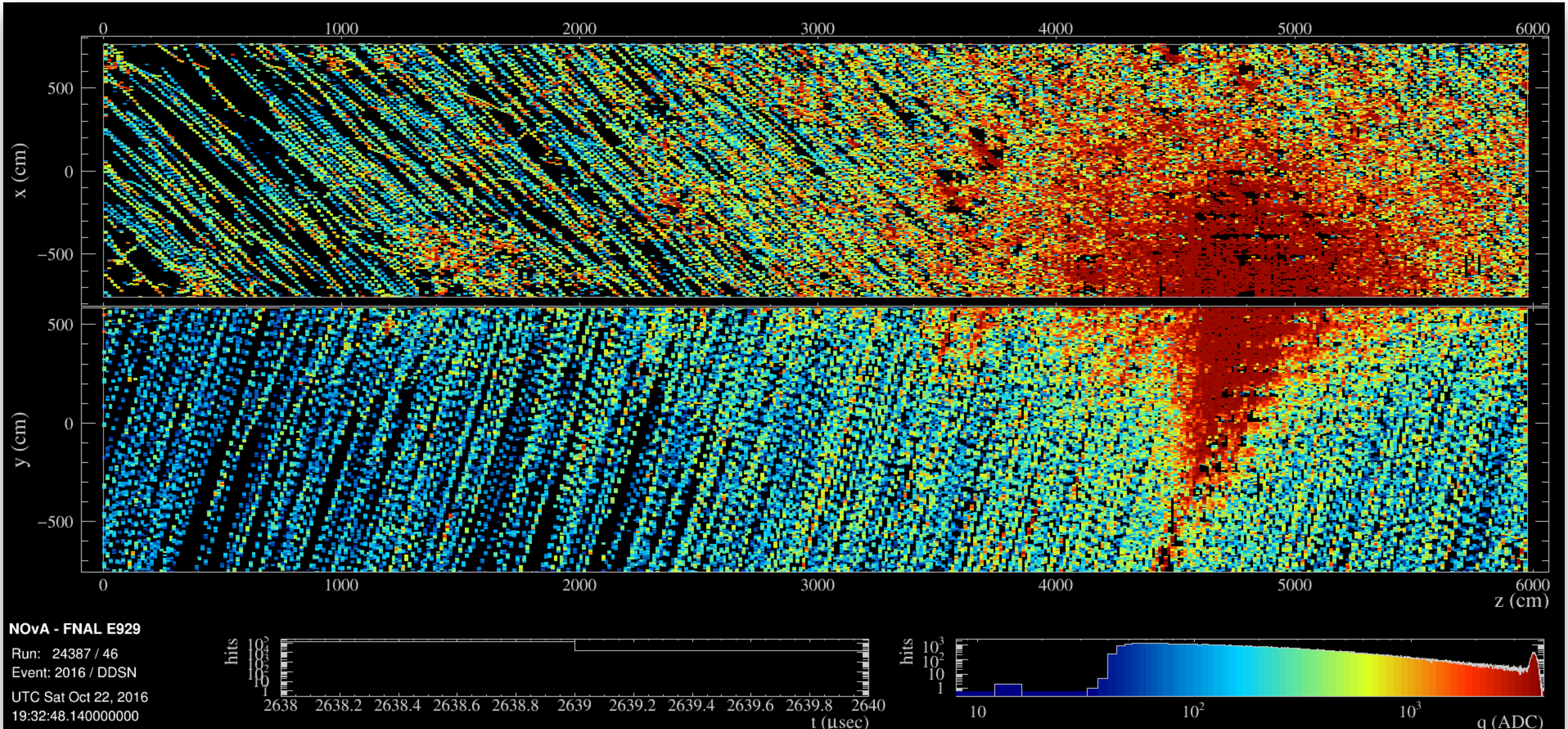


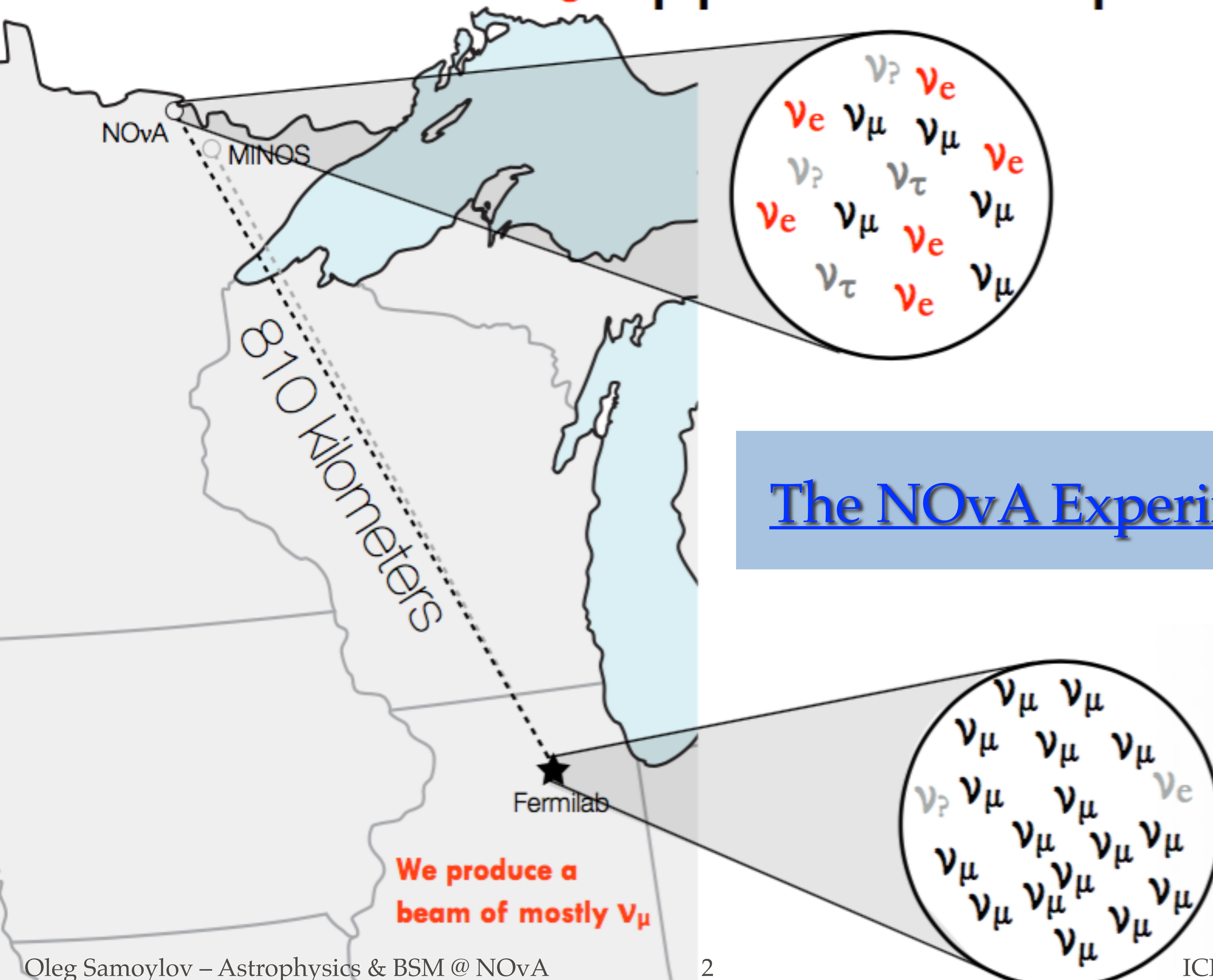
Astrophysics and beyond the Standard Model of particle physics in the NOvA experiment

Oleg Samoylov (on behalf of the NOvA Collaboration)

Joint Institute for Nuclear Research, Dubna

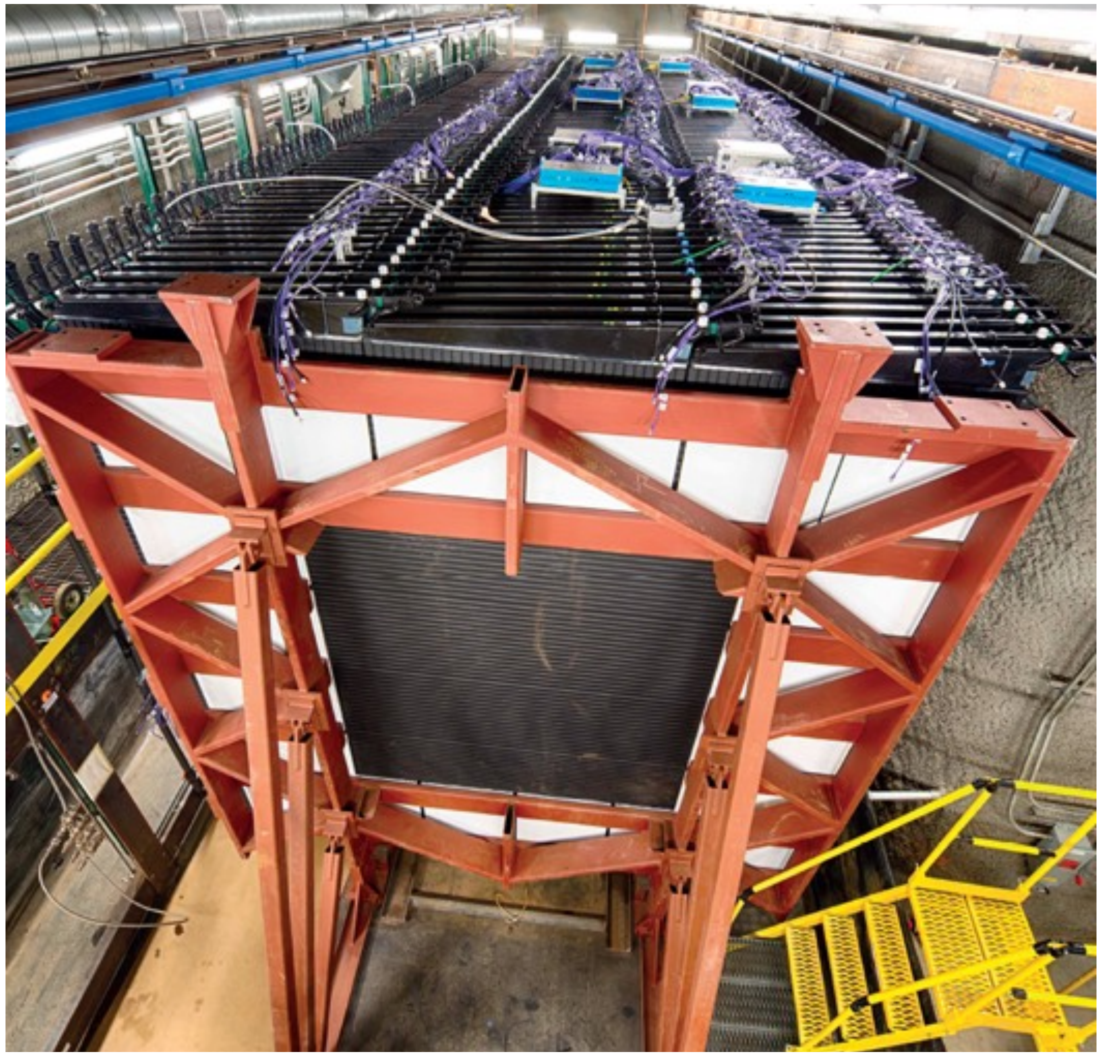
The 6th international conference on particle physics and astrophysics, Moscow (Russia), 29/11-02/12/2021

