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Шешуков Андрей Сергеевич

Анализ нейтринных взаимодействий для поиска сигналов от сверхновой

1.3.15 – Физика атомных ядер и элементарных частиц, физика высоких энергий

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ABSTRACT
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Actuality of the topic

The evolution of a massive ($M > 8\,\mathrm{M}_{\odot}$) main sequence star is expected to end in a gravitational collapse of the inner stellar core, leading to a violent supernova explosion of the remains of the outer stellar shells and the formation of a neutron star or a black hole. The physics of the core-collapse supernova (SN) is not yet fully understood despite many theoretical advancements. The modeling and understanding of the stellar dynamics involved in core-collapse supernovae events requires knowledge of the complex interplay between different physics processes including relativistic stellar magnetohydrodynamics, nuclear processes, and particle physics, which transition rapidly during the initial collapse of the star and the explosive expansion phases of the event. However it is expected that about 99 % of the gravitational collapse energy is emitted in a short burst of neutrinos, produced in the inner regions of the collapsing core within several seconds after the collapse. These neutrinos interact with the outer stellar shells driving the explosion phase and then propagate outside of the star, and can be observed on Earth in the neutrino detectors, providing the unique information about both supernova physics and neutrino physics.

Up to now the only measurement of the neutrino burst from supernova was the SN1987a event — a supernova in the Large Magellanic Cloud at 51 kpc distance from the Earth — when three neutrino experiments observed a total of 25 antineutrino interactions within 13 seconds [1, 2, 3]. This observation confirmed and constrained various supernova models, however the limited statistics didn't allow a thorough measurement. The optical signal of SN1987a explosion became visible only several hours after the neutrino burst detection, because the outer stellar shells are opaque for the photons but transparent for neutrinos.

This means that a detection of a future supernova neutrino signal can be used for two main purposes.

The energy spectrum, flavor composition, and time profile of this neutrino signal depend on the physics processes in the supernova as well as the neutrino properties, providing a unique opportunity to probe models and study effects that would otherwise be experimentally inaccessible [4]. Thus a measurement of the neutrino energy spectrum and time evolution of the neutrino flux are central to our understanding of these processes and will allow for more detailed models of the stellar dynamics to be evaluated.

On the other hand, the expected neutrino signals have common features across various models, allowing a robust supernova burst indication in real time. So the neutrino signal can be used as an early warning and pointing to supernova for additional measurements and analyses. It will allow astronomical observations of the early stages of the supernova, providing valuable information about the explosion process. Also such warning, if issued with low latency, can be used as a trigger for other detectors (including neutrino) to save their data for further joint analysis. Detected supernova neutrino signal can be used in multimessenger analysis: starting time and other parameters of the signal can enhance the efficiency of the template matching for gravitational wave searches.

Additionally, the nuclear burning processes in the late stages of stellar evolution (in particular the silicon burning phase) will produce a neutrino flux increasing in time for about a week prior to the core collapse. This so called "presupernova neutrino signal", if detected, can be used as an even earlier warning of the future supernova.

In order to achieve these goals many neutrino and dark matter detectors, potentially sensitive to neutrino signals from supernovae, implement dedicated supernova detection systems, designed to identify the presence of the supernova signal based on detected neutrino interaction candidates in one or many detectors. Such systems need to be stable and operate with low latency to stay in constant readiness for the next galactic supernova.

However the definition of "supernova signal observation" depends greatly on the experiment conditions and detection channels. A statistical analysis of the detected neutrino interactions is required to determine whether the observed portion of data contains supernova neutrino signal or is composed of the fluctuation of background events. Many neutrino experiments

[5, 6, 7] use a Counting Analysis (CA) — a simple significance evaluation using Poisson distribution based on the number of observed interactions in a sliding time window. While fast and robust, this method is suboptimal for the case of high background, because it doesn't take into account the features of the expected signal.

Goal

The goal of this dissertation is to develop a system for detection, selection and analysis of neutrino interactions in the neutrino detectors in search for signals from a core-collapse supernova, implement and deploy such system for the NOvA experiment, extend this approach for a combined analysis of data from several detectors within a SuperNova Early Warning System (SNEWS), and for the search of neutrino signals from final stages of the stellar evolution, prior to core-collapse supernova (presupernova neutrino signals).

In order to achieve this goal, the following **tasks** were completed:

1. Study the expected response of NOvA detectors for the main neutrino interaction channels from supernovae in the scintillator, taking into account the time and energy dependence of the neutrino flux. This required modifying the standard NOvA simulation chain (used for neutrino beam analysis) to simulate low-energy neutrino interactions, while preserving information about the time structure of the signal.

2. Build an algorithm for the reconstruction and selection of neutrino interactions from supernova explosions within the NOvA triggering system. Requirements for this algorithm are:

    - Processing speed: Data is processed in real time in the trigger system. This requirement limits the complexity of algorithms and imposes the use of the simplest selection methods.

  - Stability of operation in variable detector background conditions: neutrino beam switching, temperature changes, and noisy electron channels should not cause false alarms of the system.
  - The ability to process different fragments (time slices) of the data from the detectors independently of each other in parallel running processes.

3. Create an infrastructure to run the neutrino interaction selection algorithm and collect its results. The infrastructure uses existing subsystems of the experiment: a system of software triggers (Data-Driven Triggers, DDT), performing basic reconstruction of events in real time, and a central trigger node (Global Trigger). Infrastructure requirements:
   - Stability and reliability of data transfer from thousands of parallel DDT processes to the single GlobalTriger node.
   - Sorting of the received data in the GlobalTrigger buffer for further statistical analysis.
   - Handling the cases of data loss, unstable background conditions, etc.

