Record-breaking Gamma-Ray Burst observations

COLUMBIA UNIVERSITY IN THE CITY OF NEW YORK

VERITAS AND CTA AT BARNARD AND COLUMBIA

Summer Colloquium Series 2020

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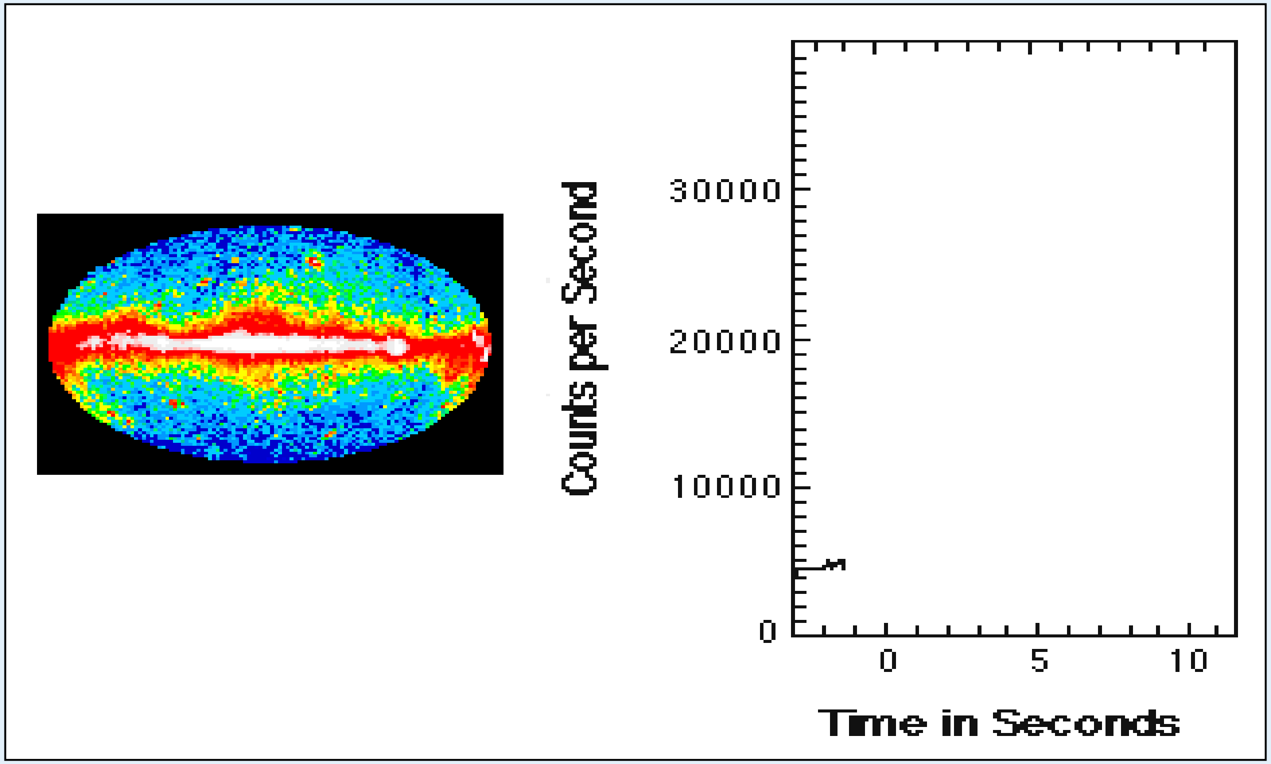
Gamma–Ray Bursts (GRBs)



Short and sudden electromagnetic signals in the gamma-ray band which, for a few blinding seconds, become the brightest objects in the Universe

Gamma–Ray Bursts

→ The keV emission kicked off the GRB show in the '70s!

THE ASTROPHYSICAL JOURNAL, 182:L85–L88, 1973 June 1

OBSERVATIONS OF GAMMA-RAY BURSTS OF COSMIC ORIGIN

RAY W. KLEBESADEL, IAN B. STRONG, AND ROY A. OLSON

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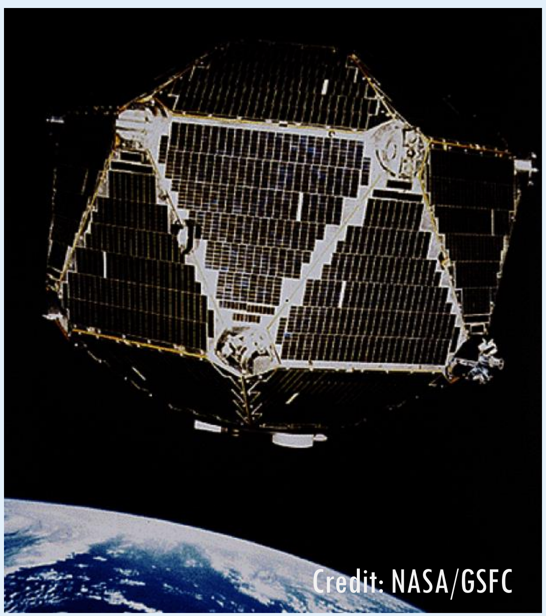
Received 1973 March 16; revised 1973 April 2

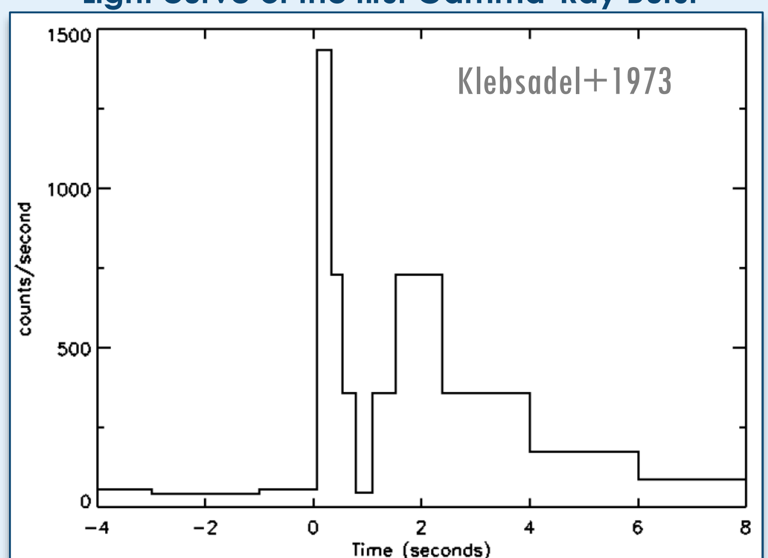
ABSTRACT

Sixteen short bursts of photons in the energy range 0.2–1.5 MeV have been observed between 1969 July and 1972 July using widely separated spacecraft. Burst durations ranged from less than 0.1 s to ~30 s, and time-integrated flux densities from $\sim 10^{-5}$ ergs cm^{-2} to $\sim 2 \times 10^{-4}$ ergs cm^{-2} in the energy range given. Significant time structure within bursts was observed. Directional information eliminates the Earth and Sun as sources.

VELA-5B satellite (1969) in low earth orbit



Light curve of the first Gamma-Ray Burst



Gamma–Ray Bursts

→ The keV emission kicked off the GRB show in the '70s!

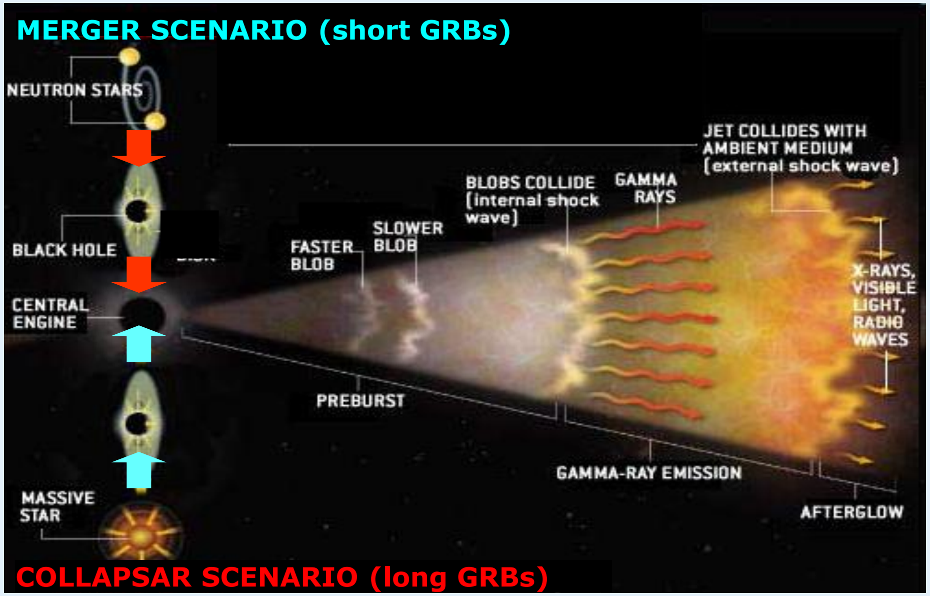
- **What we know now**:
  1. GRBs are cosmological
  2. GRBs have large bulk Lorentz factors
  3. 2 emission phases: Prompt and afterglow
  4. Long and short GRBs

Optical

Radio/ GeV

Optical/ GeV

keV/MeV



Gamma–Ray Bursts

“LONG”

Gamma–Ray Bursts

© NASA

"SHORT"

© NASA

Gamma–Ray Bursts

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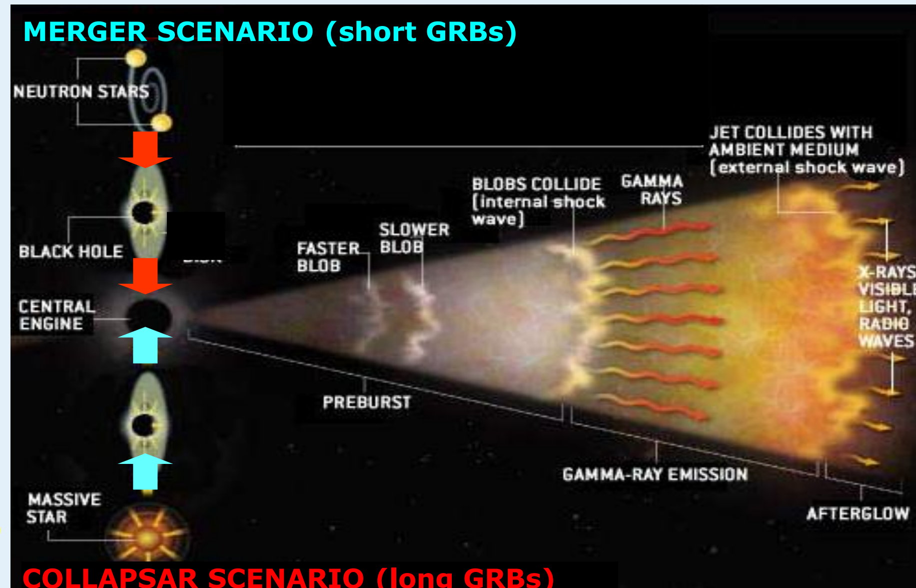
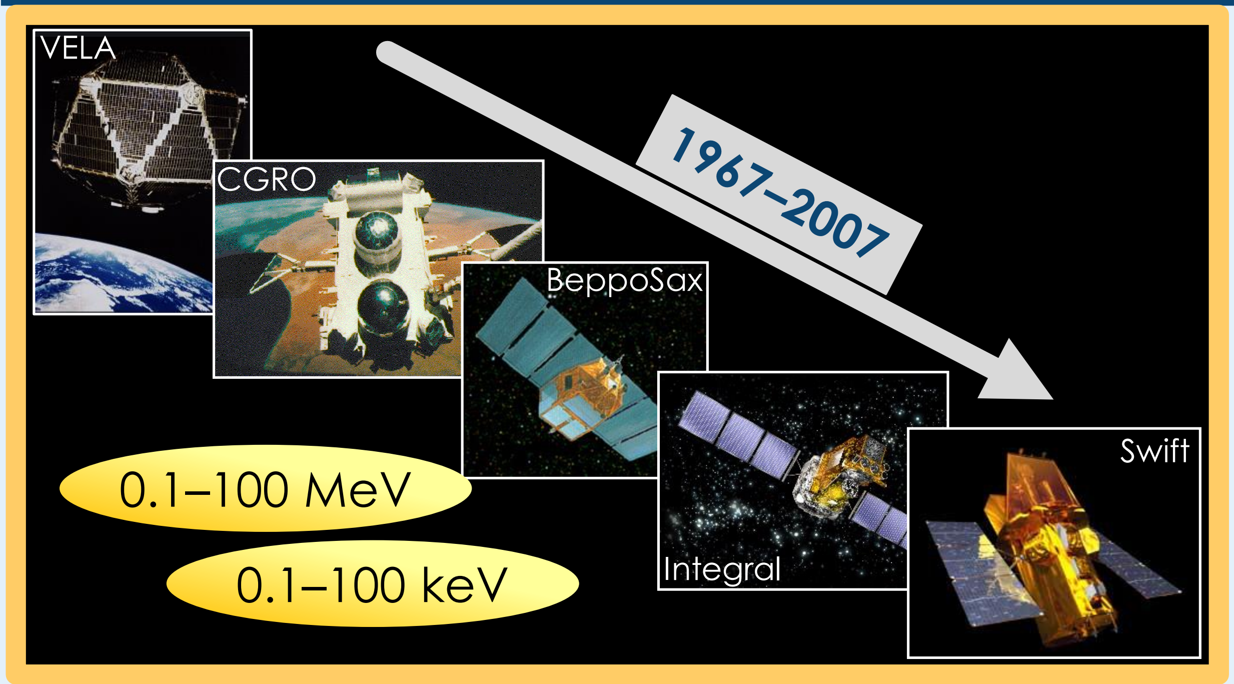
- **What we know now:**
  1. GRBs are cosmological **Optical** **Radio/ GeV**
  2. GRBs have large bulk Lorentz factors
  3. 2 emission phases: Prompt and afterglow **Optical/ GeV**
  4. Long and short GRBs **keV/MeV**
  5. Spikes have same durations
  6. Supernova connection **Optical** **X-ray/keV**
  7. Common behaviors and trends

«Pillars of knowledge» (Ghisellini 2010)



Multi-Wavelength is always the key!
Now also **Multi-Messenger**!
Synergy between instruments (and community!) is crucial

