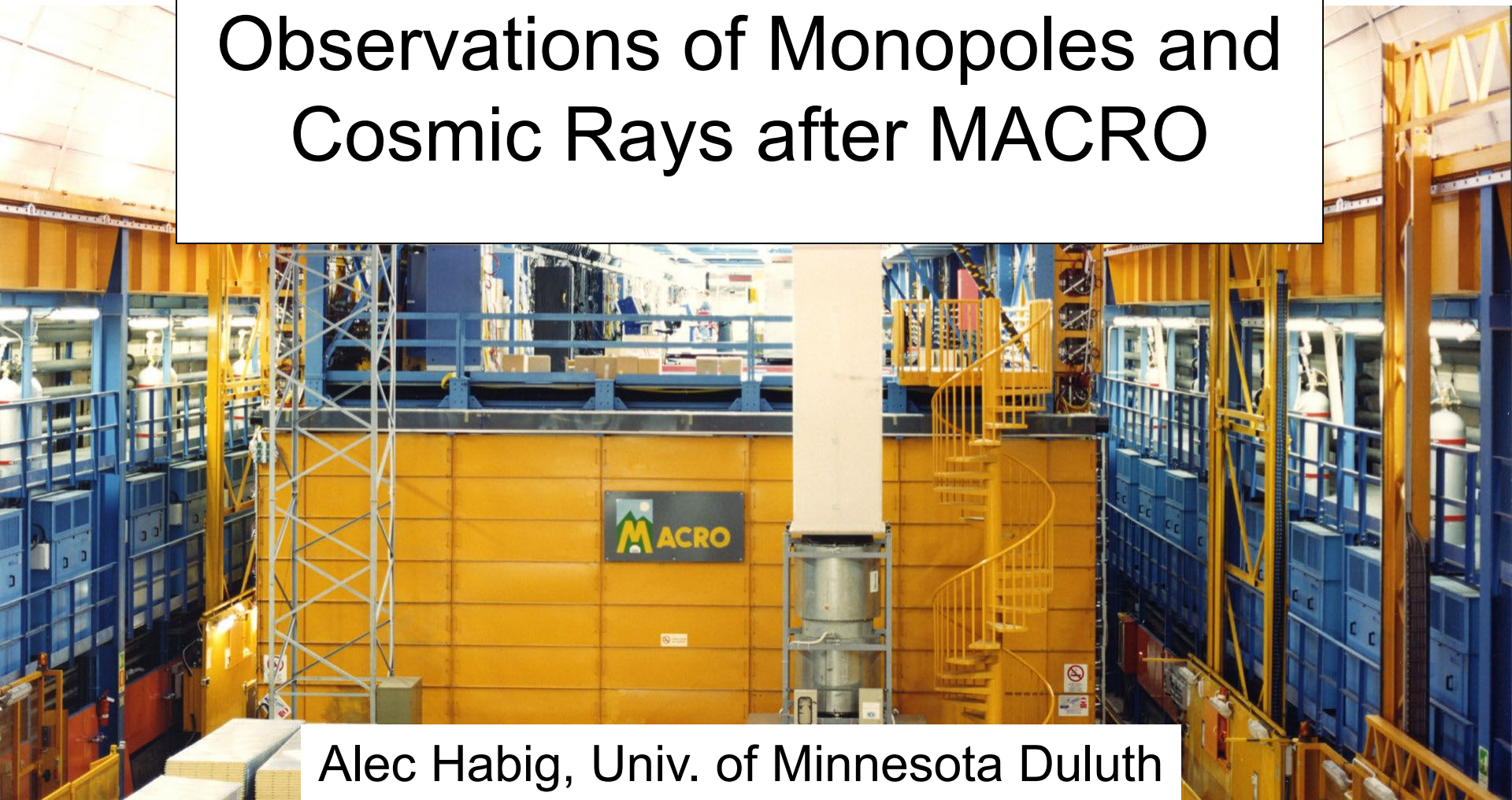
Observations of Monopoles and Cosmic Rays after MACRO



Alec Habig, Univ. of Minnesota Duluth

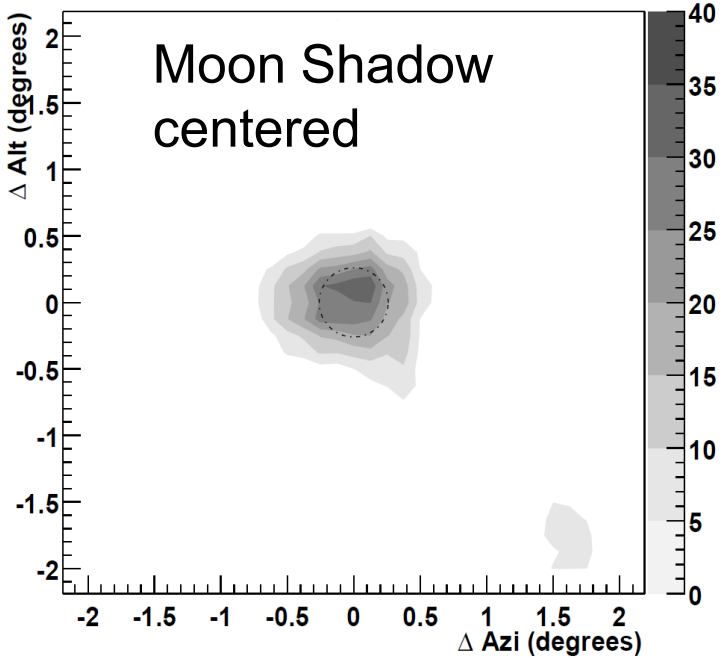
- After MACRO, I've been doing particle astrophysics using mostly particle physics experiments
  - Super-K, MINOS, NOvA, HALO, DUNE (*eventually*)
- In particular, what MACRO analyses have we built on, by (mis)using long-baseline neutrino experiments?

Moon and Sun Shadows

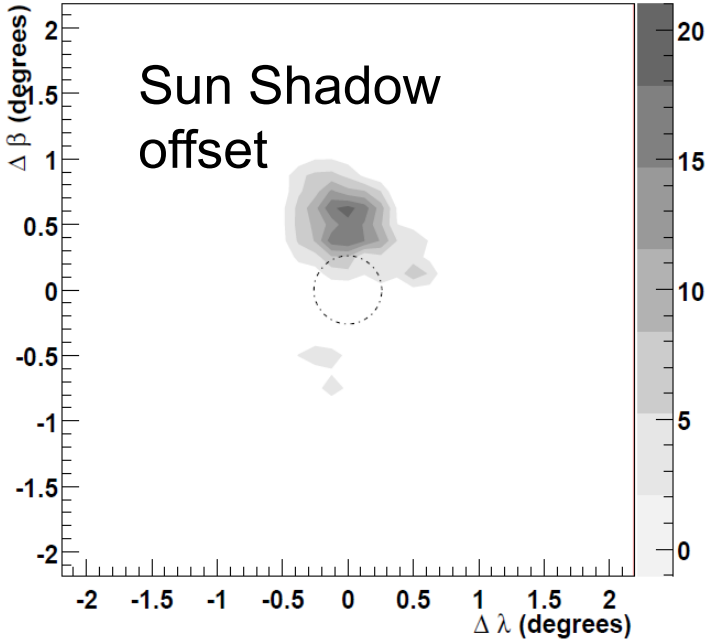
- In MACRO, we needed to see the shadows cast in the cosmic ray sky by the moon and sun in order to do any cosmic ray or neutrino astrophysics

Astropart.Phys.20:145-156,2003

  - Also constrained the CR primary p-bar content



Sun's magnetic field curving the primaries on the way here?

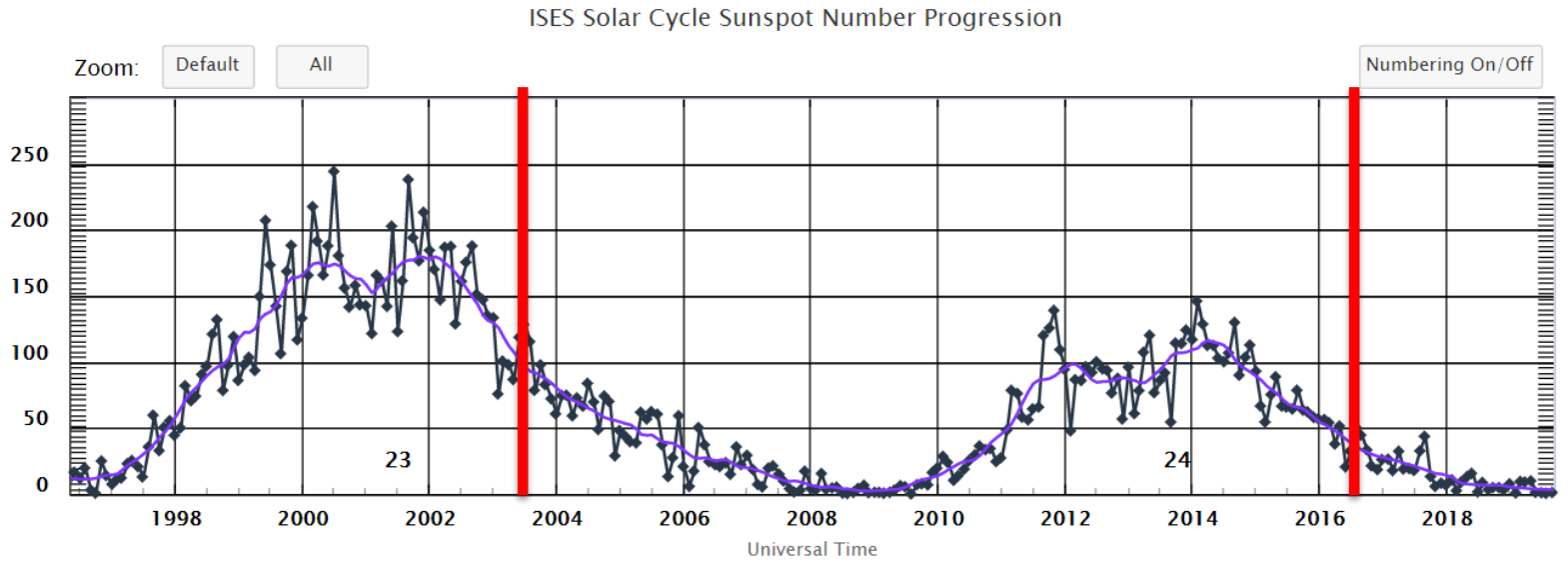


NuMI

MINOS

MINOS Shadows

- MINOS Far Detector at Soudan is somewhat smaller but shallower, so plenty of muons
- Also took data for a whole solar cycle: can we study the heliosphere as the Sun's B pushes around the primary cosmic rays??



