Real-time detection of supernova neutrino signal

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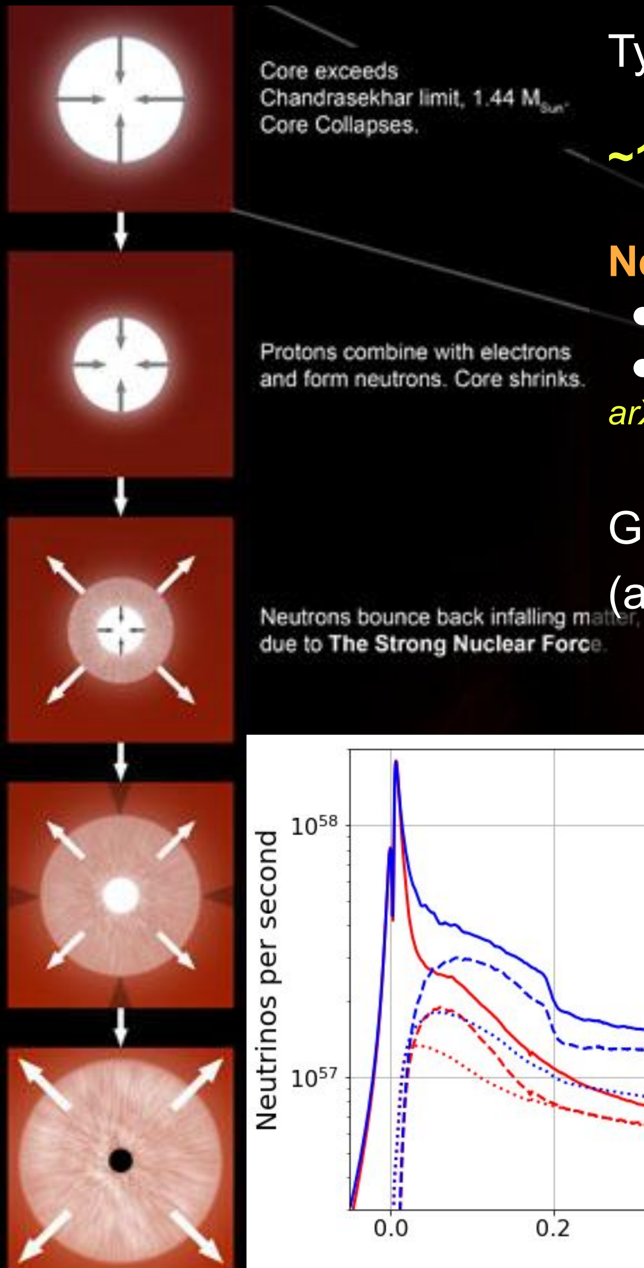
Neutrino signal from the core-collapse supernova



Type II SN radiates ~**99%** of the collapse energy in neutrinos:

~10^{58} neutrinos: **E_ν~10-60 MeV** within **T ~10s**

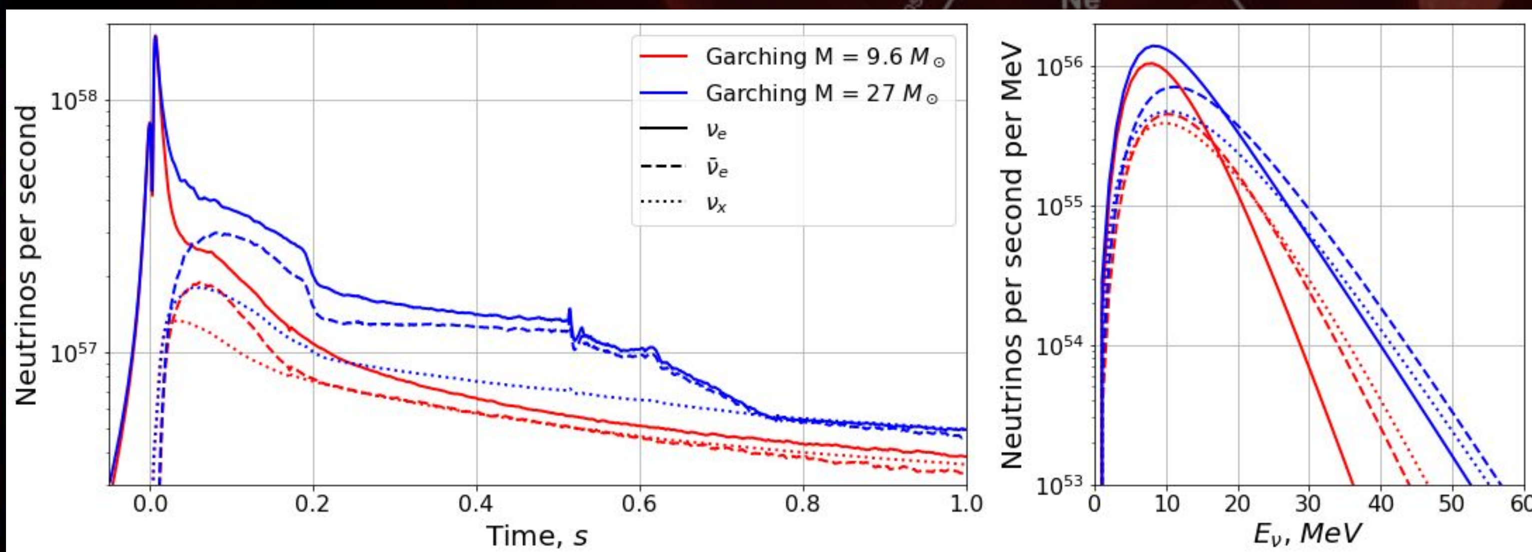
Neutrino signal: probe of

- Neutrino properties
- Supernova properties

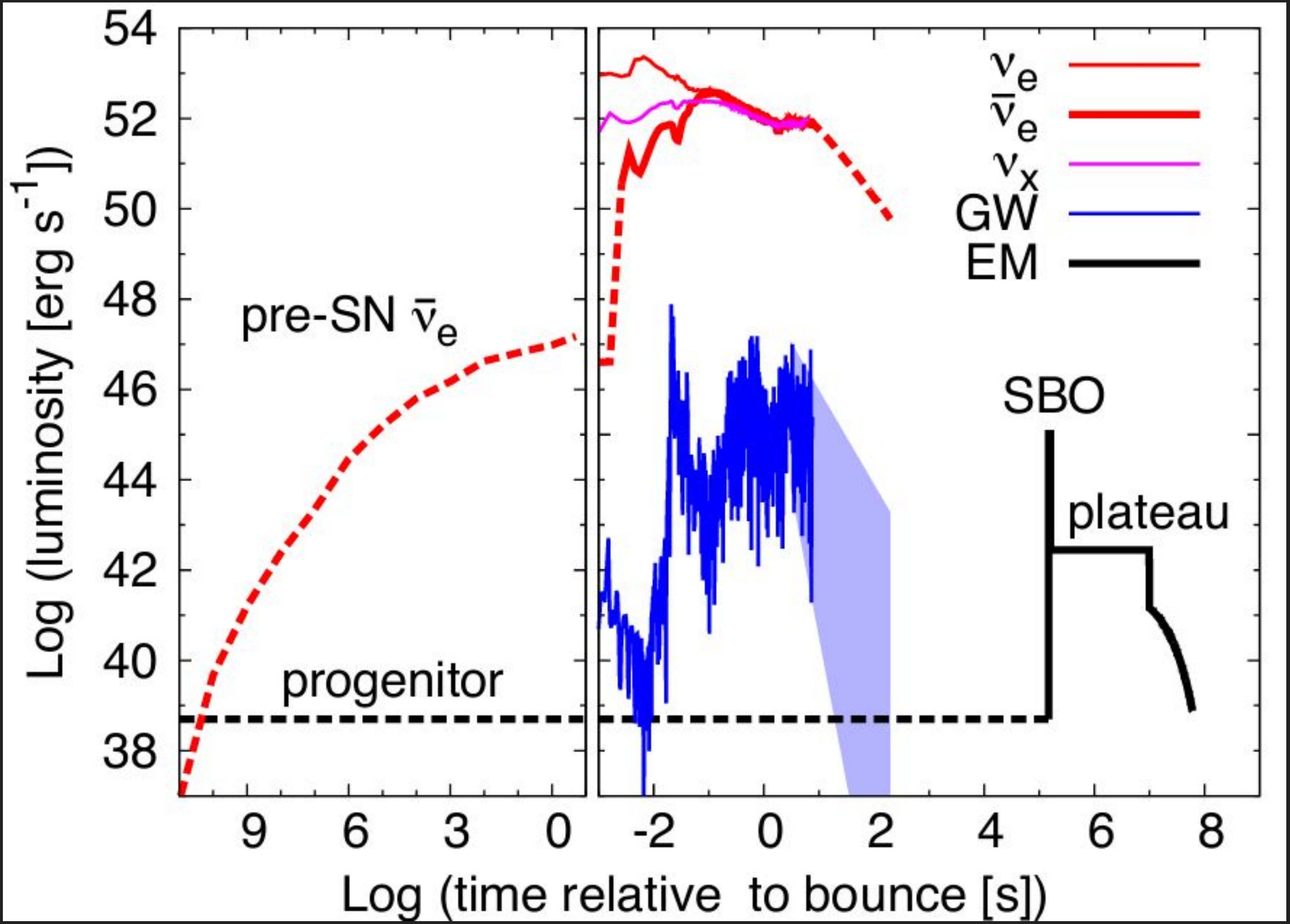
arXiv:1508.00785 [astro-ph.HE]

Galactic SN are very rare: **~1-3** per century!

(and have never been observed in the neutrinos in our galaxy)



Supernova: a multi-messenger view



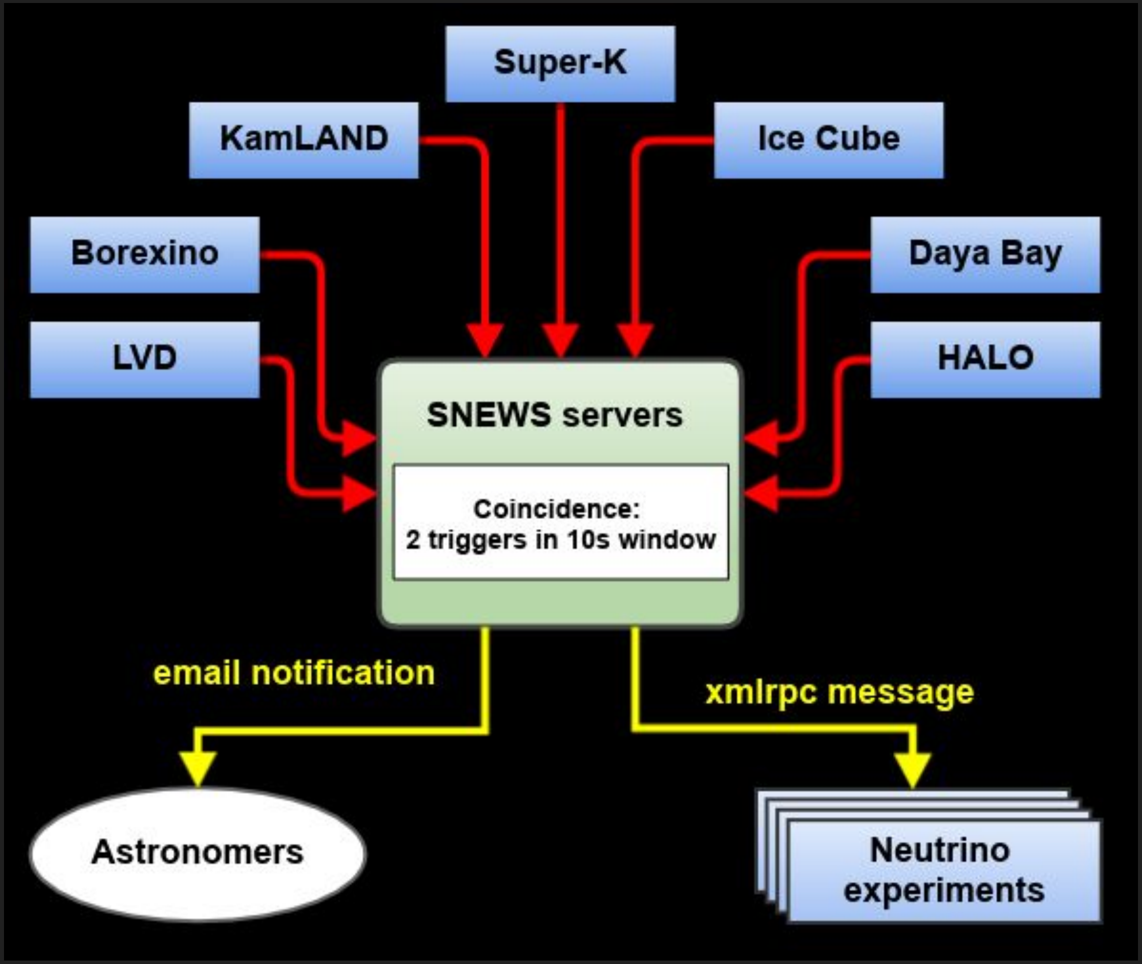
SuperNova Early Warning System

snews.bnl.gov

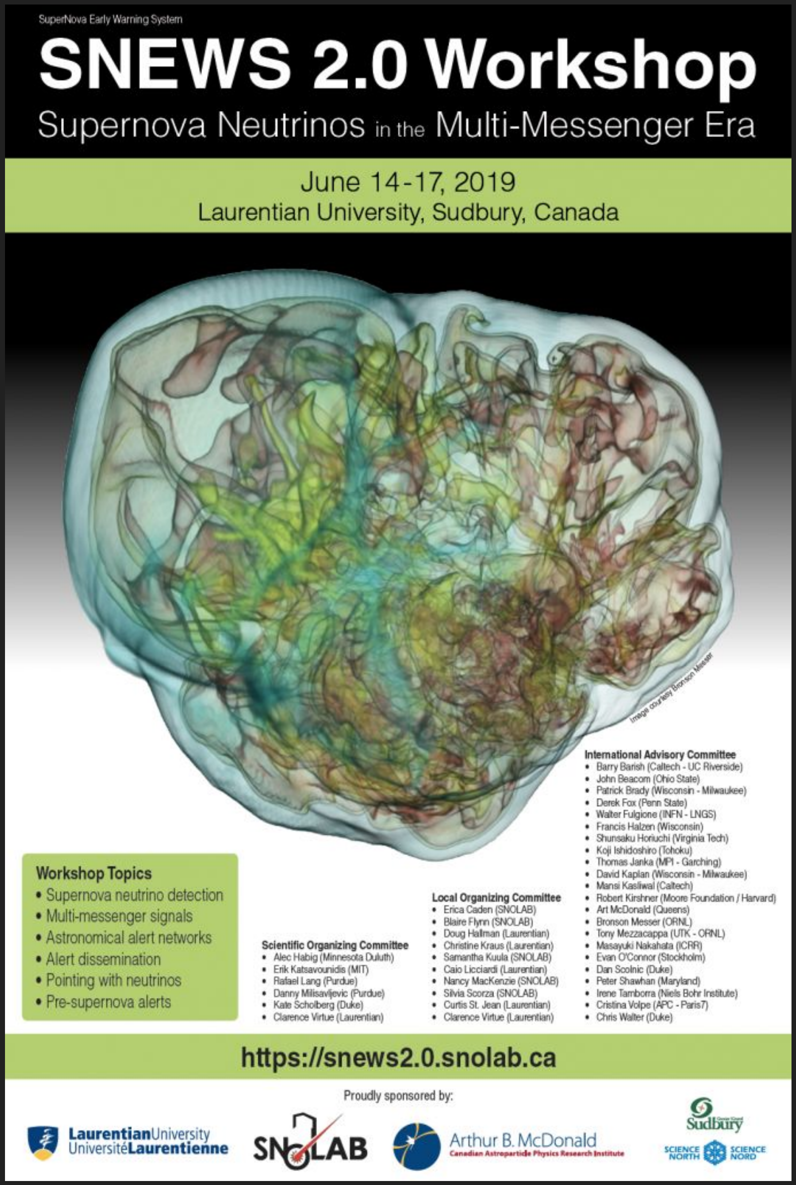
A global network to make sure we don't miss a galactic event.

