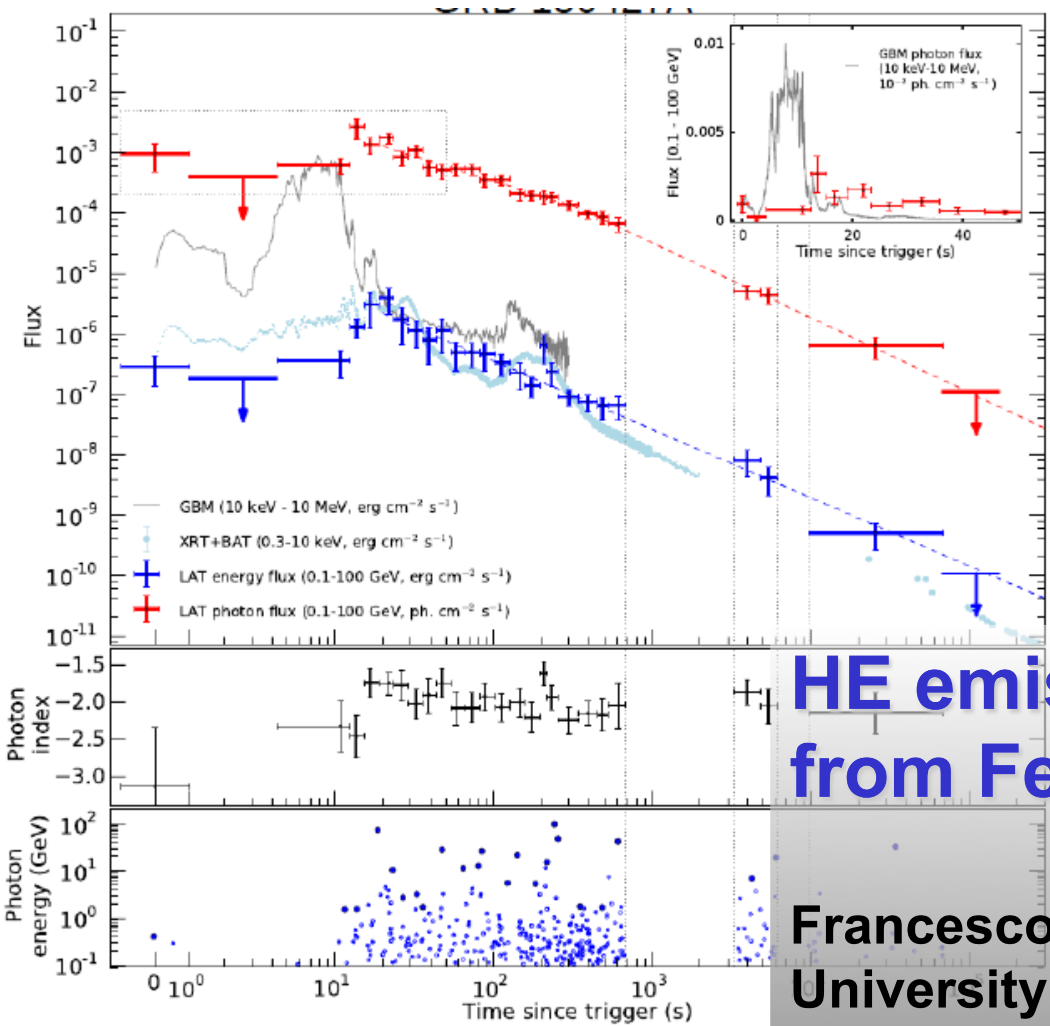
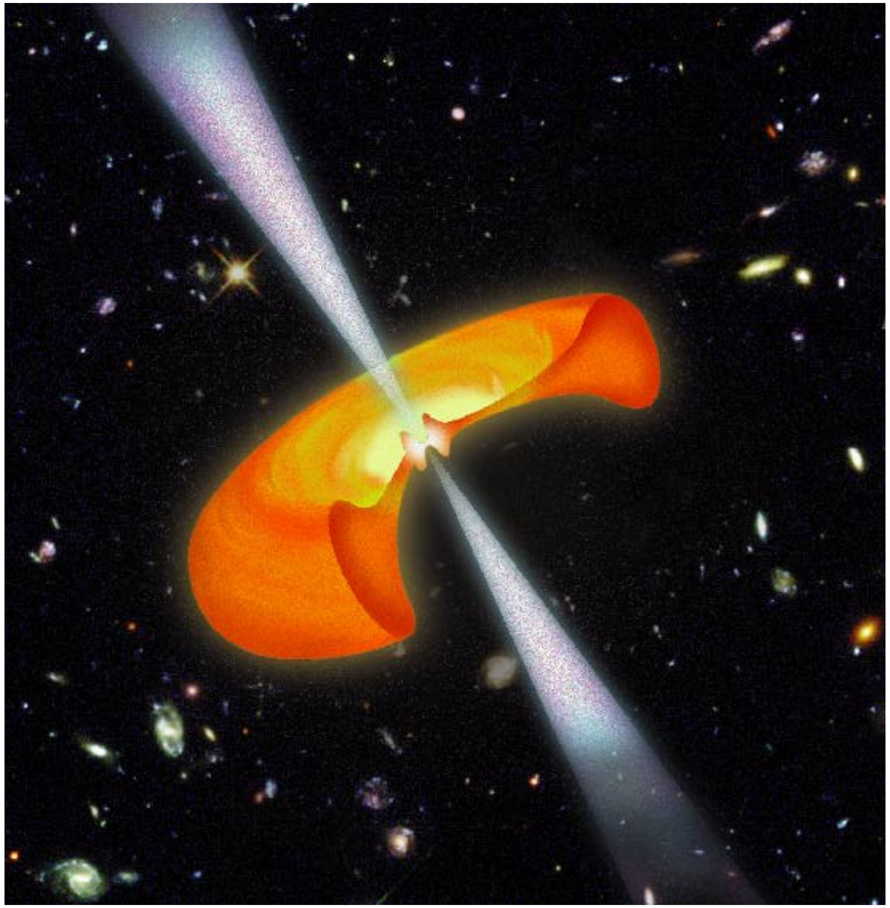


HE emission from GRBs from Fermi to IACTs

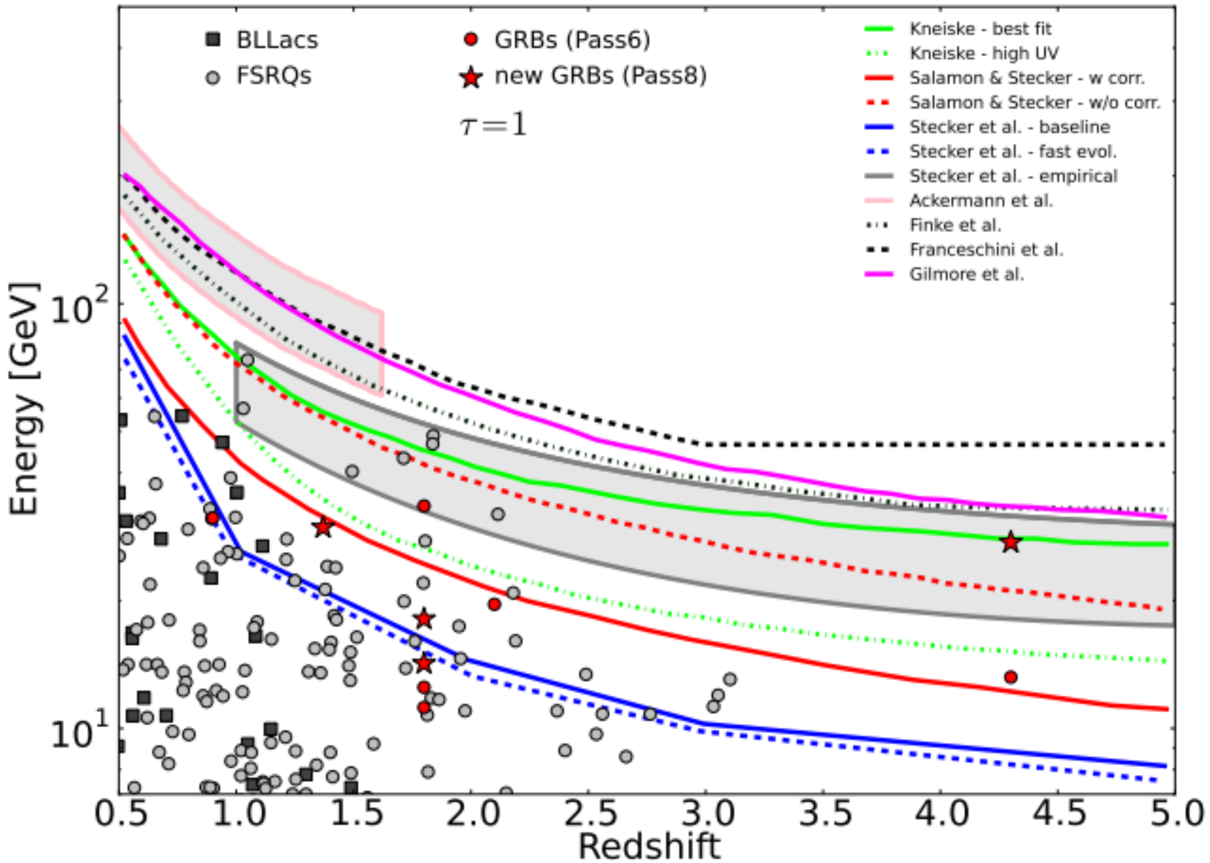
Francesco Longo
University and INFN, Trieste, Italy
francesco.longo@ts.infn.it

Outline

- GRBs at the highest energies
  - The EGRET era
    - Observations
      - GRB 930131
      - GRB 940217
      - GRB 941017
    - Interpretation
  - The AGILE/Fermi era
    - Observations
      - GRB 080916C
      - GRB 090510
      - GRB 130427A
    - Interpretation
  - The TeV era
    - Observations
      - GRB 190114C
      - GRB 190829A
      - GRB 221009A
    - Interpretation



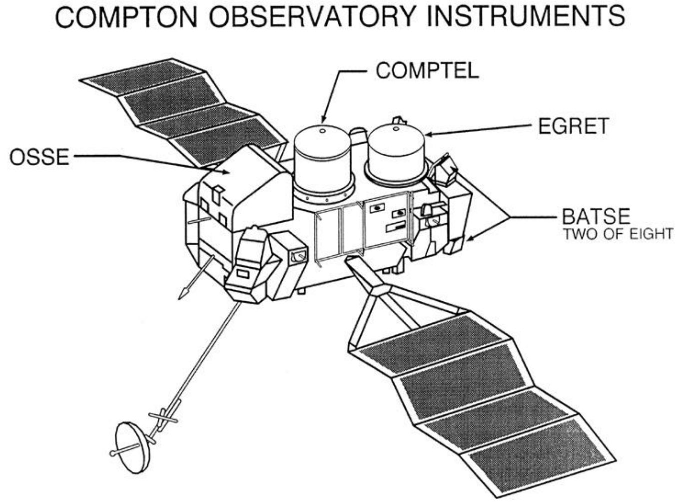
GRB at the highest energies … why is important for high redshift GRBs?

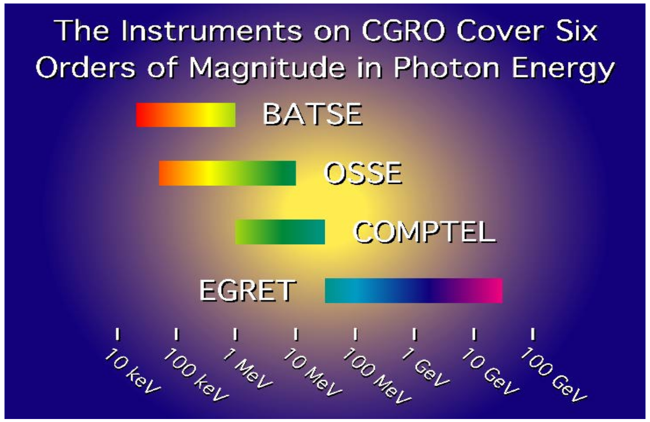


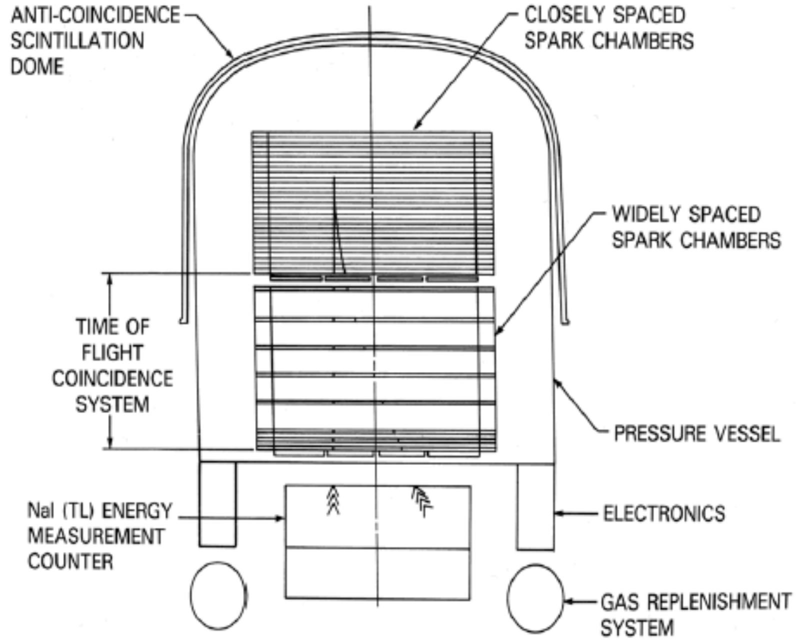
Atwood et al. 2013

High Energy Emission from GRB
“The EGRET era”

The Compton Gamma Ray Observatory



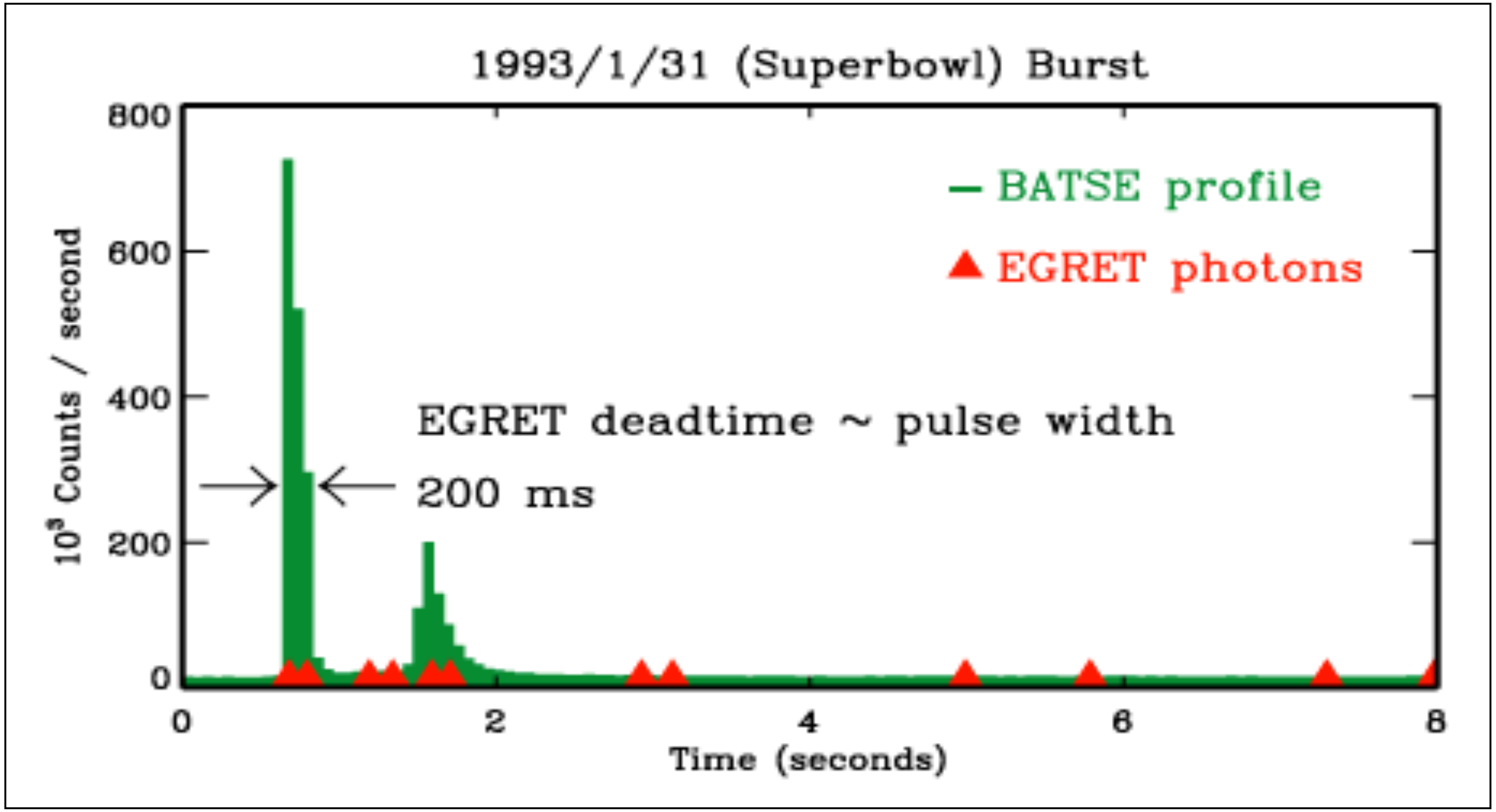




EGRET

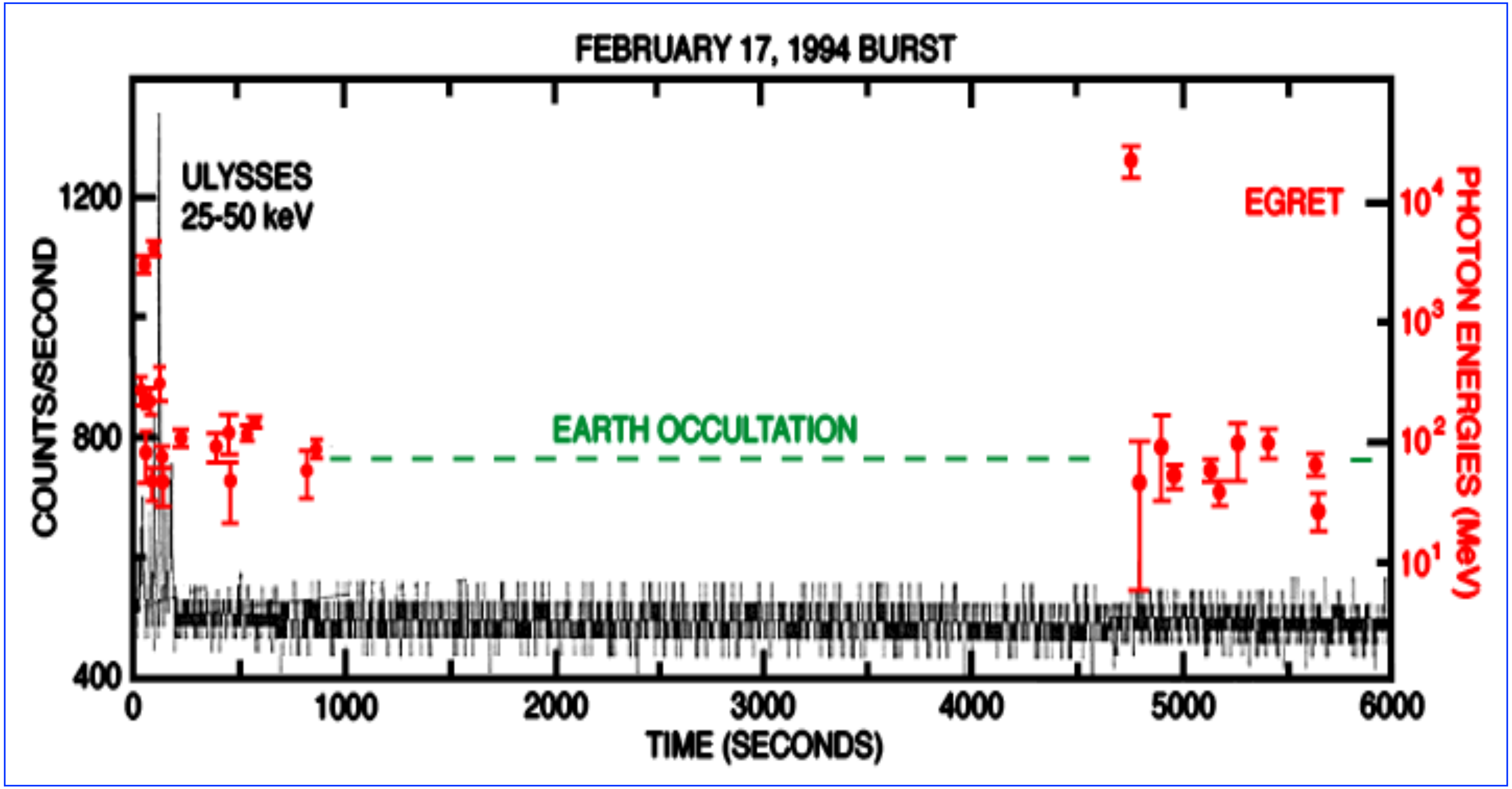
- 1991-2000
- 30 MeV - 30 GeV
- AGN, **GRB**, Unidentified Sources, Diffuse Bkg

GRB prompt emission - 930131



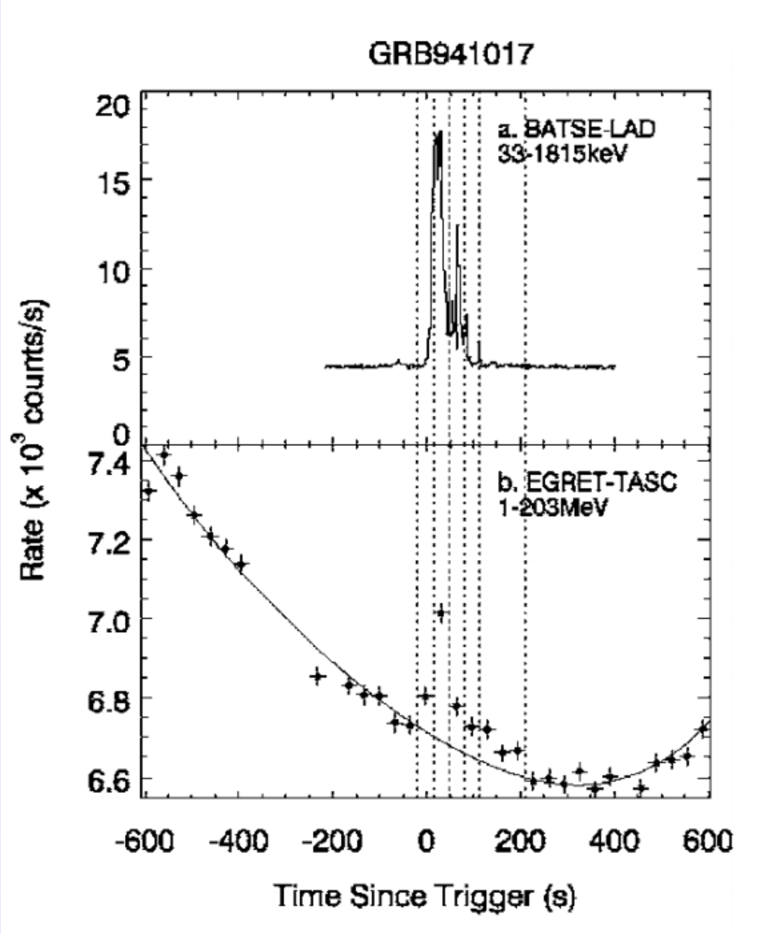
Kouveliotou et al 1994
Sommer et al. 1994

