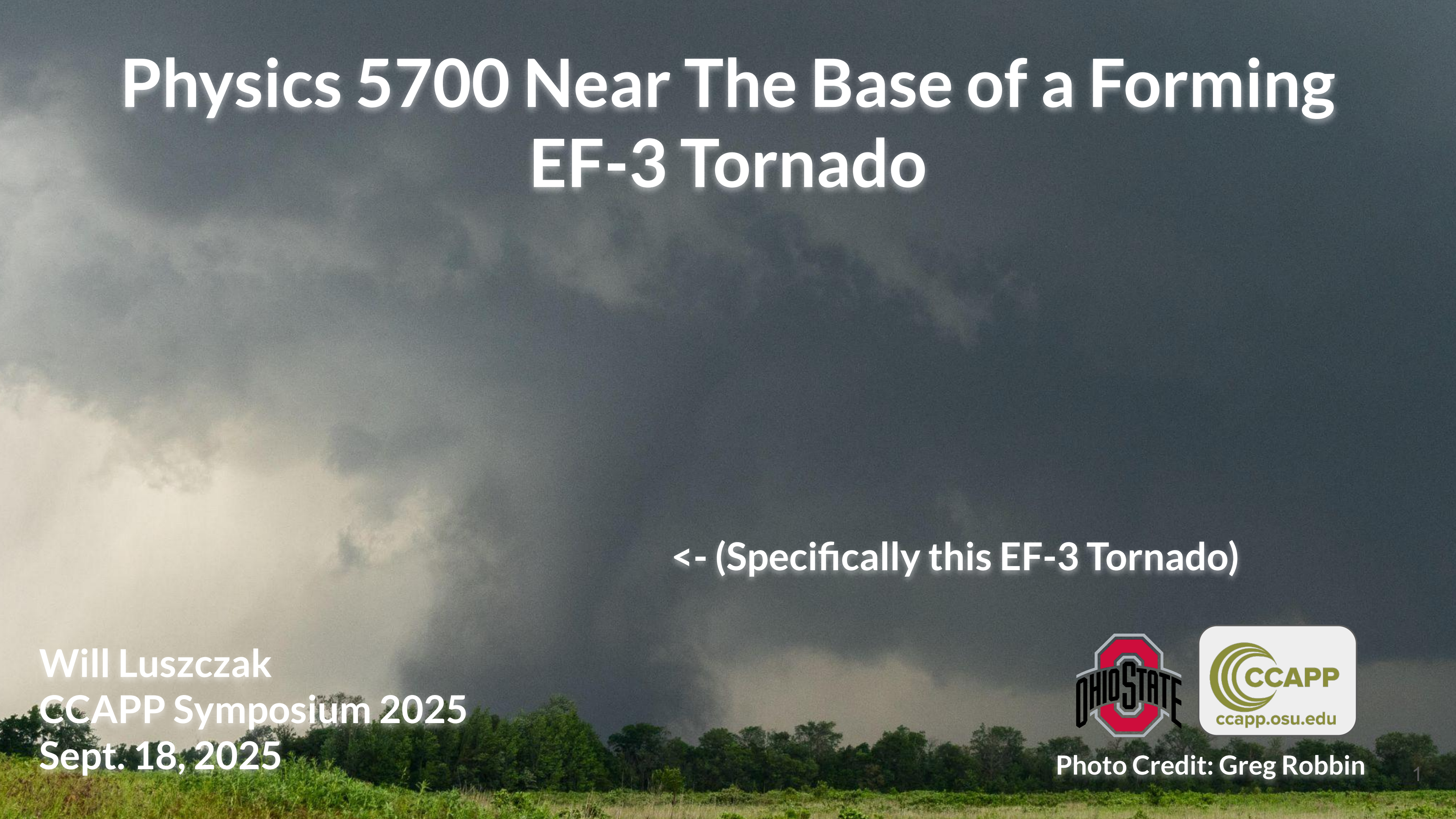
Physics 5700 Near The Base of a Forming EF-3 Tornado



<- (Specifically this EF-3 Tornado)

Will Luszczak
CCAPP Symposium 2025
Sept. 18, 2025

ccapp.osu.edu

Photo Credit: Greg Robbin

Questions You May Have

- What?!

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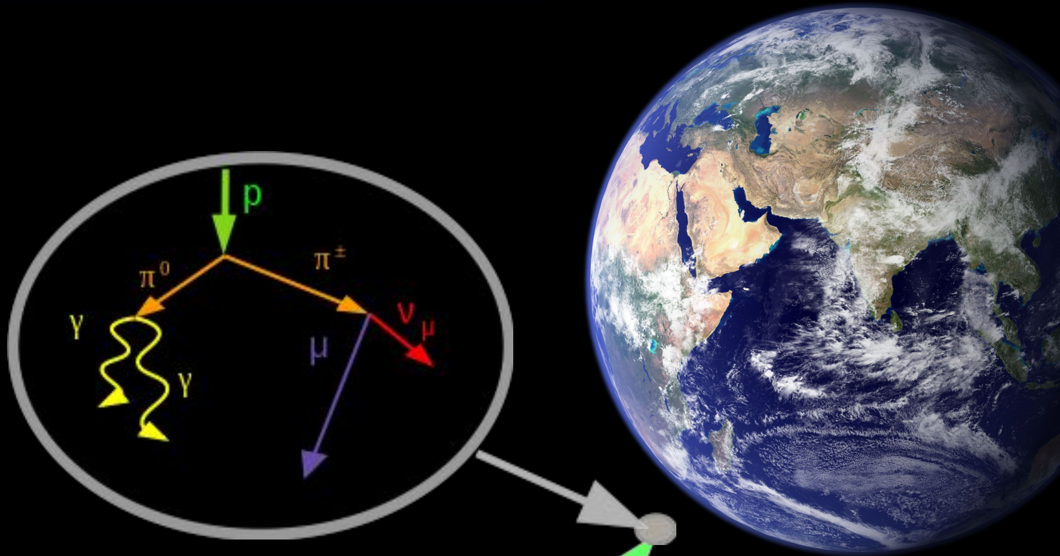
- What?!
- Why?!

