

# New analysis for the correlation between gravitational wave and neutrino detectors during SN1987A

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**Abstract** Two major problems, still associated with the SN1987A, are: (a) the signals observed with the gravitational waves detectors, (b) the duration of the collapse. Indeed, (a) the sensitivity of the gravitational wave detectors seems to be small for detecting gravitational waves and, (b) while some experimental data indicate a duration of order of hours, most theories assume that the collapse develops in a few seconds. Since recent data of the X-ray NuSTAR satellite show a clear evidence of an asymmetric collapse, we have revisited the experimental data recorded by the underground and gravitational wave detectors running during the SN1987A. New evidence is shown that confirms previous results, namely that the data recorded by the gravitational wave detectors running in Rome and in Maryland are strongly correlated with the data of both the Mont Blanc and the Kamiokande detectors, and that the correlation extends over a long period of time (1 or 2 h) centered at the Mont Blanc time. This result indicates that also Kamiokande detected neutrinos at the Mont Blanc time, and these interactions were not identified because not grouped in a burst.

## 1 Introduction

SN 1987A was the only supernova visible at naked eye after the Kepler supernova (1604). At the time of this event, four underground detectors (Mont Blanc [1], Baksan [2], Kamiokande [3], IMB [4]) and two gravitational wave antennas (in Rome and in Maryland) were running. The Mont Blanc Liquid Scintillation Detector (LSD in the following) was the only experiment designed to search for low energy neutrino interactions from stellar collapses (energy threshold  $\sim 5$  MeV). The Baksan Scintillation Telescope (BST in the following) was a multi-purpose cosmic ray detector with an

energy threshold  $\sim 10$  MeV. The Kamioka Neutron Decay Experiment (KND in the following) and the Irvine Michigan Brookhaven (IMB in the following) experiments (energy threshold  $\sim 8$  and  $\sim 25$  MeV respectively) were designed to search for proton decay candidates by observing the Cerenkov light produced in the detector water by the particles originated in the decay. These four detectors were running at different depths underground, being the Mont Blanc LSD located deeper than the others (at the minimum depth of about 5,200 m of water equivalent). This implies a much smaller background in LSD as compared with the other detectors, because of the much smaller flux of cosmic ray muons interacting in the rock around the LSD detector that produces a much smaller background of neutral particles entering inside the detector and imitating neutrino interactions. In addition the LSD detector was shielded against the local background with 200 tons of iron slabs and paraffin.

One major problem associated with a supernova explosion is the duration of the inner core collapse. According to most theories of supernova explosion, the collapse develops in a few seconds but, as we will discuss here, all the experimental data of the collapse originating this supernova indicate a duration of order of hours. In addition, one should note that almost all theories do not take into account core rotation and magnetic fields, even if young pulsars, i.e. a possible final result of the collapse, have the strongest magnetic field and the fastest rotation in the universe. However, some unconventional models based on fast rotation and fragmentation of the collapsing core have been suggested soon after the explosion to explain the experimental data from neutrino and gravitational waves detectors [5–8]. But only the recent observations of the remnant of SN1987A made by NuSTAR (Nuclear Spectroscopic Telescope Array, a satellite launched by NASA on June 2012 to study the X-ray sky) show a clear evidence of an asymmetric collapse [9]. These data, in particular the high resolution analysis of  $^{44}\text{Ti}$  lines, show a direct evidence of large-scale asymmetry in

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the explosion: *the massive star exploded in a lopsided fashion, sending ejected material flying in one direction and the core of the star in the other.* The asymmetry of the explosion is an essential requirement in support of a collapse in two stages.

At the time of SN1987A, the four underground detectors recorded statistically significant signals but not at the same time, and the origin of this time difference is still not well understood, as we will discuss. The Mont Blanc LSD detector recorded on line, i.e. on real time at the occurrence, five interactions on February 23rd at 2h 52m UT, one day before the optical discovery of this supernova. The signal was so clear that as early as a few days later (February 28th) the IAU Circular n. 4323 reporting this detection was distributed to the astronomical community by the Central Bureau for Astronomical Telegrams of the International Astronomical Union. Several days later, after the raw data were analyzed and cosmic ray muons subtracted, KND reported detection of eleven interactions at 7h35m UT. IMB reported the detection of eight interactions at 7h35m UT, BST of five interactions at 7h36m UT and also LSD detected two interactions at 7h36m UT.

Because of the different energy thresholds and masses of these detectors it was clear very soon that there is no contradiction in the data: the first burst could be due to a large flux of low energy neutrinos and the second one to a small flux of high energy neutrinos. Indeed the five low energy pulses detected by the scintillator of LSD with visible energies in the range between 5.8 and 7.8 MeV, correspond to visible energies at the limit to be detected by KND and BST, and are not detectable by IMB.

