Supernova neutrino signal detection in NOvA experiment

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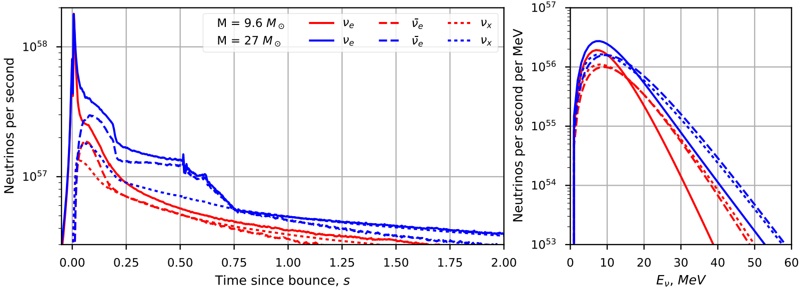
Supernova neutrino signal

Neutrino signal from core-collapse supernova:



- $N_\nu \sim 10^{58}$ neutrinos
- $E_\nu \sim 10 - 60$ MeV
- $T \sim 10s$

Models from arXiv:astro-ph/0604300

The models predict different fluxes. Also depends on the mass of the progenitor star.

Can provide valuable information about supernova physics, neutrino physics.

Very rare: 1-3/century in our galaxy.

Coincidence network

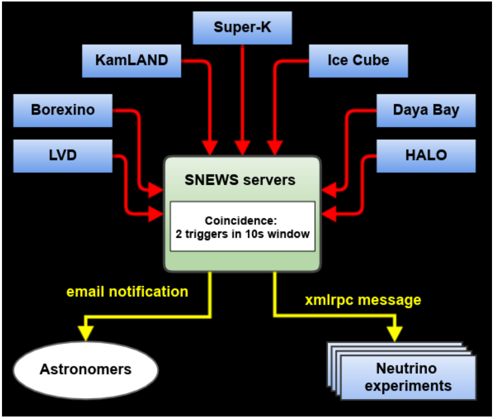
Many neutrino experiments sensitive to the SN neutrino signal.

Experiments capable of detecting this signal in real time are united in SNEWS coincidence network.

- Current mode: combining SN trigger signals from experiments.
- A better approach: combine signal significance from various experiments and do meta-analysis.

Plans for SNEWS v.2.0

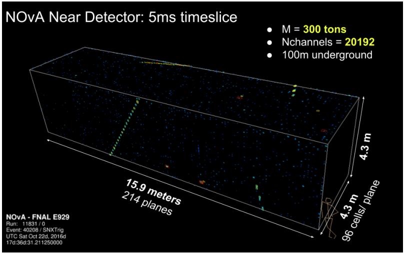
Work towards unified network with GW detectors.

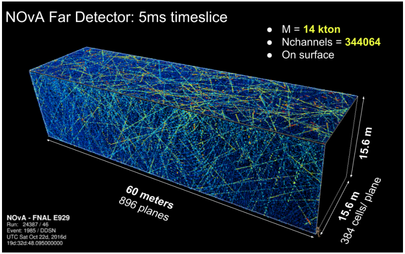


SNEWS: **S**uper**N**ova **E**arly **W**arning **S**ystem

NOvA detectors

Main goal of the NOvA experiment: study neutrino oscillations in the muon (anti-)neutrino beam, with $\langle E_\nu \rangle = 2$ GeV.



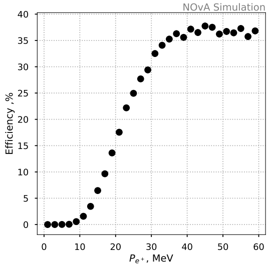


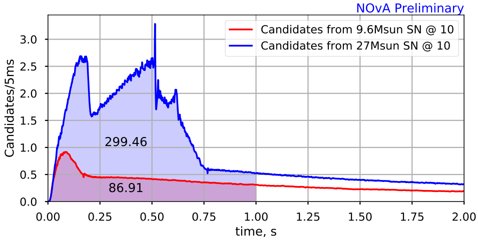
NOvA detectors are not ideal for the supernova signal detection (high background! designed for higher neutrino energies) but can still make a valuable contribution to SNEWS.

