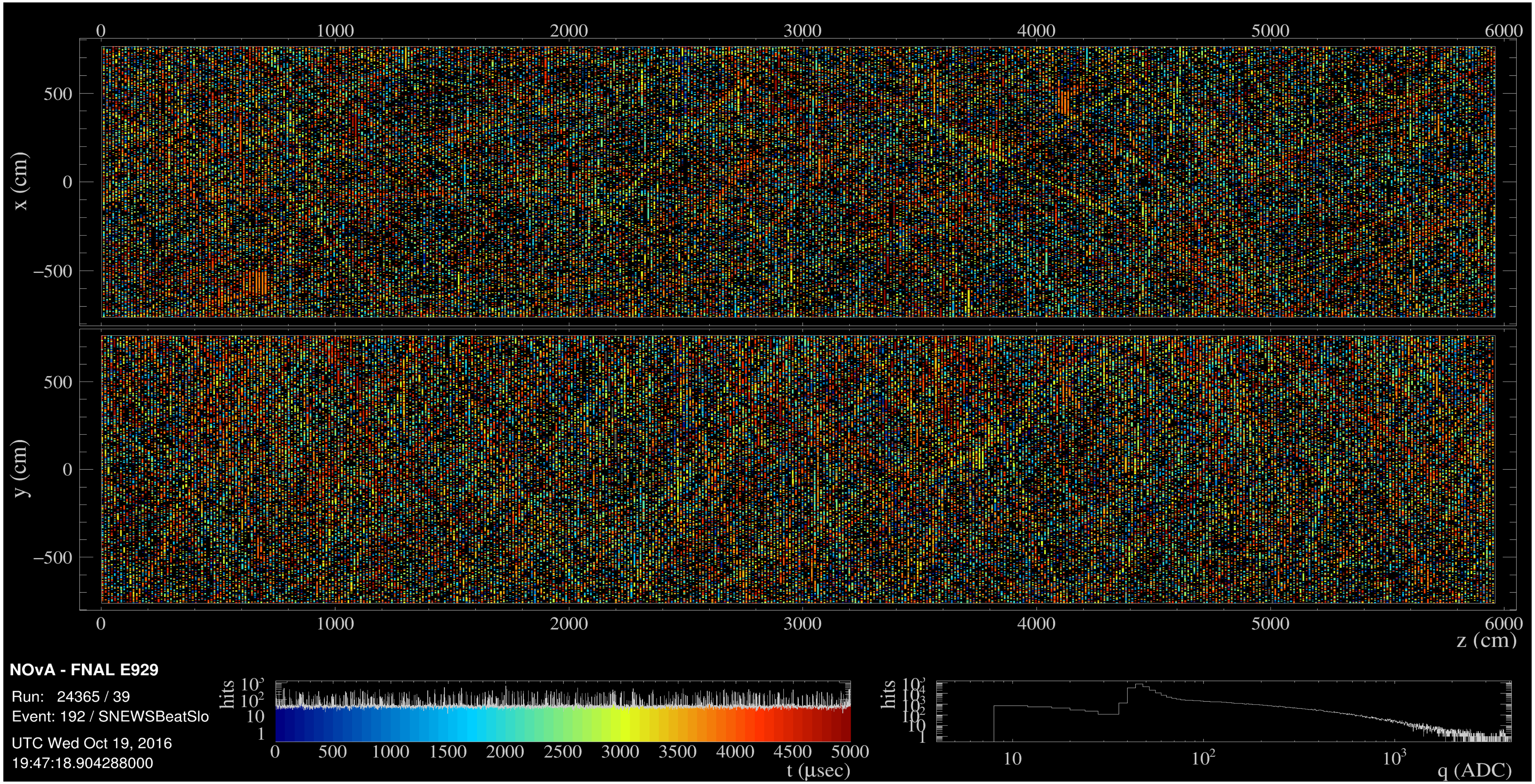


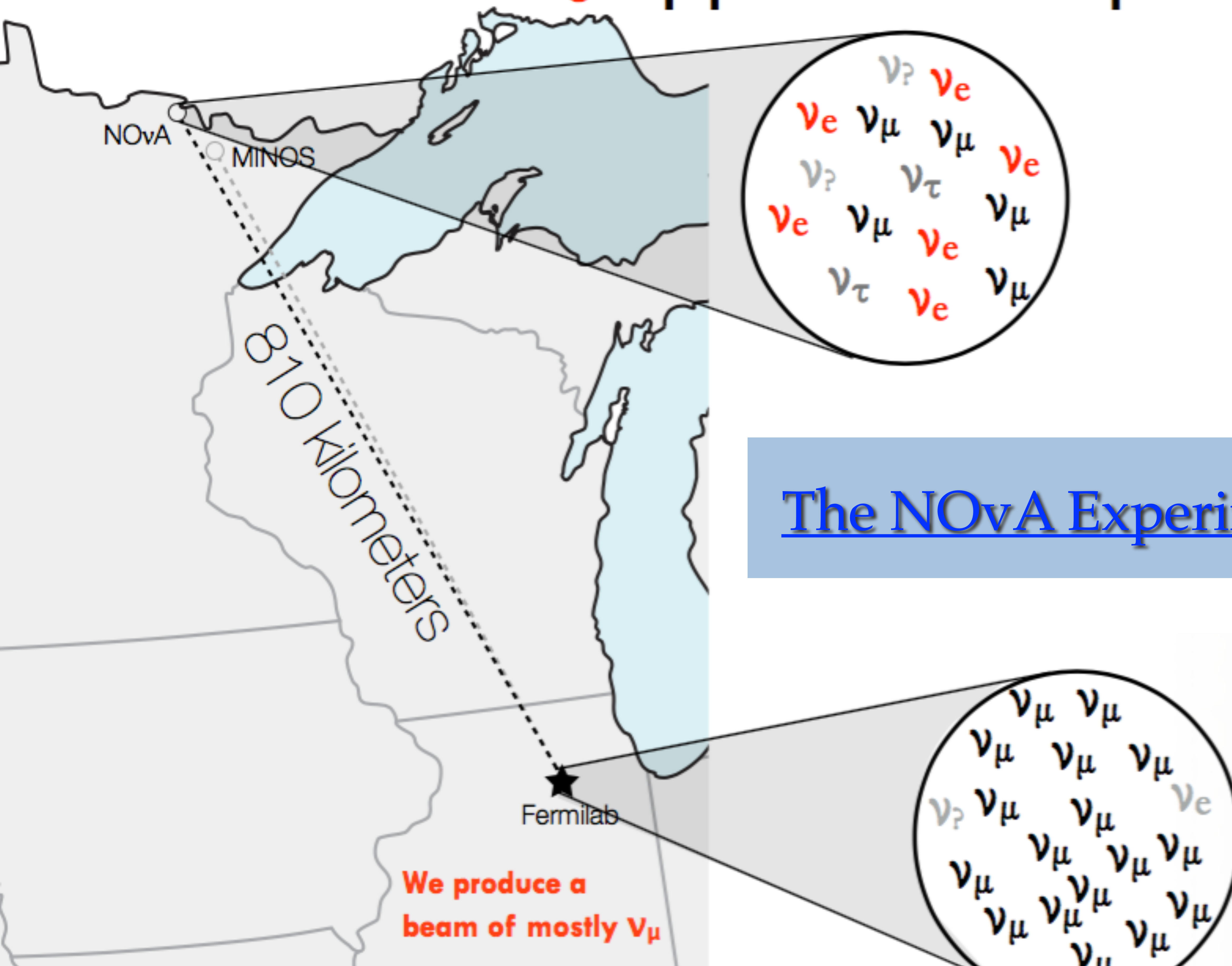
Searches for exotic physics in the NOvA experiment

Alexander Antoshkin (on behalf of the NOvA Collaboration)

Joint Institute for Nuclear Research, Dubna

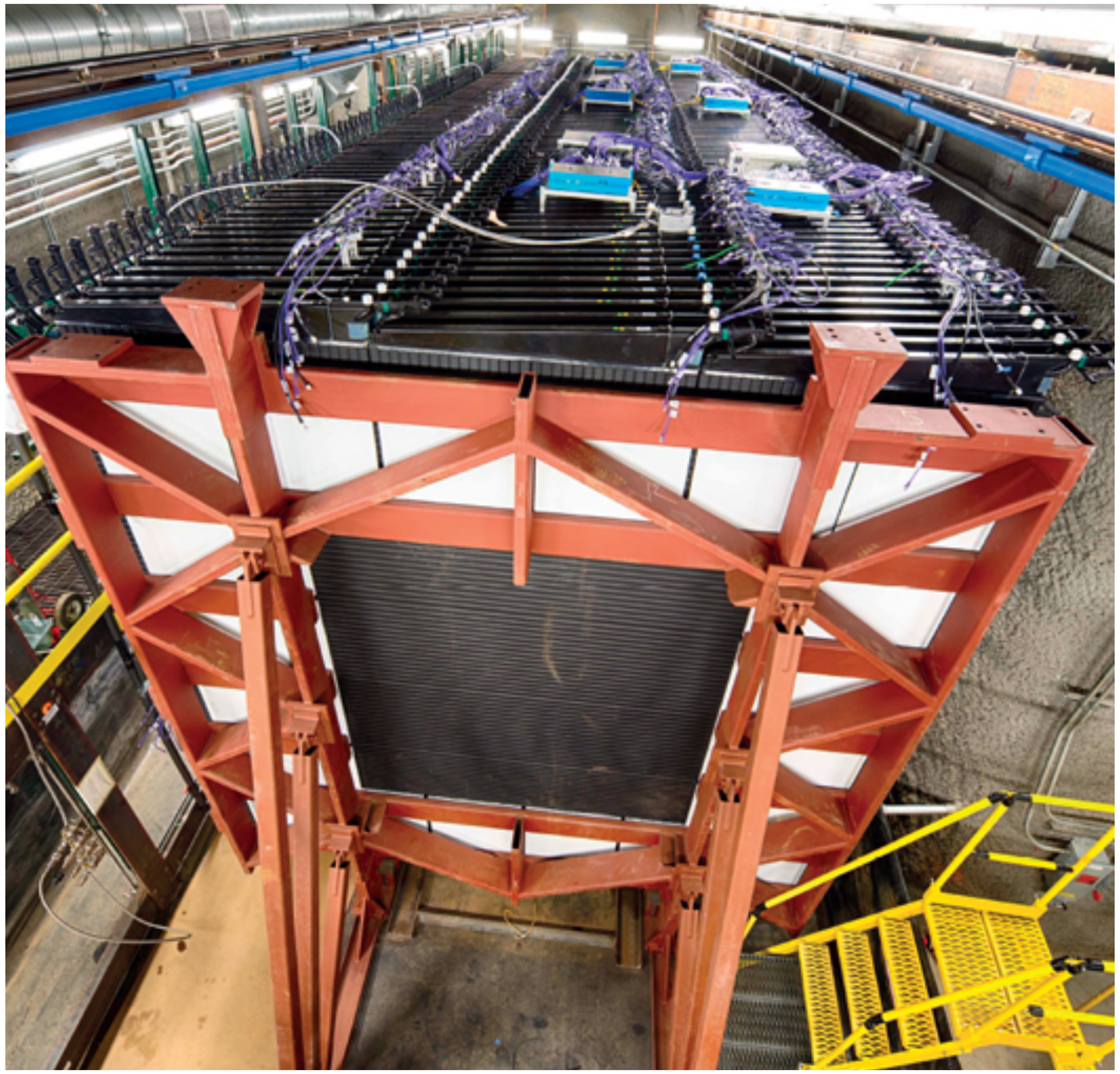
The 21th international Lomonosov conference on elementary particle physics, Moscow (Russia), 24/08-30/08/2023

