

# TGFs as a Laboratory for understanding particle acceleration

Ger Fitzpatrick for the *Fermi* GBM TGF-Team



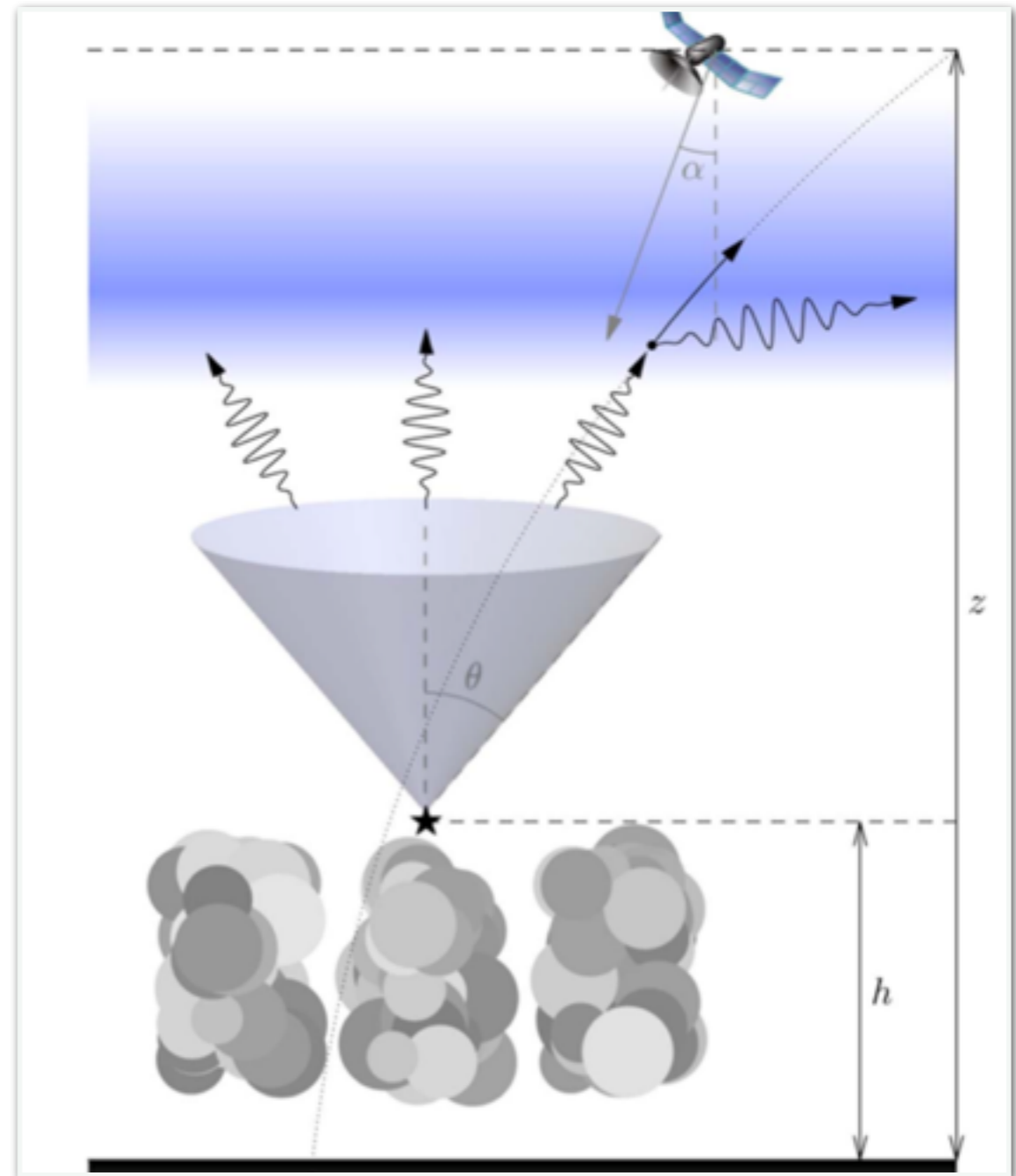
Image Credit: Reuters and NASA



# High Energy Atmospheric Phenomena

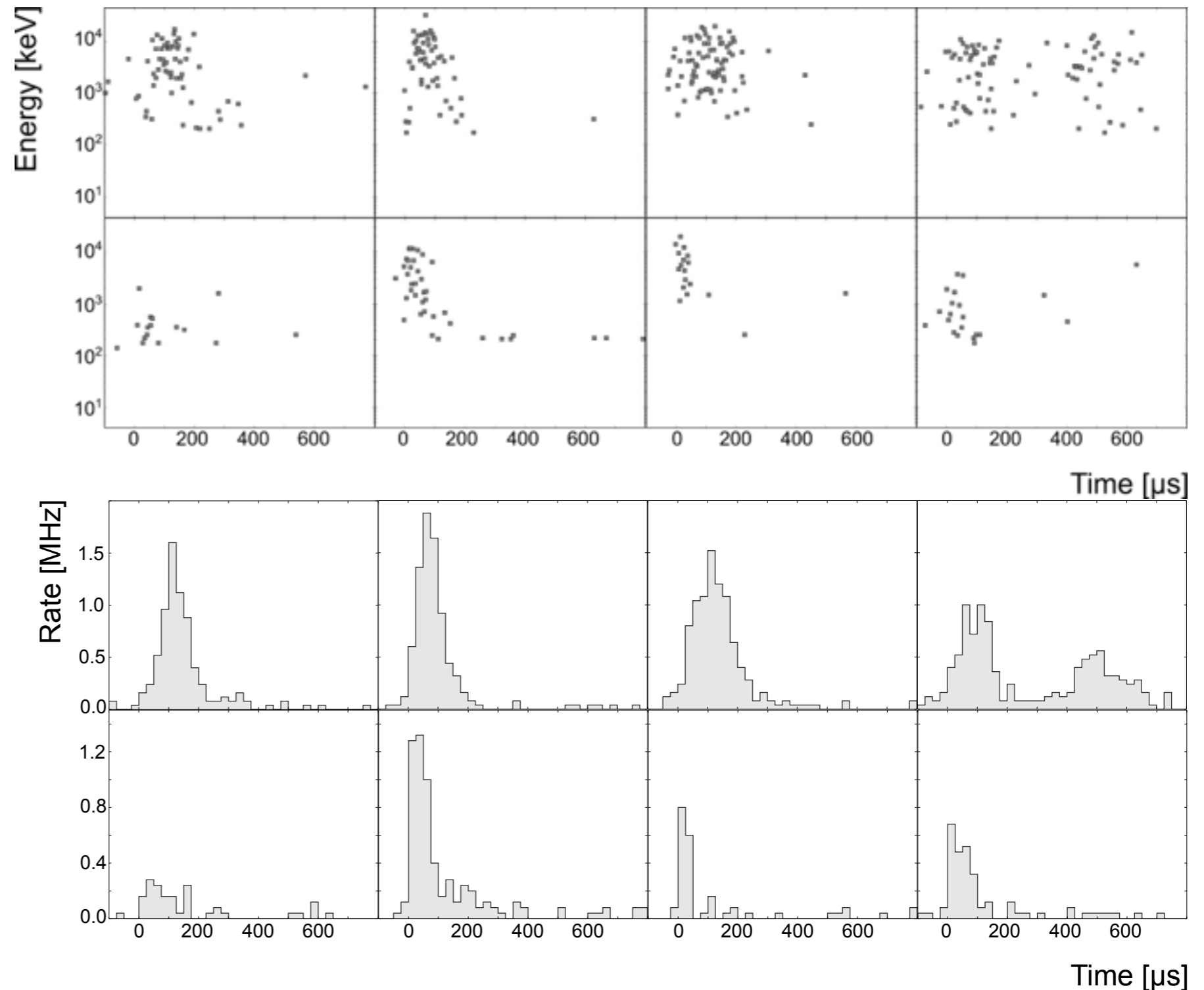
## Terrestrial Gamma-ray Flashes

- Larger family of energetic atmospheric phenomena
  - x-rays, gamma-ray flashes, gamma-ray glows
- Short intense flashes of gamma-rays
- Associated with lightning activity in thunderstorms
- Observed by gamma-ray detectors in low-earth orbits
- Discovered in 1994
- BATSE, RHESSI, AGILE, FERMI LAT/GBM



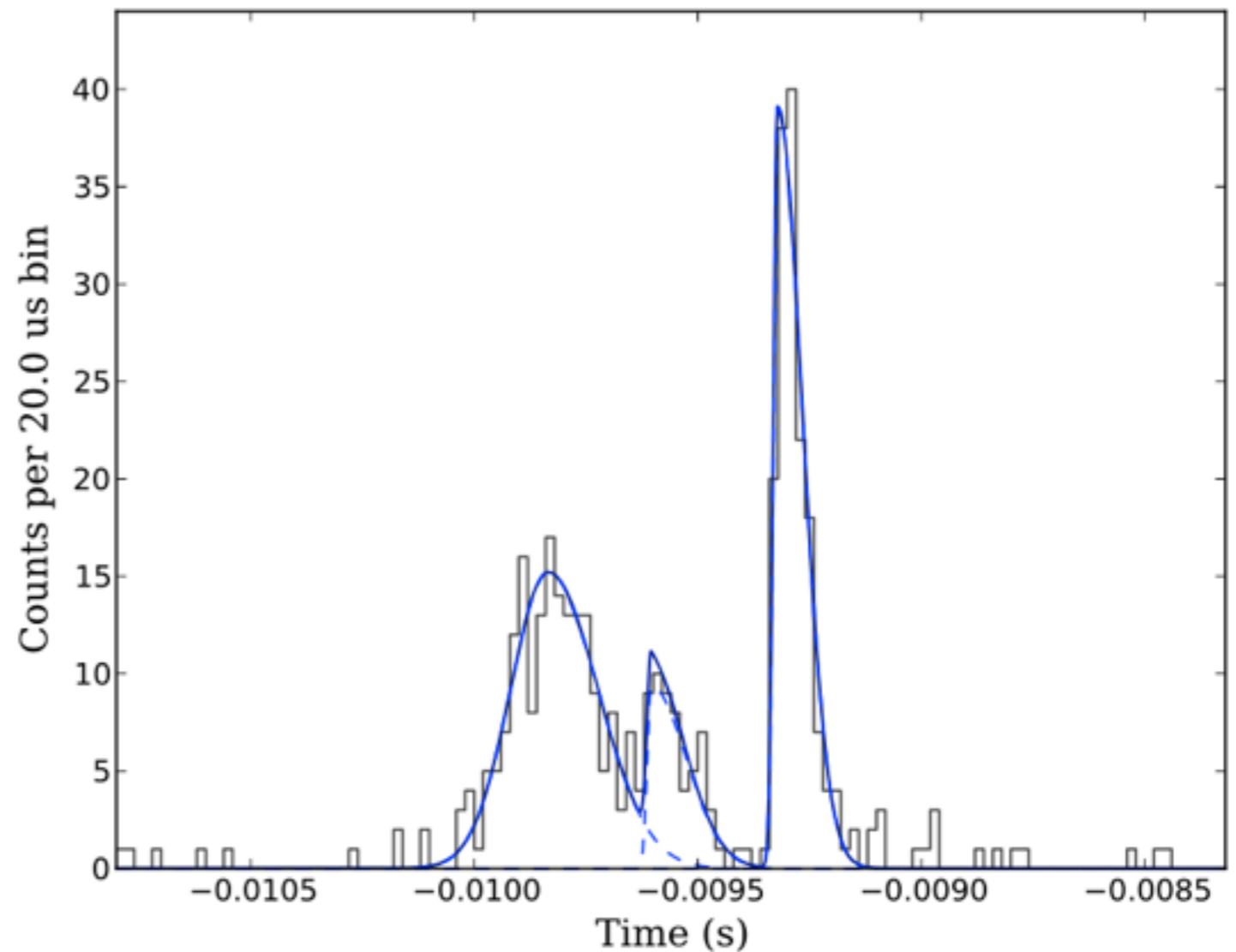
# TGF Observations

- Hard
  - 7 MeV average energy
- Beamed
  - 45 deg cone (half-angle)
- Rapid variability
- Altitude
  - < 15 km
- Source - thunderstorms
  - Correlates well with lightning
- Intra-Cloud Lightning
  - Exact connection disputed
- Meteorological conditions
  - Not well understood