Furthermore the gravitational wave detectors in Rome and Maryland (GWR and GWM respectively in the following) recorded several signals in time coincidence between them and with the five interactions detected by LSD at 2h52m UT. This unusual activity preceded the LSD signals by 1.1–1.2 s, with an absolute systematic error in timing of the order of 0.5 s. This observation was not expected because the sensitivity of the interaction of gravitational waves with the detectors seemed to be too small for detecting gravitational waves presumably produced by this extragalactic supernova. Indeed the classical cross-section for the interaction of gravitational waves with matter is far below that needed to detect GW [10–12]. However, there are considerations based on the idea that cooperative effects might occur in the detector pushing the cross-section to much larger values [13, 14]. We wish to recall that the resonant bar gravitational wave detectors are also sensitive to particles [15], different from gravitational waves.

In this paper we have reexamined some aspects of the analysis employed in the above cited literature, finding a strong enforcement of the correlation between neutrino and GW detectors. The scheme of the paper is the following:

1. We describe the correlation method used in our past analysis.
2. We comment on some criticism which was put forward on our method.
3. We point out an important aspect found in correlating neutrino and GW detectors, namely that all the analyses done show the greatest correlation on February 23rd at 2h 52m, precisely at the time of the LSD five neutrino burst.
4. We improve this result by making the correlations completely independent.
5. We go throughout a new four detector correlation analysis and find a confirmation of previous result.
6. We estimate the statistical uncertainty of our result.

We do not describe here other results obtained in the past years, namely the extraordinary correlation [16, 17] found between LSD and KND and between LSD and BST during a period of order of 2 h centered at 2h52m UT.<sup>1</sup> These results have been discussed mainly in the papers [18–21] and in the review paper [22] where various correlations among all neutrino and GW detectors were described.

## 2 The correlation algorithm

This algorithm,<sup>2</sup> called the *net excitation method* and described in detail in [18], is based on the idea to make use of all available data in underground detectors, and not only those considered to be produced by neutrino interactions. Here we shall give a brief description of this method to compare the data available from three independent detectors.

Let us consider first the gravitational wave detectors located in Rome and in Maryland and the neutrino detector LSD located deep underground in the Mont Blanc Laboratory. We have three independent files of data, that we call *events* for simplicity, even if we are well aware that most of these *events* are just background triggers. Since we sample the data of the GW antennas every second, in 1 h we have 3600 *events* for the Rome detector, and 3600 *events* for the Maryland detector. These *events* are all independent one from each other, since the integration times of the filtering procedures [23] are much smaller than 1 s. We have also a variable number of *neutrino events*, of order of 50/h for the LSD detector, most of them being triggers due to background local radioactivity.

<sup>1</sup> Prof. A. E. Chudakov was very surprised for this unexpected result, and decided to perform himself the analysis of the LSD and BST data. The result of his independent analysis confirms the same coincidence excess at the Mont Blanc time [17].

<sup>2</sup> Suggested by Sergio Frasca.

Obviously the data of these three files are completely independent. We consider the sum  $E_{RM}(t) = E_R(t) + E_M(t)$  where  $E_R$  and  $E_M$  are the measured energies (also called energy innovations, in kelvin units) of the *events* obtained with the Rome (RO) and the Maryland (MA) detectors at the same time  $t$ , 3600 values  $E_{RM}(t)$  per hour.

Then we compute the sum  $E(t) = \sum_i E_{RM}(t_i)$  where  $t_i$  is the time of the  $i$ th *event* of the LSD neutrino detector. The summation is extended over a given time interval (say 1 h) in which  $N_v$  *events* of the neutrino detector (most of them certainly due to background) are present.

The background for this algorithm is obtained by calculating  $E(t_1, t_2) = \sum_j (E_R(t_{1j}) + E_M(t_{2j}))$  at  $2 \times N_v$  times  $t_{1j}$  and  $t_{2j}$  chosen randomly within the time interval. The background has a  $\chi^2$  distribution with many degrees of freedom and approaches a gaussian distribution. Considering that we take different combinations of  $N_v$  values within 3600 values of the Rome data and combine with an equal number of combinations for the Maryland data, in 1 h we have very many independent values of  $E(t_1, t_2)$ .

