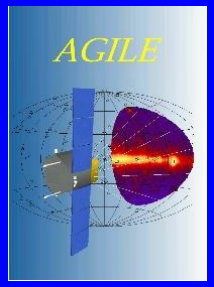


IASF Bologna

AGILE and Terrestrial Gamma-Ray Flashes

Martino Marisaldi (INAF-IASF Bologna)

F. Fuschino, C. Labanti, F. Longo,

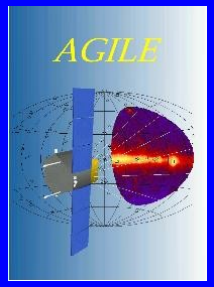
A. Argan, A. Trois, M. Tavani

on behalf of the AGILE team

7th AGILE Workshop

The Bright Gamma-Ray Sky

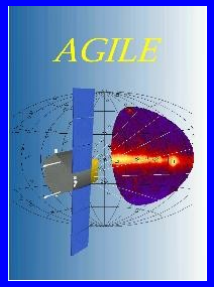
Sep. 29-30, Oct. 1, 2009, ESRIN, Frascati



Outline

IASF Bologna

- TGF, a brief overview
- AGILE-MCAL instrument and detection capabilities
- MCAL strength points in TGF science
- Characteristics of the MCAL TGF sample
- Comparison with the RHESSI 1st TGF catalog
- Work in progress
- Conclusions



Terrestrial Gamma-ray Flashes (TGF)

INAF

IASF Bologna

Gamma-ray flashes with incoming direction compatible with the Earth surface.

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

Discovered by BATSE (Fishman et al., Science, 1994)

Observed 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)

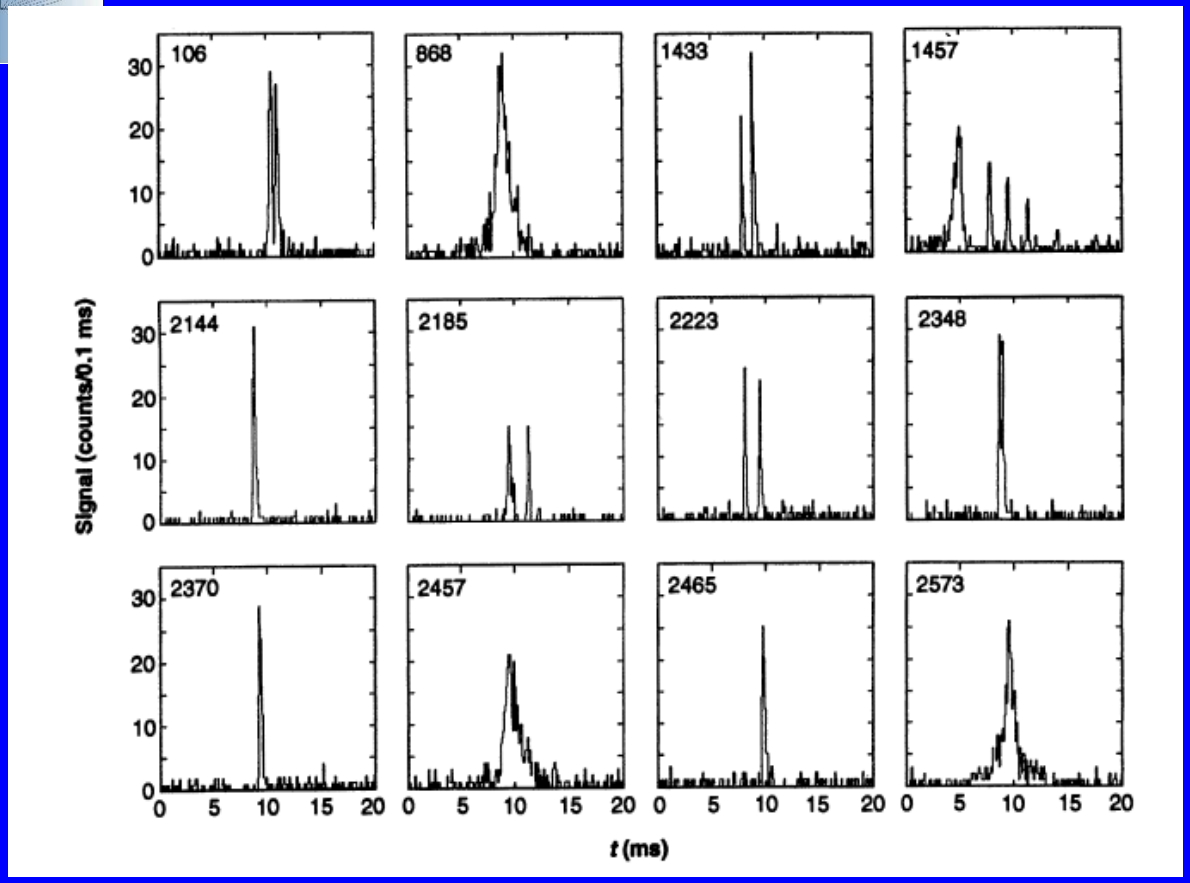
>2008: Observed by AGILE and Fermi

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

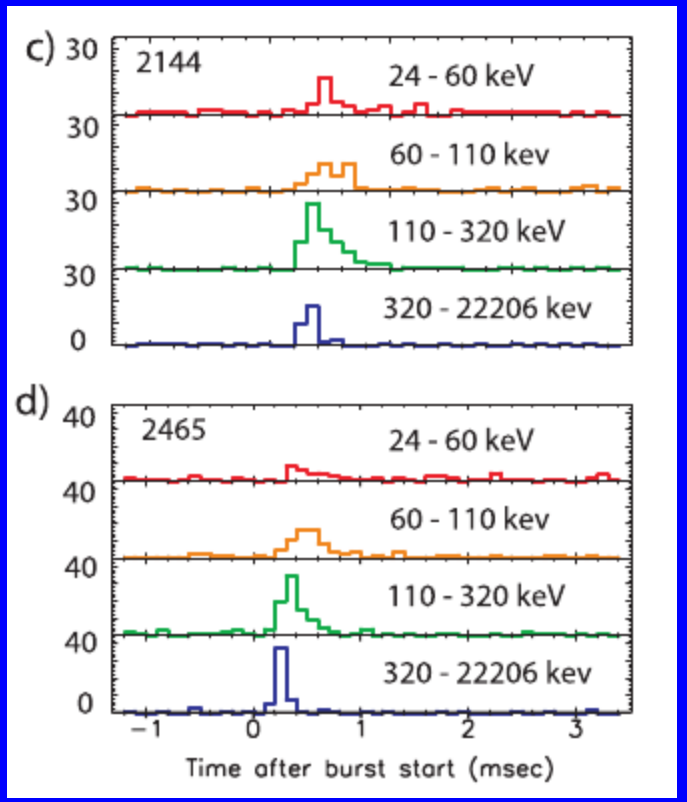
Challenging detection: timing and energy range are key issues

1994: BATSE discovery of TGF

IASF Bologna



Fishman et al., Science, 1994
Østgaard et al. 2008

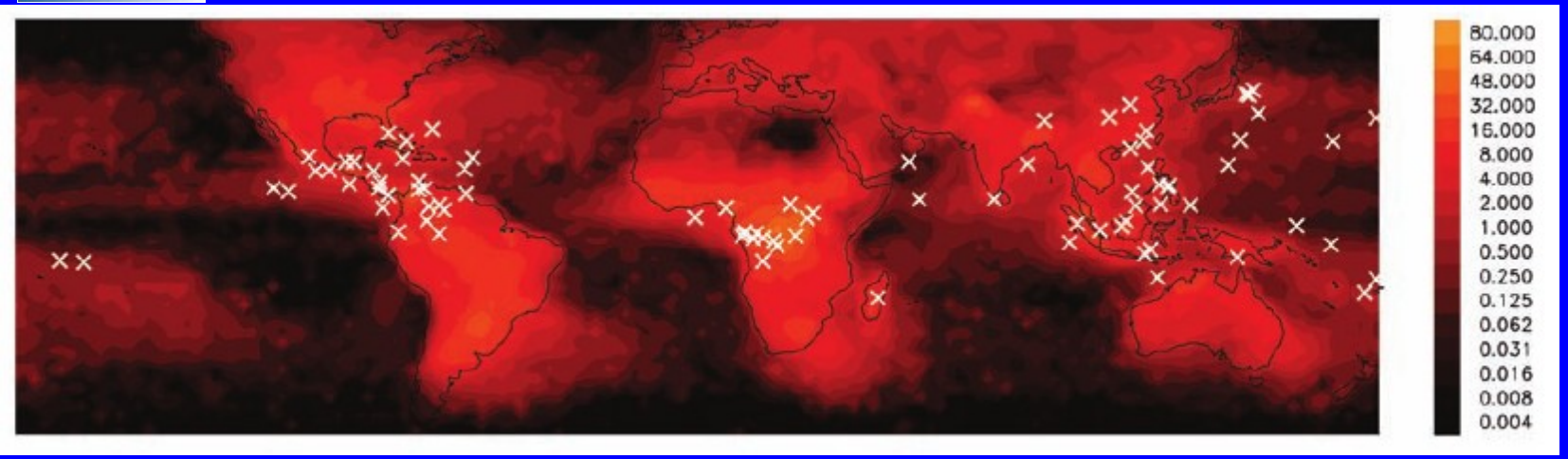


~ 70 TGF detected on 9 life-Years
typically 100 counts/TGF
Main limitations:

- On-Board Trigger Logic performances (shorter timescale 64ms)
- Large statistics BUT only 4 energy bins for time-tagged events