NuMI Off-axis ν_e Appearance Experiment

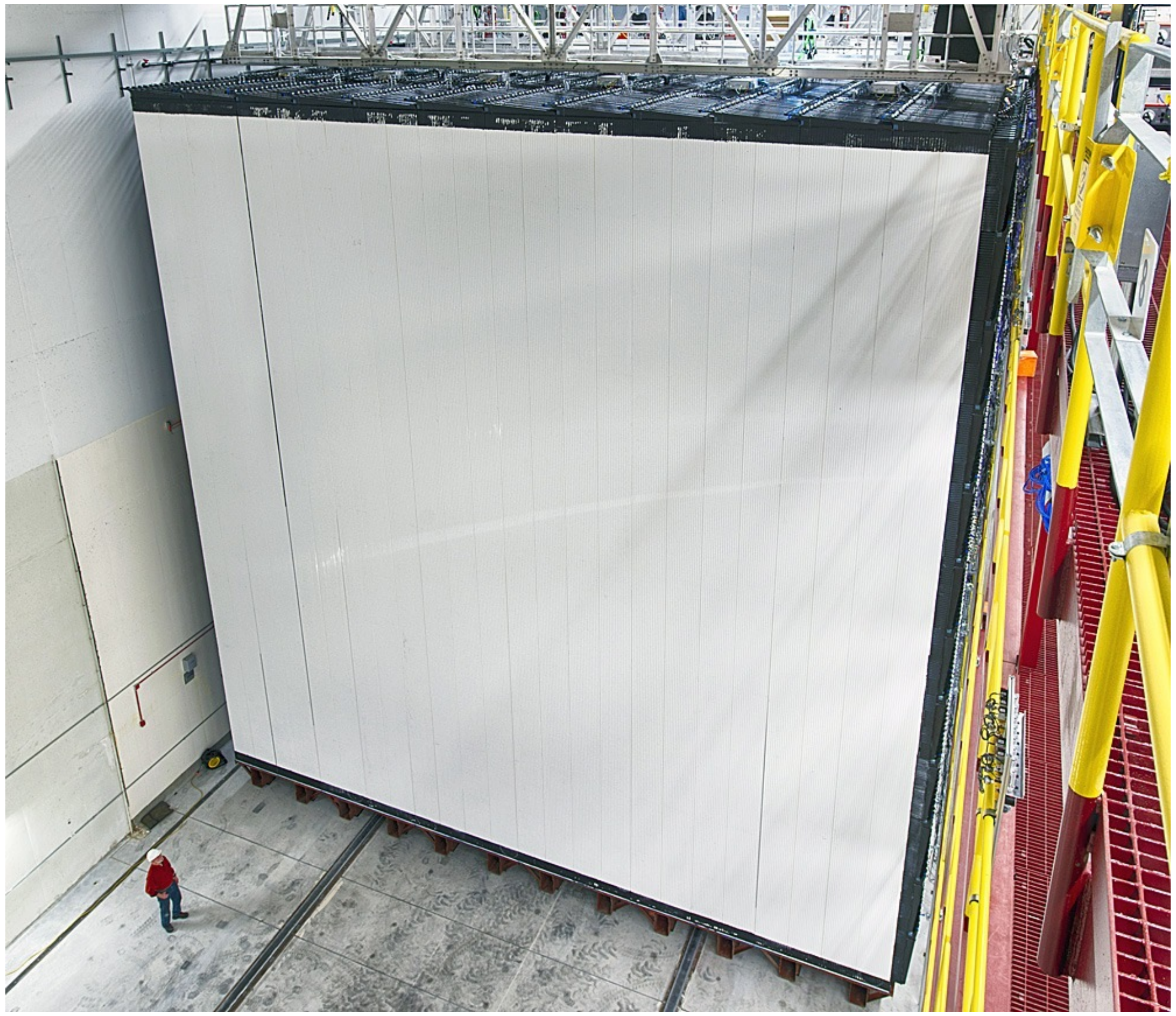


[The NOvA Experiment]

The NOvA Detectors



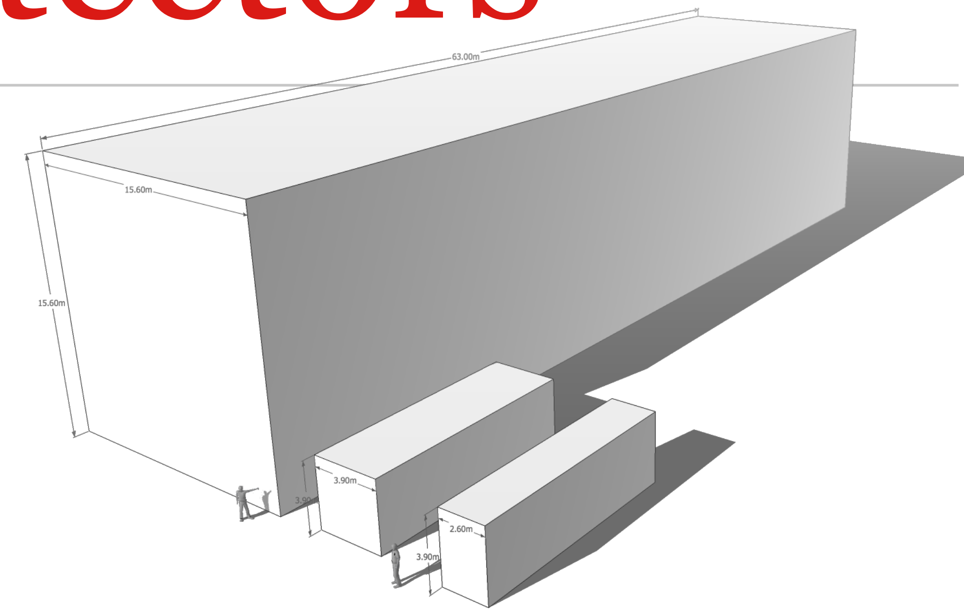
- **Near detector**
  - **100 m underground**
  - 1 km away from the accelerator, **weight 300 t**
  - measure flux composition before oscillations
  - ND data used for prediction in FD (extrapolation procedure)

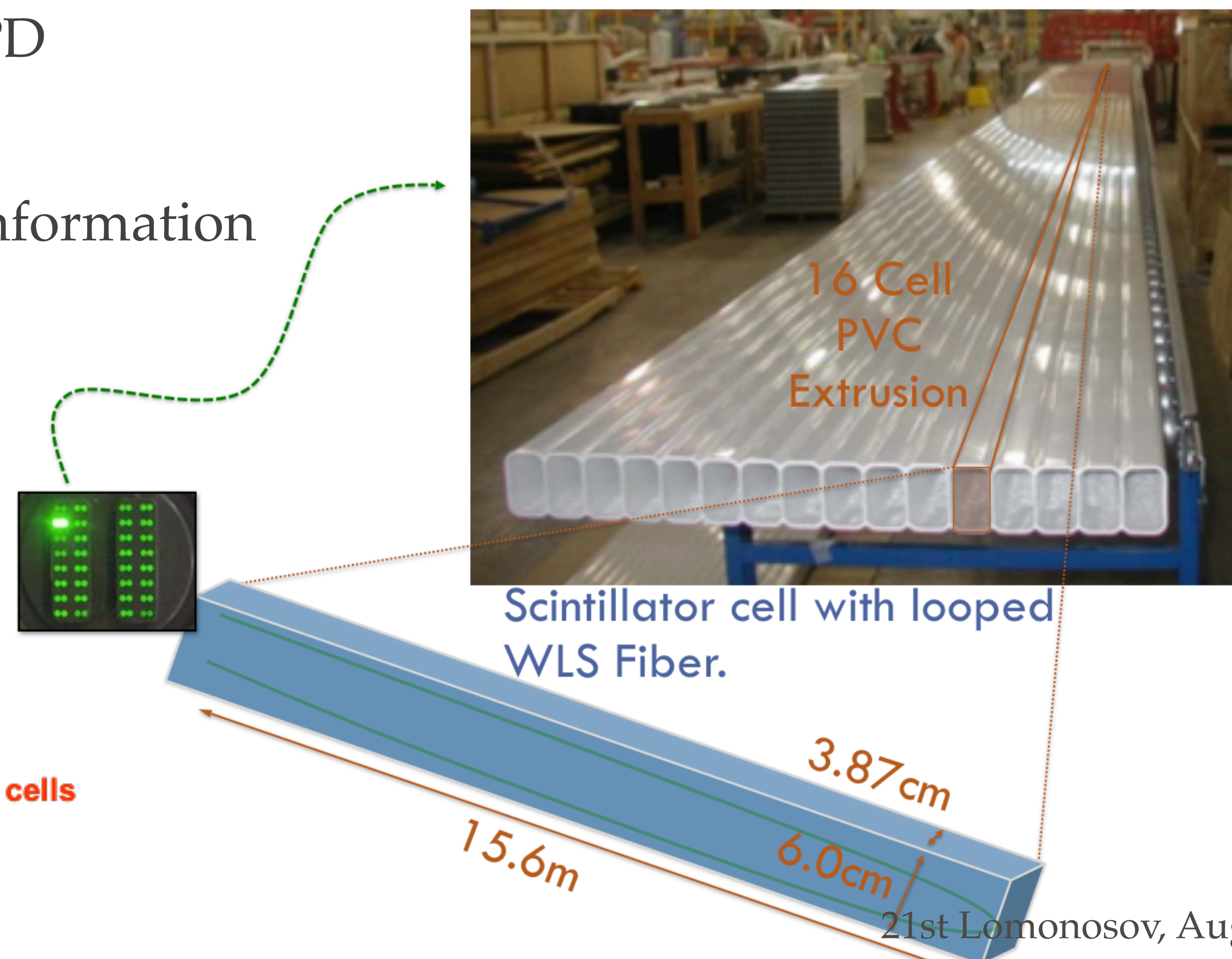


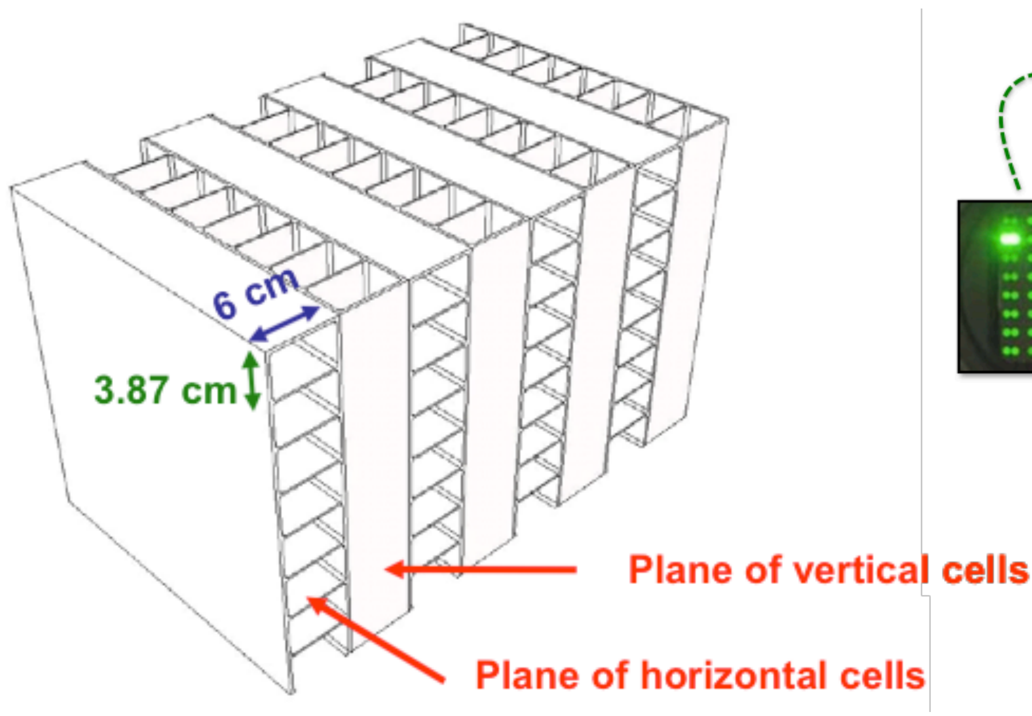
- **Far detector**
  - **On the Earth's surface**
  - 810 km away from the accelerator, **weight 14 kt**
  - measure neutrino flux after oscillations
  - extrapolation systematics
  - FD functionally identical to ND

The NOvA Detectors

- PVC extrusion filled with a Liquid Scintillator
  - mineral oil + 5% pseudocumene and some additional dopants
- Read out via WLS fiber to APD
  - FD has ≈ 344,000 channels
  - Layered planes provide 3D information

