Report on research status

Multimessenger observations and modelling of GRBs

GS
SI

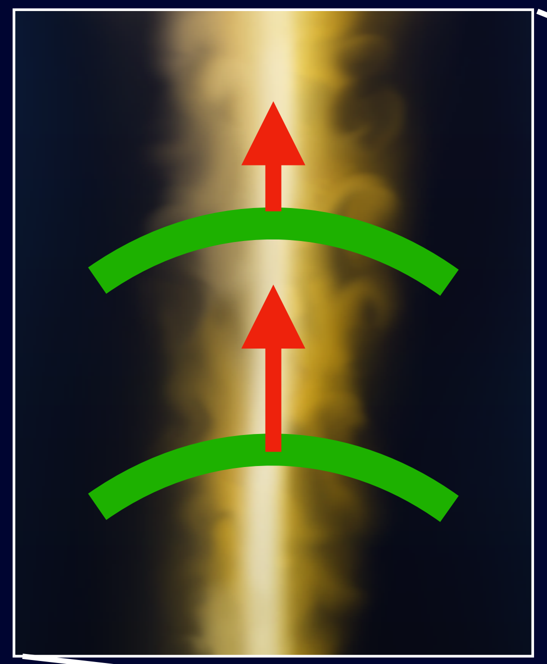
Advisors:
Marica Branchesi
Gor Oganesyan

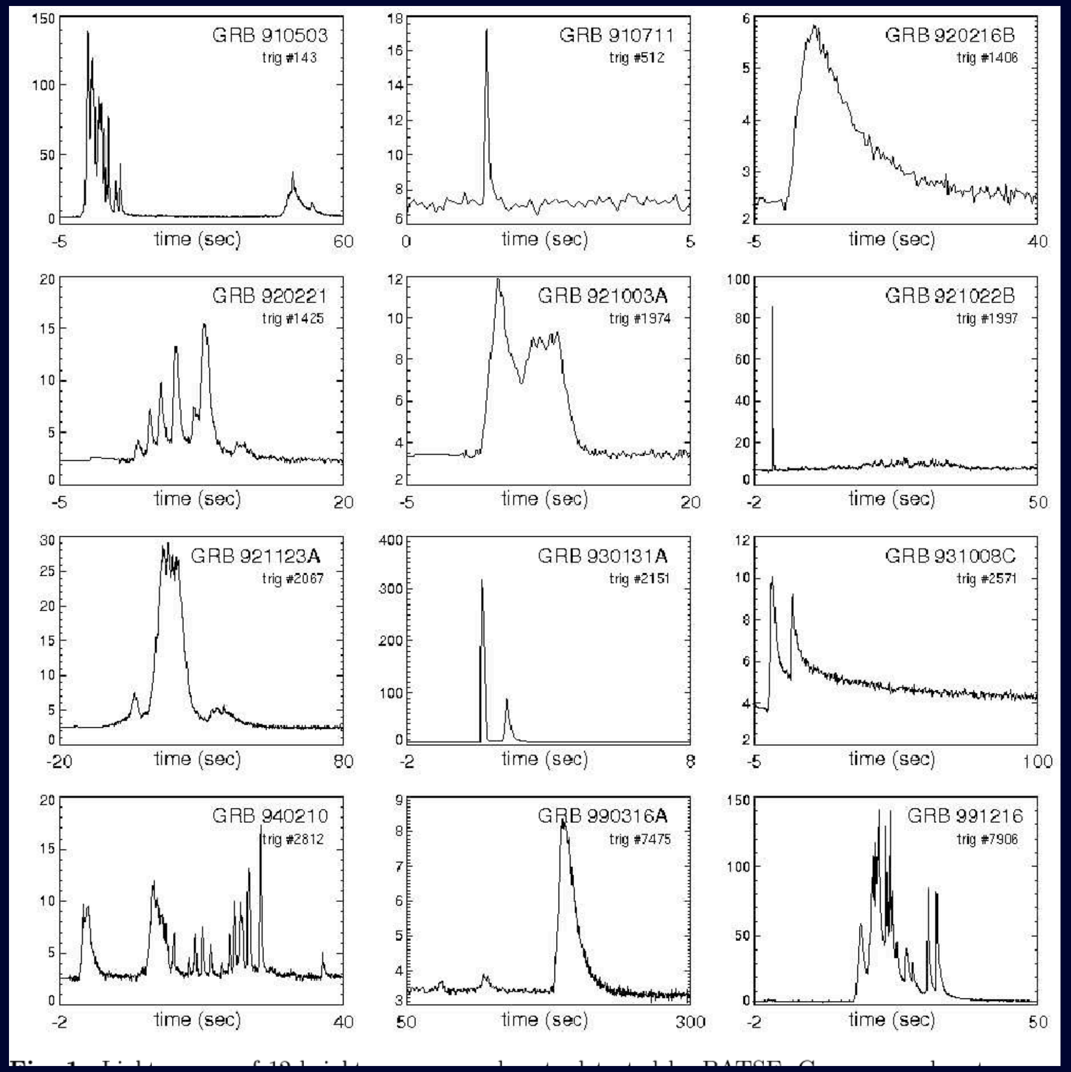
- ✴ GRBs: our knowledge after the advent of Swift and GW170817
- ✴ Physics behind the X-ray emission of GRBs
- ✴ GRBs as counterpart of GW events
- ✴ Future perspectives for multi-messenger observations

Prompt emission phase:

Energy range: keV-MeV

Variability time-scales: ms-s





Shemi & Piran (1990)

Rees & Meszaros (1994)

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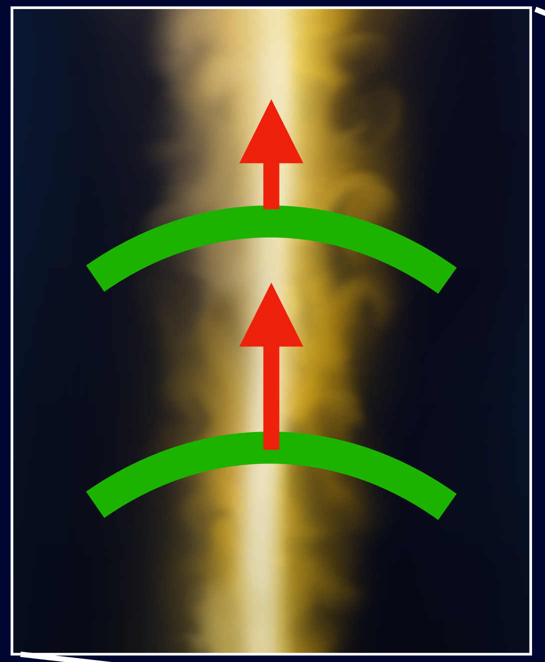
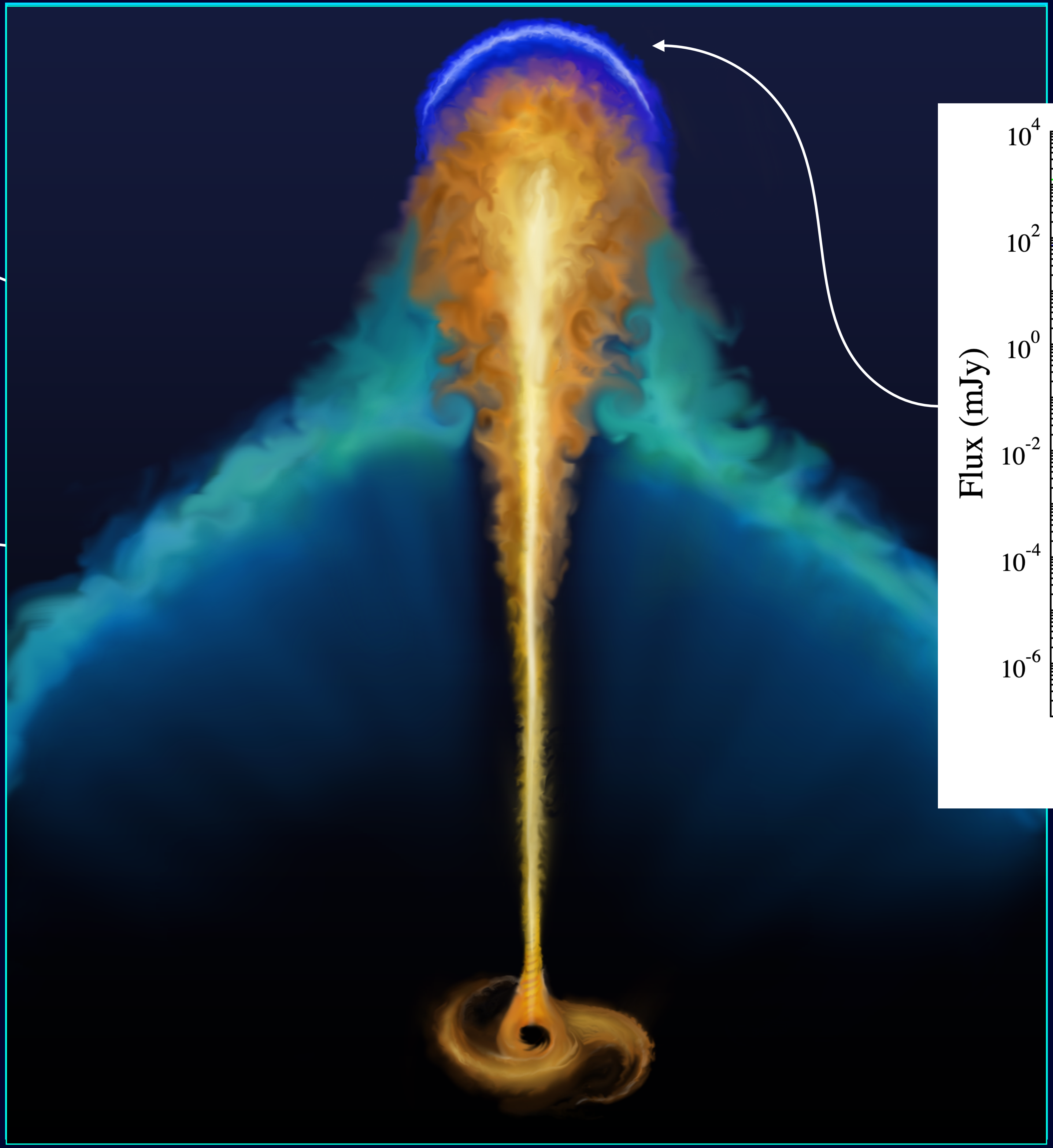
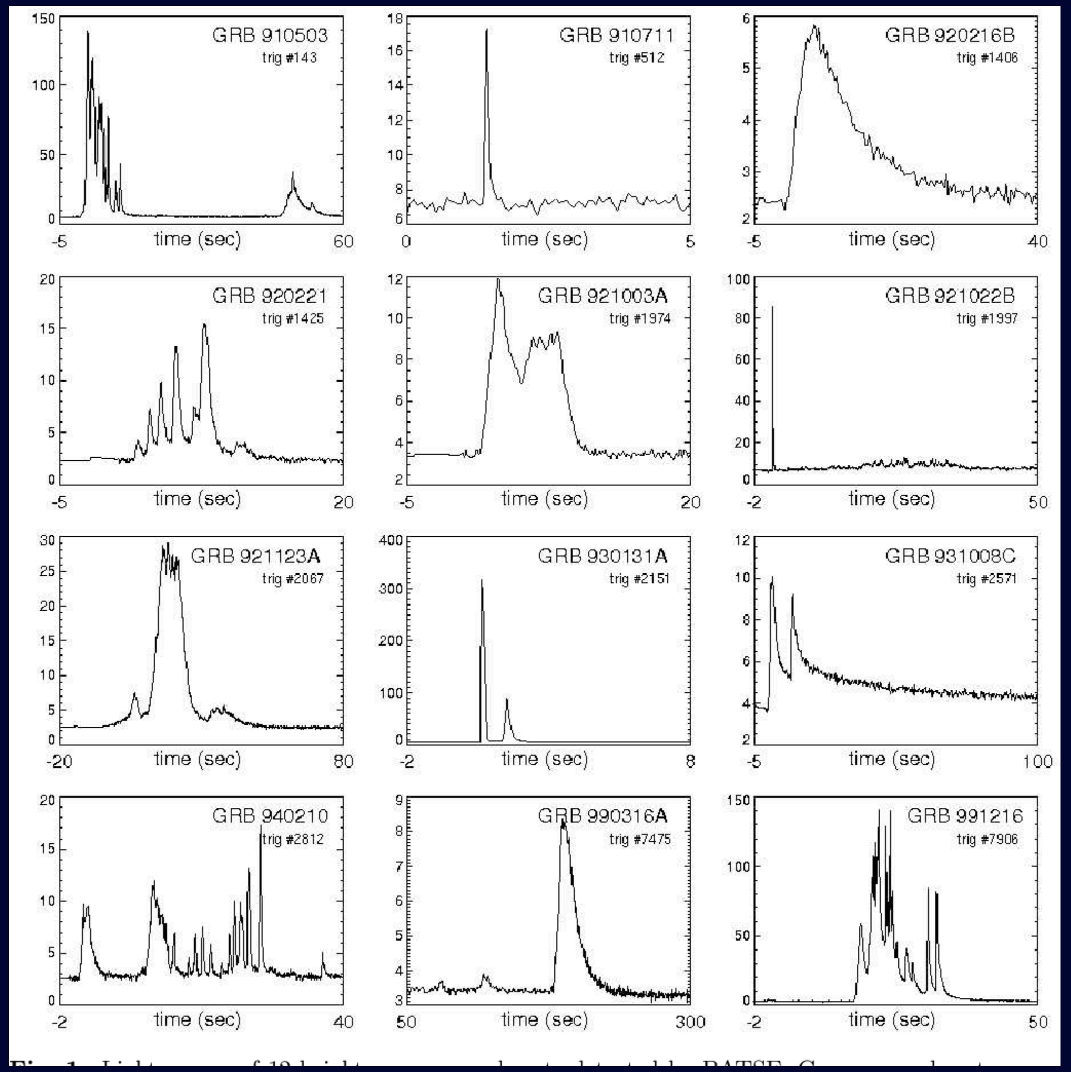


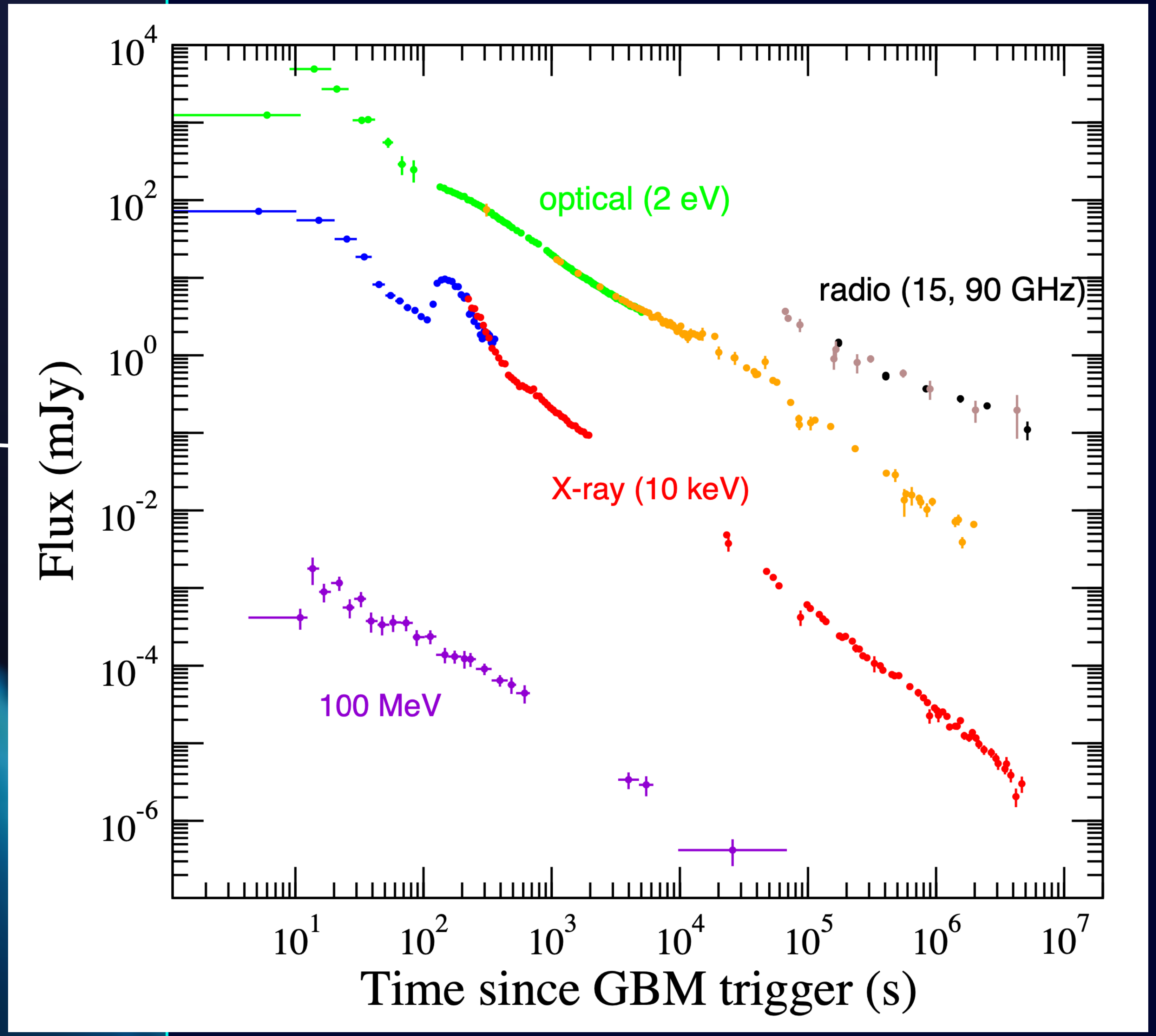




Shemi & Piran (1990)

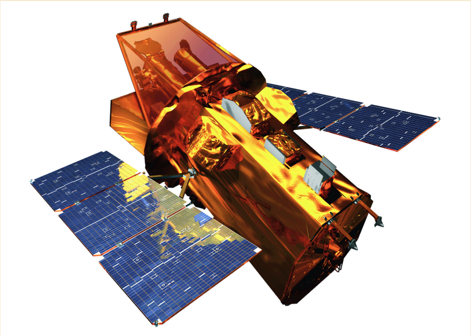
Rees & Meszaros (1994)

Afterglow phase



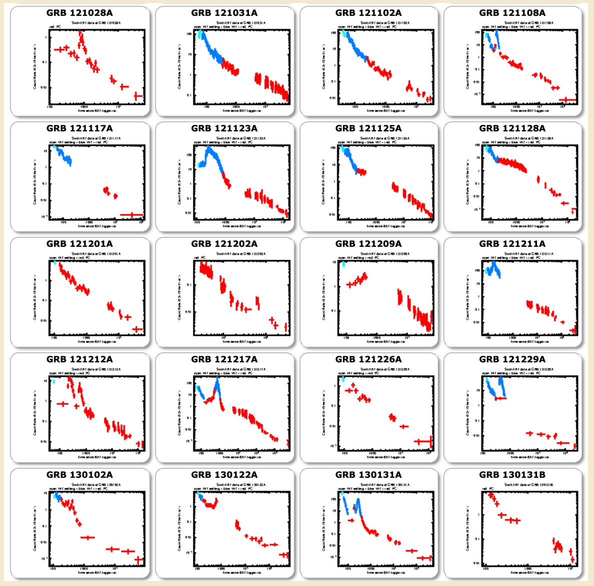
From Panaitescu et al (2013)

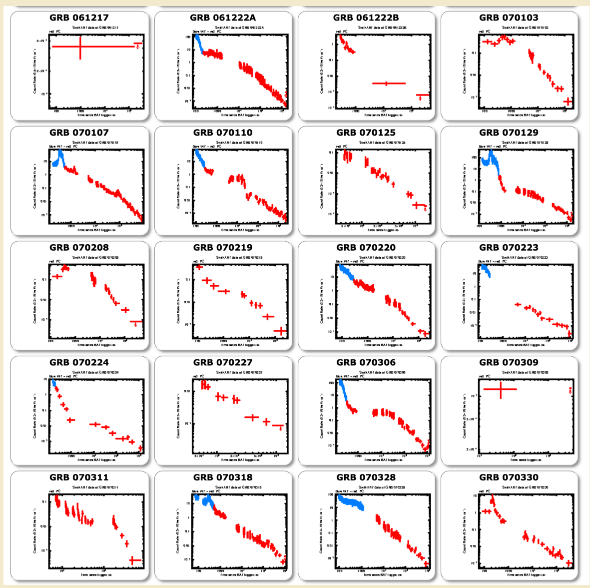
The Neil Gehrels Swift Observatory



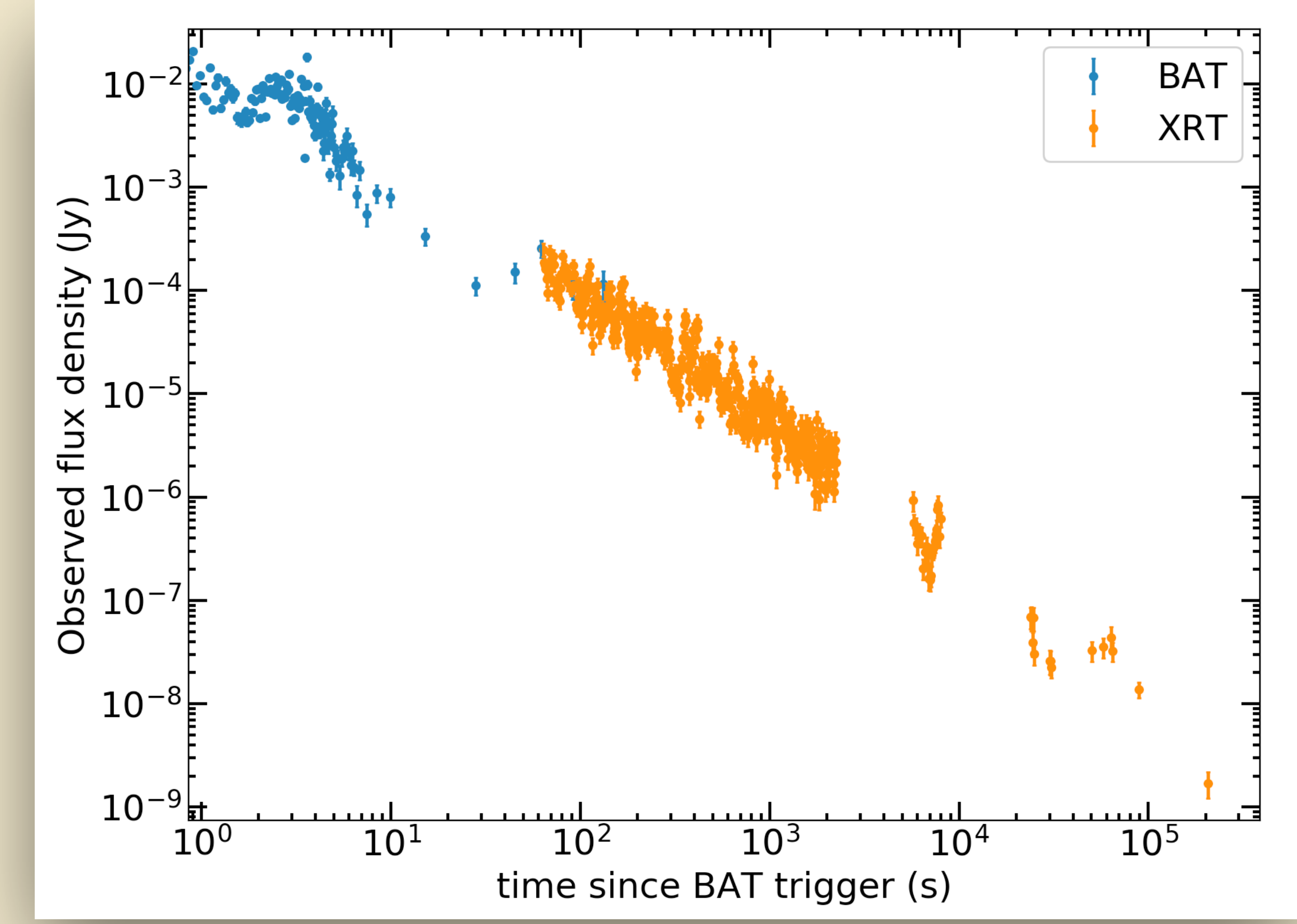
- BAT (15-150 keV)
- XRT (2-10 keV)
- UVOT (opt band)

Almost 1400 GRBs detected in 16 years



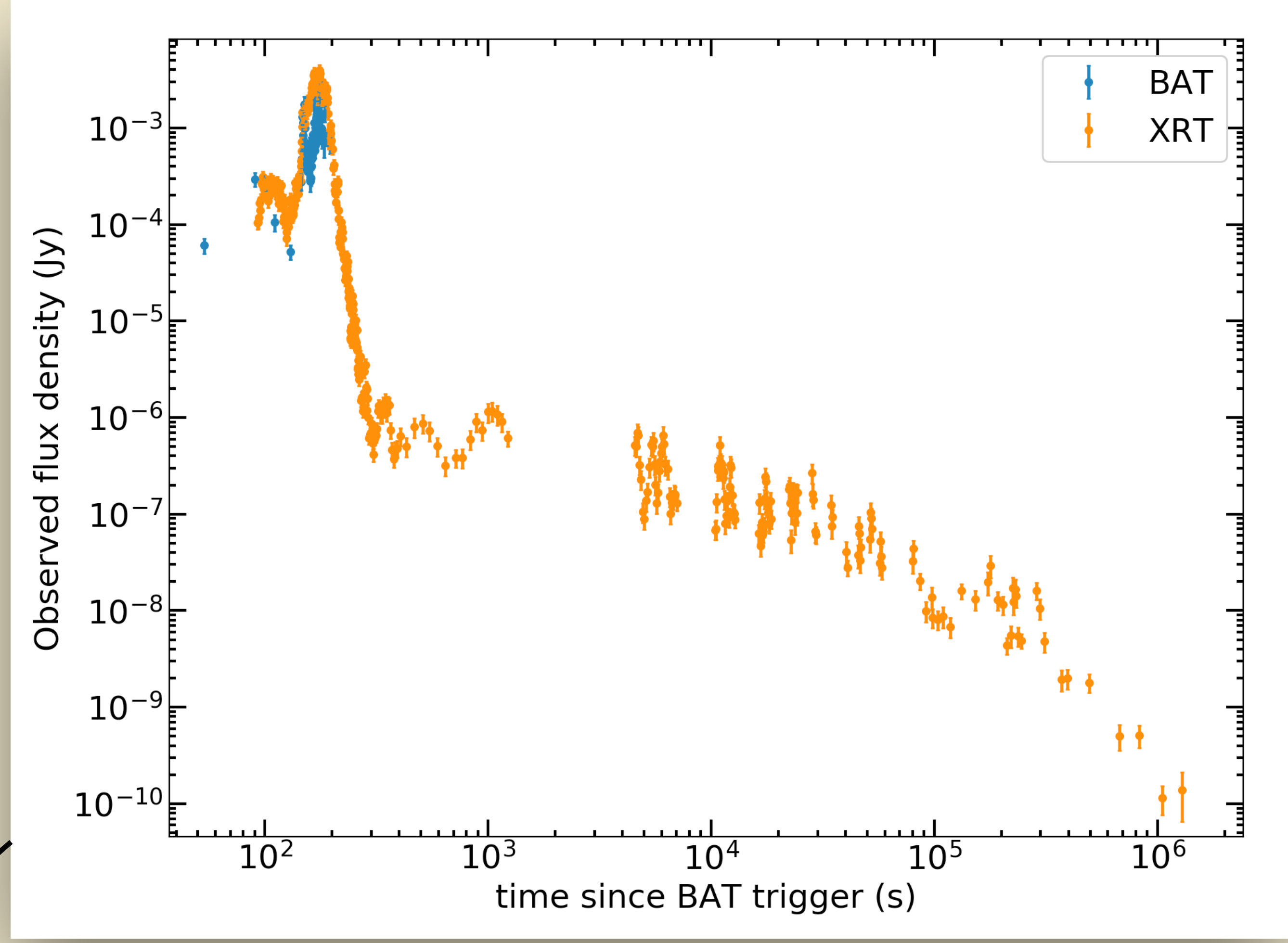


Standard power law decay given by the deceleration of the forward shock



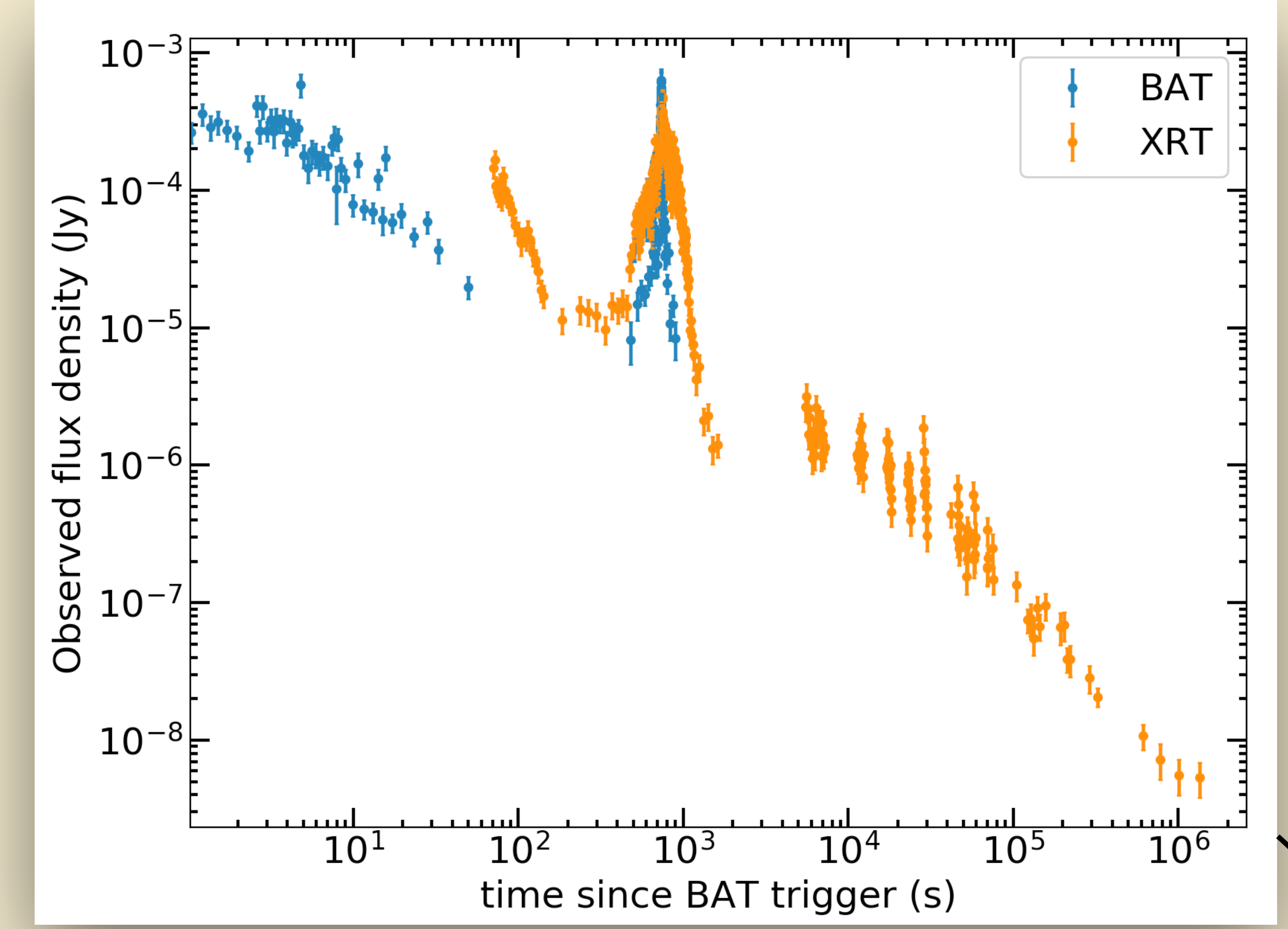
Mèszaros & Rees (1997)

Steep decay + plateau



Tagliaferri et al. (2005), Zhang (2006)

