Fermi
Gamma-ray
Space Telescope

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

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on behalf of the LAT Collaboration

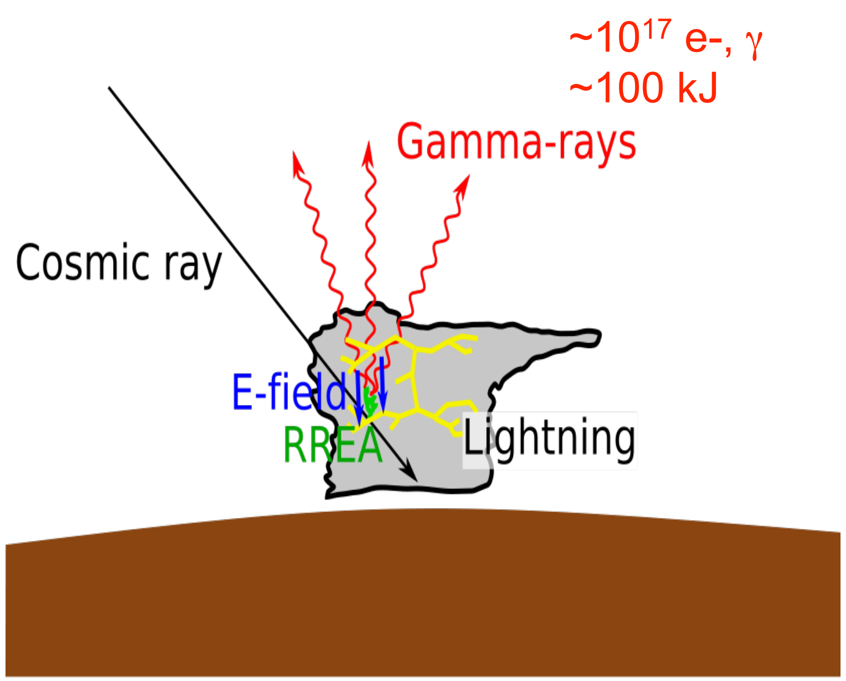
Introduction

- 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

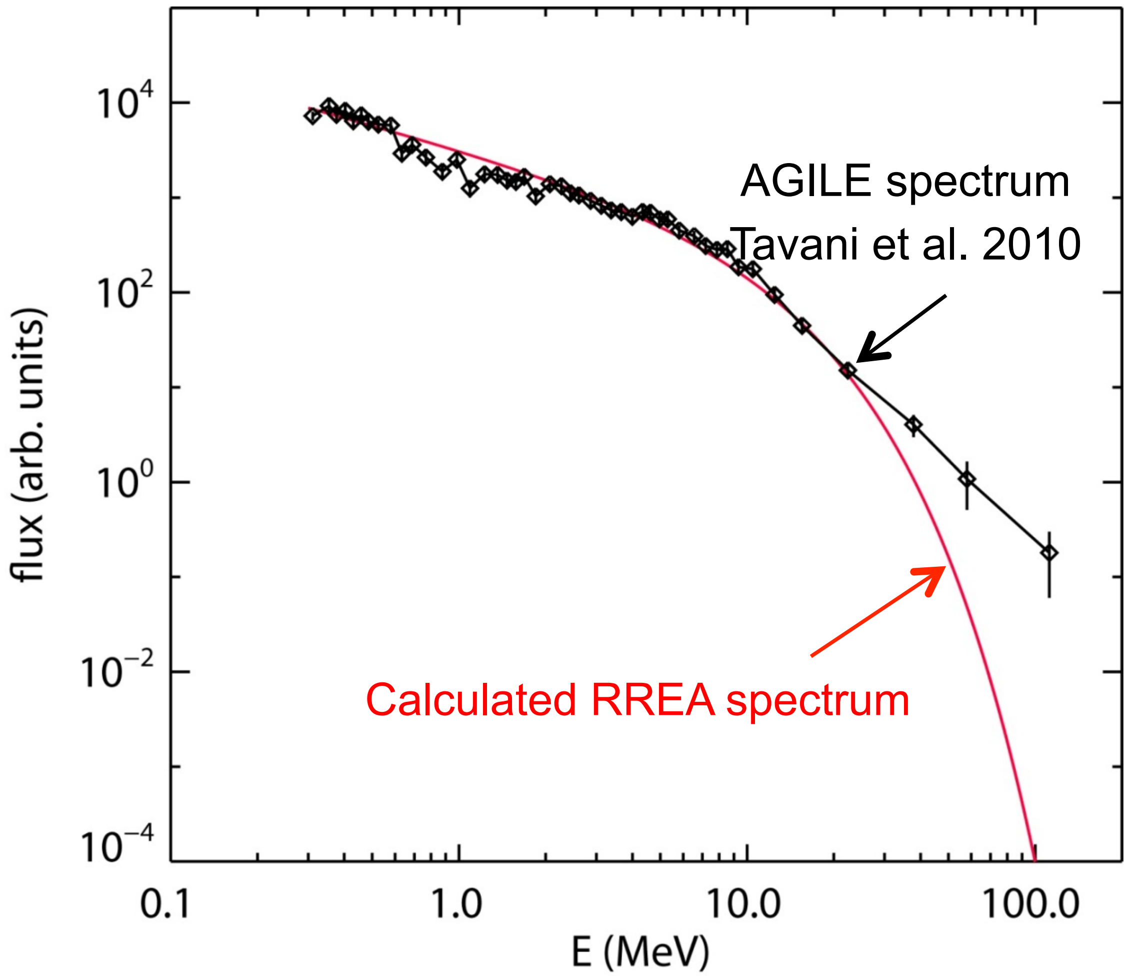
- Present model, inside thundercloud
  - Relativistic Runaway Electron Avalanche (RREA) with feedback
    - Strong E field accelerates electrons to relativistic energies before they range out
    - g-rays from electron bremsstrahlung
    - Predict ~7 MeV exponential g-ray cutoff

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?



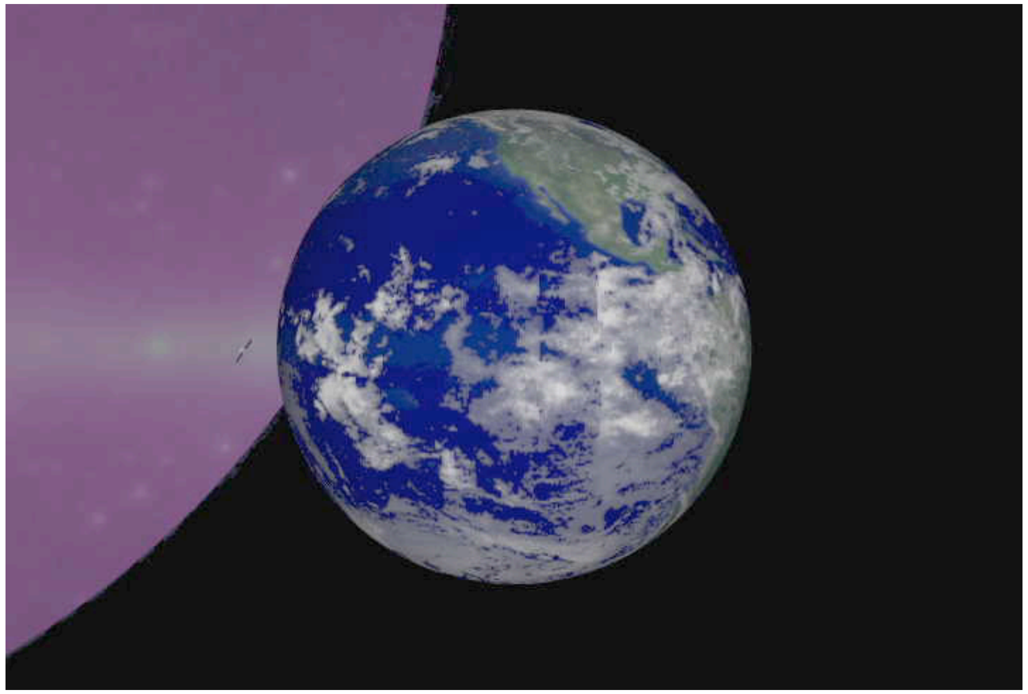
  - Fermi LAT
    - Large area, high segmentation -> high sensitivity with minimal pile-up
    - Low deadtime: 26.5 μs per event
    - Imaging and spectroscopy

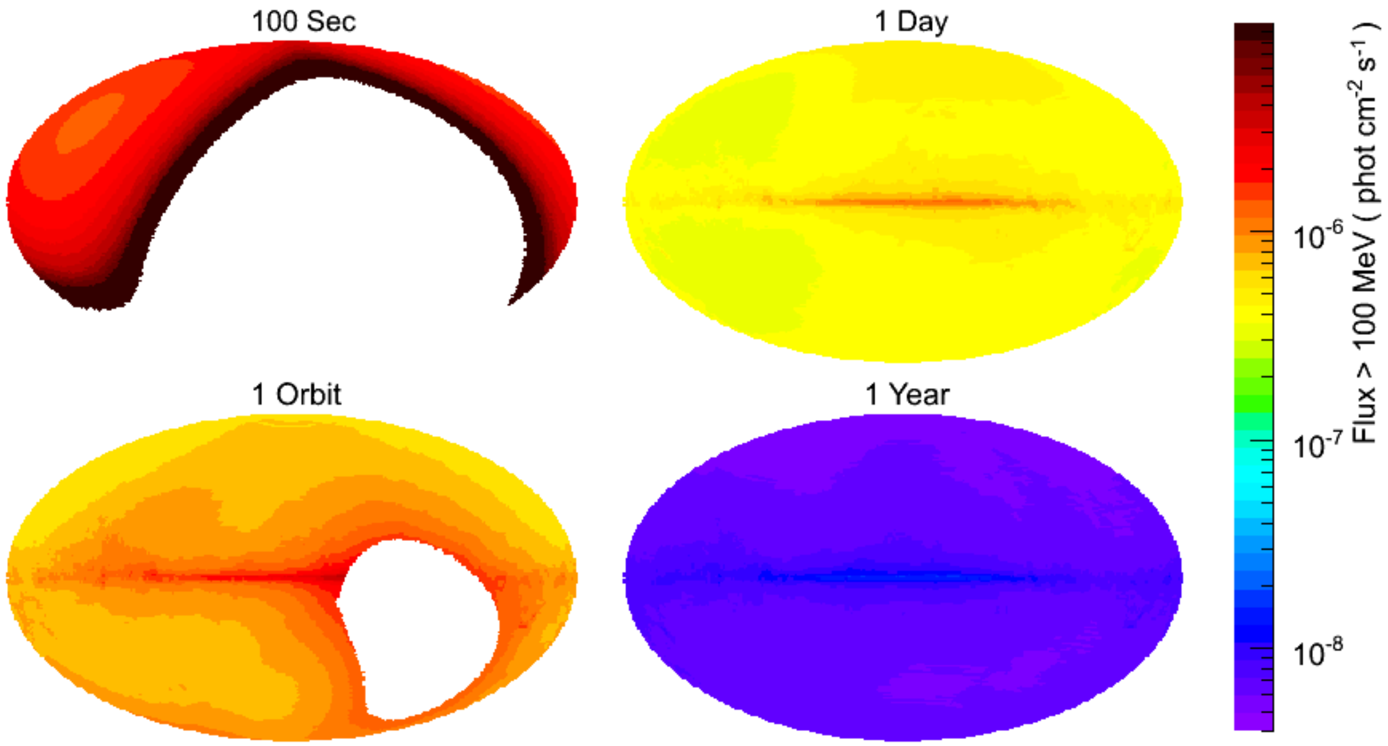
The Fermi Observatory

- **Satellite gamma-ray telescope**
  - **Large Area Telescope (LAT)**
    - **20 MeV – > 300 GeV**
  - **Gamma Burst Monitor (GBM)**
    - **8 KeV – 40 MeV**
- **Key features**
  - **Huge field of view (2.4sr)**
    - **20% sky any instant**
    - **All sky for 30’ every 3h**
  - **Huge energy range**
    - **Including unexplored 10-100 GeV range**

Fermi Mission and observing attitude

- Launched 11 june 2008, Delta II Rocket
  - Circular orbit, 565km altitude, 25.6 deg inclination
- Operations
  - Primary mode: sky survey
    - scan entire sky every 3 hours
  - Autonomous Repoint Request
  - Target of Opportunity

