Supernova detection with IceCube and beyond

THE ICECUBE COLLABORATION[1]
[1]*See special section in these proceedings*

Abstract: In its current configuration, IceCube is a formidable detector for supernovae. It can detect subtle features in the temporal development of MeV neutrinos from the core collapse of nearby massive stars. For a supernova at the galactic center, its sensitivity matches that of a background-free megaton-scale supernova search experiment and triggers on supernovae with about 200, 20, and 6 standard deviations at the galactic center (10 kpc), the galactic edge (30 kpc), and the Large Magellanic Cloud (50 kpc). Signal significances are reduced due to the noise floor and correlations between background hits. In this paper we discuss ways to improve the signal over background ratio with an improved data acquisition. We also discuss methods to track the average neutrino energy by multiple hit detection from individual interacting neutrinos. The latter relies on the ability to reject coincident hits from atmospheric muons.

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DOI: 10.7529/ICRC2011/V04/1137
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Keywords: IceCube, supernovae

1 Introduction

It was recognized early by [1] and [2] that neutrino telescopes offer the possibility to monitor our Galaxy for supernovae. IceCube is uniquely suited for this measurement due to its location and $1\,\mathrm{km}^3$ size. The noise rates in IceCubes photomultiplier tubes average around $540\,\mathrm{Hz}$ since they are surrounded by inert and cold ice with depth dependent temperatures ranging from $-43\,^\circ\mathrm{C}$ to $-20\,^\circ\mathrm{C}$. At depths between $(1450-2450)\,\mathrm{m}$ they are partly shielded from cosmic rays. Cherenkov light induced by neutrino interactions will increase the count rate of all light sensors above their average value. Although this increase in individual light sensor is not statistically significant, the effect will be clearly seen once the rise is considered collectively over many sensors.

The 5160 photomultipliers are installed in modules called digital optical modules (DOMs) and arranged in two configurations: IceCube, with $17\,\mathrm{m}$ ($125\,\mathrm{m}$) vertical spacing between DOMs (horizontal spacing between strings), and DeepCore with $7\,\mathrm{m}$ ($72\,\mathrm{m}$) spacings and equipped with high quantum efficiency DOMs, where $\epsilon_{\mathrm{DeepCore}} = 1.35\epsilon_{\mathrm{IceCube}}$ [3, 4]. With absorption lengths exceeding $100\,\mathrm{m}$, photons travel long distances in the ice such that each DOM effectively monitors several hundred cubic meters of ice. The inverse beta process $\bar{\nu}_e + p \rightarrow e^+ + n$ dominates supernova neutrino interactions with $\mathcal{O}(10\,\mathrm{MeV})$ energy in ice or water, leading to positron tracks of about $0.55\,\mathrm{cm}\cdot E_\nu/\mathrm{MeV}$ length for $E_\nu \leq 10\,\mathrm{MeV}$. Considering the approximate E_ν^2 dependence of the cross section, the light yield per neutrino roughly scales with E_ν^3. The detection principle was demonstrated with the AMANDA experiment, IceCubes predecessor [5]. Since 2009, IceCube has been sending real-time datagrams to the Supernova Early Warning System (SNEWS) [6] when detecting supernova candidate events.

Currently, the supernovae search algorithms are based on count rates of individual DOMs stored in $1.67\,\mathrm{ms}$ time bins. We plan to introduce an improved data acquisition system that will allow to store all IceCube hits for supernova candidates. We discuss below some of the improvements that we expect to be achieved using this additional information. In addition, the collaboration is discussing future extensions of the detector that would also improve the supernova detection capacity.

2 Current performance

IceCube is the most precise detector for analyzing the neutrino lightcurve of close supernovae. A paper, discussing the detector and physics performance, is close to being published. Figure 1 shows the expected significance for the detection of a supernovae as function of distance (left) and presents the expected rate distribution for the Lawrence-