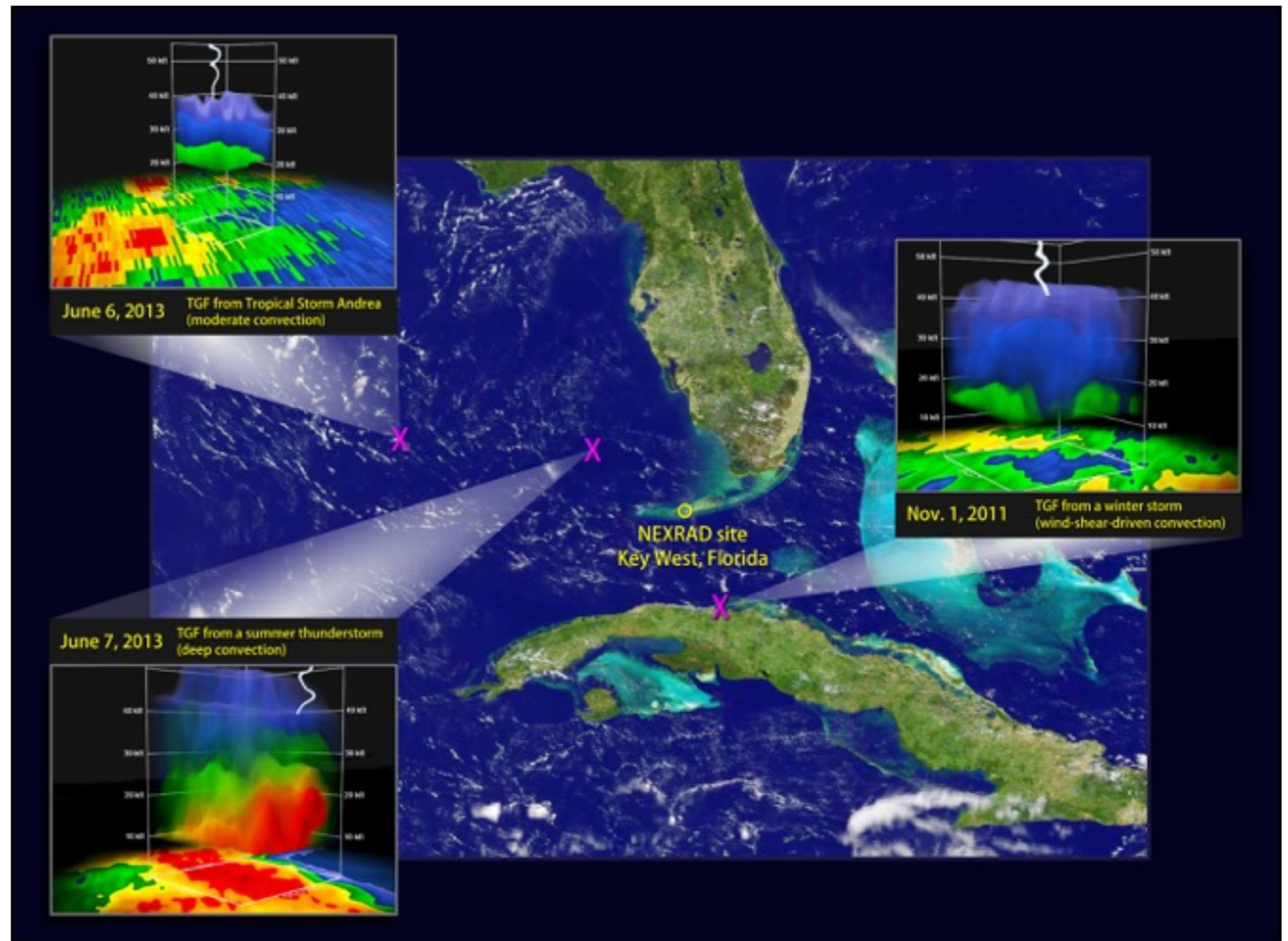
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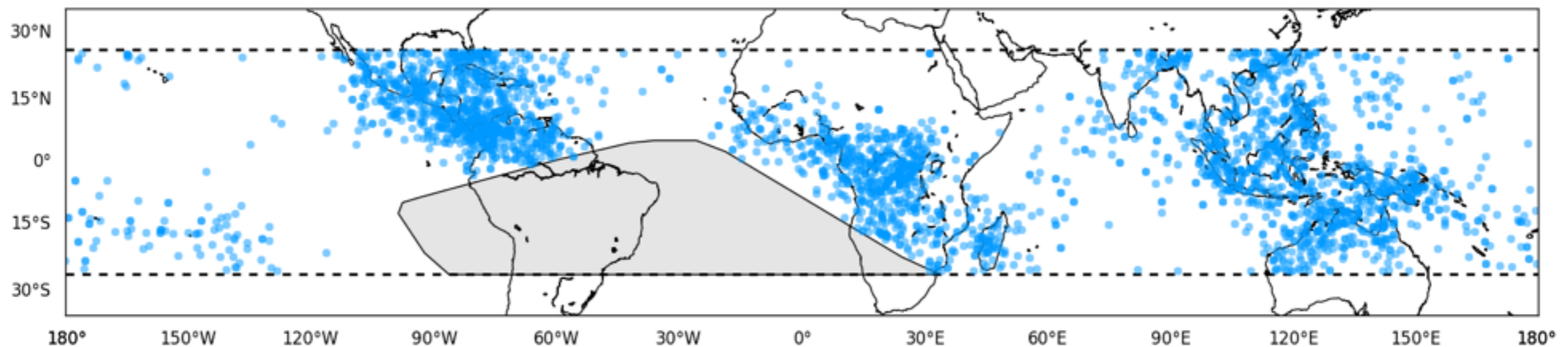
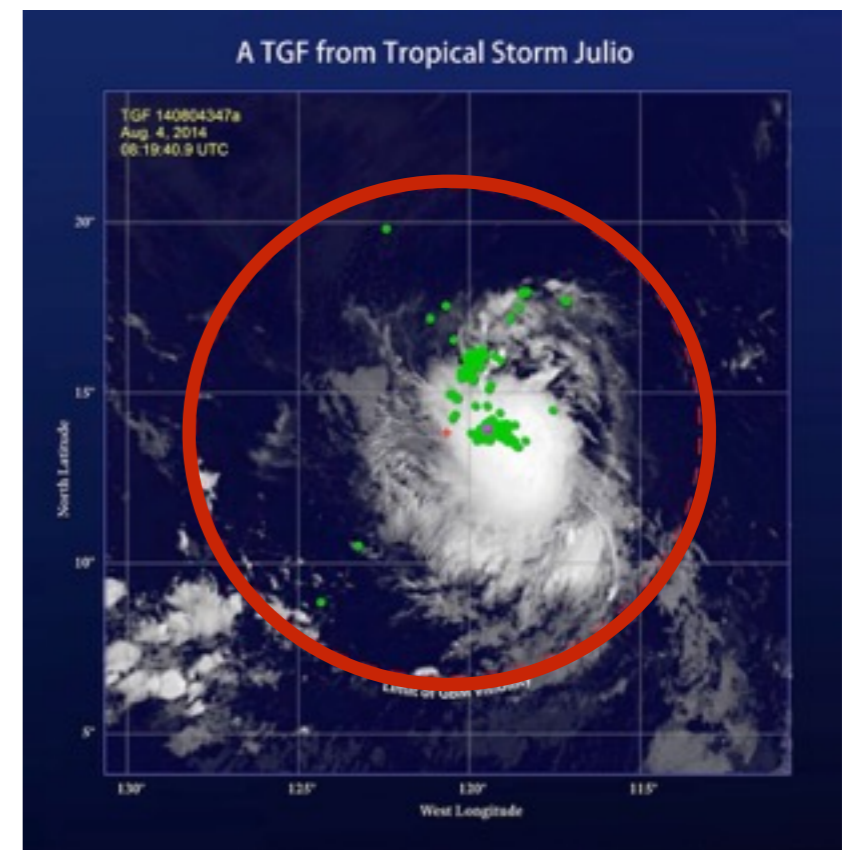
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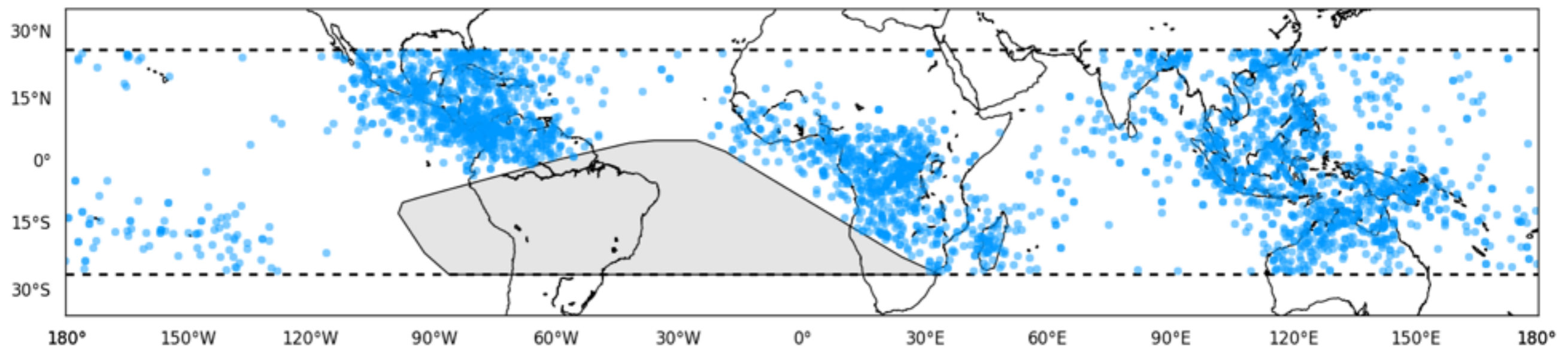
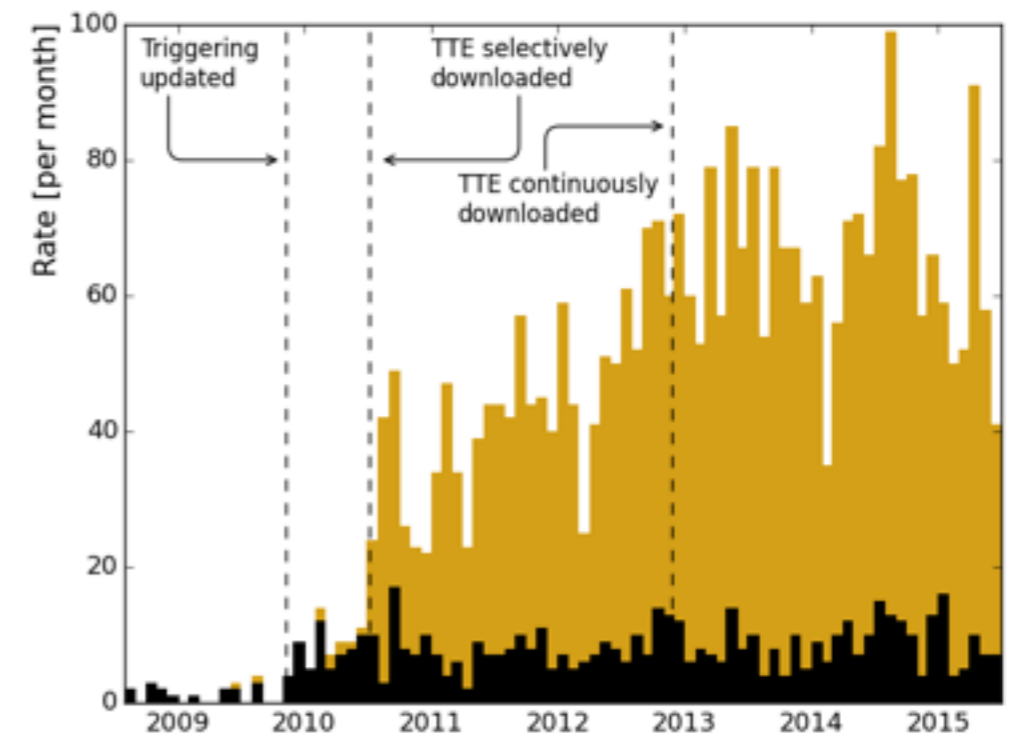
# How common are they?

- What kind of storms?
- ~750 observed per year
- How many occur in total?
- Instrument & calculation dependent
  - 400,000 per year [Briggs et al., 2013]
  - 2 million per year [Ostgaard et al., 2012]



# How common are they?

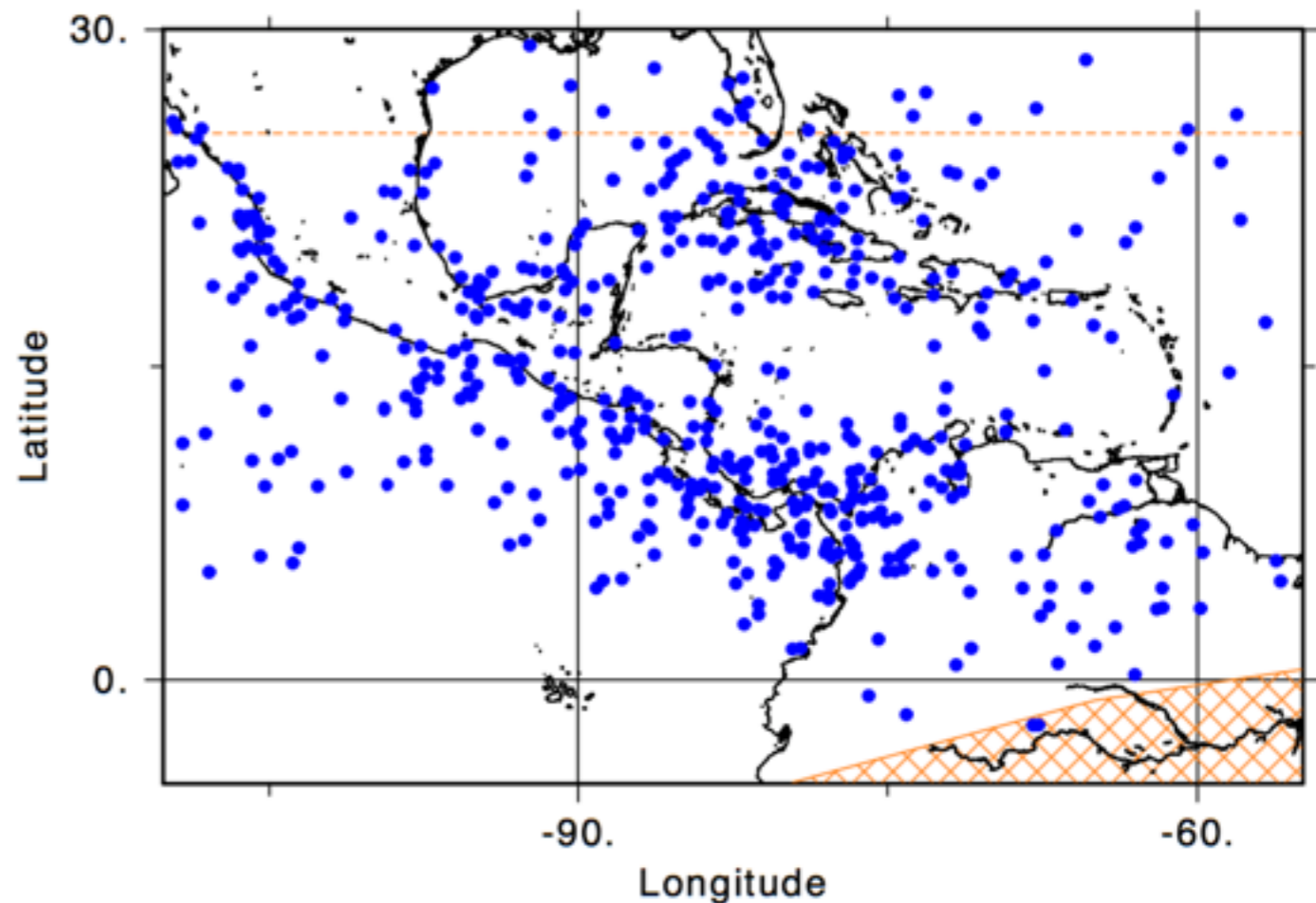
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# Multi-Wavelength observations key

Facilitates studies into:

- Production mechanisms [e.g. Connaughton et al., 2012]
- Location [e.g. Briggs et al., 2103, Chronis et al., 2015]
- Altitude [e.g. Cummer et al., 2012, 2015]
- Duration [e.g. Fitzpatrick et al., 2014]

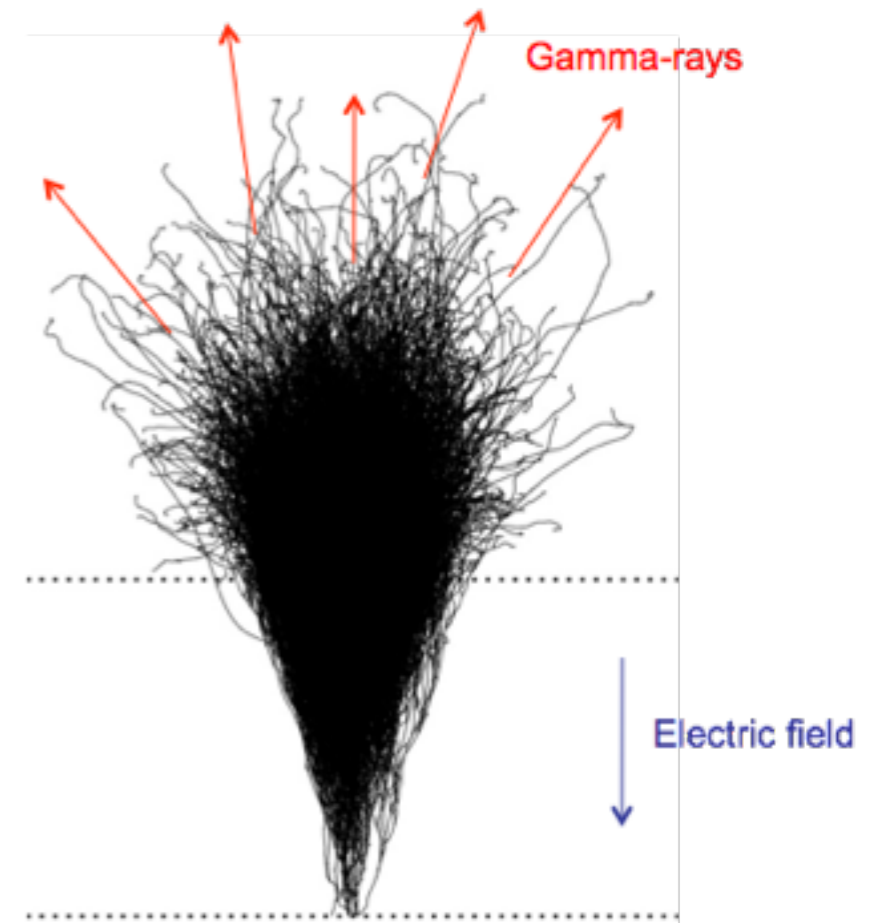
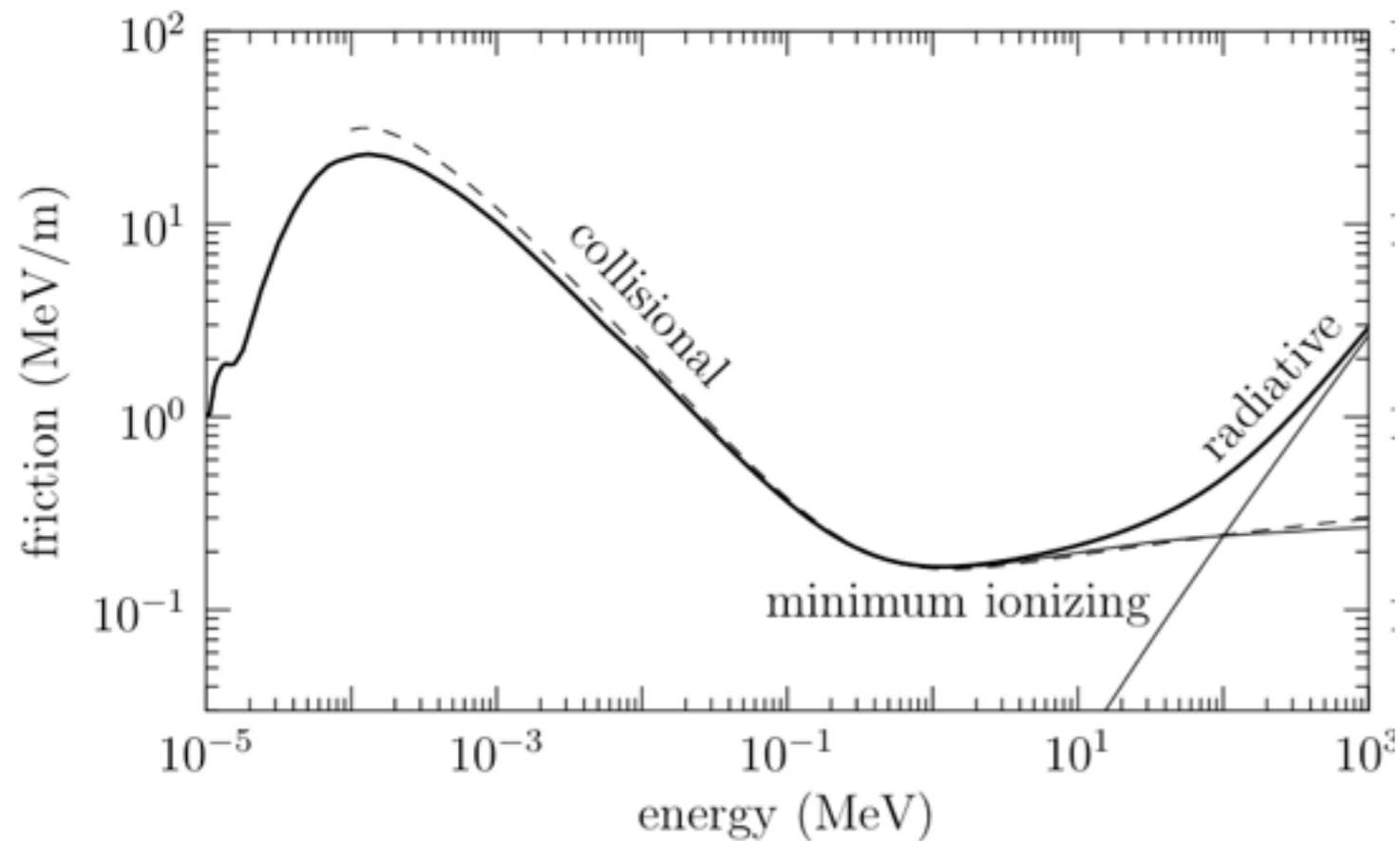