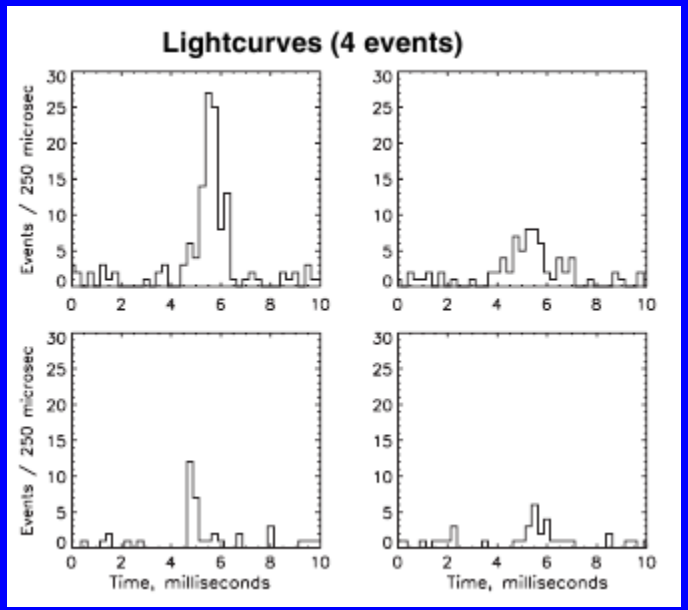
2005: RHESSI detection up to 20 MeV

IASF Bologna



TGF Distribution with lighting frequency per km^2 per Year

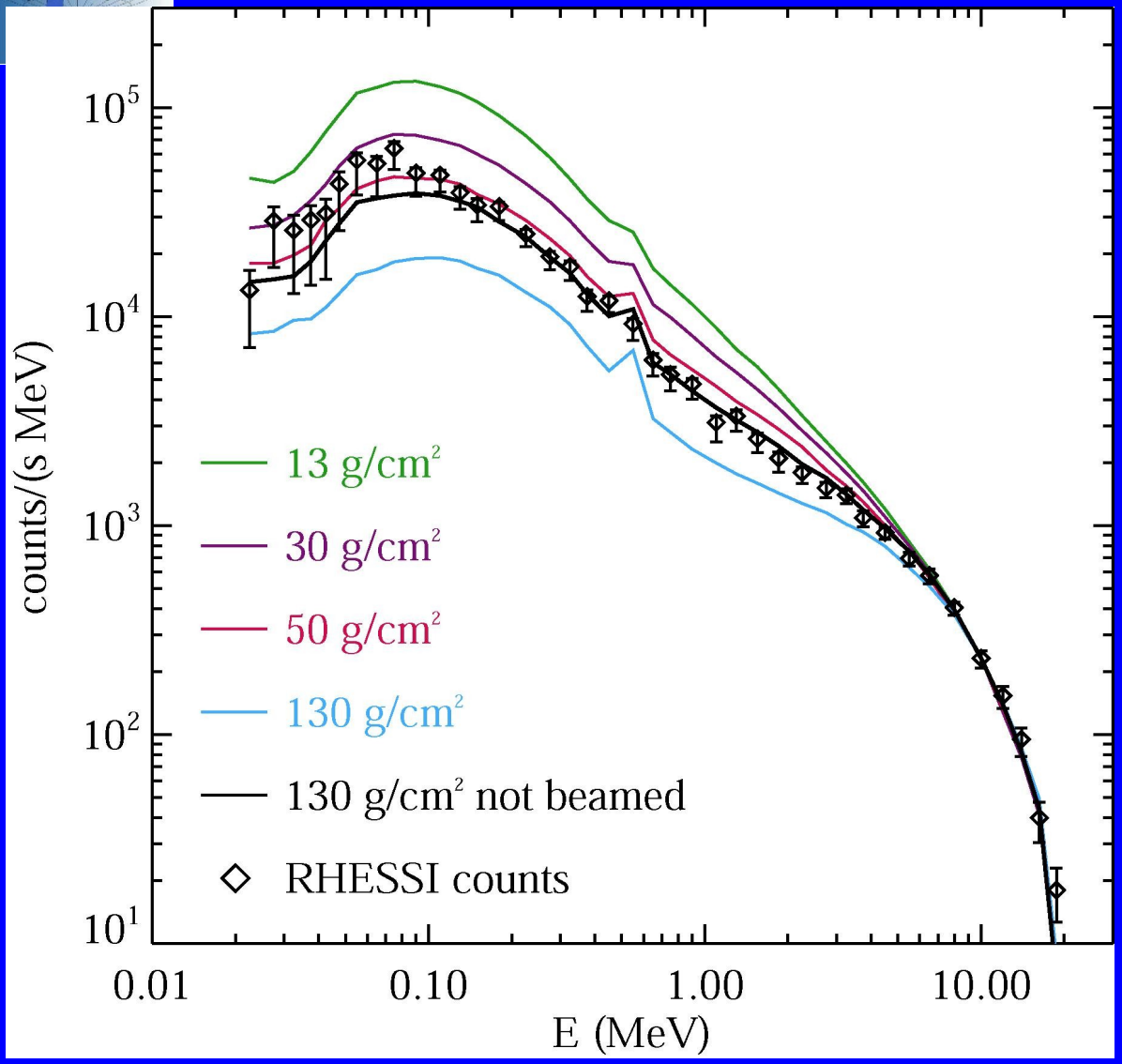
Smith et al., Science, 2005



- 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)

RREA Production model

IASF Bologna



Dwyer and Smith, GRL (2005)
Carlson, Lehtinen and Inan (2007)

Relativistic Runaway Electron Avalanche (RREA) with relativistic feedback (Dwyer 2008)

Bremsstrahlung + Compton scattering

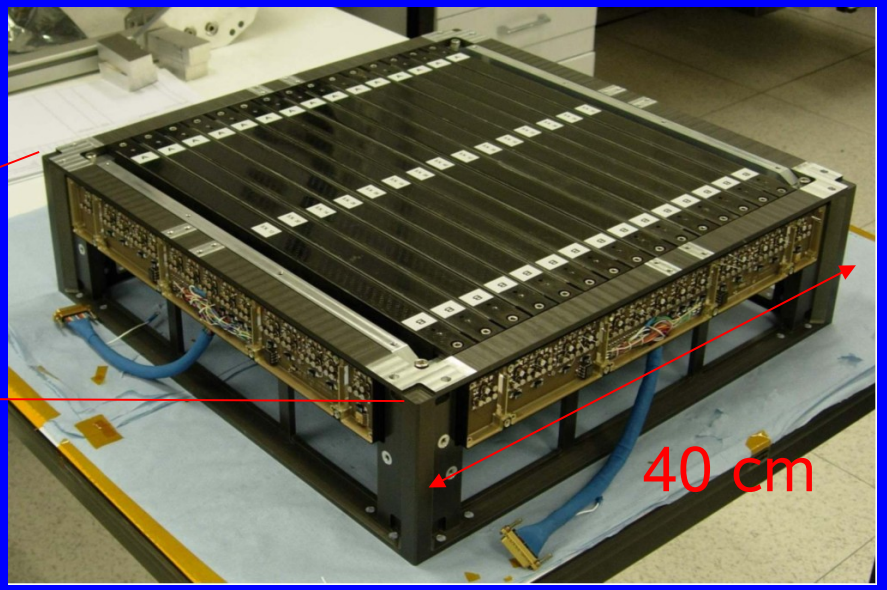
RHESSI cumulative spectrum is compatible with a production altitude of 15-21 km (just above tropical thunderstorms)

Still hint for individual spectral variability: differences in production altitudes or viewing angle?

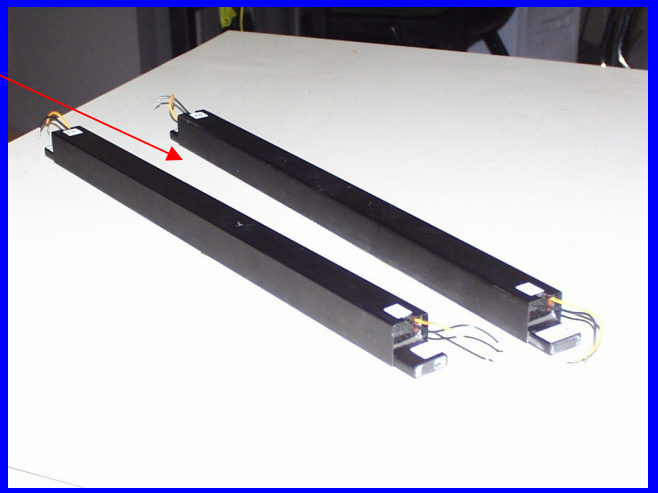
BATSE events seem produced at higher altitude (two different populations?) but discrepancy is reduced if dead-time effects are properly accounted for (Grefenstette et al., 2008; Ostgaard et al., 2008)

The AGILE Mini-Calorimeter (MCAL)

IASF Bologna



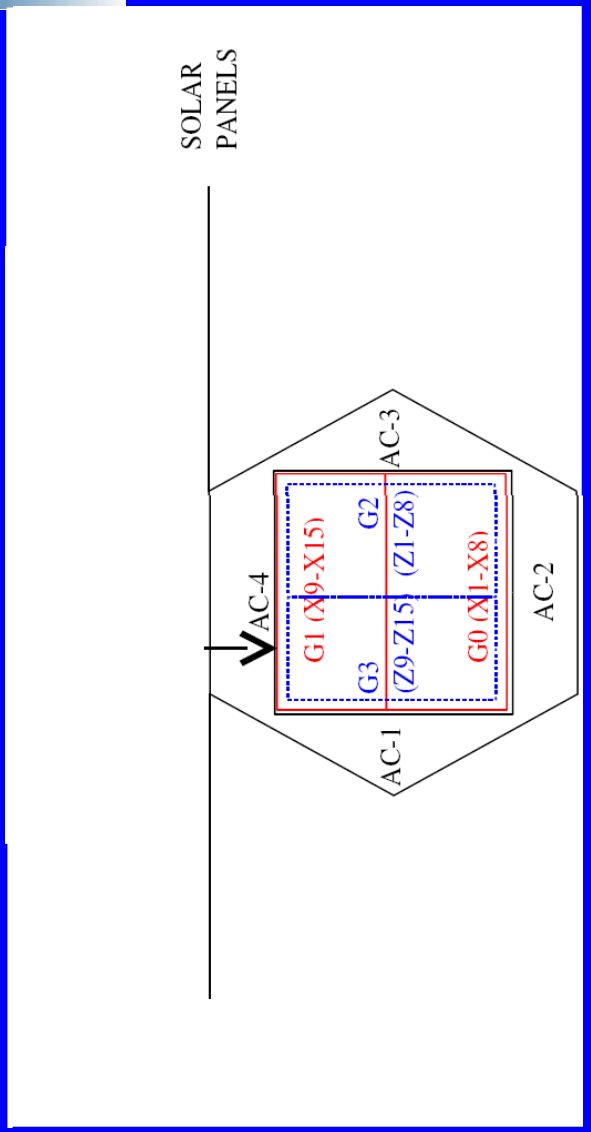
- 30 CsI(Tl) bars with Photodiode readout, like these
- 1400 cm^2 geometrical area
- ~300 cm^2 effective area @ 1 MeV
- 330 keV – 100 MeV energy range
- 14% energy resolution FWHM @ 1.3 MeV
- 2 μs timing accuracy in photon-by-photon mode
- Clever, fully-programmable trigger logic on time scales from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



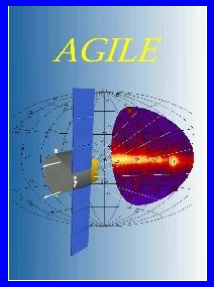
Labanti et al., NIM A (2009): instrument paper
Fuschino et al., NIM A (2008): trigger logic
Marisaldi et al., A&A (2008): GRB detections

MCAL Burst Trigger Logic

IASF Bologna



- Long (SW evaluated) time windows: 64ms, 256ms, 1.024s, 8.192s 4 spatial zones and 3 energy ranges
- Short (HW evaluated) time windows: sub-millisecond, 1ms, 16ms
  First trigger logic at ~1ms time scale
- Very flexible: more than 2000 parameters for full configuration; dedicated look-up tables to accept/reject triggers
- Current threshold settings:
  - 16ms: >22 counts
  - 1ms: >10 counts
  - 293μs: > 8 counts



Why AGILE is good for TGF science?

INAF

IASF Bologna

- MCAL energy range extended up to 100 MeV: probing the high energy tail of the TGF spectrum
- Efficient trigger at ms and sub-ms time scale(the TGF time scale): not biased toward brightest events
- segmented independent detectors: low dead time and pile-up
- photon-by-photon data download for triggered events with 2μs time resolution
- <100μs absolute timing accuracy: mandatory for sferics correlation
- AGILE orbit at 2.5° inclination is optimal for mapping the equatorial region, where most of the events take place, with exposure much larger than other missions

Paper accepted by JGR on 11/09/09

IASF Bologna

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. ???, XXXX, DOI:10.1029/,

Detection of Terrestrial Gamma-Ray Flashes up to 40 MeV by the AGILE satellite

M. Marisaldi,[1] F. Fuschino,[1] C. Labanti,[1] M. Galli,[2] F. Longo,[3]

E. Del Monte,[4] G. Barbiellini,[3,5] M. Tavani,[4,6] A. Giuliani,[7] E. Moretti,[3]

S. Vercellone,[8] E. Costa,[4] S. Cutini,[9] I. Donnarumma,[4] Y. Evangelista,[4]

M. Feroci,[4] I. Lapshov,[4,21] F. Lazzarotto,[4] P. Lipari,[10,11] S. Mereghetti,[7]

+ ~other 60 coauthors...

J. Geophys. Res., doi:10.1029/2009JA014502, in press

preprint available at AGU papers in press site:
http://www.agu.org/journals/ja/papersinpress.shtml#id2009JA014502

