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Supernova neutrino-burst search with the AMANDA detector

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Abstract. The neutrino telescope AMANDA located deep in the South Pole ice has been used to search for bursts of low energy neutrinos originating from supernova collapses. In the data sets taken during 1997 and 1998 with 302 of the detector's optical modules no candidate events were found. With this detector configuration 70% of the galaxy is covered with 90% efficiency allowing for one background fake per year. An upper limit at the 90% c.l. on the rate of star collapses in the Milky Way is derived, yielding 4.3 events per year. The new supernova readout system, which has been installed in 2000 and 2001, is discussed. With the full (19-string) system we expect to cover 97% of our galaxy.

1 Introduction

Until now, the only extra-terrestrial sources of neutrinos that have been observed are the Sun and the supernova SN1987A. In both cases, the energies seen were at or below a few tens of MeV. Although AMANDA (Antarctic Muon and Neutrino Detector Array (Andres, 2000)) is designed for the observation of TeV neutrino-sources, it has been shown (Halzen, 1994) that a detector of this type could also be used successfully to monitor our Galaxy for supernova events. AMANDA utilizes the large volume of transparent glacier ice available at the South Pole as a Cherenkov medium. The optical modules (OMs) are buried 1500-2000 m deep in the Antarctic ice sheet. Each OM is made up of a photo-multiplier tube (PMT) enclosed in a pressure-resistant glass vessel and connected to the surface electronics by an electrical cable supplying power and transmitting the PMT signals. In AMANDA the dominant detection mechanism for supernova events is the inverse β decay reaction on protons $\bar{\nu}_e + p \rightarrow n + e^+$ in the ice. During the estimated ~ 10 sec duration of a neutrino-burst, the Cherenkov light produced by the positron tracks will increase the counting rate of all the PMTs in the detector above their

average value (see Fig.1). This effect, when considered as a collective behavior, could be seen clearly even if the increase in *each* PMT would not be statistically significant. An observation made over a time window of several seconds could therefore provide a detection of a supernova, before its optical counterpart is observed. The stable and low background noise in AMANDA (absence of ^{40}K and of bioluminescence in the ice) is a clear asset for this method.
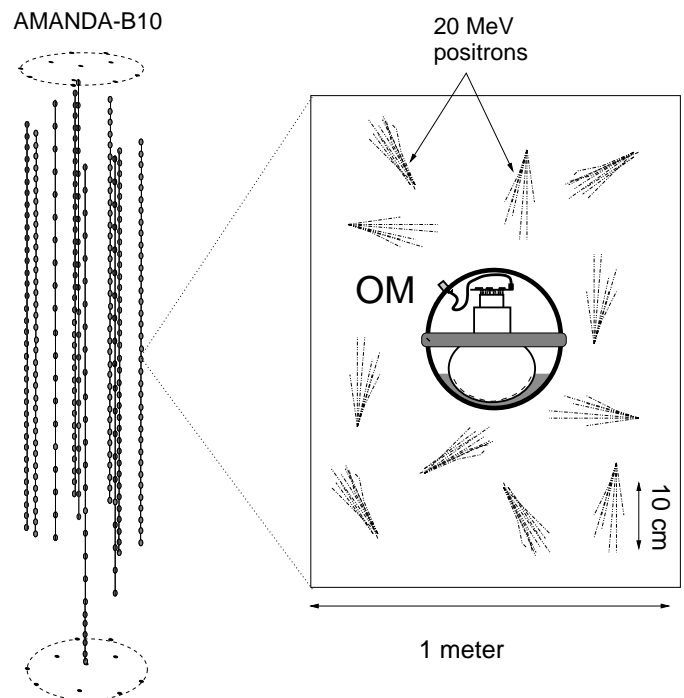

Fig. 1. View of the detector in 1997 and of the expected positron tracks produced in CC $\bar{\nu}_e$ interactions within AMANDA

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2 Analysis of 1997 and 1998 data

The AMANDA detector has been deployed over several years (Andres, 2000). Recently the analysis of the data taken in 1997 and 1998, with ten strings (302 OMs) in operation, has been completed (Ahrens, 2001),(Silvestri, 2000). In this section we summarize the analysis procedure and the results. Earlier results can be found in (Wischnewski, 1995 and 1999).

