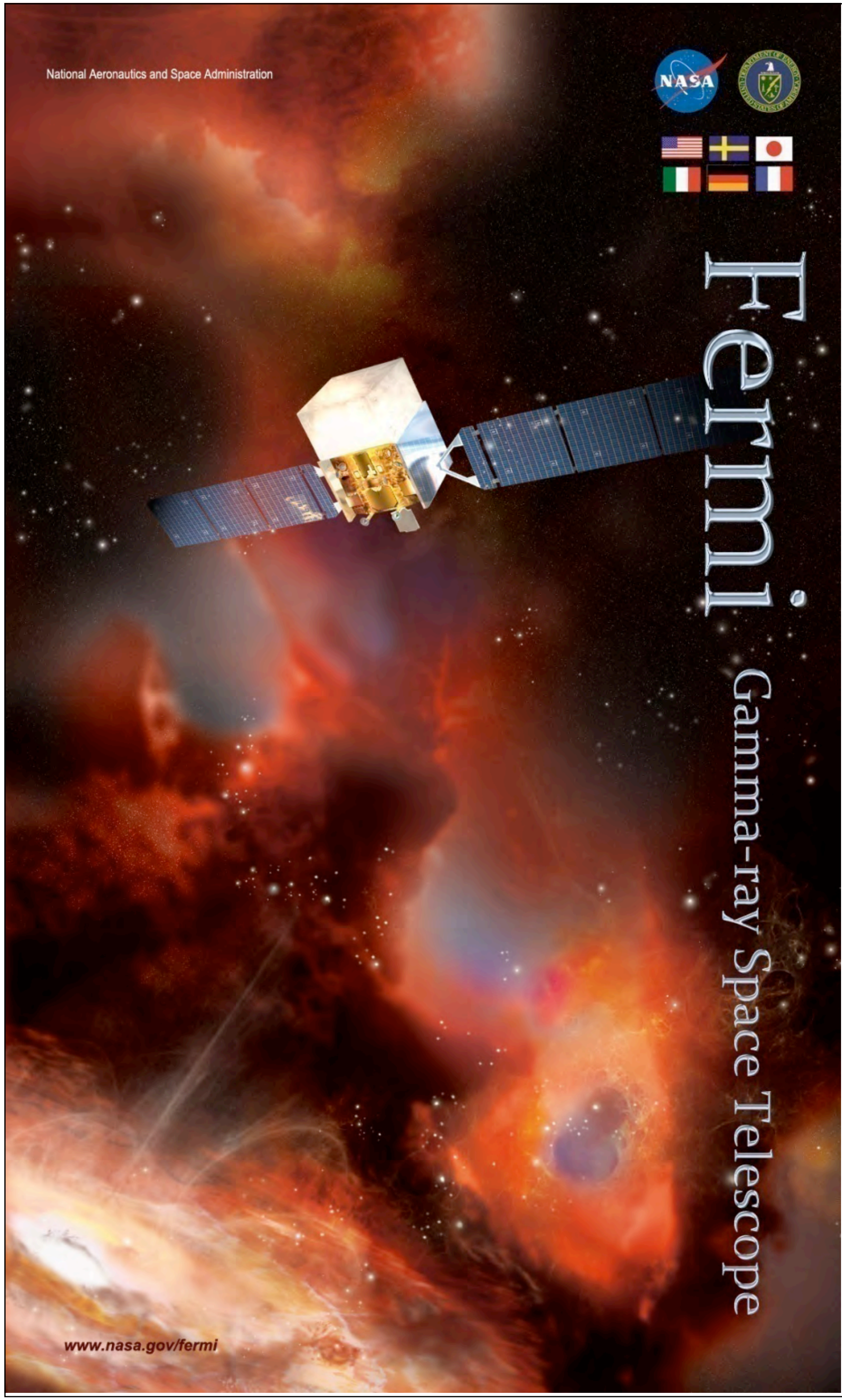


A Four-Year Survey of Terrestrial Gamma-ray Flashes (TGFs) with Fermi LAT

J. Eric Grove
Naval Research Laboratory

A. Chekhtman (GMU-NRL), M.S. Briggs (UAH), V. Connaughton (UAH), G.J. Fishman (MSFC)

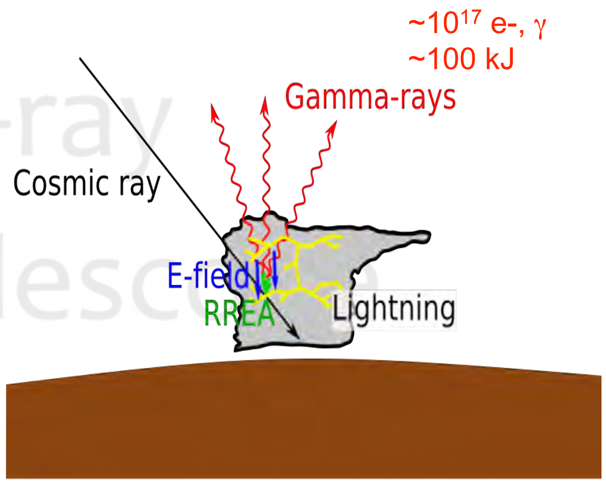
on behalf of the LAT Collaboration

Introduction

- What is a TGF and why should you care?
  - Intense (sub-)millisecond flash of MeV gamma rays from thunderstorms
  - Power in MeV flash comparable to power in lightning bolt
    - Few x 10^{17} MeV gammas in few hundred microsec
  - Thunderstorms are most powerful natural terrestrial particle accelerator
    - Accelerator at ~10-15 km altitude, accessible by aircraft