NuMI Off-axis ν_e Appearance Experiment

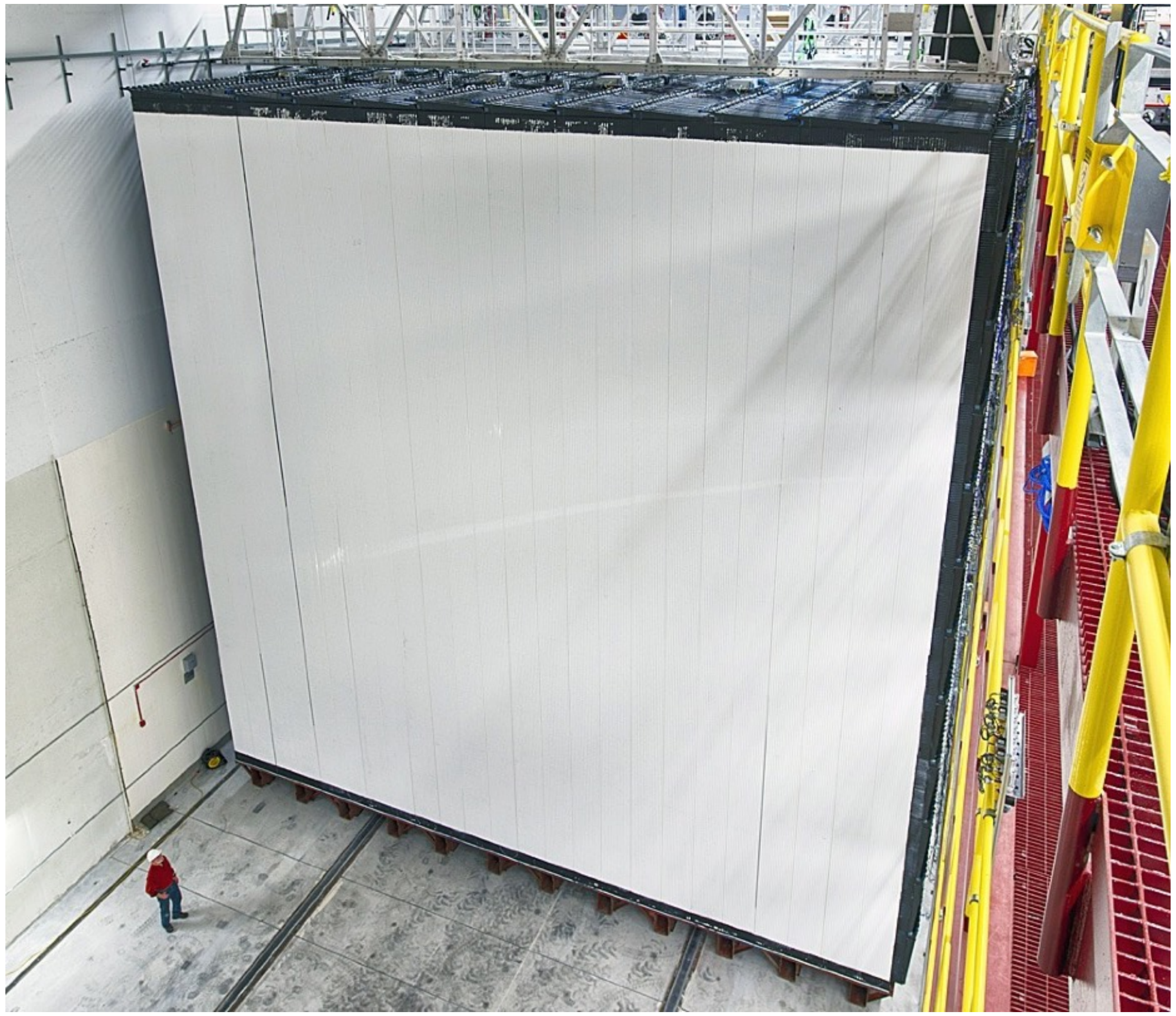


[The NOvA Experiment]

Two-detector scheme

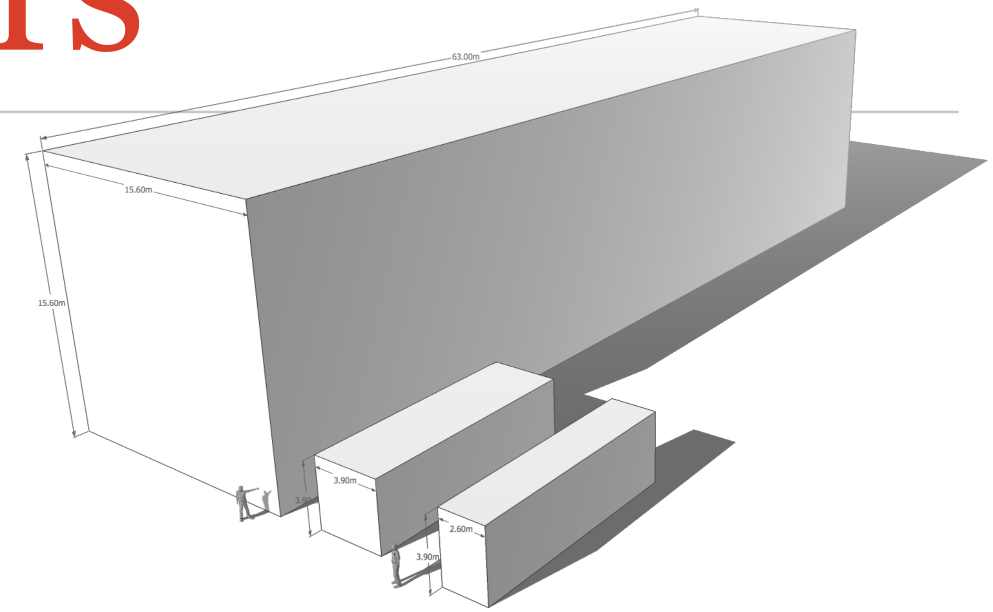


- **Near detector**
  - 1 km after target, **weight 300 t**
  - measure flux composition before oscillations
  - ND data used for prediction in FD (extrapolation procedure)
  - **100 m underground**

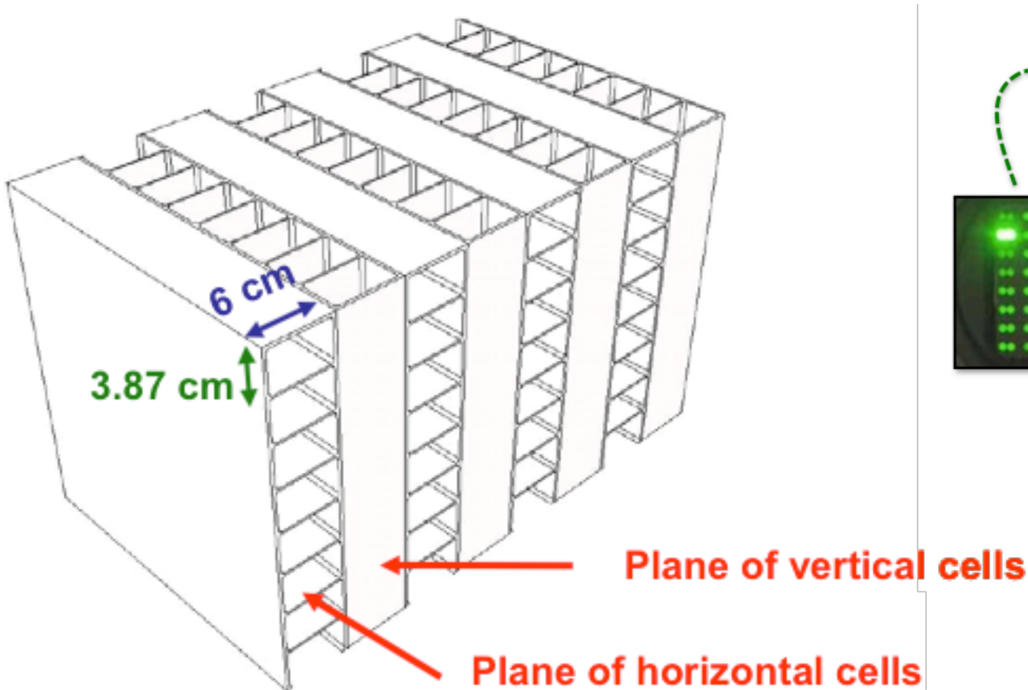


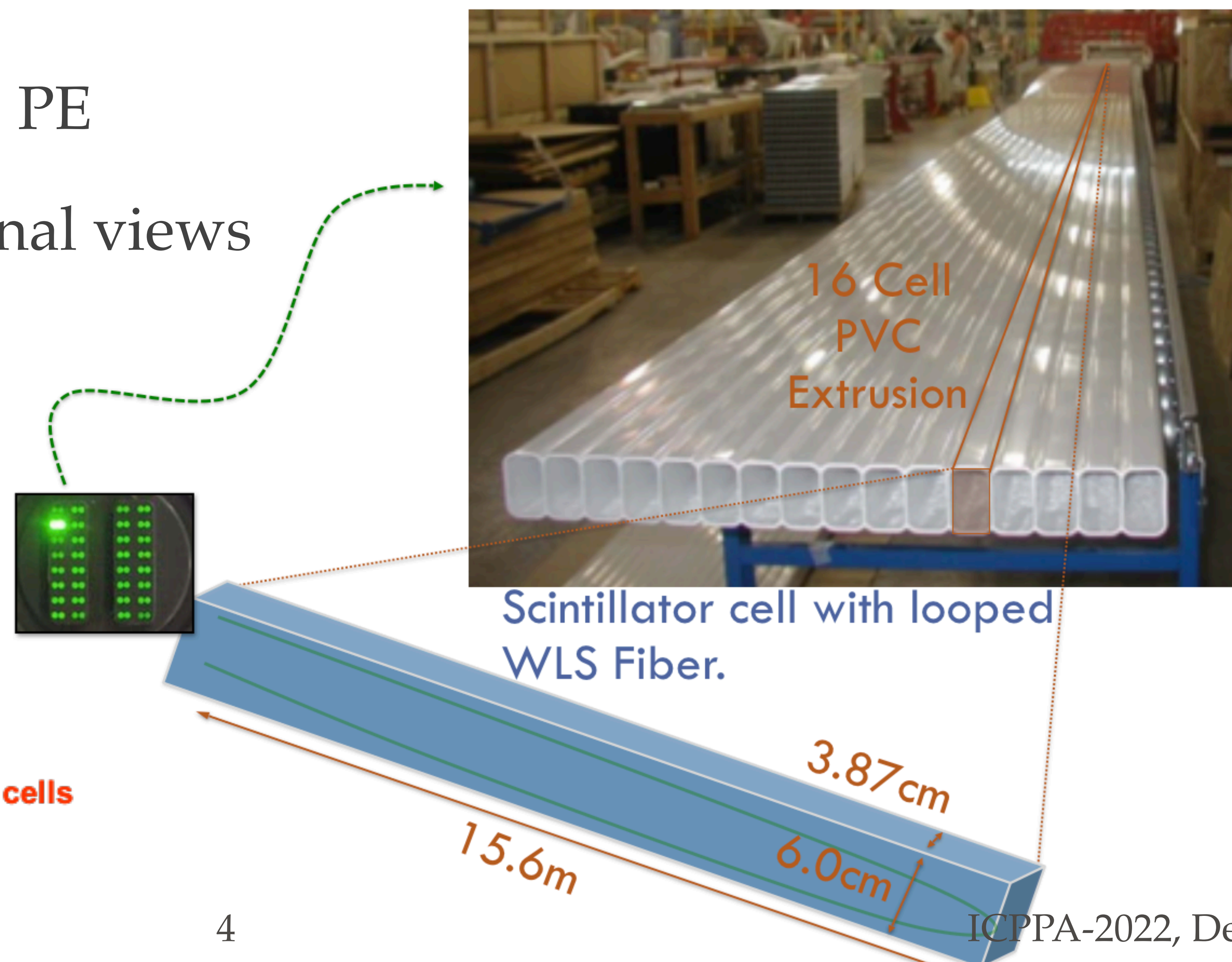
- **Far detector**
  - 810 km after target, **weight 14 kt**
  - measure neutrino flux after oscillations
  - extrapolation systematics
  - FD identical to ND
  - **On the Earth's surface**

