Detecting neutrinos from the next galactic supernova in the NOvA detectors

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Particles and Cosmology
16th Baksan School on Astroparticle Physics
11 Apr 2018

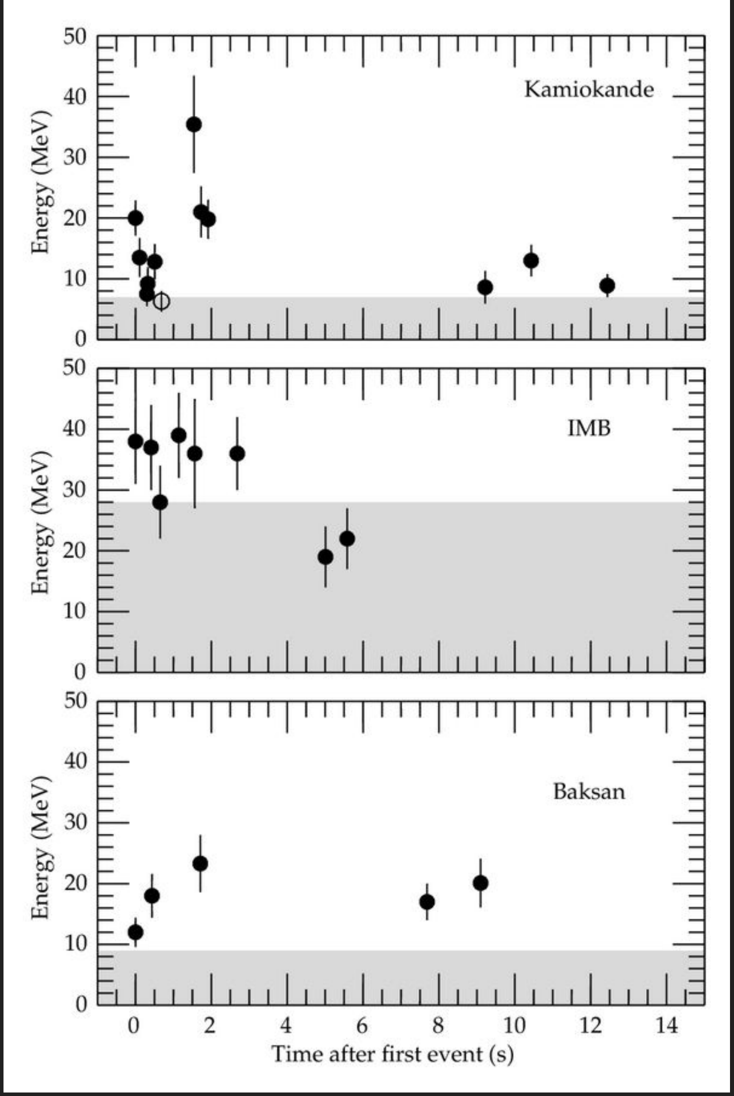
Supernova neutrino signal detection: SN1987a

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.



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**

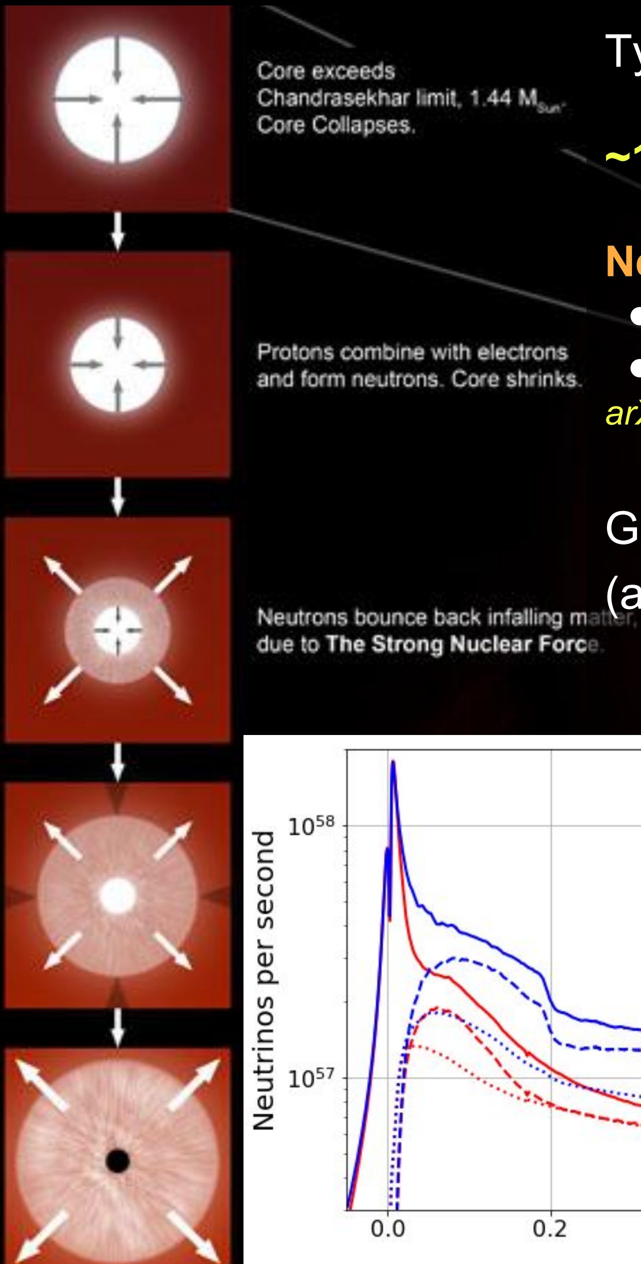
Neutrino signal: probe of

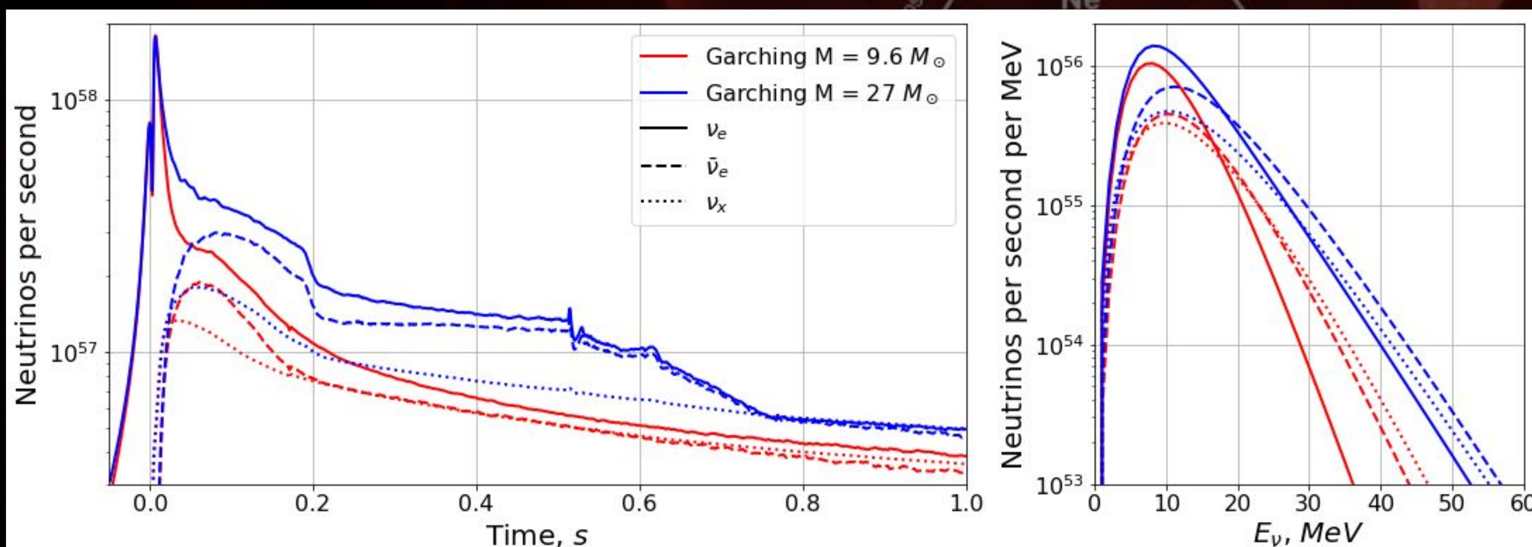
- Neutrino properties
- Supernova properties

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)