X-ray flares

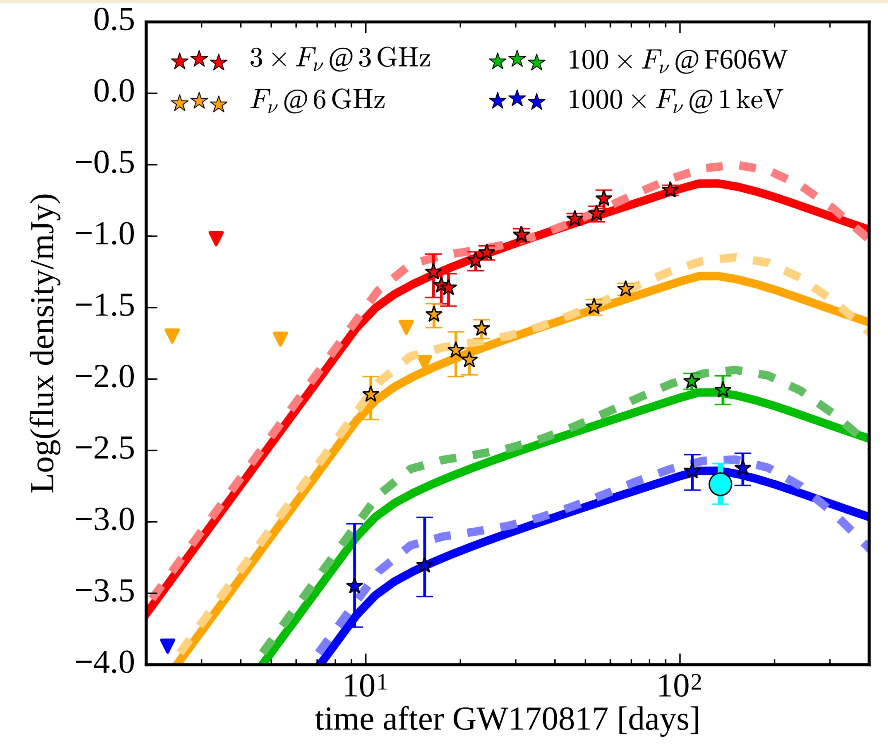


Chincarini (2007)

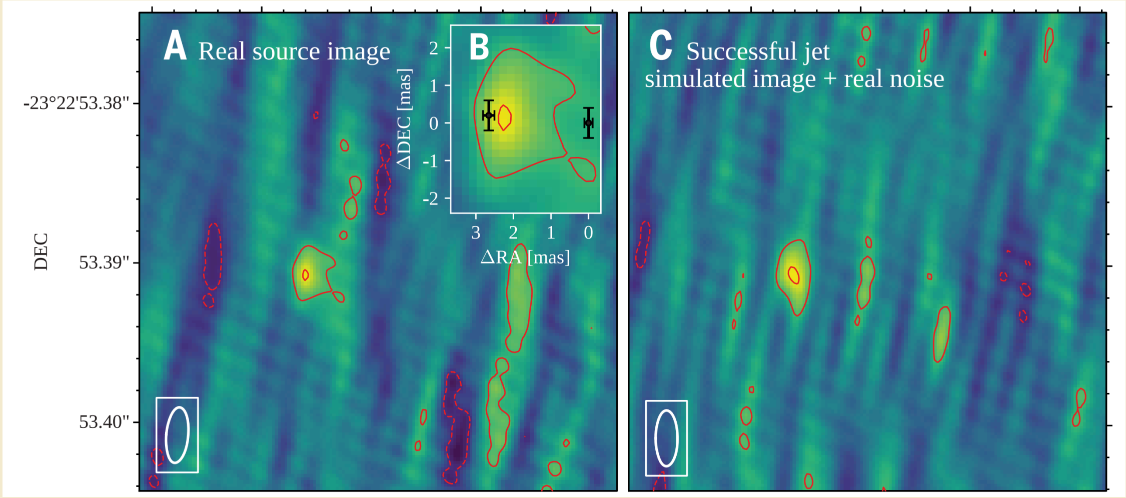
Features not compatible with standard afterglow from forward shock emission

High latitude emission from a structured jet

GW 170817

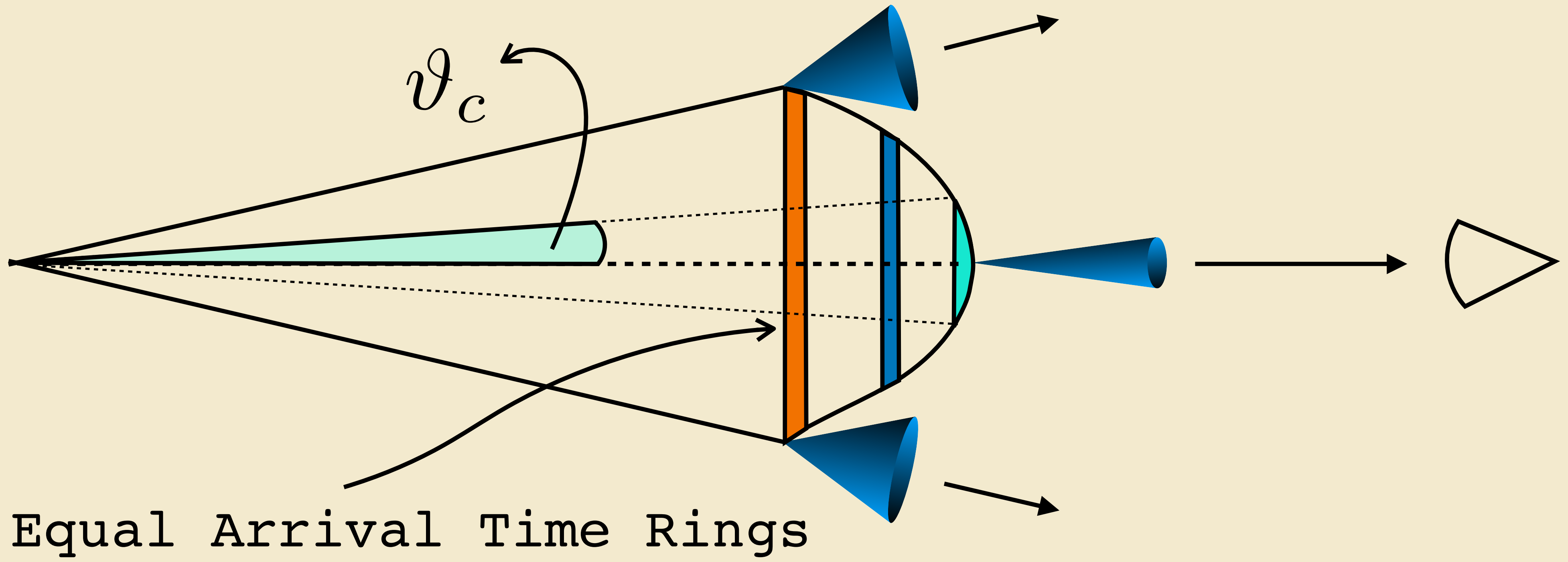


D'Avanzo et al. (2018)



Ghirlanda et al. 2018

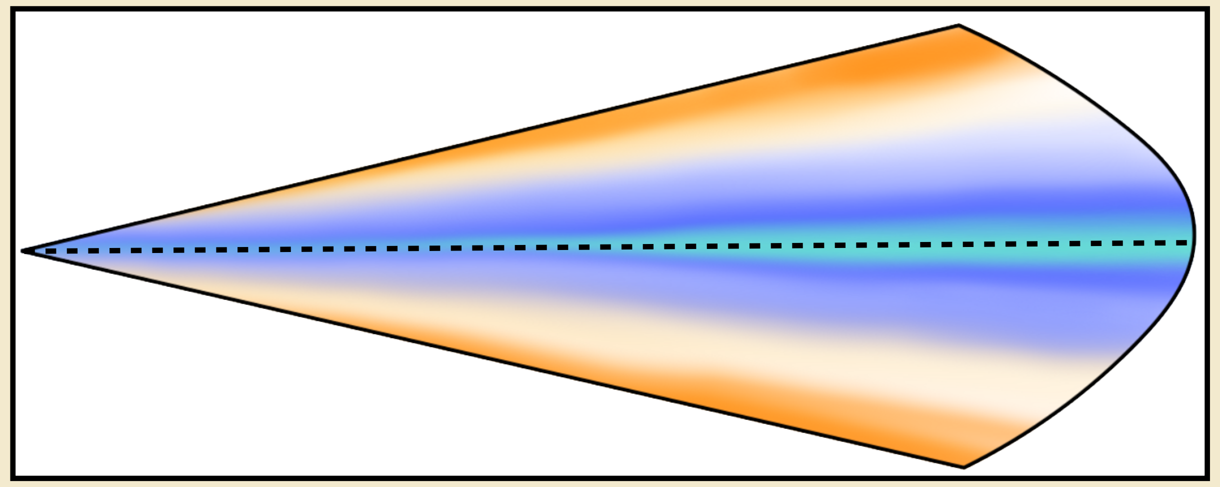
High Latitude Emission (HLE)



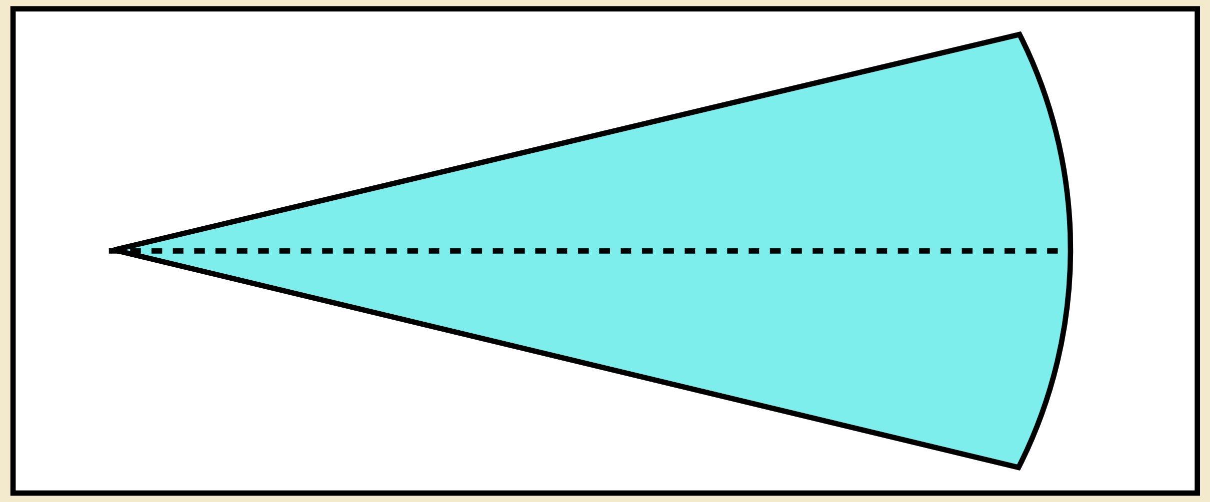
Developed by GSSI group (see Oganesyan et al. 2020, Ascenzi et al. 2020)

See also Lipunov (2001), Zhang & Mèszaros (2002)

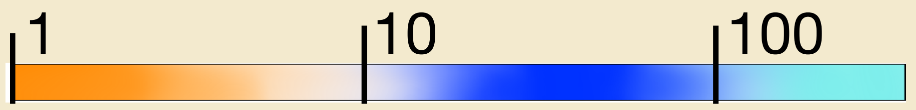
Structured



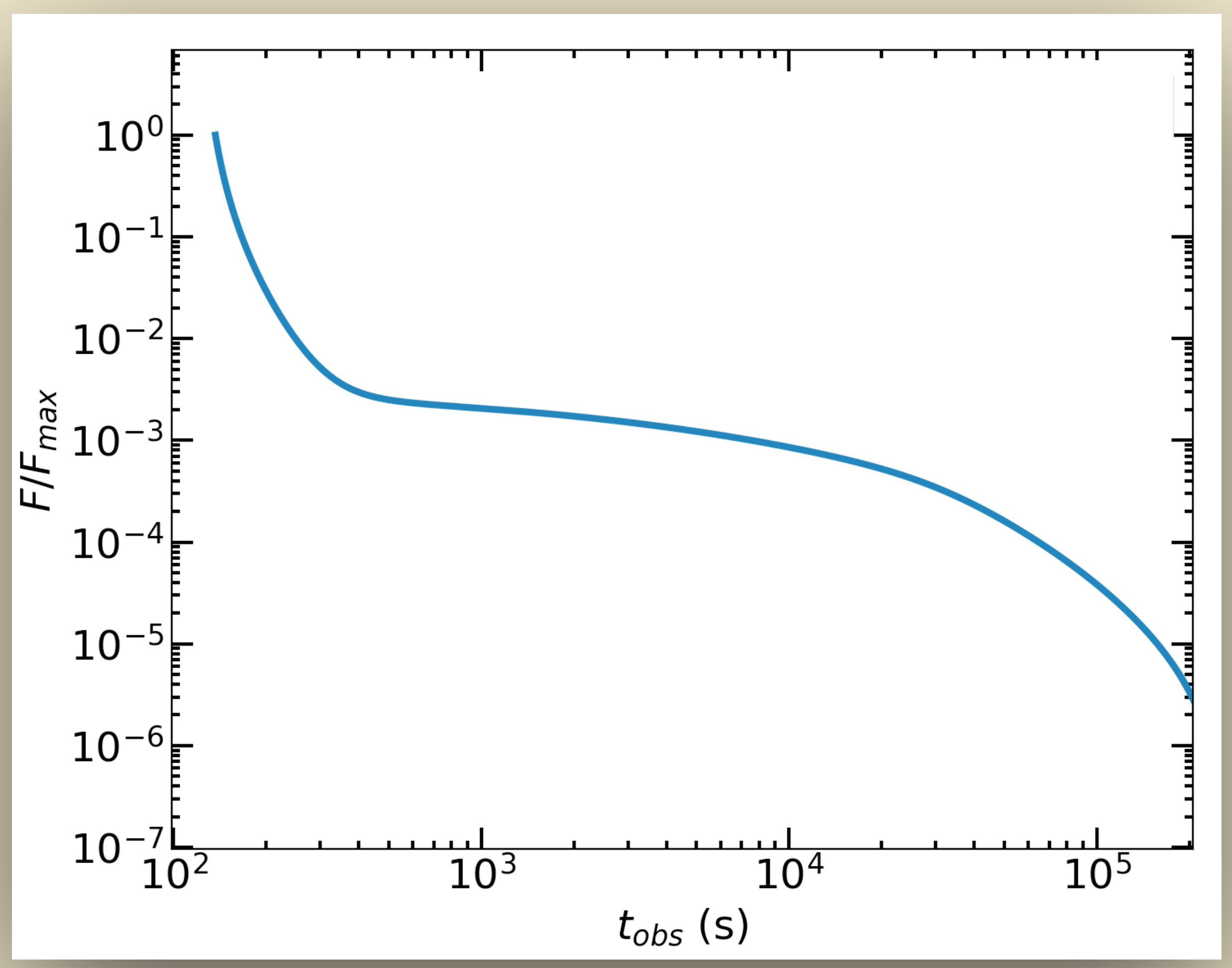
Uniform

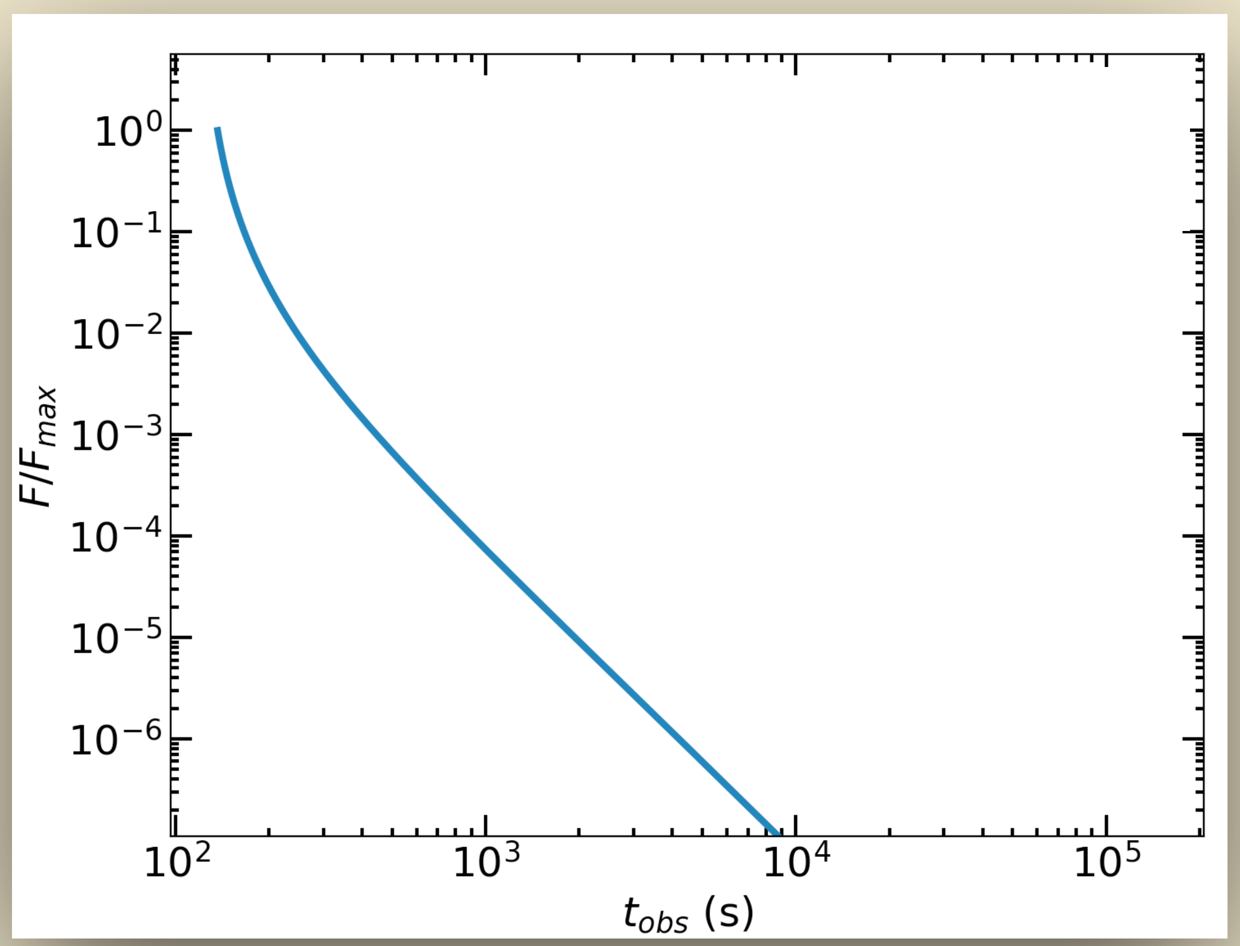


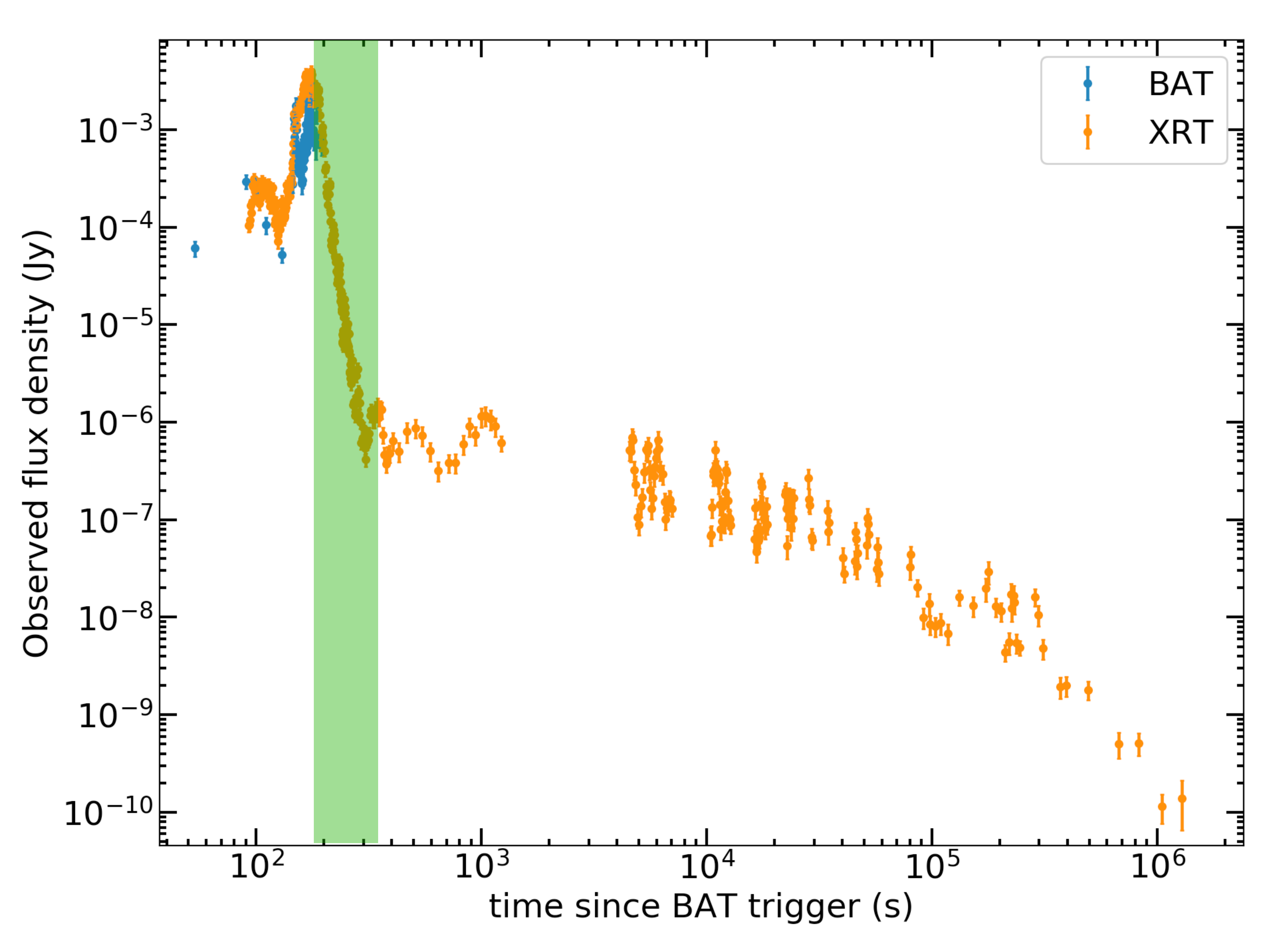
$\Gamma(\vartheta)$

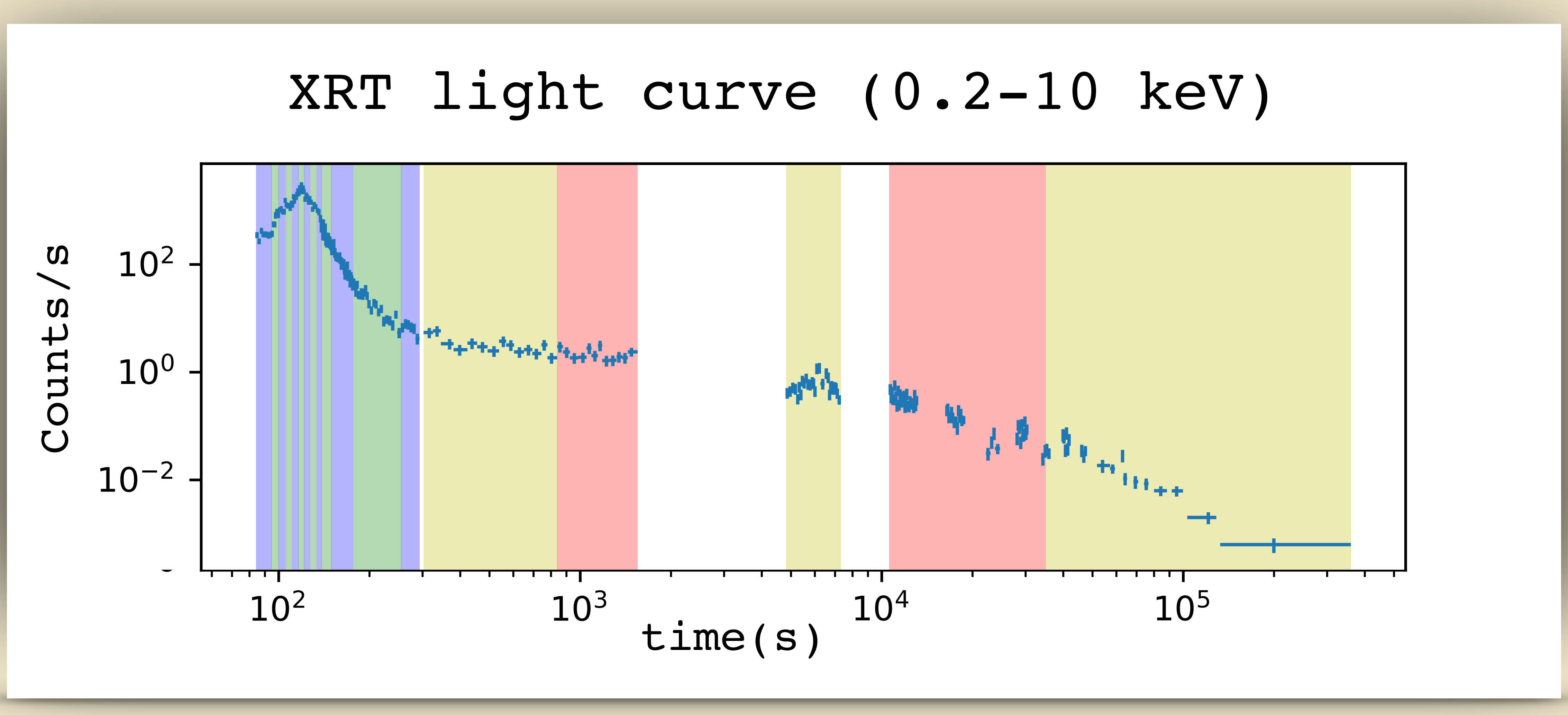


$$\Gamma(\vartheta) = \frac{1}{\sqrt{1-\beta^2(\vartheta)}} \qquad R(\vartheta, t) = c\int_0^t \beta(\vartheta, t')dt'$$

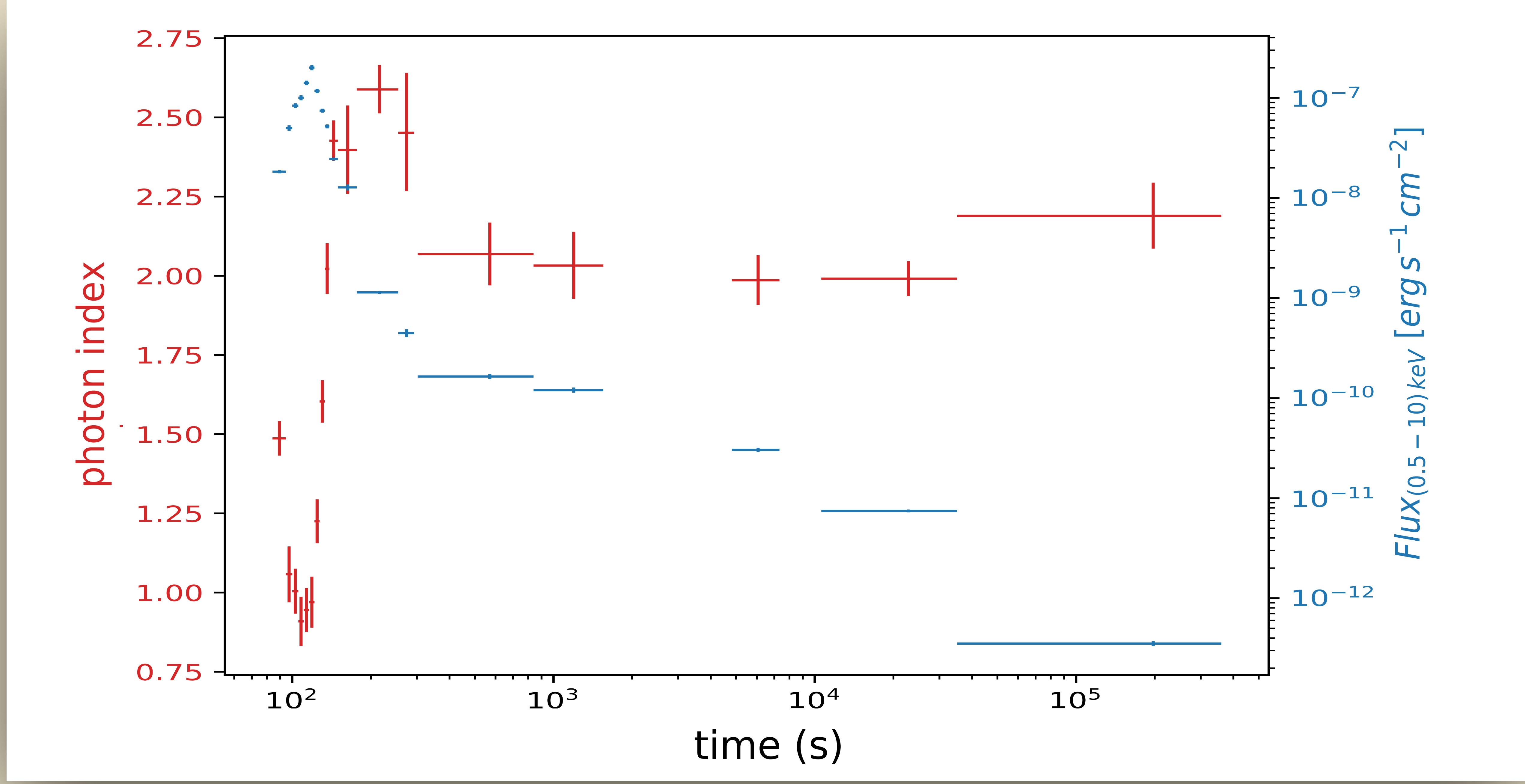


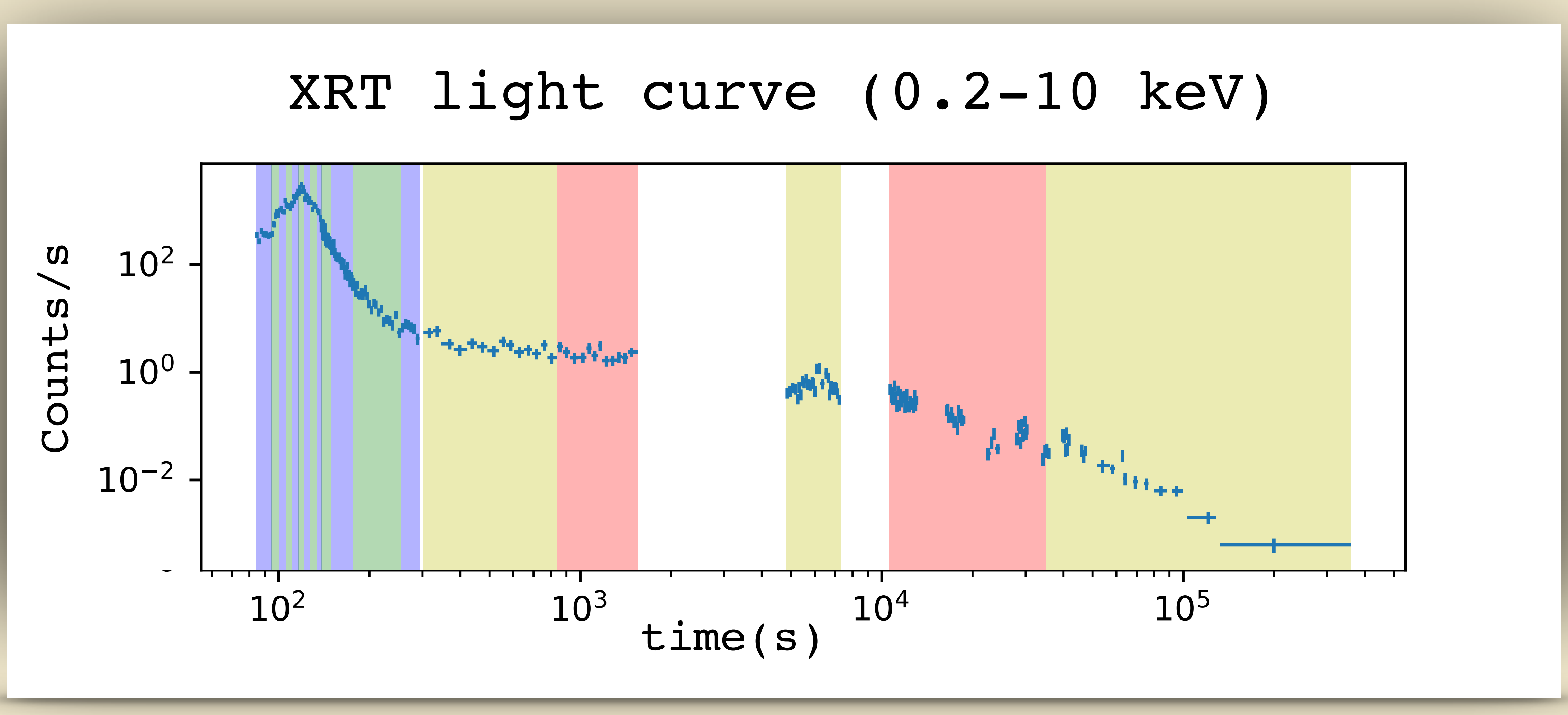



BAT
XRT
Observed flux density (Jy)
time since BAT trigger (s)
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{2}
10^{3}
10^{4}
10^{5}
10^{6}