Recent review: Dwyer, Smith, & Cummer, Space Sci Rev 2012

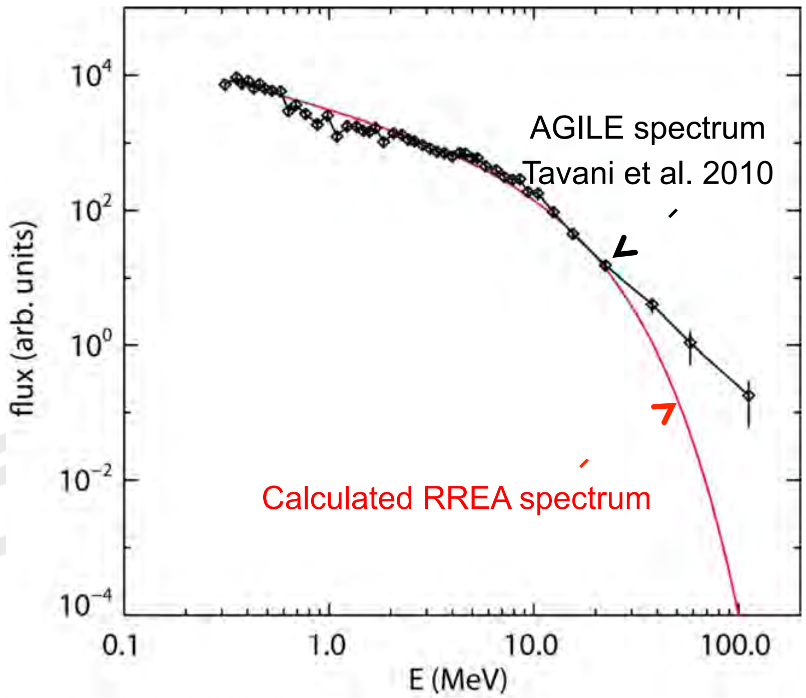
- Present model, inside thundercloud
  - Relativistic Runaway Electron Avalanche (RREA) with feedback
    - Strong E field accelerates electrons to relativistic energies before they range out
    - g-rays from electron bremsstrahlung
    - Predict ~7 MeV exponential g-ray cutoff



Gurevich et al. 1992; Babich et al. 1998; Dwyer 2003; ...; Dwyer 2011

Introduction – Above 10 MeV

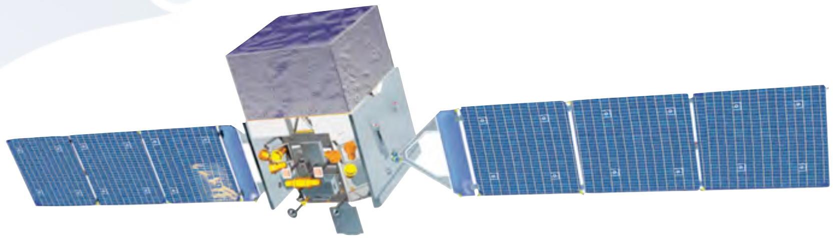
- Why is LAT useful?
  - AGILE spectral result inconsistent with RREA theory
    - Power law tail to ~100 MeV
    - Avalanche electron <E> ~ 7 MeV
  - More recently, two populations in AGILE
    - (Marisaldi, Frascati 2012)
    - Soft spectral class: ~90%
      - RREA spectrum
      - Typical TGF properties
    - Hard spectral class: ~10-15%
      - Hard power law spectrum
      - Relationship to lightning?



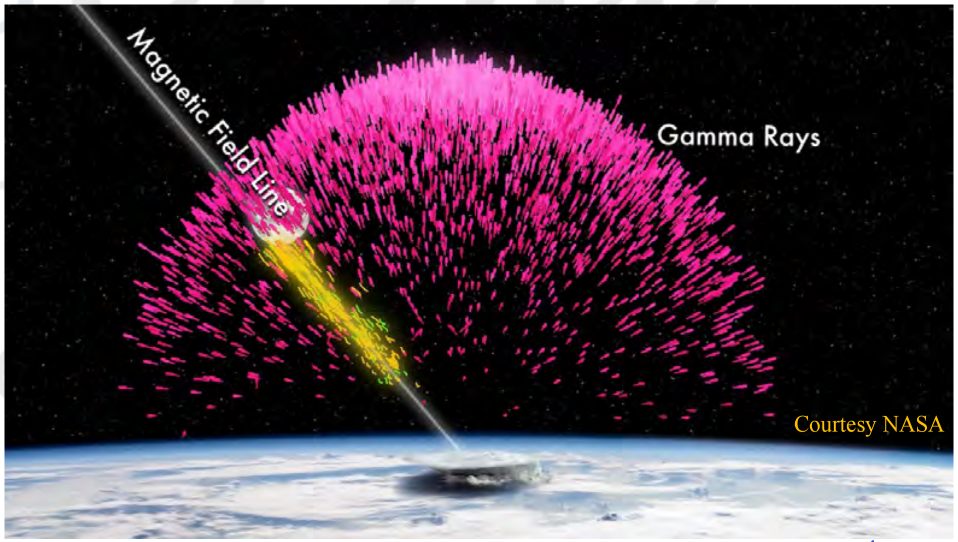
  - Fermi LAT
    - Large area, high segmentation -> high sensitivity with minimal pile-up
    - Low deadtime: 26.5 μs per event
    - Imaging and spectroscopy

Detecting TGFs in LAT

- Two observation types with Fermi LAT
  - Sky survey
    - Advantages
      - High duty cycle (>95%)
      - Good effective area
      - Many TGFs, large sample
    - Disadvantages
      - Trigger and on-board filter reject many LAT events within TGFs

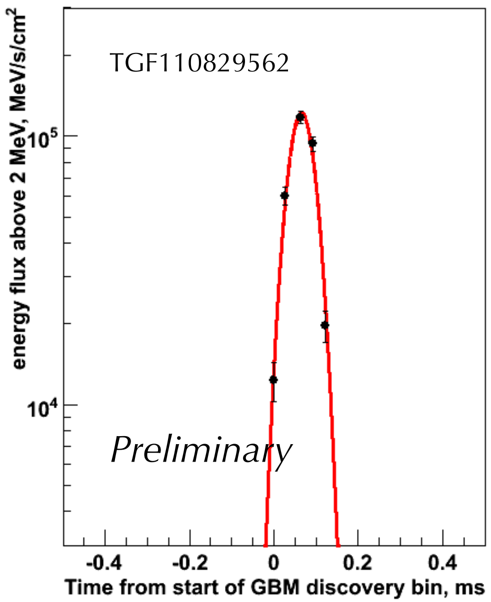


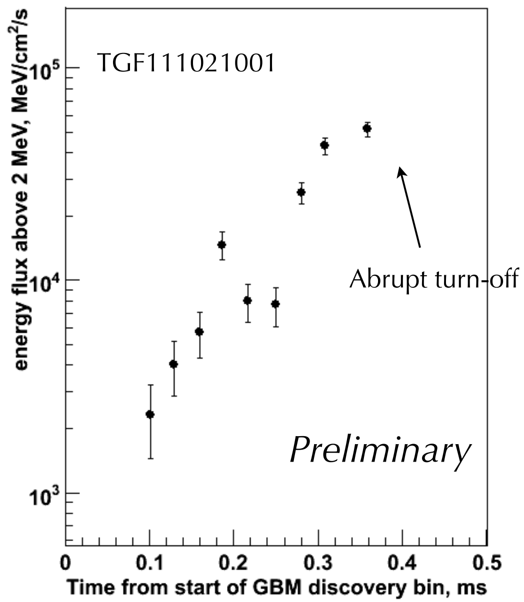
  - Nadir oriented
    - Approved Cycle 4 and 5 GI programs, 25 observations each
    - Advantages
      - Best effective area
      - Trigger config optimized
      - On-board filter disengaged
    - Disadvantages
      - Very low duty cycle (~1%)
      - LAT not in sky survey
      - Small TGF sample