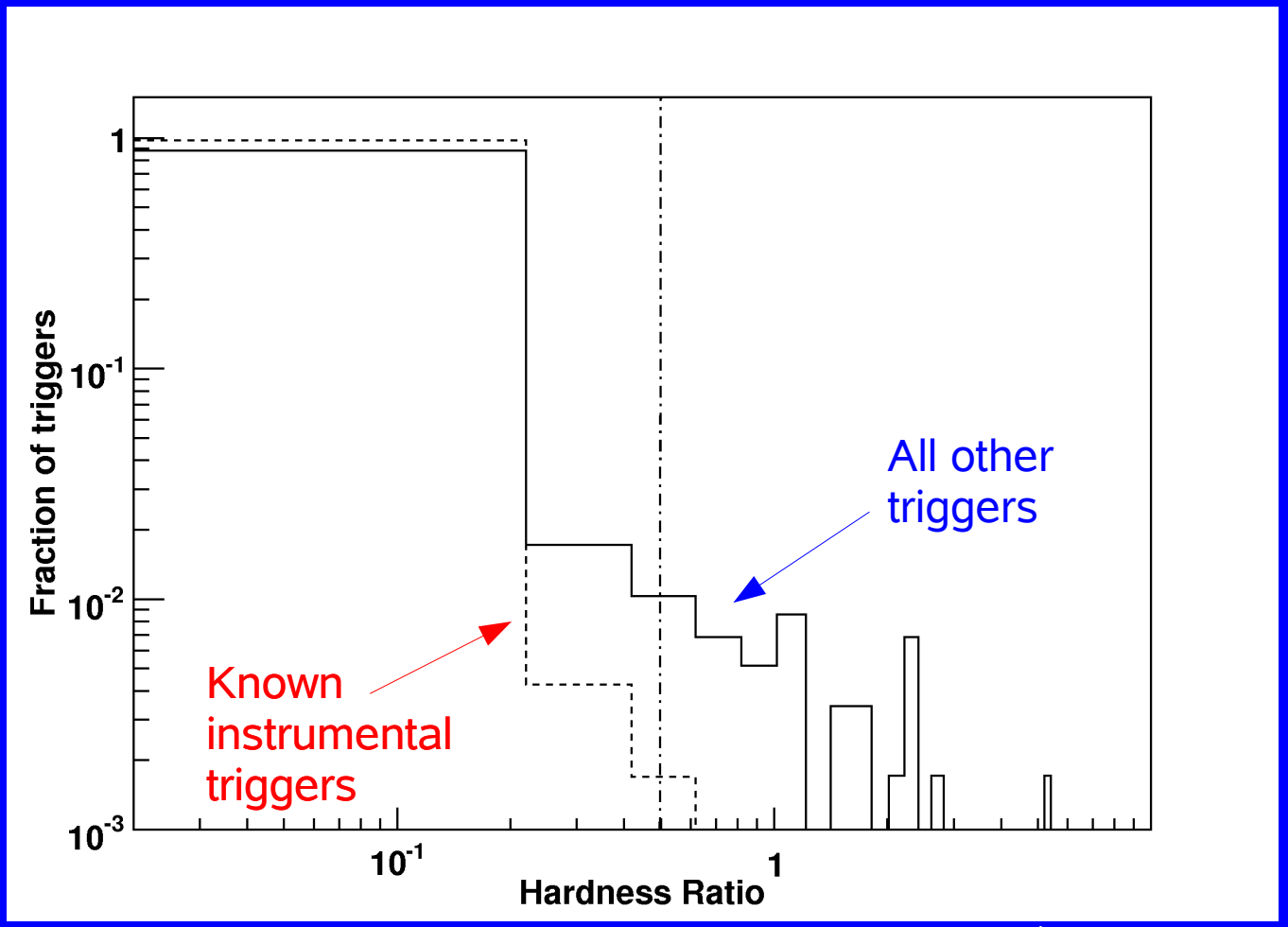
Trigger selection

IASF Bologna

Key parameter: Hardness Ratio

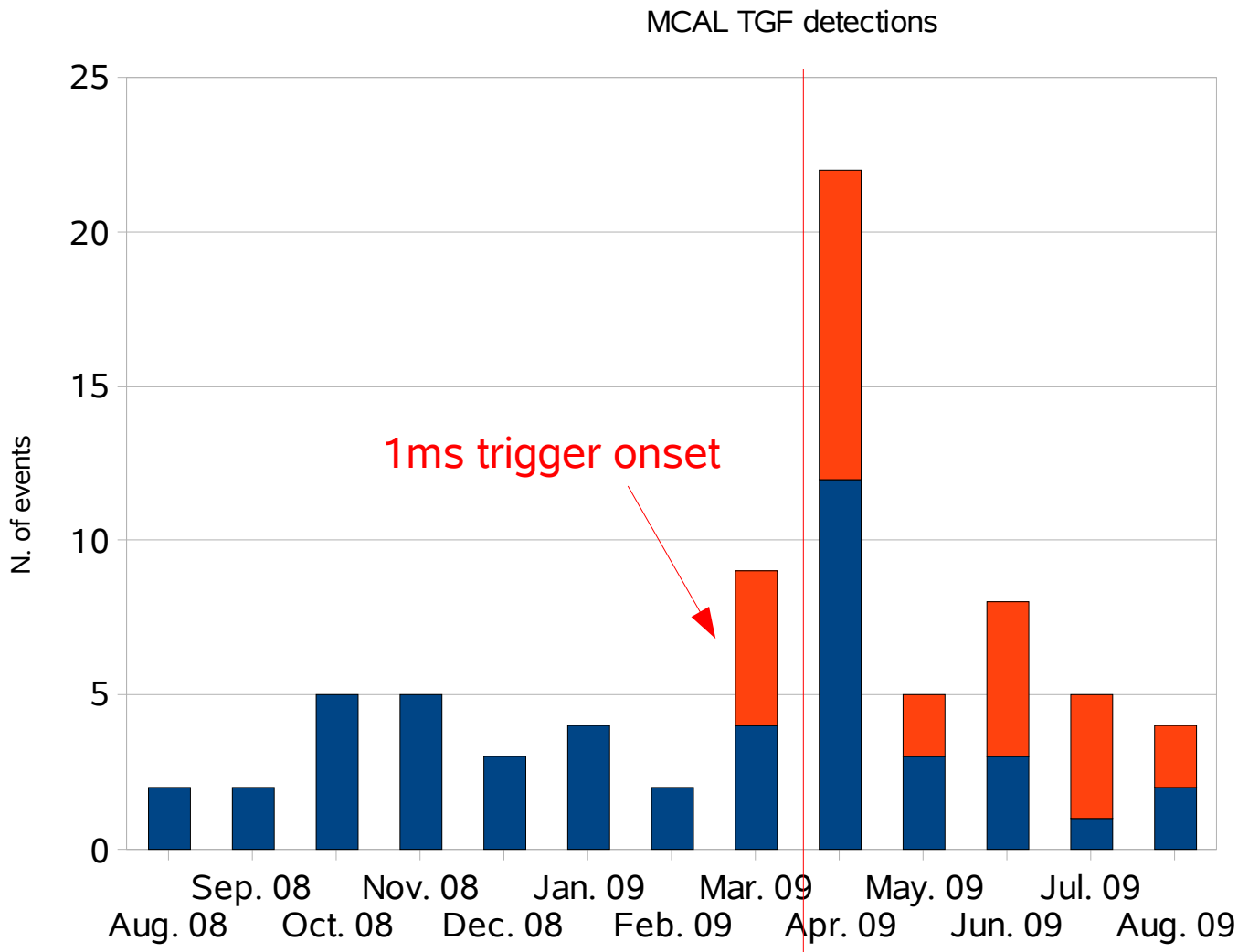
HR = (n. evt E>1.4 MeV) / (n. evt. E<1.4 MeV)

Selection criteria to reject known instrumental triggers: HR > 0.5



MCAL detection rate per month

IASF Bologna



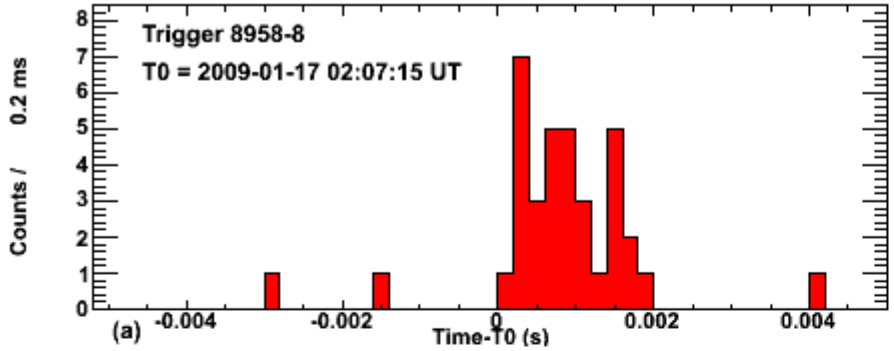
78 good candidates between June '08 – Aug. '09

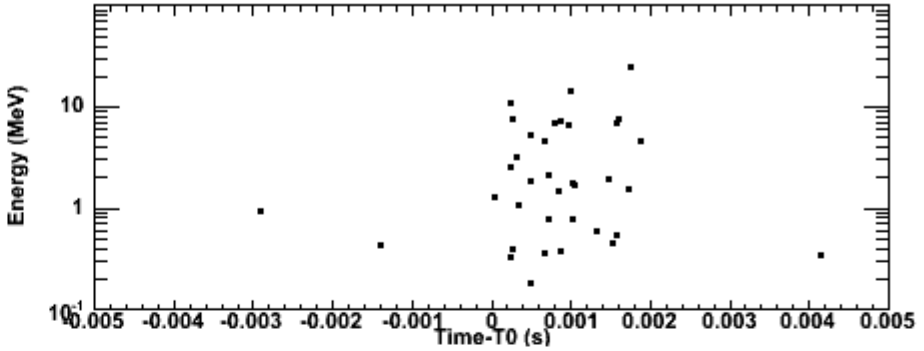
Published in M. Marisaldi et al. (2009)
J. Geoph. Res., accepted.

