Celebrating 20 years of Swift Discoveries
24–28 Mar 2025 Florence, Italy

Interpreting the 10 MeV emission line in GRB 221009A as high-latitude emission from an annihilating pair bubble

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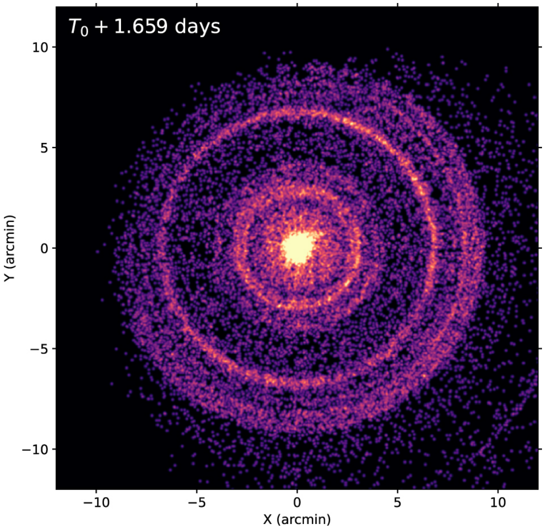
Finanziato dall'Unione europea NextGenerationEU
Ministero dell'Università e della Ricerca
Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA

background image credits: NASA's Goddard Space Flight Center Conceptual Image Lab]

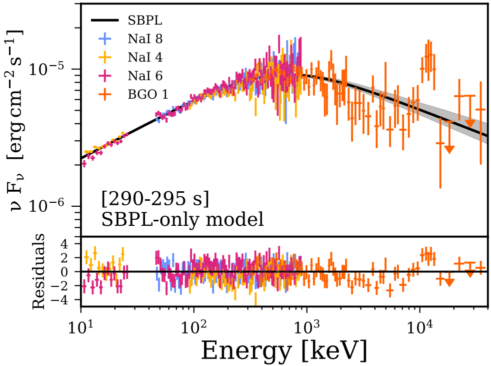
GRB 221009A - The B.O.A.T.



[Swift/XRT image of the dust rings – adapted from Williams et al. 2023]

Dr Ravasio's discovery

Fermi/GBM data of GRB 221009A



[Adapted from Ravasio, Salafia, Oganesyan, et al. 2024]

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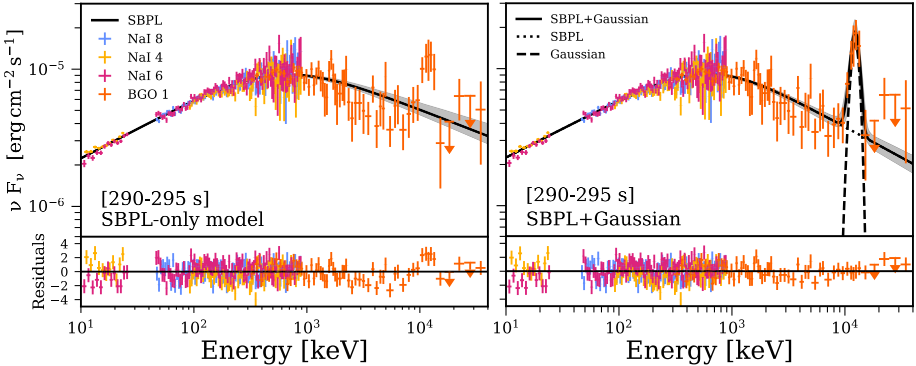

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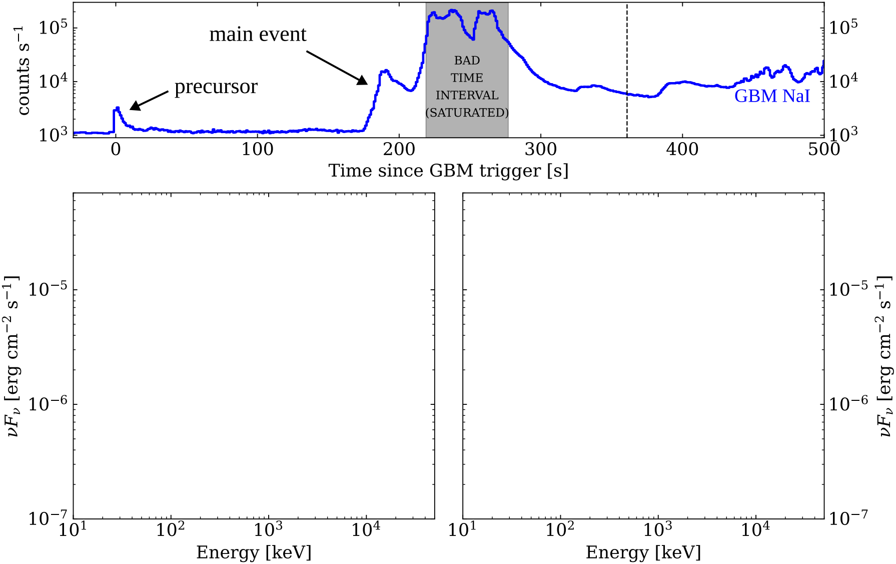
Spectral evolution



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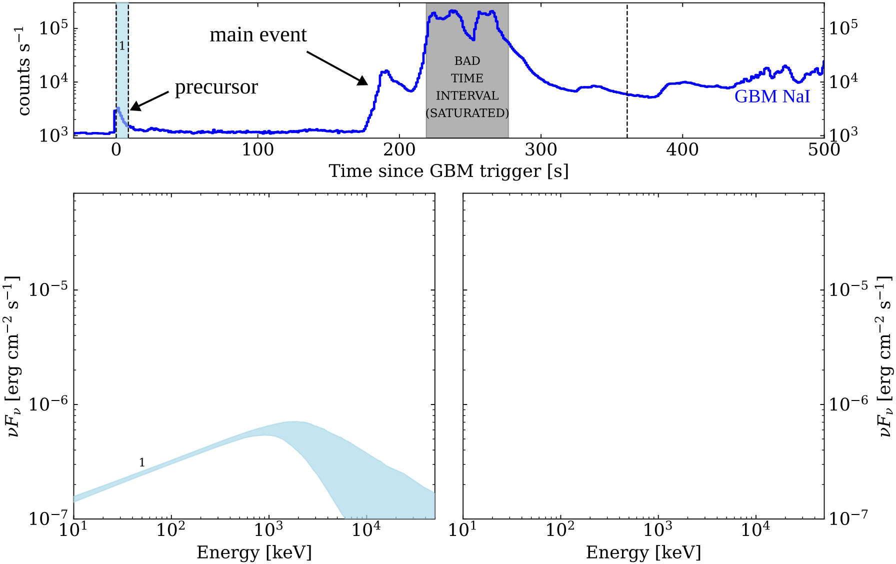

