Analysis of Individual Terrestrial Gamma-Ray Flashes with Lightning Leader Models and Fermi Gamma-Ray Burst Monitor Data

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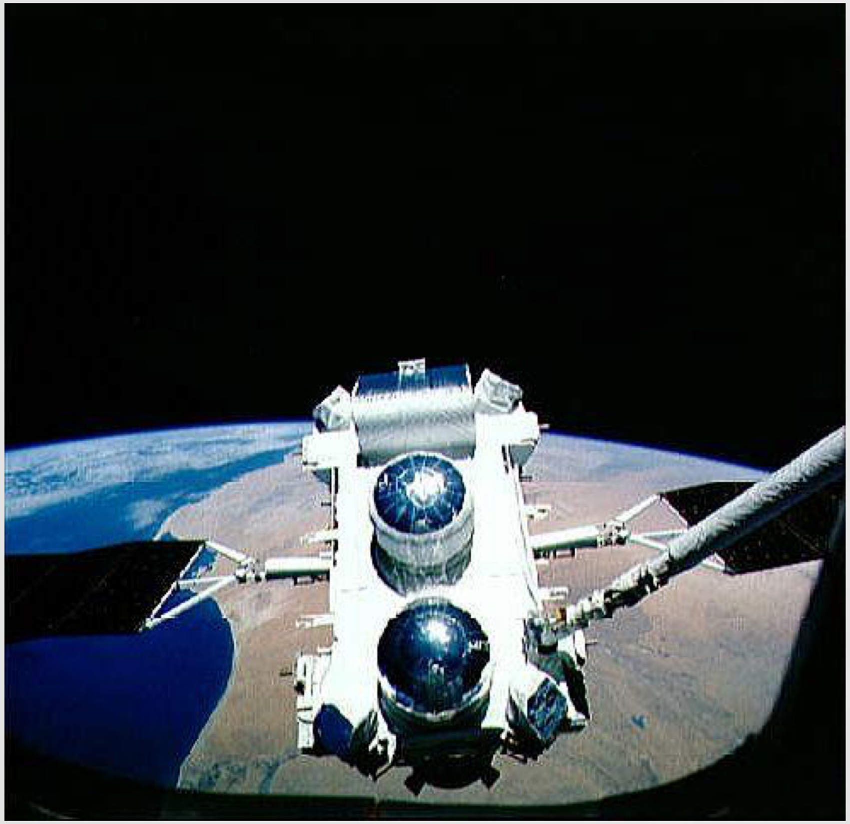
Space Research in Huntsville, AL

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 diameter by 1.27 cm thick, and a 12.7 cm diameter 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

Original Science Paper: 12 TGFs

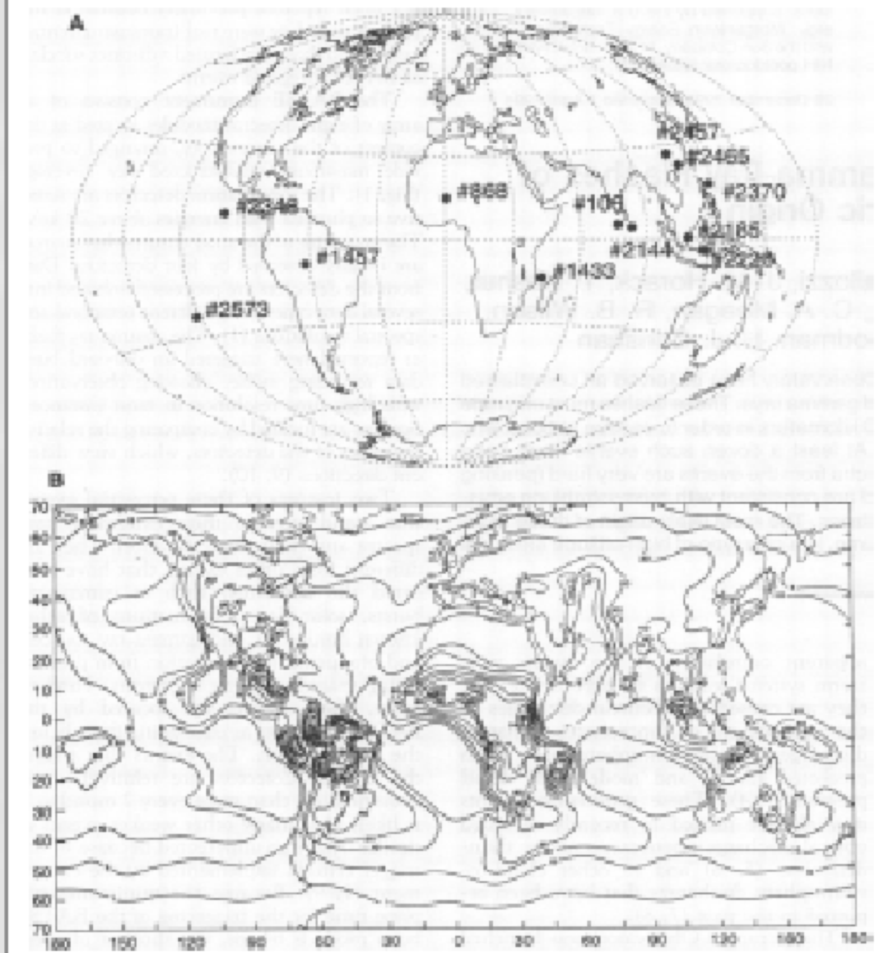
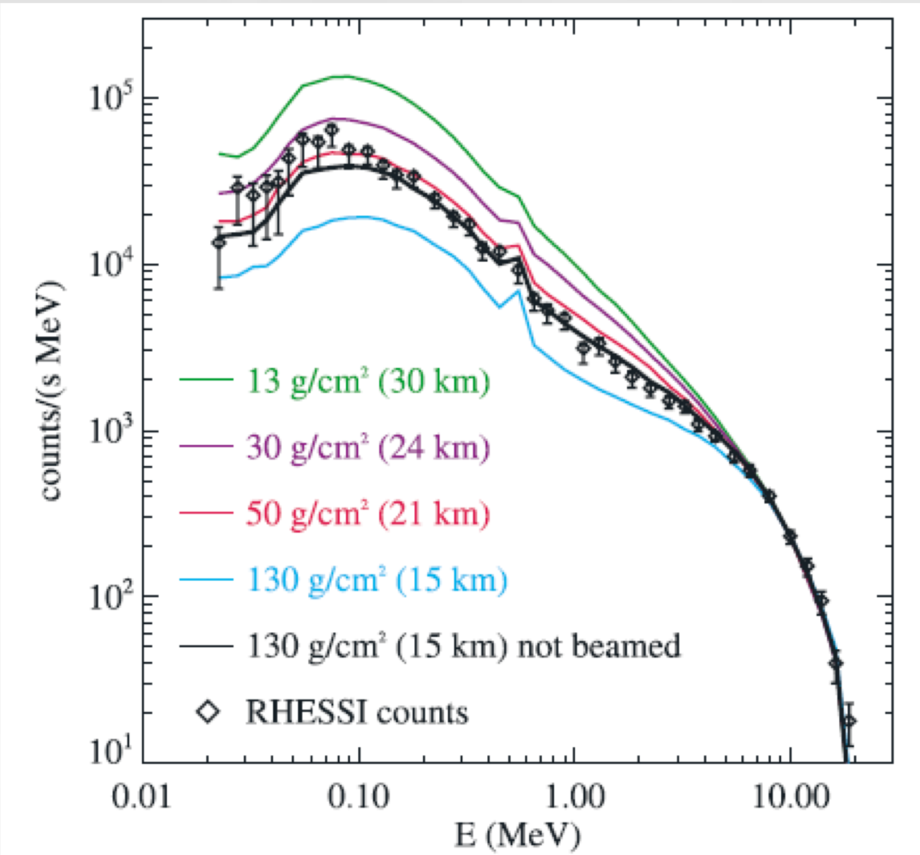
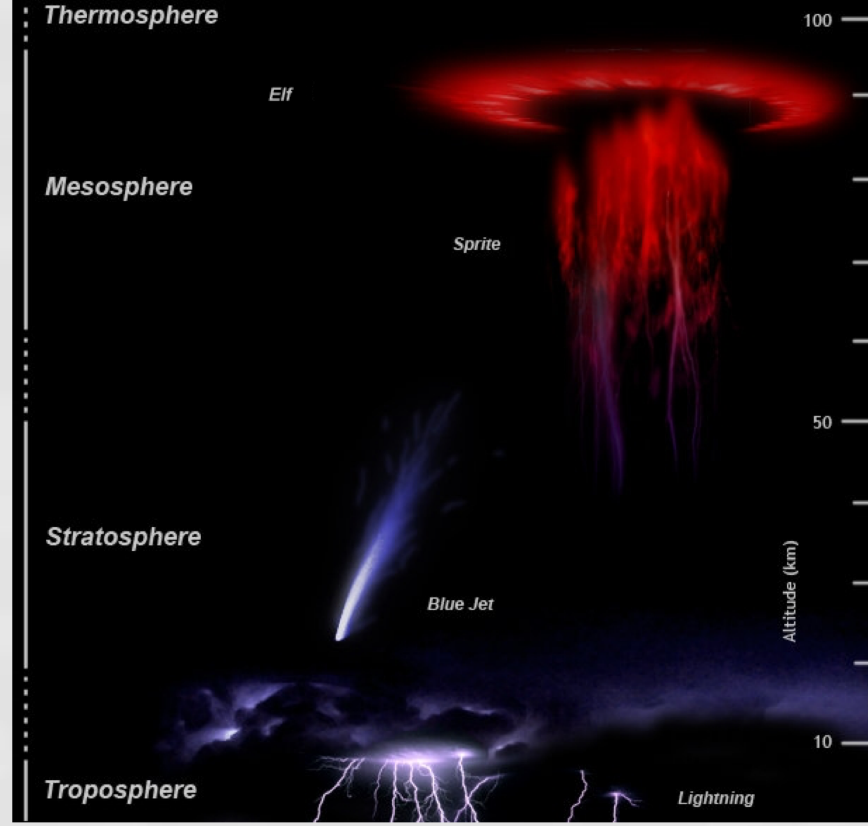


Fig. 2. (A) The approximate locations of the events of Table 1 over the Earth. (B) Contour map of the yearly thunderstorm activity over the Earth (12). Most of the events occurred over regions that have high thunderstorm activity. The spacecraft is limited by its orbital inclination to latitudes within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

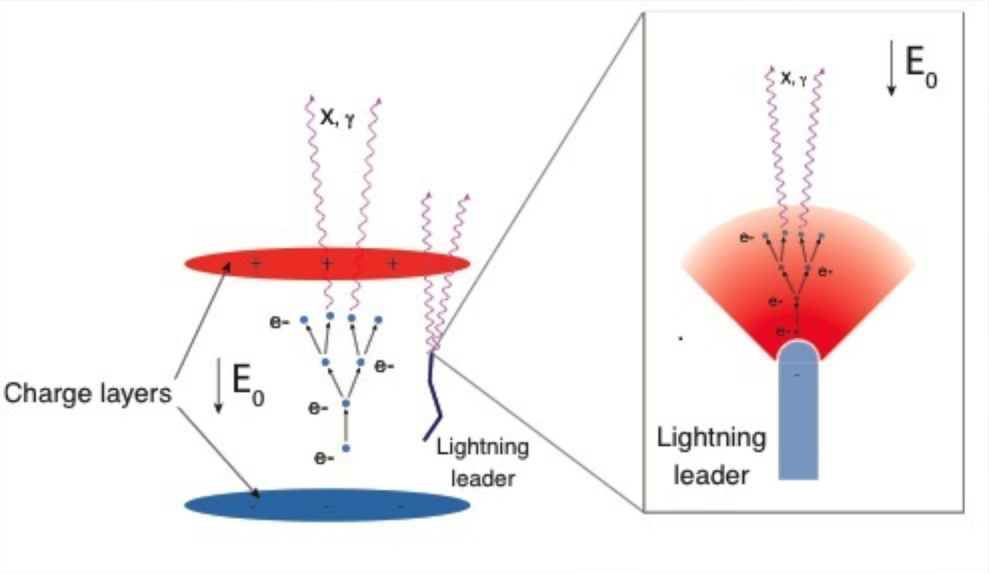
Courtesy of G. Fishman

Spectral Fit of Summed RHESSI TGFs





Dwyer and Smith (2005)