Summary of nadir observations

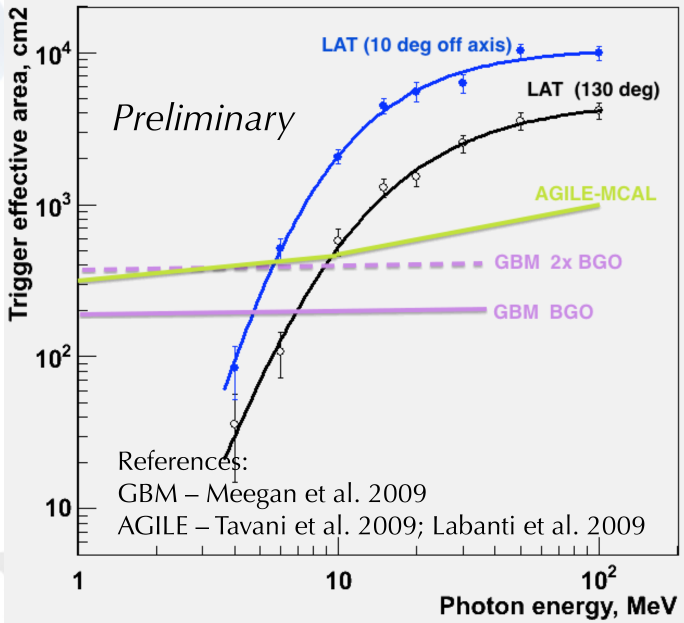
- Special nadir-observing program in progress
  - 27 three-orbit nadir pointings from 26 July 2011 to 5 Oct 2012
  - Cycle 5 program approved; expect 22 more nadir pointings to Aug 2013
- Status to date of nadir observing
  - Twenty-two TGFs detected so far in special nadir-observing configuration
  - LAT clearly, unambiguously detects GBM TGFs
  - Primary goals
    - Measure spectral hardness and endpoint from ensemble of TGFs
    - Measure energy flux, lightcurve
    - Search for weak, hard-spectrum TGFs



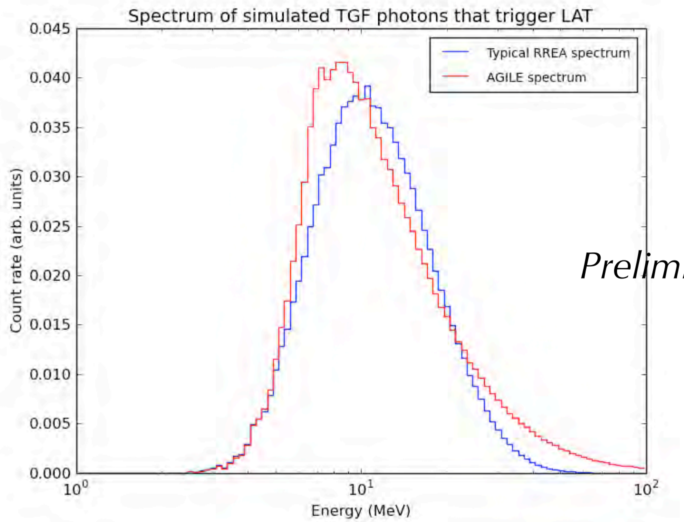


Detecting TGFs in LAT

- LAT trigger and filter
  - Which TGF photons cause trigger and read out?
    - Predominantly ~ 10 MeV
      - Only weakly a fcn of TGF spectral shape
    - Very large trigger effective area. Compare at 10 MeV:
      - ~2000 cm² near boresight, ~500 cm² at 130 deg
      - GBM BGO ~ 200 cm² per detector
      - AGILE MCAL ~ 500 cm²
    - Once triggered, detectors register photons of much lower energy
      - TKR above ~100 keV; CAL above 2 MeV
      - Detectors and electronics "integrate" deposited energy over ~3 to 5 μs
  - On-board filter
    - Rejects 80-90% of triggered events
      - (>60% of TGF events rejected)



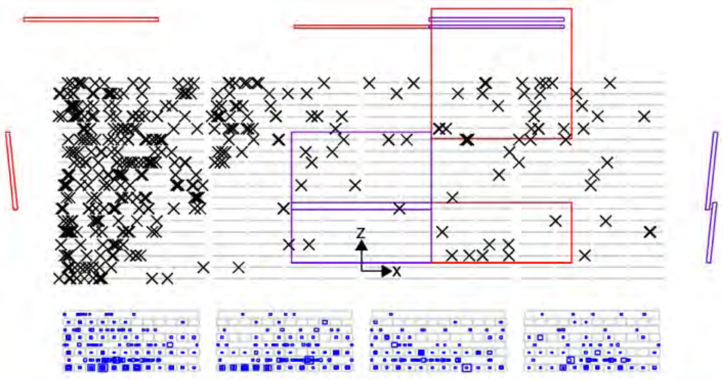
- Sky survey dataset is not optimal
  - Can fail to detect TGF
  - Many LAT events within TGF are lost