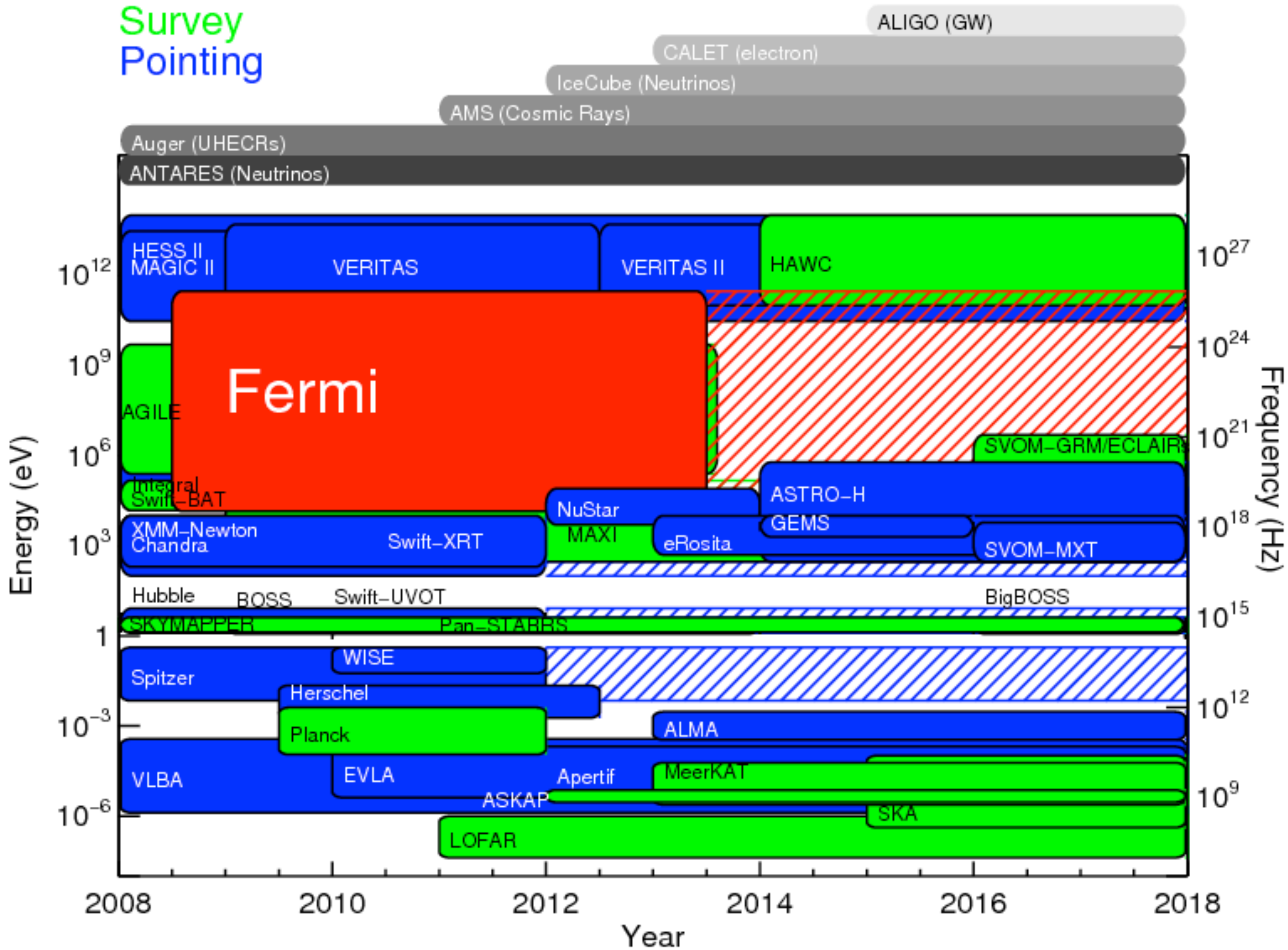




- expect modified survey soon for more exposure towards Galactic Center

- http://fermi.gsfc.nasa.gov/ssc/proposals/alt_obs/obs_modes.html

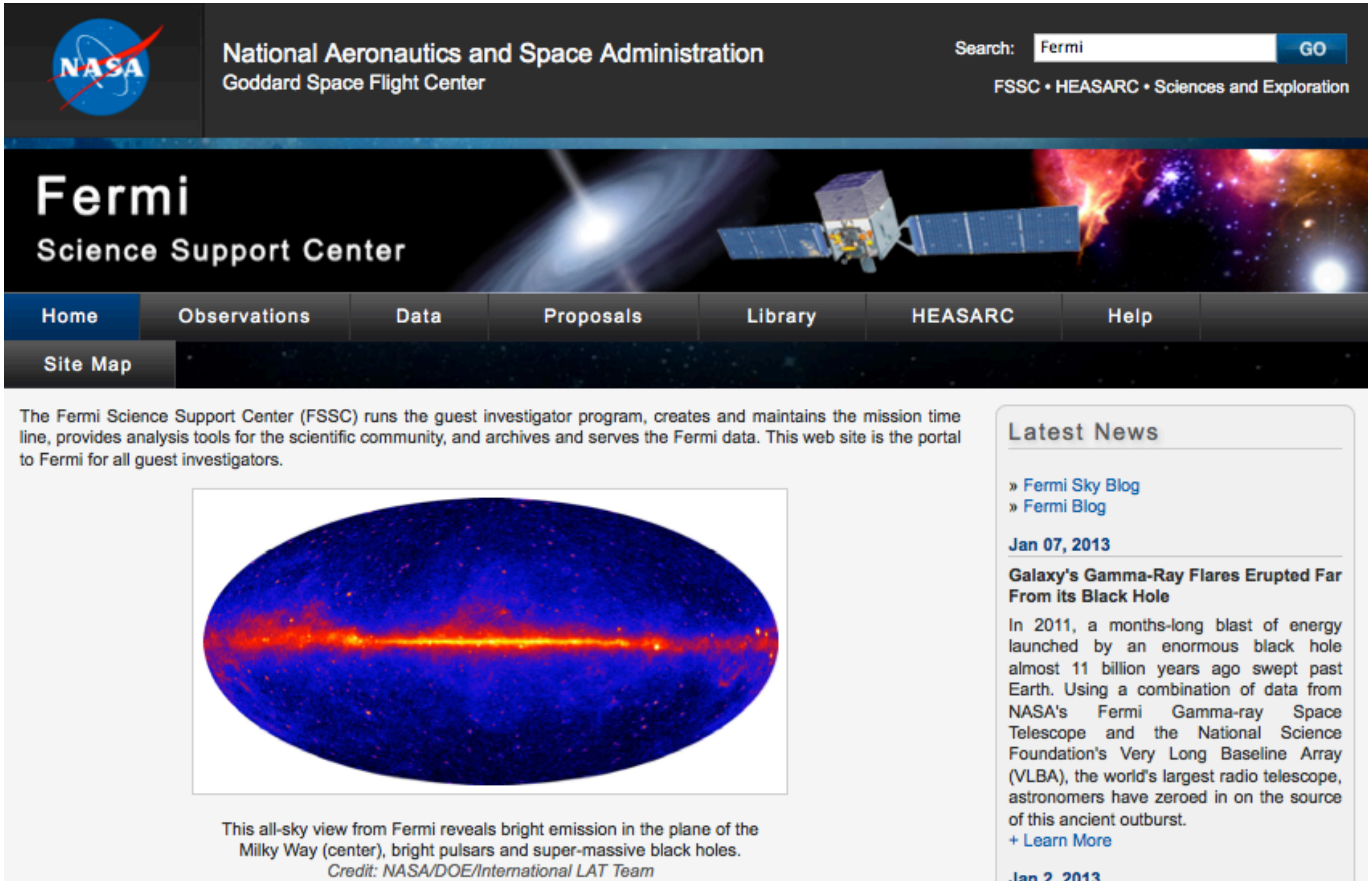
Fermi Mission timeline



- ❑ **NASA 2012 Senior Review recommended extended operations**
  - http://science.nasa.gov/astrophysics/2012-senior-review/
- ❑ **NASA HQ will extend the mission to at least 2016**

Public data and tools

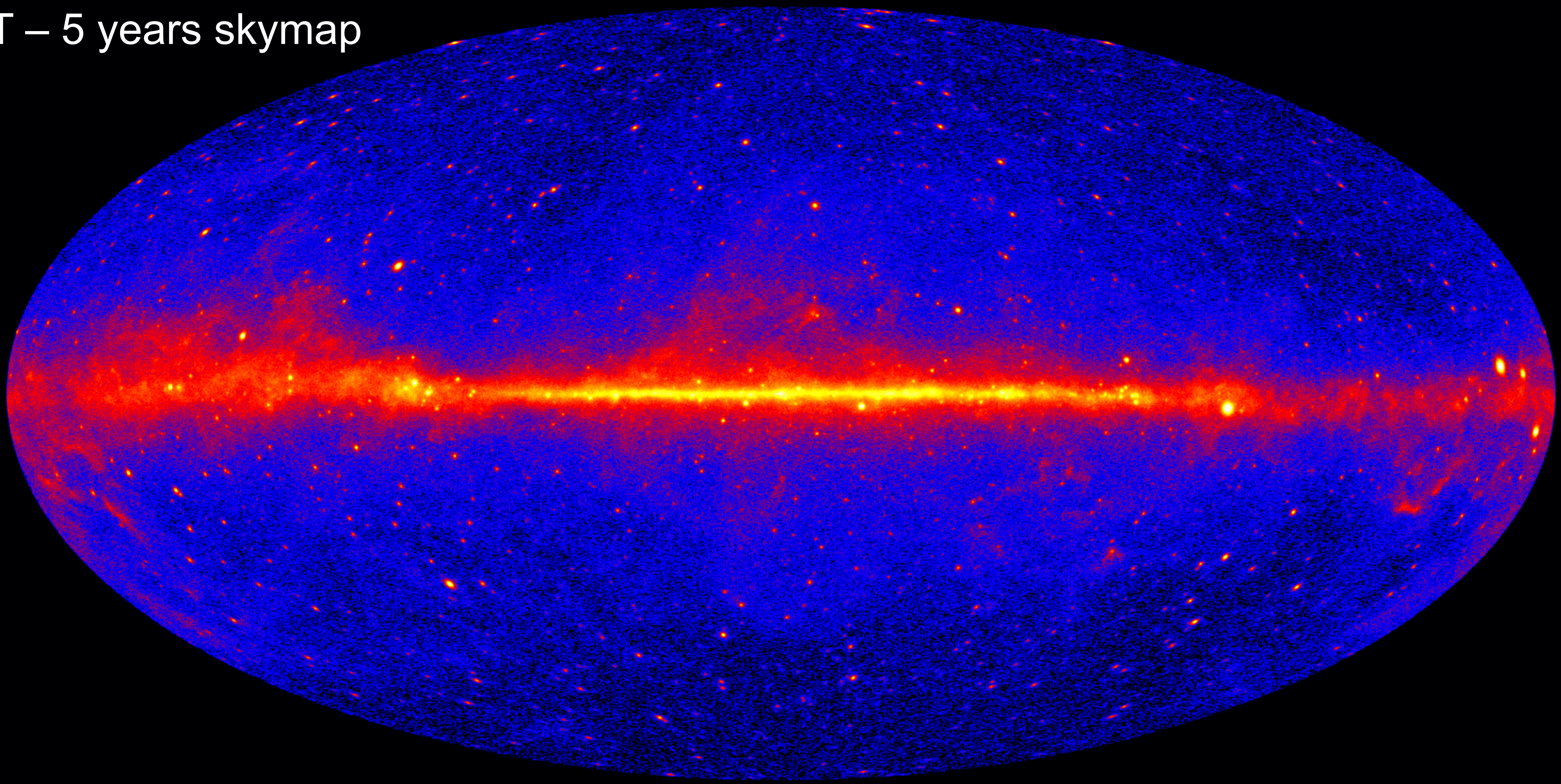
http://fermi.gsfc.nasa.gov/ssc

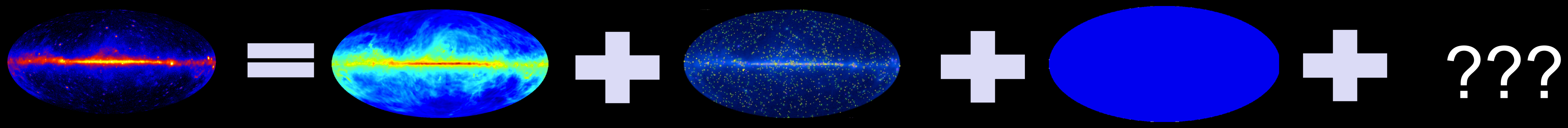


- > 800M γ and public within ~hours from trigger
  - Dedicated TGF runs with non standard configuration and electrons, which are background for photons, are currently not distributed
- Full Science Tools data analysis suite
- > 1000 papers, > 10k citations collectively

