Constraining the source properties of individual Terrestrial Gamma-ray Flashes

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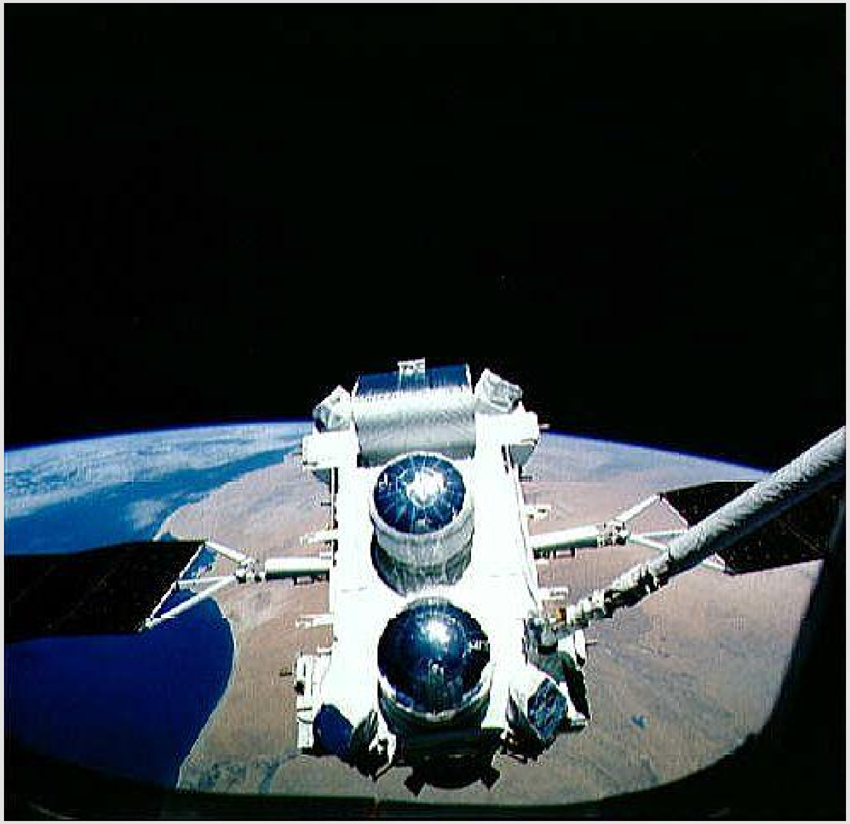
Fermi Gamma-ray Space Telescope

Oct 3, 2016, TEPA Workshop, Nor Amberd, Armenia

THE UNIVERSITY OF ALABAMA IN HUNTSVILLE

Discovery of Terrestrial Gamma-ray Flashes



Each module consisted of both a NaI(Tl) Large Area Detector (LAD) covering the 20 keV to ~2 MeV range, 50.48 cm in dia by 1.27 cm thick, and a 12.7 cm dia by 7.62 cm thick NaI Spectroscopy Detector, which extended the upper energy range to 8 MeV, all surrounded by a plastic scintillator in active anti-coincidence to veto the large background rates due to cosmic rays and trapped radiation.

The Burst and Transient Source Experiment (BATSE) detector modules are located at the 8 corners of CGRO.

The Derivation of the term *"TGF"*

BATSE was an experiment designed to study high-energy ***Celestial*** objects.
When TGFs were discovered, I felt it was necessary to emphasize their ***Terrestrial***, rather than cosmic, origin.

The word "***Flash***" was meant to imply a shorter duration event than a ***"Burst"***. *(Cosmic Gamma-ray Bursts were the primary scientific objective of BATSE.)*

If TGFs were discovered by another instrument, space-borne or otherwise, they would likely have had a different name. e.g. Sprites are not called "Terrestrial" Sprites.

Courtesy of G. Fishman

BATSE
– On-Board Trigger System
(Primarily Hard-wired)

Courtesy of G. Fishman

Limited On-Board Data Storage and Telemetry Rate – Required a trigger system

BATSE data system designed with many data types, trading energy resolution, time resolution and duration, following a trigger

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Due to these limitations:

- <u>Most TGFs were missed because they did not trigger within the (wide) 64ms trig. window</u>

Original Science Paper: 12 TGFs:

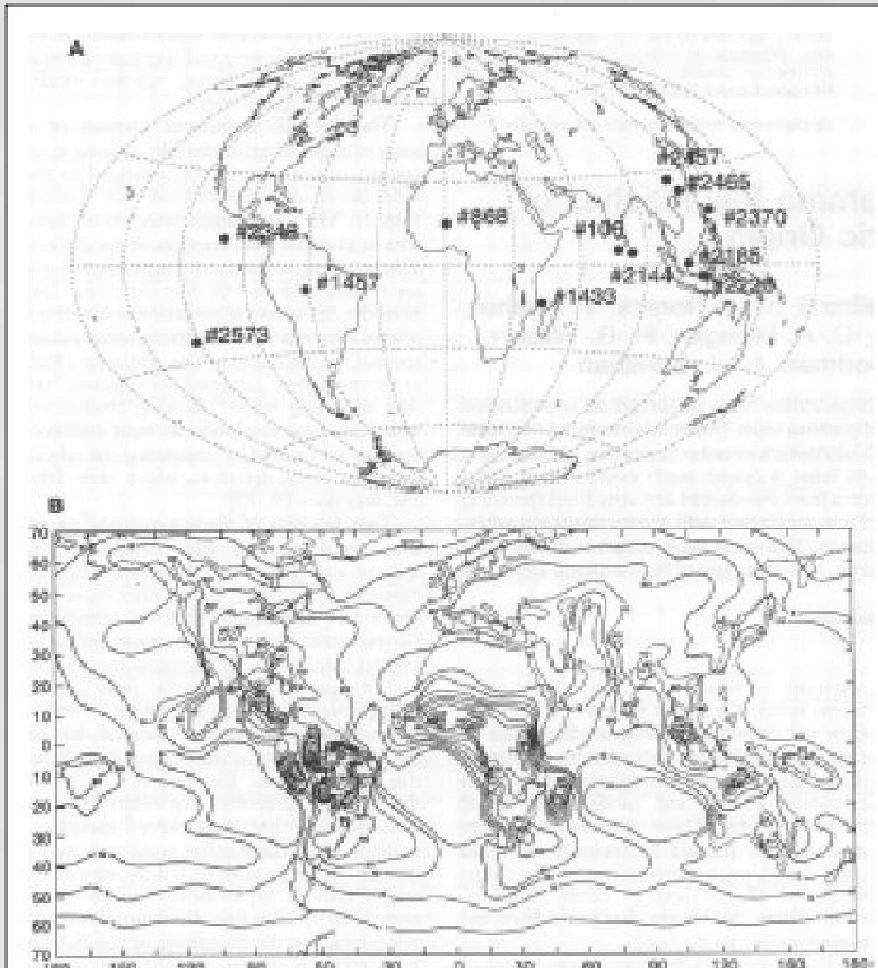


Fig. 2. (A) The approximate locations of the events of Table 1 over the Earth. (B) Contour map of the yearly thunderstorm activity over the Earth (12). Most of the events occurred over regions that have high thunderstorm activity. The spacecraft is limited by its orbital inclination to latitudes within 28.5° of the equator.

1314 SCIENCE • VOL. 264 • 27 MAY 1994

Courtesy of G. Fishman

SCIENCE - v. 264, p. 1313, May 27, 1994

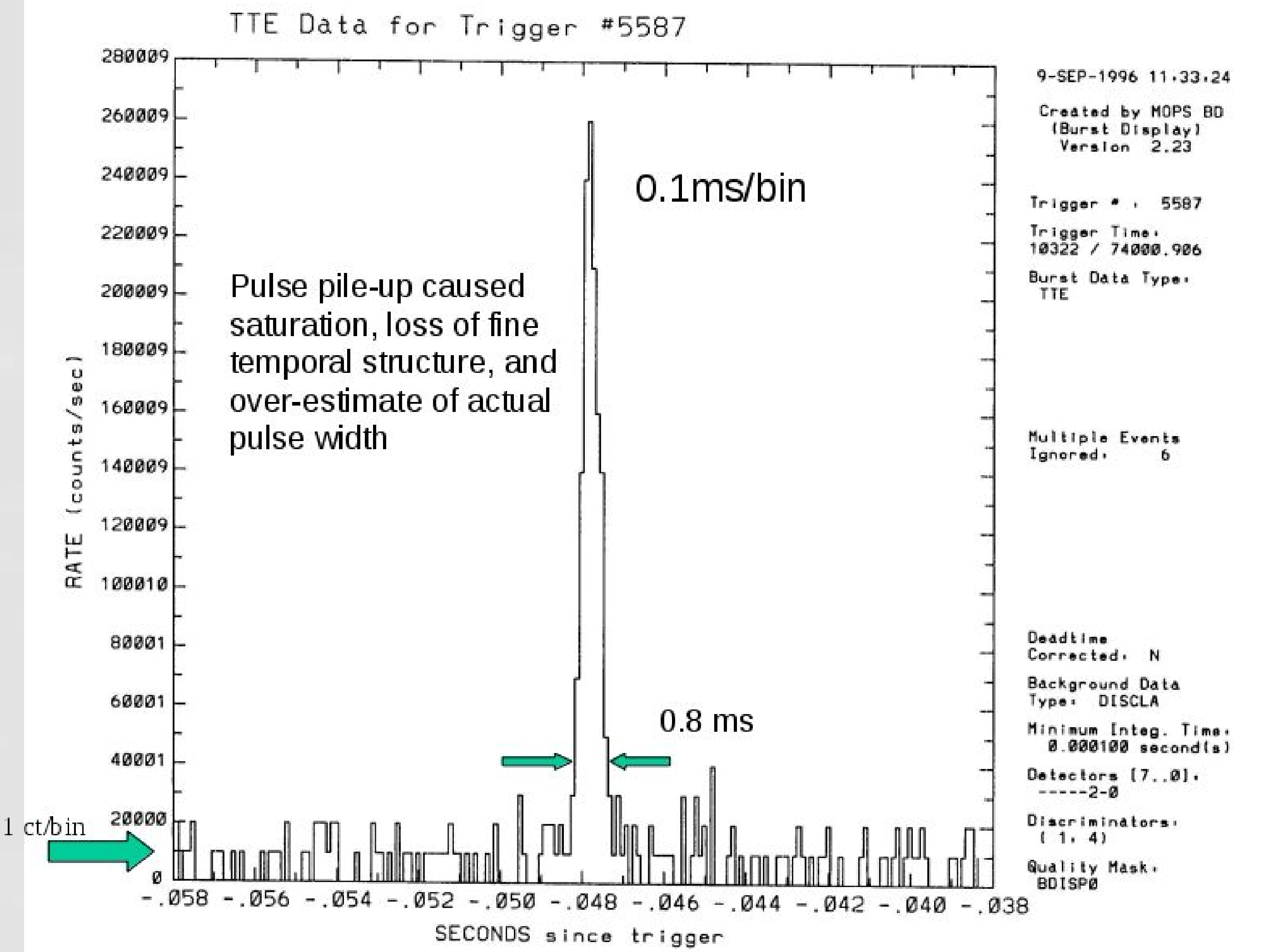
Discovery of Intense Gamma-Ray Flashes of Atmospheric Origin

Detectors aboard the Compton Gamma Ray Observatory have observed an unexplained terrestrial phenomenon: brief, intense flashes of gamma rays. These flashes must originate in the atmosphere at altitudes above at least 30 kilometers in order to escape atmospheric absorption and reach the orbiting detectors. At least a dozen such events have been

