UNVEILING THE ORIGIN OF STEEP DECAY IN γ-RAY BURSTS

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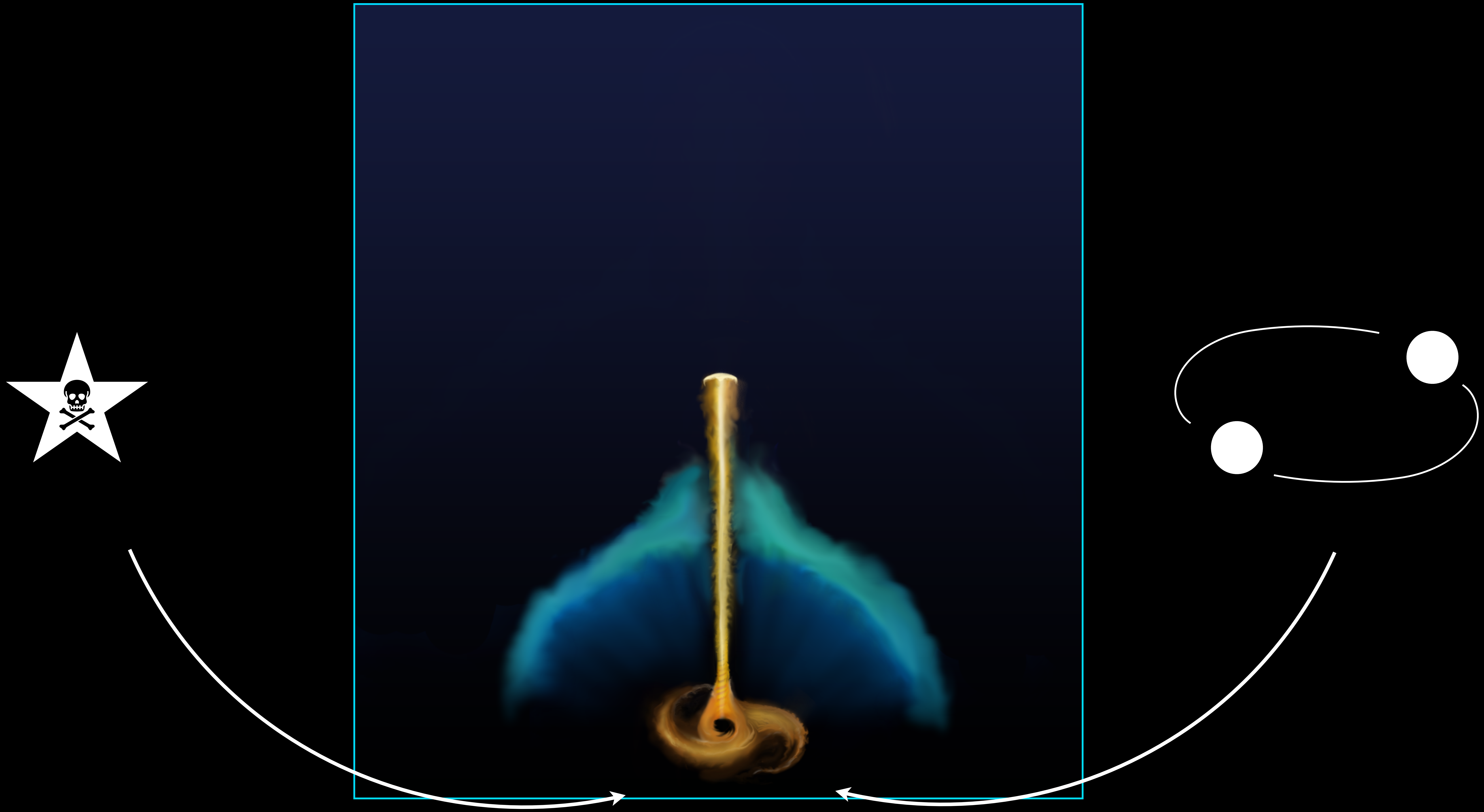
Scientific background

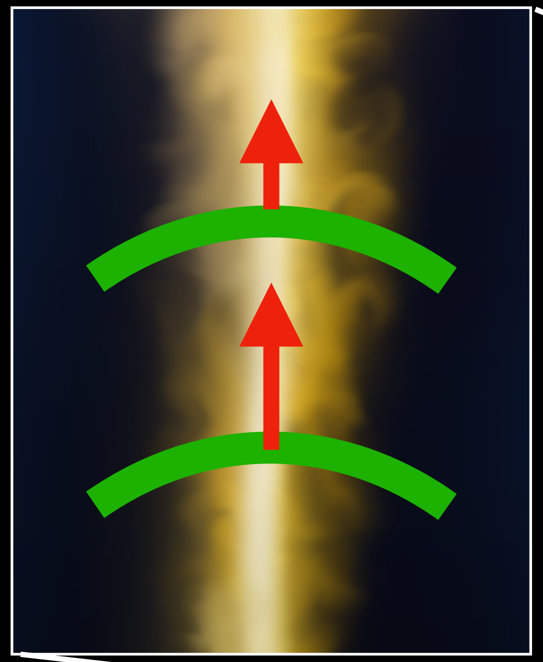


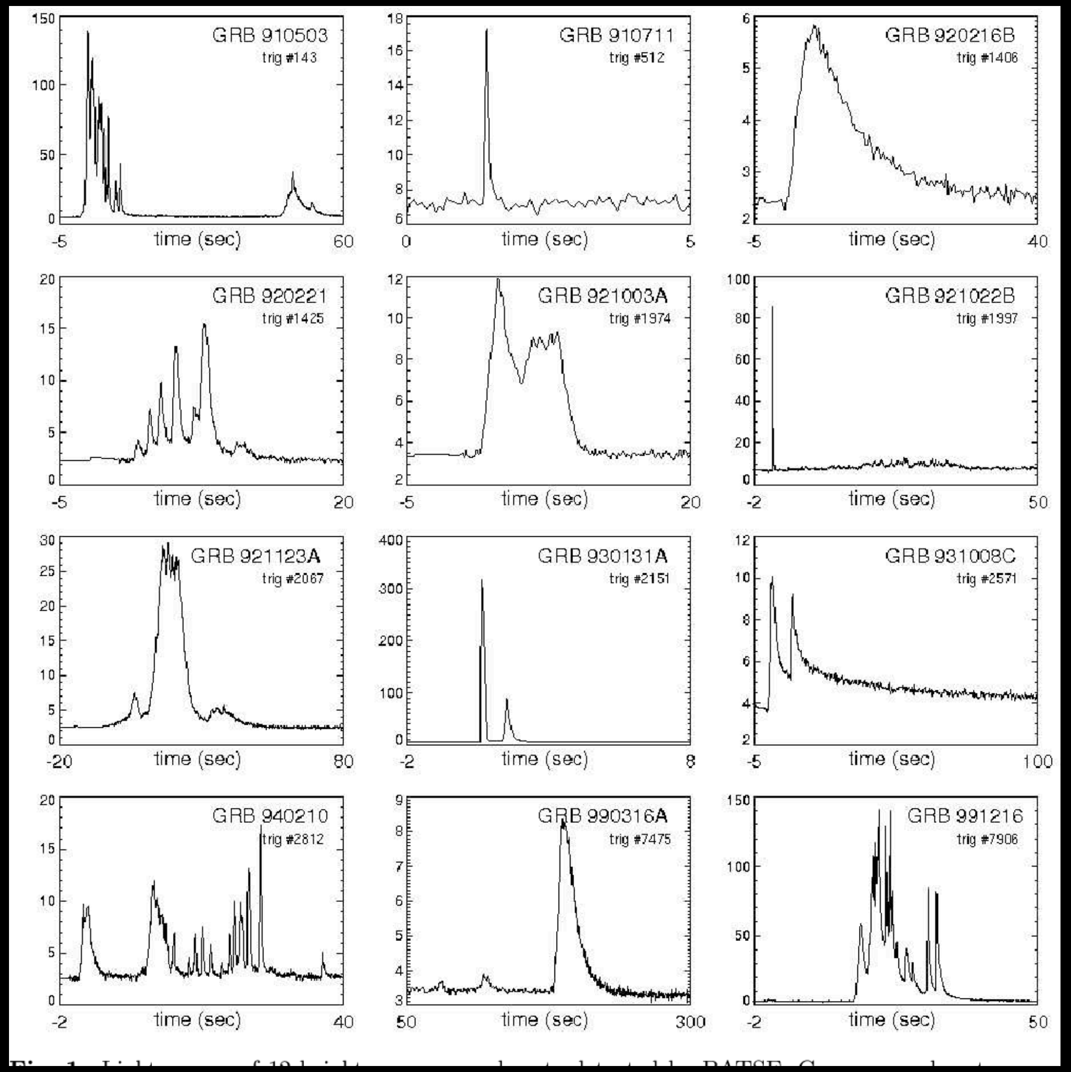
Scientific background

Prompt emission phase:

Energy range: keV-MeV

Variability time-scales: ms-s





Shemi & Piran (1990)

Rees & Meszaros (1994)

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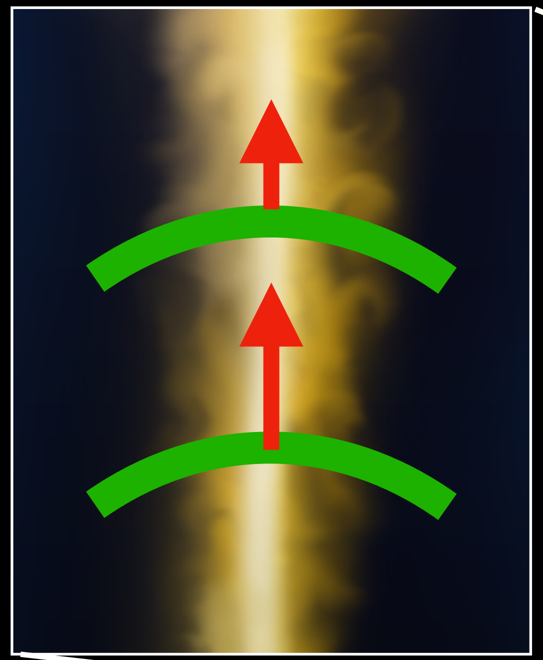

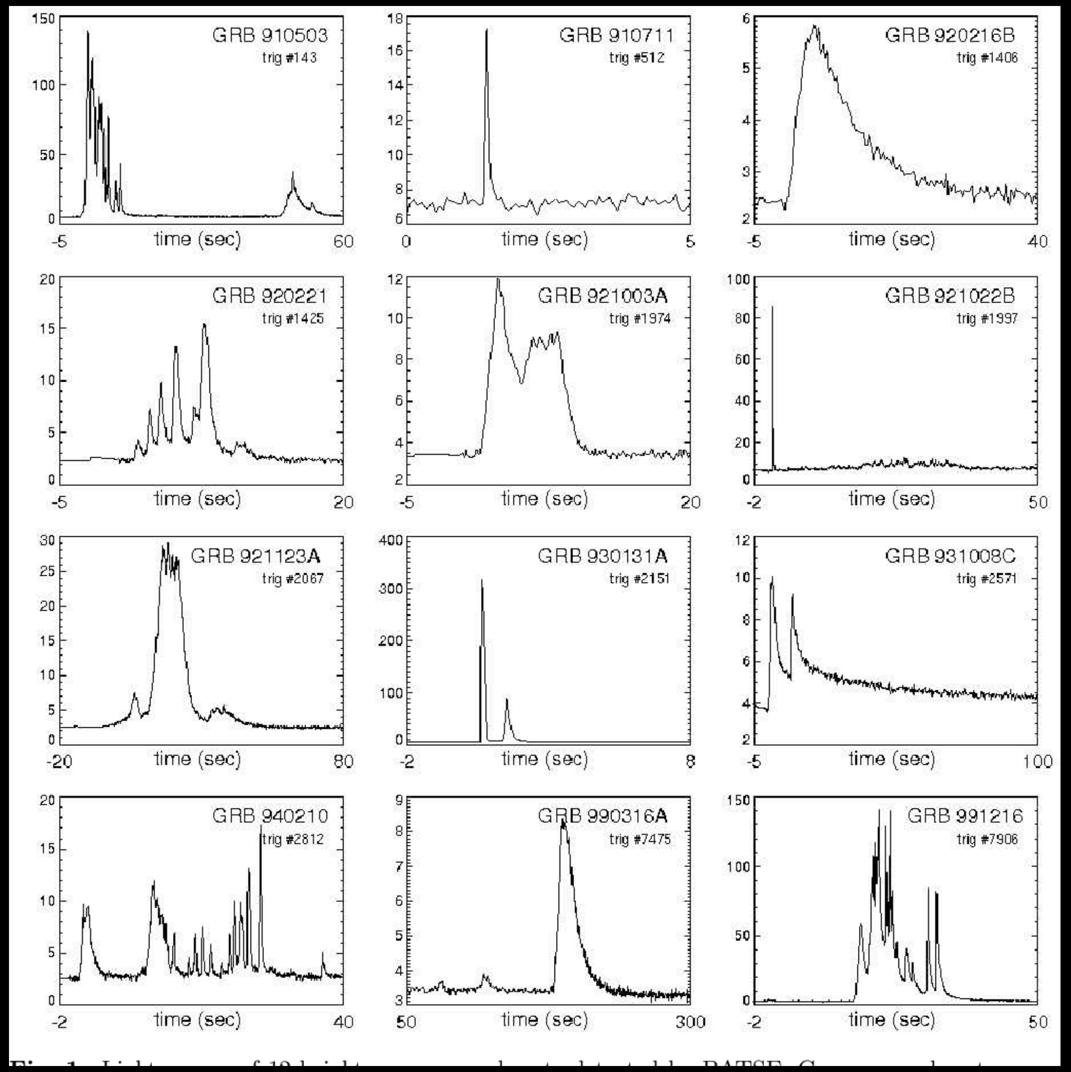

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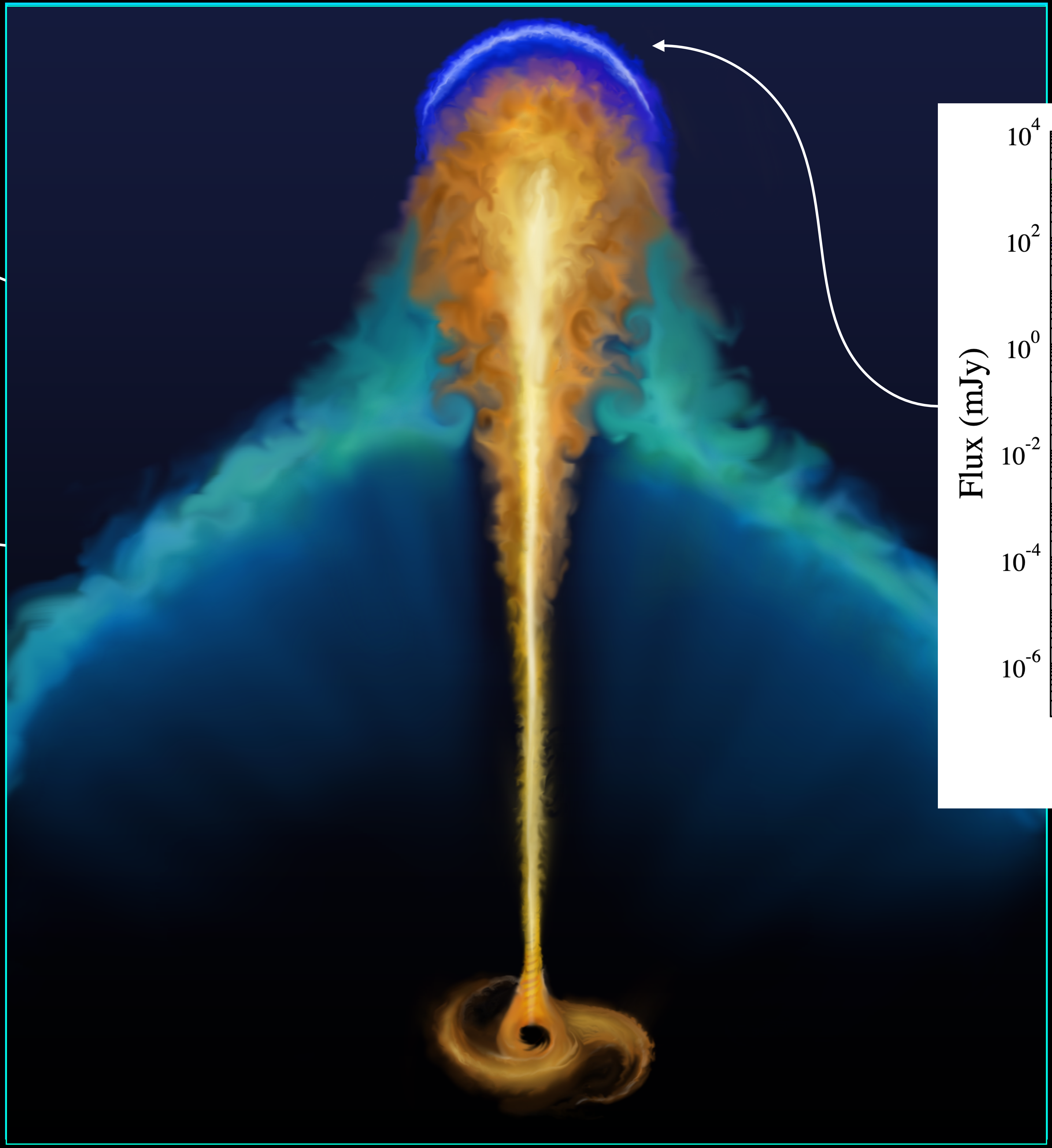
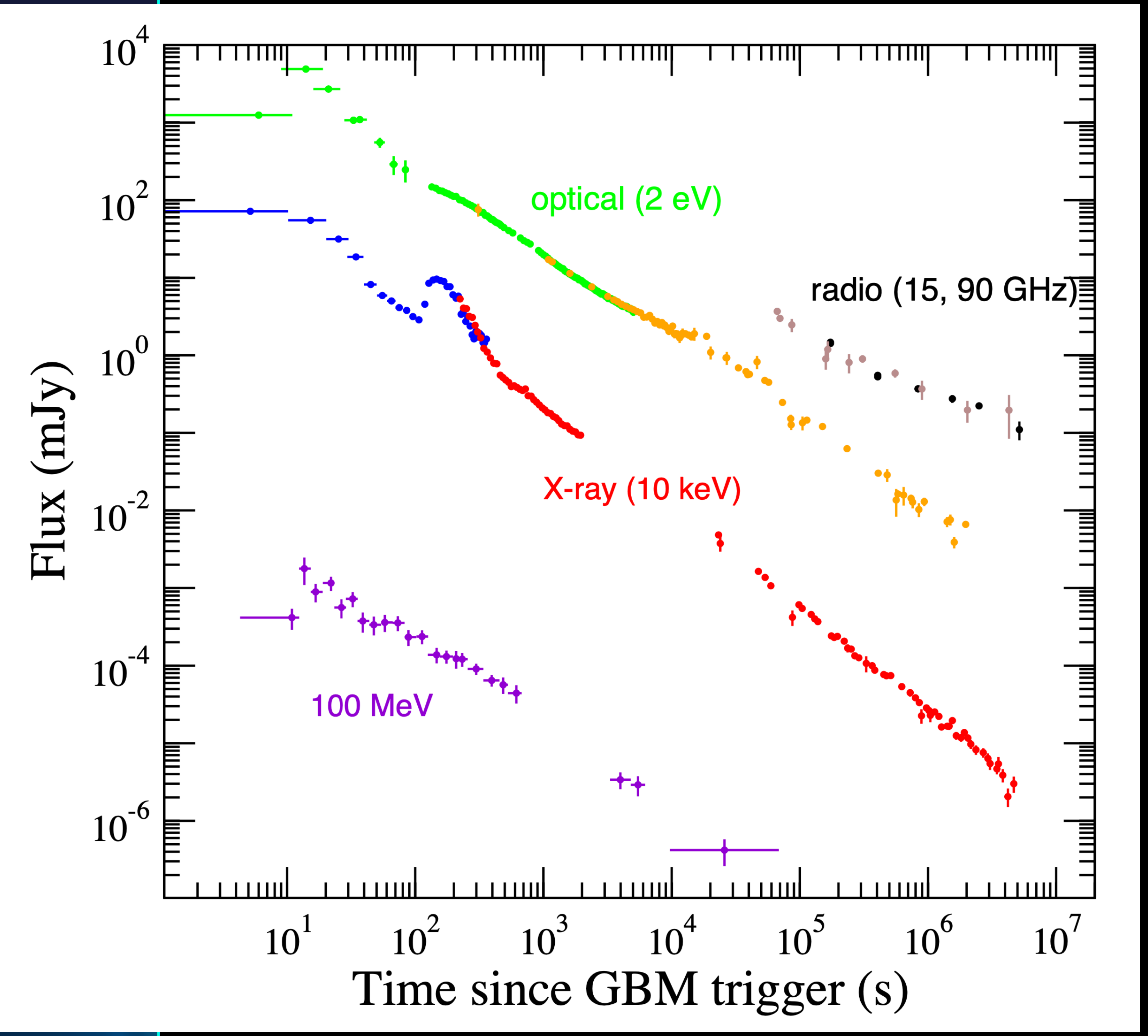


