.^{+0.76}\ \text{s},\ \ \text{t}^{off}_{BAK} = 0.^{+0.23}\ \text{s}.$$

Limited statistics manifest in relatively large errors.

Summary

Our study confirms earlier results with the 1-component model. The refined treatment of background, xsec, description of angles, inclusion of Baksan data, *etc.* does not lead to important changes.

We confirm the results of Lamb & Loredo in particular an important evidence for accretion, *when their 2-component model is adopted*.

We discussed an improved 2-component model, where the average energy and luminosity curves are constrained to be continuous, cooling follows accretion, oscillations (not very important *a posteriori*) are considered.

Best fit of τ_a, M_a, *etc.* close to expectations; binding energy 2.2×10^{53} erg lower than for 1-component model; evidence of accretion 98%.

Miscellanea

Details of the Analysis (Adopted χ^2)

We estimate the theoretical parameters by the χ^2:

$$\chi^2 \equiv -2 \sum_{d=k,i,b} \log(\mathcal{L}_d),$$

where $\mathcal{L}_d$ is the likelihood of any detector (k, i, b are shorthands for Kamiokande-II, IMB, Baksan).

The 'unbinned' likelihood of each of the 3 detectors is:

$$\mathcal{L}_d = e^{-f_d \int R(t)dt} \times \prod_{i=1}^{N_d} e^{R(t_i)\tau_d} \times \left[\frac{B_i}{2} + \int R(t_i, E_e, \cos\theta_i) \mathcal{L}_i(E_e) dE_e \right].$$

Setting $f_d = 1$ and $\tau_d = 0$, and replacing $\mathcal{L}_i(E_e) \to \delta(E_e - E_i)$ it reduces to the usual Poisson likelihood.

Details of the Model

Time dependent temperature:

$$T_a(t) = T_i + (T_f - T_i)\left(\frac{t}{\tau_a}\right)^m \textbf{\textit{ with }} \begin{cases} T_i = T_a \\ T_f = 0.6\ T_c \end{cases}$$

with $m = 1 - 2$***. Drop of the number of neutrons with time:***

$$N_n(t) = \frac{Y_n}{m_n} \times M_a \times \left(\frac{T_a}{T_a(t)}\right)^6 \times \frac{j_k(t)}{1 + t/0.5\ \boldsymbol{s}}$$

where $Y_n = 0.6$ ***and*** $j_k(t) = \exp[-(t/\tau_a)^2]$***.***

Time shift described as follows:

$$\Phi_{\bar{\nu}_e}(t) = \Phi_a(t) + (1 - j_k(t)) \times \Phi_c(t - \tau_a)$$

Details of the Treatment of Oscillations

For <u>normal</u> mass hierarchy the survival probability and the observed $\bar{\nu}_e$ flux are:

$$P = U_{e1}^2,$$

$$\Phi_{\bar{\nu}_e} = P\ \Phi^0_{\bar{\nu}_e} + (1-P)\ \Phi^0_{\bar{\nu}_\mu},$$

For <u>inverted</u> mass hierarchy $\nu - \nu$ interaction introduces a swap between the $\bar{\nu}_e$ and $\bar{\nu}_x$ so that

$$P = U_{e1}^2 P_f + U_{e3}^2 (1 - P_f),$$

$$\Phi_{\bar{\nu}_e} = P\ \Phi^0_{\bar{\nu}_\mu} + (1-P)\ \Phi^0_{\bar{\nu}_e}.$$

Earth matter effect described by PREM model.