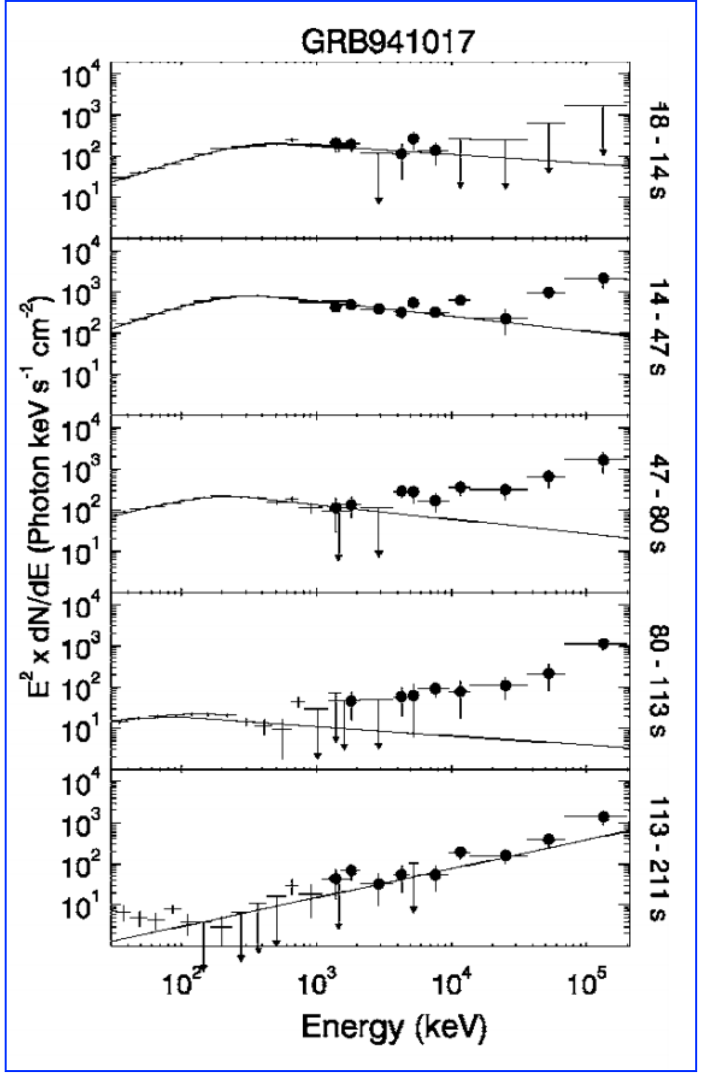
GRB delayed emission - 940217



Hurley et al. 1994

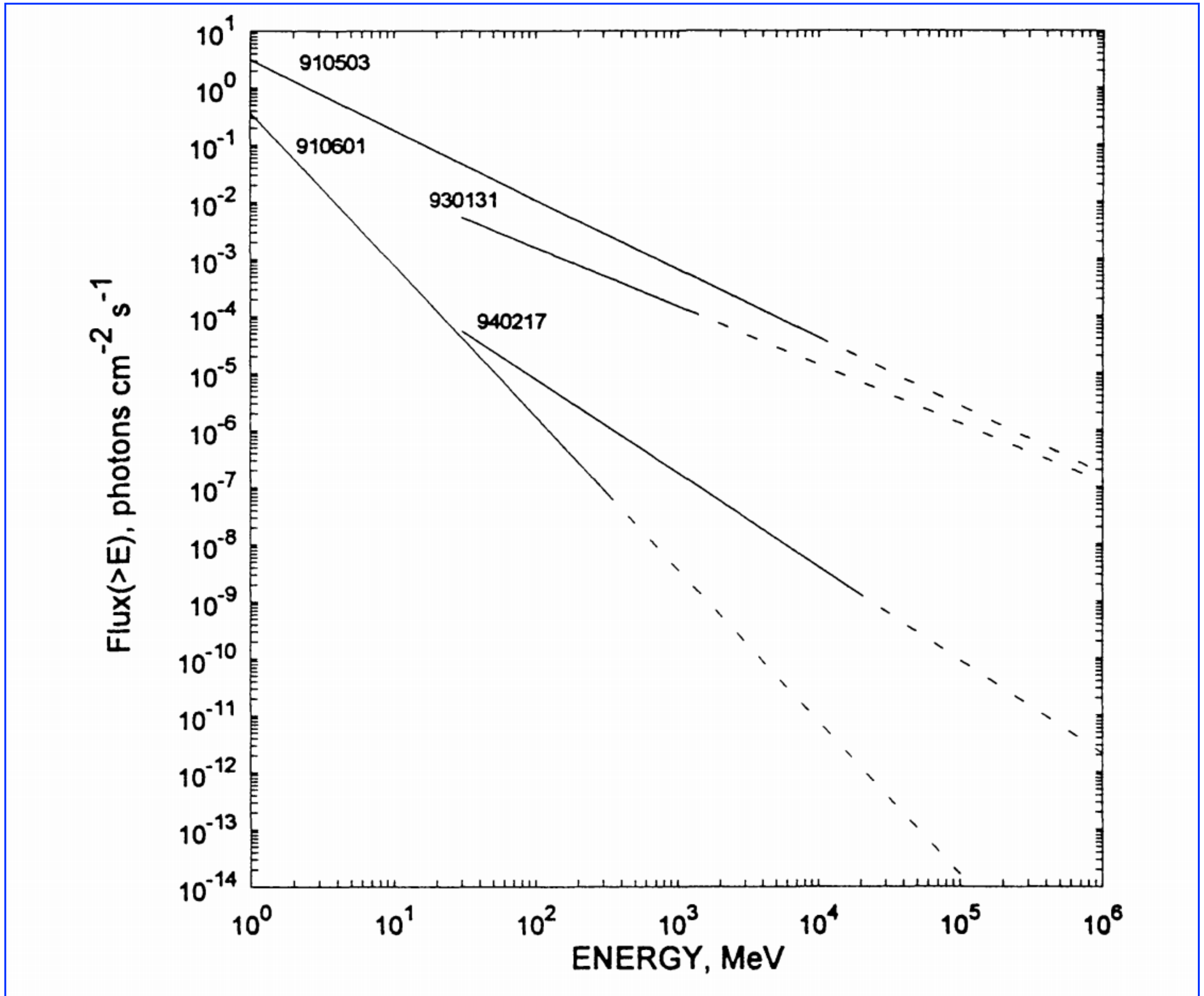
Extra Spectral Components - 941017





Gonzalez, et al. 2009

Search for GRBs at the highest energies



Hurley 1996

Theoretical Expectation

EMISSION SPECTRA FROM INTERNAL SHOCKS IN GAMMA-RAY BURST SOURCES

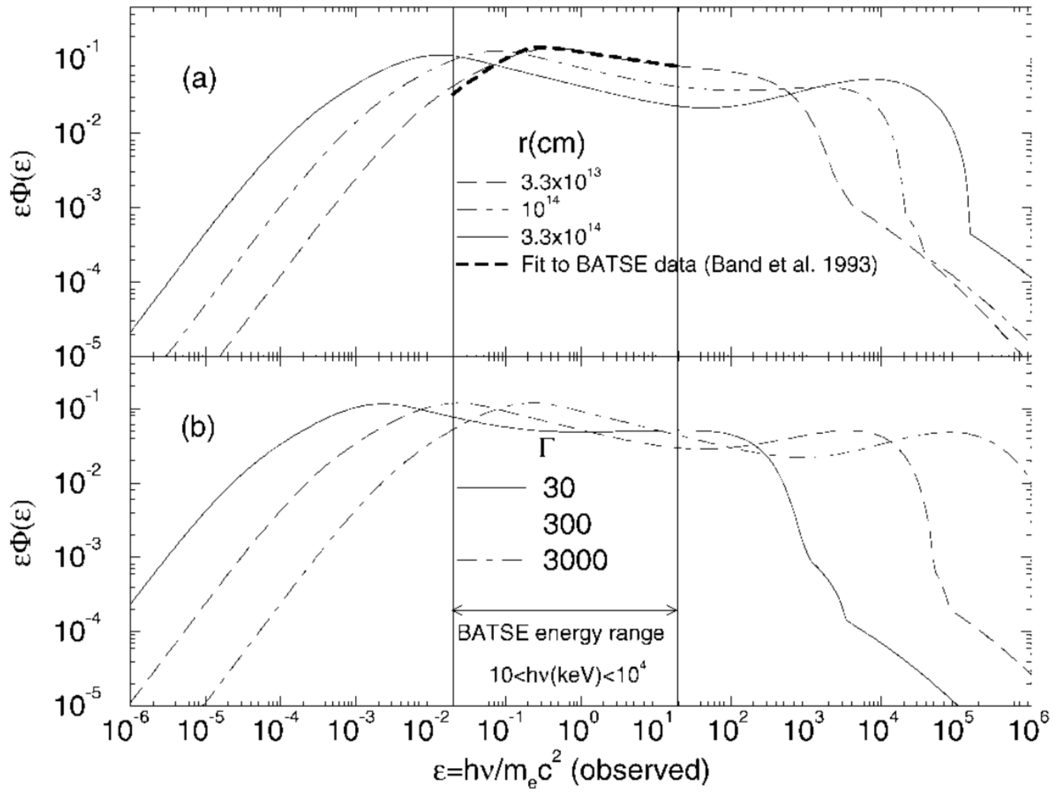
RAVI P. PILLA
Department of Physics, Columbia University, 538 W. 120th Street, New York, NY 10027; ravi@cuphyb.phys.columbia.edu
AND

Astronomy Department, Harvard University,

Received 1997 October 20; acce

Unsteady activity of γ-ray burst sources lead
the emission spectra from such shocks, assuming
and possess strong magnetic fields. The synchr
upscattered multiple times by the same electro
energies and produce e^+e^- pairs. The pairs tran
scattering. The generic spectral signature from
to the radius at which the shock dissipation take
spectrum extends over a wide range of photon en
values of the wind parameters, the calculated
observed burst spectra.

Subject headings: gamma rays: bursts — radiati



Pilla and Loeb 1998

Theoretical Expectation

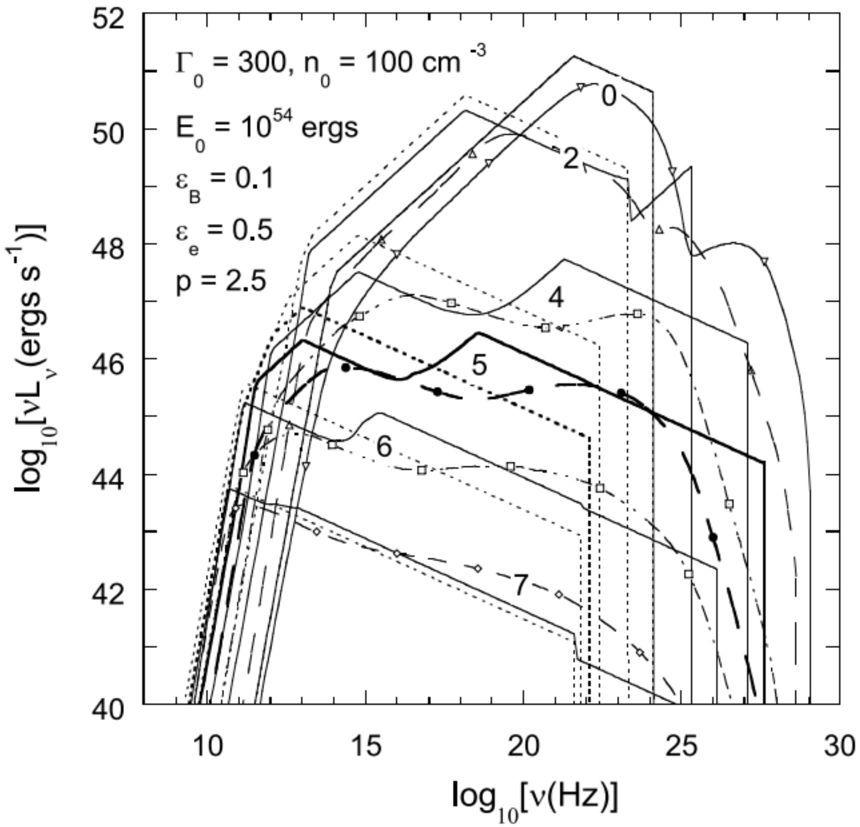
SPECTRAL ENERGY DISTRIBUTIONS OF GAMMA-RAY BURSTS ENERGIZED BY EXTERNAL SHOCKS

CHARLES D. DERMER,[1] MARKUS BÖTTCHER,[2,3] AND JAMES CHIANG[4]

Received 1999 October 18; accepted 2000 February 9

Sari, Piran, & Narayan have derived a
blast waves that are energized by sweepin
expressions to apply to general radiati
absorption. Electron energy losses due tc
very approximate way. The calculated spe
We find that the spectral and temporal br
er than the analytic formulae imply anc
results are greatest near the breaks and e
accurate (within a factor of ∼3) in the o
accurate when ϵ_e, the fraction of swept-u
The analytic results provide at best ord
regime and give poor fits to the self-Co
effects and photon-photon opacity.

Subject headings: gamma rays: bursts — g

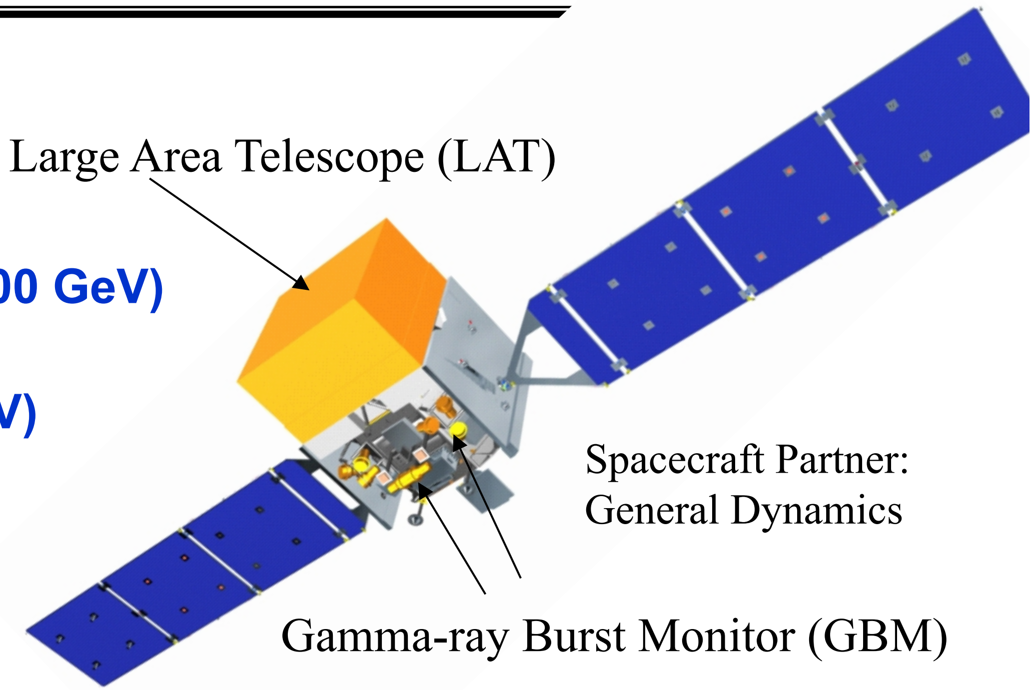


Dermer, Böttcher and Chiang 2000

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

Fermi Key Features

- **Two instruments:**
  - **LAT:**
    - **high energy (20 MeV – >300 GeV)**
  - **GBM:**
    - **low energy (8 keV – 40 MeV)**



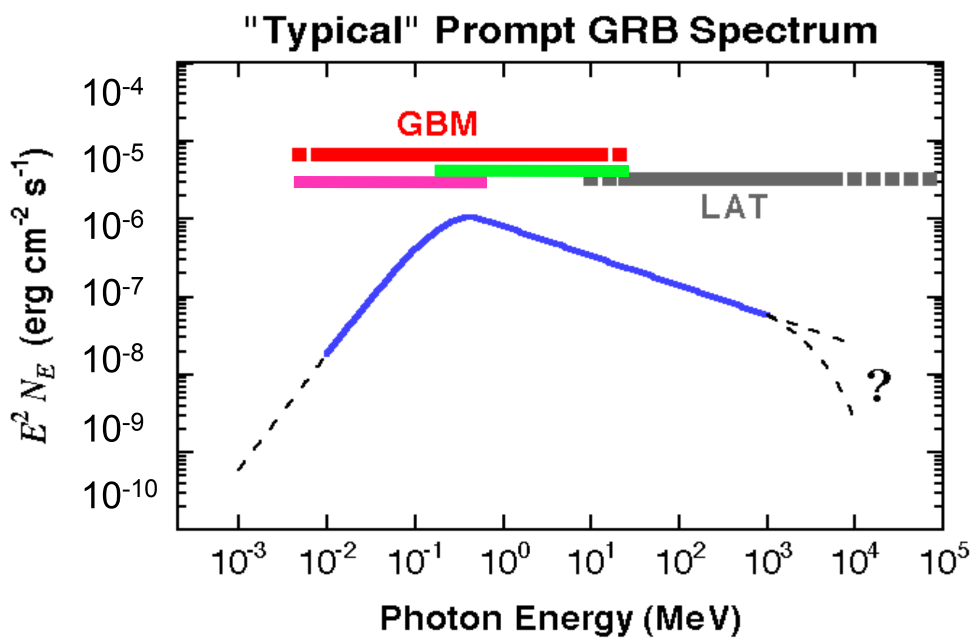
- **Huge field of view**
  - **LAT: 20% of the sky at any instant; in sky survey mode, expose all parts of sky for ~30 minutes every 3 hours. GBM: whole unocculted sky at any time.**
- **Huge energy range, including largely unexplored band 10 GeV - 100 GeV**

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**

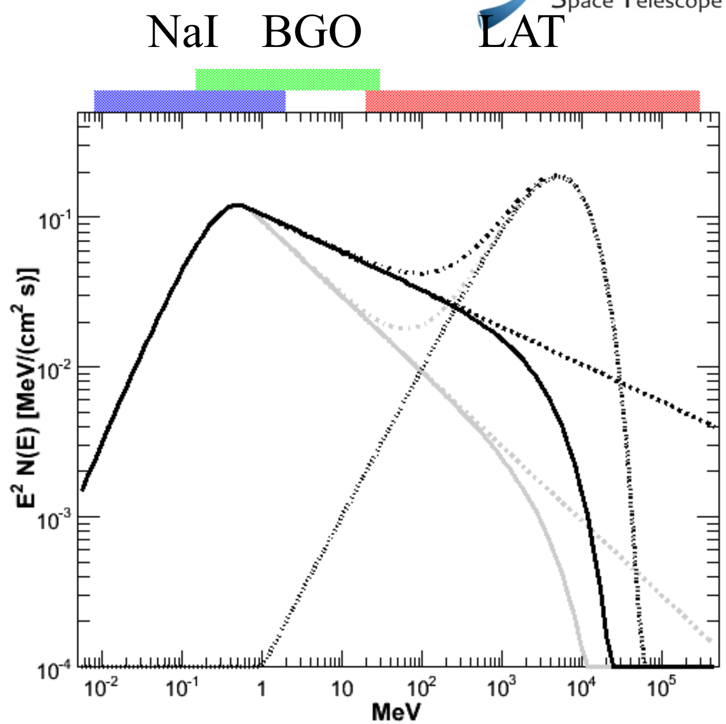
Exceptionally good spectral observations of the prompt phase of lots of GRB

Adapted from N.Omodei



Study GRB with the Fermi observatory

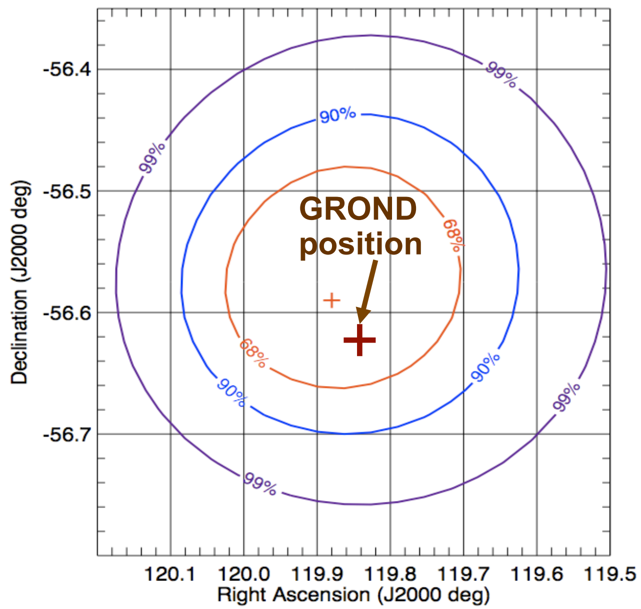
- Spectrum studied over 7 decades!
- Bright burst: study of the cut-off, if any.
- Detailed temporal/spectral evolution:
  - Is there any "extra component"?
  - How common is the extended/delayed GeV emission?
  - Pseudo-redshift estimators:
    - improve statistics
    - new relations?
  - Time Lag 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 they emit gamma-rays. Constrain the LF of the expanding shells.
- + DISCOVERIES



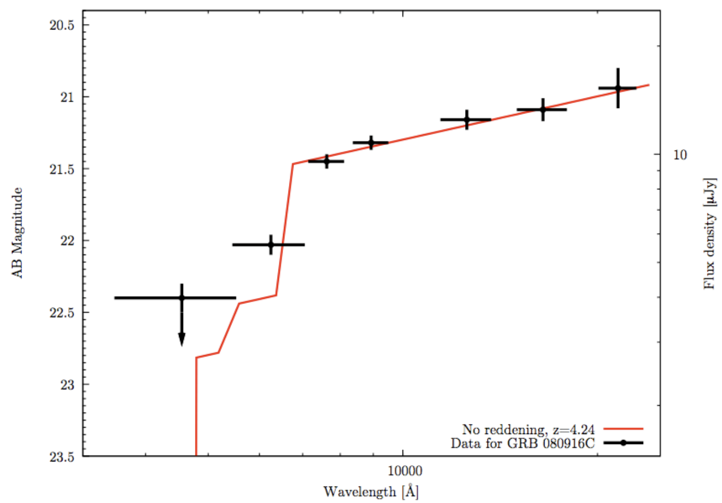
Adapted from N.Omodei

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



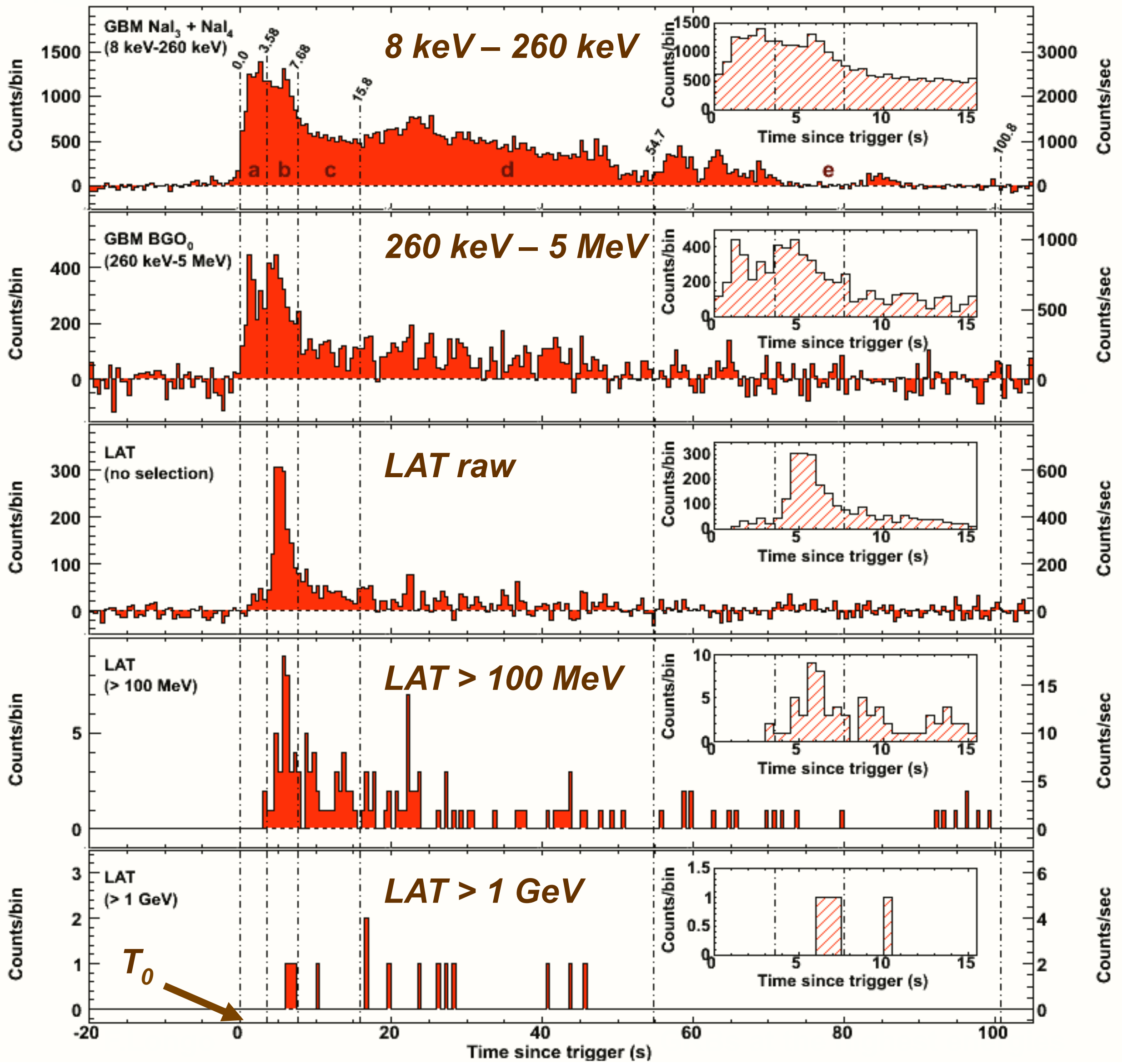
GROND optical follow up [GCN 8257, 8272]
Faint (21.7 mag at T_0+32h) and fading (T_0+3.3d) source
RA = 119.8472˚, Dec = −56.6383˚ (±0.5" at 68% C.L.)



