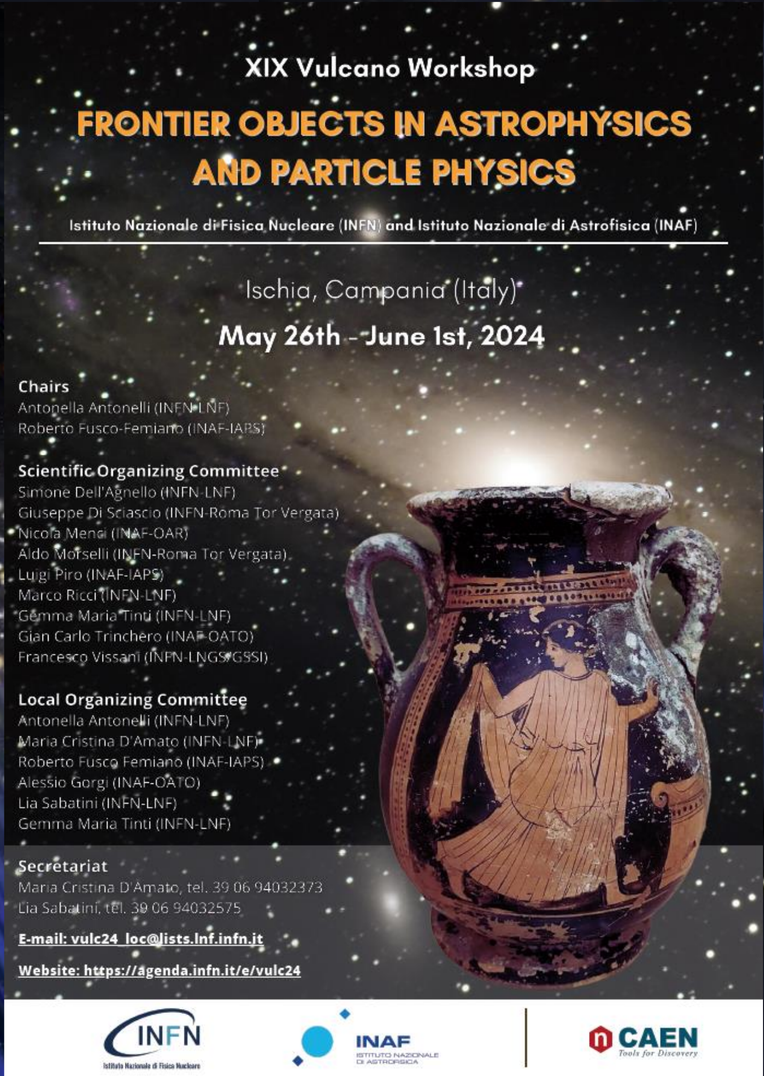
GRBs at high-energies

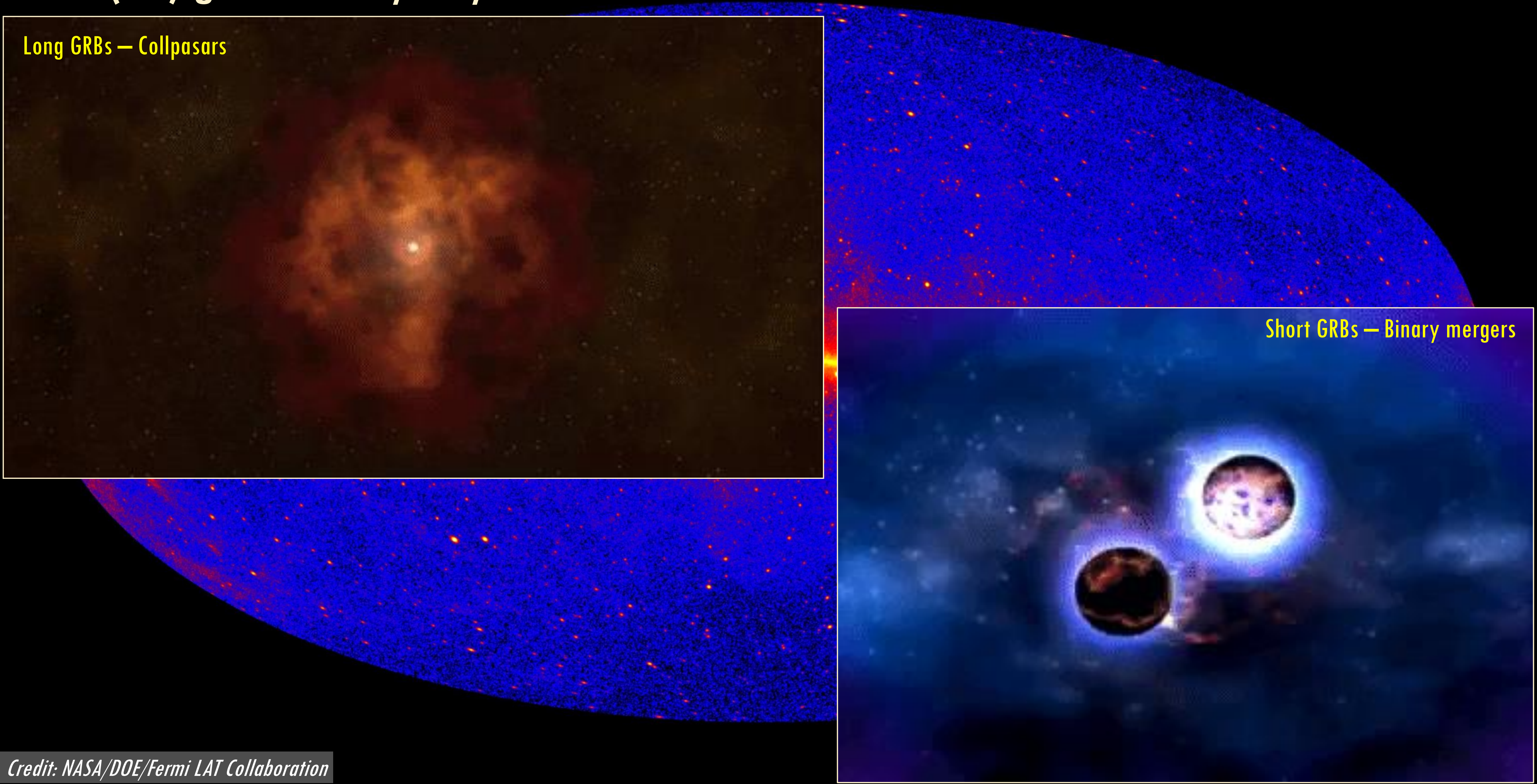
Elisabetta Bissaldi

Dipartimento Interateneo di Fisica "M. Merlin"
Politecnico & INFN Bari
elisabetta.bissaldi@ba.infn.it

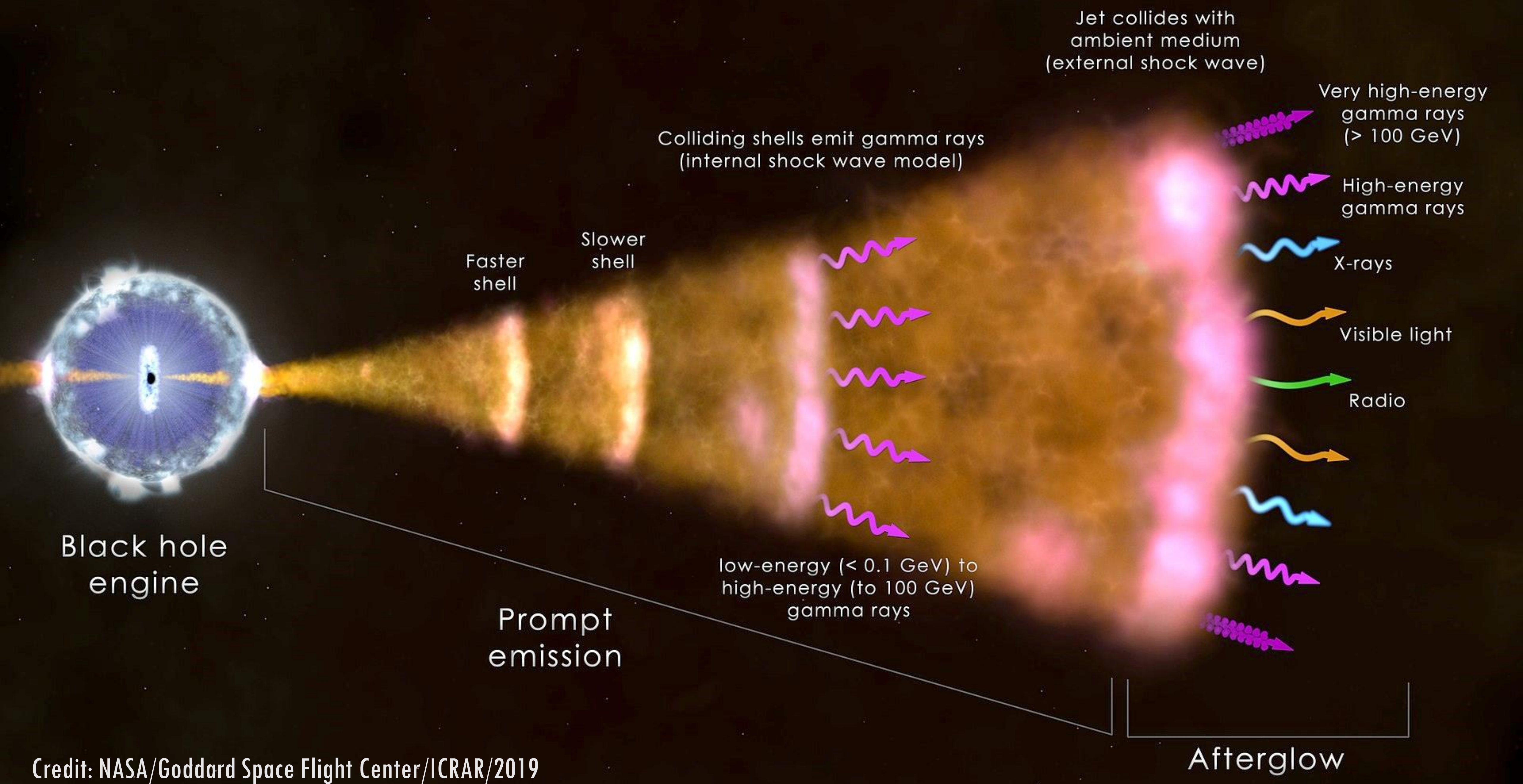
Member of the Fermi GBM and LAT Collaborations
Member of the CTAO Consortium
Affiliate member of the H.E.S.S. Collaboration



The (HE) gamma-ray sky



Credit: NASA/DOE/Fermi LAT Collaboration



Credit: NASA/Goddard Space Flight Center/ICRAR/2019

GRB studies through history

Adapted from F.Longo

Seven eras

Adapted from L.Amati

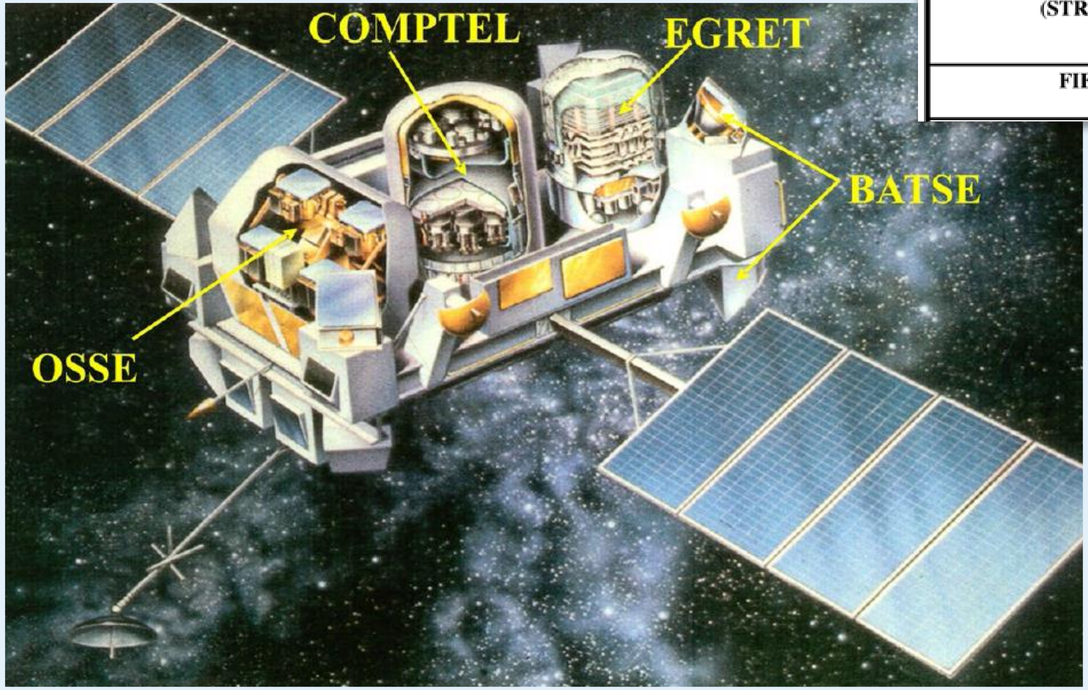
1) "Dark" era (1973-1991): discovery
   Klebesadel, Strong & Olson's discovery (1973);
2) BATSE era (1992-1996): spatial distribution
   Meegan & Fishman's discovery (1992),
   detection rate: ~1 to 3 /day, ~3000 bursts;
3) BeppoSAX era (1997-2000): afterglows
   van Paradijs, Costa, Frail's discoveries (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
7) Multimessenger era (2015–) origin of short GRB
8) VHE era (2019–) VHE emission component from GRB!

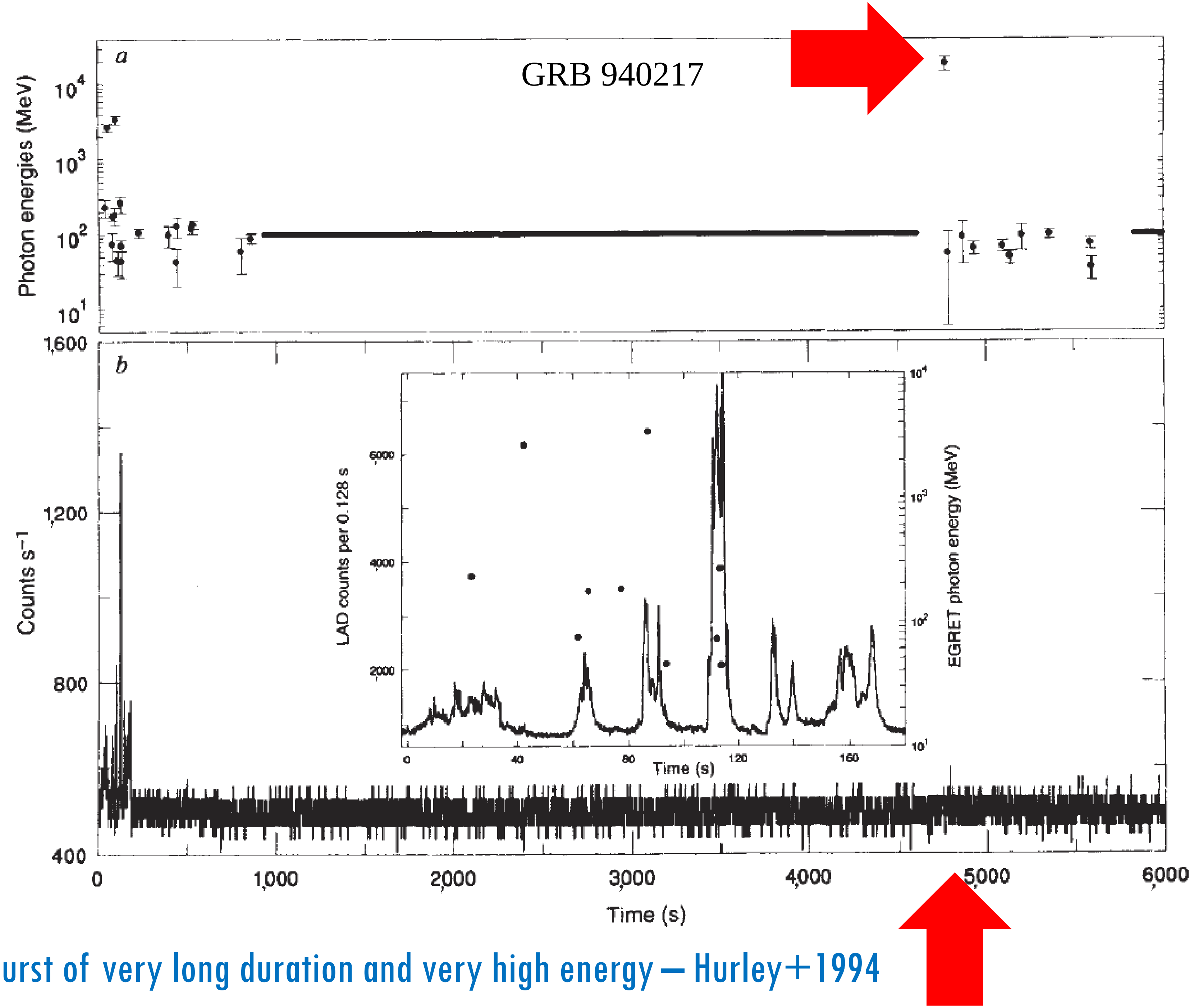
GRB studies in the 90s: BATSE+EGRET results

CGRO: 1991 – 2000

	OSSE	COMPTEL	EGRET	BATSE LARGE AREA	BATSE SPECTROSCOPY
ENERGY RANGE (MeV)	0.06 to 10.0	0.8 to 30.0	20 to 3 x 10^4	0.03 to 1.9	0.015 to 110
ENERGY RESOLUTION (FWHM)	12.5% at 0.2 MeV 6.8% at 1.0 MeV 4.0% at 5.0 MeV	8.8% at 1.27 MeV 6.5% at 2.75 MeV 6.3% at 4.43 MeV	~20% 100 to 2000 MeV	32% at 0.06 MeV 27% at 0.09 MeV 20% at 0.66 MeV	8.2% at 0.09 MeV 7.2% at 0.66 MeV 5.8% at 1.17 MeV
EFFECTIVE AREA (cm^2)	2013 at 0.2 MeV 1480 at 1.0 MeV 569 at 5.0 MeV	25.8 at 1.27 MeV 29.3 at 2.75 MeV 29.4 at 4.43 MeV	1200 at 100 MeV 1600 at 500 MeV 1400 at 3000 MeV	1000 ea. at 0.03 MeV 1800 ea. at 0.1 MeV 550 ea. at 0.66 MeV	100 ea. at 0.3 MeV 127 ea. at 0.2 MeV 52 ea. at 3 MeV
POSITION LOCALIZATION (STRONG SOURCE)	10 arc min square error box (special mode; 0.1 x Crab spectrum)	0.5 - 1.0 deg (90% confidence 0.2 x Crab spectrum)	5 to 10 arc min (1s radius; 0.2 x Crab spectrum)	3_ (strong burst)	——
FIELD OF VIEW	3.8_ x 11.4_	~ 64_	~ 0.6 sr	4 π sr	4 π sr

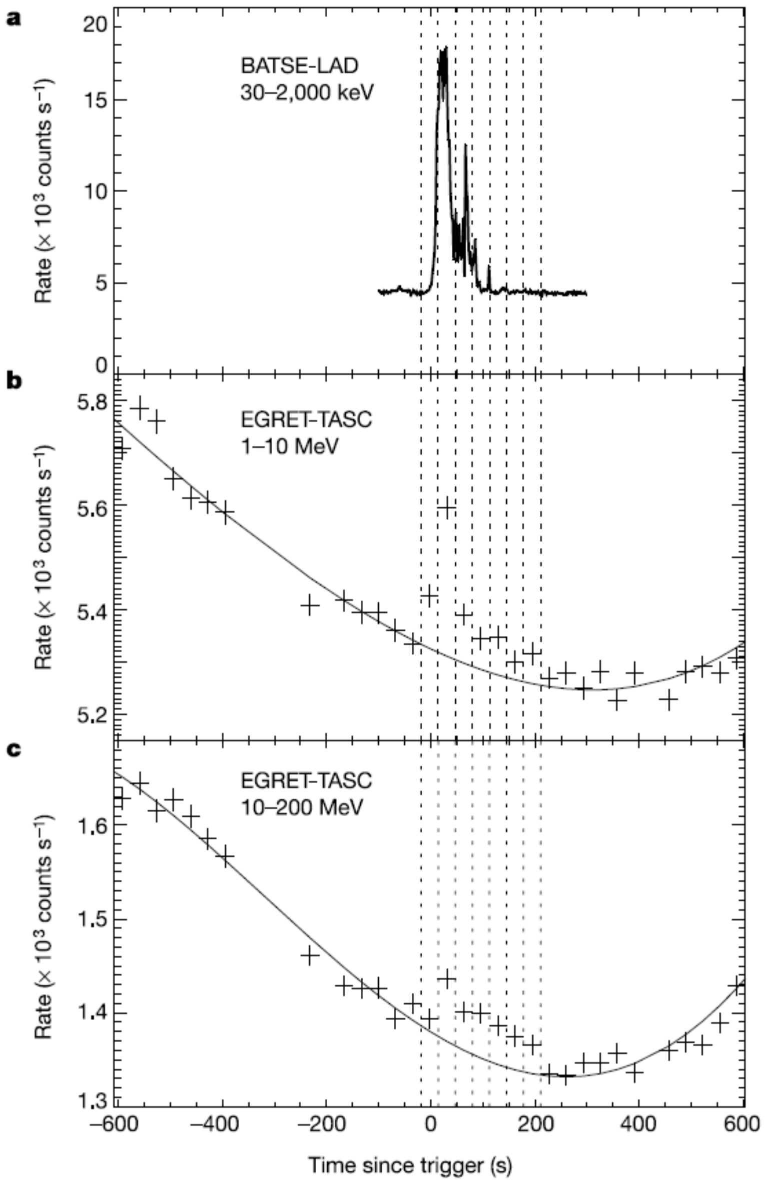


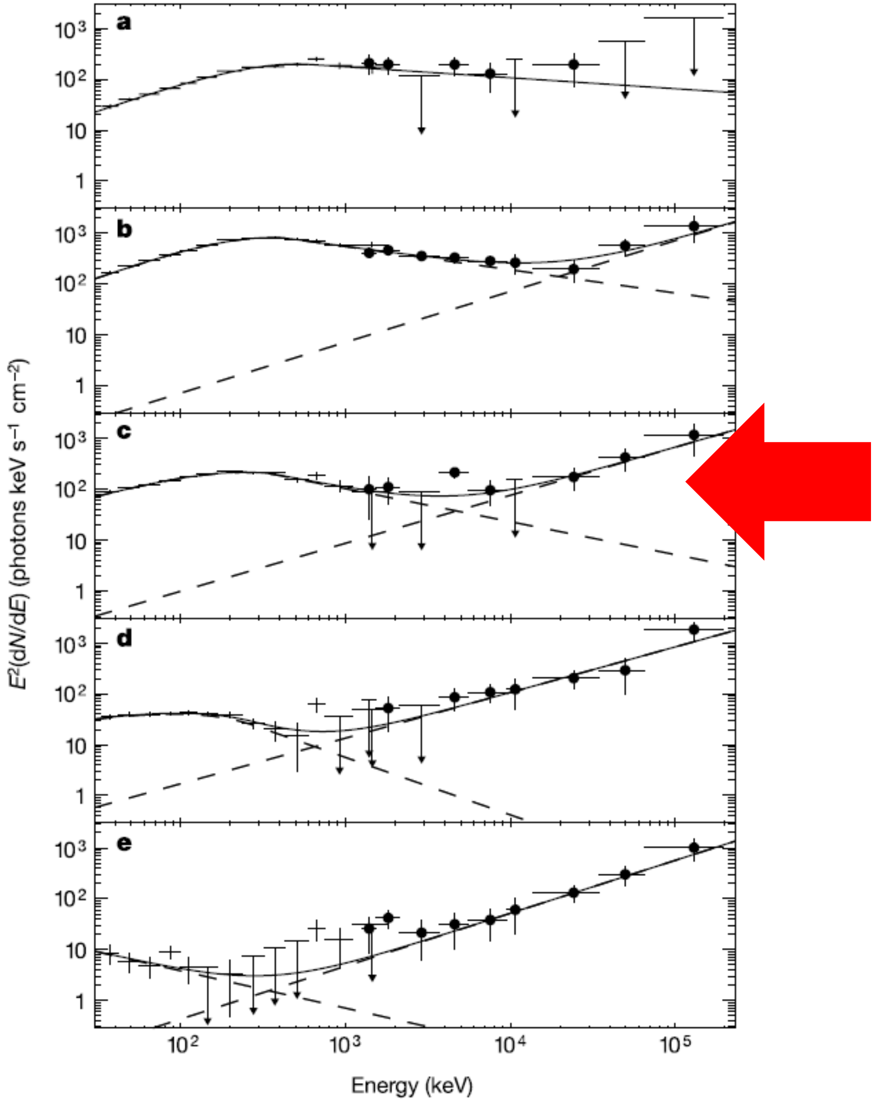
Credit: NASA



Detection of a γ-ray burst of very long duration and very high energy – Hurley+1994

