What is the Issue with SN1987A Neutrinos?

Francesco Vissani
INFN, Gran Sasso

What we did learn out of SN1987A neutrino observations? What are the most important theoretical elements to understand them? We discuss various issues debated in the vast literature on the subject: the effects of oscillations; the effect of neutrino masses; role of detailed statistical analyses of the data; specific data features; astrophysics of the neutrino emission process.

Work in collaboration with ML. Costantini, W. Fulgione, A. Ianni, G. Pagliaroli
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Is large lepton mixing excluded?

This question raised by Smirnov, Spergel, Bahcall, PRD49, 1994, who claim:
“The restriction $p < 0.23$ (0.35) at 95% (99%) CL can be considered as upper bounds in a representative supernova neutrino burst model.”

Beware: in normal hierarchy, SK, SNO, KamLAND imply that the conversion probability is $p = \sin^2 \theta_{12} = 0.31$.

In PRD65, 2001, Kachelrieß, Strumia, Tomas, Valle state instead:
“LMA-MSW solution can easily survive as the best overall solution, although its size is generally reduced when compared to fits to the solar data only.”

Also, they show increasing awareness that astrophysical uncertainties were underestimated.

With a complete fit to SN1987A data (A.Ph.09), any such hint evaporates:
Even including $p = 0.31$, “a value $T_x/T_{\tilde{e}} = 1.0 - 1.5$ or a deviation of the amount of energy stored in non-electronic neutrino species by a factor of 2 does not affect crucially the fitted $\bar{\nu}_e$ flux.”
Is earth matter effect important?

In the abstract of PRD63,2001, Lunardini & Smirnov write:

“We show that these effects can provide explanation of the difference in the energy spectra of the events detected by Kamiokande-2 and IMB detectors from SN1987A.”

However, the 1 layer approximation (Surv.04, $D \sim 1$), i.e.,

$$P(\bar{\nu}_e \to \bar{\nu}_e) = \cos^2 \theta_{12} + \varepsilon \times \frac{\sin^2 2\theta_{12}}{D^2} \times \sin^2 \left(\frac{\Delta m^2_{12} L}{4E} D\right)$$

close to full result (A.Ph.07), with earth matter effect enucleated in:

$$\varepsilon = \frac{\sqrt{2} G_F N_e}{\Delta m^2_{12} / (2E)} \sim 0.1 \frac{\rho}{4 \text{ gr/cc}} \frac{E}{20 \text{ MeV}}$$

suggests that this effect is not important.

In fact, in PRD.04 we find that, even at fixed astrophysical parameters:

“the inclusion of MSW in the Earth diminishes the expected number of IBD events in KII (respectively in IMB) only by 0.5% (respectively by 2.5%)”
A new twist of oscillations?

First, we remind the somewhat confuse history of the subject:

- Till recently, oscillations were thought to be as for solar $\nu$ e.g., Dighe & Smirnov '01.
- Today, we agree that these oscillations are non linear as argued by Pantaleone '92.
- New simple formulae for data analysis are proposed, but are them safe?

Despite entire conferences to discuss this, we do not know it yet.

Using these formulae in our analysis (A.Ph.09) we find that:

For normal hierarchy, the formulae are unchanged and thus oscillations do not modify the quality of our fit, $\Delta \chi^2 < 1$;

one case of inverted hierarchy seems to lead to some effect, but building on an incompleteness of the model used: thus, no quantitative conclusion yet.
NEUTRINO MASSES
Any role of neutrino masses?

I try to make a long story short: with present limits from lab of 2 eV, \( \nu \) masses are also irrelevant in SN1987A data analysis.

Figure 1: Bound from SN1987A, with astrophysical parameters free (blue) or fixed to best fit (red). For comparison, we show the bound from a future galactic supernova obtained by simulated data (dashed). [Ref.: A.Ph.10]
STATISTICAL TOOLS
Likelihood

The Poisson construction permits to use the available information fully.