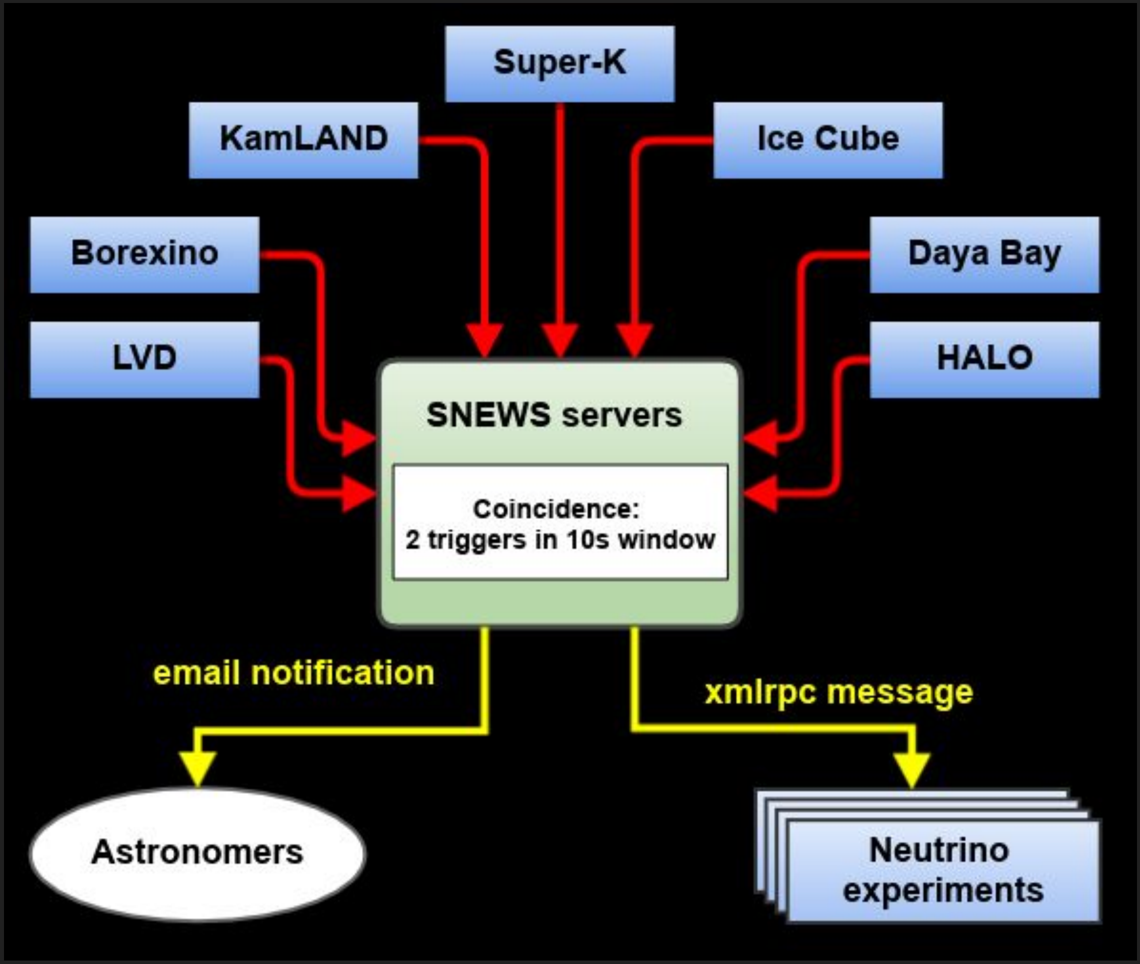
SuperNova Early Warning System

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

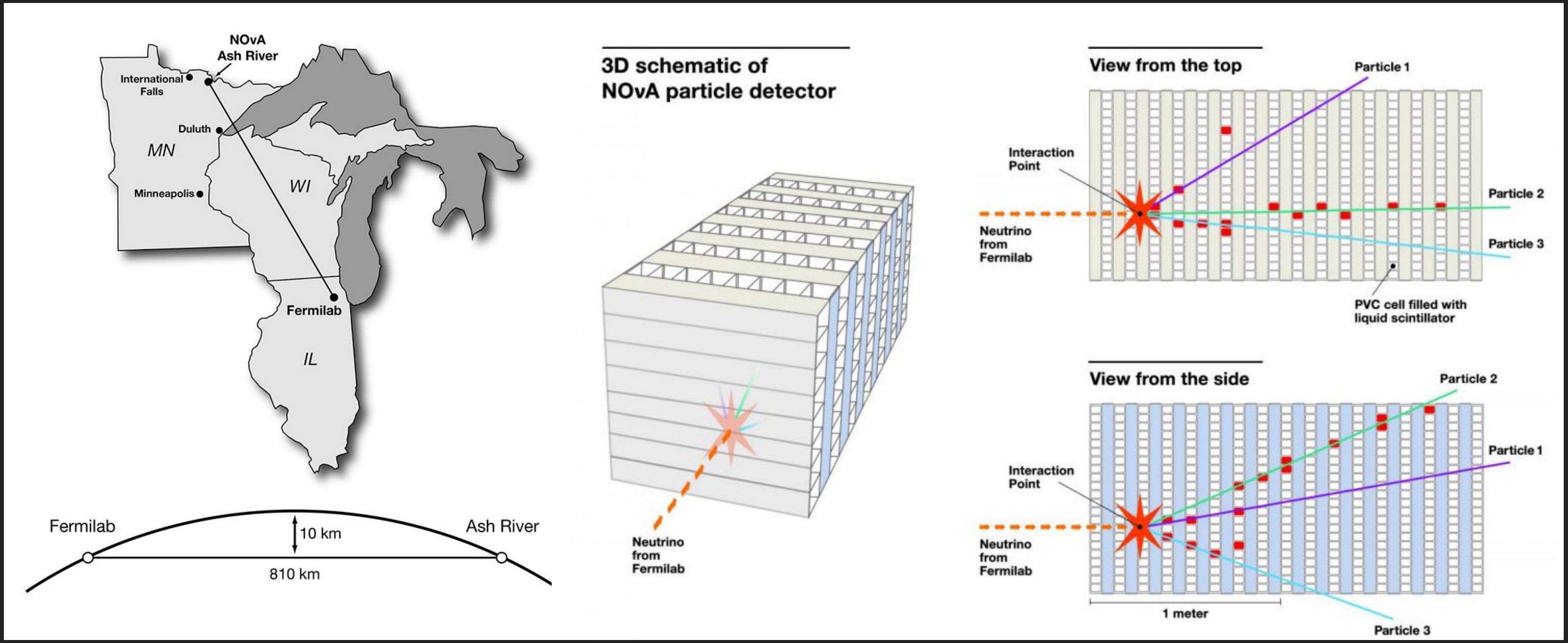
NOvA currently listens to a trigger from SNEWS, to save data in case of supernova.



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.

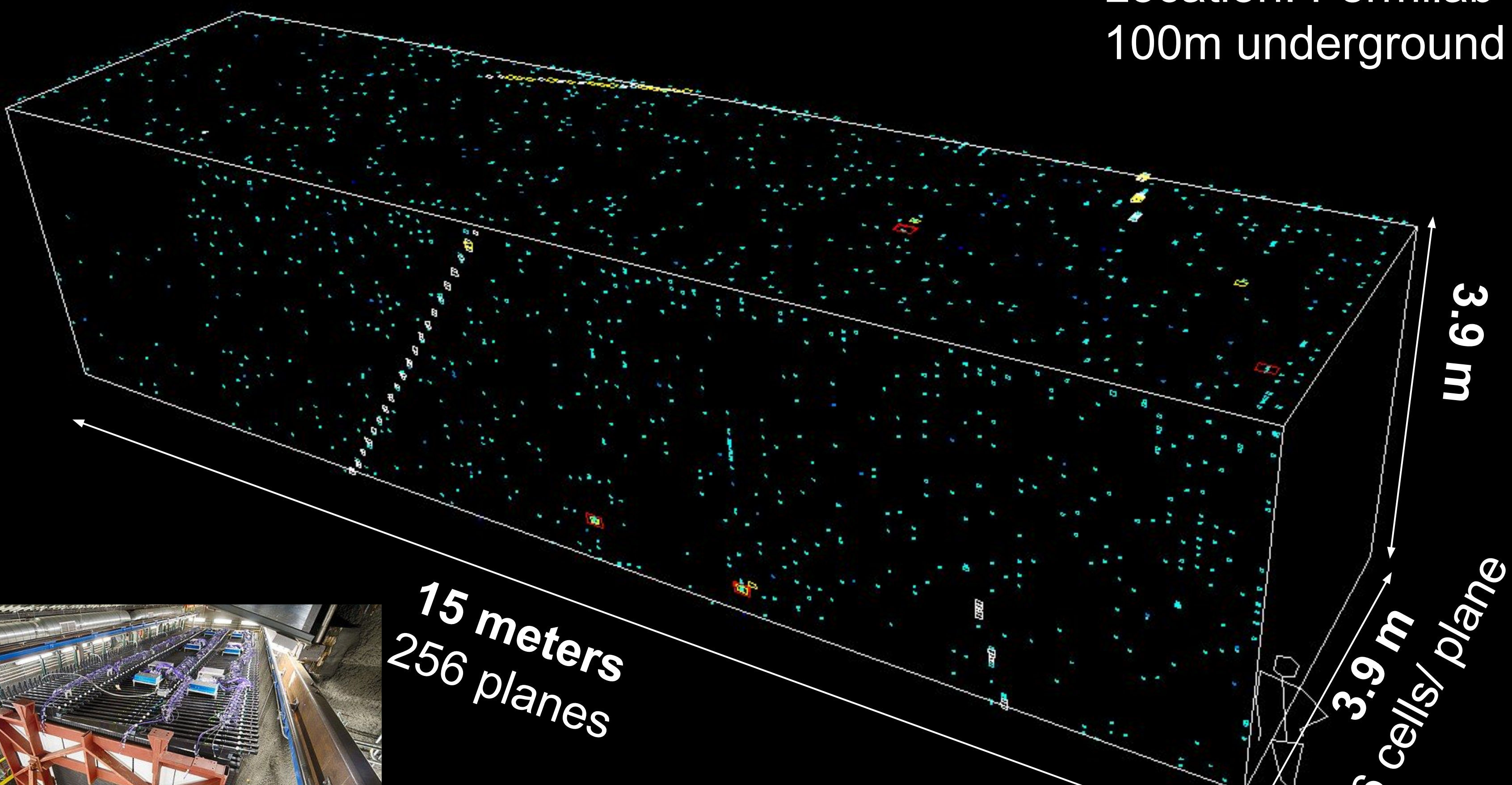
Detectors are composed of extruded PVC cells filled with liquid scintillator.
The scintillation light is transported by the wavelength shifting fibers, then read by APD



