Search for exotic physics with the NOvA detectors

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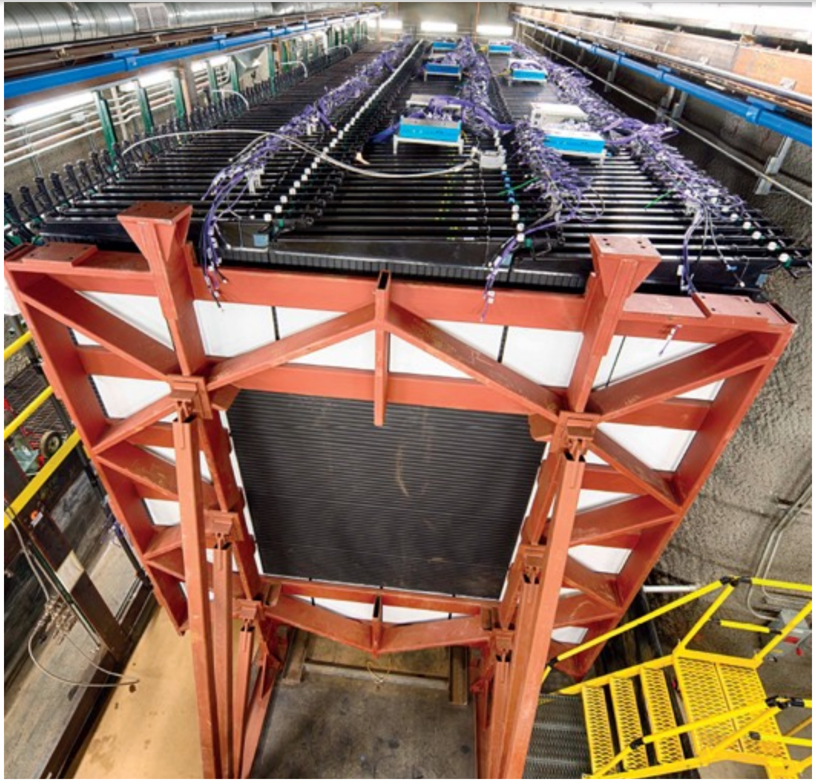
on behalf of the NOvA collaboration

The NuMI Off-Axis ν_e Appearance Experiment

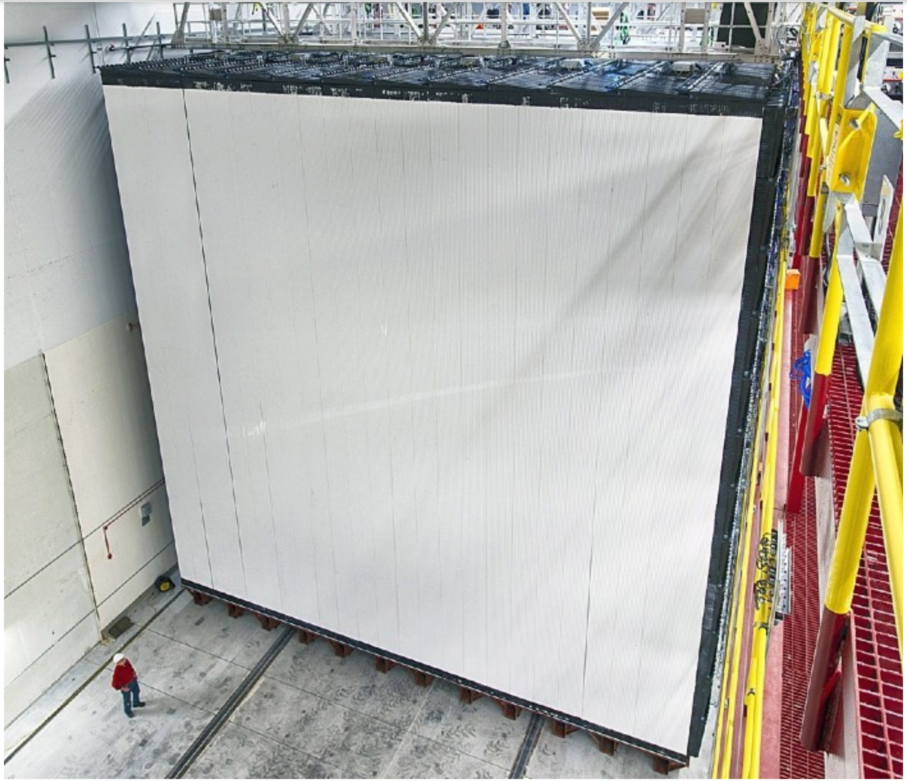
- **Origin and Concept**: NOvA was conceived as a successor to the MINOS experiment, designed to use the NuMI beamline (Fermilab) for studying electron neutrino appearance.
- **Detector Design**: Two detectors concept: near and far ones. The detectors are highly active tracking calorimeters built with low atomic-number materials to optimize electromagnetic shower identification.
- **Beamline Configuration**: Positioned 14 mrad off-axis, the detectors are exposed to a neutrino flux with energies chosen to the first oscillation maximum, minimizing high-energy neutrino backgrounds from neutral current interactions.
- **Far Detector Placement**: Located 810 km from the neutrino source, the Far Detector maximizes sensitivity to the neutrino mass hierarchy by enhancing the matter effect.
- **Broader Physics Goals**: Beyond oscillation studies, NOvA contributes to neutrino-nucleus cross-section measurements, sterile neutrino searches, astroparticle and exotic physics.

