The Fermi high-energy view of GRB 221009A

The "brightest of all time" or B.O.A.T. GRB

Astronomy Picture of the Day
15 October 2022
Credit: NASA, DOE, Fermi LAT Collaboration, R.Pillera

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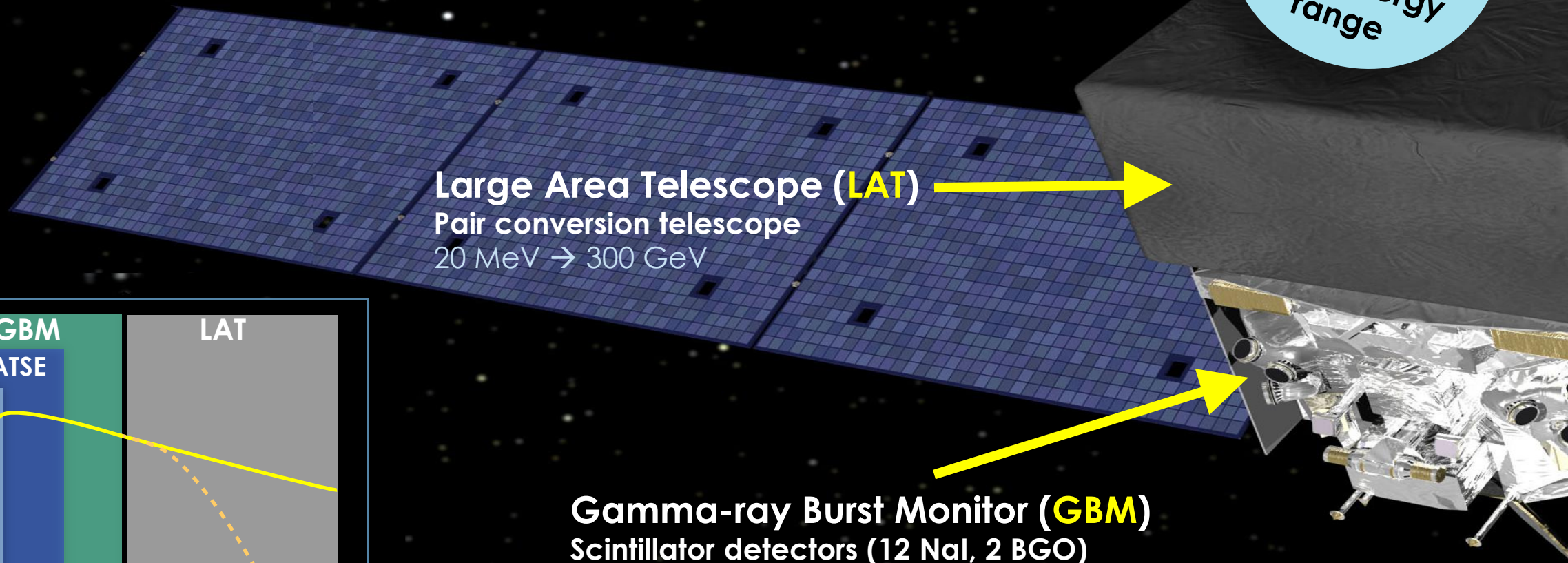
TeVPA 2023

The Fermi Mission

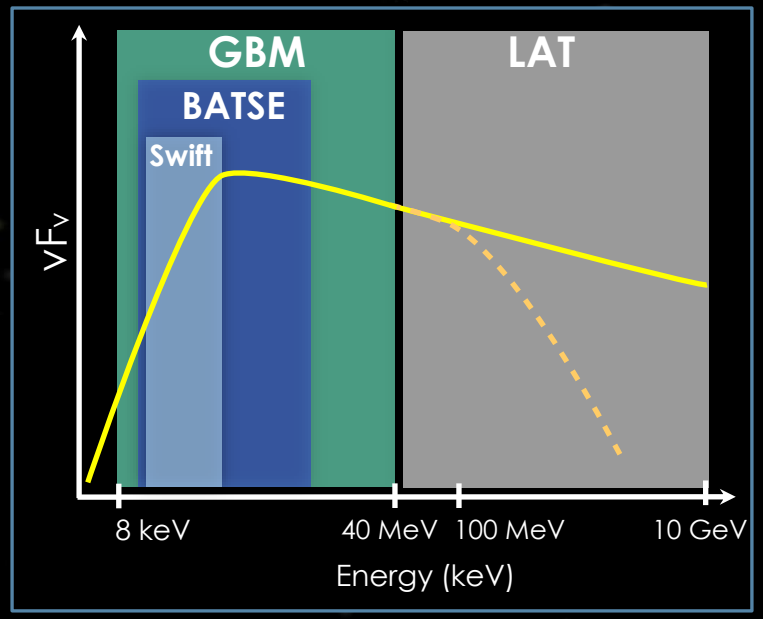
Launched on June 11, 2008

International and interagency collaboration between NASA and DOE in the US and agencies in France, Germany, Italy, Japan and Sweden

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



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



Gamma-ray Burst Monitor (GBM)
Scintillator detectors (12 NaI, 2 BGO)
8 keV – 40 MeV

GRBs @ TeV energies

- GRB 160821B
  - 3σ detection – short GRB **>0.5 TeV** **4h** post trigger (MAGIC+2021)
- **GRB 180720B**
  - 5σ detection – long GRB **>0.1 TeV** **10h** post trigger (HESS+2019 Nature)
- **GRB 190114C**
  - 50σ detection – long GRB **>0.2 TeV** **60s** post trigger (MAGIC+2019 Nature)
- **GRB 190829A**
  - 20σ detection – long GRB **>0.18 TeV** **4-50h** post trigger (HESS+2021 Science)
- GRB 201015A
  - >3σ detection – long GRB **40s** post trigger (MAGIC GCN 28659)
- GRB 201216C
  - 6σ detection – long GRB **57s** post trigger (MAGIC+PoS2023)

