SUPERNOVA NEUTRINO DETECTION with ICECUBE

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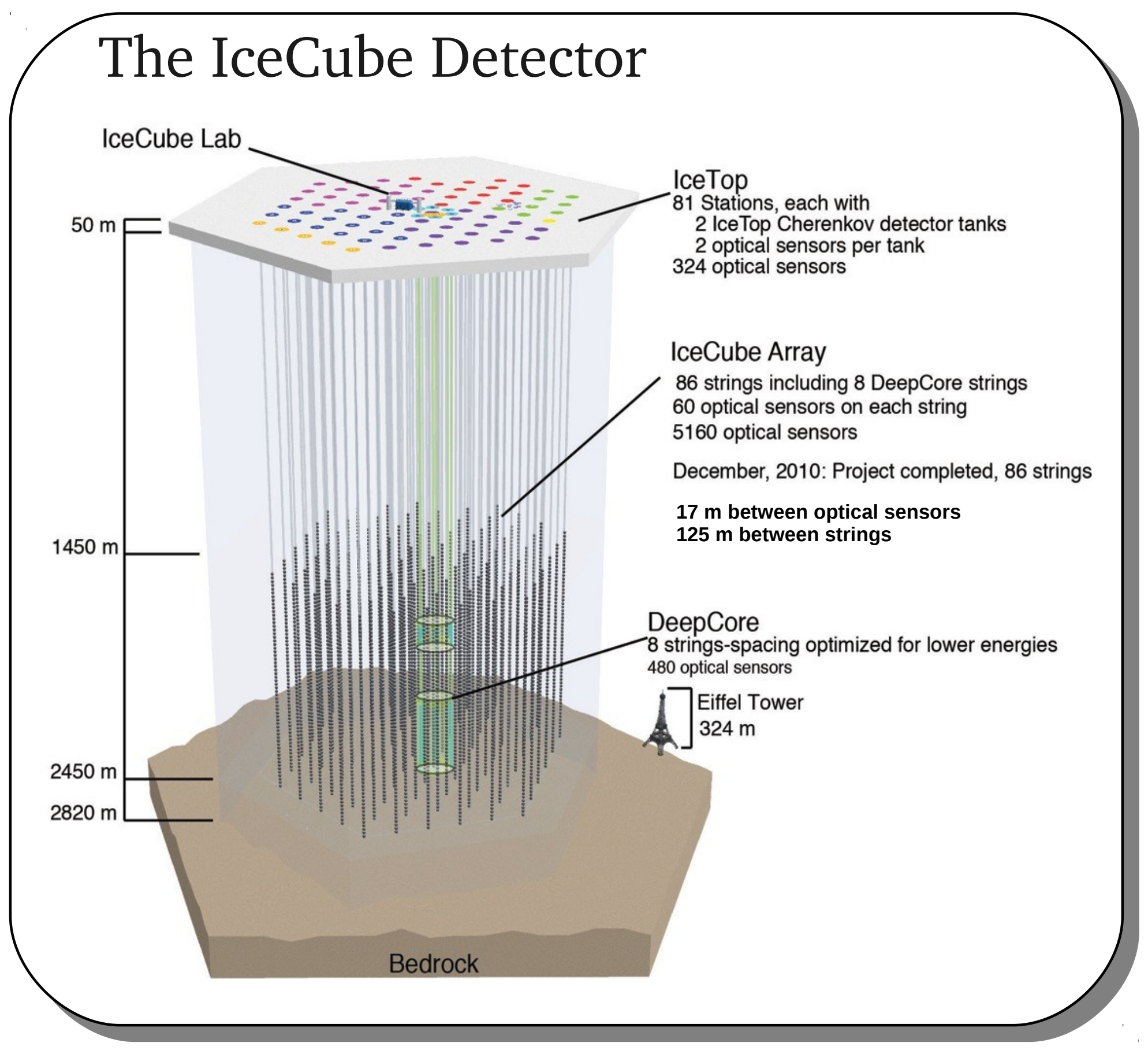
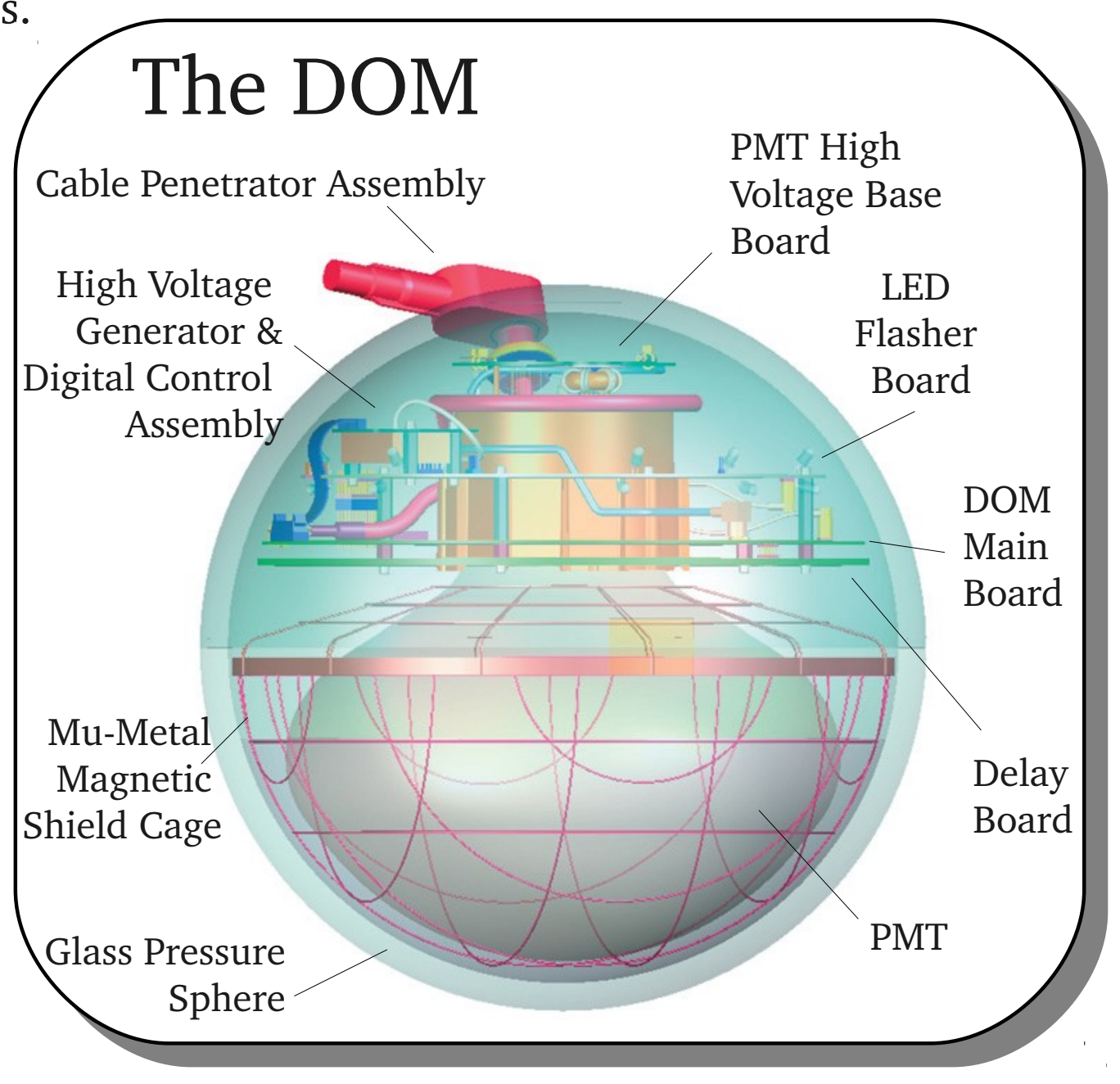
THE ICECUBE OBSERVATORY