Since we do not know whether the events we consider are real signals or background, already in our first paper [18] we stressed that *when we talk of g.w. or of neutrinos, we refer to the events recorded by the corresponding detectors, without neither presuming nor excluding that a part or all of these events are actually due to physical g.w. or physical neutrinos.*

Our analysis consists in comparing the value  $E(t)$  with the very large number of background values determined by considering non coincident signals RO and MA, observed at times uncorrelated with the neutrino *events*. In absence of any real signal we expect that  $E(t)$  be just one of the many  $E(t_1, t_2)$  background values and, on average, we expect that half of the background values be larger than  $E(t)$  and half be smaller.

An application of this method has been discussed at length in [18]. The Fig. 13 of Ref. [18] shows that the maximum correlation between the data of LSD and the GW detectors occurs when the GW data precede the LSD data by 1.1 s.

With regard to the KND data, the time measurements have an absolute error of  $\pm 1$  min. However the coincidence with the IMB data requires a time correction of +7.7 s on the KND time, in order to make the two bursts, the KND and the IMB ones, coincide in time (see Ref. [24]). While waiting for the next supernova, we have studied again in more detail the available experimental data in two distinct cases: (a) using the data RO, MA and LSD, (b) using the data RO, MA and KND.

### 3 Discussion on the net excitation method

The *net excitation* method we use for our analysis has been criticized by Dickson and Schutz [25]. In this section we want

to show that their criticism is not applicable to our analysis, as there are many points in which Dickson and Schutz have misinterpreted our work, coming to wrong conclusions.

(a) The most important point is that they apply the *net excitation* method to two simulated files of events while they could have used our real data which were available. Firstly they concentrated on our result shown in Fig. 11 of our paper [18] where we have shown a strong correlation applied to a period of 2 h centered at the LSD time (2h52m). In their paper they wrote (III-2) that *any estimation of probability from this method below a few times  $10^{-4}$  cannot, therefore be reliable.* This is certainly true if we correlated two independent files of events, one file with the *neutrino* events, say  $n_v$  events, the other file with 14400 events, 7200 events (one per second) from the Rome GW detector plus 7200 events from the Maryland GW detector. But this not what we did in our analysis. As a matter of fact we did a three-fold coincidence analysis and probably Dickson and Schutz were confused by the fact that we used the sum of the Rome events with the Maryland events, couple of events taken at the same time. But in considering the GW data as just one file they implicitly admit that the two independent GW detectors behaved just as **one** detector, sensitive in the same way at the same time to any sort of phenomena interacting with it (with them). This is, in itself, an extraordinary result. In preliminary analyses we did try to search for coincidences between the GW data of Rome with the GW data of Maryland, but in that case we found almost no correlation. Only if we selected the  $n_v$  Rome and the  $n_v$  Maryland events, much less numerous, which occur at the same times of the *neutrino* events we find a strong correlation (see ref. [26]).

(b) Dickson and Schutz wrote that *our reservation about the wisdom of varying time-delays in steps of 0.1 s when the gravitational wave data have a time resolution of 1 s.* (see C-3 of their paper). This is surprising because it is well known that considering a distribution of  $N$  measurements each one with an uncertainly  $\Delta$ , the average will have a smaller or even much smaller error than  $\Delta$ .

(c) Correlation with Kamiokande. In section B of the Dickson and Schutz paper it is stated that: *Rome, Turin and Maryland collaborations do not simply apply the same analysis method to the Kamiokande data as they used for the Mont Blanc data.*

It is evident from a previous [19] and the present papers that we did use the same algorithm. For Kamiokande the correlation extends over shorter periods of time, about 1 h, with respect to that for Mont Blanc, which extends up to 2 h. But this is not surprising, considering the different instrumentation, It is surprising instead that the correlation with Kamiokande occurs just at the same time of the correlation with Mont Blanc.

Dickson and Schutz raised the point about our correction of 7.7 s in the Kamiokande times. This correction was

found when exploring all possible correlations by varying the Kamiokande time within  $\pm 1$  min, according to the uncertainty given by the Kamiokande collaboration. The analysis was done using a preliminary list of 796 events provided on printed documentation and was presented in August 1988 at the Fifth Marcel Grossmann Meeting [27]. It was found that the best correlation with the GW data occurred with a time correction of 7.7 s. Later we were provided with a final list of events recorded on a magnetic tape (which we used afterwards, including the present paper) and it turned out that with the time correction of 7.7 s the two large events of Kamiokande and IMB at 7h35m started just at the same time, as considered also by Schramm [24]. We believe that this evidence is an additional proof of the correctness of the time adjustment. No other adjustment of the Kamiokande times has been considered.

#### 4 A new unexpected result

Among the several correlation analyses done in the past (see the cited literature) one result [28,29] appeared very striking to us. We had applied the net excitation method to periods of 1 h, stepped by 0.1 h, correlating in a first analysis RO, MA, LSD and, in a second analysis, correlating RO, MA, KND.