$$S(E) \propto A(z, N_H)E^{-\alpha}$$





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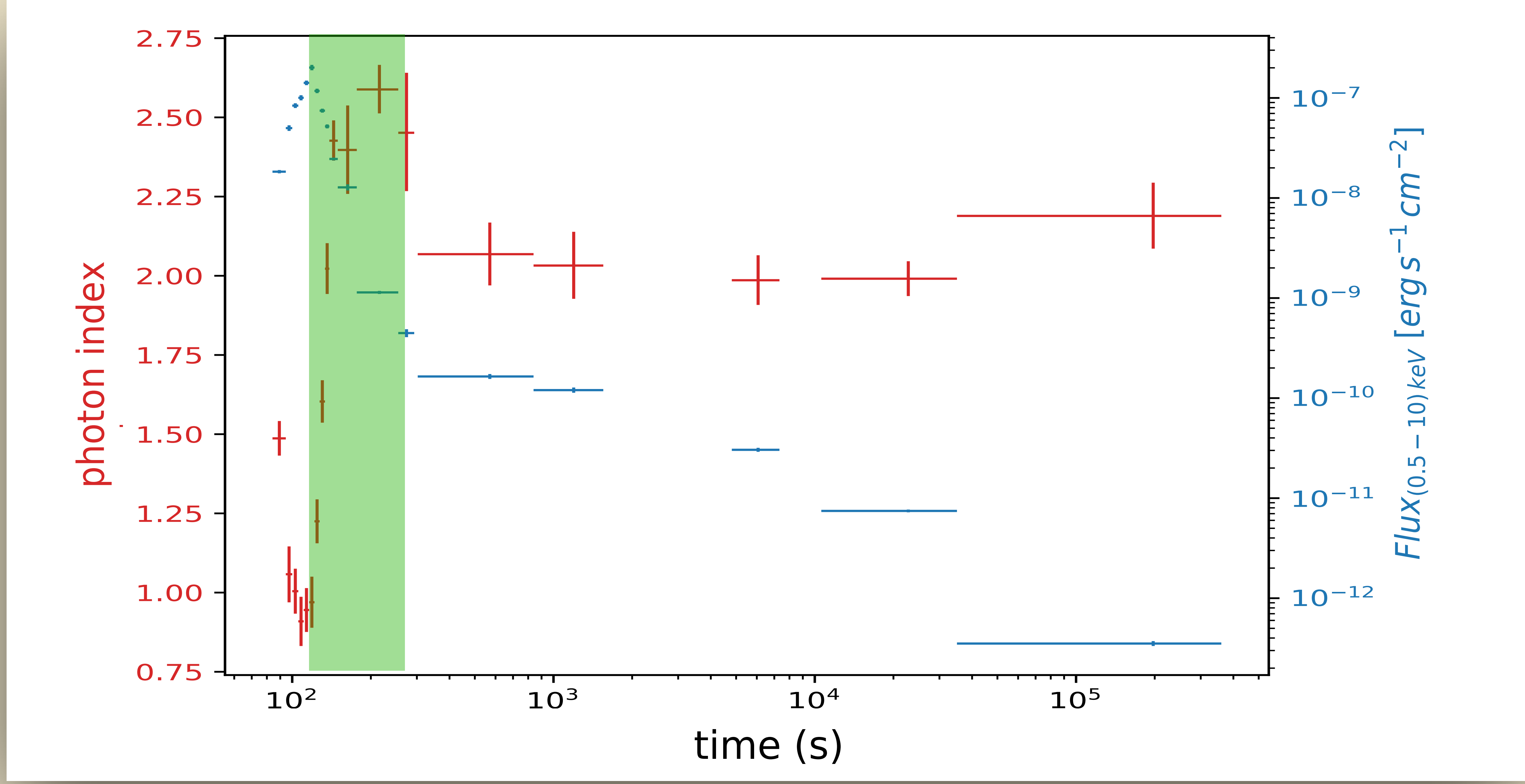
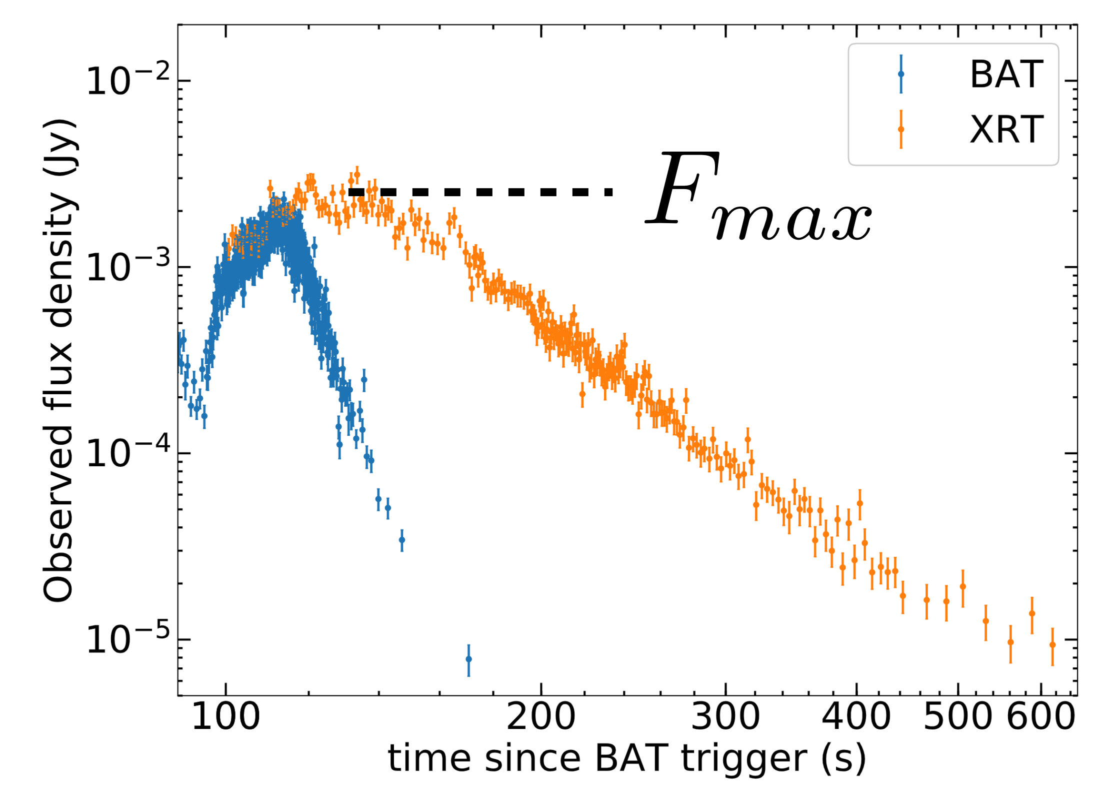




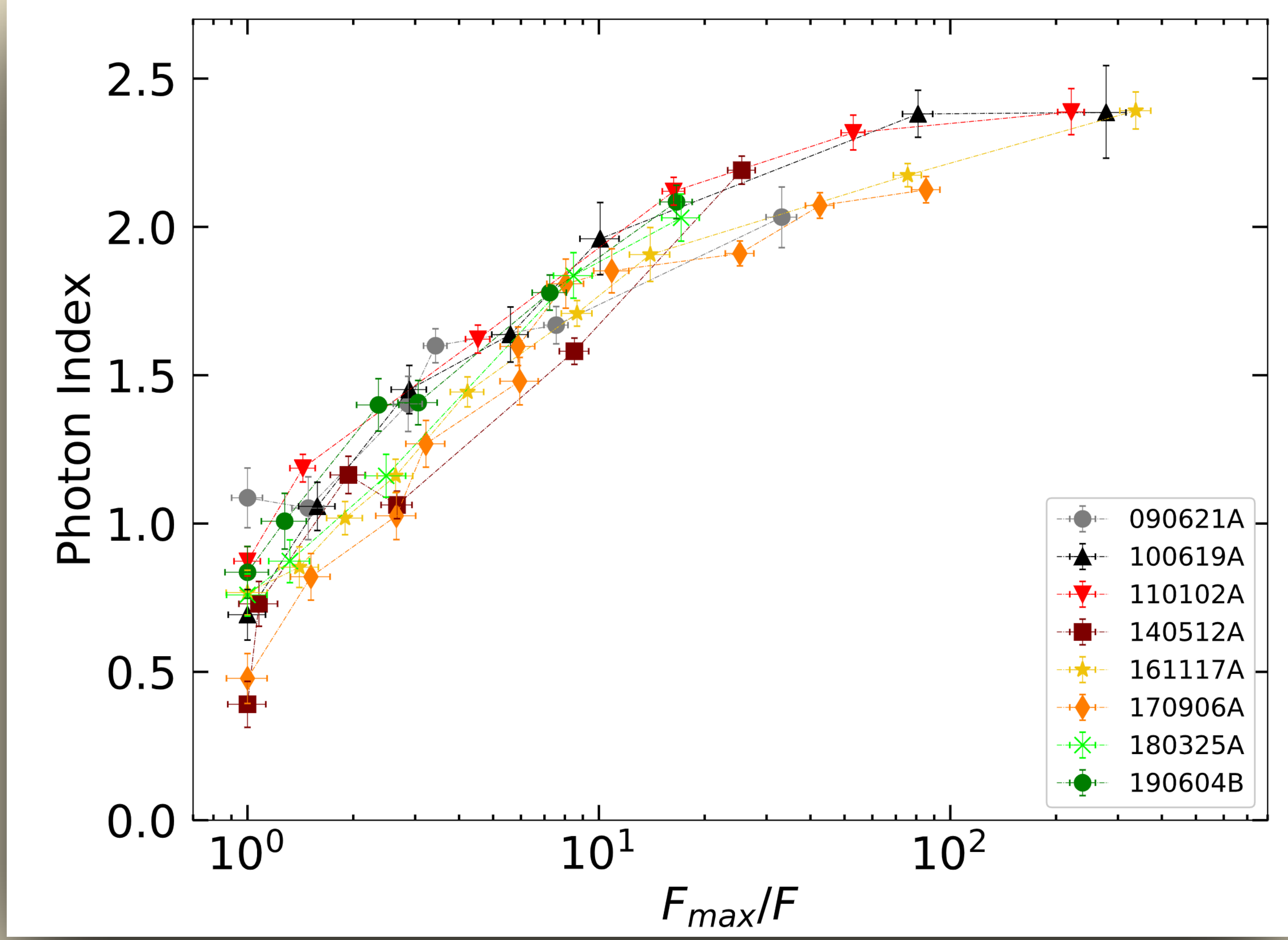
We selected a sample of GRBs such that:

- The steep decay has a well defined peak time
- The BAT emission @peak is the brightest since the trigger time

→ Tails of prompt-like pulses

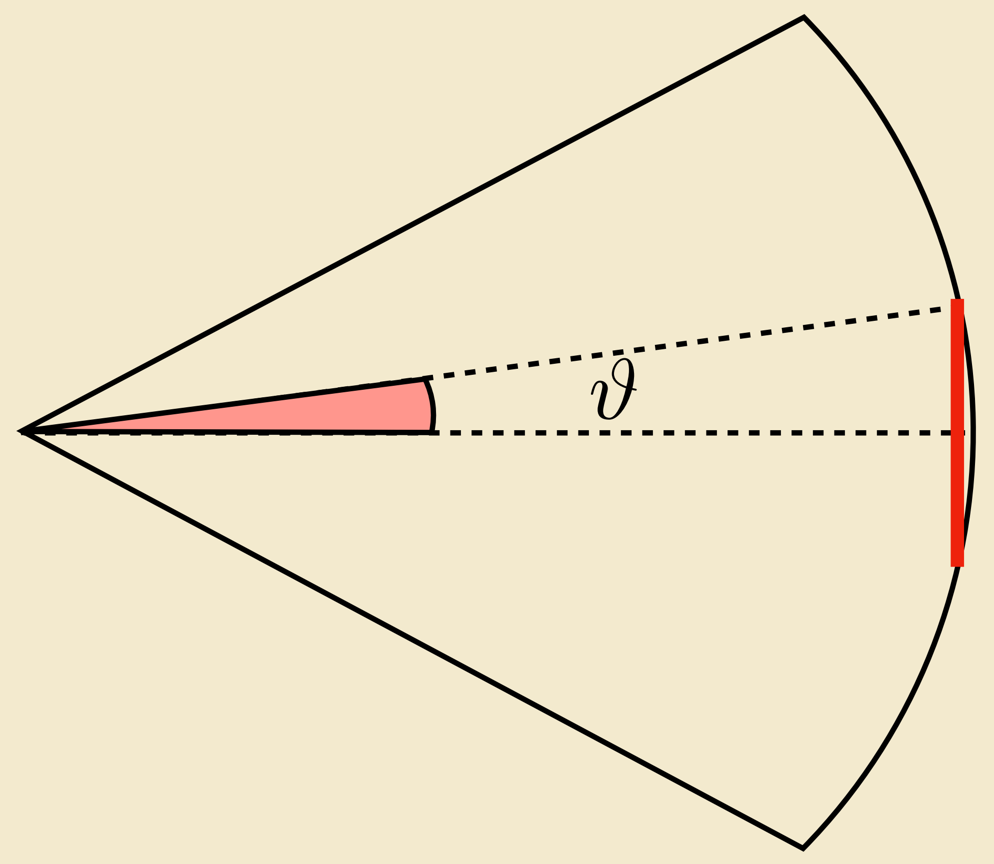
Novelty of this result:

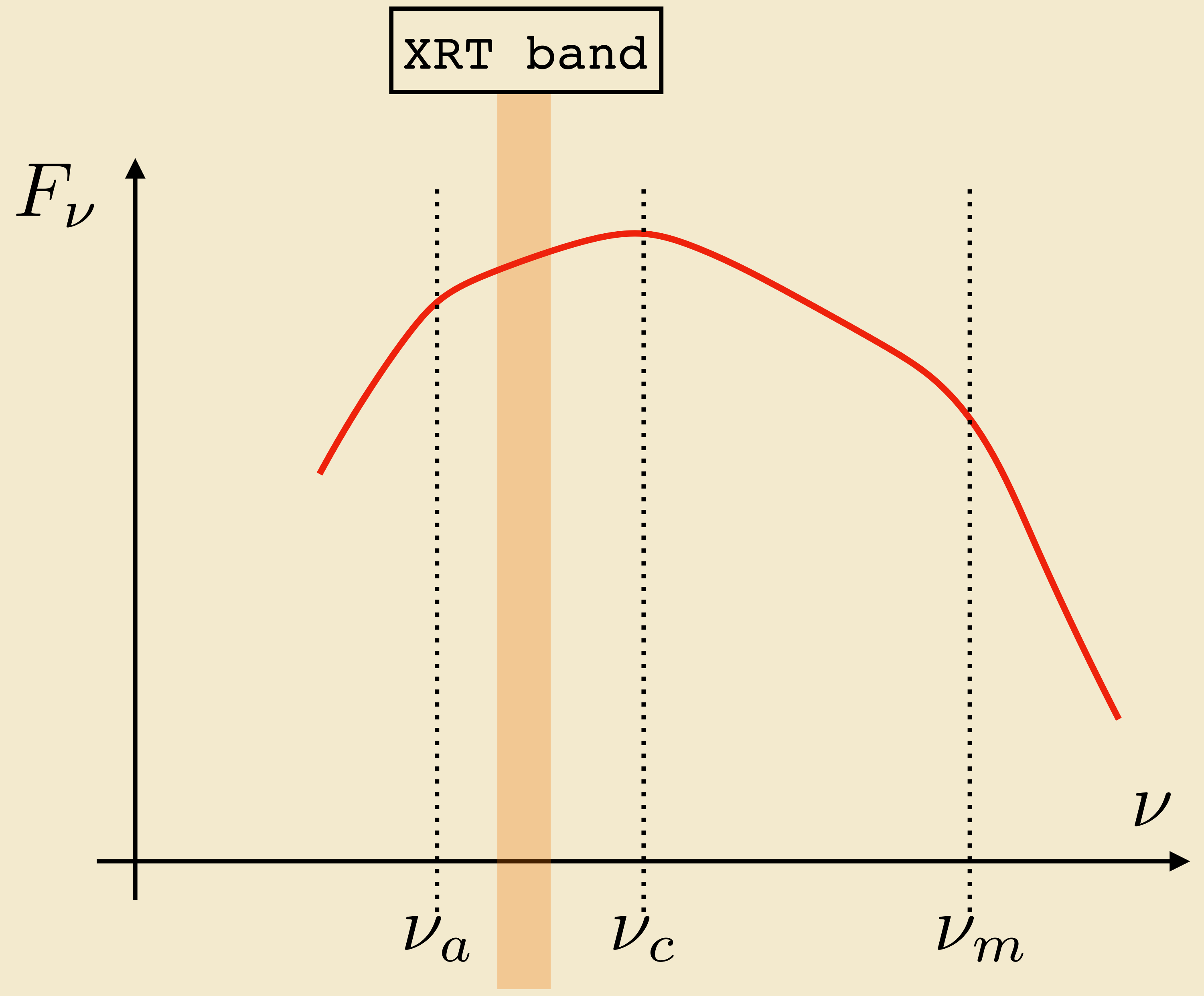
For the first time, we find a unique relation linking the flux drop and the spectral properties during the tail of prompt-like pulses



No dependency on:

- the initial time of the steep decay
- The luminosity of the GRB



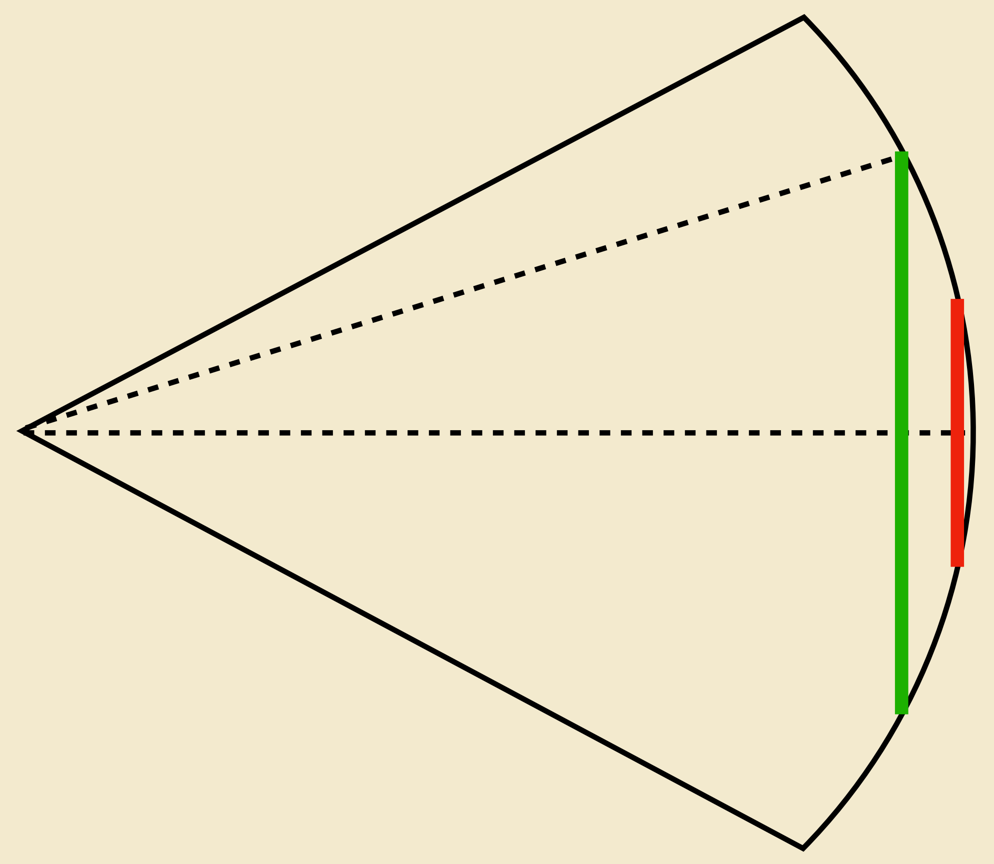


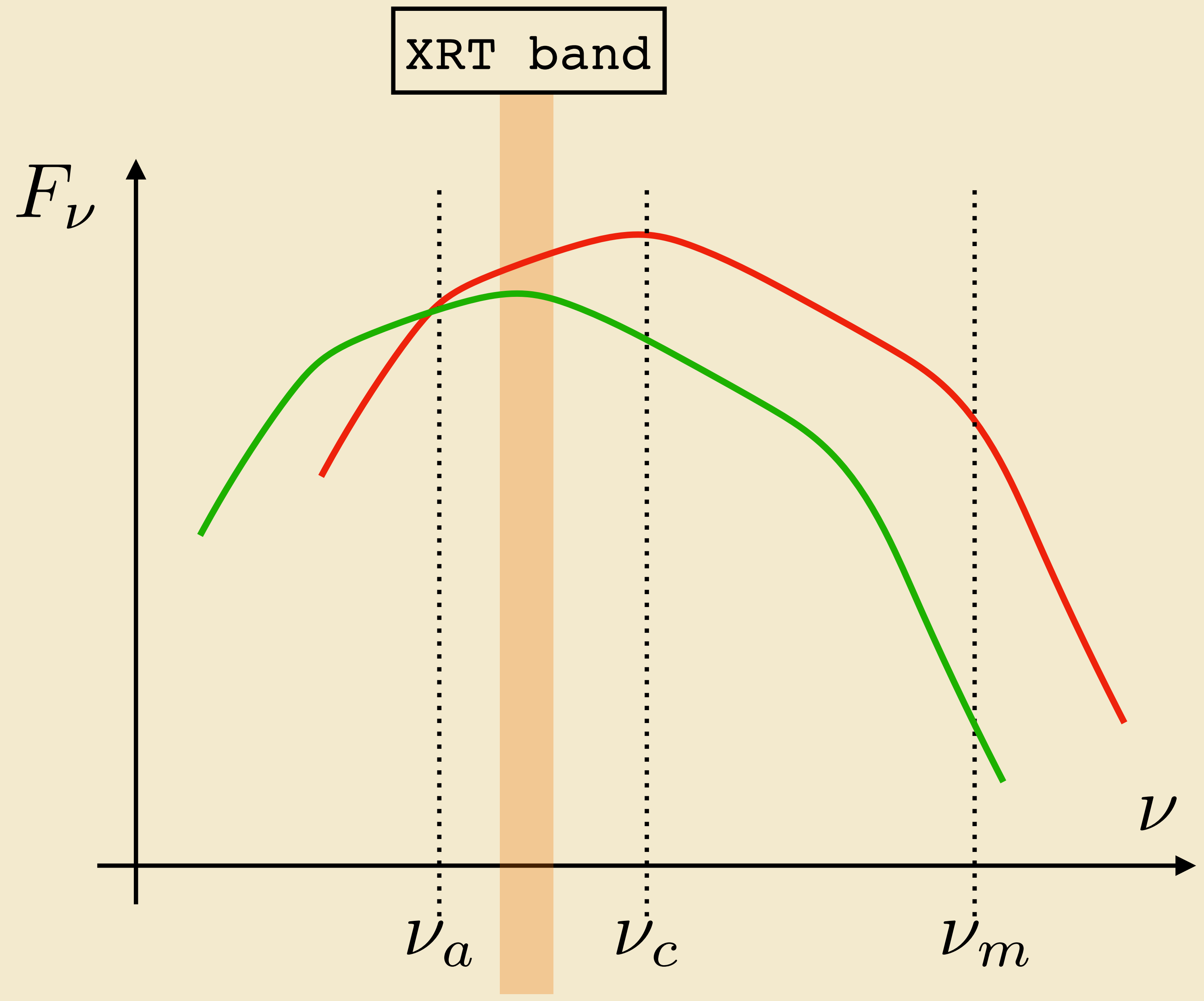
Fenimore (1996), Kumar & Panaitescu (2000)

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

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

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





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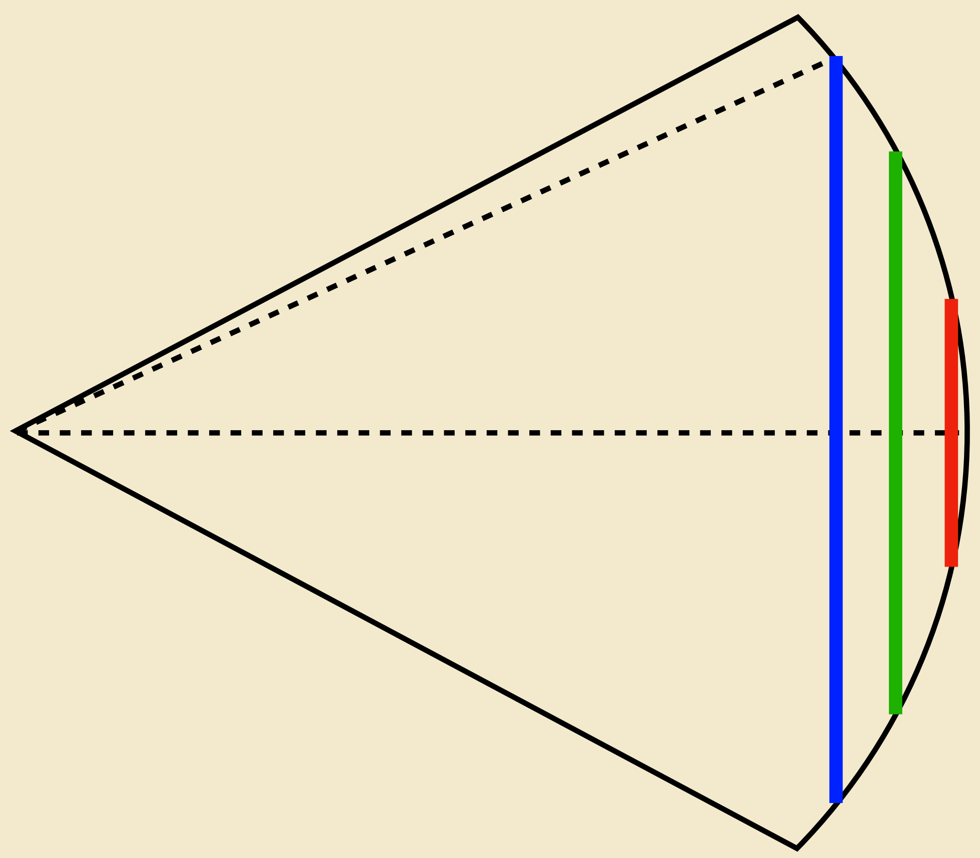