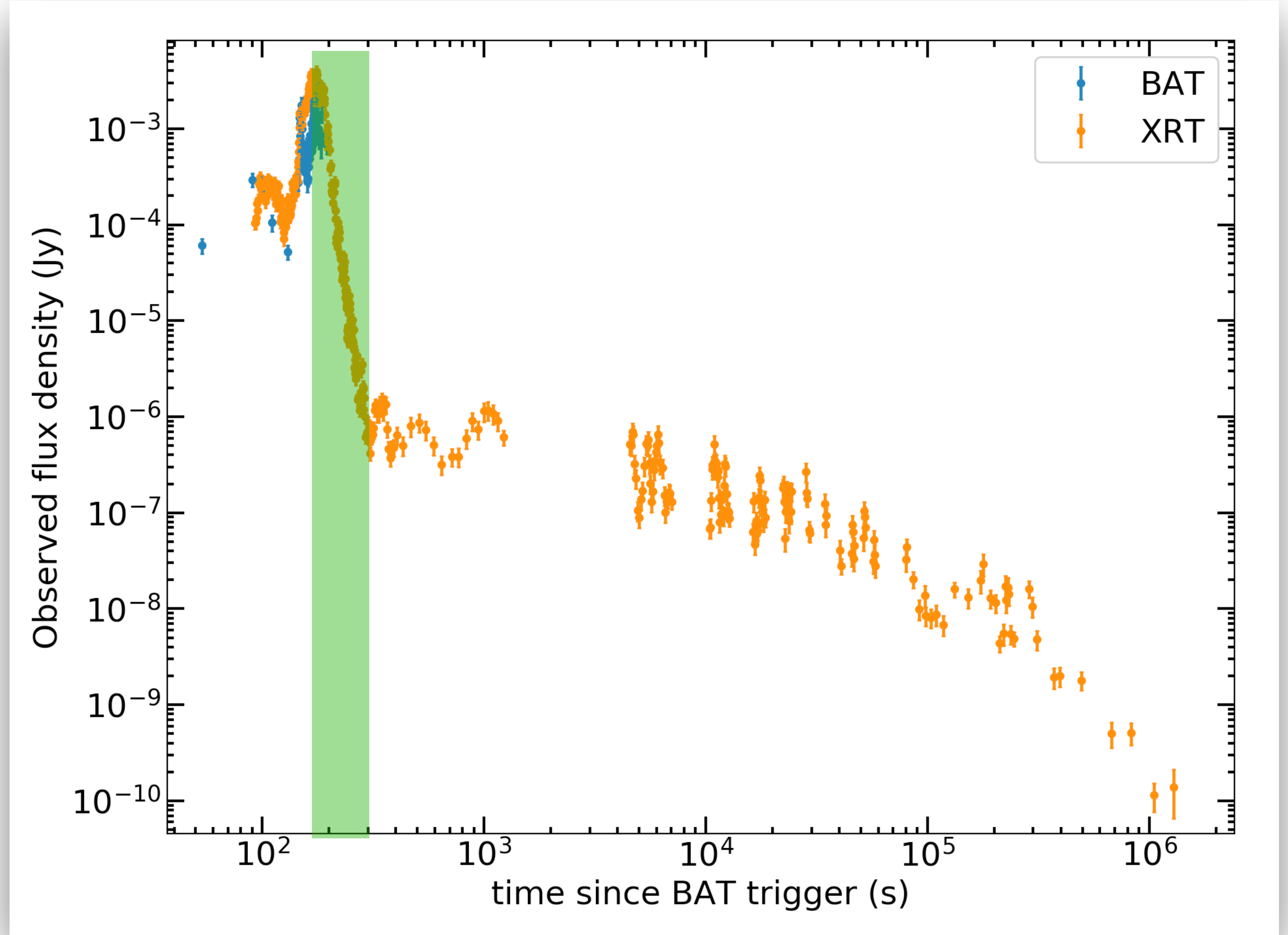
Afterglow phase



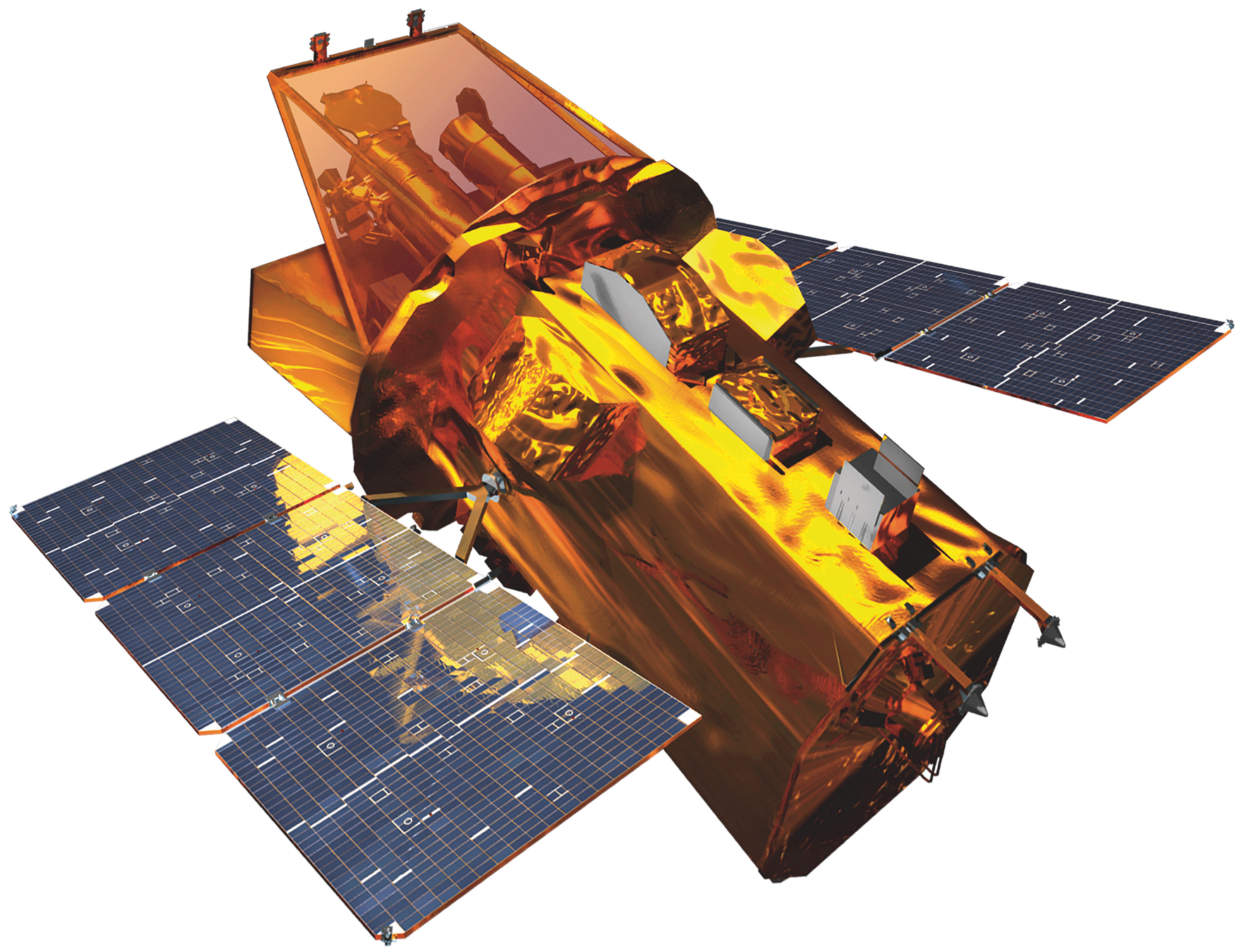
From Panaitescu et al. (2013)

The steep decay phase

Typical X-ray light curve



Neil Gehrels Swift Observatory



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

The spectral evolution during the steep decay phase

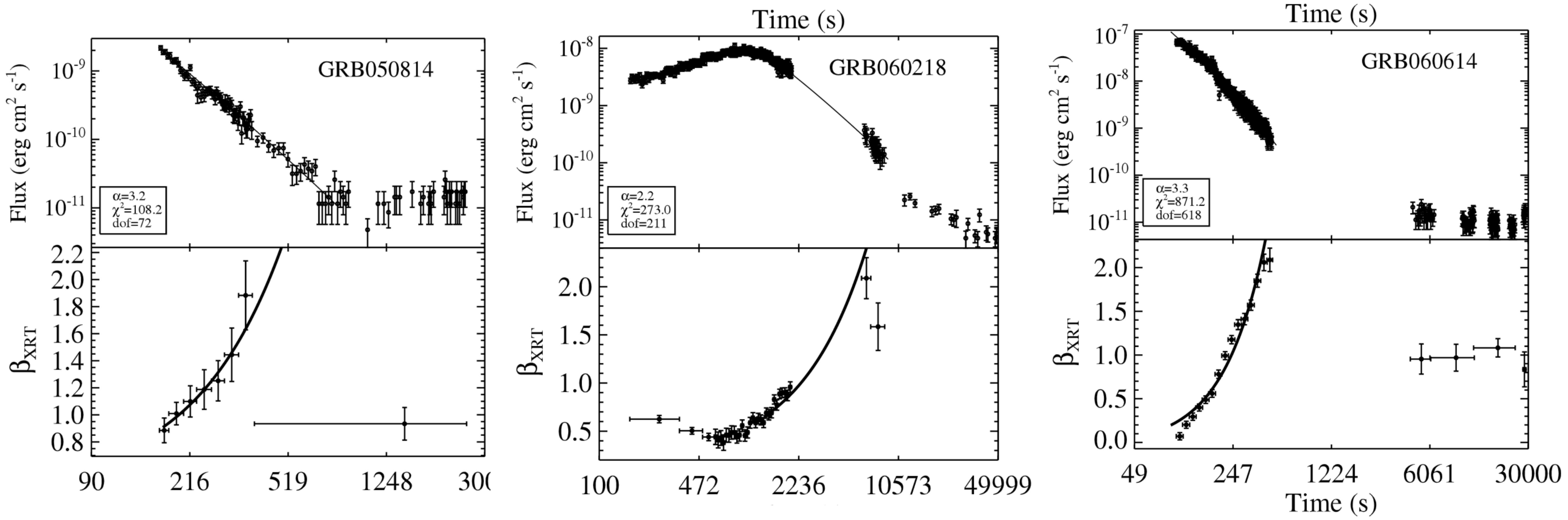
Prompt emission

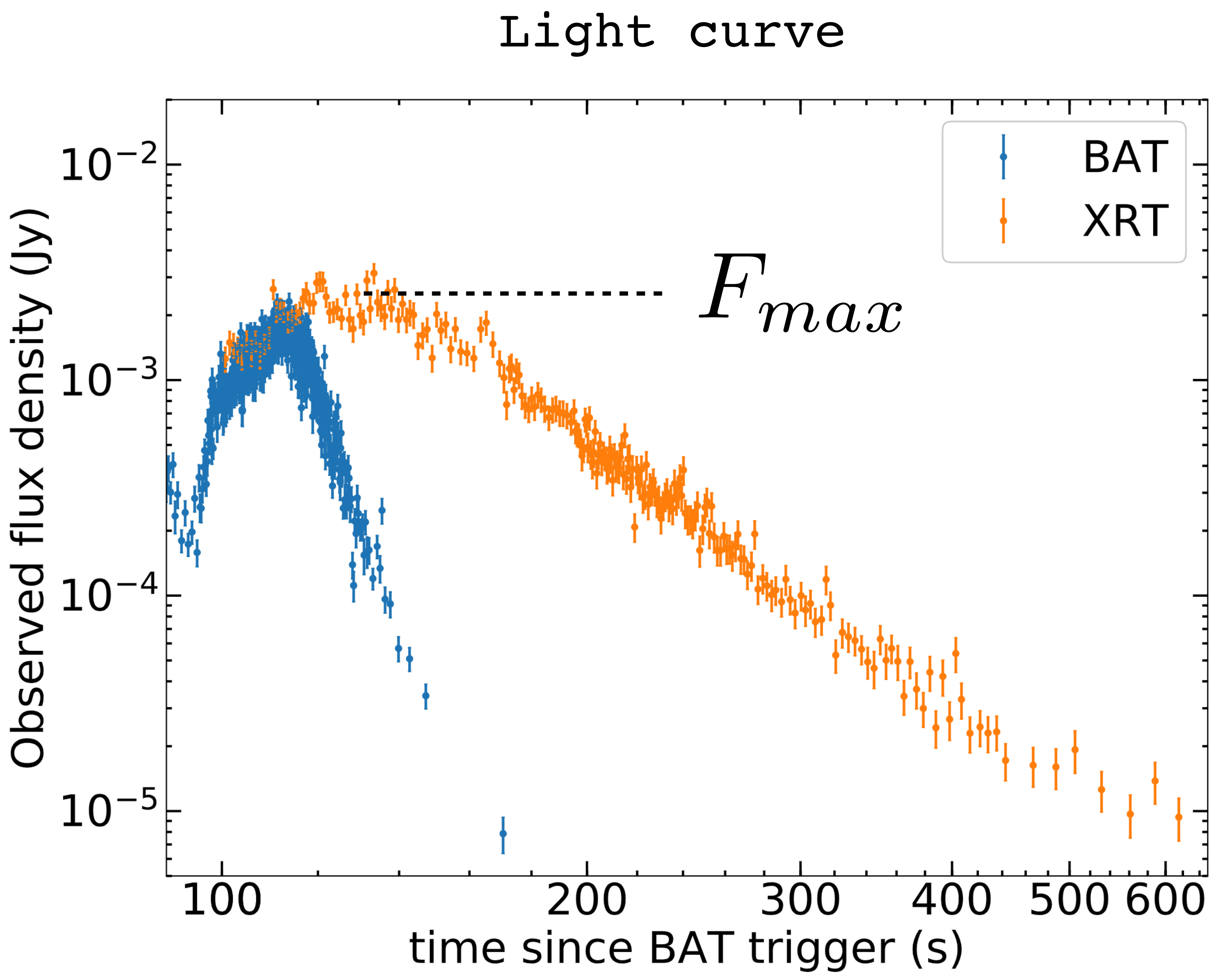
Prompt tail

The steep decay in XRT light curves is considered as the fading tail of prompt emission pulses

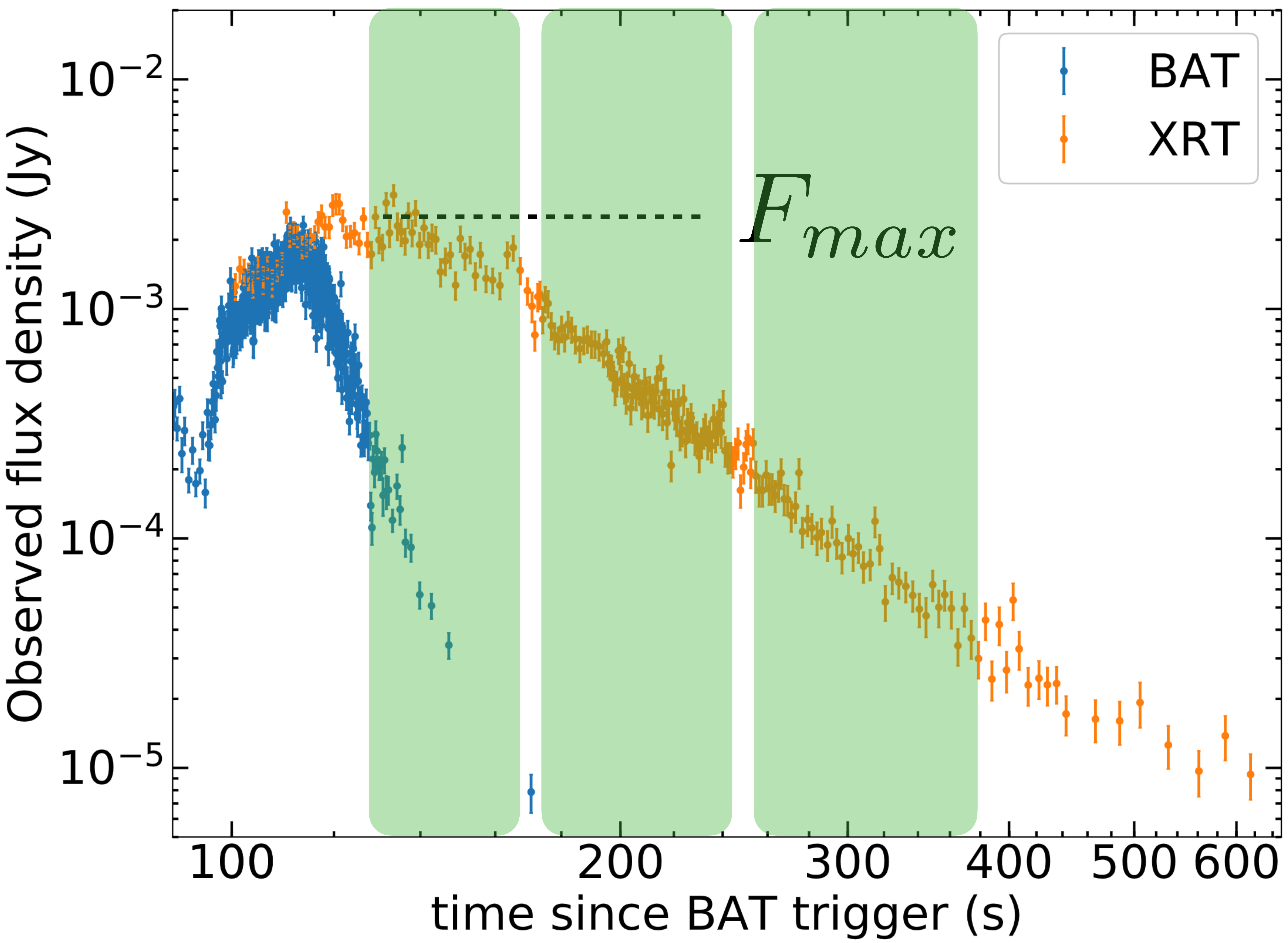
Flux and spectral evolution in this phase should shed light on the cooling of particles once the acceleration mechanism takes over

Zhang et al. 2007

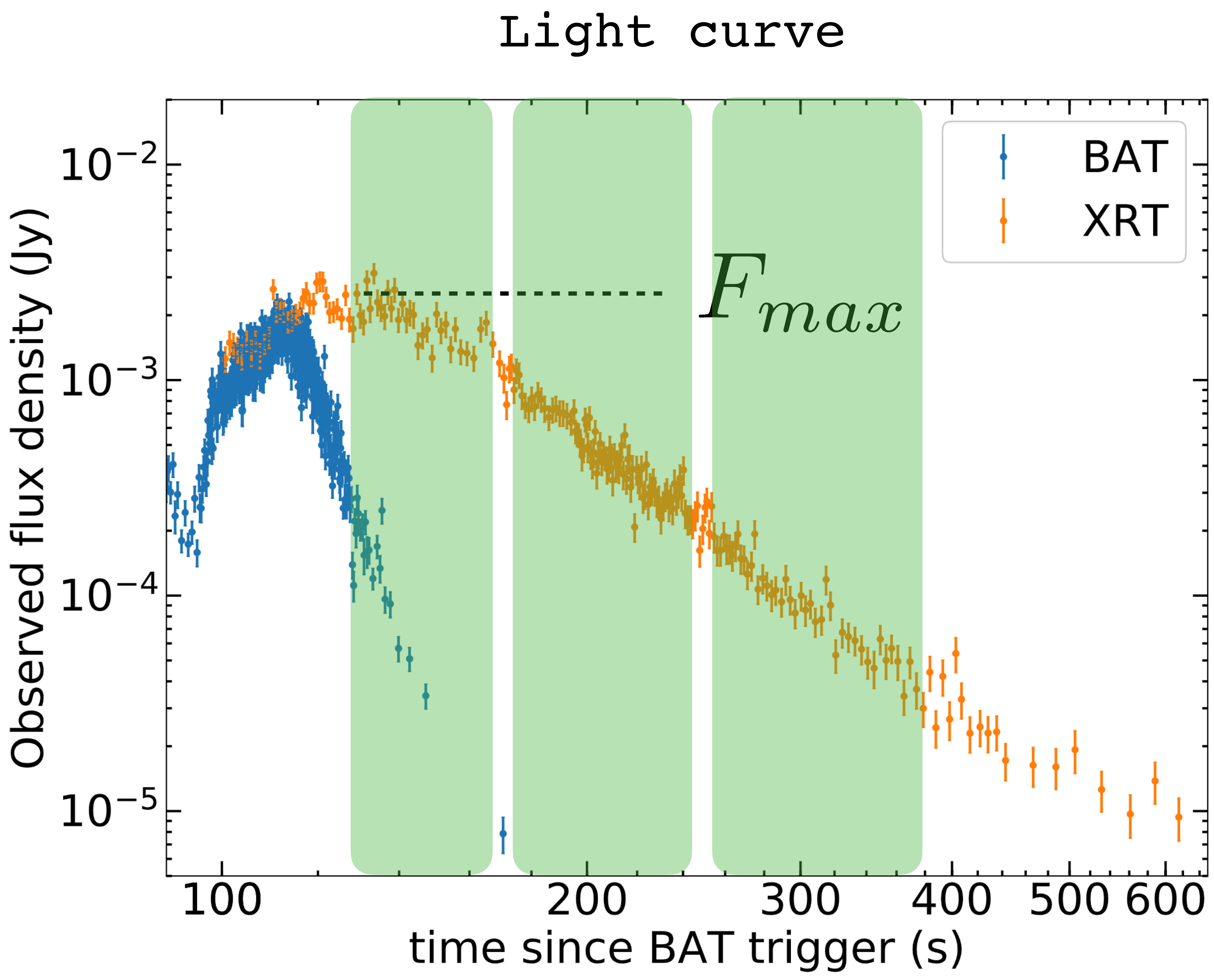


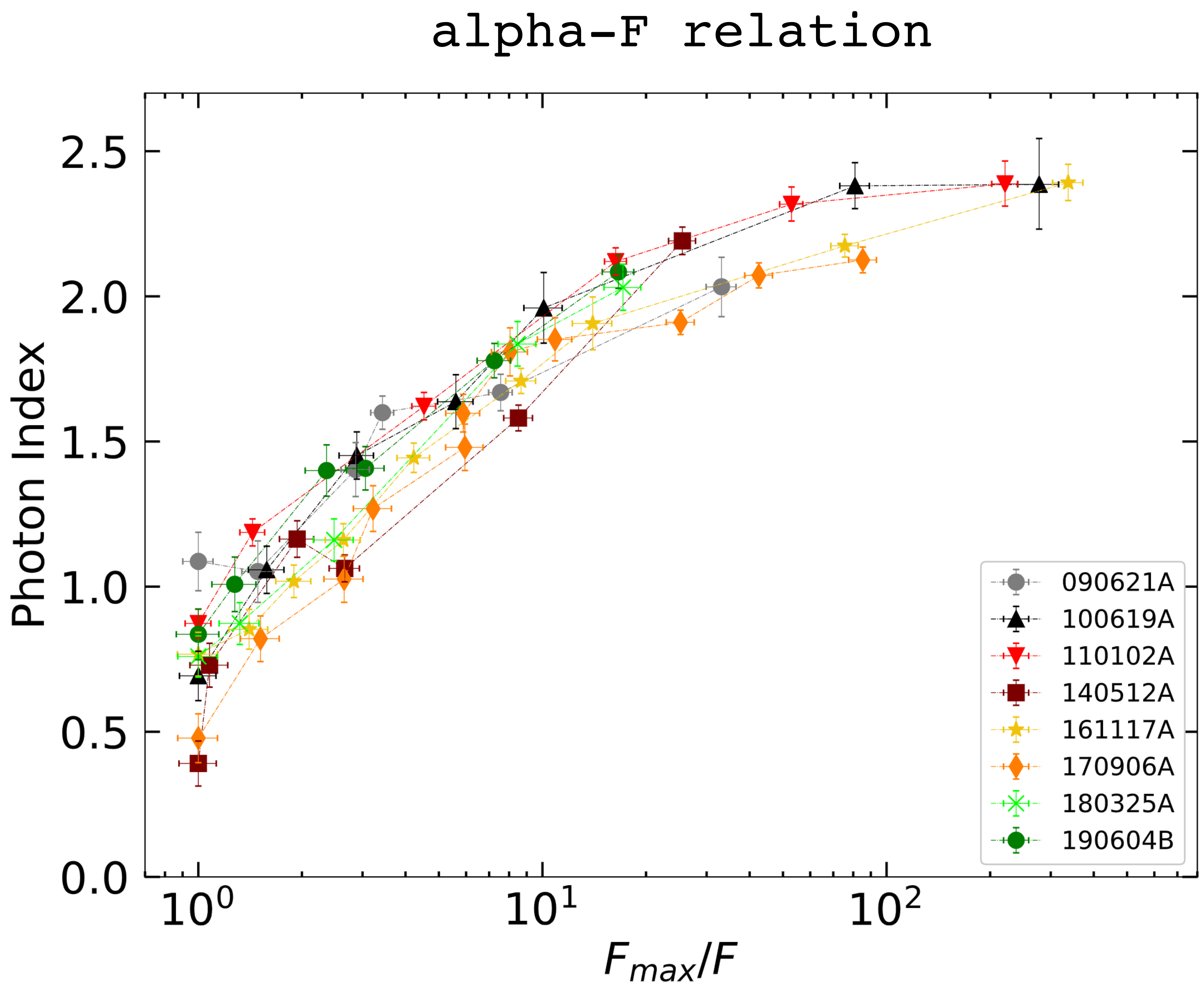

Light curve
BAT
XRT
F_{max}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
Observed flux density (Jy)
100
200
300
400
500
600
time since BAT trigger (s)