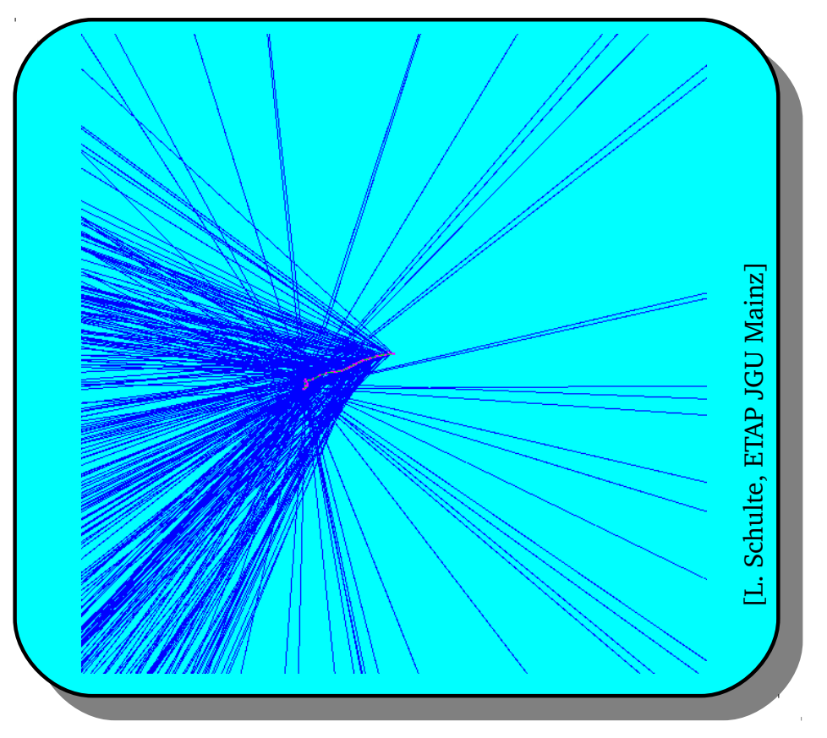
The IceCube Neutrino Observatory, situated at the geographic South Pole, was completed in December 2010. A lattice (IceCube Array) of 5160 photomultiplier tubes monitors one cubic kilometer of deep Antarctic ice in order to detect neutrinos via Cherenkov photons emitted by charged by-products of their interaction in matter. Another 324 digital optical sensors are implemented in frozen water tanks (IceTop) and can be used for vetoing downward going events.
Since IceCube's geometry was optimized to detect neutrinos with energies from 10^{10} up to 10^{21} eV .


The IceCube Detector


The DOM

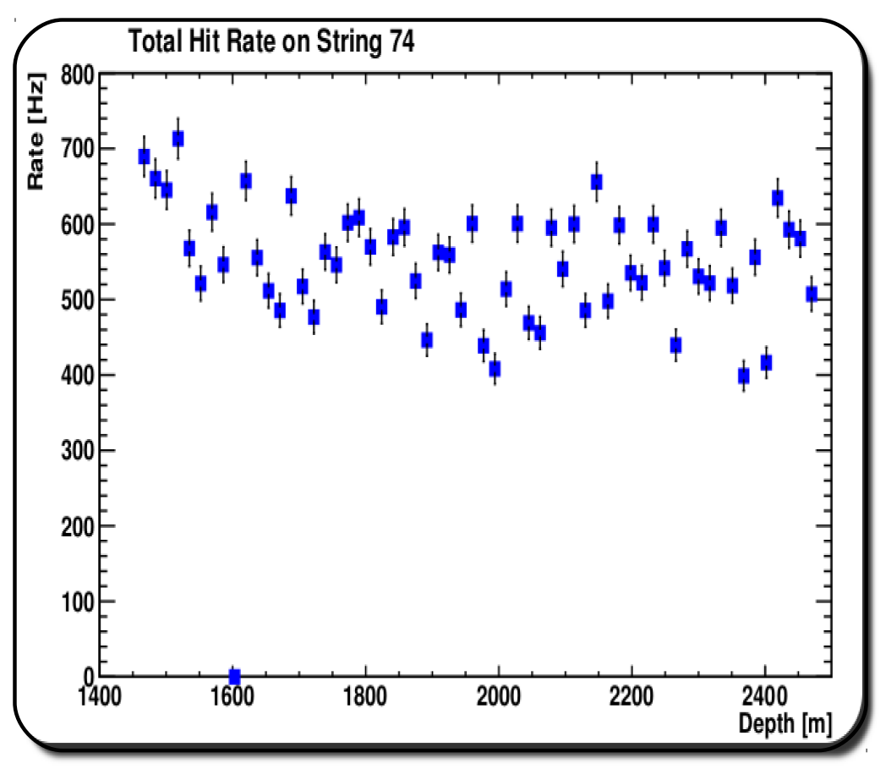
The heart of IceCube is the Digital Optical Module (DOM) which is built in a 13" (33cm) borosilicate glass pressure sphere. Besides a 10" (25.4cm) hemispherical photomultiplier tube (PMT) the DOM also houses all necessary electronics boards containing a processor, memory, flash file system and several real-time operating systems. In this way it is ensured that each DOM is able to operate as a stand-alone data acquisition system. The on-board digitization of the PMT anode pulse is a key concept in IceCube that relieves the transmission of analog signals over long distances.

DETECTION METHOD

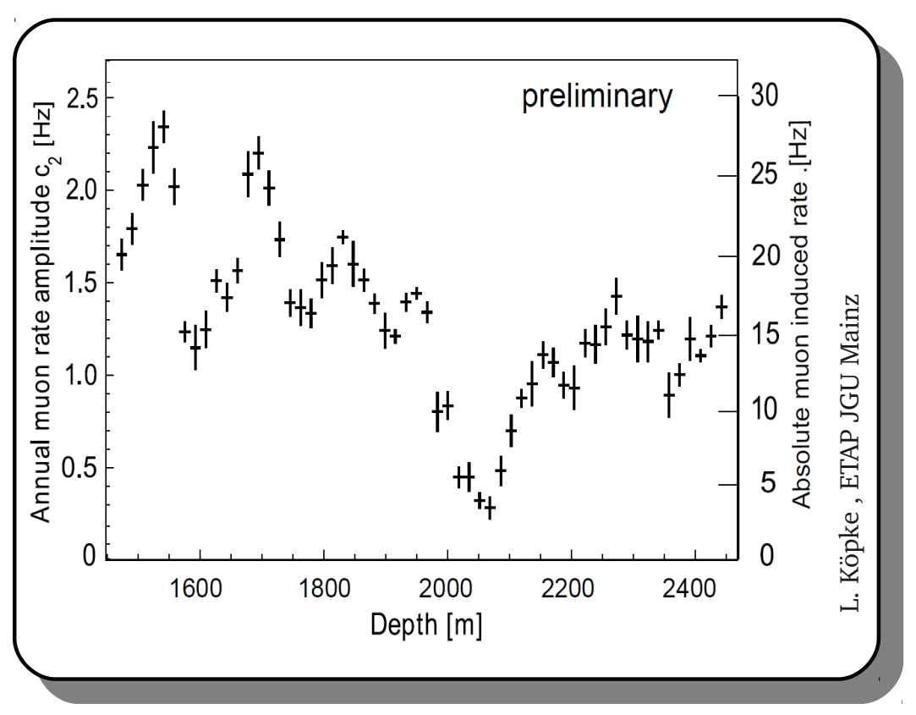


Cherenkov photons radiated by 5 MeV e^+ in a GEANT4 based simulation.

Due to subfreezing ice temperatures, the photomultiplier's dark noise rates are particularly low (order of 550 Hz). Therefore, Cherenkov photons emitted by high and ultra high energetic neutrinos are not the only observable events in IceCube. Also a large burst of MeV supernova neutrinos streaming through the detector will produce an observable signal in the PMTs. The detector will measure large numbers of MeV neutrinos by observing a collective rise in all photomultiplier rates on top of the dark noise. Due to the noise-rate based detection method a detailed understanding of the noise is fundamental.



