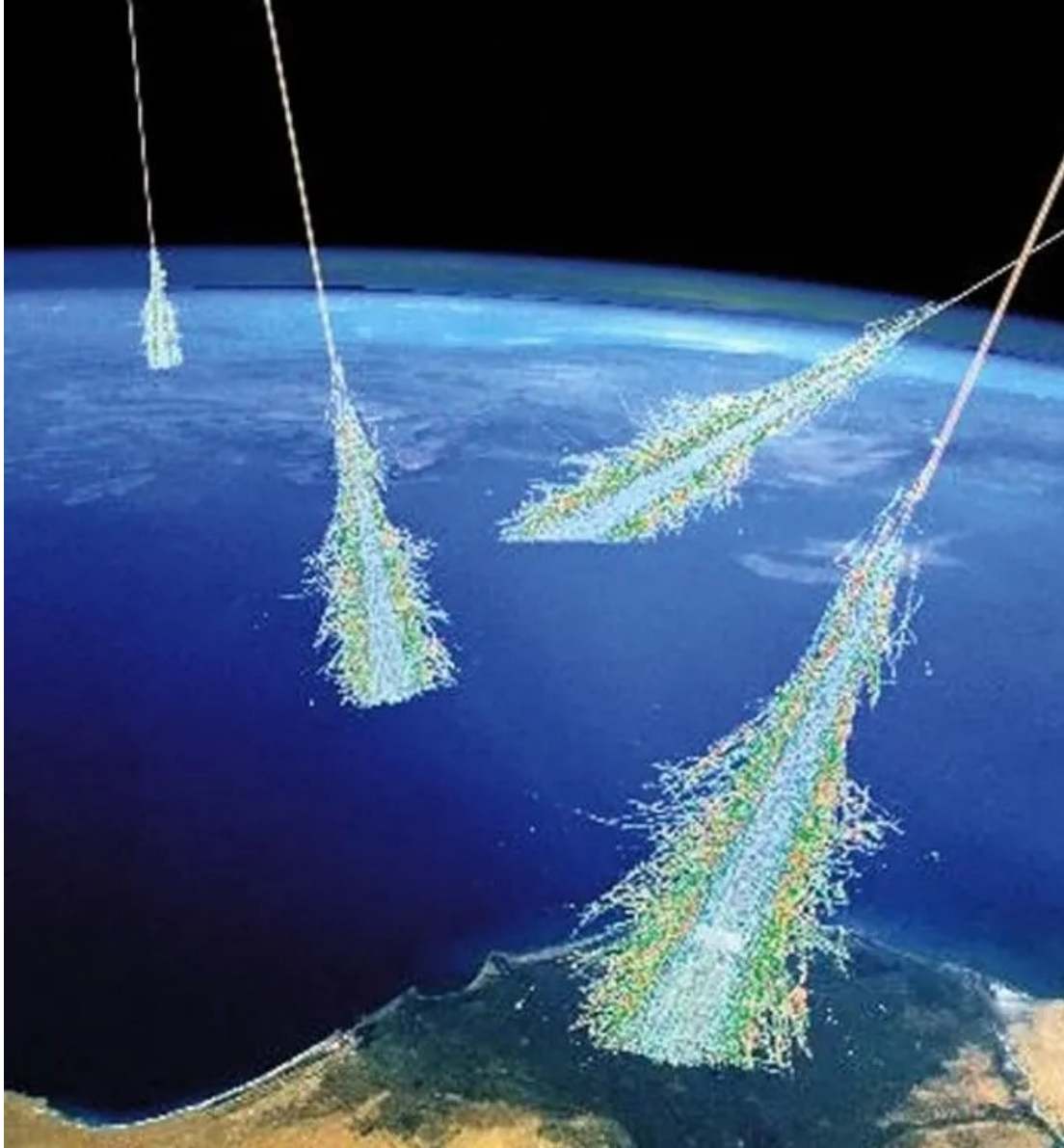
Using _____ to study _____

(Astroparticle)

(Thing we don't know much about)

William Luszczak (OSU/CCAPP)
Leigh Orf (UW/CIMSS)
CCAPP Symposium 2024



Using Muons to study Tornadoes

(Hear me out!)

https://arxiv.org/abs/2405.19311
Submitted to PRD

William Luszczak (OSU/CCAPP)
Leigh Orf (UW/CIMSS)
CCAPP Symposium 2024

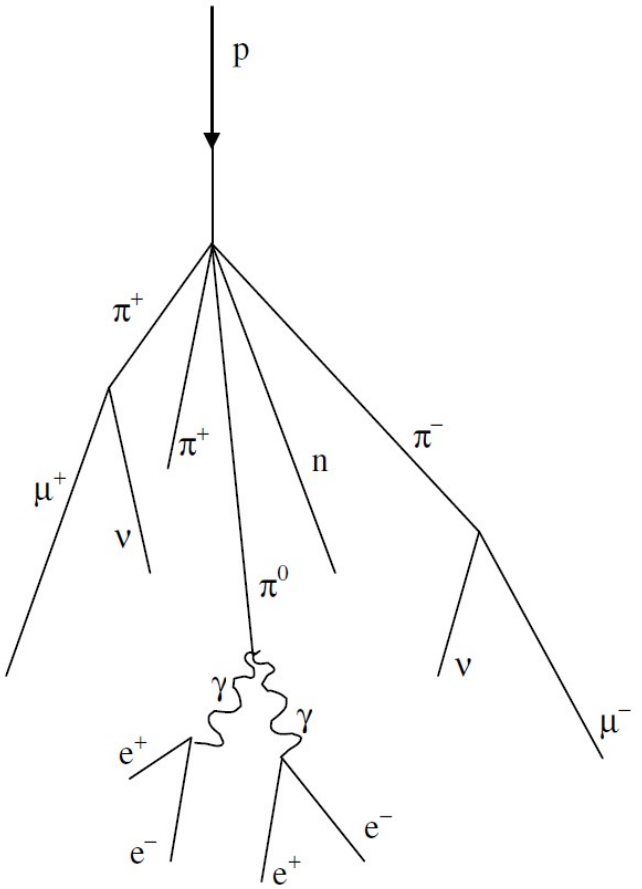
Atmospheric Muons

Cosmic rays interact in the atmosphere, producing pions

Pions eventually decay, producing neutrinos and muons:

$$\pi^{\pm} \rightarrow \mu^{\pm} + \overset{(-)}{\nu}_{\mu}$$

$$K^{\pm} \rightarrow \mu^{\pm} + \overset{(-)}{\nu}_{\mu}$$

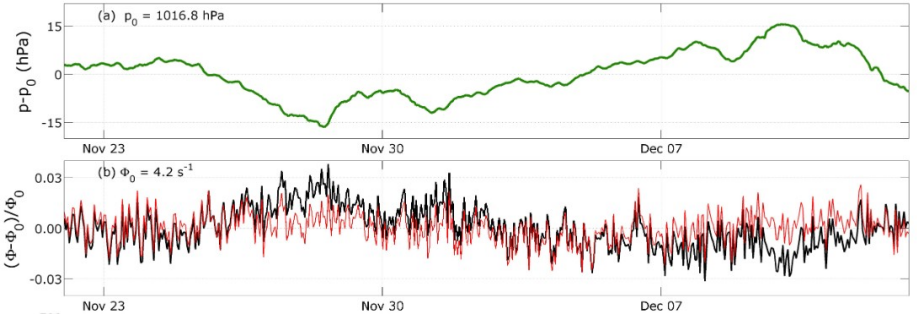


Atmospheric Muons

Atmospheric muons have nice properties:

- Numerous (~1 $cm^{-2}min^{-1}sr^{-1}$)
- Long track lengths (~km+)
- Easily detected
- Propagation through matter is well understood
- **Flux is anticorrelated with atmospheric pressure**

https://arxiv.org/abs/1504.02230



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

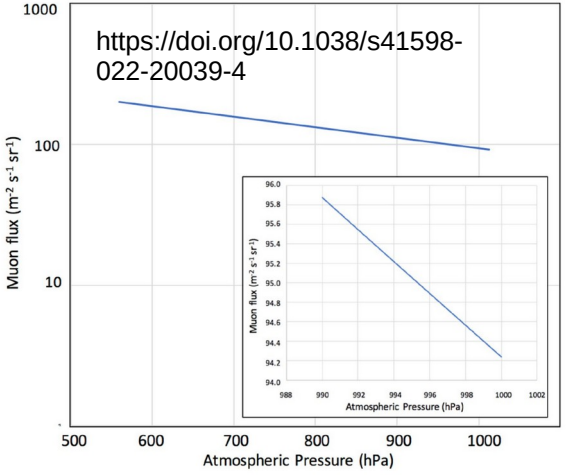


Figure 1. Vertical muon flux (N) versus atmospheric pressure (ρ). Inset illustrates the atmospheric pressure within the range between 990 and 1000 hPa.

Tornadoes

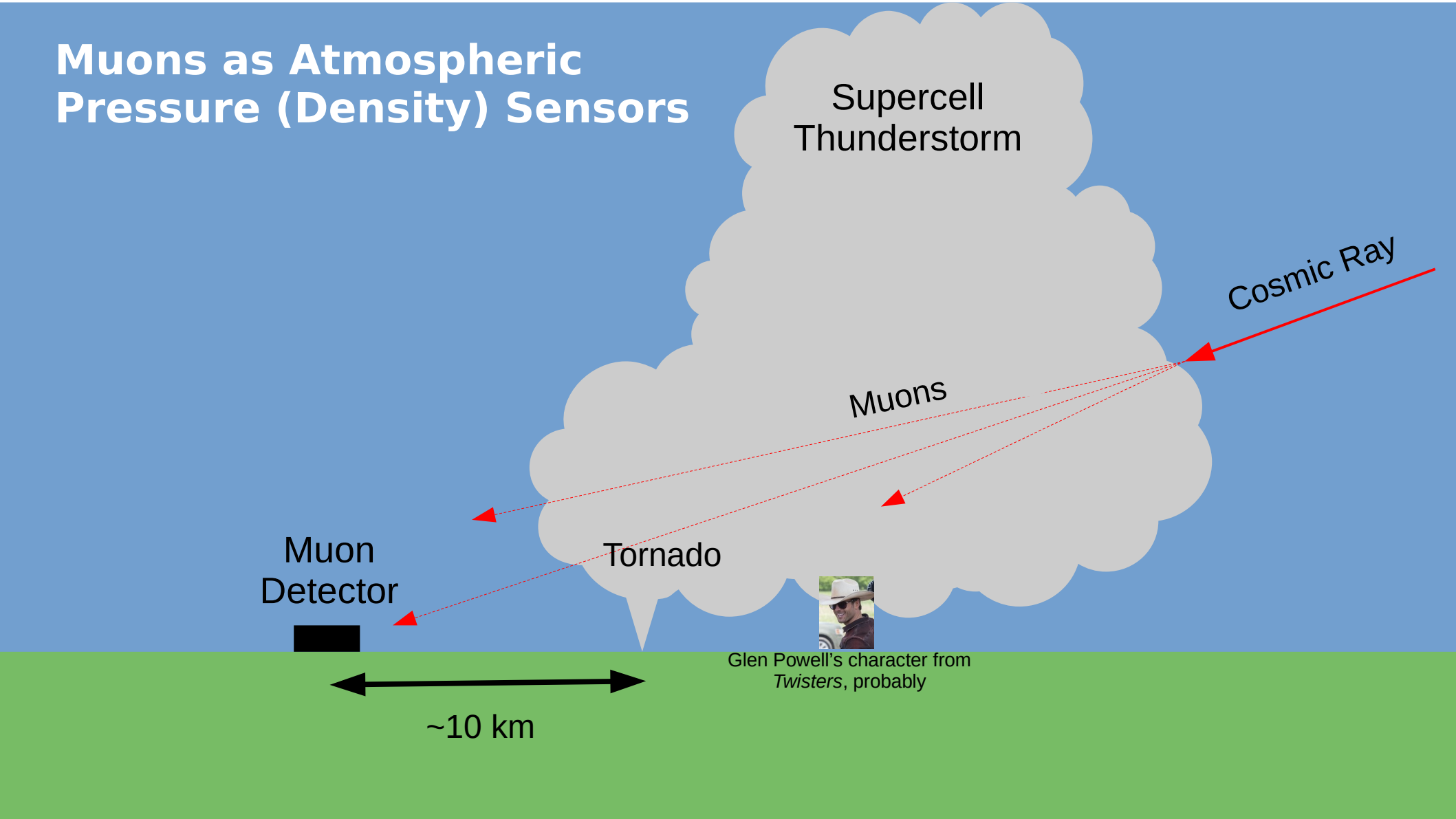
- Tornado: A violently rotating column of air connecting a cumuliform cloud with the ground
- Most extreme weather systems on Earth (wind speed/air pressure)
- Strongest tornadoes spawn from supercell thunderstorms
- Not well understood
  - Formation/propagation
  - Size
  - Interior dynamics
  - Detection/characterization

Studying Tornadoes is Hard

- Pressure measurements require in-situ detectors
  - Logistical nightmare!
- Current tech only produces point measurements
  - Extrapolating point measurements is a source of modeling error

Fig. 1 Picture of HITPR Probe.