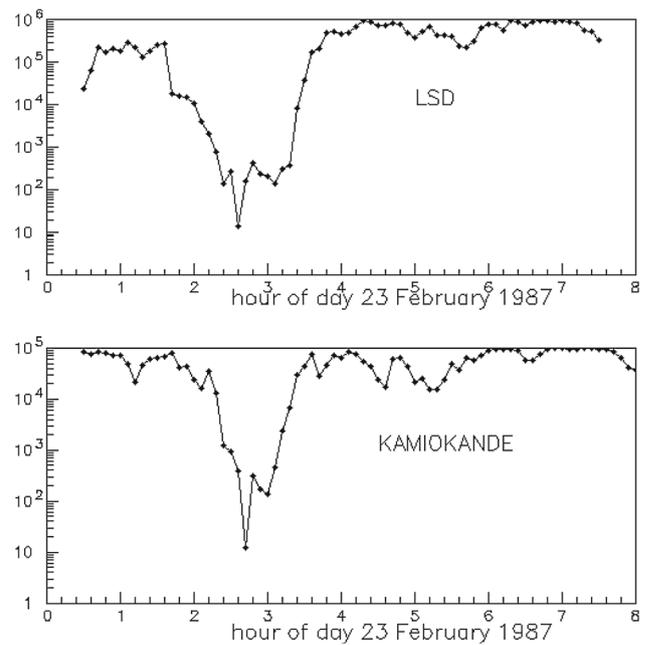
It was found that the correlation curves show an extremely similar behavior: both the RO, MA, LSD and RO, MA, KND curves have the greatest correlation at the time of the LSD event. This result was never discussed at length.

However, one objection can be raised, that the two correlation curves are not completely independent, because some of the RO–MA data used for the correlation with LSD may have been also employed for the correlation with KND, since some of the LSD events occur at the same time of some of the KND events.

In order to obtain correlation curves completely independent one from each other, in this new analysis we have searched for coincidences between LSD and KND and eliminated the RO and MA data occurring at these times, order of a few per hour.

For the correlations GW-neutrino detectors we apply again the *net excitation method*, having eliminated from the LSD and KND lists of events those in coincidence. Again we have used moving time periods of 1-h stepped by 0.1 h. We obtain the result shown in Fig. 1, where we have considered a delay of 1.1 s between the neutrino and the GW signals, as we had done in all our previous analyses [18,19].

The elimination of few events in common between LSD and KND has not changed substantially the behavior of the two correlation curves with GWR and GWM, as we find by comparing these new results with those [28,29] previously published.



**Fig. 1** The *net excitation method* is applied on 1-h time periods moved in steps of 0.1 h from 0 to 8 h of 23 February, reported on the abscissa scale. As in our previous analyses [18,19] we have introduced a delay of 1.1 s between the neutrino and the GW signals. On the ordinate scale we show the number of times, out of  $10^6$  or  $10^5$ , the GW background determinations are greater than the GW energy innovation obtained in correspondence of the neutrino events

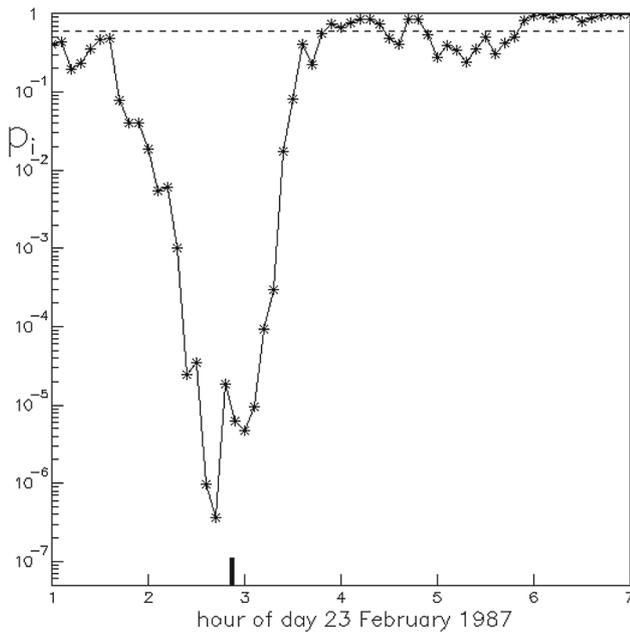
We wish to stress that each one of the two curves has been obtained with independent triple coincidences, the upper one RO–MA–LSD, the lower one RO–MA–KND. Similar correlations have been already found and discussed in our initial papers [18,19].