GRB 941017





A γ-ray burst with a high-energy spectral component inconsistent with the synchrotron shock model – Gonzalez+2004

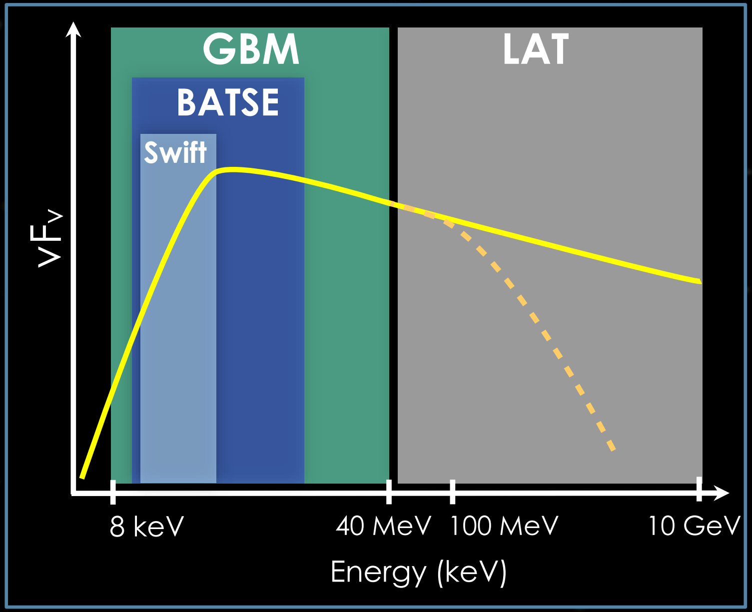
The Fermi Mission

Launched on June 11, 2008

Key features
huge **FoV**
&
large **energy range**

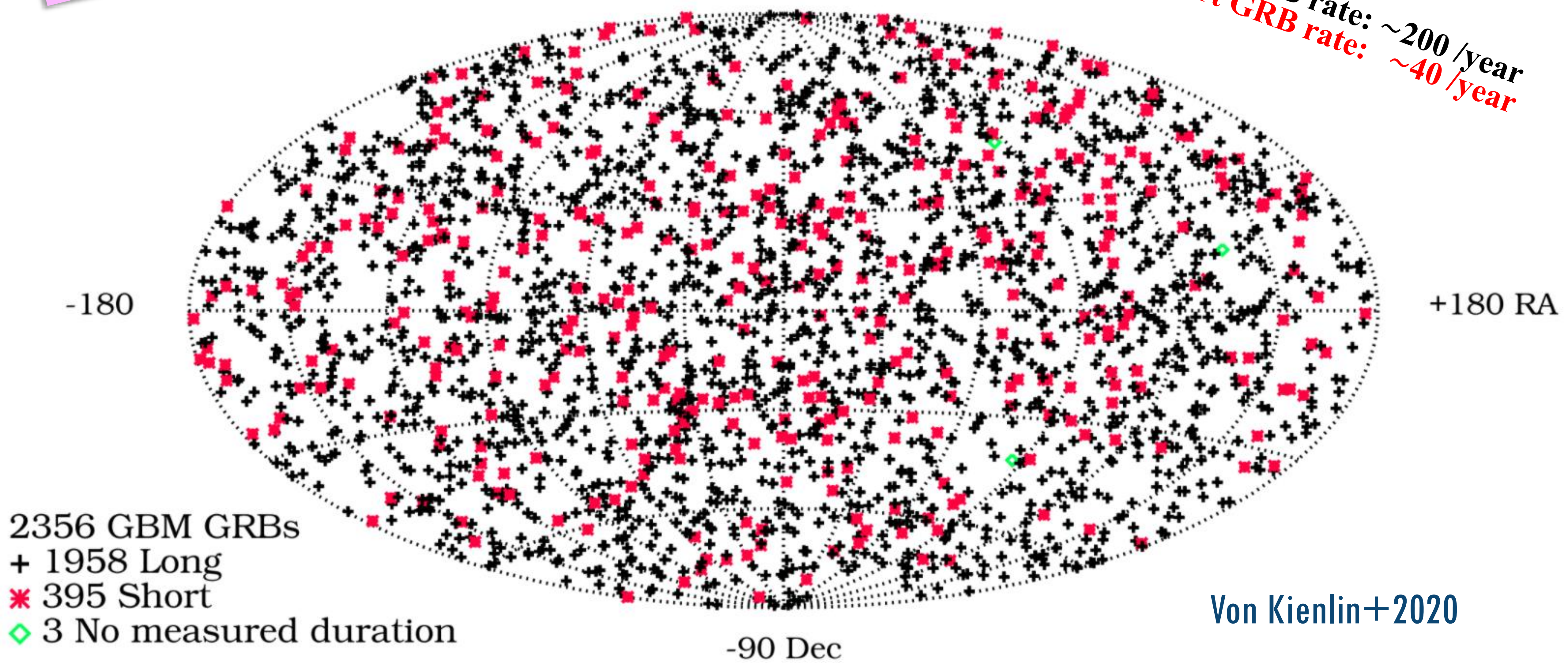
Large Area Telescope (LAT)
Pair conversion telescope
20 MeV → 300 GeV

Gamma-ray Burst Monitor (GBM)
14 Plastic scintillator detectors
8 keV – 40 MeV



Fermi GBM GRBs in first ten years of operation

As of today 3801 GRBs



Long GRB rate: ~200 /year

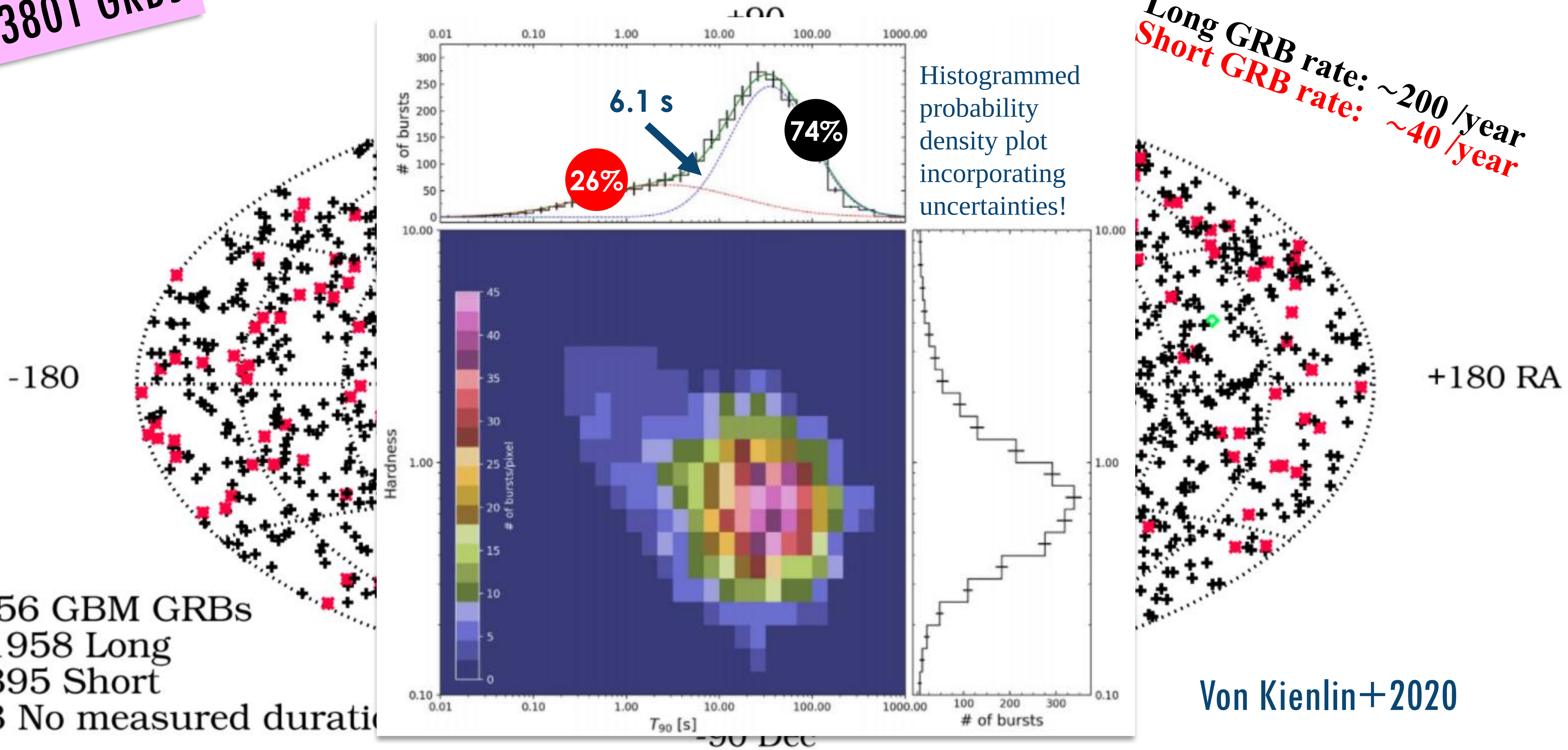
Short GRB rate: ~40 /year

Von Kienlin+2020

As of today
3801 GRBs

Fermi GBM GRBs in first ten years of operation

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



Histogrammed probability density plot incorporating uncertainties!

Von Kienlin+2020

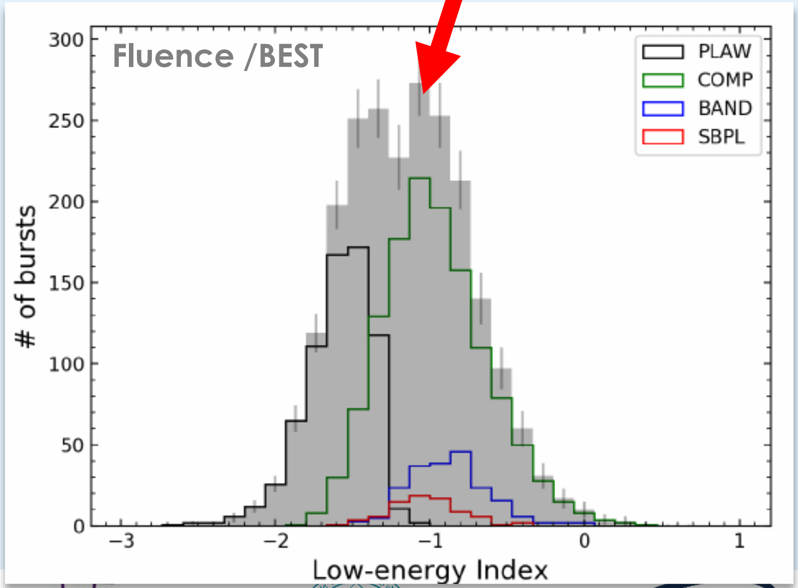
Spectral properties @MeV energies

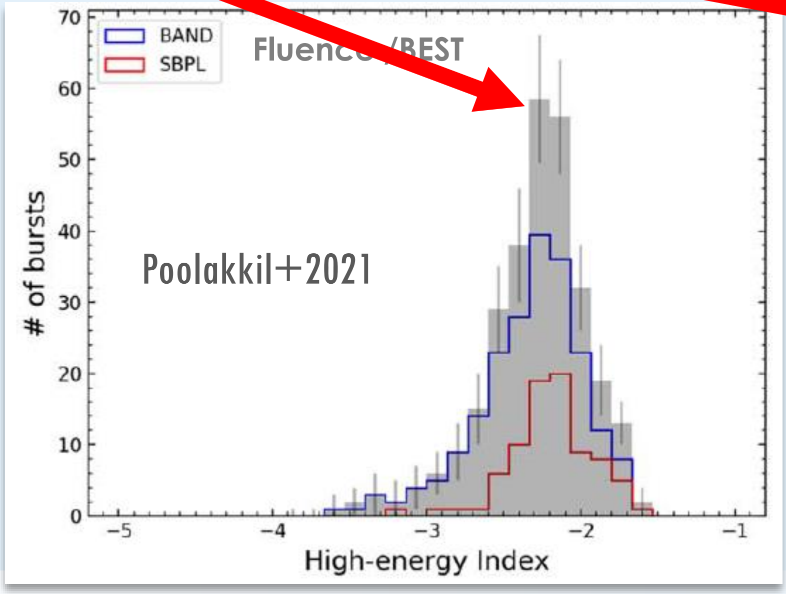
- **Parameter distributions**
  - Fluence and peak flux spectra from Fermi-GBM catalogs

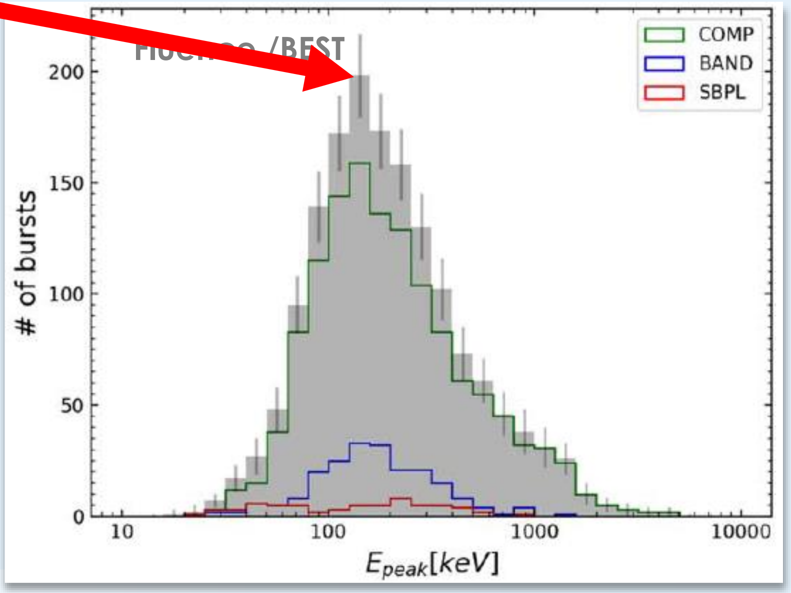
Data Set	Low-energy Index	High-energy Index	E_{peak} (keV)
This Catalog BEST	$-1.08^{+0.45}_{-0.44}$	$-2.20^{+0.26}_{-0.29}$	180^{+307}_{-88}
Gruber et al. (2014)	$-1.[illegible]8^{+0.43}_{-0.44}$	-2.14[illegible]	196[illegible]$_{-100}$
Goldstein et al. (2012)	$-$[illegible]$05^{+0.44}_{-0.45}$	$-2.25^{+0.34}_{-0.73}$	[illegible]$^{+359}$[illegible]
Kaneko et al. (2006)	[illegible]$.14^{+0.20}_{-0.22}$	$-2.33^{+0.24}_{-0.26}$	251^{+122}_{-68}

GOOD and BEST GRB Models

	PLAW	COMP	BAND	SBPL
Fluence Spectra				
This Catalog GOOD	2295 (99.9%)	1616 (70.3%)	666 (29.0%)	1013 (44.0%)
Gruber et al. (2014) GOOD	941 (99.7%)	684 (72.5%)	342 (36.2%)	392 (41.5%)
This Catalog BEST	693 (30.2%)	1311 (57.0%)	209 (9.0%)	82 (3.5%)
Gruber et al. (2014) BEST	282 (29.9%)	516 (54.7%)	81 (8.6%)	62 (6.6%)
Peak Flux Spectra				
This Catalog GOOD	2287 (99.5%)	1047 (45.5%)	328 (14.2%)	522 (22.6%)
Gruber et al. (2014) GOOD	932 (98.7%)	430 (45.6%)	153 (16.2%)	196 (20.8%)
This Catalo[illegible]EST	1248 (54.3%)	931 (40.5%)	79 (3.4%)	29 (1.2%)
Gruber et al. (2014)BEST	514 (54.4%))	375 (39.7%)	25 (2.6%)	18 (1.9%)

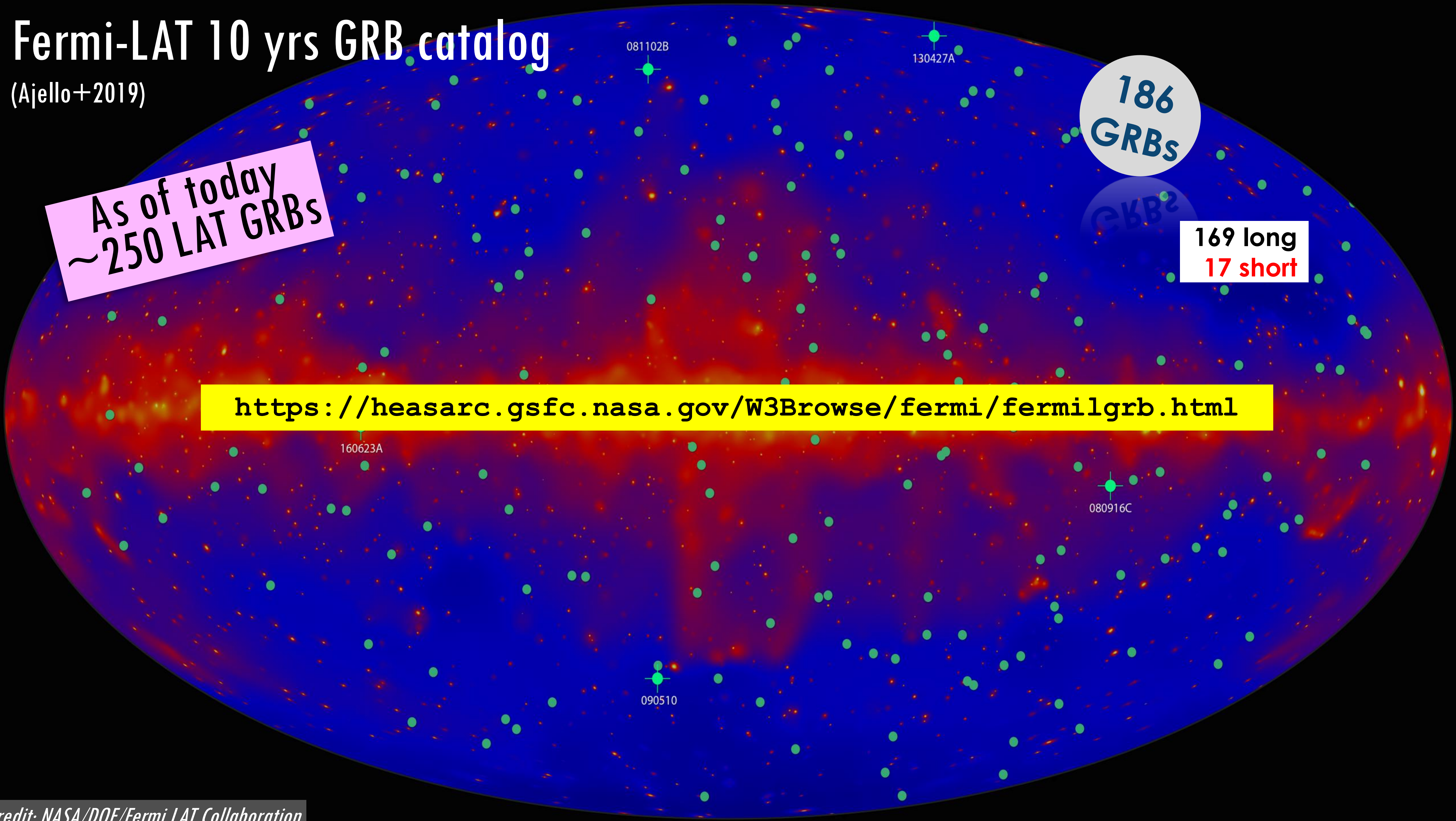






Fermi-LAT 10 yrs GRB catalog

(Ajello+2019)



