Terrestrial Gamma-Ray Flashes

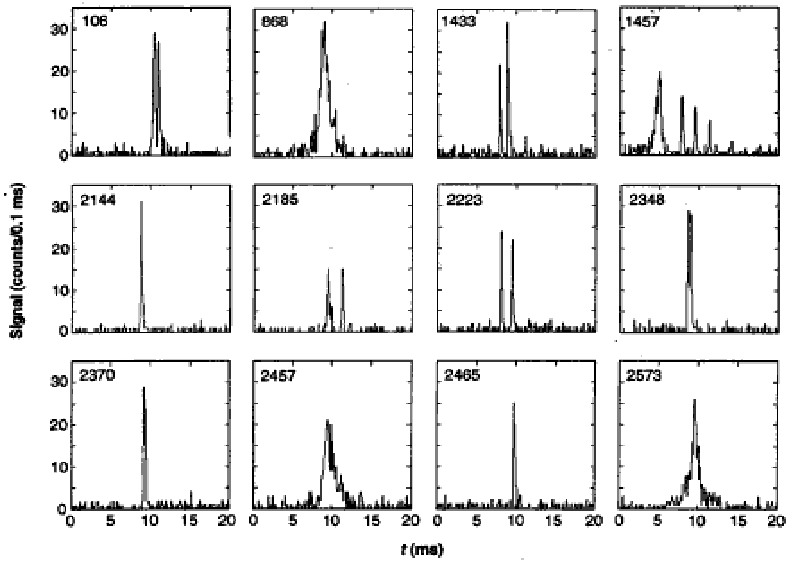
M.Tavani

(INAF and Univ. of Rome Tor Vergata)

TGFs from space: discovered by CGRO-BATSE

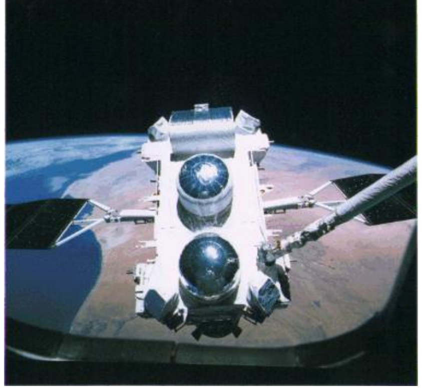
BATSE (1991-2000)
76 TGFs in 9 years
4 energy channels.
(Fishman et al., *Science,* 1994)

COMPTON Gamma-Ray Observatory



Observations of TGFs from Four Spacecraft:

1. Burst and Transient Source Experiment (BATSE) / Compton Observatory (CGRO) 1991-2000

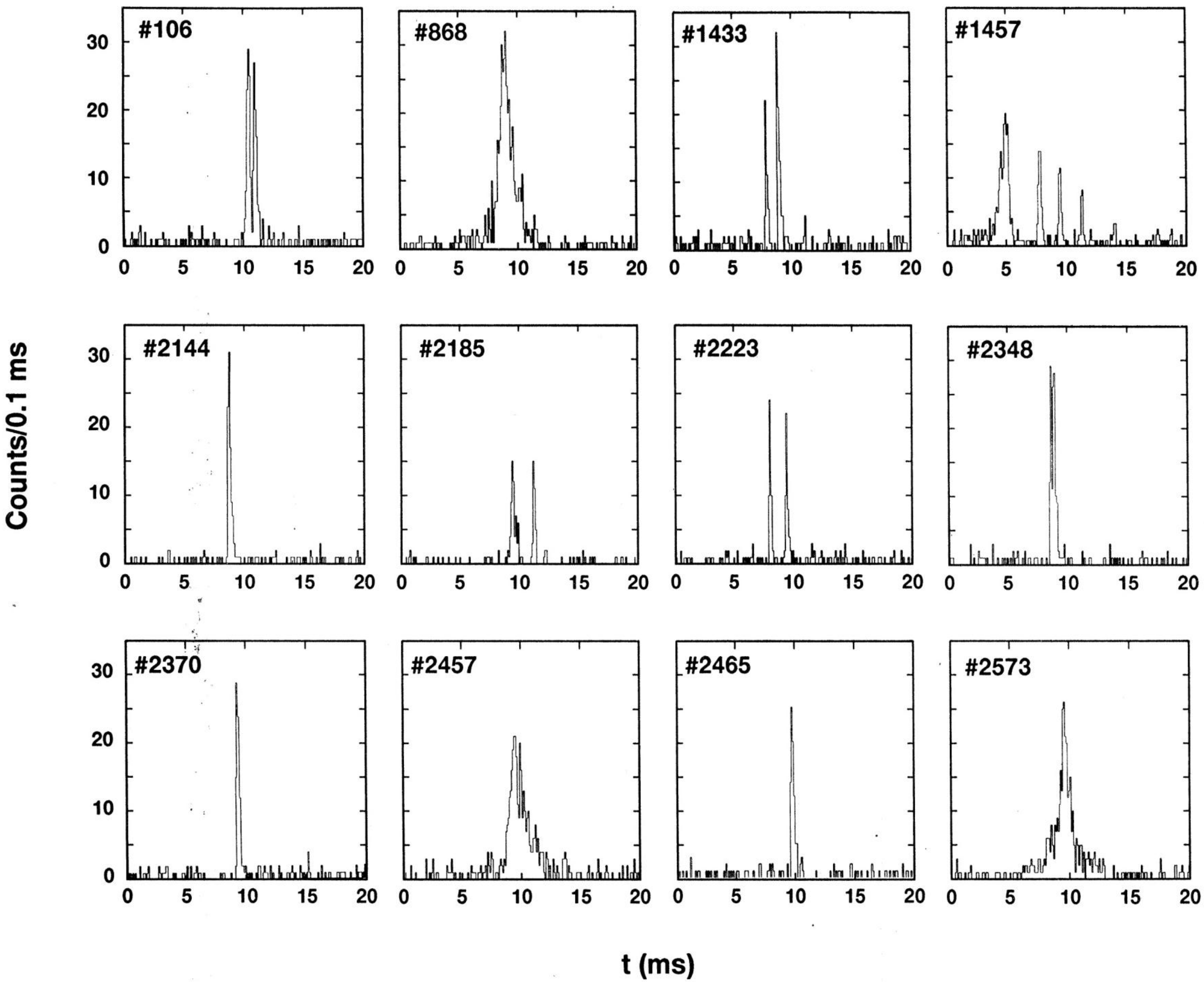


2. Ramaty High Energy Solar Spectroscopic Imager (RHESSI) (launched Feb. 12, 2002)

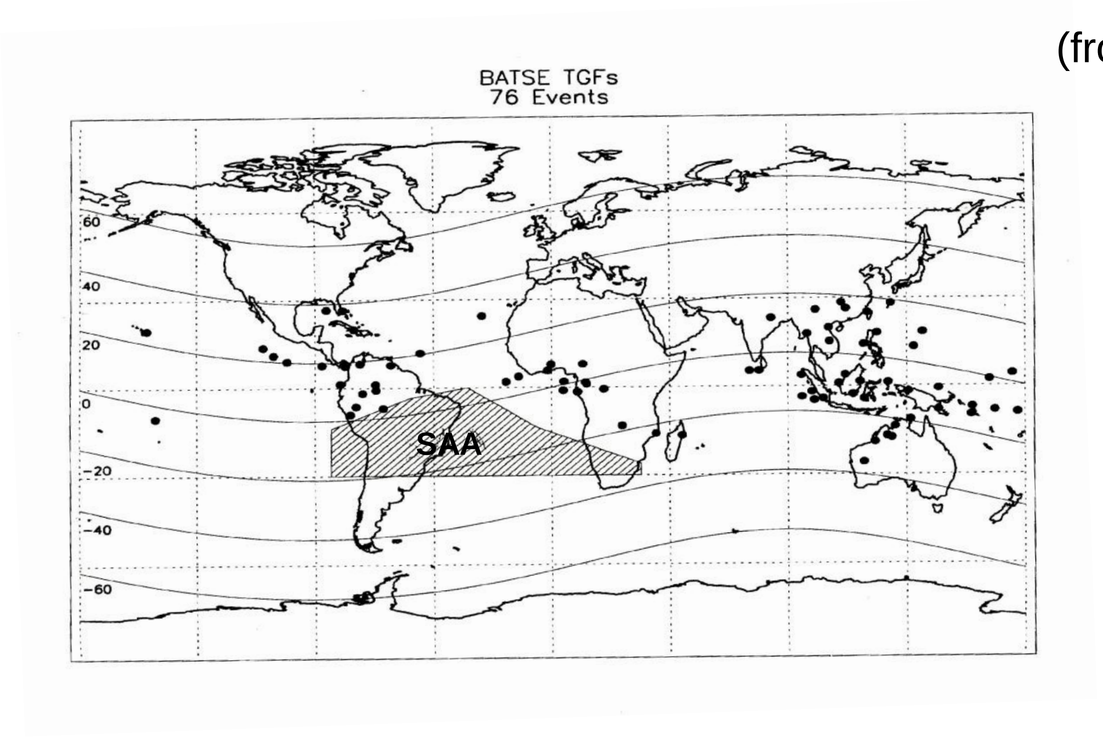
3. MCAL and GRID on AGILE (launched Apr. 23, 2007)

4. Gamma-ray Burst Monitor (GBM) on the *Fermi* Gamma-ray Space Observatory (launched June 5, 2008)

TGFs from BATSE (from Fishman et al., 1994)

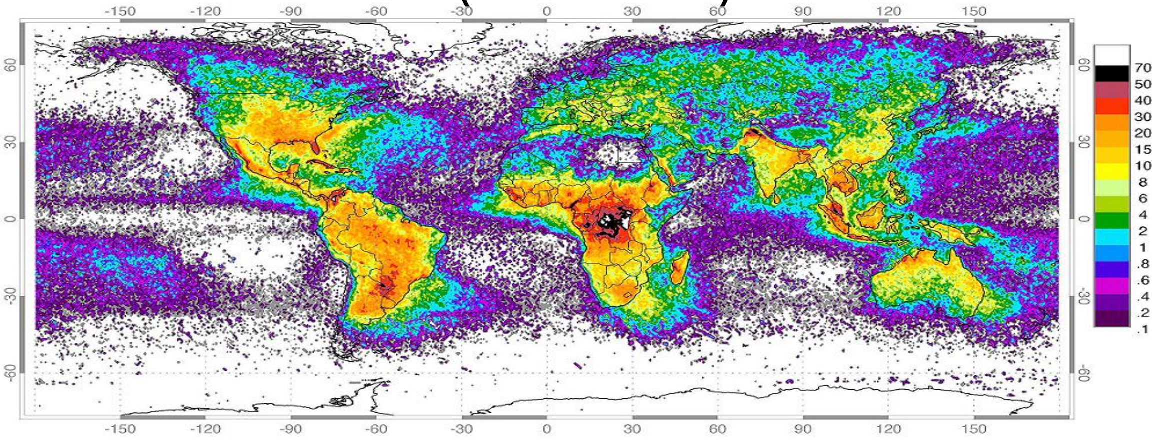


(from J. Fishman)



GLOBAL FLASH RATE - ANNUAL

(OTD & LIS DATA)



Terrestrial Gamma-ray Flashes (TGFs)

- Gamma-ray flashes with incoming direction compatible with the Earth surface. Discovered by BATSE (Fishman et al., Science, 1994) .

- Few millisecond typical duration; hard spectrum (up to tens MeV)

- Detected by RHESSI up to 20 MeV (Smith et al., Science, 2005)

- Clearly associated to lightning discharges during thunderstorms by means of correlation with VLF sferic waves detection on ground (Inan et al., GRL, 1996; Cummer et al., GRL, 2005)

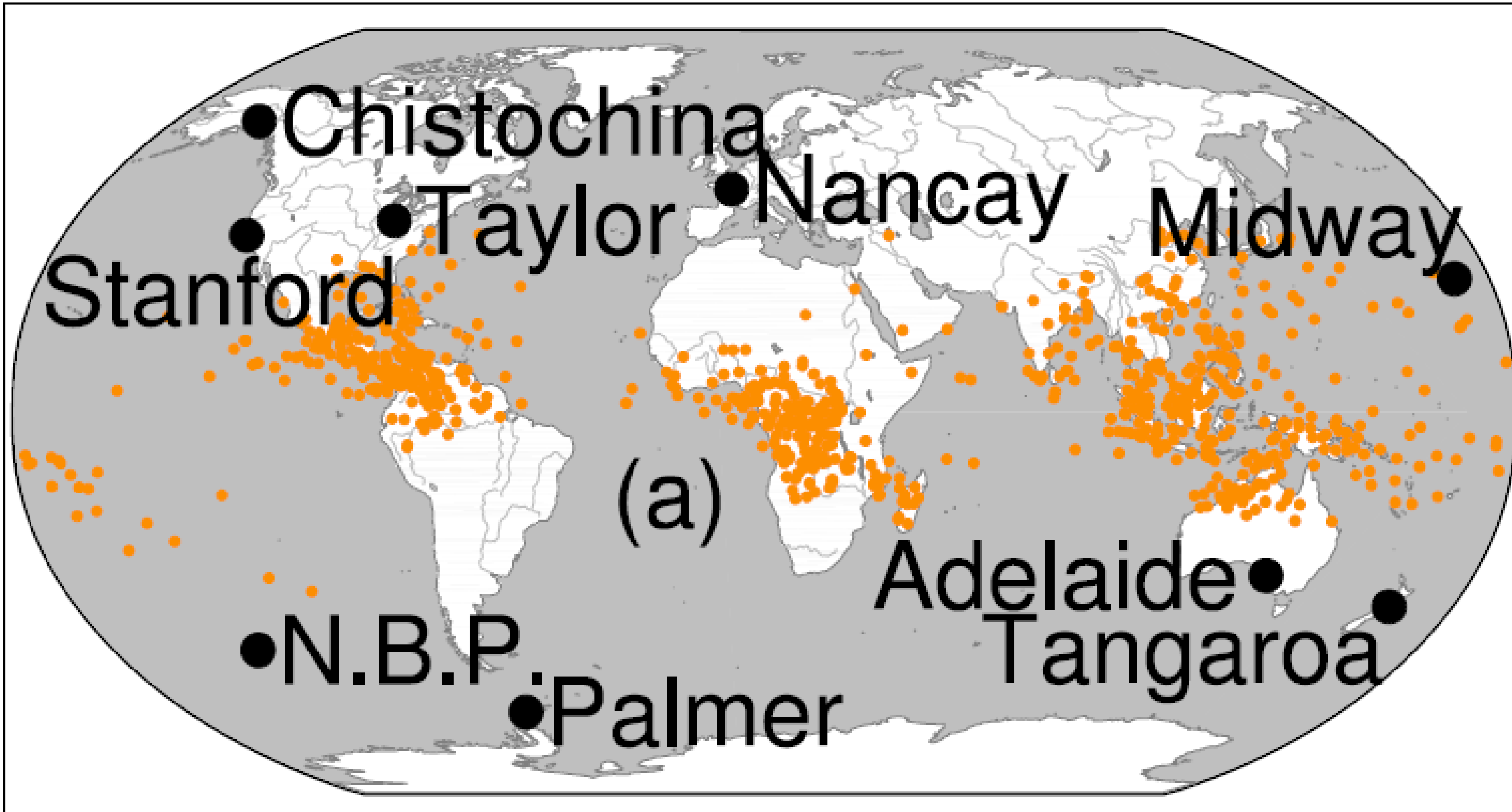
Terrestrial Gamma-ray Flashes (TGFs)

Geophysical phenomena observed from space by instruments designed for gamma-ray astrophysics

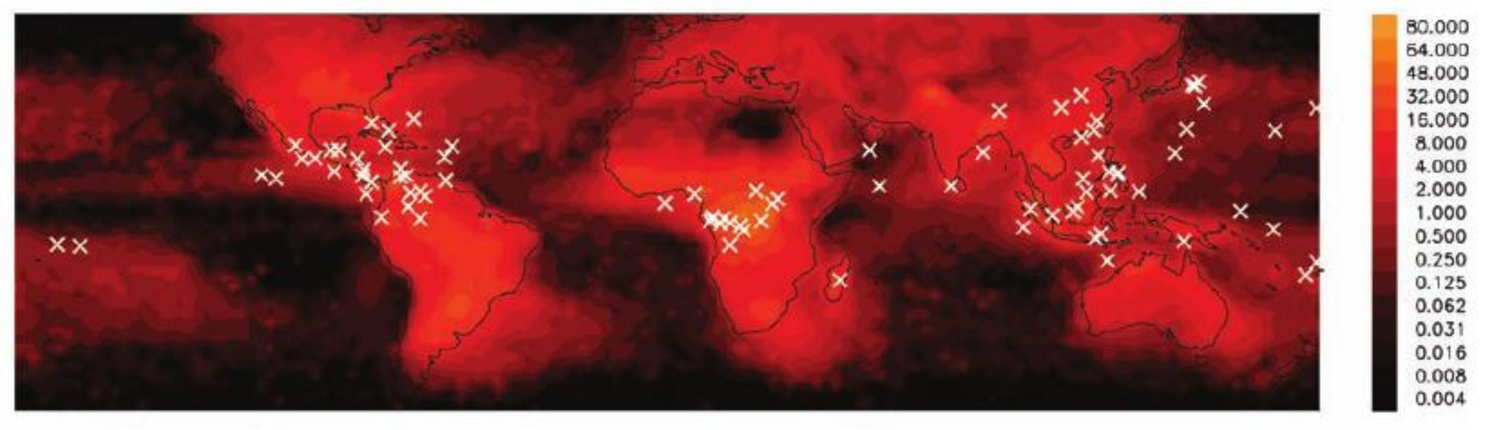
Challenging detection:

timing and energy range are key issues

TGFs detected by RHESSI (Cohen et al. 2010)