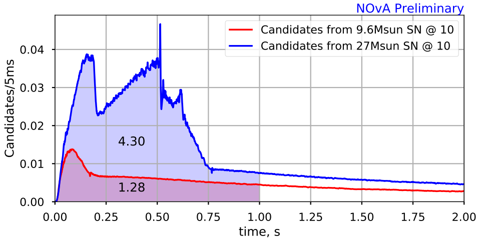
- Similar structure $\Rightarrow$ almost the same reconstruction and data processing,
- Different size and overburden $\Rightarrow$ very different BG conditions, statistics.

Detecting supernova neutrinos

Main detection channel: $\bar{\nu}_e + p \to e^+ + n$.







	N_{bg}	N_{sg}@10kpc
FarDet	2483.21	86.91
NearDet	0.52	1.28

Table: Expected number of candidates from the first second of SN, after the reconstruction and selection procedures

Supernova triggering system

A dedicated triggering system was deployed on NOvA detectors.

Characterized by:

- False trigger rate α
- Detection efficiency for particular supernova signal (model, distance)
- Reaction time.

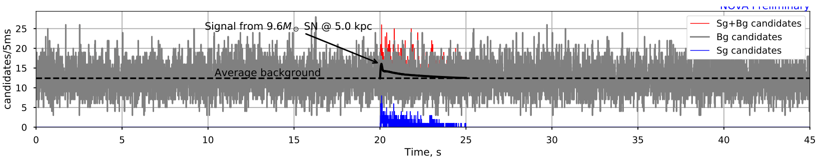
We need to process the data flow on-line:

- Reconstruction of neutrino interaction candidates performed in real time: more than 1800 parallel processes for 5ms data slices.
- Statistical analysis of interactions rate: algorithms should be computationally simple and robust.

Analyzing time series

Input data from the candidates selection: time series

$$n_i = b_i + s_i$$



The triggering system needs to distinguish between the "background only" H_0 and "background+signal" H_1 hypotheses, using data within a sliding time window $\vec{n} = \{n_i\}$

Hypothesis testing, significance

- In general: use some test statistics function $X(\vec{n})$ to discriminate between the hypotheses.
- We then need to know how the $X(\vec{n})$ is distributed in case of each hypothesis is true: $P(X|H_0)$, $P(X|H_1)$
- The signal significance is characterized by p-value:

$$p(X(\vec{n})) = \int_{X(\vec{n})}^{\infty} P(x|H_0)dx$$

- We convert significance in "sigmas" for convenience:

$$z(x) = \mathrm{erf}^{-1}\left(\frac{1-p(x)}{2}\right)$$

Trigger fires if significance exceeds threshold (whatever definition we use):

$\alpha = 1/week$ $\iff$ $p_{thr} = 8.267 \cdot 10^{-9}/5ms$ $\iff$ $z_{thr} = 5.645\sigma$

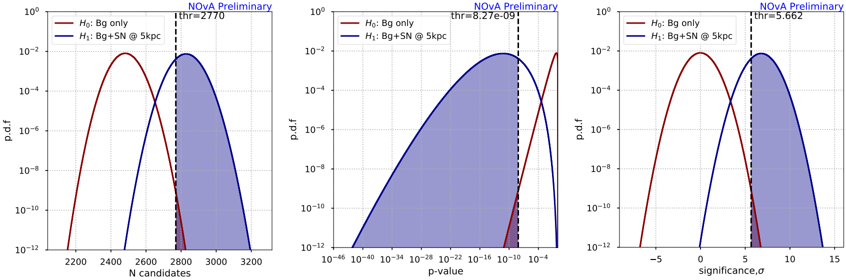
Simple example: using number of candidates in 1s