4. Develop a statistical analysis method to determine the presence of a signal from a supernova in the data stream from the detector, as well as to determine the starting time and the significance of this signal. The method should ensure the sensitivity of the NOvA detector to a supernova at a distance of 10 kiloparsecs (the approximate distance to the center of the Milky Way) with an average false alarm rate of about 1 in 7 days (as one of the conditions for subsequent use within the SNEWS system). The task is complicated by the high background level in the NOvA far detector, due to its location on the surface and its exposure to the cosmic rays, so the method of counting neutrino interactions in a fixed time window (Counting Analysis) used by other experiments is unsuitable.

5. Analyze the sensitivity of the NOvA experiment to the neutrino signal from the supernova explosions using the event selection algorithms and the statistical method of data processing developed in the previous tasks. Estimate the fraction of supernova candidate stars, the signal from which can be detected in the NOvA experiment.

6. Deploy the developed supernova detection system on the NOvA detectors, and test the stability of its operation. Since the resulting system is closely related to the complex process of detector data acquisition for various physical measurements, the stability requirements are particularly important: a failure in the supernova detection system could potentially disrupt the acquisition of the neutrino beam data for the main NOvA oscillation analyses.

7. Prepare the NOvA supernova detection system for integration into the SNEWS global network:

    - Separate the statistical analysis part into an independent software process. This would allow modifying and restarting the algorithms without stopping the main system of experiment data acquisition.
    - Provide a mechanism to send an alert to SNEWS when a supernova signal of sufficiently high significance is detected.

8. Apply the developed statistical method for the search of signals from the final stage of star evolution a few days before the supernova (presupernova neutrino signals). Since NOvA detectors are insensitive to this signal, the experiments with low background and sensitivity to low-energy neutrinos are considered: Borexino, KamLAND, SK-Gd. It is necessary to:

    - Estimate the signal detection range and time before the supernova for these detectors individually and in the case of detectors combinations, using the developed statistical method, which takes into account the signal shape.

- Compare the results of the method with the standard approaches used in the analyses of these experiments.

Scientific novelty

1. The developed algorithms and the system for supernova neutrino detection in the NOvA experiment were created for the first time. Previously, the NOvA experiment did not have a procedure and a framework for analyzing interactions of low-energy neutrinos.
2. The proposed method of statistical processing of neutrino events to search for a signal with a given time profile has not been previously formulated and has not been used to search for neutrinos from supernovae.
3. For the first time, the sensitivity of the NOvA experiment to the neutrino signal from a supernova was calculated with consideration of the measured background level and the efficiency of signal selection. Previous estimates were based only on the expected number of neutrino interactions.
4. The proposed statistical method was applied to the case of a presupernova neutrino signal for the first time. Also, for the first time the sensitivity for a combined network of experiments detecting such a signal was evaluated.
5. The detection system launched on the NOvA detectors has been connected to the SNEWS global network for searching neutrinos from supernovae. Previously, the NOvA experiment could only receive alerts from this network; now the results of the NOvA supernova search can be automatically sent to SNEWS to combine with data from other neutrino experiments and provide an early warning to the astronomical community about a supernova burst.

Practical relevance

1. The NOvA experiment plans to collect data until 2026. In the event of a supernova explosion in our galaxy, the developed system will allow the data corresponding to the neutrino signal from the supernova to be recorded for further thorough analysis.
2. The data selected and stored by the developed system are used for additional analyses, namely, the search for anomalies coincident in time with the gravitational wave signals detected by the LIGO/Virgo collaboration [8, 9].
3. The modules for data analysis and background suppression developed and running in the NOvA software trigger environment can also be applied to other NOvA tasks: monitoring the readout electronics channels condition, extracting different components of the background activity in the detector. Application of these modules, for example, to the task of searching magnetic monopoles in NOvA [10] will reduce the background level and increase the speed and efficiency of real-time event processing.
4. The developed method of statistical analysis and combination of signals from different detectors is universal and applicable for the real-time data processing. This method can be applied in other experiments separately as well as for the joint analysis within the SNEWS2.0 network.
5. Incorporating NOvA into the SNEWS2.0 network will increase the likelihood of detecting a neutrino signal from a galactic supernova in the future.

Main points of the defense

1. A procedure for reconstruction and selection of neutrino interactions from supernovae in the Far and Near detectors of NOvA experiment

has been developed.

This procedure allowed to reduce the background level from from about 75×10^6 hits/s to 2500 cands/s for the Far Detector and from about 7×10^5 hits/s to 0.52 cands/s for the Near Detector, leading to signal to noise ratio of 1 : 29(Far Detector) and 2.5 : 1(Near Detector) for the first second of the signal from $9.6\,M_\odot$ progenitor supernova at the distance of 10 kpc.

2. A dedicated statistical Shape Analysis method was developed and applied for detecting neutrino signals from a supernova.

   The method makes is applicable both for individual detectors and for the mode of joint detection in several detectors or experiments in real time or with minimal delay.

   For the NOvA case, the method increases the maximum range of supernova detection by 1-1.5 kpc (for different supernova models) compared to the standard Counting Analysis approach. The combined mode of near and far detectors will increase the detection range by another 1-1.5 kpc, compared to the individual detectors more.

   The advantages over the standard event counting method are retained even when a simplified analytical waveform is used.

   The software package that implements the developed statistical method is publicly available and is ready to be used in other experiments [11].

3. A supernova detection system based on NOvA detector data was created and launched, based on the developed reconstruction and selection procedures and statistical processing method.

   NOvA is sensitive to the neutrino signal from a supernova at up to 6.2 kpc for a star with a mass of $9.6\,M_\odot$ and up to 11.2 kpc for a star with a mass of $27\,M_\odot$. The system has a maximum signal detection latency of 60 s. The system has been running on the NOvA near and far detectors since November 1, 2017. The triggering events of the system have been studied and are in line with the expected false alarm rate due to statistical background fluctuations.

