Multi-Wavelength View of Gamma-Ray Burst Afterglow

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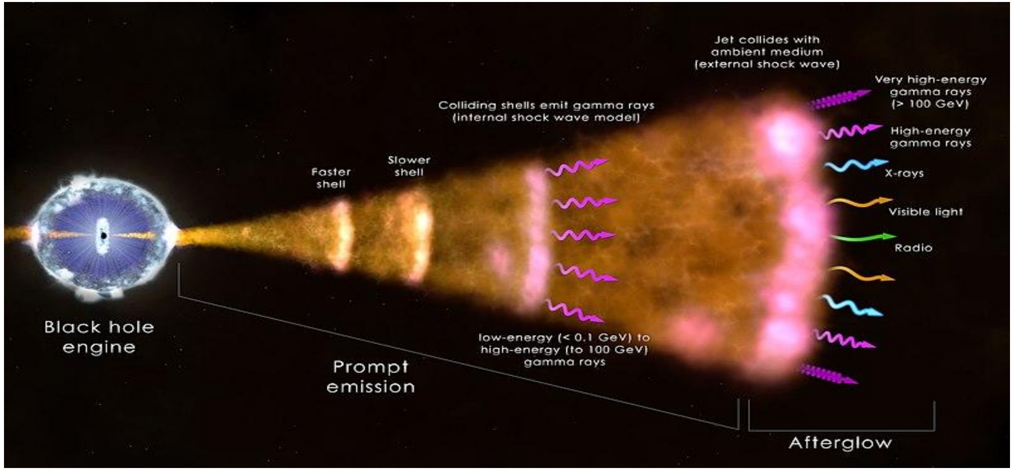
Prof. Marica Branchesi

Passage of the year, October 2025

Gamma-Ray Bursts



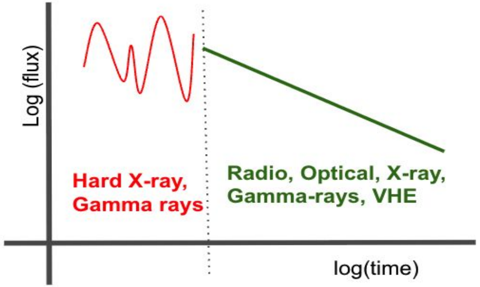
Credit: NASA/ICRAR.

Photons ~ **MeV**

Variability: **0.01-1s**

Duration: **0.1 - 1000s**

E_{iso} - **10^{50} - 10^{54} erg**



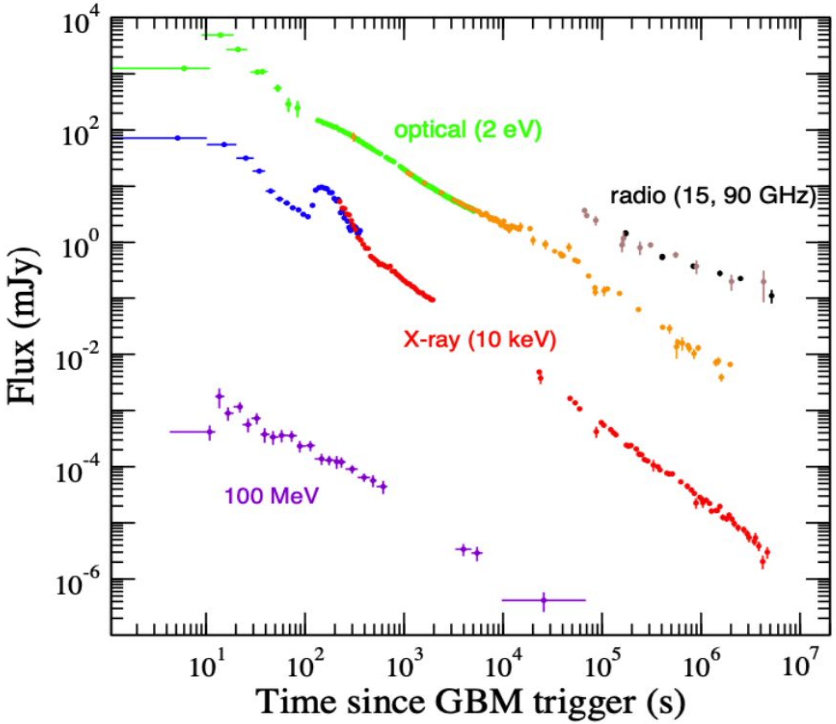
Photons ~ **Radio to VHE**

Duration: **Days to weeks**

Smoothly PL lightcurve

Non-Thermal Spectra

Afterglow



GRB 130427A, Panaitescu et. al. 2013

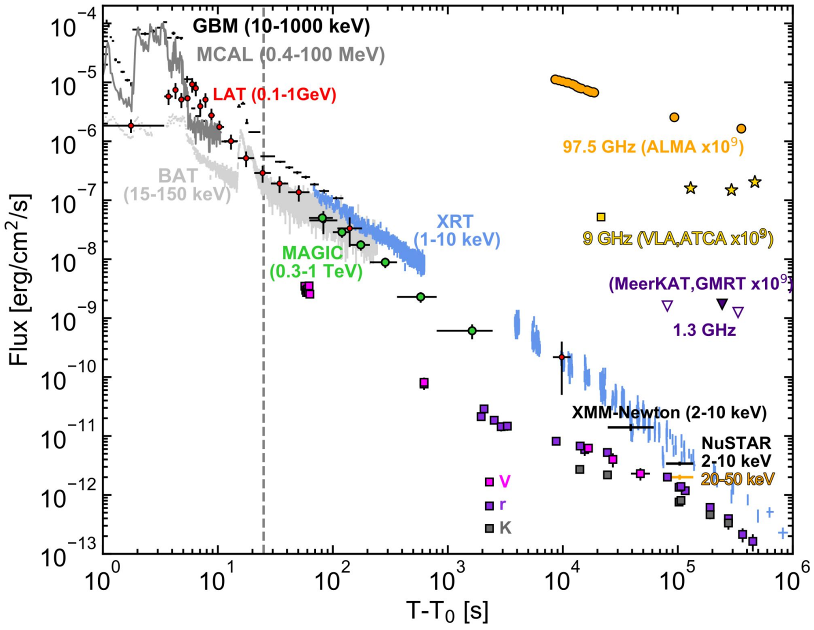
Discovered
Costa et al. 1997

Predicted
Paczynksi & Rhodes 1993
Meszaros & Rees 1997

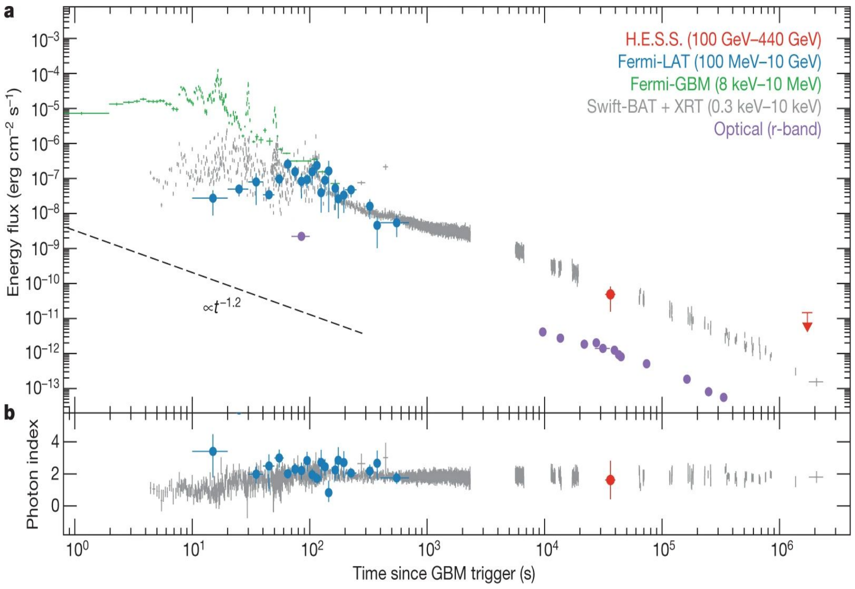
Dynamics
Blandford & Mckee 1976

Phenomenology
Sari et al. 1998

Afterglows at VHE (>100 GeV)