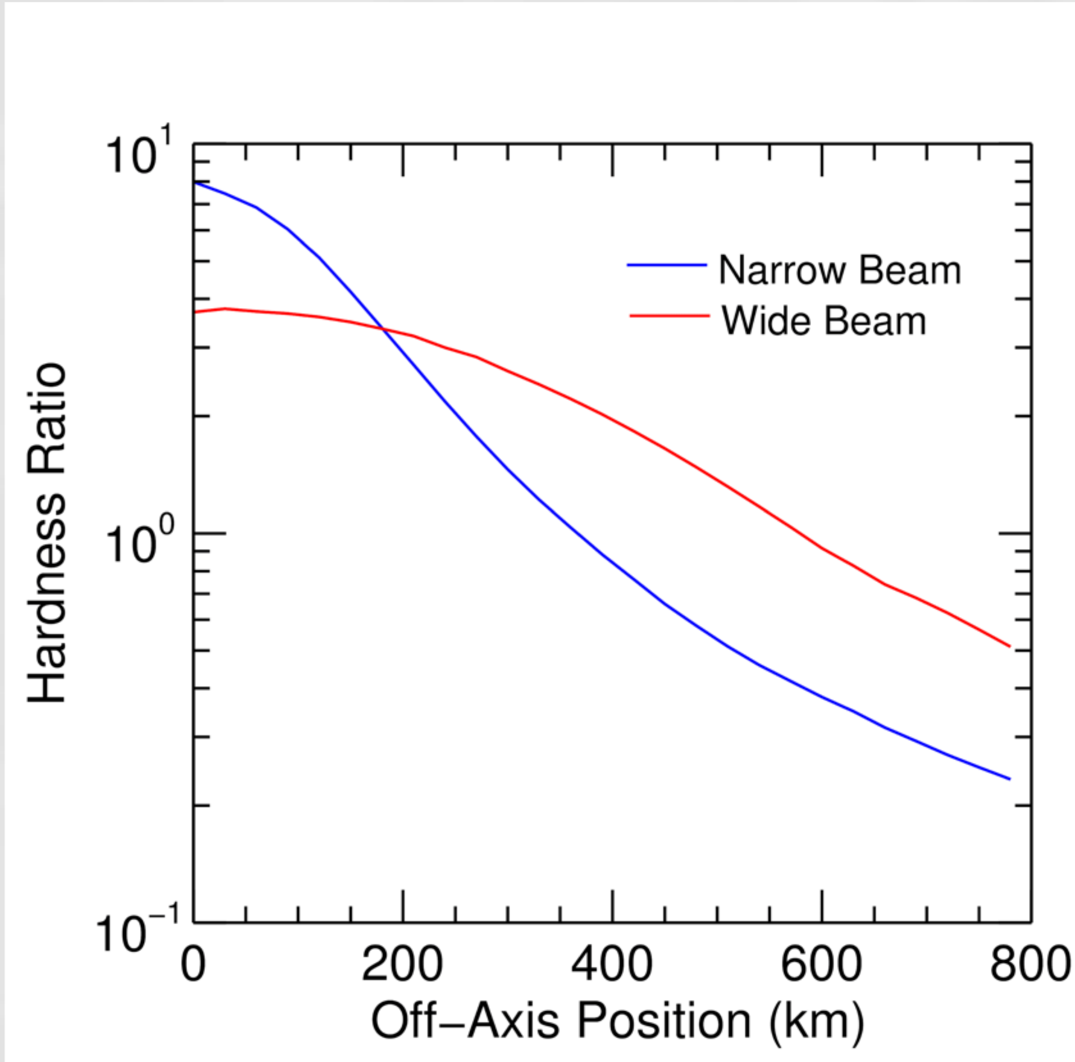
Lightning Leader Model

- 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*

The effects of compton scattering and beaming geometry

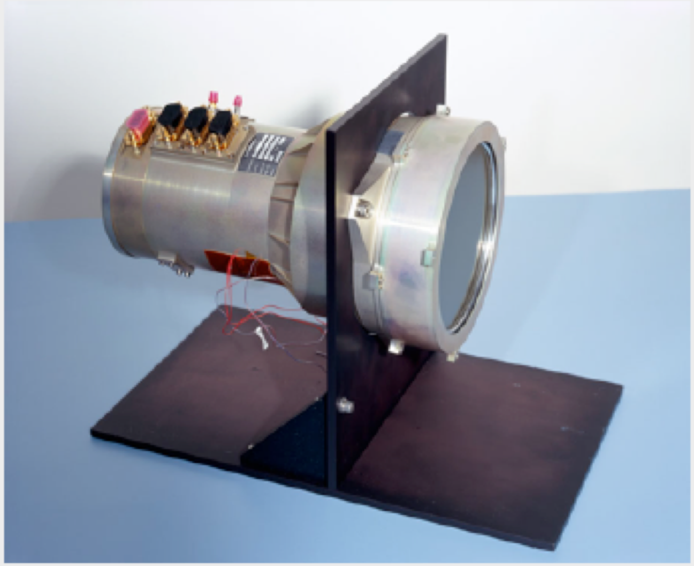


June 11, 2008 Launch of FERMI

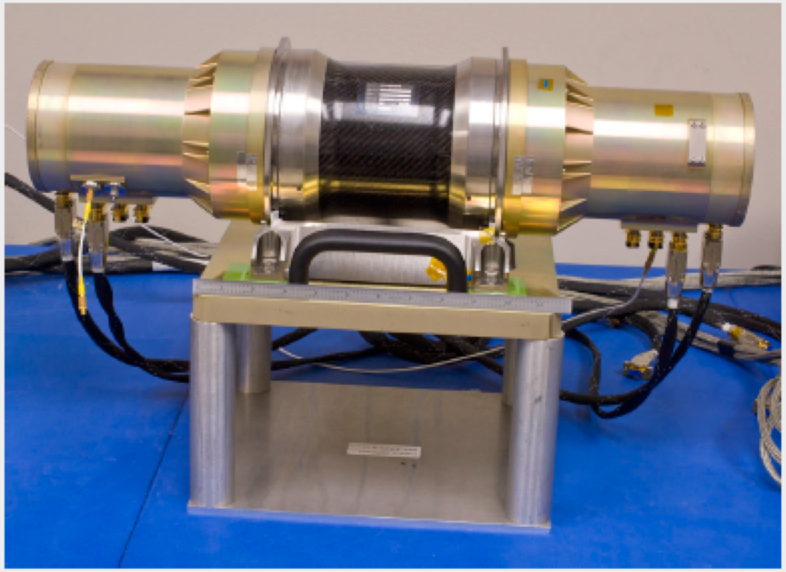
11 Years Since **Fermi Launch** from Cape Canaveral!

Fermi Gamma-ray Burst Monitor (GBM)

Fermi Gamma-ray Burst Monitor (GBM)



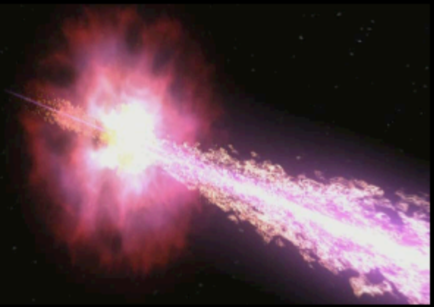
- Sodium iodide (NaI)
- 12.7 cm diameter X 1.27 cm thick
- 8 keV to 1 MeV



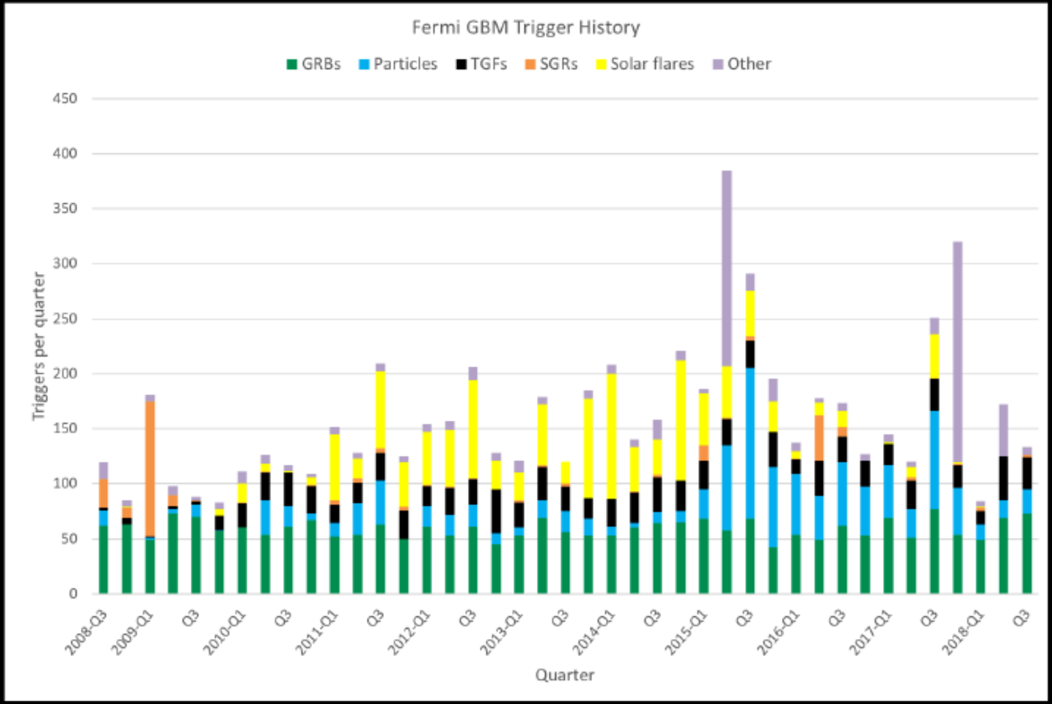
- Bismuth germanate (BGO)
- 12.7 cm diameter X 12.7 cm long
- 200 keV to 40 MeV