z = 0.162

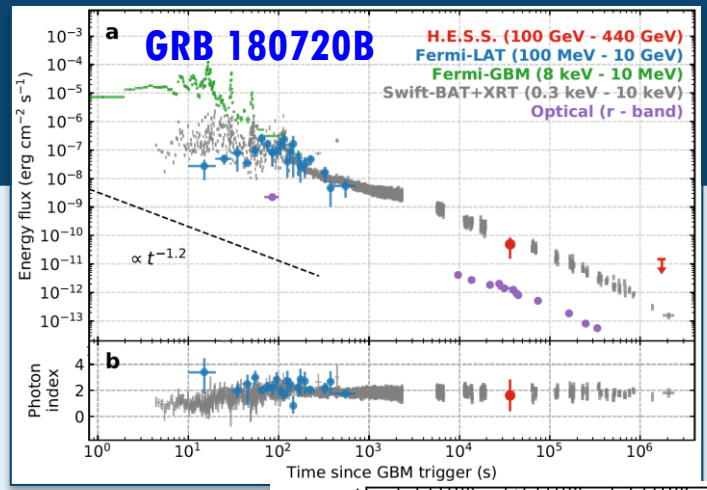
z = 0.653

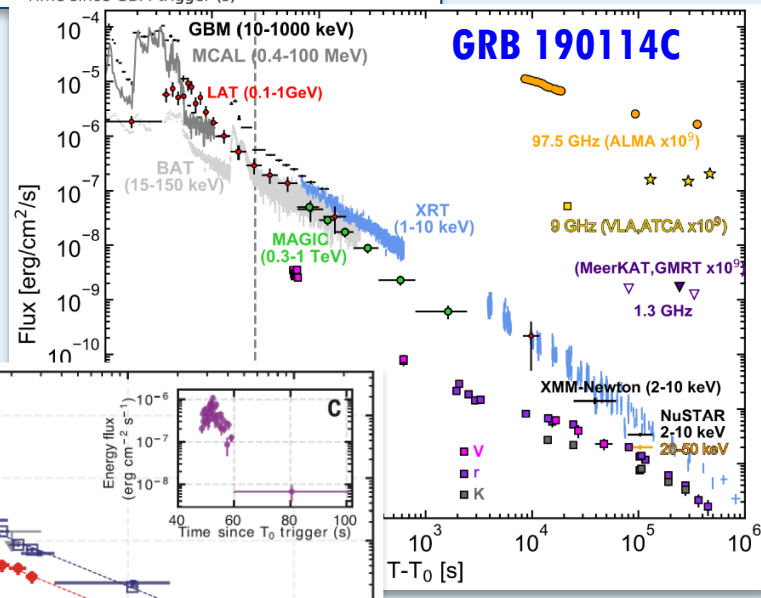
z = 0.4245

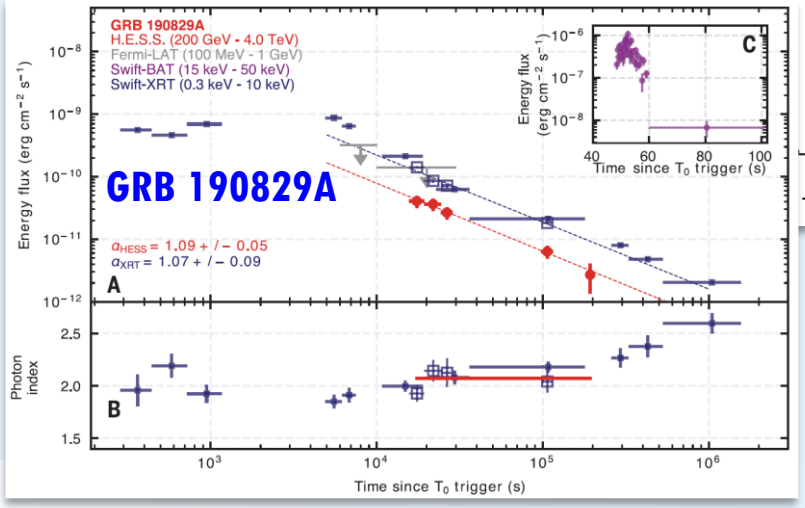
z = 0.0785

z = 0.43

z = 1.1







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**

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  - Fermi-LAT
  - within T_0+200
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  - ...upper limits 8 hours after trigger
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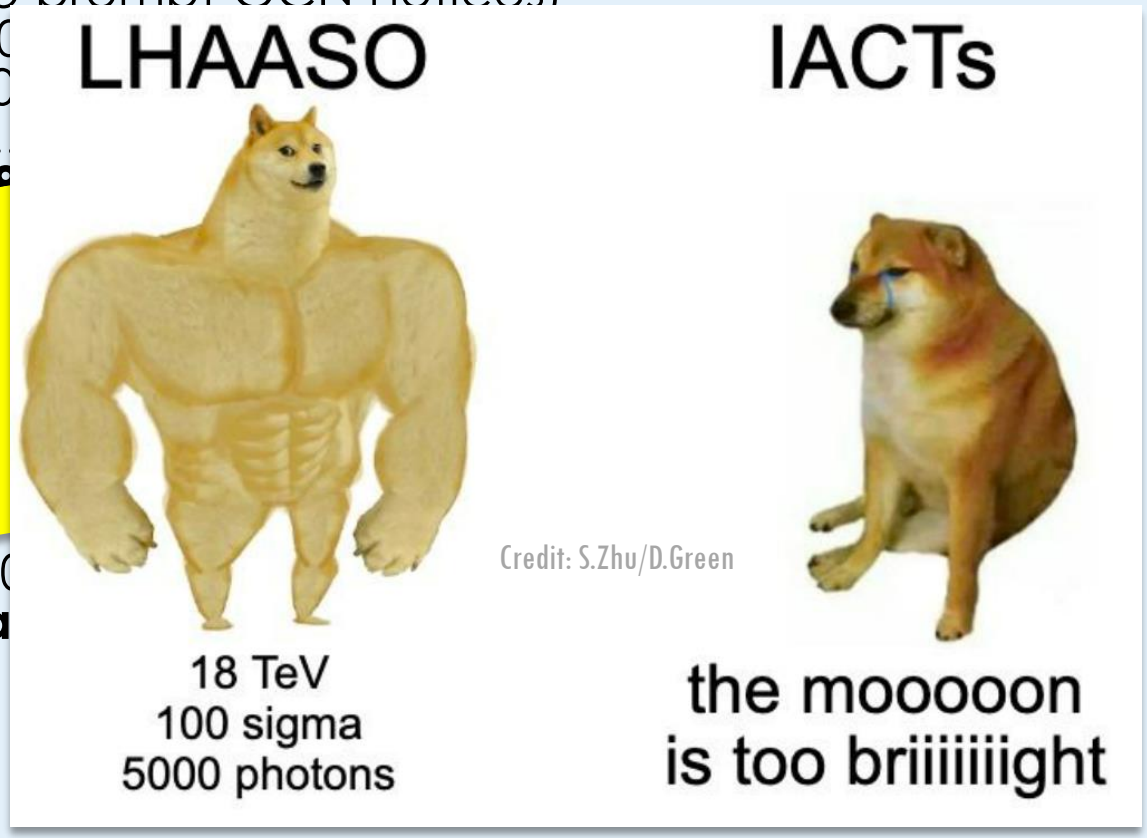
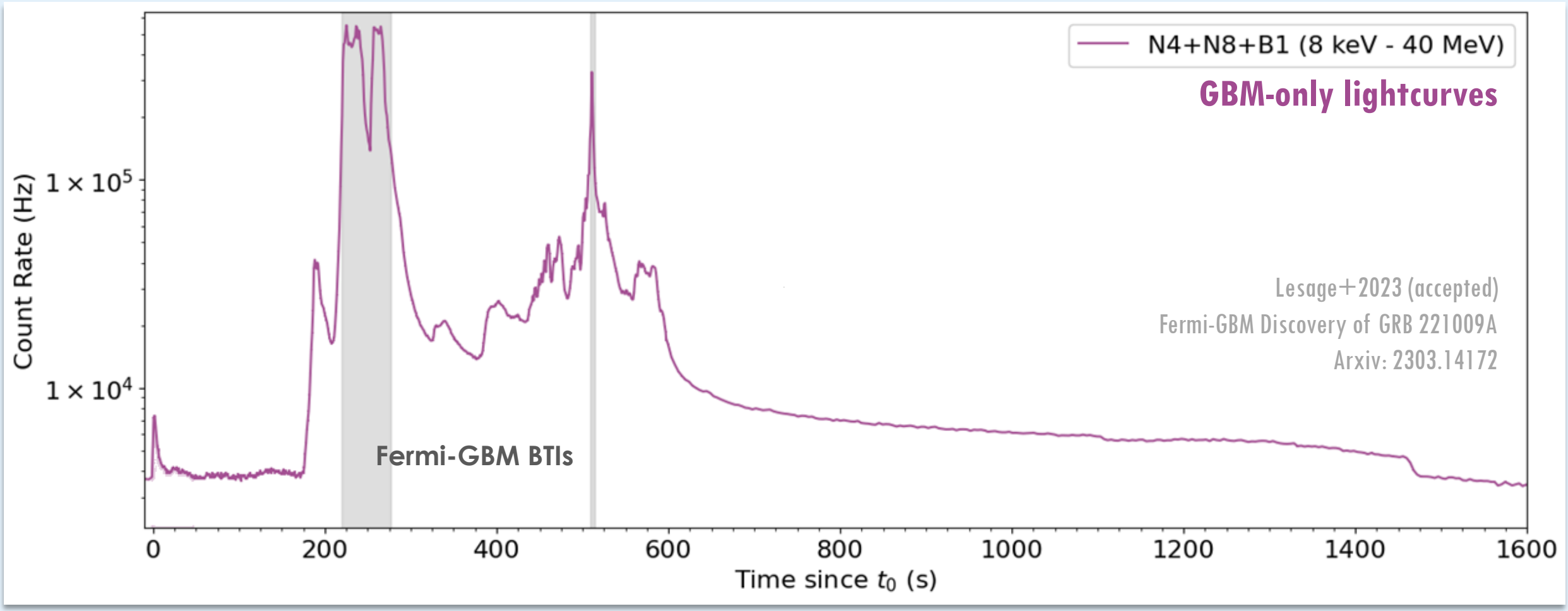
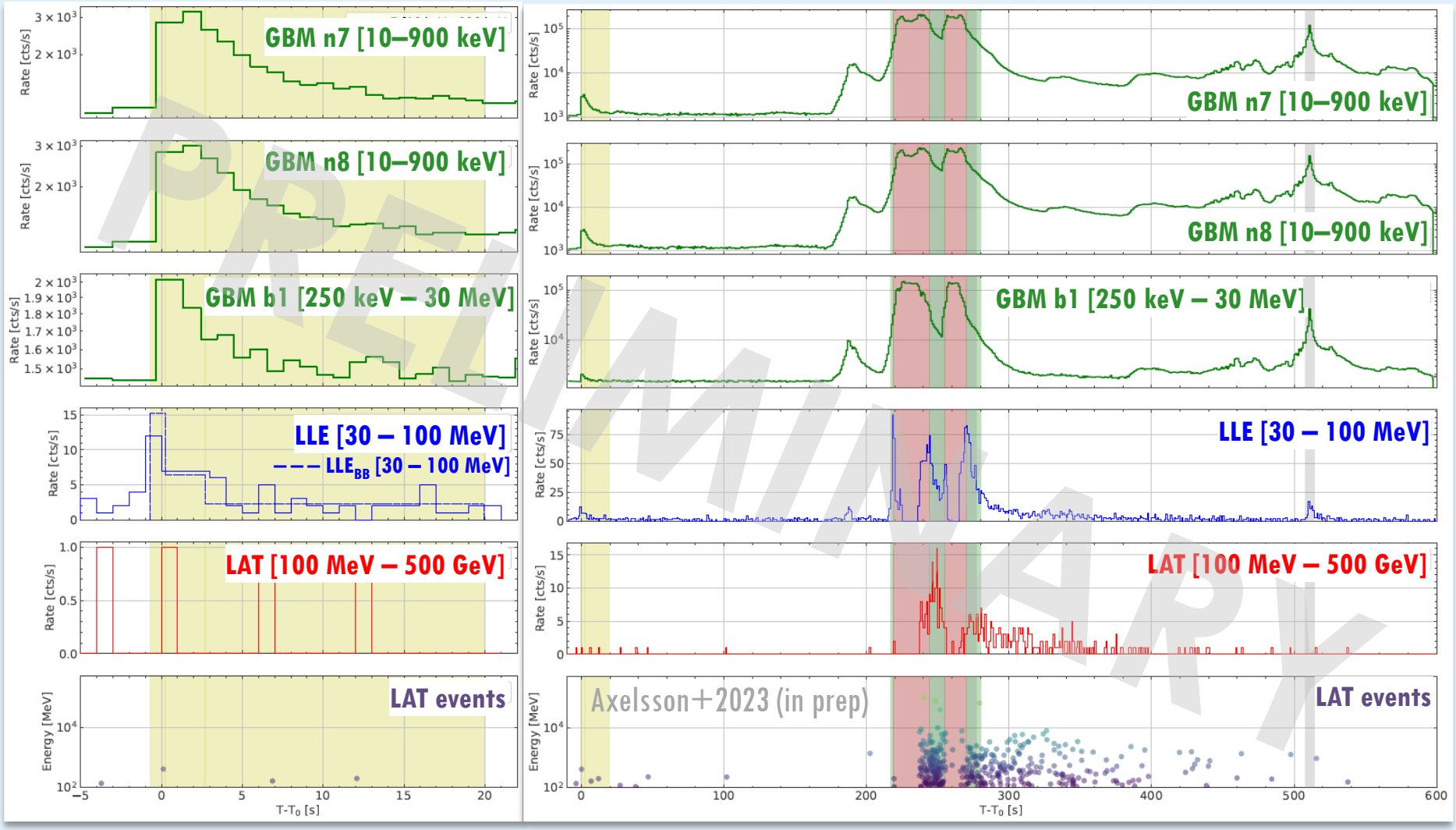
Exceptional gamma-ray keV/MeV/GeV detection
Exceptional x-ray detection
LHASO TeV detection
No IACT detection (full moon!)
No neutrino detection