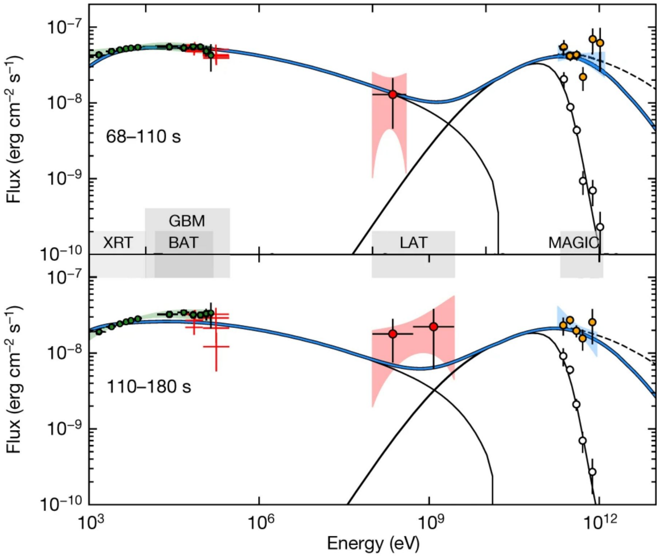
GRB190114C, MAGIC collaboration, Nature 2019



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

To date, only ***5 GRBs*** *have been conclusively detected in* ***VHE****!*

keV vs. GeV vs. TeV



GRB190114C, MAGIC collaboration, Nature 2019

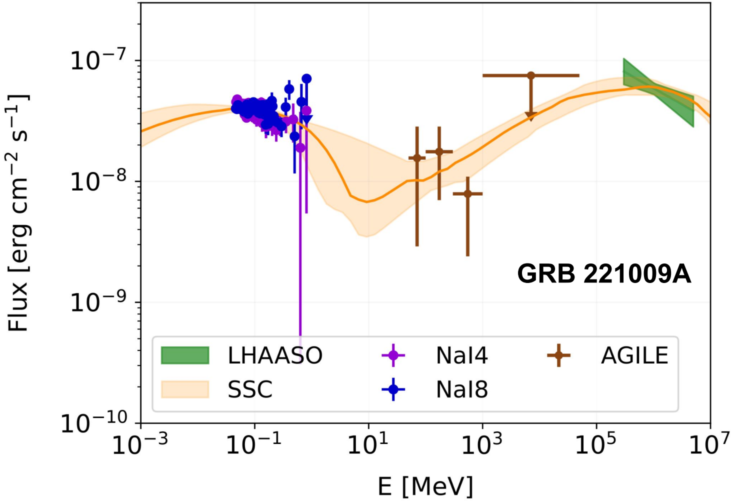
X-ray Flux ~ **TeV Flux**

GeV Flux

Spectral Index and Flux

Radiation Mechanism

Synchrotron / SSC ?



Banerjee et. al. 2024

Open Questions

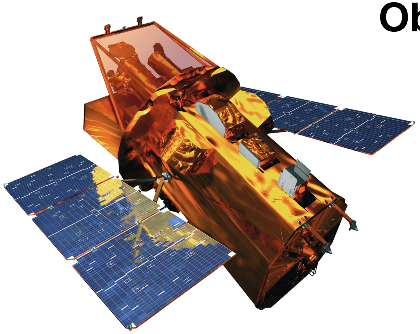
- Dominant radiation process in afterglow.
- Microphysical parameter to explain afterglow shock physics.
- Are VHE GRBs unique?

Multi-wavelength study of GRB Afterglows

➢ from 16 yrs. of combined operation of **Swift and Fermi Telescope** (2008-2024)

Fermi Gamma-Ray Space Telescope

LAT: High Energy
(30 MeV -300 GeV)



Neil Gehrels Swift Observatory

XRT: Soft X-ray (0.3-10 keV)
BAT: Hard X-ray (15 -150 keV)

Radiation processes

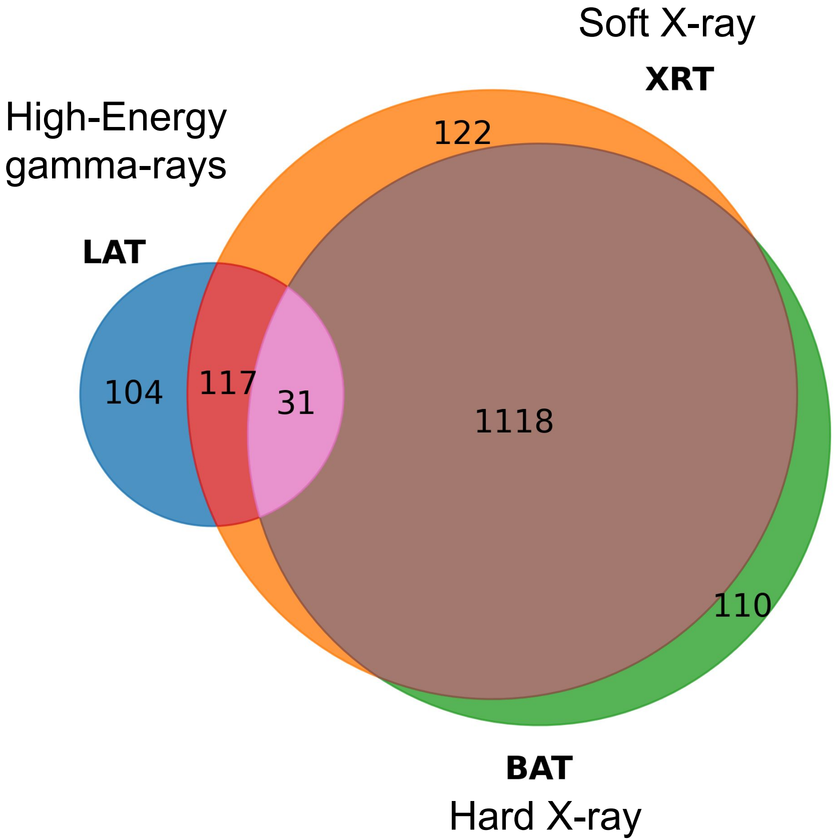
Microphysical Parameters

Circumburst medium

VHE emission

(https://arxiv.org/abs/2510.05239)

16 yrs. of Swift + Fermi (August 2008 - August 2024)