X

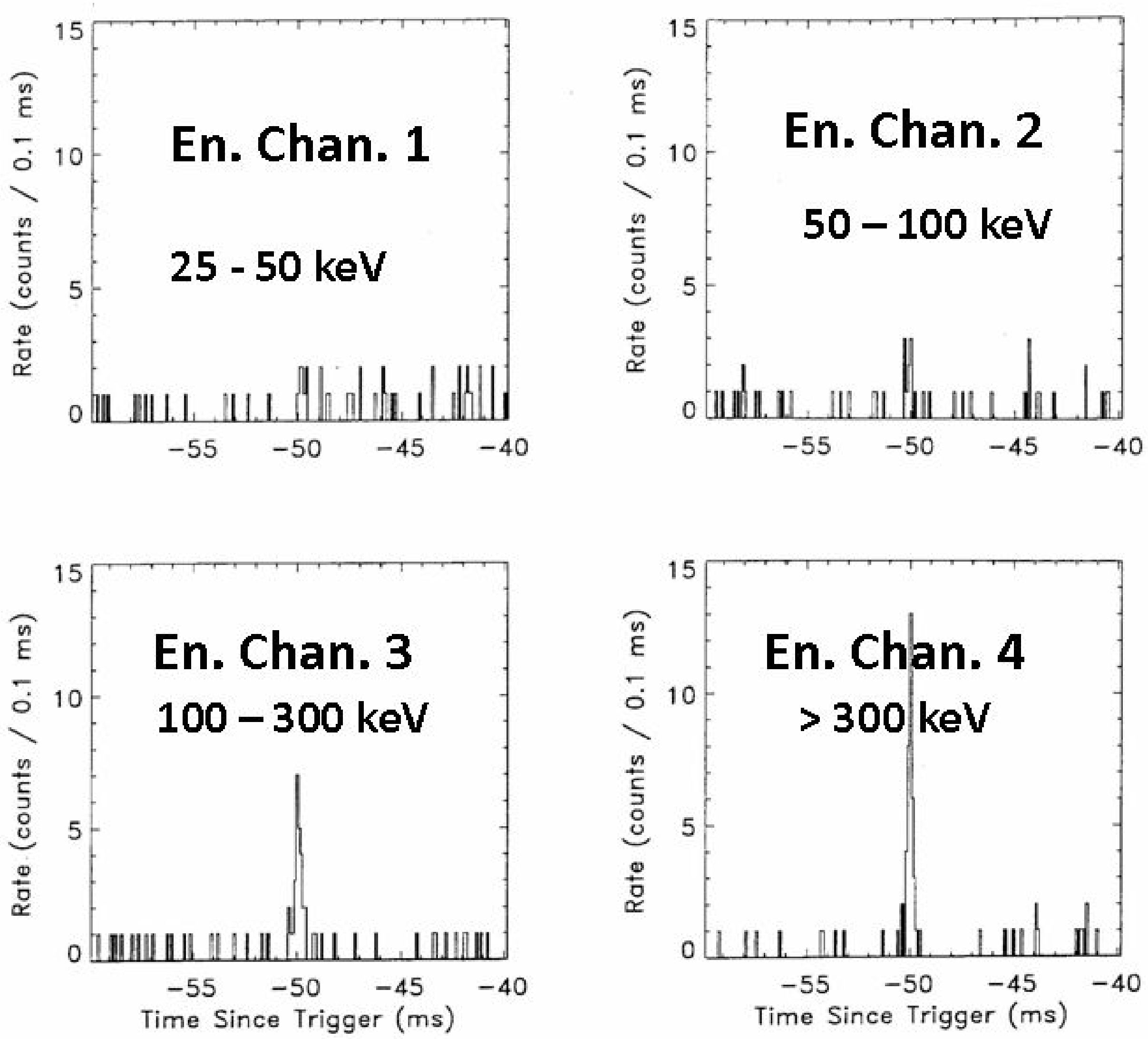
Courtesy of G. Fishman

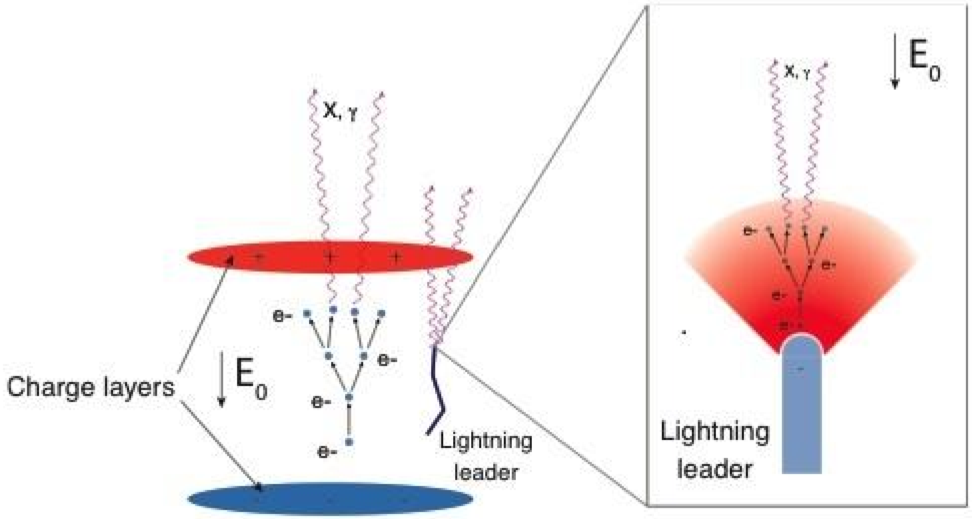
Pulse pile-up distortions



Courtesy of G. Fishman

Typ. Counts in the Four Energy Channels





Lightning Leader Model

- The region with subsequent RREA development is provided by the lightning and not the ambient thundercloud electric field e.g., *Celestin et al., 2012*

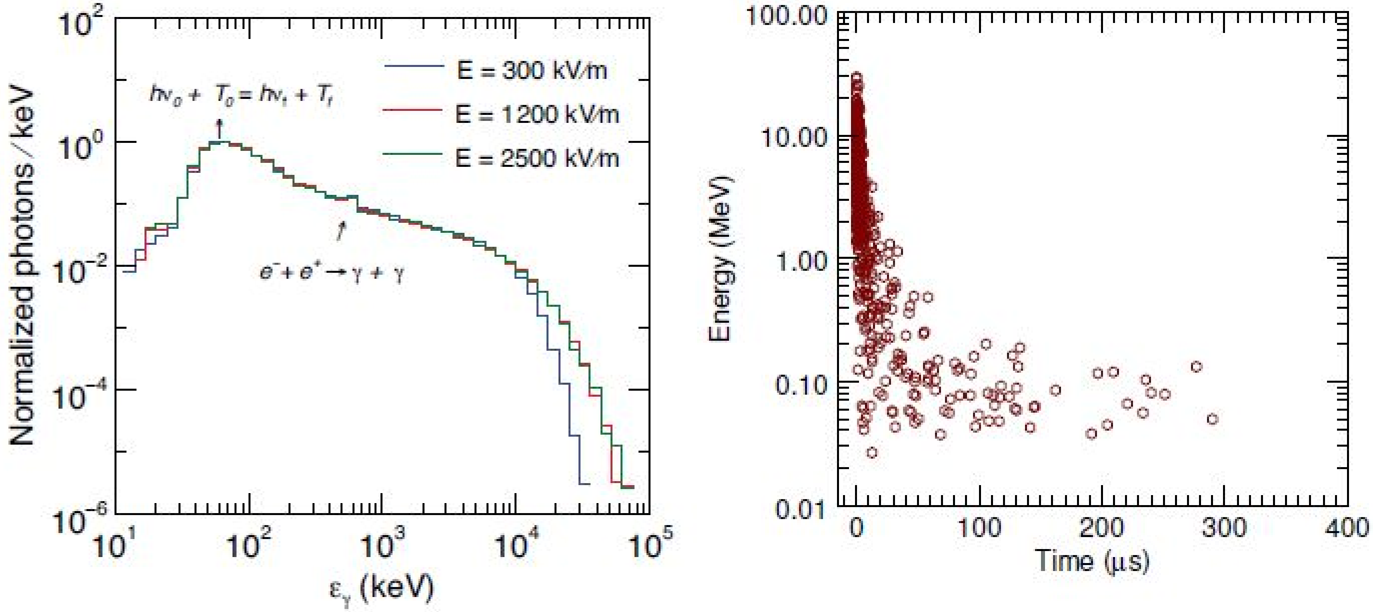
Relativistic Feedback Discharge Model (RFD)

- As thunderclouds charge, the large scale electric field approaches the relativistic feedback threshold, e.g. *Dwyer 2012*

Relativistic Runaway Electron Avalanche models

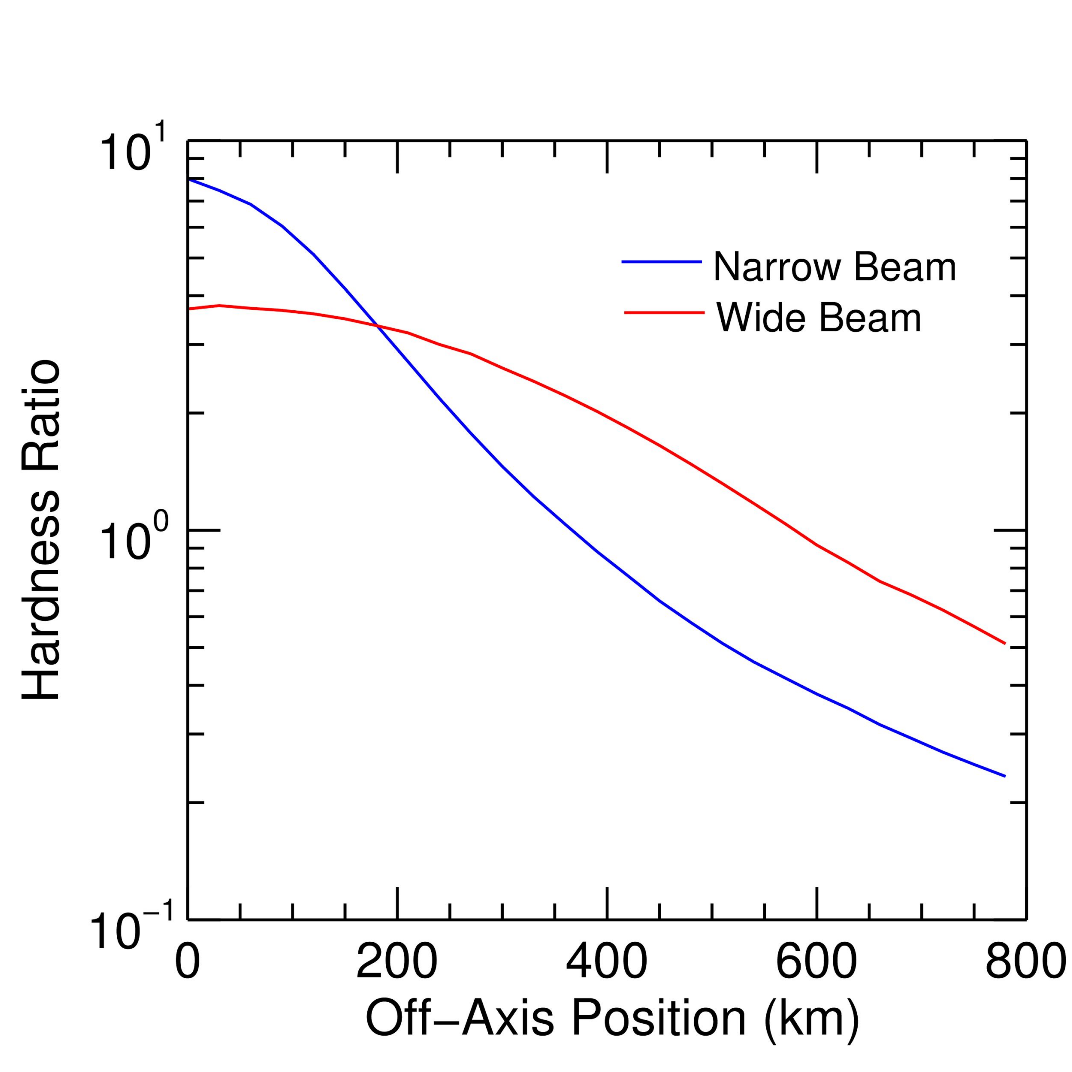
mechanism	name	new feature	flux increase over previous mechanism	discharge time (sec)
Wilson 1925	Runaway electron	Electron energy gain from electric field	x 10^1	~hours
Gurevich et al. 1992	Relativistic runaway electron avalanche	Moller scattering	Up to x 10^5	~10 sec
Dwyer 2003	Relativistic feedback	Backward propagating runaway positrons and Compton scattered x-rays	Up to x 10^{13}	< 0.1 msec