Total Hit rates for entire String 74 (60 DOMs) without artificial dead-time



Muon induced rate as a function of depth in ice

Several effects are mainly contributing to the low noise rate in IceCube:

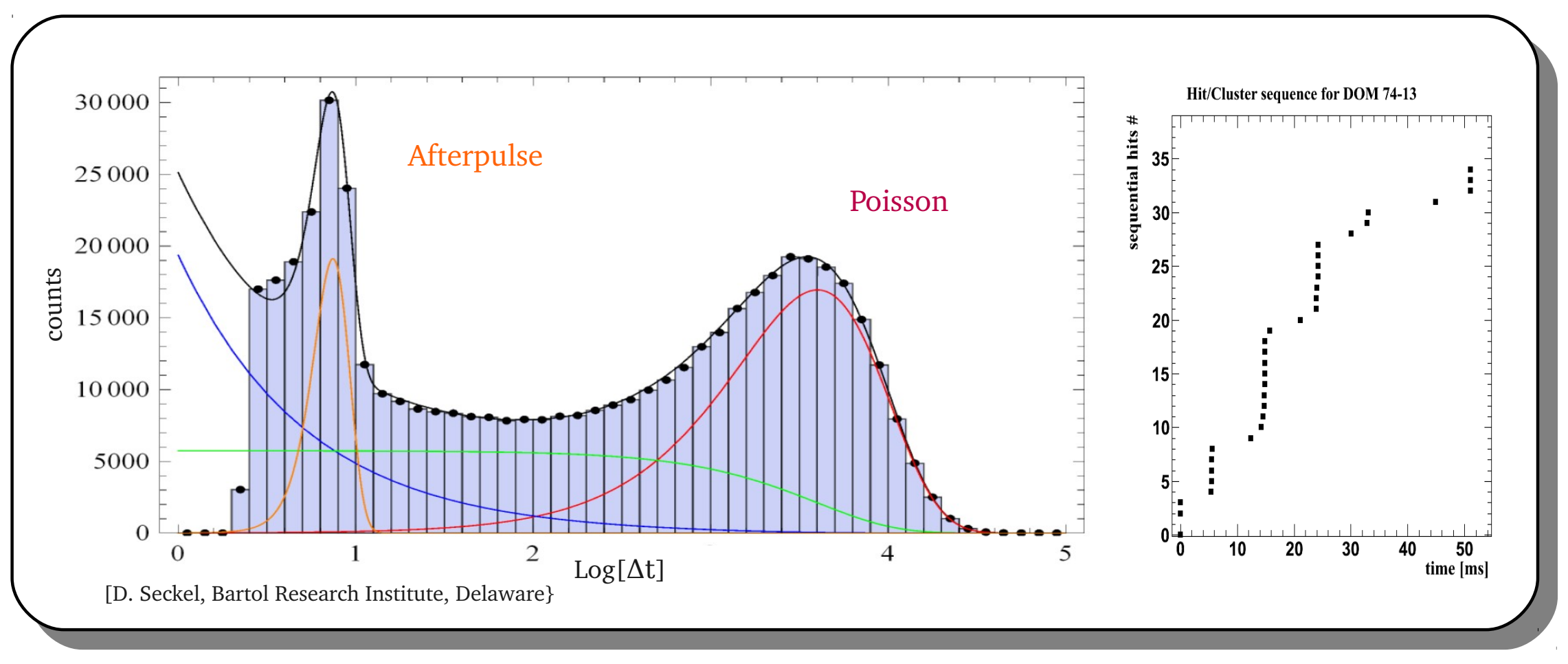
- Uncorrelated Poissonian noise:

  Radioactivity, atmospheric muons and thermal noise.

- Correlated noise contribution:

  Bursts originating most likely from scintillation of α- and β-decays from Uranium or Thorium isotopes in the glass sphere. The duration of these bursts is observed to be fractions of ms.

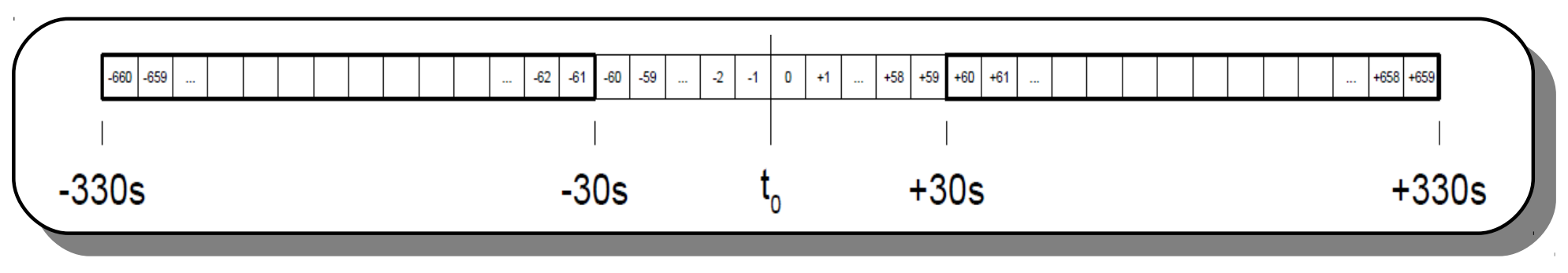
Applying an artificial dead-time τ suppresses these effects and improves the signal-to-noise ratio of the measurement and is found to be optimal at $\tau \approx 250\ \mu s$.



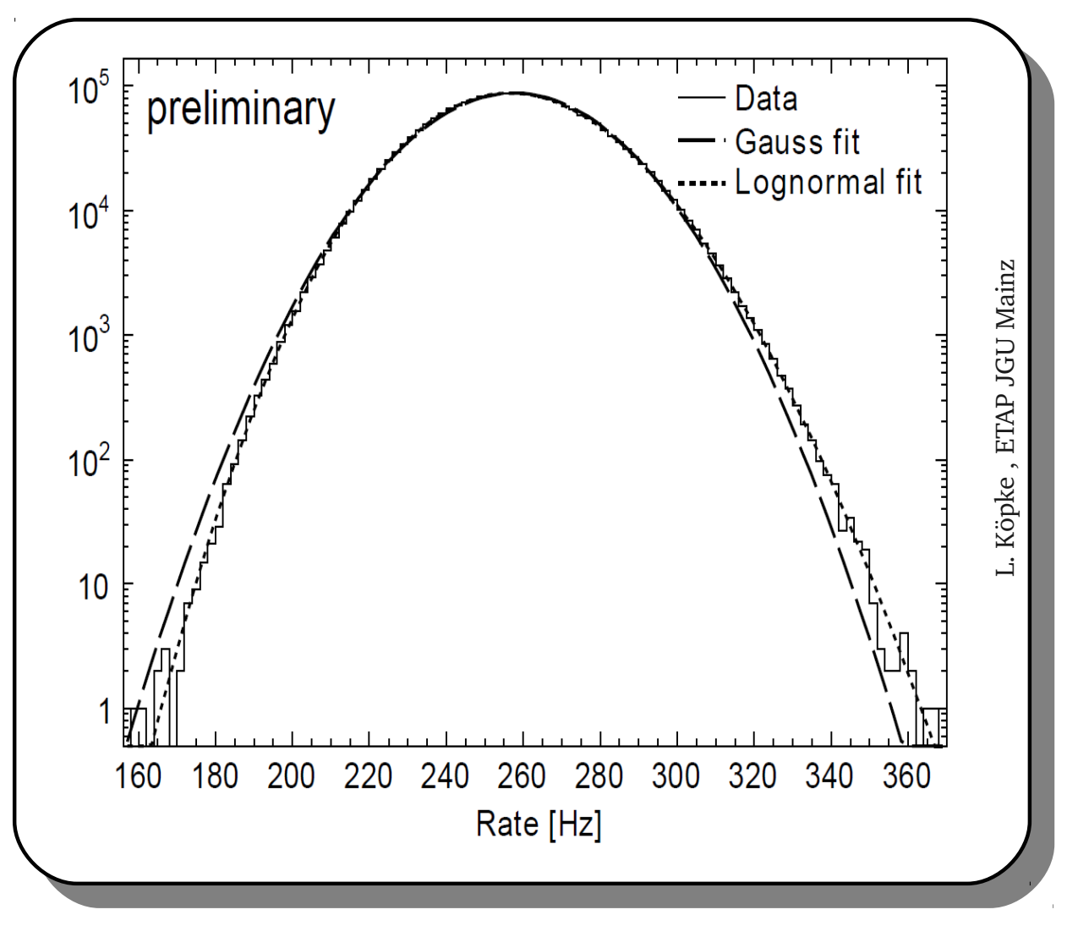
[D. Seckel, Bartol Research Institute, Delaware}

The plot on the left shows the interval distribution, i.e the time between to successive hits in a DOM. The Poissonian component following an exponential distribution (red) at the higher end and the correlated noise component of After-pulses (orange) for short time distances are visible. Two additional fits following a power law were made to please the eye. The plot the the right shows several hit clusters (bursts) with a duration in the order of fractions of a millisecond.

