Unveiling the origin of steep decay in gamma-ray bursts

S. Ronchini, G. Oganesyan, M. Branchesi et al.
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In collaboration with
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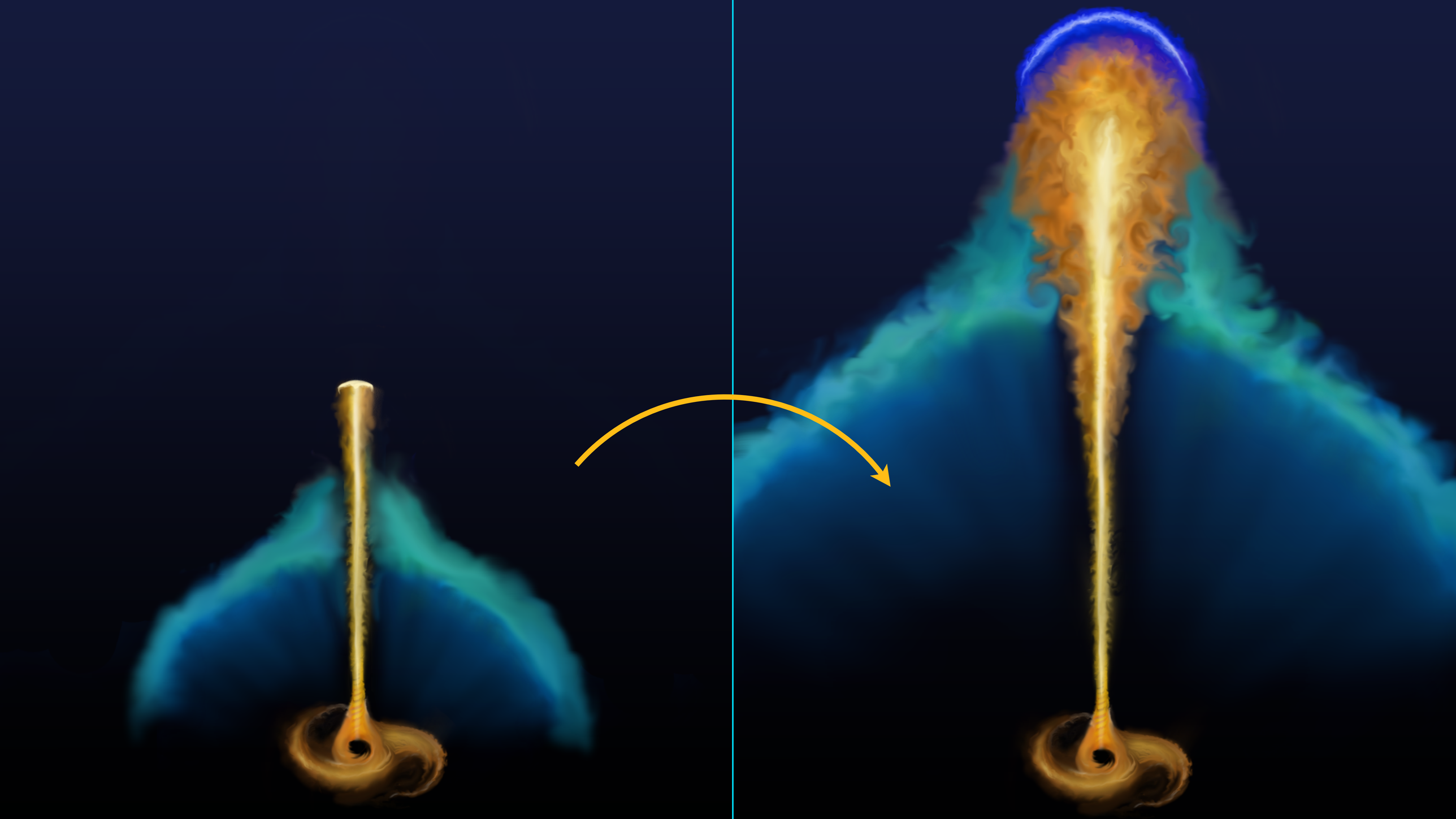
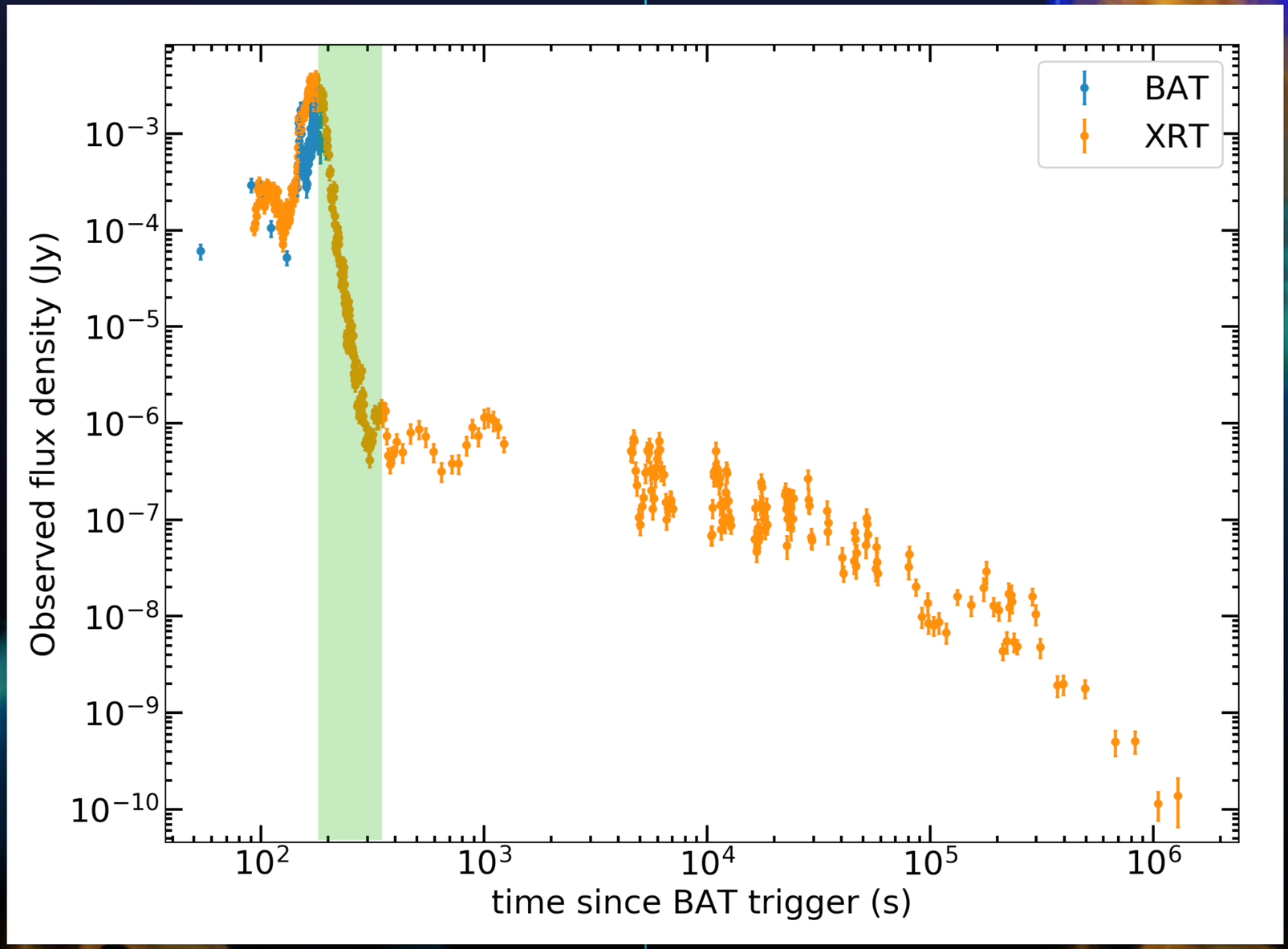
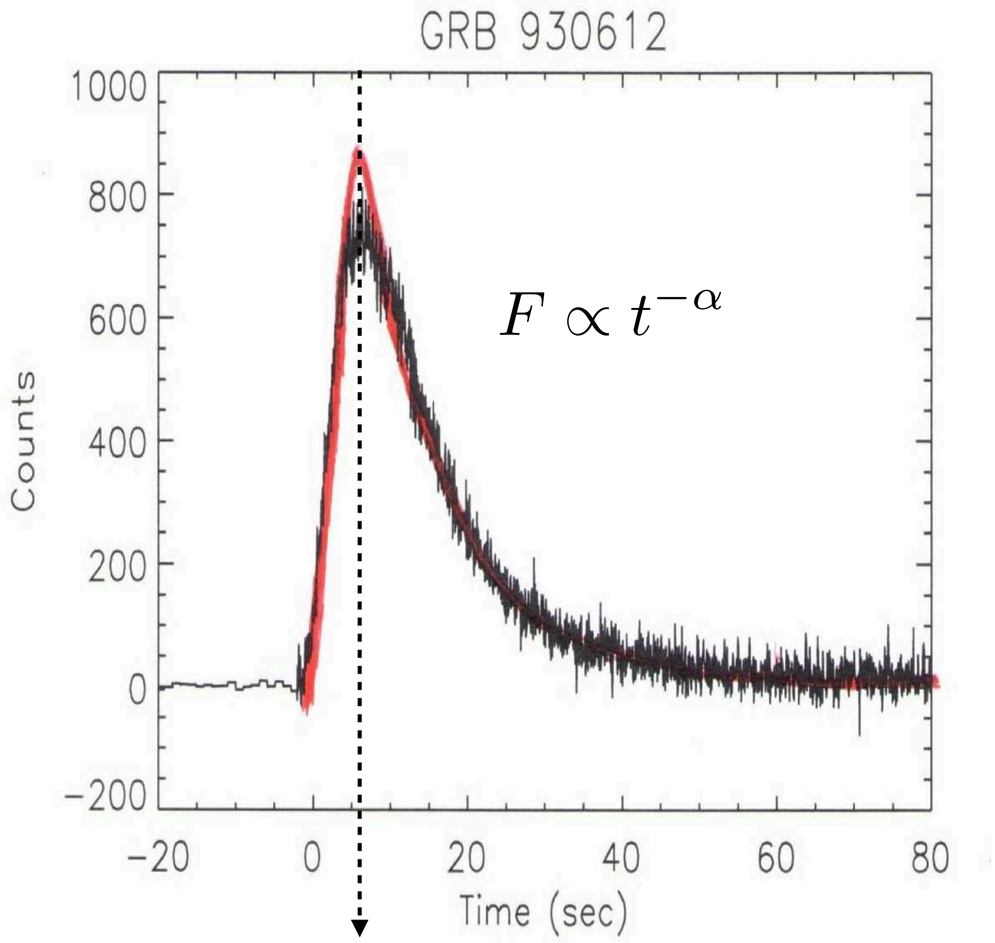
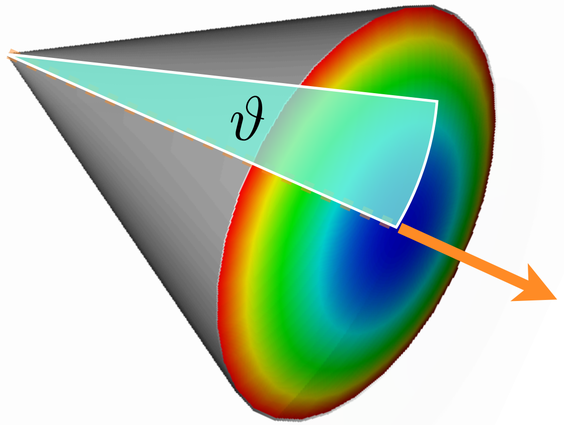