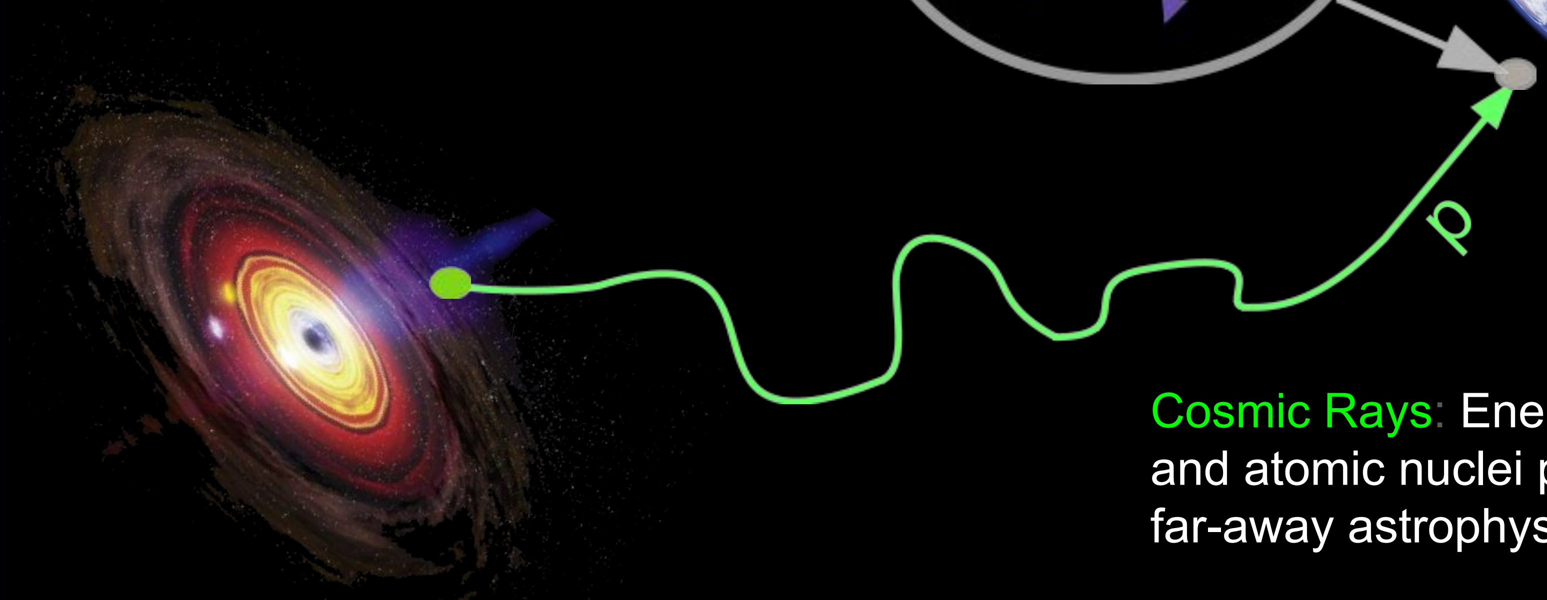
Questions You May Have

- What?!
- Why?!
- How?

What: Cosmic Rays

Atmospheric Muons: Particles produced when primary cosmic rays interact in the atmosphere



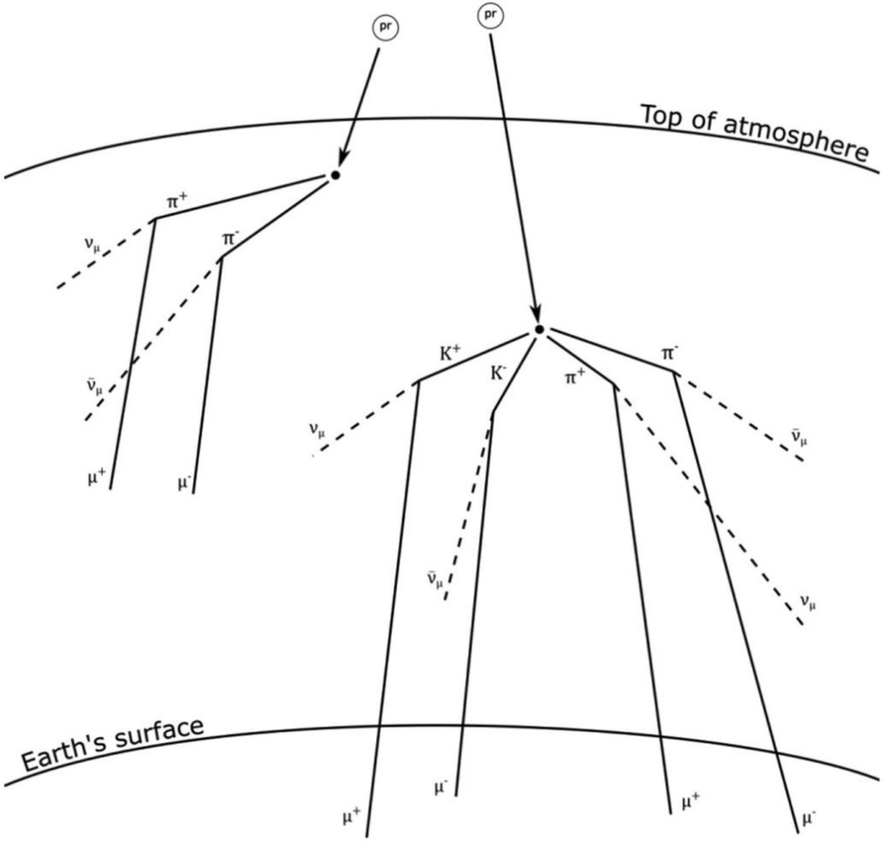


Cosmic Rays: Energetic protons and atomic nuclei produced in far-away astrophysical sources

Atmospheric Muon Production

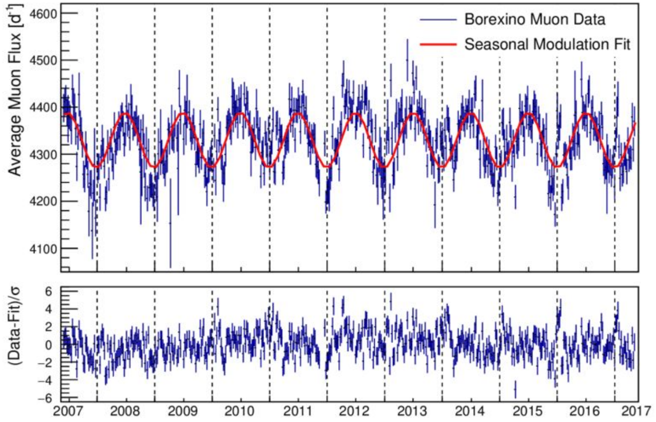
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$

$$K^+ \rightarrow \mu^+ + \nu_\mu$$
$$K^- \rightarrow \mu^- + \bar{\nu}_\mu$$



Atmospheric Muons and Air Density

https://doi.org/10.48550/arXiv.1808.04207



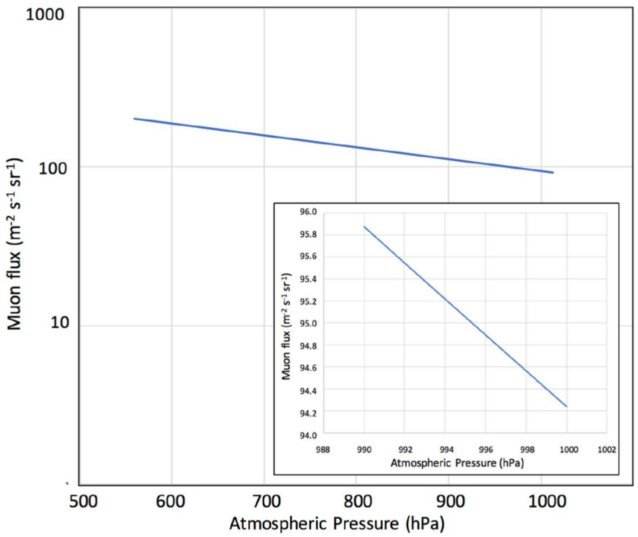
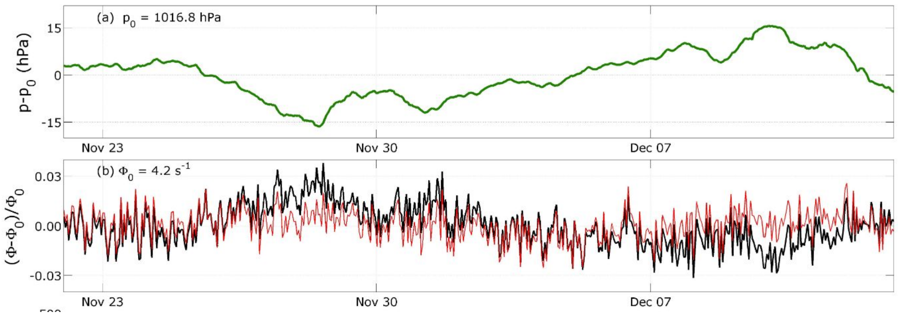


