The NOvA neutrino experiment and its astrophysics program

Matthew Strait, for the NOvA collaboration

University of Minnesota, Twin Cities

February 22, 2021

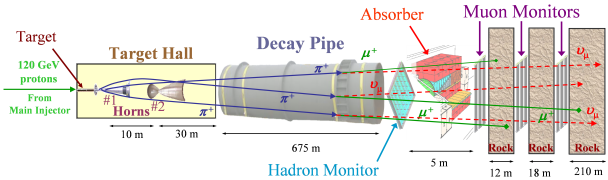
Outline

- Overview of NuMI beam and NOvA detectors
- Neutrino oscillation results (rapidly)
  - See more detail Wednesday 17:30: talk by Zoya Vallari
- Astrophysics

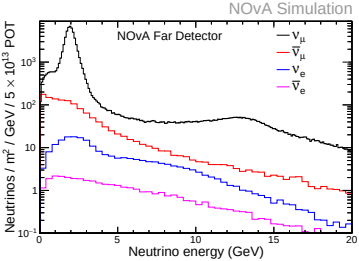
NOvA Far Detector

Design Overview

- Fermilab's NuMI beam



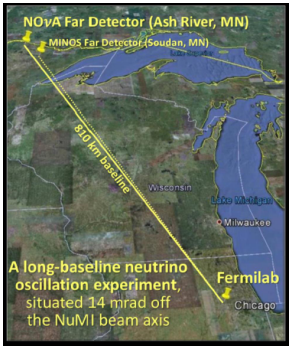
- Off-axis → narrow spectrum at 2 GeV
- 1st oscillation maximum at 810 km



- Near detector
  - Observe unoscillated beam composition, energy
- Far detector observes:

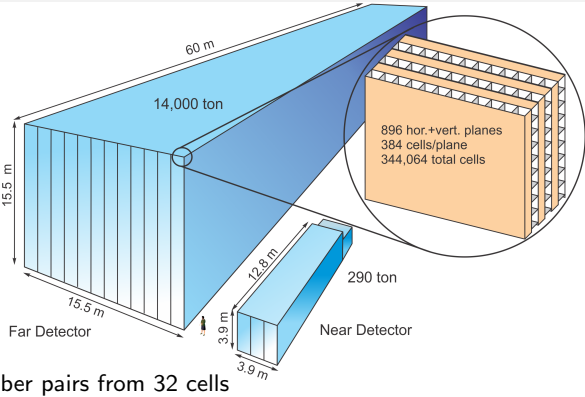
$\nu_\mu \to \nu_\mu \quad \nu_\mu \to \nu_e$

$\bar{\nu}_\mu \to \bar{\nu}_\mu \quad \bar{\nu}_\mu \to \bar{\nu}_e$

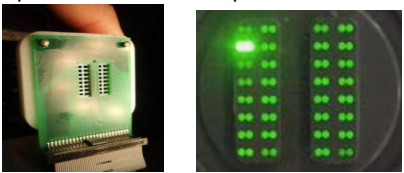


Detector Technology

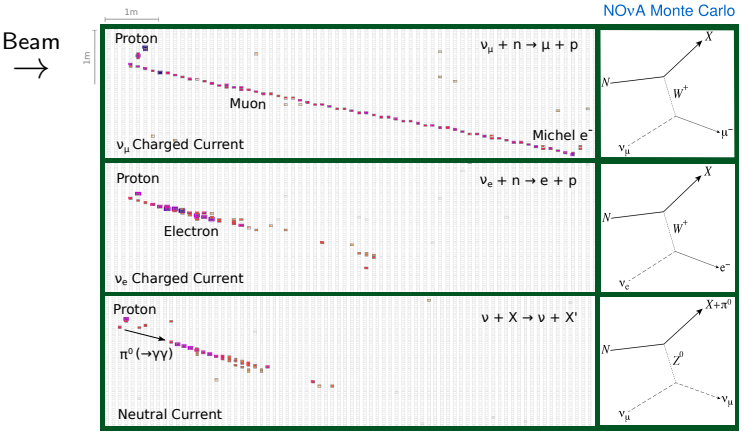
- Two functionally identical detectors
- Segmented plastic and scintillator tracking calorimeter
- 63% active
- APD readout
- Near detector is 300 t, underground, 1 km from NuMI target
- Far detector is 14 kt, on the *surface*