As of today ~250 LAT GRBs

186 GRBs

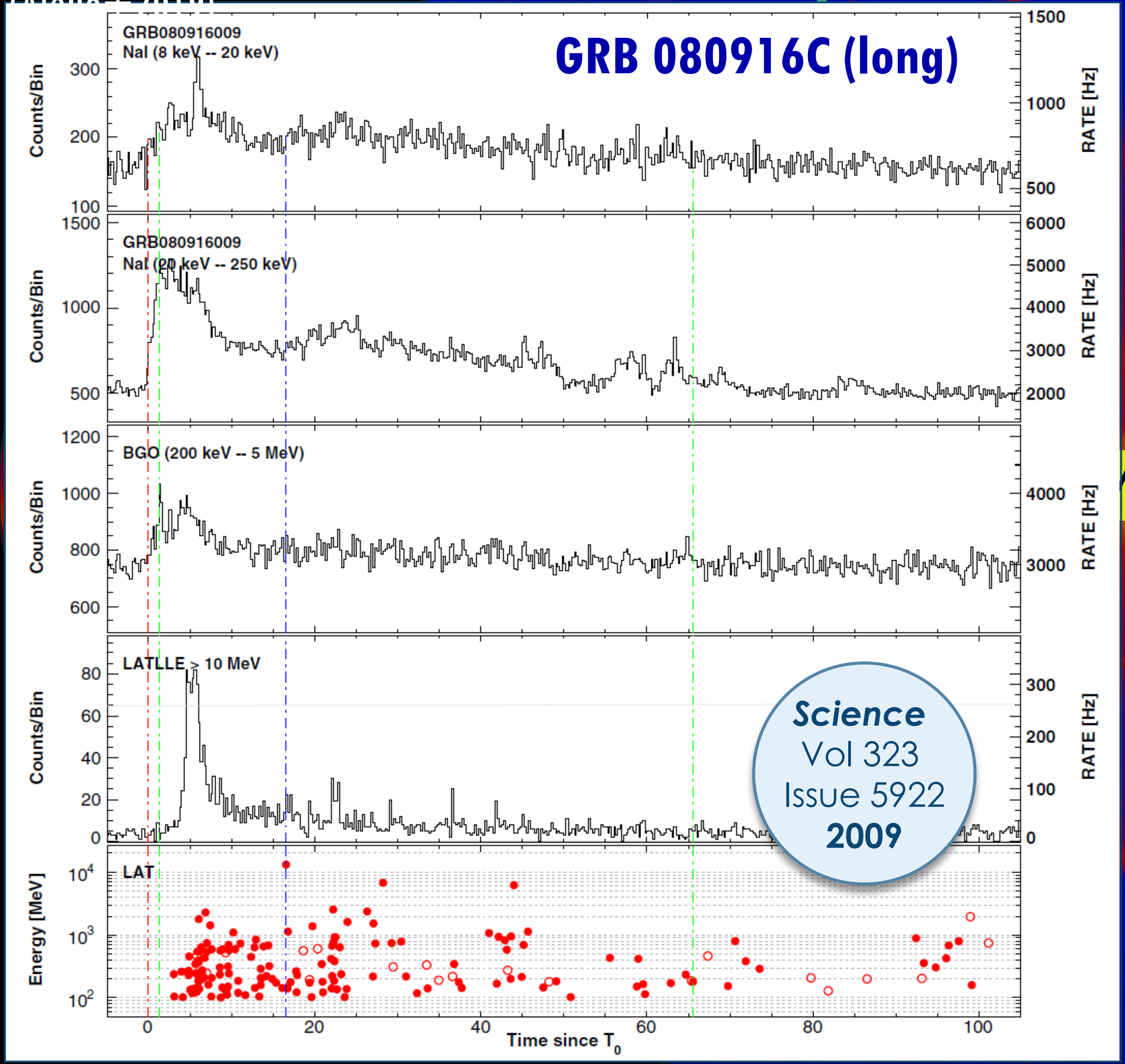
169 long
17 short

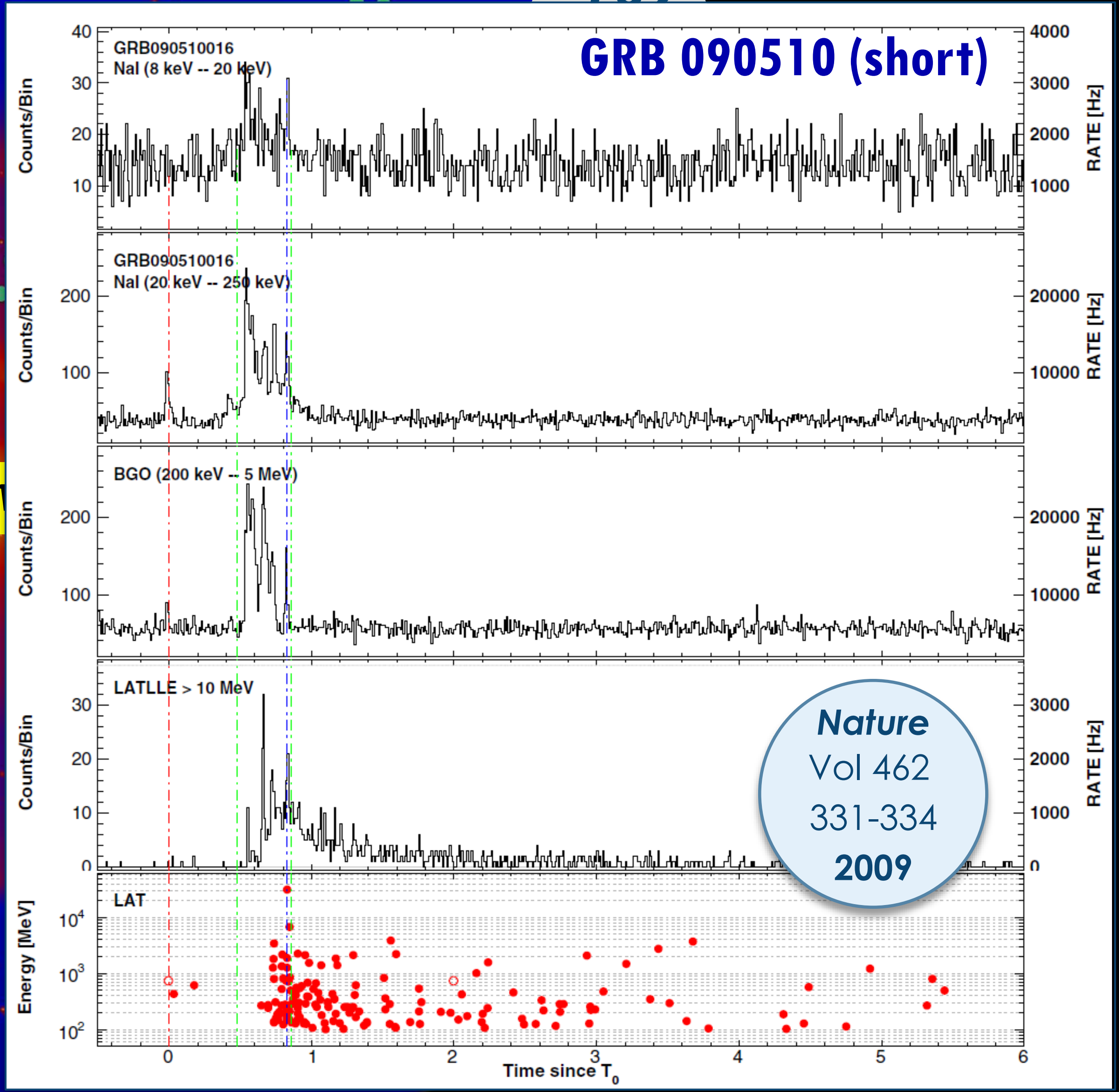
https://heasarc.gsfc.nasa.gov/W3Browse/fermi/fermilgrb.html

Credit: NASA/DOE/Fermi LAT Collaboration

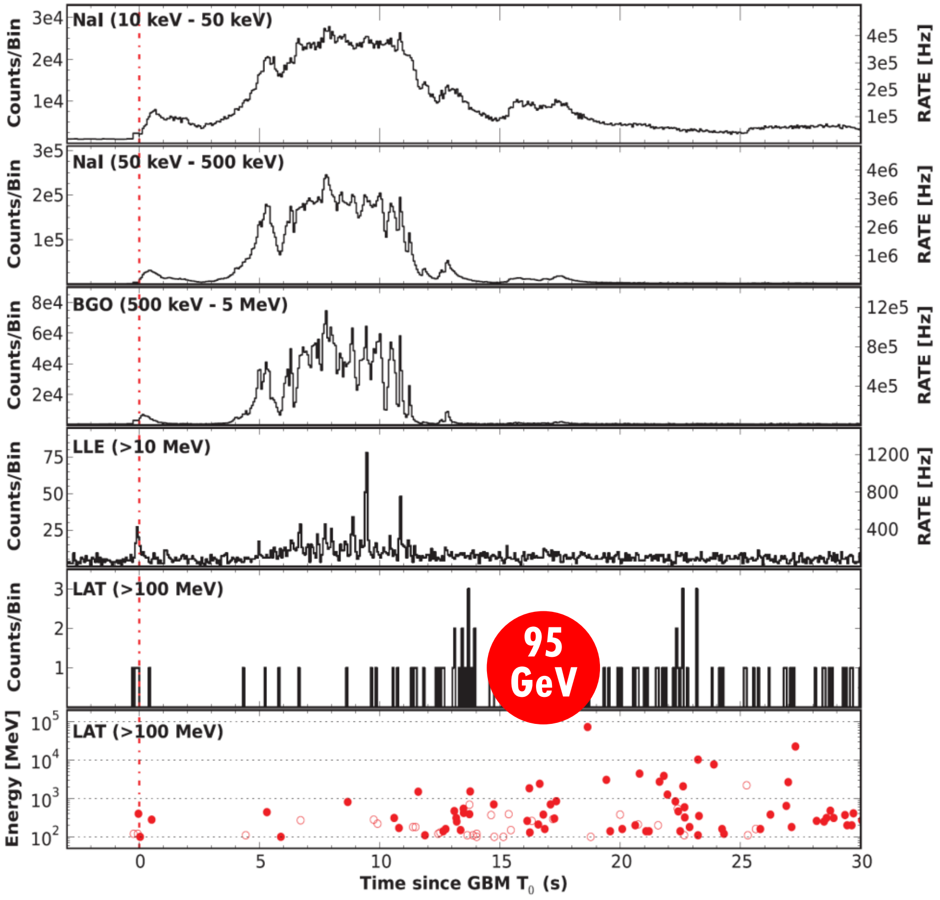
Fermi-LAT 10 yrs GRB catalog

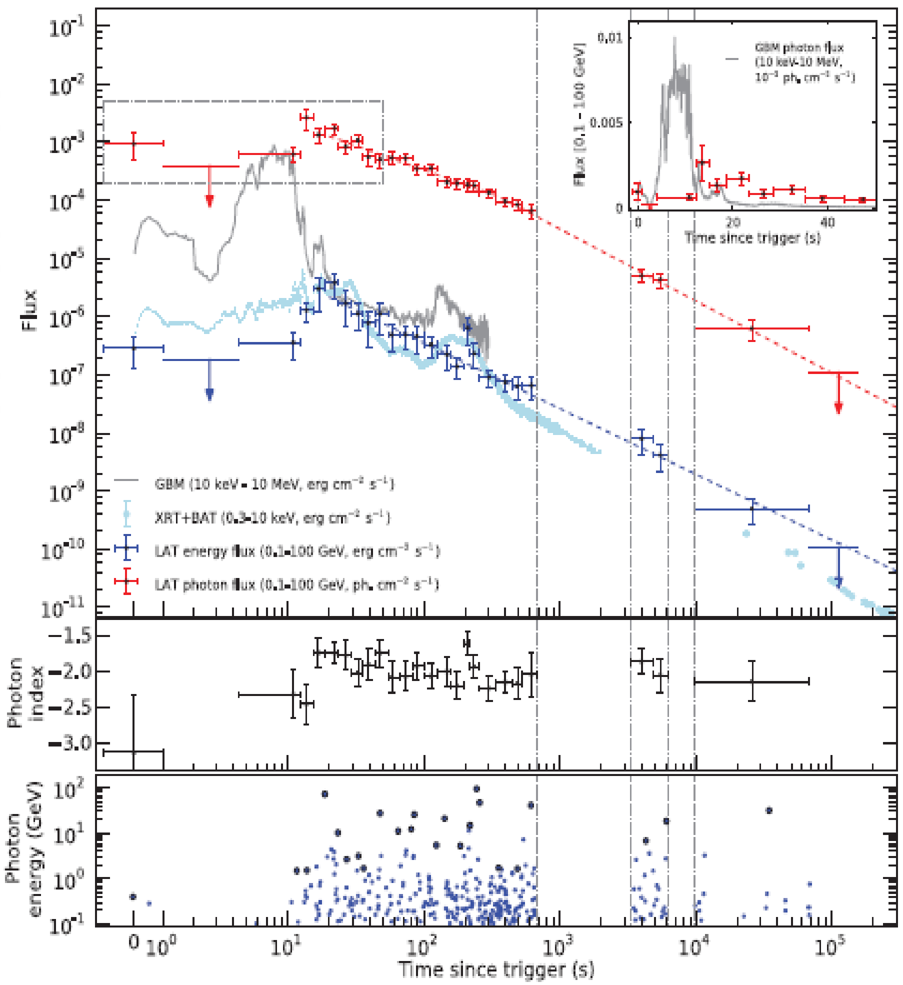
(Ajello+2019)





Credit: NASA/DOE/Fermi LAT Collaboration





Fermi-LAT Observations of the Gamma-Ray Burst GRB 130427A – Ackermann+2014

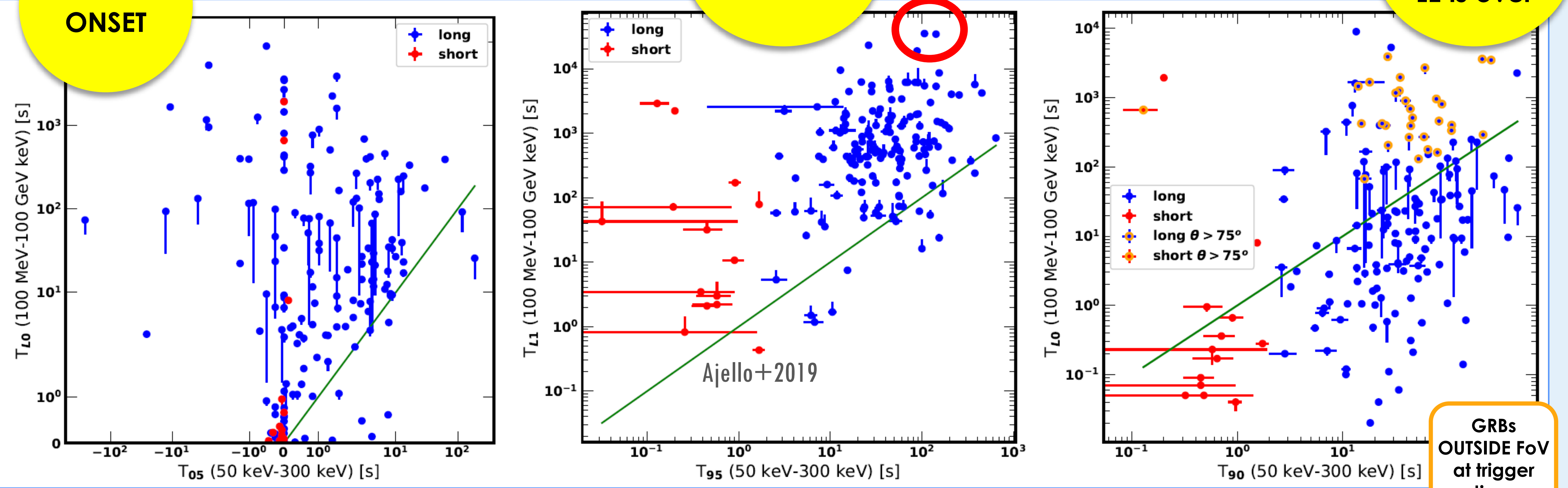
Temporal properties at @GeV energies

DELAYED ONSET

EXTENDED DURATION

34/35 ks

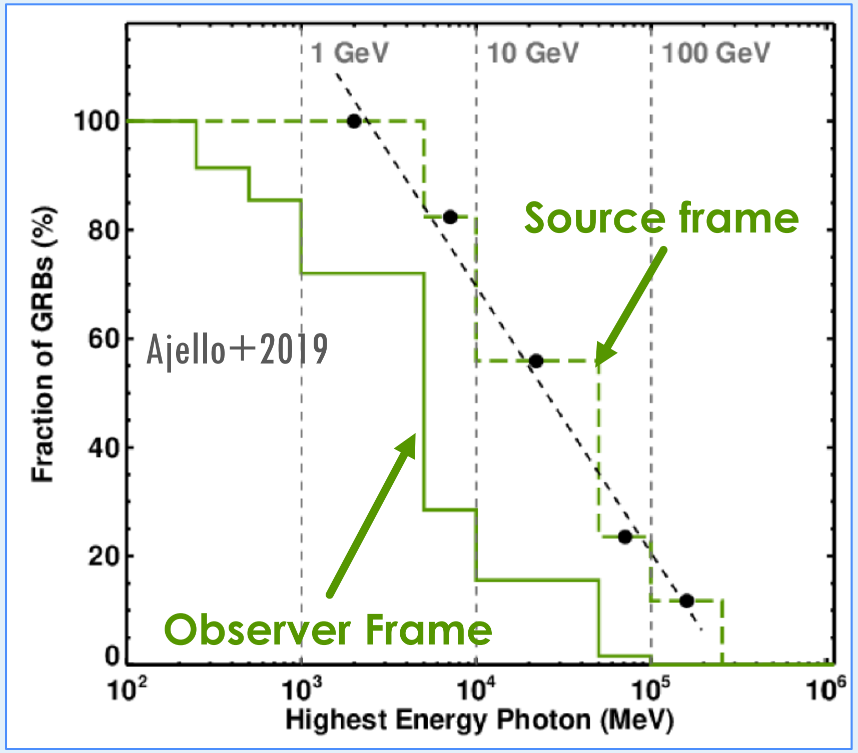
HE starting BEFORE LE is over

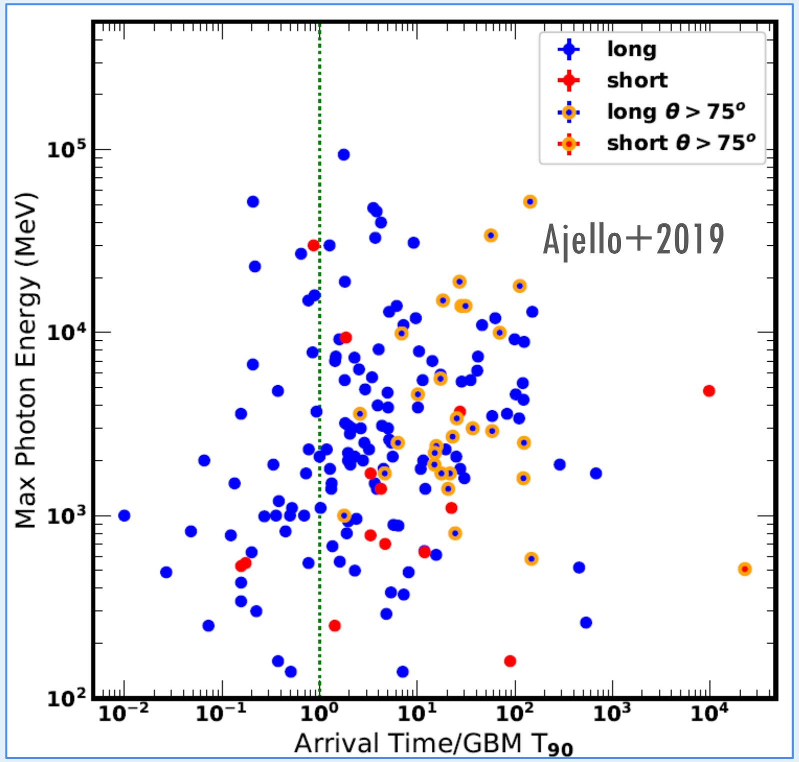


GRBs OUTSIDE FoV at trigger time

Spectral properties at @GeV energies

- **Highest-energy photons** from GRBs
  - **<5%** of GRBs have **E > 50 GeV**
  - Sharp drop @5 GeV (obs.frame)
  - (Previous!!) record holder: **GRB 130427A**
    - **95 GeV @243 s, 77 GeV @19s, 34 GeV @34 ks**



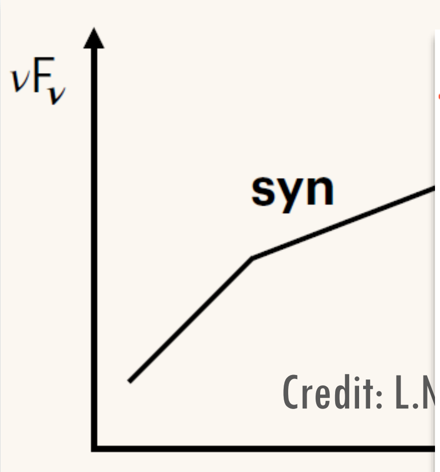


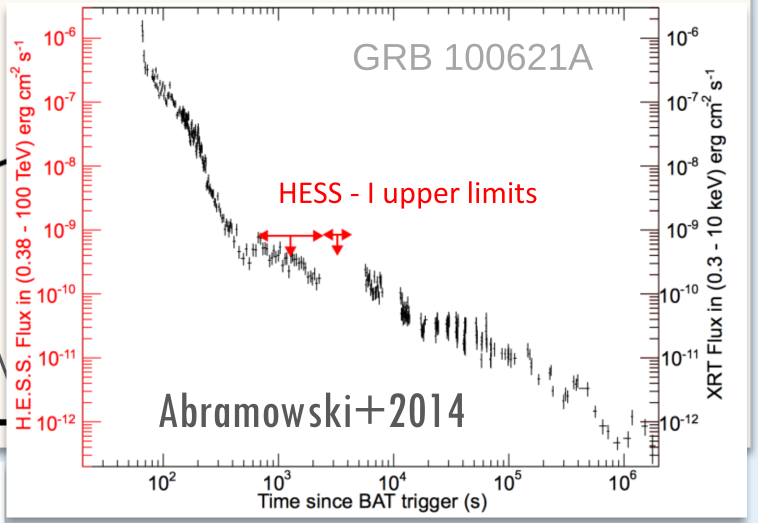
- HE photons often **arrive after the low-energy emission is over**, **BUT**

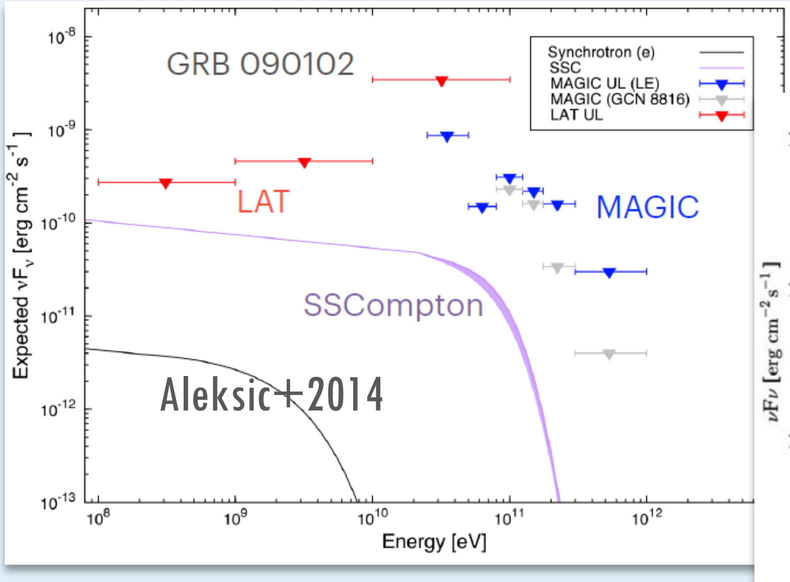
  ➡ Highest energies can be produced either very quickly or very late: challenge for models!

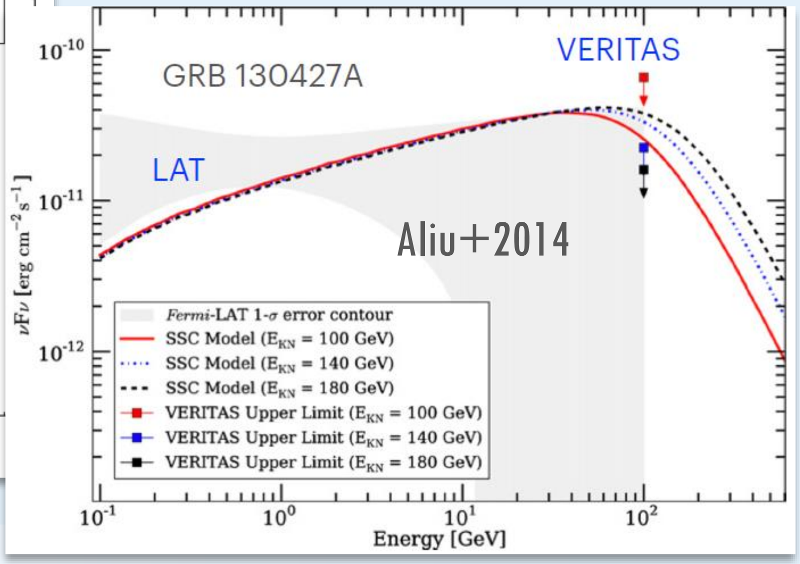
Searches for GRBs @ TeV energies

- Evidence for high-energy additional spectral components from GeV observations
- **Current generation on IACTs: MAGIC / HESS / VERITAS**
  - Number of observed GRBs:
    - Hundreds
  - Low-energy threshold:
    - 50 / 50 / 100 GeV
  - Time delay:
    - < 100 s / 100 – 1000 s
- **Tev observations until 2019:**
  ➔ no detections,
  only upper limits!