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)

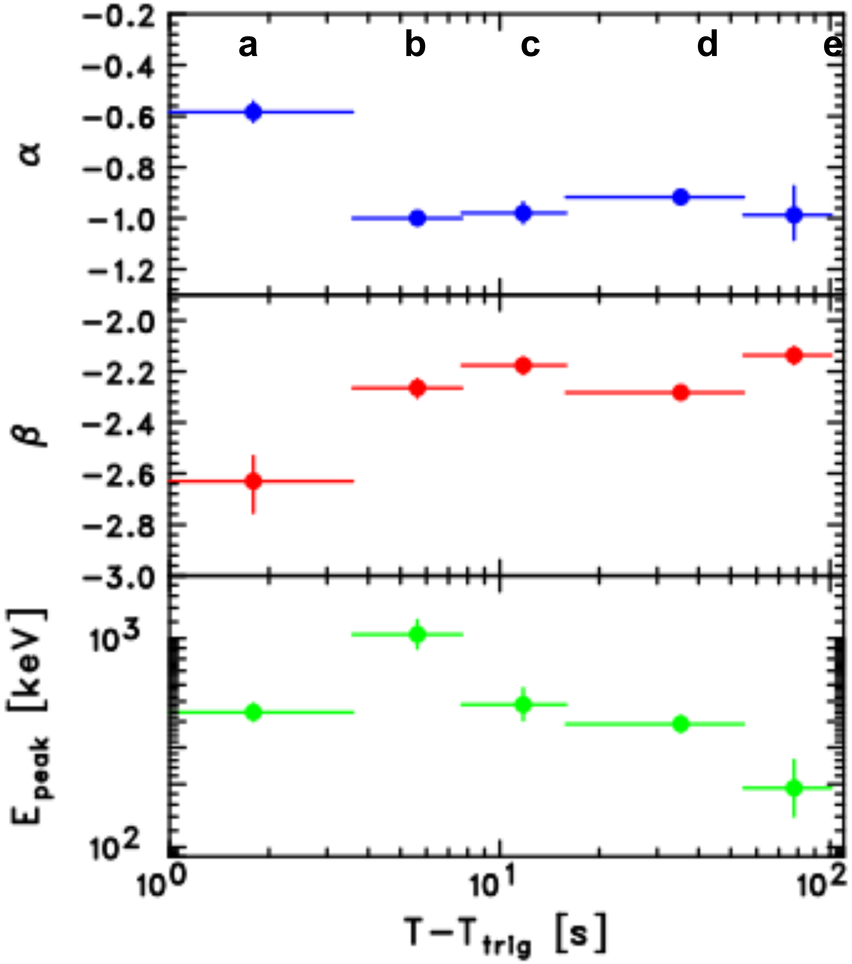
- **5 intervals for time-resolved spectral analysis:**
  0 – 3.6 – 7.7 – 16 – 55 – 100 s
- **14 events above 1 GeV**

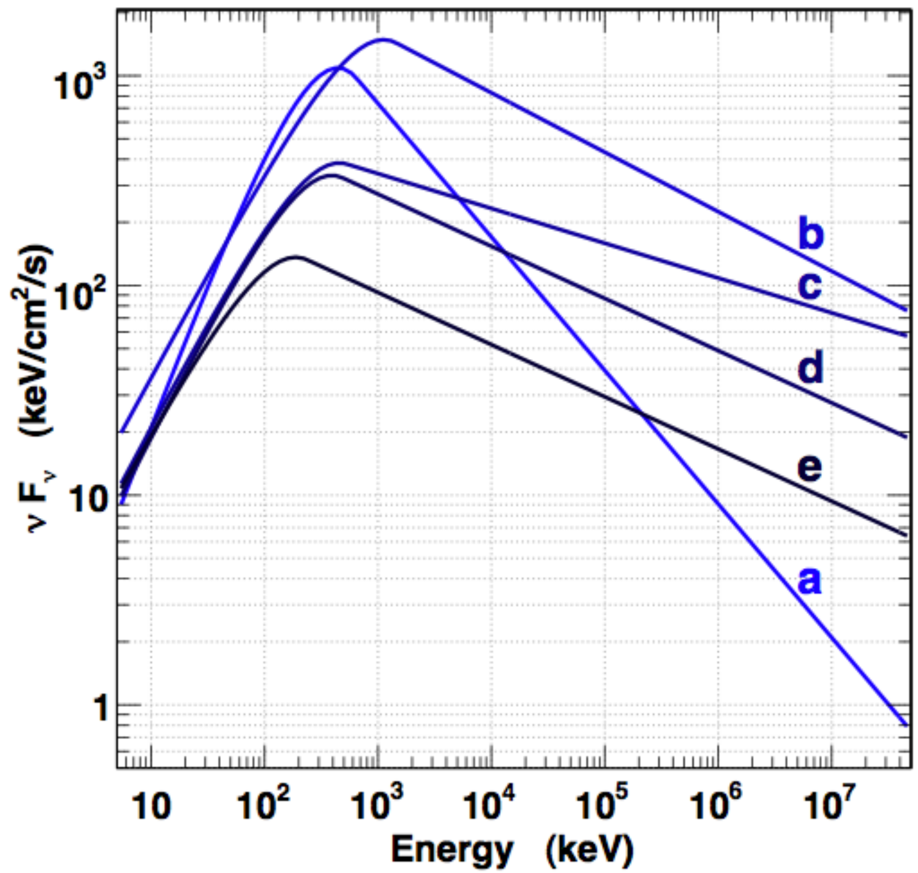
Spectral evolution

Adapted from N.Omodei

Fermi Gamma-ray Space Telescope

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



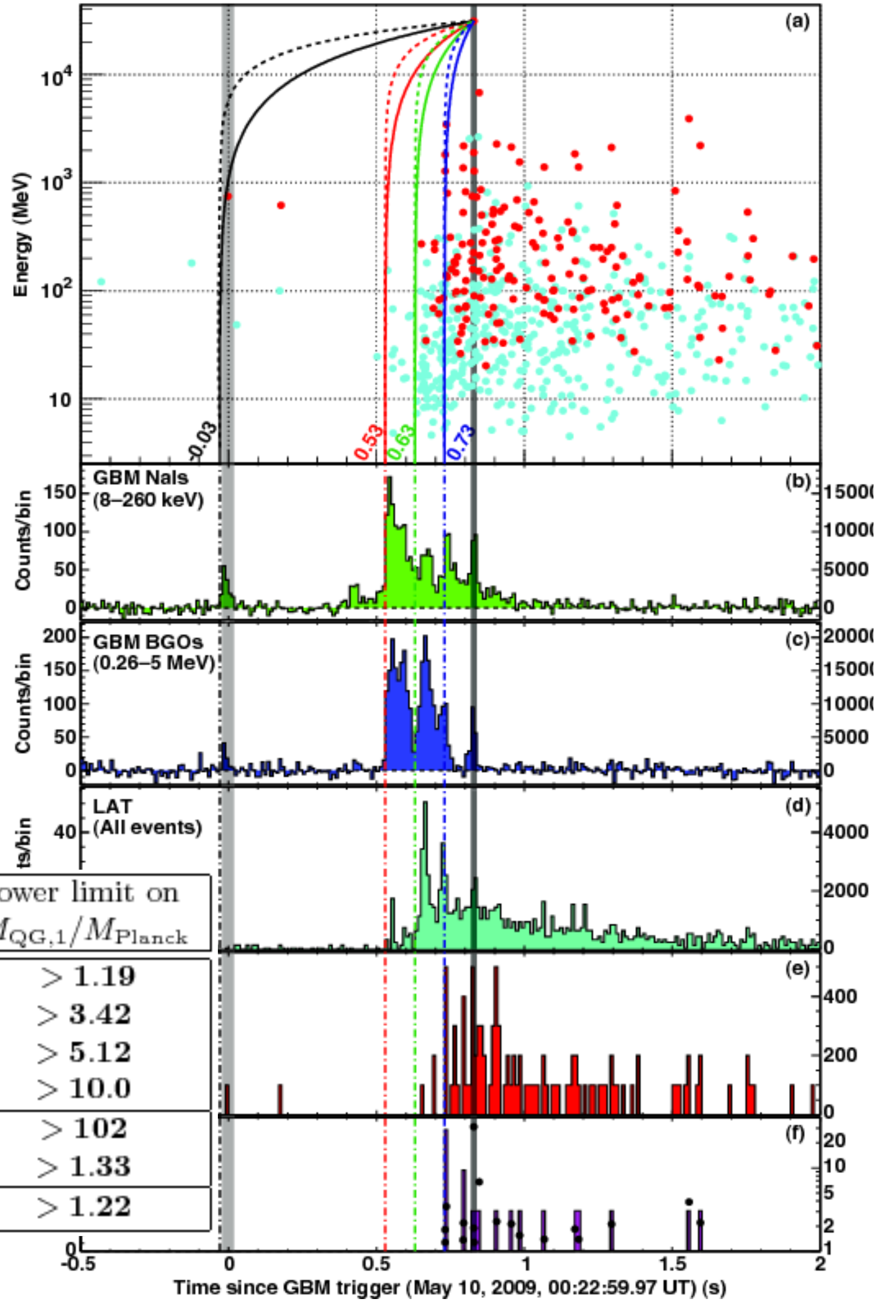


GRB 090510

- 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.

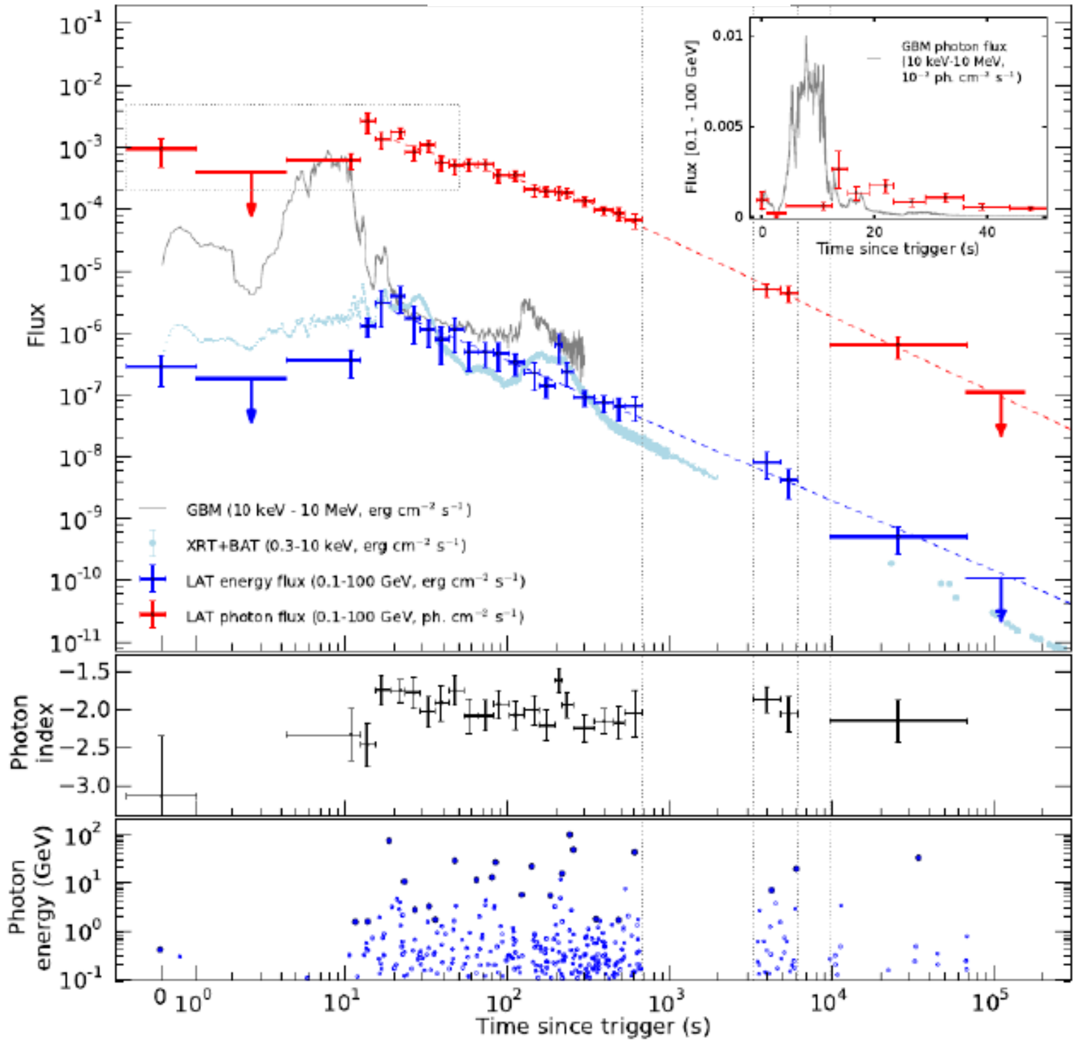
$M_{QG} > 1.19 \times M_{Plank}$

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



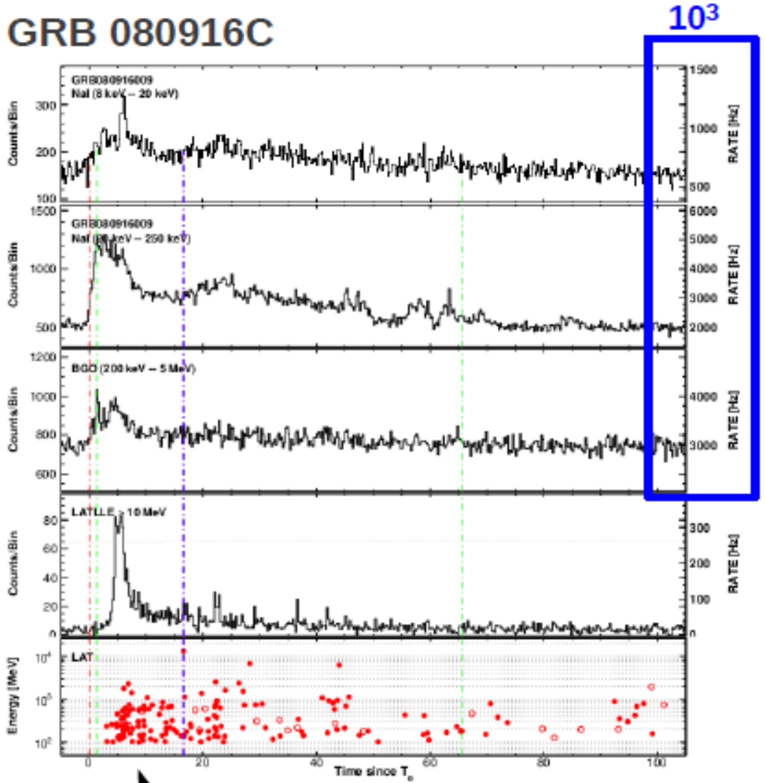
t_{start} (ms)	limit on $\lvert\Delta t\rvert$ (ms)	Reason for choice of t_{start} or limit on Δt	E_l (MeV)	valid for s_n	lower limit on $M_{QG,1}/M_{Planck}$
−30	< 859	start of any observed emission	0.1	1	> **1.19**
530	< 299	start of main < 1 MeV emission	0.1	1	> **3.42**
630	< 199	start of > 100 MeV 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**

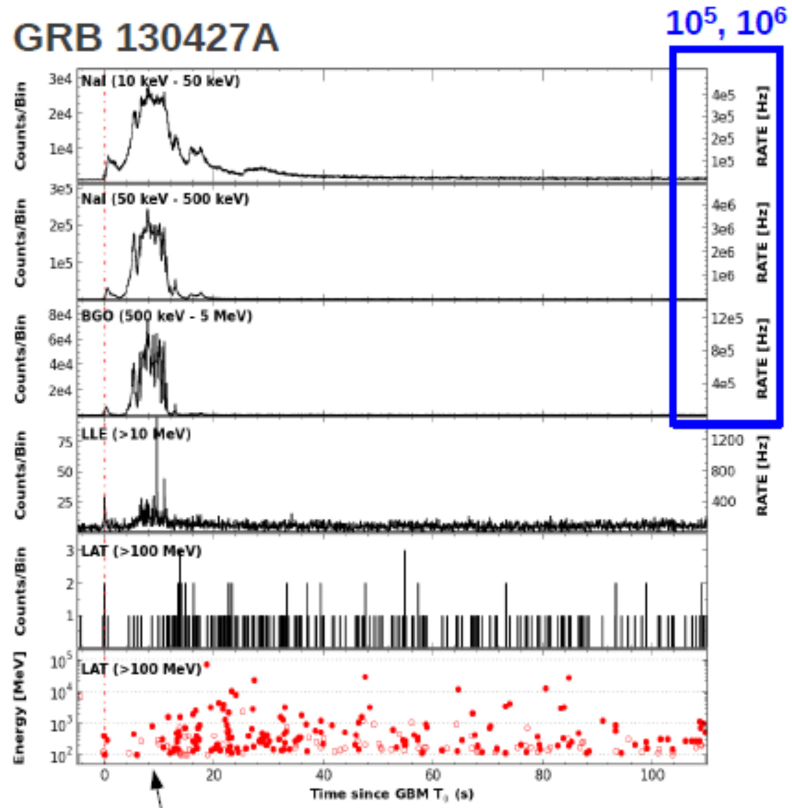
GRB 130427A



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

GRB 130427A





LAT emission dying down

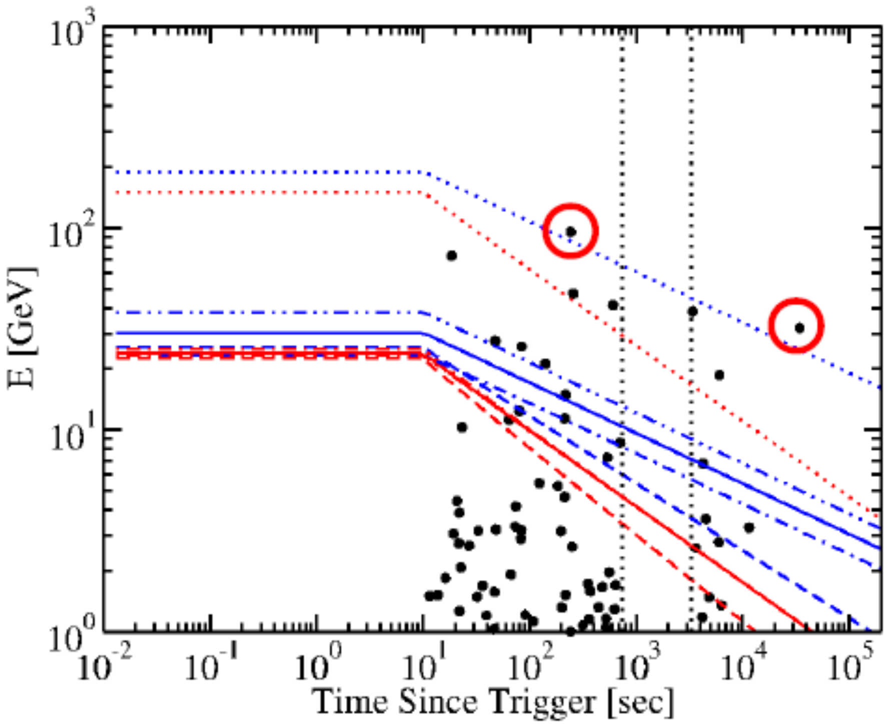
LAT emission still going

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.**



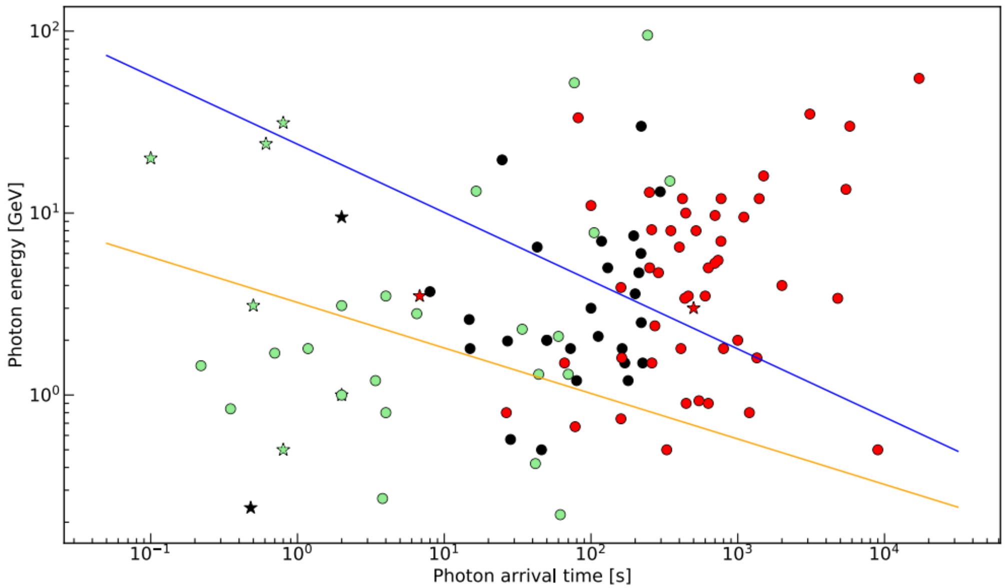
Curves of **maximum** synchrotron photon energy from external shocks, for various conditions

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

HE photons

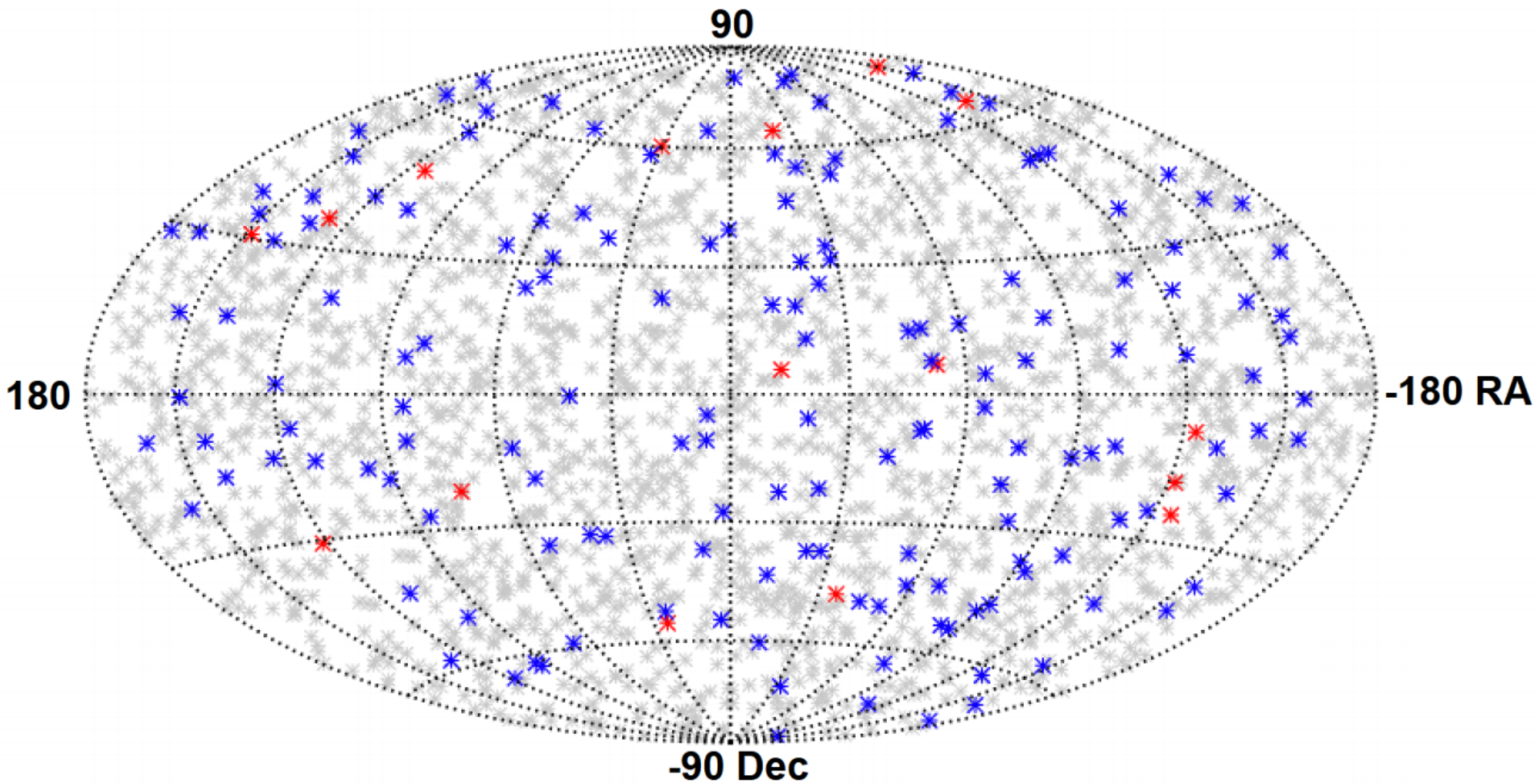


Energy of the most energetic photon fpr each GRB versus its arrival time.
Red → well after the end of the prompt phase.
Green → during the prompt phase.
Black → after the end of the prompt emission, but on a comparable timescale.
Short GRBs are marked with stars.