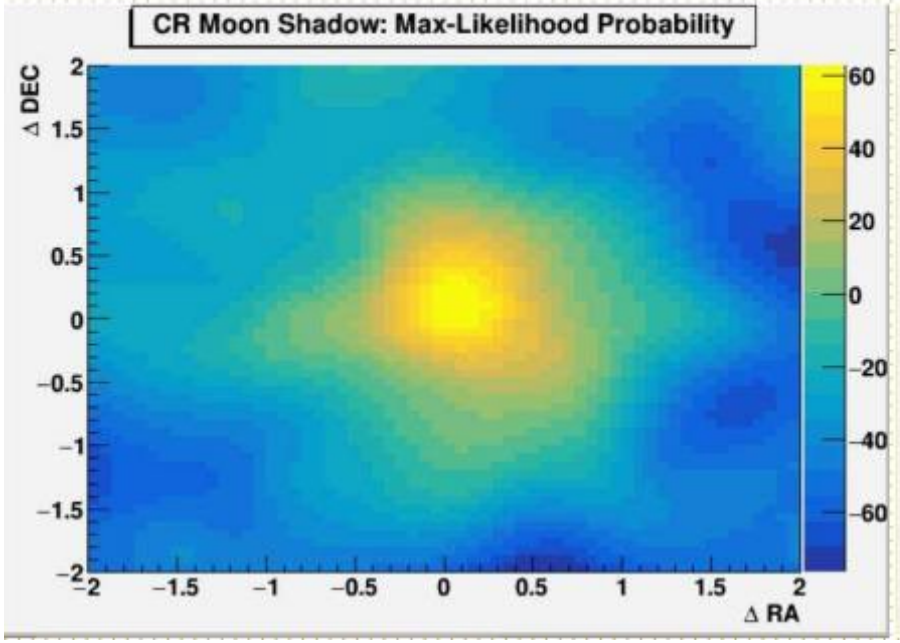
NuMI

MINOS

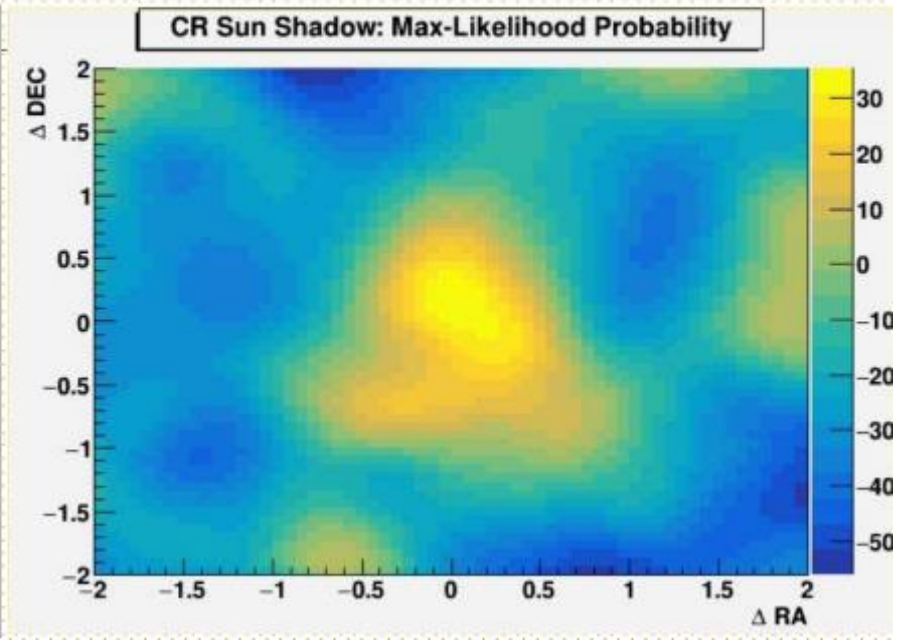
MINOS Shadows

- Overall, the moon and sun shadow shapes are similar in MINOS as MACRO

Moon shadow



Sun shadow

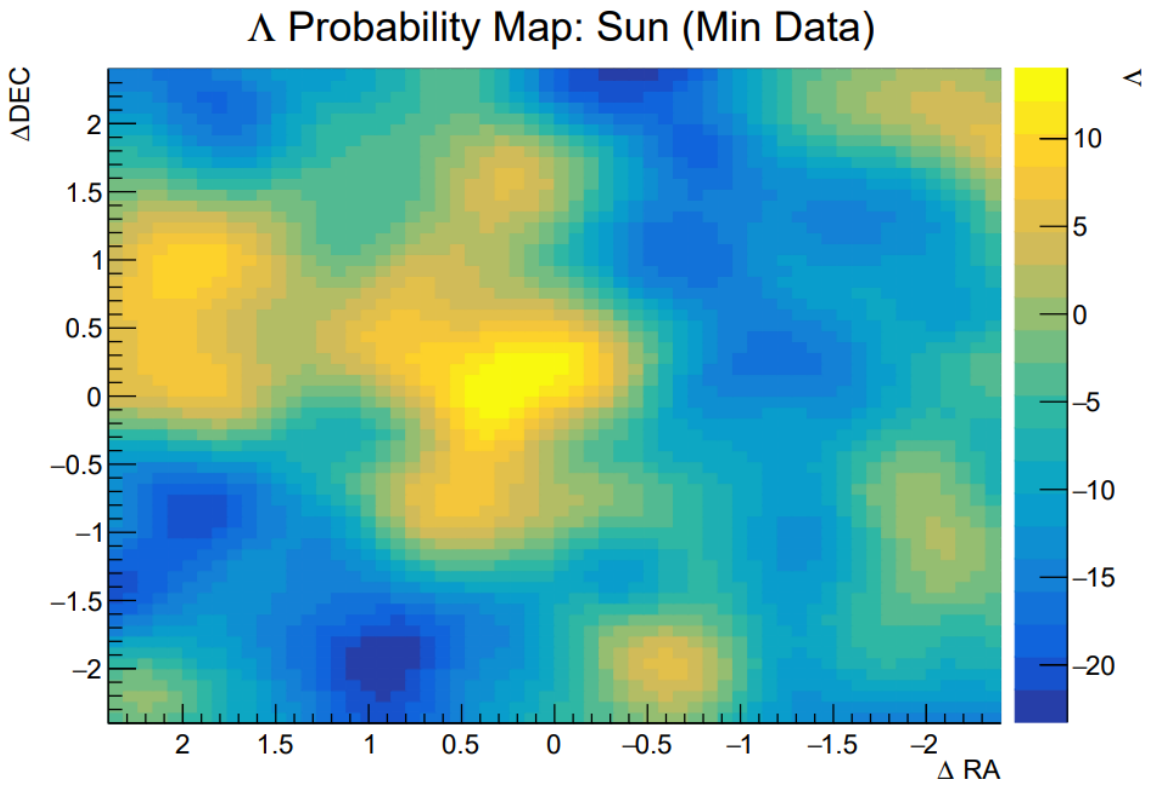


NuMI

MINOS

Solar Min

- Sun Shadow just near solar minimum (Jan 2007-Dec 2009)

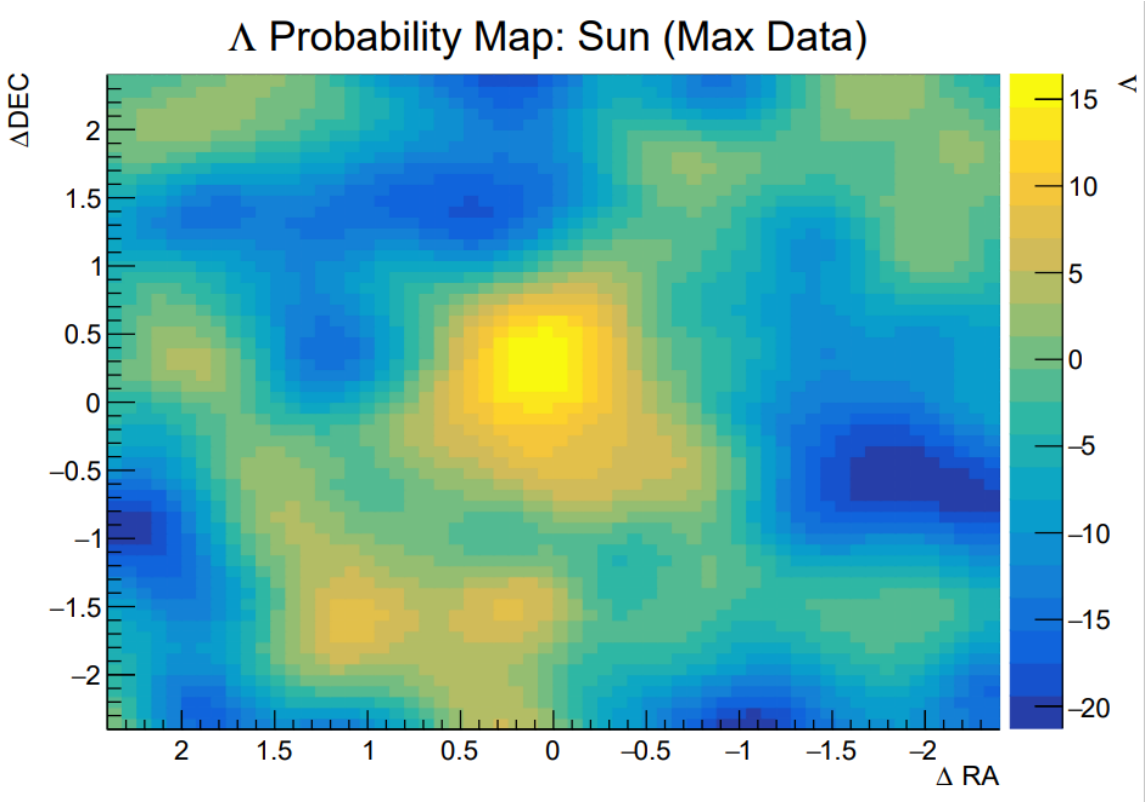


NuMI

MINOS

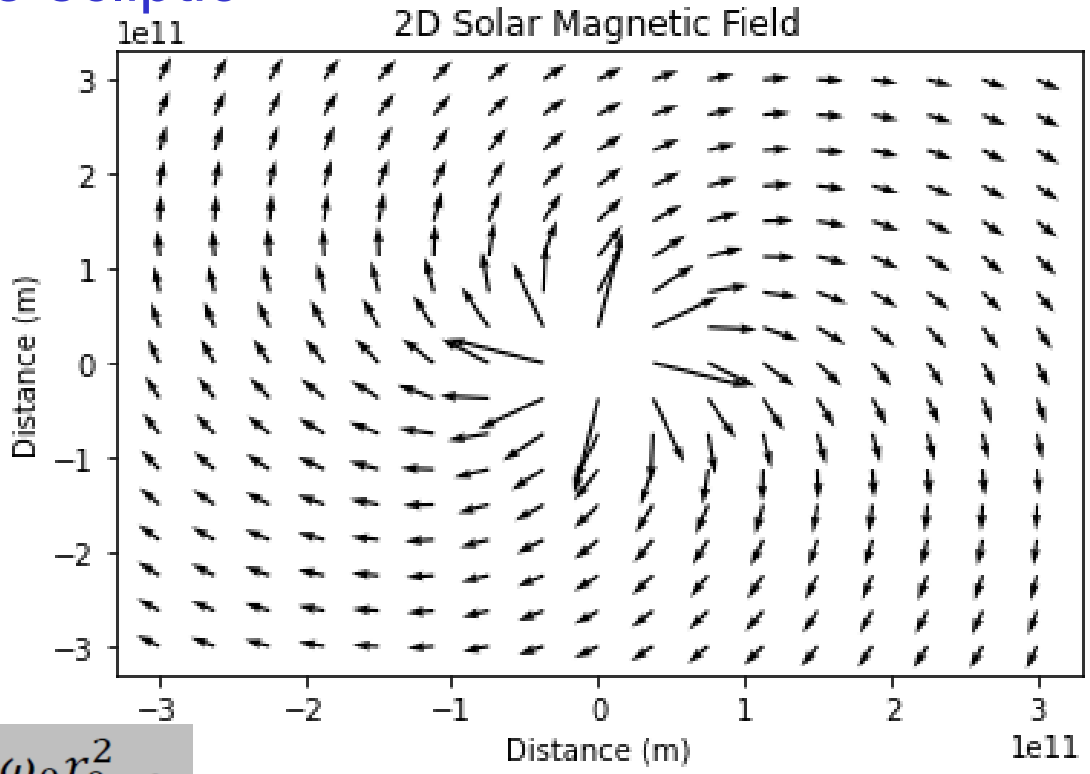
Solar Max

- Sun Shadow just near solar maximum (Jan 2012-Dec 2014)



Back-propagate the CR primaries

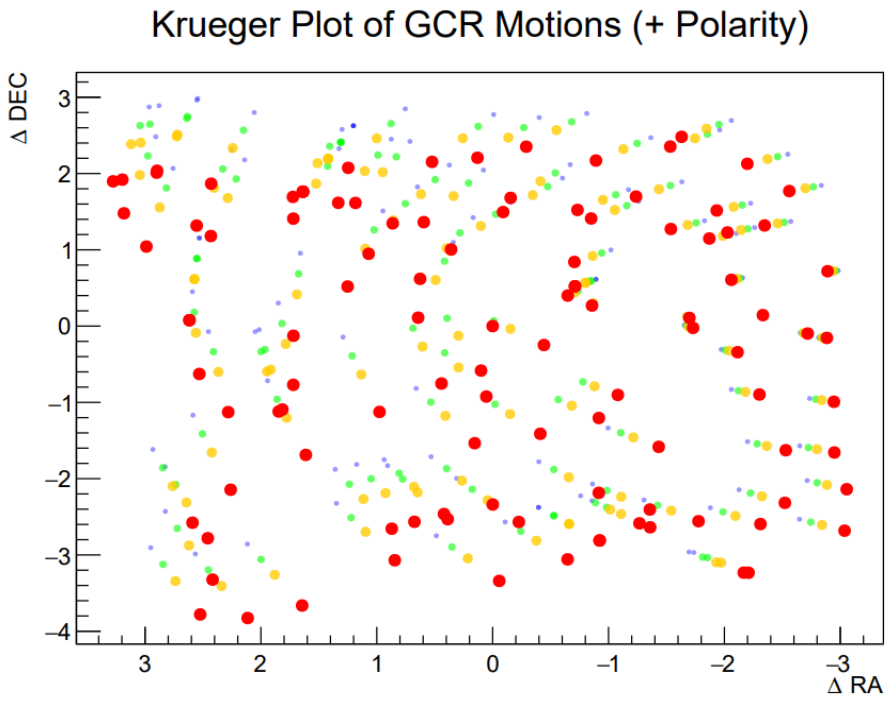
- Use a Parker Spiral model
  - The polarity of the field also comes out mixed on the ecliptic

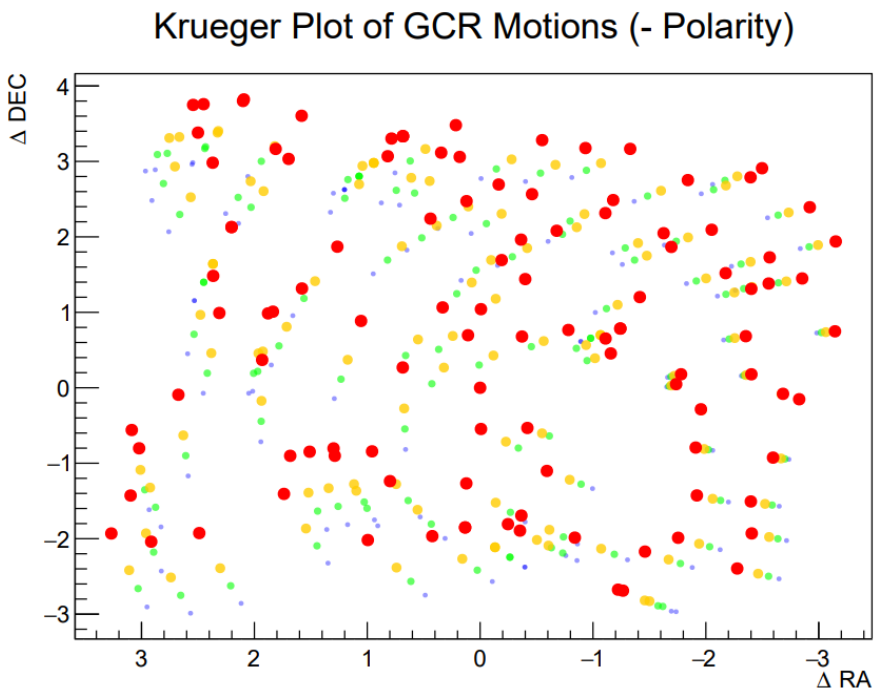


$$\boldsymbol{B} = \frac{B_0 r_0^2}{r^2}\hat{r} - \frac{B_0 \omega_0 r_0^2}{u_r r}\hat{\varphi}$$

Where do the CRs move?

- If a CR hits at the red dot, it came from the little dots (*plotted with respect to the sun*)





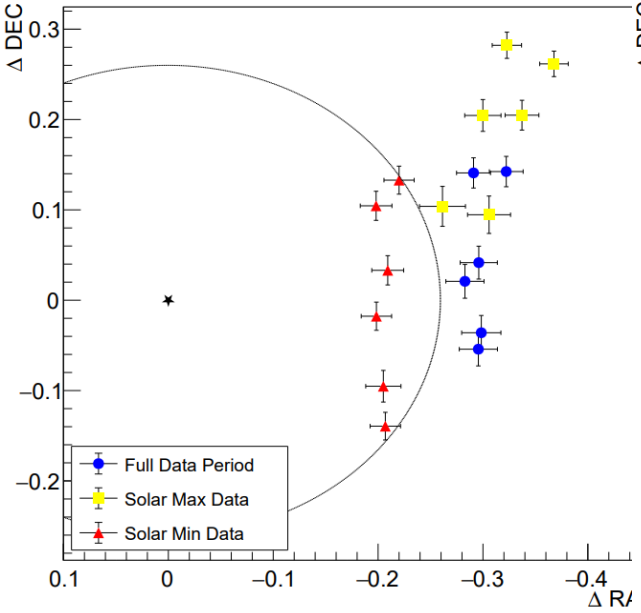
NuMI

MINOS

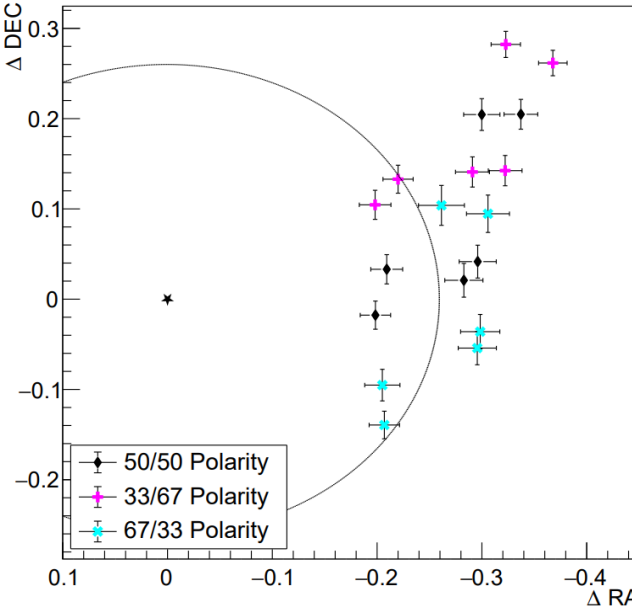
Overall Shift?