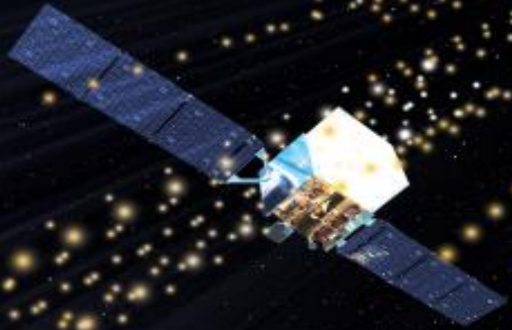








Breakthrough



Announcement
20 November 2019

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

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

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

Article | Published: 20 November 2019

Teraelectronvolt emission from the γ-ray burst GRB 190114C

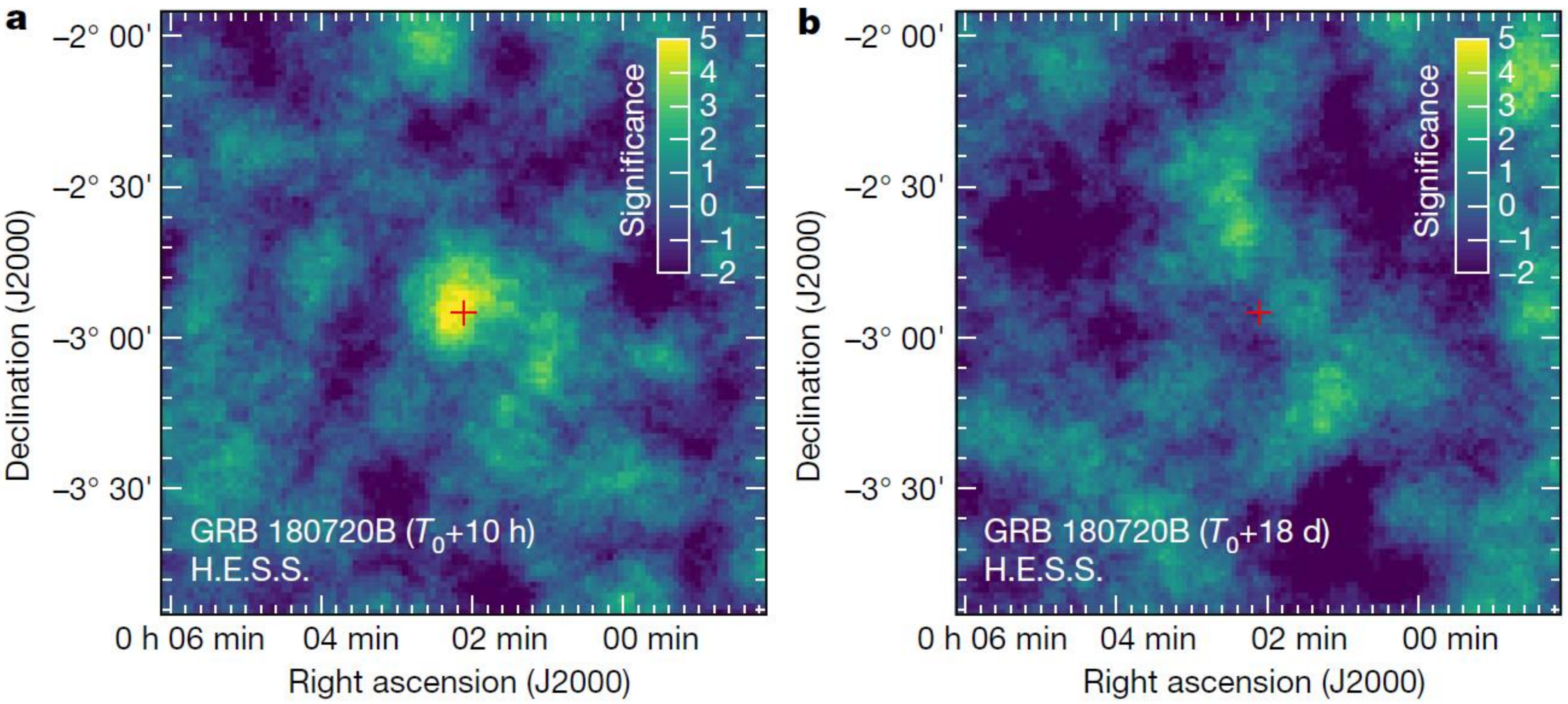
MAGIC Collaboration

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-

GRB 180720B



z = 0.653

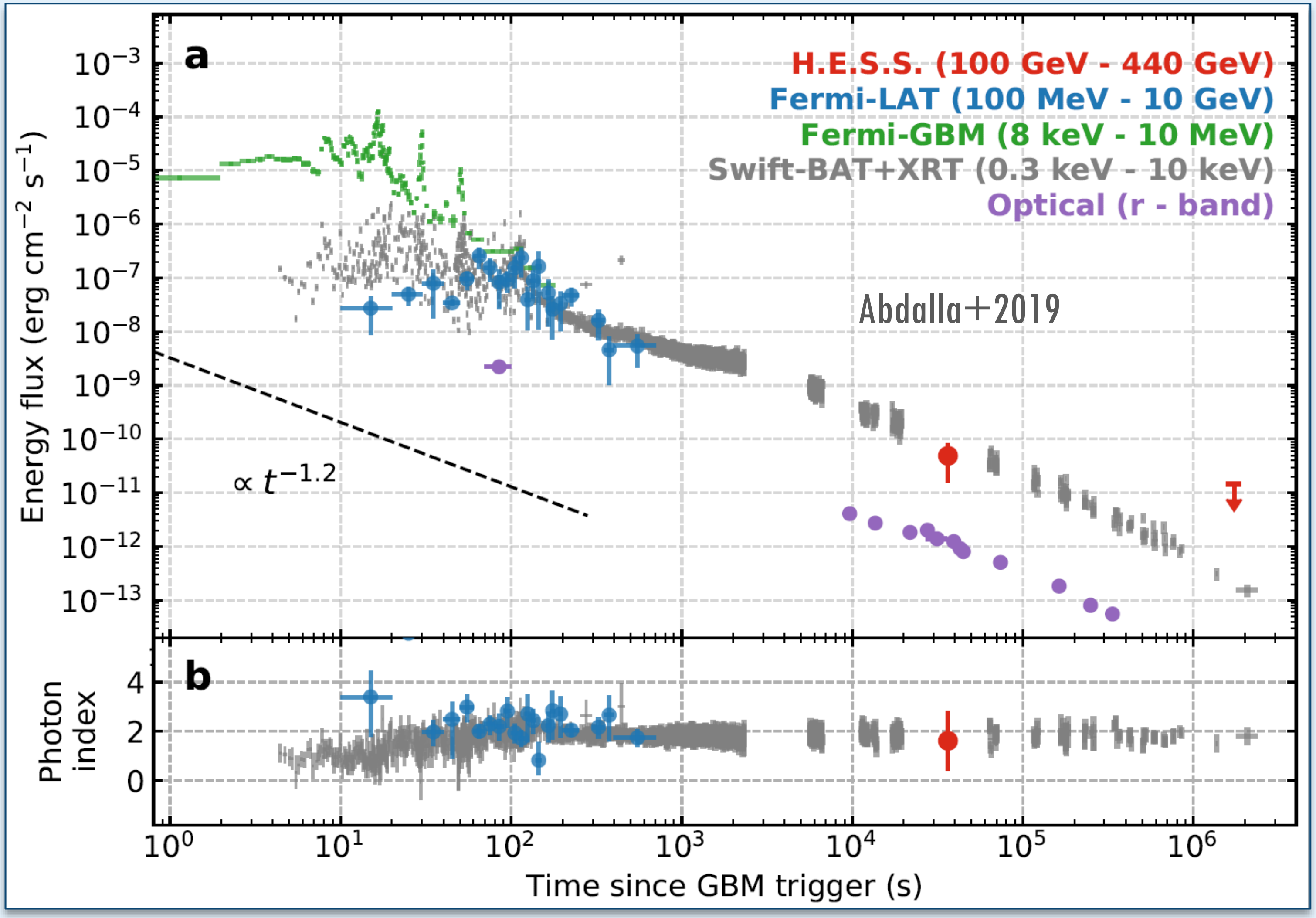
A very-high-energy component deep in the γ-ray burst afterglow – Abdalla+2019

Multiwavelength observations of GRB 180720B

2 radiation processes most plausible dominant contributors:

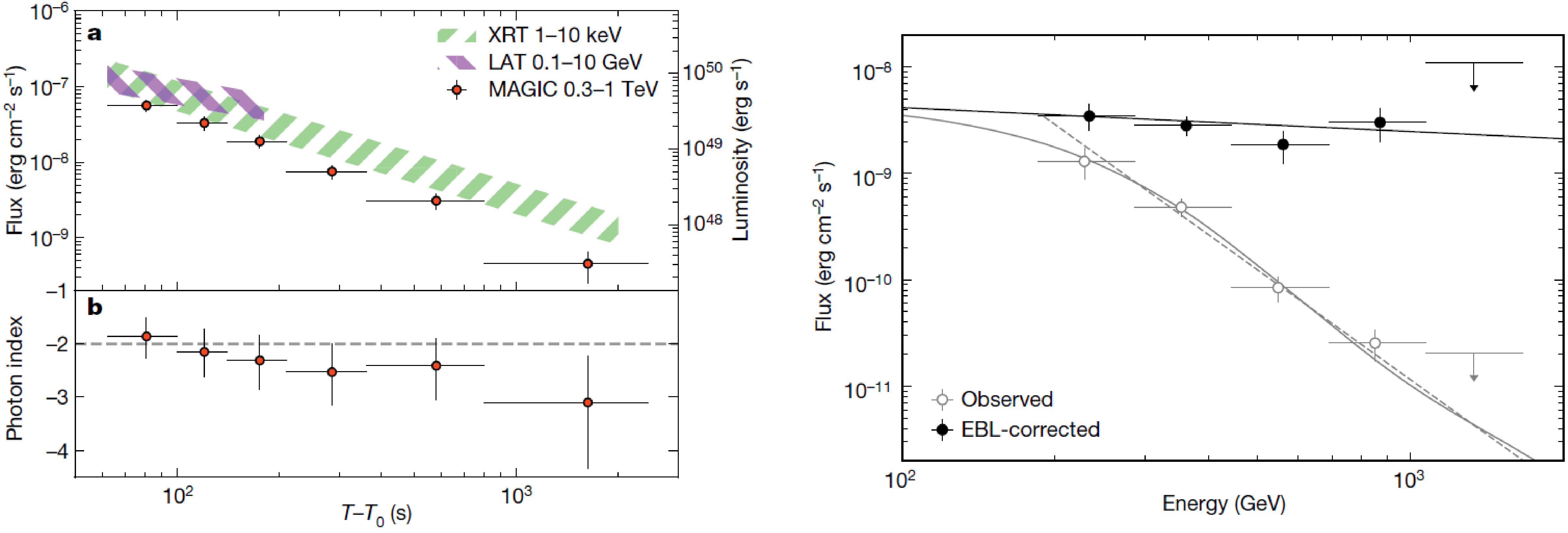
1. **Synchrotron emission** of an electron population in the local magnetic field
   - **Favours** the **similar temporal decay** in all bands
   - **Difficulty** in explaining VHE emission (would require Γ>1000)

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



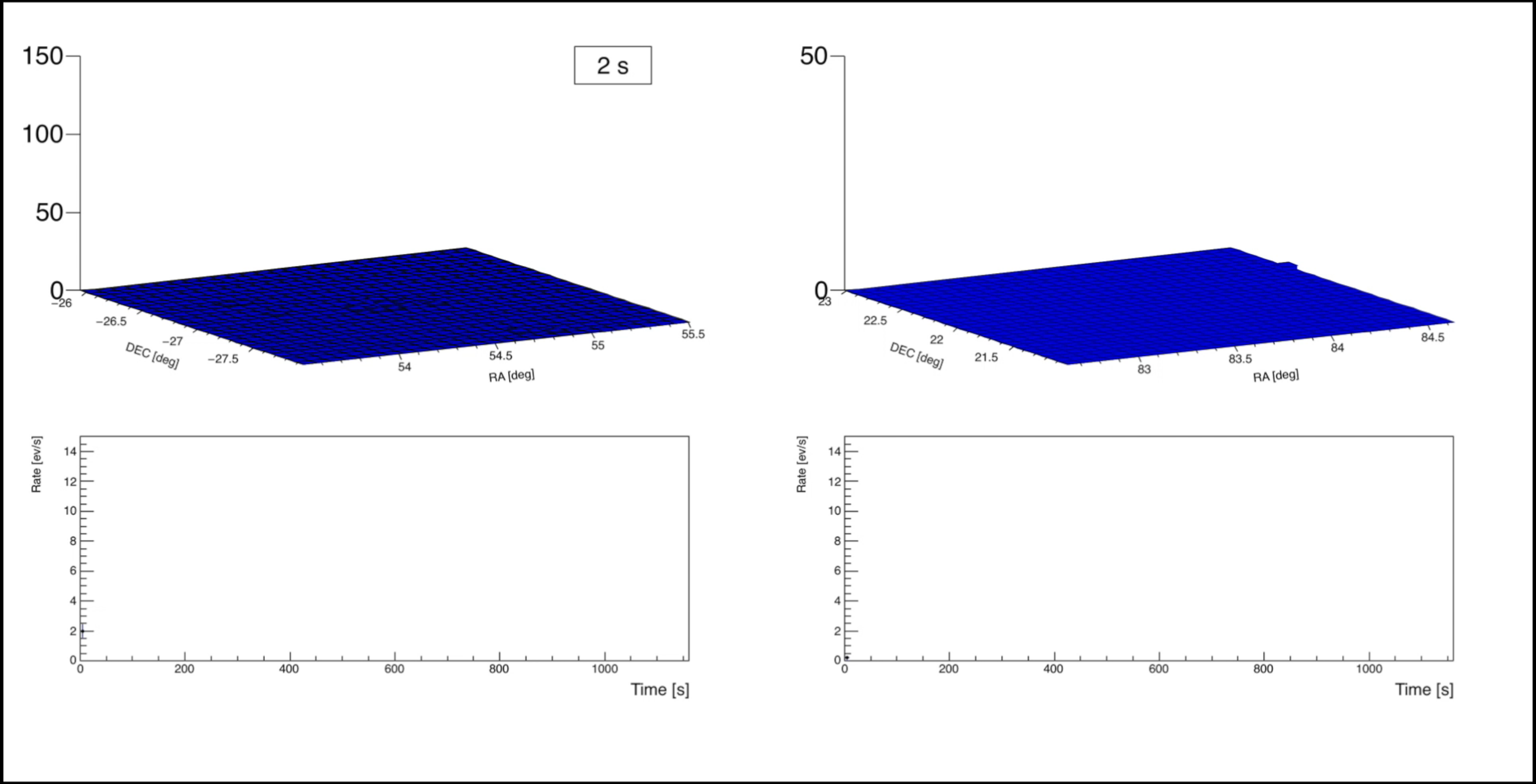
Energy flux lightcurves at different wavelengths

GRB 190114C



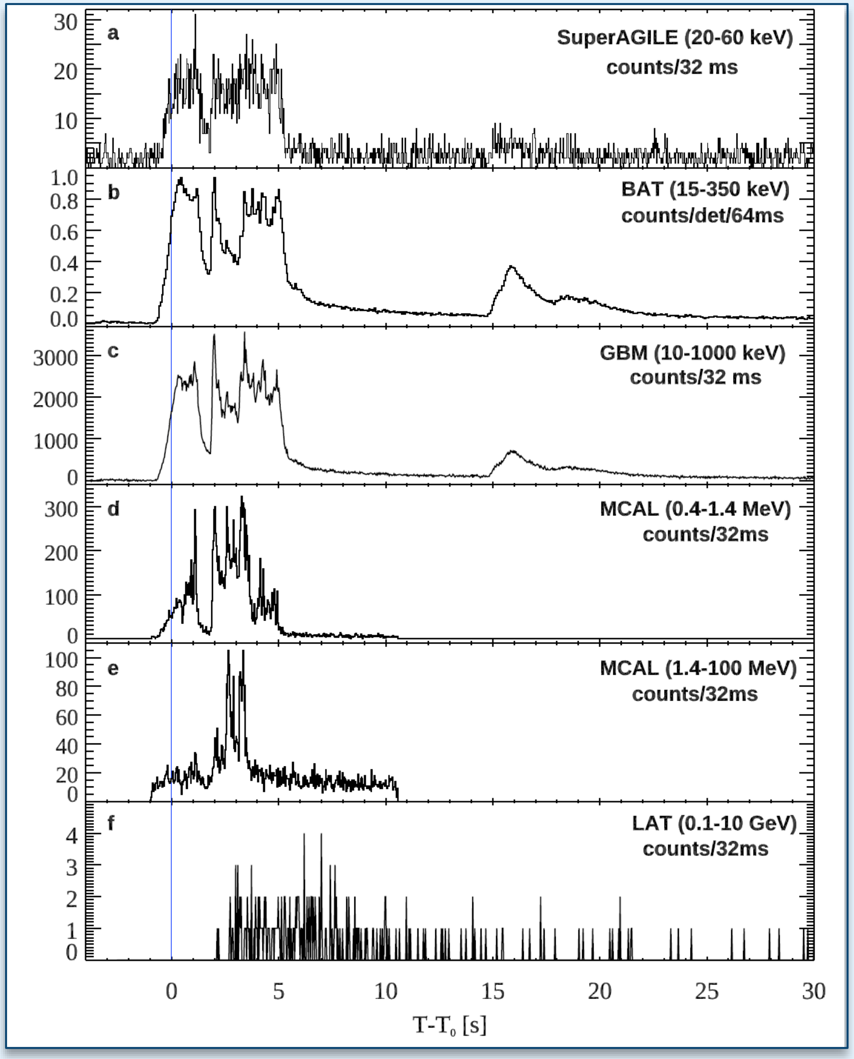
z = 0.4245

Teraelectronvolt emission from the γ-ray burst GRB 190114C – MAGIC Collaboration+2019



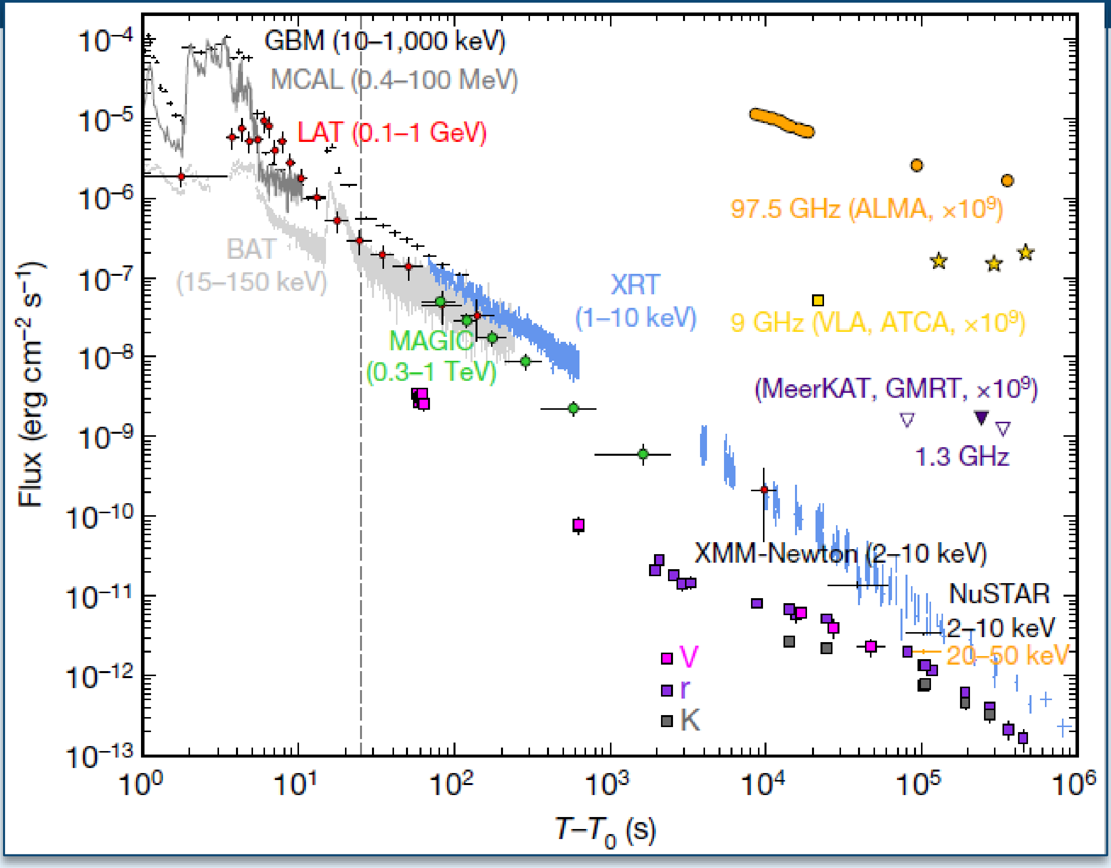
Credit: MAGIC Collaboration 2021 @IG

Multiwavelength observations of GRB 190114C



Prompt-emission lightcurves from different detectors

MAGIC Collaboration+2019



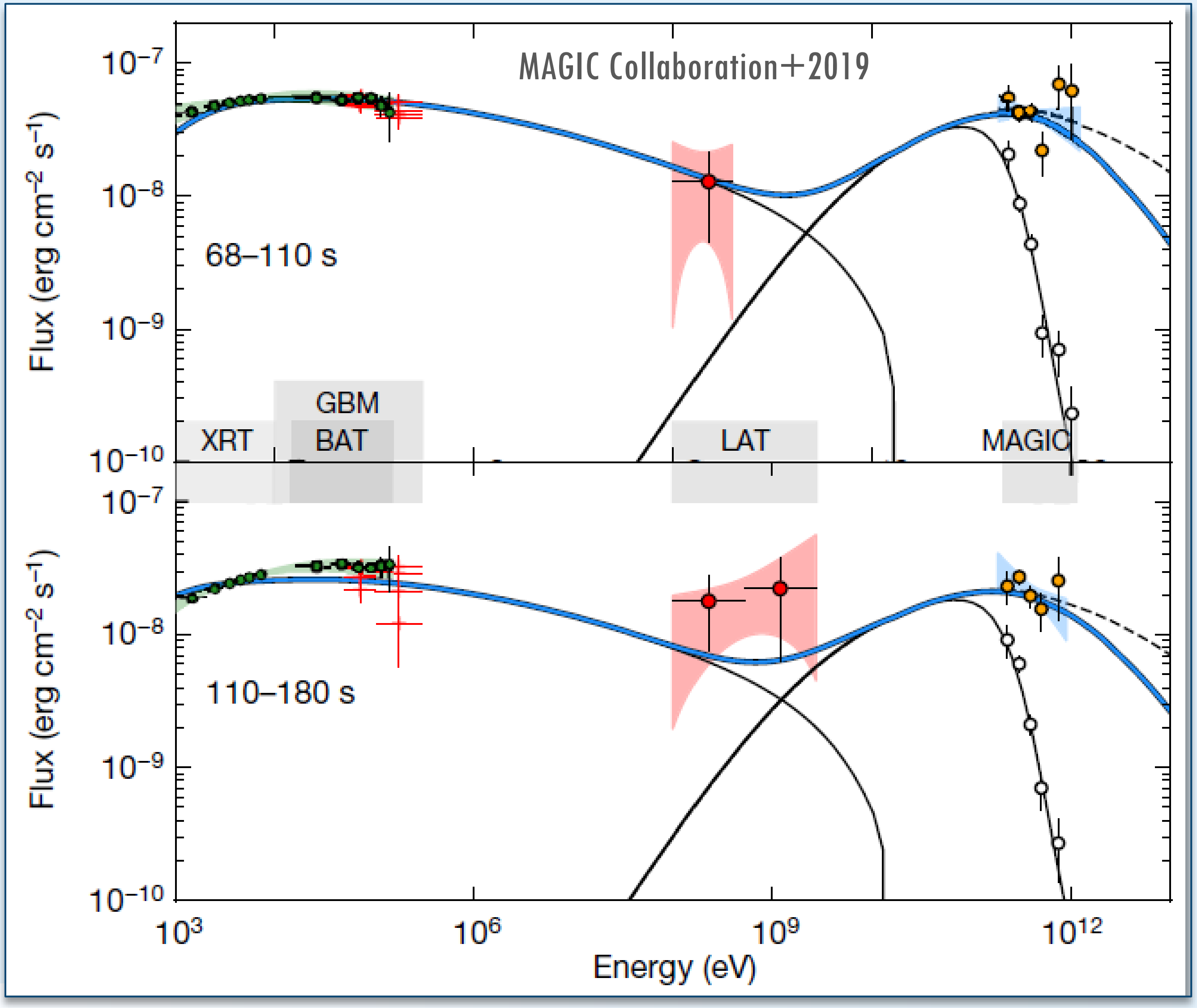
Energy flux lightcurves at different wavelengths from radio to gamma-rays