Atmospheric propagation

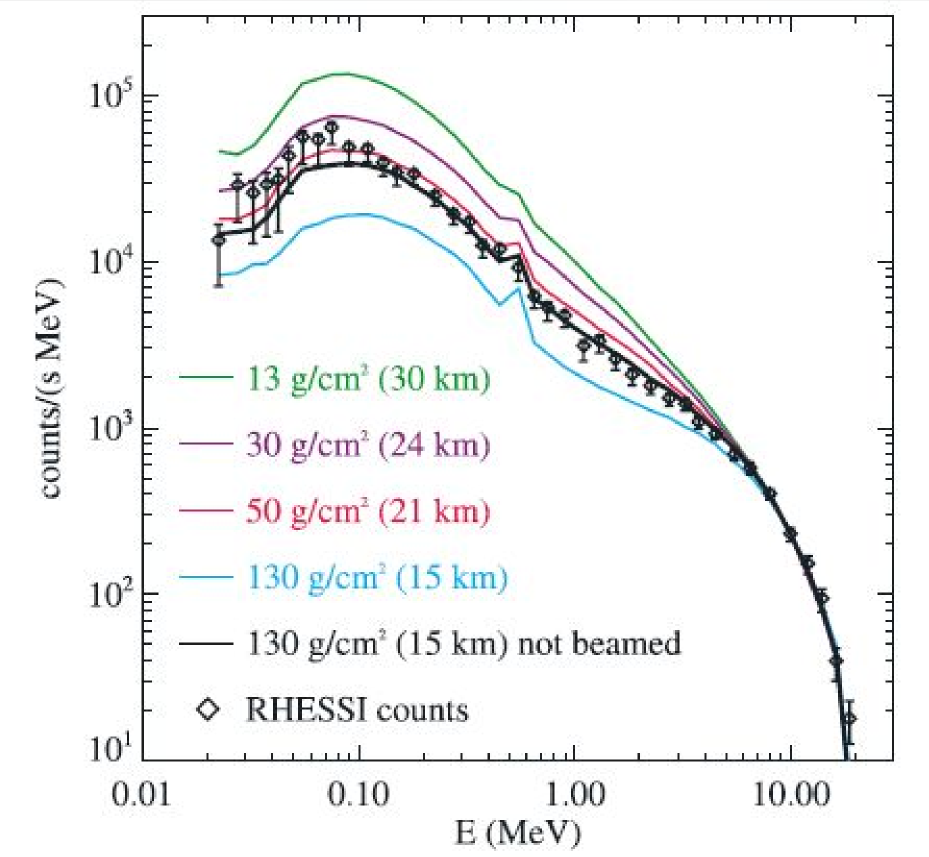


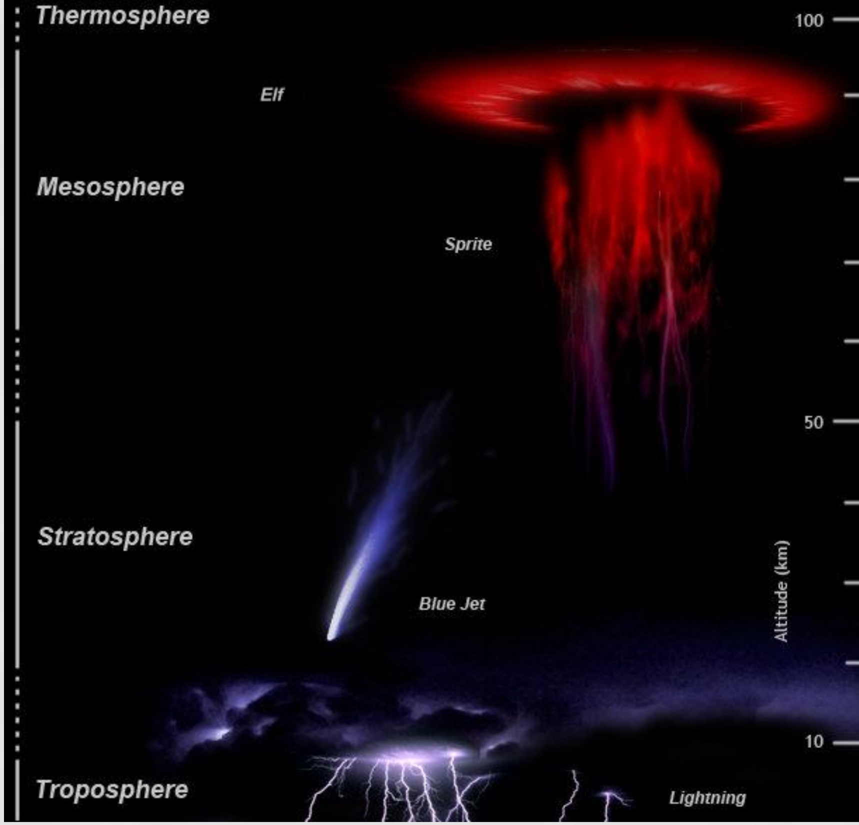
- As the photons propagate through the atmosphere, they are Compton scattered and undergo pair production
- The Compton scattered photons are delayed and produce a tail that can be seen in both simulation and data (Fitzpatrick *et al.*, 2014)

The effects of compton scattering and beaming geometry



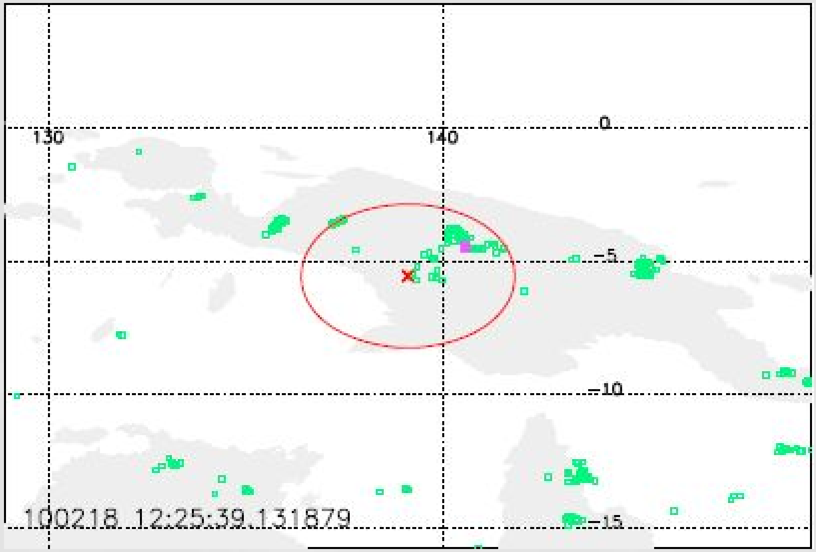
Spectral Fit of Summed RHESSI TGFs





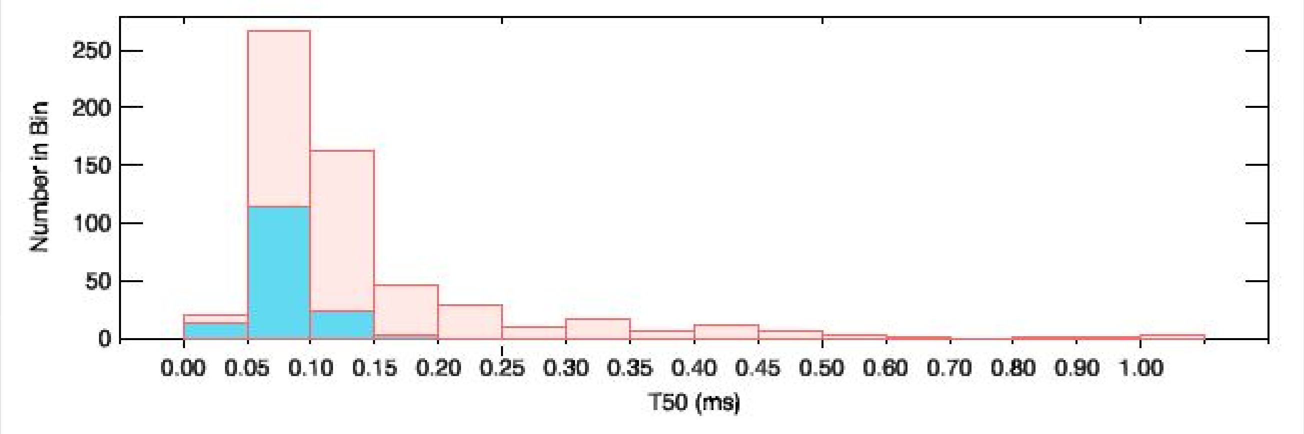
Dwyer and Smith (2005)

World Wide Lightning Location Network and TGFs

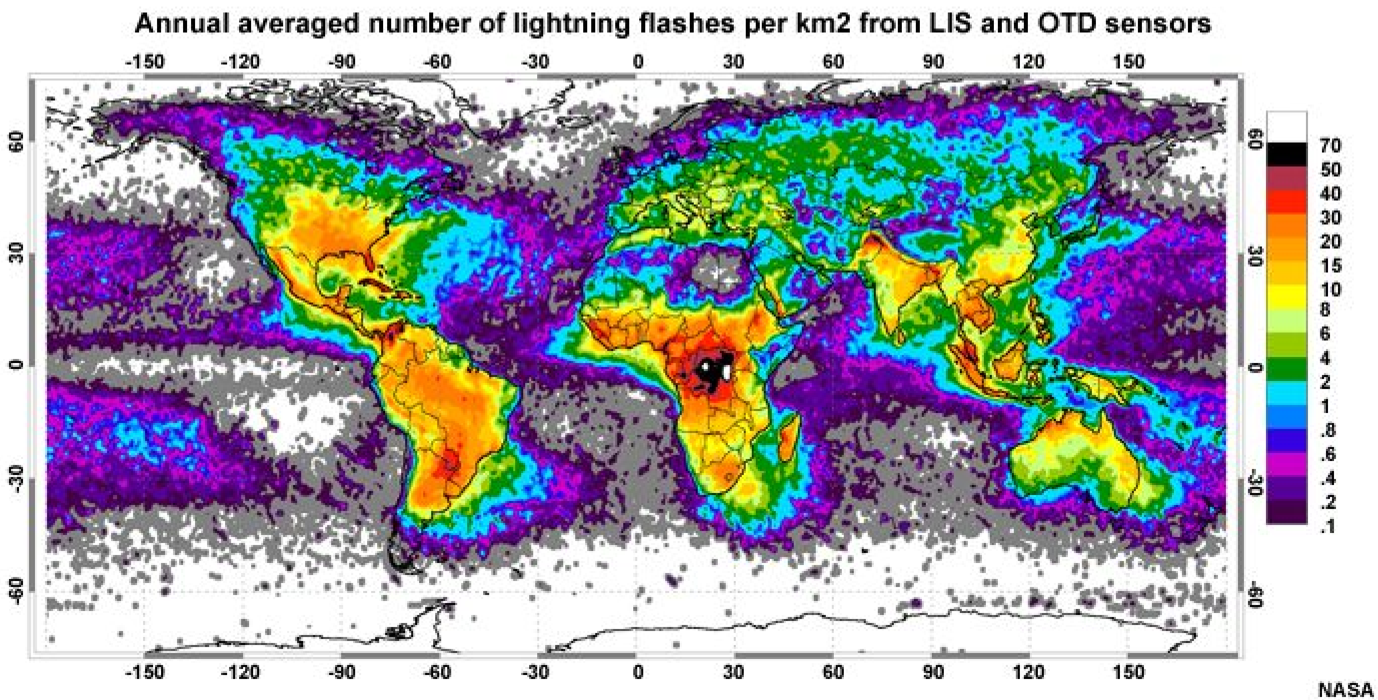


"We infer that the simultaneous VLF discharges are from the relativistic electron avalanches that are responsible for the flash of gamma rays and the nonsimultaneous VLF discharges are from related intracloud lightning strokes"