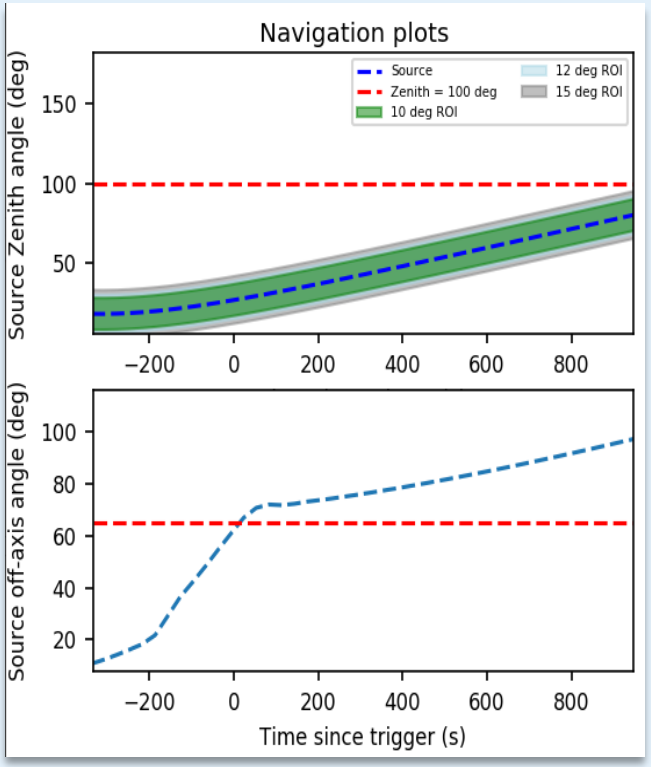
Fermi high-energy light curves



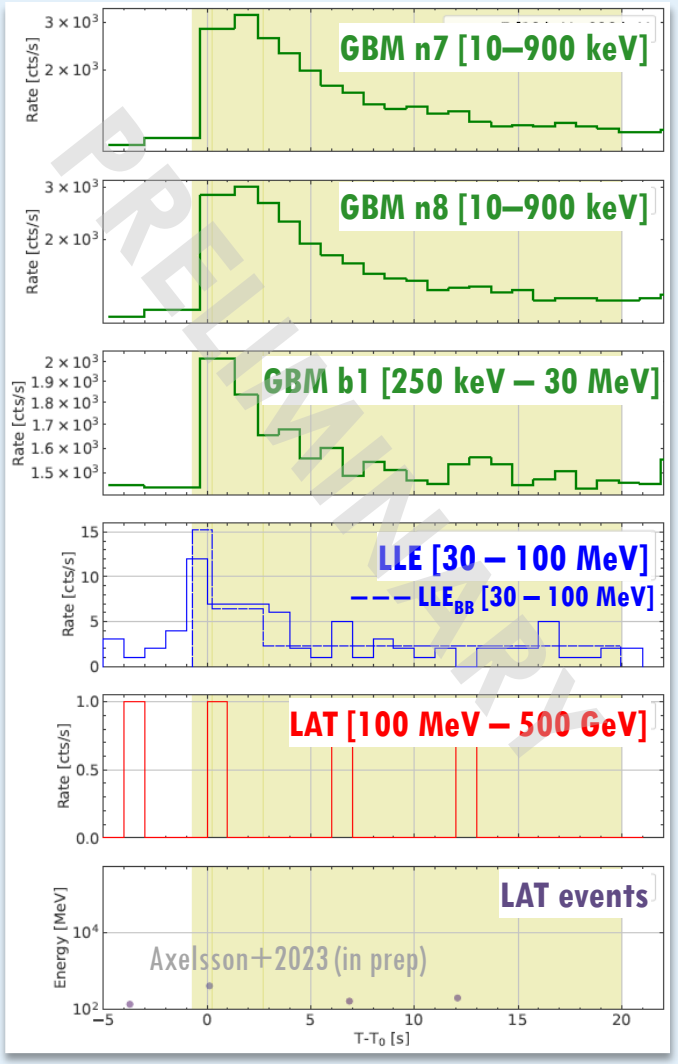
Fermi high-energy light curves



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

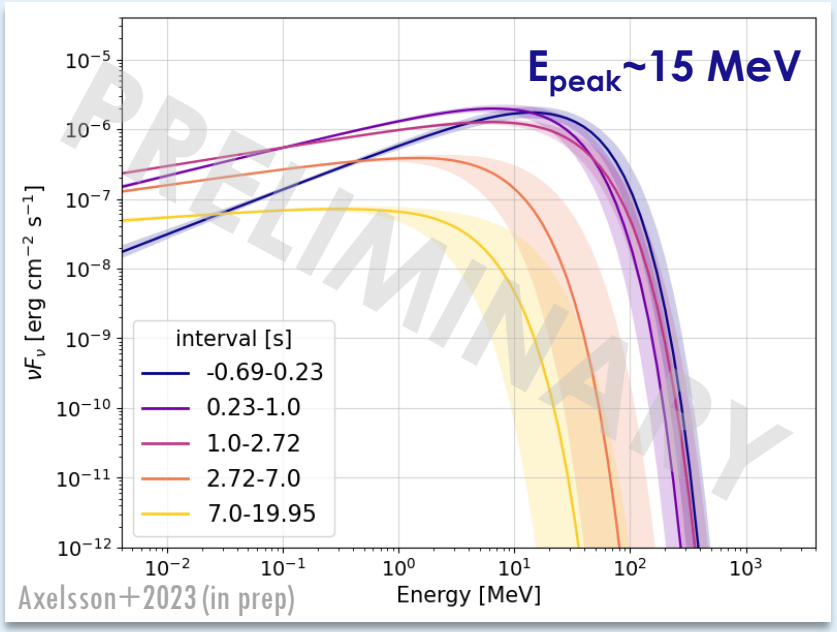


The triggering pulse



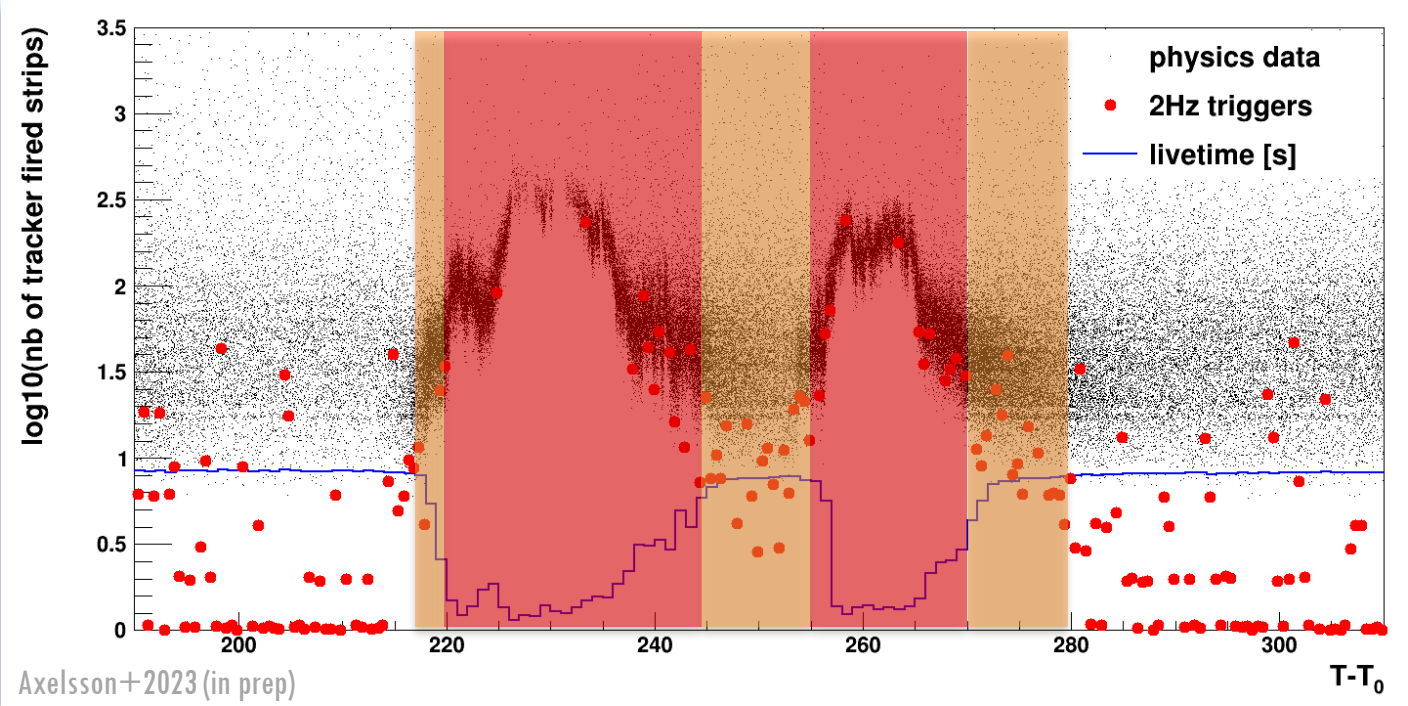
- Defined as first 20 s post GBM trigger
- At high-energies: Visible in LLE only
  - No LAT photons with p>90% association
  - Bayesian blocks (BB) algorithm applied to LLE data