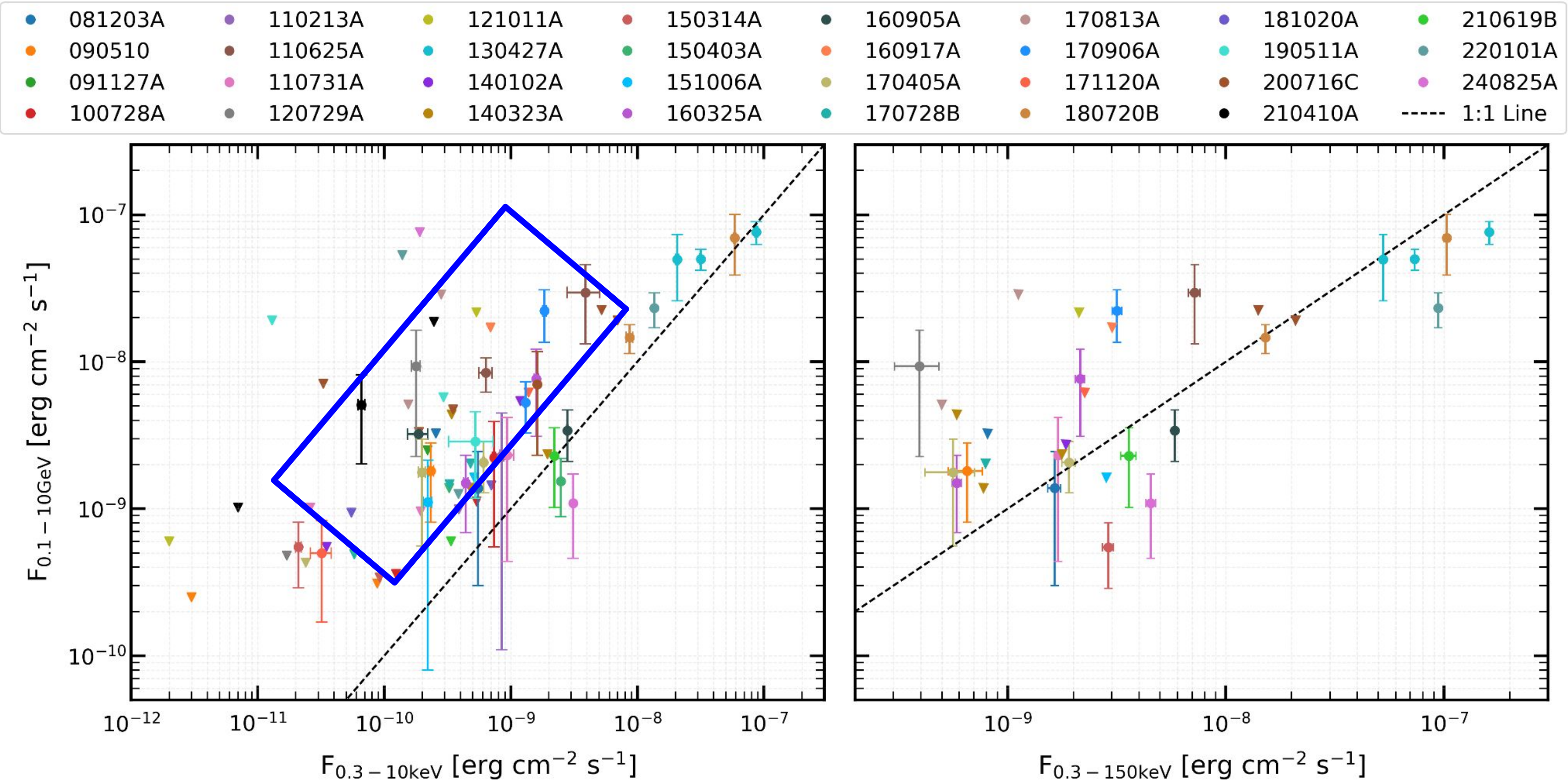


Afterglow + simultaneous observation

No. of GRB: 31
No. of time-bins: 74
Excluded flare

XRT + LAT: 74
XRT + BAT + LAT: 34

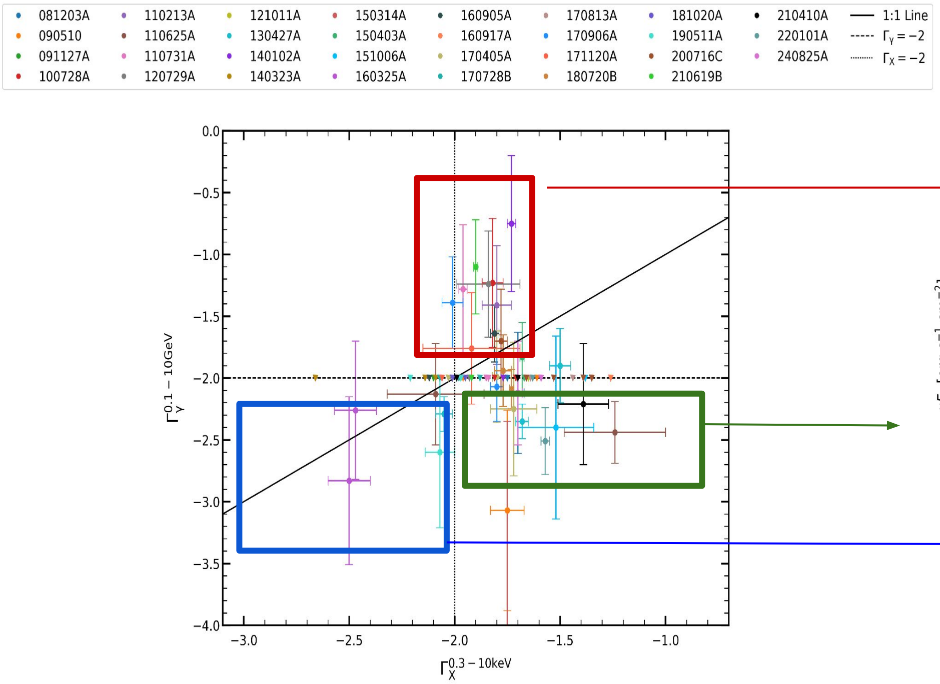
Flux vs Flux

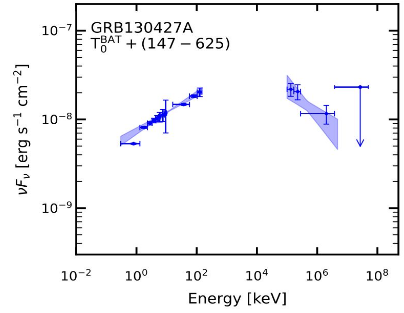


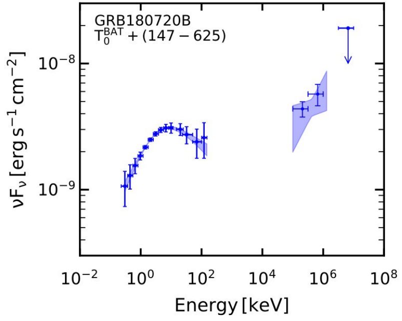
Flux Systematically higher in HE gamma-rays

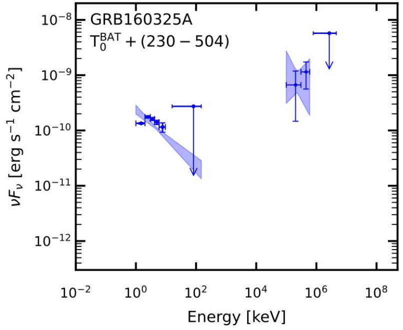
Distributed around equality line

Spectral Index





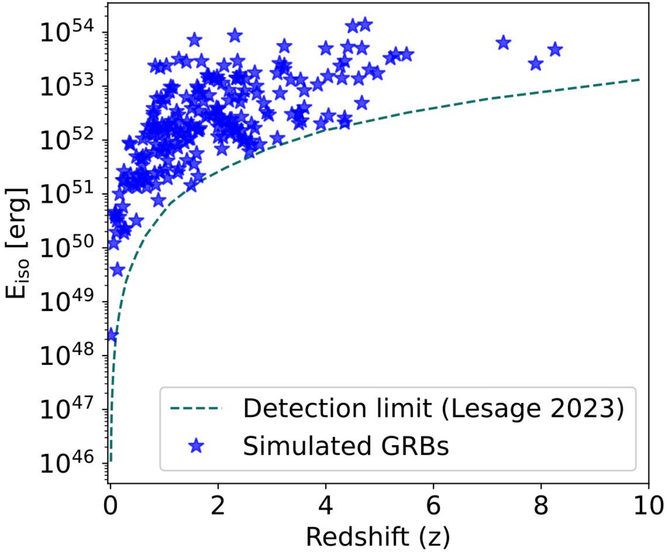




Afterglow Spectra get clustered in 3 segments:

1. **$\Gamma_X > -1.8$ (harder X-ray)**
2. **$-2.0 < \Gamma_X < -1.8$ (moderately harder X-ray)**
3. **$\Gamma_X < -2.0$ (softer X-ray)**