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

Multiwavelength observations of GRB 190114C

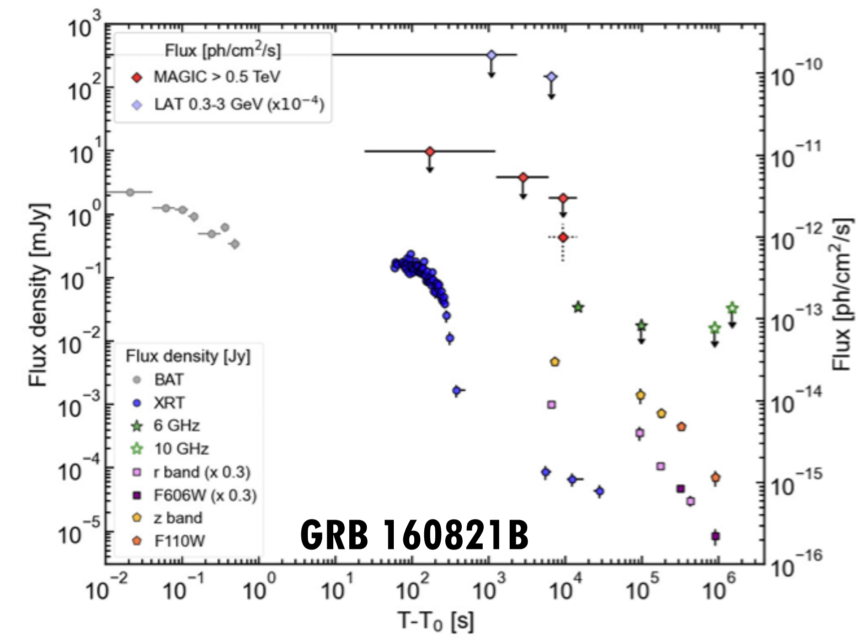
- The spectra from **X-ray to TeV** show the need for an **extra spectral component** to explain the flux increase at the **highest energies**
  ➔ Same forward shock, but **different emission processes**

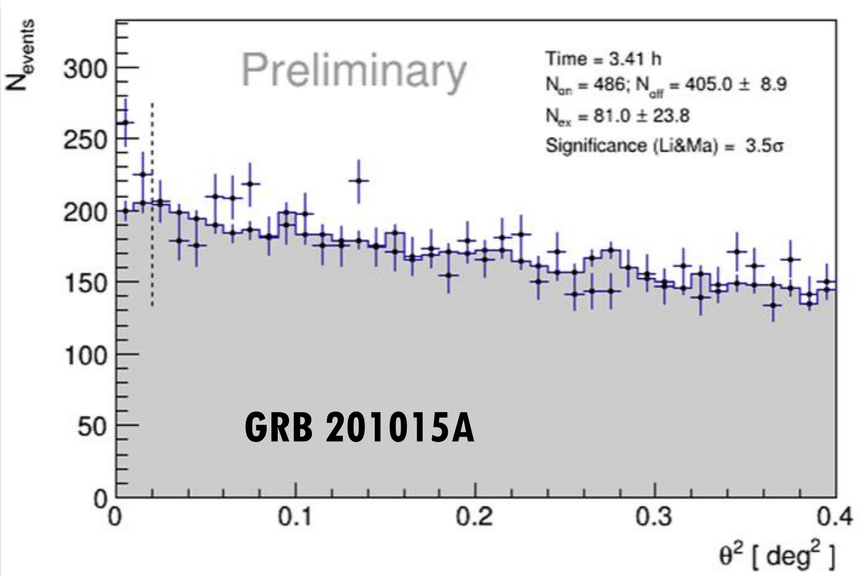
- Extra component generated by **Synchrotron Self-Compton**
  - Synchrotron photons are Compton up-scattered by the same electrons accelerated in the shocks

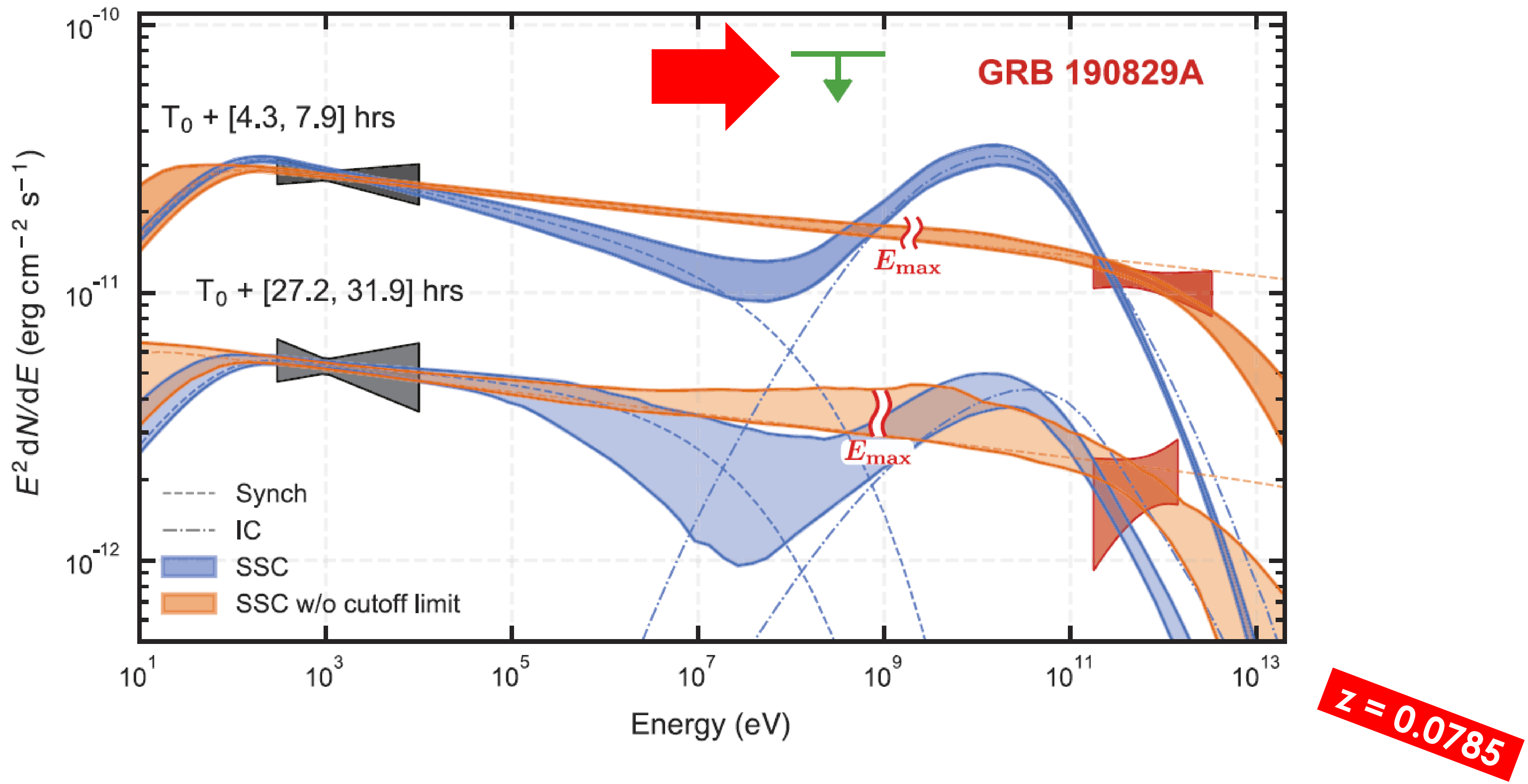


More GRBs @ TeV energies

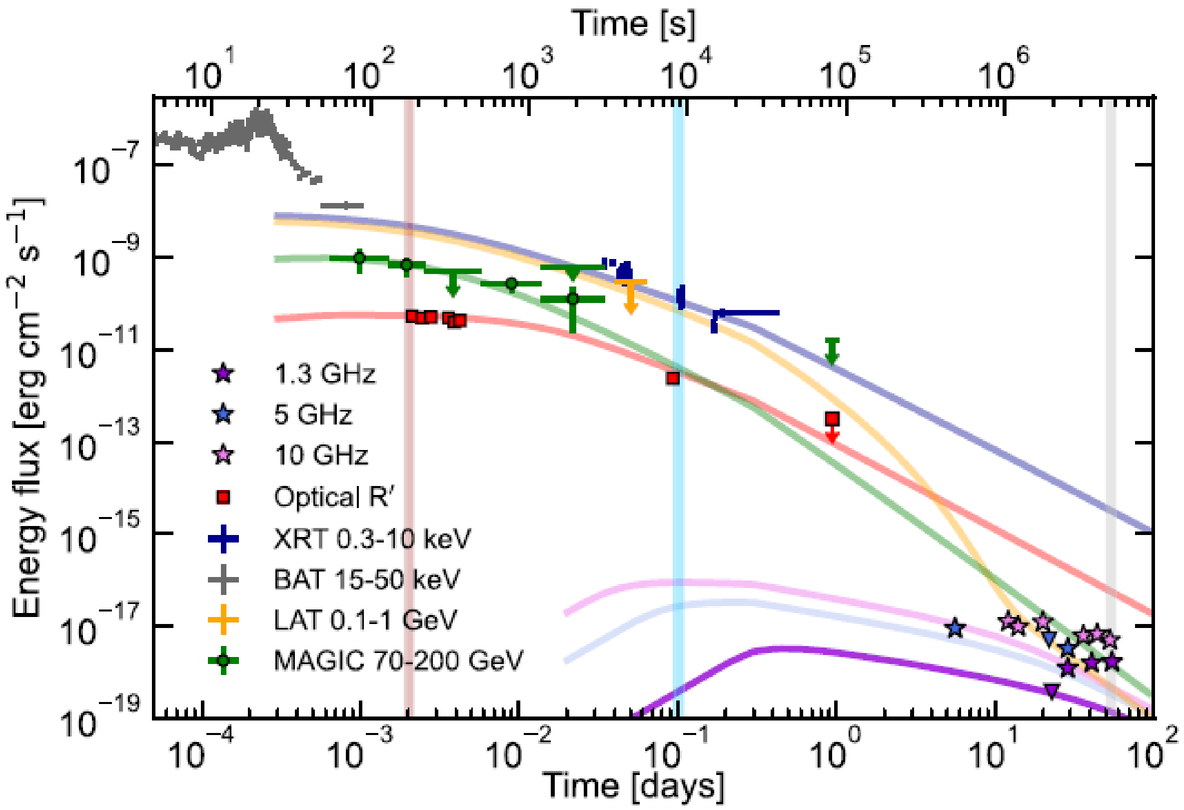
- **GRB 160821B** — **z = 0.162**
  - 3σ detection – **short** GRB, >0.5 TeV, **4h** post trigger (MAGIC+2021)
- **GRB 180720B** — **z = 0.653**
  - 5σ detection – long GRB, >0.1 TeV, **10h** post trigger (HESS+2019 Nature)
- **GRB 190114C** — **z = 0.4245**
  - 50σ detection – long GRB, >0.2 TeV, **60s** post trigger (MAGIC+2019 Nature)
- **GRB 190829A** — **z = 0.0785**
  - 20σ detection – long GRB, >0.18 TeV, **4-50h** post trigger (HESS+2021 Science)
- **GRB 201015A** — **z = 0.43**
  - 3σ detection – long GRB, **40s** post trigger (MAGIC+2022)
- **GRB 201216C** — **z = 1.1**
  - 6σ detection – long GRB >70GeV, **57s** post trigger (MAGIC+2024 MNRAS)

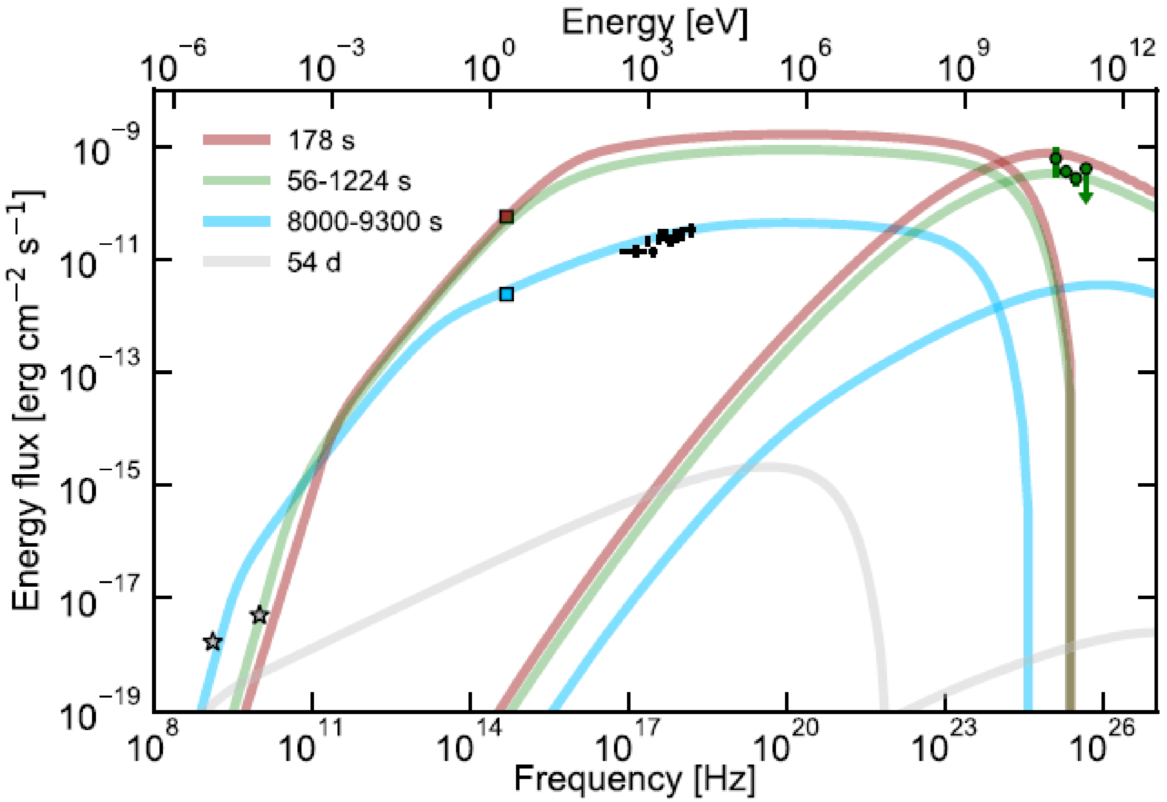






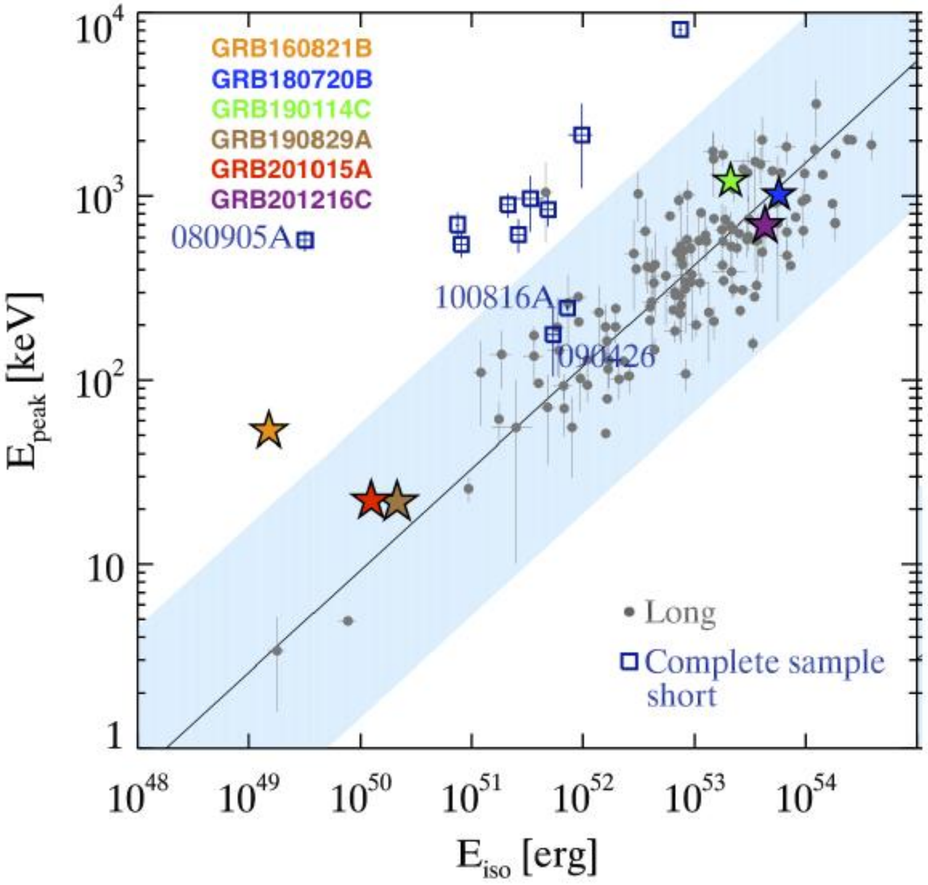
Revealing x-ray and gamma ray temporal and spectral similarities in the GRB 190829A afterglow – H.E.S.S. Collaboration 2021

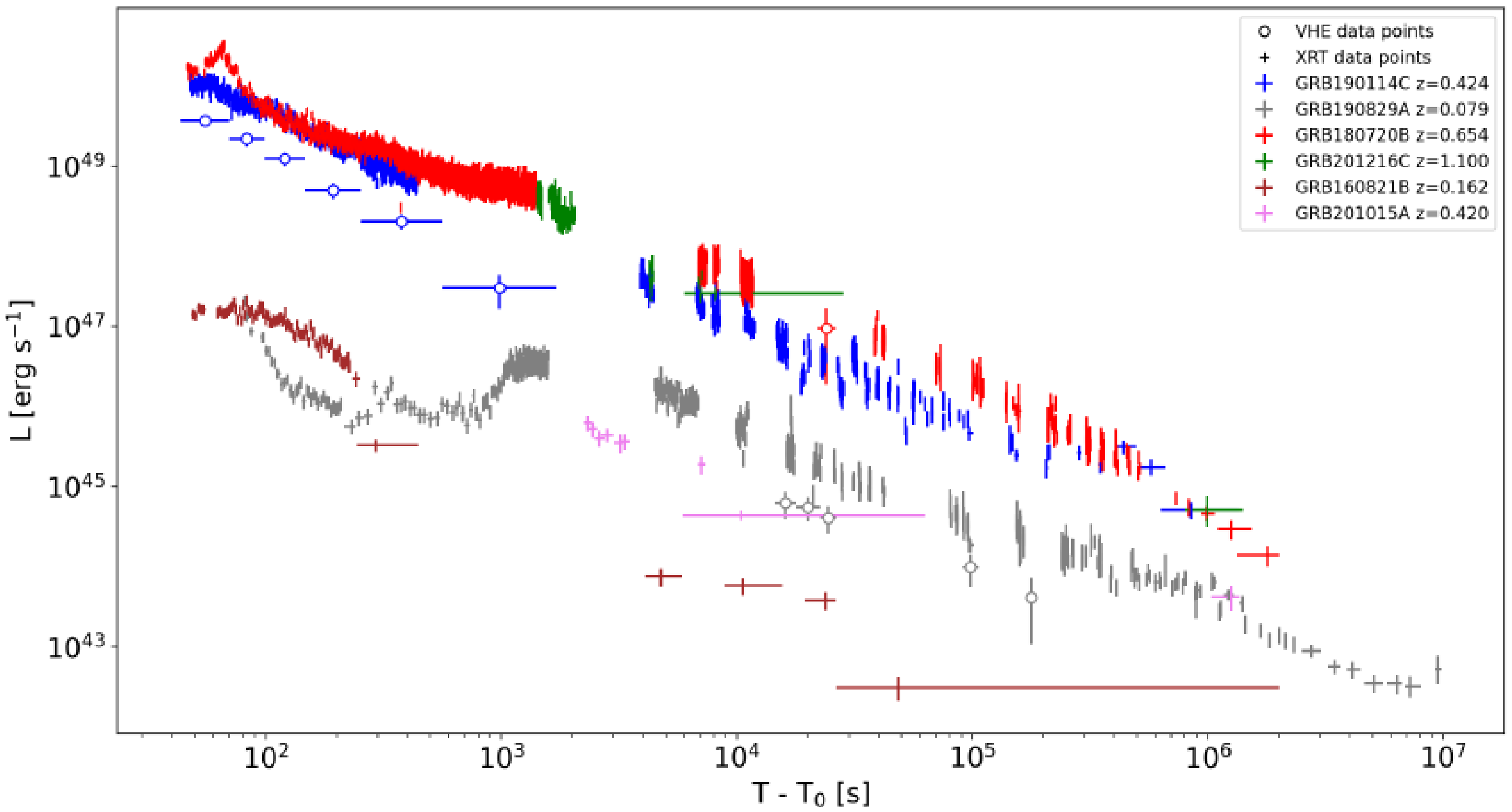




z = 1.1

MAGIC detection of GRB 201216C at z = 1.1 – MAGIC Collaboration 2024





Gamma-Ray Bursts Afterglow Physics and the VHE Domain – Miceli &Nava 2022

The «BOAT» GRB 221009A

Astronomy Picture of the Day

15 October 2022

https://apod.nasa.gov/apod/ap221015.html?fbclid=IwAR0dtOruG18ZOg9a-AhjcLkfPfvsok_C5Dvn-sjK7YpBQB5Pt_g_RShYsUE

Image Credit: NASA, DOE, Fermi LAT Collaboration, R.Pillera

GRB 221009A – Timeline of events

- **Oct.9 2022**
  - 13:16:60 UT **(T_0)** Fermi-GBM trigger 221009553 (no prompt GCN notices)
  - 14:10:17 UT **(T_0+3200s)** Swift trigger (GCN after 20min - Swift J1913.1+1946)
  - 20:54:36 UT Fermi-GBM reports that trigger 221009553 is superbright+long **GRB 221009A** → location consistent with Swift → **same event**!!!
  - 21:45:05 UT Fermi-LAT reports HE emission (**E_{max}: 8 GeV** @766 s post Swift trigger)
- **Oct.10, 2022**
  - X-shooter/VLT reports **redshift** **z = 0.151**
  - Fermi-LAT reports refined analysis (Duration **>25ks** and **E_{max}: 99 GeV** @T_0+240s)
  - IceCube reports neutrino UL (no detection)
  - Konus/WIND reports highest GRB fluence in 28 years of operation
- **Oct.11, 2022**
  - LHAASO reports **>500 GeV** emission within T_0+2000s (>100σ) + **18 TeV photon** (10σ)
  - Swift/XRT reports complex system of **bright expanding dust-scattering rings**
  - HAWC reports upper limits 8 hours after trigger
- **Oct.12, 2022**
  - Carpet-2 reports **250 TeV photon**-like air shower
- **Oct.14, 2022**
  - Xia et al. report **400 GeV photon** observed by Fermi-LAT at **T_0+0.4 d**