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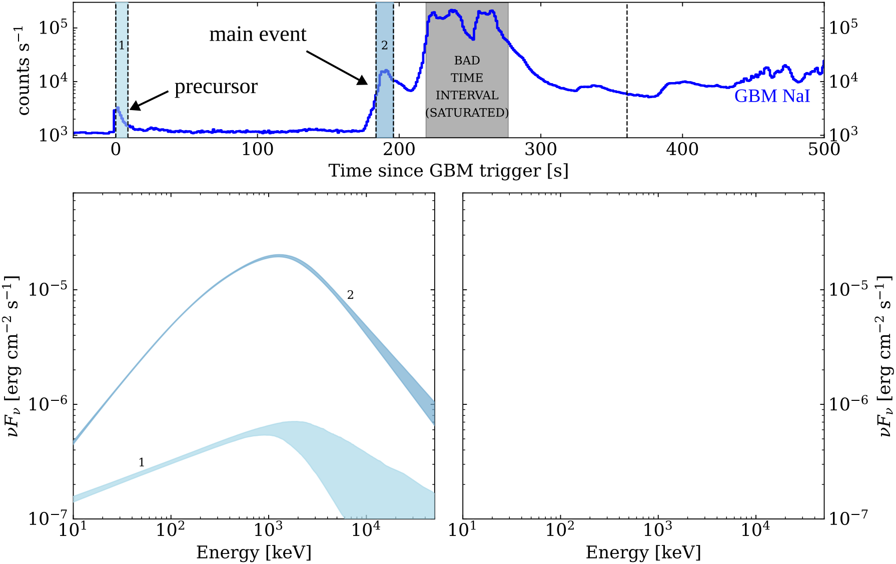

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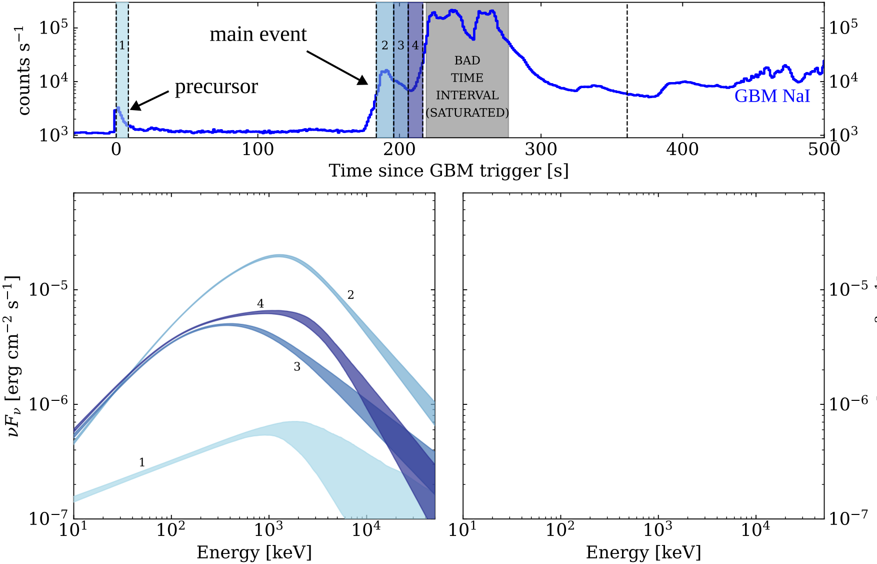

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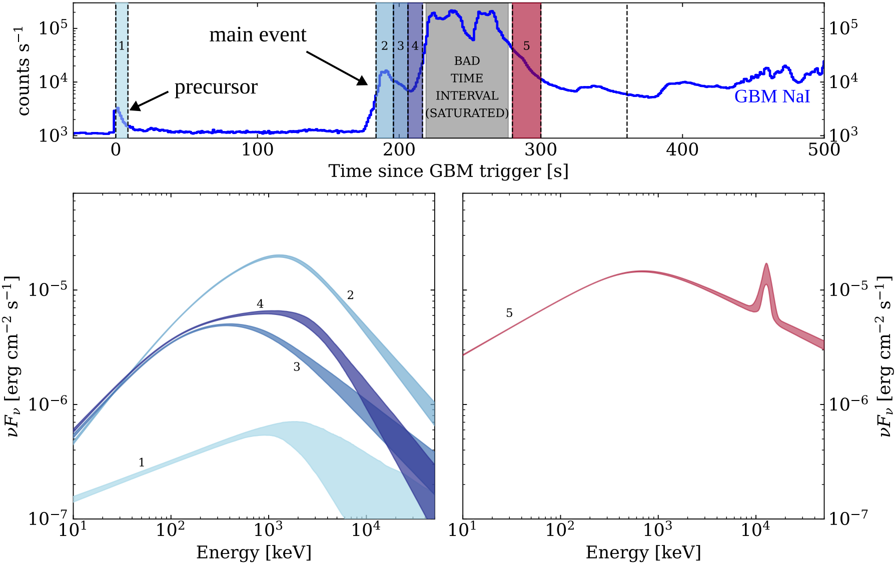