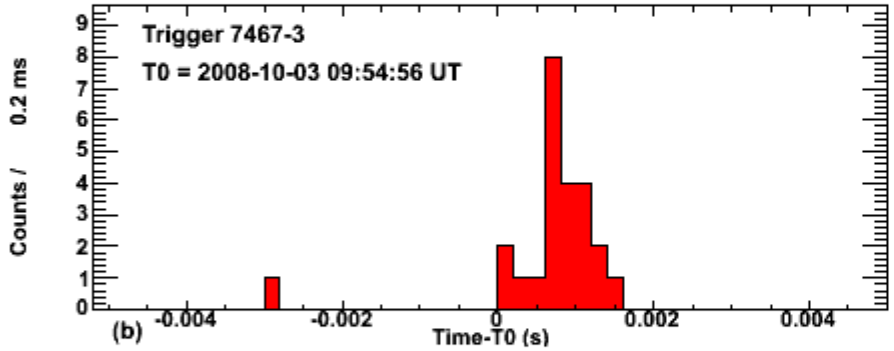
Light curves

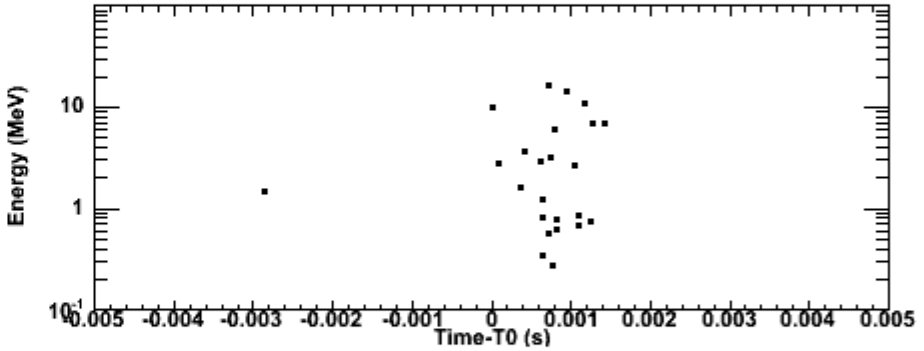
Three bright events

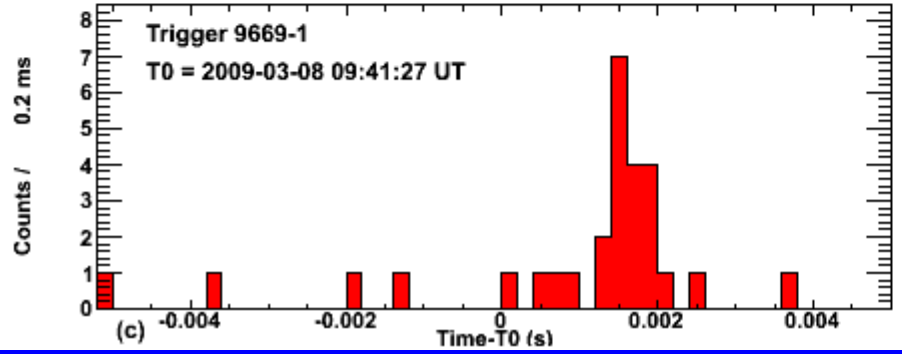
IASF Bologna

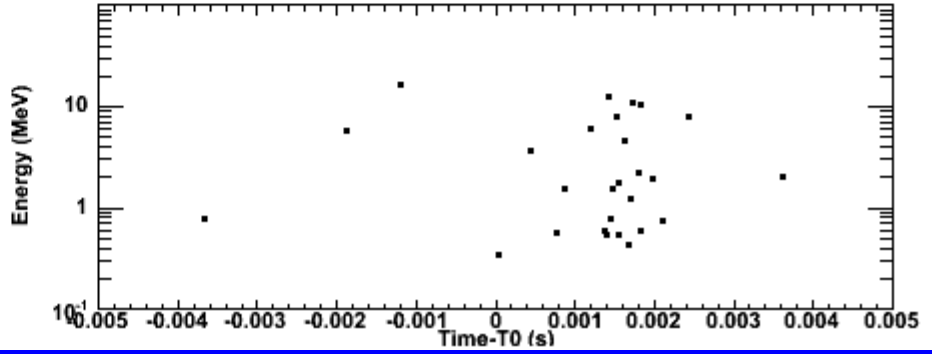






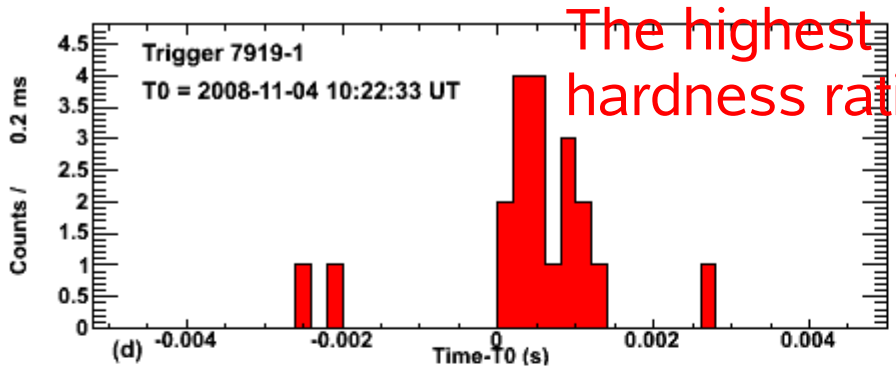




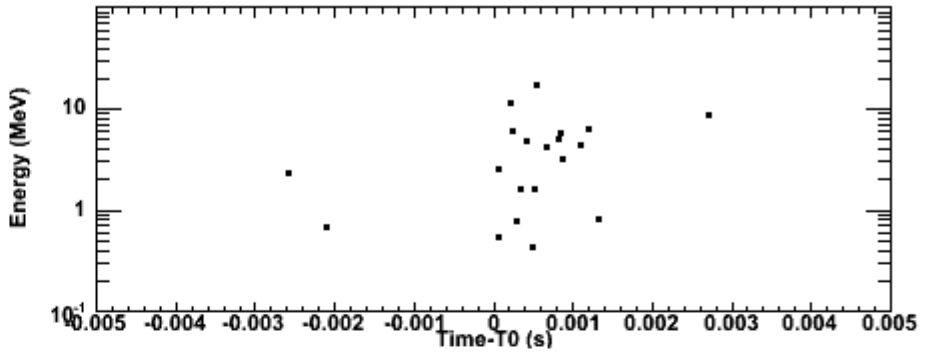


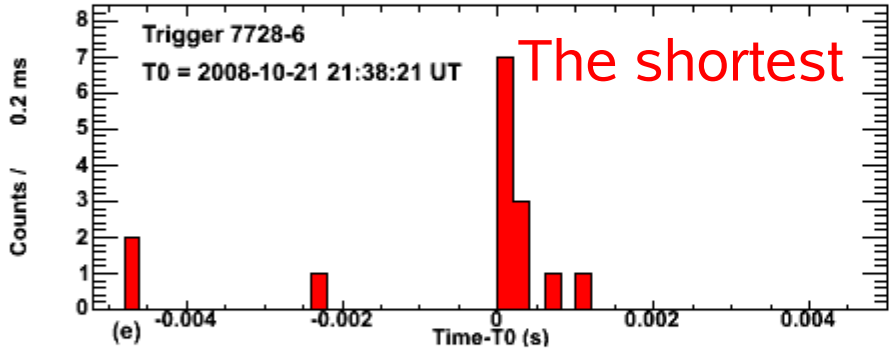
Light curves

IASF Bologna

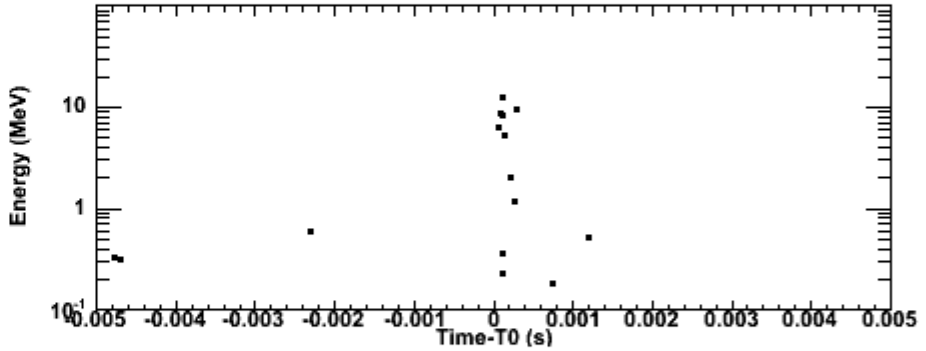


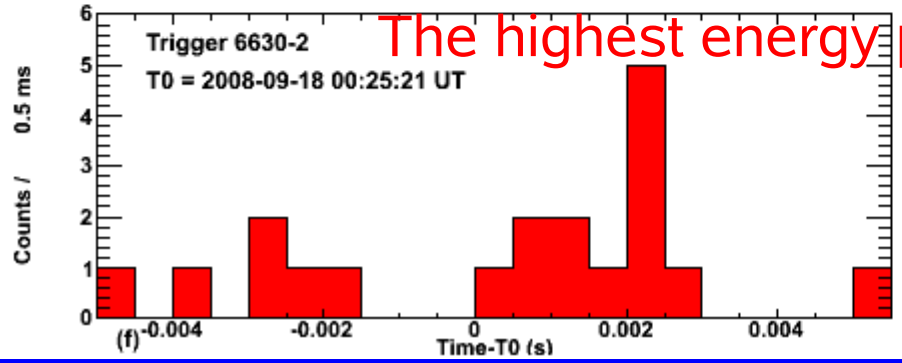
The highest hardness ratio



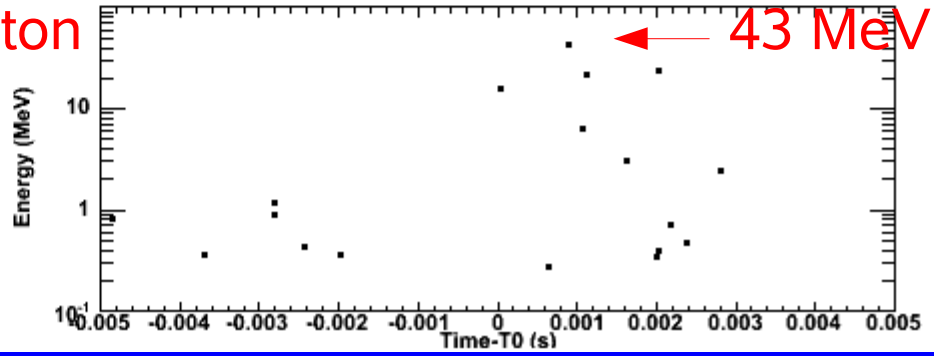


The shortest



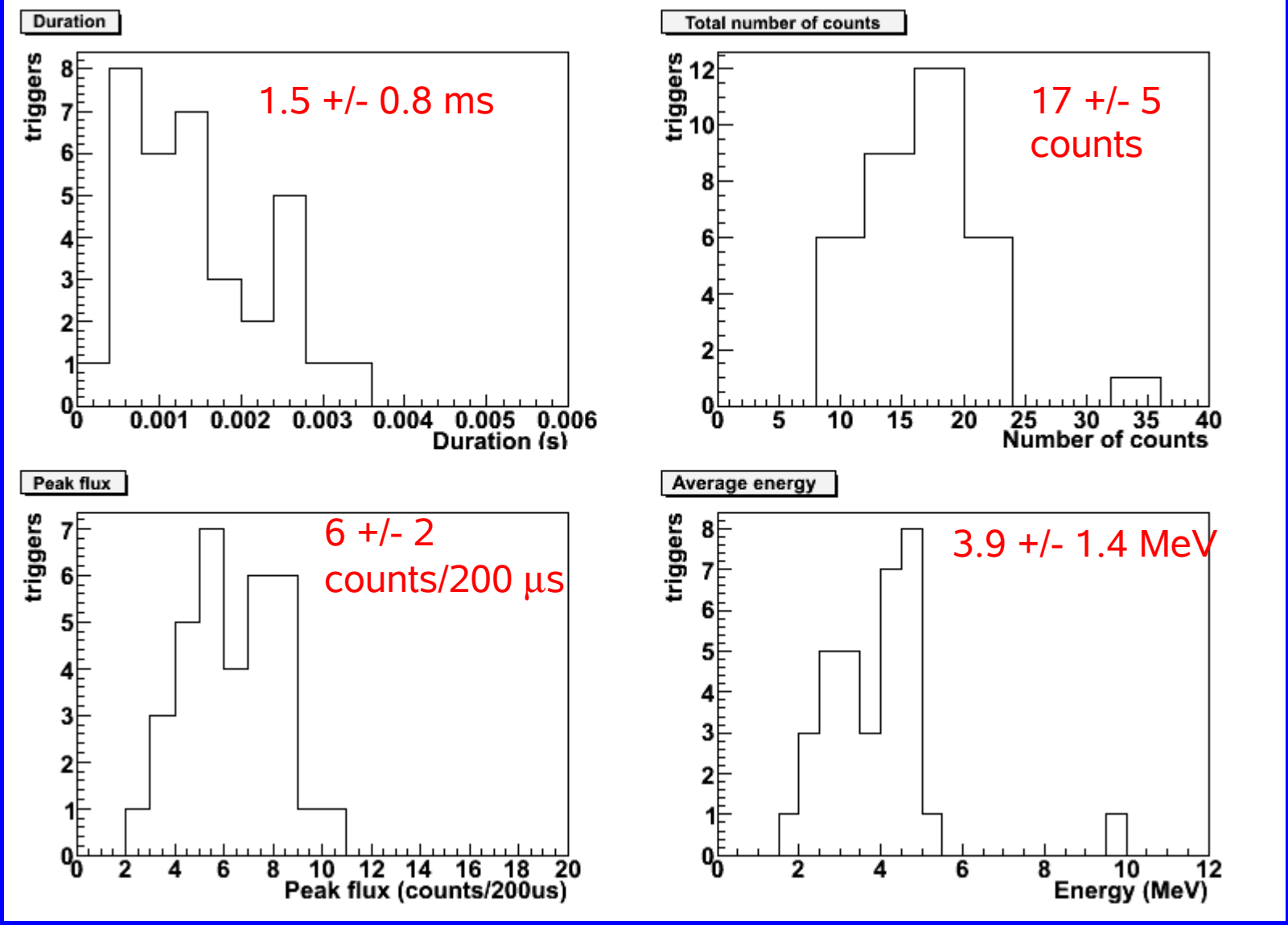


The highest energy photon



Average properties

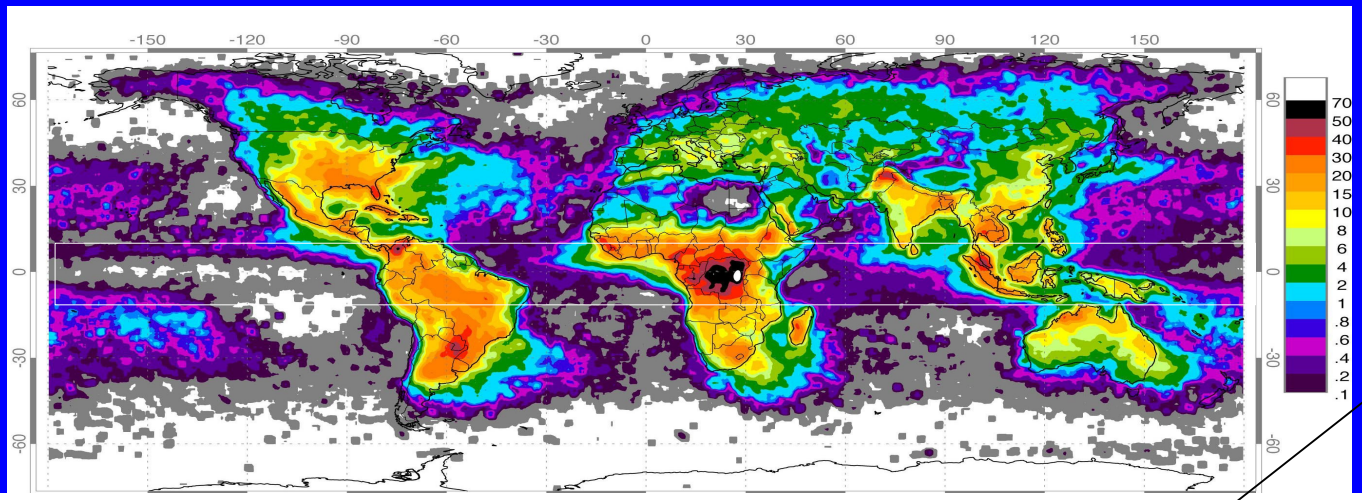
IASF Bologna



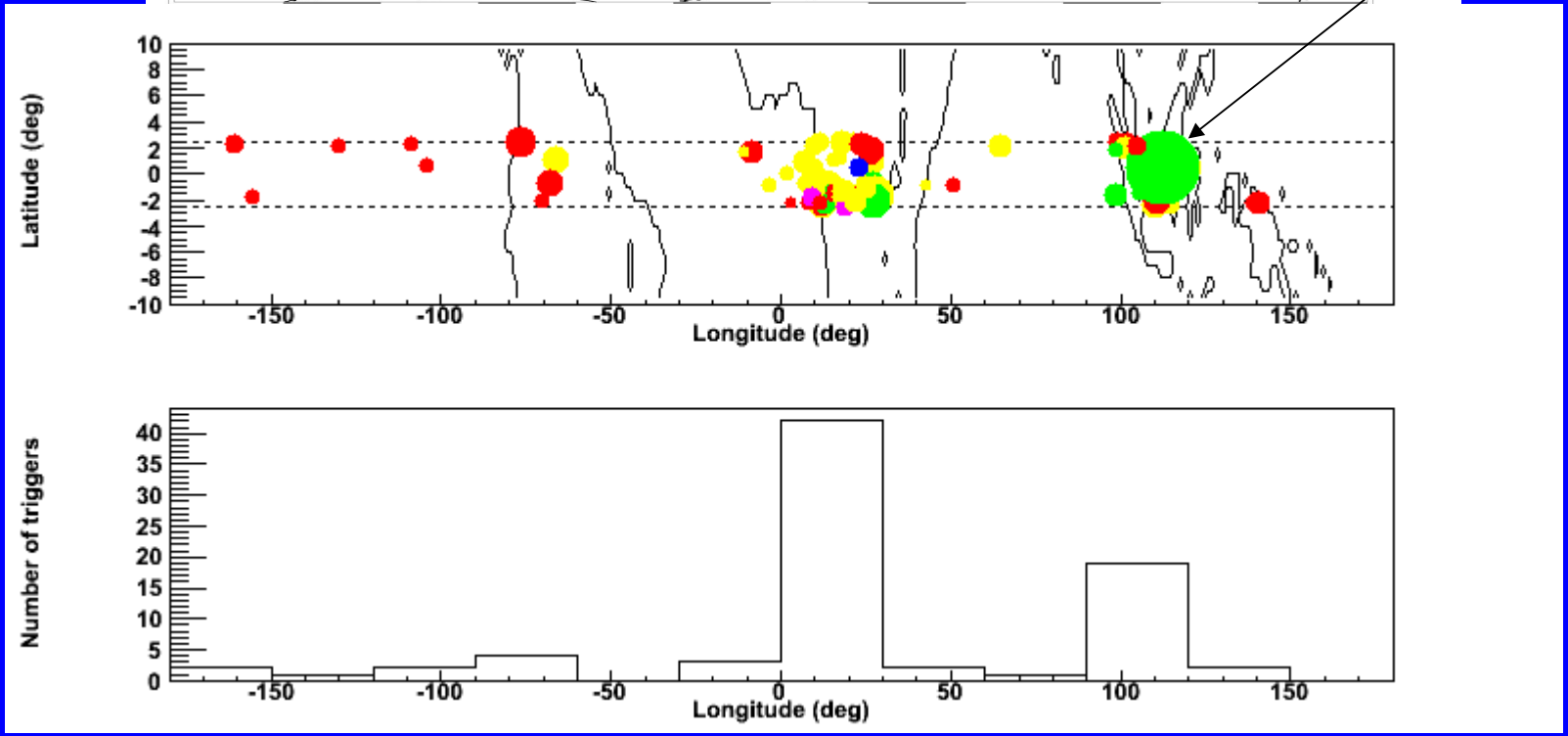
34 events
< Apr.'09 dataset