Interpretation



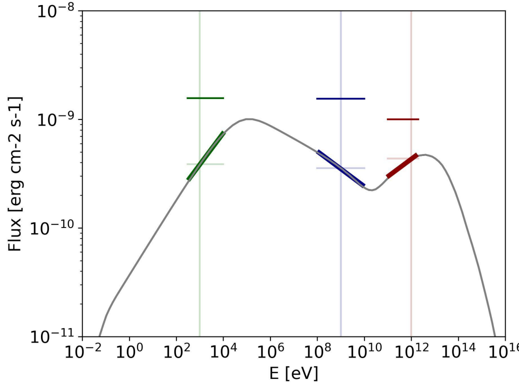
Microphysics

$\epsilon_e \sim 0.1$

$\epsilon_B \sim 10^{-4}$-10^{-2}

$p \sim 2.2, 2.3, 2.4$

Example SED



LeMoC, Stathopoulos et al. 2024

Medium: Wind/ Homogeneous

X-ray: $F_{0.3\text{-}10\ keV}$, $\Gamma_{0.3\text{-}10\ keV}$

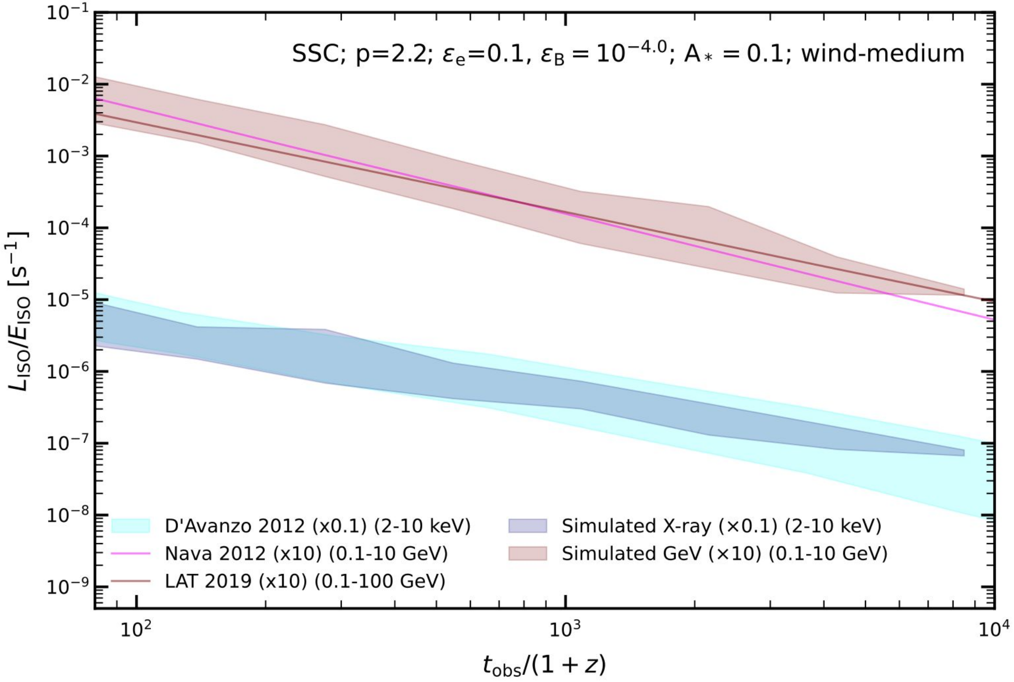
GeV: $F_{0.1\text{-}10\ GeV}$, $\Gamma_{0.1\text{-}10\ GeV}$

VHE: $F_{0.3\text{-}1\ TeV}$, $\Gamma_{0.3\text{-}1\ TeV}$

- Simulated sample of 220 random values of E_{ISO}, z and observation time between 100–10ks that mimics the observation of one year of long GRBs.
- E_{ISO} and z are selected in distributions reported in *Ghirlanda & Salvaterra 2022* and GBM detection limit (*Lesage et al. 2023*)

η: prompt efficiency ~ 0.1
ϵ_e: fraction of energy to accelerate electron
ϵ_B: fraction of energy to produce magnetic field
p: slope of distribution of injected non -thermal electrons

Prefered Parameters



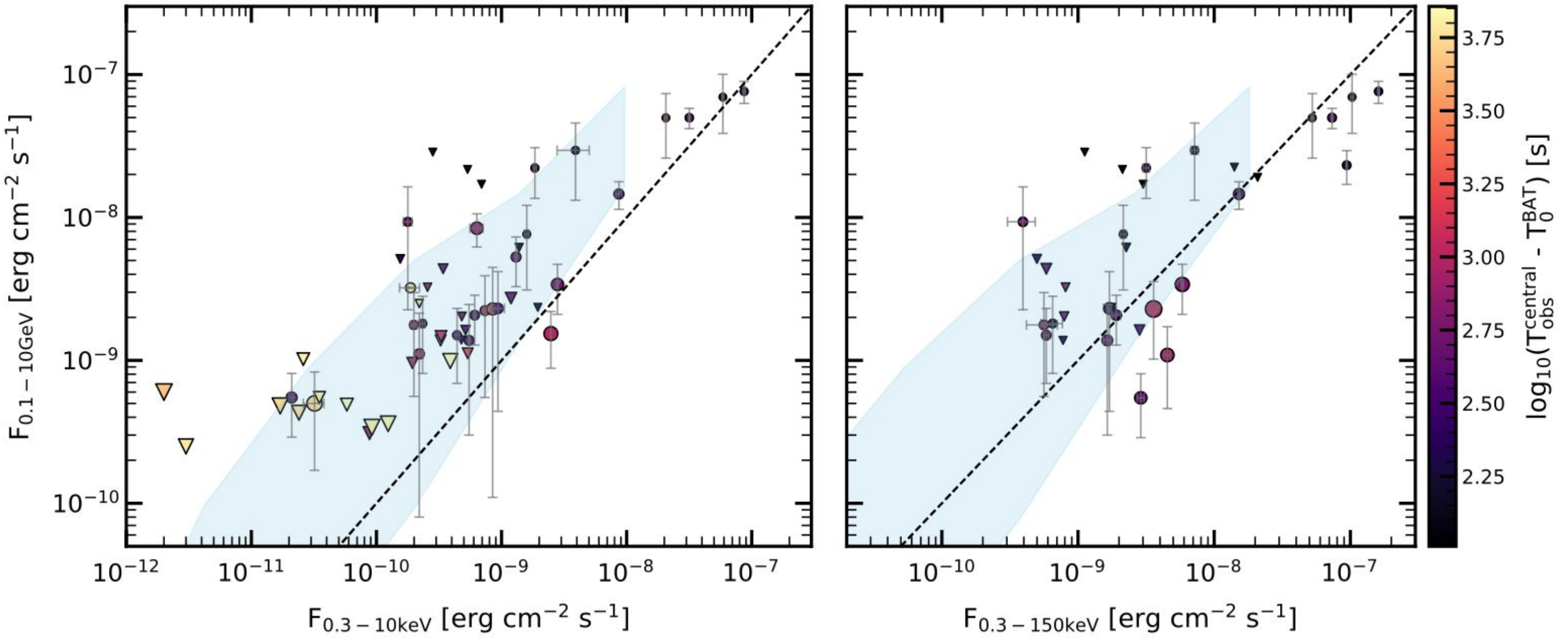
SSC in wind-medium with η=0.1, p=2.2, ϵ_e~ 0.1, ϵ_B~ 10^{-4}

Can explain:

1. **X-ray study noted in D'Avanzo 2012**
2. **GeV noted in Nava 2014, LAT 2019**