Muons as Atmospheric Pressure (Density) Sensors

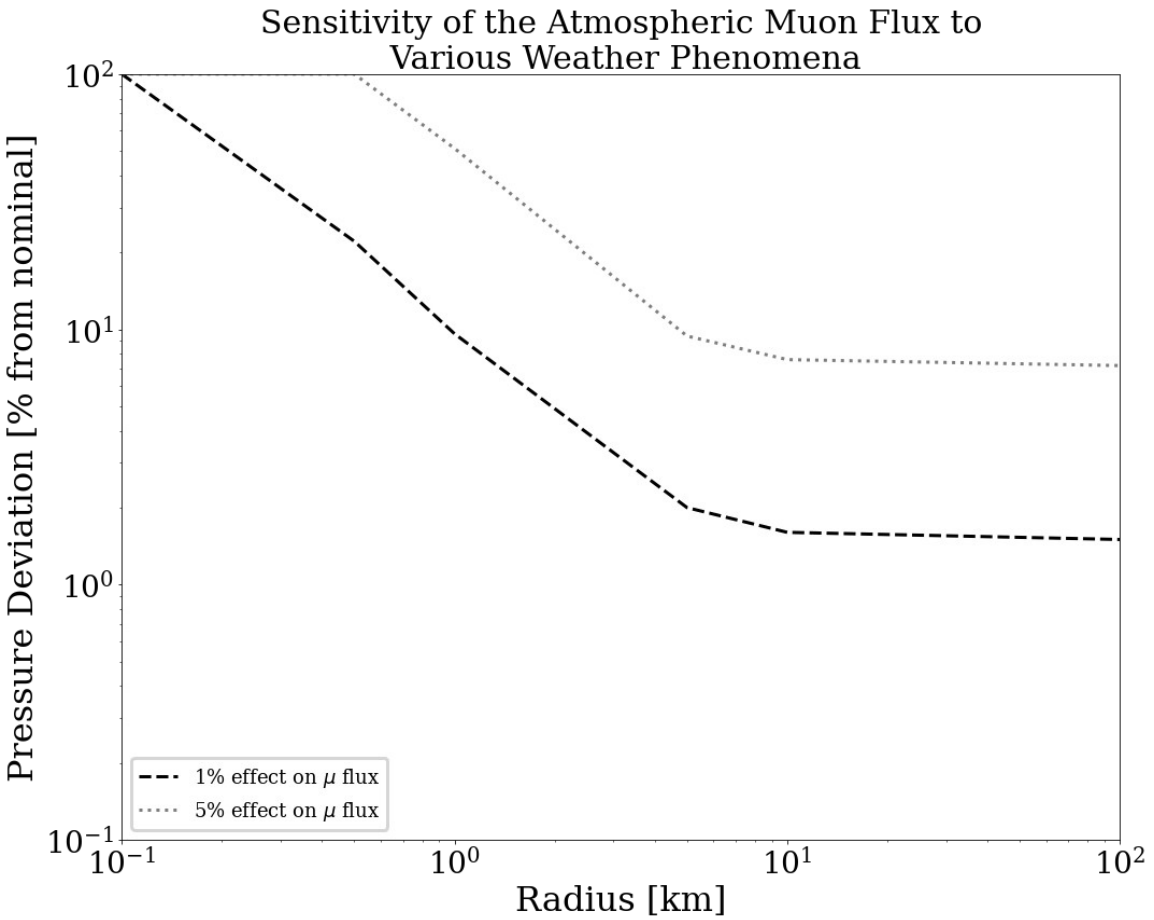


Glen Powell's character from *Twisters*, probably

Two Questions

- How large of an effect do tornadoes have on the atmospheric muon flux?
- How large of a muon detector would you need to detect this on reasonable (~1 hour) time scales?

Back-of-the-Envelope Calculation



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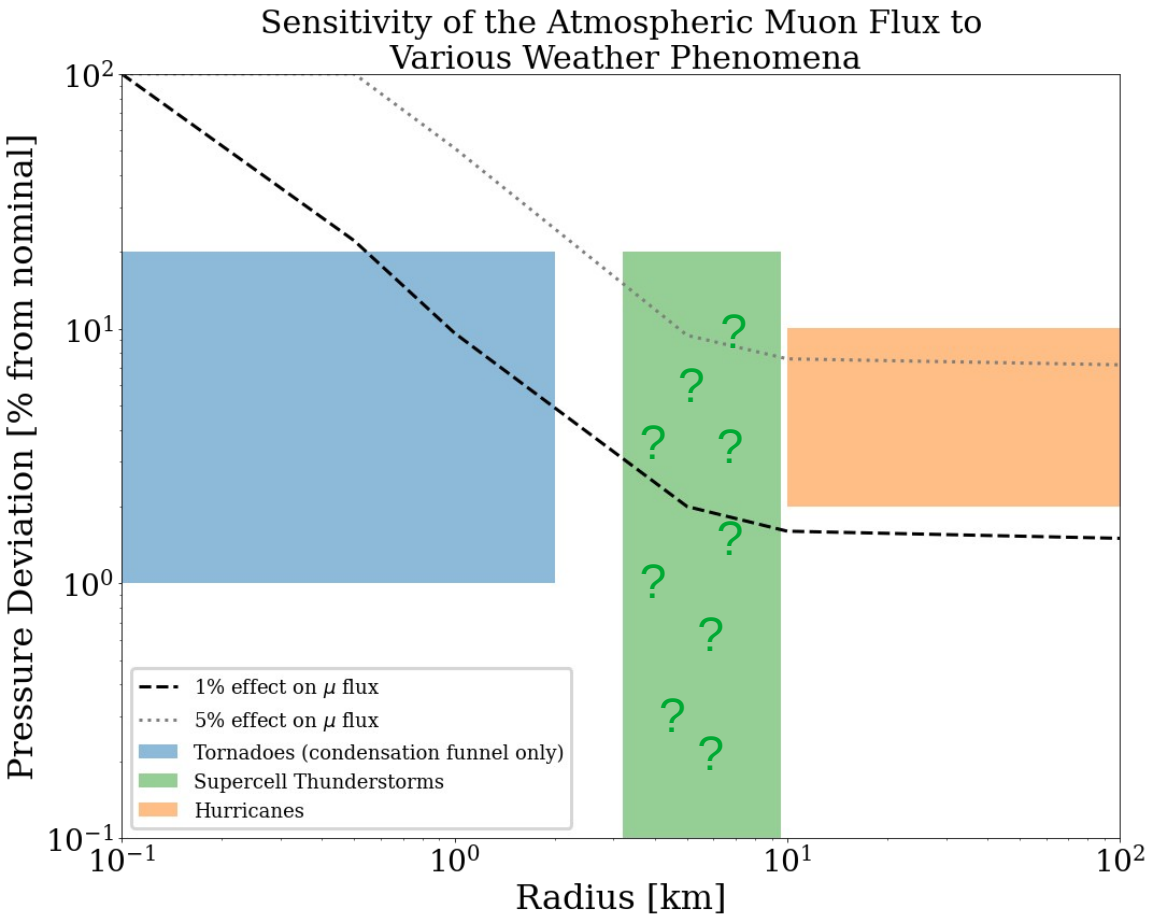

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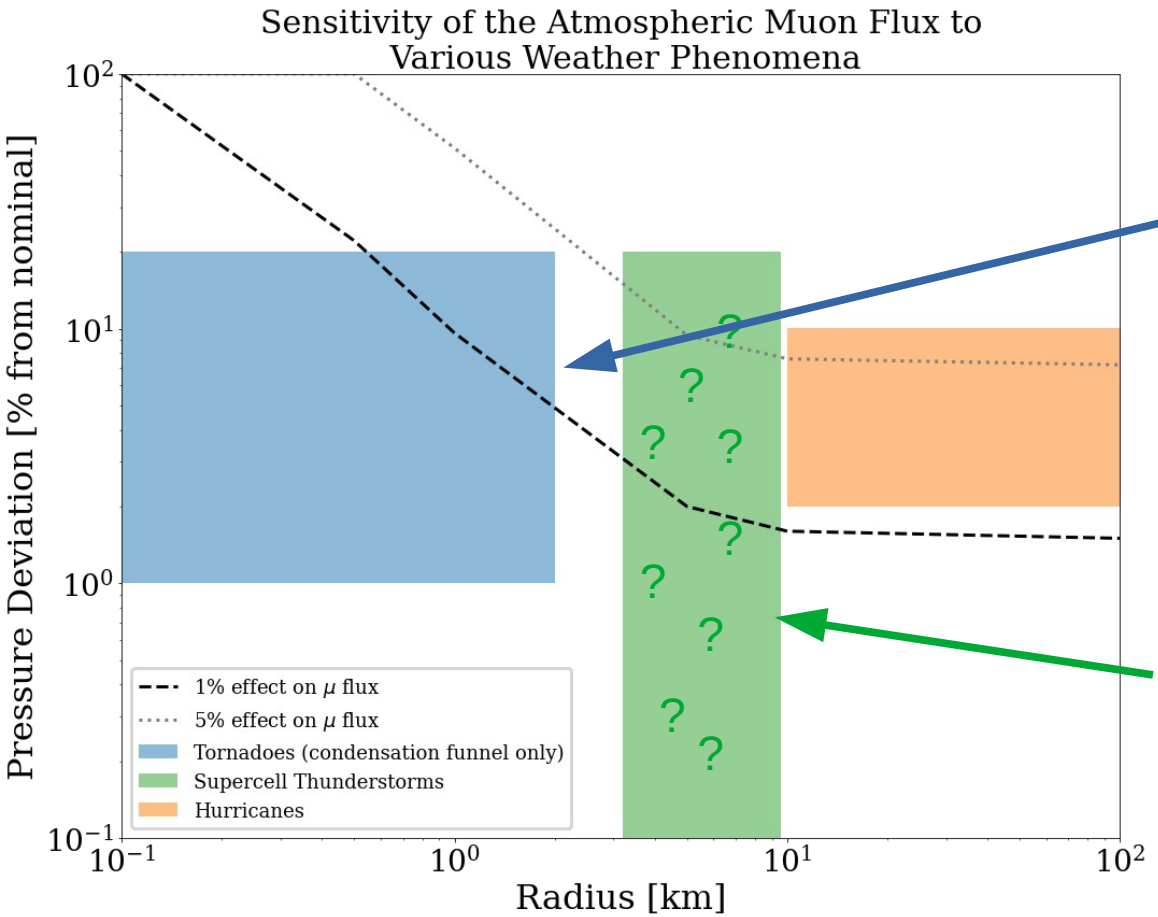
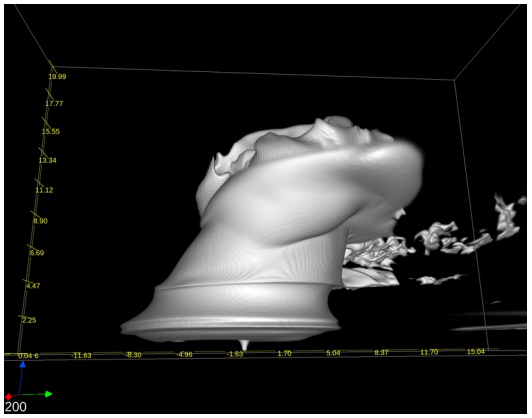


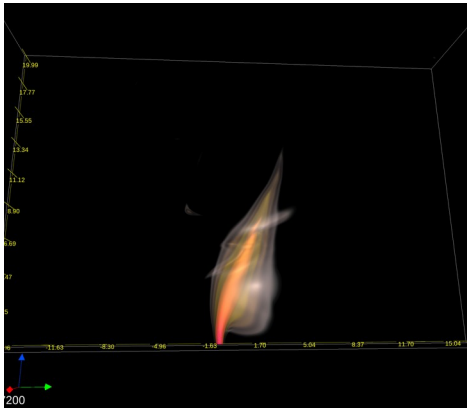
Very rough estimate:

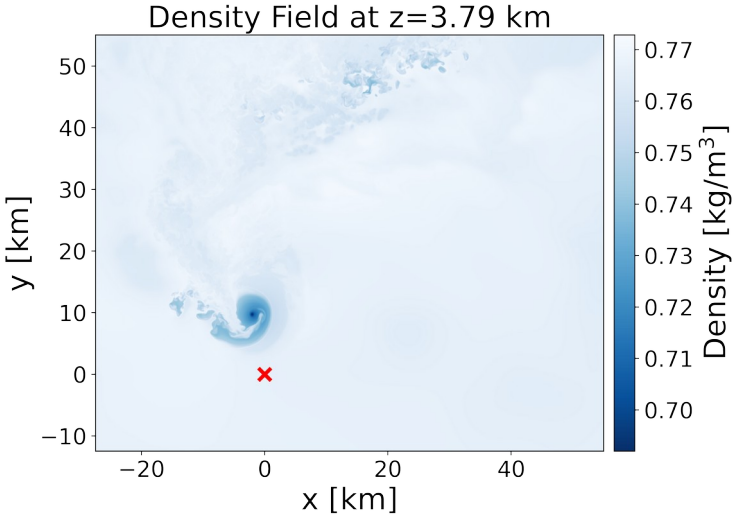
- Lack of measurements
- Tornado boundary is poorly defined

Atmospheric perturbation probably extends through the parent storm, but measurements of this are practically nonexistent

More Sophisticated Tornado Simulation (courtesy of Leigh Orf)

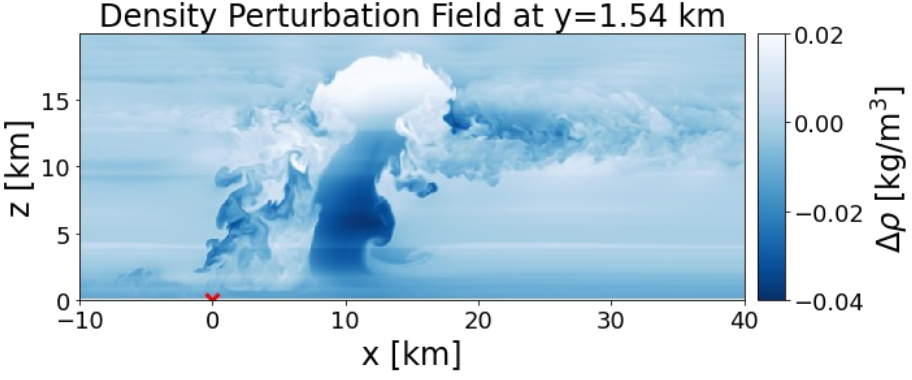






→ Modeled using May 24 2011 El Reno atmospheric conditions

→ Produced a strong, long-lived tornado



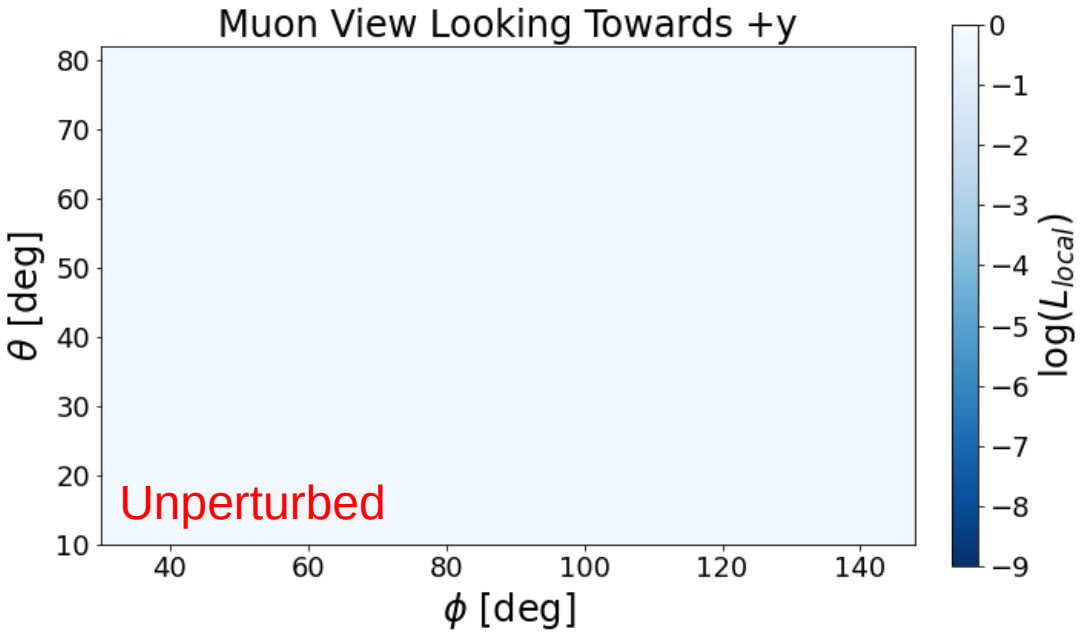
Let's just throw this into MCEq and see what happens

What a Muon Detector Might See

- Since the atmospheric muon flux varies naturally with elevation angle, it's convenient to normalize the the rate at a particular elevation:

$$L(N_{obs}) = \int_{N_{obs}}^{\infty} P(N_{exp}, x)dx$$

*As P ↑, muon flux ↓, L ↑



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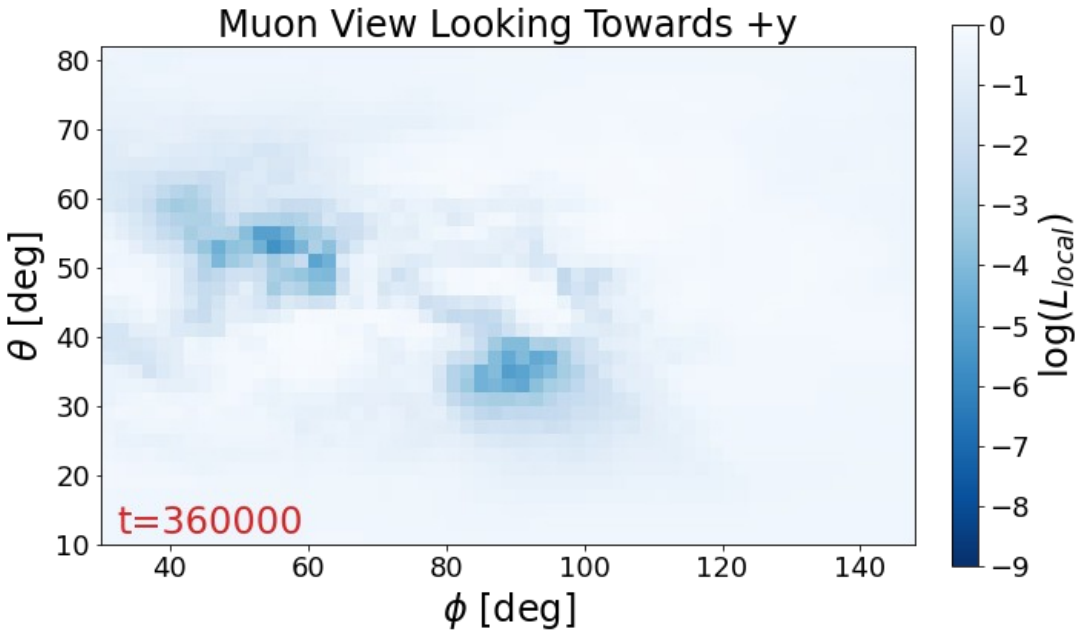

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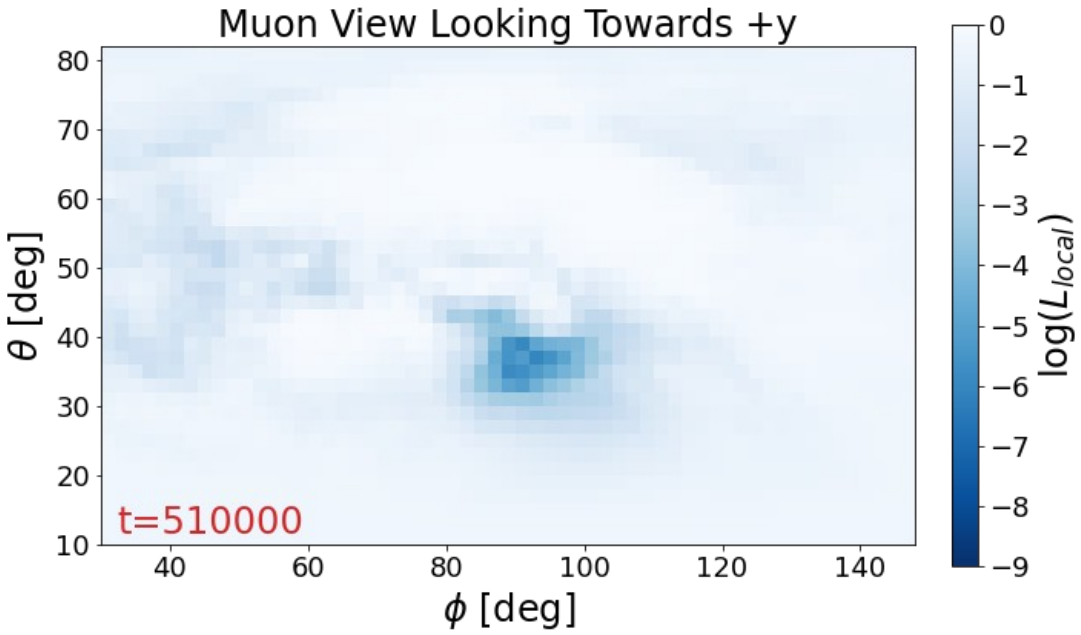

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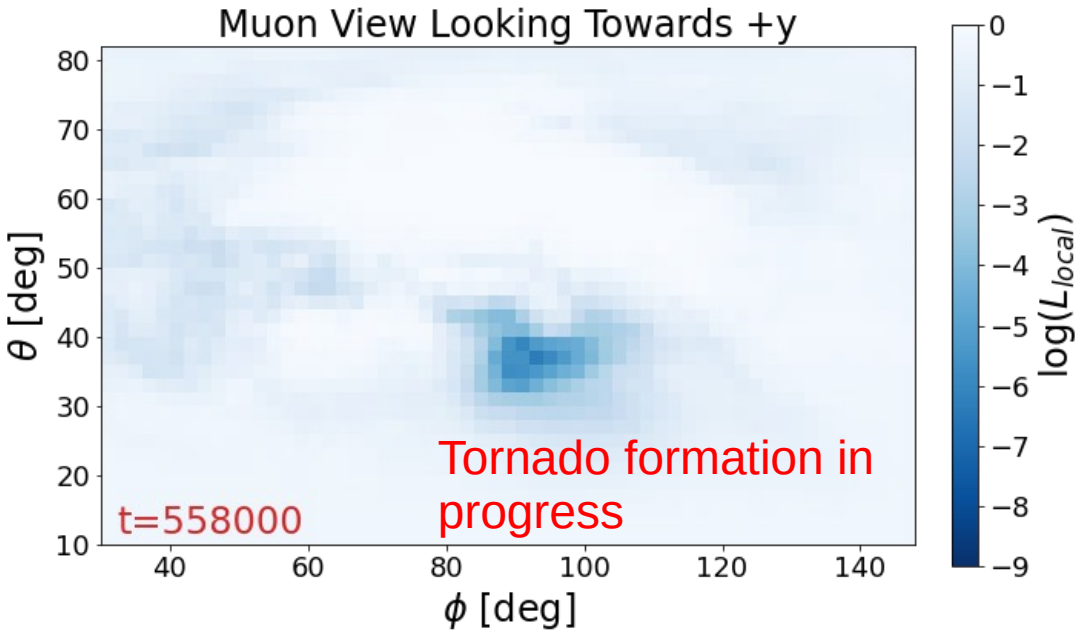