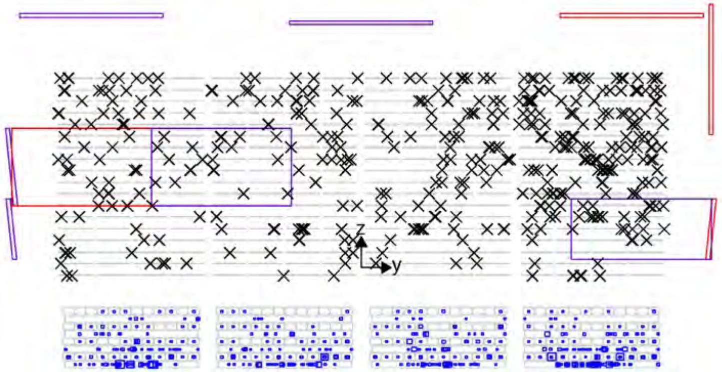
Event display

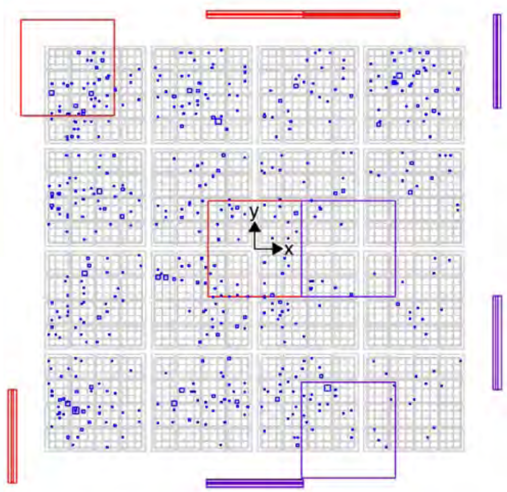
- Characteristic of TGFs in LAT
  - Trigger request rate can peak >1 MHz
    - Algorithm: search for anomalously high rate
  - Events are complex
    - High multiplicity, i.e. not single-photon events
    - Typically not one ~100 MeV photon or one ~1 GeV photon; instead ~30 or ~300 photons (respectively) from typical RREA spectrum in ~5 μs