ANALYSIS METHOD



The real-time analysis method is based on counting N_i pulses during a given time interval Δt which results in rates r_i for each DOM i (i=1...5160). The distribution of the individual r_i can be described by lognormal distributions that are approximated by Gaussians with rate expectation value $\langle r_i \rangle$ and standard deviation expectation values $\langle \sigma_i \rangle$. These expectation values are computed from moving 300s time windows before and after the investigated time bin t_0 (bin size of 2ms up to 0.5s). 30s around t_0 are excluded to avoid any impact of a wide signal on the mean rates. To evaluate the most likely ***collective rate deviation <Δμ>*** of all DOM noise rates r_i from their individual rates $\langle r_i \rangle$, one maximizes the likelihood $\mathcal{L}(\Delta\mu)$.



Single DOM rate distribution with applied artificial dead-time of τ ≈ 250 μs. The average noise rates between DOMs vary only by 10%.

$$\mathcal{L}(\Delta\mu) = \prod_{i=1}^{N_{\mathrm{DOM}}} \frac{1}{\sqrt{2\pi}\,\langle\sigma_i\rangle} \exp\left(-\frac{(r_i - (\langle r_i\rangle + \epsilon_i\,\Delta\mu))^2}{2\langle\sigma_i\rangle^2}\right) .$$

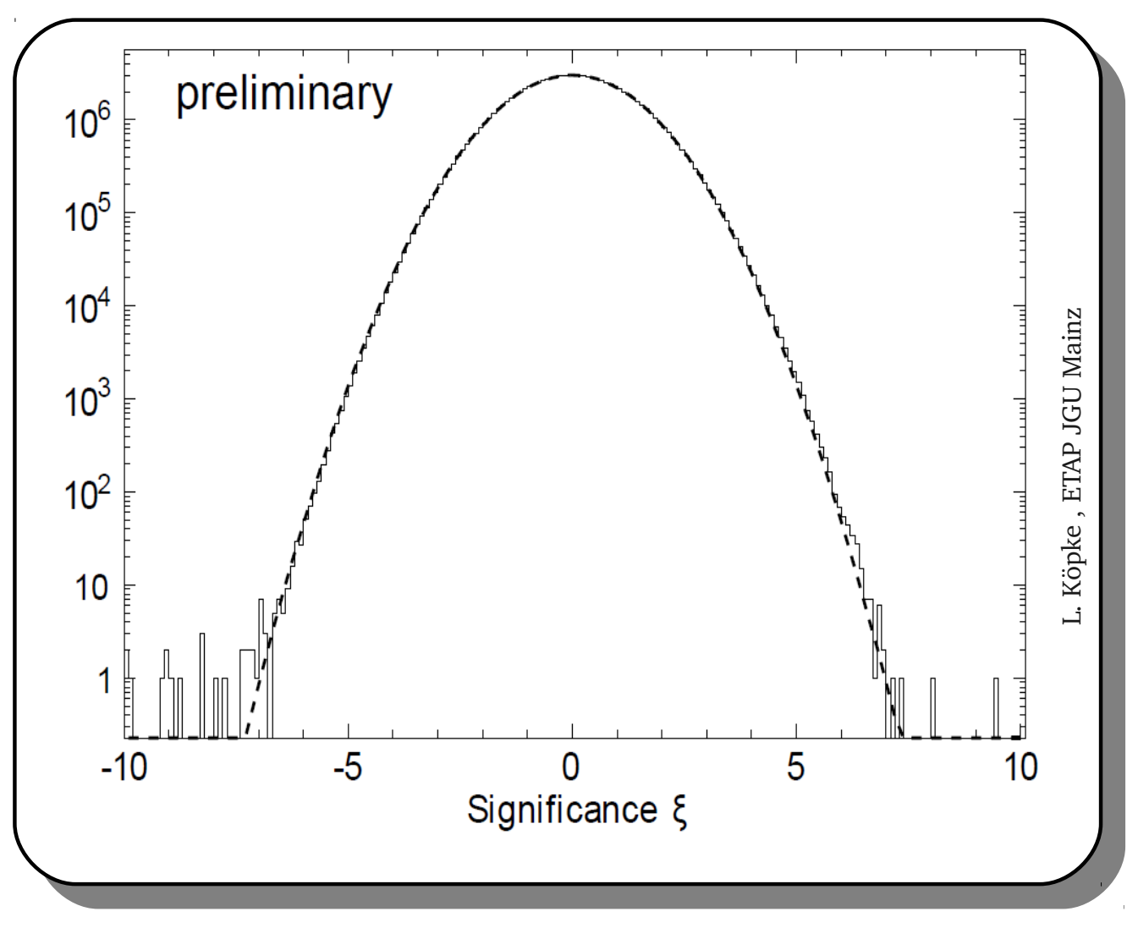
The extrema of the likelihood are found by minimizing -ln $\mathcal{L}$ which corresponds to minimizing $\mathcal{X}^2(\Delta\mu)$. This leads to:

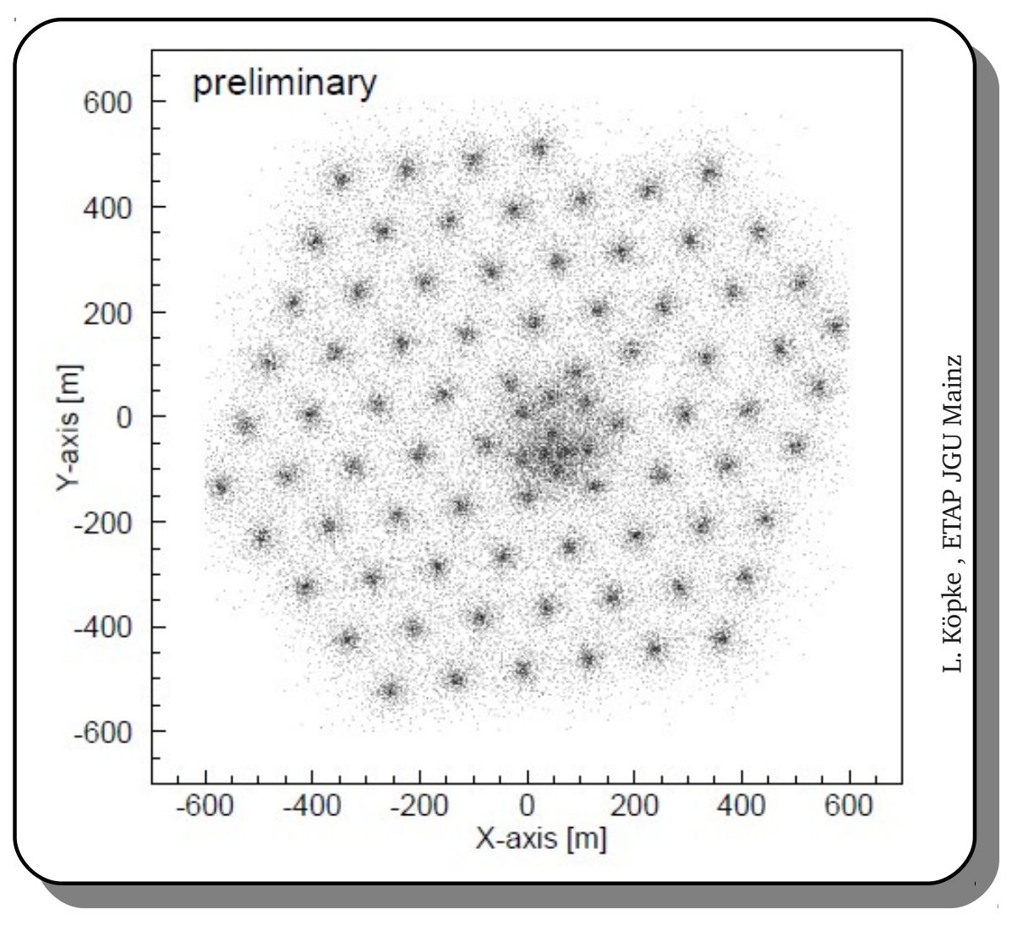
$$\Delta\mu = \sigma_{\Delta\mu}^2 \sum_{i=1}^{N_{\mathrm{DOM}}} \frac{\epsilon_i\,(r_i - \langle r_i\rangle)}{\langle\sigma_i\rangle^2} \quad \text{with} \quad \sigma_{\Delta\mu}^2 = \left(\sum_{i=1}^{N_{\mathrm{DOM}}} \frac{\epsilon_i^2}{\langle\sigma_i\rangle^2}\right)^{-1} .$$

$$\xi = \frac{\text{deviation from sliding average}}{\text{uncertainty of deviation}} = \frac{\Delta\mu}{\sigma_{\Delta\mu}}$$

