IceCube’s response to supernovae and periodic features in the count rates

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The IceCube Neutrino Observatory is highly sensitive to neutrino bursts of \(O(10)\) MeV energy that are would be generated by core collapse supernovae in our Galaxy. It will resolve temporal structures in supernova light curves particularly well. In the light of an improved understanding of the ice properties and the detector response, the effective area and the corresponding uncertainties were newly determined with a Geant4-based Monte Carlo. Uncertainties due to cross sections and oscillation effects in the Earth were also investigated. This analysis has been extended by simulating a very large sample to determine the small coincidence probability between optical modules that bears information on the average neutrino energy. These simulation results were then used to interpret the data in time and frequency space. While the availability to record data for low energy neutrinos from supernovae is close to perfect (99.2% between 2013-2020), the analysis requires that the detector works faultlessly and artifacts do not mimic the signal in the 13 years of data taken so far. An effort has been made to keep the uptime after all analysis steps similarly high. The frequency space can be studied in a range between 1 Hz and 1/year to test the detector stability with high accuracy, to study the influence of cosmic rays, and to search for periodic phenomena that lead to sub-threshold increases in the count rates. Here we discuss the results of the simulations and the corresponding systematic limitations, the method to reconstruct the mean neutrino energy for a recorded supernova, as well as aspects of the analyses of continuously taken optical module rate data in the time and frequency domain.

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1. Introduction

IceCube, which includes the more densely instrumented DeepCore subarray, is an excellent detector for measuring the neutrino light curve of a galactic supernova with high temporal precision. Neutrinos from a galactic supernova would interact in the deep clear glacial ice at the South Pole and add hits to the low $O(0.5)$ kHz dark rate of IceCube’s 5160 optical modules. While individual neutrinos would not trigger the IceCube detector due to their low energy, the collective rise in count rates during an $O(10)$ s time span can be statistically separated to provide a trigger. The physics capabilities of IceCube for supernova detection were summarized in [1] and improvements were discussed in ICRC contributions [2] and other conferences [3].

In the light of improvements of the understanding of detector and ice properties, we undertook a detailed Geant4-based study of the effective volume for supernova neutrino detection, updated the simulation with state-of-the-art cross section determinations and implemented a recent improved description of single photon-induced PMT pulses [4].

We concentrate on the dominant $\bar{\nu}_e + p \rightarrow n + e^+$ reaction (inverse beta decay) with subsequent capture of the neutron. The positron emits $\approx 180$ Cherenkov photons per MeV. Compton scattered electrons from 2.2 MeV neutron capture photons add roughly 100 photons on average. For $E_{\nu} \lesssim 20$ MeV, reactions with oxygen are negligible.

Due to the large distance between IceCube’s optical sensors (DOMs), individual MeV neutrino interactions cannot be reconstructed. Km3NeT [5] relies on coincidences between the sensors of multiple PMT optical modules to improve their supernova detection. The method lowers the effective dark rate, extends the detection horizon, and allows one to determine the average energy of the detected neutrinos. While multiple PMT optical modules will be used in the ongoing IceCube upgrade and in the future IceCube-Gen2 detector for similar studies [6], the IceCube DOM houses only one 10” PMT. Due to the low single photon resolution of PMTs, the average energy of detected neutrinos needs to be determined from coincidences between different optical modules that are 17 m (IceCube) or 6 m and 10 m (DeepCore) apart vertically and 40 – 125 m apart horizontally. The probability for such coincidences, which scales roughly quadratic with the neutrino energy, is very small ($\approx 0.04$ (0.15) percent in IceCube (DeepCore) at $E_{\nu} = 25$ MeV). Using such an approach, earlier simplified simulations confirmed that one may indeed obtain a meaningful measure of the average $\bar{\nu}_e$ energy [7, 8]. Here we present a more rigorous determination using IceCube’s simulation and reconstruction tools.

Such simulations are needed for interpreting the results of ongoing searches for supernovae and periodic countrate features in 13 years of IceCube data, for which we will present selected aspects.