BAT
XRT
Observed flux density (Jy)
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{2}
10^{3}
10^{4}
10^{5}
10^{6}
time since BAT trigger (s)

The steep decay phase



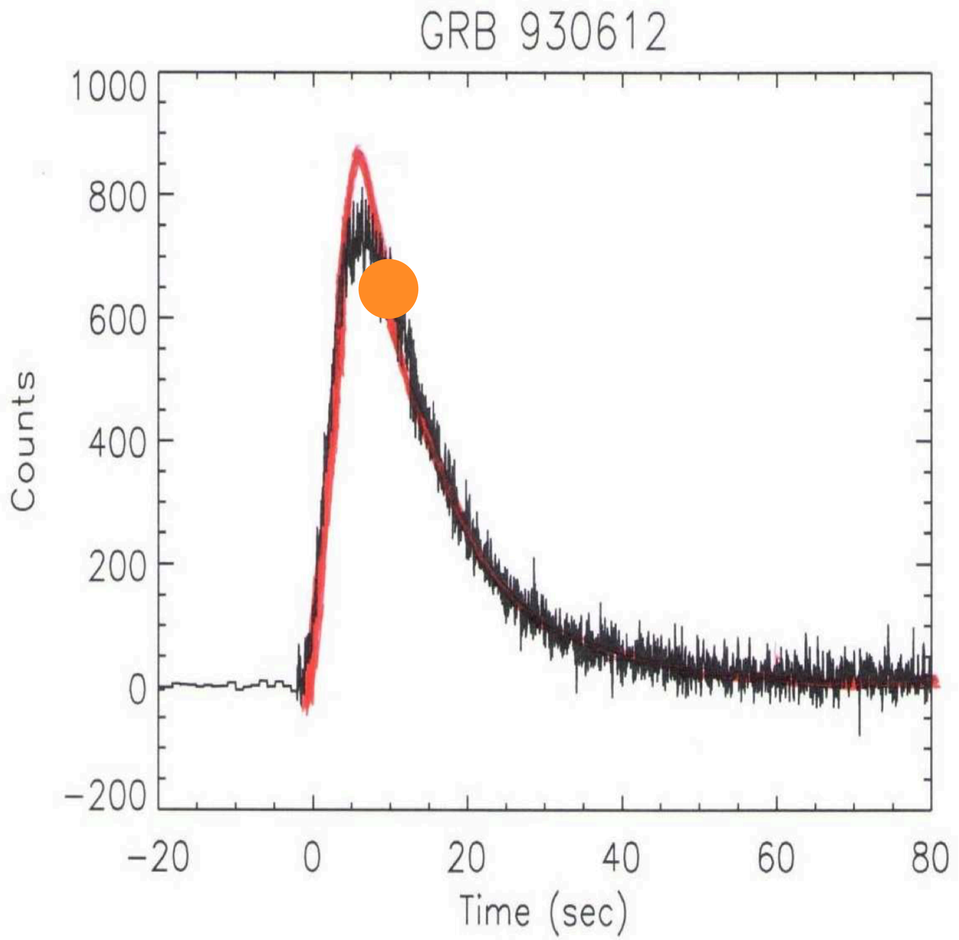
When the emission shuts down

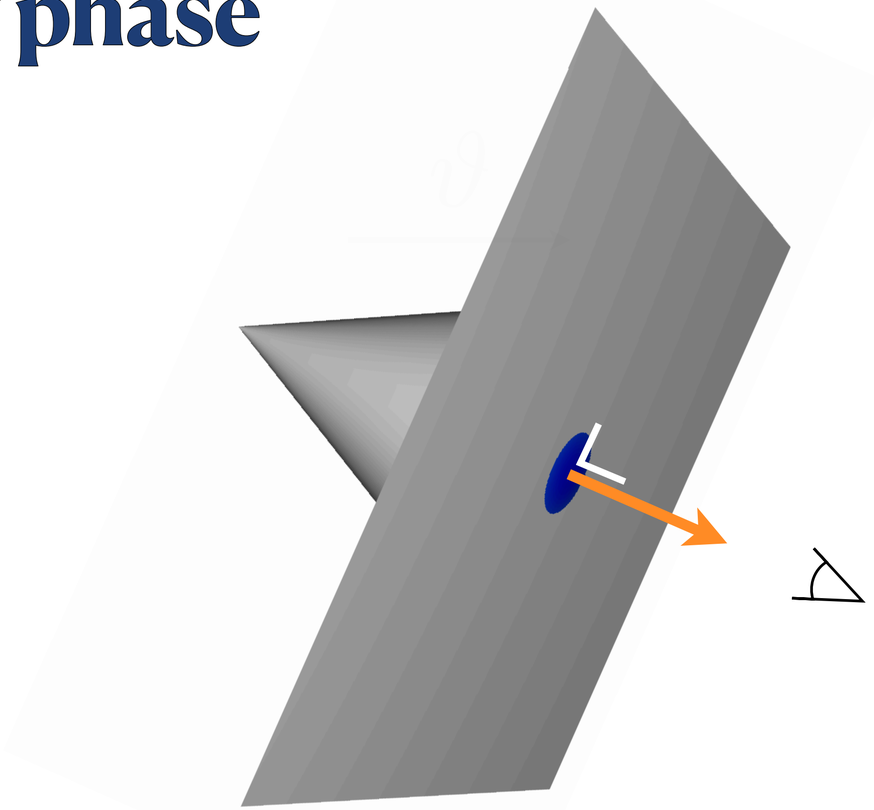


ϑ

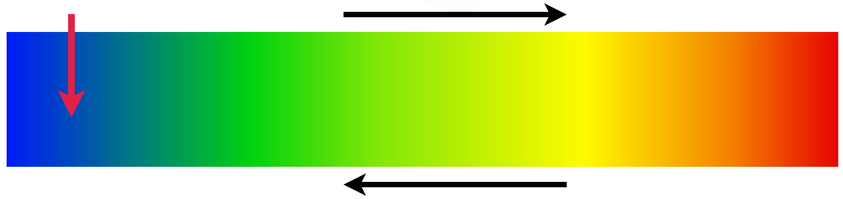
$$\mathcal{D}(\vartheta) = \frac{1}{\Gamma(1 - \beta\cos(\vartheta))}$$