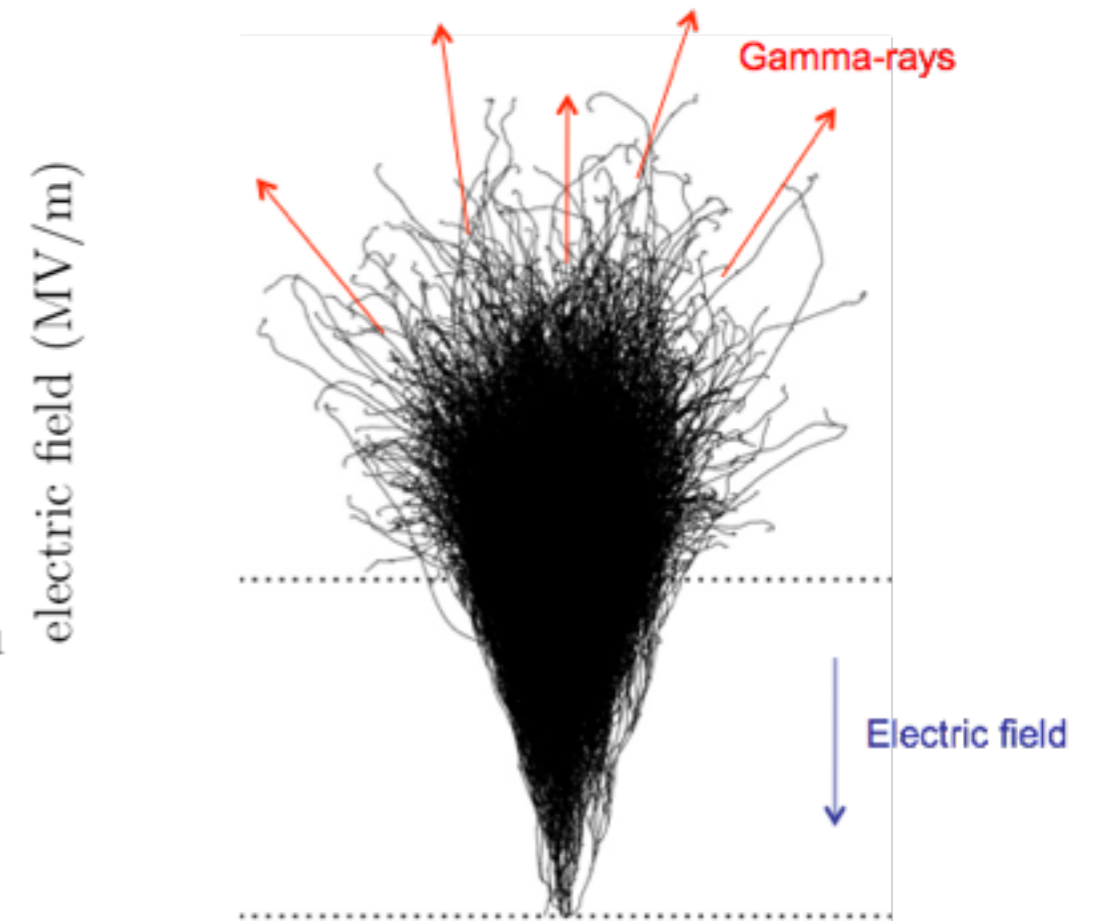
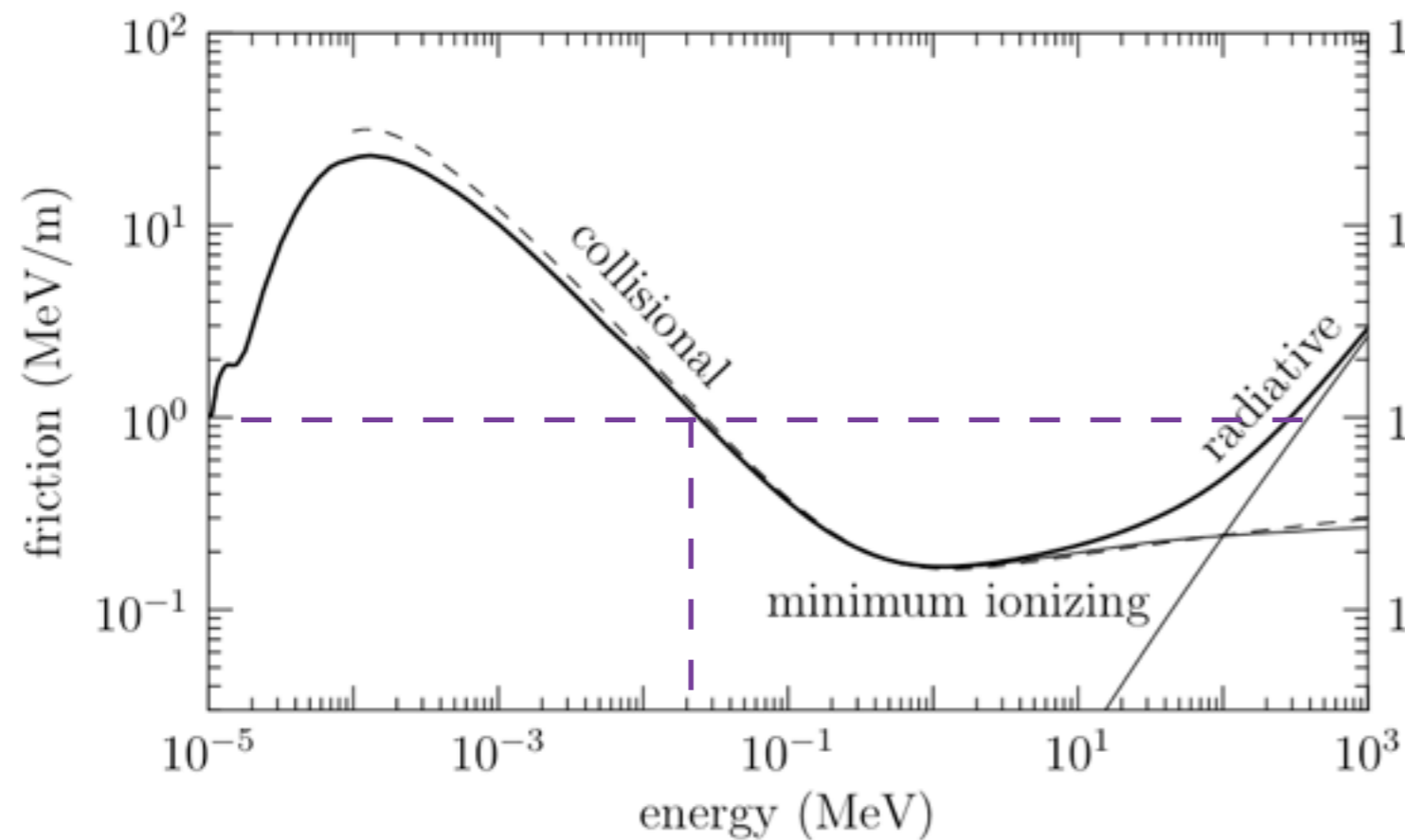


# Production Mechanisms

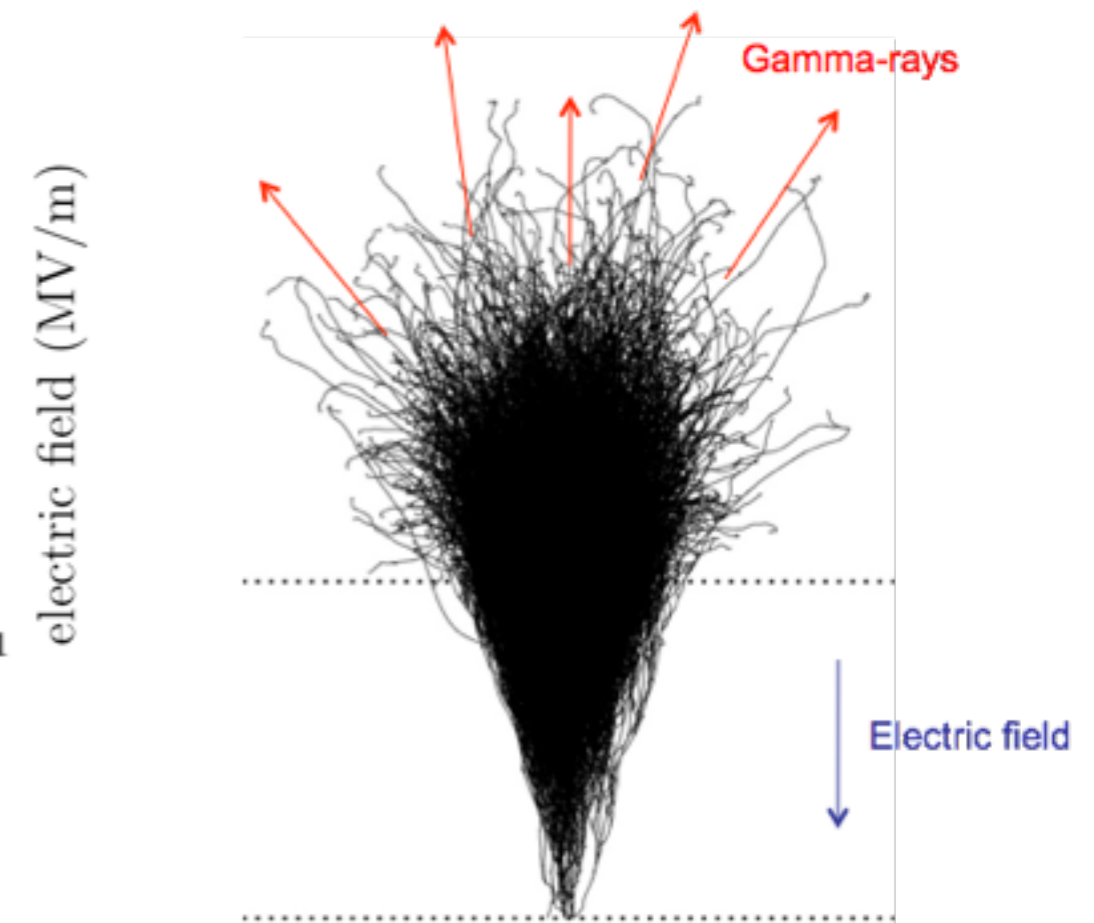
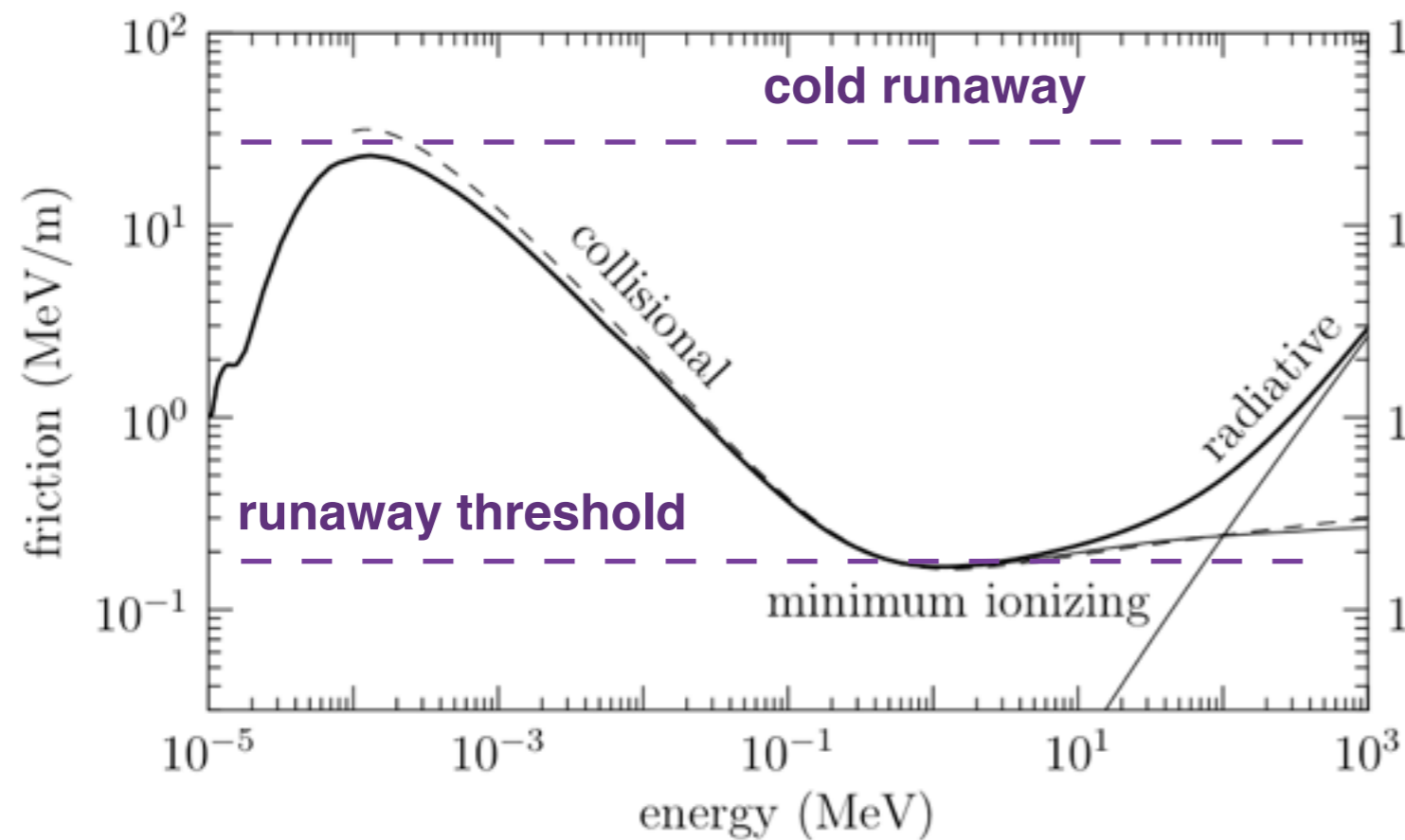
# Relativistic Runaway Electron Avalanche



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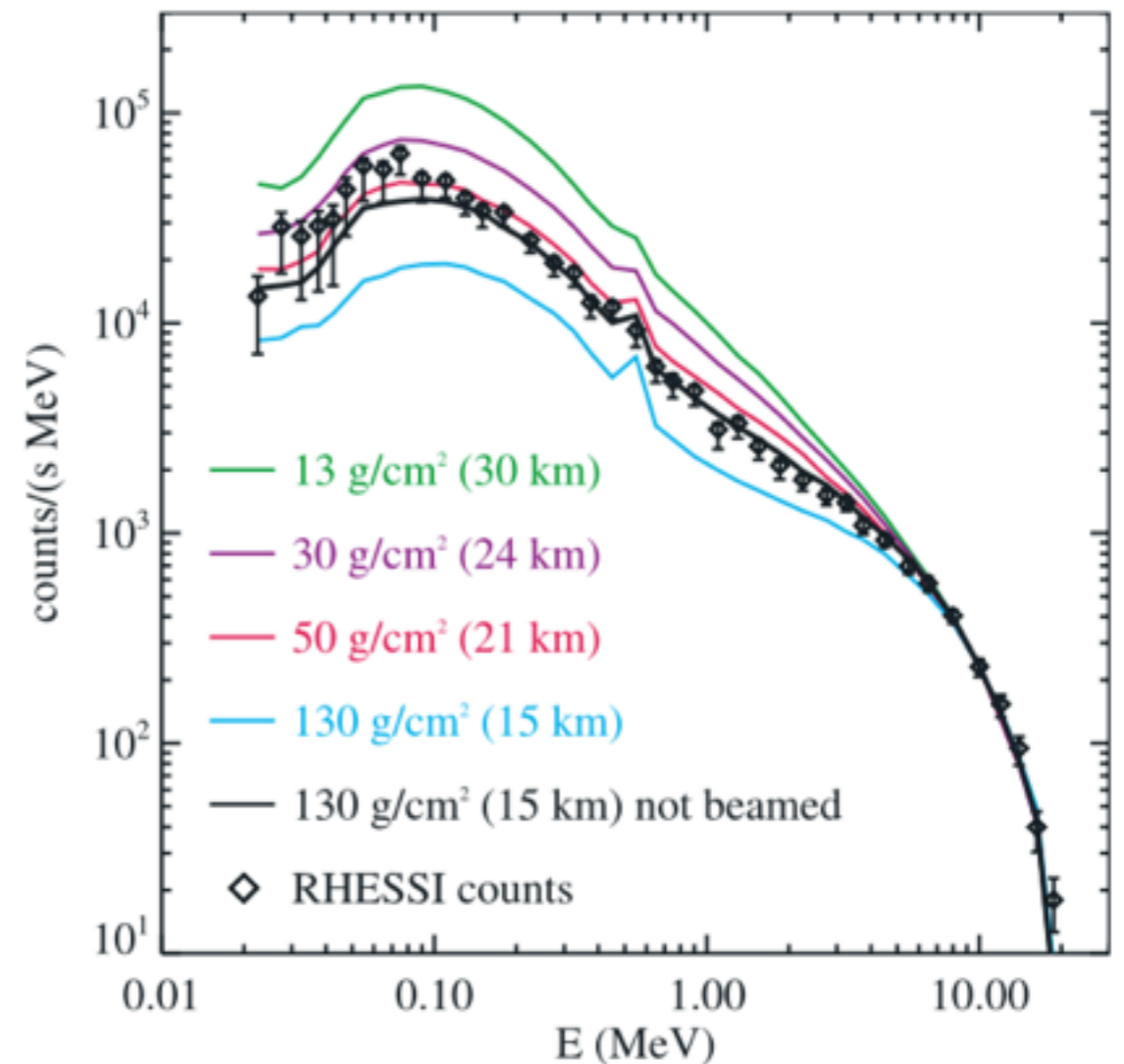