Geographical distribution

IASF Bologna



#11026-1 12/06/09
59 photons
the brightest

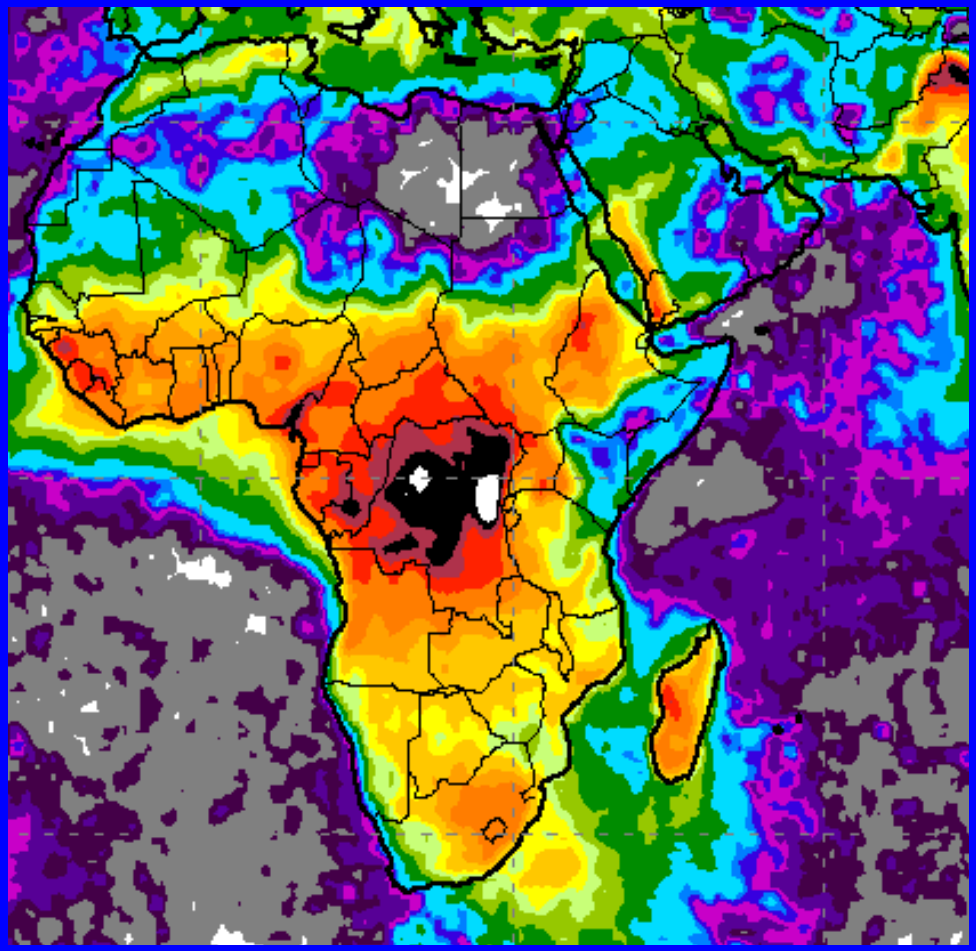


0.2 < HR < 0.5
0.5 < HR < 1.
1. < HR < 2.
2. < HR < 3.
3. < HR < 4.
HR > 4.
10 counts
20 counts
30 counts
instrumental

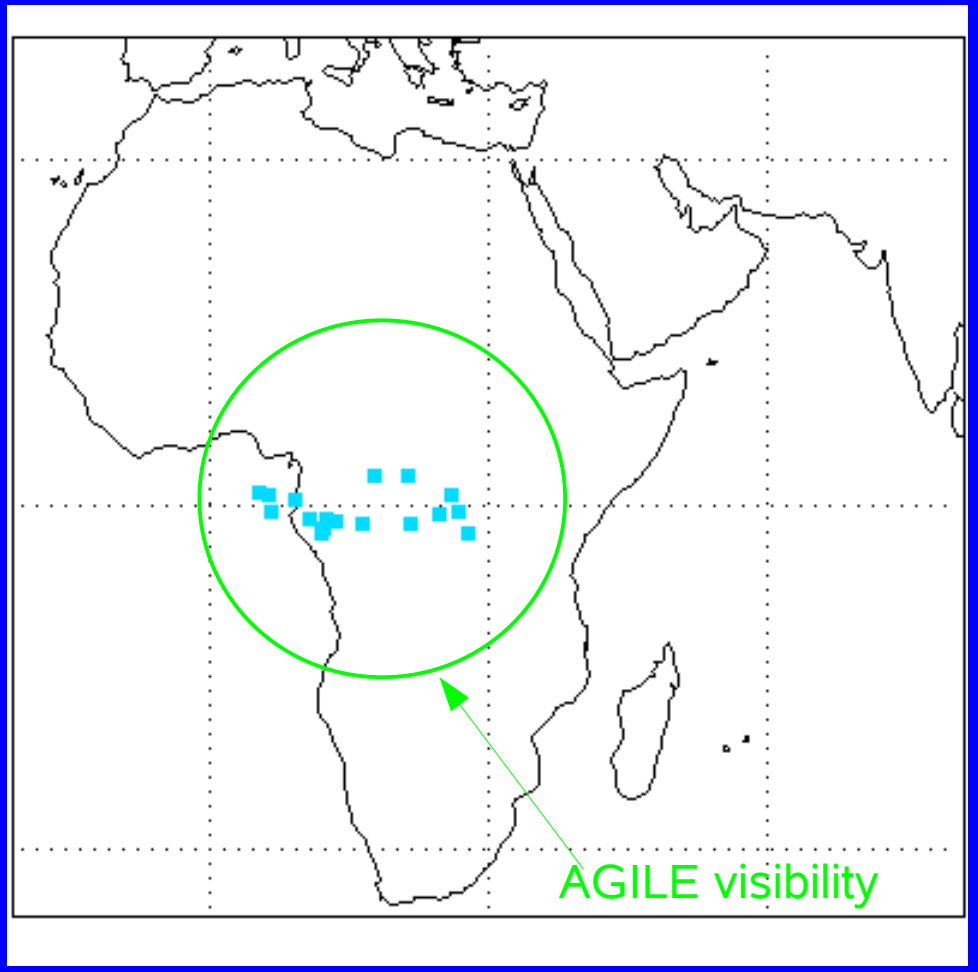
A close look to Africa

IASF Bologna

Lightning intensity map



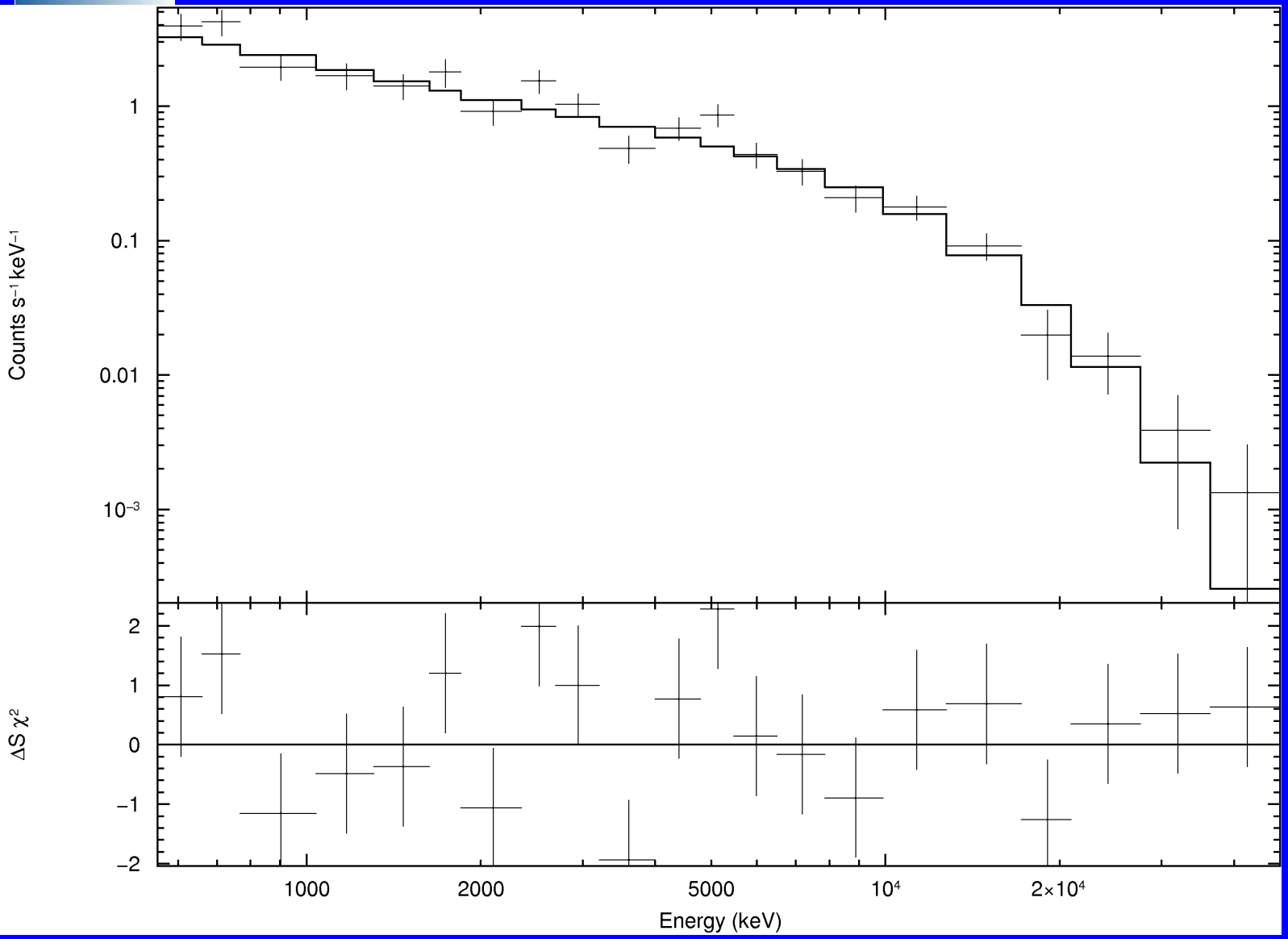
AGILE TGF sub-satellite points



Events clustering over Western Africa is consistent with TGF production <~300km close to sub-satellite point, Cummer et al., GRL (2005)

Cumulative spectrum

IASF Bologna



34 TGF dataset cutoffpl model fitting with XSPEC

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

$\alpha = 0.4 +/- 0.3$

$E_0 = 8.5 +/- 1.6$ MeV

red. $\chi^2 = 1.4$ (18 d.o.f.)