GRB hunters through history

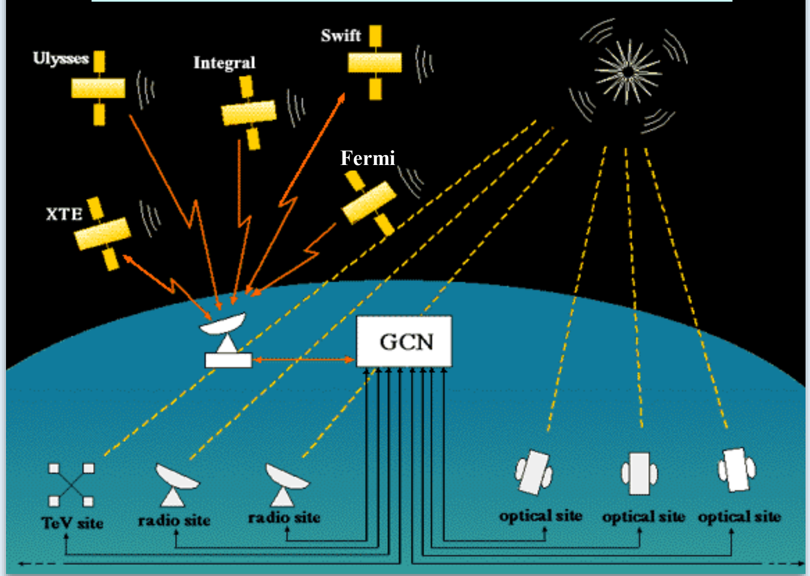


The GCN world

Gamma-Ray Burst Coordinates Network

- Disseminating **GRB locations** (**NOTICES**) detected by various spacecrafts
  - Mostly **real-time info** while the GRB is still bursting
- **Other info delayed** due to telemetry down-link delays
- **Follow-up observations** (CIRCULARS and REPORTS) made by ground and space–based observers

http://gcn.gsfc.nasa.gov/



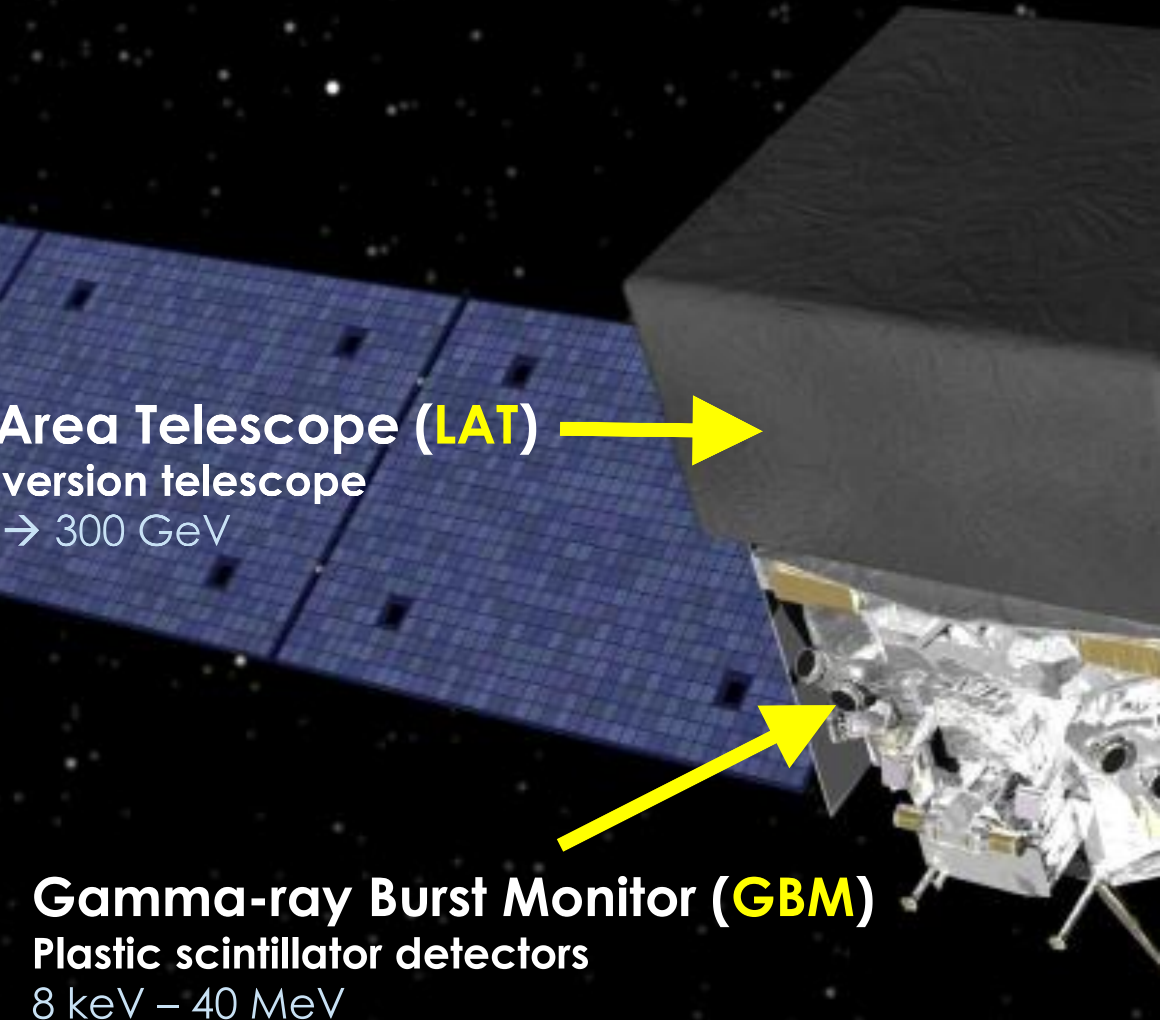
First GBM Circular!

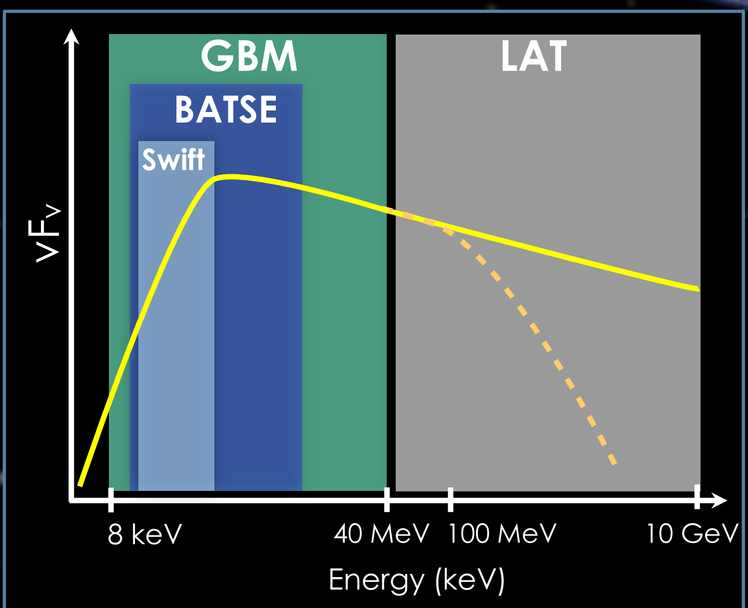
```
TITLE: GCN CIRCULAR
NUMBER: 8100
SUBJECT: GLAST Burst Monitor detection of GRB 080810
DATE: 08/08/12 21:02:21 GMT
FROM: Charles Meegan at NASA/MSFC
<charles.a.meegan@nasa.gov>

"At 13:10:12 UT on 10 August 2008, the GLAST Burst
Monitor (GBM) triggered and located GRB 080810
(trigger 240066613/080810549), which was also
detected by Swift (Page et al., GCN 8080). (…)"
```

The Fermi mission

Launched on June 11, 2008





A typical GRB spectrum

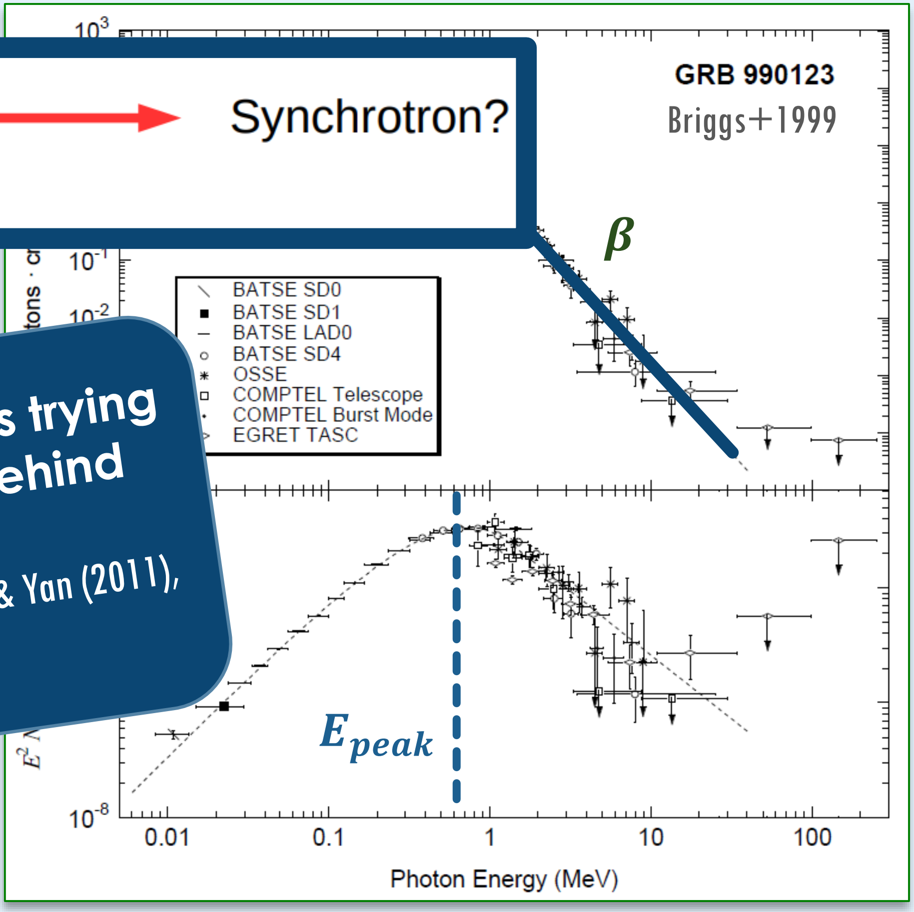
- **The phenomenological «Band» function**
  - Characterized by three spectral parameters, α, β and E_{peak}
    - Vary from burst to burst with **no universal values**

- This spectra
  - **Integrate**
    over the
  - Emission during **a certain temporal segment** of the
    (**time-re**

- The most u
  the **peak e**
  of the $\nu F\nu$

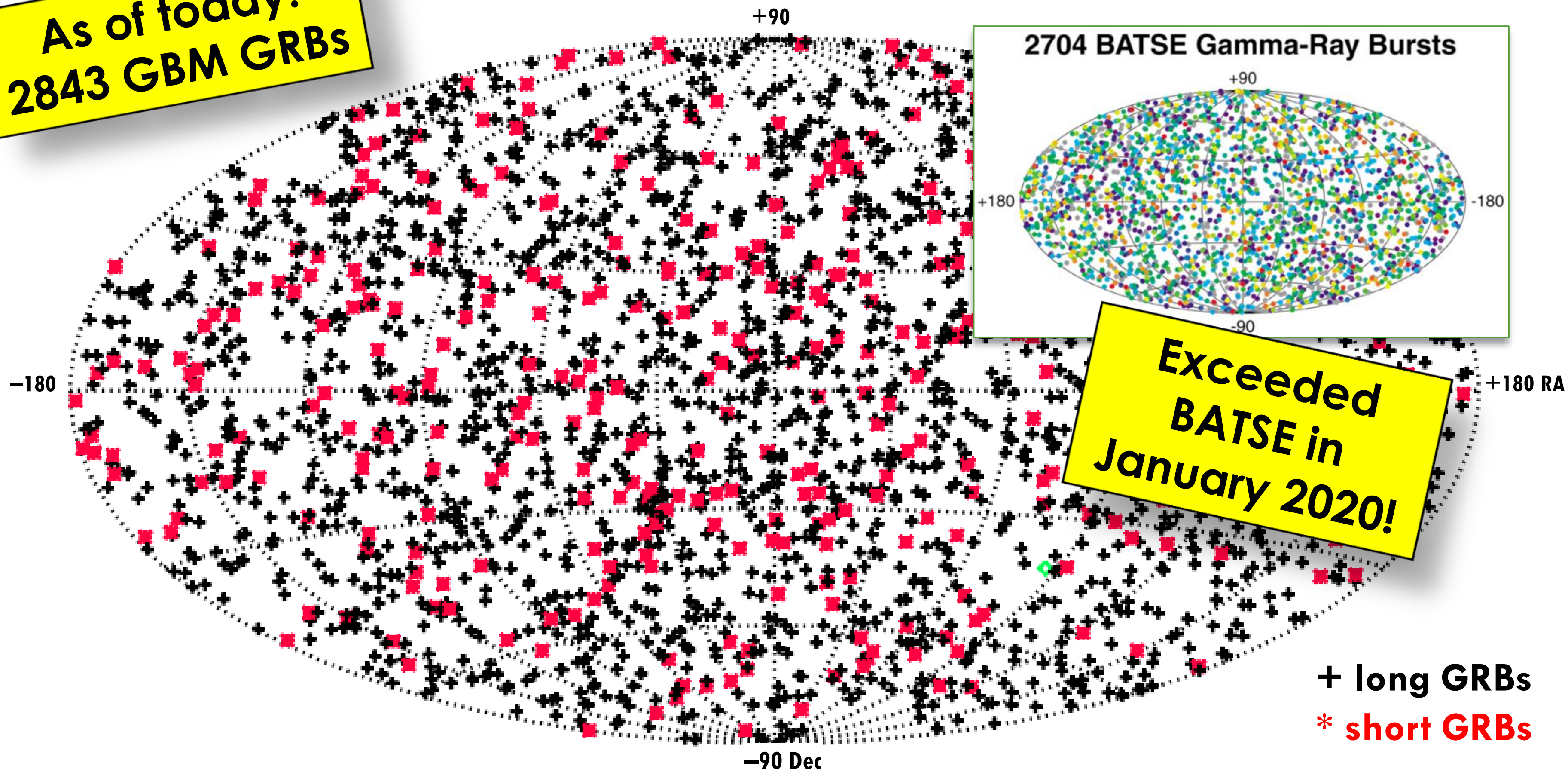
• Non-thermal spectrum
• Accelerated electrons in a magnetized region → Synchrotron?