Light curve


BAT
XRT
F_{max}
Observed flux density (Jy)
time since BAT trigger (s)
10−2
10−3
10−4
10−5
100
200
300
400
500
600

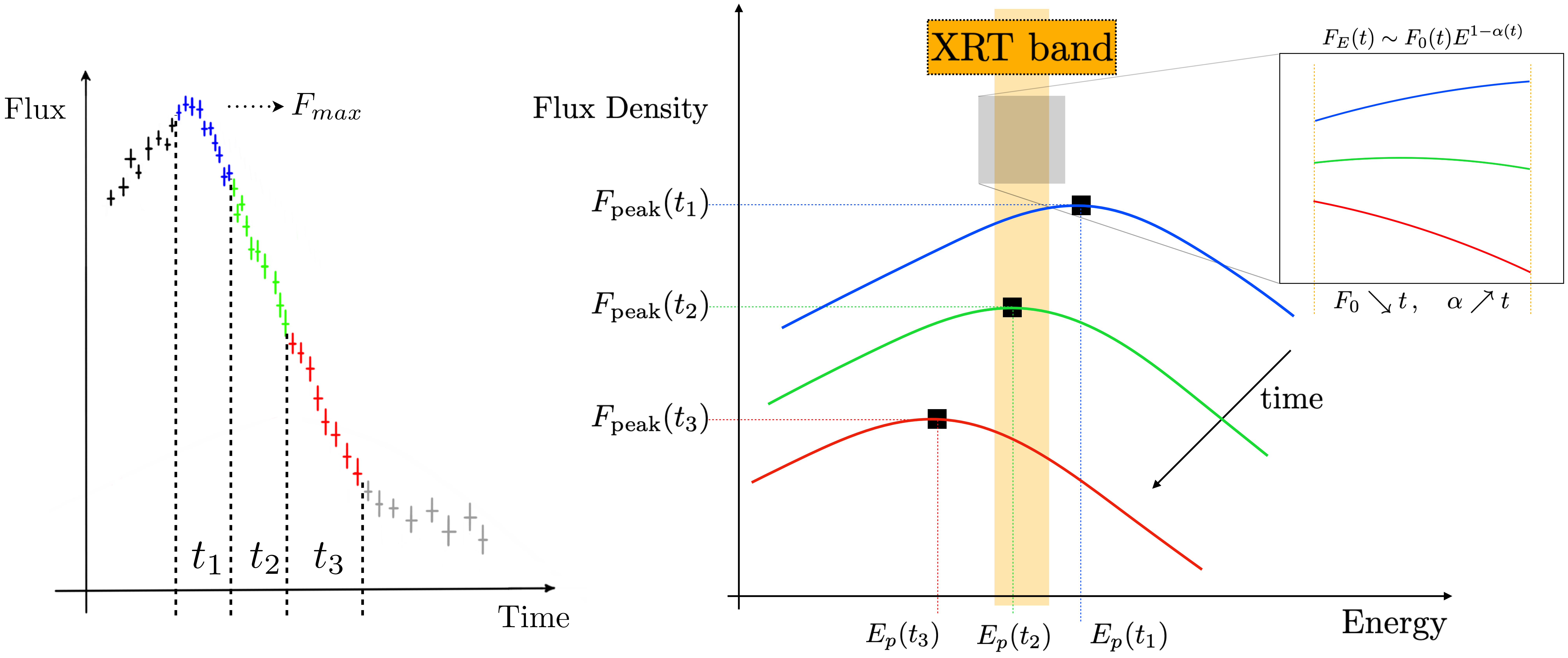
The alpha-F relation





Clear indication of a common process

The alpha-F relation



Interpreting the alpha-F relation

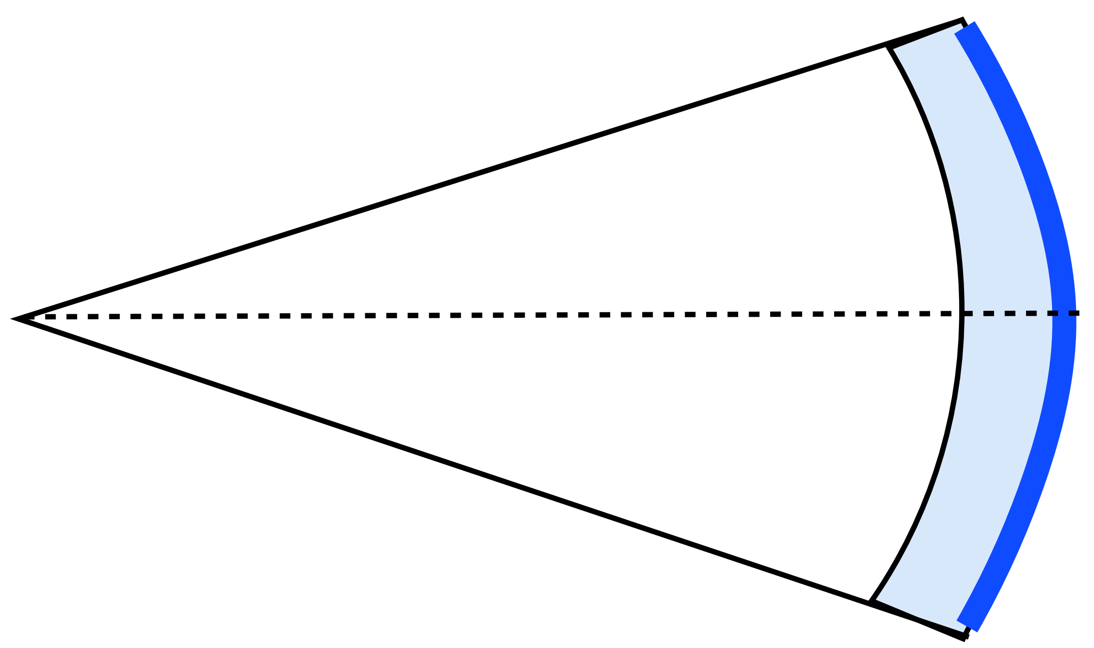
We need to define two time scales:

$$\tau_{rad} = \min\left(\tau_{Syn}, \tau_{IC}, ...\right) \qquad \tau_{dyn} = \frac{R}{2c\Gamma^2}$$

and two regimes:

Radiative regime

$$\tau_{rad} \ll \tau_{dyn}$$

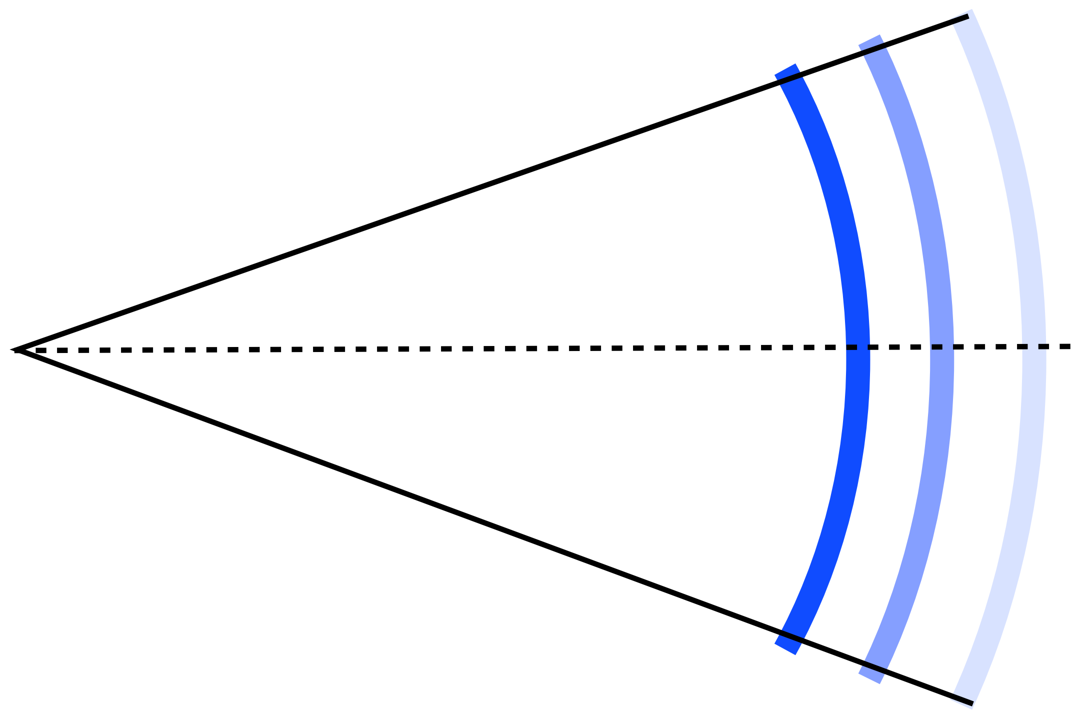


The tail emission is dominated by the last emitting surface

Spectral softening dominated by the Doppler shift due to high latitude emission

Adiabatic regime

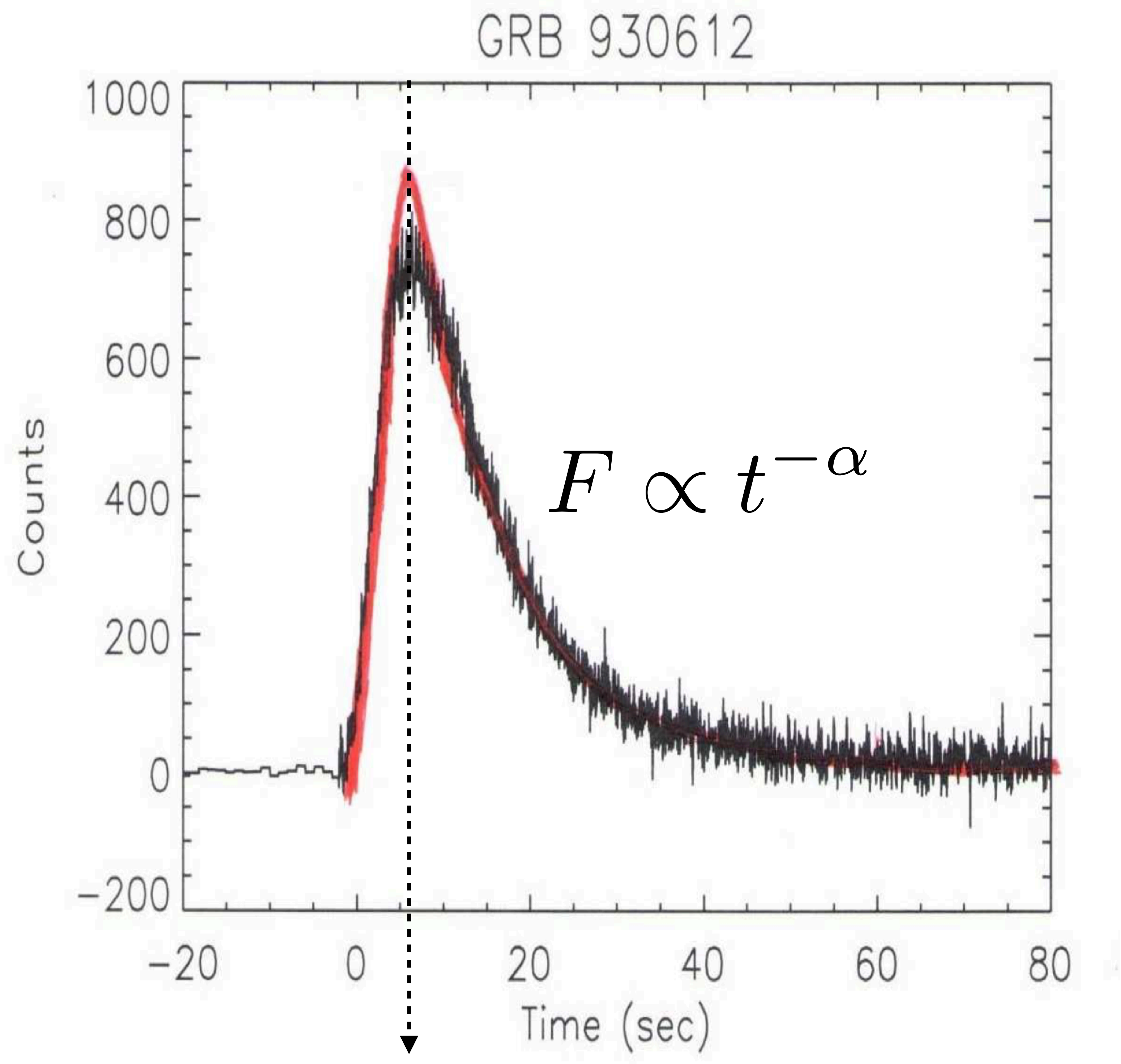
$$\tau_{rad} \gg \tau_{dyn}$$



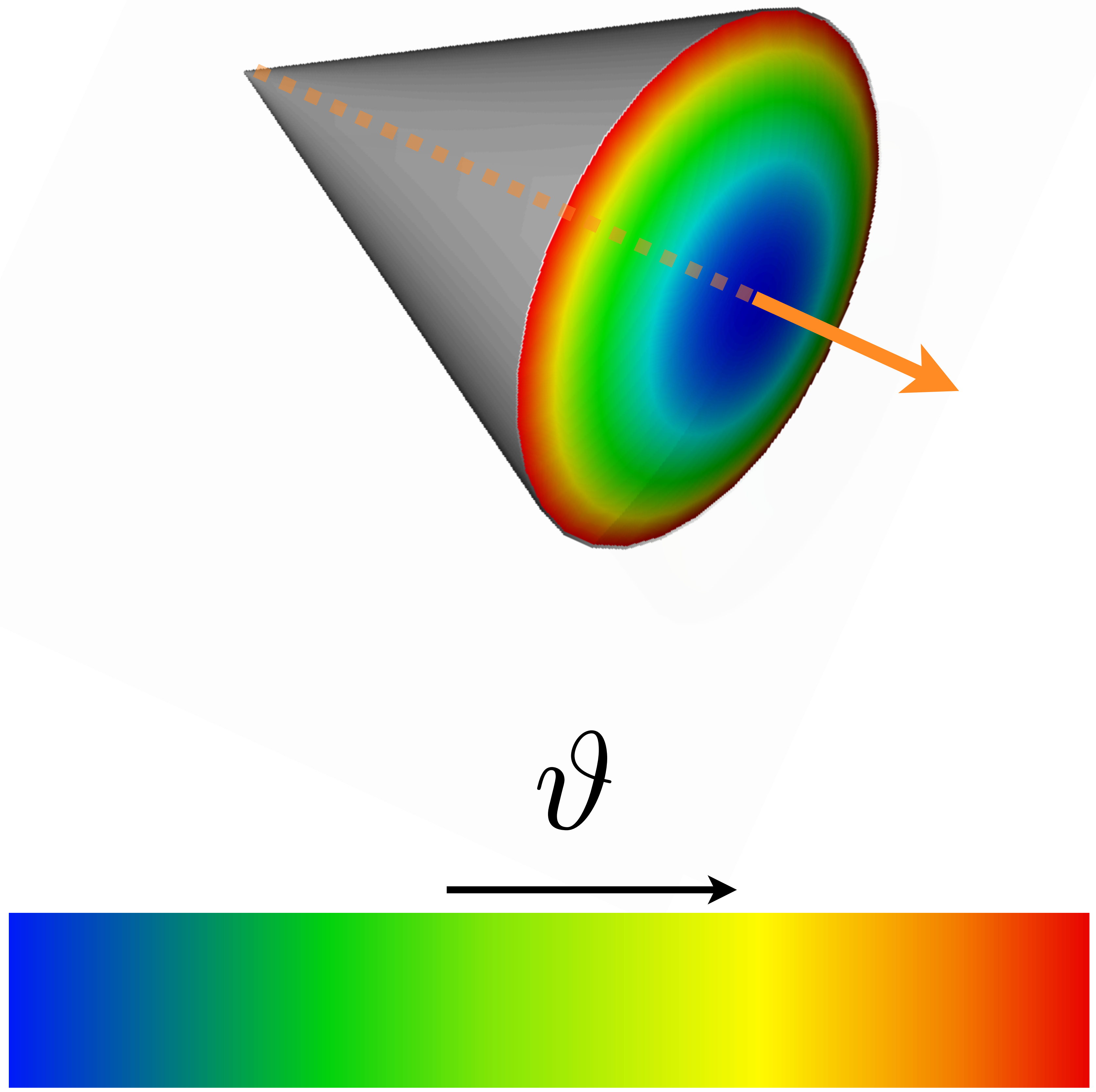
The spectrum undergoes to an intrinsic shift due to the adiabatic cooling of particles

The high latitude emission

Light curve in the gamma-rays

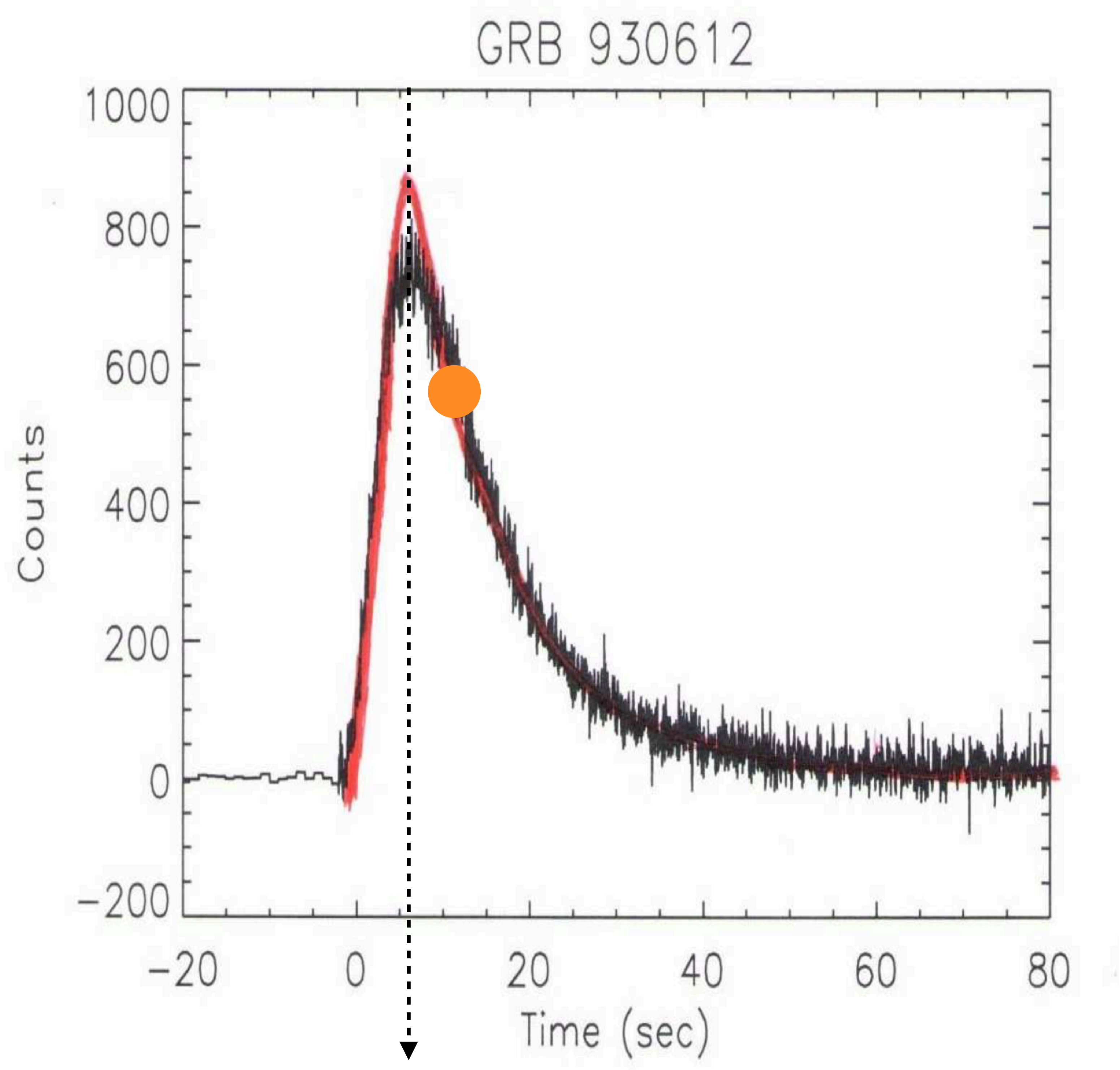


When emission shuts down



$$\mathcal{D}(\vartheta) = \frac{1}{\Gamma(1 - \beta \cos(\vartheta))}$$

The high latitude emission



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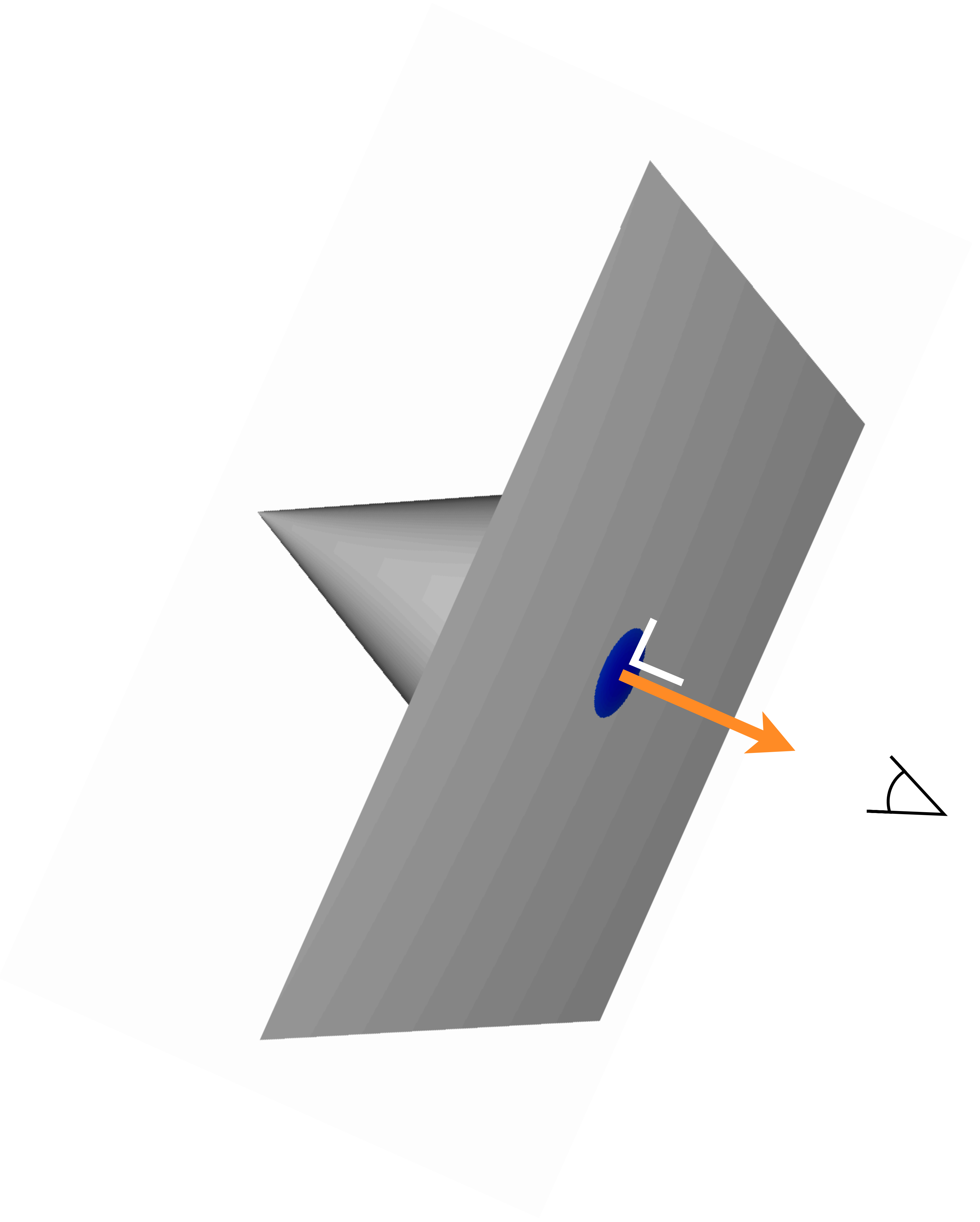

