YITP long term workshop
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Interpreting the 10 MeV emission line in GRB 221009A as high-latitude emission from a bursting pair bubble

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Ministero dell'Università e della Ricerca

Italiadomani
PIANO NAZIONALE DI RIPRESA E RESILIENZA

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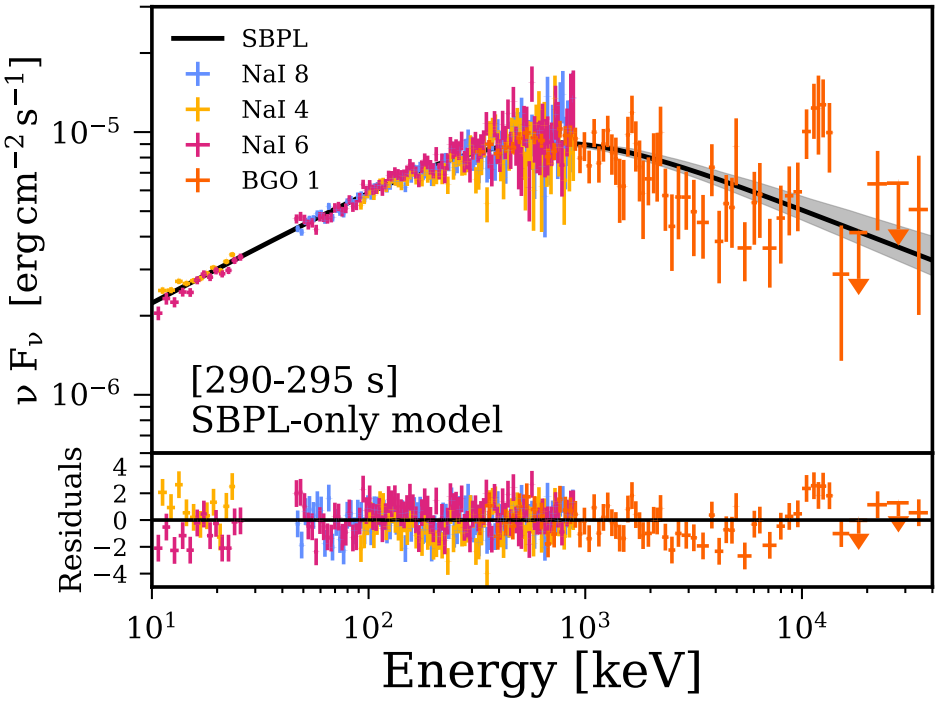
Dr Ravasio's discovery

Fermi/GBM data of GRB 221009A



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

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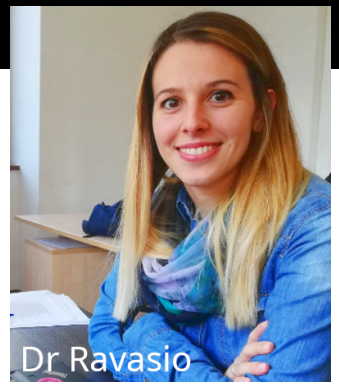

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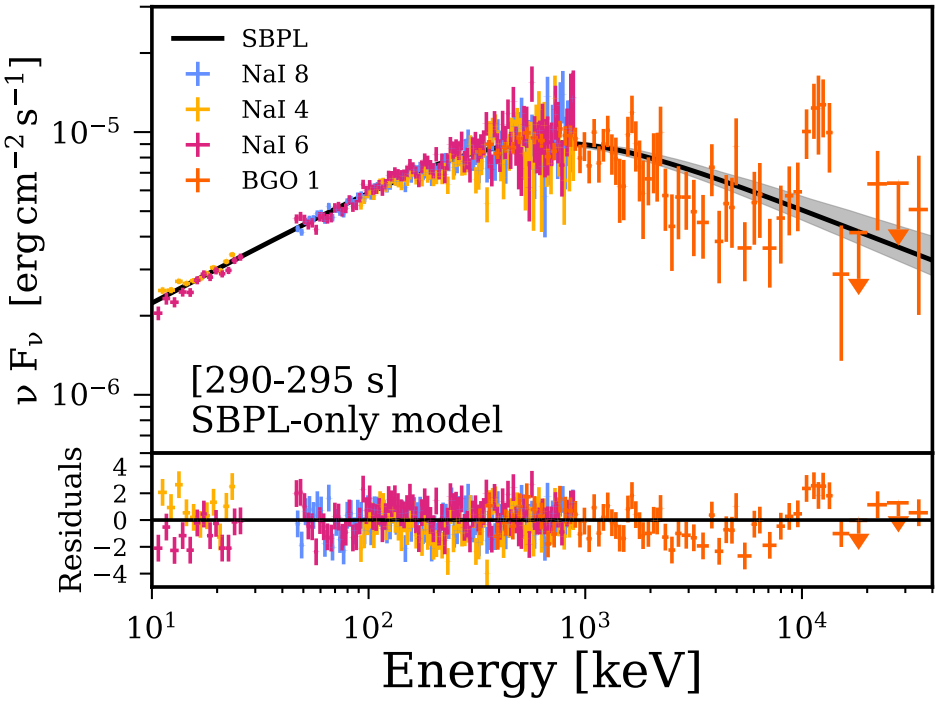

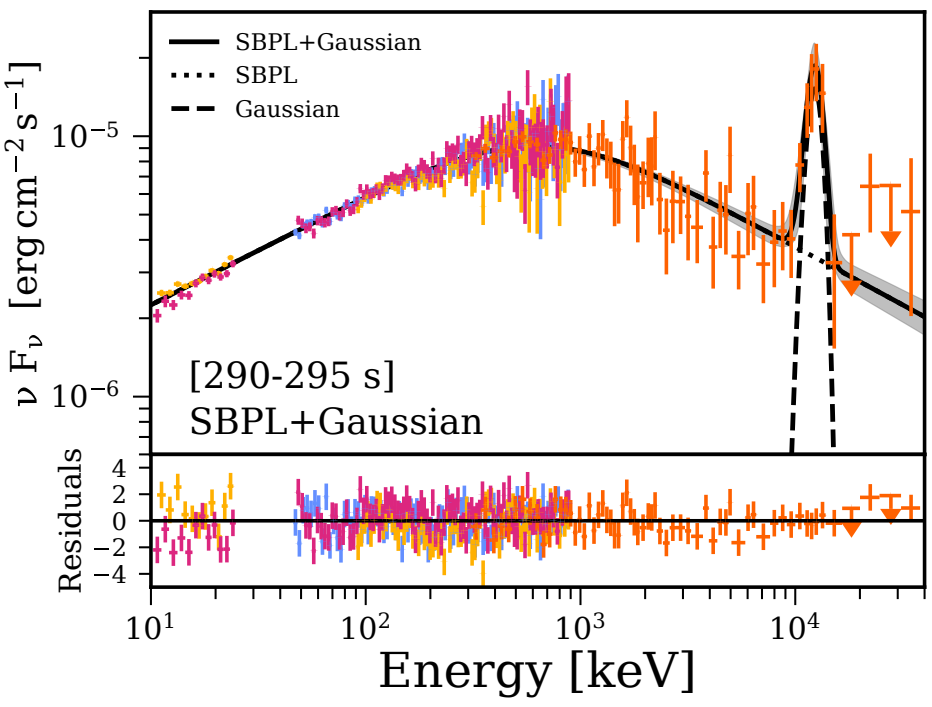

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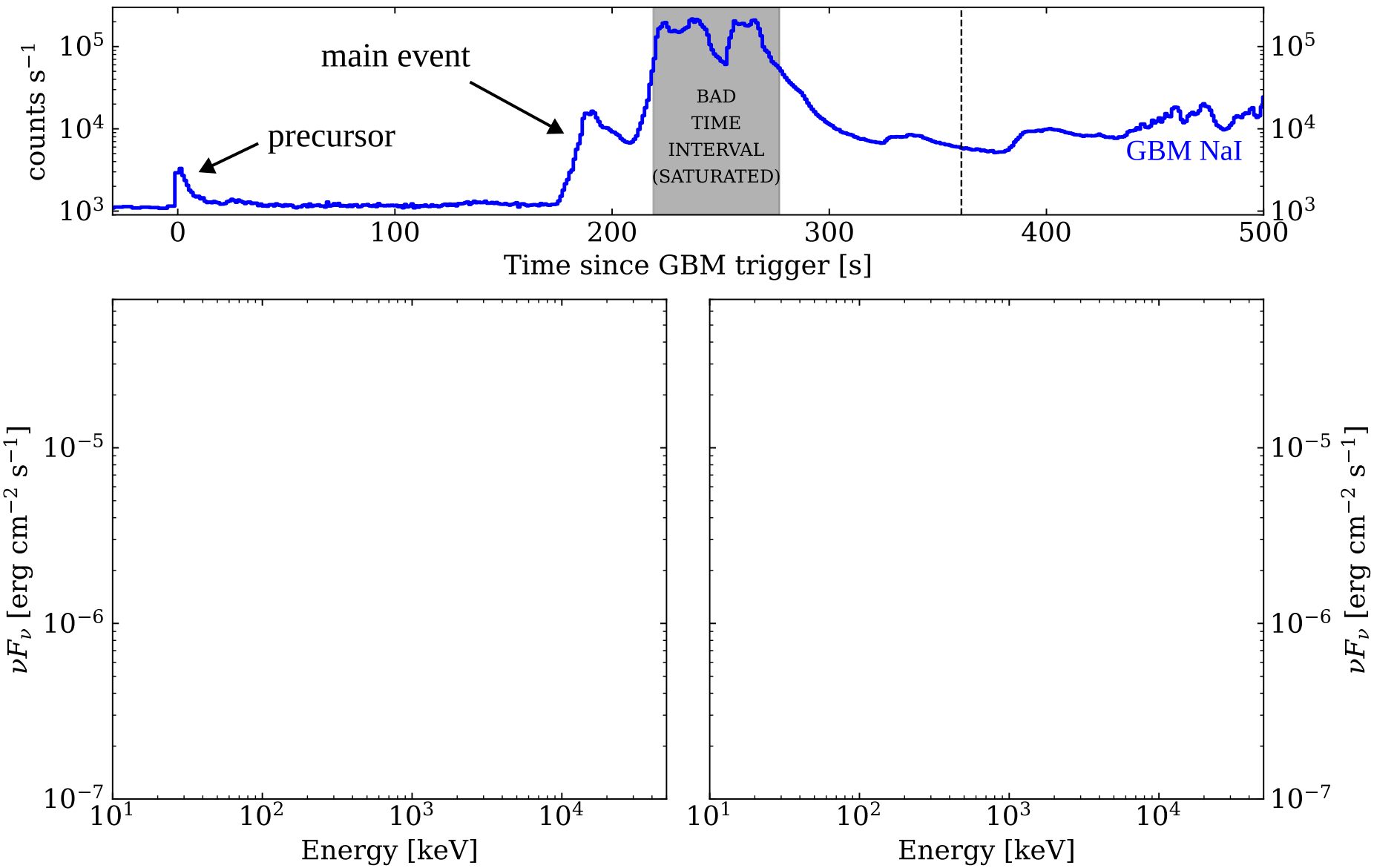
Spectral evolution



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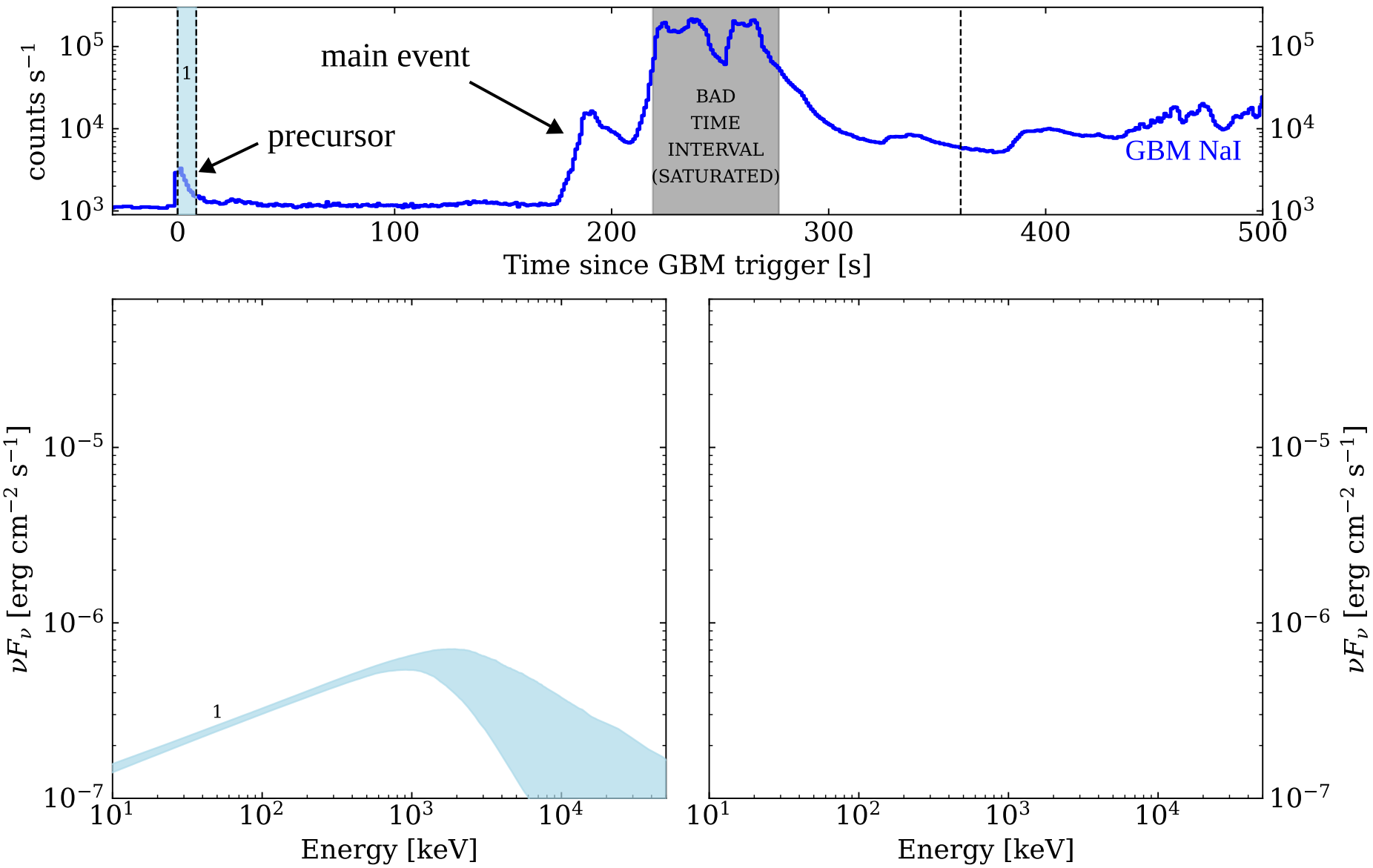

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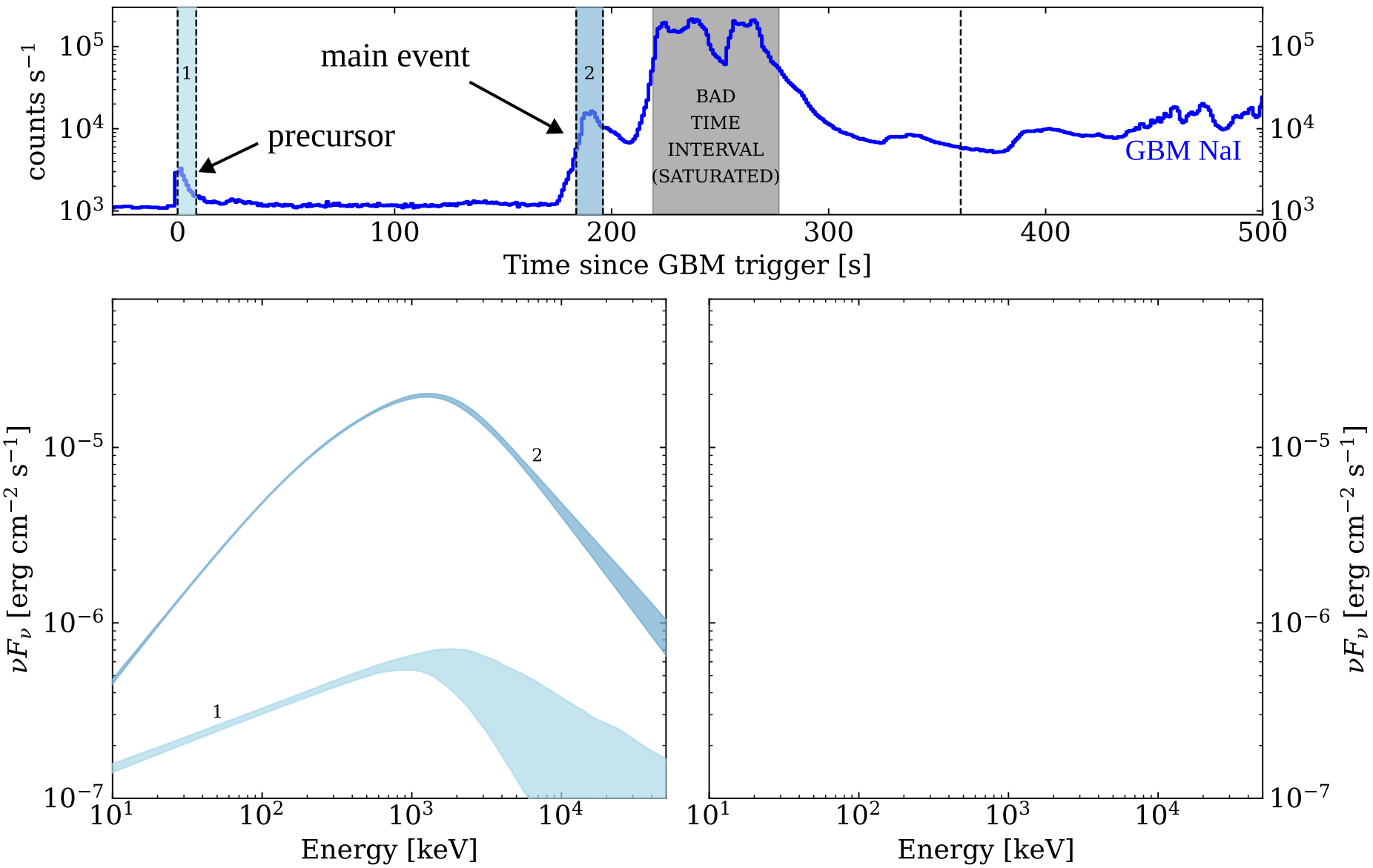

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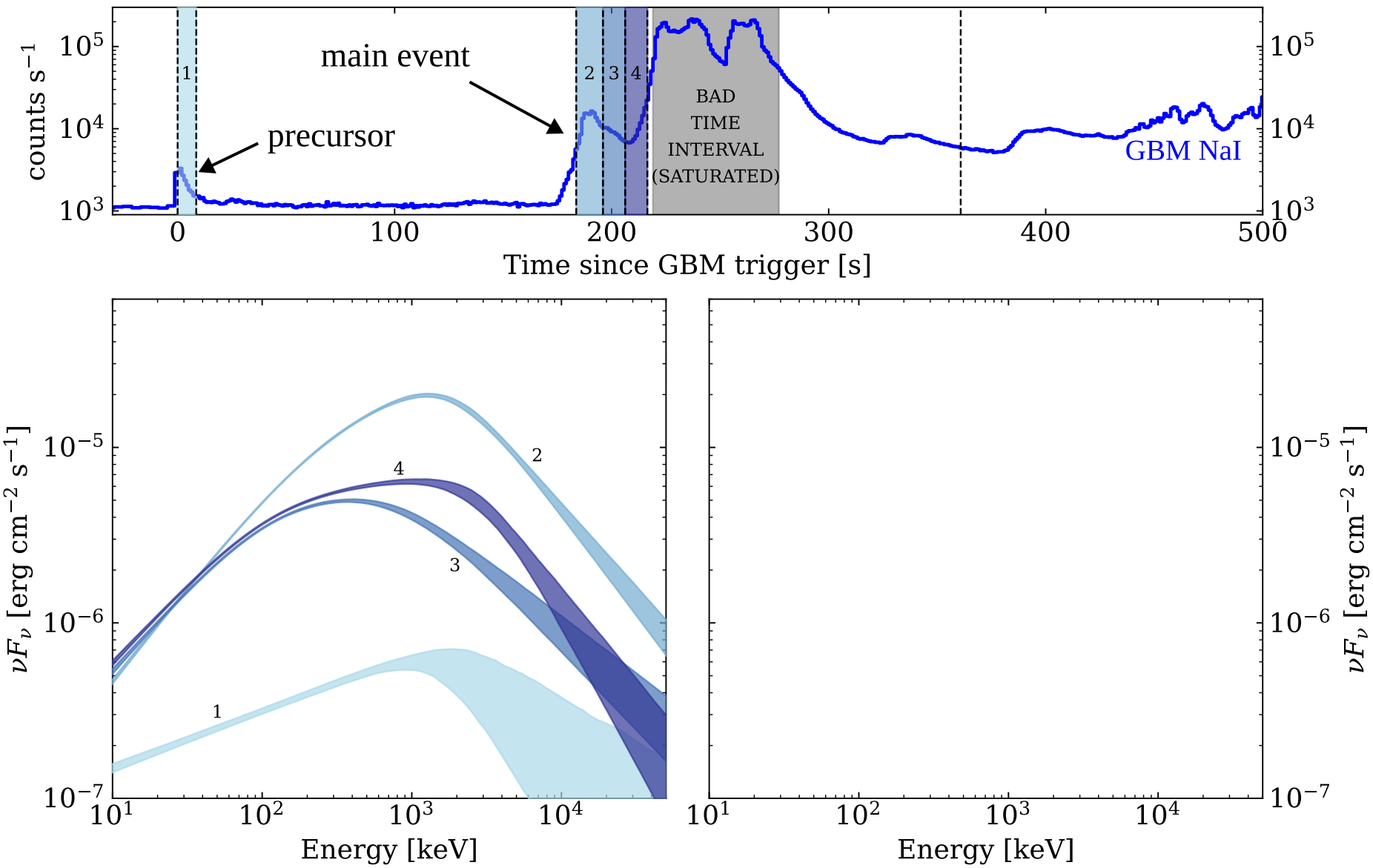

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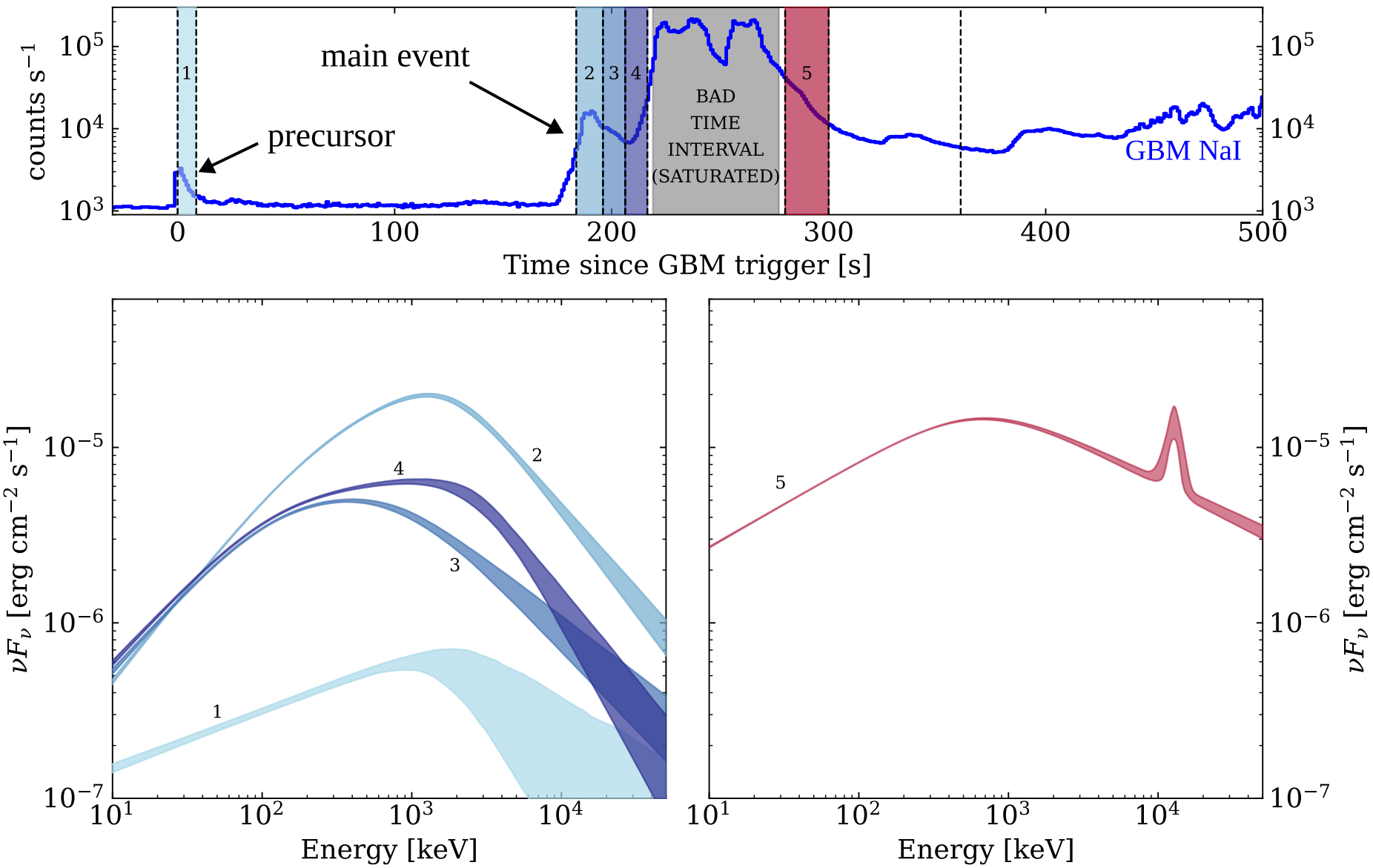

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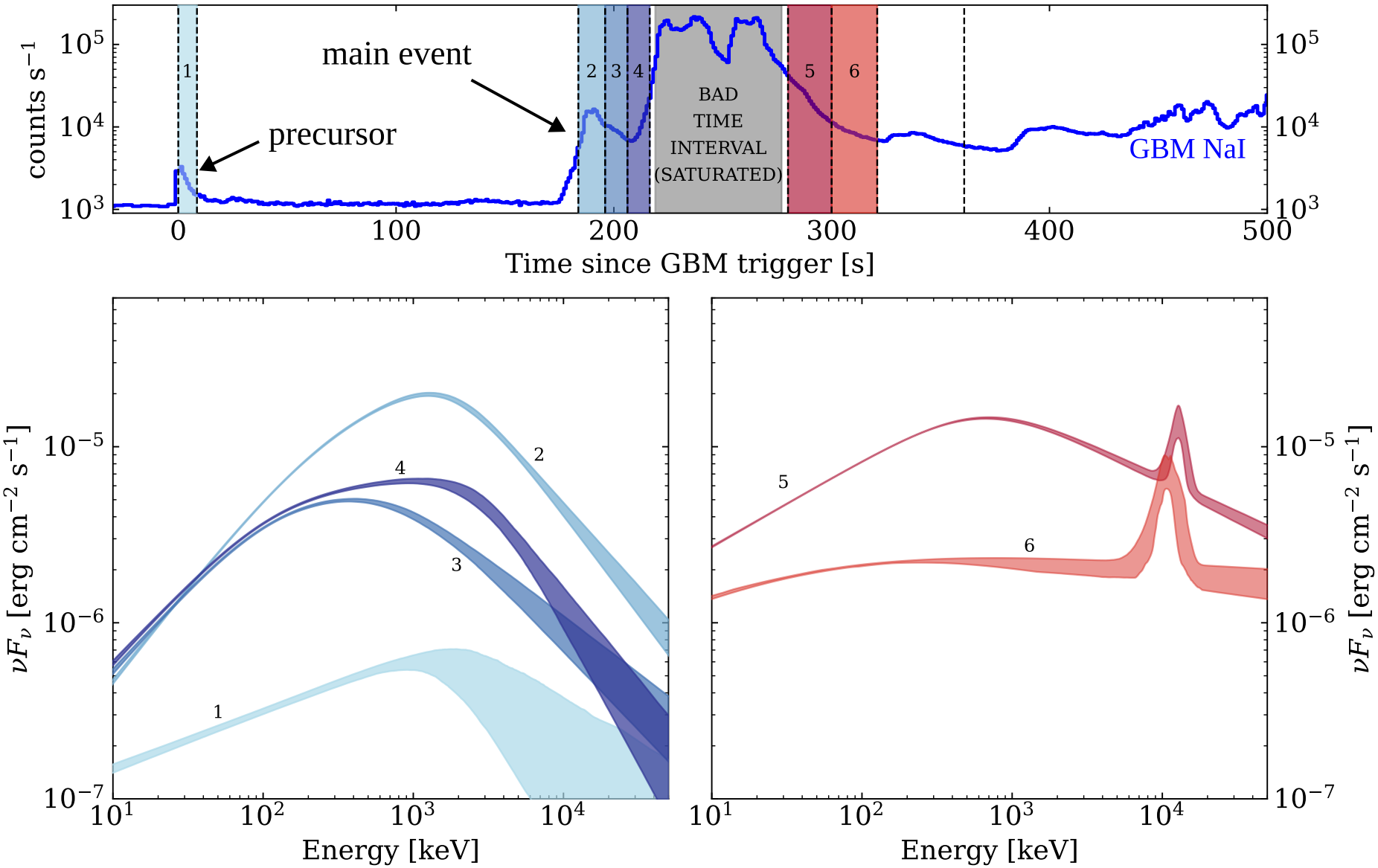

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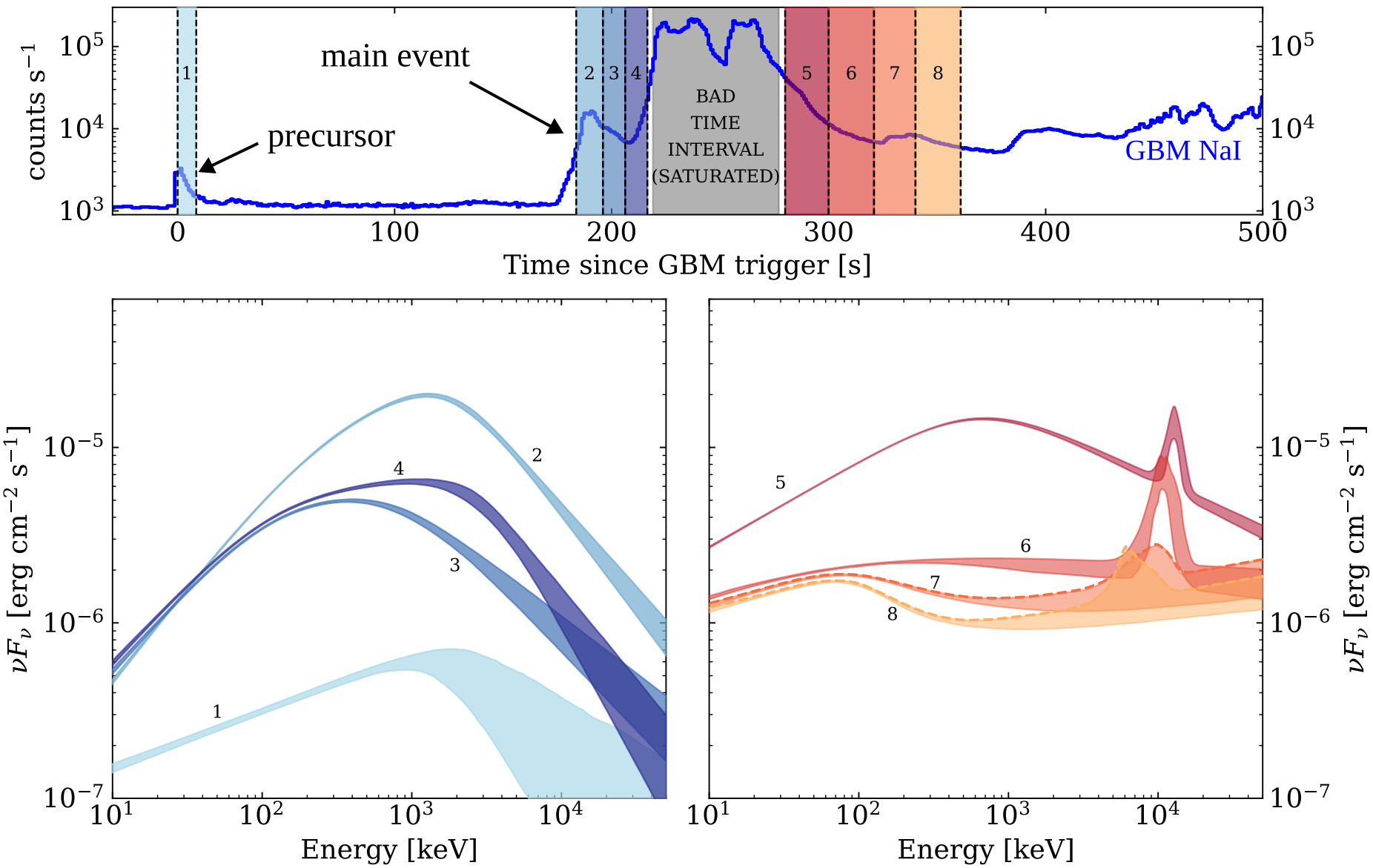

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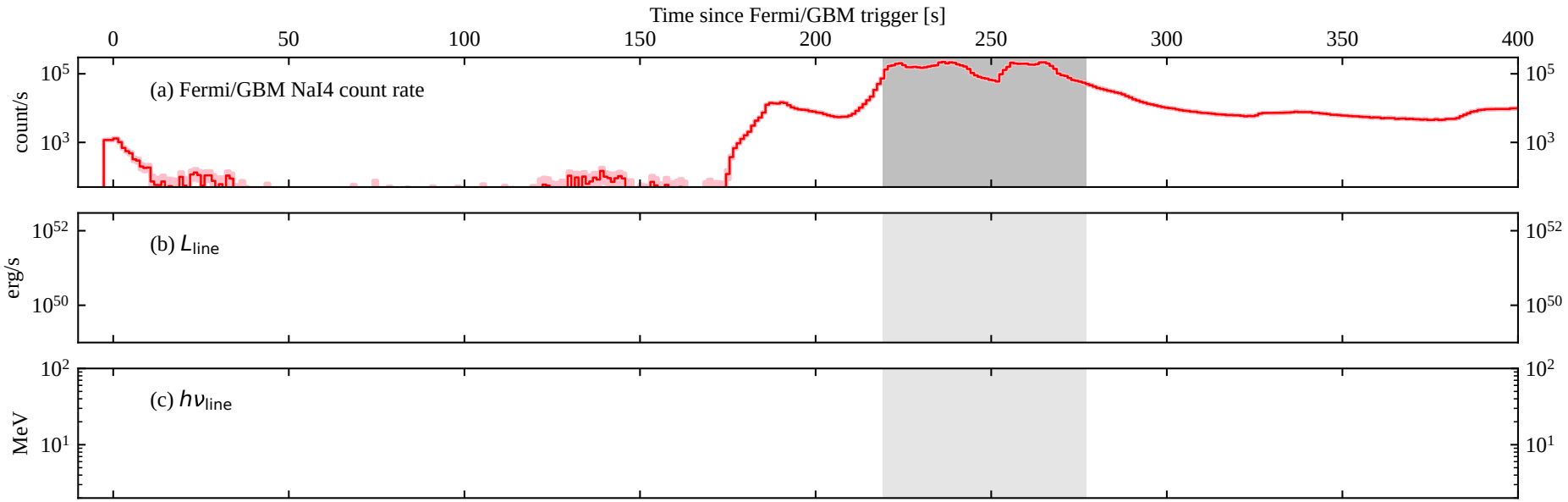
Line property evolution



[Salafia et al., 2026, arXiv:2601.14257]

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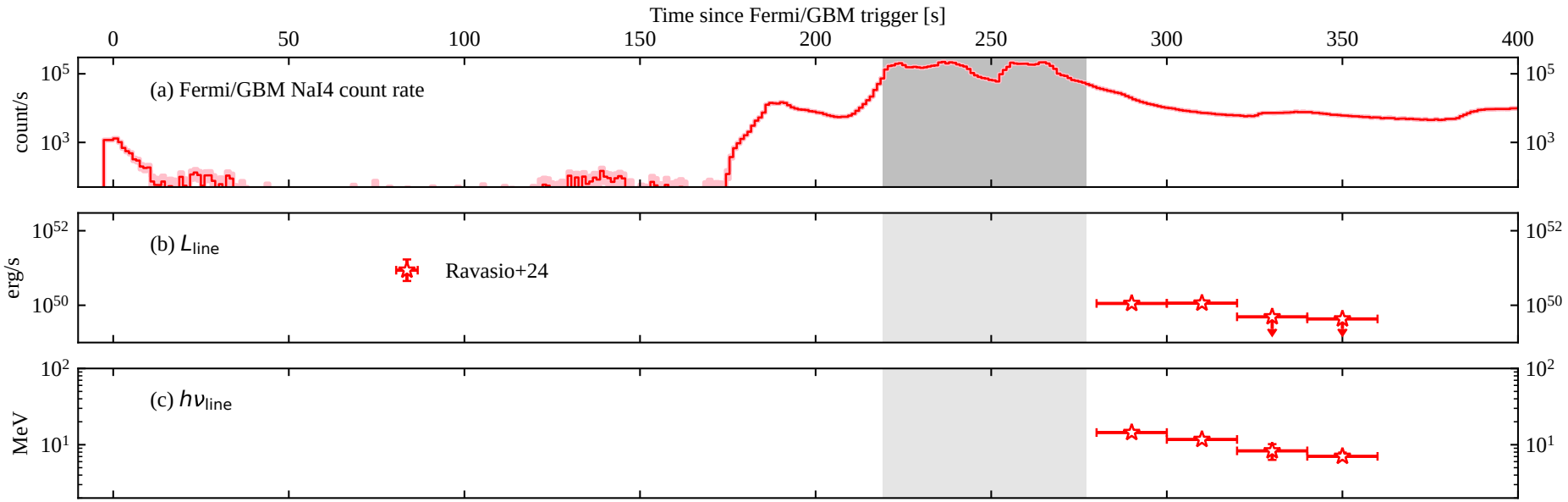

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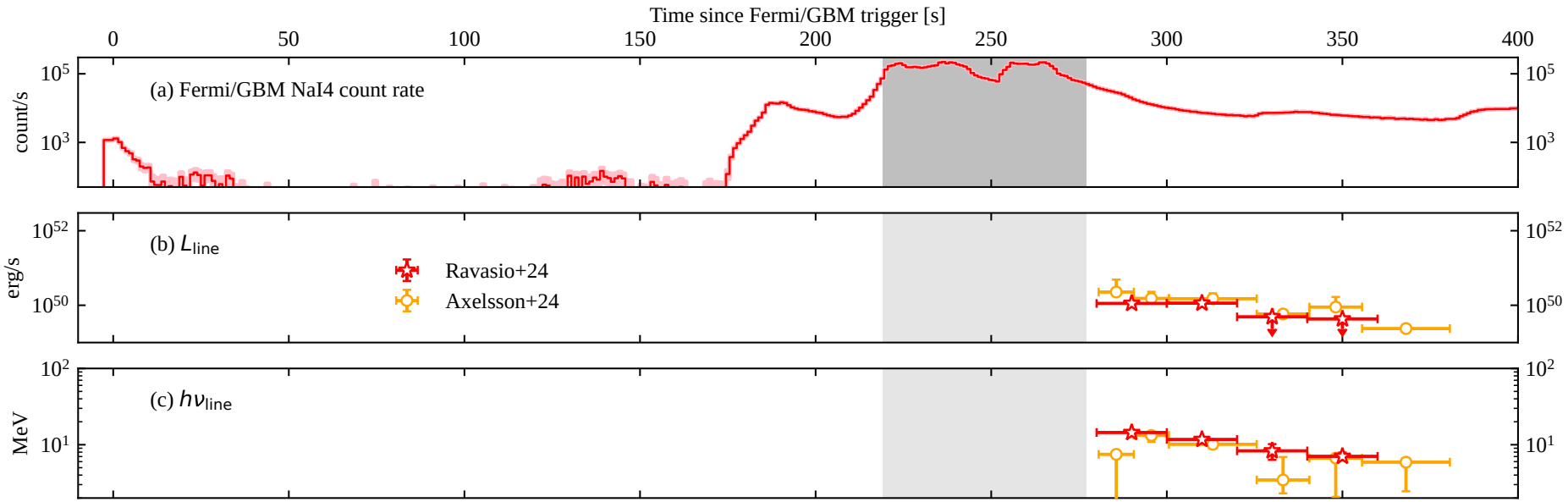

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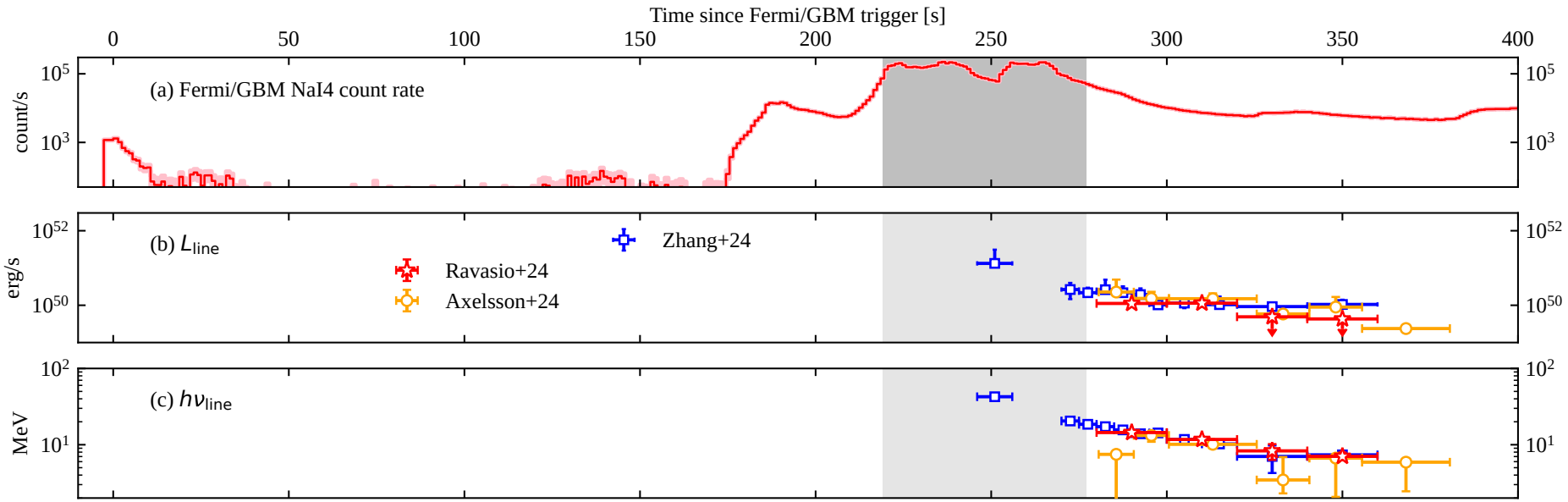

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Origin of the line?