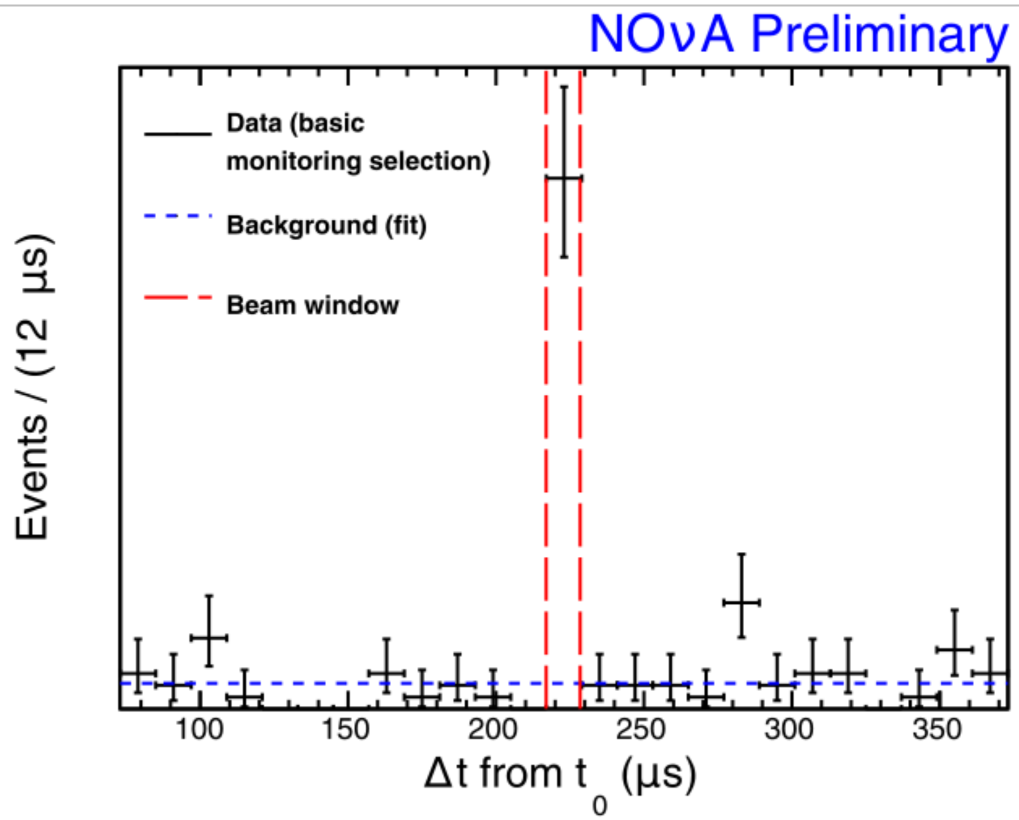


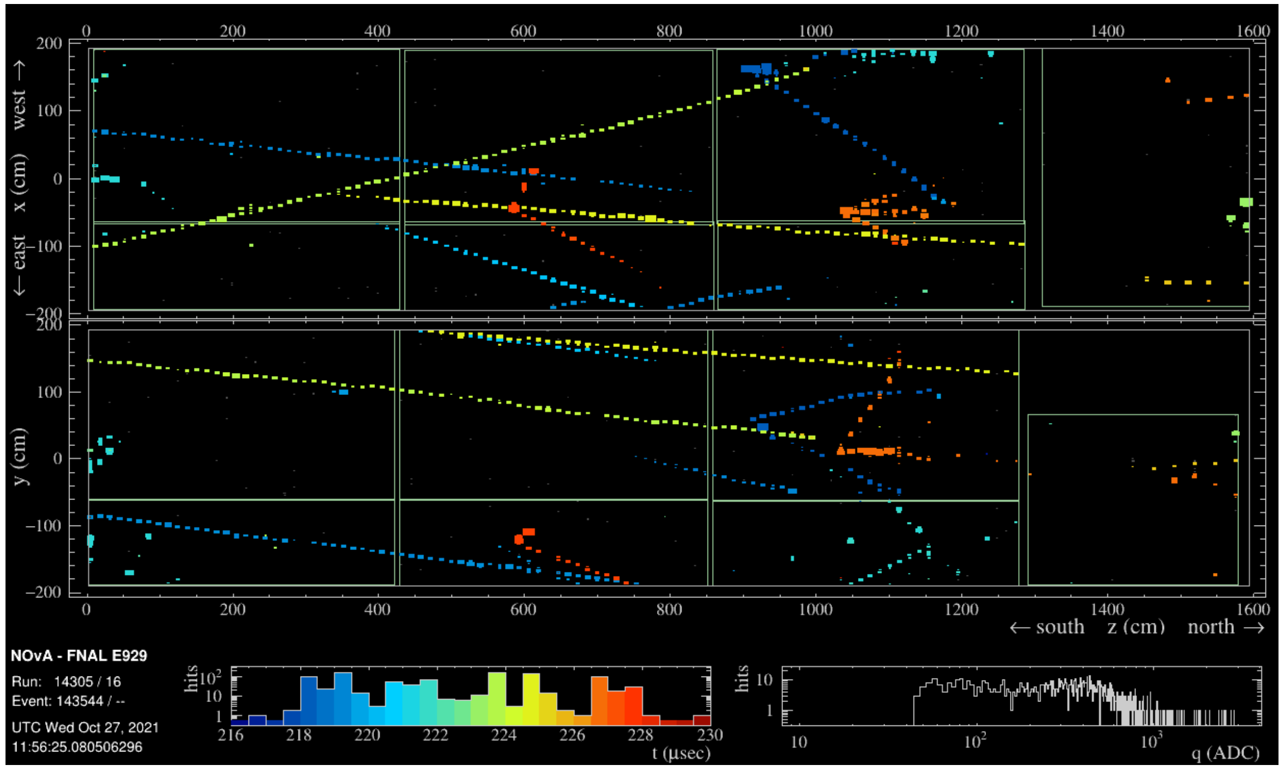


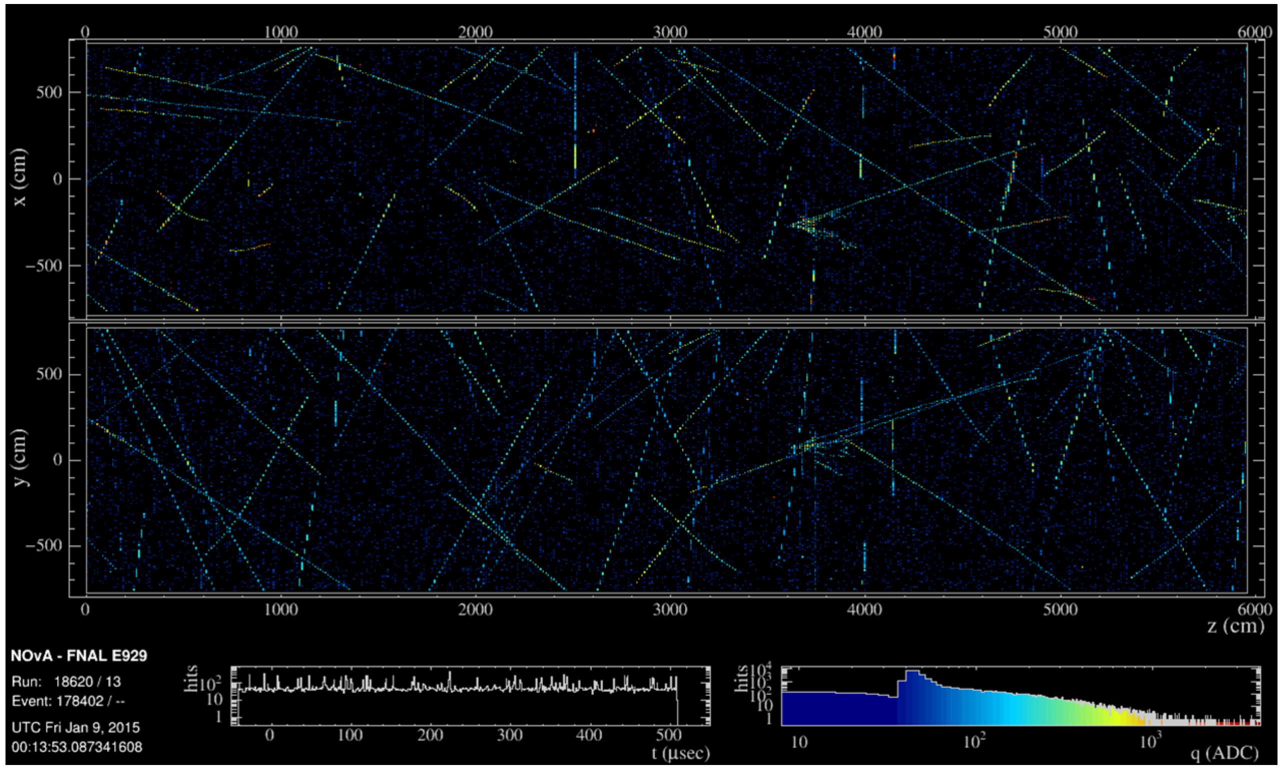


NOvA Data NuMI

- Beam trigger structure: 550 μs window, NuMI neutrinos arrive in 10 μs window starting at 218 μs







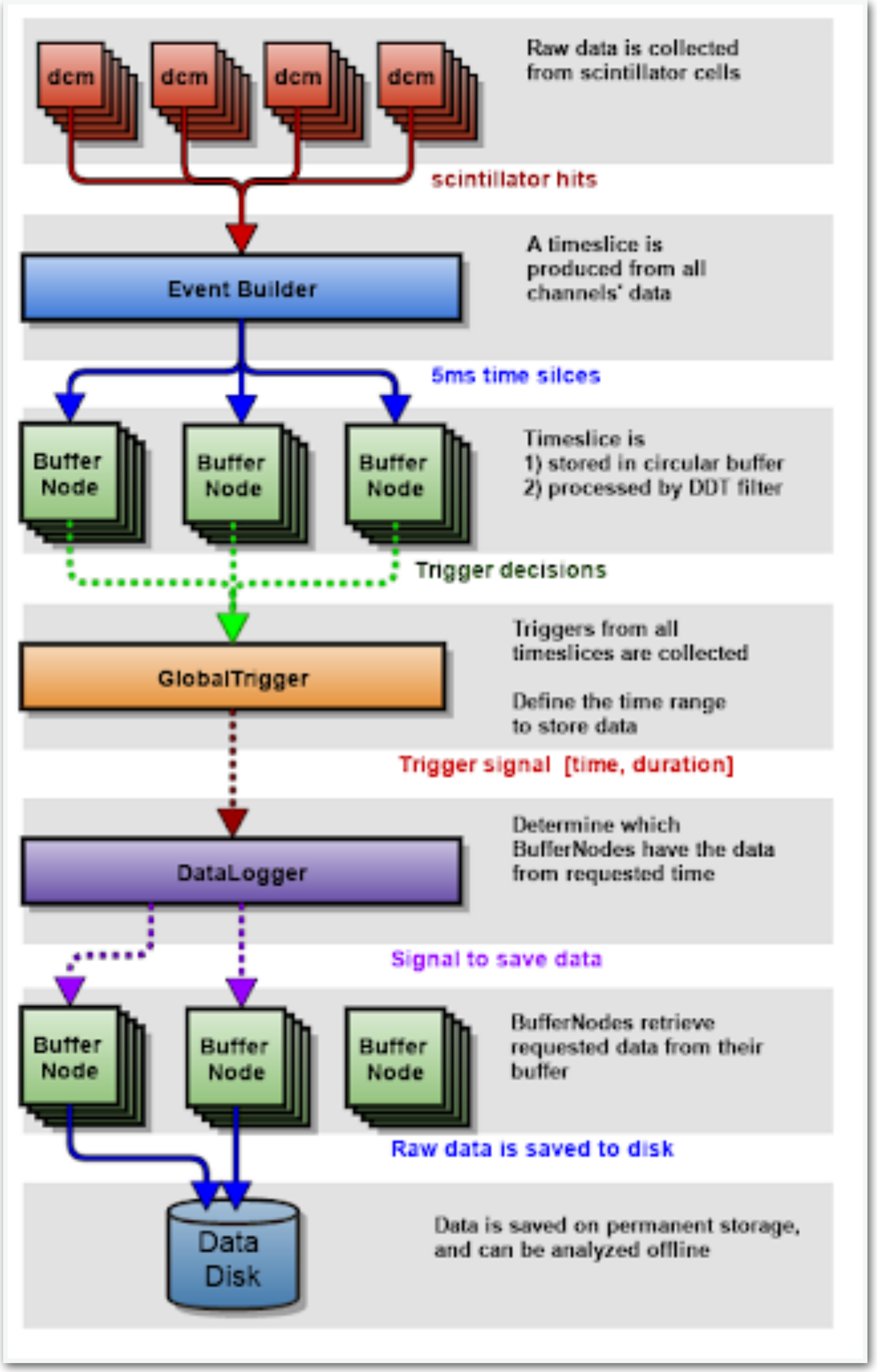
[NOvA Live Event Display Web-page]()

«Exotic» physics

- Non ν-oscillation and non ν-cross-section analyses are called «Exotic» ones.
- The mass of the detectors («target» part):
  - 14 ktons for the far detector.
  - 220 tons for the near detector.
- The detector locations:
  - FD is located on the surface.
  - ND is 100 m underground.
- Allow study of wide **Astrophysical program** beyond neutrino oscillation and neutrino cross-section measurements.
- Search for / detection of various signals from Space and the Earth's environment:
  - supernova.
  - magnetic monopole.
  - atmospheric muons and neutrinos.
  - dark matter.
  - potential signals in coincidence with the LIGO / Virgo gravitational wave events.

Data Driven Triggers

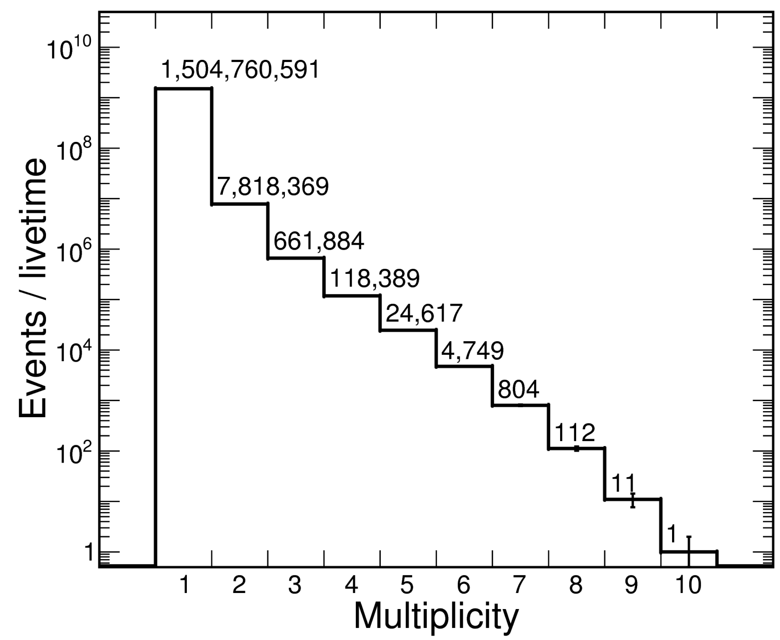
- Data rate including ≈ 100 kHz atmospheric muons is 1.2 GB/s.
- The beam spill data is selected by the time window.
- «Exotic» physics studies require specific data selection, based on its own online reconstruction algorithm.
- Detector data are formed in 5ms time slices (milliblocks) and distributed to nodes for storage in a circular buffer
  - 170 buffer nodes on Far Detector: 1350s
  - 14 buffer nodes on Near Detector: 1900s
- Milliblocks are processed in parallel DDT processes on buffer nodes (13 DDTs/node).
- DDT process performs reconstruction and selection, searching for the specific signature. If the signature is found, the trigger signal is sent.
- GlobalTrigger node receives all the the trigger signals and orders data to be saved to disk for future offline analysis.