4. Integration of the NOvA experiment into the global supernova search system SNEWS. The NOvA experiment is a full member of the network and is capable of sending supernova alerts to the SNEWS network. The existing infrastructure is optimized for future modifications that will be required in the development of SNEWSv2.0. The low latency of the NOvA supernova triggering system reduces the overall latency of SNEWS network for detecting the supernova signal.

5. The developed statistical method has been applied to search for the presupernova neutrino signal. The sensitivity to such a signal for detectors KamLAND, Borexino and SK-Gd and their combinations is estimated.

   Shape analysis method gives advantages over the standard method of counting events in the time window: in the range of detection and in the time from the detection of the neutrino signal to the beginning of the collapse of the supernova core.

   For the KamLAND experiment and the significance threshold of supernova detection at 5 sigma: the maximum detection range increases by 20–60 pc and the time from detection to supernova outburst at 200 pc increases by 30–120 minutes, depending on the signal model.

   The feasibility of using a combined analysis for several experiments was shown: the overall sensitivity of the system increases even when adding an experiment with relatively low sensitivity. For example, for one of the considered signal models, the time from detection to supernova flare for the KamLAND+Borexino system is 500 min, significantly larger than the 239 min (KamLAND) and 21 min (Borexino) for these experiments separately.

Reliability

The reliability of the results obtained is supported by the following:

1. The developed method of statistical analysis taking into account the signal shape is equivalent to the standard method of counting events in the time window, if we use a constant value within a given window as the signal shape. In this case the statistical distributions and the obtained significance of the signal observation fully coincide with the expected one described by the Poisson distribution for the number of signal and background events.

2. The NOvA supernova detection system operation was analyzed for the period from October 1, 2018 to August 15, 2019, in order to study the system stability. During this period, three bursts of false positives associated with detector malfunctions were detected. The remaining 47 system alarms during this time correspond to statistical background fluctuations and are in accordance with the designed false alarm rate (1 event per week).

Approbation of the work

The main results of this work were reported in the international conferences, workshops and seminars:

1. “Supernova neutrino detection in NOvA experiment” (poster), 27th International Conference on Neutrino Physics and Astrophysics (Neutrino 2016), London, Unighted Kingdom, July 2016

2. “Detection of the galactic supernova neutrino signal in NOvA experiment” (poster), 35th International Cosmic Ray Conference (ICRC 2017), Busan, South Korea, July 2017

3. “Trigger system and detection of Supernova in the NOvA experiment” (talk), 26th Symposium on Nuclear Electronics and Computing (NEC 2017), Budva, Montenegro, September 2017

4. “Detection of Galactic Supernova Neutrinos at the NOvA Experiment” (poster), 28th International Conference on Neutrino Physics and Astrophysics (Neutrino 2018), June 2018
5. “Supernova neutrino signal detection in the NOvA experiment” (talk), Workshop on Statistical Issues in Experimental Neutrino Physics (PHYSTAT-nu 2019), CERN, Switzerland, January 2019
6. “Supernova triggering and signals combination for the NOvA detectors” (talk), SNEWS 2.0 workshop: Supernova Neutrinos in the Multi-Messenger Era, Sudbury, Canada, 2019
7. “Detecting neutrinos from the next galactic supernova in the NOvA detectors” (talk), Conference on Neutrino and Nuclear Physics 2020 (CNNP2020), Cape Town, South Africa, Febaruary 2020
8. “Galactic Supernova Neutrino Detection with the NOvA Detectors” (poster), 29th International Conference on Neutrino Physics and Astrophysics (Neutrino 2020), online, June 2020
9. “NOvA in 10 minutes” (talk), Conference for young researchers in the Fermilab community (New Perspectives 2020), online, July 2020
10. “SuperNova Early Warning System v2.0” (poster), 6th International Conference on Particle Physics and Astrophysics (ICPPA 2022), November 2022

Personal contribution

The author of the thesis directly performed the work described in the thesis: development of methods, construction of software architecture and implementation, the deployment and maintenance of the system on the NOvA detectors; and obtained the results presented for the defense. The content of the thesis and the main statements presented for the defense reflect the author’s fundamental personal contribution to the published works.

Publications

The main results of this thesis are presented in 5 publications, three of which [12, 13, 14] are the papers published in the journals indexed by Scopus, Web of Science, and RSCI, and two [15, 16] are conference proceedings.

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Layout of the thesis

The dissertation consists of introduction, 7 chapters, conclusion, bibliography, lists of figures and tables. It contains 123 pages with 24 figures and 10 tables. Bibliography contains a list of 70 entries.

The **Introduction** chapter describes the actuality and scientific novelty of the research goals of this dissertation, formulates the tasks, presents the main results of this work and justifies their practical relevance and reliability of the obtained results.

Chapter 1. Core-collapse supernova process

This chapter reviews the physics of the core collapse supernova process.

The evolution of the main sequence star for most of its lifetime is governed by the processes of hydrostatic burning of nuclear elements in the central region of the star, where the temperature and density are maximal. This burning process produces heavier elements from the lighter ones and forms a new stellar core, composed of the heavier elements.

The star evolution passes through several phases starting from burning hydrogen and up to forming a core from iron group elements after the silicon burning phase.

These processes produce a neutrino flux which has luminosity L_ν and mean energy $\langle E_\nu \rangle$ slowly growing with time as the star passes through the burning phases and increases the core temperature and pressure. During the final silicon burning phase average energies grow to several MeV and this signal can be detected by neutrino experiments with a sufficiently low energy threshold, if the distance is not too far (up to 1 kpc) several hours before the core collapse.

After the silicon is depleted in the core during the last burning phase, the newly formed iron core starts contracting. If the iron core mass exceeds the Chandrasekar limit $M_{Ch} \approx 1.44 M_{\odot}$ the electron gas pressure cannot stabilize the core and the core experiences gravitational collapse.