DETECTOR PERFORMANCE

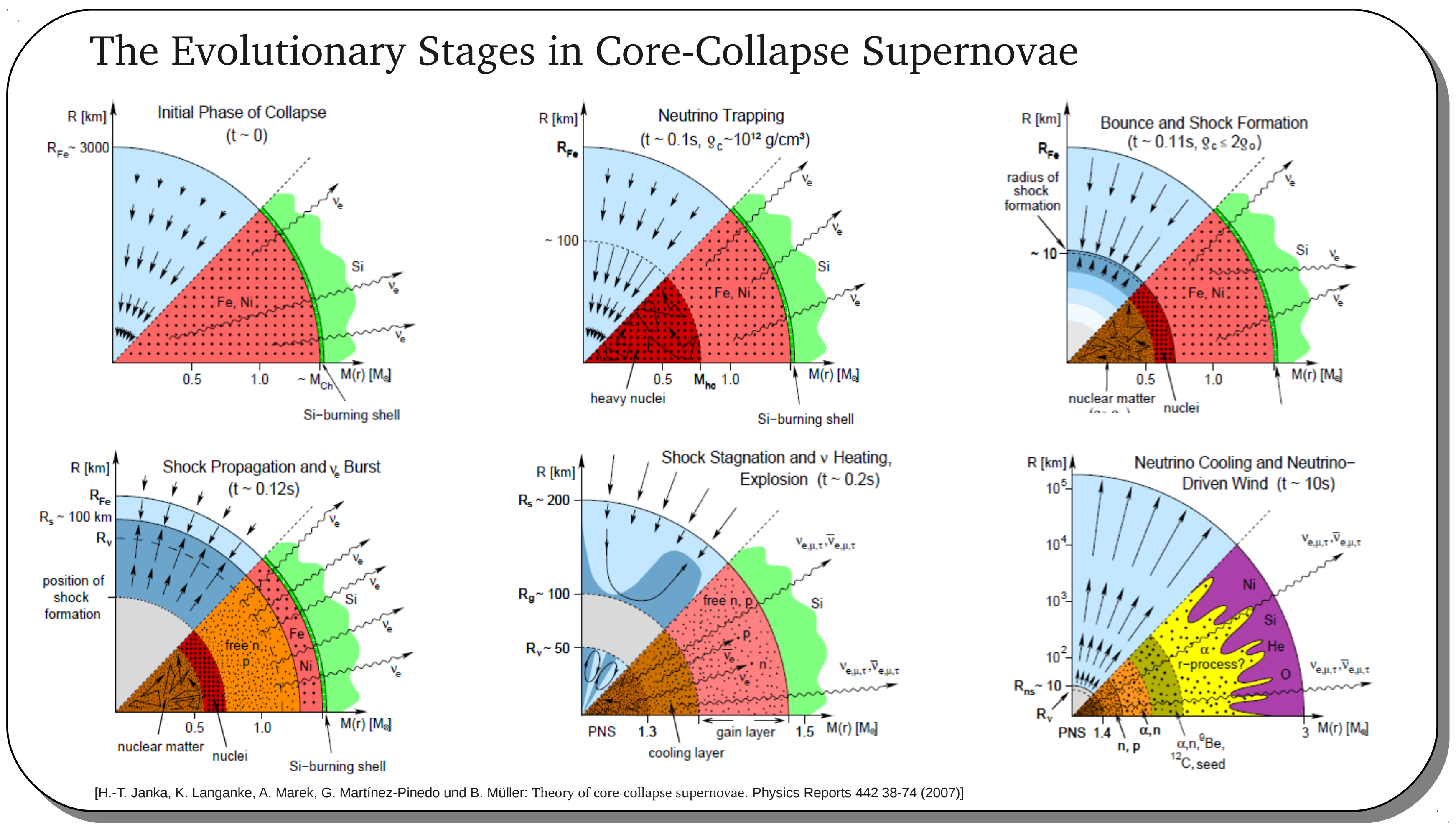
This method allows to establish an indicator for strength and homogeneity of the illumination of the ice, called significance ξ, that should follow a Gaussian distribution with unit width and centered around zero. After a detector uptime of 556 days the measured significance distribution in the IceCube's 22– and 44-String configuration (plot to the right) is broader than expected due to the above mentioned correlated noise contributions. A Gaussian with σ=1.27 is fitted.





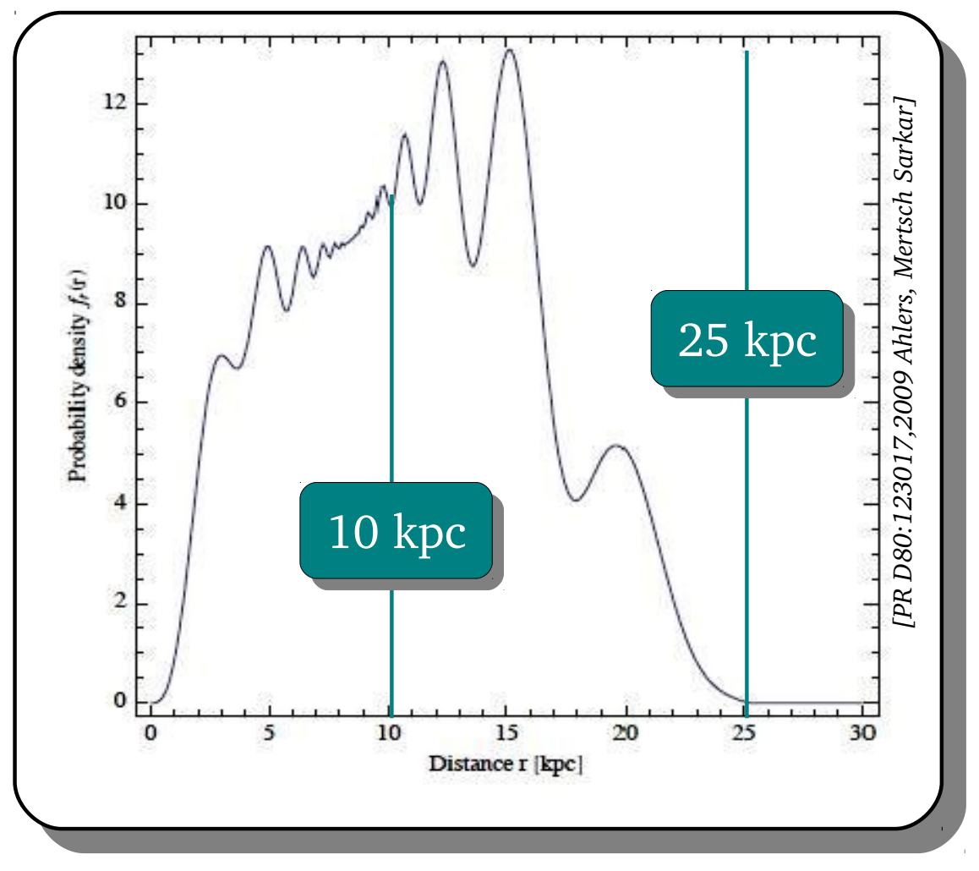
Determination of the number of detected signal hits from the overall number of neutrinos crossing the detector is can be done using a GEANT GCALOR-based simulation. With this it is possible to determine a 20% dependence of the detector sensitivity on the incoming neutrino direction for neutrino-electron-interactions. The figure on the left visualizes the effective volumes of the DOMs in IceCube by showing the clustering of detected inverse beta neutrino interactions at the position of the detector strings.