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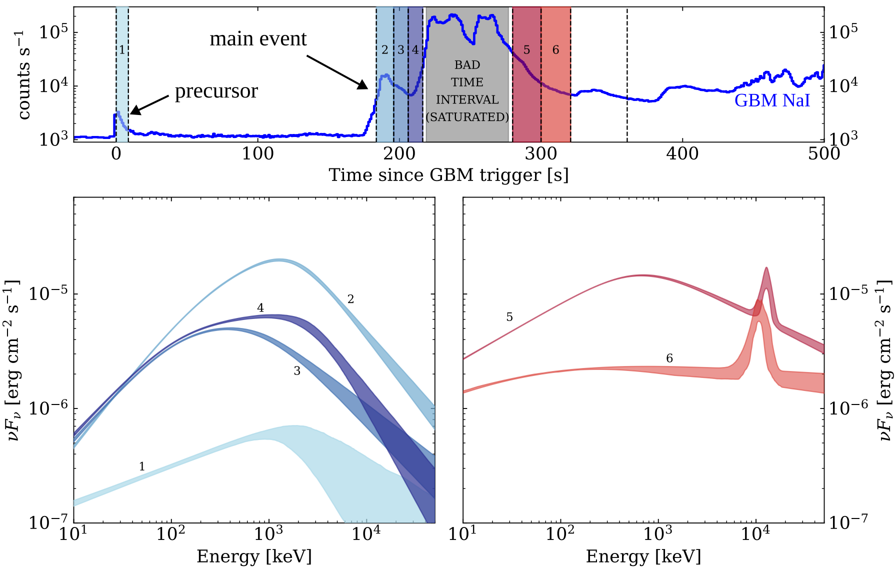

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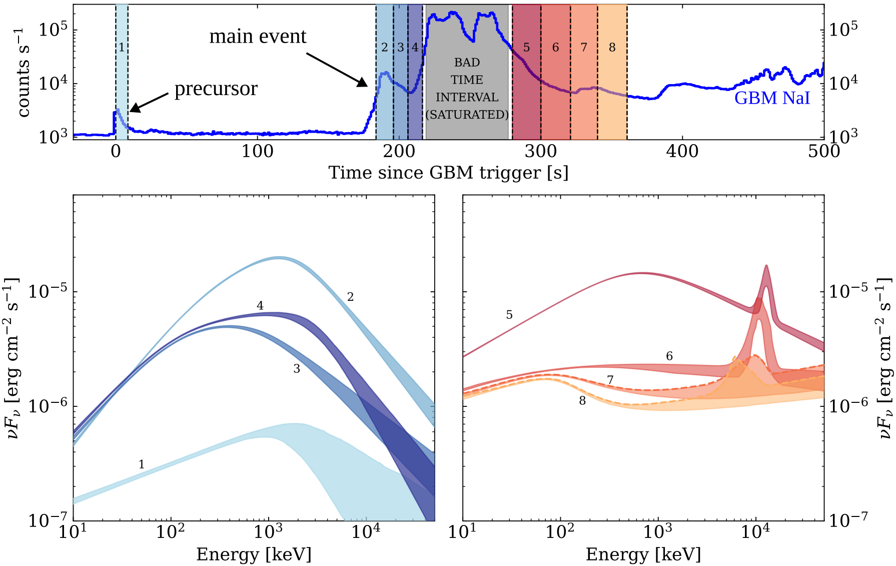

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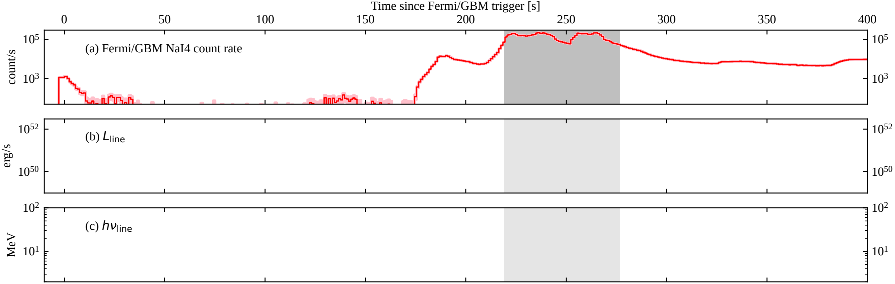
Line property evolution



[Salafia et al., in prep]

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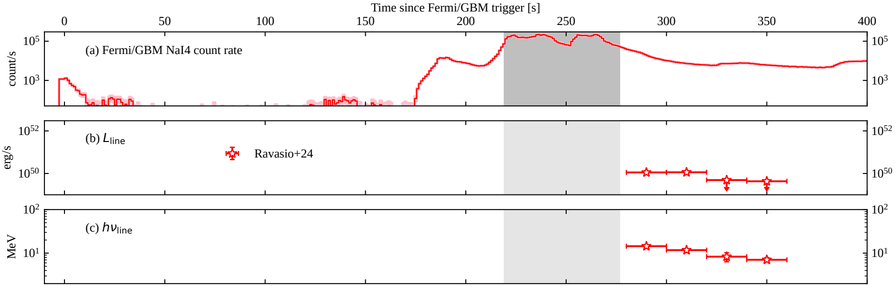

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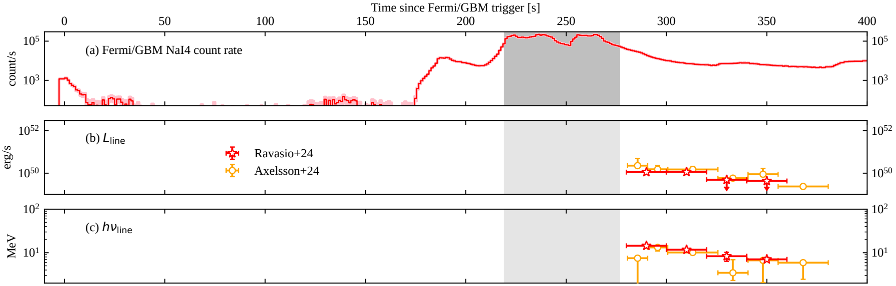

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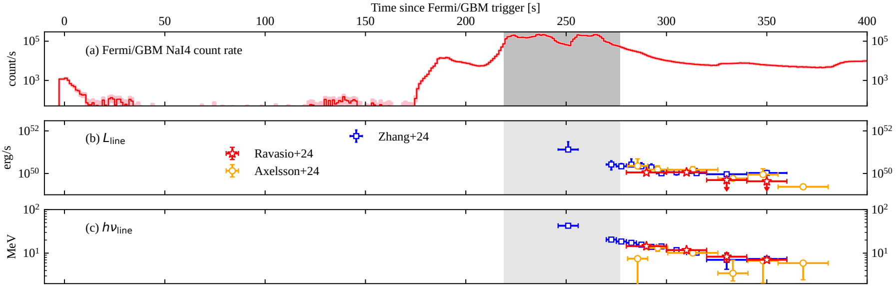

