Detection of Galactic Supernova Neutrinos at the NOvA Experiment

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Motivation

Supernova physics:

- Neutrino emission plays crucial role in the supernova explosion mechanism.
- Neutrinos produced in the early phases of the collapse carry information from the core.
- Existing models predict various neutrino luminosities & spectra.

Neutrino properties:

- Observable ν flux is affected by many aspects of neutrino physics: neutrino mixing parameters, mass hierarchy, sterile neutrinos and other.
- Enormous neutrino densities during the explosion make neutrino self-interactions important.

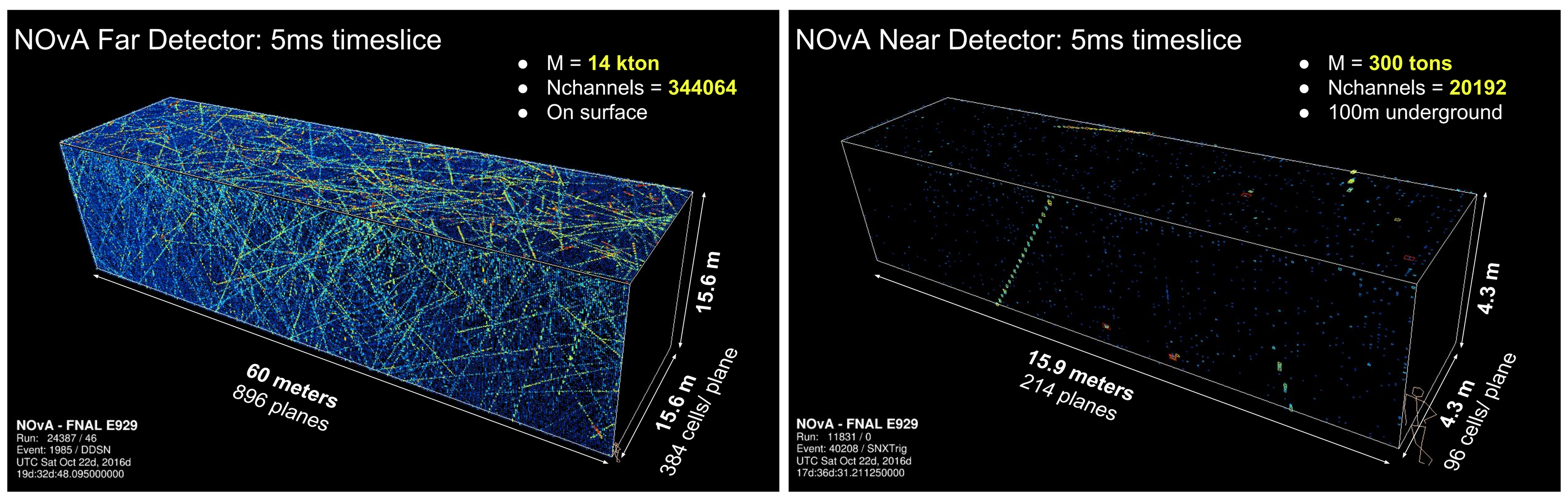
Challenging:

- Huge detectors are needed.
  Collaboration with other experiments → global network
- Previously registered only once: **SN1987a**
- Galactic supernovae are quite rare: $\sim 1-3$ per century

We need to be ready

NOvA : NuMI Off-axis ν_e Appearance

Primary goal: precise measurement of neutrino oscillations parameters, studying $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations in **2 GeV** neutrino beam.



NOvA features two segmented liquid scintillator detectors of similar structure.
The NOvA detectors can be used to register the neutrino signal from the next galactic supernova, measuring the neutrino flux and providing the trigger signal to other neutrino experiments. The detailed description of the NOvA detectors can be found in [1].

Simulation of supernova neutrino interactions

A dedicated simulation package **GenieSNova** was developed to simulate interactions of supernova neutrinos inside the NOvA detectors in a correct timing order, producing particles that can then be used in the full existing NOvA detector simulation chain.