We can use number of candidates in 1s time window: $N = \sum_{i=0}^{200} n_i$

Assuming N to have Poisson distribution around the average numbers from table, we can have the distributions fortest statistics $P(X|H_{0,1})$

	N_{bg}	$N_{sg}@10kpc$
FarDet	2483.21	86.91

Table: Expected number of candidates from the first second of SN



Probability to detect the SN @ 5kpc distance in FarDet is 86.46%, with $\alpha = 1/\text{week}$

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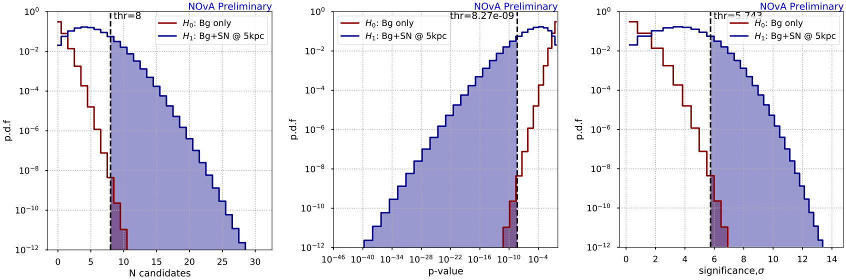
Table: Expected number of candidates from the first second of SN



Probability to detect the SN @ 5kpc distance in NearDet is 11.66%, with α =1/week

Using signal shape: log likelihood ratio

We can gain more sensitivity, if we use the information about the expected signal shape vs time.

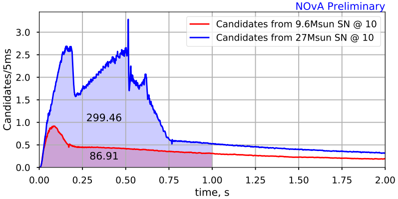
Number of candidates n_i in each of 5ms time bins should have Poisson distribution:

$$P(n_i|H_0) = B^{n_i} \cdot e^{-B}/n_i!$$

$$P(n_i|H_1) = \frac{(B+S_i)^{n_i} \cdot e^{-(B+S_i)}}{n_i!}$$

The average background rate per 5ms B is constant.

$B_{FD} = 12.42$ cands/5ms.



The average signal candidates rate per 5ms S_i, varying with the time bin i (FD).

Log likelihood ratio

$$\ell(\vec{n}) \equiv \log \frac{P(\vec{n}|H_1)}{P(\vec{n}|H_0)} = \sum_i n_i \cdot \log\left(1 + \frac{S_i}{B}\right) - \sum_i S_i$$

Log likelihood ratio (contd)

We can use ℓ as test statistics for hypothesis testing.
The constant shift $\sum S_i$ is not important and can be omitted:

Log likelihood ratio

$$\ell(\vec{n}) = \sum_i n_i \cdot A_i, \quad \text{where } A_i = \log\left(1 + \frac{S_i}{B}\right)$$

Very convenient for real-time computation:

- A linear combination of the data in considered time window.
- For trigger we want a sliding time window - this becomes a convolution of incoming data n_i with the kernel $\hat{A}$.

Next, we need to know the distributions: $P(\ell|H_{0,1})$
But a linear combination of Poisson random numbers n_i is not Poisson (in general).

We still can calculate the distribution $P(\ell|H)$ in two specific cases.