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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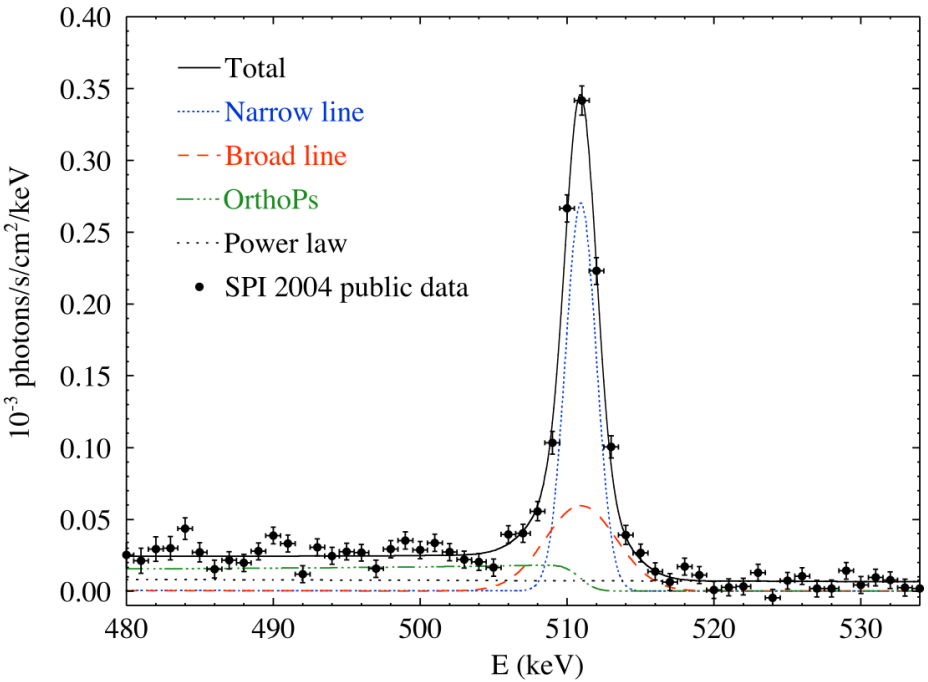

[Prantzos et al. 2011]

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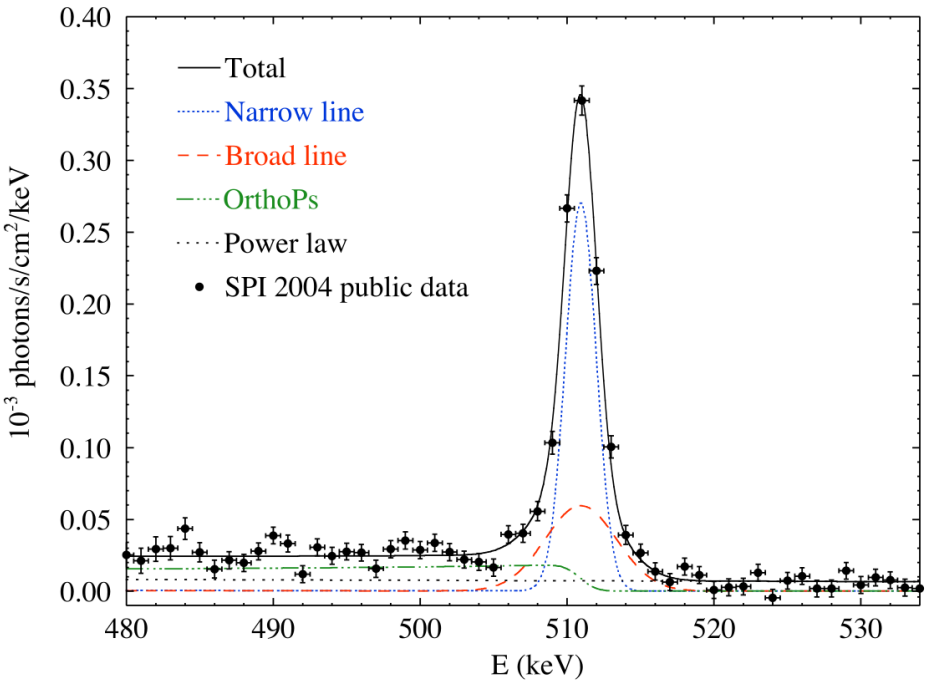


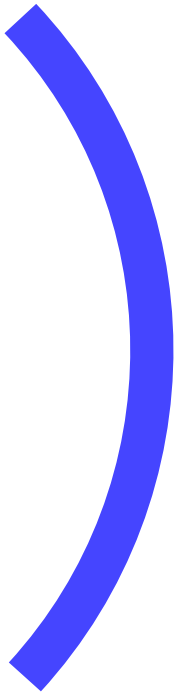
[Prantzos et al. 2011]

Doppler blueshift

Doppler factor

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

High-latitude emission (HLE)



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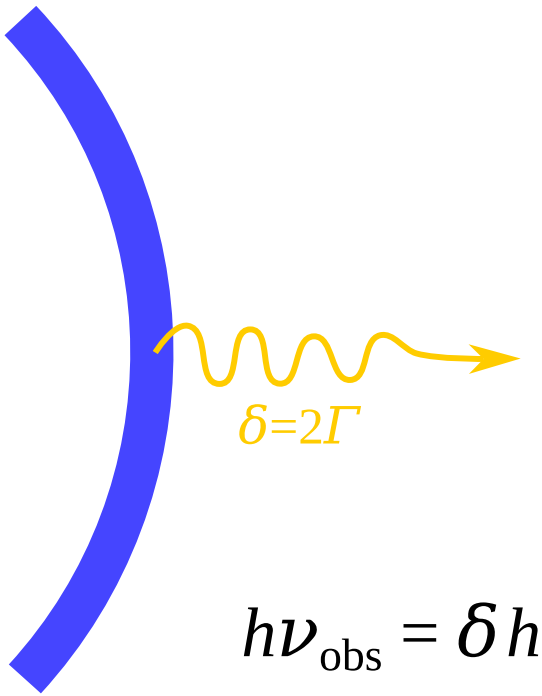

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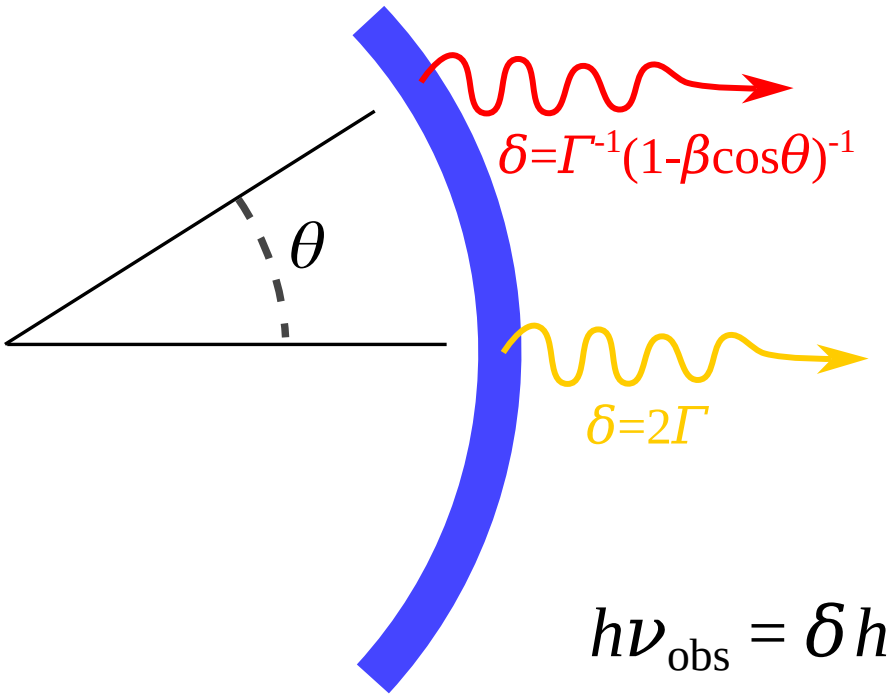

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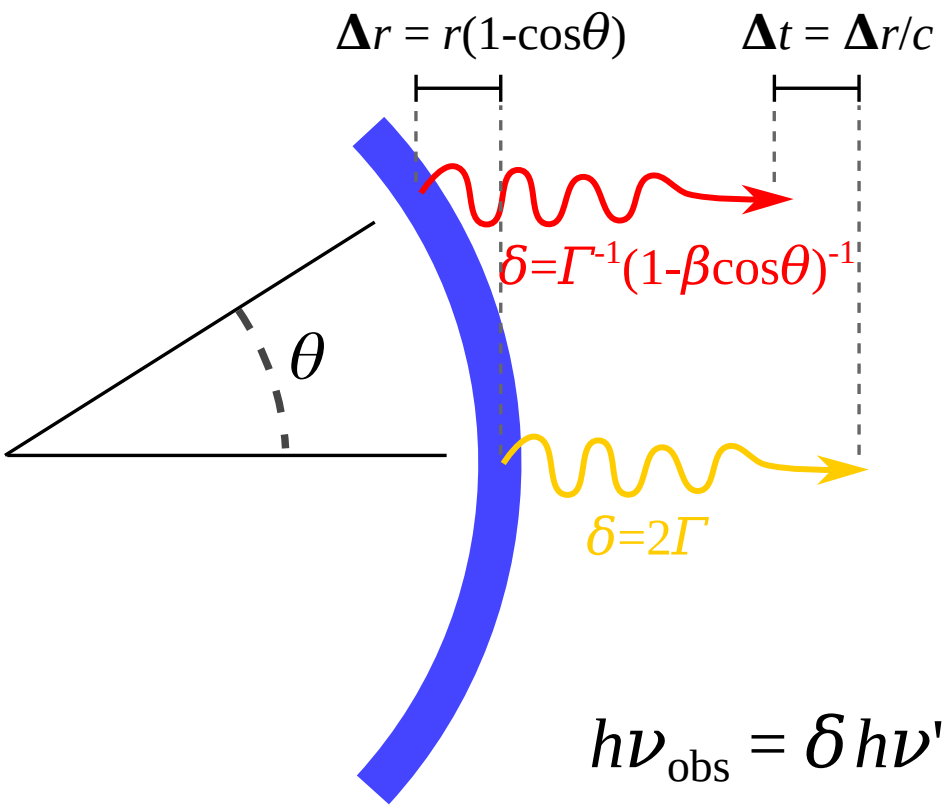

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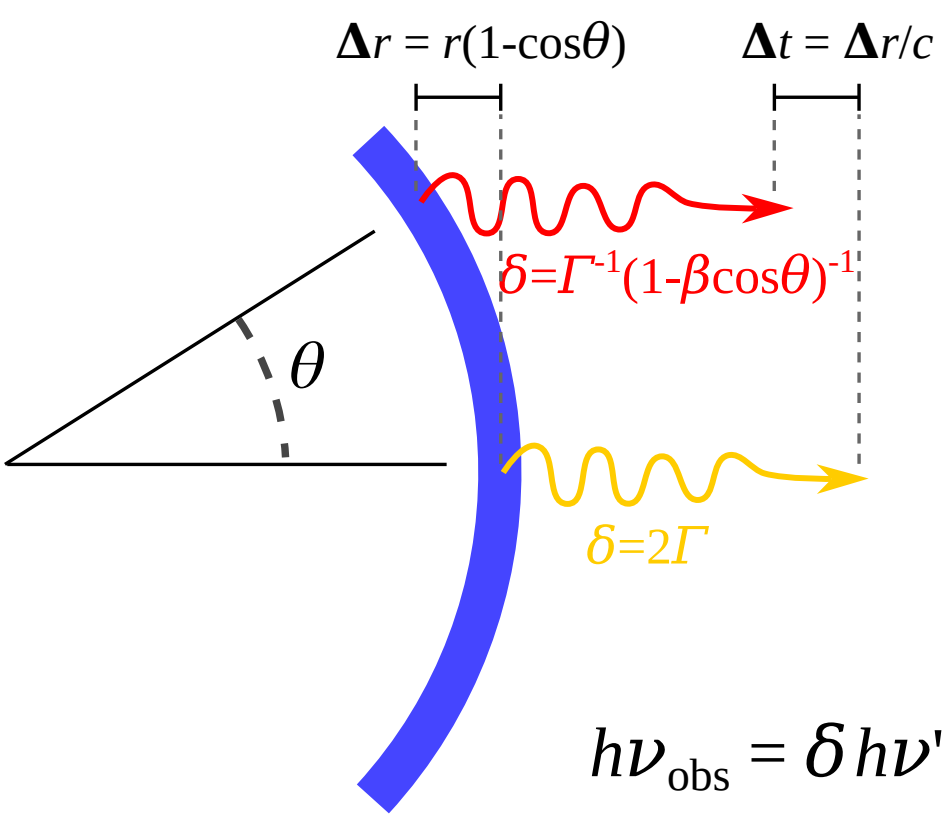

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If

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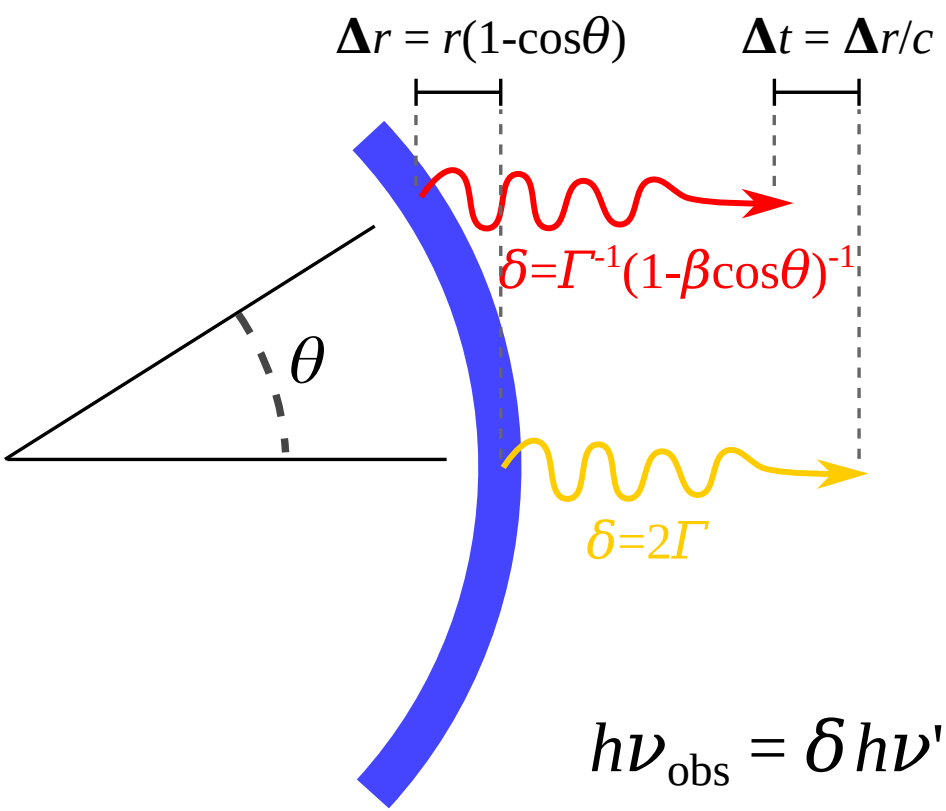

If

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then
HLE dominates time evolution,
and

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

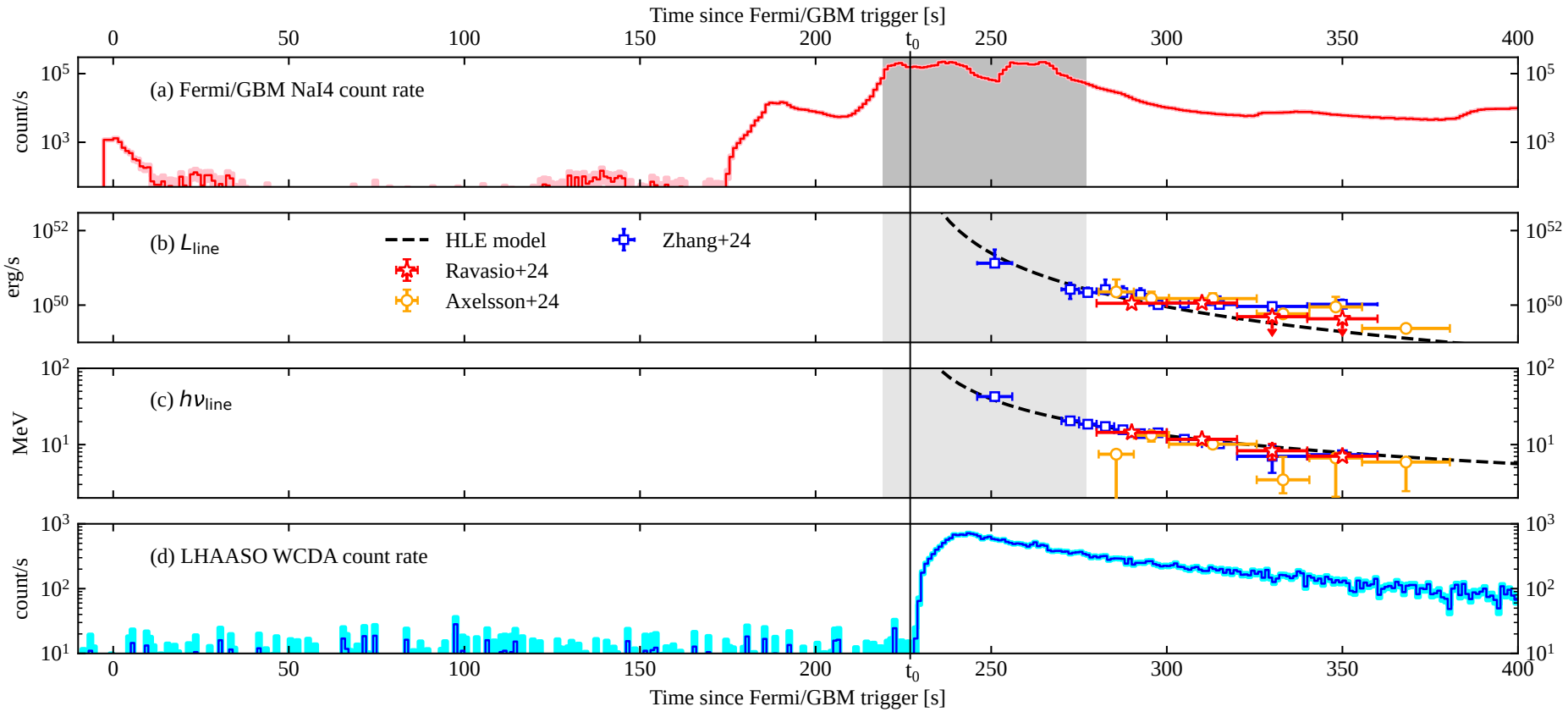
$$h\nu_{\rm obs}(t_{\rm obs}) = \frac{2\Gamma h\nu'}{(1+t_{\rm obs}/t_{\rm ang})}$$

where

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

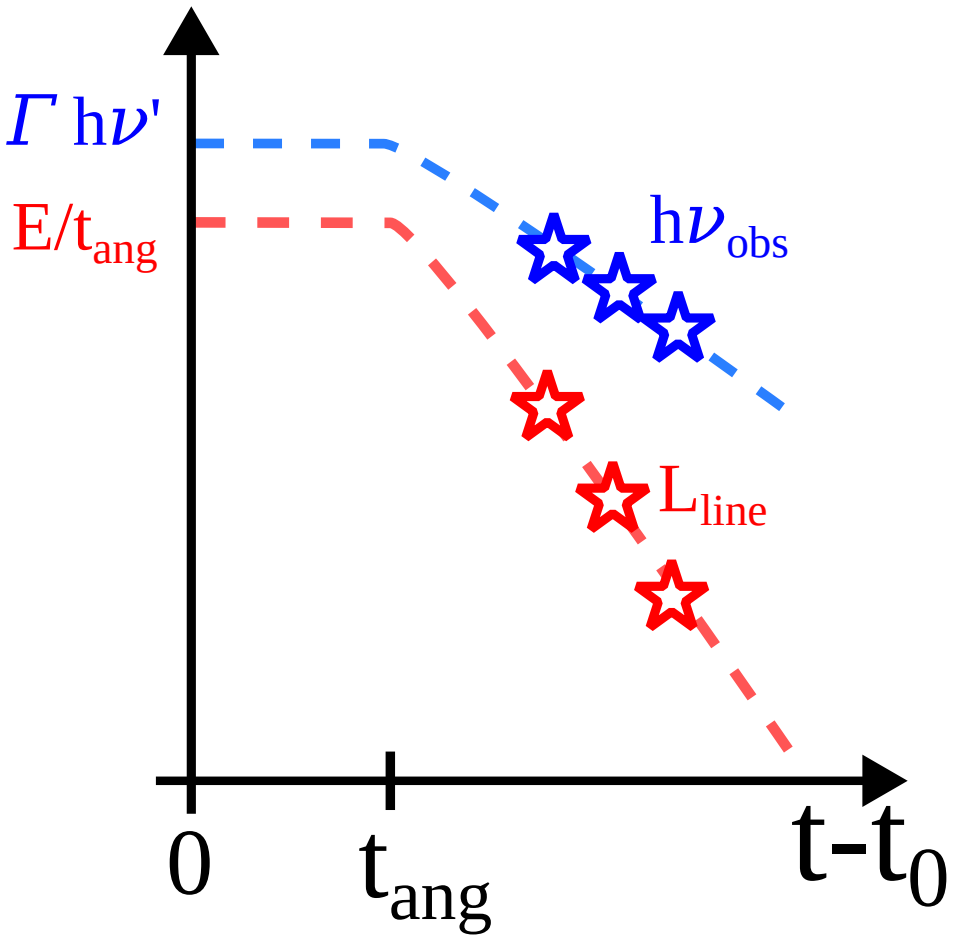
[e.g. Kumar & Panaitescu 2000; Oganesyan et al. 2020; Salafia et al., 2026]

e^+e^- annihilation line HLE



[Salafia et al, 2026; see also Ravasio et al. 2024; Zhang et al. 2024; Pe'er & Zhang 2024]

e^+e^- annihilation line HLE $\rightarrow$ parameter constraints



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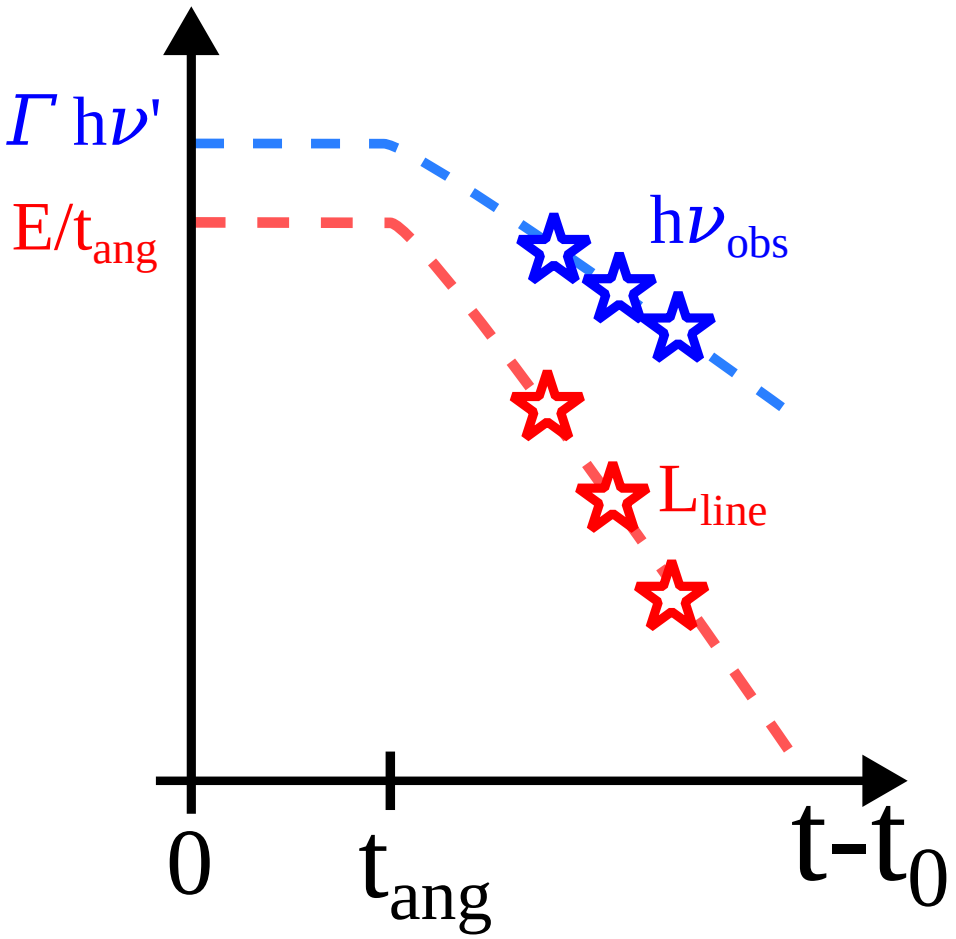

Assuming e^+e^- annihilation

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

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

$$t_{\rm ang} \sim (1+z)\frac{r}{\Gamma^2 c}$$

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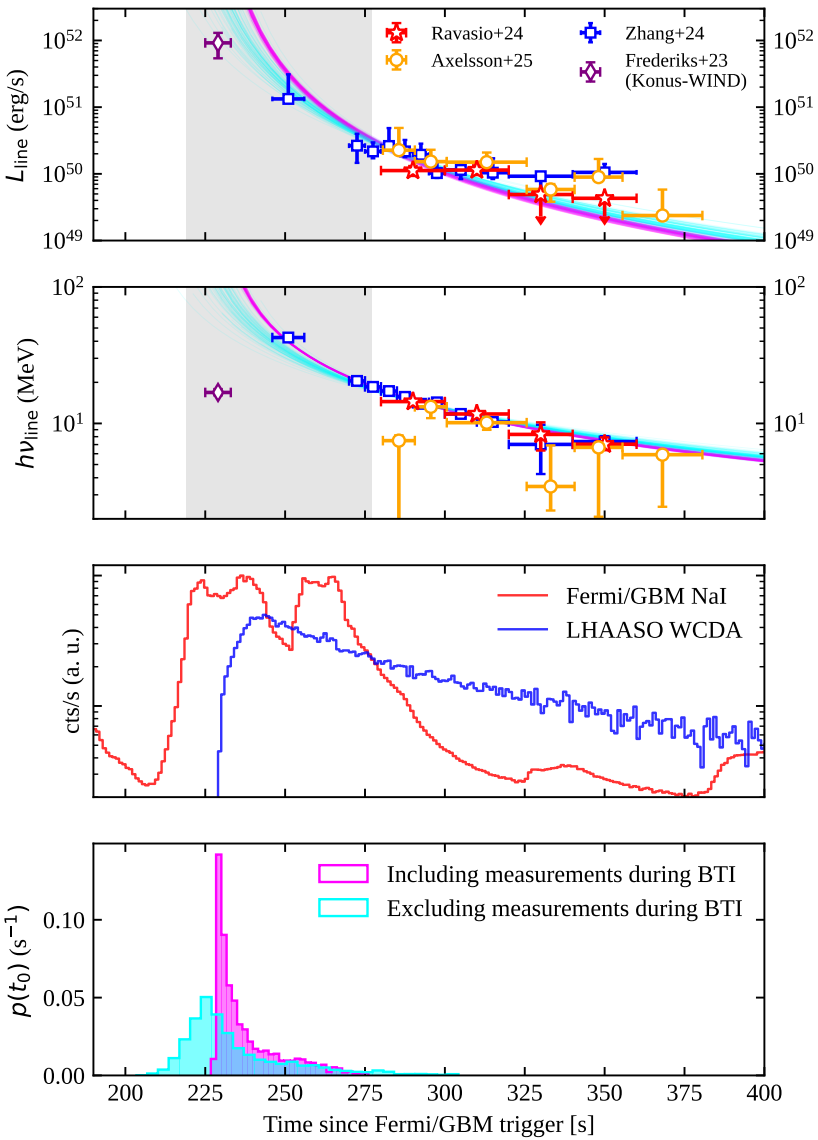

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Results

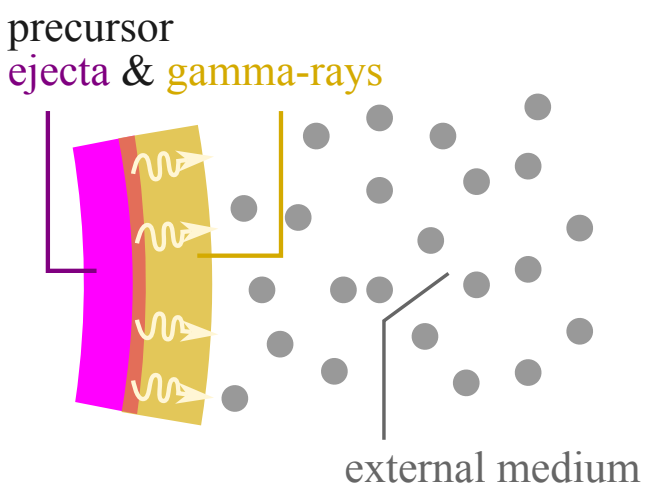
$$N_{\pm} \approx 2 \times 10^{57} r_{16} \qquad (1)$$

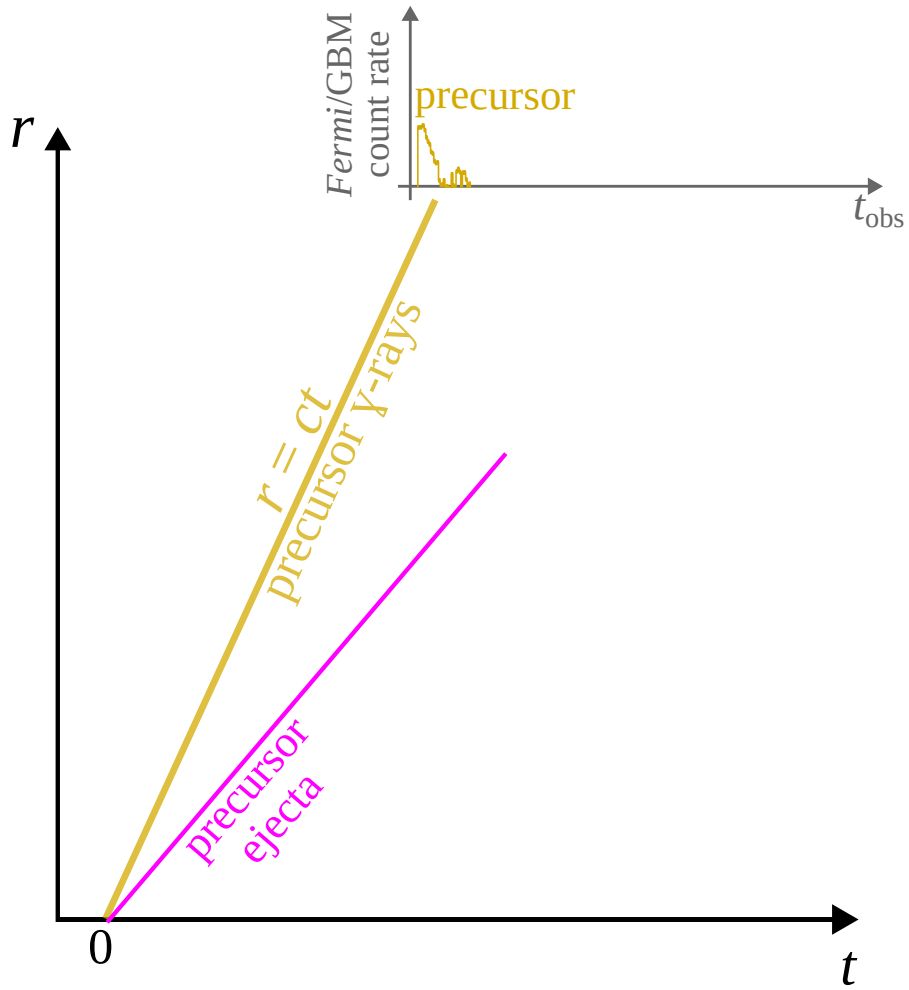
$$\Gamma \approx 200\, r_{16} \qquad (2)$$

$$r_{16} \in [0.1, 4] \qquad (3)$$

$$t_0 \sim t_{\rm onset,LHAASO} \qquad (4)$$

The scenario





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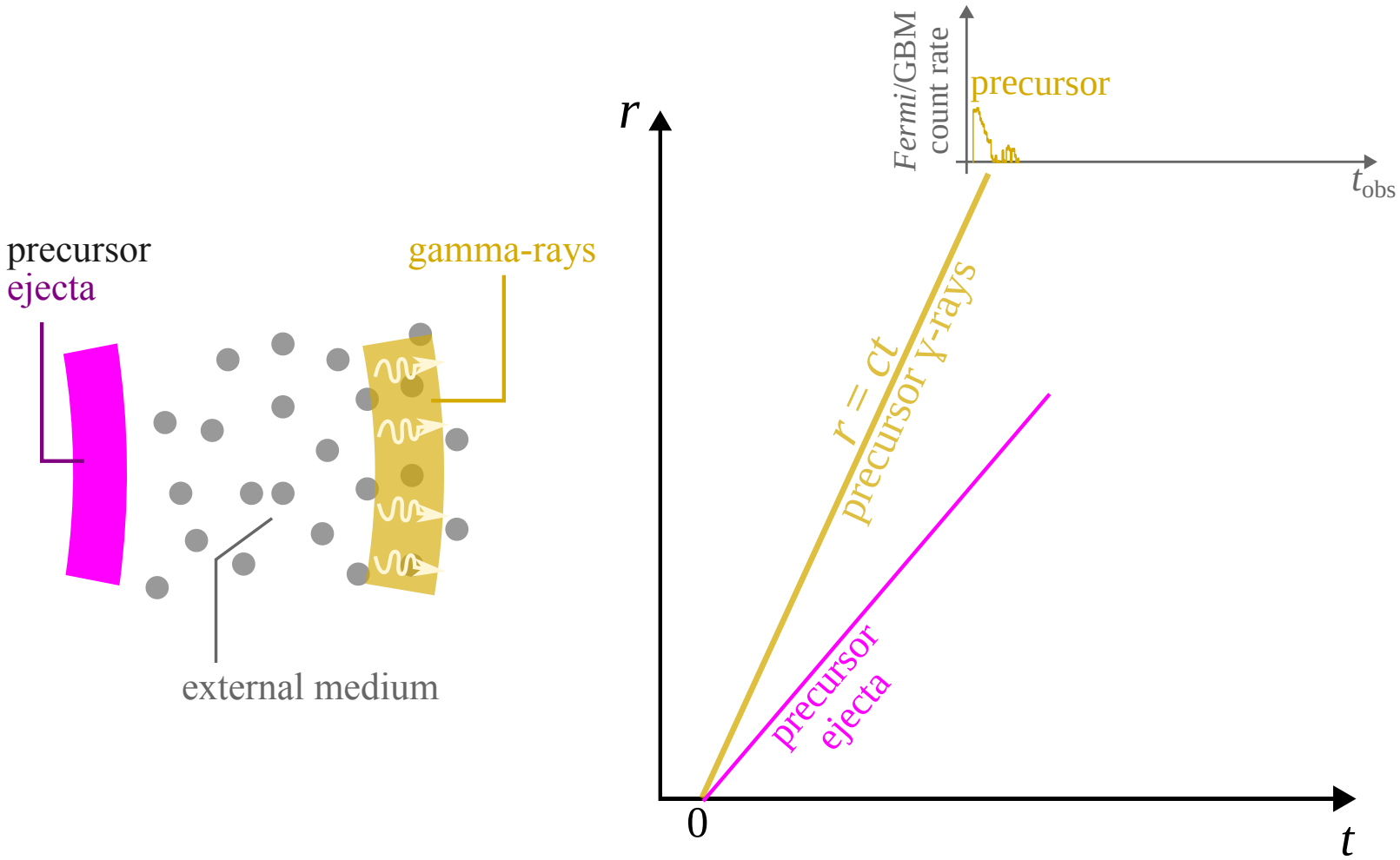

