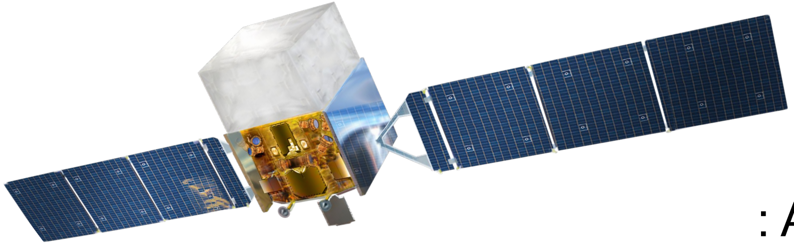
High Energy View of The Fast X-ray Transients Detected by Einstein Probe in its First Year



: Ansh Chopra

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External Supervisors: Dr. Maria Edvige Ravasio, Prof. Peter Jonker (Radboud University)

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Radboud Universiteit

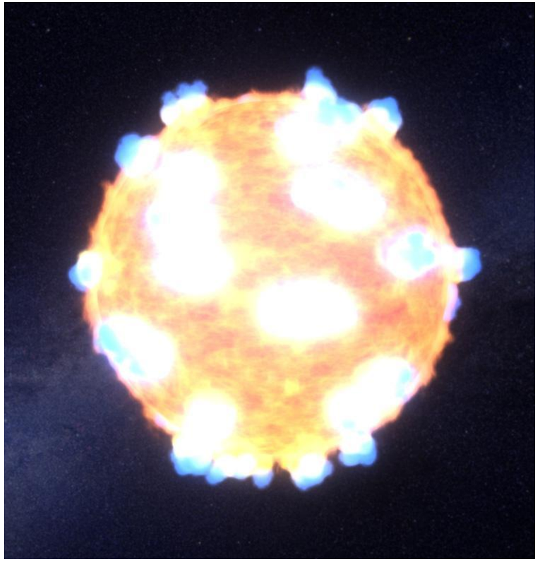
Fast X-ray Transients (FXTs)

Bright ($L_{X,Peak}$~ 10^{44}-10^{46} erg/s) and Short-lived X-ray bursts lasting from **seconds to hours**.

Possible Progenitors:

1. **Supernova Shock Breakouts**

Soderberg + (2008)



Credit: NASA/Ames/STScI

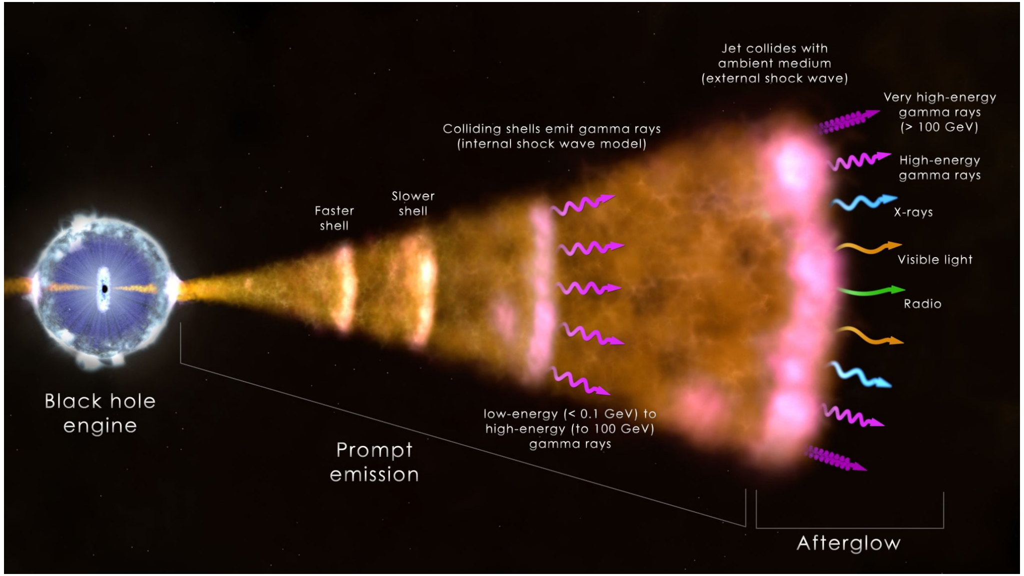
Fast X-ray Transients (FXTs)

Bright ($L_{X,Peak}$~ 10^{44}-10^{46} erg/s) and Short-lived X-ray bursts lasting from **seconds to hours**.

Possible Progenitors:

2. **Gamma Ray Bursts**

Xue + (2019); Lin + (2022)



Credit: NASA/Goddard Space Flight Center/ICRAR

Fast X-ray Transients (FXTs)

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Bright ($L_{X,Peak}$~ 10^{44}-10^{46} erg/s) and Short-lived X-ray bursts lasting from **seconds to hours**.

Possible Progenitors:

3. **Tidal Disruption Events**

Jonker + (2013)

NRAO/AUI/NSF/NASA

Fast X-ray Transients (FXTs)

Lower Luminosity ~ 10^{39}-10^{42} erg/s

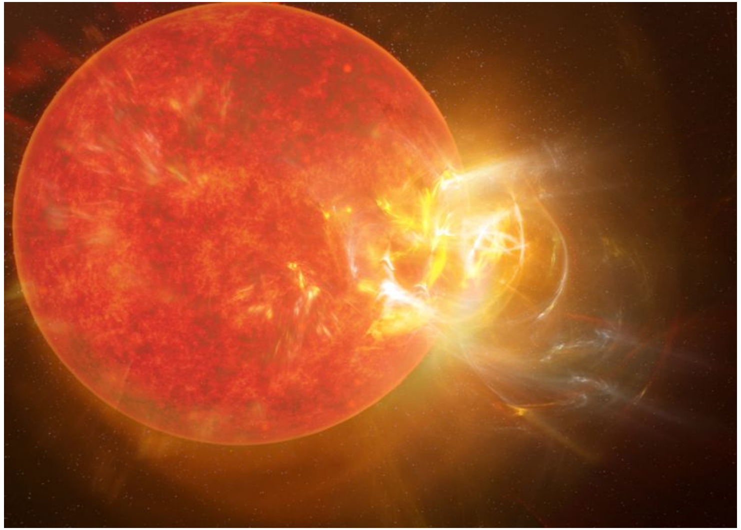
~~**Bright** ($L_{X,Peak}$ ~ 10^{44}-10^{46} erg/s)~~ and Short-lived X-ray bursts lasting from **seconds to hours**.

Possible Progenitors:

*__Stellar Flares__!

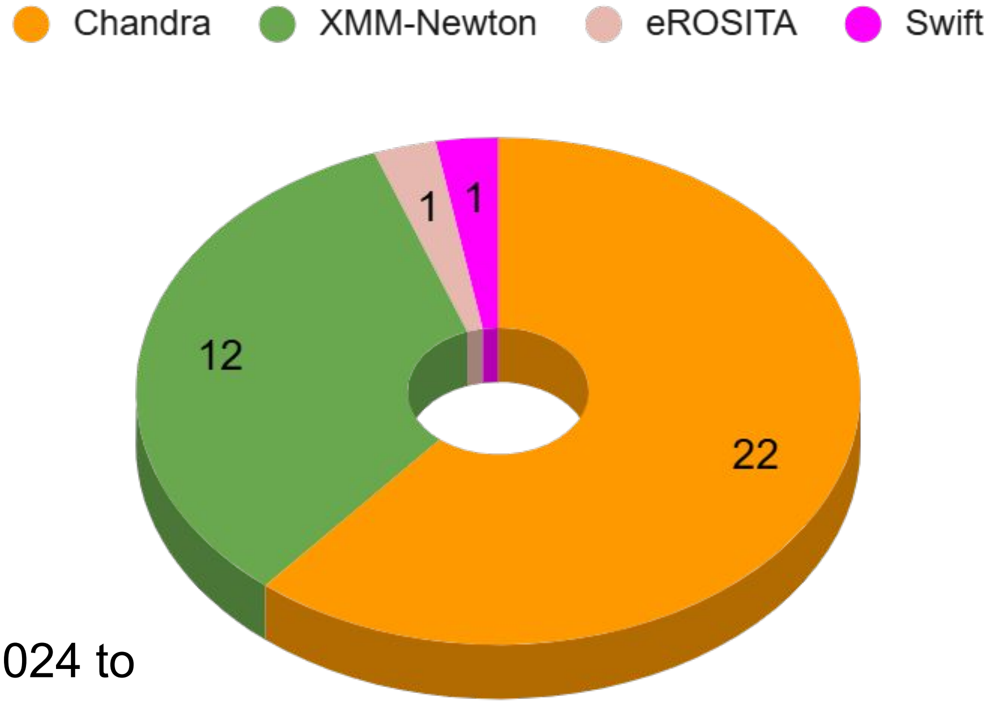
Cross-matched with existing stellar catalogues and discarded