2. Simulation

The signal hit rate $r_{SN}$ per DOM for the inverse beta decay is given by

$$r_{SN}(t) \approx \frac{n_{target} L_{\bar{\nu}_e}}{4\pi d^2} \frac{V_{\text{eff}}}{E_{\bar{\nu}_e}(t)} \int_0^\infty dE_{e^+} \int_0^\infty dE_{\bar{\nu}_e} \times \frac{d\sigma}{dE_{e^+}} (E_{e^+}, E_{\bar{\nu}_e}) f(E_{\bar{\nu}_e}, E_{\bar{\nu}_e}, \alpha, t),$$

where $f(E_{\bar{\nu}_e}, E_{\bar{\nu}_e}, t)$ is the time dependent probability density function describing the neutrino energy distribution with average $E_{\bar{\nu}_e} = \int_0^\infty dE_{\bar{\nu}_e} E_{\bar{\nu}_e} f(E_{\bar{\nu}_e}, E_{\bar{\nu}_e}, \alpha, t)$. $L_{\bar{\nu}_e}$ denotes the supernova...
energy luminosity, \( n_{\text{target}} \) is the density of targets in the ice, \( d \) is the distance to the supernova. The effective volume \( V_{e}^{\text{eff}} \) for a positron subsumes all media, detector and analysis effects.

Very roughly speaking, \( V_{e}^{\text{eff}}/E_{\bar{\nu}_e} \) may be estimated by the product of absorption length, Cherenkov photons per unit energy, DOM geometric cross section, optical module sensitivity, and the fraction of single photon hits that pass the electronic threshold for a single photon [1, 9]. Using approximations, one can analytically estimate [2] the rate of hits in IceCube from the inverse beta decay interaction for a given model with \( \approx 25\% \) precision. To go beyond such an analytic estimate, the response to supernova neutrinos interacting in the IceCube detector can be simulated with programs of increasing detail and demand on computing resources:

- **SNOwGLoBES [10]**: a fast and simple mean event rate calculator for low-energy neutrino interactions using the analytic formula discussed above.
- **Asteria [11]**: a parameterized IceCube Monte Carlo.
- **Full Geant4-based Monte Carlo using IceCube software tools (this paper).**

### 2.1 Geant4-based IceCube Monte Carlo

We generate positrons from the inverse beta decay with directions and energies corresponding to the properties of an incident neutrino plus delayed neutron capture photons. A typical interaction of a 15 MeV positron in ice is shown in Fig. 1. Further steps are performed using standard IceCube Software, Geant4 to simulate particle interactions, and a custom GPU-optimized Cherenkov photon tracker [12]. Fourteen samples of mono-energetic positrons were generated with 1 billion interactions each and samples about the expected mean neutrino energy were extended to 4 billion. Additional samples with 0.1 billion (1 billion for nominal values) interactions were created to test variations in the modeling of the ice. On average, roughly every 500th positron leads to at least one photon detected by IceCube. One billion interactions yield about 250 neighboring DOM coincidences. 90\% and 95\% of these coincidences have their corresponding interaction vertices located within 20 meters of the DOM that receives the first hit in IceCube and DeepCore, respectively. Instead of simulating PMT noise and cosmic ray muons, unbiased IceCube DOM hit rates are overlaid on the Monte Carlo events.

### 2.2 Effective volume and systematic uncertainties

Since inverse beta decays dominate, we discuss the effective positron volume per neutrino energy \( V_{e}^{\text{eff}}/E_{\bar{\nu}_e} \) in units of \( m^3/MeV \). IceCube is embedded in the Antarctic ice shield with slightly inclined layers of dust and other scattering centers. These impurities, as well as the pressure dependent
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**Figure 2:** Left: effective positron volume as function of IceCube string position. Right: effective positron volume as function of depth for IceCube (red) and DeepCore (blue).

optical properties of air-loaded ice, lead to depth-dependent absorption and scattering lengths. The most prominent dust layer is situated around 1950 m depth; below, the ice is much clearer. Figs. 2 (left) shows a bird eye view of the IceCube observatory with the color code indicating $V_{\text{eff}}^{\text{e}}/E_{\bar{\nu}_e}$. The strings with large effective volumes belong to DeepCore, which is mostly embedded in the clear ice region below a central dust layer. This becomes evident from the right hand plot, where $V_{\text{eff}}^{\text{e}}/E_{\bar{\nu}_e}$ is plotted as a function of depth for IceCube DOMs (red) and DeepCore DOMs (blue). In addition to populating clear ice, the 360 DeepCore DOMs house photomultipliers with a quantum efficiency that is about 1.35 larger than that of standard IceCube DOMs.