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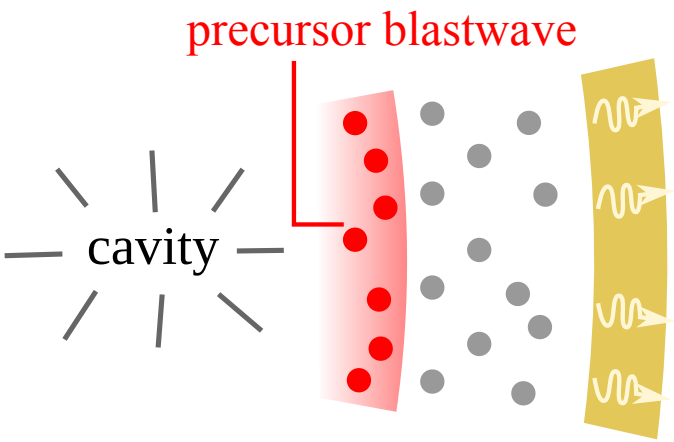

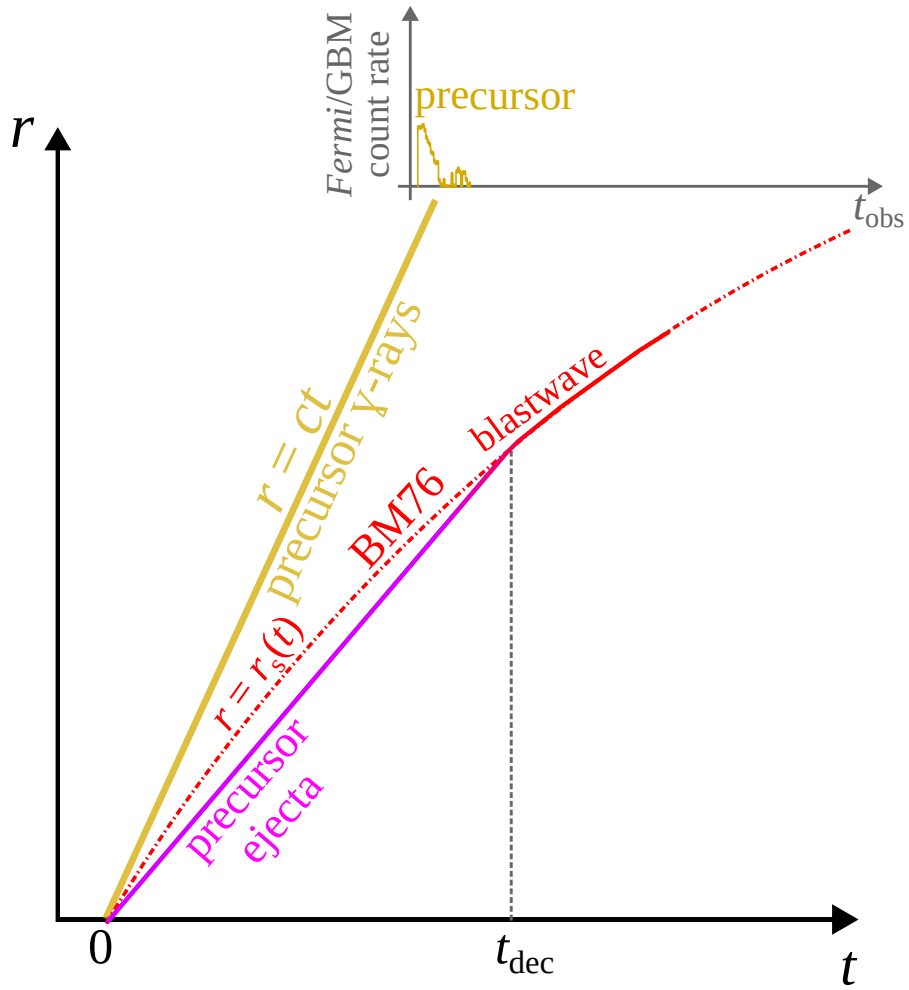

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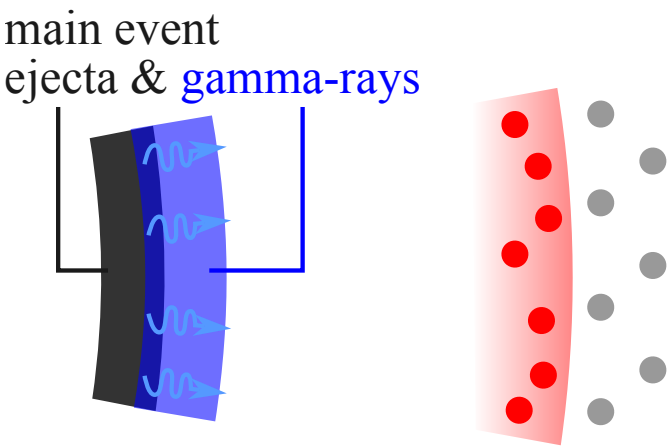

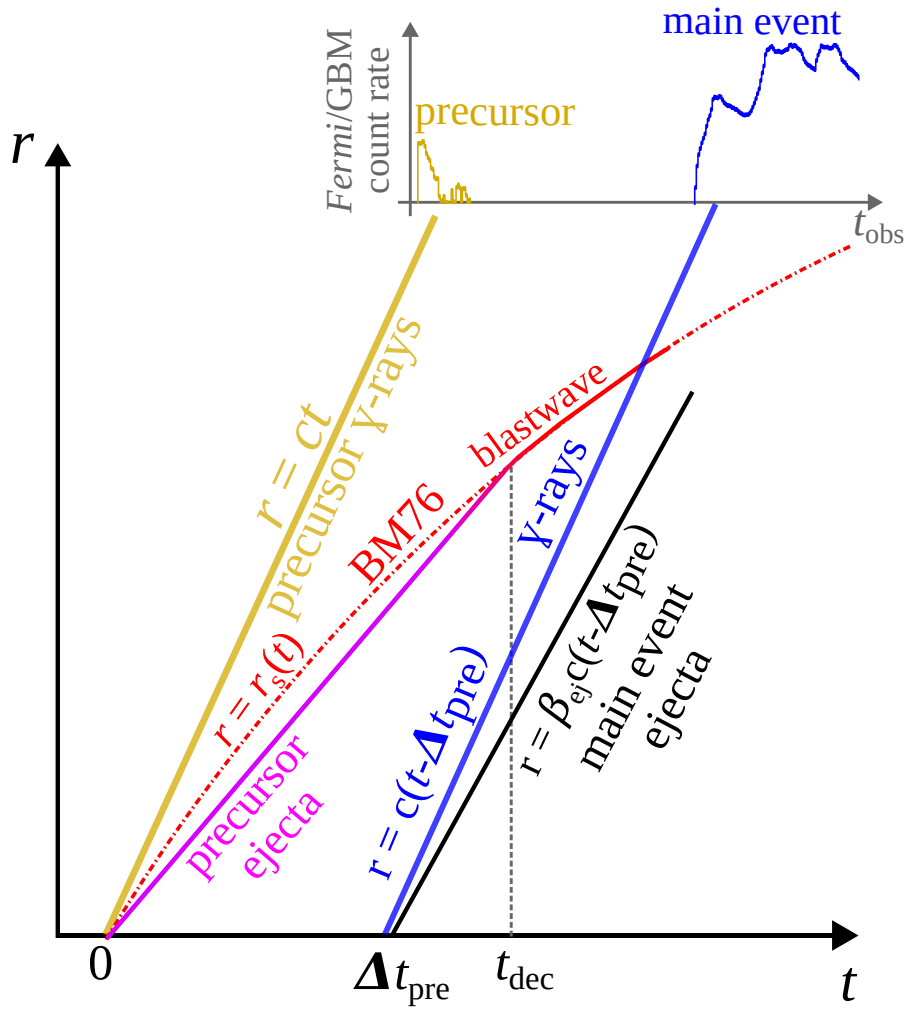

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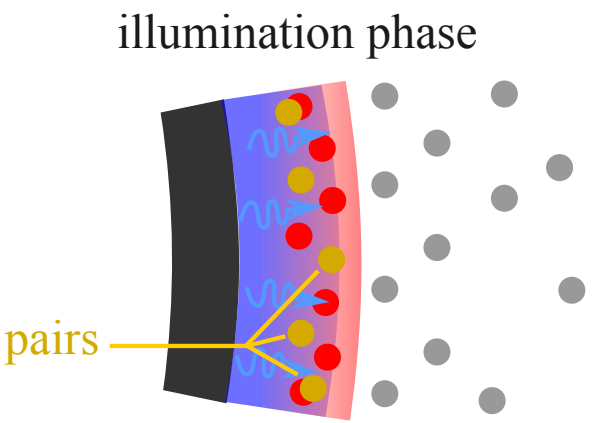

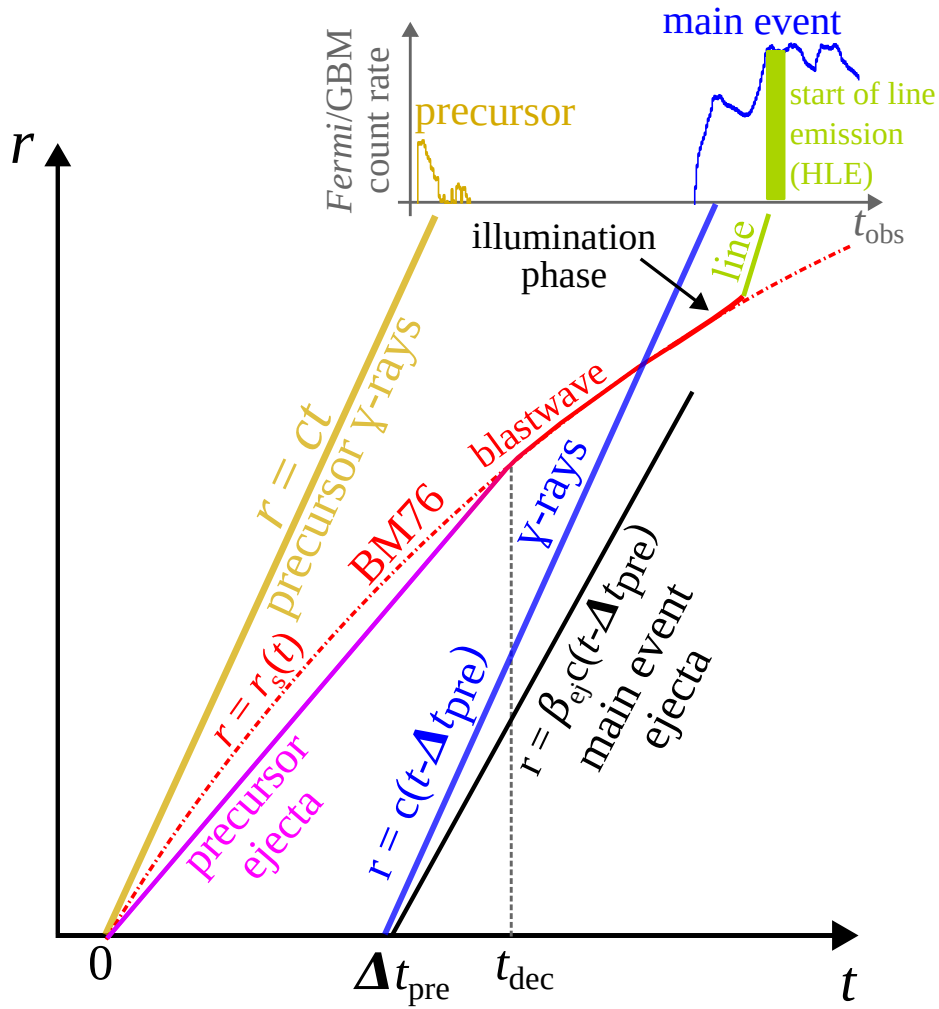

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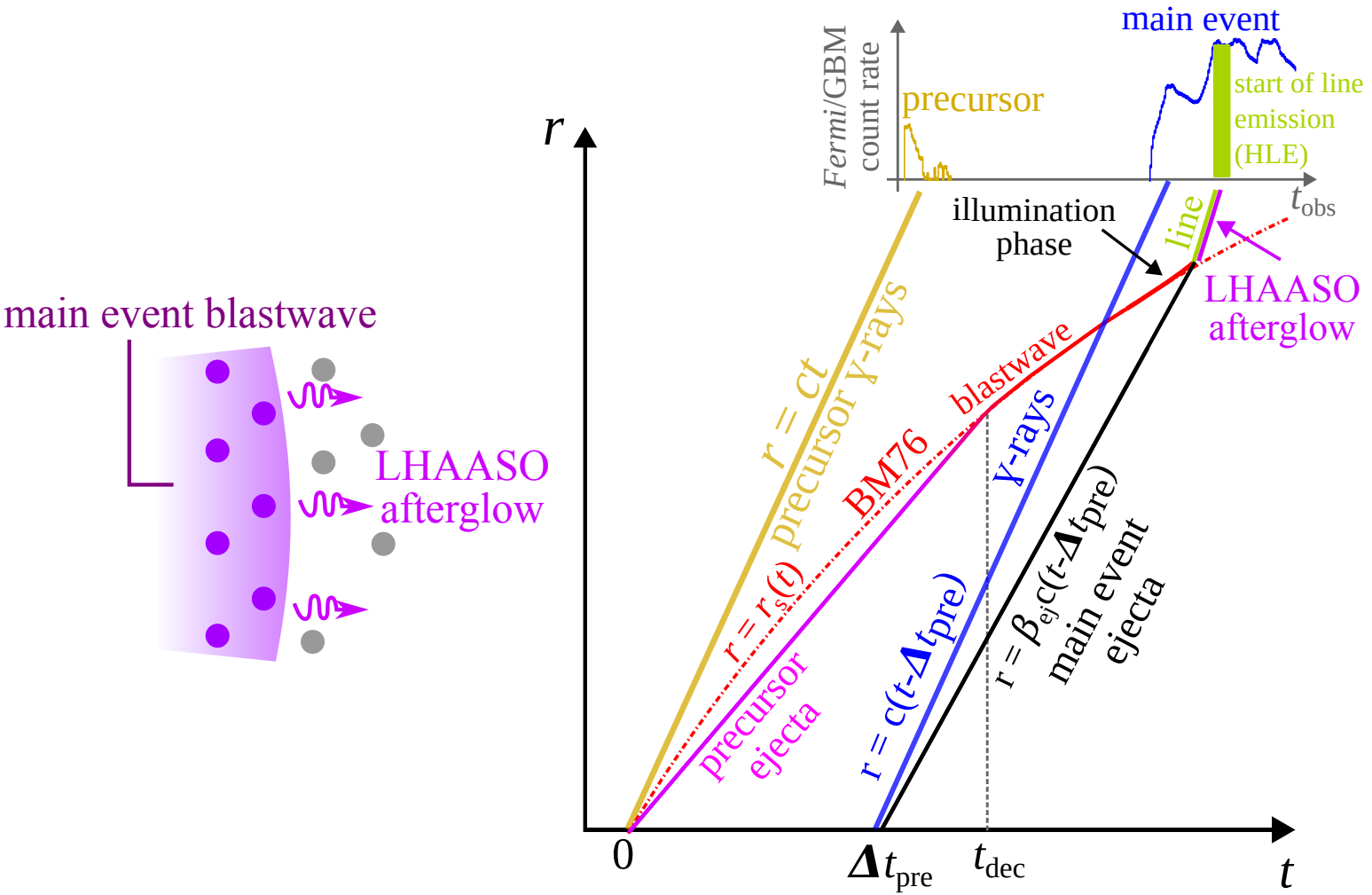

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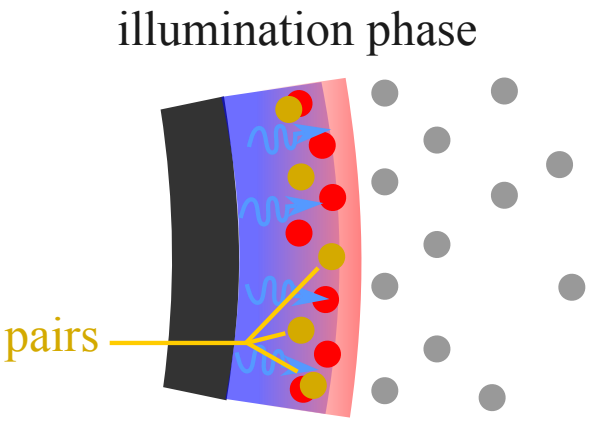
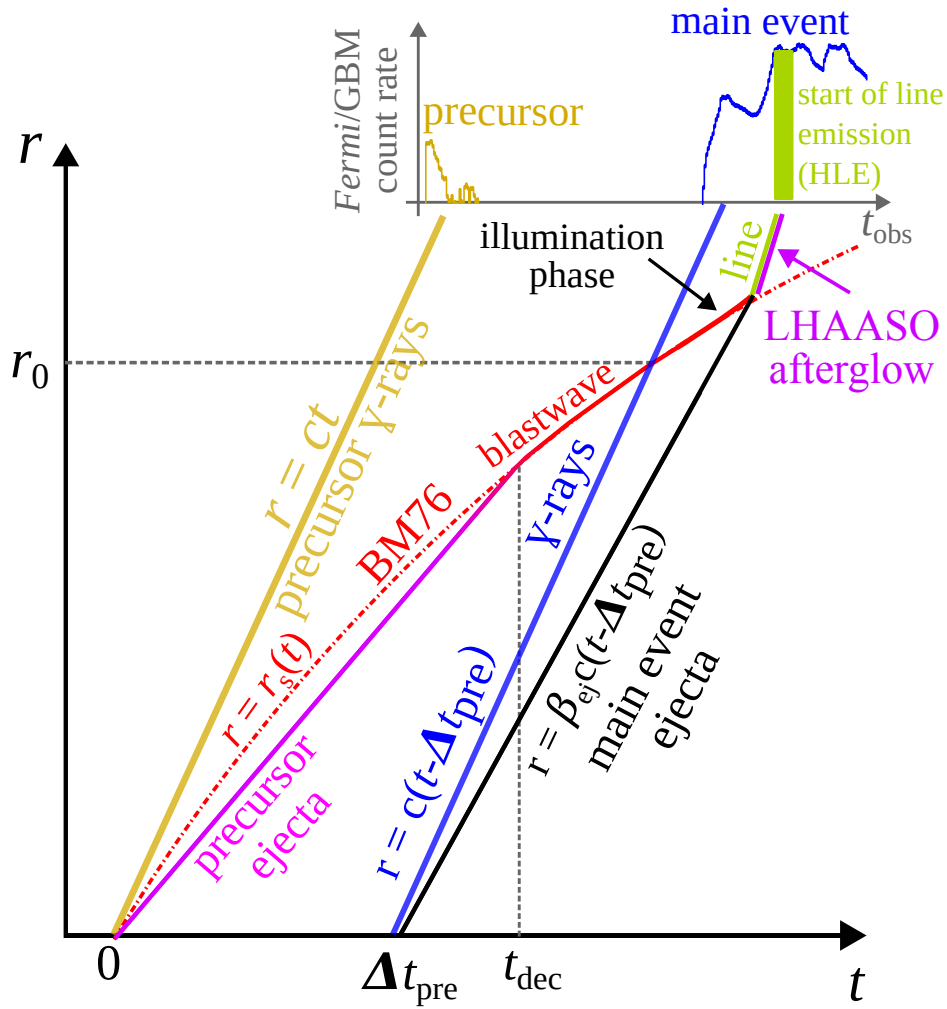
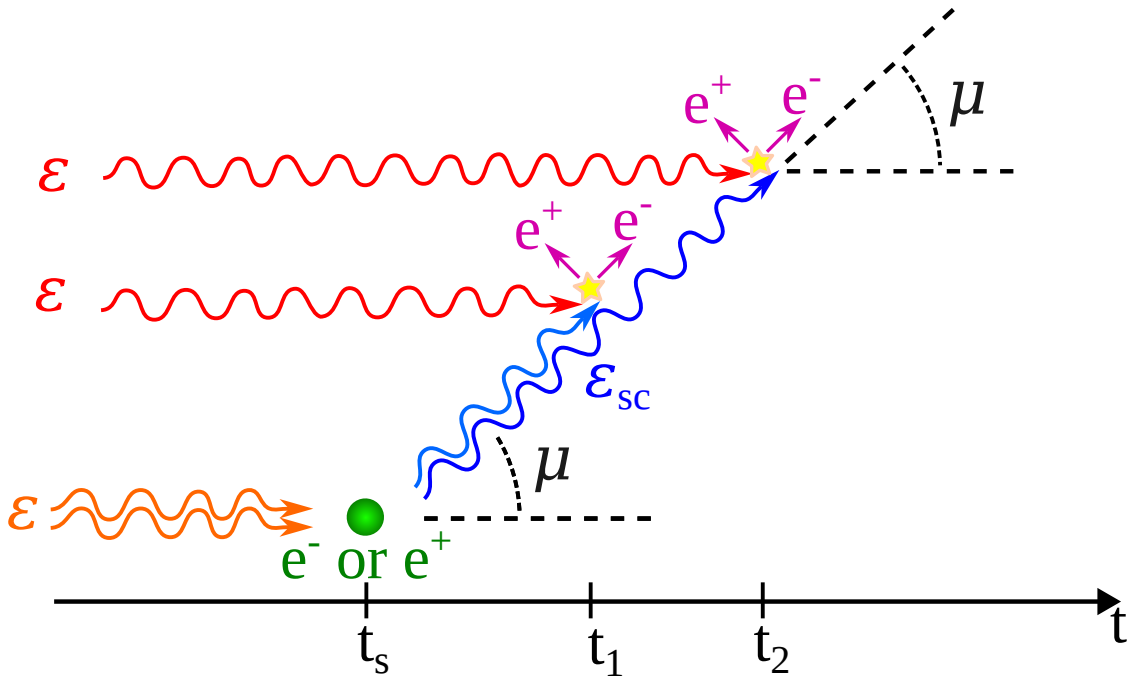




$$r_0 \propto (E_{\rm pre}/A_\star)^{1/2} \Delta t_{\rm pre}^{1/2}, \quad \Gamma_0 \propto (E_{\rm pre}/A_\star)^{1/4} \Delta t_{\rm pre}^{-1/4}$$

Pair enrichment and acceleration: the basic block



[Thompson & Madau 2000; Beloborodov 2002]

Radiative cooling

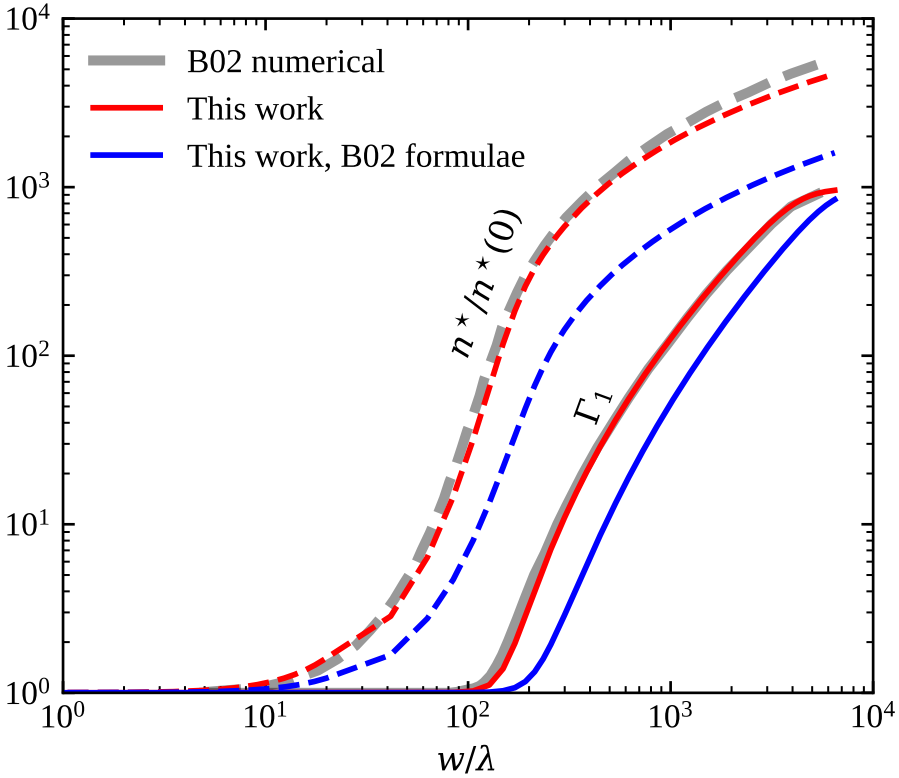
Electrons in blastwave initially relativistic.
Pairs also mildly relativistic when produced ($\gamma_\pm \sim 10$).

BUT

$$t'_{\rm cool,IC} \ll \Delta t'_{\rm illumination}$$

$\rightarrow$ leptons can be assumed cold (phew!)

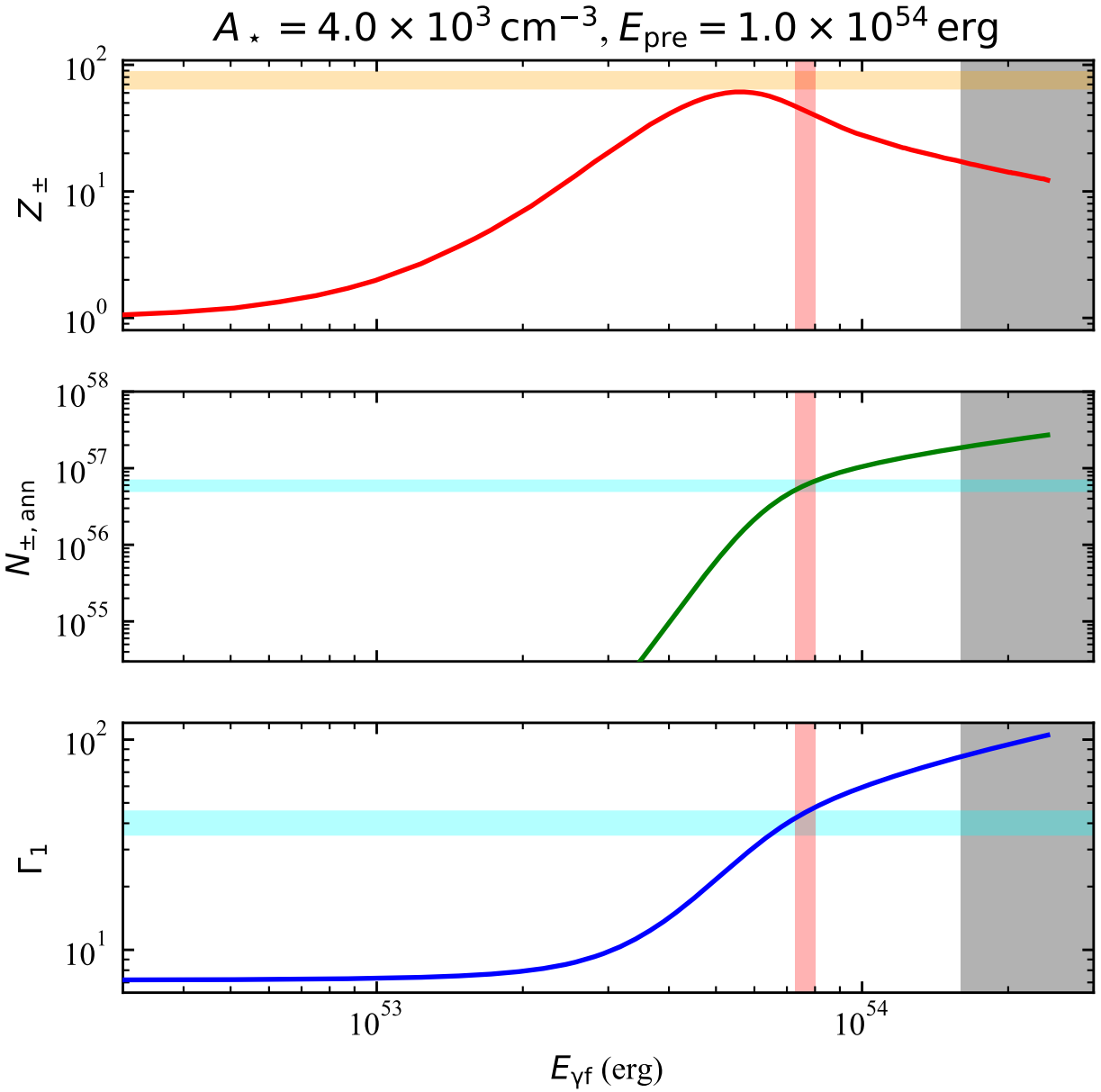
Technical note



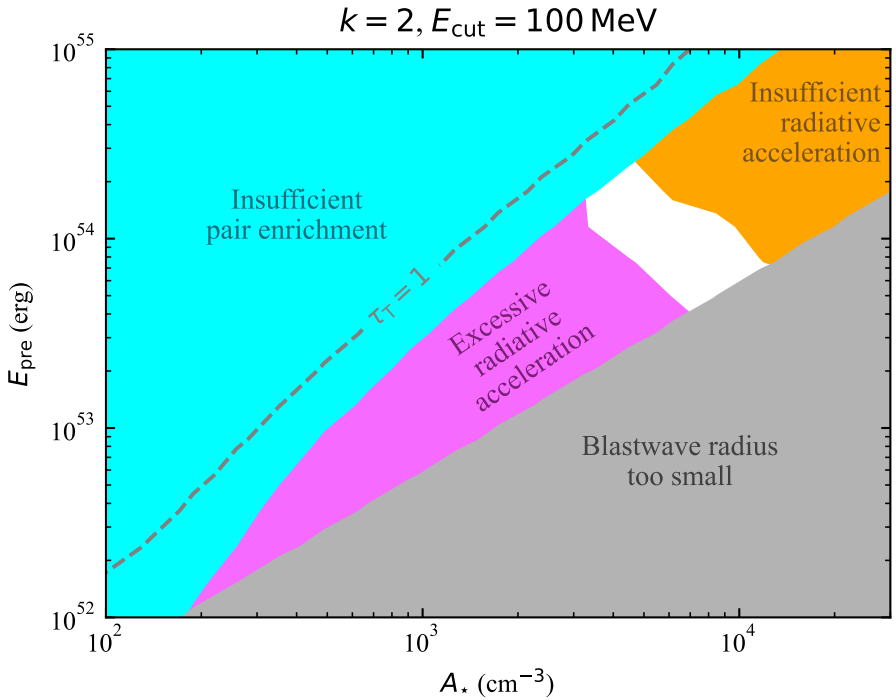
Evolution equations in Beloborodov 2002 contain typos. Correct equations in our appendix.

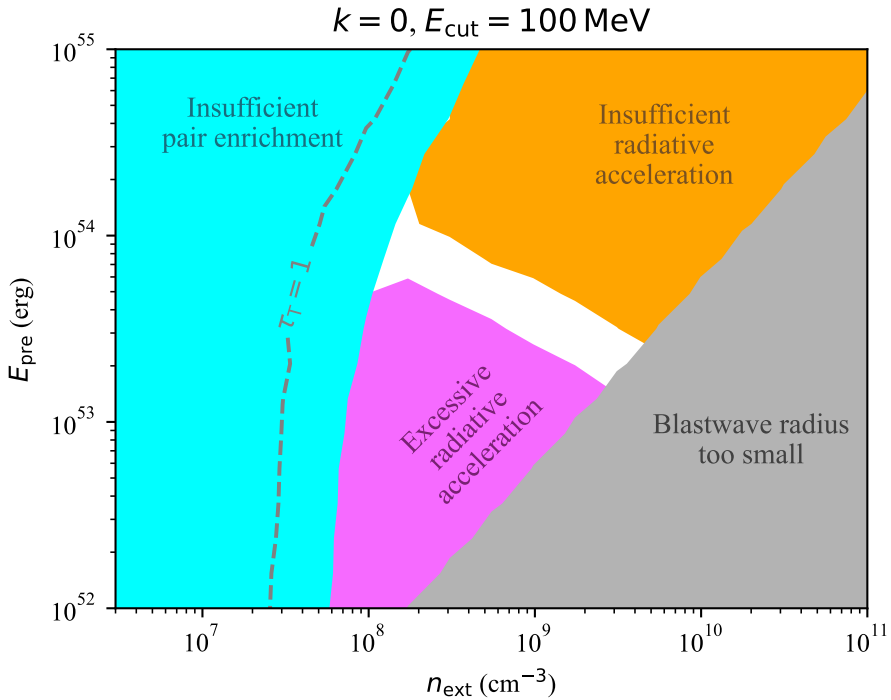
[Salafia et al. 2026]

Example blastwave evolution during illumination



Parameter space





$$A_\star = \left(\frac{\dot{M}_{\rm w}}{10^{-5}\,{\rm M}_\odot}\right)\left(\frac{\dot{v}_{\rm w}}{10^3\,{\rm km/s}}\right)^{-1} \rightarrow \dot{M}_{\rm w} = 0.1\left(\frac{A_\star}{10^4}\right)\left(\frac{\dot{v}_{\rm w}}{10^3\,{\rm km/s}}\right)\,{\rm M}_\odot$$

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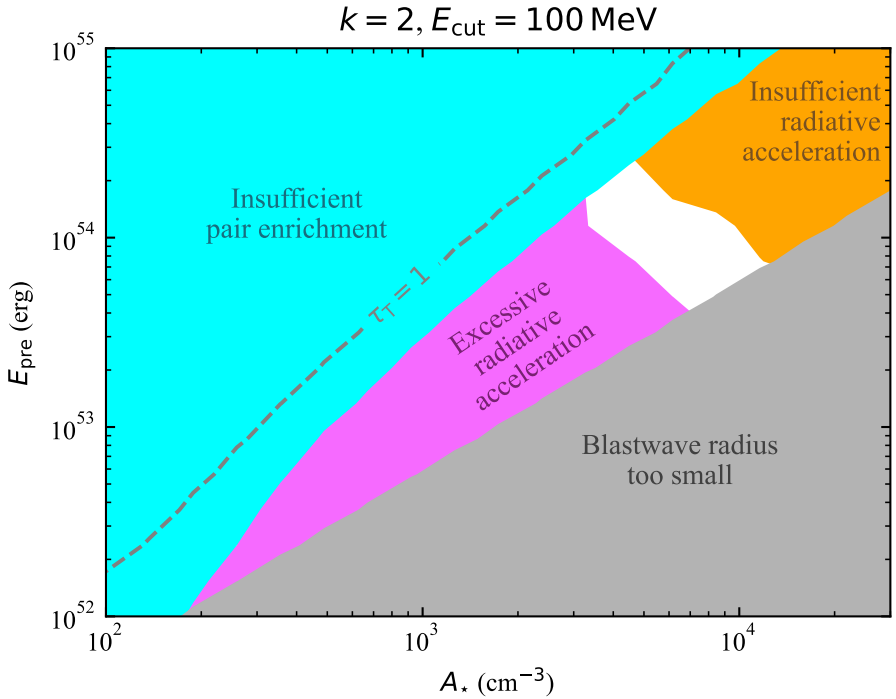

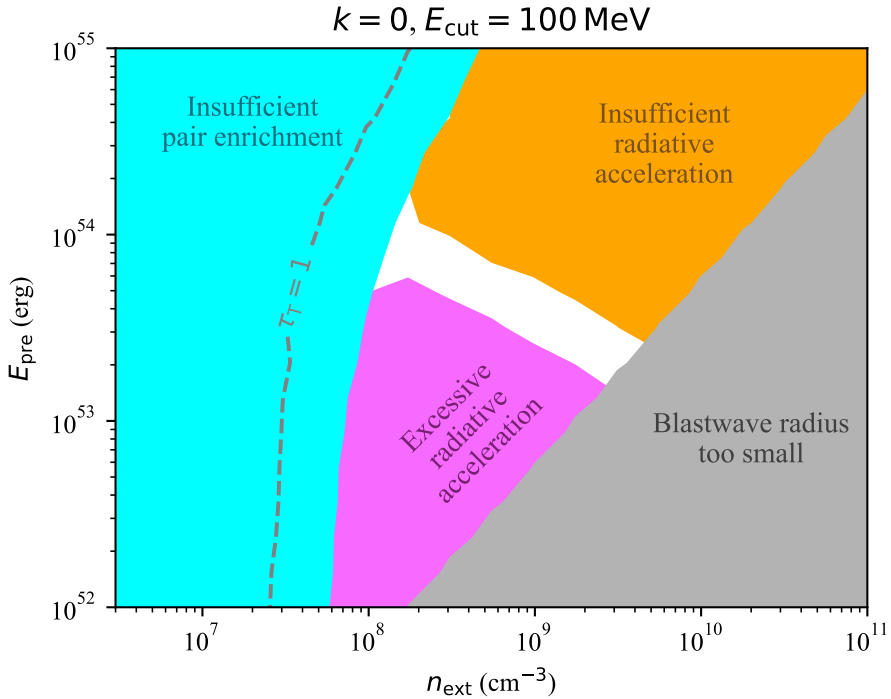

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Pair enrichment model assumptions over-conservative when $\tau_{\rm T} \gtrsim 1$

$\rightarrow$ may alleviate density requirement

IC emission from pairs

- Pairs born with $\gamma_{\pm} \sim 10$.