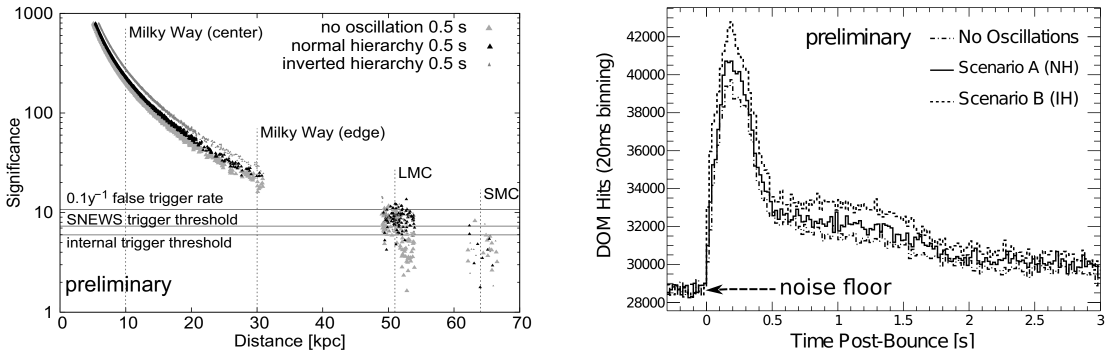

Figure 1: Left: Expected significance versus distance assuming the Lawrence-Livermore model [9] for three oscillation scenarios. The significances are increased by neutrino oscillations in the star by typically 40% in case of an inverted hierarchy. The Magellanic Clouds as well as the center and the edge of the Milky Way and various trigger thresholds are marked. For the Milky Way, the supernova progenitor distribution follows the prediction from [7], for the Magellanic Clouds it is assumed to be uniform. Right: Expected rate distribution at $10\,\mathrm{kpc}$ supernova distance assuming normal and inverse hierarchies.

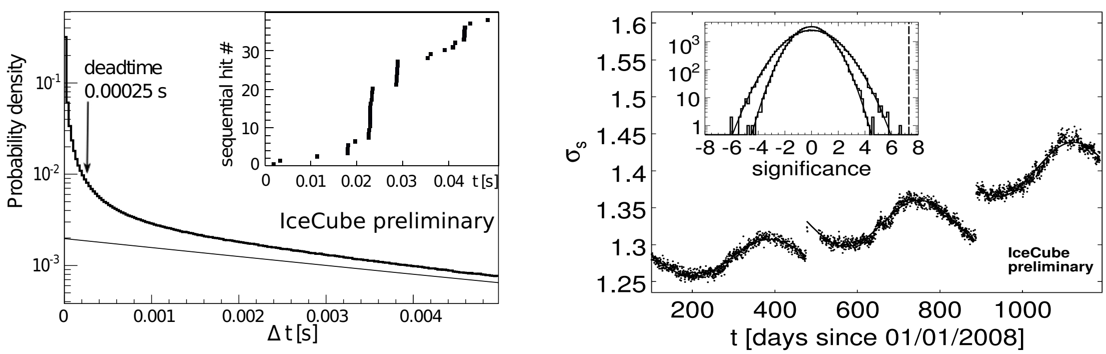

Figure 2: Left: Measured probability density distribution of time differences between pulses for noise (bold line) and the expectation for a Poissonian process fitted in the range $15\,\mathrm{ms} < \Delta T < 50\,\mathrm{ms}$ (thin line). The excess is due to bursts of correlated hits, as indicated by the $50\,\mathrm{ms}$ long snapshot of hit times shown in the inset. Right: Measured width of the significance distribution as function of time during IceCube construction with 40 (left), 59 (middle) and 79 (right) deployed strings. The inset shows the significance distribution before (wide distribution) and after (narrow distribution) suppression of hits due to atmospheric muons (79 strings). The current trigger threshold for SNEWS alarms is indicated by a dashed line.

Livermore model [9] (right). The rate distribution demonstrates the excellent resolution of details in the neutrino light curve. This includes the possibility to distinguish the neutrino hierarchy, provided that the astrophysical model is well known and $\sin^2 \Theta_{13} > 1\,^{\circ}$[7]. The present noise floor is indicated in Fig. 1 (right) which leads to a fast deterioration of the signal significance particularly at larger distances. In addition, the expected signal significance in IceCube is somewhat reduced due to two types of correlations between pulses that introduce supra-Poissonian fluctuations. The first correlation involves a single photomultiplier tube. It comes about because a radioactive decay in the pressure sphere can produce a burst of photons lasting several μs. The second correlation arises from the cosmic ray muon background; a single cosmic ray shower can produce a bundle of muons which is seen by hundreds of DOMs. The observed time difference between noise hits deviates from an exponential distribution expected for a Poissonian process (see Fig. 2, left). The inset shows a hit sequence from a single DOM, clearly indicating the bursting behavior. A significant fraction of these bursts can be rejected by an artificial non-paralyzing deadtime, currently adjusted to $\tau = 250\,\mu$s, which decreases the average optical module noise rate to 285 Hz, while keeping $\approx 87\%/(1 + r_{\mathrm{SN}} \cdot \tau)$ of supernova induced hits with rate r_{SN}.

