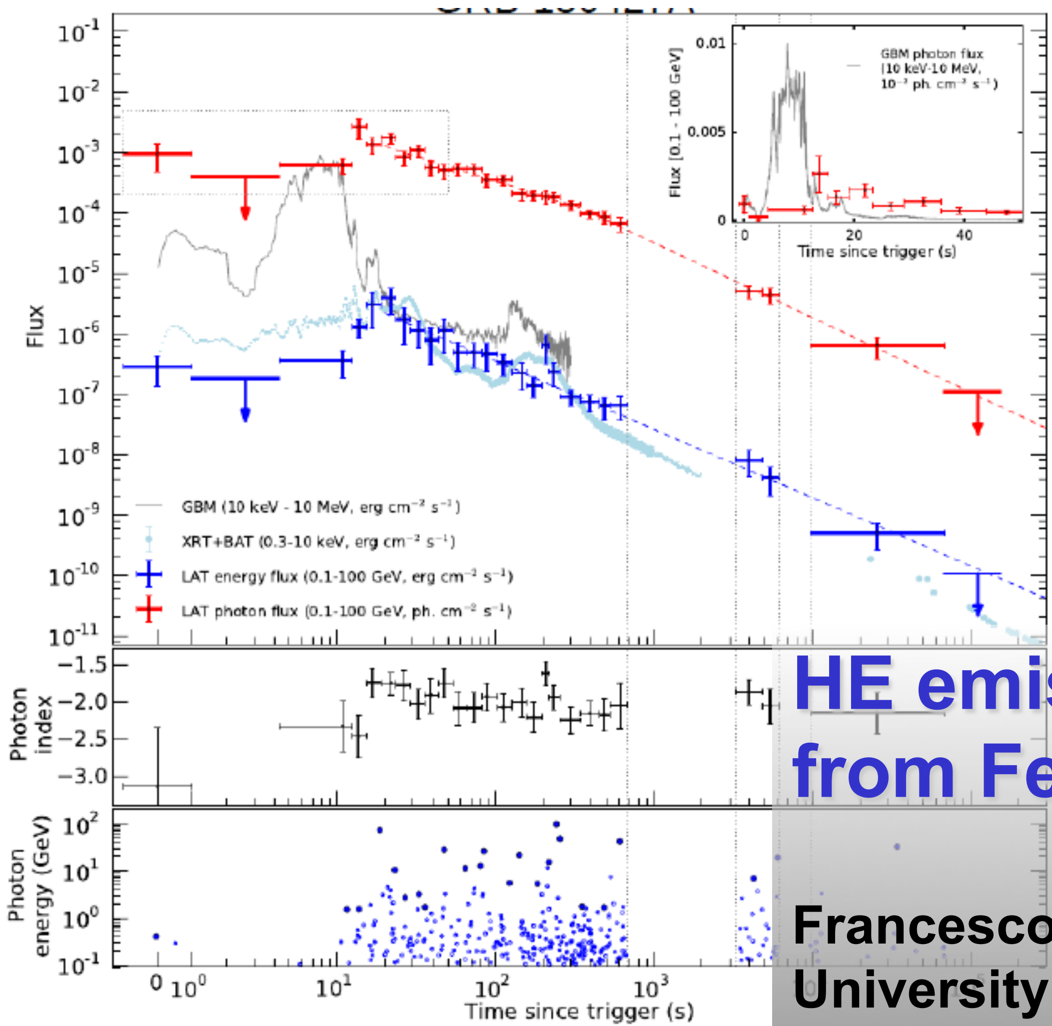

HE emission from GRBs from Fermi to IACTs

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In memory of Magnus Axelsson

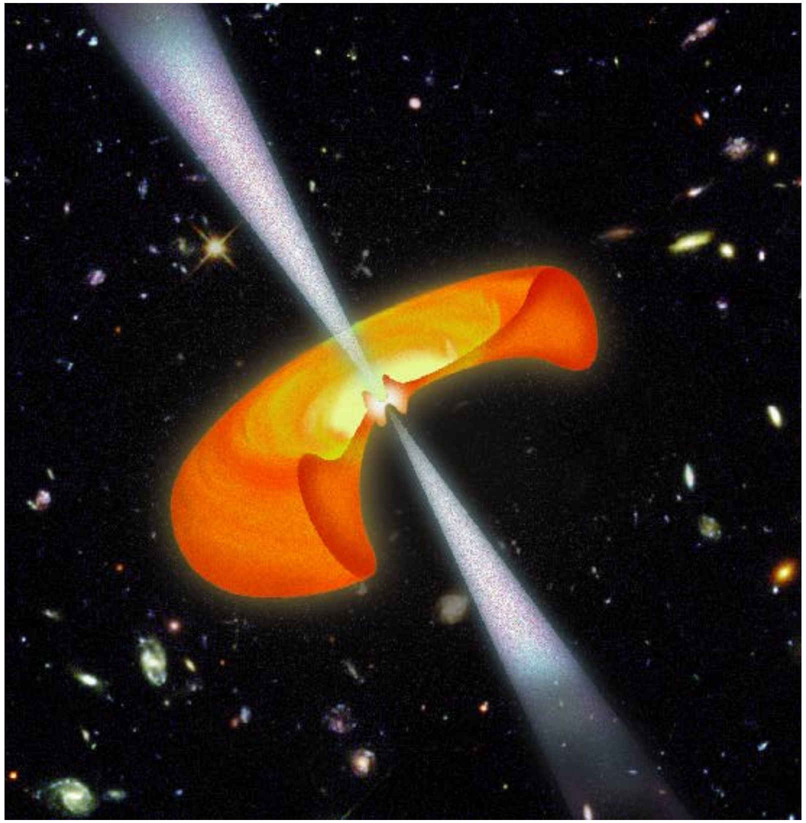
In remembrance of Magnus Axelsson

Department of Physics < News

In the middle of the summer we received the unexpected and very sad news that our colleague Magnus Axelsson has passed away. Thanks to his kindness, competence and helpfulness, Magnus was one of our most valued colleagues. His main commitment was to undergraduate education both at the Department and the Faculty.

Outline of the Lecture

- GRB a puzzle being solved?
  - Brief GRB history
    - Seven GRB eras
  - GRB observations
    - The prompt
    - The afterglow
  - HE emission from GRBs
  - VHE emission from GRBs



Seven eras

Adapted from L.Amati

1) "Dark" era (1973-1991): discovery
   Klebesadel, Strong & Olson's discovery (1973);
2) BATSE era (1992-1996): spatial distribution
   Meegan & Fishman's discovery (1992),
   detection rate: ~1 to 3 /day, ~3000 bursts;
3) BeppoSAX era (1997-2000): afterglows
   van Paradijs, Costa, Frail's discoveries (1997);
4) HETE-2 era (2001-2004): origin of long bursts
   Observations on GRB030329/SN2003dh
5) Swift era (2005-): very early afterglows, short-GRB afterglow, GRB subclasses? GRB cosmology?
6) Fermi era (2008-): High energy emission component, GW counterparts! – origin of short GRB
7) VHE era (2019-): VHE emission component from GRB!

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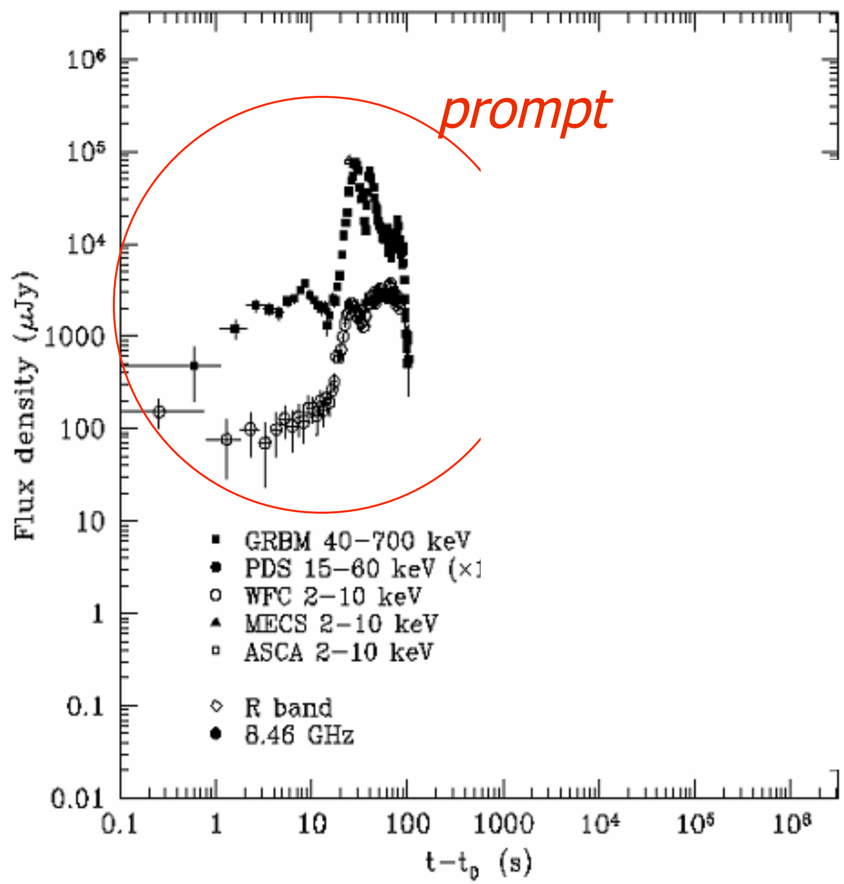
The GRB phenomenon

Adapted from L.Amati

- in 1997, thanks to BeppoSAX observations, discovery of fading X-ray, optical, radio emission following the GRB

- photons received during the classical GRB phenomenon are then called "prompt emission" and the subsequent fading emission is called "afterglow emission"

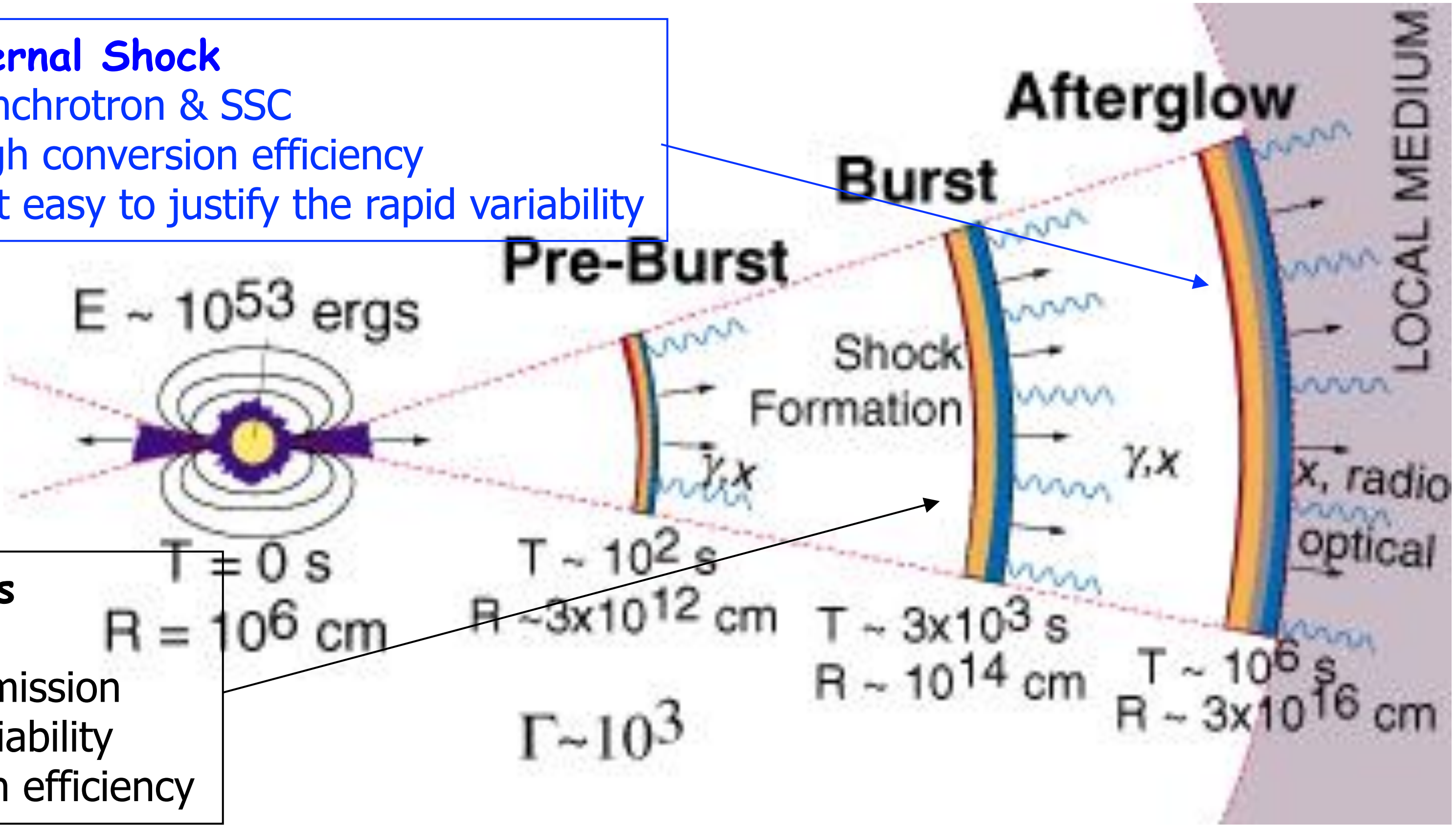


Adapted from Maiorano et al., A&A, 2005

The Fireball “standard” model

- Relativistic motion of the emitting region
- Shock mechanism converts the kinetic energy of the shells into radiation.
- Baryon Loading problem

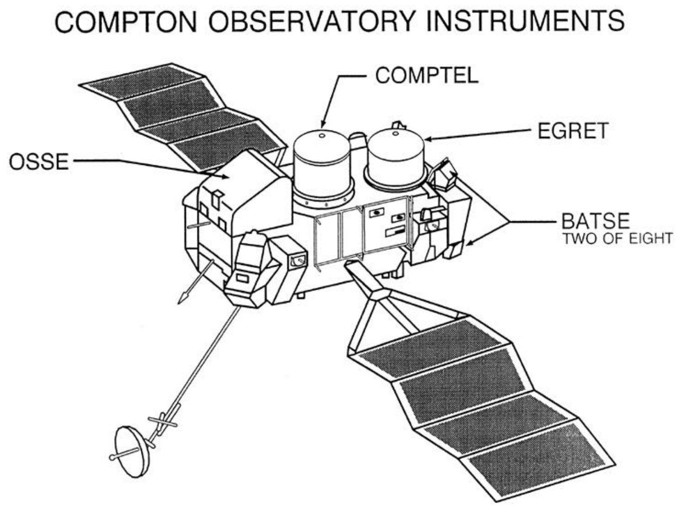
External Shock
- Synchrotron & SSC
- High conversion efficiency
- Not easy to justify the rapid variability

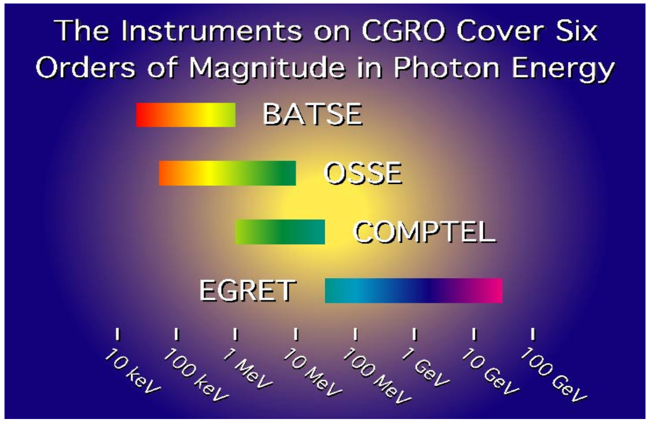


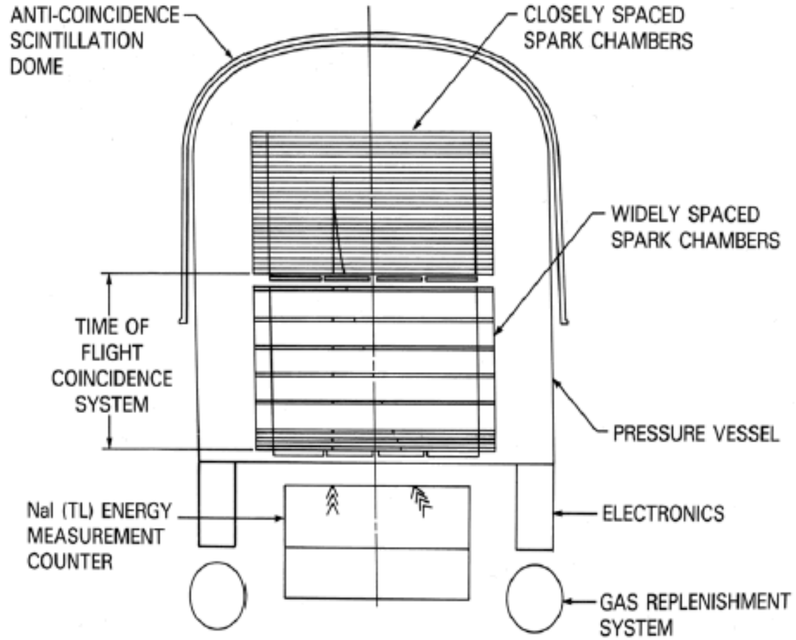
Internal Shocks
- Source activity
- Synchrotron Emission
- Rapid time Variability
- Low conversion efficiency

High Energy Emission from GRB
"The AGILE/Fermi era"