Multiple Solutions

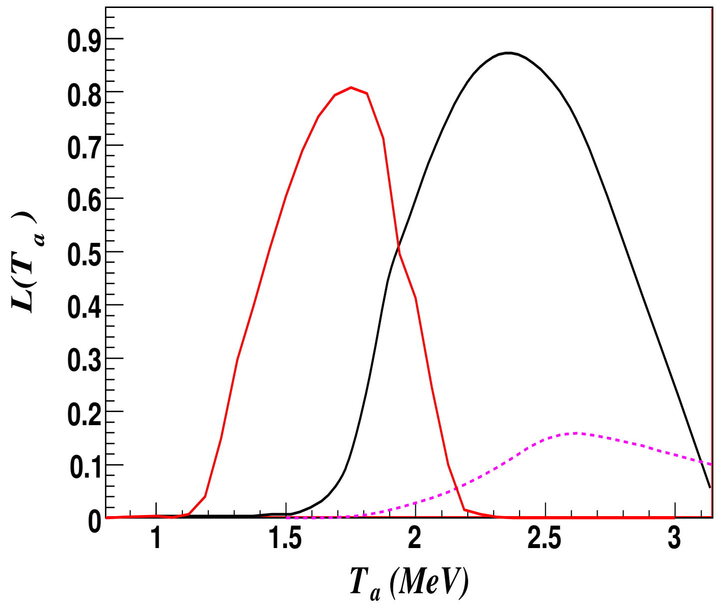


Figure 10: *One dimensional marginal distribution for T_a parameter of accretion with the complete emission model. The red line is the family of solutions with $t^{off}_{IMB} \simeq 0.5 - 1$ s and $M_a \simeq M_\odot$. The dark line is the main family of solutions with $t^{off} = 0$. The dotted line is an unphysical family of solutions with $\tau_a = 0.2$ s.*

Remarks on the Background at Baksan

Expects $b = 1$ ***background event in a 30 s window.***

With typical expectation $s = 1.6$, ***Poisson probability of 5 or more events is 2.4 %, sort of worrisome.***

Adding $b = 1$, ***this increases five times, thus fully acceptable.***

But since the energy distribution is OK, one could perhaps think that some event occurred outside the fiducial volume, thus increasing the effective mass.

A posteriori probabilities of 0,1,2 bkgr events=20,47,29%.