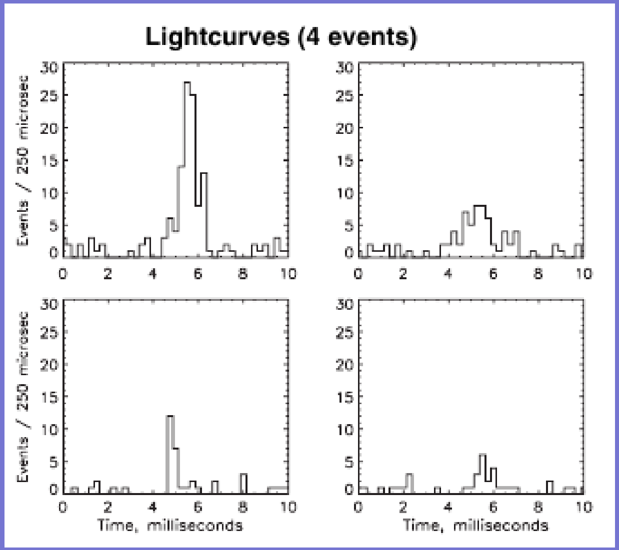


2005: RHESSI detection up to 20 MeV

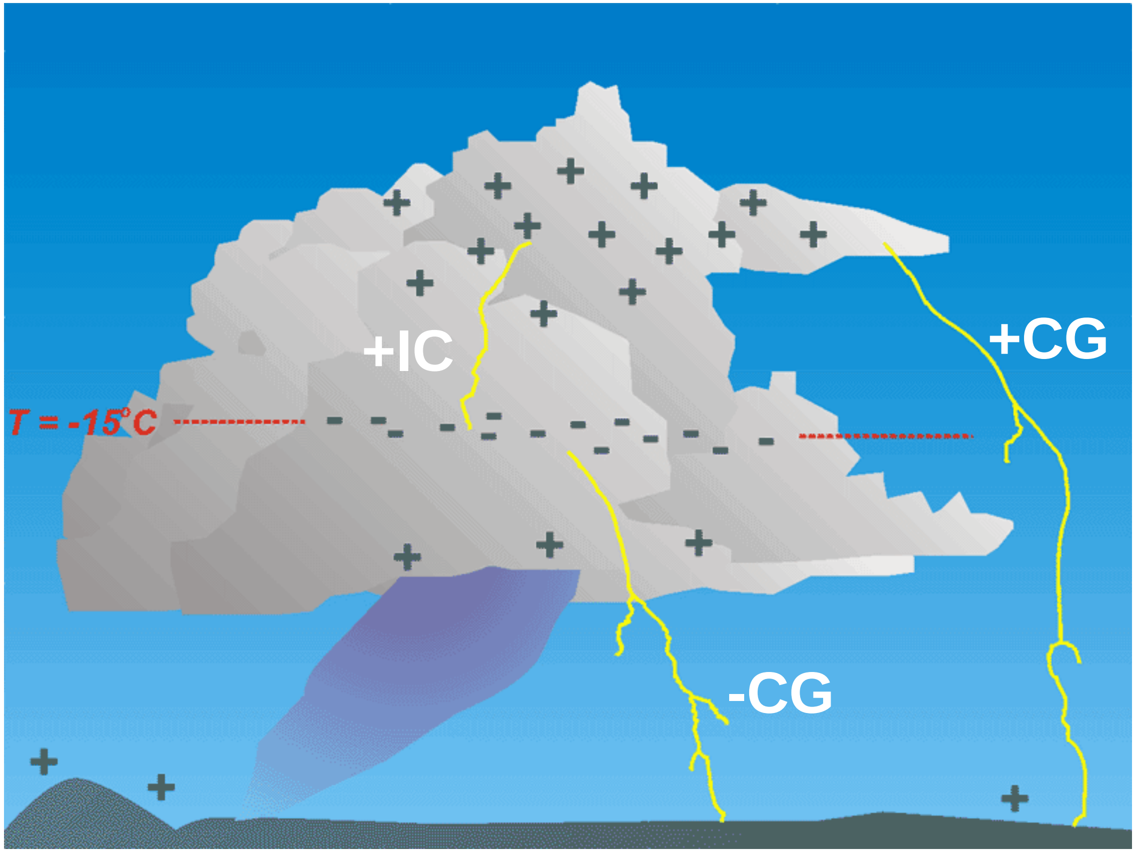


TGF Distribution with lighting frequency per km^2 per Year

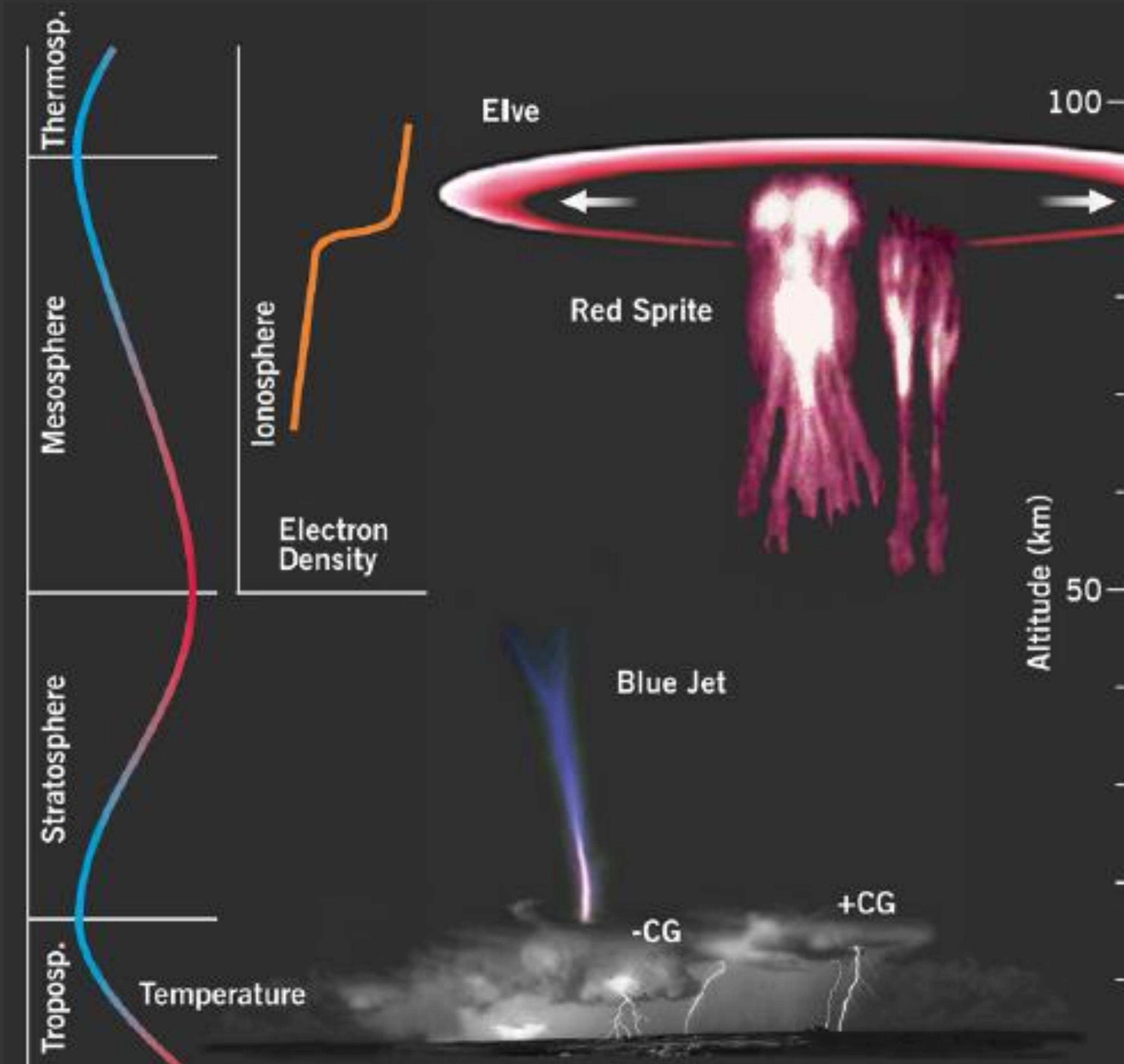
Smith et al., Science, 2005



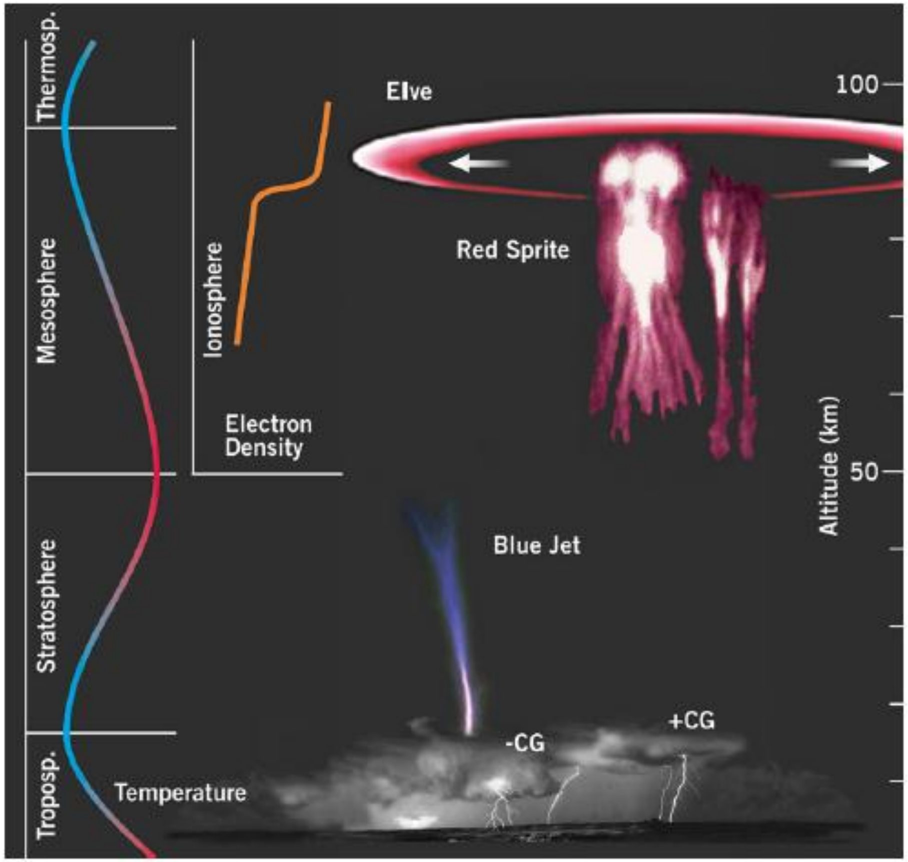
- **Contiuous time-tagged event list**
- **NO ON-BOARD TRIGGER LOGIC**
- **10– 20 TGF per month**
- **Typically 20-30 counts/TGF**
- **~800 TGFs reported in the 1st RHESSI TGF catalog (Grefenstette et al., JGR, 2009)**



Graphic: Canadian Forest Service

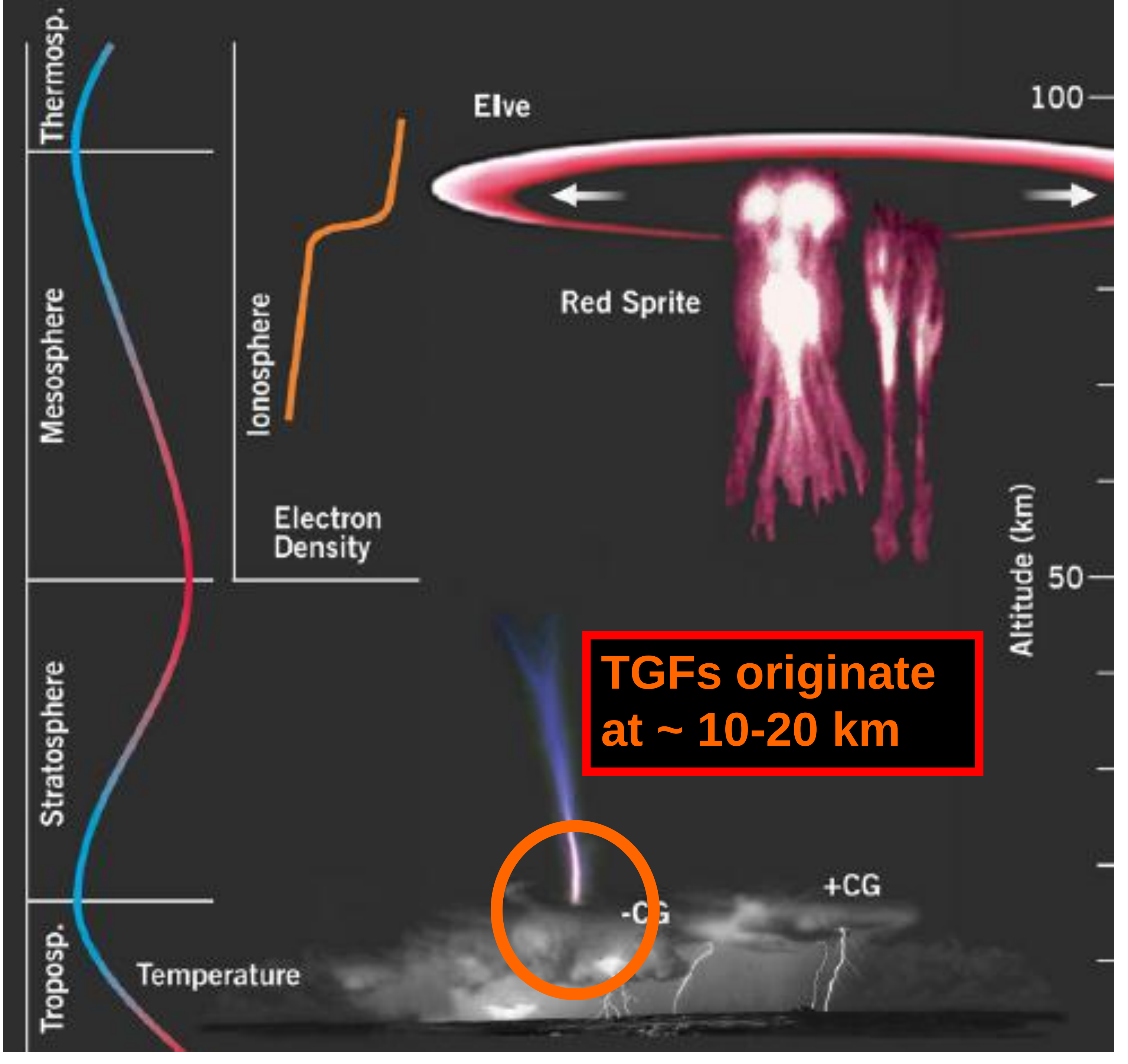


Thermosp.
Mesosphere
Stratosphere
Troposp.
Temperature
Ionosphere
Electron
Density
Elve
Red Sprite
Blue Jet
-CG
+CG
100
50
Altitude (km)



[Neurbert 2003]

- Sprites:
  - Flashes in the mesosphere
  - 10-100 ms duration
  - Generated from +CG
  - Primarily red
- Jets:
  - Injected from cloud tops
  - 100-1000 ms duration
  - Generated with or without CG activity
  - Primarily blue
- Elves
  - Rings of emissions at lower edge of the ionosphere
  - 1-10 ms duration
  - Stimulated by electromagnetic pulse from lightning
  - Primarily red

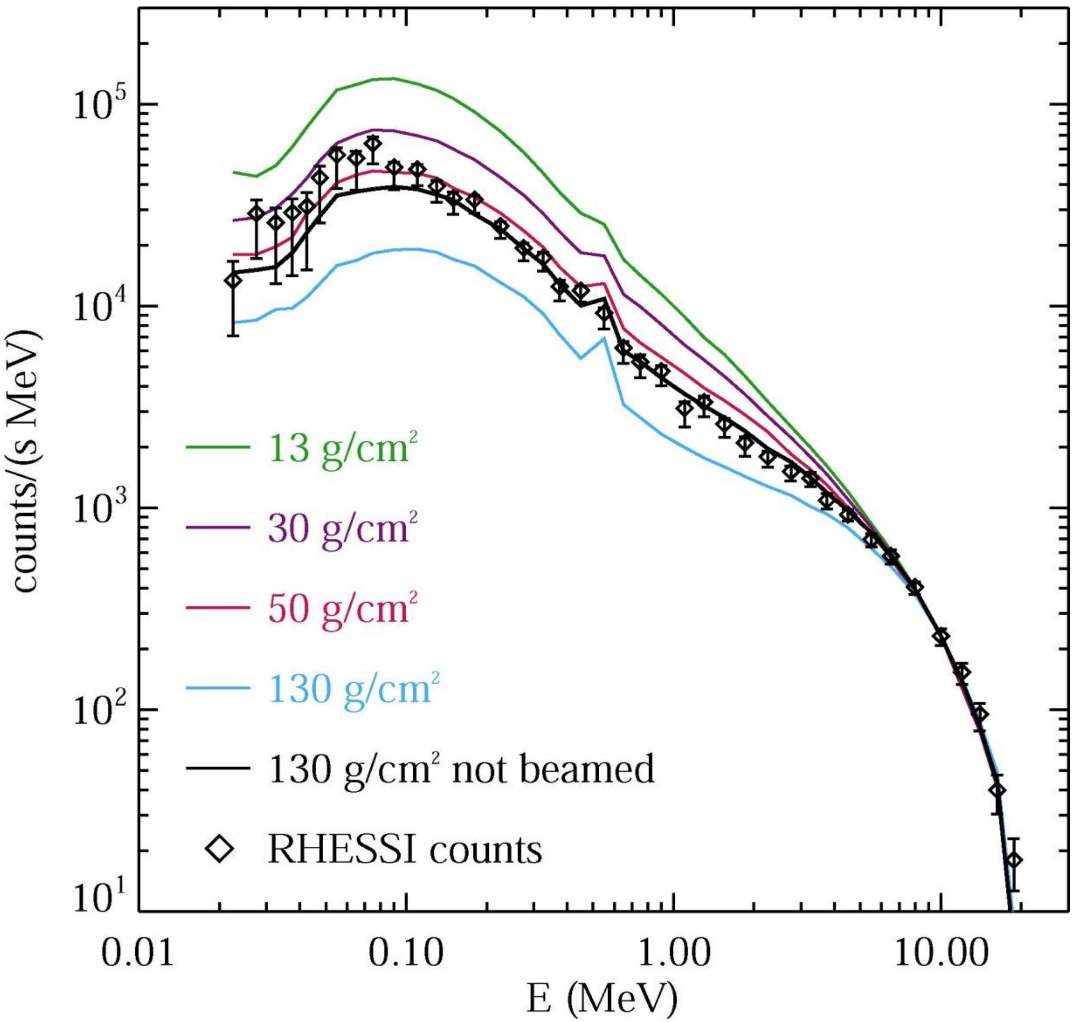


Thermosp.
Mesosphere
Stratosphere
Troposp.
Temperature
Ionosphere
Electron Density
Elve
Red Sprite
100
50
Altitude (km)
TGFs originate at ~ 10-20 km
-CG
+CG