The Compton Gamma Ray Observatory



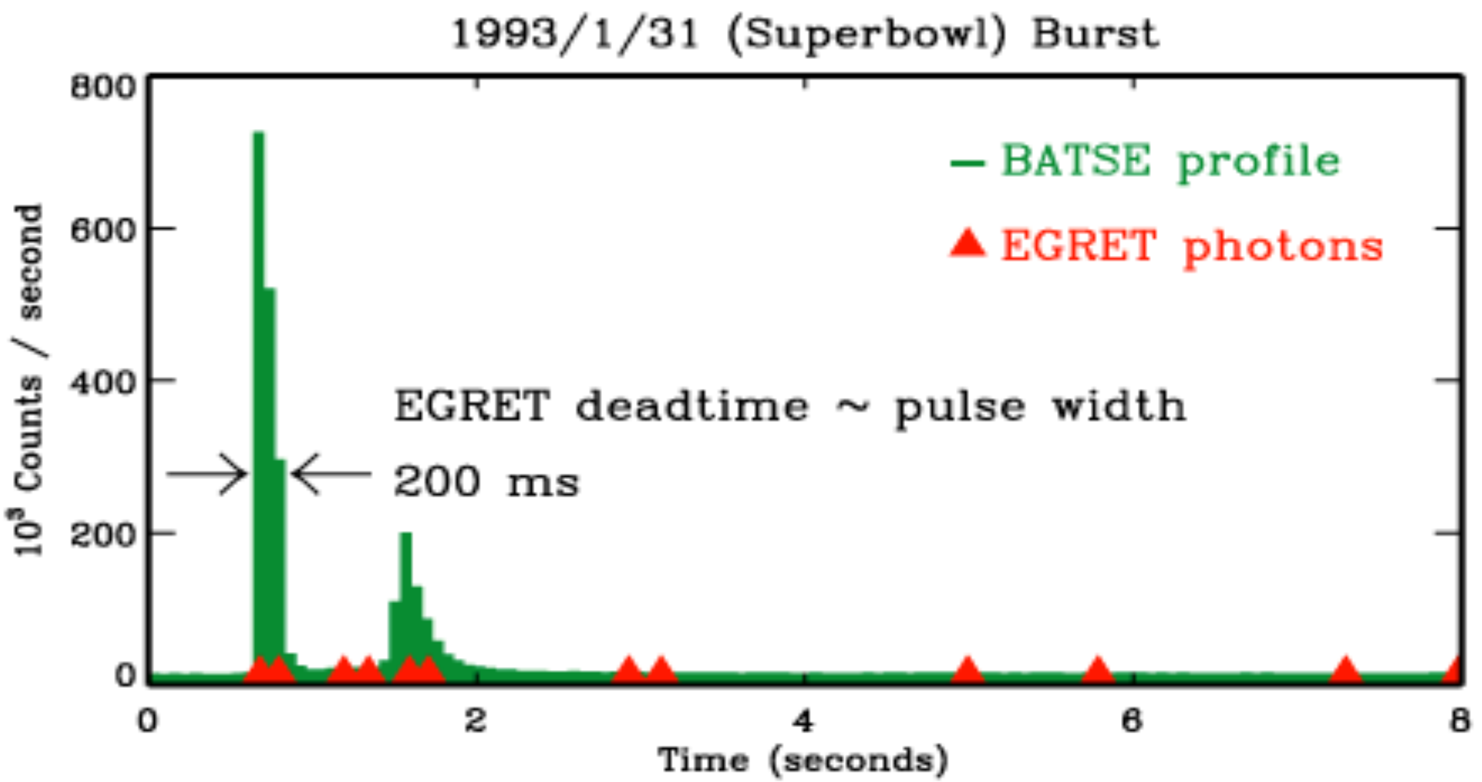




EGRET

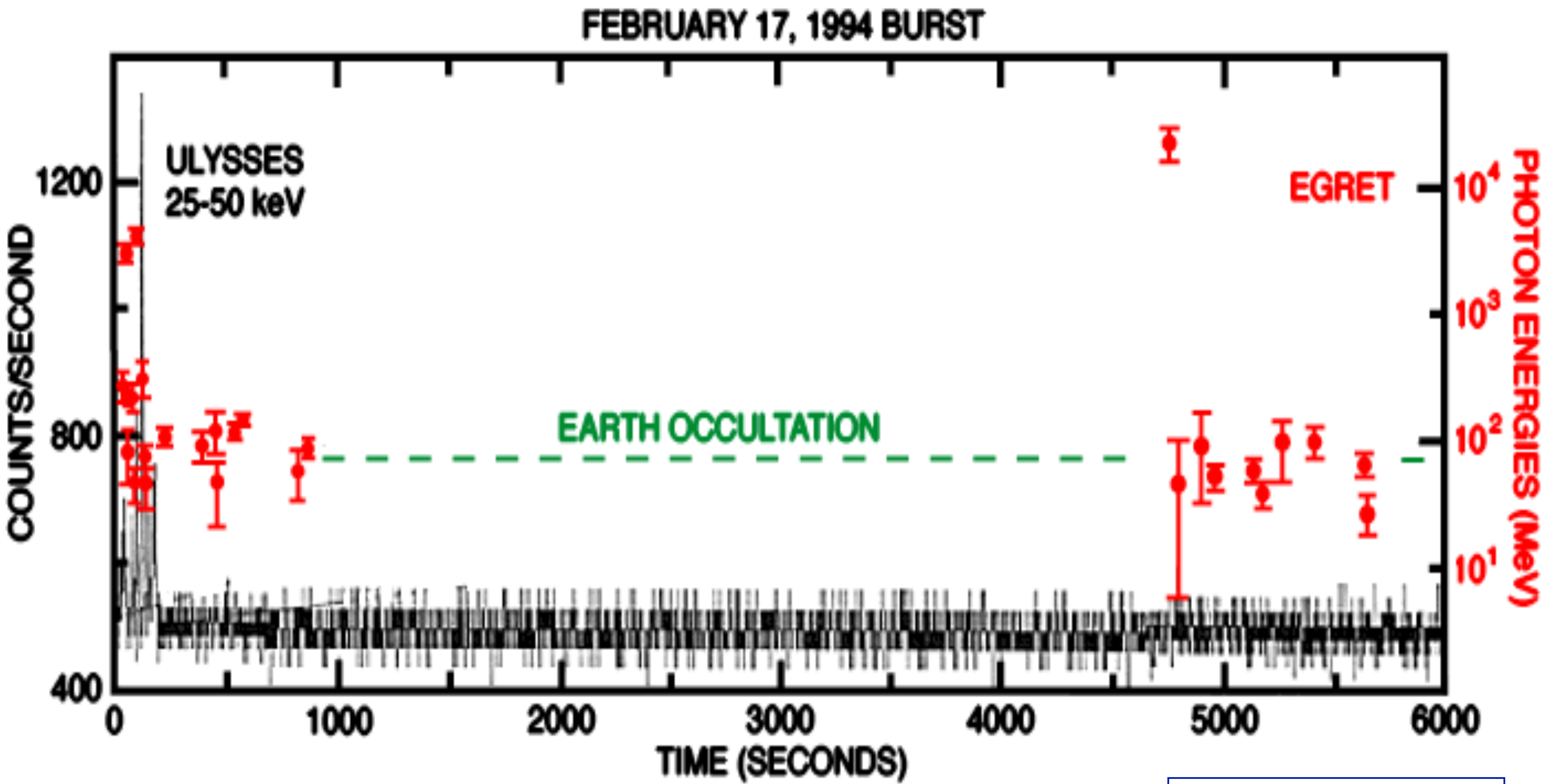
- 1991-2000
- 30 MeV - 30 GeV
- AGN, GRB, Unidentified Sources, Diffuse Bkg

GRB prompt emission



Kouveliotou et al 1994
Sommer et al. 1994

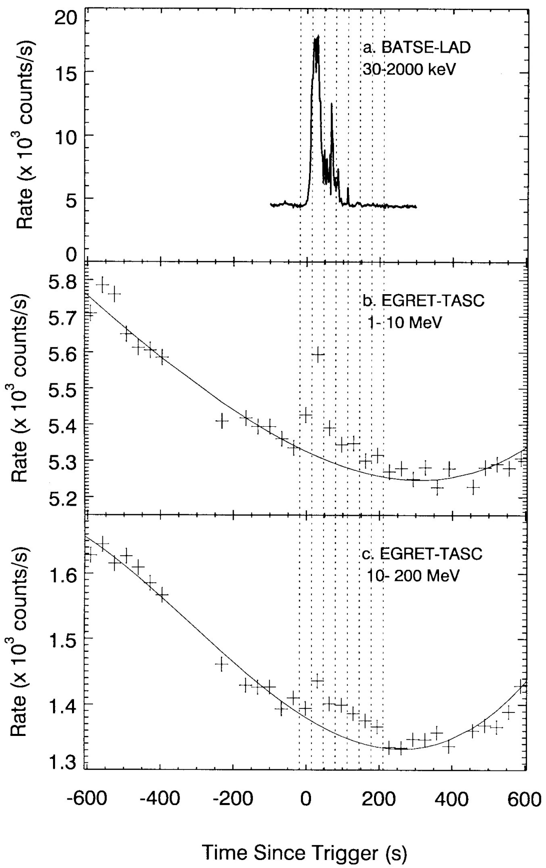
GRB delayed emission

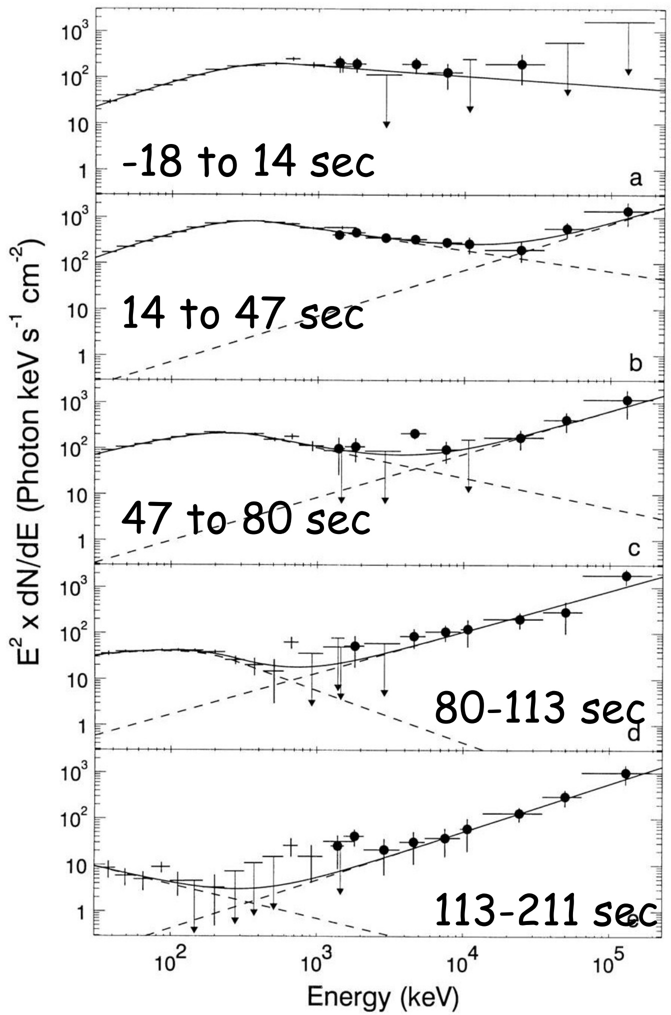


Hurley et al. 1994

Extra Spectral Components?

GRB 941017





Gonzalez, et al. 2003

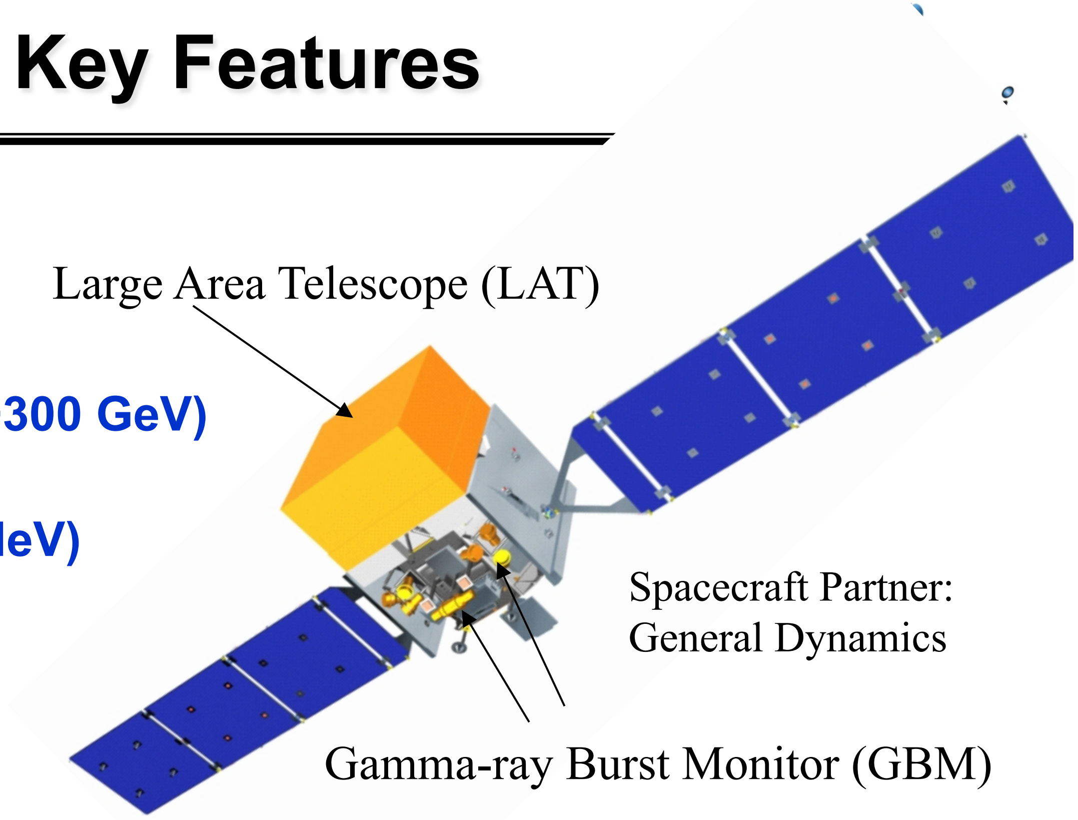
The EGRET heritage on GRBs

- Extended emission?
- Prompt emission?
- Spectral Components?
- Ubiquity of HE emission?

Fermi LAT and GRBs

Fermi Key Features

- **Two instruments:**



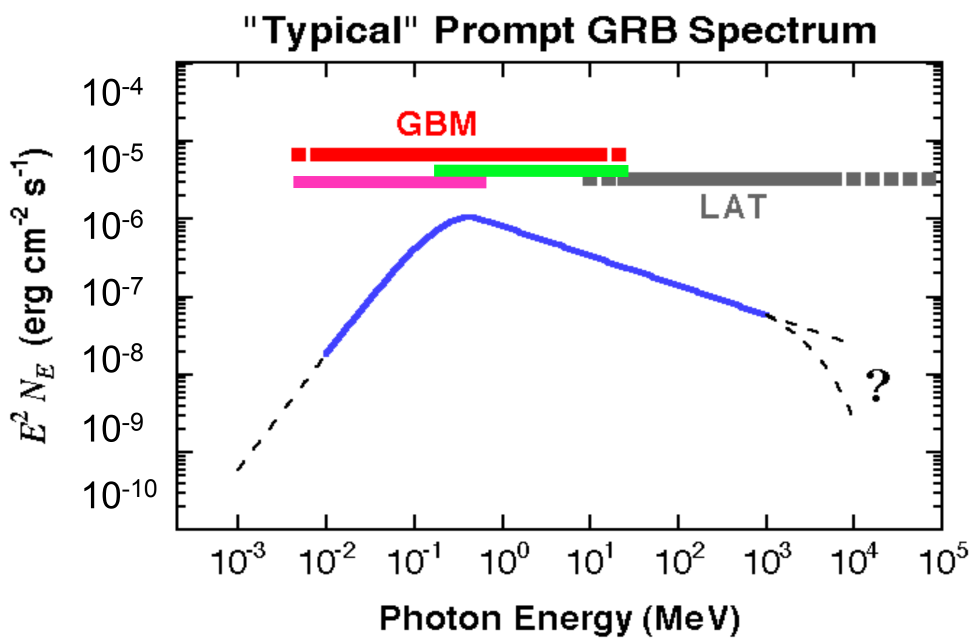
  - **LAT:**
    - **high energy (20 MeV – >300 GeV)**
  - **GBM:**
    - **low energy (8 keV – 40 MeV)**
- **Huge field of view**
  - **LAT: 20% of the sky at any instant; in sky survey mode, expose all parts of sky for ~30 minutes every 3 hours. GBM: whole unocculted sky at any time.**
- **Huge energy range, including largely unexplored band 10 GeV - 100 GeV**
- **Large leap in all key capabilities. Great discovery potential.**

Fermi and GRBs

- LAT: <20 MeV to >300 GeV. With both onboard and ground burst triggers.
- GBM: 12 NaI detectors— 8 keV to 1 MeV. Used for onboard trigger, onboard and ground localization, spectroscopy: 2 BGO detectors— 150 keV to 40 MeV. Used for spectroscopy.
- Total of >7 energy decades!
- ~200 GRB/year with observations from 8 keV to 40 MeV, ~10 GRB/year with observations from 8 keV to 300 GeV (# high energy detections is under study)

Exceptionally good spectral observations of the prompt phase of lots of GRB

Adapted from N.Omodei



Performance of the LAT

	LAT	EGRET
Energy range	20 MeV to >300 GeV	20 MeV – 30 GeV
Energy resolution (on axis, 100 MeV – 10 GeV)	<10%	10%
Peak effective area	9000 cm^2	1500 cm^2
Angular resolution (single photon, 10 GeV)	0.15°	0.54°
Field of view	>2.2 sr	0.4 sr
Deadtime per event	27 us	100 ms

- **Major improvements in capabilities for GRB observation**
  - **Efficient observing mode (don't look at Earth)**
  - **Wide FoV**
  - **Low deadtime (e***xploring dt's down to μsec)*
    - **Studies of short bursts possible**
  - **Large effective area**
  - **Good angular resolution**
  - **Increased energy coverage (to hundreds of GeV)**

Many GRBs

More photons detected from each GRB

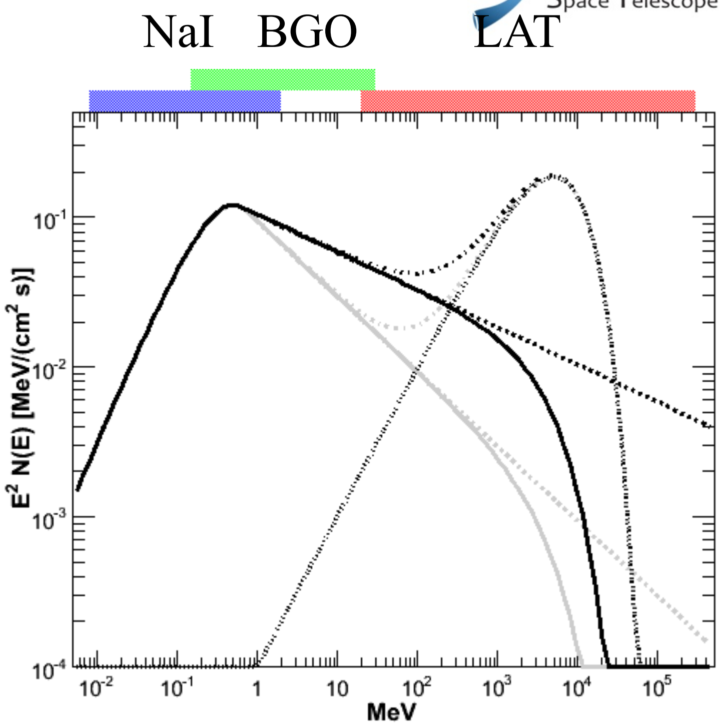
Good GRB locations

Adapted from N.Omodei

- Early result: 1 GRB / month detected by the LAT

Study GRB with the Fermi observatory

- Spectrum studied over 7 decades!
- Bright burst: study of the cut-off, if any.
- Detailed temporal/spectral evolution:
  - Is there any "extra component"?
  - How common is the extended/delayed GeV emission?
  - Pseudo-redshift estimators:
    - E_{peak}, E_{gamma},Duration, Variability, lag: provided by Fermi
    - Need redshift, T_{break}
      - improve statistics
      - new relations?
  - Time Lag in pulses as a function of energy
    - Intrinsic lag vs cosmological effect (QG)
- Observations are needed to understand how particles are accelerated in GRB, up to what energies, and how gamma-rays are emitted. Constrain the LF of the expanding shells.
- + DISCOVERIES (???)