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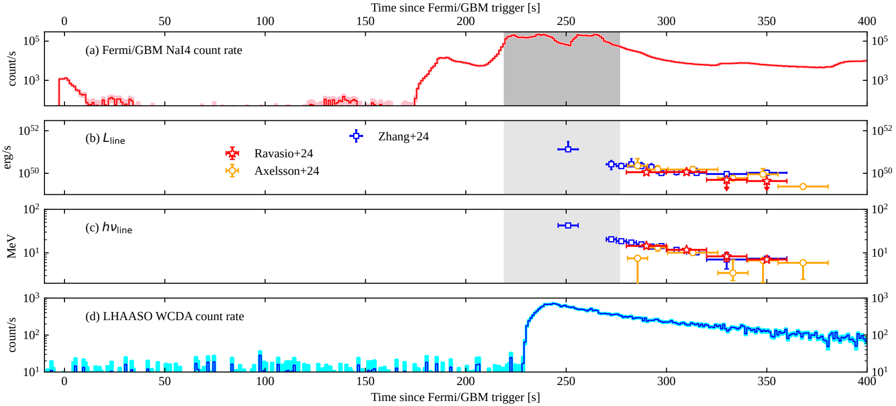

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Origin of the line?

How do you produce a narrow feature with $L \sim 10^{50}$ erg/s luminosity at $h\nu \sim 10$ MeV?

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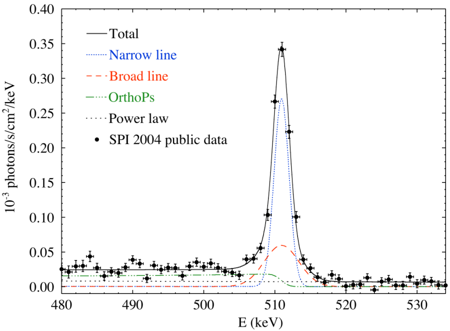
e^+e^- annihilation line



[Prantzos et al. 2011]

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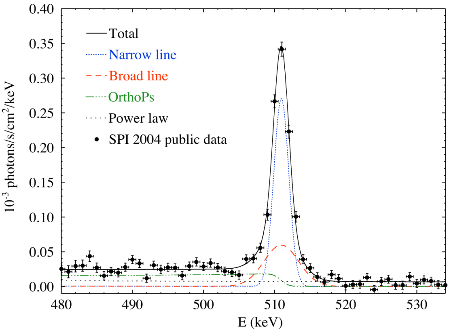


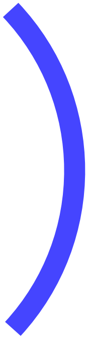
[Prantzos et al. 2011]

Doppler blueshift

Doppler factor

$$\delta = \frac{1}{\Gamma(1-\beta\cos\theta)} \sim 20$$

High-latitude emission (HLE)



[e.g. Kumar & Panaitescu 2000; Oganesyan et al. 2020; Salafia et al., in prep]

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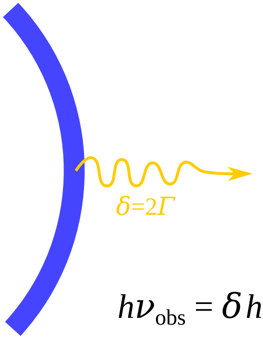

$$h\nu_{\rm obs} = \delta\, h\nu'$$

[e.g. Kumar & Panaitescu 2000; Oganesyan et al. 2020; Salafia et al., in prep]

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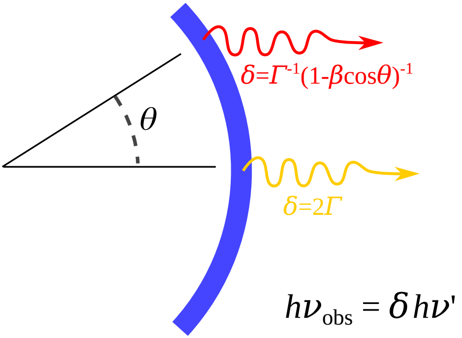

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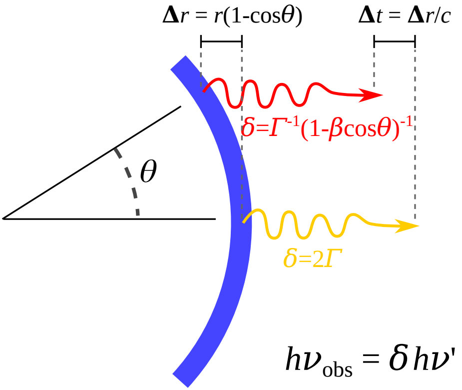

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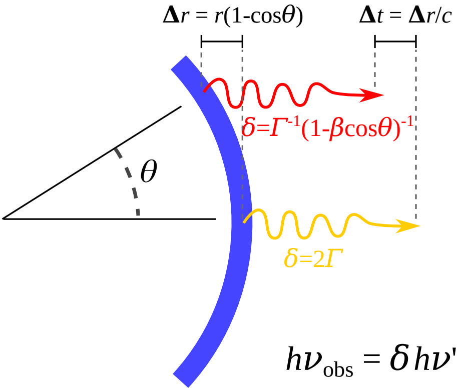

If

$$t_{em} \ll r/c$$

then
HLE dominates time evolution,
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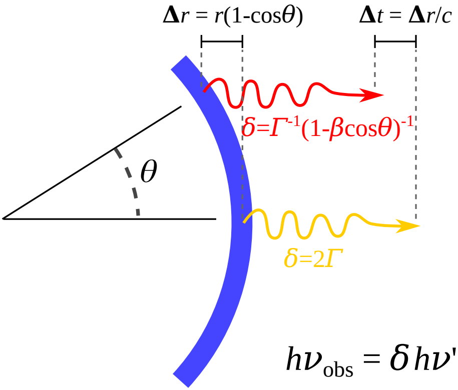