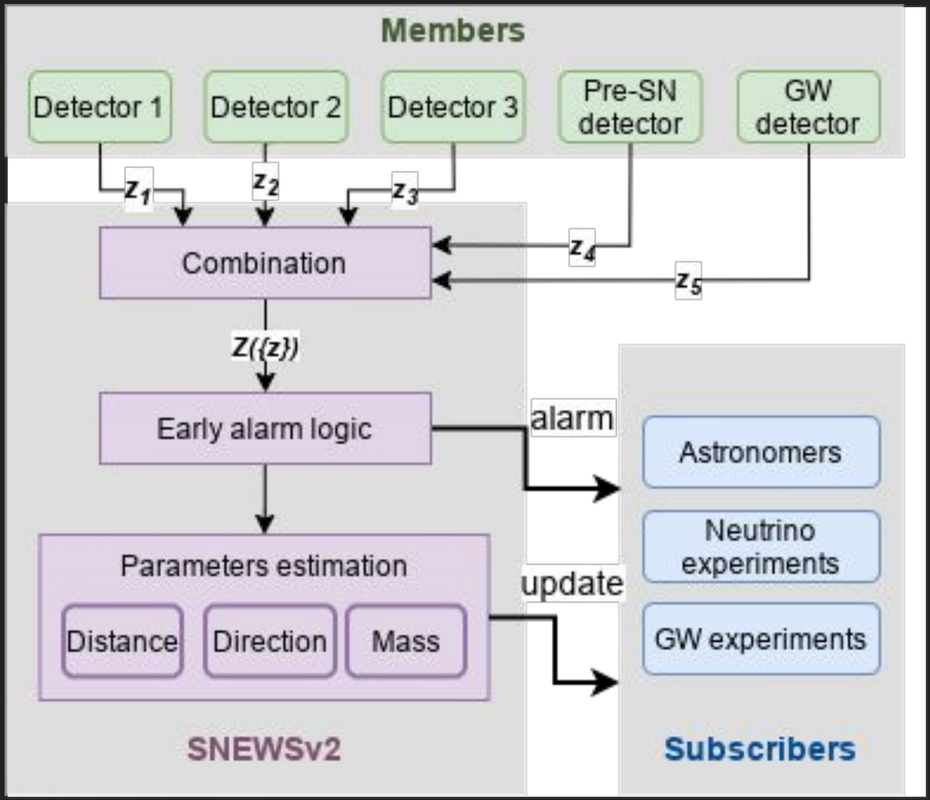
Neutrinos arrive several minutes to hours prior to optical signal

SNEWS works since 1998



A planned upgrade of SNEWS: in progress





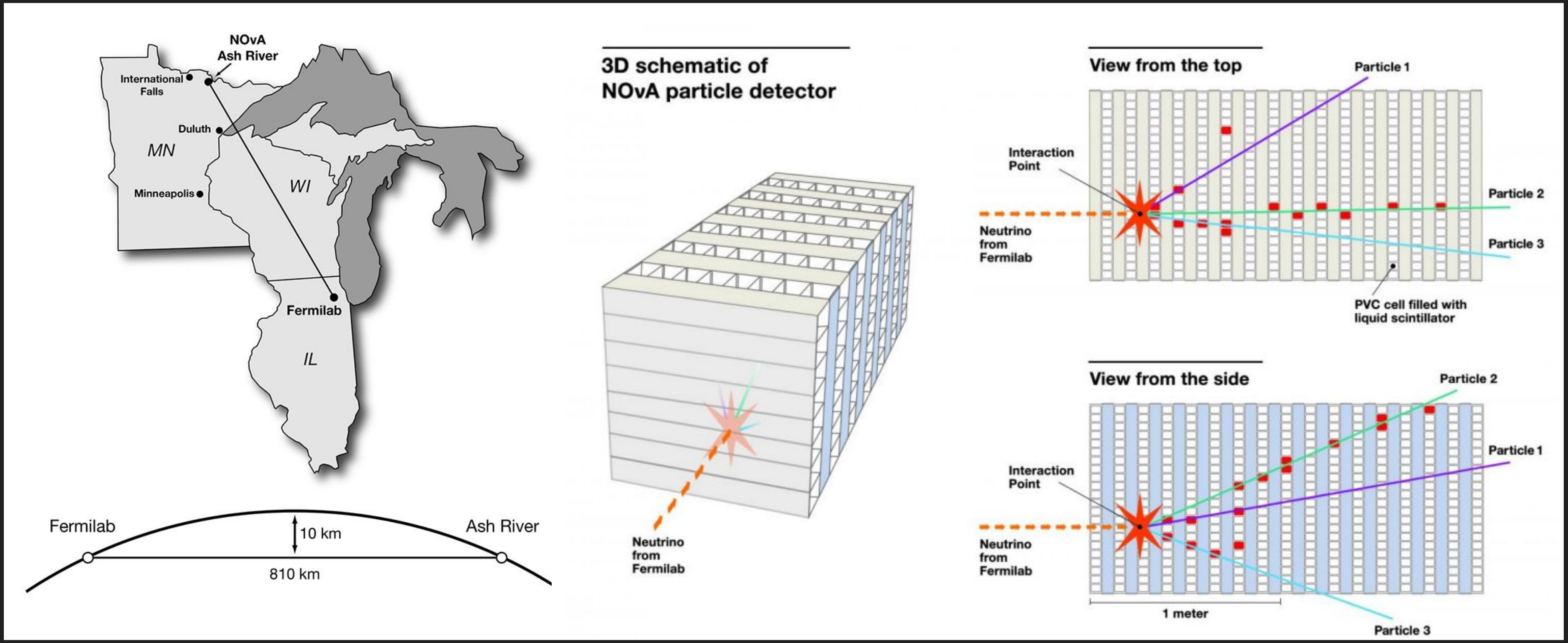
A joint effort to build a new system, combining significance and parameters estimation measurements in real-time.

Status: design and prototyping.
Many exciting tasks ahead!

The NOvA experiment

Main goal: study of neutrino oscillations in a muon neutrino beam with **<E>=2 GeV**.
NOvA uses two detectors with similar structure.

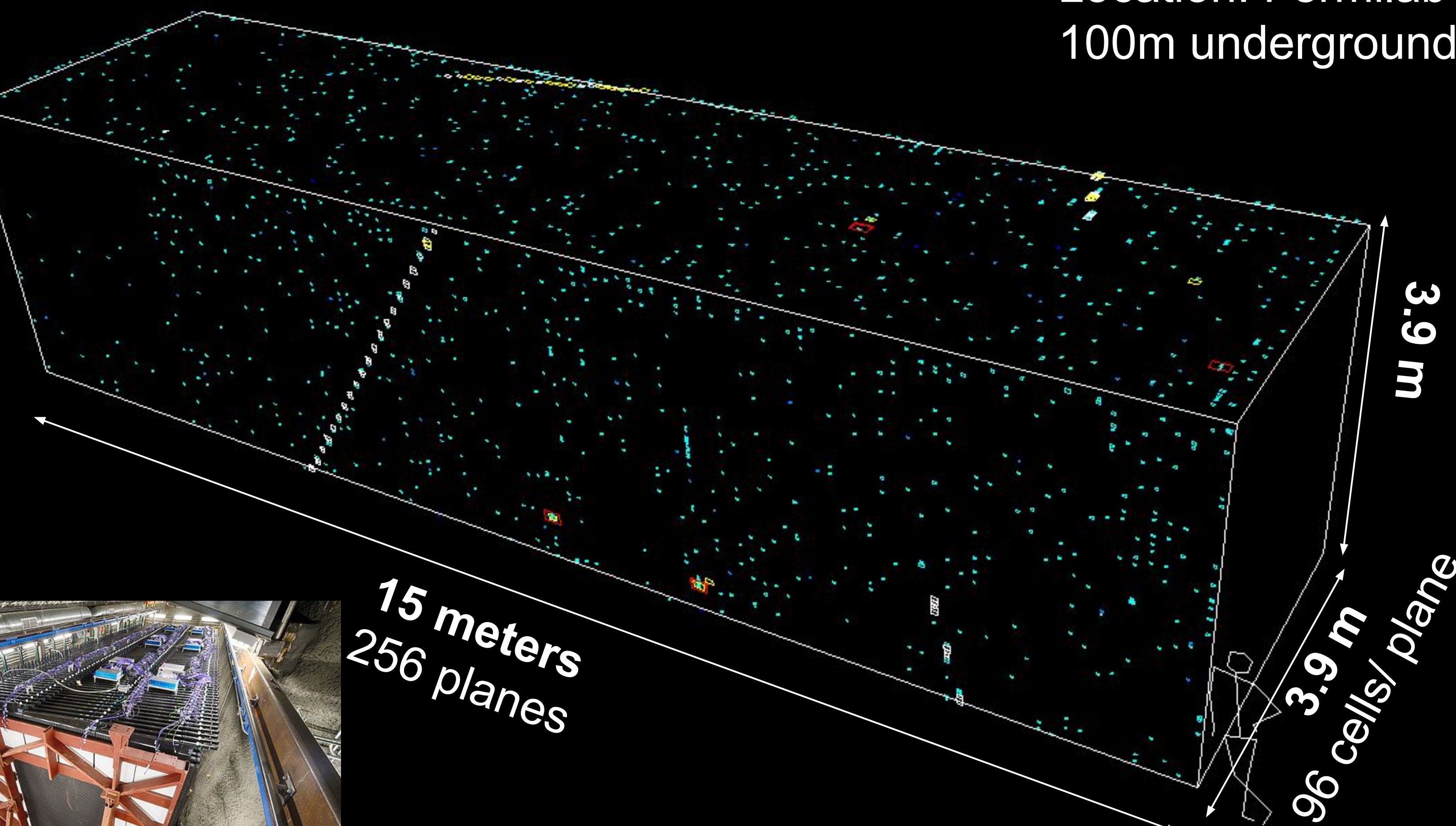
Detectors are composed of extruded PVC cells filled with liquid scintillator.
The scintillation light is transported by the wavelength shifting fibers, then read by APD

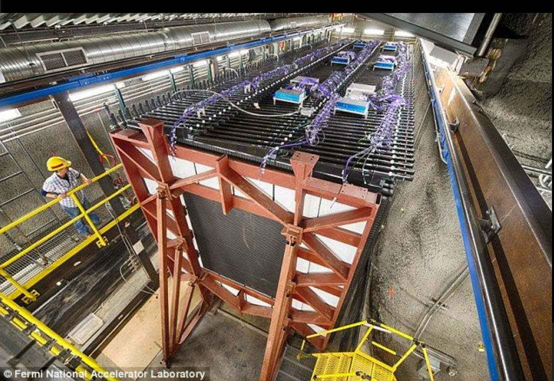


Large and segmented NOvA detectors can be used for additional physics goals.

NOvA Near detector: 5ms time slice

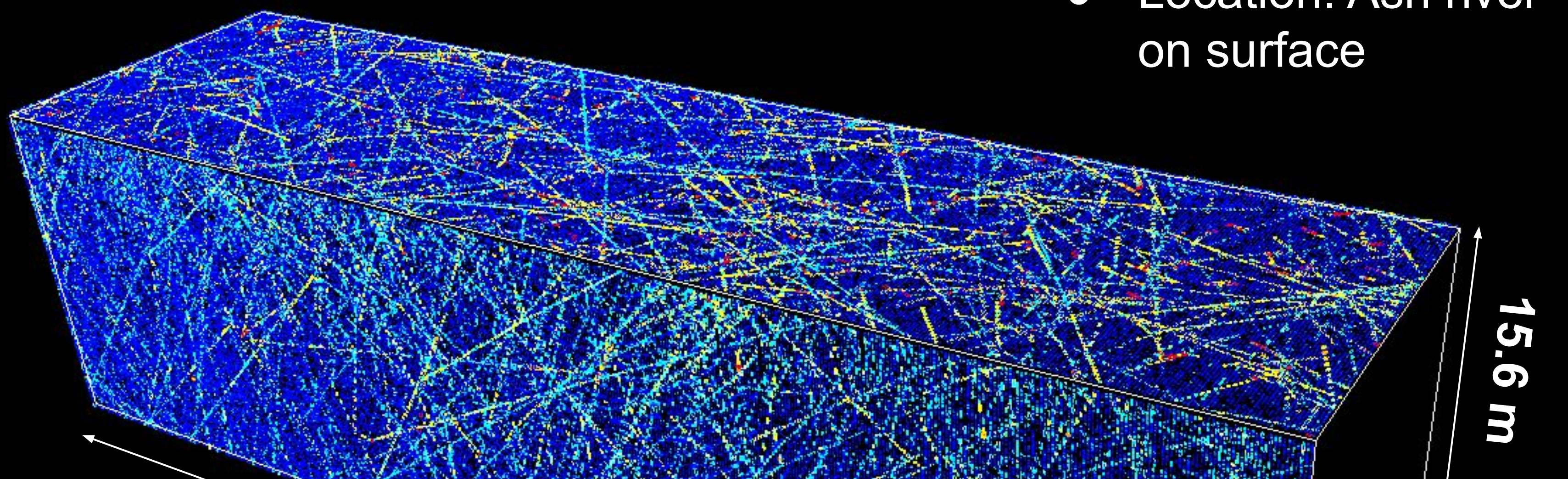
- M = **300 ton**
- Nchannels = **21504**
- Location: Fermilab 100m underground