Remarks on the Energy Distribution at Kamiokande-II

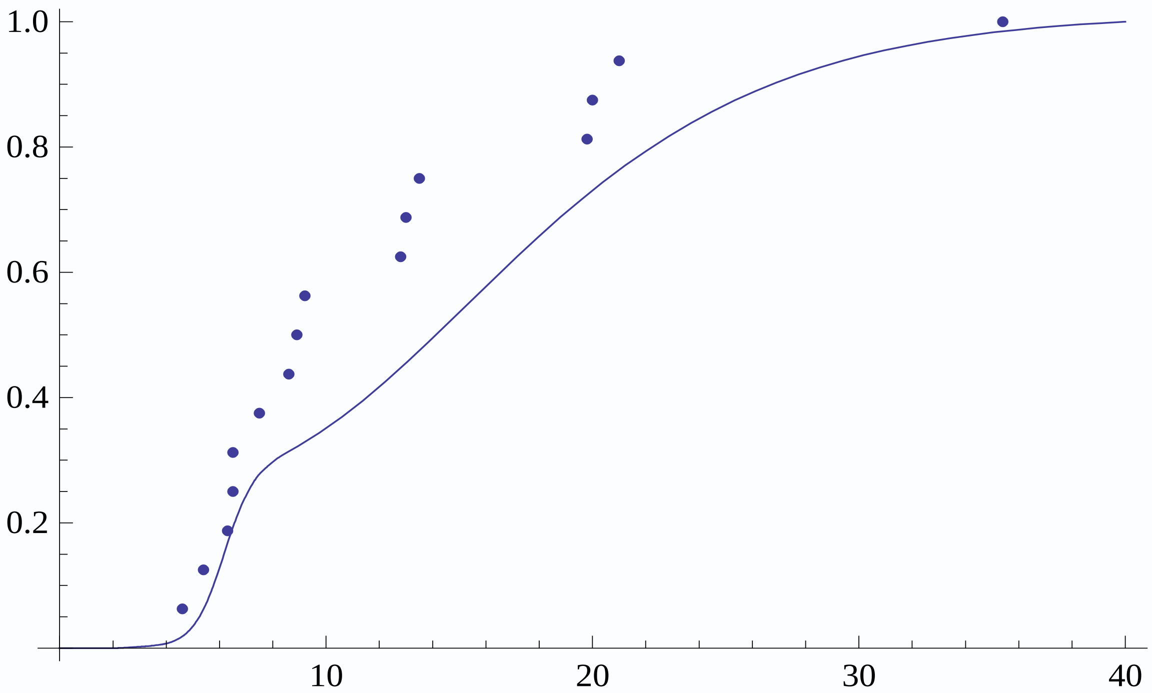


Figure 11: *Cumulative distribution in the energy (in MeV) for Kamiokande-II events. The dots are the 16 observed events. Continuous line is the expectation; the shoulder ending at ~ 7 MeV due to expected background. GOF=19%.*