In the present case, however, we have eliminated the coincidences LSD–KND, thus the RO–MA data used for the upper curve are different from those used for the lower curve and we notice that the two correlations are still extremely similar. This result again supports the idea that the supernova phenomenon lasted much more than a few seconds.<sup>3</sup>

For calculating the probability that the result of Fig. 1 was obtained by chance we consider the  $i$ th 1-h time periods. The corresponding probabilities that the correlation for LSD or KND occurred by chance are  $\frac{n}{10^6}$  and  $\frac{n}{10^5}$ , where  $n$  is the value on the ordinate axis of Fig. 1. Since the correlation GW–KND is due to data independent from the data for the correlation GW–LSD we can multiply the two independent probabilities [30].

$$P_i = \frac{n_{LSD}}{10^6} \times \frac{n_{KND}}{10^5} \times \left[ 1 - \log_e \left( \frac{n_{LSD}}{10^6} \times \frac{n_{KND}}{10^5} \right) \right] \quad (1)$$

<sup>3</sup> That the phenomenon could have lasted much longer is discussed in [5,7,8].



**Fig. 2** On the ordinate scale we show the probability  $p_i$  that the two correlation curves (RO–MA–LSD and RO–MA–KND), calculated over periods of 1-h, stepped by 0.1 h, give at each step similar probability values. The arrow indicates the time 2h52m UT of the first real neutrino interaction in the burst of five real events observed in the LSD experiment. The dashed line indicates the expected value in the case of absence of correlation

In the case of random numbers we should have  $p_i = 0.5 \times 0.5(1 - \log_e(0.5 \times 0.5)) = 0.60$ . The neighbor 1-h time periods, stepped by 0.1 h, are not independent one from each other. We plot the result in Fig. 2 that gives a quantitative estimation of the probability that the two correlations (RO–MA–LSD and RO–MA–KND) occurred at the same time.

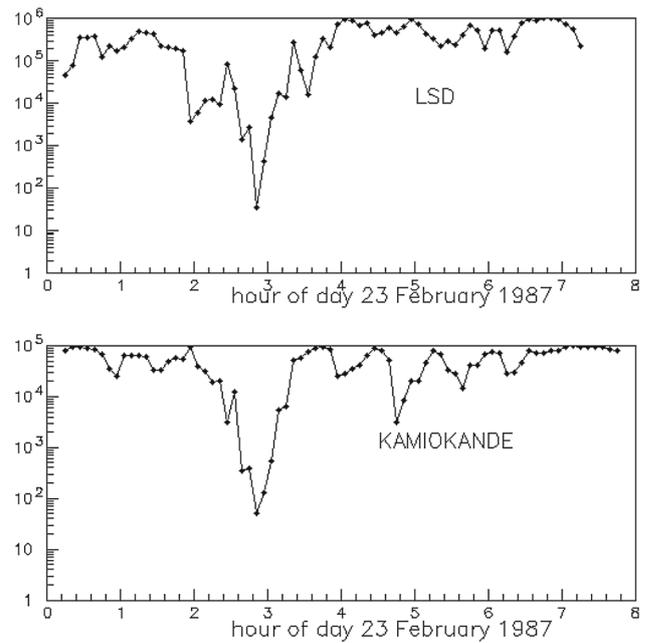
This figure shows very clearly an extremely significant peak at the time of the Mont Blanc LSD burst of 5 interactions observed at 2h52m UT, with a probability order of  $10^{-6}$ – $10^{-7}$  to be due to a random fluctuation.

We have considered periods of 1 h as done in the past. In order to increase the time resolution we try to use periods of 30 min and the result is shown in Figs. 3 and 4. We note that the best combined correlation occurs just at the time of the LSD burst of 5 interactions.

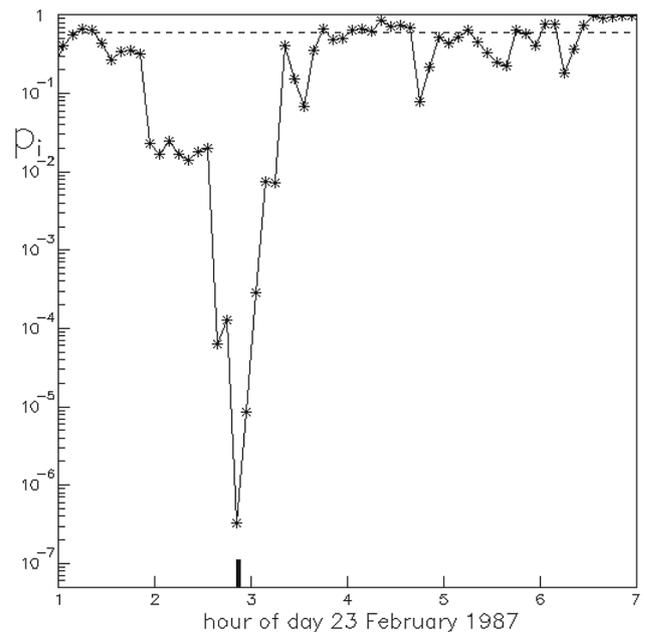
The new result, shown in Figs. 3 and 4, is very important to understand the physics of the collapse, because the best combined correlation occurs precisely at the time of the LSD burst of five neutrino interactions, i.e. 4.7 h before the second burst.