Due to remaining correlated pulses from radioactive decays and atmospheric muons, the measured sample standard deviation in data taken with 79 strings is ≈ 1.3 and ≈ 1.7 times larger than the Poissonian expectation for $2\,\mathrm{ms}$ and

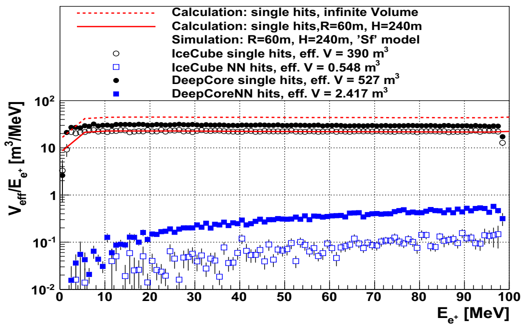

Figure 3: Effective volume per optical module and positron energy versus positron energy. Due to the chosen generation volume, the single hits effective volumes (circles) are about a factor of two too small. This is illustrated by the calculations taken from [11] (lines). The nearest neighbor coincidence modes (squares) are shown here without cut on the coincidence time. The effective volumes given in the legend are calculate according to the "Sf" model from [12] with an integration time of 4 s.

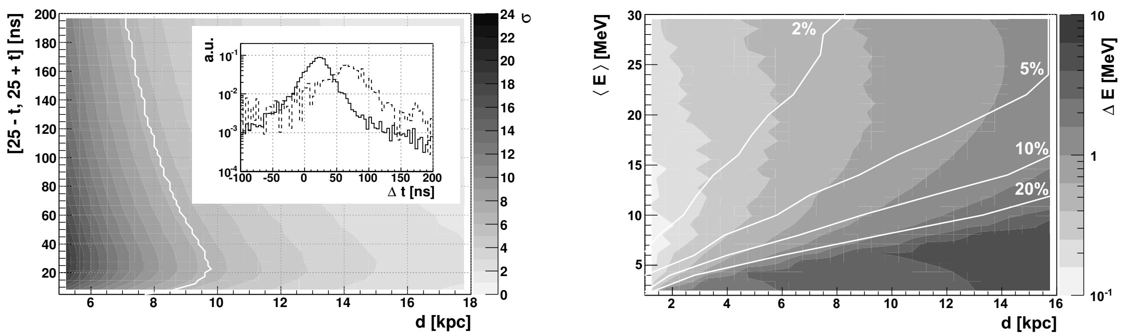

Figure 4: Left: Significance as a function of distance d and the allowed time window $[25\,\mathrm{ns} - t, 25\,\mathrm{ns} + t]$ between hits in two neighboring DOMs 7 m apart (DeepCore). The time difference distribution is shown in the inset in solid for DeepCore and dashed for IceCube. The maximum distance of about 10 kpc is reached for $t = 25\,\mathrm{ns}$ for a significance threshold of 6.7 (white line). Right: Energy resolution ΔE as a function of distance d and average energy of the emission spectrum $\langle E \rangle$. The white line show several $\Delta E/E$ contours.

500 ms time bins, respectively. For the analysis, we define the significance $\xi = \Delta\mu/\sigma_{\Delta\mu}$, where $\Delta\mu$ is the most likely collective rate deviation of all optical module noise rates from their running average. $\sigma_{\Delta\mu}$ is the corresponding deviation calculated from the data, thus accounting for non-Poissonian behavior in the dark rates. The significance should be centered at zero with unit width. Fig. 2 (right plot) shows that this is not the case; instead the width changes with the season and increases with the size of the instrumented detector. This behavior is linked to the seasonal change of the muon flux. While atmospheric muons contribute to the count rates of individual DOMs by only 3%, these hits are correlated across the detector, thus broadening the significance distribution and giving rise to a seasonal dependence of the trigger rate. At present, it is possible to subtract roughly half of the hits introduced by atmospheric muons from the total noise rate offline, as the number of coincident hits in neighboring DOMs is recorded for all triggered events. The width of the significance distribution then decreases to about 1.06, close to the expectation (see inset of Fig. 2 (right plot)).

A data acquisition that records all hits in case of a supernova trigger will permit further improvements. The time resolution on the onset of the burst will no longer be restricted by the 1.67 ms time bins in which the rates are recorded, hits associated to triggered atmospheric muons can be fully rejected, and more sophisticated methods to minimize correlated pulse bursts, e.g. by eliminating the initial hits of the bursts while keeping photomultiplier related afterpulses, can be applied. However, as the significance improves only with $1/\sqrt{N_{\mathrm{background}}}$, a much more drastic reduction of background is required in order to improve the detection significance at the edge of our galaxy, to track the average neutrino energy and maybe even provide some directional capability. This can only be achieved by detecting more than one Cherenkov photon from an interaction and applying a coincidence condition.