Many theoretical models trying to explain the physics behind the observed spectrum
e.g. Beloborodov et al. (2014), Zhang & Yan (2011), Oganesyan et al. (2018)



Fermi-GBM GRB Skymaps

As of today: 2843 GBM GRBs



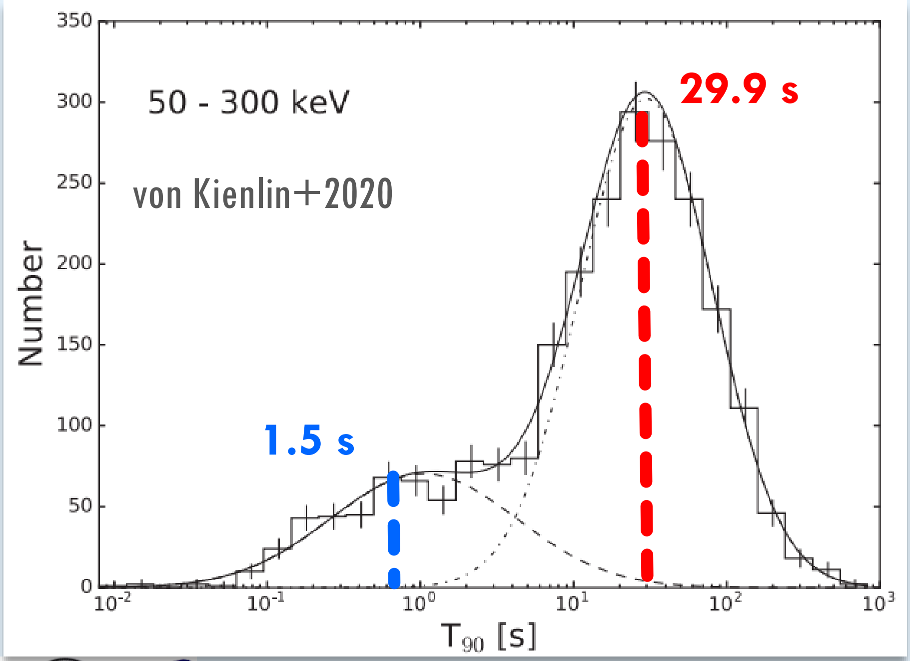
Fermi-GBM 10-year GRB map – von Kienlin et al. (2020)

Fermi-GBM highlights

4th GBM GRB Catalog (10 years catalog) – 2356 GRBs

Distribution of GRB durations

- "T_{90}" interval between the times where the burst has reached 5% and 95% of its maximum fluence
  - **17 % short, 83% long**



➔ **GRB rate: 242 ± 6 / year**

- **Long GRB rate: ~200 /year**
- **Short GRB rate: ~40 /year**

GBM: ~ 40 sGRBs/year
Swift: ~ 9 sGRBs/year

Fermi-GBM highlights

4th GBM GRB Catalog (10 years catalog) – 2356 GRBs

Distribution of GRB durations

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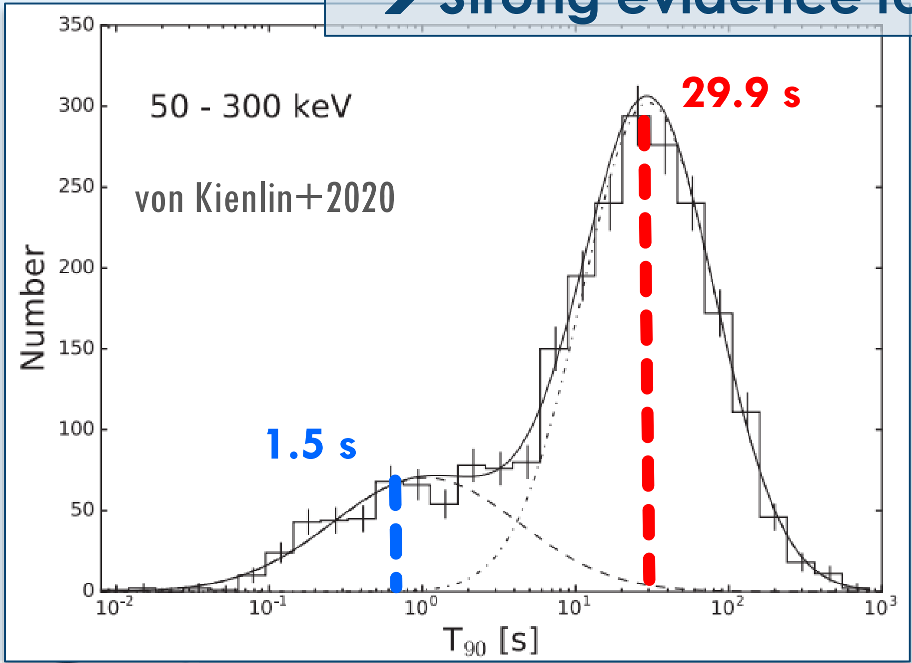
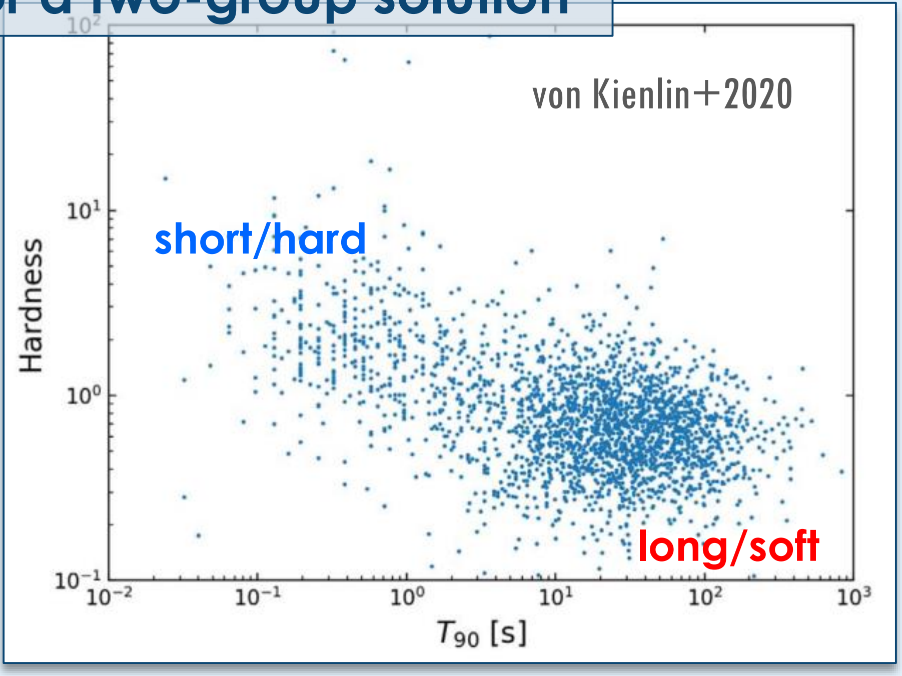
Hardness-duration diagram

- "**Hardness**": Ratio of burst fluence during the T_{90} intervals in the energy band **50–300 keV** to that in the **10–50 keV** band

➔ Strong evidence for a two-group solution

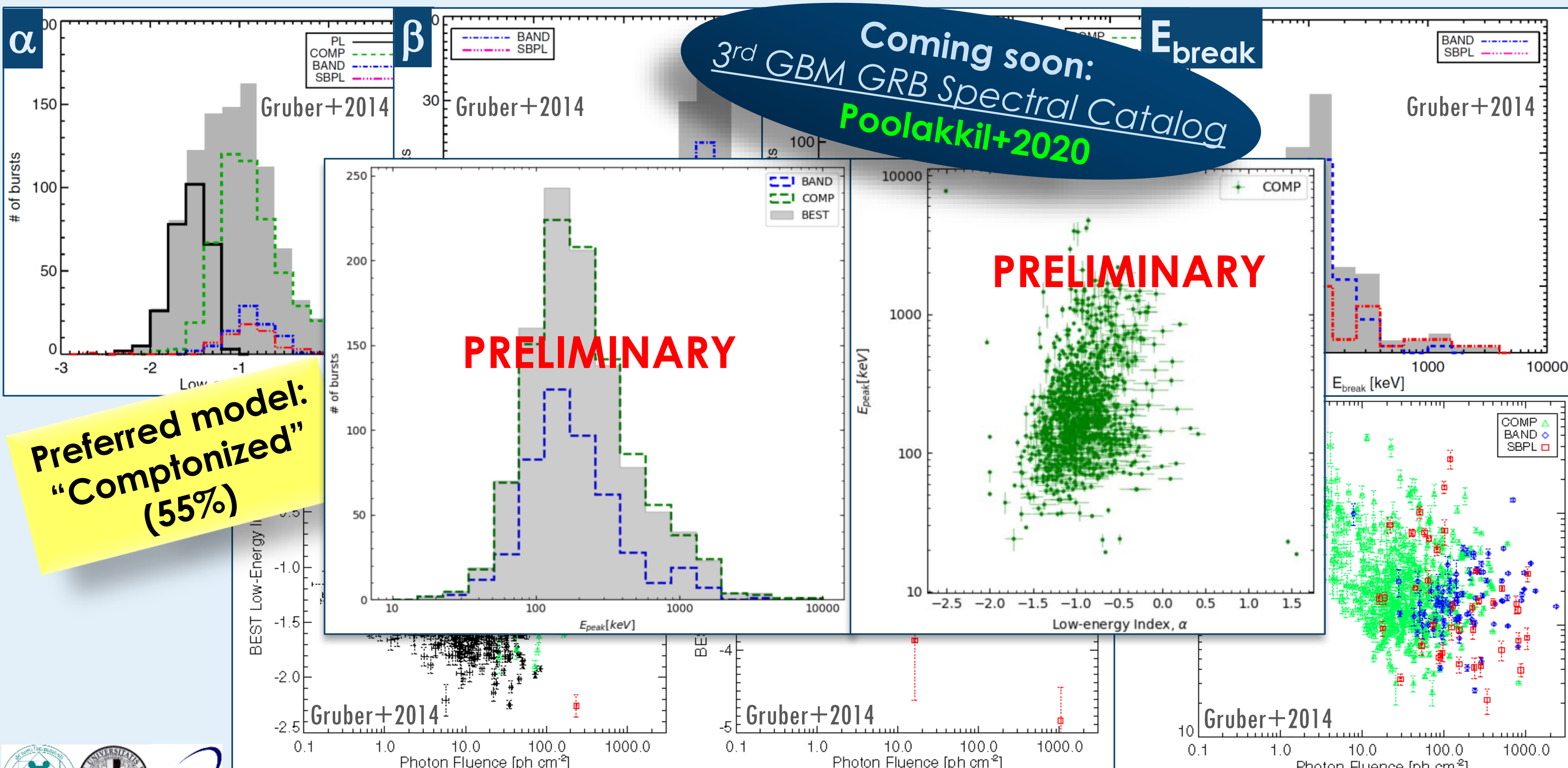




Fermi–GBM GRB highlights

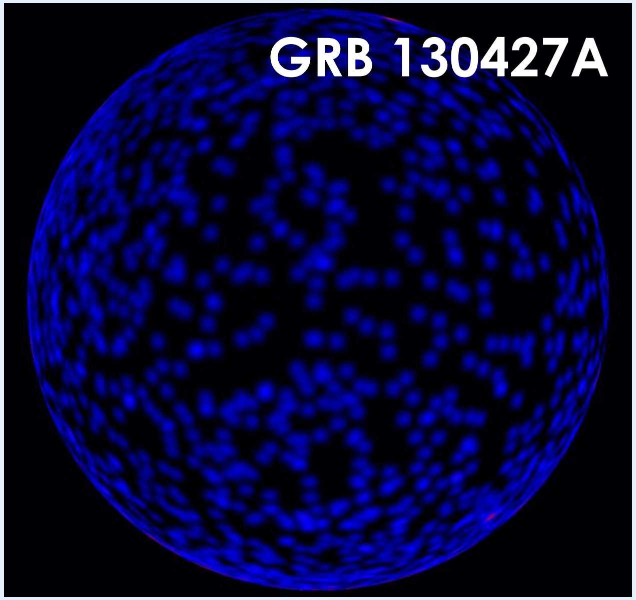
2rd GBM GRB Spectral Catalog (Gruber+2014,ApJ211)

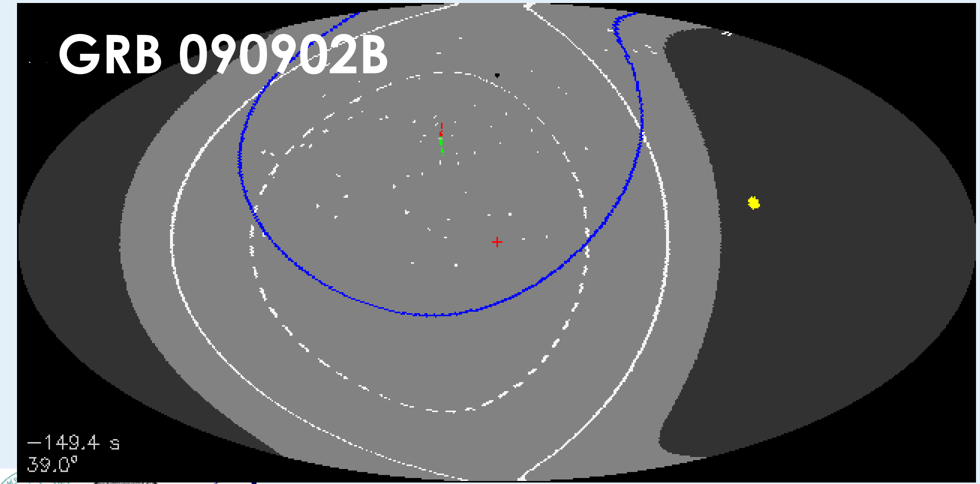
Time-integrated spectral fits + spectral fits at the brightest time bin fitted with **4 spectral models** (PL, SBPL, Band, Comp)



Follow–up of Fermi–GBM GRBs

- GBM trigger localization suffering from large uncertainties (5 – 10 deg error radius)
- **BUT**: Trigger criteria: high peak flux, or high fluence GBM to LAT → Autonomous Repoint Request (ARR)
  - Occured with rate of >1/month (>170 positive **ARRs** in 10 yrs)
  - ALSO: 6 onboard LAT triggers!
- **LAT automated pipelines** for GRB searches
  - Also triggers from **Swift, INTEGRAL, and MAXI**
  - Search for **excess emission** at trigger time plus in **various intervals** over a large RoI