As a result of the neutrino emission processes, a core-collapse supernova neutrino signal is formed of around 10^{58} neutrinos during the first seconds after the explosion. These neutrinos carry away about 99% of the gravitational binding energy released by the collapse and play a crucial role in the explosion mechanism of the star [17]. In particular, during the first 10 ms of the supernova, when the stellar core collapses to a neutron star, 1% of the total neutrino flux is produced as electron neutrinos due to the neutronization process. The enormous neutrino density interacts with the collapsing matter to power the shockwave that triggers the supernova explosion.

In this work we use the neutrino flux from the simulations by the Garching group [18] for two progenitor star masses of 9.6 and 27 solar masses (see figure 1), which the Garching group have chosen as representative of typical low- and high-mass supernovae. We do not consider complex effects of neutrino oscillations or self-interactions for purposes of more straightforward comparisons to other detectors, and take into account only adiabatic MSW effect to describe its effect on the triggering.

For the presupernova signals we consider the adiabatic MSW effect for the three presupernova neutrino simulations [19, 20, 21].

Chapter 2. Supernova neutrinos in NOvA detectors

The second chapter starts with the description of the NOvA detectors, data acquisition and data driven triggering system used in the NOvA experiment.

NOvA is a long-baseline neutrino oscillation experiment [22] using a pair of functionally identical liquid scintillator highly segmented calorime-

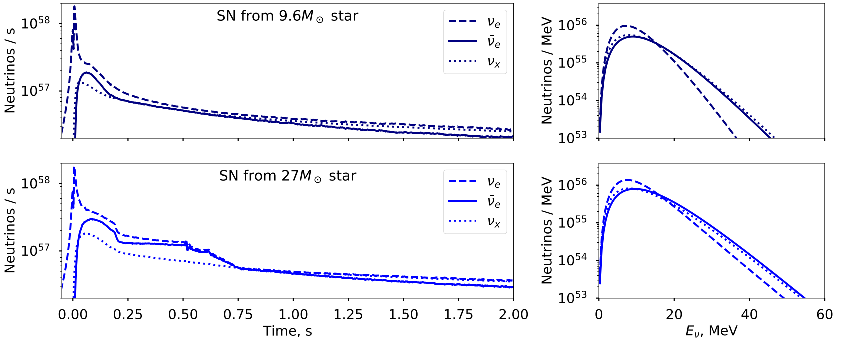

Figure 1: Expected neutrino production vs. time (left) and energy (right) from collapsing stars with a mass of 9.6 $M_\odot$ (top) and 27 $M_\odot$ (bottom), from the simulation by the Garching group [18]. This simulation does not include flavor changing effects such as neutrino oscillations and collective effects.

ters to study electron neutrino appearance in the primarily muon neutrino NuMI beam [23] with a central energy of about 2 GeV. The 14 kt Far Detector (FD) is located on the surface at the Ash River site in northern Minnesota, USA and is shielded by a concrete roof topped by an additional 15 cm of barite stone. The approximately 300 t (193 t active mass) Near Detector (ND) is situated 100 m underground at Fermilab, 1 km from the beam source. A schematic view of the NOvA detectors structure is shown on figure 2.

Scintillation light is collected and transported out of each cell via a loop of wavelength shifting fiber. This light is detected by an avalanche photodiode (APD) and the signal digitized by high speed readout electronics. The aquired data stream is broken into 5 ms time windows, which are stored in RAM buffers within the Data Acquisition System (DAQ).

The real-time examination of buffered data is performed by a dedicated software Data Driven Trigger (DDT) system. This modular and configurable system allows to perform a search of various signatures and issue

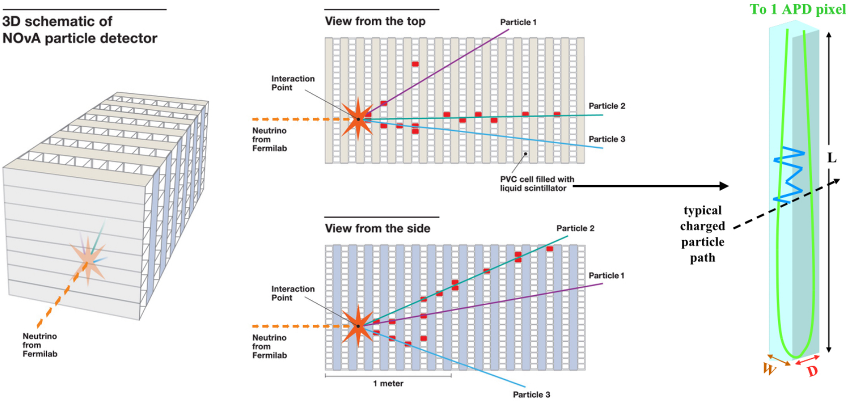

Figure 2: Schematic view of the NOvA detectors structure viewed in 3D (left) and in separate projections (middle), and the scheme of a single polyvinyl chloride (PVC) cell (right) with the wavelength shifting fiber loop, that collects the scintillation light and transports it to the avalanche photodiode (APD) for readout.

the trigger signals if a signature is found.

When the DDT system identifies a signature of interest, it designates a time window of data to record. Figure 3 shows the scheme of the data driven triggering on the NOvA detectors, and the software components and processes performing in the data taking.

Note that since each individual DDT process analyzes only a 5 ms slice of detector data, it can only perform a search for short signals. For detection of the supernova neutrino signal, which has a time scale of about 10 seconds, this system cannot be used directly.

The observation of the neutrino signal from a core-collapse supernova is highly dependent on the detector's technology and composition. For the NOvA case the prominent channels for observation of neutrinos in the tens of MeV range are inverse beta decay (IBD), elastic scattering on electrons, and neutral current interactions on carbon. These signatures, as observable in NOvA, are described in the following sections and summarized in table 1.