- Shadow Center movement, by solar state, mix of polarities in the field, and simple or distorted shadow shapes
  - There's a lot going on – we need to quantitatively match what we see to these parameters

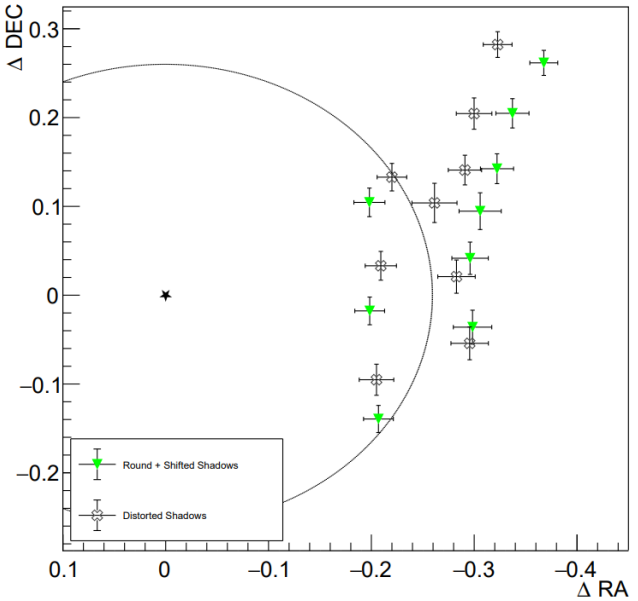
Distribution of Means: Sorted by Data Set



Distribution of Means: Sorted By Polarity Ratio

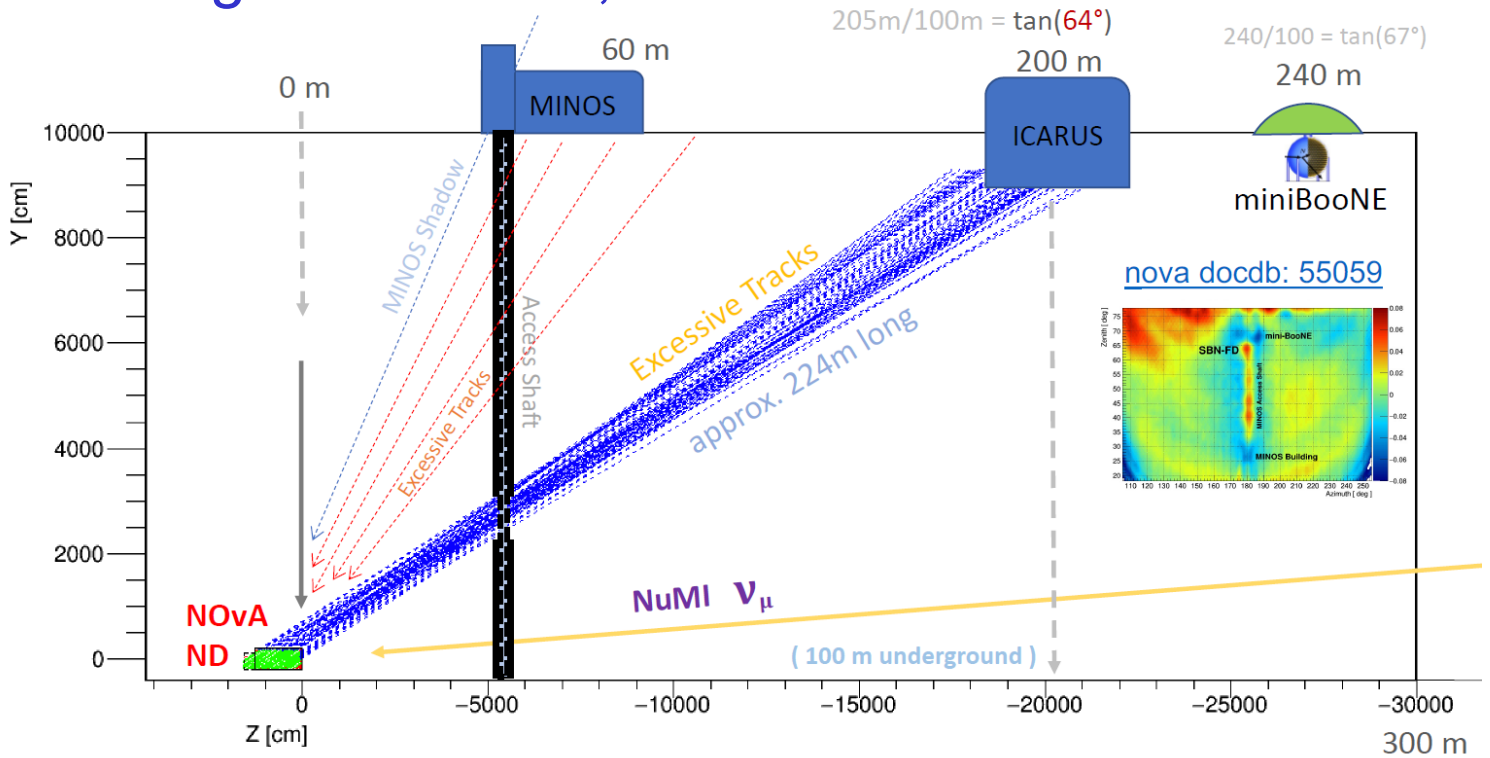


Distribution of Means: Sorted By Shadow Type



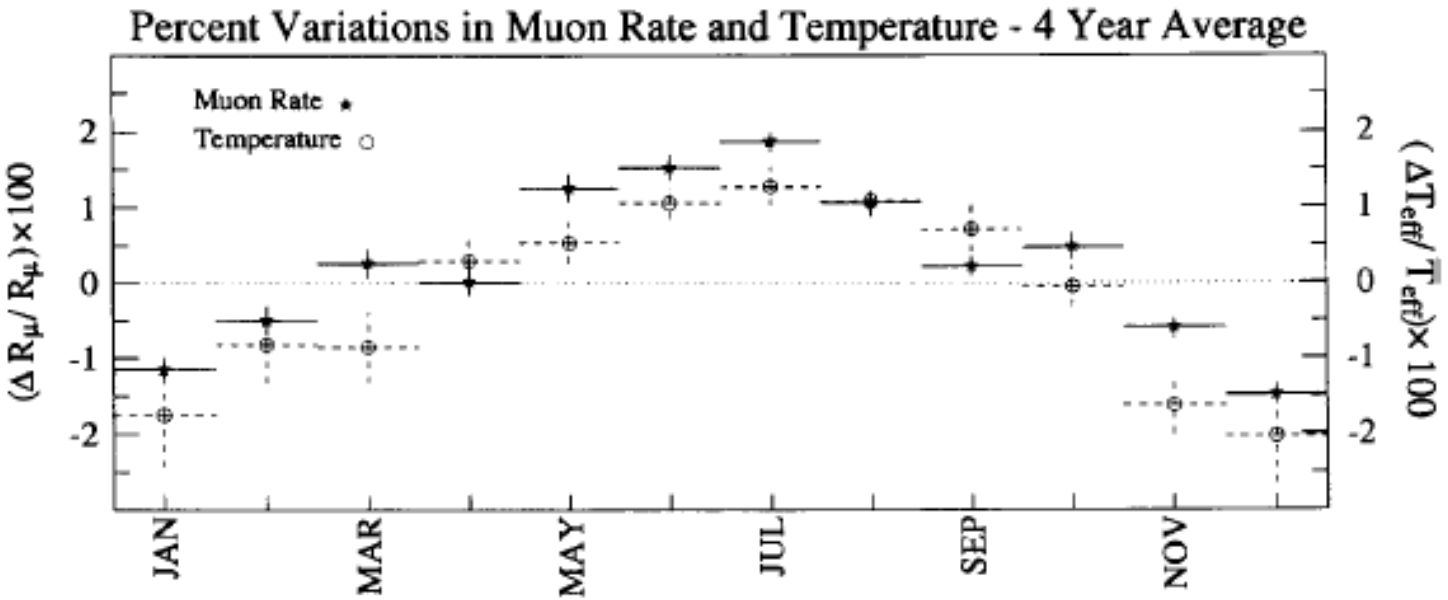
Muon tomography

- Terrestrial anti-shadows probe what's around the NOvA Near Detector 100m under
  - We were able to watch the new Icarus building being constructed, LAr filled!



CR Seasonal Variations

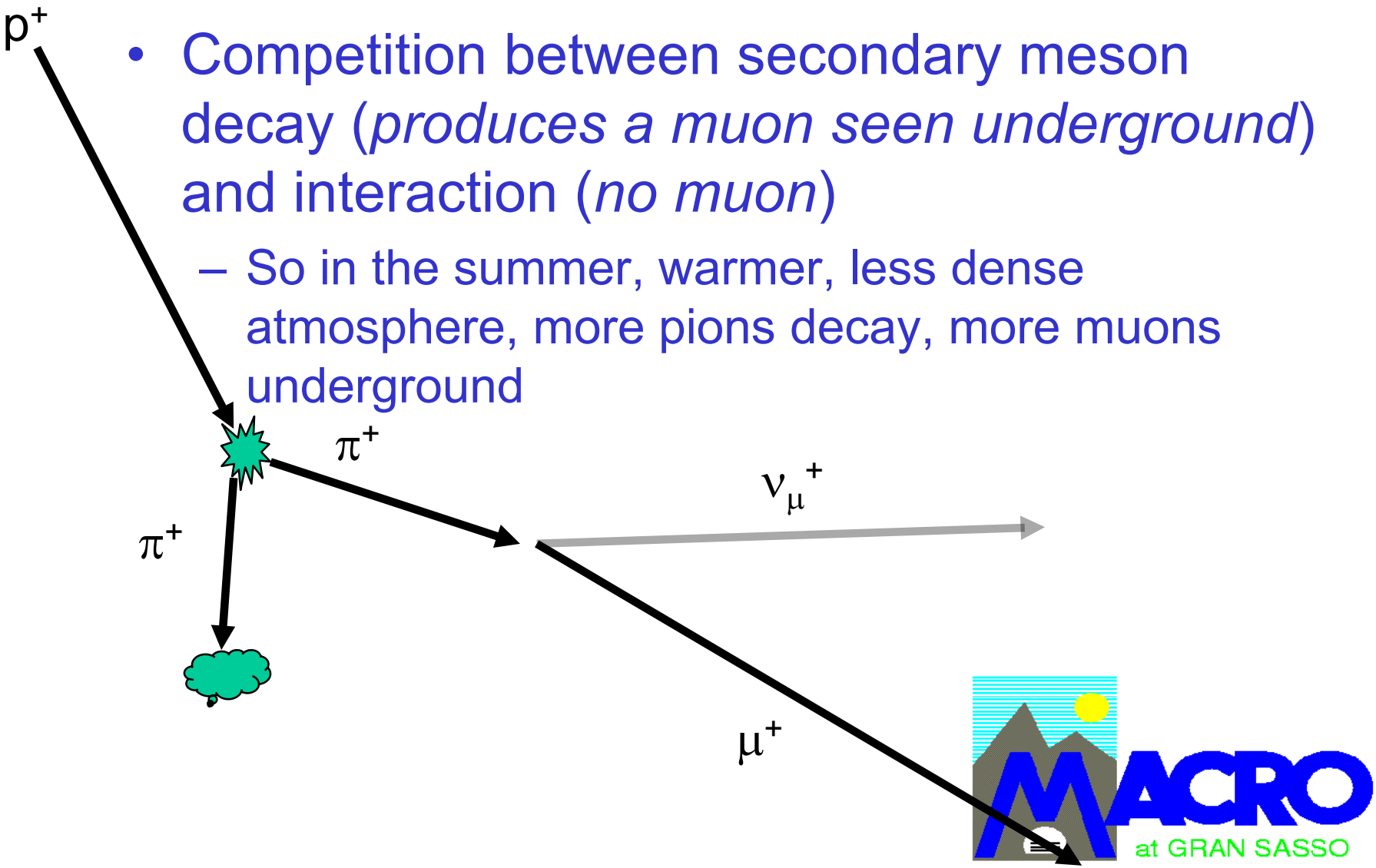
- MACRO correlated weather balloon data from the Campo (measuring temperature vs height) and the cosmic ray rate



Astropart.Phys.20:145-156,2003

Why?