Eobs_syn,max = 50 MeV×Γ/(1+z),
Blue - homogeneous medium with density n = 1 cm^{-3}
Yellow - Wind-like medium with density n = $3\times10^{35}R^{-2}cm^{-1}$

Nava 2018

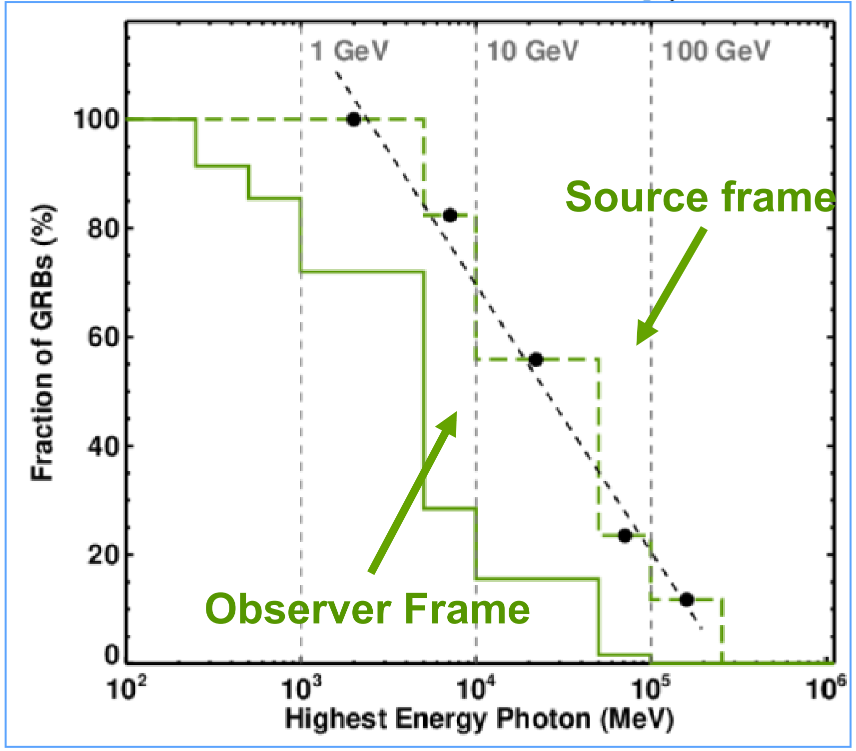
The 2nd Catalog

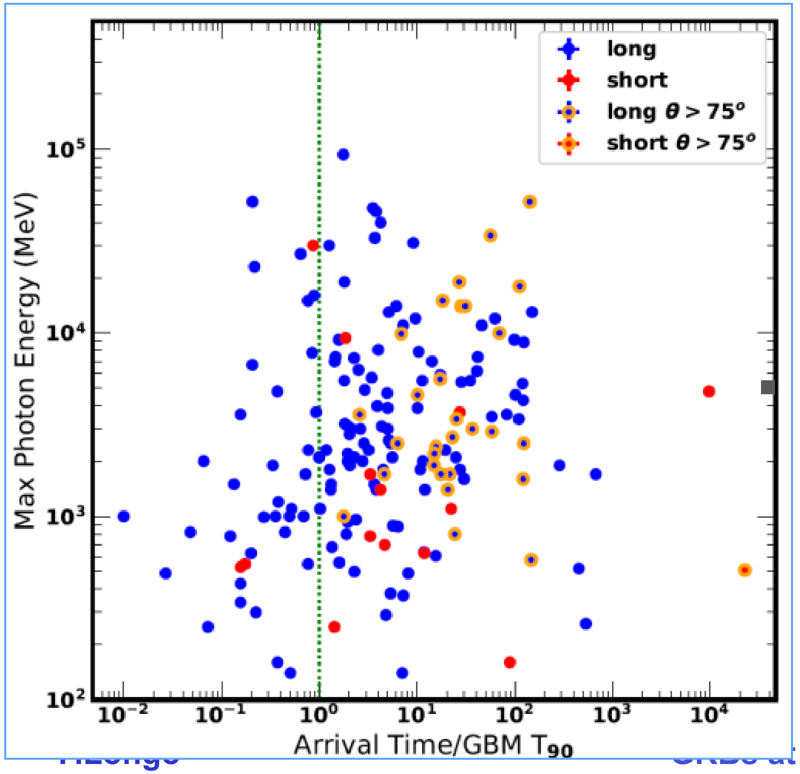


Ajello, M. et al. 2019

Highest-energy photons from GRBs

- <5% of GRBs have E > 50 GeV
- Sharp drop @5 GeV (obs.frame)
  - Record holder: GRB 130427A
    - 95 GeV @243 s
    - 77 GeV @19s
    - 34 GeV @34 ks



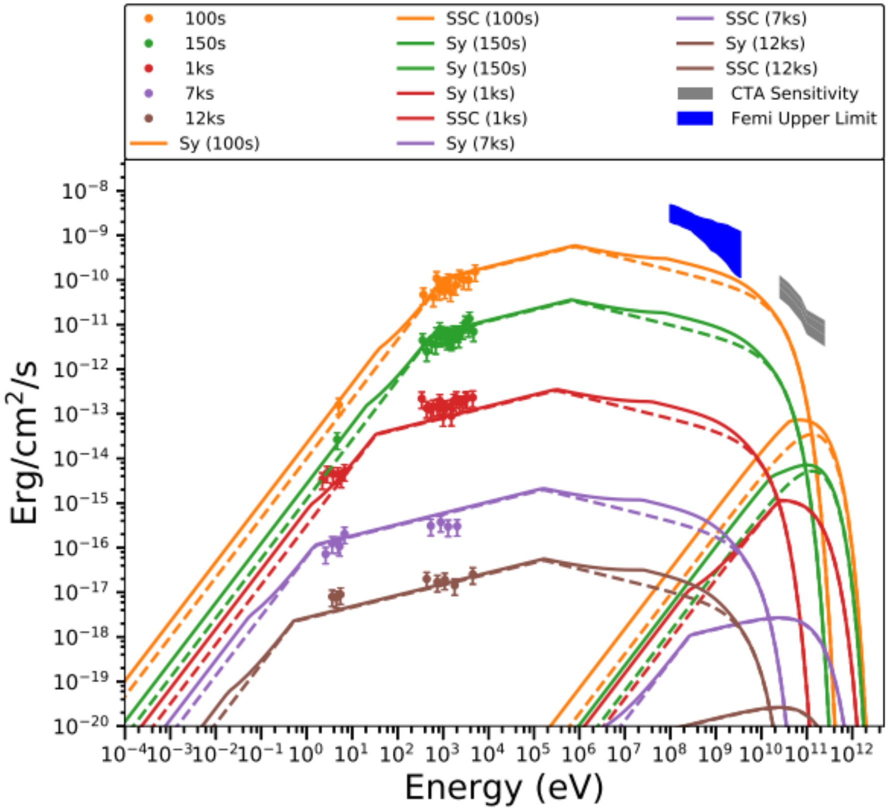


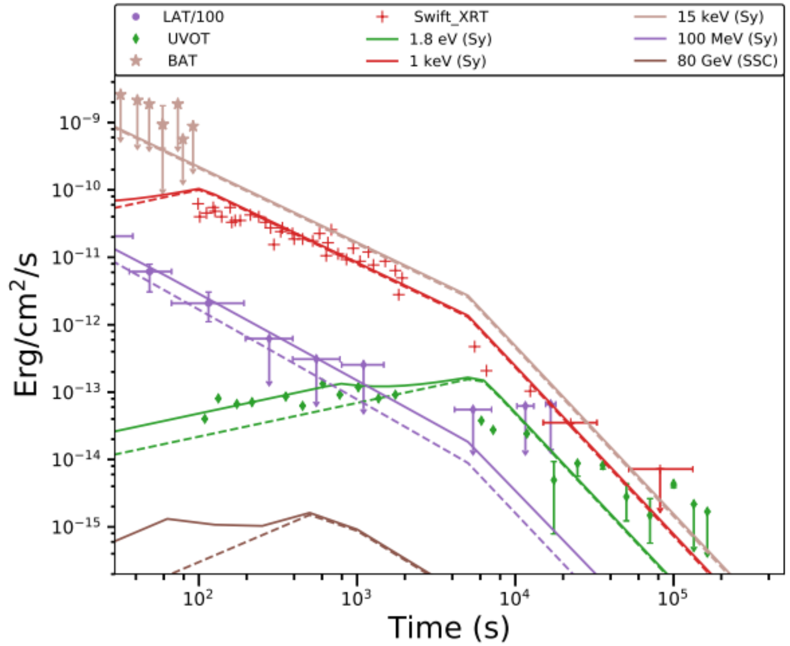
HE photons often arrive after the low-energy emission is over BUT

- Highest energies can be produced either very quickly or very late: challenge for models!

Ajello et al. 2019

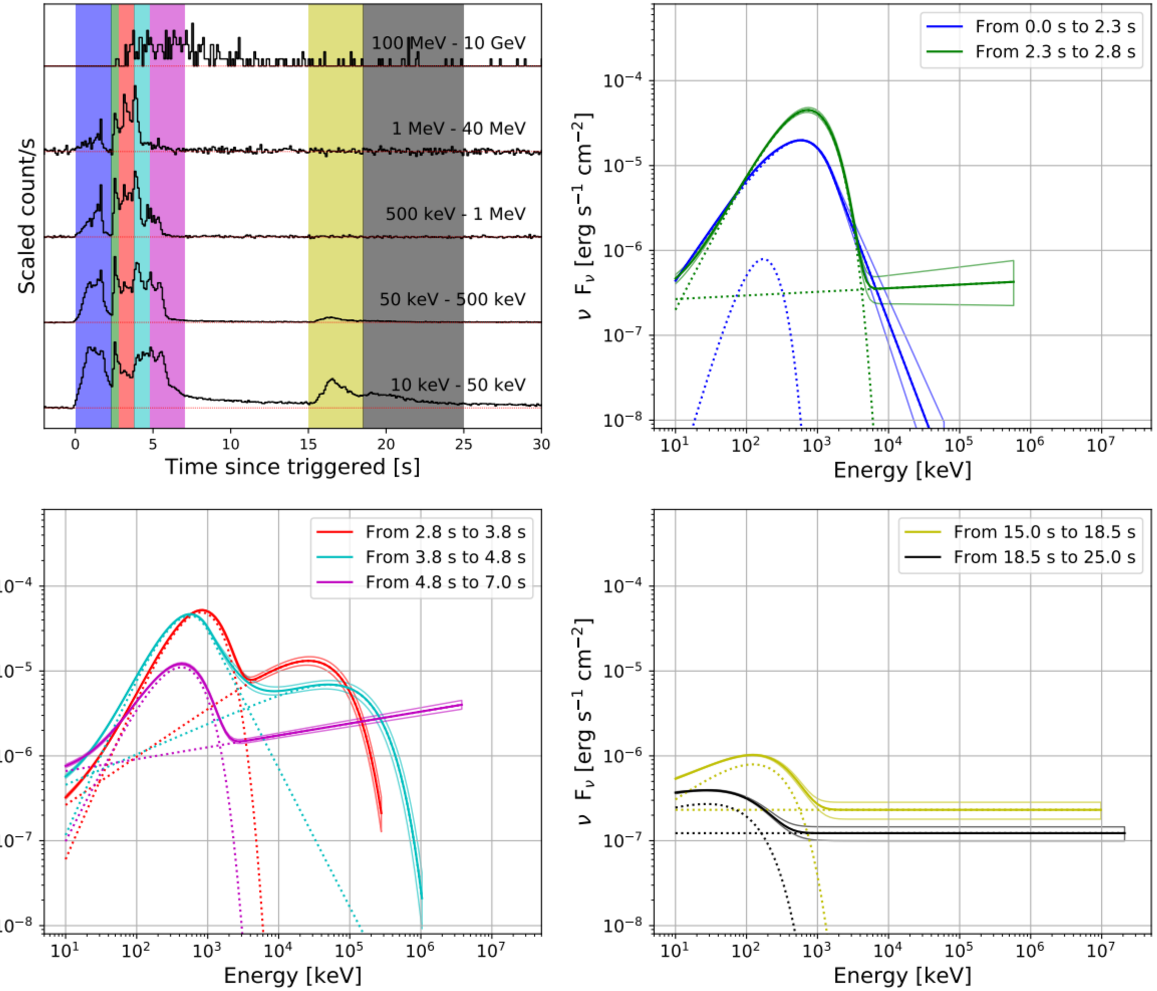
VHE emission models





Joshi and Razzaque 2019

GRB 190114C



Ajello, M. et al. 2020

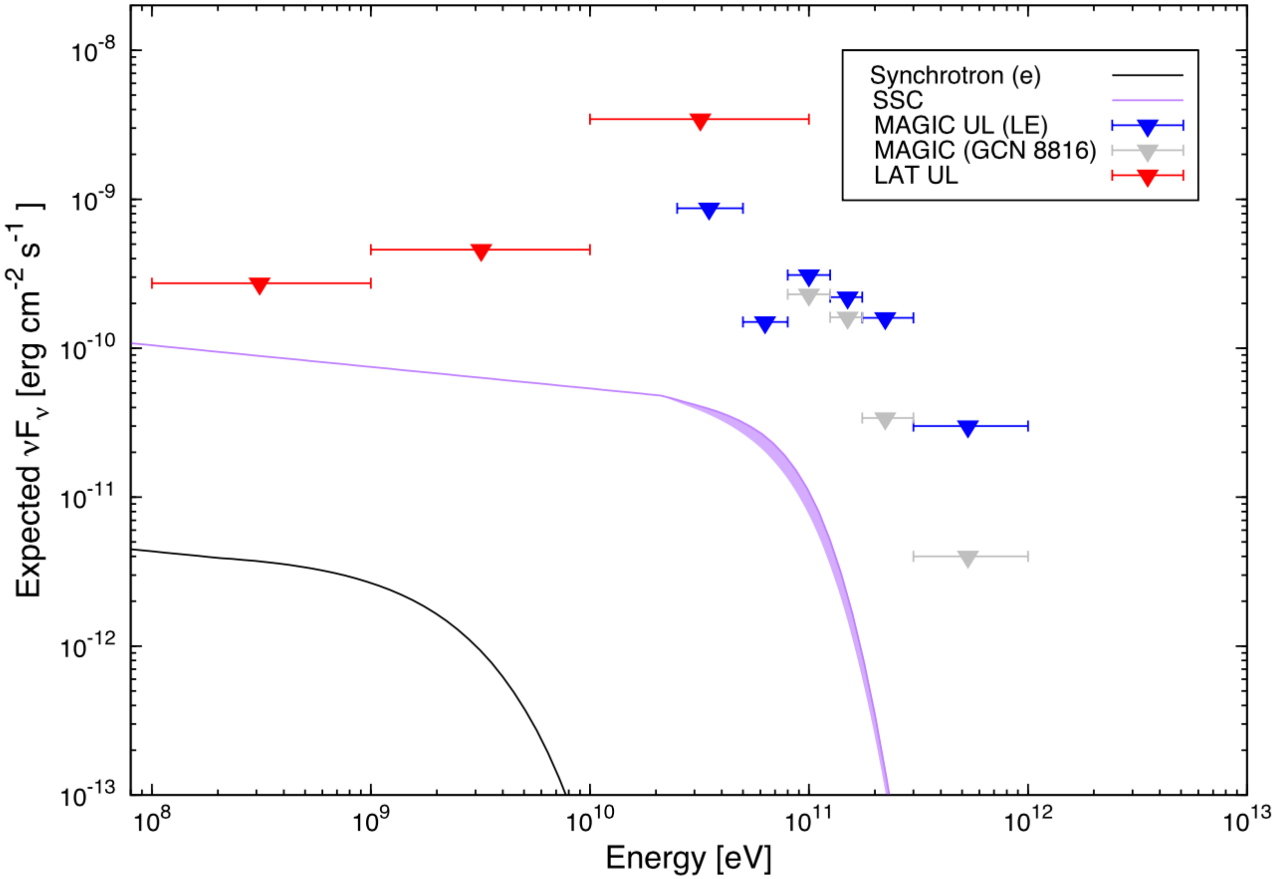
HE Emission from GRBs

- Extended emission
  - Extra long GRBs
- Prompt emission
  - Delayed onset
  - Emission mechanism
- SpectralComponents
  - 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"

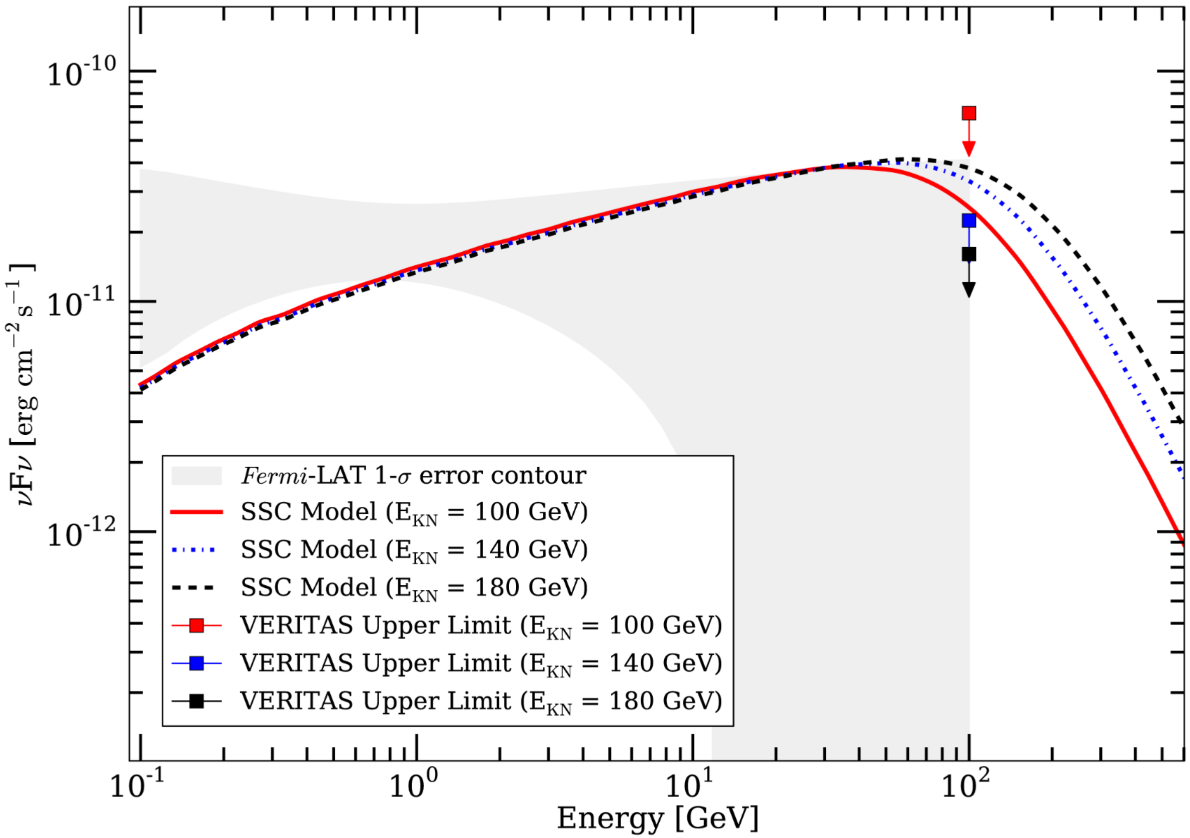
Very High Energy Emission from GRB
"The TeV era"