The NOvA Detectors



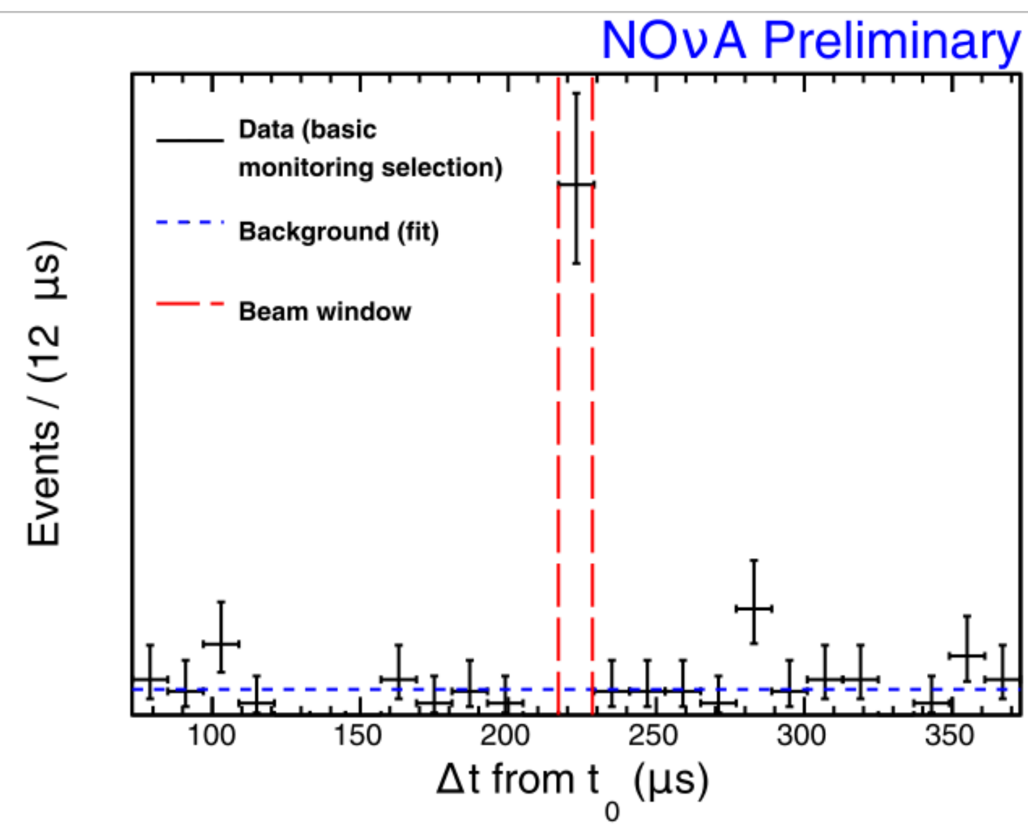
- PVC extrusion + Liquid Scintillator
  - mineral oil + 5% pseudocumene
- Read out via WLS fiber to APD
  - FD has ~344,000 channels
  - muon crossing far end ~40 PE
- Layered planes of orthogonal views