32 pixel APD sees fiber pairs from 32 cells



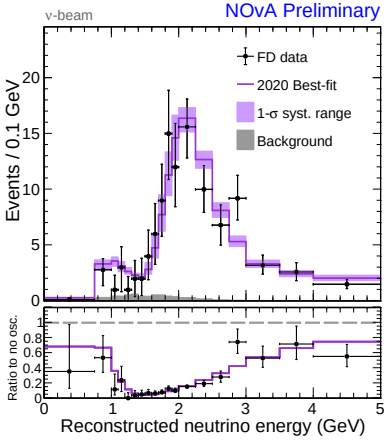
Event Topologies



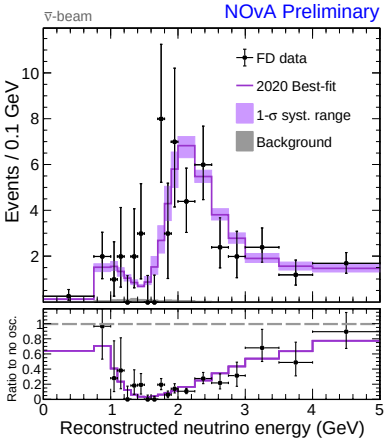
- Optimized for EM showers
- ∼6 samples per X_0
- Convolutional neural net classifier selects signal events

Far Detector Data: 2013–2020 — ν_μ disappearance

- Neutrino mode: 13.6×10^{20} POT
- 211 events selected
- Background: 9.2 events



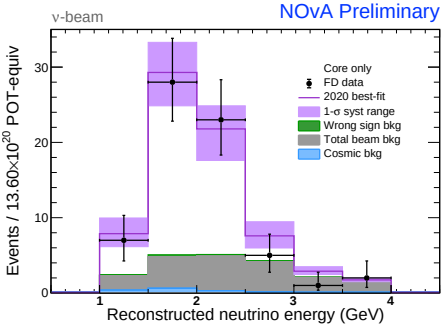
- Anti-neutrino mode: 12.5×10^{20} POT
- 105 events selected
- Background: 2.1 events

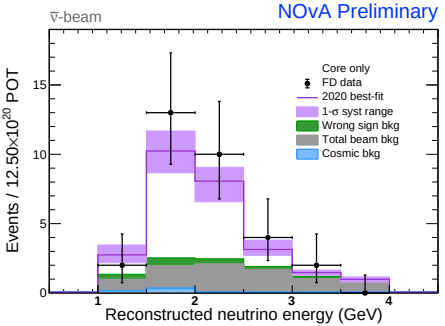


Far Detector Data — ν_e appearance

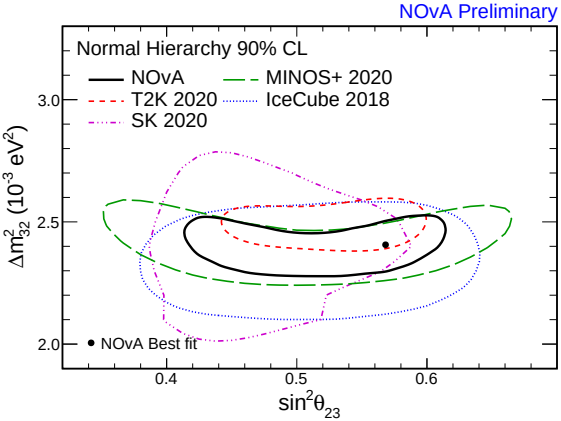
- 82 events in ν mode
- Background: 26.8 events
  - 1.0 wrong-sign (appearing $\bar{\nu}_e$)
  - 22.7 other beam (intrinsic ν_e, ν_μ, ν_τ, neutral current)
  - 3.1 cosmic