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

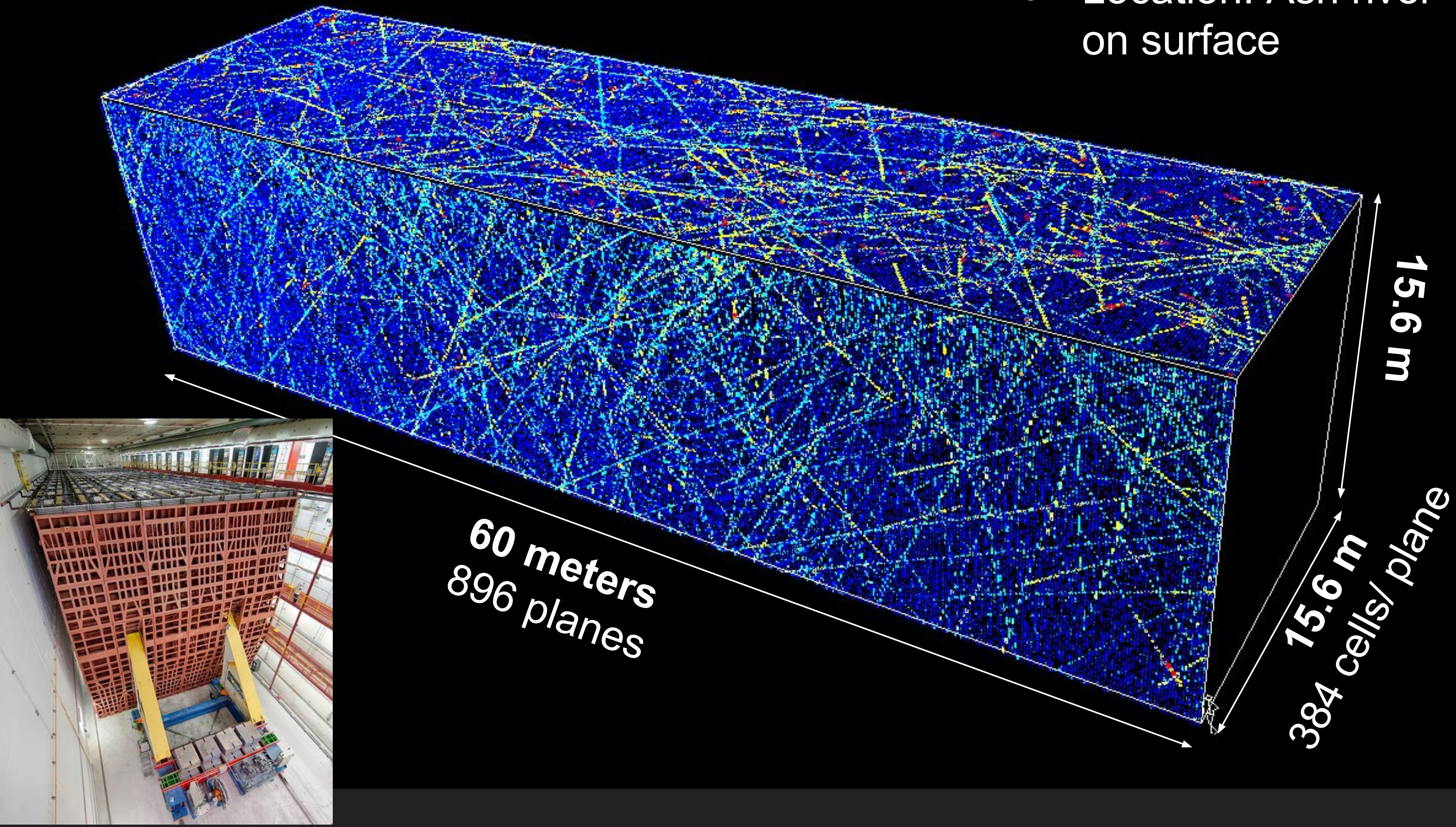
NOvA Near detector: 5ms time slice

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

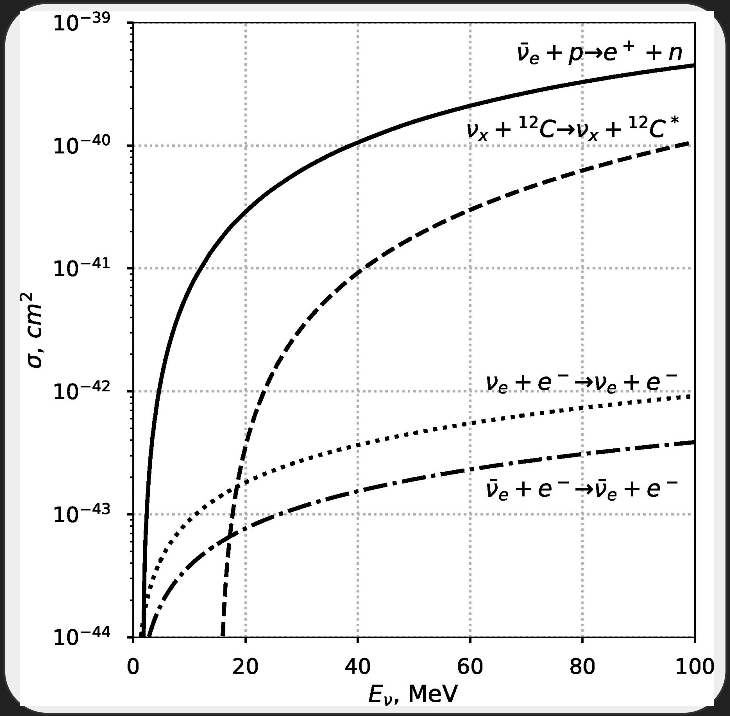


NOvA Far Detector: 5ms time slice

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

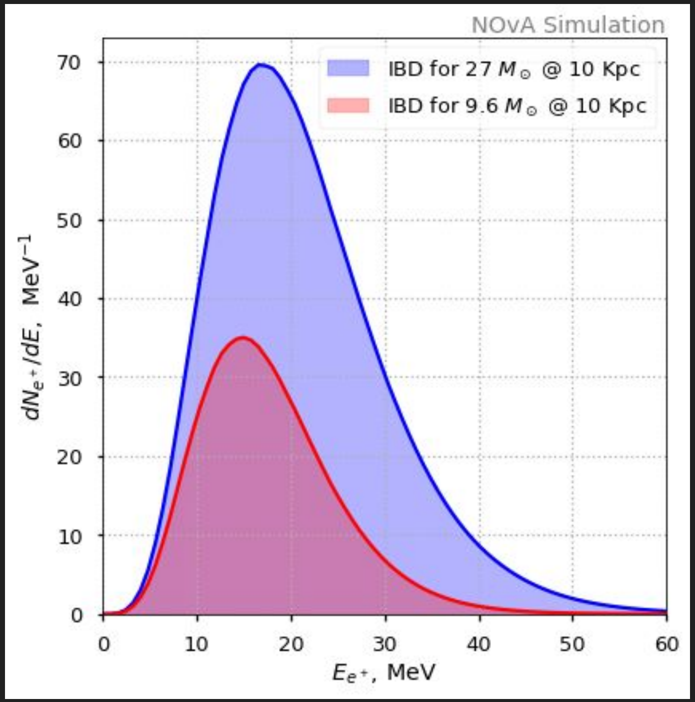


SN neutrinos interactions in the NOvA Detectors



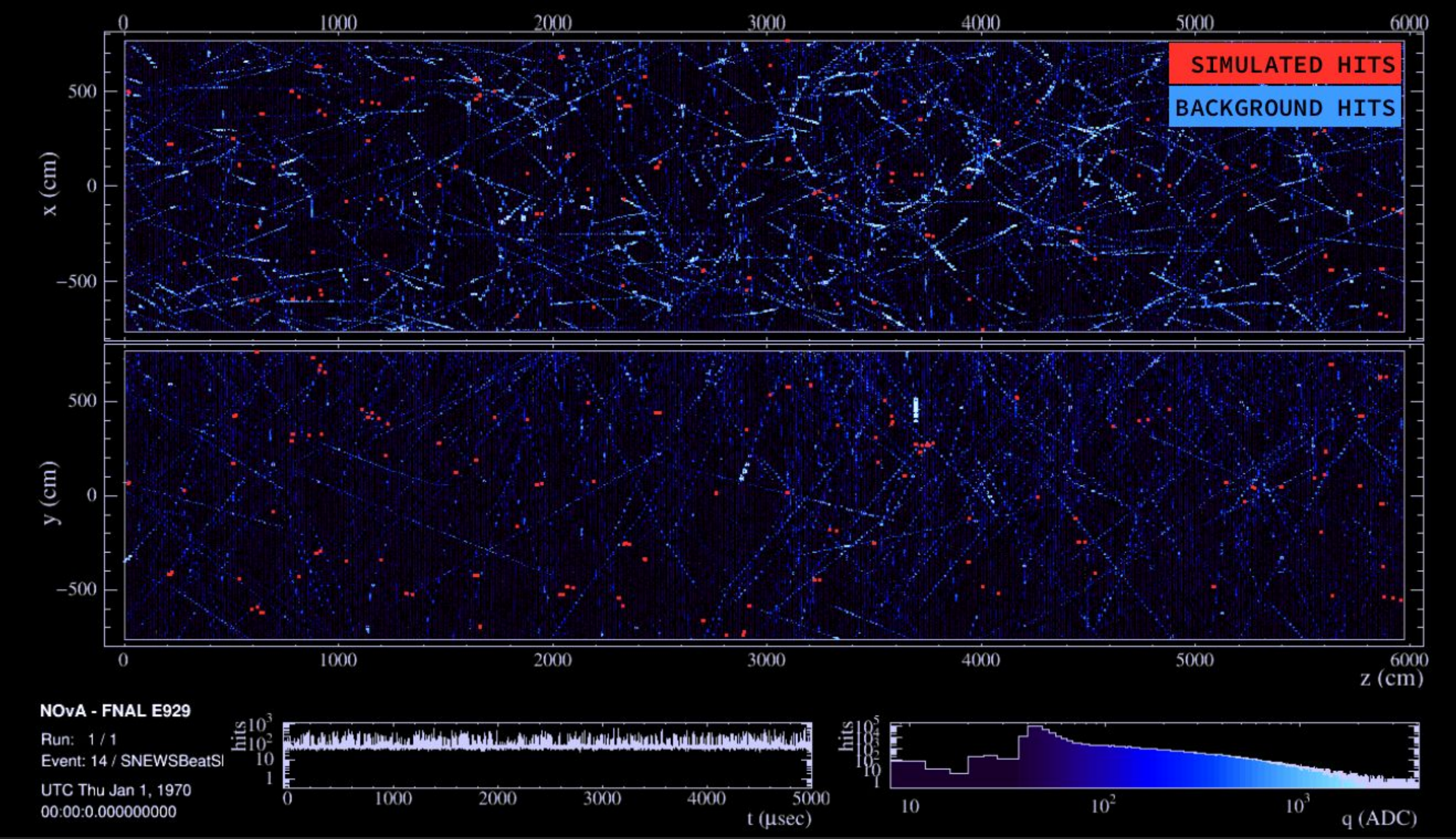
Main detection channels:

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

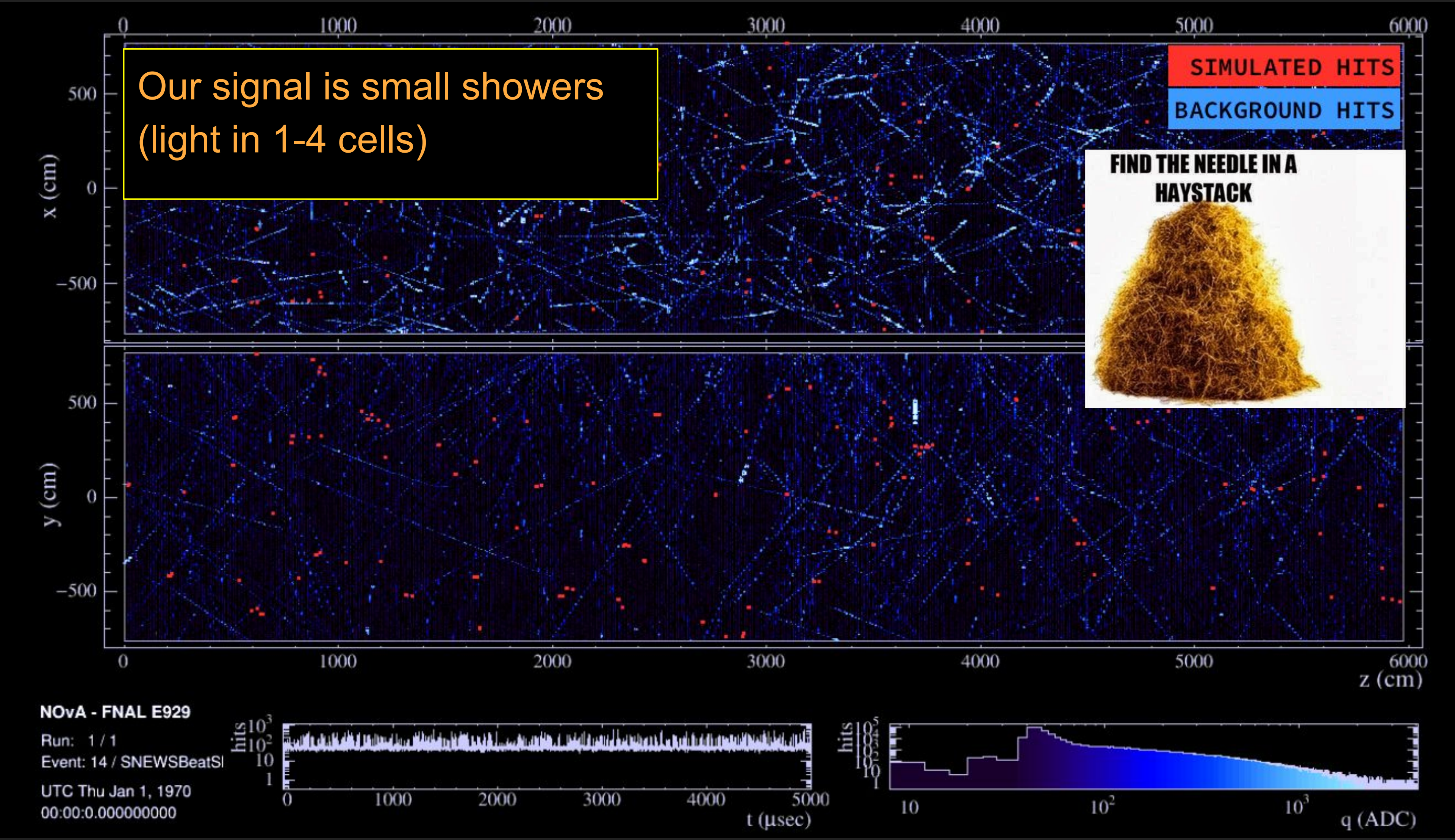


Other channels give negligible contribution: energy too low or small interaction rate.

Far Detector: 5ms of cosmic data + SN simulation



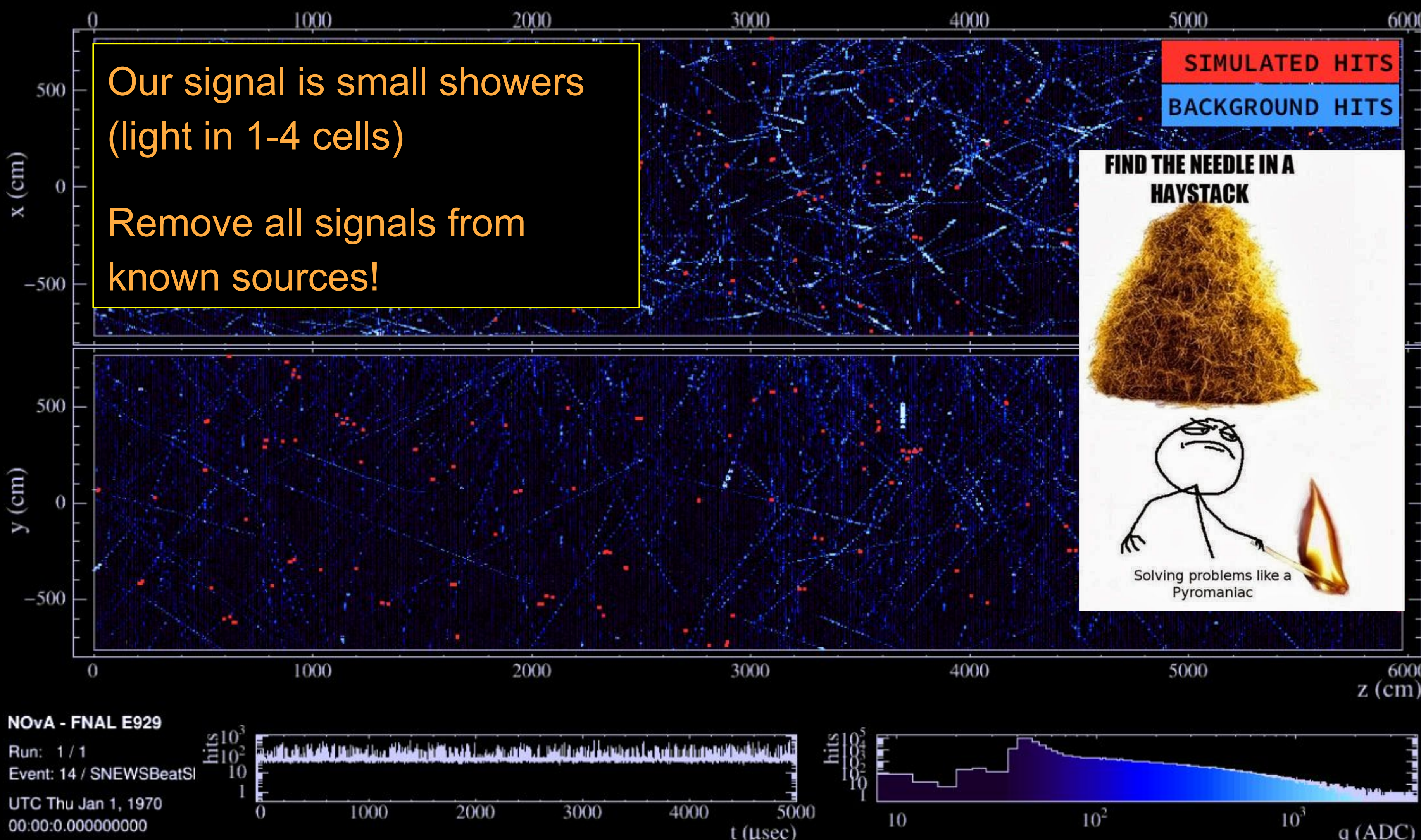
Signal selection



Signal selection

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

Remove all signals from known sources!