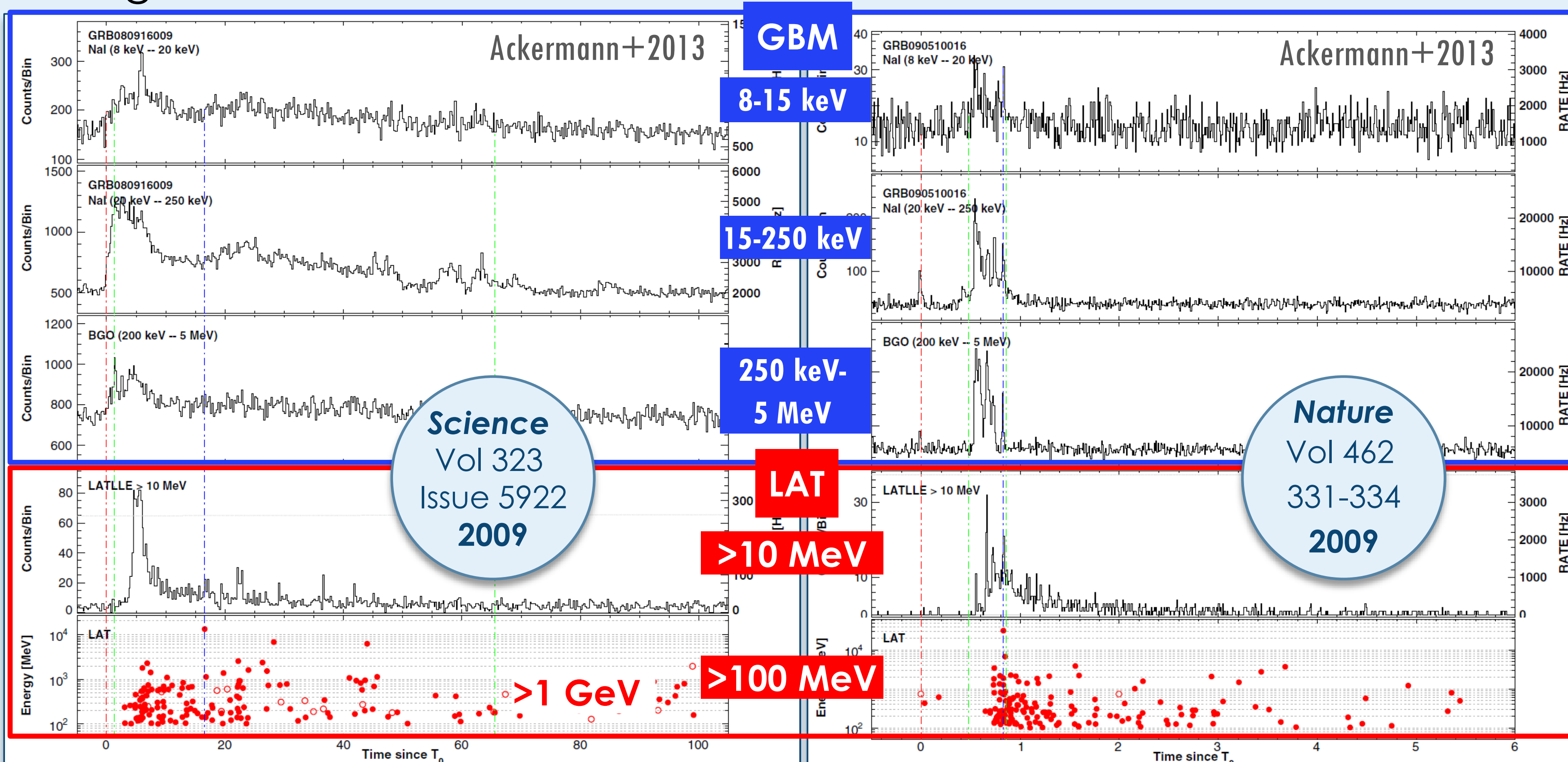
Hammer-Aitoff representation of the whole sky in celestial coordinates

RED CROSS (center)	GRB
YELLOW DOT	Sun
GREEN/RED LINES	Fermi solar panels
BLUE CIRCLE	LAT FoV
DARK AREA	Earth
WHITE CIRCLE	20° Earth avoidance
DASHED WHITE CIRCLE	50° Earth avoidance

The most “famous” LAT GRBs

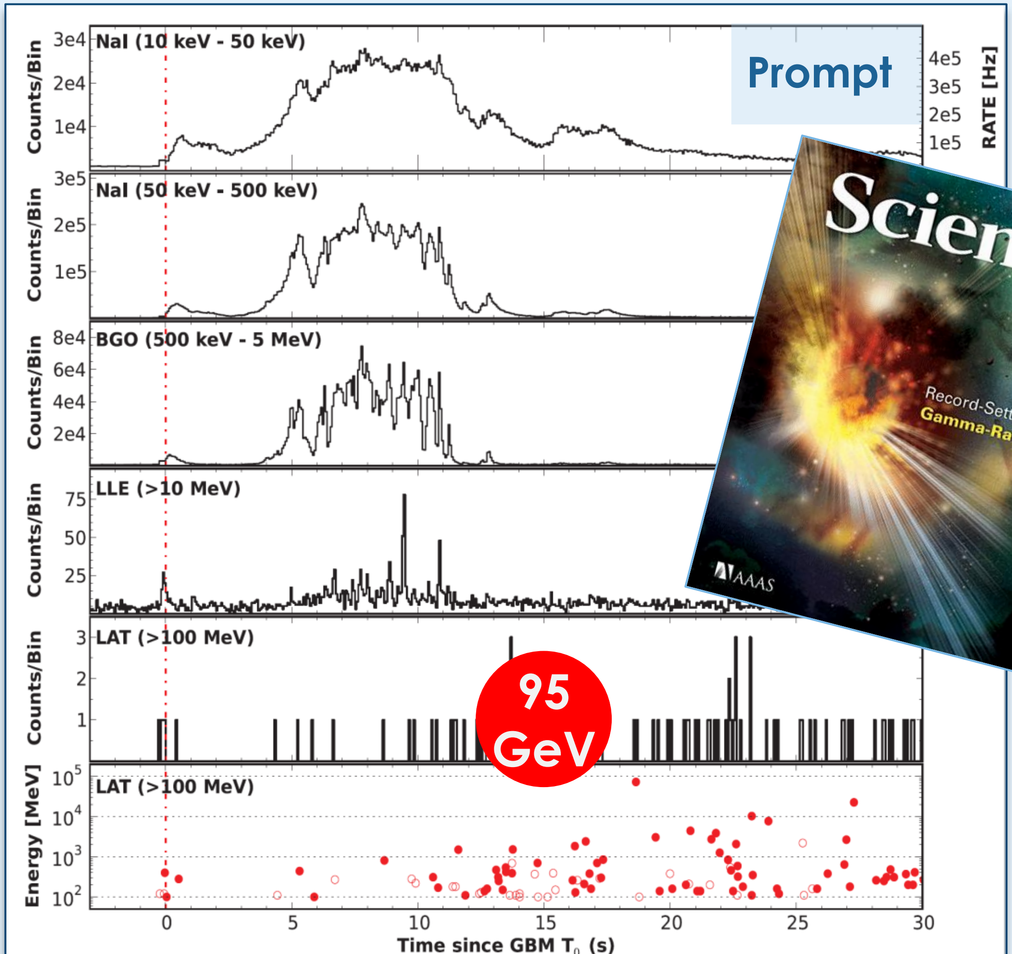
1st LAT GRB Catalog (3 years, **35 GRBs**)

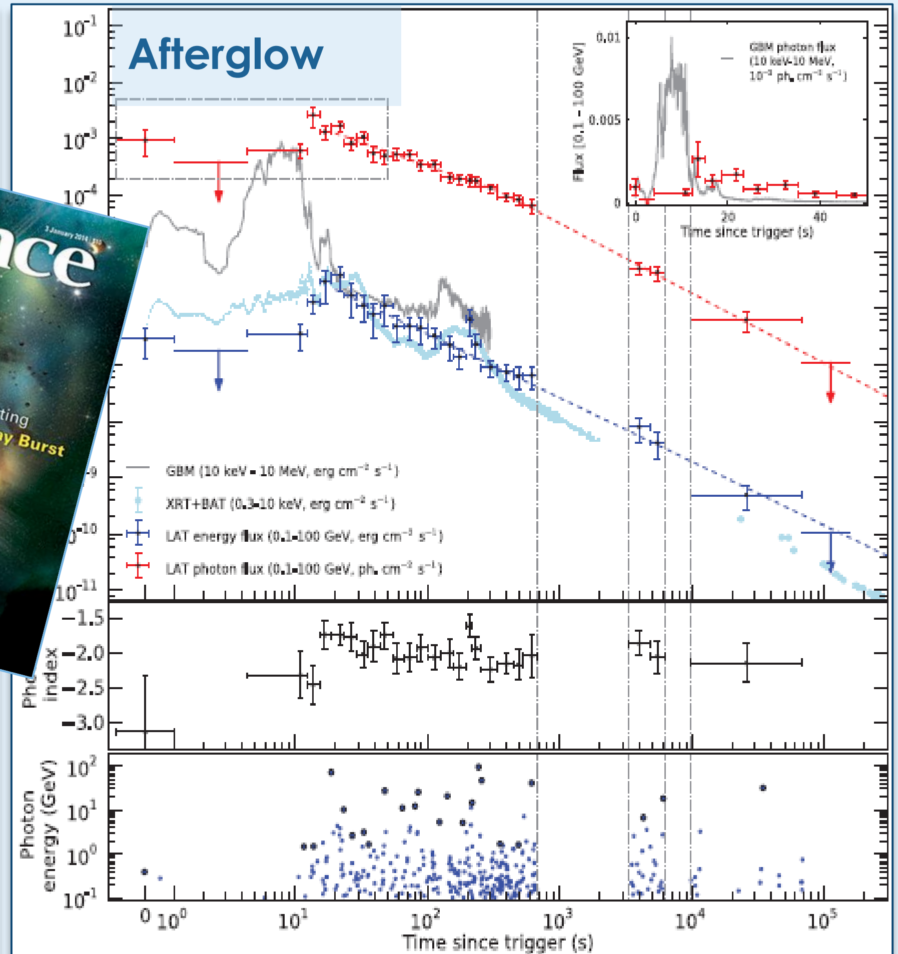
Long **GRB 080916C** Short **GRB 090510**



The most "famous" LAT GRBs

GRB 130427A – The "monster" burst

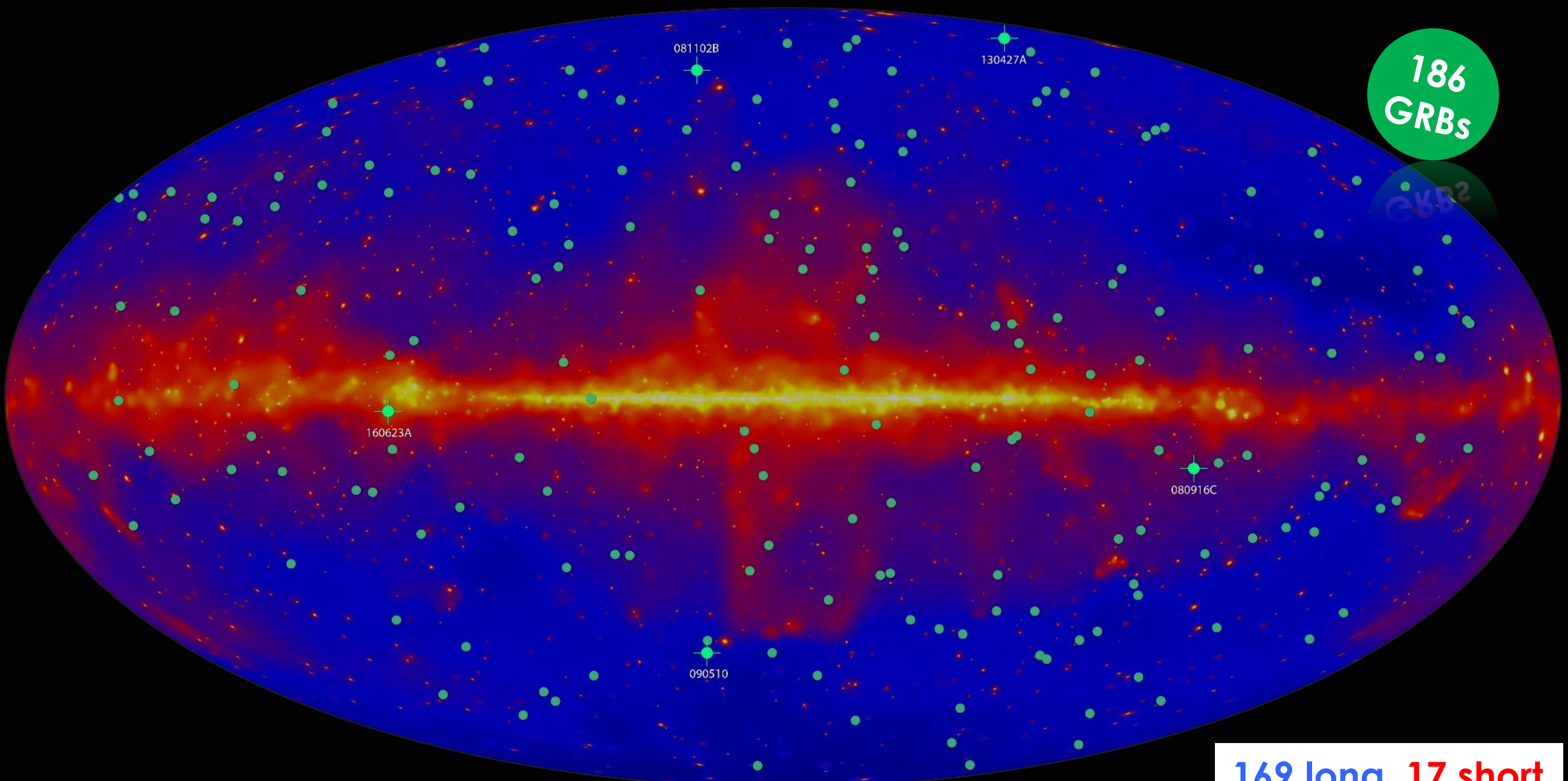




Preece+2014, Ackermann+2014 Science

The 2nd LAT GRB Catalog (2FLGC)

"A Decade of **Gamma-Ray Bursts** Observed by **Fermi-LAT:** The **Second GRB Catalog**"