Two detectors

Near Detector: 290 tons, ~4×4m^2 × 16 m

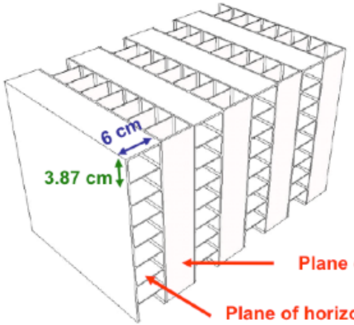


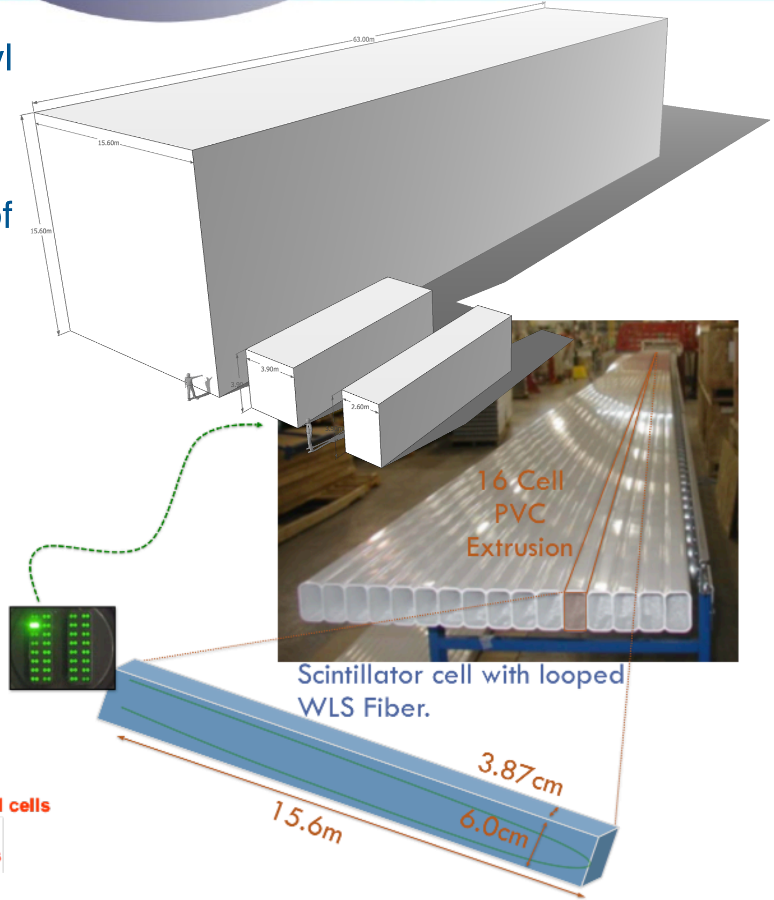
Far Detector: 14 kt, ~16×16 m^2 × 60 m



NOvA detectors

- The NOvA detectors are tracking calorimeters made of polyvinyl chloride (PVC) cells (+TiO_2) filled with liquid scintillator.
- The cells are **6.0 cm long (beam direction)** and **3.9 cm wide (transverse)**, with external walls of 4.8 mm and internal walls of 3.3 mm.
- Alternating horizontal and vertical planes improve tracking resolution.
- Scintillator: ~95% mineral oil, ~5% pseudocumene, plus trace chemicals.
- Light is captured by **wavelength-shifting fibers** running through each cell in a loop, terminating at avalanche photodiode (APD) pixels (~344,000 in the FD).
- Elemental composition (by mass): 66.7% carbon, 16.1% chlorine, 10.8% hydrogen.





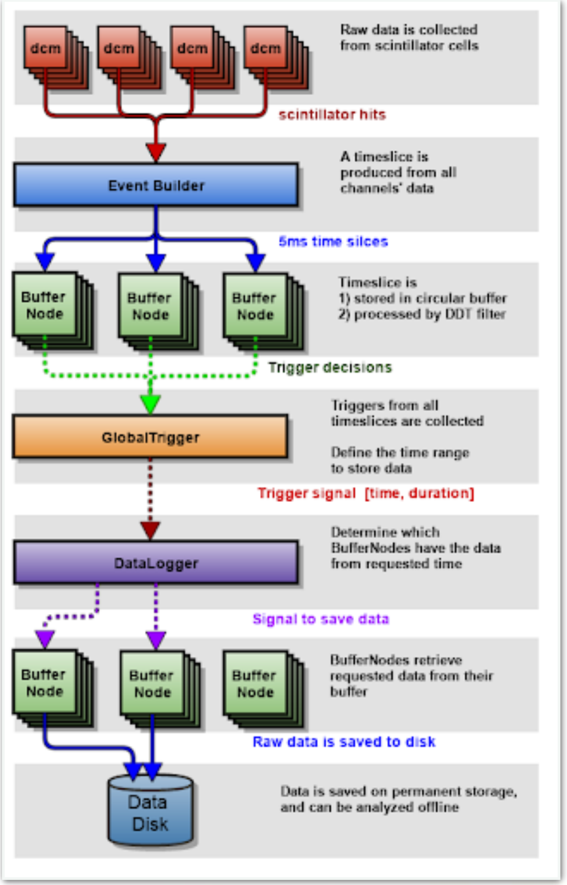
Exotics. Non ν-osc / X-sec

- The mass of the detectors target part:
  - ➡ 14 ktons for the far detector (FD)
  - ➡ 220 tons for the near detector (ND)
- 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

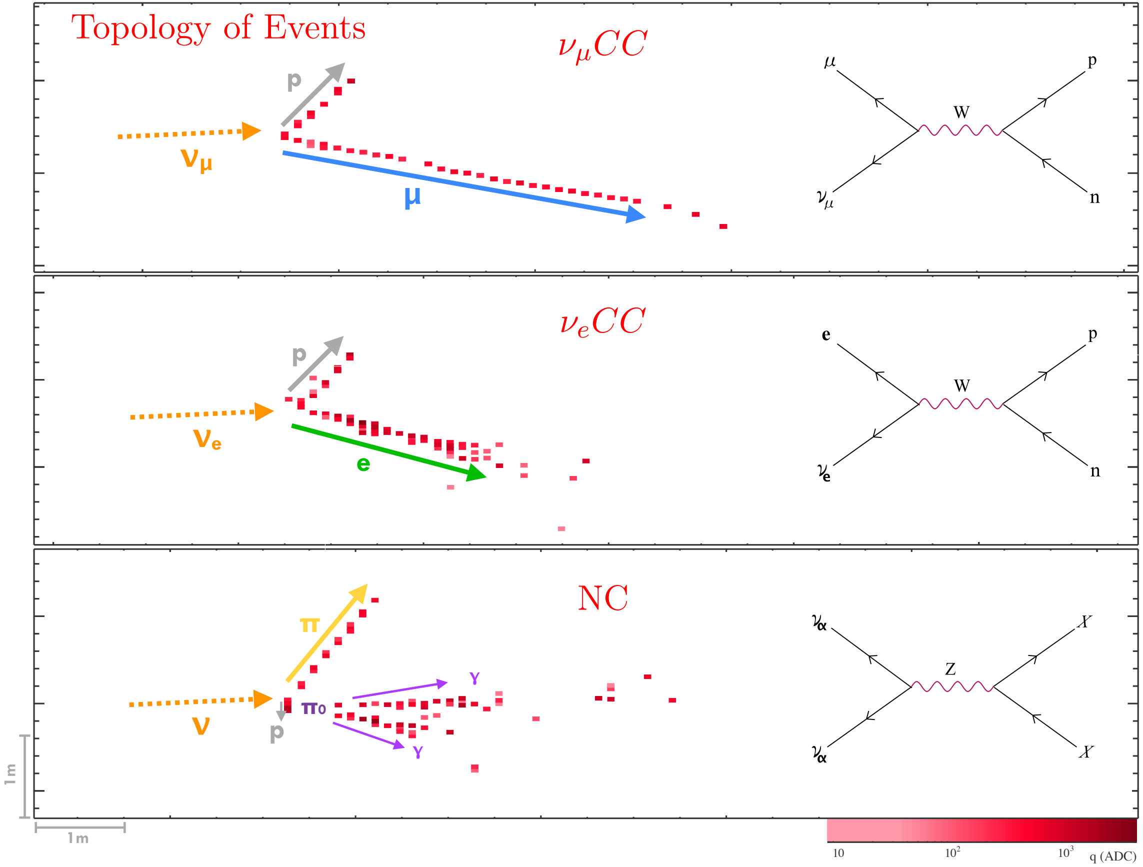
- Search and detection for different signals from Space and the Earth's environment:
  - ➡ supernova
  - ➡ magnetic monopole
  - ➡ atmospheric muons and neutrinos
  - ➡ dark matter
  - ➡ potential signals in coincidence with the LIGO/Virgo gravitational wave events
- Search for physics **Beyond the Standard Model**:
  - ➡ Light dark matter
  - ➡ Neutrino magnetic moment