Connaughton et al., 2013



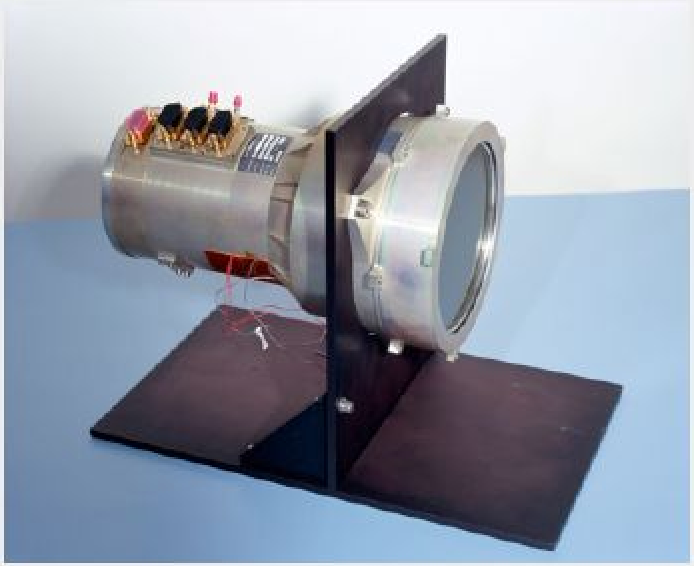
Lightning flash rates and TGFs



Region	Ratio
Americas	$(4.9 \pm 0.3) \times 10^{-4}$
Africa	$(2.3 \pm 0.2) \times 10^{-4}$
Asia	$(2.7 \pm 0.4) \times 10^{-4}$
Australia	$(8.6 \pm 1.0) \times 10^{-4}$
overall	$(3.8 \pm 0.2) \times 10^{-4}$

Briggs et al., 2013

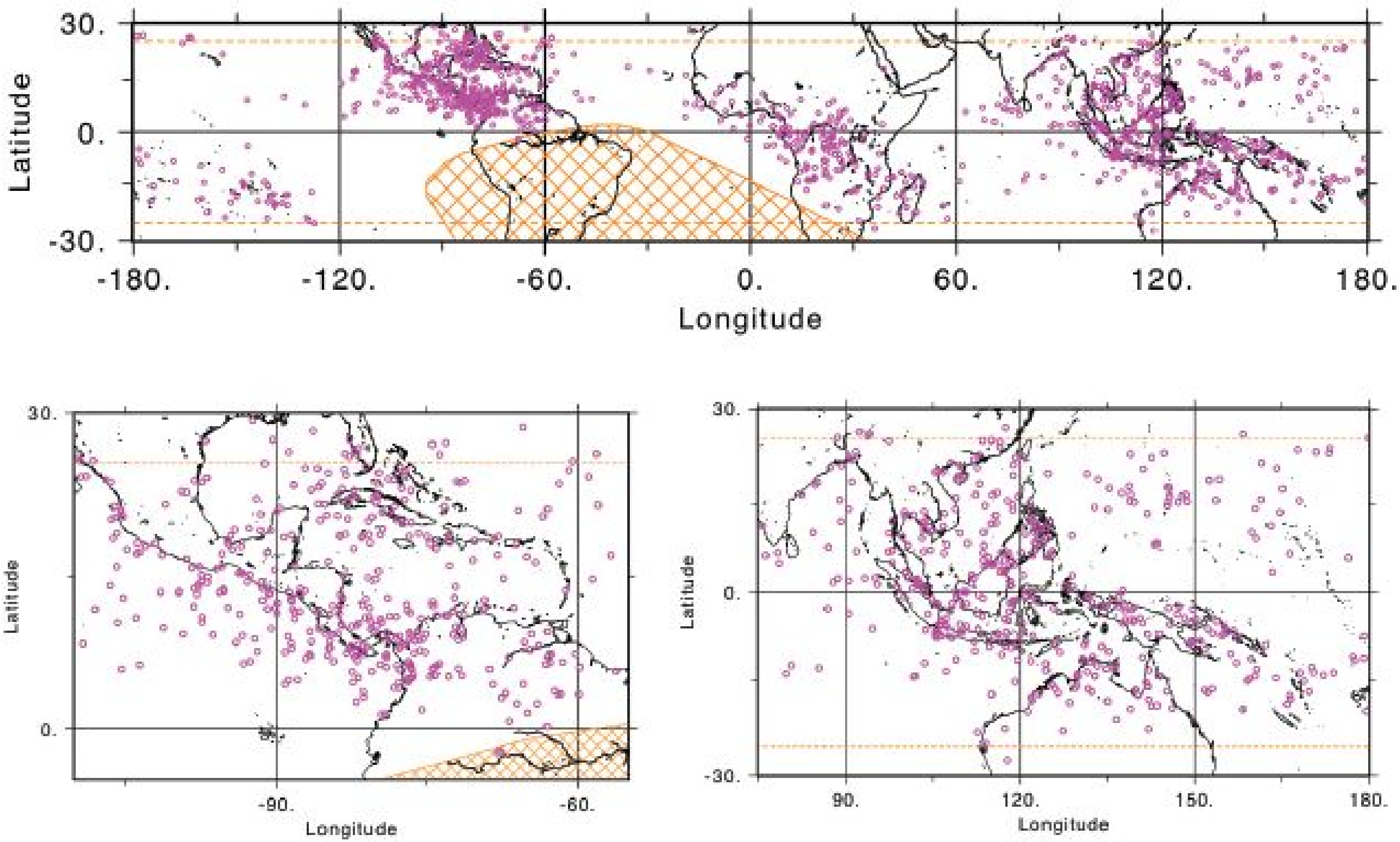
Fermi Gamma-ray Burst Monitor (GBM)



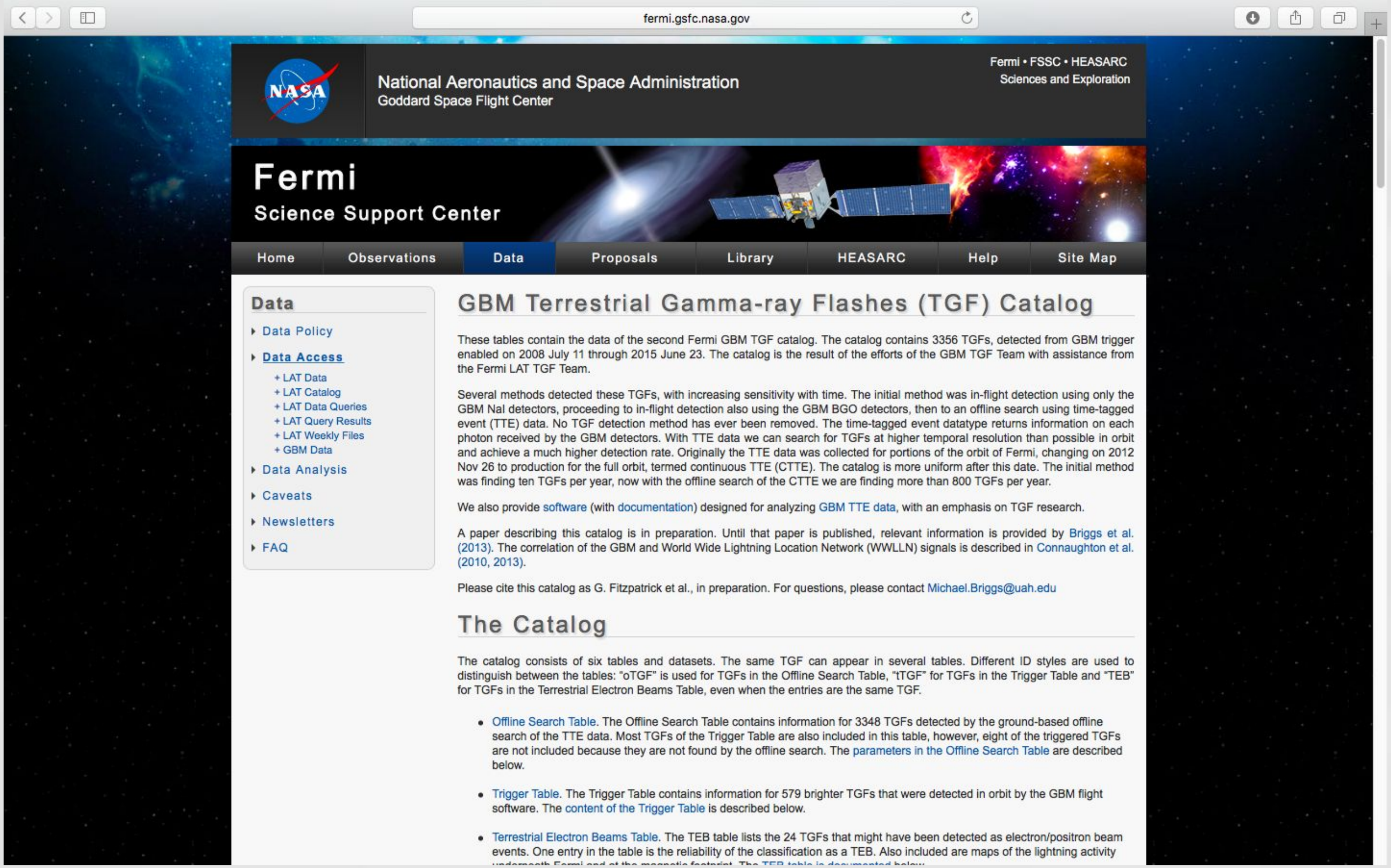
- Sodium iodide (NaI)
- 12.7 cm diameter X 1.27 cm thick
- 8 keV to 1 MeV

- Bismuth germanate (BGO)
- 12.7 cm diameter X 12.7 cm long
- 200 keV to 40 MeV

TGFs observed by Fermi GBM



Fermi GBM TGF Catalog



http://fermi.gsfc.nasa.gov/ssc/data/access/gbm/tgf/ Fitzpatrick et al., in prep.