Resolving the gamma-ray sky

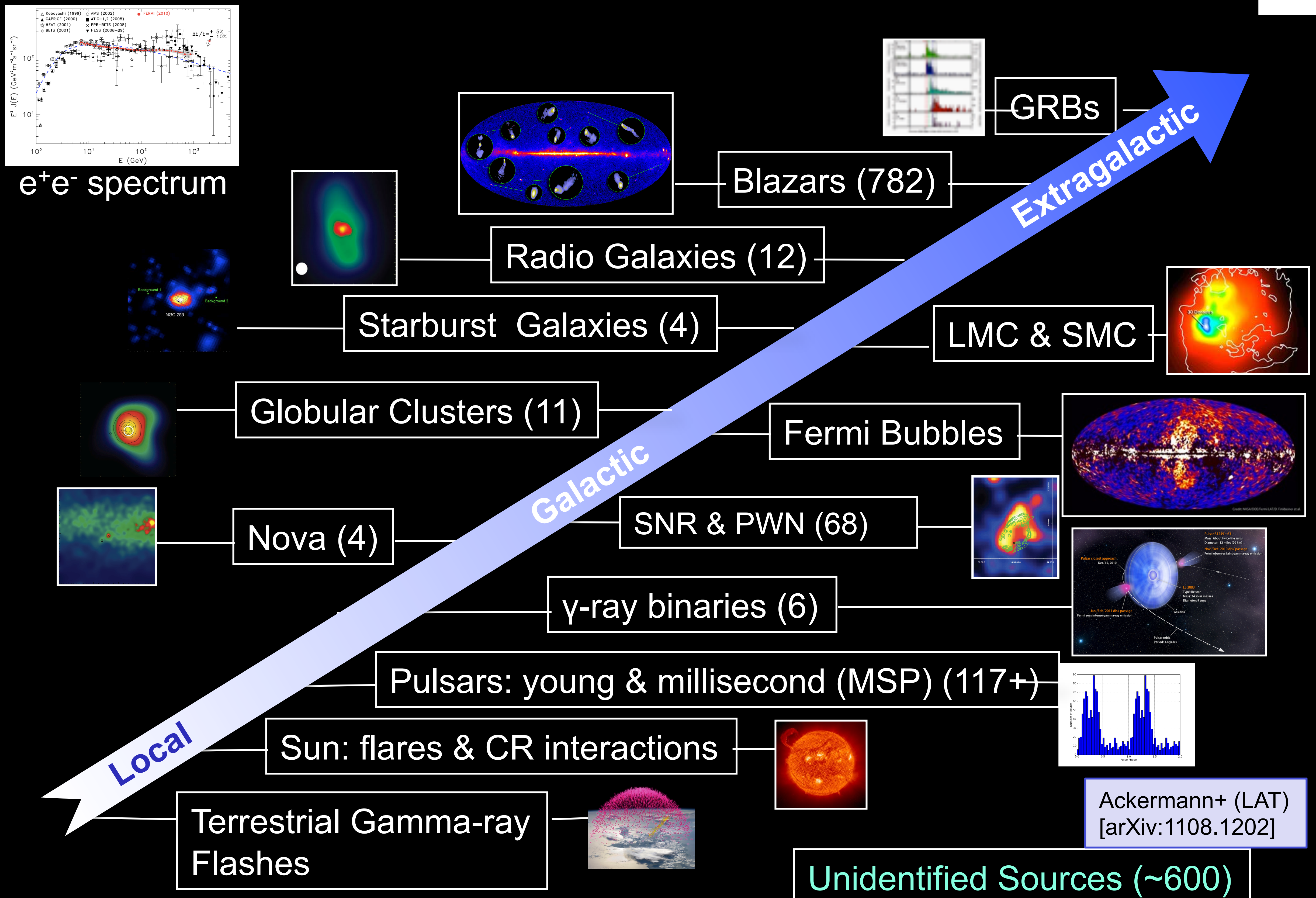
LAT – 5 years skymap





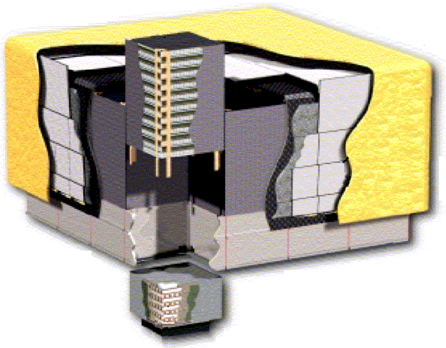
GeV Sky = Galactic + Point Sources + Isotropic + ???

Fermi Science overview



Overview of the Large Area Telescope

Atwood, W. B. et al. 2009, ApJ, 697, 1071

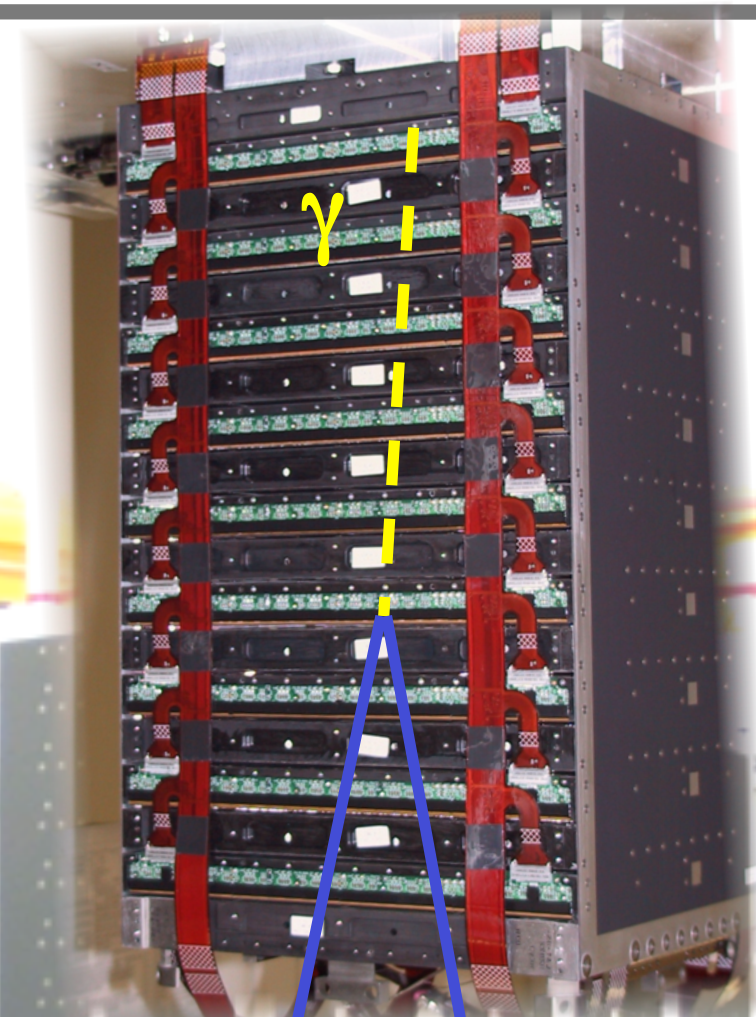


LAT:

- modular - 4x4 array
- 3ton – 650watts

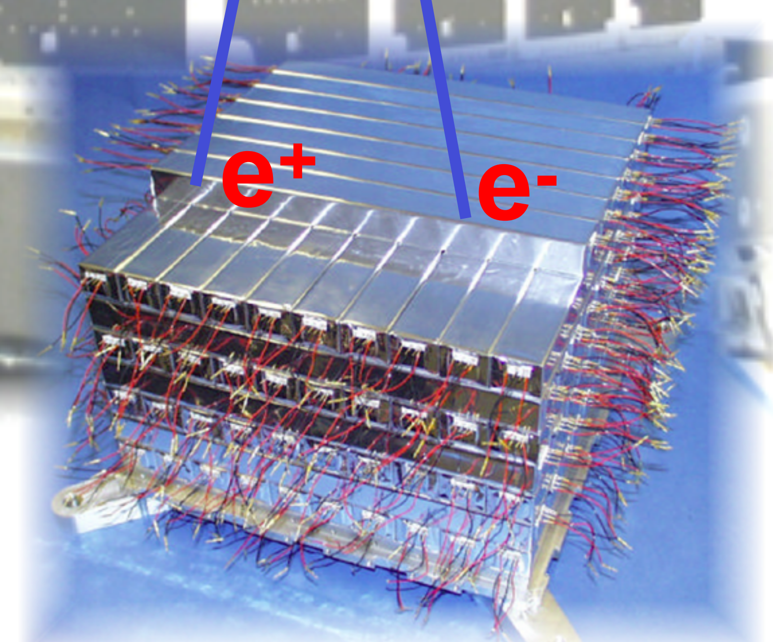
Anti-Coincidence (ACD):

- Segmented (89 tiles + 8 ribbons)
- Self-veto @ high energy limited
- **0.9997 detection efficiency**



Tracker/Converter (TKR):

- Si-strip detectors
- ~80 m^2 of silicon (total)
- W conversion foils
- **1.5 X0 on-axis**
- 18XY planes
- **~10^6 digital elx chans**
- Highly granular
- High precision tracking
- Average plane PHA

