X-ray Flares and Afterglows of GRBs at High and Very-High-Energies

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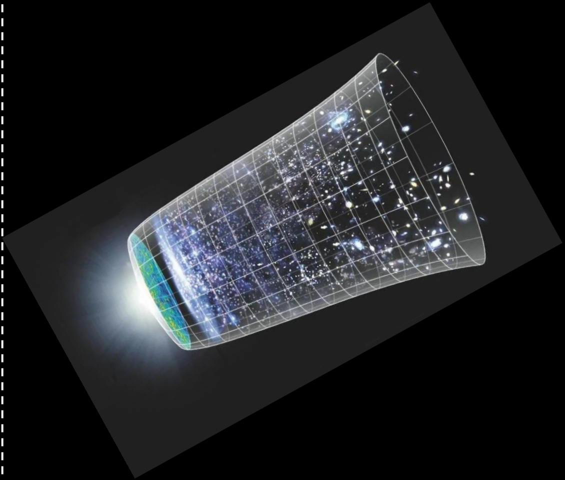
Gamma Ray Bursts

Most energetic transients in the Universe

$L_{\gamma,iso} \sim 10^{48} - 10^{55}$ erg/s

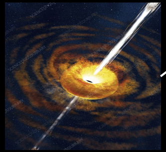
Probes of the distant Universe

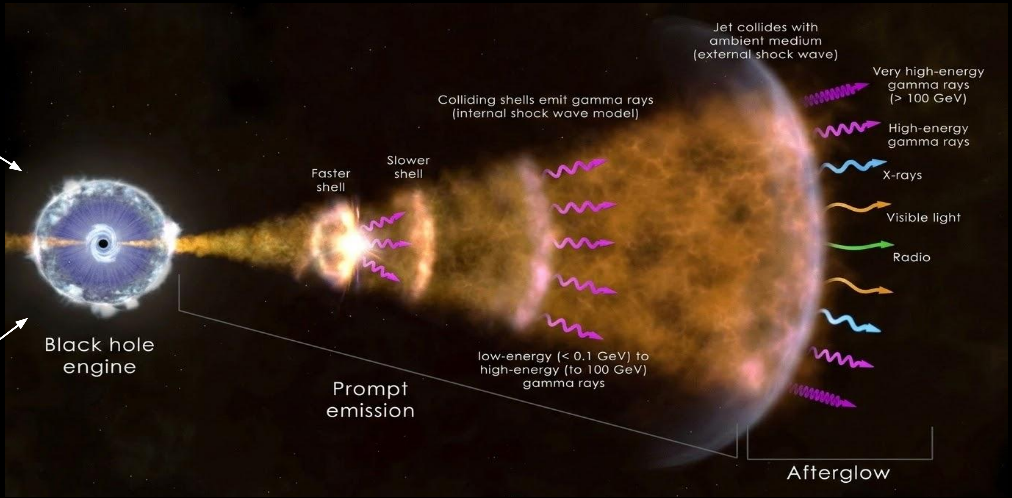


Physics of relativistic jets

Particle acceleration
Radiation mechanisms

Emission Mechanism





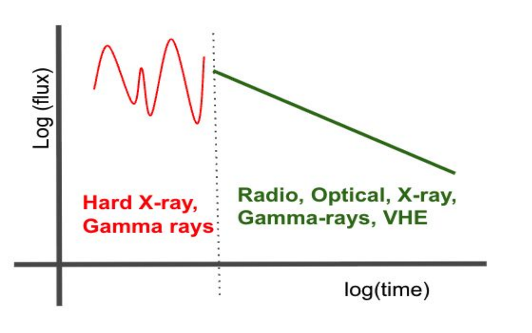
Credit: NASA/ICRAR.

Photons ~ **MeV**

Variability: **0.01-1s**

Duration: **0.1 - 1000s**

E_{iso} - $\mathbf{10^{50}}$ **-** $\mathbf{10^{54}}$ **erg**



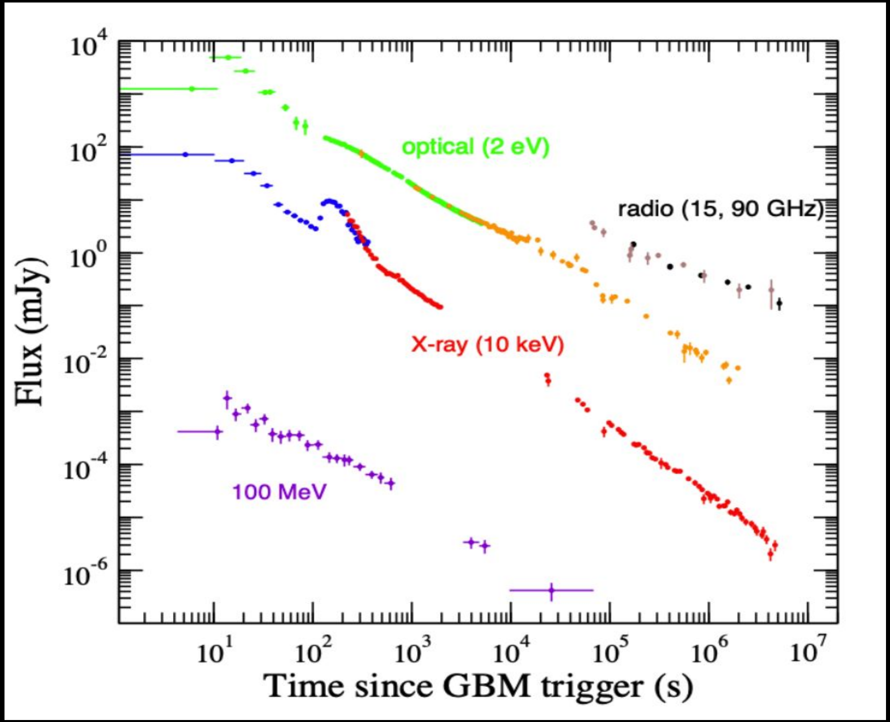
Photons ~ Radio to VHE

Duration: Days to weeks

PL temporal decay LC

Non-Thermal Spectra

Afterglow



GRB 130427A, Panaitescu et. al. 2013

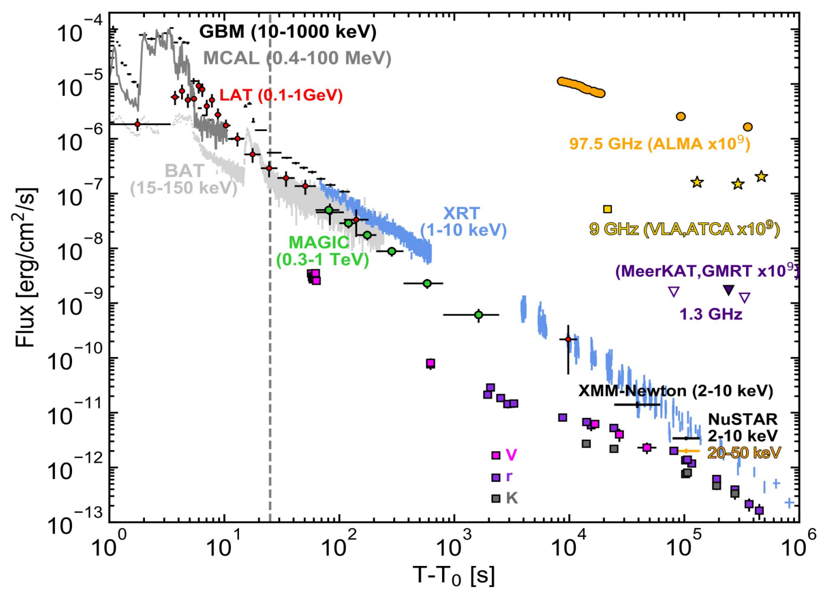
Discovered
Costa et al. 1997

Predicted
Paczynksi & Rhodes 1993
Meszaros & Rees 1997

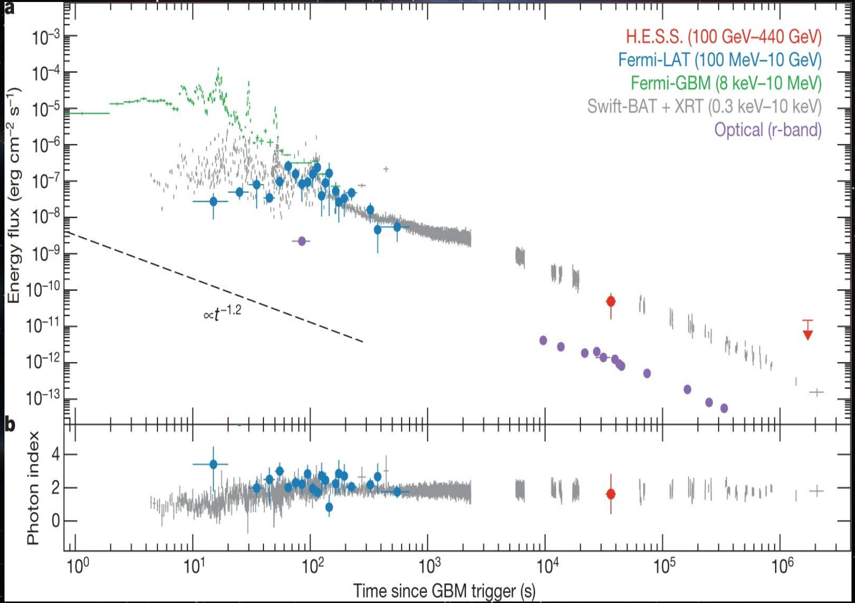
Dynamics
Blandford & Mckee 1976

Phenomenology
Sari et al. 1998

Afterglows at VHE (>100 GeV)