The steep decay phase





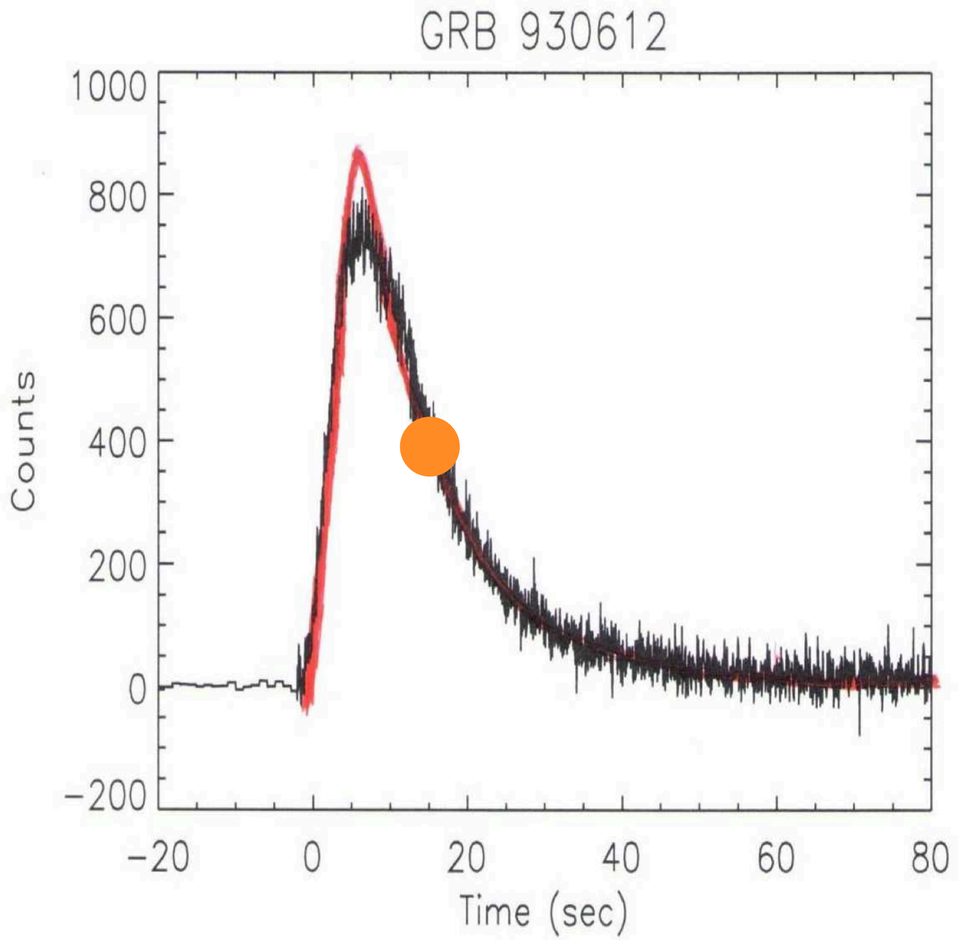
ϑ

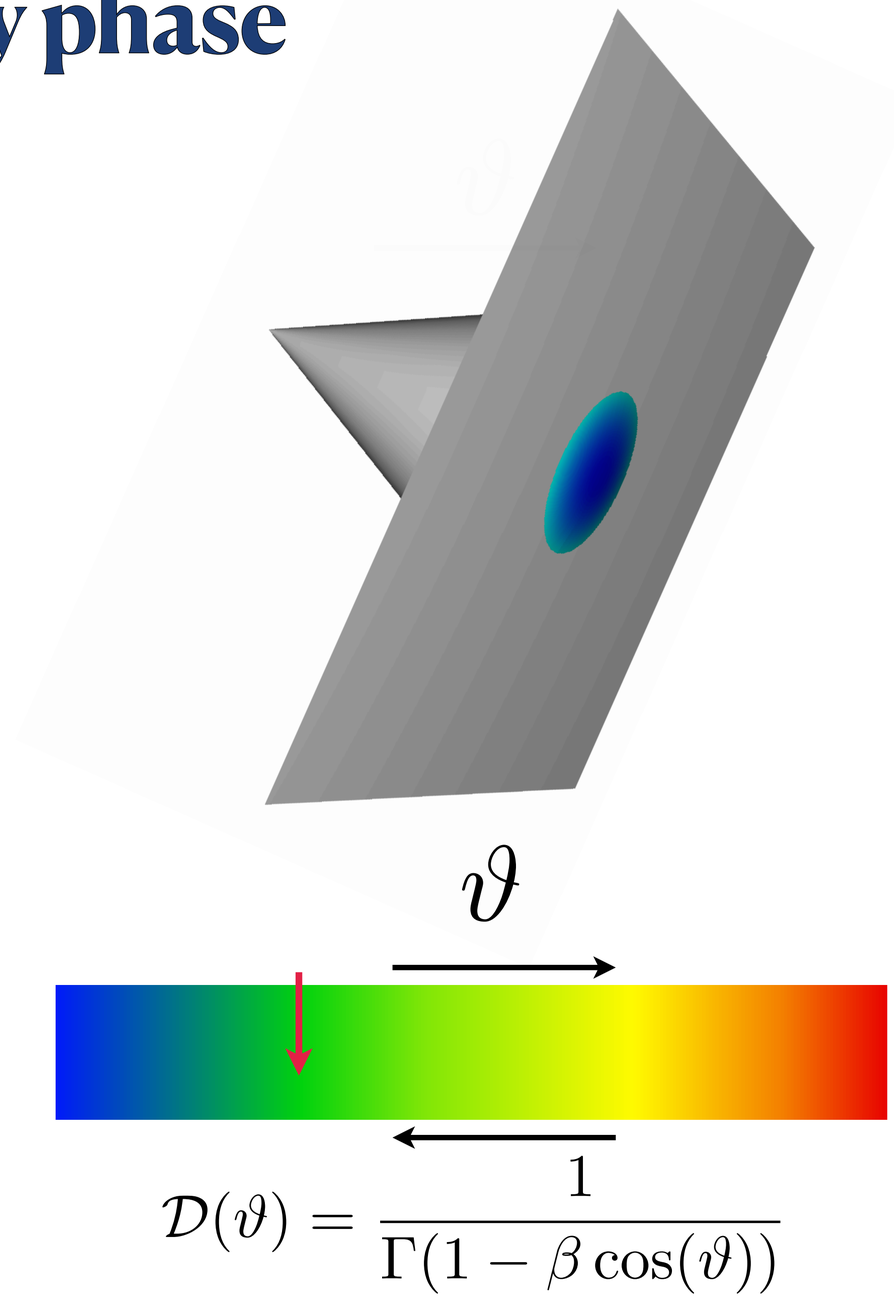


1

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

The steep decay phase





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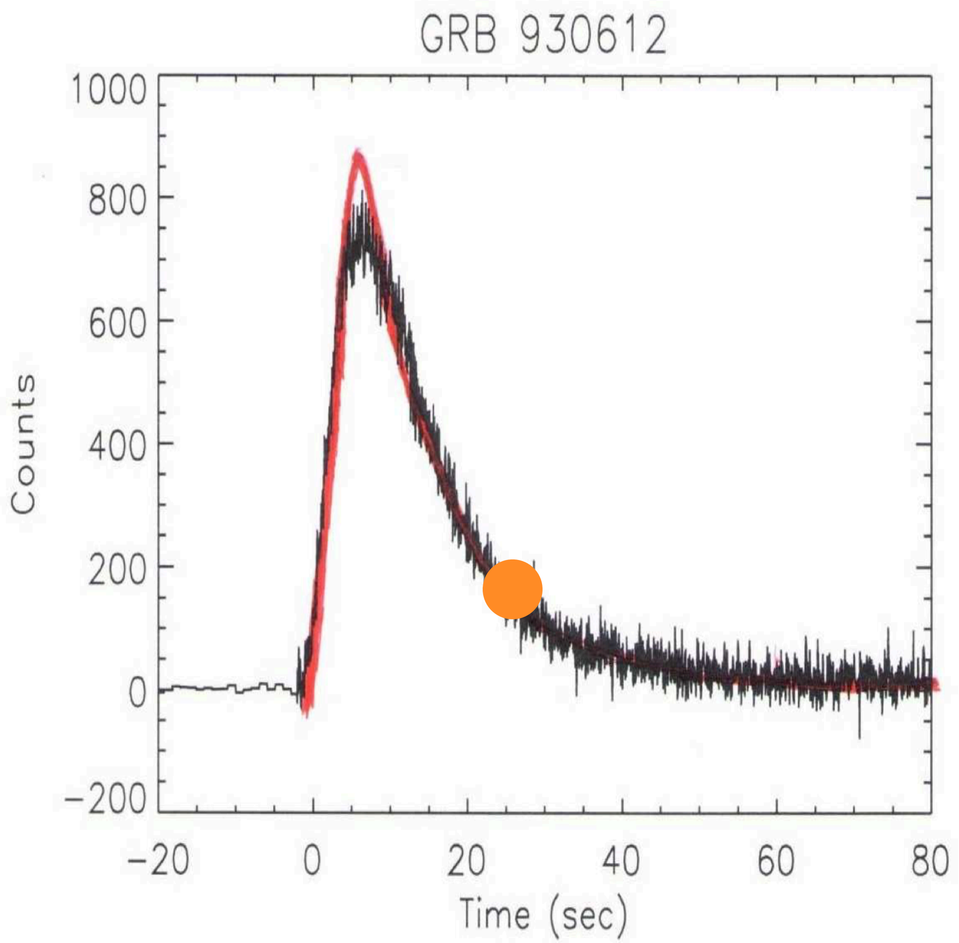
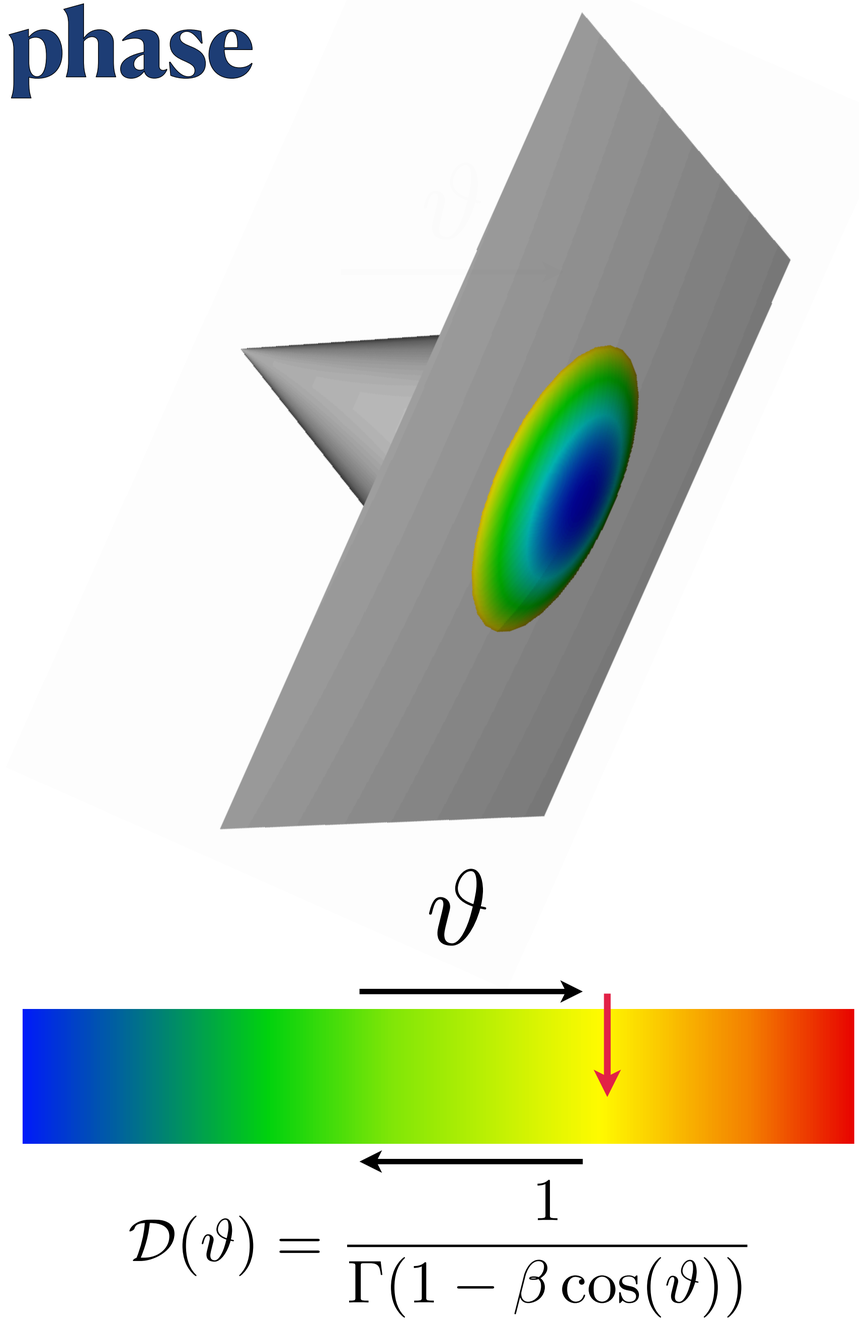
The steep decay phase