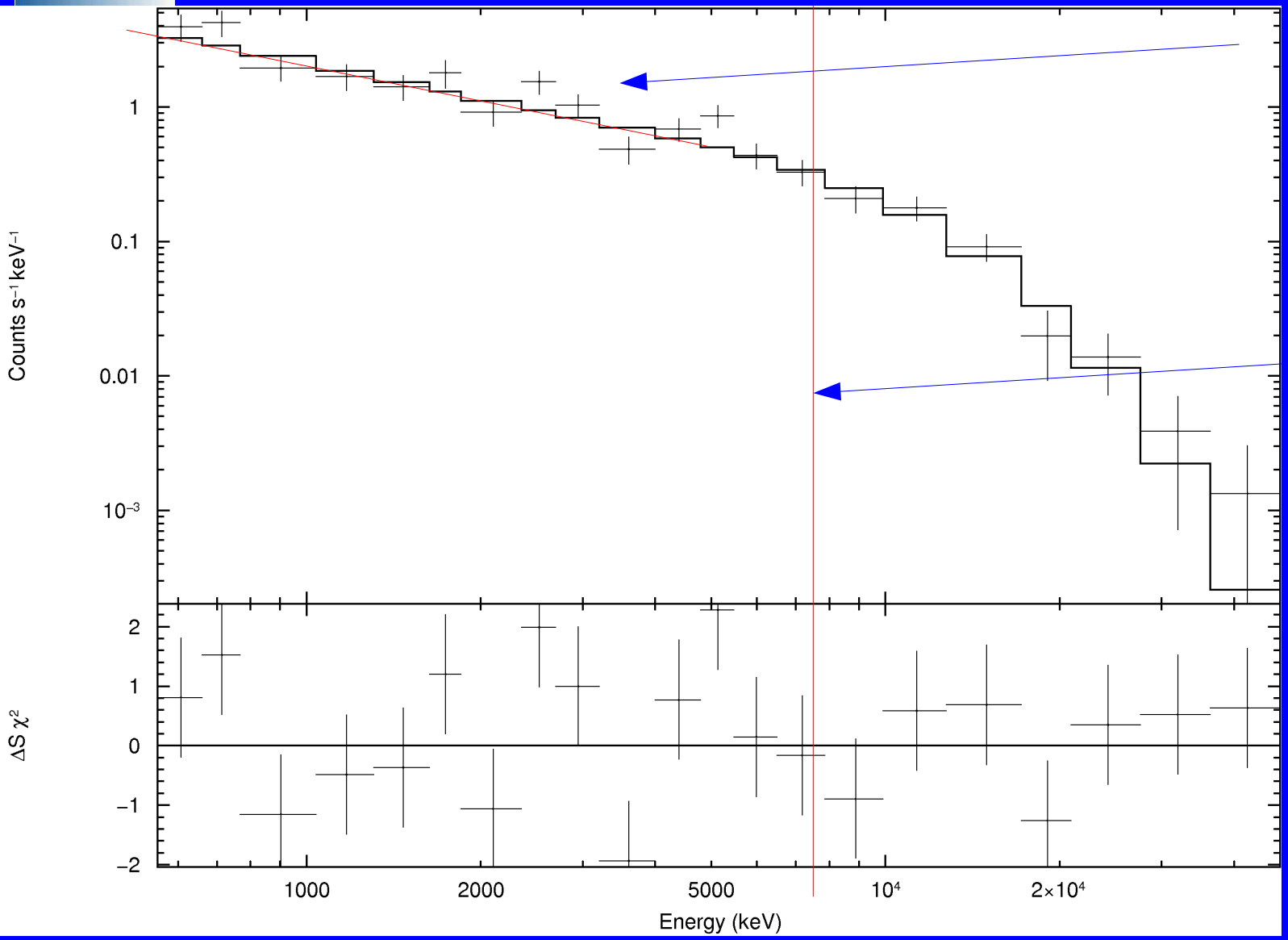
47 γ E > 10 MeV

8 γ E > 20 MeV

Aug. '09 updated dataset confirms spectral behavior

Implications for theoretical models

IASF Bologna



compatible with RREA models for 15-20 km production altitudes (Dwyer and Smith 2005)

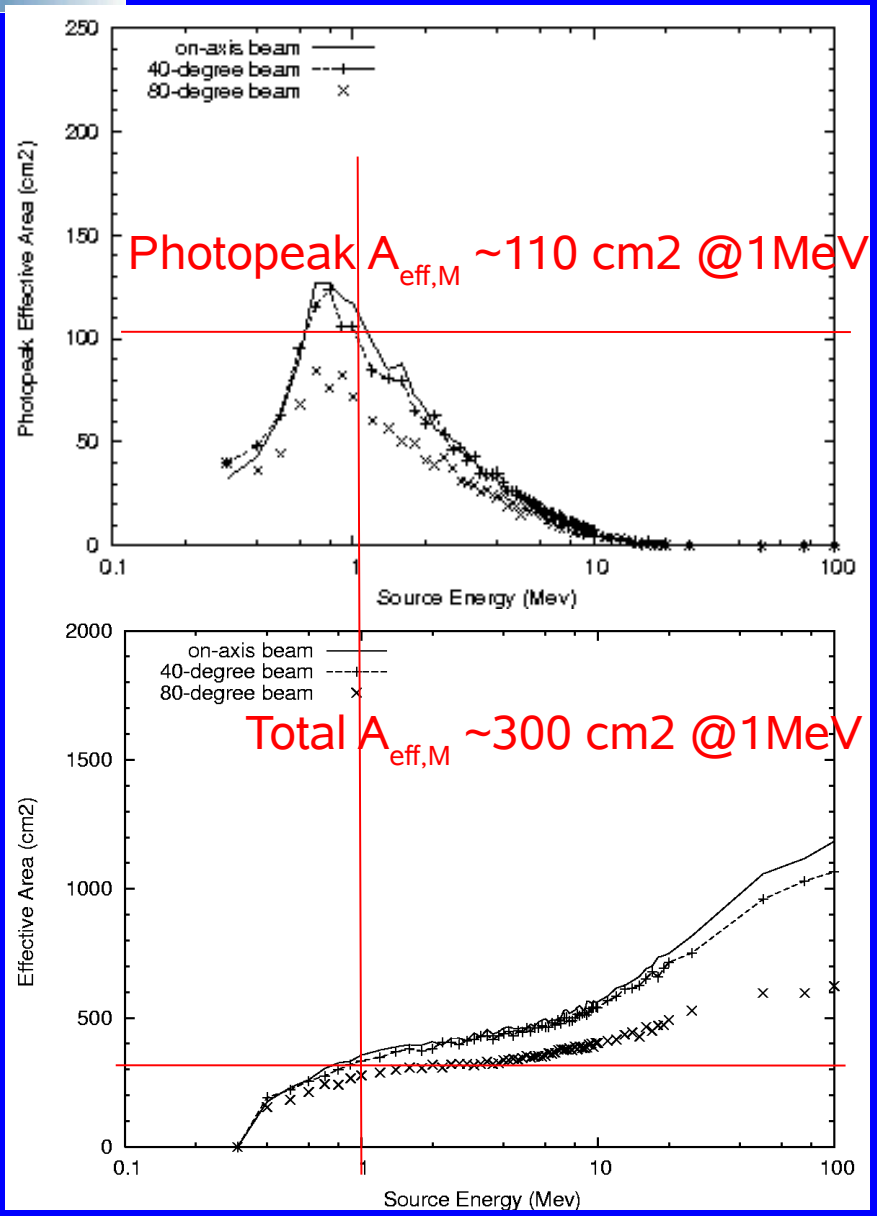
E0 compatible with the ~7.6 MeV average energy for RR electrons

detection of γ up to ~40 MeV doubles the maximum energy reported up to now: challenge for emission models

AGILE-MCAL vs RHESSI

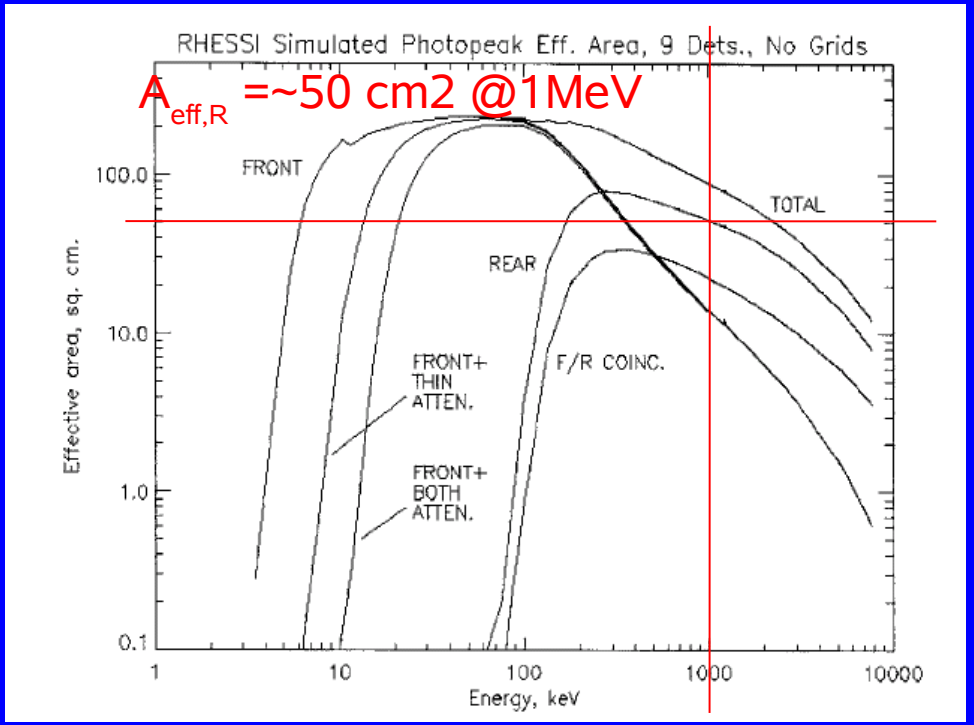
IASF Bologna

MCAL



Labanti et al., (2009)