If

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then
HLE dominates time evolution,
and

$$L(t_{\rm obs}) = \frac{2E/t_{\rm ang}}{(1+t_{\rm obs}/t_{\rm ang})^3}$$

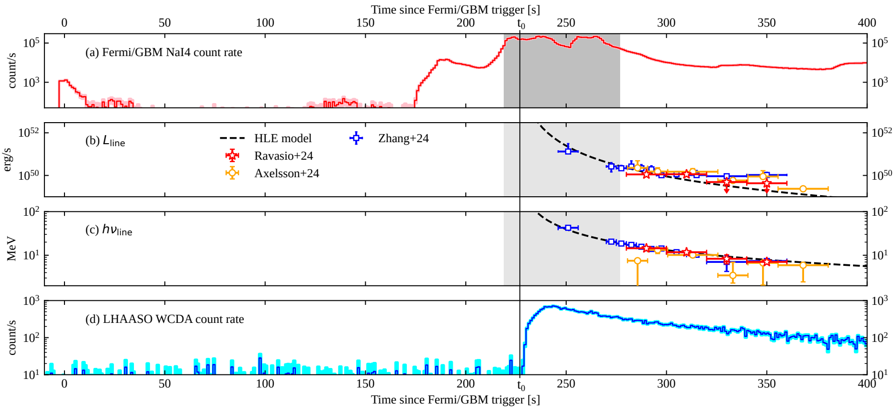
$$h\nu_{\rm obs}(t_{\rm obs}) = \frac{2\Gamma h\nu'}{(1+t_{\rm obs}/t_{\rm ang})}$$

where

$$t_{\rm ang} \sim \frac{r}{\Gamma^2 c}$$

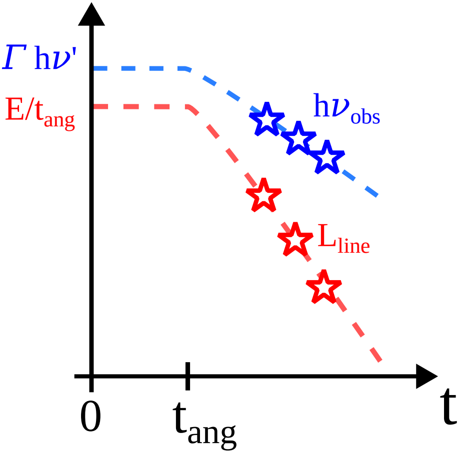
[e.g. Kumar & Panaitescu 2000; Oganesyan et al. 2020; Salafia et al., in prep]

e^+e^- annihilation line HLE



[Salafia et al, in prep.; see also Ravasio et al. 2024; Zhang et al. 2024; Pe'er & Zhang 2024]

e^+e^- annihilation line HLE → parameter constraints



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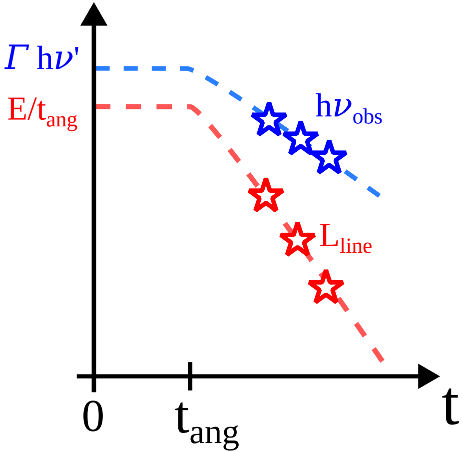

Assuming e^+e^- annihilation

$$h\nu' = m_e c^2$$

$$E = 2N_{\pm} m_e c^2$$

$$t_{ang} \sim \frac{r}{\Gamma^2 c}$$

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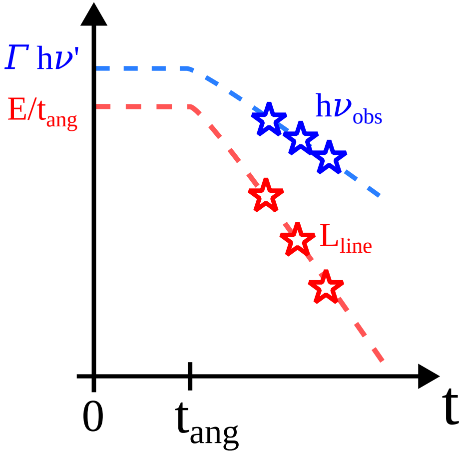

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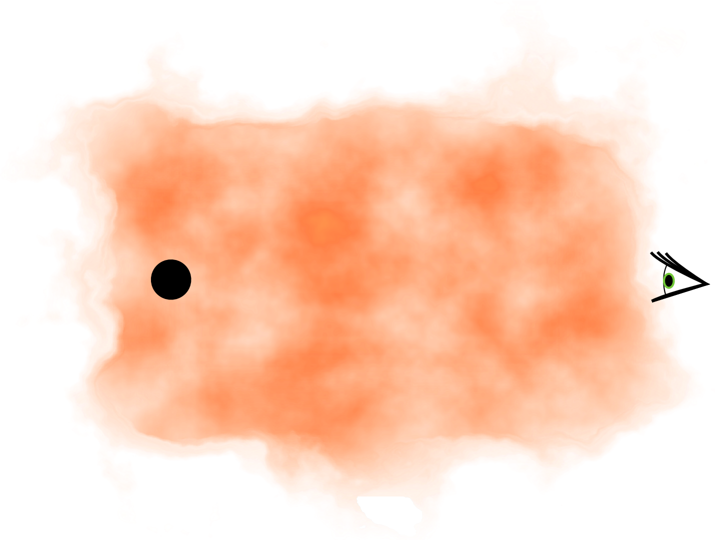
Results

$$N_{\pm} \approx 2 \times 10^{57} r_{16} \quad (1)$$

$$\Gamma \approx 200\, r_{16} \quad (2)$$

$$\tau_{T,\pm} \sim \frac{\sigma_T N_{\pm}}{2\pi r^2} \approx 2\, r_{16}^{-1} \quad (3)$$