- 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



Data issues and Bad Time Intervals (BTIs)

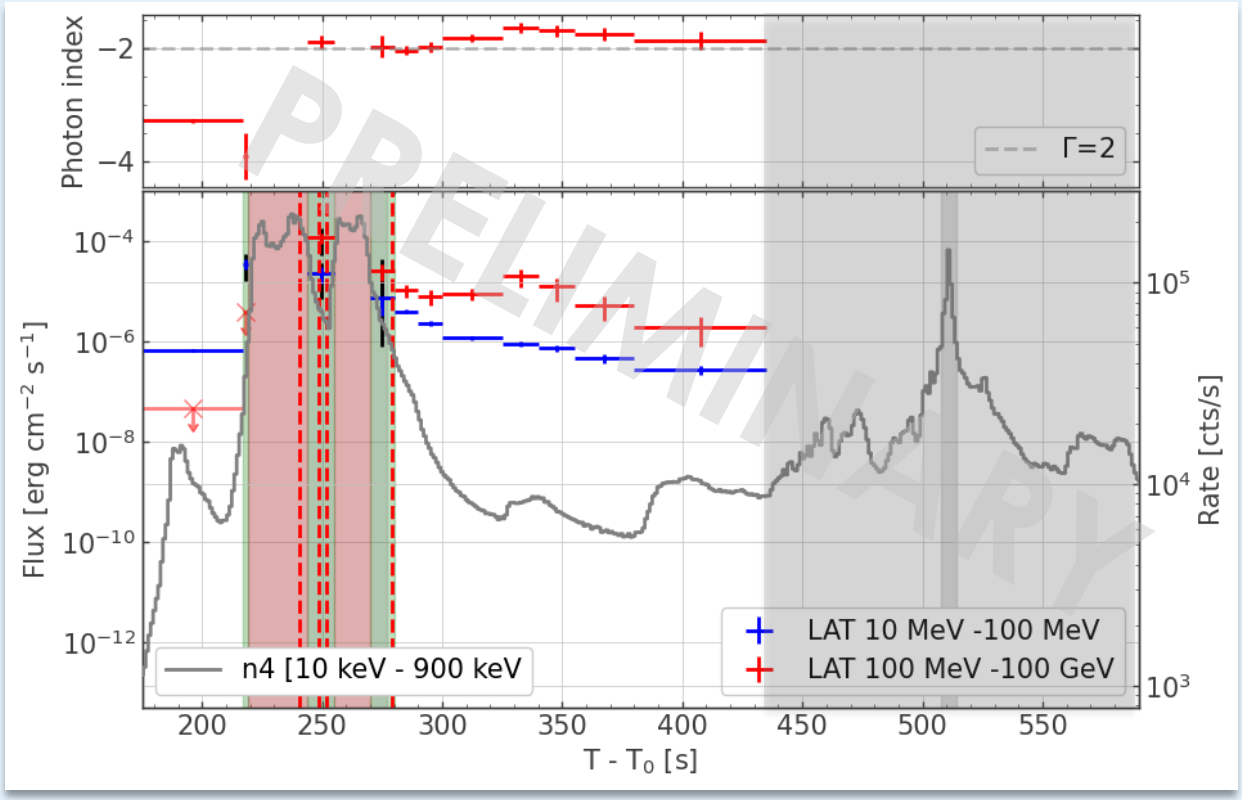
- Effects in the LAT due to high flux of X- and soft gamma rays
  - Extra energy (up to 300 MeV) deposited in the Tracker
  - Extra "hits" in the tracker
  - Decrease of the live time

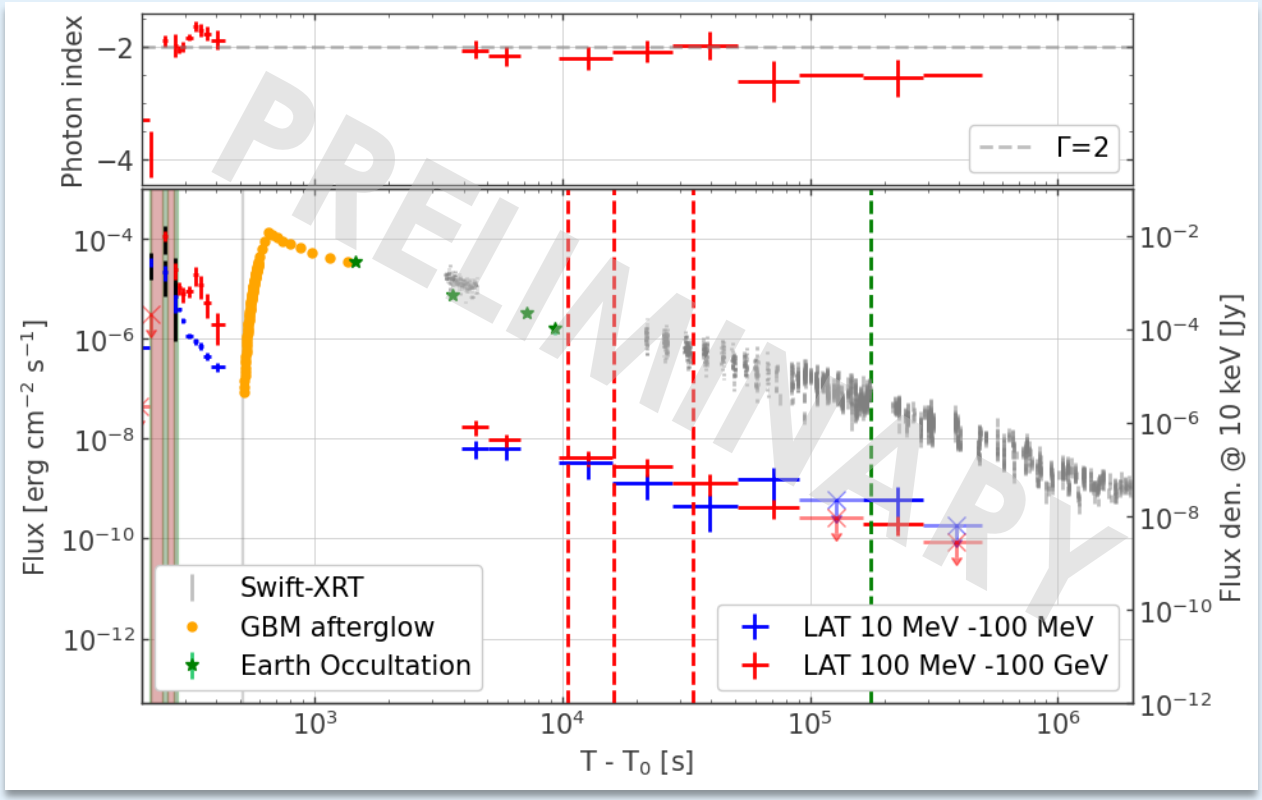


- **Data recovery**
  - Modified reconstruction algorithm to reduce extra hits in the tracker
  - **3 intervals recovered (orange boxes)**
    - Standard analysis can be performed E>125 MeV, no LLE, efficiency 75 ± 25 % with `TRANSIENT` class
- **Bad Time Intervals**:
  - **No standard analysis possible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

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

High-energy emission analysis





Early times LLE+LAT analysis

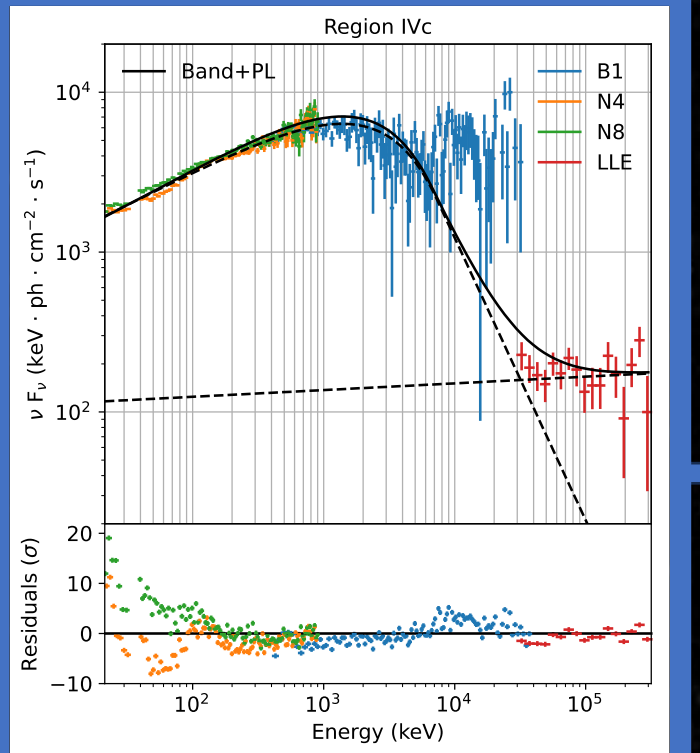
- Estimate flux maximum in the BTI
- Bulk Lorentz factor estimation from opacity arguments: **Γ>450**