Figure 1. Vertical muon flux (N) versus atmospheric pressure (ρ). Inset illustrates the atmospheric pressure within the range between 990 and 1000 hPa.

https://doi.org/10.1038/s41598-022-20039-4

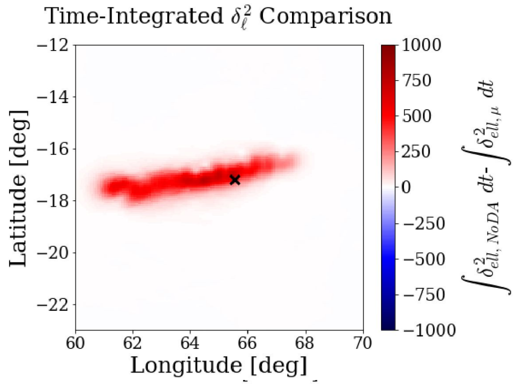


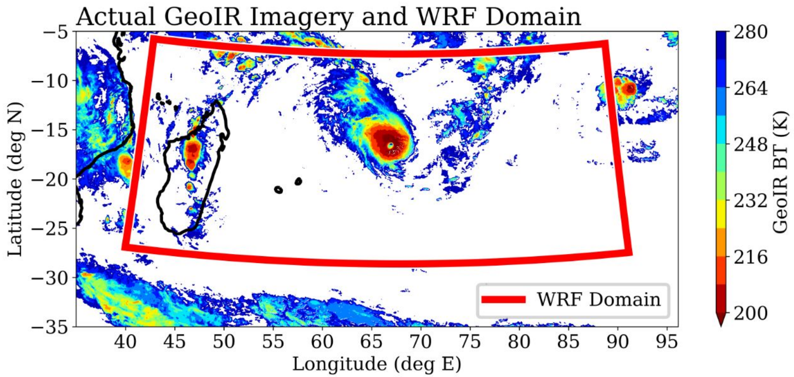
https://arxiv.org/abs/1504.02230

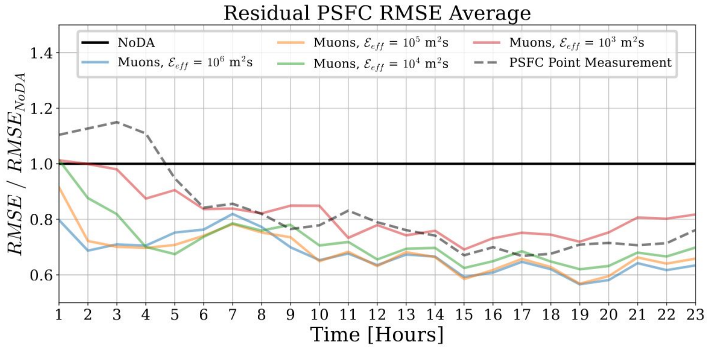
Why: Atmospheric Muons as a Meteorological Tool

Atmospheric muon flux measurements can act as a remote probe of the atmospheric density field.

This can be used to improve weather forecasts.







W. Luszczak, M.Y. Chan https://arxiv.org/abs/2509.04627, Submitted to PRD

Tornado Crash Course

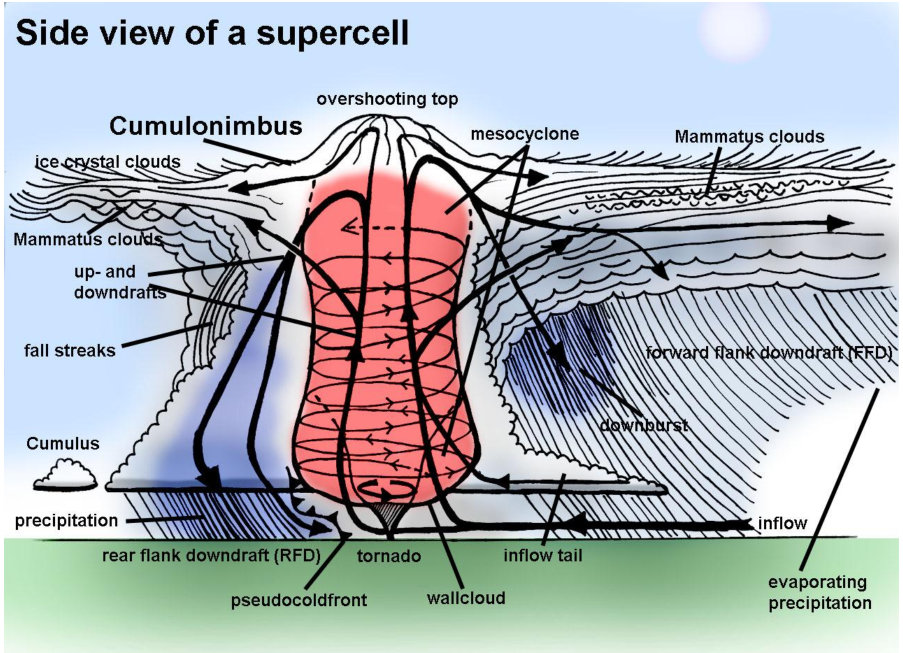
Tornadoes are violently rotating columns of air connecting cumuliform clouds and the ground.

Signature may or may not be apparent from radar information alone, sometimes eyewitnesses are needed to confirm

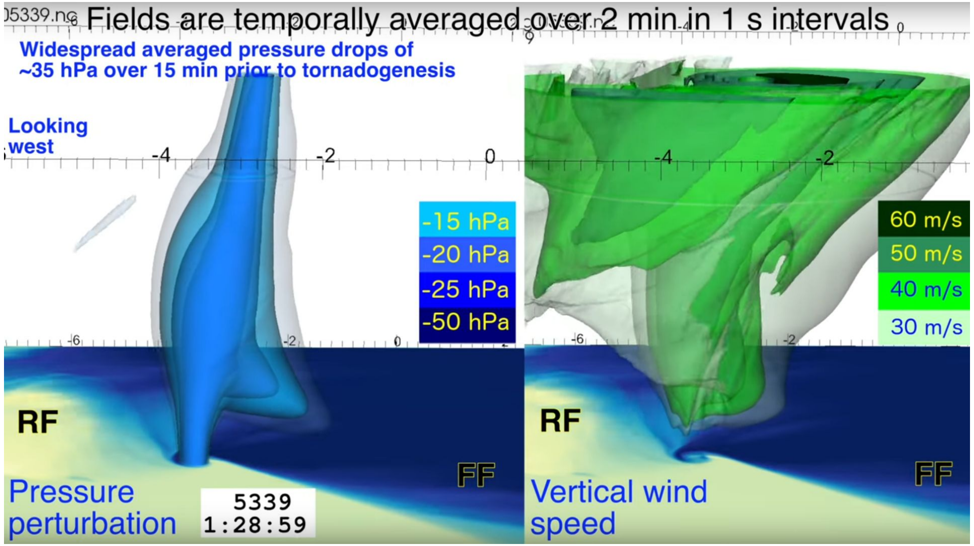
Classification (EF-0 through EF-5) relies on using damage surveys to estimate wind speed

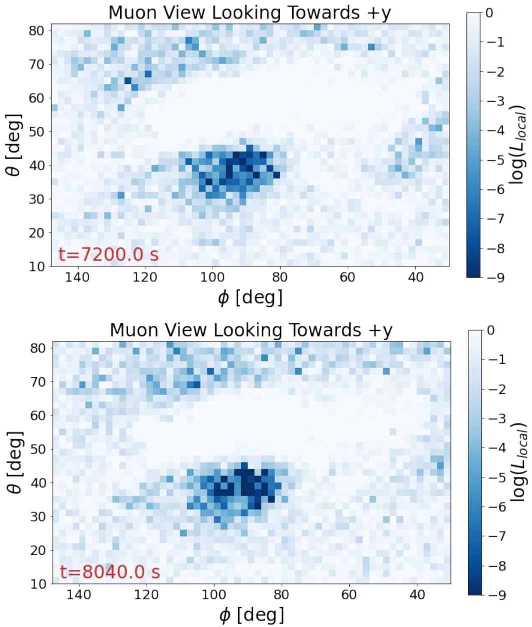
Formation process not entirely understood:

- Form within mesocyclones (large rotating updrafts within severe thunderstorms)
- Observations are difficult, storms can be unpredictable and in-situ instrumentation can be tricky to deploy
- Why do some storms form tornadoes, but others don't?