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- External inverse Compton, $2\Gamma(\gamma_\pm - 1)m_\mathrm{e}c^2$ emitted per pair.
- Emission in HLE regime: $L_\mathrm{EIC} \sim \frac{N_\pm \times 2\Gamma(\gamma_\pm - 1)m_\mathrm{e}c^2}{t_\mathrm{ang}} \sim 10^{51}\,\mathrm{erg\,s^{-1}}$.

IC emission from pairs

- Pairs born with $\gamma_\pm \sim 10$.
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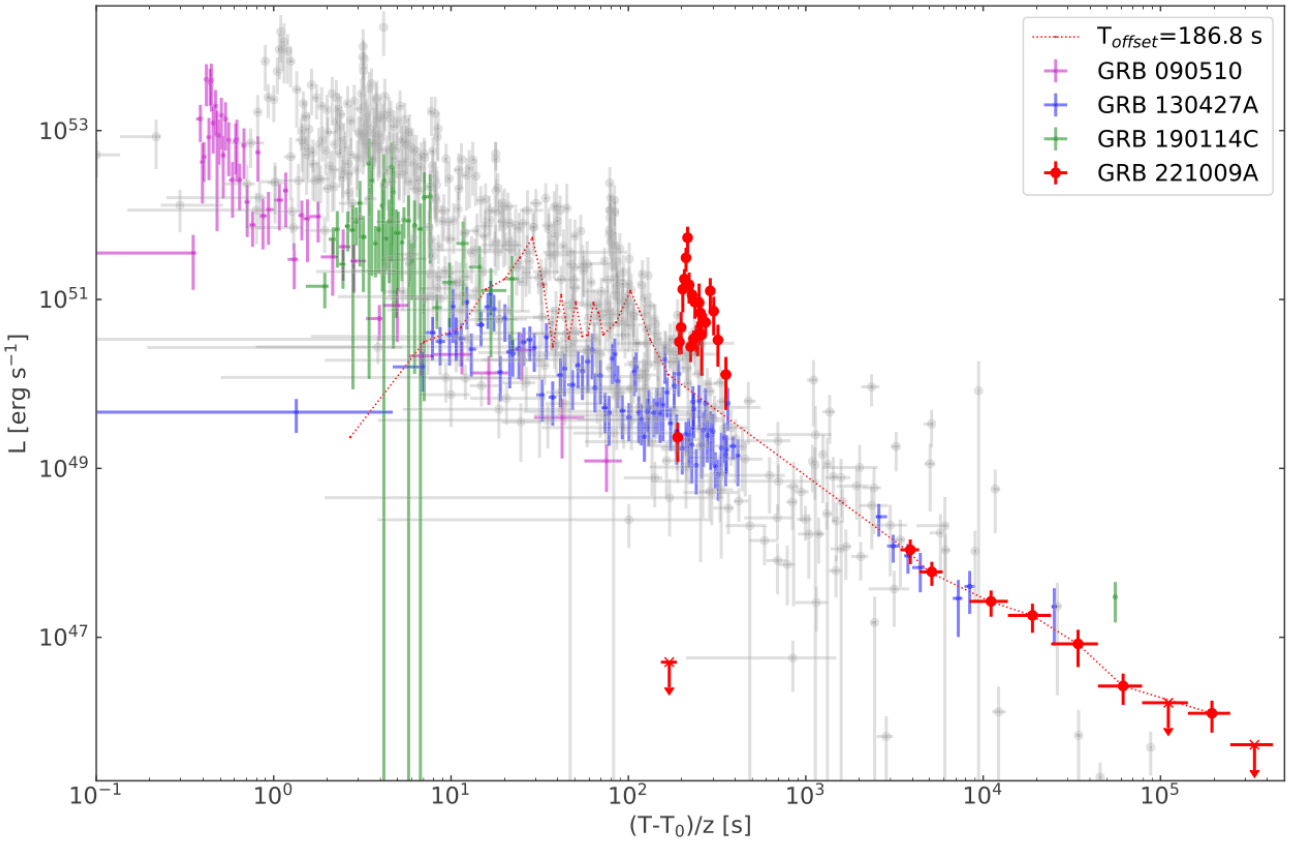

[Axelsson+2025]

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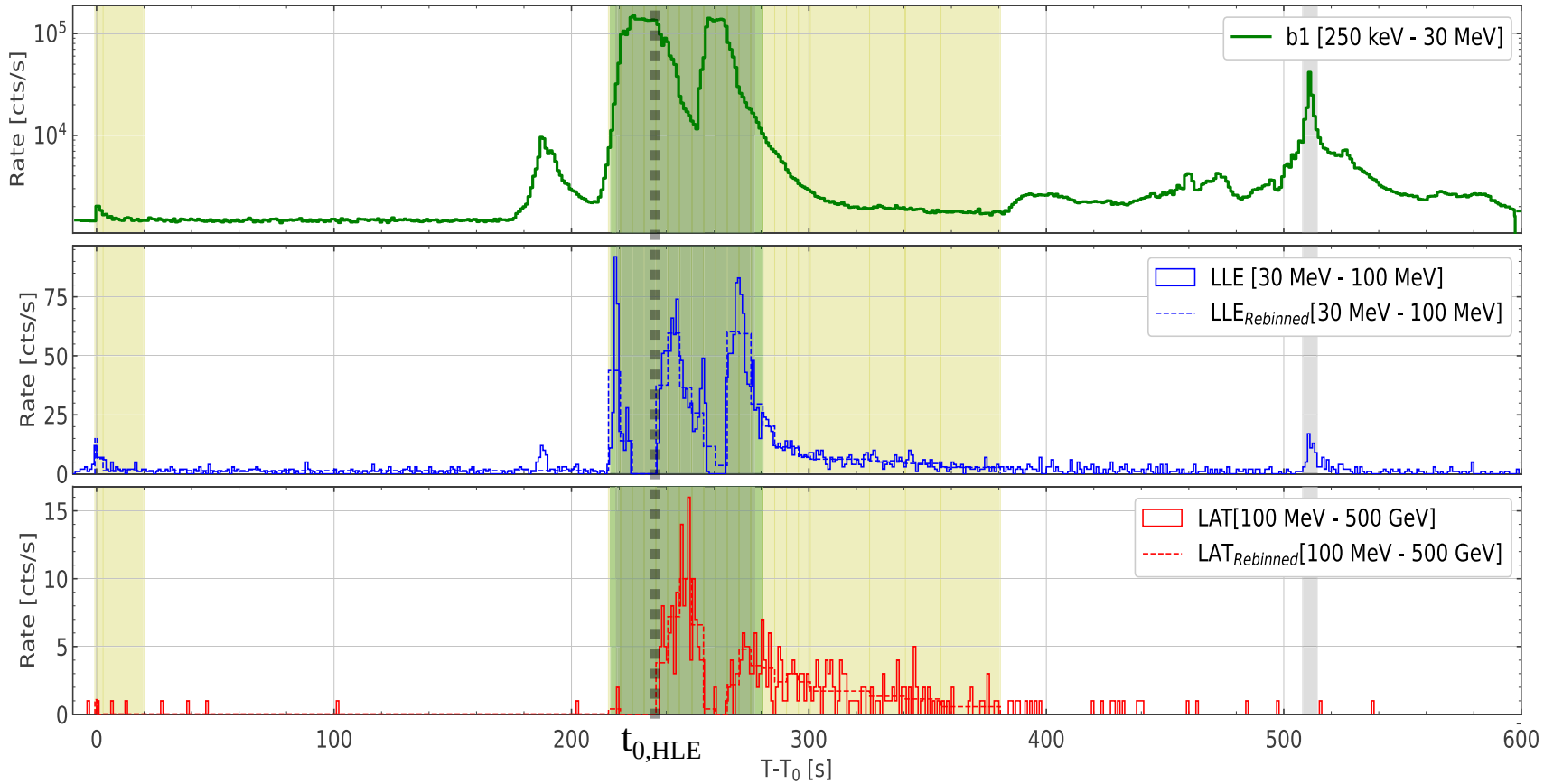


[Axelsson+2025]

Precursor radiative efficiency

$$E_{\rm pre} \sim 10^{54}\,{\rm erg} \text{ vs } E_{\gamma,{\rm pre}} \sim 10^{51}\,{\rm erg}$$

very low efficiency?

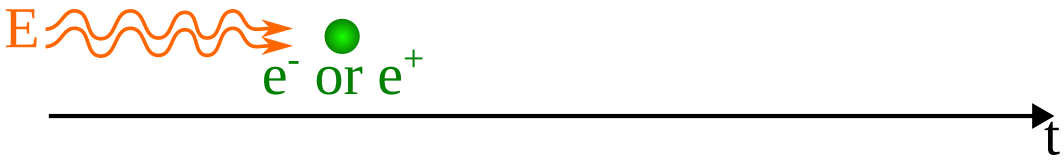
Precursor radiative efficiency

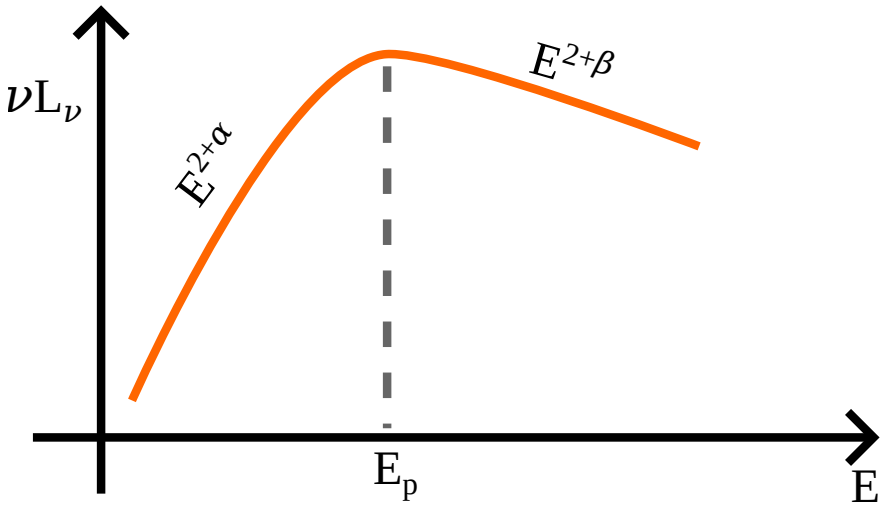
$$E_{\rm pre} \sim 10^{54}\,{\rm erg} \text{ vs } E_{\gamma,{\rm pre}} \sim 10^{51}\,{\rm erg}$$

very low efficiency?

CSM as 'Thomson screen':
optical depth dominated by low r (wind case)
If $r_\gamma \sim 10^{14}\,{\rm cm}$, then $e^{-\tau_{\rm T,CSM}} \sim 10^{-2}$

Feedback on prompt emission spectrum





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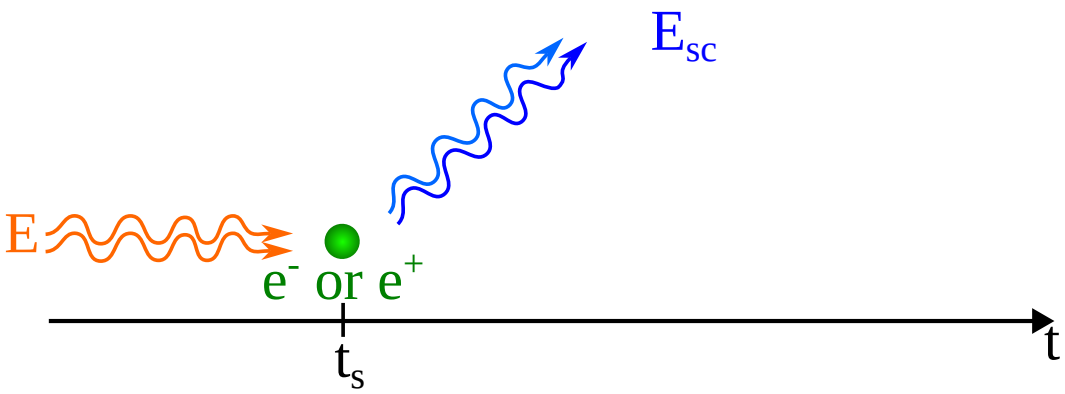

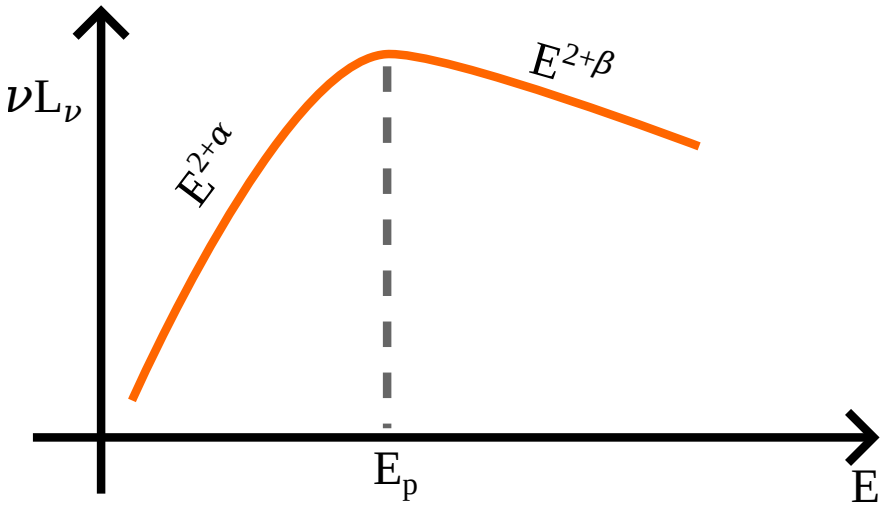

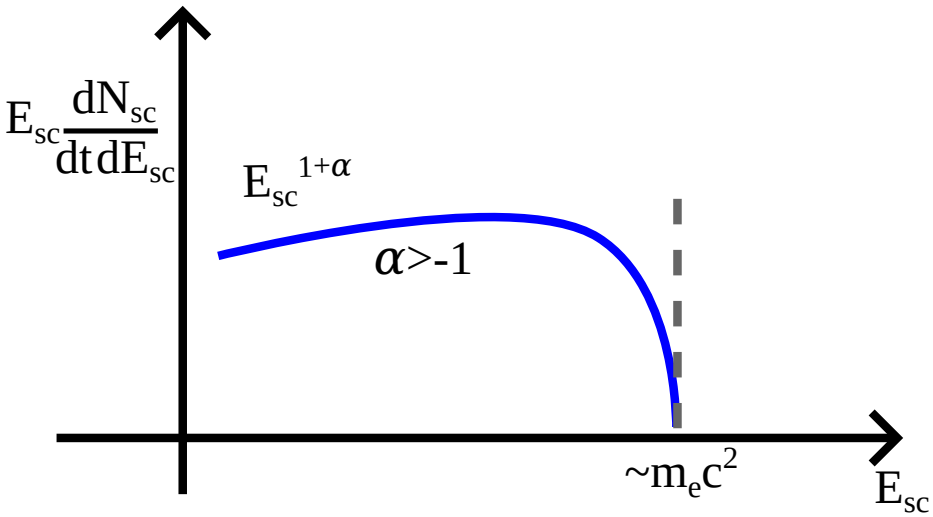

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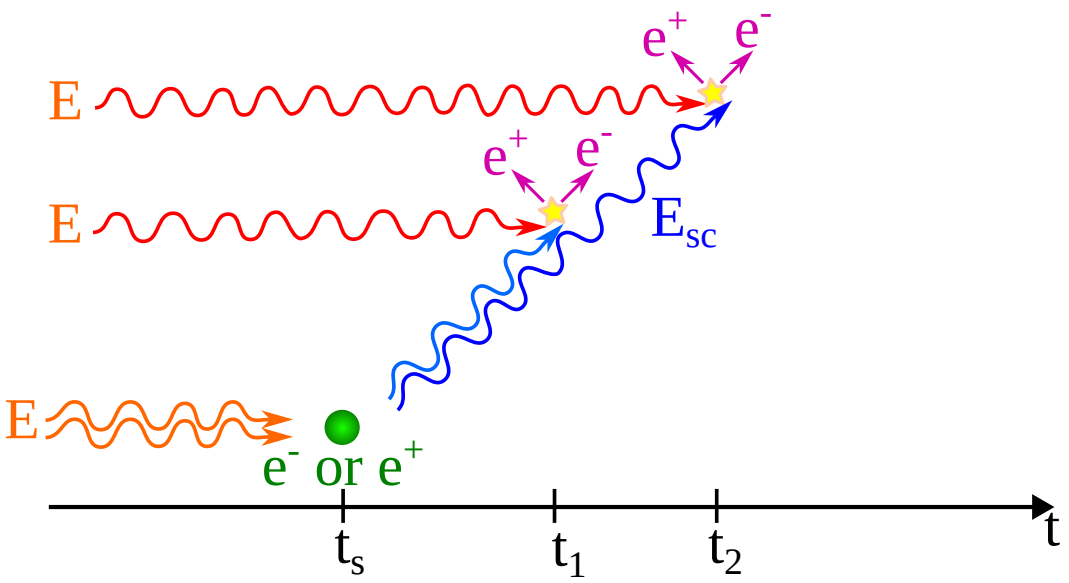

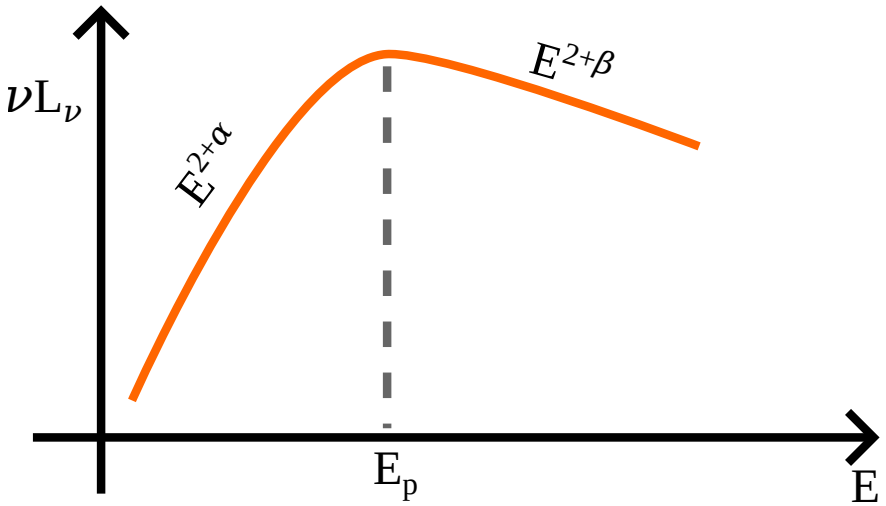

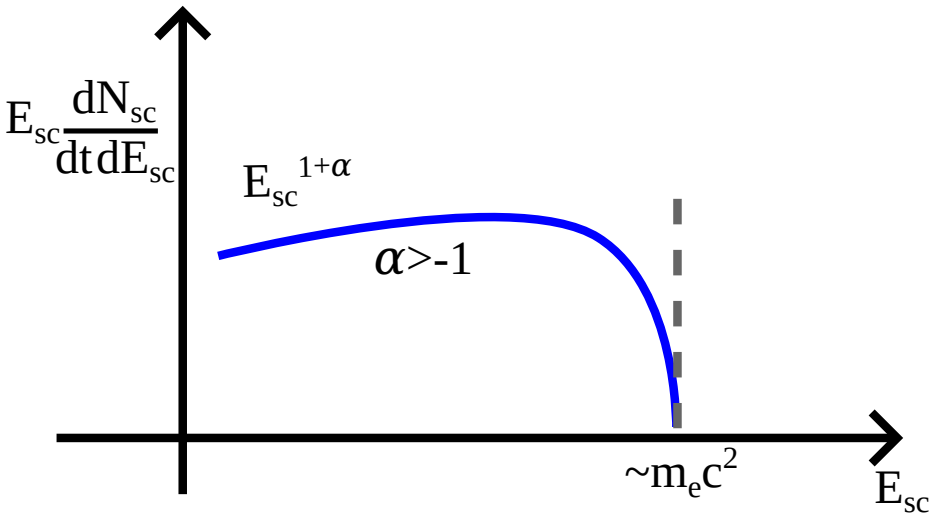

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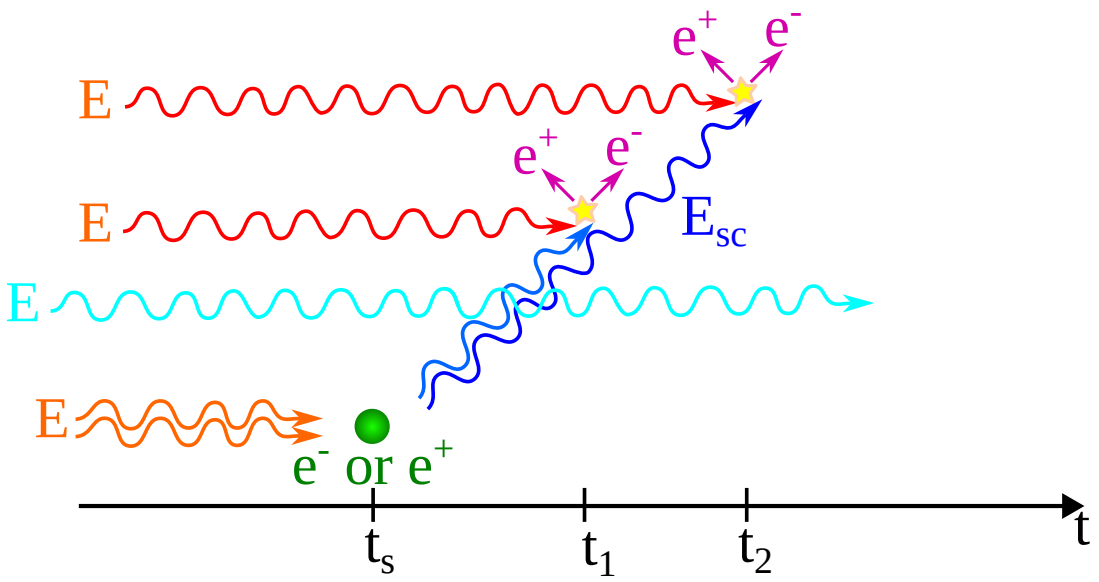

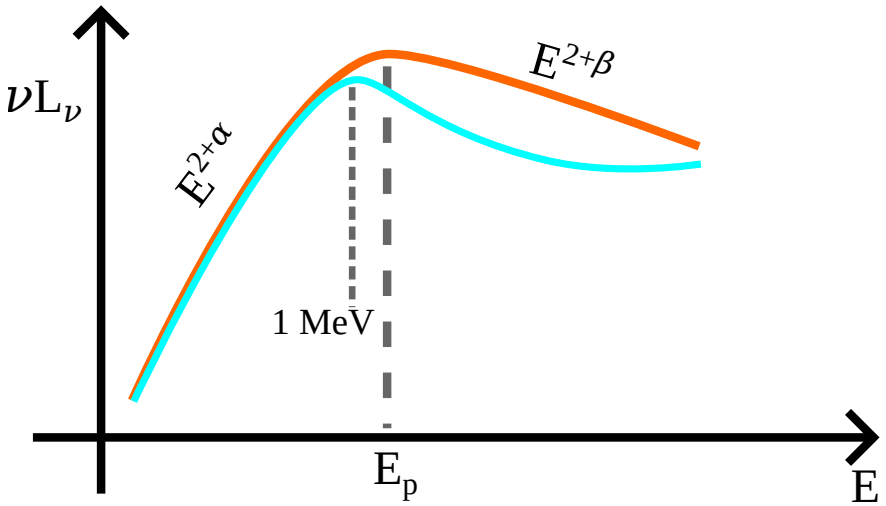

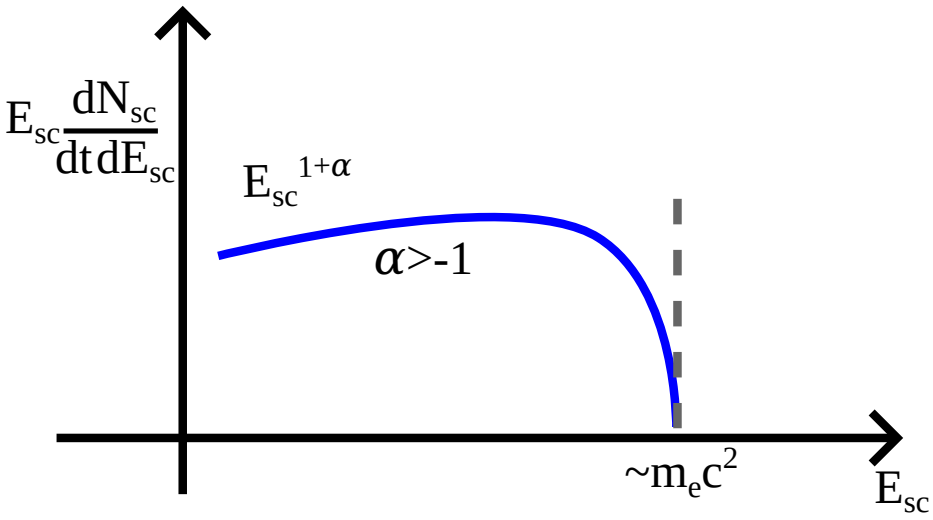

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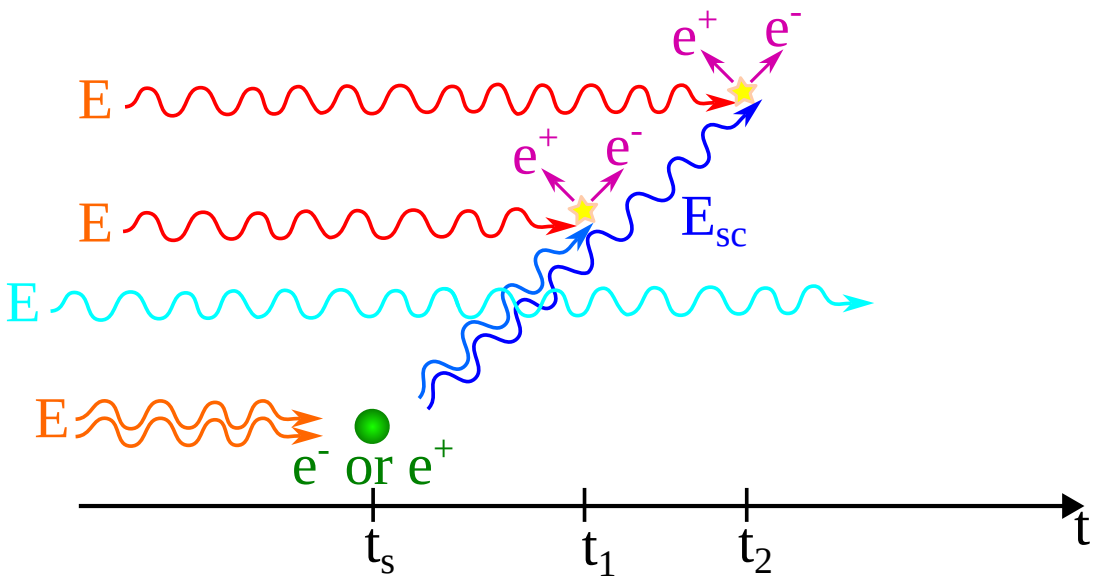
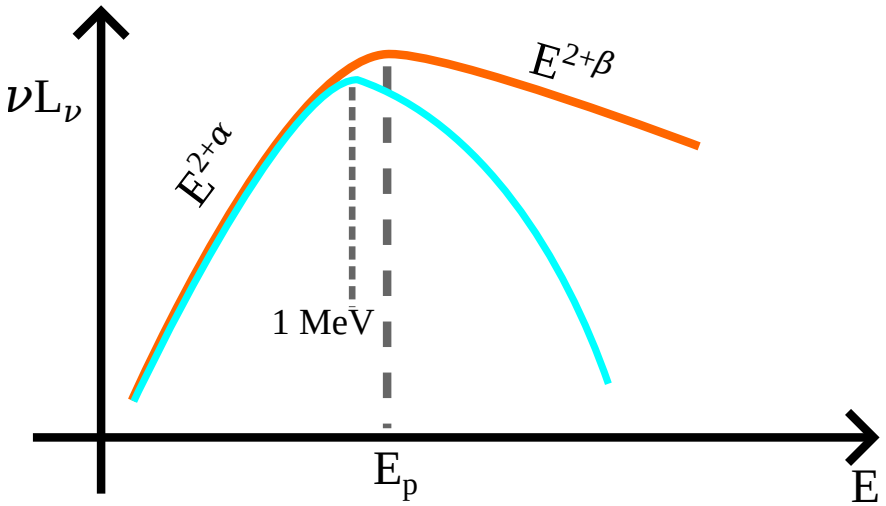
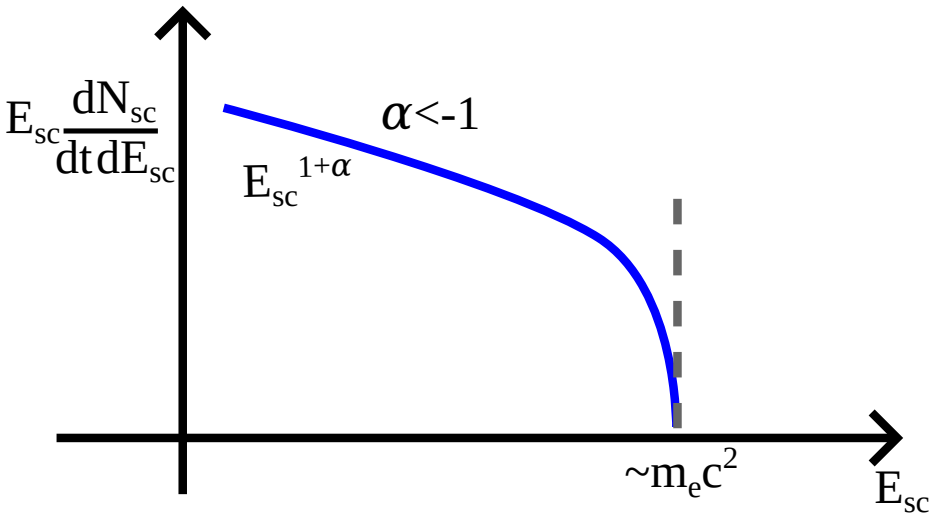
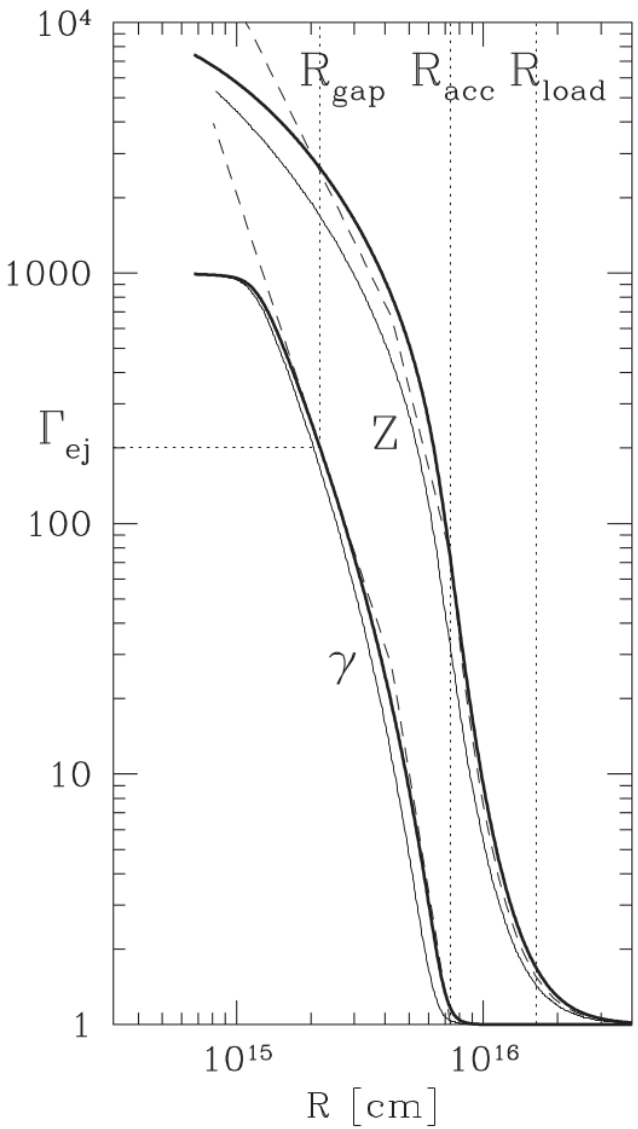






Absorption radius



[Beloborodov 2005]

Absorption from maximally pair-enriched, but not-yet-accelerated material. Assuming wind density profile:

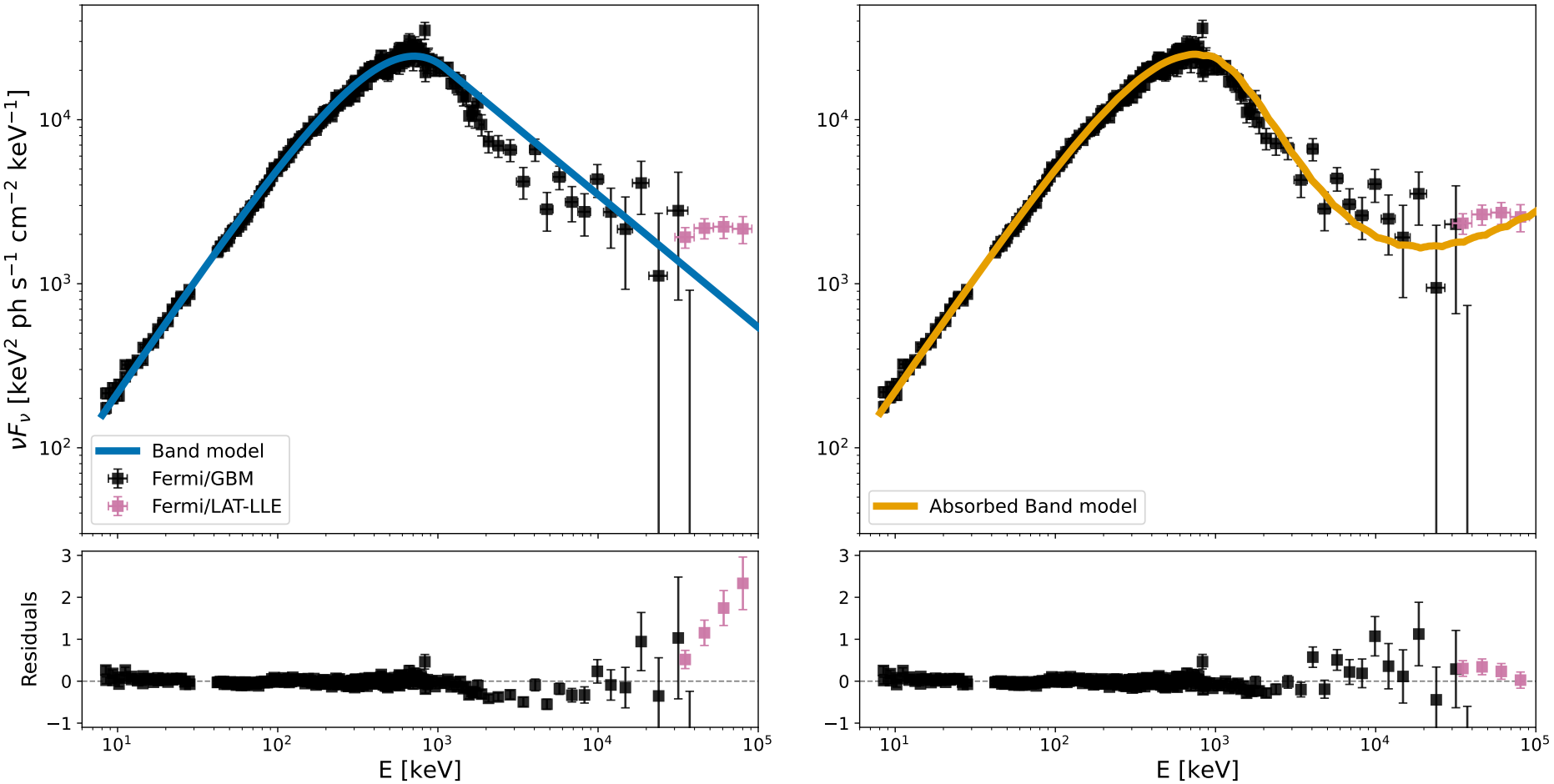
$$R_{\rm abs}(E_\gamma) \sim R_{\rm acc} \sim 8\times10^{15} E_{\gamma,53}^{1/2}\,{\rm cm}$$

$$\tau_{\gamma\gamma,\rm max} \sim \sigma_{\rm T} Z_{\pm,\rm acc} n(R_{\rm abs}) R_{\rm abs}$$

$$\tau_{\gamma\gamma,\rm max} \gtrsim 1 \text{ if } A_\star \gtrsim 530 E_{\gamma,53}^{1/2}$$