# Relativistic Runaway Electron Avalanche

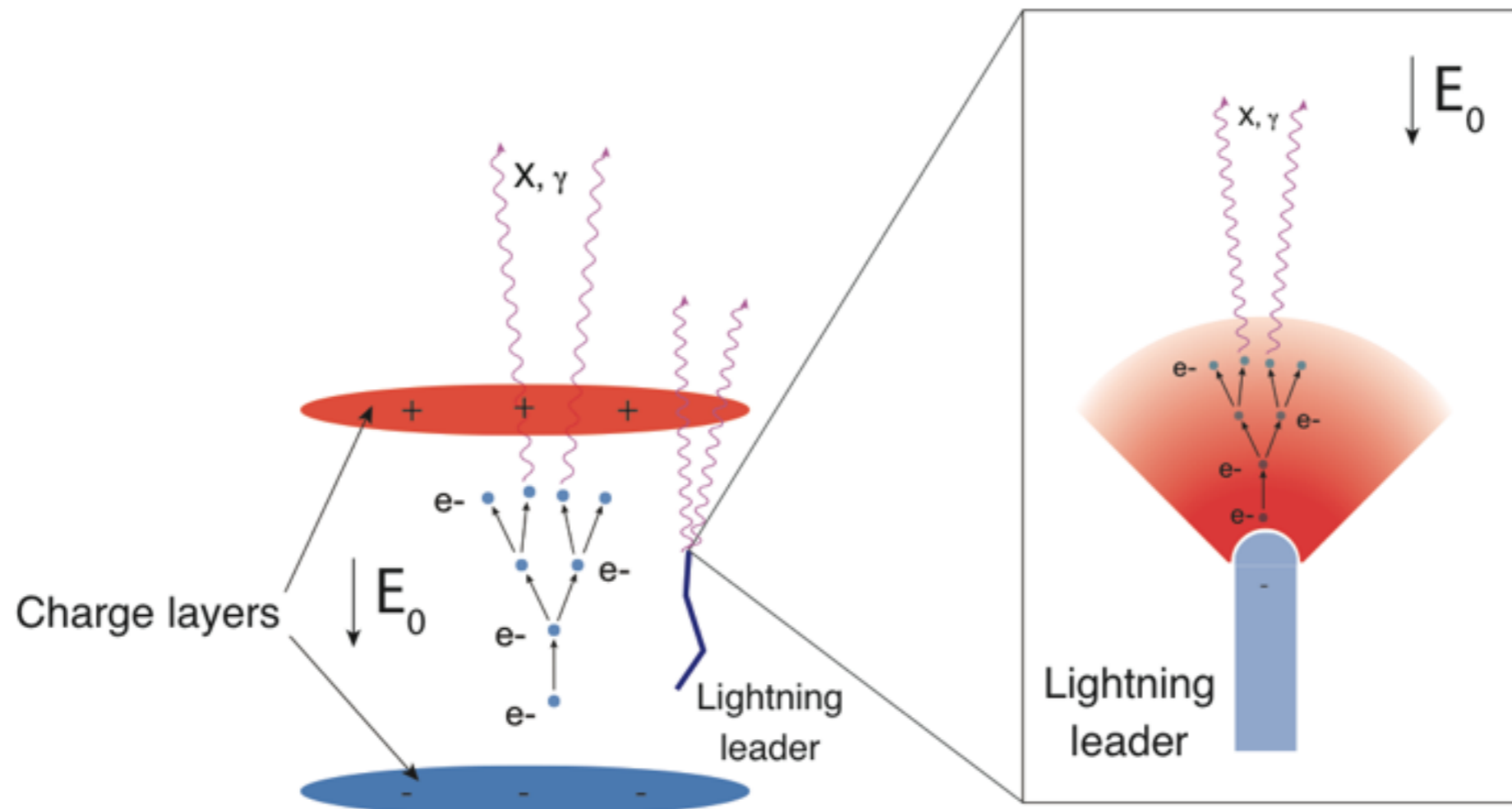


# Spectra

- Avalanche process
- Acceleration in a medium
  - multiplication of secondaries
- Canonical photon spectrum at the source is:
$$f(E) \propto E^{-1} \exp\left[\frac{-E}{7.3 \text{ MeV}}\right]$$
- Spectra at S/C altitudes will be modified by passage through the atmosphere
- Simulations imply that  $\sim 10^{17}$  energetic electrons required at the source



# Two theories - two locations



## RREA with relativistic feedback

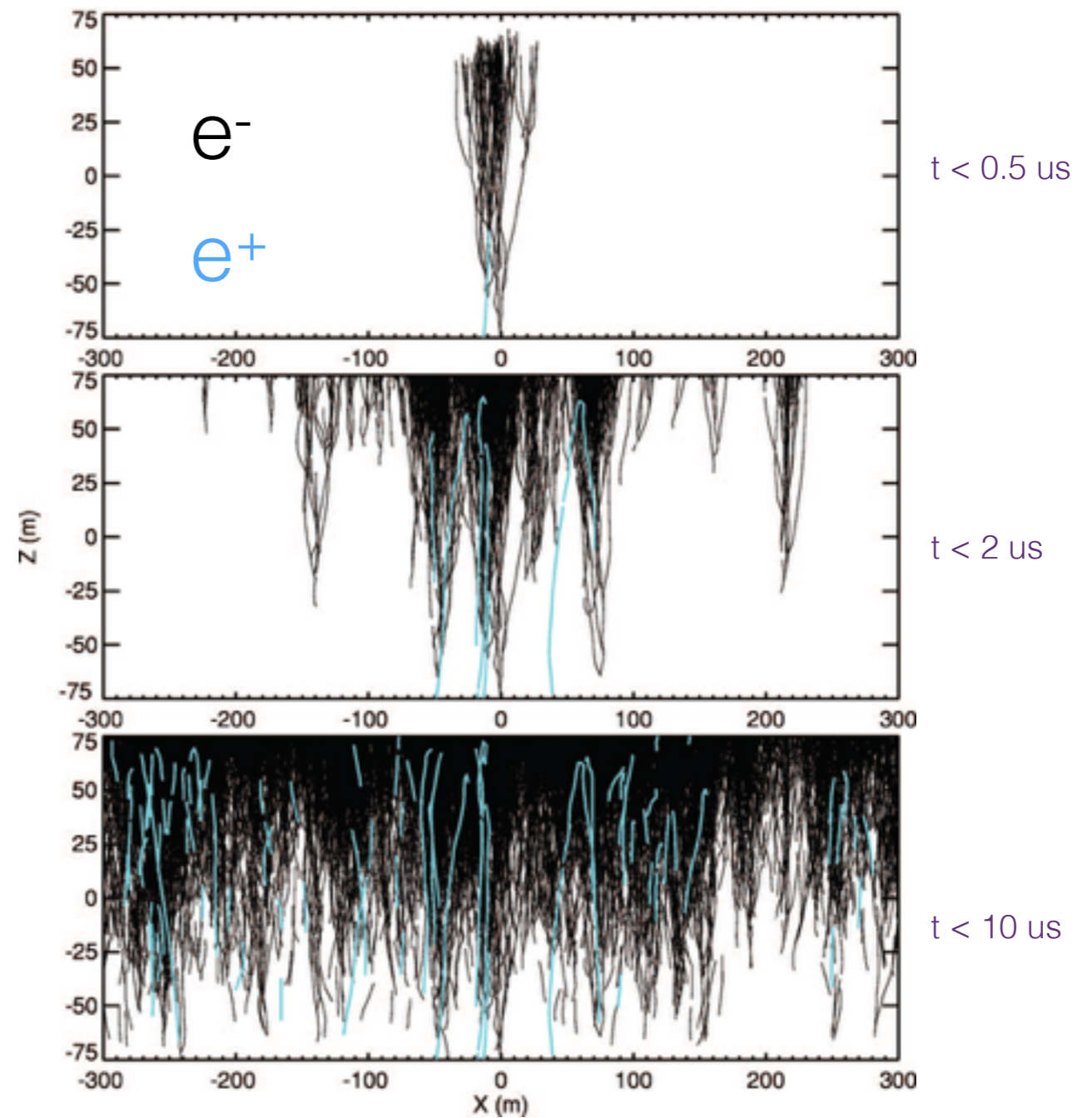
- Strong ambient electric field ( $\sim 300+$  kV/m)
- Large scale ( $\sim 100$  m to  $\sim 1$  km)

## Cold runaway in lightning leaders

- Very strong local field ( $> 10$  MV/m)
- Small scale

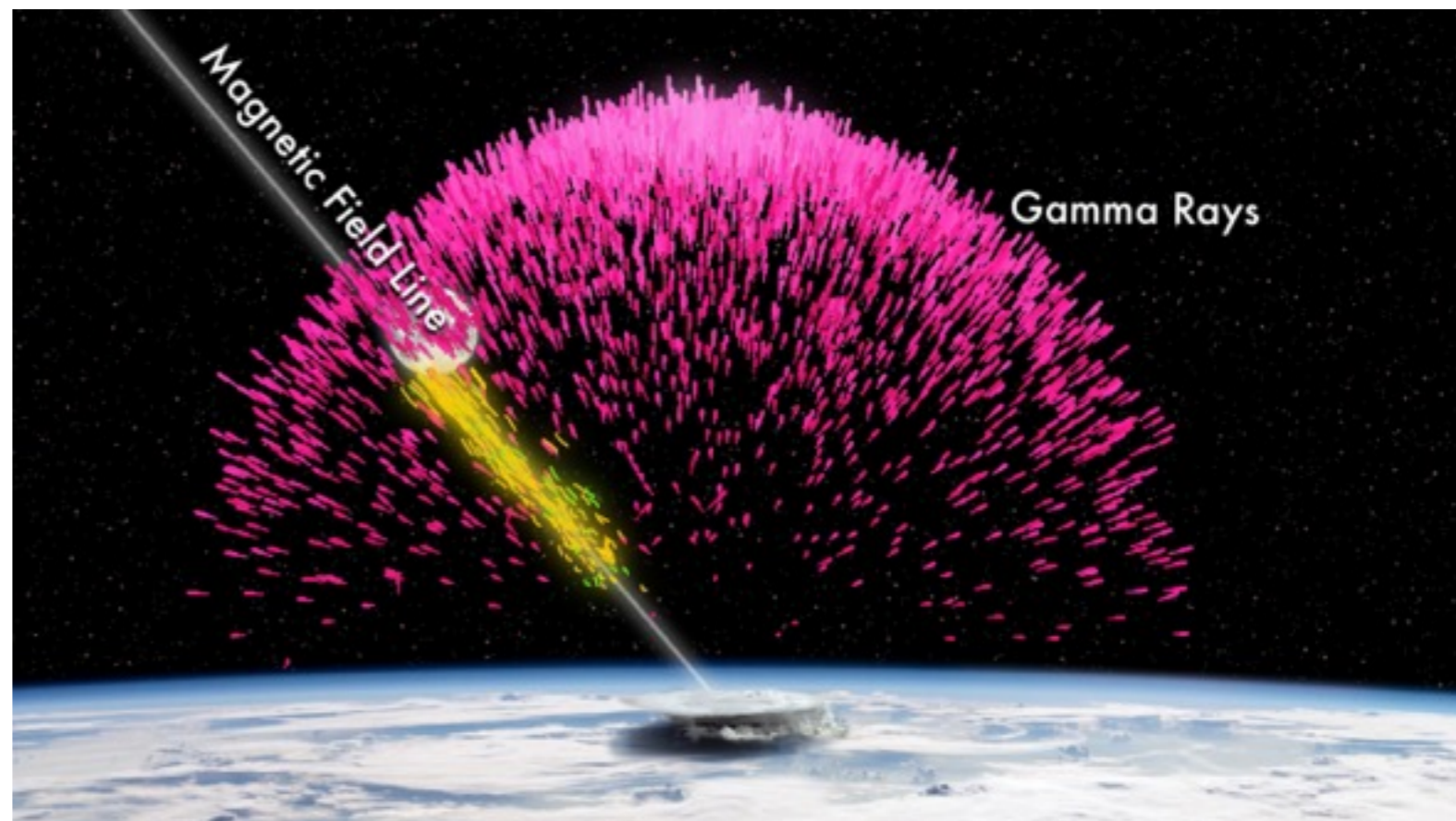
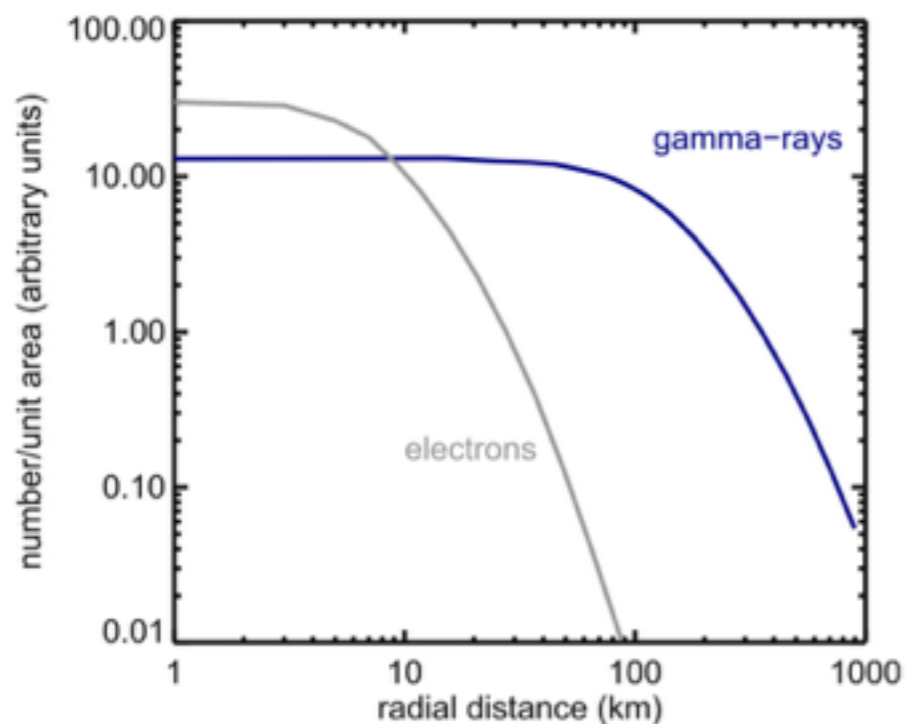
# Relativistic Feedback

- Seed electrons
- Relativistic Feedback
  - positrons
  - back-scatter x-rays
- Explains:
  - Spectra
  - Duration
  - Intensities
  - Radio detections