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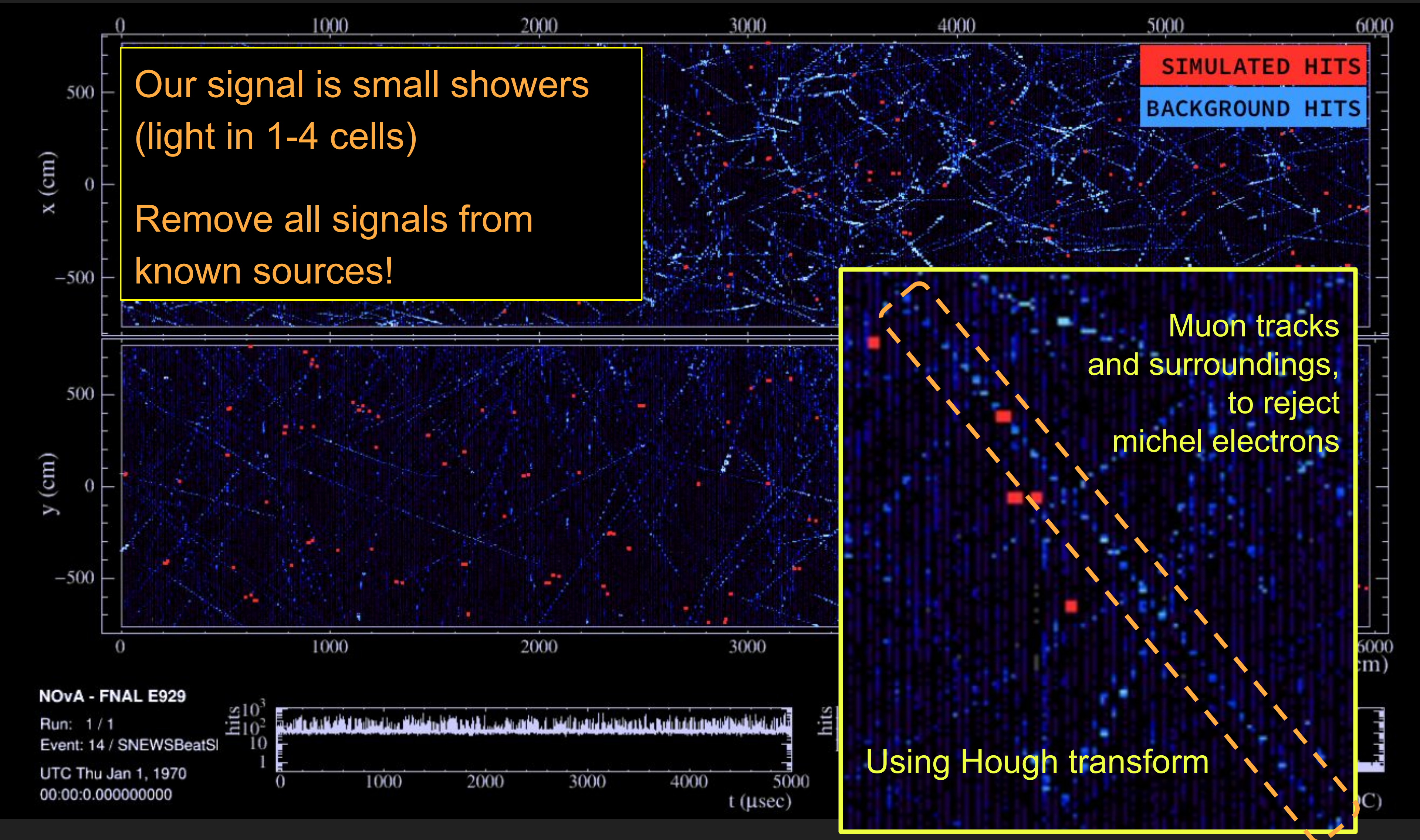

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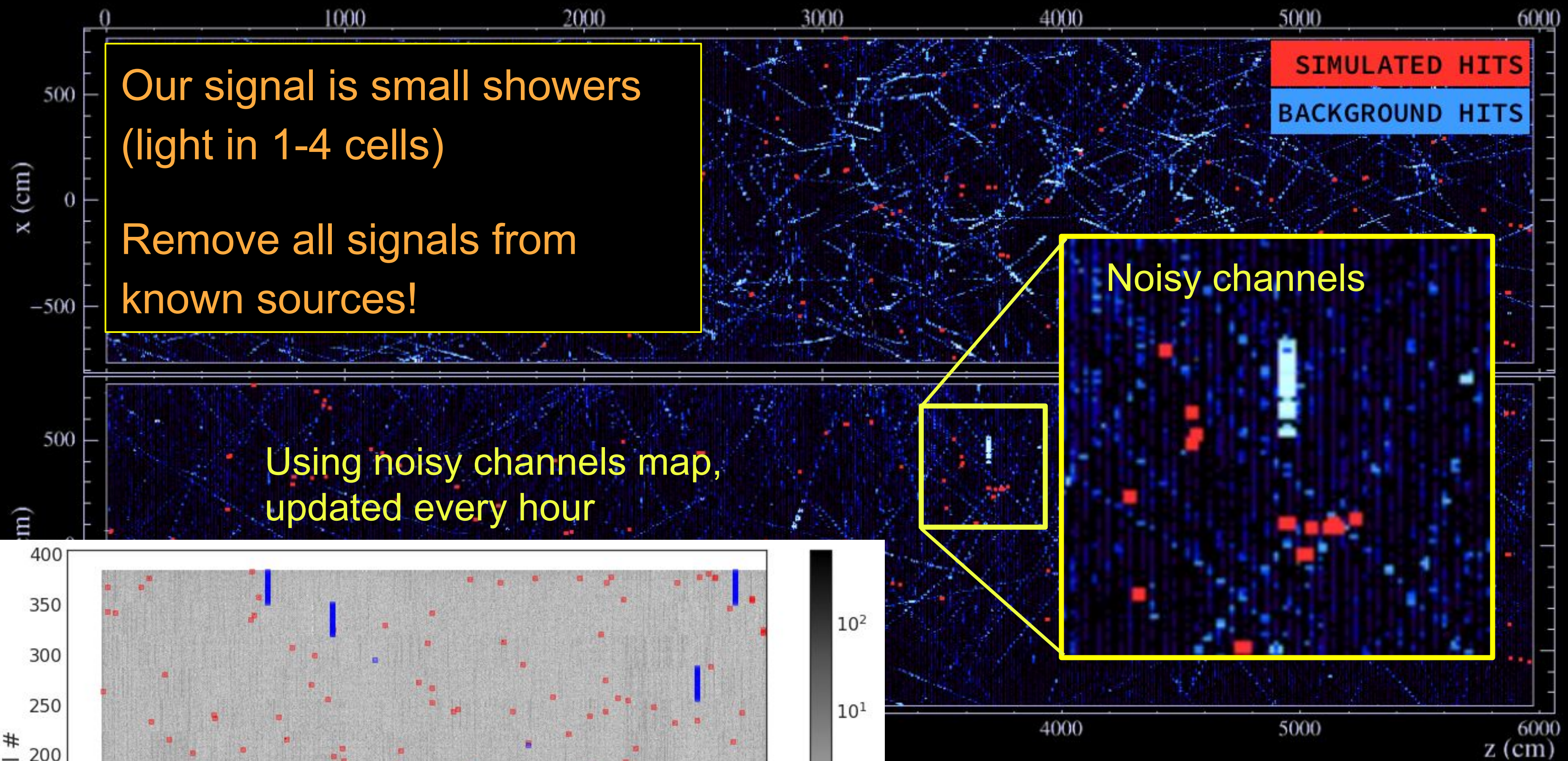
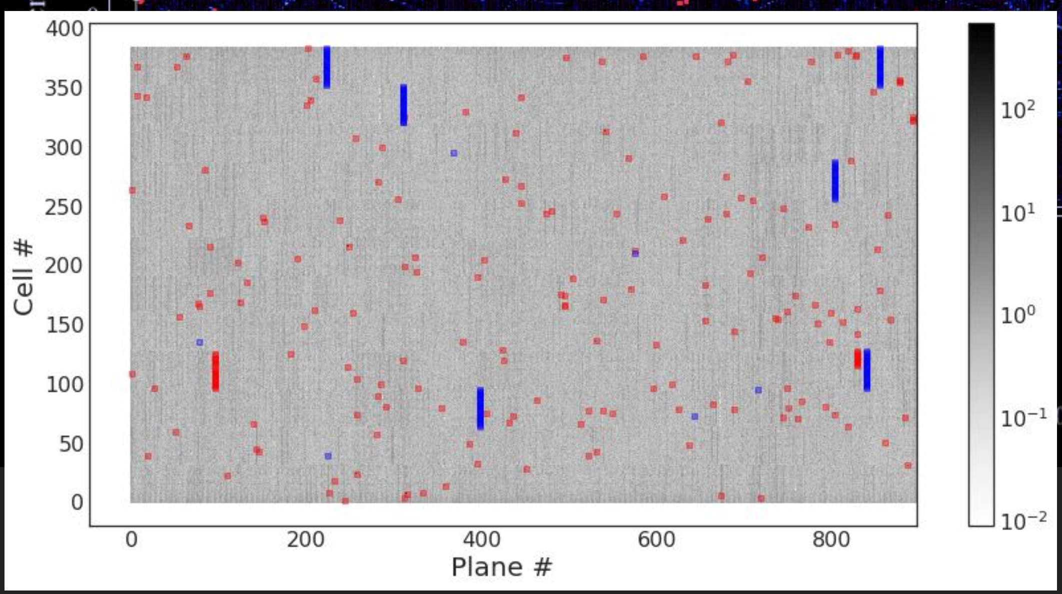
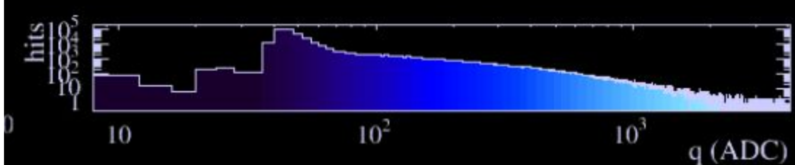
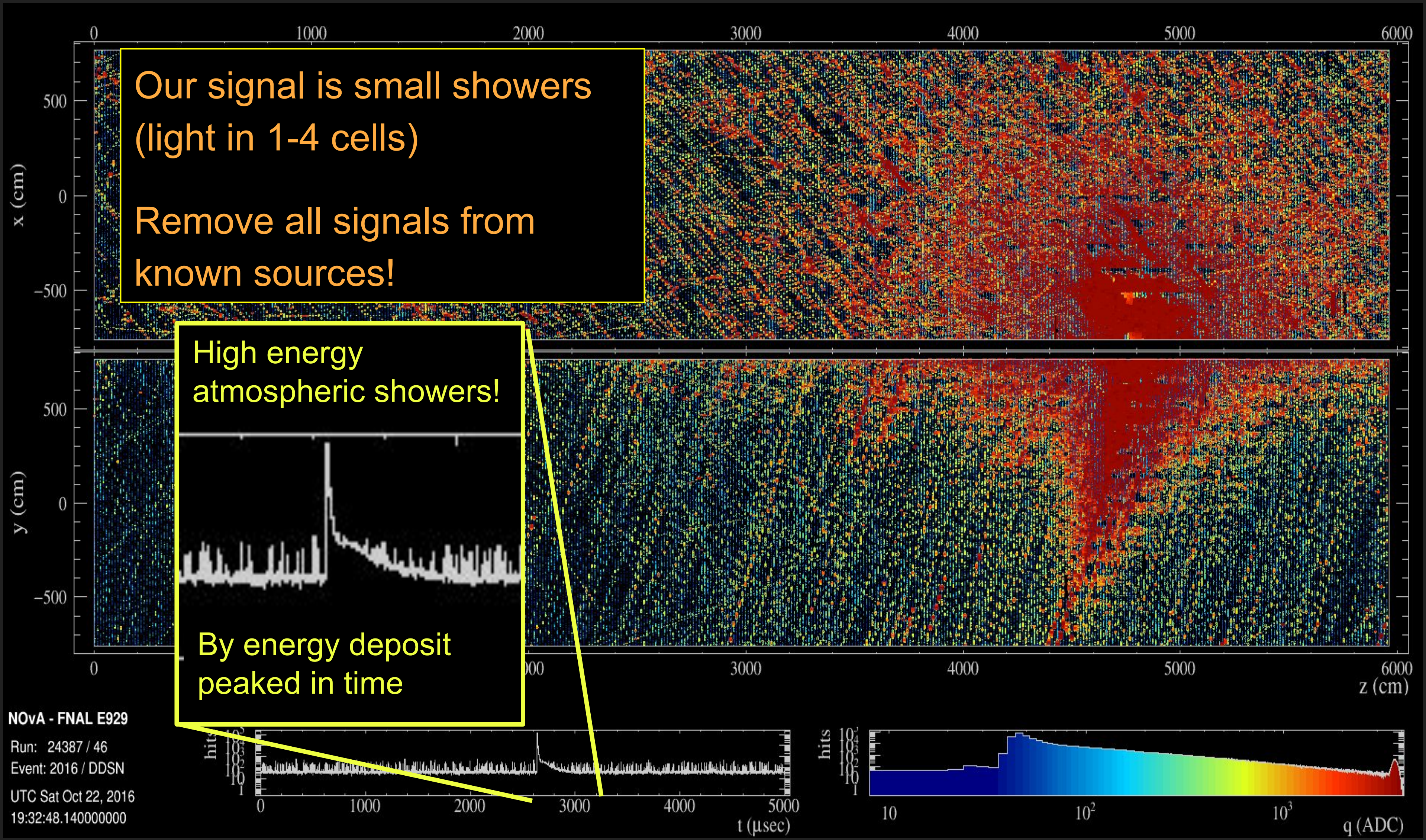