GRB 221009A – Timeline of events

- **Oct.9 2022**
  - 13:16:60 UT **(T_0)** Fermi-GBM trigger 221009553 (no prompt GCN notices)
  - 14:10:17 UT **(T_0+3200s)** Swift trigger (GCN after 20
  - 20:54:36 UT Fermi-GBM reports that trigger 22100
    → location consistent with Swift → **same event**!!
  - 21:45:05 UT Fermi-LAT reports HE emission (**E**
- **Oct.10, 2022**
  - X-shooter/VLT report
  - Fermi-LAT

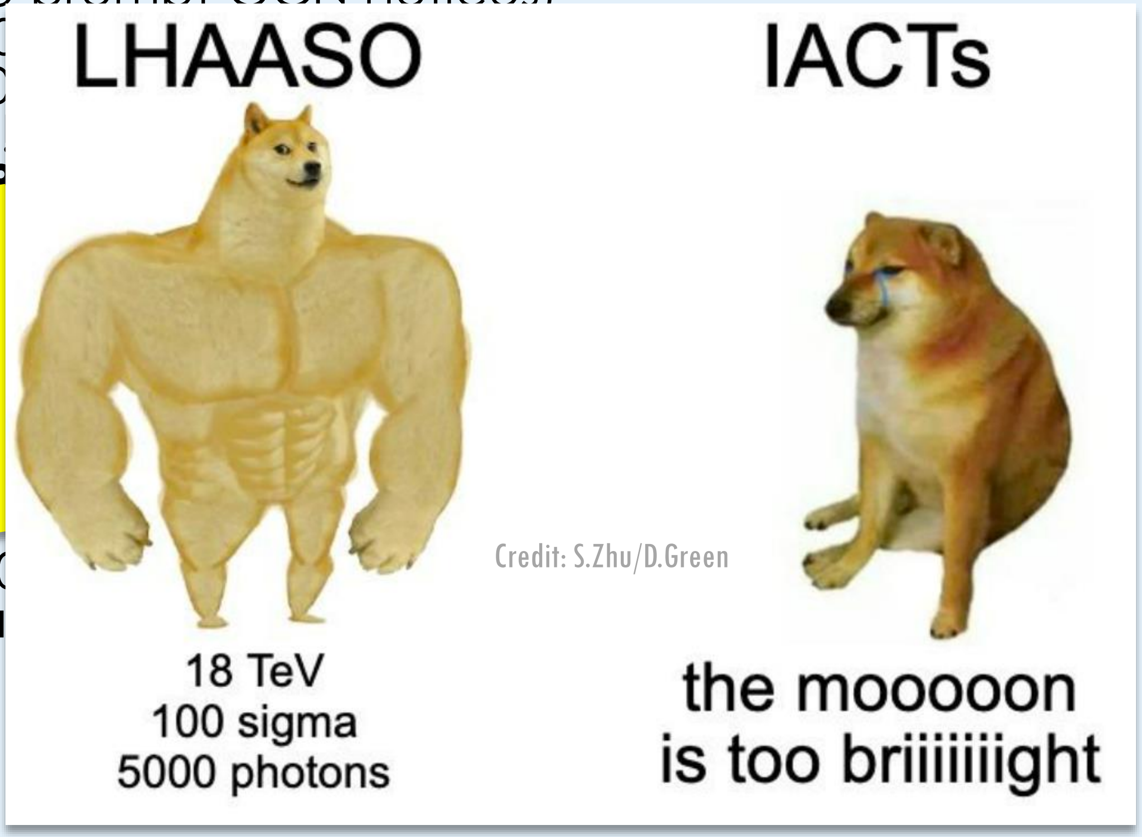
within T_0+200

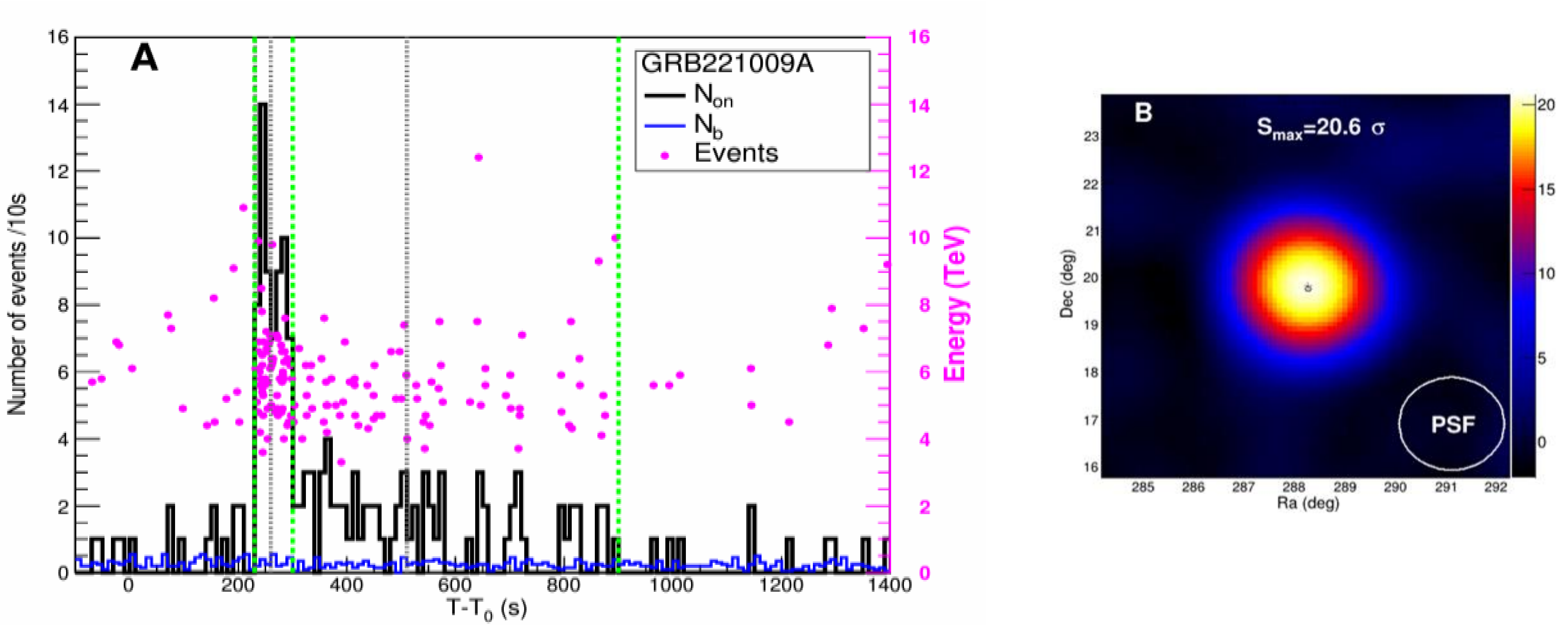
system of **bright expa**

upper limits 8 hours after trigger

- **Oct.12, 2022**
  - Carpet-2 reports **250 TeV photon**-like air shower
- **Oct.14, 2022**
  - Xia et al. report **400 GeV photon** observed by Fermi-LAT at **T_0+0.4 d**

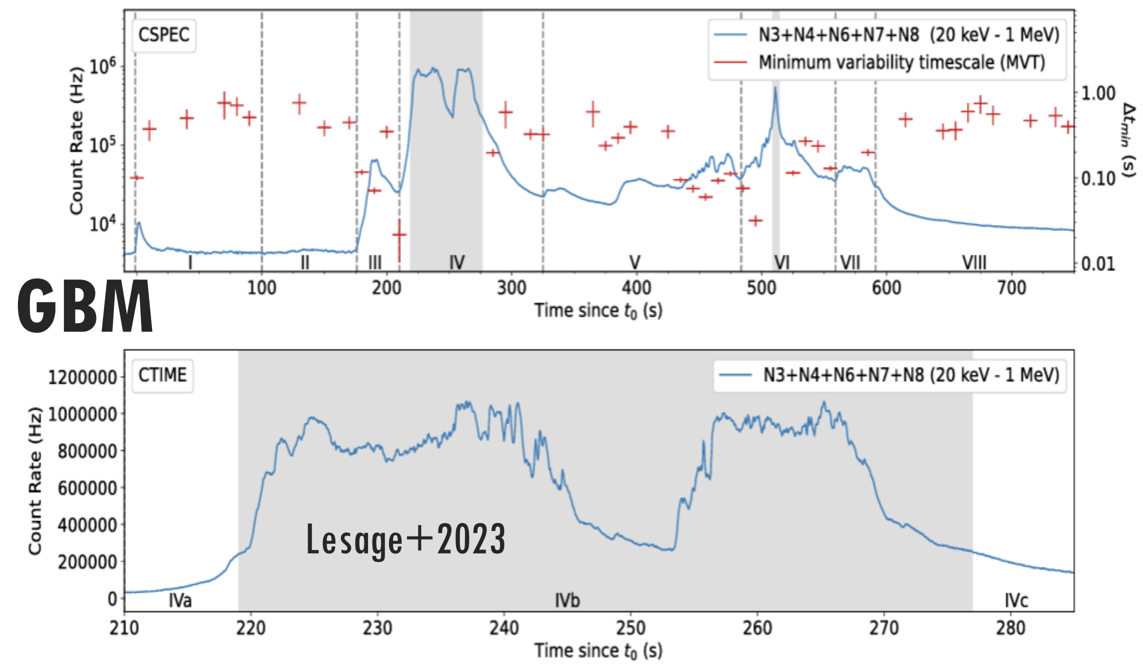
Exceptional gamma-ray keV/MeV/GeV detection
Exceptional x-ray detection
LHASSO TeV detection
No IACT detection (full moon!)
No neutrino detection

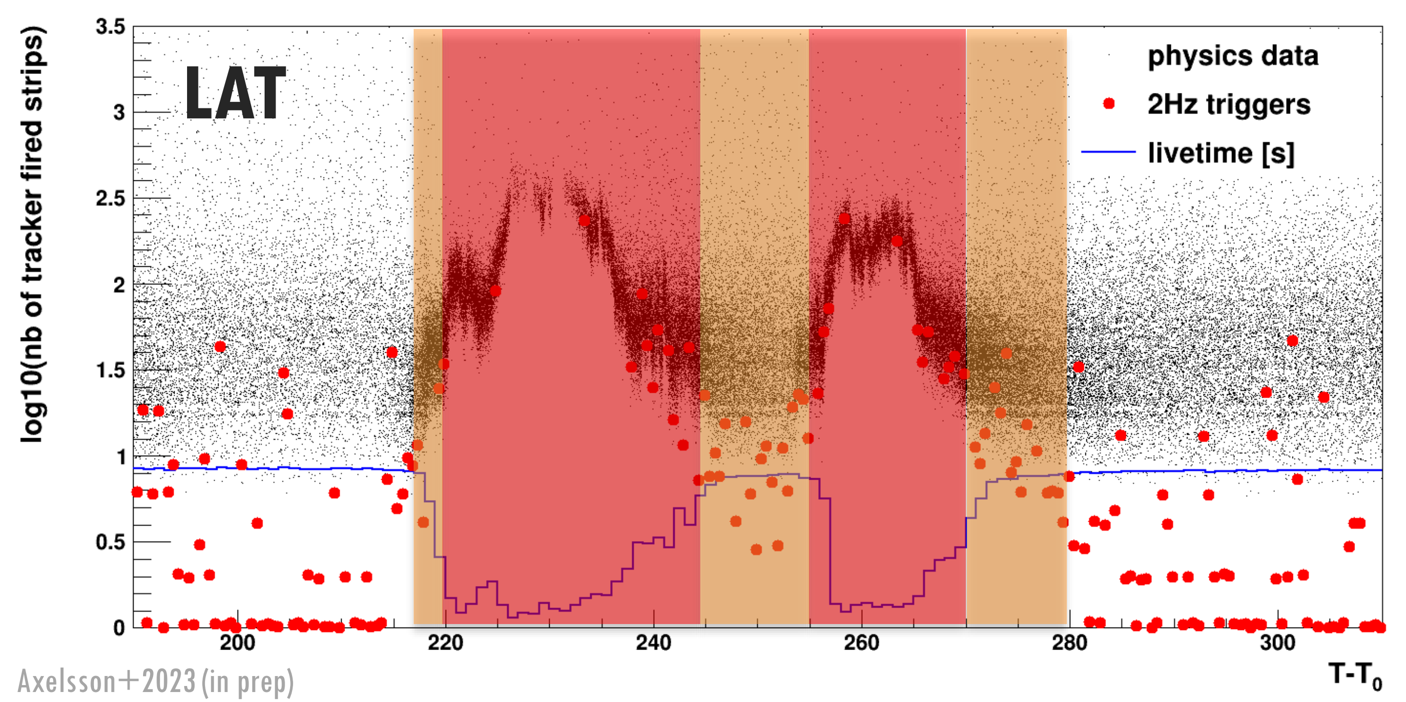




Very high energy gamma-ray emission beyond 10 TeV from GRB 221009A – LHAASO Collaboration 2023

GRB 221009A – Fermi data issues





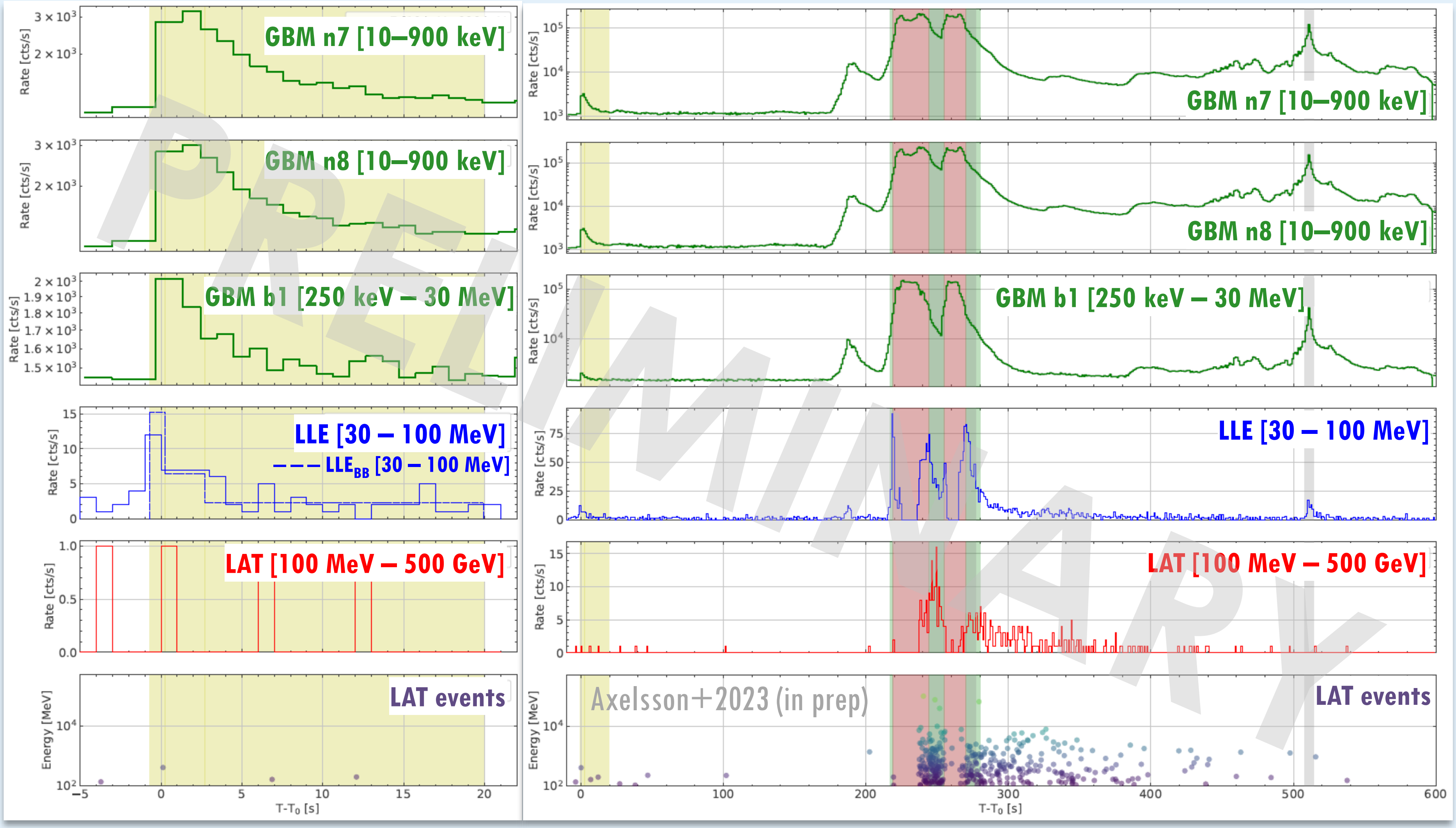
- **Saturation effects**

  Definition of Bad Time Intervals (BTIs)
  - **GBM** PPU corrections
  - **LAT** Modified reconstruction algorithm

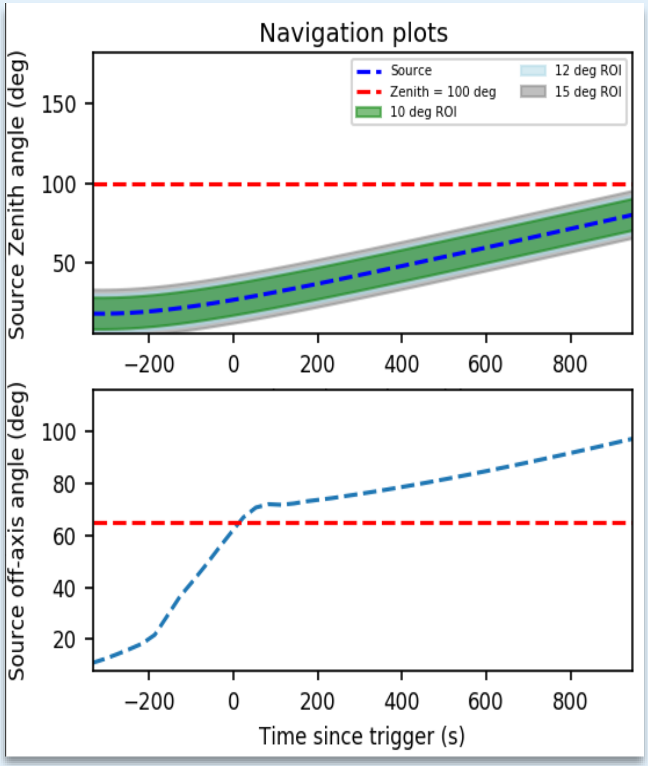
All caveats can be found here:
https://fermi.gsfc.nasa.gov/ssc/data/analysis/grb221009a.html

- **Data recovery**
  - **3 intervals recovered (orange boxes)**
    - Standard analysis can be performed E>125 MeV, no LLE, efficiency 75 ± 25 % with `TRANSIENT` class
- **Bad Time Intervals**:
  - **No standard analysis possible in 2 intervals**

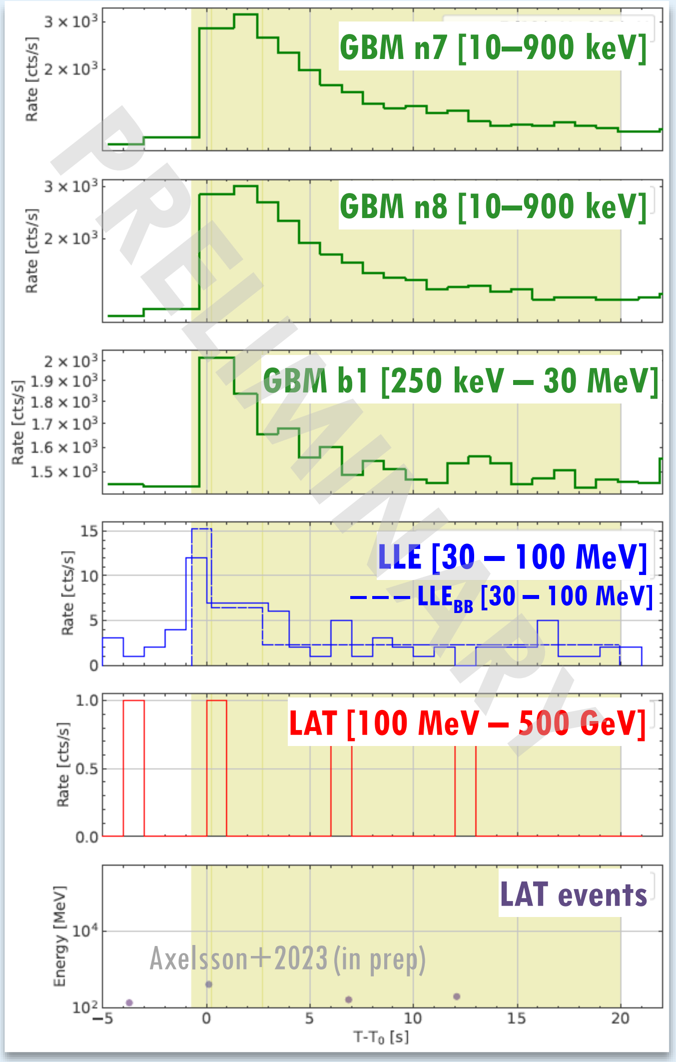
Fermi high-energy light curves



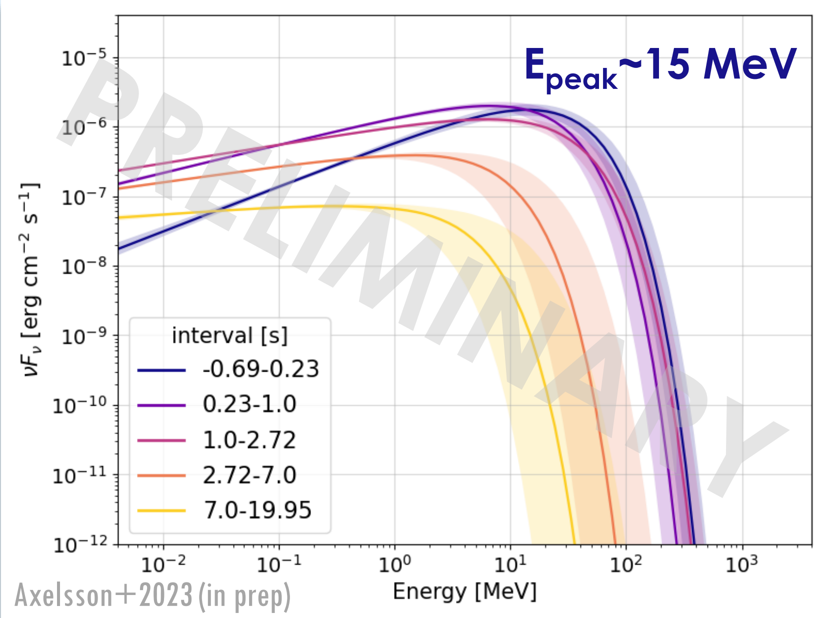
Unfortunately, the GRB position **moved very quickly out of the LAT FoV**