3 New opportunities from coincidence rates

The study in this section is motivated by an analytical framework that explores the potential of coincident hit modes [11]. Here, we investigate the "nearest neighbor coincidence hits" mode, with a hybrid GEANT-4/toy Monte Carlo simulation. We chose this mode from other possible multi-hit modes such as multiple hits in one DOM or coincident hits between any DOMs, because it has the best noise suppression potential by requiring a very short time window around the two coincident hits.

Figure 3 shows the positron effective volume per module and positron energy for the two detector configurations and two detection modes: single hits and nearest neighbor coincidence hits. The effective volumes given in the legend are calculated according to the "Sf" model from [12] with an integration time of 4 s. Both modes have a very different energy dependence, which makes the ratio $N_{\rm coinc}/N_{\rm single}$ an observable of the average energy $\langle E\rangle$ of the emission spectrum.

The inset in Fig. 4 shows the smallest time difference between hits in neighboring DOMs for both detector configurations. A cut on this time distribution was found by calculating the detection significance as a function of the supernova distance and the time window, as is shown in Fig. 4 for DeepCore. Applying a time cut of ± 25 ns around the most probable time difference of $T_0 = 25$ ns, a maximum distance of 10 kpc can be reached with the DeepCore DOM separation. A similar cut yields a smaller reach for IceCube due to the larger DOM separation.

To estimate the energy resolution of the energy observable $N_{\rm coinc}/N_{\rm single}$, the ratio was calculated using spectra according to the "Sf" model with average energies between $2 - 30$ MeV. In Fig. 4 (right plot), the deviation ΔE is shown as a function of the supernova distance and the average $\langle E\rangle$. For distance smaller than the trigger threshold (≈ 10 kpc), a resolution of around 5% can be achieved for spectra with an average energy of $10 - 15$ MeV.

The energy resolution depends on the expected noise level for the chosen selection mode. Above, the Poissonian noise levels were scaled up by 1.3, as mentioned in Sec. 2. It is possible that this underestimates the average hit probability for DOMs that were close to atmospheric muons. Preliminary studies show that light from muons can be suppressed by considering only DOMs that were around 300 m or further away from the reconstructed track position. In the worst case, when a track traverses the whole detector volume vertically, this cut reduces the usable volume by $\approx 30\%$. Alternatives to such a cut are being investigated.

4 Possible extensions of IceCube/DeepCore

Discussions on an extension of IceCube/DeepCore have started, which would also improve the supernova detection capability. We used a GEANT-4 simulation to estimate the capabilities of a hypothetic 18 string detector with IceCube DOMs spaced apart a few meters. Fig. 5 shows the effective volumes of single and multiple hits as function of distance between the DOMs. The sizable increase in the active volume of coincidence hits would strongly improve the signal over noise ratio and lead e.g. to a substantial improvement of a supernova detection at the Magellanic cloud.

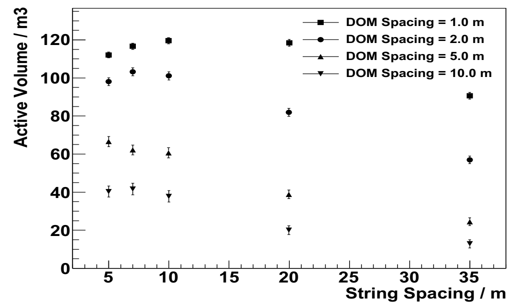

Figure 5: Effective volumes per DOM for multiple hits as function of horizontal and vertical distance between DOMs. The same neutrino spectrum was used as in Fig. 3

5 Conclusion

As a supernova detector, IceCube already offers an unmatched ability to establish subtle features in the temporal development of the neutrino flux by tracking the overall count rates of its DOMs. The correlated noise background remains one of the big challenges. The new data acquisition will permit the recording of all hits in case of a trigger signal, thus greatly improving the rejection of correlated noise sources such as atmospheric muons. It will also allow to study the influence of the correlated noise on multiple hit detection modes.

One such mode, nearest neighbor coincident hits, was introduced in this paper and shows great potential to extent the existing capabilities of IceCube by measuring the average neutrino energy. This mode also has the potential to be sensitive to the neutrino direction. Other multi-hit modes will be studied next. All these modes would greatly benefit from a very dense sub-array with inter-DOM and inter-string distance of a few meters only, extending their reach to several tens of kilo parsec and possibly beyond.

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