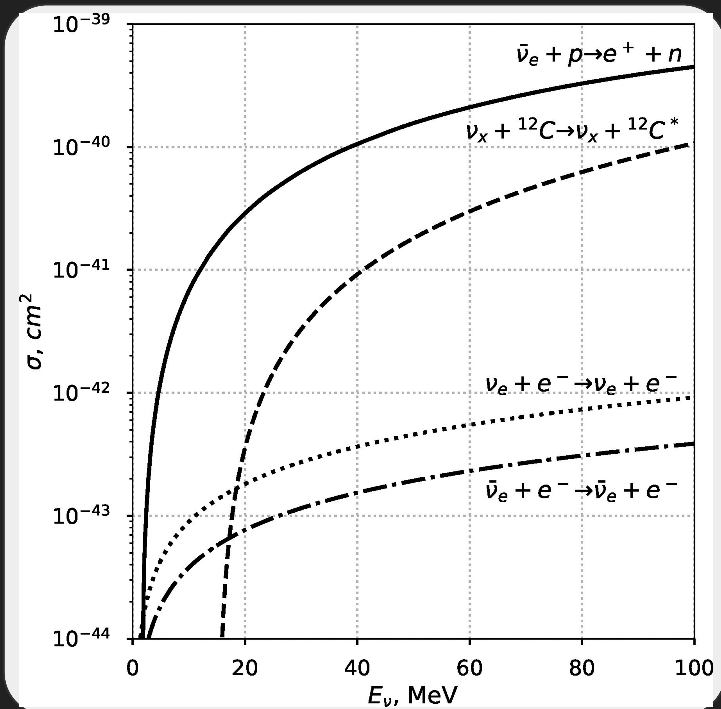


NOvA Far Detector: 5ms time slice

- M = **14 kton**
- Nchannels = **344064**
- Location: Ash river on surface

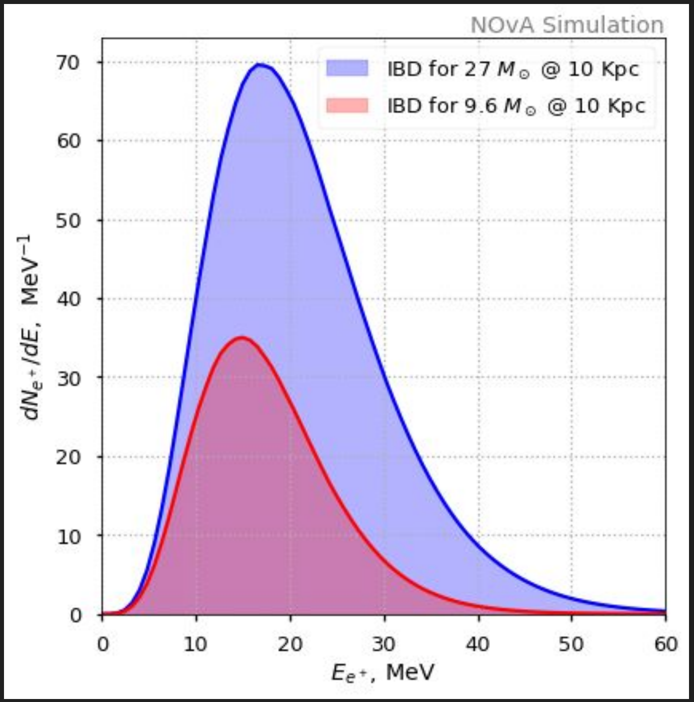


SN neutrinos interactions in the NOvA Detectors



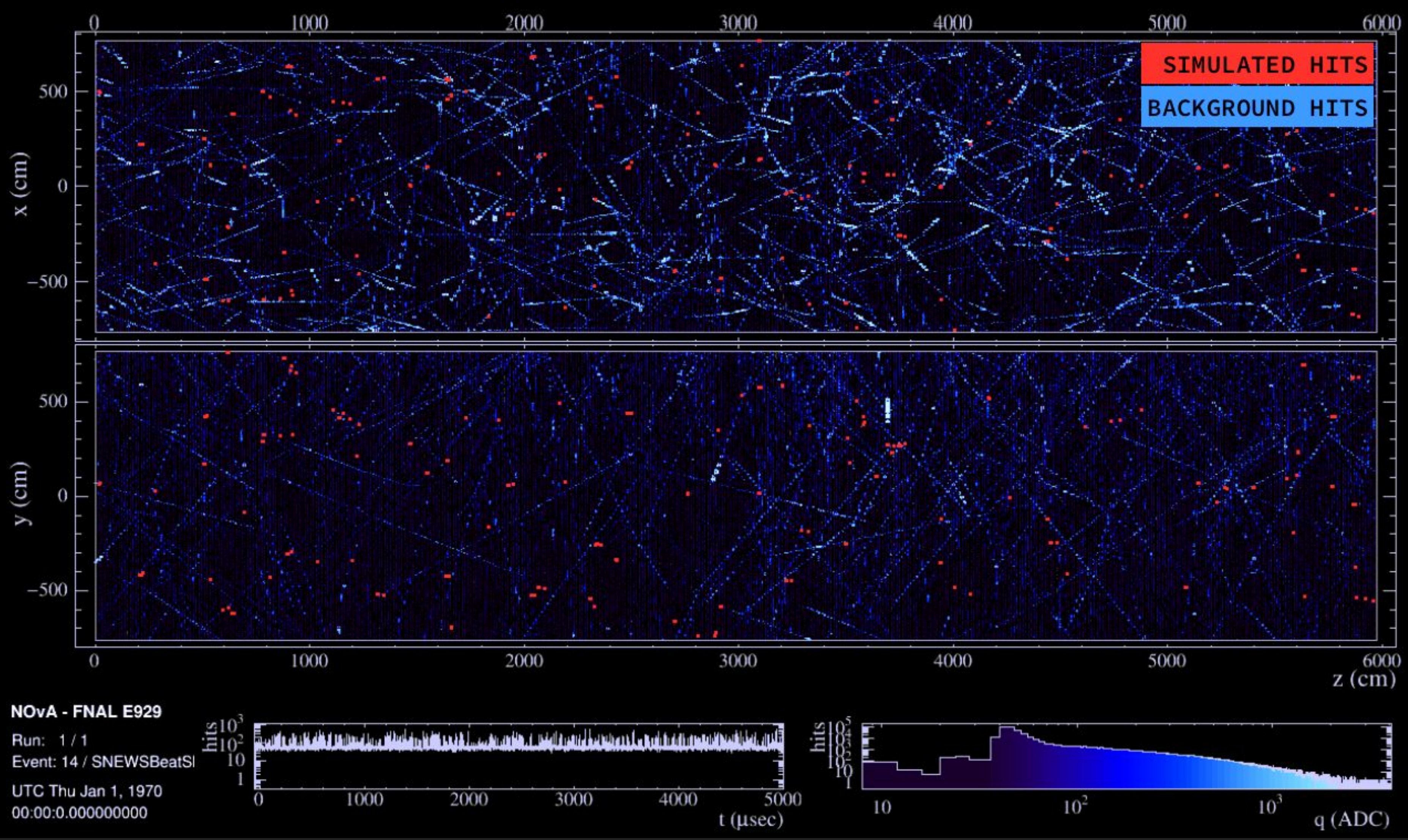
Main detection channels:

- **Inverse Beta Decay**
  - signature:
    positron shower (10-60 MeV)
- **Neutral Current**
  - signature:
    deexcitation gamma (15.1 MeV)



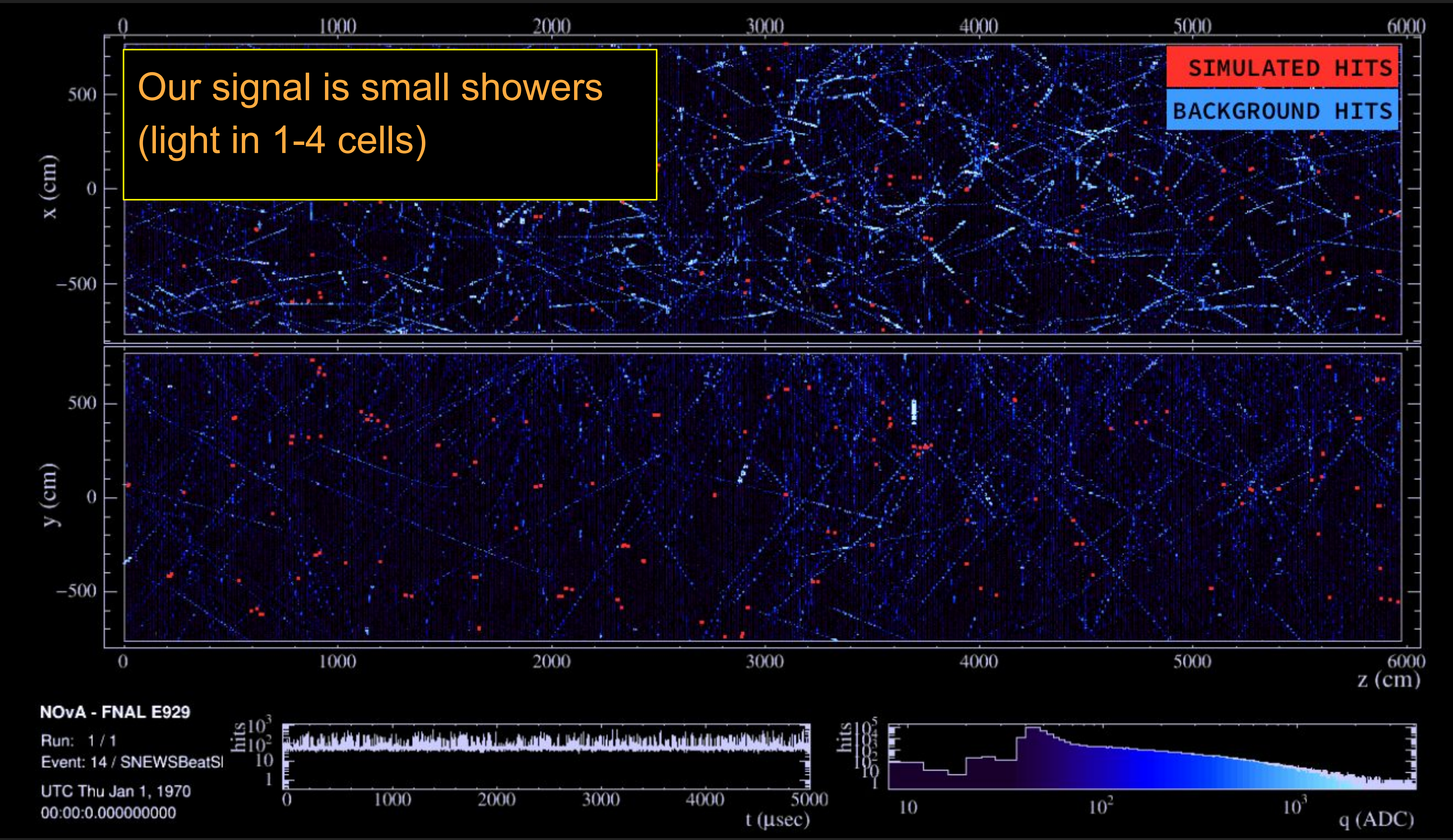
Other channels give negligible contribution: energy too low or small interaction rate.

Far Detector: 5ms of cosmic data + SN simulation



Signal selection

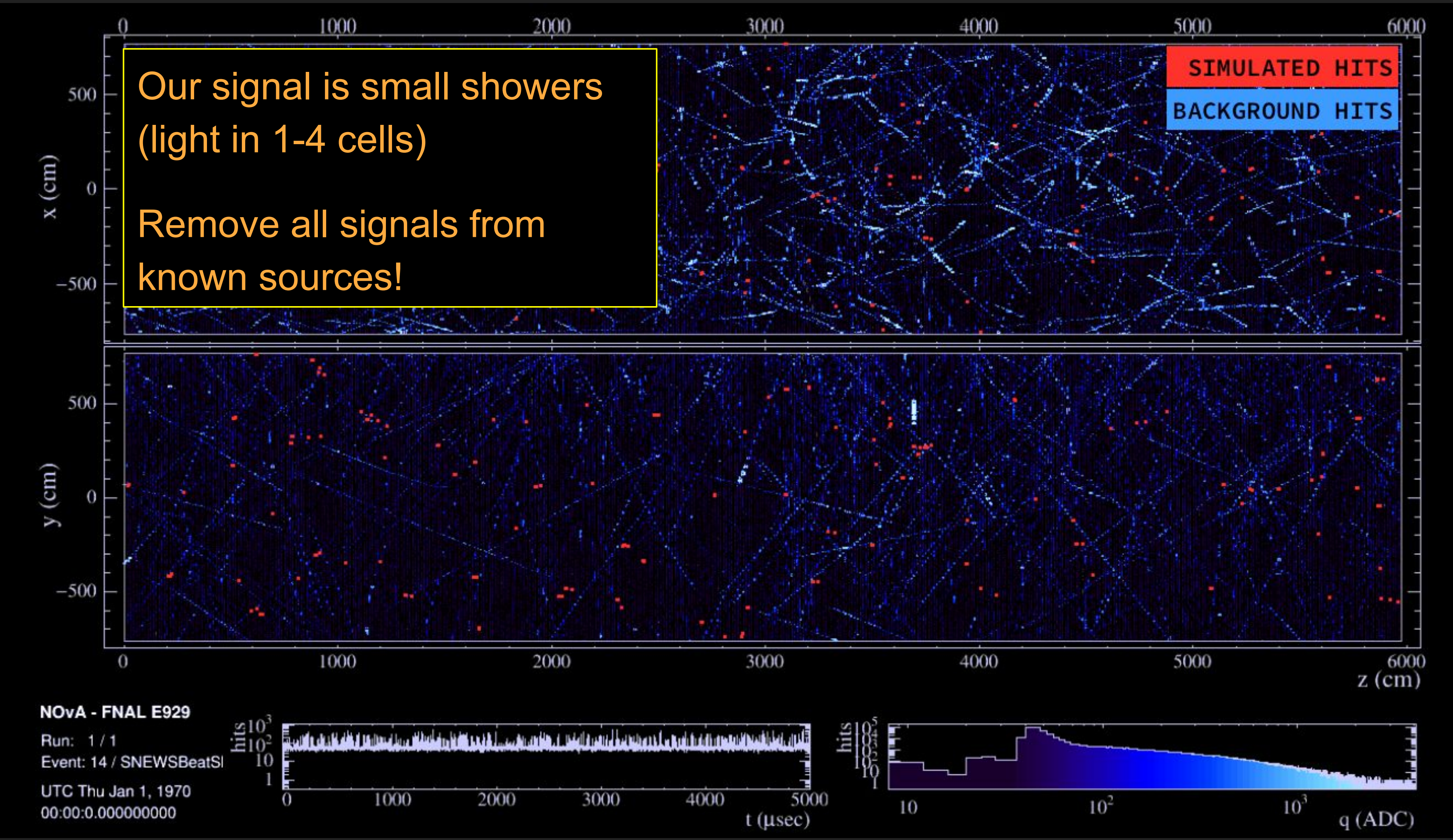
Our signal is small showers
(light in 1-4 cells)