[Oganesyan, Salafia, et al. 2026, arXiv:2601.14393]

Case study: GRB 190114C

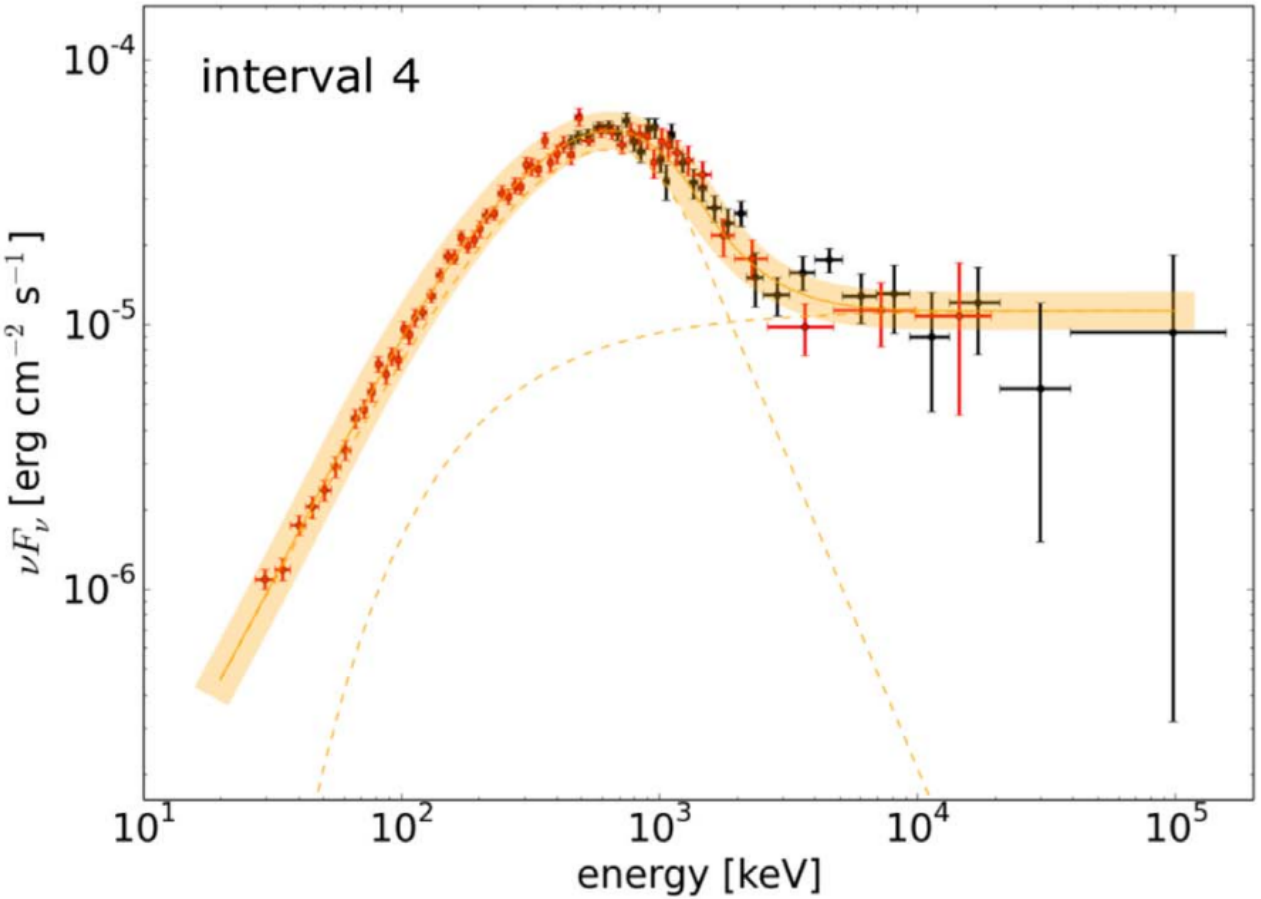


$$\Delta\mathrm{PGstat} = 147$$

[Oganesyan, Salafia, et al. 2026, arXiv:2601.14393]

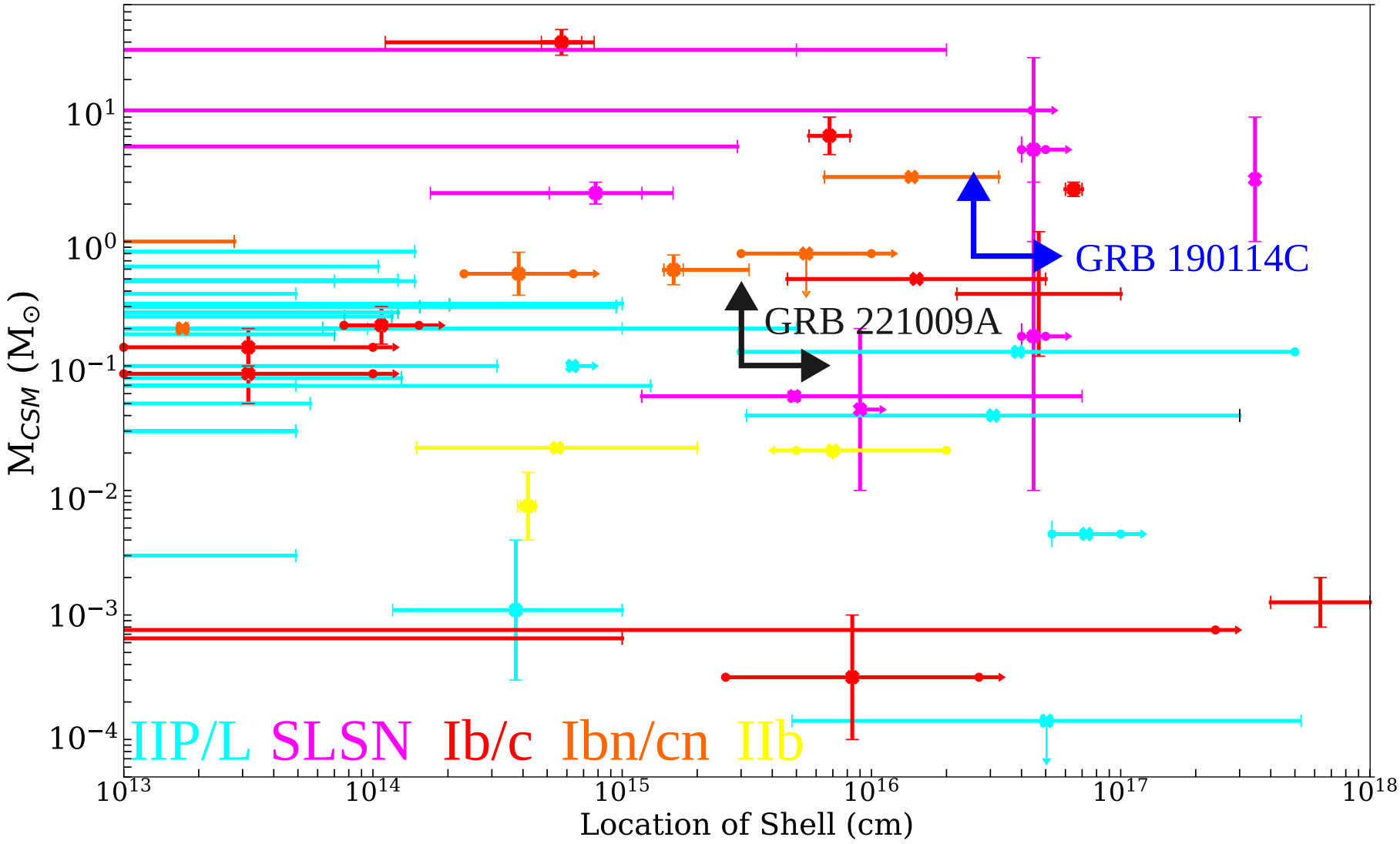
Afterglow emergence?

Konus Wind + AGILE data



[Ursi et al. 2020]

CSM comparison



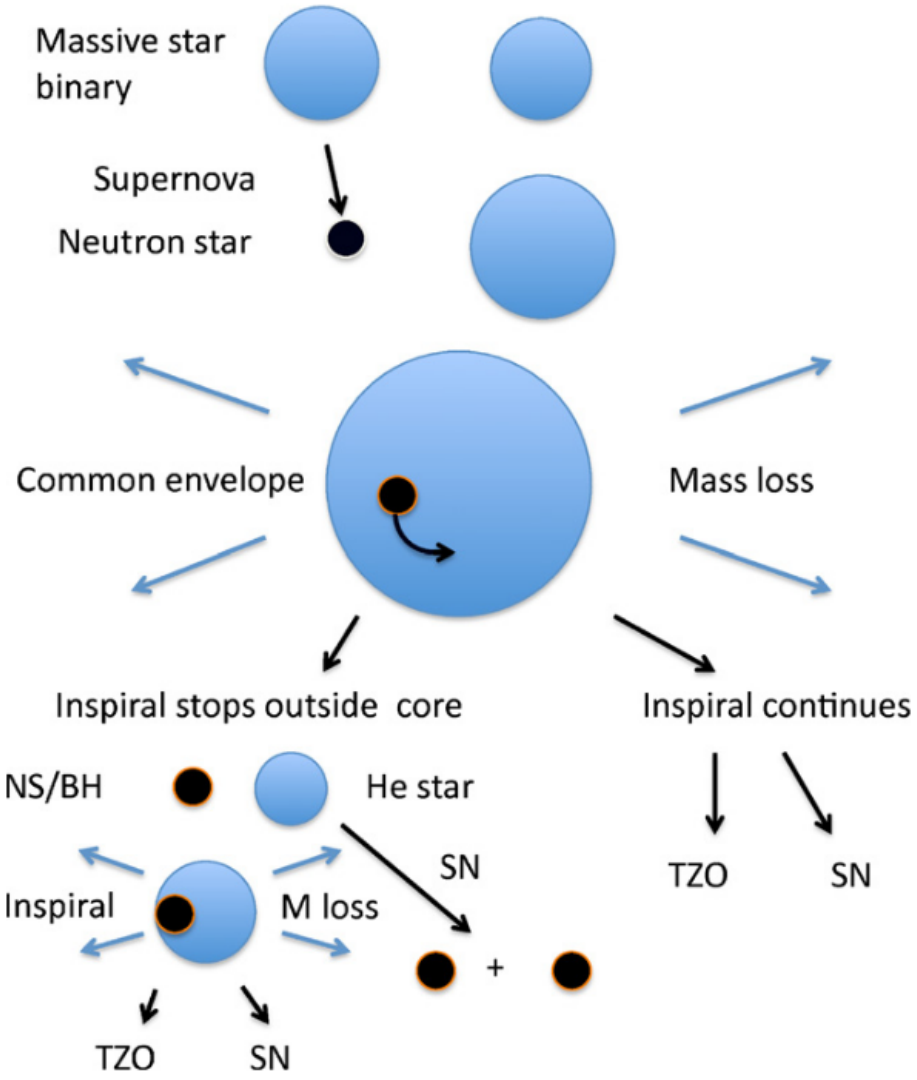
[Adapted from Brethauer et al. 2022]

Where does the CSM come from?

Pre-collapse eruptive mass ejection?

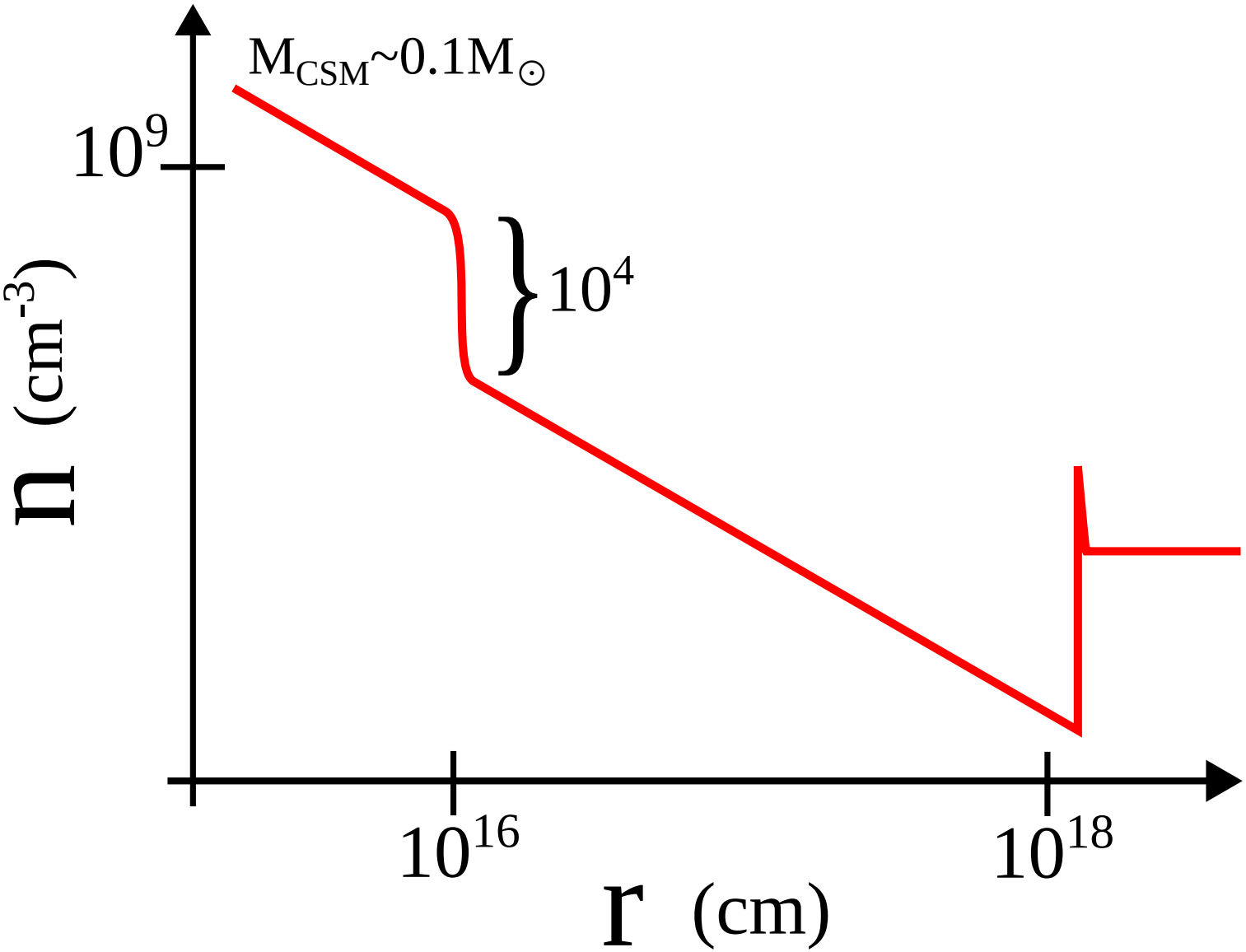
η Carinae
[NASA, ESA, Hubble; Processing & License: Judy Schmidt]

Binary interaction?



[Chevalier 2012]

Effect on the afterglow?



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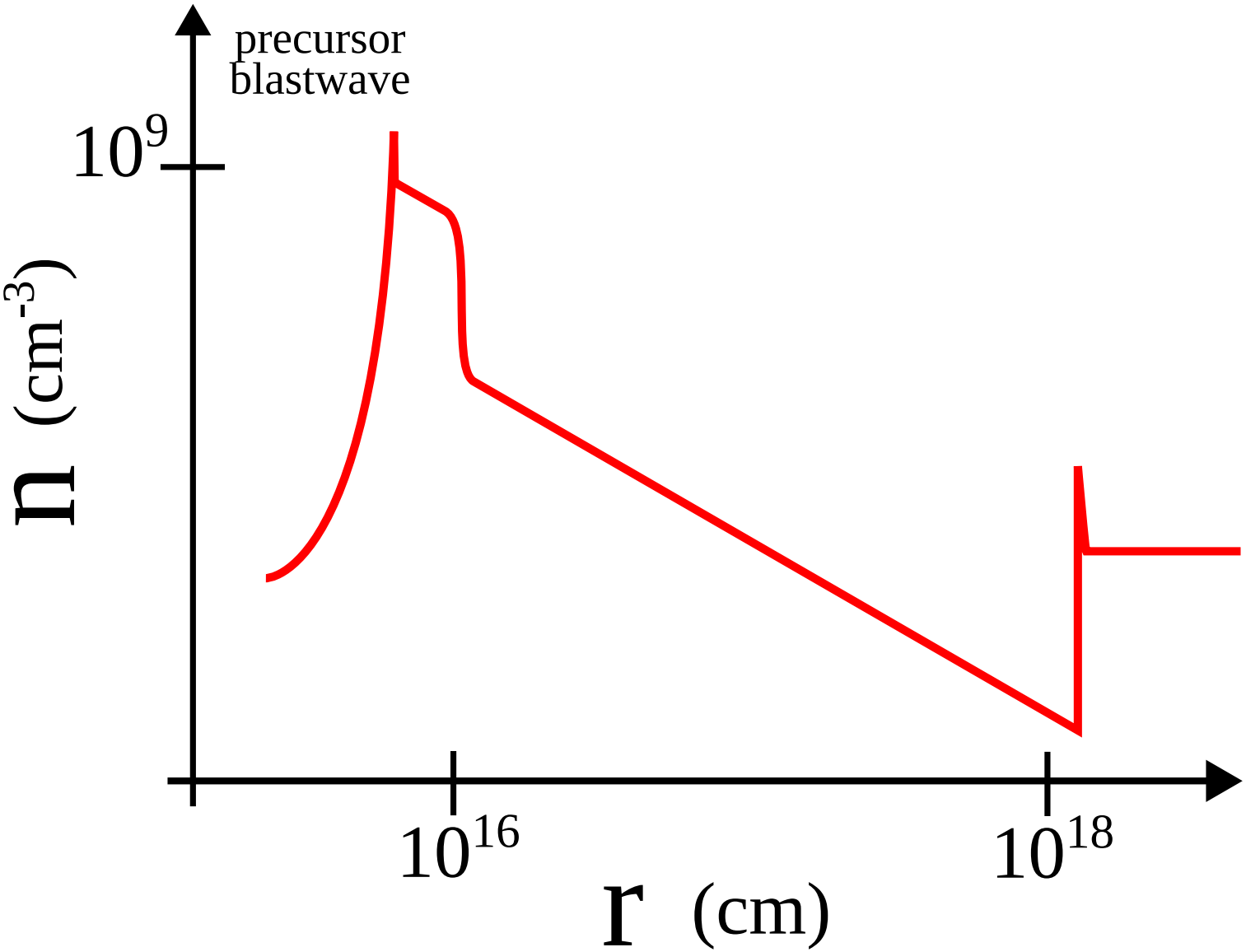

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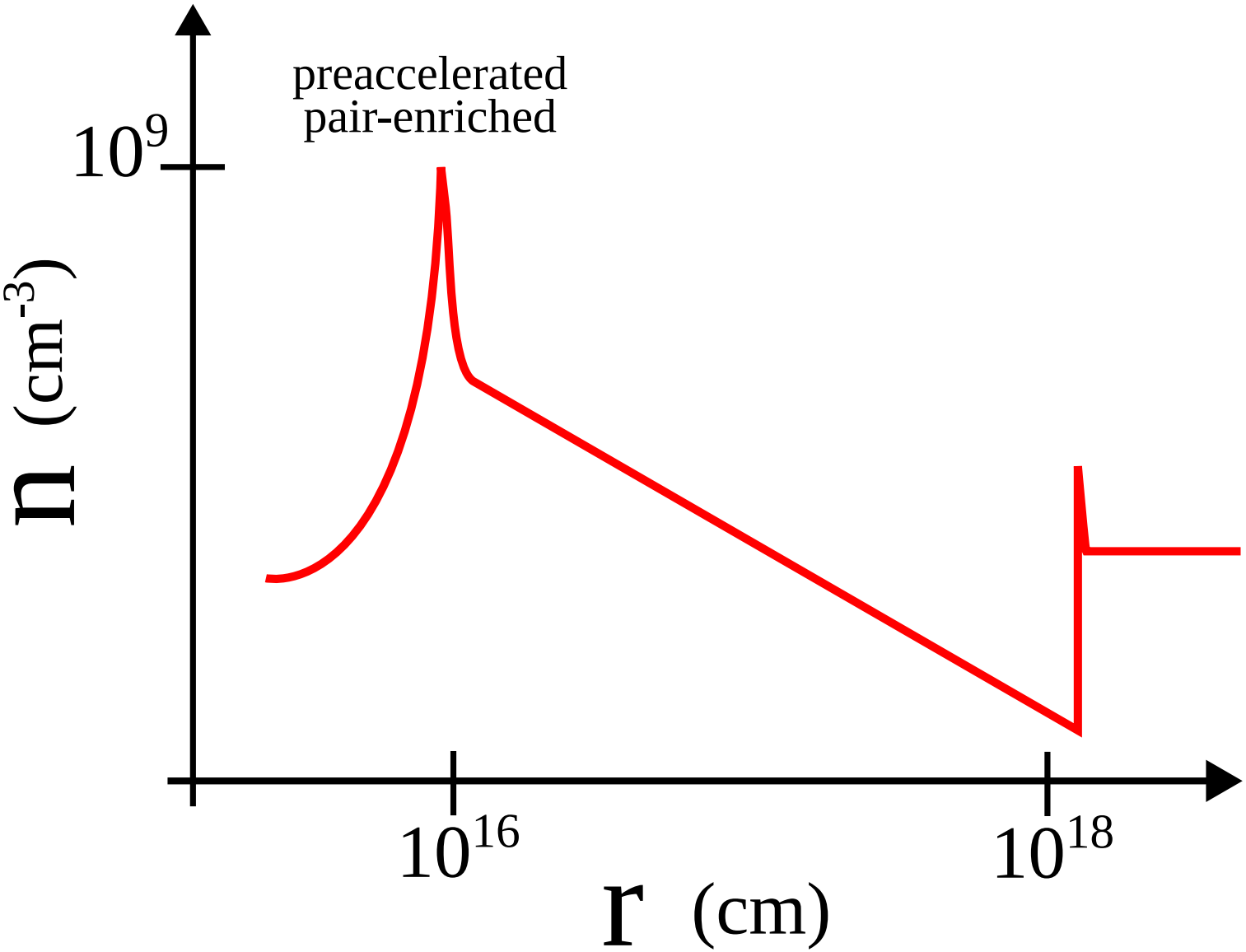

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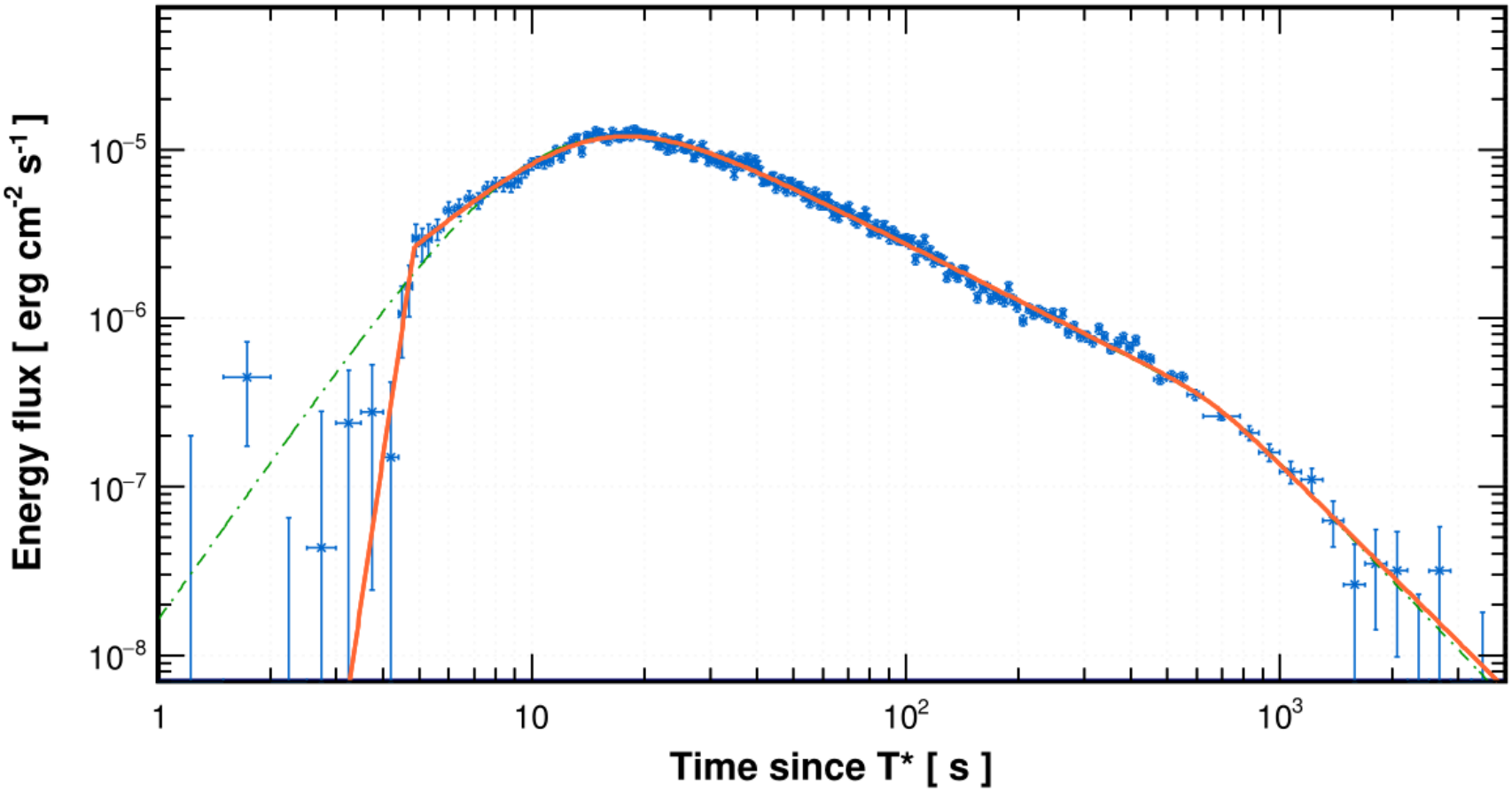


Thank you!

YITP long term workshop
Jan 26 - Feb 27 2026, Kyoto, Japan

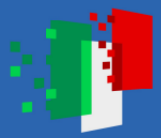
Short GRB population studies

Om Sharan Salafia

INAF – Osservatorio Astronomico di Brera
INFN – Sezione di Milano-Bicocca
Milan, Italy

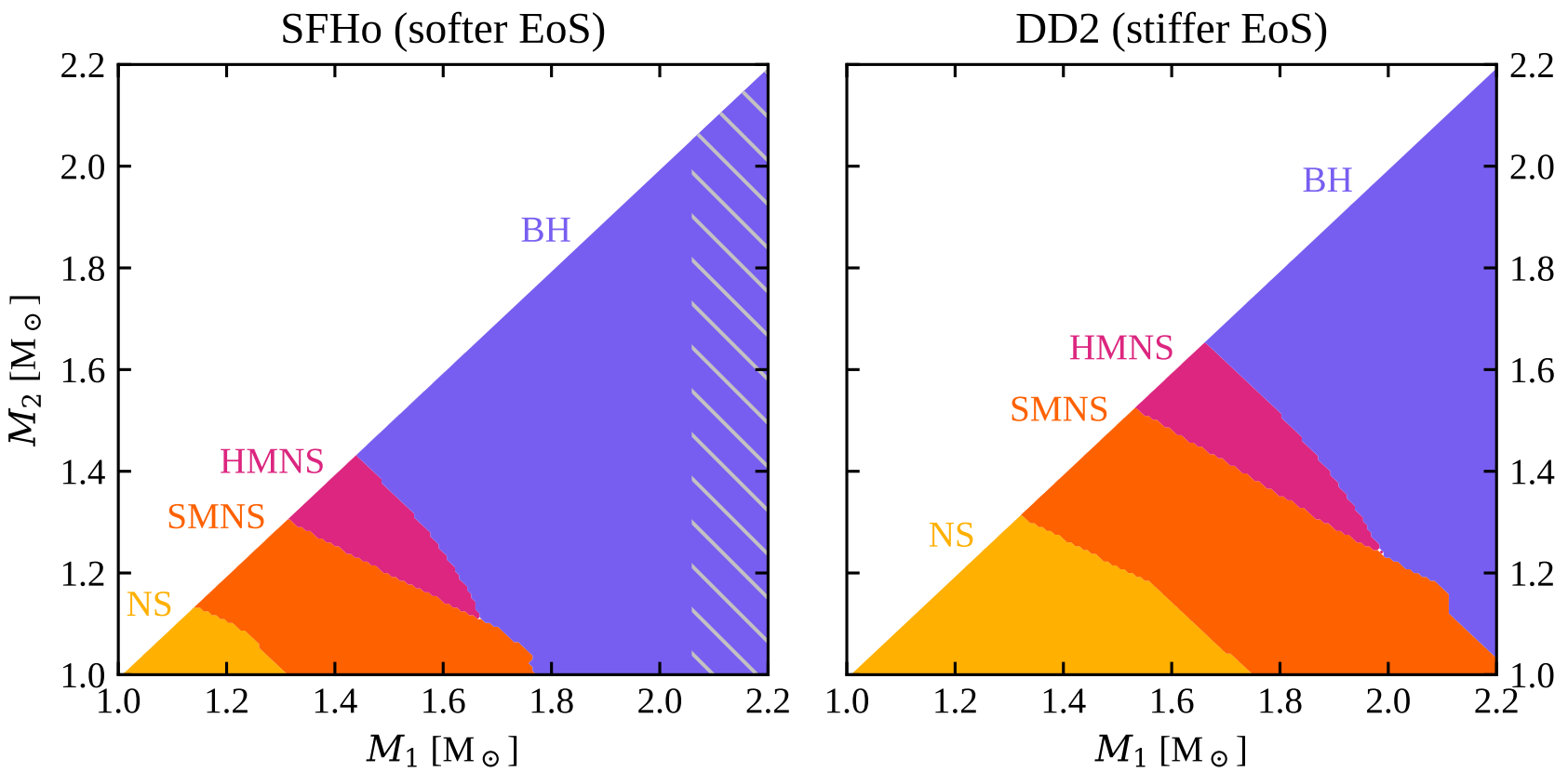

Finanziato dall'Unione europea
NextGenerationEU


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]

NS-NS merger outcomes on M_1, M_2 plane



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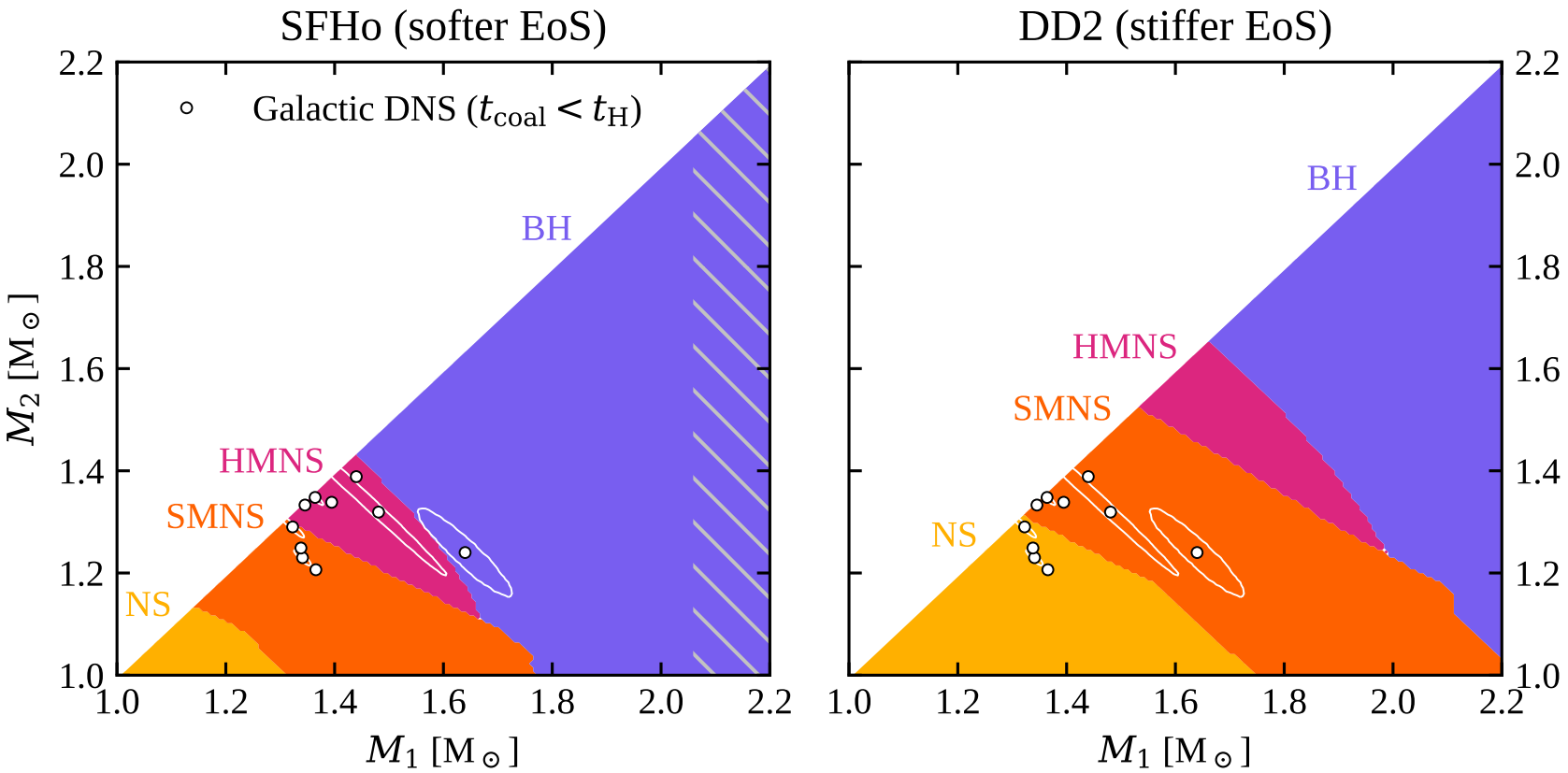

[see e.g. Piro+17; **Salafia+2022**. DNS data: Farrow+19]

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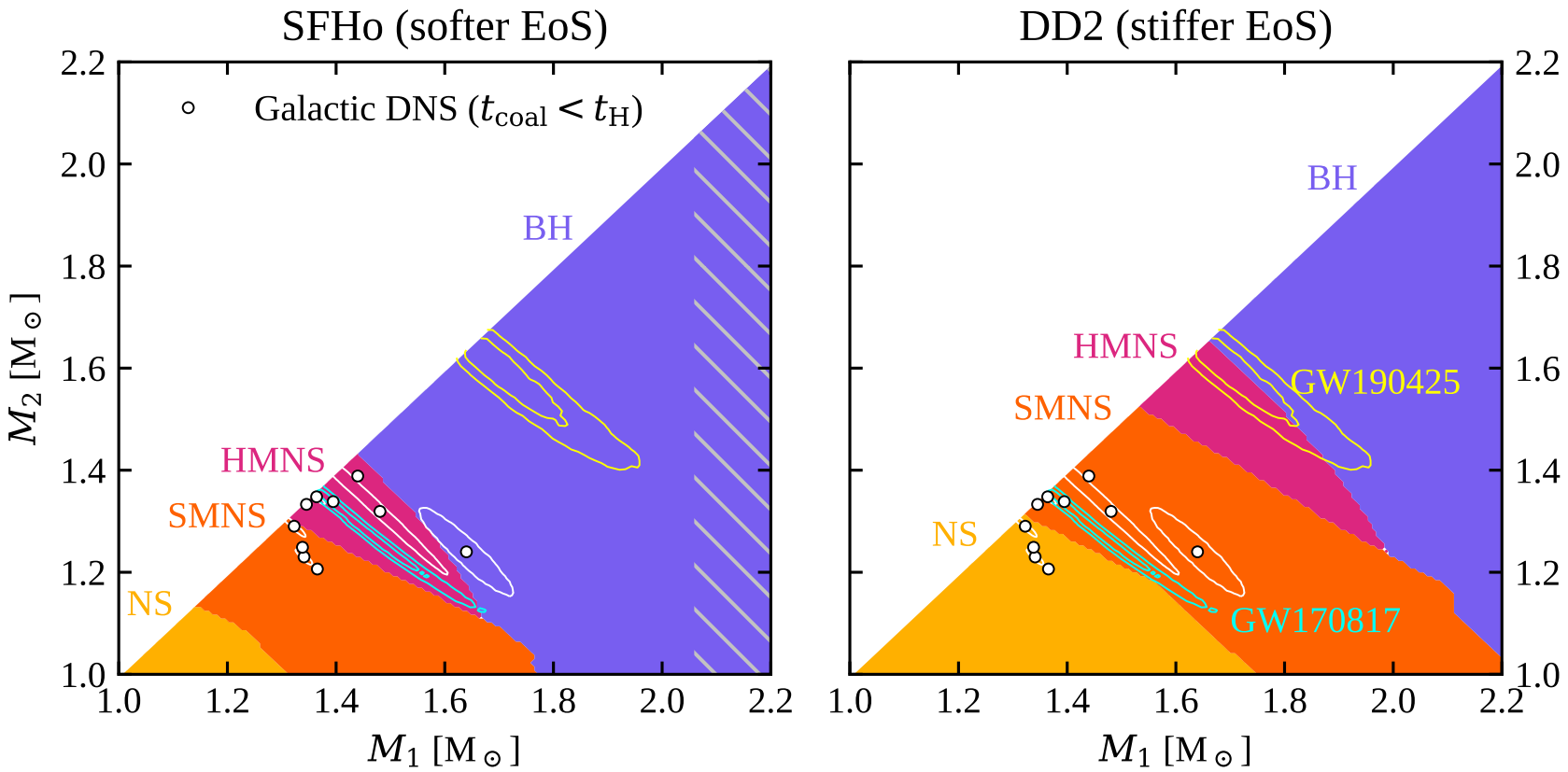