Scenario that leads to the required conditions



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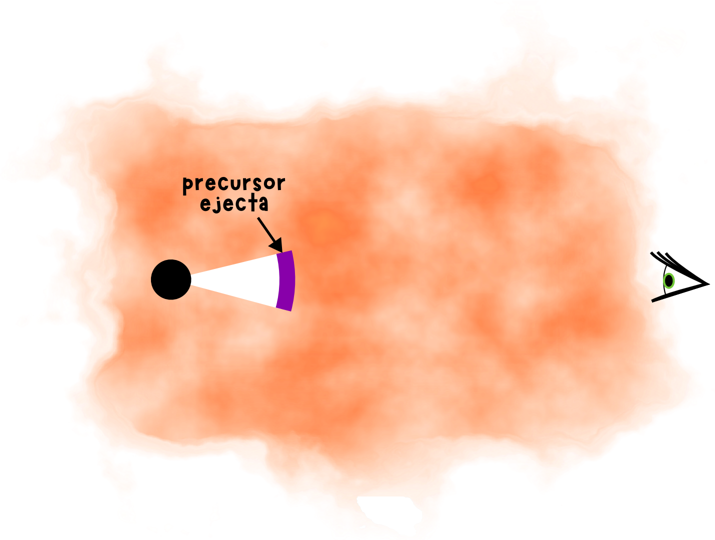

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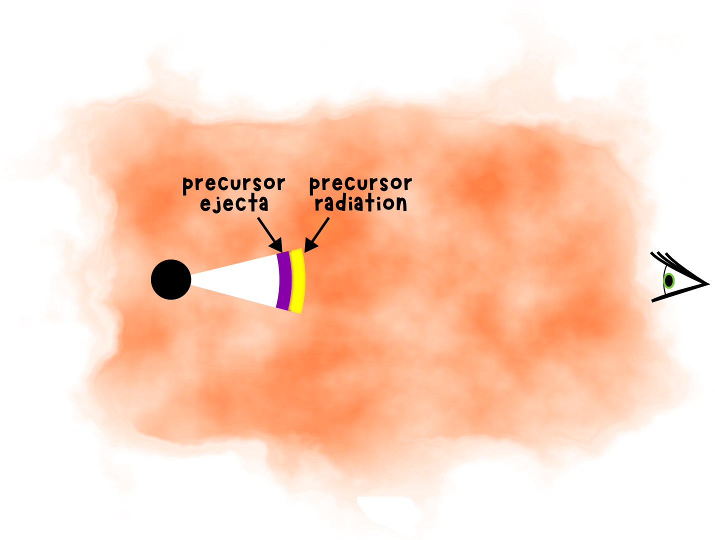

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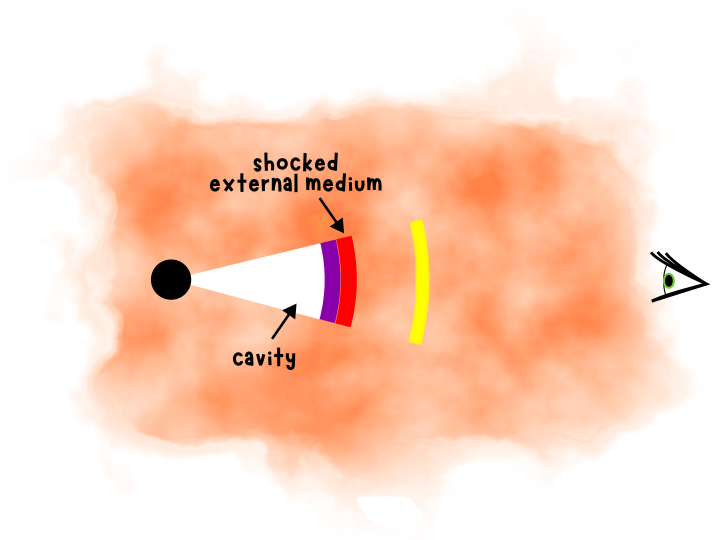

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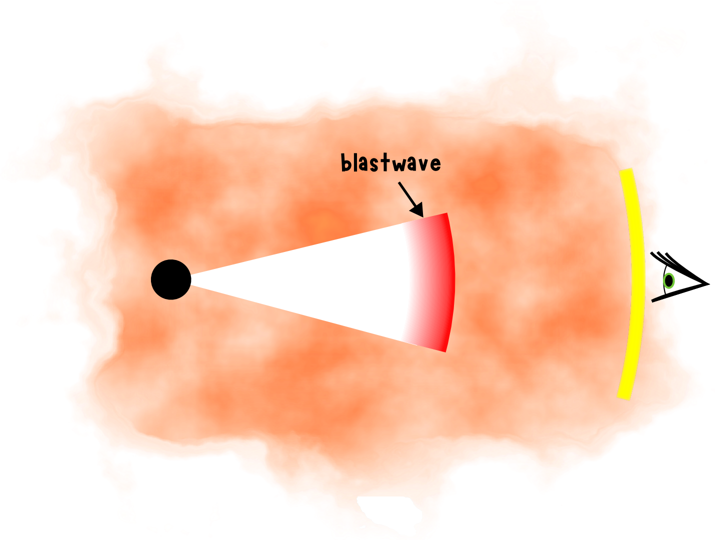

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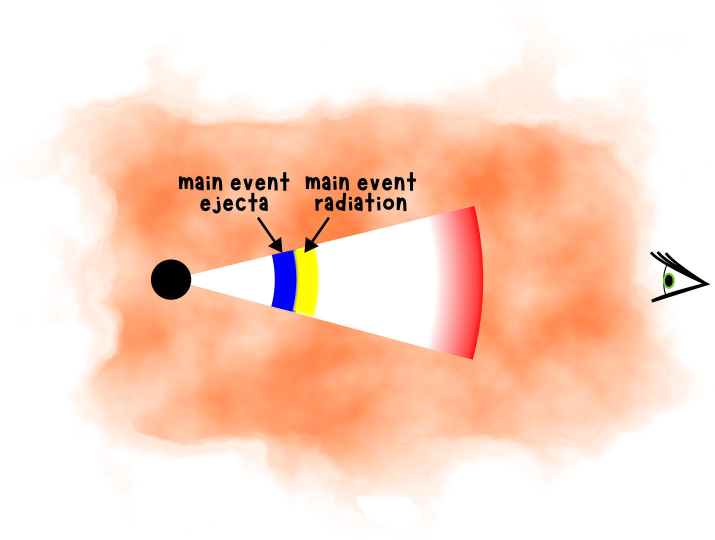