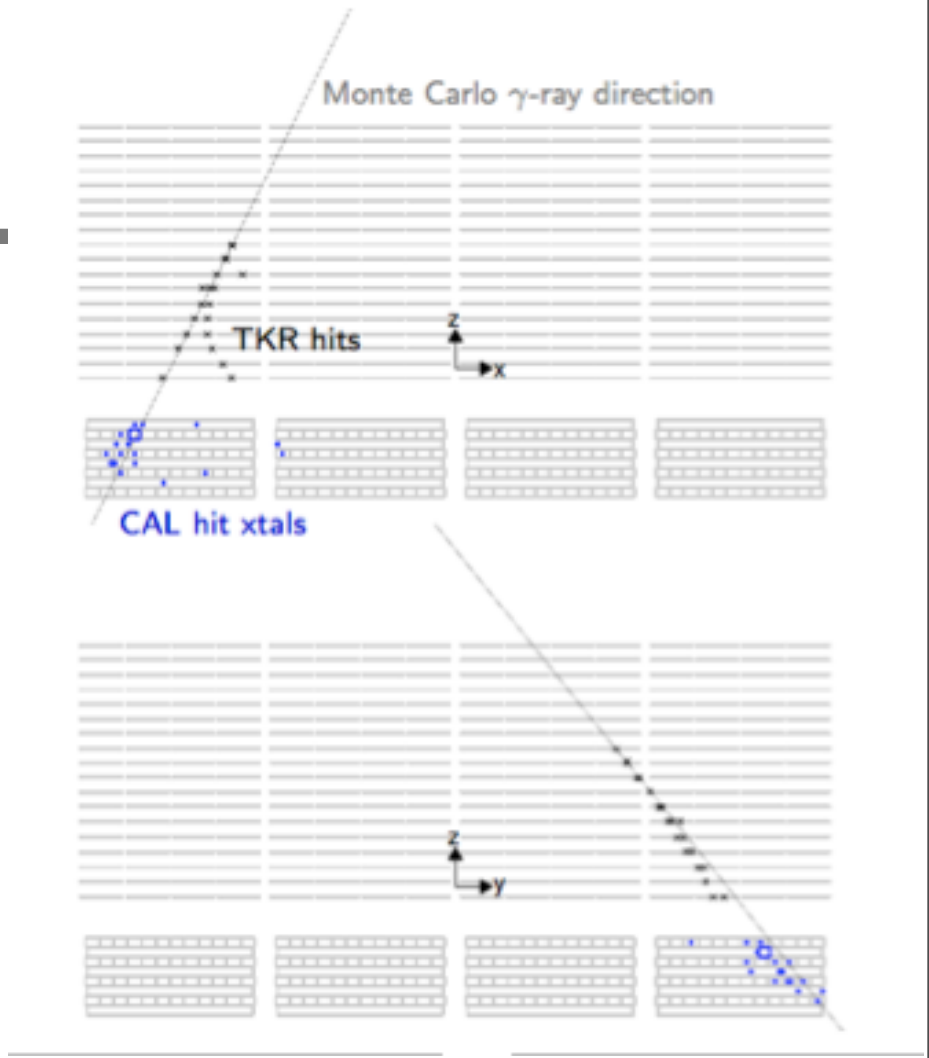


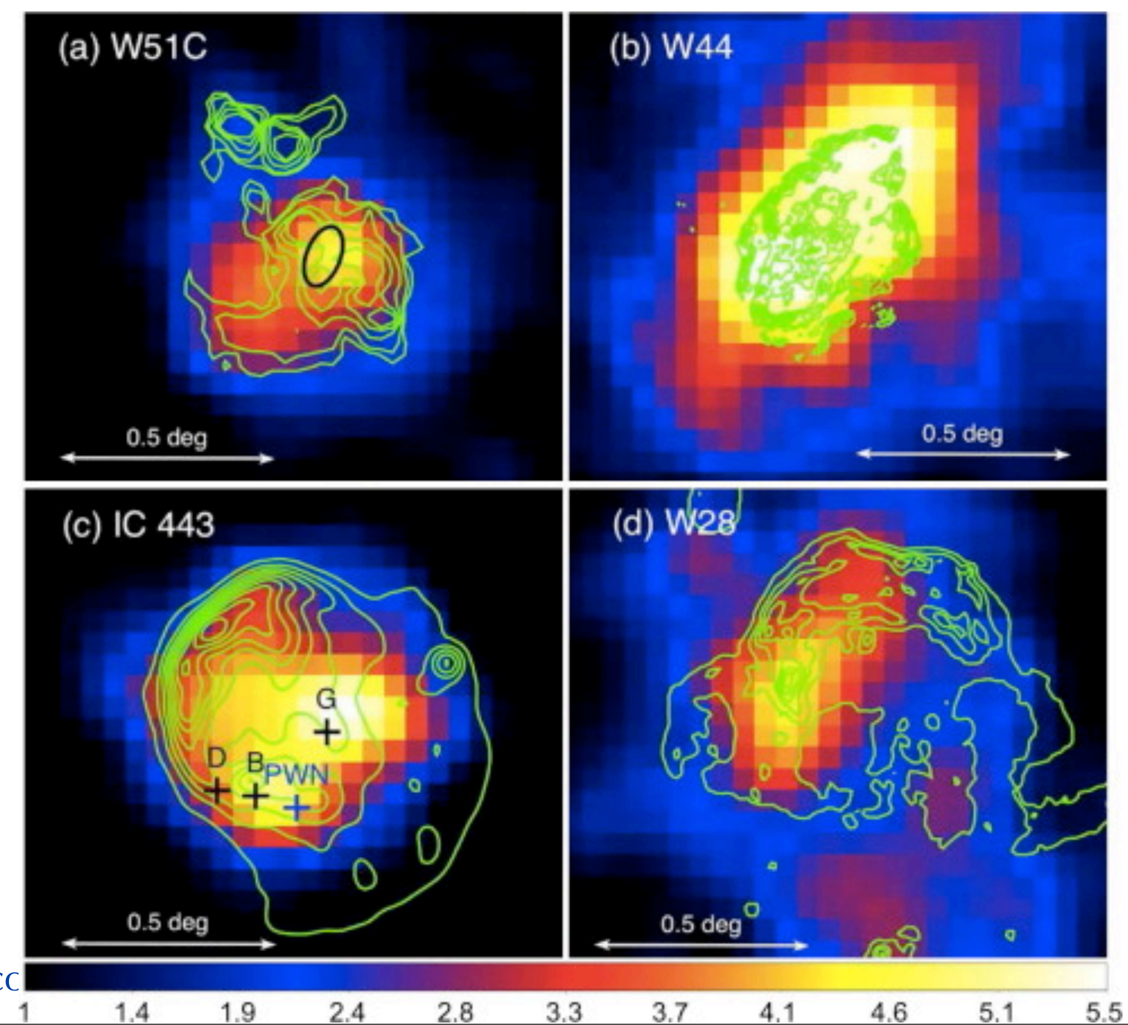
Calorimeter (CAL):

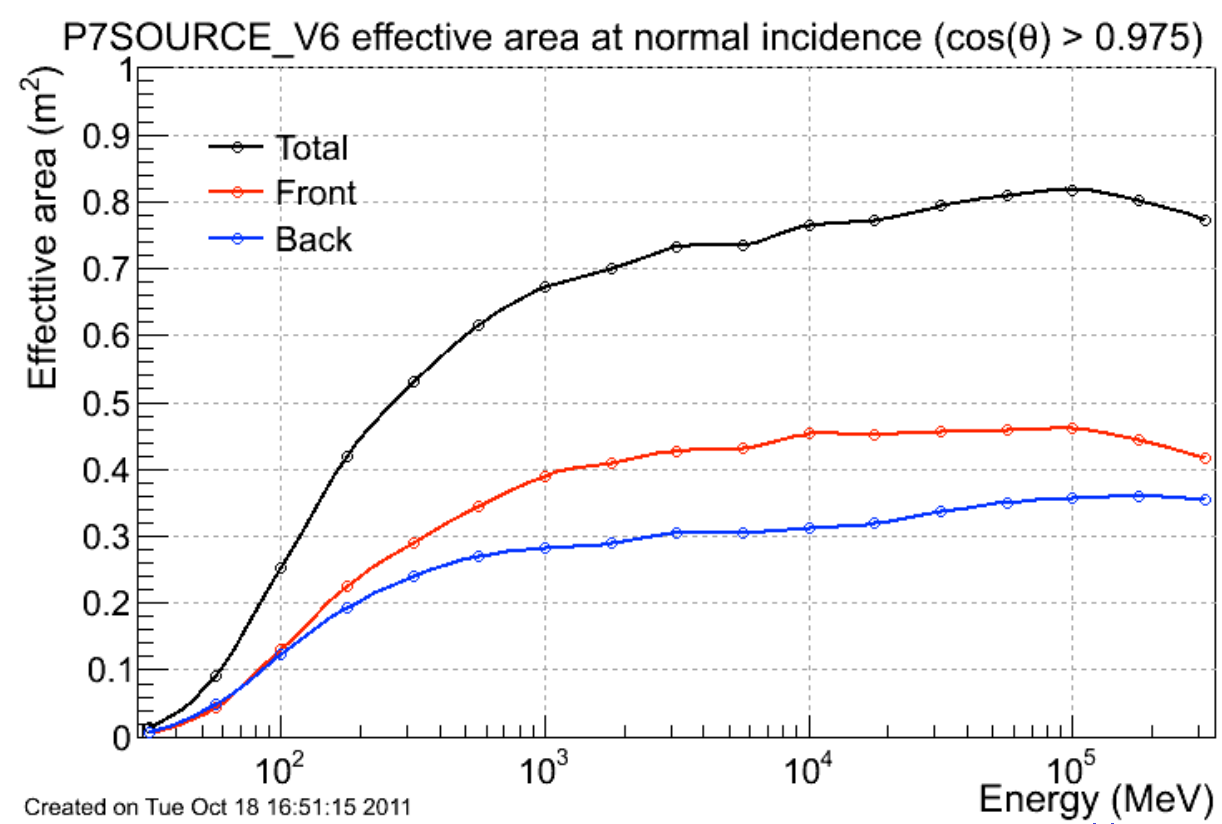
- 1536 CsI(Tl) crystals
- **8.6 X0 on-axis**
- large elx dynamic range (2MeV-60GeV per xtal)
- **Hodoscopic (8x12)**
- Shower profile recon
- leakage correction
- EM vs HAD separation

Analyzing a celestial gamma-ray

- Event-level reconstruction AND background rejection
- Map LAT performance with Instrument Response Function (IRFs)
  - combination of MC simulations and flight datasets
- Make a model of your Region of Interest (ROI) in the sky
- Fold photon events with IRFs
- Perform likelihood analysis of counts in ROI and compare models

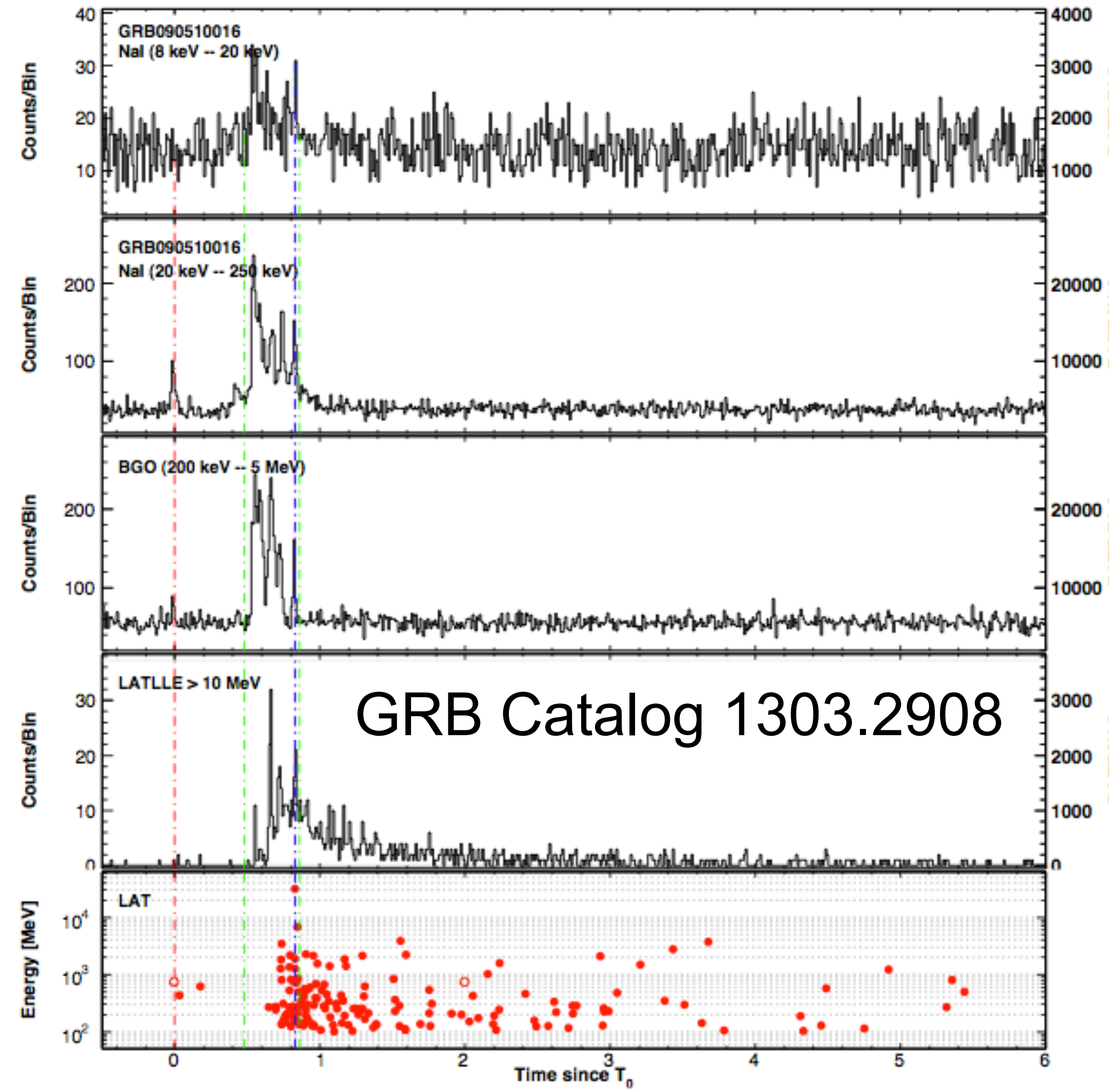






Different type of event analysis

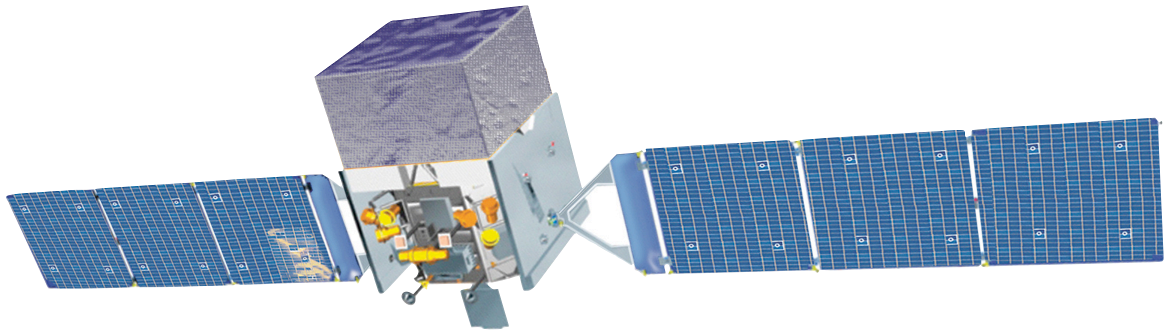
- Dedicated event selections
  - multiple event classes for standard celestial photons
  - Cosmic Ray Electrons
  - Nuclei and protons (mostly used for calibrations, work in progress for spectral studies and anisotropies)
- Minimal event selection for bright transients
  - LAT Low Energy technique for Gamma-ray Bursts (GRB) prompt emission and Solar Flares (SF), i.e. use the LAT as a counter, like GBM
- TGFs would need a dedicated reconstruction and background rejection
  - complex topology, many overlapping photons in a single trigger window
  - standard recon and IRFs will not apply