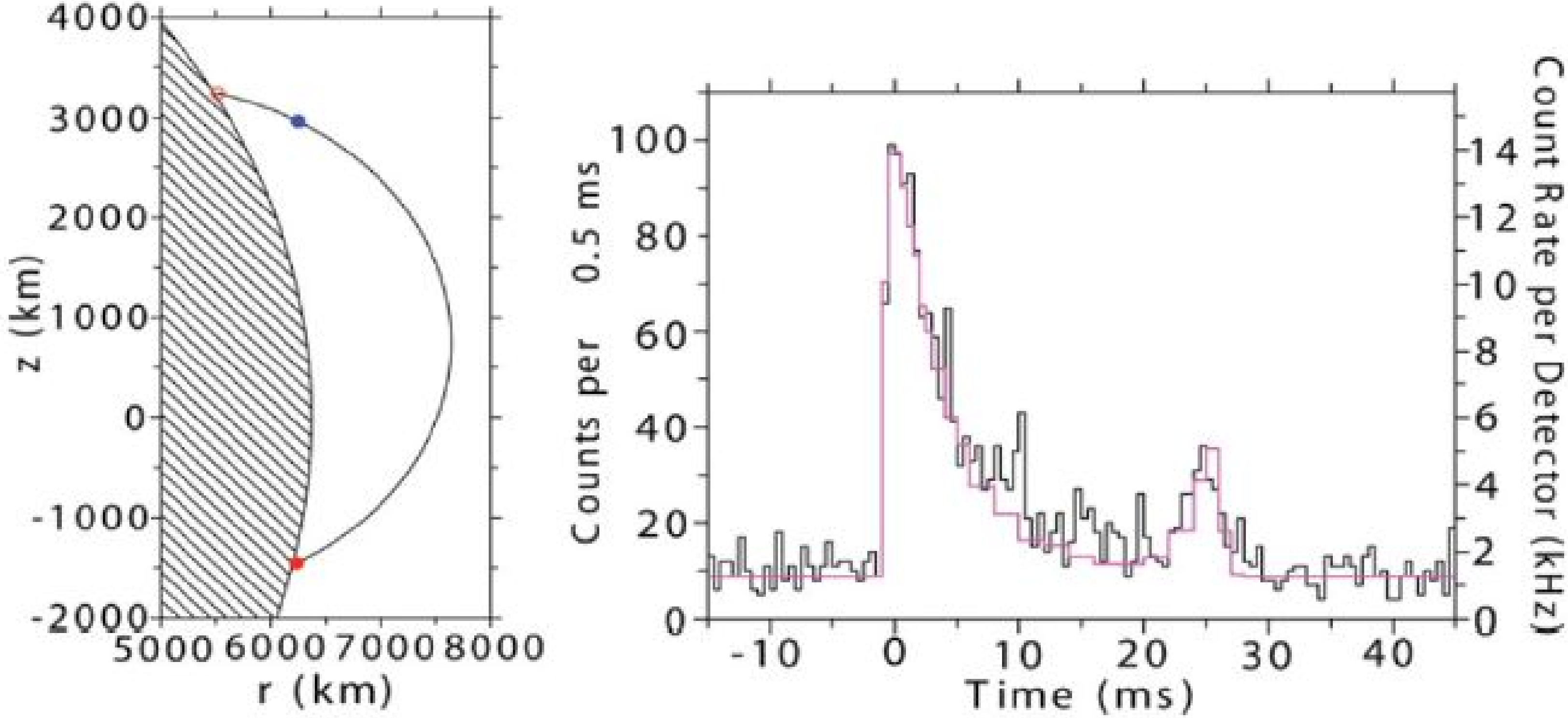
The Catalog

The catalog consists of six tables and datasets. The same TGF can appear in several tables. Different ID styles are used to distinguish between the tables: "oTGF" is used for TGFs in the Offline Search Table, "tTGF" for TGFs in the Trigger Table and "TEB" for TGFs in the Terrestrial Electron Beams Table, even when the entries are the same TGF.

- Offline Search Table. The Offline Search Table contains information for 3348 TGFs detected by the ground-based offline search of the TTE data. Most TGFs of the Trigger Table are also included in this table, however, eight of the triggered TGFs are not included because they are not found by the offline search. The parameters in the Offline Search Table are described below.
- Trigger Table. The Trigger Table contains information for 579 brighter TGFs that were detected in orbit by the GBM flight software. The content of the Trigger Table is described below.
- Terrestrial Electron Beams Table. The TEB table lists the 24 TGFs that might have been detected as electron/positron beam events. One entry in the table is the reliability of the classification as a TEB. Also included are maps of the lightning activity underneath Fermi and at the magnetic footprint. The TEB table is documented below.
- Comments and Special Cases Table. There are a few TGFs with missing values (which are denoted with "NULL" in the tables) due to unusual analysis issues or missing data. These cases are described in this table. If we are able to obtain a missing value, or if corrections are needed, updated tables will be posted.
- **WWLLN Associations Table.** The WWLLN Associations Table contains results for 1049 TGFs for which temporally-coincident radio signals of the World Wide Lightning Network (WWLLN) were found. These associations provide accurate localizations of the TGFs. More information on this table is provided below.
- WWLLN Lightning Maps and Data files. This dataset consists of maps of the lightning detections made by WWLLN for ±10 minutes relative to the TGF time. Also included are text data files with the positions and times of the lightning sferics on the maps. The content of these maps and data files are described below.

WWLLN locations are provided so Fermi GBM DRMs can be generated!

Terrestrial Electron Beams

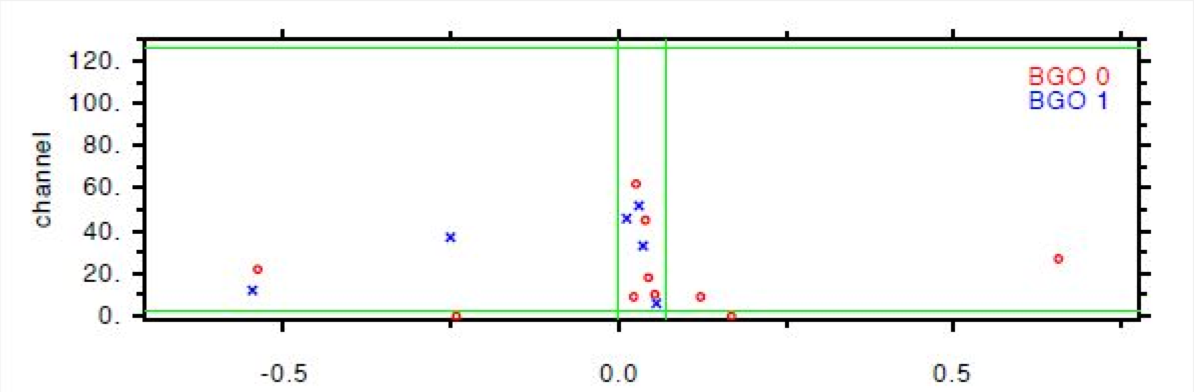


Briggs et al., 2011

Criteria of the Offline Search of Continous Time-Tagged Events (CTTE) for TGFs:

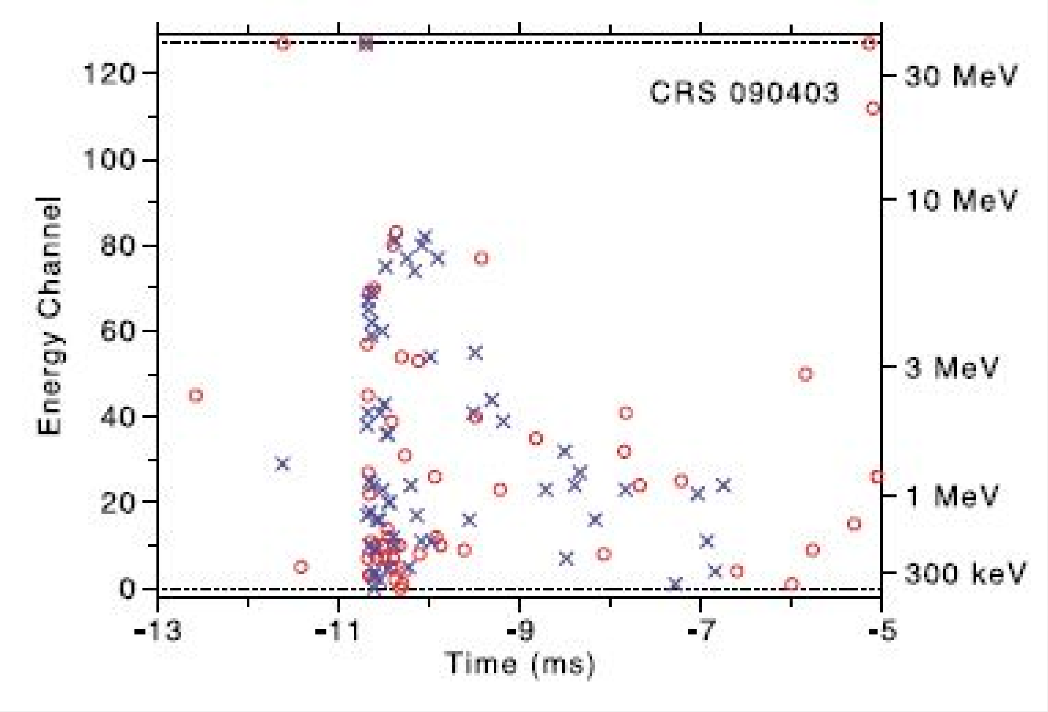
- >=4 counts in each BGO

Cosmic ray rejection!



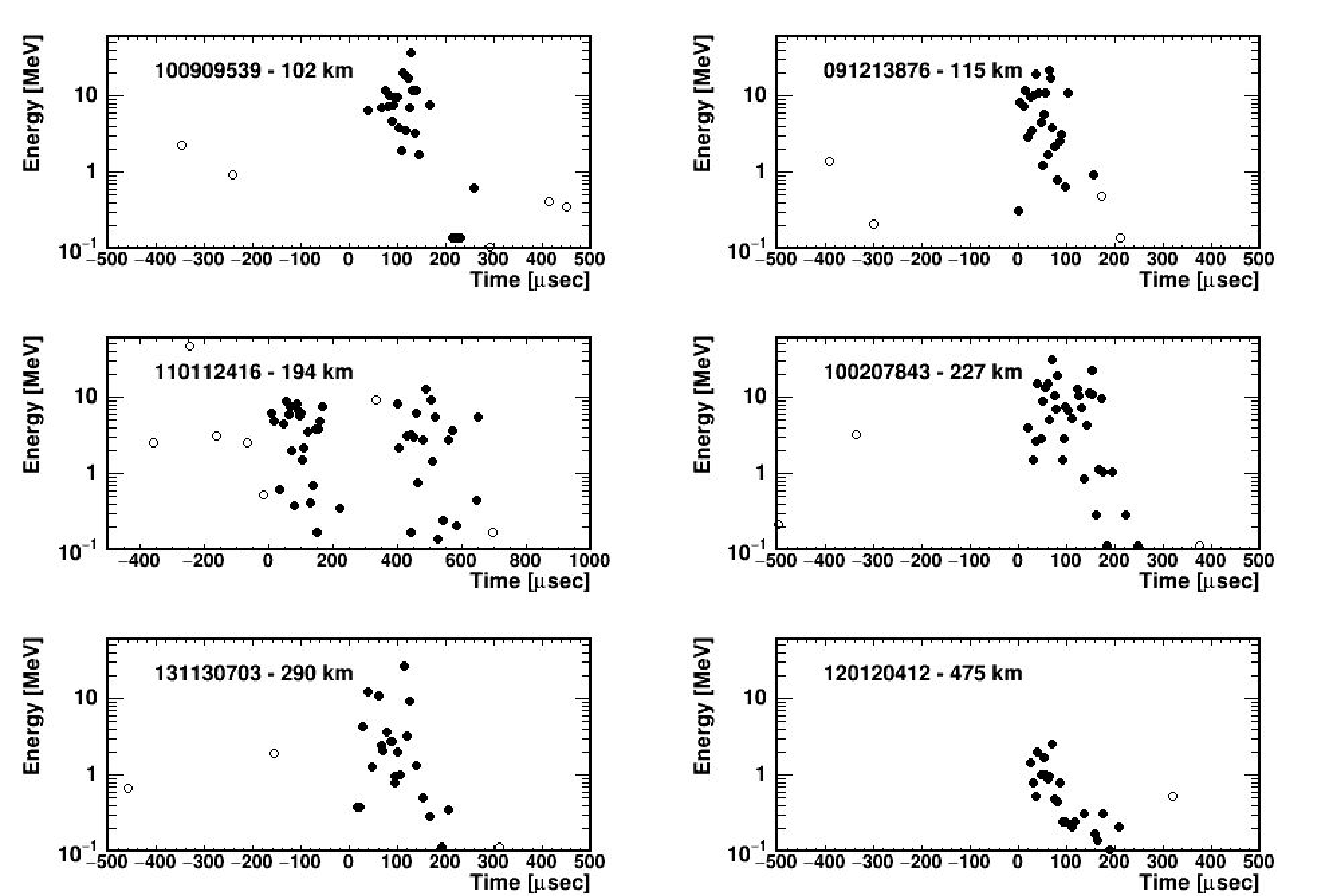
ms

Cosmic ray rejection



Briggs et al., 2010

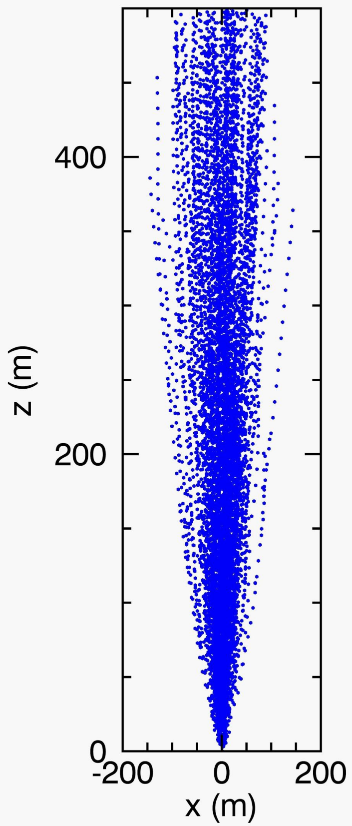
Individual TGF analysis



Data selection

- We have used Fermi GBM data of bright TGFs from BGO detectors (>20 photons > 200 keV). Azimuth angle within 60 degrees.
- From 2008 to 2015 about 3400 TGFs were observed. WWLLN and ENTLN provided the TGF radio locations for about 1000 TGFs.
- Choosing the bright events with favorable positions till the end of 2013 resulted in a sample of 46 TGFs.