Data Driven Triggers

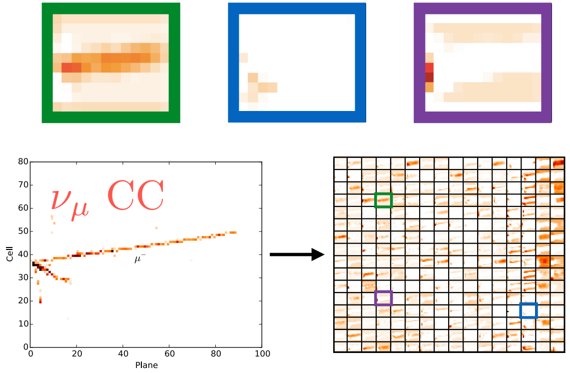
- Data rate including 100 kHz atmospheric muons is 1.2 GB/s
- The beam spill data is selected by the time window
- Additional physics studies require specific data selection, based on its own online reconstruction
- Detector data is formed in 5ms time slices (milliblocks) and distributed to nodes for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



Event topologies. Id with NN



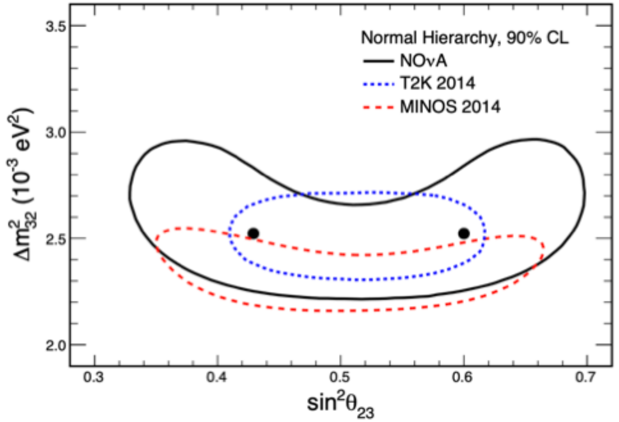
- We use convolution neural network called CVN (Convolutional Visual Network).
- Particle identification technique based on ideas from GoogLeNet (computer vision and deep learning).
- Multi-label classifier – the same network used in multiple analyses: can classify ν_e, ν_μ, ν_τ, NC and cosmic.



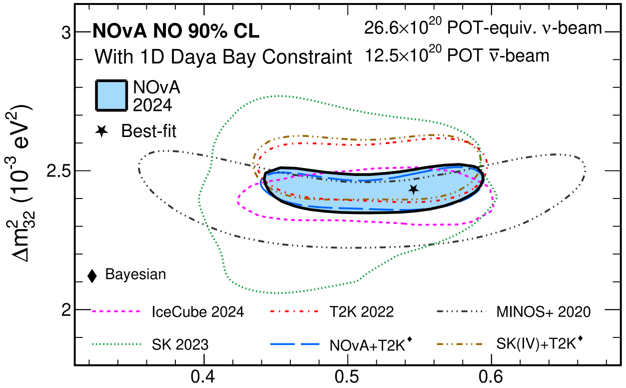
A. Aurisano et. al, JINST 11, P09001 (2016)

Neutrino Oscillation Results

- First measurement of muon-neutrino disappearance in NOvA. Phys. Rev. D 93, 051104(R) – Published 25 March, 2016
- First Measurement of Electron Neutrino Appearance in NOvA. Phys. Rev. Lett. 116, 151806 – Published 13 April, 2016
- Measurement of the Neutrino Mixing Angle θ_{23} in NOvA. Phys. Rev. Lett. 118, 151802 – Published 10 April, 2017
- Constraints on Oscillation Parameters from ν_e Appearance and ν_μ Disappearance in NOvA. Phys. Rev. Lett. 118, 231801 – Published 5 June, 2017
- New constraints on oscillation parameters from ν_e appearance and ν_μ disappearance in the NOvA experiment. Phys. Rev. D 98, 032012 – Published 24 August, 2018
- First measurement of neutrino oscillation parameters using neutrinos and antineutrinos by NOvA. Phys. Rev. Lett. 123, 151803 – Published 11 October, 2019
- Improved measurement of neutrino oscillation parameters by the NOvA experiment. Phys. Rev. D 106, 032004 – Published 3 August, 2022
- The Profiled Feldman-Cousins technique for confidence interval construction in the presence of nuisance parameters. [arXiv:2207.14353]
- Expanding neutrino oscillation parameter measurements in NOvA using a Bayesian approach. Phys. Rev. D 110, 012005 – Published 10 July, 2024