MAGIC upper limits



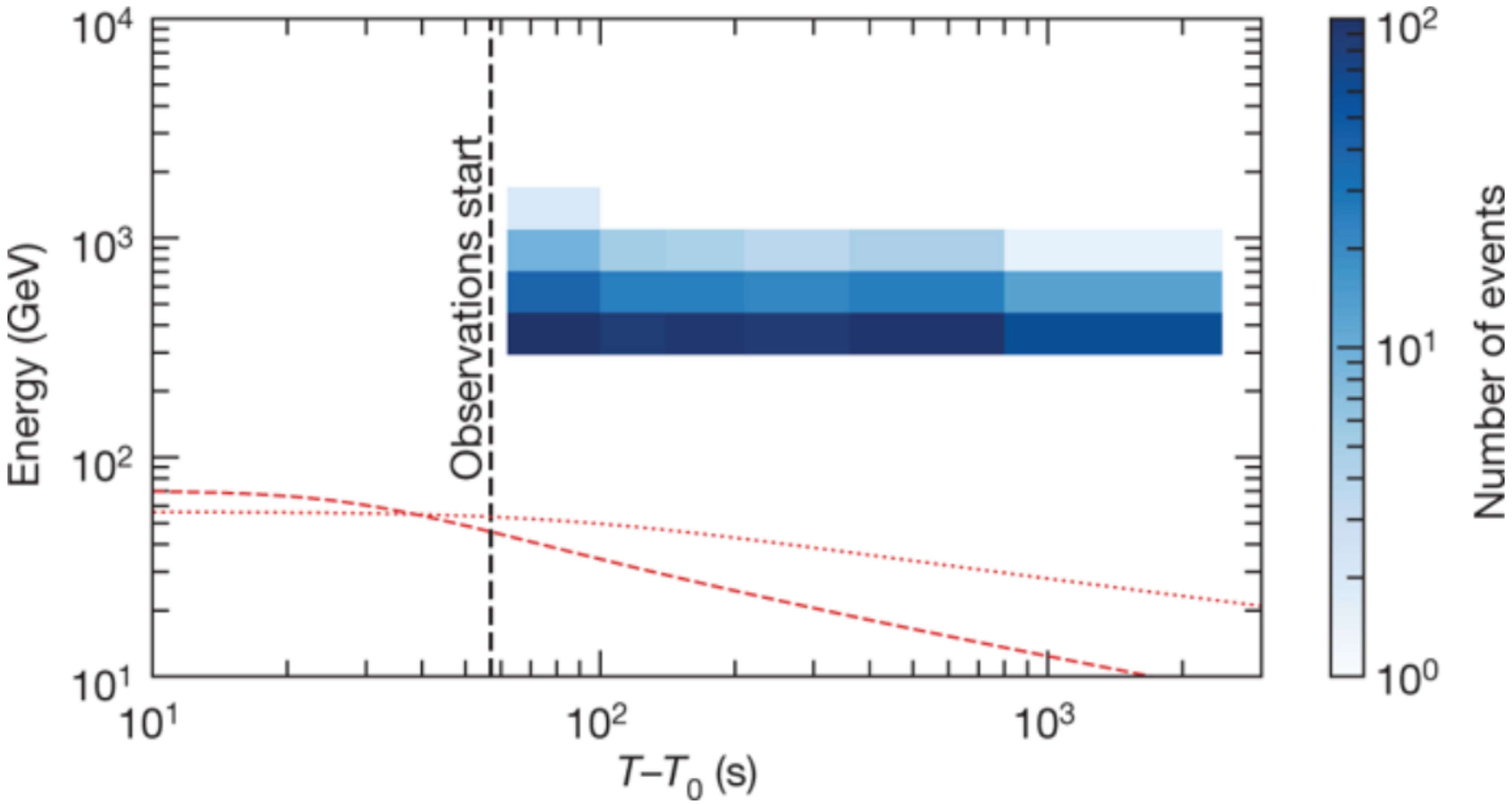
J. Aleksic et al., 2014

VERITAS upper limits



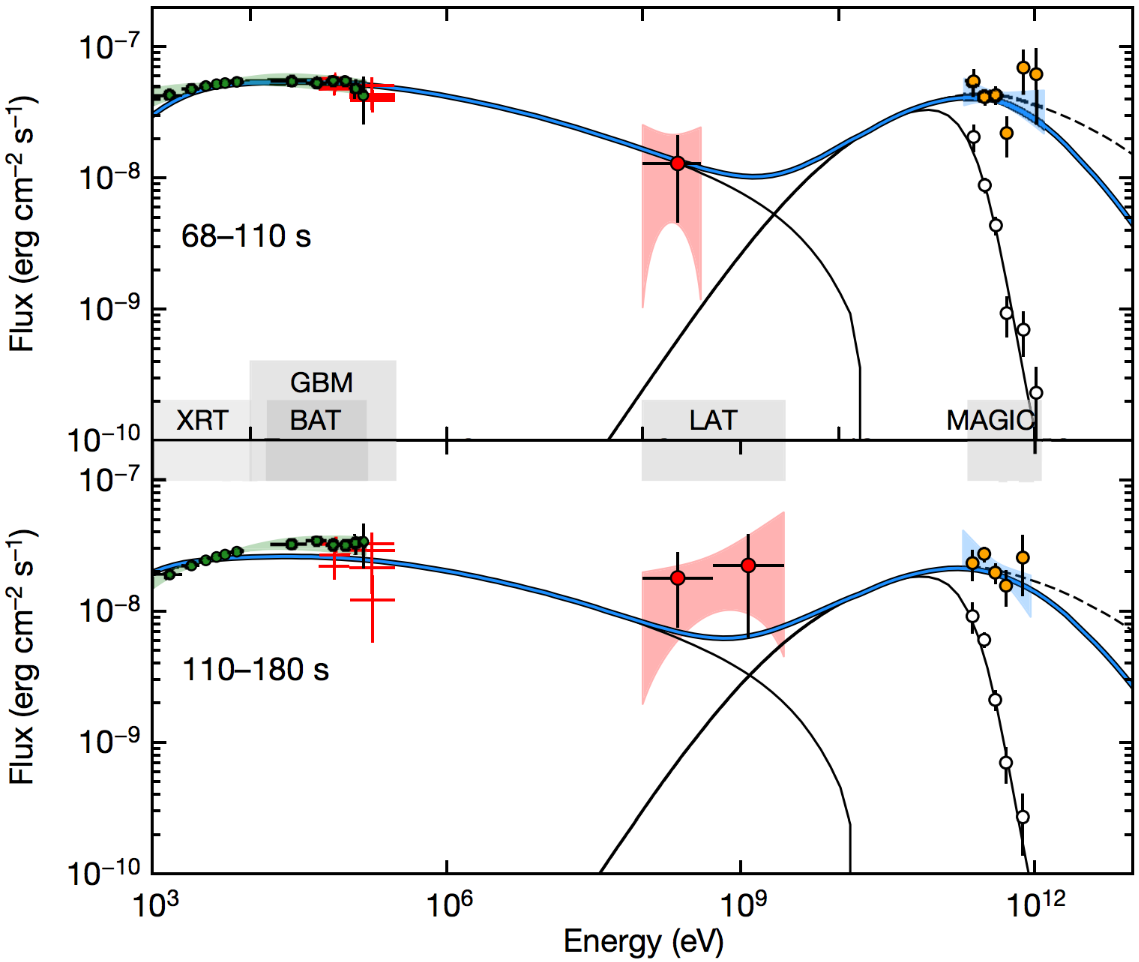
Aliu et al 2014

MAGIC detection – 190114C



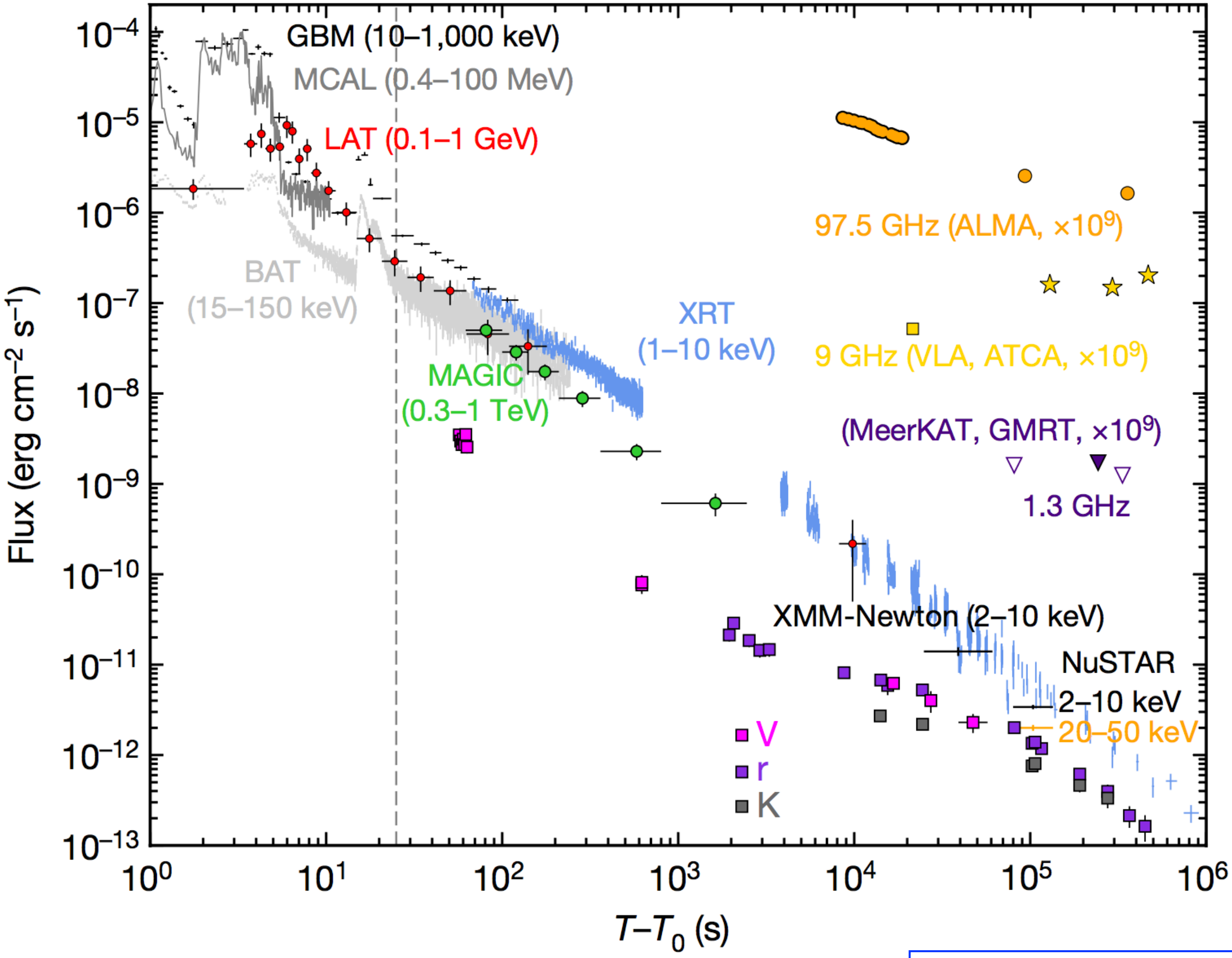
Acciari et al 2019a

MAGIC detection – 190114C



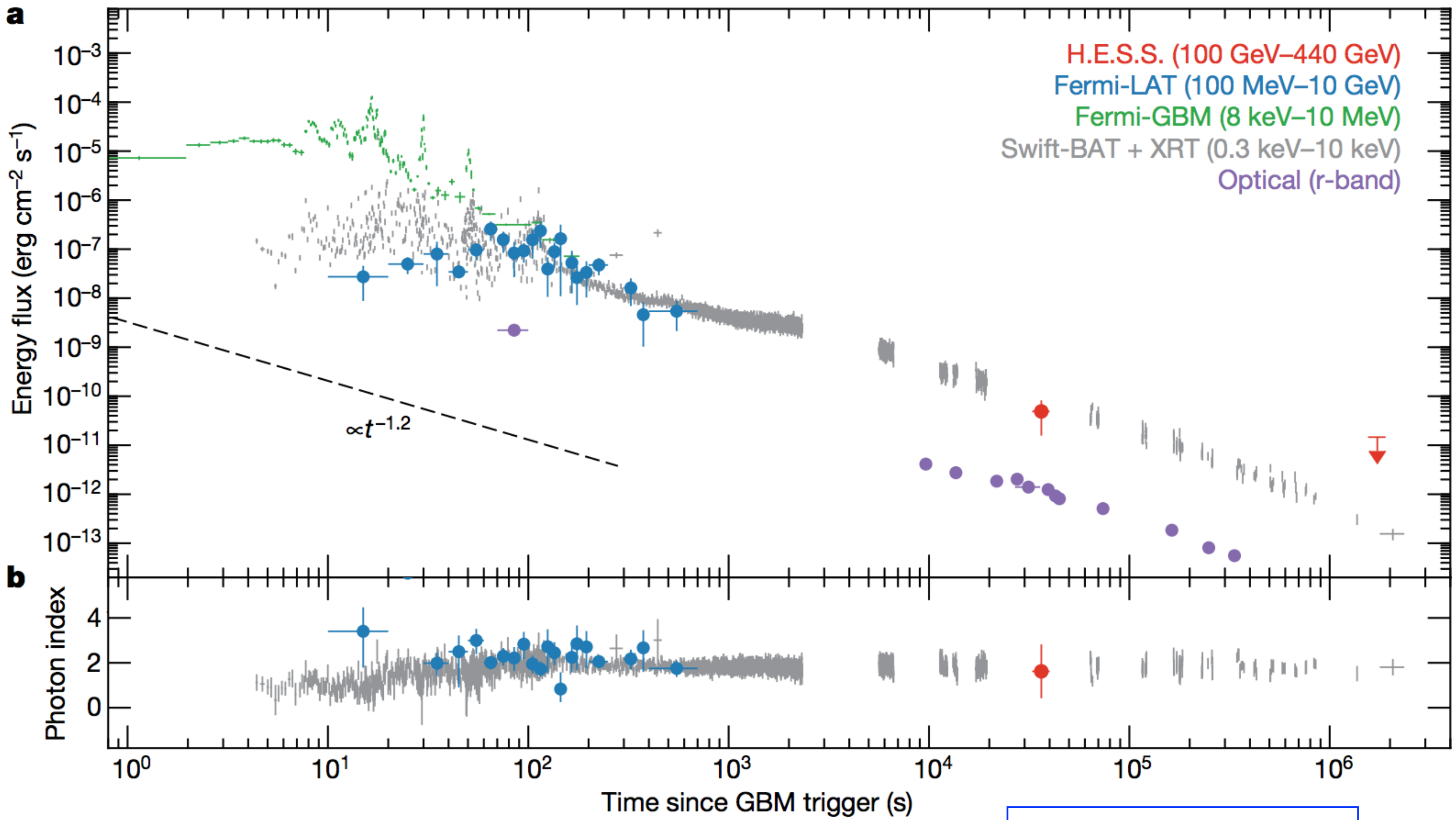
Acciari et al 2019b

MAGIC detection – 190114C



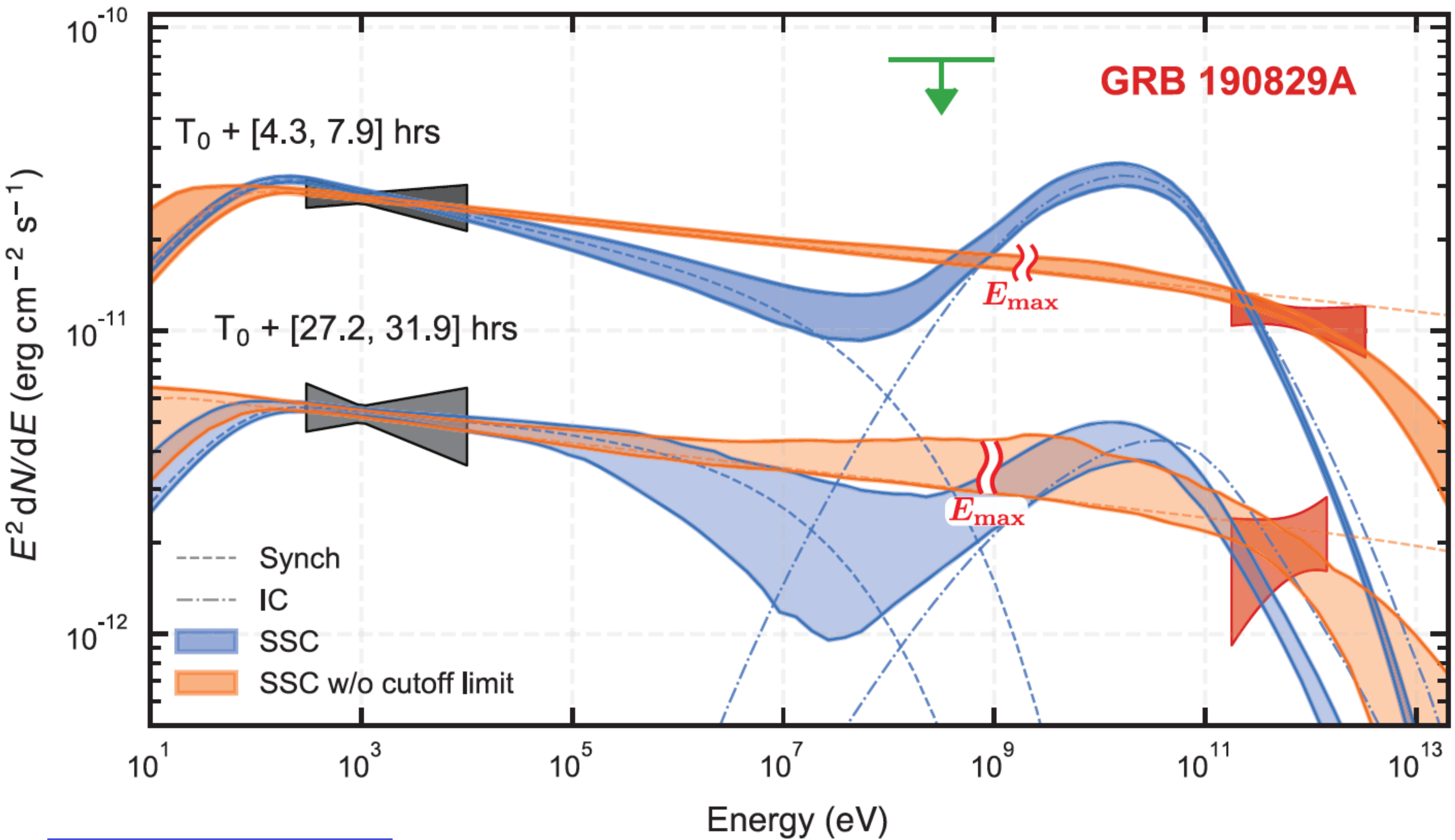
Acciari et al 2019b

HESS detection – 180720B



Abdalla et al 2019

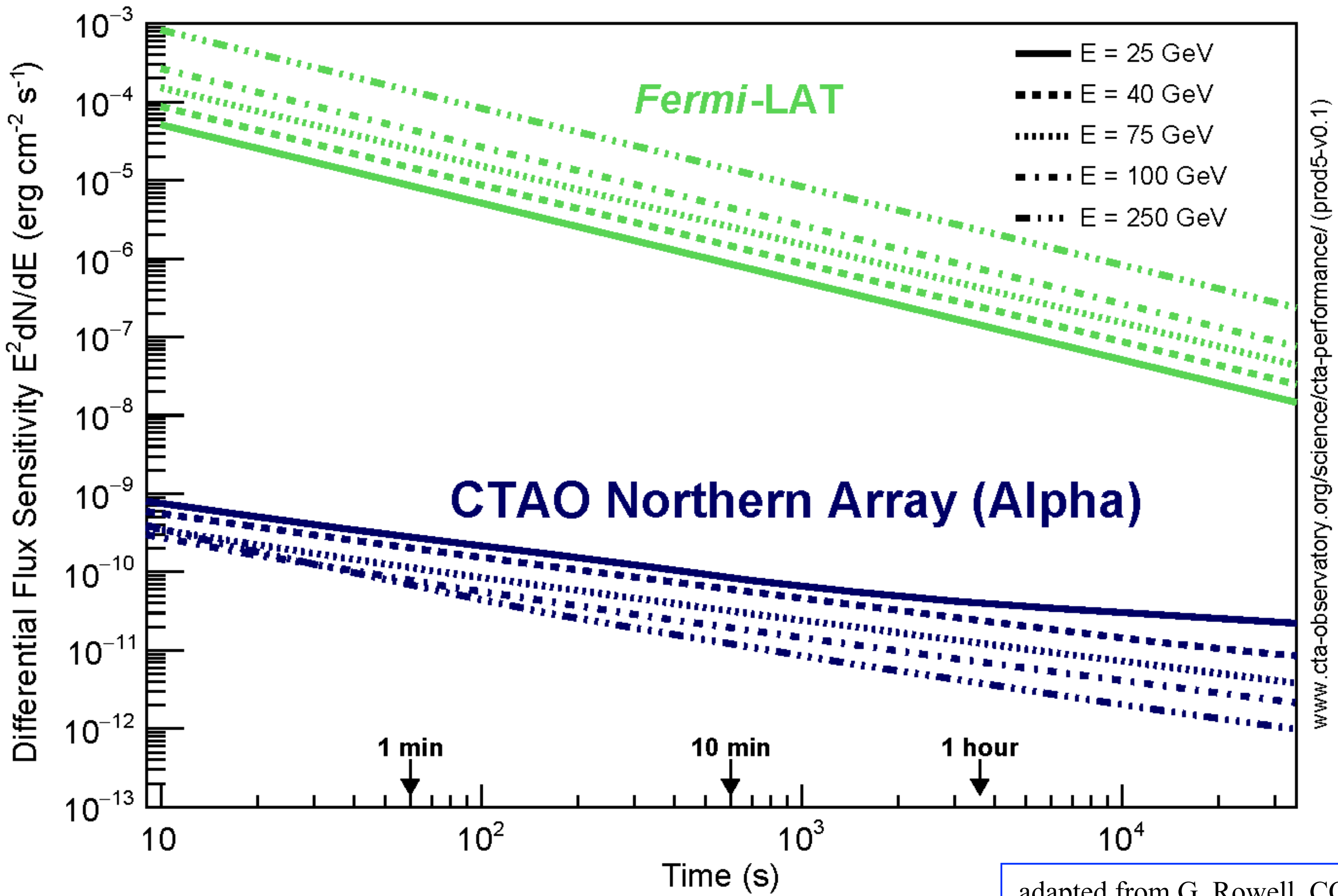
HESS detection – GRB 190829A



Abdalla et al 2021

Transients & Variable Sources: CTA Sensitivity vs. Time

(CTA Collab 2019)



adapted from G. Rowell COSPAR2020

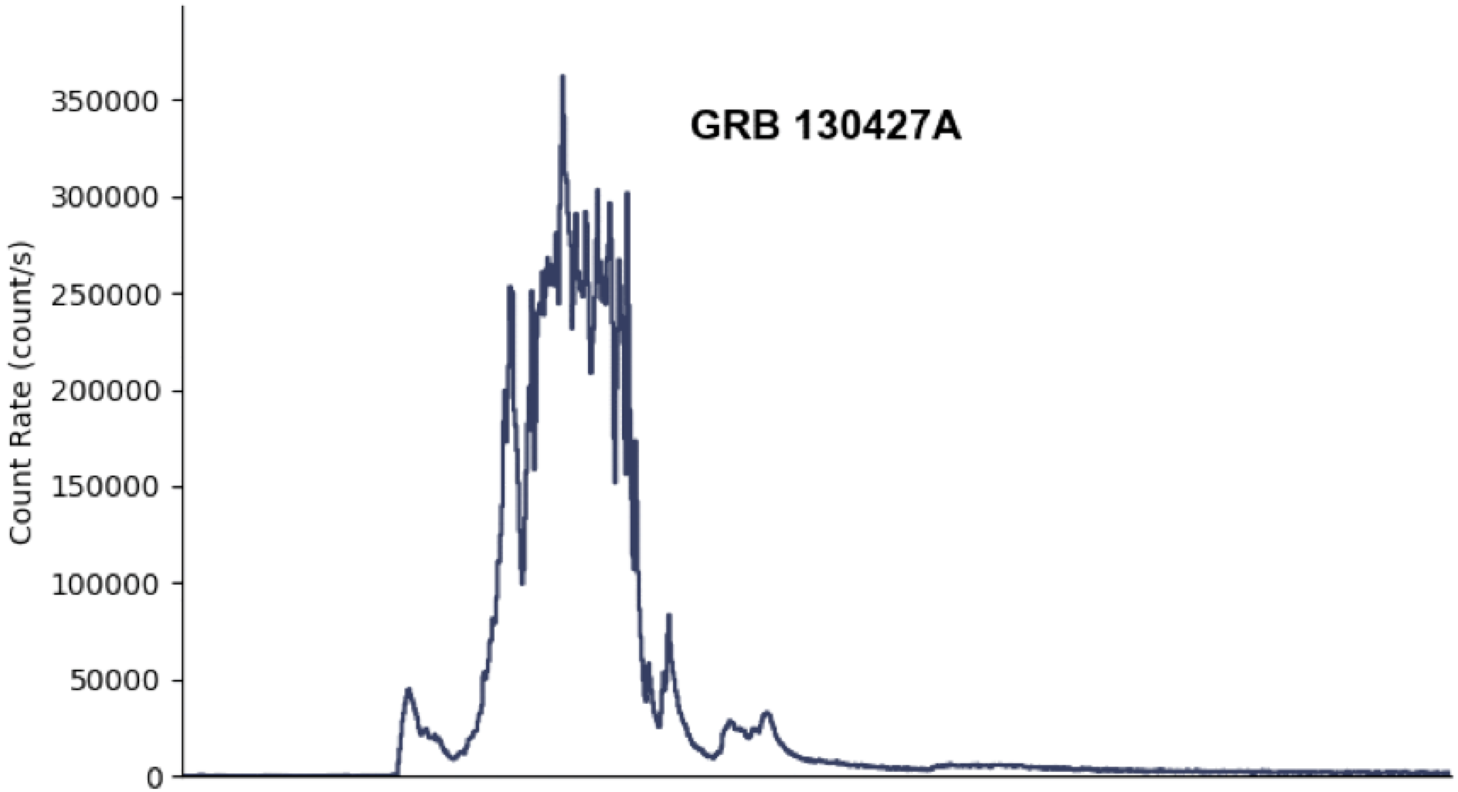
CTA >10,000 times more sensitive than Fermi-LAT in multi-GeV range

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

LHAASO detection !!!!