# Terrestrial Electron Beams

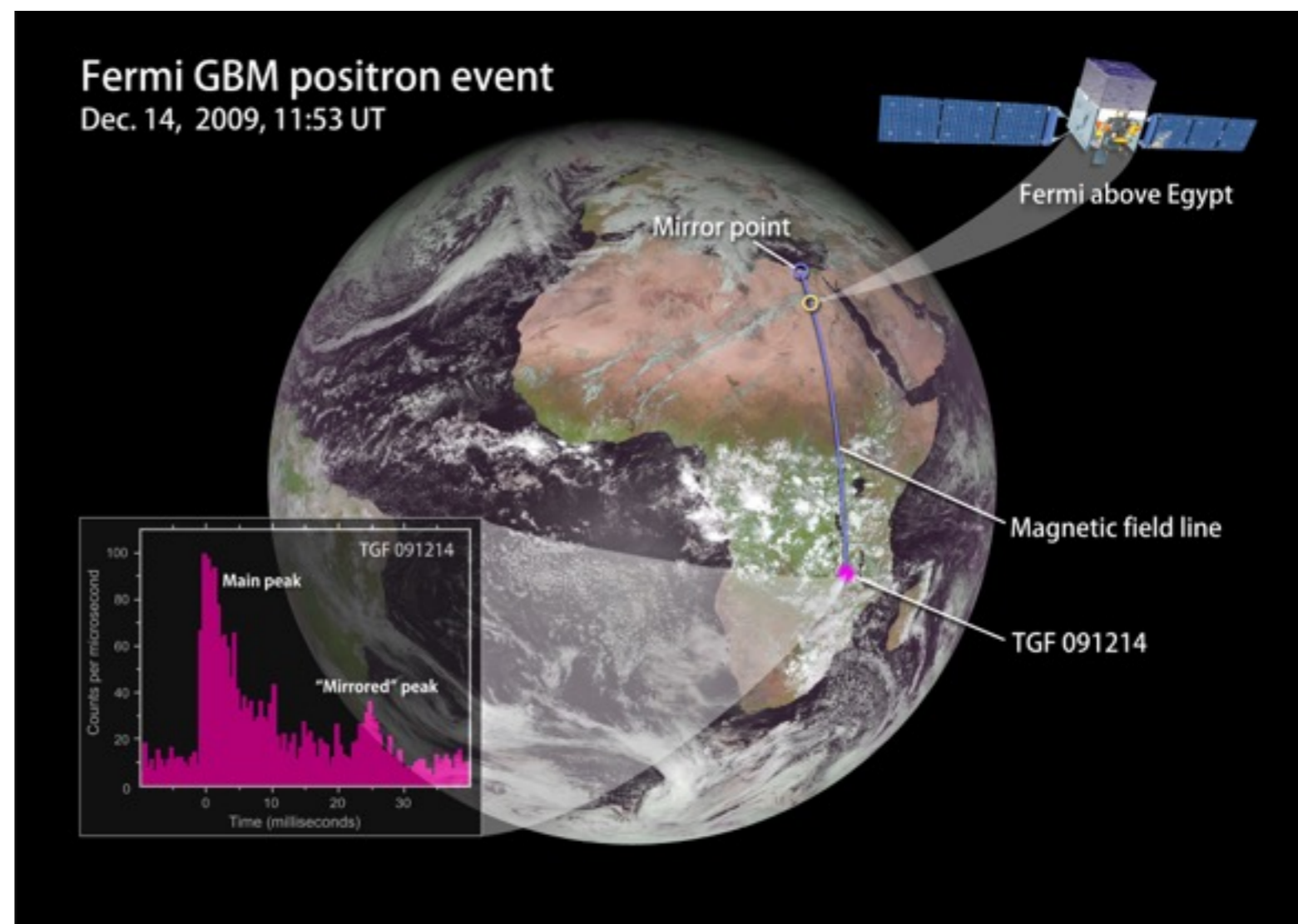
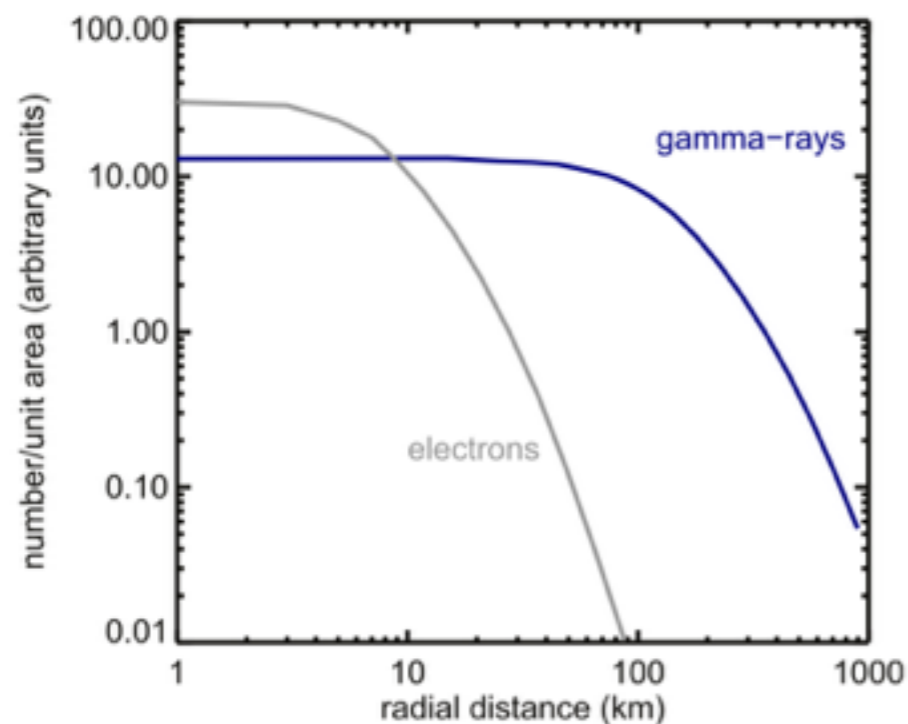
- Primary electrons absorbed, secondary leptons not (entirely)
- Distribution of pitch angles -> temporal dispersion
- Magnetic Mirroring
- positron fraction  $\sim 18\%$





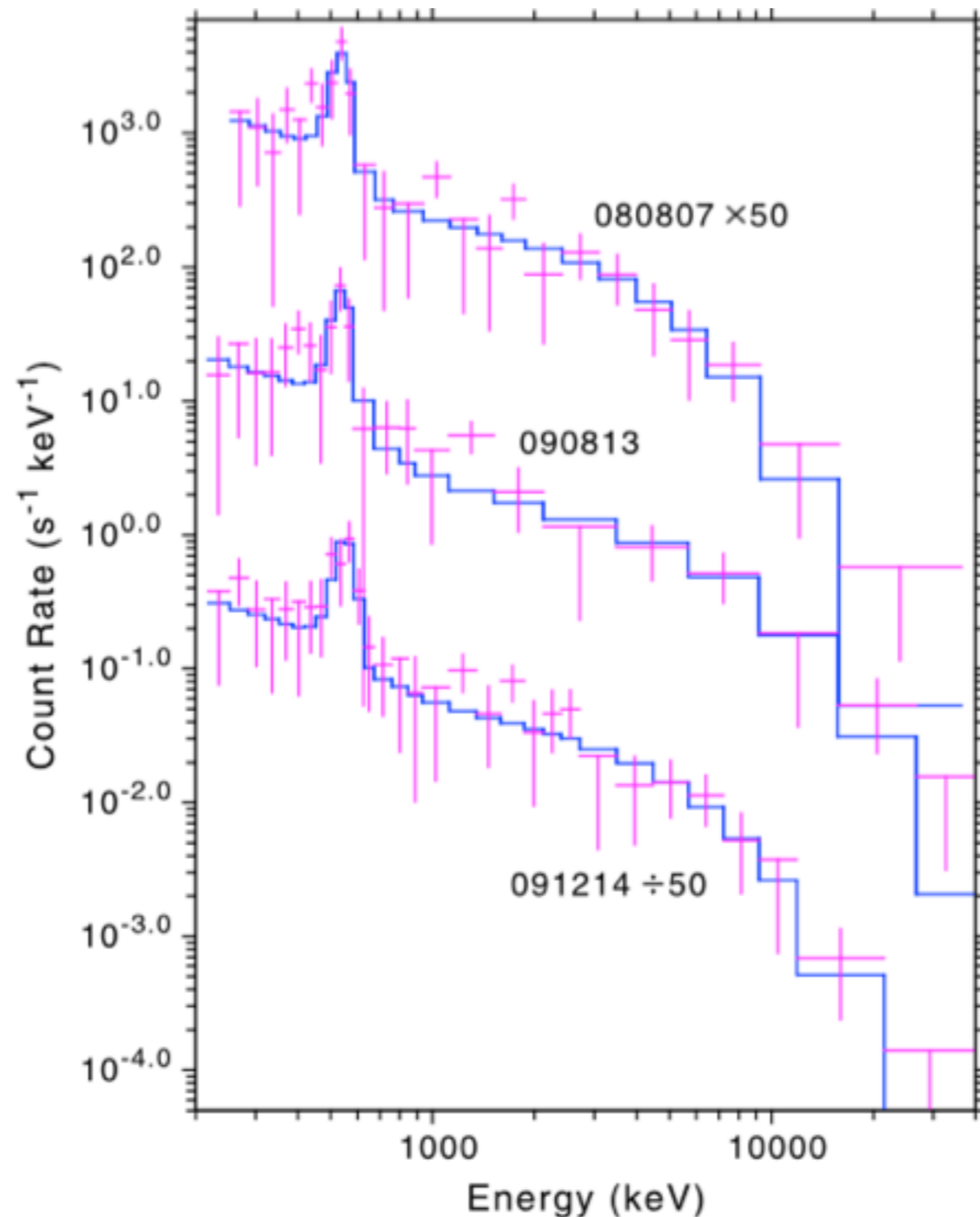
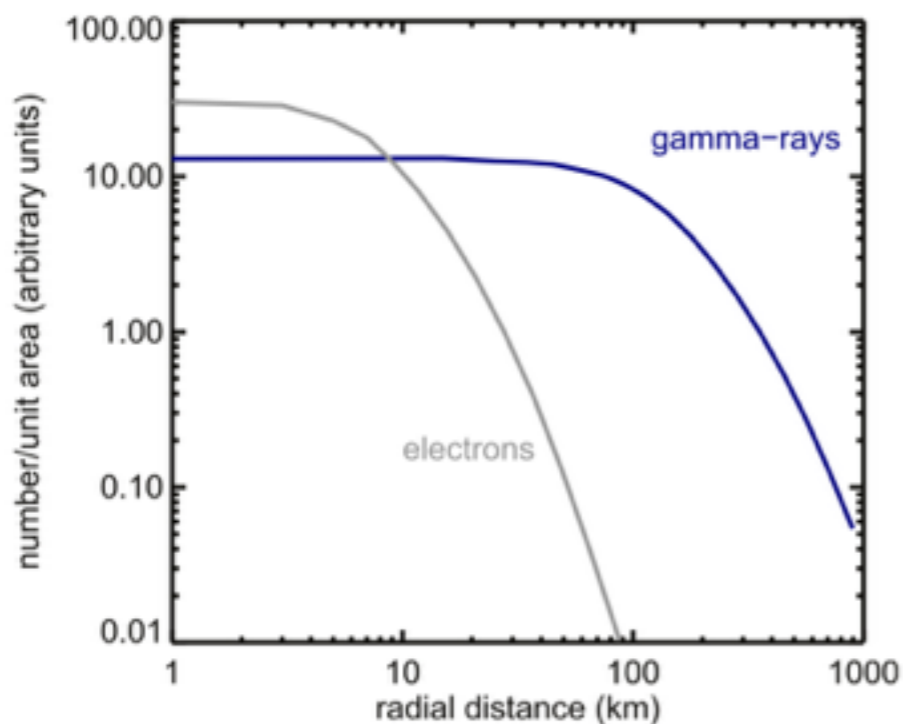
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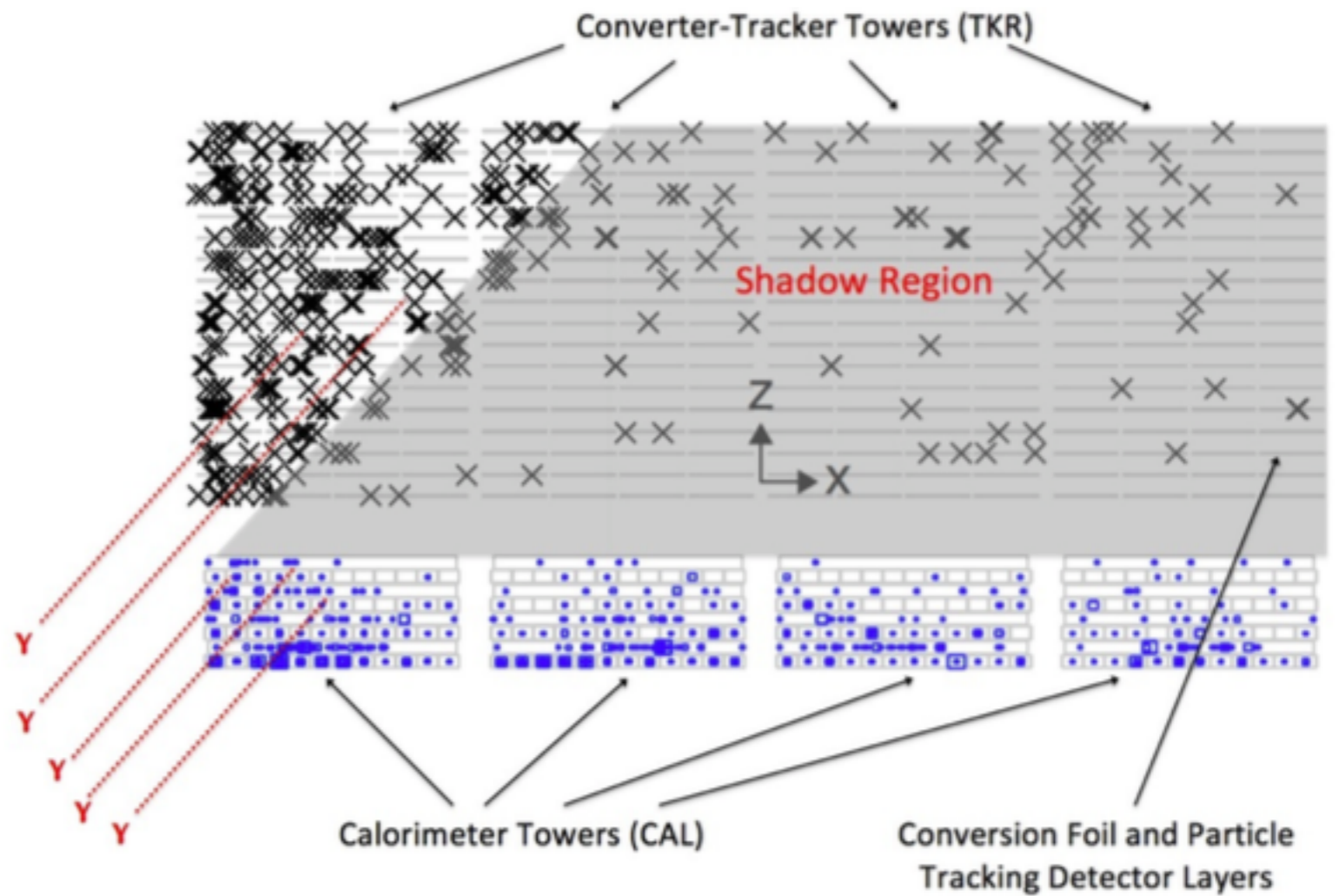


# Fermi Highlights

# LAT Observations

## Geolocating TGFs directly from gamma-ray observations

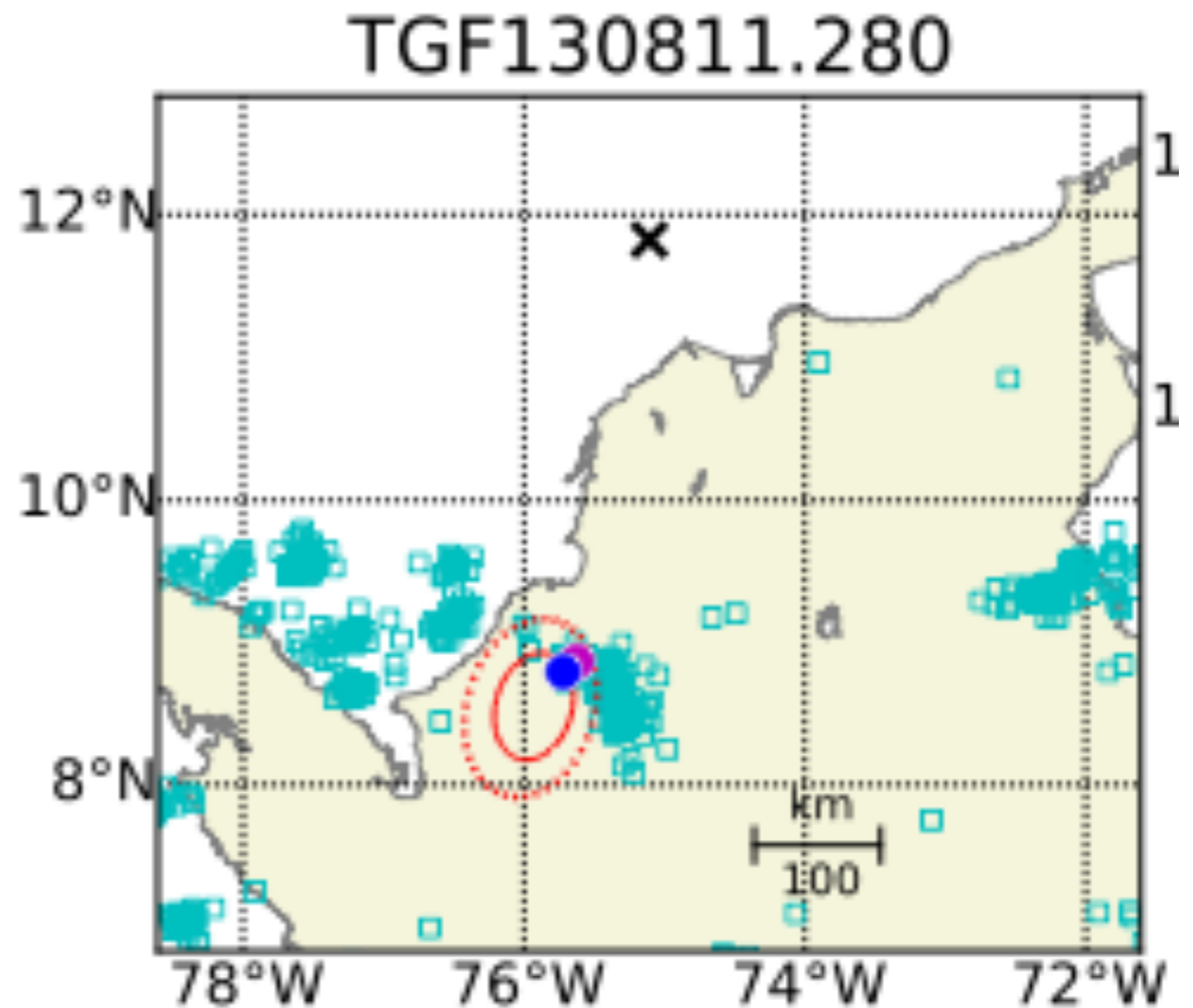
- Calorimeter casts shadow on tracker for photons coming from nadir
- TGFs are bright - complicates analysis
  - high multiplicity
  - tens or hundreds of photons per single LAT “event”



[Poster: Terrestrial Gamma ray Flashes as Seen by the Fermi LAT](#)  
J. E. Grove et al.