The supernova data-acquisition system measured the counting rates of all OM channels separately in fixed time intervals of 500 msec and stored that data for further analysis. The scalers had an adjustable artificial dead-time which was set to 10 μs in order to suppress afterpulses (see Section 3). The typical duration of a data-taking run was 14.6 hours.

In the offline-analysis the data were rebinned into 10 sec time intervals, corresponding to the expected supernova signal duration. Unstable OMs were excluded from the analysis, leaving 224 OMs in 1997 and 235 in 1998. The effective live-time was reduced to 103 days (out of 185 days in total) in 1997 and 112 days (out of 164) in 1998.

The noise rates in the OMs show long-time trends, e.g. a $\sim 2\%$ decrease per year due to PMT aging and fluctuations on a scale of several hours due to weather conditions. This is corrected for by subtracting the appropriate average noise rates. The resulting distribution of the residual summed noise rates for the whole data set is shown in Fig.2. The peak of the distribution is very well fit by a Gaussian distribution with a width of $\sigma = 265$ Hz.
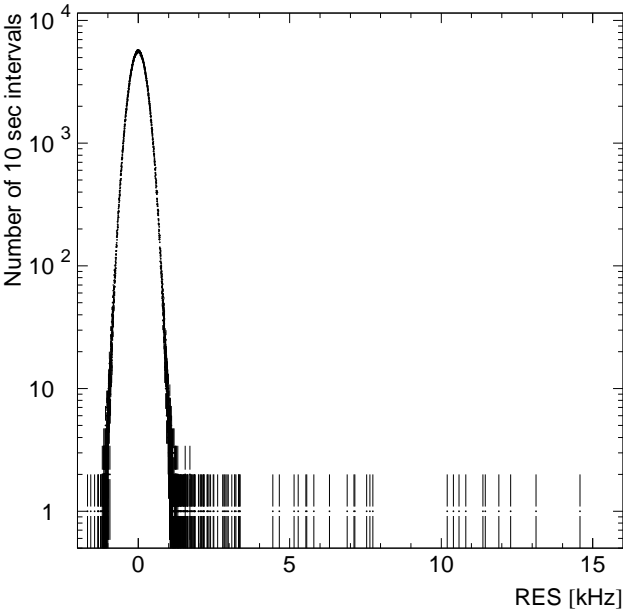

Fig. 2. Distribution of residual summed noise RES for 215 days live-time

The signature of a supernova signal is the coherent increase of the noise rates in all OMs. This is tested using the following χ^2 function:

$$\chi^2 = \sum_{i=1}^{N_{\mathrm{OM}}} \left(\frac{n_i - \mu_i - \epsilon_i \cdot \Delta\mu}{\sigma_i} \right)^2 \tag{1}$$

Here n_i is the measured noise in each of the N_{OM} optical modules , μ_i is its expectation value with standard deviation σ_i and ϵ_i is the relative sensitivity of OM_i. Minimizing Eq. 1 w.r.t. the average rate increase $\Delta\mu$ yields the resulting $\Delta\mu$ distribution for the combined 1997 and 1998 data-sets (Fig.3). Here also a cut on $\chi^2/\mathrm{n.d.f.} < 1.3$ has been applied (leaving 99.9% of events), in order to remove fake events which could still be seen in Fig.2. The vertical line is set at the level where a rate of one background event per year is expected.
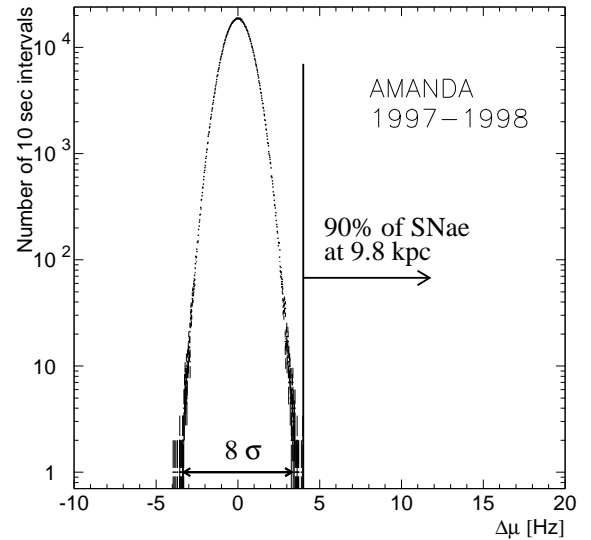