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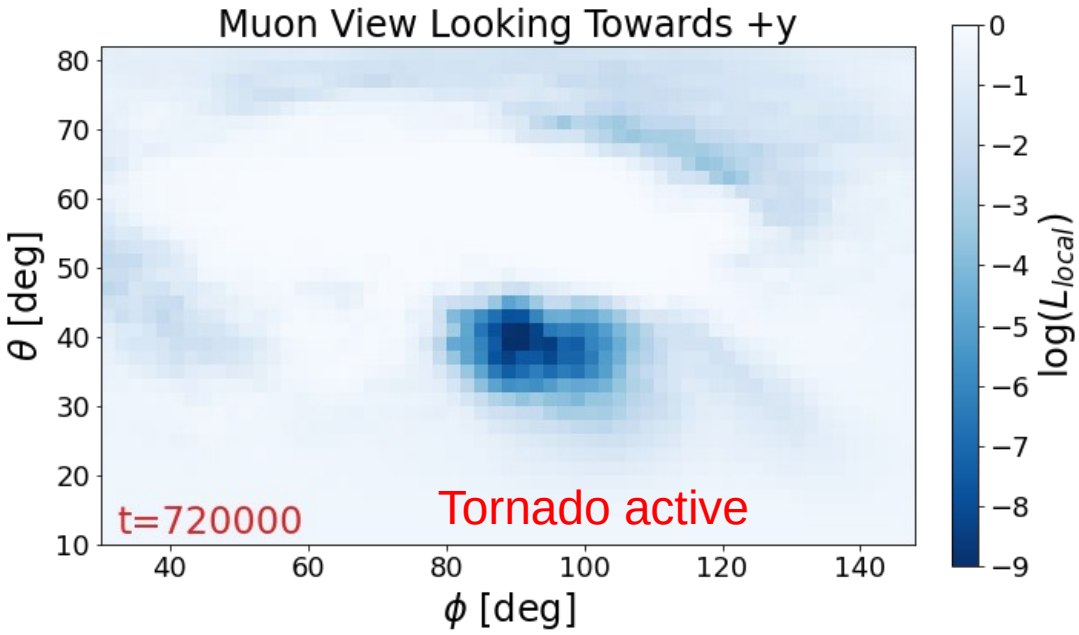

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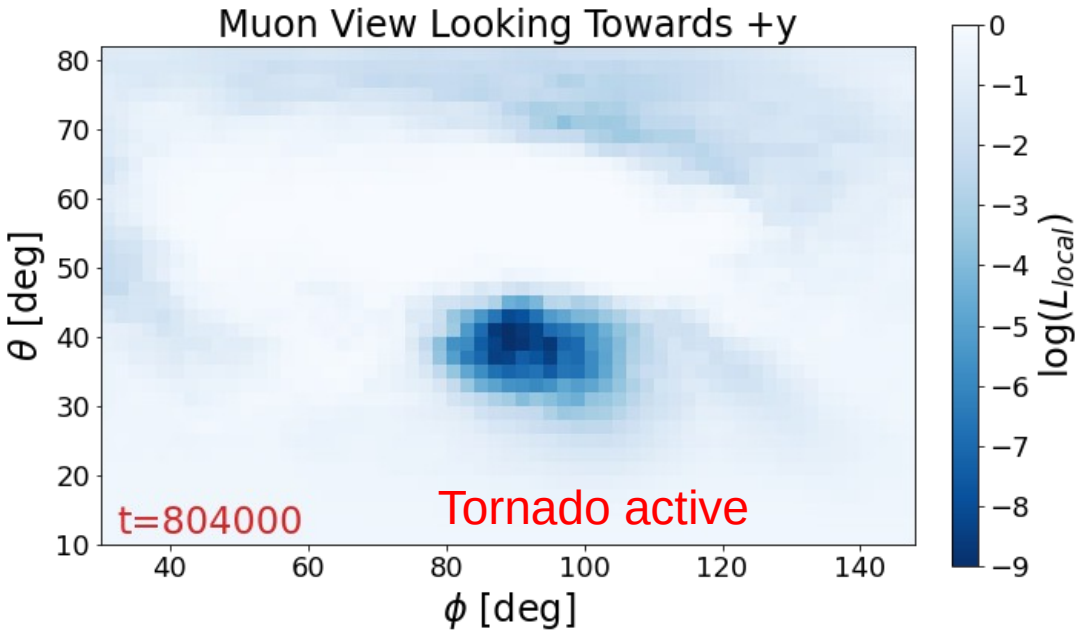

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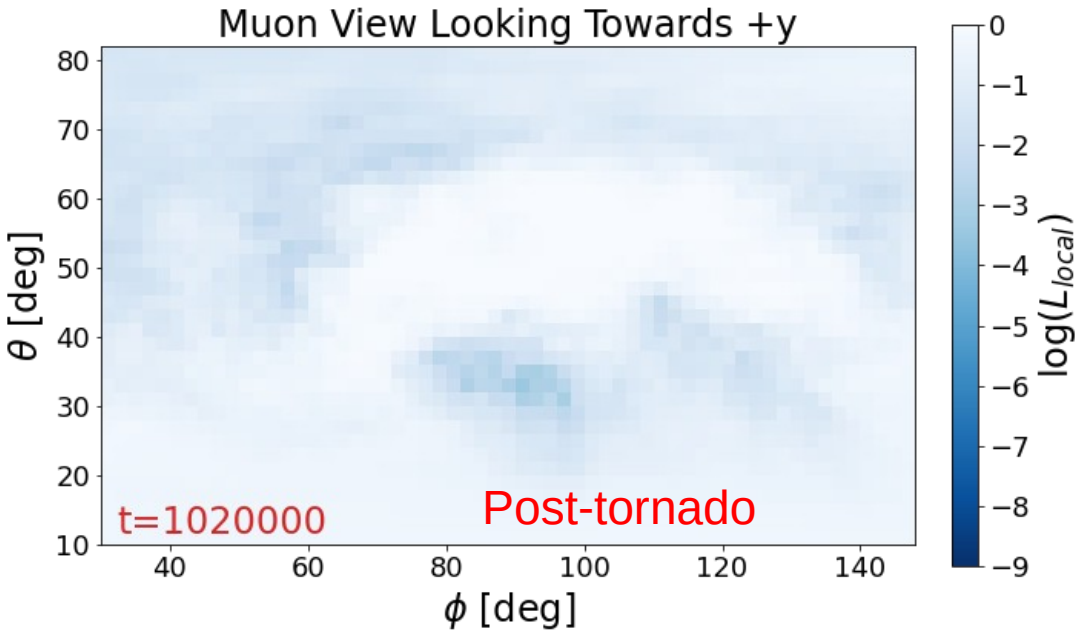
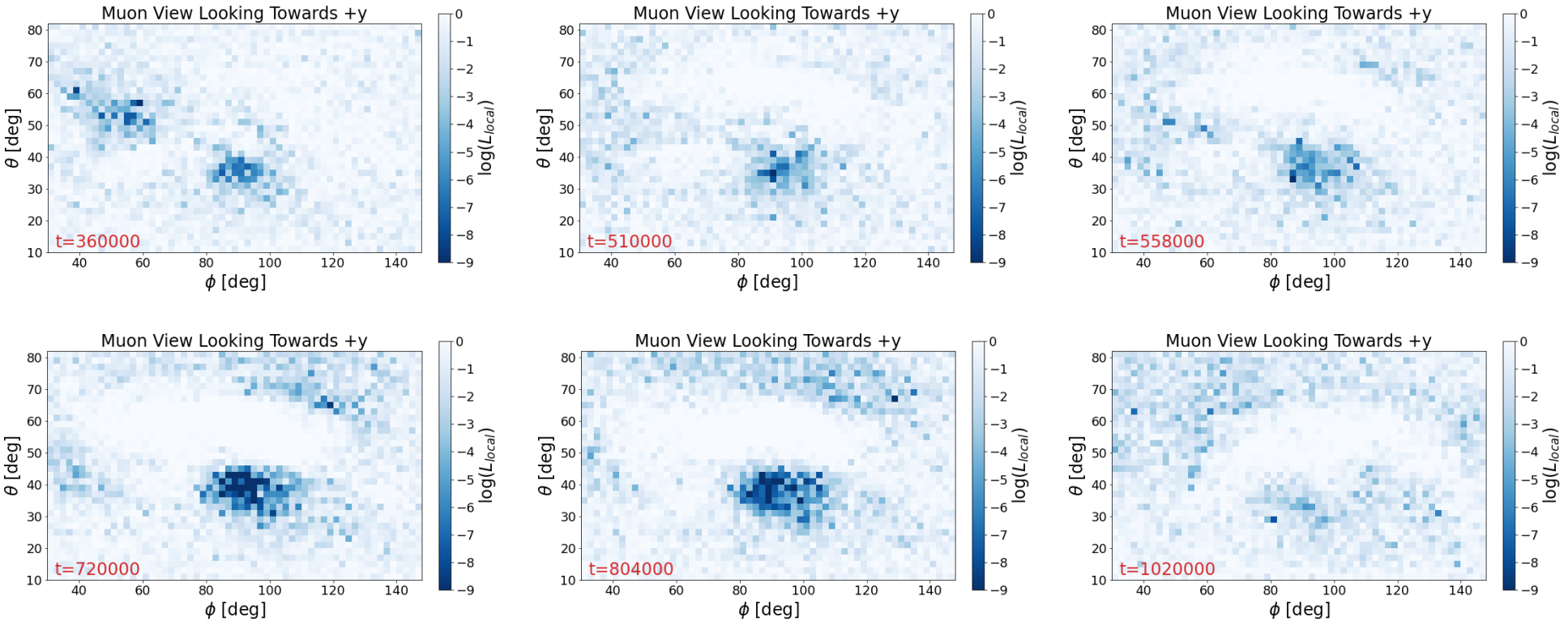
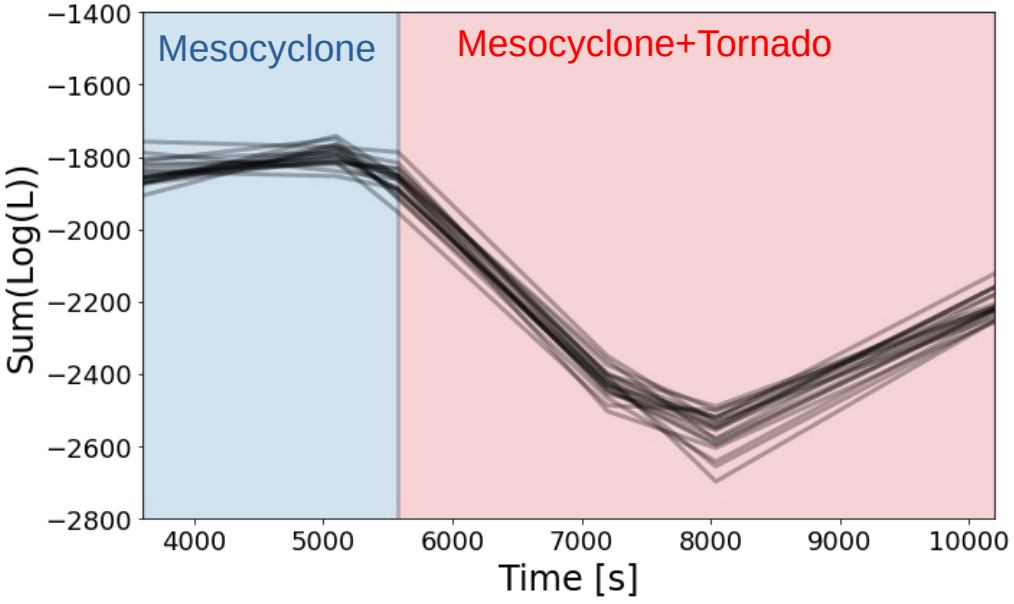


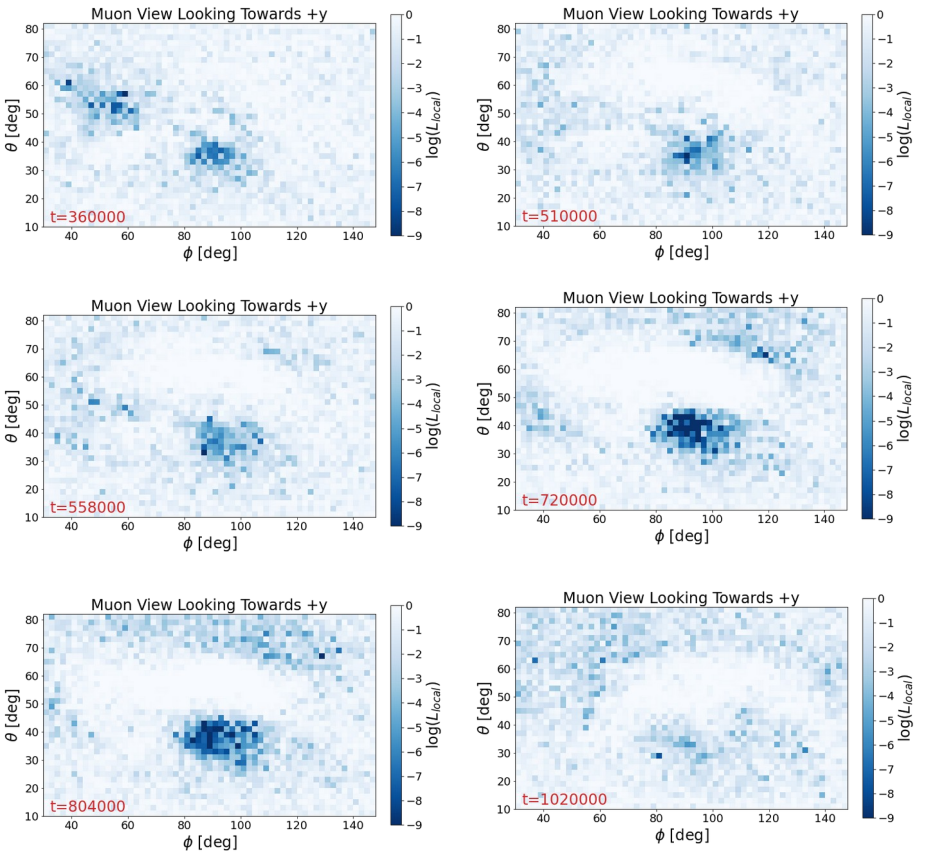
What a Muon Detector (Realistically) Might See