Using noisy channels map, updated every hour





Signal selection



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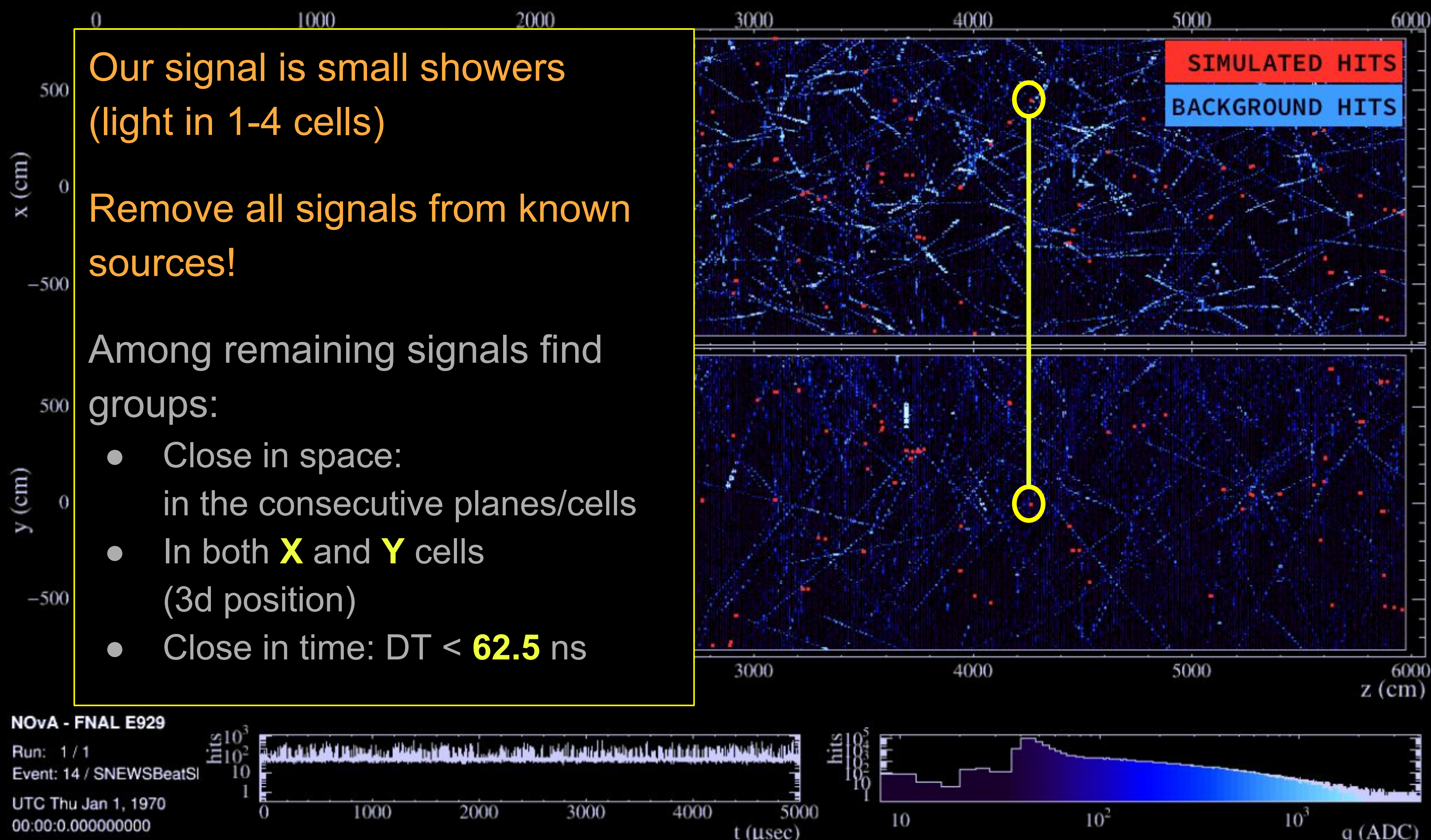
Among remaining signals find groups:

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



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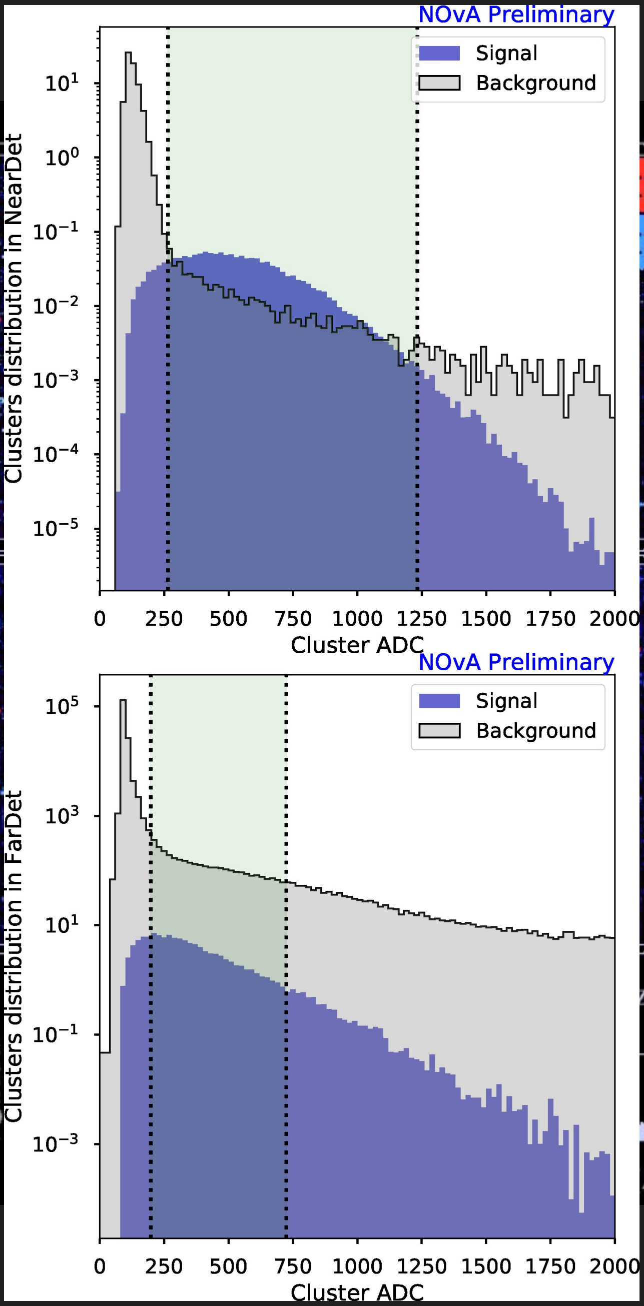
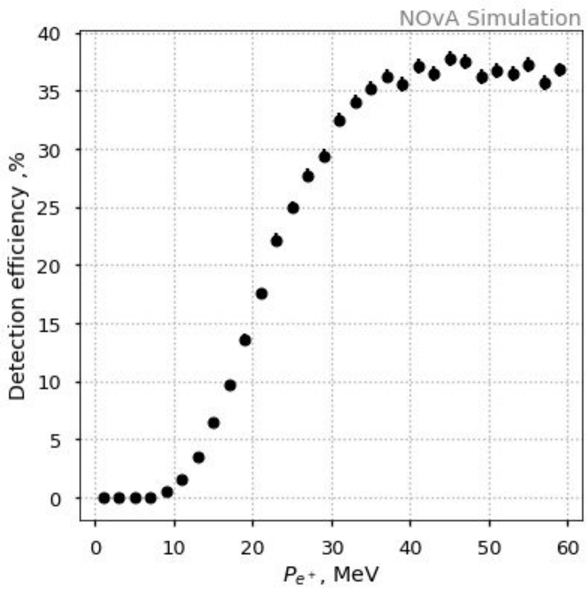
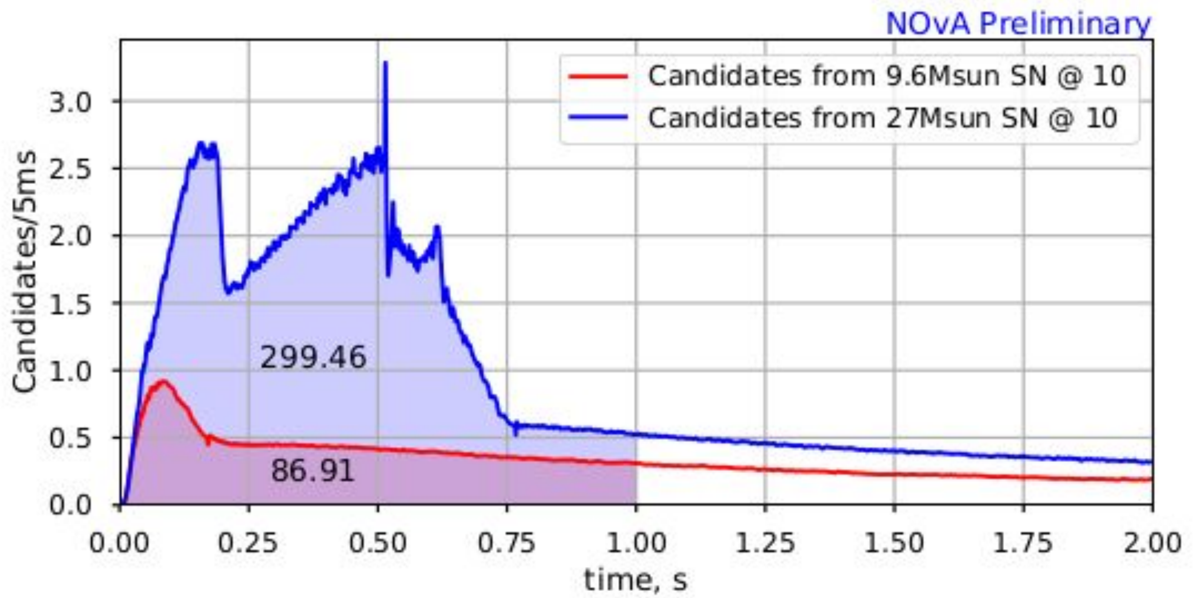
Select the signal region in the light amplitude: ADC counts



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

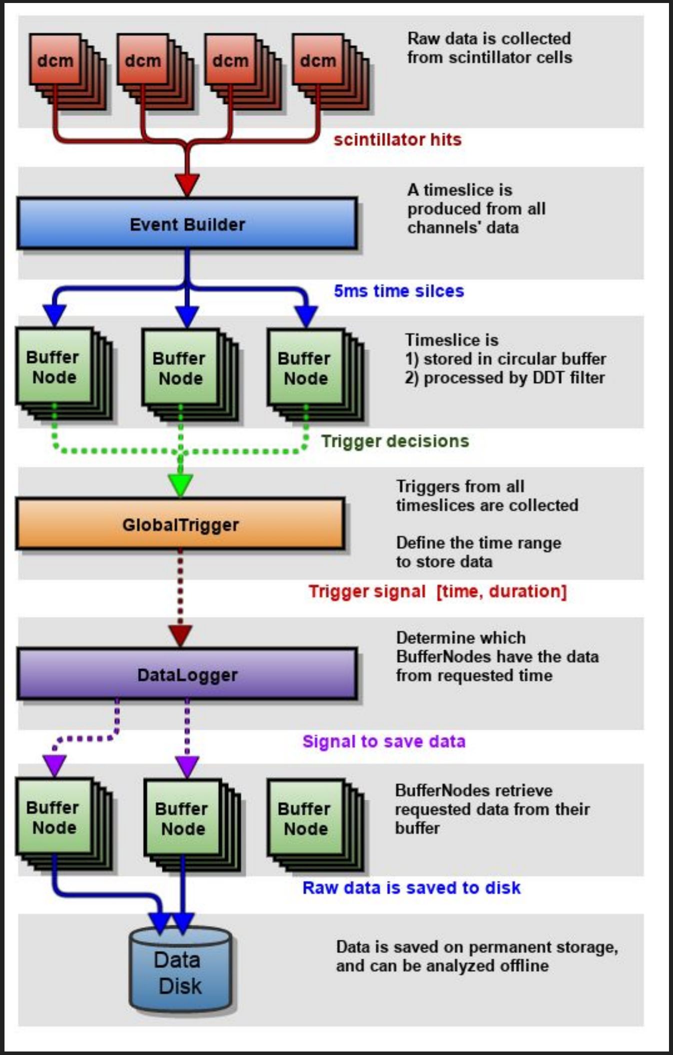
We want to react fast in case of a supernova.