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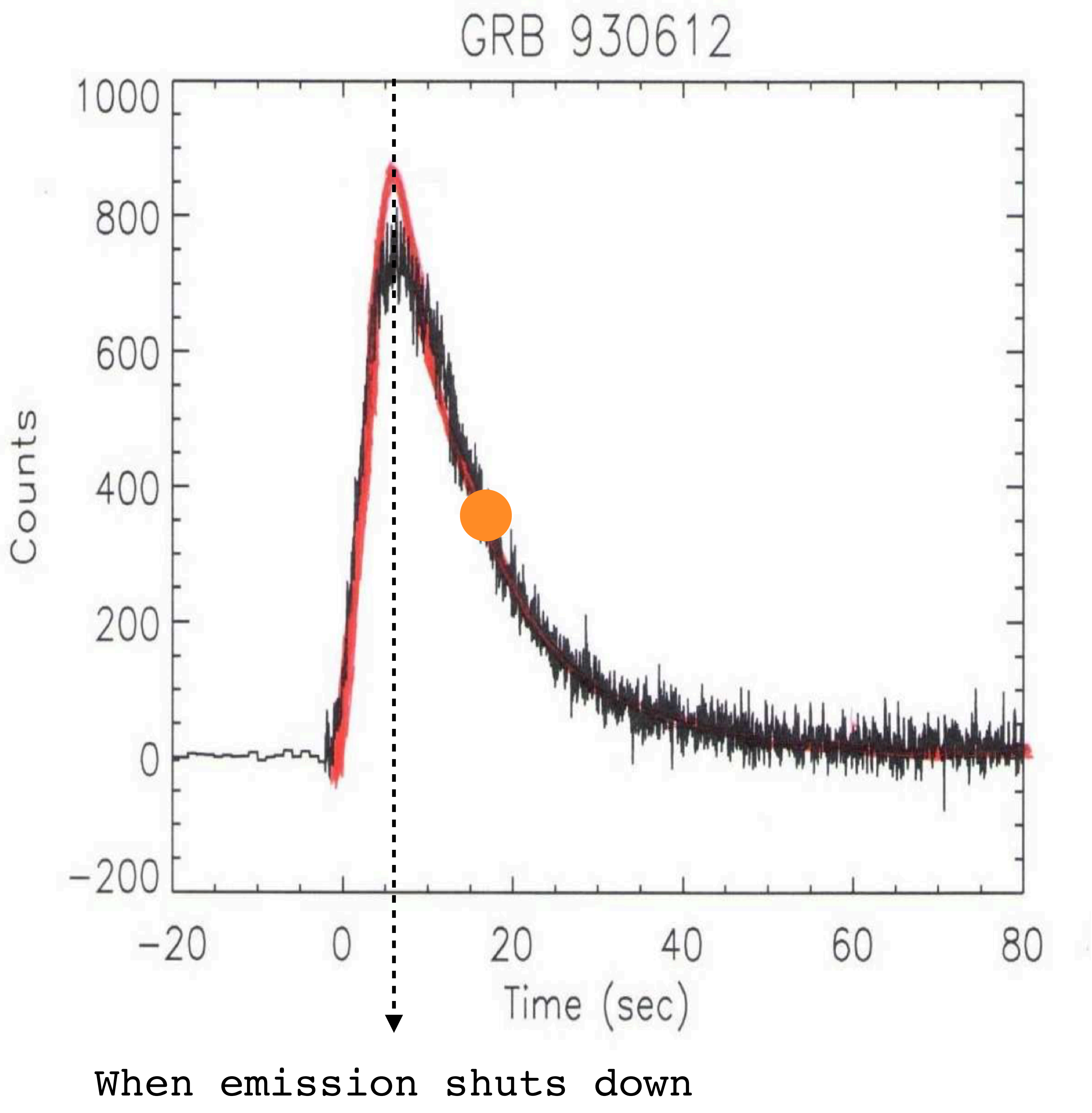
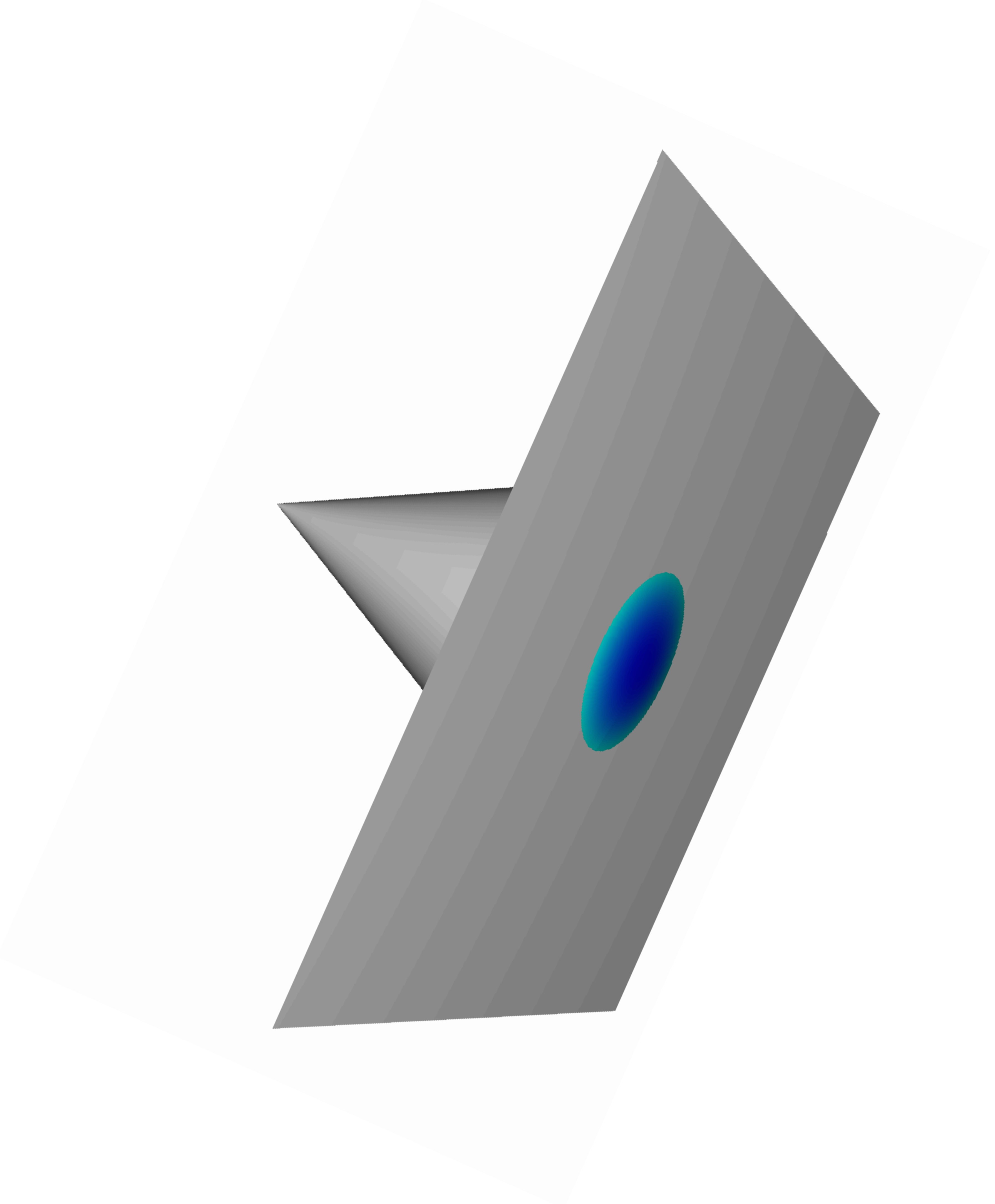
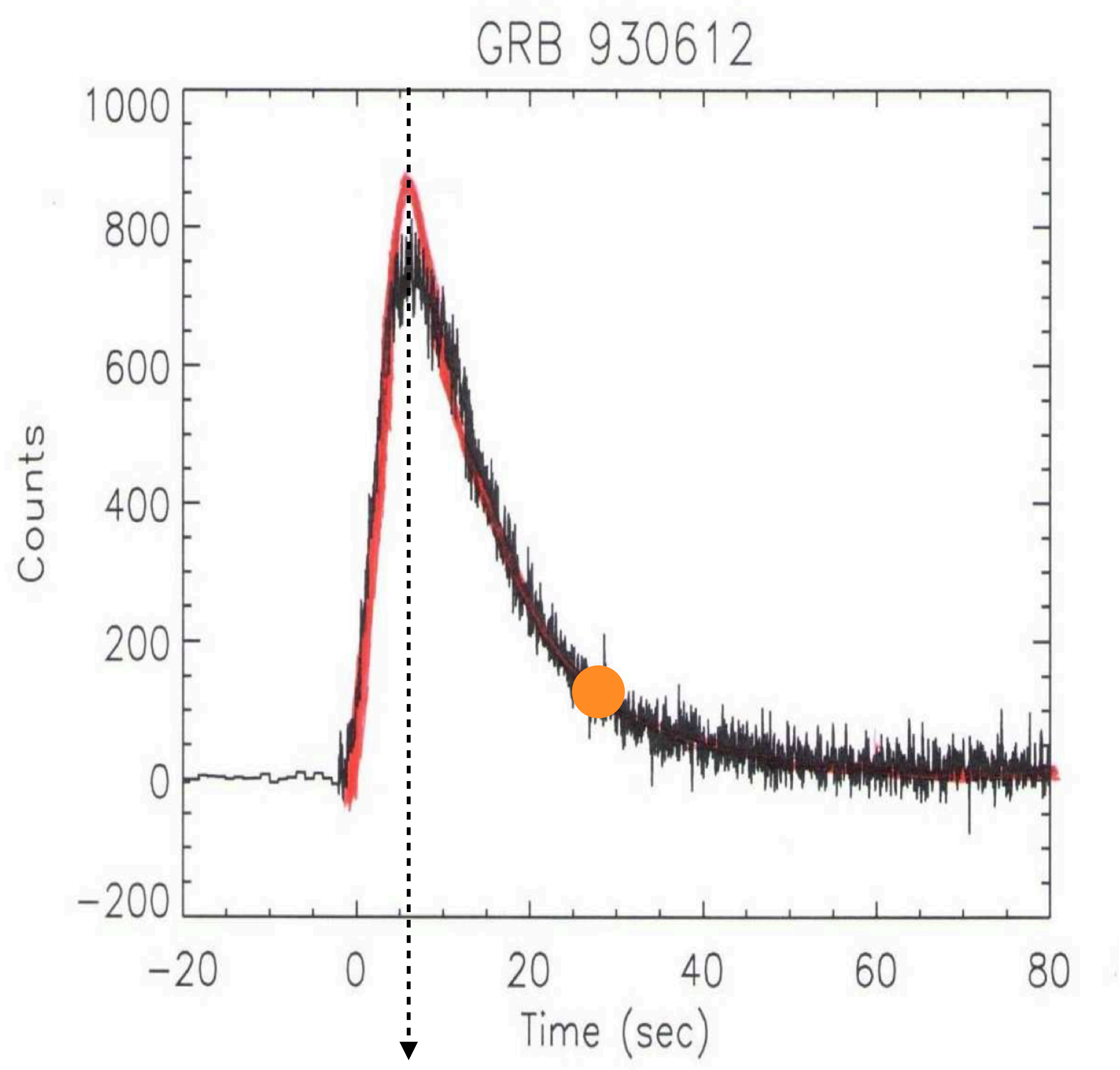




The high latitude emission



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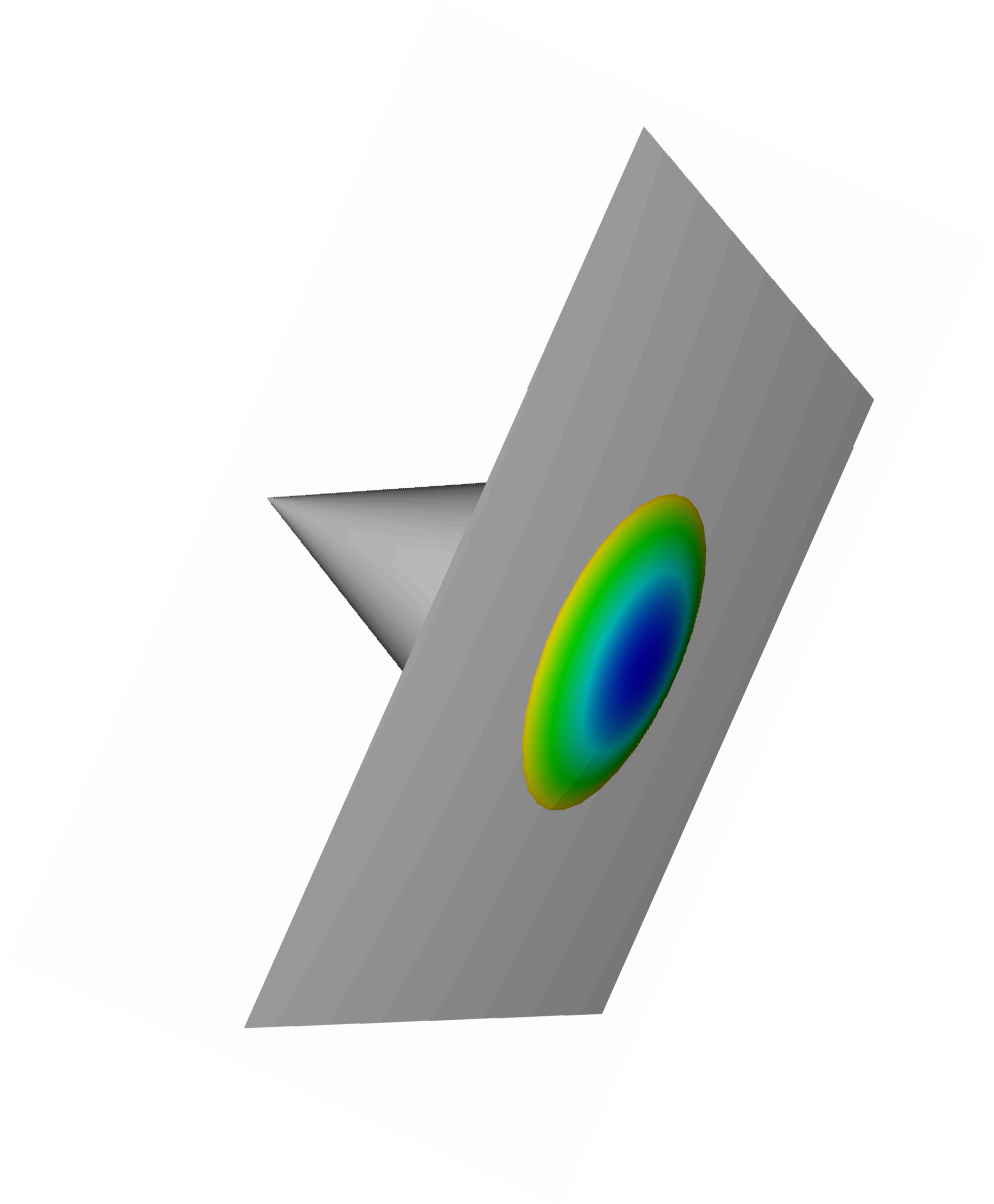
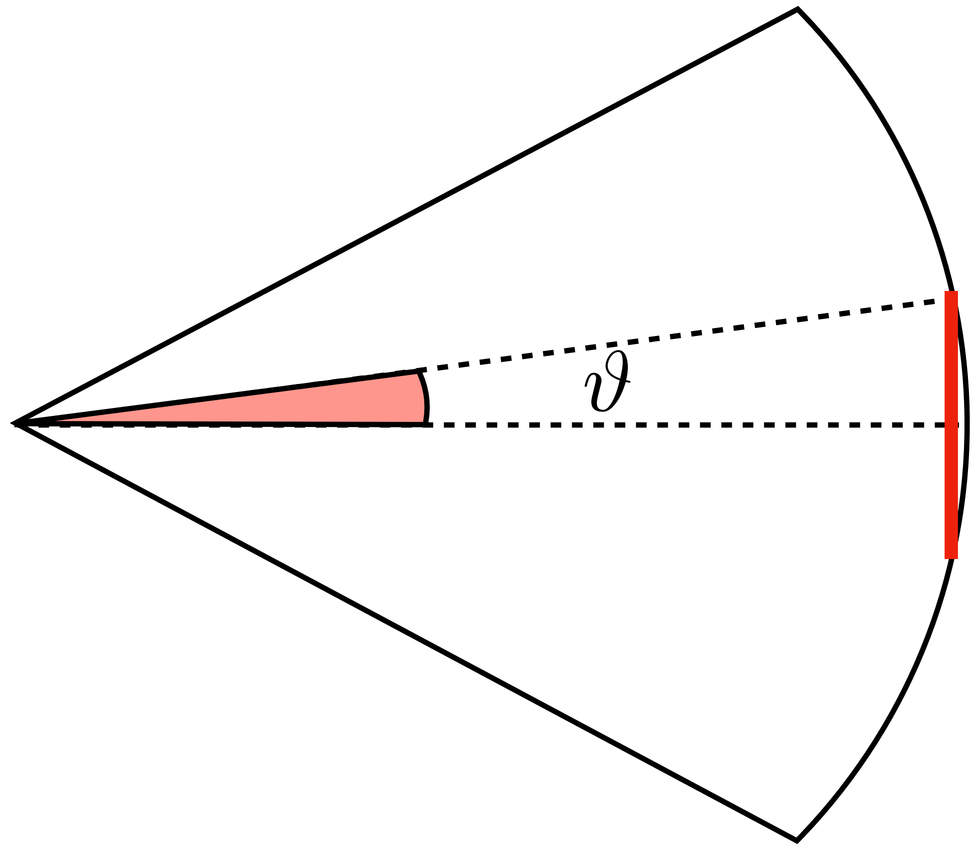
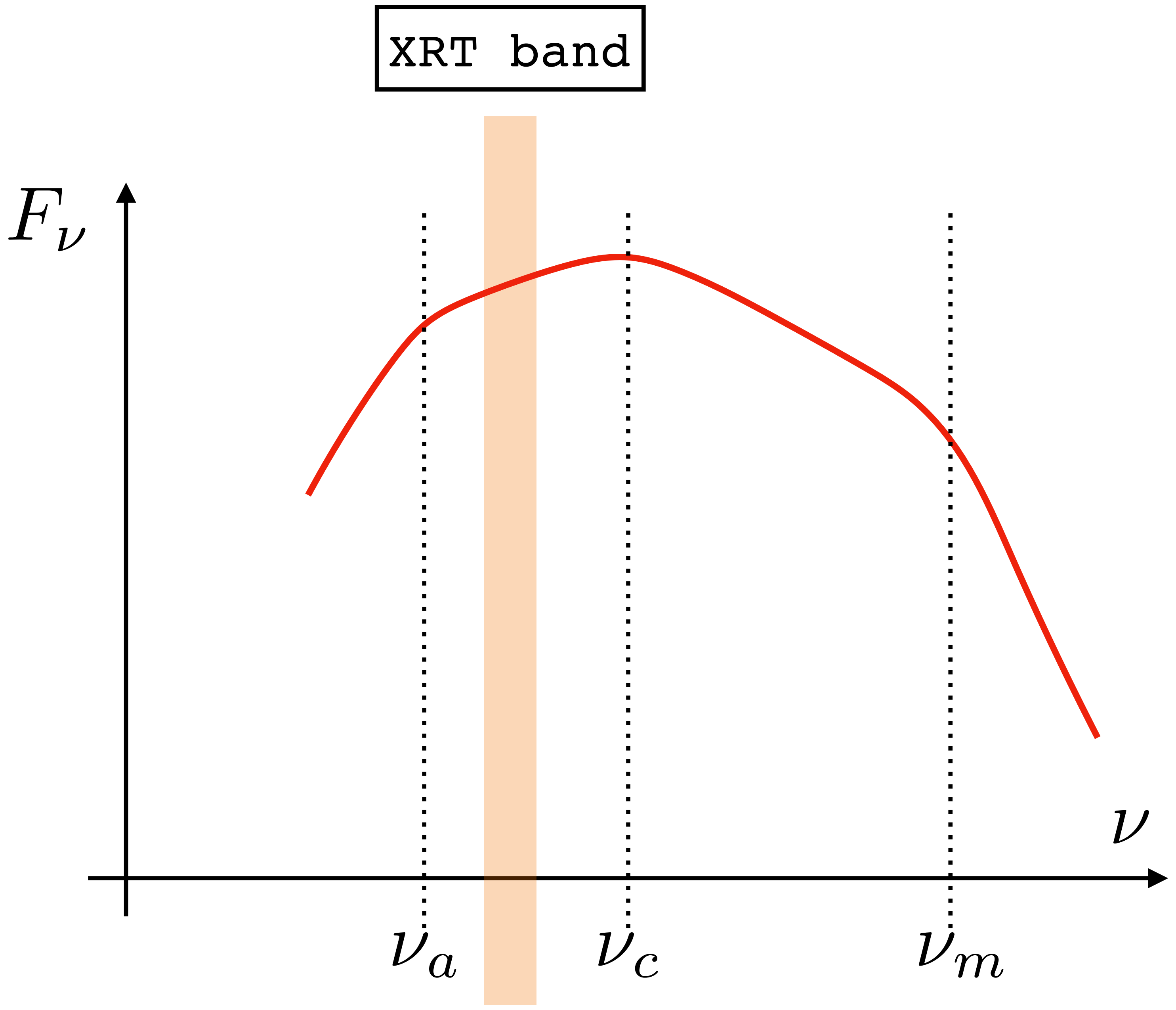