XZ projection



YZ projection



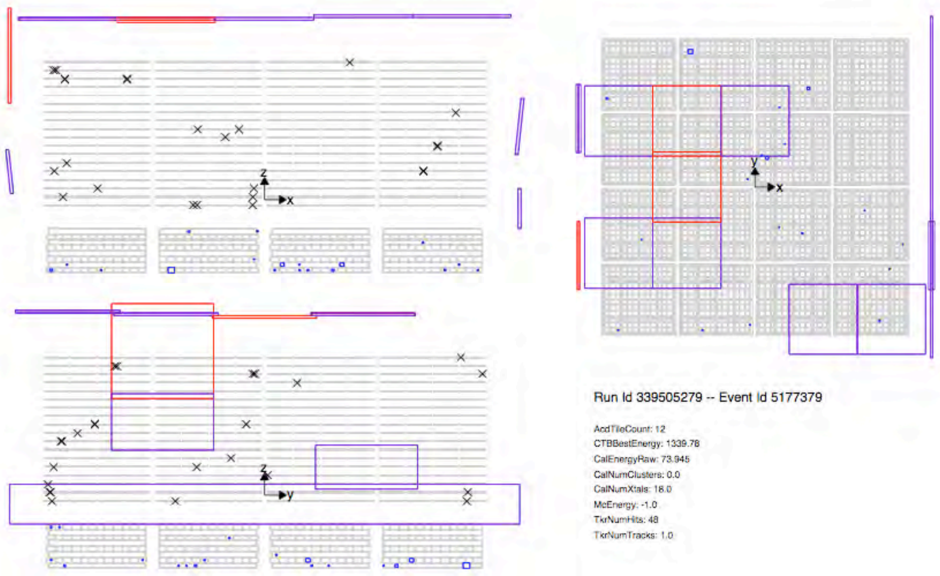


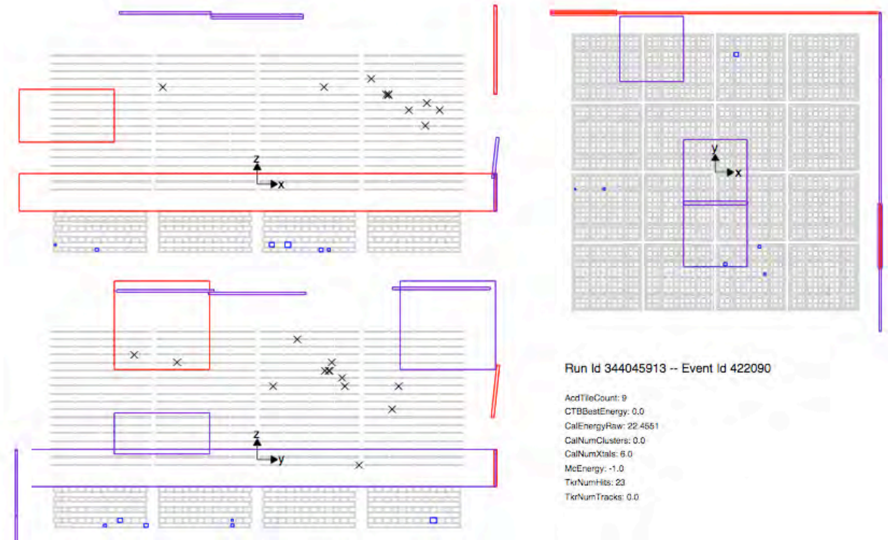
XY projection

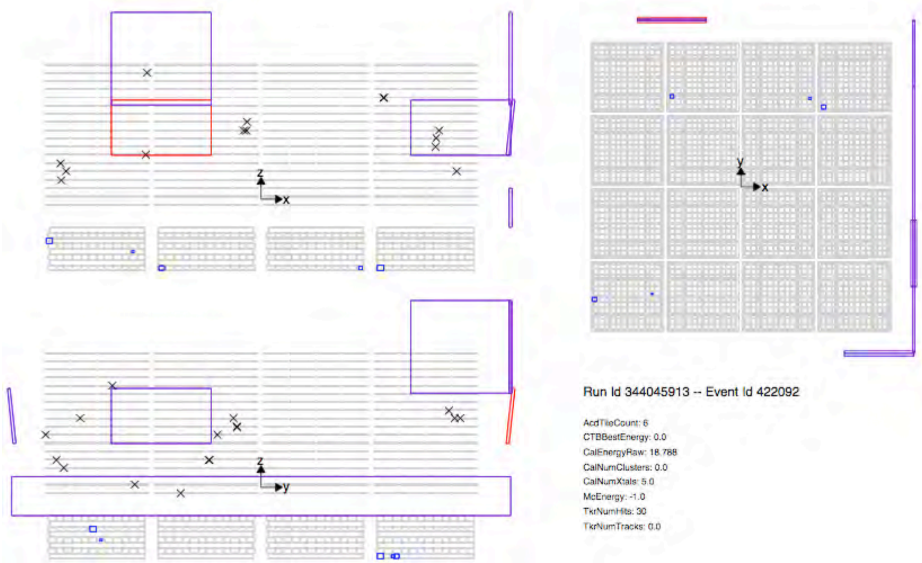
Run Id 303664775 -- Event Id 14425340

- Brightest sky-survey TGF
  - ~500 photons in ~5 μs integration

Event displays



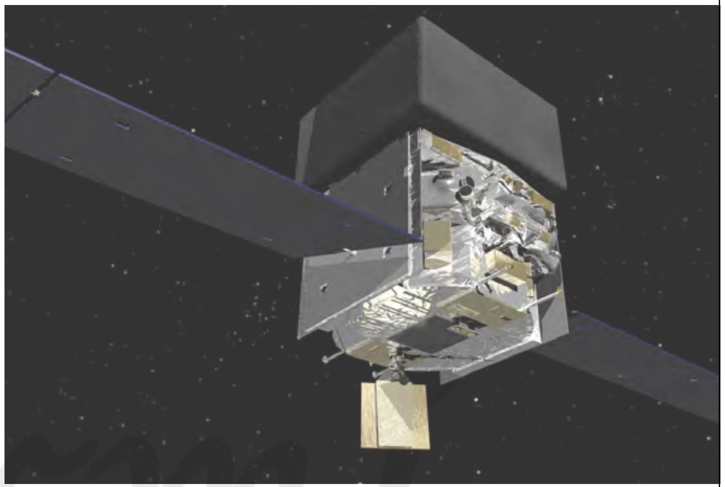




- Three TGF event displays
  - Typical or dimmer than average

TGF search during LAT sky survey

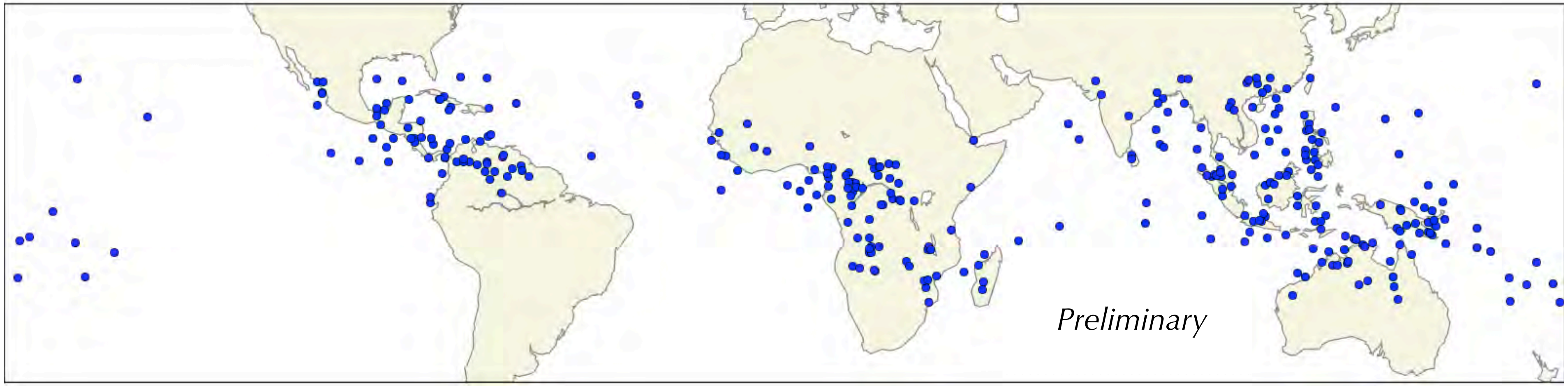
- Search algorithm
  - Find extreme outliers in trigger rate
  - Remove coincident cosmic ray showers
  - Inspect event displays to verify



- TGFs from sky-survey dataset (Aug 2008 – Jun 2012)
  - 319 high-confidence TGFs in LAT

- Comparison with GBM
  - Consistent with GBM list?
    - ~66% of LAT-detected TGFs in sky survey are also detected by GBM
    - ~80% in nadir attitude
  - Why not in GBM list?
    - Not in TTE box
      - GBM on-board flash trigger: ~10% efficiency of ground TTE search
    - Conservative detection algorithm
      - Low false-positive rate

Geographic distribution

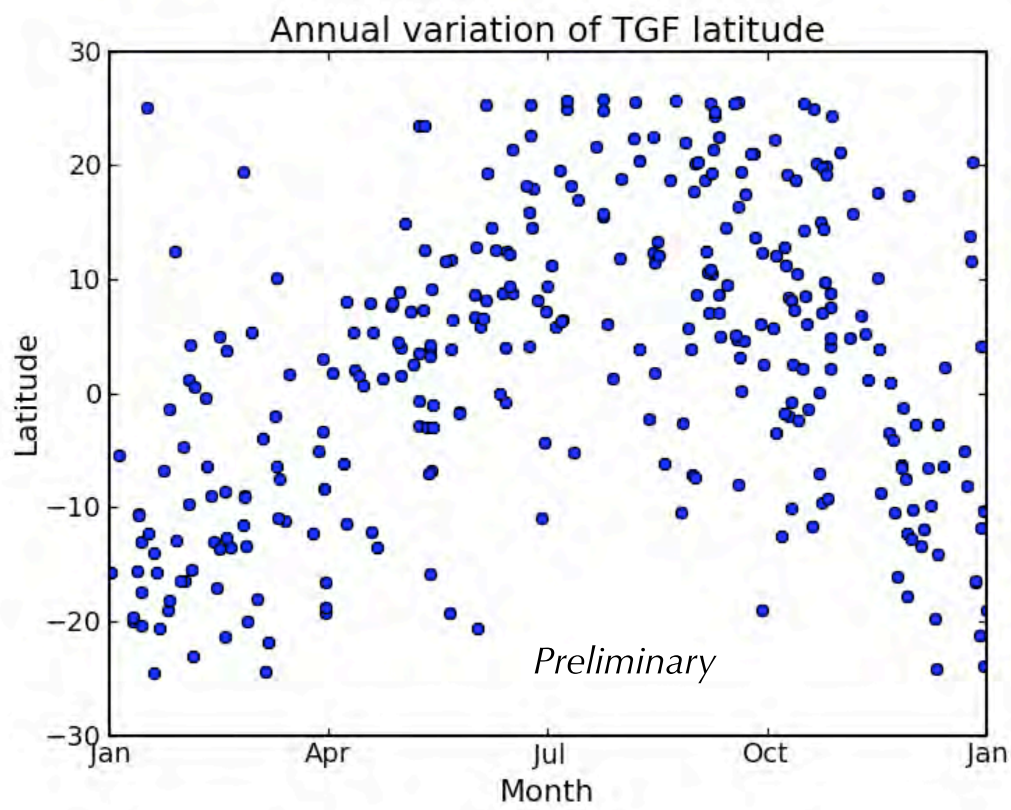


- Geographic distribution (location of Fermi at time of TGF)
  - Active TGF regions are active thunderstorm regions
  - Geographic correlation
    - Land masses, active thunderstorm regions. Coastal storms
    - Note: not possible to measure TGFs within SAA
  - Consistent with historical record of TGFs