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

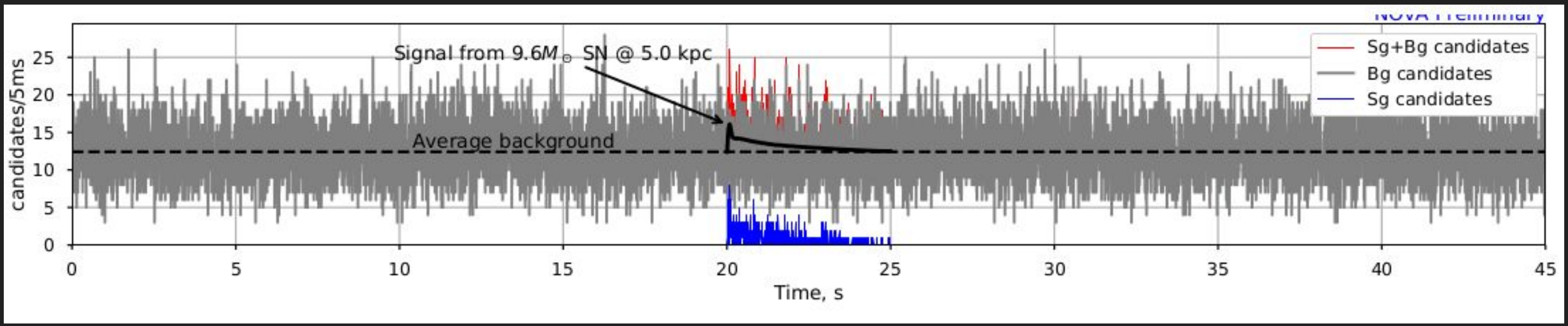
A dedicated triggering system was designed and developed to make SN detection possible.

Data is processed in parallel:
140 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 **Bg** vs **Bg+SN** hypotheses.

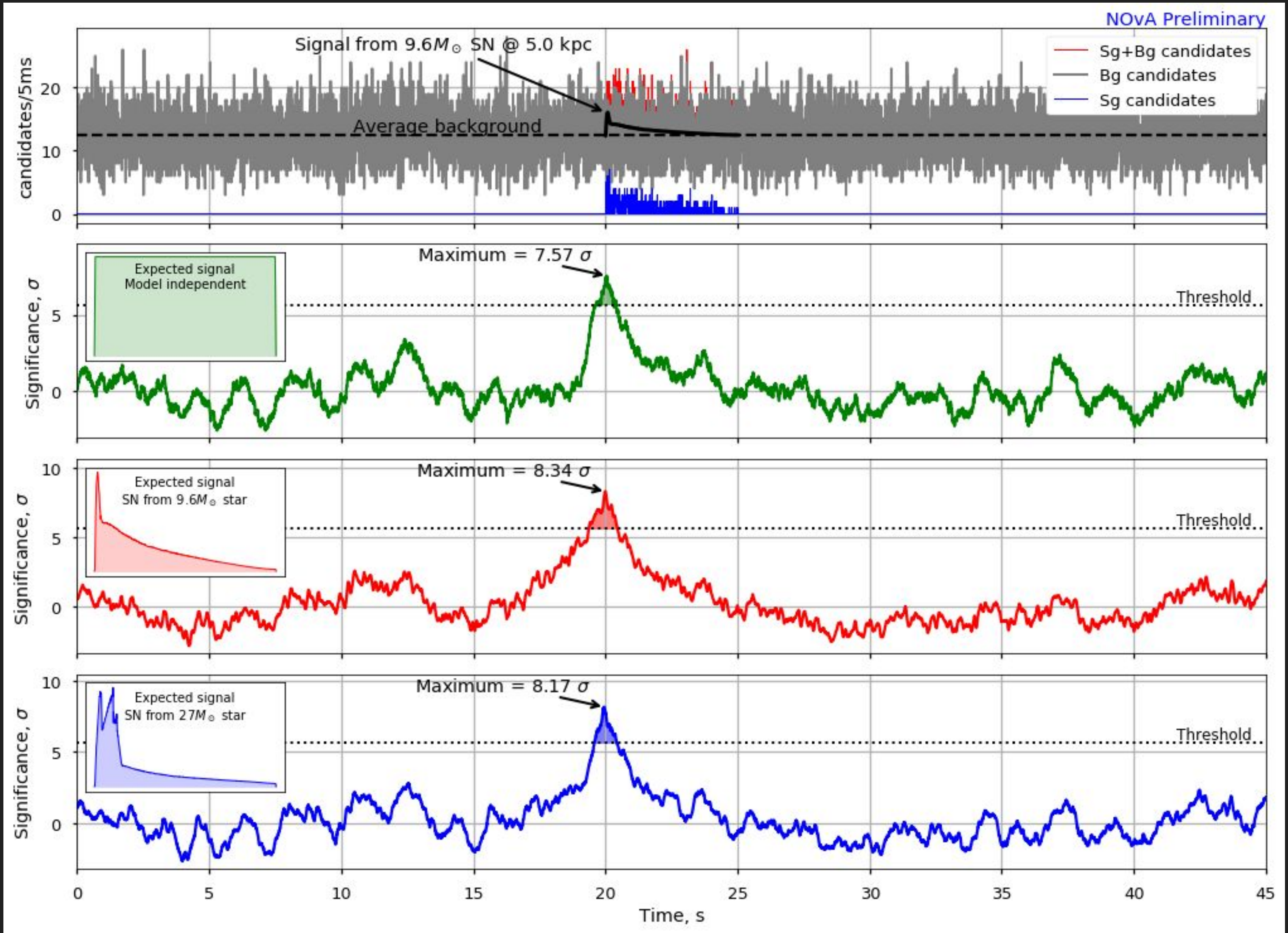
Easiest thing: just look for the N events in a sliding time window. Easy. But:

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

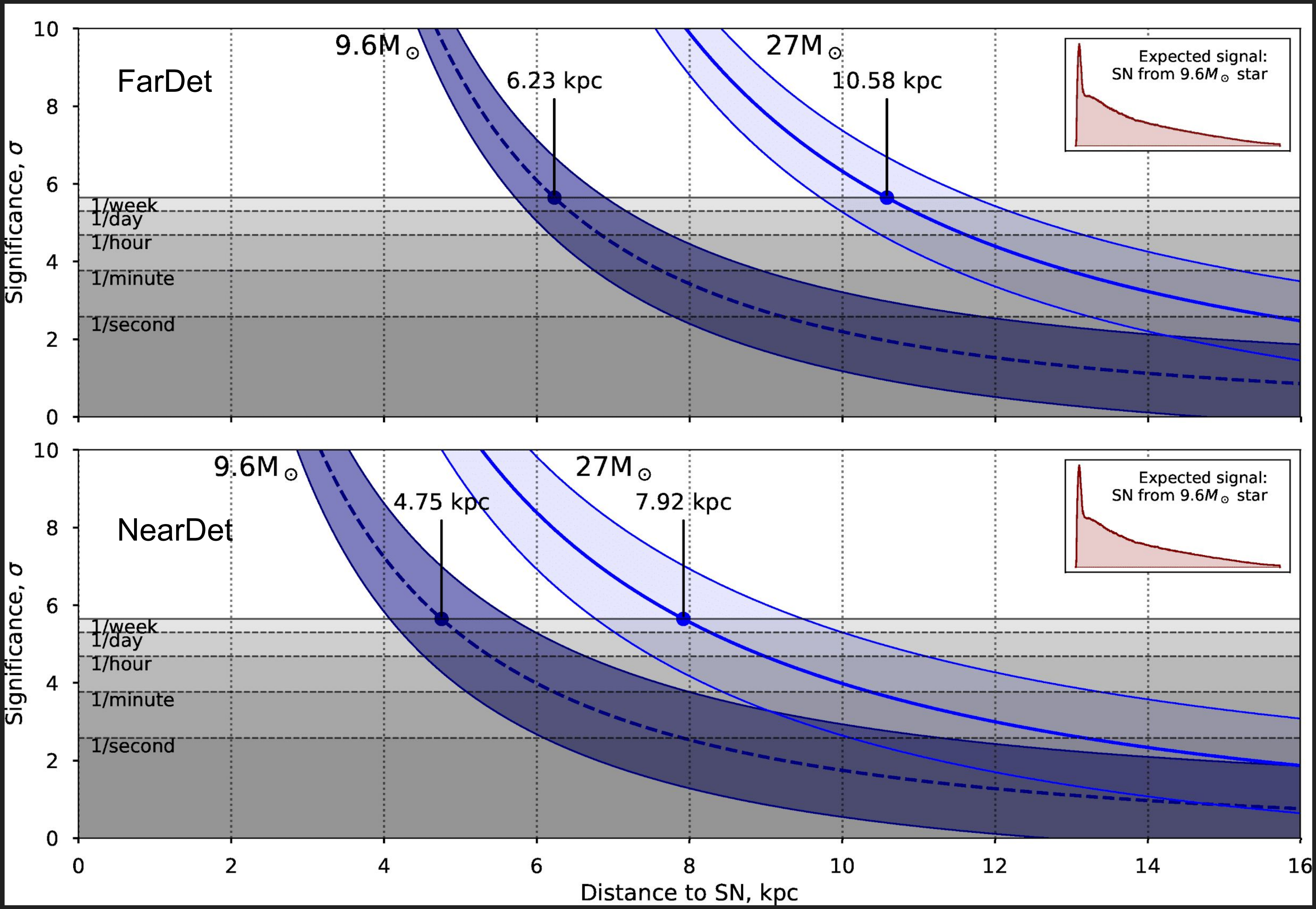
But we can use also the knowledge of the signal shape.
We use log likelihood ratio, to enhance the hypotheses discrimination:

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

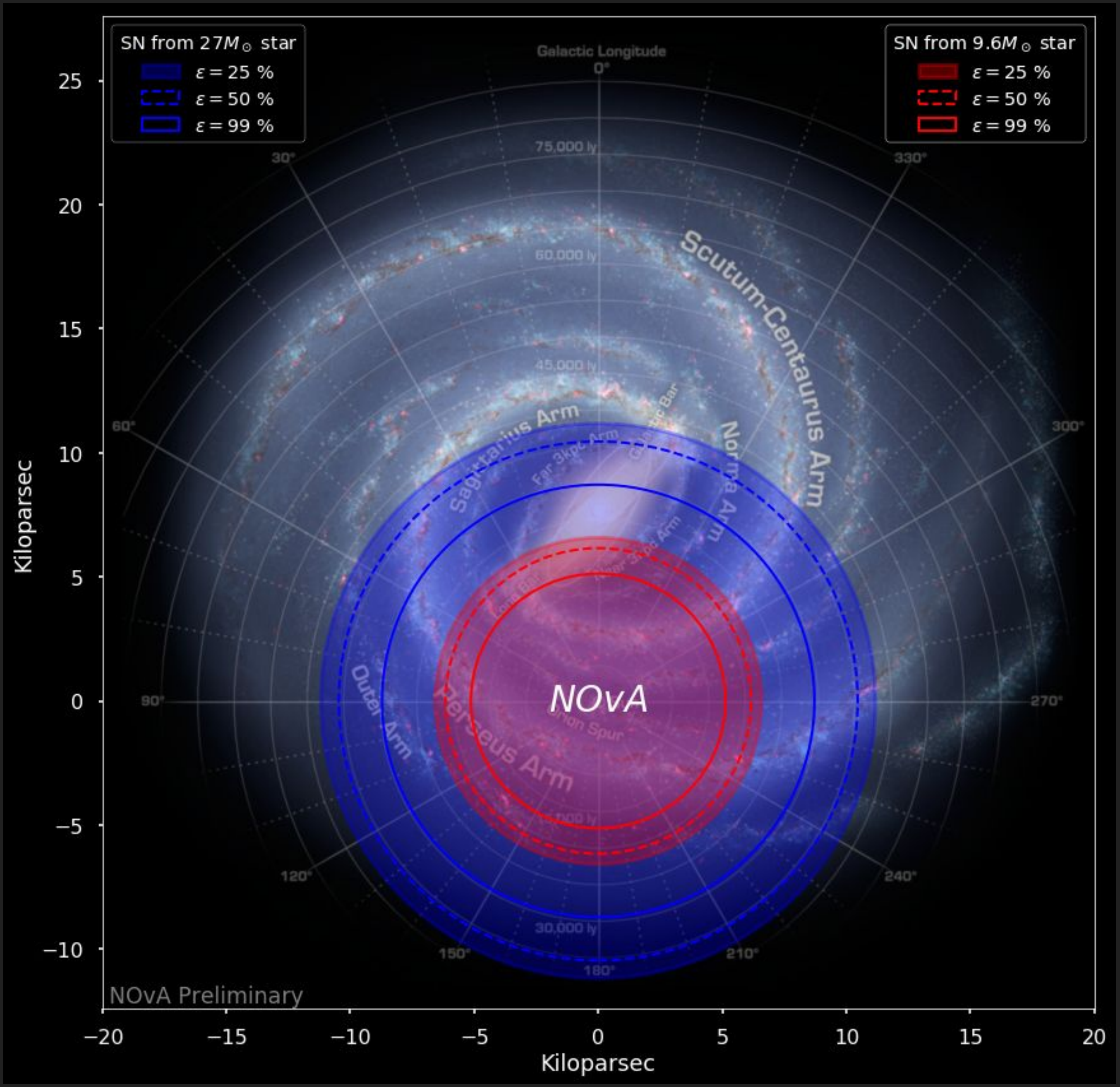
Signal processing and triggering: example