Simulated Muographic Measurements of Severe Storms



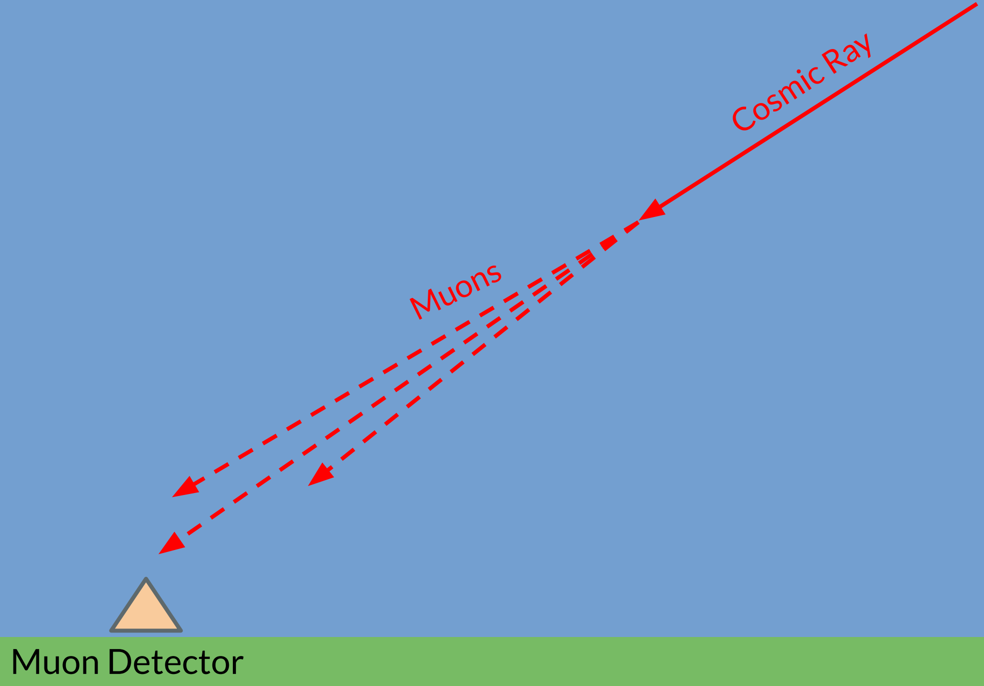


Talk by Leigh Orf:
https://www.youtube.com/watch?v=fXPCpEkjejo&t=143s

W. Luszczak, L. Orf
https://doi.org/10.1103/PhysRevD.111.023018

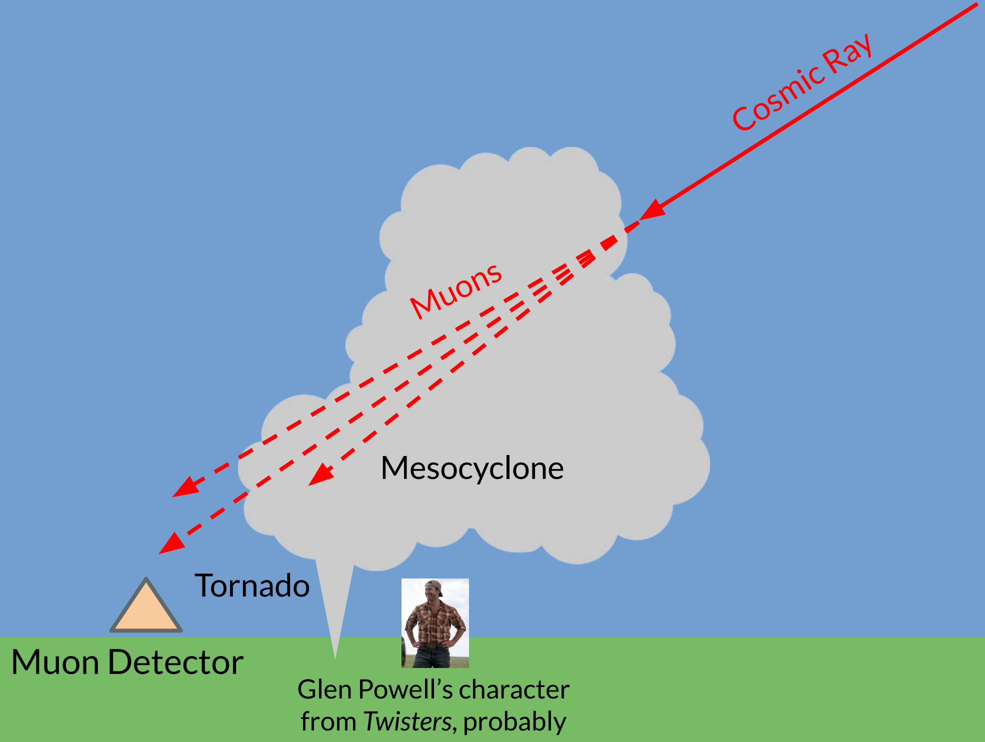
Muons as Atmospheric Pressure (Density) Sensors