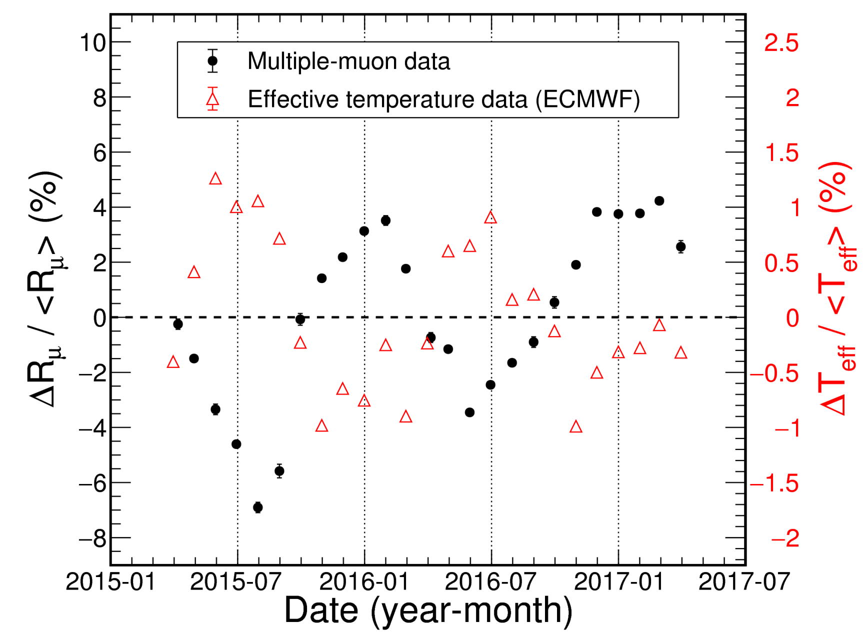


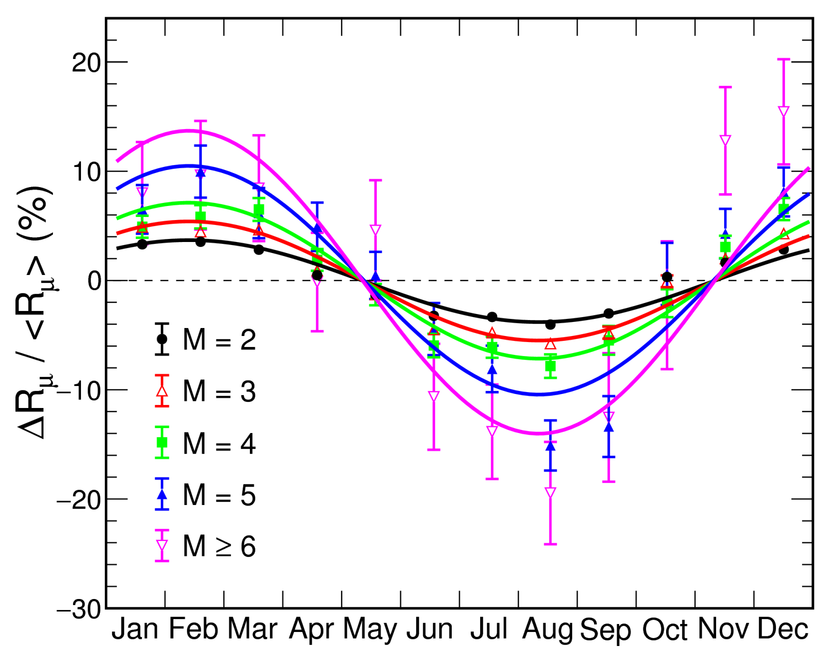
«Exotic» Analyses

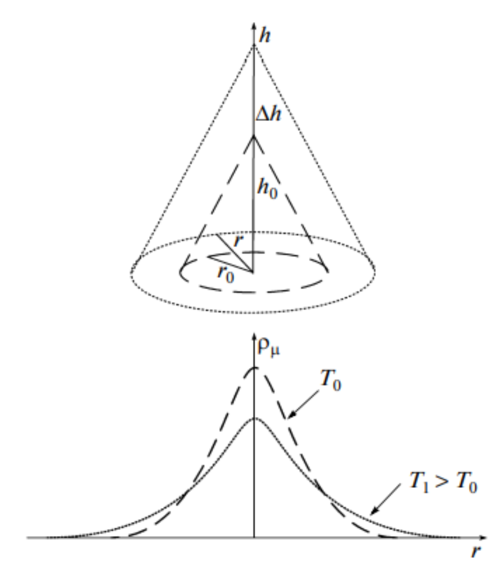
Cosmic Ray Studies: Seasonal variation

- NOvA has published a study of the seasonal variation of cosmic multi-muons in the ND (which is 100m underground) [[Phys. Rev. D 99, 122004 (2019)](https://doi.org/10.1103/PhysRevD.99.122004)]. It confirmed the MINOS observation that the rate of such events underground is unexpectedly higher in the winter.
- A run through 2025(6) provides an additional 8 annual cycles, which may or may not be enough to disentangle the relevant effects. Each additional year will provide valuable information.
- *From MC, we found the winter maximum for multimuons is a geometry effect – they come from a higher altitude in the summer, and some then miss the detector. This is consistent with all our observations, & was suggested to us by the DÉCOR group at Moscow State University.*



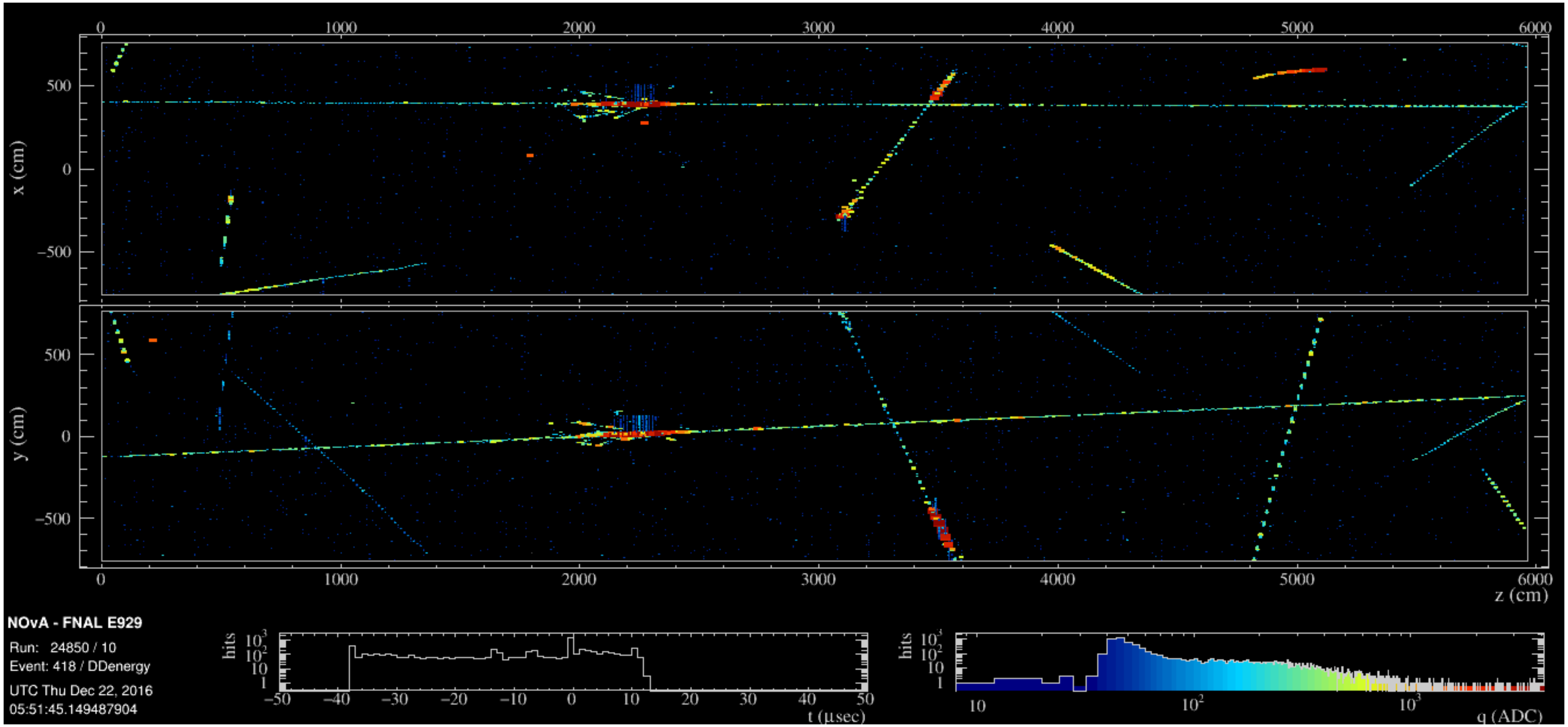






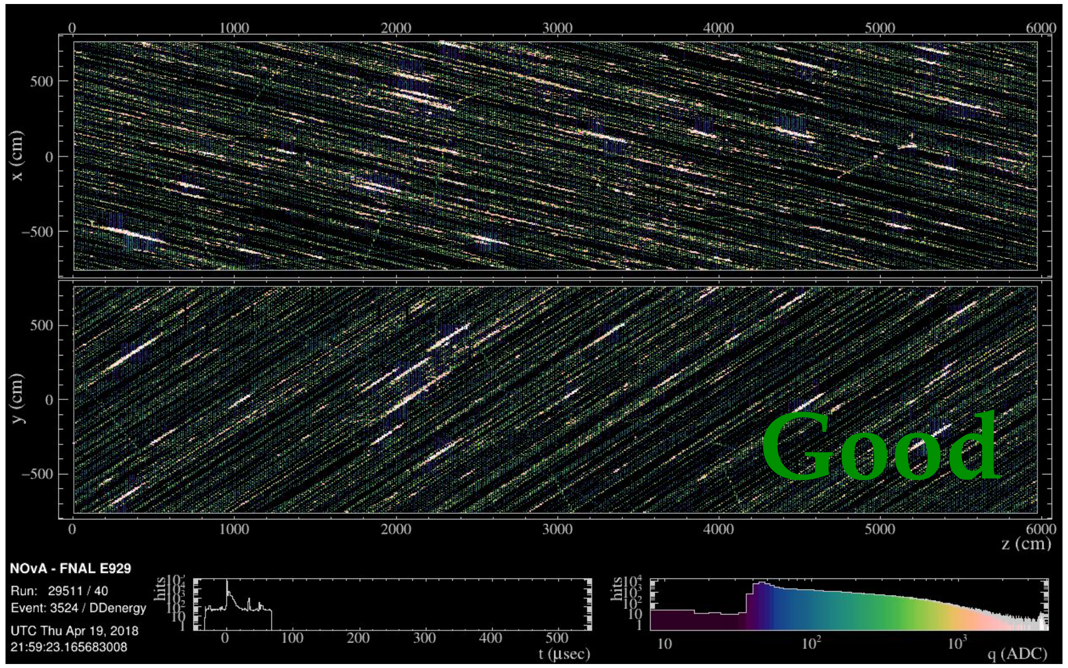
Cosmic Ray Studies: High energy muons

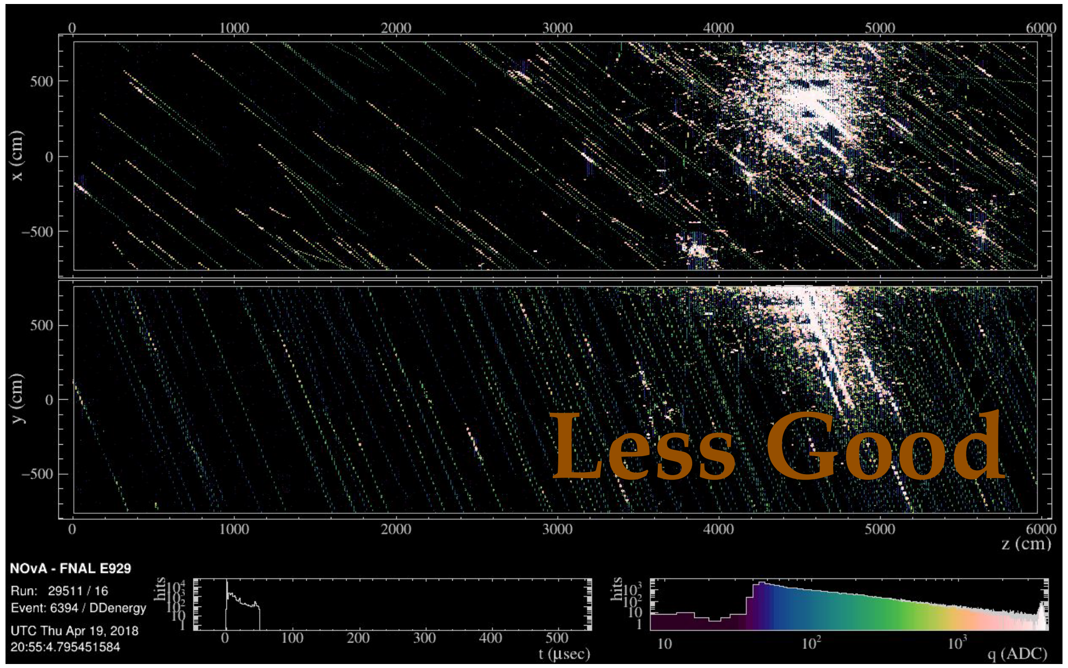
- A project has begun to study rare high energy muons in detail using NOvA's fine-grained tracking abilities, testing a spectrum-measuring technique proposed in R.P. Kokoulin and A.A. Petrukhin, "Theory of the pair meter for high-energy muon measurements," [Nucl. Instrum. Meth. A 263, 468–479 (1988)](#).