Inverse compton, lower density wind medium, ϵ_B~10^{-4}

Predicted Flux with Observed Flux



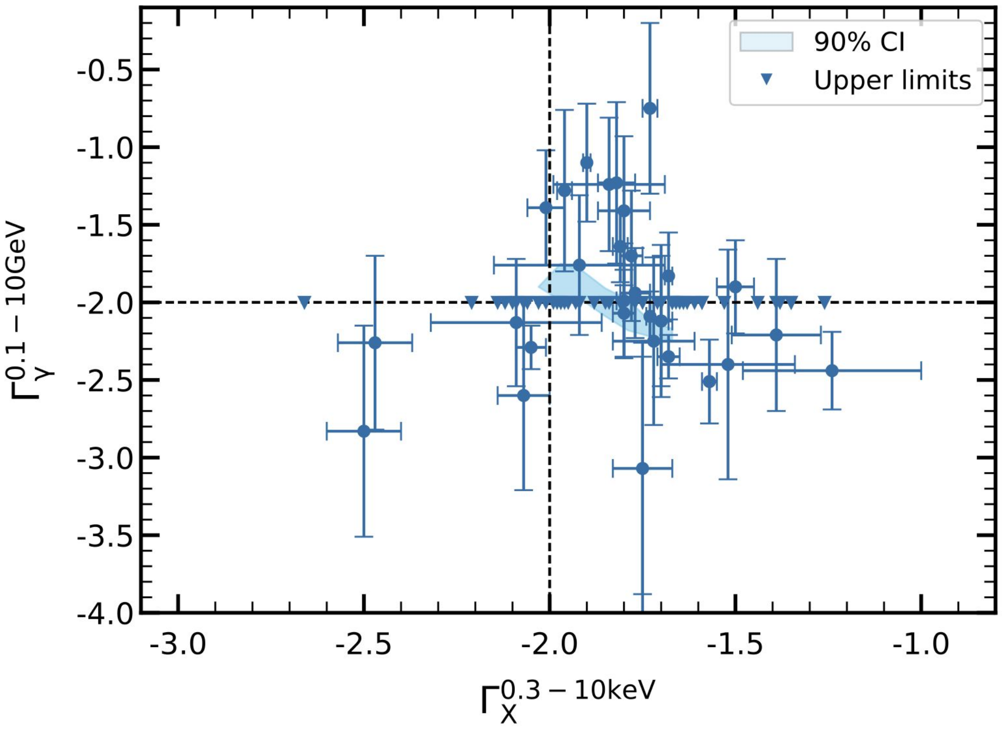
Blue shaded region is predicted emission with given parameters.

SSC in wind-medium with η=0.1, p=2.2, ϵ_e~ 0.1, ϵ_B~10^{-4}

***Size of data points represent the exposure time

**Higher flux points belongs to GRBs having Γ > 300, prompt contamination and time< 100 sec

Predicted vs Observed Spectral Index

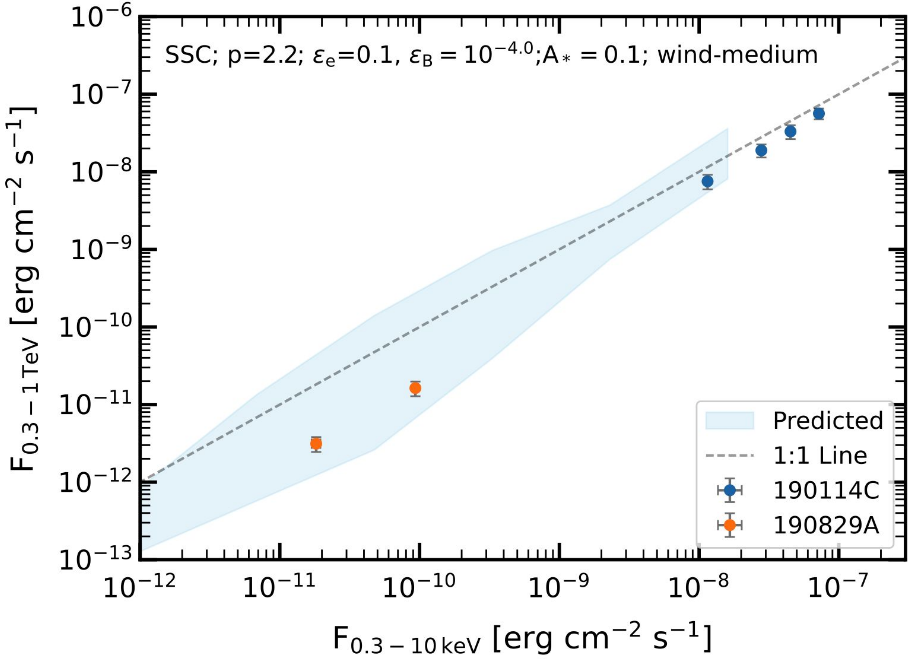


SSC in wind-medium with η=0.1, p=2.2, ϵ_e~ 0.1, ϵ_B~10^{-4}

Open Questions

- ➢ Dominant radiation process in afterglow.
- ➢ Microphysical parameter to explain afterglow shock physics.
- ➢ Are VHE GRBs unique?

VHE (intrinsic) Prediction vs. X-ray



Correlation between $F_{0.3\text{-}10\ keV}$ vs. $F_{0.3\text{-}1\ TeV}$ (intrinsic) can be noted with best setup parameter

SSC in wind-medium with η=0.1, p=2.2, ϵ_e~ 0.1, ϵ_B~ 10^{-4}

**The predicted VHE flux was computed assuming a bulk Γ < 300 and avoiding prompt contamination; therefore, it does not account for GRB 190114C (Γ > 500; MAGIC Collaboration 2019b).

We learn!

- **Inverse Compton losses** are essential to explain joint X-ray & HE gamma-ray observations.
- Evidence favors a **wind-like circumburst medium for long GRBs** with typical microphysical parameters:
  - Electron spectral index p = 2.2
  - Energy fractions $\epsilon_e = 0.1$, $\boldsymbol{\epsilon_B = 1\times10^{-4}}$
- **Intrinsic Very High Energy (VHE) flux correlates well with X-ray**, consistent with previous TeV GRB observations.
- **Study can play important role** in designing **observation strategy** for detecting VHE photons for GRBs with **current and future Cherenkov Telescope**.

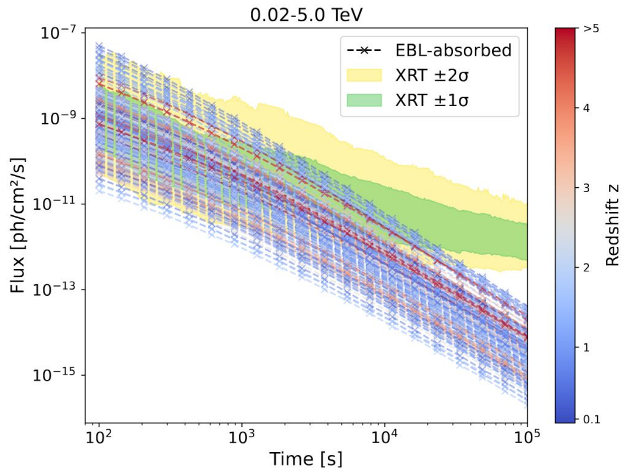
https://arxiv.org/abs/2510.05239

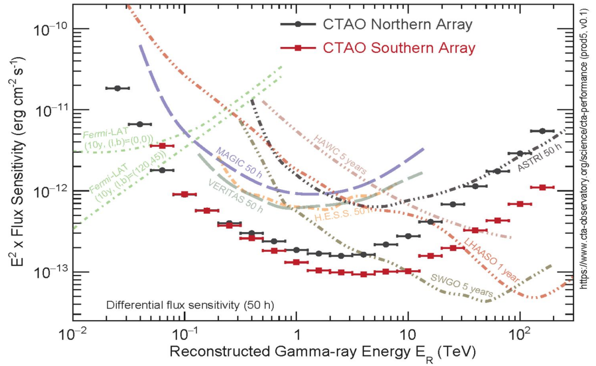
P. Tiwari, B. Banerjee, D. Miceli, G. Oganesyan, A. Ierardi, S. Macera, M. Branchesi, L. Nava, S. Mohnani, S. Agarwal, A. Shukla