Triggers up to end of 2018…

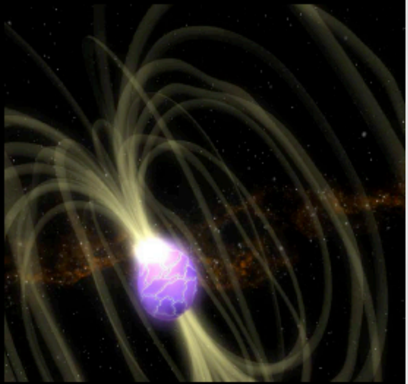
2238 GRBs



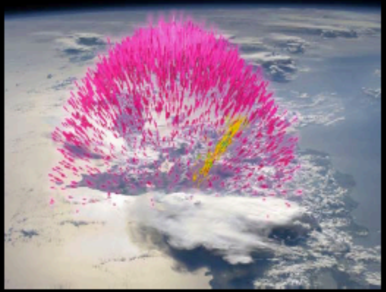
1176 Solar Flares



275 Magnetars

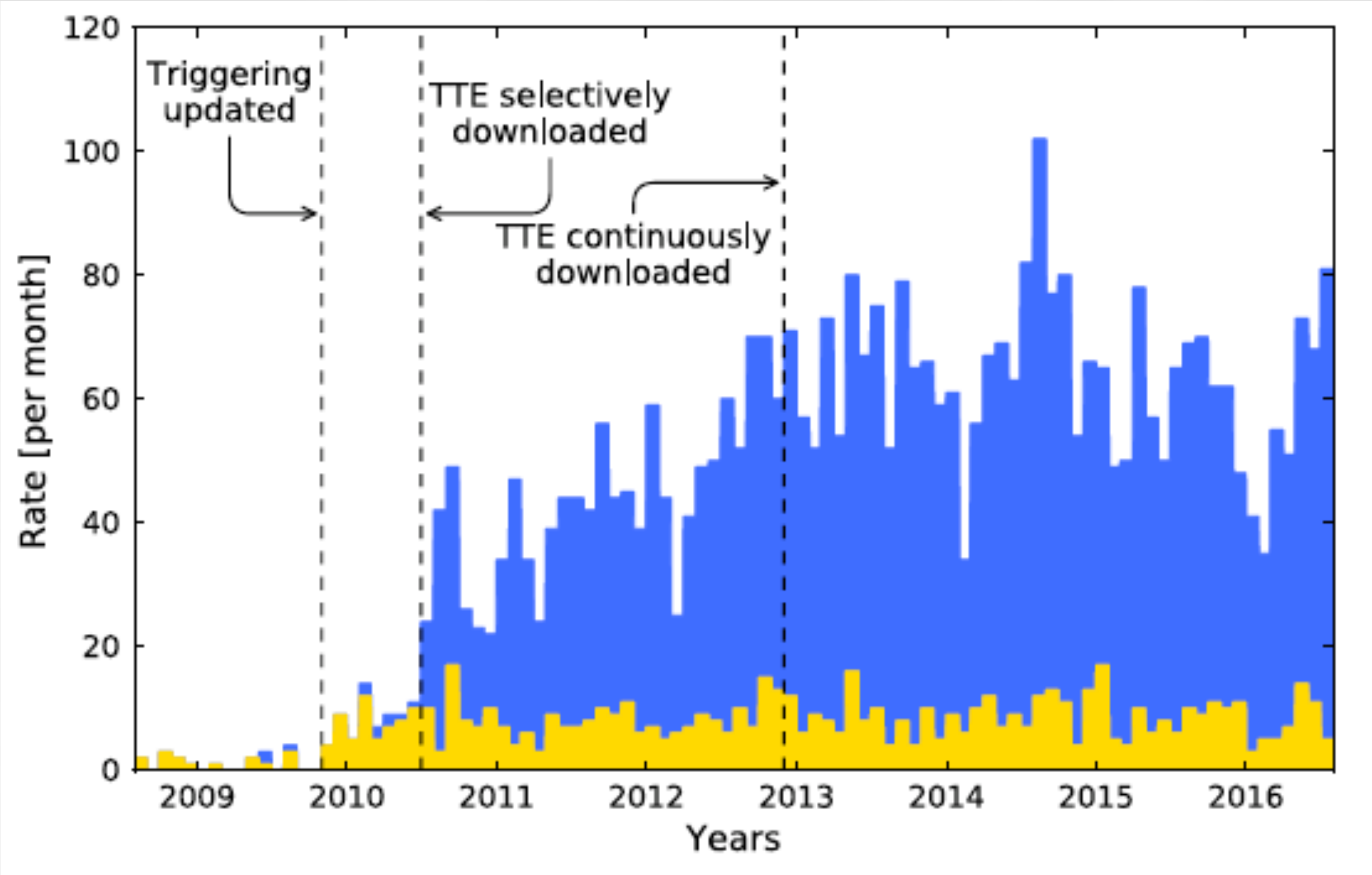


875 TGFs



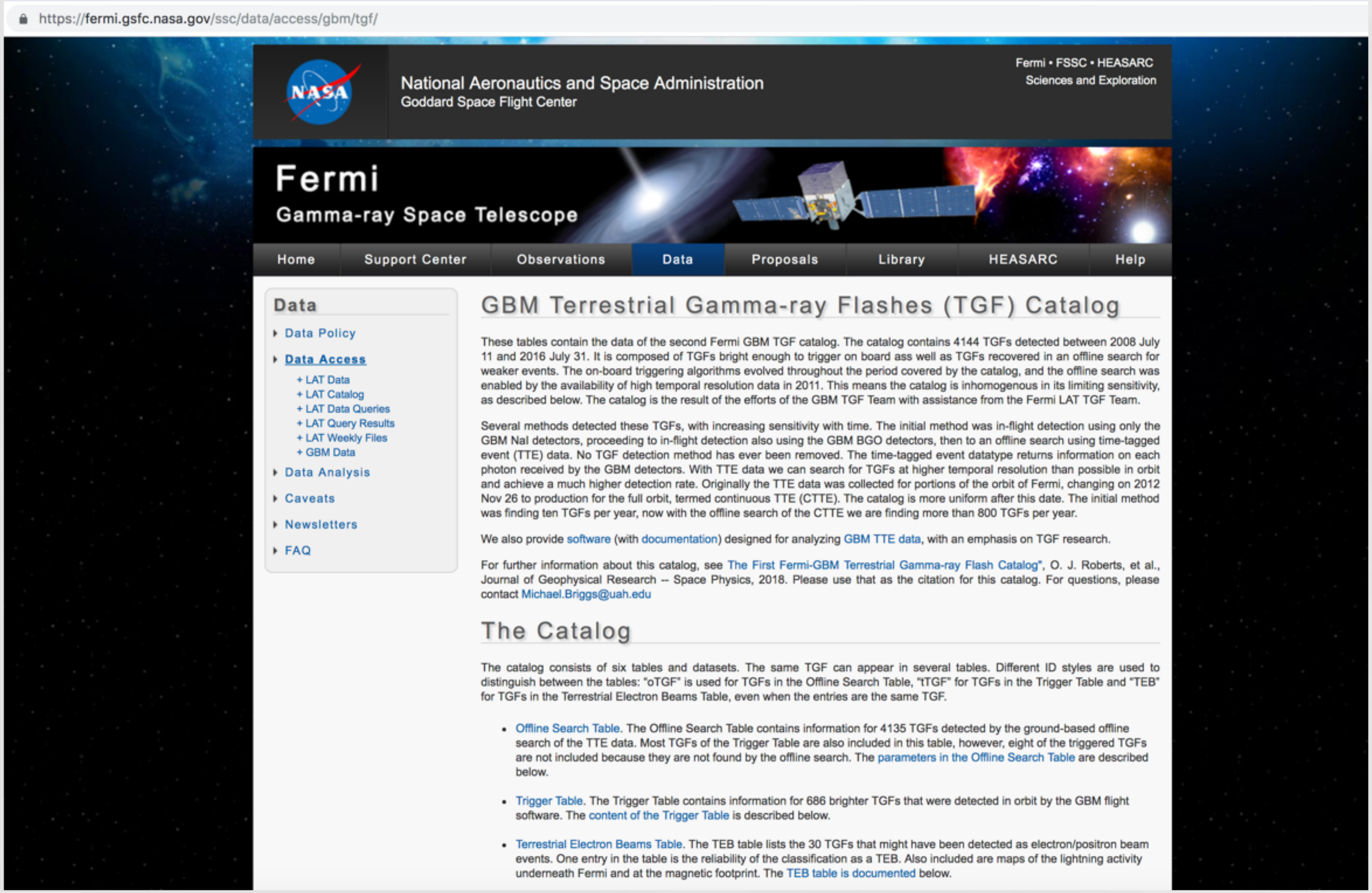
- 668 Others:
- 189 from Swift J0243.6+6124 and 169 from V404 Cyg;
- 1041 particles

Increased rate of TGFs



TGF catalog

The catalog contains 4,144 TGFs, detected from11 July 2008 (when GBM triggering was enabled) through 31 July 2016. 1,314 TGFs have a valid VLF association from WWLLN. The GBM TGF catalog is hosted on the Fermi Science Support Center (FSSC) at http://fermi.gsfc.nasa.gov/ssc/data/access/gbm/tgf .


https://fermi.gsfc.nasa.gov/ssc/data/access/gbm/tgf/

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Data
- Data Policy
- Data Access
  - + LAT Data
  - + LAT Catalog
  - + LAT Data Queries
  - + LAT Query Results
  - + LAT Weekly Files
  - + GBM Data
- Data Analysis
- Caveats
- Newsletters
- FAQ

GBM Terrestrial Gamma-ray Flashes (TGF) Catalog

These tables contain the data of the second Fermi GBM TGF catalog. The catalog contains 4144 TGFs detected between 2008 July 11 and 2016 July 31. It is composed of TGFs bright enough to trigger on board ass well as TGFs recovered in an offline search for weaker events. The on-board triggering algorithms evolved throughout the period covered by the catalog, and the offline search was enabled by the availability of high temporal resolution data in 2011. This means the catalog is inhomogenous in its limiting sensitivity, as described below. The catalog is the result of the efforts of the GBM TGF Team with assistance from the Fermi LAT TGF Team.

Several methods detected these TGFs, with increasing sensitivity with time. The initial method was in-flight detection using only the GBM NaI detectors, proceeding to in-flight detection also using the GBM BGO detectors, then to an offline search using time-tagged event (TTE) data. No TGF detection method has ever been removed. The time-tagged event datatype returns information on each photon received by the GBM detectors. With TTE data we can search for TGFs at higher temporal resolution than possible in orbit and achieve a much higher detection rate. Originally the TTE data was collected for portions of the orbit of Fermi, changing on 2012 Nov 26 to production for the full orbit, termed continuous TTE (CTTE). The catalog is more uniform after this date. The initial method was finding ten TGFs per year, now with the offline search of the CTTE we are finding more than 800 TGFs per year.

We also provide software (with documentation) designed for analyzing GBM TTE data, with an emphasis on TGF research.

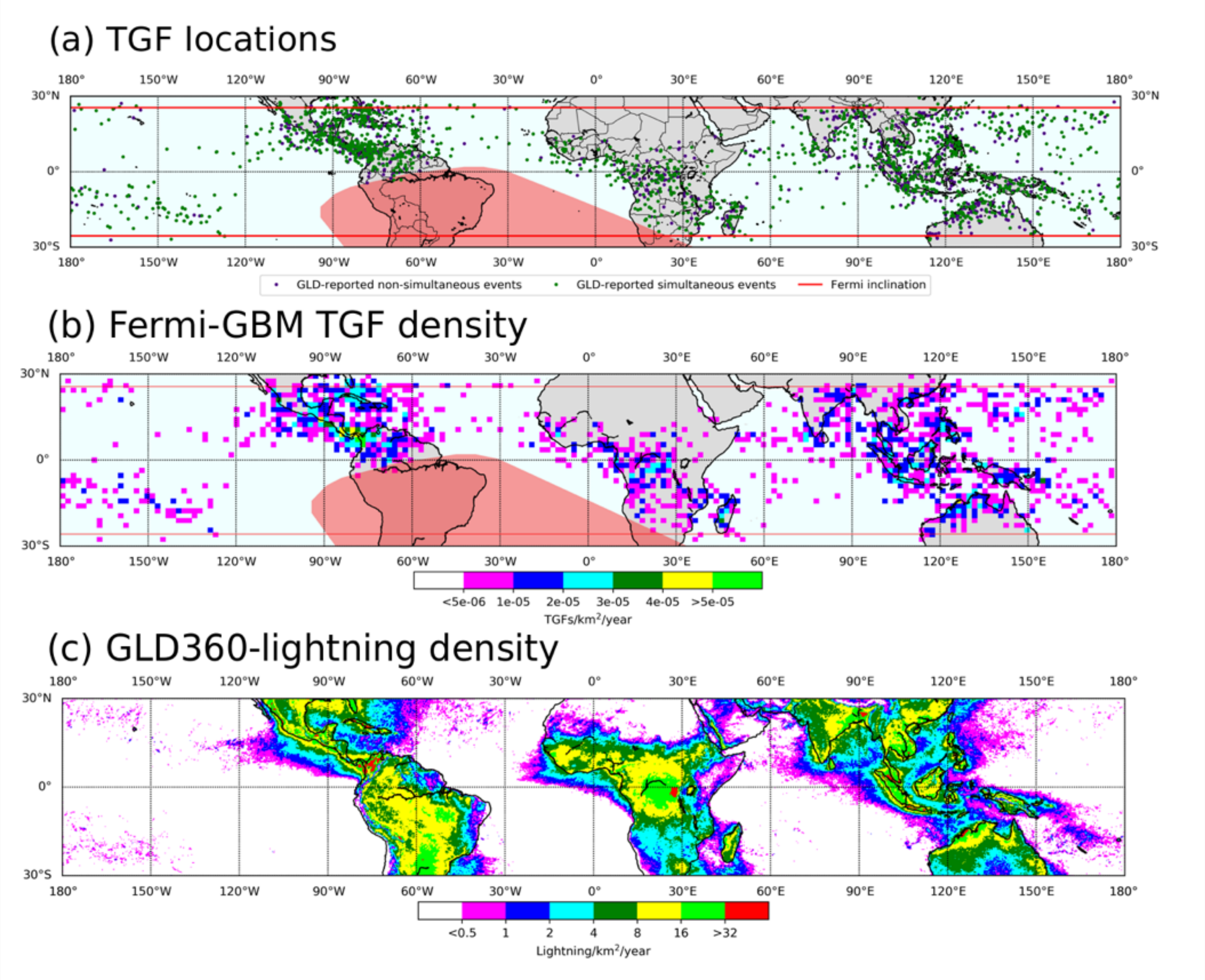
For further information about this catalog, see The First Fermi-GBM Terrestrial Gamma-ray Flash Catalog", O. J. Roberts, et al., Journal of Geophysical Research -- Space Physics, 2018. Please use that as the citation for this catalog. For questions, please contact Michael.Briggs@uah.edu

The Catalog

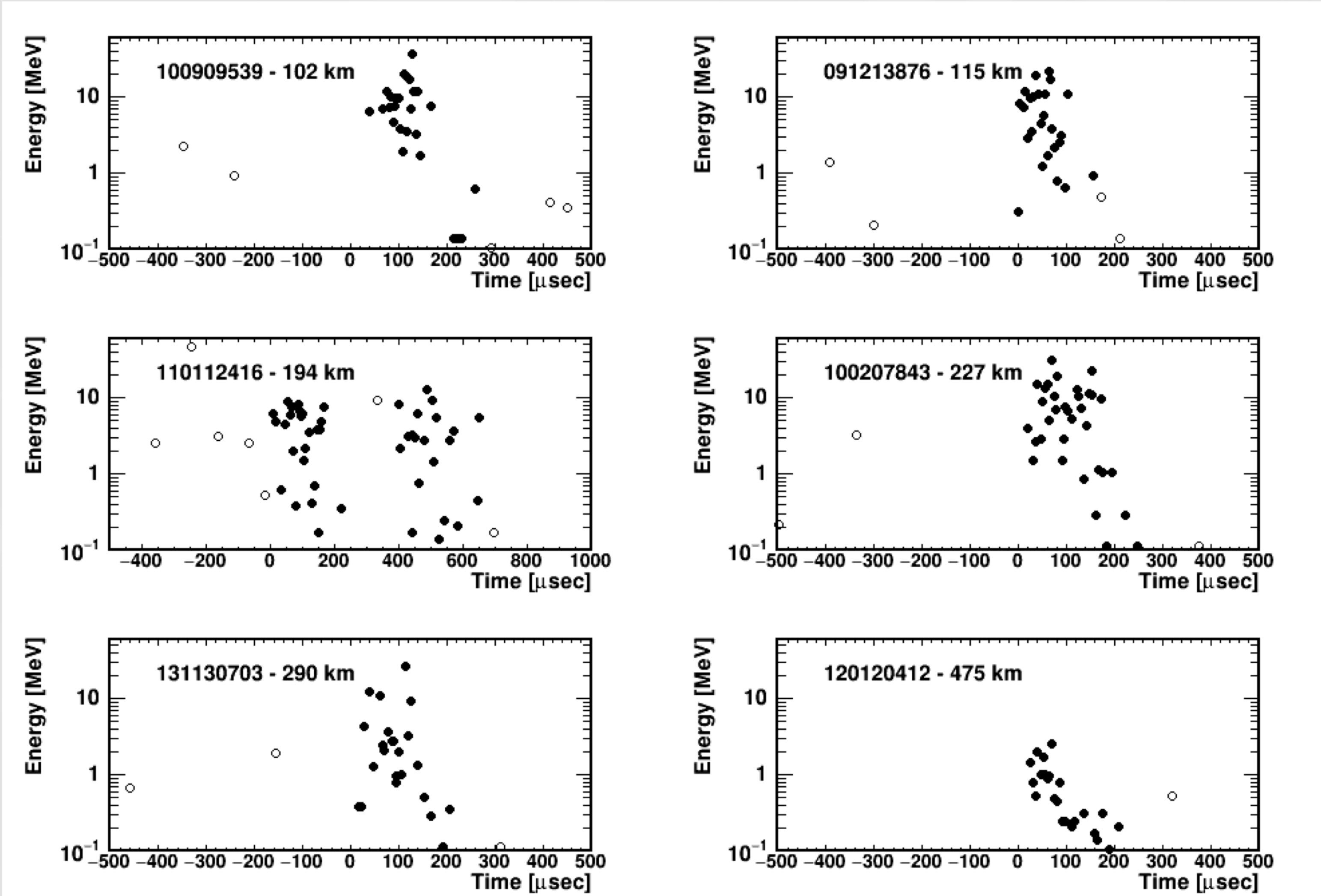
The catalog consists of six tables and datasets. The same TGF can appear in several tables. Different ID styles are used to distinguish between the tables: "oTGF" is used for TGFs in the Offline Search Table, "tTGF" for TGFs in the Trigger Table and "TEB" for TGFs in the Terrestrial Electron Beams Table,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

- Offline Search Table. The Offline Search Table contains information for 4135 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 686 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 30 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.