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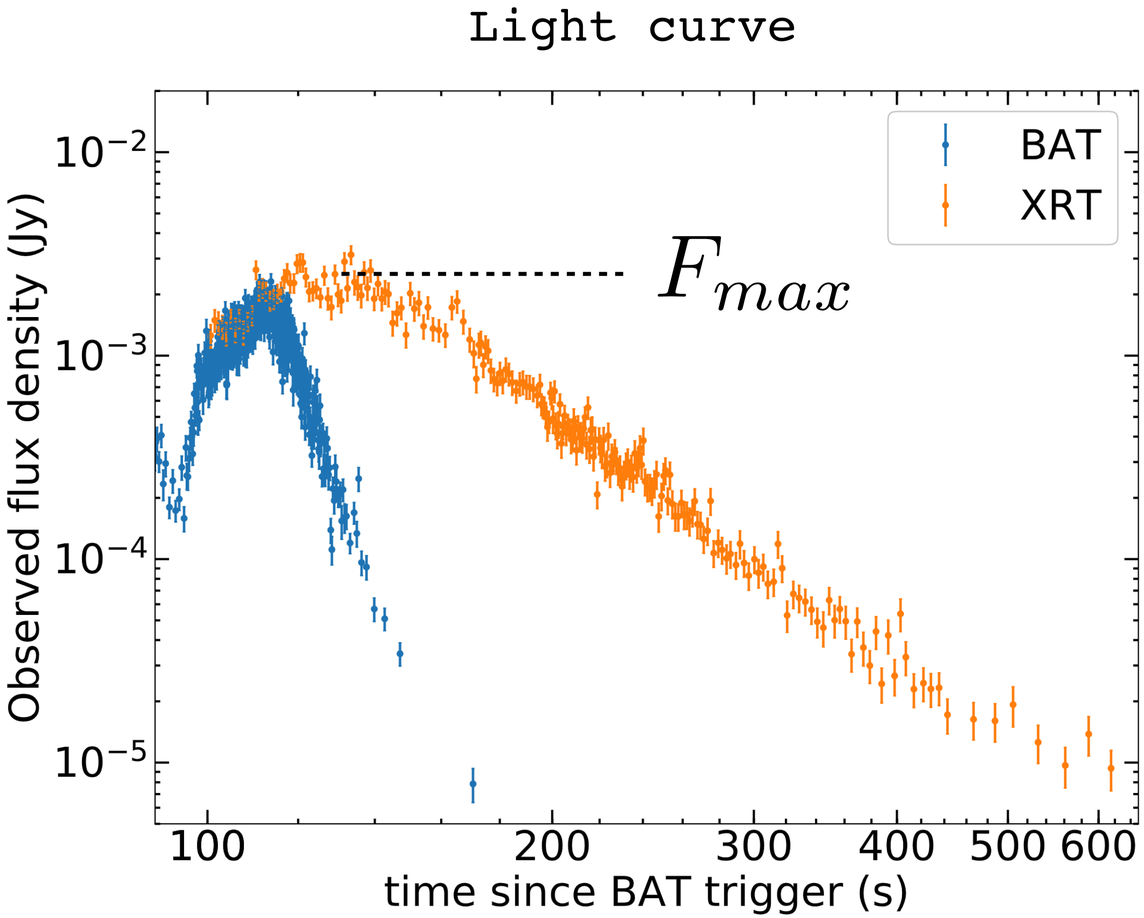
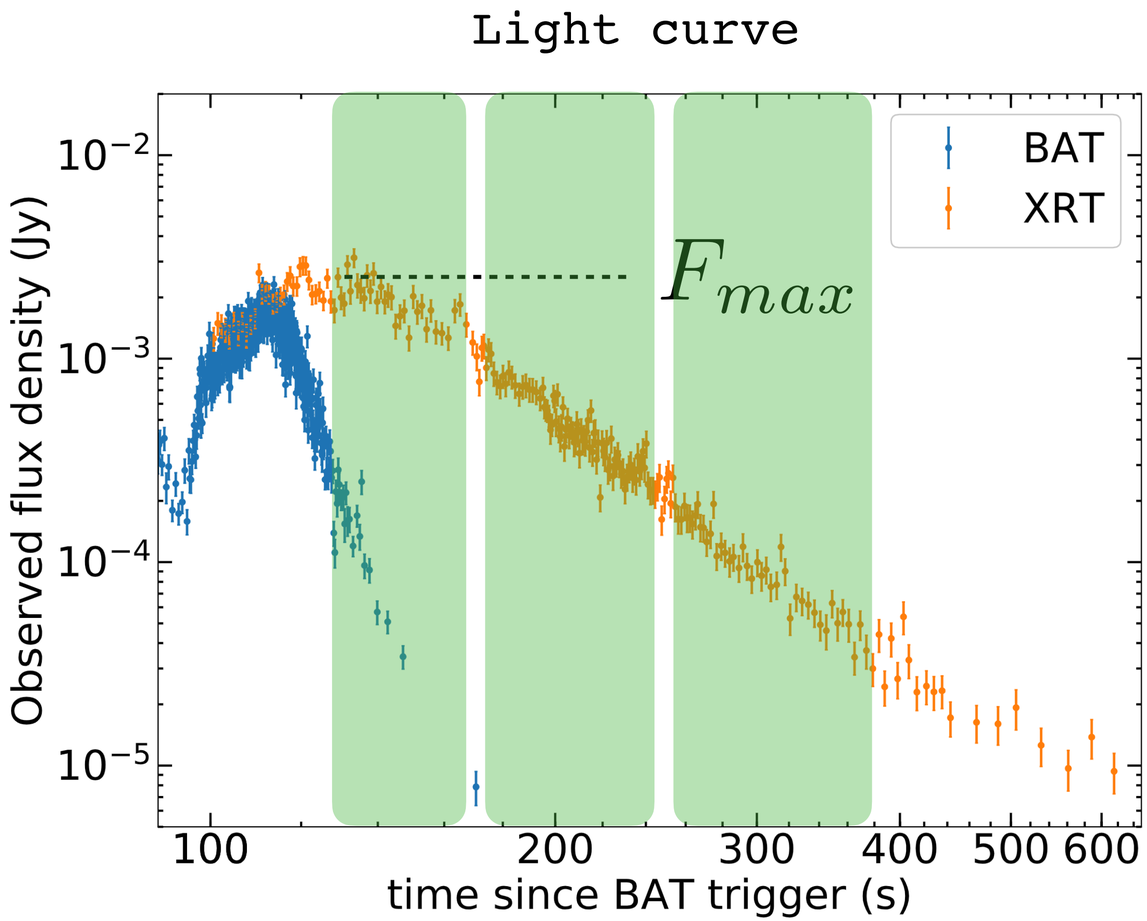

Light curve
BAT
XRT
F_{max}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
Observed flux density (Jy)
100
200
300
400
500
600
time since BAT trigger (s)


