Supernova Detection with IceCube and Beyond

The IceCube Collaboration

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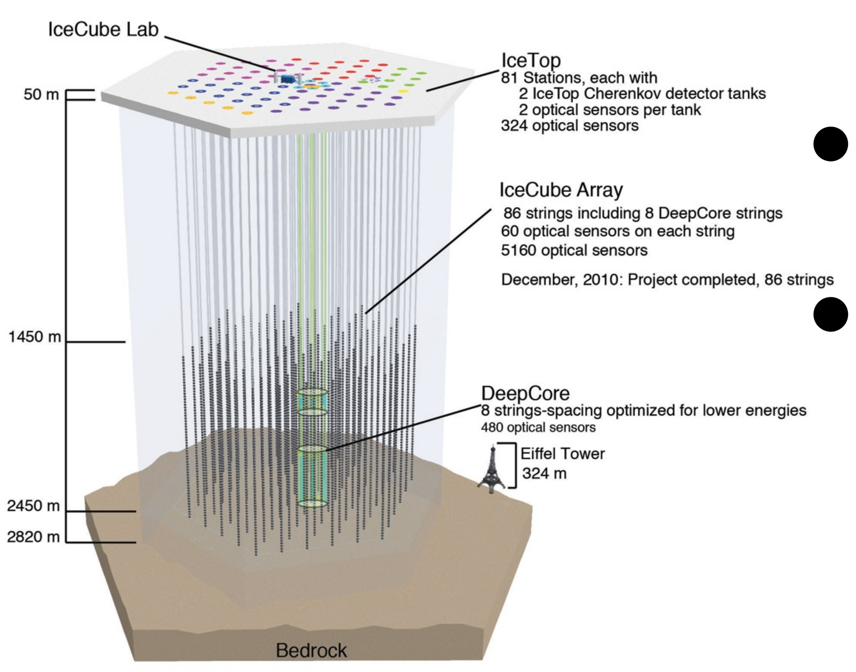
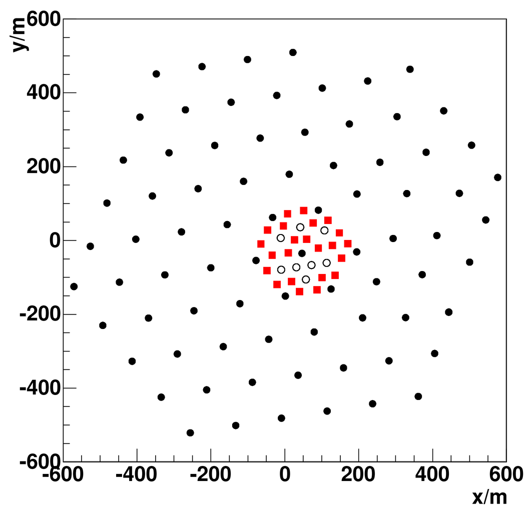
IceCube and DeepCore



- Low energy extensions of IceCube are under study (PINGU/MICA) (neutrino hierarchy, dark matter, proton decay, supernovae)
- These show promise for a supernova detection method involving multiple hit modes [1]
- This study includes a non-standard configuration with 24 strings, 120 4π sensitive detector elements, 3 meters apart

● : IceCube
○ : DeepCore
■ : Deep and Dense



Standard method

The current supernova detection [2] method relies on the collective rise of the count rate of the photomultipliers (see 'SNDaq/HitSpooling') above the nominal value, made possible by their low noise rate of about 500 Hz. Subtle features in the temporal development of the neutrino flux can be measured allowing detailed studies of a supernova and the nature of neutrinos.