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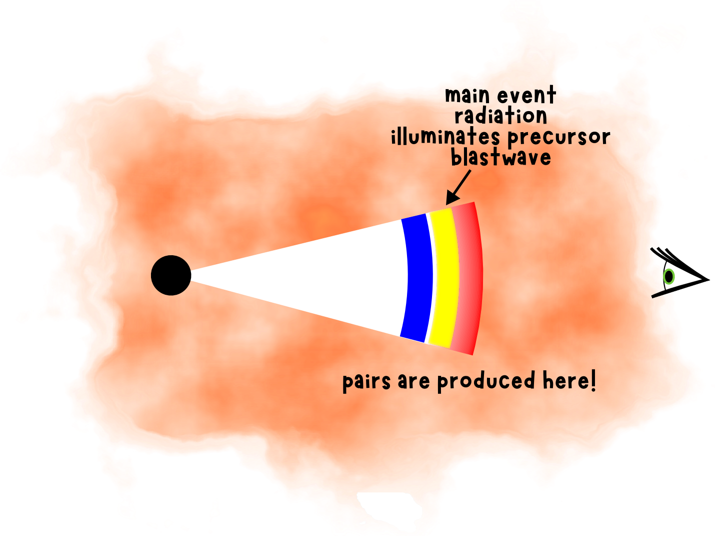

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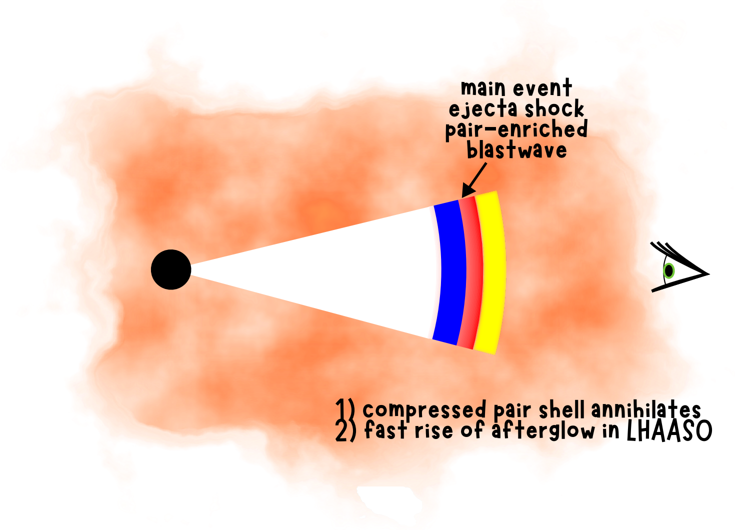

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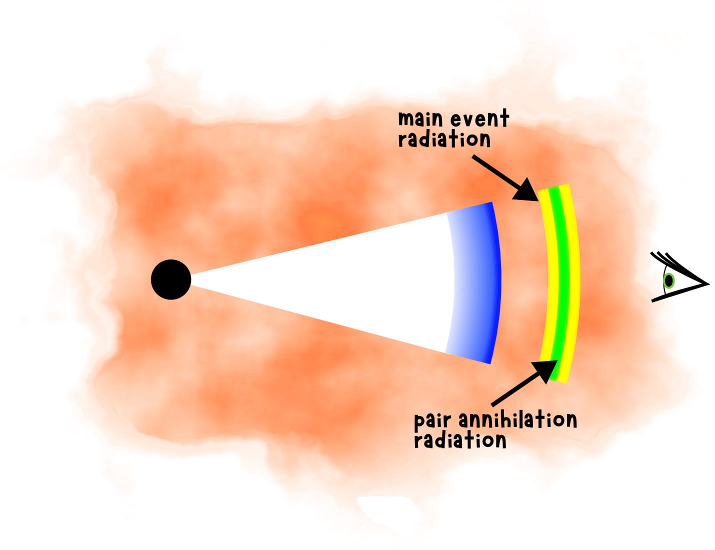

[Salafia et al., in prep]

Parameter exploration ongoing...stay tuned!

Summary

- BOAT GRB MeV line: blue-shifted e^+e^- annihilation line $+$ HLE $\longrightarrow$ precise constraints on pair enriched region

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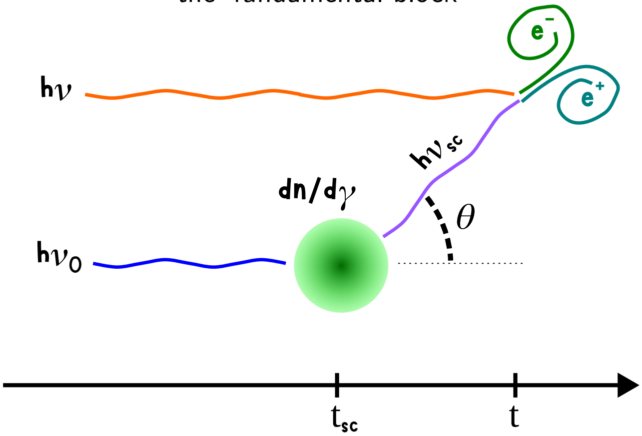
Thank you!