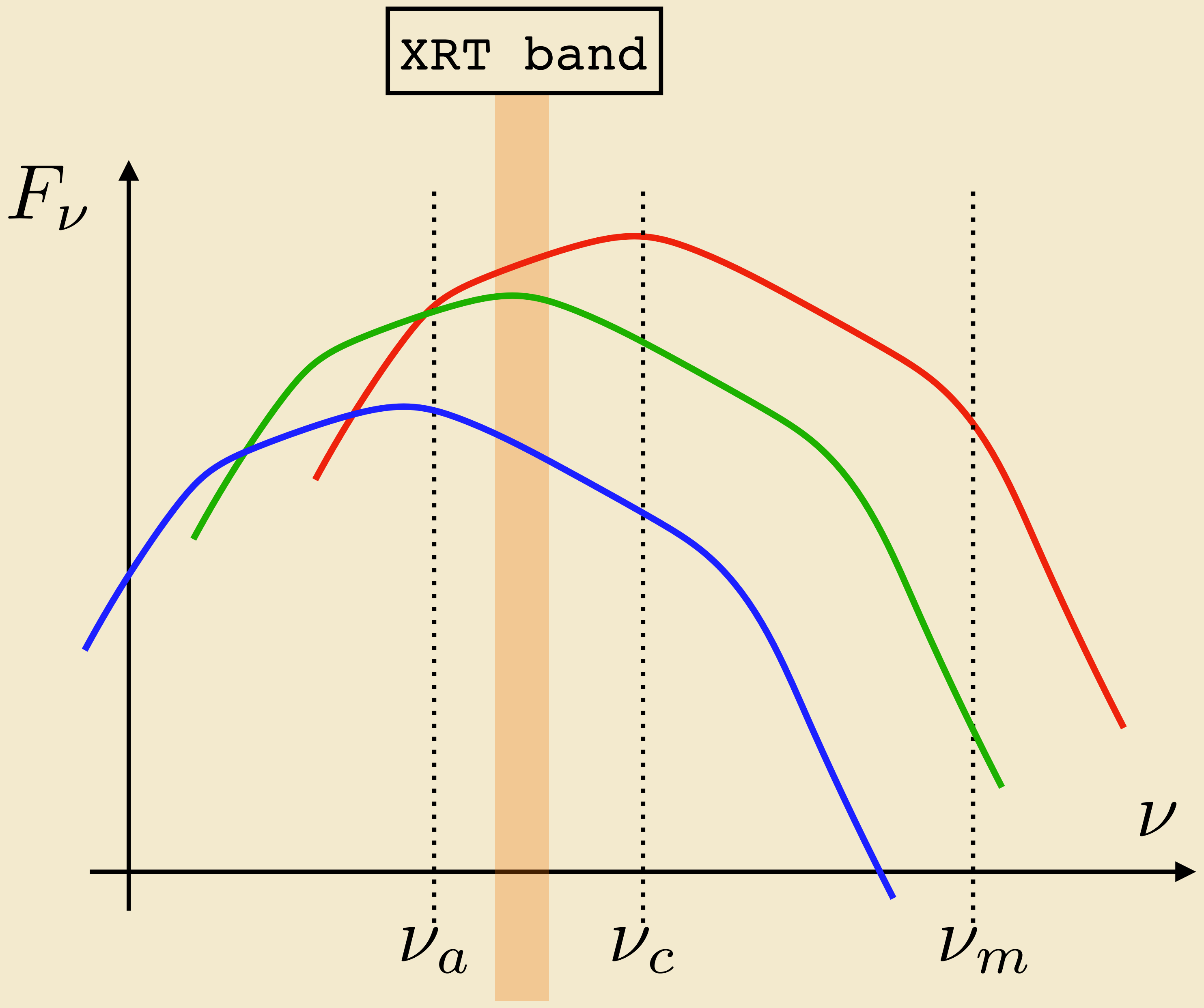

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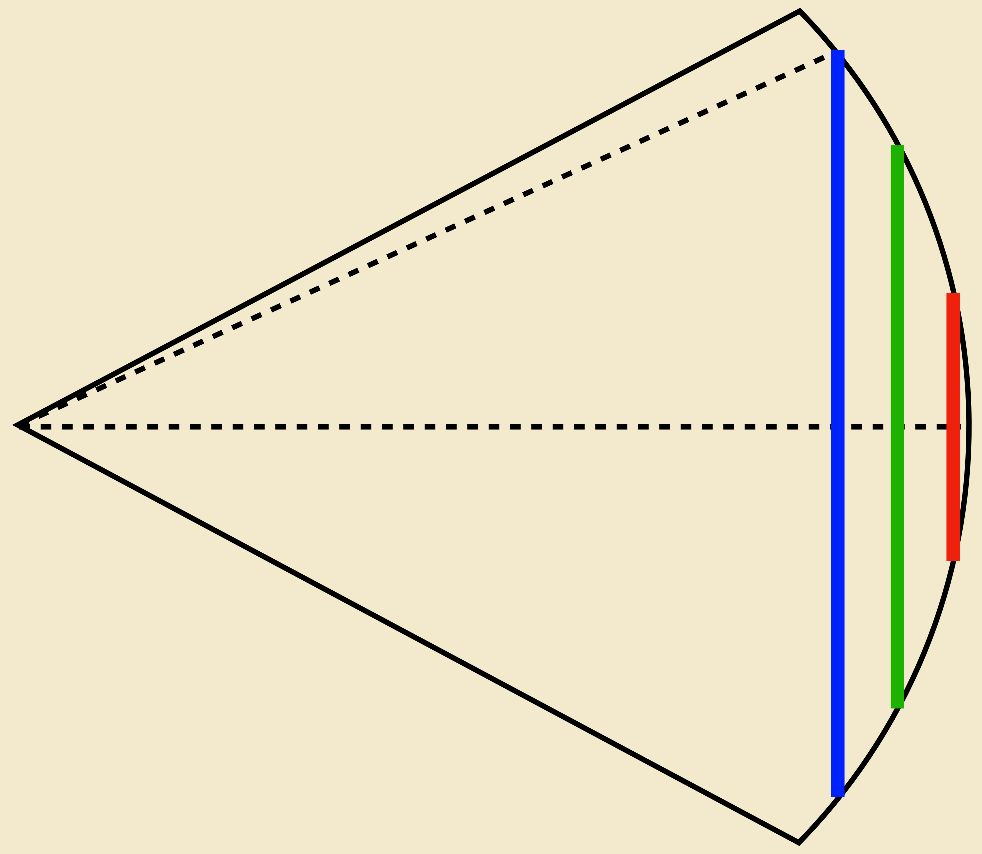
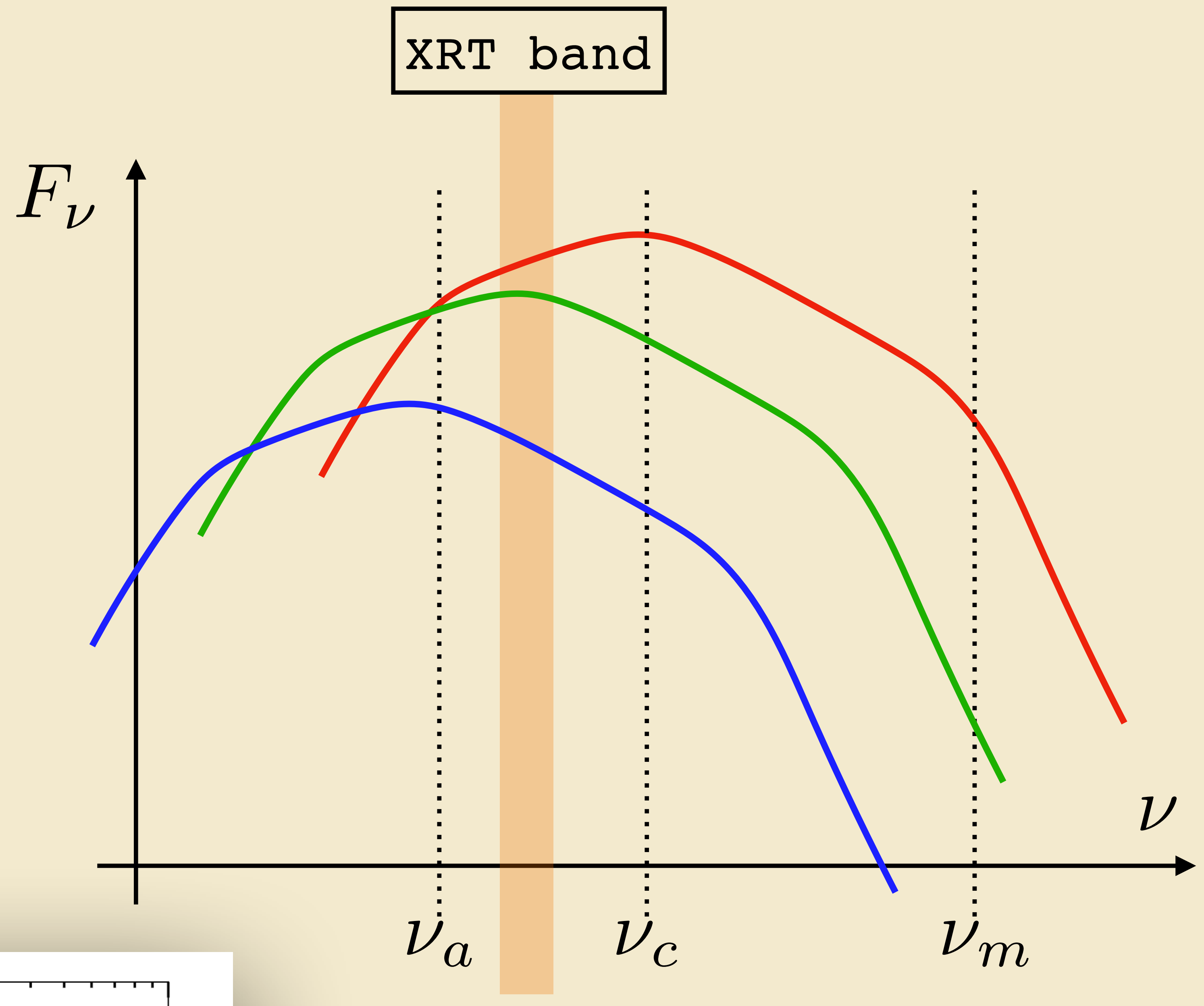
Spectral evolution expected in case of HLE





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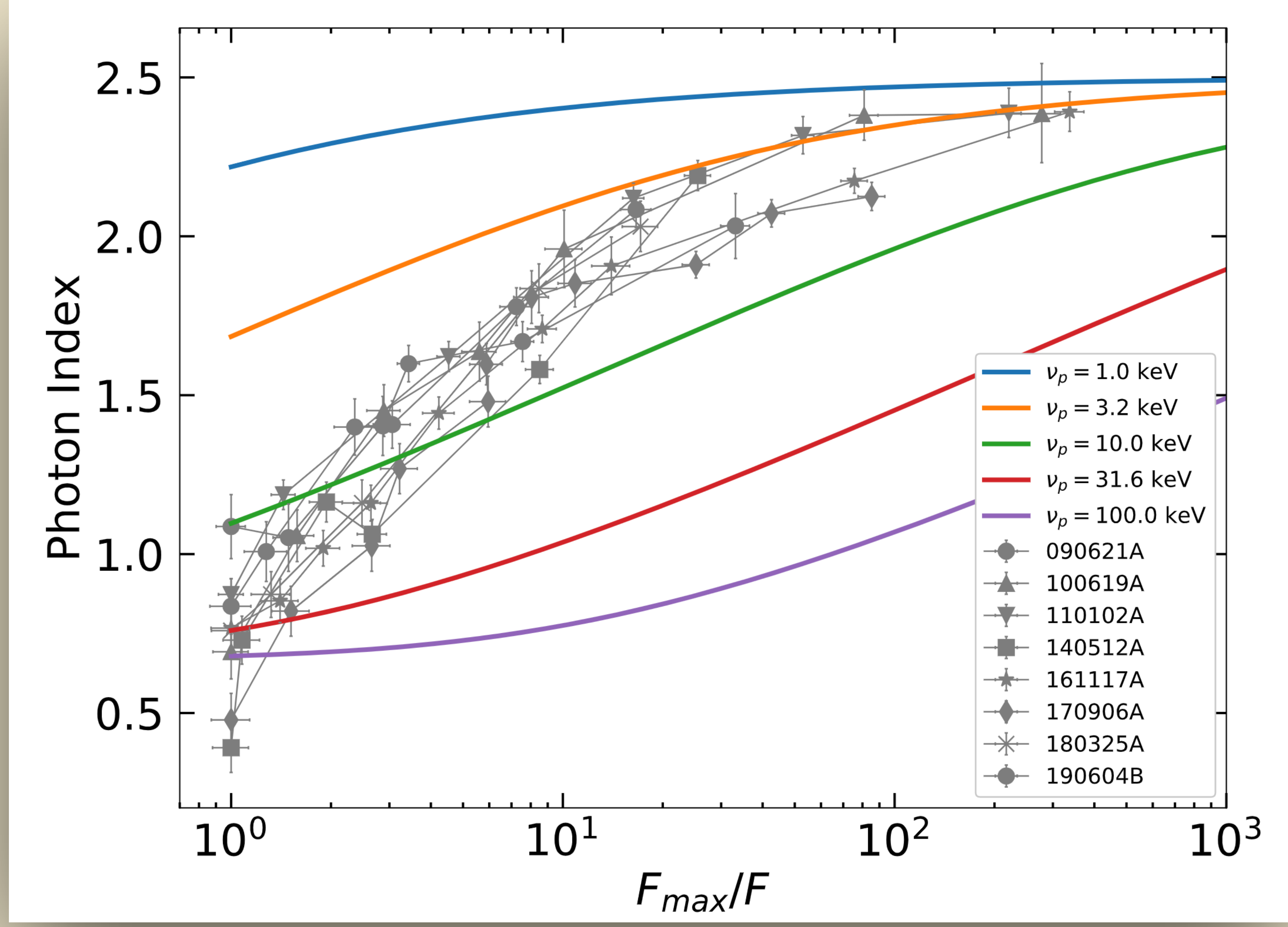
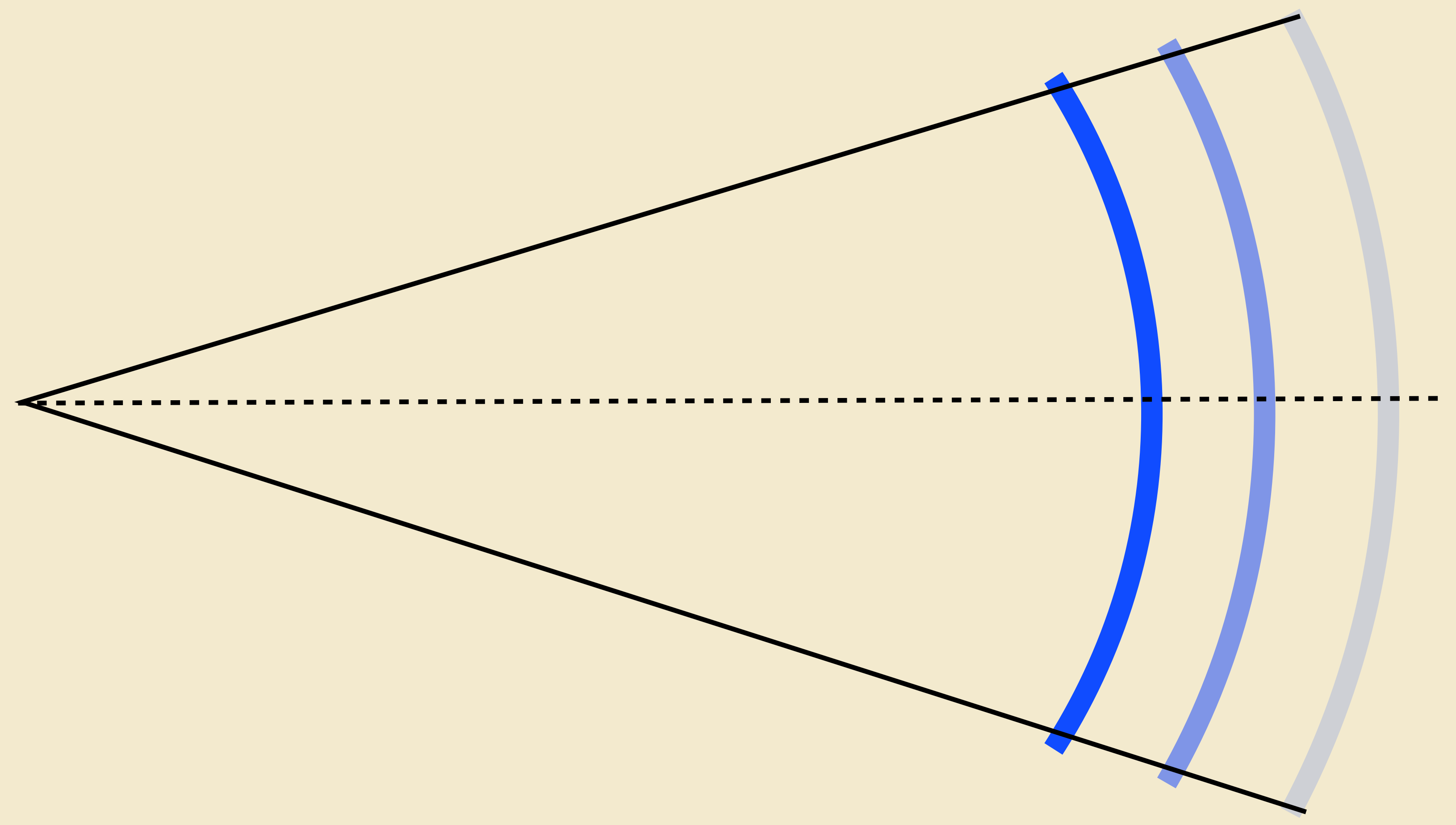


Assumptions:

- Infinitesimal duration pulse
- Unique spectrum along the entire jet surface
- Smooothly-broken power law as broad band spectrum

The disagreement with data cannot be solved, even relaxing each of these assumptions

The role of adiabatic cooling



Meszaros & Rees (1999)

Duran & Kumar (2008)

Conservation of entropy

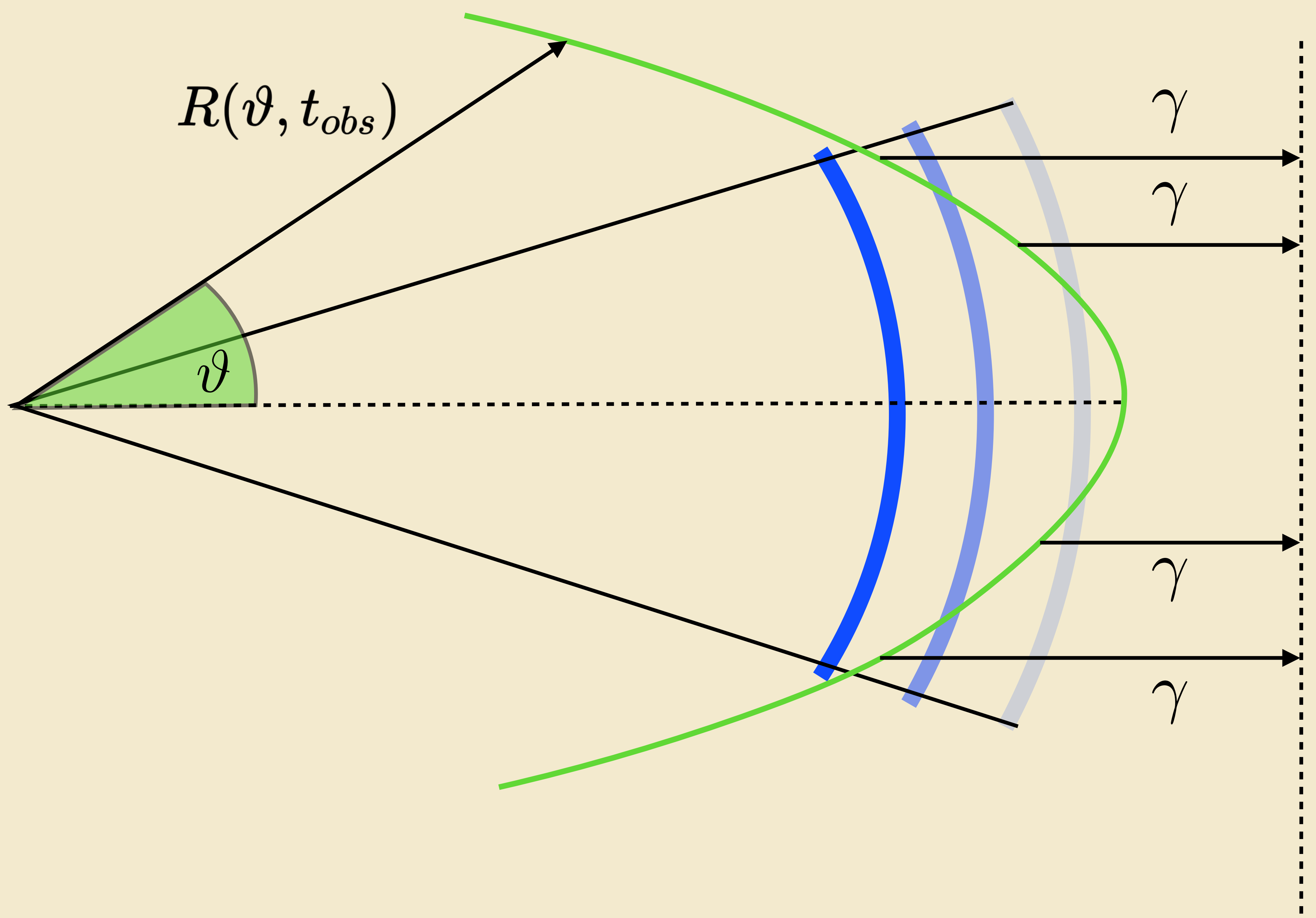
$$\langle\gamma\rangle^3 V' = \text{const}$$

For a synchrotron spectrum

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

Prescription for B evolution

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



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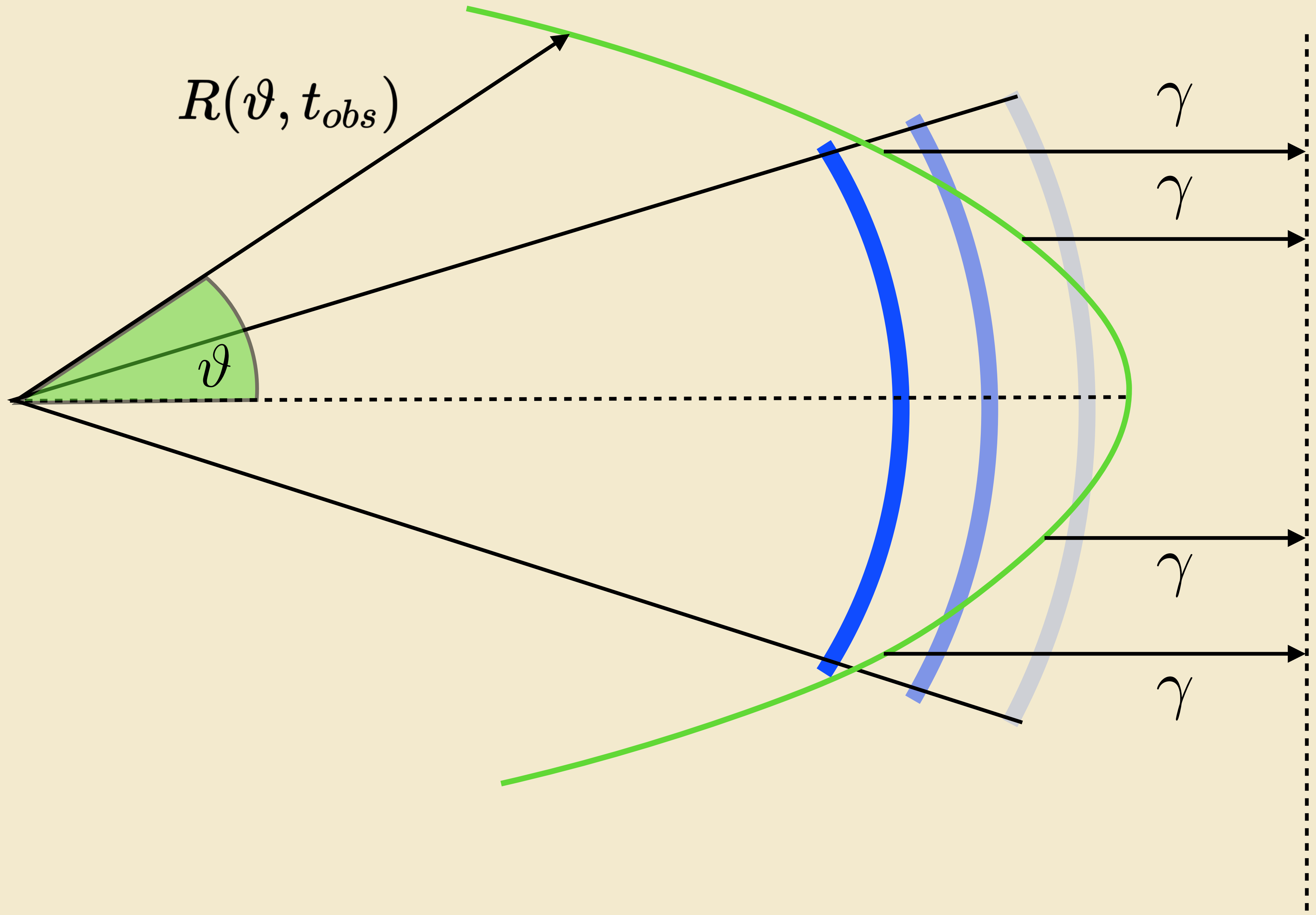
Equal Arrival Time Surfaces

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

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

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



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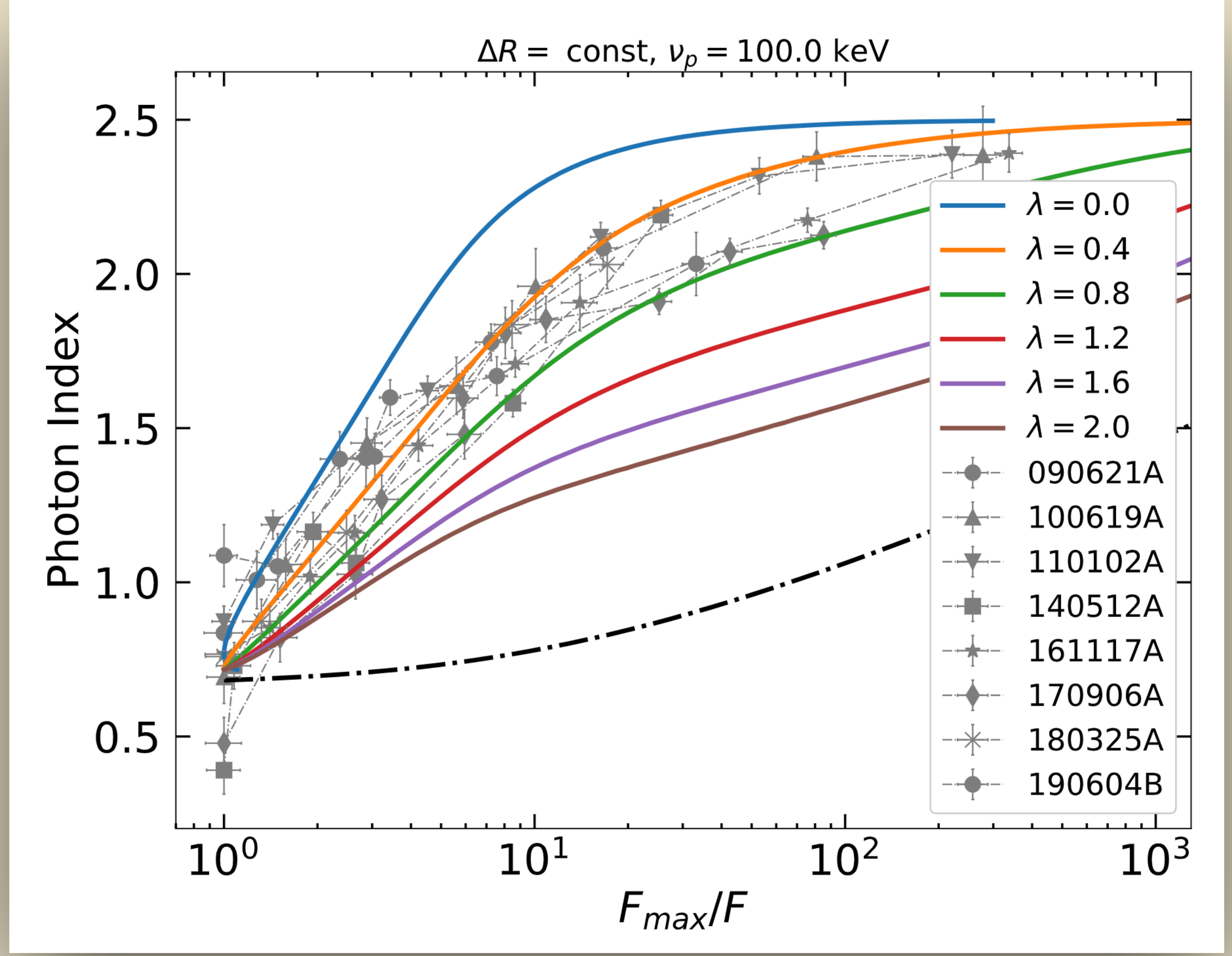


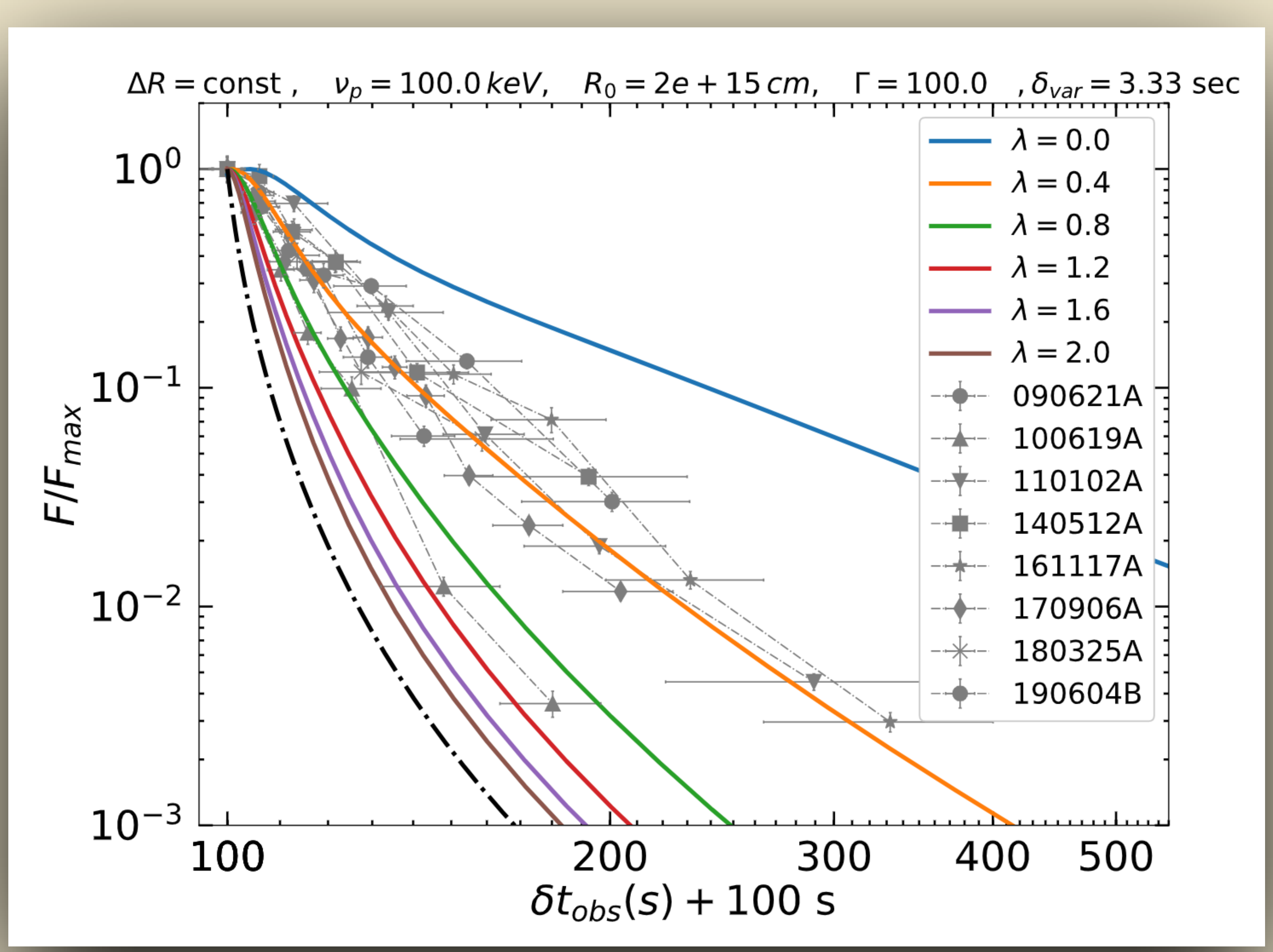
* HLE is necessary for modelling the tail of prompt pulses, but not sufficient to account for spectral evolution
* Adiabatic cooling plays a fundamental role

What we can constrain from modelling:

From the light curve

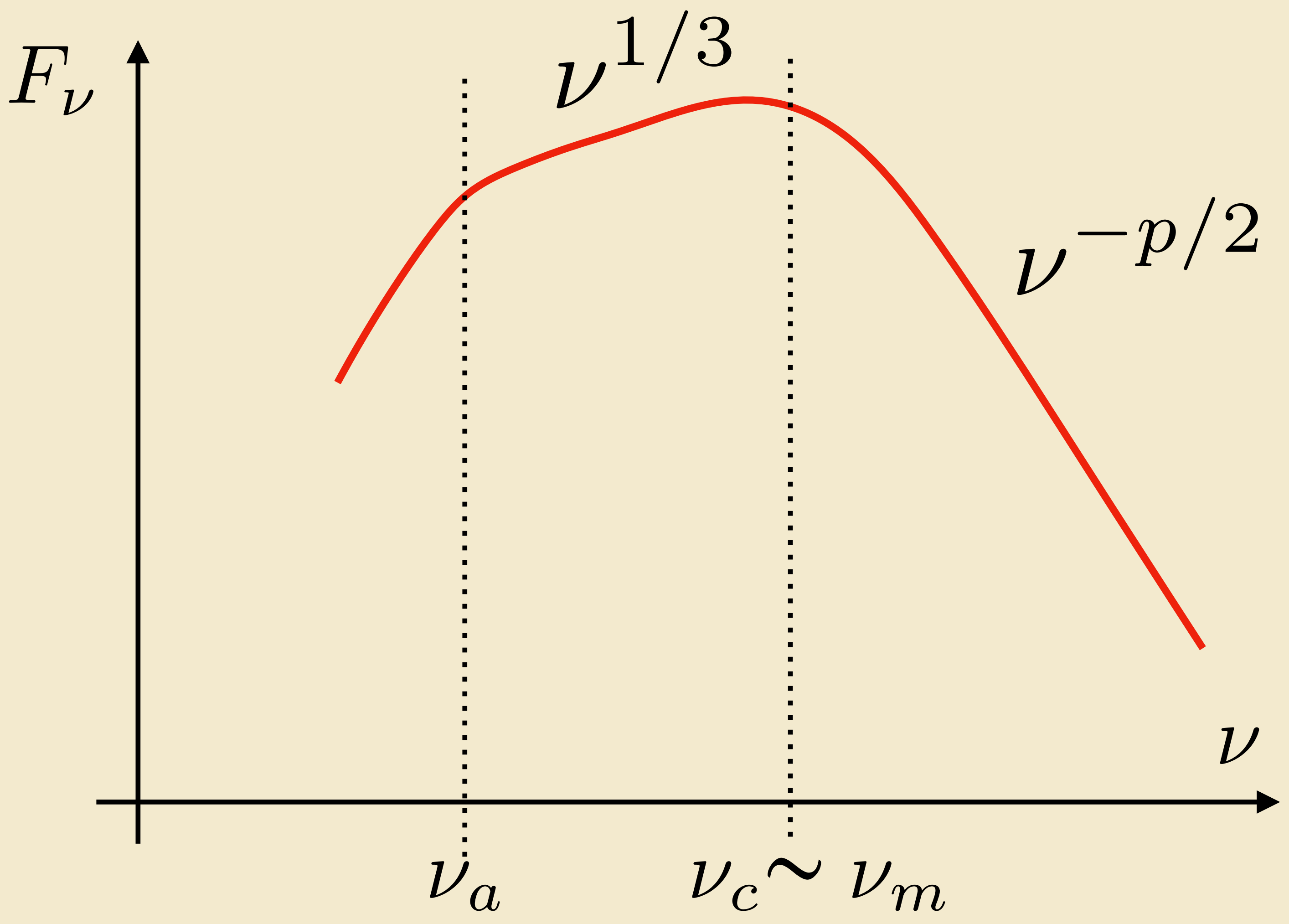
$$\tau_{ad} = R_0/2c\Gamma^2$$

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



From the α-F relation

* The spectral evolution is consistent with a synchrotron spectrum
* The radiative cooling of emitting particles is inefficient