Follow up work: Observing Strategy for IACTs

- ➢ Known: VHE prediction with X-ray emission for afterglow.
- ➢ Mock Catalog of GBM (E_{ISO}, broad loc.) +XRT (precise loc.) of 220 GRBs with redshift.
- ➢ Use of this information is to optimize (exposure time) the detectability of early VHE emission from GRBs using Cherenkov telescopes.
- ➢ VHE light curve with Fermi/GBM and Swift/XRT localization.
- ➢ Next steps: Study detectability with IACTs and tiling strategies

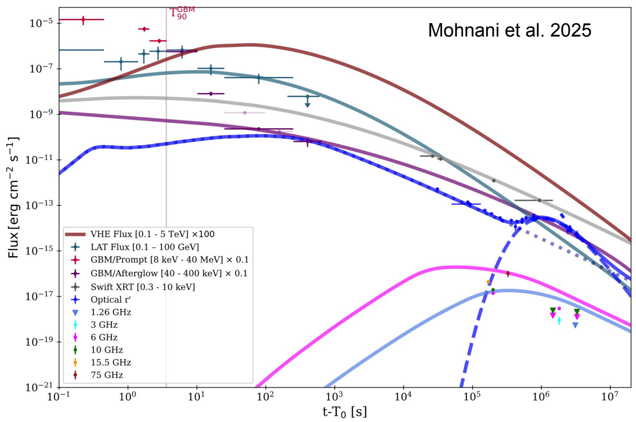
Macera et al. (including P. Tiwari in prep)

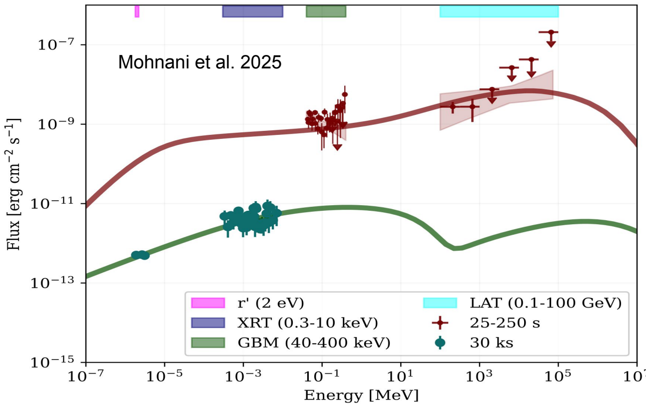




Contribution in other projects: GRB230812B

- ➢ One of the **Brightest** GRBs detected by Fermi/GBM + **72 GeV** photon in Fermi/LAT during the early afterglow phase.
- ➢ the study focuses on multiwavelength spectral and temporal in the **keV-VHE** domain
- ➢ Suggest **SSC with wind medium** in afterglow.
- ➢ The detection of **rare MeV afterglow** using alternate background estimation technique.
- ➢ Demonstrated **detection with IACT** to recover emission from **poorly localized GRBs**.

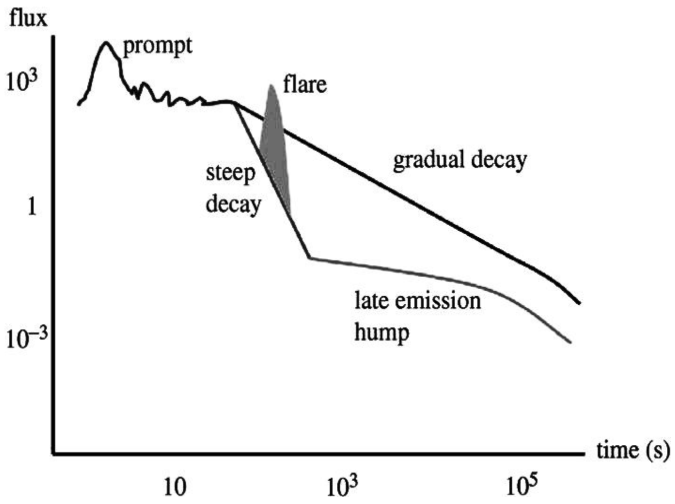




https://arxiv.org/pdf/2507.18697

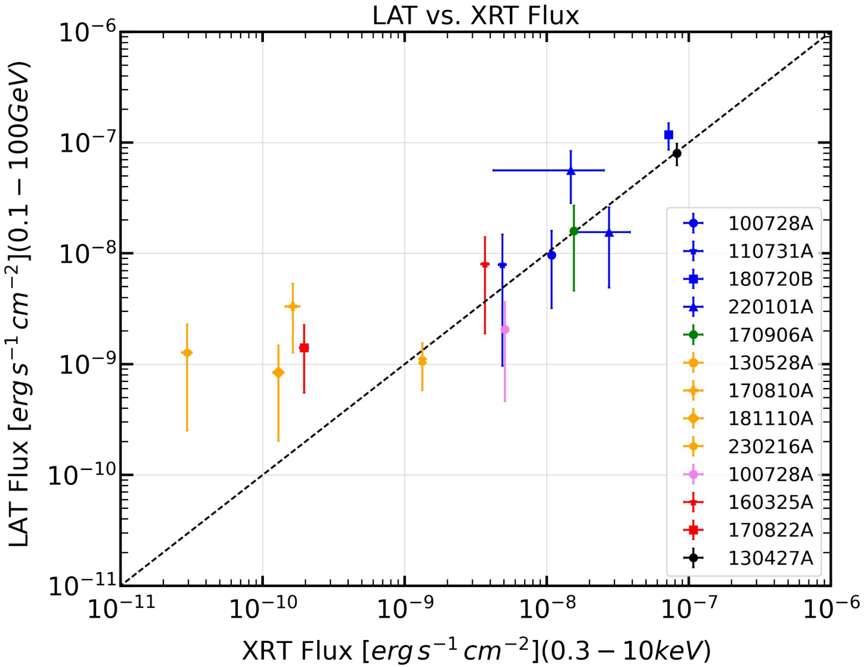
X-ray Flares

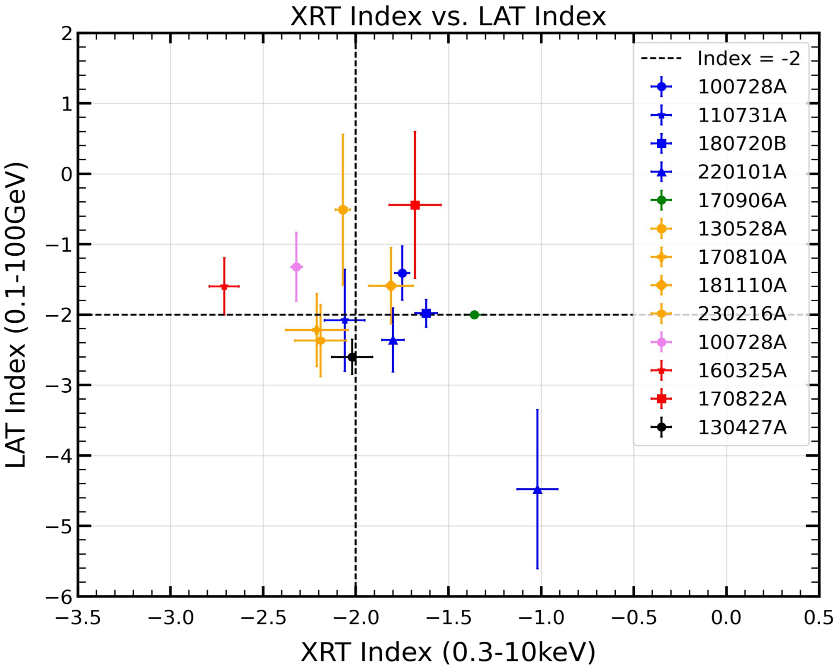
- ⅓GRBs detected by Swift-BAT exhibit flares.
- Origin Unknown
- Possibly related to late-time central engine activity or different velocity ejecta.
- **Targeted Search** for Swift detected GRBs with Flares from **2008 - 2023 performed**
- Independent of Fermi/GBM detection, **Fermi-LAT upper limit is calculated.**
- Performed **spectral** study for **X-ray (0.3-10 keV)** and **HE gamma rays (0.1-10 GeV).**