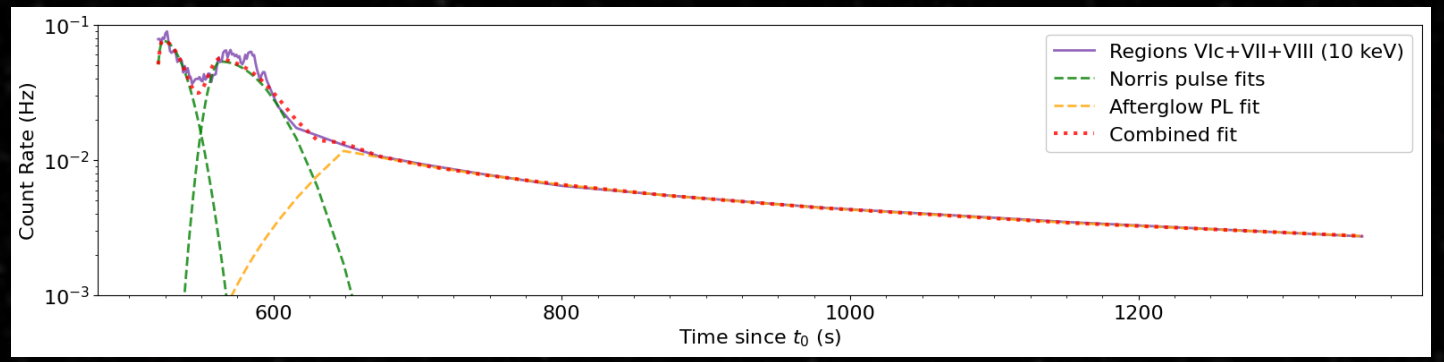
Late times LAT analysis

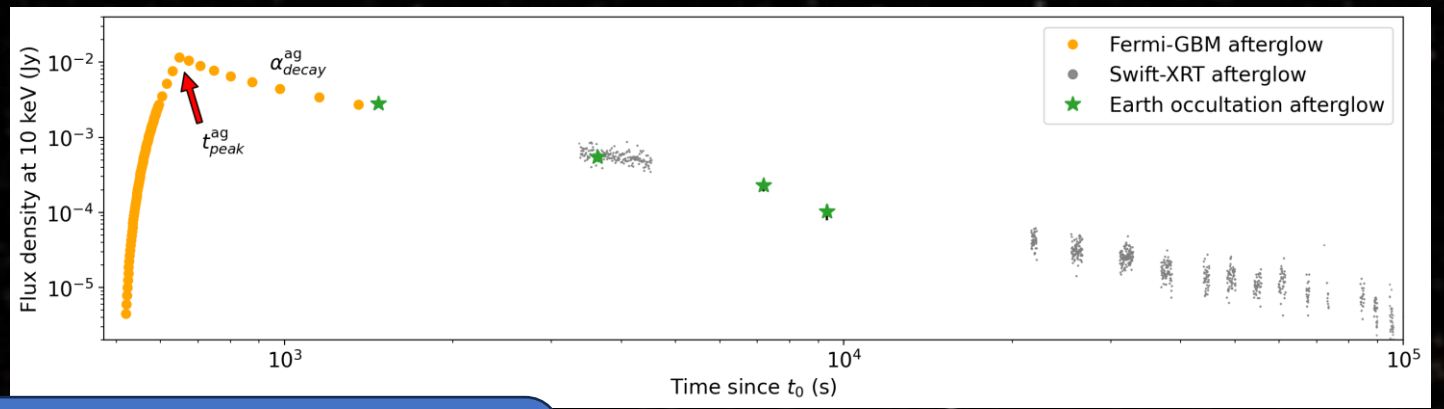
- GRB duration: **175 ks** (~ 2 days: record!)
- Afterglow flux PL decay (index ~ **−1.3**)