Ongoing work: publication of our results

Under review in Nature Communications

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Unveiling the origin of steep decay in γ-ray bursts

Samuele Ronchini, Gor Oganesyan, Marica Branchesi, Stefano Ascenzi, Maria Grazia Bernardini, Francesco Brighenti, Simone Dall'Osso, Paolo D'Avanzo, Giancarlo Ghirlanda, Gabriele Ghisellini, Maria Edvige Ravasio, Om Sharan Salafia

DOI: 10.21203/rs.3.rs-74350/v1 Download PDF

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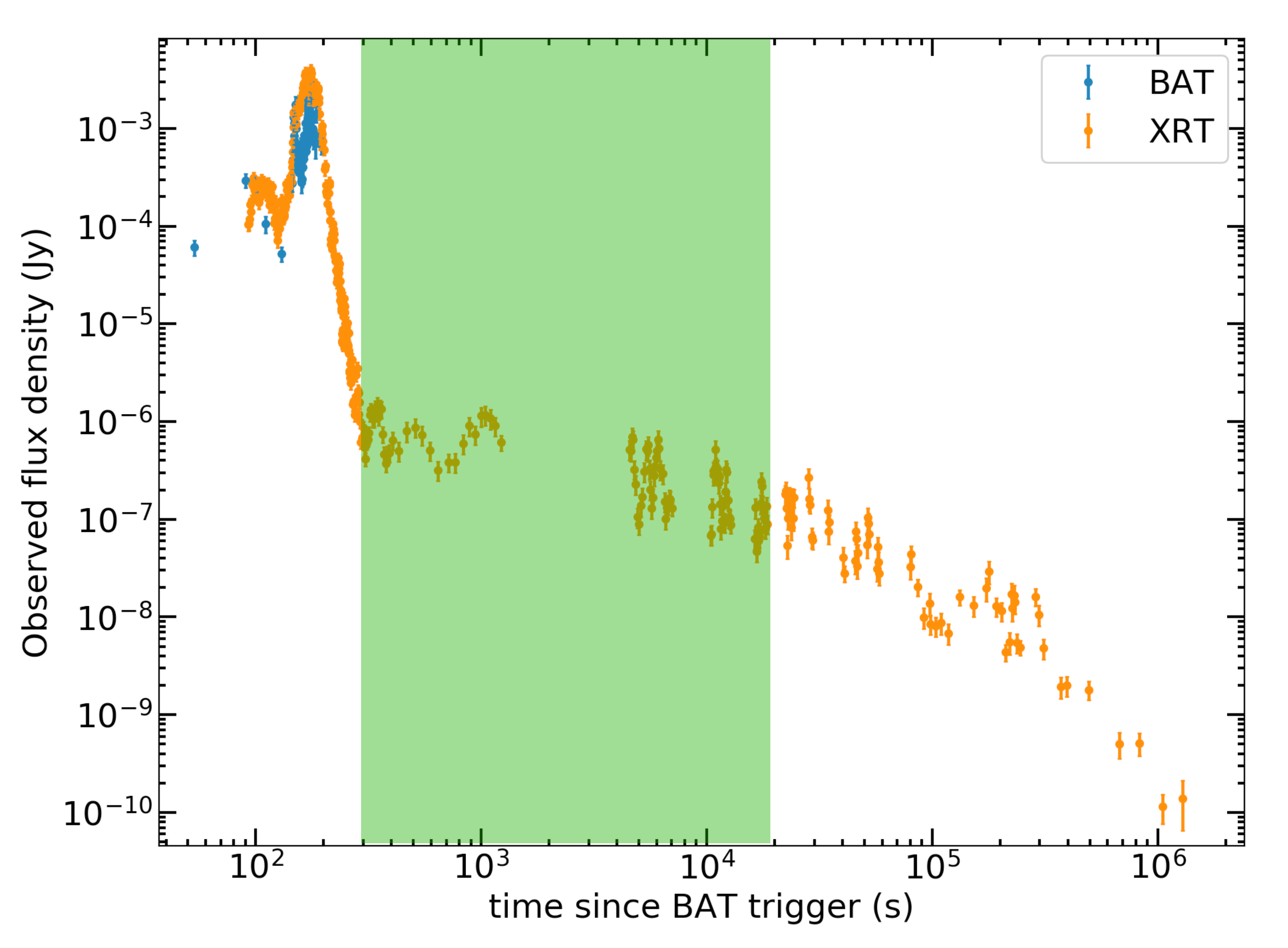
PEER REVIEW TIMELINE

CURRENT STATUS: UNDER REVIEW

Version 1

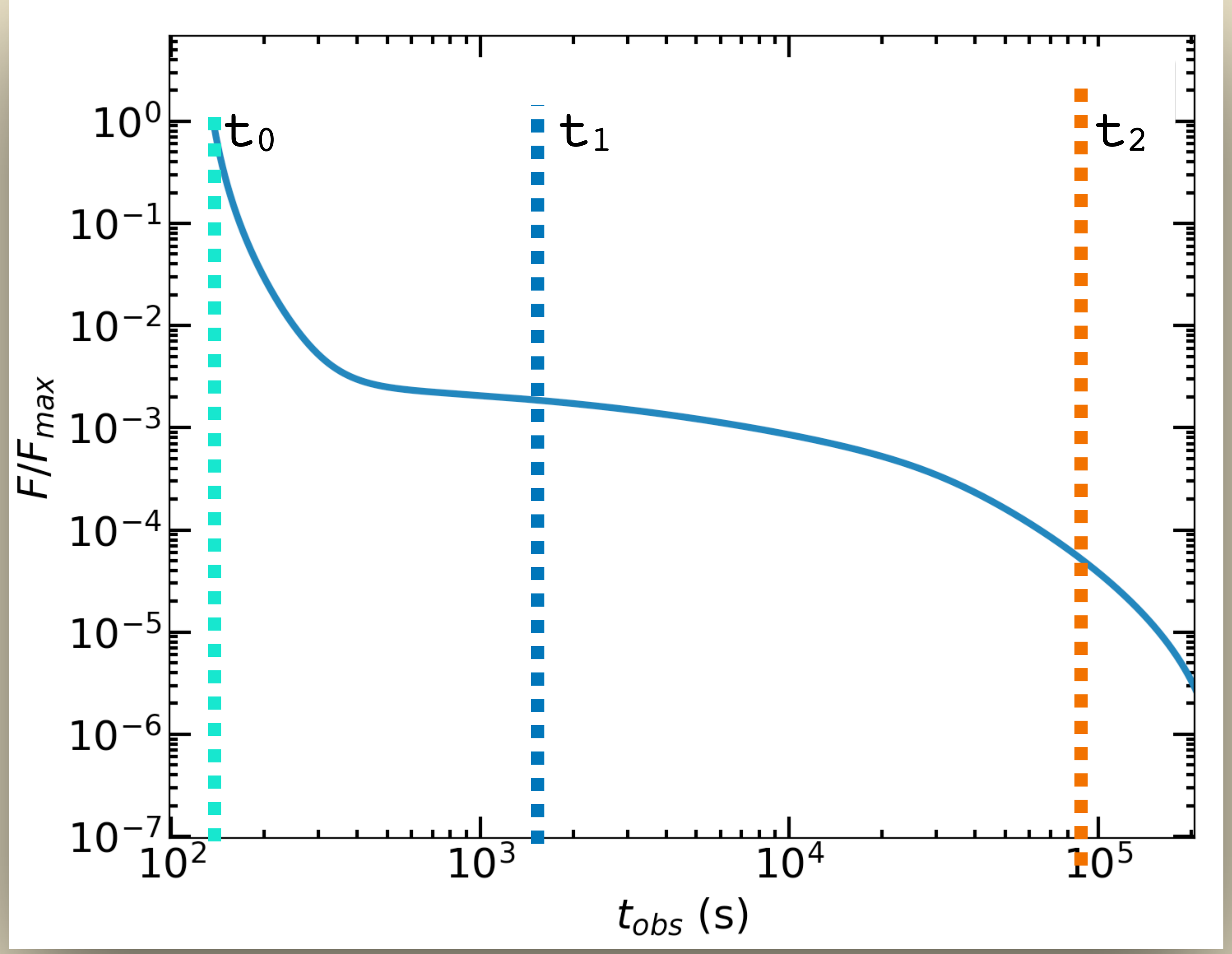
Posted 18 Sep, 2020

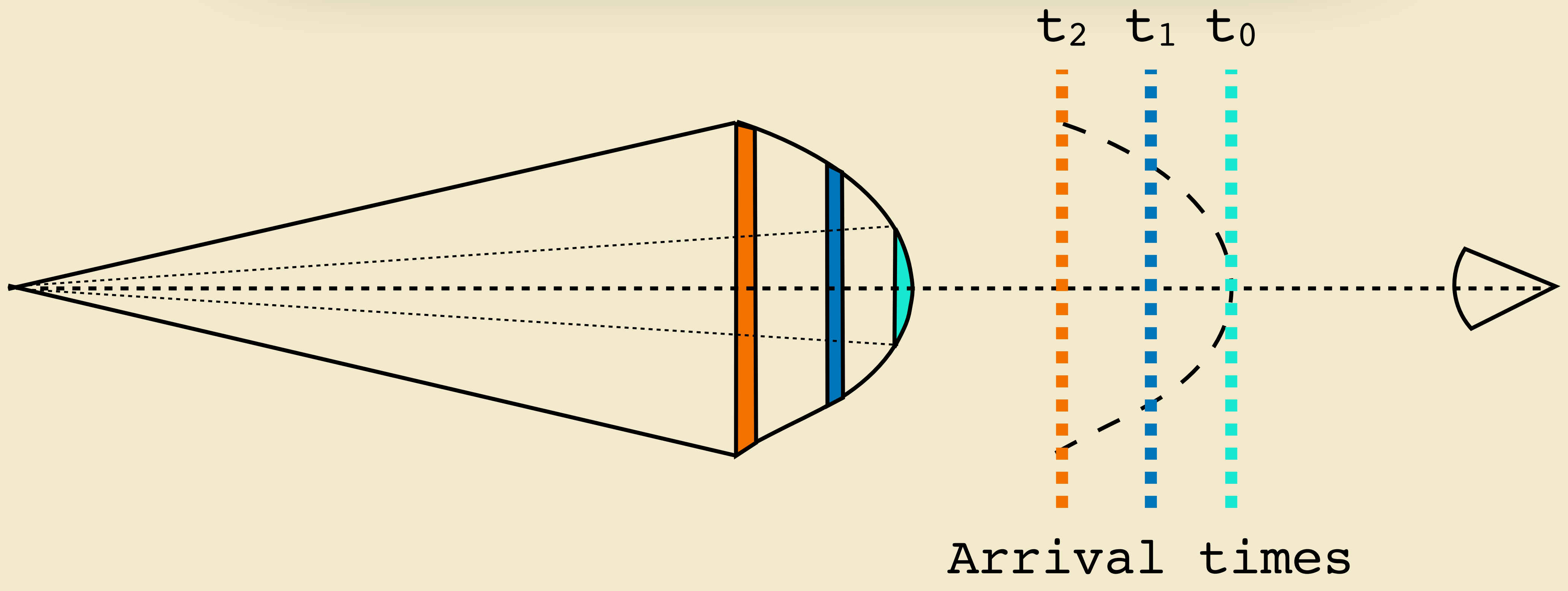
Ongoing work: improve our understanding of the plateau phase



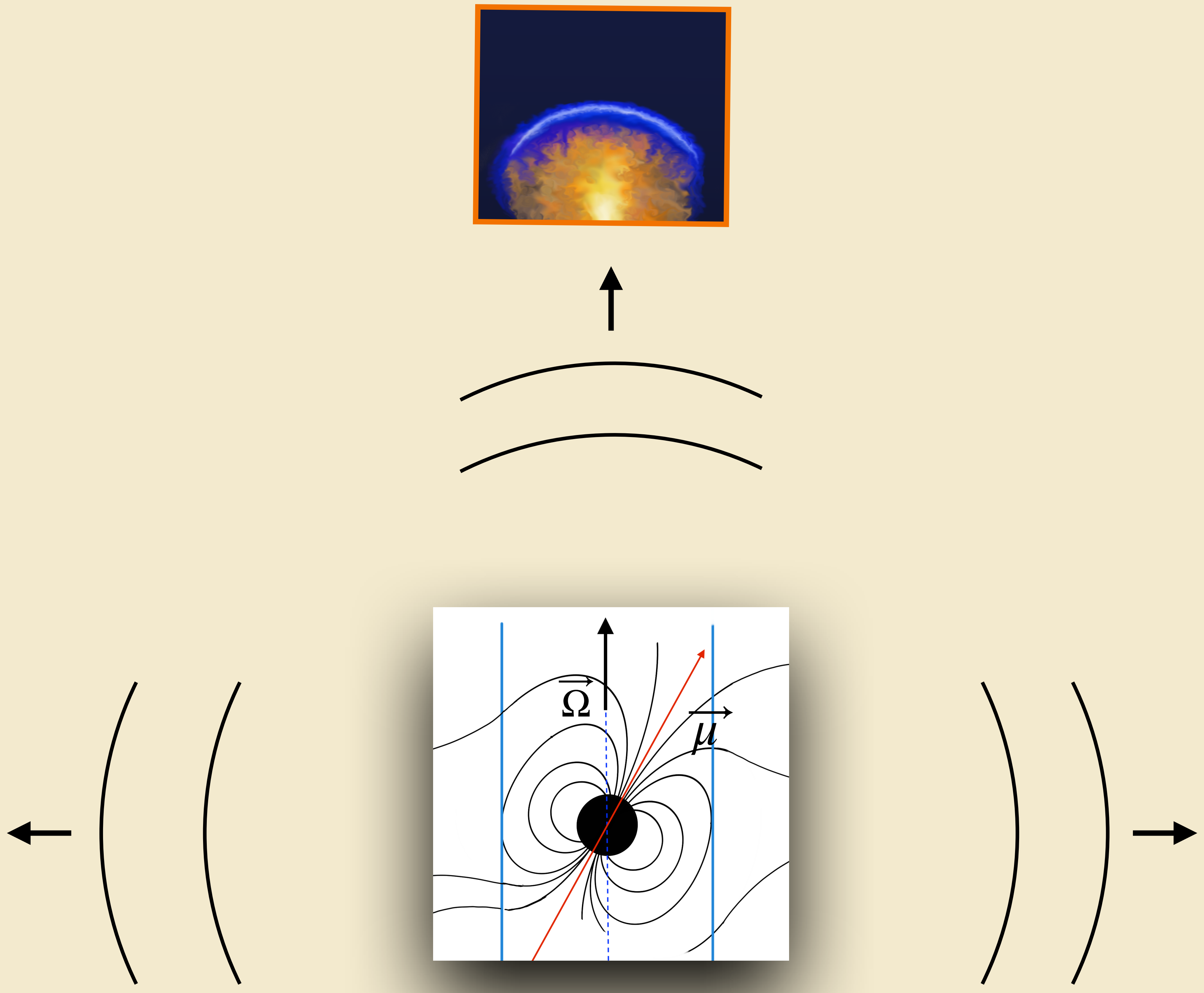
HLE from a structured jet

Oganesyan et al. 2020, Ascenzi et al. 2020





Energy injection scenario



$$L_{SD} = -I\Omega\dot{\Omega} \longrightarrow L_{SD} \propto \frac{1}{(1+t/\tau)^2} \longrightarrow E_{sh}$$

Rees & Meszaros (1998)

Ongoing work: improve our understanding of the plateau phase

1. Collect a complete sample of GRBs with plateau

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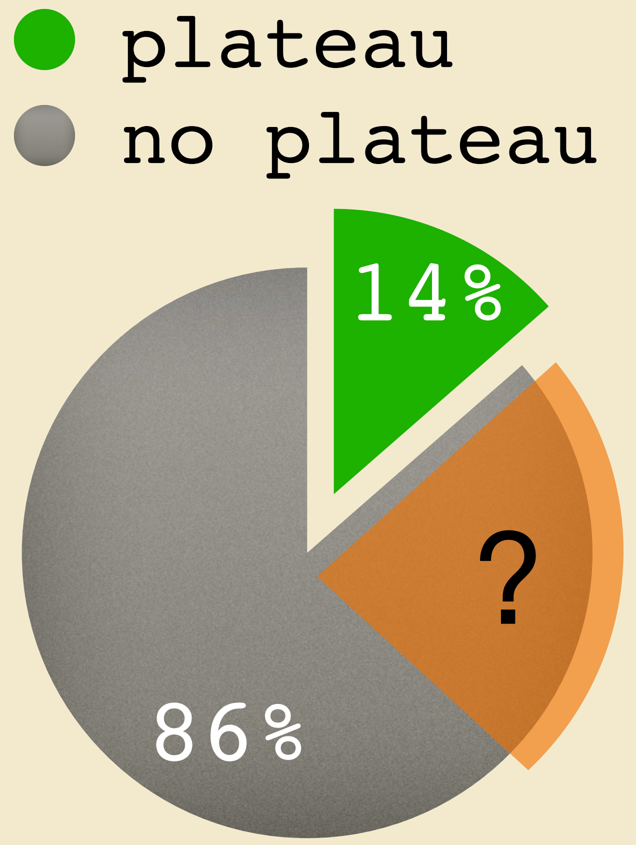
Is the fraction of GRBs with plateau related to the nature of the progenitor?

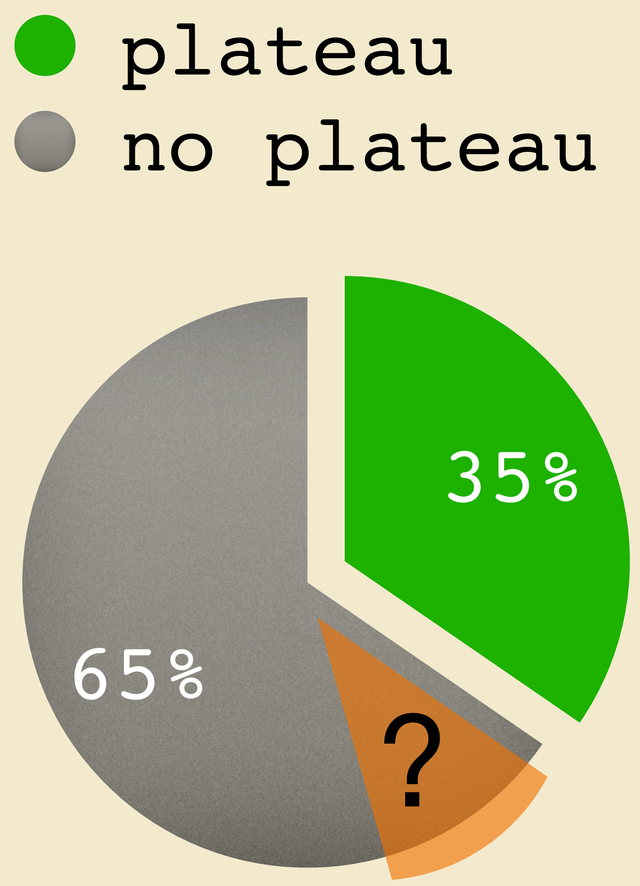
Short GRBs



We need to consider several caveats:

- A large fraction of SGRBs light curves has a low S/N and/or is not well sampled
- The plateau can be present before the XRT temporal window

Long GRBs



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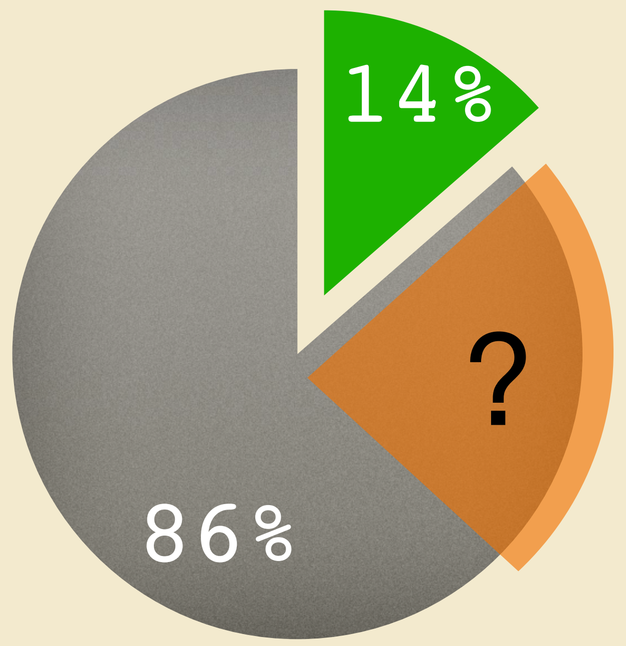
Short GRBs

- plateau
- no plateau



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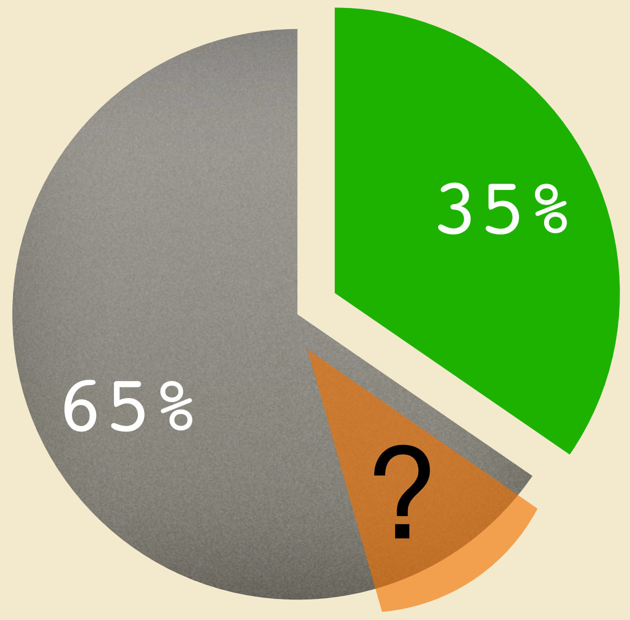
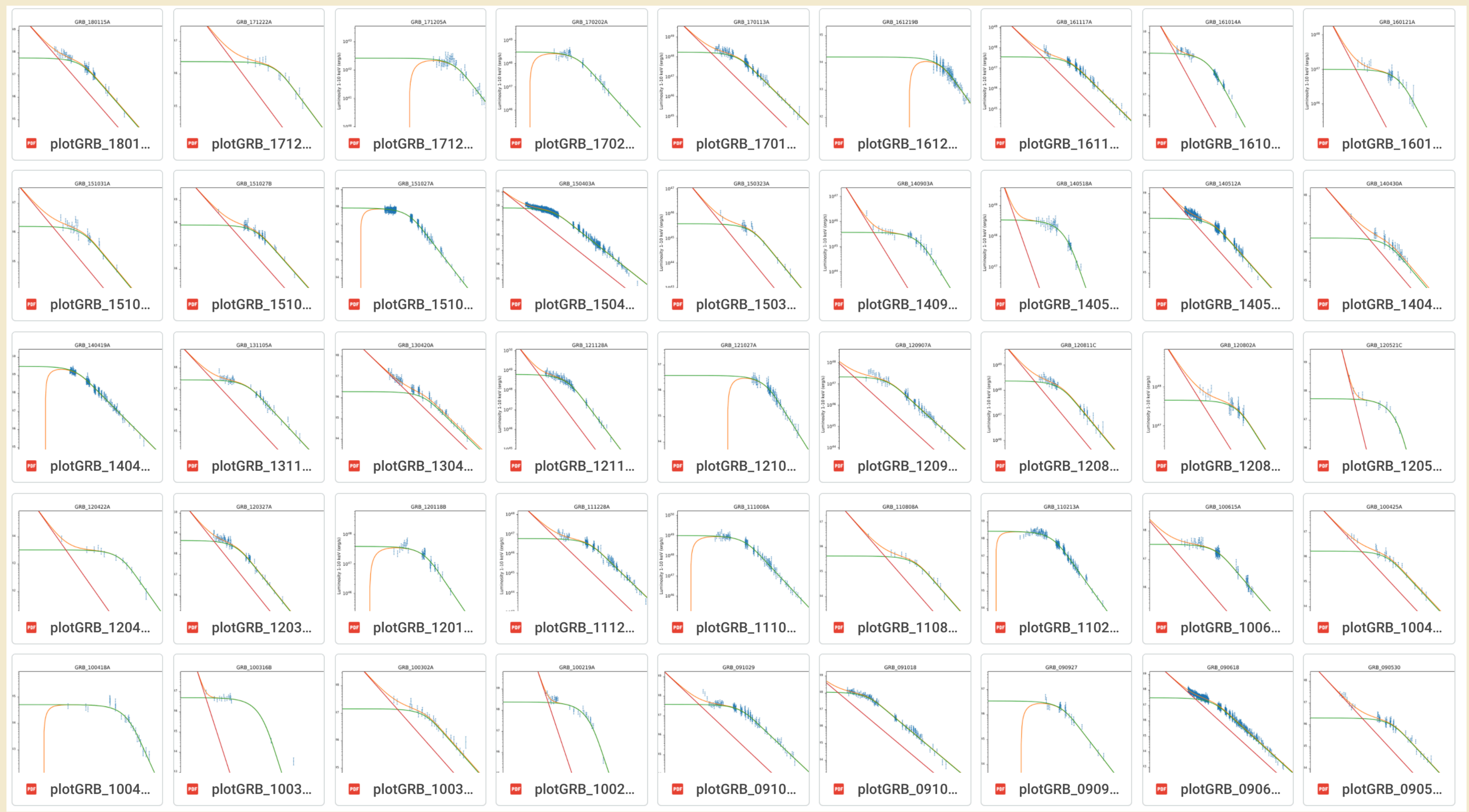


Systematic fit of the magnetar model, improving the work of Stratta et. al 2018



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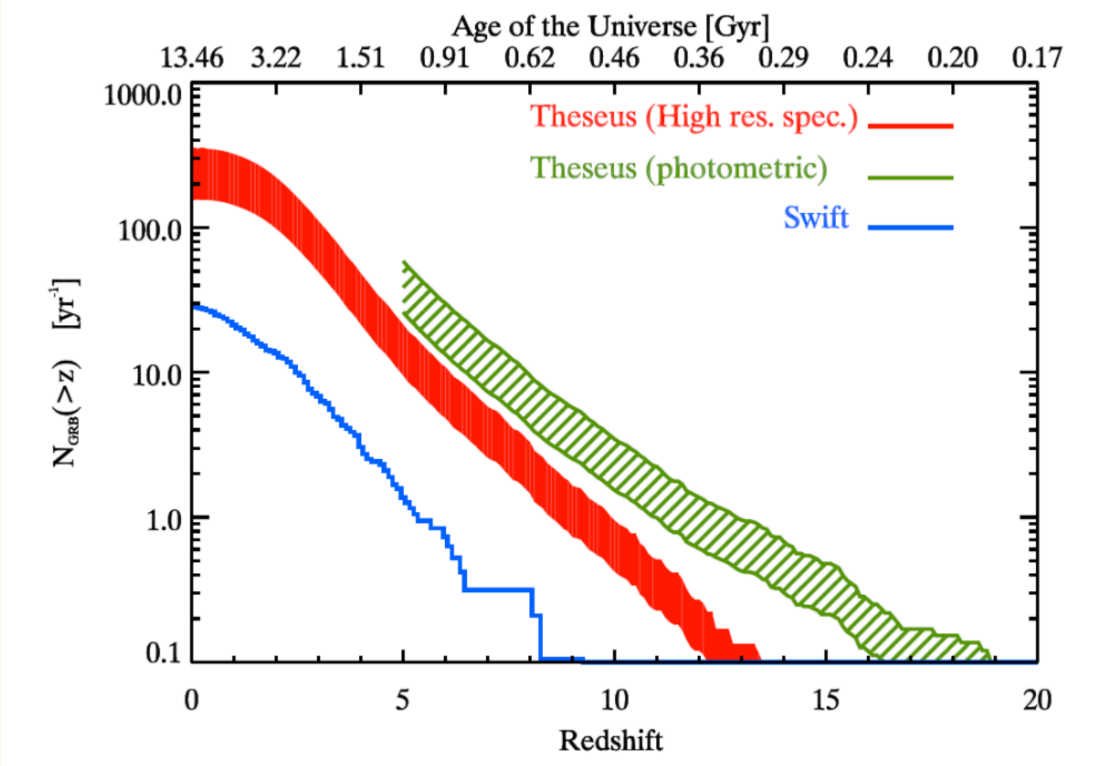
Involvement in the science case of THESEUS:

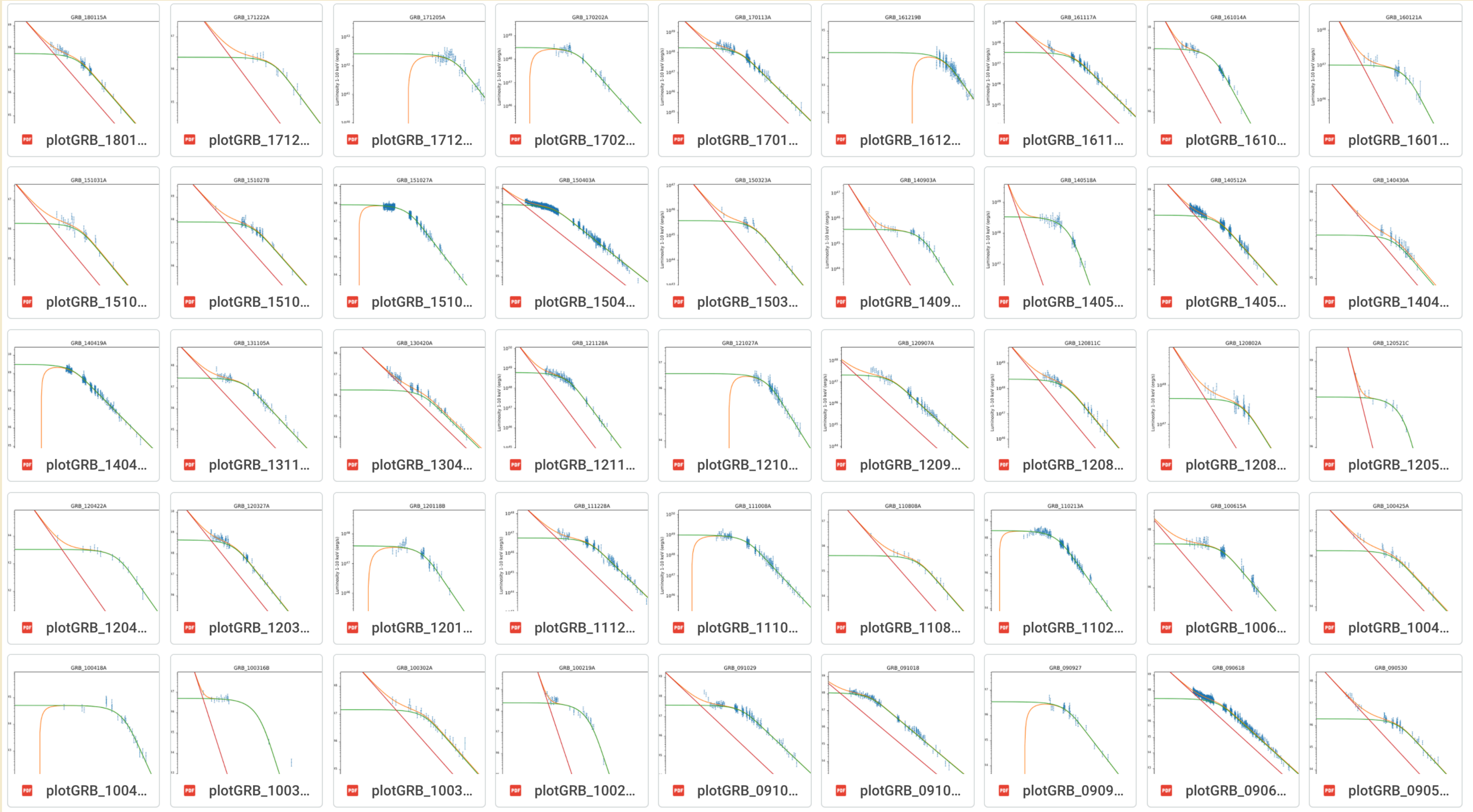
-Study of the detection capability of the instruments

-Potential role for multi-messenger astronomy



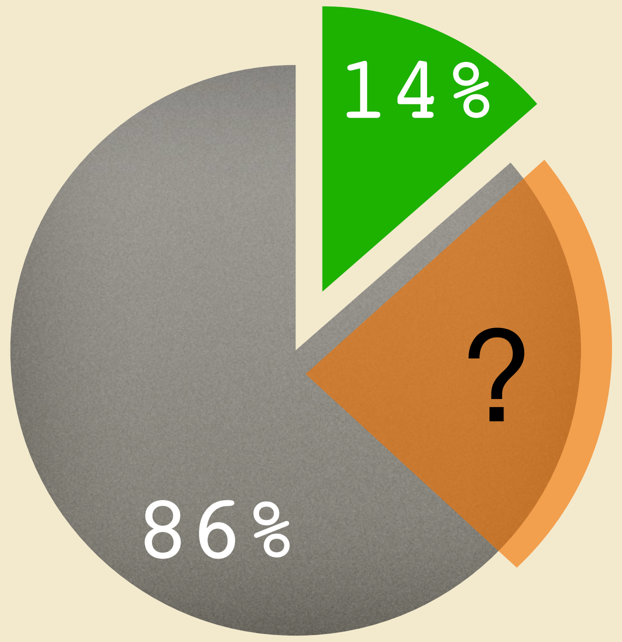
Is the fraction of GRBs with plateau related to the nature of the progenitor?