169 long 17 short

Ajello et al 2019, The Astrophysical Journal, Volume 878, Number 1

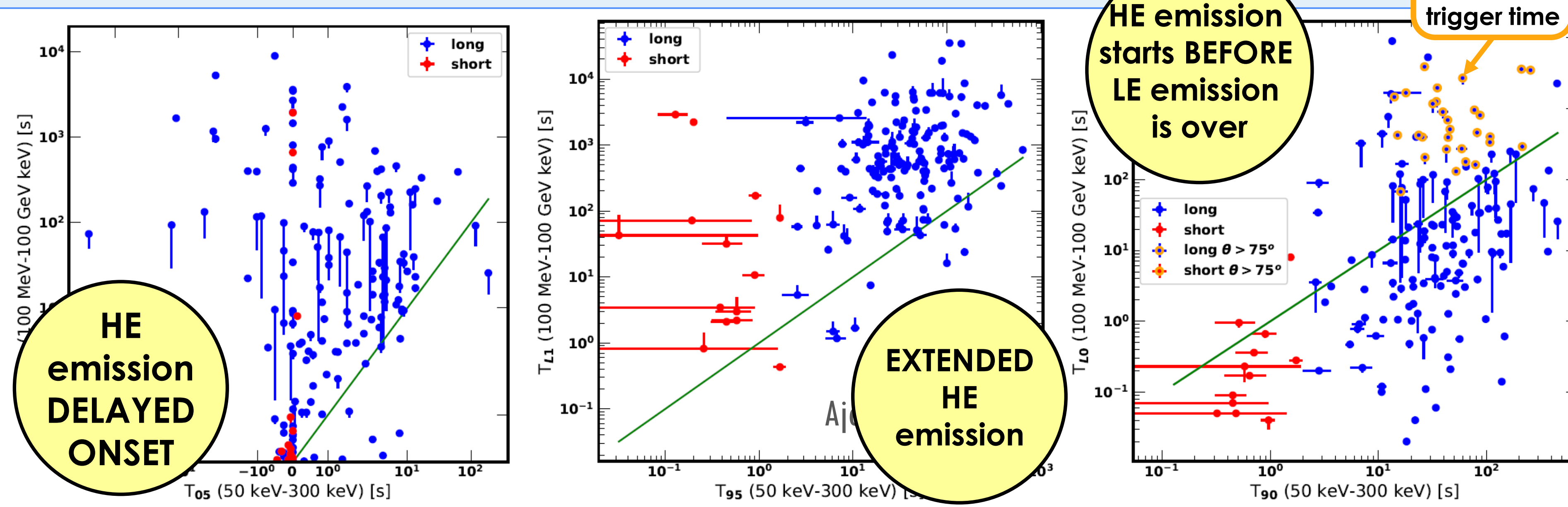
Corresponding authors: M. Axelsson, E. Bissaldi, N. Omodei, G. Vianello

HE GRB temporal properties

Detailed study of the **onset** and **duration** of the high-energy emission

- **T_{L100}** = GRB duration measured by LAT [**100 MeV – 100 GeV**]
- T_{L100} = **T_{L1}** – **T_{L0}** (Arrival time of last and first photon, respectively)

- **High-energy Emission** (>100 MeV)
  - Systematically **delayed** and **longer** wrt the low-energy emission



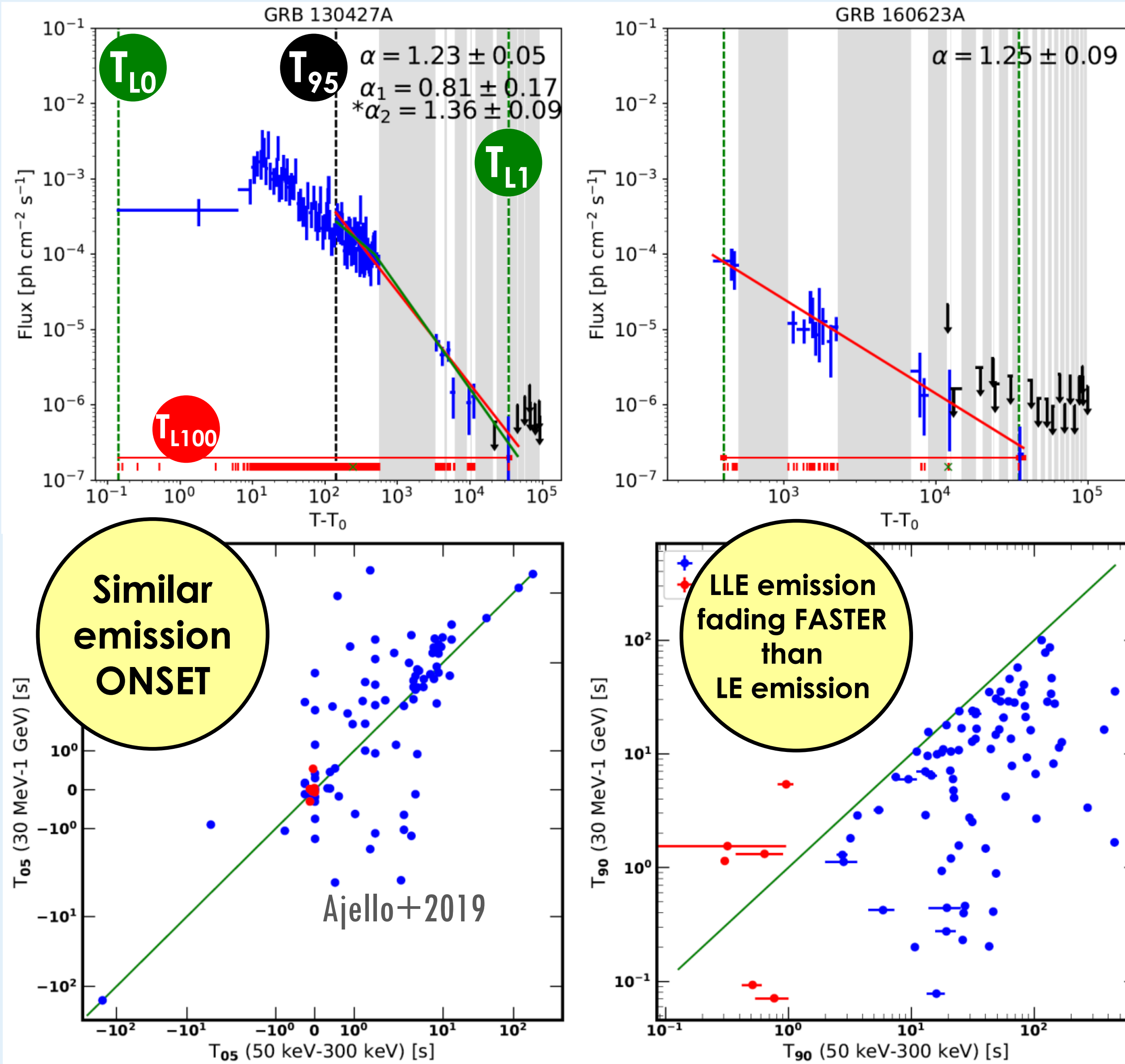
HE GRB temporal properties

Longest bursts

1. GRB 130427A
   T_{L100} = 34 ks
2. GRB 160623A
   T_{L100} = 35 ks

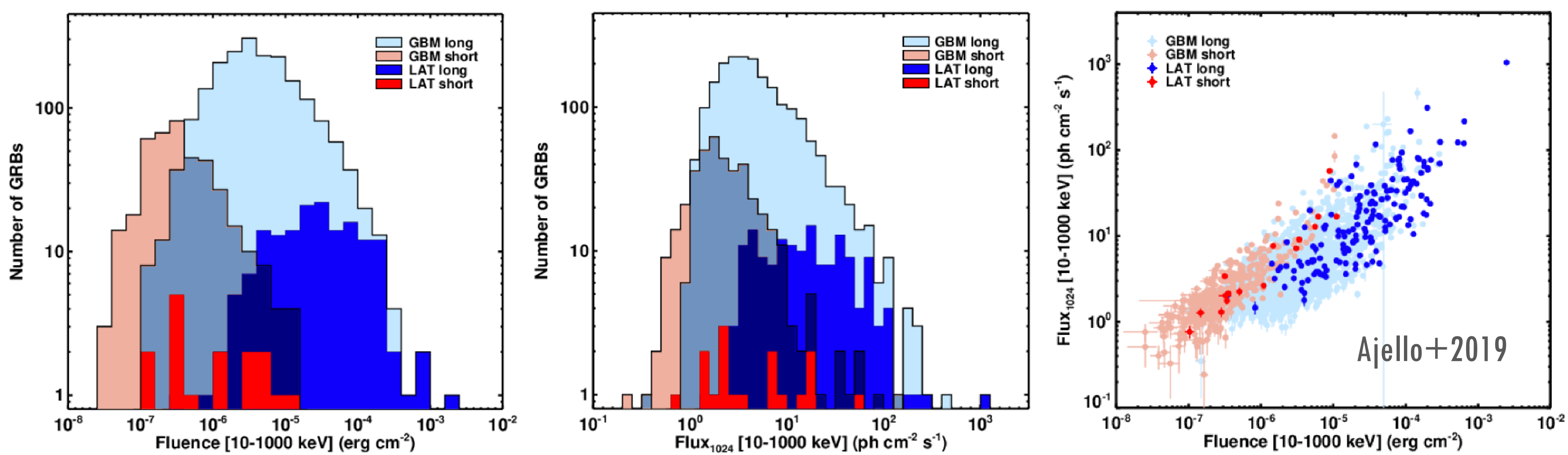
At lower energies (LLE: **30 MeV – 1 GeV**)

- Definition of duration similar to the GBM
- Behavior similar to low-energy emission



HE GRB energetics

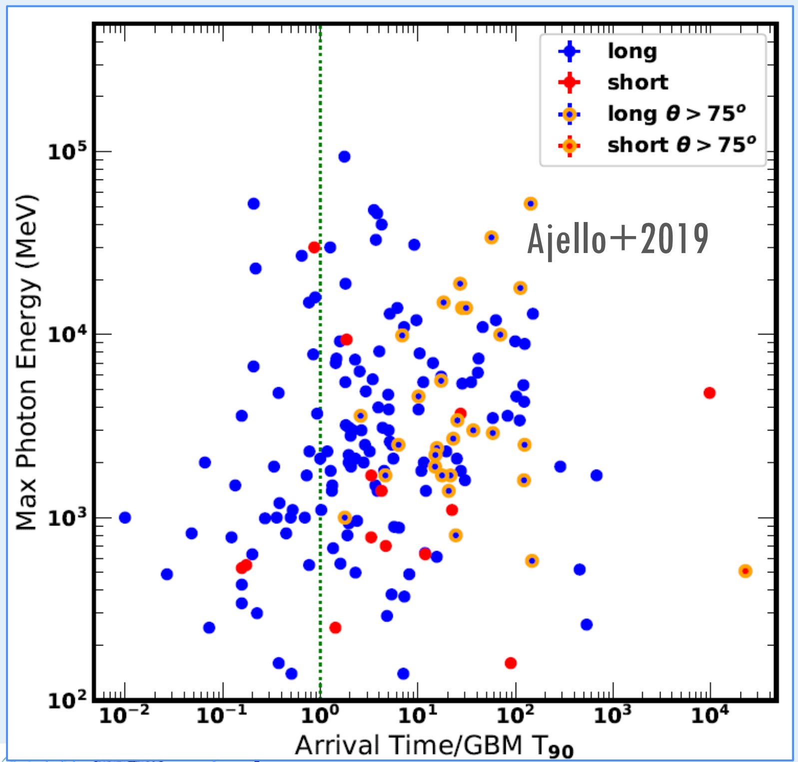
- Comparison of low-energy properties of LAT-detected GRBs with the entire **10yr GBM sample** (**~2400 GRBs**)

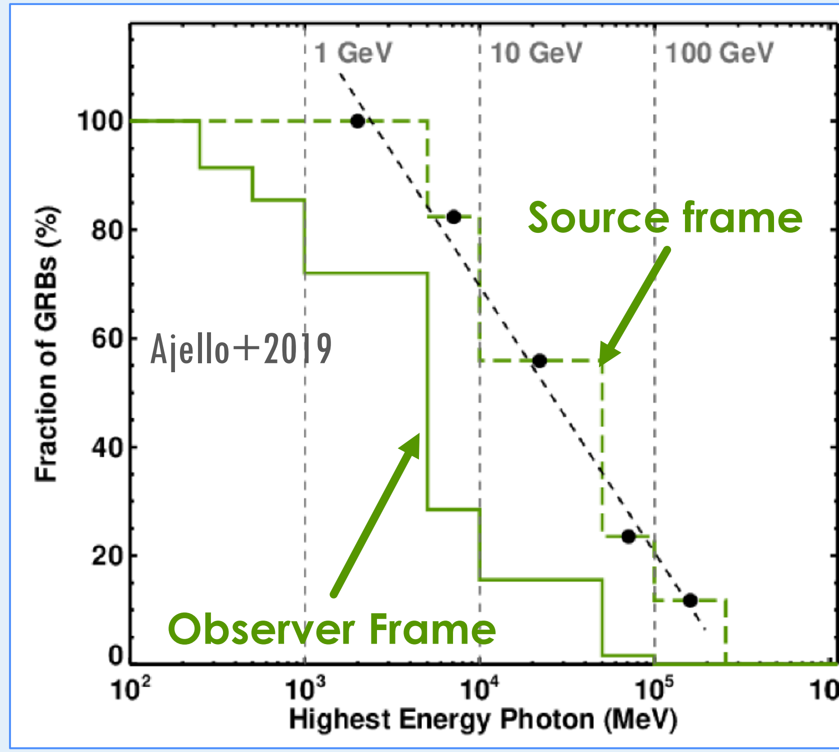


- Distribution of short and long bursts are **different**
- LAT tends to sample brighter bursts
  - BUT: **MUCH LARGER SPREAD** now than in the first LAT catalog!
    - Detection of HE emission also **from weak GBM bursts**!

High energy photons

- **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!