CORE-COLLAPSE SUPERNOVA


The Evolutionary Stages in Core-Collapse Supernovae

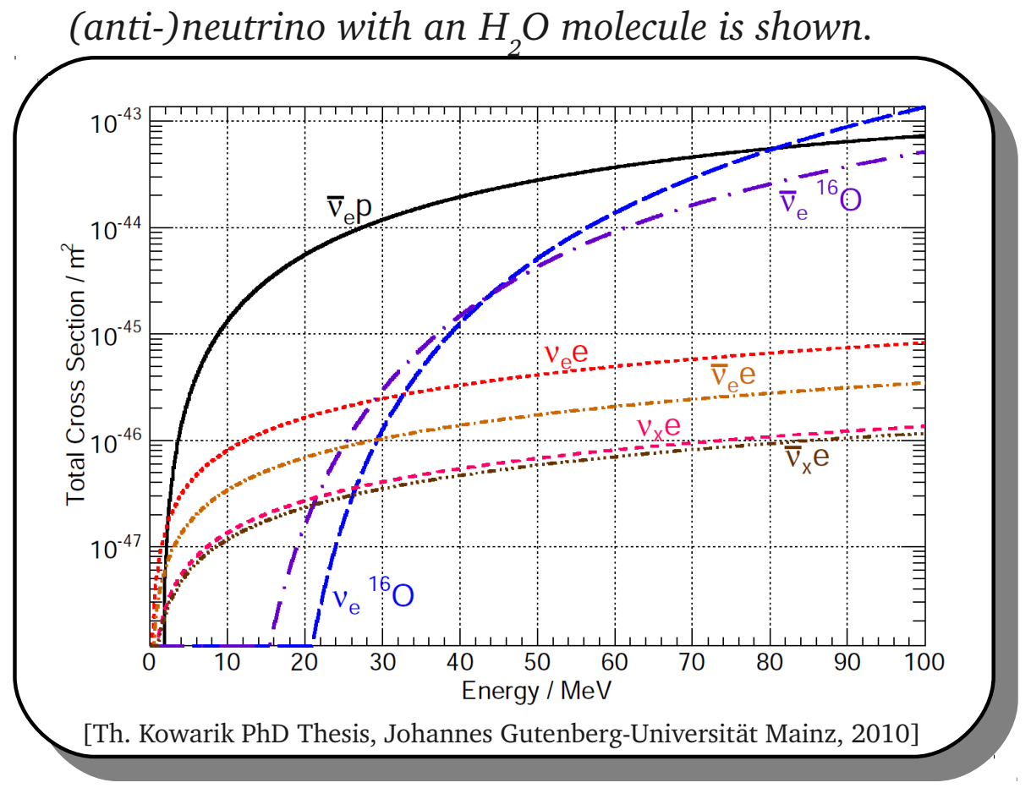
[H.-T. Janka, K. Langanke, A. Marek, G. Martínez-Pinedo und B. Müller: Theory of core-collapse supernovae. Physics Reports 442 38-74 (2007)]

Probability distribution for Supernova progenitor in Milky Way

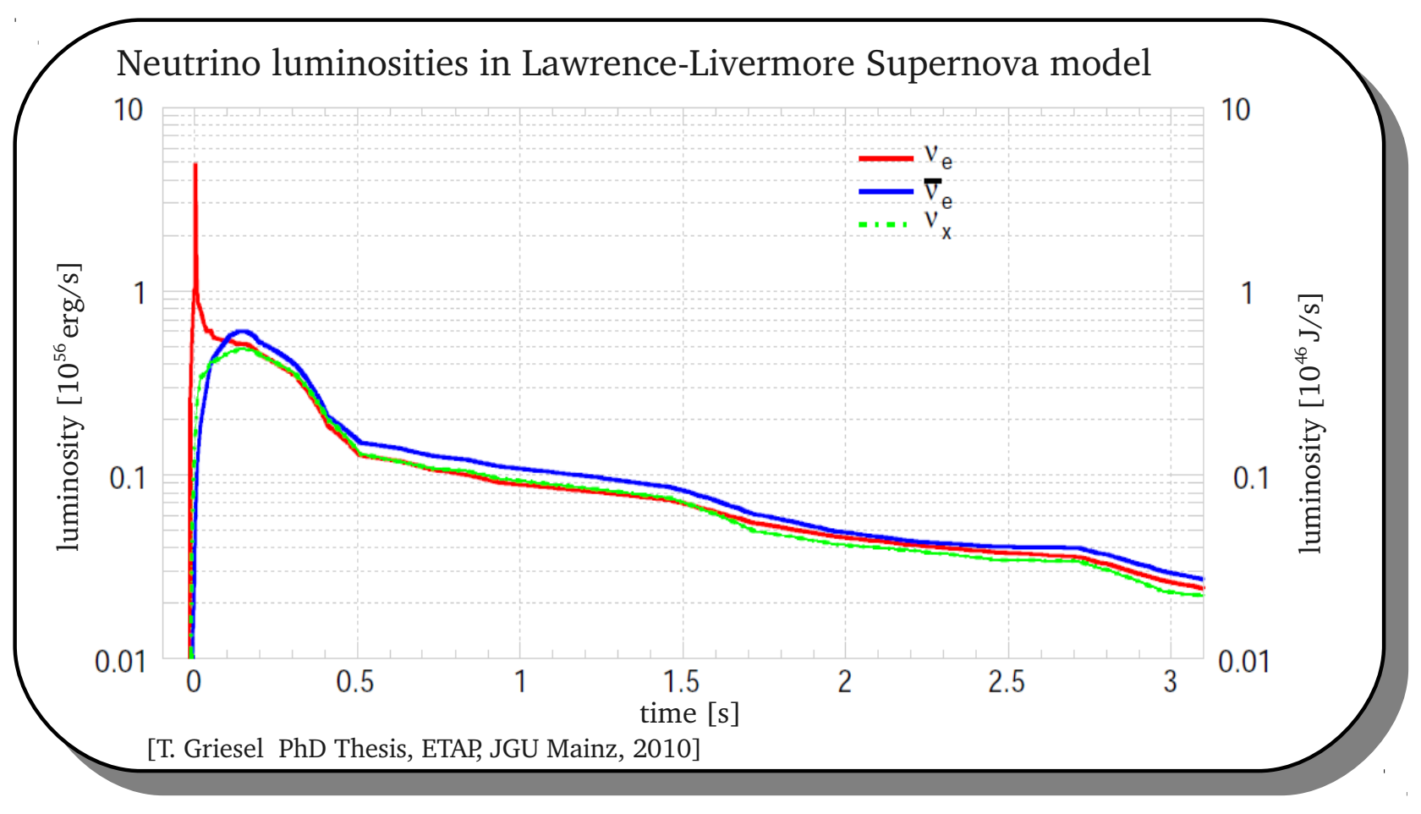


Although it is still unclear how Supernova candidates follow the star distribution one can only give a probability density for our galaxy. The dominant signature (~94%) of Supernova neutrinos in ice is the inverse beta decay of an electron anti-neutrino resulting in a detectable positron: $\bar{\nu}_e + p \rightarrow e^+ + n$.
The total cross sections of all channels for neutrino interactions in ice are shown on the right.
Using the so-called *Lawrence-Livermore* model one can determine the energy and luminosities of the incident neutrino. This spherical symmetric model is performed from the onset of the collapse up to 18 s after the core bounce. It assumes a 20 $M_\odot$ progenitor star and its modeled after the SN1987A. All characteristics of neutrino emission are visible. The more detailed *Garching* model is used to determine the energy spectrum of ν_e (red) $\overline{\nu}_e$ (blue) and all other flavors ν_x (green dashed).