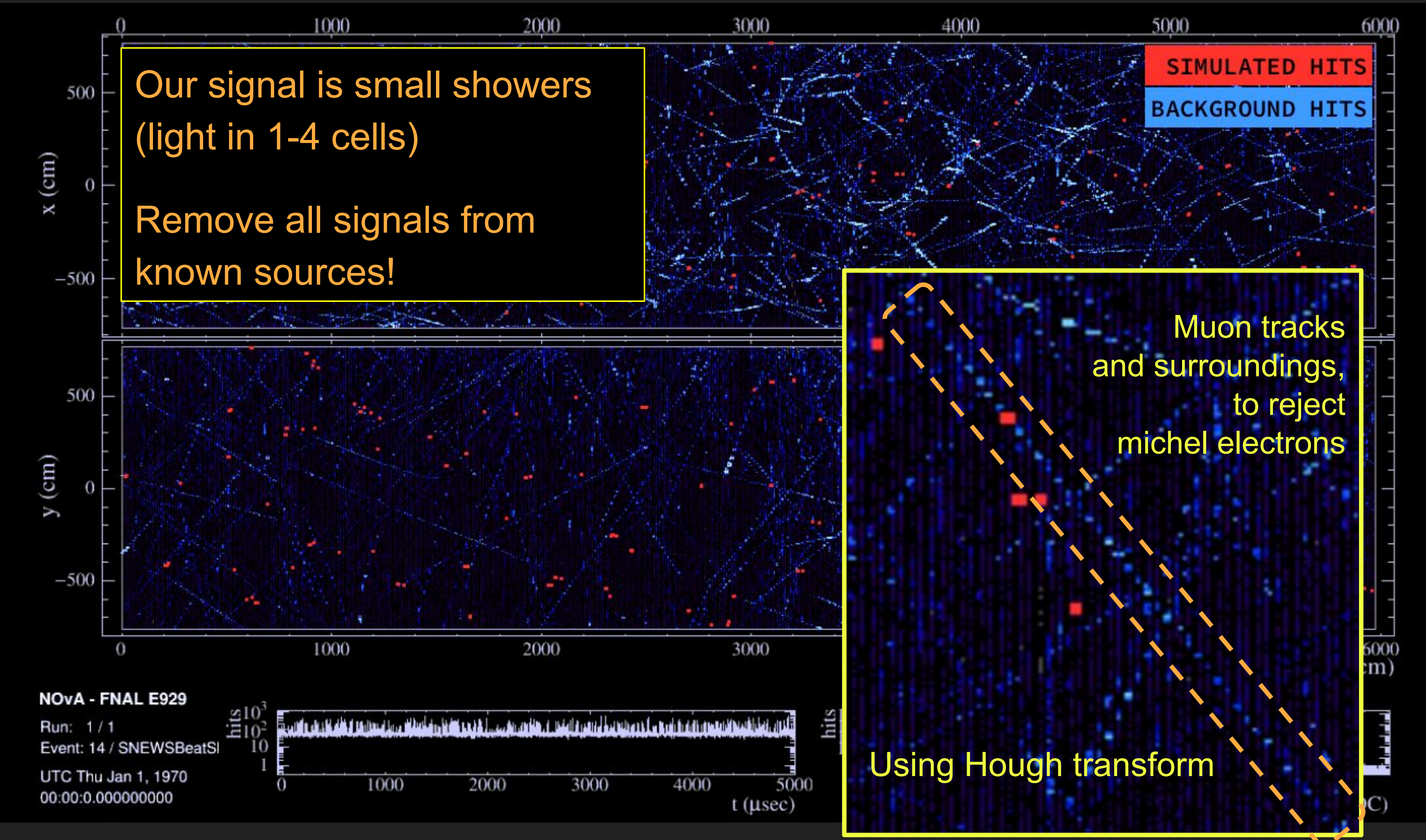
Signal selection

Our signal is small showers (light in 1-4 cells)

Remove all signals from known sources!



Signal selection



Our signal is small showers (light in 1-4 cells)

Remove all signals from known sources!

Muon tracks and surroundings, to reject michel electrons

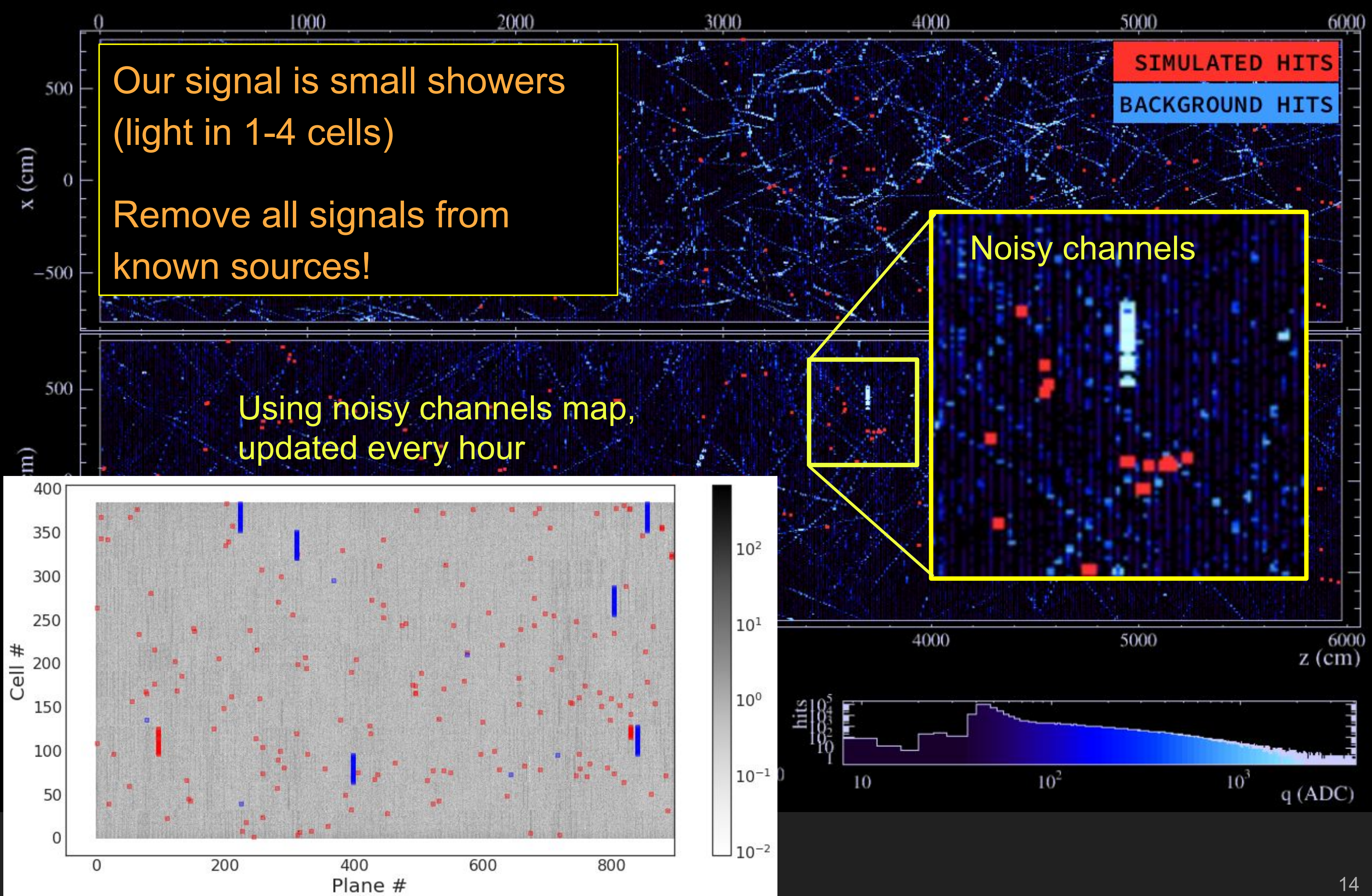
Using Hough transform

Signal selection

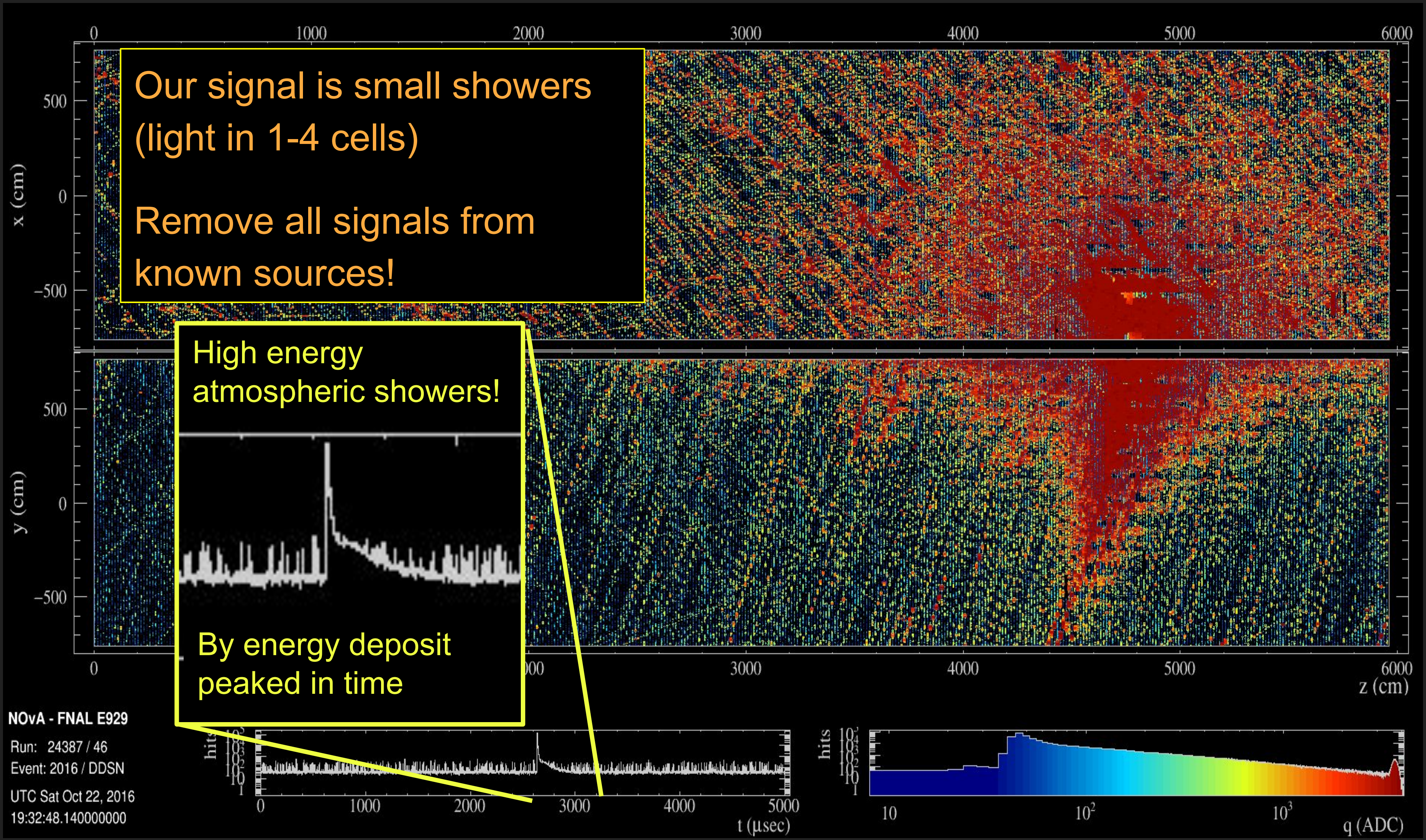
Our signal is small showers (light in 1-4 cells)

Remove all signals from known sources!

Using noisy channels map, updated every hour



Signal selection



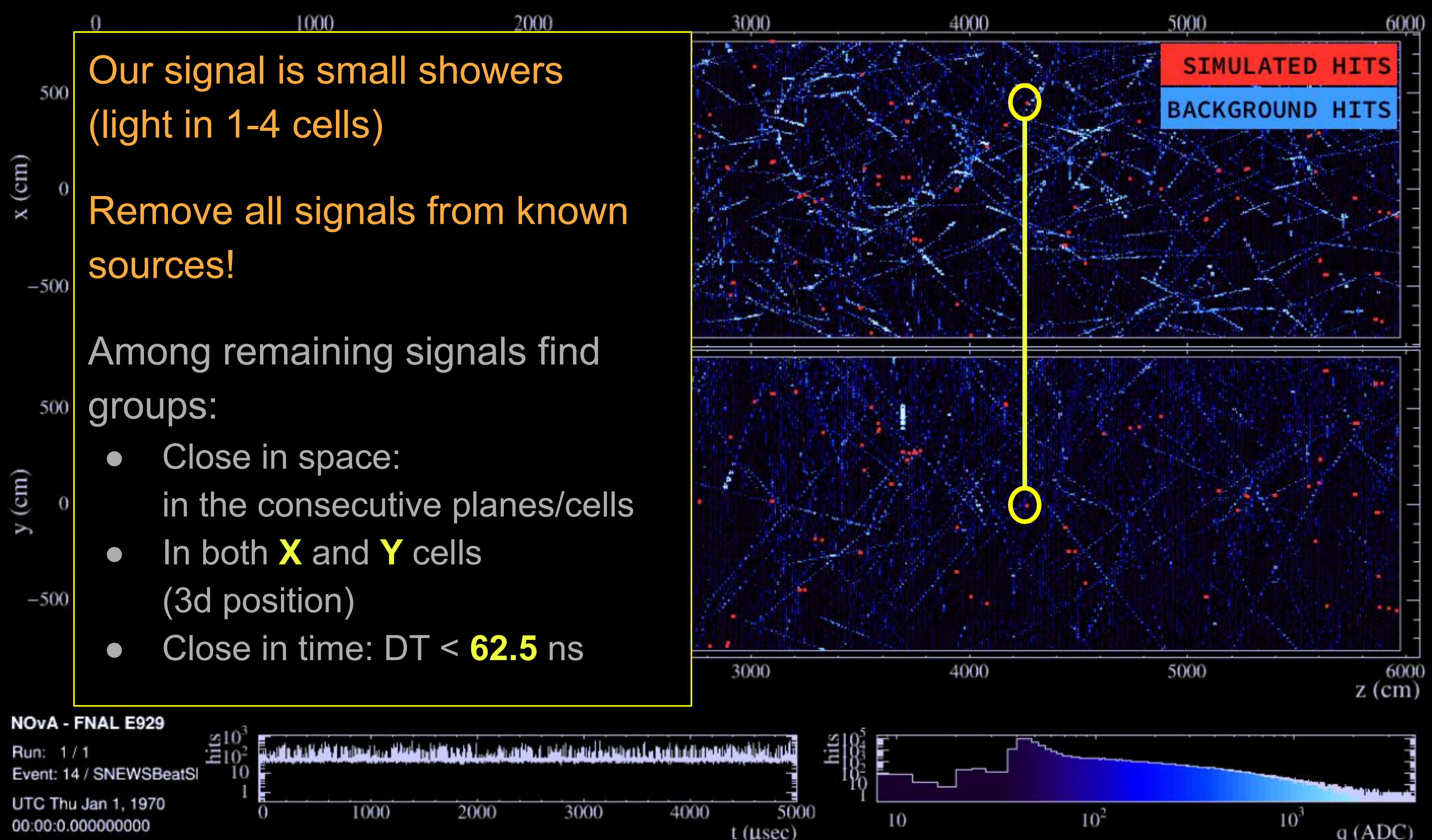
Signal selection

Our signal is small showers (light in 1-4 cells)