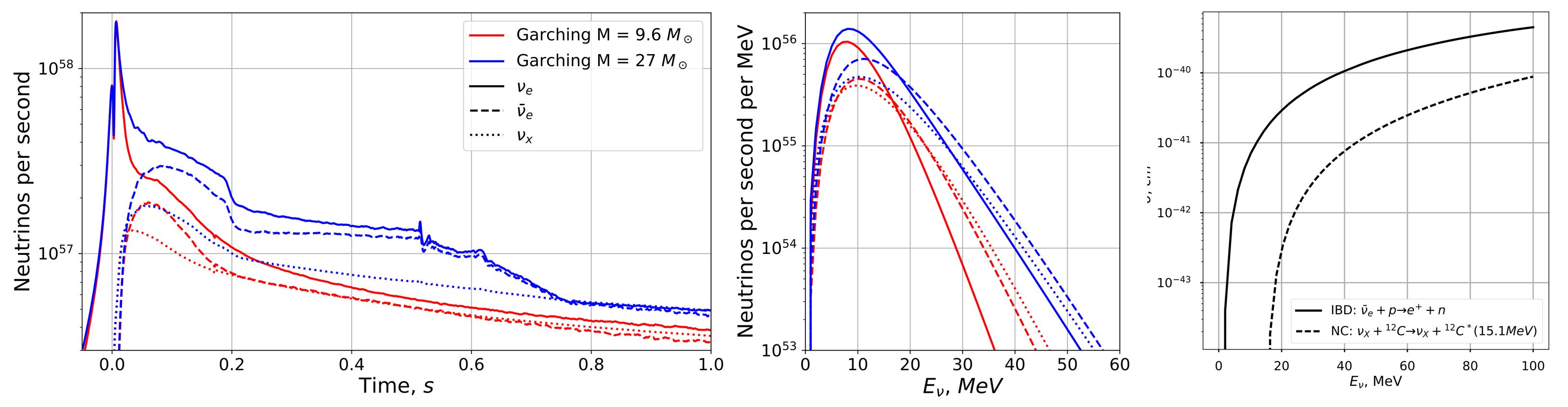


Figure 1: We use SN neutrino flux models for progenitor star masses $9.6 M_\odot$ and $27 M_\odot$ described in [2].

Selection of interaction candidates in NOvA Far detector

The main signal signatures in the detector are a positron from IBD process with energies up to tens of MeV, and a 15.1 MeV photon from $^{12}C^*$ de-excitation. These particles produce small showers, which light up **1-4** scintillator cells, producing clusters of hits.

In order to detect such candidates, we have to:

1. Reject the signals associated with: muon tracks, Michel electrons, high energy showers and noisy electronic channels.
2. Find clusters of signals, close in time and space.
3. Request signals in both **X** and **Y** planes: reduce the background from electronic noise.
4. Apply fiducial volume cut: reject background from outside
5. Select clusters in the amplitude range.

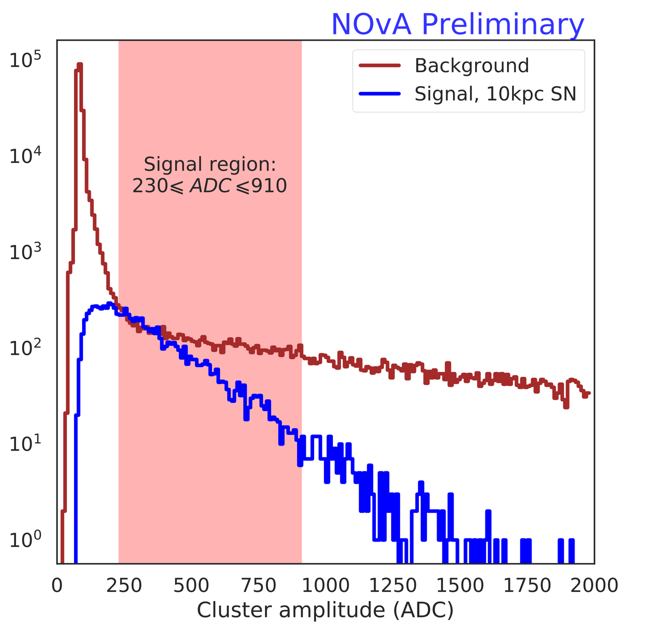


Figure 2: ADC range for IBD candidates selection was defined to maximize $\frac{s}{\sqrt{b}}$ for SN at **5 kpc** distance.