RHESSI TGF Bremsstrahlung spectrum

absorbed Relativistic Runaway electron spectrum

(Dwyer & Smith 2008)

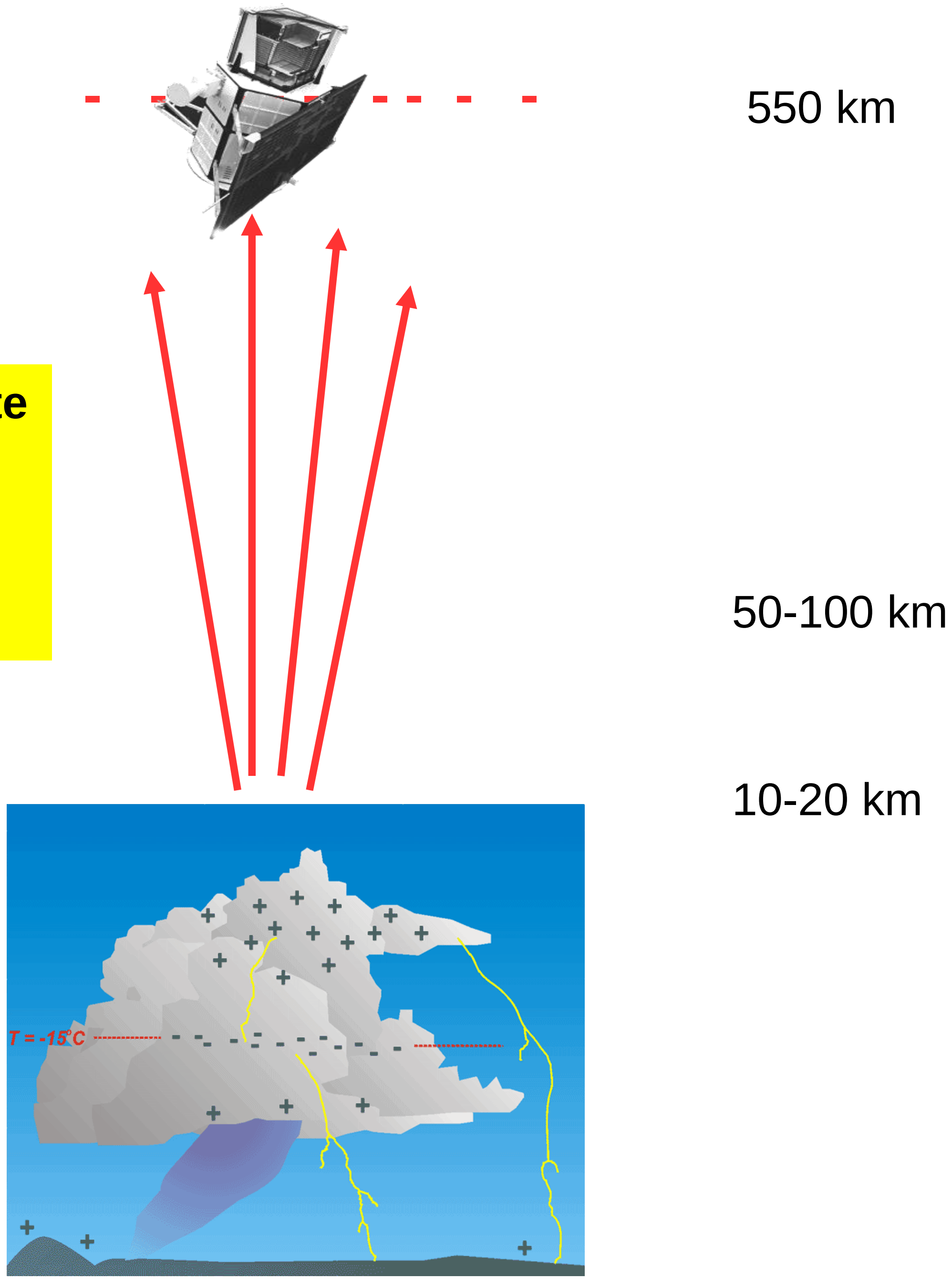


Flattening of spectrum @ 1 MeV requires production altitude **10-20 km**: near tropical tropopause (just above thunderclouds)

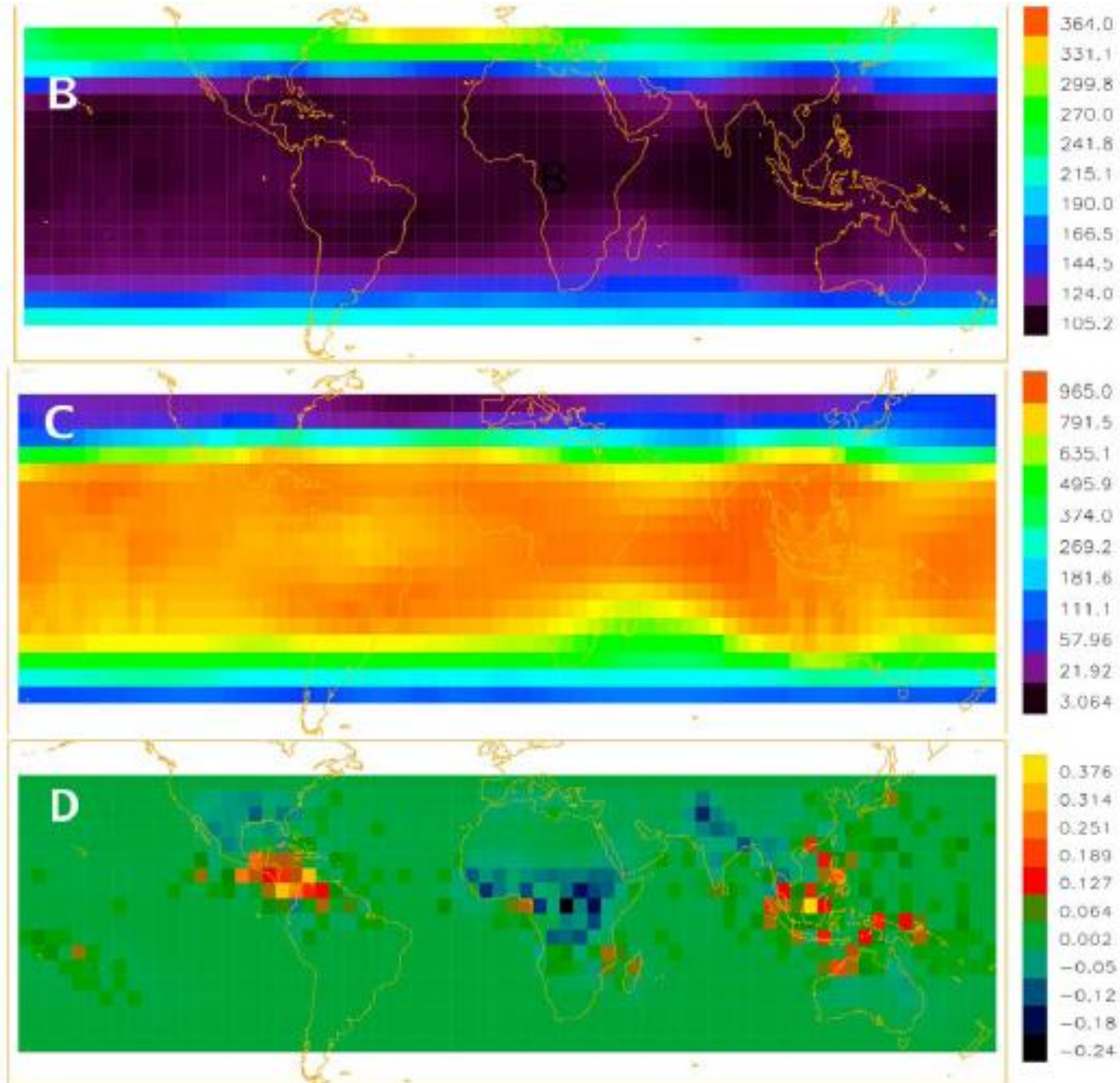
Dwyer & Smith 2005
Carlson, Lehtinen and Inan 2007

not easy to propagate up to 550 km

selection effects important



(from D.Smith et al., 2010)



NCEP/NCAR tropopause height map, January, overlying air mass (in g/cm^2)

Gamma-ray transmission map based on tropopause height data (MC)

Difference between HESSI TGF map and transmission-corrected map

(from D.Smith et al., 2010)

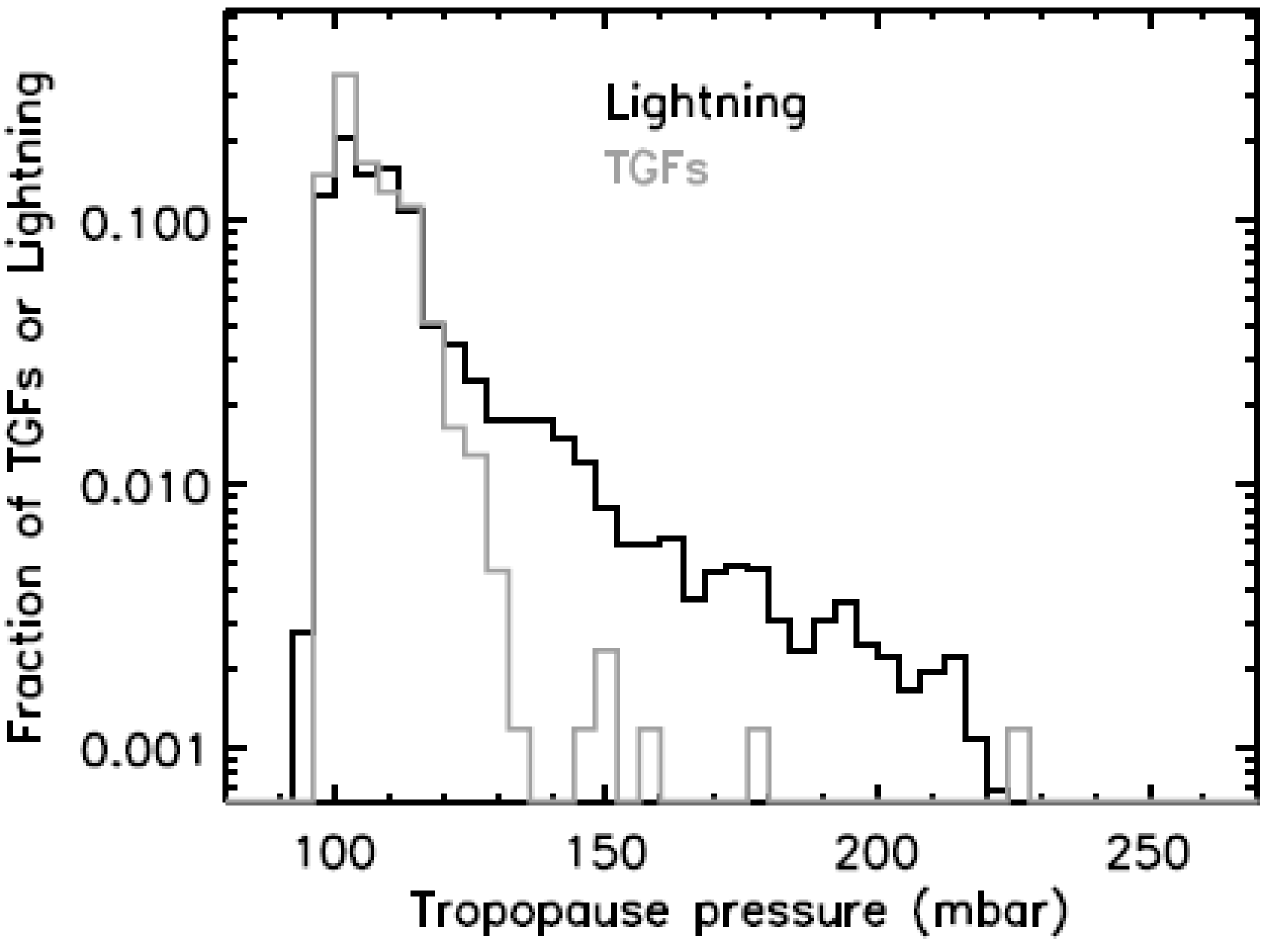


Figure 9. Histograms of tropopause pressure (mbar) for TGFs (gray) and lightning (black), showing the preference of TGFs for high altitudes.

(from D.Smith et al., 2010)

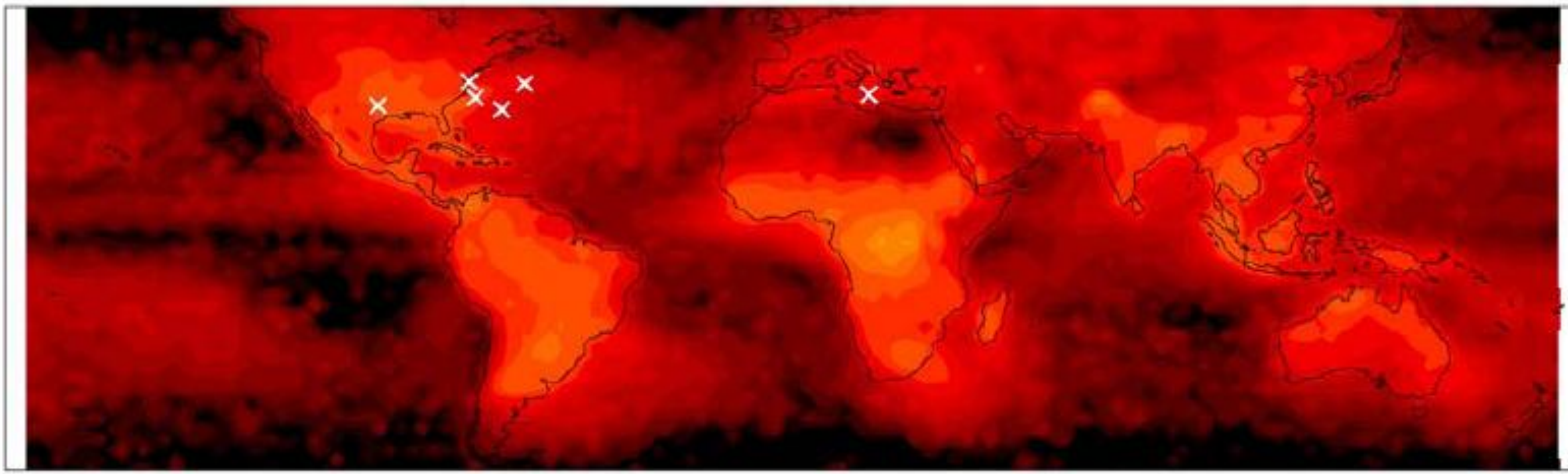


Figure 10. Position of the six TGFs with tropopause pressures >140 mbar; see Figure 5. The brightness scale beneath is another rendering of the LIS/OTD map (Figure 4a).