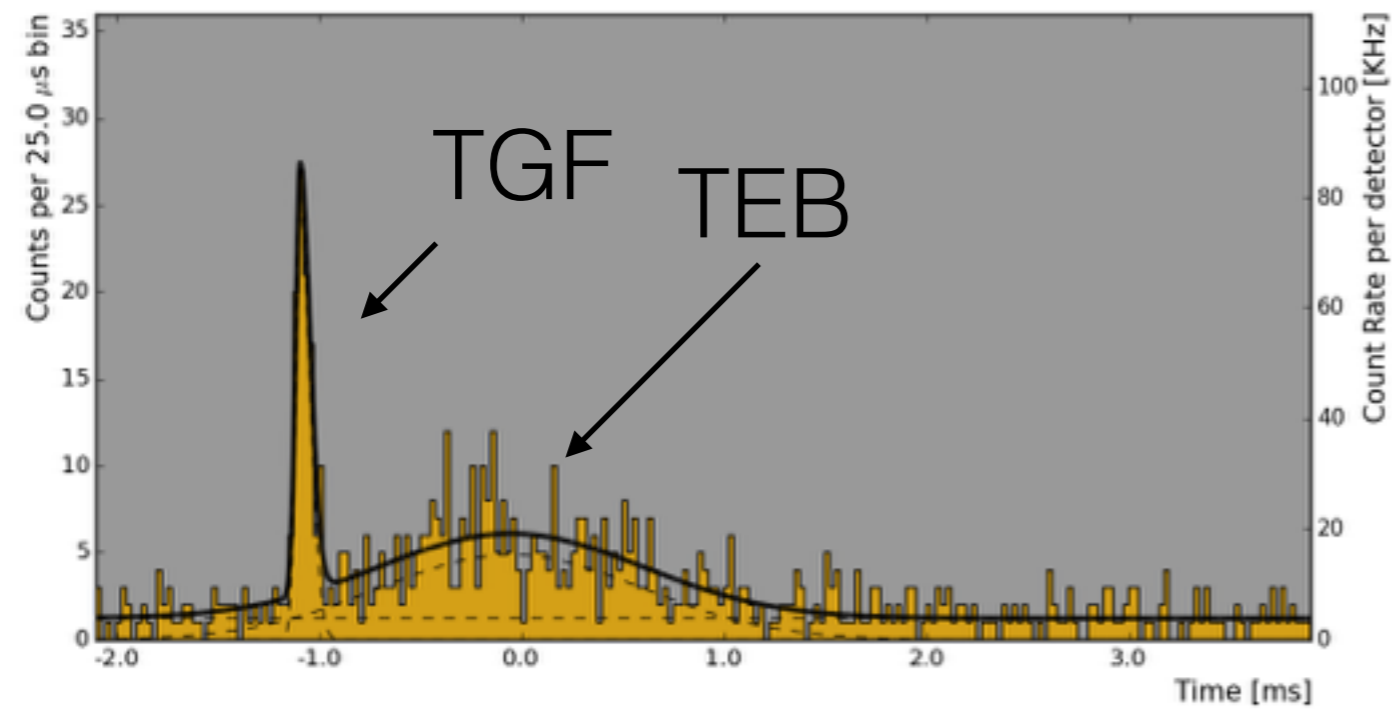
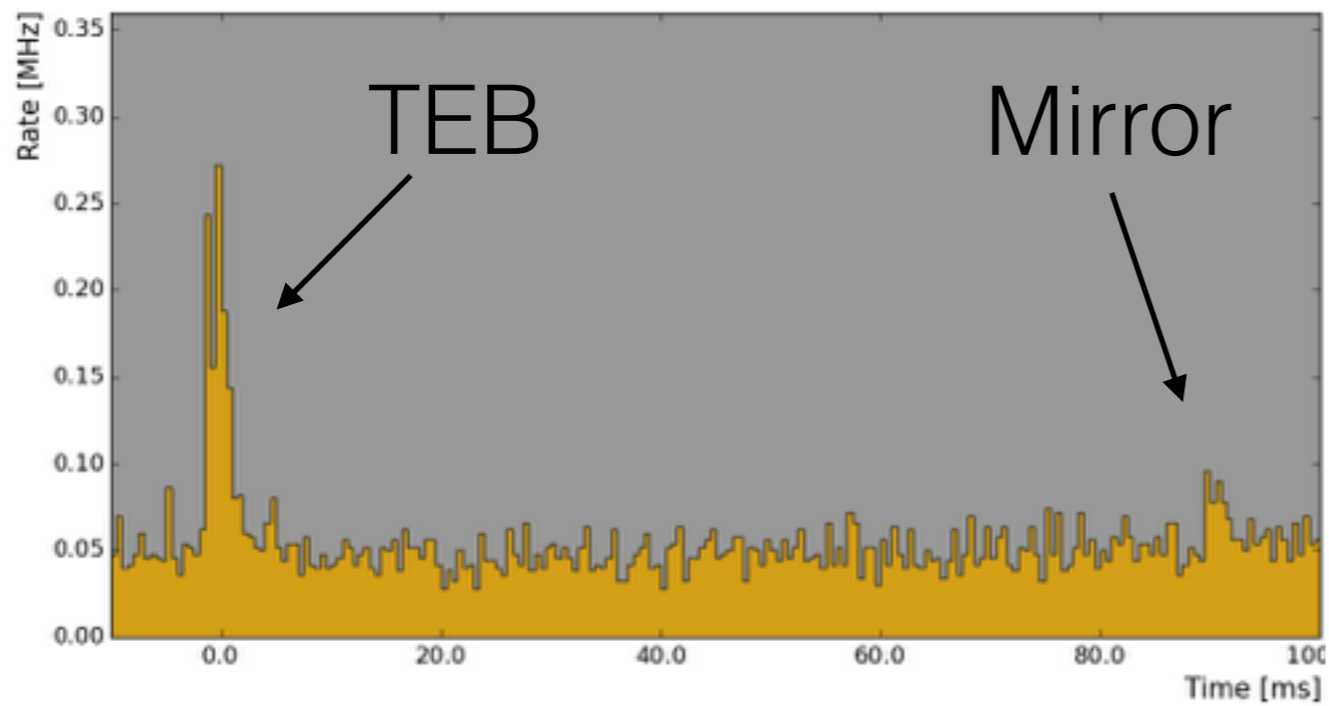
# LAT Observations

- More than 150 TGFs geolocated from gamma-rays
  - 19 have both good gamma and radio locations
- Gamma & radio spatially and temporally coincident
  - Supports hypothesis that gamma and radio have a common origin
- Storms with modest lightning activity can produce bright TGFs

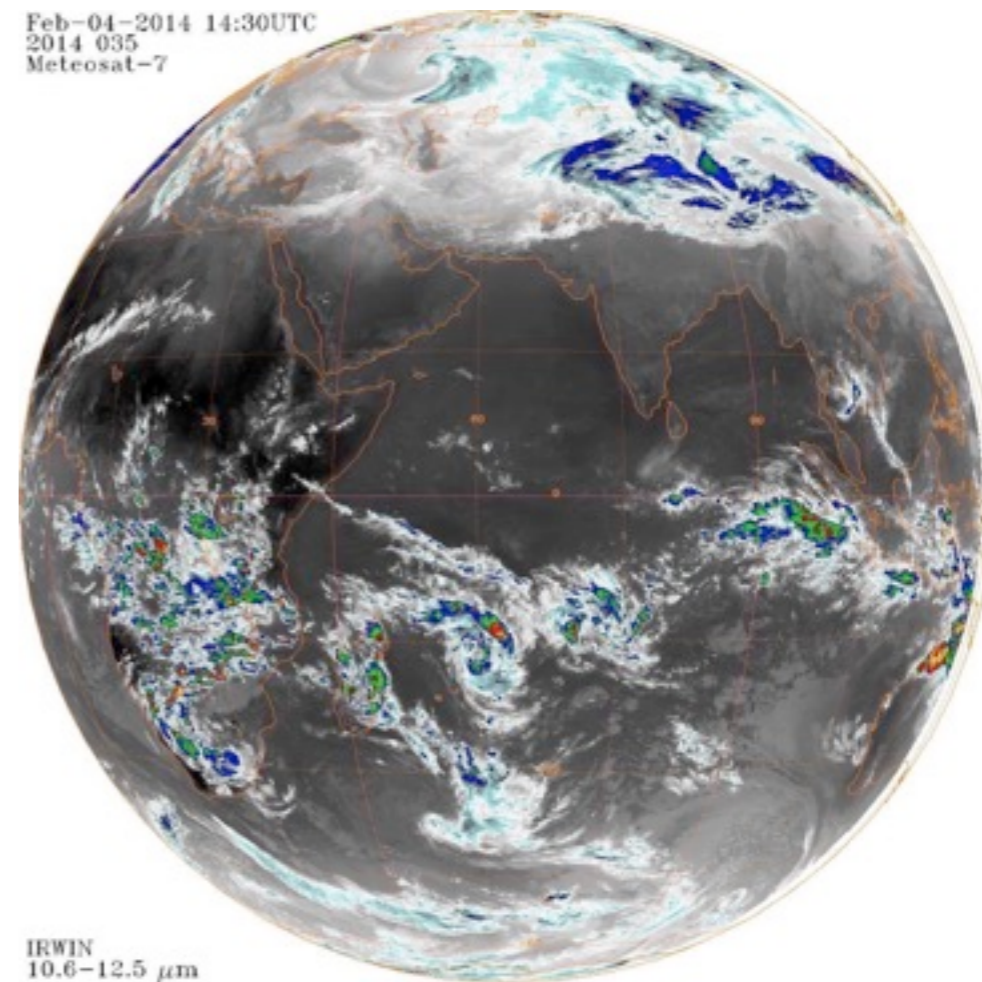


**Poster: Terrestrial Gamma ray Flashes as Seen by the Fermi LAT**  
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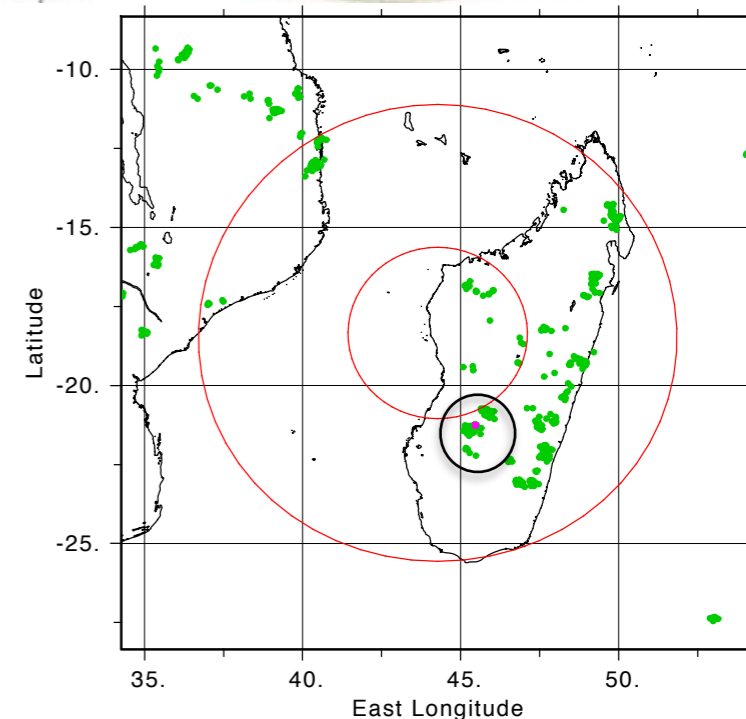
# TGF 140204