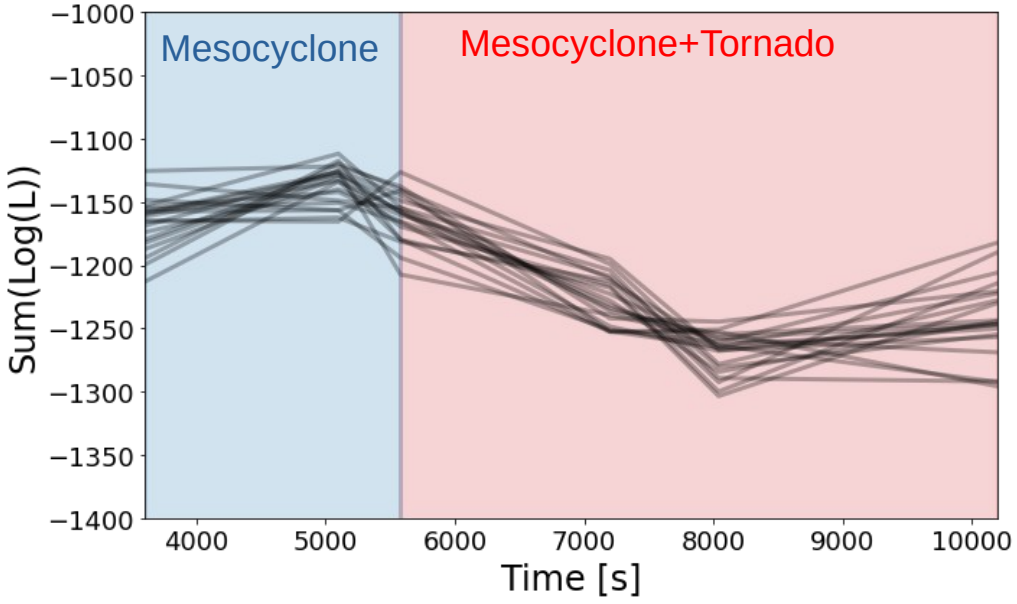
- 1000 m^2 muon detector, data for each snapshot integrated over past hour

Integrated Effect

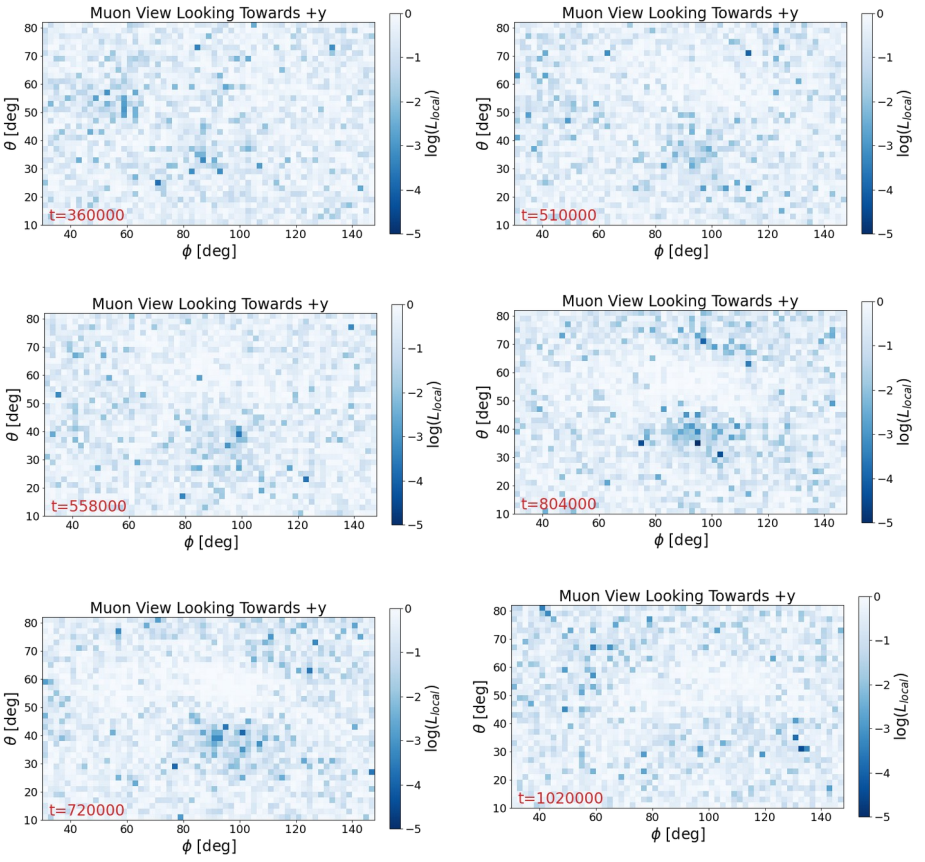




100 m^2 Detector



^This algorithm is dumb (but effect of tornado is still visible!)

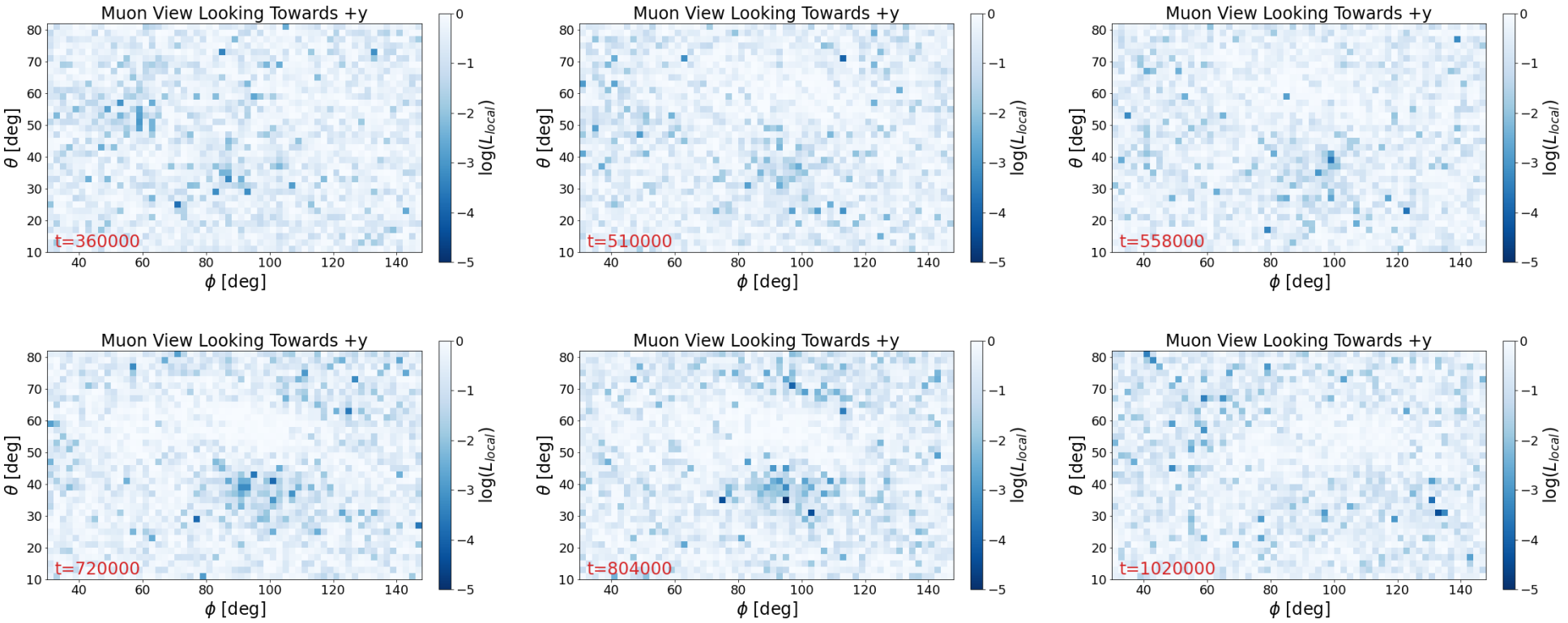


I’m Probably Out of Time By This Point

- Q: How large of an effect do tornadoes have on the atmospheric muon flux?
  - A: ~1-2%
- Q: How large of a muon detector would you need to detect this on reasonable (~1 hour) time scales?
  - A: Storm evolution can be probably be seen in detectors smaller than 100 m^2
- Technique is potentially **very** interesting for atmospheric scientists
  - Anemometer → Radar, Barometer → Muons?
  - Remote pressure measurement opens up a new way to observe weather
  - Particularly useful for systems that are difficult to study with current methods
  - Large area pressure measurements potentially useful for weather forecasting (EnsDA)

Backup Slides

What a Muon Detector (Realistically) Might See



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Tornado Tracks, 1950-2023

Show Touchdown Points NOTE: Some tornadoes are only visible as a touchdown point.

Filter by Magnitude: NOTE: F/EF U tornadoes represent tornadoes of unknown magnitude. They have a title of F-9 in the SPC database.

- F/EF U
- F/EF 0
- F/EF 1
- F/EF 2
- F/EF 3
- F/EF 4
- F/EF 5

Filter by Year Range:

2013 through 2023

Filter by Month:

All Months

Filter by Casualties:

- Injuries > 0
- Fatalities > 0

For more information, click any:

- Track/Point (for tornado data)
- County (for county image, updated through 2021)

Please note: Attempting to view many tracks may significantly hinder performance. Some tornadoes are only visible after zooming in on an area of the map. Data includes a start and end point for tornado touchdown and liftup with a straight line applied for the track. This track may not represent the actual tornado ground path.