Recent observations of TGFs and lightning



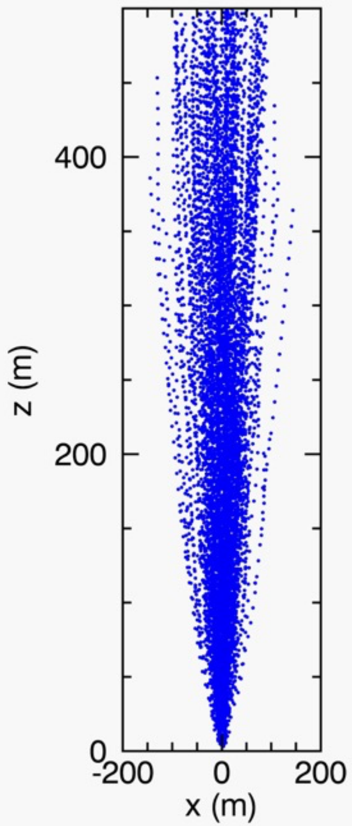
The Energy Spectra Terrestrial Gamma-ray Flashes



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 2016 about 4000 TGFs were observed. WWLLN and ENTLN provided the TGF radio locations for about 1300 TGFs.
- Choosing the bright events with favorable positions till the end of July 2016 resulted in a sample of 66 TGFs.

RREA Model

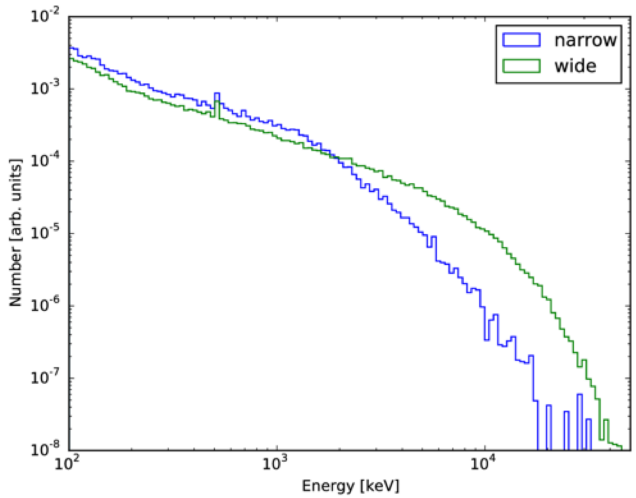


The acceleration of electrons and consequent emission of gamma rays with further propagation of the particles were simulated using REAM code (Dwyer, 2007).

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.

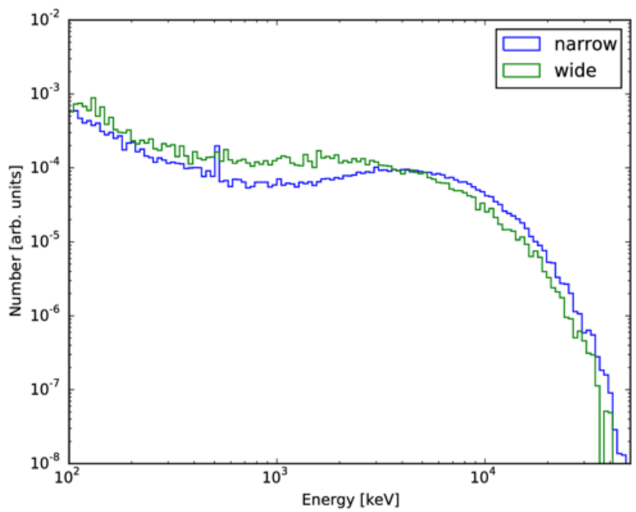
The altitudes correspond to atmospheric column densities given by MSIS model used in REAM code.
http://omniweb.gsfc.nasa.gov/vitmo/msis_vitmo.html

RREA Modeling



High offset

Simulated photon energy spectra at spacecraft altitude for **narrow** and **wide** models the source altitude of 13 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.

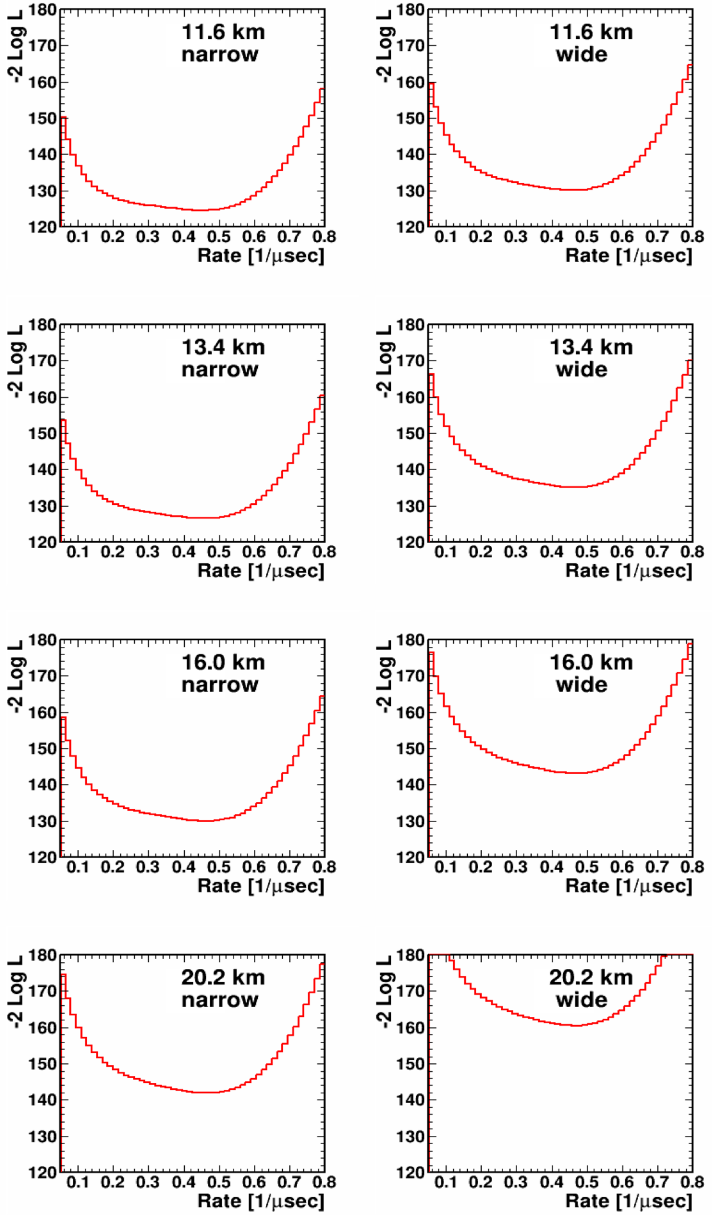
Simulated detector counts

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

Pulse-pileup corrected counts

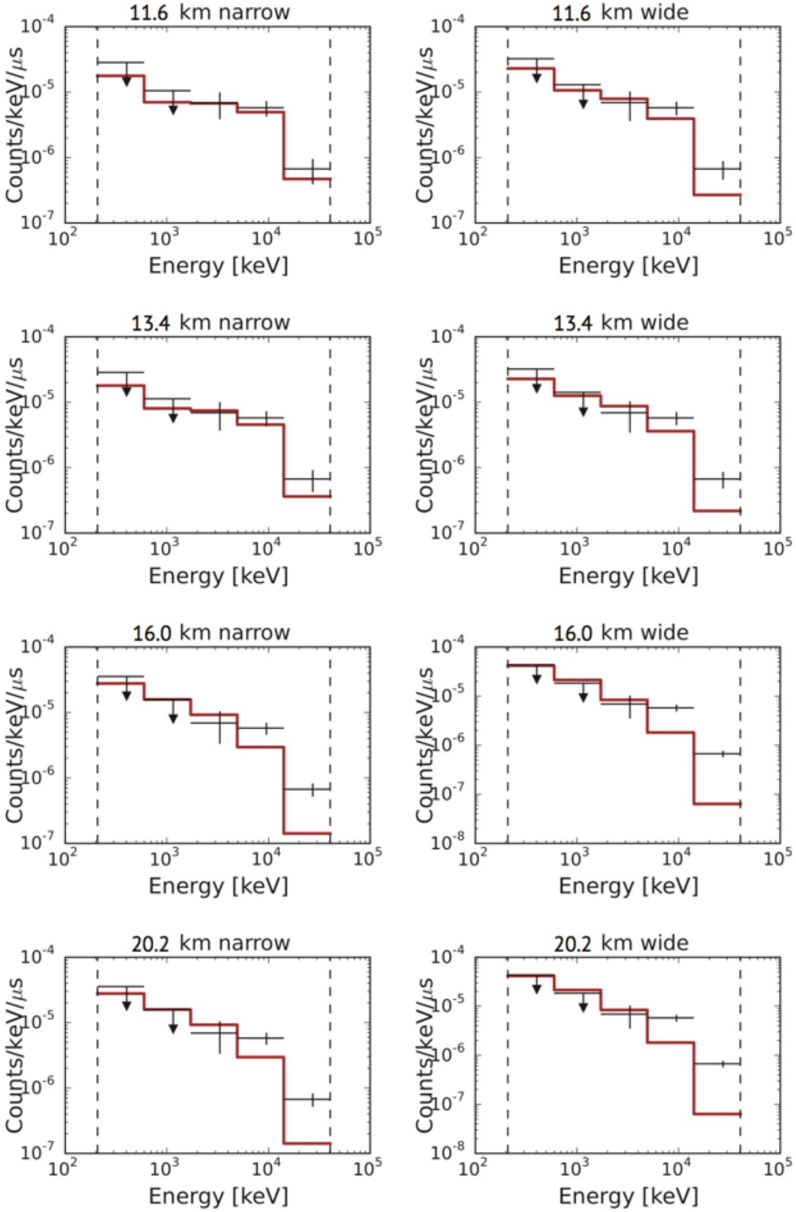
Likelihood analysis: iterating over the models choosing acceptable/rejected ones.