“Extragalactic” Fast X-ray Transients



Credit: NSF/AUI/NSF NRAO/S. Dagnello

Historical FXTs



Only 36 seen in the Archival data in > 20 Years

Enters Einstein Probe!

EP detected **72 FXTs** from Feb 2024 to Feb 2025

Sample size x 2

Quirola-Vásquez + (2022, 2023)
Alp & Larsson + (2020)
Couch + (2011)

Einstein Probe

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Monitors the sky in the soft X-ray band

Wide Field X-ray Telescope
EP/WXT (0.5 - 4.0 keV)

- FoV ~ 3,600 sq. degrees
- $F_{sensitive}$ ~ 2.6 x 10^{-11} erg/s/cm^2 for 1000s Exposure
- Angular resolution of ~ 5 arcmin

Follow-up X-ray Telescope
EP/FXT (0.3 - 10 keV)

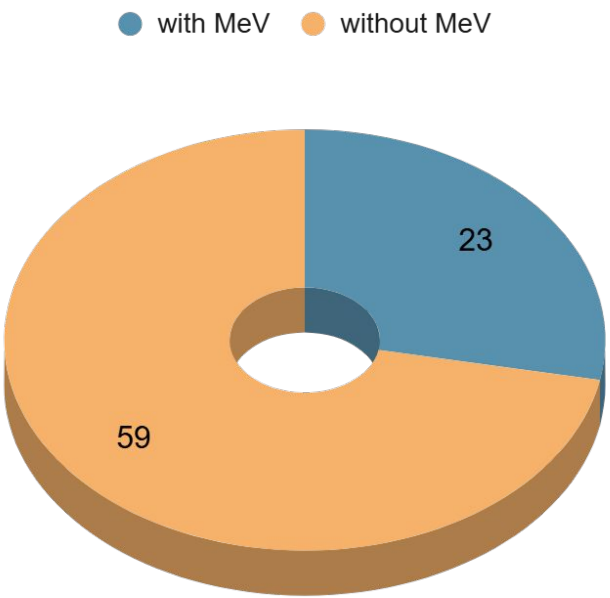
- Effective Area ~ 700 cm^2 @ 1 keV
- $F_{sensitive}$ ~ 5 x 10^{-14} erg/s/cm^2 for 25 minute Exposure
- Angular resolution ~ 30 arcsec

EP detected FXTs

EP detected **72 FXTs** from Feb 2024 to Feb 2025

Sample size x 2

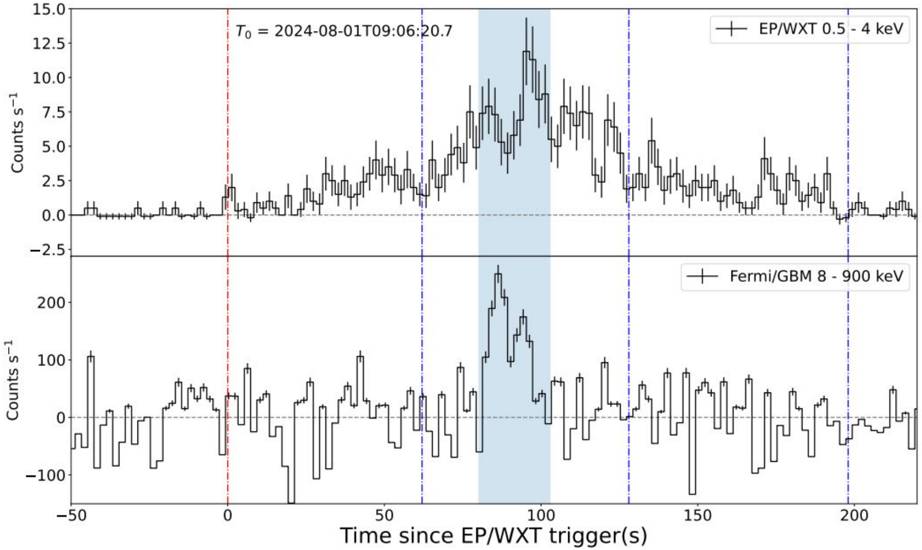
23 confirmed as GRBs



EP detected FXTs

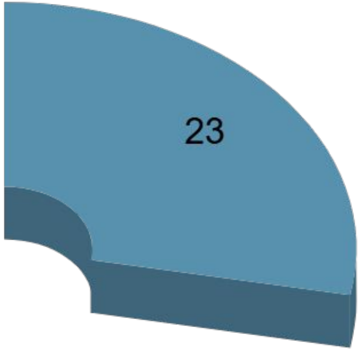
EP/WXT is seeing the X-ray counterpart of the GRB prompt emission

EP240801a



(Shuai-Qing Jiang + 2025)

with MeV



ΔT_{WXT} = 266 s
ΔT_{GBM} = 23 s

EP detected FXTs

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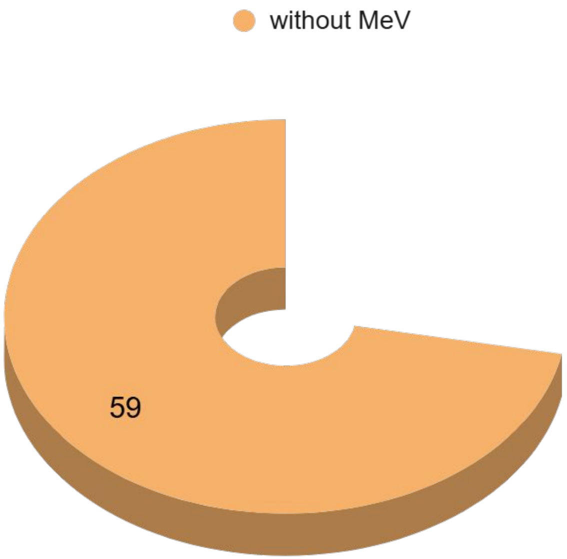
72% without any MeV counterpart



GRBs?

- Off-axis GRBs
- On-axis GRBs, but
  - With Low Luminosity
  - At High redshift

Or some different Astrophysical Phenomena!