MRCC Midwestern Regional Climate Center

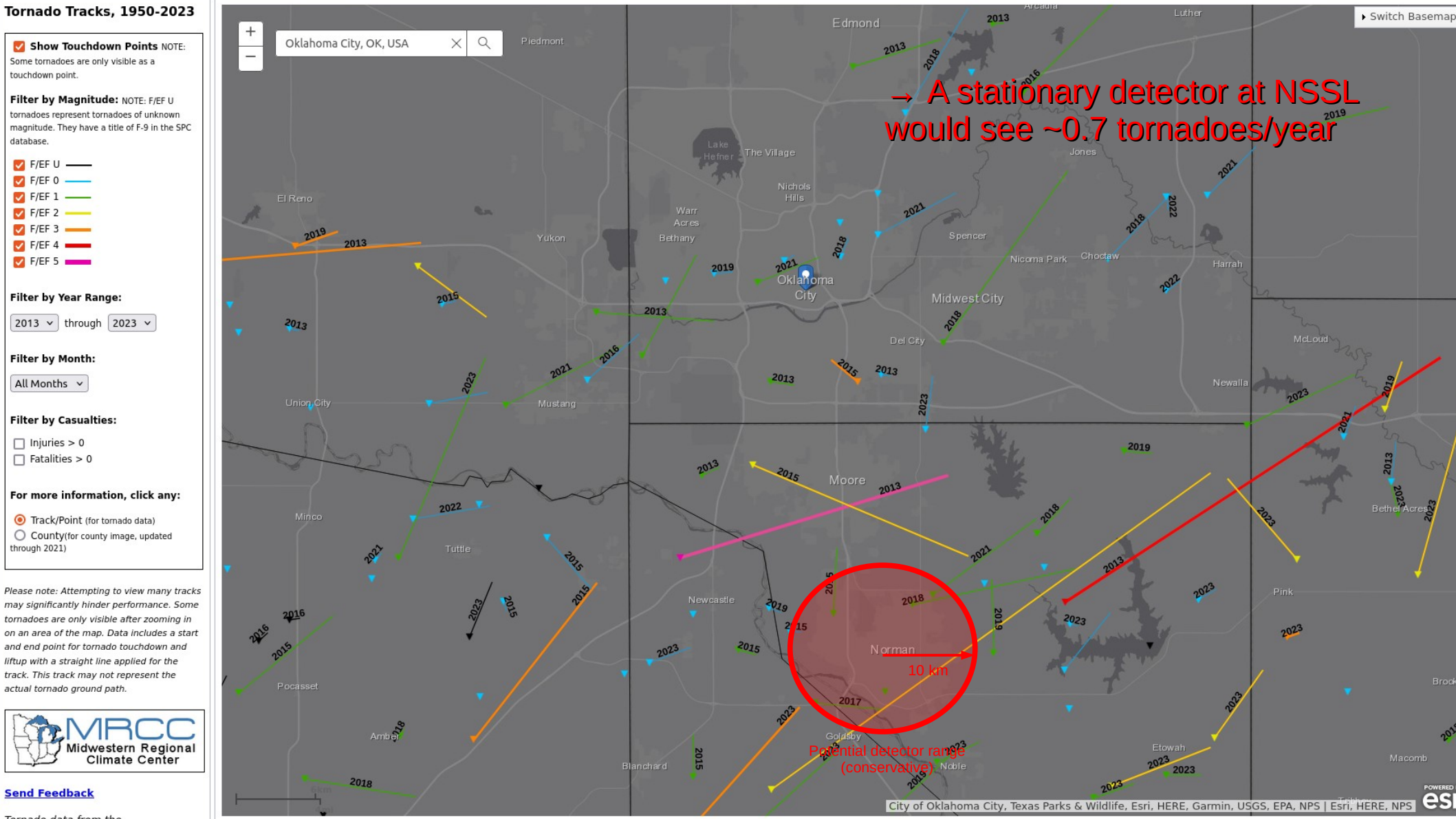
Send Feedback

Oklahoma City, OK, USA

Switch Basemap

Edmond, Piedmont, Arcadia, Luther, Lake Hefner, The Village, Jones, El Reno, Nichols Hills, Warr Acres, Bethany, Yukon, Spencer, Nicoma Park, Choctaw, Harrah, Oklahoma City, Midwest City, Del City, McLoud, Newalla, Union City, Mustang, Moore, Minco, Tuttle, Bethel Acres, Newcastle, Norman, Pink, Pocasset, Amber, Blanchard, Goldsby, Noble, Etowah, Macomb

City of Oklahoma City, Texas Parks & Wildlife, Esri, HERE, Garmin, USGS, EPA, NPS | Esri, HERE, NPS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MRCC Midwestern Regional Climate Center
Send Feedback
Oklahoma City, OK, USA
Switch Basemap
→ A stationary detector at NSSL would see ~0.7 tornadoes/year
10 km
Potential detector range (conservative)
Edmond
Piedmont
Luther
Lake Hefner
The Village
Jones
Nichols Hills
El Reno
Warr Acres
Bethany
Yukon
Spencer
Nicoma Park
Choctaw
Harrah
Oklahoma City
Midwest City
Del City
McLoud
Newalla
Union City
Mustang
Moore
Minco
Tuttle
Bethel Acres
Newcastle
Norman
Pink
Pocasset
Goldsby
Etowah
Blanchard
Noble
Macomb
City of Oklahoma City, Texas Parks & Wildlife, Esri, HERE, Garmin, USGS, EPA, NPS | Esri, HERE, NPS

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MRCC Midwestern Regional Climate Center

Send Feedback

Columbus ohio

Switch Basemap

→ 2024 tornadoes not shown

Monroe Twp
Orange Twp
Jerome Twp
Liberty Twp
Darby Twp
Westerville
Dublin
Sharon Twp
Worthington
Plain Twp
Pike Twp
Granville
Granville Twp
Norwich Twp
Hilliard
Upper Arlington
Harrison Twp
Pataskala
Monroe Twp
Union Twp
Columbus
2018
Whitehall
Reynoldsburg
Etna Twp
Somerford Twp
Deer Creek Twp
Prairie Twp
Violet Twp
Franklin Twp
Blacklick Estates
Jackson Twp
Pickerington
Walnut Twp
London
Union Twp
2020
Madison Twp
Grove City
2018
Groveport
Canal Winchester
Baltimore
Paint Twp
Fairfield Twp
Hamilton Twp
Bloom Twp
Greenfield Twp
2023
Pleasant Twp
Scioto Twp
Darby Twp
2023
2023
Pleasant Twp
Harrison Twp
Range Twp
2014
Mt Sterling
South Bloomfield
Ashville
Lancaster

Esri, HERE, NPS | Franklin County Auditor, Esri, HERE, Garmin, USGS, EPA, NPS

POWERED BY esri

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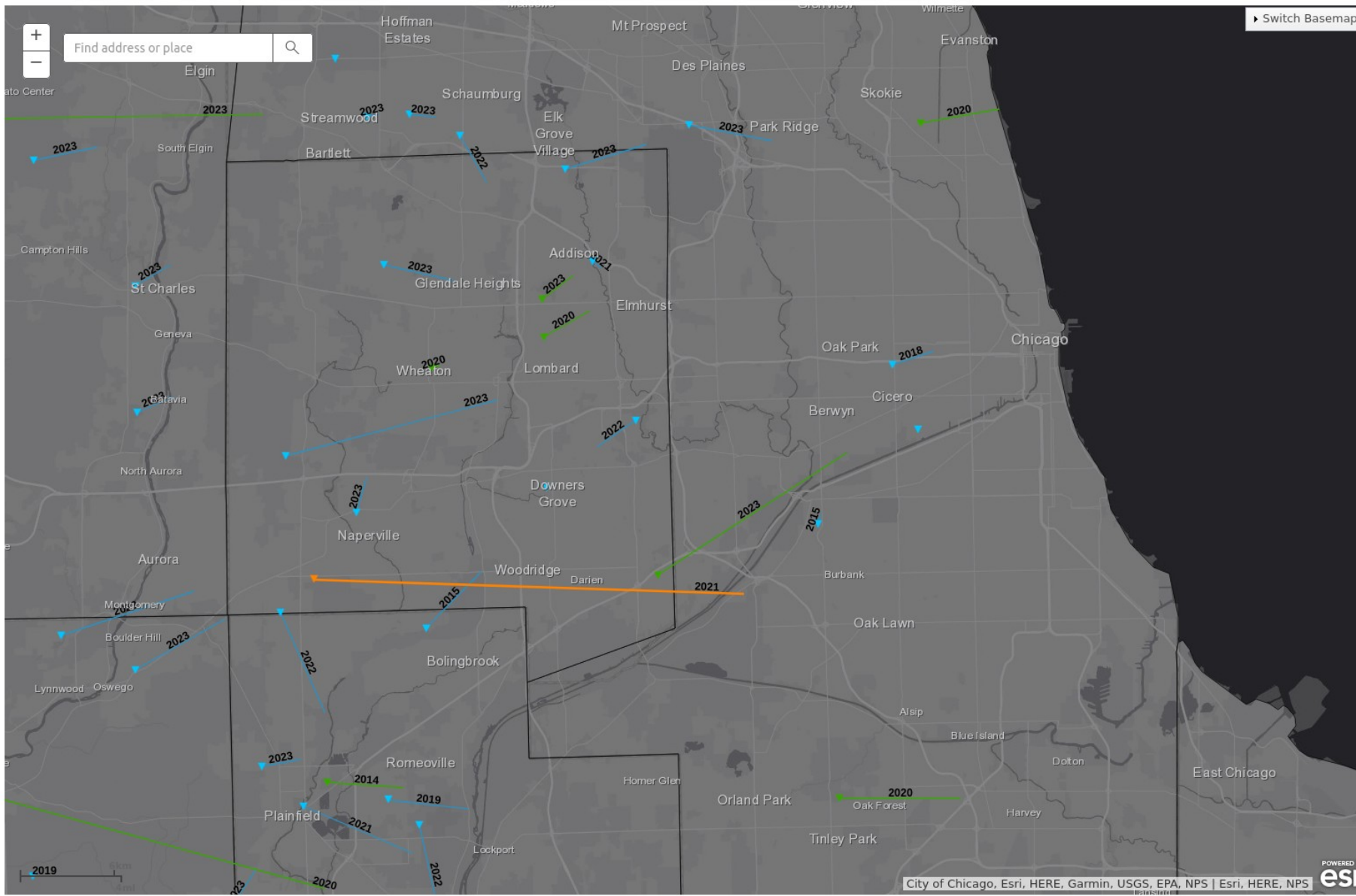
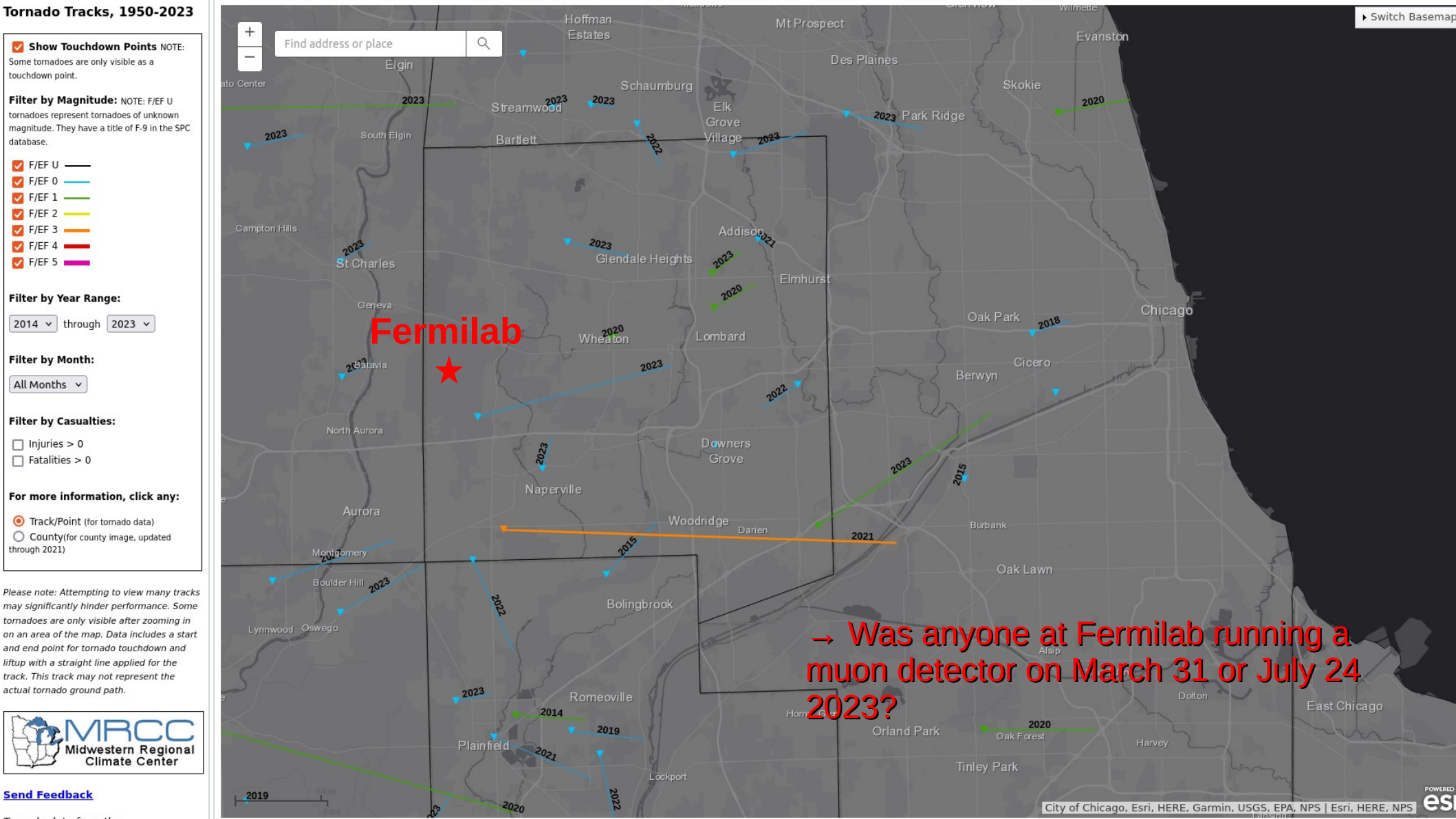
MRCC Midwestern Regional Climate Center