Best fit model



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

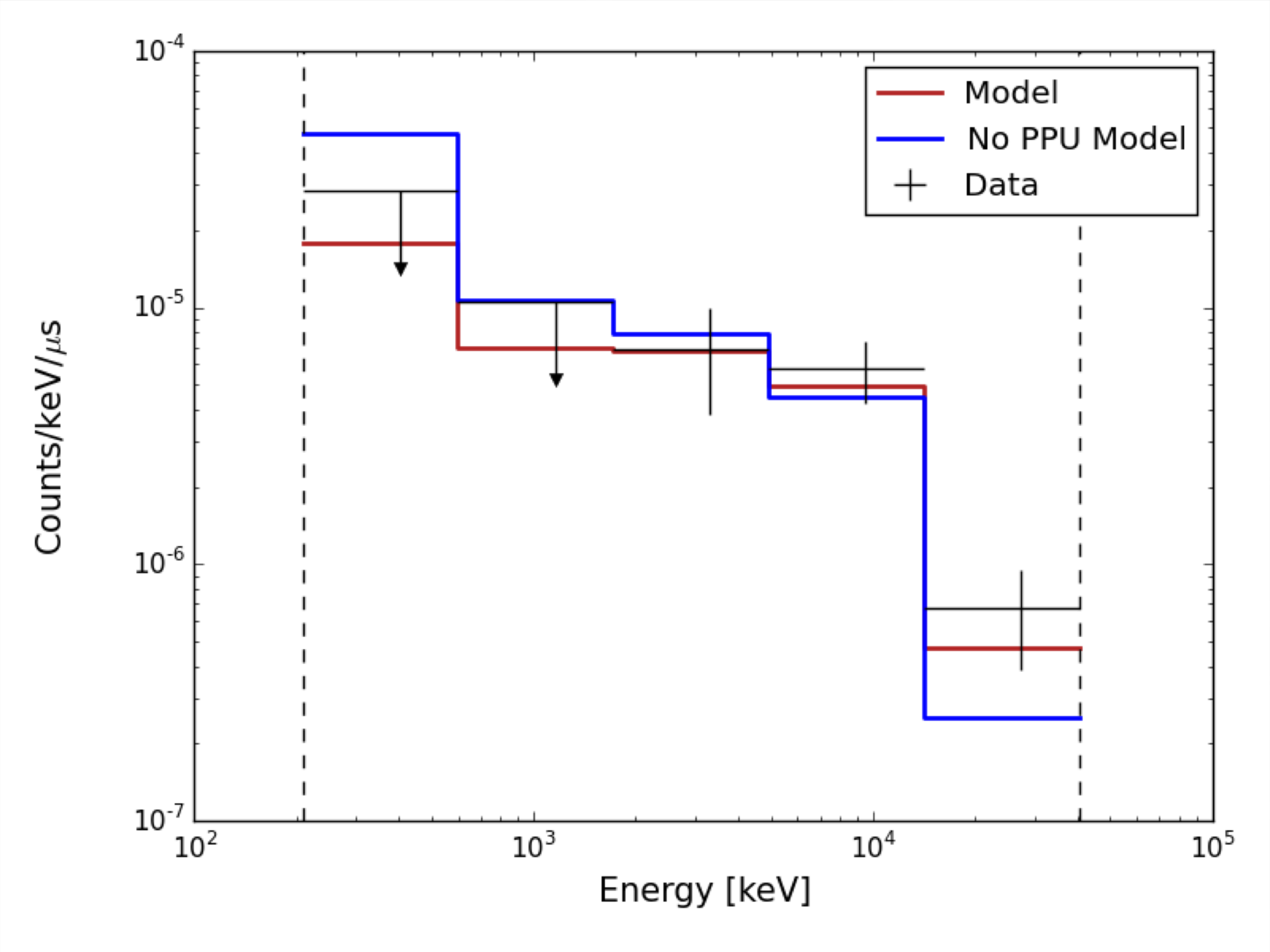
Deep narrow models are the best fit to the data!

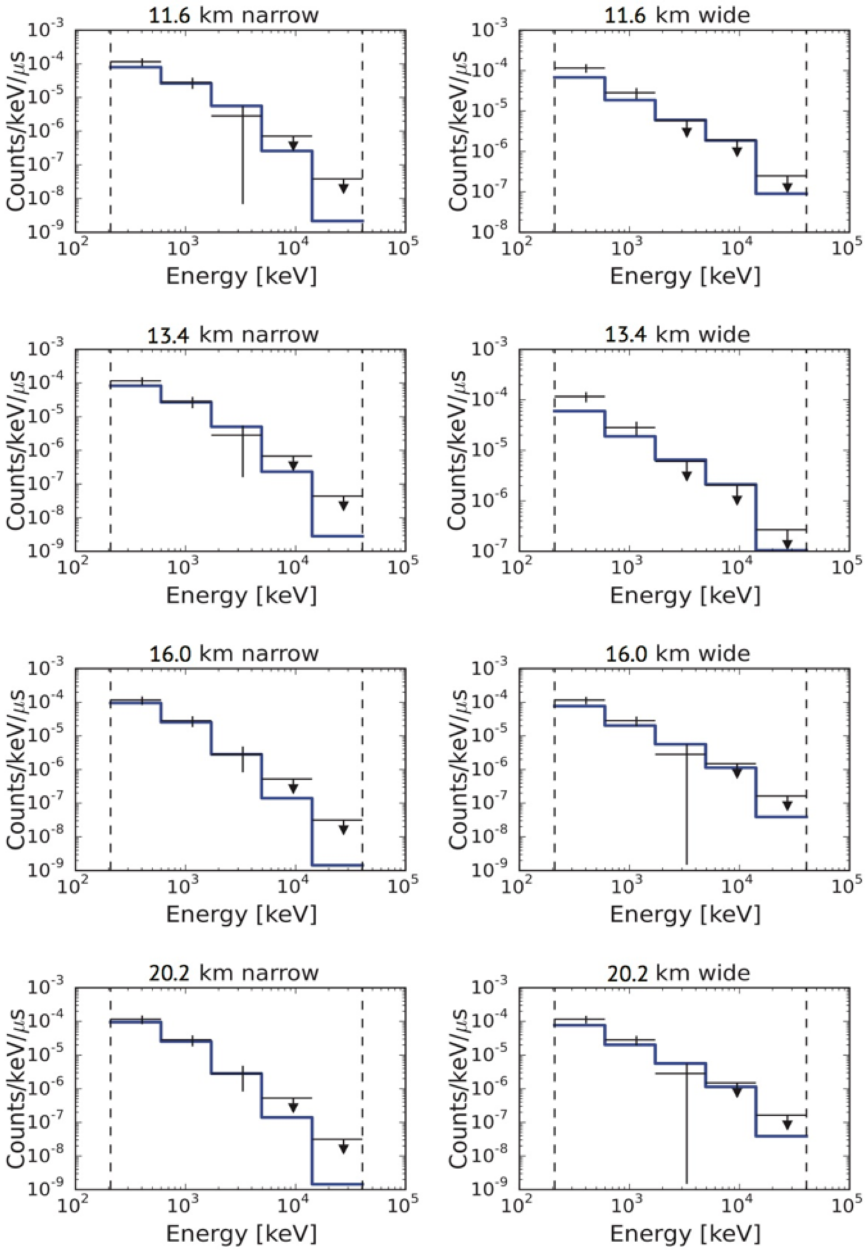


Results: TGF100909539

Low altitude narrow models can explain the observed hard spectrum.

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

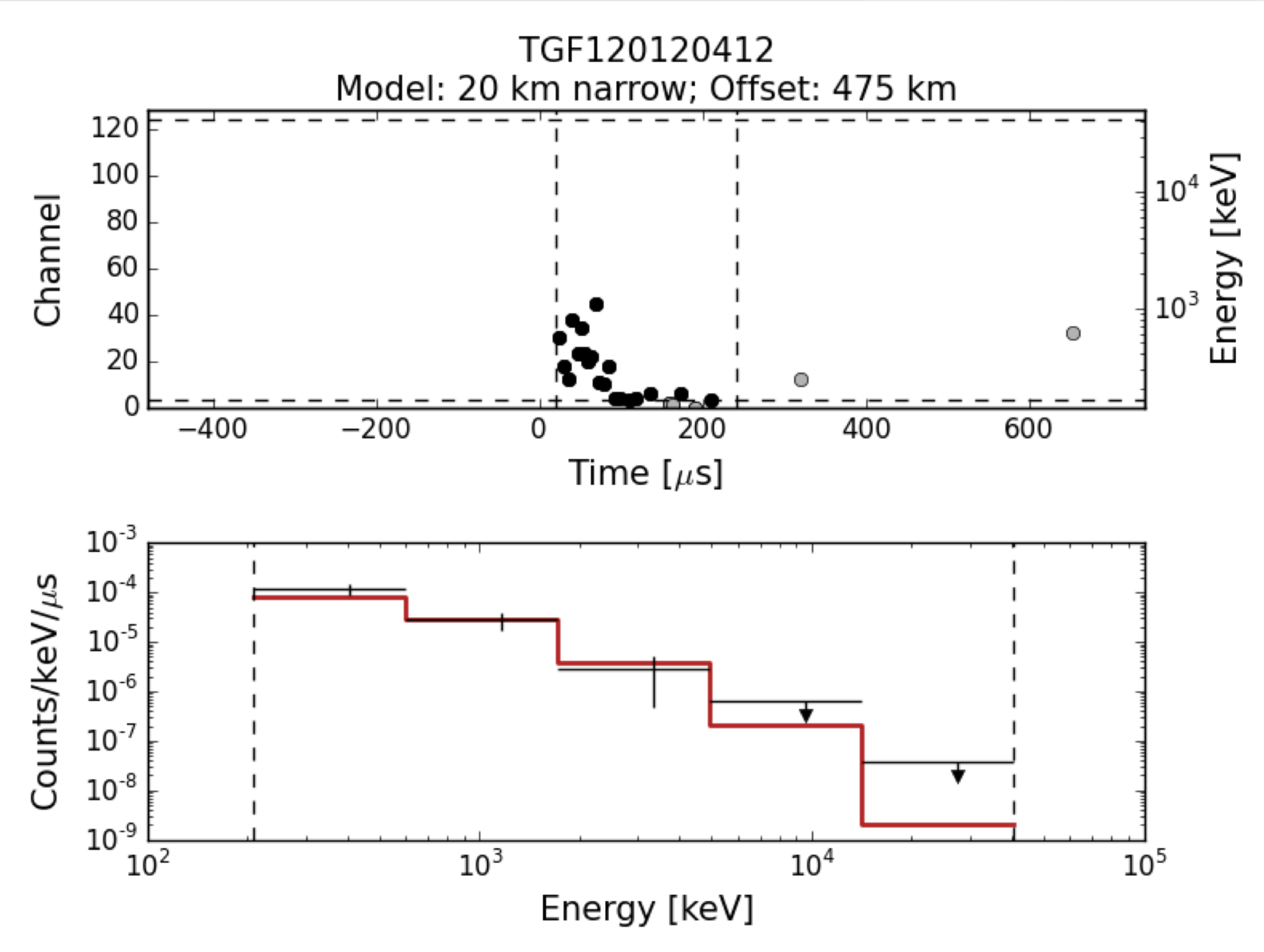




Results: TGF120120412 (475 km source-nadir offset)

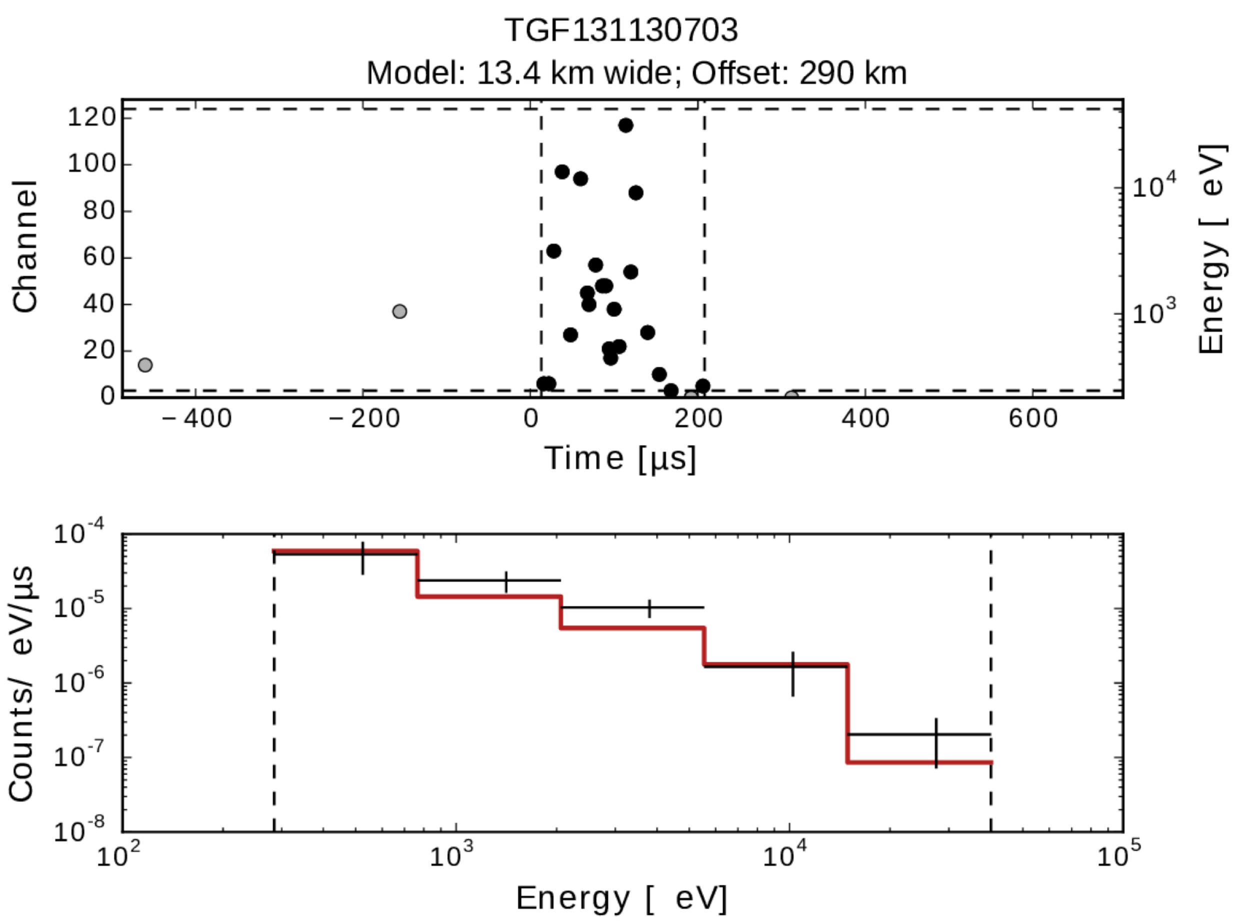
High altitude narrow models and low pulse pile-up can explain the observed soft spectrum.