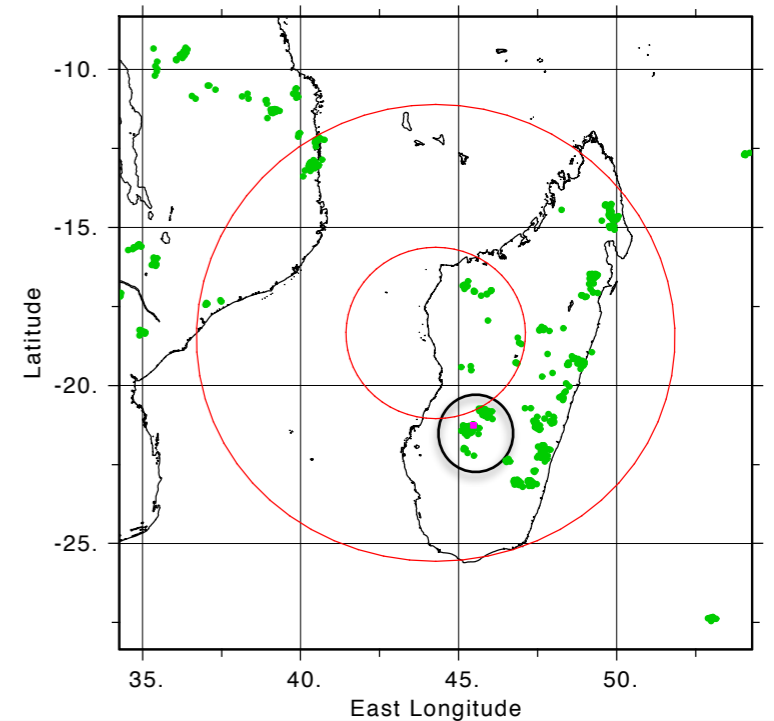
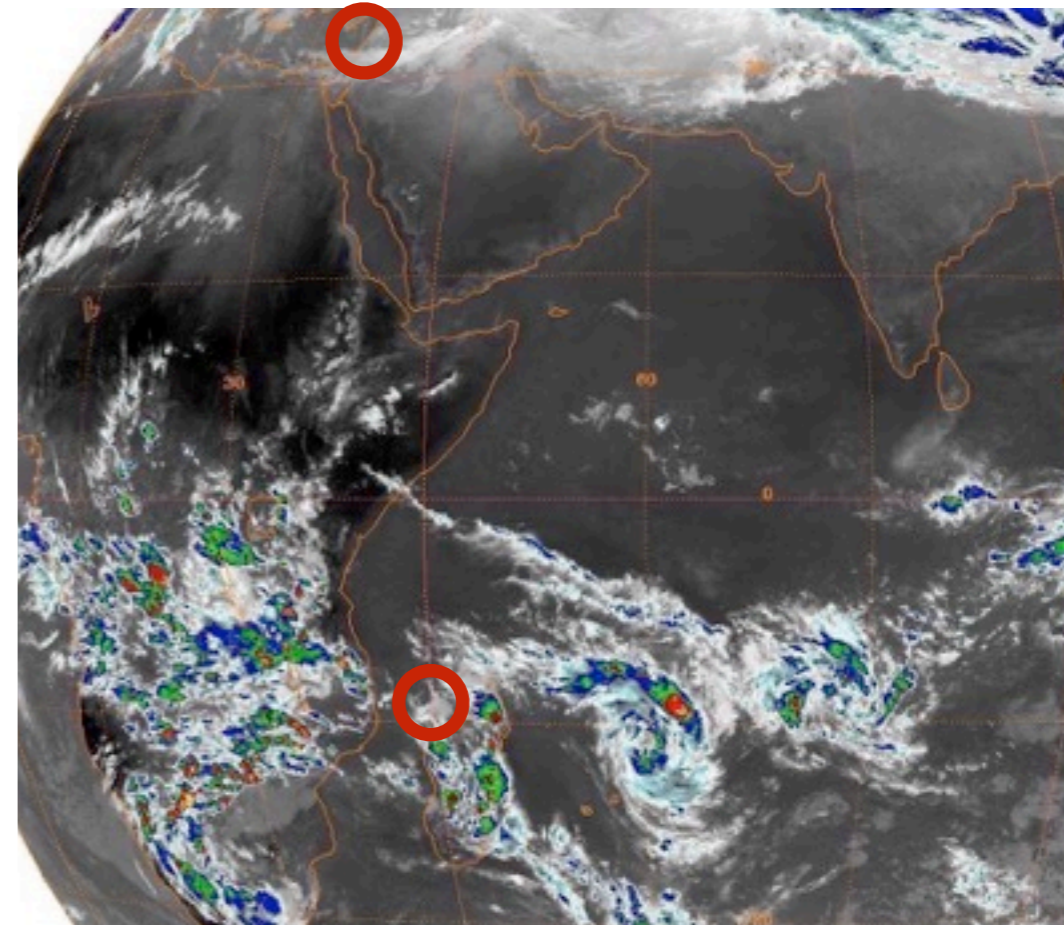
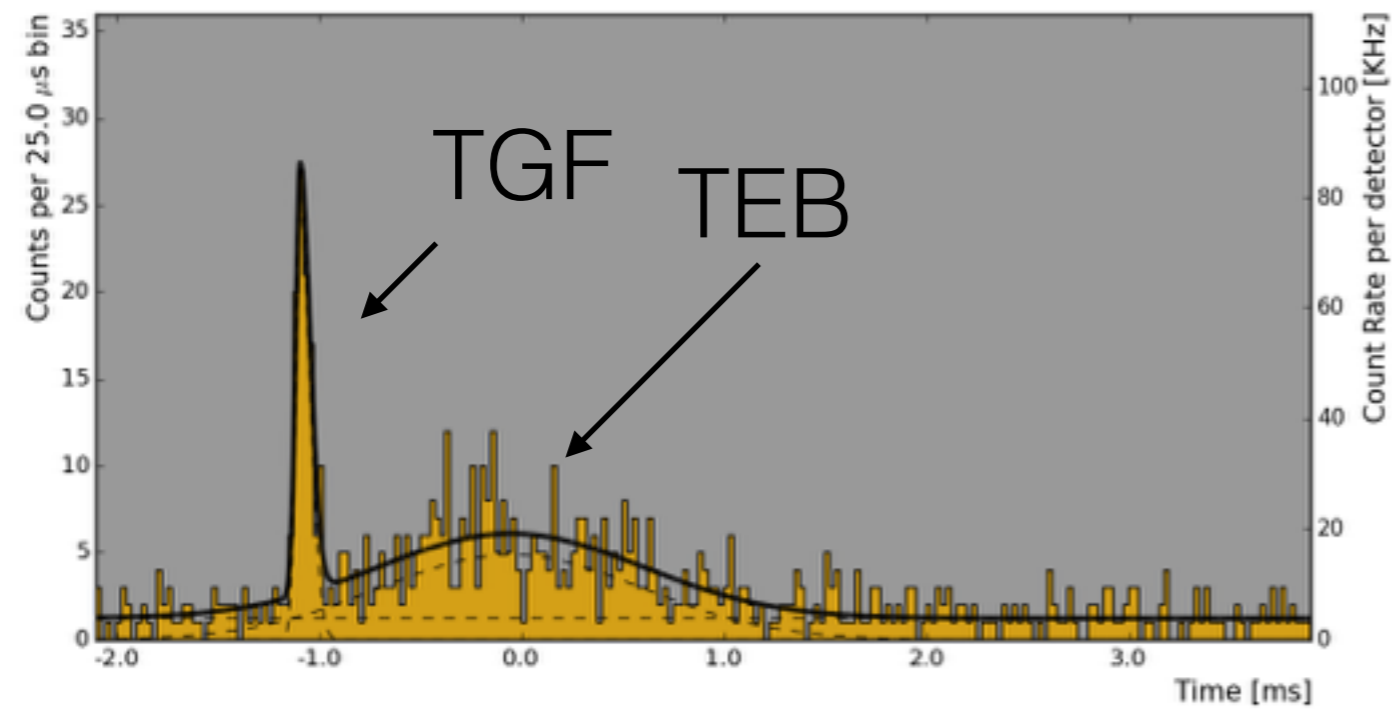
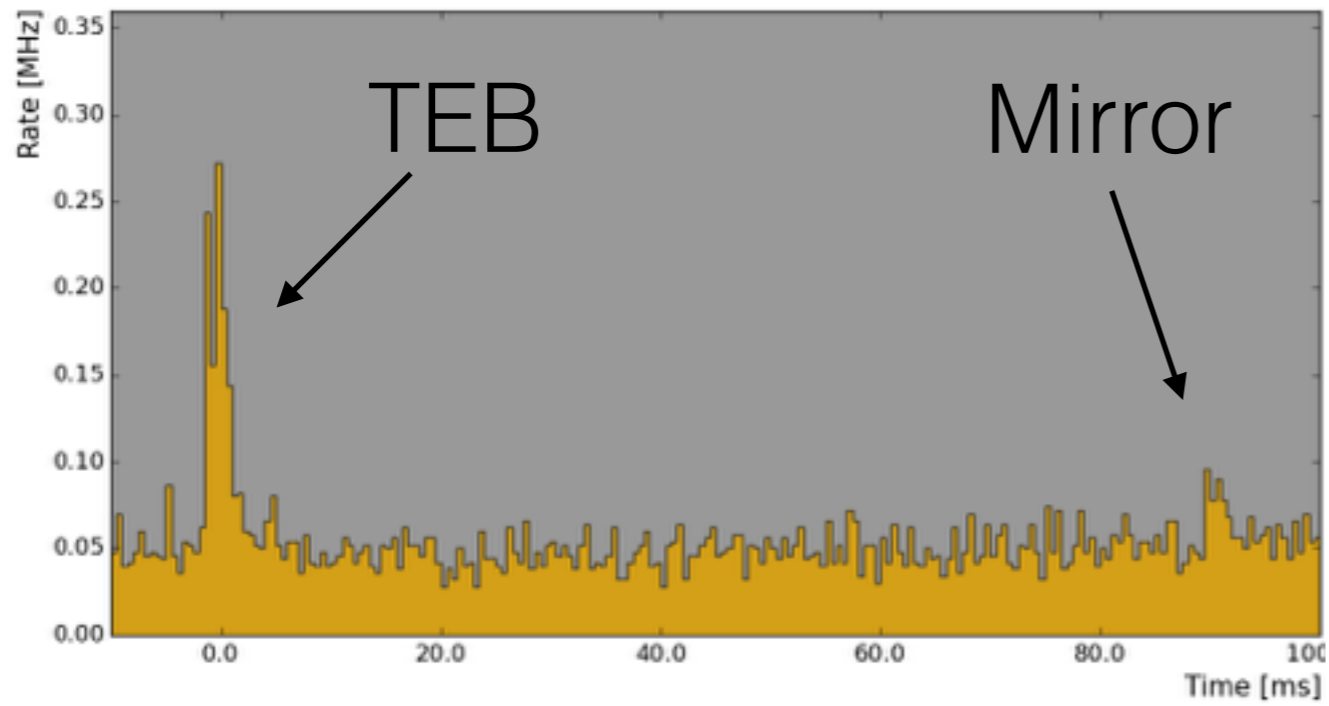
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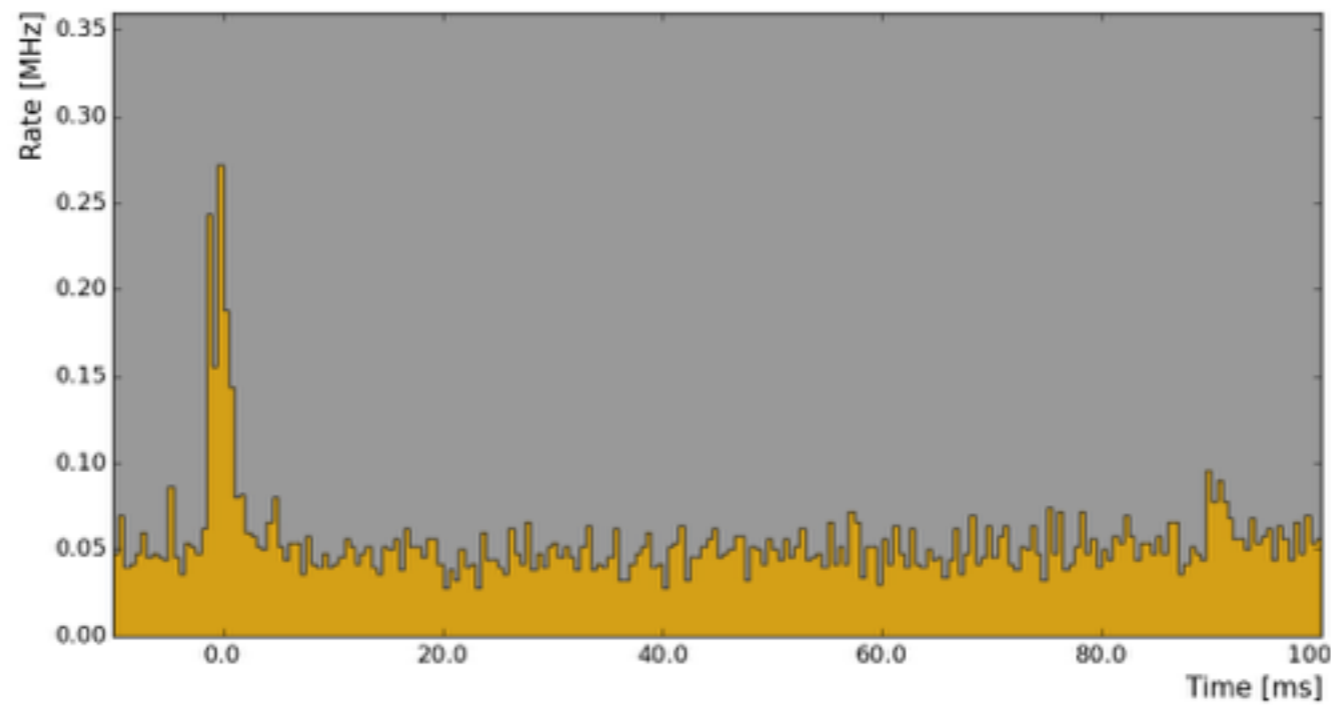
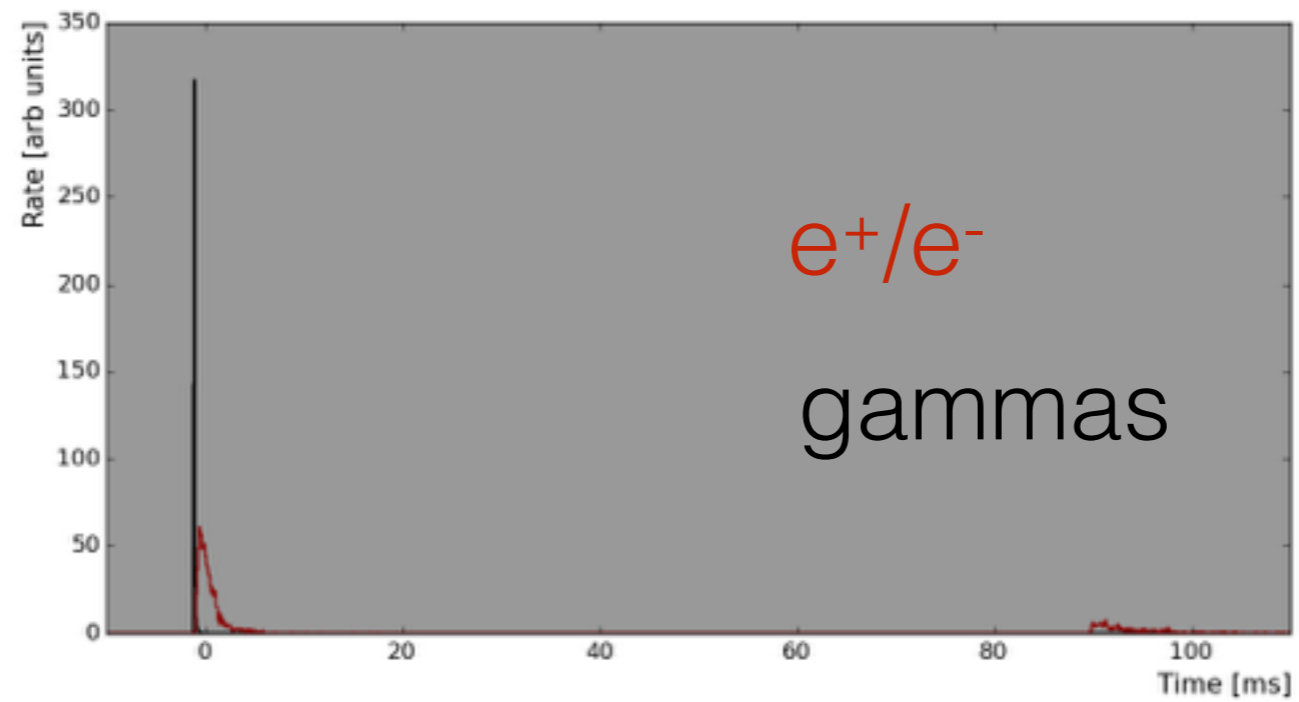
IRWIN  
10.6-12.5  $\mu$ m