Fig. 3. Distribution of $\Delta\mu$ after application of cuts, for 215 days of live-time. The vertical line is set at the level where a rate of one background event per year is expected. 90% of supernova neutrino bursts located at 9.8 kpc distance would be seen above that cut.

The expected signal for a SN1987A-type supernova has been simulated (Halzen, 1996; Jacobsen, 1996), yielding a predicted excess in the number of photo-electrons per PMT:

$$N_{\mathrm{p.e.}} \sim 11 \cdot \left[\frac{\rho_{\mathrm{ice}} \cdot V_{\mathrm{eff}}}{M_{\mathrm{Kam}}} \right] \left[\frac{52 \,\mathrm{kpc}}{d_{\mathrm{kpc}}} \right]^2 \tag{2}$$

where 11 is the number of events detected by Kamiokande II, M_{Kam} is the effective mass of Kamiokande II and d_{kpc} is the distance between the supernova and Earth. The value of M_{Kam} is 2.14 kton, times a factor 0.8 to correct for the fact that Kamiokande II had an energy threshold, whereas the AMANDA supernova system does not (Jacobsen, 1996). The average ice density, ρ_{ice}, is 0.924 g/cm^3. Following Eq.2, we expect $\sim$100 counts/OM during 10 sec (Halzen, 1994) for a SN1987A-like supernova at 8 kpc distance from the Earth. With the present analysis we would detect a SN

1987A-like supernova located at a distance of 9.8 kpc with 90% efficiency. Since no candidate event is found after all cuts, an upper limit at the 90% c.l. on the rate of star collapses in the Milky Way can be derived, yielding 4.3 events per year.

3 Improvements with the new Supernova system

In the antarctic summer seasons of 99/00 and 00/01 a new supernova system has been installed at South Pole. The first step includes 468 optical modules, and in the second step all 677 OMs of the new AMANDA II set-up and 48 OMs of AMANDA A will be connected to the readout. (See (Wischnewski, 2001)).

The new scalers measure the noise rates in time bins of 10ms. In order to keep the data volume at a reasonable level, data normally are stored at 500ms time binning. However, if the system detects a significant increase in rate the data are recorded also in 10ms time bins for a limited period. All AMANDA supernova data are available online and transferred to the Northern hemisphere with a delay of the order of days at most. The detection of a supernova candidate could be communicated even quicker, allowing AMANDA to participate in the Supernova Early Warning System (SNEWS).

The performance of the supernova system can be jugded by the ratio of expected signal over the standard deviation of the noise. For a Poissonian behaviour of the dark noise one would expect the standard deviation to behave like the square root of the mean noise. Due to afterpulsing in the optical modules one finds the standard deviation to be larger by a factor of about 1.5 to 1.9 (depending on OM type).

A histogram of the time differences between dark noise hits in one OM can be seen in Figure 4. The straight line fit corresponds to the principal Poissonian behaviour. The excess at small time differences is due to correlated noise.

Recent studies have shown that the afterpulsing can be described by three exponential components with time constants of approximately $7\mu s$, $40\mu s$, and $250\mu s$ respectively, plus a peak-like structure around $6\mu s$. This implies afterpulses with a delay of up to milliseconds.

To account for the afterpulsing an artificial non-paralyzable dead-time is applied after each hit. The new system offers extended options on its length. Increasing the dead time from $10\mu s$ to $250\mu s$ improves the SN-sensitivity of the system by a factor of 1.4.