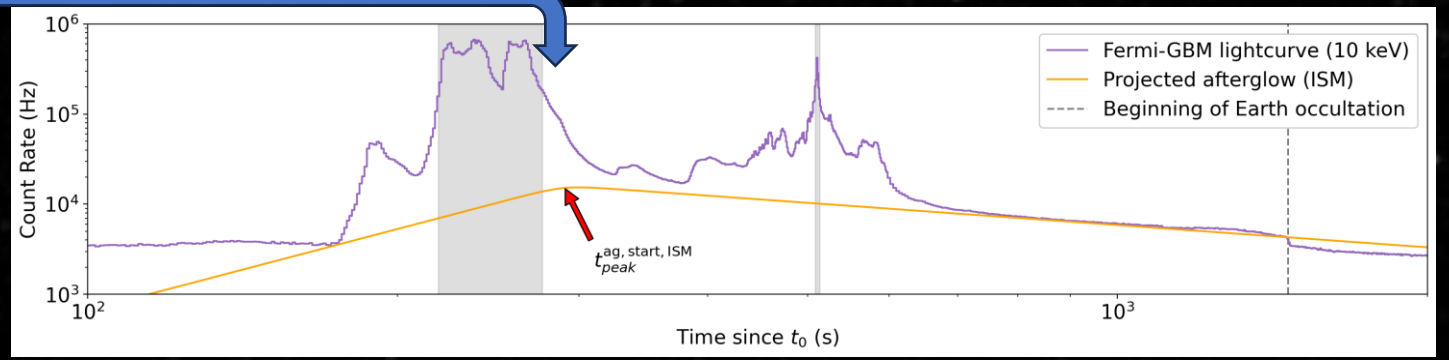
Afterglow

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

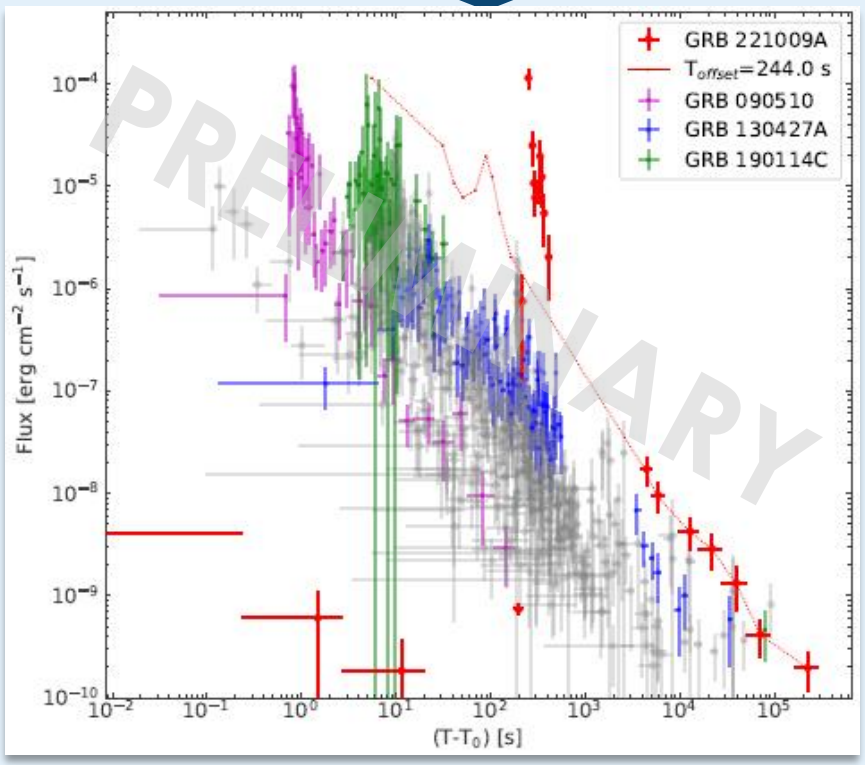


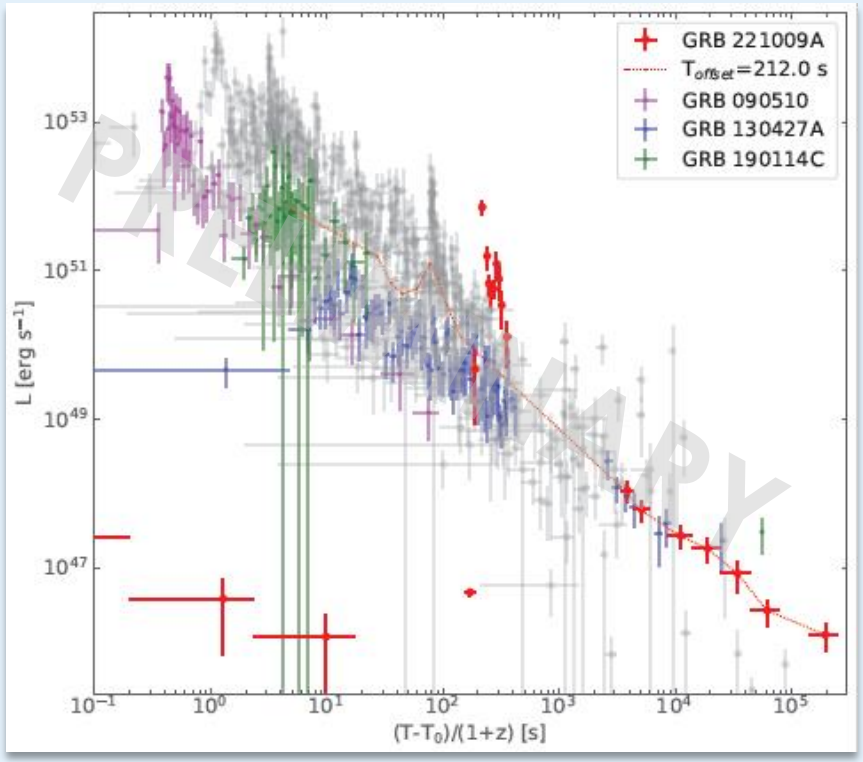


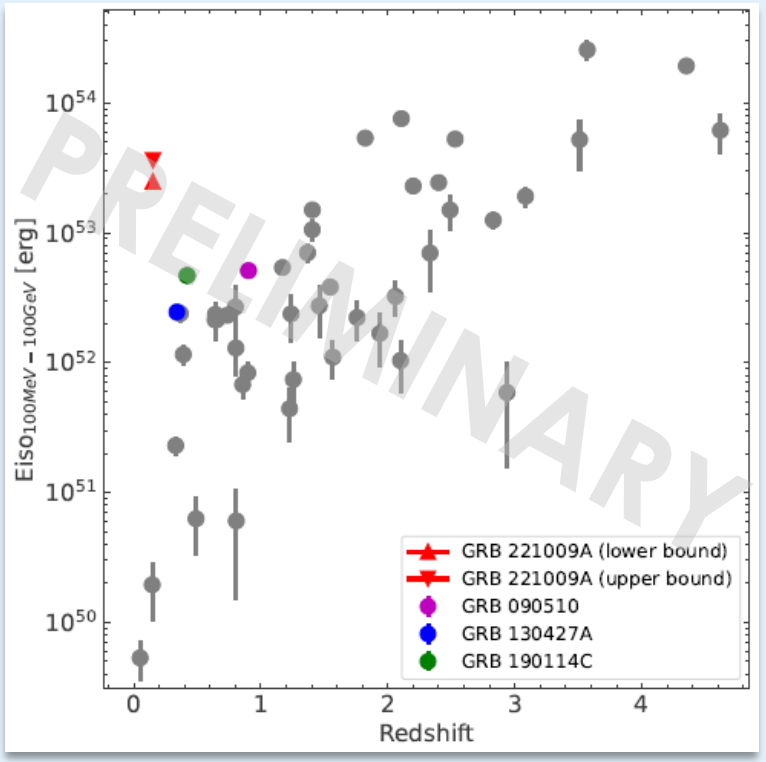




GRB 221009A in the context of other LAT GRBs

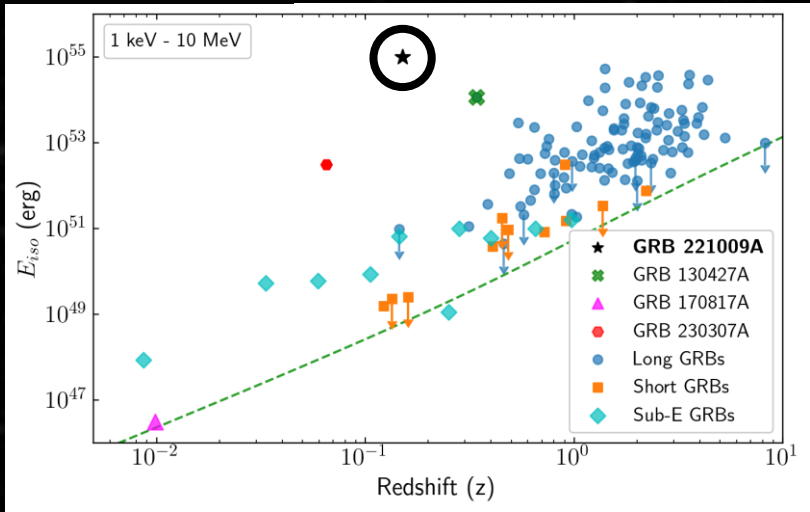






- **Record breaking** in terms of highest fluence, longest GeV afterglow and highest photon energy (100 and 400 GeV photons)
- Not quite exceptional in terms of E_{iso}
  - Comparable to high-redshift LAT detected GRBs, but very close: **Extremely rare**!

Energetics
(4 measures)

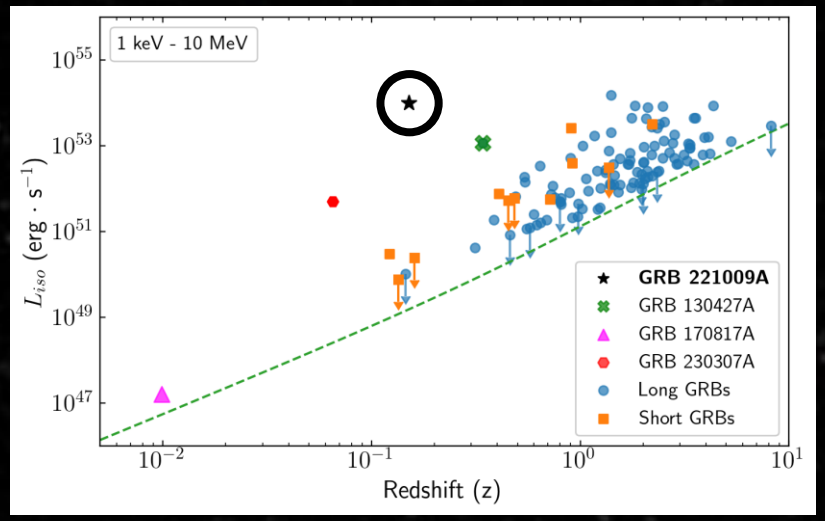


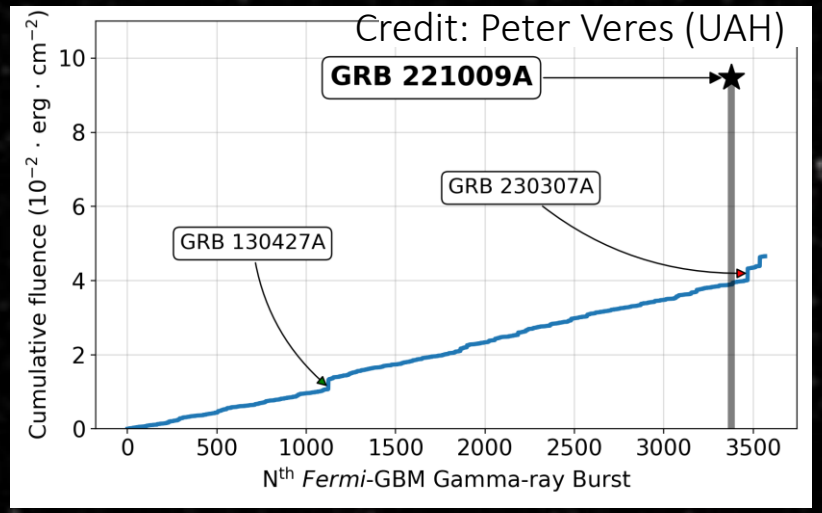
E_{iso} ~ **1.0 x 10^{55} erg**

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}**





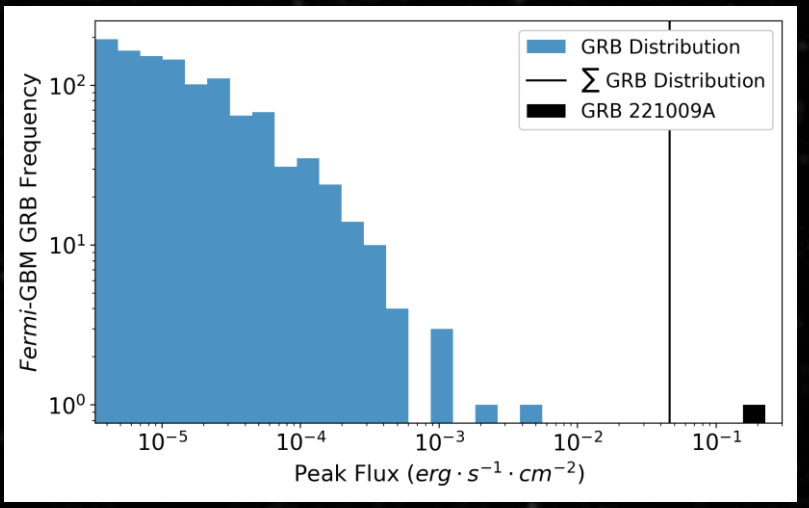
Consistent with:

Konus-WIND

GRBAlpha

Insight-HXMT

GECAM-C



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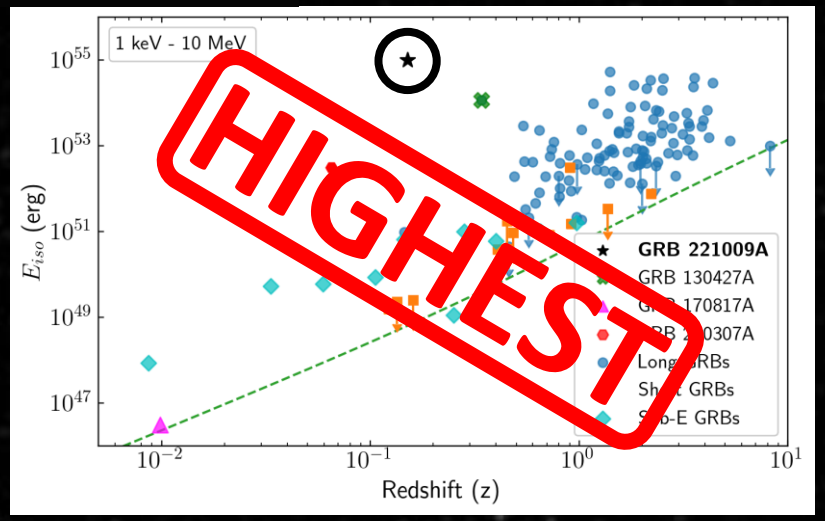

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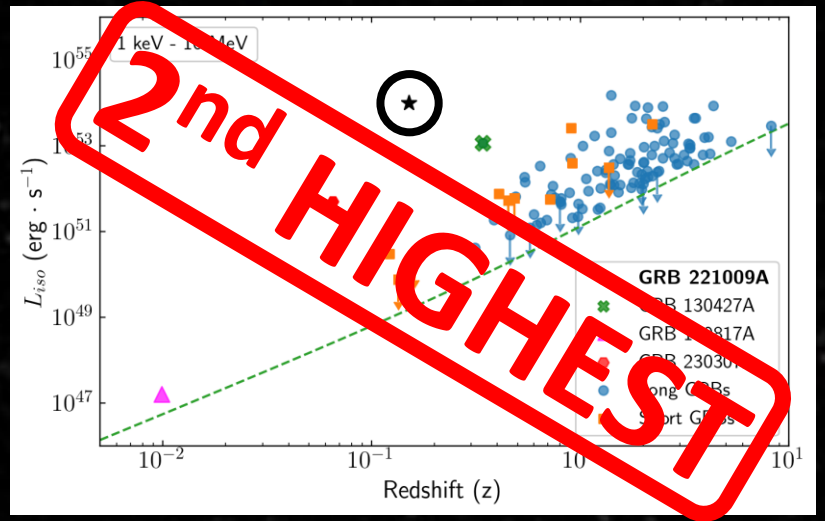

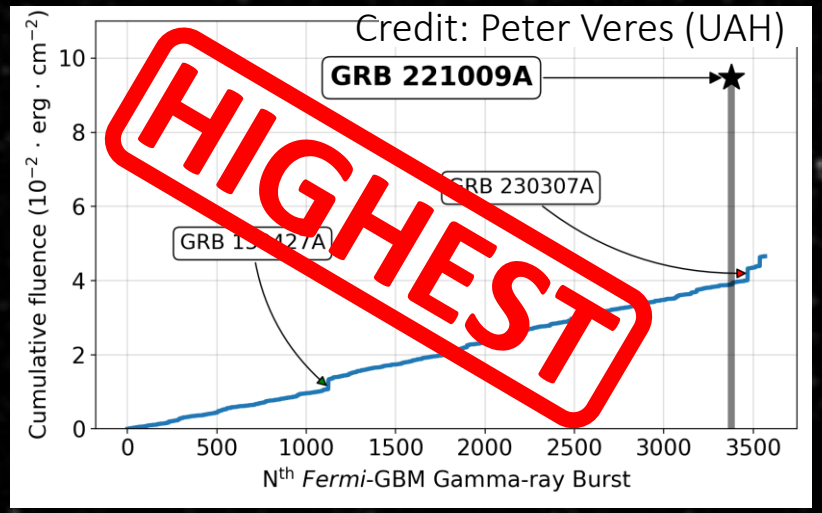

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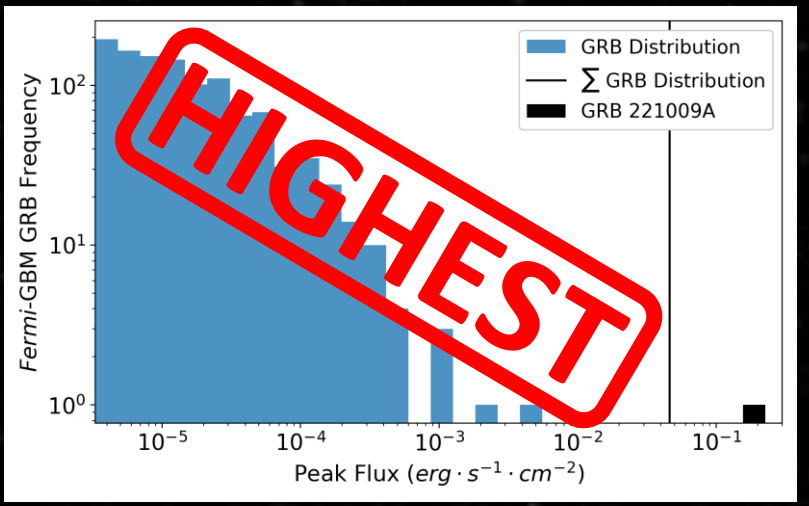
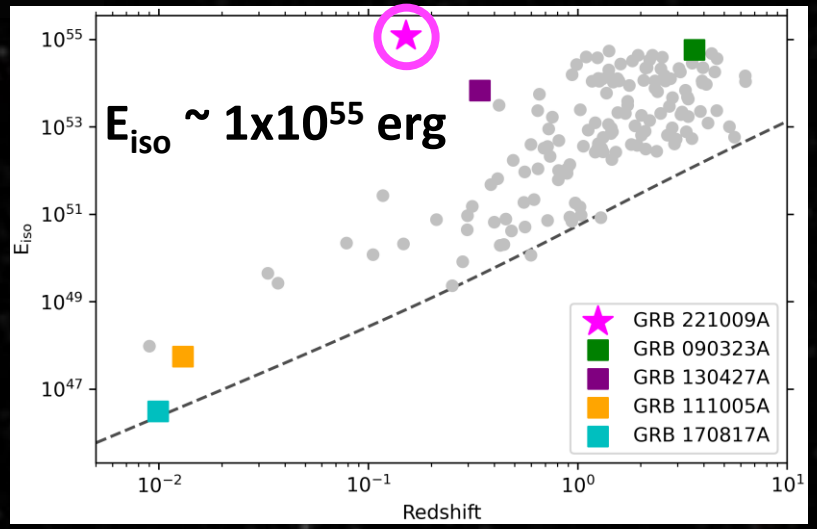
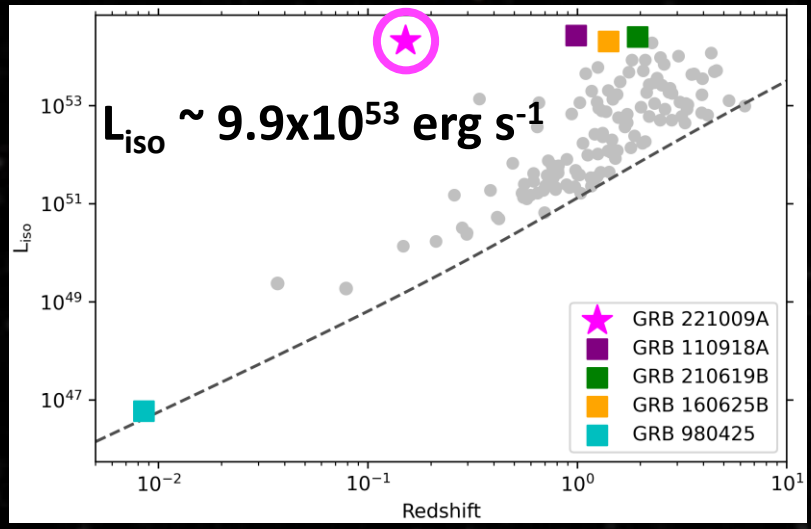
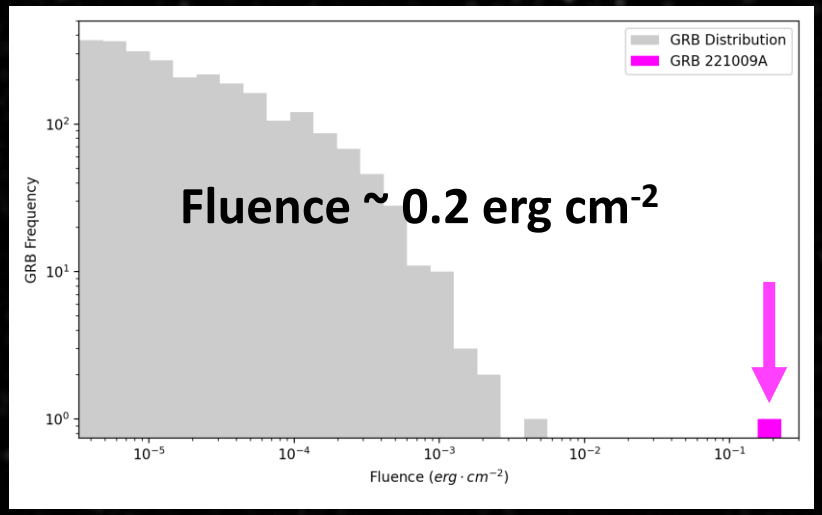


Is it the B.O.A.T.?