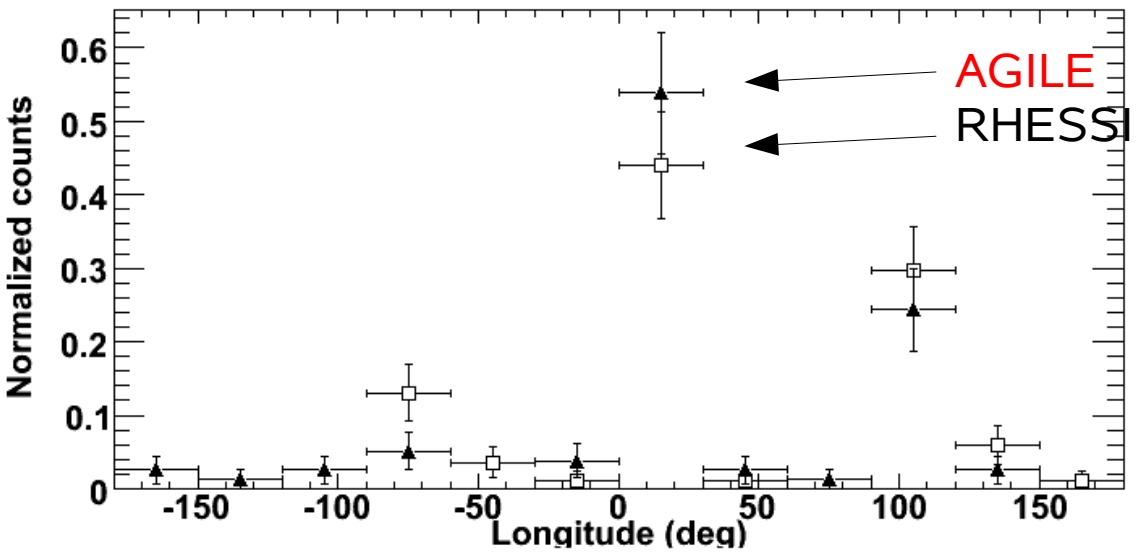
RHESSI

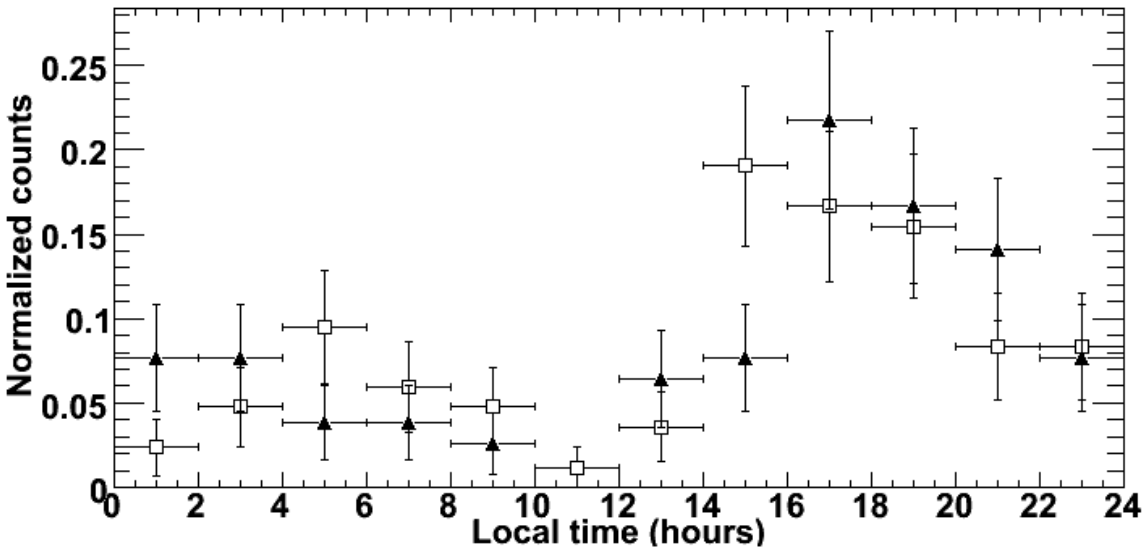


Smith et al., (2002)

AGILE vs RHESSI: longitude and local time

IASF Bologna





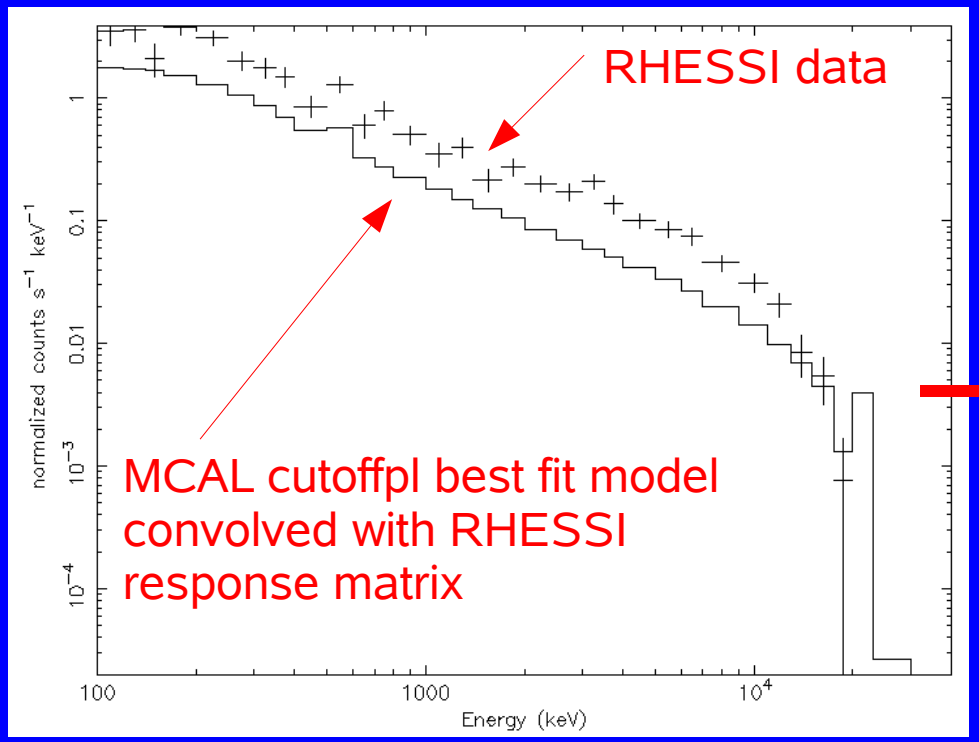
1st RHESSI TGF catalog Grefenstette et al., JGR, (2009)

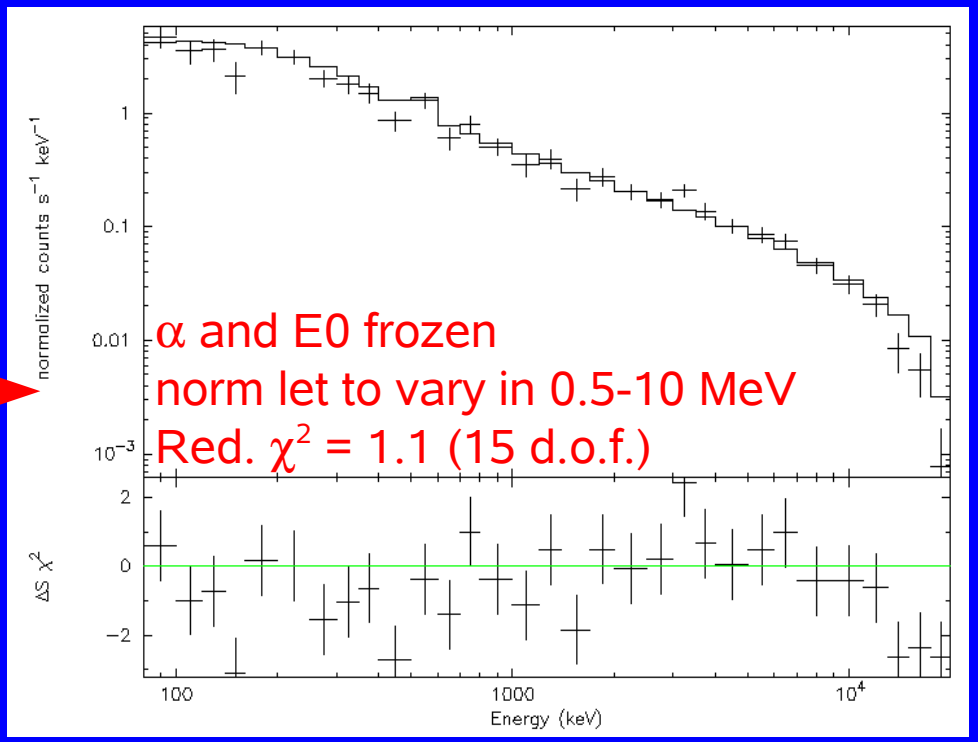
selected RHESSI TGFs in a +/- 2.5° latitude belt (like AGILE orbit) T_0 < 1st Jan. 2006

Longitude and local time distributions are compatible

AGILE vs RHESSI: cumulative spectrum

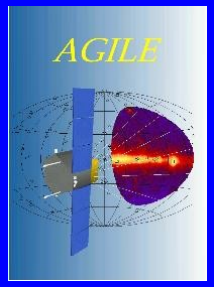
IASF Bologna





Spectral shape is the same
Factor ~2.5 in normalization constant (different populations, calibration, dead-time effects)