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!

Previous work Mailyan et al., 2016

- 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.

Mailyan, B. G., Briggs, M. S., Cramer, E. S., Fitzpatrick, G., Roberts, O. J., Stanbro, M., Connaughton, V., McBreen, S., Bhat, P. N., and Dwyer, J. R. (2016), The spectroscopy of individual terrestrial gamma-ray flashes: Constraining the source properties, *J. Geophys. Res. Space Physics*, 121, 11,346– 11,363.

The geometry used for simulating lightning-produced beams of source bremsstrahlung photons

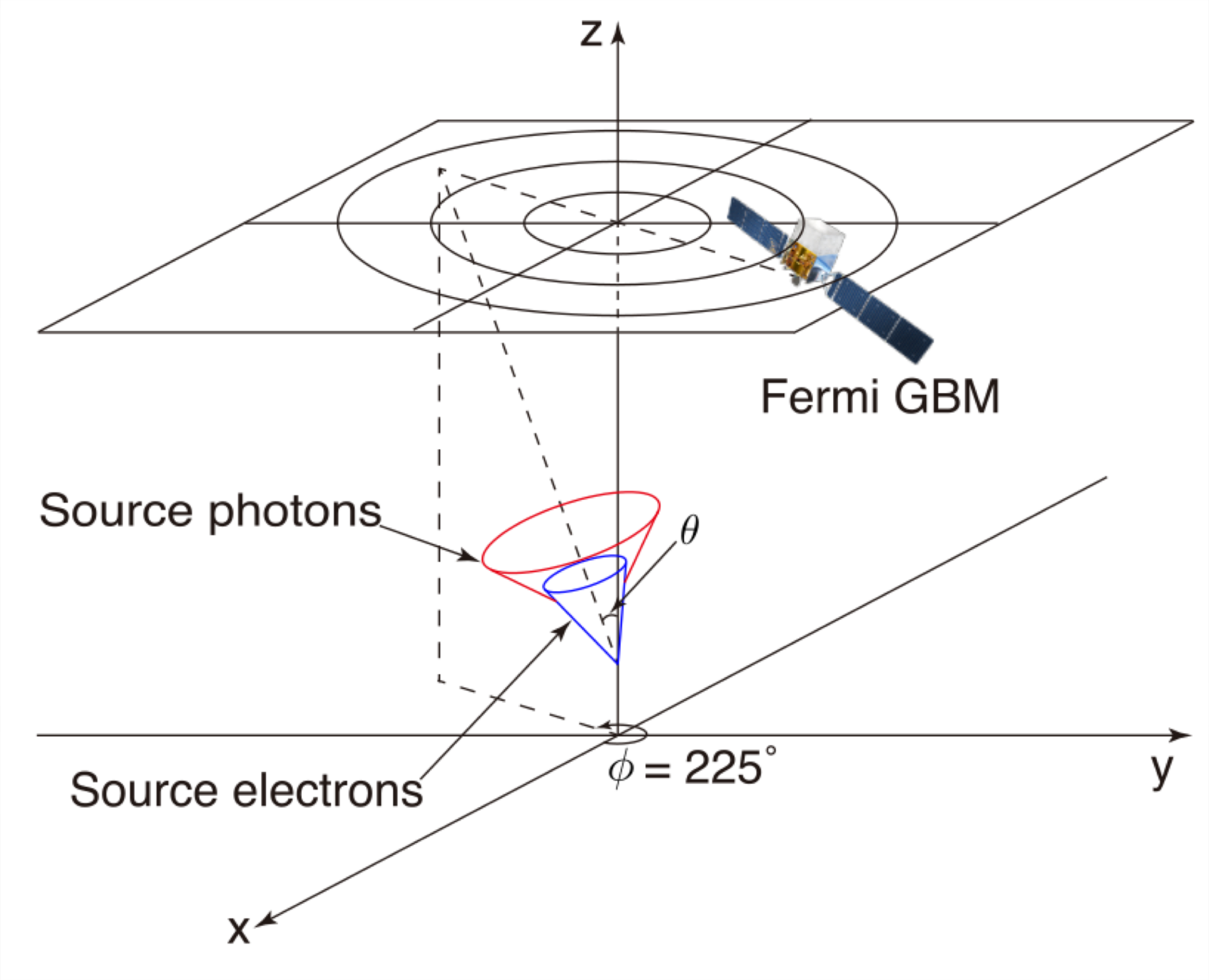
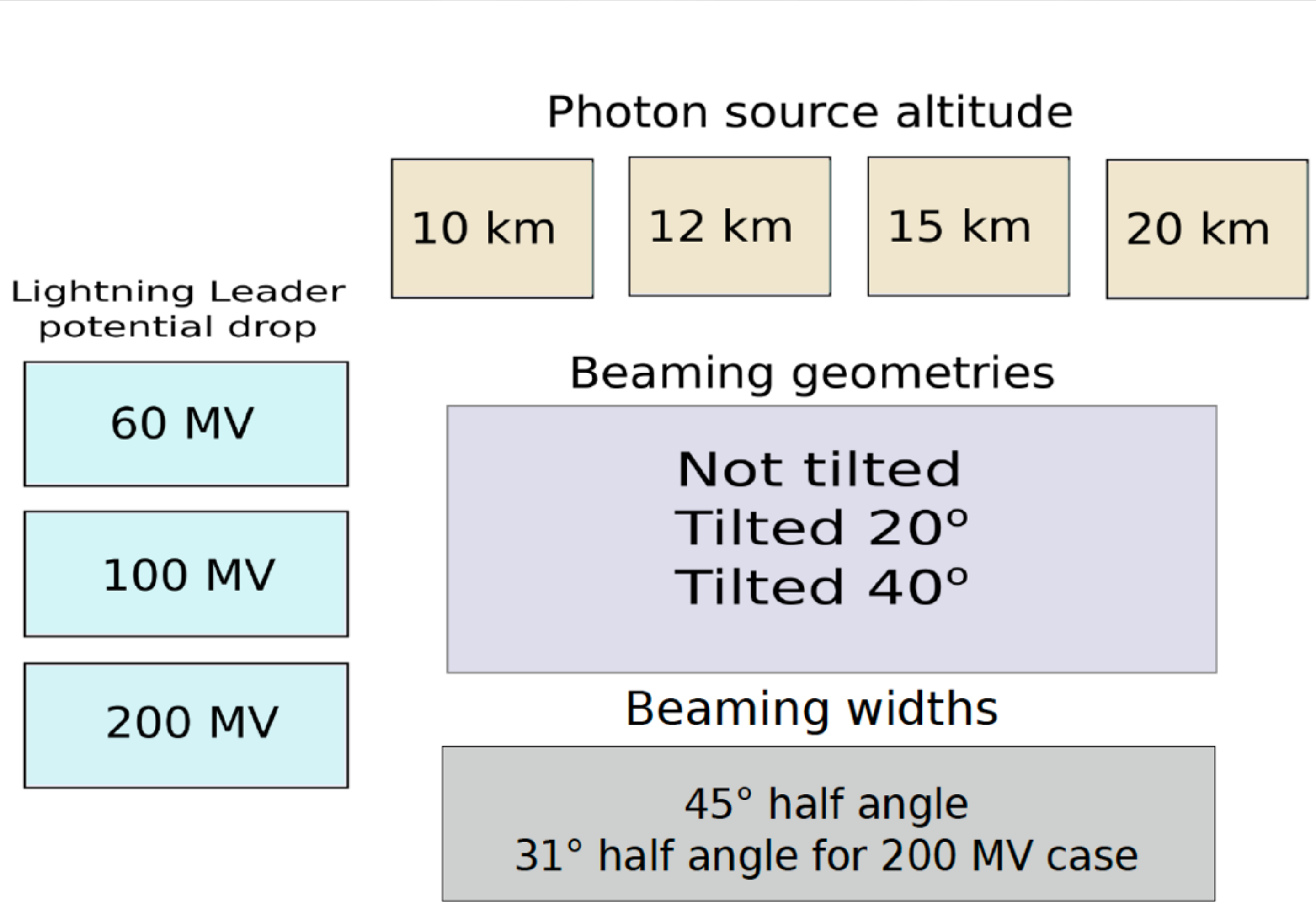
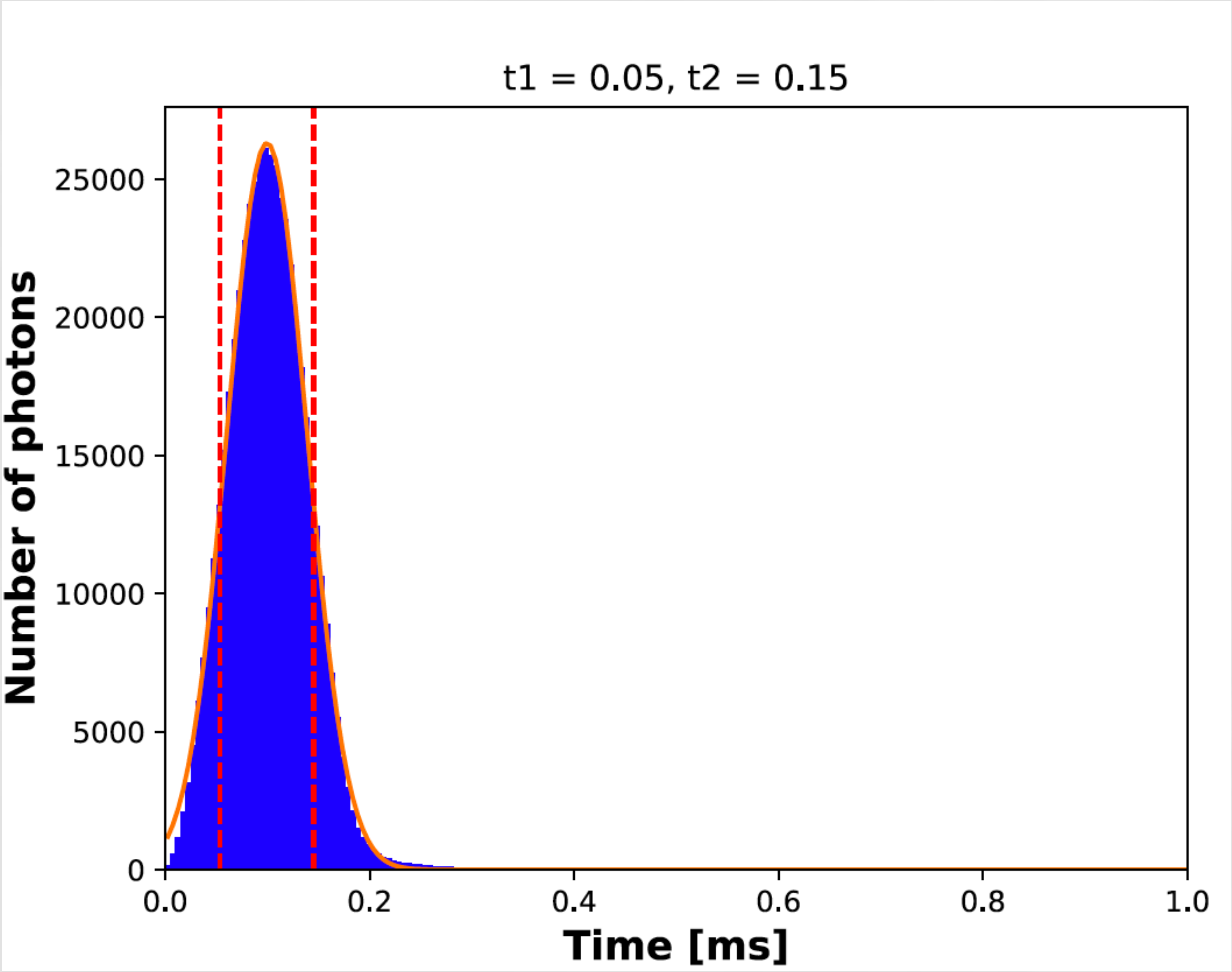