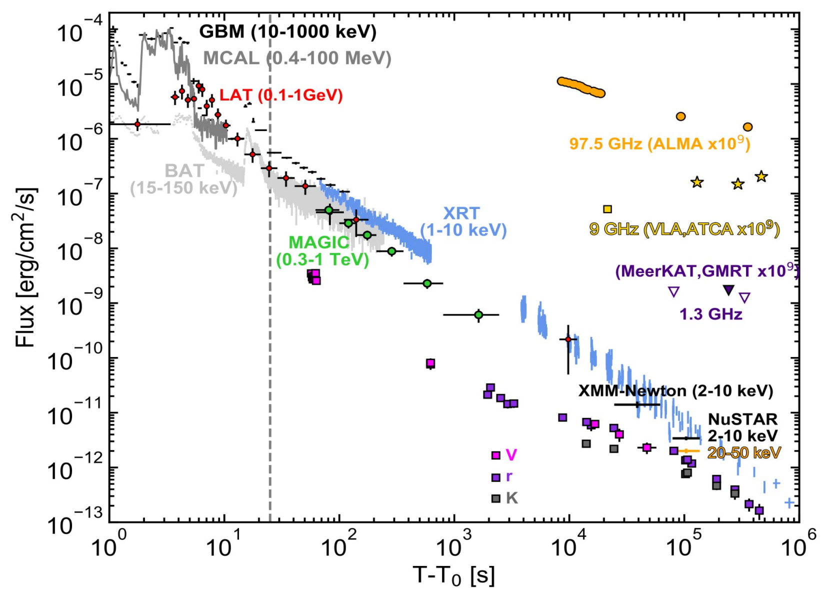


GRB190114C, MAGIC collaboration, Nature 2019



GRB180720B, H.E.S.S. collaboration, Nature 2019

Afterglows at VHE (>100 GeV)



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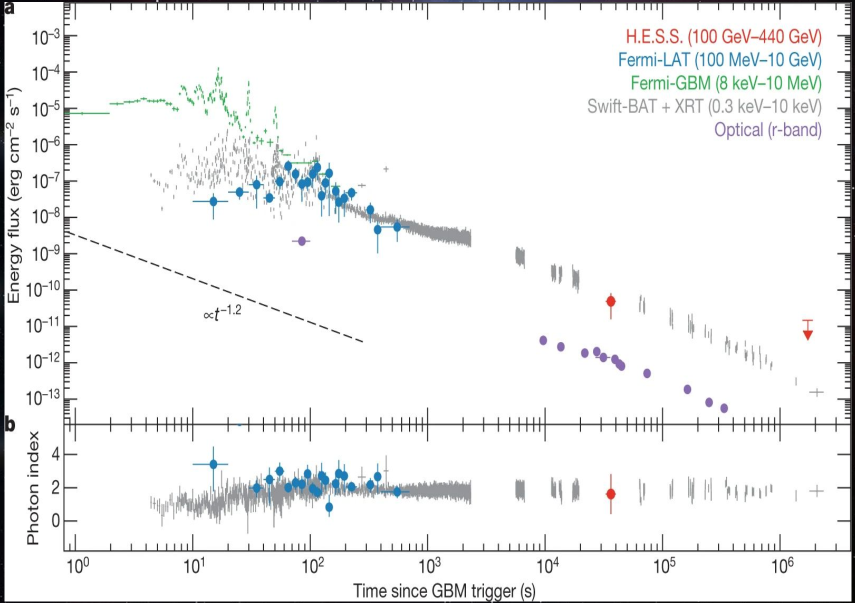
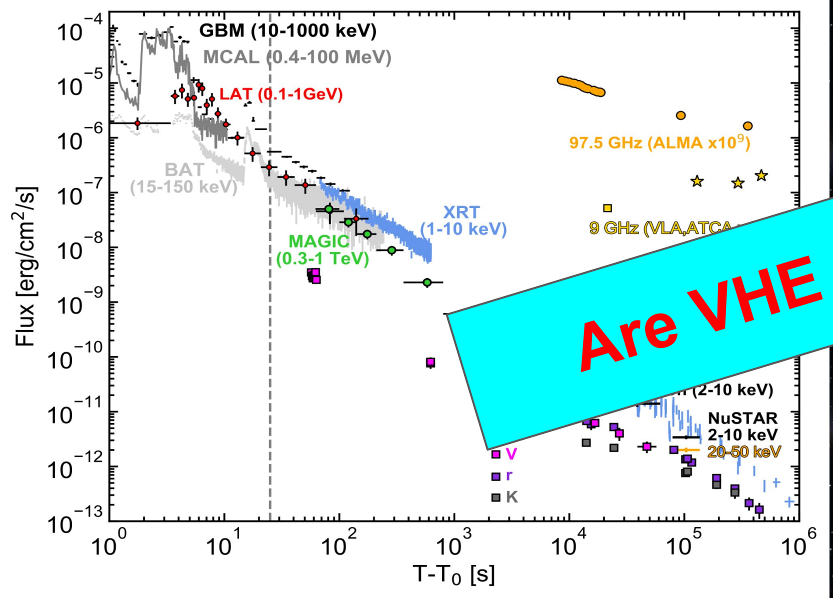


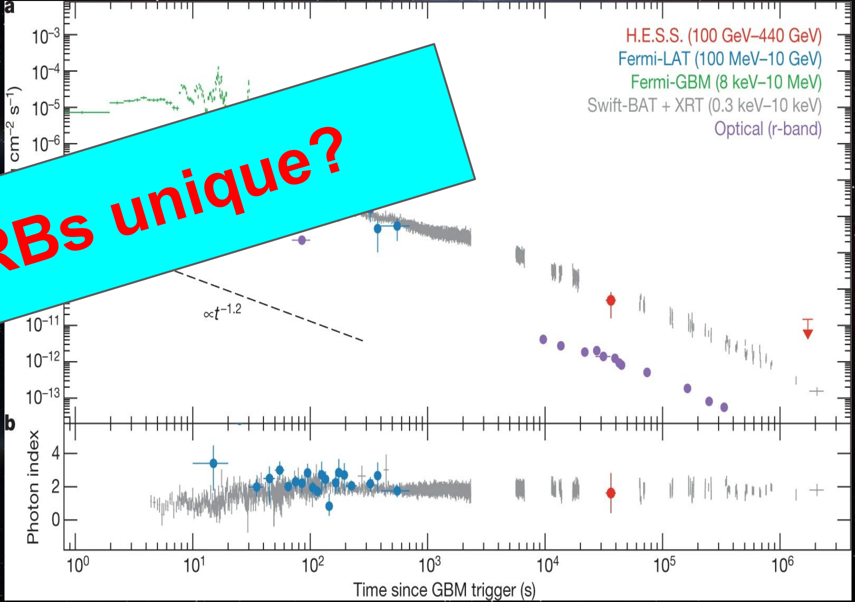
GRB180720B, H.E.S.S. collaboration, Nature 2019

*Only **5 GRBs at VHE** with definite detection so far!*

Afterglows at VHE (>100 GeV)



GRB190114C, MAGIC collaboration, Nature 2019



GRB180720B, H.E.S.S. collaboration, Nature 2019

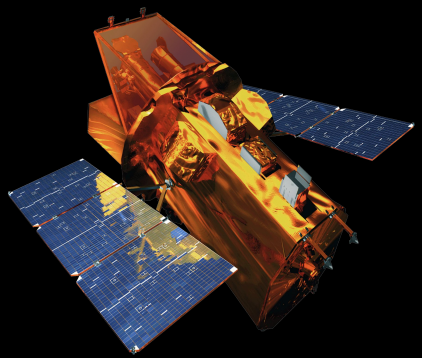
Are VHE GRBs unique?

*Only **5 GRBs at VHE** with definite detection so far!*

Multi-wavelength view of Afterglow

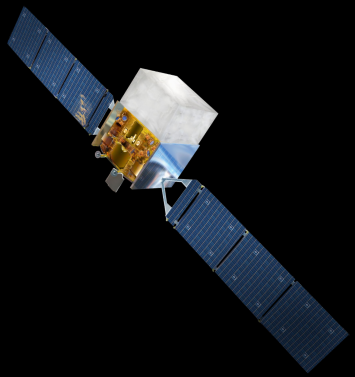
- ➢ Are VHE GRBs unique?
- ➢ Dominant radiation process in afterglow.
- ➢ Microphysical parameter to explain afterglow shock physics($\boldsymbol{\epsilon_e}$, $\boldsymbol{\epsilon_B}$, **p, medium, n**).