### 5 Quadruple correlation: LSD, KND, RO and MA

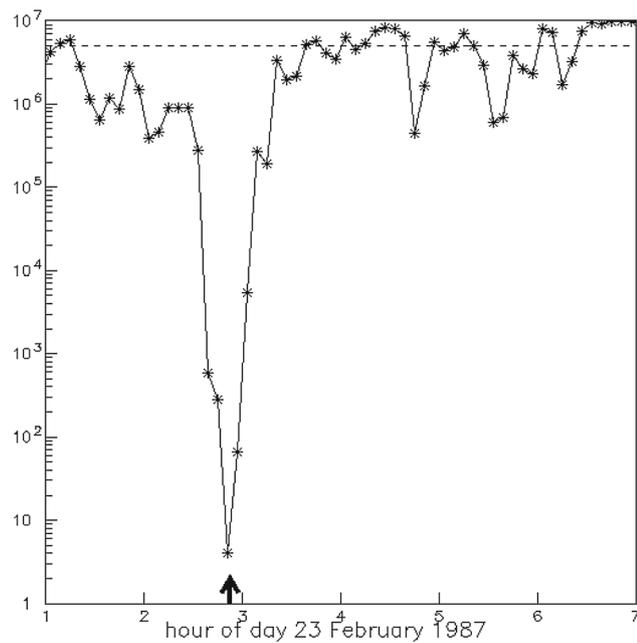
We have applied the *net excitation* method also to search for correlations between GW detectors and a single list of events,



**Fig. 3** The *net excitation* method is applied on 30-min time periods moved in steps of 0.1 h from 0 to 8 h UT of 23rd February, shown on the abscissa scale. As in our previous analyses [18,19] we have introduced a delay of 1.1 s between the neutrino and the GW signals. On the ordinate scale we show the number of times, out of  $10^6$  or  $10^5$ , the GW background determinations are greater than the GW energy innovation obtained in correspondence of the neutrino events



**Fig. 4** On the ordinate scale we show the probability  $p_i$  that the two correlation curves (RO–MA–LSD and RO–MA–KND), calculated over periods of 30-min, stepped by 0.1 h, give similar probability values at each step. The arrow indicates the time 2h52m UT of the first real neutrino interaction (out of five) observed by the LSD collaboration. The dashed line indicates the expected value in the case of absence of correlation



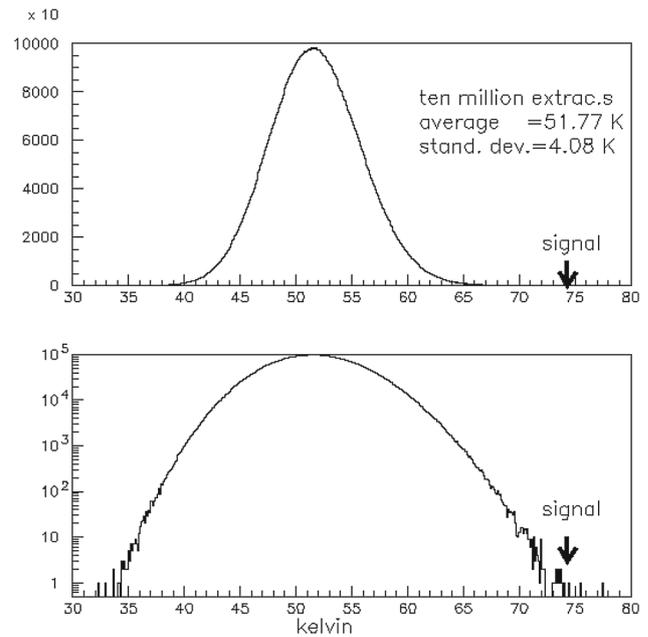
**Fig. 5** The *net excitation method* is applied to quadruple coincidences on 30 min time periods moved in steps of 0.1 h from 0 to 8 h UT of 23rd February, shown on the abscissa scale. As in our previous analyses [18, 19] we have introduced a delay of 1.1 s between the neutrino and the GW signals. On the ordinate scale we show the number of times  $N$ , out of  $10^7$ , the GW background determinations are greater or equal than the GW energy innovation obtained in correspondence of the neutrino events that includes both the LSD and the KND data. At the LSD time we have  $N = 4$ , corresponding to a probability of  $4 \times 10^{-7}$  that the correlation is accidental. The *dashed line* indicates the expected value in the case of absence of correlation

obtained by adding together the LSD and KND data. Using one-half hour periods stepped by 0.1 h we obtain the result shown in Fig. 5.