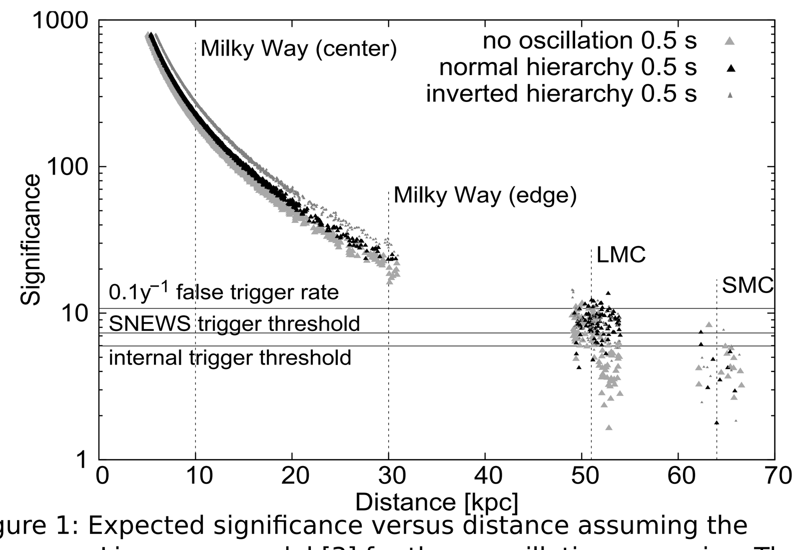


Figure 1: Expected significance versus distance assuming the Lawrence-Livermore model [3] for three oscillation scenarios. The significances are increased by neutrino oscillations in the star by typically 40% in case of an inverted hierarchy. For the Milky Way, the supernova progenitor distribution follows the prediction from [4], for the Magellacnic Clouds it is asssumed to be uniform. (LMC/ SMC: Large/Small Magellanic Cloud)

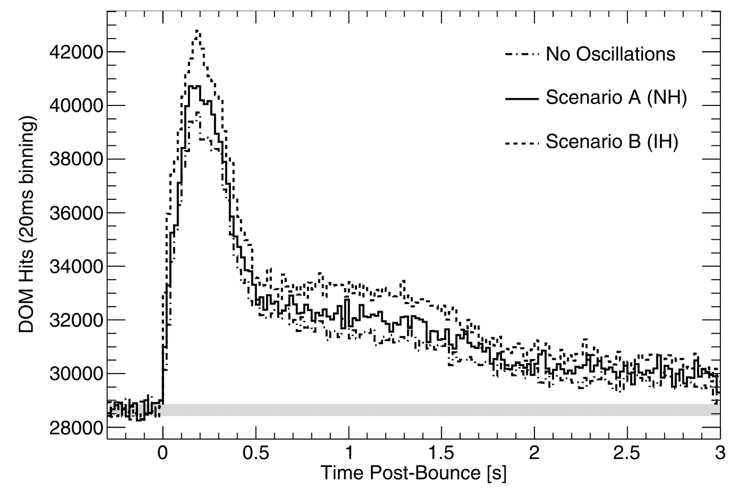


Figure 2: Expected rate distribution at 10 kpc supernova distance assuming normal and inverse hierarchies

Coincident hit method

- Coincident photon hits can be used to extract additional information
- Example hit modes :
  - (1,1): two nearest-neighbour DOMs
  - (2,0): two photons on one DOM
- Noise suppression through small coincidence windows
- Observables:
  - Average energy (see figure 3)
  - Time dependent supernova spectral features
  - Direction

- Uncorrelated random noise is a limiting factor and is treated in [1]
- Here, we study correlated noise from cosmic ray muons
  - Extended a GEANT-4/Toy simulation [5]
  - Consider "Garching" model supernova [6] at 10 kpc with <E>=12.5 MeV