Neils Gehrels Swift Observatory



Swift/XRT: 0.3-10 keV
Swift/BAT: 15-150 keV

Fermi Gamma-ray Space Telescope



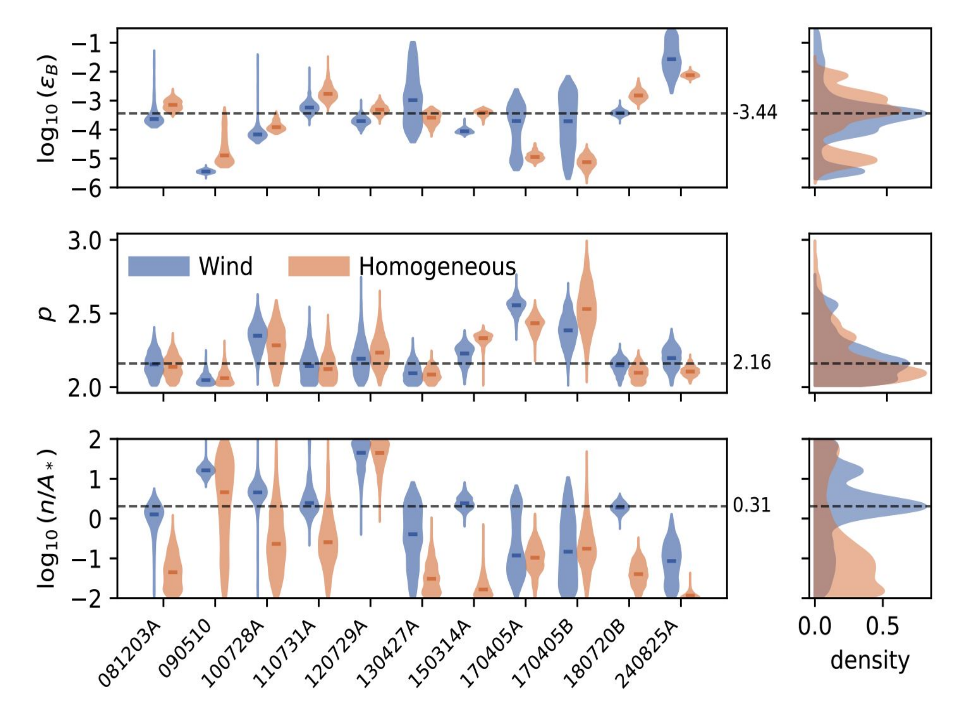
Fermi/LAT: 100 MeV - 300 GeV

Tiwari et al. 2025

Afterglow Physics - Microphysical parameters

SSC in wind-medium with η=2.04, p=2.16, ϵ_e~ 0.1, ϵ_B~ $10^{-3.44}$

Can explain both X-ray and GeV simultaneously.



Tiwari et al. 2025

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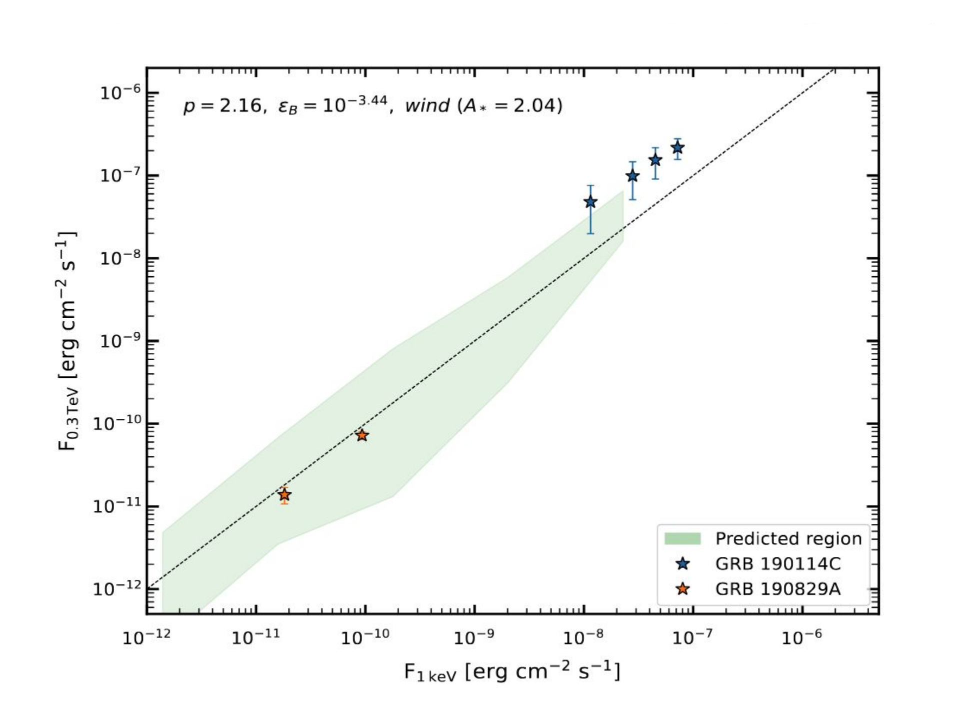
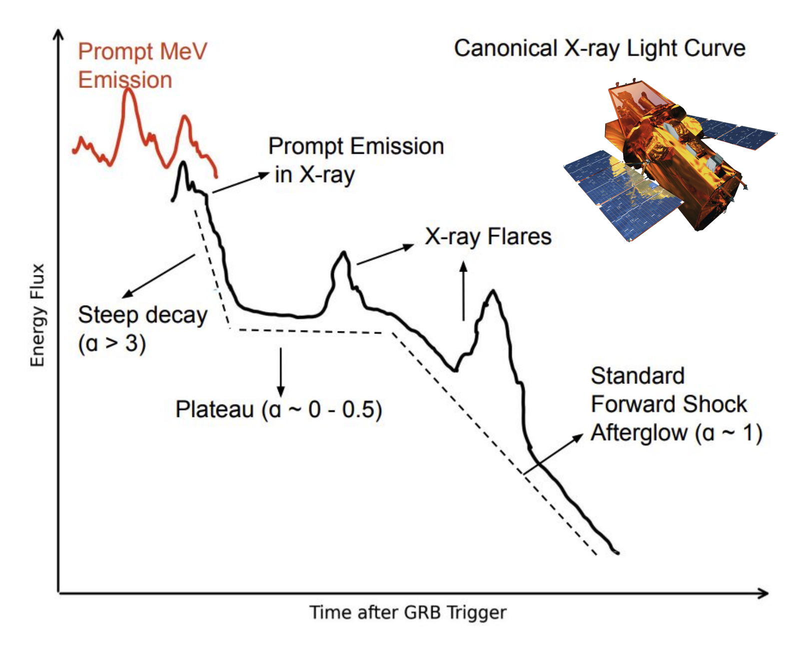
Also predict TeV ~ X-ray



Inverse compton, wind medium and lower ϵ_B

Tiwari et al. 2025

Complexity in X-ray



Tiwari et al. 2026 (under review)

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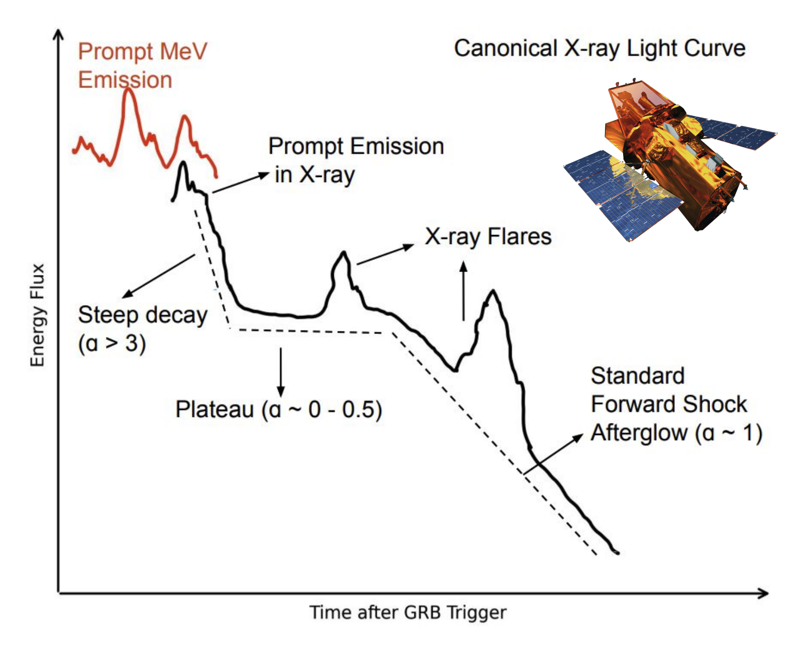


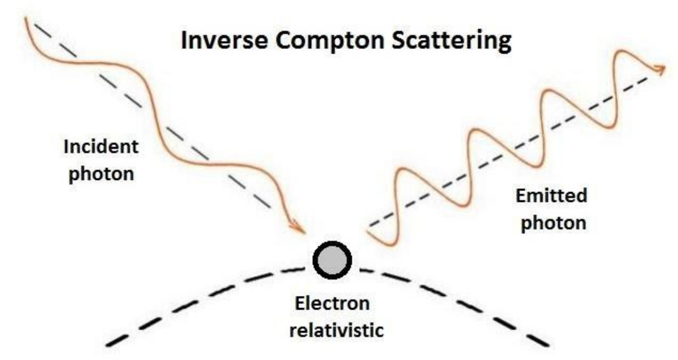
X-ray Flares

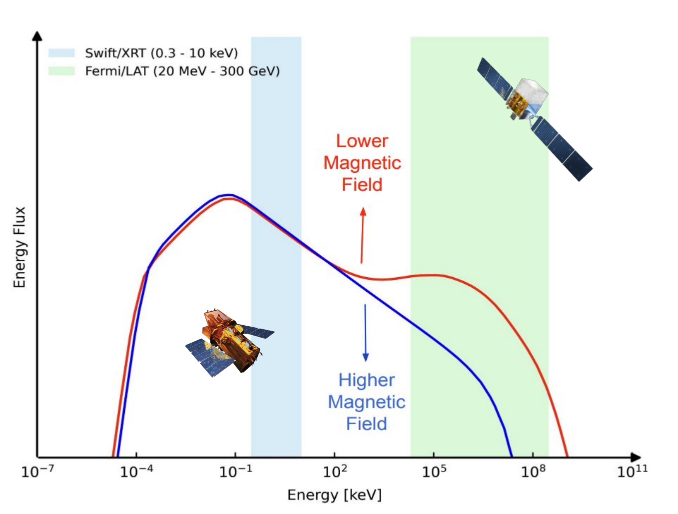
- Sudden re-brightening in X-ray lightcurve after end of prompt MeV emission.
- Variability in minutes.
- Unknown origin
- Temporal and spectral analyses ~ properties like the prompt emission
- Internal shock origin (δt/t ~ 0.1)
- HE studies can help!