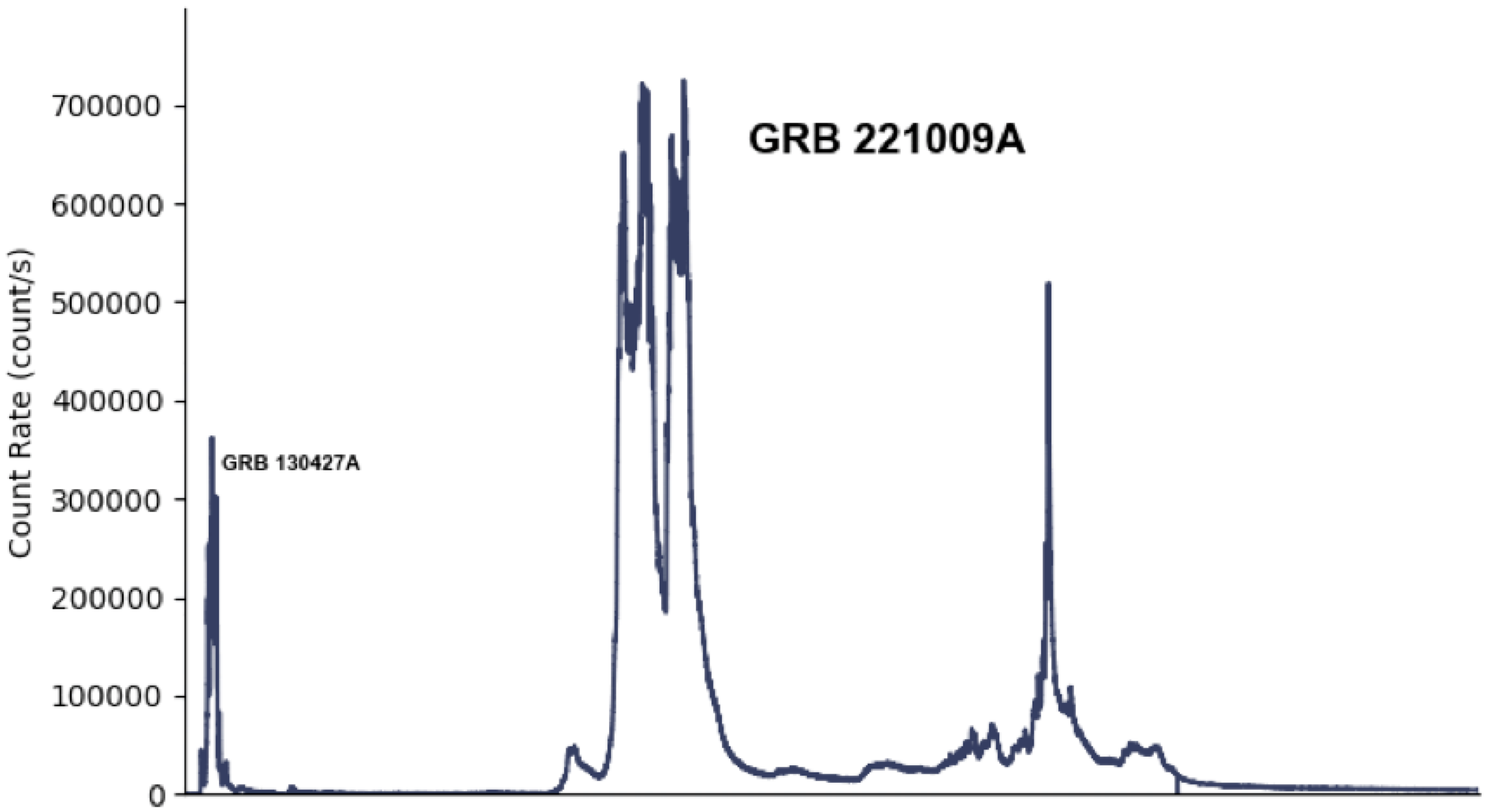
```
TITLE:   GCN CIRCULAR
NUMBER:  32677
SUBJECT: LHAASO observed GRB 221009A with more than 5000 VHE photons up to around 18 TeV
DATE:    22/10/11 09:21:54 GMT
FROM:    Judith Racusin at GSFC  <judith.racusin@nasa.gov>

Yong Huang, Shicong Hu, Songzhan Chen,  Min Zha, Cheng Liu, Zhiguo Yao and
Zhen Cao report on behalf of the LHAASO experiment

We report the observation of GRB 221009A, which was detected by Swift (Kennea
et al. GCN #32635), Fermi-GBM (Veres et al. GCN #32636, Lesage et al. GCN #32642),
Fermi-LAT (Bissaldi et al. GCN #32637), IPN (Svinkin et al. GCN #32641) and so on.

GRB 221009A is detected by LHAASO-WCDA at energy above 500 GeV, centered at
RA = 288.3, Dec = 19.7 within 2000 seconds after T0, with the significance above
100 s.d., and is observed as well by LHAASO-KM2A with the significance about 10 s.d.,
where the energy of the highest photon reaches 18 TeV.

This represents the first detection of photons above 10 TeV from GRBs.

The LHAASO is a multi-purpose experiment for gamma-ray astronomy (in the energy
band between 10^11 and 10^15 eV) and cosmic ray measurements.
```

GRB 221009A



Credit: A. Goldstein (USRA)

GRB 221009A



Credit: A. Goldstein (USRA)

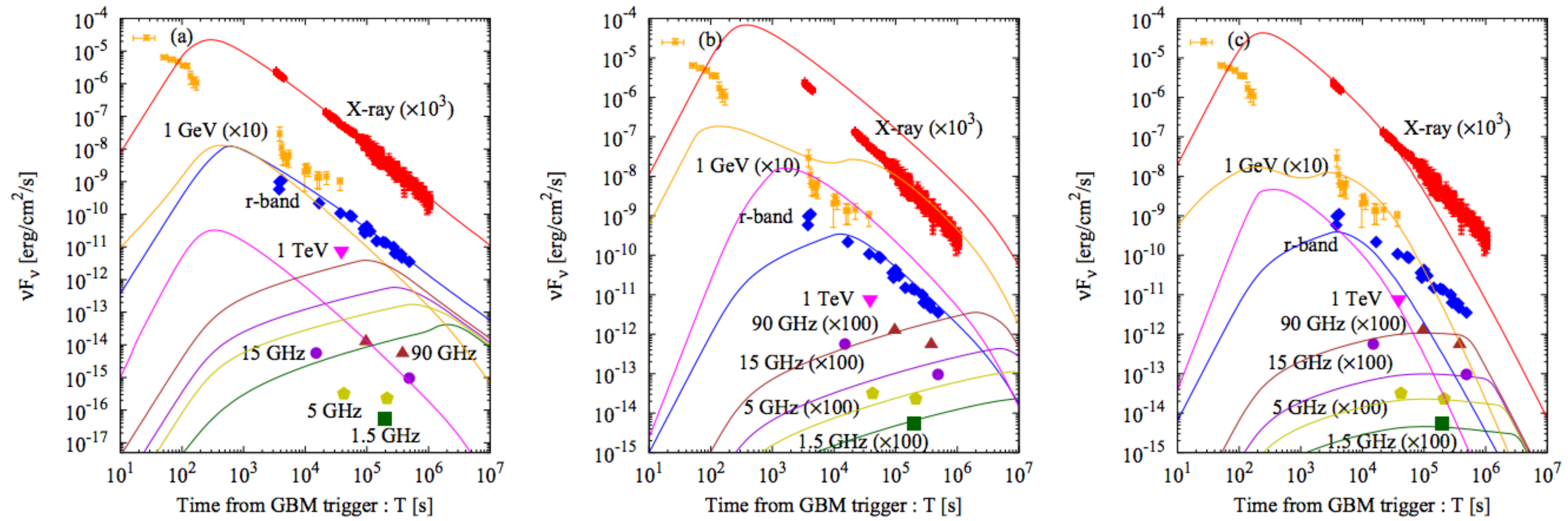
Interpretation

ABSTRACT
Recently gamma-ray bursts (GRBs) have been detected at very high-energy (VHE) gamma-rays by imaging atmospheric Cherenkov telescopes, and a two-component jet model has often been invoked to explain multi-wavelength data. In this work, multi-wavelength afterglow emission from an extremely bright gamma-ray burst, GRB 221009A, is examined. The isotropic-equivalent gamma-ray energy of this event is among the largest, which suggests that similarly to previous VHE GRBs, the jet opening angle is so small that the collimation-corrected gamma-ray energy is nominal. Afterglow emission from such a narrow jet decays too rapidly, especially if the jet propagates into uniform circumburst material. In the two-component jet model, another wide jet component with a smaller Lorentz factor dominates late-time afterglow emission, and we show that multi-wavelength data of GRB 221009A can be explained by narrow and wide jets with opening angles similar to those employed for other VHE GRBs. We also discuss how model degeneracies can be disentangled with observations.

Key words: gamma-ray bursts: individual: GRB 221009A — radiation mechanisms: non-thermal

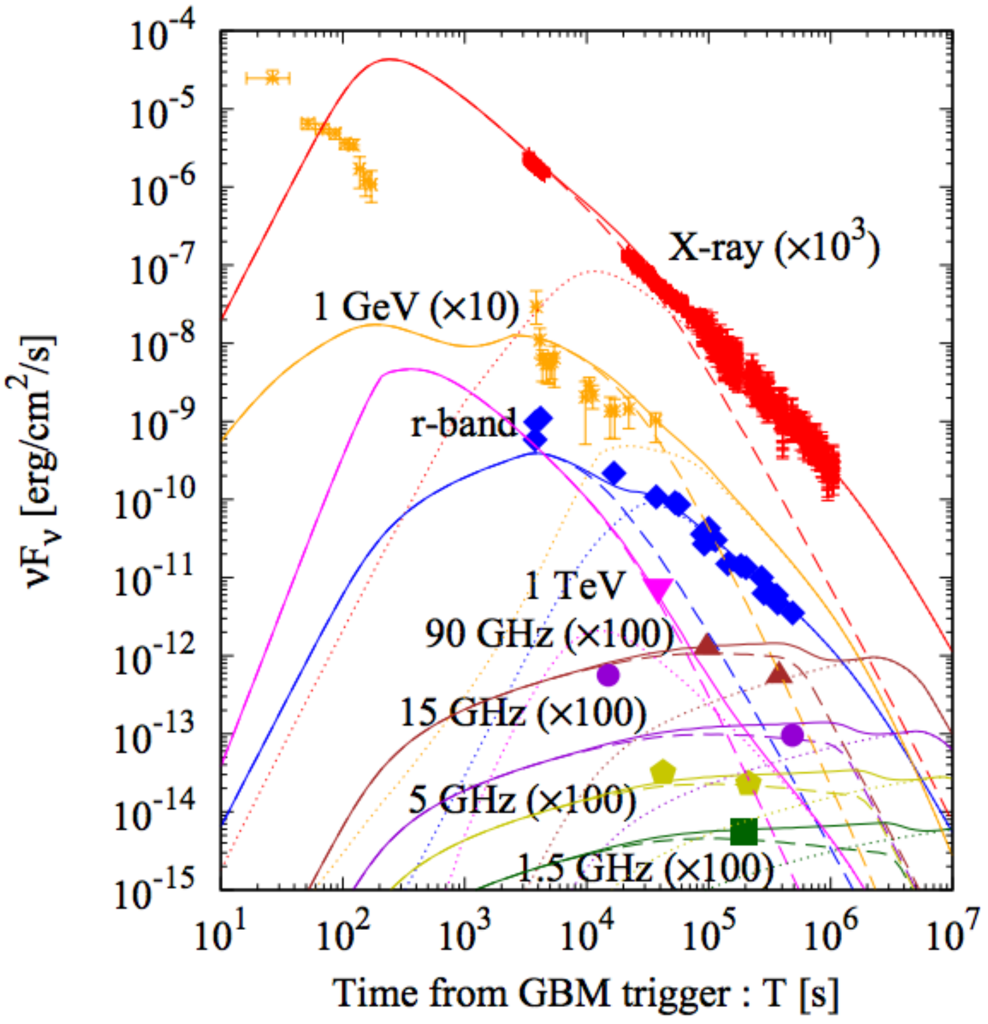
Sato et al. 2022

Interpretation



Sato et al. 2022

Interpretation



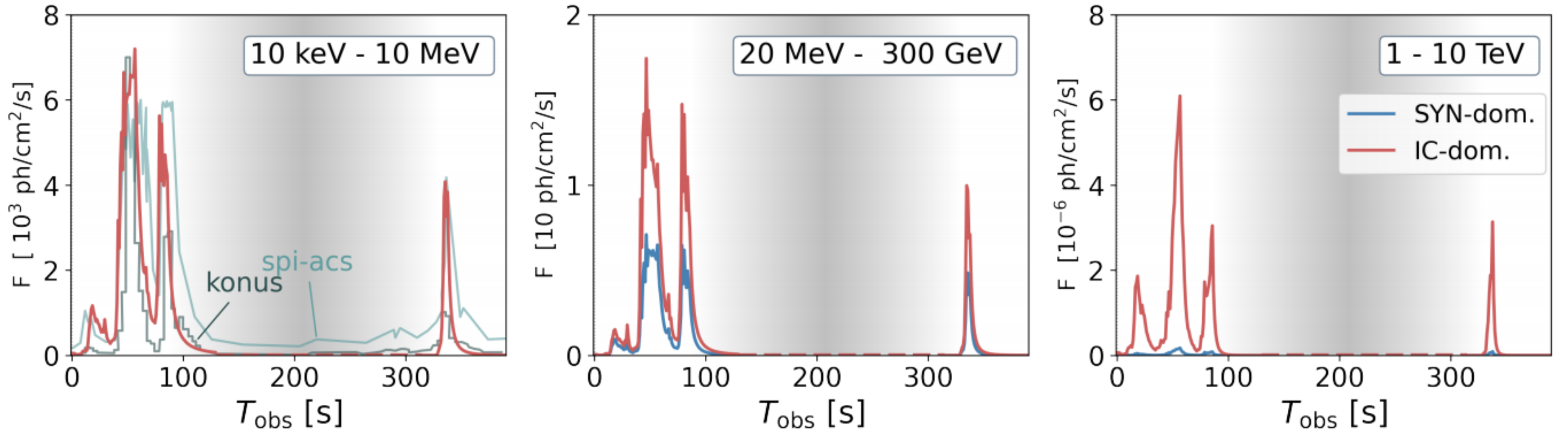
Sato et al. 2022

Interpretation

We present a multi-messenger model for the prompt emission from GRB 221009A within the internal shock scenario. We consider the time-dependent evolution of the outflow with its impact on the observed light curve from multiple collisions, and the self-consistent generation of the electromagnetic spectrum in synchrotron and inverse Compton-dominated scenarios. Our leptohadronic model includes UHE protons potentially accelerated in the outflow, and their feedback on spectral energy distribution and on the neutrino emission. We find that we can roughly reproduce the observed light curves with an engine with varying ejection velocity of ultra-relativistic material, which has an intermediate quiescent period of about 200 seconds and a variability timescale of ~ 1 s. We consider baryonic loadings of 3 and 30 that are compatible with the hypothesis that the highest-energetic LHAASO photons might come from UHECR interactions with the extragalactic background light, and the paradigm that energetic GRBs may power the UHECR flux. For these values and the high dissipation radii considered we find consistency with the non-observation of neutrinos and no significant signatures on the electromagnetic spectrum. Inverse Compton-dominated scenarios from the prompt emission are demonstrated to lead to about an order of magnitude higher fluxes in the HE-range; this enhancement is testable by its spectral impact in the Fermi-GBM and LAT ranges.

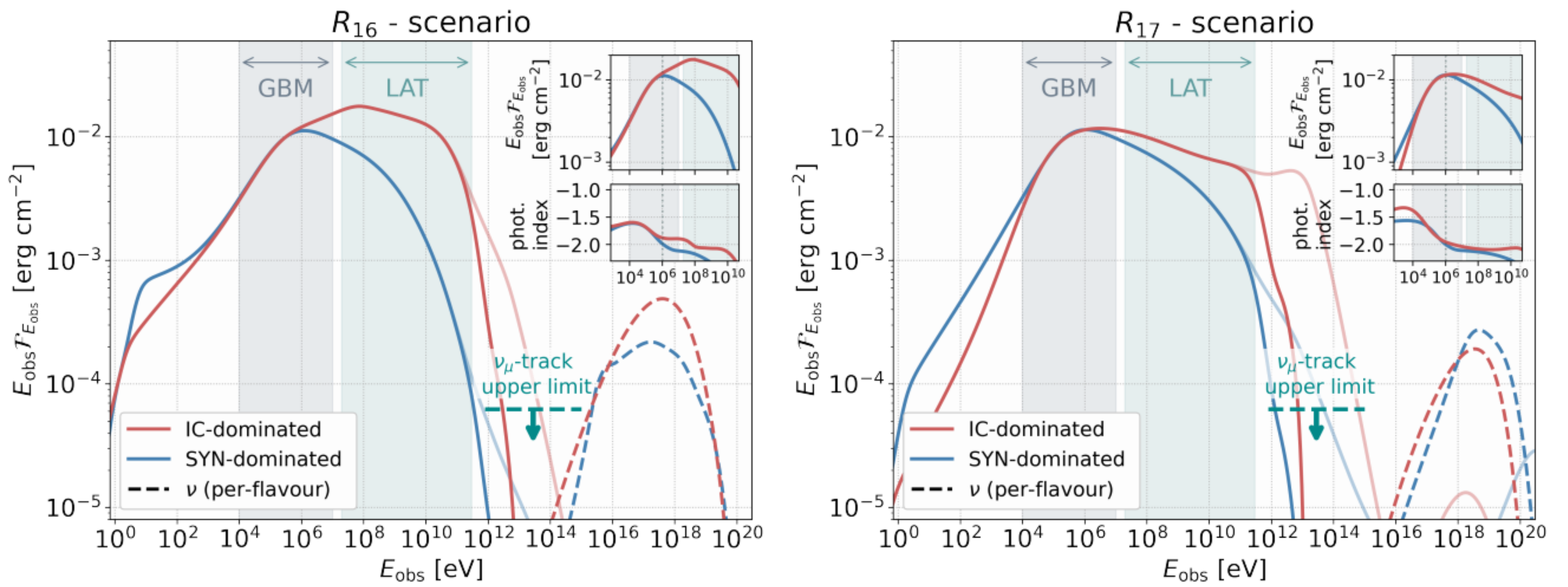
Rudolph et al. 2022

Interpretation



Rudolph et al. 2022

Interpretation



Rudolph et al. 2022

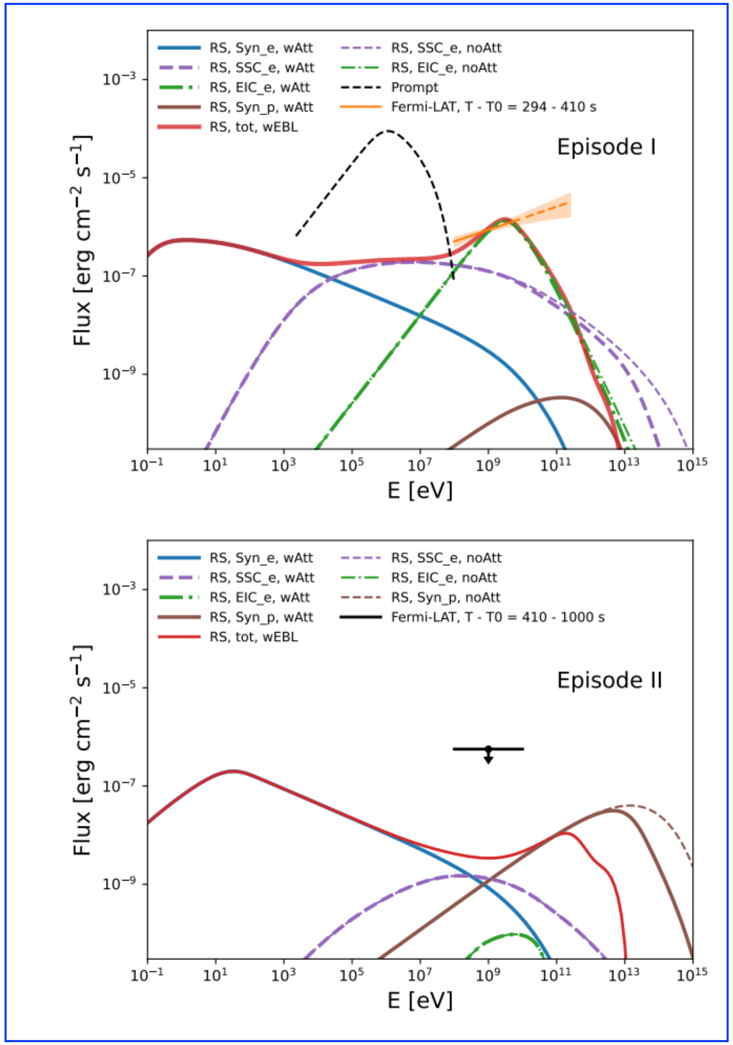
Interpretation

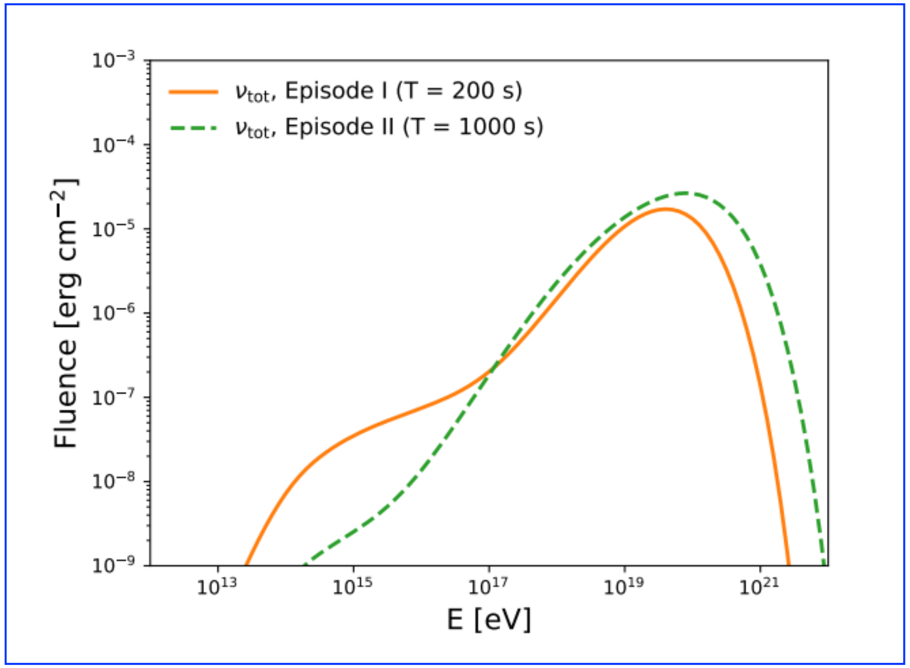
ABSTRACT

The detection of the hyper-bright gamma-ray burst (GRB) 221009A enables us to explore the nature of the GRB emission and the origin of very-high-energy (VHE) gamma-rays. We analyze the *Fermi*-LAT data of this burst and investigate the GeV-TeV emission in the framework of the external reverse shock model. We show that the early $\sim 1-10$ GeV emission can be explained by the external inverse-Compton mechanism via upscattering MeV gamma-rays by electrons accelerated at the reverse shock, in addition to the synchrotron self-Compton component. The predicted early optical flux could have been brighter than that of the naked-eye GRB 080319B. We also show that proton synchrotron emission from accelerated ultra-high-energy cosmic rays (UHECRs) is detectable, and could potentially explain $\gtrsim$ TeV photons detected by LHAASO or constrain the UHECR acceleration mechanism. Our model suggests that the detection of $\mathcal{O}(10$ TeV) photons with energies up to ~ 18 TeV is possible for reasonable models of the extragalactic background light without invoking new physics, and predicts anti-correlations between MeV photons and TeV photons, which can be tested with the LHAASO data.