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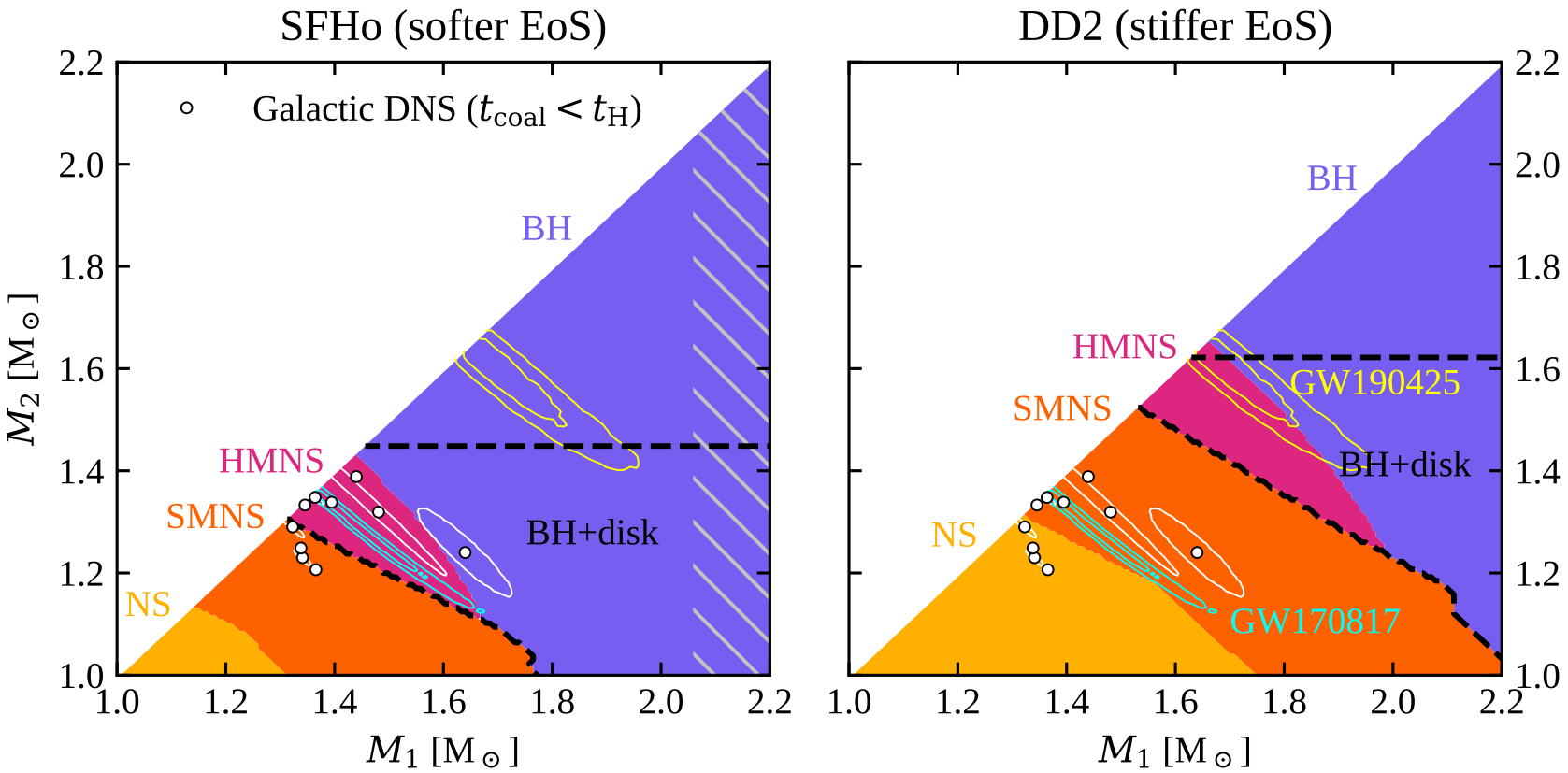

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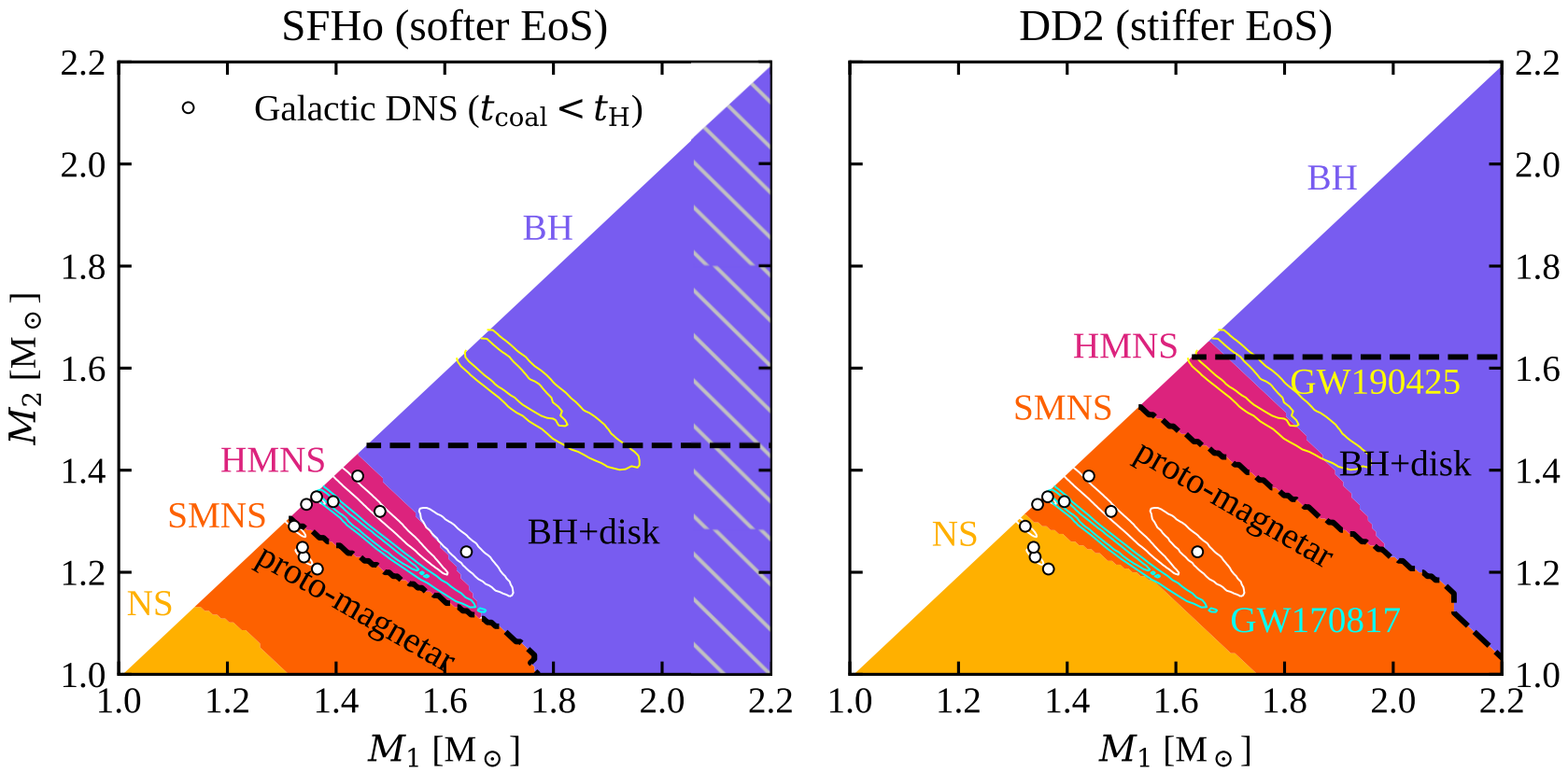

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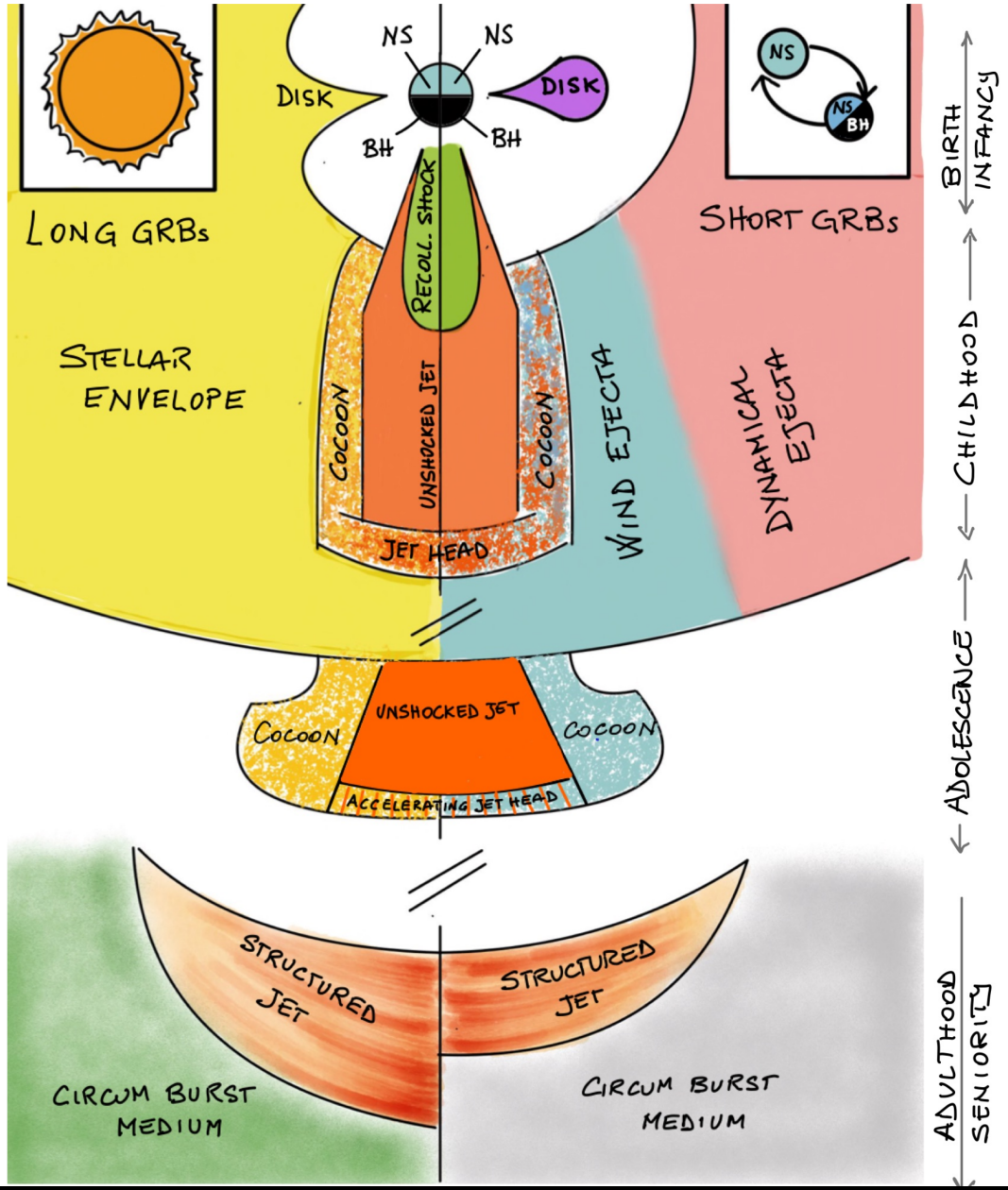
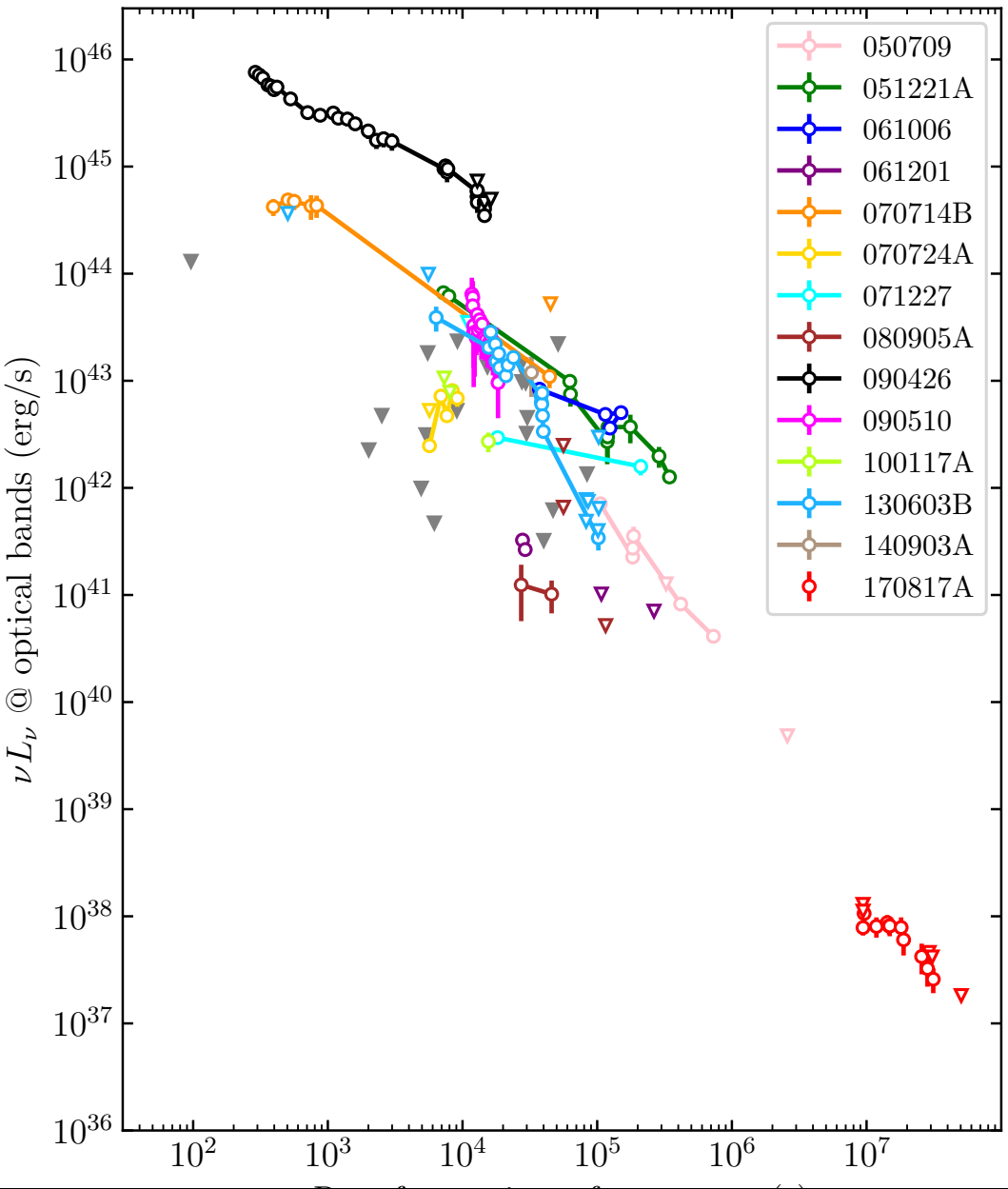
Jet structure



← Salafia & Ghirlanda 2022

[Jet propagation and breakout: see e.g. Matzner 03, Bromberg+11, Salafia+19, Lazzati & Perna 19, Hamidani+20,21, Gottlieb+18,20,21,22,23 ...]

A quasi-universal jet?



- If GRB170817A were on-axis, its afterglow would resemble that of a typical SGRB

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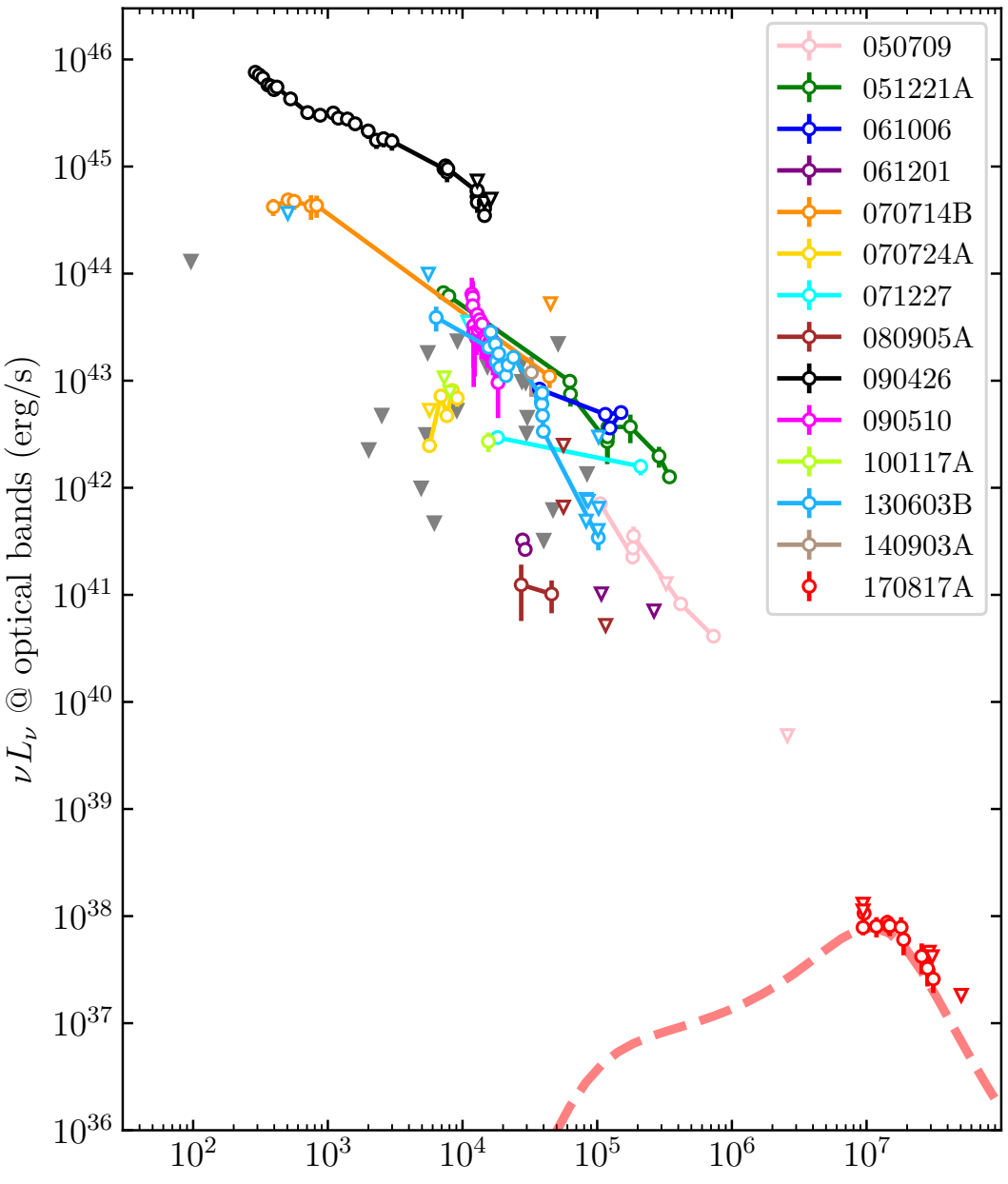

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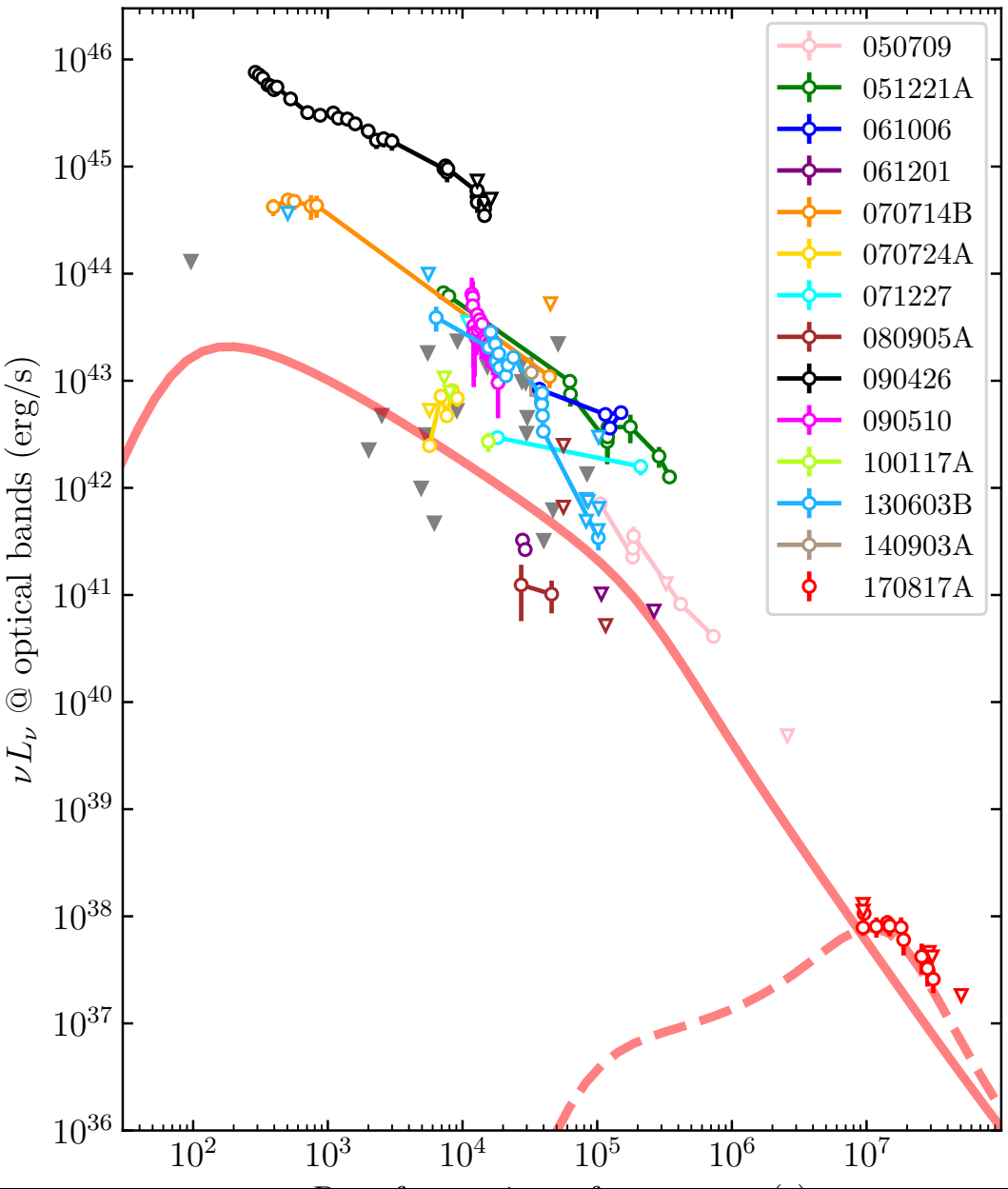

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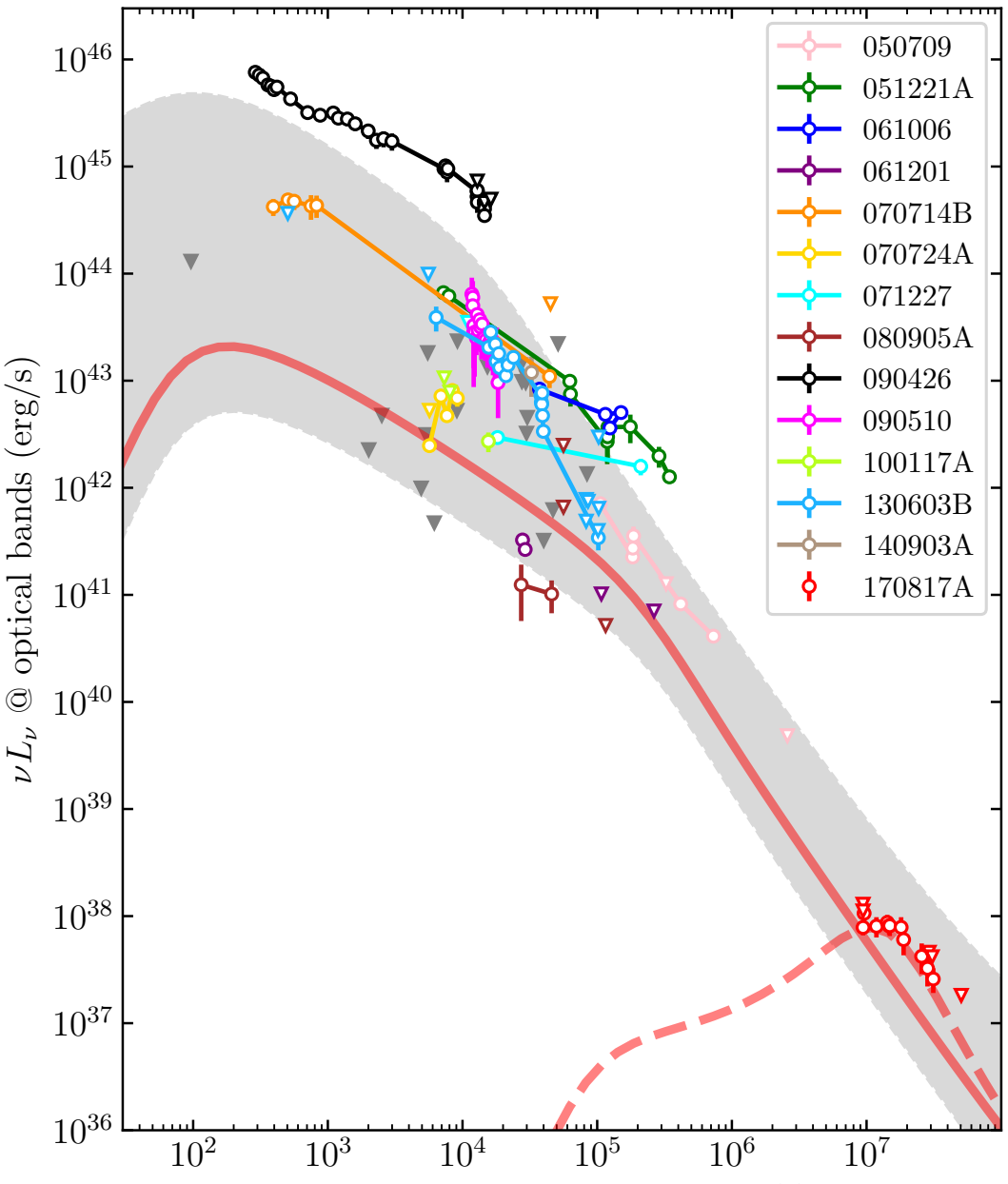

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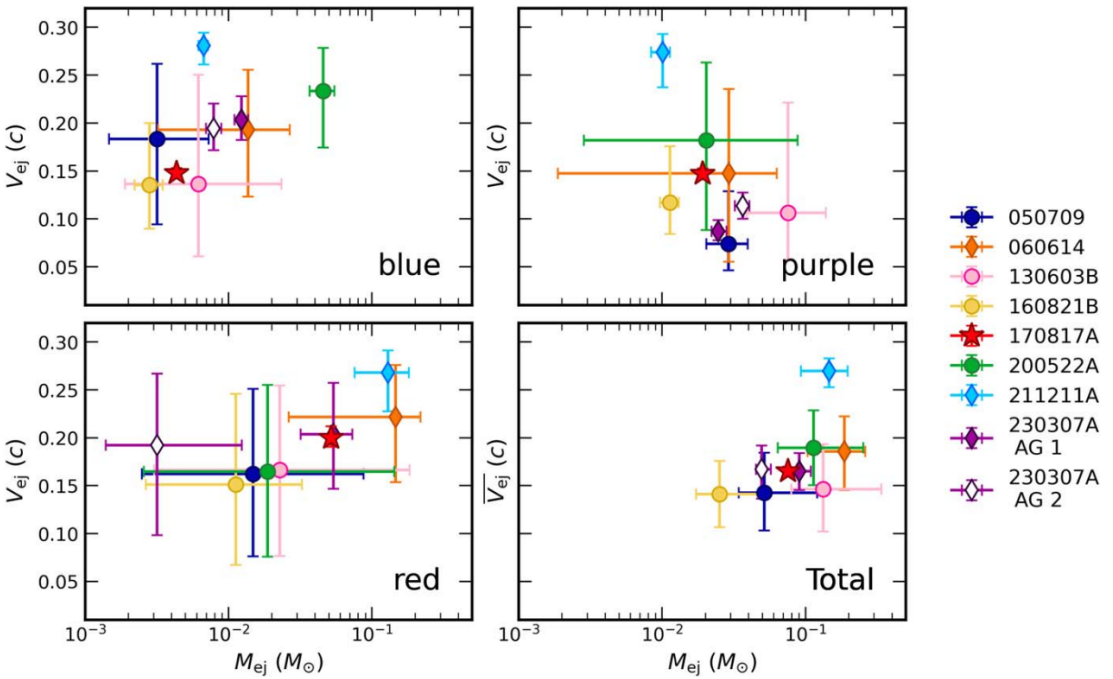

$$\Delta M_{\rm ej}/M_{\rm ej} \sim 10$$
$$\Delta E_{\gamma,\rm iso}/E_{\gamma,\rm iso} \sim 600$$

[Rastinejad+25, see Andrew Levan's talk]

- If GRB170817A were on-axis, its afterglow would resemble that of a typical SGRB
- Allowing for a factor of 3 spread in energy and ISM densities $n \in [10^{-4}, 1]$ explains most of the diversity
- Kilonovae much less diverse than associated SGRBs $\rightarrow$ extrinsic source of diversity such as viewing angle?

Population study

"The short gamma-ray burst population in a quasi-universal jet scenario"
Salafia et al. 2023, A&A, 680, A45

- Focus on *Fermi*/GBM SGRBs
  ($T_{90} < 2\,\mathrm{s}$)

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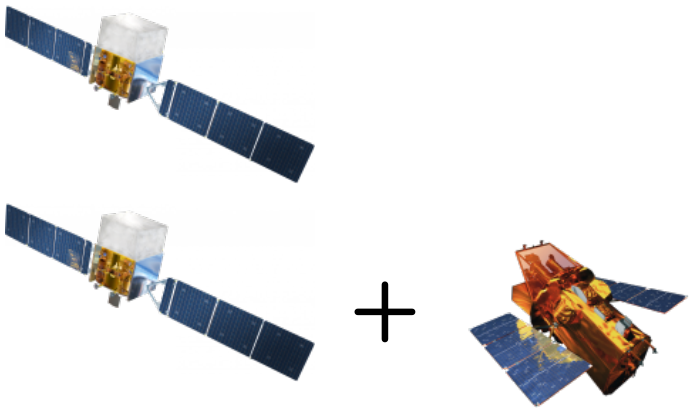

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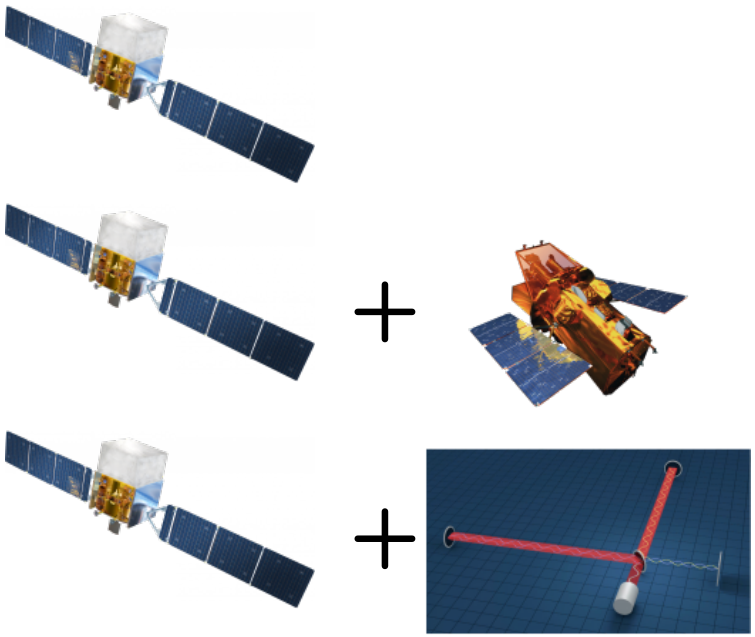

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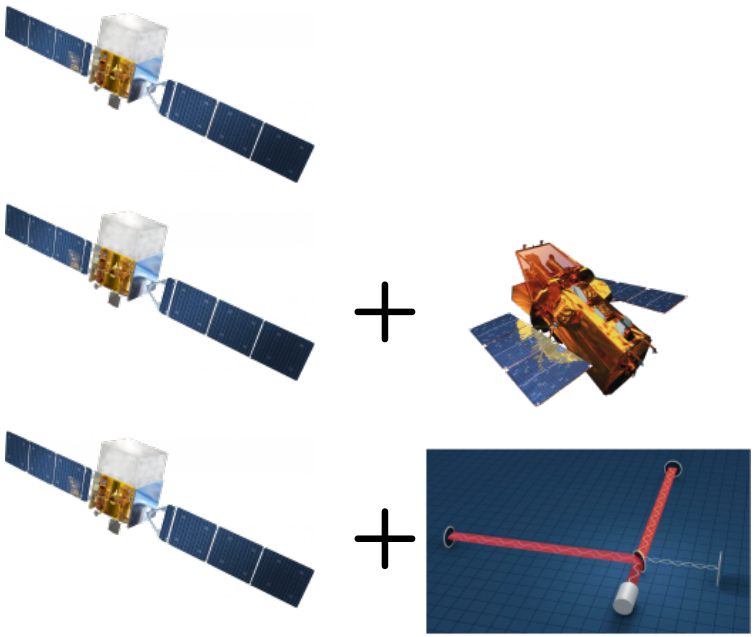
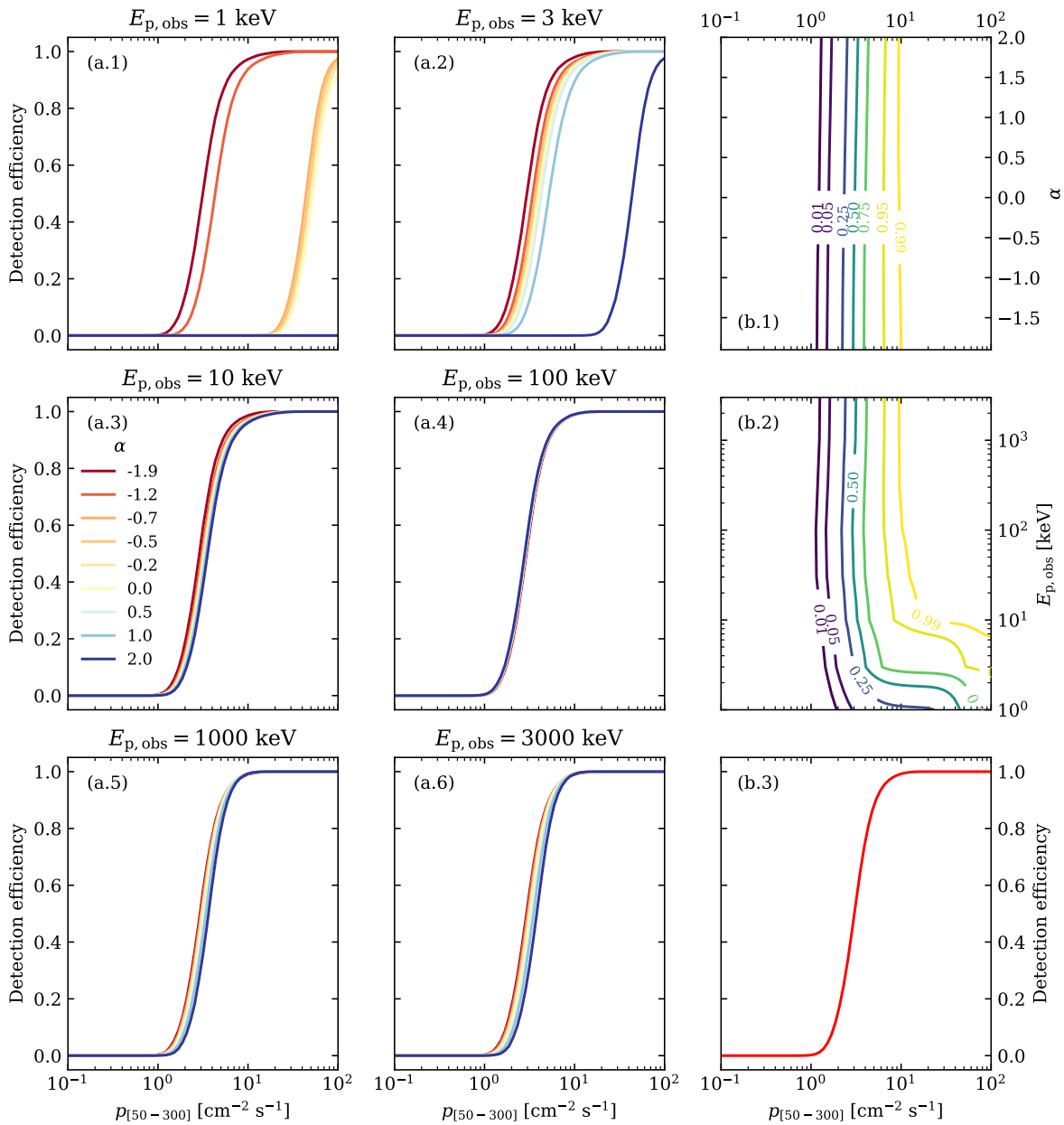
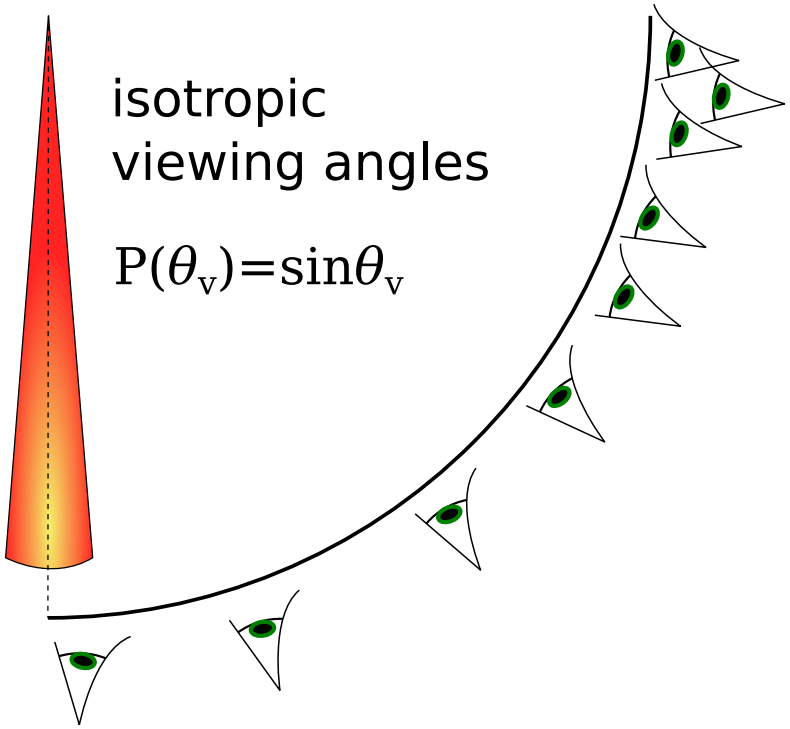


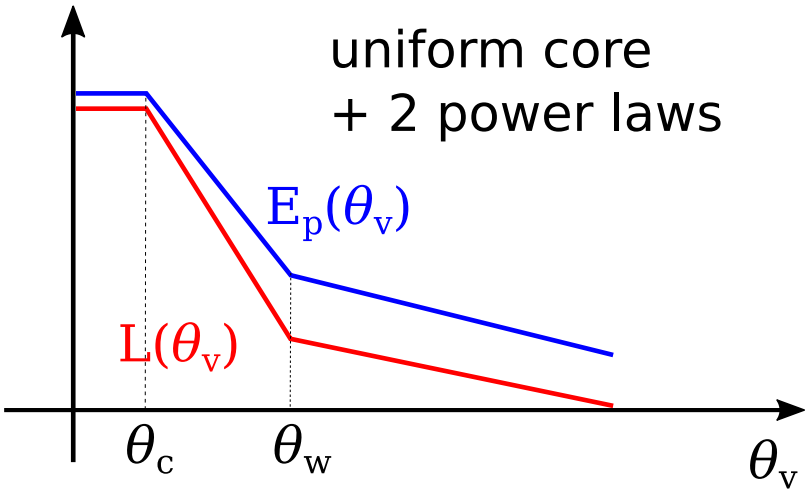
¡ Careful modelling of selection effects !
(we did our best, but still space for improvement!)