Tiwari et al. 2026 (under review)

GeV search for flares?

- ★ Inverse Compton scattering: relativistic electrons up-scatter photons - SSC / EIC
- ★ HE and VHE probe property of dissipation region in optical thin region.
- ★ Controlled by magnetic field, SSC model.
- ★ LAT potential to search GeV: wide foV and average flux of flare in X-ray.

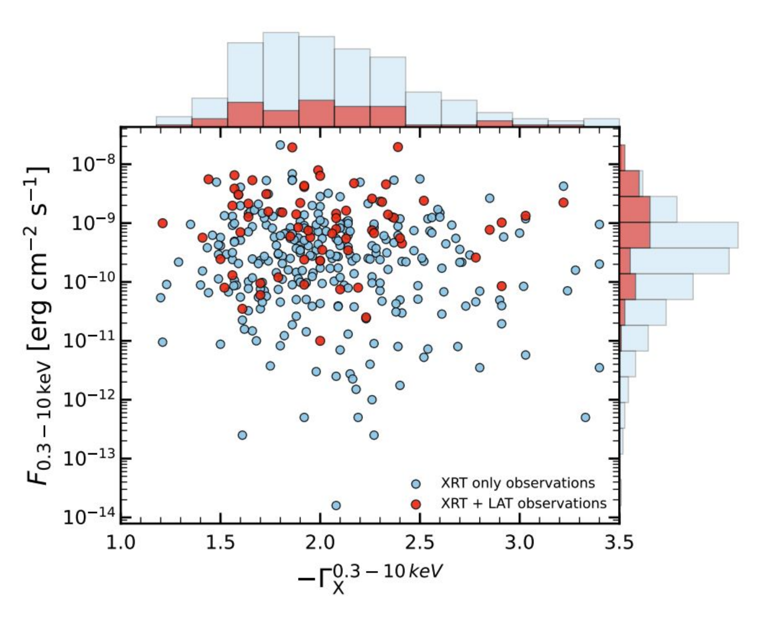




Tiwari et al. 2026 (under review)

Properties of Flares in X-ray Band

- ★ Photon Index (soft X-ray)
  - ○ Spans from -1.5 to - 2.5
  - ○ Optical to Hard X-ray rays: $E^{sync,peak}$
- ★ Energy Flux (soft X-ray)
  - ○ 10^{-8} to 10^{-12} erg cm^{-2}s^{-1}
  - ○ Few cases even lower ~ $10^{-13/14}$

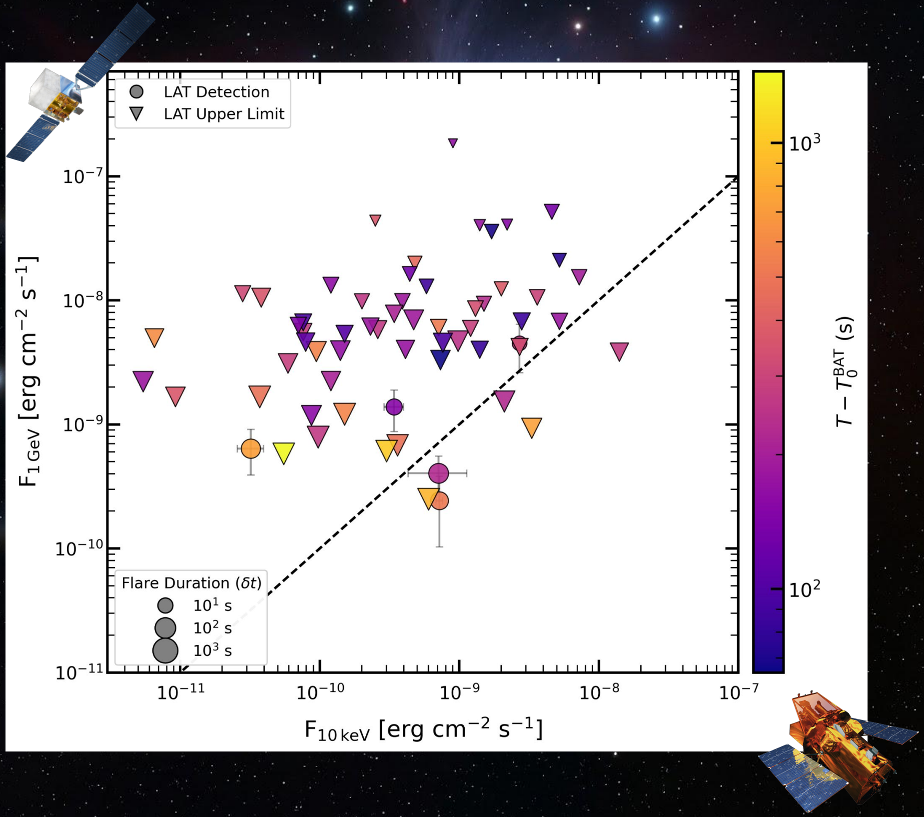


Tiwari et al. 2026 (under review)

Results

Detection in GeV

★ **GRB 100728A (z=1.56), 160325A, 170810A, 171120A**



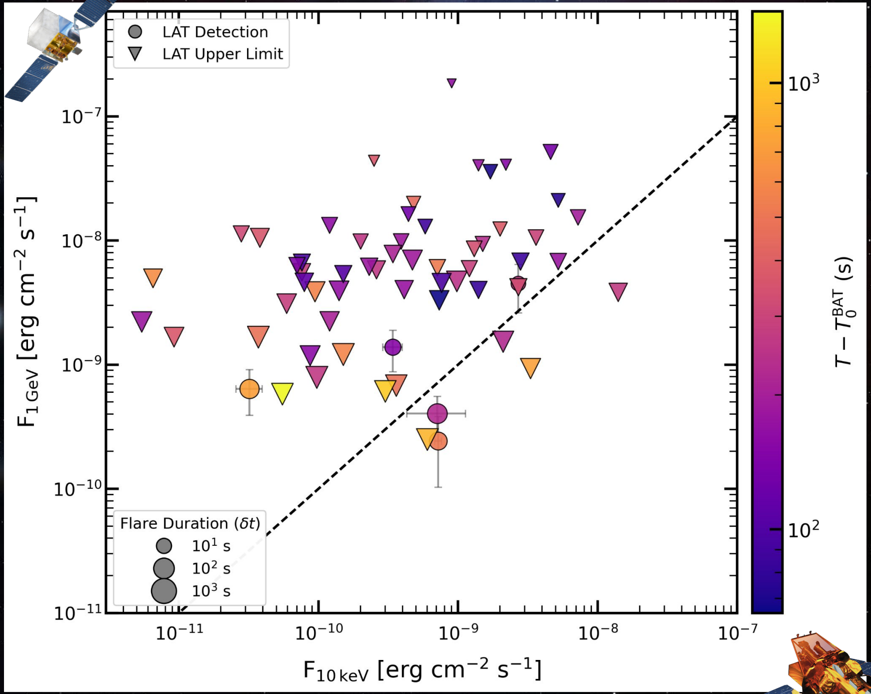
Tiwari et al. 2026 (under review)

Results

Detection in GeV

★ **GRB 100728A (z=1.56), 160325A, 170810A, 171120A**

GeV emission during flares related to the flare itself or Forward shock afterglow?