- 33 events in $\bar{\nu}$ mode
- Background: 14.0 events
  - 2.3 wrong-sign
  - 10.2 other beam
  - 1.6 cosmic
- $> 4\sigma$ electron anti-neutrino appearance

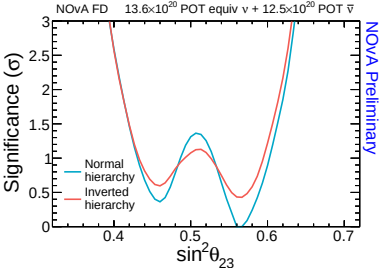




Combined Appearance/Disappearance Results — θ_{23}, Δm^2_{32}



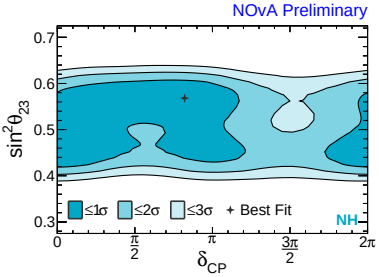
- $\Delta m^2_{32} = (2.41 \pm 0.07) \times 10^{-3}\,\mathrm{eV}^2$ (normal hierarchy)



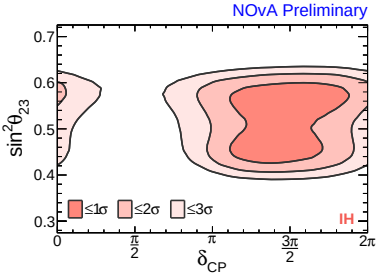
- Slight preference for upper octant, normal hierarchy
- $\sin^2\theta_{23} = 0.57^{+0.04}_{-0.03}$

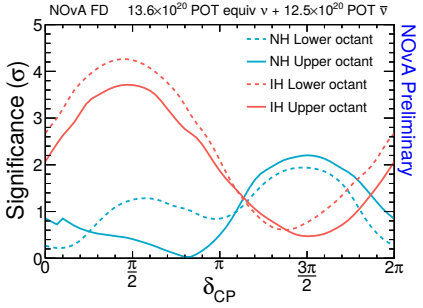
Combined Appearance/Disappearance Results — Mass ordering, θ_{23}, δ_{CP}

Normal hierarchy



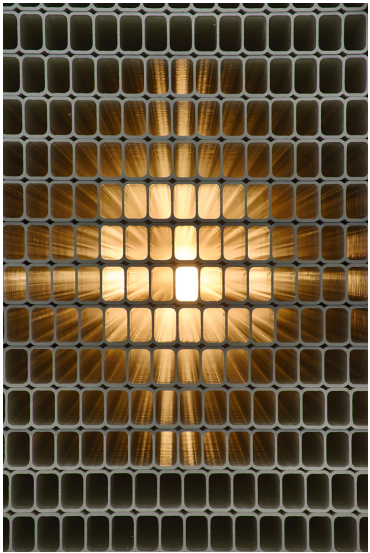
Inverted hierarchy





- All values of δ allowed
- Prefer normal hierarchy by 1.0σ
- Prefer **upper octant** by 1.2σ
- Exclude $\delta = \pi/2$ in IH at $> 3\sigma$

Astrophysics

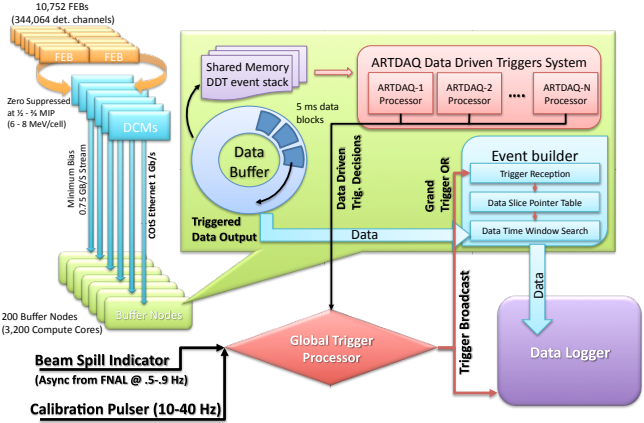


NOvA Far Detector

- As a large fine-grained detector, the Far Detector supports a variety of astrophysical analyses
  - Some benefit from the FD's location on the surface
  - Some can be done in spite of it
  - Cosmic muon rate: 150 kHz
- Near Detector: 100 m underground — much smaller, but much quieter
  - 36 Hz of cosmics