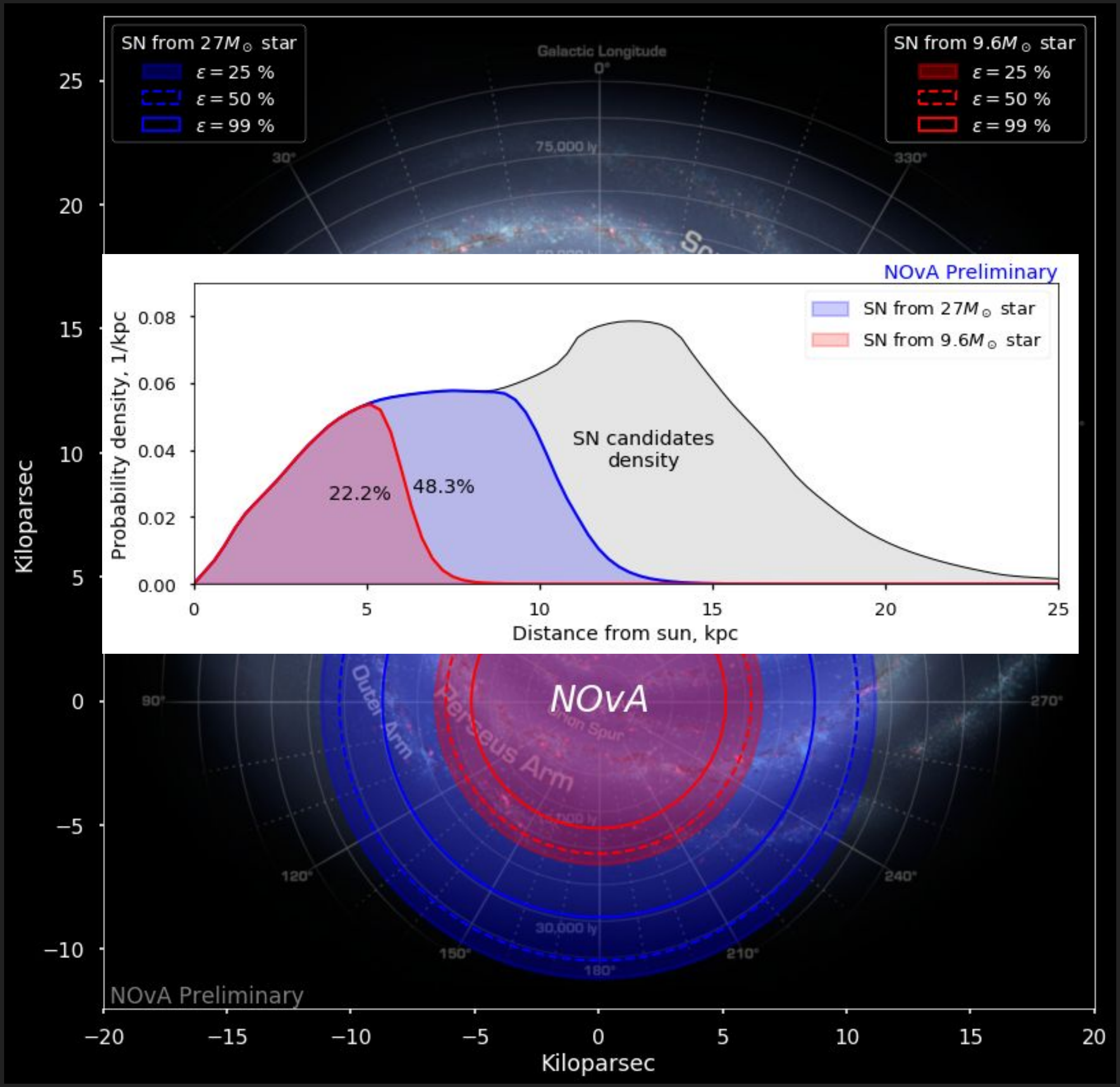
Supernova significance vs. distance



NOvA supernova trigger sensitivity



NOvA supernova trigger sensitivity



What about detectors combination?

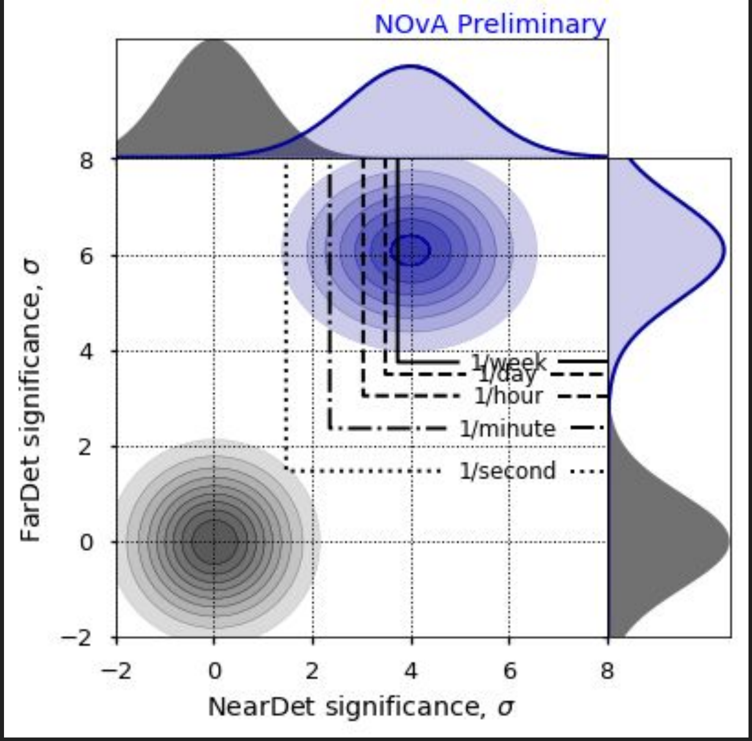
We could gain the sensitivity, if we combine the NearDet and FarDet signal significance in real time.

On a broader view: combining significance from many experiments => global SN network.

SNEWS is currently just combining the trigger signals.
Planned upgrade to SNEWSv2: combine significances.

NOvA experience might be helpful for future global SN networks.

Work on on-line significance combination server is in progress.



Many open questions:

- How conservative should we be?
- How model-independent?

Summary

NOvA is different from many experiments, sensitive to supernova neutrinos:

- Small overburden (high background)
- Two detectors (coincidence network)

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.
- Fast reaction time for SN (~5.6s ND and 40-60s).

Plans and perspectives

- Combination of detectors' significances can improve sensitivity.
- We're sensitive to the signal shape:
  - let's study the possibilities of SN models discrimination
- We're getting ready to contribute to SNEWS.
- We're getting ready to contribute to a search for coincidence with gravitational waves

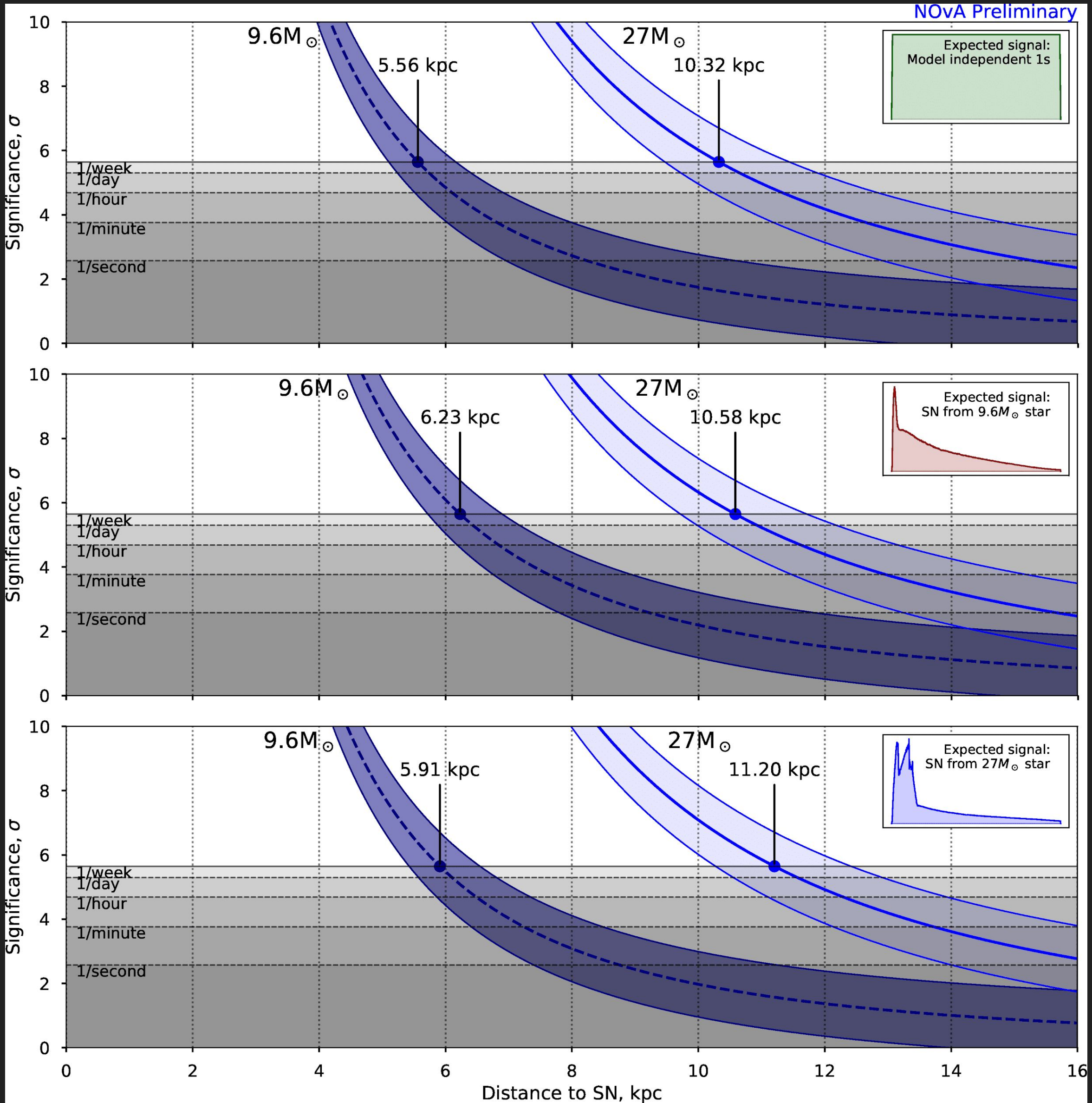
Backup

Candidates selection: first second of SN signal

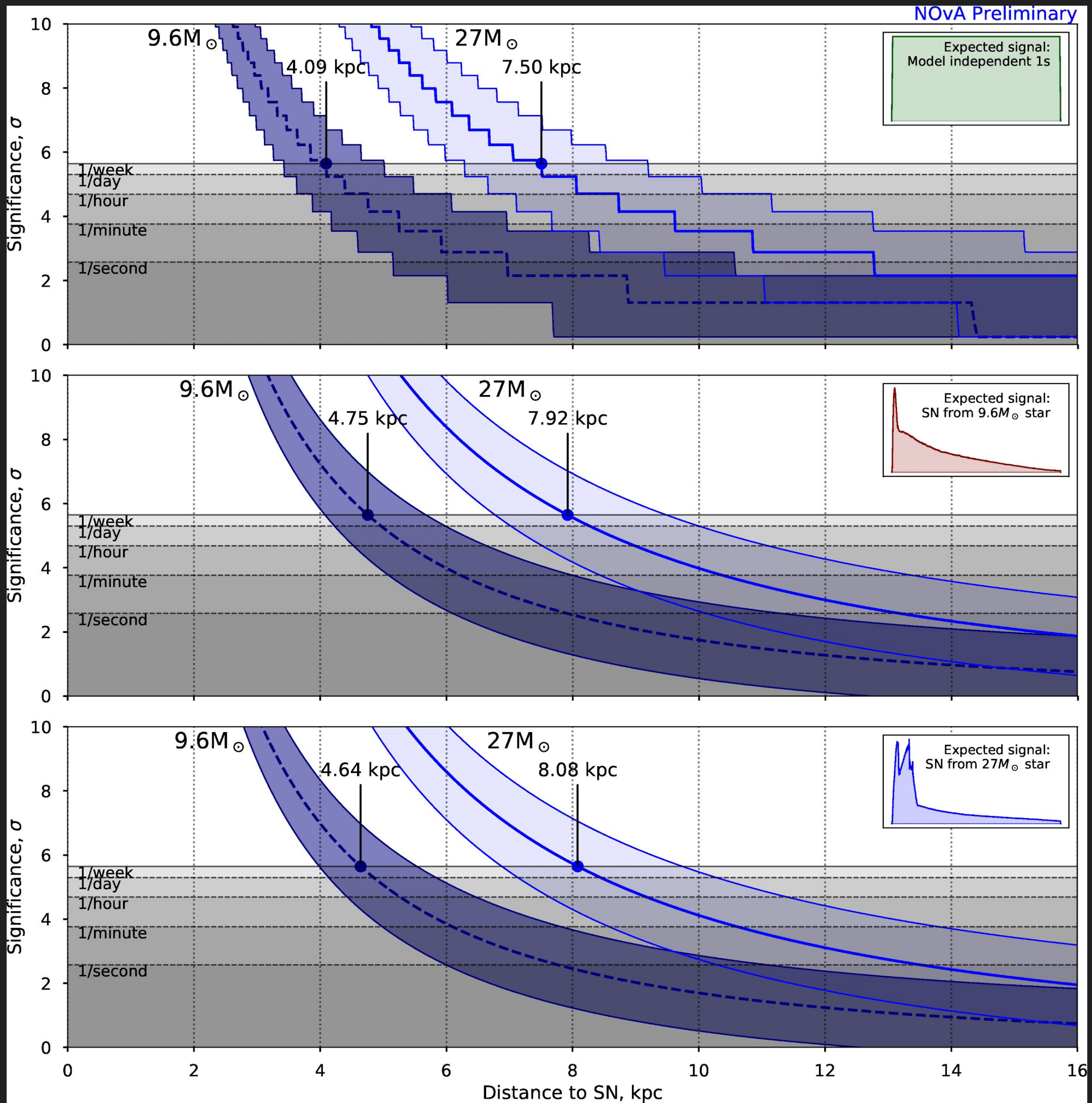
Far Detector	N_{sg}	ε_{sg}	N_{bg}	ε_{bg}	$N_{sg}/\sqrt{N_{bg}}$
Total	725.14	nan%	nan	nan%	nan
Reconstructed	316.24	43.61%	322811.99	nan%	0.5566
XY hits	145.16	45.90%	231866.53	71.83%	0.3015
Nhits cut	144.29	99.40%	224420.72	96.79%	0.3046
Fiducial Volume cut	117.77	81.62%	170436.38	75.95%	0.2853
ADC 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