Adapted from N.Omodei

GRB080916C - Bright LAT burst

GRB080916C

LAT on-ground position [GCN 8246]

On-ground Automated Science Processing triggered

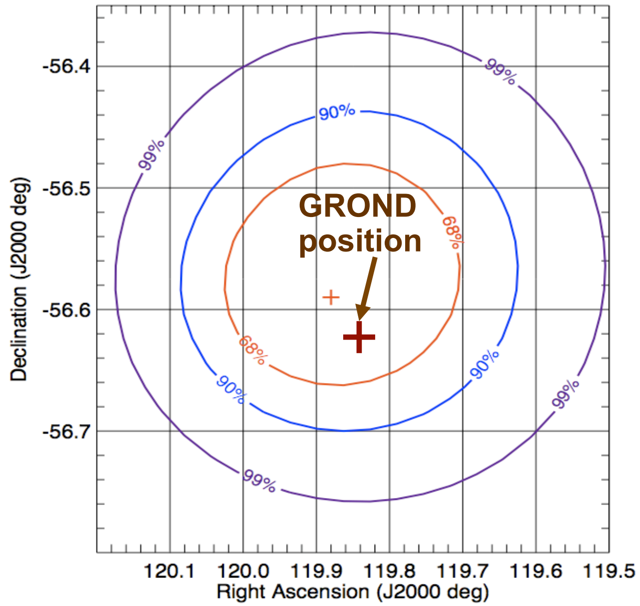
Considered a region 20 deg around GBM location - more than 10 photons > 1 GeV

RA = 119.88˚, Dec = −56.59˚

Statistical error = 0.09˚ (0.13˚) at 68% (90%) C.L.

Systematic error < 0.1˚ (preliminary)

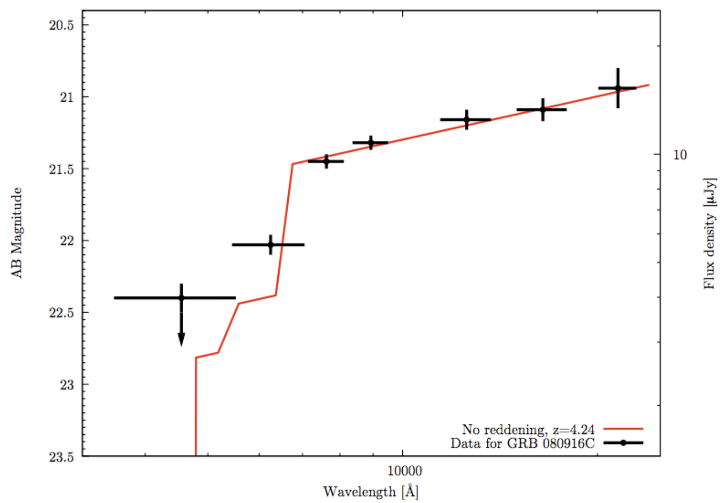
Consistent with GBM location



GROND optical follow up [GCN 8257, 8272]

Faint (21.7 mag at T_0+32h) and fading (T_0+3.3d) source

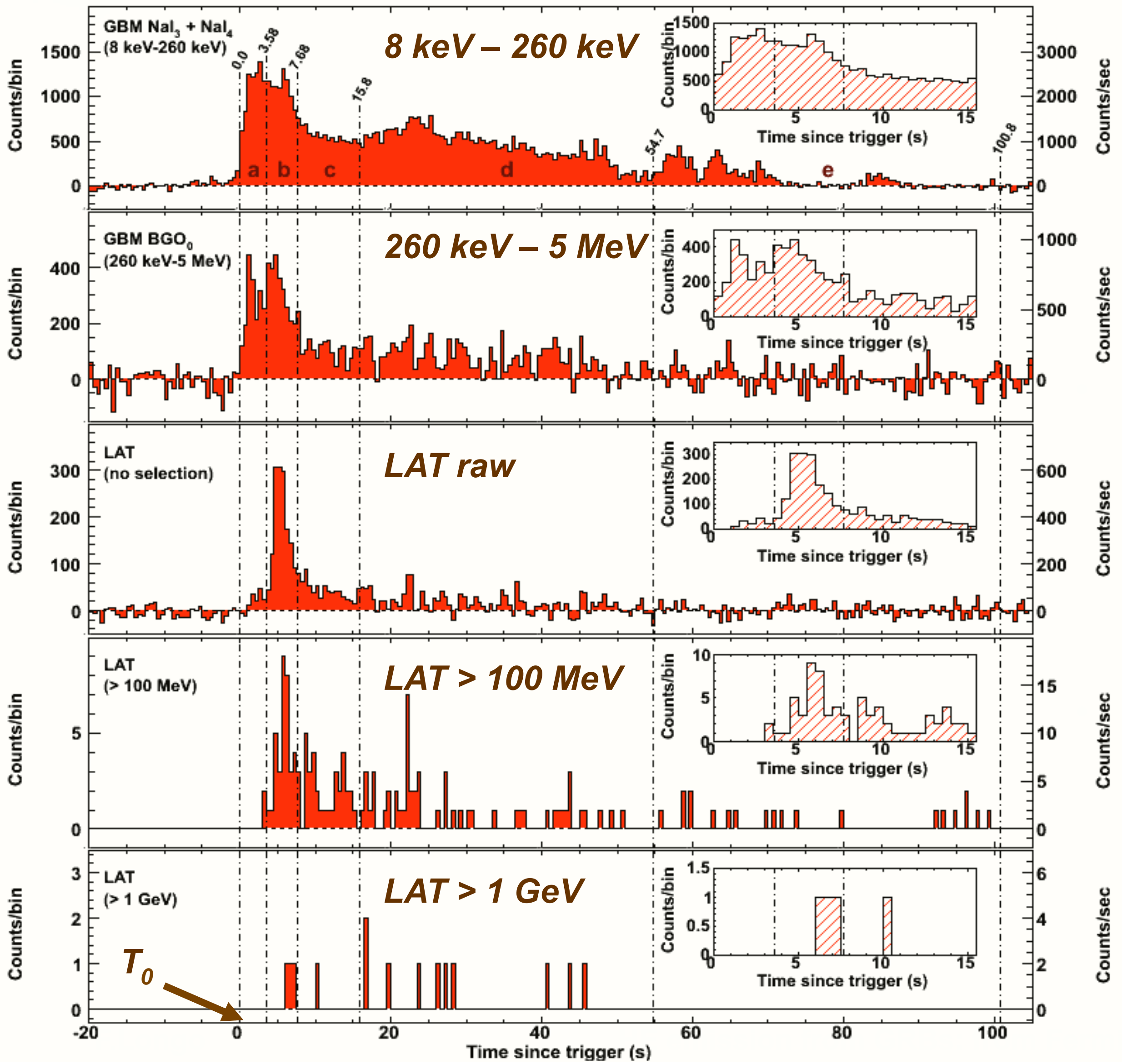
RA = 119.8472˚, Dec = −56.6383˚ (±0.5” at 68% C.L.)



Photometric redshift of z=4.2 +/- 0.3

Adapted from N.Omodei

GRB080916C - Multiple detector light curve



Adapted from N.Omodei

First 3 light curves are background subtracted

The LAT can be used as a counter to maximize the rate and to study time structures above tens of MeV

- **The first low-energy peak is not observed at LAT energies**

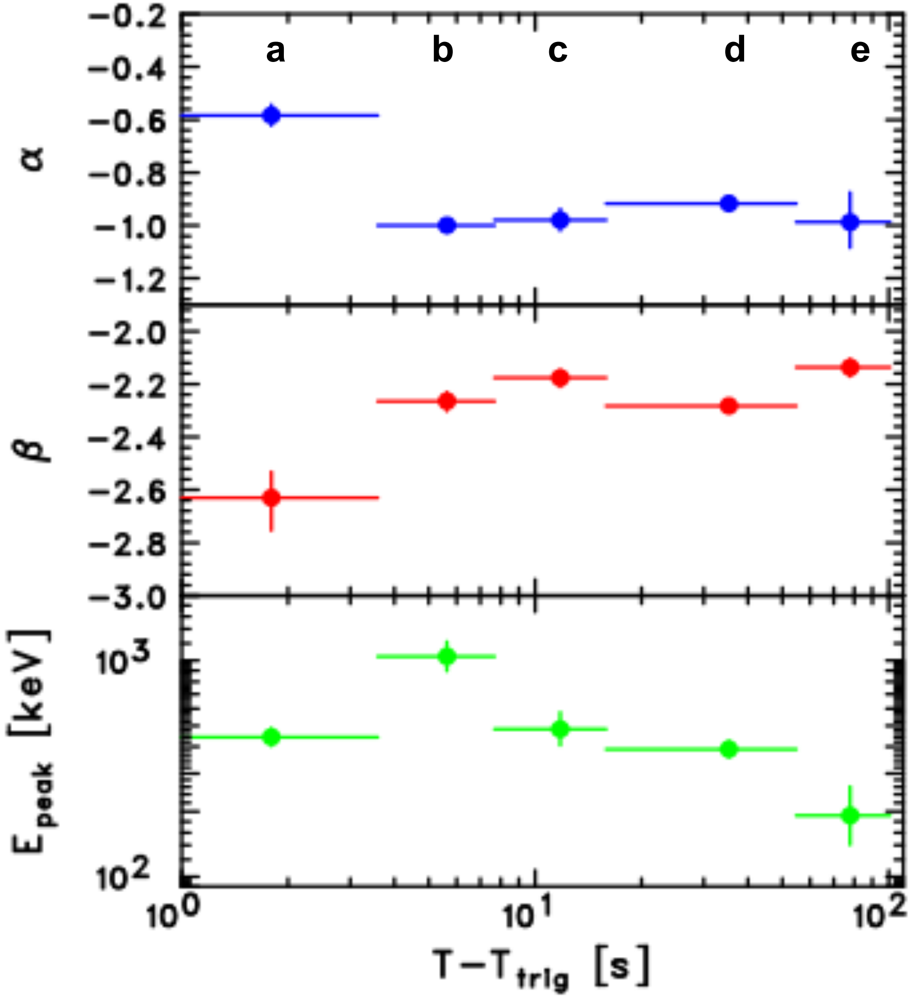
Spectroscopy needs LAT event selection (>100 MeV)

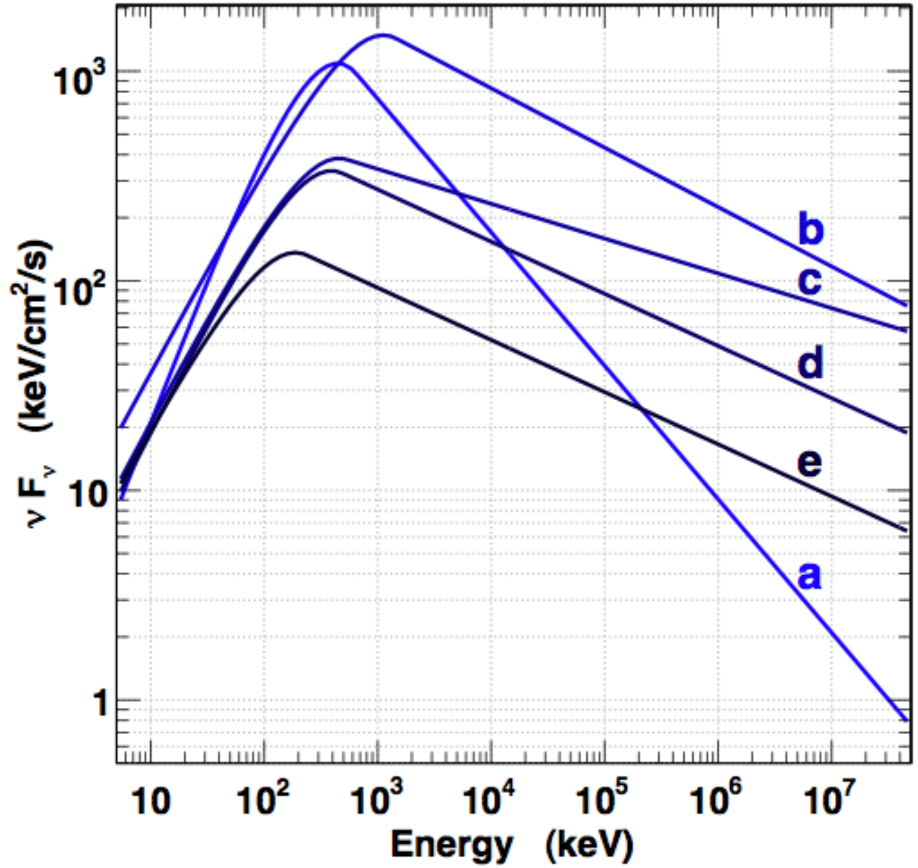
- **5 intervals for time-resolved spectral analysis: 0 – 3.6 – 7.7 – 16 – 55 – 100 s**
- **14 events above 1 GeV**

Spectral evolution

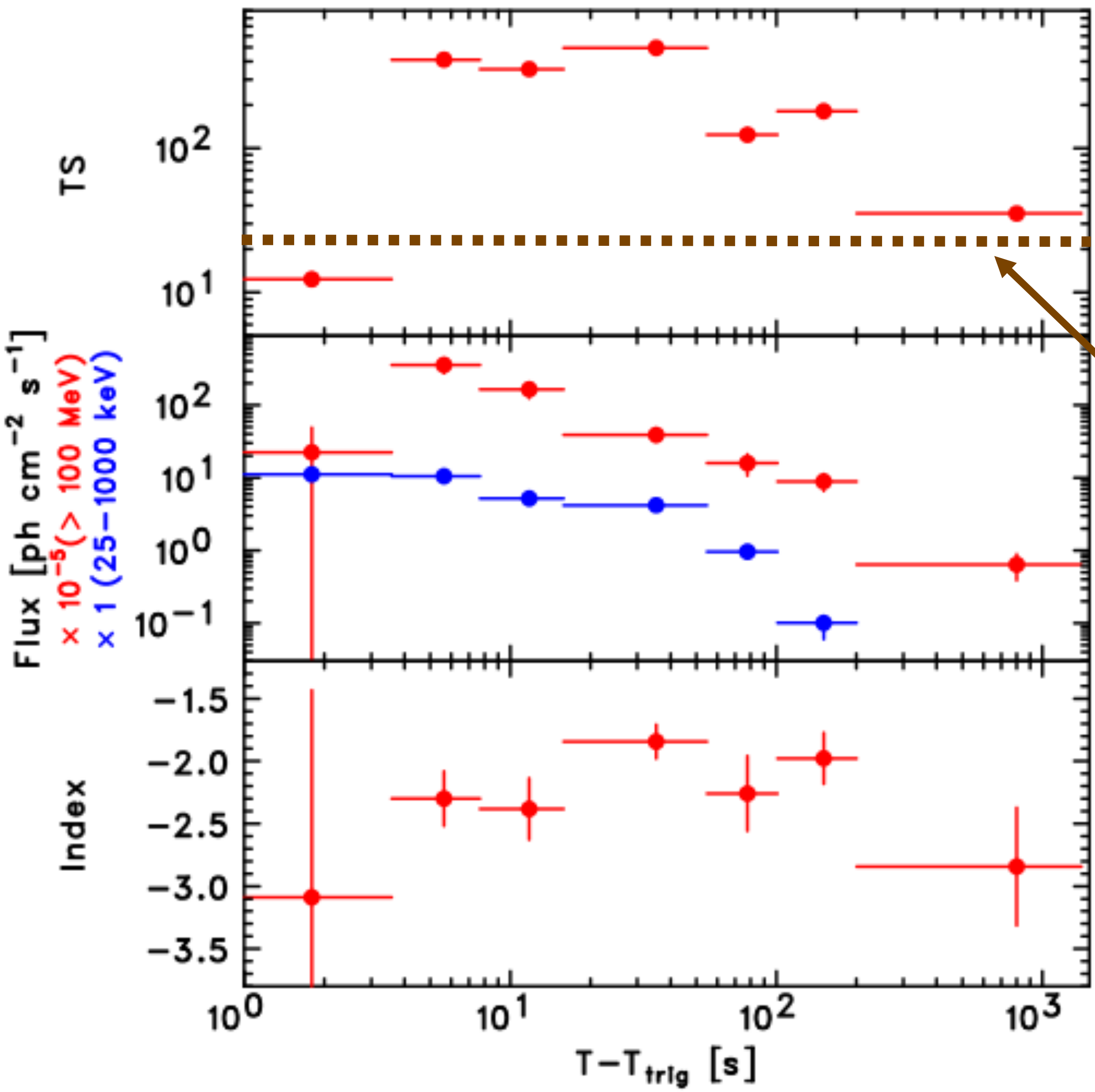
Adapted from N.Omodei

Soft-to-hard, then hard-to-soft evolution





Temporally-extended LAT emission



- **GBM emission drop-off ~55 seconds after T_0**
- **Significant LAT emission from T_0+3.6 s to T_0+1400 s**
  - **Tighter event selection cuts, optimized for weak sources**
  - **Test Statistics with position fixed at GROND location: TS > 25 (square of significance)**
  - **Still significant (5.9σ between T_0+200 s and T_0+1400 s, and consistent with the trend from the prompt emission**

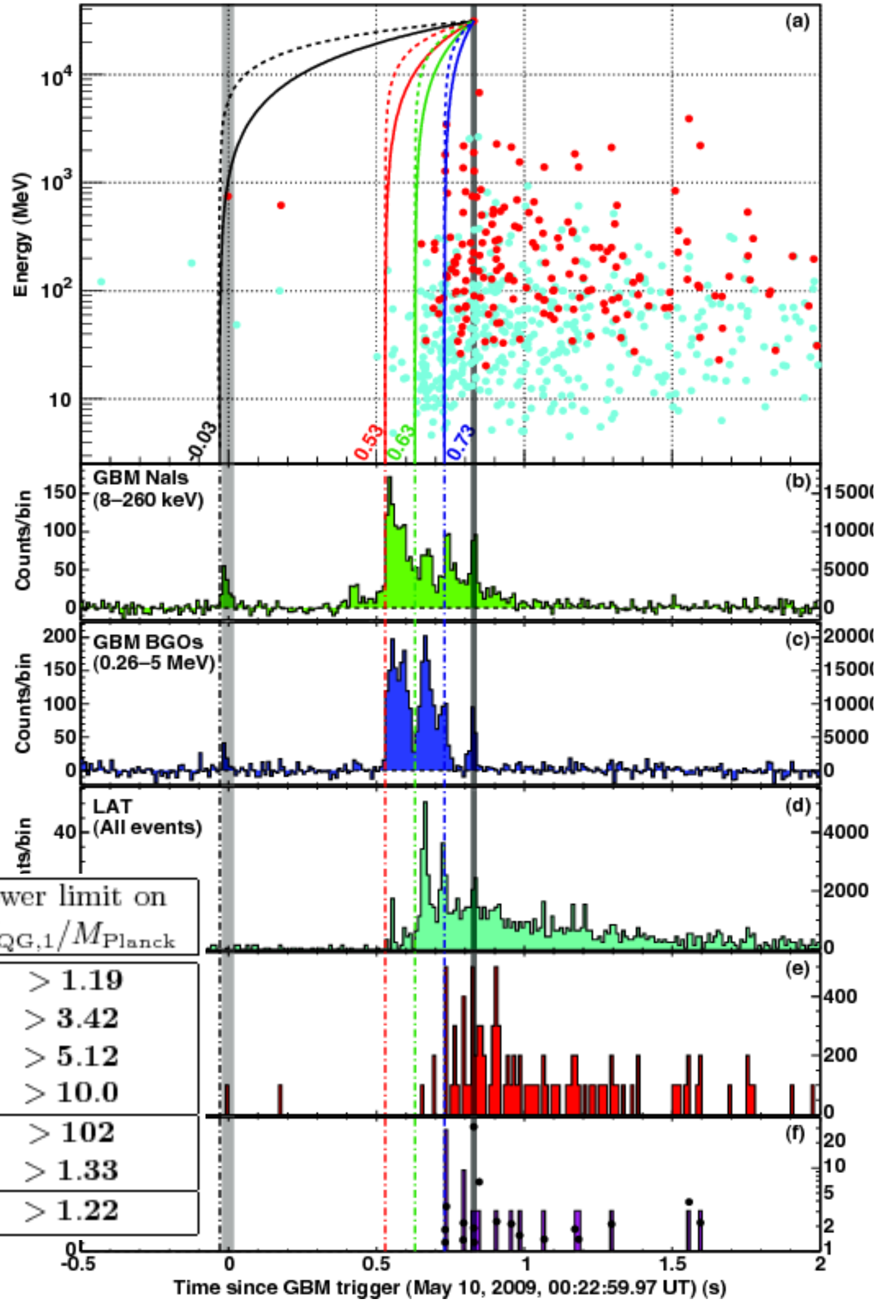
Adapted from N.Omodei

GRB 090510

- **A short bright burst with**
  - **A 31 GeV photon associated**
  - **redshift determination (z~0.9)**
- **allows to set stringent lower limits on LIV effect in photon time arrival.**