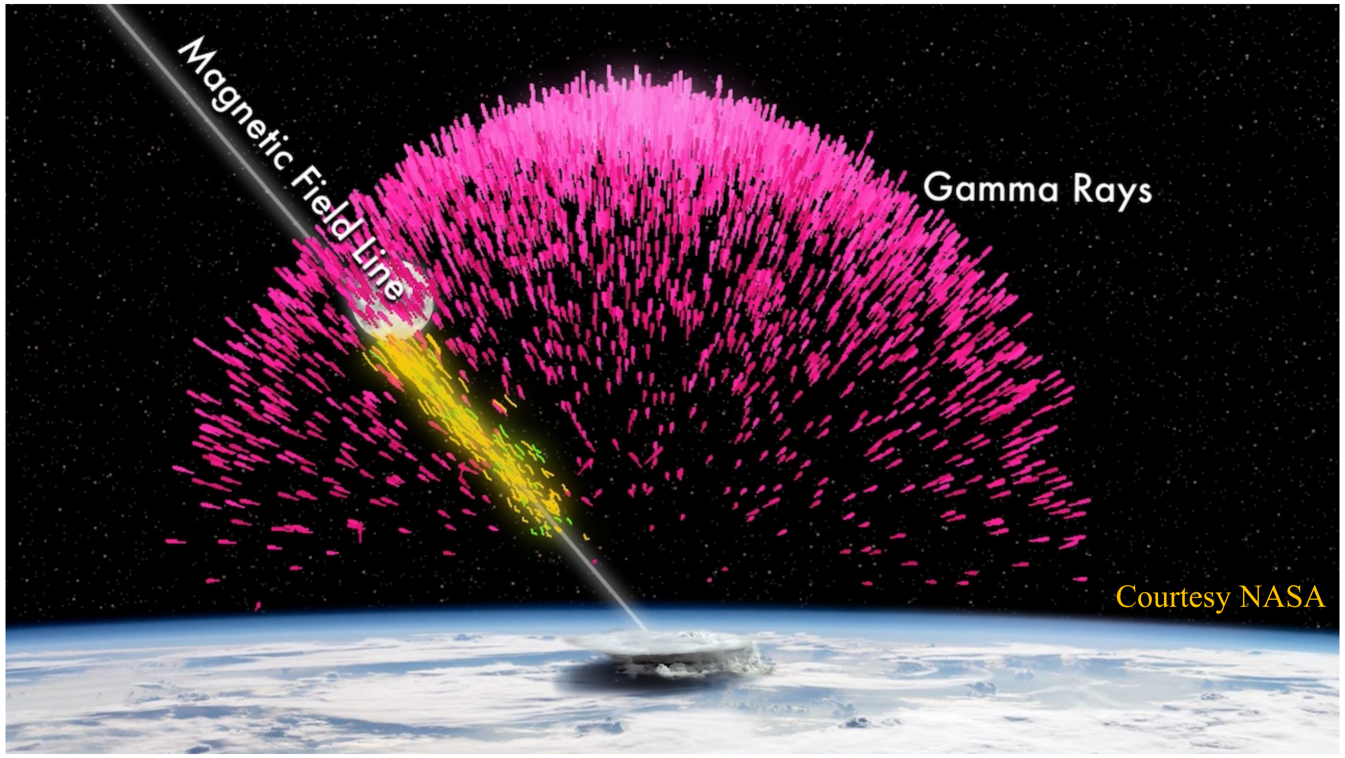
Positron Fraction
PRL 108 (2012)

Detecting TGFs in LAT

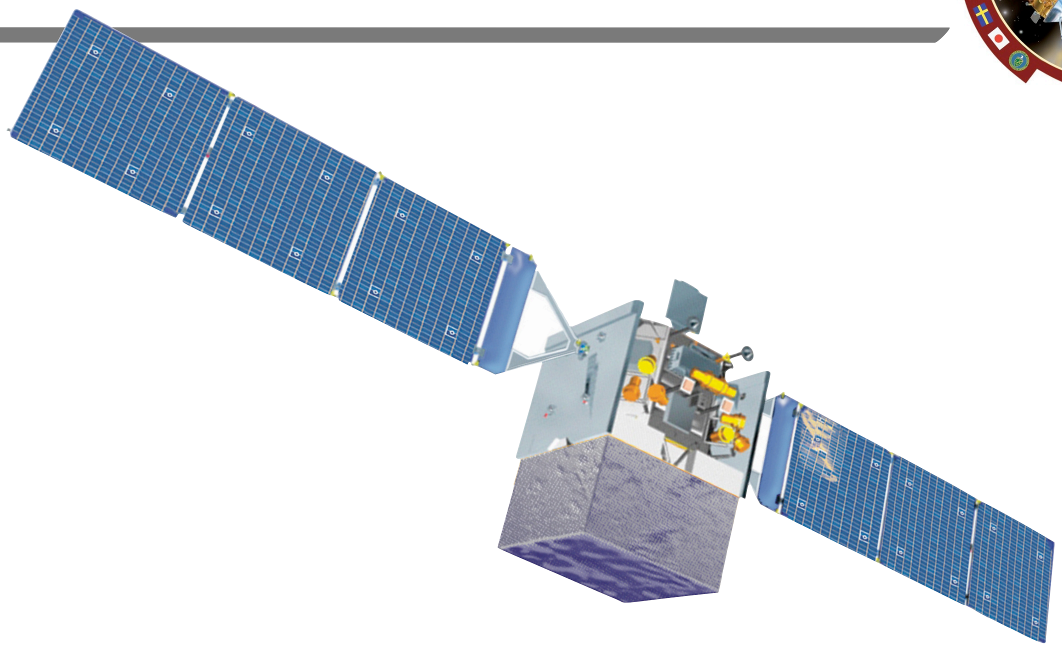
- Two observation types with Fermi LAT
  - Sky survey
    - Advantages
      - High duty cycle (>95%)
      - Good effective area
      - Many TGFs, large sample
    - Disadvantages
      - Trigger and on-board filter reject many LAT events within TGFs



  - 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



Detecting TGFs in LAT



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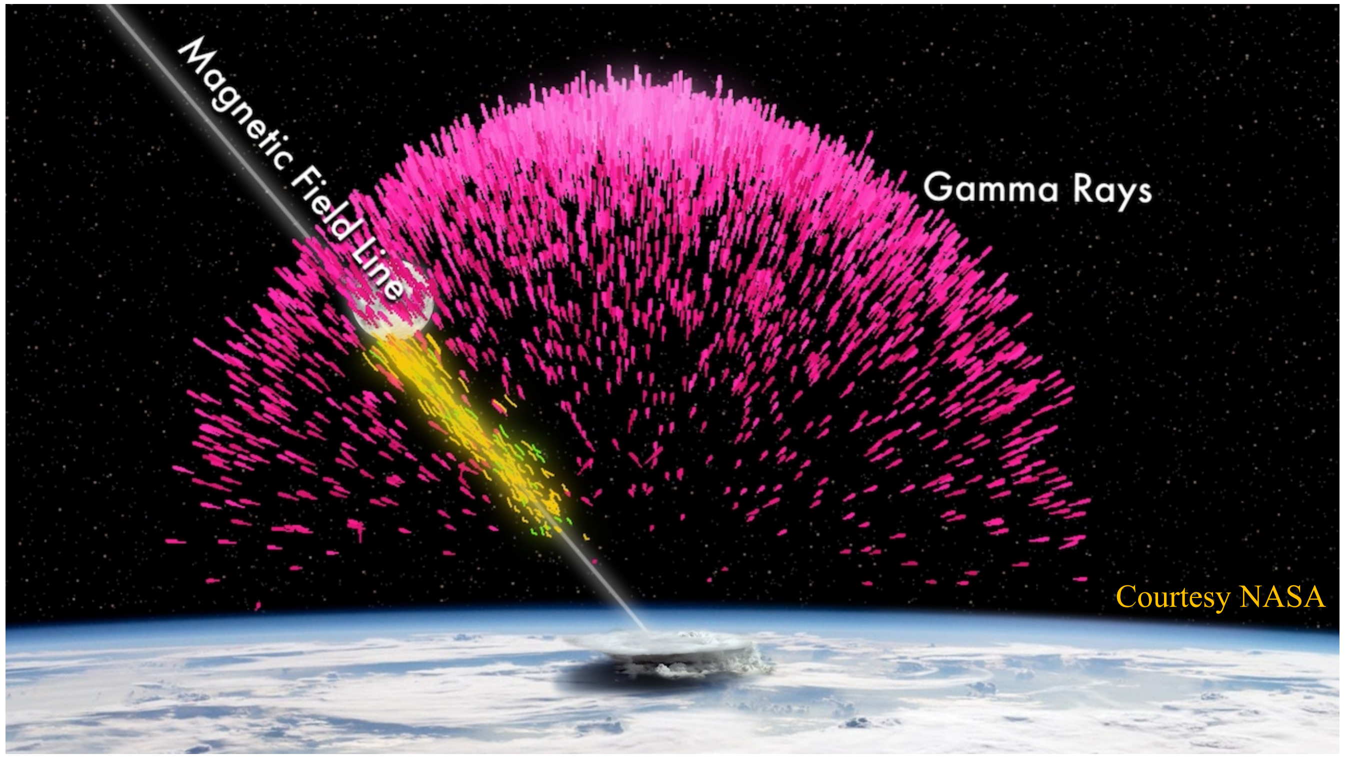
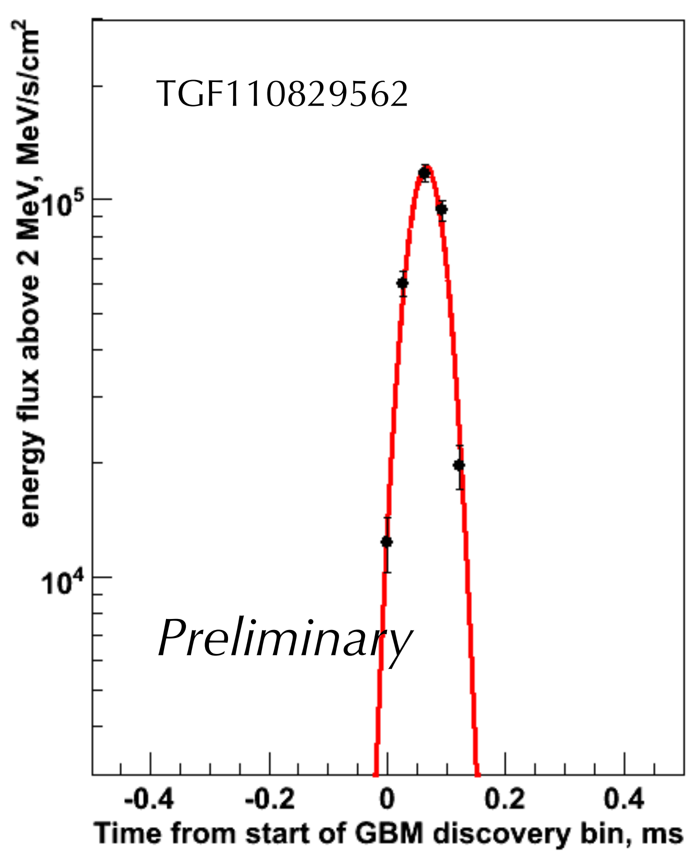
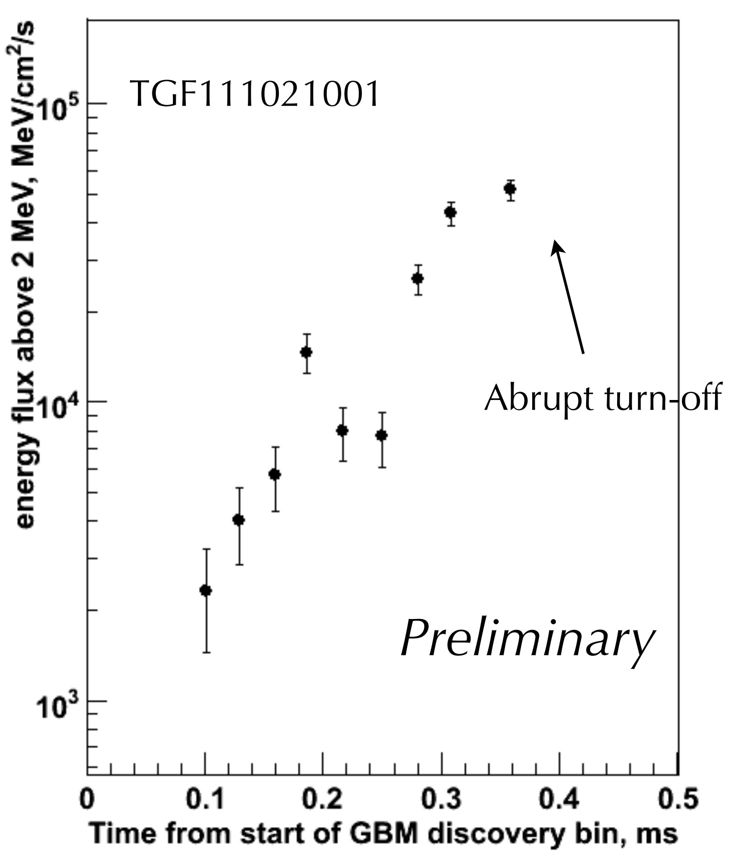