Temporal distributions

- Annual variation of latitude
  - Follows distribution of thunderstorm activity
  - Active in local summer

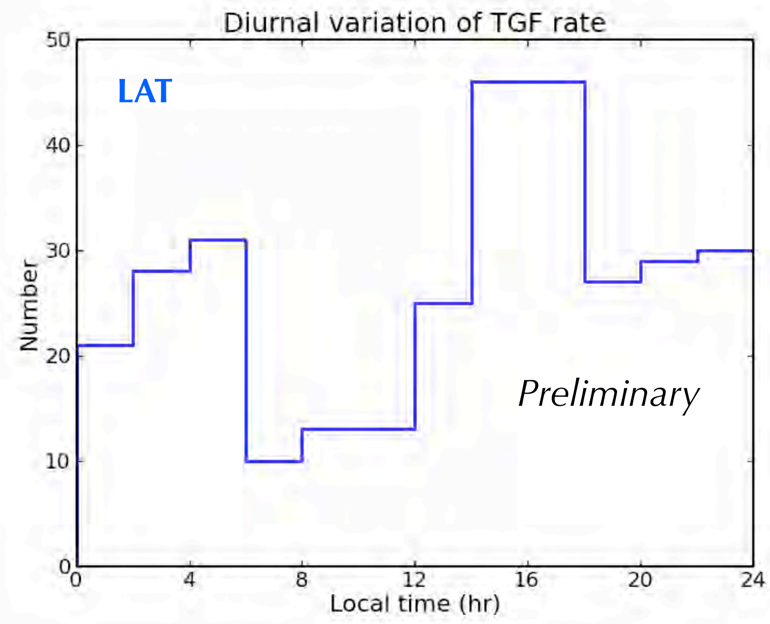
- Consistent with known TGF behavior
  - BATSE, RHESSI, GBM

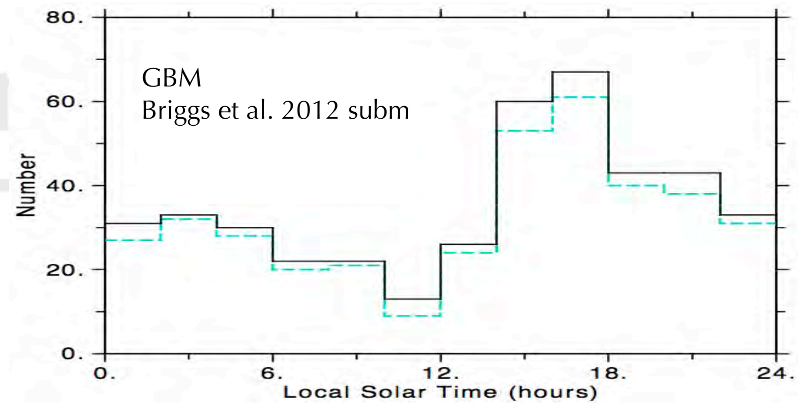


Temporal distributions

- Diurnal variation
  - Peak in local afternoon
  - Rare in local morning
  - High in pre-dawn hours
    - relative to thunderstorm activity

- Consistent with known TGF behavior
  - BATSE, RHESSI, GBM



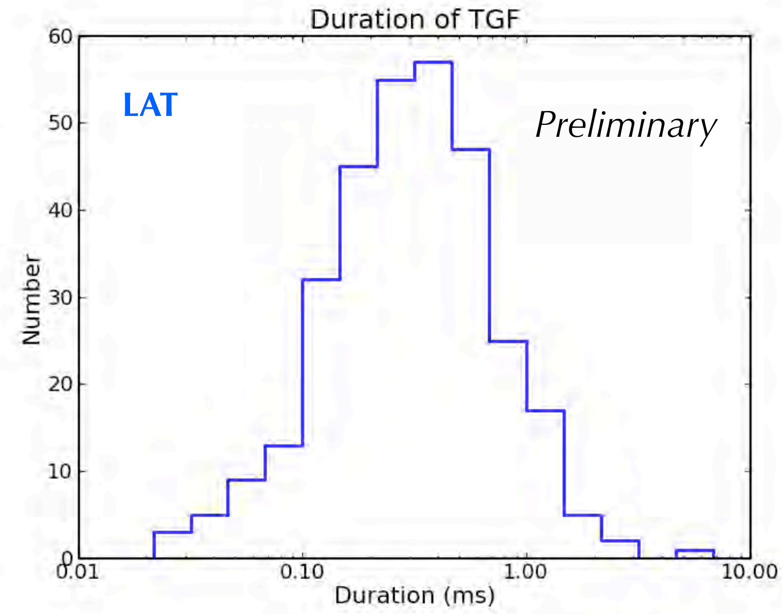


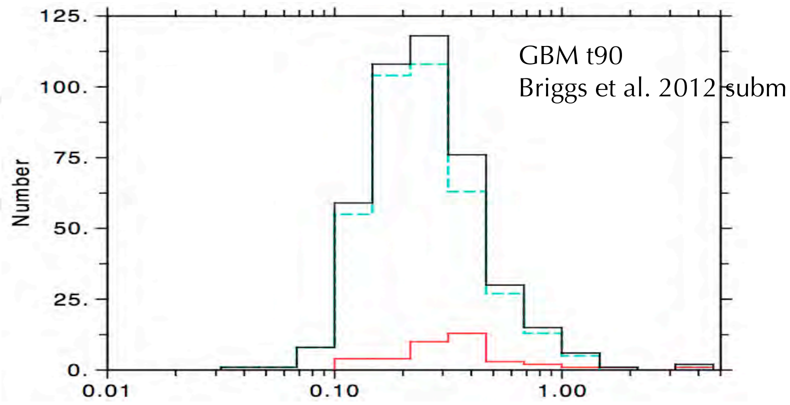
TGF durations

- Duration of MeV flash
  - Typically <1 ms

- Consistent with known TGF behavior
  - RHESSI, GBM
    - (Shorter than AGILE TGFs)
  - Compare t90 from GBM sample