The similarity between Figs. 4 and 5 indicates the robustness of our result. During the period from hour 2h36m UT to hour 3h6m UT, that includes the LSD five-neutrino event at hour 2h52m UT, LSD has recorded 32 events and KND 51 events. Thus the list of neutrino events to be compared with the energy innovations recorded by GWR and GWM (as done in all our previous analyses) contains 83 data. By definition, the average energy innovation in the GW detectors is given by the 83 energy innovations of RO plus MA (all in coincidence with the 83 neutrino events) divided by 83. We have obtained an average energy innovation of 74.349 K, while the average background was 51.771 K during the half an hour.<sup>4</sup>

Since, by definition, the total number of different permutations of 83 elements out of 1800 elements is a huge number, in our analysis we limited to 10 millions the background determinations, a very large number, that makes our result

<sup>4</sup> The average noise of the RO detector is 28.6 K, that of MA is 22.1 K [18].



**Fig. 6** Background distribution. The distribution in linear and logarithmic scale of ten million determinations of the background obtained by means of  $10^7$  random extractions. The energy innovation in coincidence with the 83 neutrino events (32 from LSD and 51 from KND) is 74,349 K (the signal). From this graph we determine the experimental probability to have the above signal by chance,  $4 \times 10^{-7}$ , about twenty times larger than in the case the background distribution were gaussian

reliable from the statistical point of view. Figure 6 shows the distribution of this sample of ten millions independent background determinations obtained during the above half an hour time. The standard deviation is  $\sigma = 4.08$ . If the distribution of the background were gaussian we would have a difference between the signal and the average background equal to  $74.349 - 51.771 = 5.5 \sigma$  for a probability that our result was due to chance of  $1.9 \times 10^{-8}$ . Our probability estimation of  $4 \times 10^{-7}$  does not make any assumption about the experimental distribution.

The background determinations were calculated by choosing randomly 83 energy innovations (32 from the LSD event times and 51 from the KND event times) among the 1800 energy innovations of the RO detector and the 1800 energy innovation of the MA detector that are available in the half an hour period. It is important to remark that only three determinations of background, out of  $10^7$ , have values larger than 74.349 K, i.e. the energy innovations in coincidence with the 83 neutrino events. This demonstrate the extraordinariness of the correlation.

## 6 Discussion

Since one of the comments we have often received in the past was that the LSD event is a statistical fluctuation in the data, a *noise*, here again we stress that the Mont Blanc LSD signal

is not only self consistent, but additionally supported by all the experiments running at that time, as shown in this paper and by the previous LSD KND and LSD BST correlation analyses [17, 19].

We want to stress again that these new results have been obtained by comparing six independent files of events recorded in four different experimental apparatuses located at intercontinental distances one from the other, furthermore exactly during the explosion of the only supernova visible at naked eye since 1604.

In more than thirty years of data taking from January 1985 in the Mont Blanc Laboratory with the LSD Experiment, and from June 1992 to nowadays in the Gran Sasso Underground Laboratory with the Large Volume Detector (LVD) with a mass of 1000 tons of liquid scintillator, no evidence of neutrino signals has been found [31] a part the event printed on line in the night of February 23rd, 1987, just one day before the detection of the only supernova visible at naked eye since 1604. This event could certainly be a noise, but with very low probability. We conclude that the chance that the results here discussed are due to a statistical fluctuation in the data is so small that a deep discussion is imposed, and we feel forced to try to find a possible explanation to this peculiar supernova that was unusual under many other aspects [32] and not only for the recent NuSTAR observations, even if this costs the use of a collapse scenario different from the current scenarios.

Among the neutrino *events* observed in the neutrino detectors very few have been attributed, by the researchers, to real neutrino interactions. However in our algorithm we make use of additional signals, other than those recognized as due to neutrino events. In our attempt to explain the experimental result described in this paper we suggest that several signals among those considered background (we recall a background with a counting rate per hour of about fifty for LSD and more than one hundred for KND) are real events due to neutrinos (or to any other exotic particles) that were not identified because not grouped in a burst.