Angular Distribution

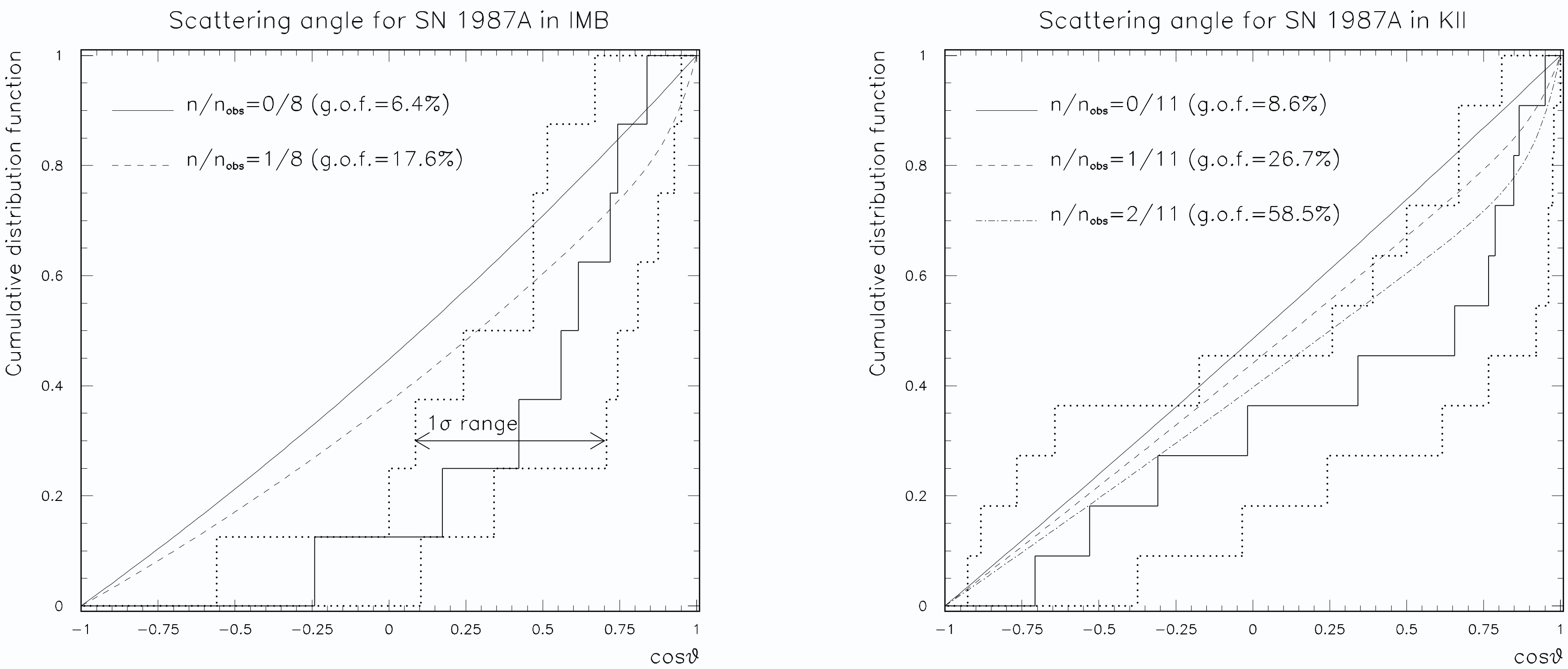


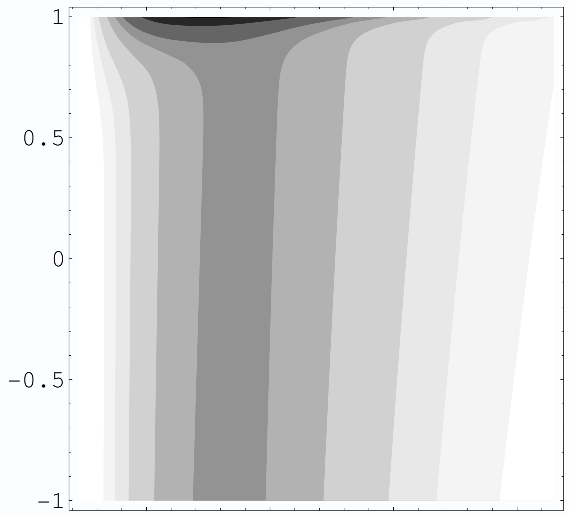
Figure 12: *Angular distributions in IMB and in KII, with and without a small number of ES events on top of the IBD events of the 'reference model'.* All hypotheses can be accepted at CL=5% (SCVM test).

With the correct angular distribution (dictated by the IBD cross section, by the model and by the angular bias) no need of a deviations from IBD hypothesis. E.g, $N_{ES} = 0.3 - 0.6$ ***are* expected *in KII which means that 1 or 2 ES events have a GOF of 42% or 15% for reference model when combined with the angular distribution;*** *see Costantini et al, 2004 for details.*

My bottom-line: the discrepancy with expectations is not very large and does not seem to be a real obstruction to a conventional interpretation.

Remarks on the First Event of Kamiokande-II

Figure 13: *Expected 2-dimensional (energy,cosine)-distribution for KII. The angular distribution of ES events is dictated by instrumental effects.*



Assuming 'equipartition' within a factor of 2 (Janka), the time-averaged probability that the most directional event of KII (the first) is due to ES can reach 30 %.

Thanks a lot for the attention!

(and also thanks to my daughter Claudia for this masterpiece)

Discussion

`Q [P. Vogel]:` ***Don't angular distributions disagree with expectations? In particular, IMB's? If you find the GOF is bad, you could doubt that such an analysis is legitimate.***

`A:` ***The GOF of the angular distribution is discussed at page 24 from our previous publication, PRD70:043006,2004. You can check that the GOF of the angular distribution is better than the conventional 5%, so the problem is not so severe as one may feel. Our re-evaluation of GOF and also the analysis uses the newly calculated cross section (PLB564:42-54,2003) and the published angular bias of IMB (PRD37:3361,1988).***
Again on IMB, there is an important point to note: the events of IMB cannot be elastic scattering events, because they are not so directional. And even being ready to consider something exotic taking place, it is hard to imagine a reaction that is forward peaked but too much, as needed to locate half of the events of IMB

in the region where they are, $30^\circ < \theta < 60^\circ$*. All in all, I believe that the hypothesis that they are inverse beta decay events is the most reasonable and conservative.*

Other Authors explore the hypothesis that IMB analysis could be biased, e.g., Malgin (Nuovo Cim.C21:317-329,1998): this is not the case of our work on SN1987A events.

Q [V. Berezinsky]: *The role of rotation is important and should be included in the analysis.*

A: *We tried to avoid linking our analysis to a specific model, and we kept the parameters free. I believe that these results could be used as follows: Suppose that a certain model with rotation produces an initial temperature of accretion* T_a *much lower than the one of our best fit value; then, one could be entitled to conclude that this model with rotation is disfavored.*

Q [V. Matveev]: *Could some events be due to neutrino interactions with iron?*

A: *Yes the most complete analysis should take into account all the interactions happening in the detectors. We tried to keep this analysis as simple as possible and this is the reason why we mainly focussed on the parameterization of the most important flux, namely, the one of electron antineutrinos. As emphasized in the paper of Imshennik and Ryazhskaya, in order to assess the importance of the interactions with iron, we would need to describe the electron neutrino flux, too.*