EP FXTs as on-axis GRBs

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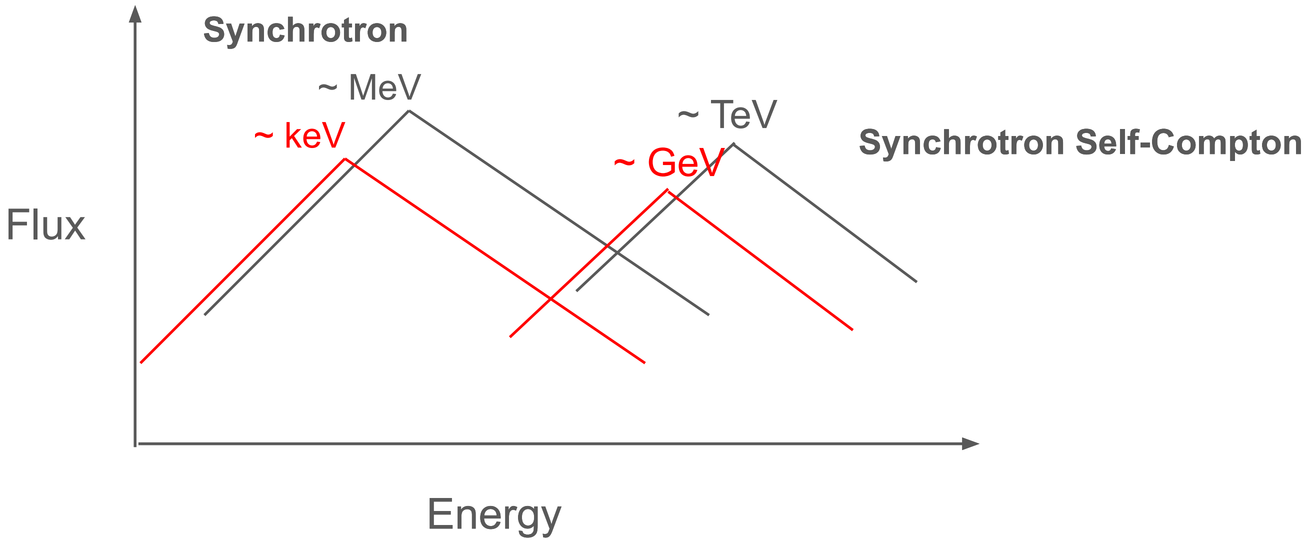
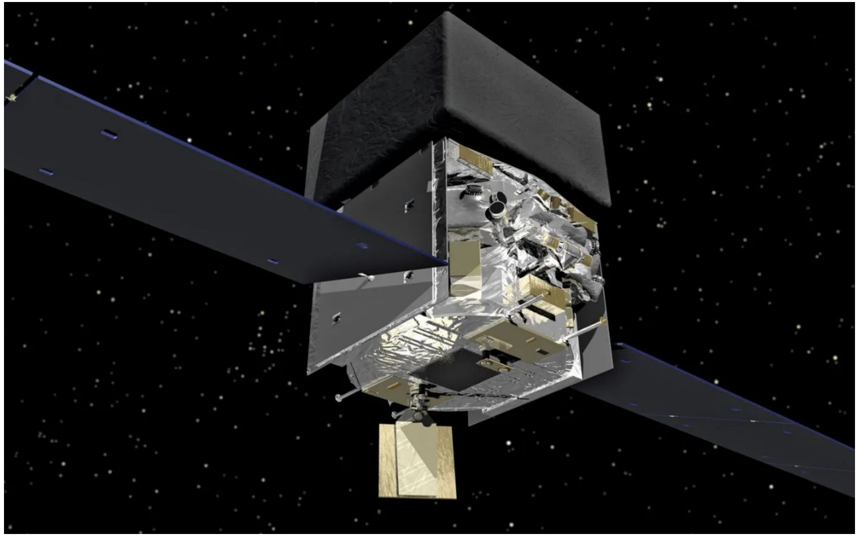
For High Redshift
and/or Low Luminosity (low peak energy) events



Fermi/GBM



Credit: *NASA*

Fermi Gamma-ray Burst Monitor

- Primary GRB trigger instrument on Fermi.
- FoV ~ 8 sr (nearly full sky)
- Energy range 8 keV – 40 MeV

Scintillator Detectors to measure photons
12 NaI detectors → 8 keV – 1 MeV
2 BGO detectors → 150 keV – 40 MeV

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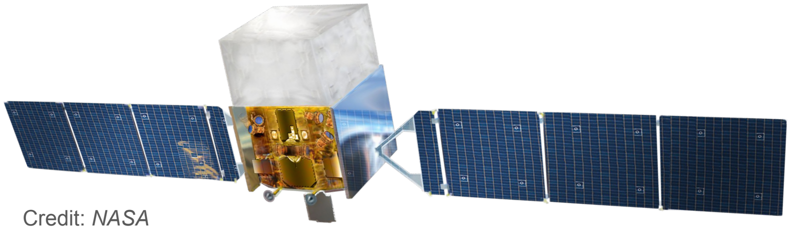
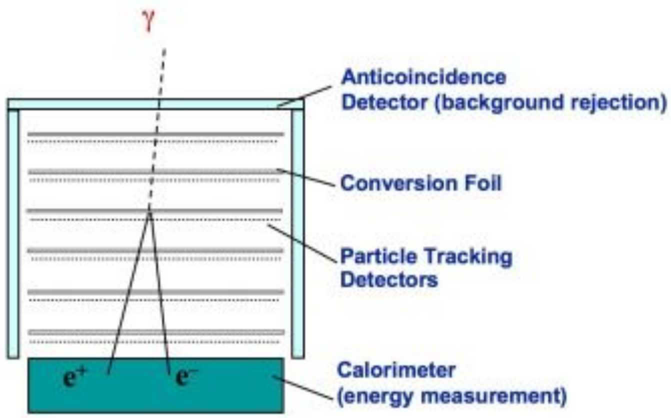
Fermi Large Area Telescope



Credit: *NASA*



Credit: *NASA*

Pair Conversion γ-ray Telescope

Covers ~ 20% of the sky at a time in 50 MeV to 300 GeV energy range

Scans the entire sky in 2 orbits (~ 3 hrs)

Source Selection

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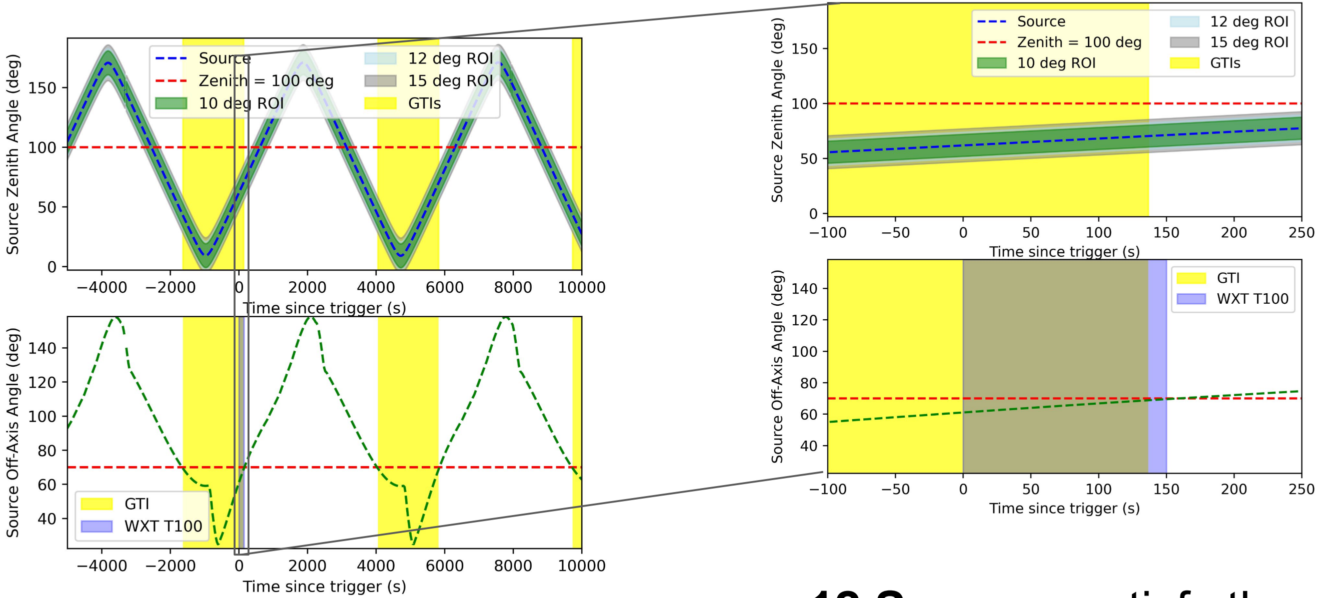
1. $\Theta_{zenith} \leq 100^o$
2. $\Theta_{off\text{-}axis} \leq 70^o$