Light curve
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10^{-2}
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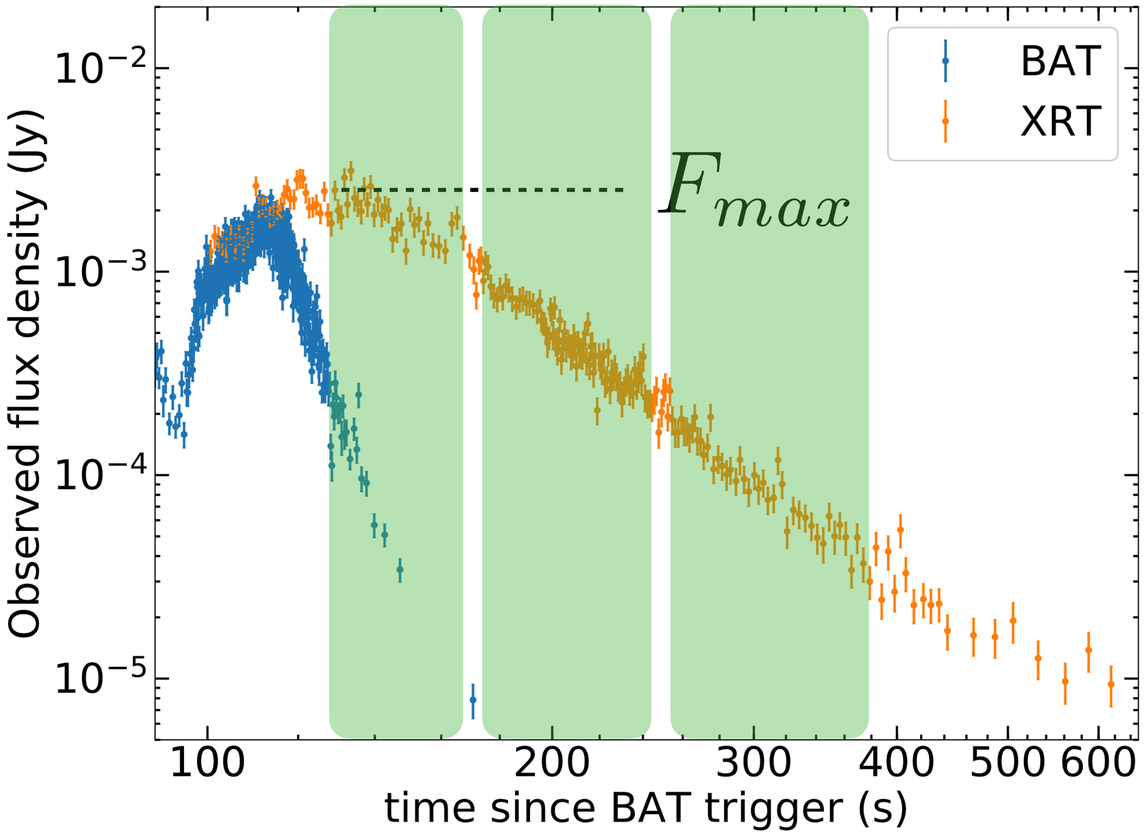
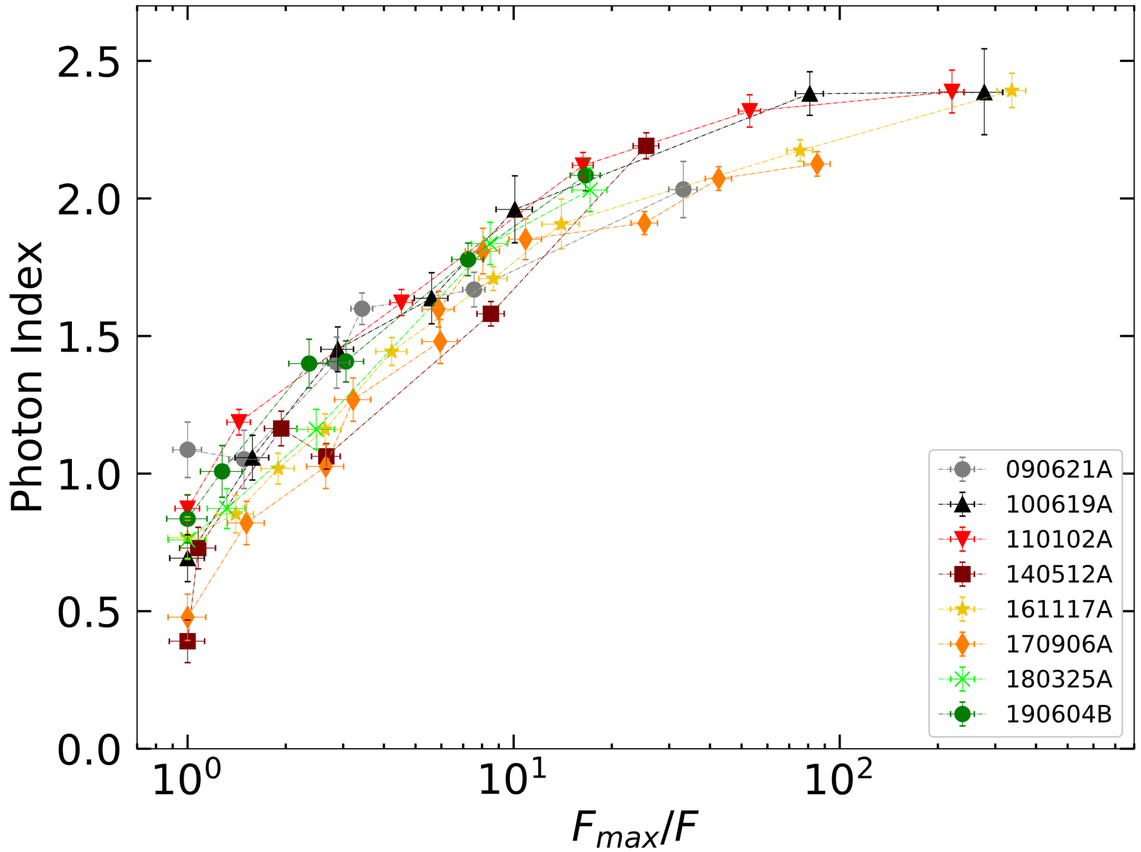
Light curve



alpha-F relation



Clear indication of a common process

Interpreting the alpha-F relation

We need to define two time scales:

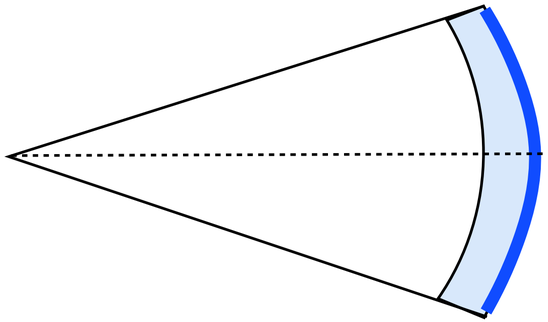
$$\tau_{rad} = \min\left(\tau_{Syn}, \tau_{IC}, ...\right)$$

$$\tau_{dyn} = \frac{R}{2c\Gamma^2}$$

and two regimes:

Radiative regime

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

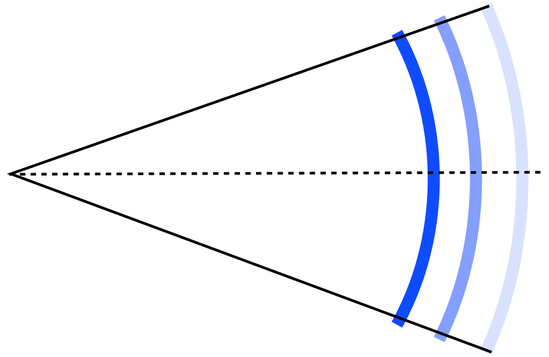


The tail emission is dominated by the last emitting surface

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

Interpreting the alpha-F relation

We need to define two time scales:

$$\tau_{rad} = \min\left(\tau_{Syn}, \tau_{IC}, ...\right)$$

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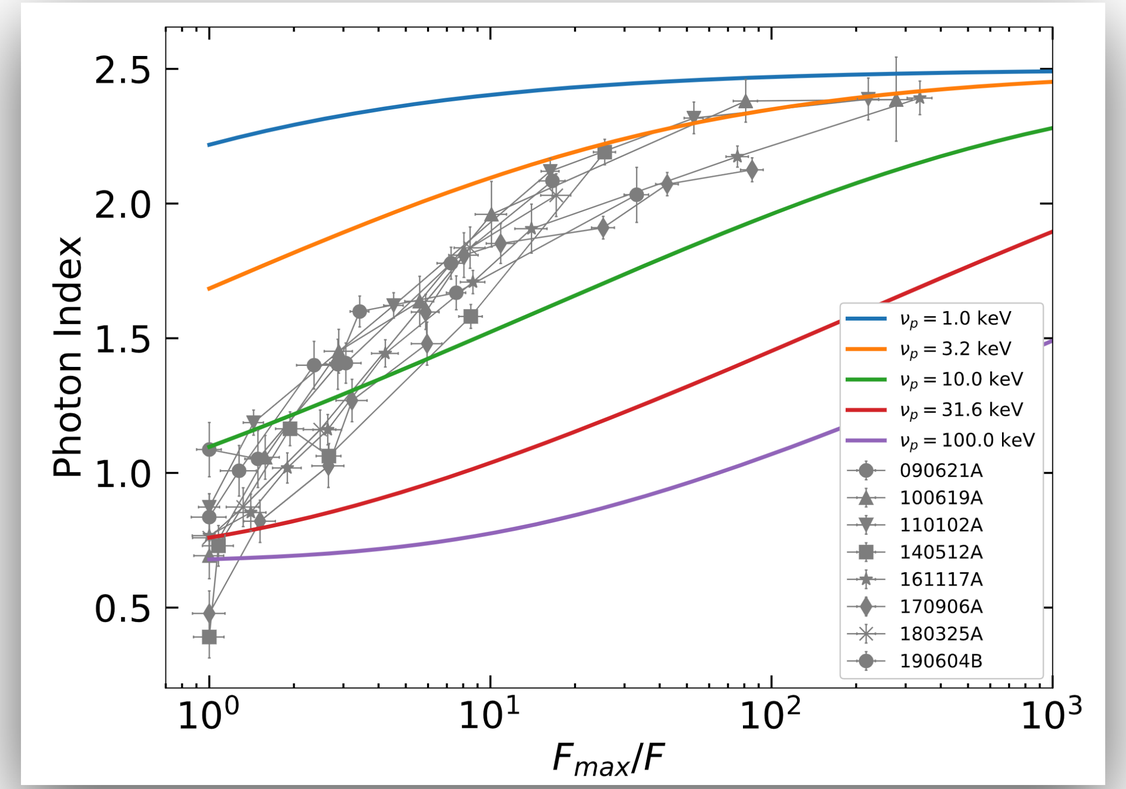
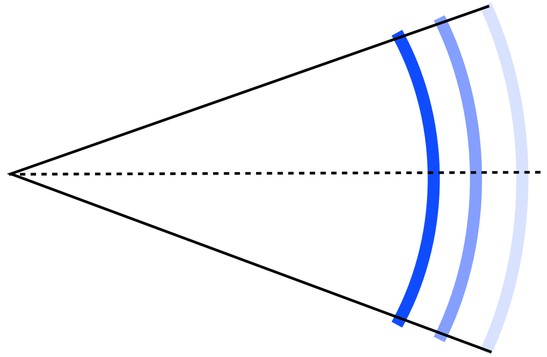
Radiative regime