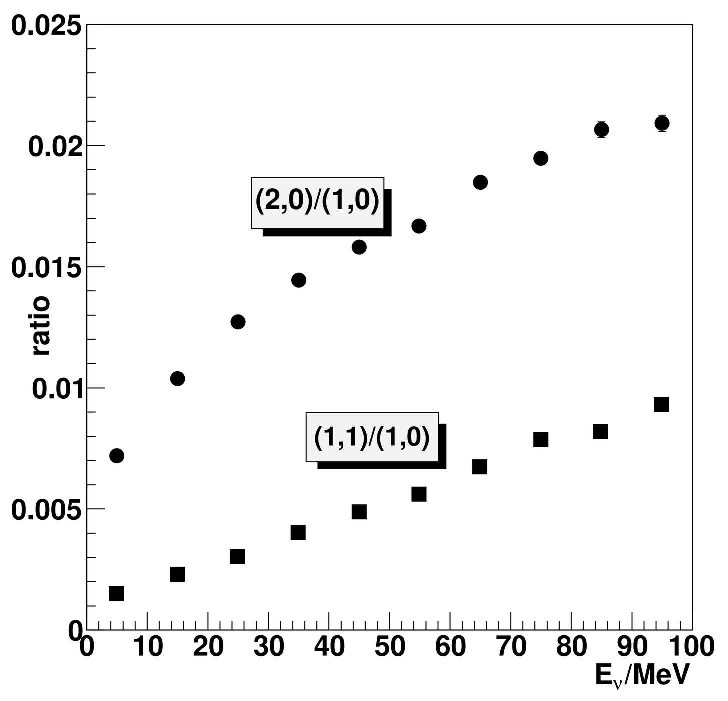


Figure 3: Ratios of rates nearest-neigbour (1,1) and double hit (2,0) coincidences over single hit rate (1,0) in IceCube as function of neutrino energy.

Atmospheric Muon Background

Despite the 1300 m overburden, cosmic ray muons form a background for both detection methods.

Current Method :

Regarding the significance distributions of the supernova data, one observes a remarkable deviation from the formally expected Poissonian behaviour: The significance ($\xi = \Delta\mu/\sigma_{\Delta\mu}$ with dark noise rate deviation $\Delta\mu$) distribution is clearly broadened by a factor ≈ 1.2 - 1.5. The major reason for this broadening is the influence of atmospheric muons, which is indicated by a seasonal variation of the standard deviation. In order to subtract atmospheric muons, the correlation between significance and atmospheric muon rate n_μ is removed by calculating a corrected significance ξ' in the following way: $\xi = b \cdot n_\mu + a$; $\xi' = \xi - b \cdot n_\mu - a$, with offset a and slope b according to the linear fit showed in figure 6 l.h.s.. This particular candidate (29/02/2012, run 119716) was chosen because of the high ξ = 8.59. In figure 6 r.h.s. is observable that the candidate is basically caused by the high muon hit rate and that the corrected significance is not even the highest in the run. A longterm investigation for the date between 01.04.2008 to 13.5.2011 (figure 7) shows that the muon subtracted distribution is clearly more Poissonian than the original distribution. For this dataset, the number of significances higher than 6 could be reduced from 1151 to 7. After applying the corrections, there is still a non-Poissonian part which might be caused by the fact that only nearest neighbor coincident HLC hits were used in the analysis. Newer data also contains single SLC hits.