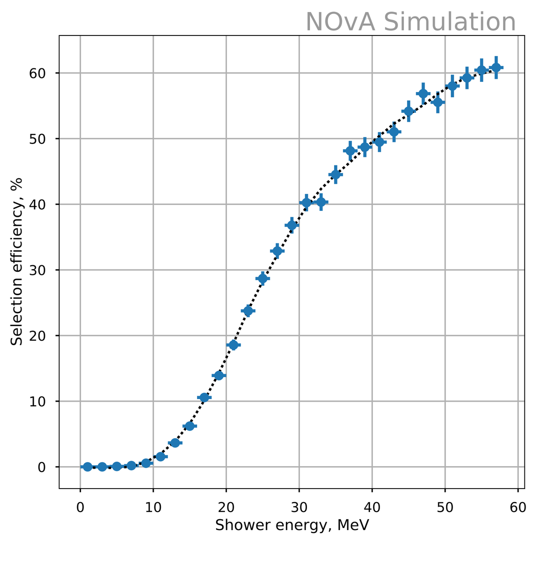


Figure 3: Using simulated sample of positrons, we determine the efficiency of the IBD candidate reconstruction

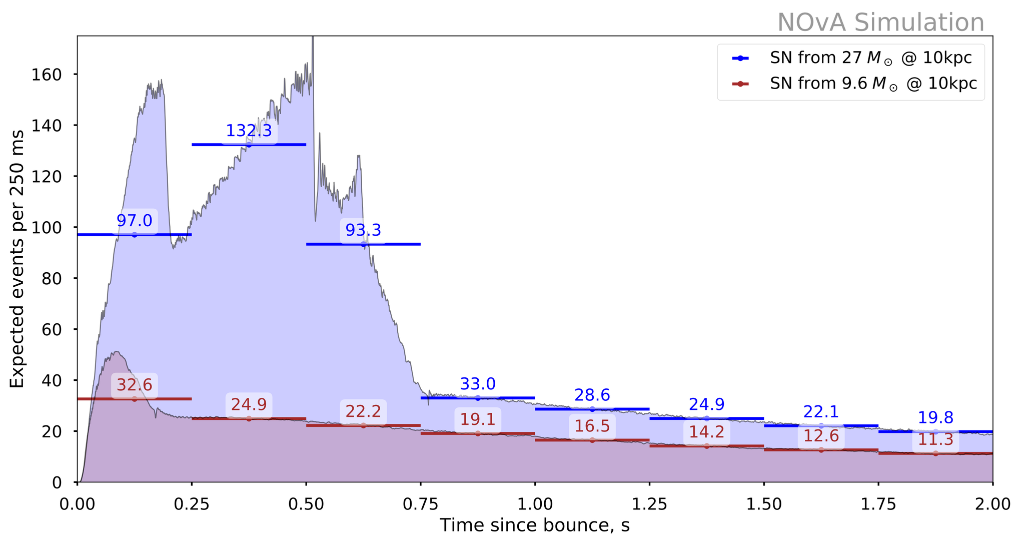


Figure 4: Number of signal IBD interactions after candidate selection procedures. We use 250ms time bins to define the signal shape. The $27 M_\odot$ signal shows a specific structure during first 750ms after bounce. Both models share a general feature: exponential tail in the cooling phase.

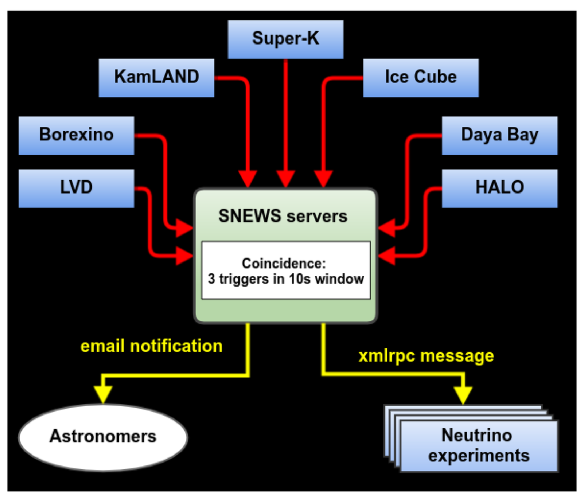
Supernova triggering system

External trigger signal: SNEWS

Super**N**ova **E**arly **W**arning **S**ystem[3] is a service that:

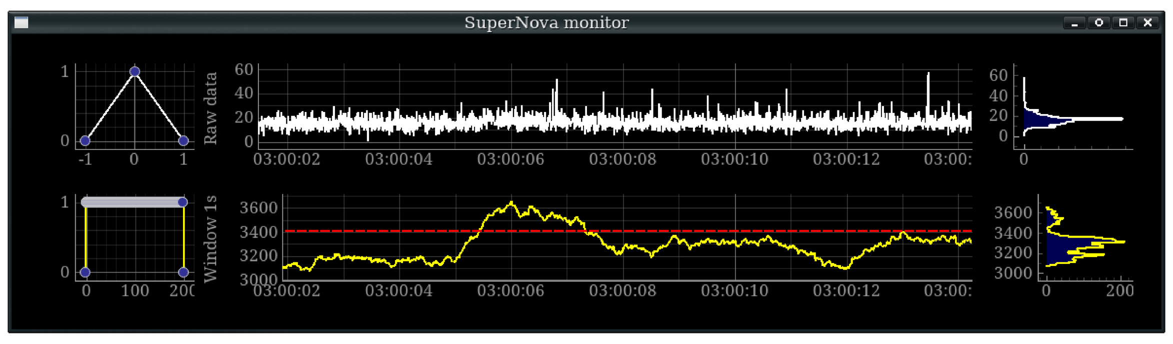
- Collects supernova triggers from 7 neutrino experiments.
- Provides notifications to other experiments and astronomers.

NOvA is currently triggered externally by a SNEWS coincidence, so we can record data from a galactic supernova for further analysis.



Internal NOvA trigger

We can detect supernova explosion, observing a short-time ($\tau \sim 1-10s$) increase in low-energy neutrino interactions rate.



Supernova trigger system uses existing NOvA triggering infrastructure:

- More than **1000** processes on about **160** nodes
- Analyze the data from detectors in **5ms** time slices in parallel
- Reconstruct neutrino candidates and count the interaction rate per slice
- Background level and variance is measured dynamically, accumulating data every 1 minute, so we can mitigate the slow changes in background.

Using signal shape information

To use the expected signal shape information, we can calculate the **likelihood** that the data follows expected shape in time.
We detect $n_i = s_i + b_i$ interaction candidates per i-th time bin. Then, assuming the Poisson distributions for events in time bin:

$$s_i \sim Poisson(\lambda = S_i) \quad b_i \sim Poisson(\lambda = B)$$

we can define the log likelihood ratio function:

$$LLR(\vec{n}) = \sum_i n_i \cdot \log(1 + S_i/B) - \sum_i S_i$$

Triggering signal is sent when this LLR value exceeds given threshold.

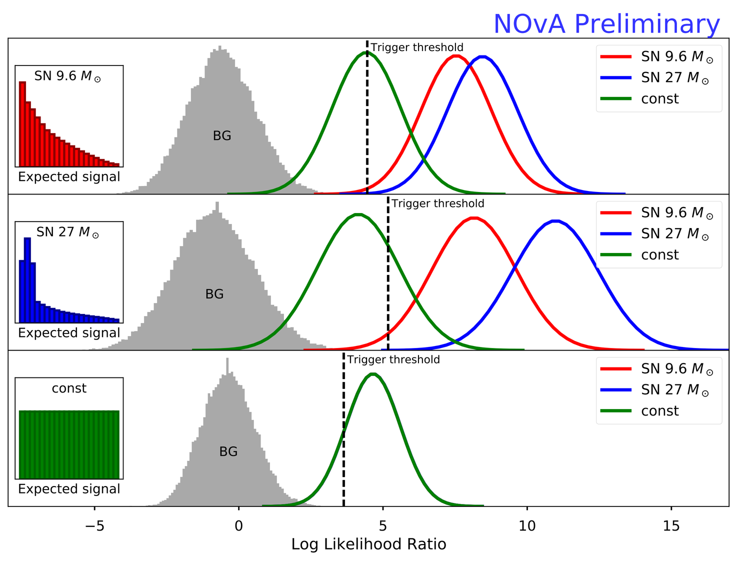
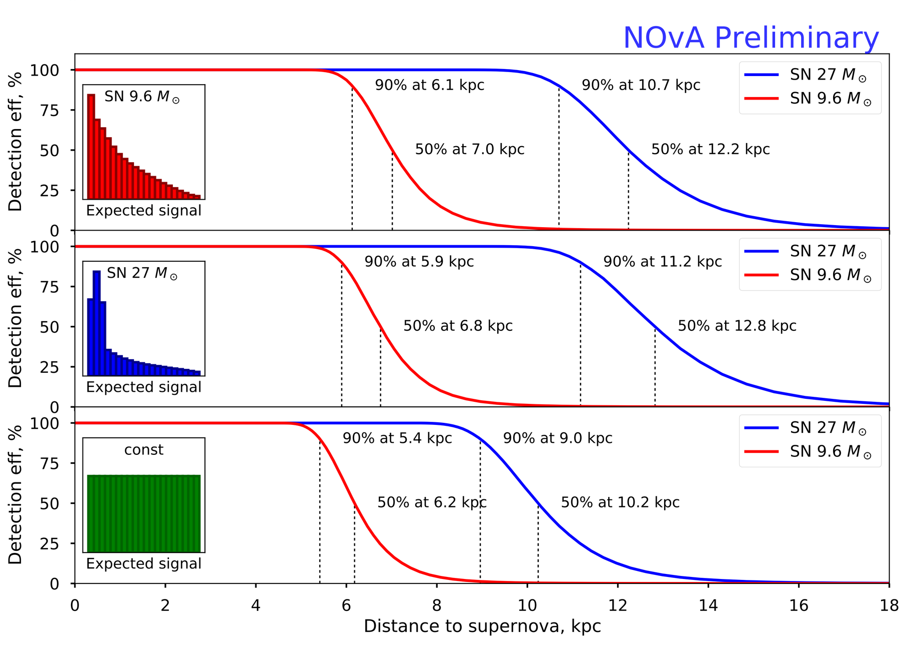