Adiabatic regime

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



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

Interpreting the alpha-F relation

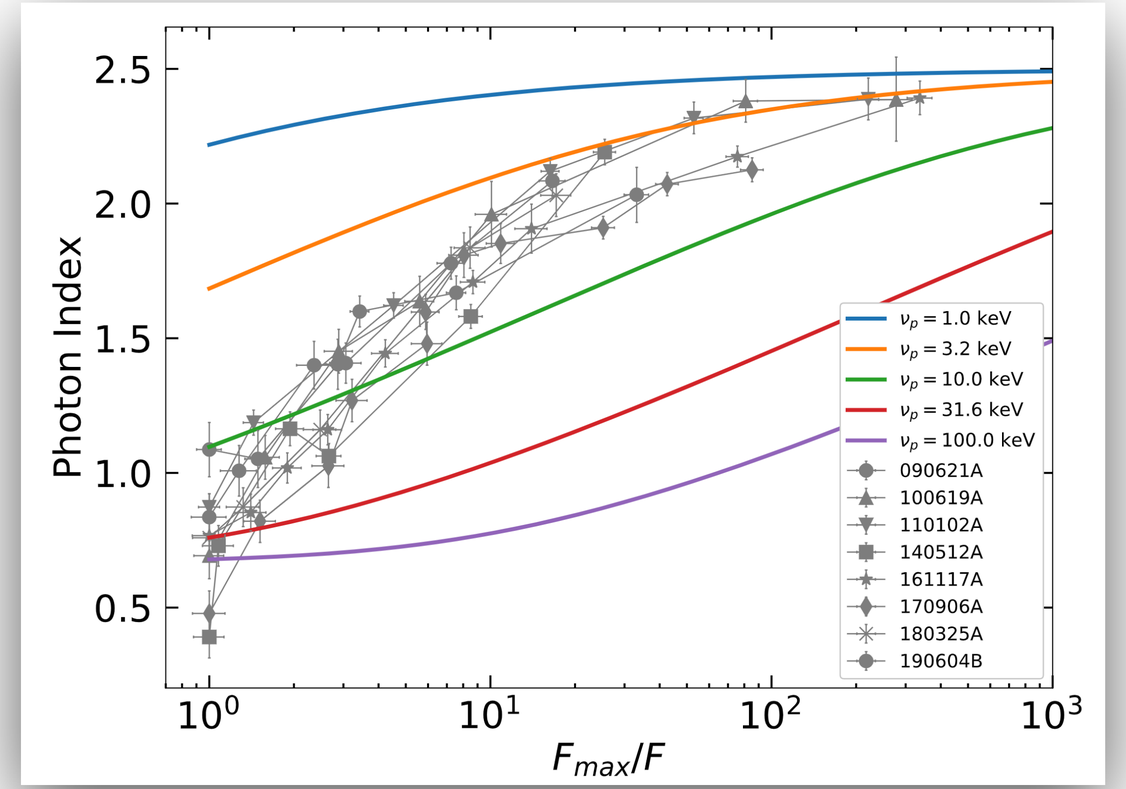
We need to define two time scales:

$$\tau_{rad} = \min\left(\tau_{Syn}, \tau_{IC}, ...\right)$$

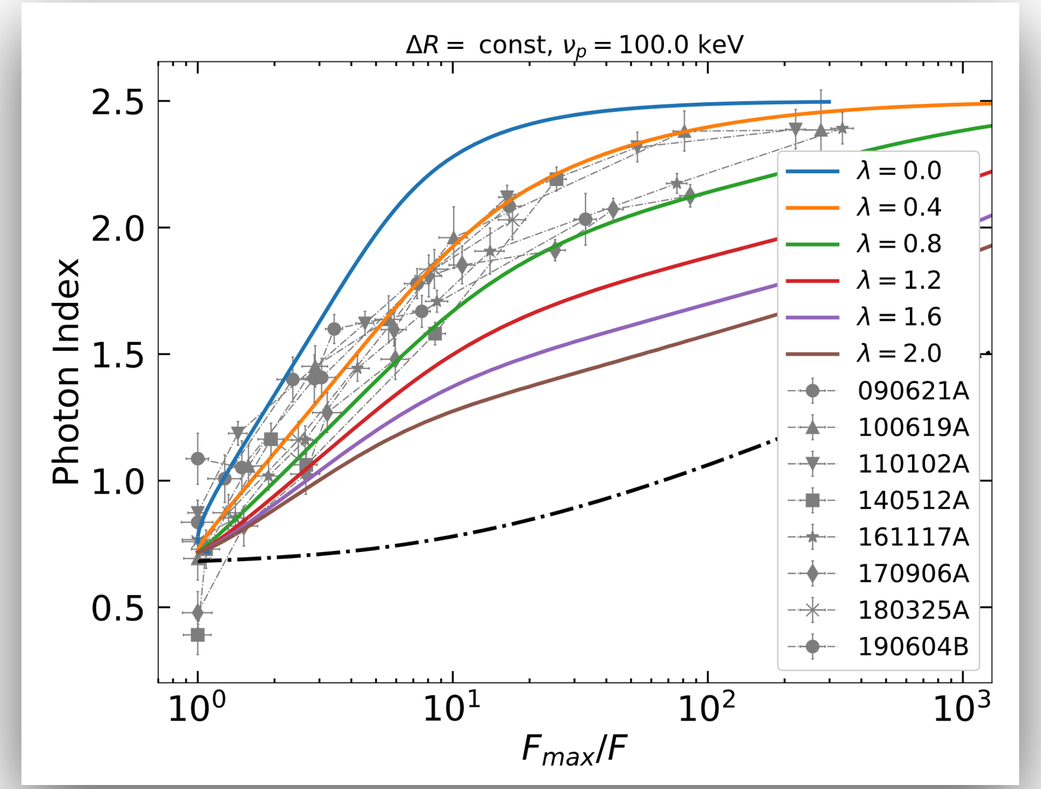
$$\tau_{dyn} = \frac{R}{2c\Gamma^2}$$

and two regimes:

Radiative regime



Adiabatic regime

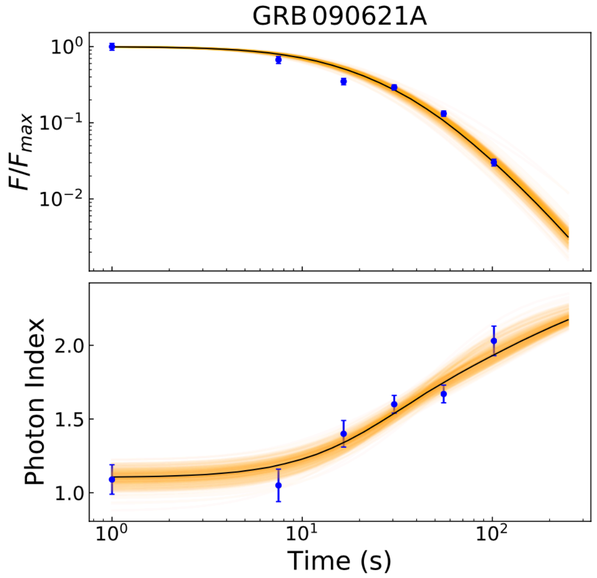


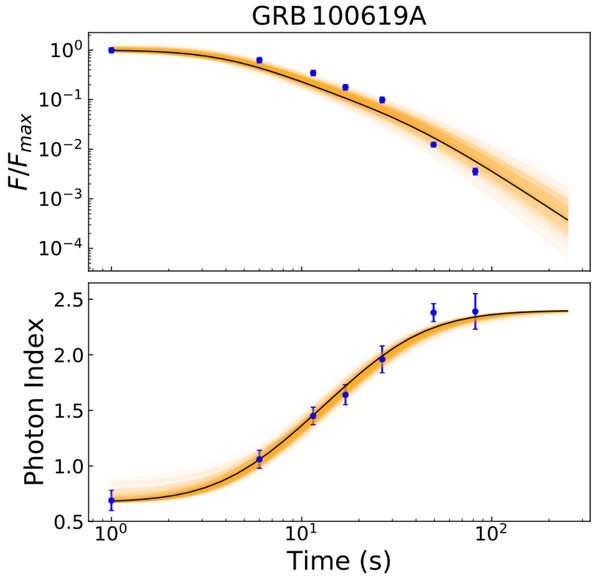
Conclusions

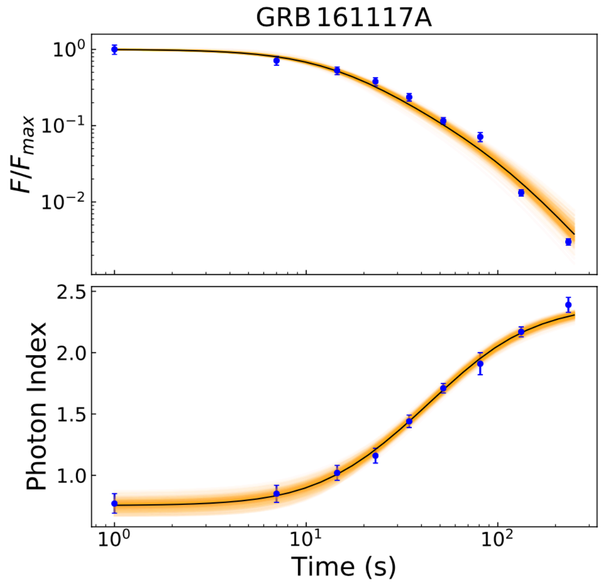
- The spectral evolution during the steep decay of prompt-like pulses in GRBs is characterised by a **unique relation**
- The standard **high latitude emission** scenario cannot account for the spectral evolution during the steep decay.
- Our results disfavour an **efficient particle cooling**
- The 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

THANKS!!