Log likelihood ratio distributions: high background

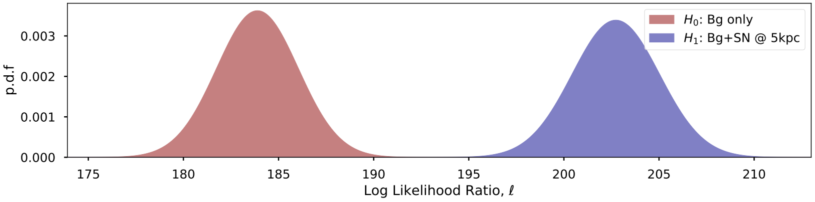
If the background B in the time bin is high enough, n_i can be considered normally distributed:

$$P(n_i|H_1) = \mathcal{N}(\mu = B + S_i, \sigma = \sqrt{B + S_i})$$

and linear combination of normal random variables is also normal:

$$P(\ell|H_1) = \mathcal{N}\left(\mu = \sum_i (B + S_i) \cdot A_i, \ \ \sigma = \sqrt{\sum_i (B + S_i) \cdot A_i^2}\right)$$

This case can be applied to Far Detector, if we make the time bins large enough: for $\delta t = 50ms$, $B = 124.2$



Log likelihood ratio distributions: low background

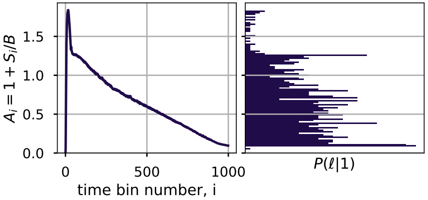
Consider total number of candidates in time window $N = \sum n_i$.

$$P(\ell|H_0) = \sum_{N=0}^{\infty} P(\ell|N, H_0) \cdot P(N|H_0)$$

Here $P(N|H_0) = B^N e^{-B}/N!$ decreases fast, if B is low. So we can stop at some order.

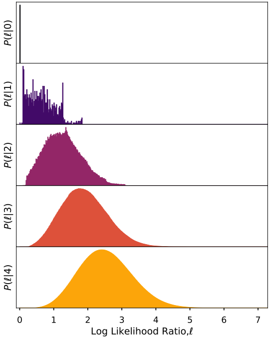
How to calculate $P(\ell|N)$?

- $P(\ell|0)$ is trivial — no candidates means $\ell = 0$
- $P(\ell|1)$: $\ell = A_i$ if candidate gets to the i_{th} time bin.



- $P(\ell|N+1)$: $\ell = \ell_N + A_i \quad \Rightarrow \quad P(\ell|N+1) = P(\ell|N) * P(\ell|1)$

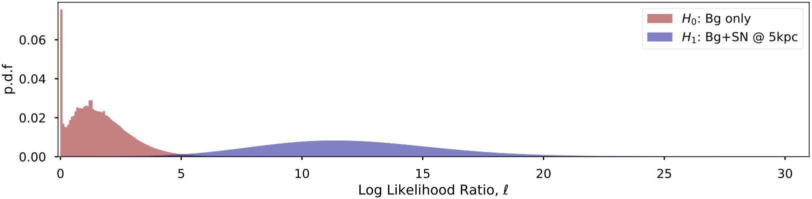
Log likelihood ratio distribution: low background (continued)



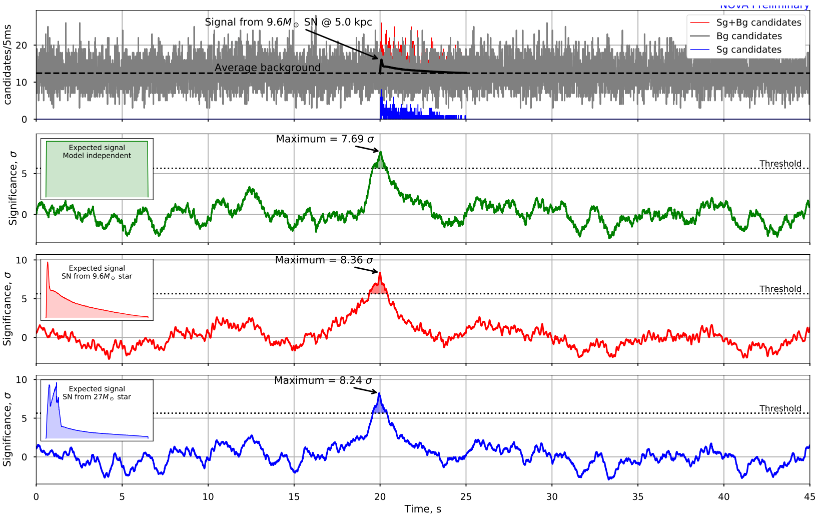
Summing up with correct Poisson probability $P(N|H_0)$ we get the result distribution.