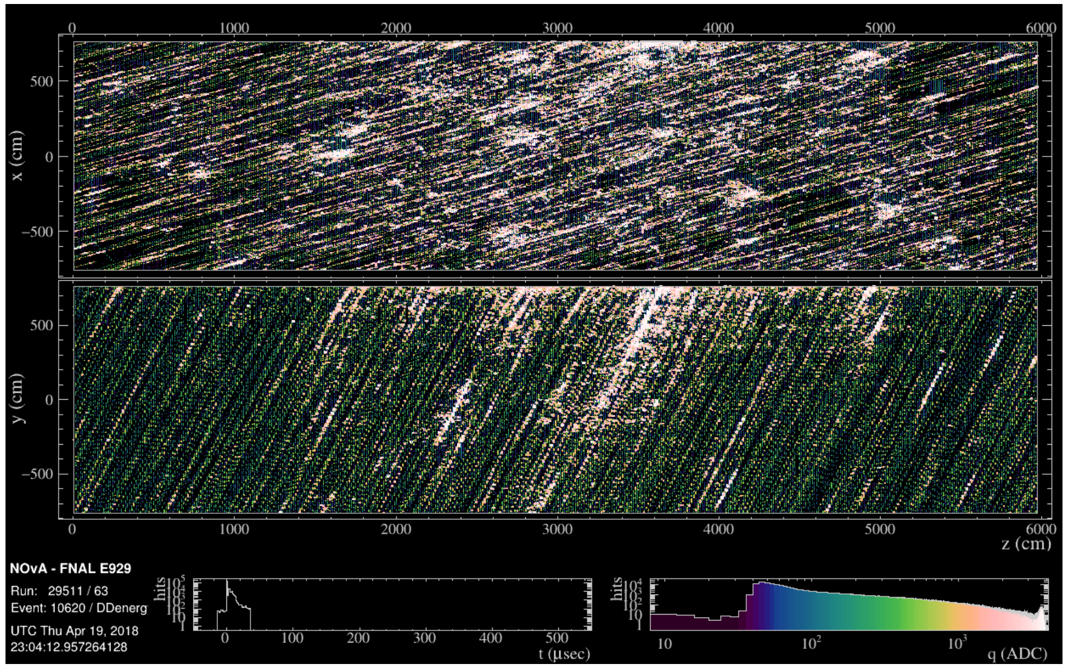


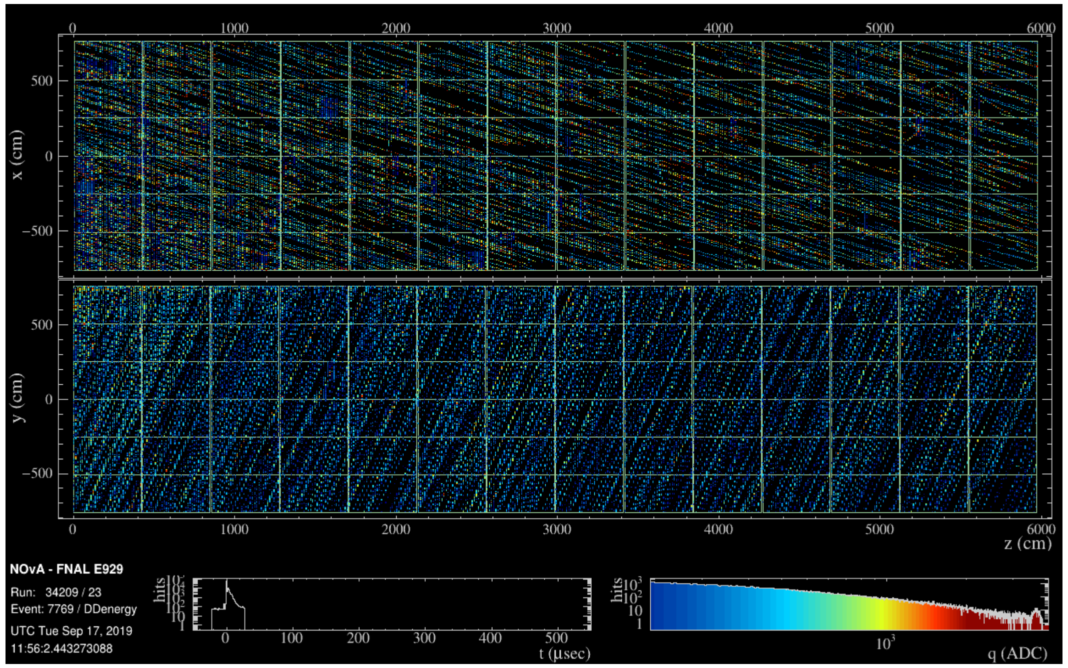
Cosmic Ray Studies: Ultra-high energy showers

- Started exploring distribution of shower origins on the sky.

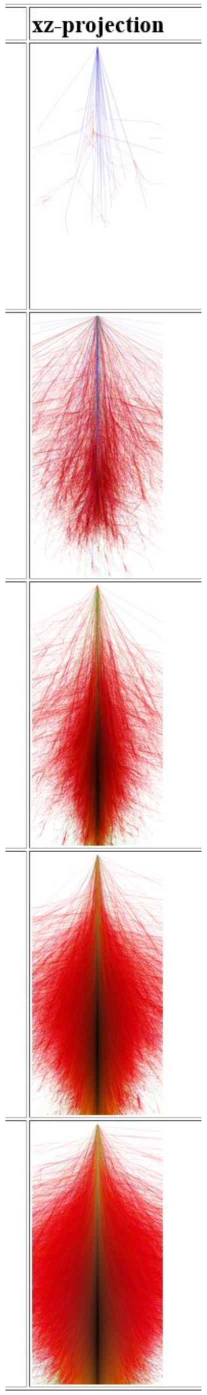






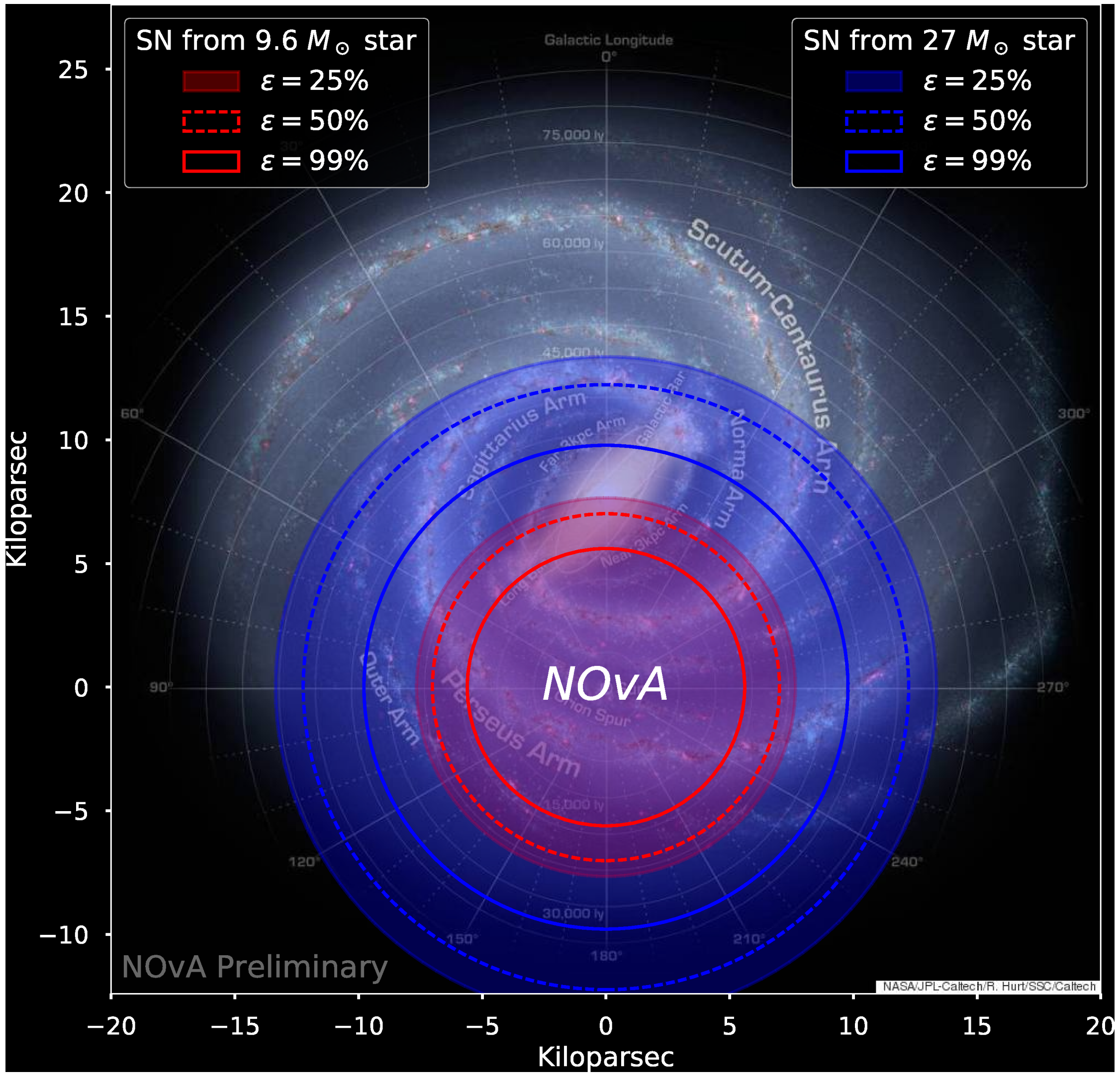


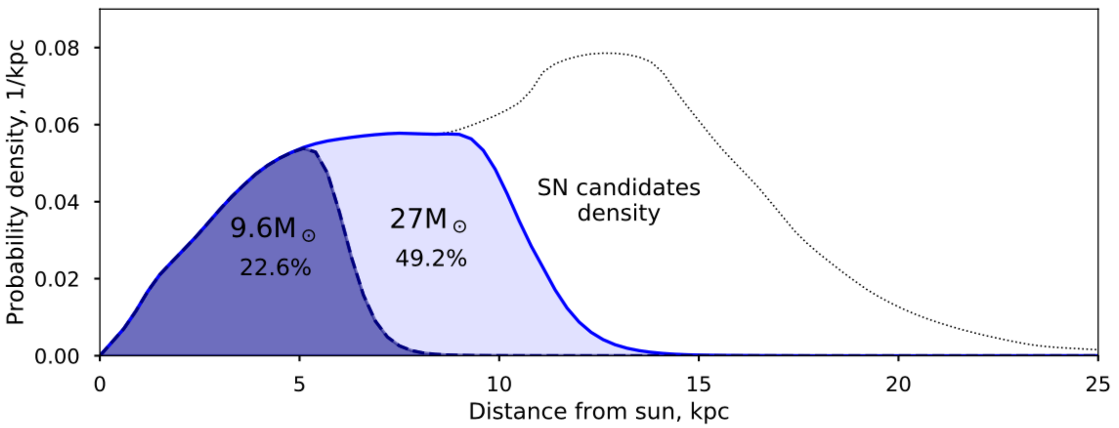
CORSIKA



Supernovae

- NOvA is the largest carbon-based supernova detector currently operating.
- In the event of a **Galactic supernova**, it will provide invaluable data which, in combination with detectors using other target materials, will constrain the flavor content of the supernova burst.
- The FD has better supernova capabilities than the ND but ND's small mass is compensated by its low background so the ND is still quite good for this analysis.
- NOvA can both selftrigger on a supernova burst, if it is within 7 kpc (13 kpc) for a 9.6 (27) solar mass star [JCAP10(2020)014], and be triggered by alerts from SNEWS.
- Given the estimated Galactic supernova rate of 3 per century, there is a 15% probability that NOvA observes a supernova burst through 2025(6), with the probability increasing linearly with each additional year.