The high latitude emission



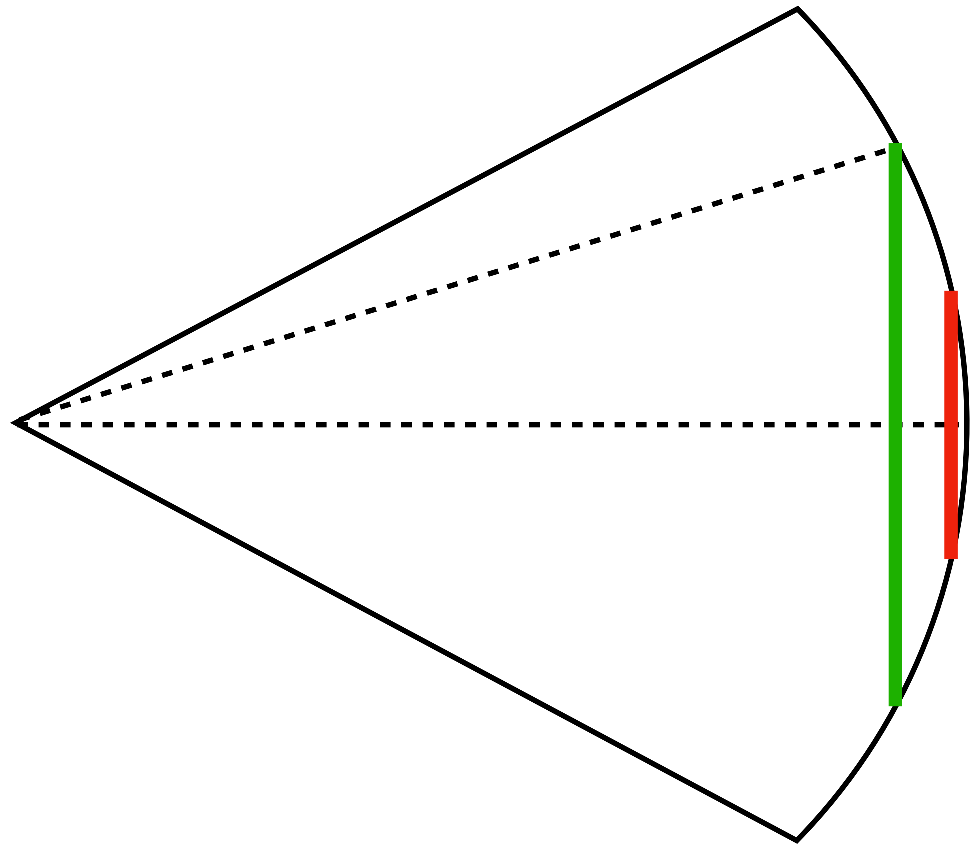


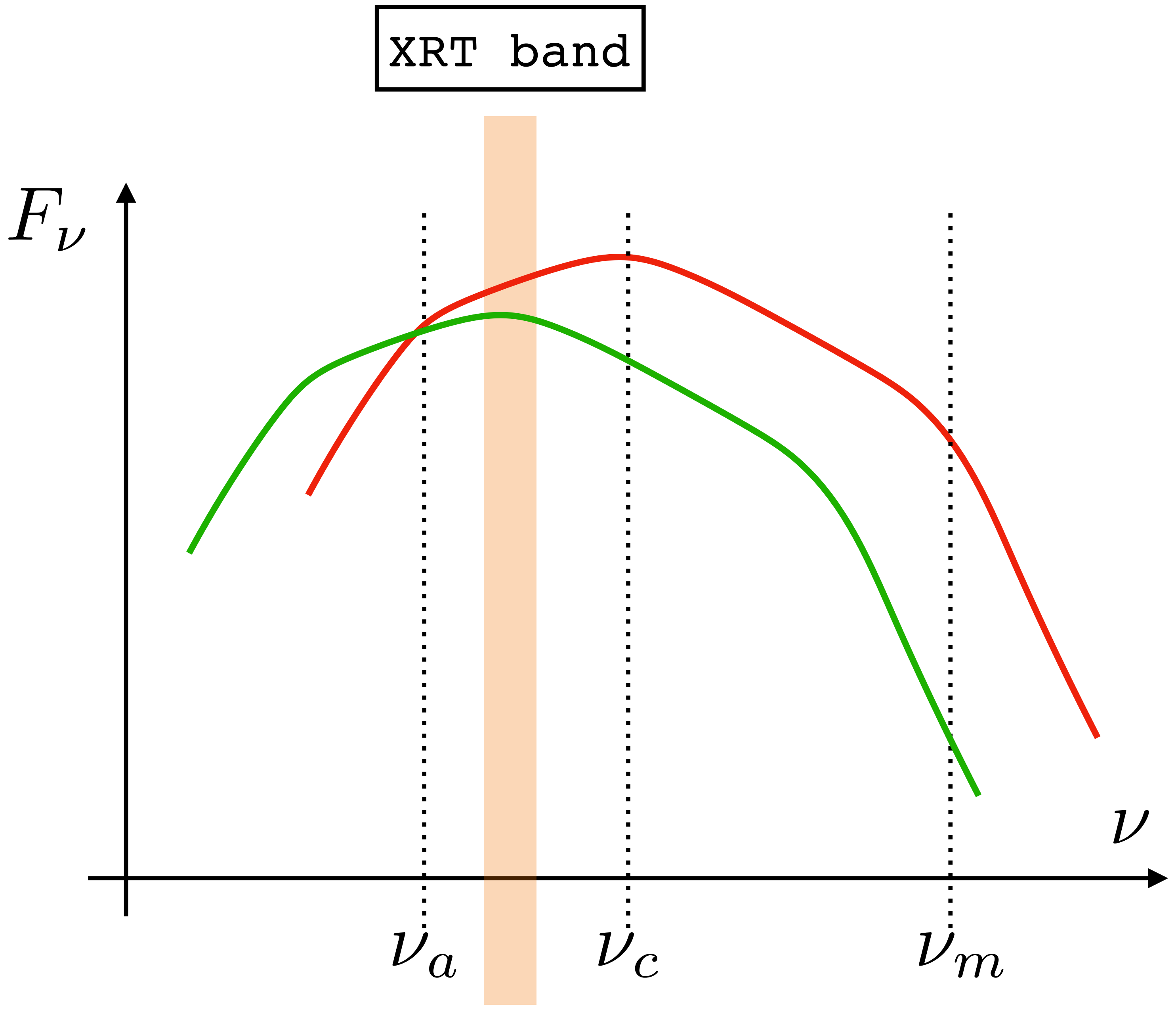
$$t_{obs} = t_{em}(1 - \beta cos(\theta))$$

$$\nu' = \frac{\nu}{\mathcal{D}[\theta(t)]} \qquad \mathcal{D}(\vartheta) = \frac{1}{\Gamma(1 - \beta\cos\vartheta)}$$

$$F_\nu(t) \propto S(\frac{\nu'}{\nu'_0})\,\mathcal{D}^2[\theta(t)]\,cos[\theta(t)]$$

The high latitude emission





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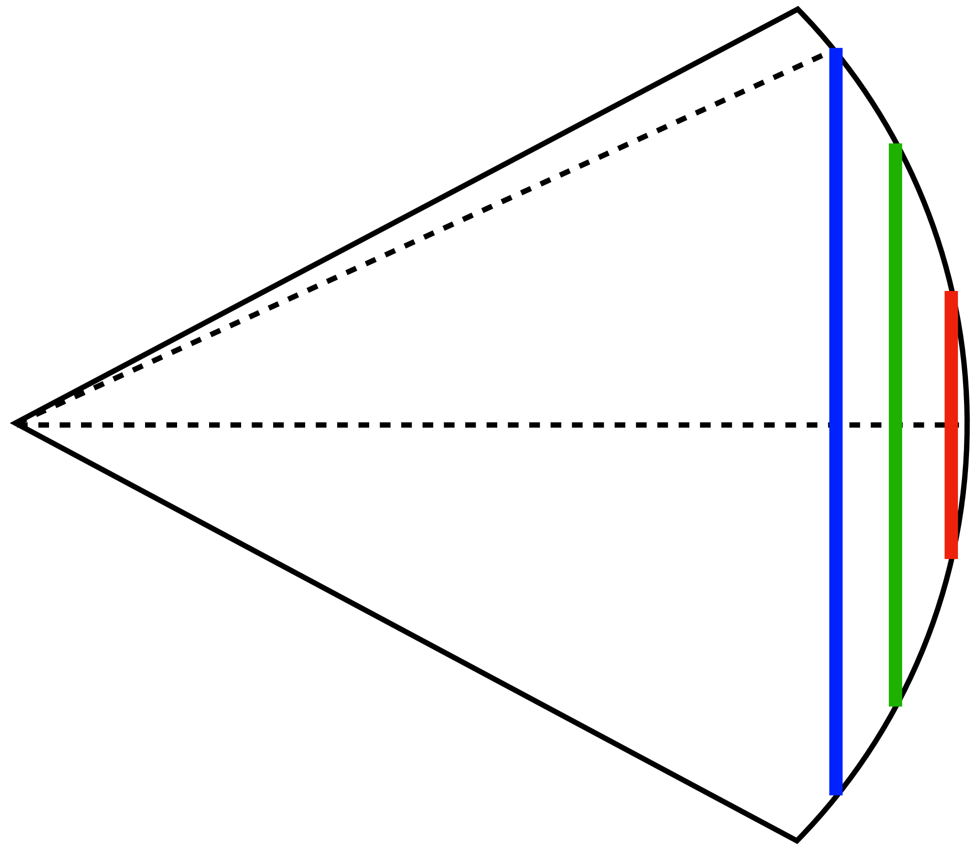

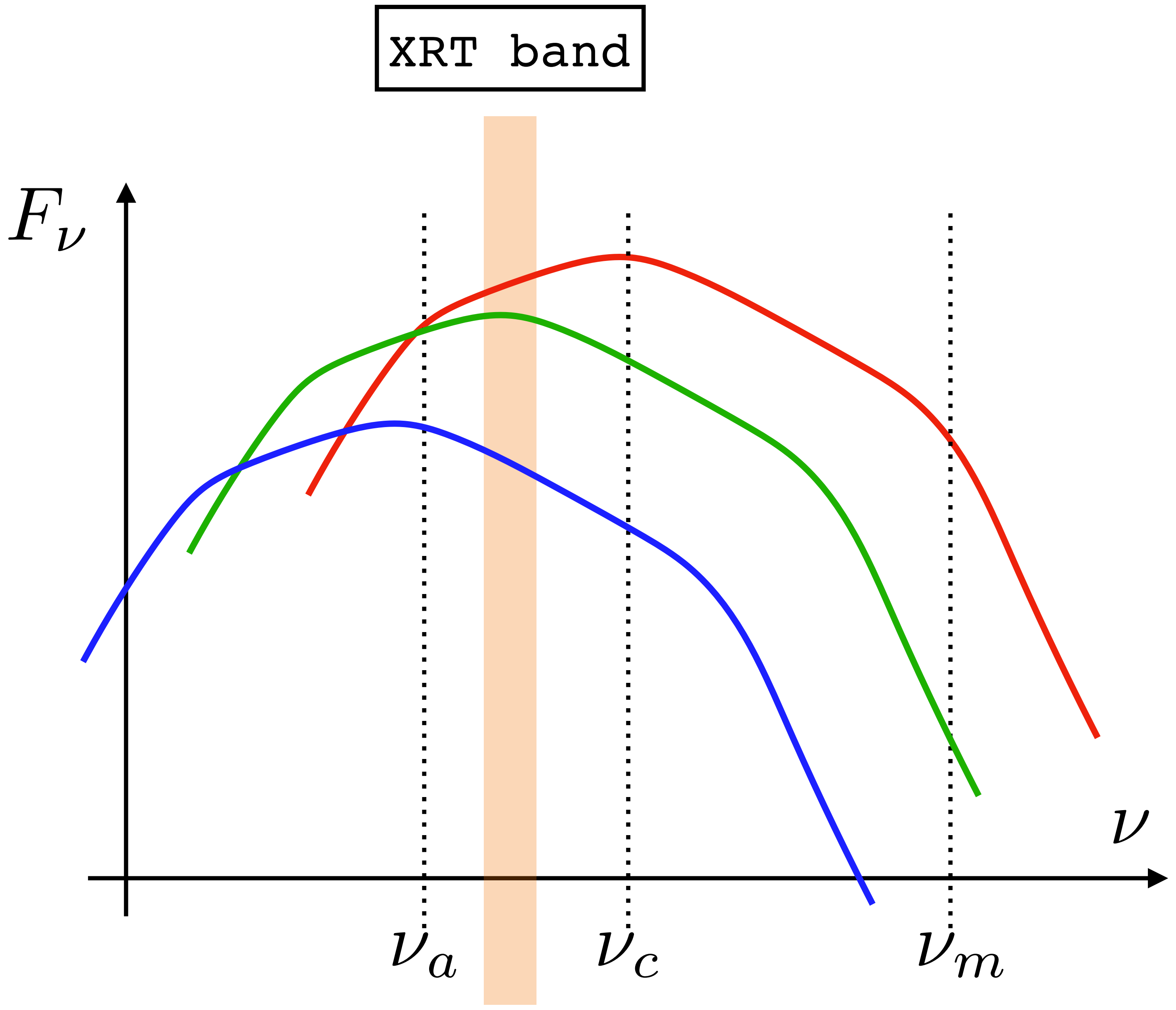

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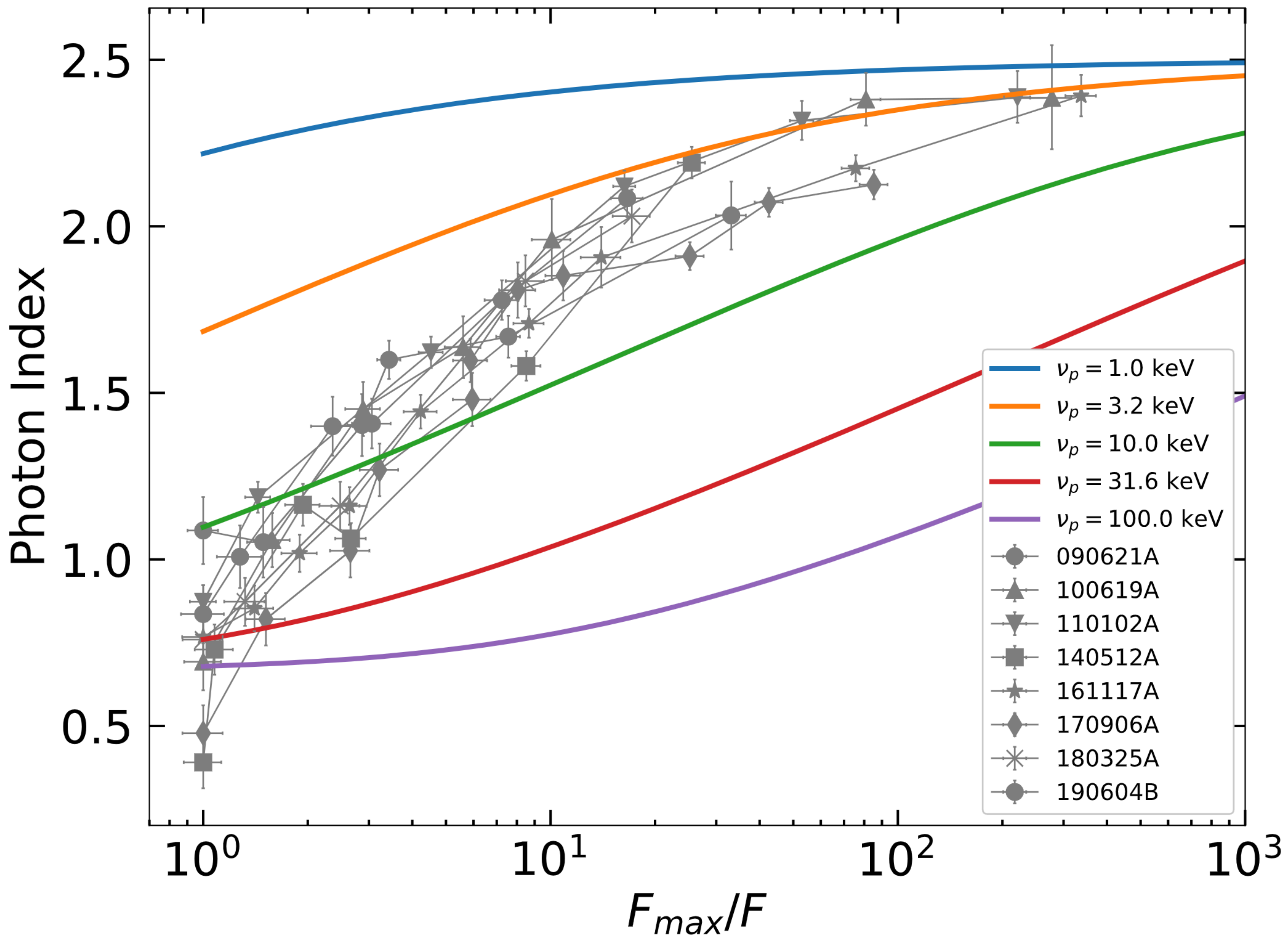
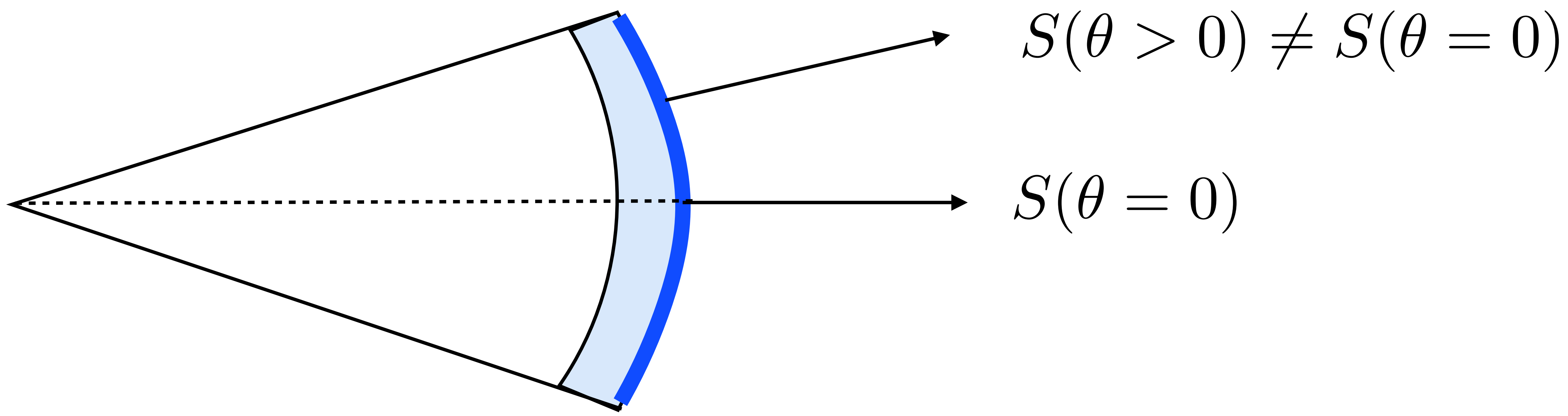
Interpreting the alpha-F relation