Send Feedback

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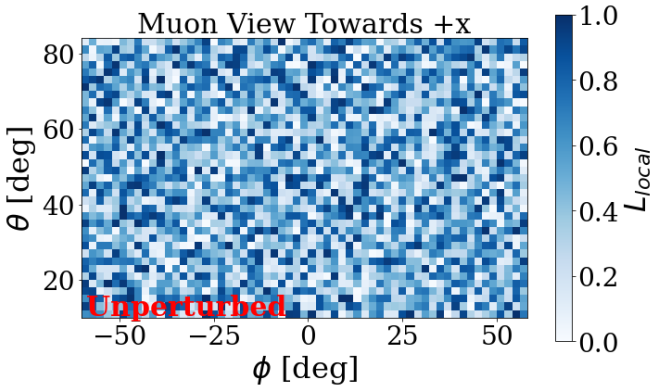
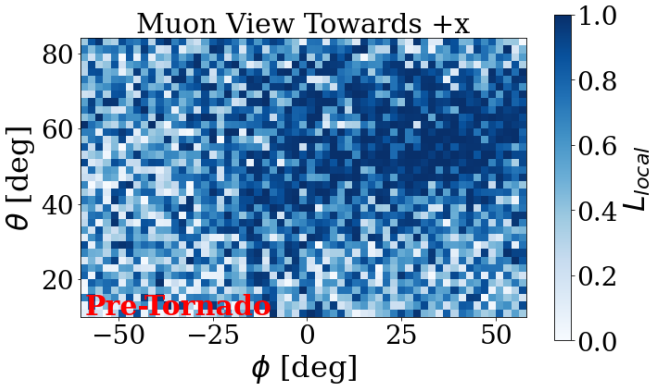
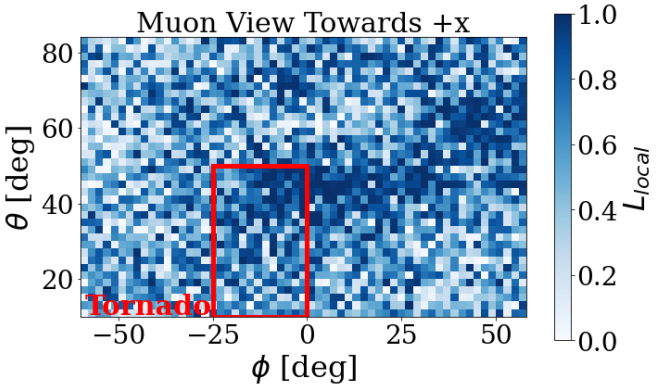
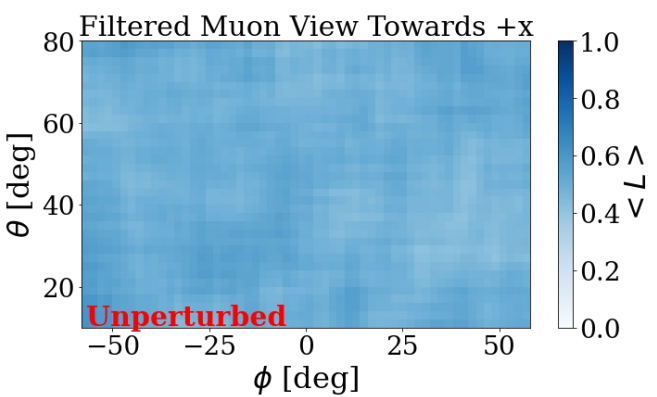
MRCC Midwestern Regional Climate Center
Send Feedback
Find address or place
Switch Basemap
Fermilab
→ Was anyone at Fermilab running a muon detector on March 31 or July 24 2023?
Hoffman Estates
Mt Prospect
Evanston
Elgin
Des Plaines
Schaumburg
Skokie
Streamwood
Elk Grove Village
Park Ridge
South Elgin
Bartlett
Campton Hills
Addison
St Charles
Glendale Heights
Elmhurst
Geneva
Oak Park
Chicago
Wheaton
Lombard
Cicero
Berwyn
North Aurora
Downers Grove
Naperville
Aurora
Woodridge
Darien
Burbank
Oak Lawn
Boulder Hill
Bolingbrook
Lynnwood
Oswego
Romeoville
Plainfield
Orland Park
Oak Forest
Harvey
Tinley Park
Lockport
Dolton
East Chicago
City of Chicago, Esri, HERE, Garmin, USGS, EPA, NPS | Esri, HERE, NPS

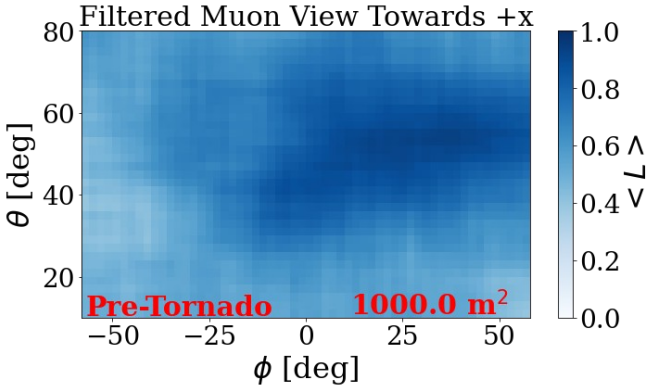
What a Muon Detector (Realistically) Might See

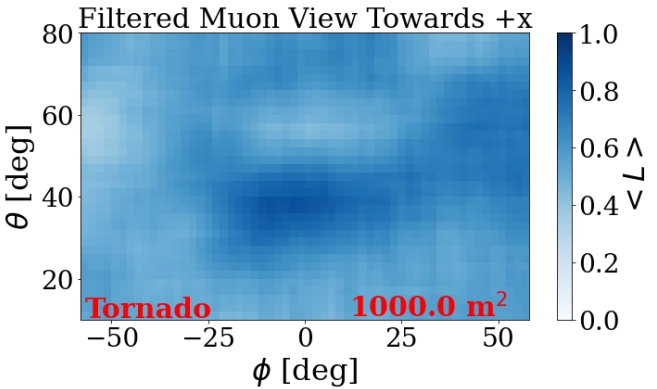








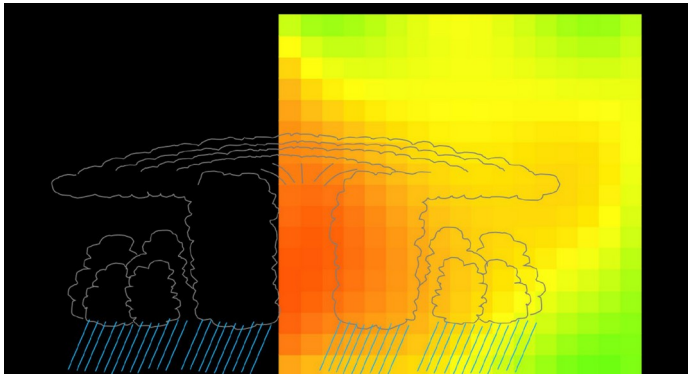


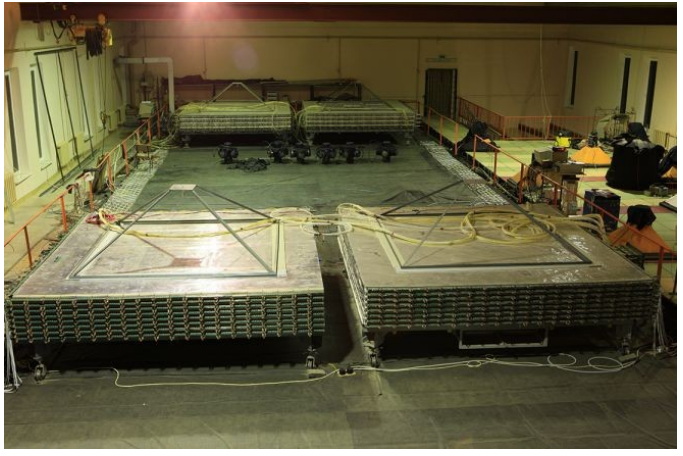


→ Can average together nearby pixels to examine larger scale storm evolution

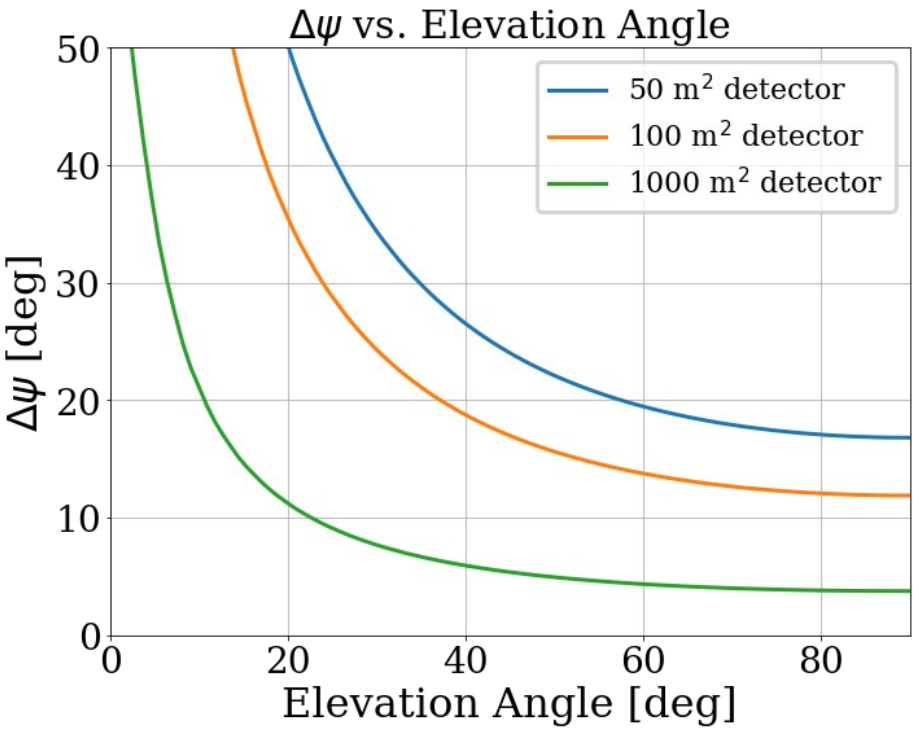
Previous Studies By Other People

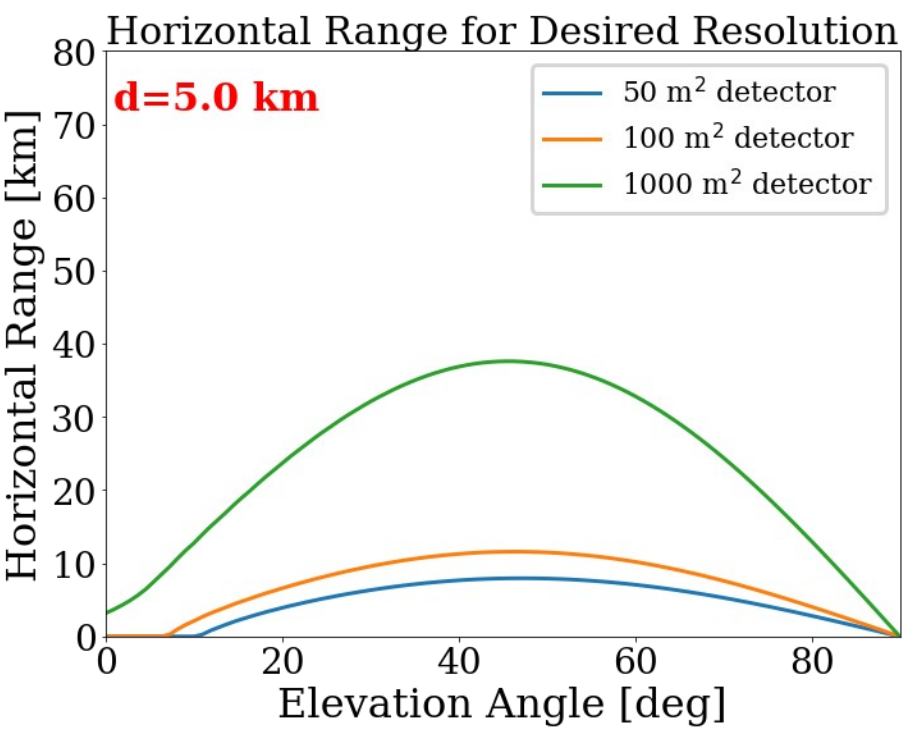
- Japanese group that imaged typhoons: https://doi.org/10.1038/s41598-022-20039-4
  - Only a 4 m^2 detector!
- Russian detector that looked at non-tornadic thunderstorms: https://doi.org/10.1016/j.asr.2015.06.003
  - 40 m^2 detector
- Thunderstorms studied using TA and GRAPES-3 data:
  - TA: https://doi.org/10.1103/PhysRevD.105.062002
  - GRAPES: https://link.aps.org/doi/10.1103/PhysRevLett.122.105101