- Competition between secondary meson decay (*produces a muon seen underground*) and interaction (*no muon*)
  - So in the summer, warmer, less dense atmosphere, more pions decay, more muons underground



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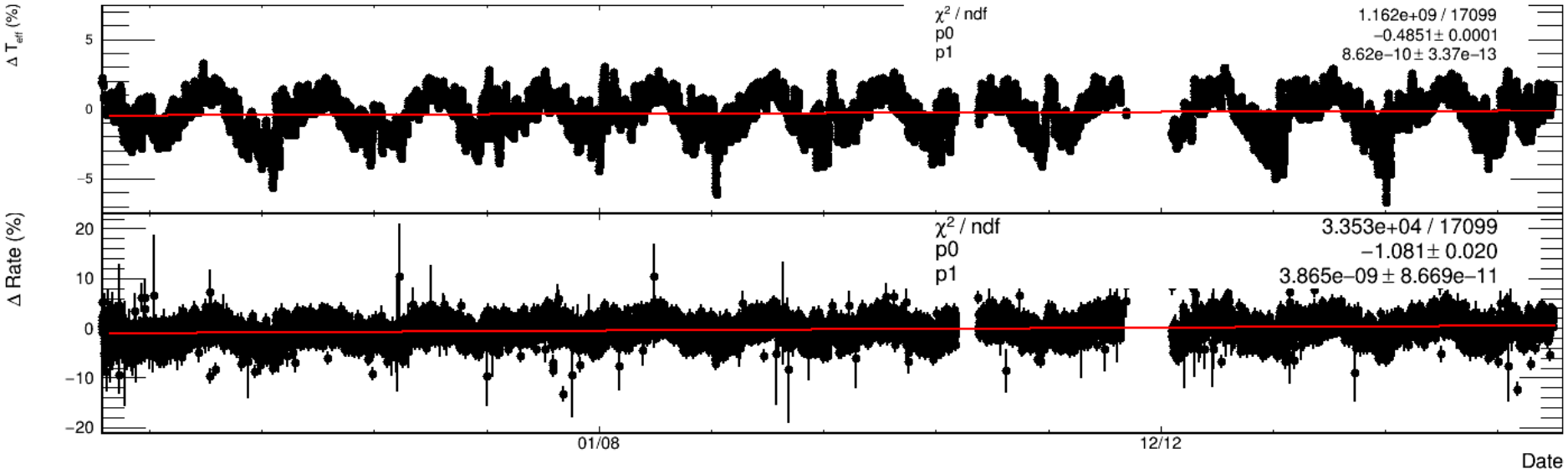
MINOS

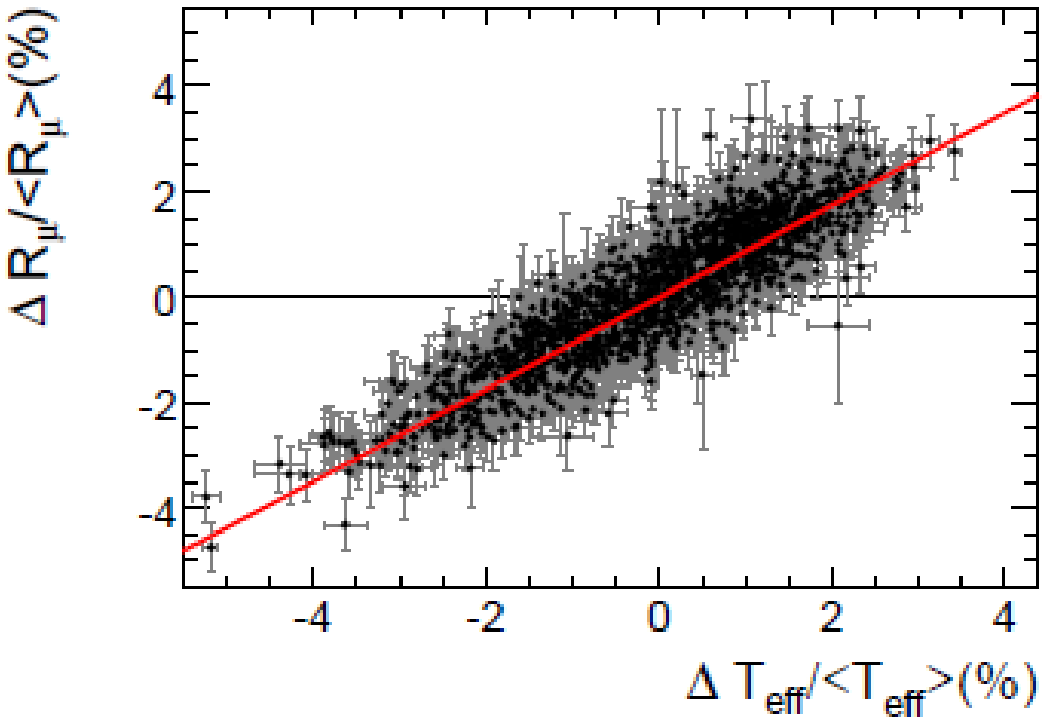
In MINOS

- Bin the data more finely, get atmosphere data from ECWMF grid weather model
  - See the same thing!
  - Over a solar cycle, no change in trend



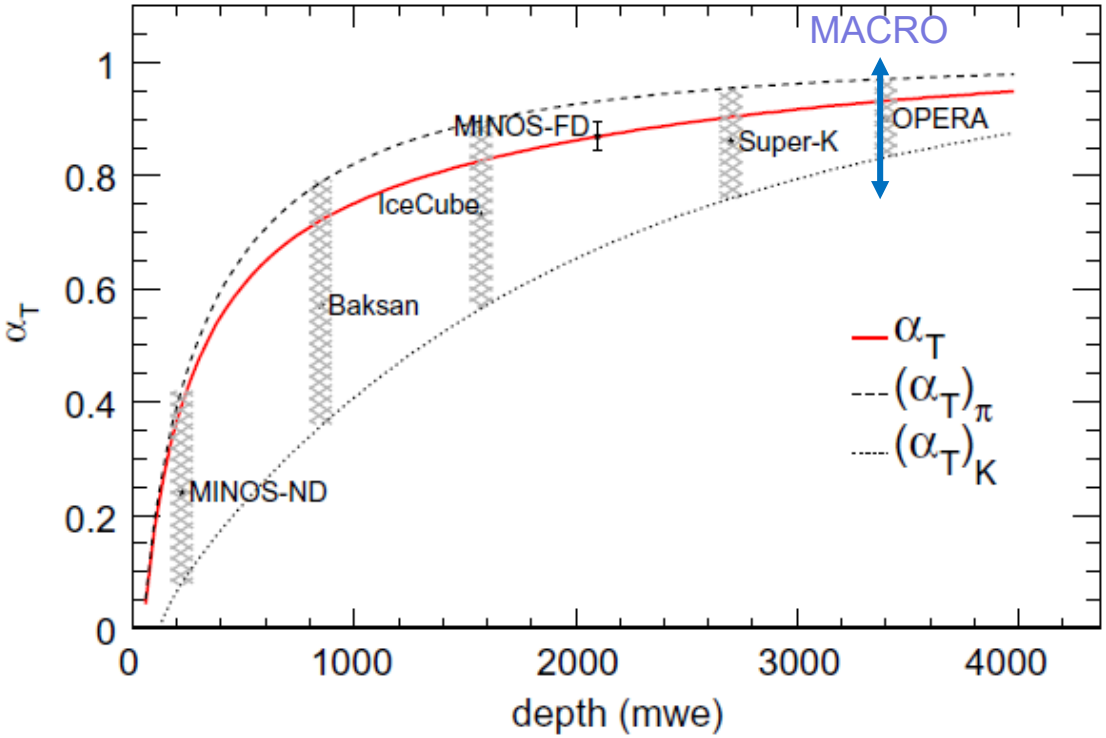
In MINOS

- Bin the data more finely, get atmosphere data from ECWMF grid weather model
  - Plot delta-rate vs. delta-T, get α correlation



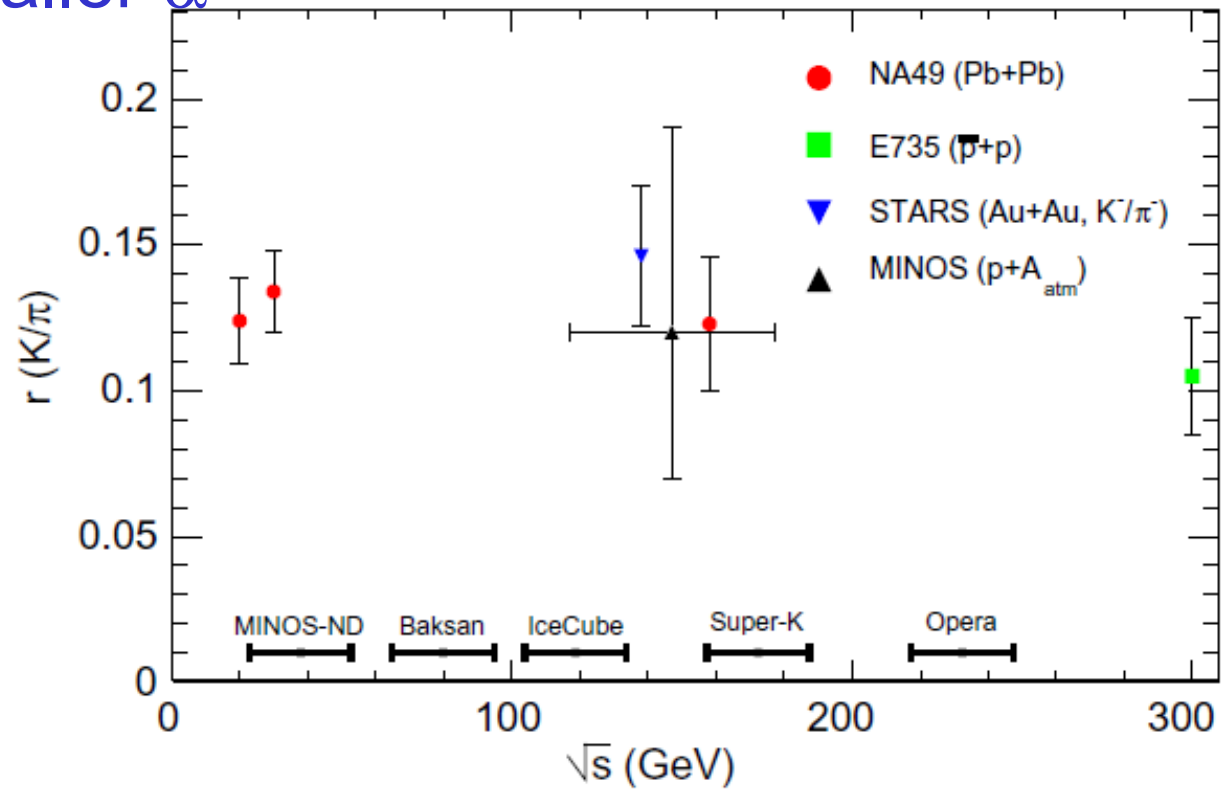
Compare vs depth (energy)

- Deeper experiments: larger α since more energetic pions last longer, hit more air
- Kaons instead of pions? Always decay, smaller α



K/π production ratio at high energy

- Deeper experiments: larger α since more energetic pions last longer, hit more air
- Kaons instead of pions? Always decay, smaller α



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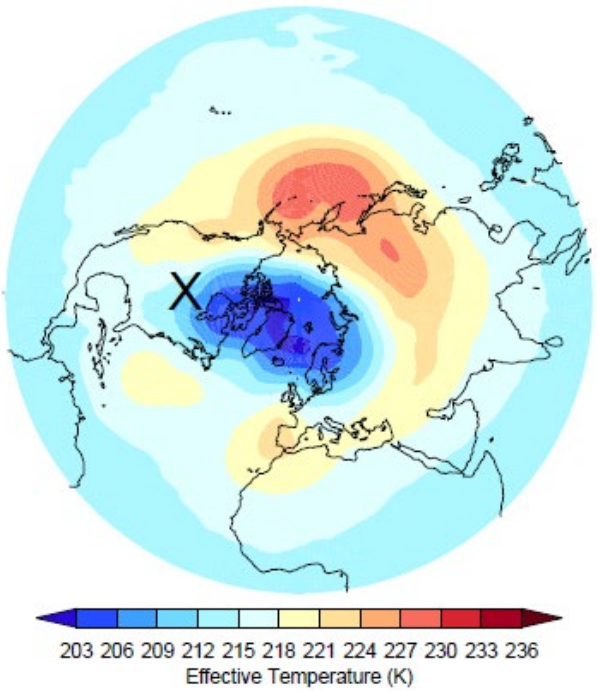
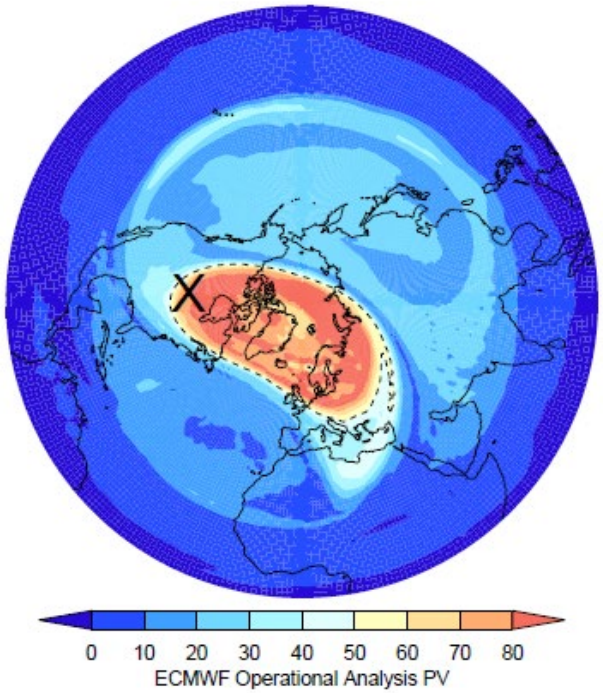
MINOS

Polar Vortex!

- Cosmics seen deep underground watch the weather at a point above weather balloons and below satellites
  - Saw a record Polar Vortex bring arctic temperatures to the US in Feb. 2005