Triggers for Astrophysics

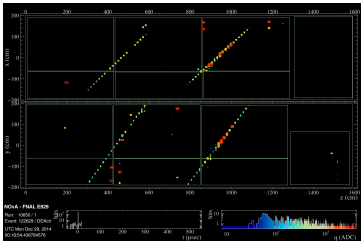
- All data continuously digitized
- Buffered for ∼20 minutes while trigger decisions are made
- Beam triggers
- Other external triggers
- Data-driven triggers

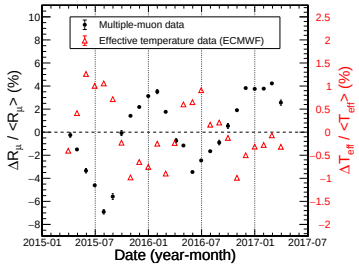


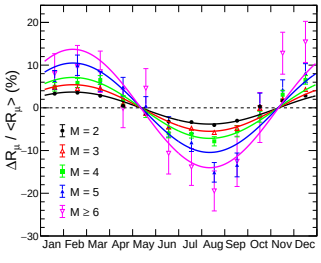
- Triggers request anywhere from 50 μs (e.g. cosmic showers) to 45 seconds (supernova)
- No dead time: triggers do not interfere with each other

Cosmic ray multi-muon seasonal effect at the Near Detector

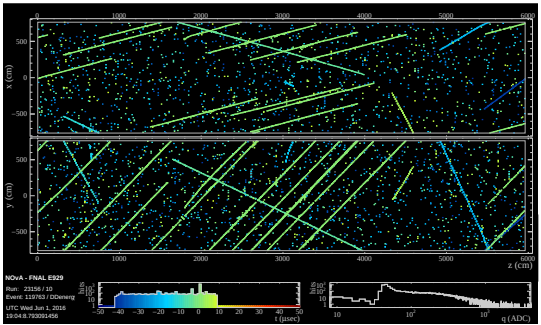
- Well-known: underground cosmic rate higher in summer
- Less dense summer atmosphere $\rightarrow$ more π decay before interacting
- But we observe *more* multi-μ in winter
  - *Phys.Rev.D* 99 (2019) 12, 122004
- Effect larger with higher multiplicity
- No clear explanation

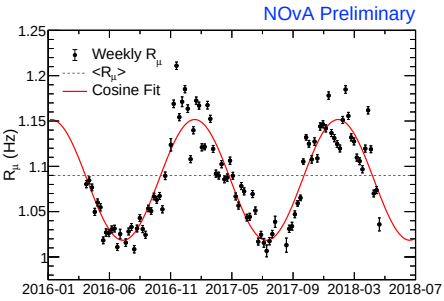






Seasonal multi-muon effect in the Far Detector

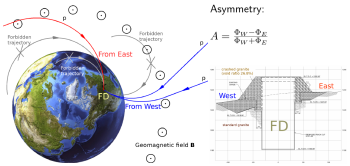




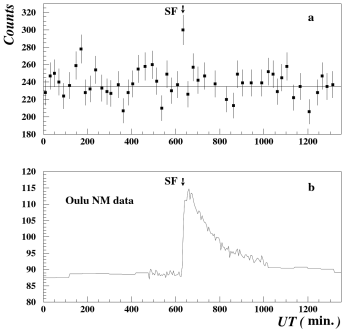
- Study sample of muon showers with multiplicity > 15
- Also observe winter maximum
- Simulation work underway to find explanation of effects in both Near and Far