Mechanisms of air breakdown (decreasing E) (Smith 2008):

Cold runaway

Any e- goes relativistic

Conventional (Townsend)

Ionization > attachment

Streamer

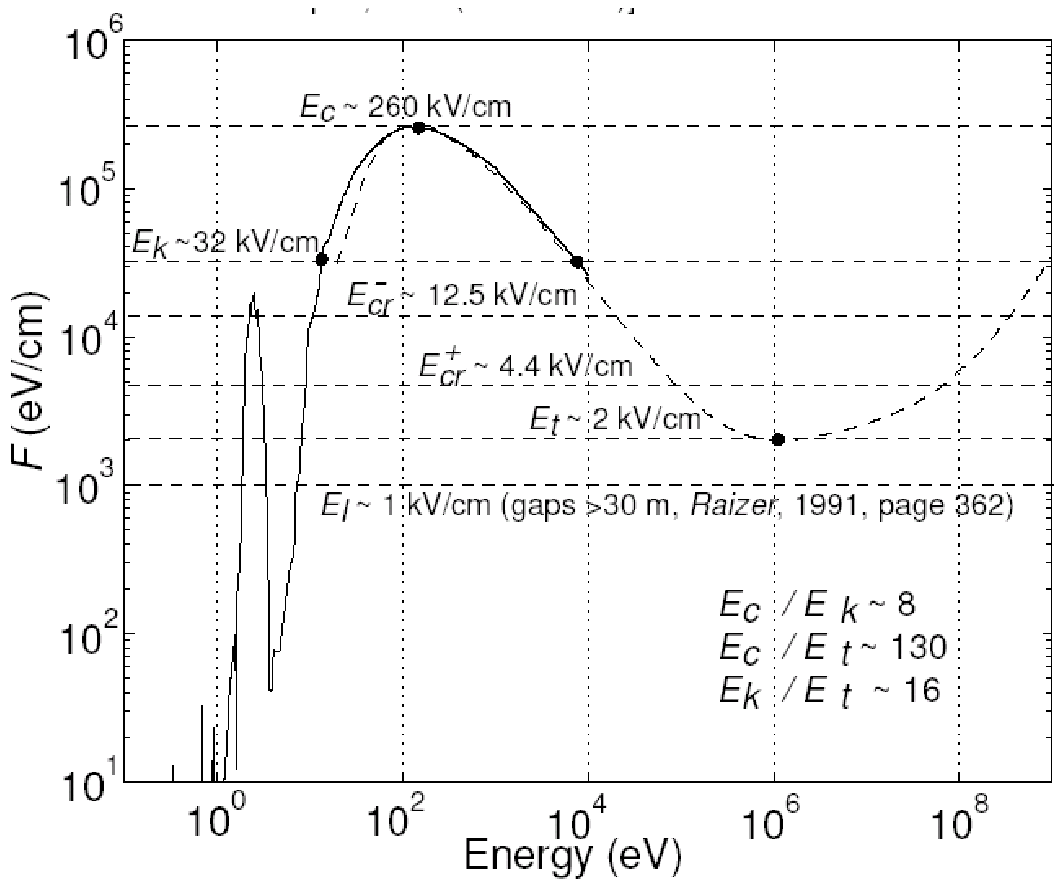
Self-propagating

RREA (Relativistic Runaway Electron Avalance)

Rel. seed electron(s)

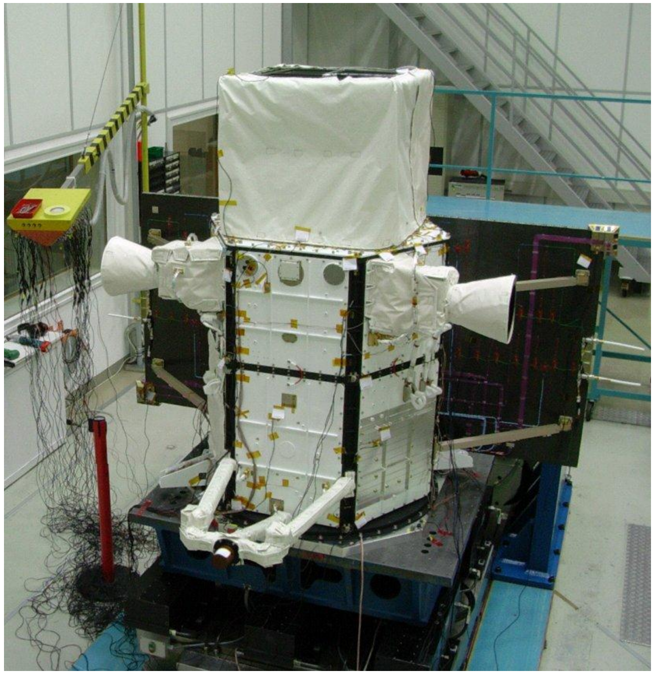
Leader

Thermal ionization



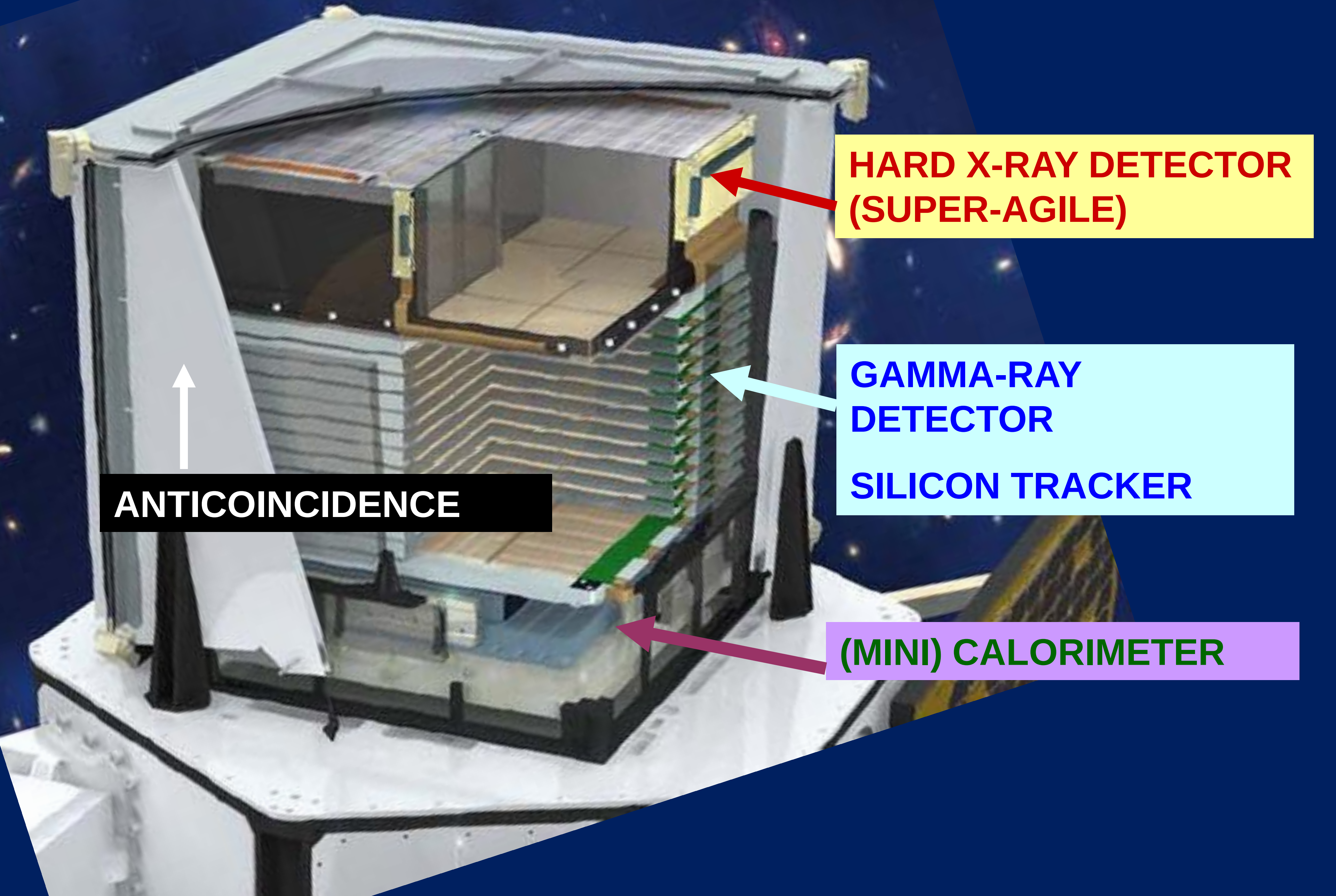
Frictional force produced by the motion of electrons through air.

what makes AGILE unique for TGFs:

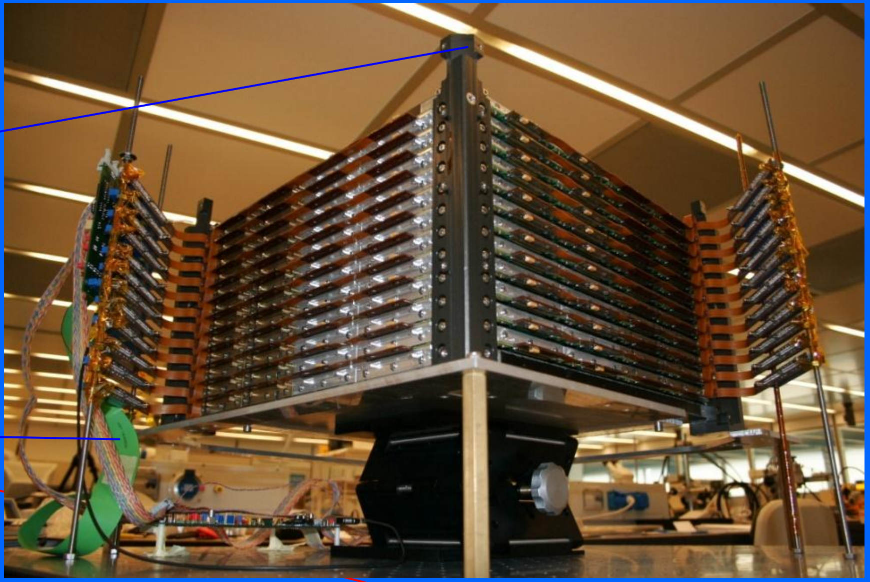


- Only instrument in equatorial orbit
  - low-background
- Only instrument with sub-msec trigger capability
- Instrument with the best capability at E > 30-40 MeV

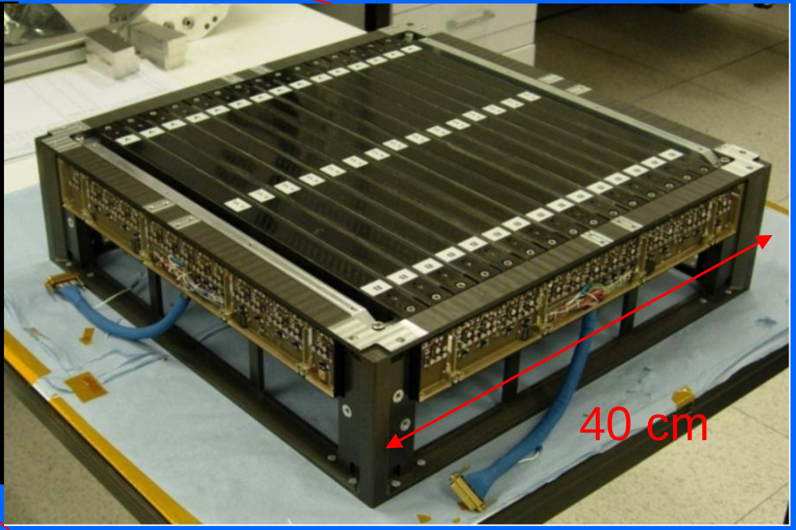
AGILE: inside the cube…



The AGILE payload

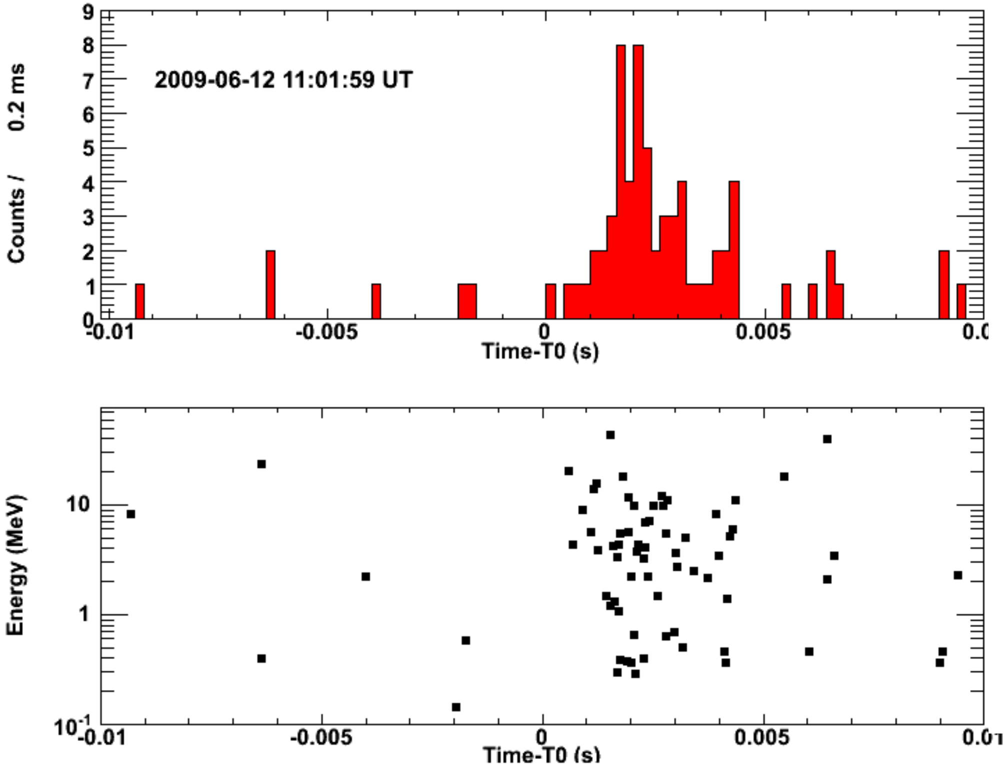


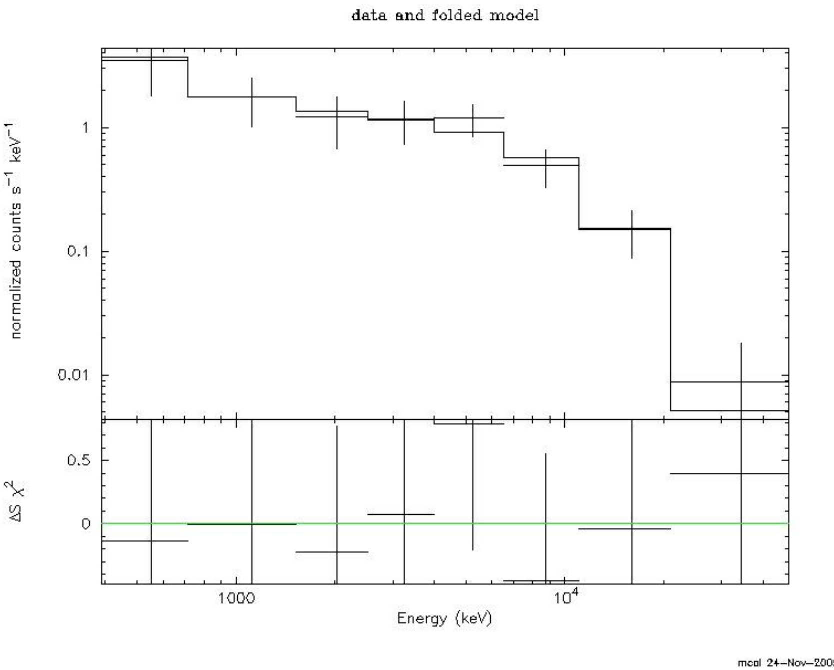
30 CsI(Tl) bars with Photodiode readout
1400 cm^2 geometrical area
~300 cm^2 effective area @ 1 MeV
330 keV – 100 MeV energy range
14% energy resolution FWHM @ 1.3 MeV
2 μs timing accuracy in photon-by-photon mode
Clever, fully-programmable trigger logic on time scales from 8s to <u>16ms, 1ms and 300μs</u>



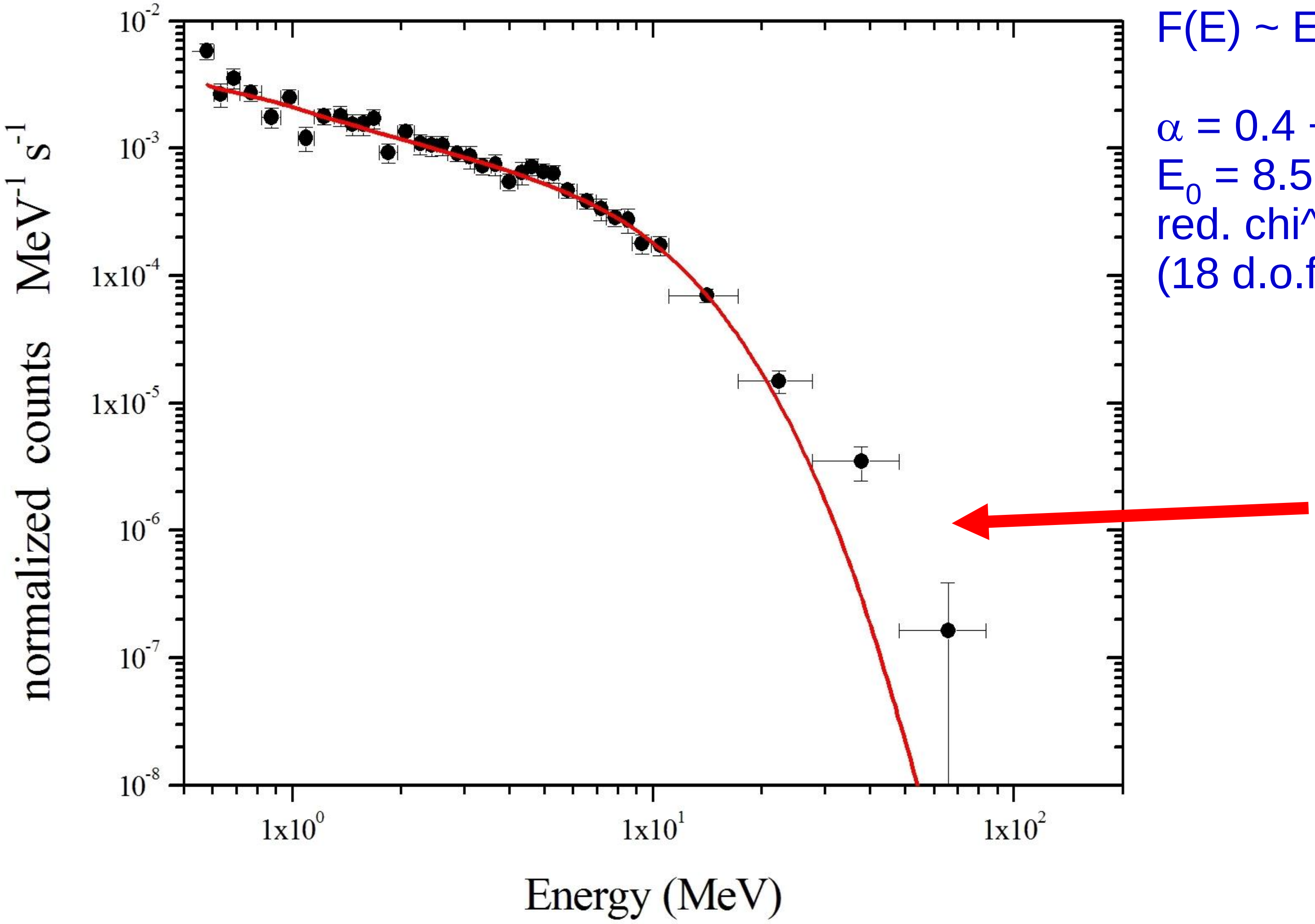
Labanti et al., NIM A (2009): instrument paper
Fuschino et al., NIM A (2008): trigger logic
Marisaldi et al., A&A (2008): GRB detections
Marisaldi et al., JGR (2010): TGF detections