Consider the expected event number in $i^{th}$ bin, function of a few parameter

$$n_i = n_i^{\text{bkgr.}} + n_i^{\text{sign.}}(\theta)$$

Since $P_i = e^{-n_i}$ if no events are seen, $P_i = n_i e^{-n_i}$ if 1 event is seen:

$$P(\theta) = \prod_i P_i = e^{-\sum_j n_j} \prod_{i=1}^{N_{ev}} n_i$$

Finally, we model the detector writing

$$n_i^{\text{sign.}}(\theta) = \sum_j R_{ij}^{\text{det.}} n_j^{\text{ideal}}(\theta)$$

where $R_{ij} \equiv G_{ij} \epsilon_j$ is the response function and $\epsilon_j \leq 1$ the efficiency.

Lamb and Loredo 2002 proposed a difference prescription, which we demonstrated to bias the analysis of SN1987A observations (PRD09).
Figure 2: Allowed parameters from SN1987A data analyses for the simplest model, i.e., black body emission (largely discussed later in this talk).

The effect of the bias is visible in the figure. It should be noted instead that, with the same likelihood, the Bayesian analysis of Lamb and Loredo and our frequentist analyses give pretty similar result [Ref. PRD09].
FEATURES of the DATA
The SN1987A events

Several neutrino detectors searched for a signal in the few hours preceding the astronomical observation — and found it as expected!

LSD neutrino detector (90 t of scintillator, 200 t of iron) saw 5 events and claimed correlation with gravity wave detectors. 4.5 hours later:

- Kamiokande-II (H$_2$O, 2140 tons) 11 or 16 events
- IMB (H$_2$O, 6800 tons) 8 events
- Baksan (C$_9$H$_{20}$, 200 tons) 5 events

29 events

The discrepancy in time could indicate a 2 stage collapse; however, no satisfactory model for the emission is available yet. Thus, we postpone the interpretation of LSD events and focus the discussion on the second group of events [please ask for more discussion].
The time distribution shows a steep ramp: in the 1\textsuperscript{st} second KII, IMB and Baksan saw a large number of events; 6, 3, 2 respectively [Ref. Astr.Lett.09].
ASTROPHYSICS of EMISSION
Generality and energetics

The gravitational core collapse of stars above $\sim 8M_\odot$ forms compact stellar objects: neutron stars, hybrid stars or black holes.

The released kinetic energy, $\sim 10^{51}$ erg, imparted to the shells surrounding the core, leads to a wide variety of optical supernovae: SN II and possibly Ib & Ic.

10-20% of the rest mass of the core, namely a huge amount of energy:

$$E_{bind} \sim \frac{G_N M^2}{R} = 3 \times 10^{53} \text{ erg} \left(\frac{M}{M_\odot}\right)^2 \left(\frac{10 \text{ km}}{R}\right)$$

has to be carried away to permit the formation of the compact object.

A principal role of neutrinos is to fulfil this task.
Black body neutrino emission

In black body approximation, the neutrino luminosity of the hot compact object is:

\[ L_{\text{cool}} \sim R_c^2 T_c^4 \sim 5 \times 10^{51} \text{ erg sec} \left( \frac{R_c}{10 \text{ km}} \right)^2 \left( \frac{T_c}{5 \text{ MeV}} \right)^4 \]

that is impressive. \( T_c \) is the neutrino temperature in the region where the object becomes transparent, so called “neutrino-sphere”, with radius \( R_c \).

Such a luminosity correctly indicates the time scale of neutrino emission:

\[
\frac{3 \times 10^{53}}{6 \times (5 \times 10^{51})} = 10 \text{ sec.}
\]

where 6 are the neutrino types: \( \nu_e, \nu_\mu, \nu_\tau, \bar{\nu}_e, \bar{\nu}_\mu \) and \( \bar{\nu}_\tau \).