NOvA Preliminary



NOvA Data NuMI events

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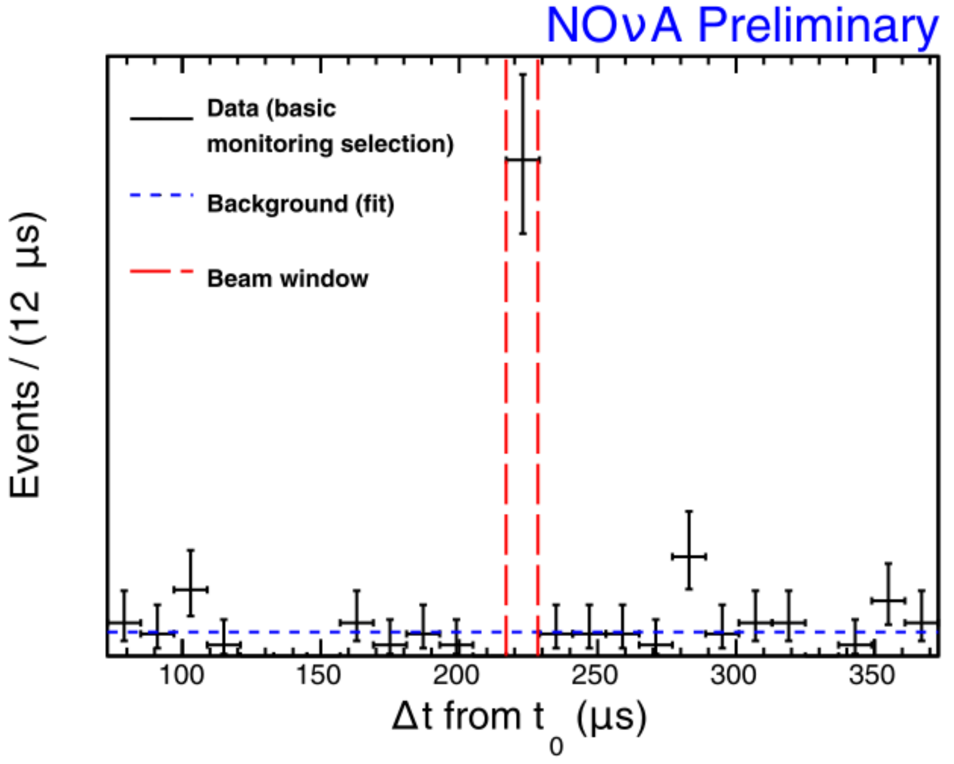
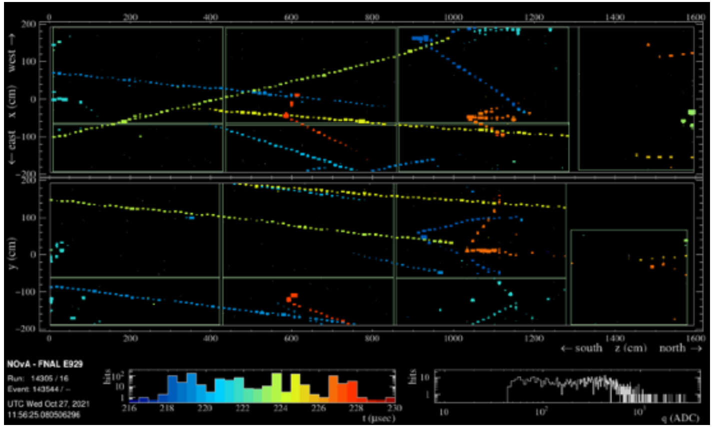
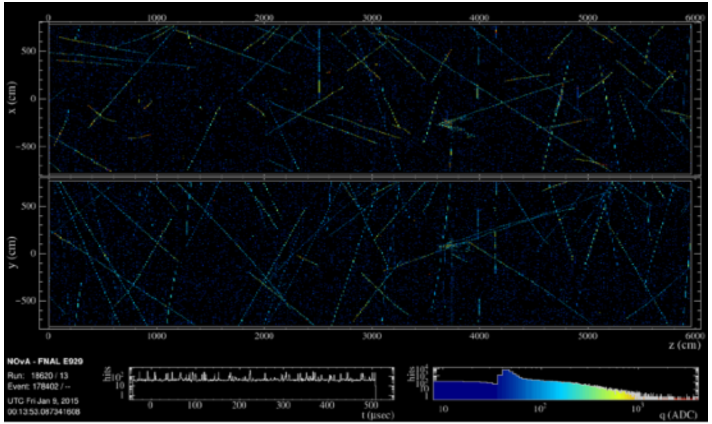
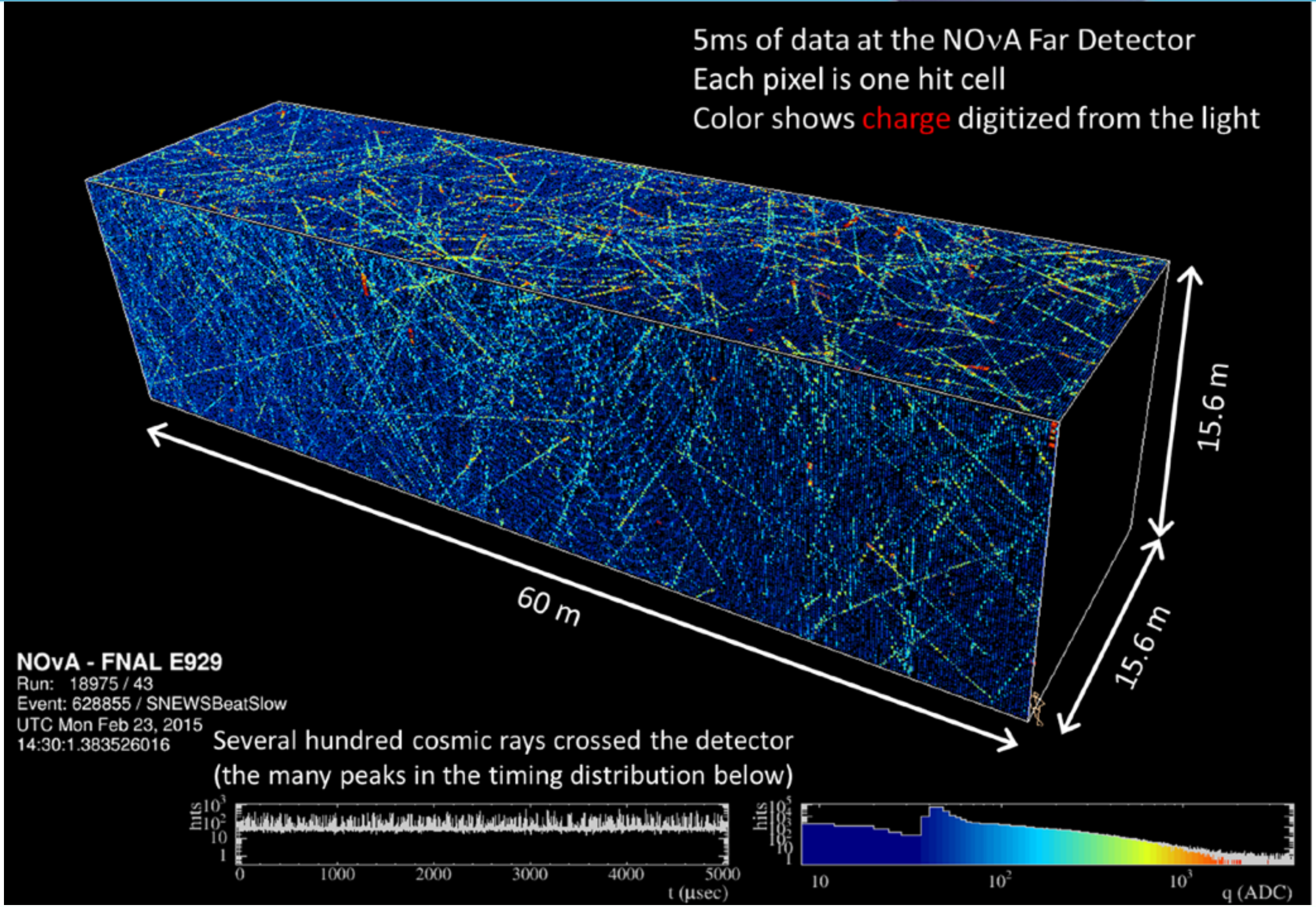
- Beam trigger structure: 550 μs window, NuMI neutrinos arrive for 10 μs starting at 218 μs