Example of a TGF detected by AGILE





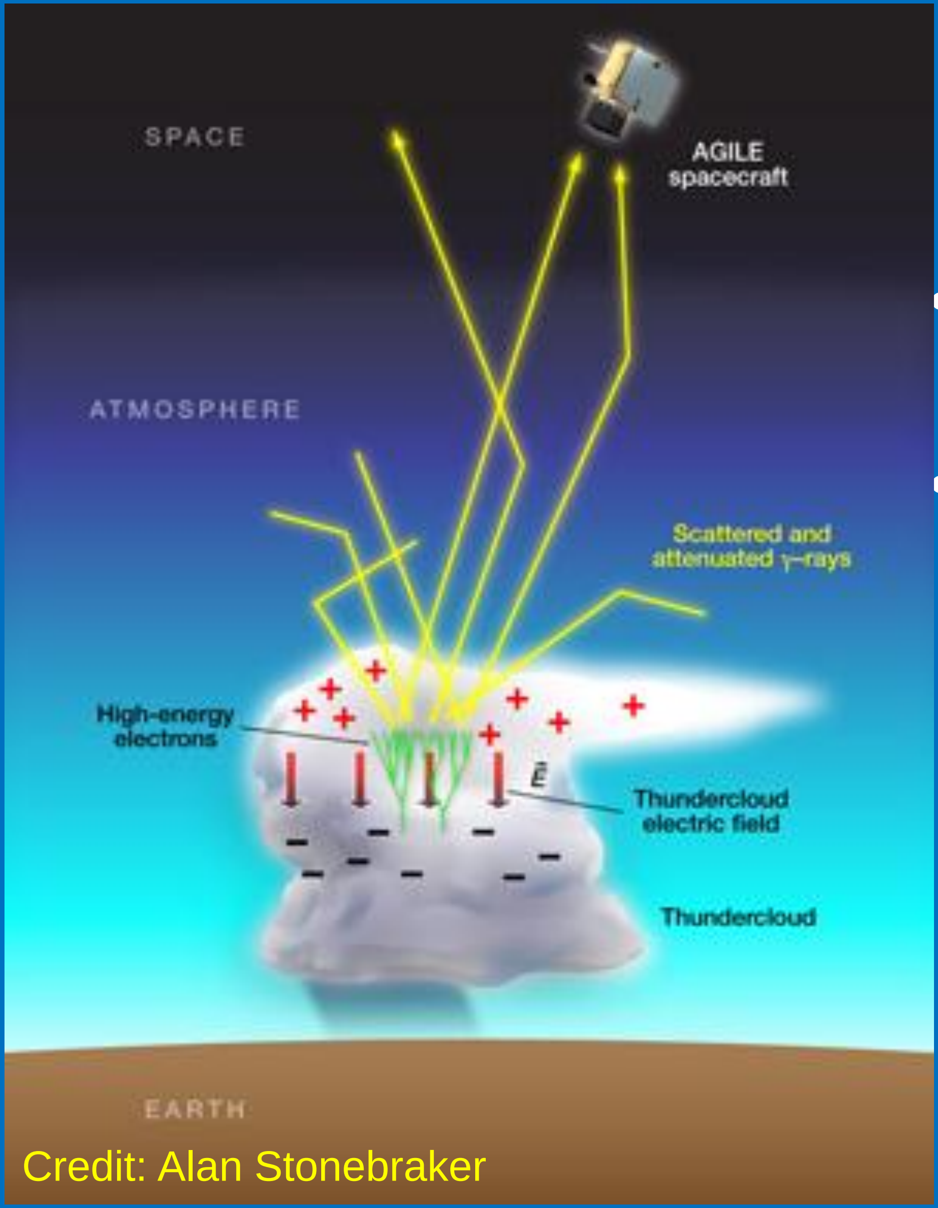
(early) AGILE/MCAL TGF cumulative spectrum (2009)



cutoff PL model

$F(E) \sim E^{-\alpha} e^{-E/E0}$

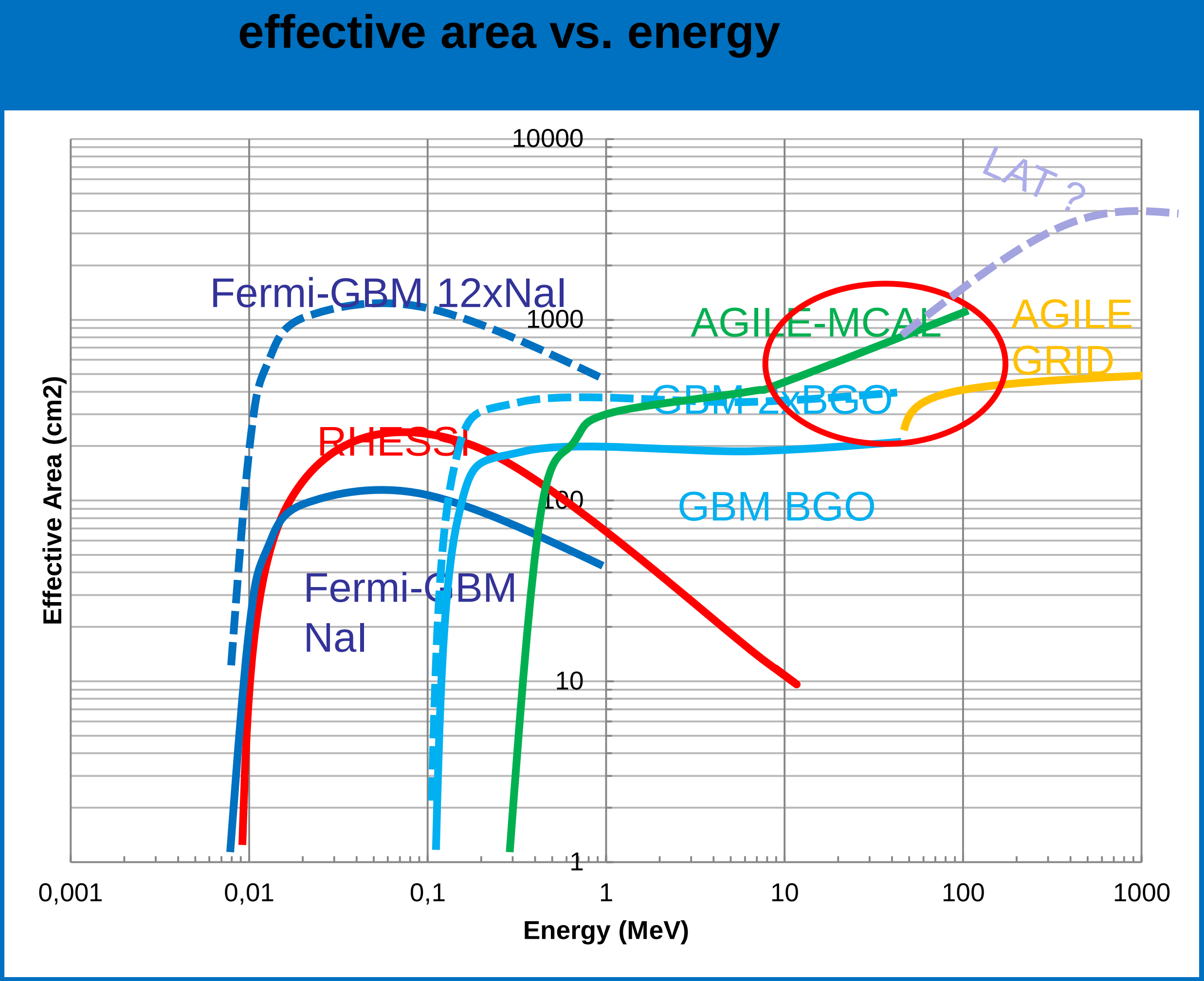
α = 0.4 +/- 0.3
E_0 = 8.5 +/- 1.6 MeV
red. chi^2 = 1.4
(18 d.o.f.)



AGILE high energy results:

- Localization of TGFs in gamma-rays from space
- High energy spectrum

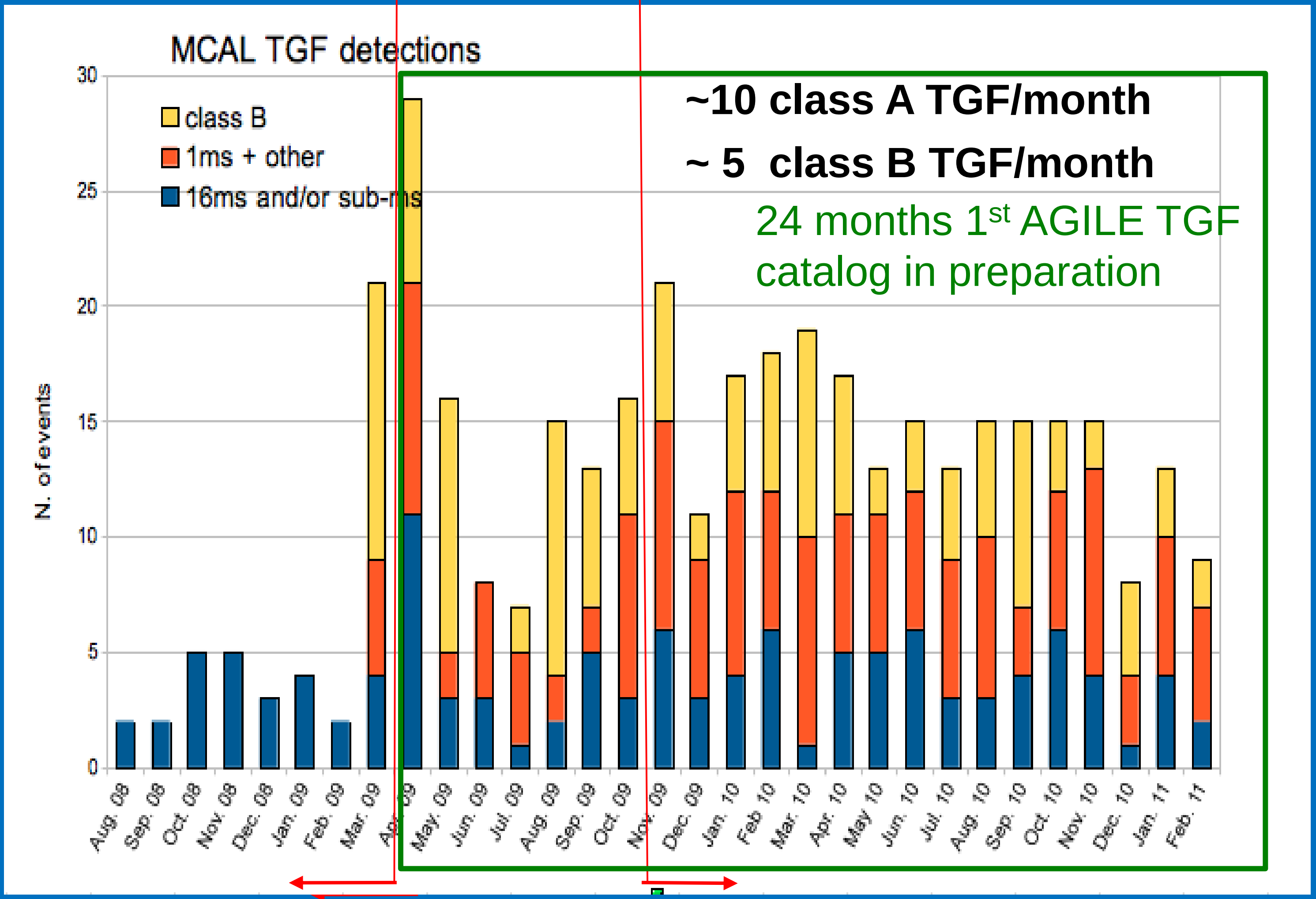
Operating TGF detectors



Data from: Smith et al. (2002), Meegan et al. (2009), Labanti et al. (2009), Tavani et al. (2009)

MCAL TGF detection rate

> 300 class A TGFs + ~200 class B TGFs since June2008



34 TGFs Published in M. Marisaldi et al., J. Geoph. Res., 115, A00E13, 2010.

entering spinning mode

- **AGILE special trigger capability**
- **MCAL burst search from sub-ms to seconds**
  - **TGFs detected by the trigger logic working in the timescale range 0.3 ms < τ < 16 ms**

***** about 600 TGFs detected since 2009**

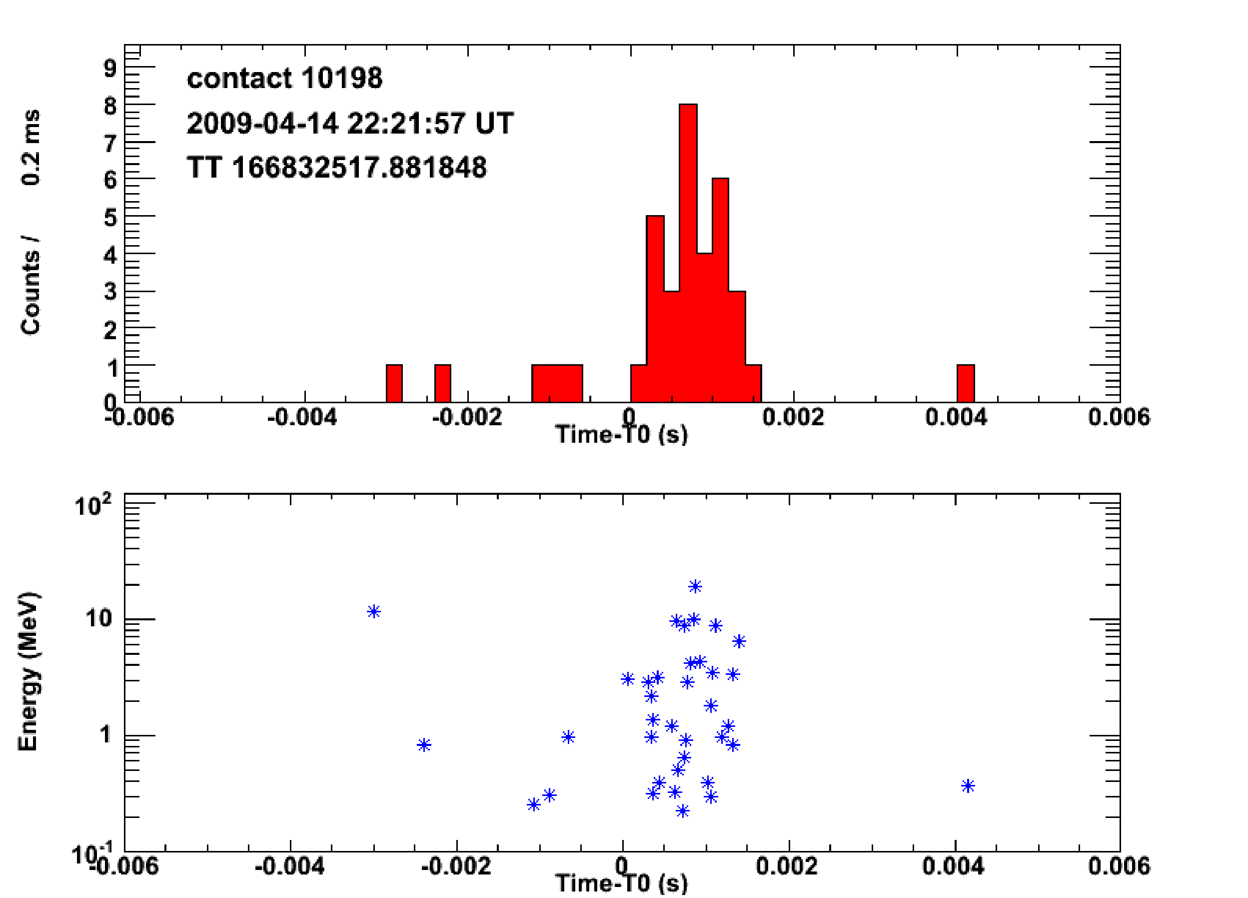
***** about 300 are with good S/N ratio**

energy range 0.4 – 100 MeV

a number of issues

- high-energy range above 30-40 MeV
- discovery in 2010 of a substantial power-law contribution to the spectrum above 40 MeV
  - origin ???
  - what kind of TGFs ?
  - what is the largest photon energy emitted by TGFs ?
  - impact of HE-TGFs