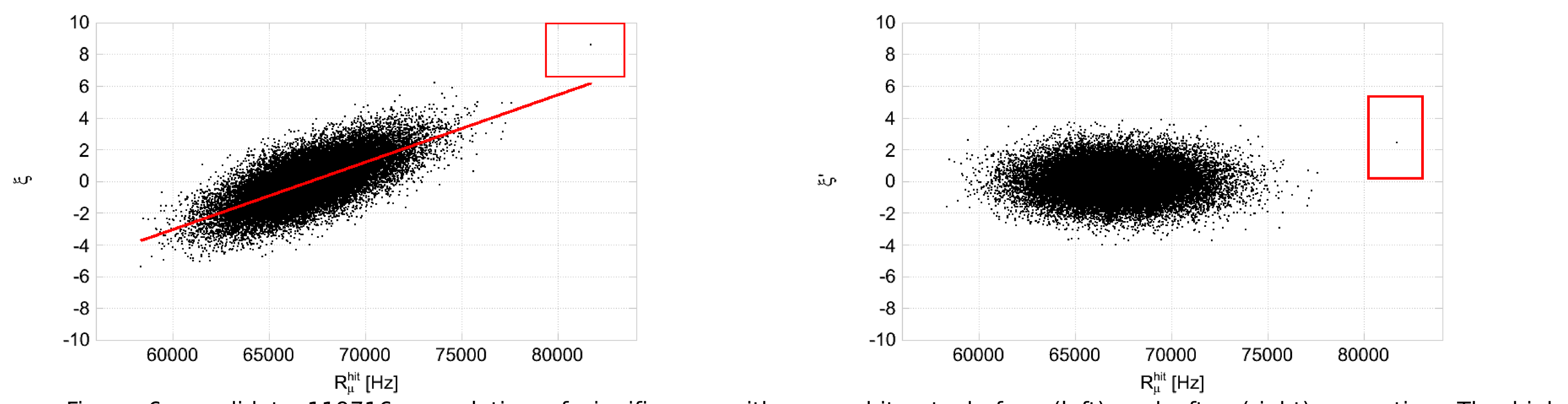


Figure 6: candidate 119716: correlation of significance with muon hit rate before (left) and after (right) correction. The high significance of the candidate bin is obviously correlated with a high muon hit rate (SLC hits included).

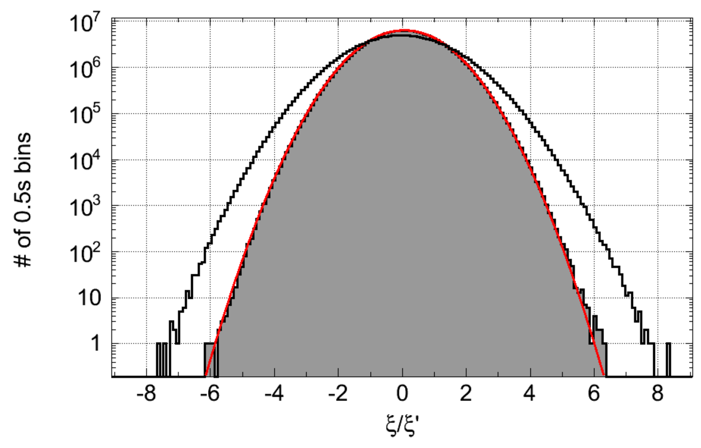


Figure 7:Histogram of the original (unfilled) and of the muon subtracted (gray filled) significance distribution for a data set (HLC hits only) from 01.04.2008 to 13.5.2011. The red curve is a fit to the significancedistribution using a combination of three Gaussian functions.

Coincident hit method :

Supernova neutrino interaction signature is local (compared to muons) →
- Narrow time window for coincidences (figure 8)
- Low mulitiplicity of coincident DOMs (figure 10)

(use as cuts) → Large reduction of cosmic ray muon background (figure 11)

Requires availability of all hits during supernova (finding isolated coincidences) : HitSpooling (see box)

In a 'Deep and Dense' detector, the multiplicity differences between supernova neutrino interactions and cosmic ray muons is enlarged