Breakthrough: GRB detections @VHE

- On **November 20, 2019**, the **MAGIC** and **H.E.S.S.** experiments published several papers in **Nature** where they announced the detection of **VHE emission from two GRBs**
  1. MAGIC observation of **GRB 190114C**
  2. H.E.S.S. observation of **GRB 180720B**

nature
DOI: 10.1038/s41586-019-1750-x

Article | Published: 20 November 2019

Teraelectronvolt emission from the γ-ray burst GRB 190114C

MAGIC Collaboration

Nature **575**, 455–458(2019) | Cite this article

Abstract

Long-duration γ-ray bursts (GRBs) are the most luminous sources of electromagnetic radiation known in the Universe. They arise from outflows of plasma with velocities near the speed of light that are ejected by newly formed neutron stars or black holes (of stellar mass) at cosmological distances[1,2]. Prompt flashes of megaelectronvolt-energy γ-rays are followed by a longer-lasting afterglow emission in a wide range of energies

nature
DOI: 10.1038/s41586-019-1754-6

Article | Published: 20 November 2019

Observation of inverse Compton emission from a long γ-ray burst

MAGIC Collaboration, P. Veres, [...] D. R. Young

Nature **575**, 459–463(2019) | Cite this article

Abstract

Long-duration γ-ray bursts (GRBs) originate from ultra-relativistic jets launched from the collapsing cores of dying massive stars. They are characterized by an initial phase of bright and highly variable radiation in the kiloelectronvolt-to-megaelectronvolt band, which is probably produced within the jet and lasts from milliseconds to minutes, known as the prompt emission[1,2]. Subsequently, the interaction of the jet with the surrounding medium

nature

Article | Published: 20 November 2019

A very-high-energy component deep in the γ-ray burst afterglow

H. Abdalla, R. Adam, [...] O. J. Roberts

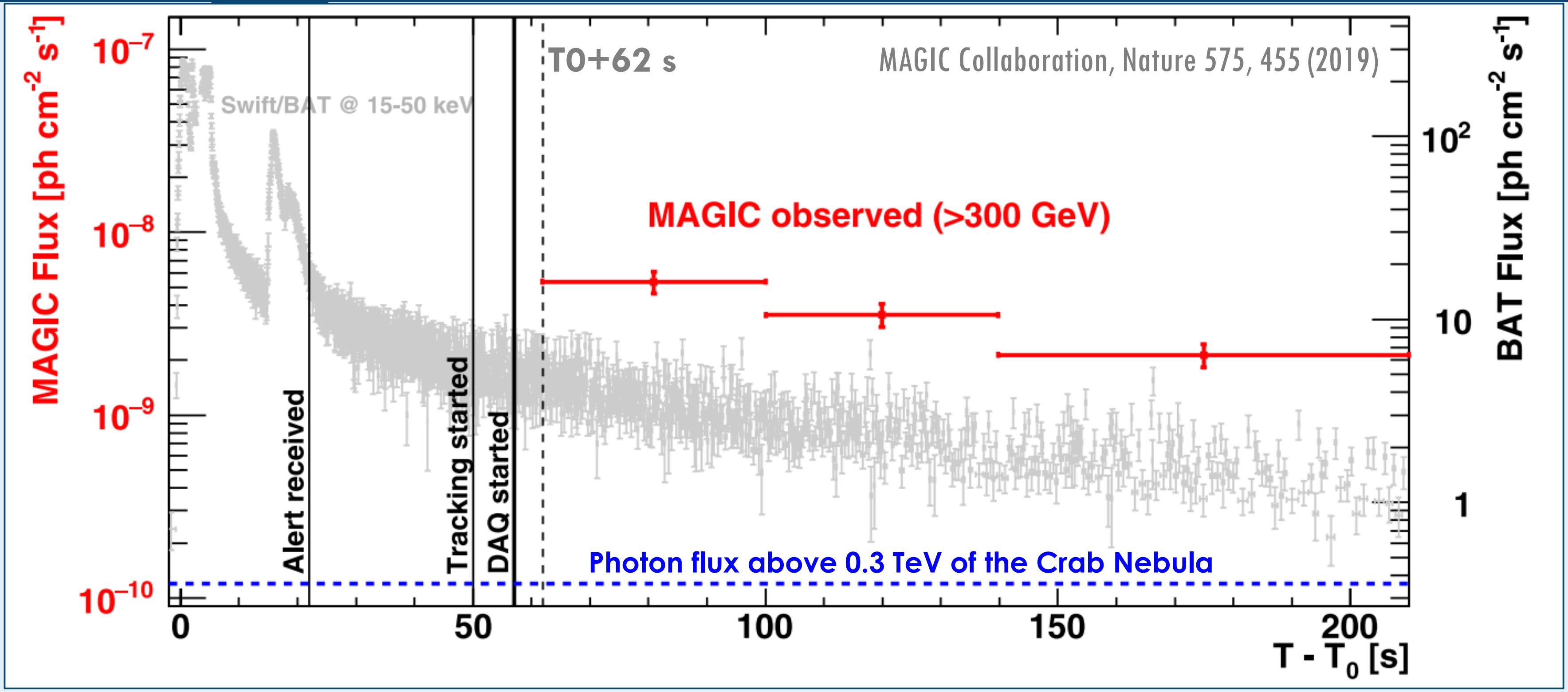
Nature **575**, 464–467(2019) | Cite this article

Corresponding authors
F. Aharonian, E. Bissaldi, C. Hoischen, R. D. Parson, Q. Piel, E. Ruiz-Velasco

Abstract

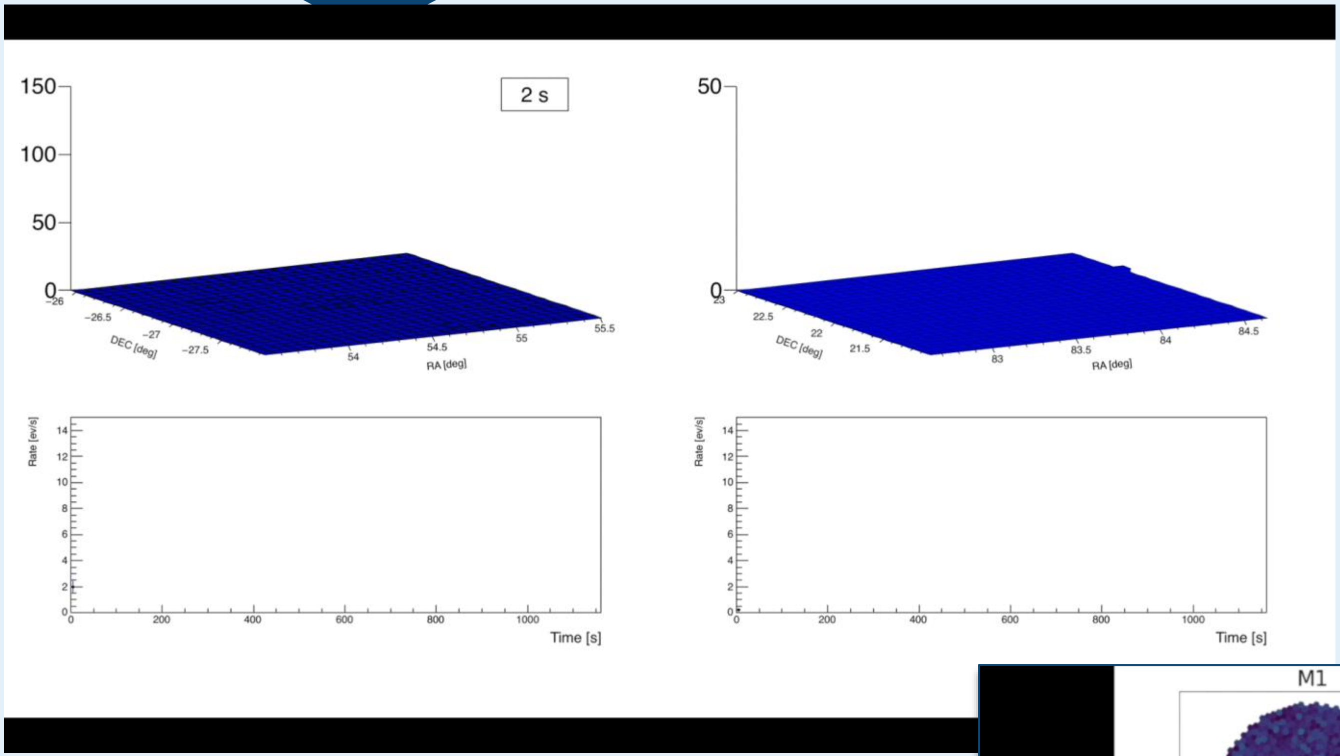
Gamma-ray bursts (GRBs) are brief flashes of γ-rays and are considered to be the most energetic explosive phenomena in the Universe[1]. The emission from GRBs comprises a short (typically tens of seconds) and bright prompt emission, followed by a much longer afterglow phase. During the afterglow phase, the shocked outflow—produced by the interaction between the ejected matter and the circumburst medium—slows down, and a gradual decrease in brightness is observed[2]. GRBs typically emit most of their energy via γ-rays with energies in the kiloelectronvolt-to-megaelectronvolt range, but a few photons with

GRB 190114C seen by MAGIC



- **Photon flux lightcurves**
  - **MAGIC** lightcurve **above 0.3 TeV**
    - Vertical dashed line indicates when the DAQ became stable
  - **Swift-BAT** lightcurve between **15 keV and 50 keV**

GRB 190114C seen by MAGIC



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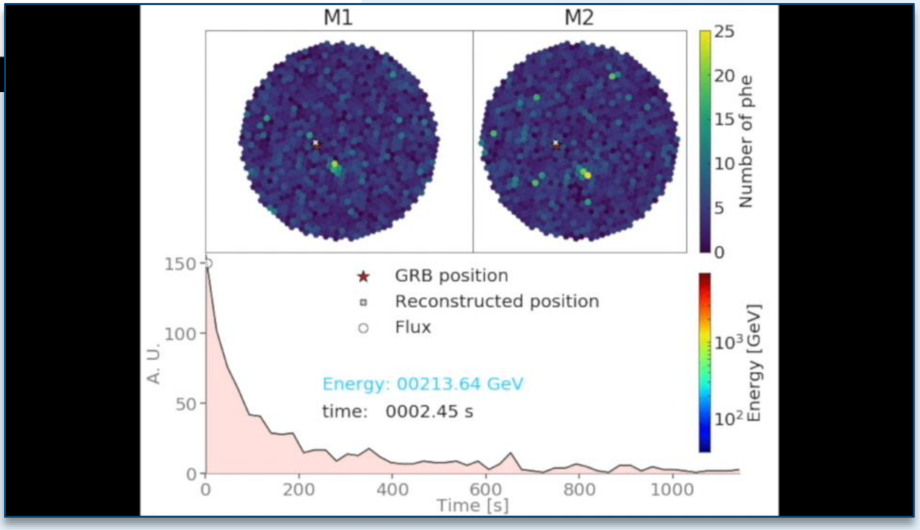
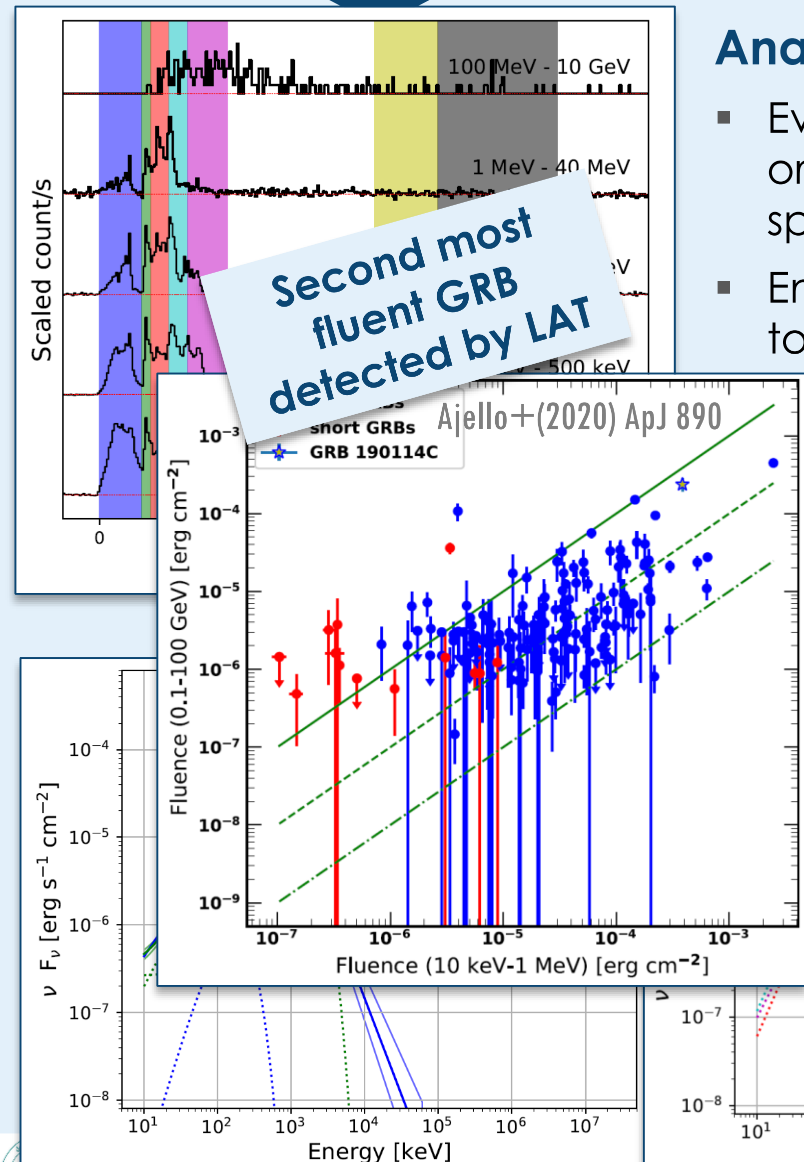


GRB 190114C seen by Fermi



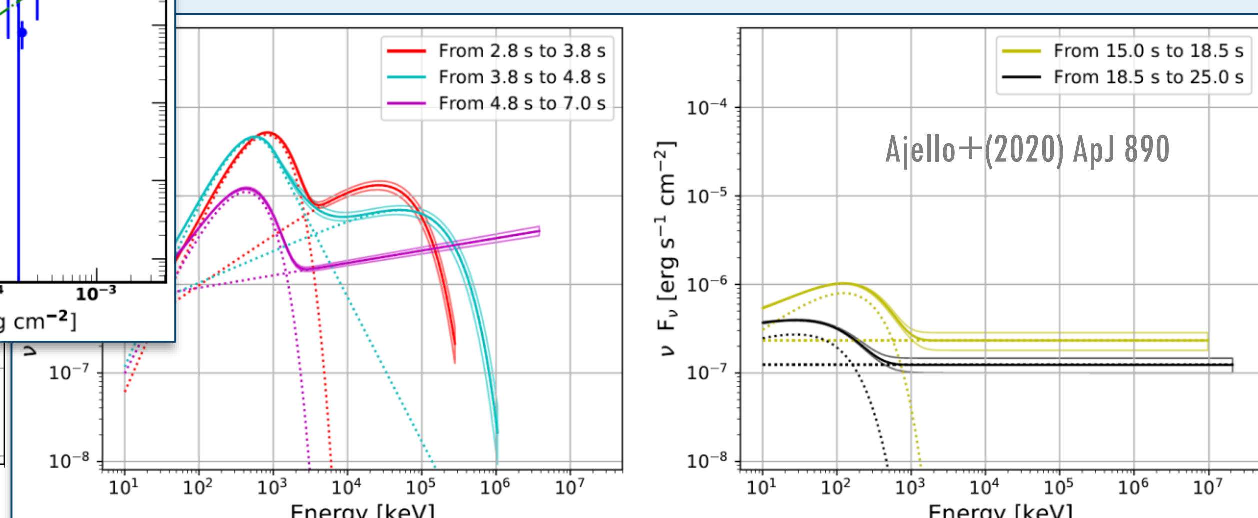
Second most fluent GRB detected by LAT

Analysis of prompt emission with GBM+LAT data

- Evidence for both **thermal** (BB) and **non-thermal** (CPL or Band) spectral components commonly seen in GRB spectra
- Emergence of an **additional PL component** extending to high energies