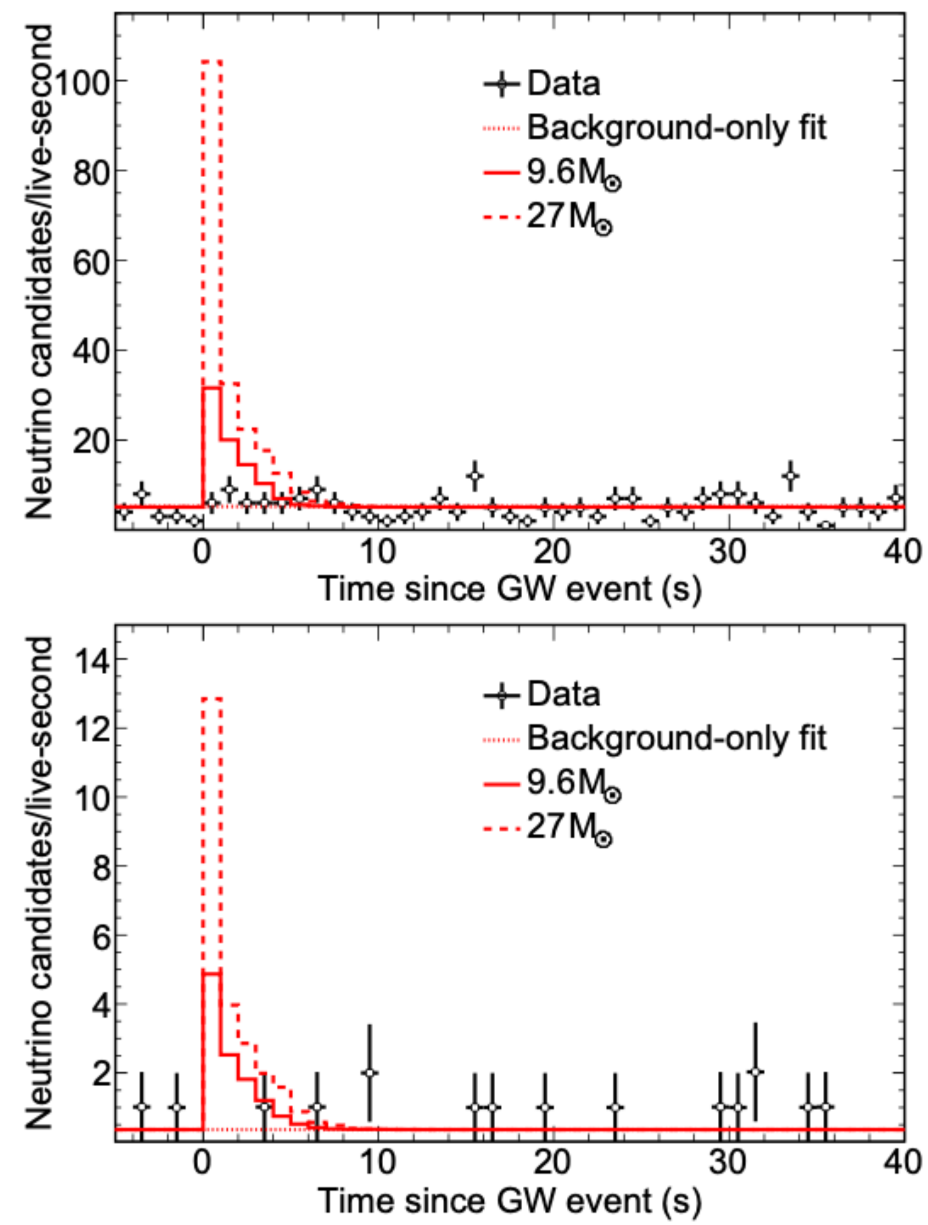


Gravitational Wave Coincidence

- NOvA triggers on gravitational wave events observed by LIGO/Virgo as part of its multimessenger astronomy program [Phys. Rev. D 101, 112006 (2020), Phys. Rev. D 104, 063024 (2021)]. Our primary observable is a possible flux of supernova-like neutrinos. This could be from an actual supernova, or it could be from an exotic source. We are also sensitive to GeV neutrinos and other similar activity. Gravitational wave astronomy is still a nascent field and there may be surprises in the near future.

Name	ND	FD	$SN_{27\odot}$	$SN_{9.6\odot}$
GW150914	Untriggered	Bad	—	—
GW151012	Untriggered	No data	—	—
GW151226	Untriggered	Untriggered	110	190
GW170104	Untriggered	Untriggered	300	500
GW170608	Untriggered	Untriggered	400	700
GW170729	Untriggered	Untriggered	240	400
GW170809	Untriggered	Untriggered	110	190
GW170814	Untriggered	Untriggered	120	200
GW170817	Untriggered	Untriggered	110	190
GW170818	Untriggered	Untriggered	180	330
GW170823	Untriggered	Untriggered	260	500
GW190408_181802	No data	No data	—	—
GW190412	Untriggered	Untriggered	170	280
GW190421_213856	Untriggered	Untriggered	210	400
GW190425	Untriggered	Untriggered	120	190
GW190426_152155	44.7 s	Untriggered	13	19
GW190503_185404	Untriggered	Untriggered	150	270
S190510g	Untriggered	Untriggered	170	280
GW190512_180714	Untriggered	Untriggered	190	330
GW190513_205428	24.7 s	Untriggered	14	20
GW190517_055101	Untriggered	Untriggered	120	200
GW190519_153544	Untriggered	Untriggered	140	250
GW190521	45.0 s	45.0 s	6	10
GW190521_074359	Untriggered	Untriggered	170	280
GW190602_175927	45.0 s	45.0 s	6	12
GW190630_185205	45.0 s	45.0 s	5	9
GW190701_203306	45.0 s	45.0 s	6	11
GW190706_222641	45.0 s	17.5 s	2.5	5
GW190707_093326	Untriggered	Untriggered	220	400
GW190413_052954	Untriggered	Untriggered	170	280
GW190413_134308	Untriggered	Untriggered	160	270
GW190424_180646	Untriggered	Untriggered	140	240
GW190514_065416	Untriggered	Untriggered	280	500
GW190527_092055	Untriggered	Untriggered	140	240
GW190620_030421	Untriggered	Untriggered	270	400
GW190708_232457	Untriggered	Untriggered	150	270
S190718y	18.3 s	Untriggered	17	23
GW190719_215514	Untriggered	Bad	—	—
GW190720_000836	45.0 s	45.0 s	4	6
GW190727_060333	45.0 s	45.0 s	5	9

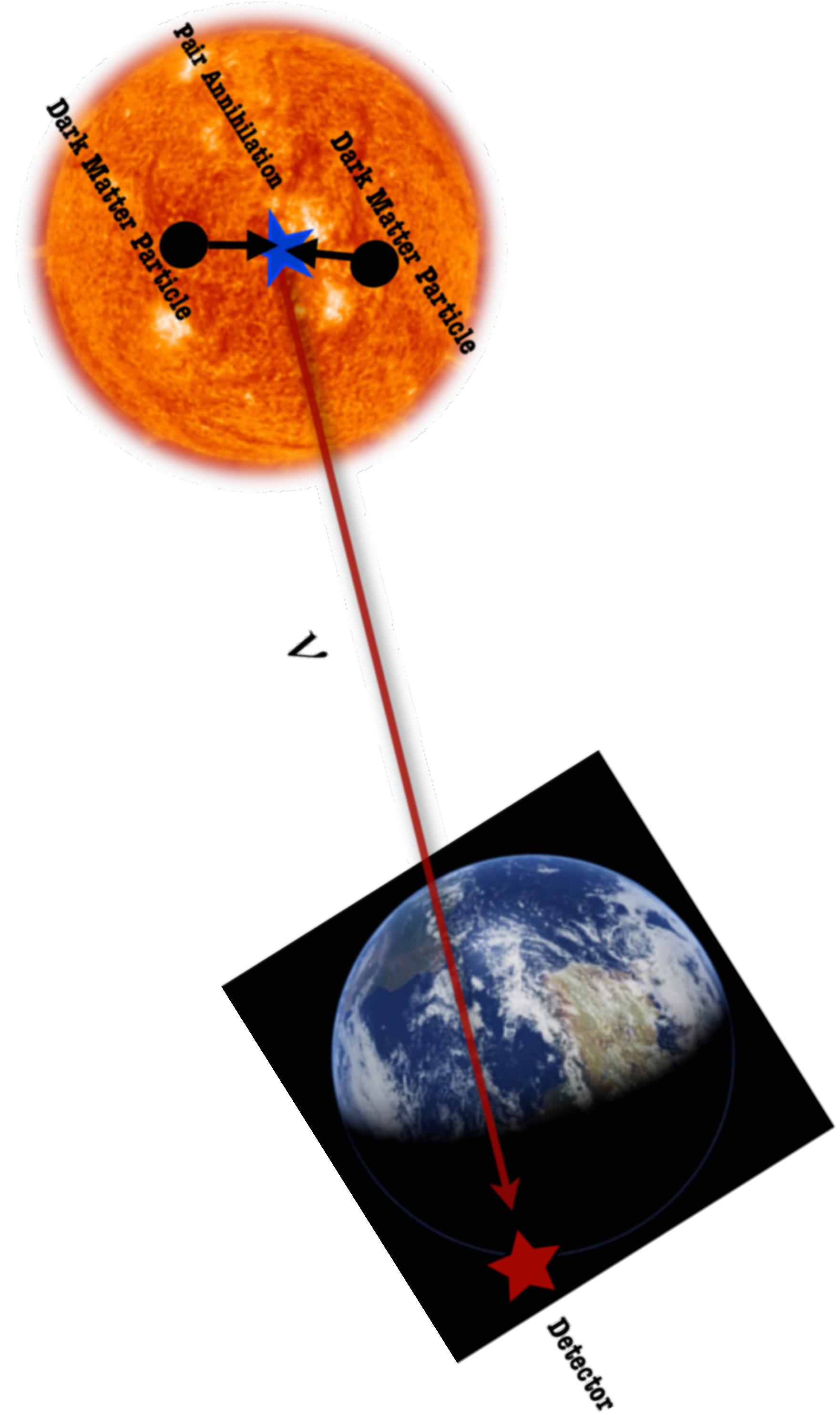
Name	ND	FD	$SN_{27\odot}$	$SN_{9.6\odot}$
GW190728_064510	45.0 s	29.6 s	3.2	5
GW190731_140936	Untriggered	Untriggered	210	400
GW190803_022701	Untriggered	Untriggered	140	230
GW190814	45.0 s	Untriggered	14	22
GW190828_063405	45.0 s	18.1 s	6	10
GW190828_065509	45.0 s	Untriggered	16	21
S190901ap	45.0 s	45.0 s	3.1	6
GW190909_114149	Untriggered	Untriggered	110	190
S190910d	45.0 s	45.0 s	4	7
S190910h	45.0 s	45.0 s	2.7	5
GW190910_112807	Untriggered	Untriggered	120	190
GW190915_235702	45.0 s	45.0 s	3.0	6
S190923y	45.0 s	45.0 s	3.2	6
GW190924_021846	45.0 s	45.0 s	4	7
GW190929_012149	Untriggered	Untriggered	200	340
GW190930_133541	45.0 s	45.0 s	7	13
S190930t	45.0 s	45.0 s	5	10
S191105e	Untriggered	Untriggered	180	310
S191109d	45.0 s	45.0 s	5	8
S191129u	Untriggered	Untriggered	230	400
S191204r	Untriggered	Untriggered	300	500
S191205ah	45.0 s	45.0 s	2.7	6
S191213g	45.0 s	45.0 s	3.4	7
S191215w	45.0 s	45.0 s	4	7
S191216ap	45.0 s	29.5 s	2.7	5
S191222n	45.0 s	45.0 s	4	7
S200105ae	Untriggered	Untriggered	230	400
S200112r	45.0 s	No data	16	23
S200114f	45.0 s	45.0 s	9	15
S200115j	45.0 s	45.0 s	2.1	4
S200128d	45.0 s	45.0 s	5	8
S200129m	45.0 s	45.0 s	3.2	6
S200208q	45.0 s	45.0 s	5	7
S200213t	45.0 s	45.0 s	5	10
S200219ac	Untriggered	Untriggered	190	300
S200224ca	45.0 s	No data	22	29
S200225q	45.0 s	45.0 s	3.4	6
S200302c	45.0 s	45.0 s	4	8
S200311bg	45.0 s	No data	16	21
S200316bj	45.0 s	45.0 s	2.9	5



A typical GW event with both FD (top) and ND (bottom) continuous readout, S200213t. Two supernova models are shown, normalized to 10 kpc.