GRBs Light Curve based on Swift-XRT data

Preliminary Results - Xray Flares



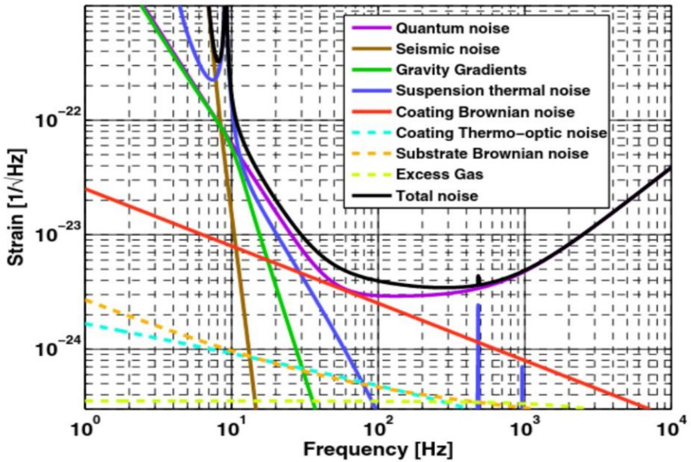


Future work:

- ➢ Inclusion of hard X-ray and UV data observed by Swift-BAT and UVOT resp.
- ➢ Interpretation of Results to explain multiwavelength dataset.

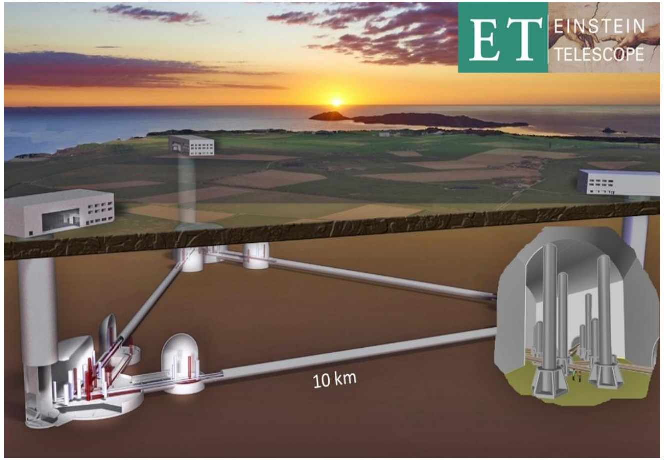
Contribution in other projects: LIGO- VIRGO- KAGRA

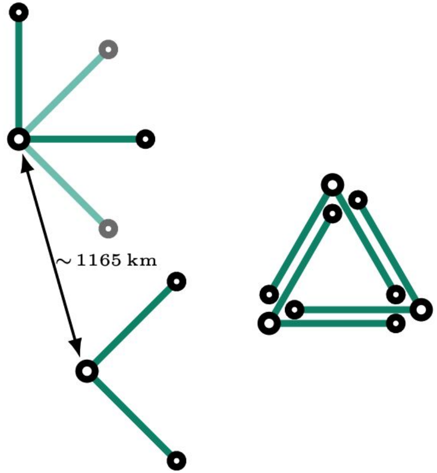
- ➢ Rapid Response Team Shifts.
- ➢ Offline GW Signal Searches connected to GRBs with XPipeline and pyGRB for O4a run.



Contributing in other projects: Einstein Telescope (ET)

- ➢ Scientific performance of ET for different technical requirements, focusing on the compact binary coalescences (CBCs) merger science case with *gwfish*.
- ➢ Planned to contribute in writing part of ET Science paper.





ET Collaboration 2023

Summary for year 2025

- From X-rays to High-Energy Gamma-rays: A Comprehensive Multi-Wavelength Study of Early Gamma-Ray Burst Afterglows (https://arxiv.org/abs/2510.05239)
- Follow up studies:
  - X-ray Flares.
  - Observational strategy for detecting TeV photons (Macera et al. in prep)
- Contributed in other projects:
  - GRB230812B (Mohnani et al. 2025)
  - rTDE (Oganesyan et al. 2025)
  - GRB prompt emission spectra at high energies (Macera et al. 2025)
- Multimessenger Studies
  - With LVK and ET

Thank you for your attention!!

Summary 2025

Publications

- From X-rays to High-Energy Gamma-rays: A Comprehensive Multi-Wavelength Study of Early Gamma-Ray Burst Afterglows. (Tiwari et al. 2025)

  Pawan Tiwari, Biswajit Banerjee, Davide Miceli, Gor Oganesyan, Annarita Ierardi, Samantha Macera, Marica Branchesi, Lara Nava, Shraddha Mohnani, Sushmita Agarwal and Amit Shukla

- Transient MeV radiation from a relativistic tidal disruption candidate. (Oganesyan et al. 2025)

  Gor Oganesyan, Elias Kammoun, Annarita Ierardi, Alessio Ludovico De Santis, Biswajit Banerjee, Emanuele Sobacchi, Felix Aharonian, Samanta Macera, **Pawan Tiwari,** Alessio Mei, Shraddha Mohnani, Stefano Ascenzi, Samuele Ronchini, Marica Branchesi

- Broadband Modelling of GRB 230812B Afterglow: Implications for VHE -ray Detection with IACTs. (Mohnani et al. 2025)

  Shraddha Mohnani, Biswajit Banerjee, Davide Miceli, Lara Nava, Gor Oganesyan, **Pawan Tiwari**, Annarita Ierardi, Alessio L. De Santis, Samanta Macera, Amit Shukla, Marica Branchesi, Swarna Chatterjee, Sushmita Agarwal, Abhirup Datta, Kuldeep Kumar Yadav, G.C. Anupama

- Gamma-ray burst prompt emission spectra at high energies. A&A 700, A88 (2025)

  Samanta Macera, Biswajit Banerjee, Alessio Mei, **Pawan Tiwari**, Gor Oganesyan, Marica Branchesi.

- Gigaelectronvolt emission from a compact binary merger. Nature 612, 236–239 (2022).

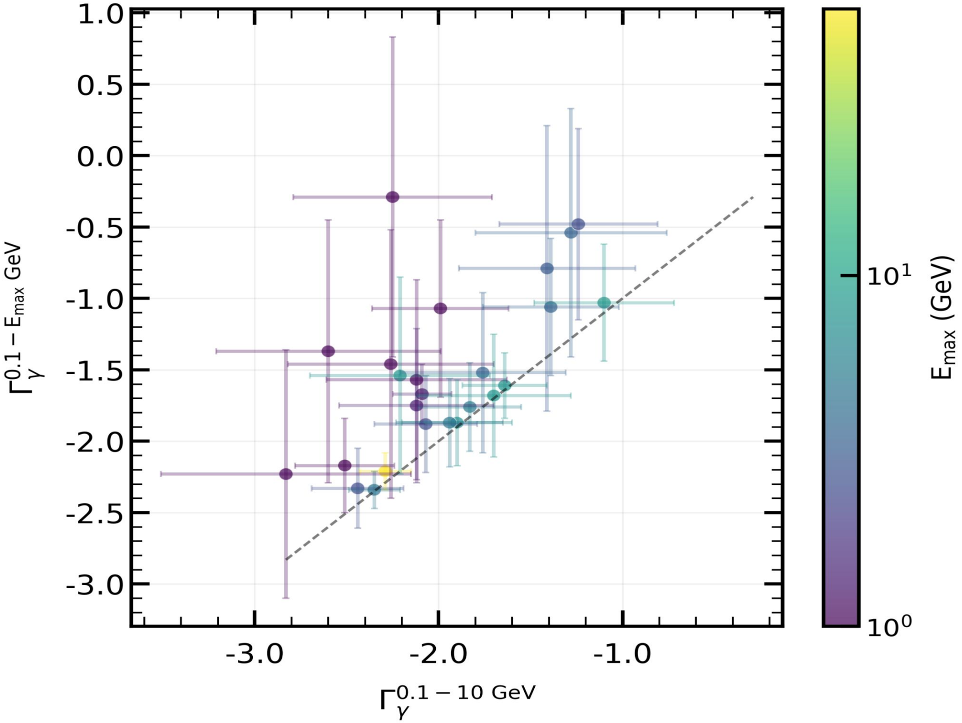
  Alessio Mei, Biswajit Banerjee, Gor Oganesyan, Om Sharan Salafia, Stefano Giarratana, Marica Branchesi, Paolo D’Avanzo, Sergio Campana, Giancarlo Ghirlanda, Samuele Ronchini, Amit Shukla, **Pawan Tiwari**.