Other Cosmic Ray Studies

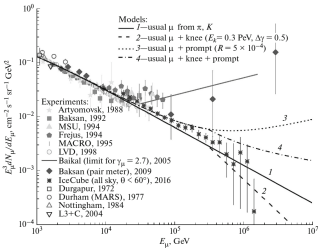
1. Measurement of low-energy east-west asymmetry
   - Caused by Earth's B field
2. Short-term weather effects
   - Known, but understudied
3. Solar flare correlation?
   - Claimed by L3+C
4. Measure muon rates above 100 TeV
   - Resolve Baksan/IceCube discrepancy?



L3+C:

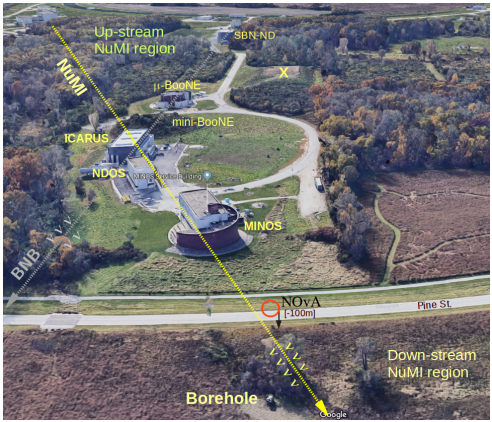


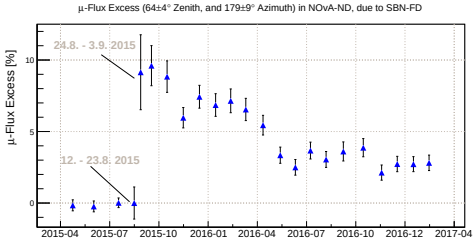
A&A 456, 351



Phys.Part.Nucl. 49 (2018) 4, 639

Discovery of ICARUS

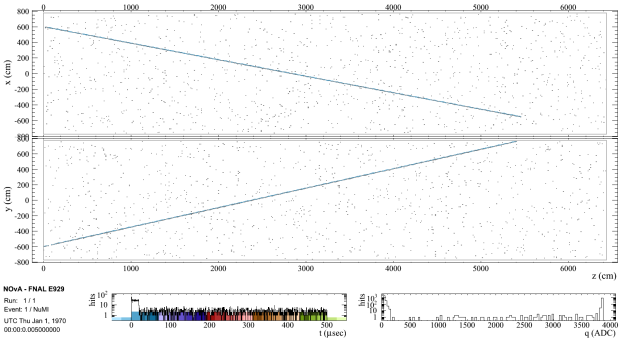




Magnetic Monopole Search

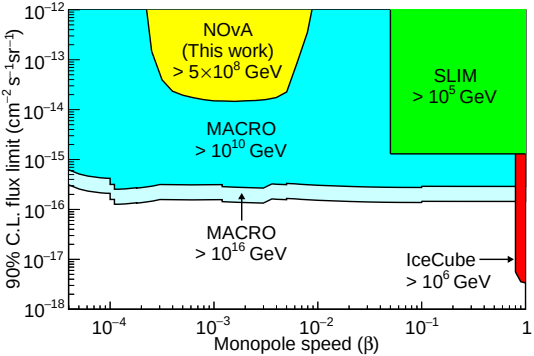
- Search for a monopole component of cosmic rays in the Far Detector
- Large surface area — catch rare events
- On surface — sensitive to lighter monopoles that don't reach far underground
- Signals:
  - If $\beta \gtrsim 10^{-2}$: highly ionizing, like a charge of 68.5e
  - If $\beta \lesssim 10^{-2}$: slow track
- NOvA sensitive down to $\beta \approx 10^{-4}$

Simulation



Magnetic Monopole Search Results

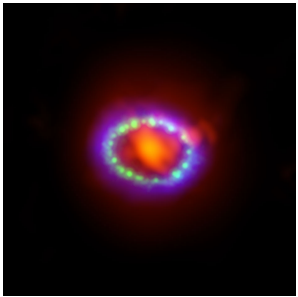
- Slow monopole search:
  - 95-day exposure: *Phys.Rev.D* 103 (2021) 1, 012007
  - ∼2000 days of exposure (with different detector conditions) to be analyzed
- Fast monopole search: in progress