The AGILE TGF sample



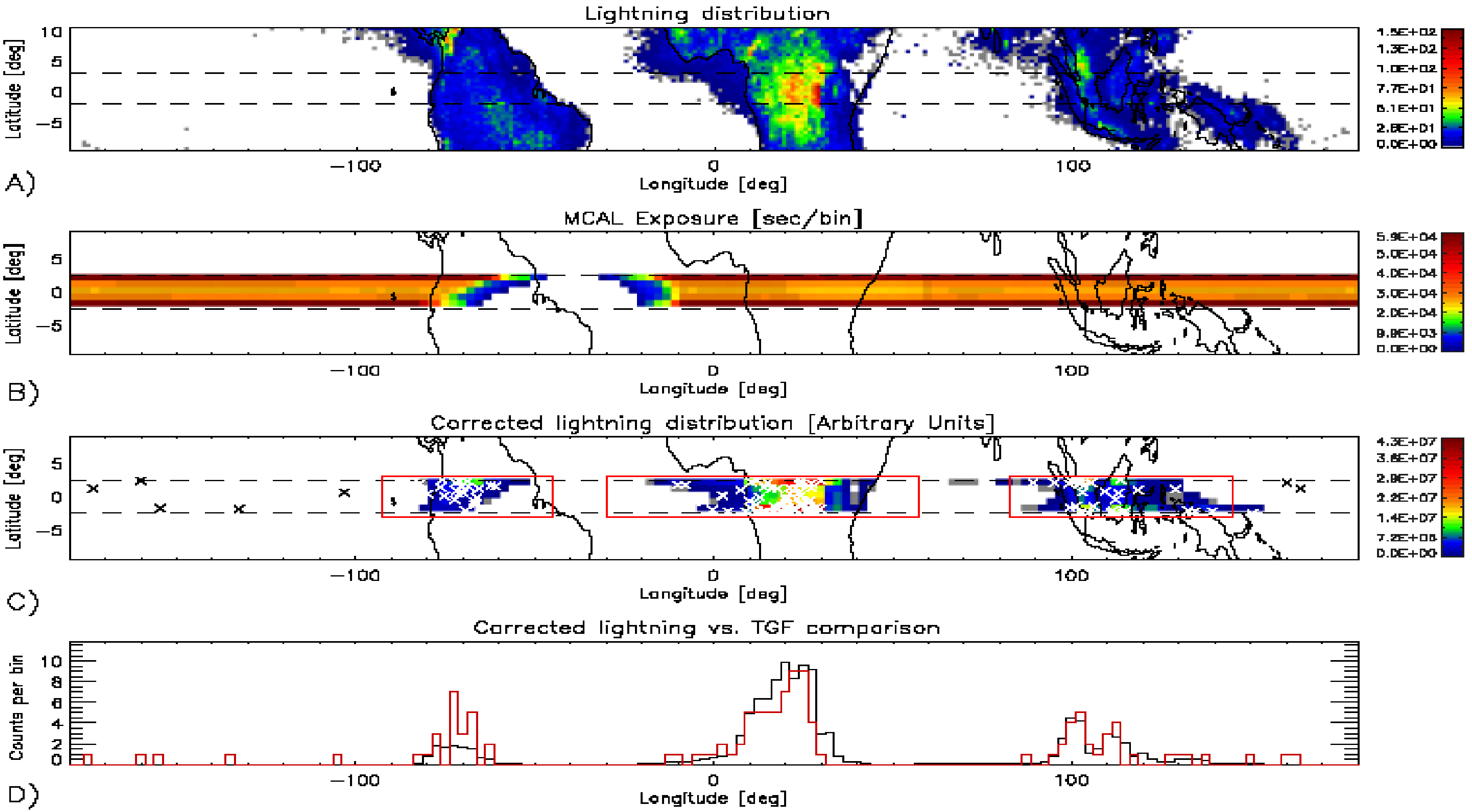
Average properties A AND B class:

Number of counts = 14 +/- 9

Duration (= (0.8 +/- 0.4) ms

Energy = (4.0 +/- 1.7) MeV

TGF-lightning correlation



0.68 correlation coefficient for a global fit

F. Fuschino et al. 2011

LIS-OTD high resolution full climatology available at http://thunder.msfc.nasa.gov/

(F. Fuschino et al. 2011)

Continental region	TGF / flash ratio
America	$1.5\ 10^{-4}$
Africa	$6.0\ 10^{-5}$
South East Asia	$7.5\ 10^{-5}$
All	$7.8\ 10^{-5}$

AGILE TGF/lightning: a statistical comparison

• Assuming the spread of TGF / flash ratio holds at all latitude, and considering 44 ± 5 flash/s (Christian et al. 2003), we obtain 220 ÷ 570 TGFs / day, in agreement with Carlson et al. 2009.

Fuschino F., et al., GRL (2011)

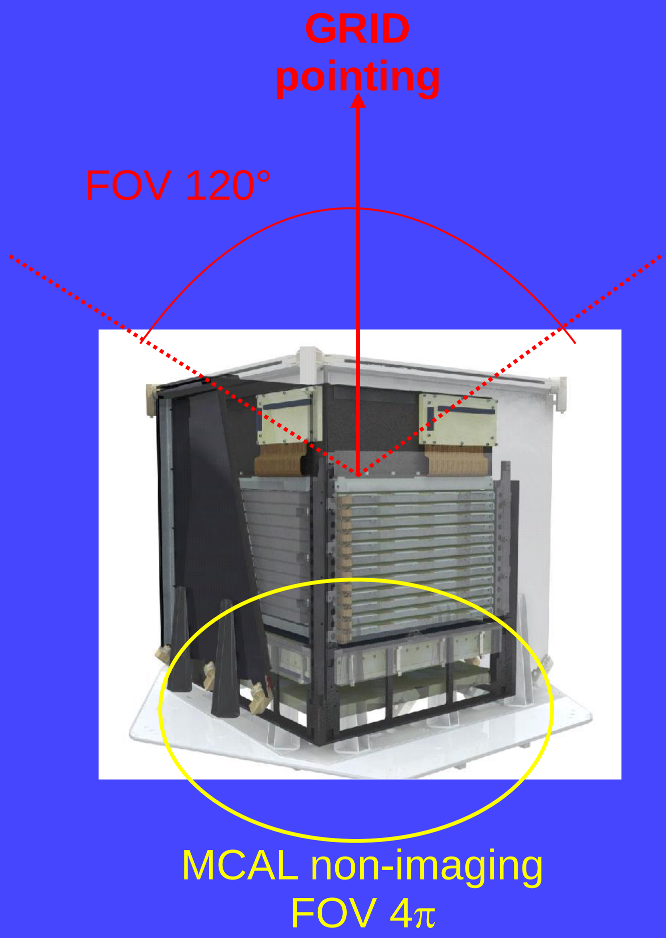
• The excess of TGFs over Central America and South East Asia with respect to Africa is confirmed (Smith et al., 2010)

• The high degree of correlation obtained for South East Asia suggests that global lightning activity over this region is by far a better proxy for TGFs than on other continental regions. Climatic effect? (Splitt et al., 2010)

• Thanks to the low inclination orbit AGILE provides the highest TGF detection rate surface density, good for seasonal/annual variability studies

Imaging TGFs from space

(Marisaldi et al. 2010)

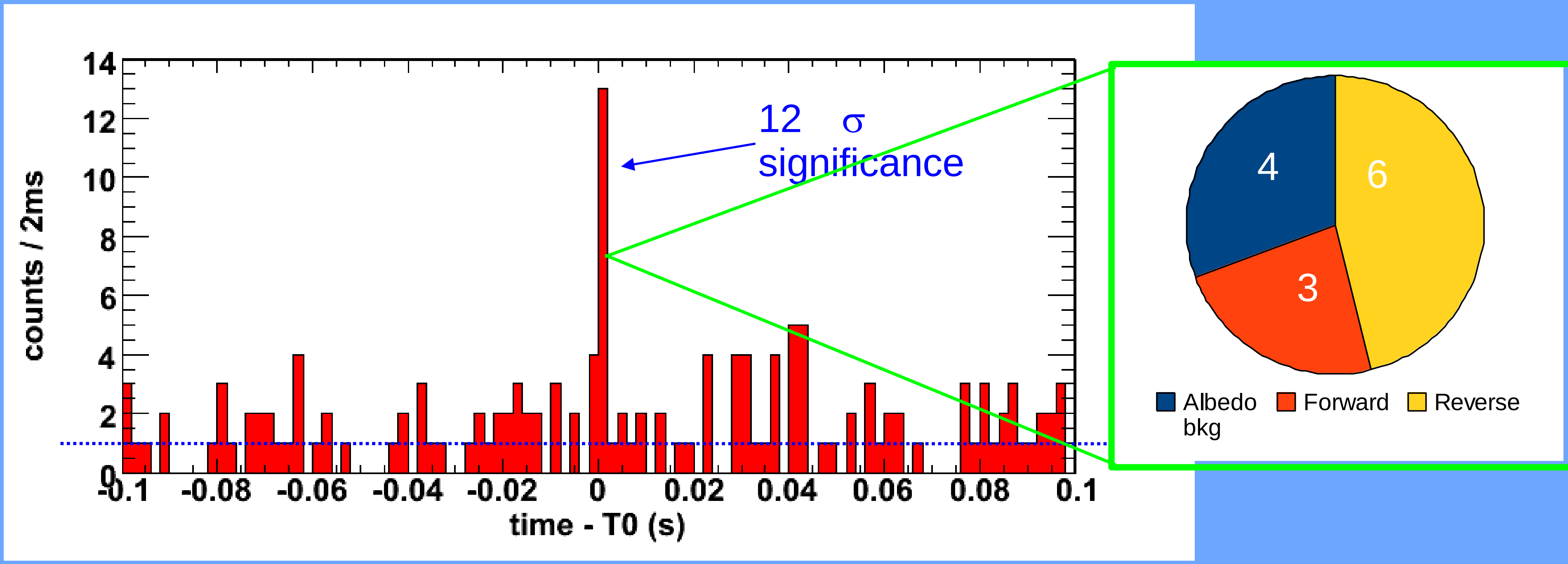


- MCAL is detecting TGF photons up to 100 MeV
- why don't we look at detections by the AGILE gamma-ray imager (GRID) sensitive above 20 MeV?
- It would be the first direct localization of TGFs in gamma-rays

direct imaging of TGFs from space (using γ-rays !)

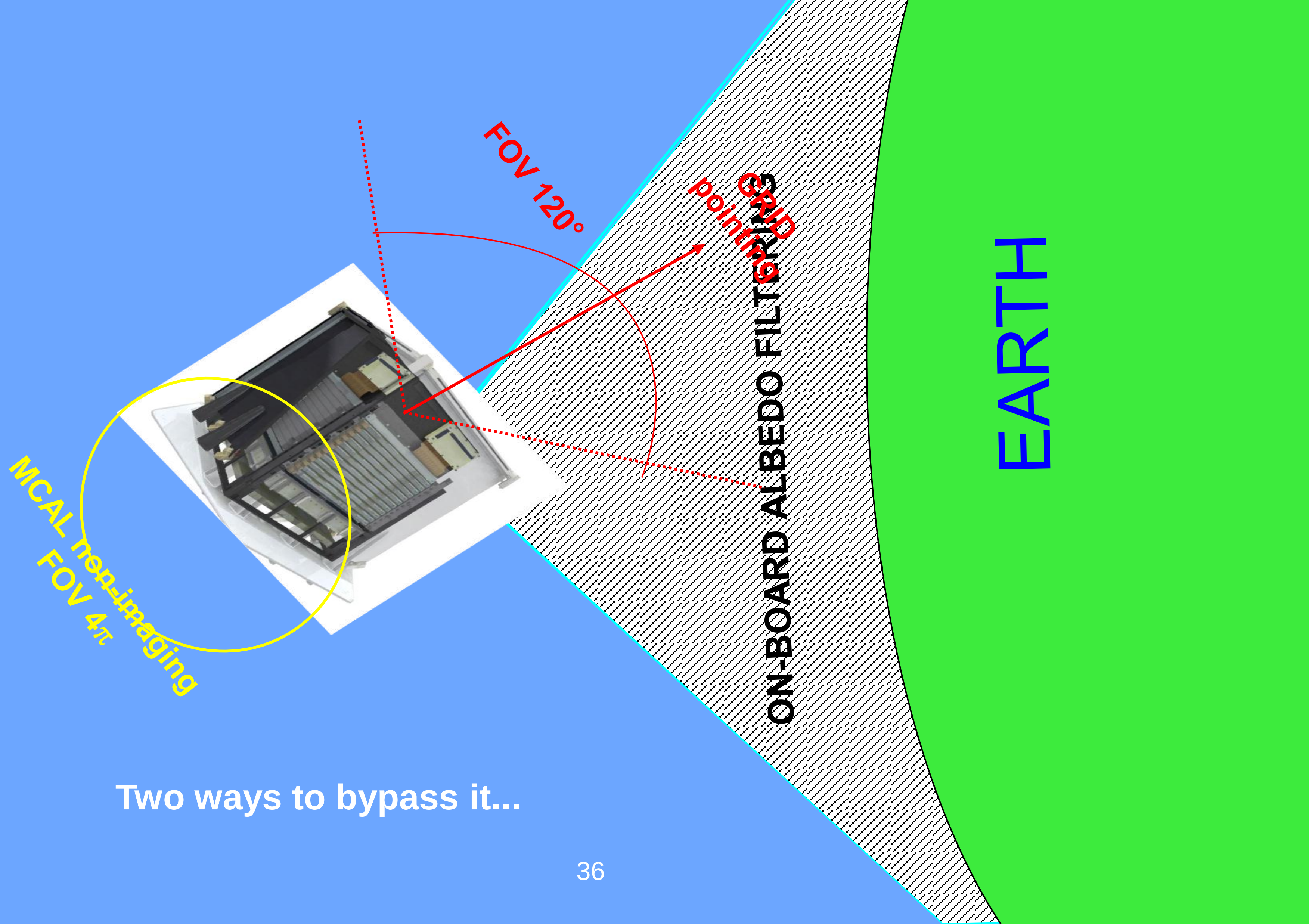
(Marisaldi et al. 2010)

Search for GRID events in temporal coincidence with 119 MCAL TGFs detected between Jun. 2008 – Dec. 2009



13 GRID events within 2 ms from TGFs T0!

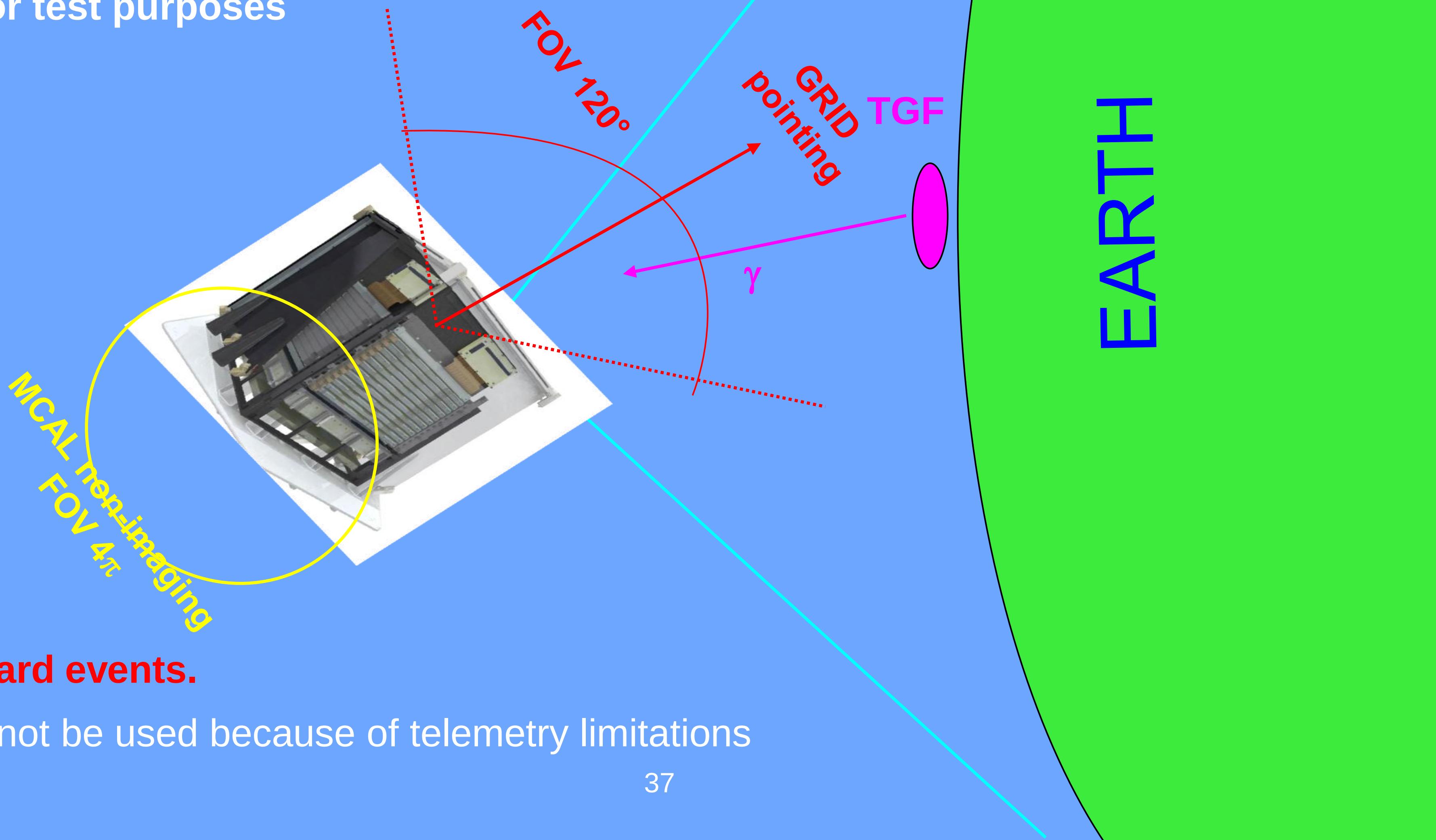
Imaging TGFs from space with the AGILE GRID



Two ways to bypass it...