NuMI

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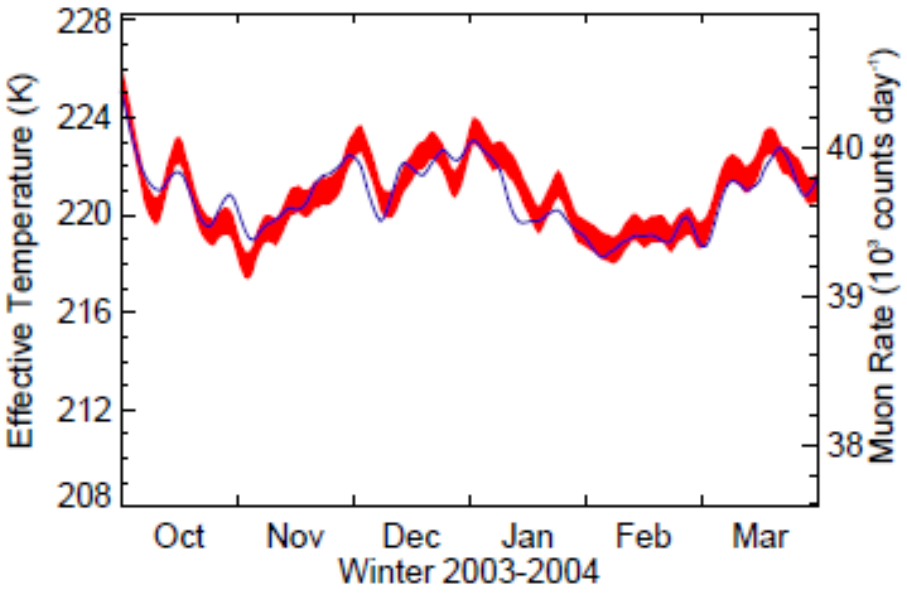
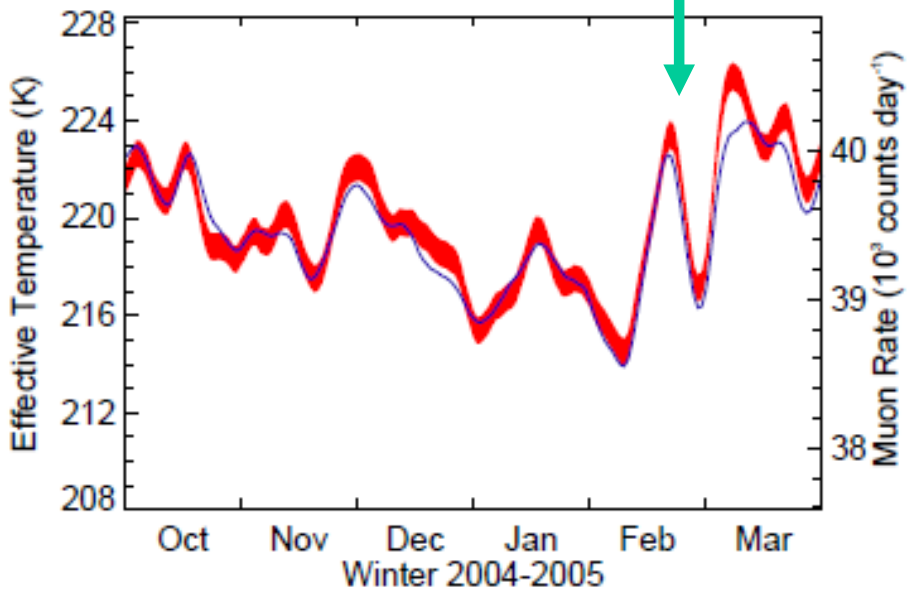
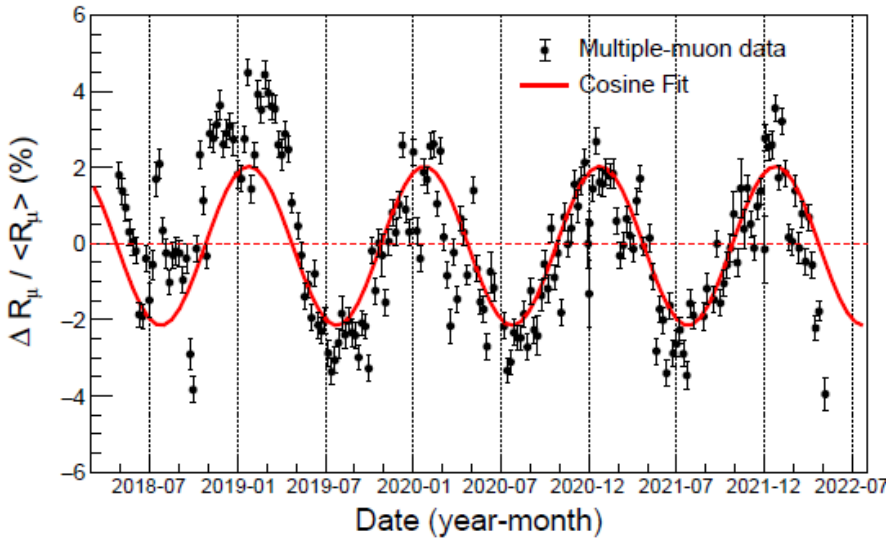
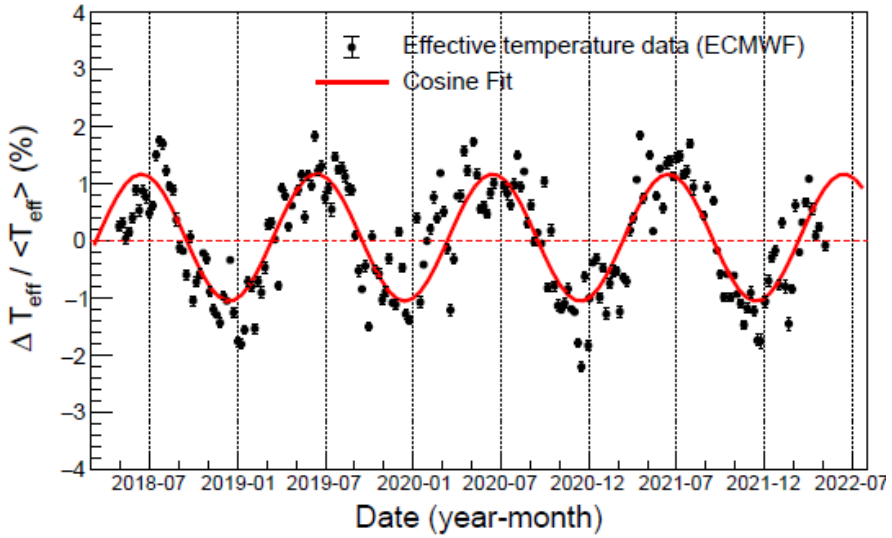




Seasonal Weirdness?

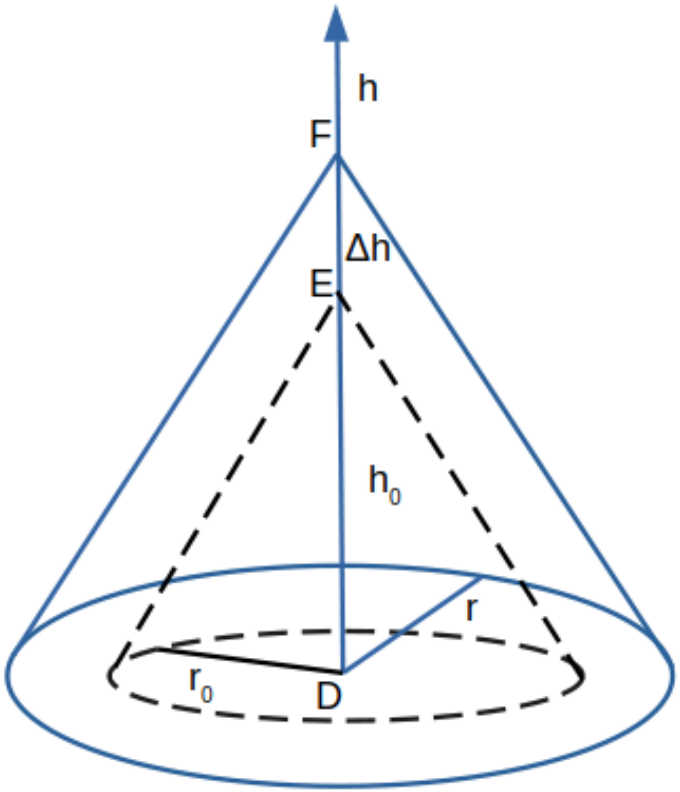




- Multiple muons have the opposite variation
  - MINOS ND (100m)
  - MINOS FD at high multiplicity (714m)
  - NOvA ND (100m)
  - NOvA FD at super-high multiplicity on the surface
- What is going on with these winter high rates?

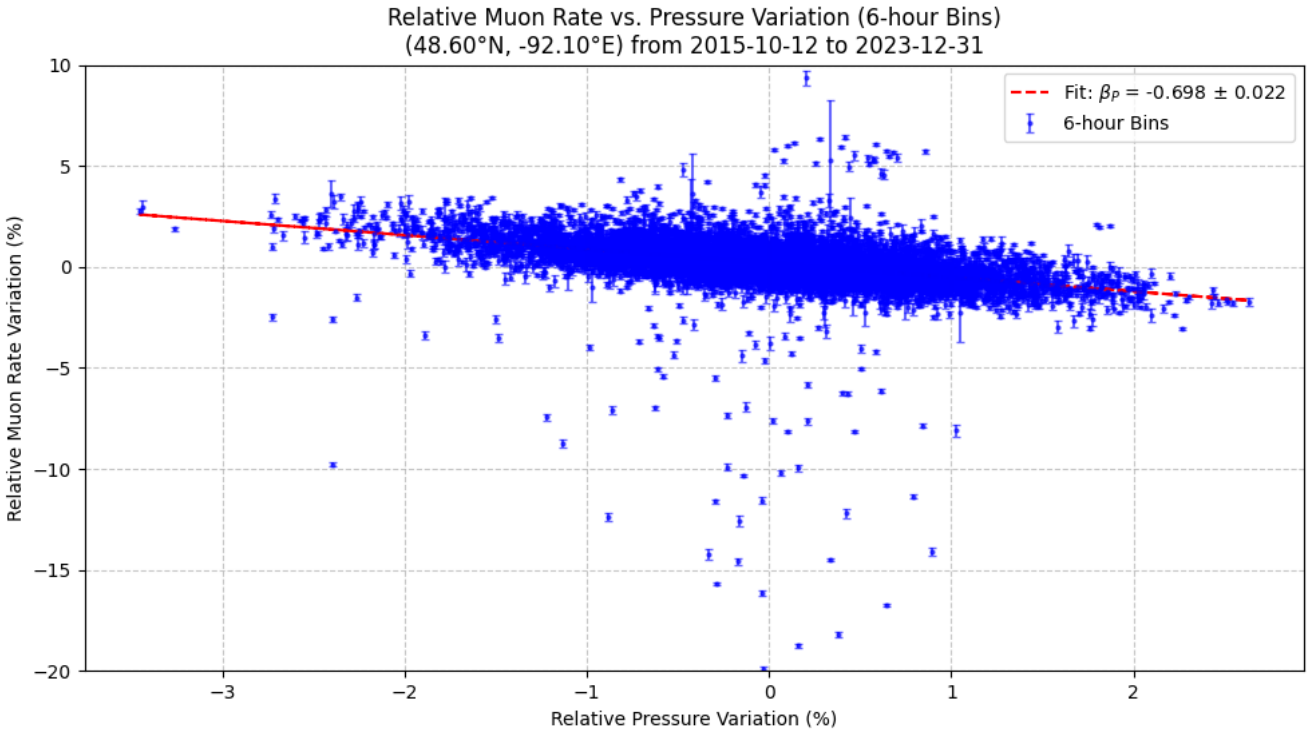
Geometry Selection Effect

- Finally nailed this down: it's related to the multiple muon decoherence seen in MACRO
  - Multi-mus made higher above ground gives muons more of a chance to miss the detector, and thus the shower is counted as a lower multiplicity (or even as a single muon)
- Qualitatively explains all the multi-mu issues

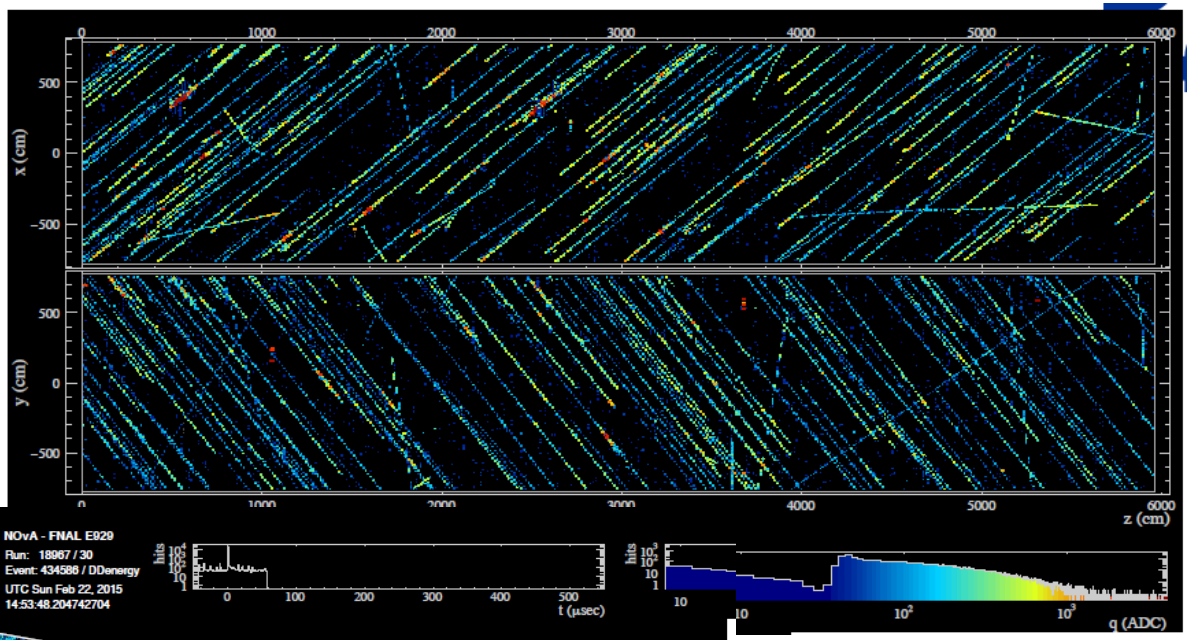


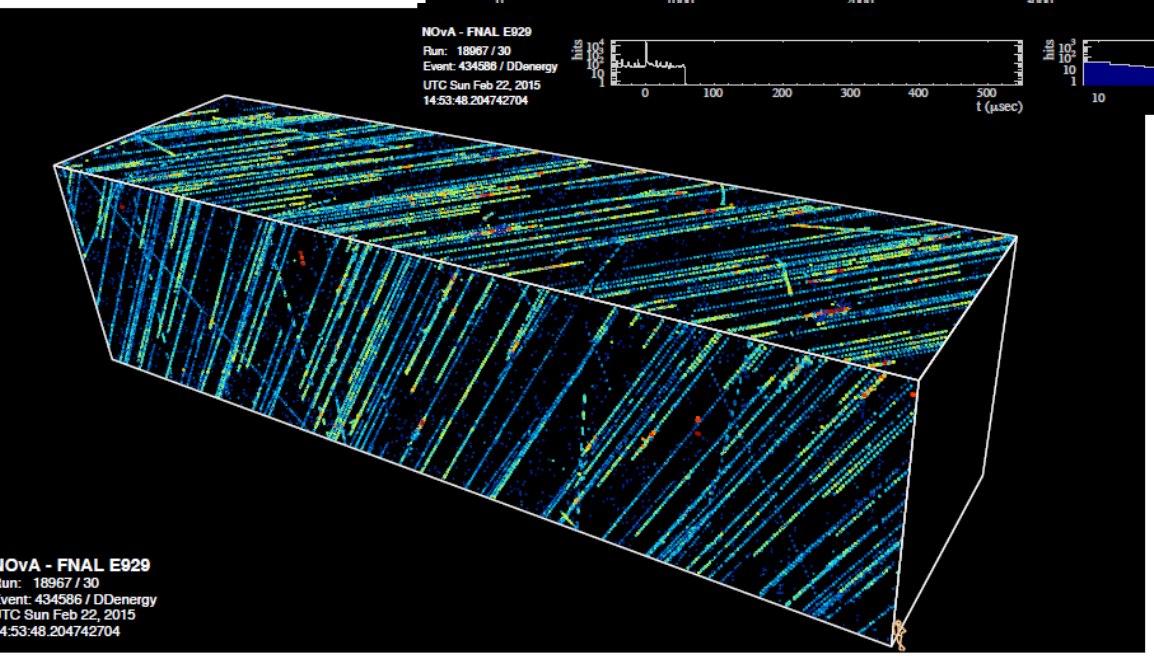
Also the β term

- In surface detectors, low-energy μ can decay
- Higher atmospheric pressure, muons made higher, more decay, you see fewer
- The NOvA FD shows this correlation