Backup slides


GRB 090621A
F/F_max
Photon Index
Time (s)


GRB 100619A
F/F_max
Photon Index
Time (s)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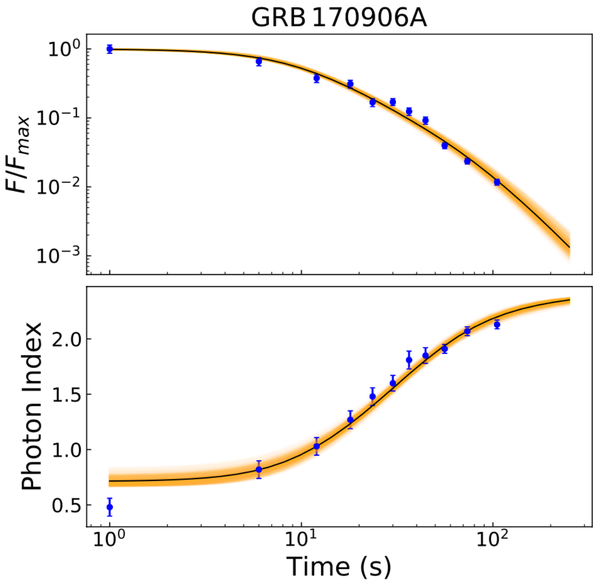
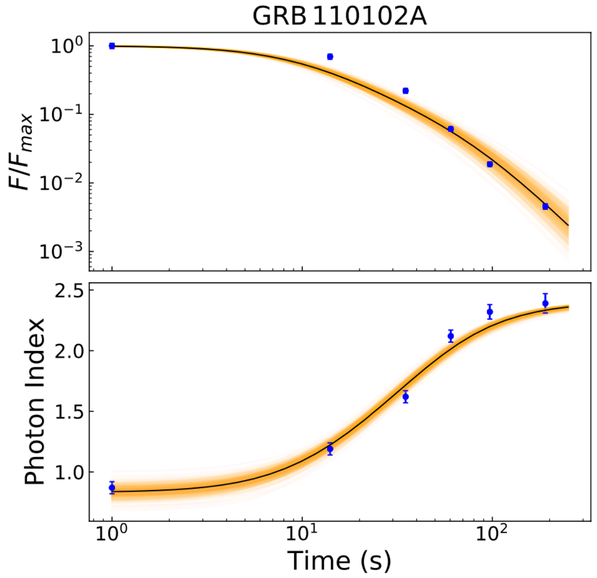
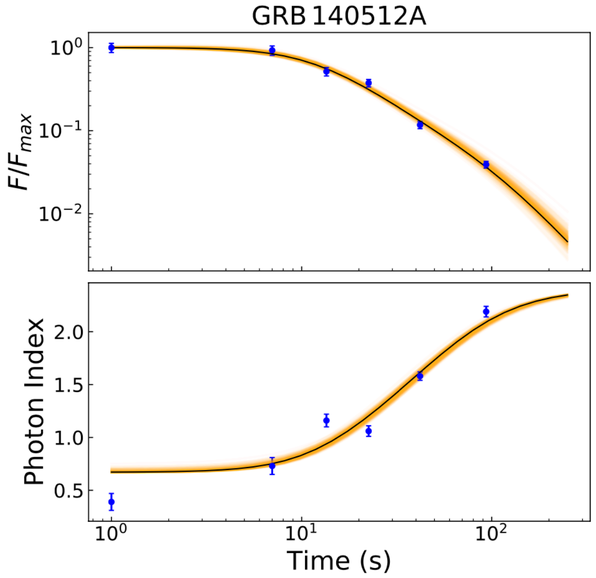
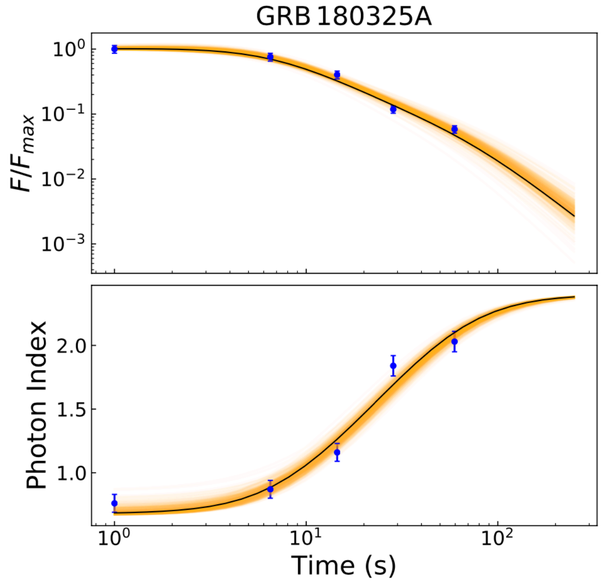
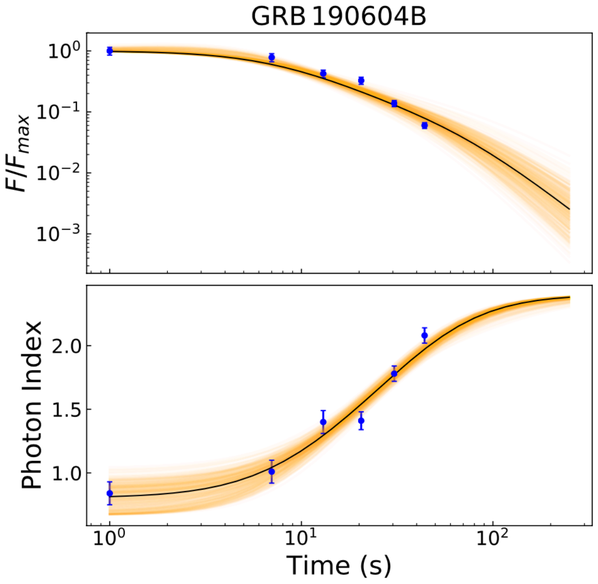
F/F_max
Photon Index
Time (s)


GRB 170906A
F/F_max
Photon Index
Time (s)


GRB 110102A
F/F_max
Photon Index
Time (s)


GRB 140512A
F/F_max
Photon Index
Time (s)