Dark Matter

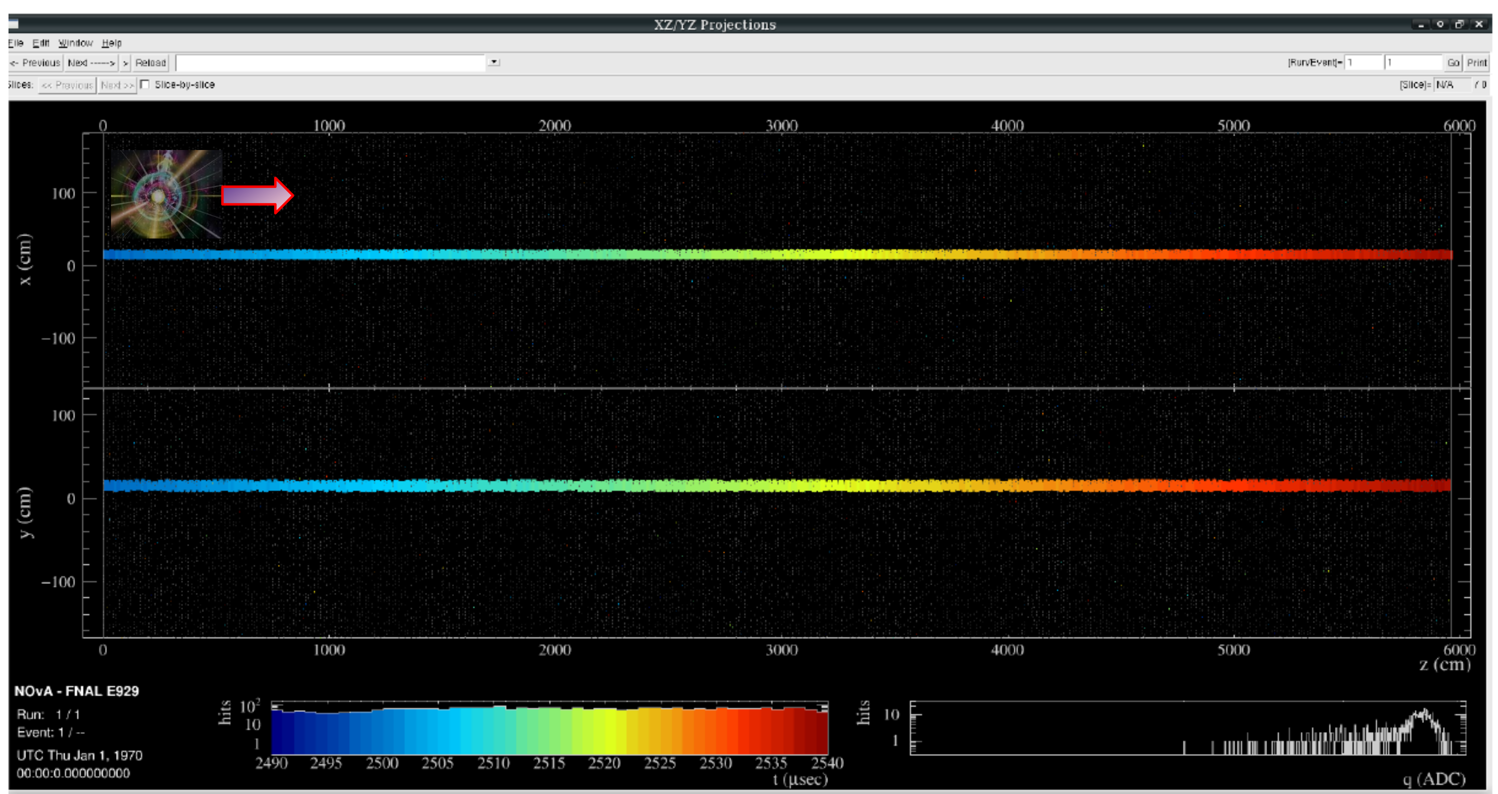
- Dark Matter may accumulate in the Sun and annihilate, producing GeV neutrinos. The signal is an upwards-going muon in the FD that points back to the Sun. Because of NOvA's low threshold and high segmentation, we may be more sensitive than Super-K for dark matter masses 1–4 GeV. The search is likely background-limited by atmospheric neutrinos, so the sensitivity scales as the square root of exposure.
- It is also possible to search for dark matter produced in the NuMI beam using the NOvA ND. The signal would be an excess of very forward EM showers.



Magnetic Monopole Search

- The NOvA far detector (**FD**) is well suited for finding exotic particles due to its technical features. With a surface area of 4,000 m^2 and a location near the earth's surface, the 14 kt FD provides unique sensitivity to potential magnetic monopoles at various betas.

$\beta = \upsilon/c$ = velocity/speed of light



50 µs → β = 10^{-3}   Highly ionizing particle

Technically we can record tracks as slow as $\beta \approx 10^{-4}$

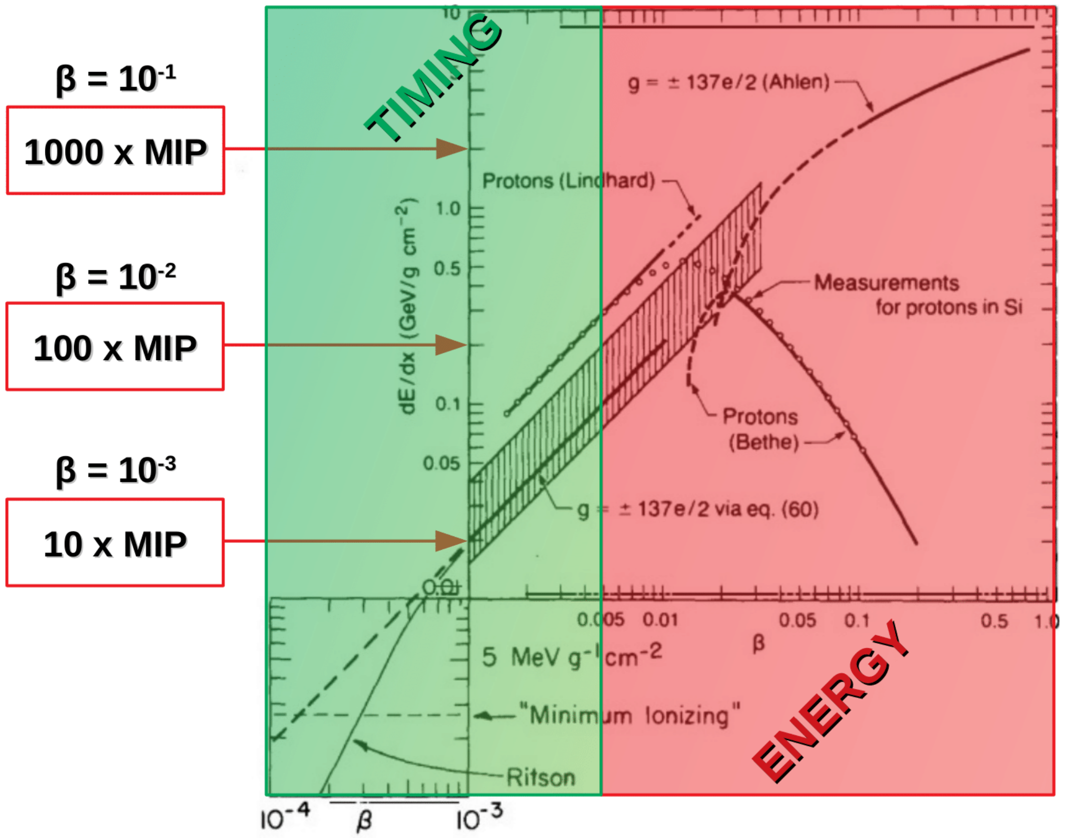
Magnetic Monopole Search

- Why we are interested in monopoles? Quantum mechanical formulation of the magnetic monopoles was made by Paul Dirac in 1931. Searches for these particles are very important for several reasons:
  - Their existence would explain the quantization of electric charge.
  - It is possible to restore symmetry between electricity and magnetism by means their introduction into the theory of electromagnetism.
  - Magnetic monopole naturally appears in Grand Unified Theories (GUT).

Magnetic Monopole Search

- We separate the monopole search into two regimes: fast and slow. For the slow one the most distinctive aspect of the signal is the track speed and for the fast is extreme ionization. Both searches are expected to be background free, and so the flux limits scale linearly with exposure.

"Slow" monopoles with $\beta < 10^{-2}$ and less can be identified due to their linear tracks with long transit times through the detector.

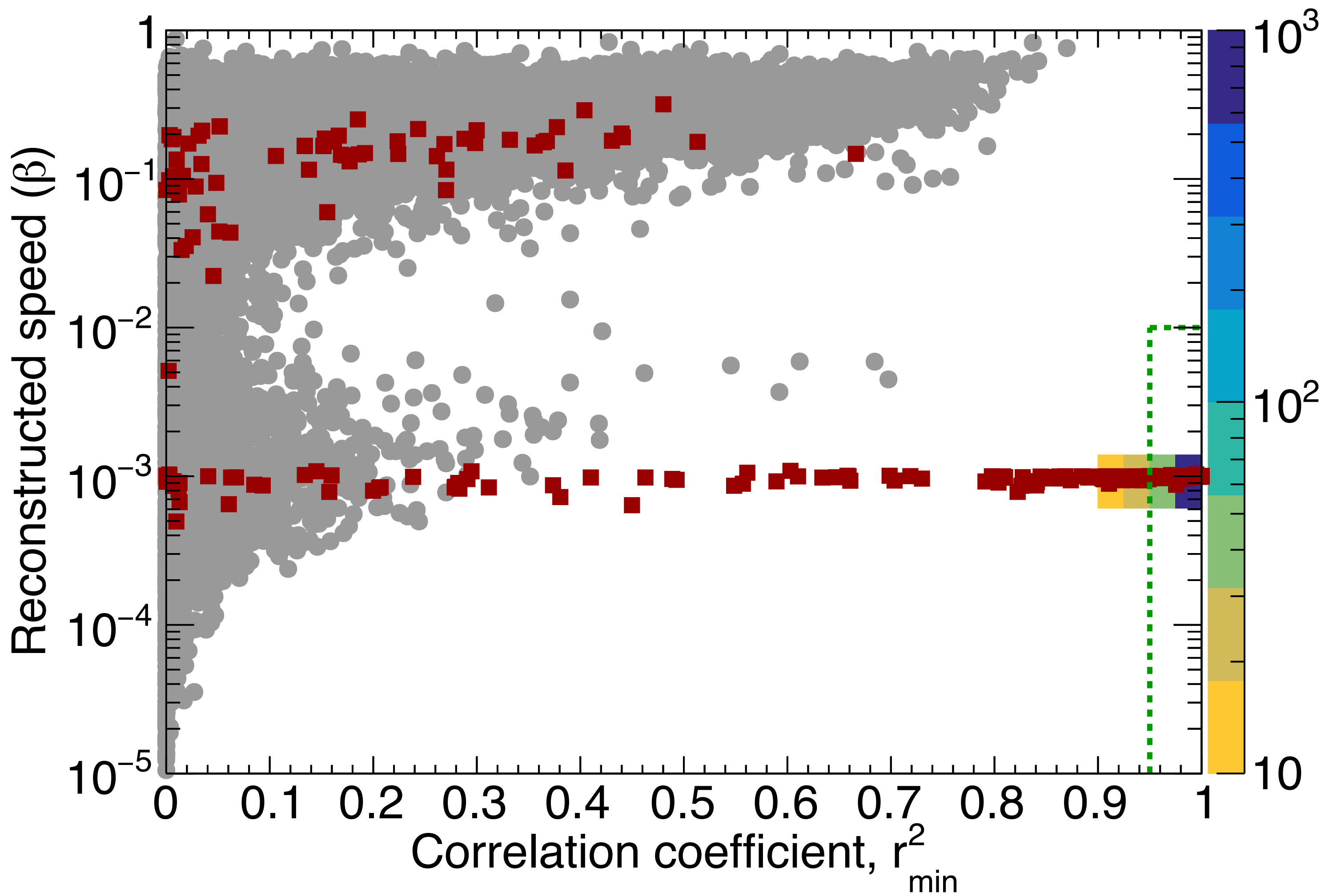


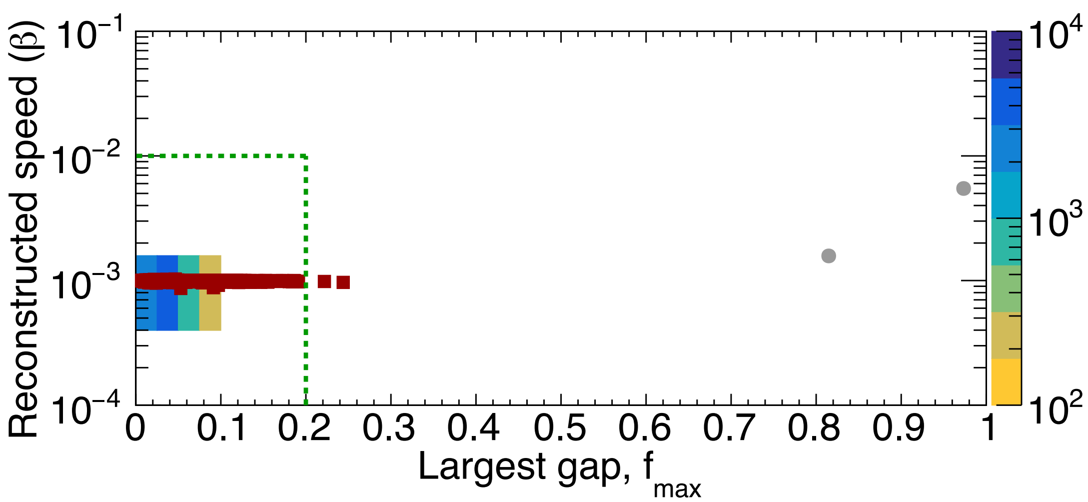
Magnetic Monopole Search

- **Analysis algorithm**:
  - **Slow monopole trigger** — trigger looks at the live data and tries to identify straight lines of hits that would be consistent with a slow track.
  - **Pre-selection** — The main goal is to decrease the resulting dataset size and event count by removing obvious background.
  - **Reconstruction** — The Far Detector electronics collect data in two projected views separately, the xz- and yz-views. The y-direction is the vertical dimension while the z-direction points along the neutrino beam. Reconstruction starts by extracting two-dimensional information from each view separately and then combines this 2D information into 3D objects known as monopole tracks.