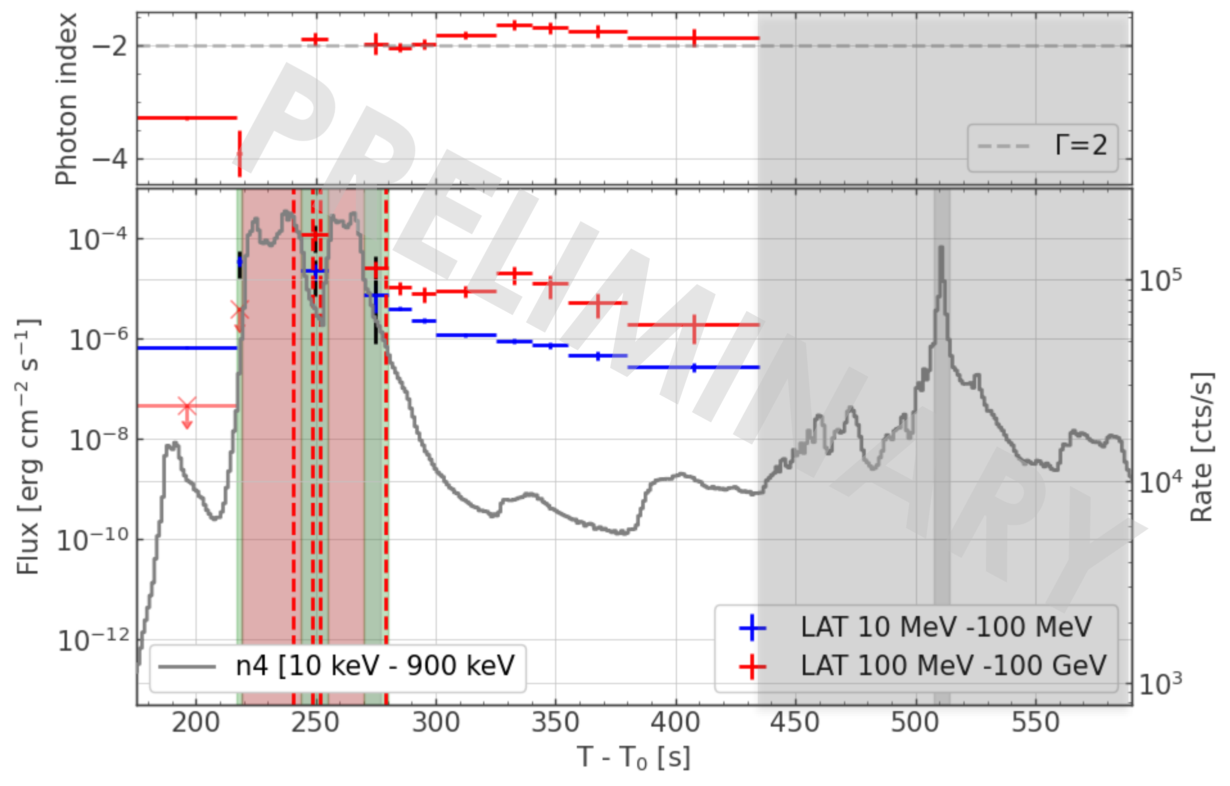
The triggering pulse

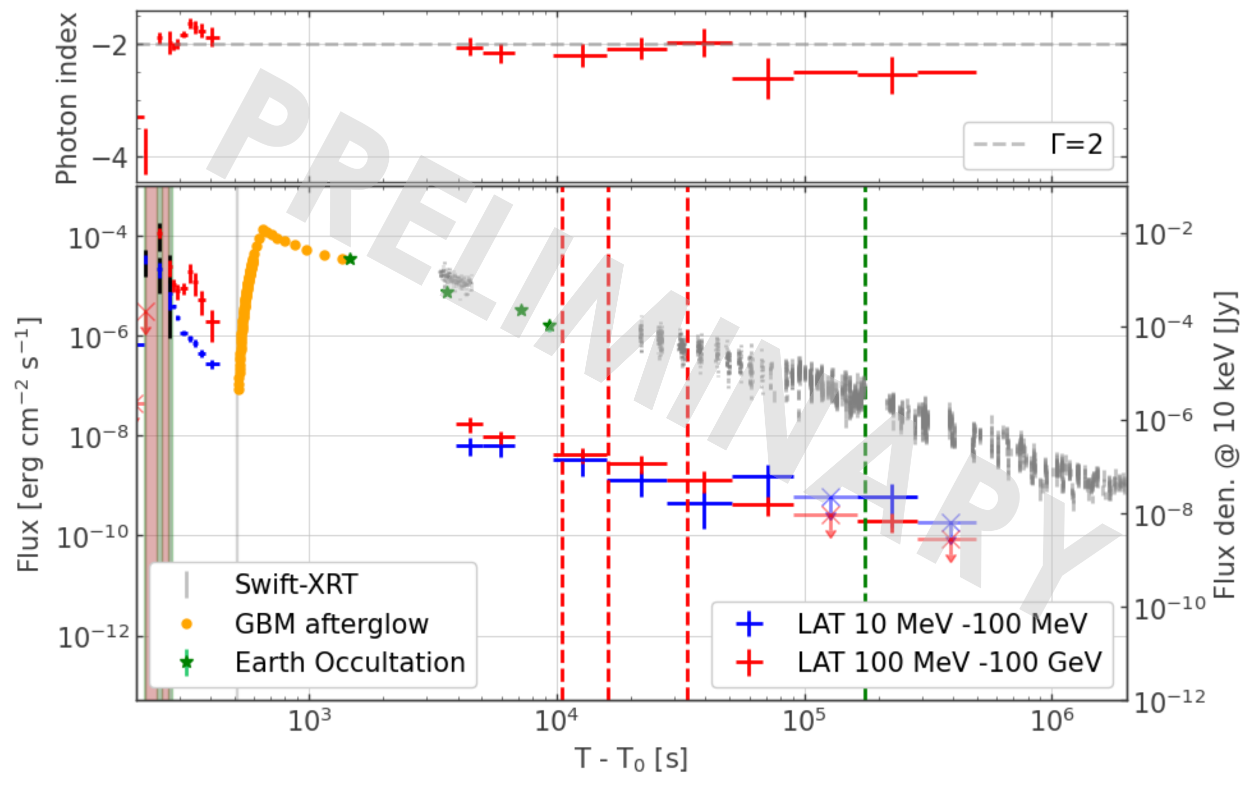


- Defined as first 20 s post GBM trigger
- At high-energies: Visible in LLE only
  - No LAT photons with p>90% association
  - Bayesian blocks (BB) algorithm applied to LLE data
- Joint time-resolved spectral analysis with 3ML
  - Tested models:
    PL, COMP, Band, 2BPL
    + extra PL
  - Applying Bayesian Information Criterion (BIC)
    COMP preferred model
    - Very hard first pulse with subsequent softening



High-energy emission analysis





Early times LLE+LAT analysis

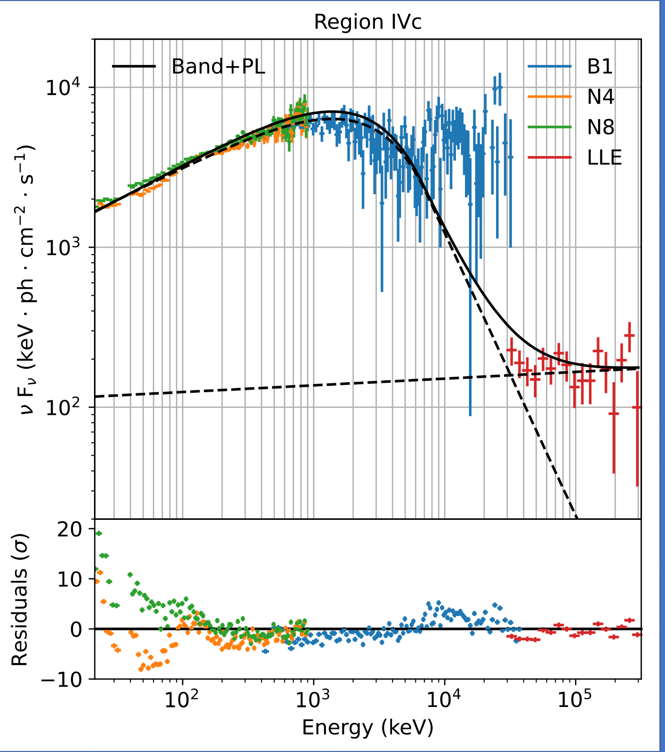
- Estimate flux maximum in the BTI
- Bulk Lorentz factor estimation from opacity arguments: **Γ>450**

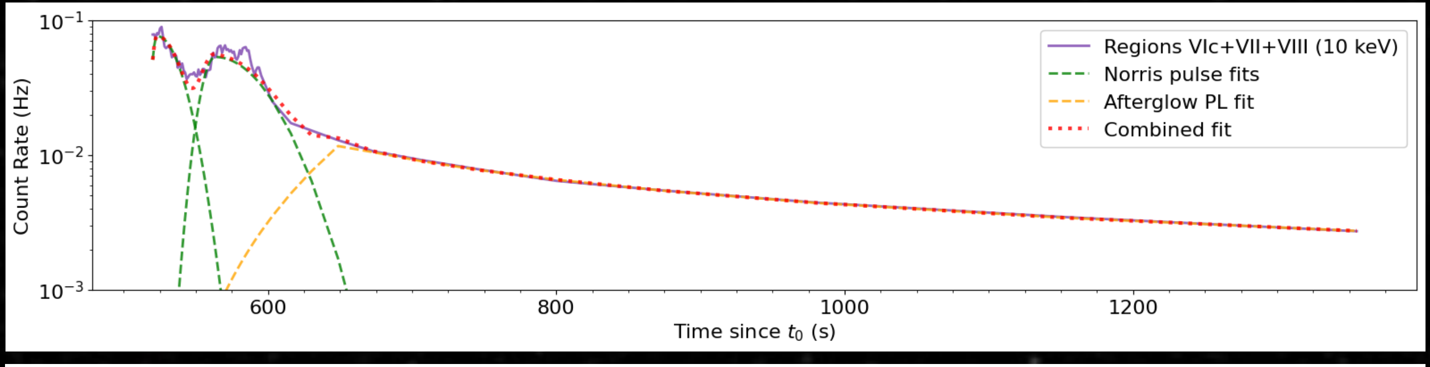
Late times LAT analysis

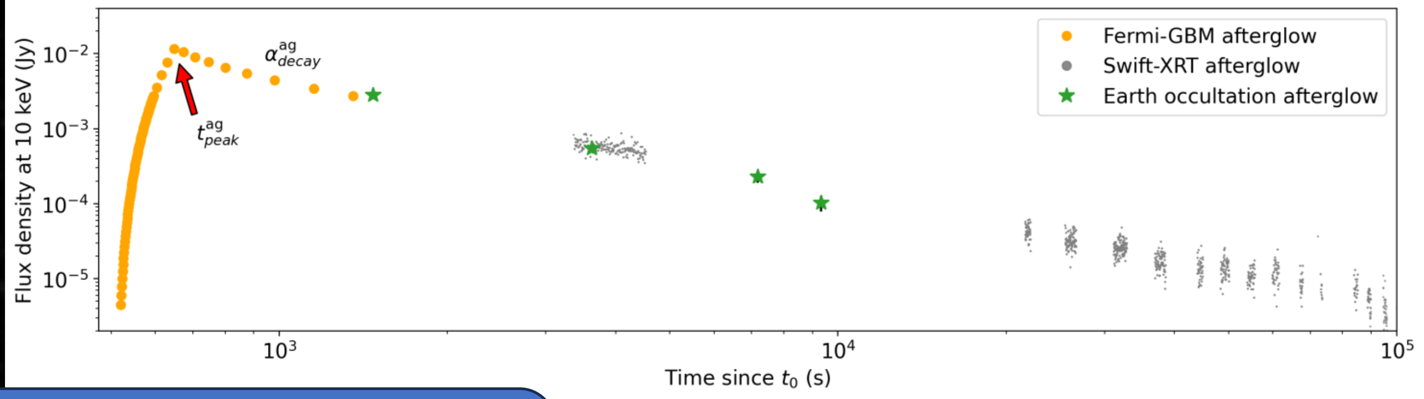
- GRB duration: ~**180 ks** (**2 days: record!**)
- Afterglow flux PL decay (index ~ **−1.3**)

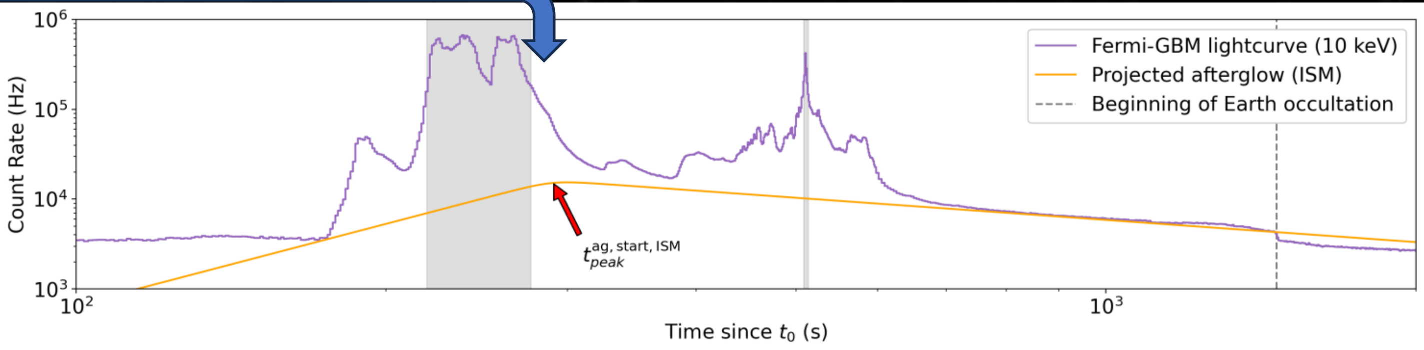
Afterglow

$t_{peak, ag} \gtrsim t_0 + 280$ s
Consistent with LHAASO



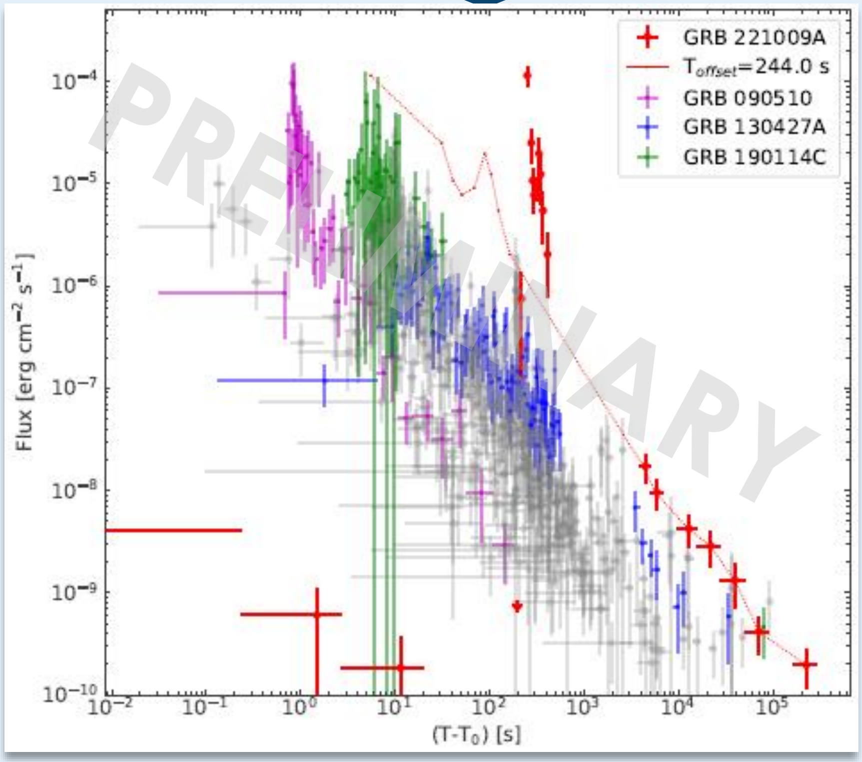


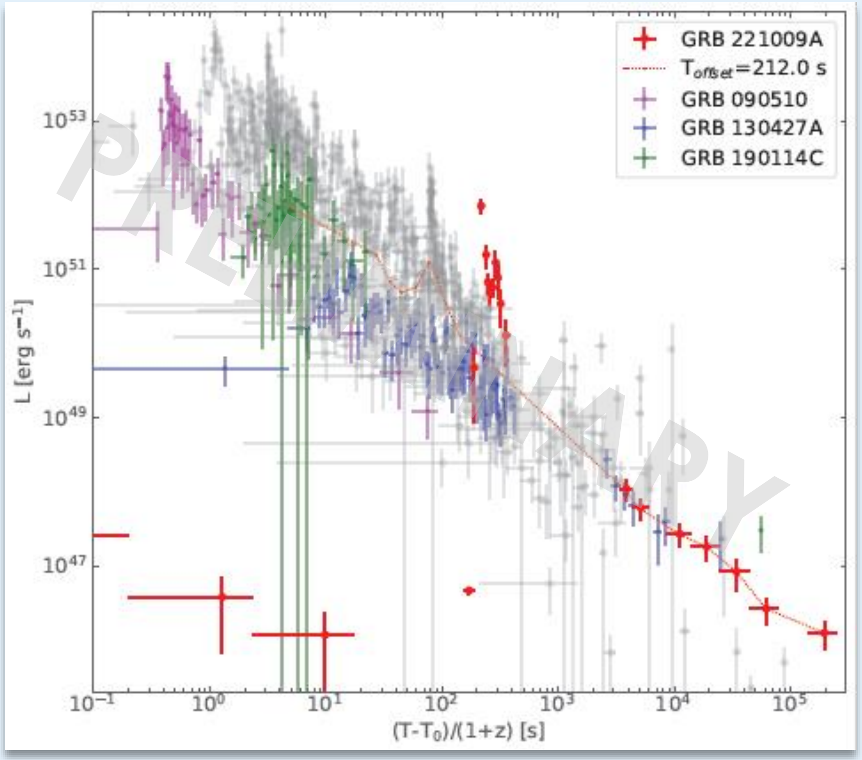


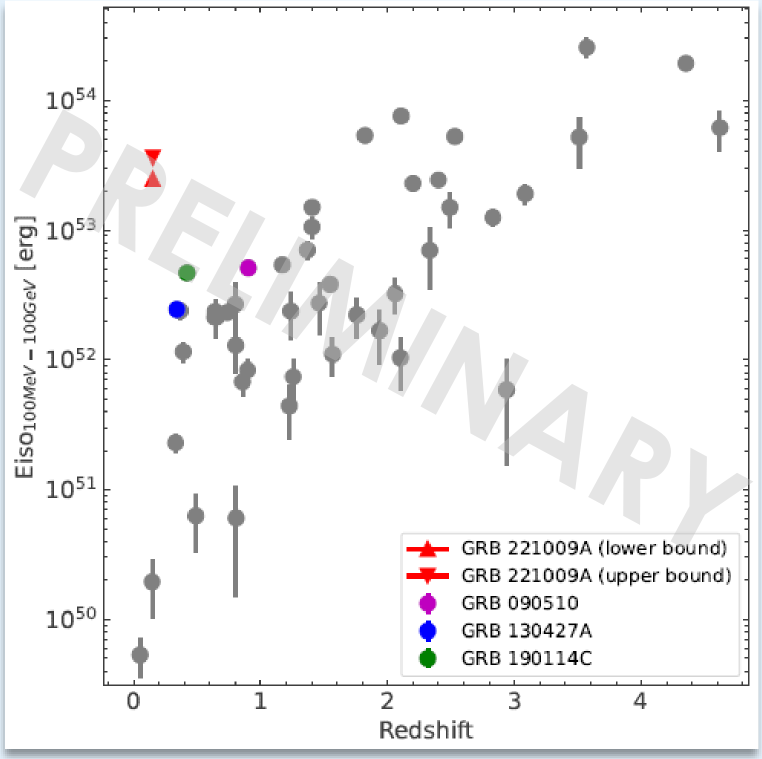


Slide courtesy of S. Lesage, *Fermi*-GBM | GRB50

GRB 221009A in the context of other LAT GRBs







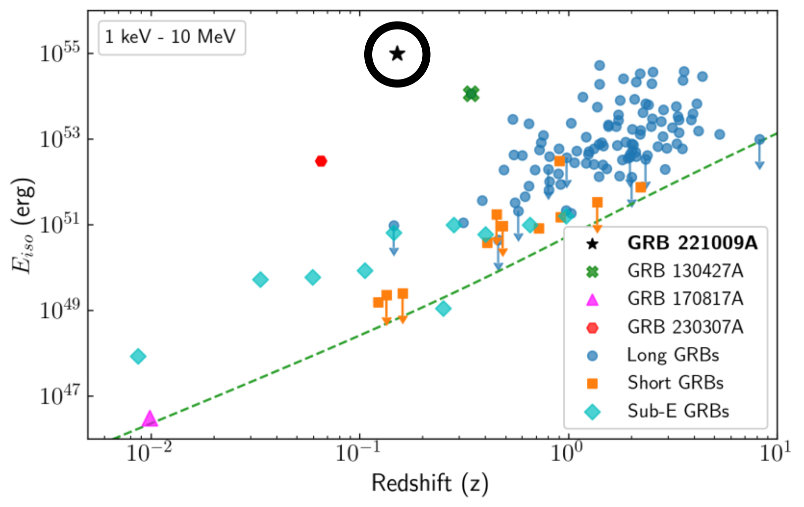
- **Record breaking** in terms of highest fluence, longest GeV afterglow and highest photon energy (100 and 400 GeV photons)
- Not quite exceptional in terms of E_{iso}
  - Comparable to high-redshift LAT detected GRBs, but very close: **Extremely rare**!