Summary of nadir observations

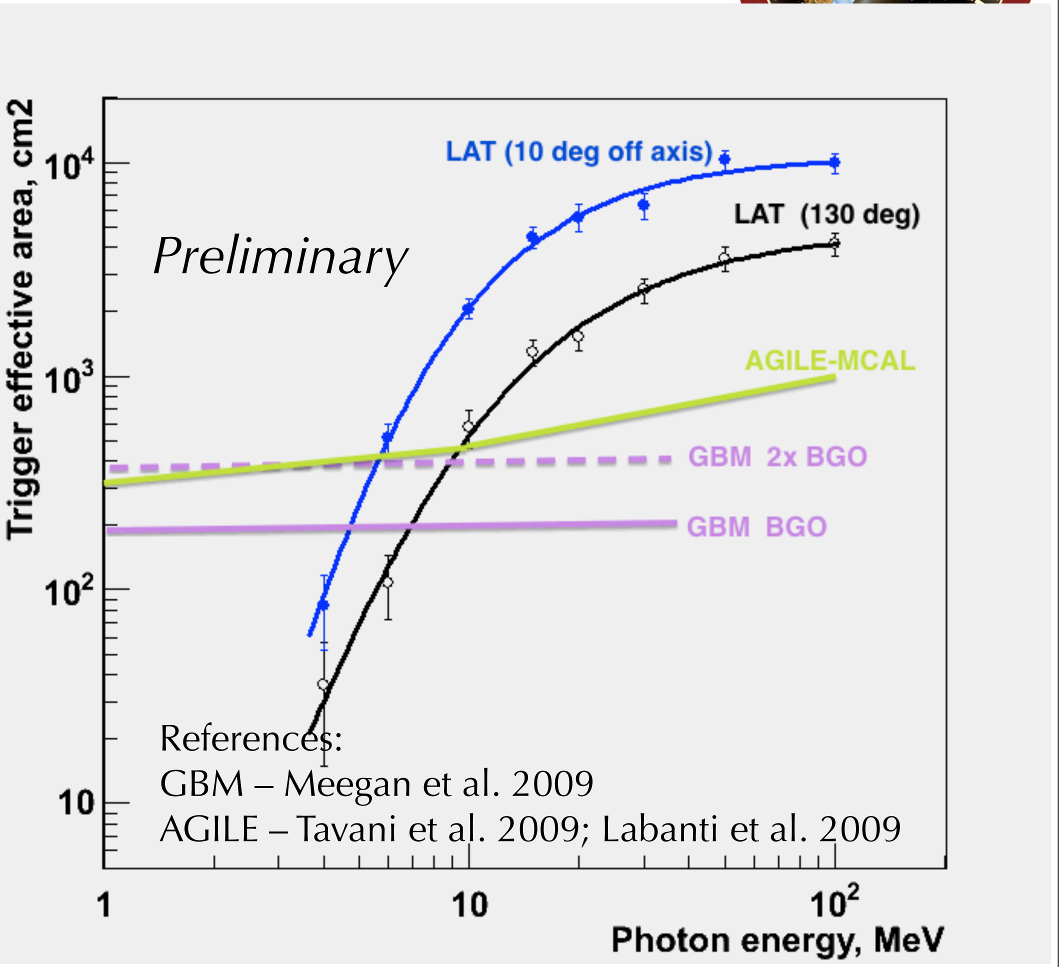
- Special nadir-observing program in progress
  - 27 three-orbit nadir pointings from 26 July 2011 to 5 Oct 2012
  - Cycle 5 program approved; expect 22 more nadir pointings to Aug 2013
- Status to date of nadir observing
  - Twenty-two TGFs detected so far in special nadir-observing configuration
  - 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



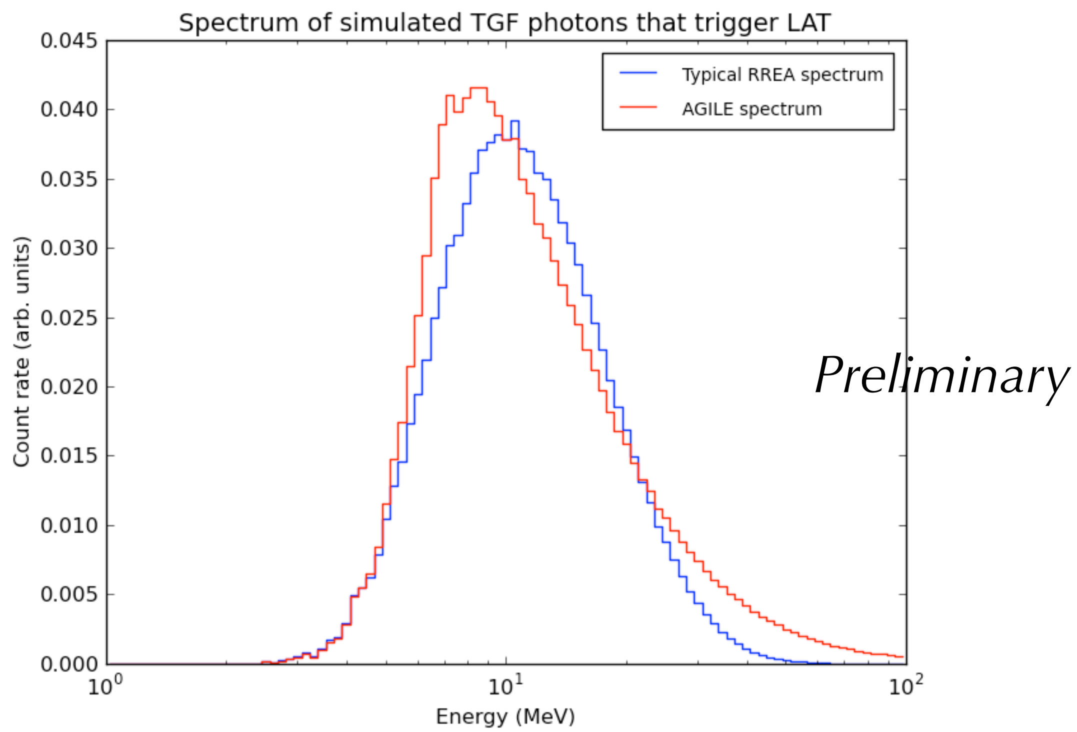


Detecting TGFs in LAT

- 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)

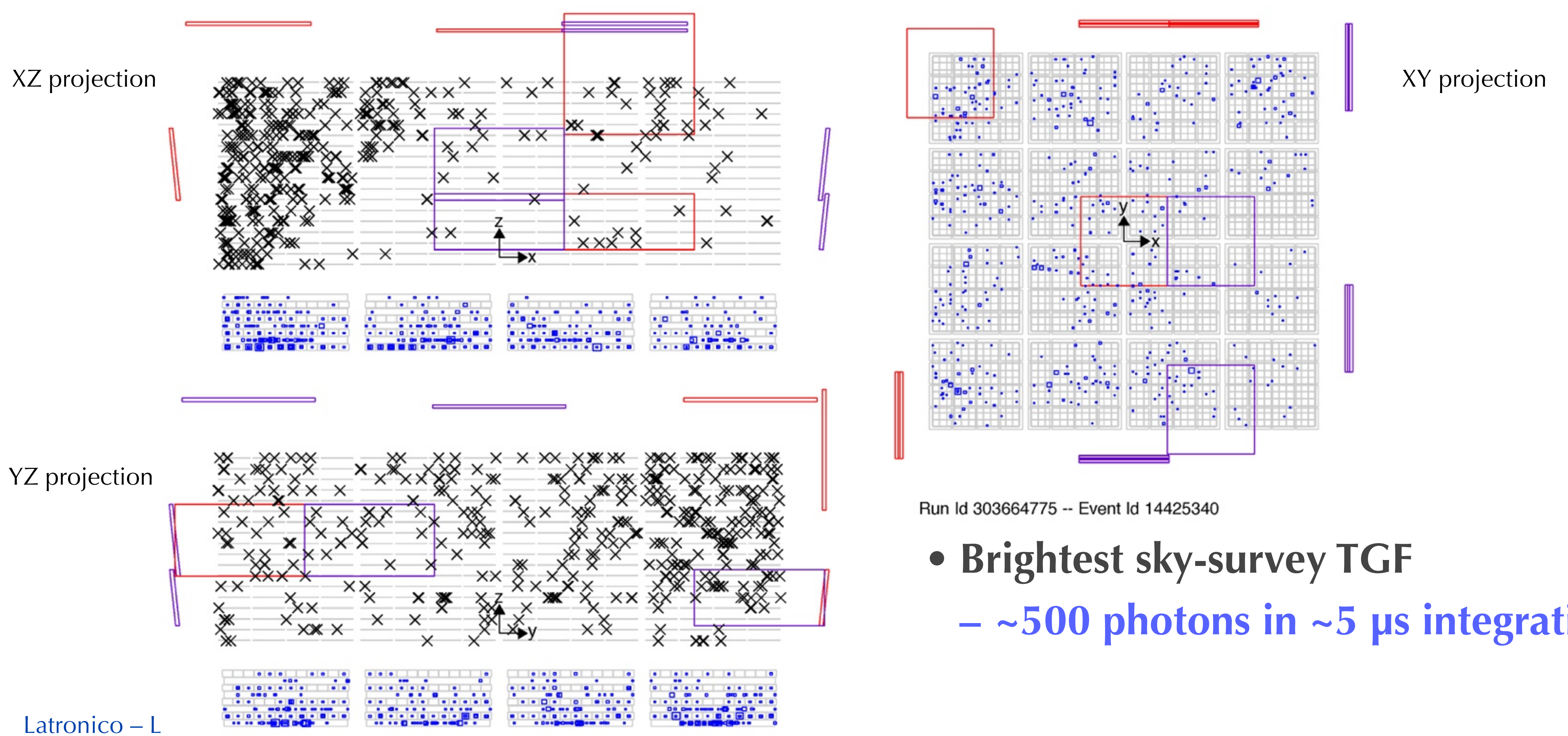


- Sky survey dataset is not optimal
  - Can fail to detect TGF
  - Many LAT events within TGF are lost