It is even more difficult to understand the cause of the signals in the GW detectors. As well known the predicted (but never measured) classical cross section of the bar-detectors for GW is at least one thousand times smaller than what would be needed to interpret the signals as due to GW, unless cooperative mechanisms are active in the bars, as already indicated in the Introduction [13, 14], or we were so lucky to intercept beamed fluxes of gravitational waves. However we believe that we must not discard experimental results simply because we do not have a model, or even an explanation for them. Again we feel we must proceed in our attempt to explain what it is, in any case, an extraordinary experimental result.

There are still two crucial points to be discussed. The first one is the time lag in the correlation between the GW and the neutrino detectors, and the second point is the astrophysical

scenario of the supernova explosion. As far as the first point is concerned, we have found a time lag of 1.1 s. The absolute time error for the GW apparatus in Maryland is of the order of 0.1 s, while the absolute time error for the GW apparatus in Rome has been discussed at length in paper [18]. We can have a possible systematic error of 0.5 s at most, which would reduce the time lag to about 0.6 s. The UT time of LSD is measured by a clock with an absolute time error of 2 ms. The absolute time error for KND is 1 min (more than enough for a proton decay experiment) so that, in our analysis, we have corrected the timing of the KND data by assuming that the two bursts at 7h 35m UT of KND and IMB (whose clock precision is 5 ms) start at the same time as usually done [24].

In conclusion, we find a non-zero time gap between the GW and the underground detectors. To explain this gap it is necessary that the particles responsible for the signals in the GW detectors be emitted by the star 1.1 s (or 0.6 s) before the particles detected in the neutrino detectors, or that they are emitted simultaneously but the particles interacting in the neutrino detectors have a larger mass and arrive later. In the case of simultaneous emission, from the observed delay of  $1.1 \pm 0.5$  s between the first and the second signals, we deduce that the neutrino mass should be in the interval from 2.3 to 3.9 eV, not much different from the lower bound of 2 eV quoted in [33] and the upper bound of 5.8 eV quoted in [34]. In both cases we must imagine that the collapse mechanism be such that the two types of particles be emitted more or less simultaneously during a period of 1 or 2 h.

Since the two neutrino bursts detected at 2h52m UT and 7h35m UT extend over a few seconds (7 s for LSD and 10 s for KND) at different times we are forced to consider the following scenario:

- (a) during several hours particles and perhaps gravitational waves are emitted by SN1987A,
- (b) the 7 s burst in LSD and the 10 s burst in KND are due to events which have been detected because recorded in a short time interval,
- (c) the long lasting correlation with the GW detectors is due to massive neutrinos (or to exotic particles), not identified from the background because not grouped together but distributed over long times.

Even if it seems difficult to attribute the signals of the GW detectors to real gravitational waves or to particles, the recent observation of NuSTAR, [9] mentioned in the introduction, shows a direct evidence of a large-scale asymmetry in the explosion: *the massive star exploded in a lopsided fashion, sending ejected material flying in one direction and the core of the star in the other*. This experimental result not only is an important evidence of the fragmentation of the core, that involves a long duration of the collapse [7, 8], but it is also an essential requirement for the emission of gravitational

waves, eventually along a narrow beam as it happens for optical and radio emission of pulsars. Finally, we have the experimental information that the collapse was asymmetric, a very important information to understand the mechanism of the collapsing inner core of the massive blue supergiants Sanduleak –69.202.

## 7 Conclusion

We are aware that the experimental results described in this paper do not follow most theories on the supernova phenomenon, but our aim is not to confirm theoretical models but to give experimental informations useful to explain this peculiar supernova.

We also believe that it is important to make experimental results available to the scientific community for future experiments and/or theories, when it has been proved that, with very large probability, they are not due to accidental mechanisms.

We wish to remark once again the great similarity between the correlations of the GW data with LSD and with KND, as shown in Figs. 1 and 3, with a probability, quantified in Figs. 2 and 4, lower than one in one million. This result, reinforced by the analysis described in Figs. 5 and 6, adds up to all previous correlation studies published in the above literature and induces us to think that they are not due to chance.

We conclude that this new analysis of the experimental data, obtained with the gravitational waves and neutrino detectors, strongly enforces the idea that between 2 and 4 h UT of 23rd February 1987 both the neutrino and the GW bar-detectors were invested by intense fluxes of particles, not all of them identified from the background because not grouped together but distributed over long times, presumably originated from the SN1987A. As well known, particles continued to arrive until 7h35m UT not detected by the gravitational waves detectors and with only two interactions detected by the LSD experiment at 7h 36 m UT. Obviously, something has changed in the structure and dynamics of the collapsing core in this 4.7 h time interval between the first neutrino burst and the second one.

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