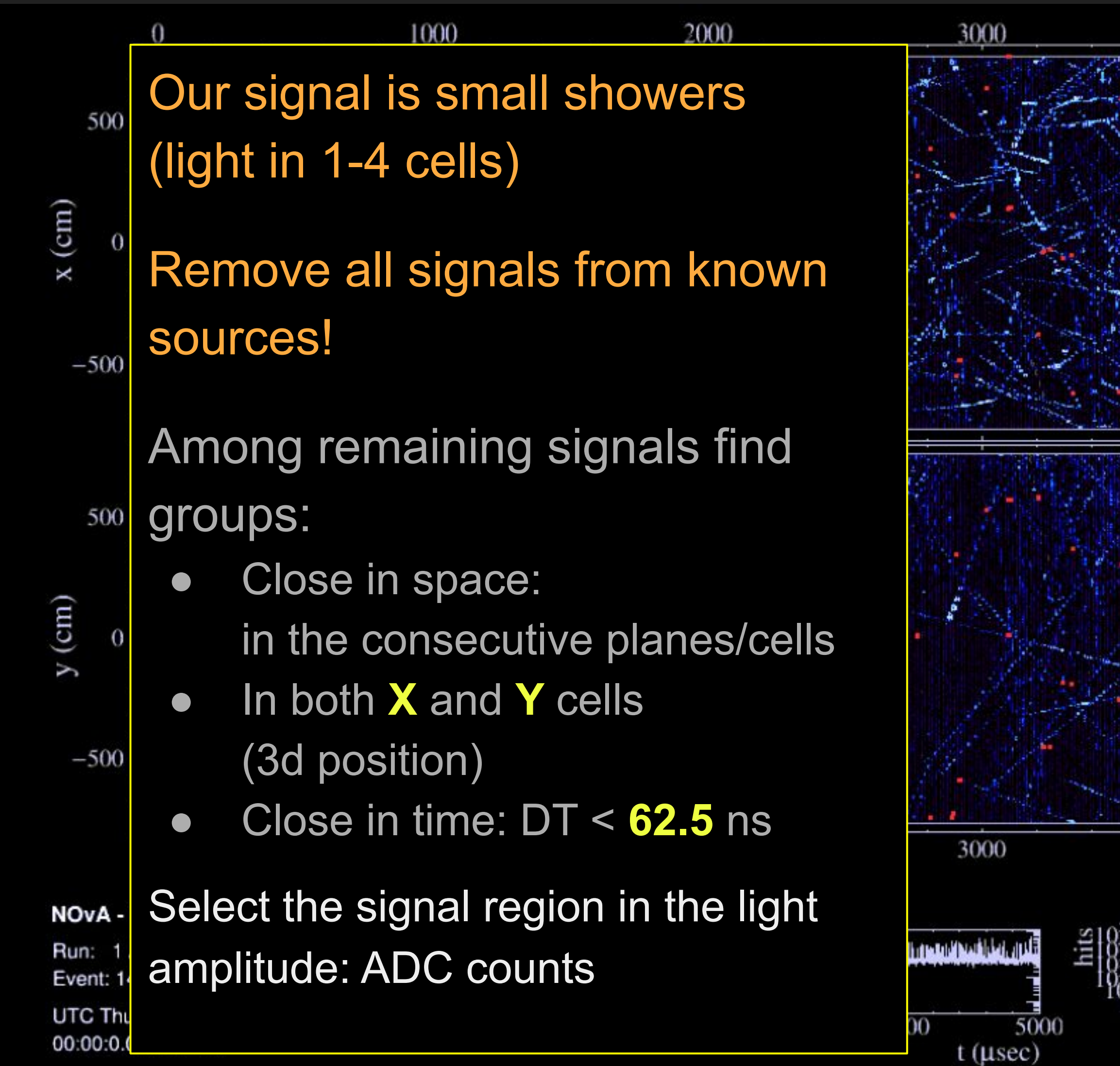
Remove all signals from known sources!

Among remaining signals find groups:

- Close in space: in the consecutive planes/cells
- In both **X** and **Y** cells (3d position)
- Close in time: DT < **62.5** ns



Signal selection



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Remove all signals from known sources!

Among remaining signals find groups:

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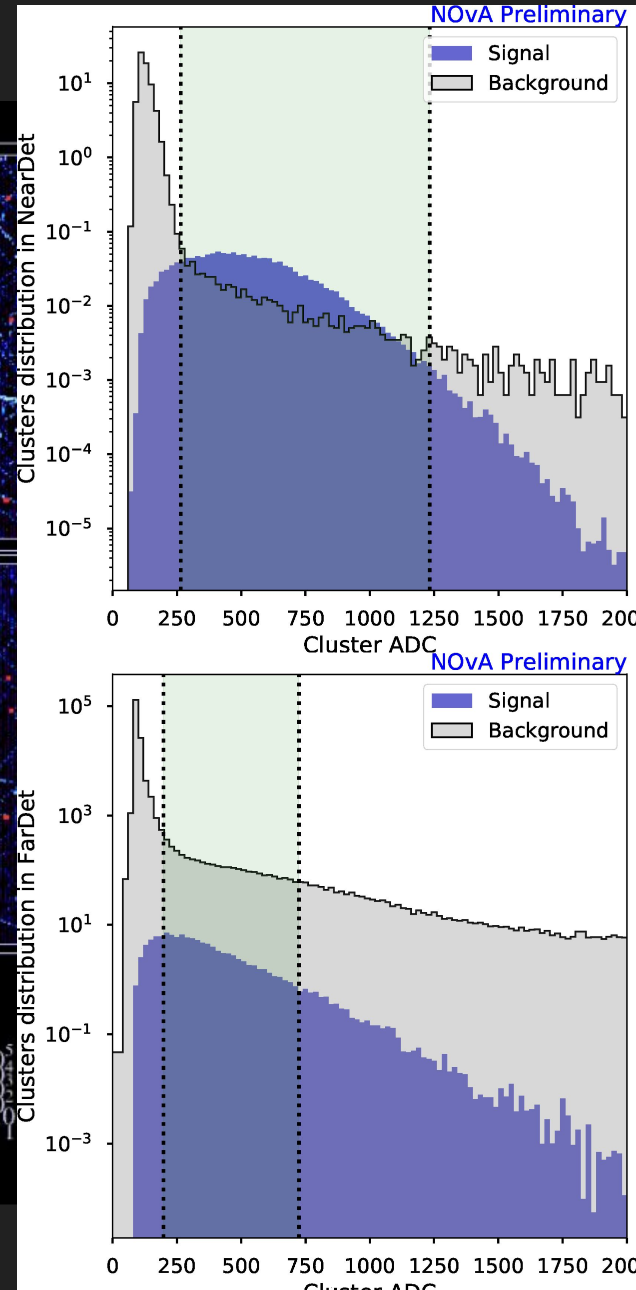
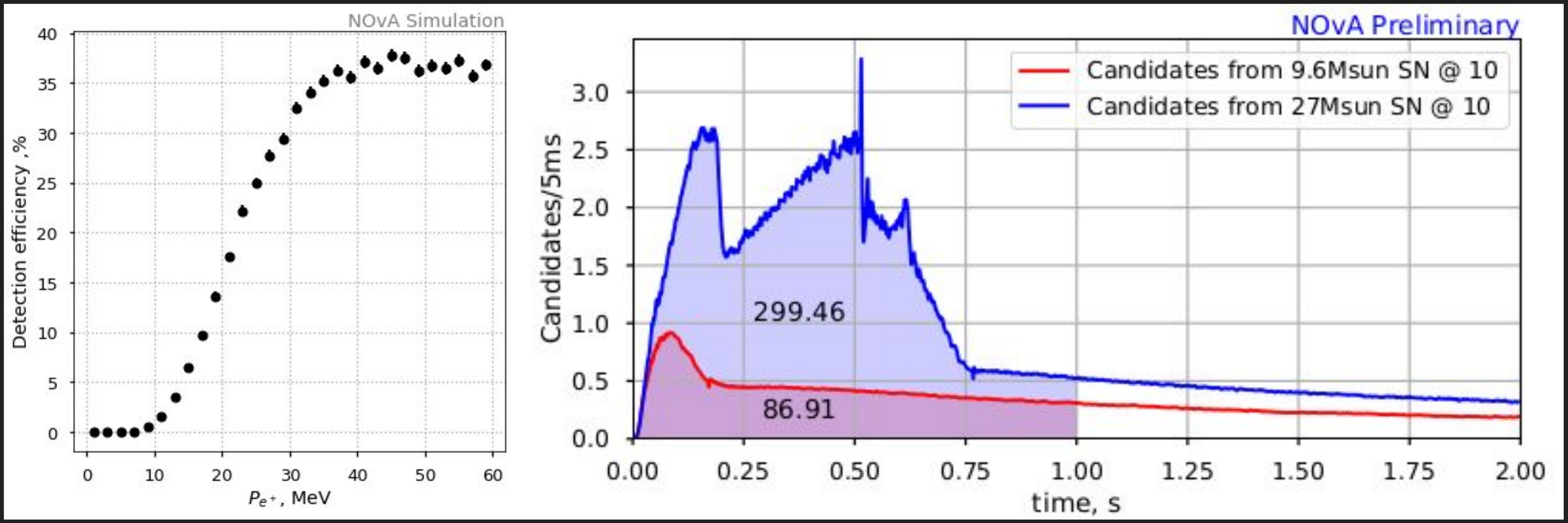
- Close in time: DT < **62.5** ns

Select the signal region in the light amplitude: ADC counts



Results of the neutrino candidates selection



In order to trigger on the galactic supernova neutrino signal, we need to observe the signal excess above the background fluctuations.

This has to be performed in realtime

Detector	Signal	Background
Near	1.28/s	0.52/s
Far	87/s	2500/s

If the observed signal significance exceeds threshold, the trigger saves the SN data for offline analysis.

SN triggering system for NOvA

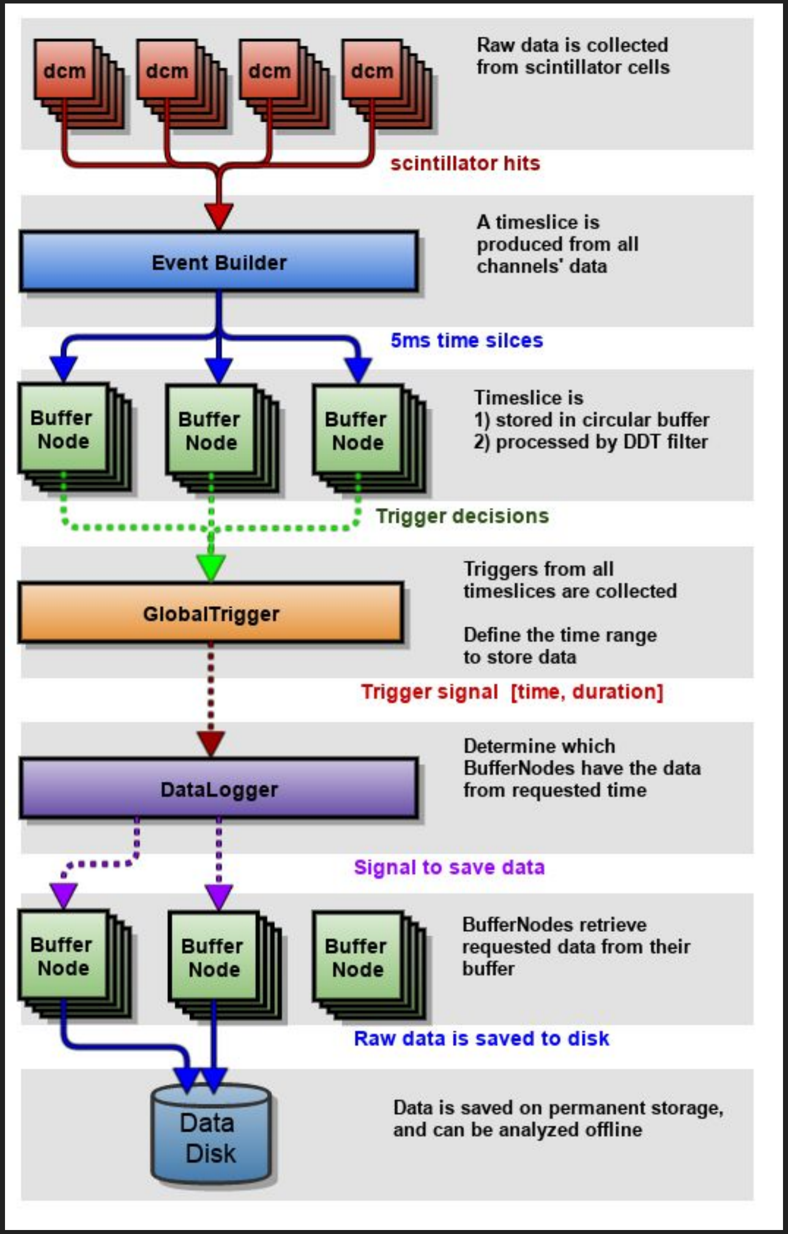
We want to react fast in case of a supernova.

A real-time reconstruction is needed, to decide if we see the signal.