3. T(blue ∩ yellow)/T(blue) ≥ 50%
or LAT saw the source during WXT peak

EP240806a



12 Sources satisfy the criteria

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Unbinned Likelihood

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Likelihood Fit (unbinned) → fitting observed data to estimate the model parameters

No. of events

Model parameters

$$\mathcal{L}(\boldsymbol{\theta}) = \prod_{i=1}^{N} P(\mathbf{x}_i \mid \boldsymbol{\theta}) \quad \Rightarrow \quad \log \mathcal{L}(\boldsymbol{\theta}) = \sum_{i=1}^{N} \log P(\mathbf{x}_i \mid \boldsymbol{\theta})$$

Observed parameters of the i^{th} photon

Test Statistic (TS) → compares the likelihood of the data under two hypothesis:

H_0 : Source is Absent → $\ln \mathcal{L}(H_0)$

H_1 : Source is present → $\ln \mathcal{L}(H_1)$

$$TS = 2 \ln \frac{\mathcal{L}(H_1)}{\mathcal{L}(H_0)} \longrightarrow TS = 2[\ln \mathcal{L}(H_1) - \ln \mathcal{L}(H_0)]$$

$$\sigma \sim \sqrt{TS}$$

LAT Upper Limits

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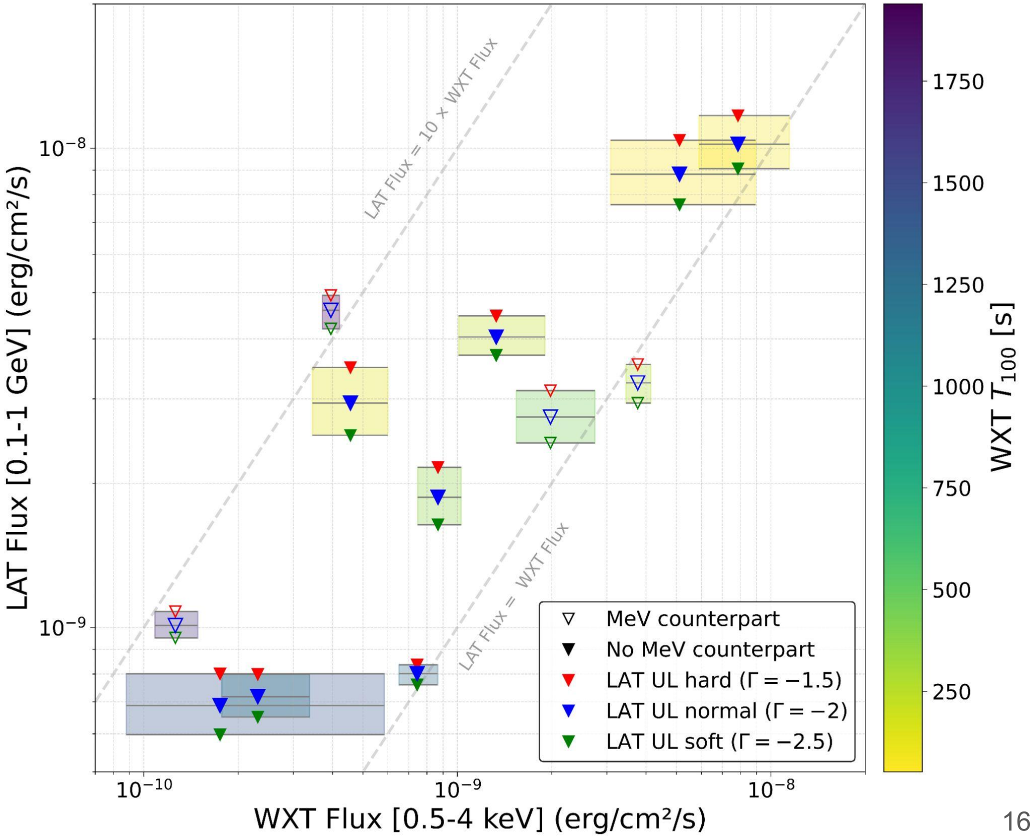
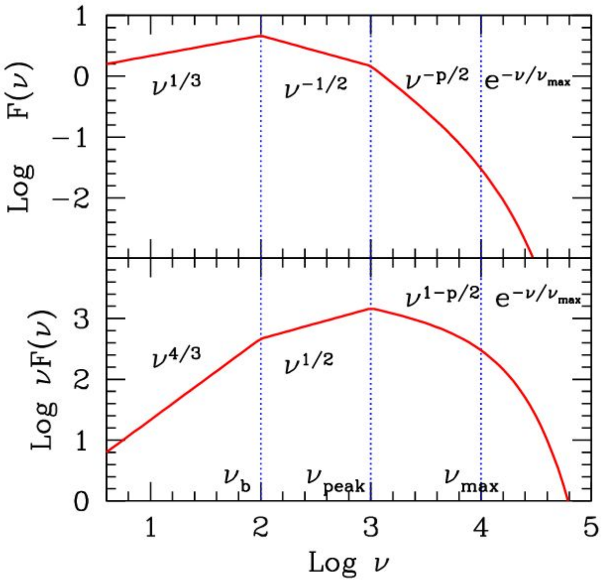
No Fermi-LAT detections during the T_{100} of EP/WXT → ($0 \leq TS \leq 3$)

LAT ULs < 10 $Flux_{WXT}$

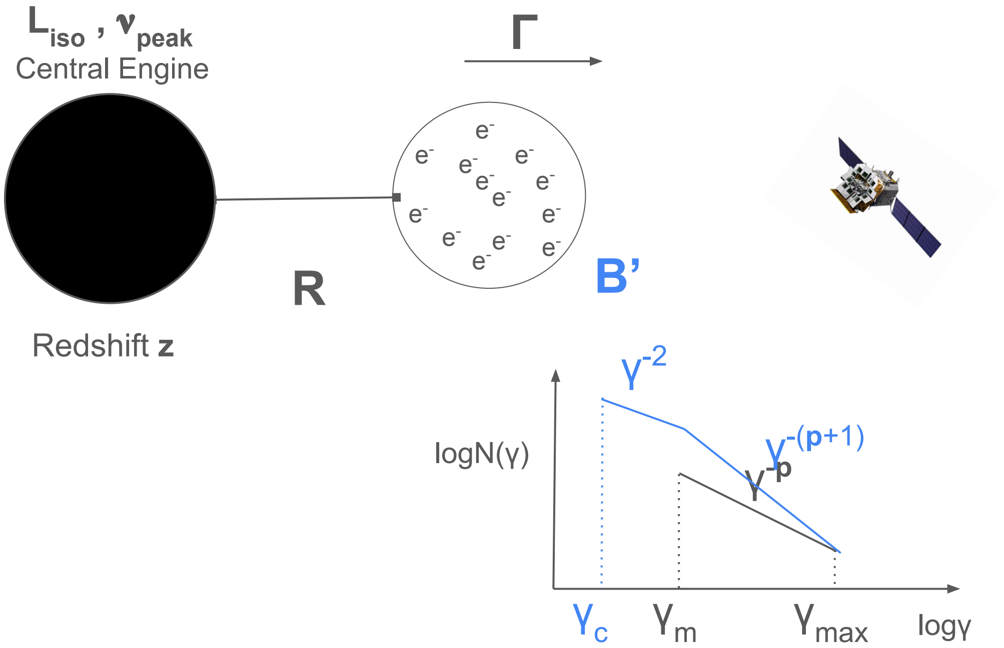
Even the ULs can help us constrain the physical parameters of the Jet like the Emission Radius **R** and the Magnetic Field in the comoving frame **B'**



