Supernova neutrino signal in IceCube

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IceCube has been completed in December 2010 and now forms a lattice of 5160 photomultiplier tubes covering a volume of $\sim$km^3 in the deep Antarctic ice. Its main design goal is to detect neutrinos with energies greater than 100 GeV. Owing to subfreezing ice temperatures and potassium free glass, the photomultiplier dark noise rates are particularly low. Hence IceCube can also detect MeV neutrinos if they arrive in large numbers by observing a collective rise in all photomultiplier rates on top of the dark noise. Recent work has been focussed on deepening the understanding and subsequently removing several dark noise contributions. IceCubes supernova data aquisition provides a 2 ms time resolution, allowing to to track subtle features in the temporal development of a supernova neutrino burst. Assuming a supernova at the galactic center, the detector's sensitivity compares to a background-free megaton-scale supernova search experiment. The sensitivity decreases to 20 standard deviations at the galactic edge (30 kpc) and 6 standard deviations at the Large Magellanic Cloud (50 kpc). Since 2009, IceCube's supernova alert system has been sending real-time triggers from potential supernovae to the Supernova Early Warning System.

1 Detection principle

IceCube is uniquely suited to monitor our galaxy for supernovae due to its 1 km^3 size and favorable conditions of the south polar ice. With its photomultipliers surrounded by inert and cold ice at depths between (1450 – 2450) m they are partly shielded from cosmic rays and the temperature in the ice ranging from $-43\,^\circ$C to $-20\,^\circ$C leads to low average noise rates around 540 Hz.

With the inverse beta processes being the dominant interaction in water Cherenkov detectors for the typical $\mathcal{O}(10MeV)$ supernova neutrinos, the light yield per neutrino in IceCube roughly scales with E_ν^3. This accrues from the cross section of the inverse beta process showing an approximate E_ν^2 dependence, the resulting positron track lengths in ice of about 0.5 cm$\cdot E_\nu/$ MeV long and the Cherenkov light production being directly proportional to this track length. Our Monte Carlo studies yield an average number of 178 photons per MeV energy of the positron, considering only a range of wavelengths from 300 nm to 600 nm accessible to our optical modules.

The spacing between Digital Optical Modules (DOMs) of 17 m vertically and 125 m horizontally is large in comparison to the $\mathcal{O}(cm)$ positron tracks from inverse beta processes. Therefore the probability to detect light from a single interaction in more than one DOM is $\mathcal{O}(1\%)$. This gives rise to our detection principle, where small light yields in individual DOMs add up to a statistically significant collective rise in the noise rate of all 5160 photomultipliers. These noise rates are continously analyzed by an online algorithm using a maximum likelihood approach analyzing a rolling time window.

Since September 2009, IceCube has been sending real-time datagrams to the Supernova Early Warning System (SNEWS) [3] when detecting supernova candidate events.

2 Background Noise

The Digital Optical Module (DOM) is the fundamental element in the IceCube architecture. Housed in a 13" (33 cm) borosilicate glass pressure sphere, it contains a Hamamatsu 10" hemispherical photomultiplier tube [1] as well as a custom build computer based on ARM architecture that allows each DOM to operate as a complete and autonomous data acquisition system [2].

Several effects contribute to the prevailing noise rate of 540 Hz: a Poissonian noise contribution from radioactivity, atmospheric muons and remaining thermal noise, as well as correlated noise from Cherenkov radiation and scintillation originating in the glass of the photomultiplier and the pressure vessel. The majority of hits are due to scintillation of residual cerium energized by β and α decays from trace elements in the uranium/thorium decay chains causing a series of pulses.

The observed time difference between noise hits deviates from an exponential distribution that would be expected for a Poissonian process. With typical times between correlated noise pulses of $\mathcal{O}(100\,\mu\text{s})$, the signal-to-noise ratio of the measurement can be improved by adding an artificial dead time that is configurable by a field programmable gate array in the DOM. The optimal setting for the dead time with respect to the signal over noise ratio for supernovae was found to be $\tau \approx 250\,\mu$s. This reduces the noise rate from 540 Hz to 286 Hz while introducing only 13% dead time for the signal.