This is the mode for the Near Detector. Average background rate is 0.5 candidates/sec.

This procedure is rather fast. It is done every time the background level is measured (every 10 minutes)



Example: triggering on Far Detector

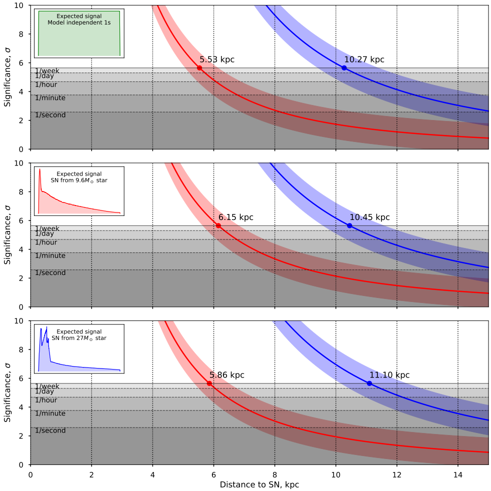


Significance vs. distance

Different expected signal shapes S_i.

And we can get the unexpected signal $\tilde{S}_i$, different from S_i.

Note: when S_i is flat, we get $\ell \sim \sum n_i$, i.e. get the simple triggering on the N_{cands} in a time window.



Significance in the Far detector.

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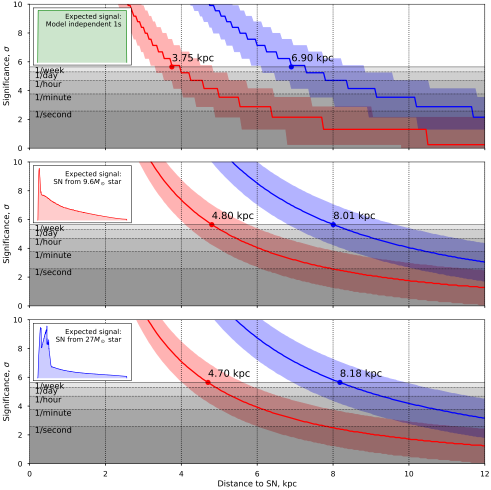
"Steps" from Poisson distribution are visible



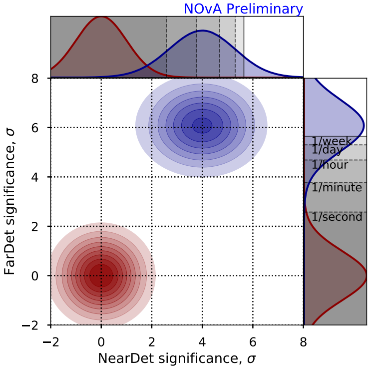
Significance in the Near detector.

Combining detectors

Currently the detectors perform hypothesis test separately.

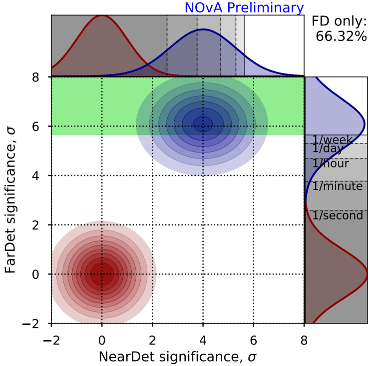
If we can get the synchronized significance scores from both detectors, we can perform meta-analysis using these two parameters.