Analytical Model



Ghisellini + 2020



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Analytical Model

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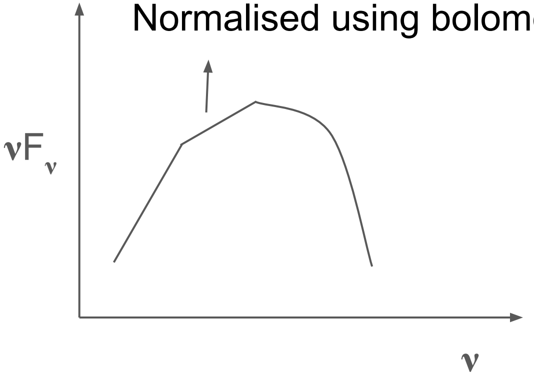
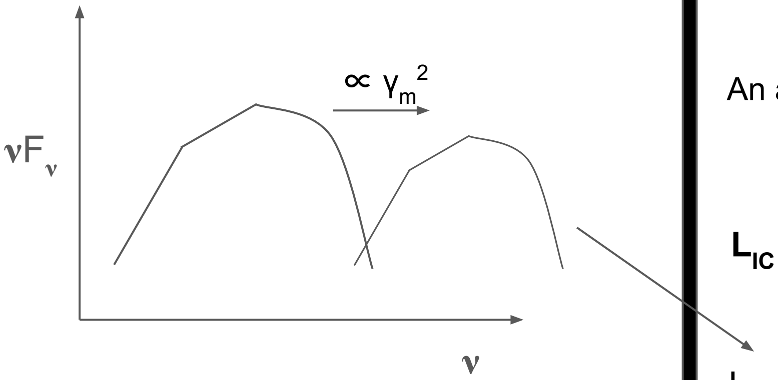
Ghisellini + 2020

Normalised using bolometric L_{iso}





Total Radiation energy density

$$U'_r = \frac{L'_{iso}}{4\pi R^2 \Delta R'}\frac{\Delta R'}{c} = \frac{L_{iso}}{4\pi R^2 c \Gamma^2}$$

An electron with lorentz factor γ loses energy by scatter a fraction **f(γ)** of ***U'_r*** in the Thomson regime

$$f(\gamma) = \frac{\int_0^{1/\gamma} U'_r(x')\,dx'}{U'_r}$$

Where, $x = h\nu/m_e c^2$

An additional cooling mechanism decreases $\gamma_c \rightarrow \gamma_c^{syn} / [1+f(\gamma_c)U'_r/U'_B$

L_{IC} = Y x L_{syn} ; where

$$Y = \frac{U'_r}{U'_B}\frac{\int_1^{\gamma_{max}} N(\gamma)\gamma^2 f(\gamma)d\gamma}{\int_1^{\gamma_{max}} N(\gamma)\gamma^2 d\gamma}$$

L_{IC} used to normalise the SSC spectrum

Caveats with the model

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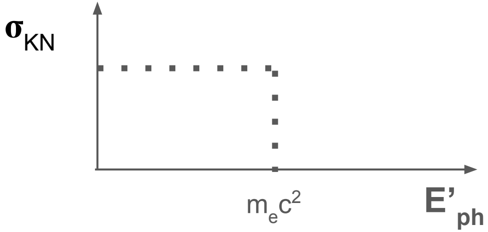
1. SSC doesn't affect the Synchrotron spectra → No Self-Consistent Solution.
2. Scattering only in Thomson regime → Klein-Nishina cross section assumed to be $\boldsymbol{\sigma}_{KN} = \boldsymbol{\sigma}_{Th}$ for all the photon energies $E'_{ph} < m_e c^2$ and $\boldsymbol{\sigma}_{KN} = 0$ otherwise.



3. Pair Production effect not accounted for → γγ interaction can kill the SSC spectrum.

Case of EP240801a

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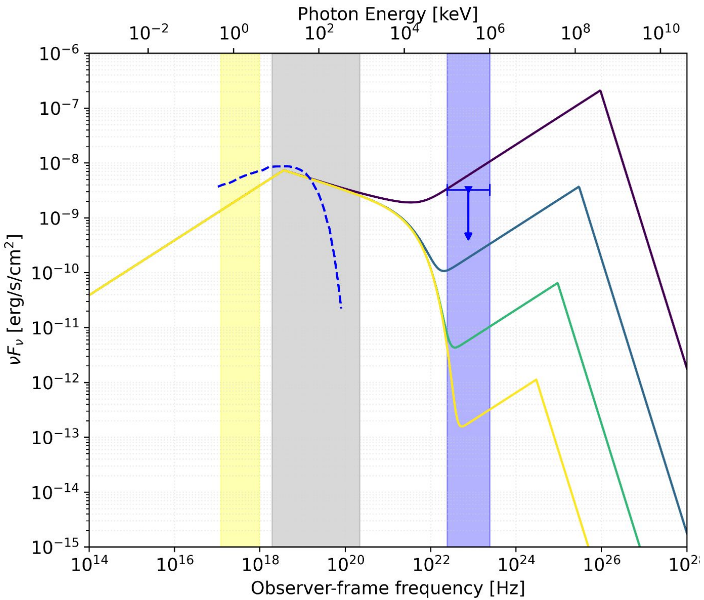
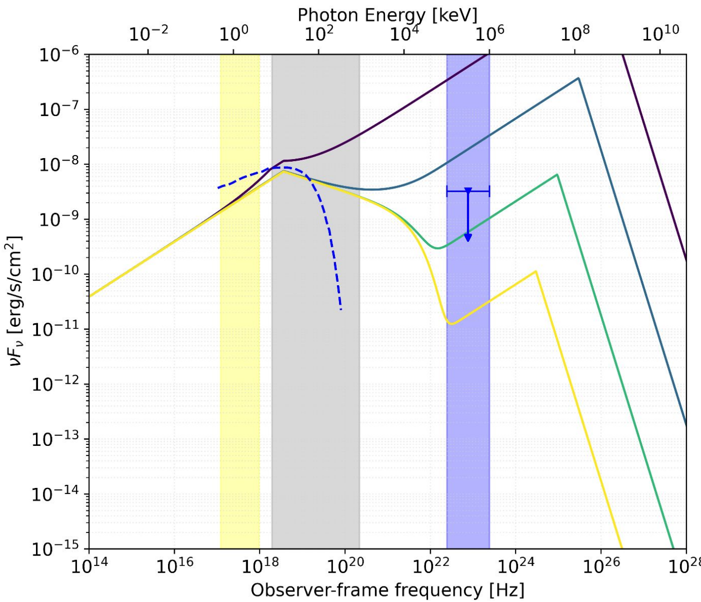
A Long GRB at z = 1.67 seen by EP/WXT with peak energy at 15 keV

- EP/WXT Band (0.5–4 keV)
- GBM Band (8–900 keV)
- LAT Band (0.1–1 GeV)
- EP240801a
- LAT UL
- B' = 10 G
- B' = 100 G
- B' = 1000 G
- B' = 10000 G