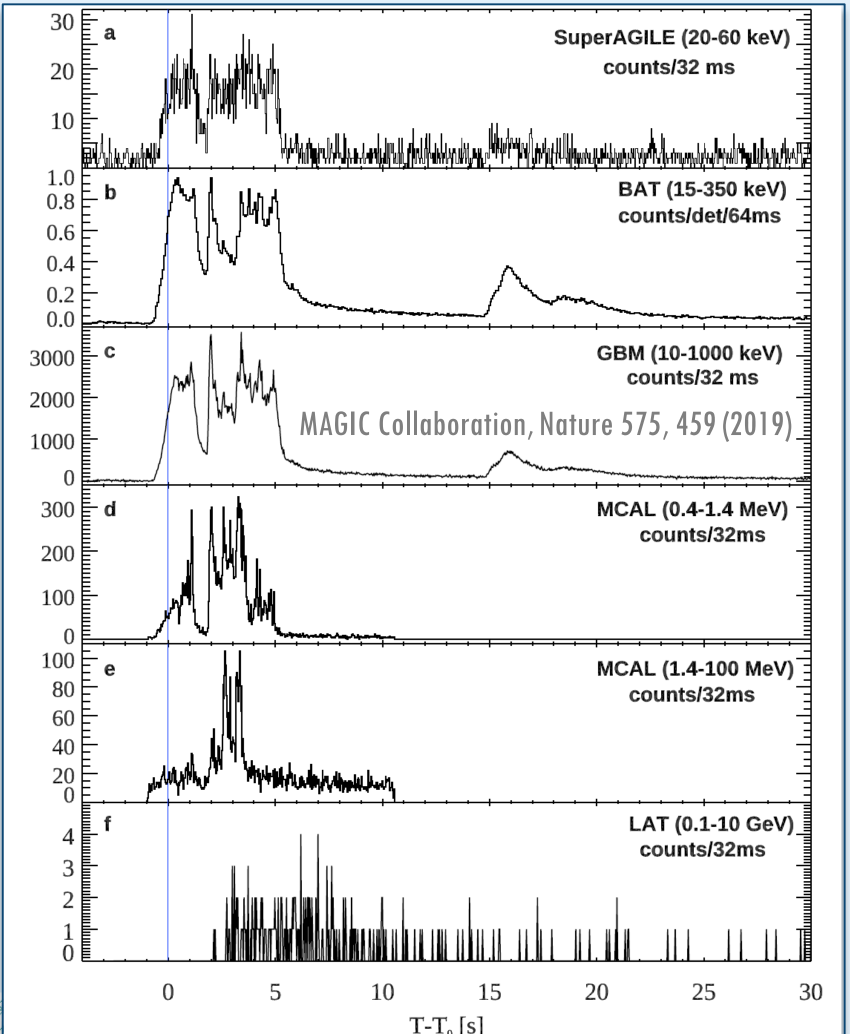
Explaining the **delayed onset** of the LAT-detected emission

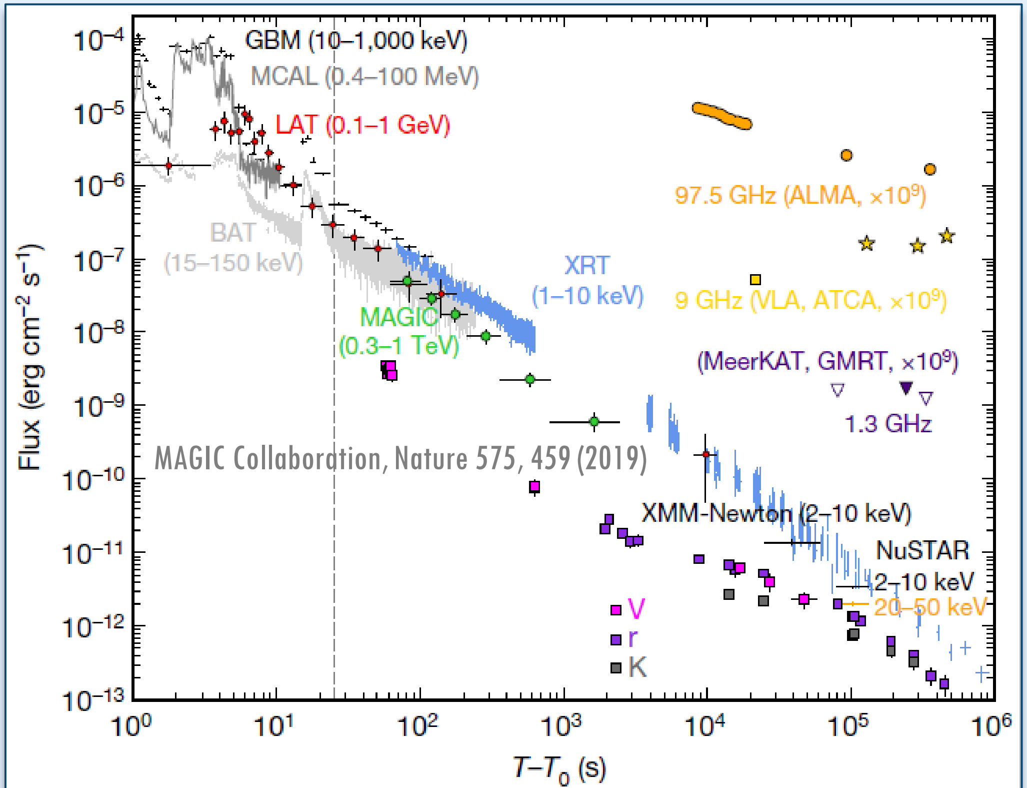
Showing strong evidence for spectral attenuation >40 MeV in the first few seconds of the burst, before transitioning to a **harder spectrum** that is consistent with the afterglow emission observed by XRT+BAT at later times



GRB 190114C in the multiwavelength context

Prompt-emission lightcurves from different detectors





Energy flux lightcurves at different wavelengths, from radio to gamma-rays

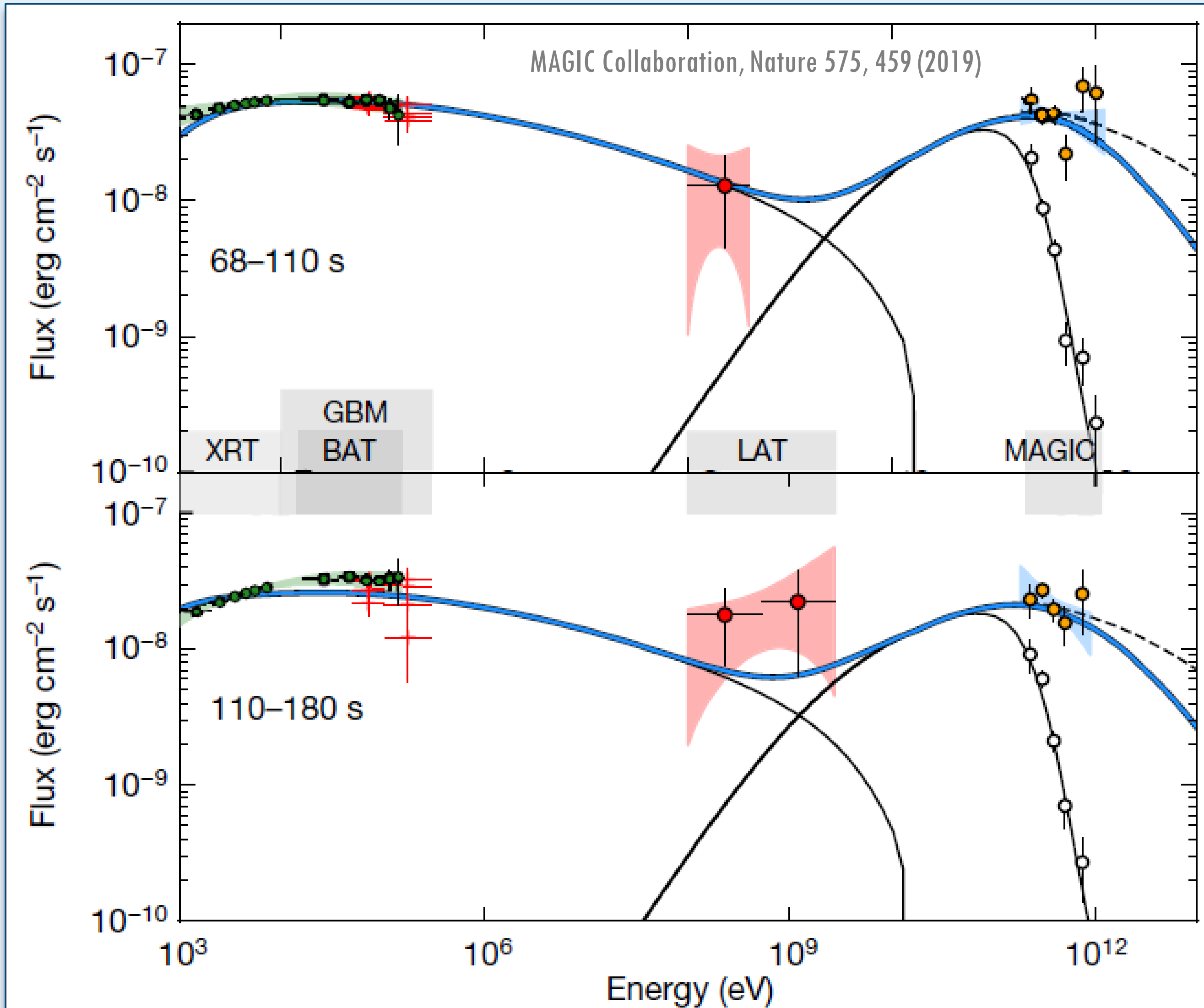
➔ Vertical dashed line: end of the prompt-emission phase, identified as the end of the last flaring episode

GRB emission model: a complete picture!

- The spectra from **X-ray to TeV** show the need for an **extra spectral component** to explain the flux increase at the **highest energies**

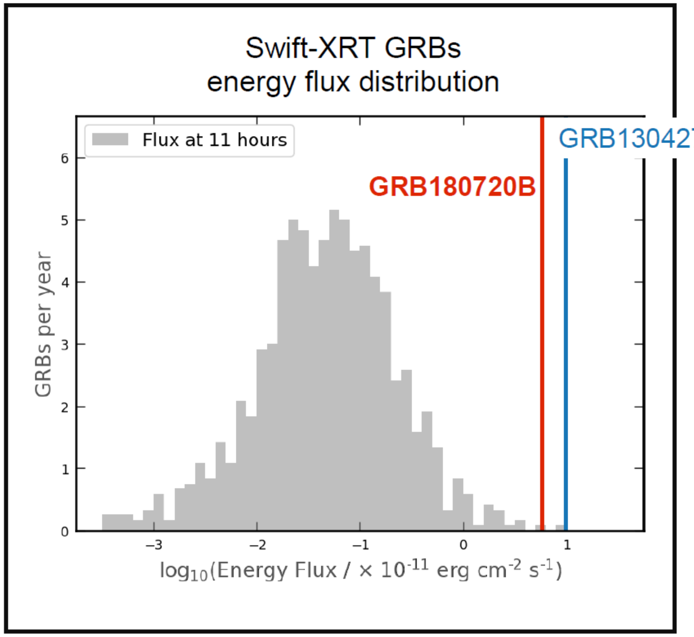
  ➔ Same forward shock, but **different emission processes**

- Extra component generated by **Synchrotron Self-Compton**
  - Synchrotron photons are Compton up-scattered by the same electrons accelerated in the shocks



GRB 180720B – Fermi/Swift trigger info

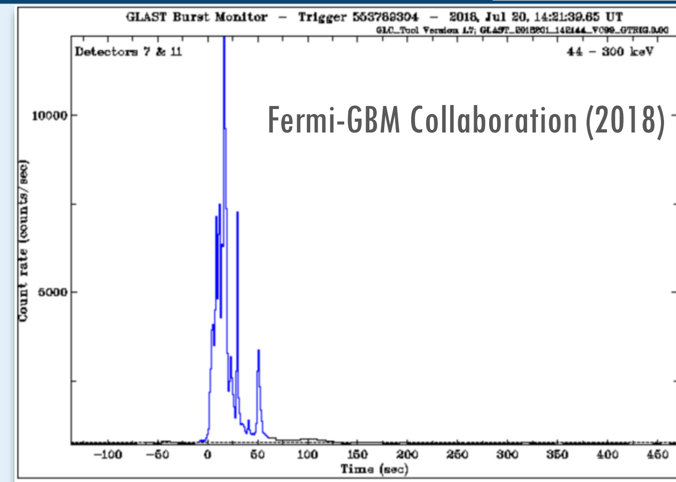
- Bright GRB on **July 20th, 2018**
  - Triggered **Fermi-GBM** at 14:21:39.65 UT (`Roberts+2018, GCN #22981`)
    - GBM T_{90} (50-300 keV) = **48.9 ± 0.4 s**
    - E_{iso} = (6.0 x 0.1) 10^{53} erg – **7° brightest** in GBM
  - Triggered **Swift-BAT** 5 s later, at 14:21:44 UT (`Siegel+2018, GCN #22973`)
  - Multiple **follow-up observations**
    - Redshift **z = 0.653** by VLT/X-Shooter (`Vreeswijk+2018, GCN #22996`)
    - Swift XRT: **2° highest energy flux** at T_0+11 hrs (after GRB130427A)
      - XRT **bright afterglow** remained detectable for ~30 days