While a remarkable effort has gone into the in-situ calibration of the ice properties, there are uncertainties associated with it [13]. The ice density is known to better than 0.2%. However, the uncertainties on the scattering and absorption coefficients are presently estimated at 5% each. Fig. 3 (left) shows the result of studies with Monte Carlo samples, where the scattering and absorption lengths were varied within 10%. A quantitative evaluation shows correlation between the relative uncertainties of effective volumes and absorption coefficients of $-0.78 \pm 0.02$ for IceCube and $-0.81 \pm 0.04$ for DeepCore. The correlation with the scattering length, on the other hand, is very small: $0.037 \pm 0.015$ and $-0.018 \pm 0.037$ for IceCube and DeepCore, respectively. The color bands in Fig. 3 (left) show the 5% uncertainty contours for IceCube and DeepCore; the result published in [1] is compatible with the new determination that uses the best current knowledge of the ice properties. Ice properties are not the only source of detector-related uncertainties (see Table 1). For example, the absolute DOM efficiency in-situ is presently known to 10%. In addition, there are uncertainties on the cross sections. Neutrino interactions with oxygen are poorly known; however, they only play a role at neutrino energies beyond 20 MeV (see Tab. 1). Their contributions for 8.8 $M_{\odot}$ progenitor [14] and Black Hole forming [16] models are only 1% and 14%, respectively.

We also studied potential uncertainties due to neutrino oscillations in the matter of the Earth. These become relevant when comparing the results of detectors at locations with different neutrino path lengths in the Earth or when the supernova position is unknown. Oscillation effects only play a role if either cross sections, fluxes, or energy spectra vary between flavors. While these are
similar during the cooling phase, substantial differences in the early phase of neutrino emission may strongly modify the neutrino light curve. Fig. 3 (right) shows the energy weighted ratio of total registered hits with and without Earth oscillations as function of the zenith angle for model [14]. If studied as function of time (not shown), the largest effect (factor 2.3) is seen around 0.015 s. Note that the highest probability for a galactic supernova is in the Southern sky, where neutrinos do not cross the Earth’s core and the oscillation effects are smooth (gray shaded exposure area in Fig. 3, scale on right). Finally, large uncertainties in the modeling of supernovae may remain even if an optical counterpart can be studied in detail, as well as MSW and collective neutrino oscillations in the core of the developing supernova. Addressing these goes beyond the scope of this paper.

| mean e^+ track length in ice | 5% |
|----------------------------|----|
| positron effective volume  | +15 | =13 |
| cross sections (inverse beta, e^- scattering, oxygen) | <1%, <1%, [0.2, 1.4]% |
| angle dependent MSW Earth oscillation | [-0.2, 4.9]% |

Table 1: Summary of systematic uncertainties on the photon flux from supernovae (detector and media properties, cross sections for models [14, 16], variation in total hits from Earth oscillations for model [14]).

2.3 Average energy of detected neutrinos from coincidences between DOMs

For supernova neutrino candidate events, raw detector data are stored that allow one to determine the noise and signal rate with high timing accuracy and to check for coincidences between modules [17]. We restrict ourselves to coincidences between the nearest neighbors. The average neutrino energy
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can be determined using a Poissonian likelihood with the following parameters:

\[ N_{\text{comb}} \equiv \text{number of combinations} \]
\[ r_{\text{noise}}, r_{\text{signal}} \equiv \text{noise and signal rates} \]
\[ r_{\text{coinc}} \approx a \cdot r_{\text{signal}} \cdot E_{e^+} \equiv \text{coincidence rate from same neutrino interaction} \]
\[ N(T) \equiv \text{number of observed events for duration of experiment } T \]

The number of coincidences depends on the gate width \( \Delta t \) and thus on the module distance and scattering length. The coefficient \( a \) must be determined by Monte Carlo. Optimized gate widths \(-64(\sim 96) \text{ns} < \Delta t < 128(192) \text{ns}\) for IceCube (DeepCore) were found \(^1\) by comparing the time distributions of noise-related coincidences, which show a flat behavior, coincidences arising from supernova neutrinos and cosmic ray muons, that result in a shifted peak.