B.T. Zhang et al. 2022

Interpretation



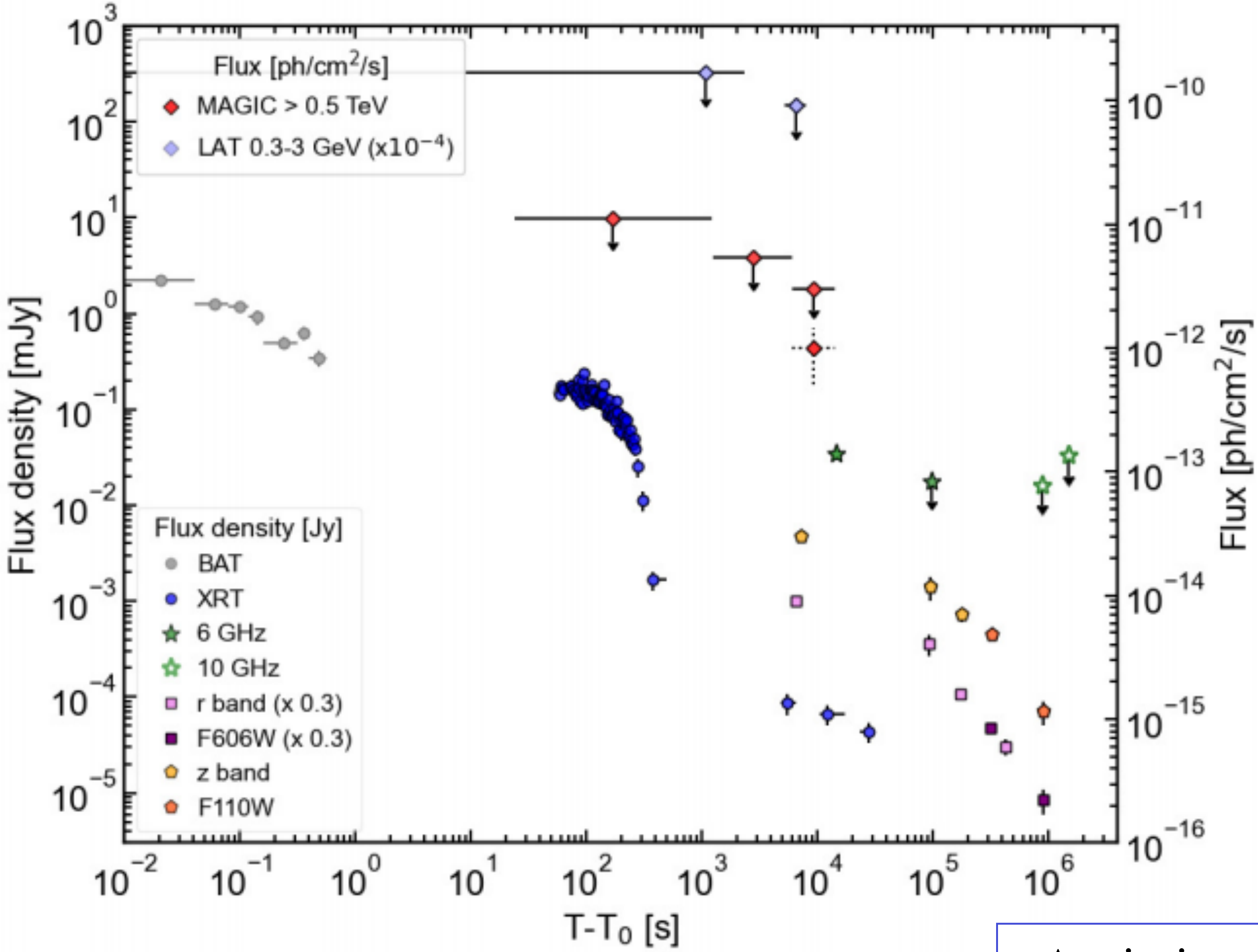


B.T. Zhang et al. 2022

Conclusions

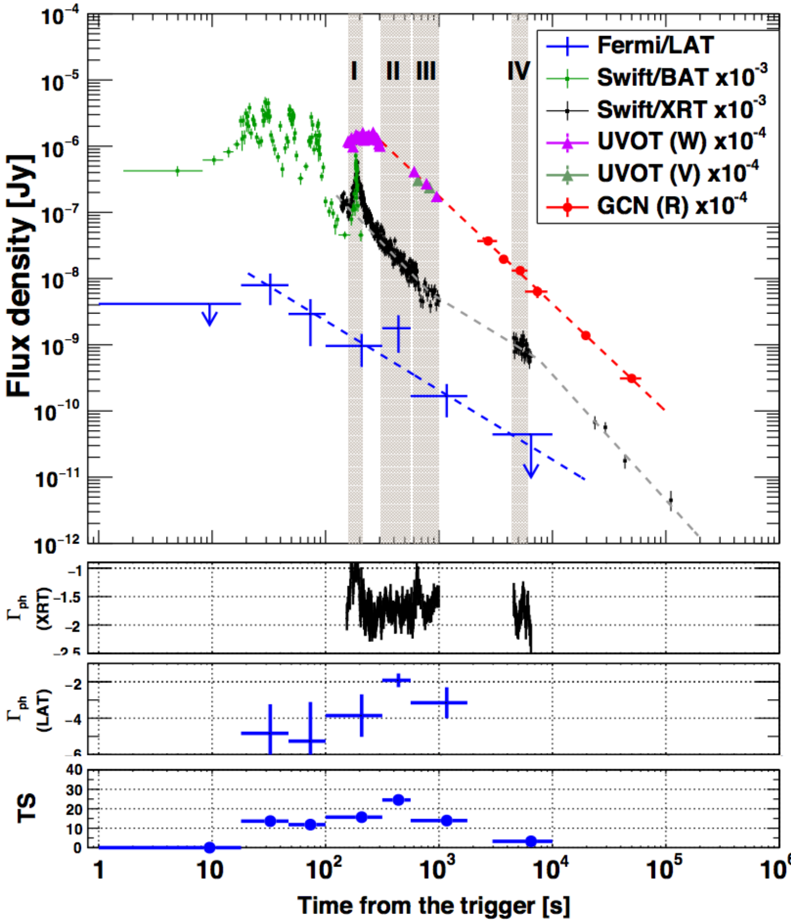
- HE satellites observations are shedding light (?) into the emission mechanism of GRBs
  - Prompt soft phase
- The HE emission seems correlated to afterglow phenomenology
  - Temporal decay
  - Extended emission
- Detection of VHE counterparts of GRB
  - VHE emission on the afterglow phase
  - VHE emission in the prompt?
- Stay tuned !
  - Need to acquire more statistics

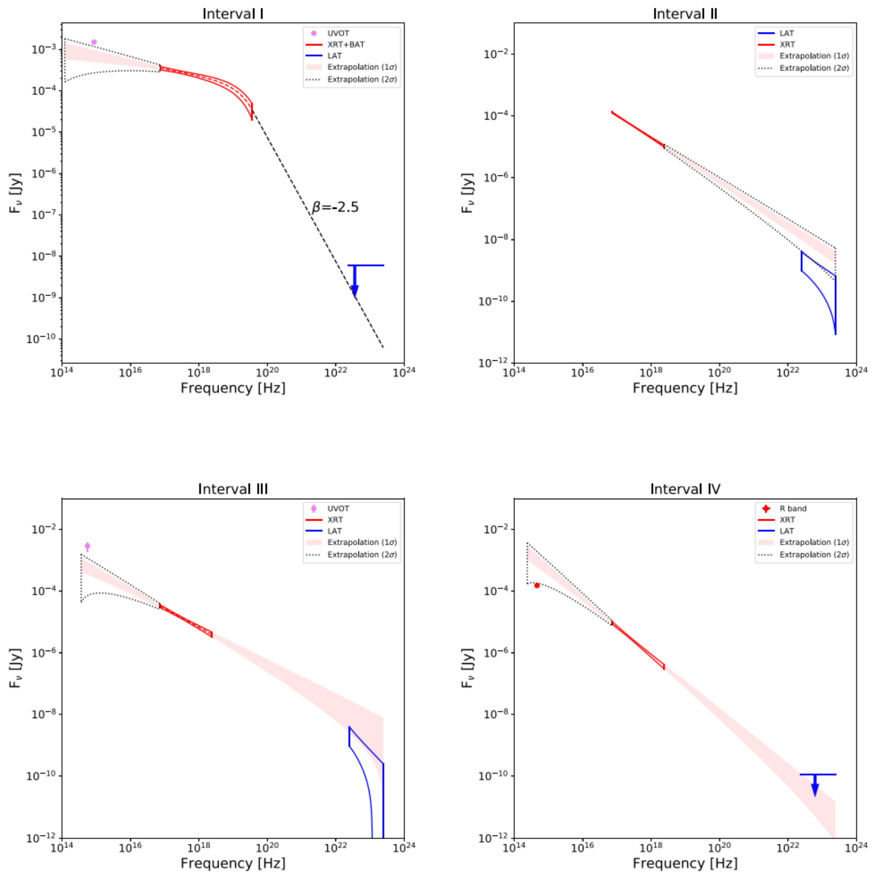
GRB 160821B



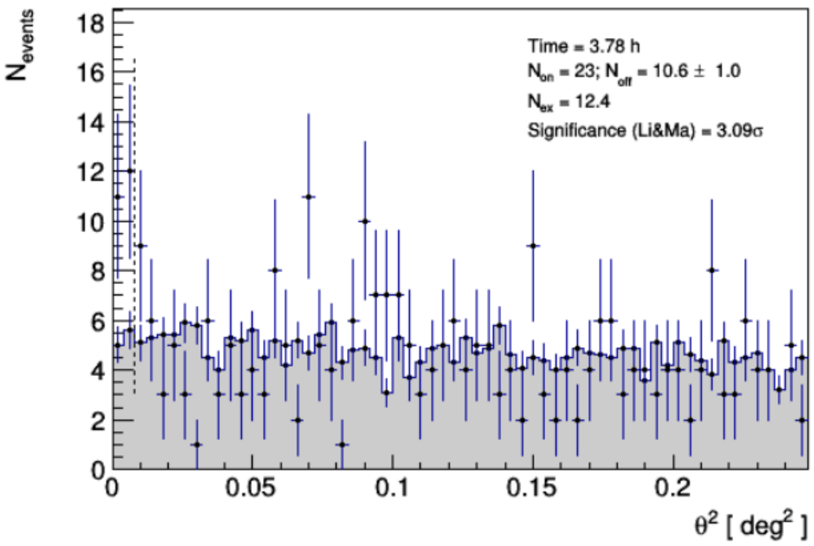
Acciari et al. 2021

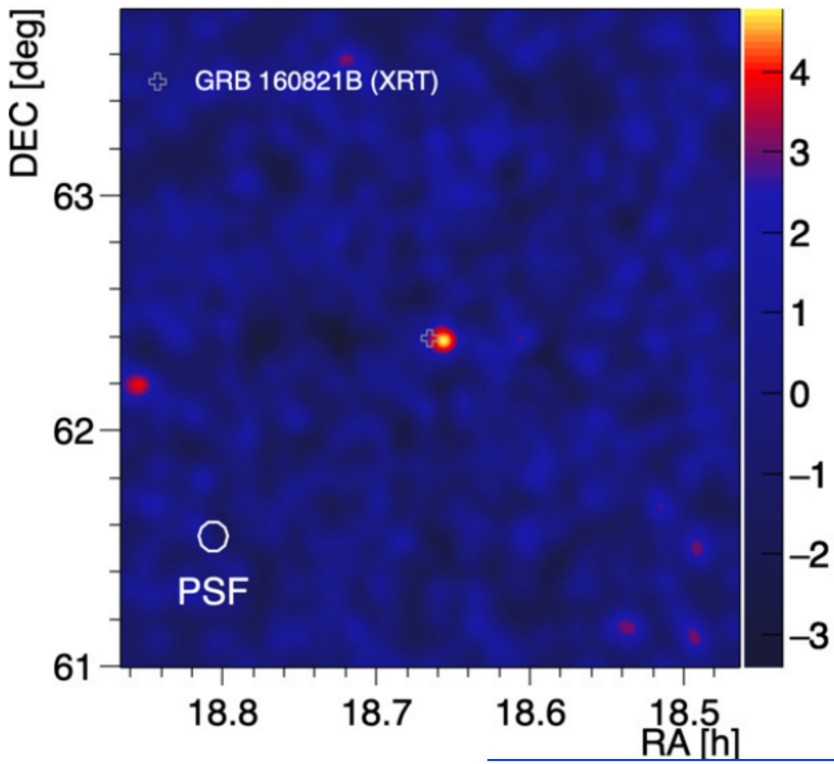
GRB 170405A





Arimoto et al. 2020





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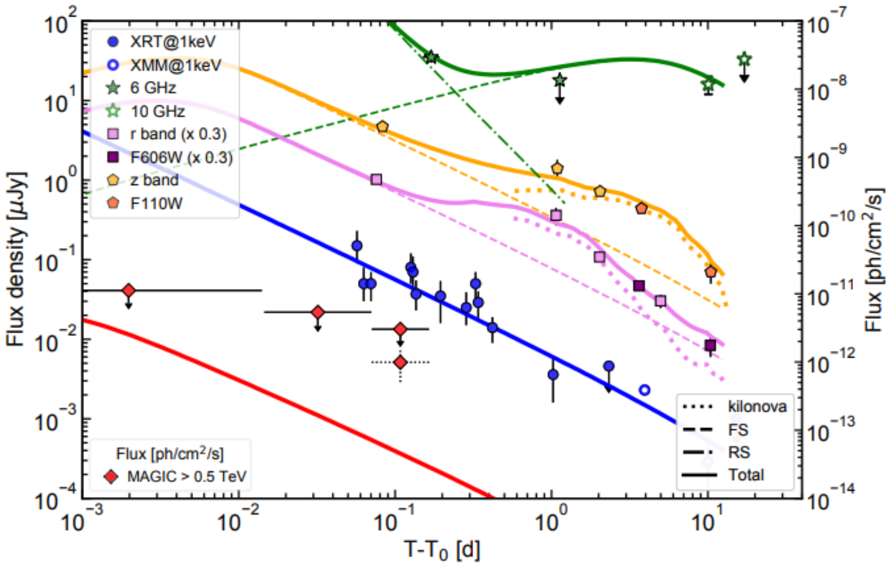
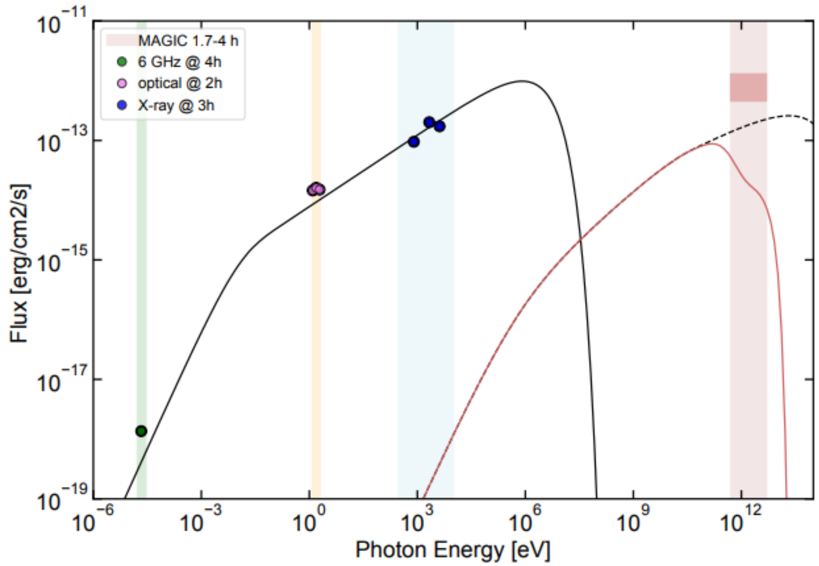
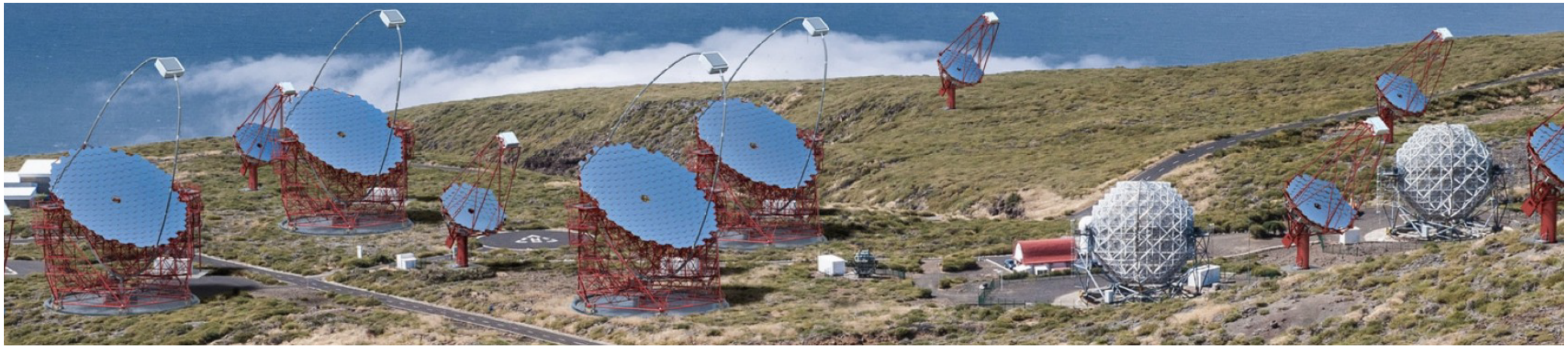
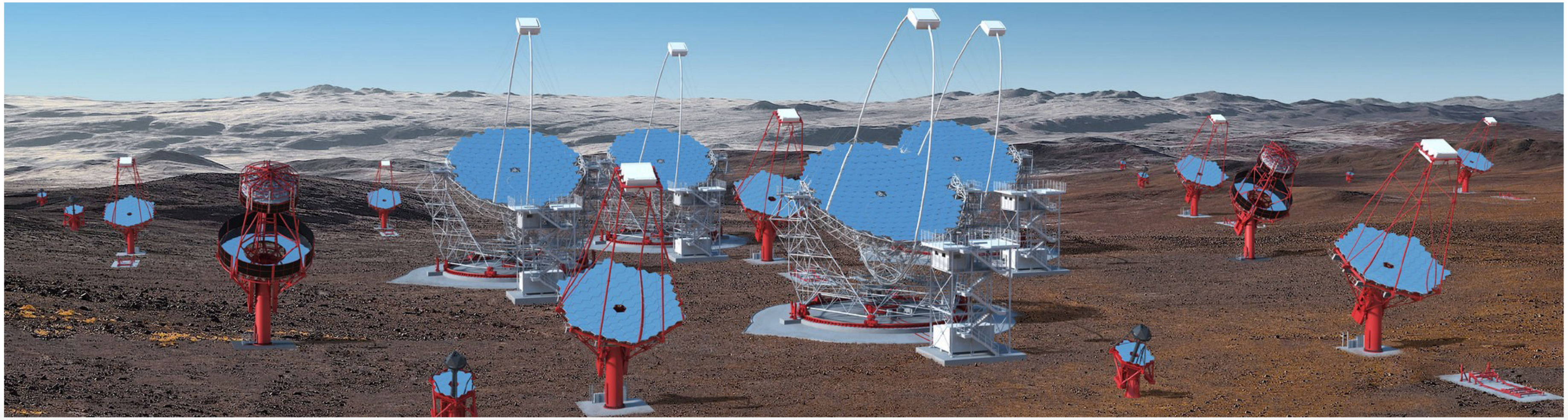




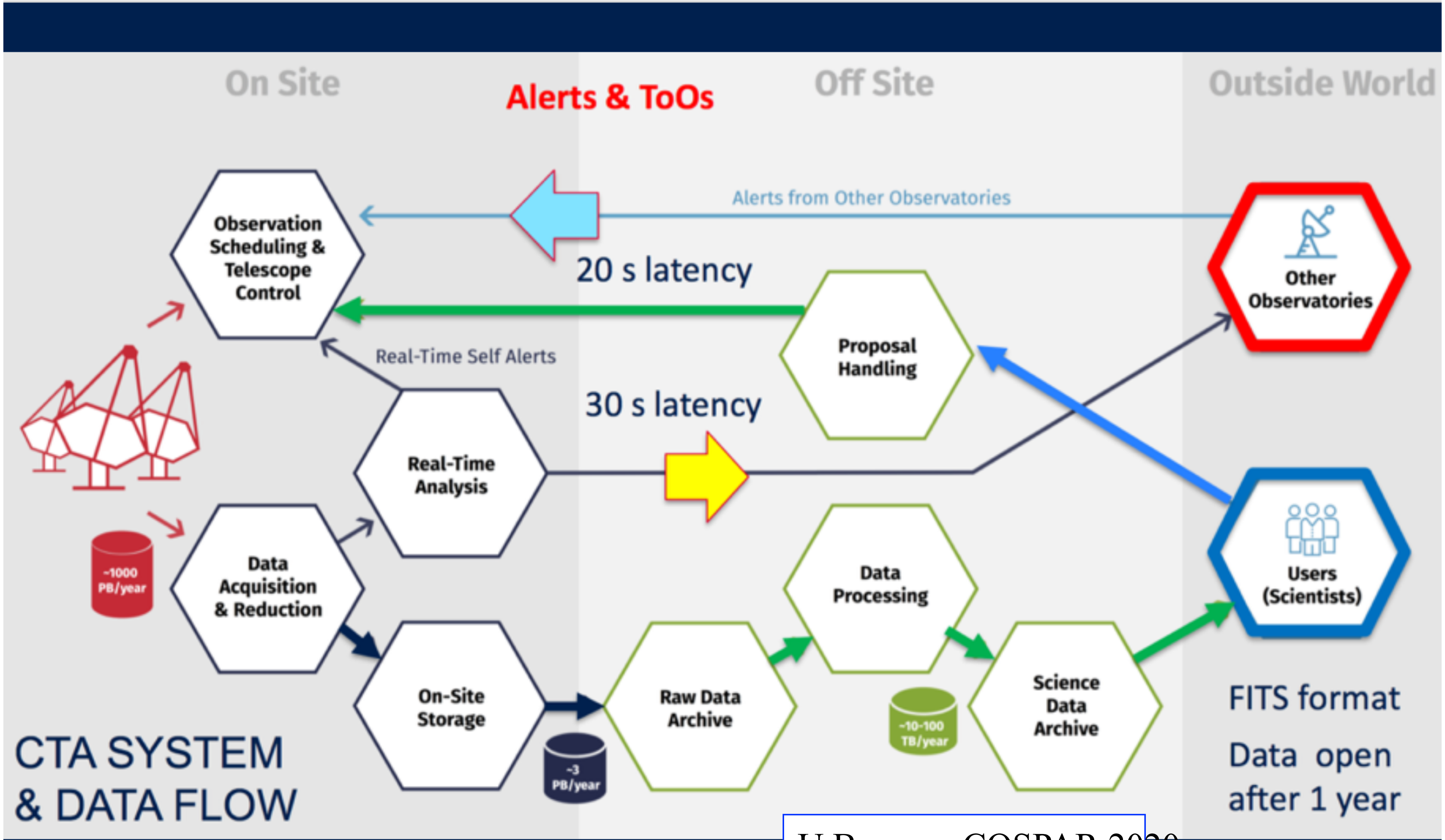
CTA North & CTA South

Alpha		CTA Construction
Northern Array	Number of LSTs	4
	Number of MSTs	9
Southern Array	Number of LSTs	0
	Number of MSTs	14
	Number of SSTs	37
Total		74