Systematic fit of the magnetar model, improving the work of Stratta et. al 2018



Short GRBs

- plateau
- no plateau

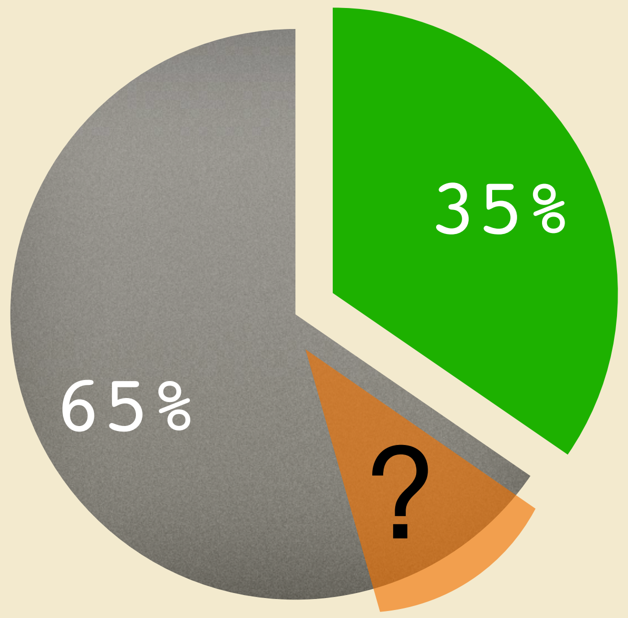


We need to consider several caveats:

- A large fraction of SGRBs light curves has a low S/N and/or is not well sampled
- The plateau can be present before the XRT temporal window

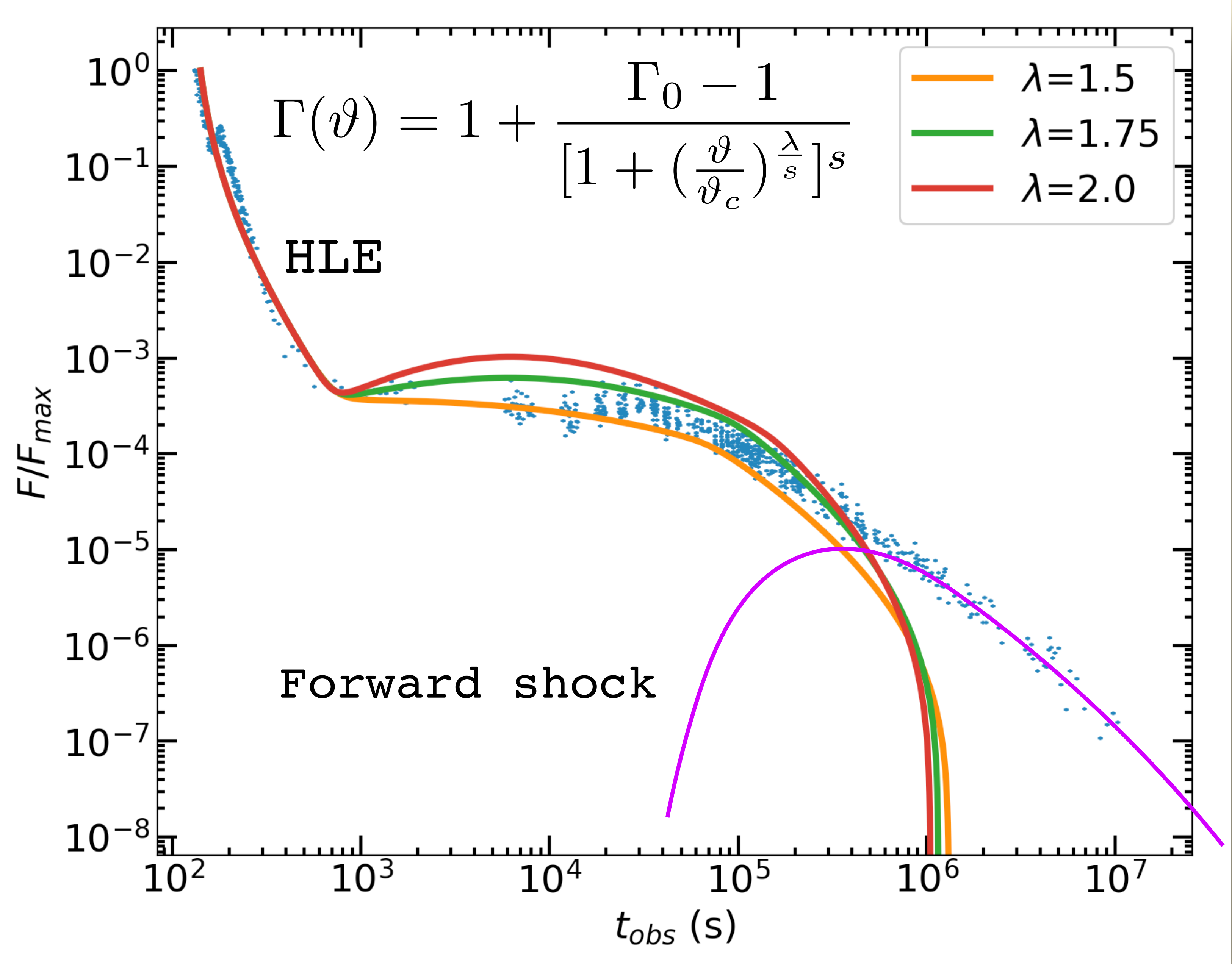
Long GRBs

- plateau
- no plateau



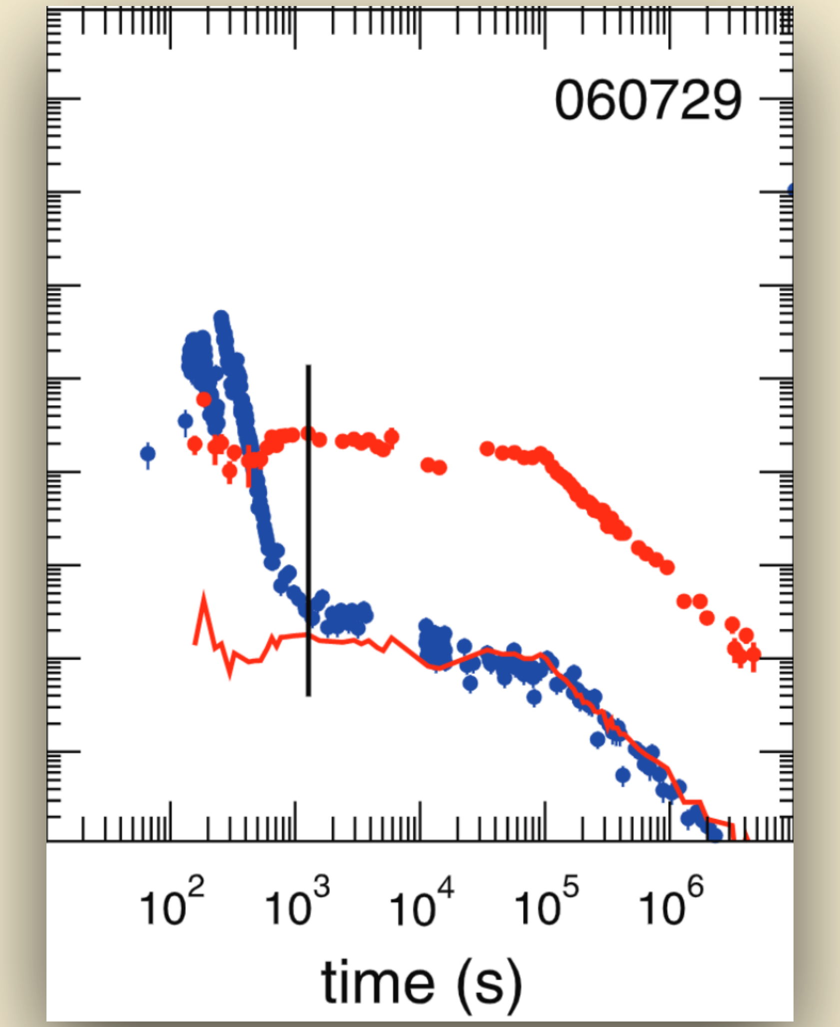
2. Carry on the investigation on the origin of plateau

- ✶Improve the parametric study of HLE from a structured jet
- ✶Include the afterglow emission from the forward shock
- ✶Obtain a unique tool for X-ray light curve fitting

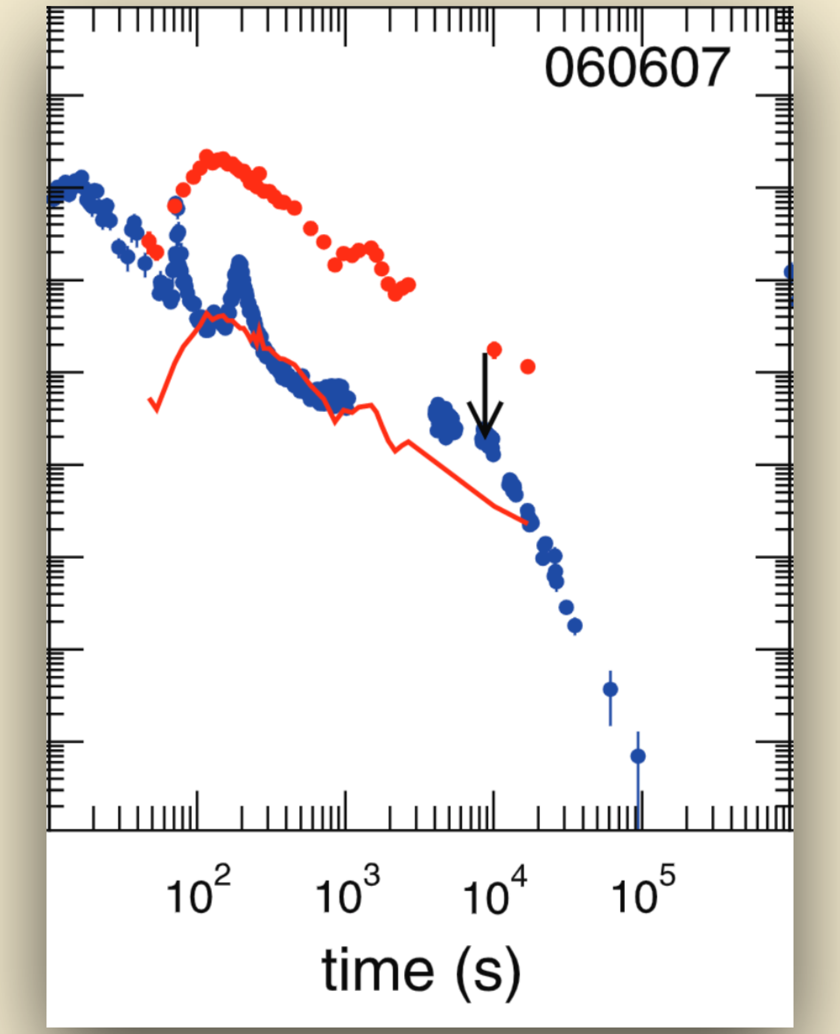


- ✶ Consider archival optical data to study the broad band spectrum and test the validity of the HLE model

Achromatic



Chromatic



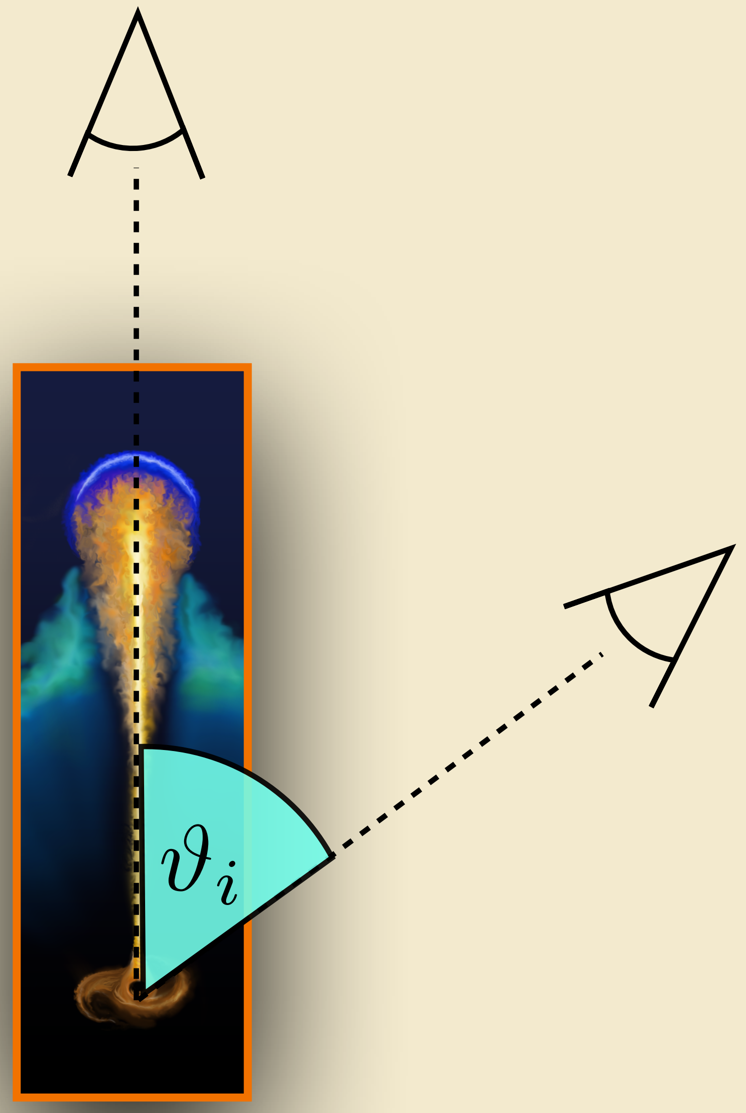
From Panaitescu & Vestrand (2011)

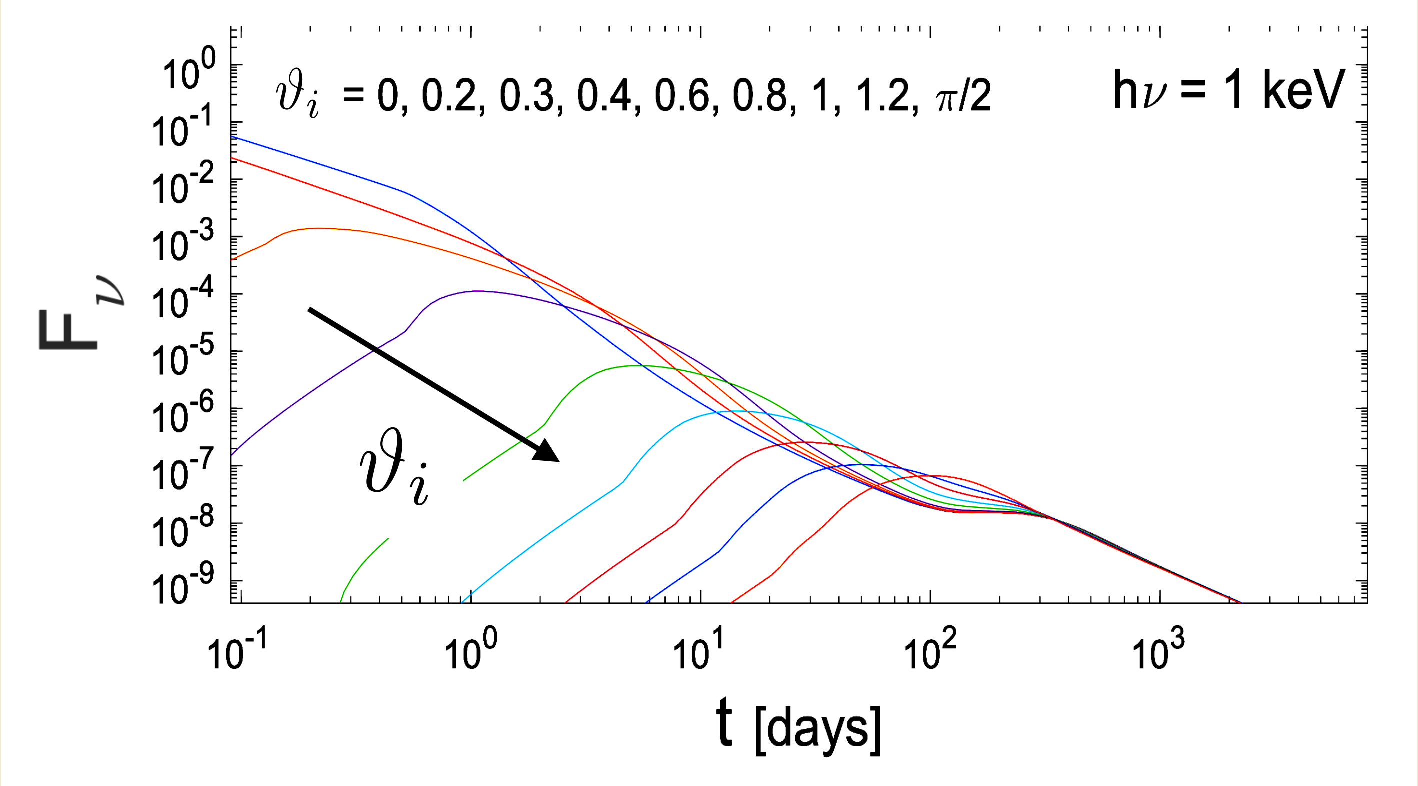
Answer to the question:

How many EM counterparts we will observe with future synergy between GW observatories and astronomical facilities?

Prediction of the typical light-curve of a short GRB (using HLE + afterglow), based on the analysis of the Swift database

Extension to off-axis observer



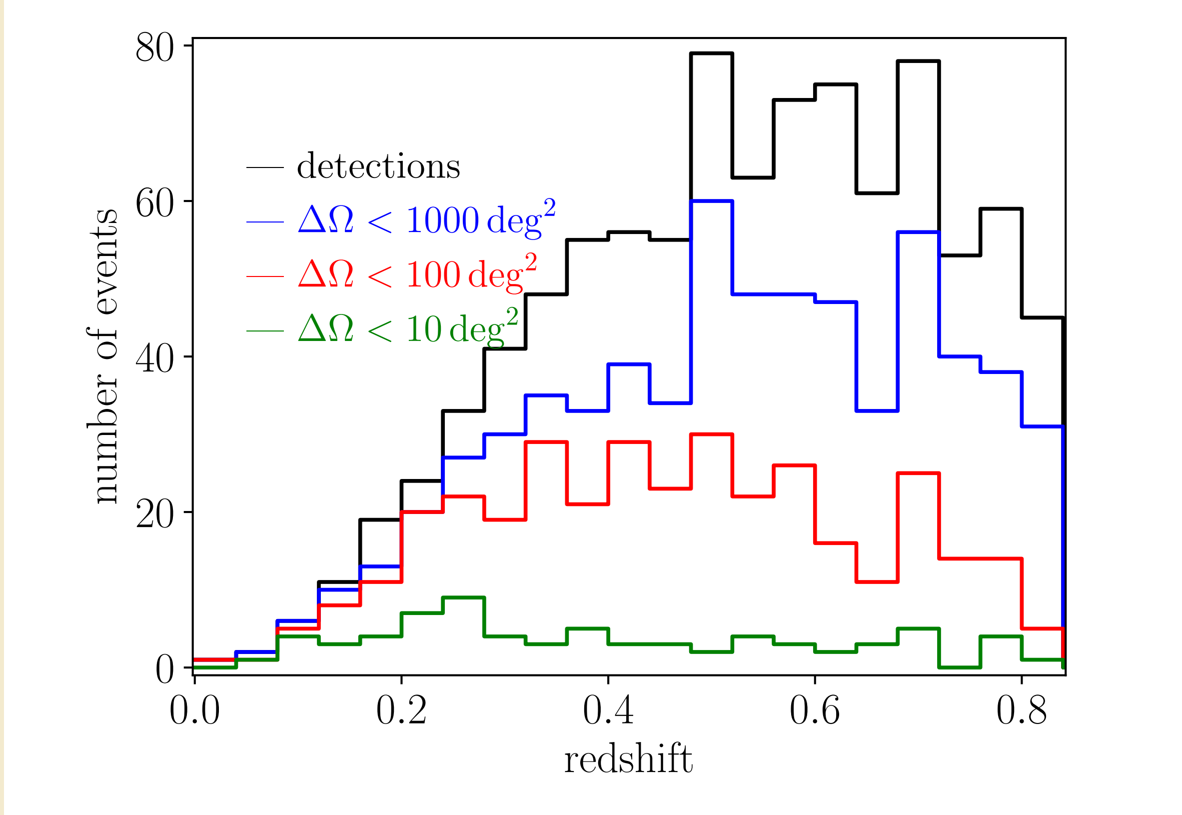


Granot et al. (2017)

+

NS-NS + NS-BH merger rate from population synthesis + GW parameters estimation

1 week of NS-NS detections with ET+CE

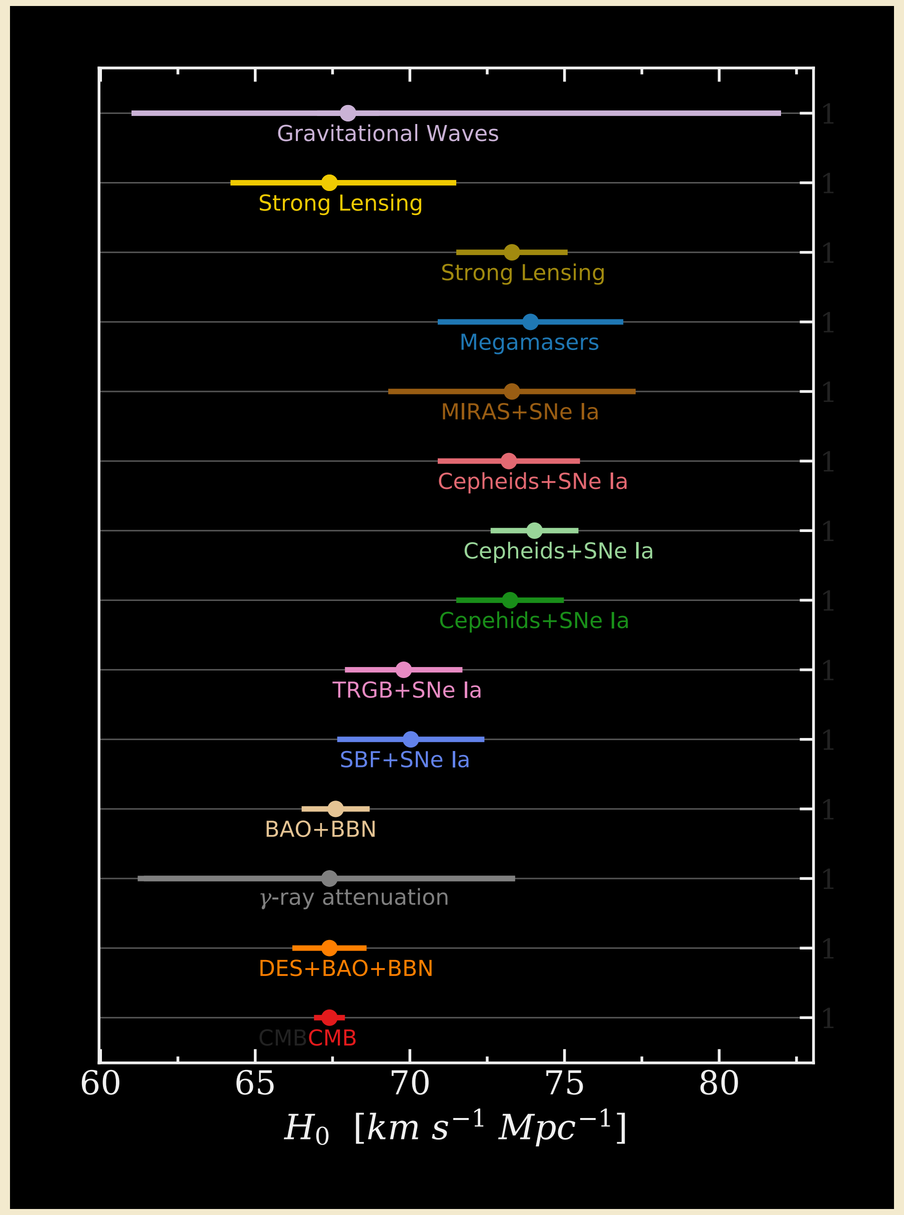


From the PhD work of Stefan Grimm

Instrument characteristics (e.g. flux sensitivity, field of view, slewing time…)

$$R_{\mathrm{det}}(z, F_{lim}, \vartheta_i, \dots)$$

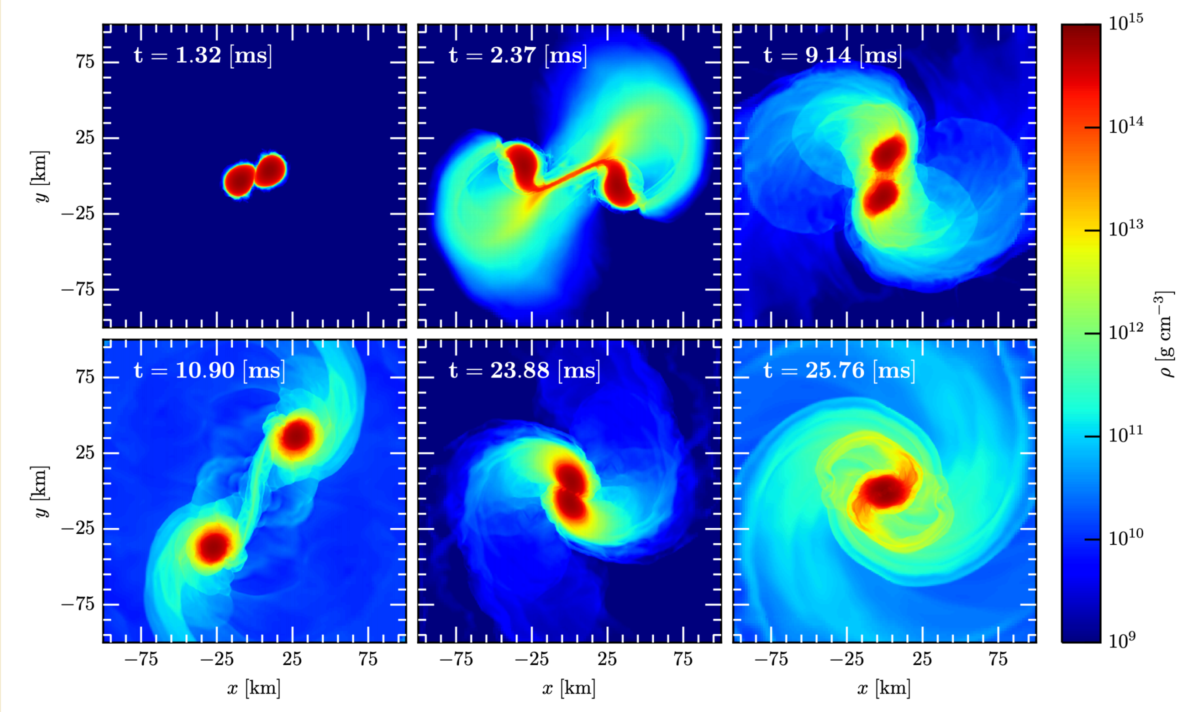
H_0 tension



From Khetan et al. 2020

Cosmology with GWs+EM counterparts

EOS of NS: determines the remnant as well as the fraction of accreted mass



From Radice et al. 2016

$$R_{\rm det}(z, F_{lim}, \vartheta_i, \ldots)$$

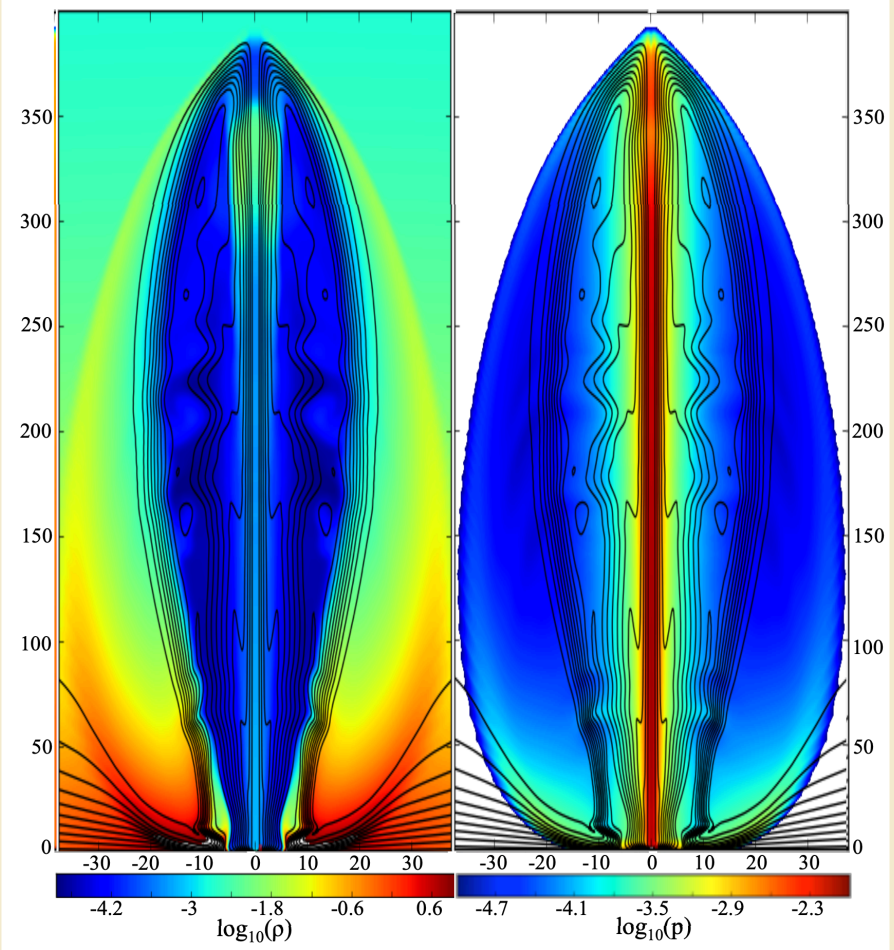
Relation between the nature of the progenitor, merger remnant and the properties of the SGRB

BH NS ?