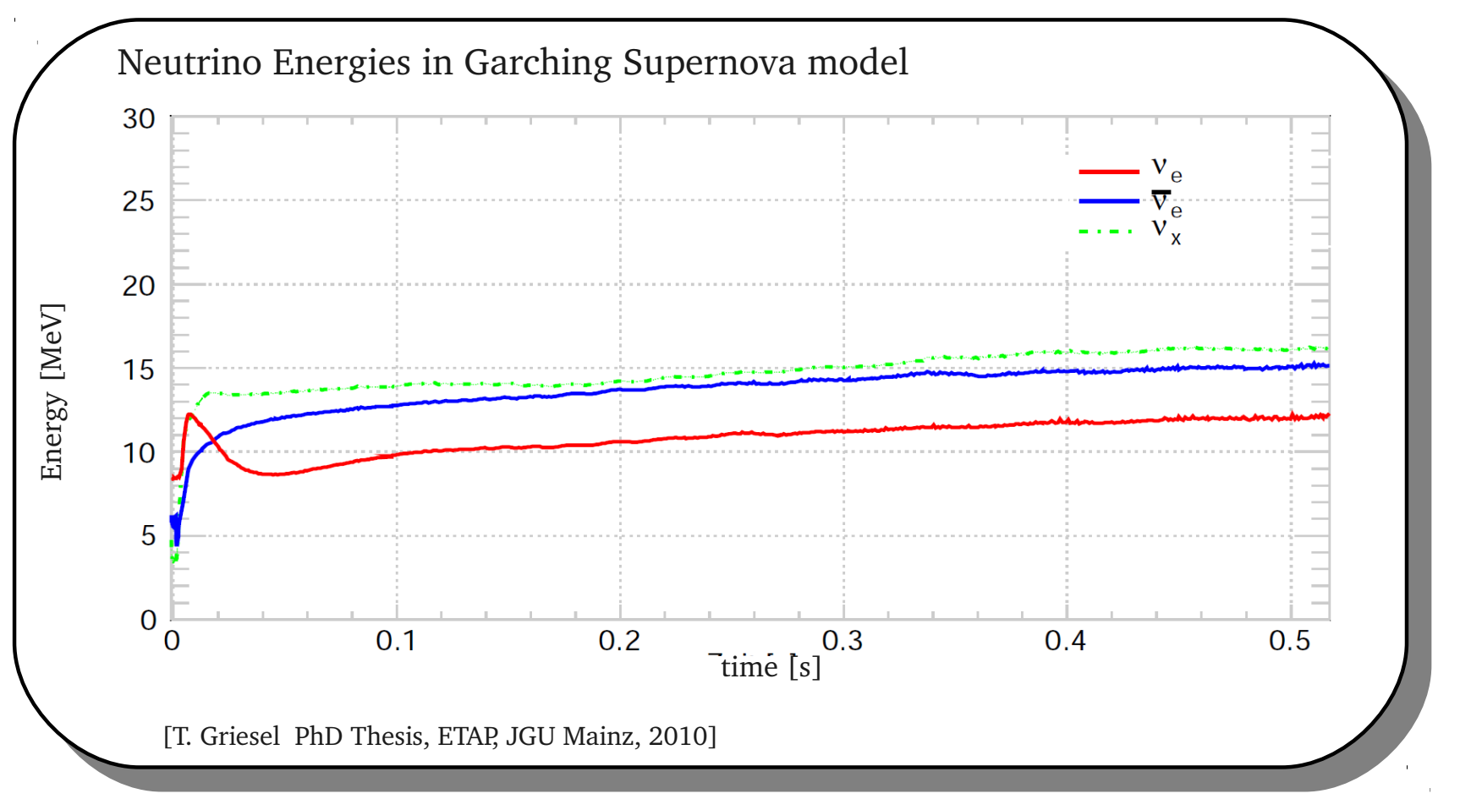
Neutrino interaction cross sections in the ice. The cross section for the interaction of a single (anti-)neutrino with an H_2O molecule is shown.



[Th. Kowarik PhD Thesis, Johannes Gutenberg-Universität Mainz, 2010]


Neutrino luminosities in Lawrence-Livermore Supernova model

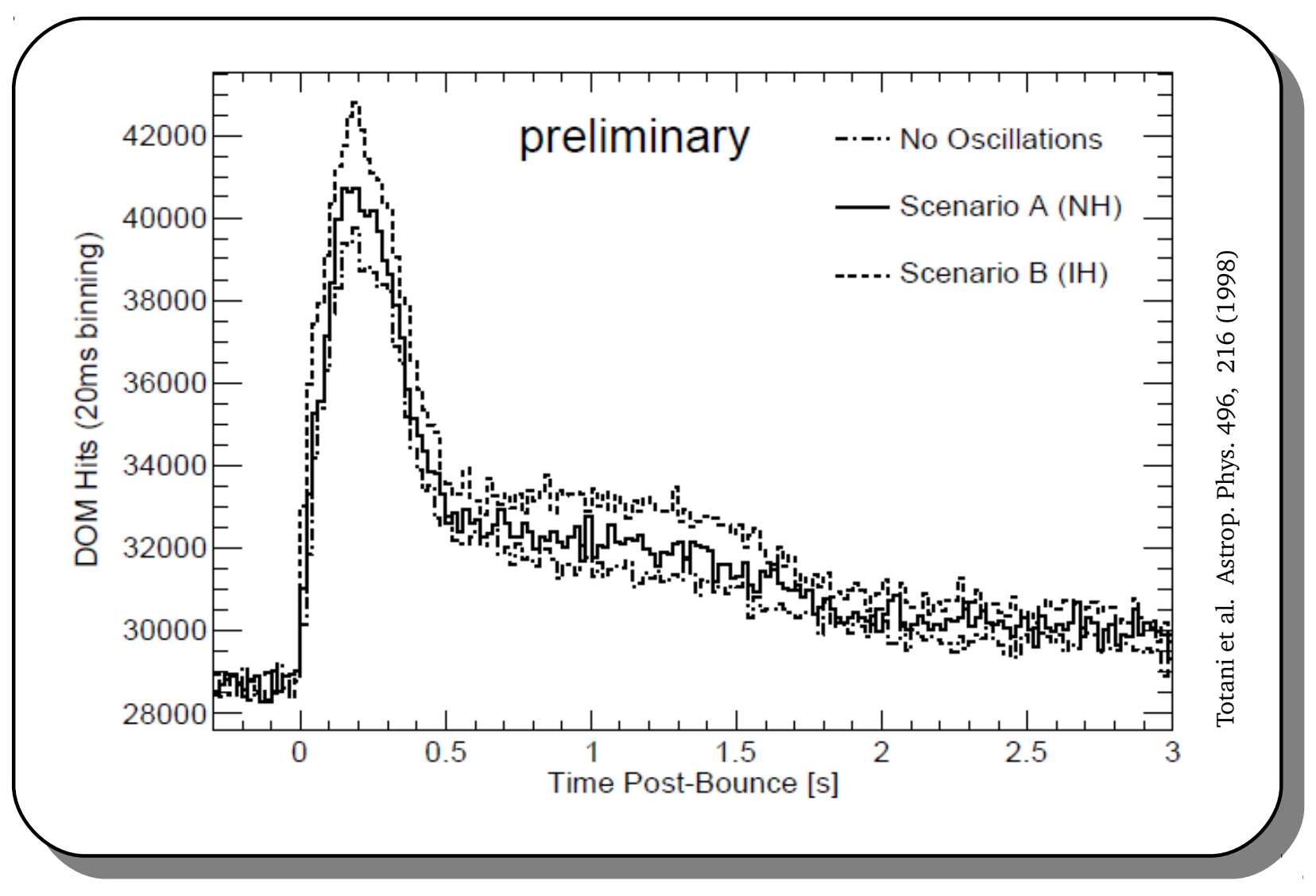
[T. Griesel PhD Thesis, ETAP, JGU Mainz, 2010]