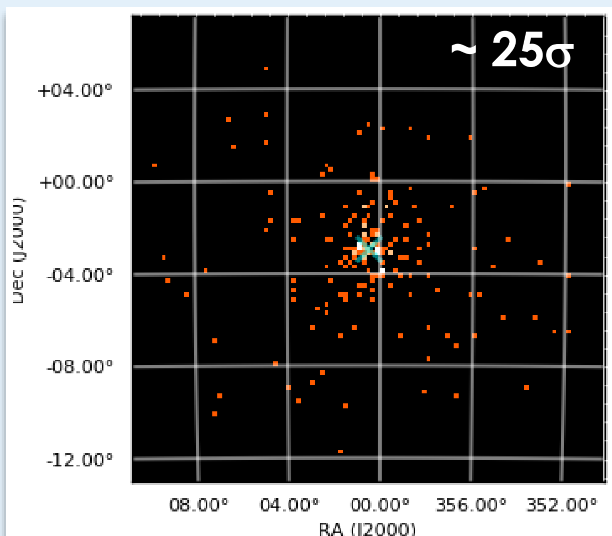


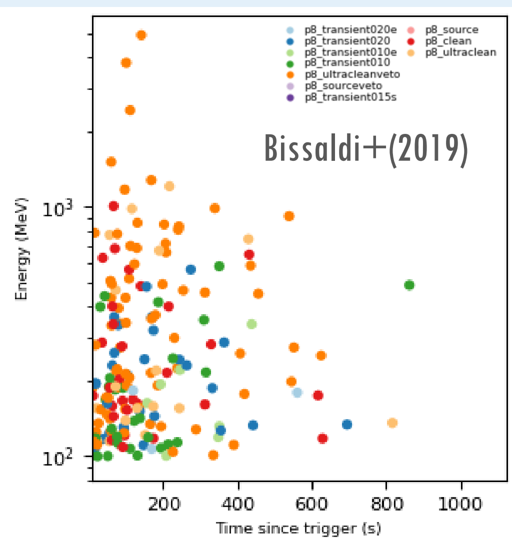
Seglar-Arroyo+(ICRC 2019)

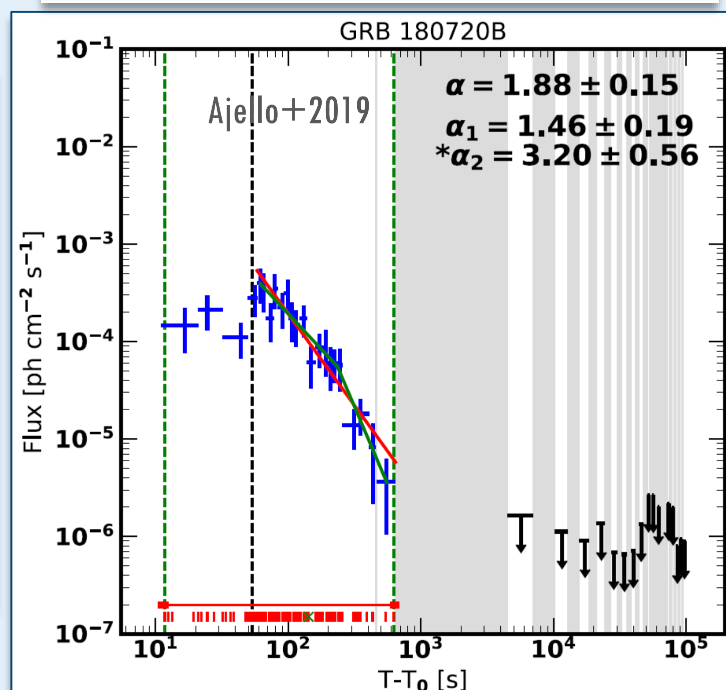
GRB 180720B – Fermi observations

- Clear **Fermi-LAT detection** during first observational window (0-1000 s) (`Bissaldi+2018, GCN #22980`)
  - Max photon energy: **5 GeV** @T_0+142 s
- But: GRB rapidly moving **out of the LAT FoV**
  - ➔ **No further LAT detection** beyond T0+700 s



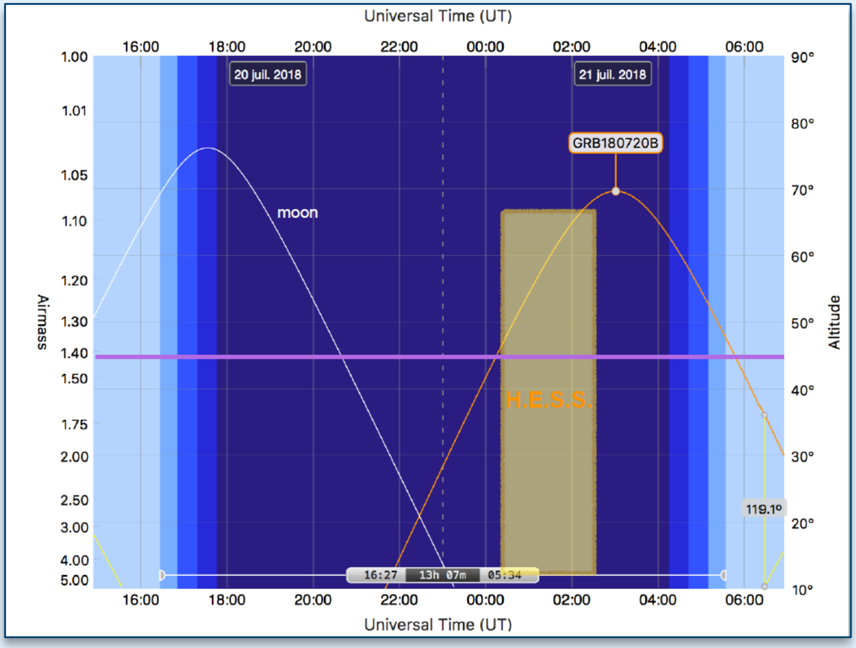






GRB 180720B – H.E.S.S. observations

- H.E.S.S performed **follow-up observations** of GRB180720B based on GCN alerts:
  - Observations for GRBs that become observable only at later times are **scheduled manually** and triggered by burst advocates
  - GRB180720B was observed at **T_0+10 hours** (36–42 ks) and **T_0+18 days** (when it came back in the FoV)
  - Low energy threshold: analysis of **CT5 data in monoscopic** mode
    - Average zenith angle **~30.1°** => energy threshold **~100 GeV**



Seglar-Arroyo+(ICRC 2019)

GRB 180720B – H.E.S.S. results

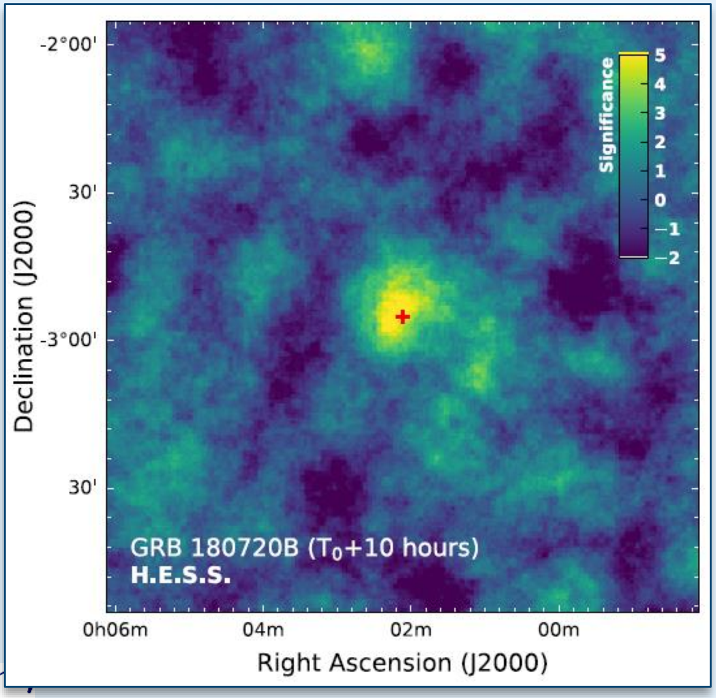
- H.E.S.S. detection: ~5.3σ pre-trial, **5.0σ post-trial** accounting for 5 similar searches
  - Detailed studies of **systematic uncertainties** have been performed
    - Cross-check analysis, background estimation methods, trigger rate stability, etc.

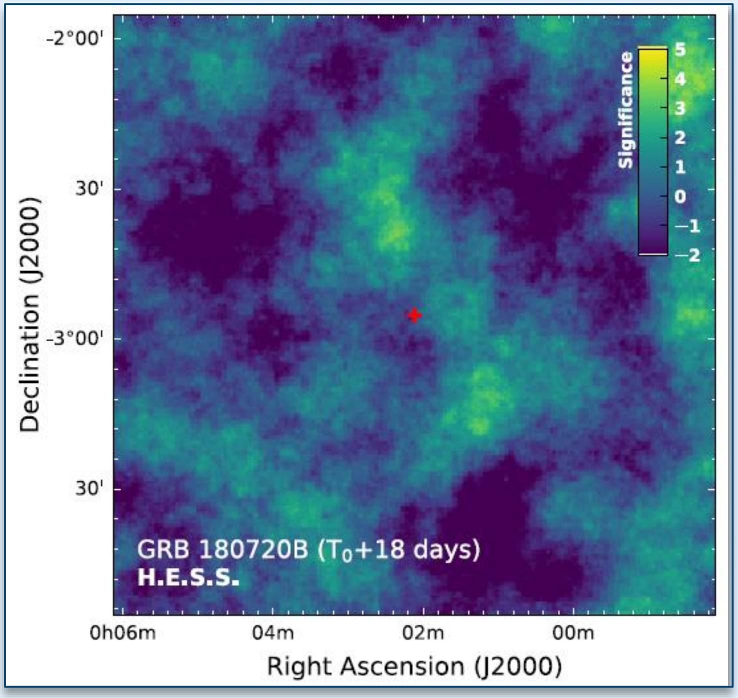
H. Abdalla+(2019) Nature 575, 464

Verification dataset

2 hrs exposure

@T_0+10 hrs





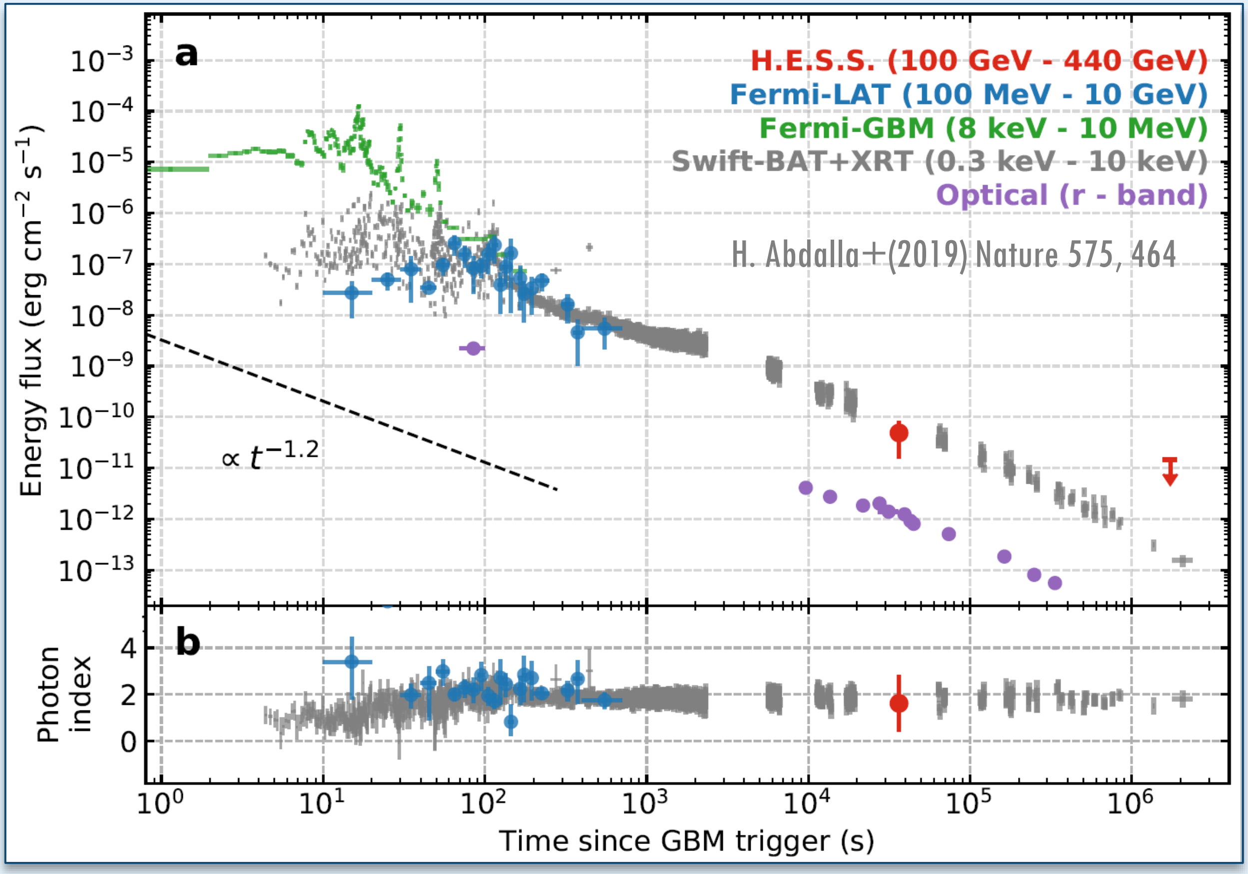
6.5 hrs exposure

@T_0+18 d

GRB 180720B – Interpretation

2 radiation processes most plausible dominant contributors:

1. **Synchrotron emission** of an electron population in the local magnetic field
   - **Favours** the **similar temporal decay** in all bands
   - **Difficulty** in explaining VHE emission (would require Γ>1000)



2. **Synchrotron self-Compton (SSC)** scattering
   - VHE at late times is energetically much more easily achievable

Summary and future prospects

- Since 12 years, the **Fermi mission** constantly provides a great dataset for GRB science
  - **GBM (>2840)** and **LAT (>210)** are the **most prolific GRB instruments** in their respective energy band
  - Together with Swift-BAT, **GBM and LAT** GRB detections are fundamental in order to trigger **multiwavelength** and **multimessenger** follow-up campaigns
    - Tricky to **simultaneosly explain all LAT results**! Difficulty in explaining both delayed onset and long duration at the same time

- The **first VHE GRB detections** with **H.E.S.S.** and **MAGIC** during the early to late afterglow phases provided additional insight into the **nature of GRBs**
  - **NEW** H.E.S.S. detection of **GRB 190829A**: another important confirmation of VHE GRB emission!
  - **Looking forward to the Cherenkov Telescope Array (CTA)**, which will have ~10 times better sensitivity than current instruments

  ➔ **Boost VHE** GRB detection rate in both **prompt** and **afterglow** emission phases

Thank you!

Artistic impression of the CTA, image courtesy G. Perez, SMM, IAC