(4 measures)

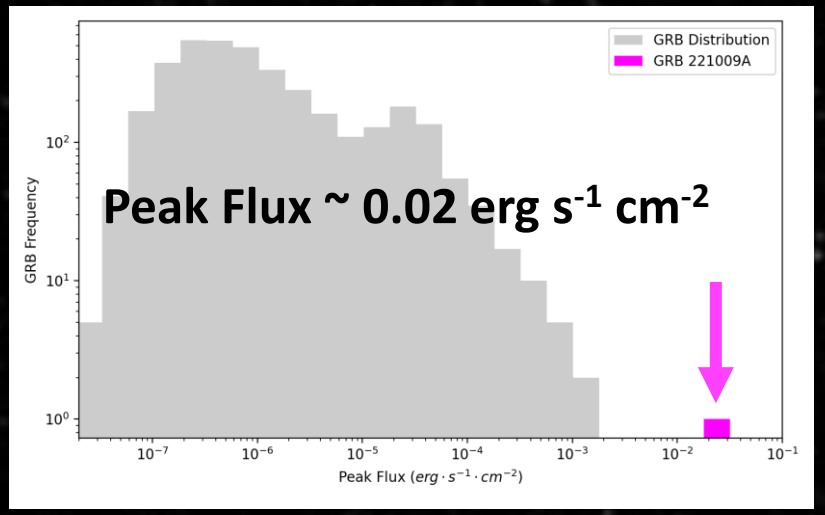






55 years of data

Burns et al. (2023)

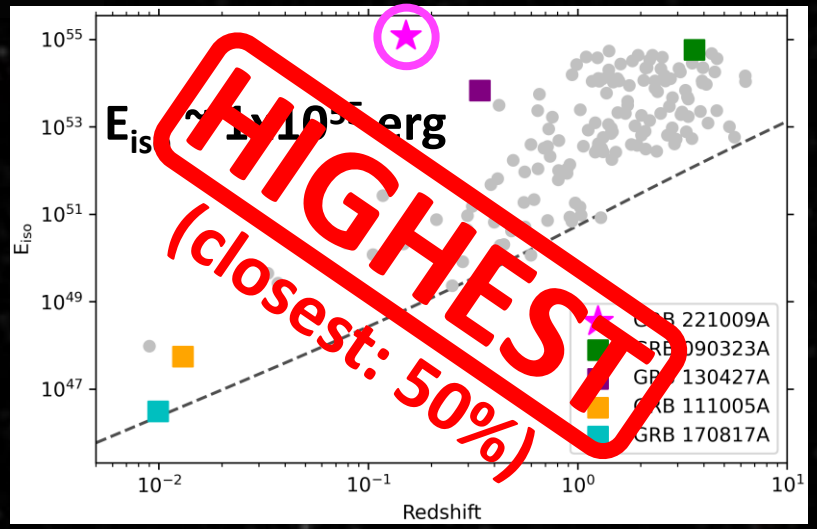


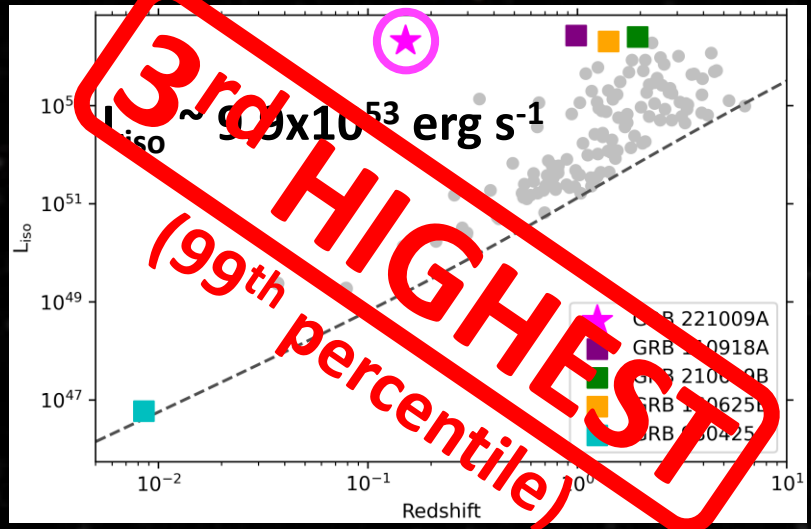
Is it the B.O.A.T.?

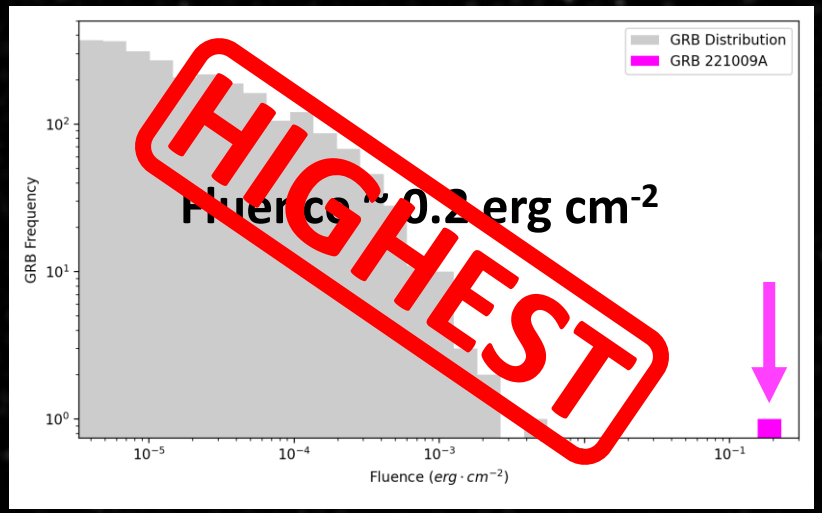
(4 measures)

YES!

YES!







¾ measures of brightness

55 years of data

Burns et al. (2023)

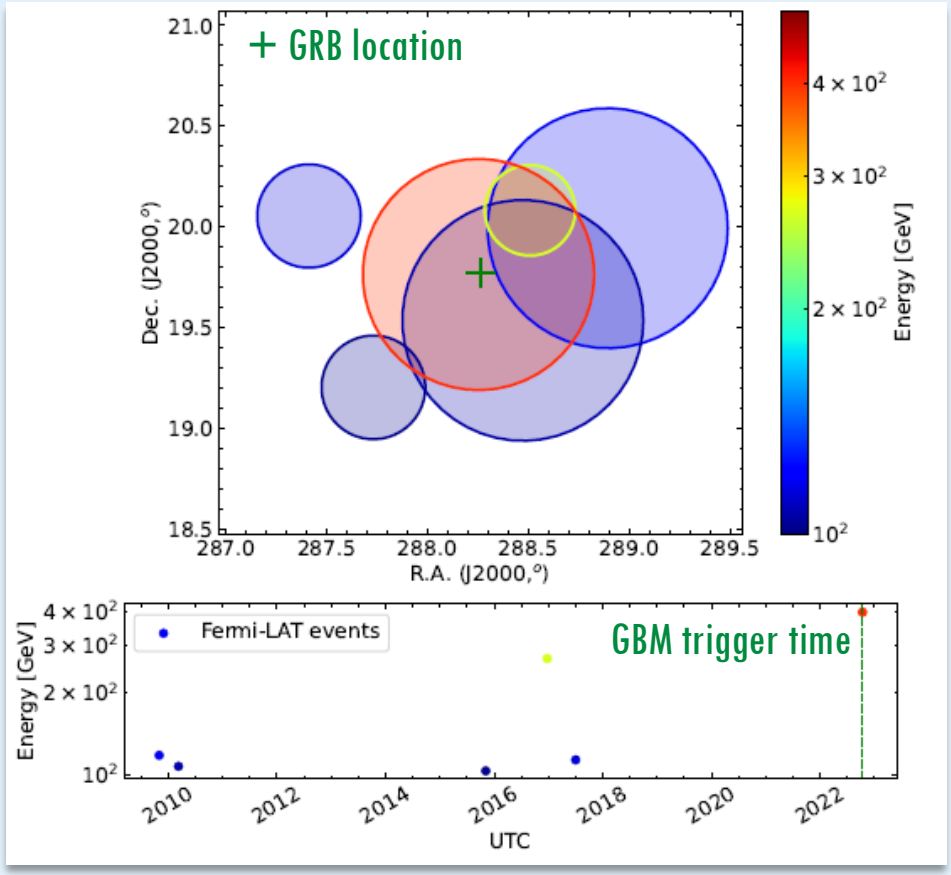
The 400 GeV event

- **Highest energy event**
  - Direction compatible with GRB location
  - Arriving @ T0+33 ks
  - Conversion in lower part of the LAT tracker (thicker tungsten layers, slightly worse PSF)

- Considering the entire Fermi mission elapsed time, calculation of chance probability of such an event is **slightly below 4 σ**
  - Cannot firmly exclude that the photon is a background event, likely associated with Milky Way diffuse emission

- Assuming the event to be indeed associated with the GRB, the probability that it is generated from the high-energy extrapolation of the low-energy part of the spectrum is relatively low (**~ 5 σ**)
  - Event not related to the GRB?
  - Event produced by unconventional emission mechanism?

Arrival direction (top) and times (bottom) of all photons in the Fermi mission with E>100 GeV within 1° of GRB location [Radii of circles = 95% containment PSF radius]



Conclusions

- GRB 221009A is the **brightest GRB** ever detected by GBM and LAT
  - …and by many other instruments!

- **Complex event**
  - Required a lot of unconventional analysis (In progress)
  - Many records have been broken
    - Fluence, high energy events, duration!

- Stay tuned for **more analysis and interpretation** to come in the upcoming publication(s)!

Credit: NASA's Goddard Space Flight Center and Adam Goldstein (USRA)