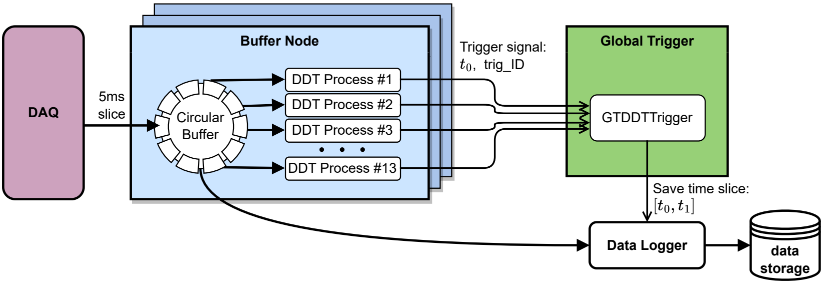

Figure 3: Schematic view of the DDT system deployed on the near and far NOvA detectors.

Interaction channel	Far Detector		Near Detector	
	9.6 M$_\odot$	27 M$_\odot$	9.6 M$_\odot$	27 M$_\odot$
Inverse beta decay	1593	3439	24	51
Elastic scattering on e^-	143	259	3	5
Neutral current on ^{12}C	67	166	1	3
Total	1803	3864	28	59

Table 1: Estimated average number of neutrino interactions in the NOvA detectors for dominant interaction and detection channels for Garching supernova neutrino flux simulations from $9.6\,M_\odot$ and $27\,M_\odot$ progenitor stars at a distance of 10 kpc.

Chapter 3. Selection of supernova neutrino interactions in NOvA

This chapter describes the procedure for search and selection of neutrino interactions in NOvA detectors.

Each neutrino interaction channel under consideration results in an observable signal from a low energy electron, positron, or photon. Identifying these low energy signals is challenging in both the Near and Far NOvA detectors. IBD positrons from a supernova have detectable energies of 10–30 MeV and induce only 1–4 hits in the scintillator cells.

The difficulty of detecting low energy interaction hit clusters is further compounded by the high rates of background activity in the NOvA detectors.

The first step for a trigger trying to find low energy clusters consistent with neutrino interactions from a supernova is thus to remove hits from other physics processes: atmospheric muons, Michel electrons and high energy atmospheric showers, or readout noise.

The hits remaining after the removal of background activity potentially belong to low energy neutrino interactions. The identification of these interactions requires a multi-stage process of hit clustering and pattern recognition which form the interaction candidates. As a result of the clustering algorithm the total noise rate is further suppressed by a factor of 240 from 56.3 MHz to 232 kHz.

Table 2 summarizes the additional cuts on total amplitude (in ADC counts) and fiducial volume, applied to each cluster to be considered a neutrino candidate.

Cut	Near Detector	Far Detector
ADC range	$[280, 1430]$	$[230, 910]$
Fiducial volume	$8 \leqslant \text{X cell} \leqslant 88$ $8 \leqslant \text{Y cell} \leqslant 88$ $8 \leqslant \text{Z plane} \leqslant 184$	$16 \leqslant \text{X cell} \leqslant 368$ $16 \leqslant \text{Y cell} \leqslant 360$ $8 \leqslant \text{Z plane} \leqslant 888$

Table 2: The selection criteria cuts for neutrino interaction candidates.

Applying the described selection procedure, we can estimate the detection efficiency using a simulated sample of positrons uniformly distributed within the detector and with random directions. This allows the calculation of the efficiency of detecting an individual positron as a function of positron energy, as shown in figure 4. This produces a signal to noise ratio of 1:29 at the FD and 2.5:1 at the ND for a simulated 9.6 $M_\odot$ supernova at 10 kpc.

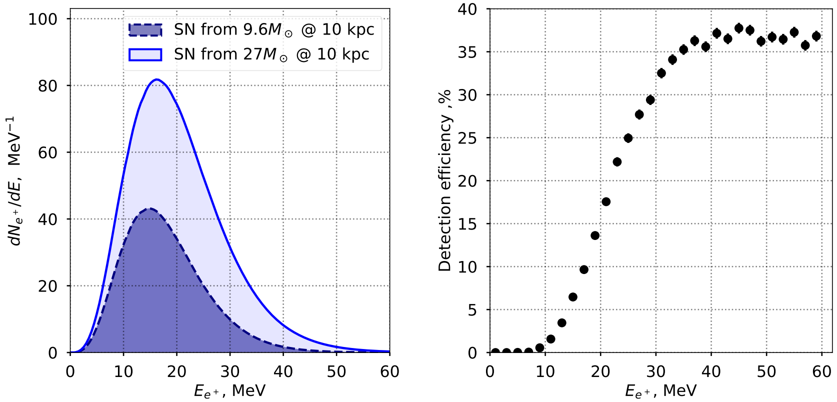

Figure 4: Positron spectrum from simulated supernova neutrino IBD interactions in the Far Detector (left) and efficiency of positron detection as a function of positron energy (right)

As we have shown the developed procedure allows to separate the signal events, however because of low overburden of NOvA detectors the remaining background rate is still quite high. At this stage, most of the obvious non-SN related candidates have been removed. The methods used here are simple and robust, because this procedure has to be applied in real time to all the data incoming from the detector, to produce time series with the neutrino interaction candidates rate for every 5 ms time slice.

Chapter 4. Shape analysis method

In this chapter we approach a general problem of statistical analysis of the time series (individual events with time stamps) in search of a signal of specific time profile but of unknown location and amplitude.

We propose the Shape Analysis (SA) and compare it to a common Counting Analysis (CA) method used for searching for supernova signals in many low-background experiments [24, 25, 26].

Consider an experiment that measures timestamps of individual neutrino interaction candidates $\{t_i\}$. To discriminate between two hypotheses, H_0 (background only) and H_1 (background + supernova), one has to define a *test statistic* as a function of the incoming data: $\ell(\{t_i\})$.