But, evidently, the black body formula:

\[
dN_{\bar{\nu}_e} = \frac{\pi R_c^2 c dt \times d^3 p / h^3}{1 + \exp(E/T_c)}
\]

is a poor description of the underlying physical processes that lead to \( \bar{\nu}_e \) emission.
Expected time dependence of neutrino emission

All calculations (Nadyozhin78; Bethe&Wilson85; etc, till most recent ones) find that, on top of a quiet phase of emission, there is also a very intense neutrino emission during a rapid “accretion” phase in the first (fraction of a) second; astrophysicists are still working to understand it fully.

Figure 4: A sketch of the expected $\nu_e$ and $\bar{\nu}_e$ luminosity curves.
Which is the role of the phase of high luminosity?

Another general feature of theoretical calculations is that the shock wave initially stalls into the core **without triggering the explosion**.

*The main hope to explain the explosion is that the stalled shock wave is **refueled** by the neutrino pressure: namely, a fraction of the $3 \times 10^{53}$ erg enters the $10^{51}$ erg budget. This conjecture, called “delayed scenario” for the explosion, does require an initial phase of high neutrino luminosity, that can be tested by neutrino observations.*

SN1987A data analyses describe $\bar{\nu}_e$ emission in black body approximation, and, quite often, time is even integrated away! But, much worse, the black body formula forbids adequate modeling of the physical emission processes—including this one.

Thus, we use a more complete model to describe the emission and to analyze the data, improving on the proposal of Lamb and Loredo 2002.
How to model the initial $\bar{\nu}_e$ emission

The idea: on top of the black body emission that cools the compact object (in grey) a dense $e^+e^-$ plasma formed during very rapid accretion leads to release of $\bar{\nu}_e$ via

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

Such an emission from the transparent atmosphere around the compact object greatly increases the initial luminosity: the yellow dots symbolize the individual reactions.

In other words, the initial emission is from the volume rather than from the surface.
A check of the luminosities in the two phases

The new component of the $\bar{\nu}_e$ flux gives:

$$L_{\text{accr}} \sim N_n \langle \sigma_{e+n} \rangle T^4 \sim 5 \times 10^{52} \frac{\text{erg}}{\text{sec}} \left( \frac{M_a}{0.1 M_\odot} \right) \left( \frac{Y_n}{0.6} \right) \left( \frac{T_a}{2 \text{ MeV}} \right)^6$$

one order of magnitude more luminous than the other component:

$$L_{\text{cool}} \sim R^2_c T^4_c \sim 5 \times 10^{51} \frac{\text{erg}}{\text{sec}} \left( \frac{R_c}{10 \text{ km}} \right)^2 \left( \frac{T_c}{5 \text{ MeV}} \right)^4$$

the only one usually included – e.g., in Bahcall’s classical analyses.

Theory says that both emissions are present, thus, we include them in the fit.

*The last two parameters are the time scales of the two $\bar{\nu}_e$ emission phases.*

*In summary, we have 3+3 free astrophysical parameters.*
A NEW FIT of Kamiokande-II IMB and Baksan
Technical details of SN1987A data analysis

⋆ We analyze Kamiokande-II, IMB and Baksan data;
⋆ We adopt a Poissonian likelihood;
⋆ We analyze 30 s analysis window;
⋆ We consider energy, time and direction of each event;
⋆ We describe the background, finite detection efficiency and energy resolution in each detector;
⋆ We include dead times and live-time fraction;
⋆ We use only the relative times;
⋆ We describe the delay of detector responses and the clock mismatches by 3 free parameters;
⋆ We update the cross sections;
⋆ We improve on the description of the energy and time distributions;
⋆ We account for neutrino oscillations;
⋆ We apply frequentist techniques of inference;
⋆ But, most of all, we use a model with physical basis to describe $\bar{\nu}_e$ emission.