- Set mass limits in flux/speed space: NOvA has best limits in yellow region
- Background-free: limits scale linearly with exposure
- Expect to reach $4 \times 10^{-16}\,\mathrm{cm^{-2}s^{-1}sr^{-1}}$ for $3 \times 10^{-4} < \beta < 0.8$
  - ≈ MACRO limits across most of the plot, but extending to lower masses

Supernova neutrinos

- Core collapse supernovae release 99% of their energy in neutrinos
- $\sim$ 10–60 MeV
- Burst lasting 10s of seconds
- Only one SN observed in neutrinos: 1987a



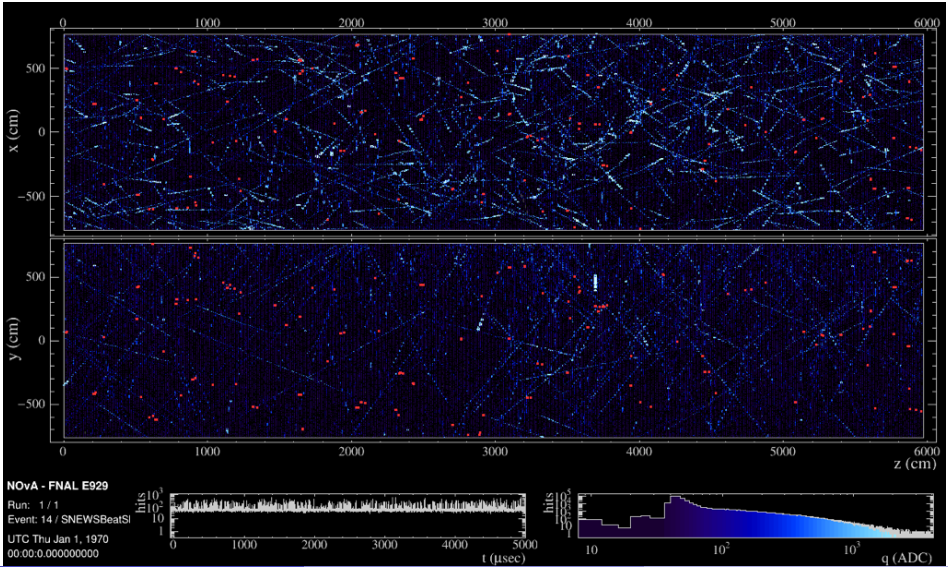
- NOvA is mostly sensitive to $\bar{\nu}_e$:

At Galactic center:

	Far	Near
$\bar{\nu}_e + p \to e^+ + n$	2163	46
$\nu_x + {}^{12}\mathrm{C} \to \nu_x + {}^{12}\mathrm{C}^*$	393	9
$\nu_e + {}^{12}\mathrm{C} \to e^- + {}^{12}\mathrm{N}$	137	3
$\bar{\nu}_e + {}^{12}\mathrm{C} \to e^+ + {}^{12}\mathrm{B}$	139	3
$\nu_x + e^- \to \nu_x + e^-$	199	4

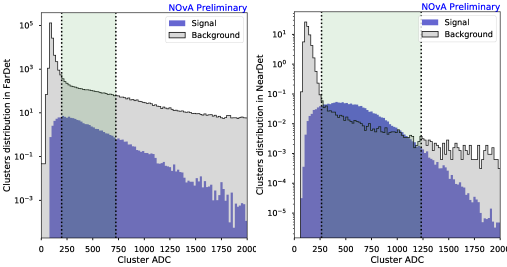
- Primary signal: 1–7 hits from positron
  - Neutron capture on ^{35}Cl marginally visible
- Largest operating carbon-based detector
- Complementary to water/lead/argon detectors for constraining flavor content