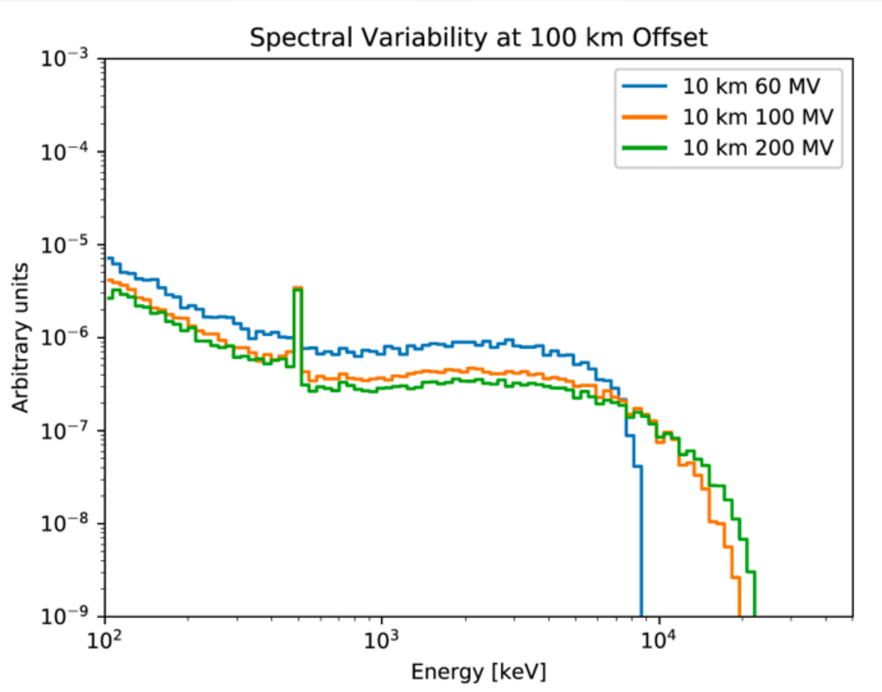
Diagram of the lightning leader models used

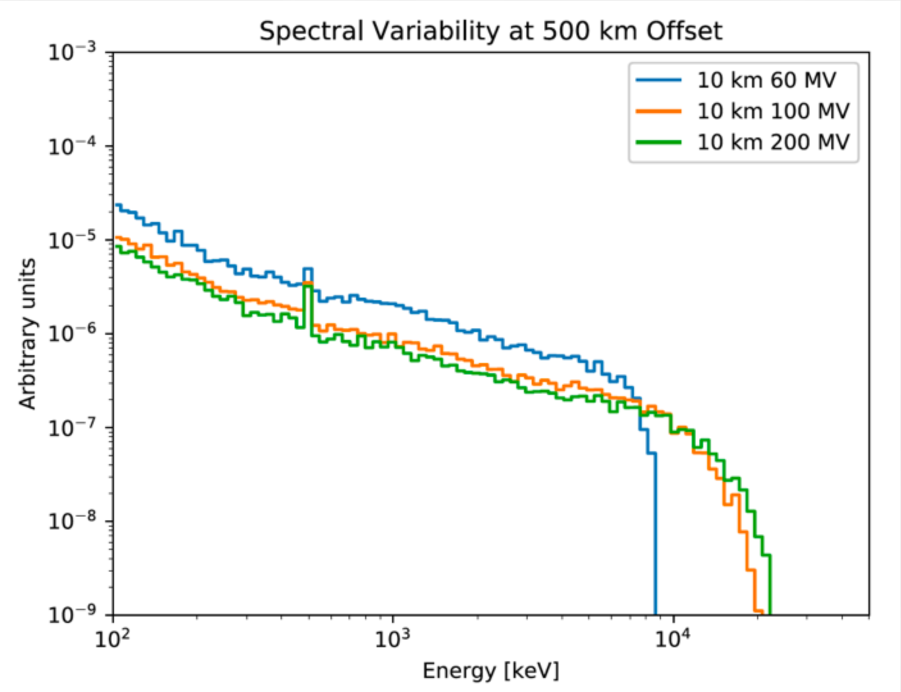


The time distribution of a 15 km altitude 100 MV lightning leader model fitted by a Gaussian. The vertical and horizontal lines are to indicate the 1-sigma region.

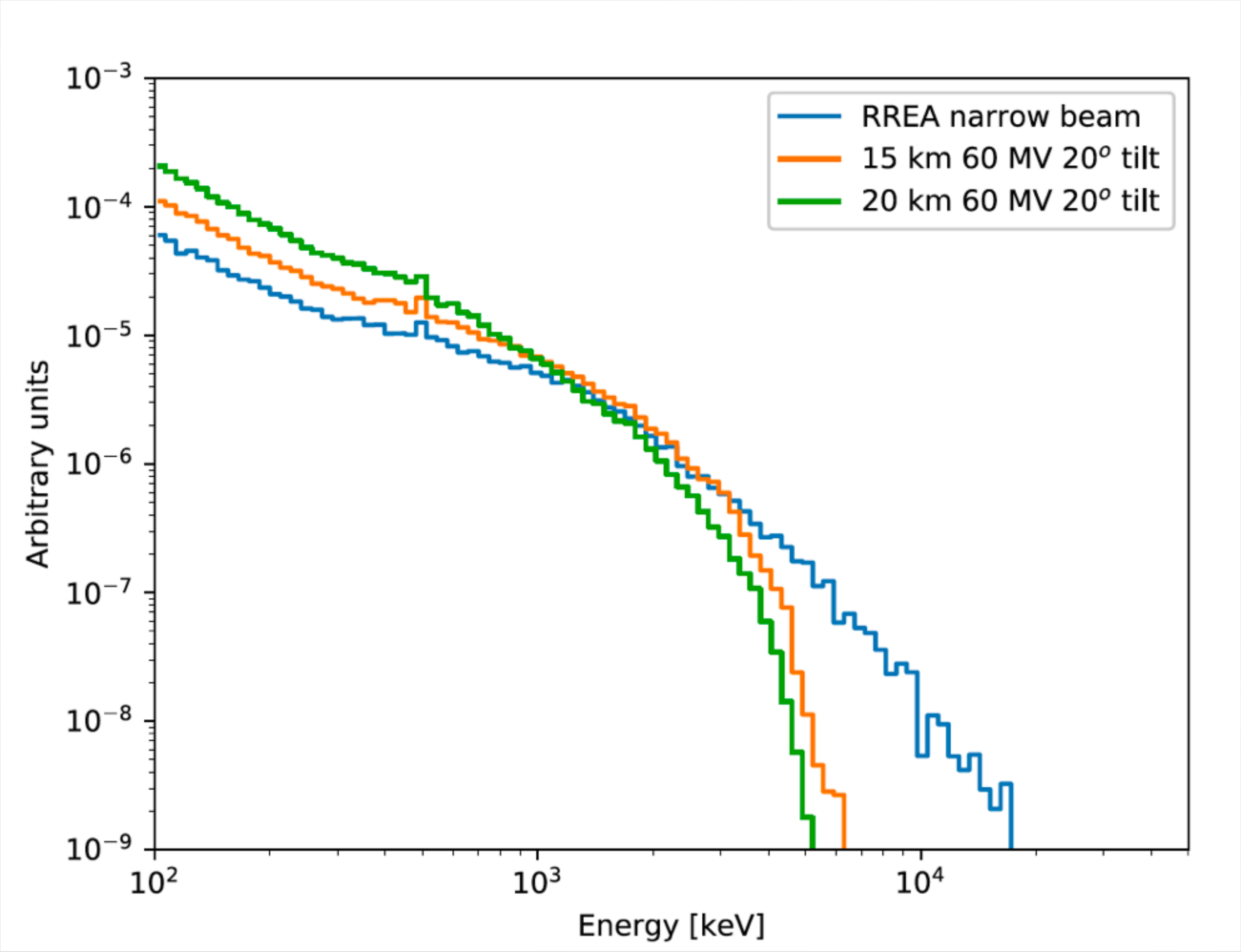


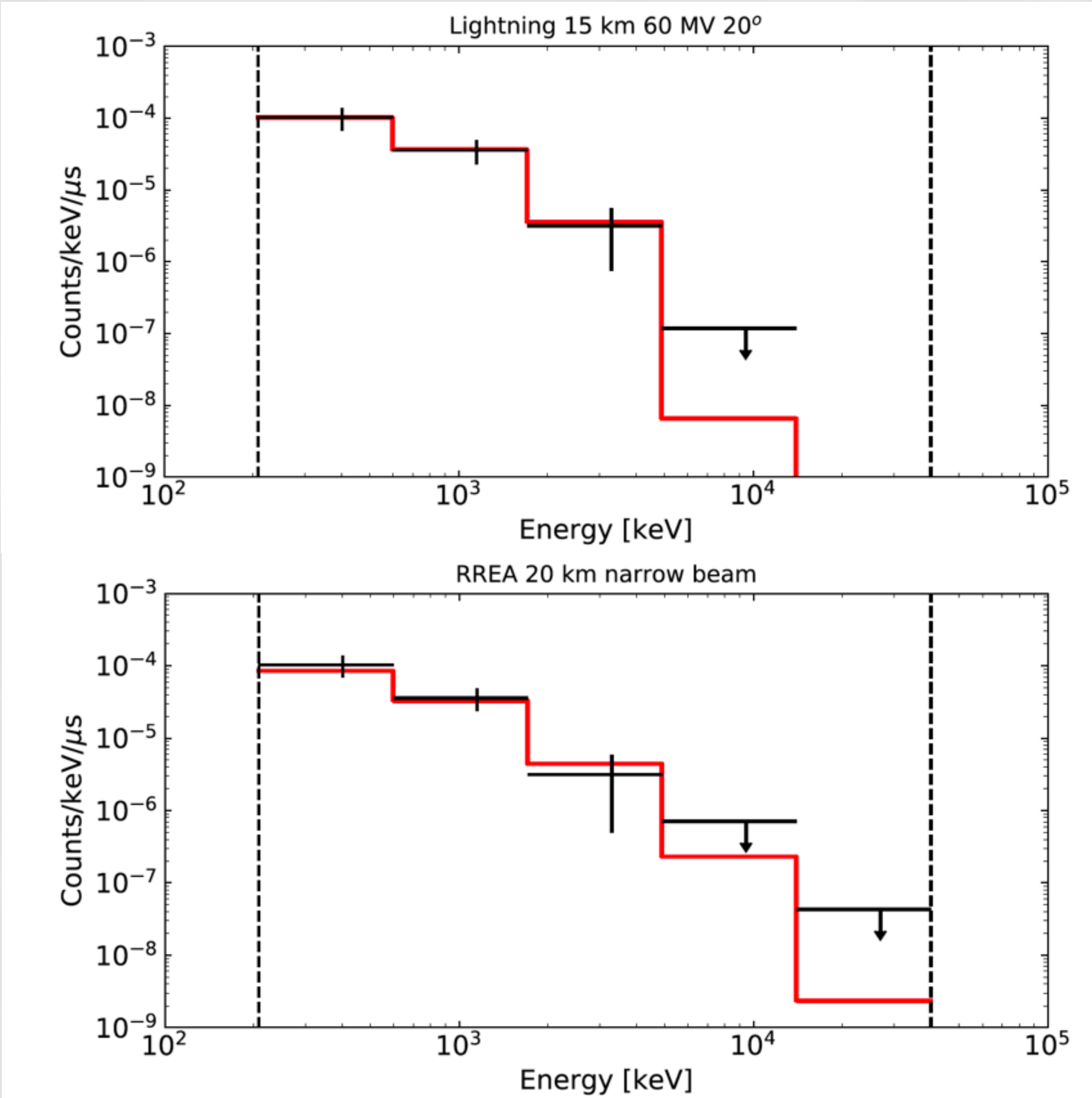
The differential energy spectra of 10 km altitude lightning leader models with 60 MV, 100 MV and 200 MV leader potentials at 100 km and 500 km offset distances.