$$\Phi \,[Hz] = \Phi_0 \,[Hz]$$

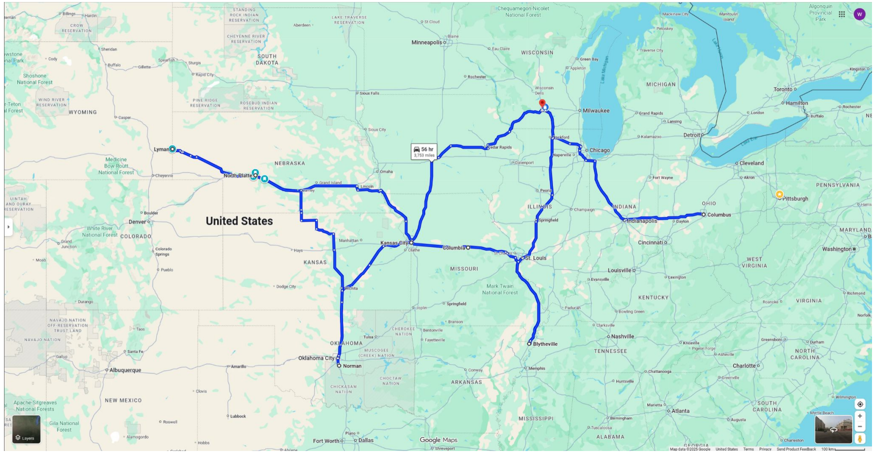


Muons as Atmospheric Pressure (Density) Sensors

$$\Phi \text{ [Hz]} = \Phi_0 \text{ [Hz]} \times R$$



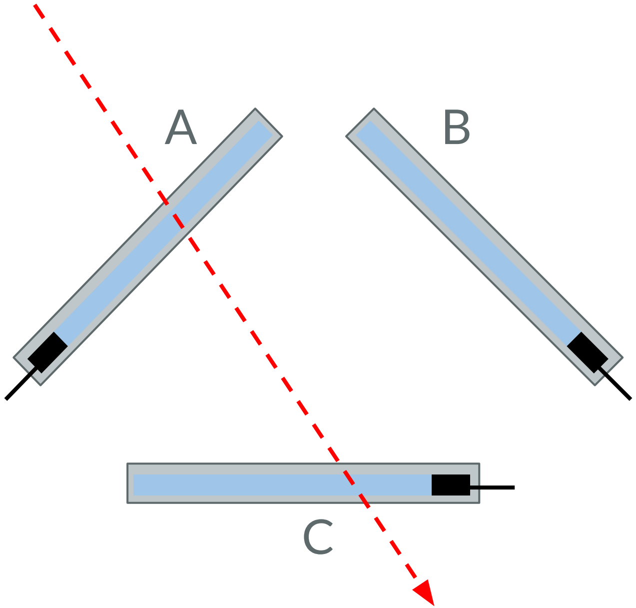
How: OSU Was Actually Willing to Fund This



Special thanks to my collaborators: Jana Houser (OSU) and Matt Kauer (UW)!

And also the students of ATMOSSC 5701 for letting me use photos they took during deployment

The Detector



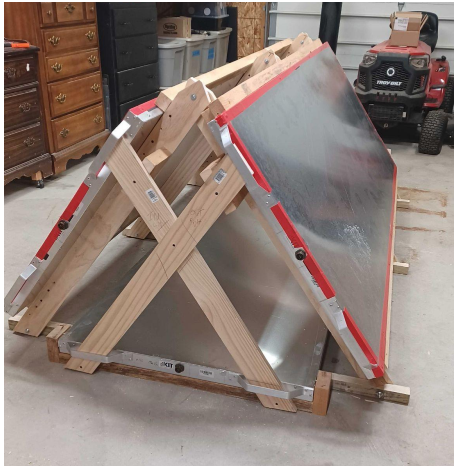
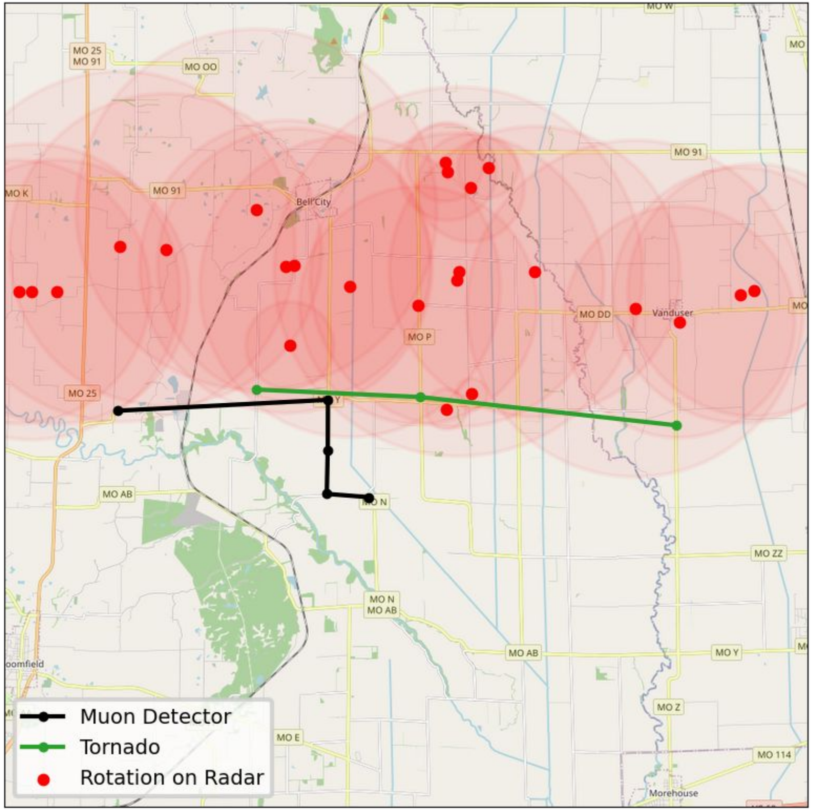