NS NS ✔

Short GRBs

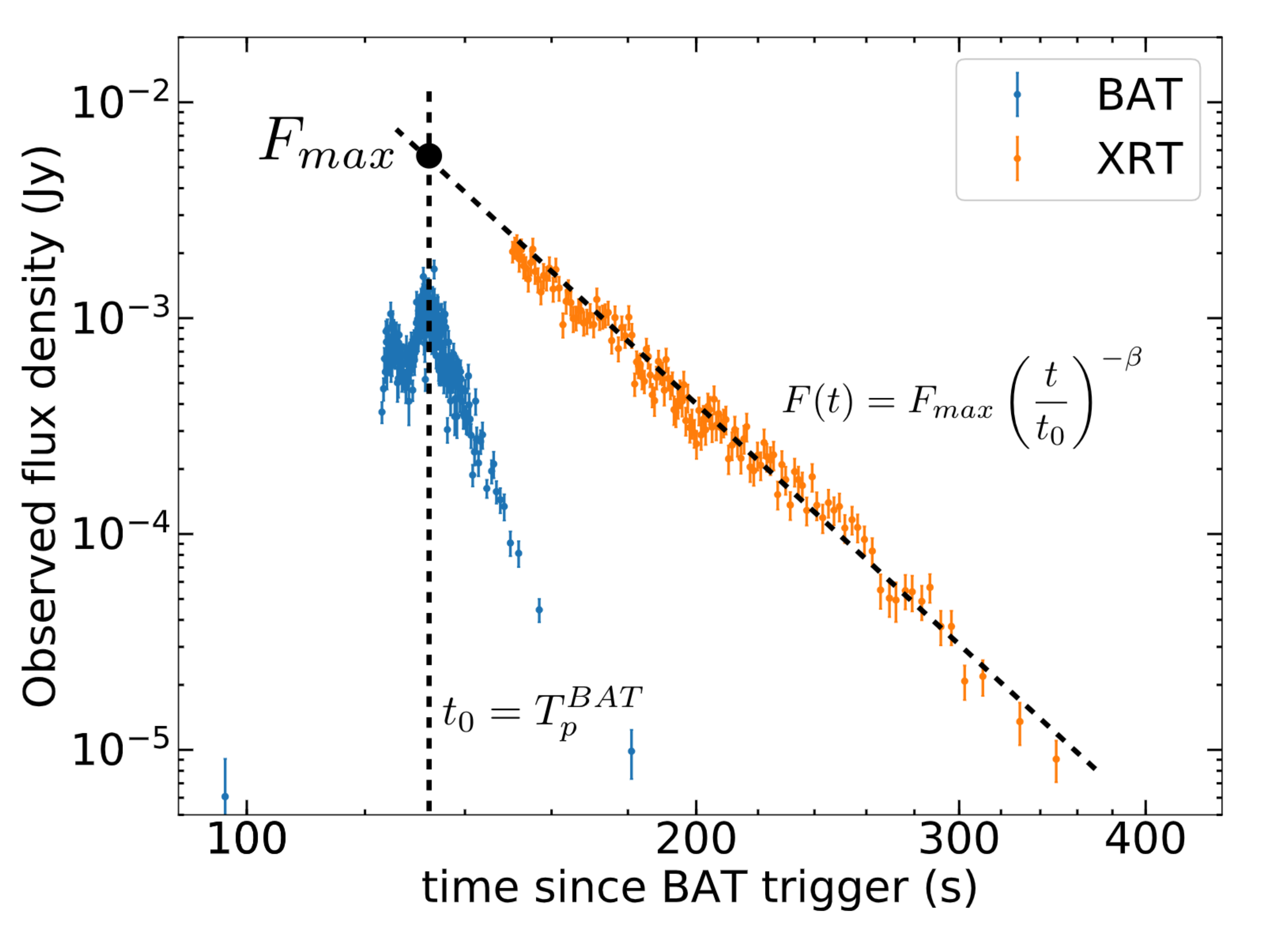
Physics of the relativistic jets: launching, dissipation and structure

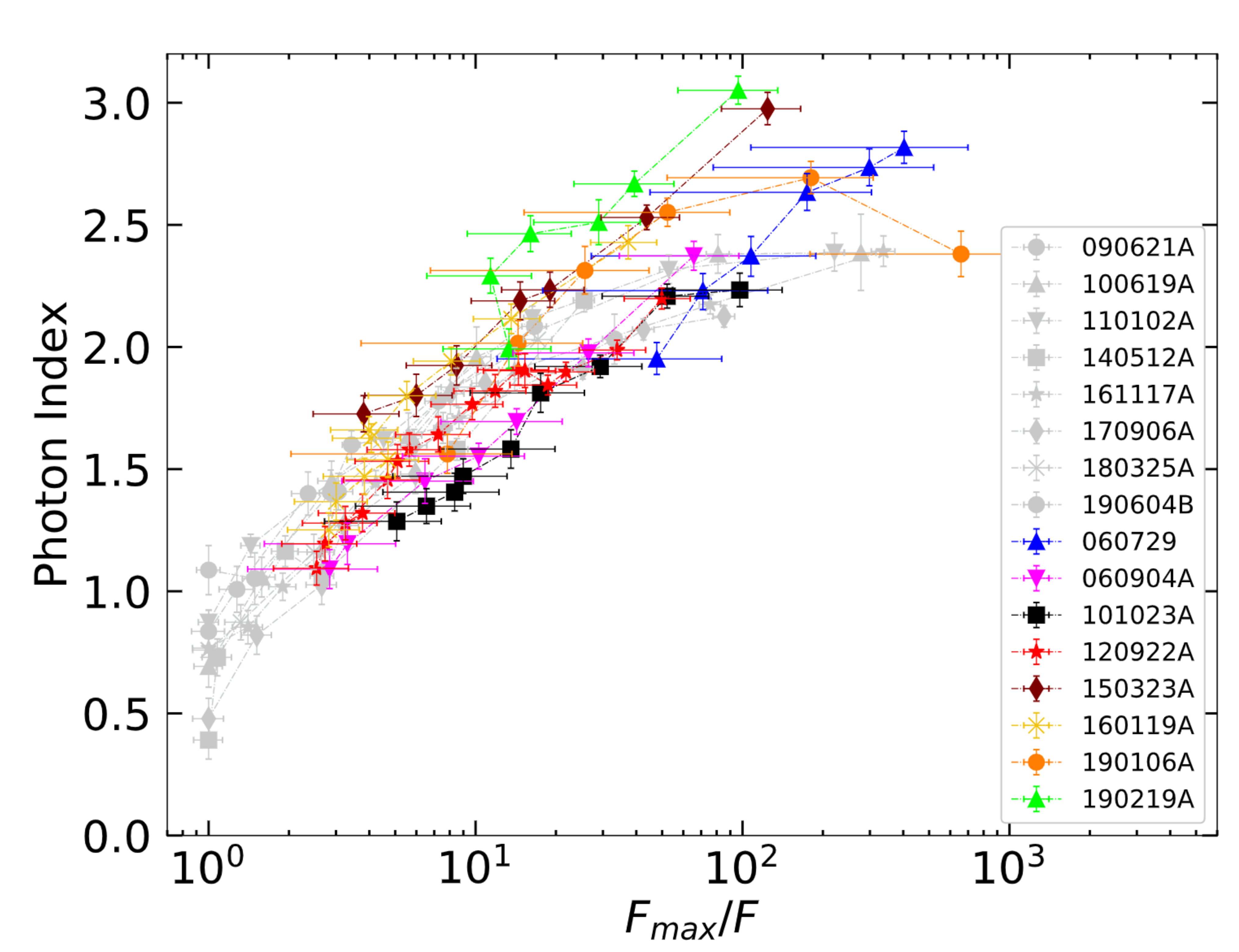


From Bromberg & Tchekhovskoy (2015)

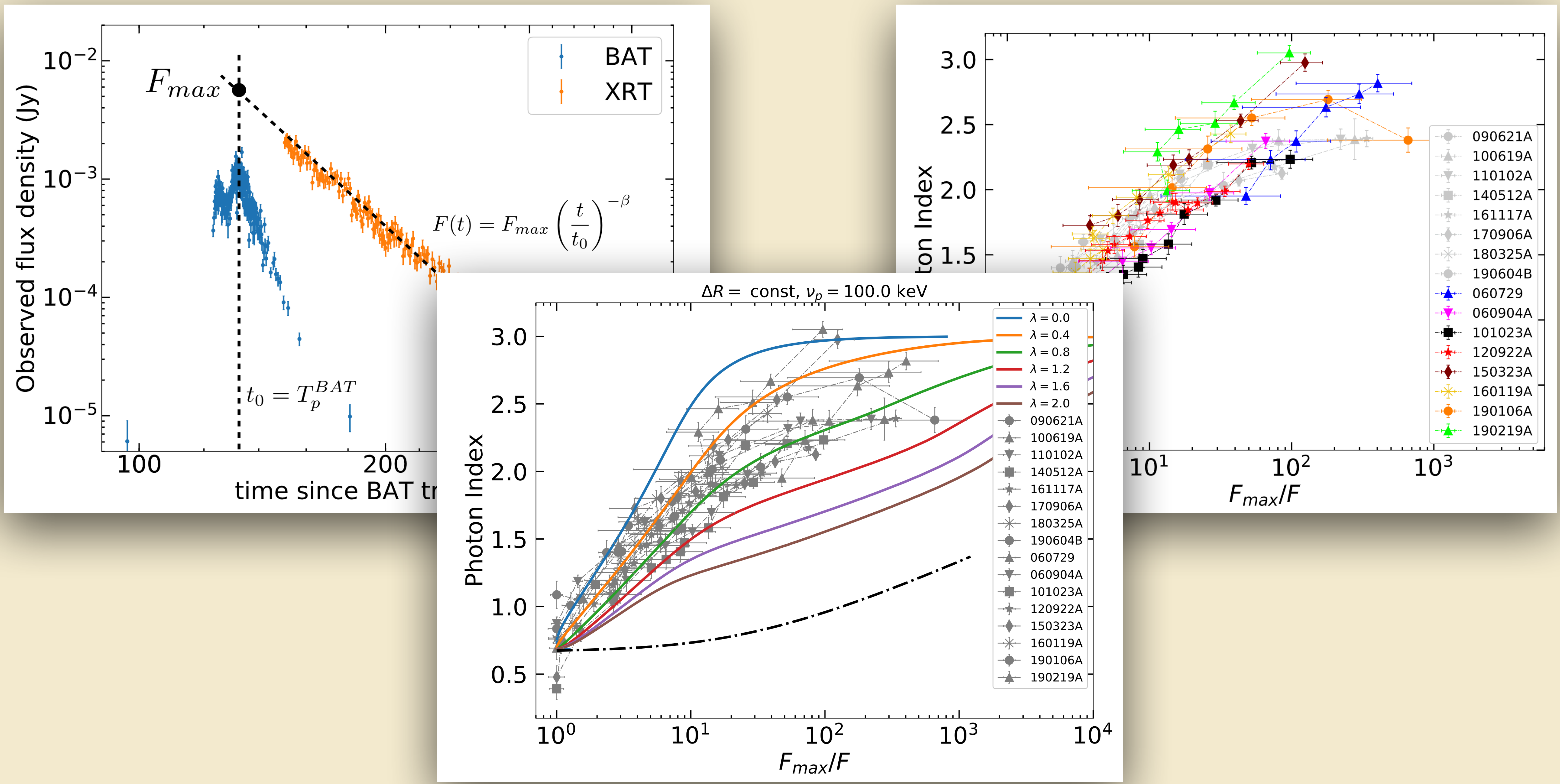
Thanks!

Backup slides


BAT
XRT
F_{max}
$F(t) = F_{max}\left(\frac{t}{t_0}\right)^{-\beta}$
$t_0 = T_p^{BAT}$
Observed flux density (Jy)
time since BAT trigger (s)
10^{-2}
10^{-3}
10^{-4}
10^{-5}
100
200
300
400


Photon Index
F_{max}/F
3.0
2.5
2.0
1.5
1.0
0.5
0.0
10^0
10^1
10^2
10^3
090621A
100619A
110102A
140512A
161117A
170906A
180325A
190604B
060729
060904A
101023A
120922A
150323A
160119A
190106A
190219A

The extended sample



The origin of plateau

Energy injection in the forward shock

HLE from a structured jet

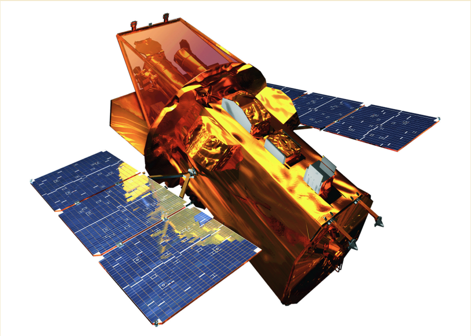
Both can reproduce the light curve flattening

How to discern among them?

Investigating the spectral evolution before, during and after the plateau

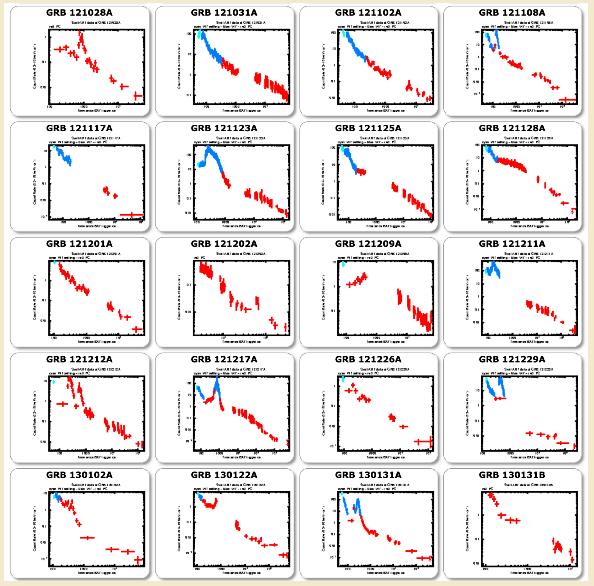
The revolution made by Swift

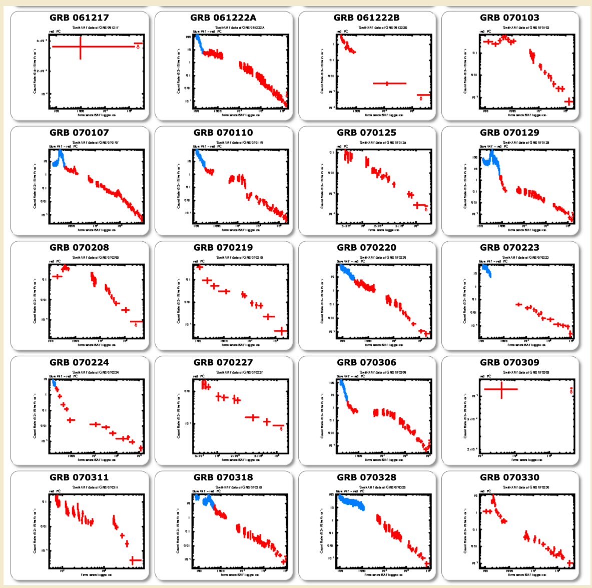
The Neil Gehrels Swift Observatory



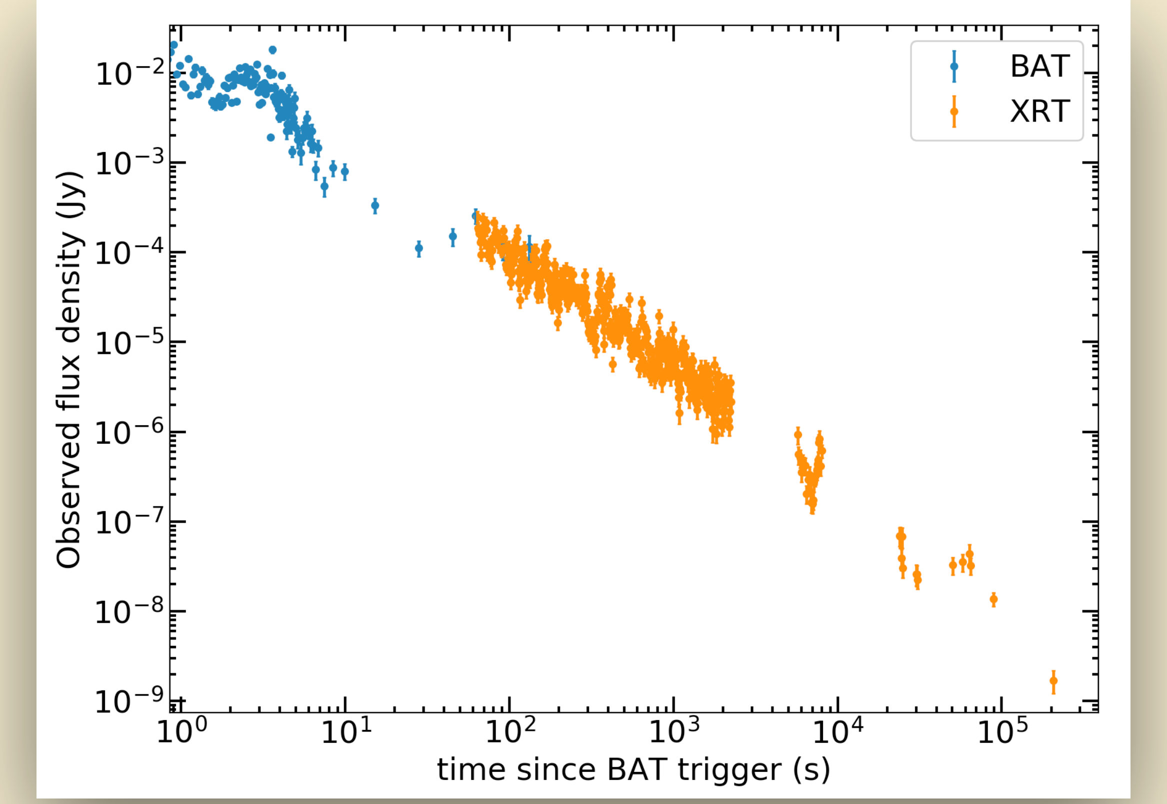
- BAT (15-150 keV)
- XRT (2-10 keV)
- UVOT (opt band)

Almost 1400 GRBs detected in 16 years



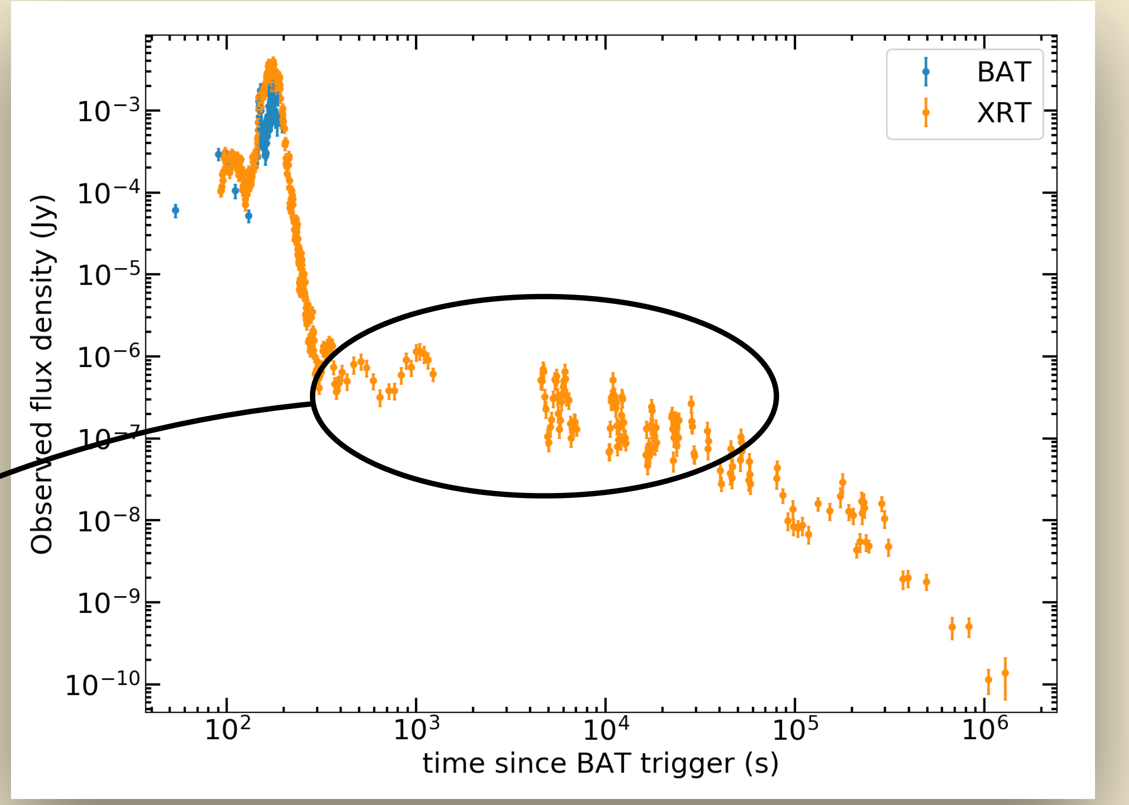


Standard power law decay given the deceleration of the forward shock



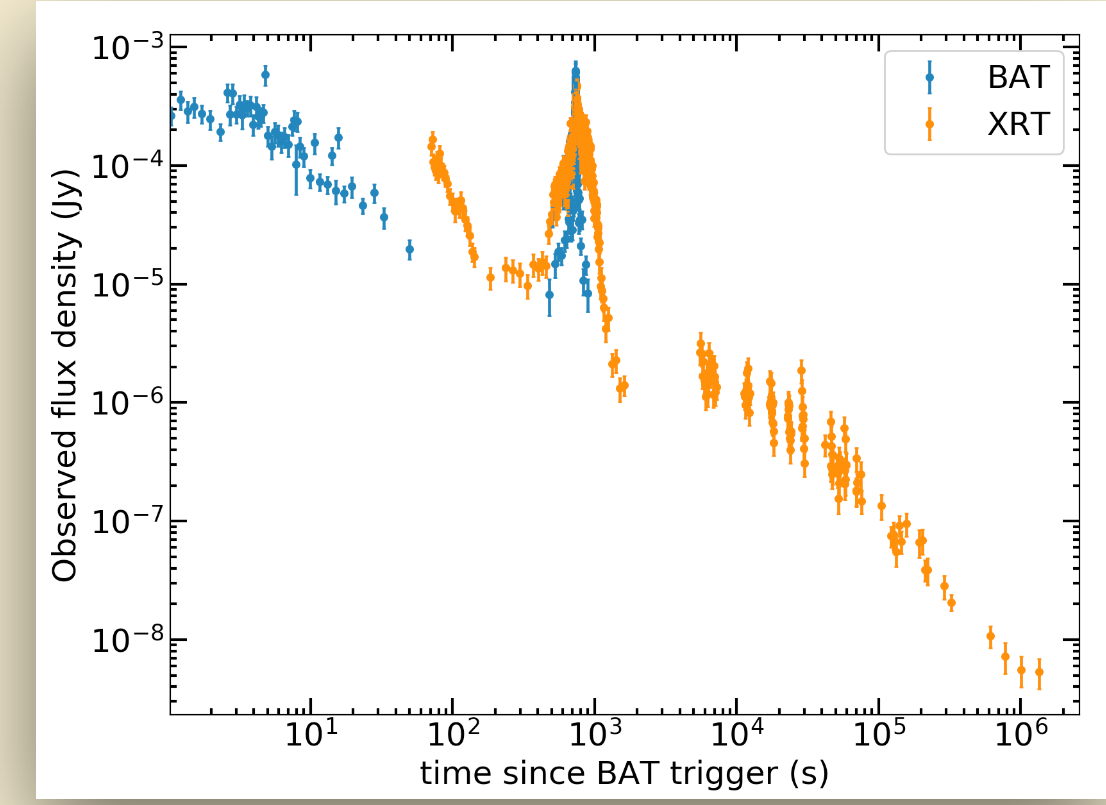
Mèszaros & Rees (1997)

Steep decay + plateau



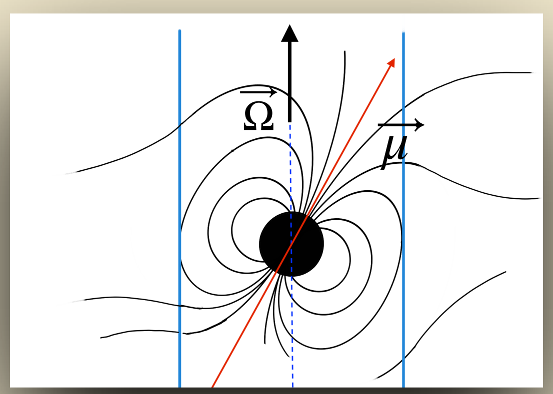
Tagliaferri et al. (2005), Zhang (2006)

X-ray flares

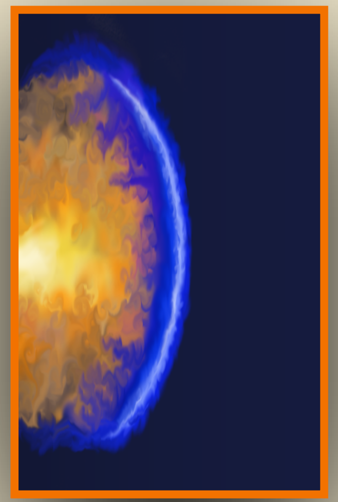


Chincarini (2007)

Energy injection scenario



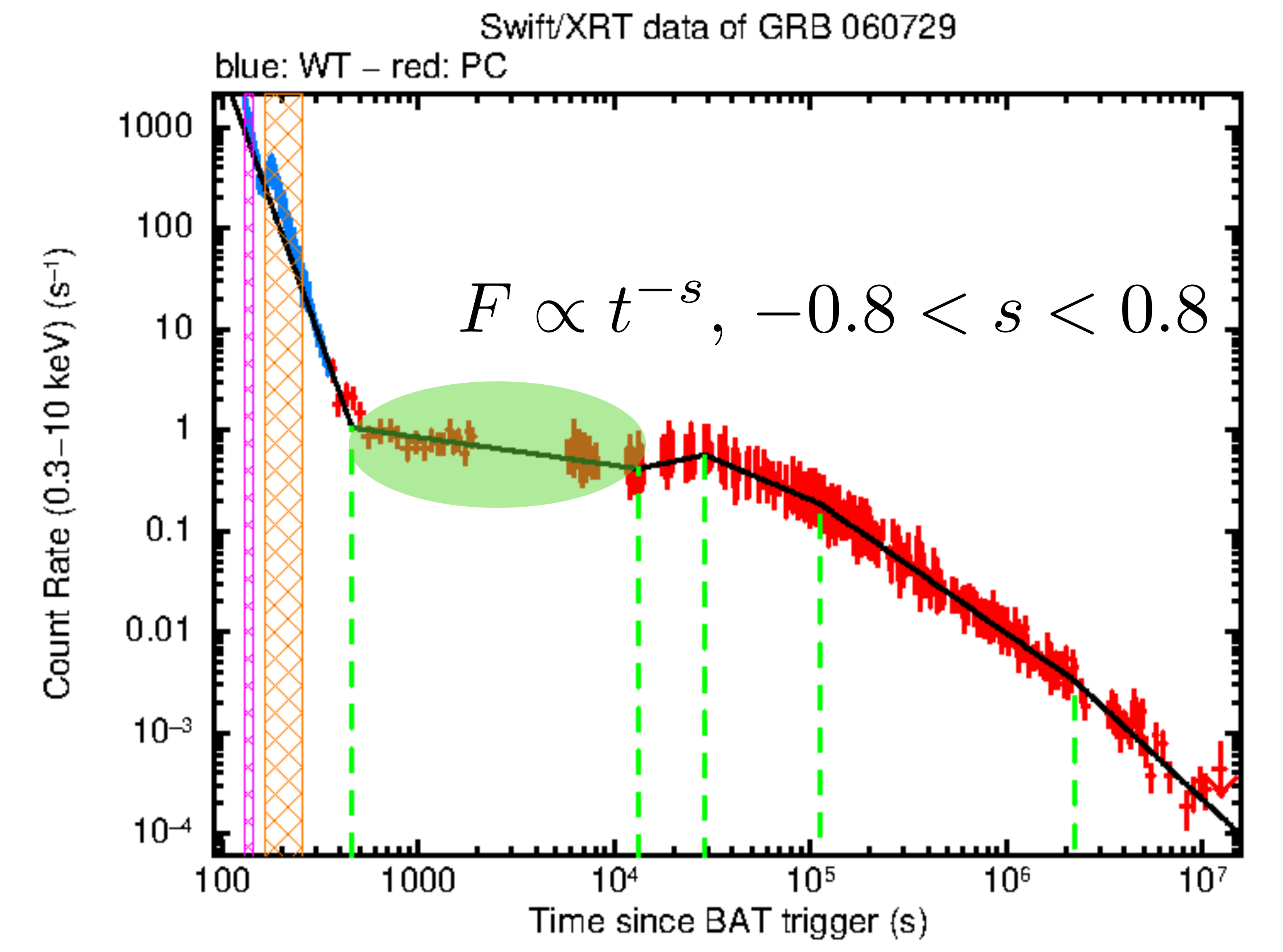
$$L_{SD} = -I\Omega\dot{\Omega} \longrightarrow L_{SD} \propto \frac{1}{(1+t/\tau)^2} \longrightarrow E_{sh}$$



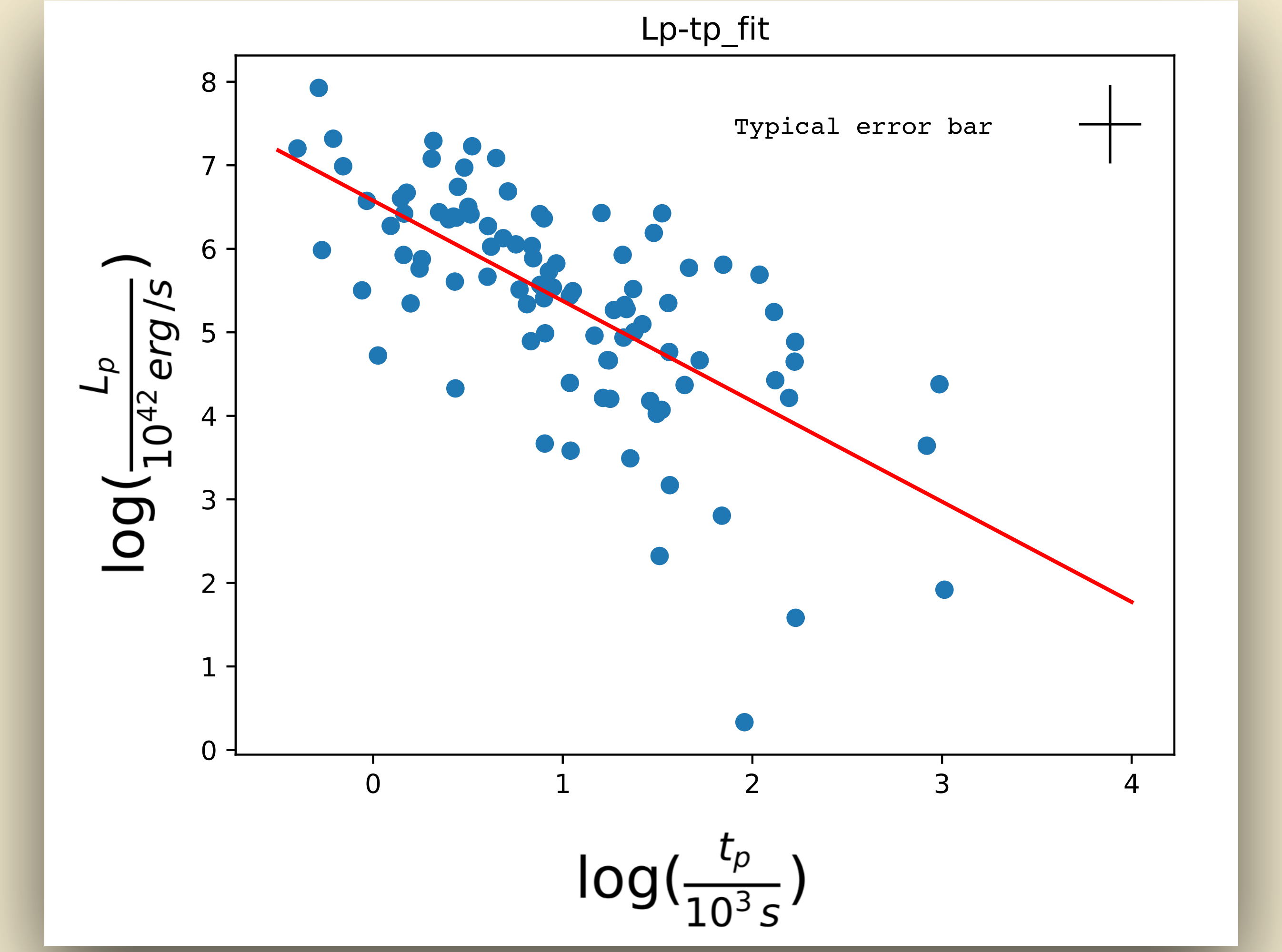
Rees & Meszaros (1998)