Why we allow for many free parameters? To account for the astrophysical uncertainties and for the limitations of the detectors.
Results and remarks

The best fit values of the astrophysical parameters of accretion and cooling emission phases are:

\[ R_c = 16^{+9}_{-5} \text{ km} \quad T_c = 4.6^{+0.7}_{-0.6} \text{ MeV} \quad \tau_c = 4.7^{+1.7}_{-1.2} \text{ s,} \]

\[ M_a = 0.22^{+0.68}_{-0.15} M_\odot \quad T_a = 2.4^{+0.6}_{-0.4} \text{ MeV} \quad \tau_a = 0.55^{+0.58}_{-0.17} \text{ s} \]

that describe intensity, average energy, and duration of each phase.

- The relatively large errors are due to the very limited statistics;
- The results are reasonable and pretty close to what we expect from the standard collapse, in particular we get \( \mathcal{E}_{bind} = 2.2 \times 10^{53} \text{ erg}; \)
- There is a 2.5 \( \sigma \) evidence for the accretion phase.
The fit returns a parameterized flux that, by construction, smoothly interpolates between the 2 emission phases [can be downloaded at http://theory.lngs.infn.it/astroparticle/sn.html]

Figure 5: Properties of the best fit model. Left, $\bar{\nu}_e$ luminosity; right, average $\bar{\nu}_e$ energy. The presence of an accretion phase is clearly visible.

The result of the fit resembles closely the expectations of the standard collapse.
SUMMARY and DISCUSSION
We discussed SN1987A data and their interpretation. While we do not pretend to solve all the important problems raised by this epochal observation here, we did our best to settle a number of issues discussed in the recent literature:

- There is no evidence that $\nu$ masses or oscillations are relevant to understand SN1987A observations.

- Adequate statistical tools to extract most effectively information from small event samples exist and can be usefully adopted.

- The time distribution of the events seen by Kamiokande-II, IMB and Baksan is particularly interesting and important.

- The data sets fit nicely in a model built to resemble the standard emission and provide a 2.5 sigma support in its favor or of something alike...

Thanks for the attention!
MORE
ISSUES
There are many issues for SN1987A and we list 3 types of them: those we add “just for completeness”, those that “need discussion” and finally the “really open” issues.

- Observable signal in neutrino detectors
- Energy-cosine distribution for Kamiokande-II
- Number of events for a standard emission
- Energy distribution of SN1987A events
- Angular distribution of SN1987A events
- Comparison with Loredo and Lamb 2002
- Is inverse hierarchy probed?
- Multiple neutrino emissions?
- Missing neutron star?
Observable signal in neutrino detectors

In water Čerenkov or scintillators detectors the signal is mostly due to one of the six types of neutrinos, i.e., electron antineutrinos:

The main reaction is ‘inverse beta decay’ (IBD) weakly directional:

\[
\bar{\nu}_e + p \rightarrow e^+ + n, \quad \text{followed by } e^+ + e^- \rightarrow \text{some } \gamma \quad \text{and by } np \rightarrow D\gamma(2.2 \text{ MeV})
\]

Elastic scatterings (ES) give a directional event:

\[
\nu + e \rightarrow \nu + e, \quad \text{where } \nu = \nu_e, \bar{\nu}_e, \nu_\mu, \bar{\nu}_\mu, \nu_\tau, \bar{\nu}_\tau
\]

We neglect reactions on nuclei that are less clearly characterized and also in view of the small data-set from SN1987A.
Energy-cosine distribution for Kamiokande-II

Only $\sim 1/30$ events are due to ES.

Note that ES events have lower energy, due to the final state invisible neutrino and that the angular distribution of ES is due to instrumental effects.
Number of events for standard emission

- With the IBD cross section at $E_{\bar{\nu}_e} \sim 15$ MeV:
  \[
  \sigma_{\bar{\nu}_e p} \sim G_F^2 E_{\bar{\nu}_e}^2 \sim 10^{-41} \text{ cm}^2
  \]

- with a $\bar{\nu}_e$ fluence:
  \[
  F_{\bar{\nu}_e} = \frac{\mathcal{E}_{\text{bind}}/6E_{\bar{\nu}_e}}{4\pi D^2} \sim \frac{2 \cdot 10^{57}}{10 (50 \text{ kpc})^2} \sim 10^{10} \frac{\bar{\nu}_e}{\text{cm}^2}
  \]