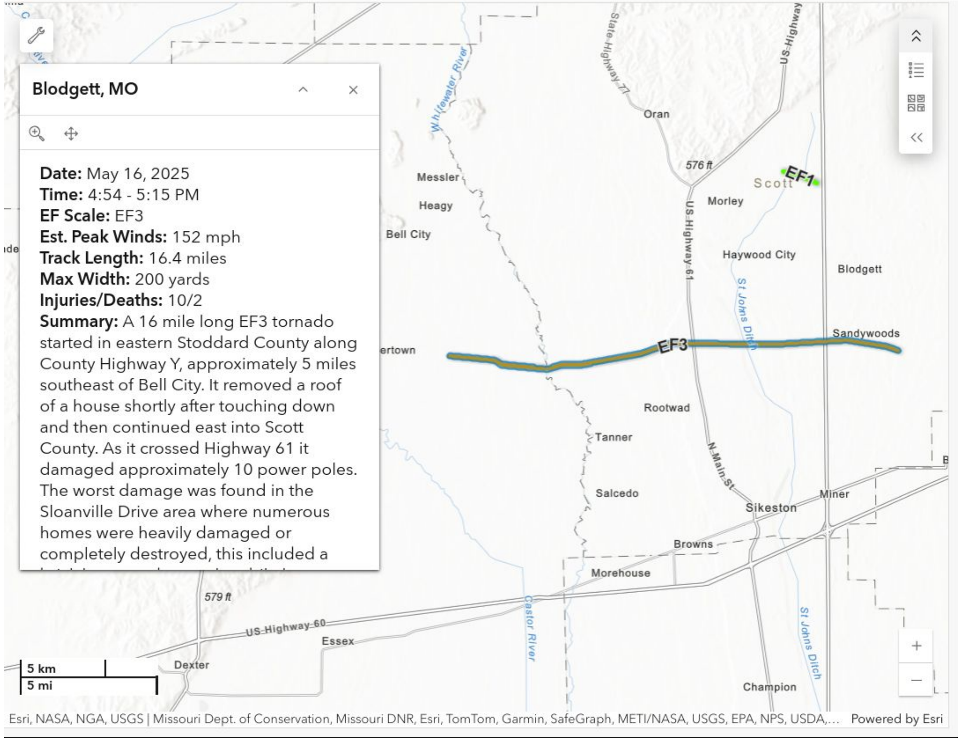

Photo credit: Ashlee Ziegler


Photo credit: Greg Robbin

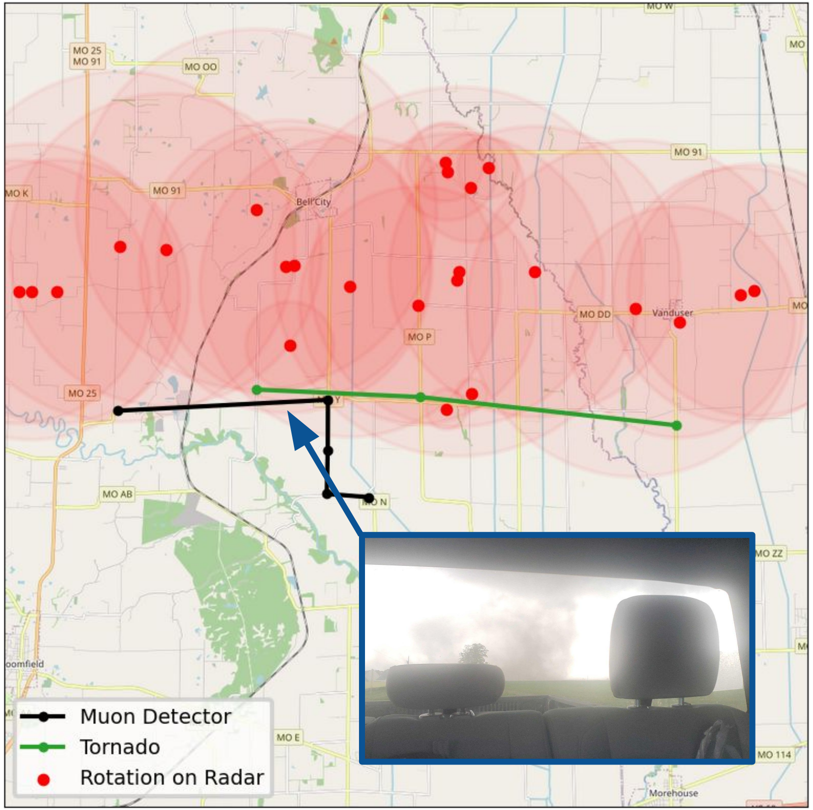

Photo credit: Aiden Ridgway

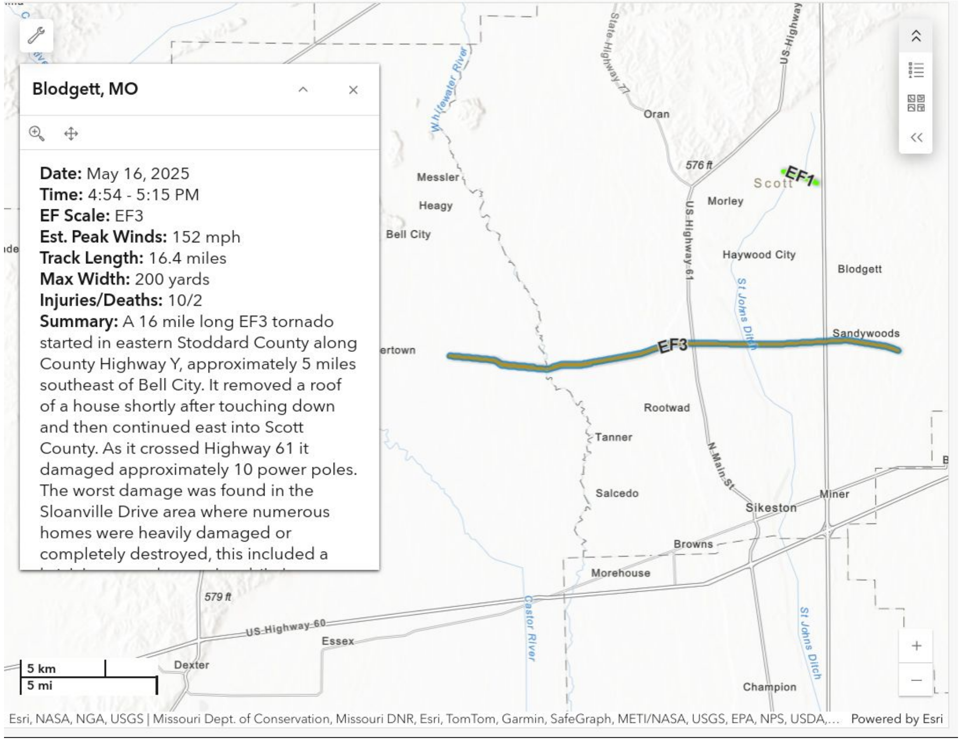
Blodgett, MO EF-3





Blodgett, MO EF-3



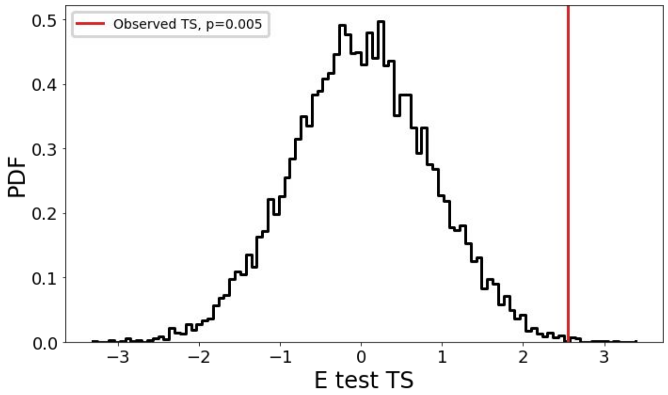


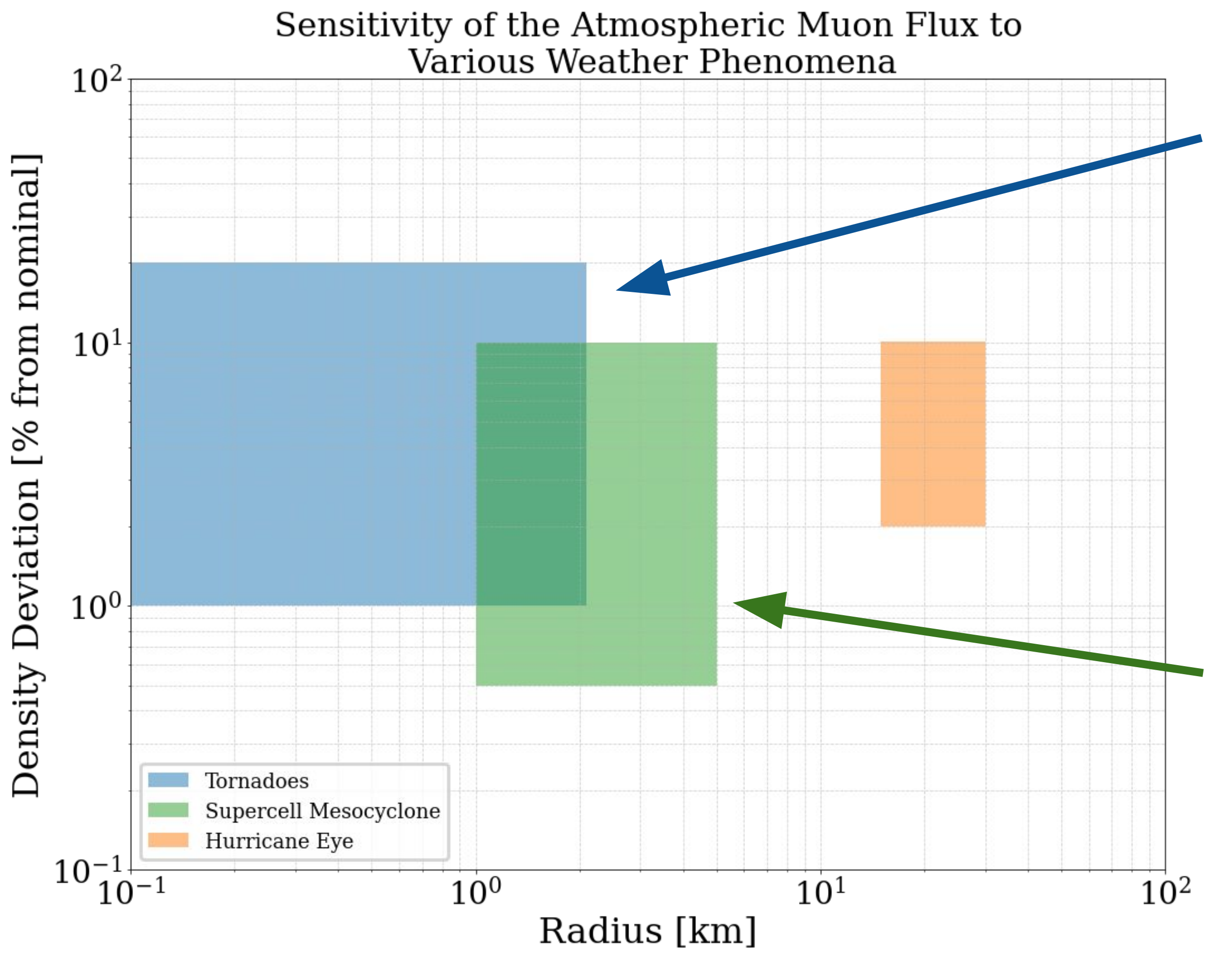
Results

Time Window	Location (lon/lat)	Weather	Average Muon Rate	E Test p-value
5:34-6:11	(36.921, -89.314)	Clear (control measurement)	182.17 +/- 0.30 Hz	-
3:47-3:59	(36.961, -89.891)	Tornado	183.66 +/- 0.51 Hz	0.005
4:52-5:11	(36.964, -89.152)	Distant Mesocyclone*	181.85 +/- 0.48 Hz	0.708

*Meso was suspected from radar data to be too distant to produce a measurable effect on the muon flux, but we checked anyway

-> 2.6σ muon flux excess observed for the time period corresponding to tornado observation



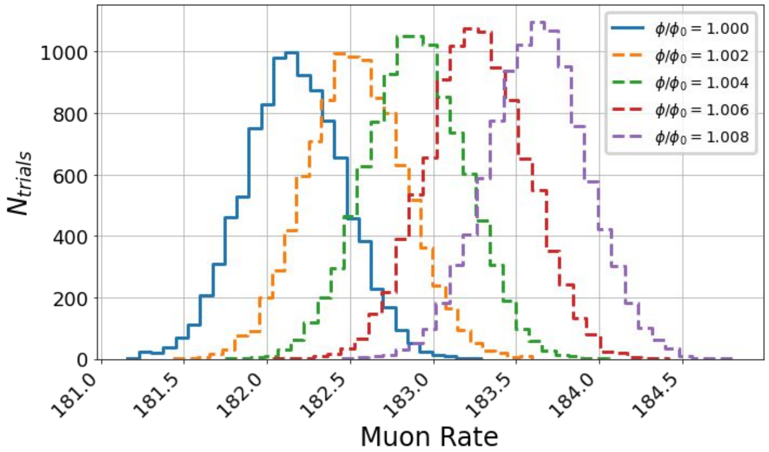


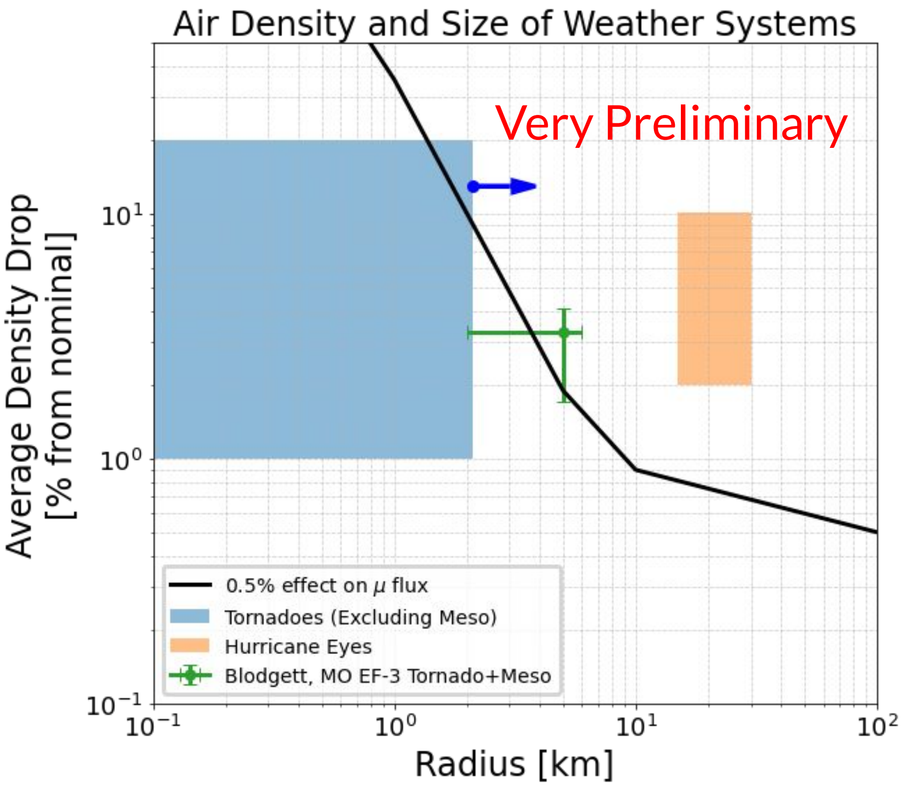
Very rough estimate:

- Lack of measurements
- Tornado boundary is poorly defined

Measurements of this are practically nonexistent

Density Field Fit





-> Use cosmic ray/atmospheric simulation to map muon excess to average density drop for a given storm radius

I Am Cautiously Optimistic?

First deployment of a mobile muon detector near tornadic storms

2.6σ muon flux excess observed when near a forming tornado

Lots of important lessons learned, hopefully applicable for a v2.0:

- Mobile data collection capabilities are crucial
- Tilt information is very important
- SiPMs are a pain to manage at high temperatures
- No trailers!!!


Photo credit: Jessica Zhang


Photo credit: Ashlee Ziegler


Photo credit: Virag Patel

Photo credit: Virag Patel

Thanks for listening!

Measuring Tornadoes Is Hard

Tornadoes are small and short lived

Signature may or may not be apparent from radar information alone, sometimes eyewitnesses are needed to confirm