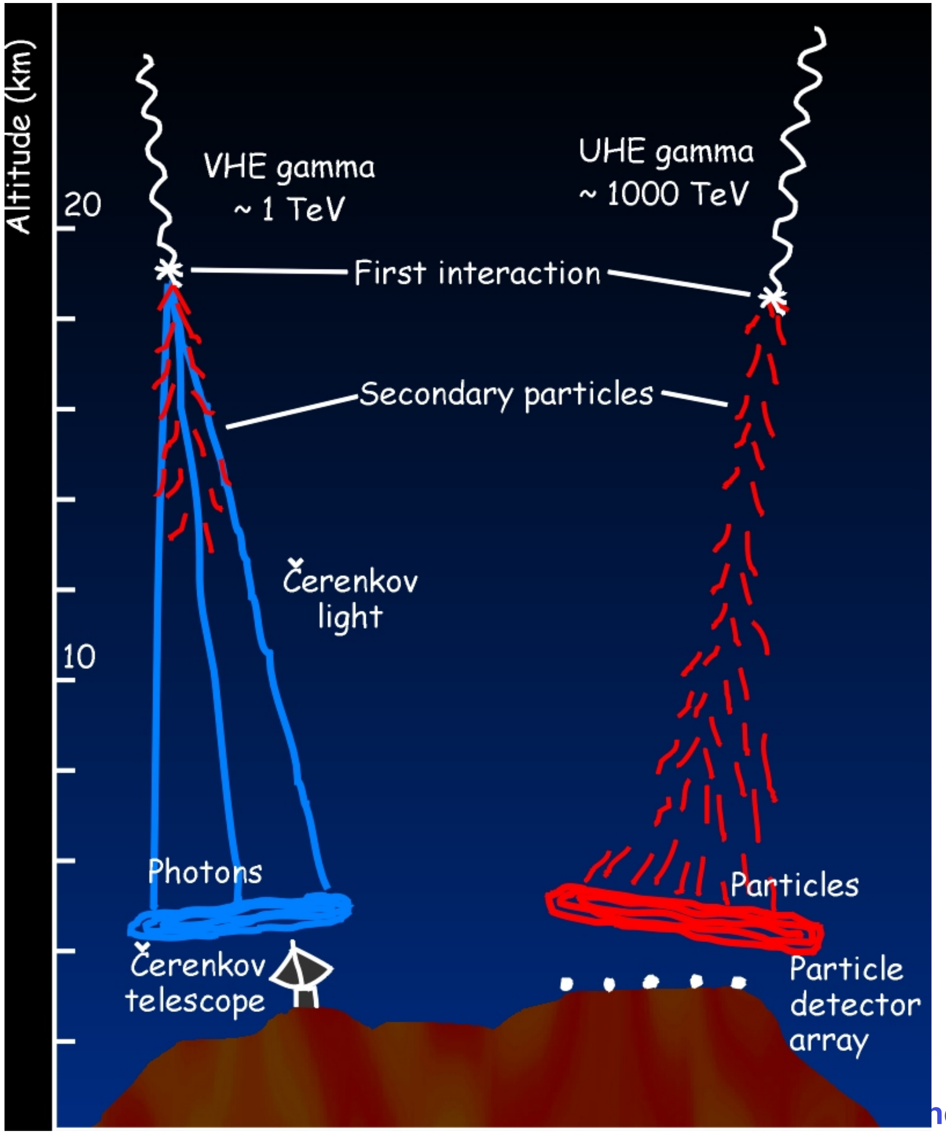




CTA Transients Science



IACT & EAS experiments



- Cherenkov experiments consist of almost-optical telescopes devoted to detect Cherenkov light.
- EAS (Extensive Air Shower) experiments are huge arrays or carpets of particle detectors.
- Cherenkov experiments have lower energy thresholds, but also a lower duty-cycle as well as a smaller field of view.

In memory of Magnus Axelsson

Denna sida på svenska

Magnus Axelsson

Stockholm University

About me

My field of research lies in high-energy astrophysics, and in particular the processes that occur around black holes. I obtained my PhD from Stockholm University, and have done post docs and research fellowships in Lund, at KTH and in Tokyo. I am now back in Stockholm where I split my time between the Departments of Astronomy and Physics.

In addition to research I have always enjoyed teaching and pedagogical development. Through funding from the university I have conducted several projects to improve the pedagogical environment, and together with Emma Wikberg at the Department of Physics I am running a long-term project aimed at improving the transition to university for first-year bachelor students.

Research

CONTACT

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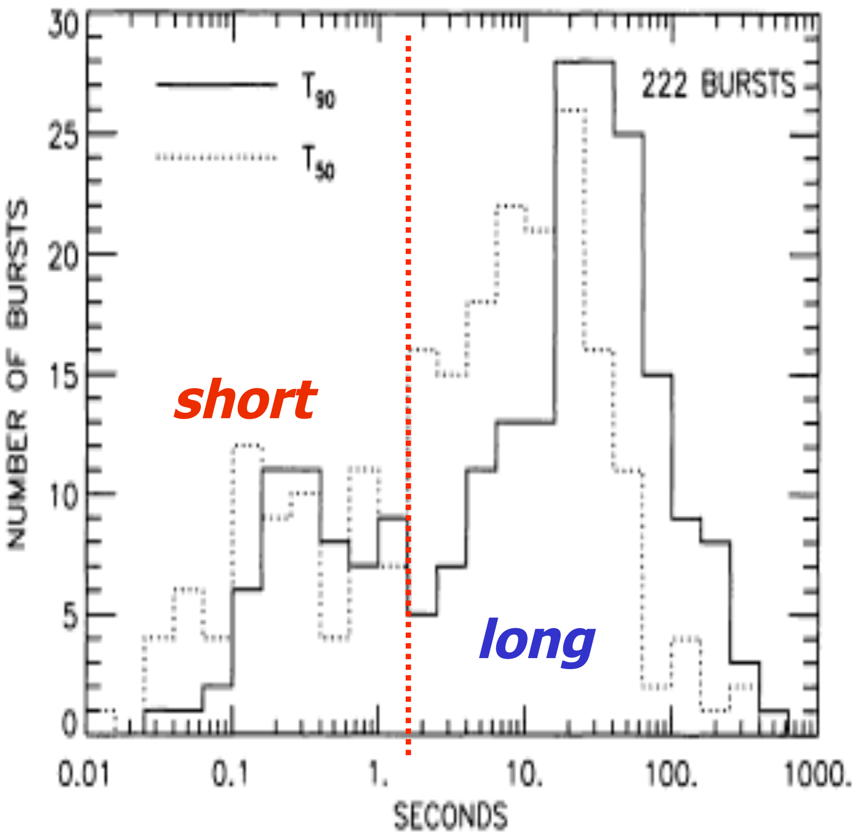
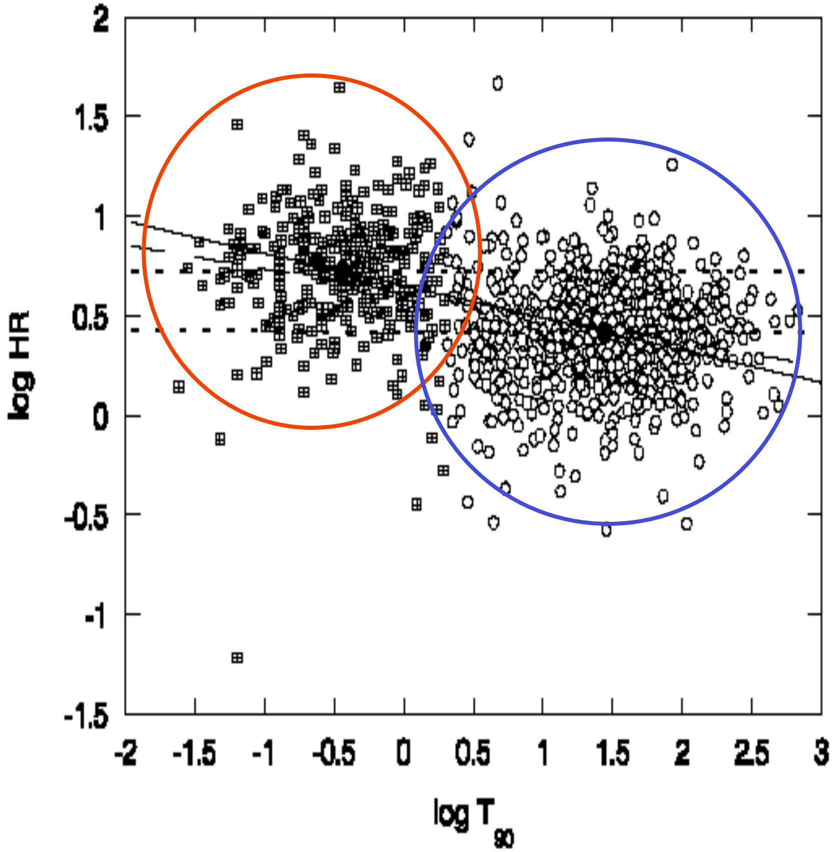
Department of Physics

Adapted from L.Amati

The GRB phenomenon

- bimodal distribution of durations: short and long GRBs
- short GRBs tend to be spectrally harder than long GRBs

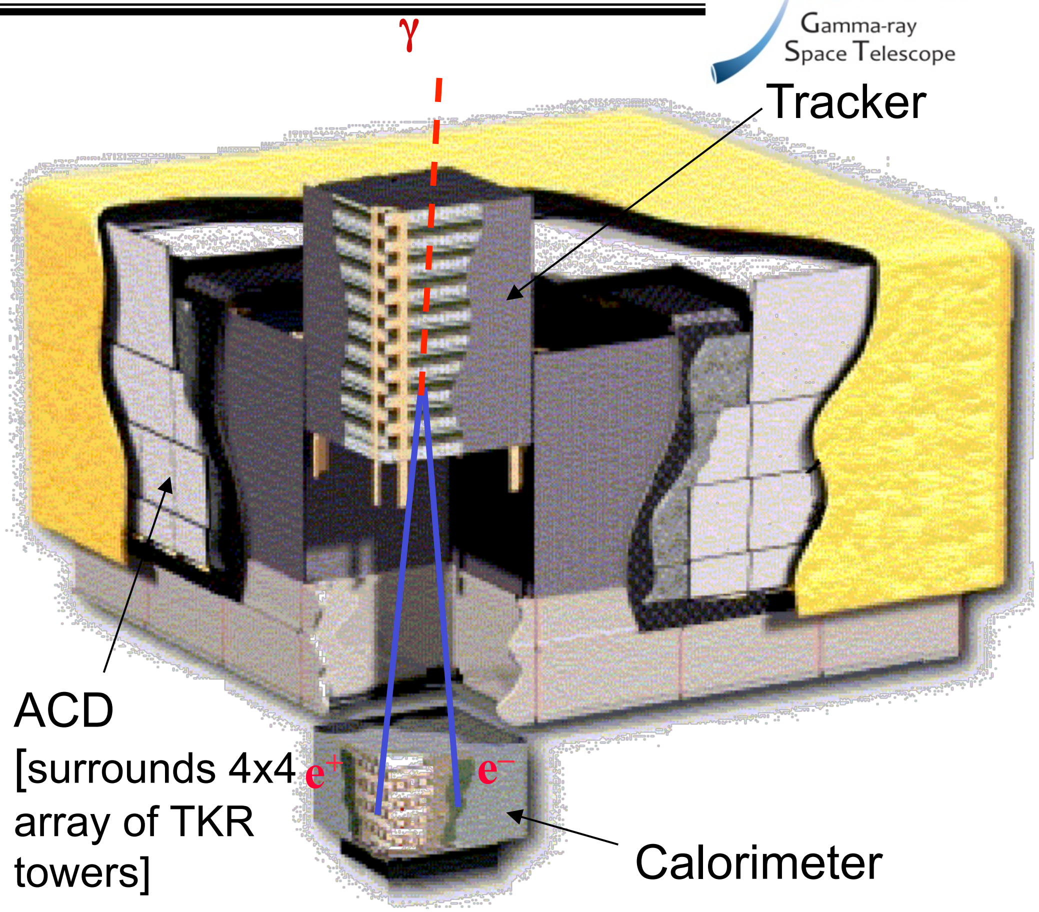




HR: flux (100-300 keV)/flux (50 -100 keV)

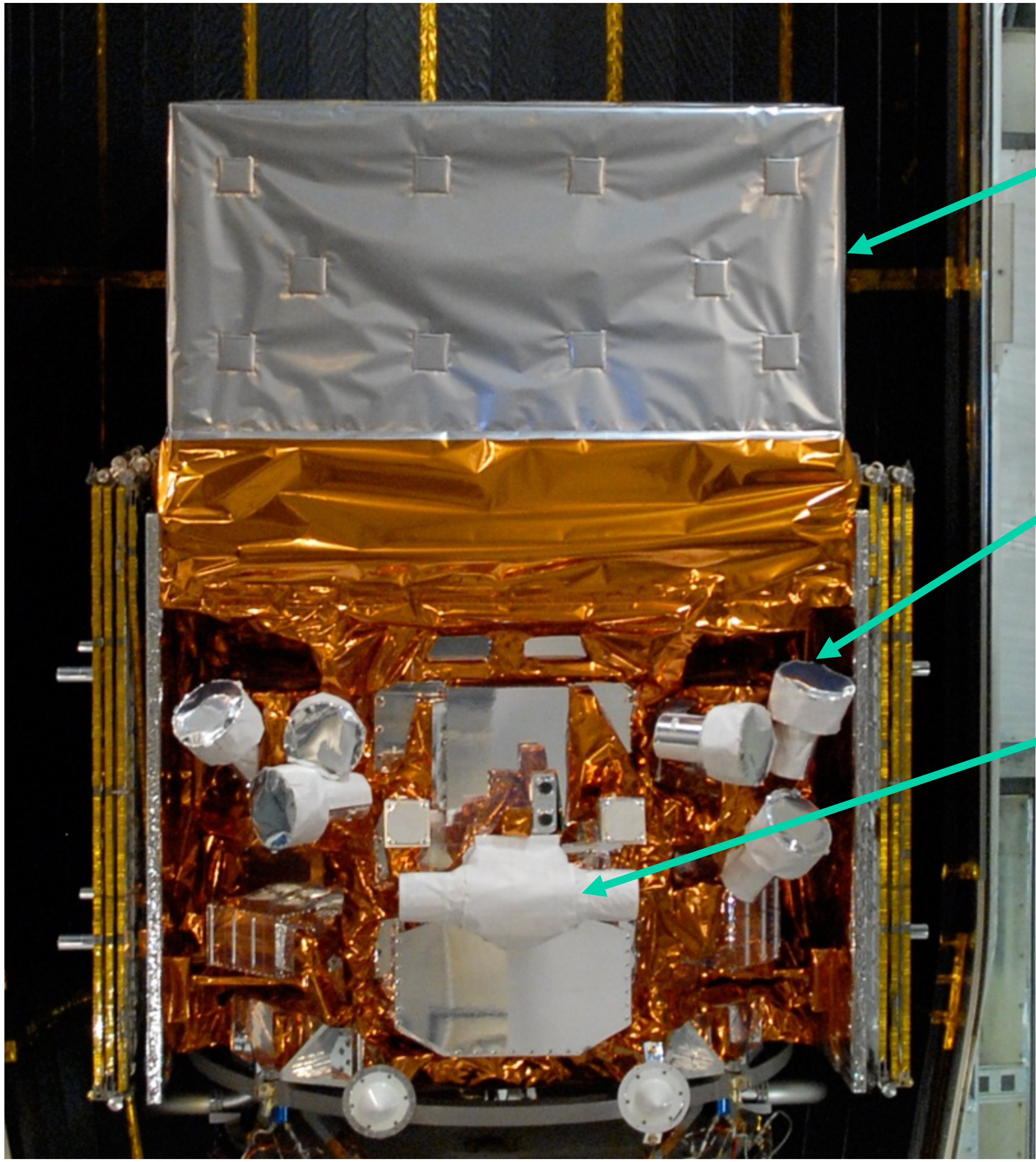
Large Area Telescope

- Precision Si-strip Tracker (TKR) 18 XY tracking planes. Single-sided silicon strip detectors (228 μm pitch) Measure the photon direction; gamma ID.
- Hodoscopic CsI Calorimeter(CAL) Array of 1536 CsI(Tl) crystals in 8 layers. Measure the photon energy; image the shower.
- Segmented Anticoincidence Detector (ACD) 89 plastic scintillator tiles. Reject background of charged cosmic rays; segmentation removes self-veto effects at high energy.
- Electronics System Includes flexible, robust hardware trigger and software filters.

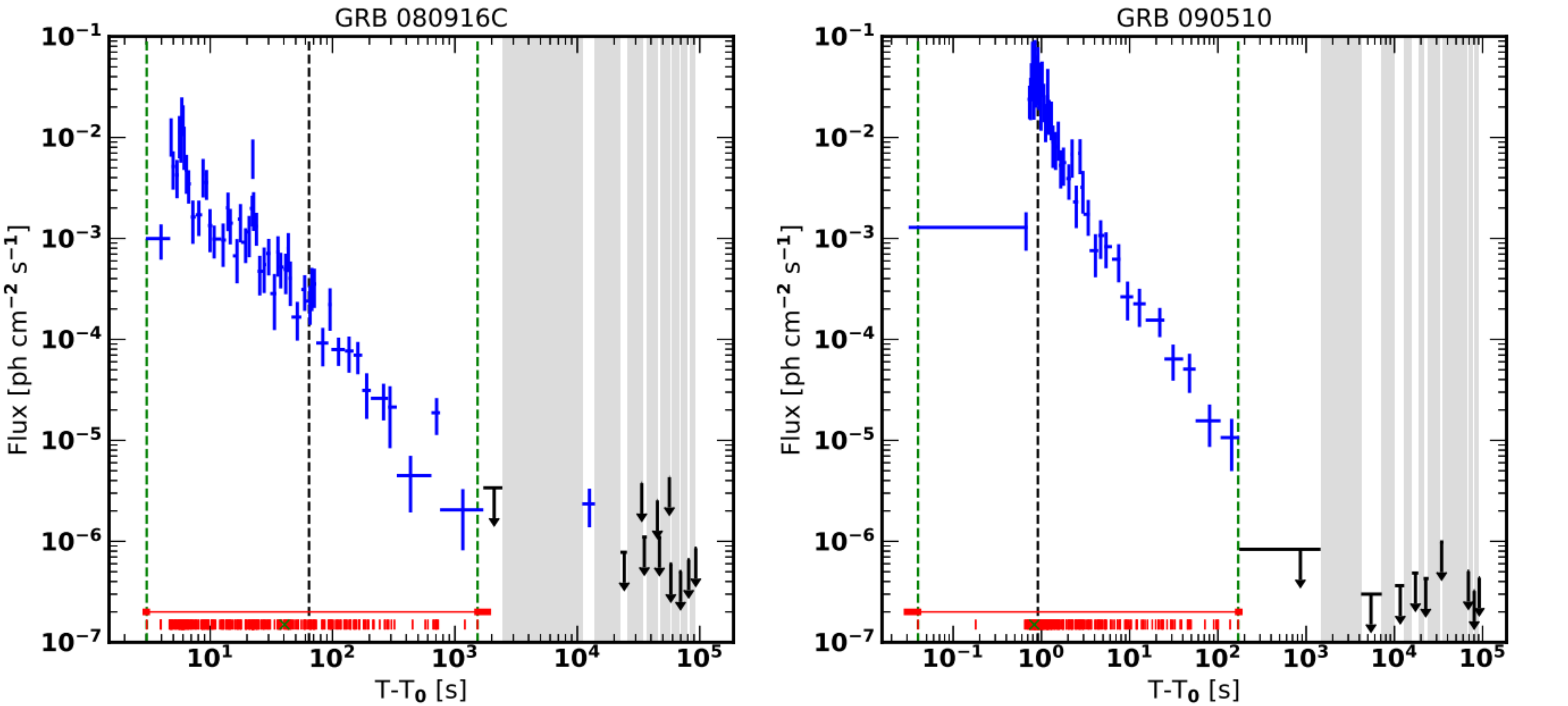


Systems work together to identify and measure the flux of cosmic gamma rays with energy 20 MeV - >300 GeV.

The Observatory

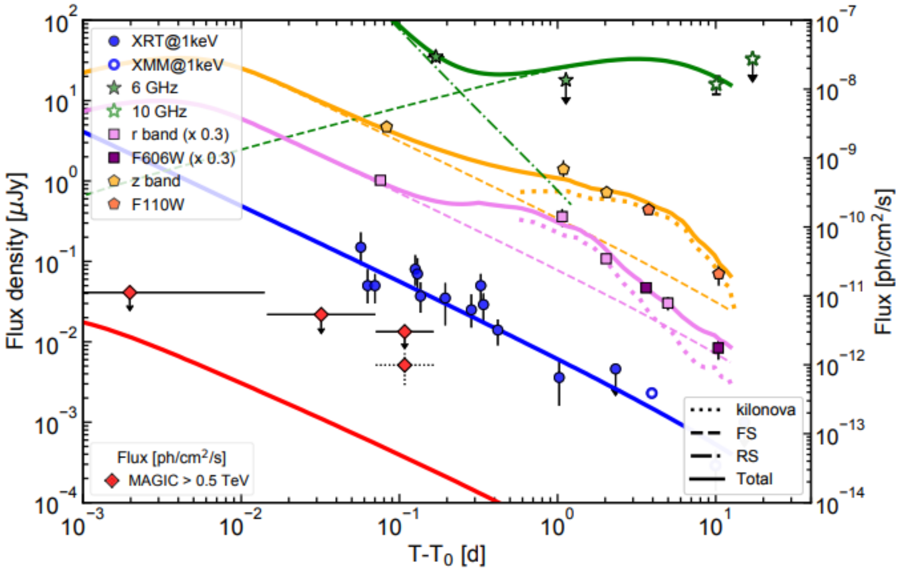


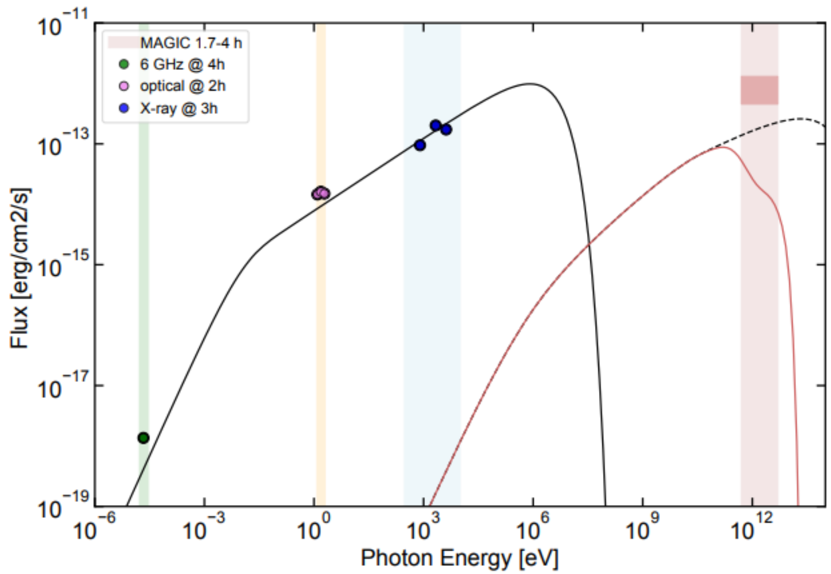
The 2nd Catalog



https://arxiv.org/pdf/1906.11403.pdf

GRB 160821B





Acciari et al. 2021