Talks, Conferences, School and Workshop

- Talks:
  a. 4th Astro-COLIBRI Multimessenger Astrophysics Workshop, Paris, France October 2025
  b. 14th Young Researcher Meeting, L'Aquila, Italy September 2025
  c. 39th International Cosmic Ray Conference, Geneva, Switzerland July 2025
  d. 2nd VHE-GAM Meeting, Bari, Italy May 2025
  e. Challenges and Future Perspectives in GW Astronomy: O4 and Beyond Workshop, Leiden, Netherlands October 2024
- Posters:
  a. 8th Heidelberg International Symposium on High-Energy Gamma-Ray Astronomy, Milan, Italy September 2024
  b. EAS Annual Meeting, Padova, Italy July 2024
- Conferences, School and workshop
  a. 3rd Nanjing GRB Conference, Suzhou, China May 2024
  b. First Collaboration Meeting on Multi-Messenger Astronomy, Indore, India January 2024
  c. IV Gravi-Gamma-Nu Workshop, L'Aquila, Italy October 2023
  d. PRECISE Summer School, Institute of Physics, Warsaw, Poland July 2023
  e. Summer School on the Transient Universe, IESC Cargese, France June 2023

Extra!

LAT Index Comparison



For 0.1-10 GeV: Uncertainties in photon indices due to inclusion of photons greater than highest energy photon (E_{max})

Previous Study shows:

D'Avanzo 2012 (X-ray) & Nava 2014 (GeV)

$\eta \sim 0.1$

$\epsilon_e \sim 0.1$

$\epsilon_B \sim 10^{-2}$

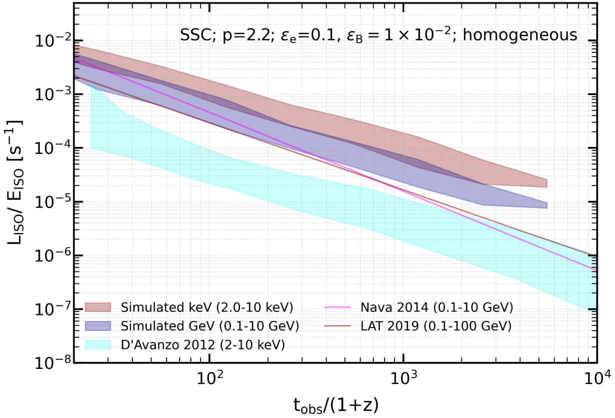
p ~ 2.2 and 2.3

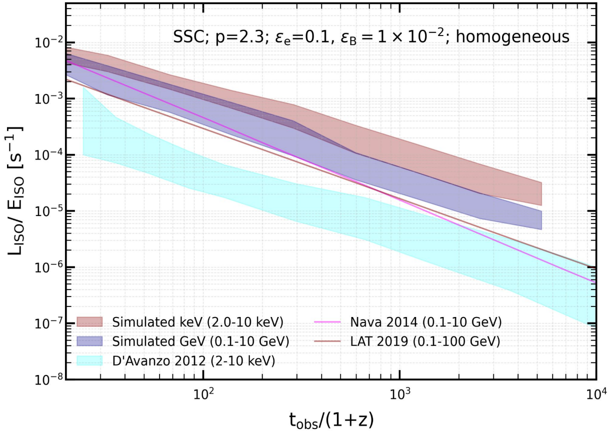
Circumburst medium: Wind/ Homogenous ?

GeV and X-ray Previous studies parameter prediction

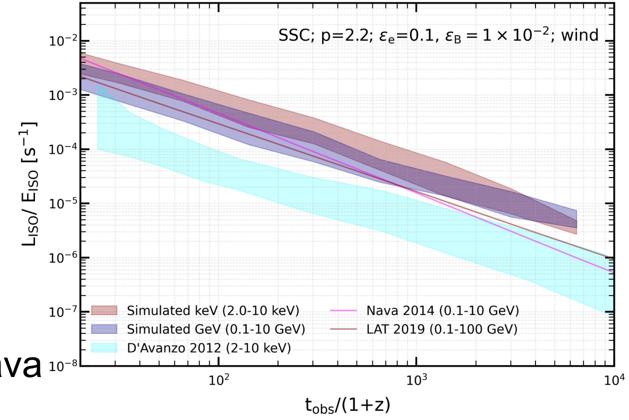
Homogeneous case

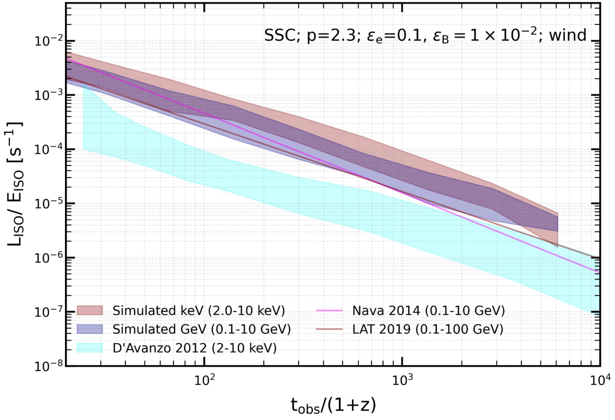
GeV, X-ray are overproduced





Wind case





D'Avanzo 2012 (X-ray) & Nava 2014 (GeV)

KS Test

Preferred parameters				KS test: p-values		
p	ϵ_B	medium	density (n/A$_*$)	$\bar{p}_\gamma$	$\bar{p}_x$	Combined
2.2	10^{-4}	wind	0.1	0.84	0.94	0.97
2.3	10^{-4}	wind	0.1	0.74	0.91	0.94
2.4	10^{-4}	wind	0.1	0.62	0.89	0.88
2.2	10^{-3}	wind	0.1	0.37	0.83	0.67
2.4	10^{-3}	wind	0.1	0.28	0.93	0.61
2.3	10^{-3}	wind	0.1	0.24	0.88	0.54
2.2	10^{-2}	wind	1.0	0.18	0.29	0.21
2.3	10^{-2}	wind	1.0	0.13	0.32	0.16
2.2	10^{-2}	homogeneous	1.0	0.03	0.12	0.02
2.3	10^{-2}	homogeneous	1.0	0.02	0.18	0.02

Table B.1. Kolmogorov–Smirnov (KS) test results for the preferred parameters in both wind and homogeneous (ISM) environments, assuming $\epsilon_e = 0.1$ and $\eta = 0.1$. $\bar{p}_x$ and $\bar{p}_\gamma$ represent the probability of agreement between 220 simulated GRBs and the clustering in X-rays and GeV energies, respectively. The last column report the joint probability.