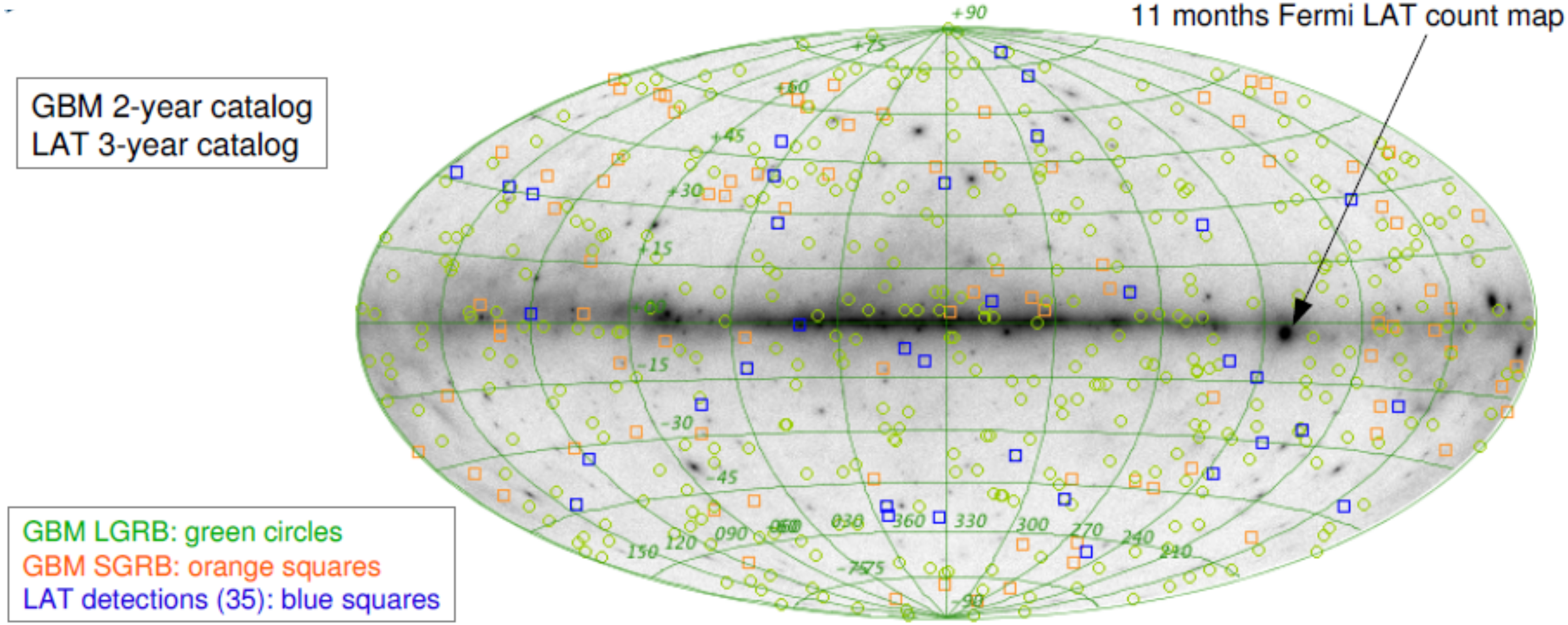
$M_{QG} > 1.19 \times M_{Plank}$

- **If $M_{QG} \sim M_{Planck}$ is expected, *Fermi* starts to disfavor linear effect**
- **Abdo et al., Nature, 462, 331**



t_{start} (ms)	limit on $\lvert\Delta t\rvert$ (ms)	Reason for choice of t_{start} or limit on Δt	E_l (MeV)	valid for s_n	lower limit on $M_{QG,1}/M_{Planck}$
−30	< 859	start of any observed emission	0.1	1	> **1.19**
530	< 299	start of main < 1 MeV emission	0.1	1	> **3.42**
630	< 199	start of > 100 MeV emission	100	1	> **5.12**
730	< 99	start of > 1 GeV emission	1000	1	> **10.0**
—	< 10	association with < 1 MeV spike	0.1	±1	> **102**
—	< 19	if 0.75 GeV γ is from 1st spike	0.1	±1	> **1.33**
$\lvert\frac{\Delta t}{\Delta E}\rvert < 30\ \frac{ms}{GeV}$		lag analysis of all LAT events	—	±1	> **1.22**

The GRB catalog

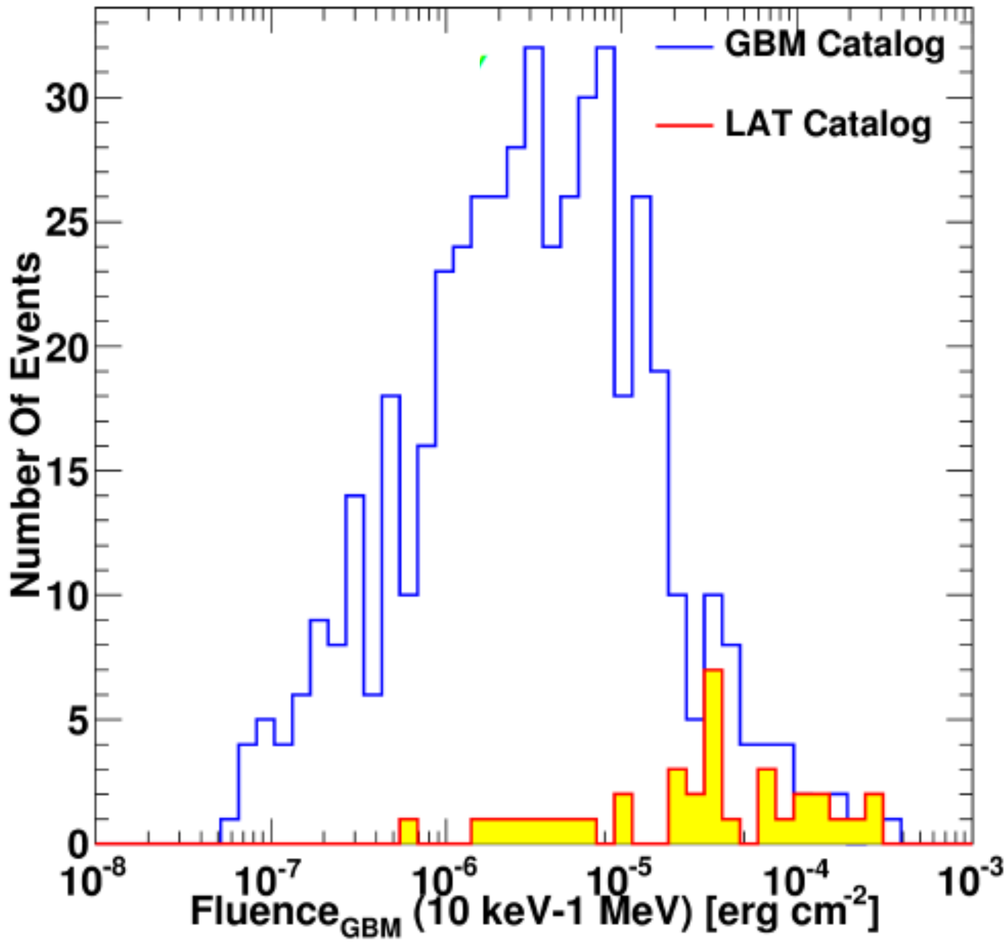


- The GBM detects ~250 GRBs / year, ~half in the LAT FoV

  Paciesas et al. 2012, ApJS 199, 18; Goldstein et al. 2012, ApJS 199, 19

- The LAT detected 35 GRBs in 3 years (30 long, 5 short), including 7 "LLE-only" GRBs
  - Bright LAT bursts with good localizations are all followed-up by Swift
  - 10 redshift measurements, from z=0.74 (GRB 090328) to z=4.35 (GRB 080916C)
  - 4 joint BAT-GBM-LAT detections: GRBs 090510, 100728A, 110625A, 110731A

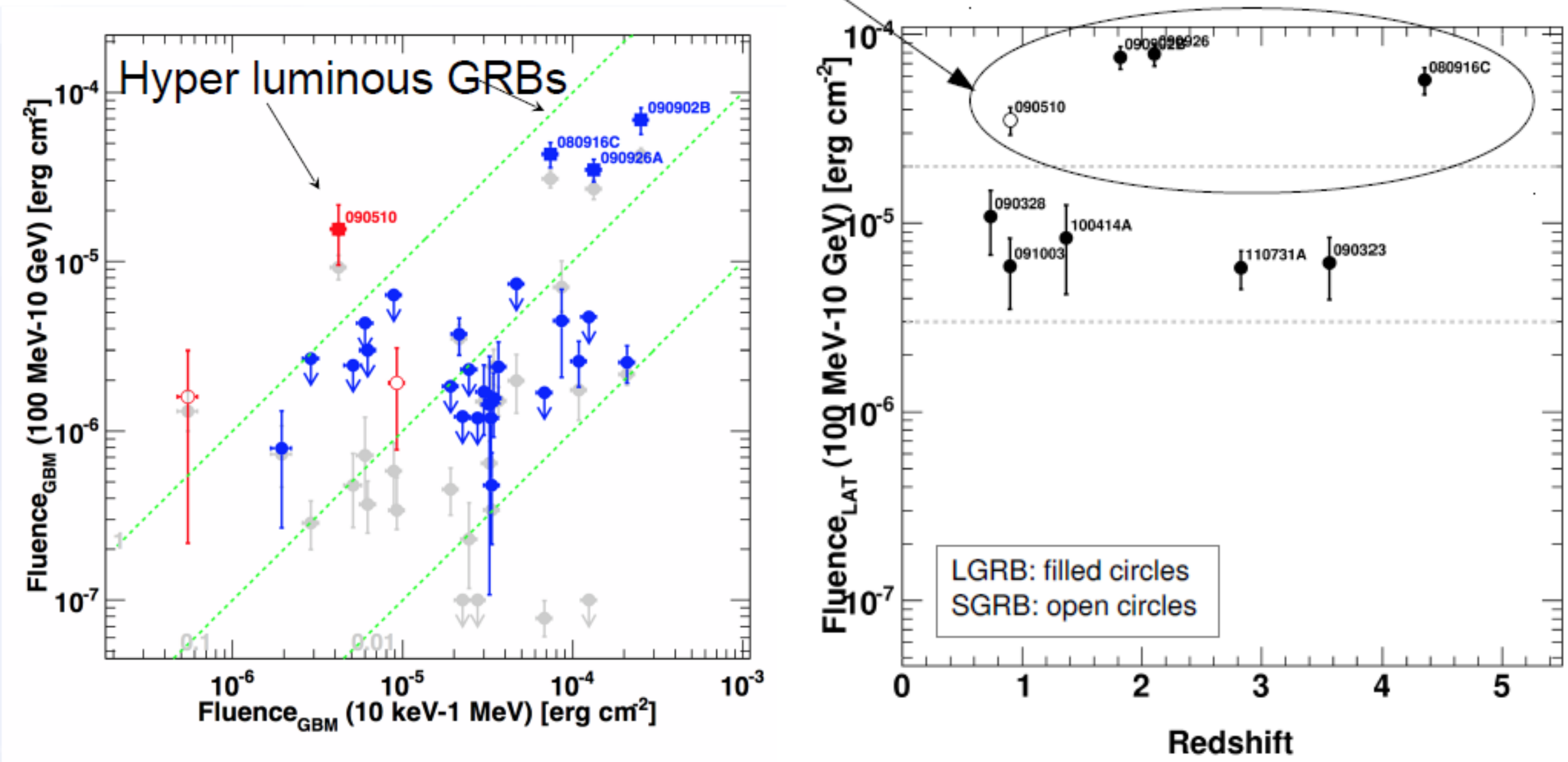
< 1 MeV of LAT GRB



- Fluence in GBM energy range and "GBM" time window
  - LAT bursts vs. entire sample in GBM spectral catalog (Goldstein et al. 2012)
- Not surprisingly, LAT bursts are among the brightest GBM bursts
  - Selection effects (autonomous repointings) are possible though

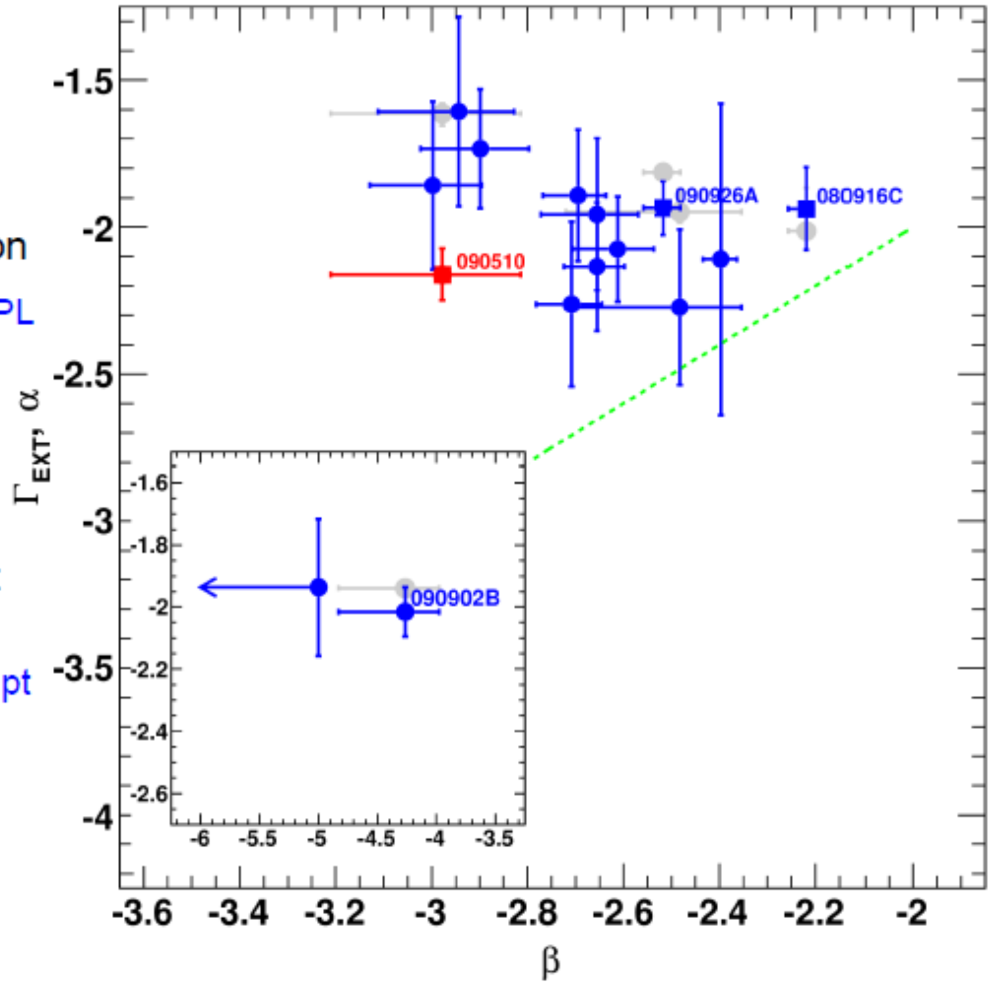
GBM and LAT fluence

- GBM and LAT fluences computed in "GBM" and "LAT" time windows, respectively
  - Short GRBs (LAT fluence > GBM fluence) are harder than long GRBs (LAT/GBM fluence ~10%)
- A hyper-energetic class of long bursts? GRBs 080916C, 090902B, 090926A are exceptionally bright
  - They do not appear bright because they are systematically closer to us

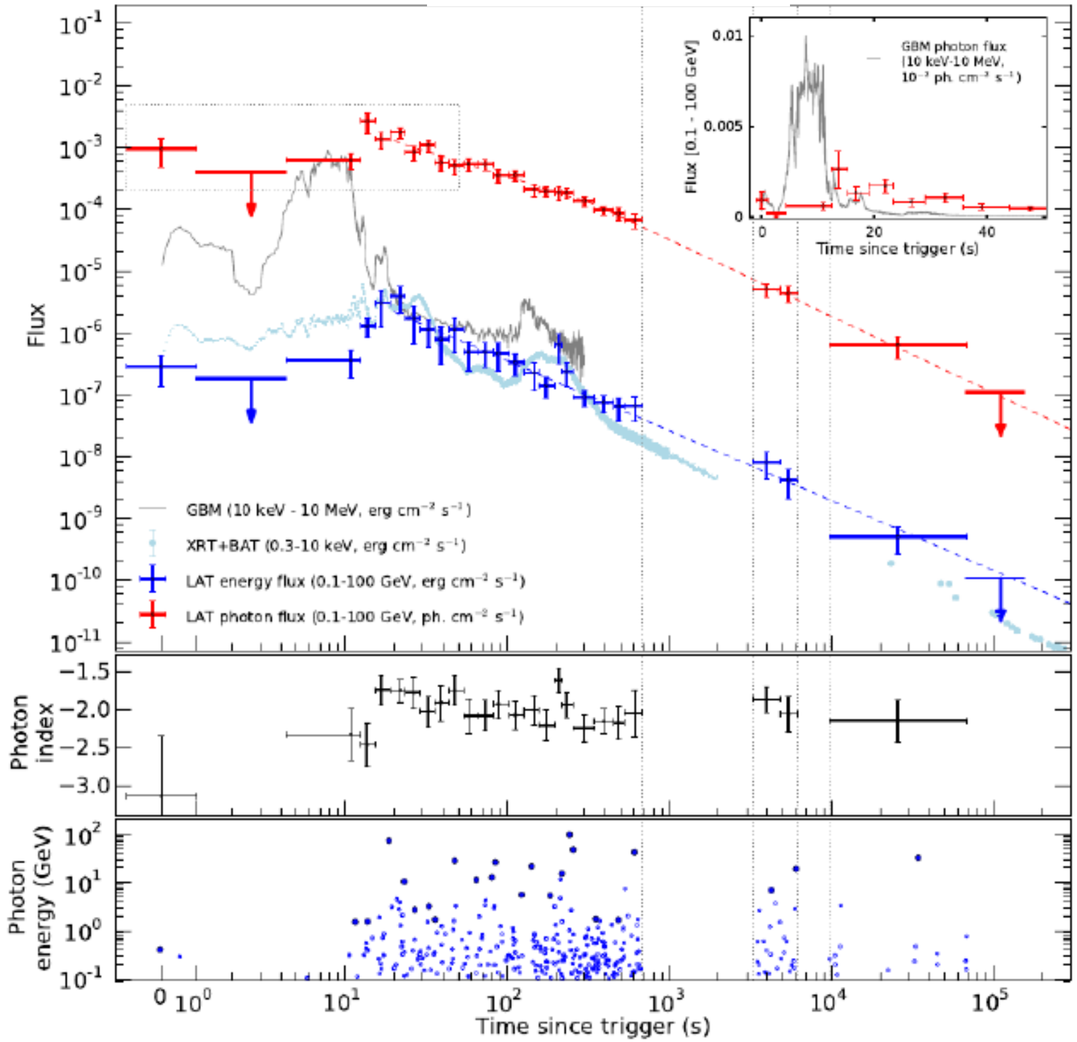


Extended and Prompt Spectra

- $\beta=\beta_{BAND}$ here: spectral index of Band function in the prompt phase
- Γ_{EXT} : spectral index of extended emission
  - α (grey points): spectral index of extra PL from GBM-LAT joint fit in the prompt phase
- Prompt and extended phase spectra not correlated
  - Stronger spectral variability in the prompt phase