Far Detector: 5 ms cosmic data + SN simulation

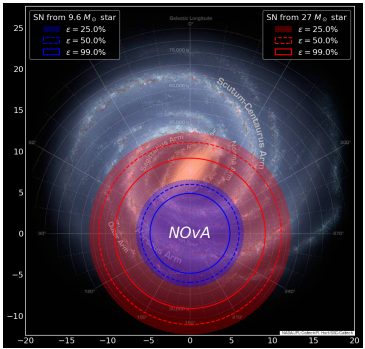


Supernova Trigger

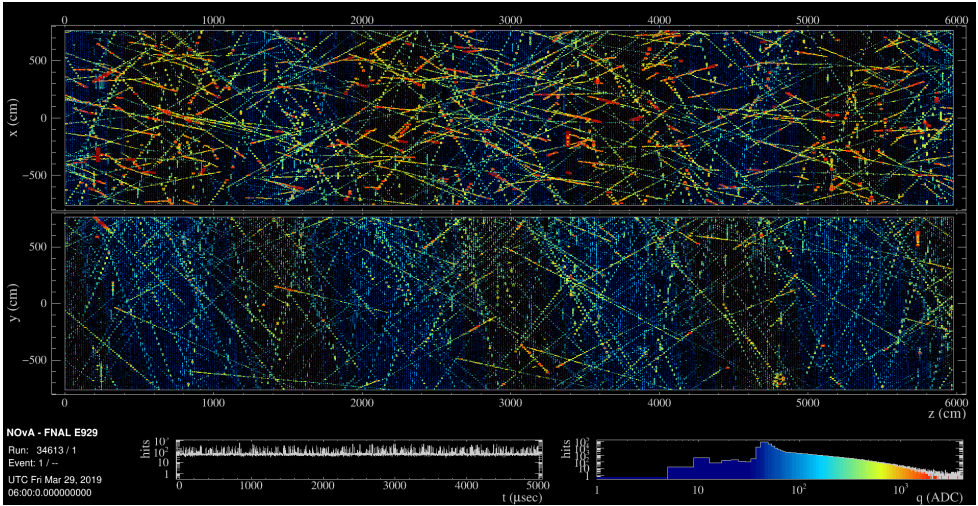
- Remove muon tracks, activity near tracks
- Filter by supernova candidate cluster energy



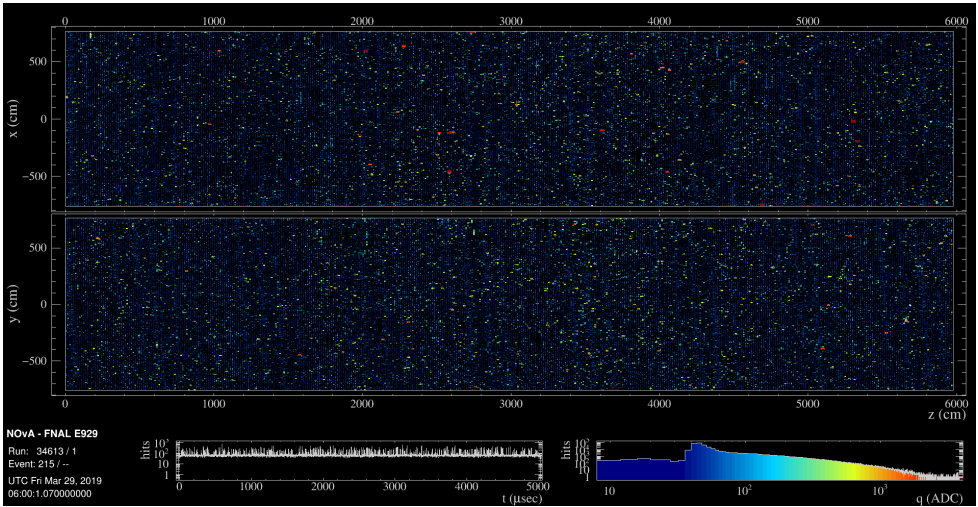
- Trigger covers half the galaxy
- SNEWS alerts cover the rest
- Plan to also send triggers to SNEWS soon
- JCAP 10 (2020) 014