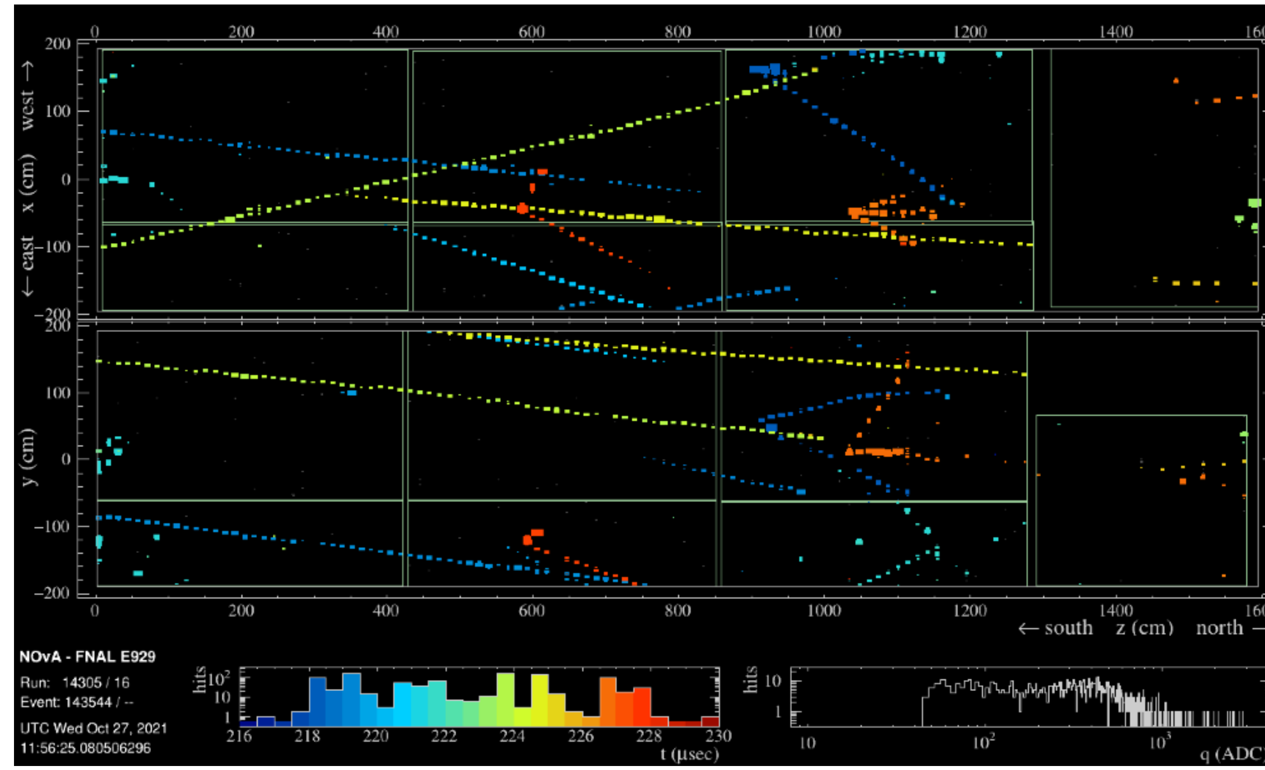


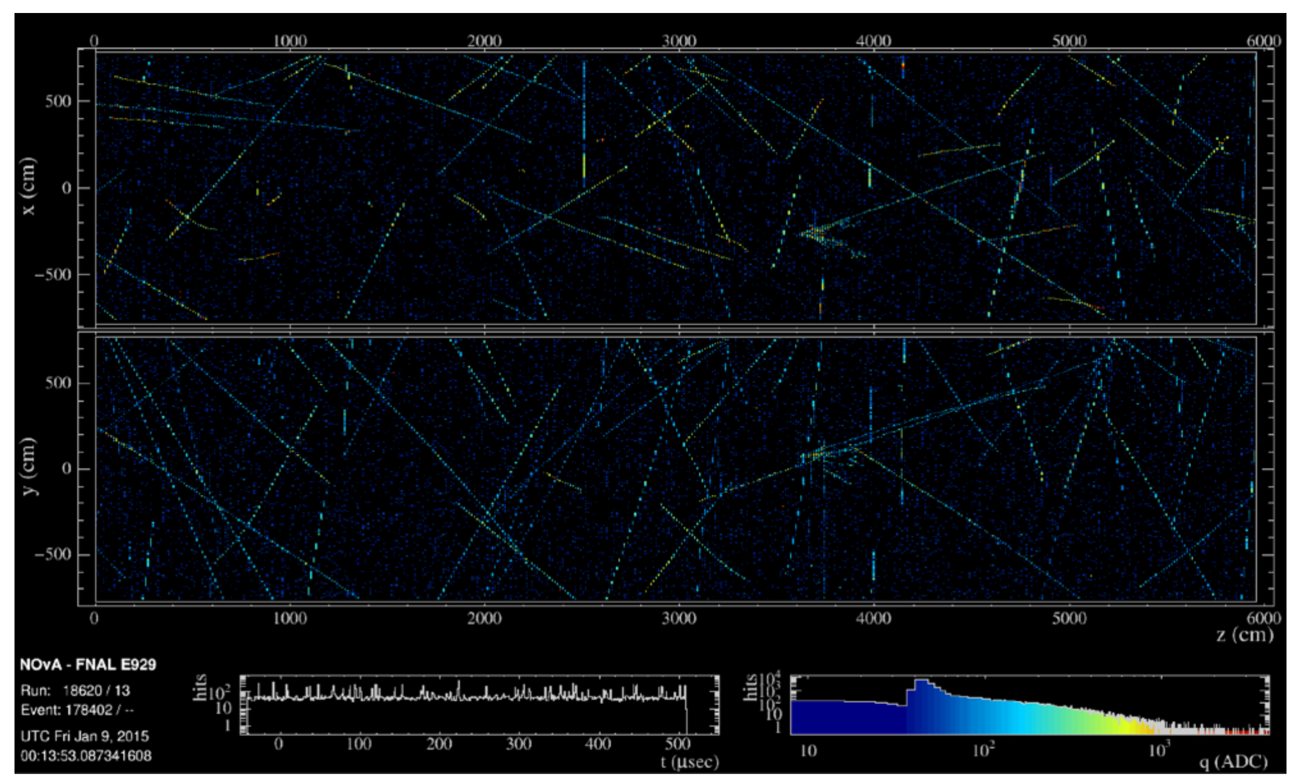


NOvA Data NuMI events

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

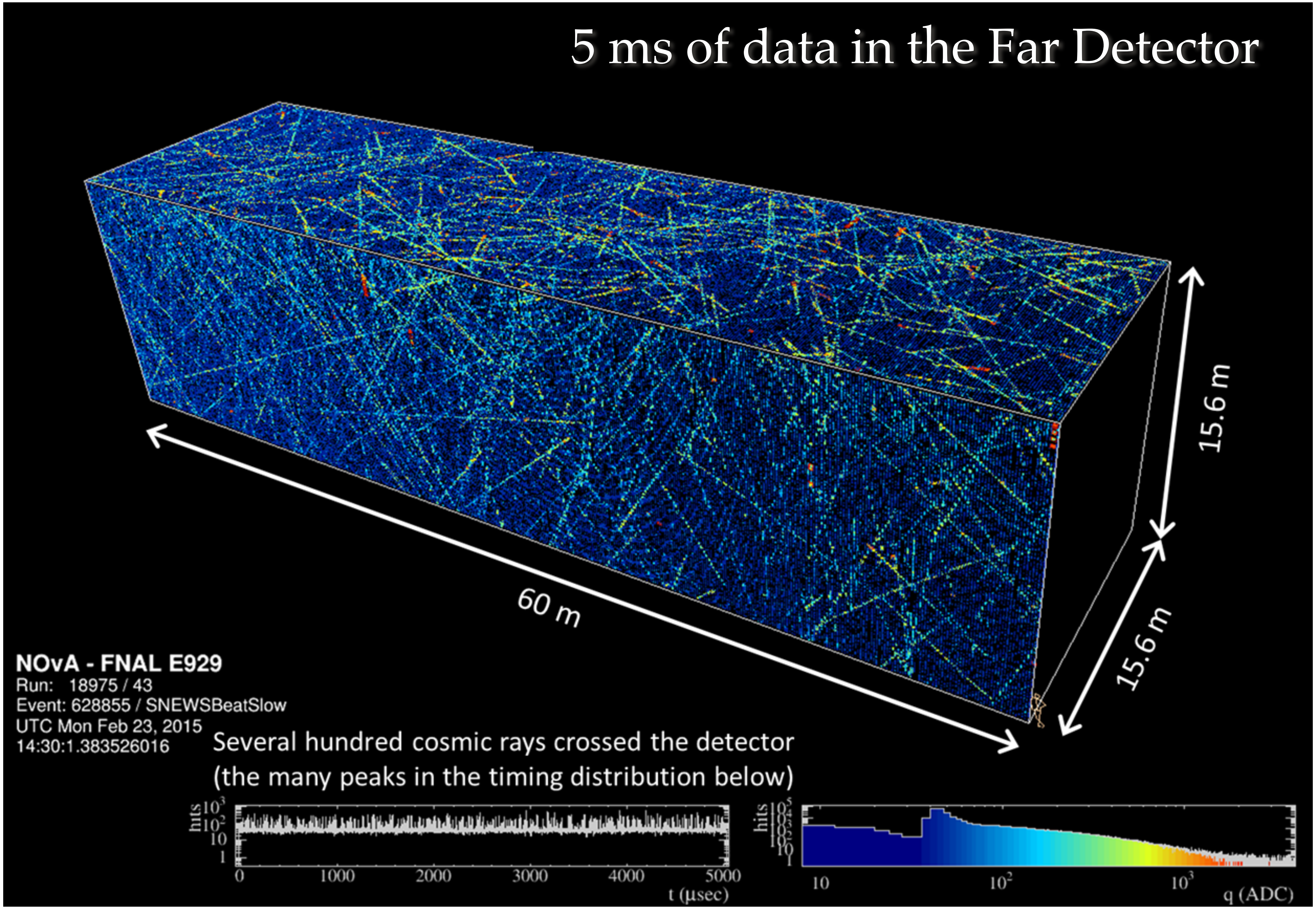




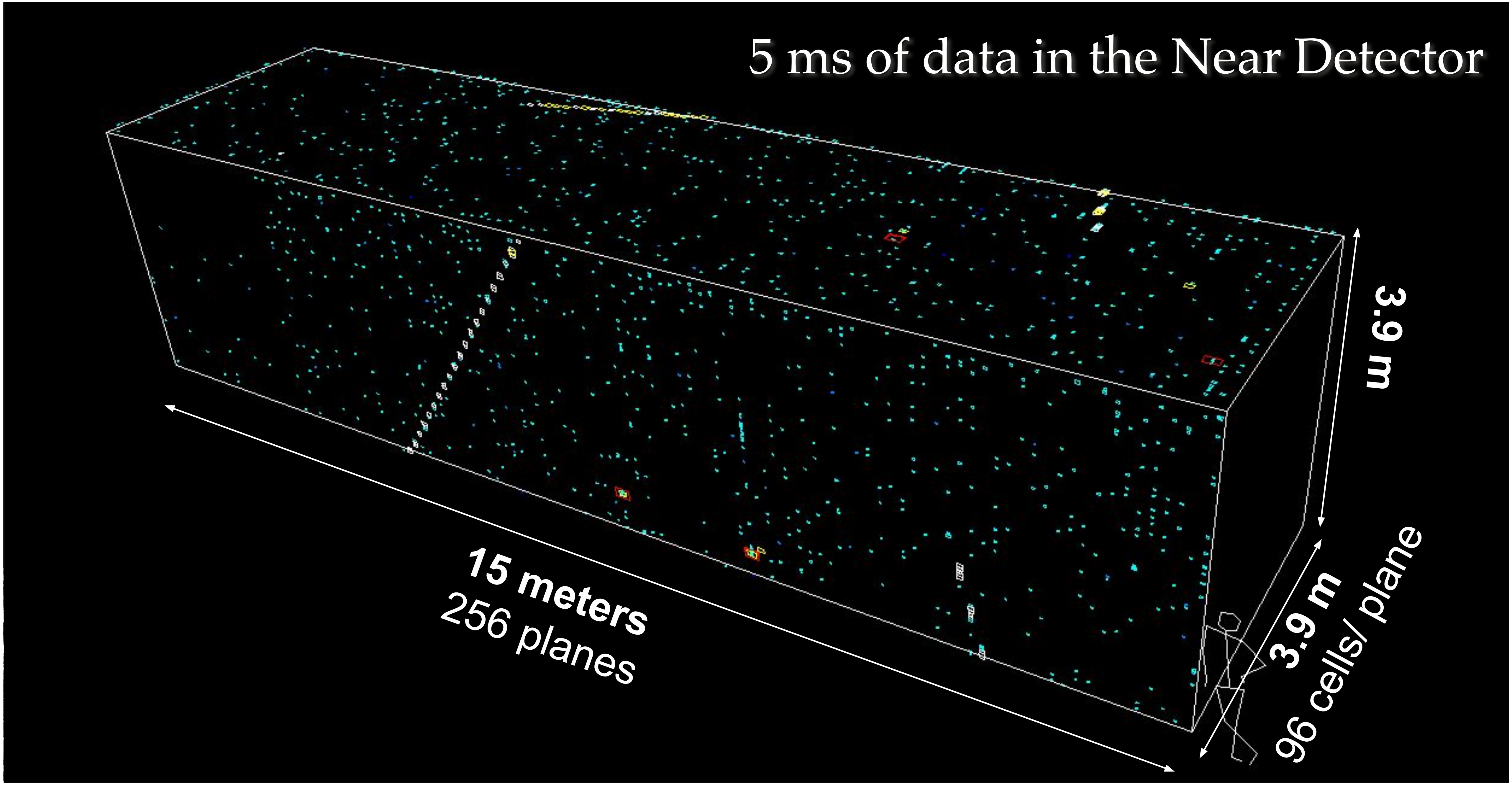


[NOvA Live Event Display Web-page]

NOvA Data Non-NuMI events



NOvA Data Non-NuMI events

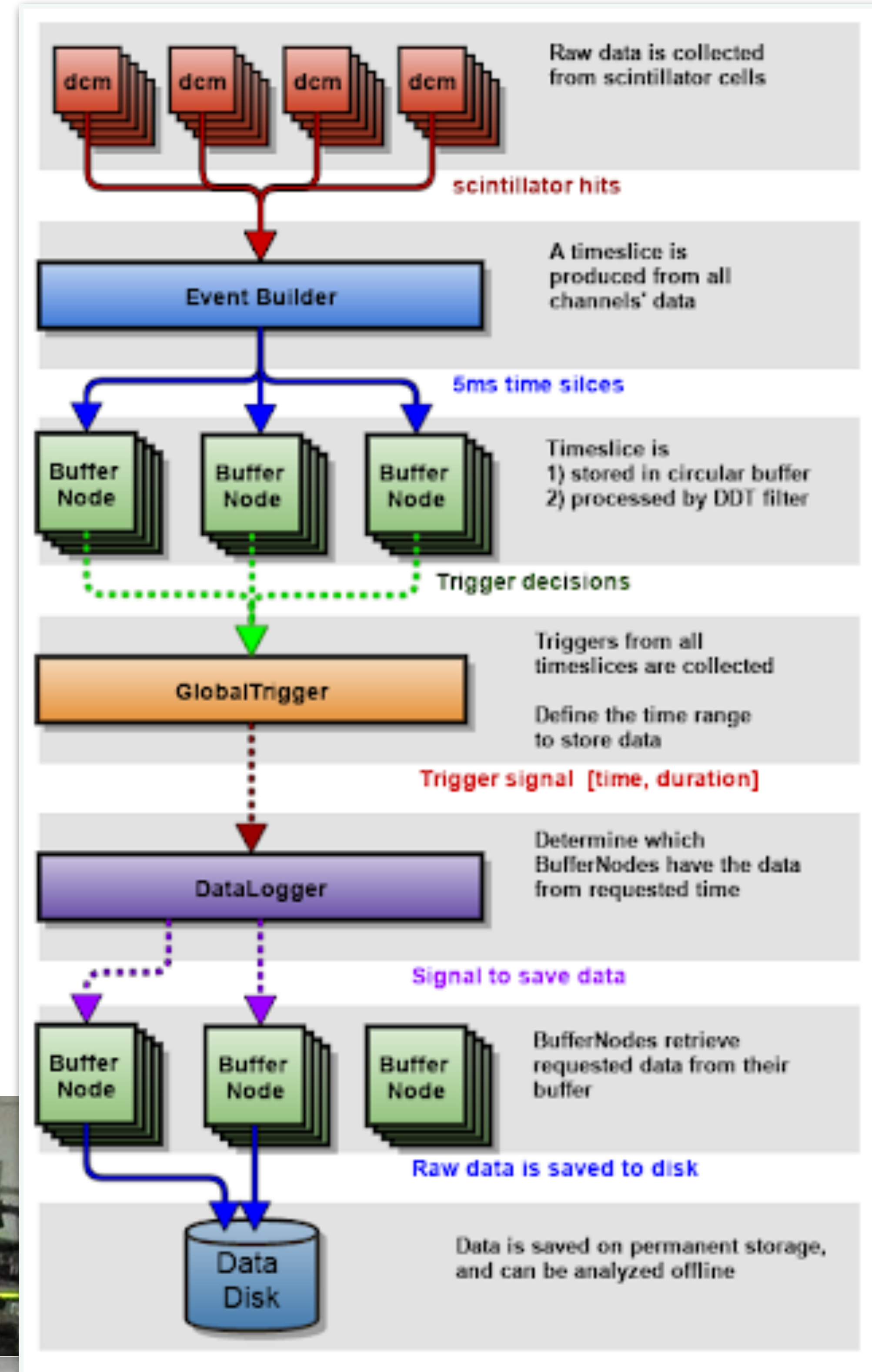


Non ν-oscillation and non ν-cross-section analyses

- The mass of the detectors target part:
  - 14 ktons for the far detector,
  - 220 tons for the near detector,
- The detectors location:
  - FD is on the surface,
  - ND is 100 m underground,
- Providing to study wide **Astrophysical program** beyond neutrino oscillation and neutrino cross-section measurements,
- Search and detection for different 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.
- Search for physics **Beyond the Standard Model**:
  - Light dark matter,
  - Neutrino magnetic moment.

Data Driven Triggers

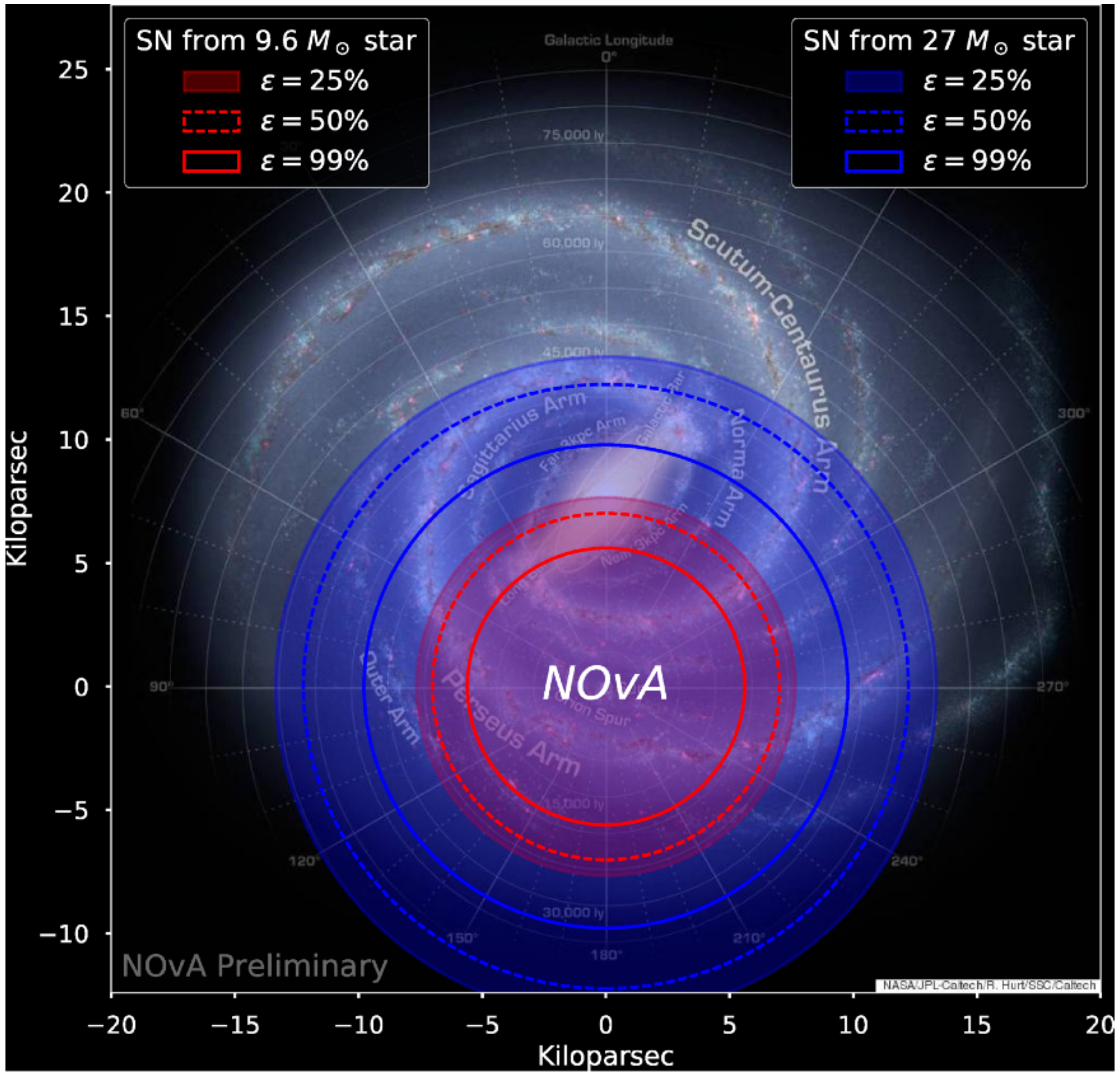
- Data rate including 100 kHz atmospheric muons is 1.2 GB/s.
- The beam spill data is selected by the time window.
- Additional physics studies require specific data selection, based on its own online reconstruction.
- Detector data is formed in 5ms time slices (milliblocks) and distributed to nodes 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.