GRB 130427A

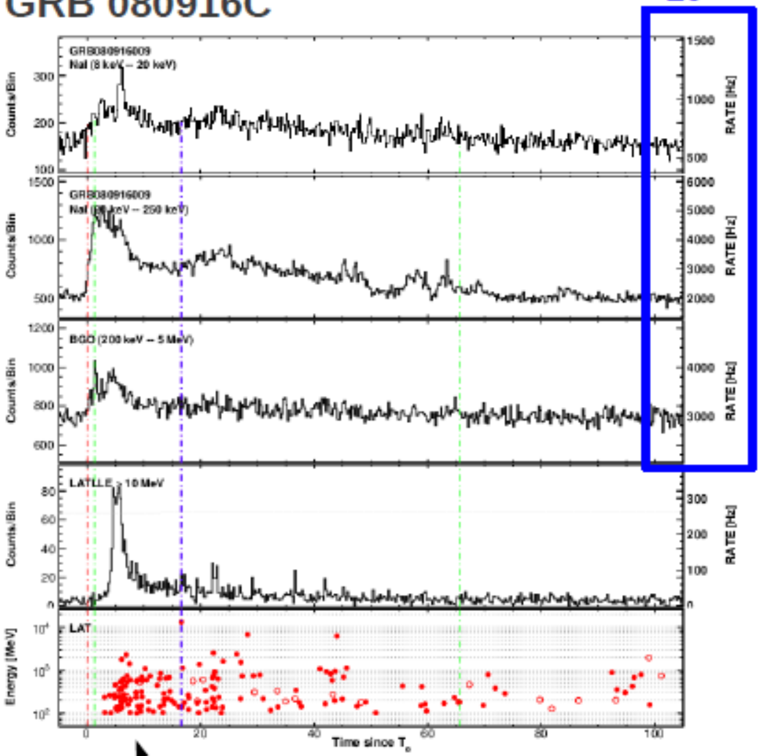


(Ackermann et al., Science, Vol. 343 no. 6166 pp. 42-47)

GRB 130427A

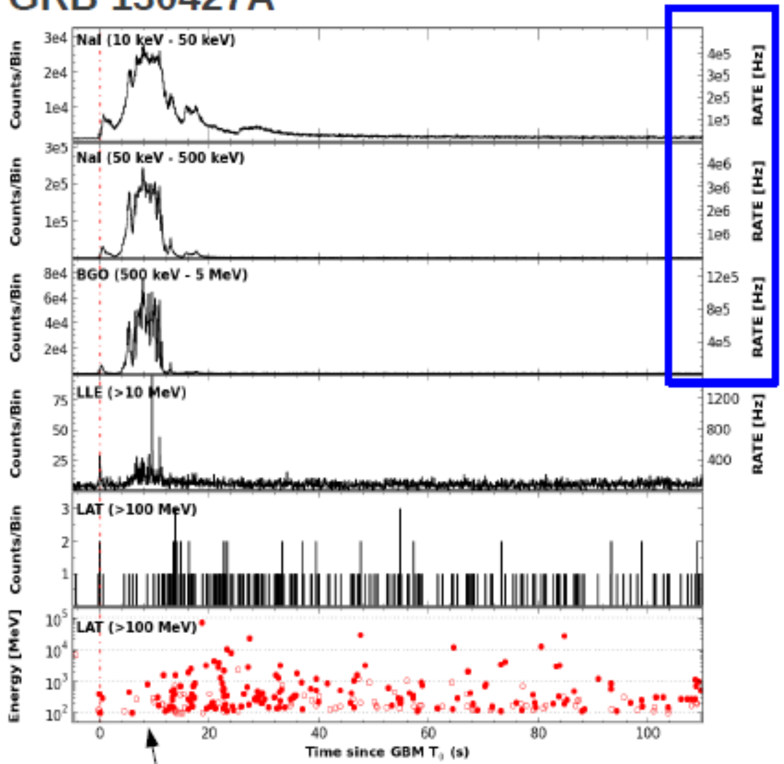
GRB 080916C

10^3



GRB 130427A

10^5, 10^6



LAT emission dying down

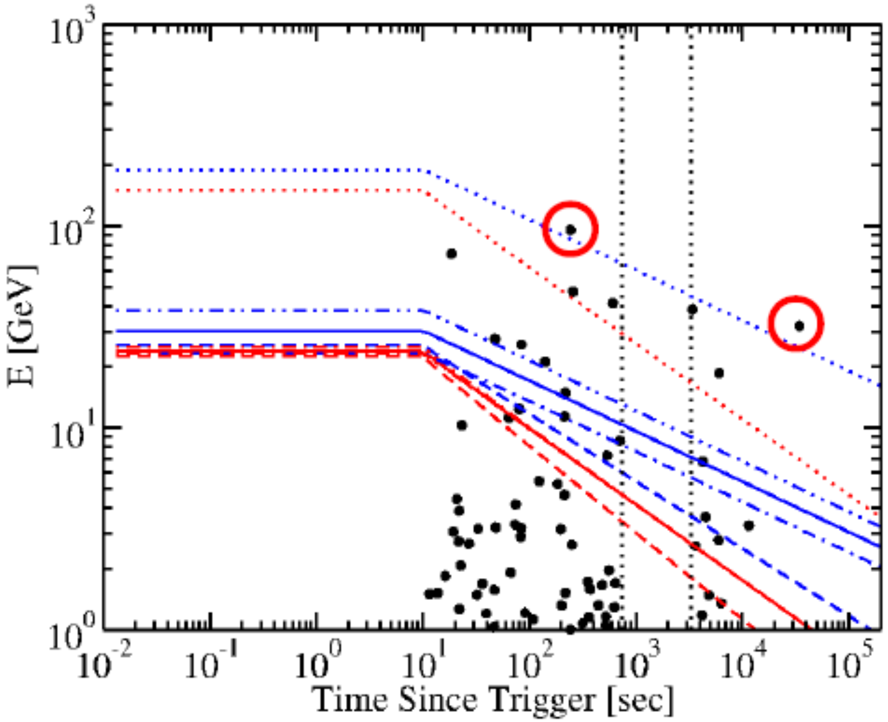
LAT emission still going

Very little LAT emission when GBM emission is bright

LAT and GBM are bright at the same time

GRB 130427A

- Jet interacts with circumburst medium.
  - Charged particles are accelerated.
  - These particles then emit photons via synchrotron emission.
- This prescribes a maximum synchrotron photon energy.



Curves of **maximum** synchrotron photon energy from external shocks, for various conditions

Black dots: LAT photons

Circumburst medium:
Red → constant density
Blue → density ~ r^{-2}

Dotted lines: more "extreme" (i.e., unrealistic) scenarios
→ LAT photons *still* lie above these lines

Towards the 2nd Catalog

- Low-level event reconstruction algorithms in all subsystems improving mistracking at high energy and large angles and supression of ghost events, effectively increasing the instruments Eff. Area and FoV
- New event class selections
- Improved background rejection
- Improved Monte Carlo Simulations

P8 is a **complete LAT upgrade** resulting in a large improvement in acceptance ($\sim 100\%$ below 100 MeV and $\sim 25\%$ above 1 GeV) and a significant improvement in localization and background rejection. Additional improvements are expected in energy coverage and a better understanding of the systematic uncertainty.

PASS8 new reconstruction
(e.g. Racusin et a. AAS 2014)

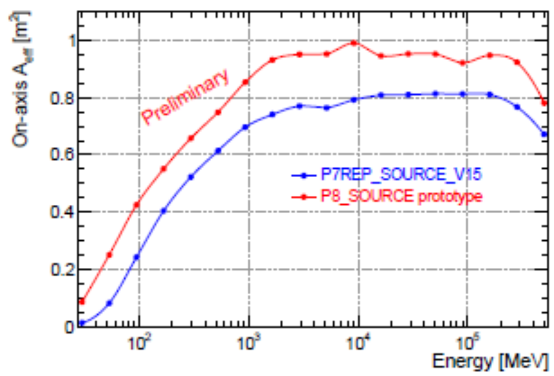


Figure 1: *Prototype P8 event class vs. P7 effective area as a function of energy.*

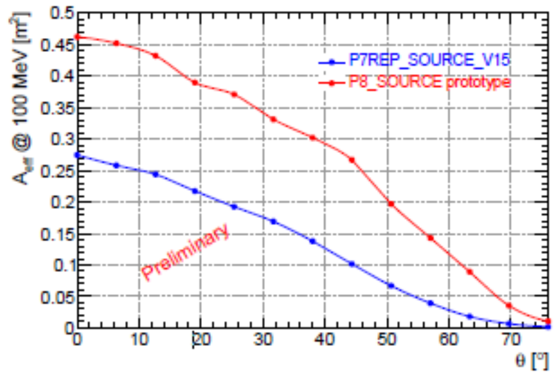
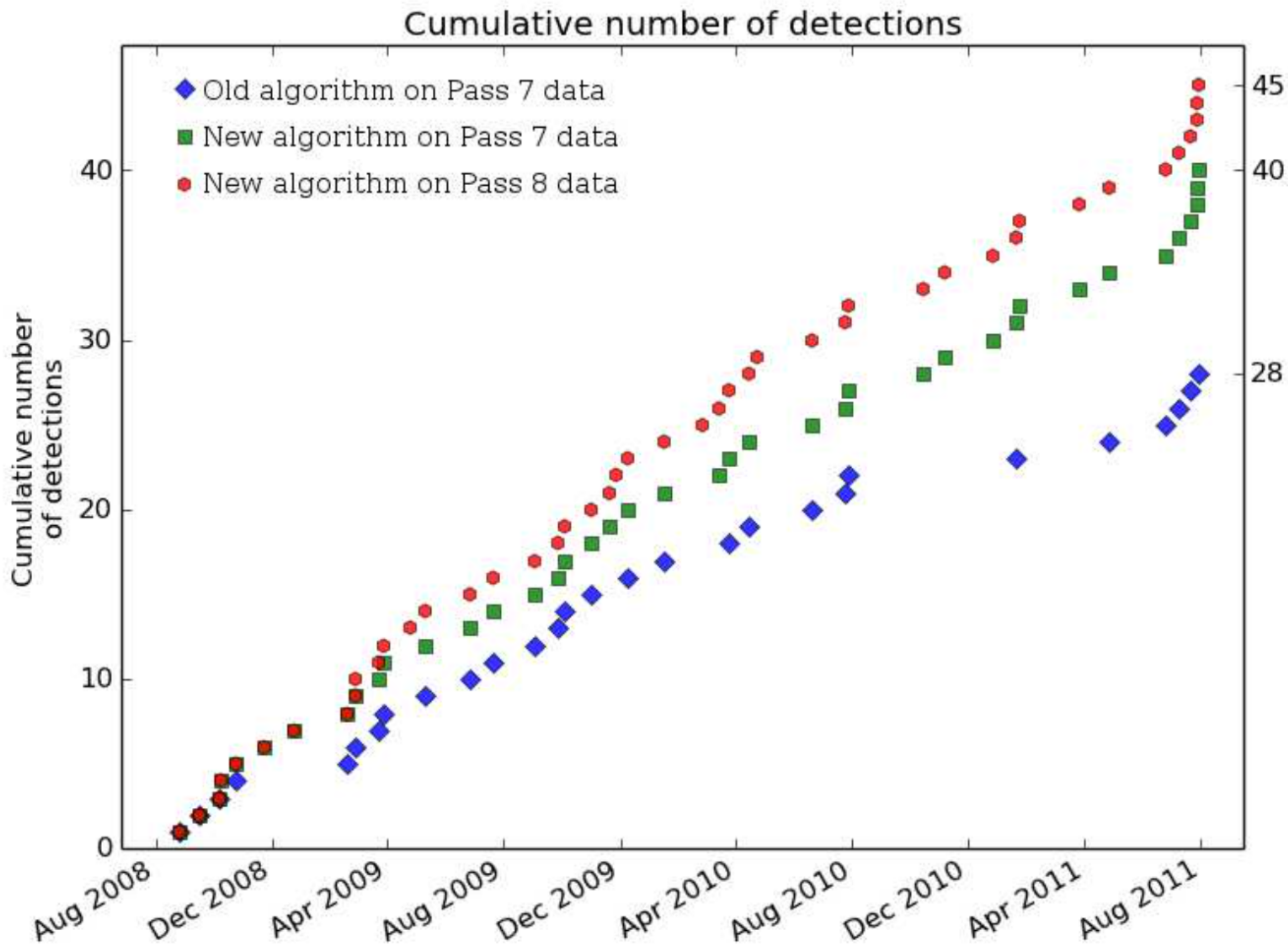


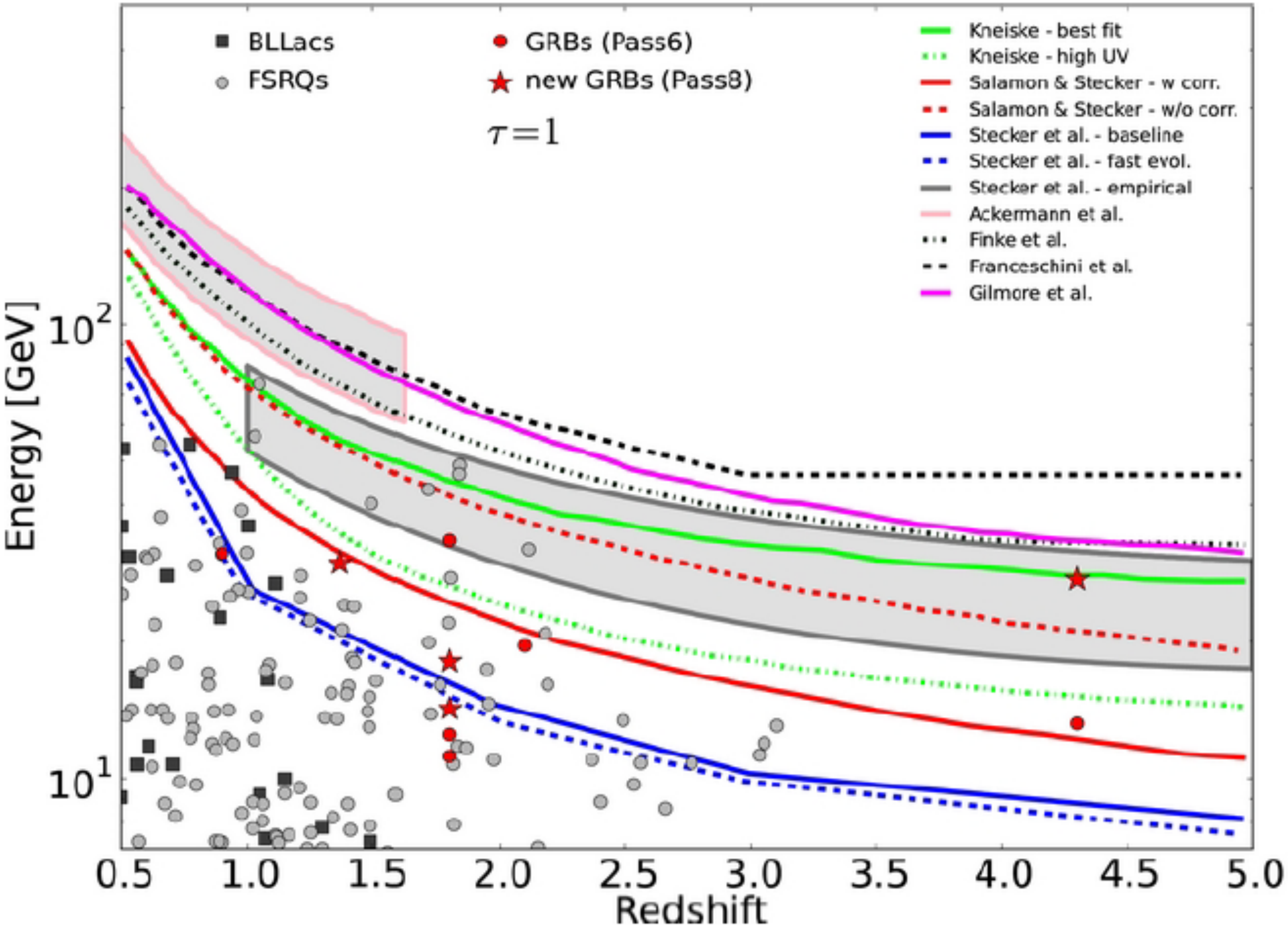
Figure 2: *Prototype P8 event class vs P7 effective area at 100 MeV as a function of the angle from the boresight.*

The new Pass8 data



Vianello & Omodei

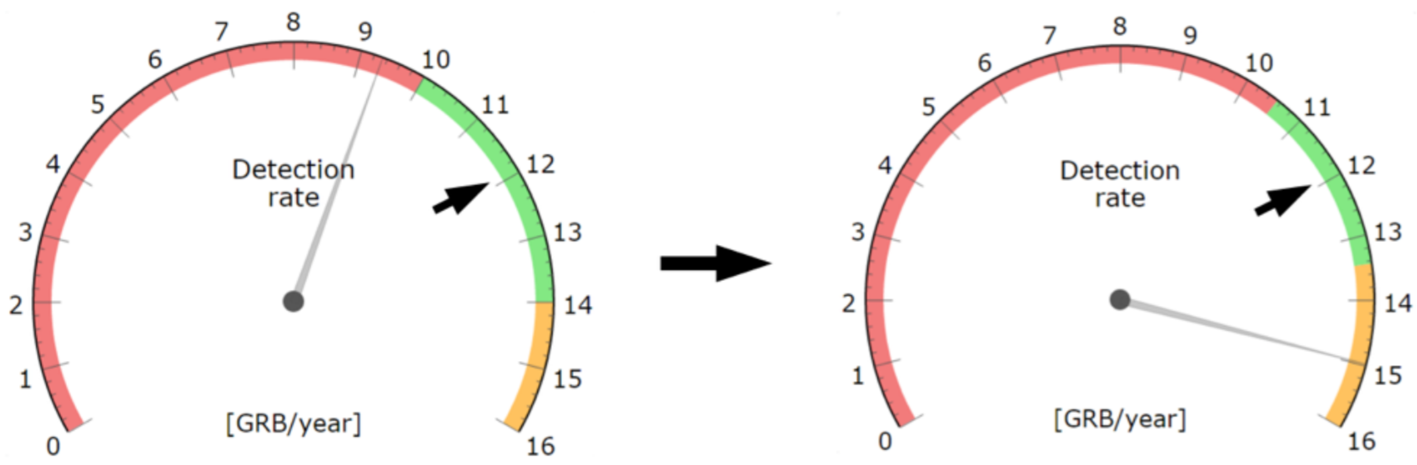
Towards the 2nd Catalog



Atwood at al. 2013

Towards the 2nd LAT catalog

The Case of the Missing GRBs



(Pass 6, old algorithm)