The additional number of OMs also improves the detector performance by a factor of $\sqrt{\frac{N_{\text{new}}}{N_{\text{old}}}}$. Taking into account the different noise rates this corresponds to another factor of 1.25 in going from 302 to 468 OMs and a factor of 1.5, once last technical issues with the second installment will be solved.

The current detection capabilities of the new AMANDA supernova system are such that – with 90% efficiency and allowing one fake per year – about 90% of our galaxy are covered. This increases to about 97% when the complete array can be used.
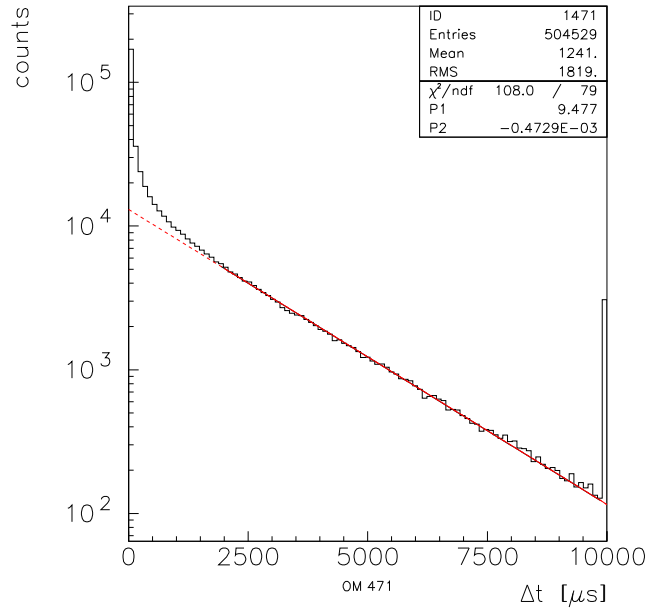

Fig. 4. Histogram of the time differences between noise hits in one optical module. A exponential fit is applied to show the principal Poissonian behaviour. Towards smaller time differences the histogram increasingly exceeds a straight line. This excess is due to afterpulses. Approximately every third hit is an afterpulse.

4 SN-Triangulation with AMANDA and IceCube

A Monte Carlo study has been performed in order to estimate the timing precision on the beginning of the neutrino emission in a supernova. Figure 5 shows the expected counting rates in AMANDA in time bins of 50 ms for a supernova in the center of our galaxy, assuming a time profile with a risetime of 30 ms and an exponential decay with 3 sec decaytime.

Given a known template for the time evolution, the start of the pulse can be measured with an accuracy of 14 ms. For the proposed IceCube detector (Goldschmidt, 2001) with 4800 OMs and low-noise glass spheres an accuracy of 1-3 ms can be achieved (Fig. 6).

Combining the timing information of the three detectors Super-Kamiokande, SNO and IceCube will give the supernova direction by triangulation with an expected accuracy of 5 to 20 degrees. This is similar to the angular resolution of Super-K using the electron direction. Fig. 7 shows the χ^2-contours of the reconstructed supernova direction for a randomly chosen supernova event.

5 Summary

Although the primary goal of AMANDA is the detection of high-energy neutrinos, it has been successfully operated as a supernova detector. The data taken in 1997 and 1998 have been analyzed and an upper limit of 4.3 star collapses per
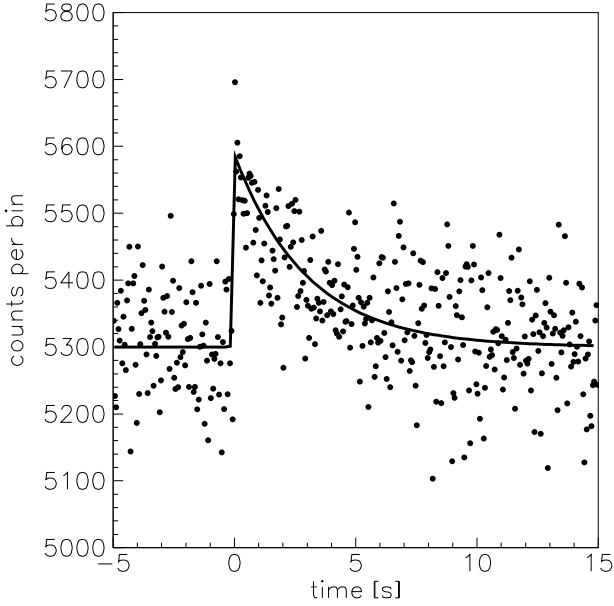
Examples for χ^2 contours