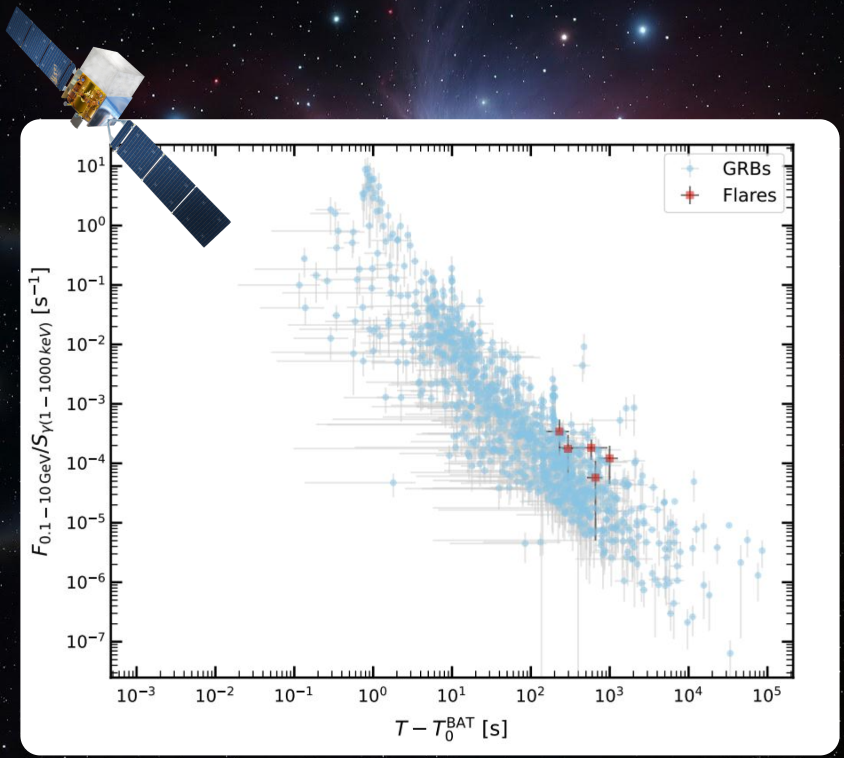


Tiwari et al. 2026 (under review)

Interpretation

Flares vs FS Afterglow in GeV:

- ★ Clustering in GeV LC for external forward shock afterglow (Nava et al. 2014, Ajello et al. 2019, Tiwari et al. 2025)
- ★ Flares GeV data points are well inside cluster.
- ★ GeV emission associated with flares lies beneath the afterglow.
- ★ To interpret correctly: Joint FS + flares is modelling is needed!



Tiwari et al. 2026 (under review)

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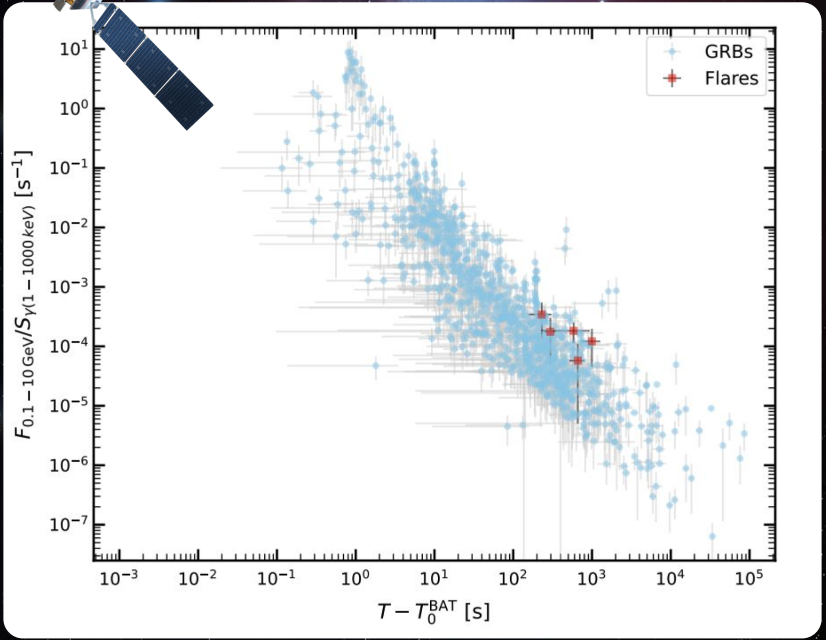


GeV emission is associated/dominant with/by FS Afterglow !

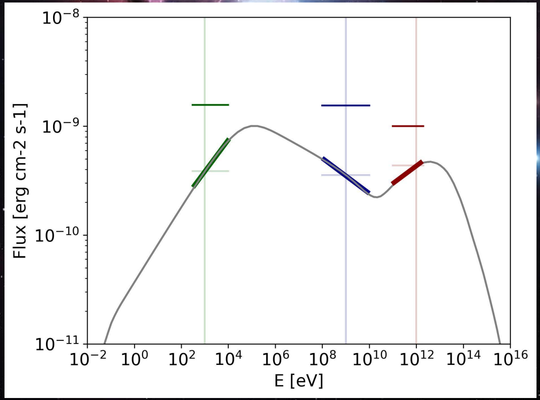
Tiwari et al. 2026 (under review)

Interpretation

Consideration for model:

- Flares are produced as jet internal dissipation.
- Flares emission mechanism is same as prompt emission
- Optical thin region with fast cooling regime
- Free parameters:
    - synchrotron peak,
    - Luminosity of electron = luminosity of photons,
    - Magnetic field
    - Bulk Lorentz factor

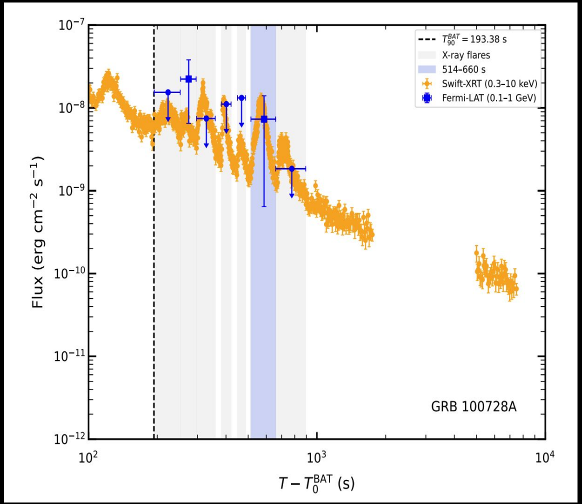
LeMoC (*Stathopoulos et al. 2024*)

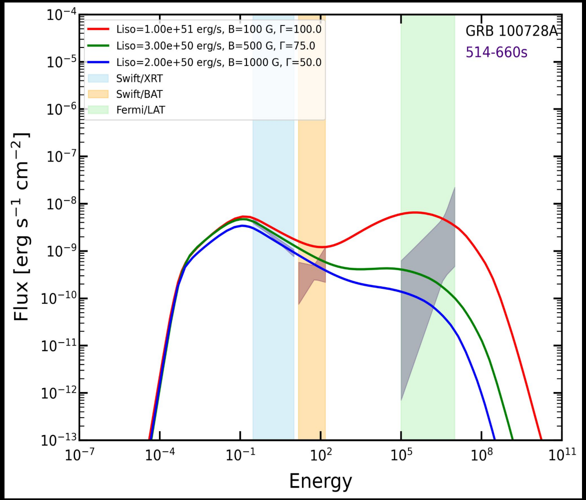


GeV emission during flares is considered as U.Ls.

Tiwari et al. 2026 (under review)

Interpretation (ex. GRB 100728A)





Tiwari et al. 2026 (under review)

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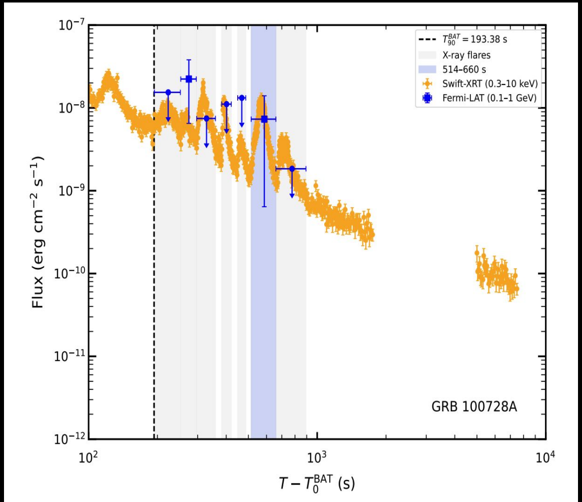

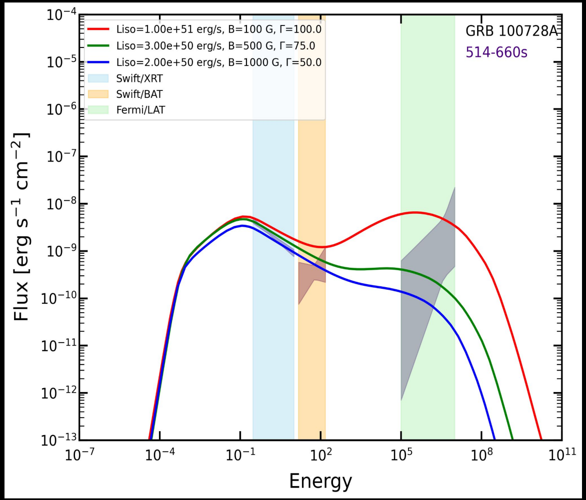

SED modelling curves suggests: a wide range of physical parameters can successfully reproduce the observed X-ray emission while remaining below the GeV U.L.