- **Optimistic predictions?**
- **New GRB physics?**

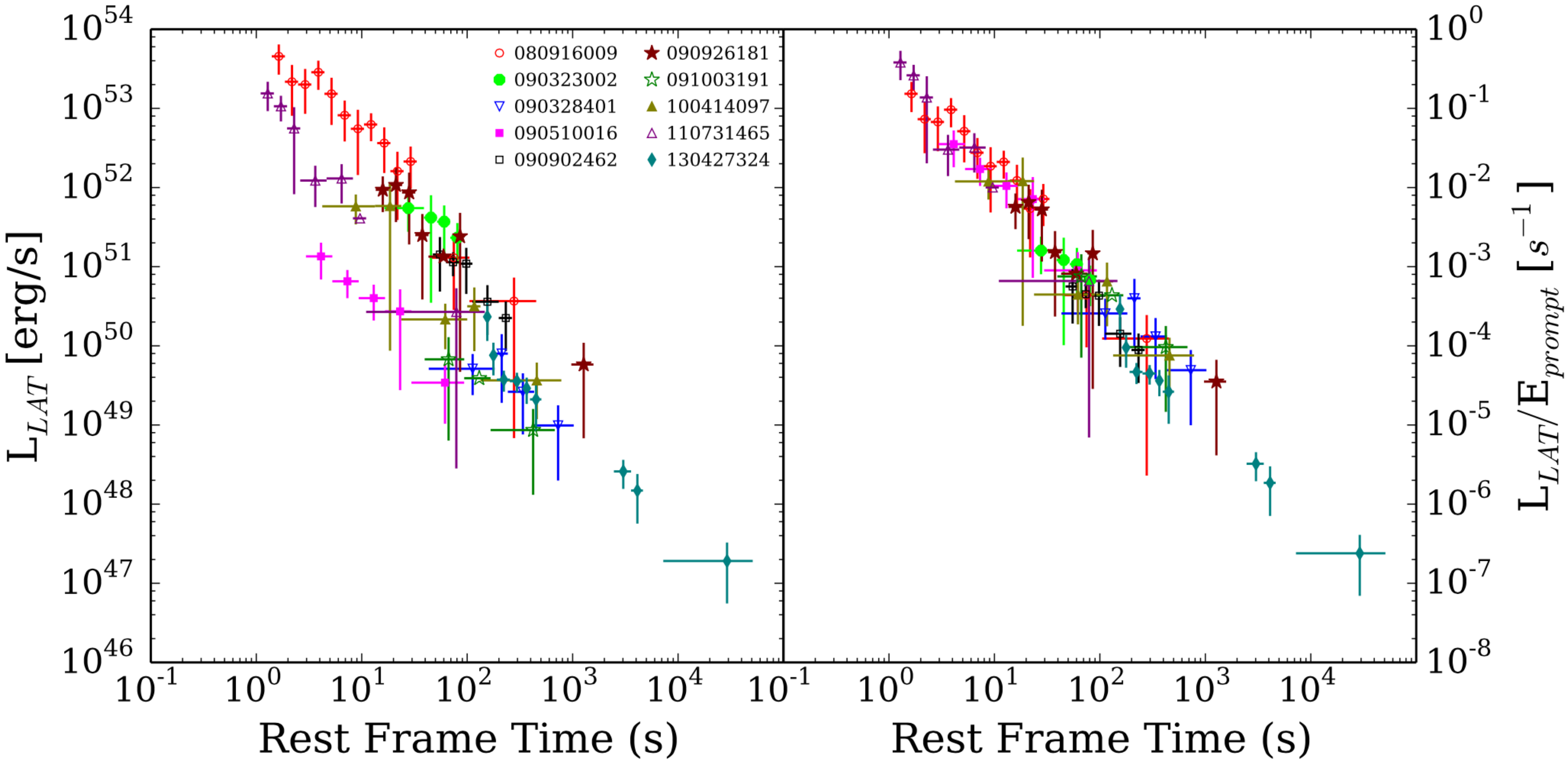
(Pass 8 + new algorithm)

- **New GRB physics?**
  - **The high-energy emission is probably related with the afterglow**

Omodei et al. 2016

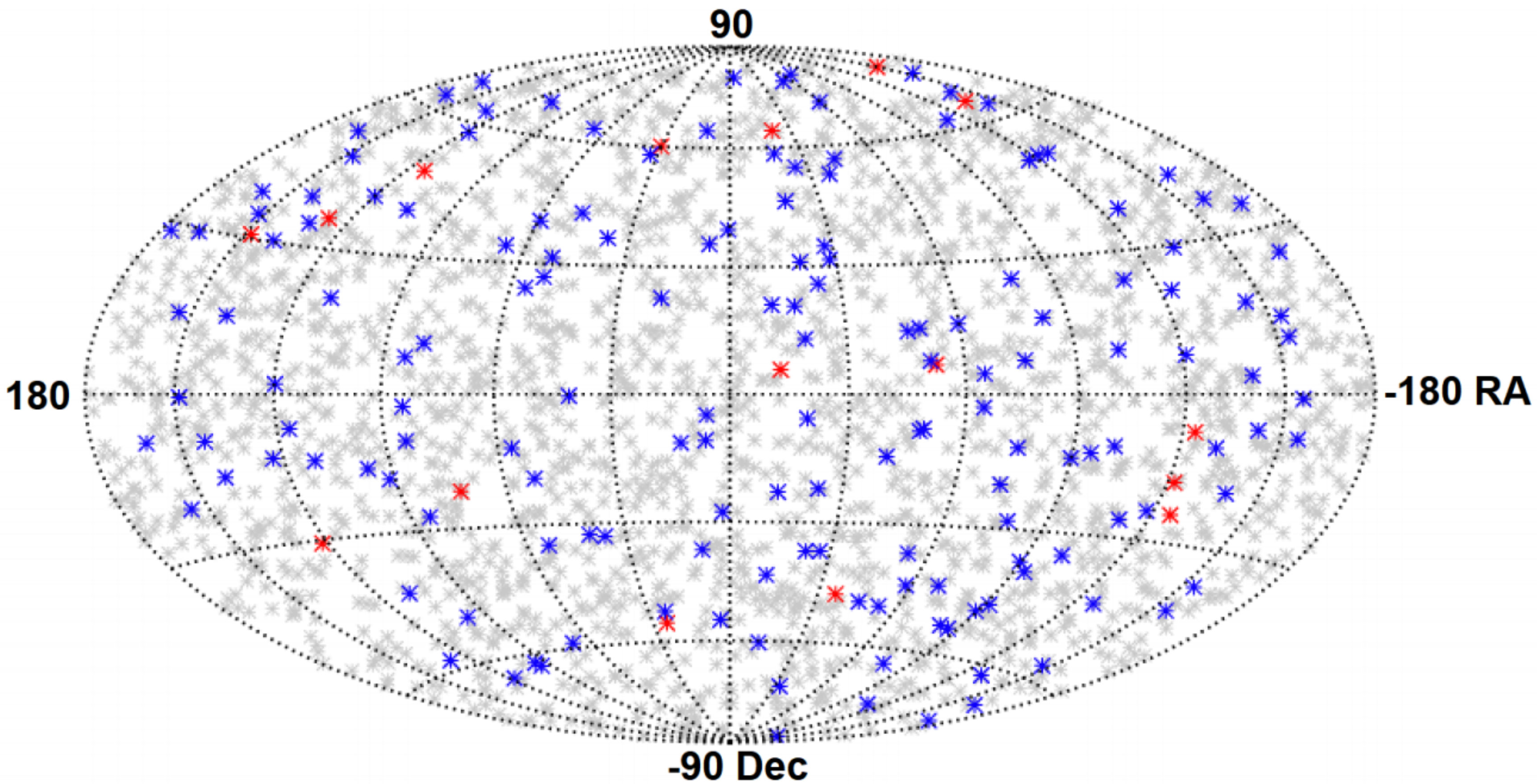
Nicola Omodei – Stanford/KIPAC 11

Clustering of LAT light curve



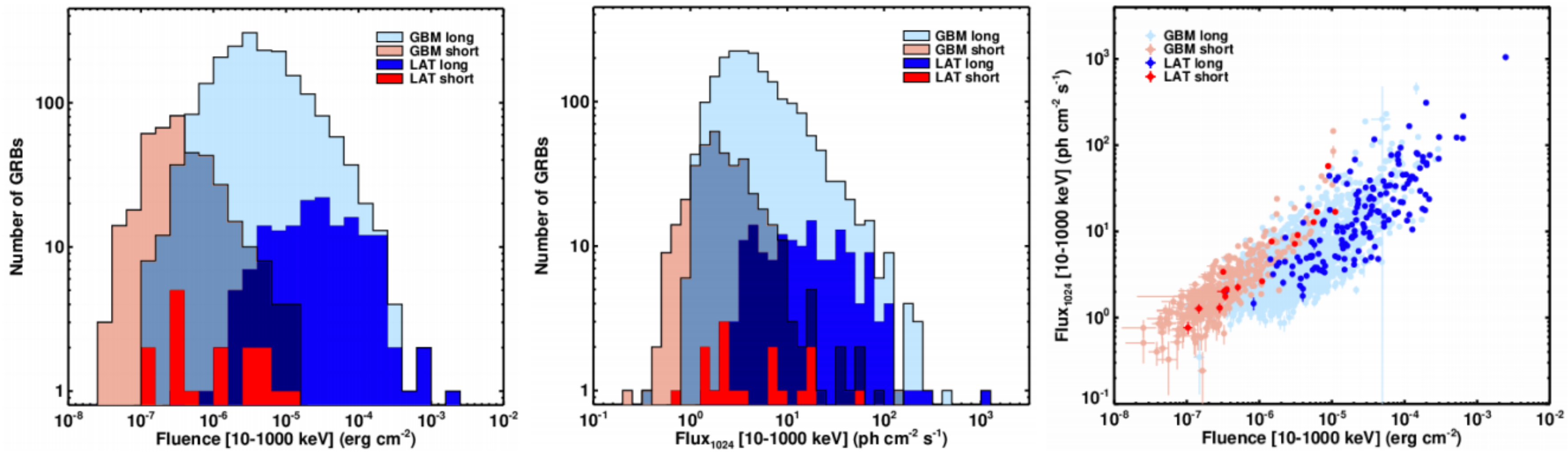
Nava et al. 2014

The 2nd Catalog



Ajello, M. et al. 2019, ApJ, 878, 52

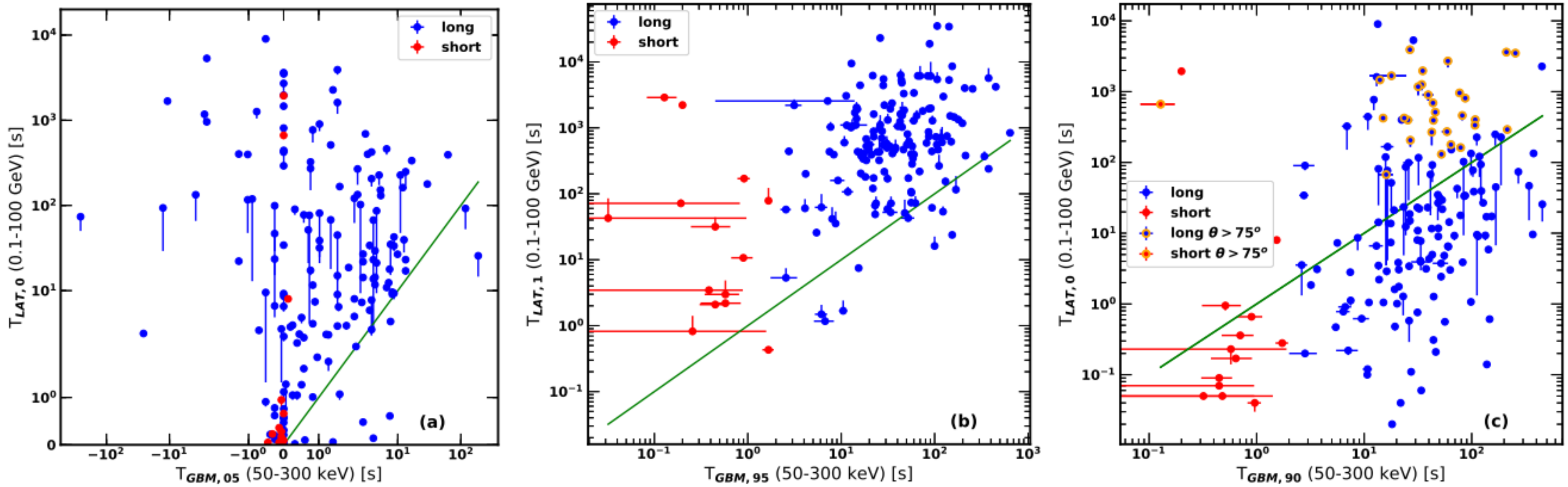
The 2nd Catalog



Flux and fluence: LAT vs GBM distribution

Ajello, M. et al. 2019, ApJ, 878, 52

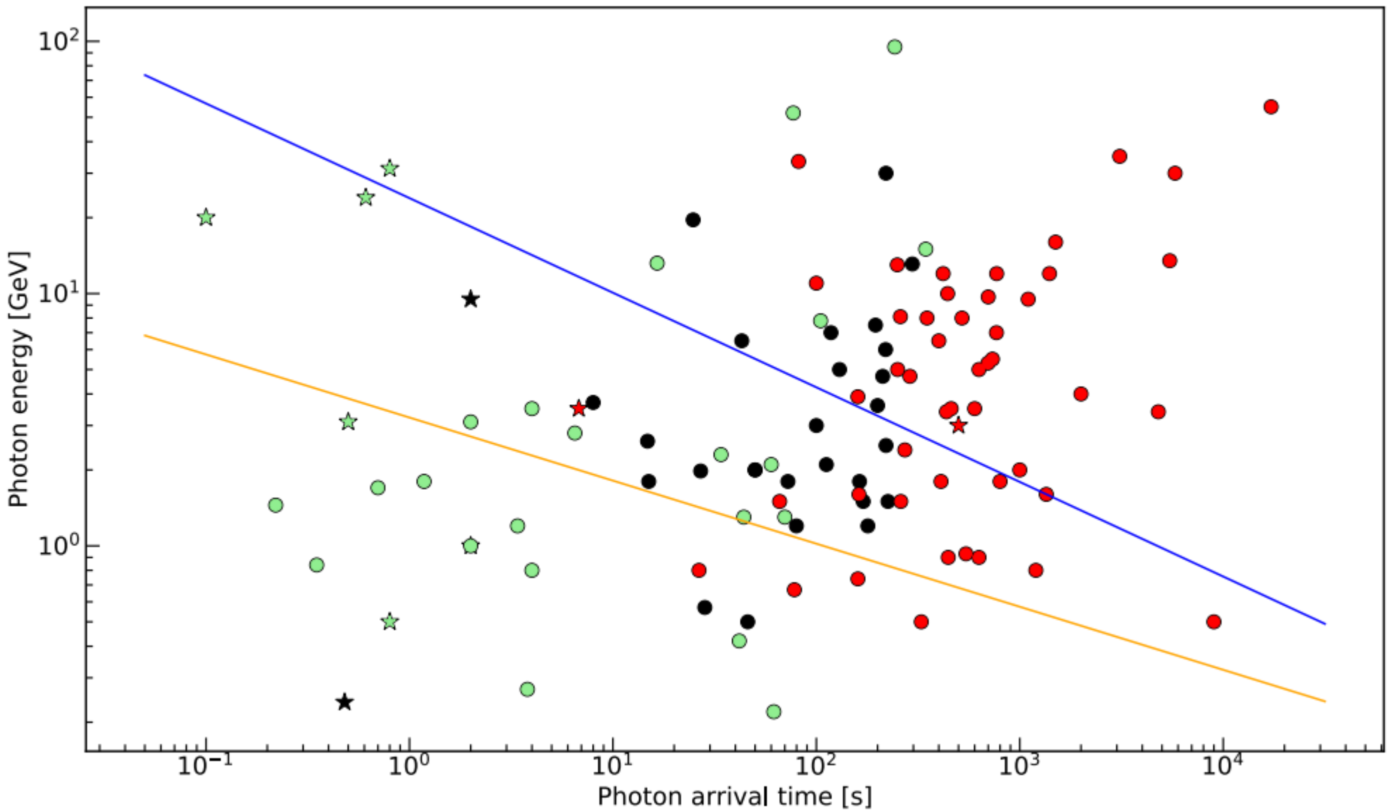
The 2nd Catalog



Temporal properties: LAT vs GBM

Ajello, M. et al. 2019, ApJ, 878, 52

HE photons



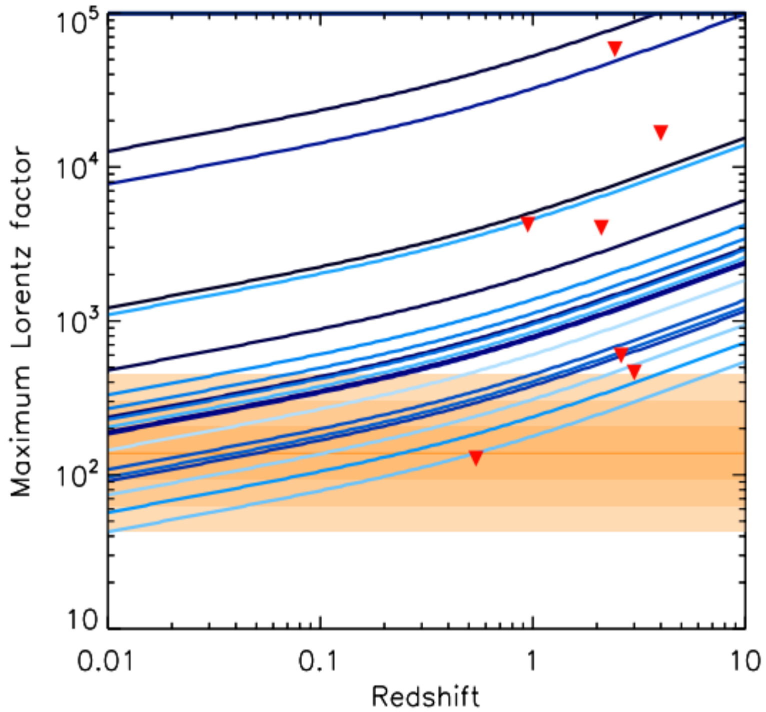
Arrival time vs Photon Energy in prompt and external phases