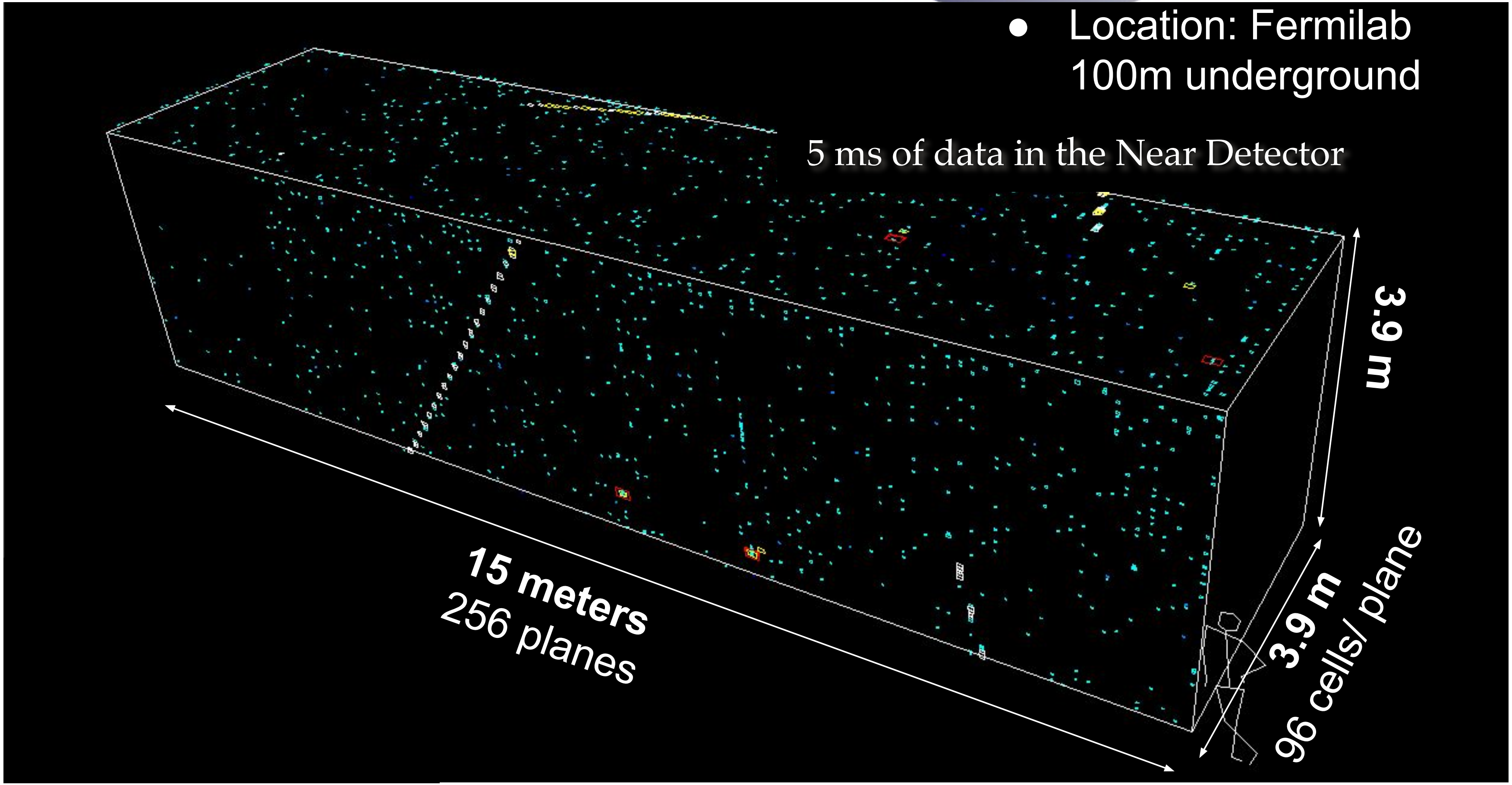


NOvA Data Non-NuMI events



NOvA Data Non-NuMI events

- Location: Fermilab 100m underground



NOvA Data Non-NuMI events

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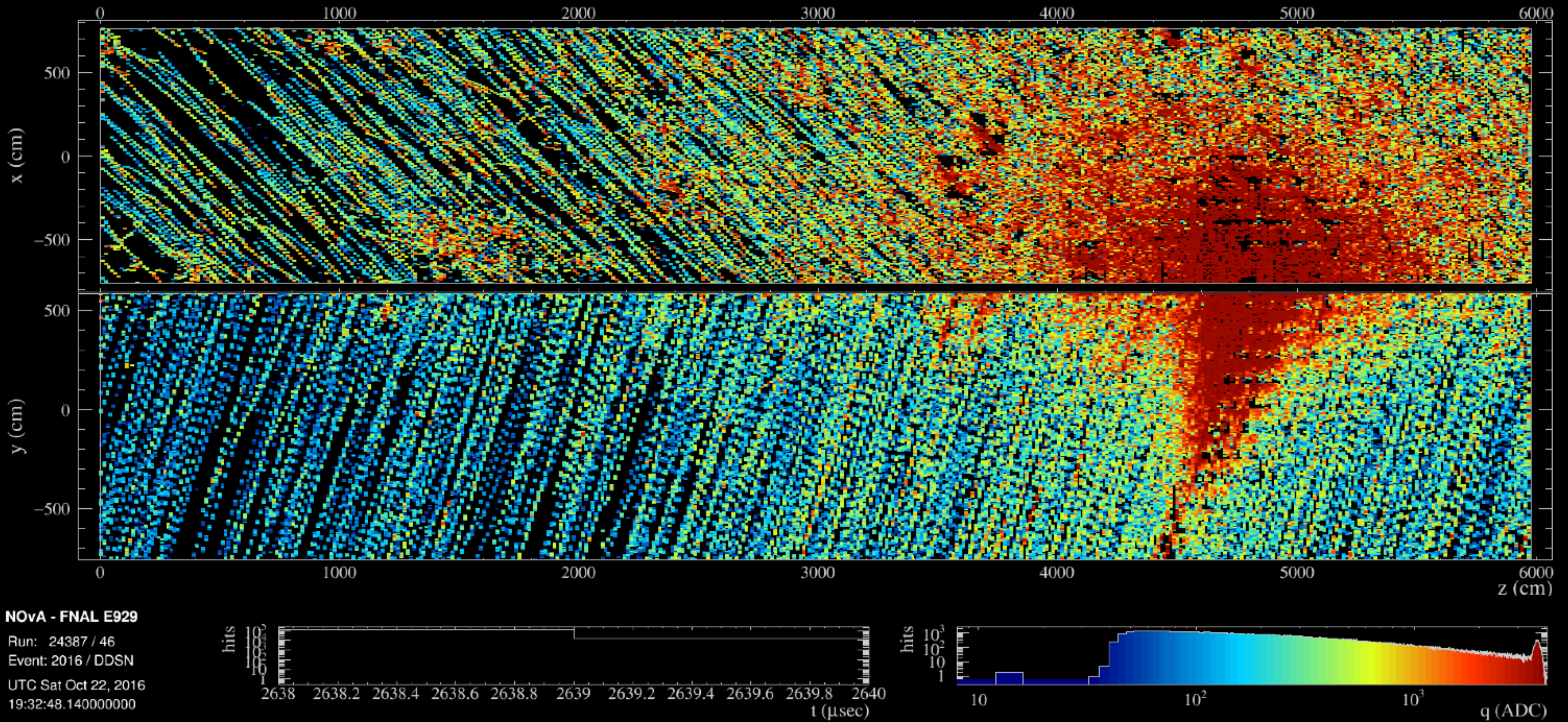
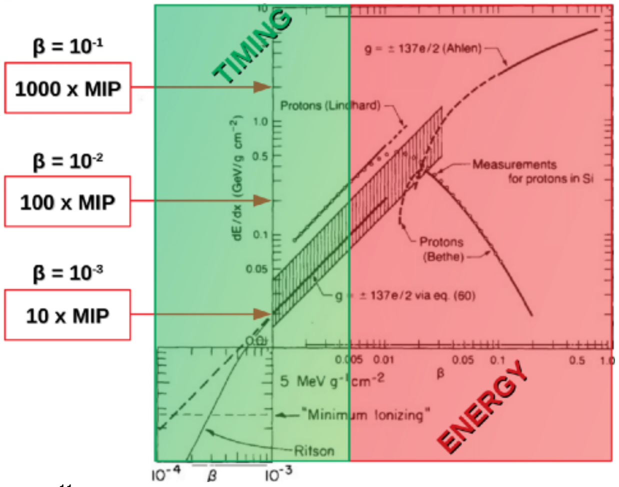
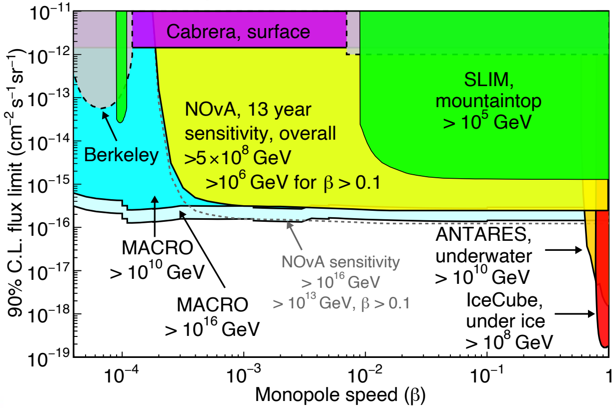