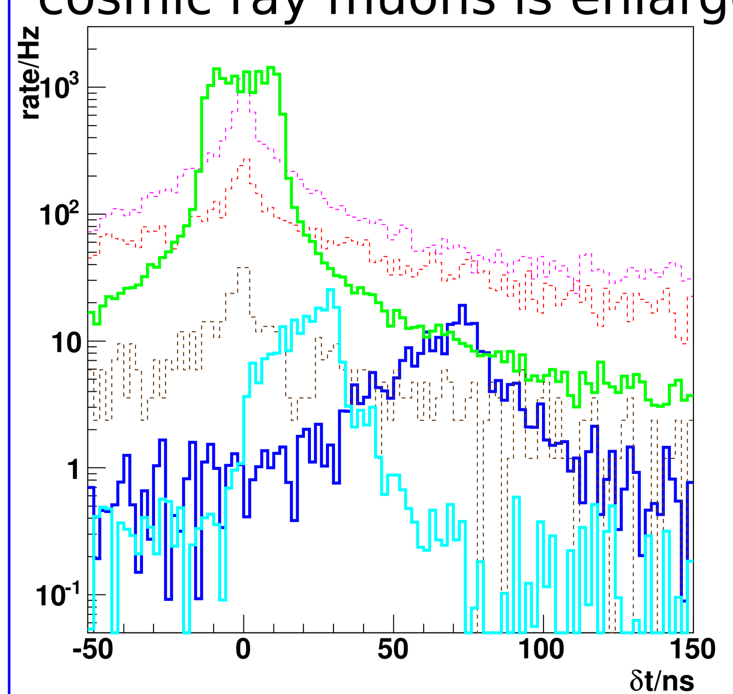


Figure 8: Difference in hit arrival times between two nearest-neighbour DOMs (upper-lower, see figure 9). Thick lines are neutrino signals for IceCube (blue), DeepCore (turquoise) and Deep and Dense (green). Dashed lines are cosmic ray muon hits for IceCube (red), DeepCore(brown) and Deep and Dense (purple)

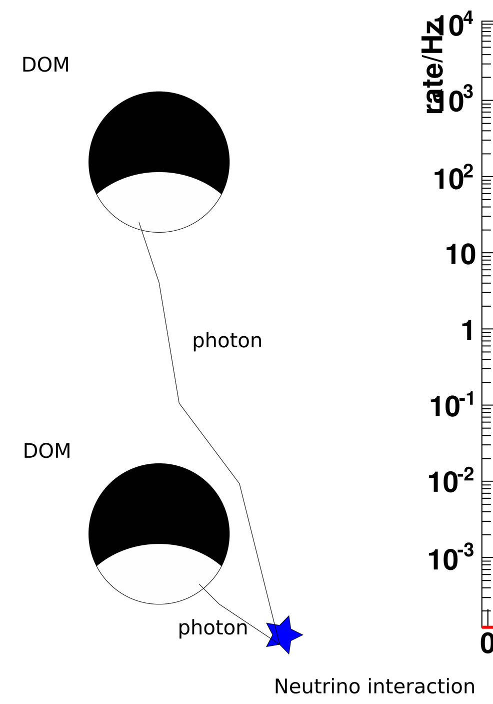


Figure 9: Downward orientation of DOMs in IceCube and DeepCore leads to asymmetric time difference distribution for point-like supernova neutrino interactions, this can be used to distinguish them from muon hits.

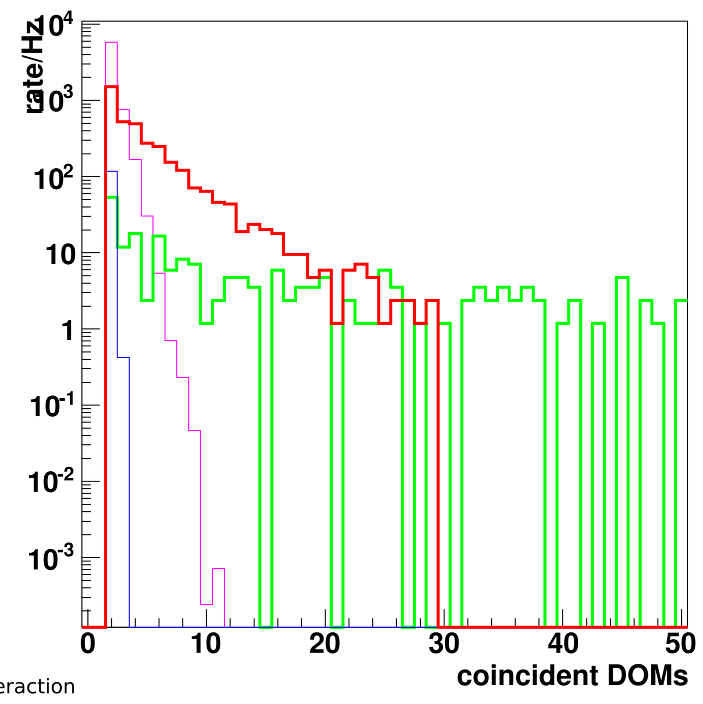


Figure 10: Distributions of the number of coincident DOMs. The gates are set to 150 and 50 ns for the IceCube and Deep and Dense configuration. Thick lines indicate cosmic ray muon hits, thin lines indicate supernova neutrino hits. IceCube: blue and red, Deep and Dense: purple and green. Muon hits for Deep and Dense (green) extends to 500.