  - Caveat
    - Durations from LAT sky survey sample are susceptible to biases
      - On-board filter
      - Max readout rate: 1 event per 26.5 μs

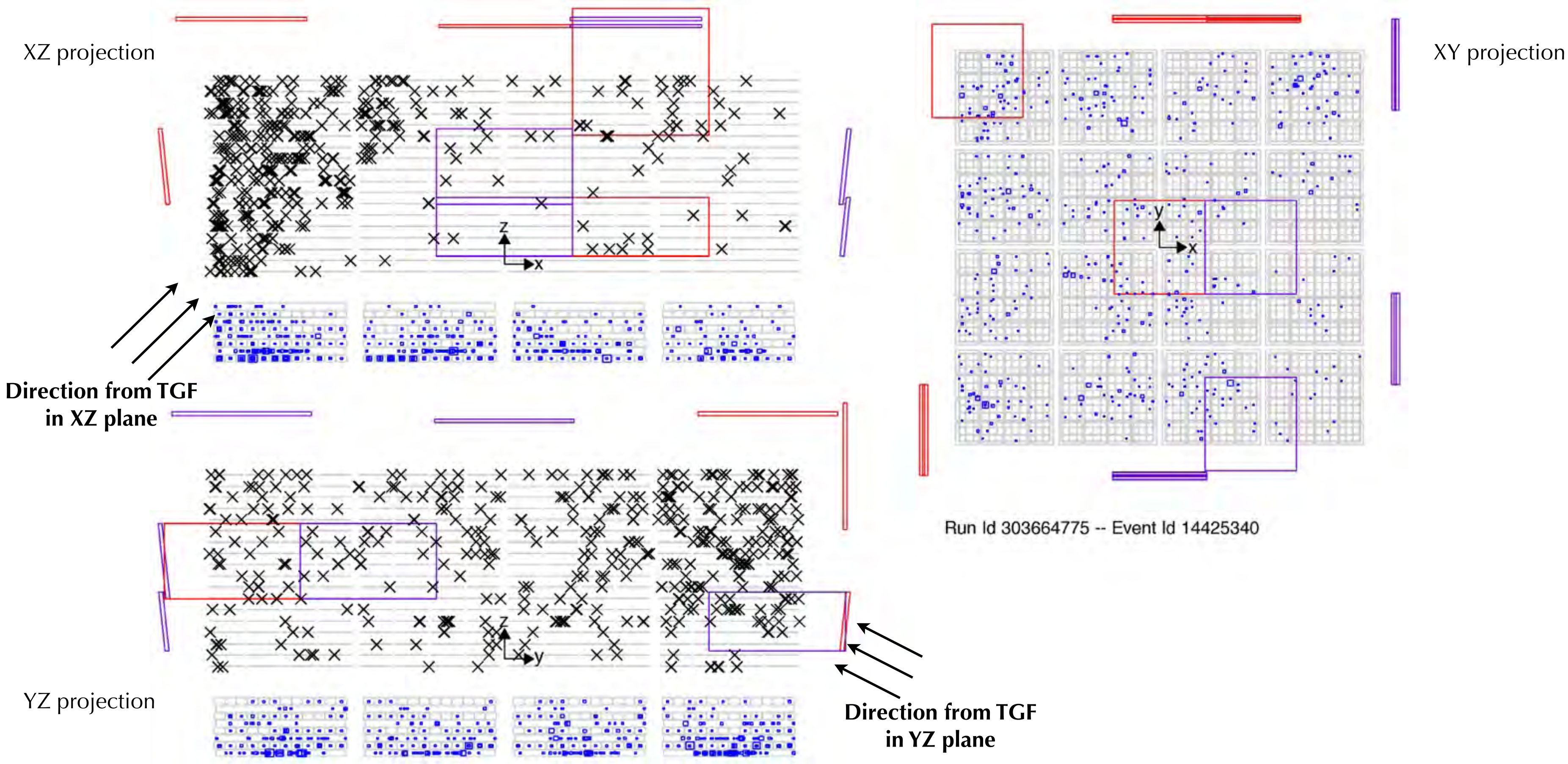




Imaging TGFs with LAT

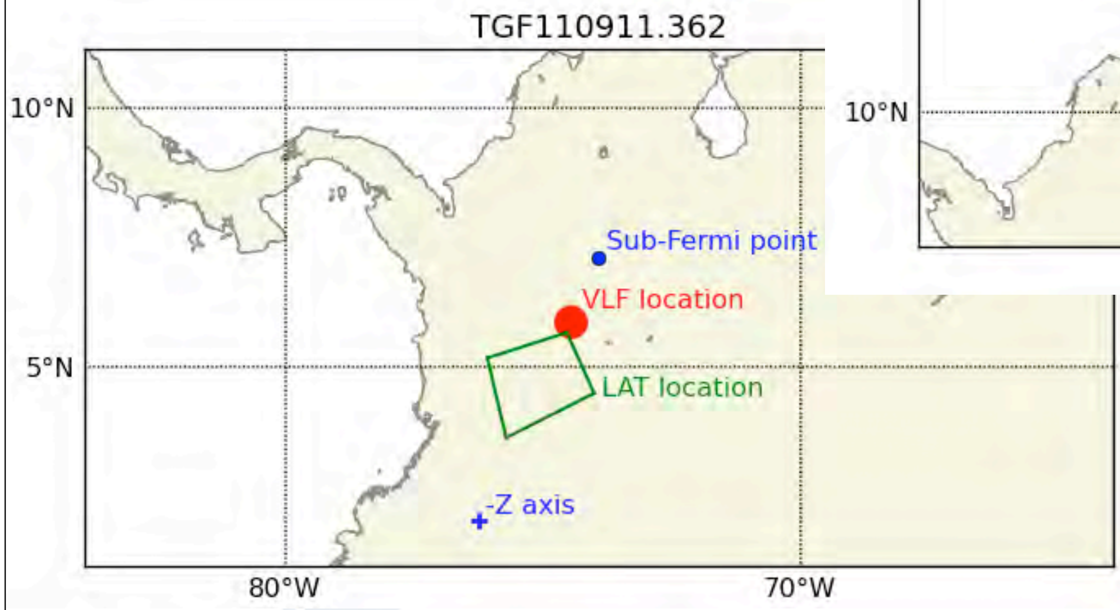
- Standard LAT photon direction and source image reconstruction difficult for TGFs
  - Too many near-simultaneous photons; Too much Compton scattering
- Use shadow cast by CAL on TKR