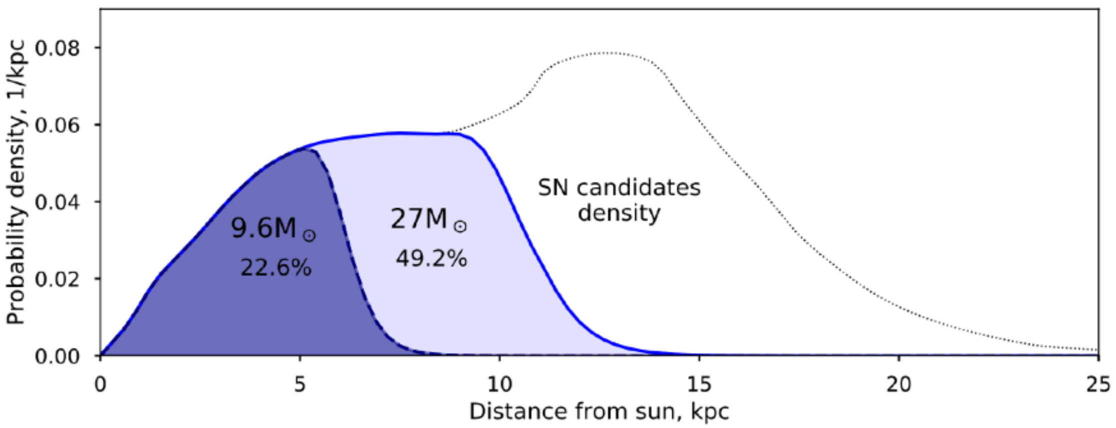


Astrophysics and Particle Physics Analyses

Supernovae

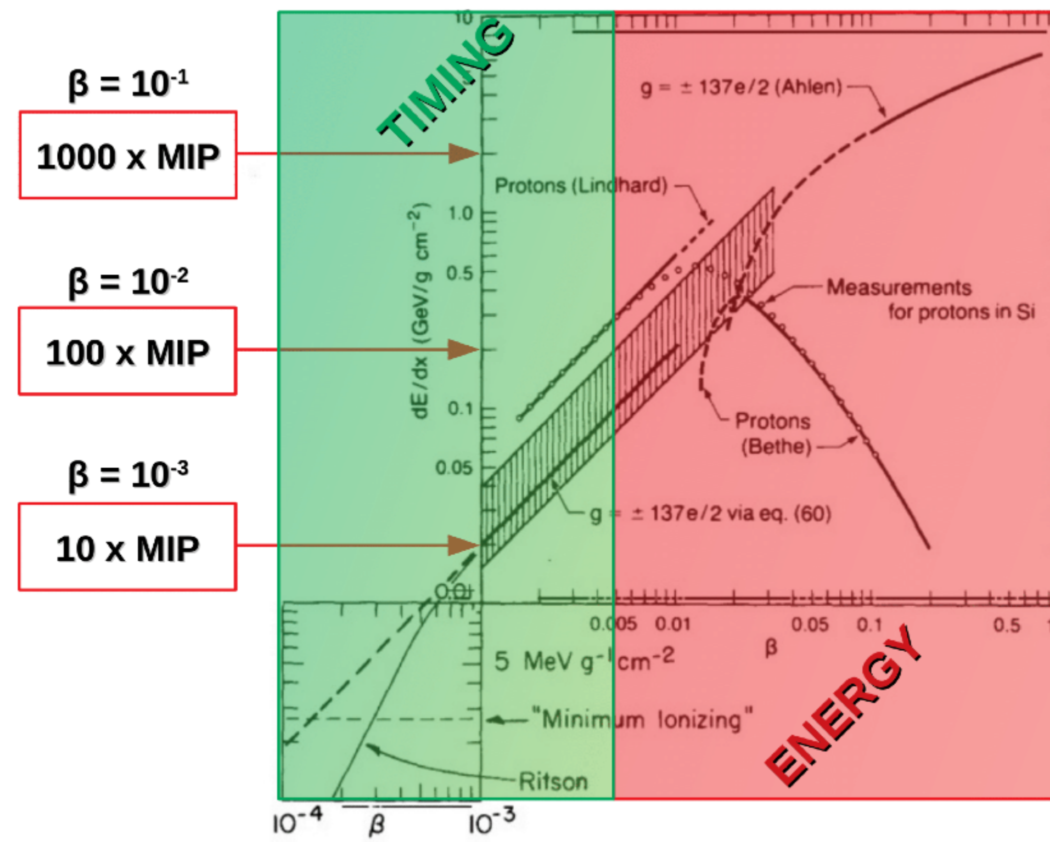
- NOvA is the largest carbon-based supernova detector currently operating.
- In the event of a **Galactic supernova**, it will provide invaluable data which, in combination with detectors using different target materials, will constrain the flavor content of the supernova burst.
- The ND and FD have roughly equivalent supernova capabilities, with the ND's small mass being balanced by its low background.
- 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.

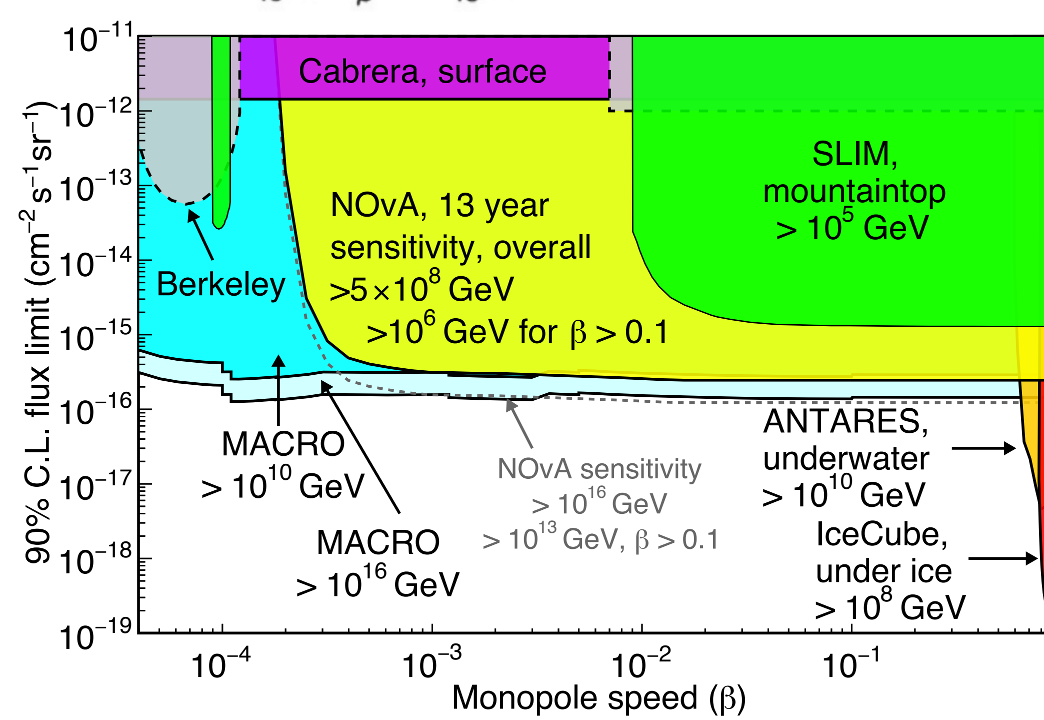




Magnetic Monopole Search

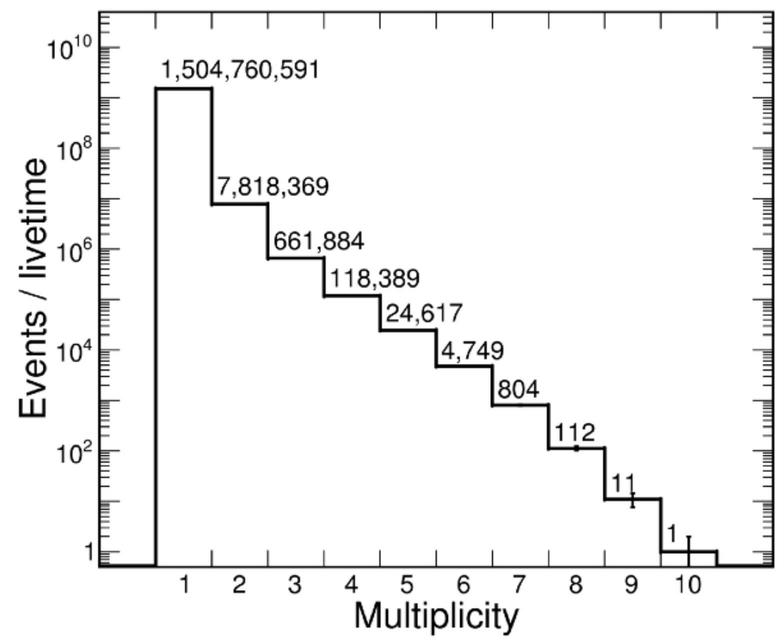
- As a large tracking detector on the Earth's surface, the FD has the unique capability to detect low-mass (< 10^{10} GeV) monopoles that would not reach underground detectors while setting much more stringent flux limits than previous surface detectors. It is also able to record tracks as slow as $\beta \approx 10^{-4}$, setting it apart from many previous monopole experiments. [Phys. Rev. D 103, 012007 (2021)]
- We separate the monopole search into slow and fast regimes, in which the most distinctive aspect of the signal is the track speed and extreme ionization, respectively. Both searches are expected to be background free, and so the flux limits scale linearly with exposure.
- A run that continues through 2025(6) 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.