Imaging TGFs from space with the AGILE GRID

1. Albedo filtering disabled
~ 100 days between 2008 – 2009
for test purposes

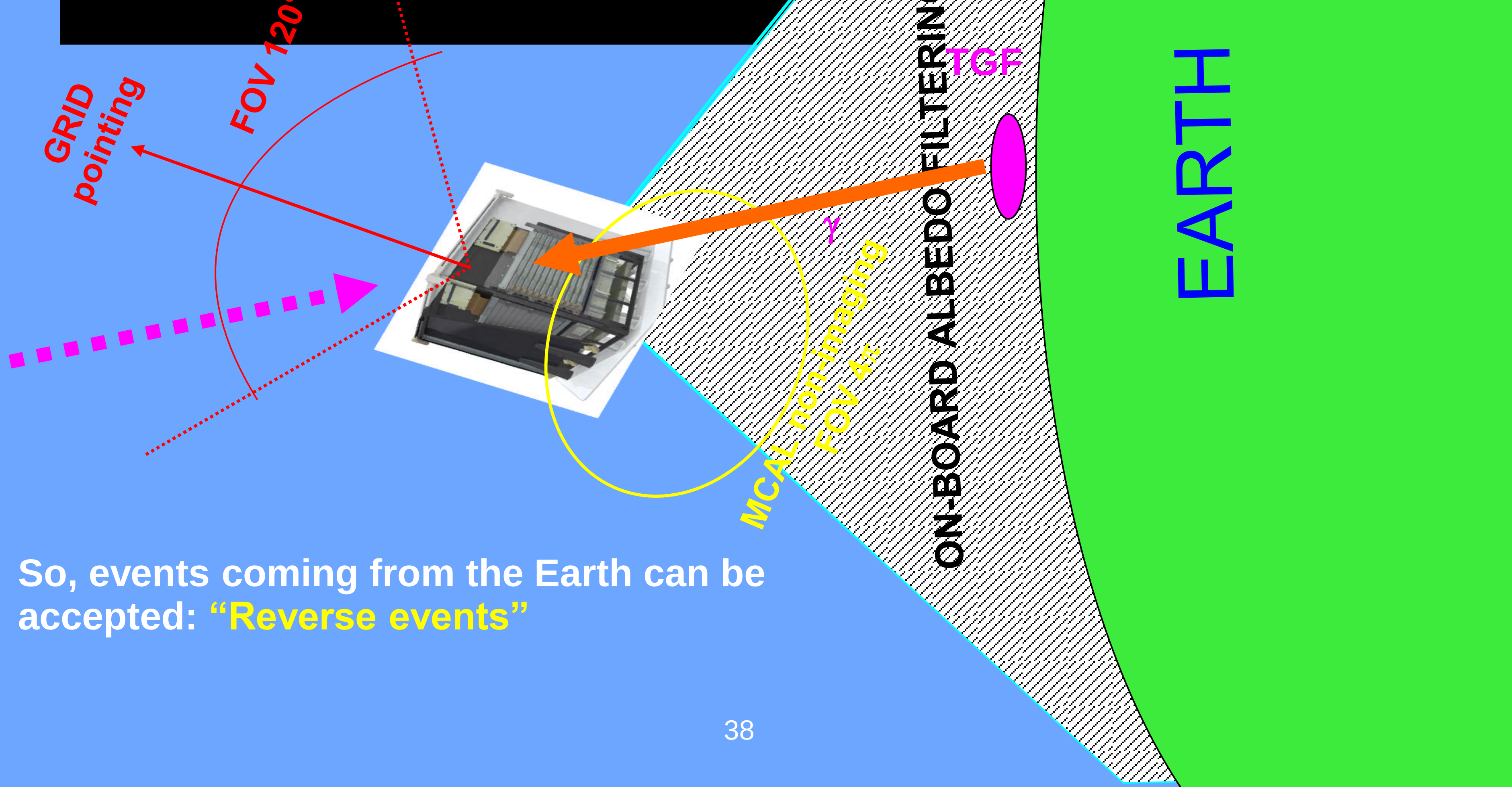


Forward events.

It cannot be used because of telemetry limitations

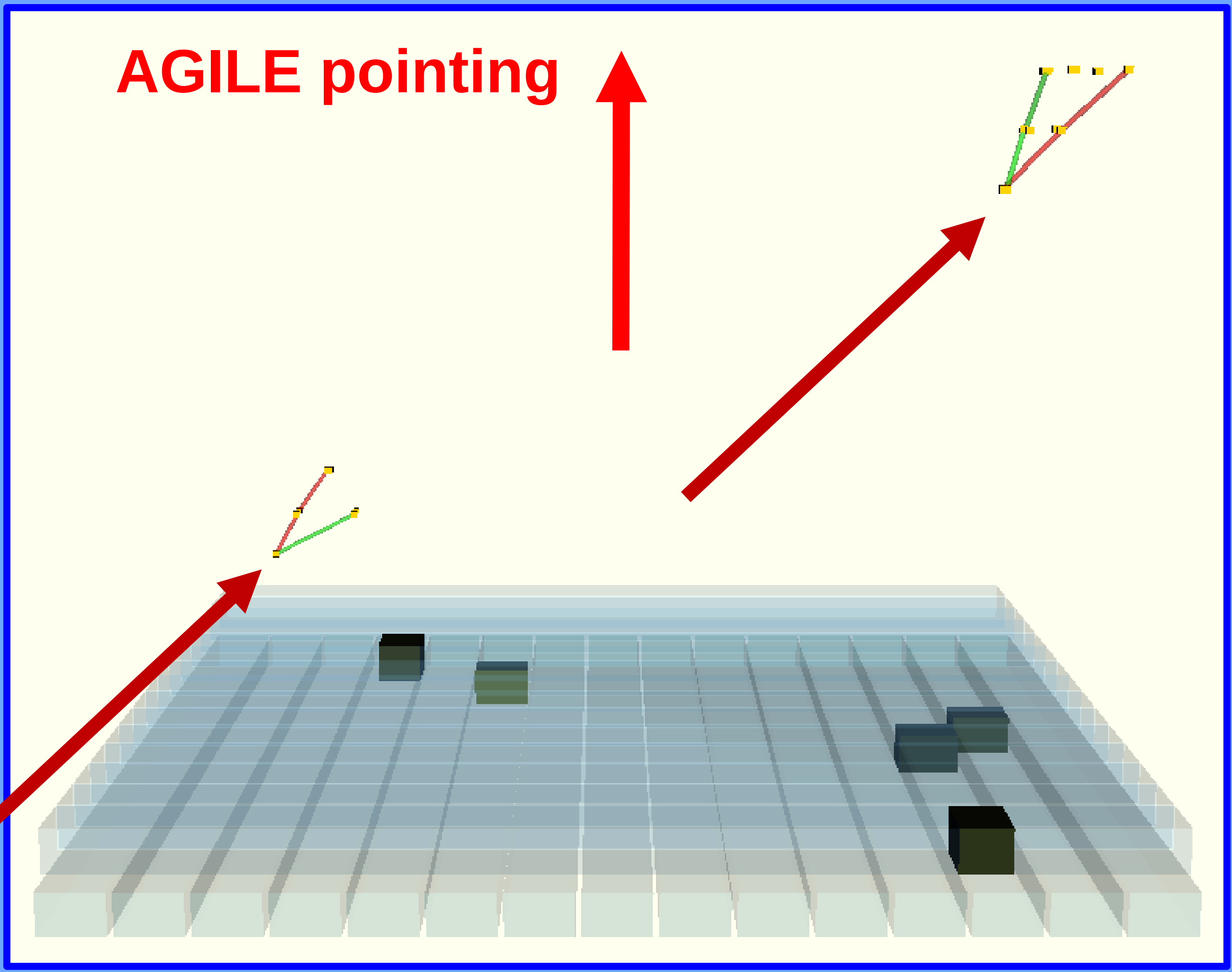
Imaging TGFs from space with the AGILE GRID

2. the albedo filter logic is not optimized for events from below, which can be taken as originating from the front side



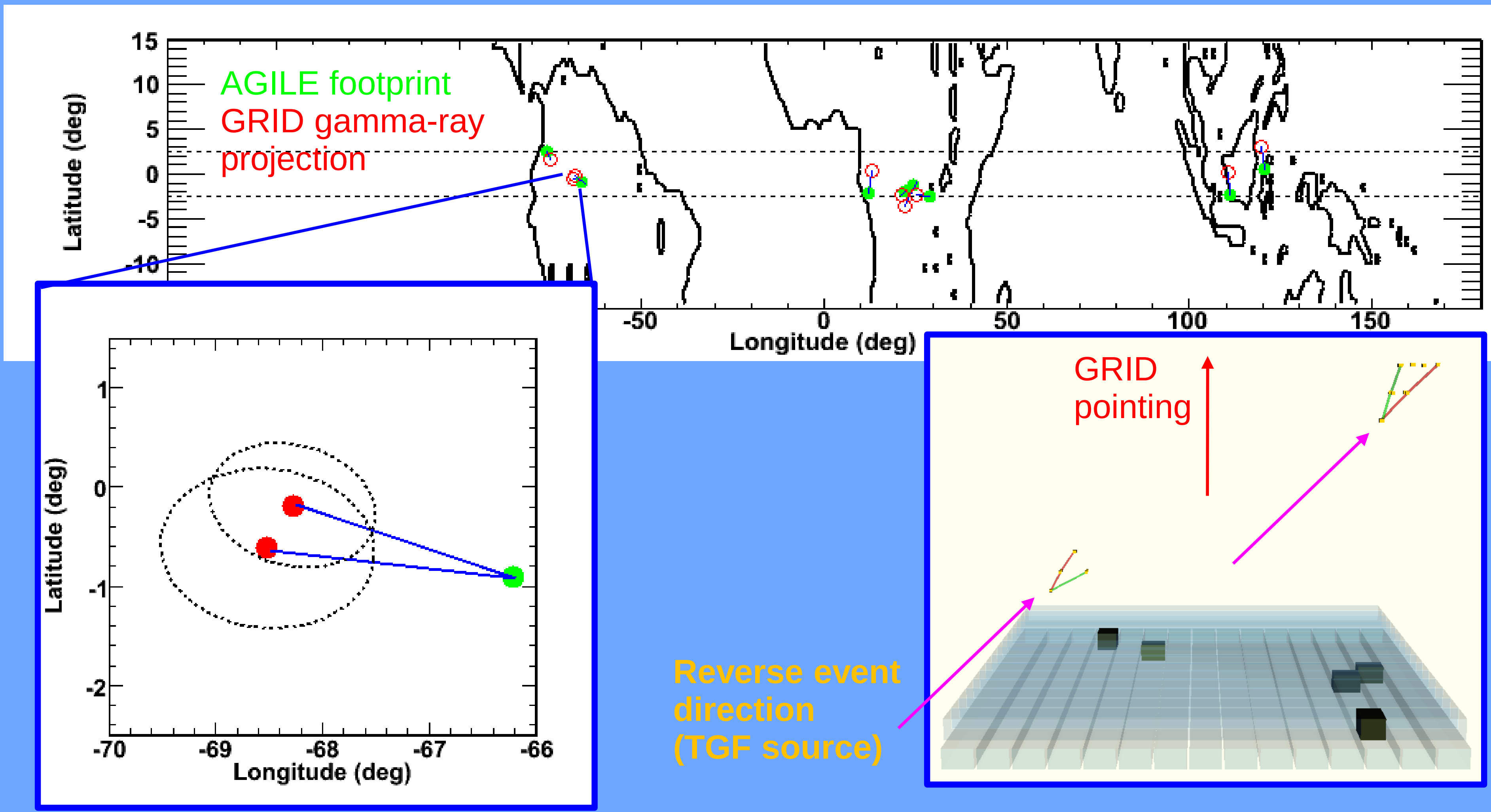
So, events coming from the Earth can be accepted: "Reverse events"

AGILE TGF 12809-19
(2010 Oct. 16 20:44:55 UT)



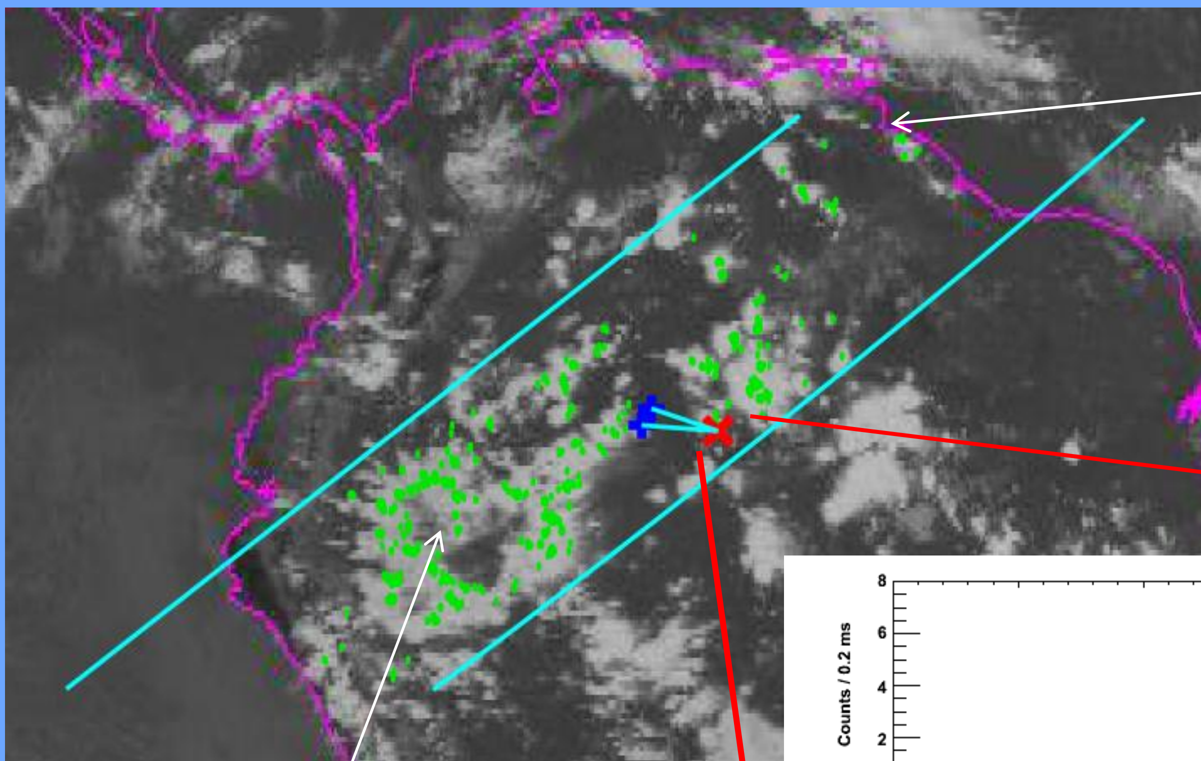
"reverse event" direction (TGF source)

Geographical distribution of a subset



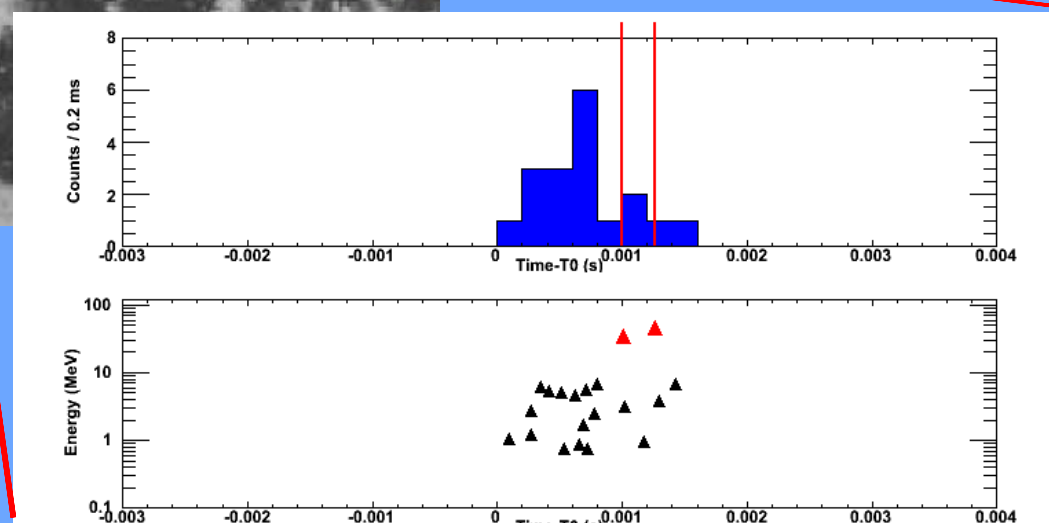
TGF 12809-19 in details
(2010 Oct. 16 20:44:55 UT)