Radiative regime

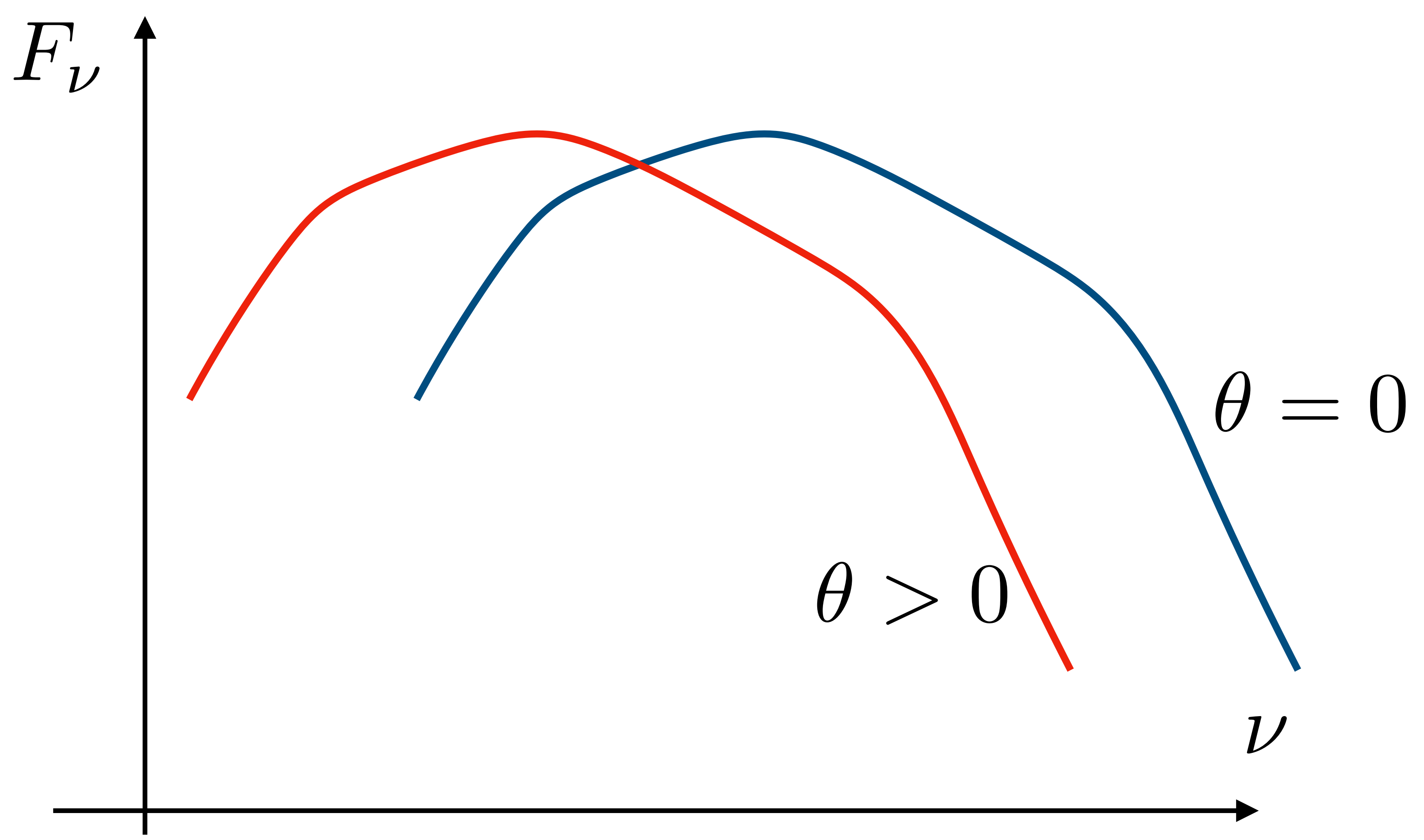


Predicted spectral evolution systematically shallower than the observed one

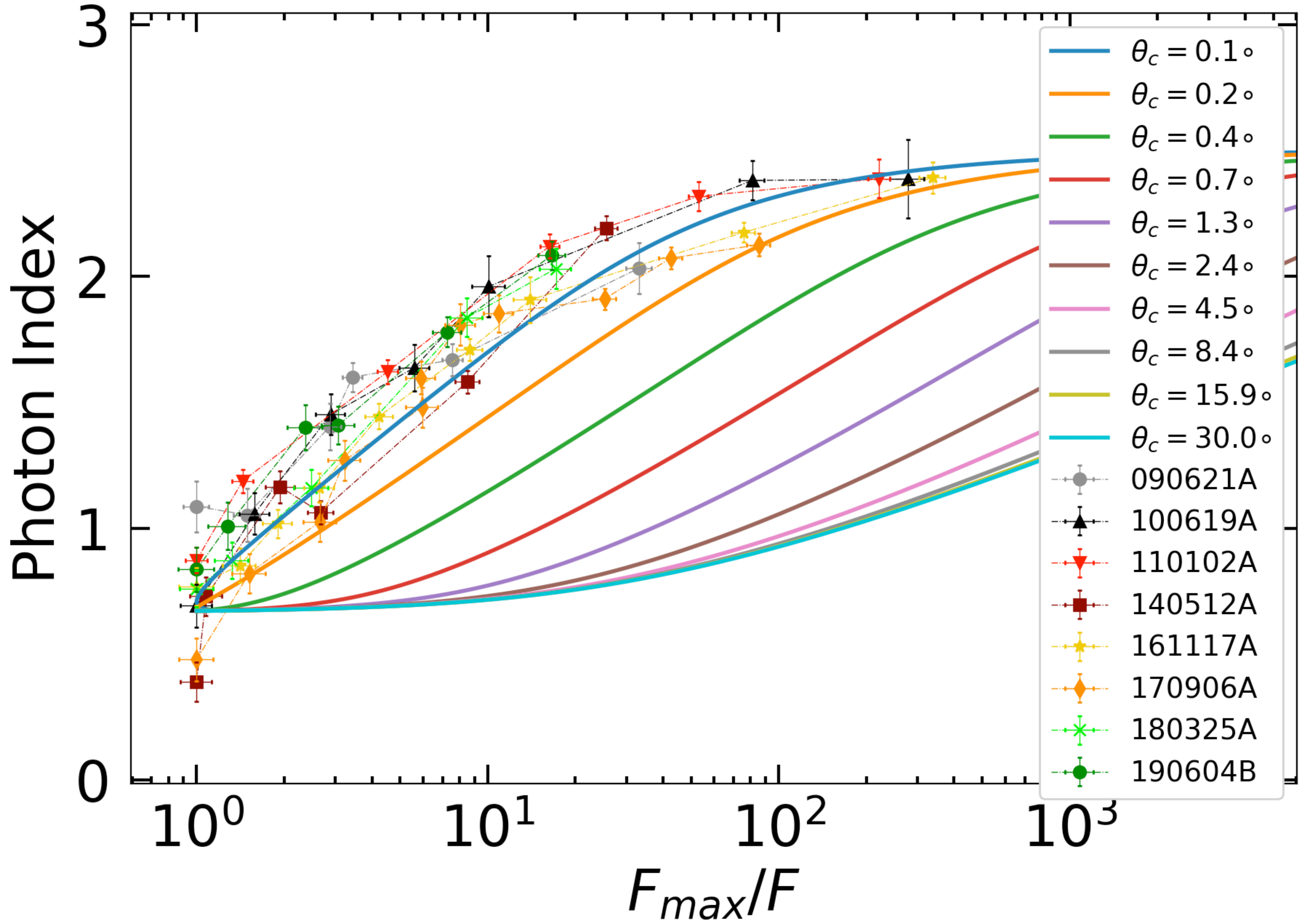
What if the spectrum is not the same along the jet surface?



Comoving frame



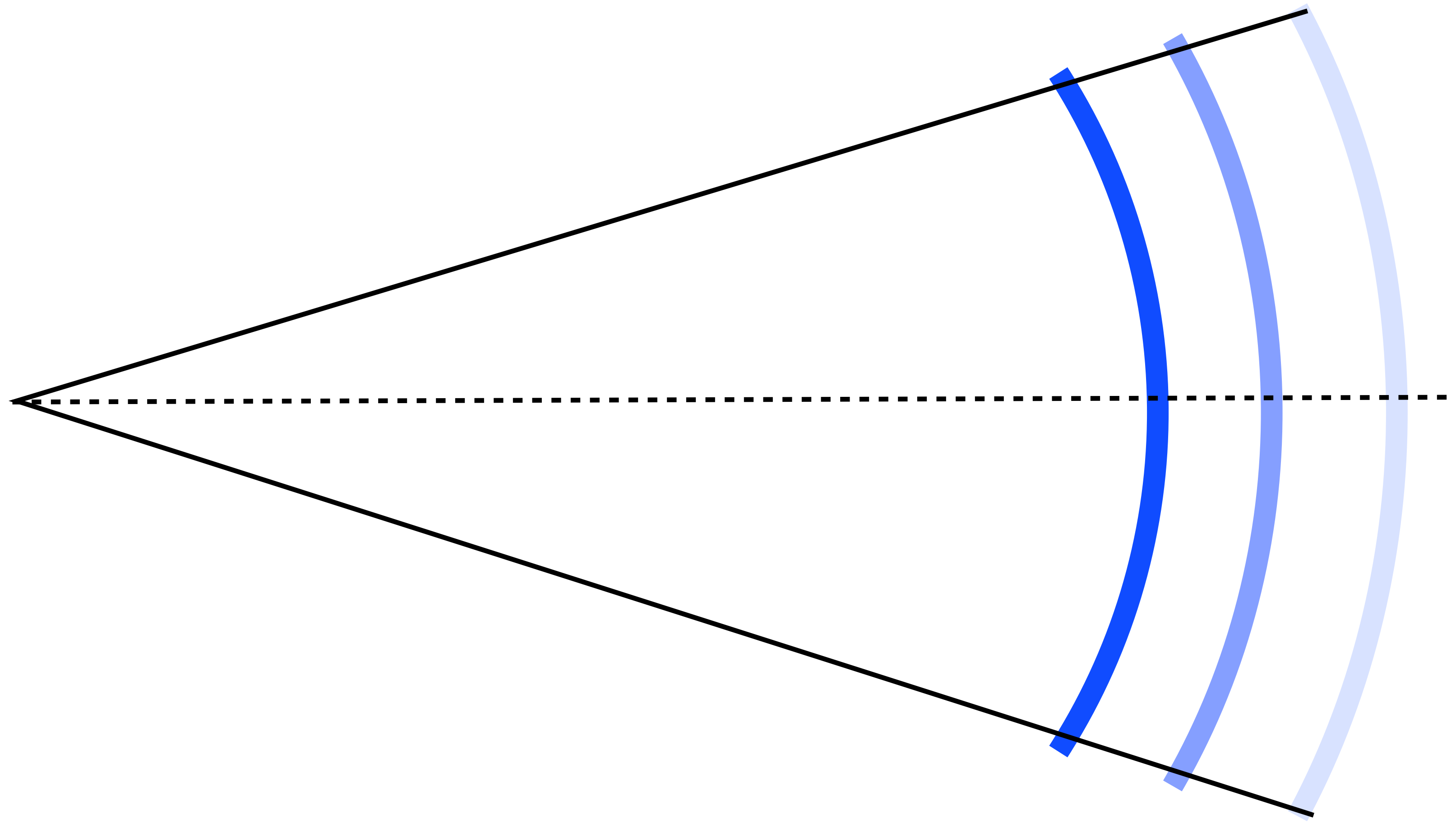
$$\nu_p(\theta) = \frac{\nu_{p,0}}{1 + (\frac{\theta}{\theta_c})^n}$$



Weak points of this scenario:

- All the GRBs of the sample should share the very same angular structure with extremely small core aperture angle
- All the GRBs of the sample should be observed exactly on axis

Adiabatic cooling



Conservation of entropy

$$\langle\gamma\rangle^3 V' = \text{const}$$

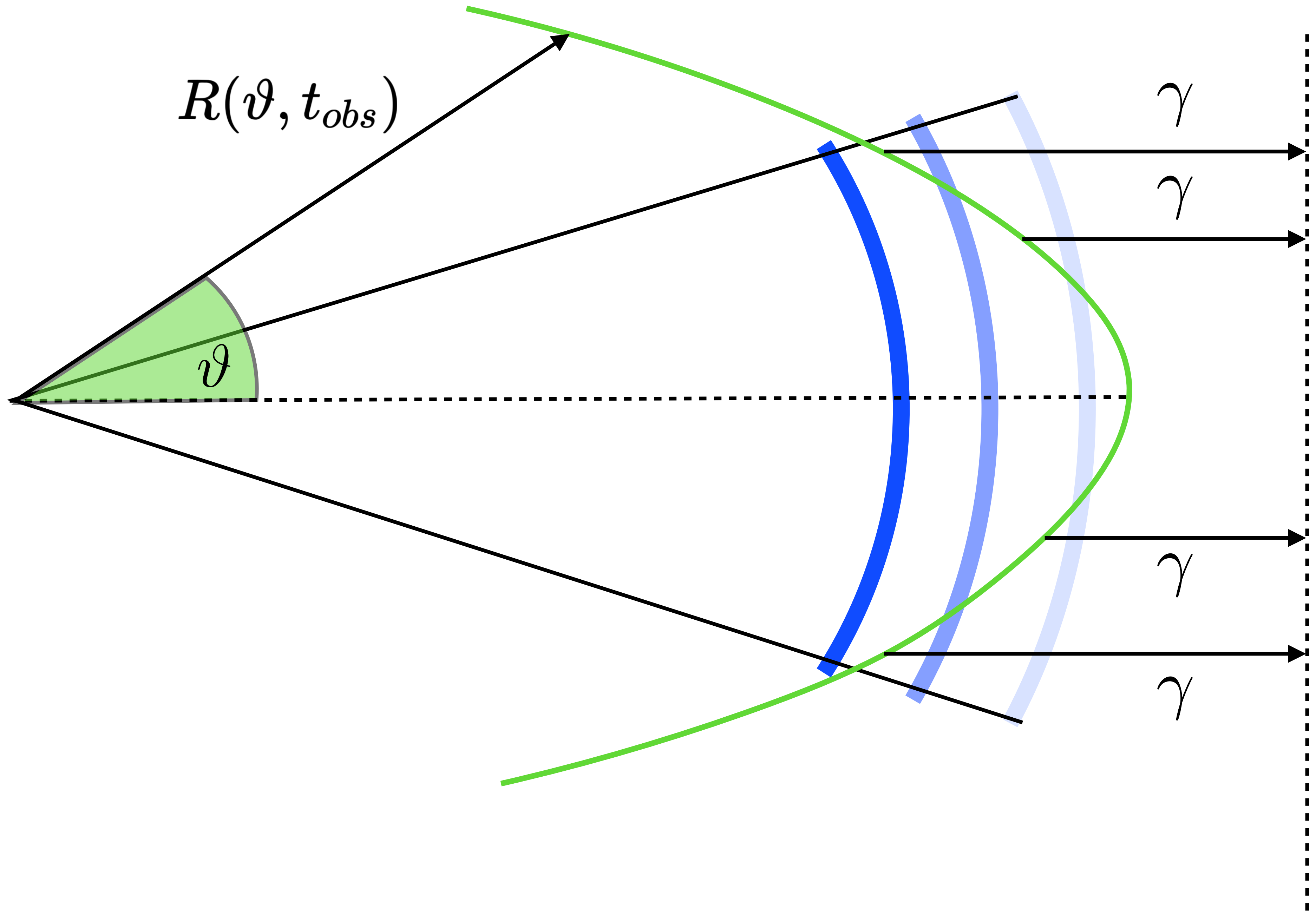
For a synchrotron spectrum

$$\nu_p \propto \langle\gamma\rangle^2 B$$

Prescription for B evolution

$$B = B_0 \left(\frac{R}{R_0}\right)^{-\lambda}$$

Adiabatic cooling



Equal Arrival Time Surfaces

$$R(\vartheta, t_{obs}) = \frac{\beta c t_{obs}}{1 - \beta \cos\vartheta}$$

$$F_\nu(t_{obs}) = \int_{\mathrm{EATS}} I_\nu(\vartheta_{obs}) \cos(\vartheta_{obs}) d\Omega_{obs}$$

$$F_\nu(t_{obs}) \propto \int_0^{\vartheta_j} S_{\nu'}(\nu/\mathcal{D}(\vartheta)) \left(\frac{R(\vartheta, t_{obs})}{R_0}\right)^{-\lambda} \mathcal{D}^3(\vartheta) \sin\vartheta \cos\vartheta d\vartheta$$

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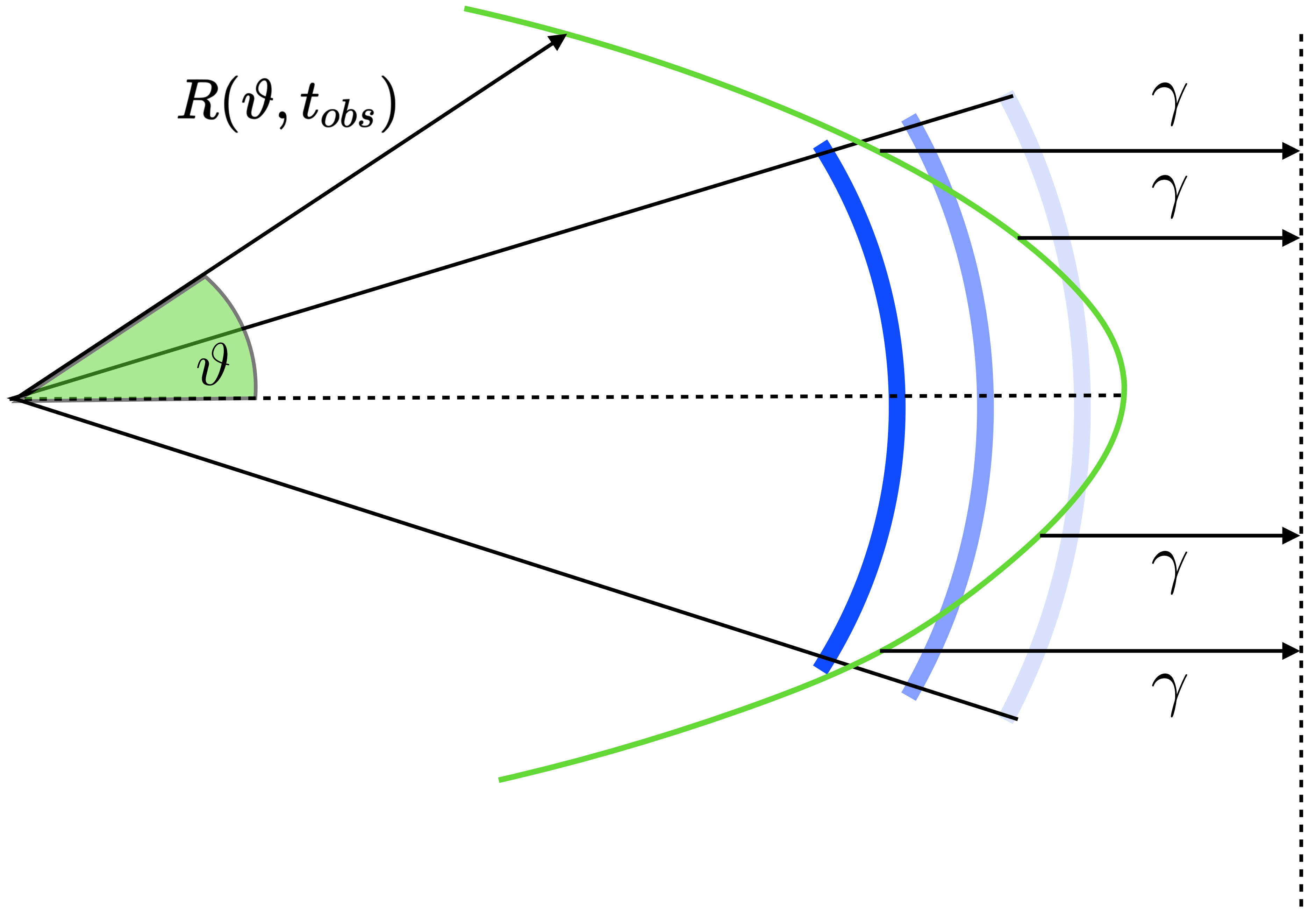

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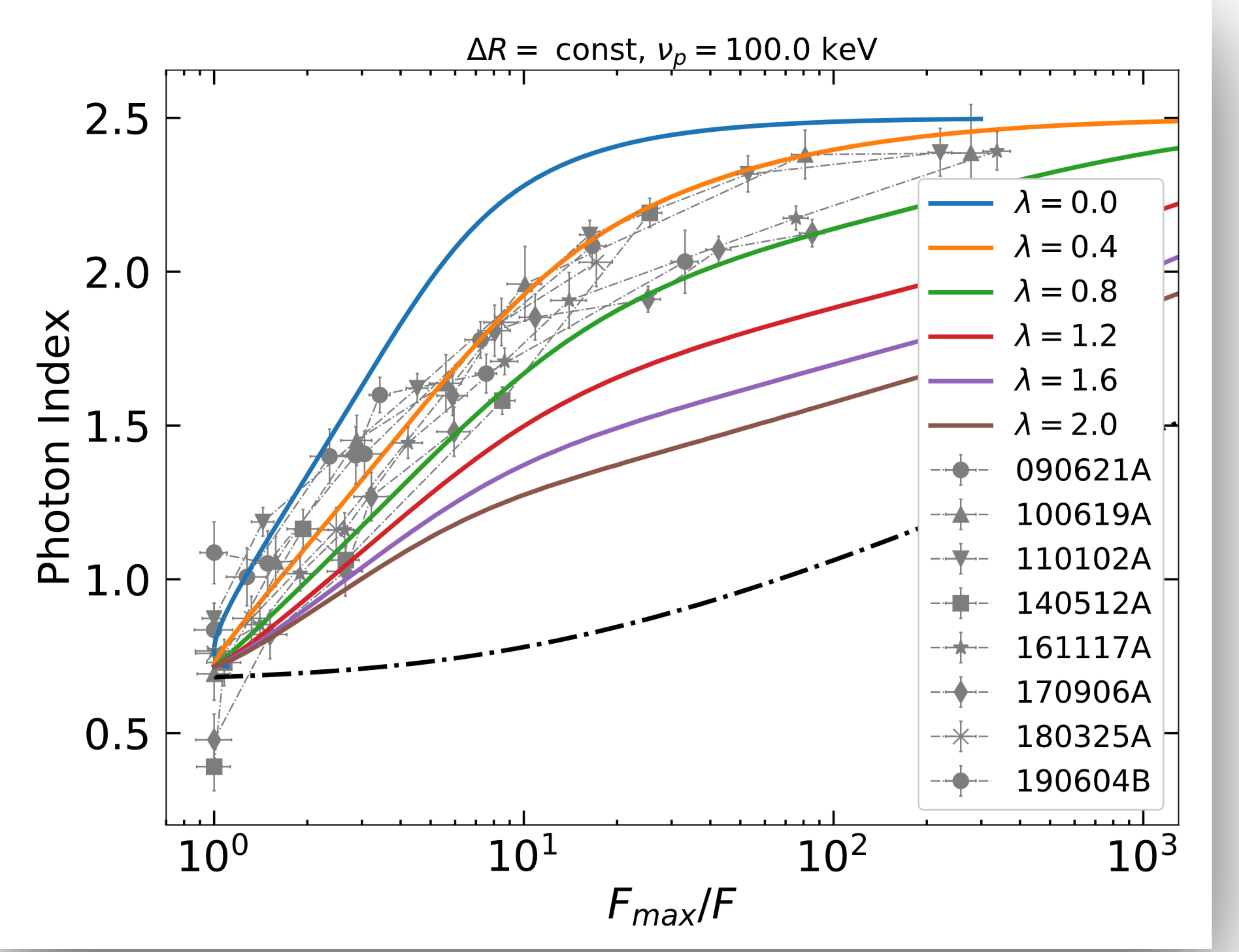
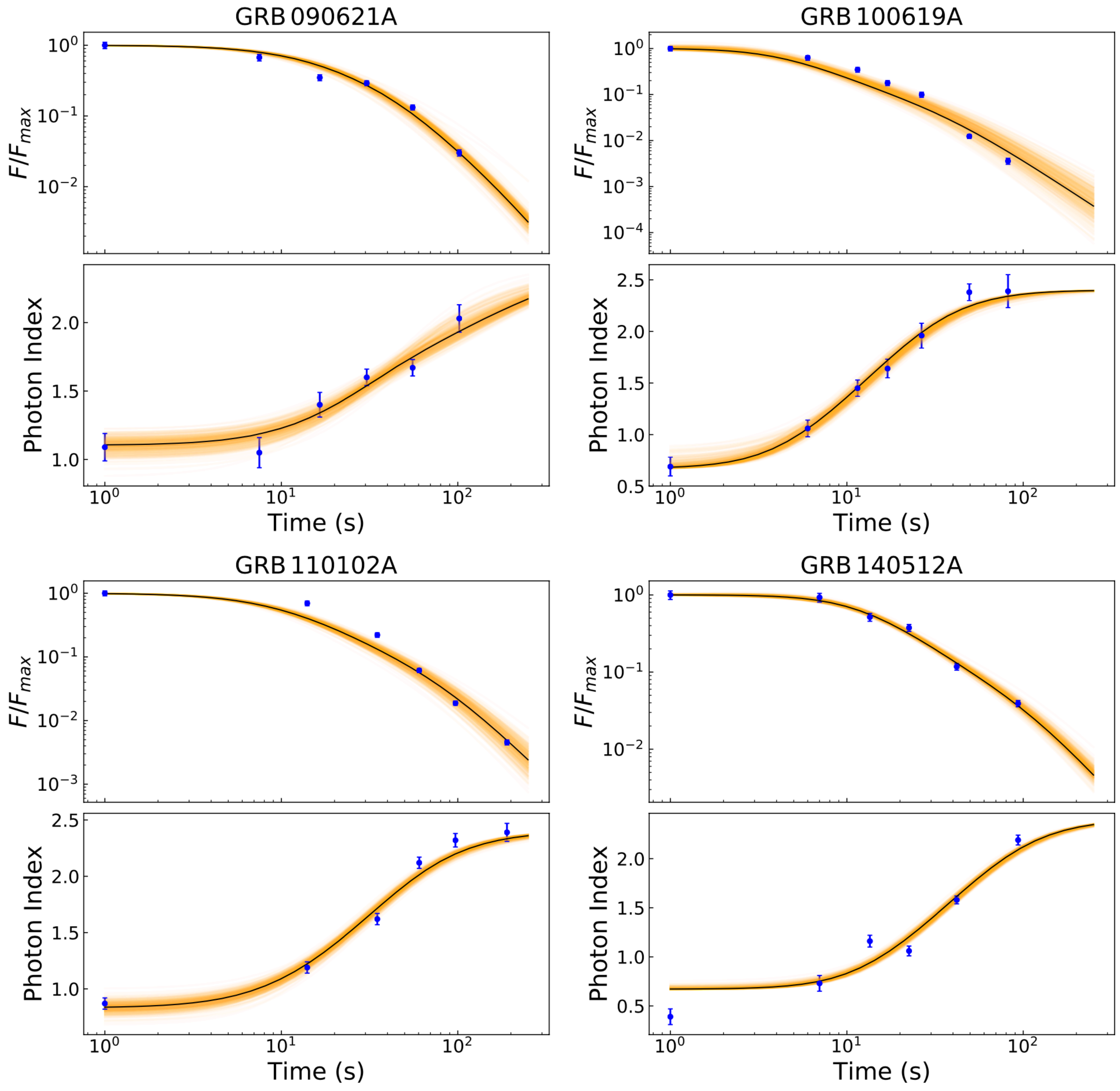