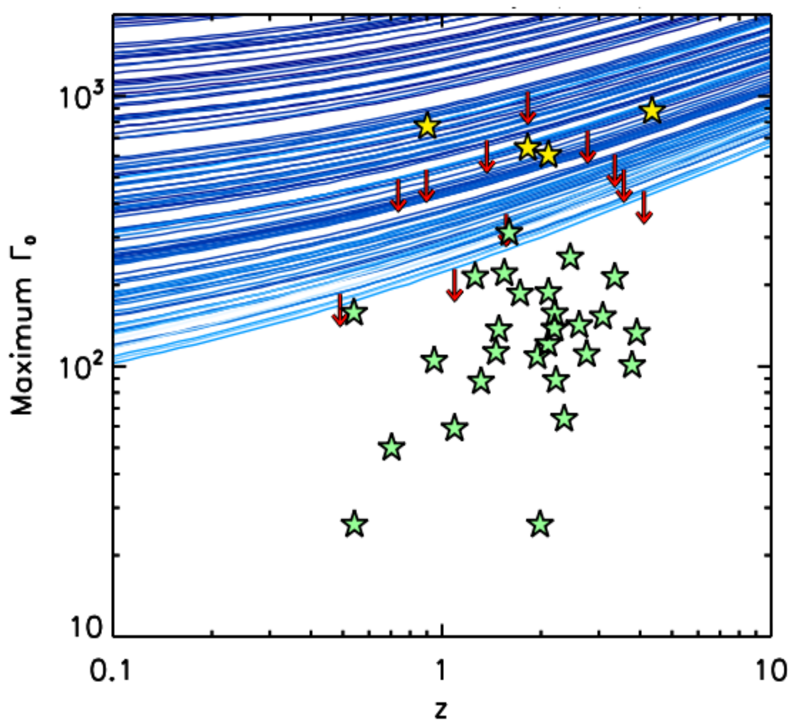
Nava 2018

Upper Limits

Longo et al. 2012

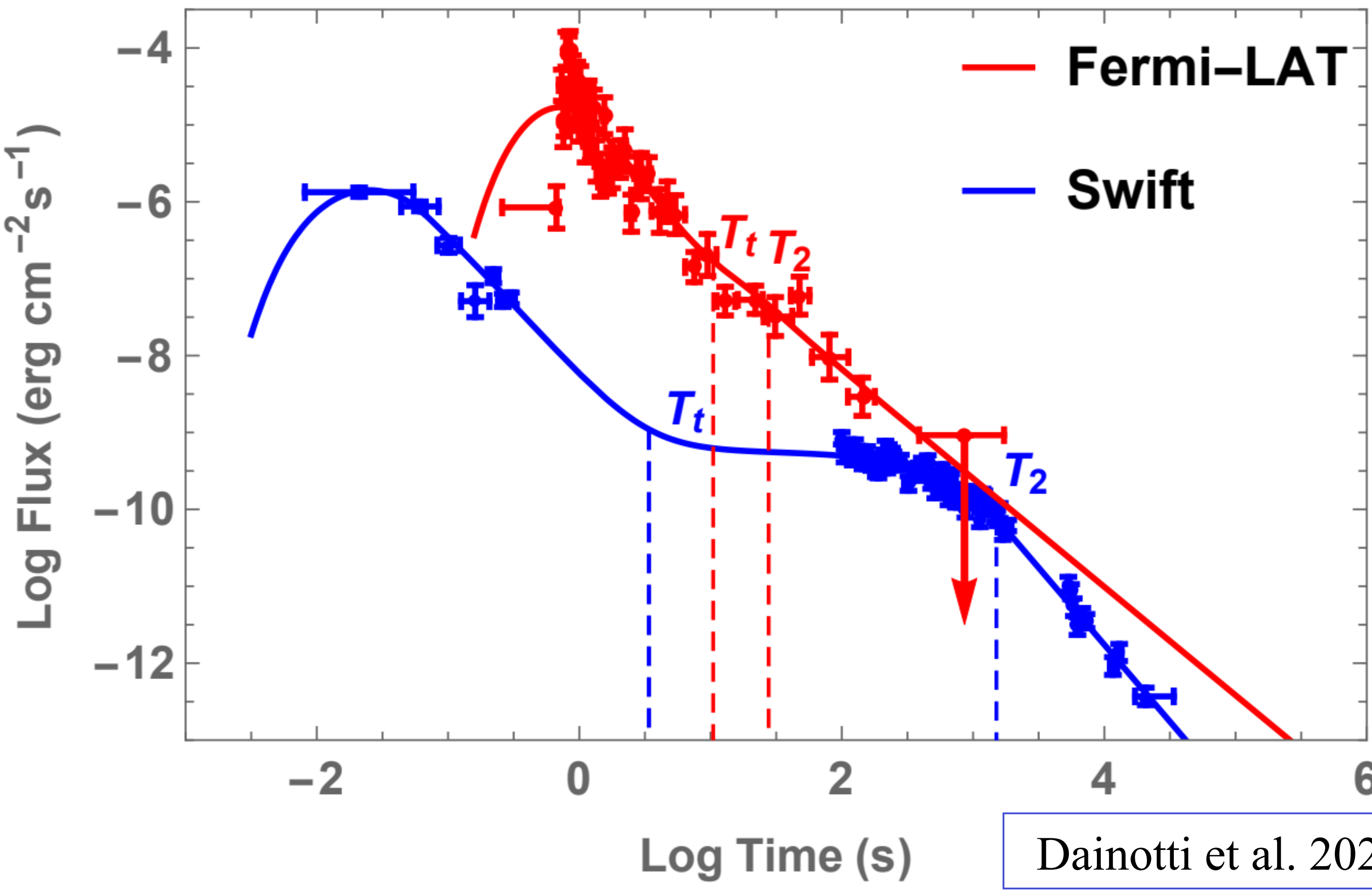
Nava et al. 2017





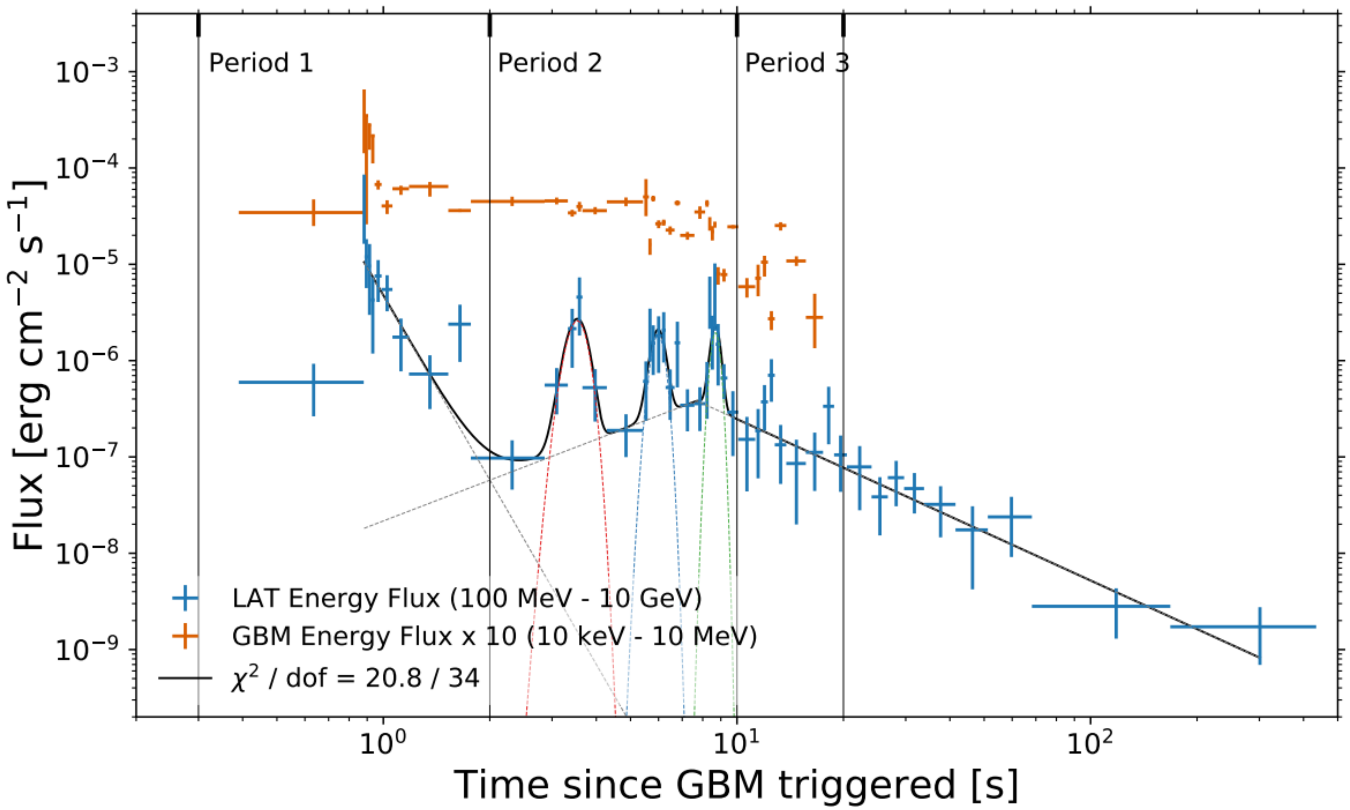
Upper limits from AGILE and Fermi-LAT GRBs vs Max Lorentz Factor for leptonic Ext Shock

Light curves in the Early afterglow



Dainotti et al. 2021

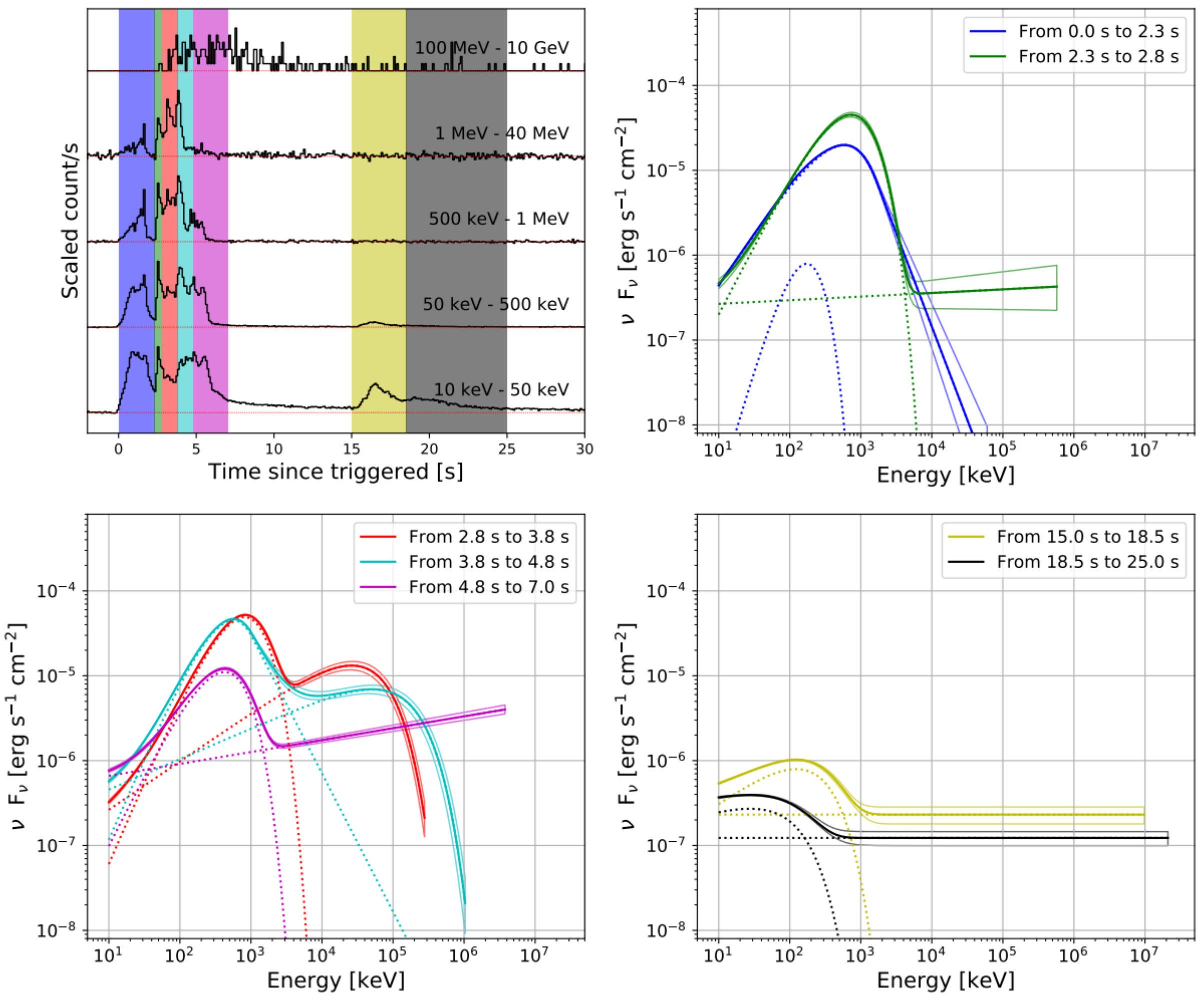
GRB 131118A



Flares in the prompt phase

Ajello, M. et al. 2020

GRB 190114C



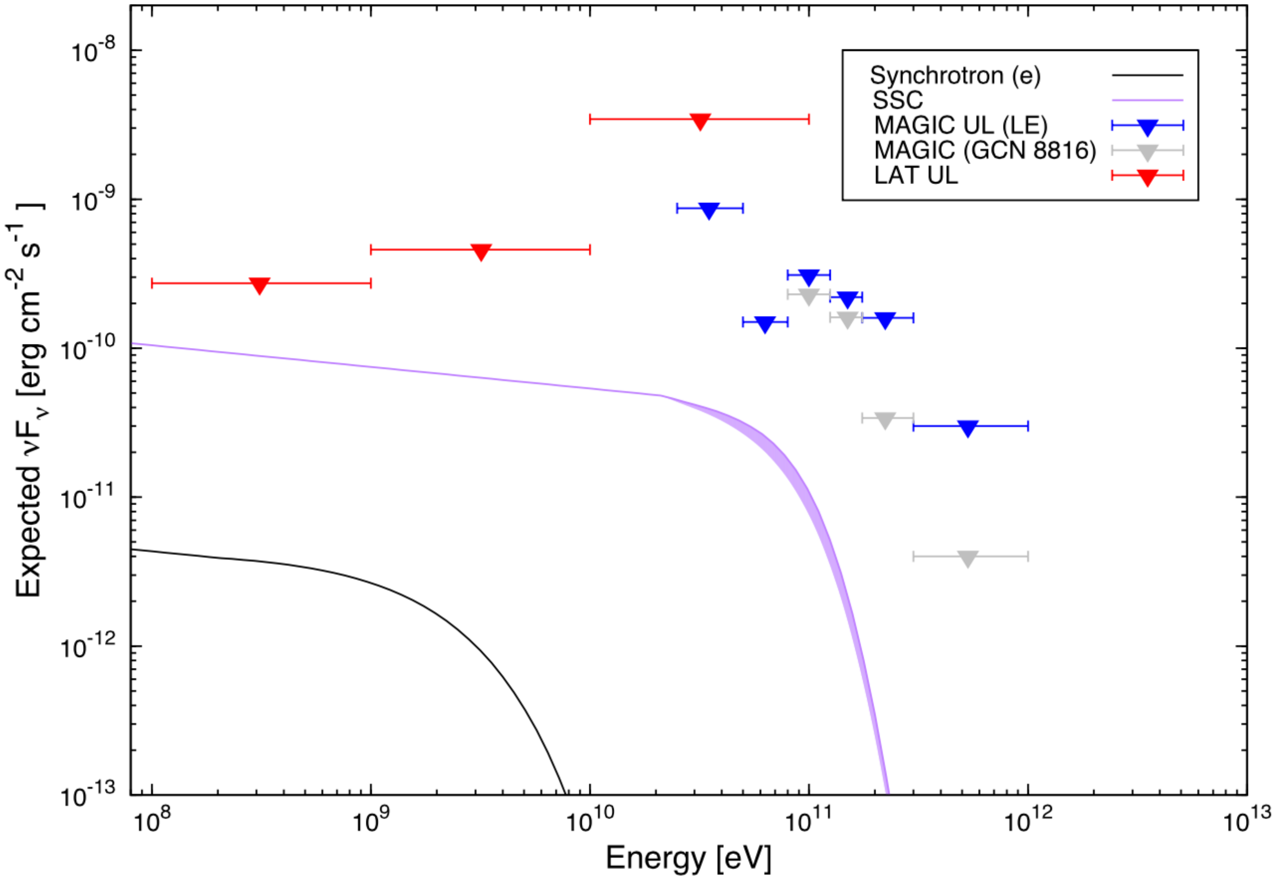
Ajello, M. et al. 2020

HE Emission from GRBs

- Extended emission
  - Extra long GRBs
- Prompt emission
  - Delayed onset
  - Emission mechanism
- Spectral Components
  - Extra components
  - Multiple components
- Ubiquity of HE emission
  - Upper Limits in the > 100 MeV regime
- Population of VHE emitting GRB
  - IACT detection ?

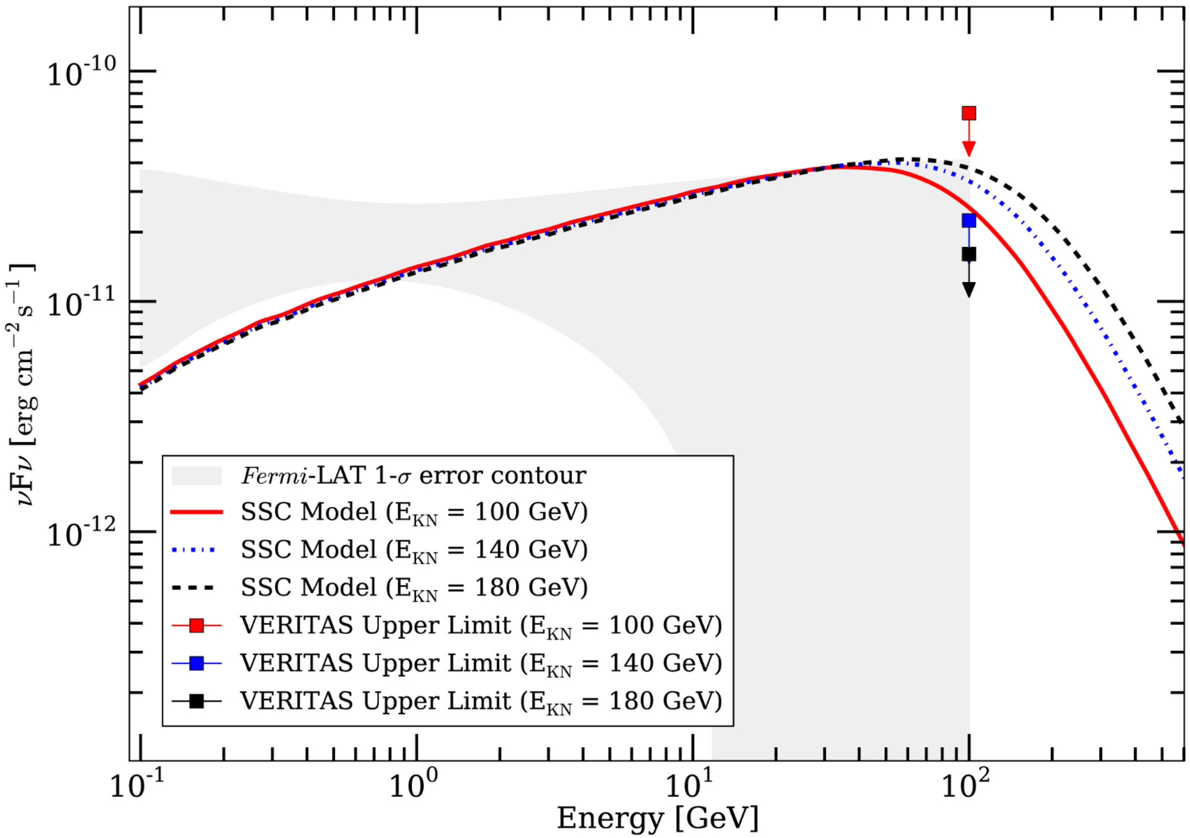
Very High Energy Emission from GRB
"The IACT era"