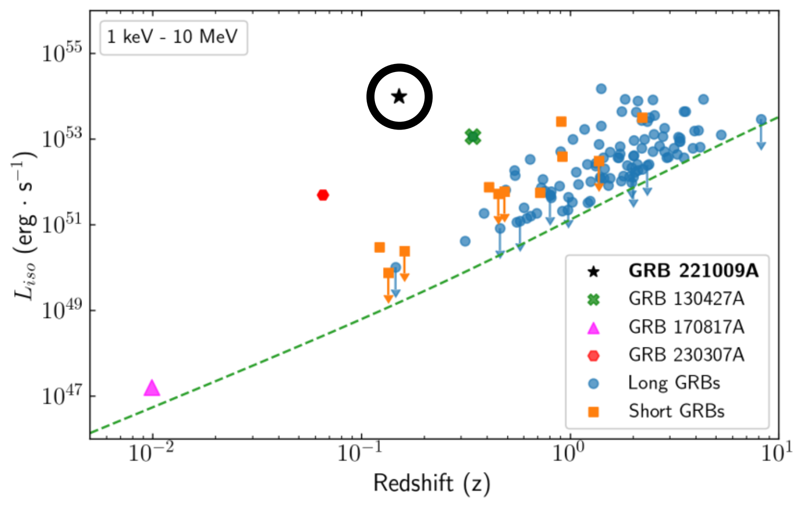
Fermi Gamma-ray Space Telescope

THE UNIVERSITY OF ALABAMA IN HUNTSVILLE

Energetics

(4 measures)



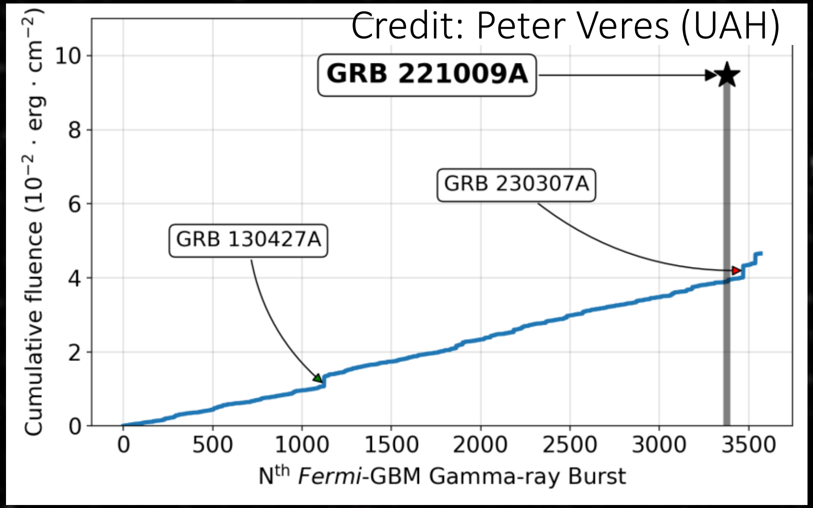


E_{iso} ~ **1.0×10^{55} erg**

L_{iso} ~ **9.9×10^{53} erg s^{-1}**

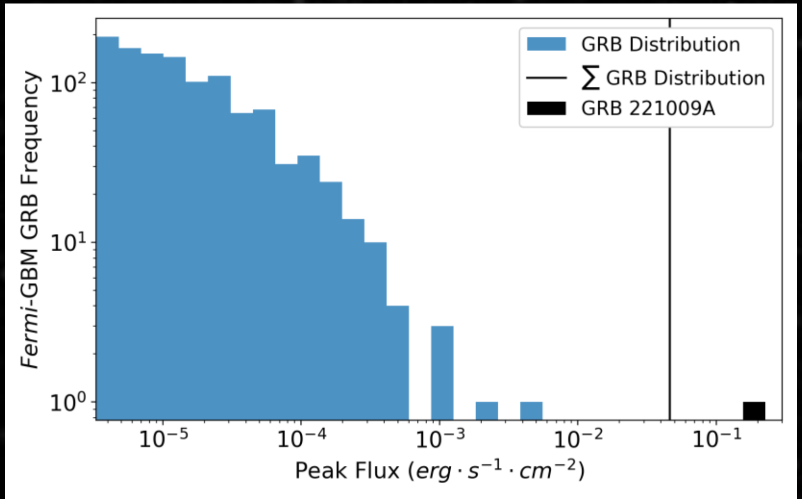
Fluence ~ **0.2 erg cm^{-2}**

Peak Flux ~ **0.02 erg s^{-1} cm^{-2}**



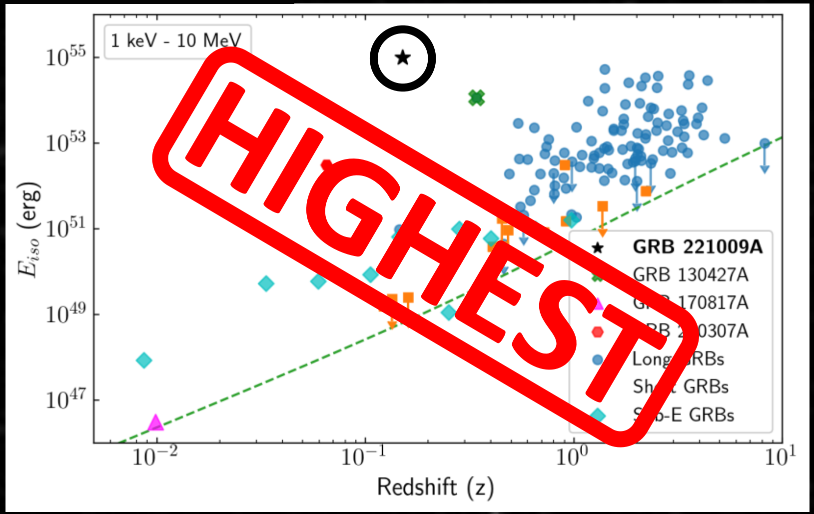
Consistent with:

Konus-WIND
GRBAlpha
Insight-HXMT
GECAM-C



Energetics

(4 measures)

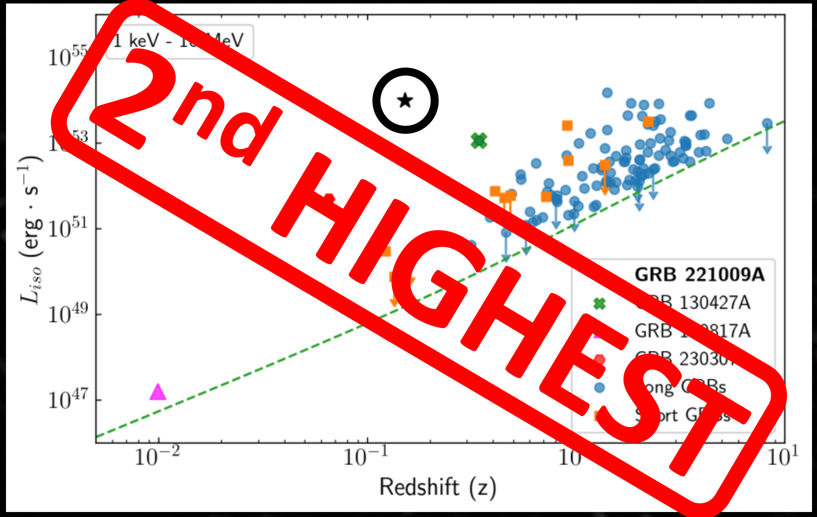


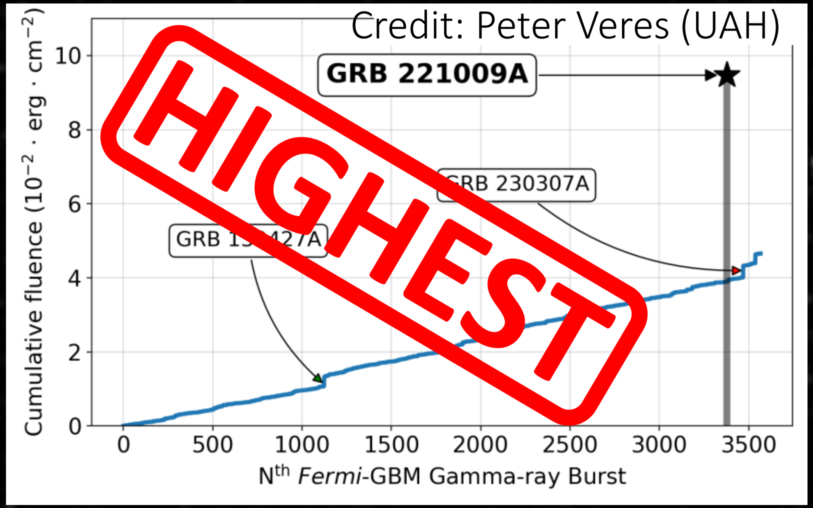
E_{iso} ~ **1.0 x 10^{55} erg**

L_{iso} ~ **9.9 x 10^{53} erg s^{-1}**

Fluence ~ **0.2 erg cm^{-2}**

Peak Flux ~ **0.02 erg s^{-1} cm^{-2}**





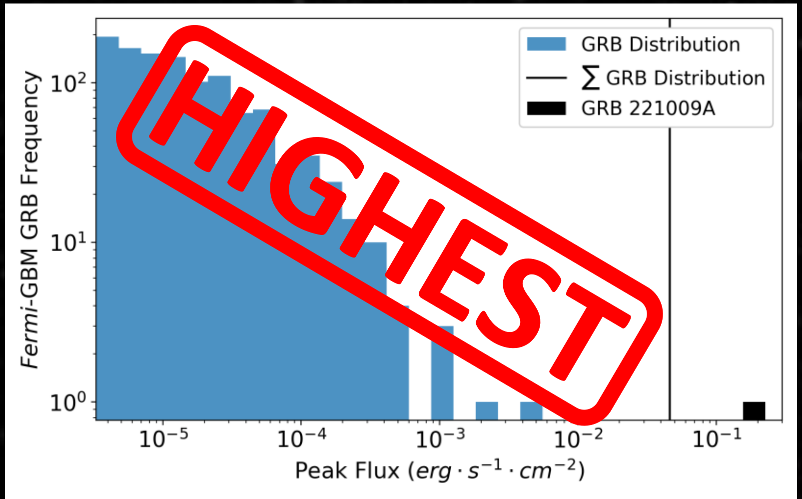
Consistent with:

Konus-WIND

GRBAlpha

Insight-HXMT

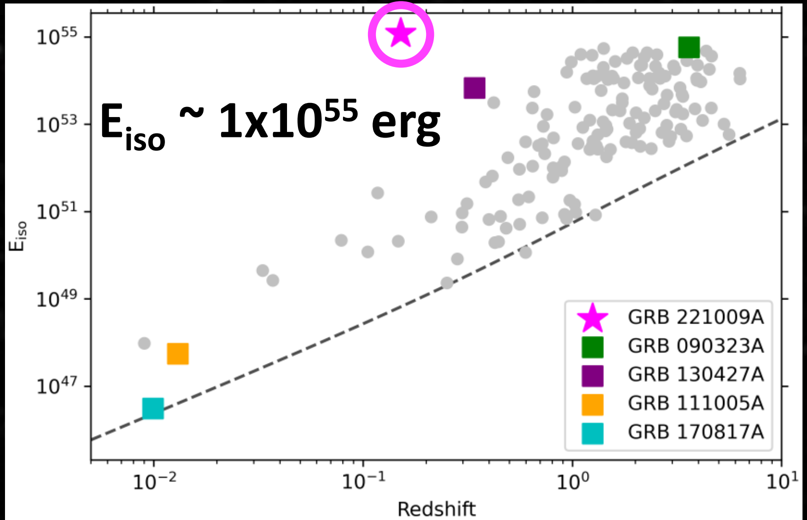
GECAM-C

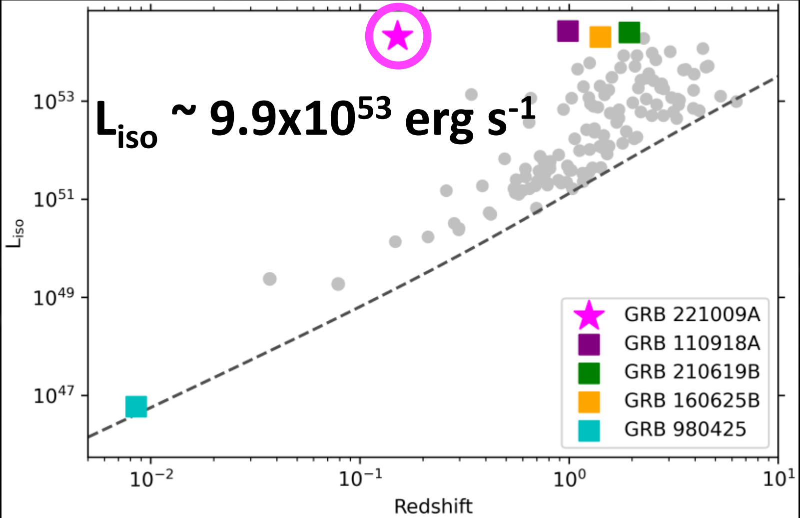


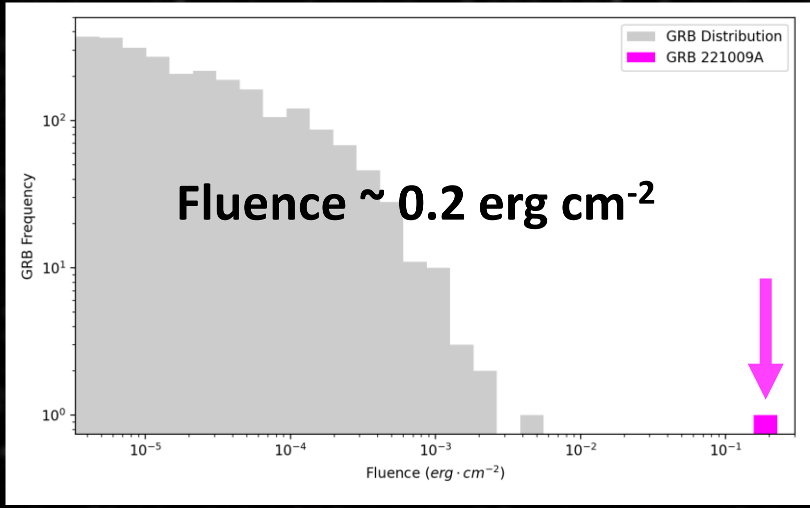
Slide courtesy of S. Lesage, *Fermi*-GBM | GRB50

Is it the B.O.A.T.?

(4 measures)

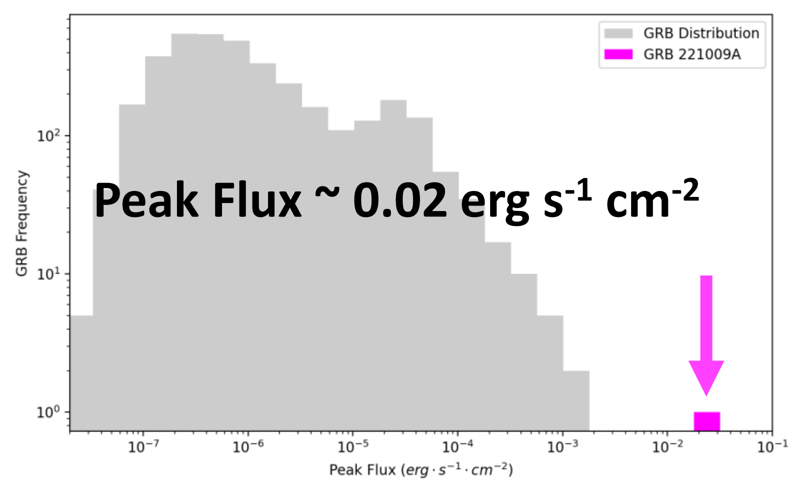






55 years of data

Burns et al. (2023)

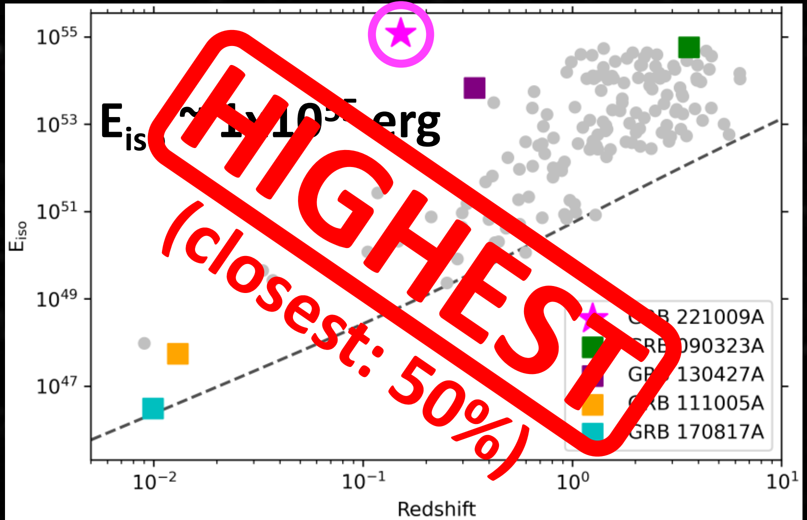


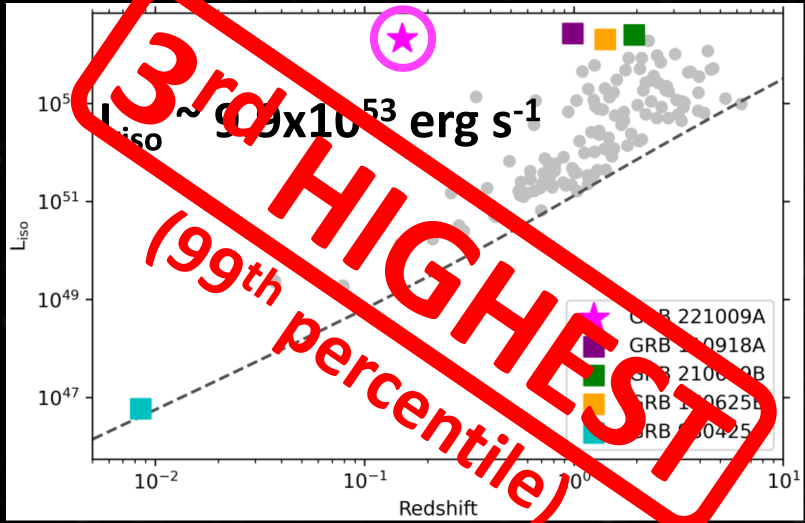
Slide courtesy of S. Lesage, *Fermi*-GBM | GRB50

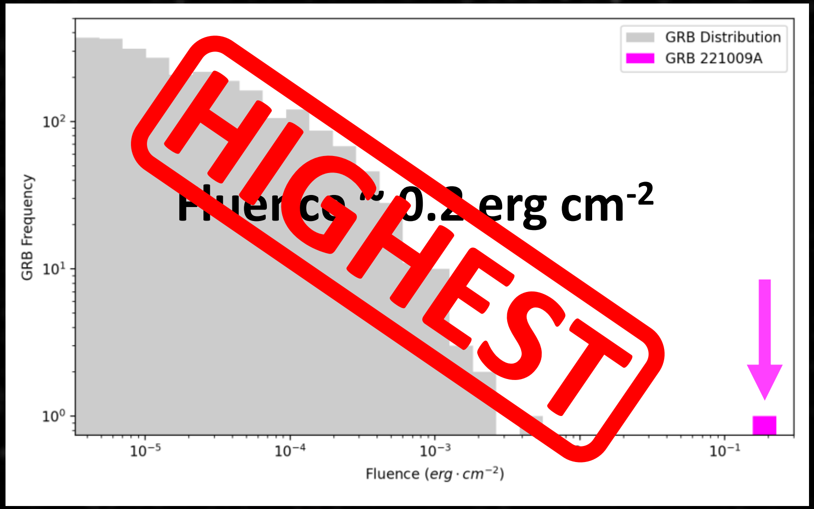
Is it the B.O.A.T.?

(4 measures)

YES! YES!



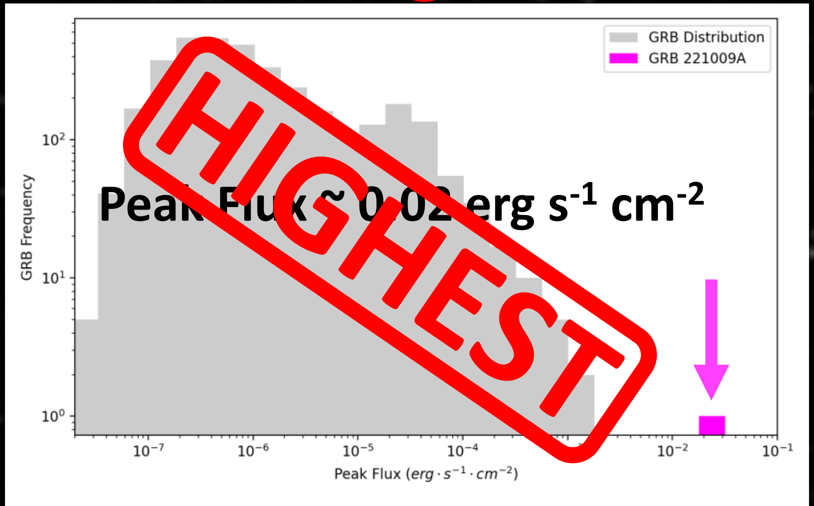




¾ measures of brightness

55 years of data

Burns et al. (2023)

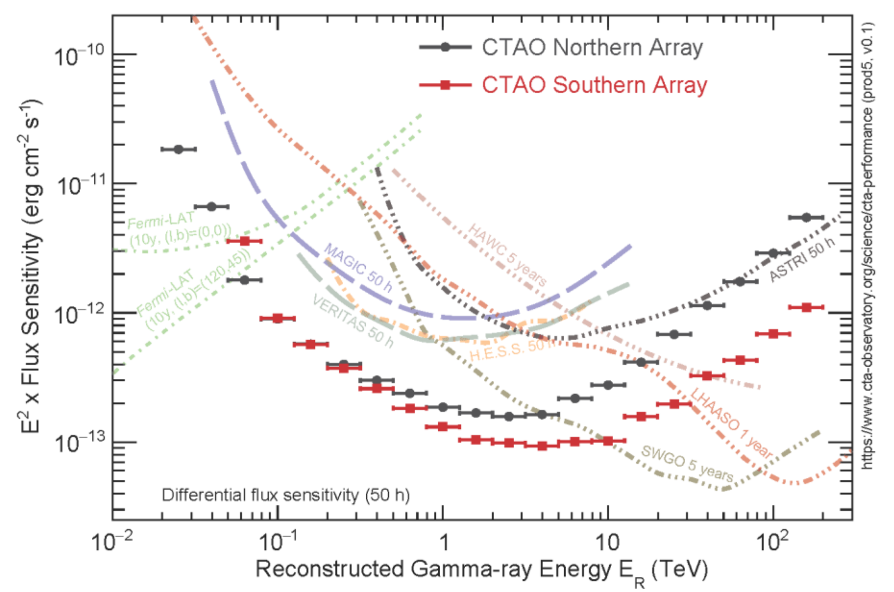


Slide courtesy of S. Lesage, *Fermi*-GBM | GRB50

Summary and future prospects

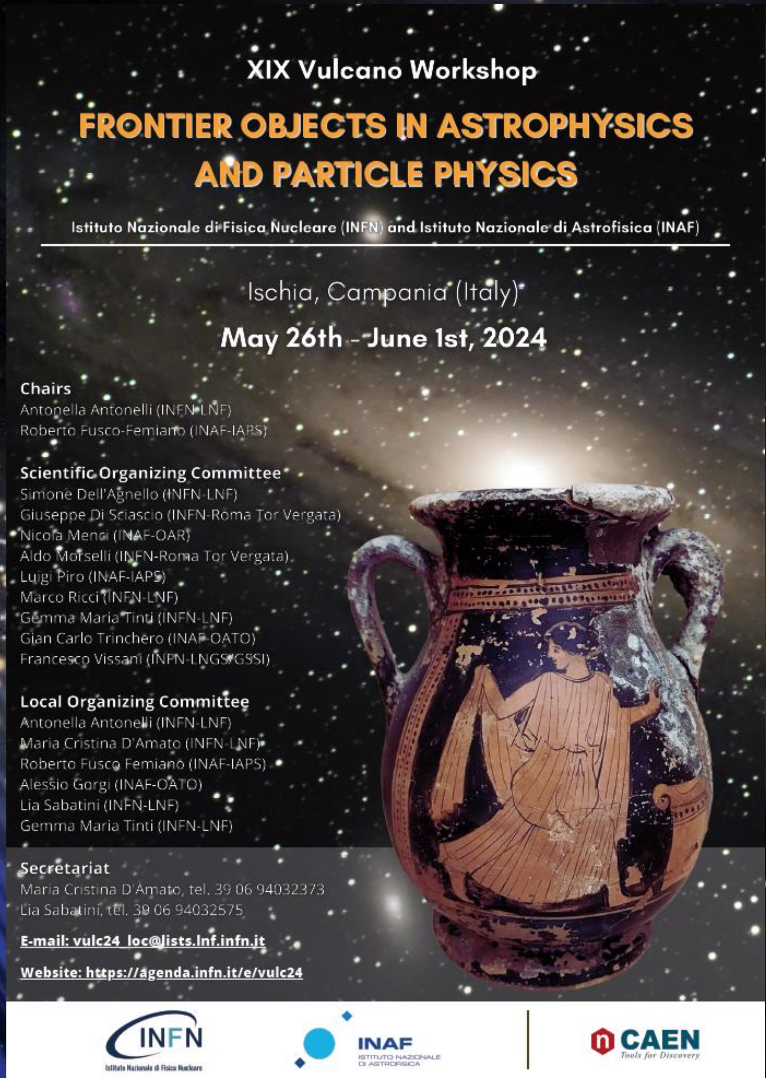
- Looking forward to the **Cherenkov Telescope Array Observatory CTAO**, with ~10 times better sensitivity than current instruments
  ➔ **Boost VHE GRB detection rate in both prompt and afterglow emission phases**
  - Consortium paper on GRB detection prospects in preparation!

https://www.ctao.org/for-scientists/performance/



- Open questions:
  - Does **SSC interpretation** hold for all detected GRBs?
  - Conditions required to produce VHE component? How common are they?
  - Nature of TeV emission always the same or competing processes can dominate the TeV range?
  - VHE emission in short GRBs: understand differences short/long (environment, jet,…)

Thank you!



Elisabetta Bissaldi

elisabetta.bissaldi@ba.infn.it