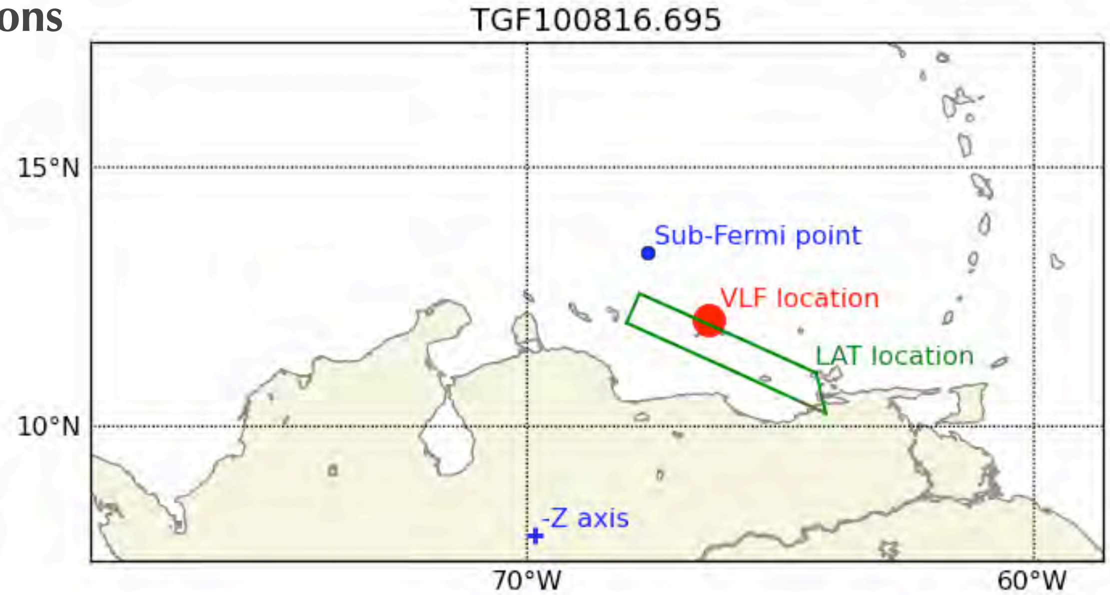
TGF100816.695



Geolocation with LAT and VLF radio

- VLF lightning location networks (WWLLN, ENTLN)
  - Typically ~20 km location uncertainty from VLF
  - Good fraction of TGFs have coincident VLF pulse (~10% to ~50%)
- Compare with LAT shadow directions
  - VLF pulse is temporally and spatially coincident with TGF



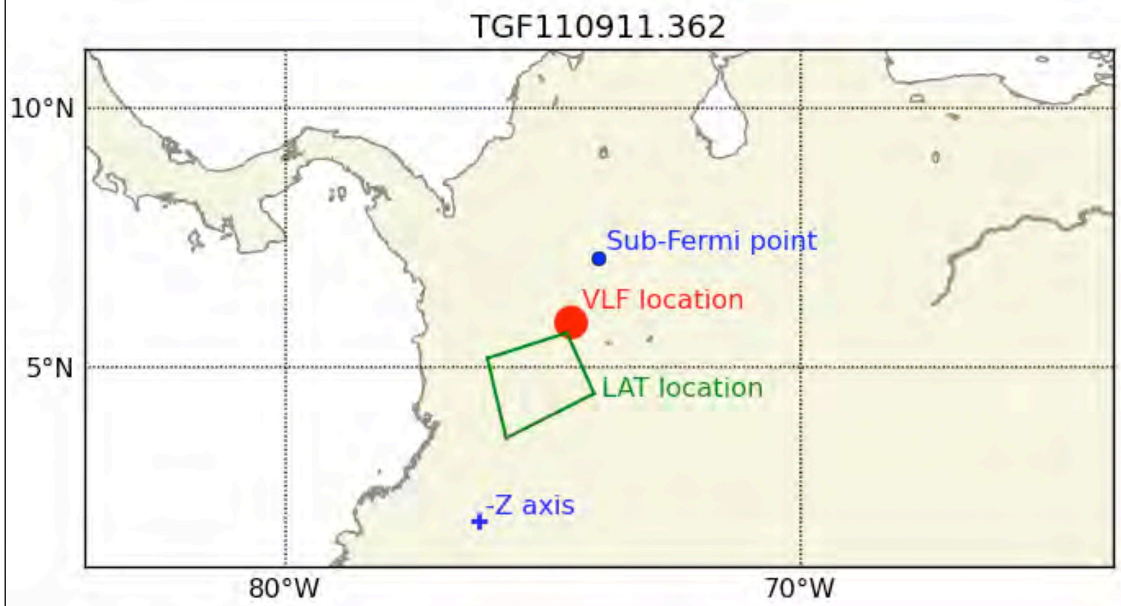


- More to come...

Blue circle: Fermi sub-satellite point
Red circle: VLF geolocation, ~20 km radius
Blue cross: Fermi -Z axis
Green boundary: LAT 68% confidence geolocation

Conclusions

- LAT has large effective area for TGF detection at 10 MeV and above
- LAT clearly, unambiguously detects TGFs in sky survey and special nadir obs
  - LAT joins GBM, RHESSI, and AGILE
- Spectral measurements in progress
- First simultaneous geolocations in gamma rays and VLF
  - Gamma rays and VLF transient are temporally and spatially coincident



Backup slides

Acknowledgements

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Comparison with GBM list

- Why not identical?
  - TGFs in GBM missed by LAT
    - On-board filter and LAT trigger logic
      - Bright TGFs: Too many ACD hits
      - Weak TGF: Events lost to filter
    - Unfavorable geometry
      - TKR occulted by CAL for TGFs near -Z axis
    - Soft spectrum, weak TGF
      - LAT doesn't trigger below 5 MeV
  - TGFs in LAT missed by GBM
    - Not in TTE box
      - GBM on-board flash trigger: ~10% efficiency of ground TTE search
    - Conservative detection algorithm
      - Low false-positive rate
    - Unfavorable geometry
      - Occulted by CAL