MAGIC upper limits: GRB 090102



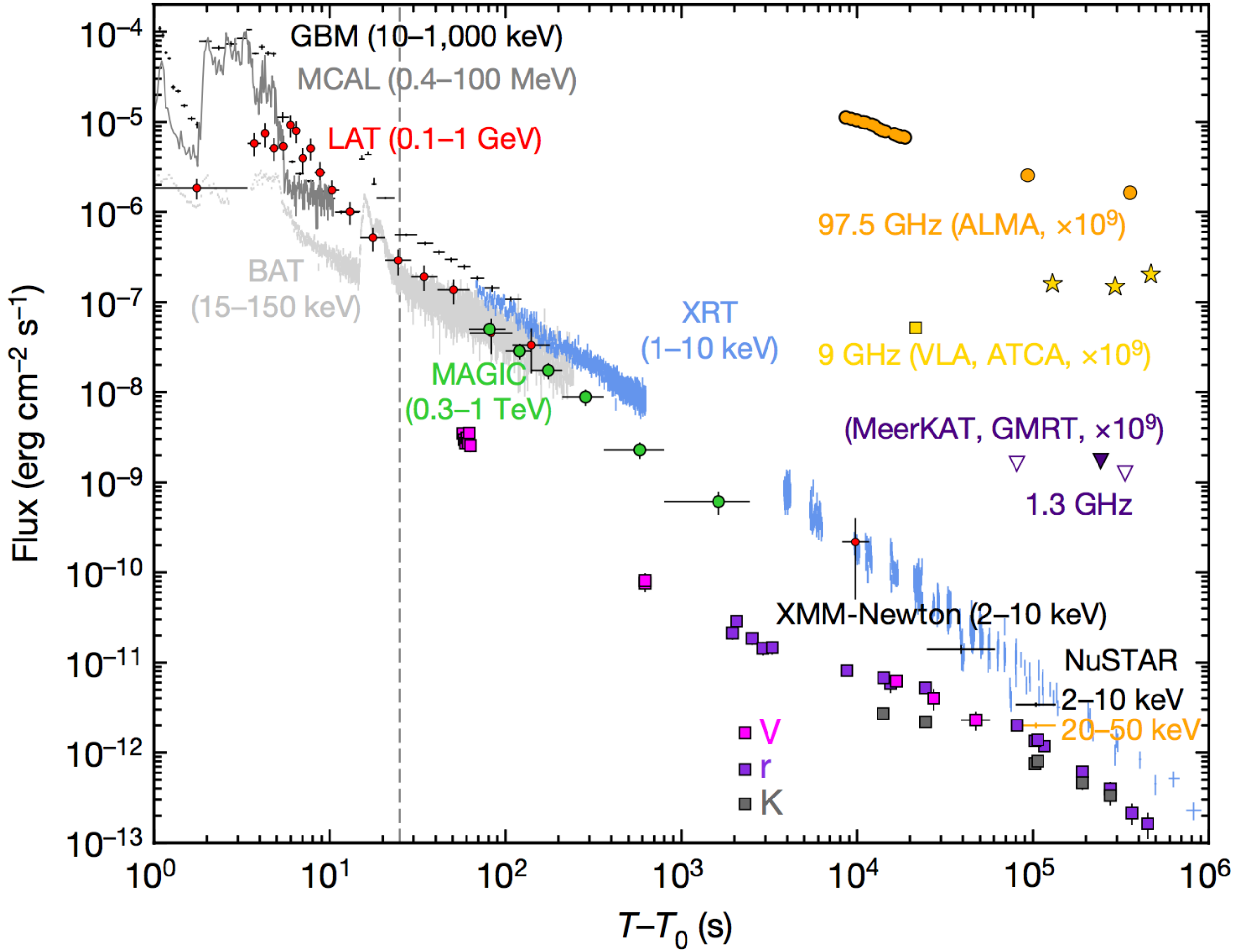
J. Aleksic et al., MNRAS (2014)

VERITAS upper limits: GRB 130427A



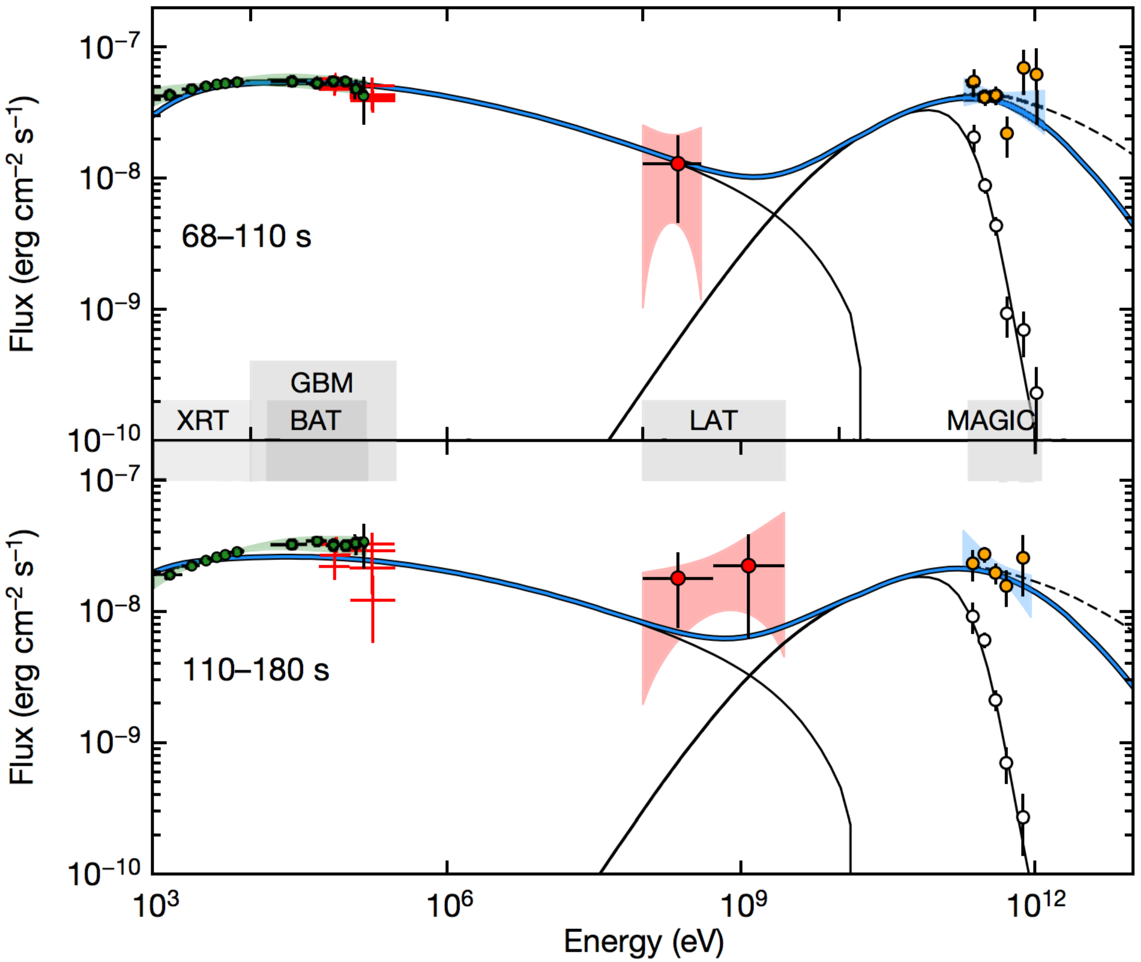
Aliu et al. ApJ 2014

MAGIC detection: GRB 190114C



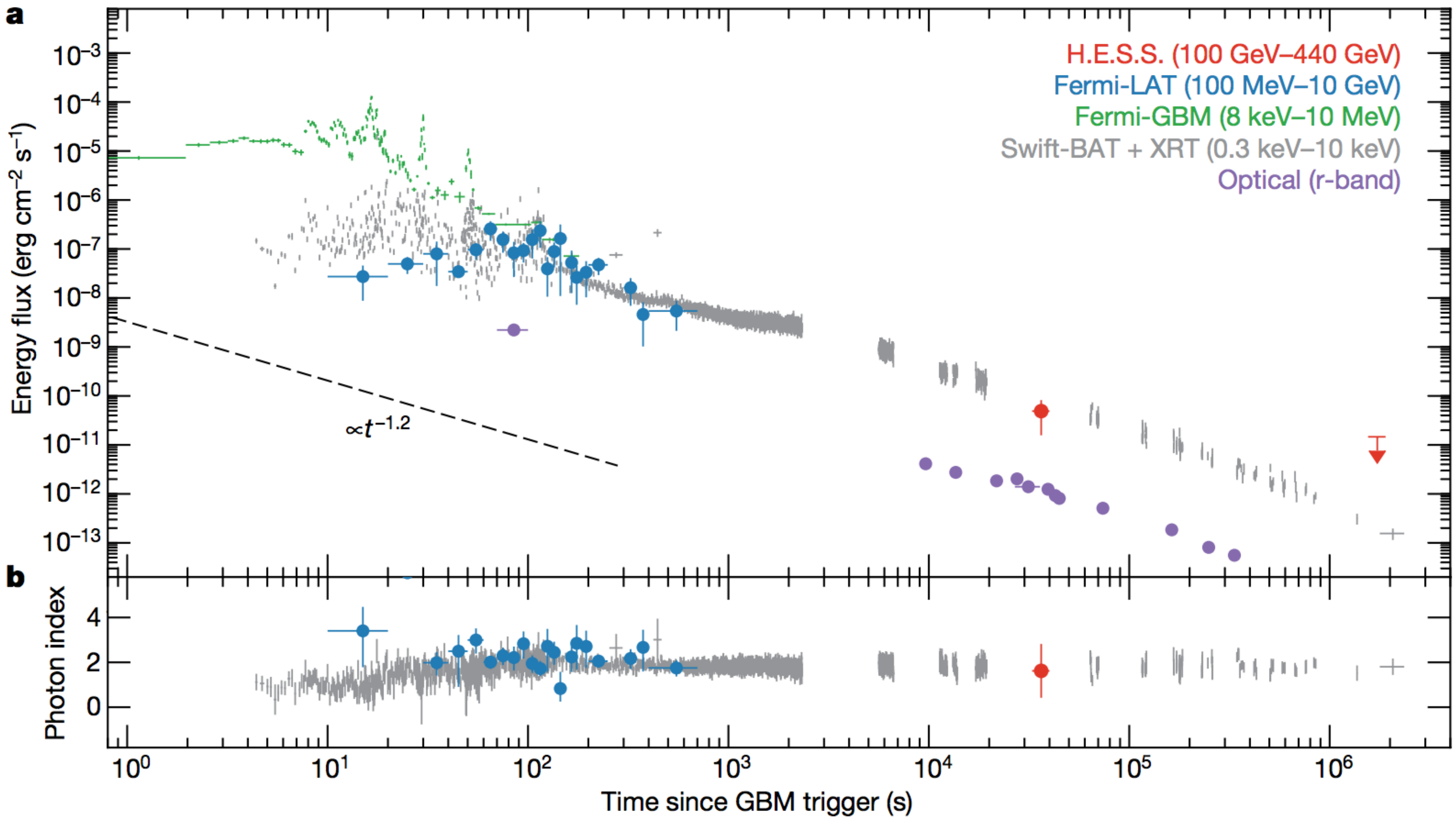
Acciari et al Nature 2019b

MAGIC detection: GRB 190114C



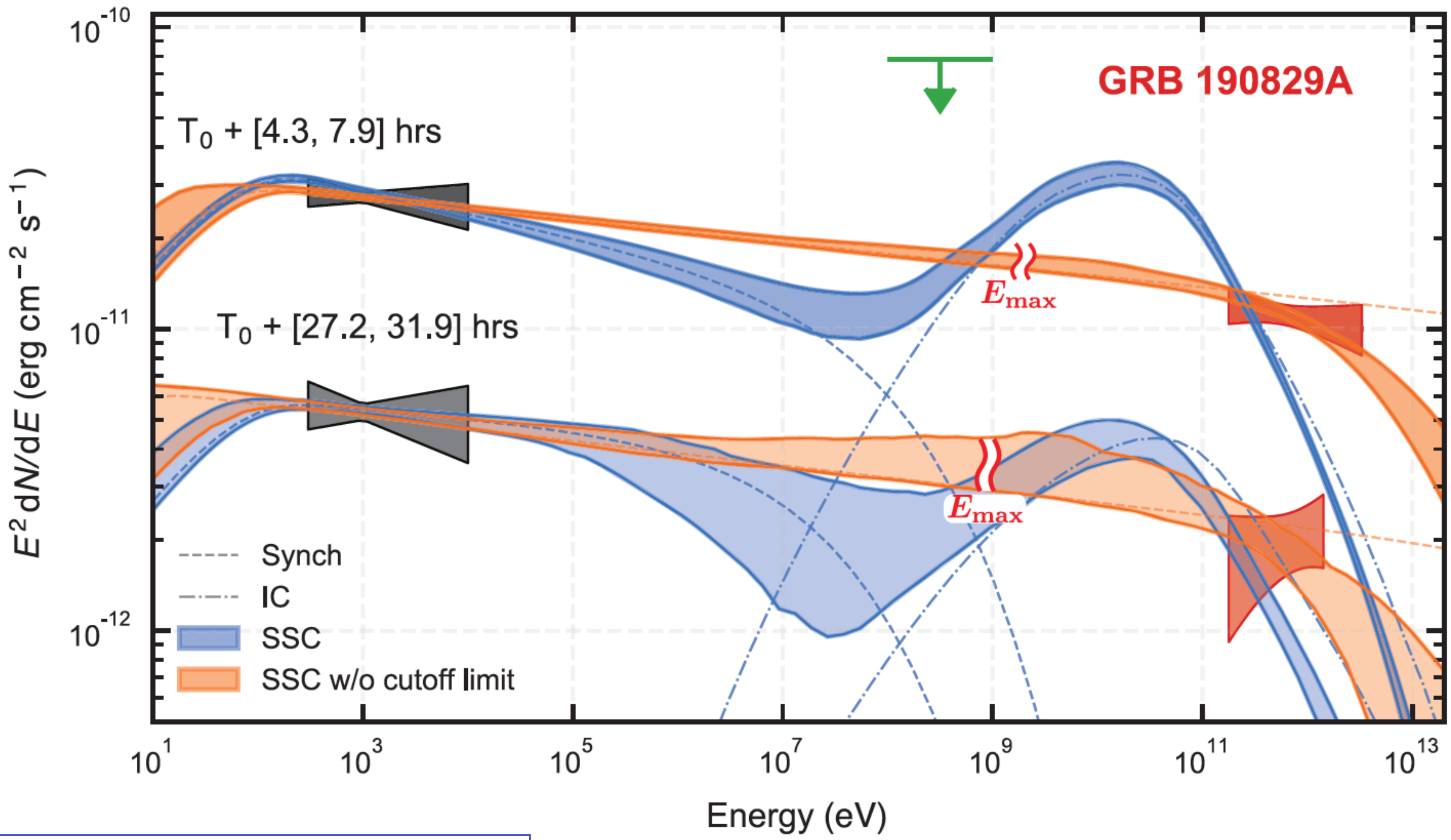
Acciari et al Nature 2019b

HESS detection: GRB 180720B



Abdalla et al Nature 2019

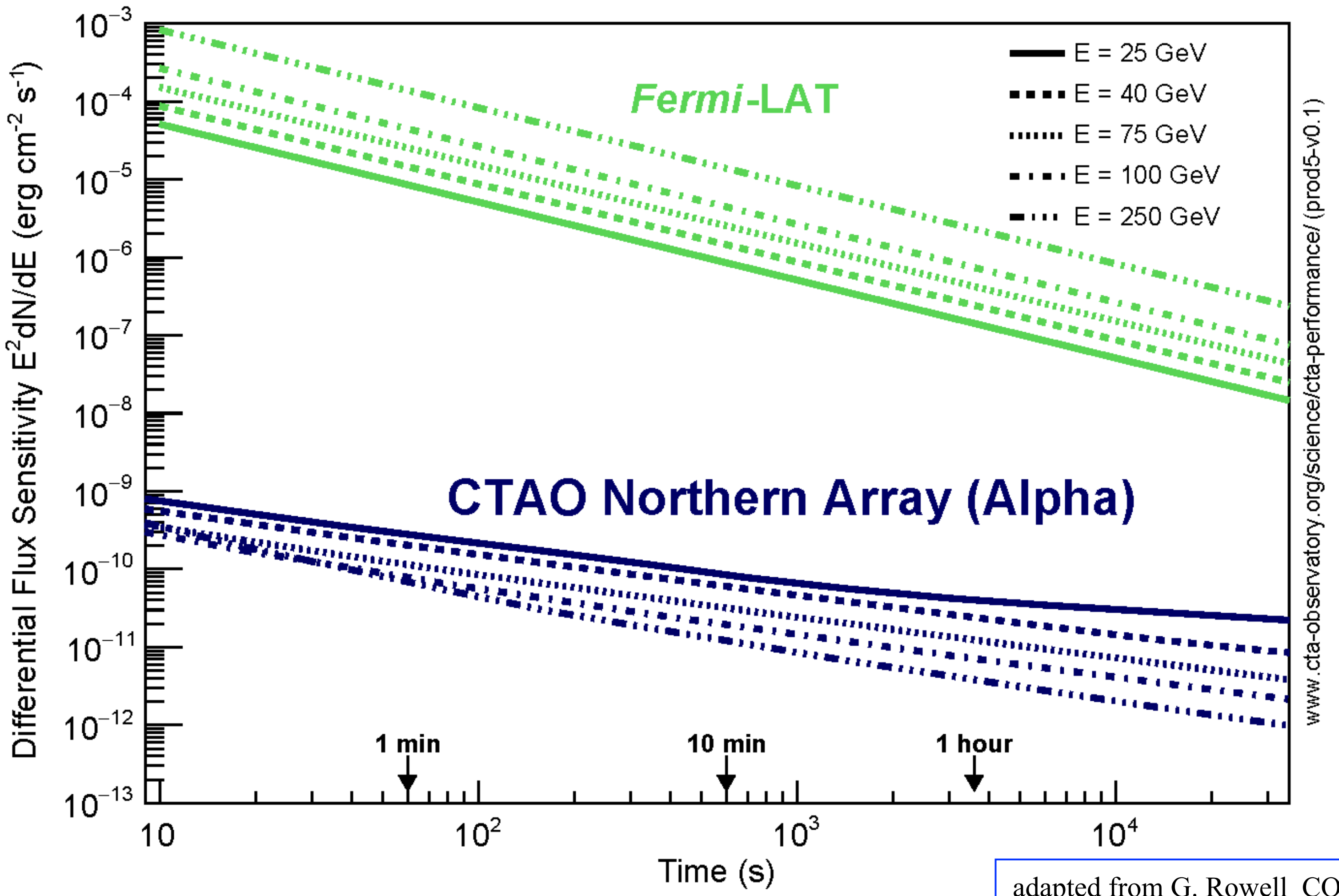
HESS detection: GRB 190829A



Abdalla et al Science 2021

Transients & Variable Sources: CTA Sensitivity vs. Time

(CTA Collab 2019)



adapted from G. Rowell COSPAR2020

CTA >10,000 times more sensitive than Fermi-LAT in multi-GeV range

→ GRBs, AGN, giant pulses, FRBs, GW, SGR bursts......

Conclusions

- HE satellites observations are shedding light (?) into the emission mechanism of GRBs
  - Prompt soft phase
  - Upper limits on the prompt phase
- The HE emission seems correlated to afterglow phenomenology
  - Temporal decay
  - Extended emission
- We were able to get detection of the VHE counterparts of GRB
  - VHE emission on the afterglow phase
  - VHE emission in the prompt?
- Stay tuned !