Tiwari et al. 2026 (under review)

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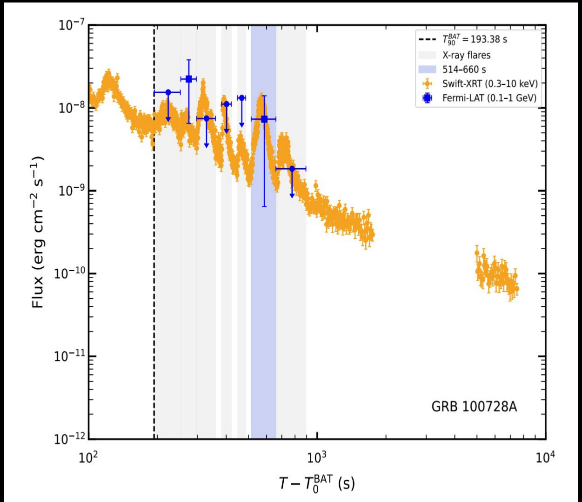
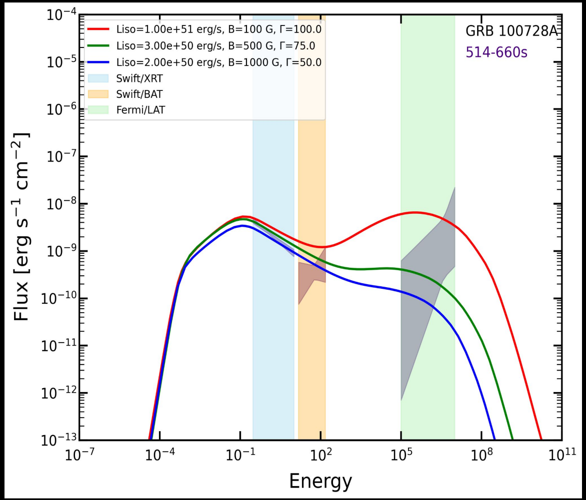
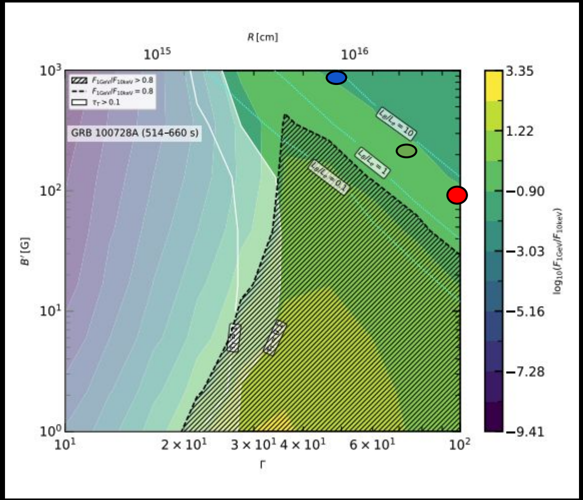




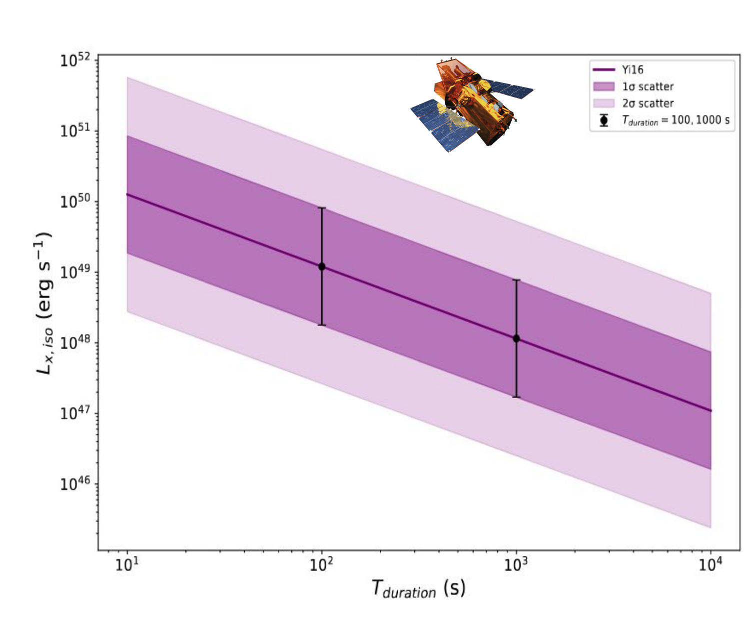


SED modelling curves suggests: a wide range of physical parameters can successfully reproduce the observed X-ray emission while remaining below the GeV U.L.

Tiwari et al. 2026 (submitted)

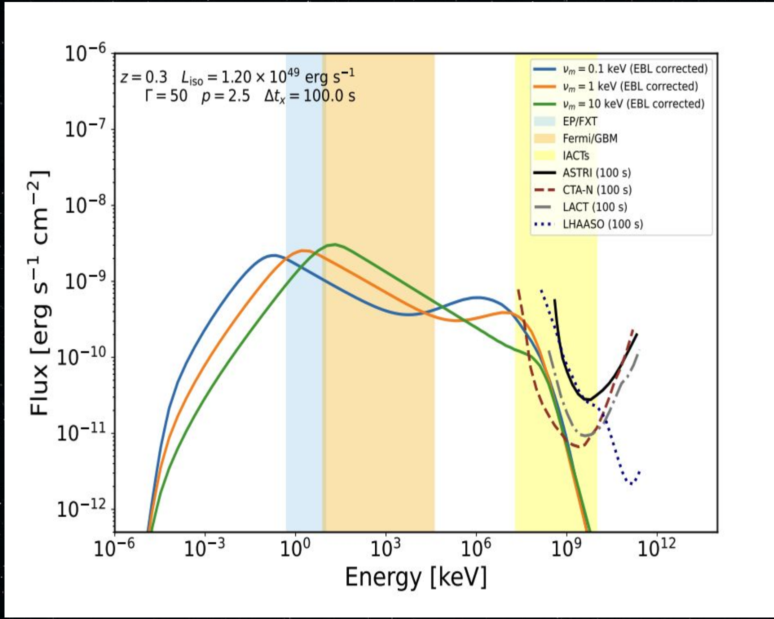
Predictions: VHE (> 100 GeV)

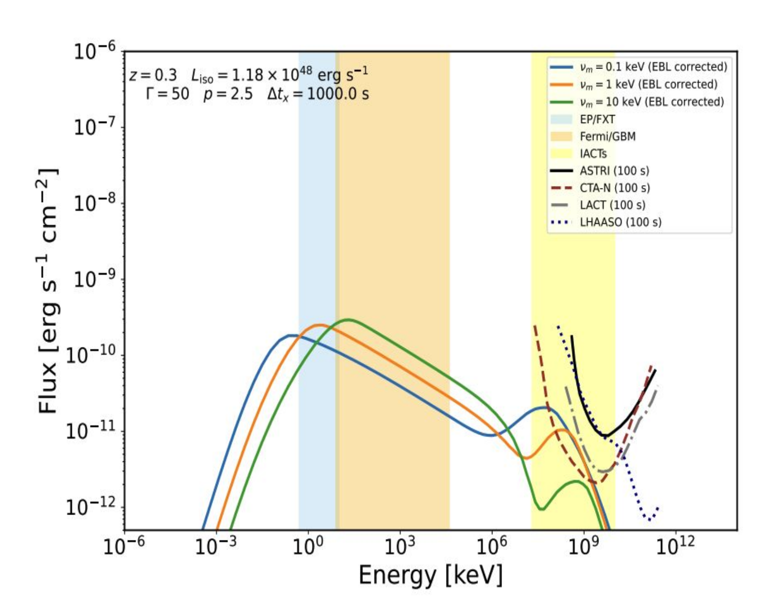
- ★ Isotropic X-ray Luminosity for flares associated with duration (100, 1000s) (Margutti et al. 2010, Yi et al. 2016)
- ★ $L_B/L_E \sim 1$
- ★ Bulk Lorentz factor < 100
- ★ z =0.3 (EBL effect)
- ★ Peak synchrotron frequency: 0.1, 1, 10 keV



Tiwari et al. 2026 (under review)