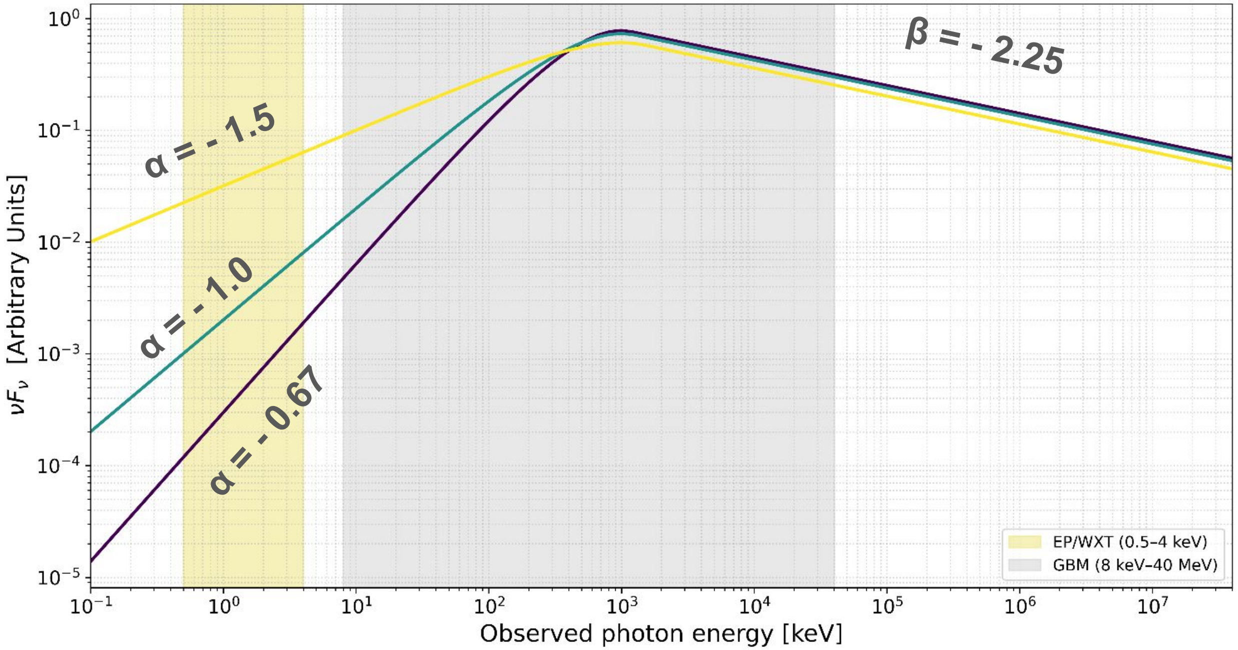
R = 10^{16} cm, L_{iso} = 2 x 10^{51} erg/s



R = 10^{15} cm, L_{iso} = 2 x 10^{51} erg/s

Band Function

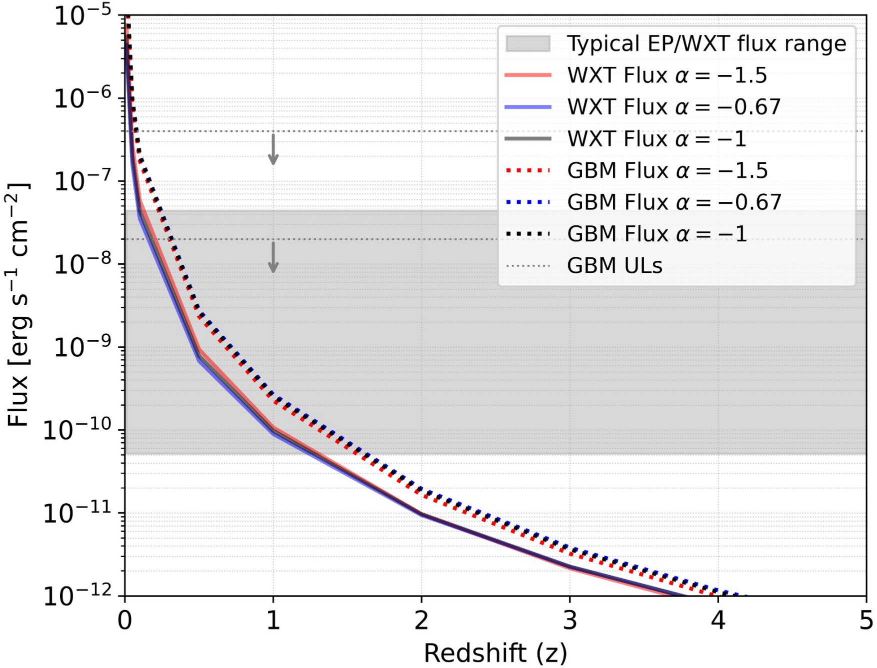
I take the function which is used to fit most of the Prompt GRB spectra in the observer frame

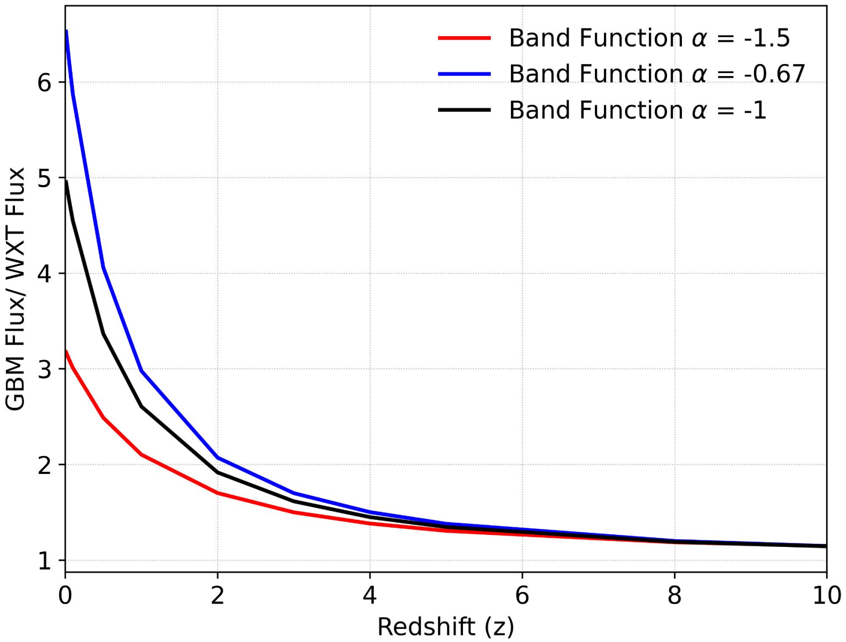


Band + 1993

Results from the Band Function

Low Luminosity GRB → $L_{iso} = 10^{49}$ erg/s ; $E_{p,z}$ = 10 keV





Results from the Band Function

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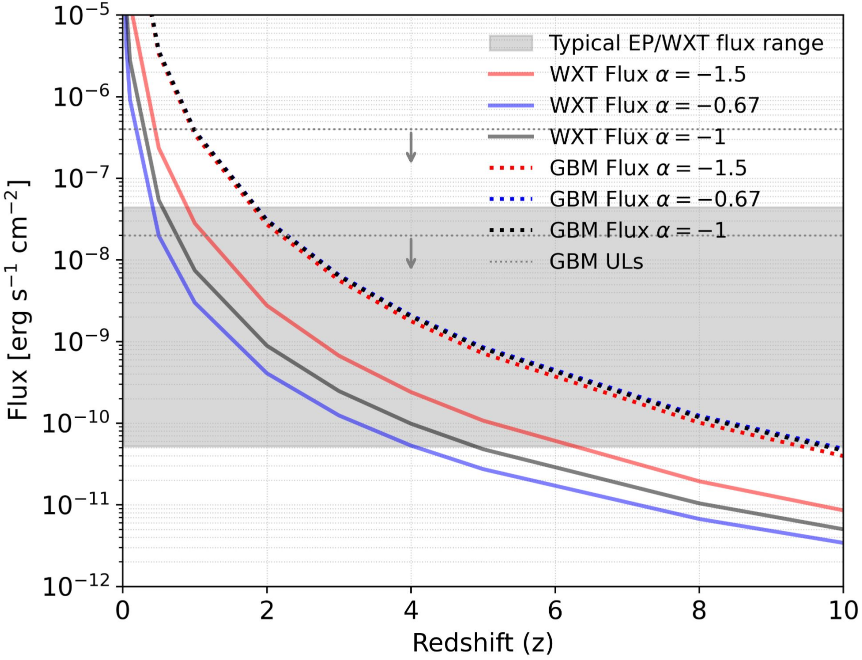
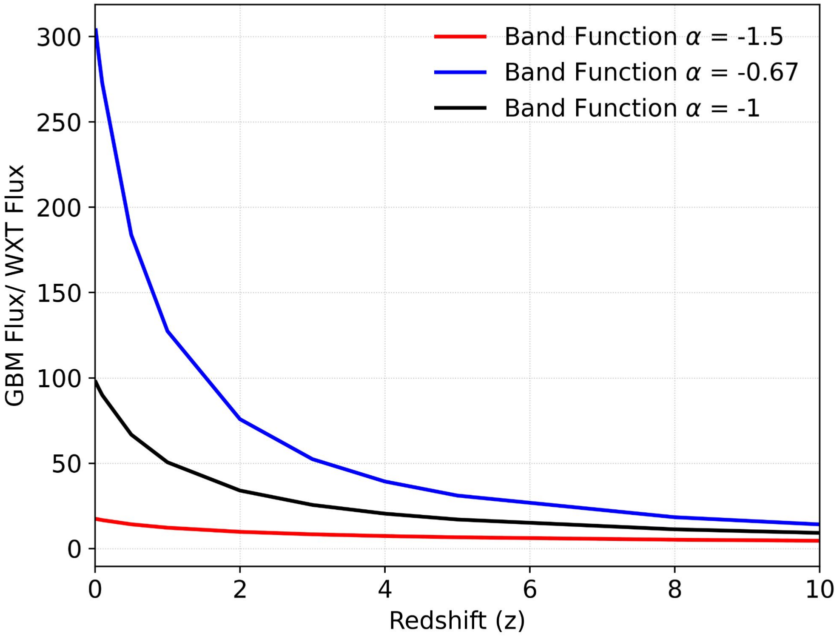
Typical GRB → $L_{iso} = 10^{52}$ erg/s ; $E_{p,z}$ = 200 keV