Neutrino Energies in Garching Supernova model

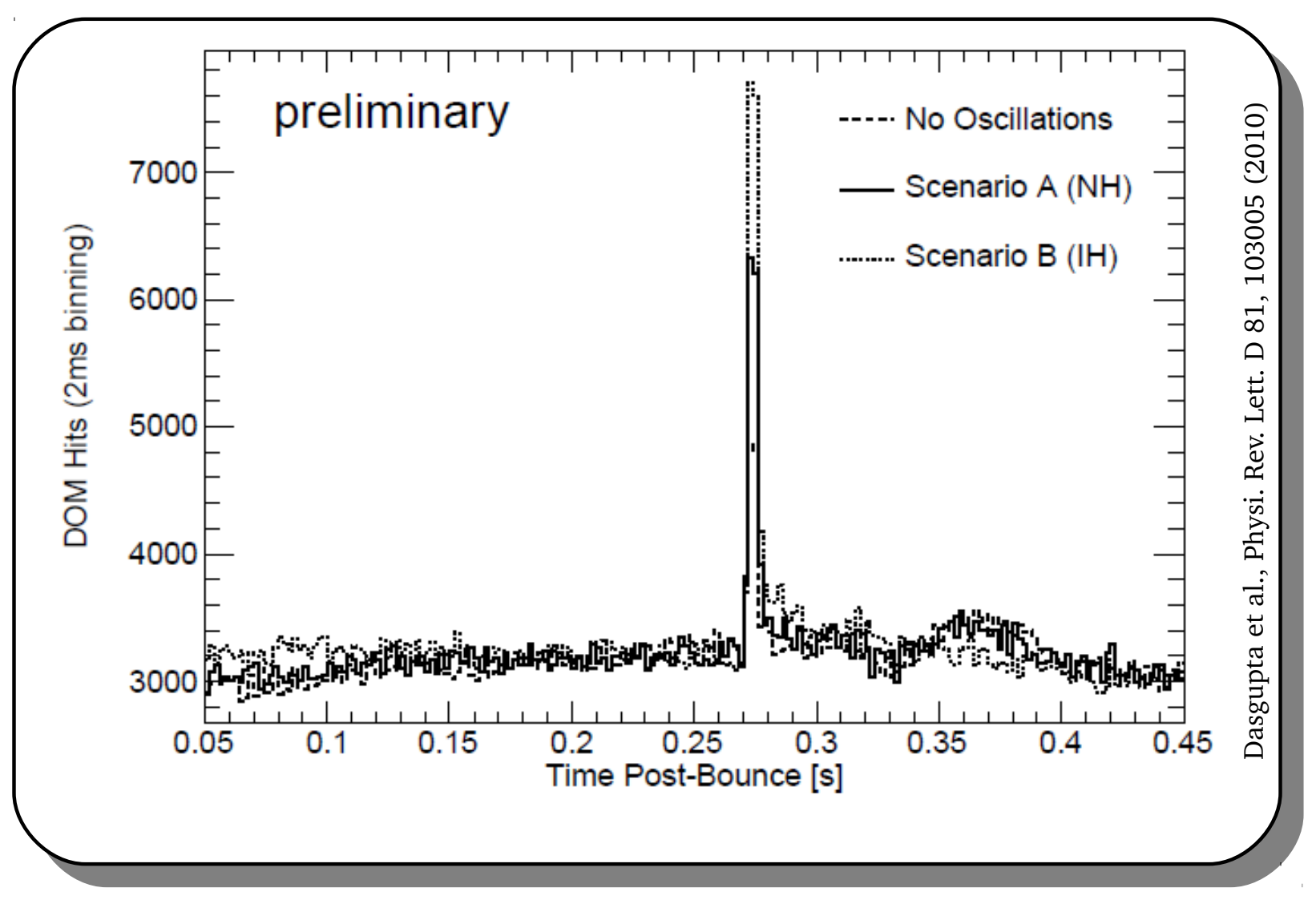
[T. Griesel PhD Thesis, ETAP, JGU Mainz, 2010]

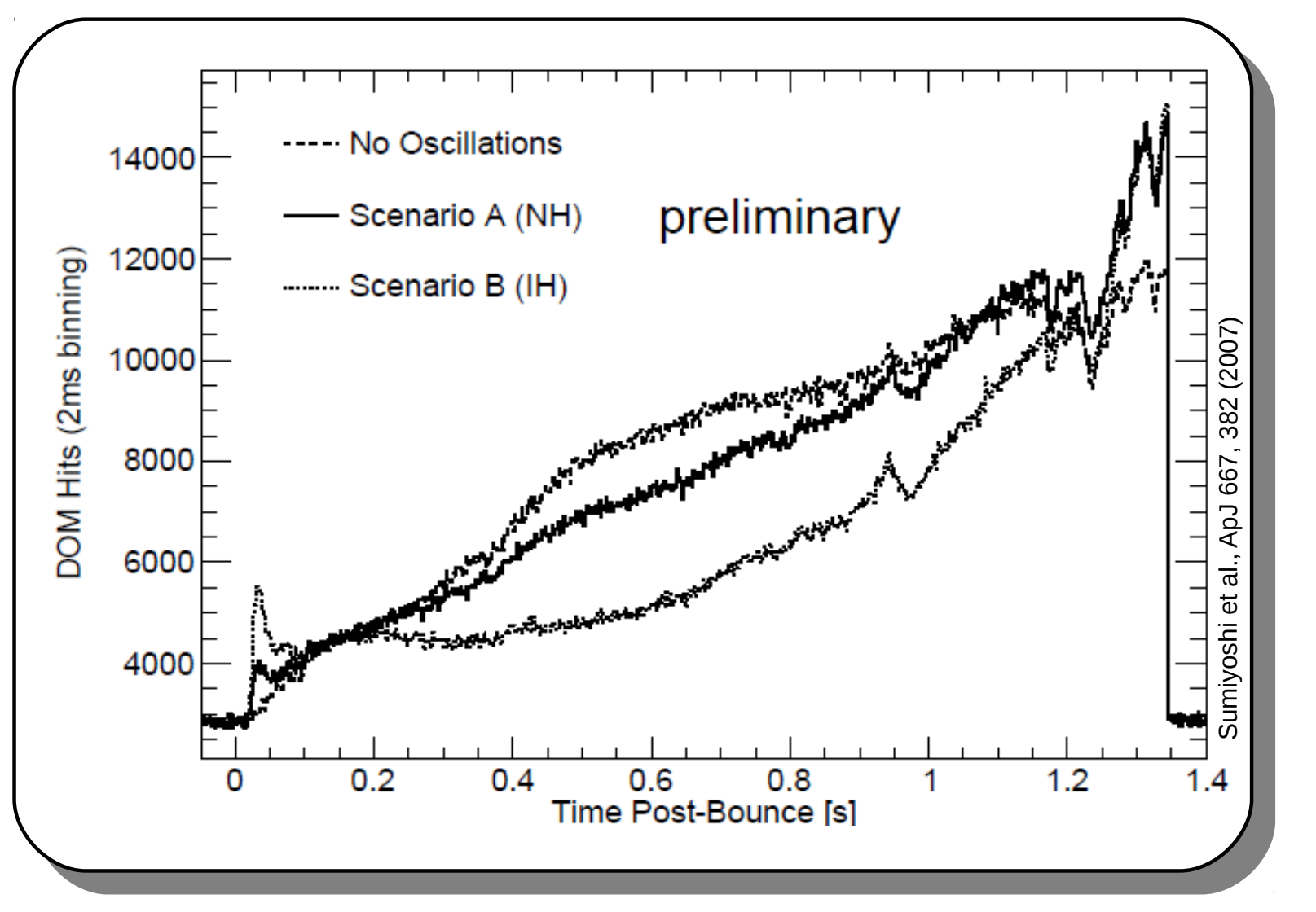
PHYSICS PERFROMANCE

Information about energy and direction of the incident neutrinos is difficult to reconstruct due to the short track-length of only a few cm. However, in the case of a supernova at the galactic center, IceCube's sensitivity matches that of a background free megaton-scale supernova search experiment and decreases to 20 and 6 standard deviations for star explosions at the galactic edge (30 kpc) and the Large Magellanic Cloud (50 kpc), respectively.



This plot addresses IceCube's sensitivity to the neutrino hierarchy problem. Since any oscillations of neutrinos depend on the squared neutrino mass it is not possible to predict the absolute mass of neutrinos but only to set limits .
These leads to an uncertainty in the hierarchy of the three neutrino mass eigenstates that build the neutrino flavor eigenstates via the *MNS*-matrix that includes all mixing angles and a CP-violating phase.
Regarding a Lawrence-Livermore modeled supernova in 10 kpc distance IceCube would see clear differences in signal shapes for normal mass hierarchy (Scenario A) and inverted hierarchy (Scenario B).





Another way to distinguish the two scenarios A & B is by using a different model that predicts a spike in the $\overline{\nu}_e$ flux at 257ms < t < 261ms after the onset of the neutrino emission (plot on the left). Height and shape of the peak are neutrino hierarchy-dependent. The two scenarios can be distinguished at 90% C.L. for supernovae in distances up to 30 kpc. Another simulation is based on model predictions for the formation of a black hole after the collapse of a 40 $M_\odot$ progenitor (plot on the right). In this case, electron neutrinos reach energies as high as 27 MeV and have a correspondingly large detection probability. Therefore they produce very clear evidence for the formation of the black hole after 1.3 s at higher than 90% C.L. regarding our Galaxy and the Magellanic Clouds.

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Lawrence Berkeley National Lab.
University of Kansas
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