VHE from flares + Detectability with Cherenkov Telescope

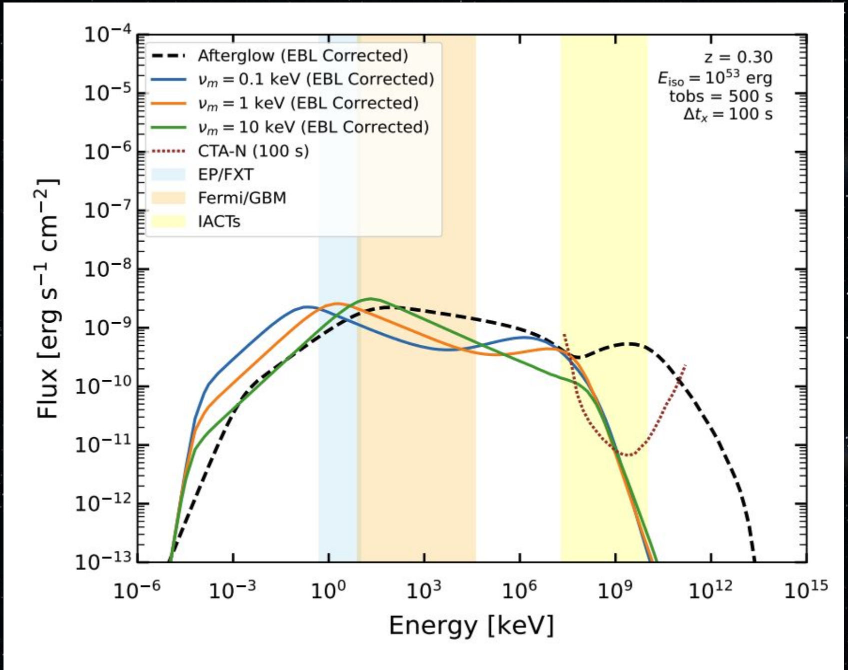


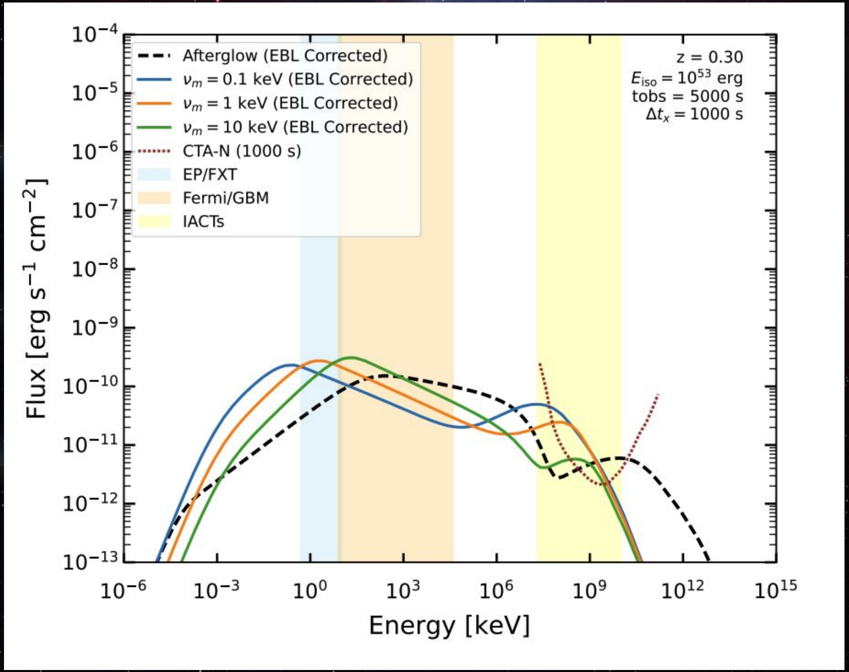


CTAO - N can play important role in detecting VHE emission from flares!

Tiwari et al. 2026 (under review)

Distinguish between flare and FS afterglow at HE/VHE?





Flare with higher variability at later times, VHE and X-ray observations is essential!

Tiwari et al. 2026 (under review)

Distinguish b … at HE/VHE?

Flare with higher variability at later times, VHE and X-ray observations is essential!

Tiwari et al. 2026 (under review)

ChatGPT

Summary

“Last Breadth of dying star”

★ Performed a detailed time-resolved spectral analysis of GRB X-ray flares using joint X-ray and GeV observations. Applied a synchrotron self-Compton (SSC) framework

★ Found properties of dissipation region

★ Flares resemble delayed prompt emission, making them ideal targets for VHE observations with IACTs despite their pointing constraints.

★ Flares at later epoch can overshines afterglow.

★ CTAO- N can play crucial role.

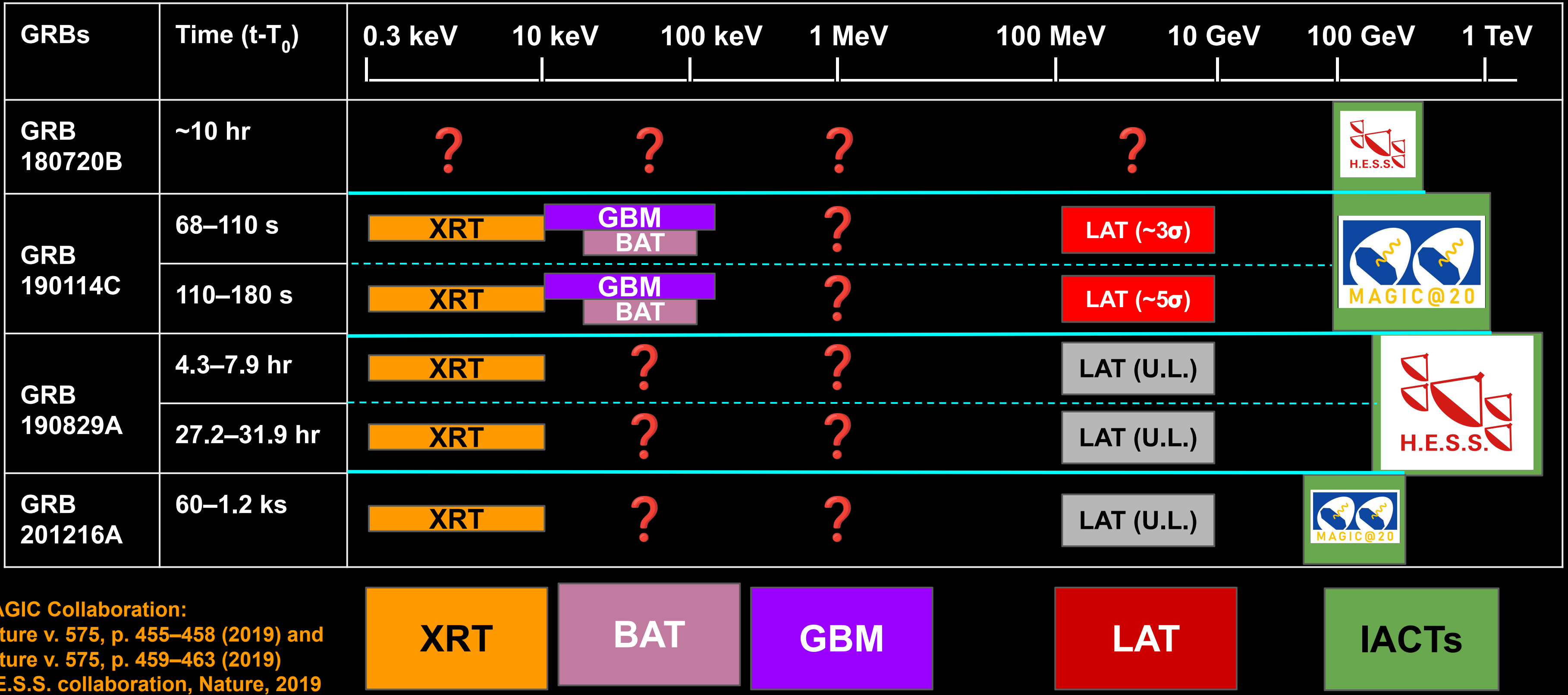
★ X-ray observatories: Einstein Probe, SVOM will play important role in MWL.

Paper on arxiv today!

Thank you for your attention !

Extra Slides

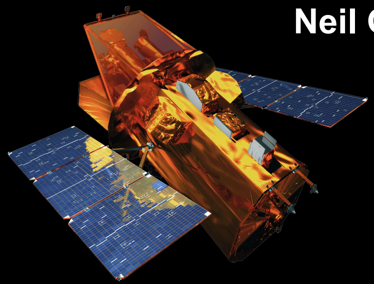
TeV GRBs



MAGIC Collaboration:
Nature v. 575, p. 455–458 (2019) and
Nature v. 575, p. 459–463 (2019)
H.E.S.S. collaboration, Nature, 2019
H.E.S.S. collaboration, Science, 2021
MAGIC Collaboration, MNRAS, 2024

Instrument Overview

Neil Gehrels Swift Observatory



Three Instruments:
- BAT
- XRT
- UVOT

Swift BAT:
- Wide field, coded mask
- FoV ~ 1.4 sr
- 15 - 150 keV

  Positional Accuracy

  arcminutes within second of trigger

Swift XRT:
- Grazing-incidence focusing telescope
- 0.3-10 keV
- Localization accuracy ~ **1-3`**

Fermi Gamma-Ray Space Telescope

Two Instruments:
- GBM
- LAT

Fermi LAT:
- Pair-conversion telescope
- **~30 MeV - 300 GeV**
- FOV ~ 2.4 sr
- Observing entire sky every 2 orbits (~3 hr)

Sample Selection

1. Initial Catalog

17 years of Swift/BAT detected GRBs with X-ray Flares.

Time Range:

June 2008 – June 2025

332 GRBs

2. Refining Cuts

- Flares strictly after T90 of BAT.
- At least one full X-ray flare per GRB.

Filtered Sample:

206 GRBs

3. LAT GeV Search

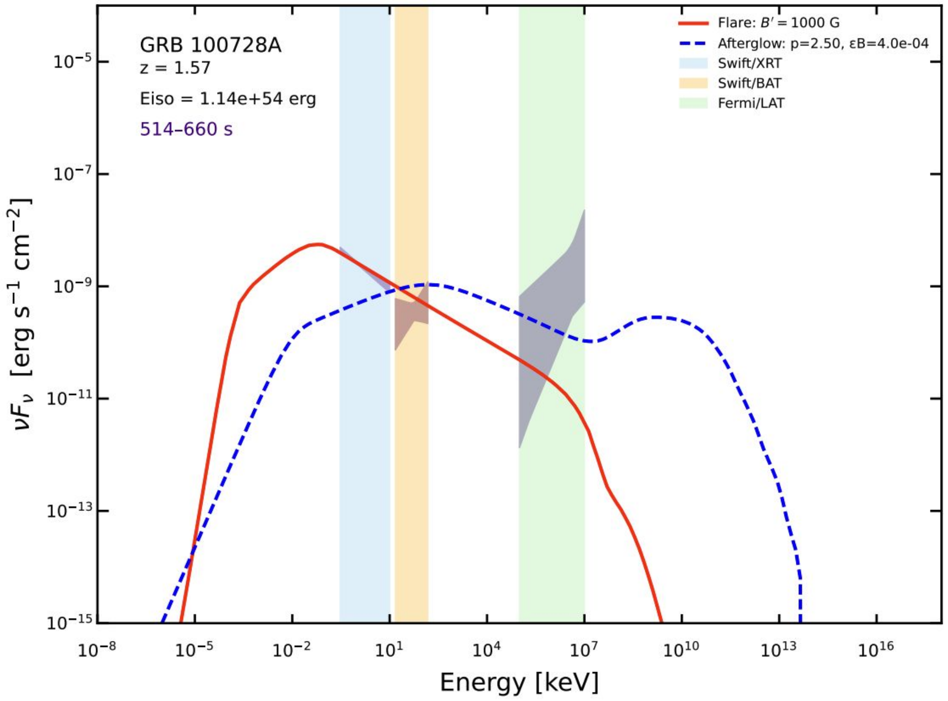
Searching within the LAT GeV Band.