Magnetic Monopole Search

- Monopole track **requirements**:
  - > 10 m length
  - Sensible r^2 for time vs. position
  - $\beta < 0.01$
  - No large gaps





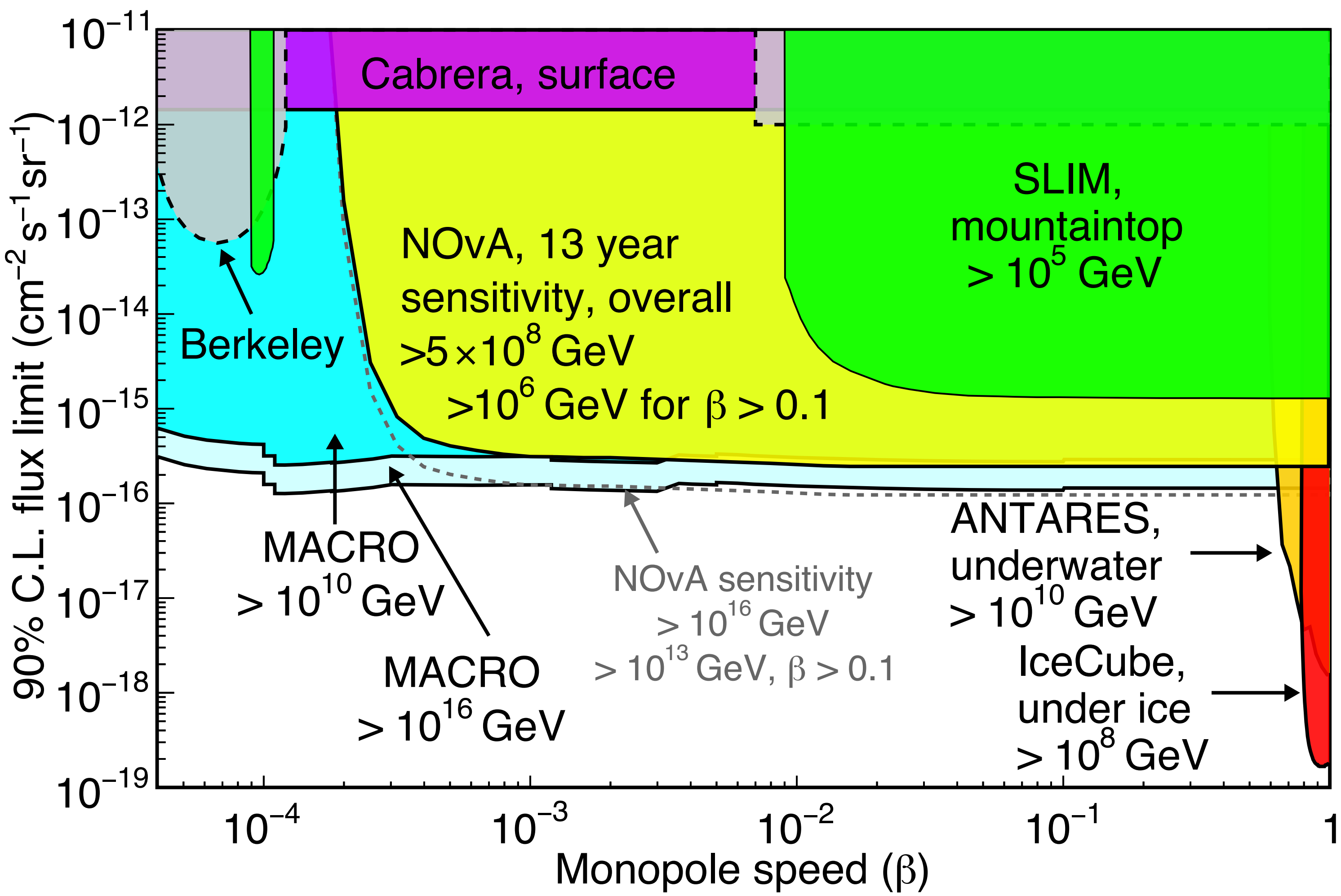
- **Low** APD gain data:
  - Data events are shown as grey circles
  - Simulation for $\beta = 10^{-3}$ both as red squares and as a heat map
- Events should be inside dashed green areas to be considered monopole candidates

Magnetic Monopole Search

- All collected data were divided into sub parts according to detector's photosensor **gain** or slow monopole trigger **settings**:
  - **APD low gain data** — first 95 days dataset in the very beginning of FD operation. Was totally analyzed and published. [Phys. Rev. D 103, 012007 (2021)]
  - Further **4 high** APD **gain** data periods — were pre-selected. Pre-selection procedure is a powerful tool that helped to lower the size of final dataset (**filtered**) by more than **20** times.
  - **Reconstruction** — algorithm was tested using Monte-Carlo simulation and FD usual activity. Final criteria are ready for filtered high APD gain dataset analysis.

Magnetic Monopole Search

- 13 years of data would give an estimated flux limit of 4×10^{-16} cm^{-2}s^{-1}sr^{-1} for monopoles with $3\times10^{-4} < \beta < 0.8$, matching or surpassing the MACRO and SLIM flux limits while covering a wider range of monopole masses.



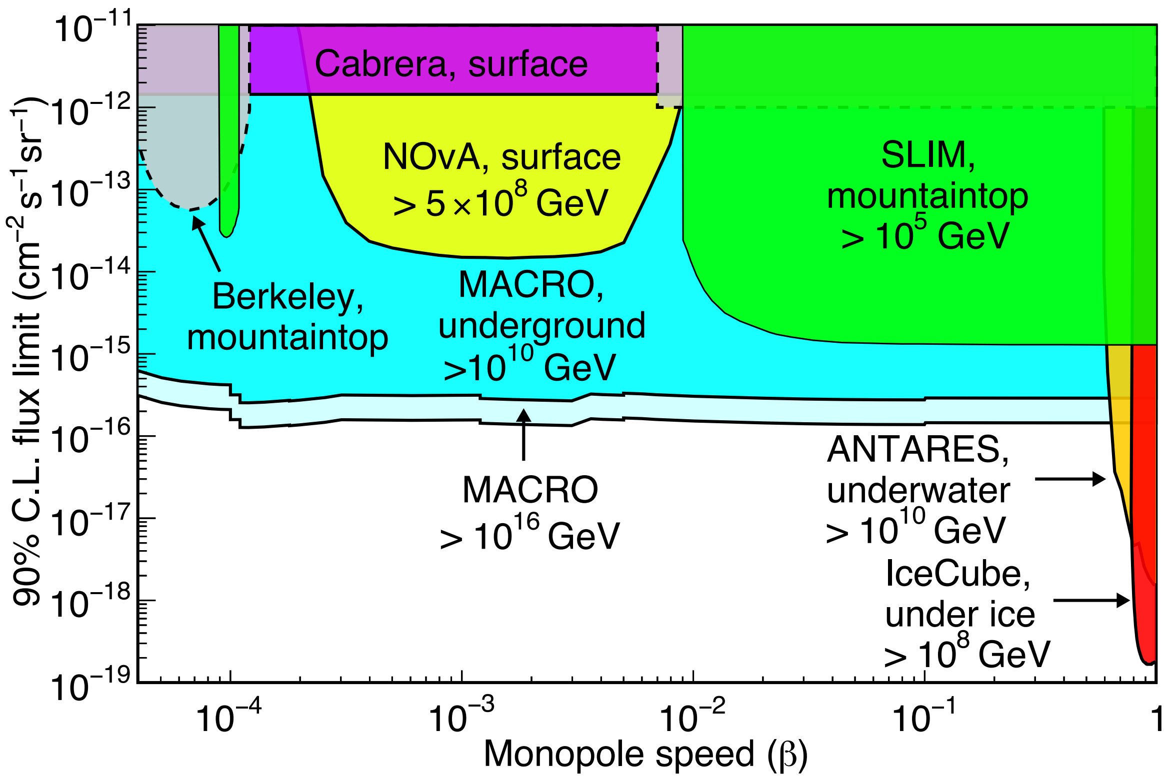
Summary

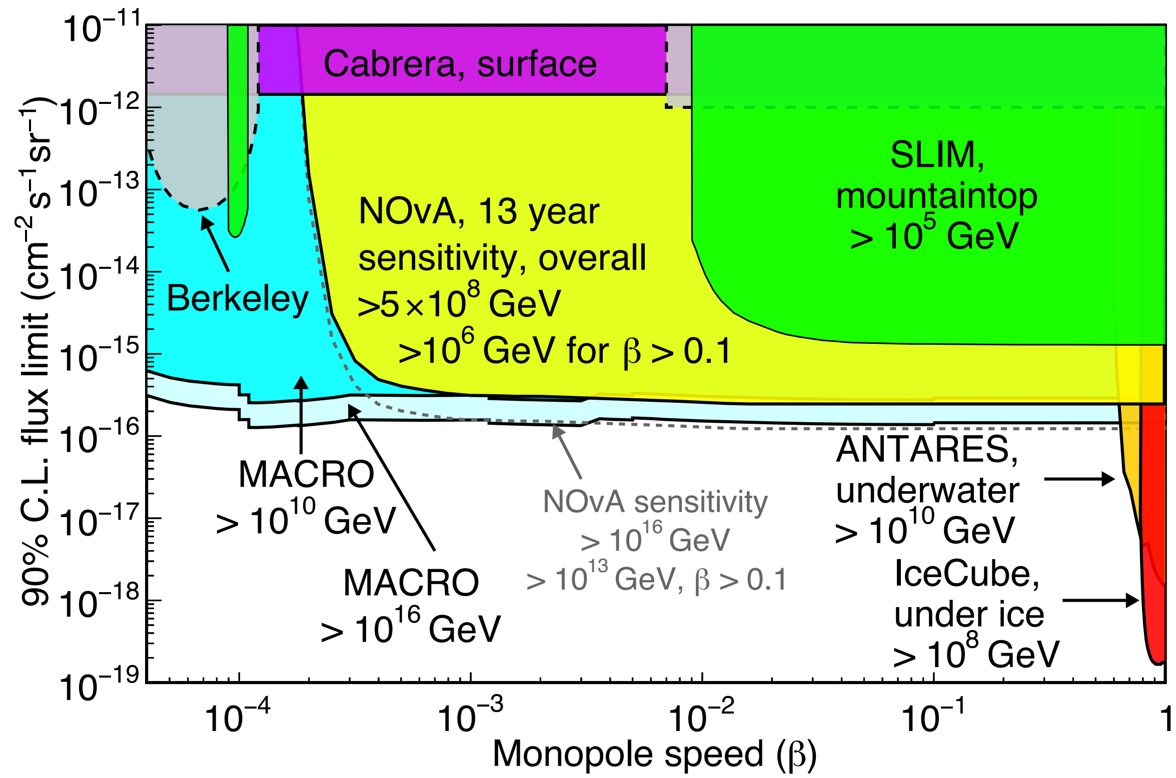
- The NOvA experiment allows us to investigate wide range of particle physics phenomena beyond neutrino oscillation and neutrino cross-section measurements.
- «Exotic» analyses help to modernize the NOvA subsystems: DAQ, Trigger, Detector simulation.
- 7 paper already published and many analyses ongoing…
- Including slow magnetic monopole analysis:
  - Low gain APD dataset was analyzed and published.
  - High gain APD dataset was divided into **4** pieces according to trigger settings.
  - **Pre-selection** was made for the majority of the data. Pre-selection procedure reduced the final dataset by factor of ~ 20.
  - **Reconstruction cuts** were optimized using MC simulation and FD activity.
  - We are almost ready to move to the final step — work with the filtered dataset.

Thank you for your attention!

Backup

Low vs High APD gain data





- **Low gain:**
- **95-day exposure**
- Set **mass limits** in flux / speed space

- **High gain:**
- **~ 4000 days of exposure**
- Majority of the data were **pre-selected**: significantly reduced the dataset size and required CPU time for further analysis
- Reconstruction cuts are the same
- Background free — limits scale linearly with exposure