Credits: B. Carlson, Univ. Bergen

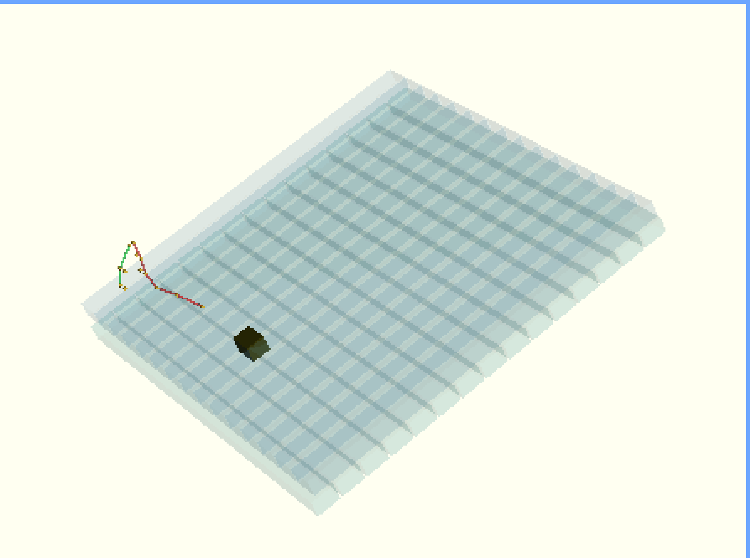


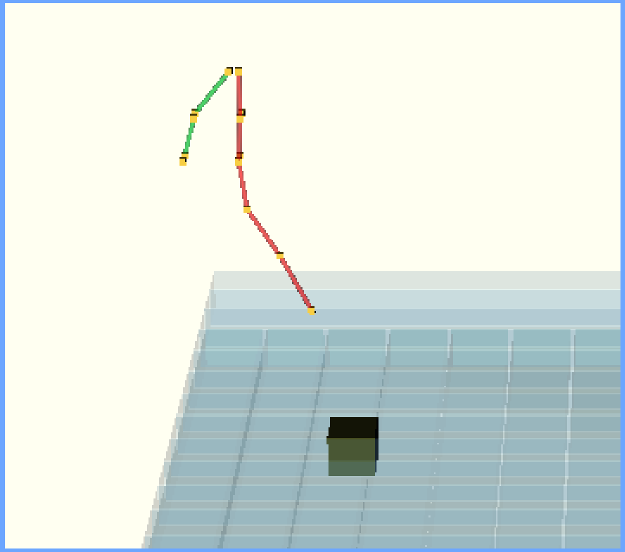
GOES IR image ~5 minutes before TGF

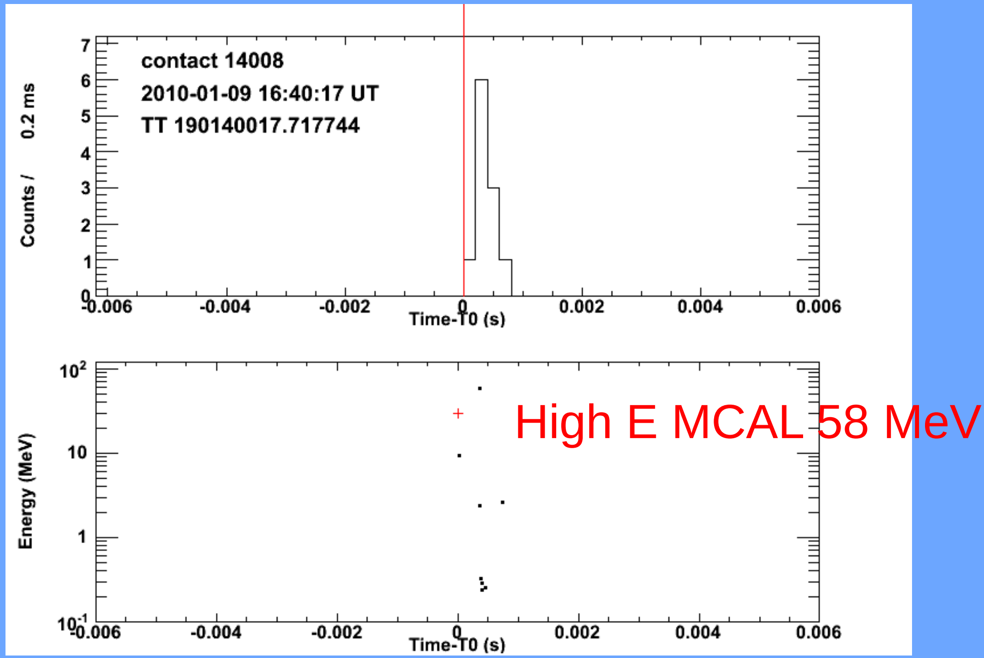
TRMM-LIS pass ~1 hour earlier

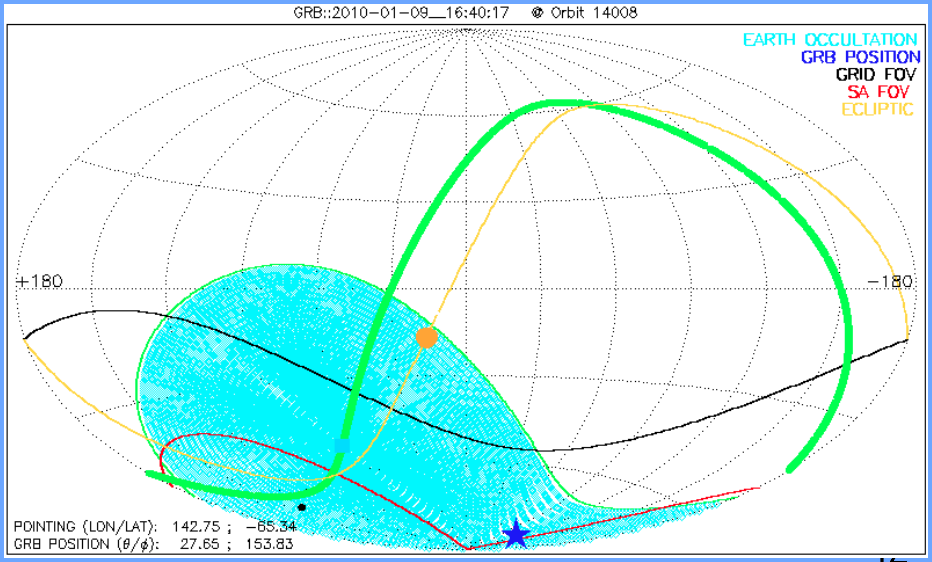


14008

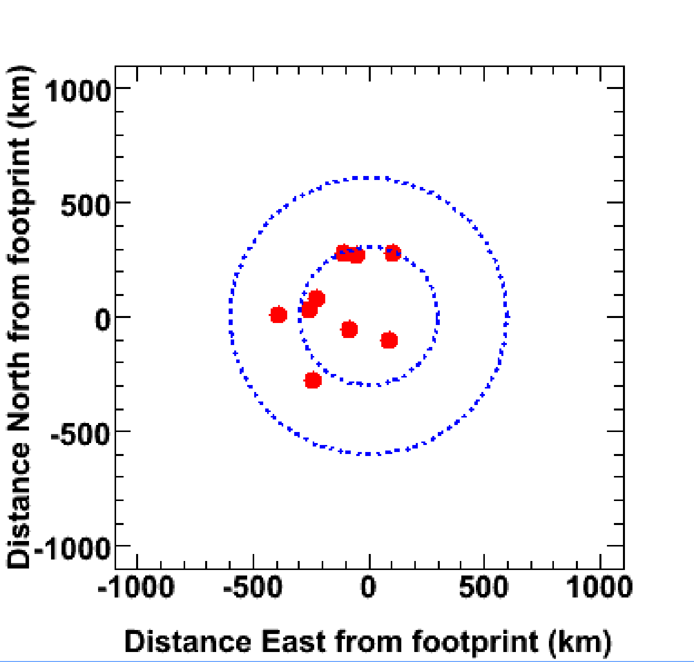


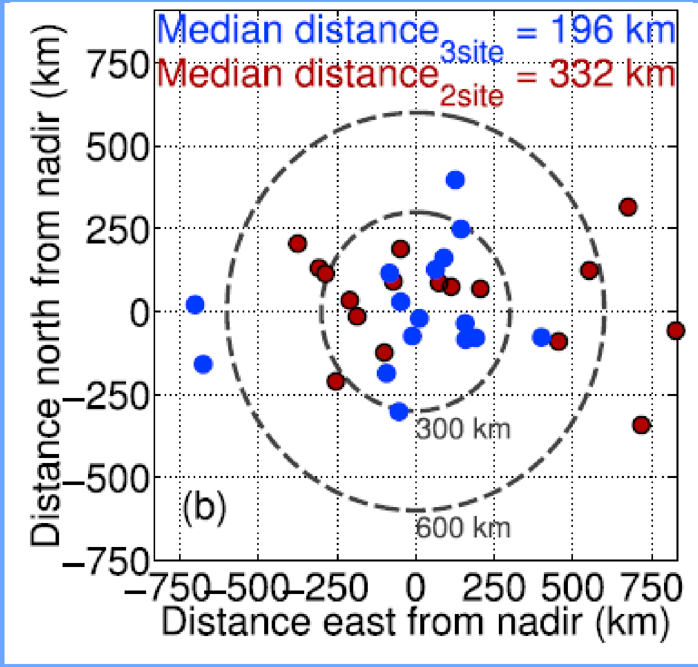



contact 14008
2010-01-09 16:40:17 UT
TT 190140017.717744
Counts / 0.2 ms
Time-T0 (s)
Energy (MeV)
High E MCAL 58 MeV


GRB::2010-01-09__16:40:17 @ Orbit 14008
EARTH OCCULTATION
GRB POSITION
GRID FOV
SA FOV
ECLIPTIC
+180
-180
POINTING (LON/LAT): 142.75 ; -65.34
GRB POSITION (θ/φ): 27.65 ; 153.83

AGILE TGF reconstructed positions





Cohen et al., GRL 2010

Event clustering at < 400 km from AGILE footprint

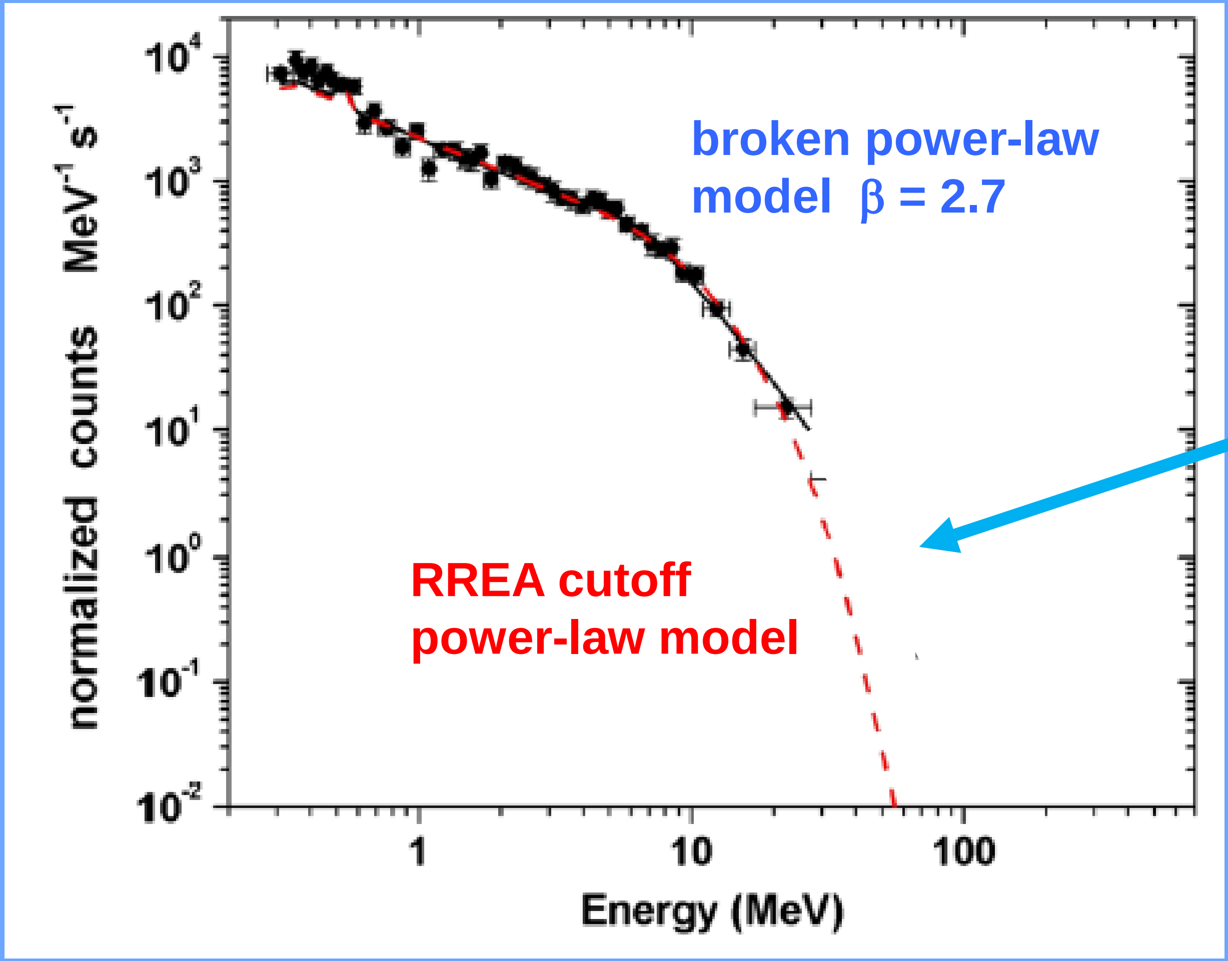
Consistency with pervious detections based on RHESSI TGFs and sferics (Cummer et al., GRL 2005, Cohen et al., GRL 2010)

Marisaldi et al., Phys. Rev. Letters 105, 128501 (2010)

TFG cumulative spectrum

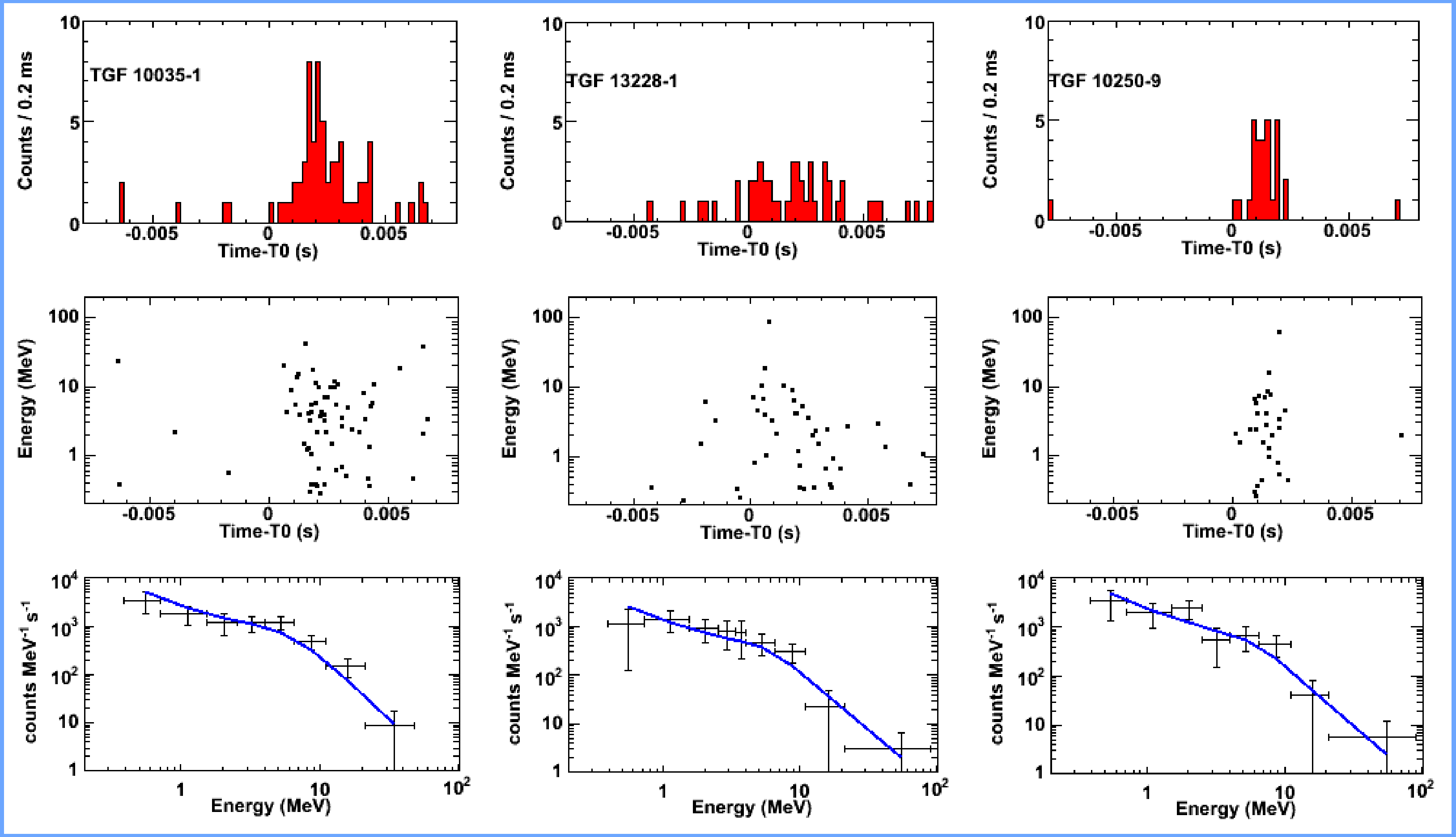
Tavani et al., Phys. Rev. Letters 106, 018501 (2011)

110 TGFs **26 events E_{max} > 20 MeV**



significant detection of γ–rays with E>40 MeV unexplained by standard RREA models: a challenge for emission models

High energy events



Issues and impact

origin of TGF high-energy emission up to 100 MeV, a challenge to current RREA models,

a very efficient accelerator !

lightning-TGF connection: which lightning ?

how often do TGFs occur ? mapping, monitoring… local climate, climate change connections

impact of TGFs HE-emission on the atmospheric environment: chemistry, radiation effects

electrons, gamma-rays, neutrons

(A. Pesoli, F. Palma, M.T., 2012)

neutron production, simulation

source at h = 3800 m
ground at 3200 m a.s.l