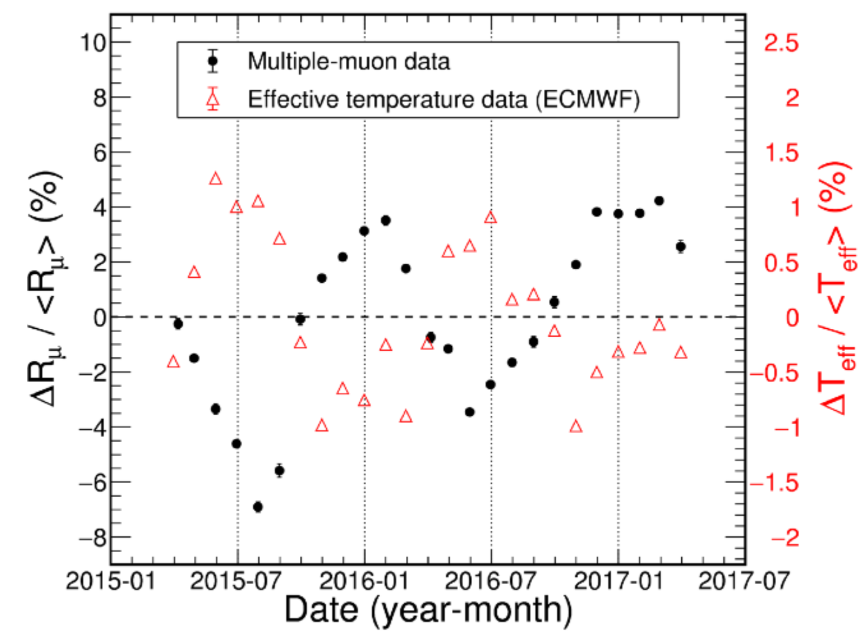


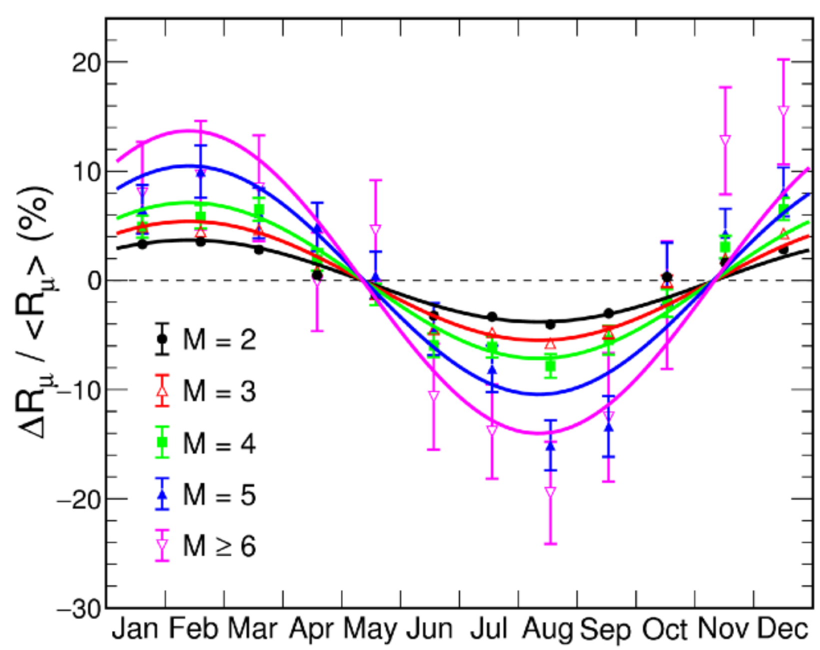


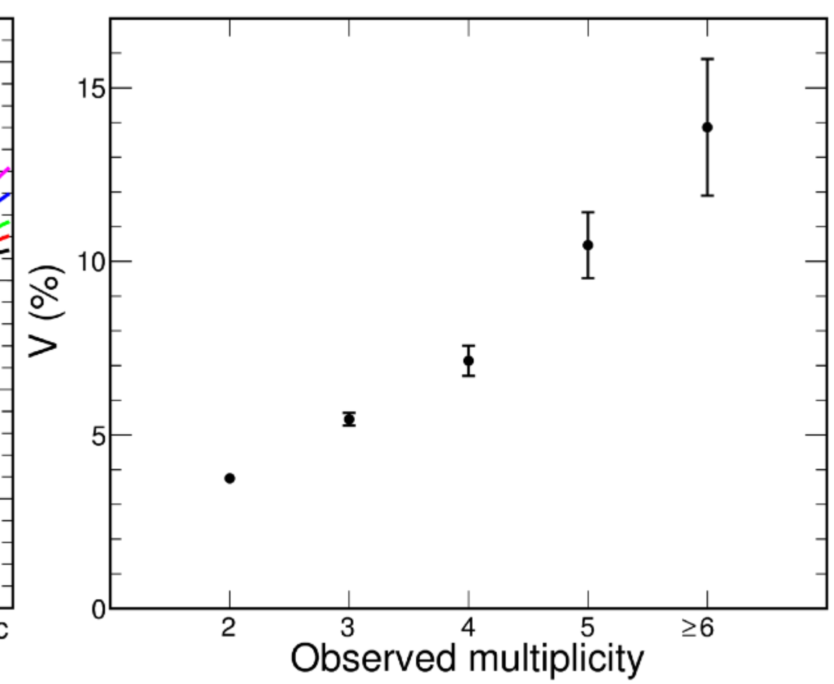
Cosmic Rays Studies: Seasonal variation

- 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)]. It confirmed the MINOS observation that the rate of such events underground is unexpectedly higher in the winter.
- The origin of this effect is unknown, although plausible explanations have been put forward. NOvA's analysis thus far has covered two annual cycles. Collecting data for as many annual cycles as possible provides benefits both quantitative and qualitative. The quantitative benefit comes from the need for statistics in the high-multiplicity bins, where the effect is strongest.
- But perhaps more importantly, the two years analyzed so far showed rather different characteristics, with no clear explanation. This is not a question of statistics, but must be related to some unidentified conditions that differ from one year to the next.
- A similar study using FD (on surface) data is published in 2021 [Phys.Rev.D 104 (2021) 1, 012014]. It was also seen seasonal dependence in the rate of multiple-muon showers, which varies in magnitude with multiplicity and zenith angle.
- 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.