Modeling

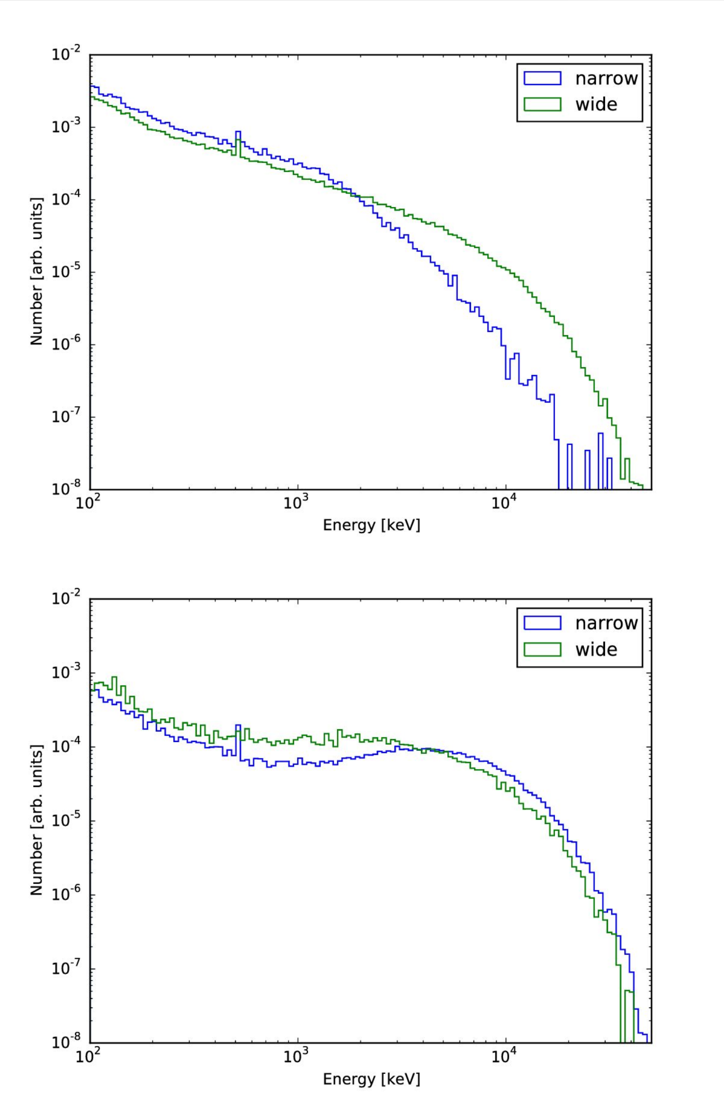


The acceleration of electrons and consequent emission of gamma rays with further propagation of the particles were simulated using REAM code (Dwyer, 2007).

4 kV/cm field was used for 5 avalanche lengths and 10000 seed electrons.
11.6, 13.4, 16.0, 20.2 km narrow and wide sources were tested.

The altitudes correspond to atmospheric column densities given by MSIS model used in REAM code.
http://omniweb.gsfc.nasa.gov/vitmo/msis_vitmo.html

Modeling



High offset

Simulated photon energy spectra at spacecraft altitude for **narrow** and **wide** models the source altitude of 13.4 km and at the source-nadir offset of 475 km (top) and 102 km (bottom).

Low offset

Wide models, having broader photon angular distribution, provide more high energy particles at large offsets.

Fit procedure

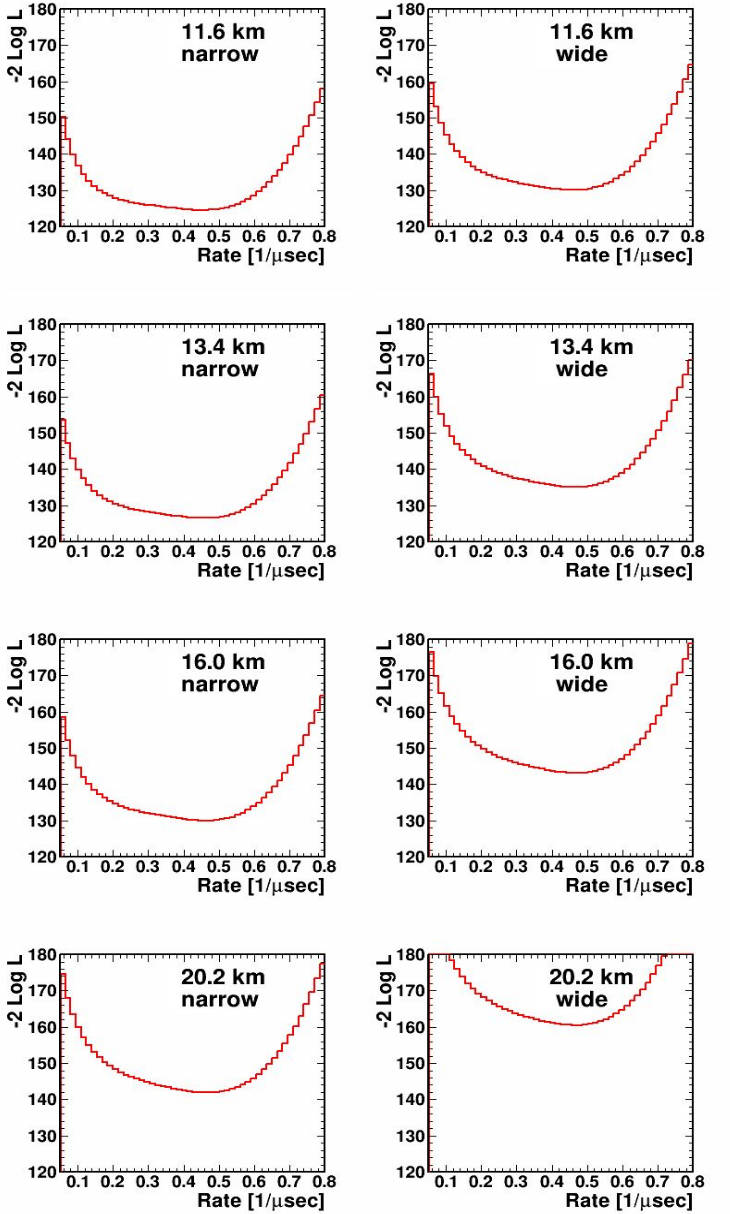
Model TGF ↓ Relativistic Electron Avalanche Model (REAM).

Simulated photons at detector ↓ Calculating detector response matrices using radio location.

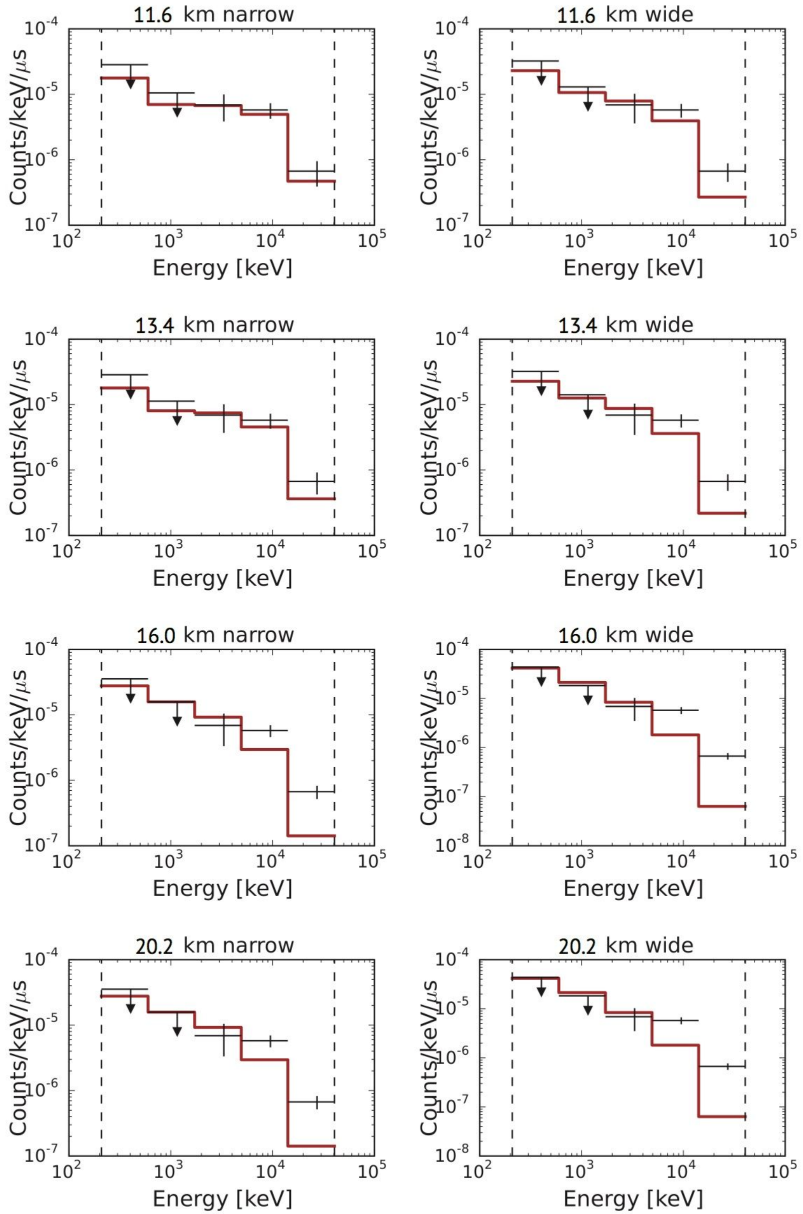
Simulated detector counts ↓ Pulse Pile-up (PPU) code developed by Chaplin et al., (2013).

Pulse-pileup corrected counts ↓ Likelihood analysis: iterating over the models choosing acceptable/rejected ones.