- and with a number of targets (free protons) in a typical mass of water:
  \[
  N_p \sim 1 \text{ kton} \times \frac{10^9 \text{ g}}{\text{kton}} \times \frac{6 \cdot 10^{23}}{\text{g}} \times \frac{2}{18} \sim 10^{32}
  \]

we expect about:

\[
N \sim N_p \times F_{\bar{\nu}_e} \times \sigma_{\bar{\nu}_e p} \sim 10 \text{ events due to IBD}
\]
Energy distribution of SN1987A events

Figure 6: Cumulative energy distribution of the SN1987A events of KII.

The comparison with the energy distribution of a thermal spectrum shows a mild fluctuation toward low energies since the GOF=19%; similarly but in opposite sense for IMB.

Conclusion: the difference between KII and IMB average energies is not a problem. It can be explained by good efficiency and background at low energies of KII. Note that early KII events have particularly low energy.
Angular distribution of SN1987A events

Figure 7: Cumulative angular distribution of the SN1987A events of KII.

Some excess in forward direction. All events could be due to IBD, however $0.3 - 0.6$ ES events are expected.

Summary: not a serious trouble. Same in IMB, where new xsec and angular bias give GOF=6.4%. In IMB, the ‘anomaly’ is in $30^\circ < \theta < 60^\circ$, unlikely to be explained on physical bases. Anyway, this is not very relevant for data analysis.
Comparison with Loredo and Lamb 2002

Our analysis is similar, but departs from LL’s in several important respects:

- LL use a wrong likelihood, biased in favor of low energy events.
- LL have a composite neutrino spectrum (high energy and low energy components are independent).

As a consequence, also the results differ;

- In Bahcall type of analysis, LL find higher $R_c$ and lower $T_c$.
- LL get an unphysical best fit $M_a \sim 5 M_\odot$.
- LL have a higher evidence of accretion: no KII-IMB tension.

In other regards, we agree; in particular we confirm their key result that the data prefer an accretion phase lasting about 0.5 s.
**Is mass hierarchy probed by the data?**

Again from Lunardini & Smirnov well-known paper, PRD63.2001, it seems we learned something: “The hierarchy can be inverted if $U_{e3} \ll 10^{-3}$”

The simplified statistical fit performed by Barger, Marfatia, Wood leads to the opposite conclusion, that: Supernova 1987A did not test the neutrino mass hierarchy, Phys.Lett.B 532: 19-28, 2002; in agreement with Kachelrieß 01.

Finally, as discussed above, the most detailed analysis (A.Ph.09) concluded that certain important information on physics and astrophysics is still missing.
Multiple neutrino emissions?

Ways of reconciling presence of events in LSD and absence in the other detector:

- They were very low energy $\bar{\nu}_e$, close to LSD threshold [De Rujula 1987; Castagnoli et al. 1988].
- They were high energy $\nu_e$ [Imshennik & Ryazhskaya, 2004].

The first requires enormous energy and/or beaming, not very plausible; the second requires an intense neutronization of a rapidly rotating object.

The next trouble is the nature of the emission seen by KII, IMB, Baksan:

- Could be due to black hole transition.
- Could be due to quark (hybrid) star transition.

But these ideas are not developed at the level of the ‘standard model’. Thus, we are not ready to interpret LSD events and we can only focus on the other ones.
**Missing neutron star?**

The standard theory of cooling of neutron star predicts the existence of an intense X ray source, with luminosity \( L \propto R_{ns}^2 T_{ns}^4 \).

The existing bound is 4 times more stringent than the expectations!

There are various ways to avoid the contradiction and among them:

- The remnant is a quark (hybrid) star which cools faster.
- The compact object is a black hole.
- The star is shrouded in dense materials.

that however imply the presence of an X ray source at some level.

Possibly relevant points: the relatively large mass of the progenitor, considerations on the rotation state, LSD, etc.