GBM SGRB detection efficiency

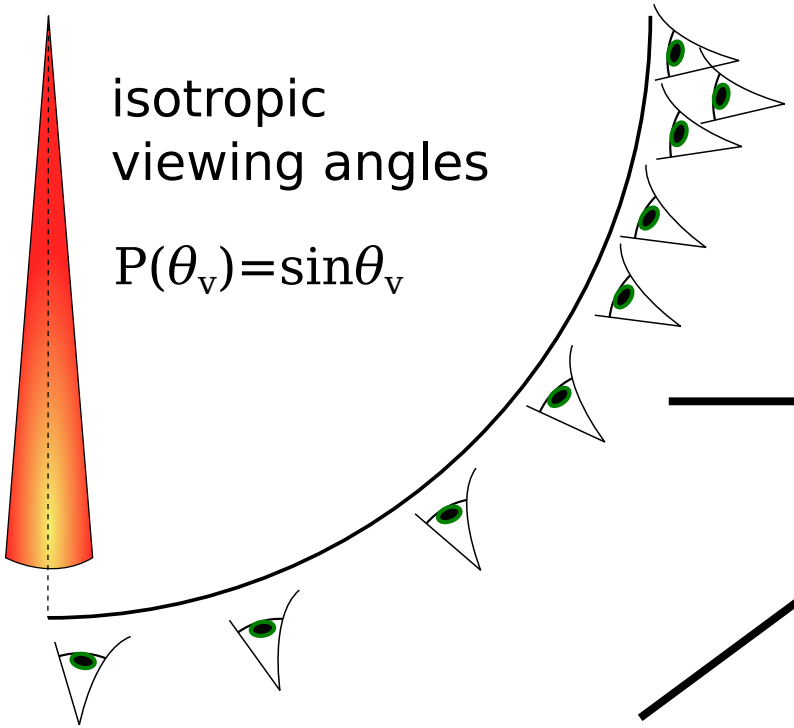


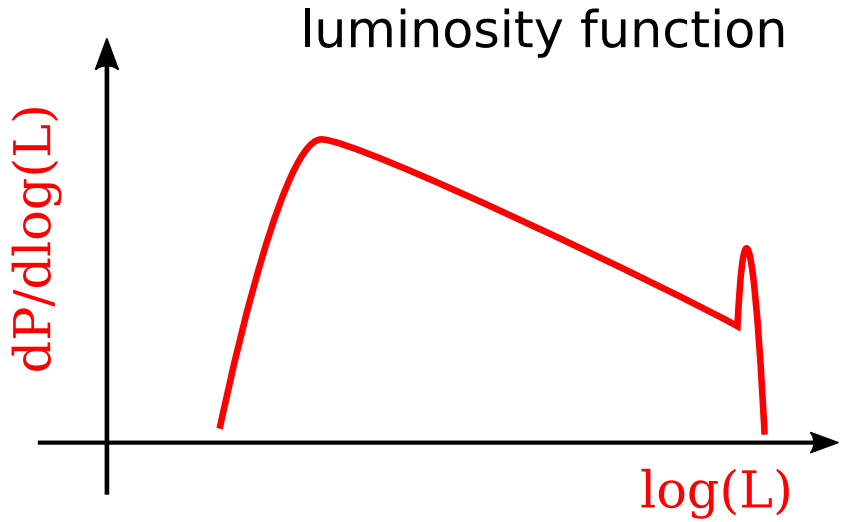
The population model: quasi-universal jet

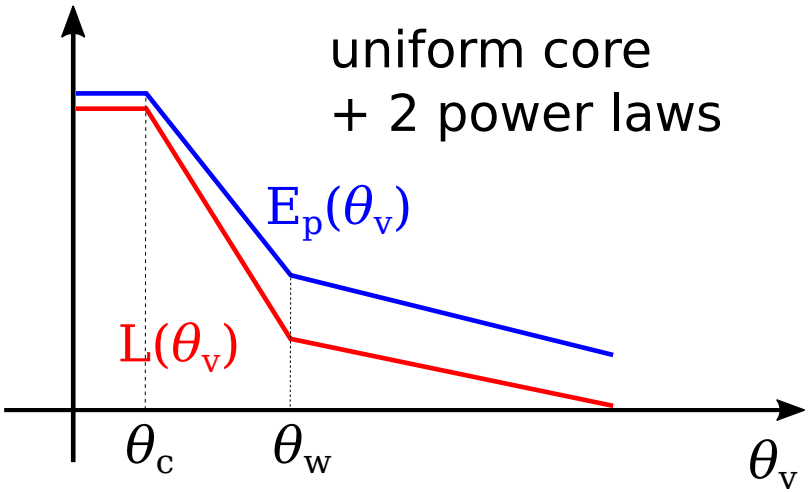




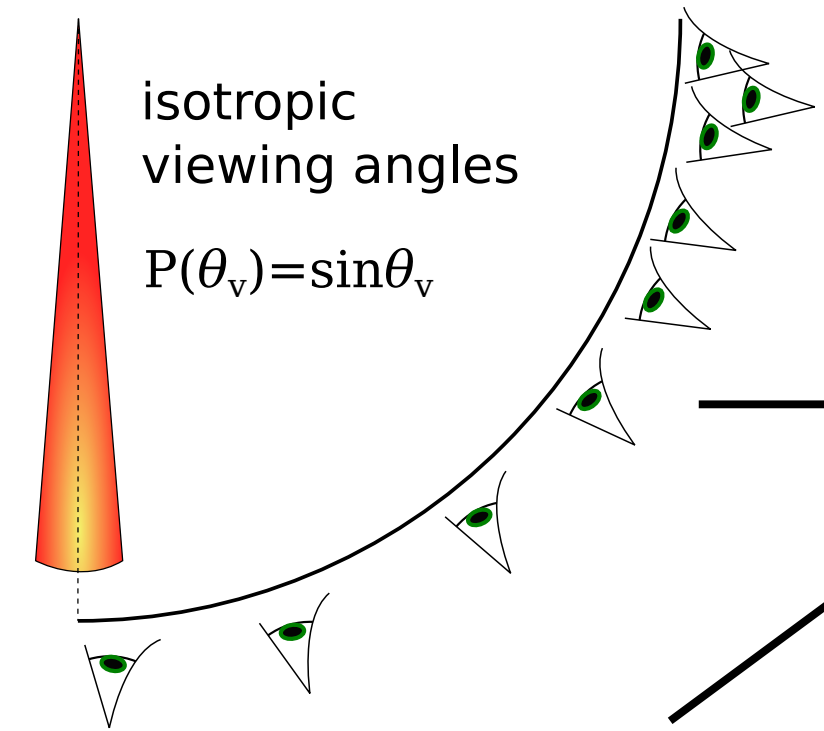
The population model: quasi-universal jet