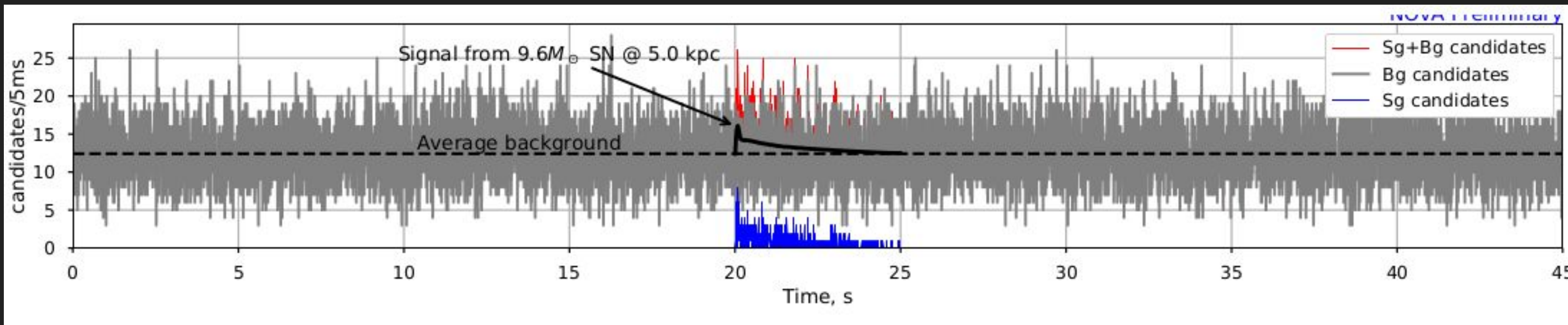
A dedicated triggering system was designed and developed to make SN detection possible.

Data is processed in parallel:
170 nodes * 13 processes,
each processing a 5ms “milliblocks”

Rate of neutrino candidates vs time
is analyzed, to decide if we see a supernova.



Signal processing and triggering: example



Trigger system needs to distinguish between **H_0=Bg** vs **H_1=Bg+SN** hypotheses.

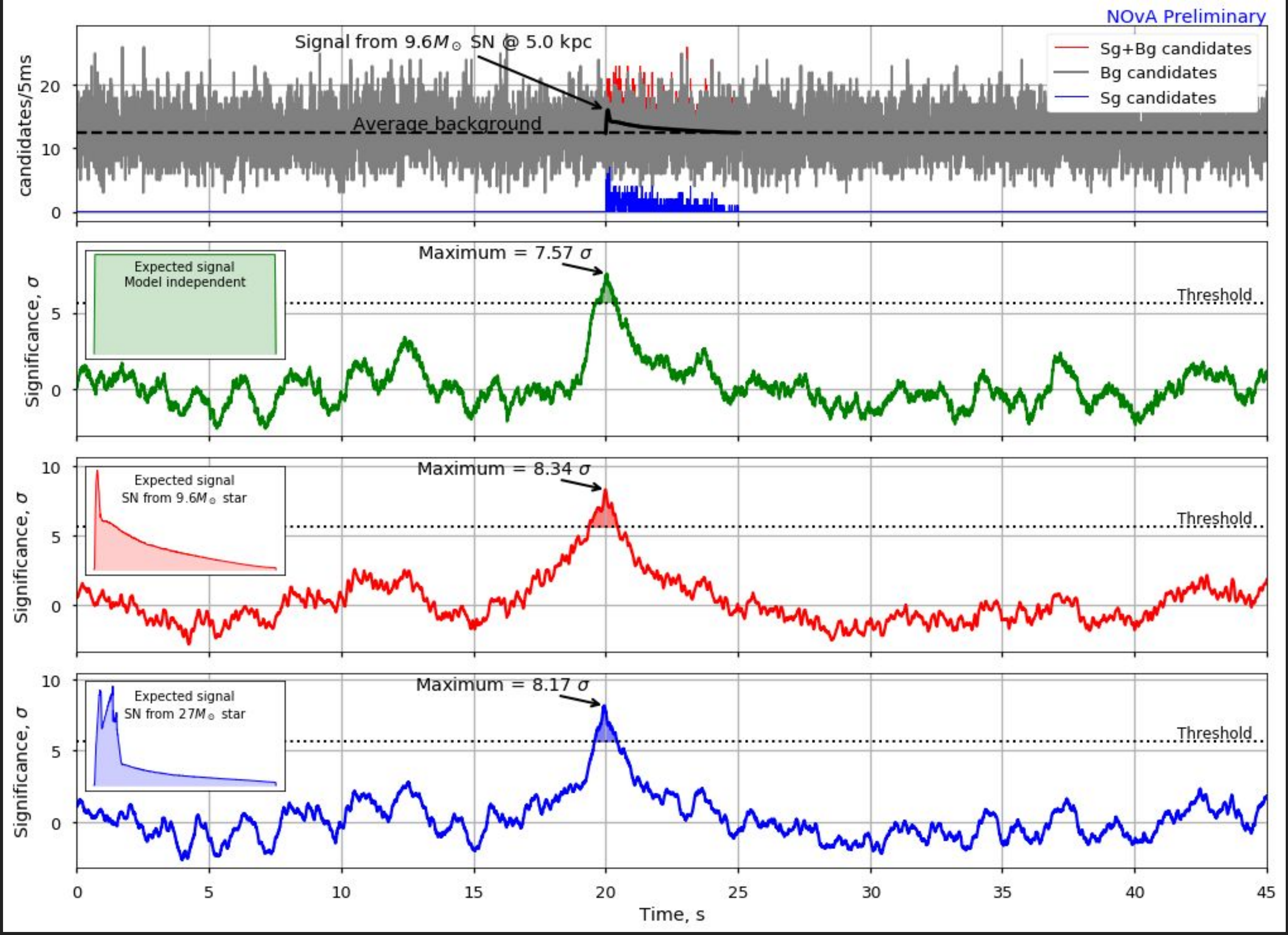
Easiest thing: just look for the N events in a sliding time window. Easy. But:

- Short window (1s): we lose a lot of signal
- Long window (10s): we gain a lot of background

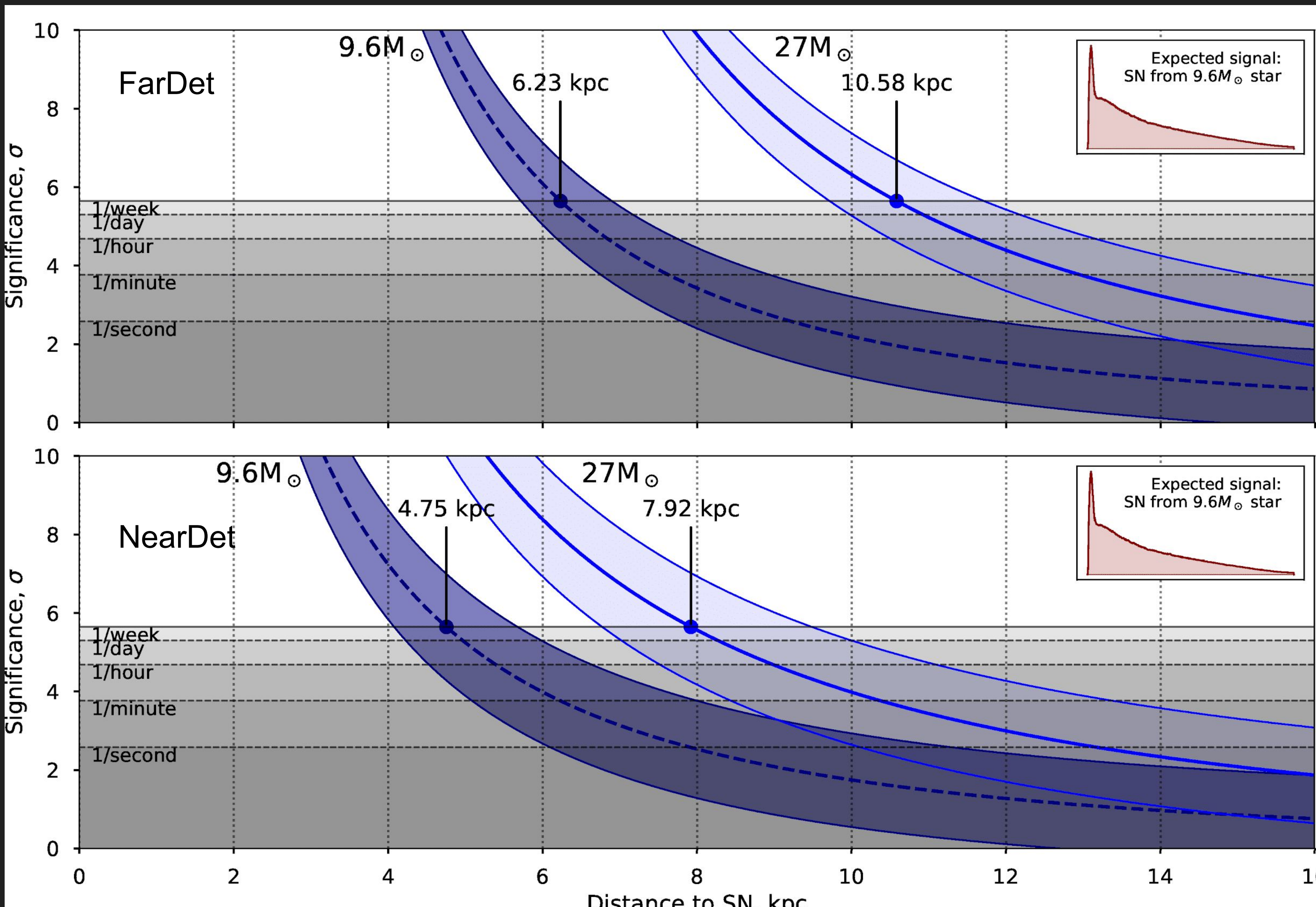
But we can use also the knowledge of the signal shape.
We use log likelihood ratio, to enhance the hypotheses discrimination:

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

Signal processing and triggering: example



Supernova significance vs. distance



What about detectors combination?

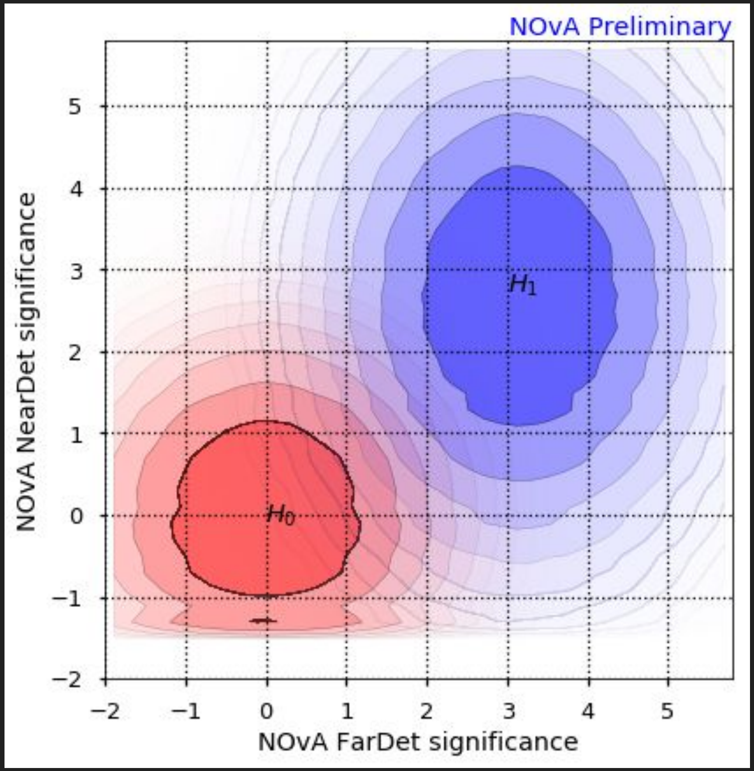
Previously the trigger in each detector performed hypotheses discrimination: ***H_0*** vs ***H_1*** using the input data.

Several detectors, measuring significance:

$$\{z\} = \{z_1, z_2, \ldots, z_N\}$$

Define some function $X(\{z\})$ - test statistics to discriminate the hypotheses.

There are many ways to define this function.



NOvA can be used as a small coincidence network => Prototype for SNEWSv2.
For NOvA case: $\{z_{Near}, z_{Far}\}$.

What about detectors combination?

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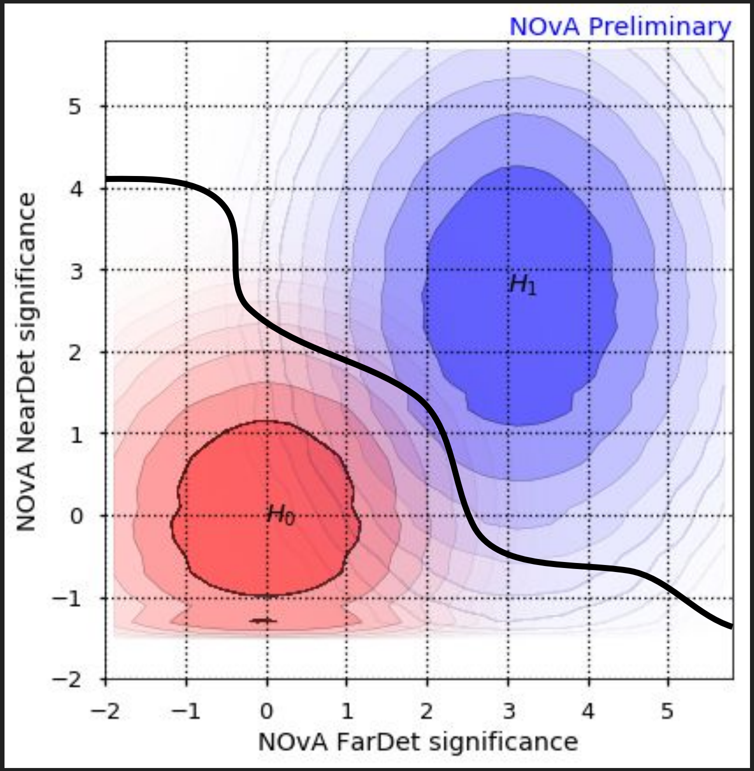
There are many ways to define this function.

- Requirements: high X for H_1, low X for H_0, maximal separation



Threshold on X defines the trigger - if the {z} are in “background” on “signal” region.

What about detectors combination?

Previously the trigger in each detector performed hypotheses discrimination: ***H_0*** vs ***H_1*** using the input data.