Weak points of this scenario:

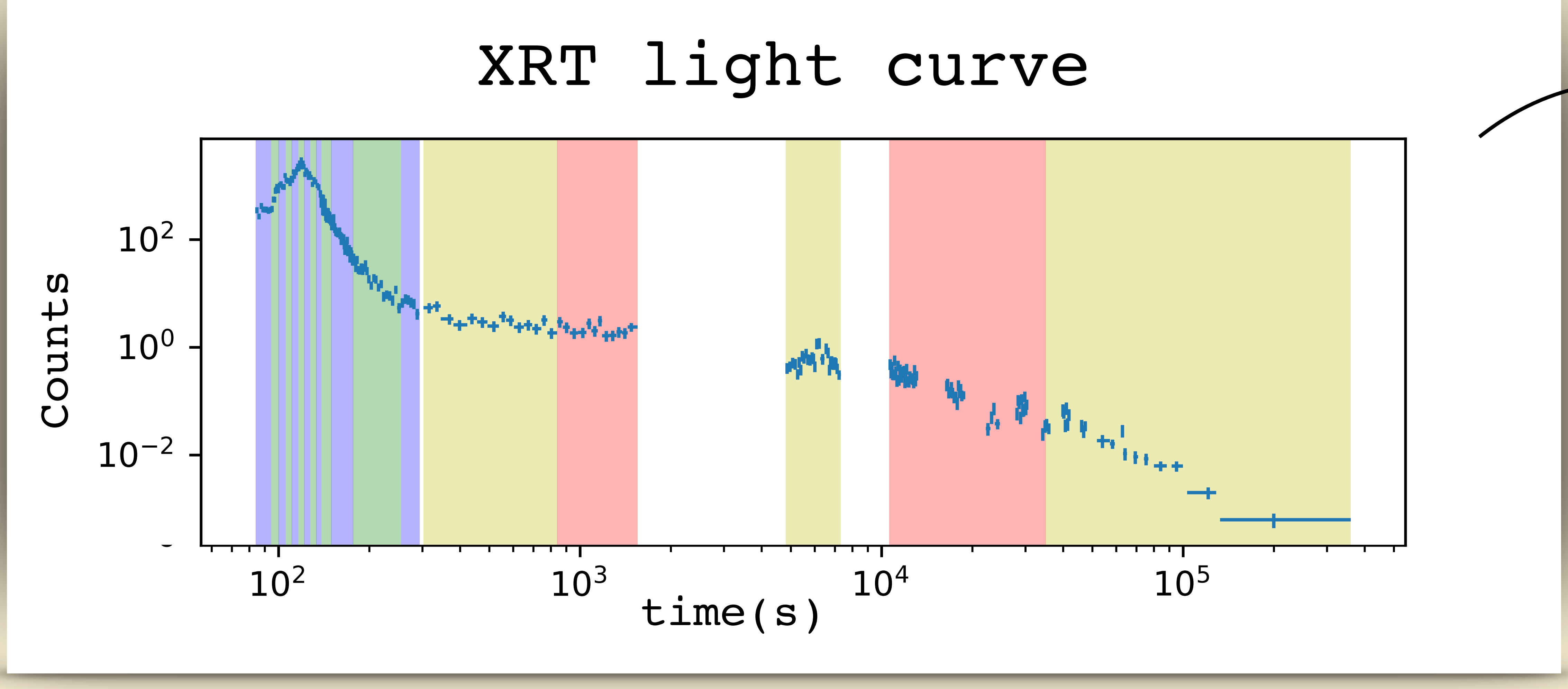
- Current MHD simulations are not able to reproduce a collimated jet from an accreting magnetar. Large (ad hoc) initial magnetic field and efficient amplification mechanisms are necessary
- In case of NS-NS merger, the formation of the jet is strongly affected by baryon pollution due to post-merger ejecta
- chromatic behaviour of optical/X-ray light curves
- energy requirements for the prompt emission



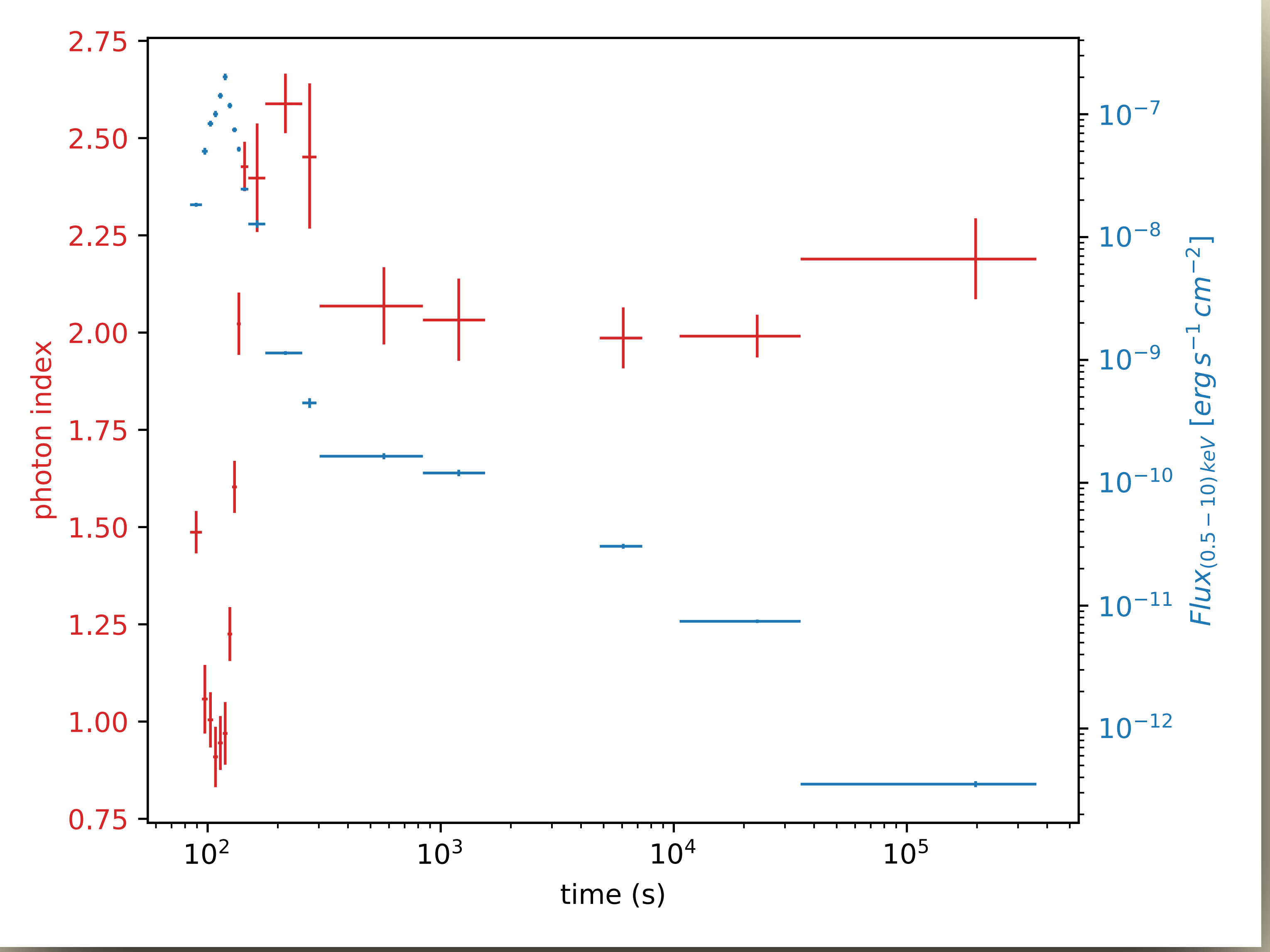
$$L_p \propto t_p^{-k}, \quad k \sim 1$$

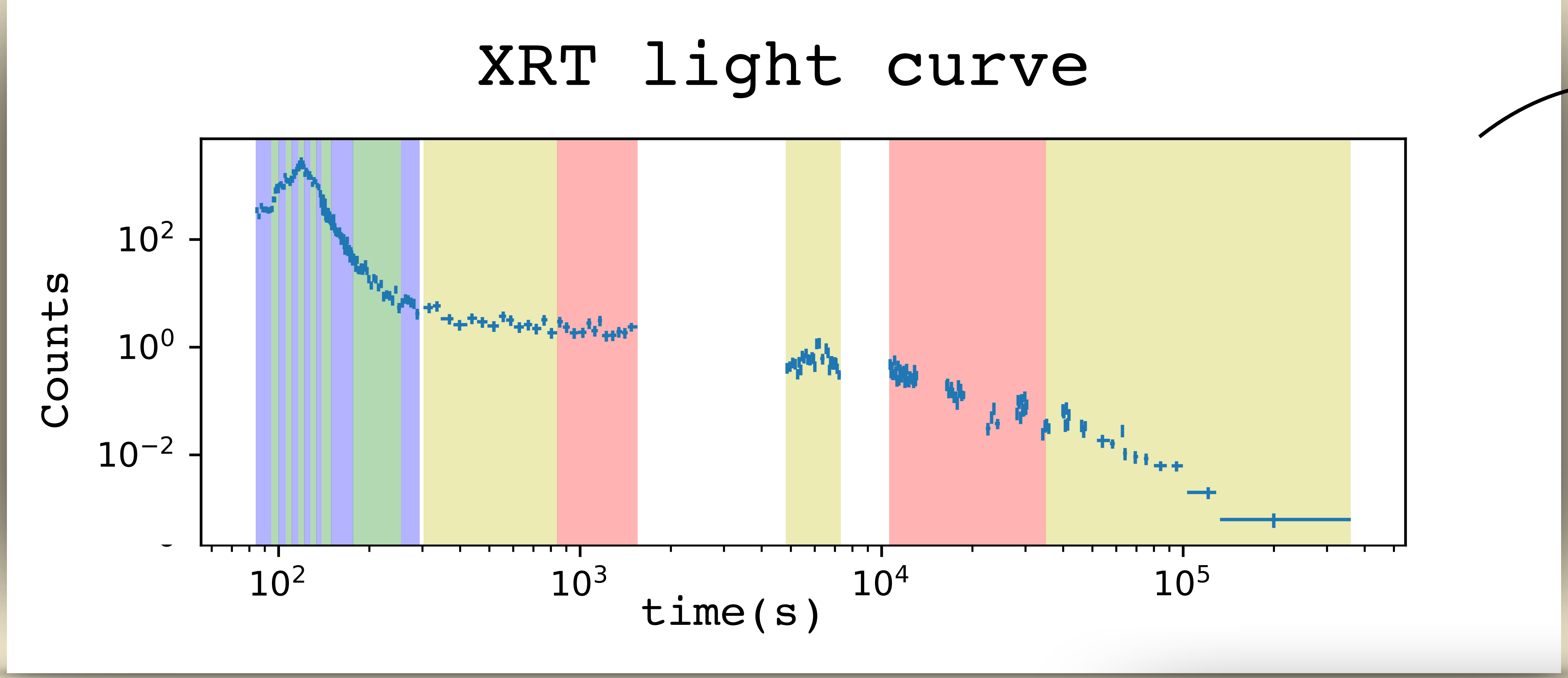


Study of the statistical properties of the sample

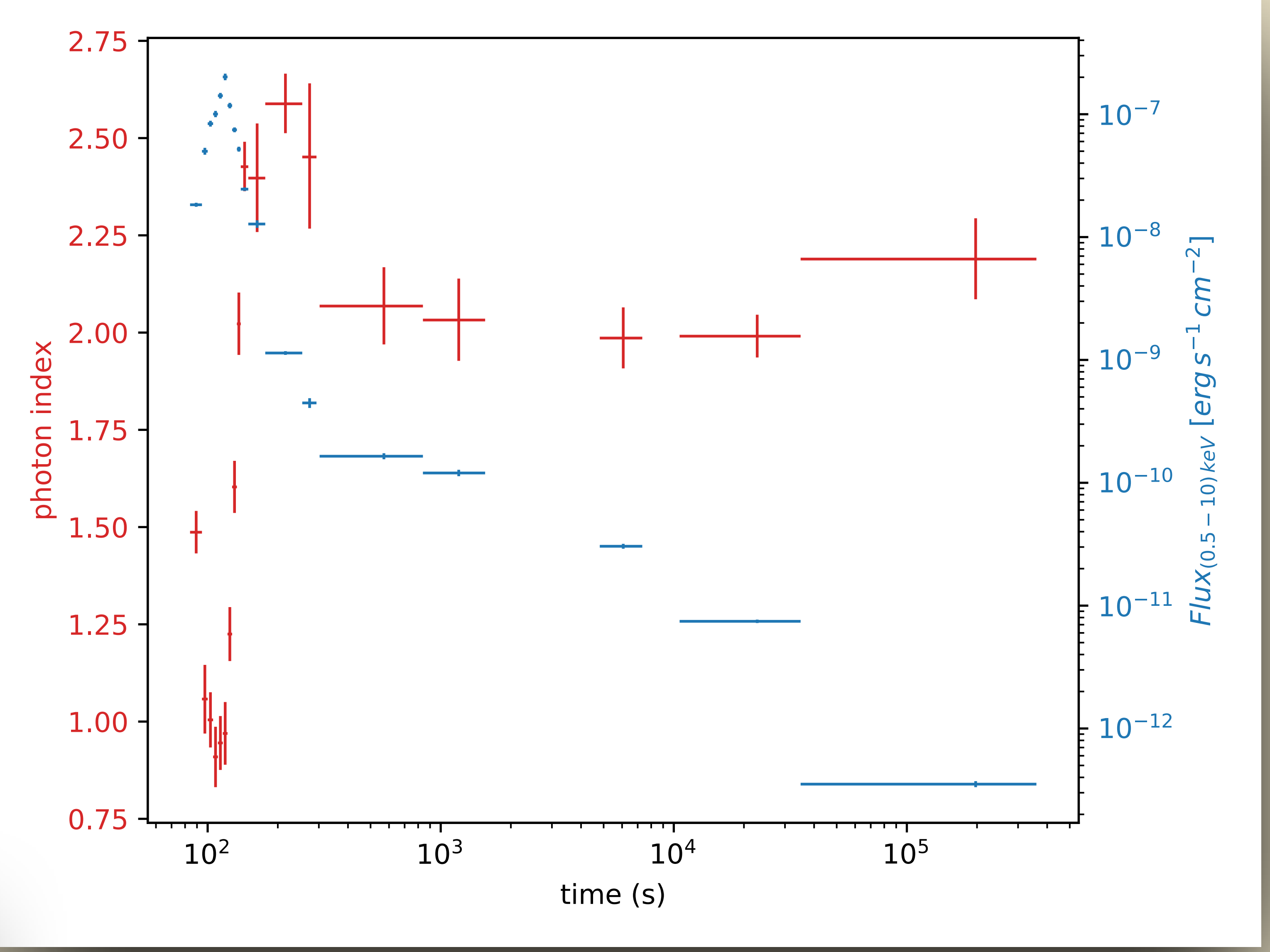


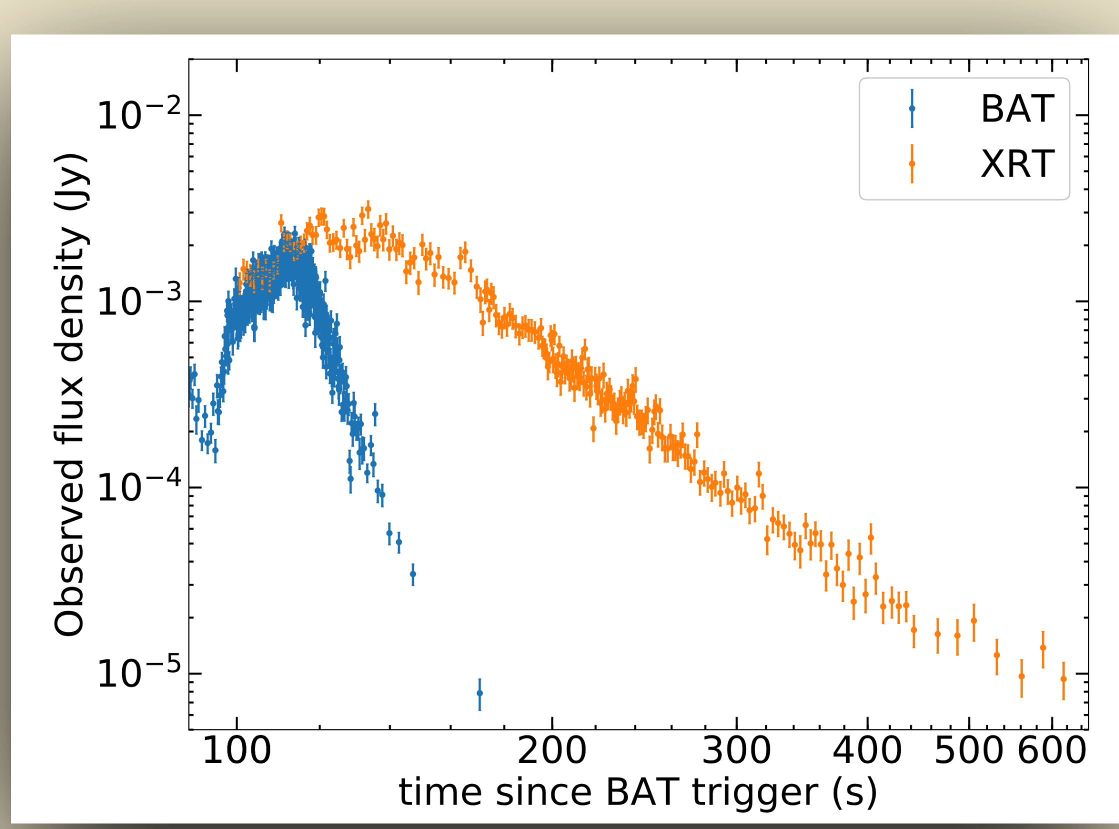
$$S(E) \propto A(z, N_H) E^{-\alpha}$$

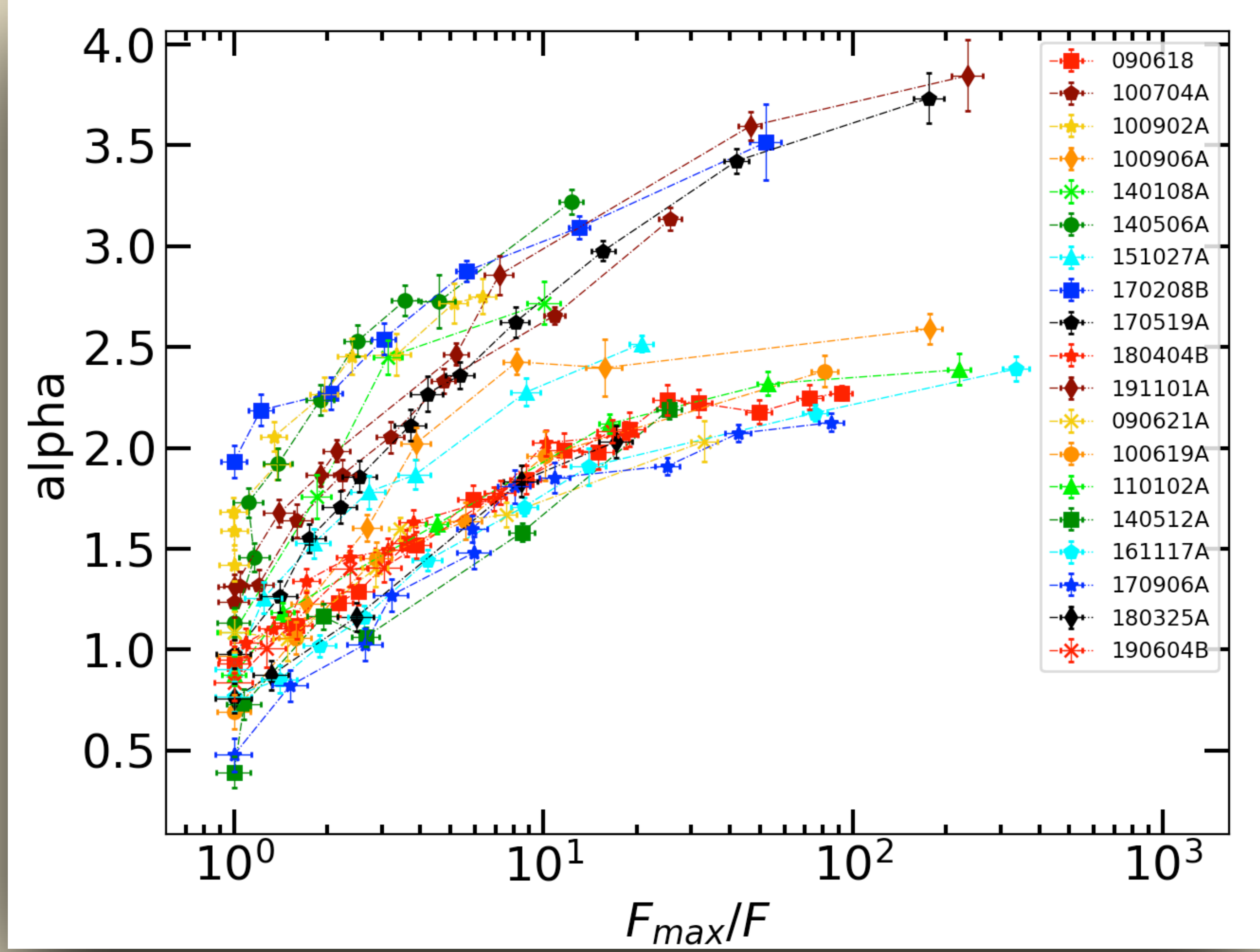




$$S(E) \propto A(z, N_H) E^{-\alpha}$$



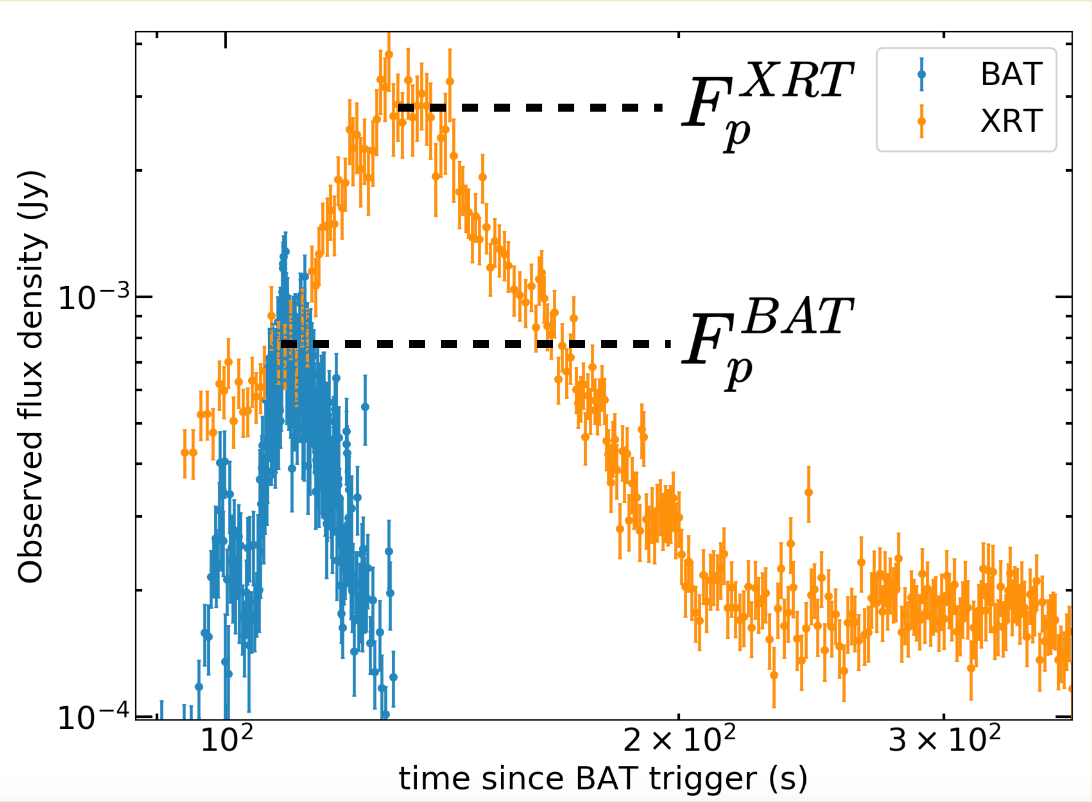


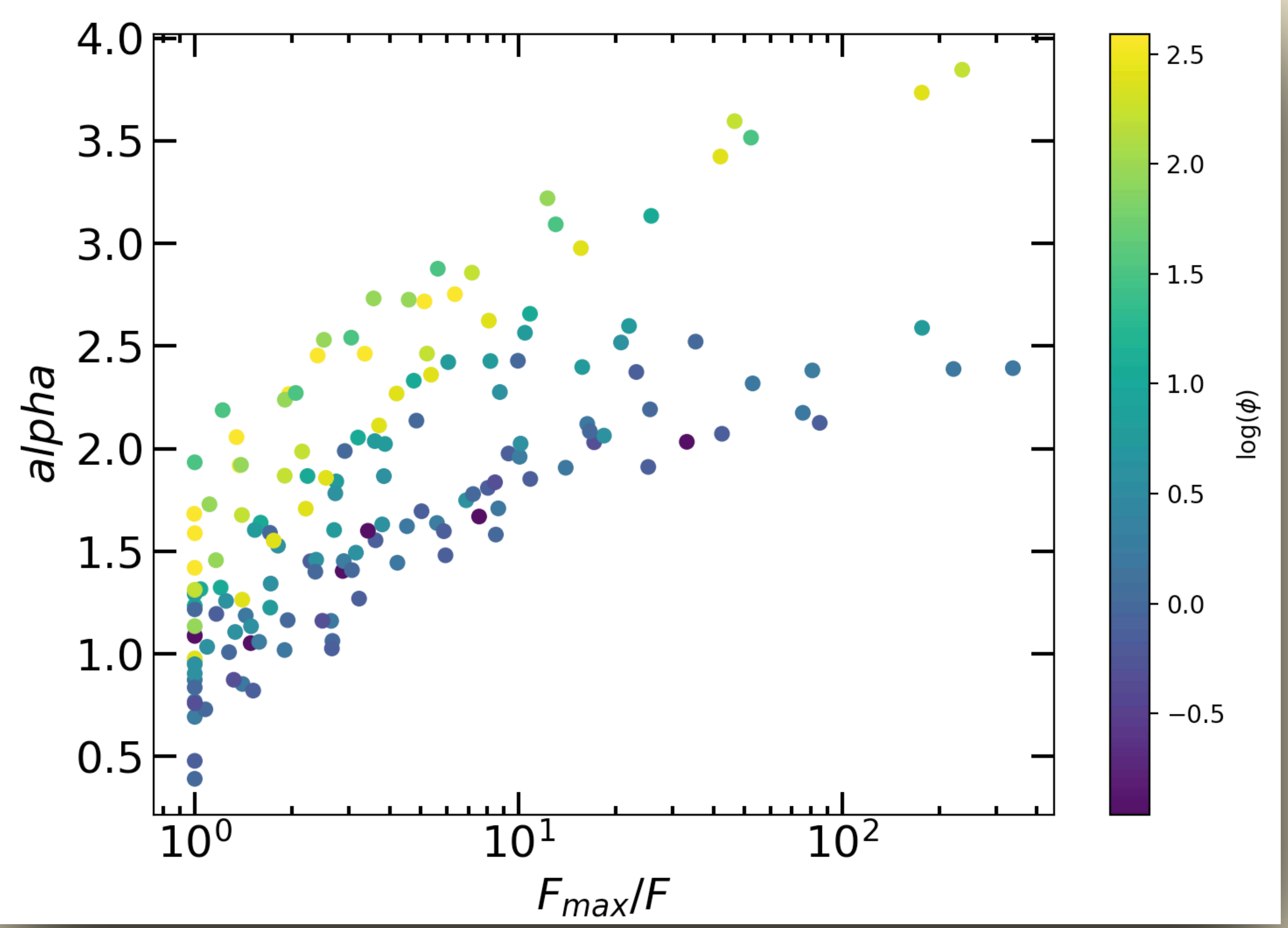


No dependency on:

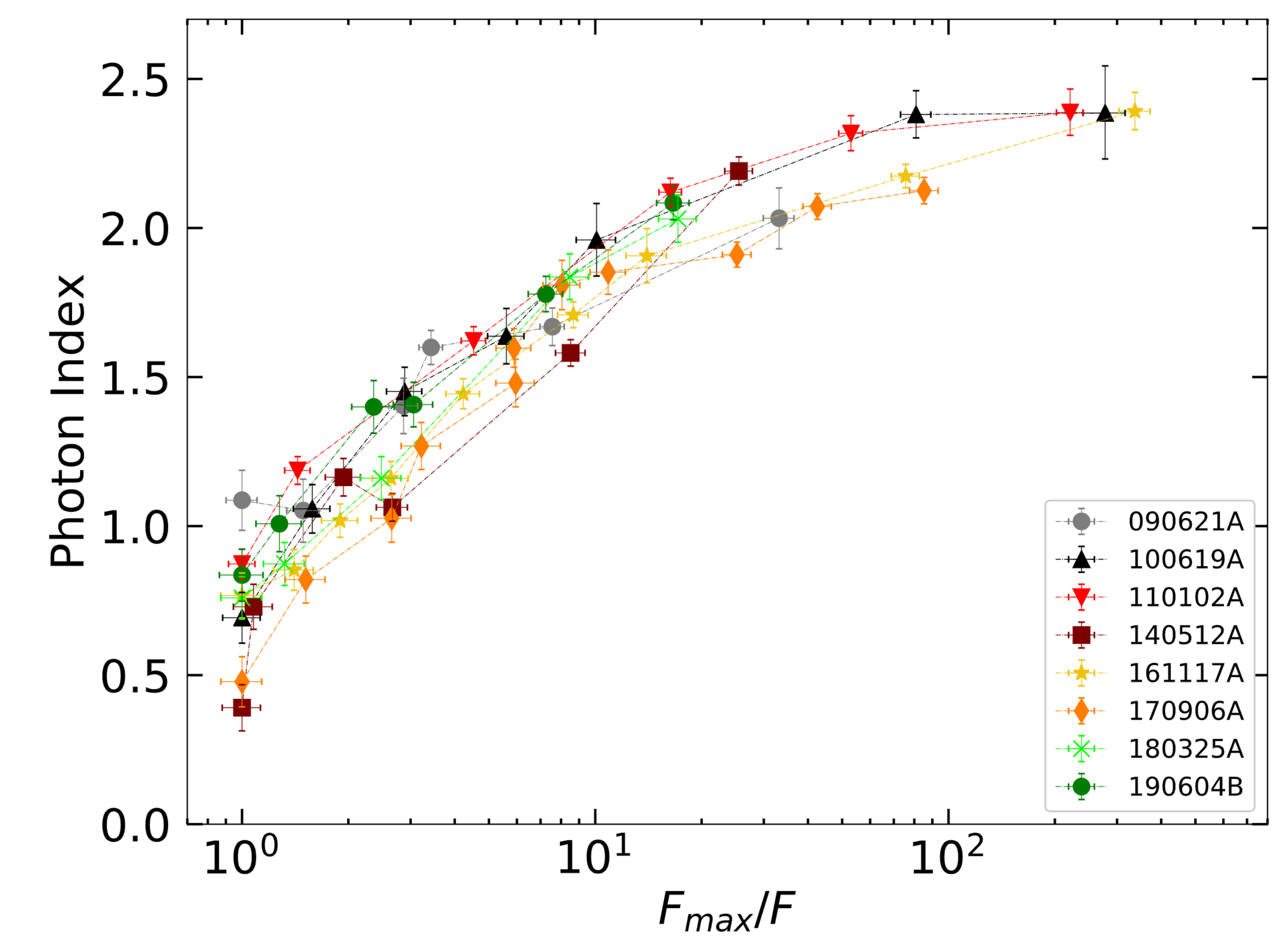
- the initial time of the steep decay
- The luminosity of the GRB

$$\phi = F_p^{XRT}/F_p^{BAT}$$





Brightest BAT peak since the trigger time



Tails of prompt-like pulses