Magnetic Monopole Searches

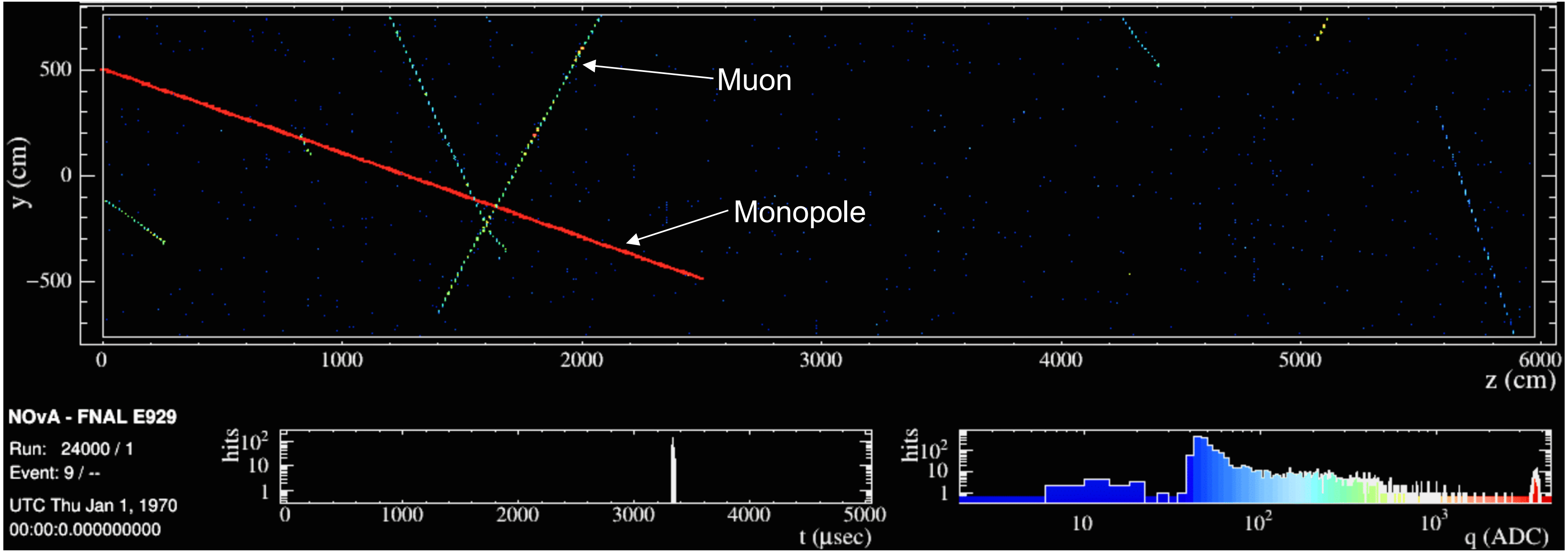
- As a large tracking detector on the Earth's surface, the FD has the unique capability to detect low-mass (< 10^{10} GeV) monopoles that would not reach underground detectors while setting much more stringent flux limits than previous surface detectors. It is also able to record tracks as slow as $\beta \approx 10^{-4}$, 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.





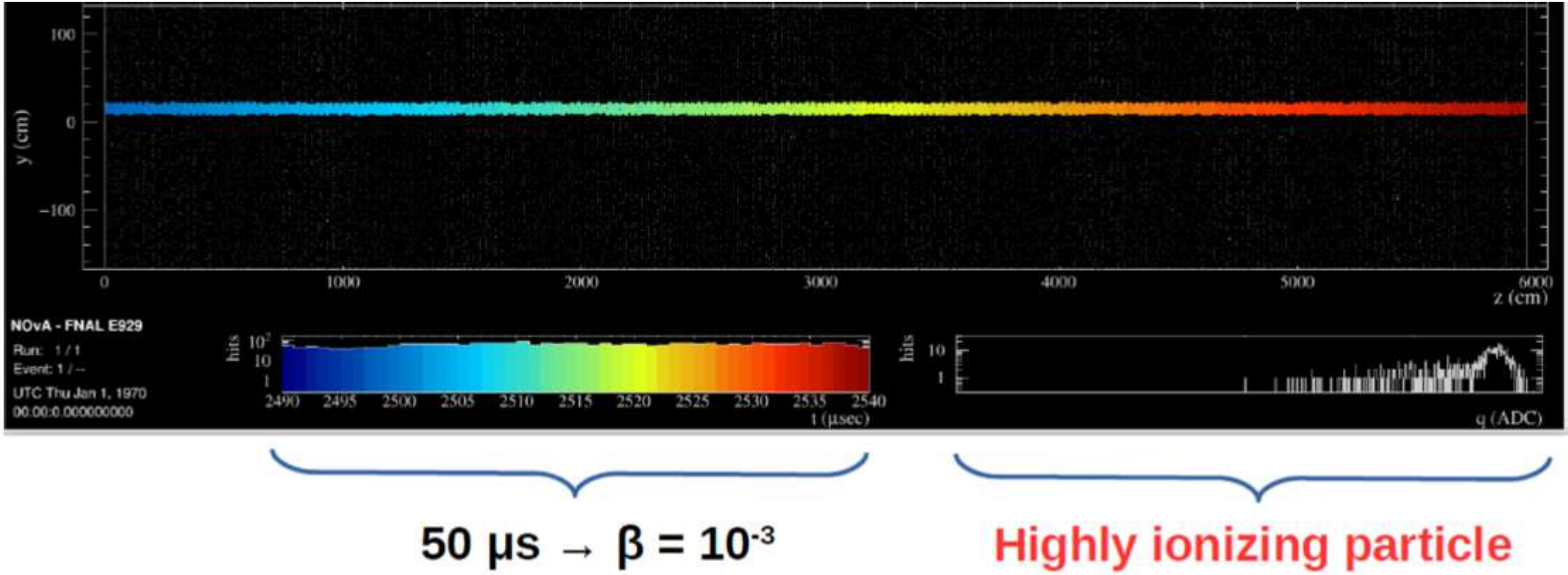
Energy Triggered Monopole

- Fast monopole ($\beta \gtrsim 10^{-2}$) can be identified by their linear tracks with high energy depositions (color scale = energy deposition)



Time Triggered Monopole

- Slow monopole ($10^{-2} > \beta > 10^{-4}$) can be identified by their linear tracks with slow passing the detector (color scale = time)