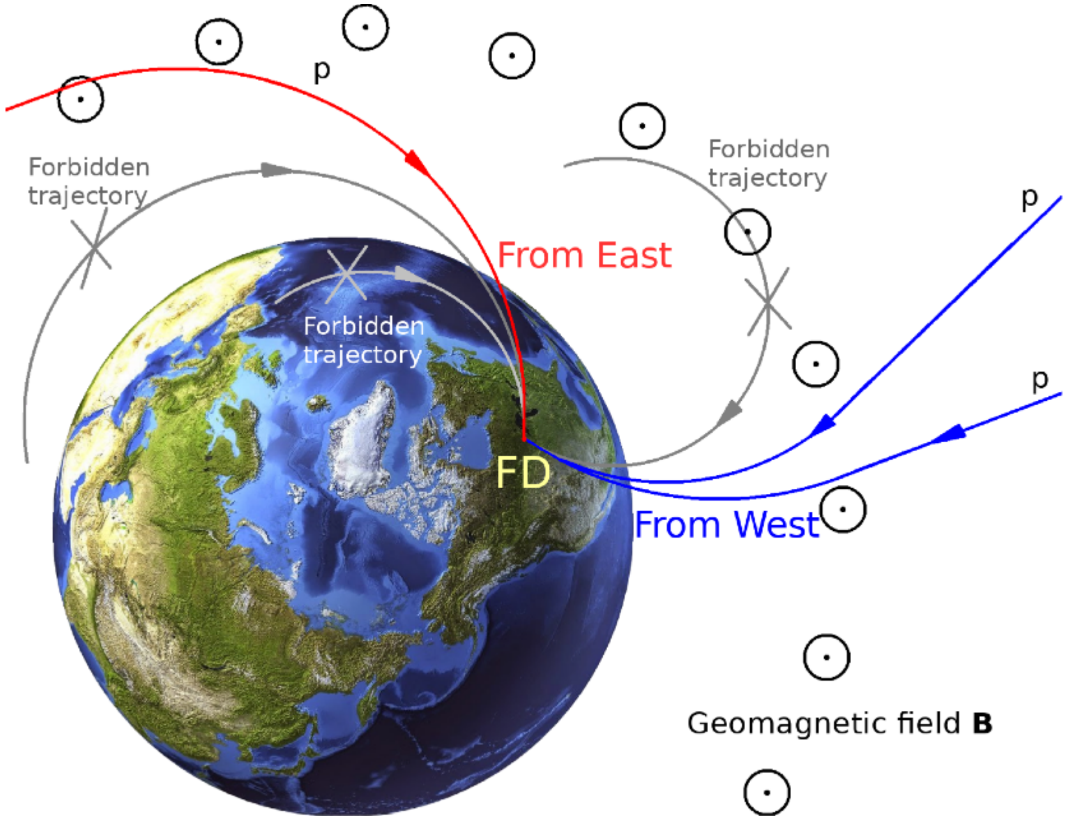


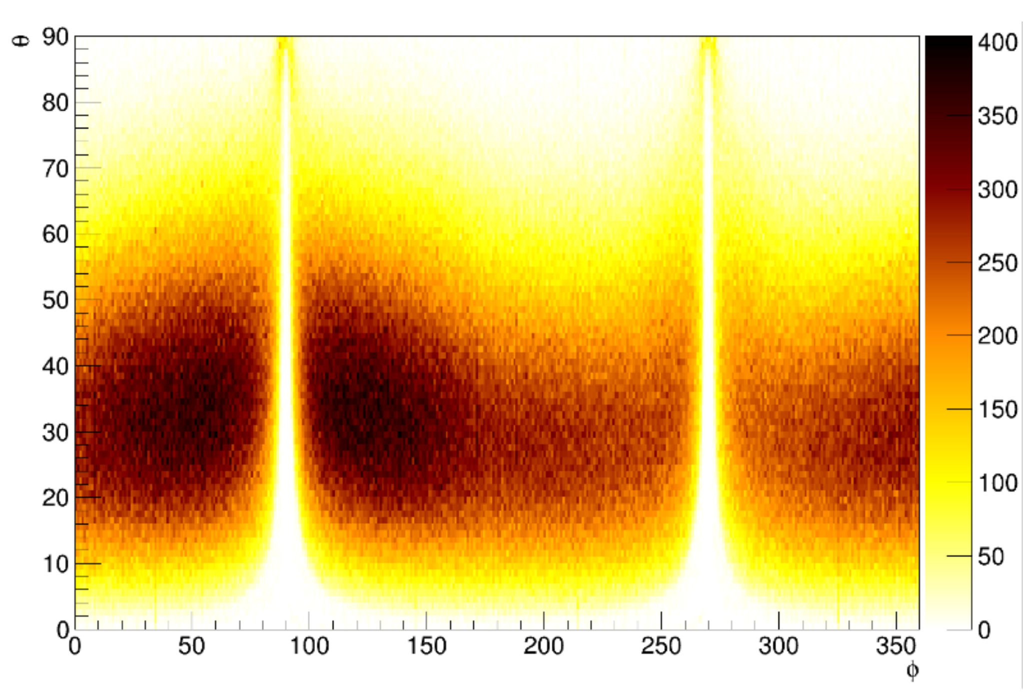




Cosmic Rays Studies: East-West effect

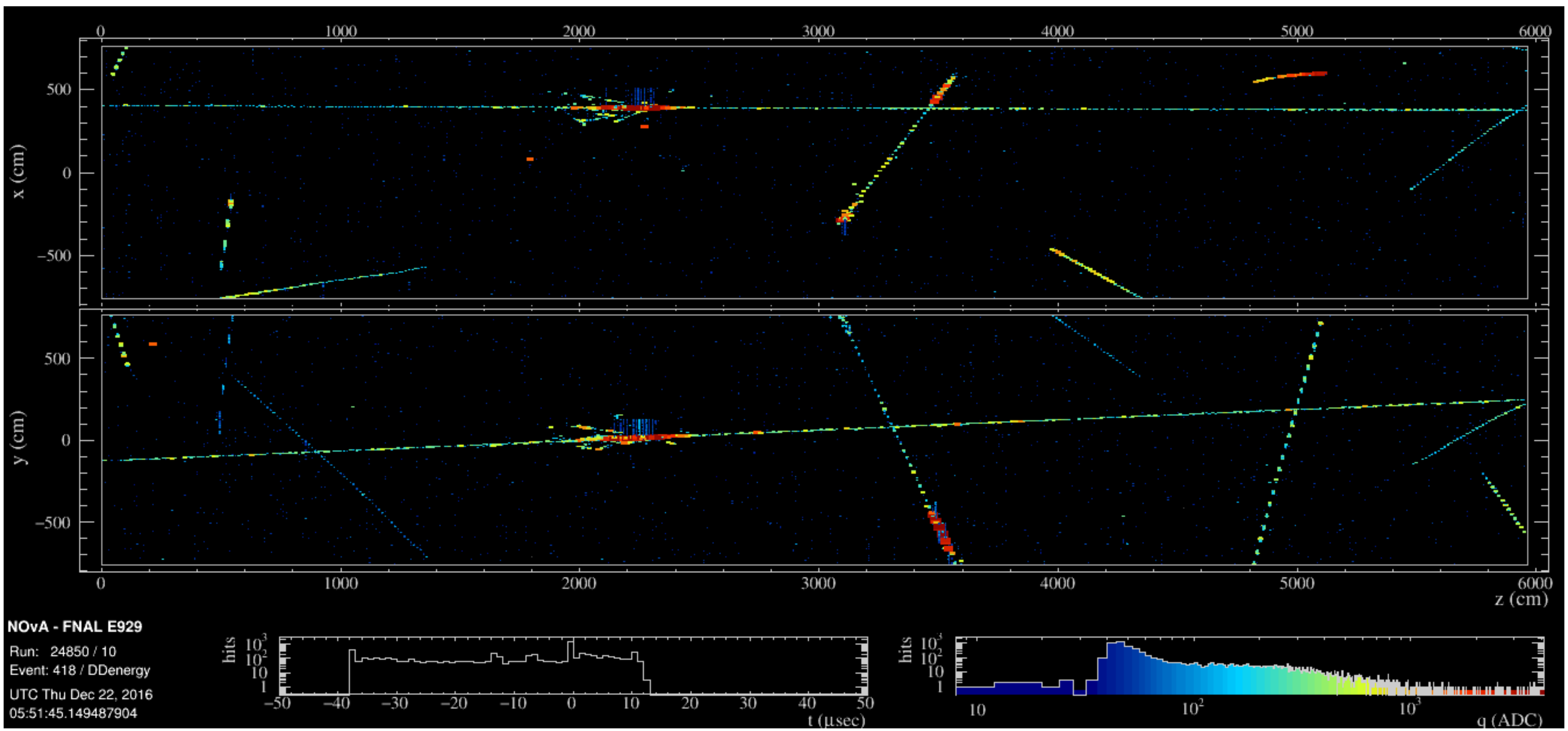
- We are studying NOvA's ability to measure the east-west asymmetry of the low-energy cosmic ray flux caused by the Earth's magnetic field.
- It is related to low-energy atmospheric neutrinos which form an important background to future proton decay searches.
- The most difficulty in this study in the NOvA Far Detector is to separate this effect from similar ones from overburden hill asymmetry and reconstruction inefficiency.
- We expect that the data we have collected so far is sufficient to reach a systematics-limited measurement.





Cosmic Rays 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).



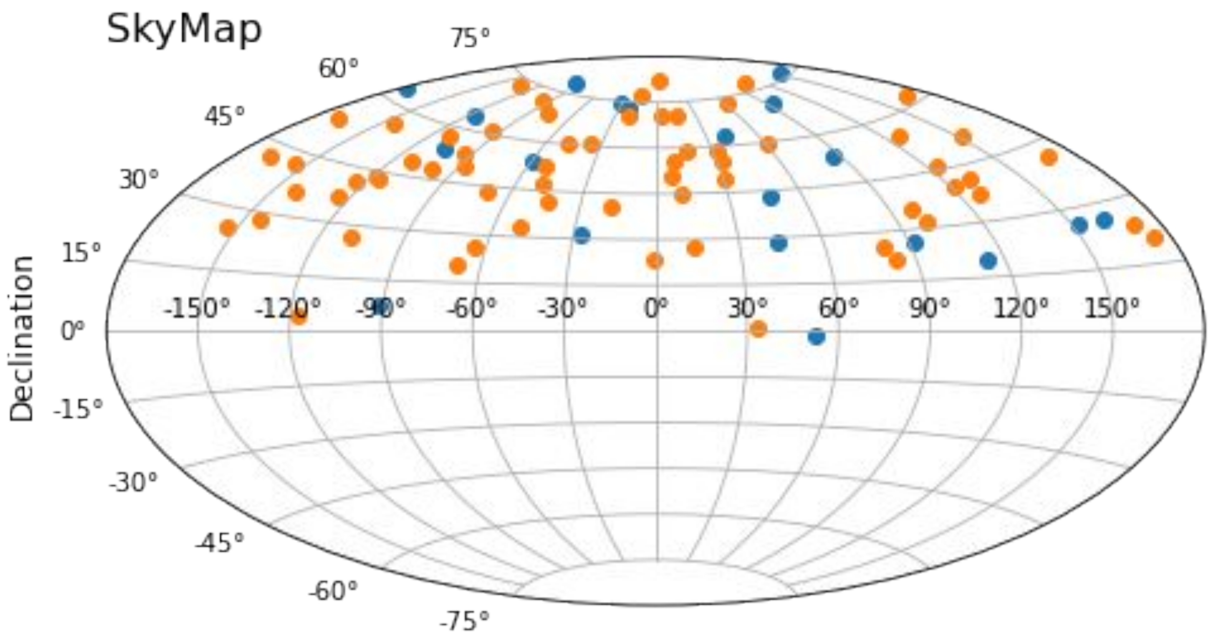
Cosmic Rays Studies: Ultra-high energy showers

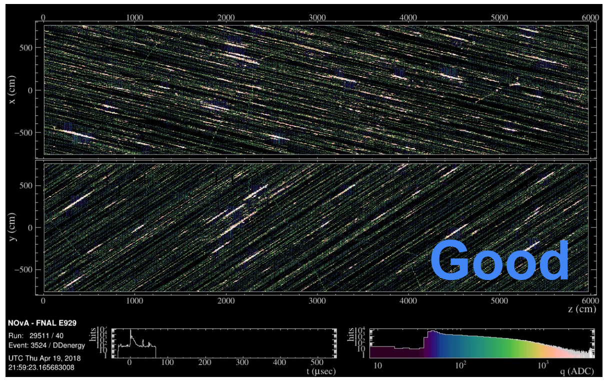
Shower Origins

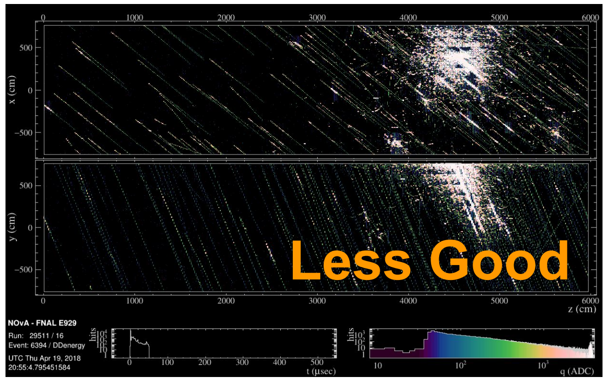
Started exploring distribution of shower origins on the sky.

Compared to Fermi-LAT point source catalog and AGN catalog

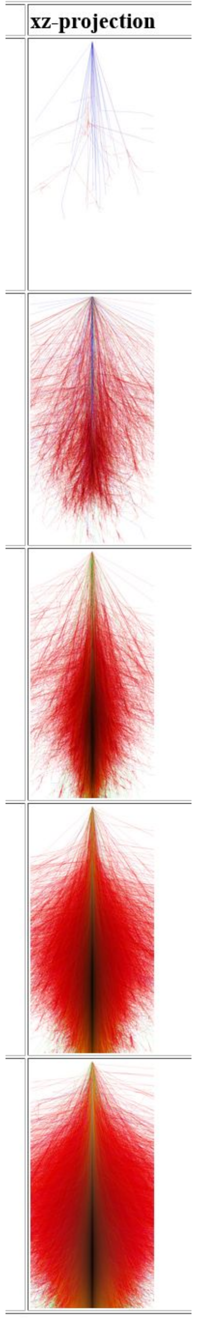
	Fraction < 2 degrees	
	Point Source	AGN
Good	0.73	0.64
Not Good	0.85	0.60
Bad	0.85	0.62







CORSIKA



Cosmic Rays Studies: Variation with solar and weather events

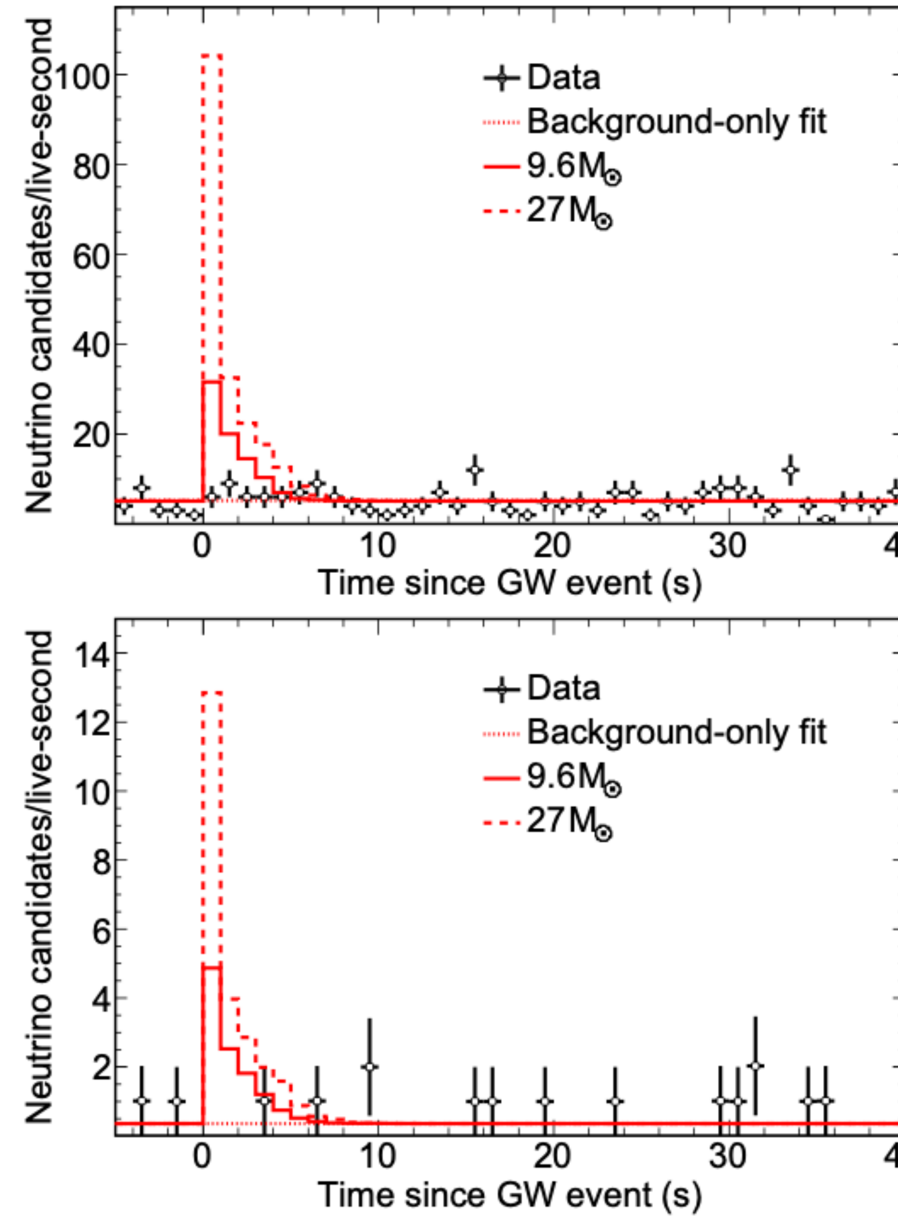
- We plan to use ND cosmic data to examine the influence of short-term weather on the underground muon rate, a known but understudied effect.
- We also seek to follow up on claims of cosmic ray variability during solar flares.
- Study of these phenomena rely on sporadic events outside our control, each of which is likely to have different characteristics.
- Every additional year of running improves the prospects in proportion to the added exposure.