Trigger 11026-1 in details



INAF

Light curve

Position distribution

Energy vs time

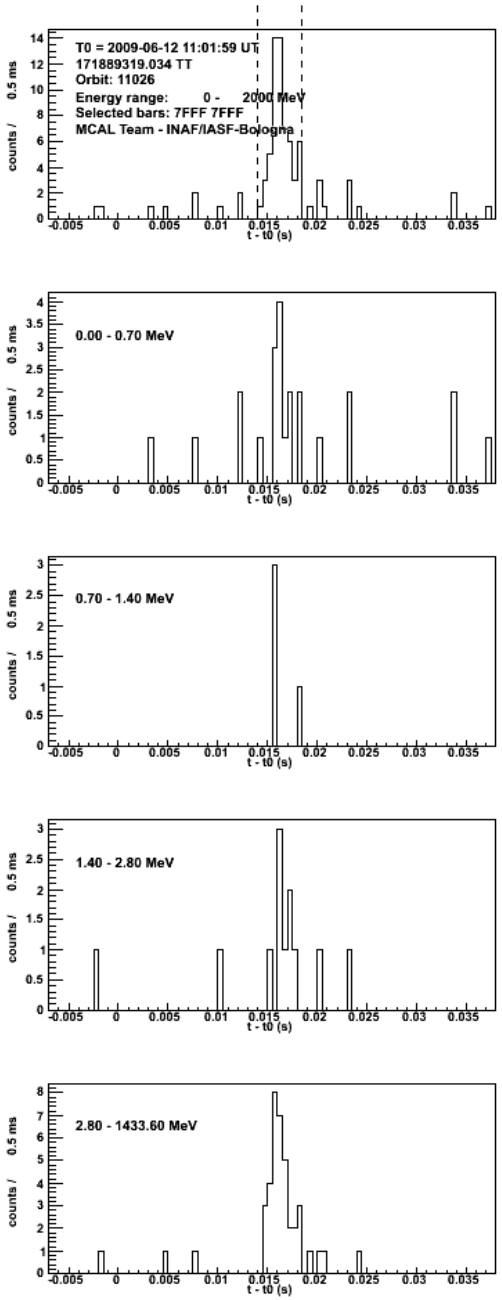
All range

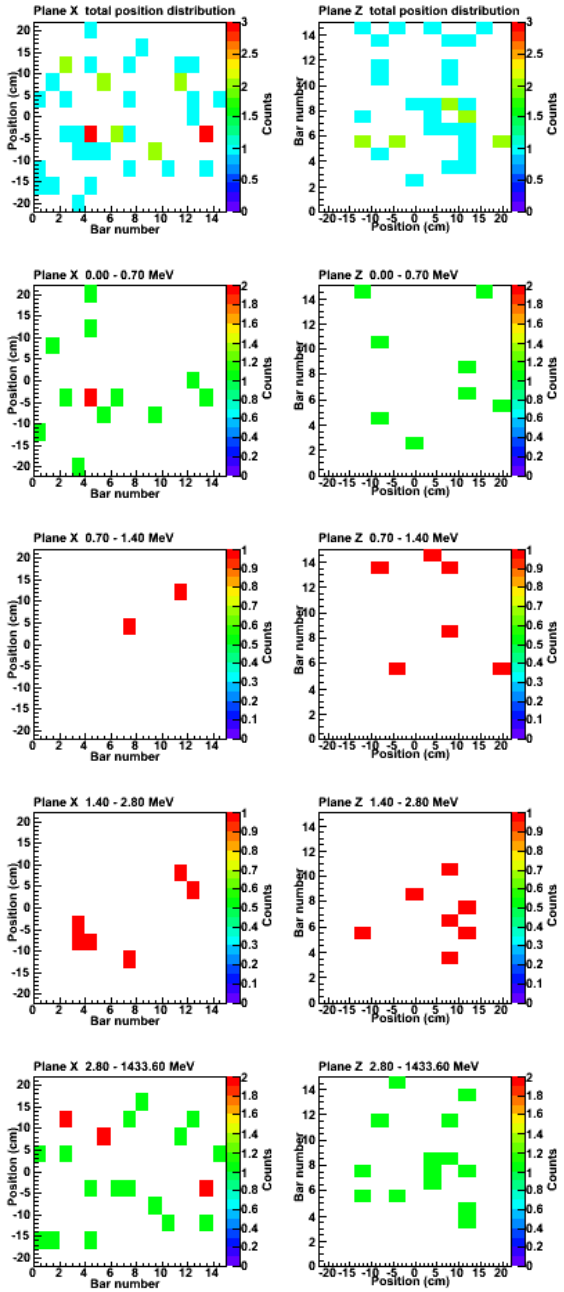
<0.7 MeV

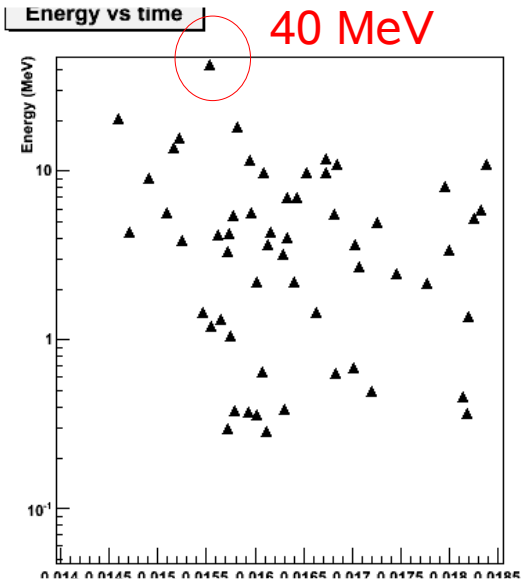
0.7-1.4 MeV

1.4-2.8 MeV

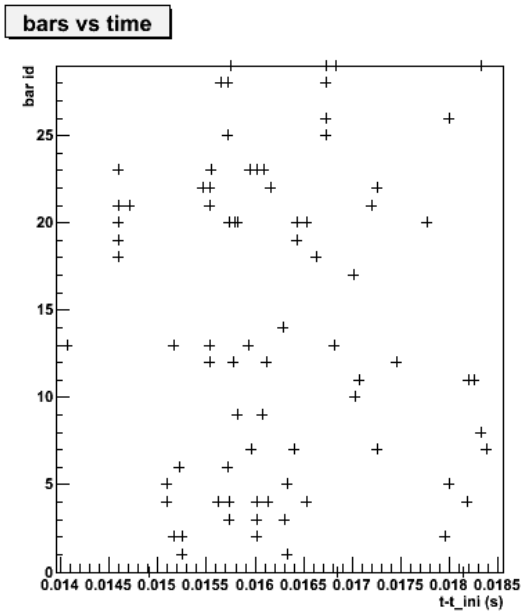
>2.8 MeV







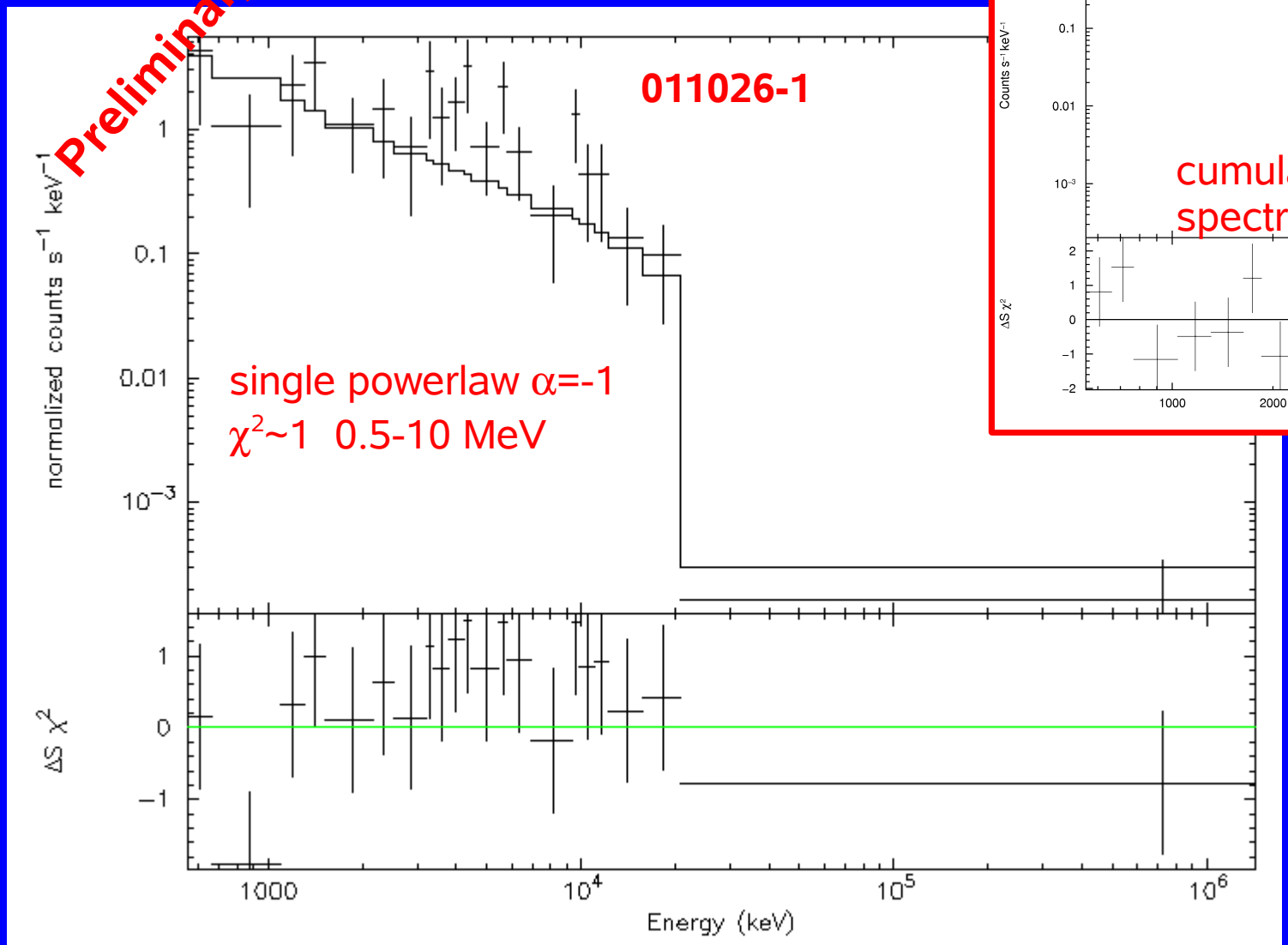
Bar address vs time

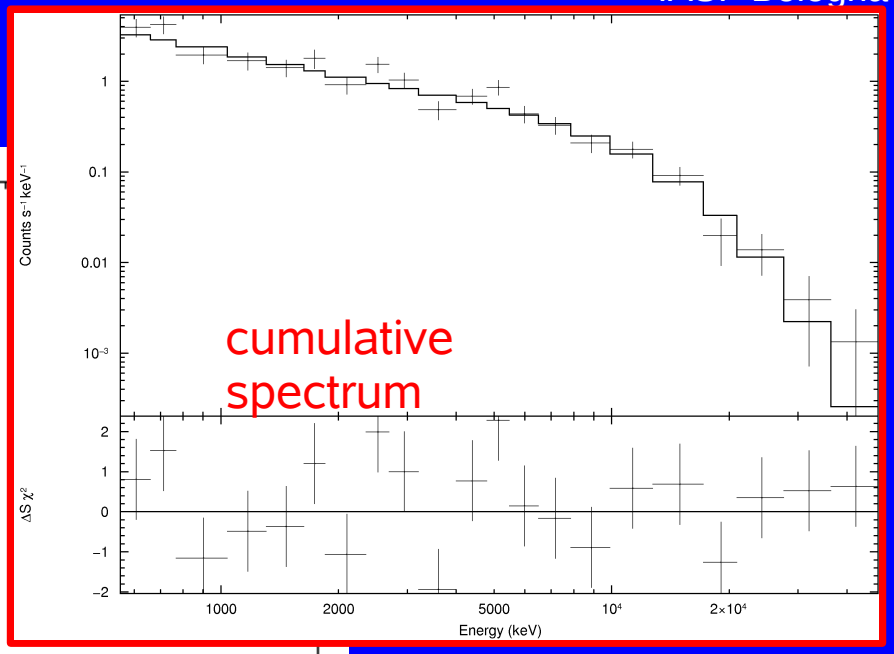


Single TGF energy spectrum

IASF Bologna

Preliminary!





Compatible with higher production altitude?

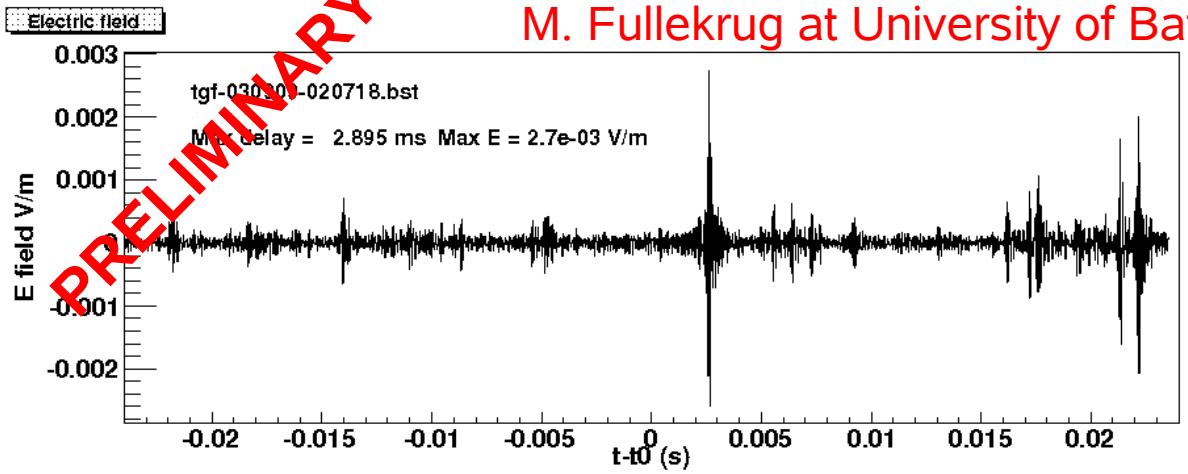
The cumulative model still gives χ^2~0.8

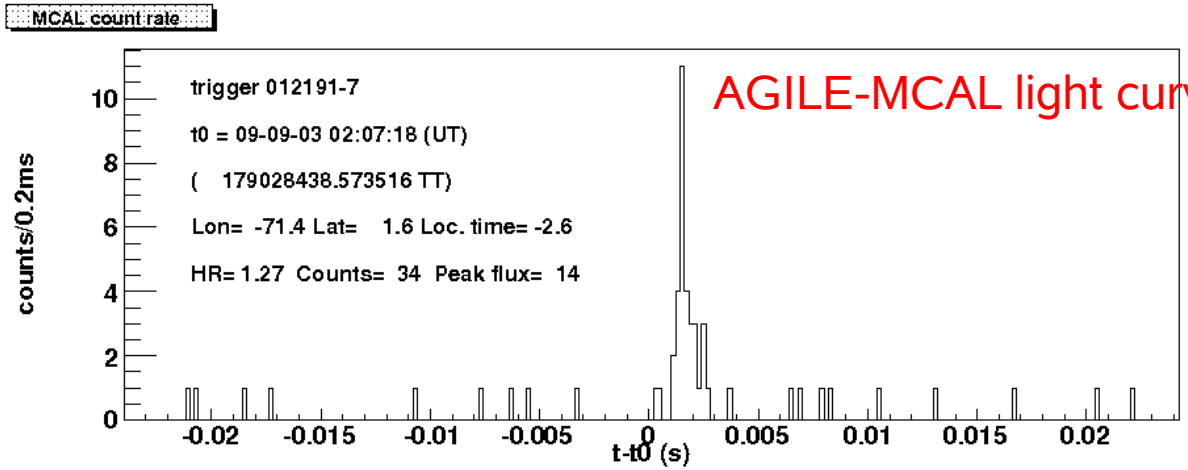
Need more bright events

Correlation with Sferics

IASF Bologna

Broad-band VLF measurements taken by M. Fullekrug at University of Bath (GB)

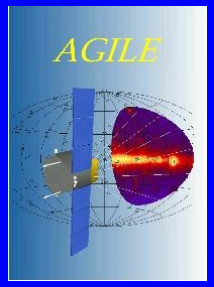




AGILE-MCAL light curve

Correlation with VLF measurements is useful to extract the main parameters of the lightning possibly associated to the TGF

Collaboration established with M. Fullekrug, University of Bath, UK (good for Africa), and with S. Cummer, University of Durham, NC, USA (good for Central America)



Conclusions

IASF Bologna

- AGILE-MCAL detects TGFs.
- Moreover, AGILE is very well suited for TGF science (energy range, <1ms trigger logic, photon-by-photon with μs timing, ~equatorial orbit)
- Paper with detections prior to March 2009 accepted by J. Geophysical Res. preprint available at AGU papers in press site: http://www.agu.org/journals/ja/papersinpress.shtml#id2009JA014502
- AGILE and RHESSI TGF samples are consistent concerning longitude, local time distribution and spectral shape
- Events detected since April 2009 confirm previous findings with better statistics
- Improvements in the trigger selection criteria are possible
- Spectral analysis of bright events is possible
- Work in progress: correlation with VLF sferics, real-time TGF monitoring and alert