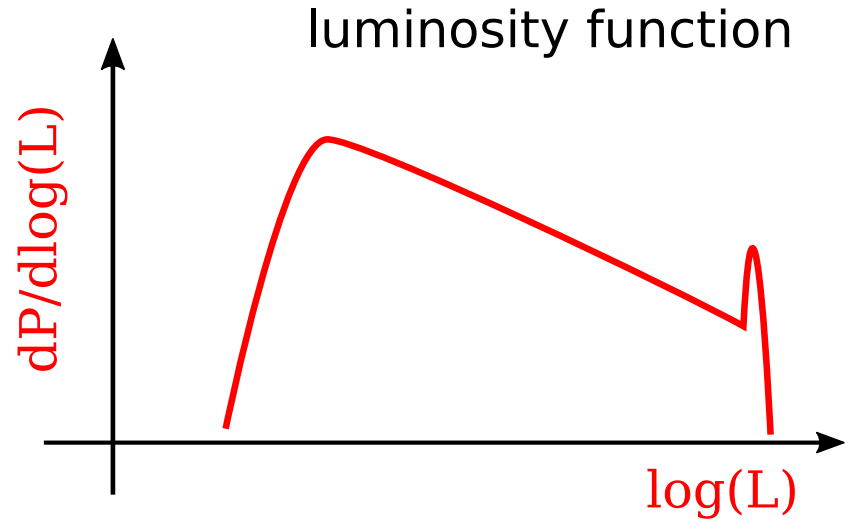


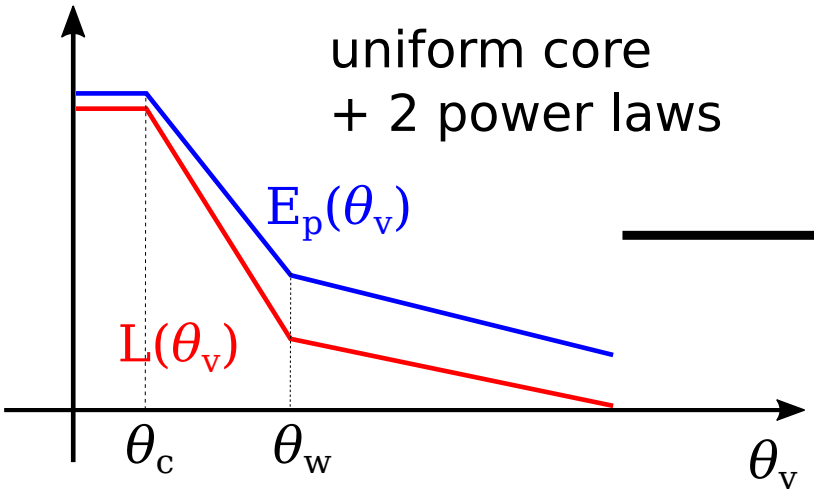


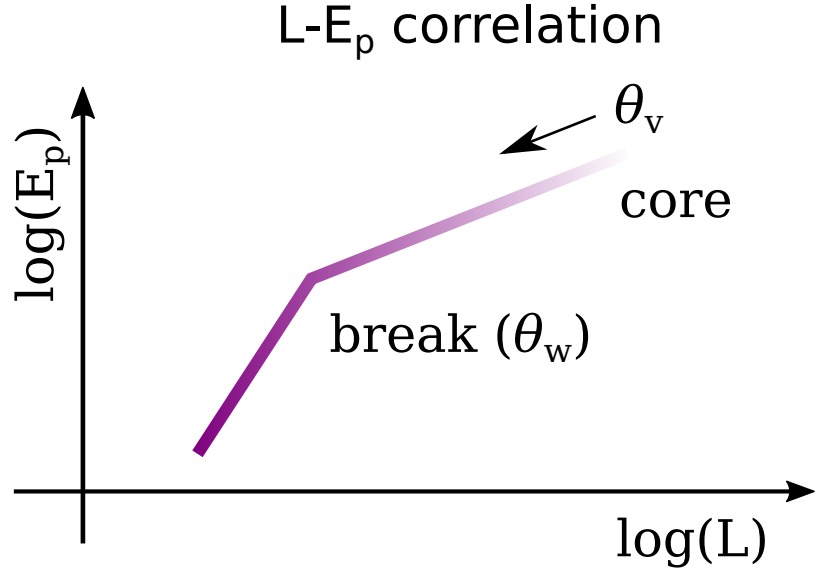


The population model: quasi-universal jet

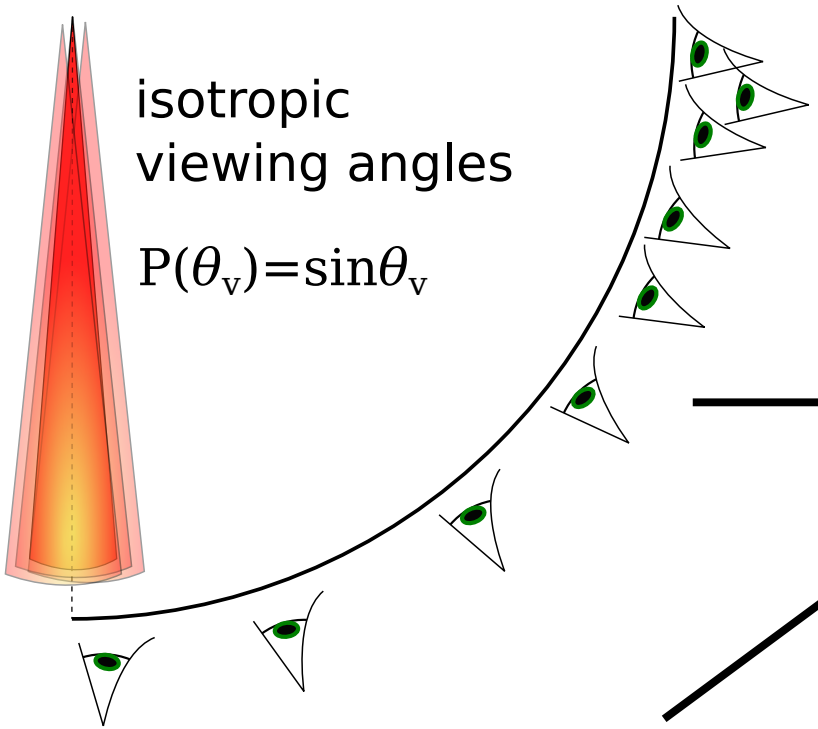


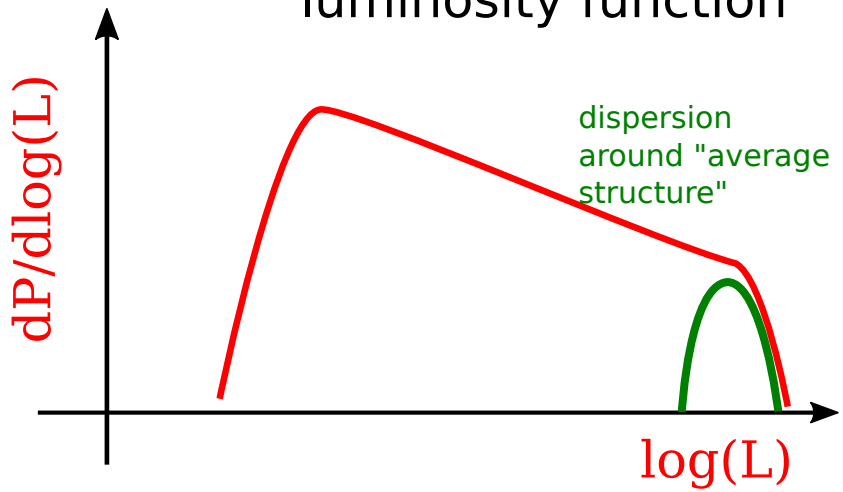


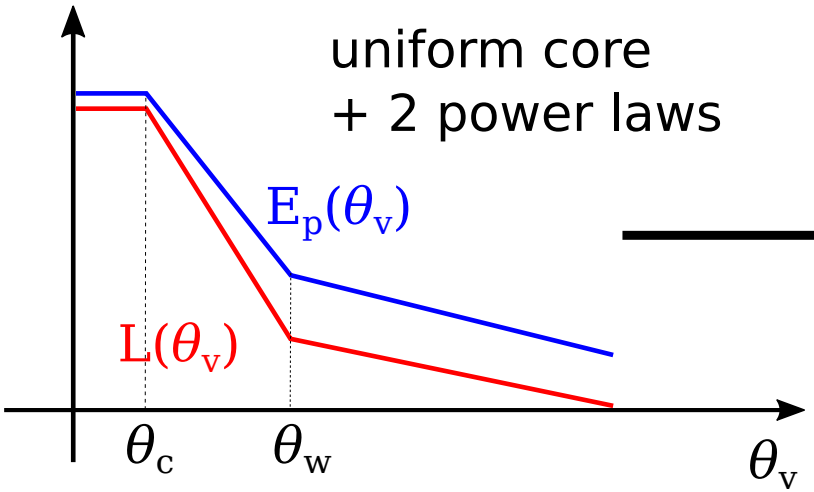


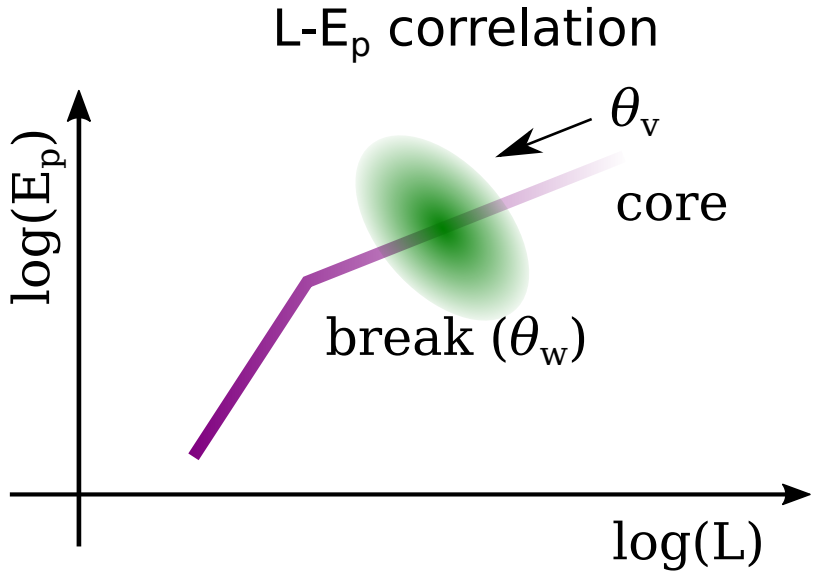


The population model: quasi-universal jet

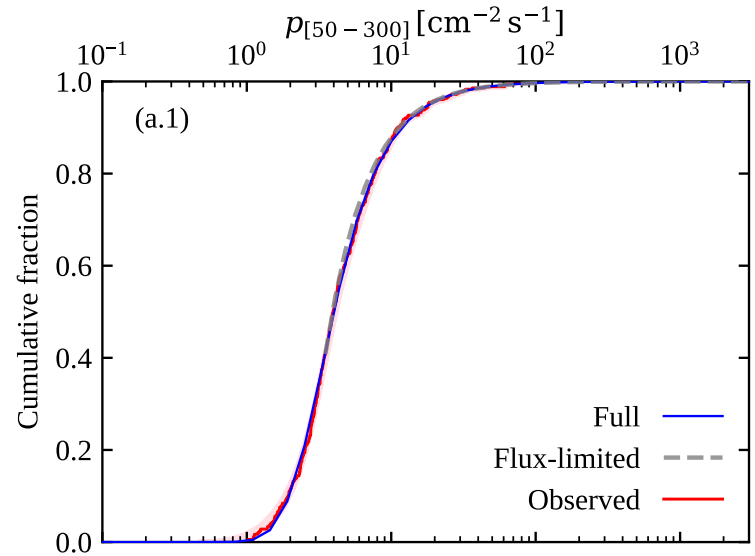


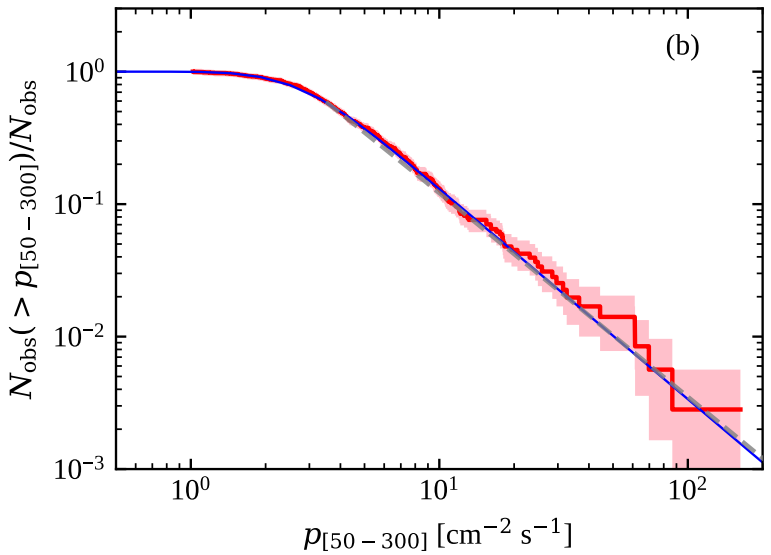


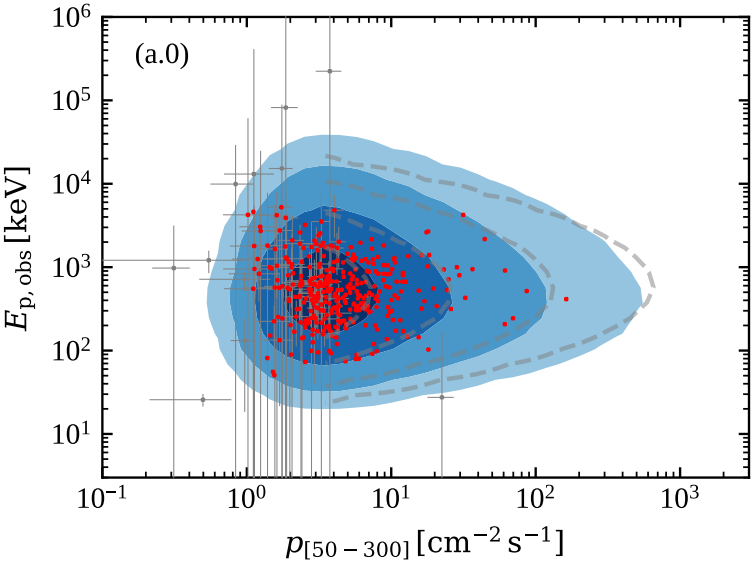


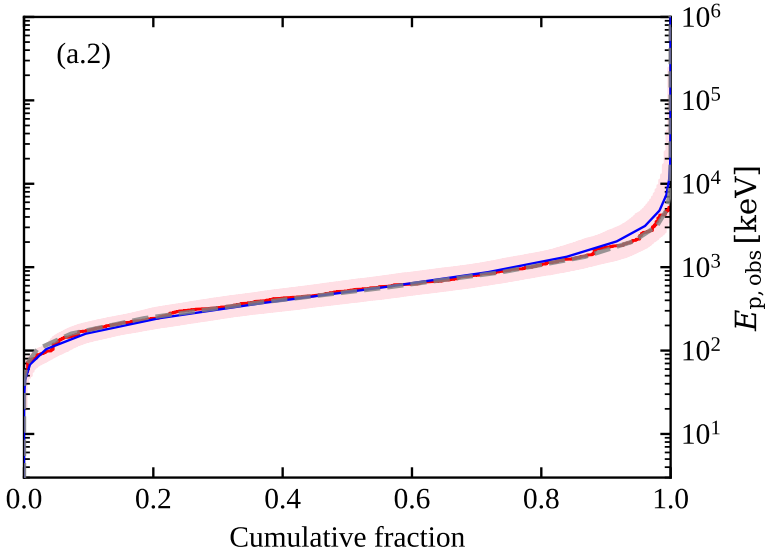


Model compared to GBM sample

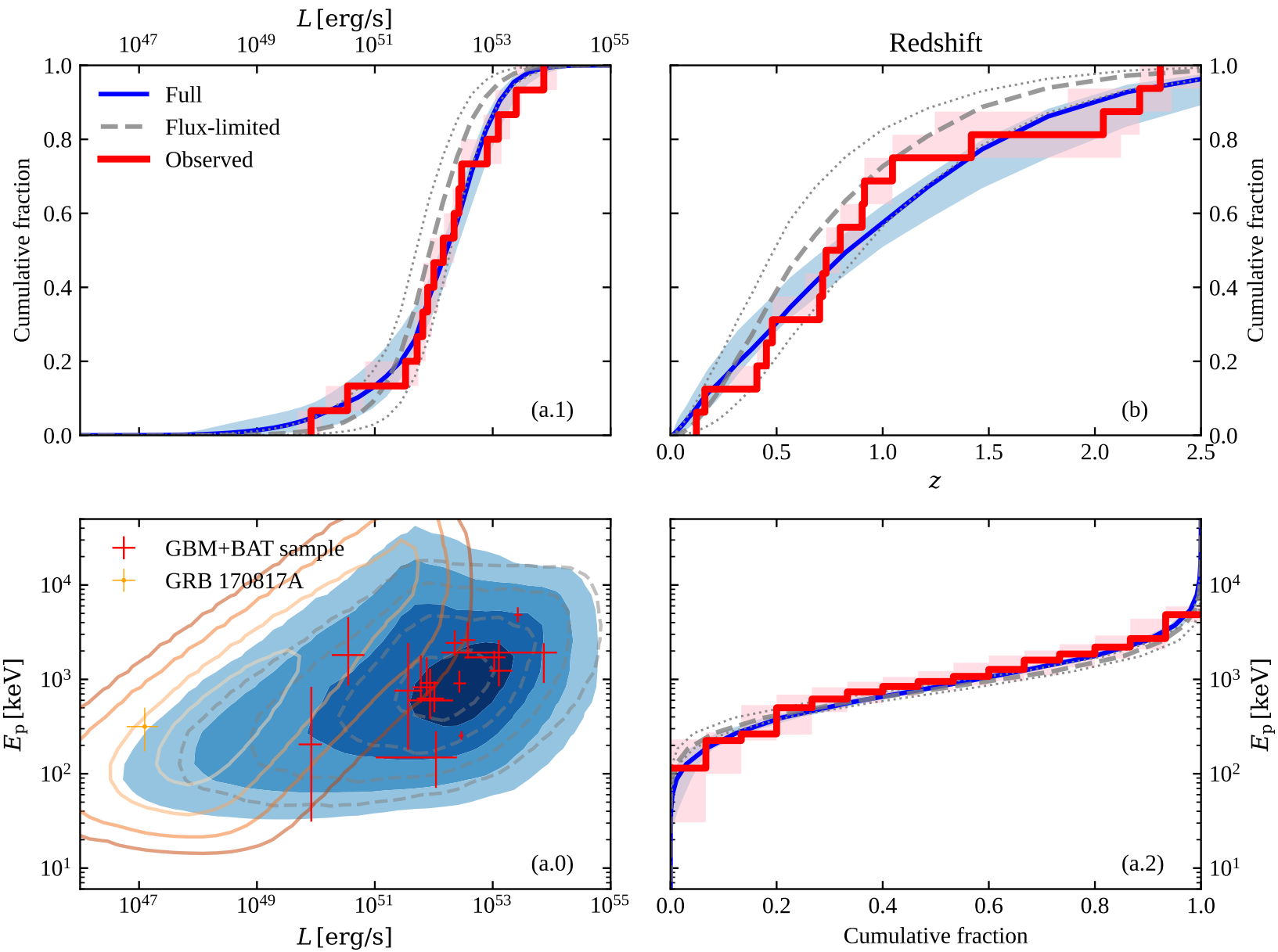




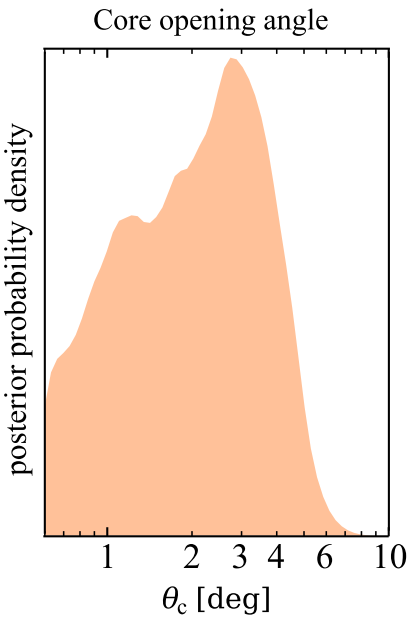


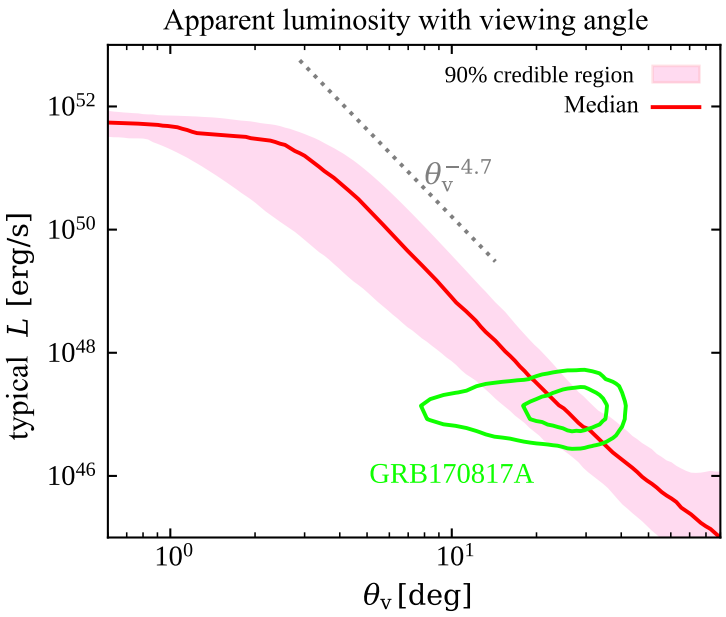


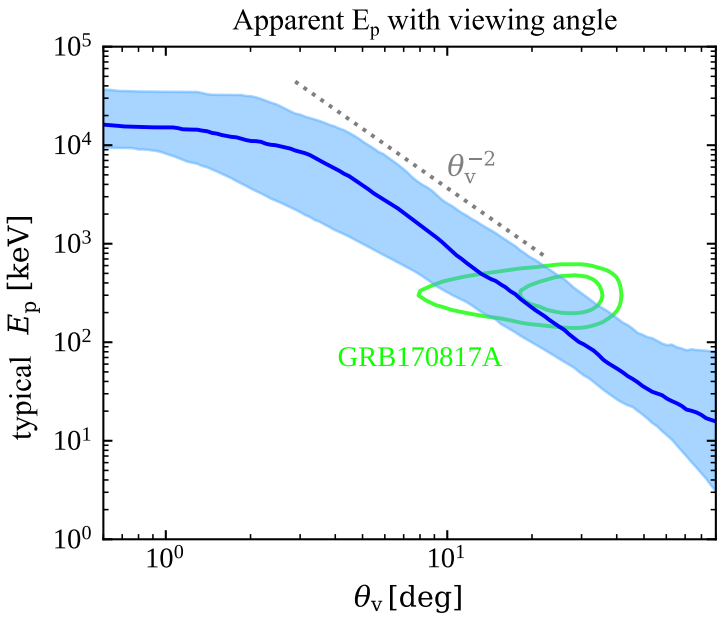
Model compared to GBM+BAT sample



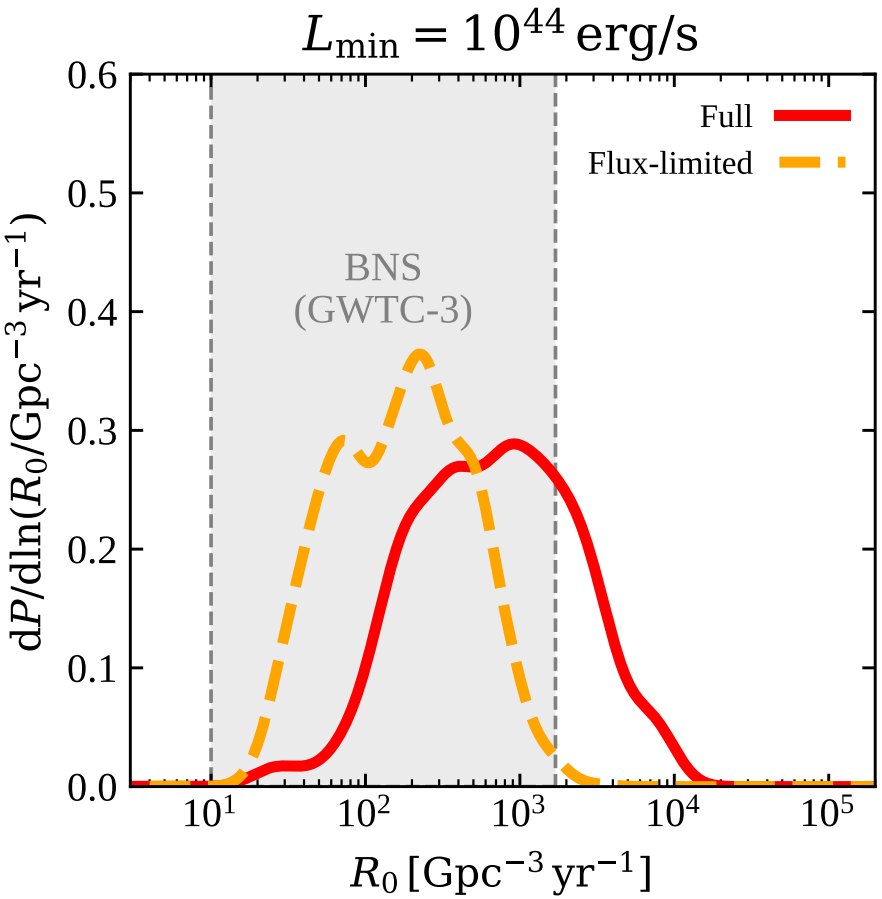
‘Apparent’ structure

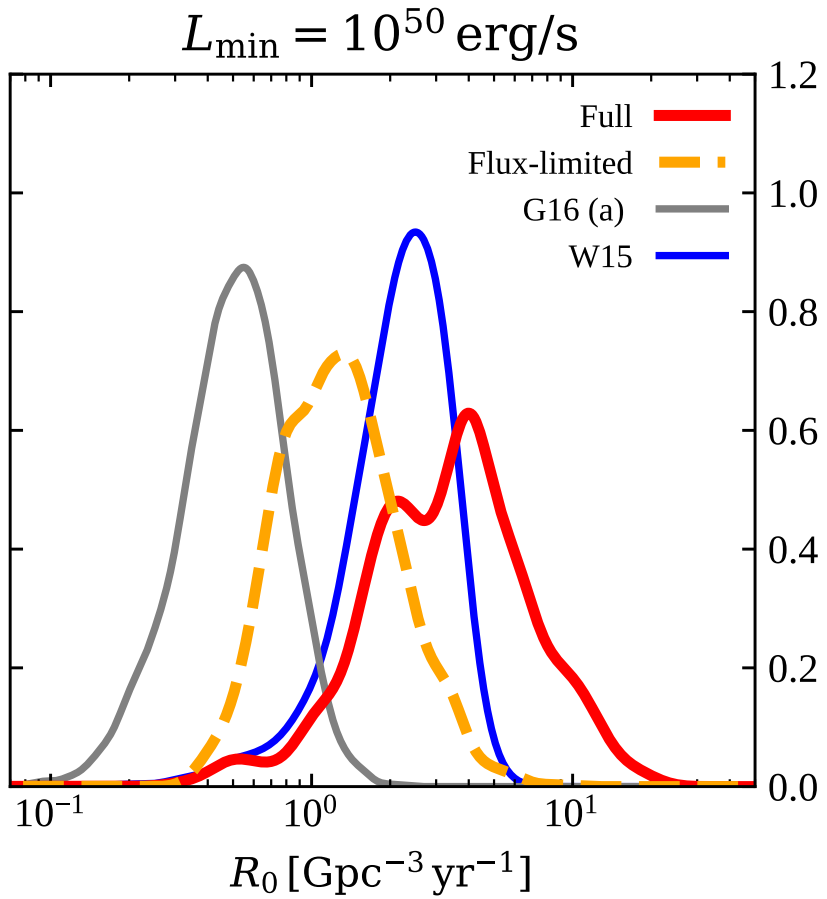




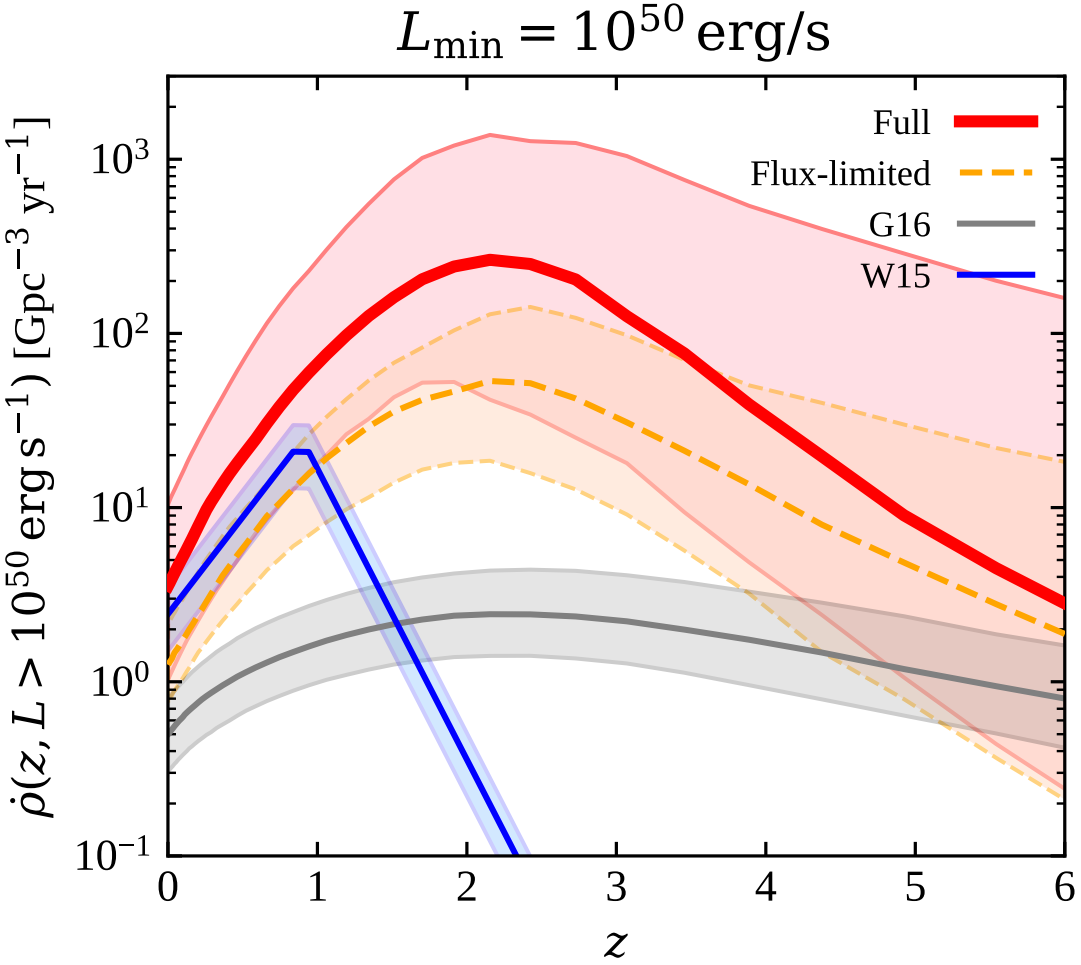


Rate density

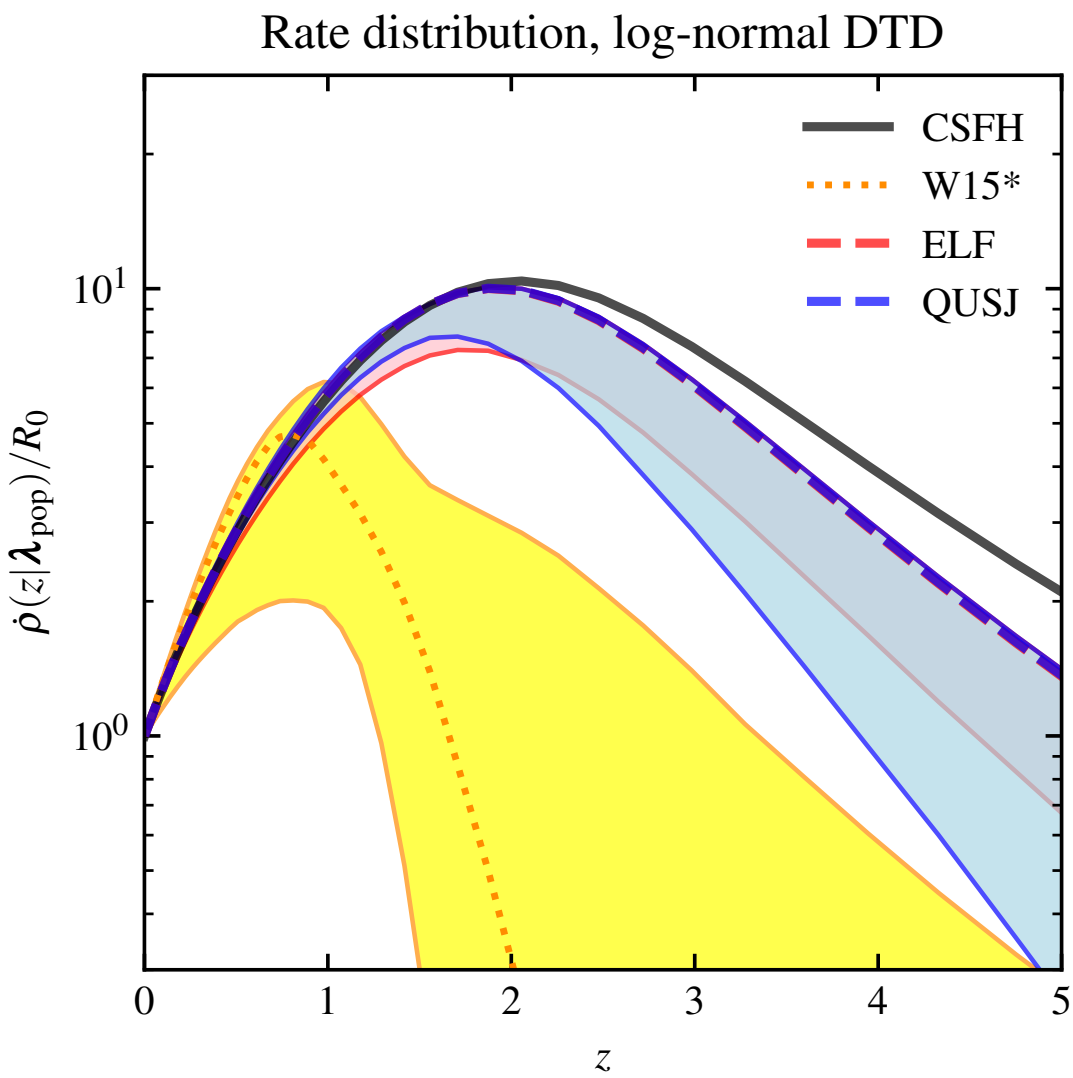




Rate density evolution

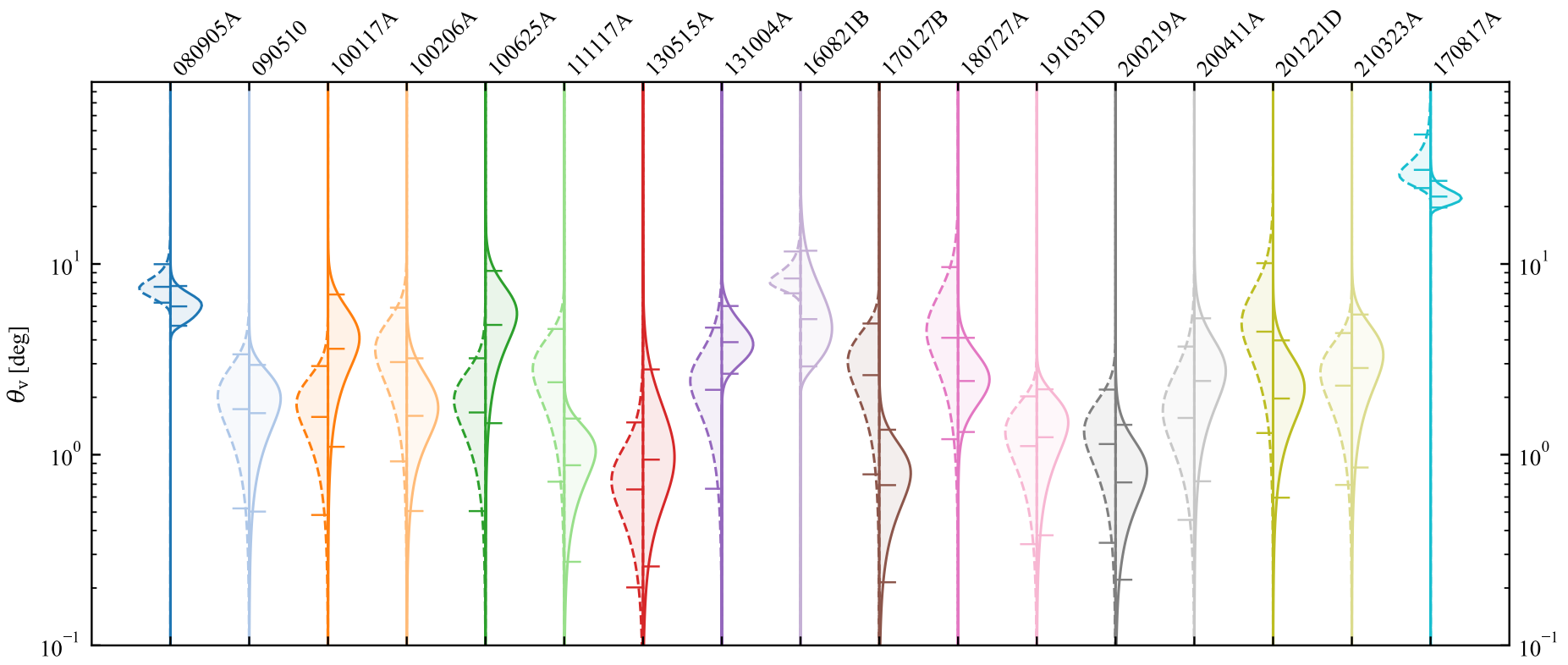


Delay time distribution

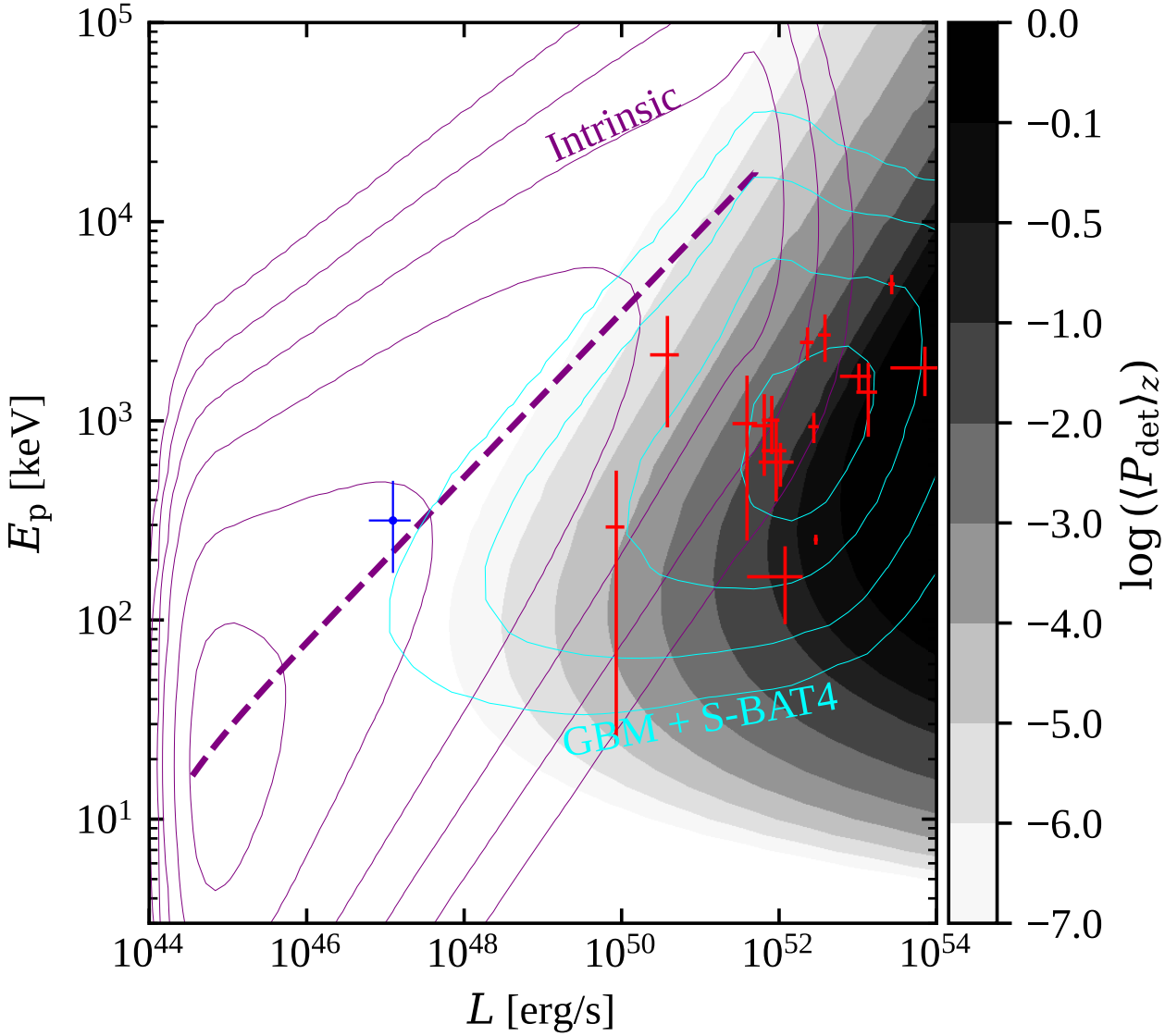


[Pracchia & Salafia 2026, arXiv:2601.03861]

Viewing angles of SGRBs with measured z



Selection effects shape apparent Yonetoku correlation



Selection effects modelling in transient population inference

Selection effects

Transient population

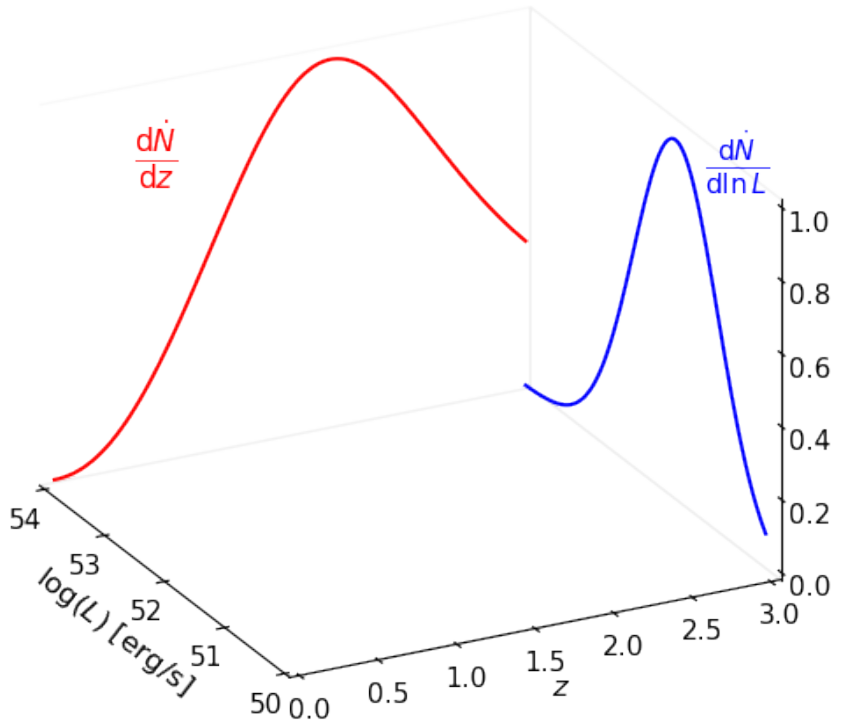
- Event rate per unit redshift:

$$\frac{\mathrm{d}\dot{N}}{\mathrm{d}z} = \frac{\dot{\rho}(z)}{1+z}\frac{\partial V_\mathrm{c}}{\partial z}$$

- Luminosity function:

$$\frac{\mathrm{d}p}{\mathrm{d}\ln L} = L\frac{\mathrm{d}p}{\mathrm{d}L} = \frac{1}{\dot{N}}\frac{\mathrm{d}\dot{N}}{\mathrm{d}\ln L}$$

(simple z-independent case)

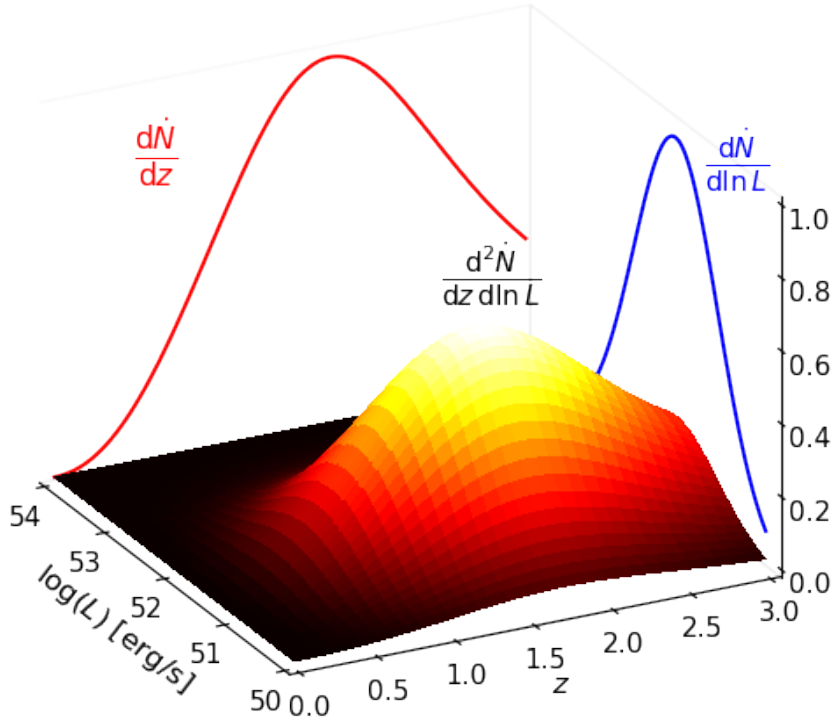


Selection effects

Transient population

- density in $(z, \ln L)$ space:

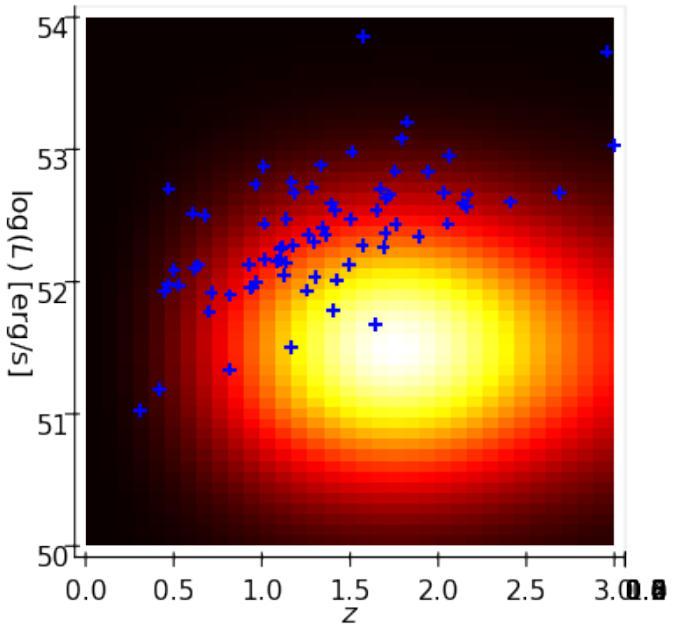
$$\frac{\mathrm{d}^2 \dot{N}}{\mathrm{d}z \, \mathrm{d} \ln L}$$



Selection effects

Observed population,
(e.g. by our favourite satellite)

Most transients in the Universe are missed (typical situation).

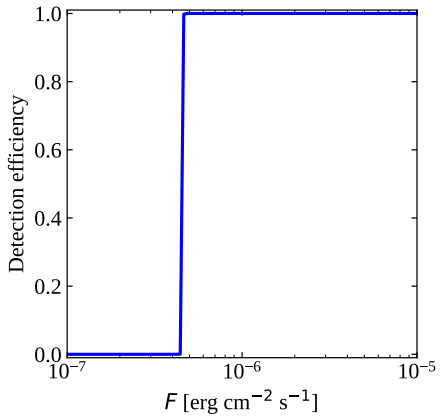


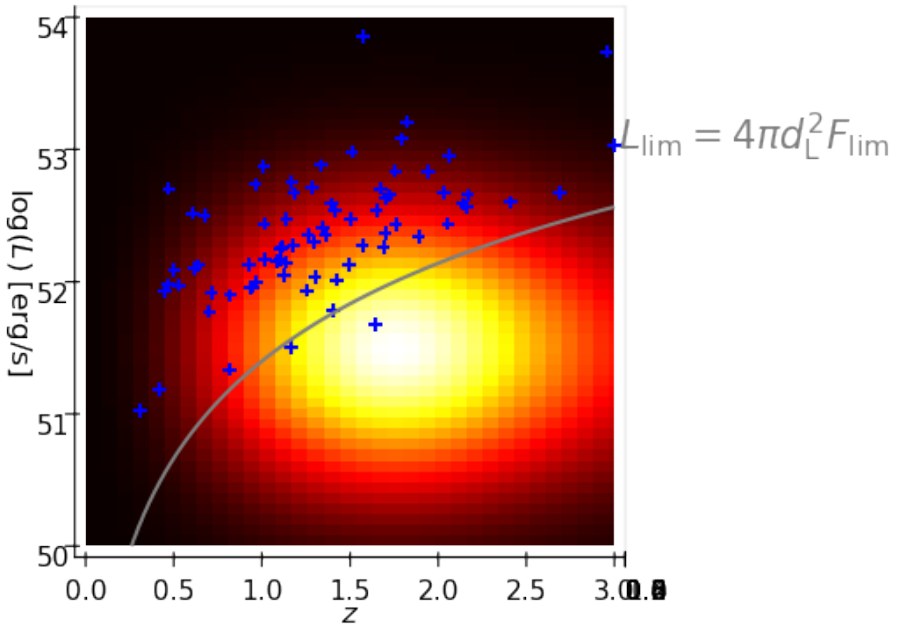
Selection effects

Naive selection effect modelling:
limiting flux $\rightarrow$ limiting luminosity

$$L_{\rm lim}(z) = 4\pi d_{\rm L}^2 F_{\rm lim}$$

Detection efficiency: step function.





Selection effects

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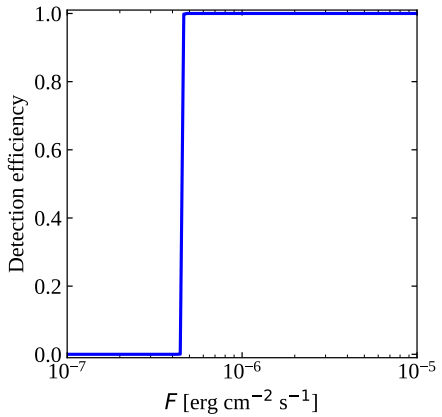
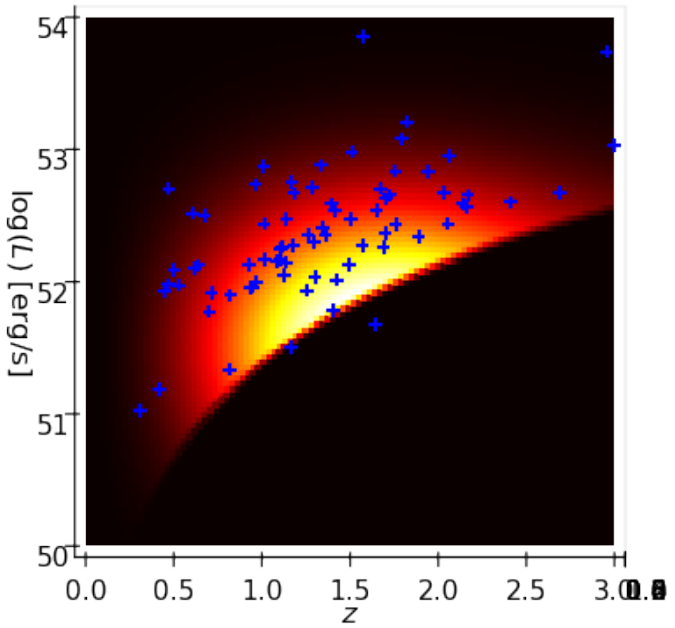
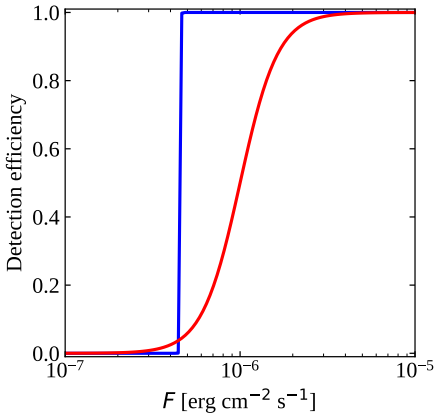


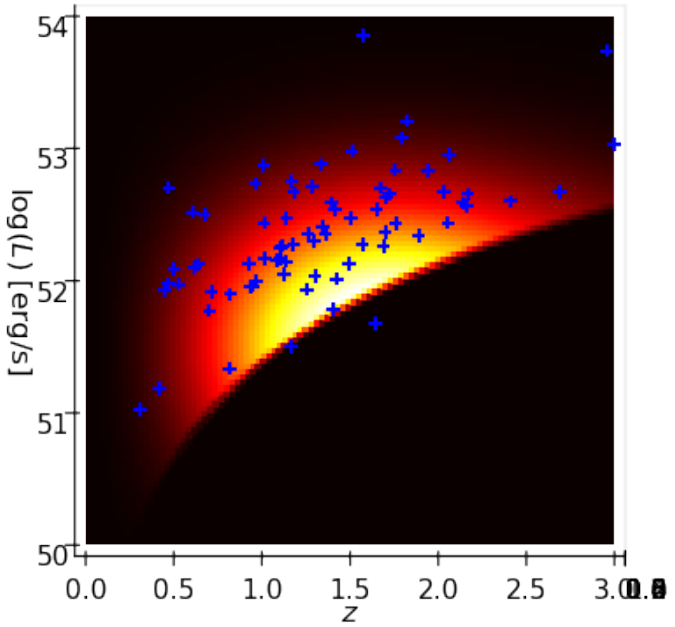
Peak density at threshold.



Selection effects

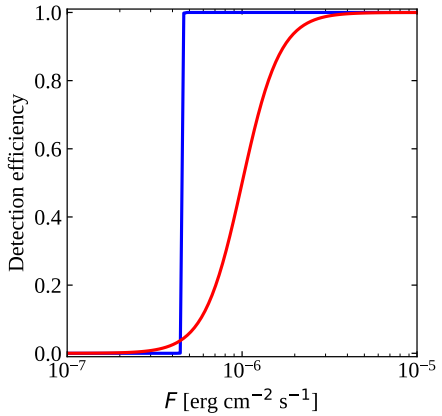
Actual detection efficiency typically rises to 100% over $\sim 1\,\mathrm{dex}$ in F.



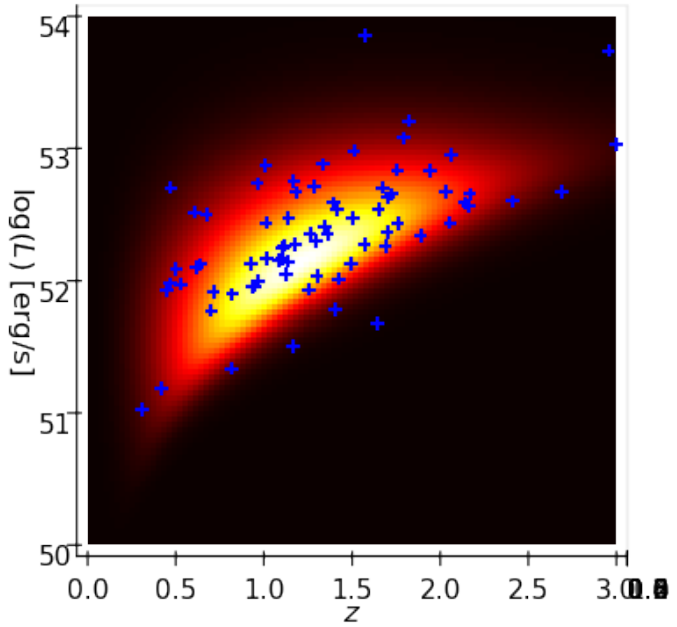


Selection effects

Actual detection efficiency typically rises to 100% over $\sim 1\,\mathrm{dex}$ in F.

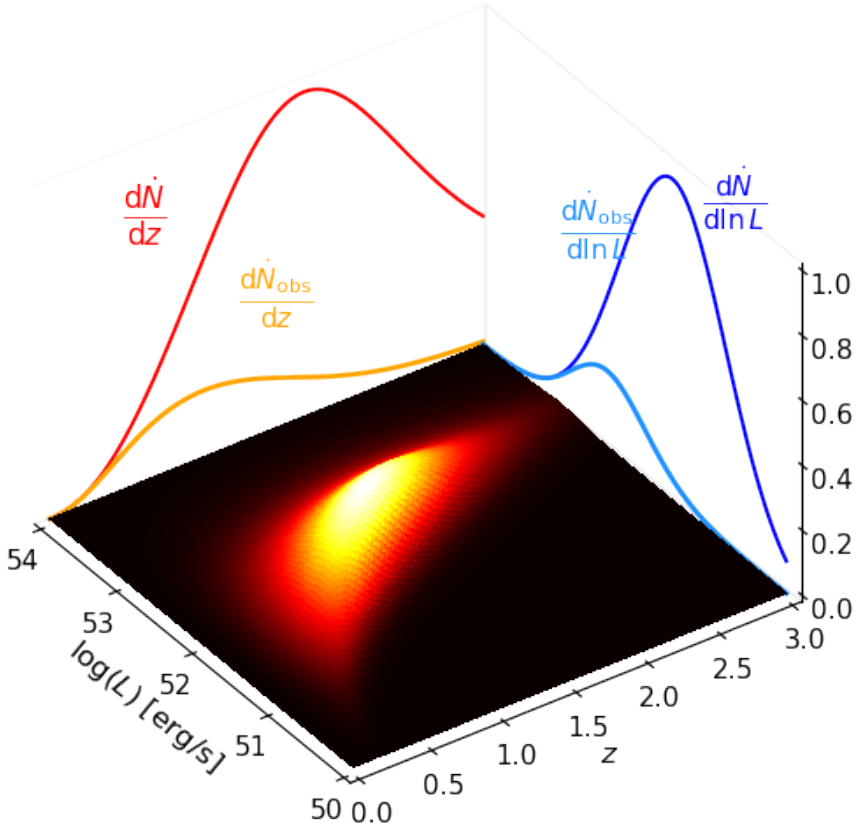


Peak density significantly above threshold.



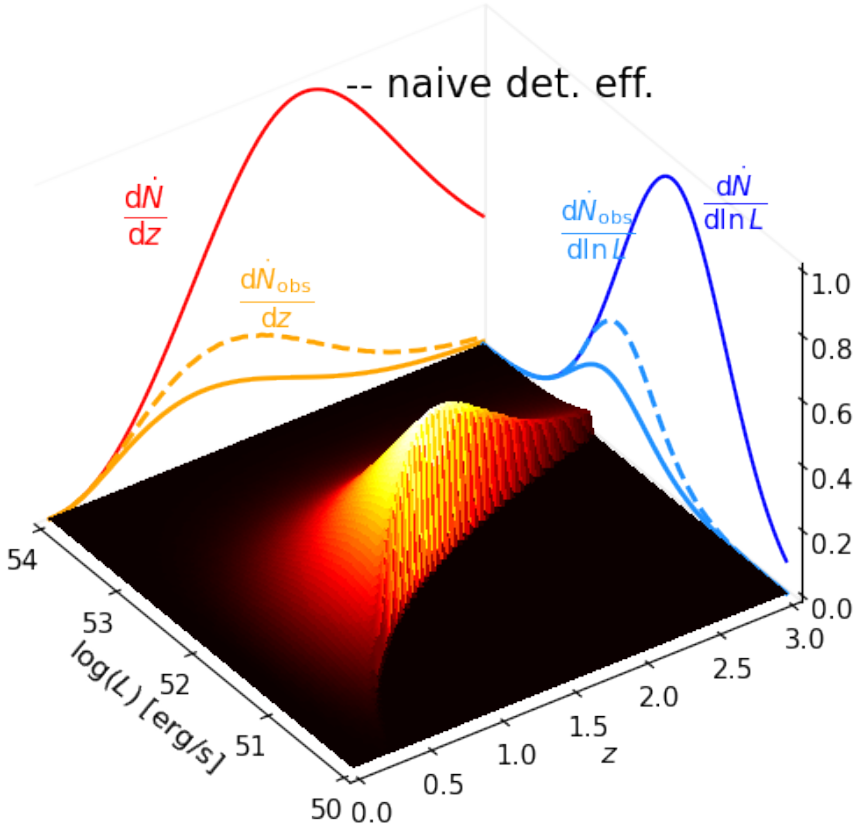
Selection effects

Observed distributions



Selection effects

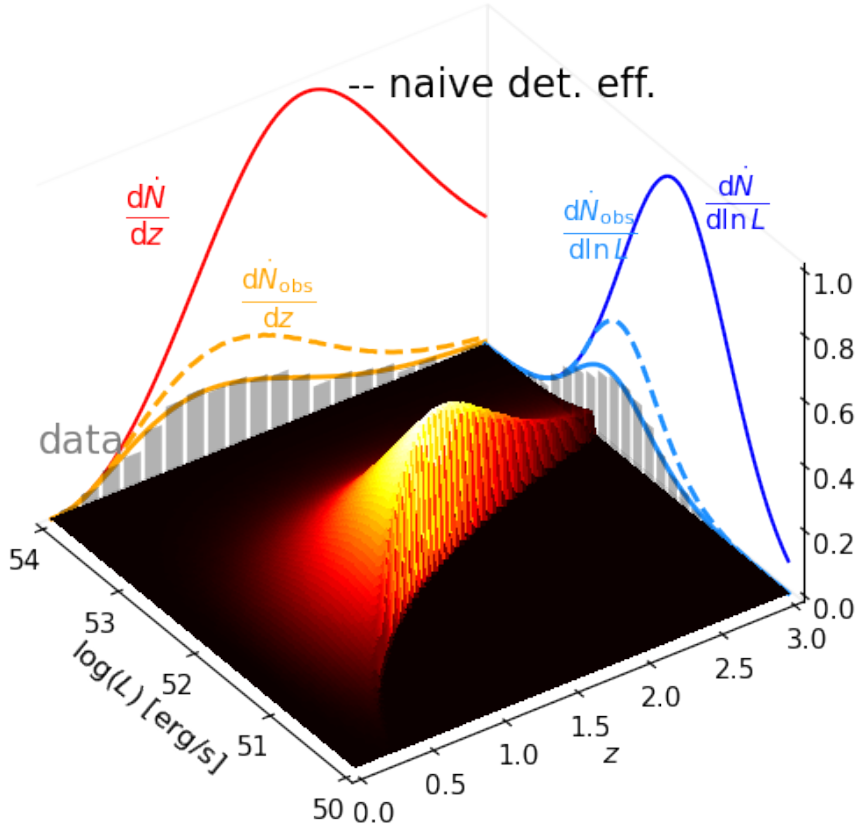
Observed distributions



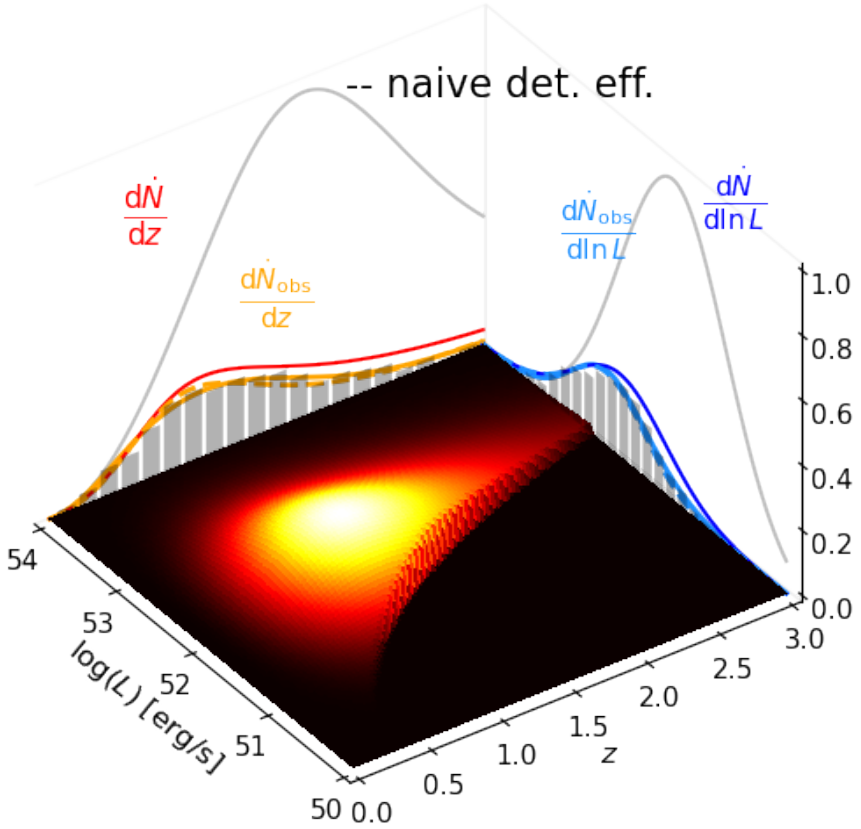
Selection effects

Gedankenexperiment:

- Naive $F_{\rm lim}$ model
- Data (grey histograms): true population + actual selection effects
- Can we still fit the data assuming the naive model?



Selection effects



Selection effects

Yes, but with large biases!