# TGF 140204

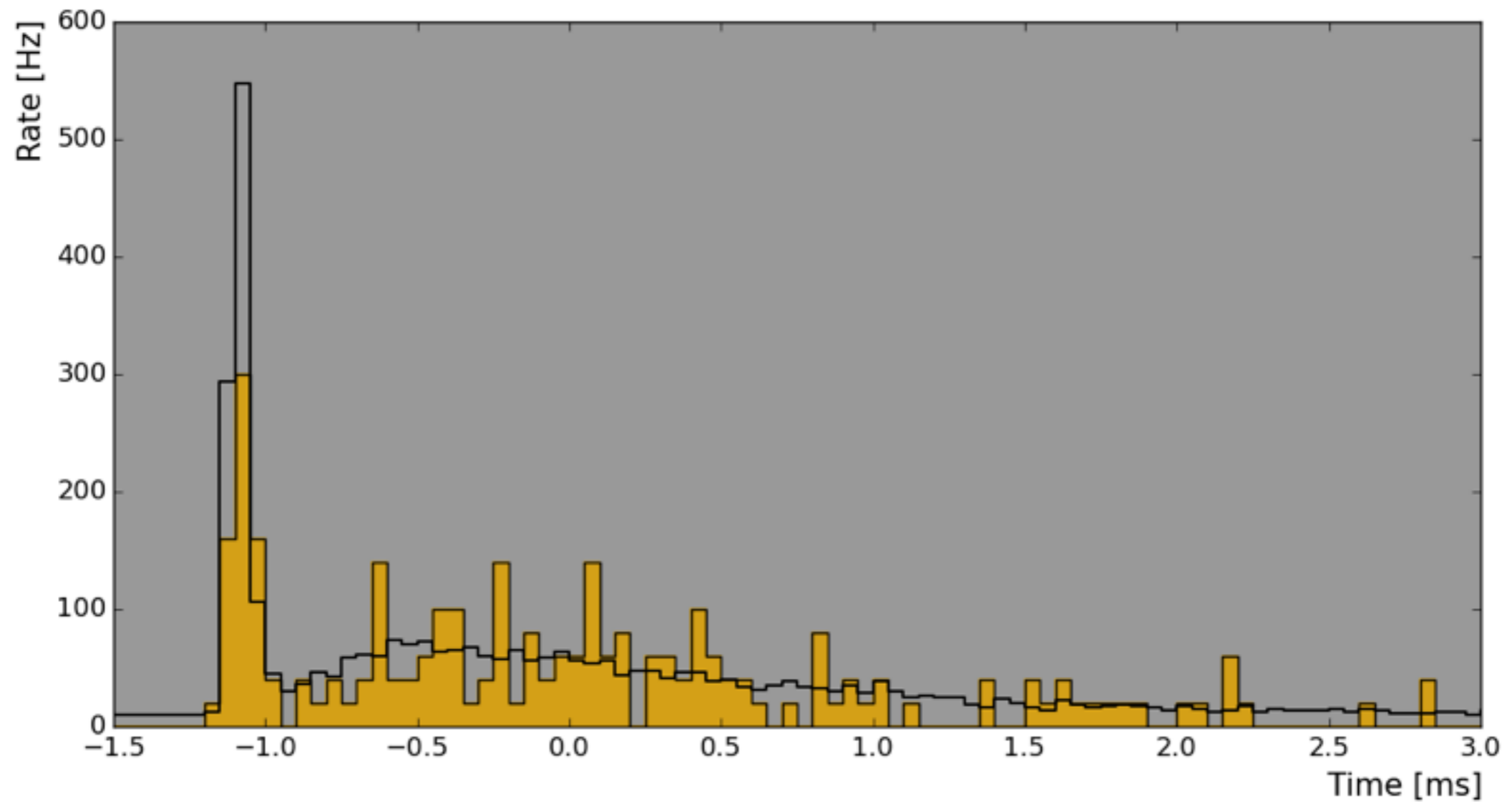


# TGF 140204: Simulations



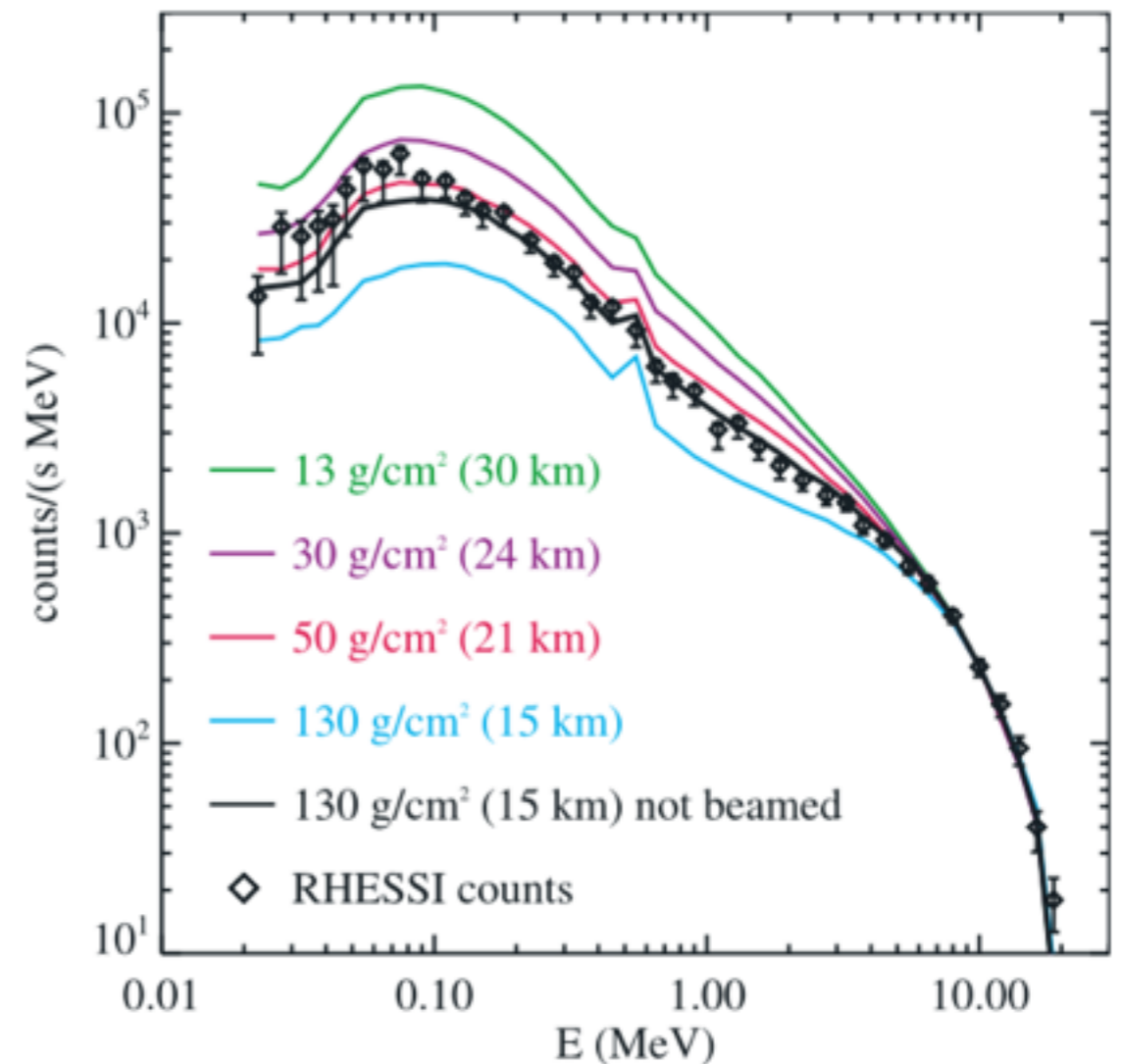


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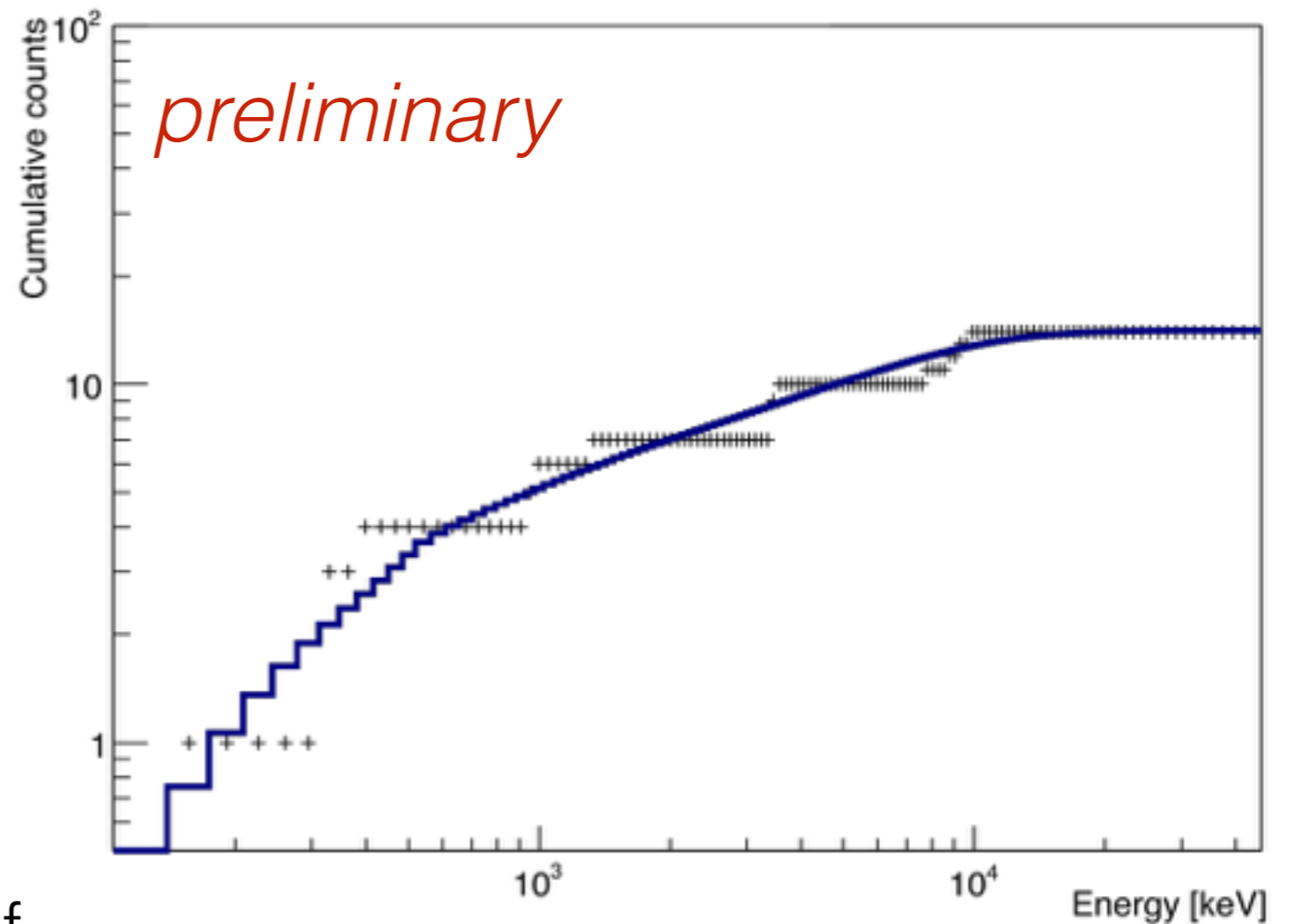
# Spectral Analysis

- Source spectrum always has the same shape
- Propagation effects
- Beam angle distribution
- Previous analyses have stacked multiple TGFs
- smearing of spectra
- Dead Time & Pulse Pile up are issues



# TGF 140204: Spectral Analysis

- Fermi observations are sufficiently bright that individual TGFs can be studied
  - Dead Time & Pulse Pile Up
- Template fitting
- Can directly estimate the beam geometry and altitude of the source



# Summary

- TGFs - novel particle acceleration in our backyard
- Fermi provides an unique opportunity to facilitate multi-wavelength observations
  - key to untangling source mechanisms
- Fermi continues to make new discoveries, e.g. TGF/TEB 140204, individual spectral analysis

## Key Papers

- Briggs et al., 2013
- Dwyer et al., 2012
- Celestin & Pasko 2012
- Dwyer 2008
- Moss et al., 2006
- Dwyer & Smith 2005

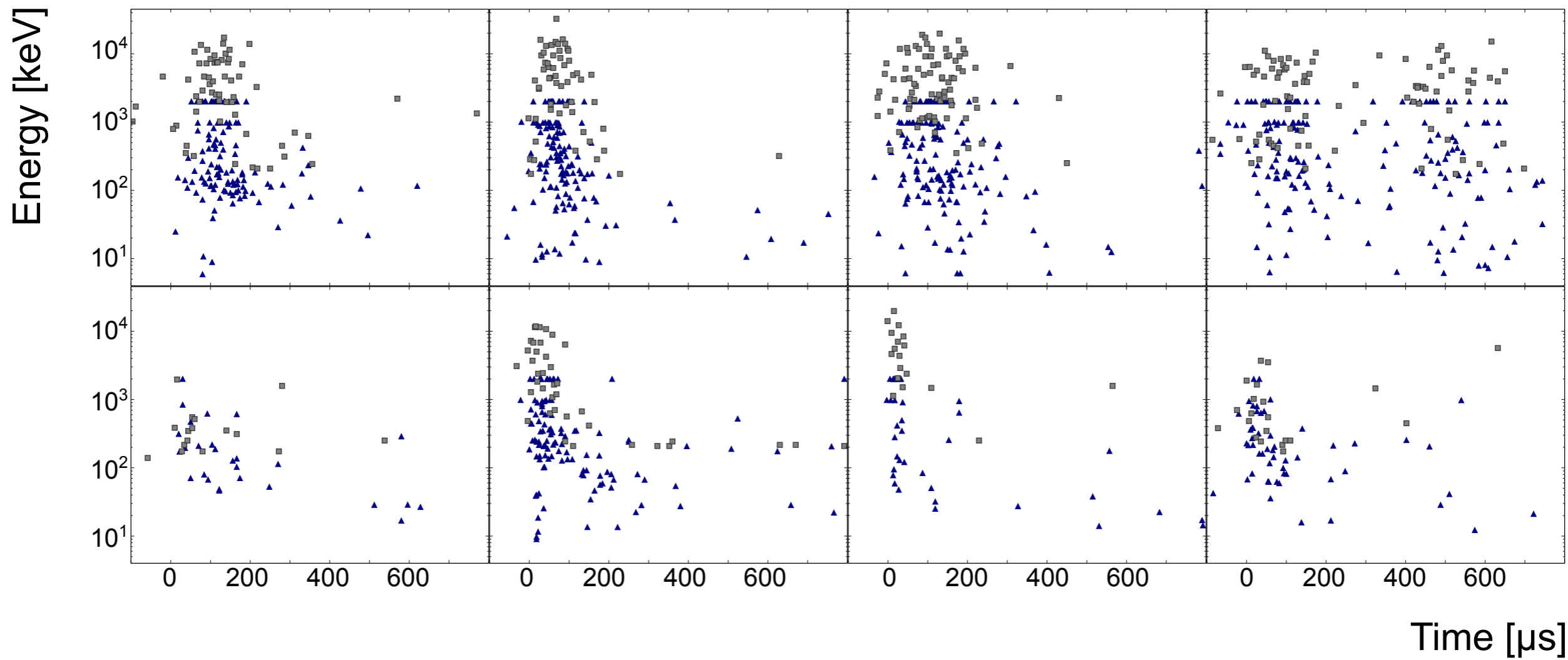
## Acknowledgements

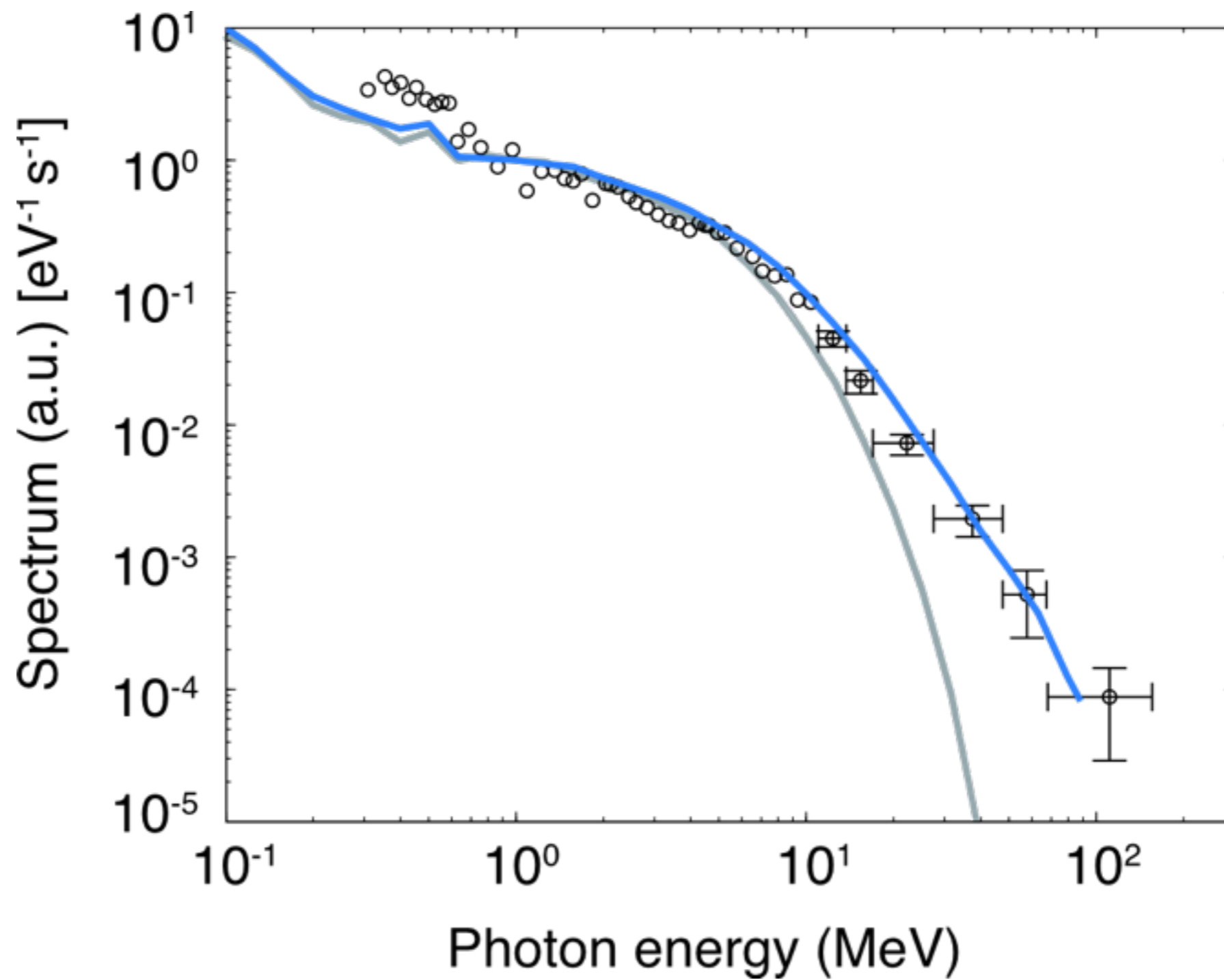
Jacobs - M. Gibby & M. Giles  
USRA - W. Cleveland  
WWLLN & ENTLN Collaborations



A horizontal banner at the top of the slide features a photograph of a bright, jagged lightning bolt striking down from a dark, stormy sky. The lightning is a vibrant yellow and white, contrasting sharply with the deep blue and black tones of the clouds.

Back up slides

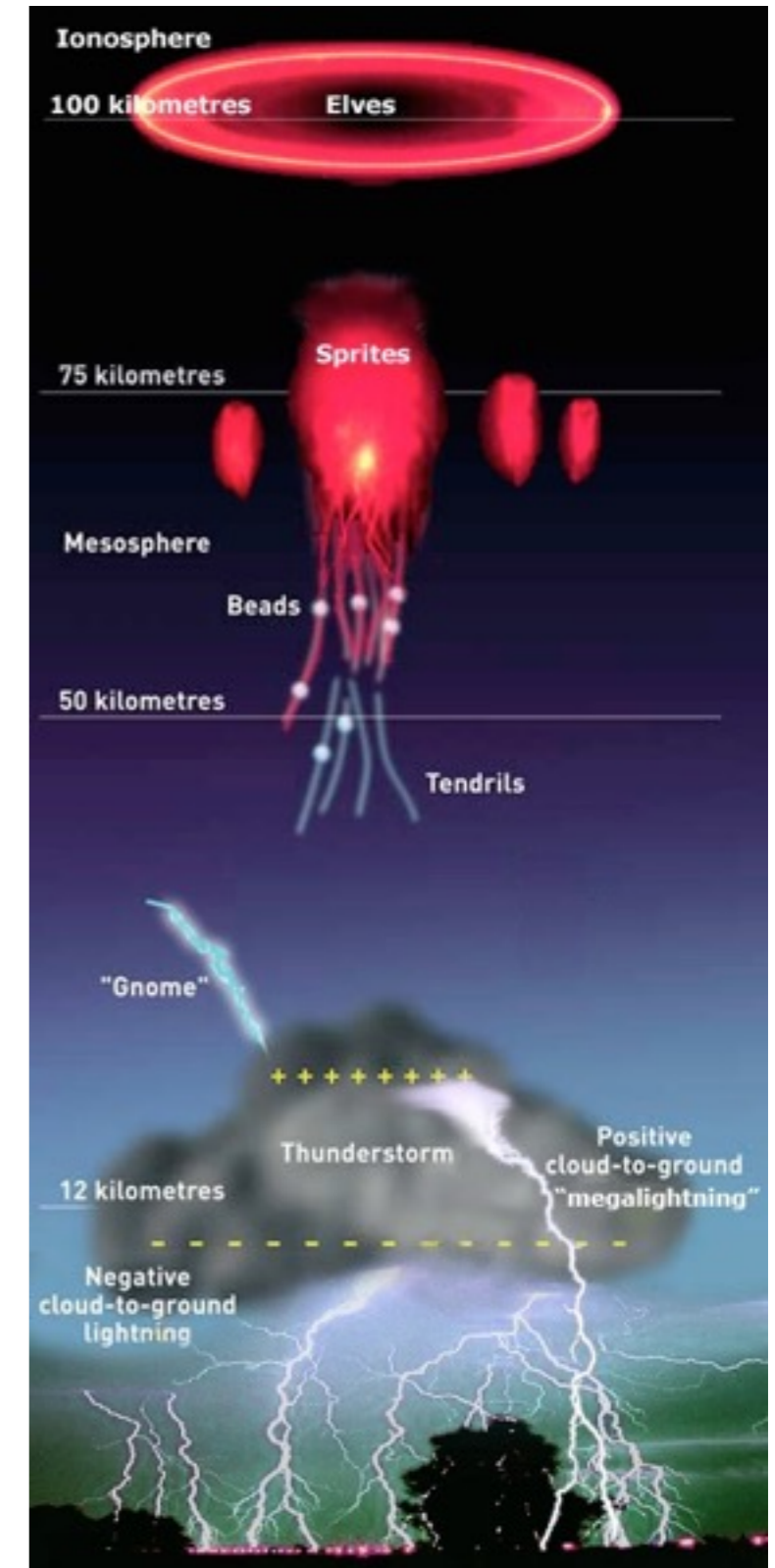






# Transient Luminous Events (TLEs)

- TLEs are not directly related to TGFs
- Sprites
  - ~10 ms, luminous “jellyfish” sprays
  - Related to strong positive cloud-to-ground (+CG) lightning
- Elves
  - ~1 ms, expanding luminous ring in ionosphere
  - Related to EMP from strong negative cloud-to-ground (-CG) lightning?
- Blue jets, gnomes
  - ~300 ms, luminous jet from top of thunderhead
  - Not directly triggered by lightning discharges
  - Correlated with intense hail?



Grove – T'storm accelerator