Fig. 5. Simulated counting rates for a supernova in the center of our galaxy, for the AMANDA detector.
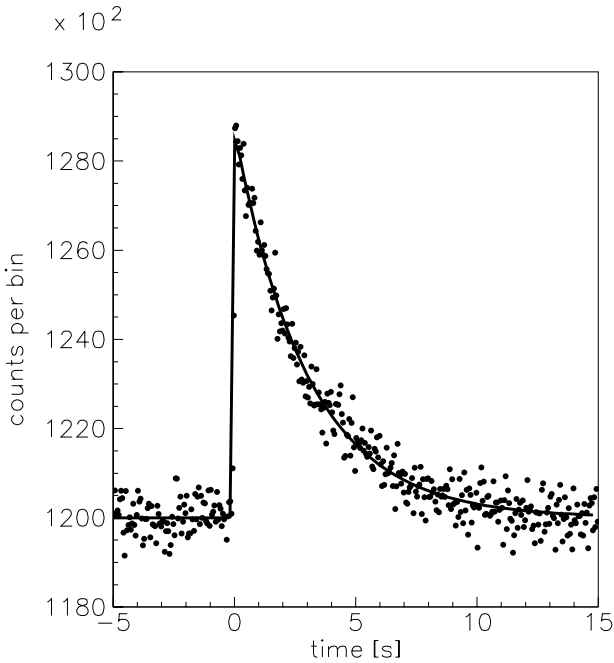

Fig. 6. Simulated counting rates for a supernova in the center of our galaxy, for the IceCube detector.
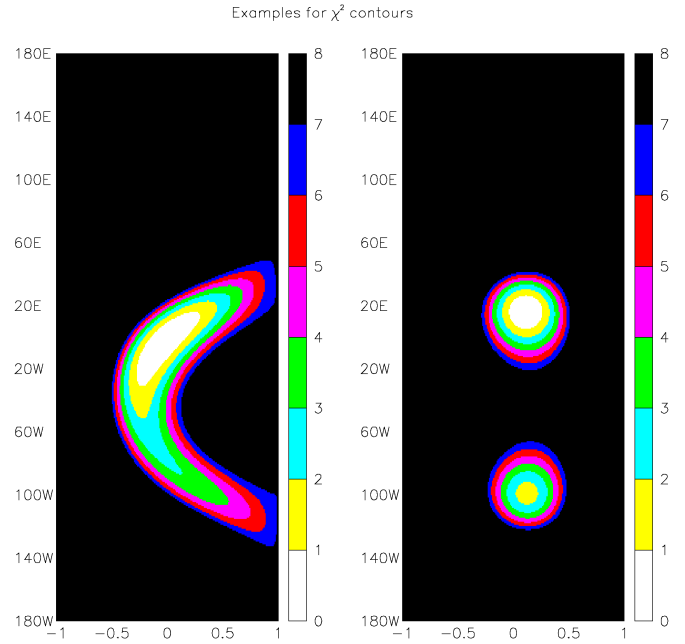

Fig. 7. χ^2-contours of the reconstructed supernova direction for the combined timing data from Superkamiokande, SNO and AMANDA (left) or IceCube (right). The true direction was $\cos\theta = -0.1, \phi = 3\,\mathrm{deg}$.

year in the Milky Way has been established. With the improved supernova system and the complete AMANDA II detector 97% of our galaxy can be covered, allowing for one fake event per year. For a supernova in the center of the galaxy the beginning of the neutrino emission can be determined with an accuracy of 14 ms.

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