The significance of observing deviations from the null hypothesis H_0 using the test statistic ℓ is defined by the tail of the distribution:

$$p(\ell) = \int_{\ell}^{\infty} P(\ell'|H_0)\, d\ell'. \tag{1}$$

For convenience this can be converted to a z-score, defined as

$$z(\ell) = \Phi^{-1}(1 - p(\ell)), \tag{2}$$

where Φ is the cumulative standard normal distribution function.

The most common approach for detection of supernova (and presupernova) neutrinos is to count the number of events n within a time window $[t^*, t^* + \Delta t]$, where t^* is the assumed supernova starting time, and use it as the test statistic.

A more efficient discrimination between signal and background hypotheses can be achieved by taking into account the shape of the expected signal and background rates over time. While we avoid using the curve fit procedure with many signal parameters, it's possible to maximize the discrimination for a specific signal model by using the log likelihood ratio [27] for hypotheses H_0 and H_1 as the test statistic function:

$$\ell_{SA}(t^*, \{t_i\}) = \log \frac{P(\{t_i\}|H_1)}{P(\{t_i\}|H_0)} = \sum_i \log\left(1 + \frac{S(t_i - t^*)}{B(t_i)}\right), \tag{3}$$

where $B(t)$ is the background event rate, and $S(t)$ is the expected signal event rate over time, relative to supernova start time t^*.

In case of multiple experiments each using their own test statistic functions $\{\ell_n(t)\}$, their combination is nontrivial.

However, if each of ℓ is a log likelihood ratio $\ell(t) = \log \frac{P(t|H_1)}{P(t|H_0)}$ and all the experiments use the same hypotheses H_0 and H_1, these values are additive:

$$\ell_{comb} = \sum_{n=1}^{N_{exp}} \ell_n(\{t_i^n\}) = \sum_{n=1}^{N_{exp}} \sum_{i} \ell_n(t_i^n),$$

where N_{exp} is number of experiments to combine.

The shape analysis method described above is implemented as a python package and is available at [11]. Computationally the shape analysis method is more complicated than the counting analysis, which relies only on the Poisson distribution. However, the calculation of the test statistic distribution needs to be done only when the background level (or expected signal) has changed, so in practice these reevaluations can be done with large time intervals, leading to a smaller computational load and latency on average.

Figure 5 shows an example of such computation for an experiment with a background rate $B = 0.1\,\text{event/s}$ and a signal with total expected $\int S(t)dt = 3\,\text{events}$, injected at time $T = 0$.

We described an advanced method of real-time detection of a particular neutrino signal based on accounting for the signal's expected time profile. The proposed Shape Analysis uses the log likelihood ratio as a metric for the hypothesis discrimination. This metric provides a pronounced enhancement of signal significance with respect to the commonly used Counting Analysis (CA), as seen on the provided example. It also allows a fast and easy way to combine measurements of different detectors for a joint significance calculation.

Chapter 5. Supernova neutrino triggering system in NOvA

This chapter describes the implementation of the real time system for the supernova detection in NOvA, using the selection procedure described in chapter 3 and statistical method from chapter 4. The work and results described in this chapter were published in [12] and [14].

The supernova trigger system in NOvA is implemented as an extension of a standard DDT infrastructure: parallel processes perform the reconstruction and search of the supernova neutrino interaction candidates, and send the calculated candidate rates to the Global Trigger node, where the

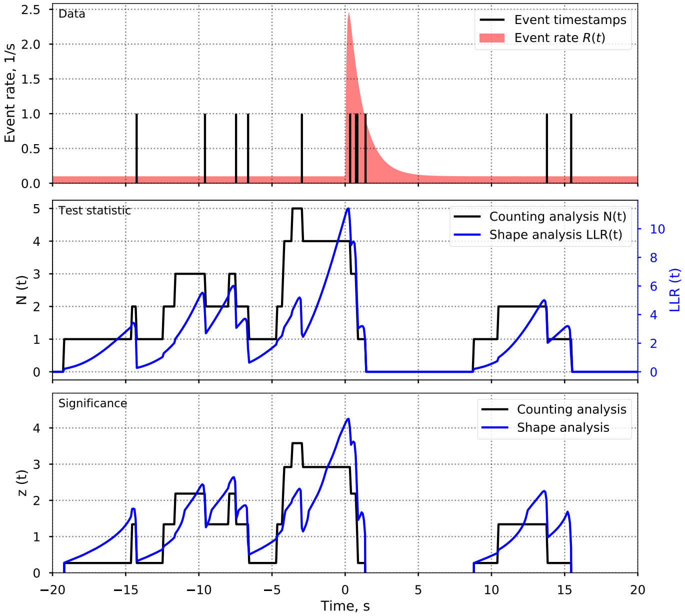

Figure 5: Example of applying the shape analysis and the counting analysis methods to a set of measured events. The top panel shows the expected event rate over time (filled area) and sampled events timestamps (vertical lines). The middle panel plots test statistic values vs. assumed time of the supernova for both methods: number of events N(t) for CA, and log likelihood ratio LLR(t) for SA. The bottom panel shows the calculated significance of the expected signal starting at each time.

significance of the supernova observation is calculated using the shape analysis method described in chapter 4.

When the significance exceeds a threshold set within the trigger system, a trigger signal is generated which causes the DAQ system to initiate the recording of a 45 s time window around the region of interest. This region captures the supernova neutrino burst and activity both prior and subsequent to it, where the intervals are intended to yield a pre-sideband and a trailing tail that can extend out to black hole formation.