Summary. Non-ν / Exotics

- 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, releasing ones soon
- Many benefit from data collected throughout the full run to 2026 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
- By the end of NOvA running NOvA 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

Backup slides : all the other analyses
To discuss now or during coffee-brake

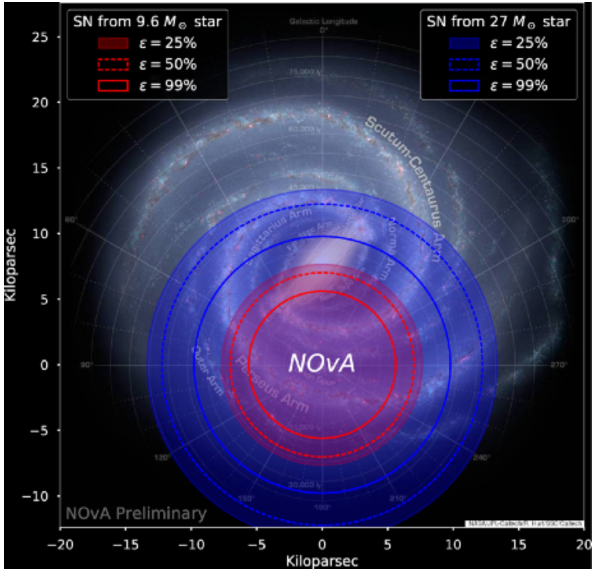
Summary. Neutrino

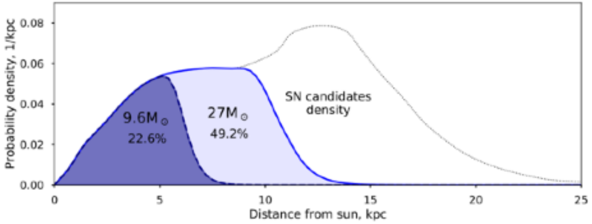
- Over decade (2014-2024) of operation and data analysis, NOvA has published numerous works on neutrino oscillations.
- Several papers have been published on neutrino interactions with matter and cross-section measurements.
- Research has also been published on the search for exotic phenomena such as sterile neutrinos and magnetic monopoles.
- In addition, NOvA monitors signals from space and Earth's atmosphere, for example, detecting neutrinos from supernovae, gravitational waves, atmospheric neutrinos, and muons.
- List of NOvA publications NOvA has a running total number of **32** (including technical ones).
- Expected Results (by 2027 or so):
- NOvA: Measurement of the neutrino mass hierarchy and δCP with significance levels of $\leq 4\sigma$ and $\leq 2\sigma$, respectively.

Astrophysics and Particle Physics Analyses

Supernovae

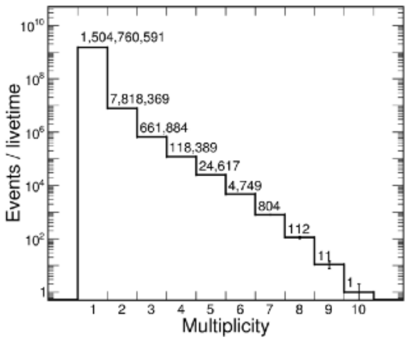
- NOvA is the largest carbon-based supernova detector currently operating.
- In the event of a **Galactic supernova**, it will provide invaluable data which, in combination with detectors using different target materials, will constrain the flavor content of the supernova burst.
- The ND and FD have 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.

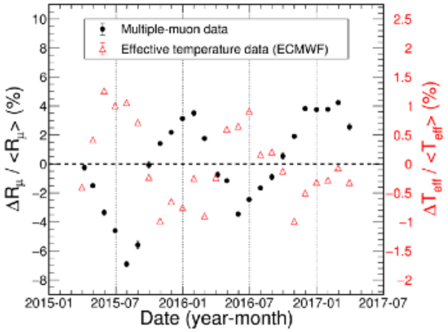


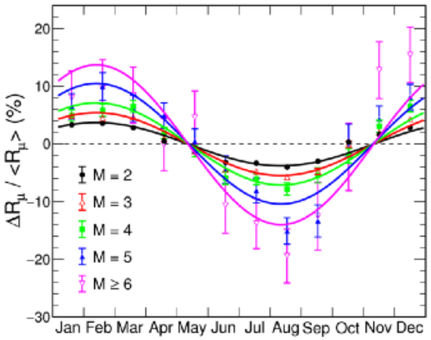


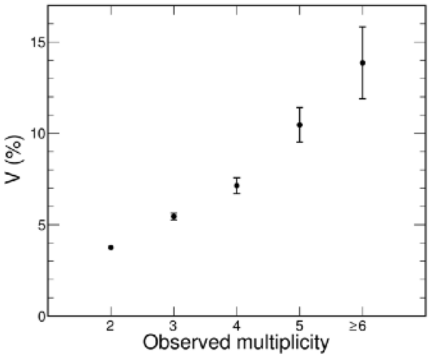
Cosmic Rays Studies: Seasonal variation

- 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.



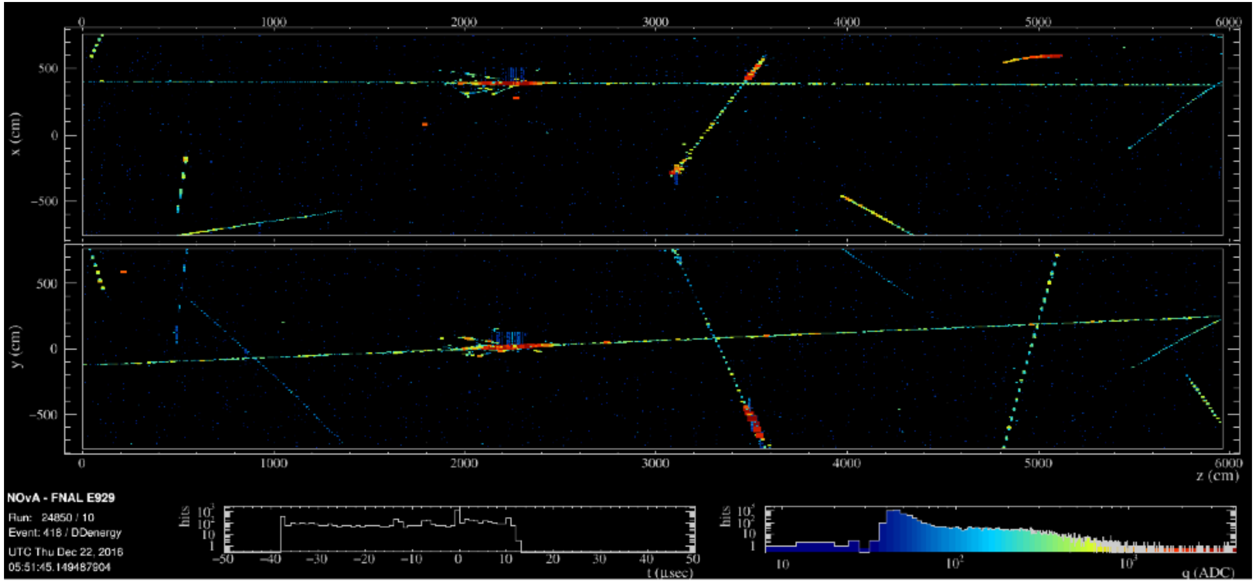






Cosmic Rays Studies: High energy muons

- 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).