In a recent study the rate distribution for data taken in 2010 after application of this artificial dead time still shows a broadening by a so called fano factor of $\sqrt{F} = \frac{\sigma}{\sqrt{<\mu>}} = 1.78$. This effectively reduces the number of DOMs by a factor of three, compared to an ideal detector with unit fano factors. In addition this correlation also broadens the width of our significance distribution. For the data from 2010 this effectively amounted to a factor of 1.43 and therefore a trigger with a measured significance 8.0 does only represent a deviation of about 5.6 standard deviations.

We believe the main reason for this broading to be the influence of correlated hits from atmospheric muons (see Fig. 1 right). We have then taken steps to eliminate this correlation by subtracting hits assiciated with atmospheric muons in an offline cleaning algorithm. We were able to reduce the fano factor from $\sqrt{F} = 1.78$ down to $\sqrt{F'} = 1.32$ and subsequently our significance distribution narrowed from a width of 1.43 to 1.05 (see Fig. 1 left).

3 IceCube performance

IceCube was completed in December 2010 and is comprised of 5160 photomultiplier tubes. Since 2009 it supersedes AMANDA in the SNEWS network. With a 250 μs artificial dead time setting, the average DOM noise rate is 286 Hz. The data taking is very reliable and covers the whole calendar year, the uptime has continuously improved and has reached 99.0 % since June 2011. IceCube's sensitivity corresponds to a megaton scale detector for galactic supernovae, triggering on supernovae with about 200, 20, and 6 standard deviations at the galactic center (10 kpc), the

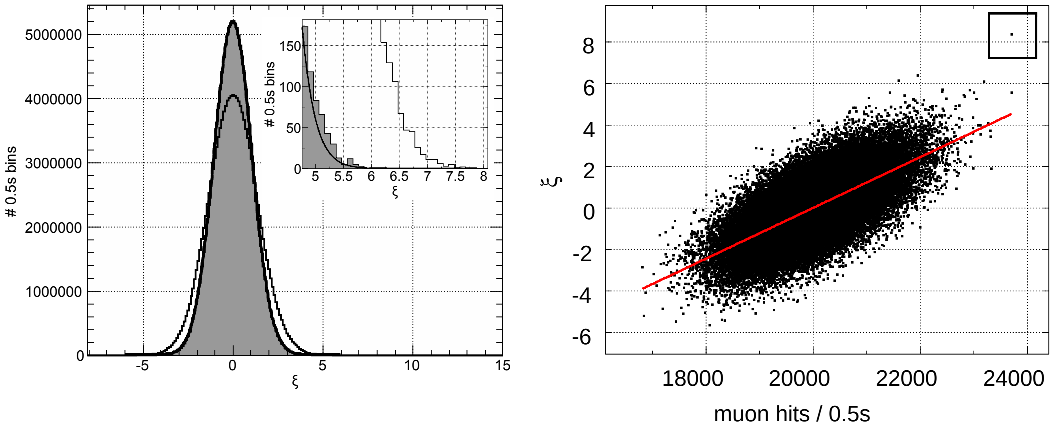

Figure 1: (color online) *Left:* This plot shows a significance distribution for data taken over 3 years, with IceCube configuration of 40, 59 and 79 strings. With offline post-processing we were able to reduce its width from originally 1.35 down to 1.05. *Right:* This correlation plot between the significance measured by IceCube's Supernova DAQ and the rate of reconstructed muons was used to rotate the significances around a "center of gravity" in order to decorrelate and thus effectivily subtract the muon influence. The 8 hour run shown contains the highest significance event before atmospheric muon subtraction.

galactic edge (30 kpc), and the Large Magellanic Cloud (50 kpc). IceCube cannot determine the type, energy, and direction of individual neutrinos and the signal is extracted statistically from rates that include a noise pedestal. On the other hand, IceCube is currently the world's best detector for establishing subtle features in the temporal development of the neutrino flux. The statistical uncertainties at 10 kpc distance in 20 ms bins around the signal maximum are about 1.5 % and 3 % for the Lawrence Livermore and Garching models, respectively.