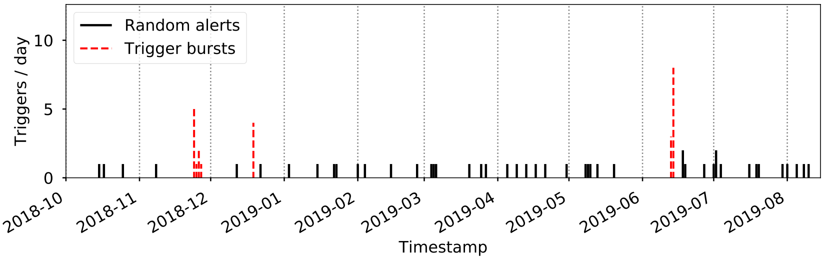

Figure 6: Time distribution of NOvA SN triggers issued by the system on the Far Detector during the commissioning period. Red dashed lines show trigger bursts associated with unstable detector or readout conditions.

The significance threshold for this trigger process has been set to balance the trigger efficiency for detection of a supernova event with the false positive rate resulting from Poisson variation in the detector's activity.

The delay of the supernova triggering system was measured on both detectors and is 40-60 s for the Far Detector and 5.7 s for the Near Detector.

During the 318 day commissioning period from October 1, 2018 to August 15, 2019, the NOvA Far Detector triggering system issued 71 supernova triggers. Each trigger requests the data readout within 45 s. The time distribution of the issued triggers is shown in figure 6.

Out of the observed 71 supernova triggers, 24 were concentrated in three trigger bursts. These bursts were caused by readout instabilities. The remaining 47 supernova triggers during the commissioning period are considered to be the result of the expected random background fluctuations. Their average rate of $1/(6.77 \pm 0.98\,\text{days})$ is in agreement with the expected one trigger per week.

During this period, there has been neither an optical observation nor a neutrino based observation from other experiments of a Milky Way supernova that is coincident with these triggered events. We have found the triggering rate to be consistent with expected statistical fluctuations in the detector backgrounds and with periods of known instability in the detector readouts.

Chapter 6. The NOvA experiment's sensitivity to supernova

This chapter shows the resulting sensitivity of NOvA experiment to the detection of the galactic supernova. This sensitivity is calculated using two approaches.

First in section 6.1 the detection sensitivity for each detector separately based on the trigger system described in chapter 5 is evaluated with a strict significance cut $z_0 = 5.645\,\sigma$, corresponding to one false alarm per week, as required by SNEWS system.

The next section 6.2 shows the capabilities of the NOvA as a two detector system with less restrictions, thus the sensitivity calculations are done for the less strict threshold of $z_0 = 5\,\sigma$, and the combination method is used. Moreover we study the stability of the methods used for the detection with respect to the expected and received signal shape, using expected signals for various neutrino hierarchies and a simple analytic approximation of the signal. The results presented in this chapter were published in [12, 13].

After the parallel DDT processes have performed searches for IBD interaction candidates, data on the candidate rate per 5 ms are sorted and accumulated in a time series $\{t_i, n_i\}$. In order to decide if this time series contains a signal from a supernova, we apply the Shape Analysis (SA) method, described in chapter 4 to calculate the test statistics ℓ_{SA} for the incoming data, assuming different values of the signal start time t^* and calculating the significance score z.

If the significance score exceeds threshold $z_0 = 5.645\,\sigma$, the trigger signal is sent. This threshold corresponds to the average rate of one false trigger from background fluctuations per week, the target rate for SNEWS input.

During the trigger system operation the background level B is estimated at the end of every ten minutes period based on the activity in this period. Thus the triggering system can adapt to slow changes in background conditions, maintaining the same false alarm probability: this does not appreciably change the supernova sensitivity. Sudden background changes on timescales less than ten minutes can cause the false trigger alarms, as observed during the commissioning. Large background changes are indicative of detector problems, and quickly fixed lest all of NOvA's analyses be degraded.

The operational trigger system uses the expected signal shape from the 9.6 $\mathrm{M}_\odot$ model to make its decision, as it represents the most general features of the supernova neutrino signal.

NOvA supernova triggering system with the current setup has a 22.6% and 49.2% chance to detect the next galactic supernova from 9.6 $\mathrm{M}_\odot$ and 27 $\mathrm{M}_\odot$ progenitor stars, respectively, assuming the same spatial distribution for both progenitor masses.

Table 3 summarizes the results of the calculation of the expected NOvA reach, assuming a lower detection threshold $z_{thr} = 5\,\sigma$ and detection efficiency $\varepsilon = 50\,\%$, for various signal models and depending on the applied analysis. This calculation shows that using the shape analysis for individual detectors allows detection about 1 kpc further than counting analysis. An additional increase of about 1 kpc is achieved by applying the combined shape analysis.

We have shown that the Shape Analysis approach provides a better sensitivity and time precision than the Counting Analysis method. Even for the case when the expected signal shape is different from the actual signal in the data the advantages of the Shape Analysis remain true.

Metric	Model	Near detector		Far detector		Far+Near
		CA	SA	CA	SA	Joint SA
d, kpc	$27M_\odot$ IH	7.08	8.58	10.13	11.27	12.36
	$27M_\odot$ NH	7.56	8.70	10.80	11.81	12.85
	$9.6M_\odot$ IH	5.03	6.10	7.17	8.02	8.80
	$9.6M_\odot$ NH	4.50	5.47	6.38	7.18	7.89
z_{mean}	$27M_\odot$ IH	2.88	3.95	5.12	6.24	7.47
	$27M_\odot$ NH	2.88	4.05	5.82	6.87	8.06
	$9.6M_\odot$ IH	1.30	2.29	2.58	3.00	3.95
	$9.6M_\odot$ NH	1.30	1.92	2.04	2.30	3.20

Table 3: Comparison of the distance and significance metrics using CA and SA for individual detectors, and then using a combined shape analysis (Joint SA). Metrics are: maximal supernova distance, where the detection efficiency exceeds 50 % (top part), and value for z_{mean} expected for supernova distance 10 kpc (bottom part). Models correspond to various progenitor star masses and neutrino mass hierarchies.

Chapter 7. Presupernova neutrino signal

In this chapter we consider the application of this method to detection of a presupernova neutrino signal.