Future Work

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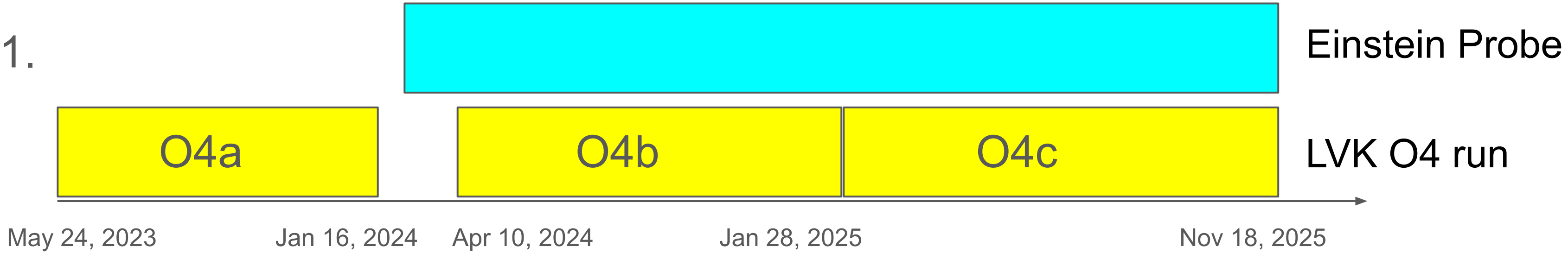
1.



Using Offline GW Analysis Pipelines (eg. X-Pipeline) (Sutton+ 2010)

- Searching GW counterparts of the Einstein Probe Detected FXTs
- In case of Non-detection, calculate their Maximum Exclusion Distance

2. Study the Afterglow of the Fast X-ray Transients with Multi-wavelength data

CONCLUSION

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- Einstein Probe is detecting a large number of Fast X-ray transients with most of them not seen in the MeV band.
- For the on-axis GRB scenario, LAT upper limits show that the Synchrotron self-Compton emission is possibly suppressed, which discard low values of emission radius and local magnetic field.
- For low luminosity GRBs, EP can only see events with $z<2$.
- Afterglows of FXTs can help us understand their emission mechanism better.
- Performing X-Pipeline search to look for GW counterparts of the FXTs in future can help further constrain their nature.

Extra Slides

Source Selection for Fermi/LAT

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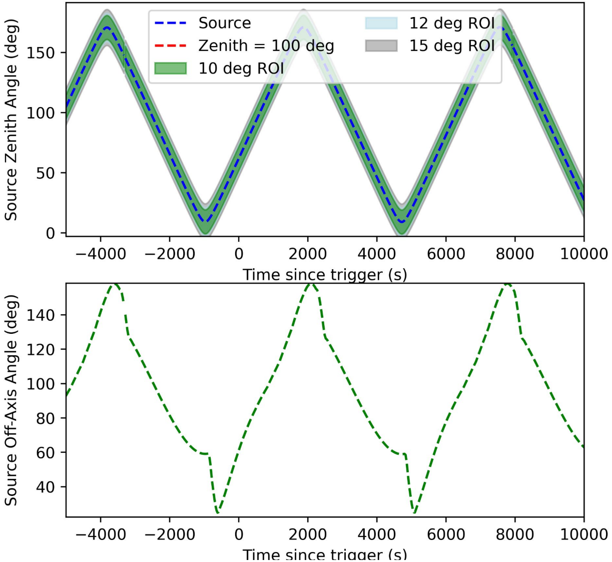
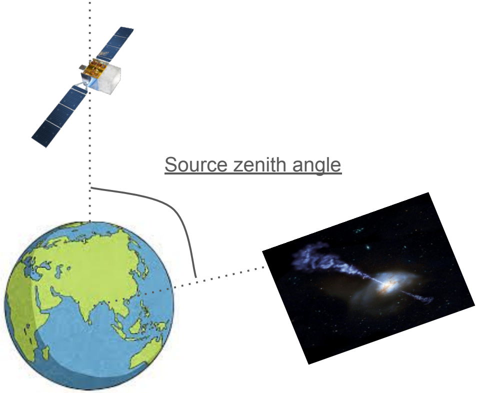
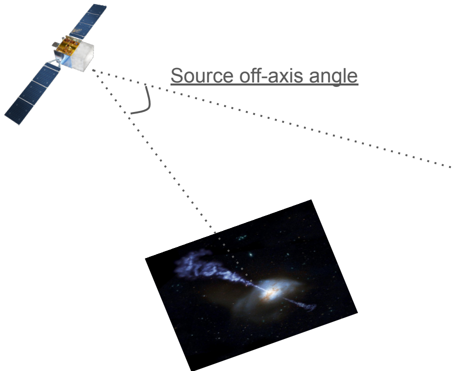
How well did Fermi/LAT cover the transient

EP240806a → 62.08° → 150s







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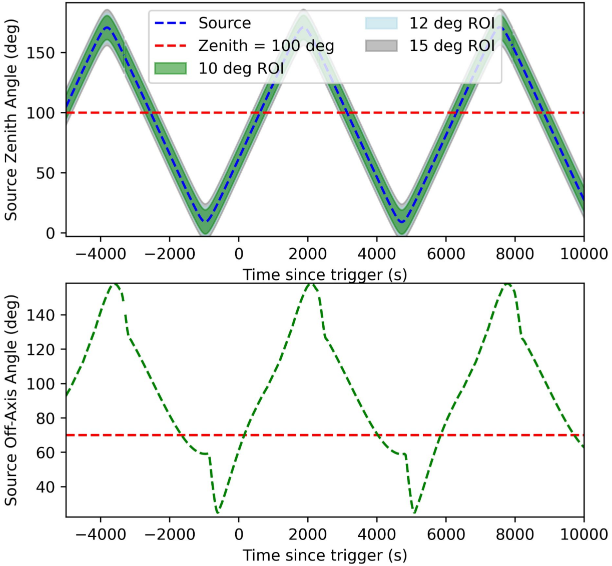
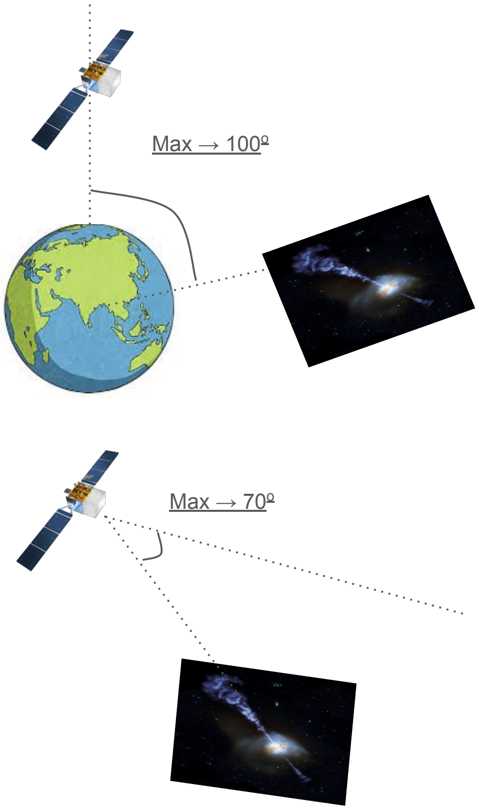
On-axis GRB scenario