Figure 5: Signals with the same total number of events but different shapes, produce different distributions of LLR. This makes our trigger more sensitive to particular signal shapes.

Sensitivity to galactic supernovae

- SNEWS requires false triggering rate below **1/week**
- False trigger rate and LLR distribution for background define the triggering thresholds.
- Efficiency of supernova detection: probability for a SN signal to exceed the threshold.



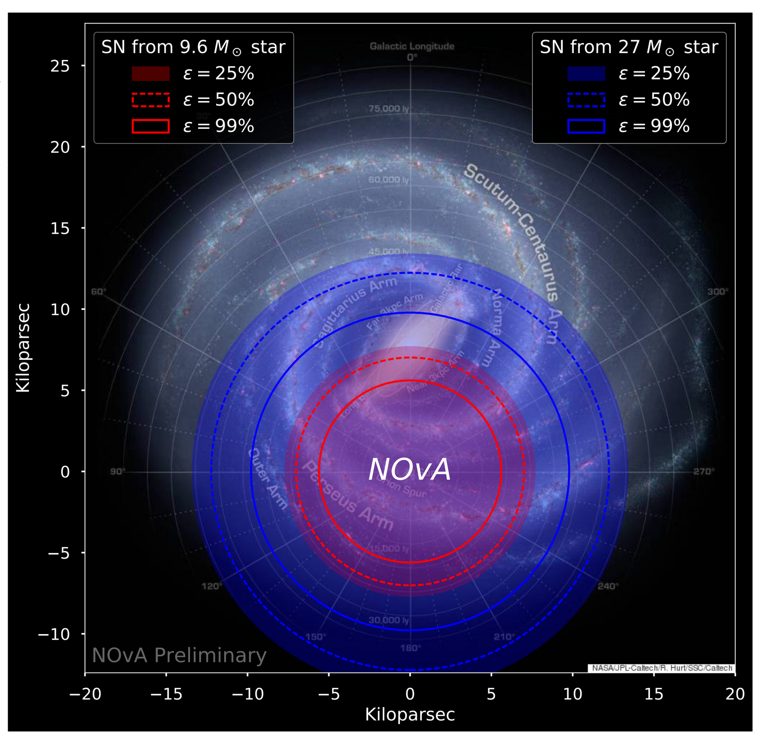


Figure 6: Probability of supernova detection in NOvA for the model with $27 M_\odot$ and $9.6 M_\odot$ progenitor star mass, using the expected shape of $9.6 M_\odot$ signal.

Summary and current status

- The supernova triggering system is working on NOvA detectors since November 2017, with a false positive rate < 1/week. We plan to start sending trigger signals to SNEWS.
- Using the time profile of expected signal and the background distribution, the trigger can be sensitive to the supernovae in the galactic center (7 kpc).
- The next upgrade of the system is planned for summer 2018. With improved reconstruction algorithms and monitoring system, we expect to increase the stability and efficiency of the trigger.
- The GENIE-based simulation package for supernova neutrinos' interaction is being developed. We plan to include more interaction channels and supernova models.
- An understanding of NOvA's physics sensitivity and an offline analysis of the supernova neutrino signal is currently being developed.

[1] P. Adamson et al. (NOvA Collaboration), Phys. Rev. **D93** 051104 (2016)
[2] A. Mirizzi et al., Rivista del Nuovo Cimento Vol. **39**, N. 1-2 (2016)[arXiv:1508.00785]
[3] P. Antonioli et al, New Journal of Physics **6** (2004) 114