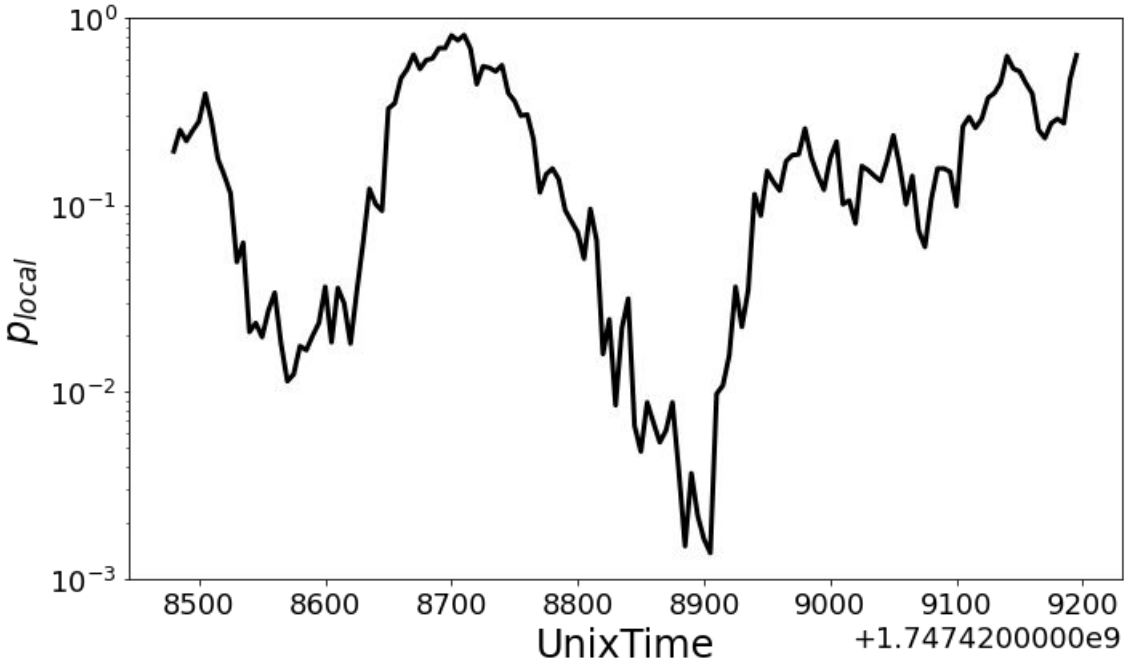
Classification relies on using damage surveys to estimate wind speed

Lots of current research depends on simulation-driven approaches

DOD	Damage description	EXP	LB	UB
1	Threshold of visible damage	65	53	80
2	Loss of roof covering material (<20%), gutters and/or awning; loss of vinyl or metal siding	79	63	97
3	Broken glass in doors and windows	96	79	114
4	Uplift of roof deck and loss of significant roof covering (>20%); collapse of chimney; garage doors collapse inward; failure of porch or carport	97	81	116
5	Entire house shifts off foundation	121	103	141
6	Large sections of roof structure removed; most walls remain standing	122	104	142
7	Exterior walls collapsed	132	113	153
8	Most walls collapsed, except small interior rooms	152	127	178
9	All walls	170	142	198
10	Destruction of engineered and/or well constructed residence; slab swept clean	200	165	220

The Enhanced Fujita Scale

I Am Cautiously Optimistic?



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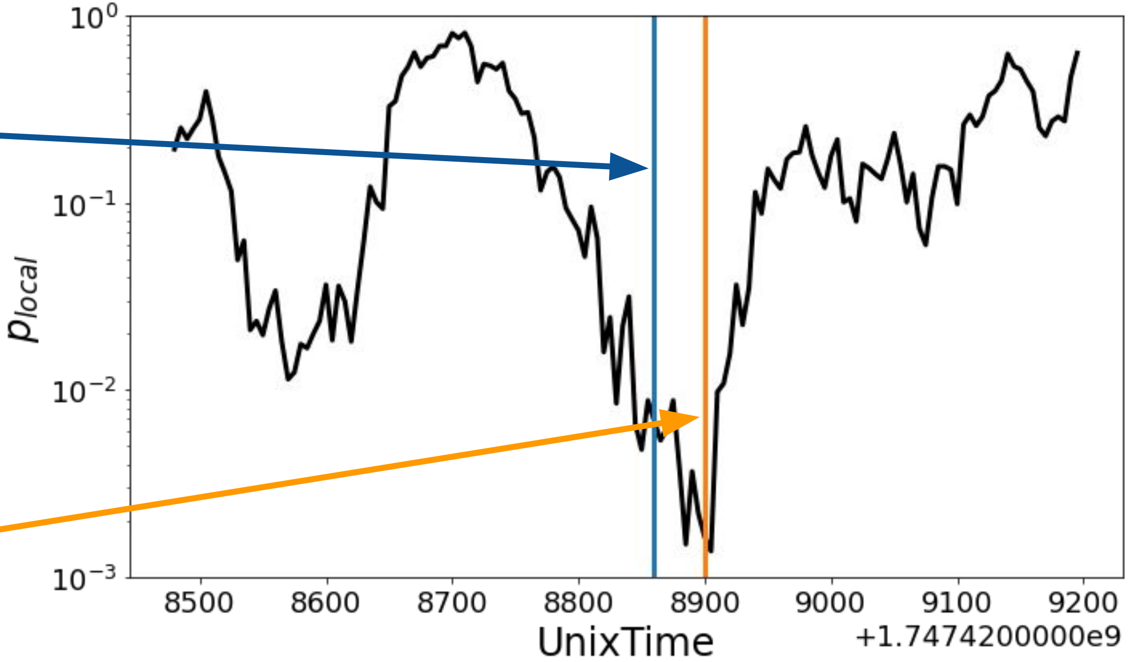
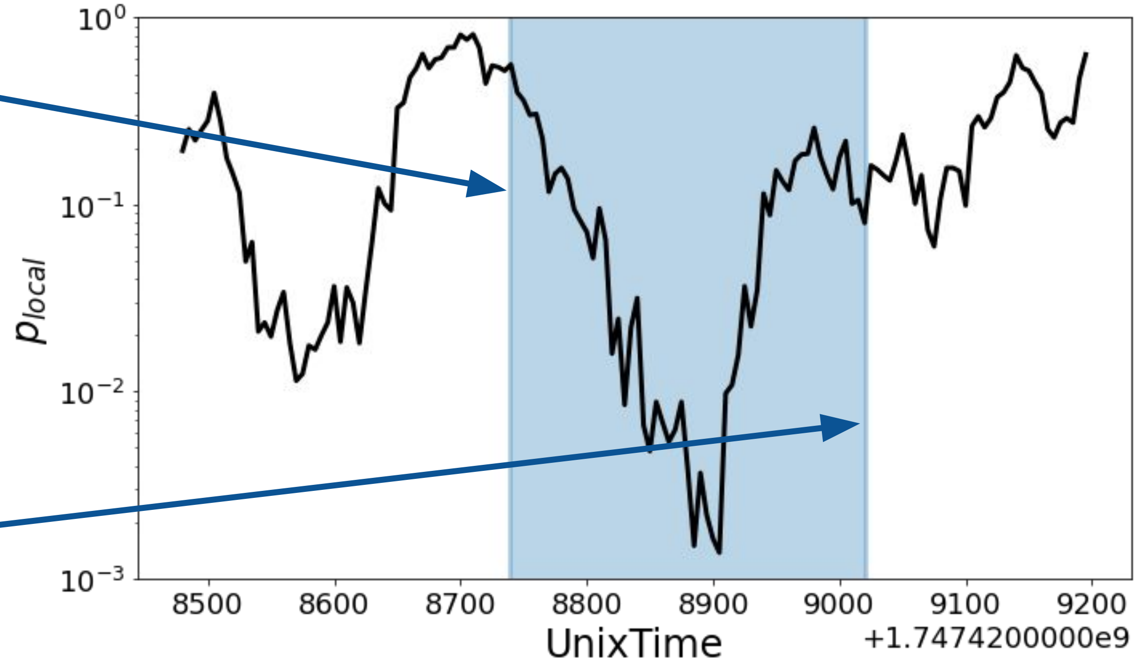


I Am Cautiously Optimistic?

First dust swirls observed

Tornado moves away from us while we are parked on the side of the road



The Plan

Measure the atmospheric muon rate when far (>30 km) from any storms

Measure the atmospheric muon rate when close to a tornadic mesocyclone

Compare the muon rate during the two periods

Control for:

- Long timescale rate variations
- Detector tilt
- Detector temperature
- Elevation changes (though Missouri is *impressively* flat)