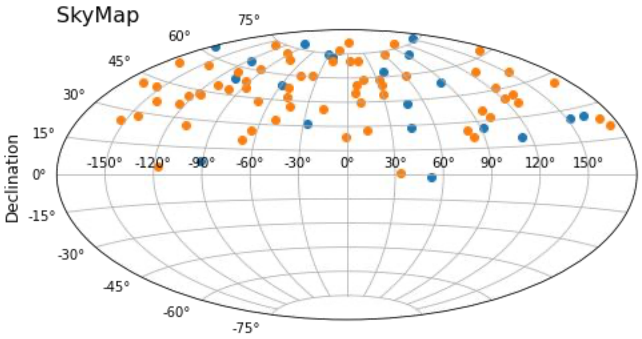
Cosmic Rays Studies: Ultra-high energy showers

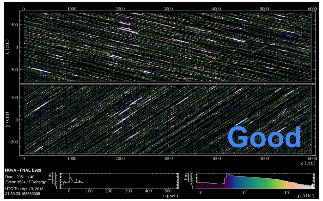
Shower Origins

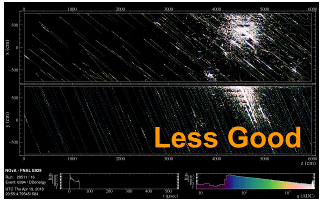
Started exploring distribution of shower origins on the sky.

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







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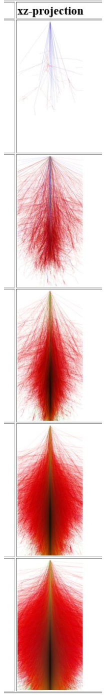


Cosmic Rays Studies: Variation with solar and weather events

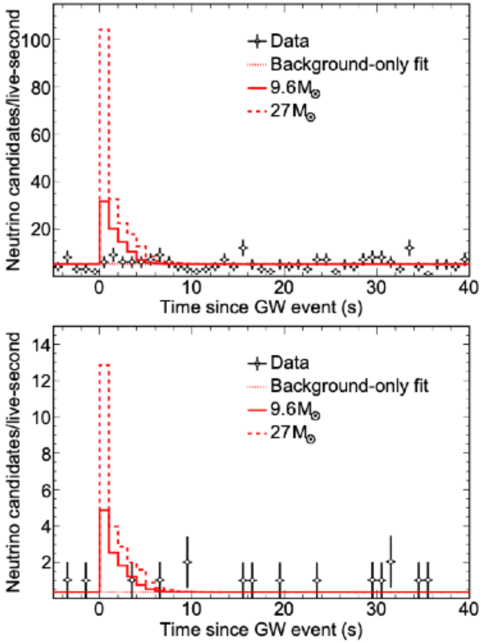
- We plan to use ND cosmic data to examine the influence of short-term weather on the underground muon rate, a known but understudied effect.
- We also seek to follow up on claims of cosmic ray variability during solar flares.
- Study of these phenomena rely on sporadic events outside our control, each 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

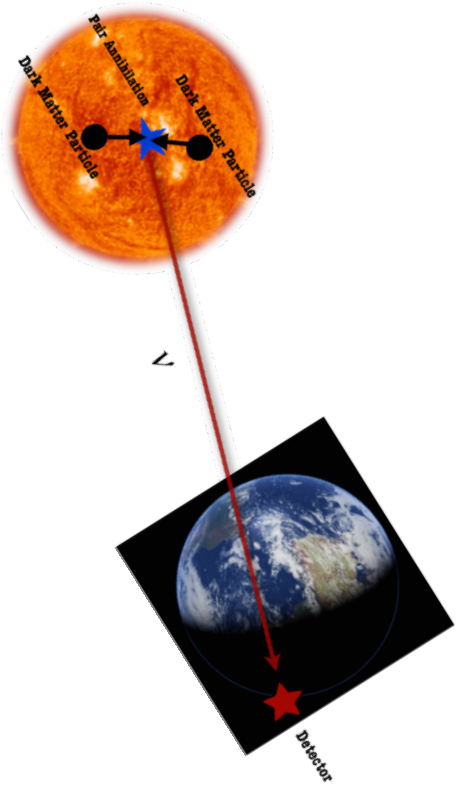
Name	ND	FD	$SN_{27\odot}$	$SN_{9.6\odot}$
GW190728_064510	45.0 s	29.6 s	3.2	5
GW190731_140936	Untriggered	Untriggered	210	400
GW190803_022701	Untriggered	Untriggered	140	230
GW190814	45.0 s	Untriggered	14	22
GW190828_063405	45.0 s	18.1 s	6	10
GW190828_065509	45.0 s	Untriggered	16	21
S190901ap	45.0 s	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.

Dark Matter

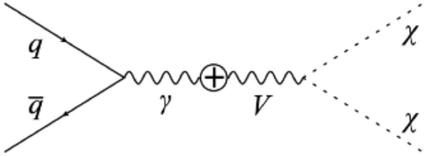
- Boosted Dark Matter may accumulate in the Sun and annihilate, producing GeV neutrinos. The signal is an upwards-going muon in the FD that points back to the Sun. Because of NOvA's low threshold and segmentation, we may be more sensitive than Super-K for dark matter masses 1–4 GeV. The search is likely 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.

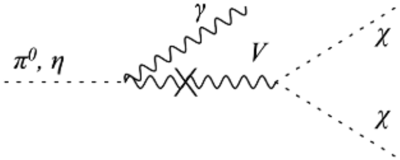


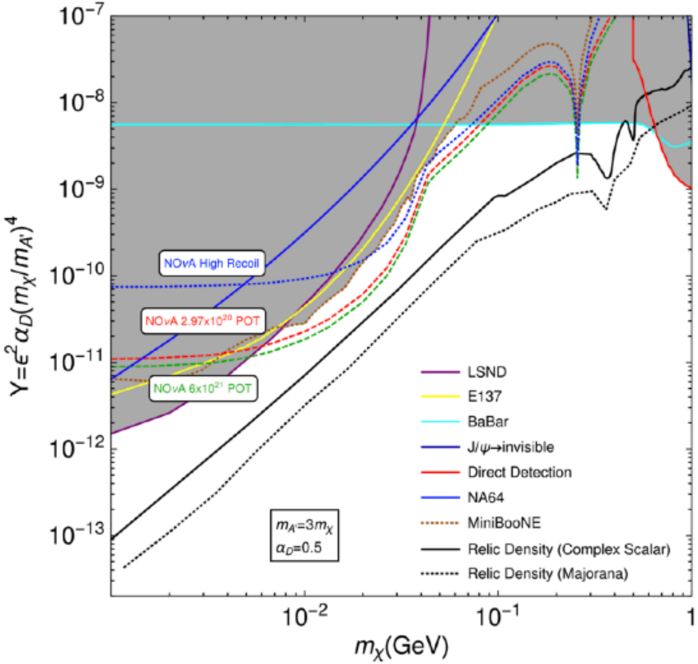
Beyond the Standard Model of the Particle Physics Analyses

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







NOνA 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)]