Best fit model



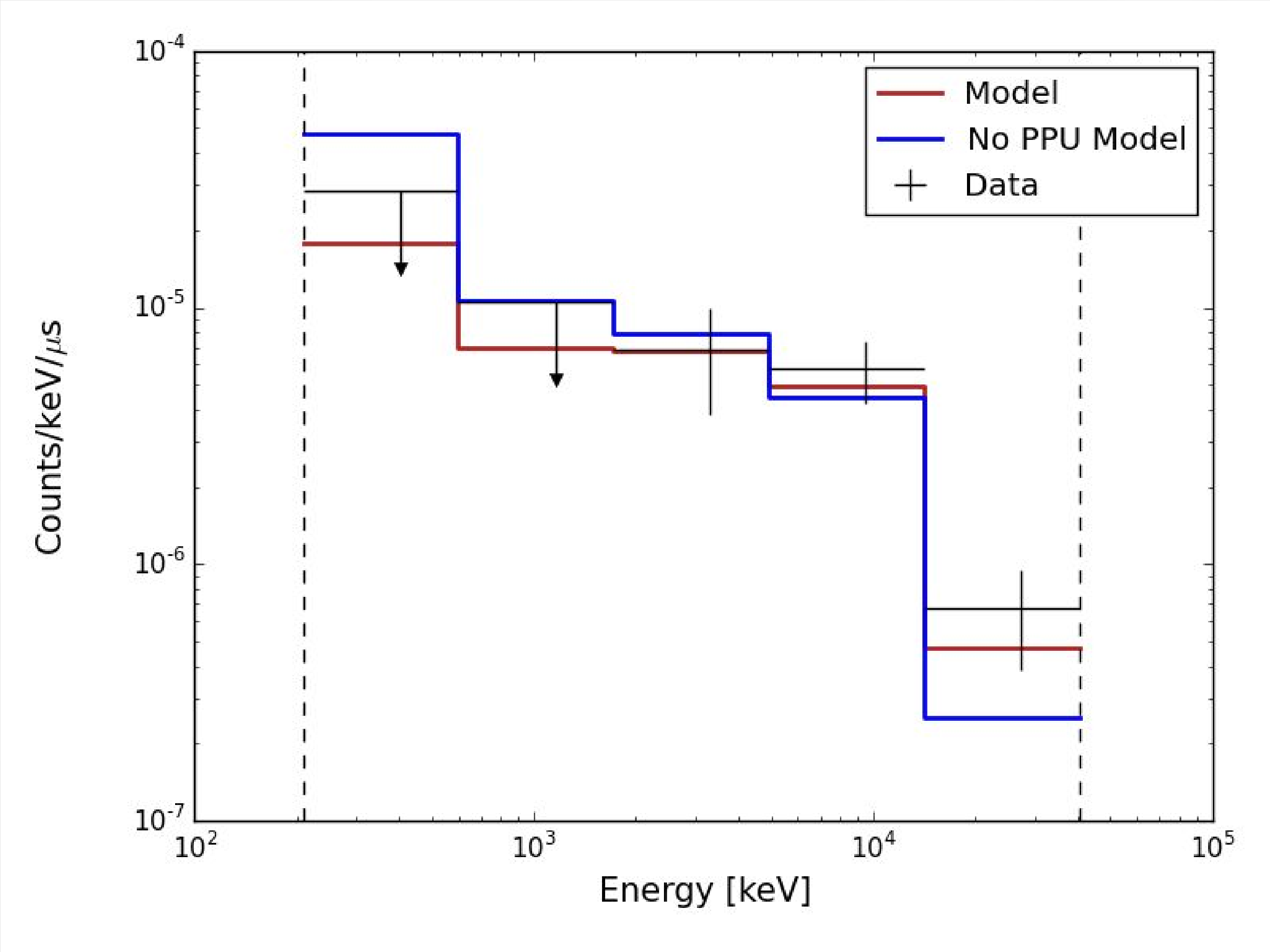
Results: TGF100909539 (102 km source-nadir offset)- Likelihood analysis



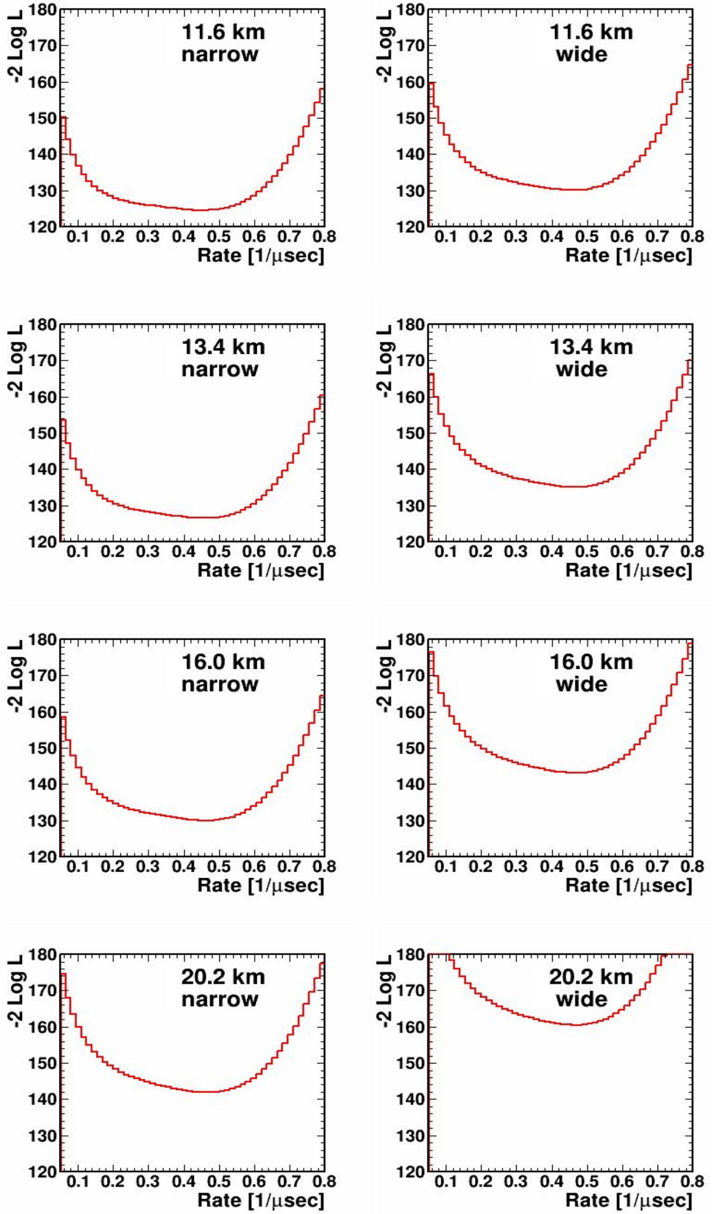
Results: TGF100909539

Low altitude narrow models can explain the observed hard spectrum.

Results: TGF100909539 best fit model and pulse pile-up effects

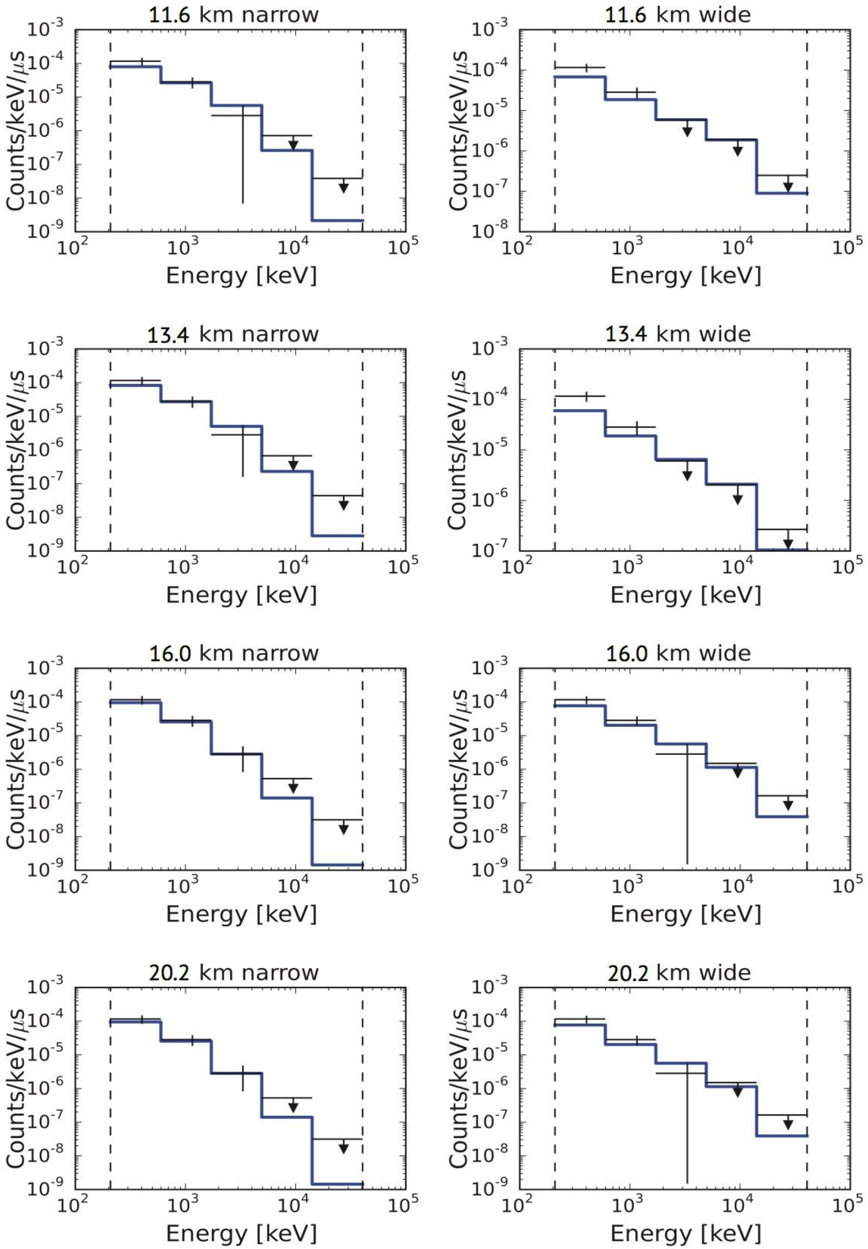


Fermi Gamma-ray Space Telescope



Results: TGF100909539 (102 km source-nadir offset)- Likelihood analysis

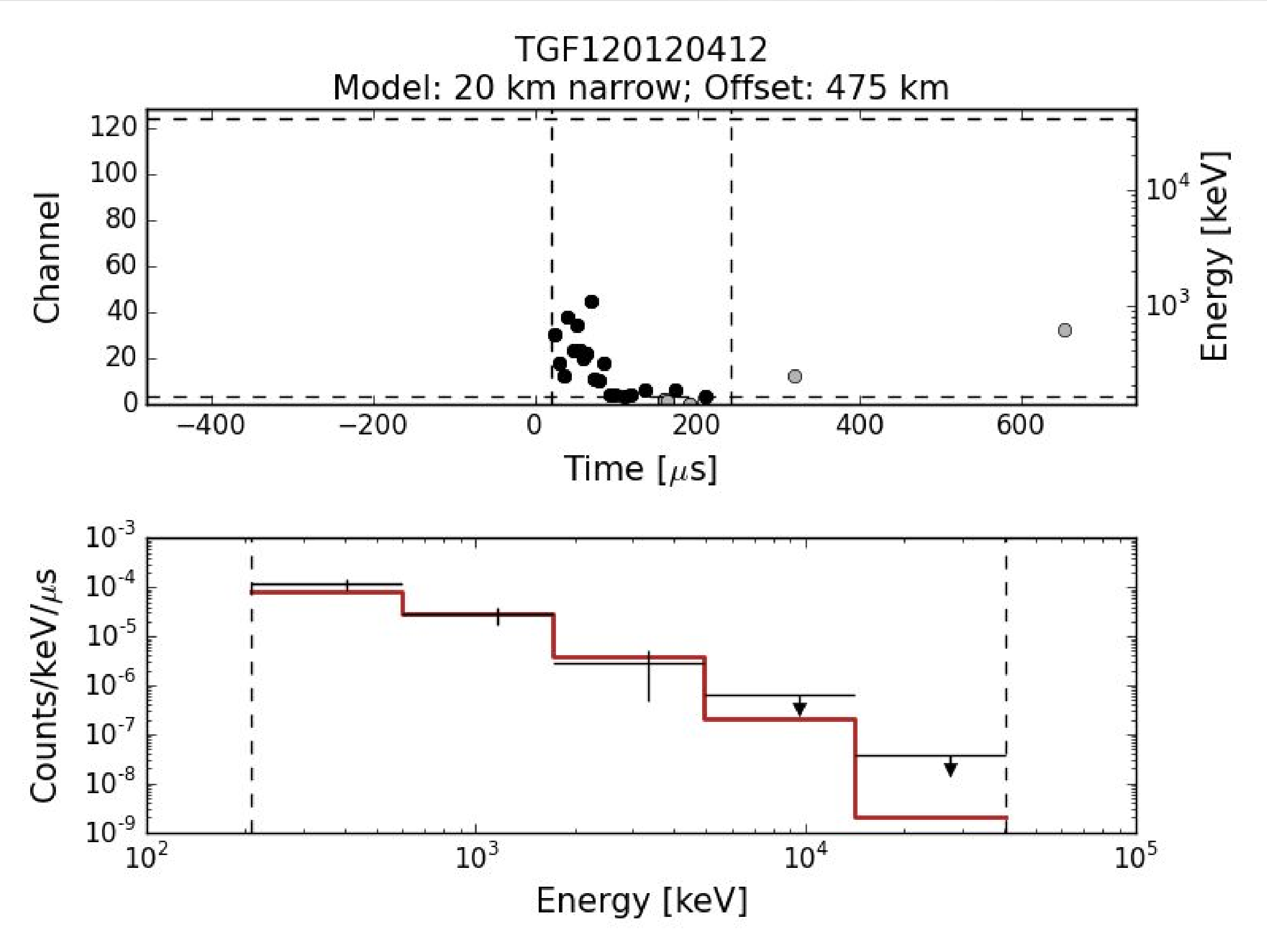
Deep narrow models are the best fit to the data!