Can we read out Betelgeuse? This is 5 ms of everyday data:

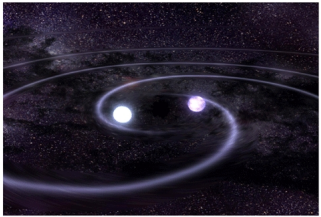


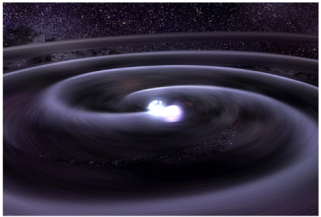
Simulated peak flux from Betelgeuse, 5 ms, cosmic tracks removed:

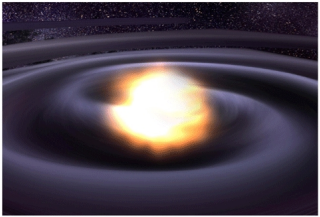


Multimessenger search with gravitational waves

- NOvA receives triggers from LIGO/Virgo
- Save 45 s of continuous data around each gravitational wave candidate
- Same as for a supernova candidate

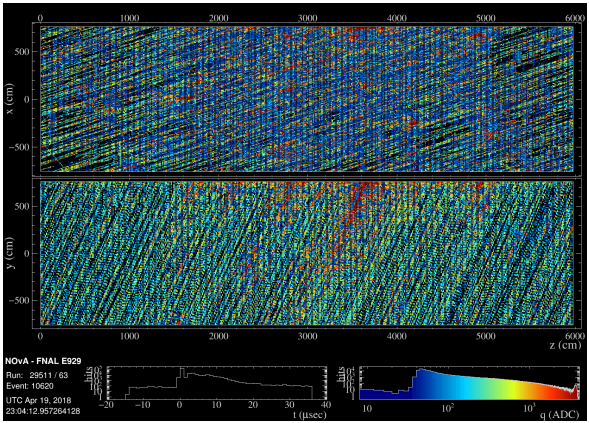






General multimessenger search

- Any unusual activity coincident with gravitational waves?
- Looked between MeV, 100s of TeV
- None found
- PRD 101, **11** 112006

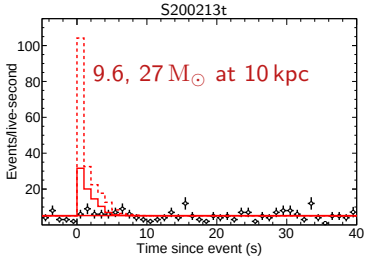


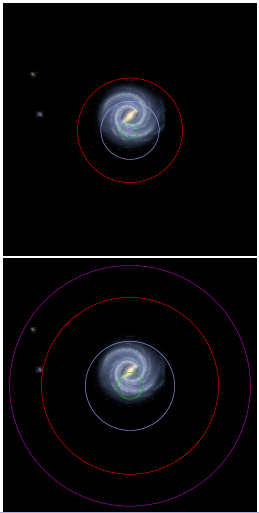
- Cosmic event with $\sim$ 2000 muons
- Not coincident with a gravitational wave event

Search for supernova-like neutrinos coincident with gravitational waves

90% limits: 9.6, 27 $M_\odot$ supernova
Red: median case for triggered FD

- Most likely signal for NOvA would be supernova neutrinos
- New multivariate analysis improves cosmic rejection
- Reduces FD background from 450 Hz to 5 Hz





- Searched using 75 LIGO/Virgo events
- No excesses found

Conclusions

Neutrino oscillations

- Appearance of $\bar{\nu}_e$ in a $\bar{\nu}_\mu$ beam at $> 4\sigma$
- Inverted hierarchy, $\delta \approx \pi/2$ excluded at $> 3\sigma$
- See talk Wednesday 17:30 for more details

Broad astrophysics program

- Made possible by trigger system, complementary Near and Far Detectors
- More results and new analyses to come


NOVA
MAY 2020