Range


Δψ vs. Elevation Angle
50 m² detector
100 m² detector
1000 m² detector
Δψ [deg]
Elevation Angle [deg]
0
10
20
30
40
50
0
20
40
60
80

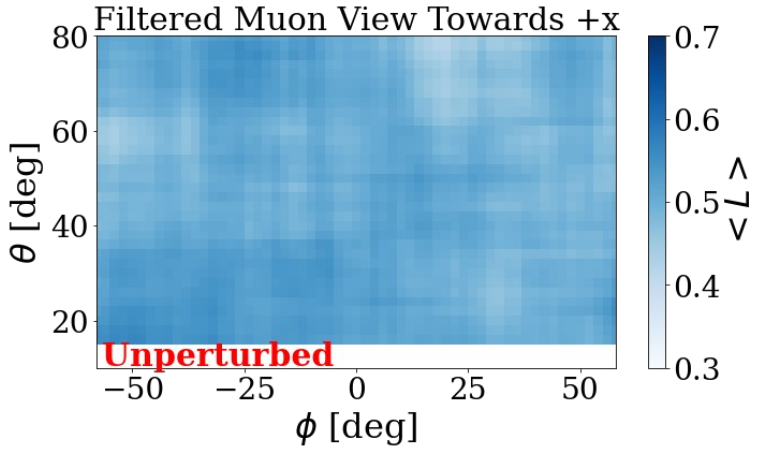

Horizontal Range for Desired Resolution
d=5.0 km
50 m² detector
100 m² detector
1000 m² detector
Horizontal Range [km]
Elevation Angle [deg]
0
10
20
30
40
50
60
70
80
0
20
40
60
80

Further Studies

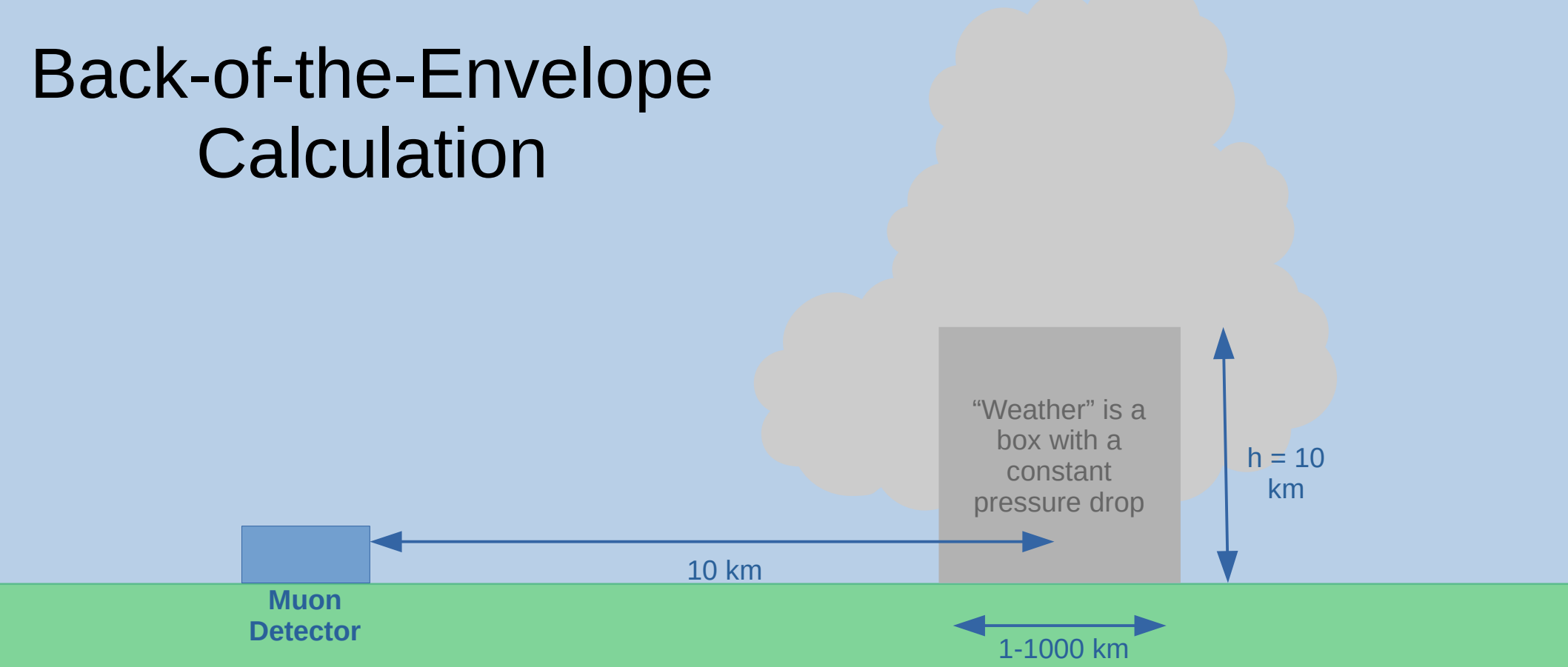
- Effect of hydrometeors (rain, hail)?
- Potential studies with existing detectors?
  - IceCube, P-ONE, KM3NET, Auger, TA, others?
- Capabilities of something portable?
- Best detector design?
- Applications to other weather systems?
  - Hurricanes, derechos, microbursts
  - Muon data as an input for weather/climate forcasting?

A Portable Detector?

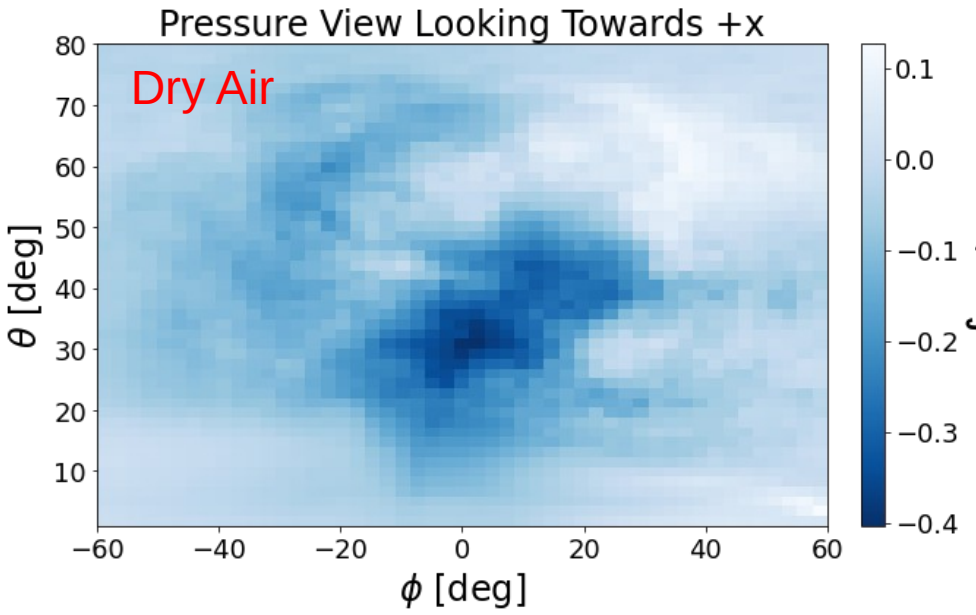
- Smaller detectors result in a weaker signature, but potentially still detectable
- Portable (truck-sized) detectors could probably observe a pressure drop in the direction of the storm, but not the tornado itself
- ~10s of m^2 isn't unrealistic!
  - Being far from the storm means setup times can be much longer

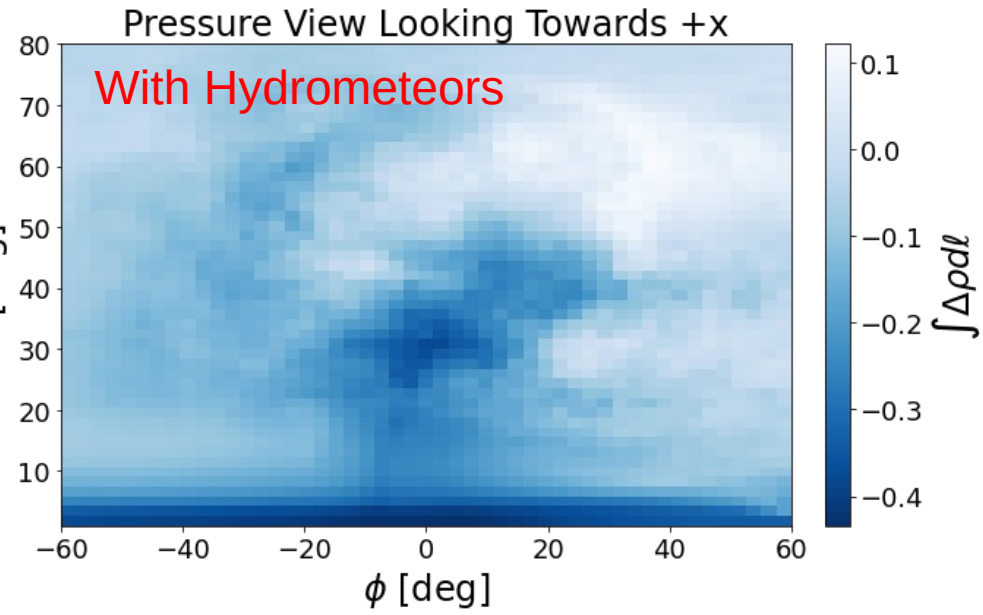


Back-of-the-Envelope Calculation

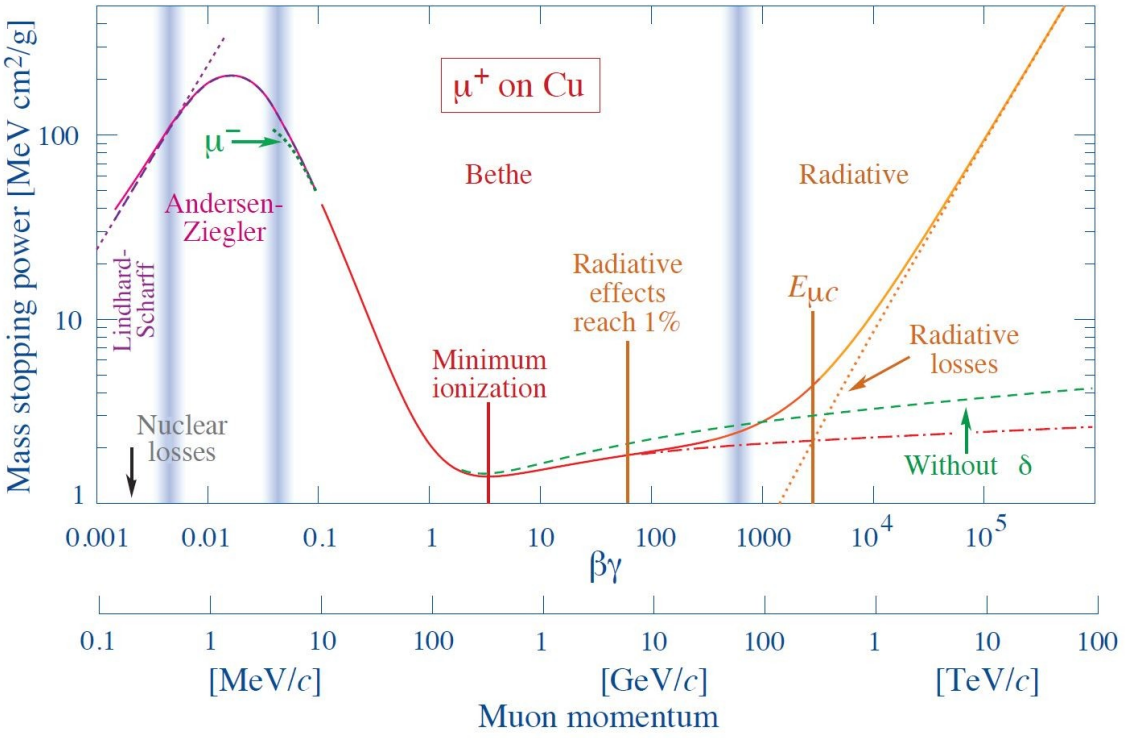


Hydrometeors





Atmospheric Muons



Atmospheric muons have nice properties:

- Numerous (~1 $cm^{-2}min^{-1}sr^{-1}$)
- Long track lengths (~km+)
- Easily detected
- Propagation through matter is well understood

Flux is attenuated by matter

Residual to L Comparison