- We need to define a combined "significance", which can then be used as test statistics: $S(z_{near}, z_{far})$.
- The threshold on S defines a region in (z_{near}, z_{far}) space where the trigger occur.
- The ways to define this function are infinite, depending on what we want:
  - Maximize the efficiency for specific signal?
  - Keep as model independent as possible?
  - Minimize the data flow between detectors?

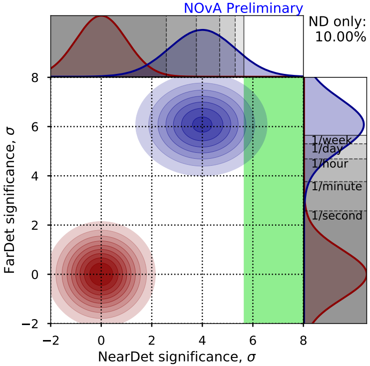


Combining detectors: examples

The signal (blue distribution) is for $9.6M_\odot$ SN signal at 5 kpc distance.
The background (red distribution) integral over the green area is fixed to $\alpha = 1/\text{week}$
Detectors triggering separately:



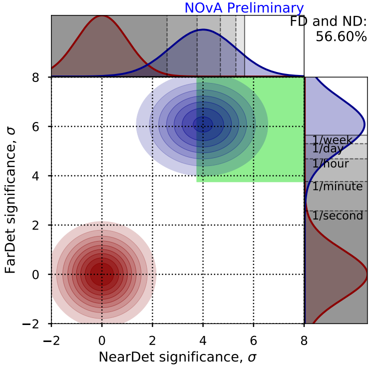
$S = z_{far}$



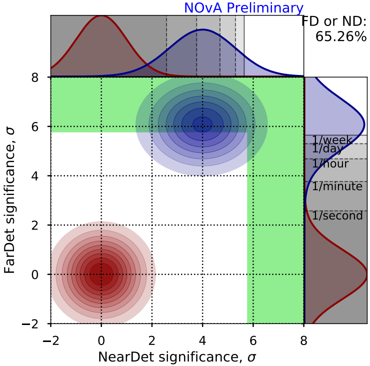
$S = z_{near}$

Combining detectors: examples

The signal (blue distribution) is for $9.6 M_{\odot}$ SN signal at 5 kpc distance.
The background (red distribution) integral over the green area is fixed to $\alpha =$1/week
Trigger signals combined (each detector still makes its own decision, but we combine the results):



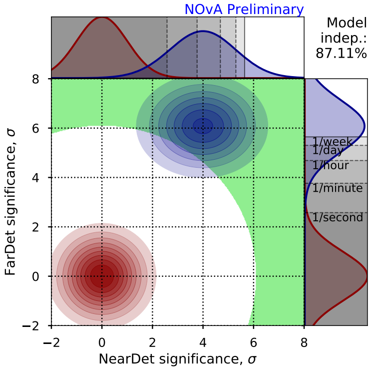
$S = \min(z_{far}, z_{near})$



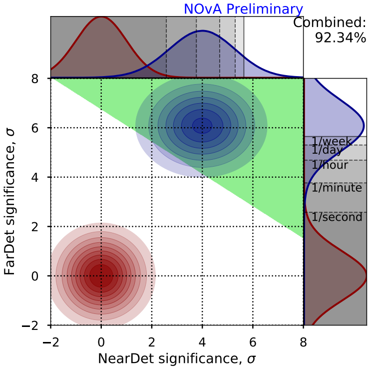
$S = \max(z_{far}, z_{near})$

Combining detectors: examples

The signal (blue distribution) is for $9.6M_{\odot}$ SN signal at 5 kpc distance.
The background (red distribution) integral over the green area is fixed to $\alpha = 1/\text{week}$
Significance combined (significance score collected for every 5ms time bin):