Backup

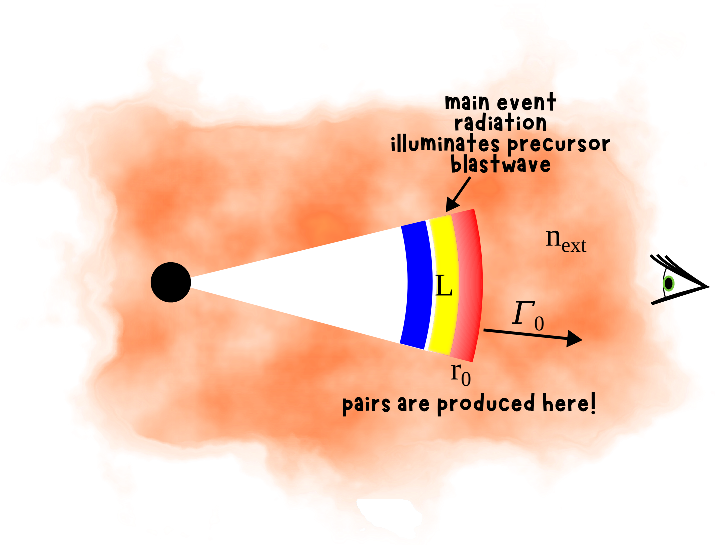
Pair enrichment

the 'fundamental block'

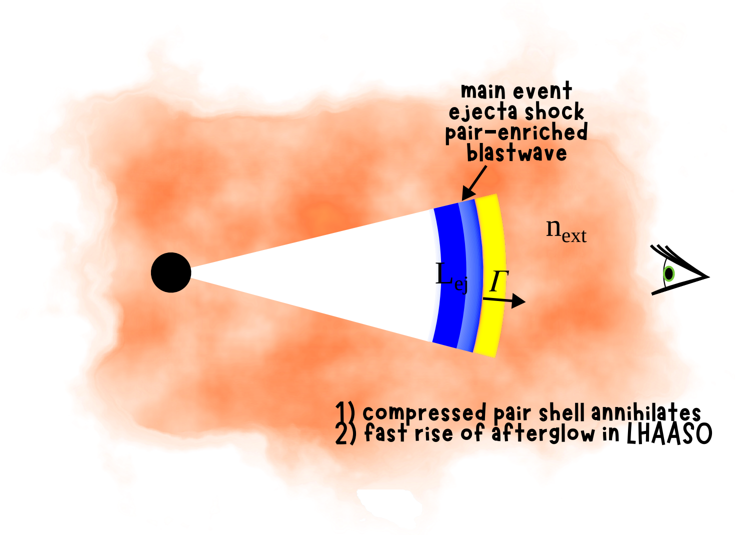


[similar to Beloborodov 2002, but hot electrons and pairs]

Parameters

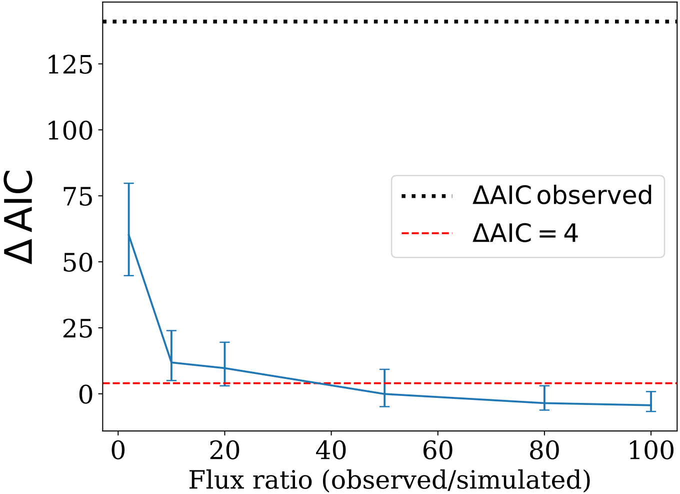

main event
radiation
illuminates precursor
blastwave
n_{ext}
L
Γ_0
r_0
pairs are produced here!

Parameters

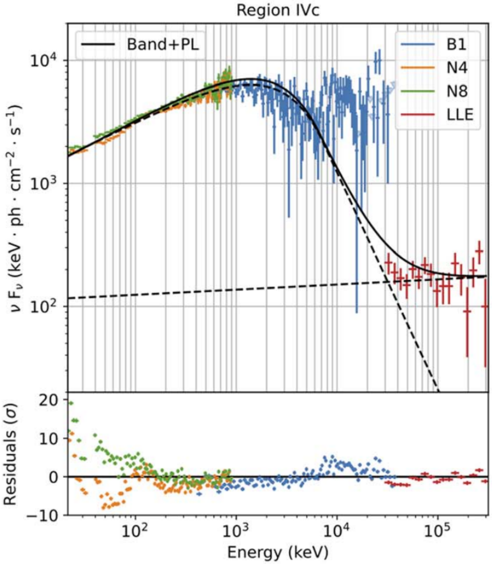

main event
ejecta shock
pair-enriched
blastwave
n_{ext}
L_{ej}
Γ
1) compressed pair shell annihilates
2) fast rise of afterglow in LHAASO

Why have we not seen this before

1. Emission needs be very bright

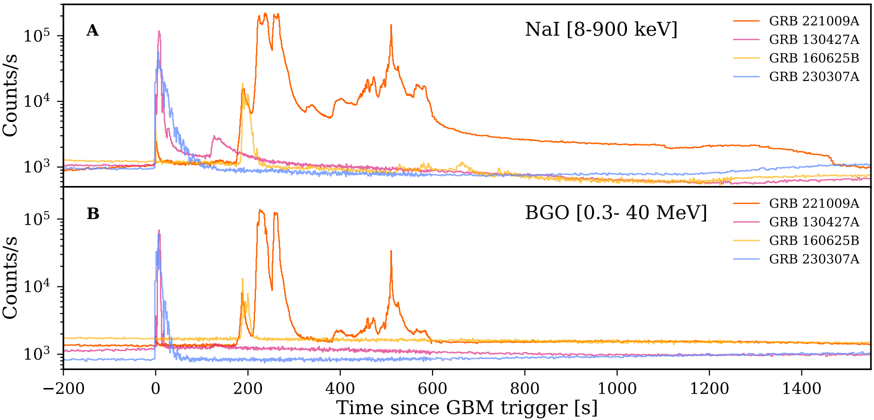


2. We usually do not look for this kind of feature



Fermi/GBM team analysis paper [Lesage et al. 2023]

Search in other bright GRBs



No clear features in three next brightest Fermi/GBM GRBs.

But narrow needle in a haystack.