Speaking of multi-mus…

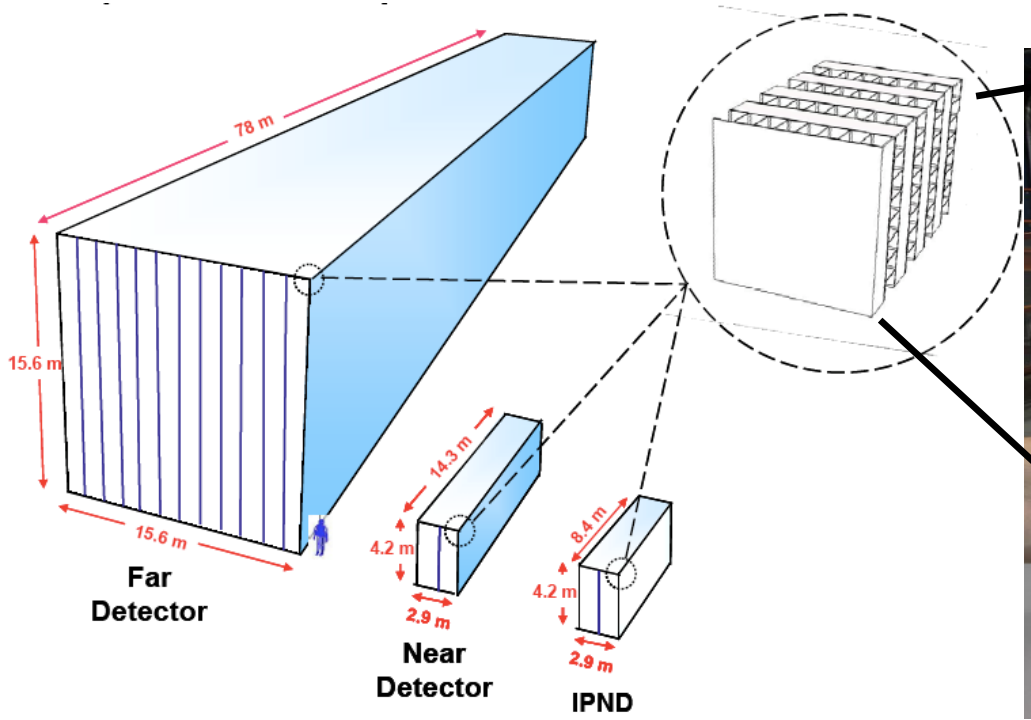


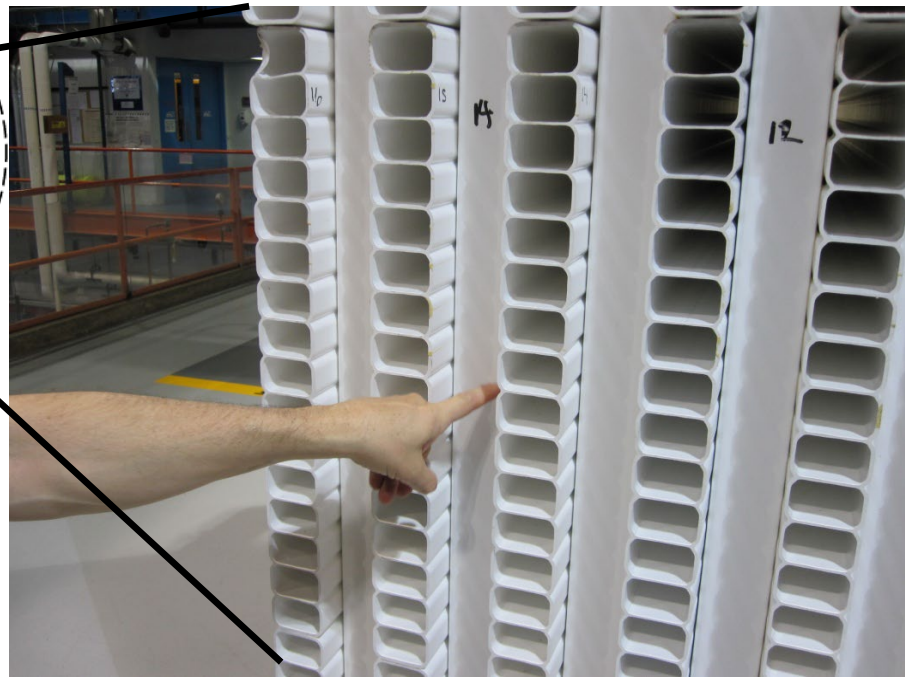


- NOvA sees a lot of whoppers! Trying to dig out some physics

Monopoles?

- NOvA is 60x15x15m, comparable size to MACRO
  - Scintillator timing, O(cm) spatial resolution
  - Could see monopoles!
- But is on the surface, ~10kHz cosmic rate





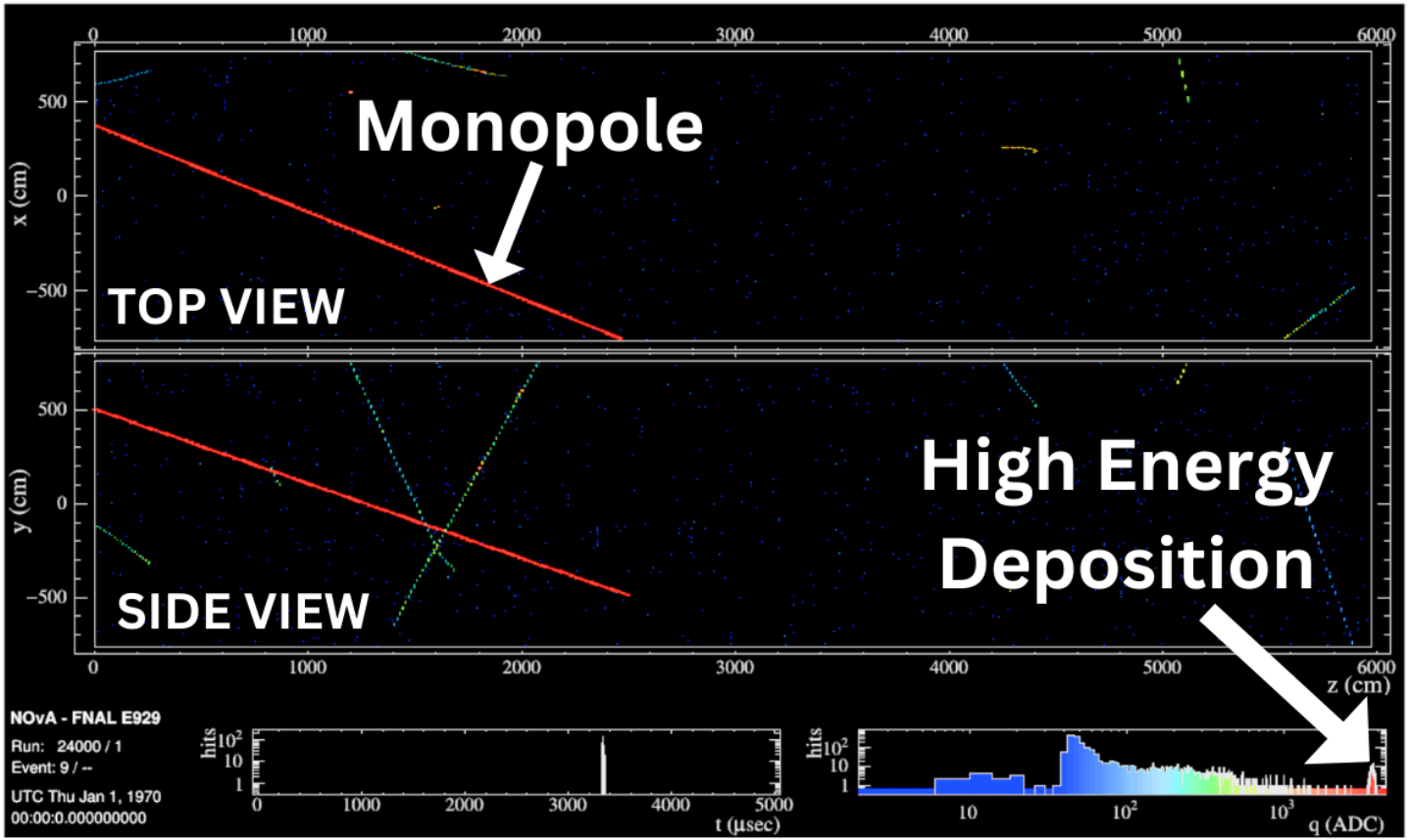
Slow vs Fast

- For the same reasons as MACRO:
  - "Fast" software trigger, looks for tracks with high energy loss
  - "Slow" software trigger, looks for tracks with slow speed (only down to $\beta > 5 \times 10^{-4}$)
- Triggers reduce data rate to ~10Hz each, and have been running for more than a decade
- Bonus – being on the surface means a low-mass monopole can make it through the air to NOvA, but not through the mountain to MACRO
  - So, NOvA would be sensitive to wimpier monopoles

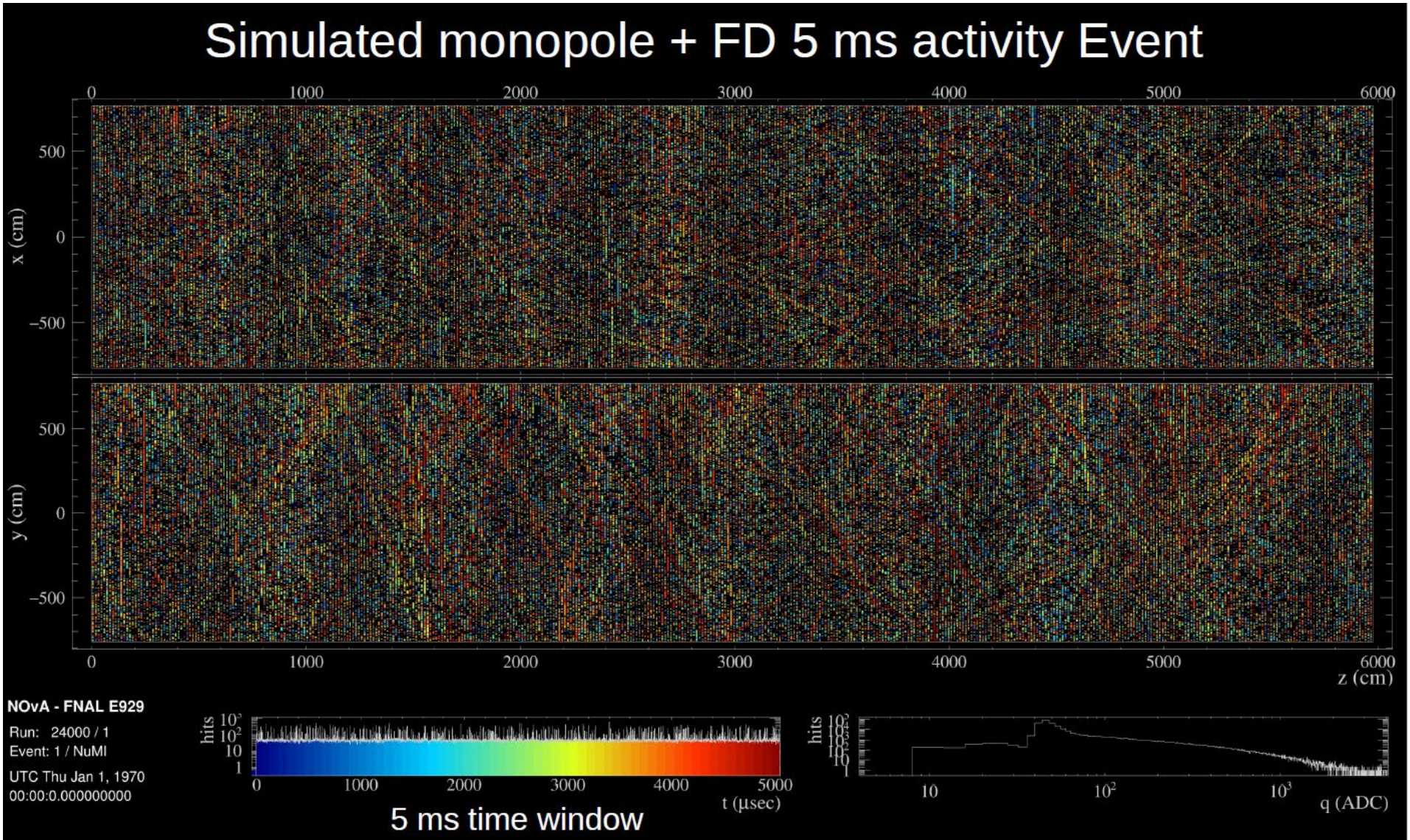
Fast Monopoles

- Look for high ADC tracks, slower than a muon, consistent dE/dx along track (to eliminate brehming muons)