- Flare must be in Fermi-LAT Field of View.
- 10 events have redshift data.

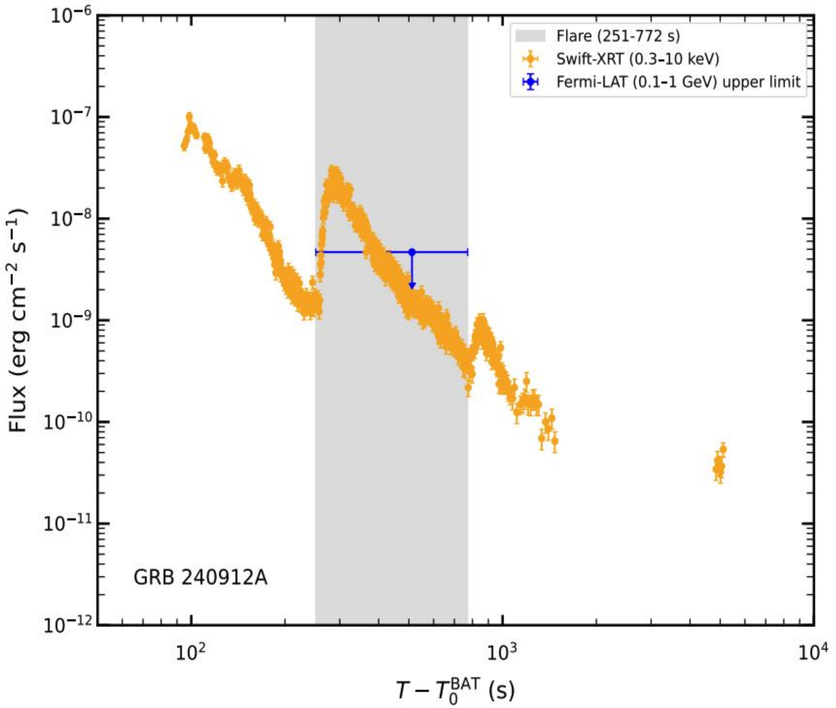
Final Sample:

47 GRBs

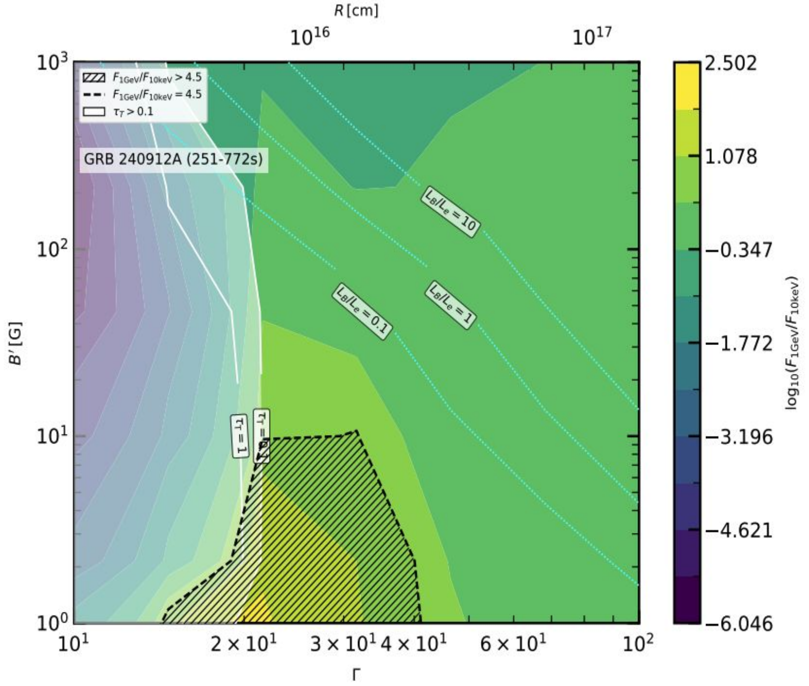
100728A; Afterglow + Flare



GRB 240912A

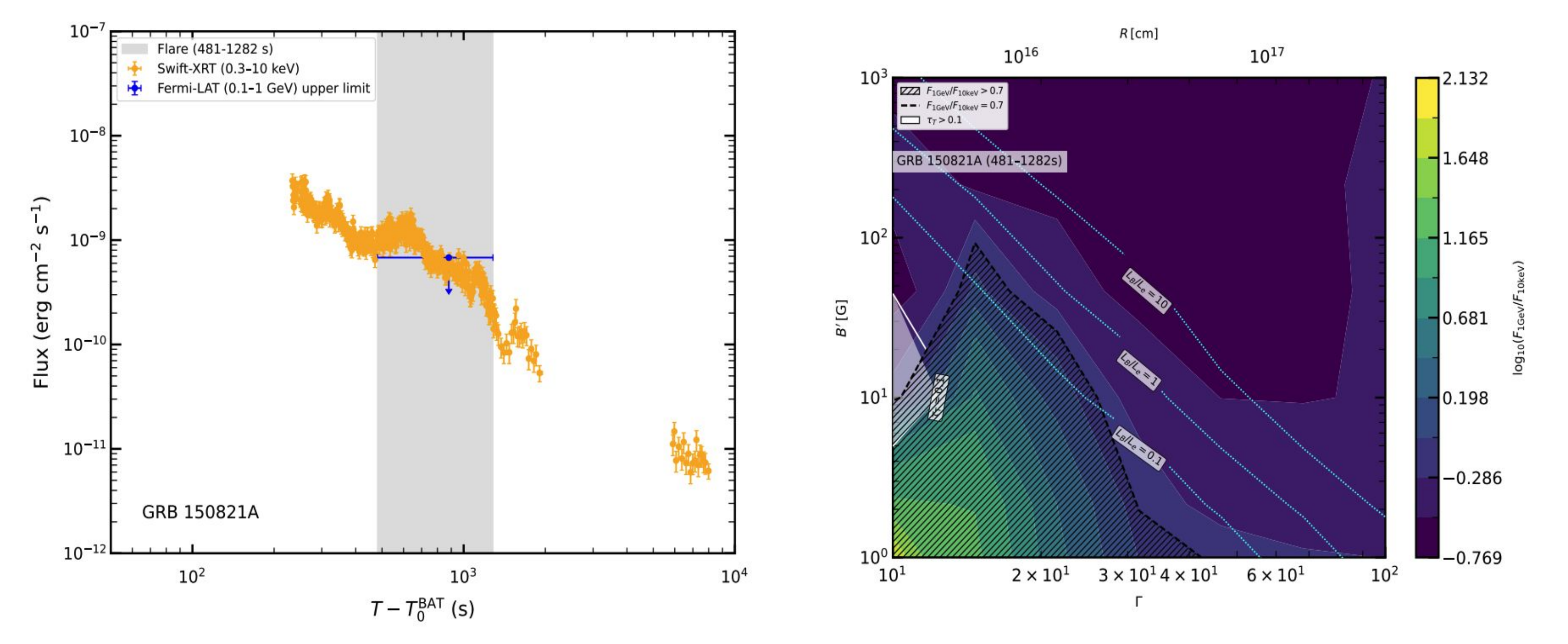


Flare (251-772 s)
Swift-XRT (0.3-10 keV)
Fermi-LAT (0.1-1 GeV) upper limit
GRB 240912A
Flux (erg cm^{-2} s^{-1})
$T - T_0^{BAT}$ (s)



R [cm]
$F_{1GeV}/F_{10keV} > 4.5$
$F_{1GeV}/F_{10keV} = 4.5$
$\tau_T > 0.1$
GRB 240912A (251-772s)
$L_B/L_e = 10$
$L_B/L_e = 0.1$
$L_B/L_e = 1$
$\tau_T = 1$
B' [G]
Γ
$\log_{10}(F_{1GeV}/F_{10keV})$

GRB 150821A


Flare (481-1282 s)
Swift-XRT (0.3-10 keV)
Fermi-LAT (0.1-1 GeV) upper limit
GRB 150821A
Flux (erg cm^{-2} s^{-1})
$T - T_0^{BAT}$ (s)
R [cm]
GRB 150821A (481-1282s)
$F_{1GeV}/F_{10keV} > 0.7$
$F_{1GeV}/F_{10keV} = 0.7$
$\tau_T > 0.1$
$L_B/L_e = 10$
$L_B/L_e = 1$
$L_B/L_e = 0.1$
B' [G]
Γ
$\log_{10}(F_{1GeV}/F_{10keV})$
2.132
1.648
1.165
0.681
0.198
−0.286
−0.769