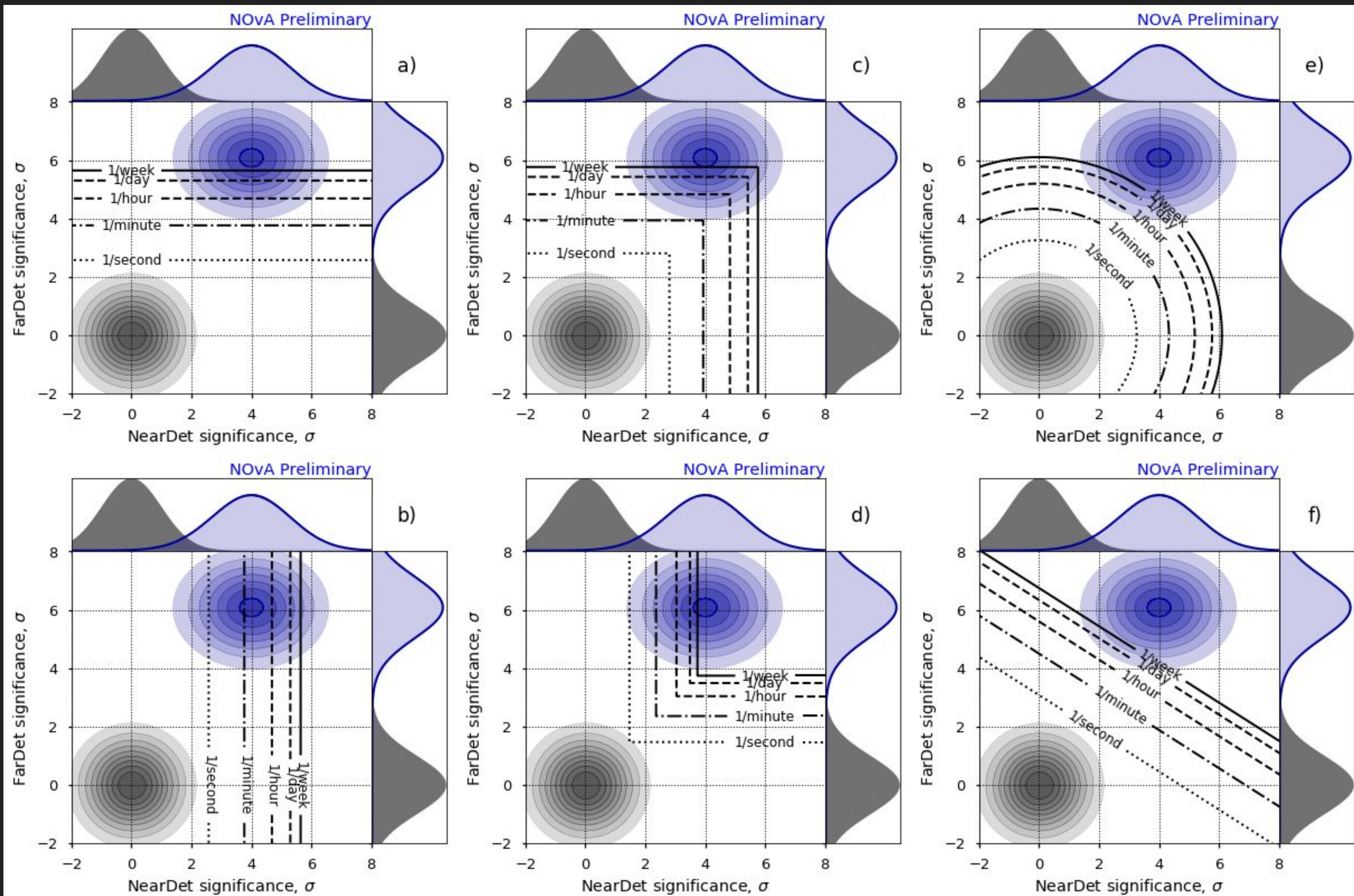
Supernova significance vs. distance: FarDet



Supernova significance vs. distance: NearDet

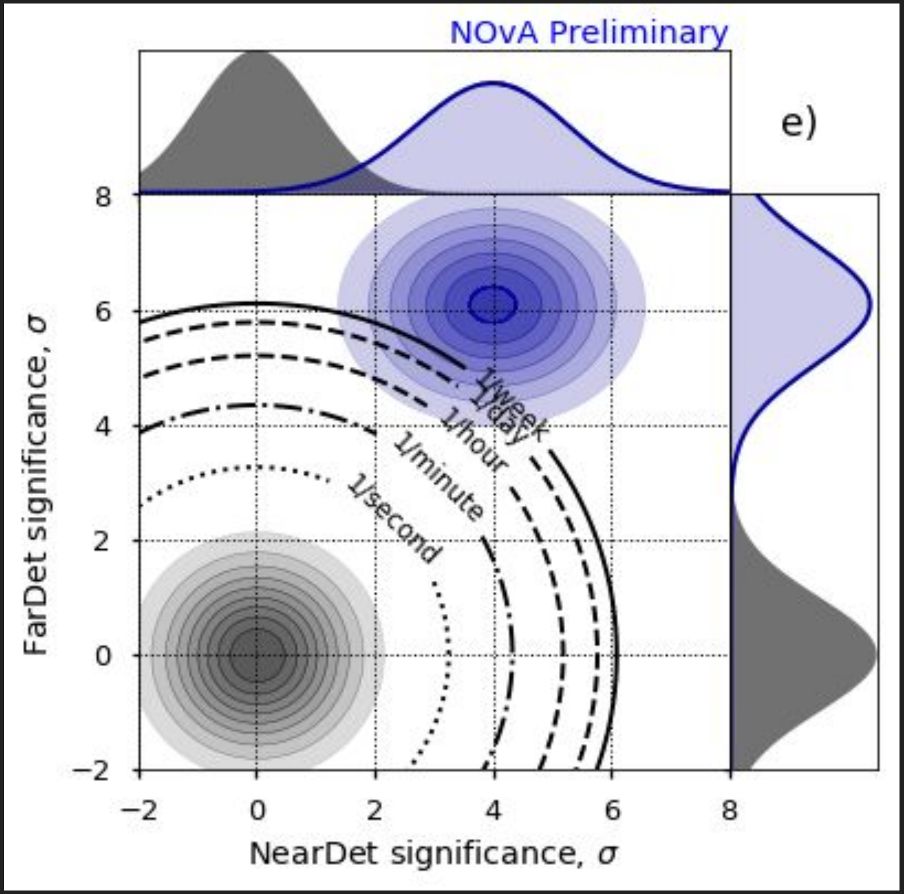


Combining detectors' significance: many ways to do.



“Model independent” combination

$$S = \sum_{i}^{N} z_i^2$$



This corresponds to Ficher’s combination of p-values:

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

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

Advantage:

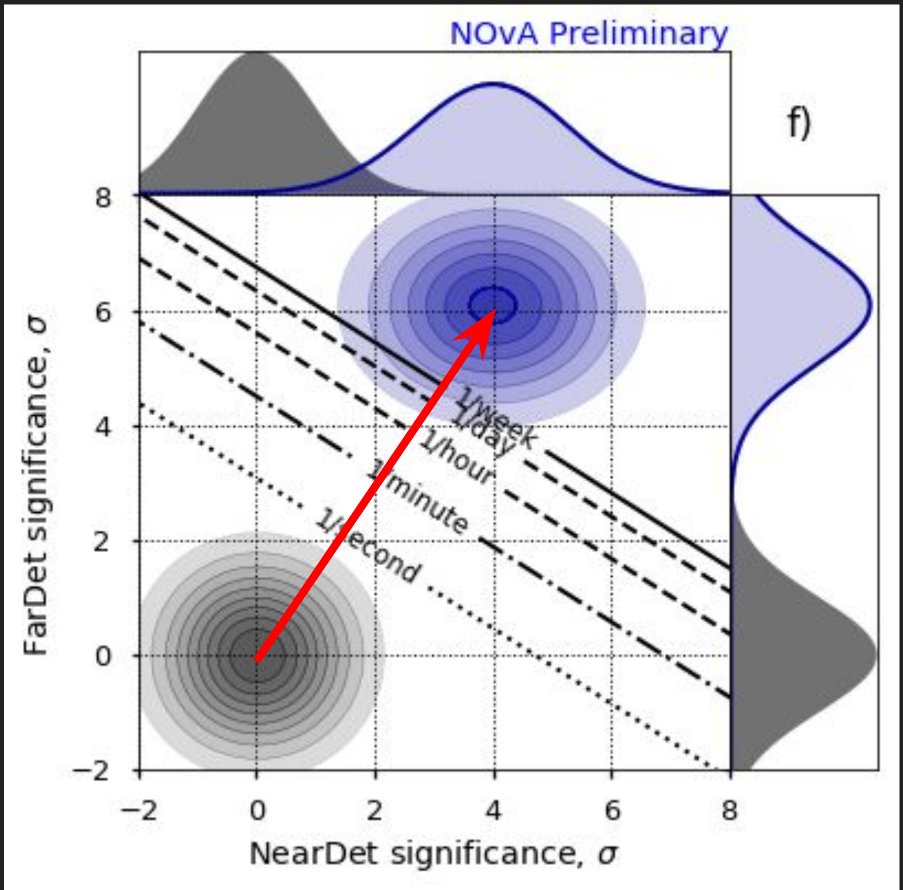
- Less dependent on the SN model

Disadvantages:

- Ignorant about experiments sensitivity to SN.
  - Weak experiment decreases sensitivity!
- Nonlinear

Weighted linear combination

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



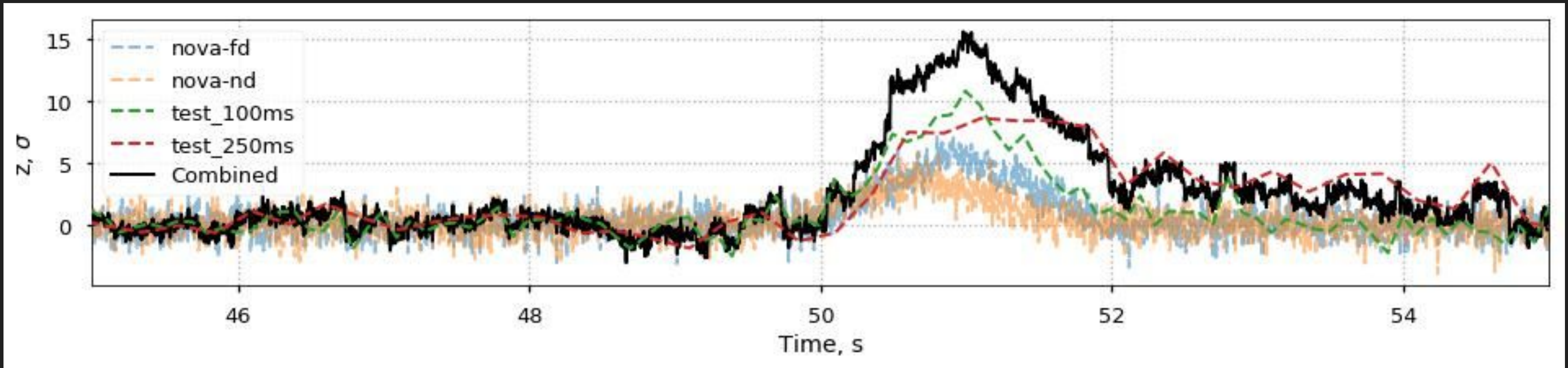
(Stouffer's z-score combination)

S has a standard normal distribution:
mean=0, sigma=1

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

Toy example of joint SN detection



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

Work in progress.