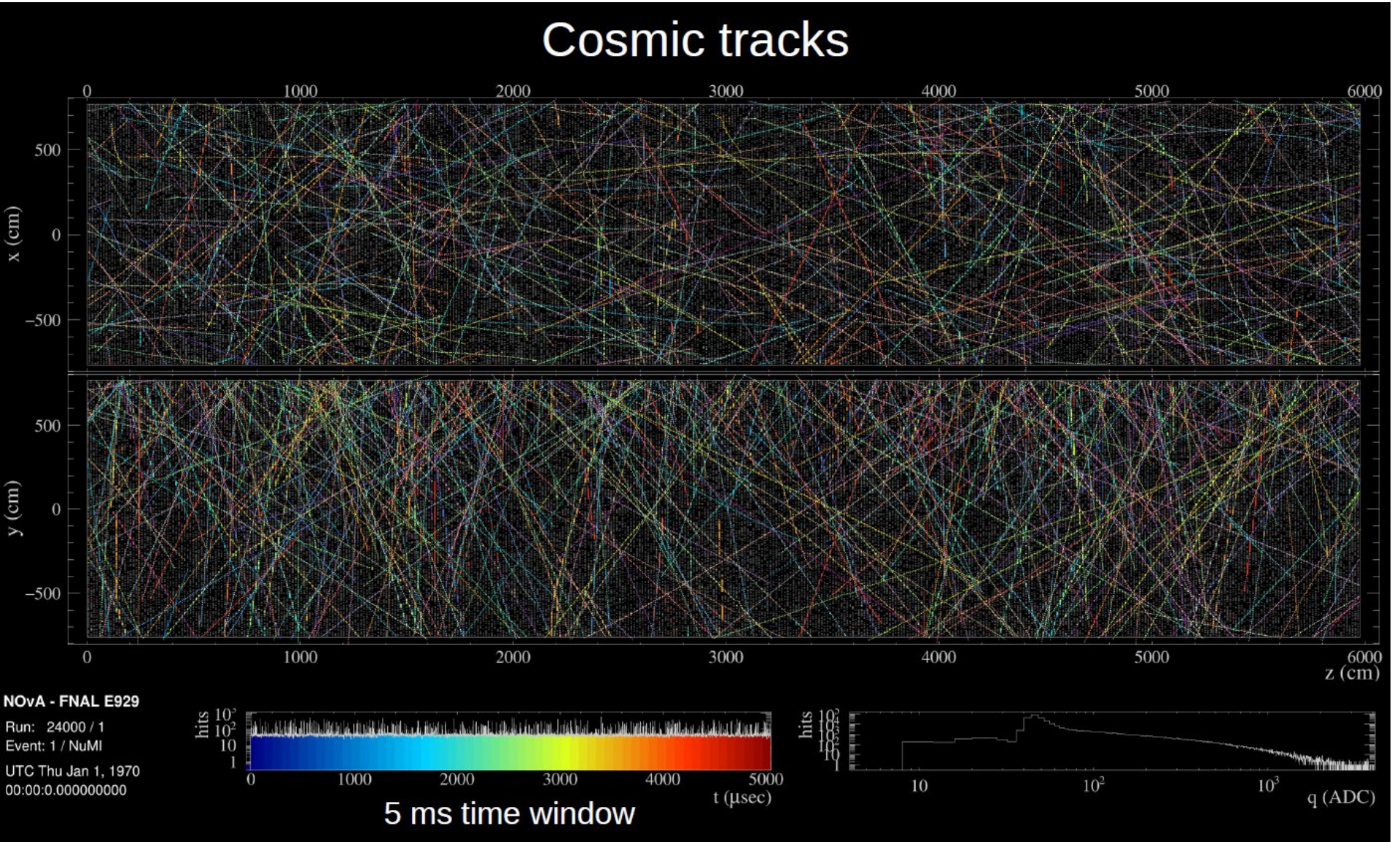
simulation



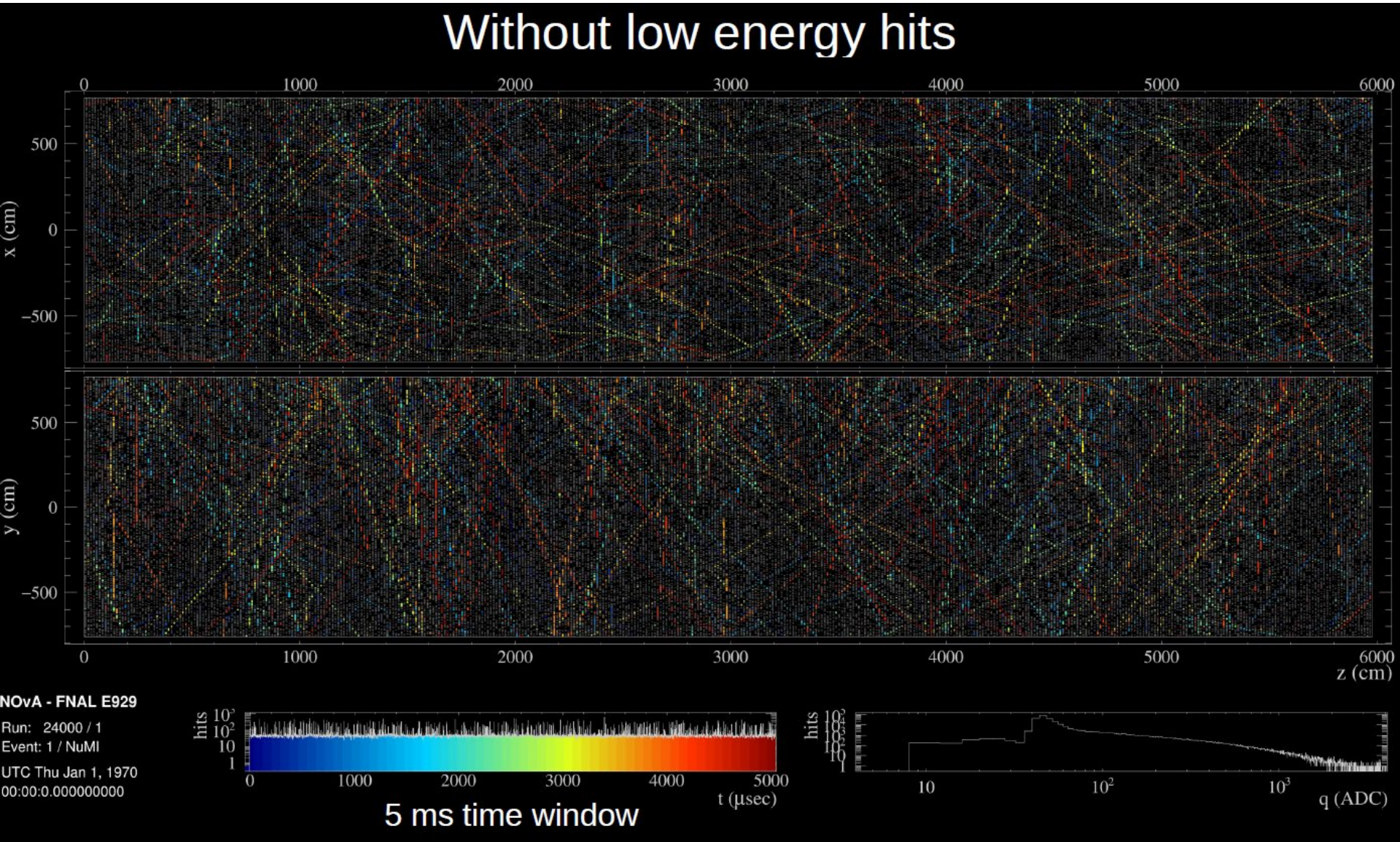
Slow Monopoles



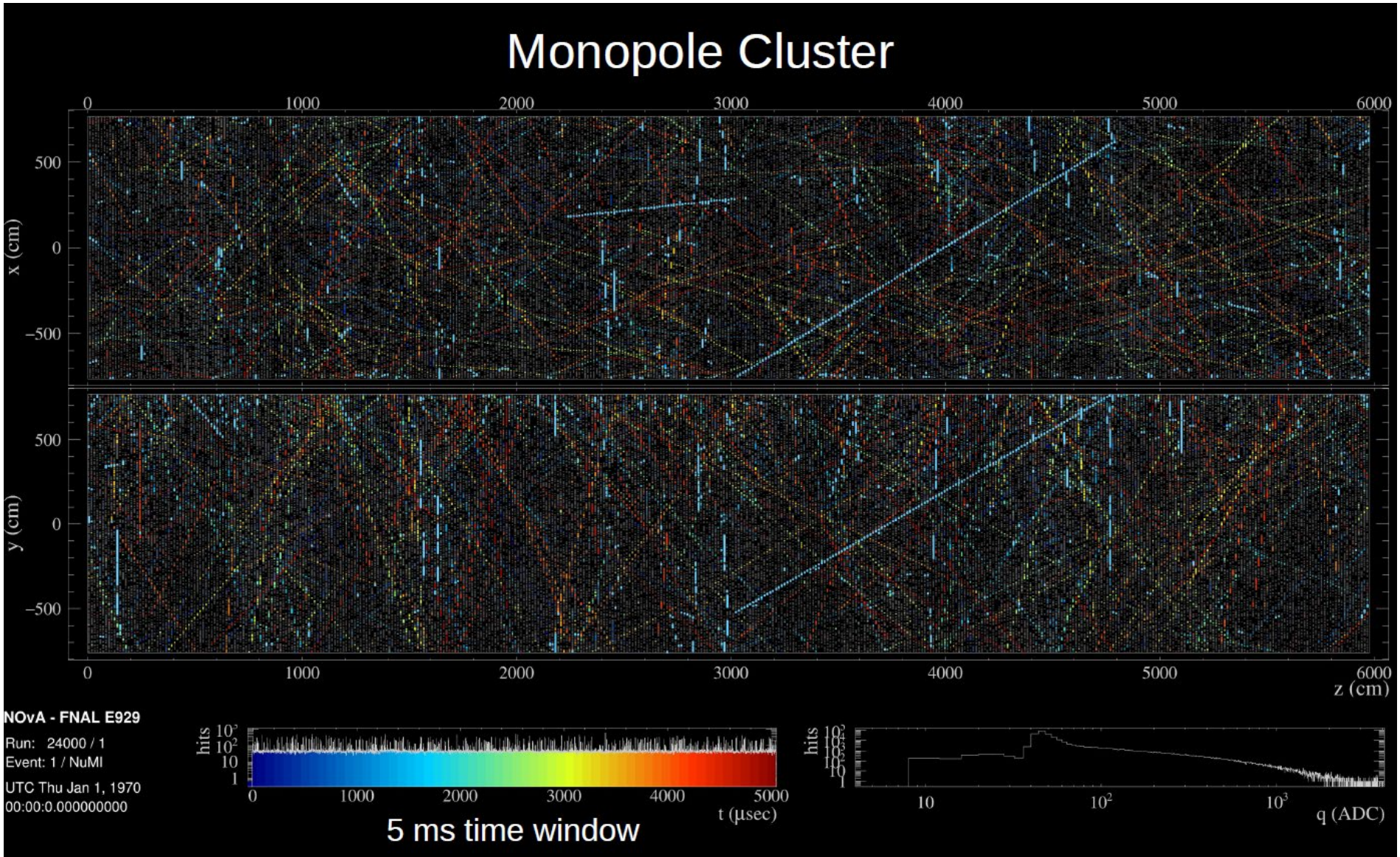
Slow Monopoles



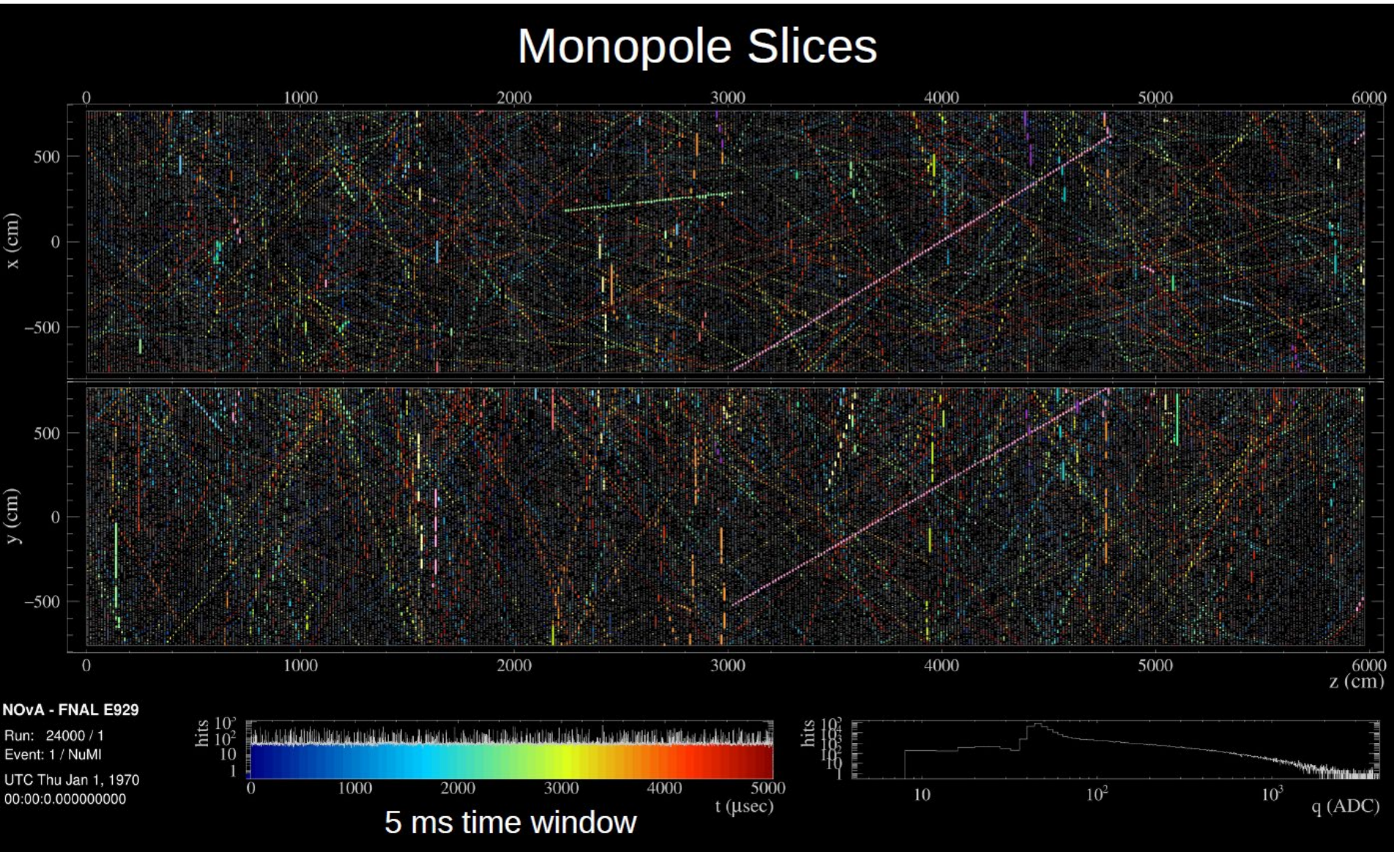
Slow Monopoles



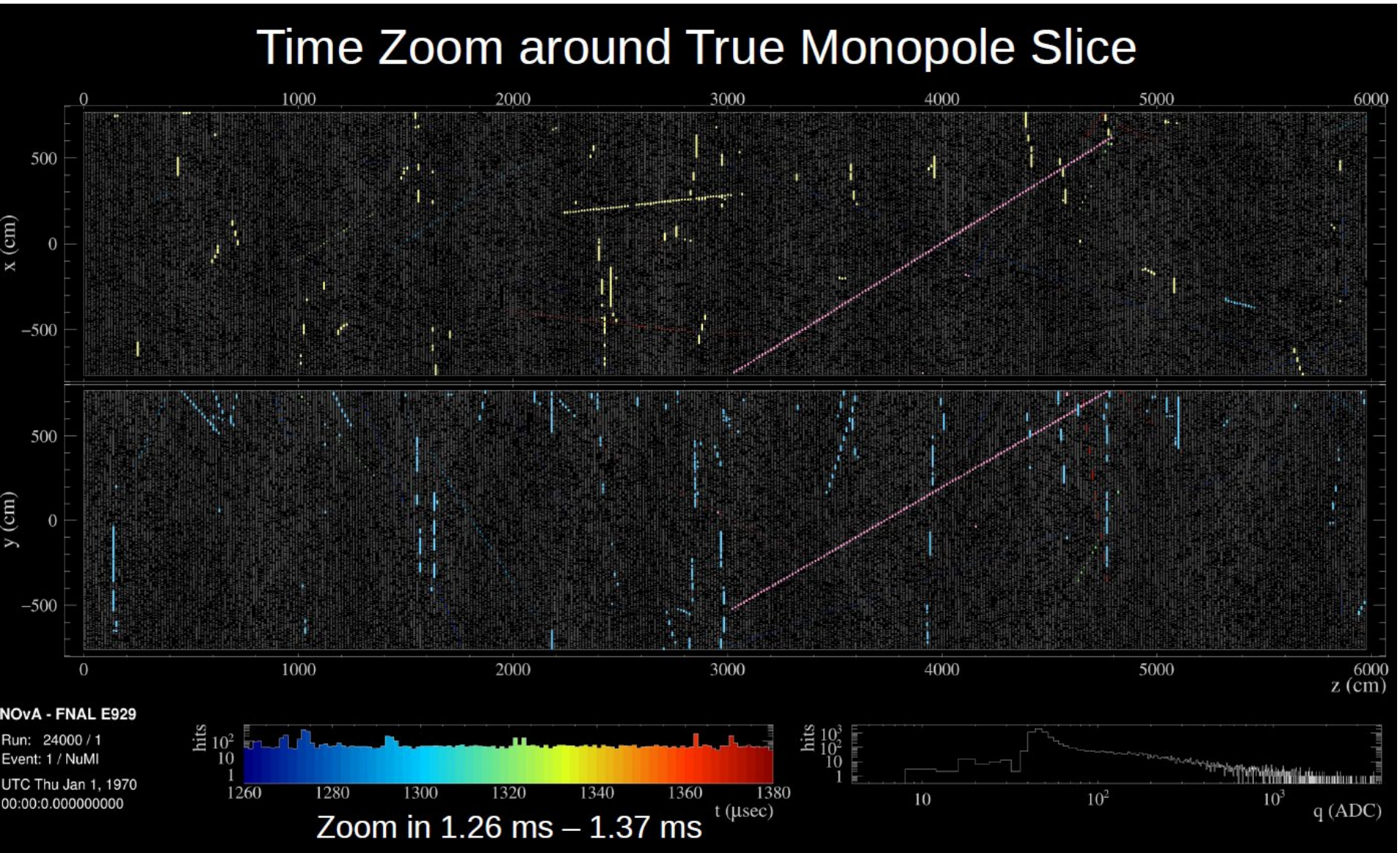
Slow Monopoles



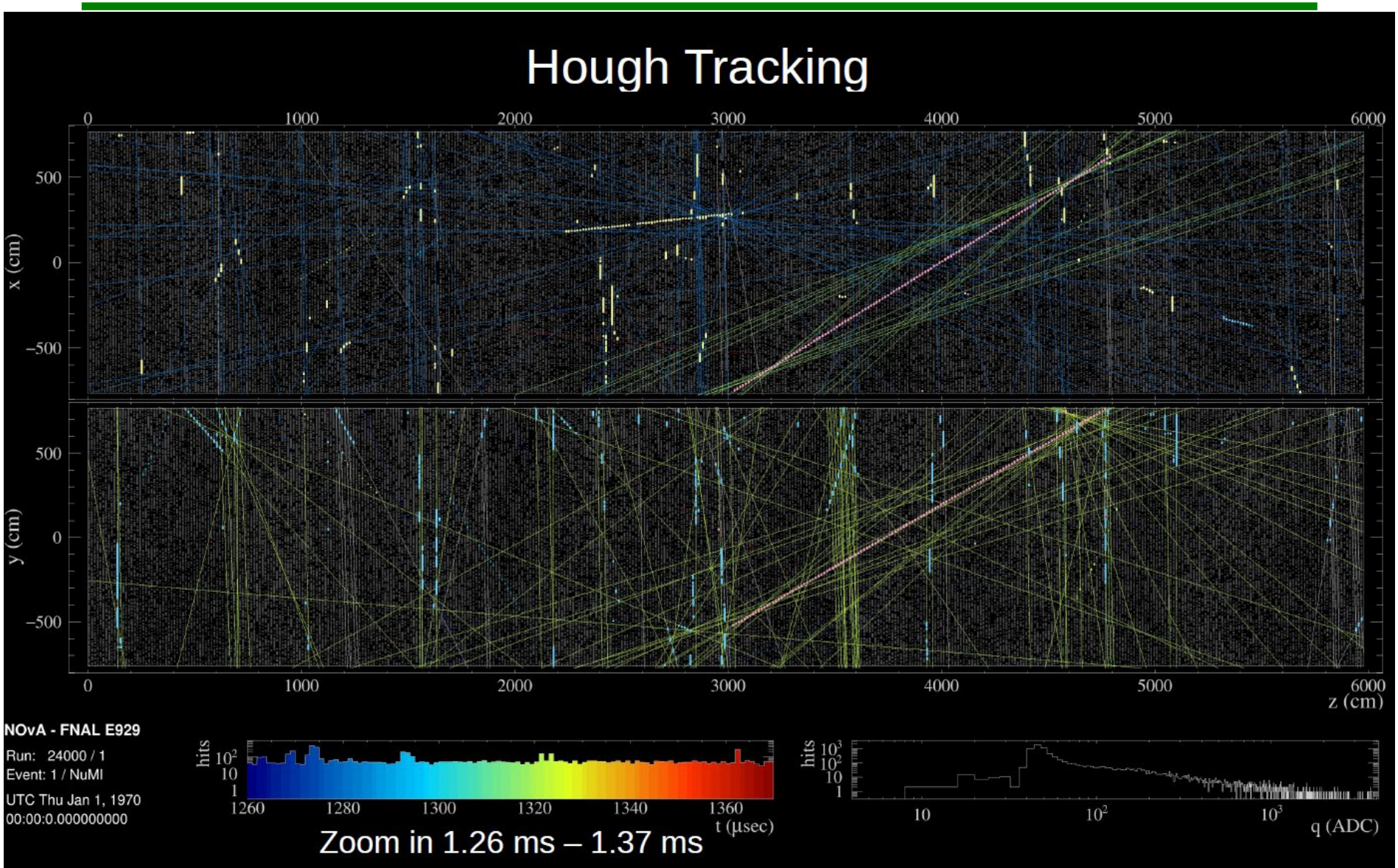
Slow Monopoles



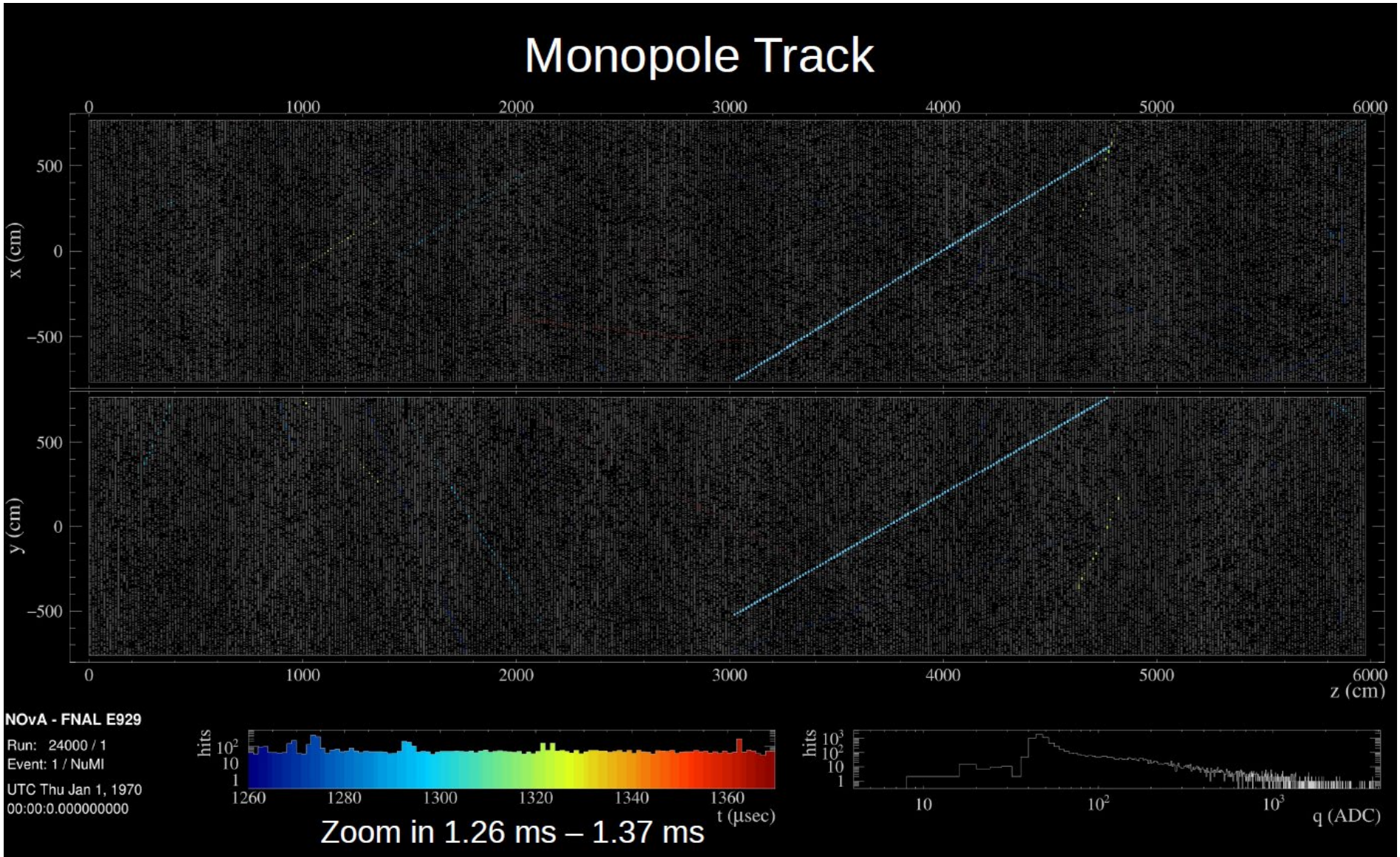
Slow Monopoles



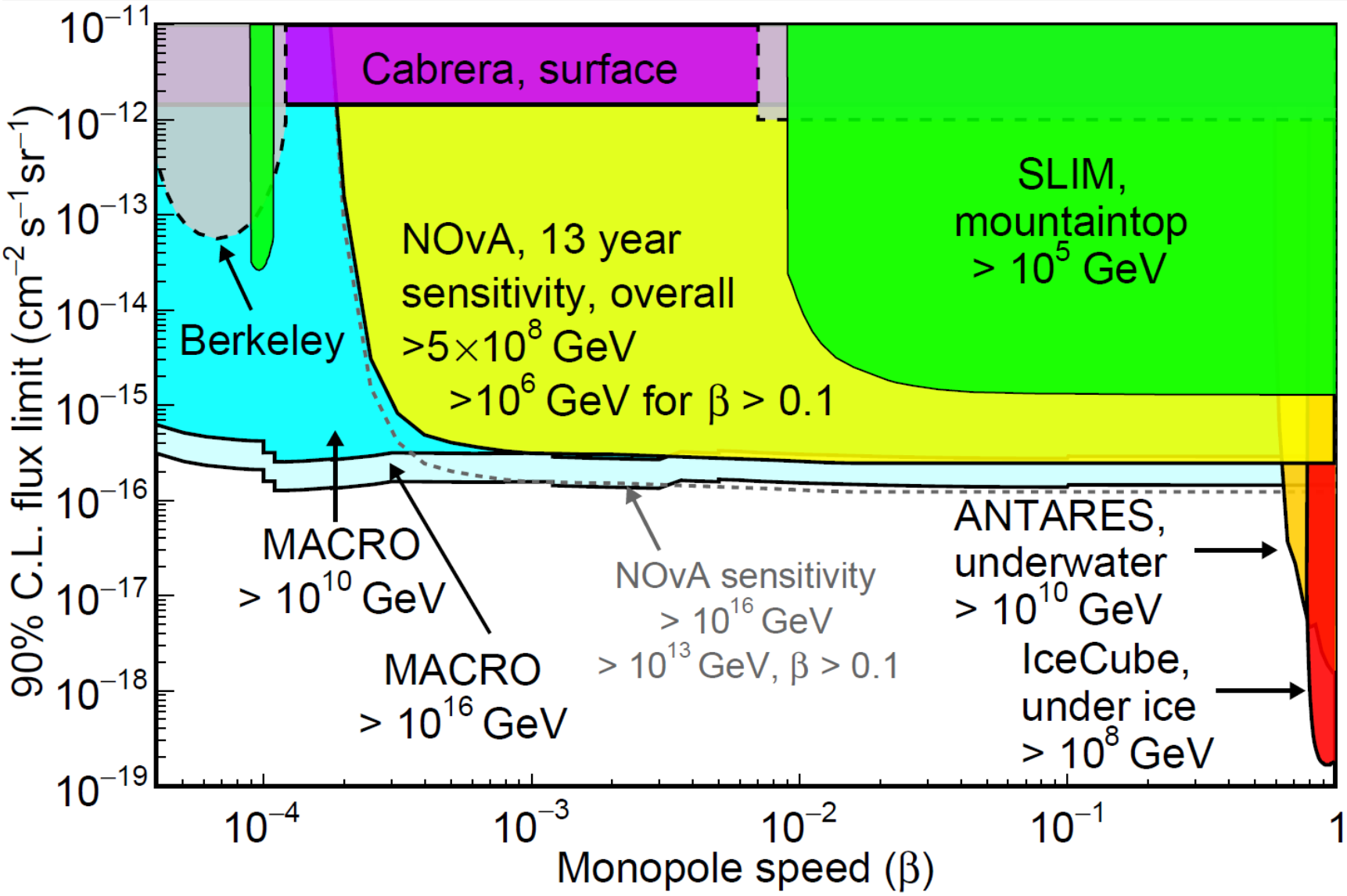
Slow Monopoles



Slow Monopoles



Sensitivity



Monopole Status

- There's a lot in there in terms of metrics and cuts and sidebands etc for both analyses
  - Details omitted for this talk
- Of course, NOvA doesn't have three different ways to see a monopole
  - If we saw one in MACRO, no question as to what it would be!
- Box has been opened
  - stay tuned for the students doing the work to present stuff and publish papers
  - For all the details, invite them to give a seminar!

Summary

- MACRO analyses have continued with newer detectors, despite their intended purpose as long-baseline neutrino experiments
  - Cosmic Ray Shadows
  - Seasonal variations probing atmospheric effects
  - Magnetic monopole searches
- Many of my students learn about MACRO as they start their work
  - Have found a couple errors in my thesis, actually