GRB 090621A
GRB 100619A
GRB 110102A
GRB 140512A
F/F_{max}
Photon Index
Time (s)

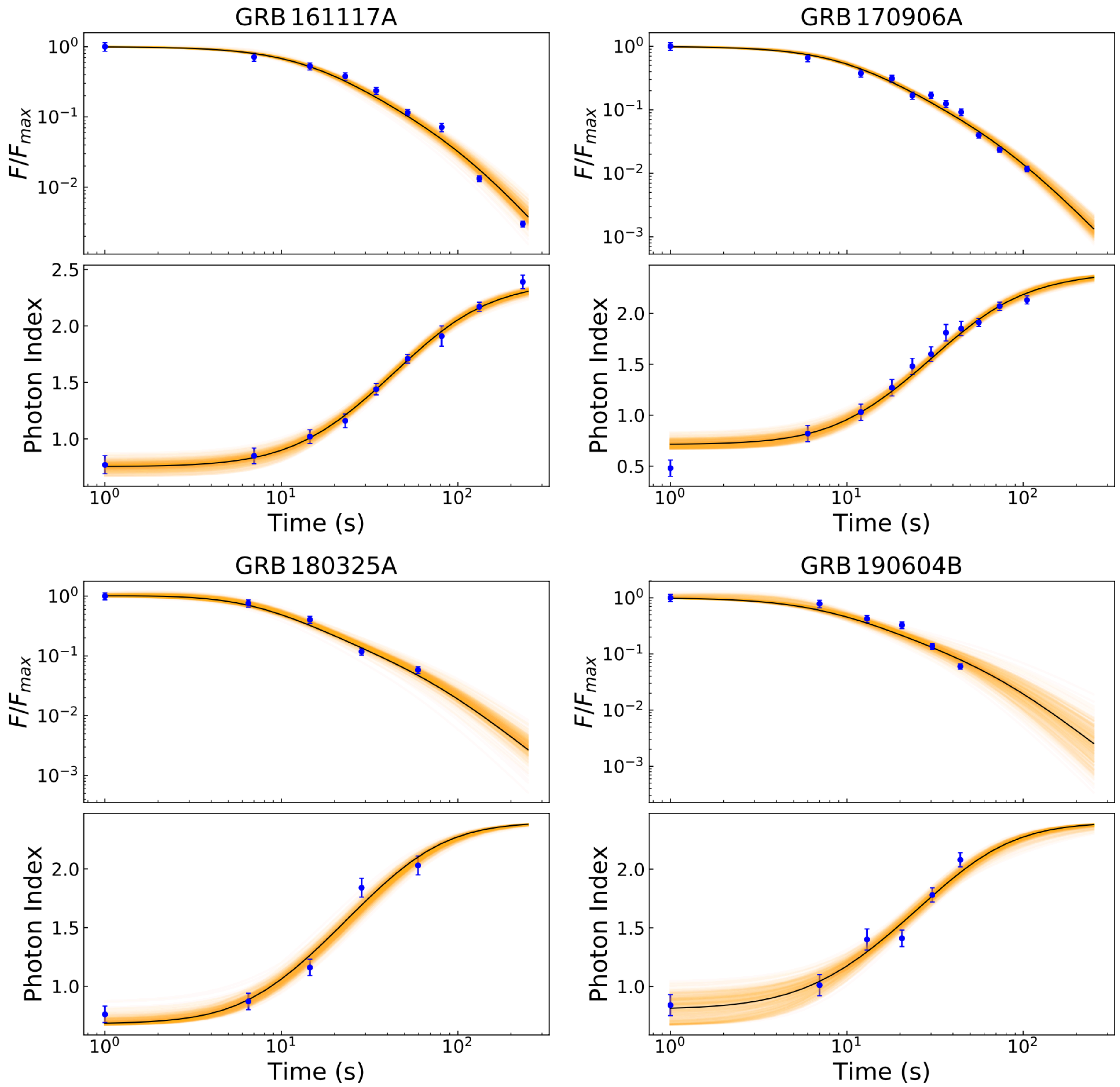

GRB 161117A
GRB 170906A
GRB 180325A
GRB 190604B
F/F_{max}
Photon Index
Time (s)

Table 1 Results of the parameter estimation via MCMC, adopting the adiabatic cooling model.

GRB	E_{peak} (keV)	λ	τ_{ad} (s)
090621A	18^{+3}_{-2}	$2.11^{+0.56}_{-0.54}$	$24.4^{+4.7}_{-3.0}$
100619A	>129	$0.47^{+0.11}_{-0.07}$	$0.3^{+1.0}_{-0.2}$
110102A	46^{+15}_{-9}	$0.61^{+0.10}_{-0.10}$	$5.8^{+1.9}_{-1.1}$
140512A	>323	$0.48^{+0.04}_{-0.03}$	$0.9^{+0.9}_{-0.4}$
161117A	80^{+55}_{-21}	$0.69^{+0.10}_{-0.10}$	$6.2^{+2.0}_{-2.3}$
170906A	135^{+204}_{-53}	$0.66^{+0.10}_{-0.09}$	$3.0^{+1.6}_{-1.5}$
180325A	>122	$0.39^{+0.06}_{-0.05}$	$0.8^{+1.3}_{-0.5}$
190604B	54^{+227}_{-20}	$0.45^{+0.25}_{-0.15}$	$3.5^{+2.6}_{-2.8}$

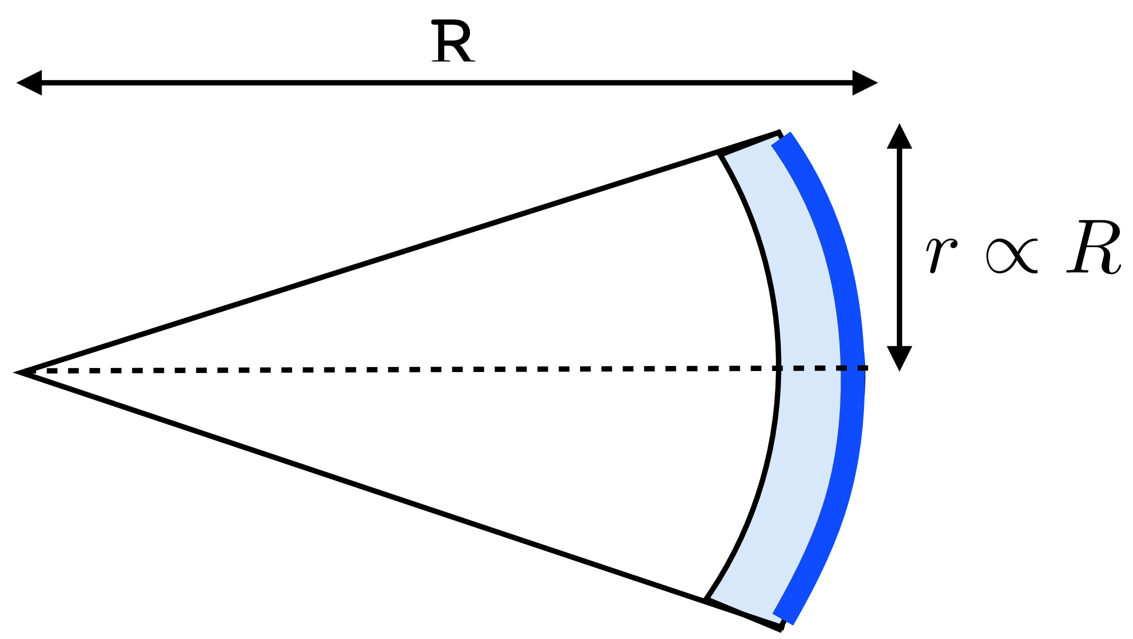
The confidence intervals and the lower limits represent the 16th, 50th, and 84th percentiles of the samples in the marginalized distributions (i.e., 1σ level of confidence).

Rule of thumb estimation of the expected values of λ

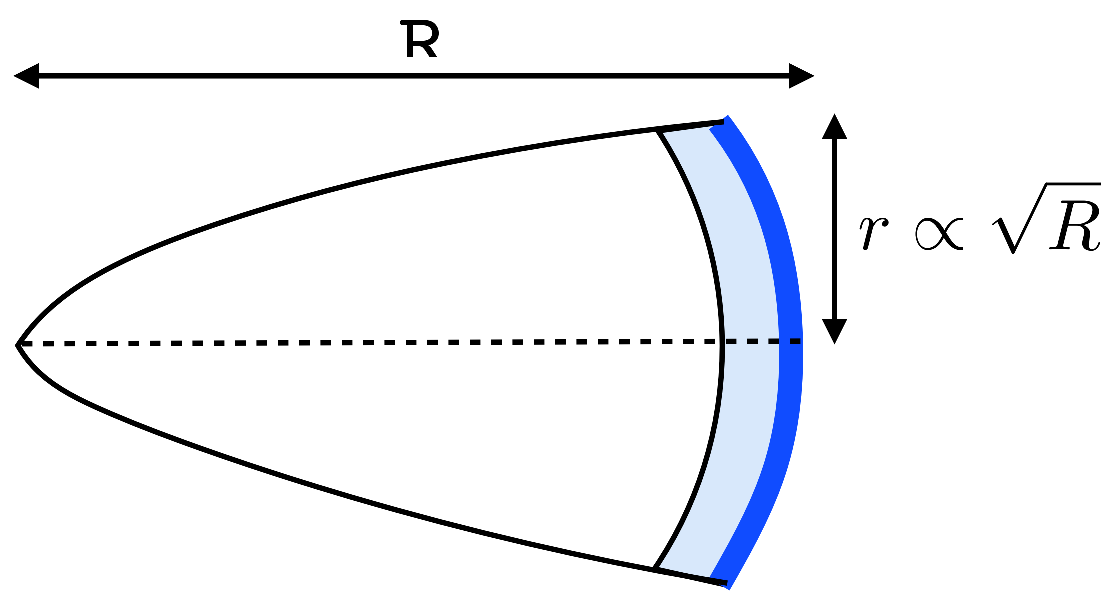
From the fit of alpha-F relation:

$$0.2 \lesssim \lambda \lesssim 0.8$$

Conical jet



Parabolic jet



- in case of equipartition: $B^2 \sim \frac{kT}{V} \sim V^{-1/3} \cdot \frac{1}{V} \sim V^{-4/3}$ $\quad V \sim \Delta R \cdot r^2$

$$B \propto V^{-2/3} \propto R^{-4/3} \rightarrow \lambda = 4/3$$

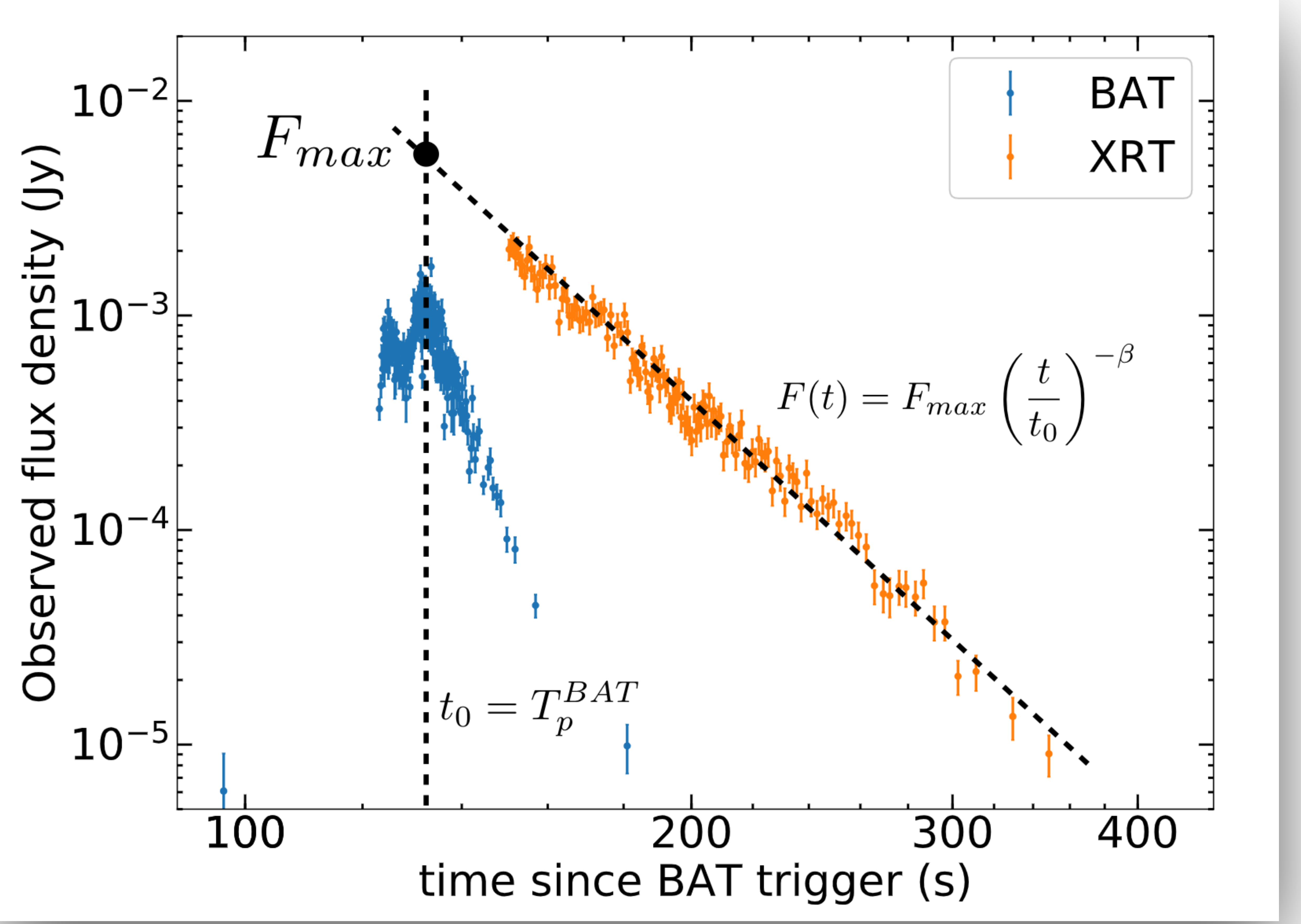
$$B \propto V^{-2/3} \propto R^{-2/3} \rightarrow \lambda = 2/3$$

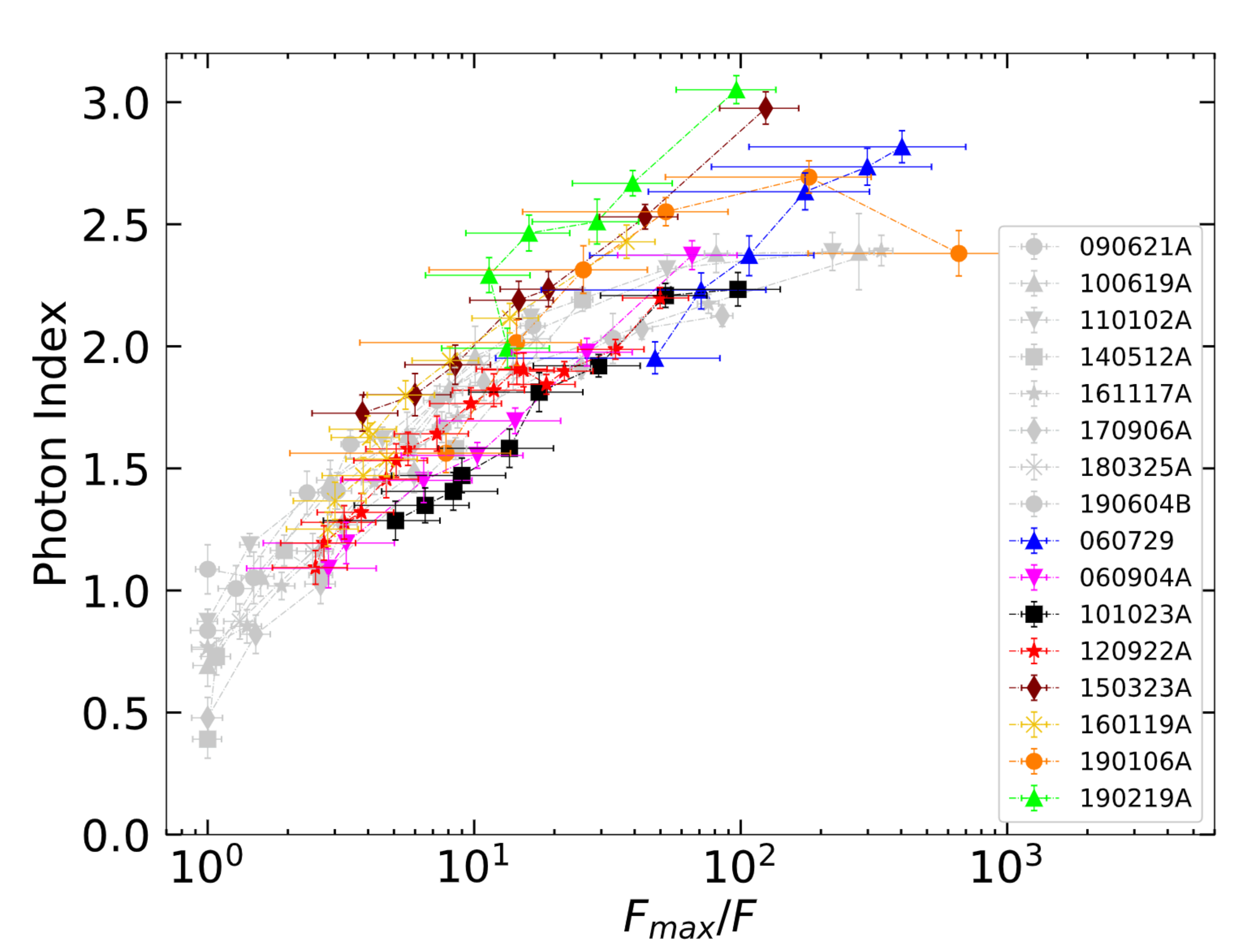
- in case of magnetic flux conservation: $B_\perp \sim \frac{1}{\Delta R \cdot r}, \quad B_{//} \sim \frac{1}{r^2}$

$$B = \sqrt{B_\perp^2 + B_{//}^2} \propto R^{-1} \rightarrow \lambda = 1$$

$$B = \sqrt{B_\perp^2 + B_{//}^2} \propto R^{-1/2} \rightarrow \lambda = 1/2$$

The extended sample





For more details, check our paper here:

https://doi.org/10.1038/s41467-021-24246-x

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https://doi.org/10.1038/s41467-021-24246-x OPEN

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Spectral index-flux relation for investigating the origins of steep decay in γ-ray bursts