Coincidences occur between noise pulses, noise and signal pulses, pulses from different signal events, and pulses from the same neutrino interaction. Disregarding all constants, the combined likelihood is a product of likelihoods with \( i \in \{\text{DeepCore, IceCube}\} \):

\[
- \log L(E_{e^+}) = \sum_{i} T \left[ N_{\text{comb},i} \cdot \Delta t_i \left( \epsilon \cdot r^2_{\text{noise}} + \epsilon' \cdot r_{\text{noise}} r_{\text{signal}} + \epsilon'' \cdot r^2_{\text{signal}} + \frac{r_{\text{signal}} \cdot a_i E_{e^+}}{\Delta t_i} \right) \right] - N \cdot \log \left( \epsilon \cdot r^2_{\text{noise}} + \epsilon' \cdot r_{\text{noise}} r_{\text{signal}} + \epsilon'' \cdot r^2_{\text{signal}} + \frac{r_{\text{signal}} \cdot a_i E_{e^+}}{\Delta t_i} \right). \tag{2}
\]

For pure Poissonian noise without contributions from atmospheric muons, \( \epsilon = \frac{1}{2} \epsilon' = \epsilon'' = 1 \); in practice, \( \epsilon, \epsilon' \) need to be determined as nuisance parameters from data and Monte Carlo. For an ideal detector, \( a_i = \text{const} \). Fig. 4 (left) shows a fit to the \( a_i \) parameters for each simulated energy, showing a slight energy dependence due to the finite detector volume. The relative energy resolution and bias can be deduced from Fig. 4 (right). Interestingly, the dense DeepCore strings contribute more to the resolution than the 13 times larger number of DOMs in the IceCube strings. The bias (dashed red line) is consistent with zero, the resolution improves as expected with energy. The actual resolution depends on the number of coincident photons and thus on the distance and the model. The resolution shown in Fig. 4 corresponds to a 27 M\(_\odot\) progenitor model at 4 kpc distance with 24 MeV average energy of the interacting neutrinos (\( E_{e^+} \) spectrum shown in gray).

3. DOM hit rate analyses in time and frequency space

The simulation results discussed so far will be used to quantify the analysis of 13 years of IceCube DOM hit rates in time and frequency space. After a brief introduction of the rate data, we will concentrate on a method to study the corresponding frequency space.

DOM rates are continuously counted in 1.6384 ms time bins by the on-board firmware. A dedicated online software system re-bins the data to 2 ms and searches the data stream for collective rate increases that are characteristic of supernovae in various choices of time bins. Data binned in 500 ms intervals are available independent of a trigger. The data acquisition system incorporates an

\(^1\Delta t < 0\) denotes a first hit in the upper DOM and \( \Delta t > 0 \) refers to a first hit in the lower DOM.
artificial dead time of 250 $\mu$s to suppress photons from glass luminescence, which – on average – lowers the DOM noise rate to about 300 Hz. A contribution from atmospheric muons is corrected for both online and offline by unfolding hits from triggered muon tracks.

The Lomb-Scargle periodogram \cite{18, 19} is designed to detect periodic signals in unevenly covered observations. The results are equivalent to fitting a sinusoidal function in each frequency bin. A white noise distribution at a fixed frequency is $\chi^2$ distributed under the null hypothesis. Otherwise, there are no obvious advantages w.r.t. a discrete Fourier transform \cite{20}. Fig. 5 (left) shows the rate per day for data taken with the completed IceCube detector between 2013-2020. The data taking availability was 99.2%. When rejecting problematic data taking periods, the uptime decreased to 96.6%; the cosmic muon rejection further lowers the uptime to 94.6%. Fig. 5 (right) shows the same data as a power density in frequency space. Note that the rejection of atmospheric muons leads to a strongly decreased seasonal effect due to atmospheric pressure changes. The monotonically falling rate contribution mostly stems from a very slow decrease in photomultiplier noise rate with time. This depth-dependent effect, which is leading to a diffractive pattern in the frequency space, may have to do with a decrease of triboluminescence as the ice releases stress.

4. Summary and outlook

With our best current knowledge of the ice properties, detector effects, and neutrino cross sections, we determine effective volumes that are consistent with our previous result \cite{1}. Using rare coincidences between neighboring modules, one can determine the average energy of interacting neutrinos in the event. The search for hidden or obscured supernovae in 13 years of data taken in time and frequency space will be published soon. As discussed in \cite{2}, IceCube will detect 99% of all Galactic core collapse supernovae with neutrino fluxes equal or higher than in the conservative 8.8$M_{\odot}$ Hüdepohl model at $> 9\sigma$ significance. We will use the periodogram method defined above.
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Figure 5: Left: Summed rate in the completed IceCube detector with and without atmospheric muon suppression. Right: Lomb-Scargle periodogram for low frequency range (factor 5 oversampling). The frequency of 1/year (dashed line) sticks out.

to analyze all frequencies and quantify any excess from the expected background, as well as artifacts from changing run conditions and from the rejection of small faulty chunks of data.

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