As described in section 1.1, presupernova neutrinos are emitted in the late stages of stellar evolution as the degenerate core of the star becomes hot enough that the dominant cooling mechanism is neutrino emission, producing a flux which gradually increases with time for several days up to the moment of the core collapse.

To probe how the choice of models might effect the calculations, we consider several predictions of the presupernova neutrino flux: the calculations by Odrzywolek [19], Patton et al. [20] and Kato et al. [21] for a 15 $M_\odot$ progenitor star.

Results of this chapter were presented in the publication [13].

As in the case of the core-collapse supernova neutrino burst, the presupernova neutrinos can be detected by various neutrino and dark matter experiments in several interaction channels [28]. Here we will limit our consideration to inverse beta decay (IBD) channel in three experiments: KamLAND, Borexino and Super-Kamiokande with Gadolinium (SK-Gd).

The detection efficiencies of the considered detectors vs. anti-neutrino energy E_ν, as well as presupernova anti-neutrino energy spectra in the considered models, are depicted in figure 7. Figure 8 shows the resulting presupernova event rates versus time expected in the KamLAND experiment for the models considered in this work.

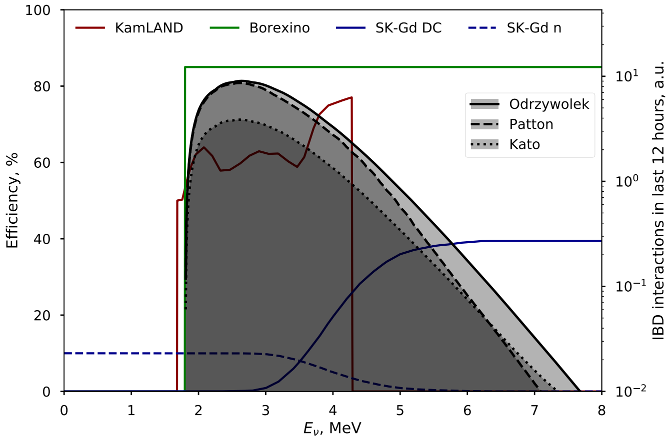

Figure 7: IBD detection efficiencies vs. $\bar{\nu}_e$ neutrino energy for various experiments and detection modes (solid and dashed lines), compared to the expected $\bar{\nu}_e$ spectra in last 12 hours before the supernova for the three models considered (shaded regions).

It is shown shown that Shape Analysis method is suitable for the searches of the signals different from the core-collapse neutrino burst.

Applied to the detection of the presupernova neutrino signal in KamLAND, Borexino and SK-Gd, the shape analysis gives advantages over the standard method of counting events in the time window: in the range of

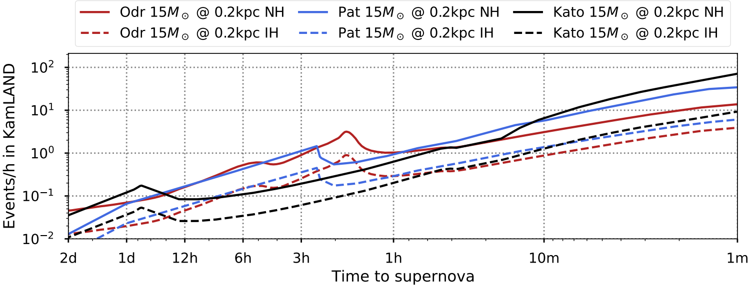

Figure 8: Expected event rates from a presupernova signal in the KamLAND detector. Three flux models and two neutrino mass hierarchies are considered for a progenitor mass $M_\odot = 15\,\mathrm{MeV}$ at a 200 pc distance.

detection and in the time from the detection of the neutrino signal to the beginning of the collapse of the supernova core.

For the KamLAND experiment and the significance threshold of supernova detection at 5 sigma: the maximum detection range increases by 20–60 pc and the time from detection to supernova outburst at 200 pc increases by 30–120 minutes, depending on the signal model, compared to the standard counting analyses used in this experiment.

As the results of the shape analysis depend on the chosen signal model, the highest significance is reached in the case of a model corresponding to the actual detected signal. However, since (pre)supernova signal shapes share common features, even a wrong choice of the model gives a better sensitivity reach compared to the counting analysis.

Joint analysis of the detectors provides an additional improvement of the presupernova signal detection efficiency. Figure 9 shows the regions with 90 % efficiency for separate shape analyses and their combinations. Including of the analyses with low sensitivity to the presupernova signal, such as Borexino or SK-Gd neutron mode, still increases the combined reach.

For example, for the considered signal model, the pre-supernova signal detection for the KamLAND+Borexino system can be done 500 minutes prior to the core collapse, which is significantly larger than the 239 min (KamLAND) and 21 min (Borexino) for these experiments separately.

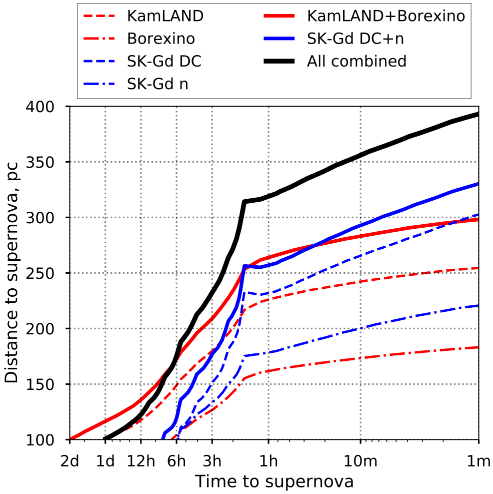

Figure 9: Presupernova detection reach with 90 % efficiency for the shape analyses for the individual detectors (dashed, dashdot lines) and their combinations (solid lines). Odrzywolek NH model is assumed for both expected and received signals.

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