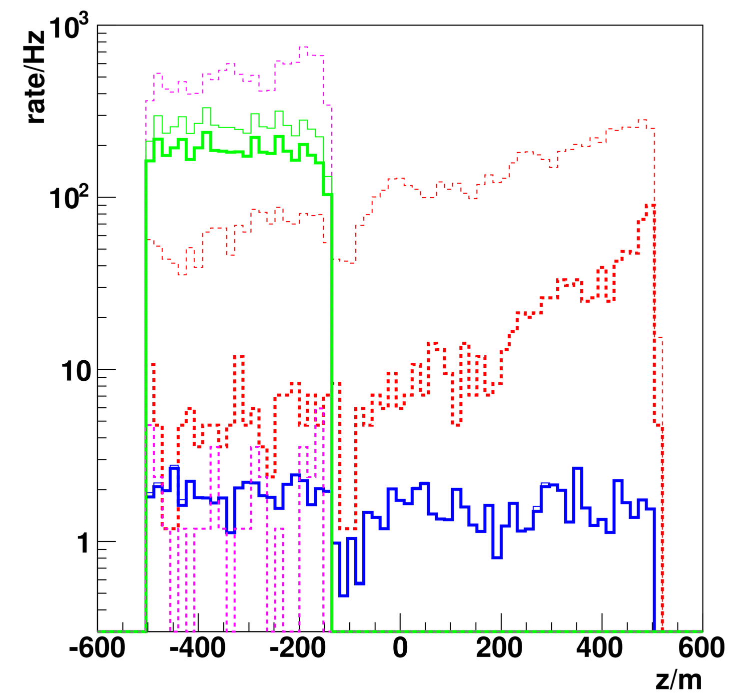


Figure 11: Coincidence rates as function height, before and after cuts. IceCube: muons (red) ,neutrinos (blue), Deep and Dense: muons (purple), neutrinos (green). Dashed indicates before cuts, thick after (unoptimized) cuts. For IceCube (Deep and Dense) the background is reduced by a factor of ~17 (300) while ~87 (73) % of the signal is kept.

SNDaq/HitSpooling

The current Supernova Data Acquisition System is based on comparing the overall noise rate increase in the detector with a sliding window analysis. This is done within a data stream containing only noise counts ("scaler data") of the photomultipliers (PMTs) . A future improvement to this DAQ system will be the accessibility of the complete raw data coming from the PMT that will be stored in a round robin file system, so called "HitSpool System". In case of an alert, triggered by the scaler data, the time-corresponding HitSpool data will be transferred North and analyzed. In this way, it is possible to study the noise behavior of the detector and to develop an atmospheric muon subtraction procedure of the data. Furthermore, one aims for studies of the energy distribution and directionality of Supernova neutrinos.

DOM: Digital optical module, the basic detection unit: a glass pressure sphere with a photomultiplier and electronics.
SLC: the baseline operation mode of IceCube, only hits with a local coincidence (nearest- or next-to-nearest neighbour) contain a full waveform, others contain coarser data.
HLC: Hard local coincidence, only hits with a local coincidence are considered.

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Summary/Outlook

- Current detection mode based on the collective noise rate of all photomultipliers has a reach up to 50 kpc with significances from 3 to 6σ depending on model.
- The temporal evolution of the neutrino signal can be followed with high statistics allowing supernova and neutrino properties to be studied.
- Progress is being made in the understanding and rejection of the background caused by cosmic ray muons.
- The efficiency of cosmic ray muon background rejection increases for future projected dense arrays, while prospects for supernova neutrino emission characterization is largely improved by means of coincident hit modes
- A new DAQ is planned that will record the full set of hit information of all IceCube sensors for supernova candidates. By the use of these data the limited time resolution of 2 ms will be overcome, the noise background can be further reduced, and multiple hit information can be used to estimate the average energy and to reject correlated background hits.

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