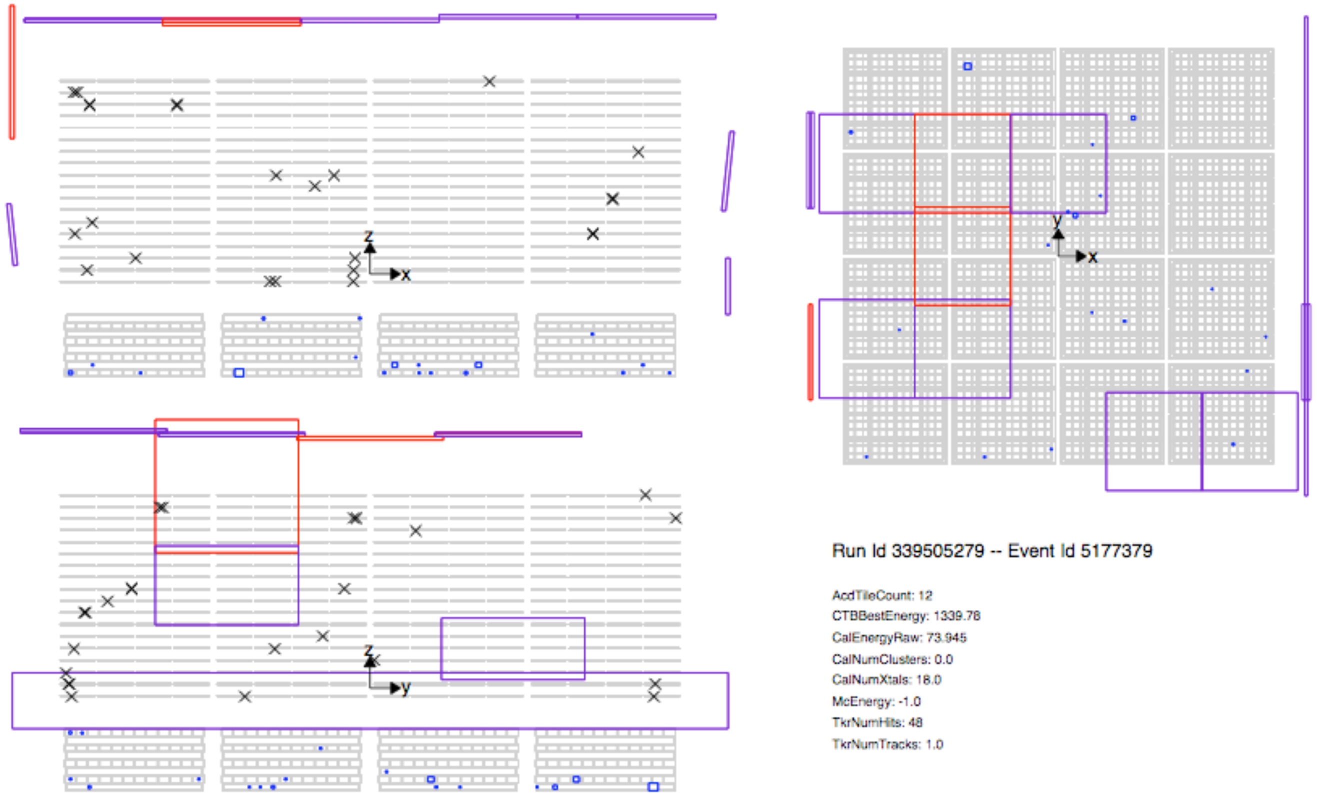
Event display

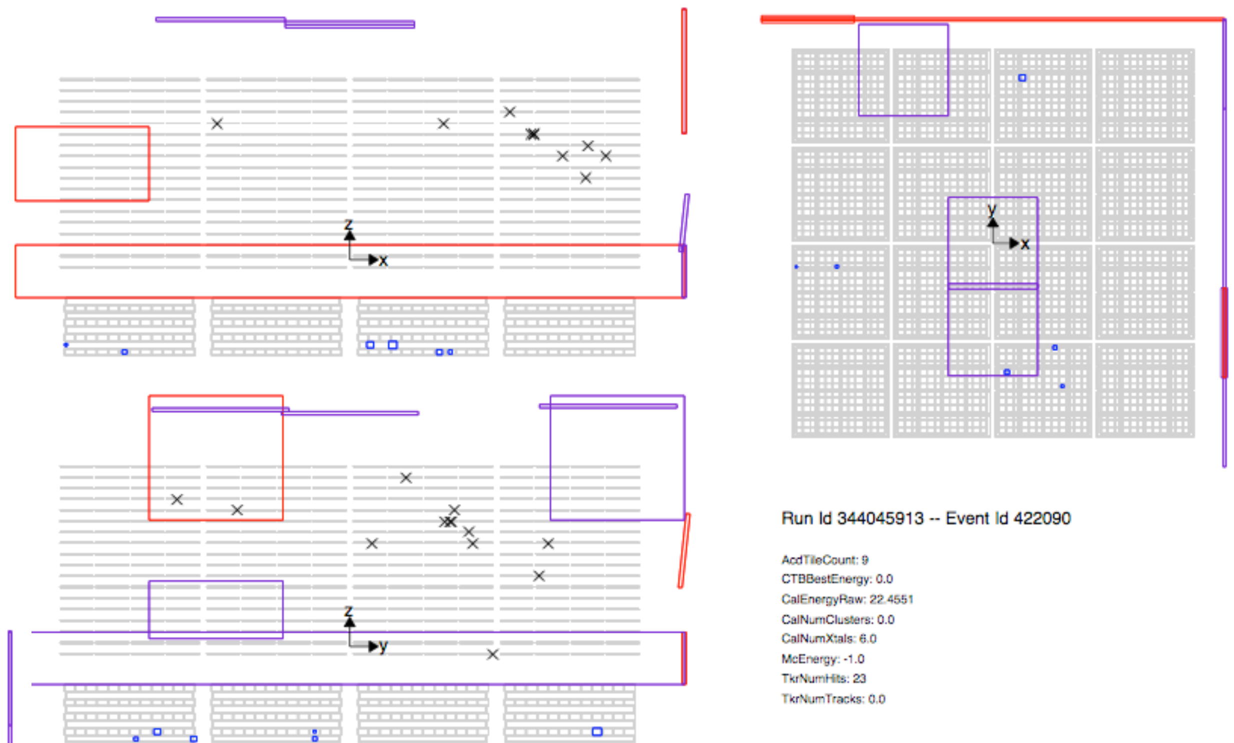
- Characteristic of TGFs in LAT
  - Trigger request rate can peak >1 MHz
    - Algorithm: search for anomalously high rate
  - Events are complex
    - High multiplicity, i.e. not single-photon events
    - Typically not one ~100 MeV photon or one ~1 GeV photon; instead ~30 or ~300 photons (respectively)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

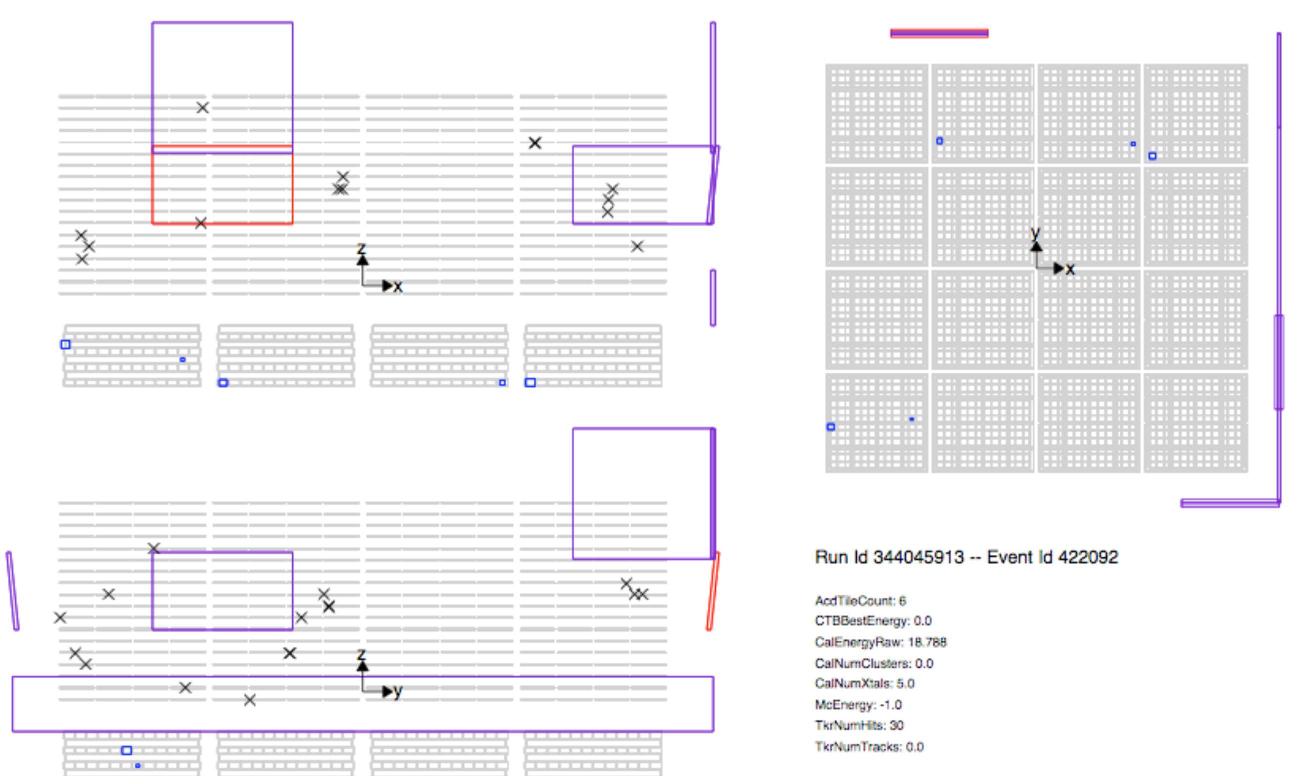


- Brightest sky-survey TGF
  - ~500 photons in ~5 μs integration

Event displays



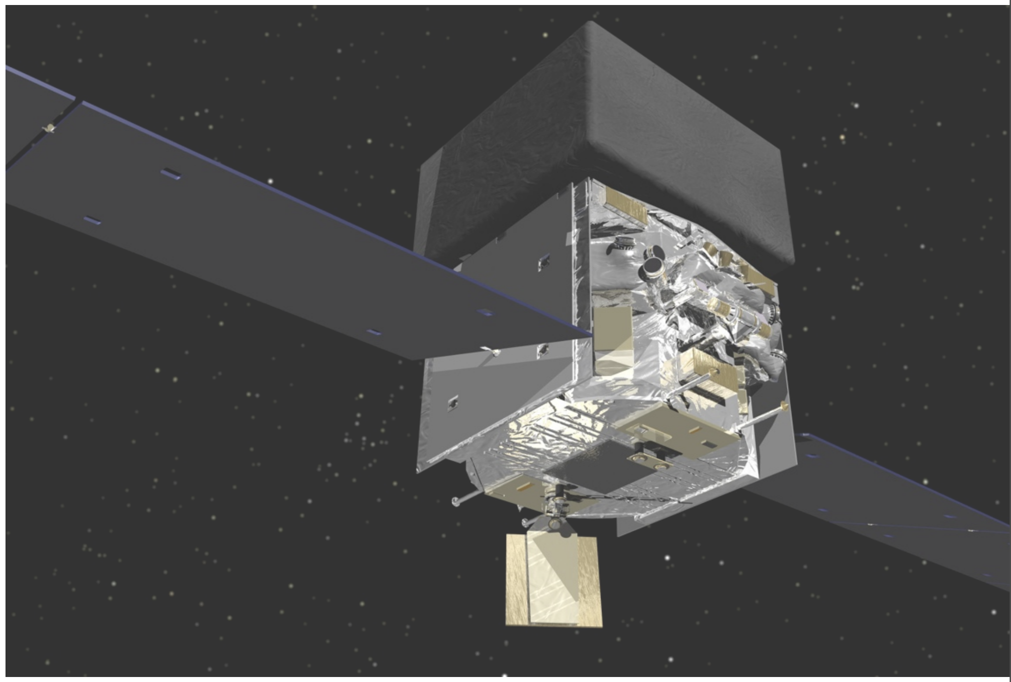




- Three TGF event displays
  - Typical or dimmer than average

TGF search during LAT sky survey

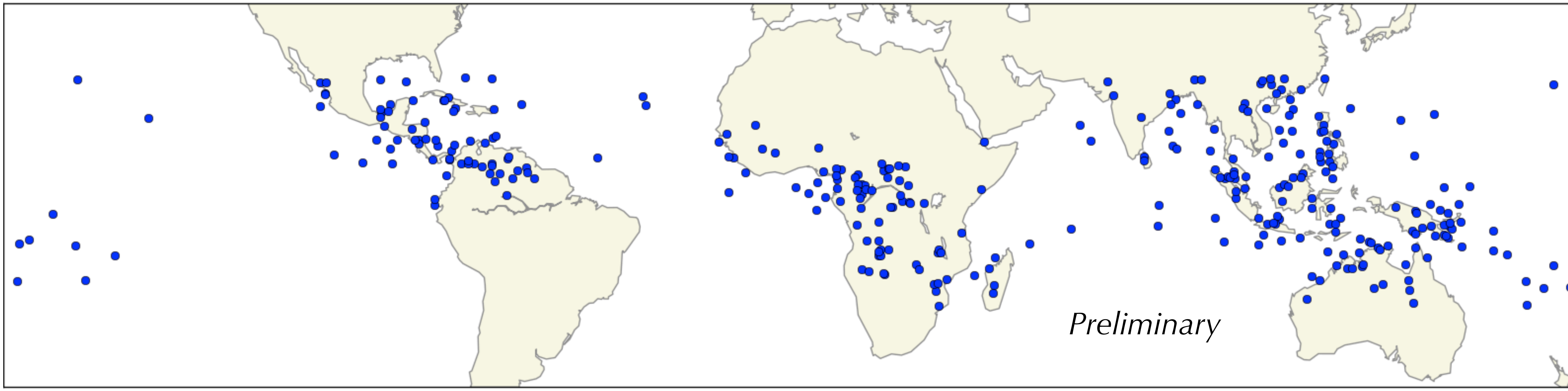
- Search algorithm
  - Find extreme outliers in trigger rate
  - Remove coincident cosmic ray showers
  - Inspect event displays to verify