$$S = \sqrt{z_{far}^2 + z_{near}^2}$$



$$S = a \cdot z_{far} + b \cdot z_{near}$$

Combining detectors

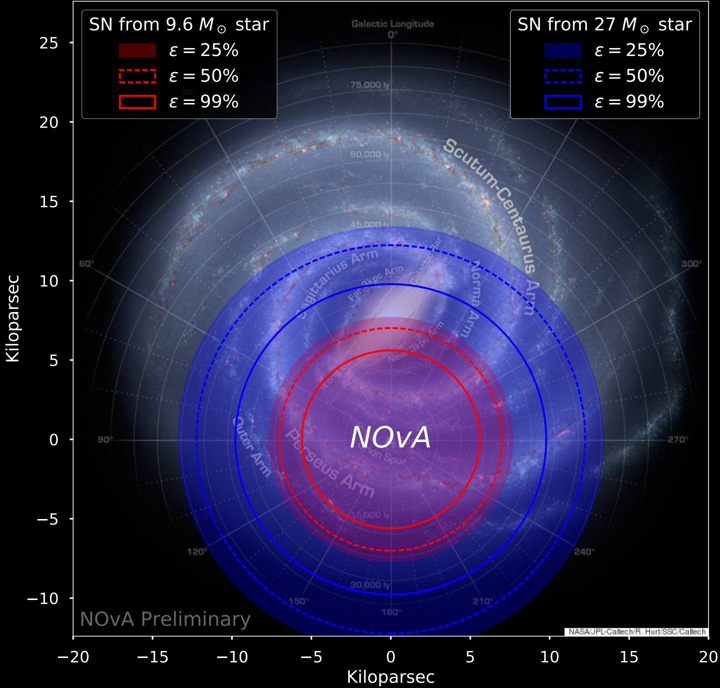
Mode	$S(z_{far}, z_{near})$	ε for SN @ 6 kpc ($9.6 M_\odot$)	Data sent every
FD only	z_{far}	66.32%	1 week
ND only	z_{near}	10.0 %	1 week
ND and FD	$\min(z_{far}, z_{near})$	56.6%	55 seconds
ND or FD	$\max(z_{far}, z_{near})$	65.26%	2 weeks
Model indep.	$\sqrt{z_{far}^2 + z_{near}^2}$	87.11%	5 ms
Combined	$a \cdot z_{far} + b \cdot z_{near}$	92.34%	5 ms

Expanding to many experiments network (SNEWS, GWNU):

- Time synchronization will be worse — larger time windows
- Need weighted approach, so less sensitive experiments don't decrease overall sensitivity
- Other signals will have a different position in (z_{far}, z_{near}). Different detectors sensitive to different signals.
- Mode depends on our requirements, and on the range of H_1 we want to be sensitive to.
- It's hard to stay model independent.

Summary

- NOvA detectors require slightly different statistical approaches, because of different conditions.
- Using the log likelihood ratio to take into account the expected signal shape improves sensitivity. This is model-dependent, but SN neutrino signals have many common features.
- The calculation of significance is done online. This requires the fast way to calculate $P(X|H_{0,1})$,
- NOvA SN triggering system can be considered as a small coincidence network for SN detection.
  So we can try out various methods of combining the measurements from detectors.
- We still need to define the most promising strategy. Currently we're working in the "OR" mode.



SN from 9.6 $M_\odot$ star
$\varepsilon = 25\%$
$\varepsilon = 50\%$
$\varepsilon = 99\%$
SN from 27 $M_\odot$ star
$\varepsilon = 25\%$
$\varepsilon = 50\%$
$\varepsilon = 99\%$
Galactic Longitude
0°
75,000 ly
60,000 ly
45,000 ly
30,000 ly
15,000 ly
60°
90°
120°
150°
180°
210°
240°
270°
300°
Scutum-Centaurus Arm
Sagittarius Arm
Norma Arm
Outer Arm
Perseus Arm
NOvA
NOvA Preliminary
NASA/JPL-Caltech/R. Hurt/SSC/Caltech
Kiloparsec
Kiloparsec
25
20
15
10
5
0
−5
−10
−20
−15
−10
−5
0
5
10
15
20