Depending on the model, in particular the progenitor star mass, the assumed neutrino hierarchy and neutrino mixing, the total number of recorded neutrino induced photons from a burst 10 kpc away ranges between $\approx 0.17 \times 10^6$ (8.8 $M_\odot$ O-Ne-Mg core), $\approx 0.8 \times 10^6$ (20 $M_\odot$ iron core) to $\approx 3.4 \times 10^6$ for a 40 $M_\odot$ progenitor turning into a black hole. For a supernova in the center of our Galaxy, IceCube's high statistics would allow for a clear distinction between the accretion and cooling phases, an estimation of the progenitor mass from the shape of the neutrino light curve, and for the observation of short term modulation due to turbulent phenomena or forward and reverse shocks during the cooling phase. IceCube will be able to distinguish inverted and normal hierarchies for the Garching, Lawrence-Livermore and black hole models for a large fraction of supernova bursts in our Galaxy provided that the model shapes are known and $\theta_{13} > 0.9°$. The slope of the rising neutrino flux following the collapse can be used to distinguish both hierarchies in a less model dependent way for distances up to 6 kpc at 90 % C.L. As in the case of the inverted hierarchy, coherent neutrino oscillation will enhance the detectable flux considerably. A strikingly sharp spike in the $\bar{\nu}_e$ flux, detectable by IceCube for all stars within the Milky Way, would provide a clear proof of the transition for neutron to a quark star as would be the sudden drop of the neutrino flux in case of a black hole

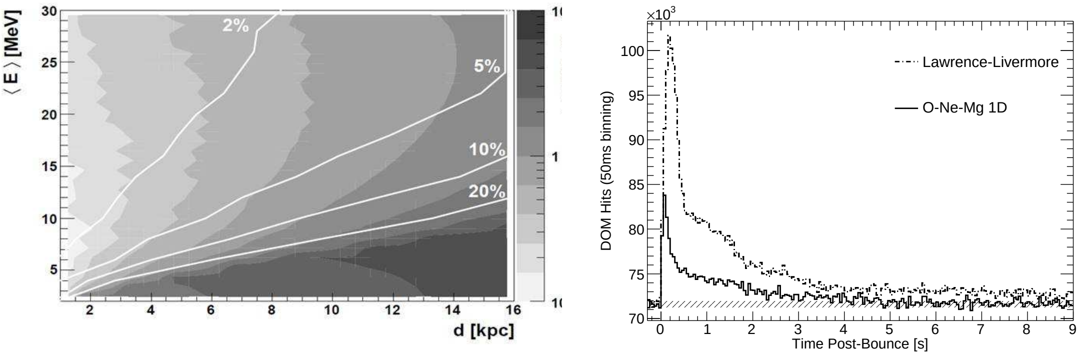

Figure 2: (color online) *Left:* This plot shows the result of a recent Monte Carlo study [4], where we were able to infer an average energy through the ratio between single and multiple coincidence hits. The ratio between the mean energy shown on the y-axis and its error shown as contour color gives the relative precision of our measurement shown as white contour lines. *Right:* This plot shows a comparison of expected supernova signal for two different models, the Lawrence Livermore [6] and the Hüdepohl/Garching model [5]. A 1 sigma-band corresponding to the measured detector noise is shown as a hatched area.

formation.

4 Outlook

As of late several projects concerning further optimizations to the data acquisition, analysis and Monte Carlo have started. We will upgrade IceCube's low level data processing logic to not only read out time binned scaler data, but to also store all photomultiplier hits with their respective timestamps in case of a high significance alert (i.e. the one we would sent to SNEWS). This will enable us to improve the time resolution beyond the current 2 ms and will pave the way for energy estimations using coincidences (see Fig. 2). As a first step, we consider the following nearest neighbour coincidences: **"1+0"** (single hit, no coincidence), **"1+1"** (double hit, two DOMs) and **"2+0"** (double hit on one DOM). Our calculations [4] show a clear energy dependence of the ratios $(1+1)/(1+0)$ and $(2+0)/(1+0)$. We found for the $(1+1)/(1+0)$ ratio a statistical error of 5% corresponding to an energy resolution of about 1 MeV, assuming a SN flux from a 8.8 solar mass Garching model [5] and 10 kpc distance.

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