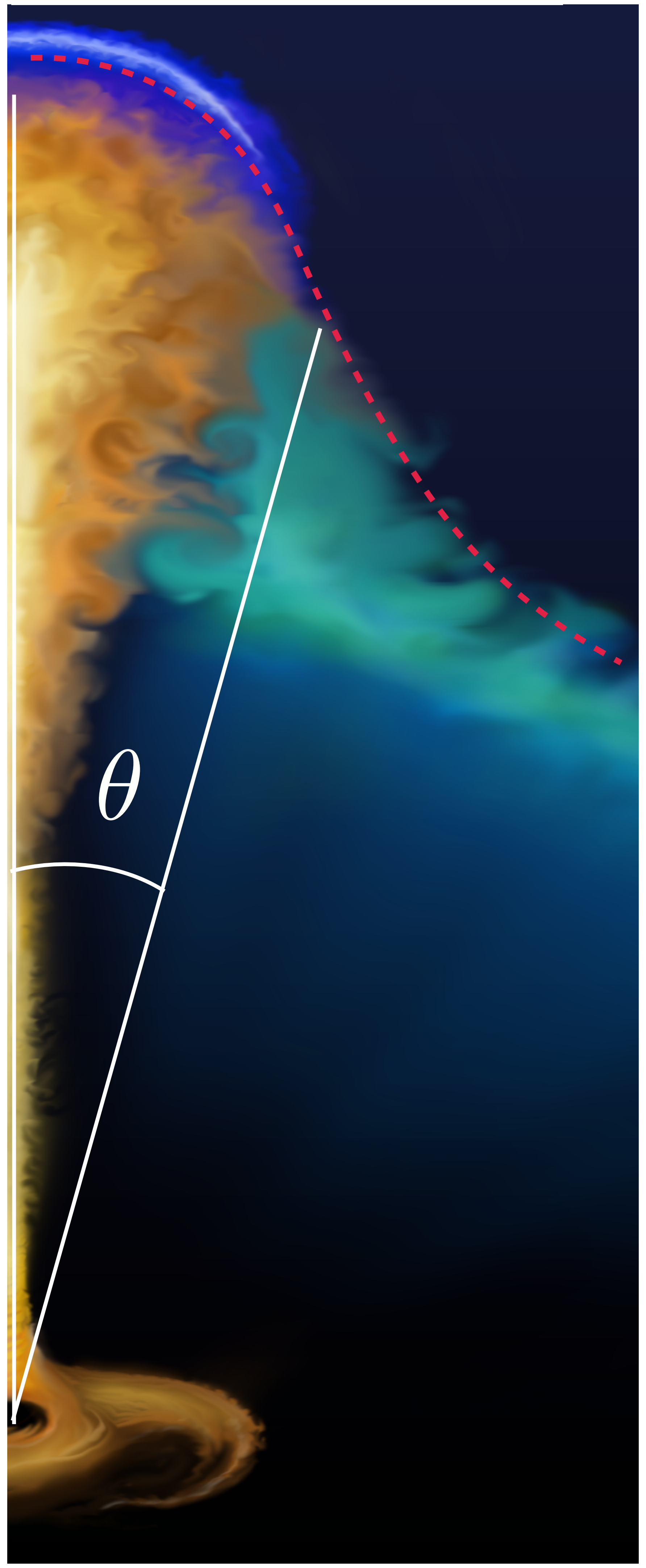
Samuele Ronchini[1,2,3]✉, Gor Oganesyan[1,2,3], Marica Branchesi[1,2,3], Stefano Ascenzi[4,5,6], Maria Grazia Bernardini[4], Francesco Brighenti[1], Simone Dall'Osso[1,2], Paolo D'Avanzo[4], Giancarlo Ghirlanda[4,7], Gabriele Ghisellini[4], Maria Edvige Ravasio[4,7] & Om Sharan Salafia[4,8]

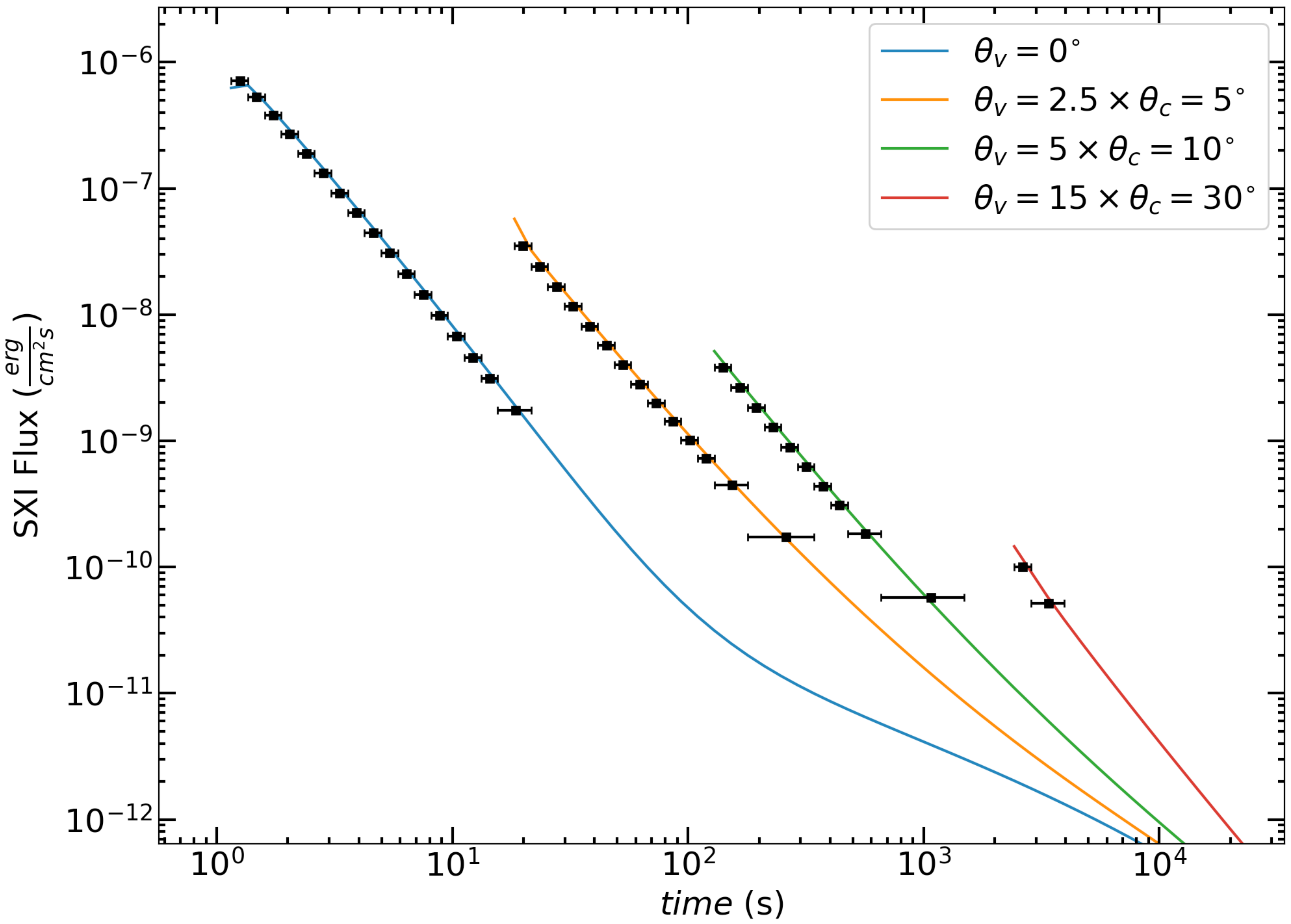
Conclusions

- The spectral evolution during the steep decay of prompt-like pulses in GRBs is characterised by a **unique relation**
- The standard **high latitude emission** scenario cannot account for the spectral evolution during the steep decay.
- Our results disfavour an **efficient particle cooling**
- The inclusion of **adiabatic cooling** of particles well explains the observed alpha-F relation
- The **inefficient radiative cooling** of particles in GRB outflows is in contrast with energy dissipations from electrons, suggesting a proton-synchrotron origin of the emission

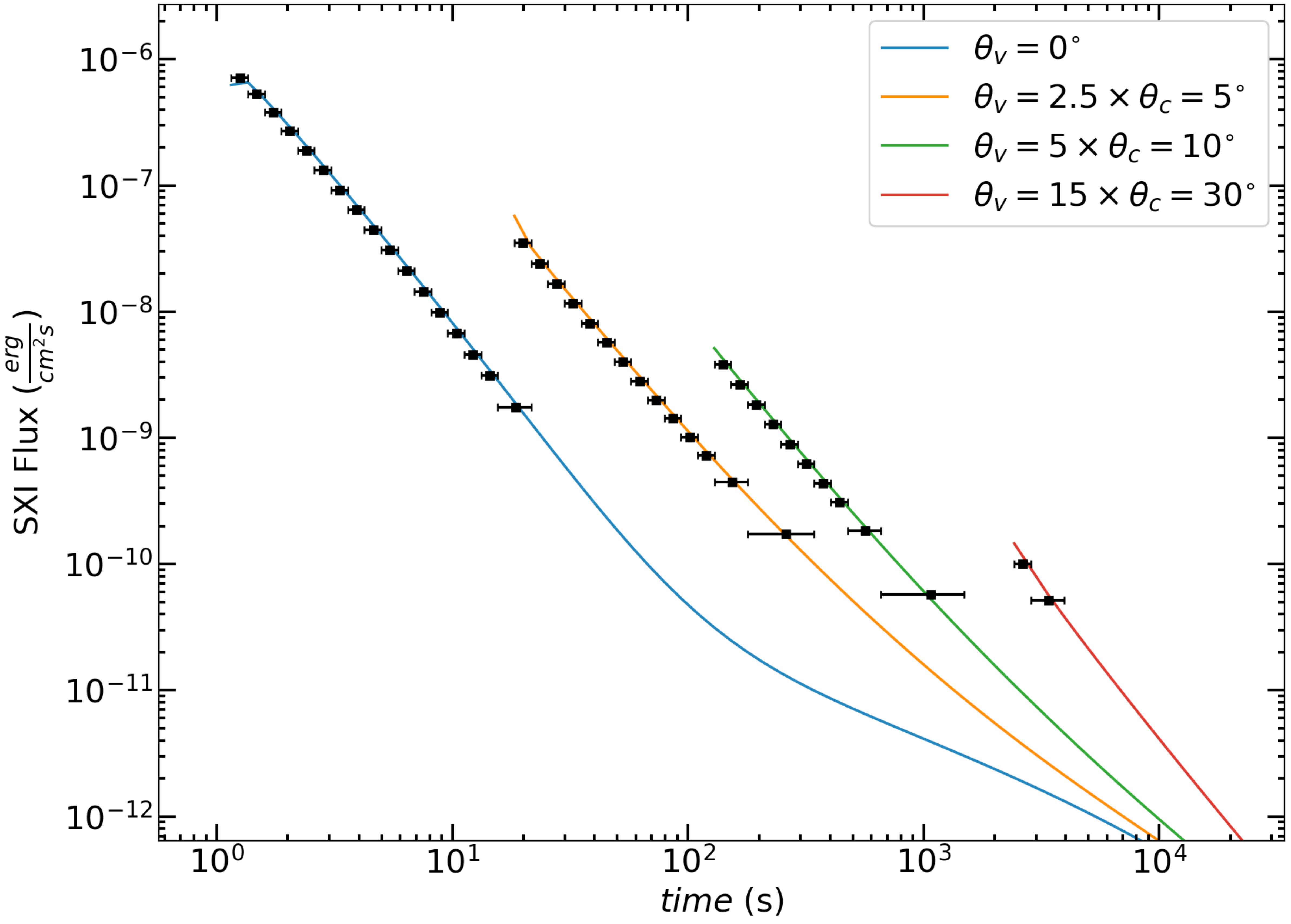
Perspectives for the future

$$\Gamma(\theta) = 1 + \frac{\Gamma_c - 1}{1 + (\theta/\theta_c)^s}$$



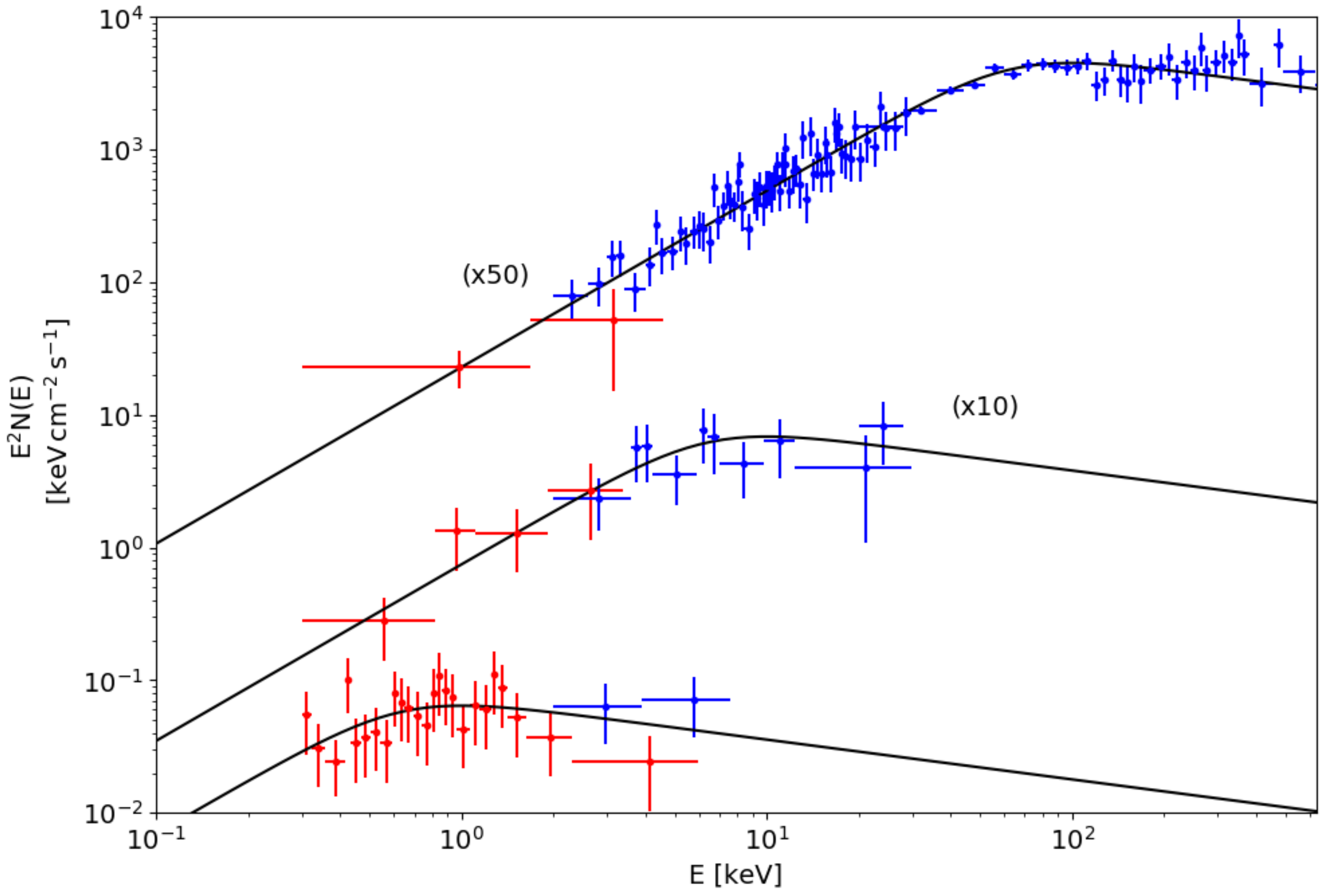


Perspectives for the future

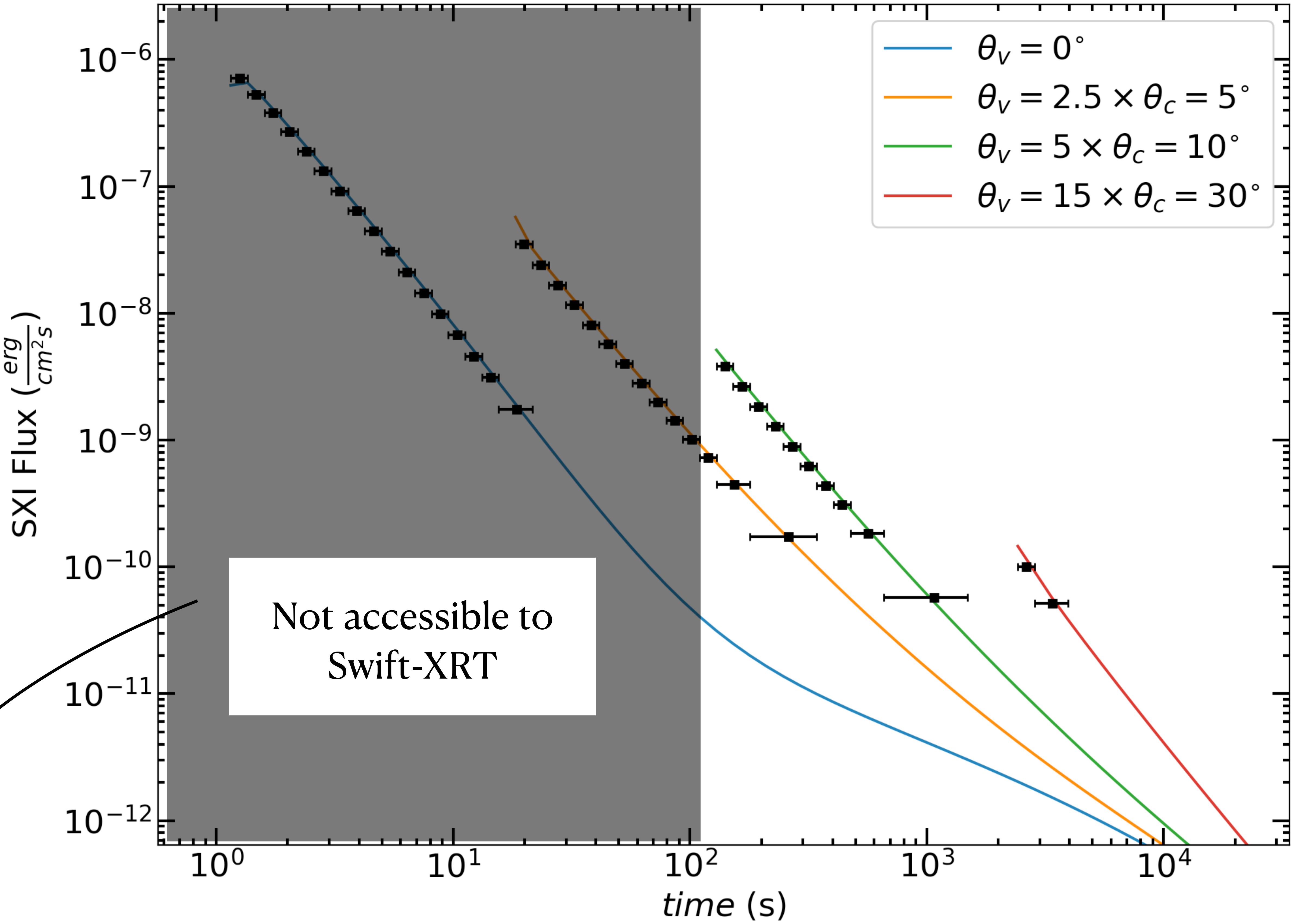


theseus
TRANSIENT HIGH ENERGY SKY AND EARLY UNIVERSE SURVEYOR

XGIS: 2 keV - 20 MeV
SXI: 0.3 - 5 keV



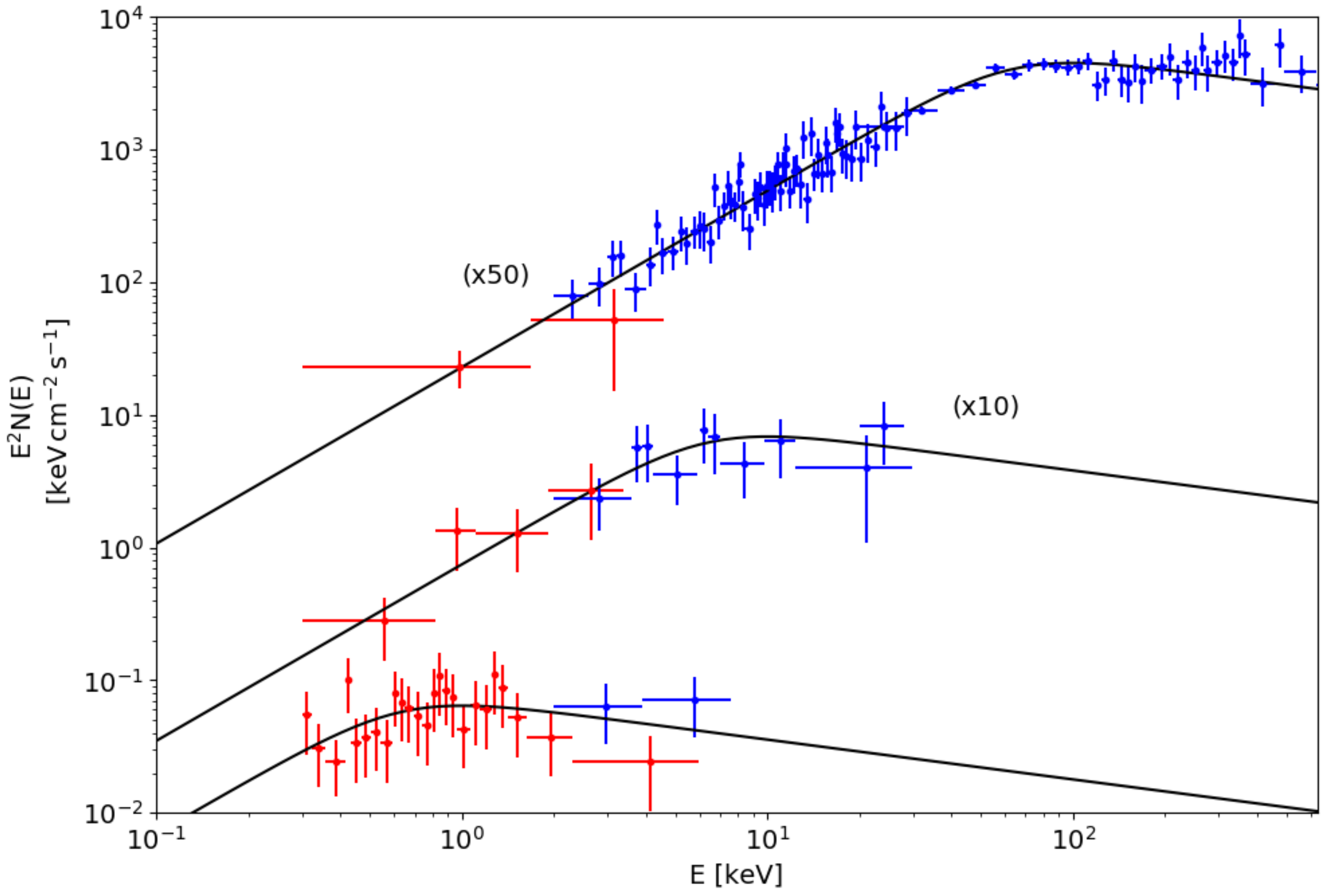
Perspectives for the future



At the moment we do not have a wide-field telescope capable to monitor the X-ray emission during the first instants after the trigger

theseus
TRANSIENT HIGH ENERGY SKY AND EARLY UNIVERSE SURVEYOR

XGIS: 2 keV – 20 MeV
SXI: 0.3 – 5 keV



Thanks for your attention!