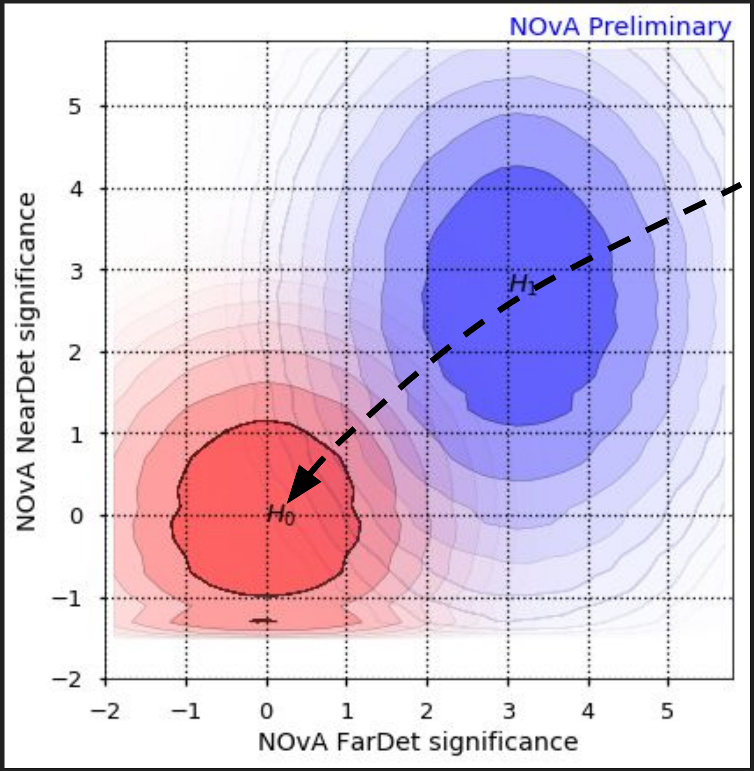
Several detectors, measuring significance:

$$\{z\} = \{z_1, z_2, ..., z_N\}$$

Define some function $X(\{z\})$ - test statistics to discriminate the hypotheses.

There are many ways to define this function.

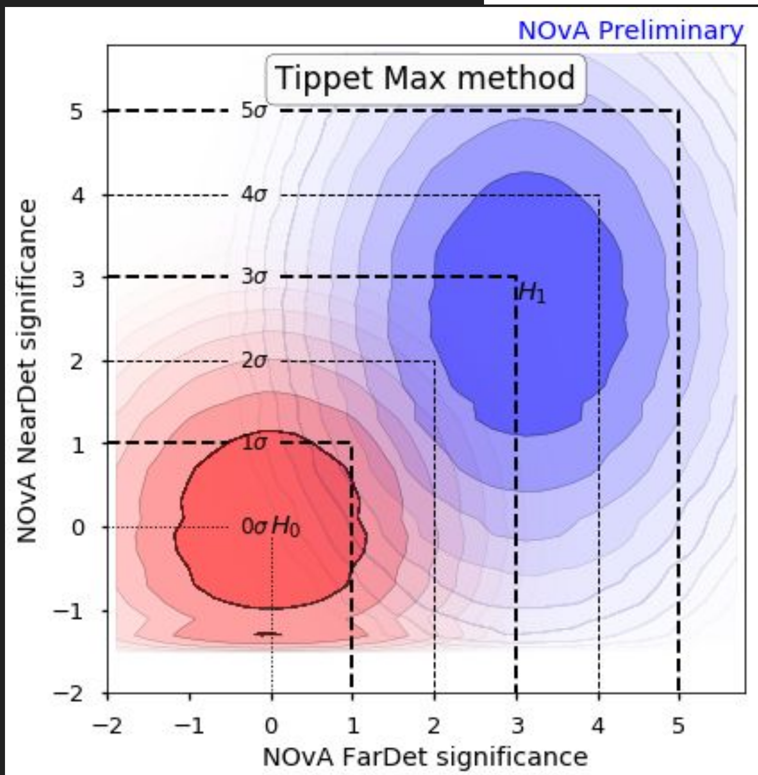
- Requirements: high X for H_1, low X for H_0, maximal separation
- Should be valid for SN on various distances (and various models)



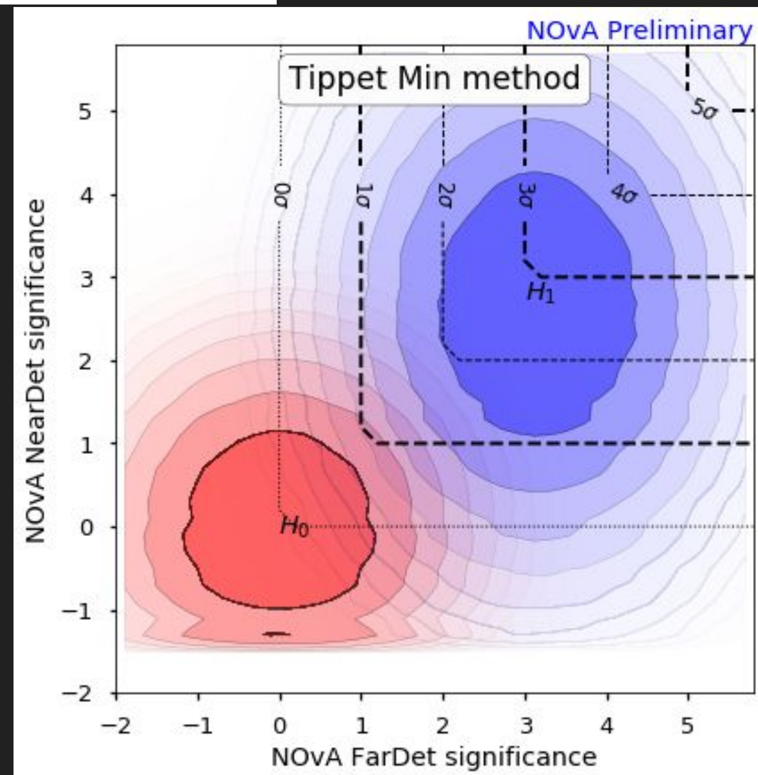
As SN distance grows, the H_1 center moves along the dashed line.

Tippet's combination method

X=n-th smallest of($\{z\}$)



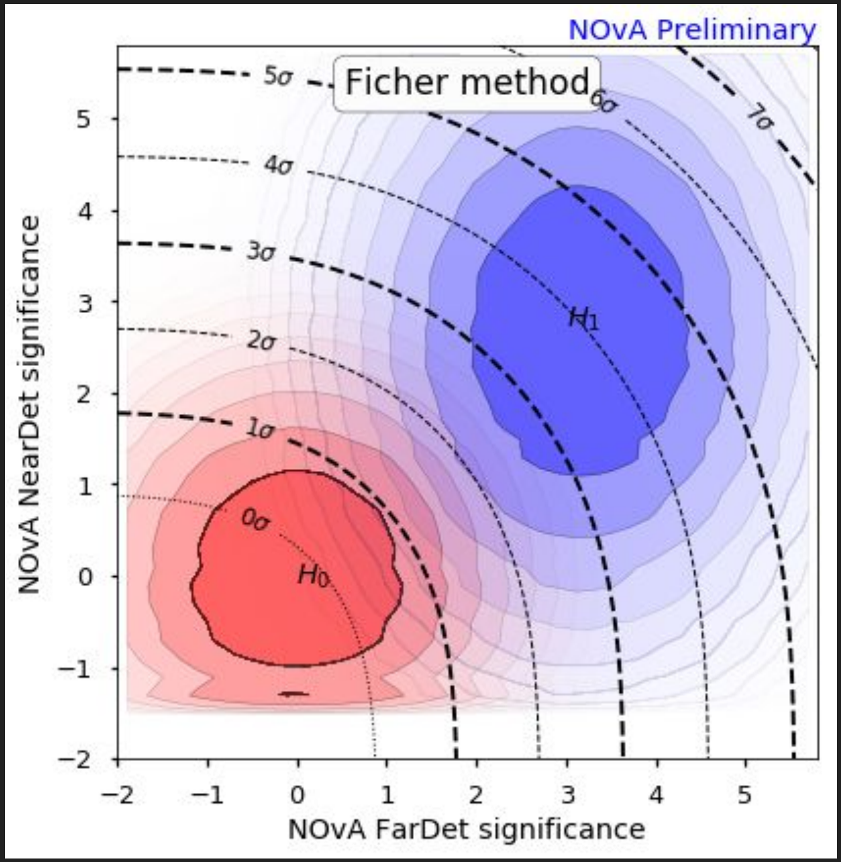
FarDet OR NearDet



FarDet AND NearDet

- Corresponds to logical AND/OR combination of triggers
- Low discrimination power
- This is the mode, SNEWSv1 operates.

Fischer's combination method



$$X_N^2 = -2 \sum_{i}^{N} \ln p_i$$

X has a chi2 distribution with N_{exp} DOFs.

Advantages:

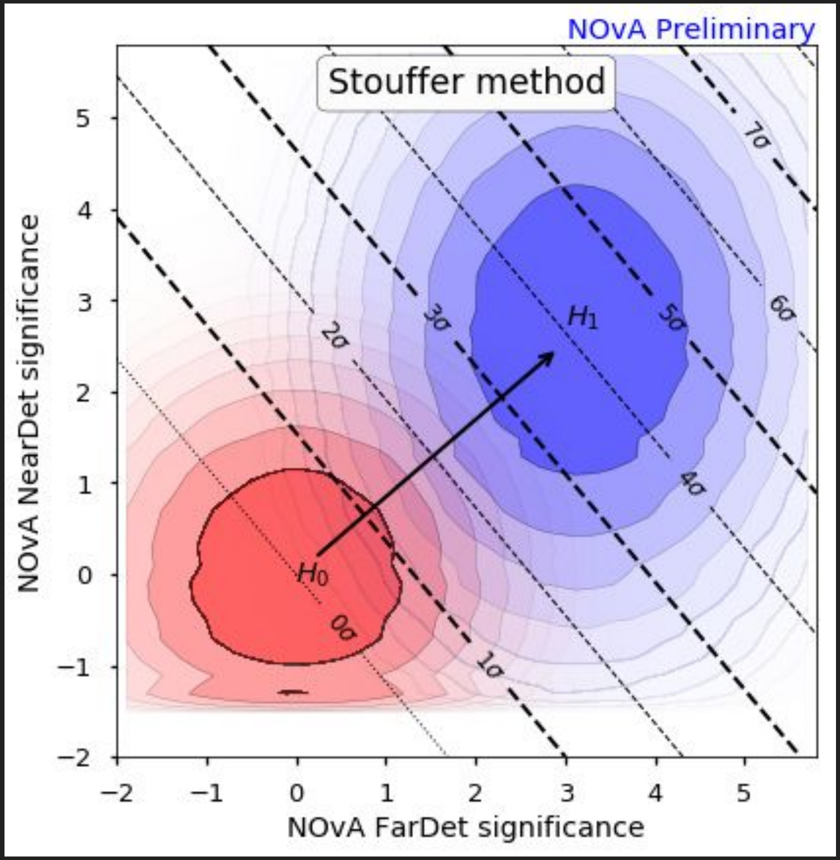
- Most commonly used method
- Discrimination power is quite high in most cases.
- Works for low and high BG

Disadvantages

- Computationally complex, might be bad for real-time systems
- Depends on number of experiments connected
- Low sensitivity experiment can spoil the total sensitivity

Stouffer's combination

$$S = \sum_{i}^{N} w_i z_i = (\vec{w} \cdot \vec{z})$$



S is resulting significance score

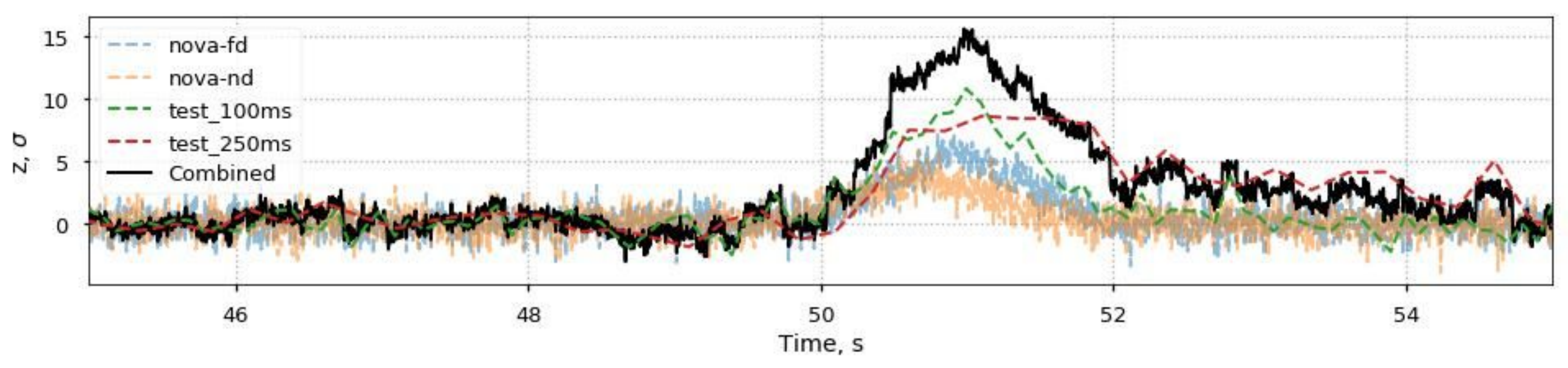
Advantages:

- Always the same distribution for any number of experiments.
- Weights are proportional to mean significance of "standard candle" supernova observation
- Linear! If we want to integrate in time, same result if done before combining or after.
- Easy to account for correlations

Disadvantages:

- Works bad for low statistics (low BG)

A prototype SN combination server was developed



- Features:
  - Security - SSL encryption
  - Client authentication
  - Adapting to the connected detectors
  - Using Stouffer’s method for significance combination

NOvA detectors and couple of two additional “test experiments” produce a good significance combined (fake data test).

Plans: use this combination for NOvA detectors for triggering.

Summary

- Real-time detection of SN signals is crucial for studying supernova.
- The dedicated SN triggering system extends the NOvA physical program.
    - Signal selection and reconstruction in real time.
    - Operating since Nov 2017, tuned to false triggering rate ~1/week.
    - Expected signal shape is used for hypotheses testing.
- SNEWS alert network was operating since 1998,
    - now SNEWS v2.0 is being designed.
- Proposed significance combination method (Stouffer's weighted linear combination):
    - good for the case of high background experiments (like NOvA of Ice-Cube)
    - applicable for pre-supernova signals in low-BG experiments.
- Server prototype was developed and soon will be tested on NOvA detectors.

Stay tuned!