- 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

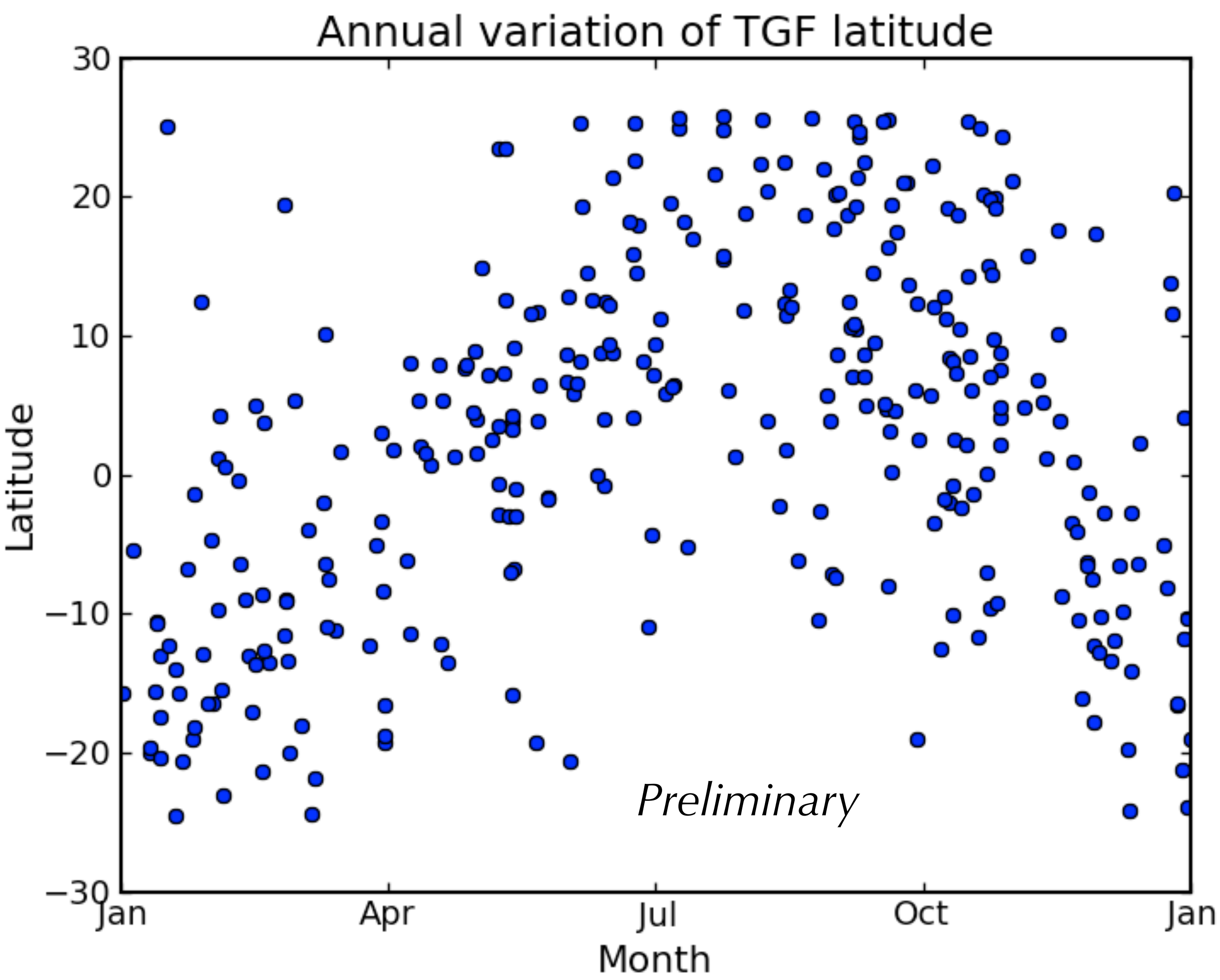


- Geographic distribution (location of Fermi at time of TGF)
  - Active TGF regions are active thunderstorm regions
  - Geographic correlation
    - Land masses, active thunderstorm regions. Coastal storms
    - Note: not possible to measure TGFs within SAA
  - Consistent with historical record of TGFs

Temporal distributions

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

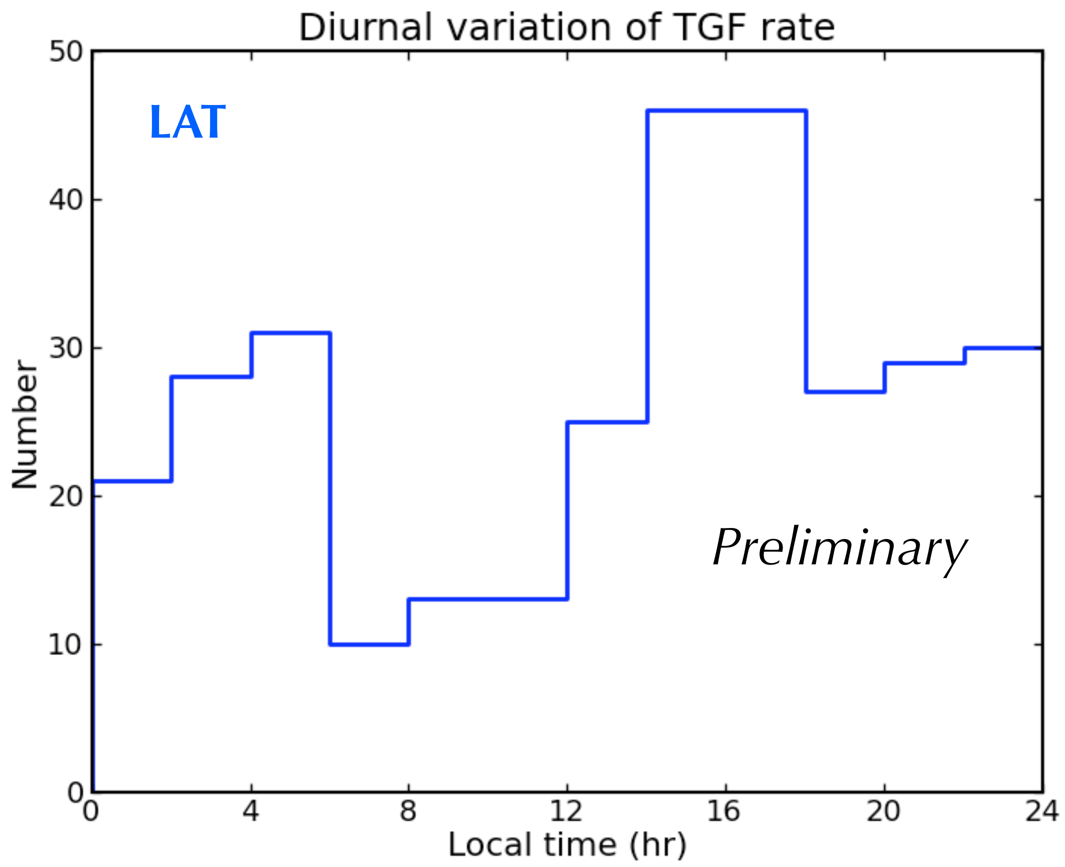
- **Consistent with known TGF behavior**
  - BATSE, RHESSI, GBM

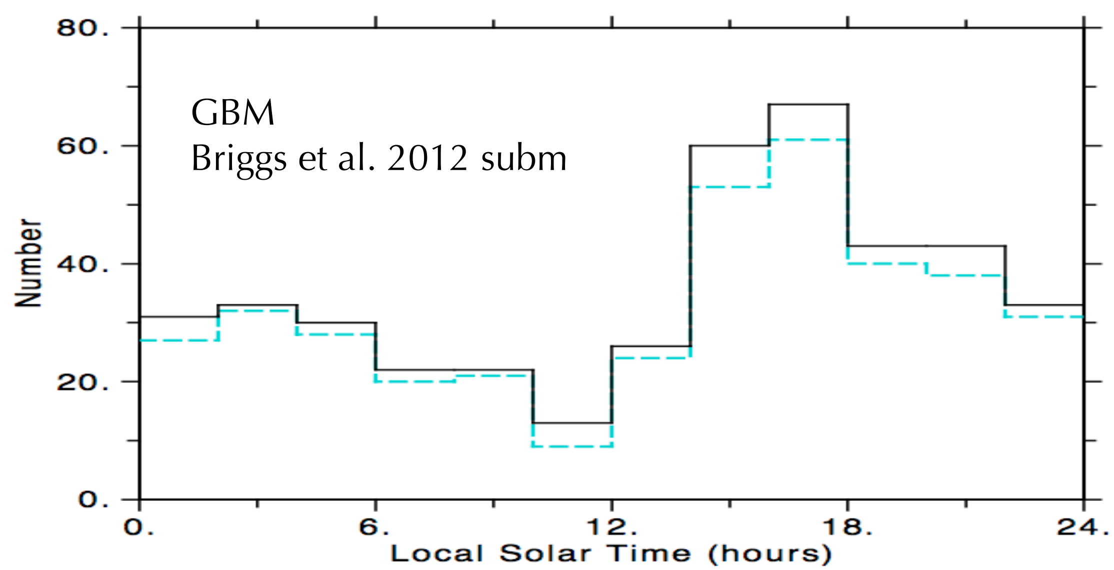


Temporal distributions

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

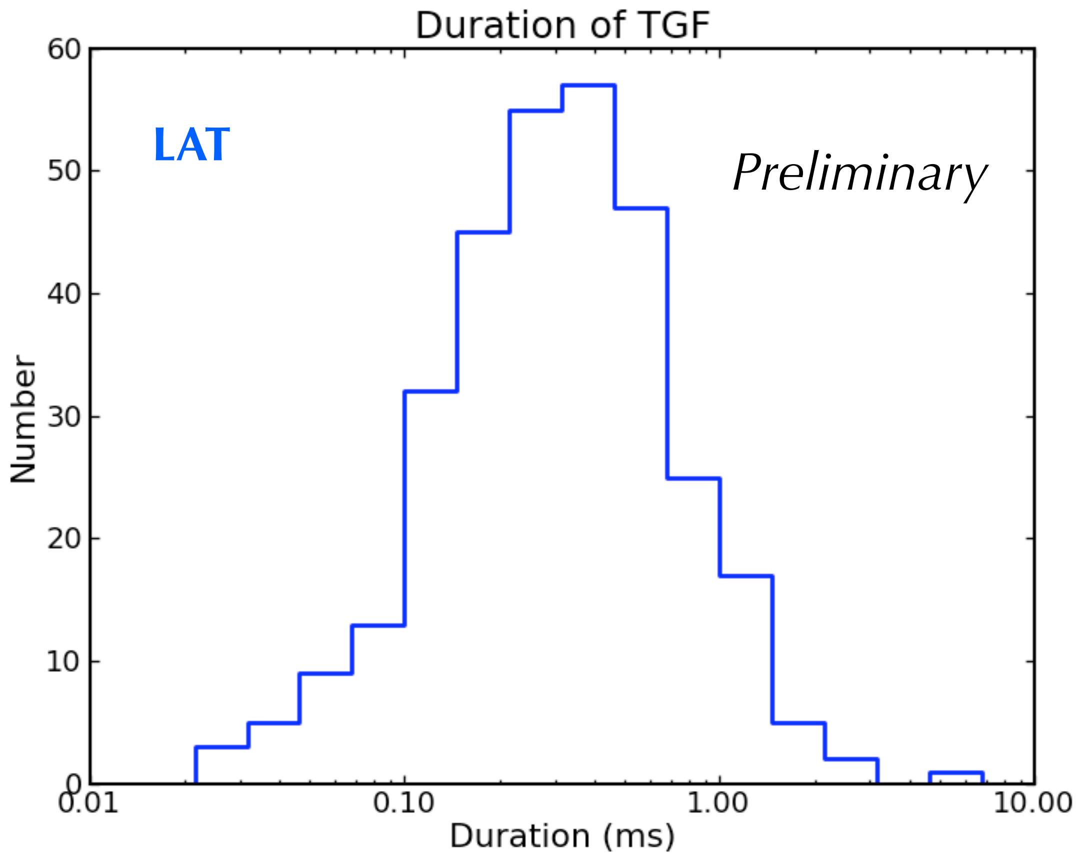
- Consistent with known TGF behavior
  - BATSE, RHESSI, GBM

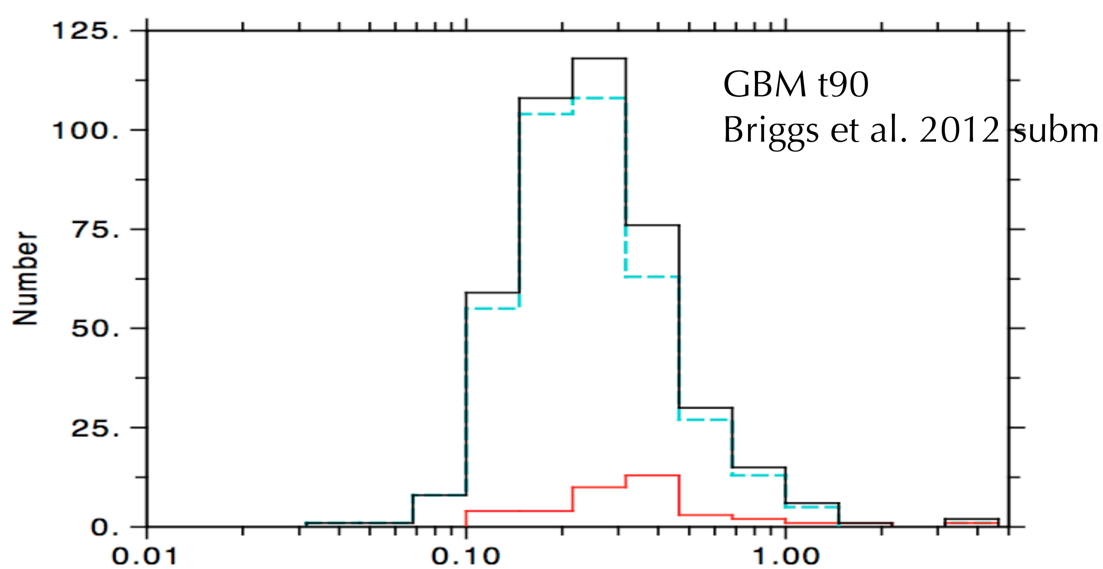




TGF durations

- **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





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
- TGF duration, temporal variation and geographical location (from satellite position) match current knowledge
- Spectral measurements in progress

Backup slides

Acknowledgements

- We wish to thank the World Wide Lightning Location Network (http://wwlln.net), a collaboration among over 50 universities and institutions, and the Earth Networks Total Lightning Network (http://earthnetworks.com/Products/TotalLightningNetwork.aspx) for providing the lightning location data

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- This work was performed at NRL under sponsorship by NASA DPR S-15633-Y.

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