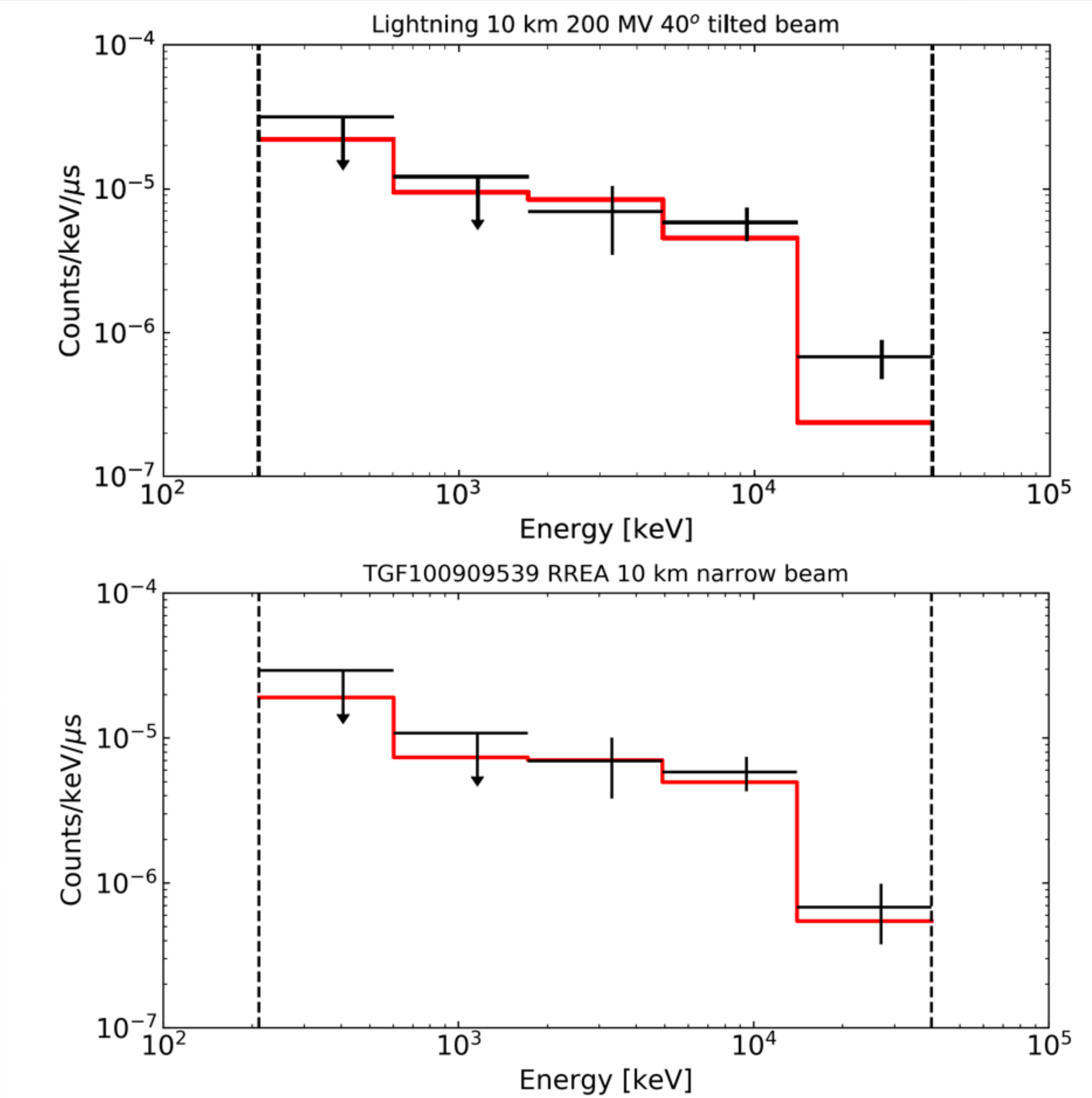


The modeled energy spectra of TGF120120412 at 475 km offset distance. RREA narrow 20 km model along with 20 km 60 MV lightning leader and 15 km 60 MV models with 20 tilt.





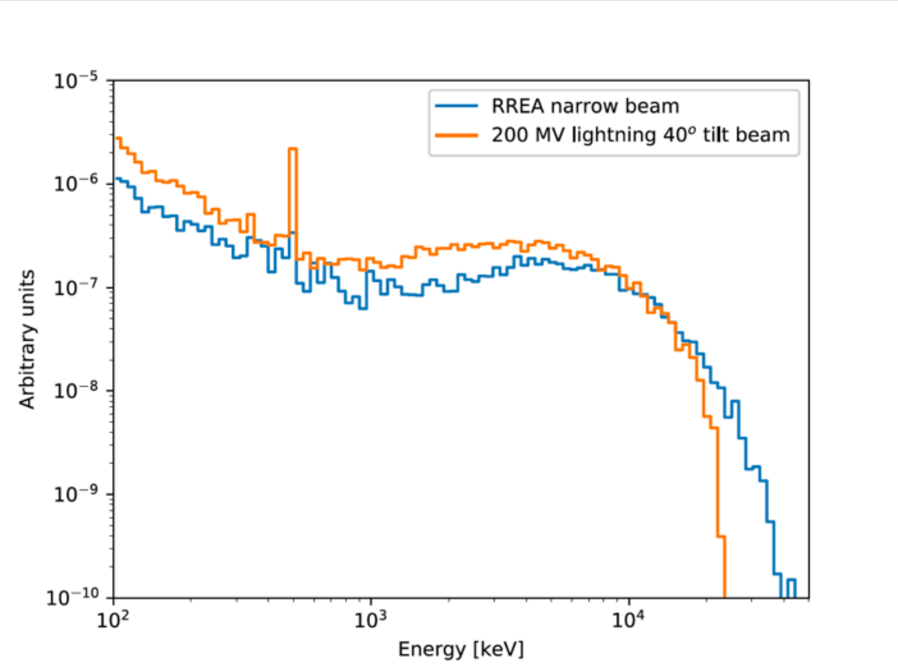
The modeled and measured energy spectra of TGF120120412 at 475 km offset distance. RREA narrow 20 km model (top plot) and 15 km 60 MV lightning leader models with a 20 tilt opposite to the spacecraft (bottom plot).

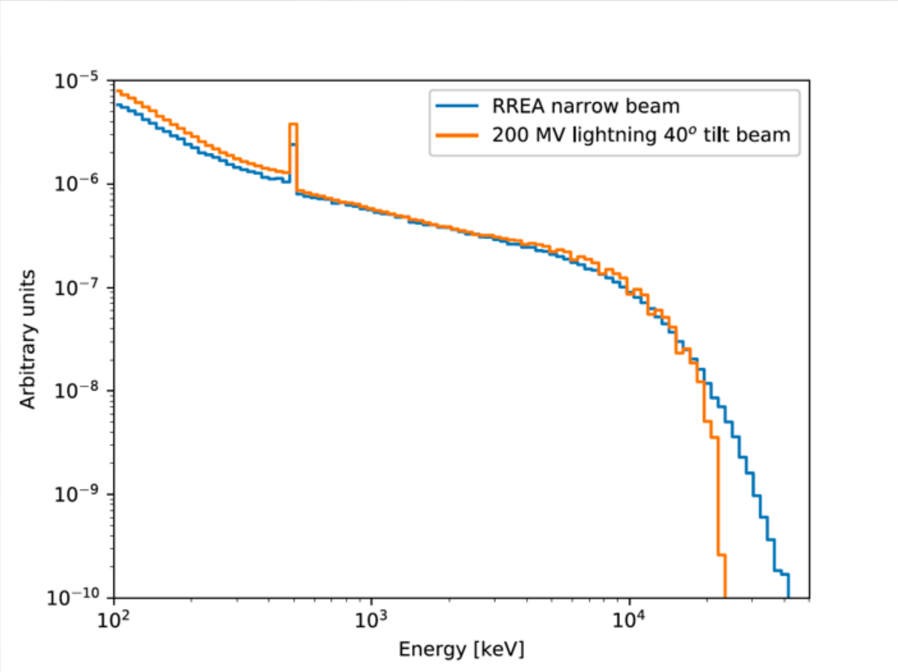


The modeled and measured differential energy spectra of TGF100909539 observed at 102 km offset distance.

RREA narrow 10 km model along with (bottom plot) lightning leader 10 km 200 MV model with 40 deg. tilt towards the detector (top plot) and observed TGF data at 102 km offset distance.

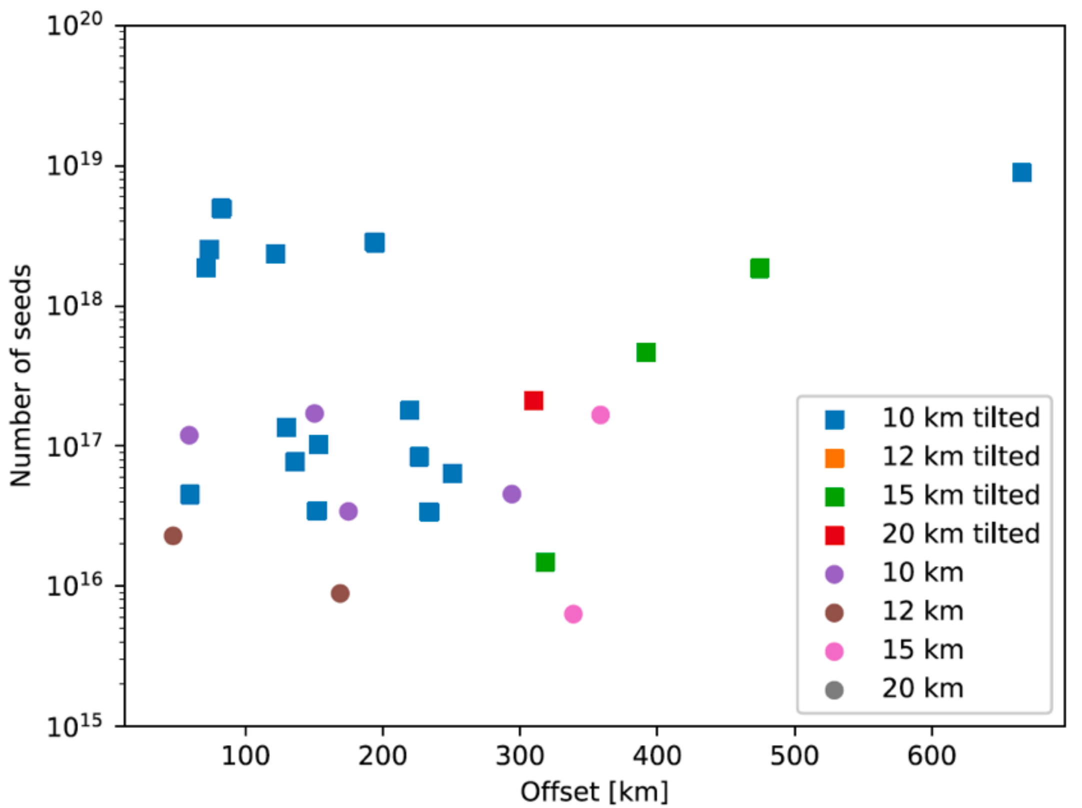
The modeled differential energy spectra of TGF100909539 observed at 102 km offset distance.





RREA narrow 10 km model along with lightning leader 10 km 200 MV model with 40 tilt towards the detector for all particles (on the right) and photons at 102 km offset distance only (on the left).

Total number of seed electrons with energies greater than 10 keV versus sub-satellite offset distance of different TGF events measured by Fermi GBM.



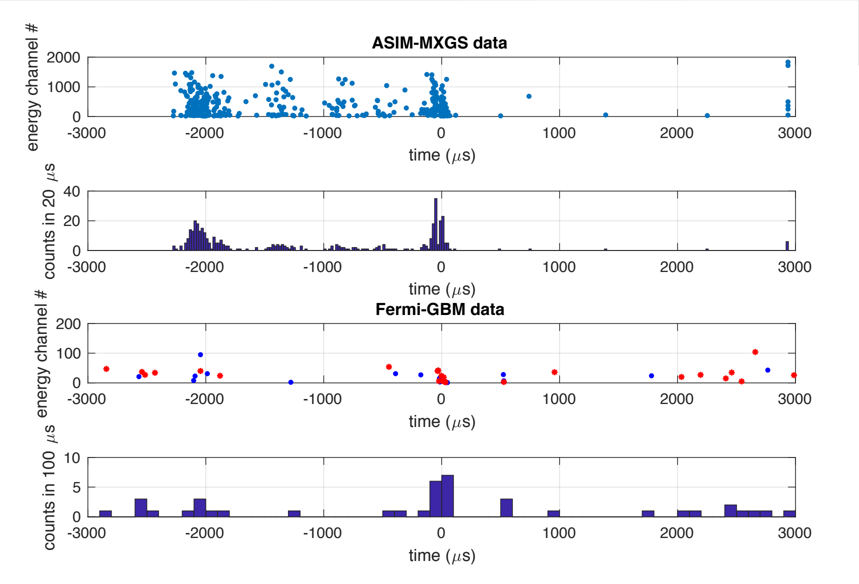
The results are obtained using the best-fit lightning models. The production altitude of TGF source is indicated by different colors. Most of the best-fit models are tilted.

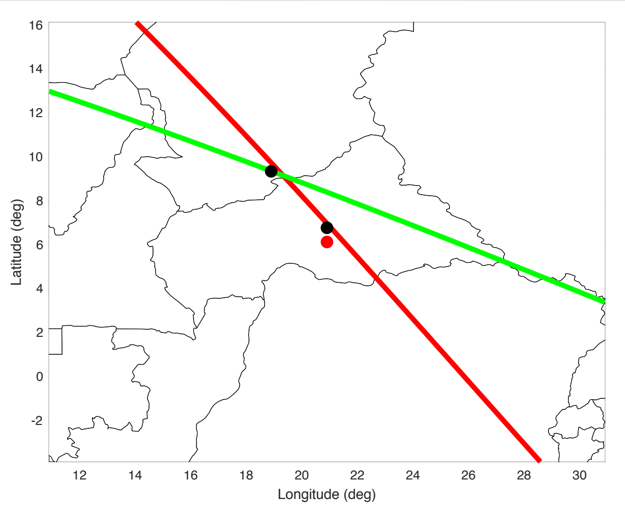
Conclusions

- In the dataset considered, **39 TGFs** (out of 66 TGFs) can be best fit with **RREA** models, while **27** events can be best fit using the **lightning leader** models.
- From lightning leader models, 200 MV leader models with and without a tilt towards the spacecraft are preferred as they provide harder spectra.
- There are only four events were RREA models only were preferred (over lightning leader models) and all of them had hard energy spectra with photon counts **above 20 MeV**.
- *Mailyan, B. G., Xu, W., Celestin, S., Briggs, M. S., Dwyer, J. R., Cramer, E. S., et al. (2019). Journal of Geophysical Research: Space Physics, 124, 7170– 7183.*

What's next?

Joint ASIM-Fermi observations





An example of joint TGF observations by ASIM-MXGS and Fermi-GBM. Although they are two independent instruments, their orbits overlap allowing for "stereo" observations.