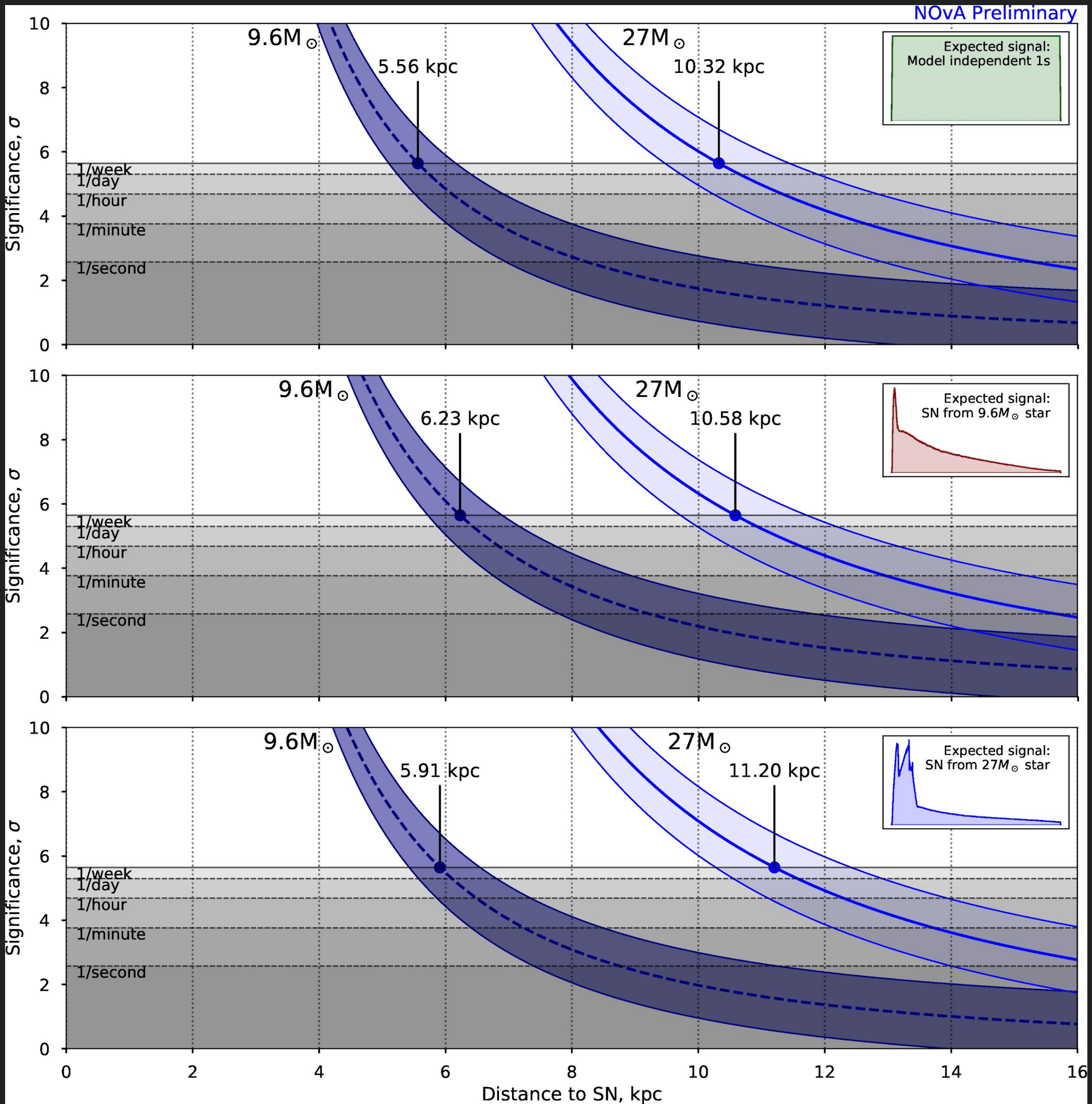
Backup

Candidates selection: first second of SN signal

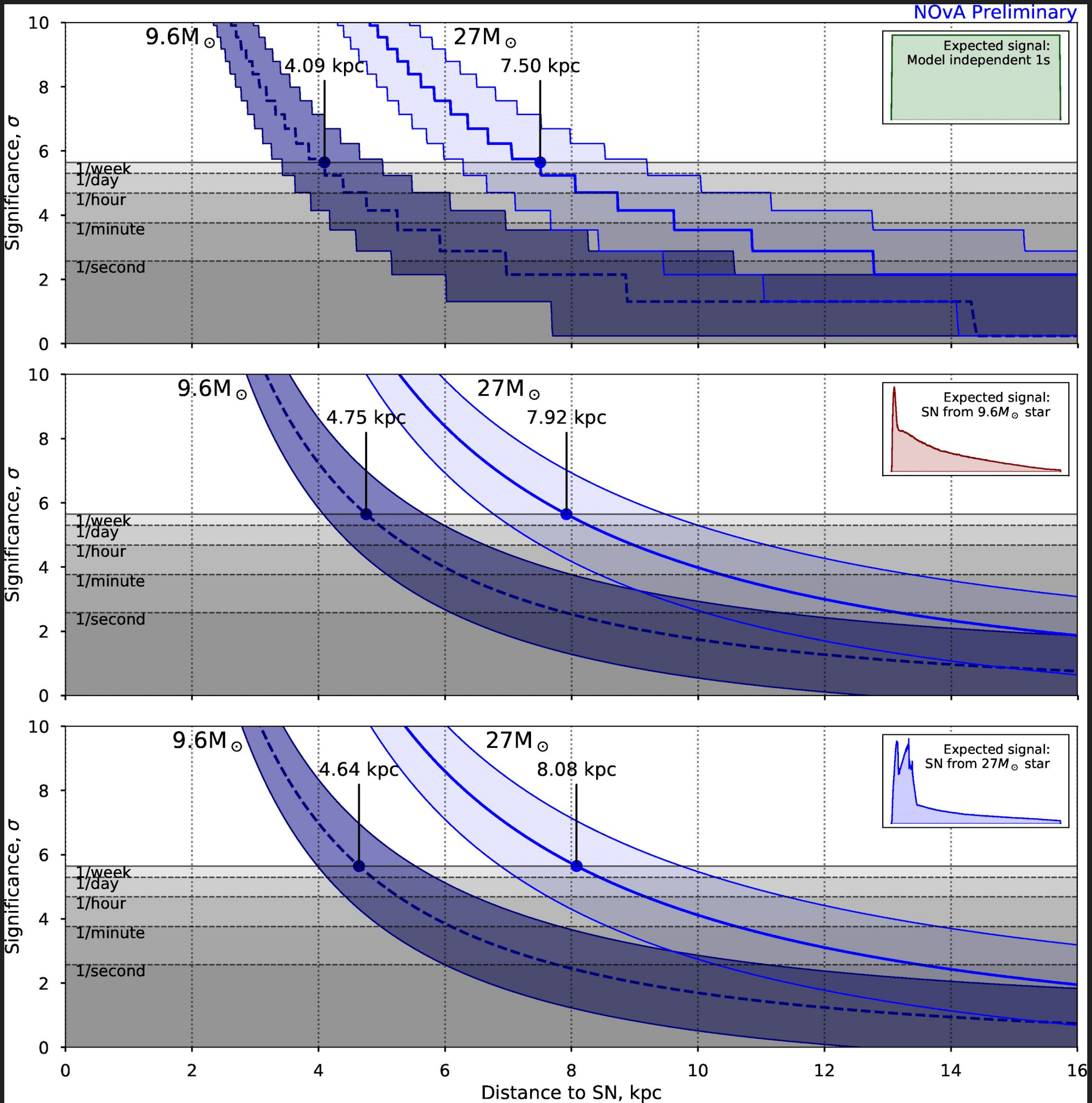
Far Detector	N_{sg}	ε_{sg}	N_{bg}	ε_{bg}	$N_{sg}/\sqrt{N_{bg}}$
Total	725.14	nan%	nan	nan%	nan
Reconstructed	316.24	43.61%	322811.99	nan%	0.5566
XY hits	145.16	45.90%	231866.53	71.83%	0.3015
Nhits cut	144.29	99.40%	224420.72	96.79%	0.3046
Fiducial Volume cut	117.77	81.62%	170436.38	75.95%	0.2853
ADC cut	86.75	73.66%	3429.27	2.01%	1.481
Group removal	86.64	99.87%	2483.21	72.41%	1.739

Near Detector	N_{sg}	ε_{sg}	N_{bg}	ε_{bg}	$N_{sg}/\sqrt{N_{bg}}$
Total	10.83	nan%	nan	nan%	nan
Reconstructed	3.16	29.16%	403.95	nan%	0.1572
XY hits	2.19	69.35%	215.64	53.38%	0.1492
Nhits cut	2.18	99.54%	208.86	96.85%	0.1509
Fiducial Volume cut	1.48	68.05%	67.63	32.38%	0.1804
ADC cut	1.28	86.06%	0.55	0.82%	1.715
Group removal	1.28	100.00%	0.52	93.42%	1.774

Supernova significance vs. distance: FarDet



Supernova significance vs. distance: NearDet



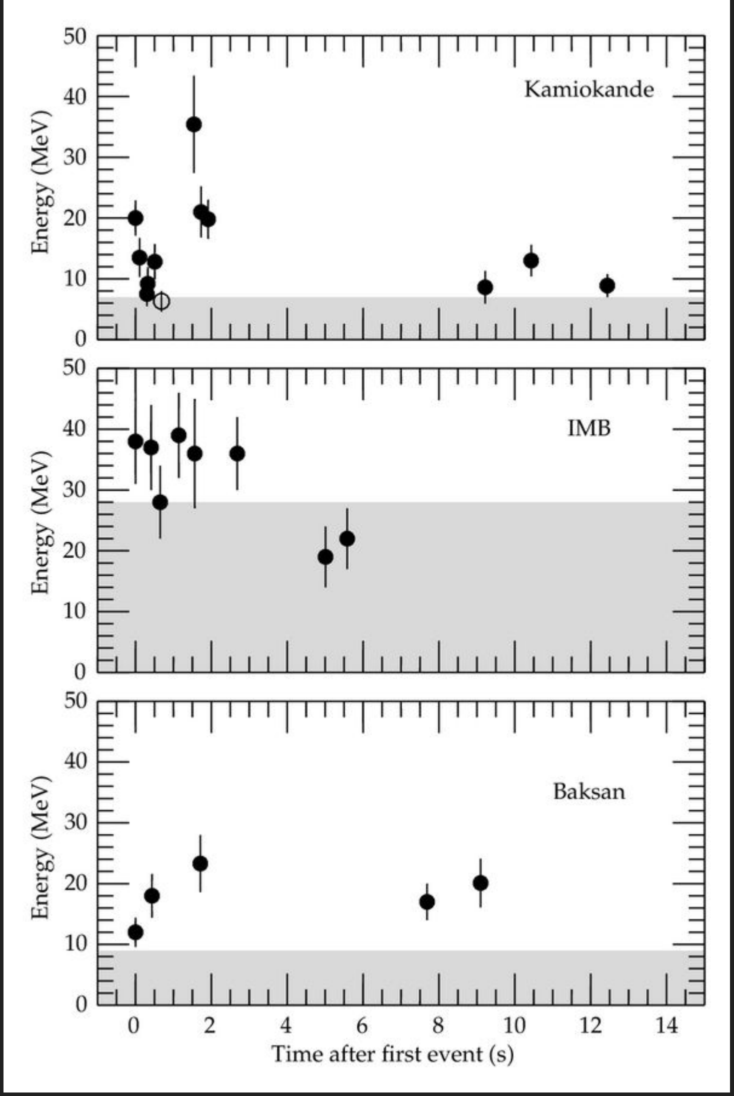
Supernova neutrino signal detection: SN1987a

23 Feb 1987, 7:35 UTC

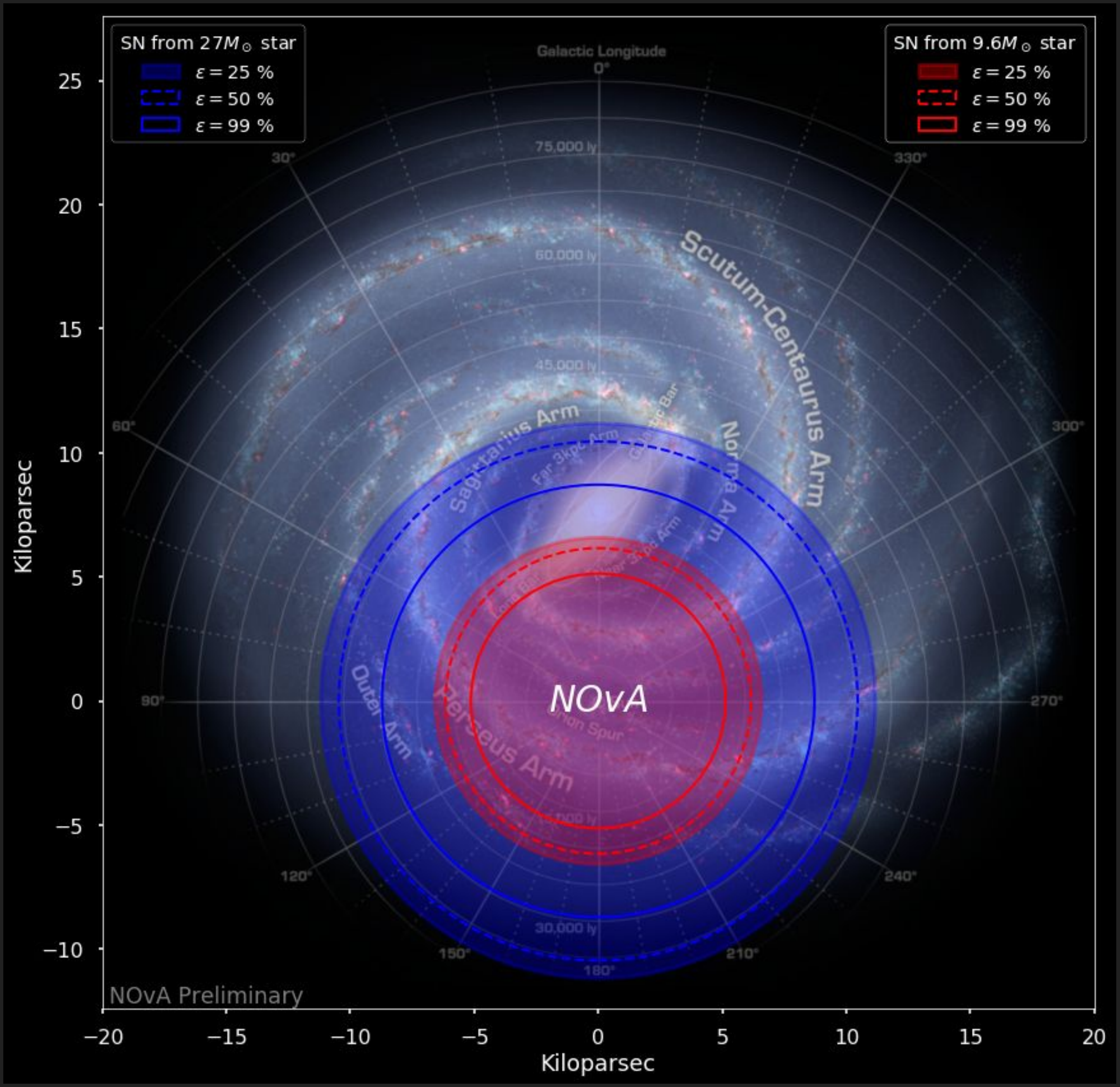
A burst of **25** neutrino events within **13** seconds observed in three underground neutrino experiments.

Light signal appeared 2-3 hours later: a supernova explosion in the Large Magellanic cloud (51 kpc away)

Low-background neutrino experiments: they were able to look back at the data in the region of interest.



NOvA supernova trigger sensitivity



NOvA supernova trigger sensitivity