EP240806a → 62.08° → 150s



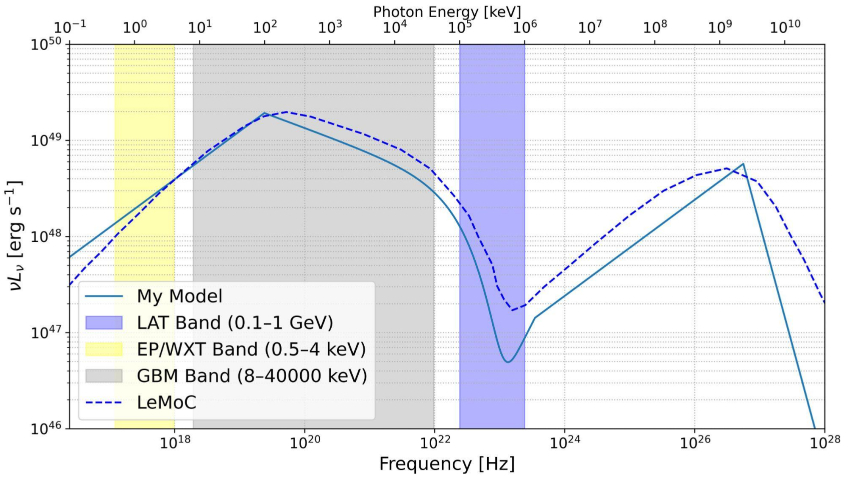


Comparison between LeMoC and the Analytical Code

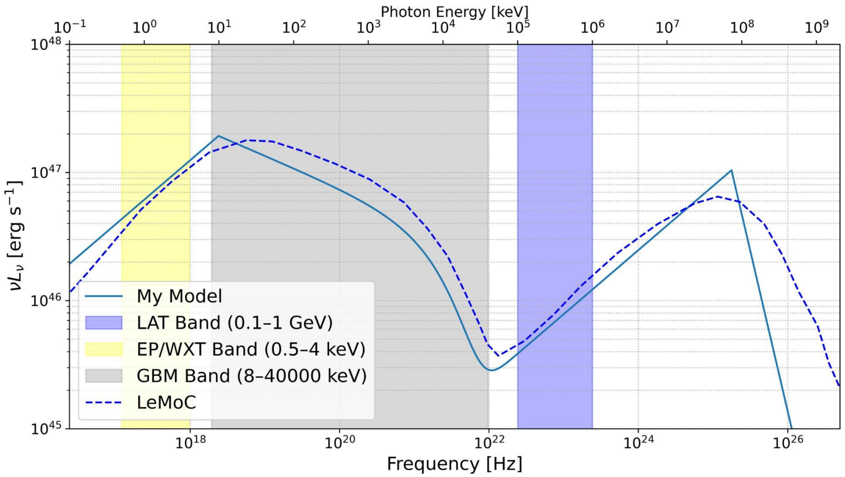
Numerical SSC code based on LeMoC (Leptonic Modeling Code) used for Blazars

Here the pair-production was not considered in the LeMoC code

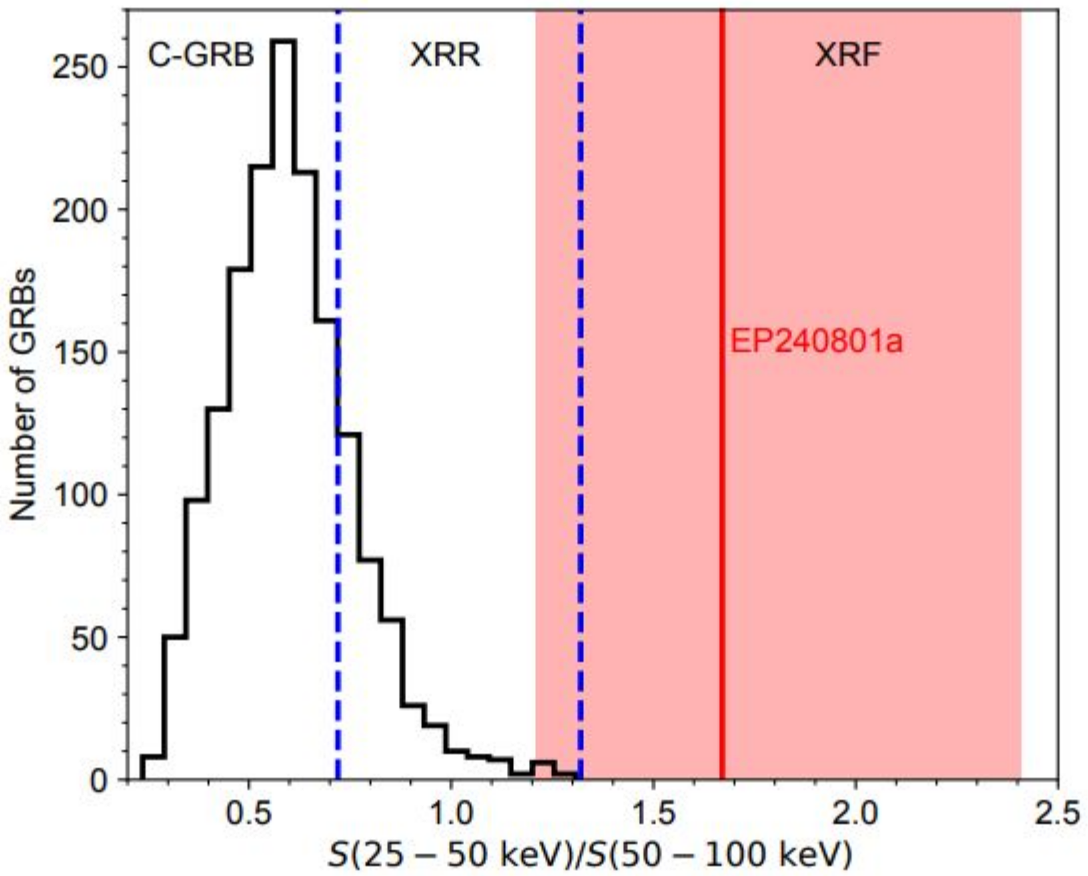
$\Gamma = 100$; $B' = 10$ G; $L_{iso} = 10^{50}$ erg/s; $E_{p,z} = 100$ keV; $R = 10^{16}$ cm



$\Gamma = 10$; $B' = 10$ G; $L_{iso} = 10^{48}$ erg/s; $E_{p,z} = 10$ keV; $R = 10^{15}$ cm



* The two models don't match when KN effects starts becoming prominent (for <u>lower B' and R</u>) and when <u>pair production</u> flag is turned-<u>on</u>



(Shuai-Qing Jiang + 2025)