Results: TGF120120412 (475 km source-nadir offset)

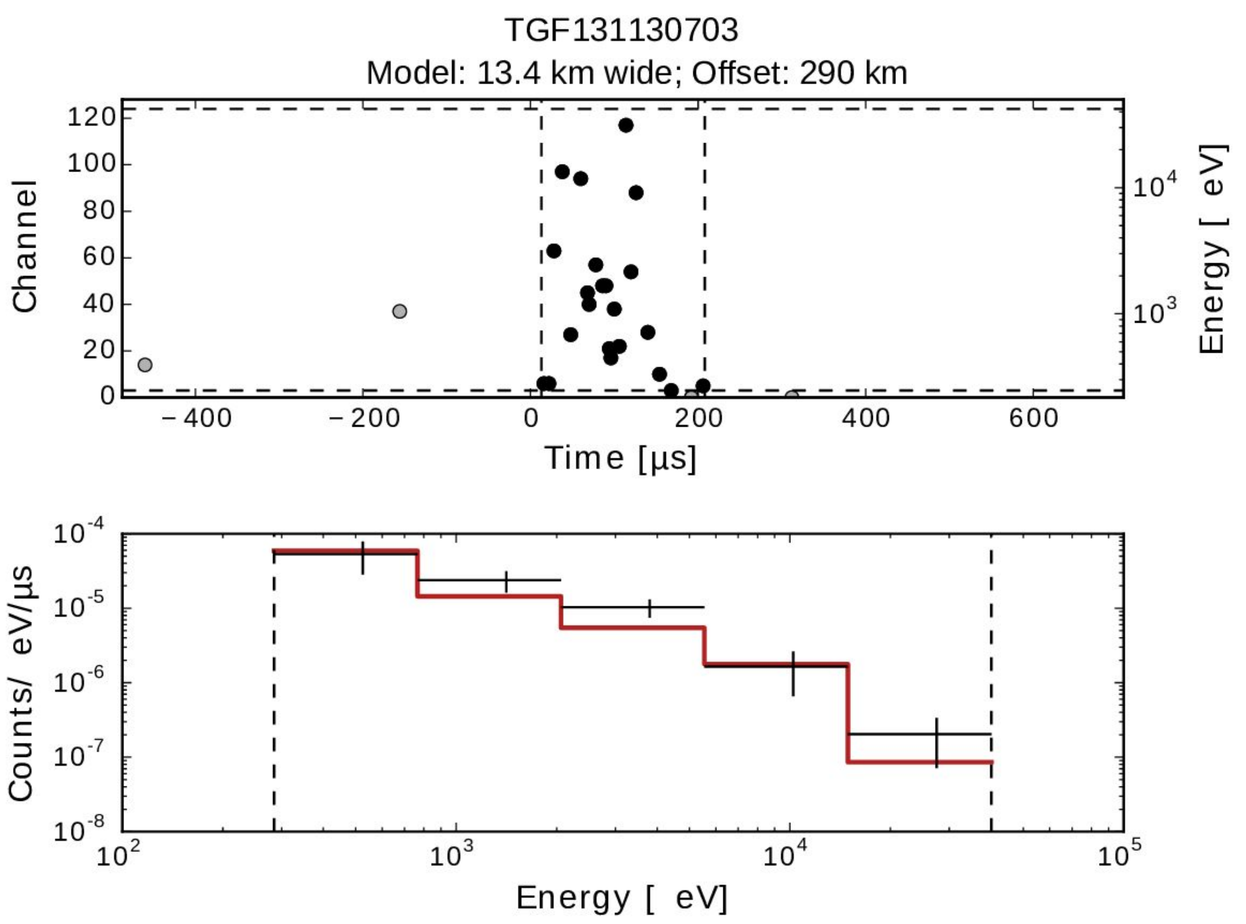
High altitude narrow models and low pulse pile-up can explain the observed soft spectrum.

Results: TGF120120412



- High altitude
- Narrow beam
- Small pulse pile-up

Results: TGF131130703 - Wide beams are the best fit!

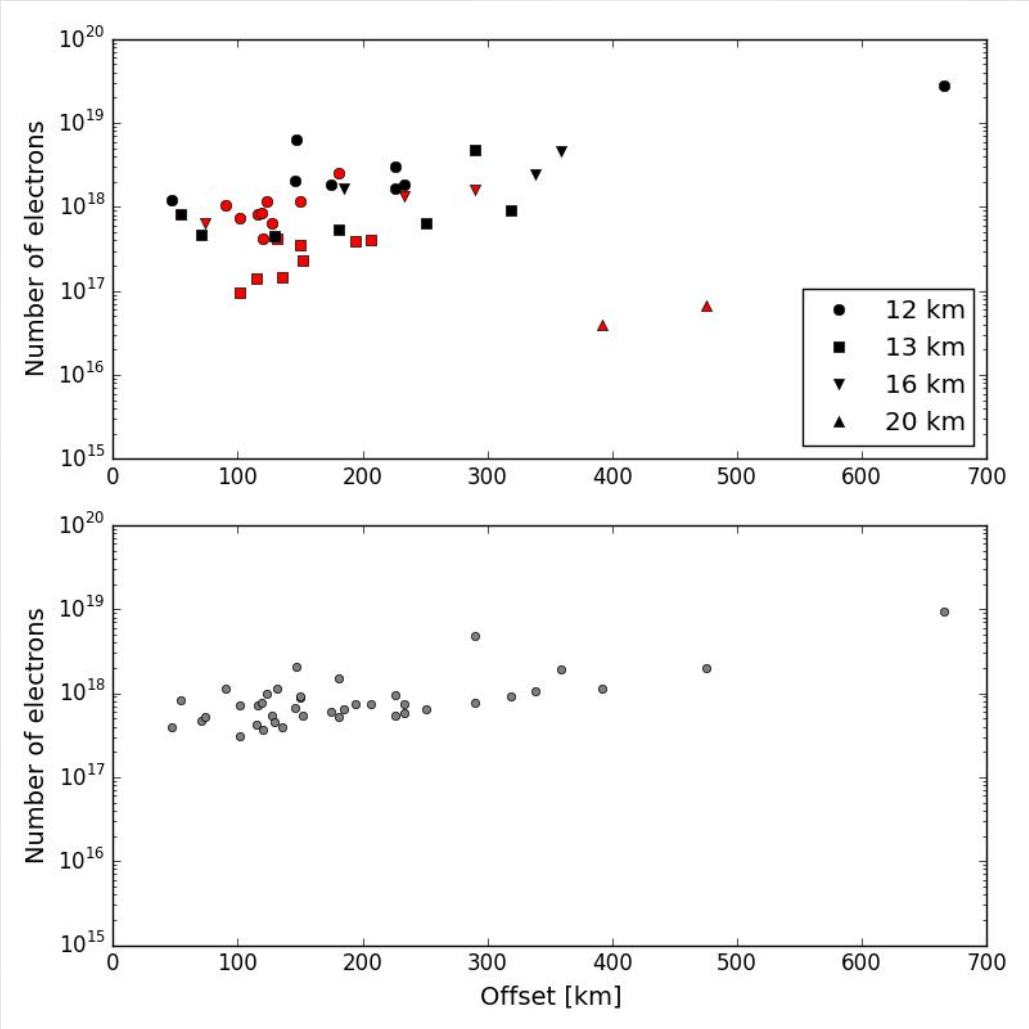


Wide beams send more high energy photons to the spacecraft!

Summary

- Of the 46 TGFs studied, 4 are unambiguously best fit by narrow models and another 2 unambiguously best fit by the wide beam model.
- For 6 TGFs, it was not possible to obtain a good fit.
- For most TGFs in our sample, it is not possible to distinguish between the narrow and wide beam models. However, the fact that some can be constrained is important as all previous published results based on summed TGF spectra have favored the wide beam models.

Summary: intrinsic brightness of TGFs



Assuming the best fit model source altitude

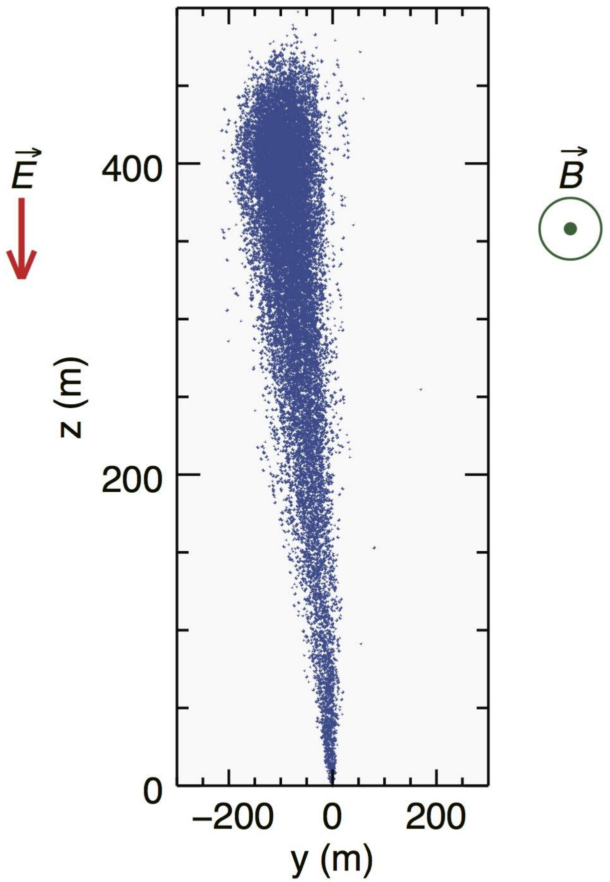
Assuming 13 km source altitude wide model

Narrow and wide beam models are indicated by red and black colors respectively

Conclusions

- Observations exhibit spectral diversity of TGFs
- Some TGFs can be best fit by narrow (large-scale RREA in organized electric fields), some others by wide beam models (acceleration at lightning leader tips or large-scale RREA in chaotic electric fields)
- Spectral analysis of individual TGFs put constraints on the source altitudes
- Pulse pile-up effects

Tilted beams and the effects of magnetic field



- Electron beams may experience tilts up to18 degrees (detectable ?)
- Electrons under the influence of the electric fields near Eth require a larger distance to avalanche multiply
- The average energy of the runaway electrons will decrease due to more collisions with air in the tilt direction