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



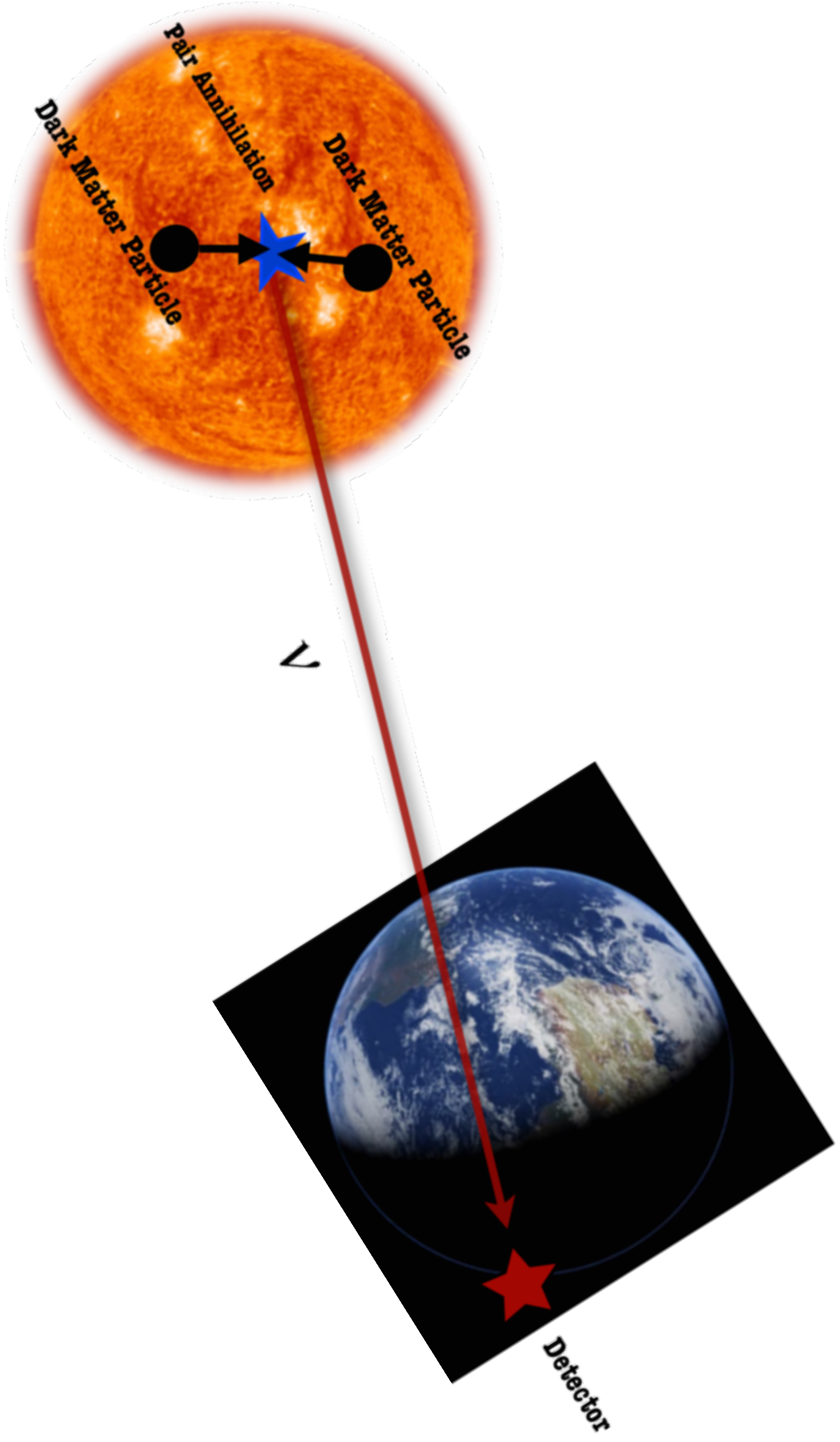
A typical GW event with both FD (top) and ND (bottom) continuous readout, S200213t. The two supernova models are shown, normalized to 10 kpc.

Gravitational Wave Coincidence

- A run through 2025(6) would mean participation in multimessenger astronomy with gravitational waves including LIGO/Virgo/KAGRA's O4 run (2021–2023), planned to be an exposure at least 4 times larger than all gravitational wave observations to date, and a year of the O5 run (beginning 2025), which will monitor a volume of space 10 times larger than before, potentially making available new classes of events and new surprises.
- As gravitational wave astronomy observatories gain power, each additional year of NOvA running has more potential than the last.

Dark Matter

- Boosted 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 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 ~ 10 GeV EM showers.

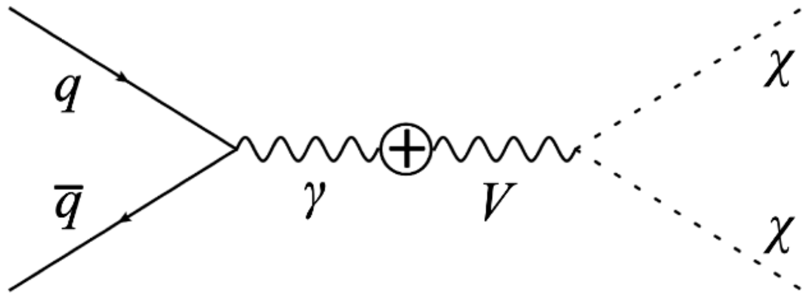


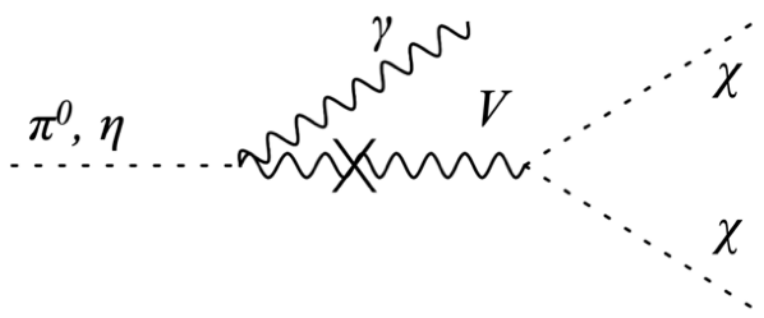
Beyond the Standard Model of the Particle Physics Analyses

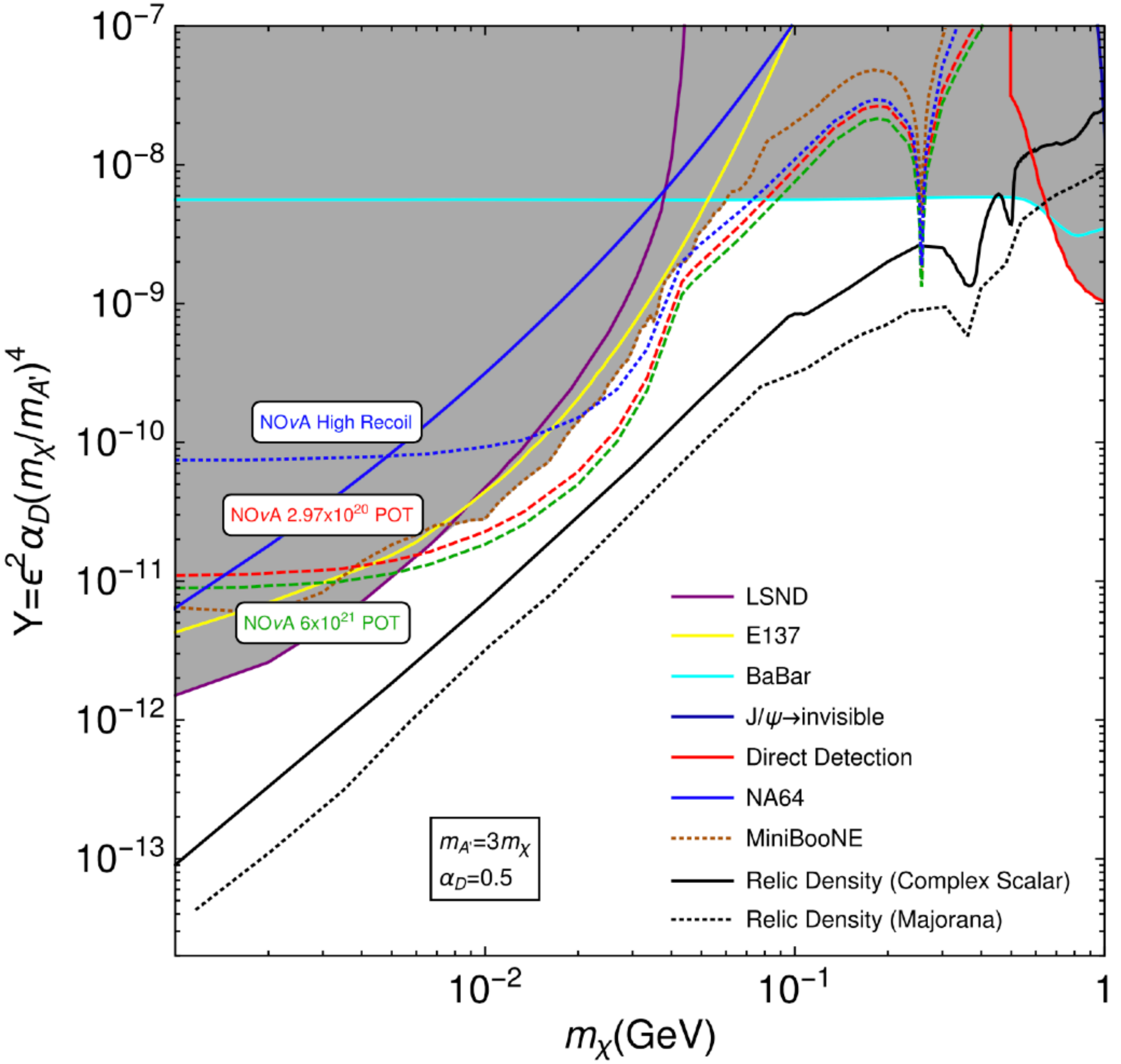
Light Dark Matter

- LDM is could be described in the models of feeble coupling of Dark sector particle to Standard model particle.

- Vector portal — mediator V (Dark photon)
  - Created in pp collisions, decays to DM $\chi\chi$
  - Indirect production (meson decay) dominant for low m_χ







NOvA estimated sensitivity to a dark photon decaying into $\chi\chi^\dagger$ pairs for the benchmark point $\alpha_D = 0.5$ and $m_{A'} = 3m_\chi$. [Phys. Rev. D 99, 051701(R)]

Summary

- The NOvA experiment provides wide astrophysical program and other particle physics searches beyond neutrino oscillation and neutrino cross-section measurements.
- These additional physics analyses stimulate development of the NOvA subsystems: DAQ, Trigger, Hardware, Detector simulation.
- 7 paper already published and many analyses ongoing.
- Many benefit from data collected throughout the full run to 2025(6) or longer, particularly the background-free search for magnetic monopoles (FD), studies of the variability of the cosmic ray flux (ND+FD), and our multi-messenger neutrino astronomy program with supernovae and gravitational waves (ND+FD), all of which improve linearly with time.
- The next 5 years of NOvA running will provide unique opportunities to search for new phenomena.
- Possible application in the future projects: the DUNE experiment, the SNEWS(v2) system, Multi-messenger astronomy.
- As a member of JINR group, I would like to thank Russian Science Foundation, which support our researches under grant № 18-12-00271.

Computing Support at JINR

- A dedicated to the local NOvA group computing infrastructure was created at JINR:
  - Dedicated set of computing resources within the JINR Cloud for hosting virtual machines.
  - Cloud storage for the analysis data storage.
- A number of services were deployed based on the cloud infrastructure to provide JINR researches with the required tools:
  - A JupyterHub service for interactive data analysis via Jupyter notebooks.
  - An HTCondor batch cluster for massive batch job processing with the ability to run both local and Grid jobs from the Open Science Grid infrastructure.
  - A dCache pool service for accessing the analysis data via the Grid protocols.
  - A CephFS pool for POSIX-like data access.
- The works on computing infrastructure creation for specific data analysis of the NOvA experiment were supported by the Russian Science Foundation under grant № 18-12-00271