GRB 180325A
F/F_max
Photon Index
Time (s)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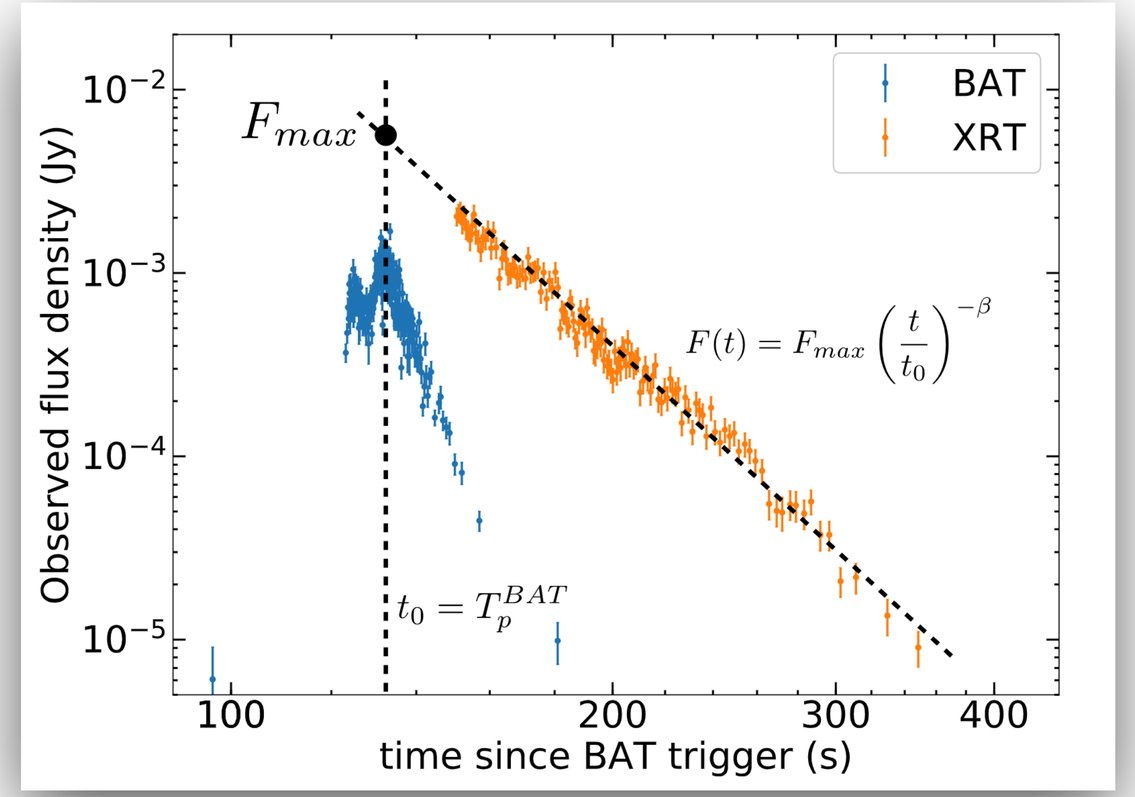
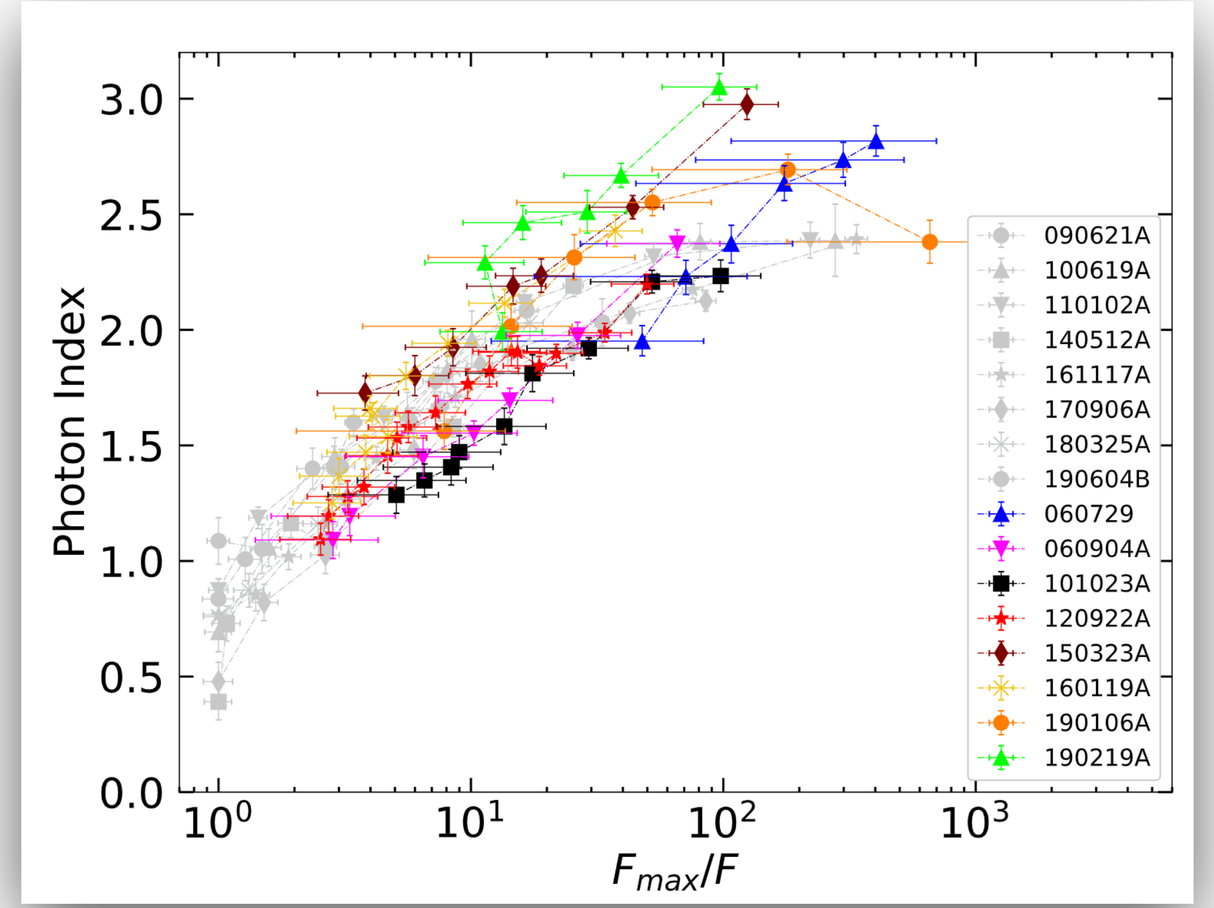
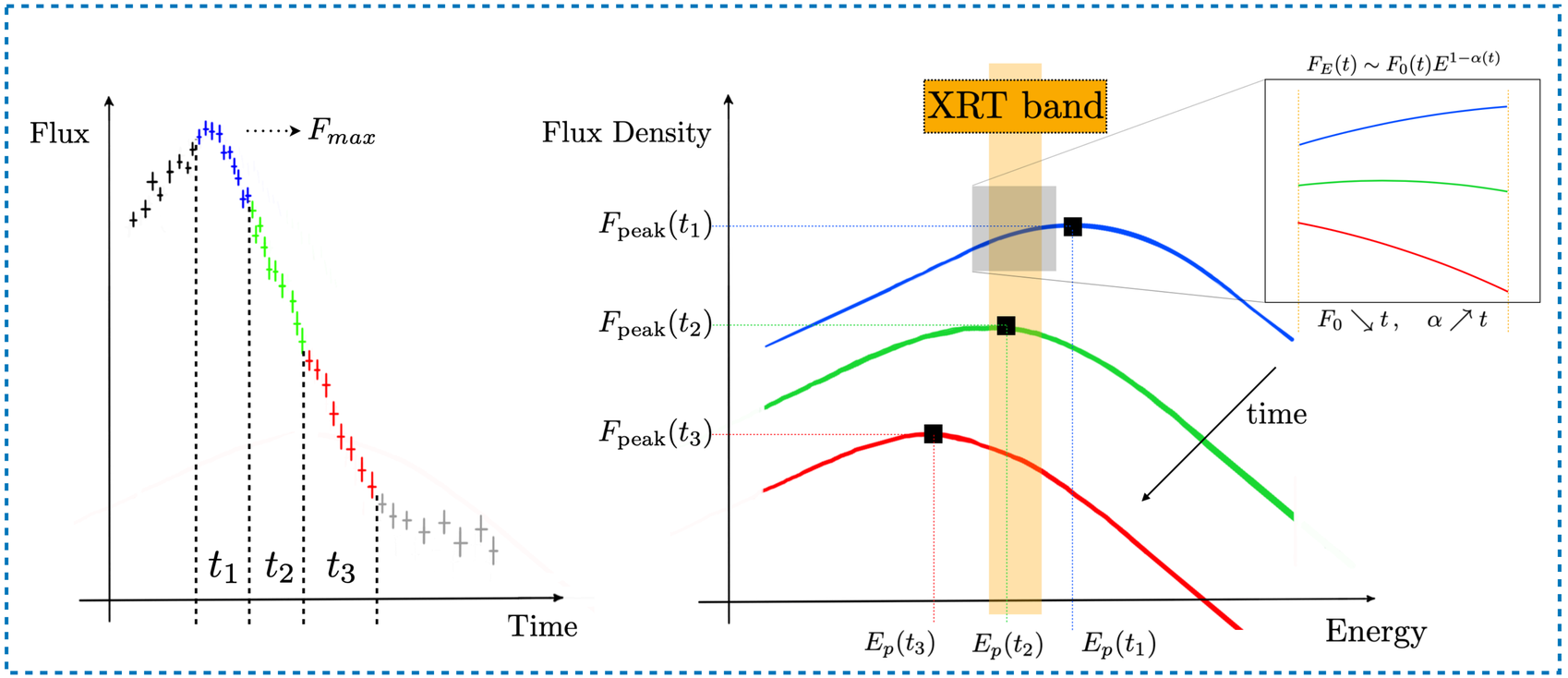
F/F_max
Photon Index
Time (s)


BAT
XRT
F_{max}
$t_0 = T_p^{BAT}$
$F(t) = F_{max}\left(\frac{t}{t_0}\right)^{-\beta}$
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
0.0
0.5
1.0
1.5
2.0
2.5
3.0
10^0
10^1
10^2
10^3
090621A
100619A
110102A
140512A
161117A
170906A
180325A
190604B
060729
060904A
101023A
120922A
150323A
160119A
190106A
190219A


Flux
F_{max}
t_1
t_2
t_3
Time
Flux Density
XRT band
$F_E(t) \sim F_0(t)E^{1-\alpha(t)}$
$F_0 \searrow t\,, \quad \alpha \nearrow t$
$F_{\rm peak}(t_1)$
$F_{\rm peak}(t_2)$
$F_{\rm peak}(t_3)$
time
$E_p(t_3)$
$E_p(t_2)$
$E_p(t_1)$
Energy

The problem of cooling time scales

The typical time scale of adiabatic cooling,
derived from light curve fitting:

$$0.8\mathrm{s} \lesssim \tau_{ad} \lesssim 8\mathrm{s}$$

If adiabatic cooling dominates the spectral evolution, these values represent a lower limit for the radiative timescale of the emitting particles

$$t_{cool} \sim 5 \times 10^{-8} B_6^{-3/2}\, s$$

If the magnetic energy is converted in kinetic energy

Low levels of magnetisation are required, i.e. B~1-10 G

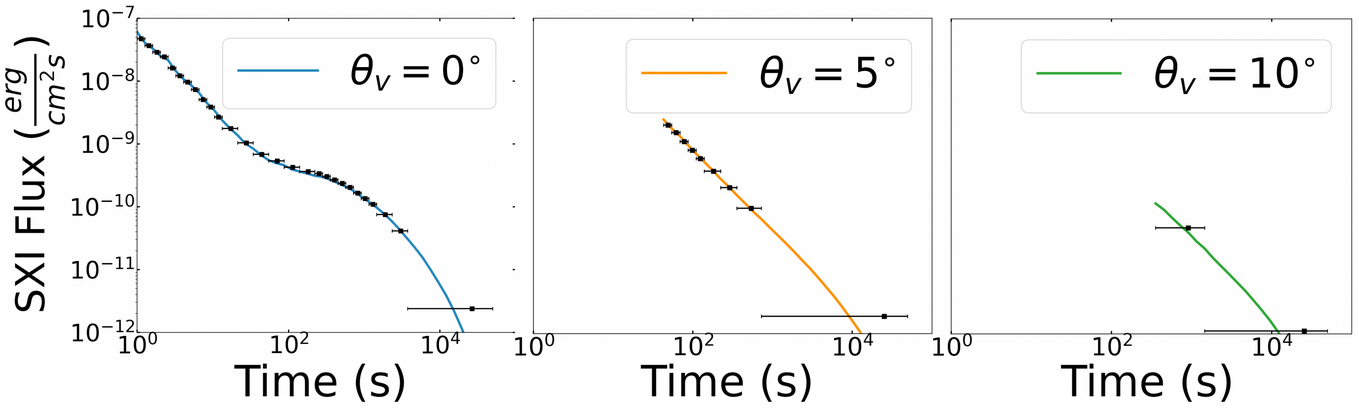
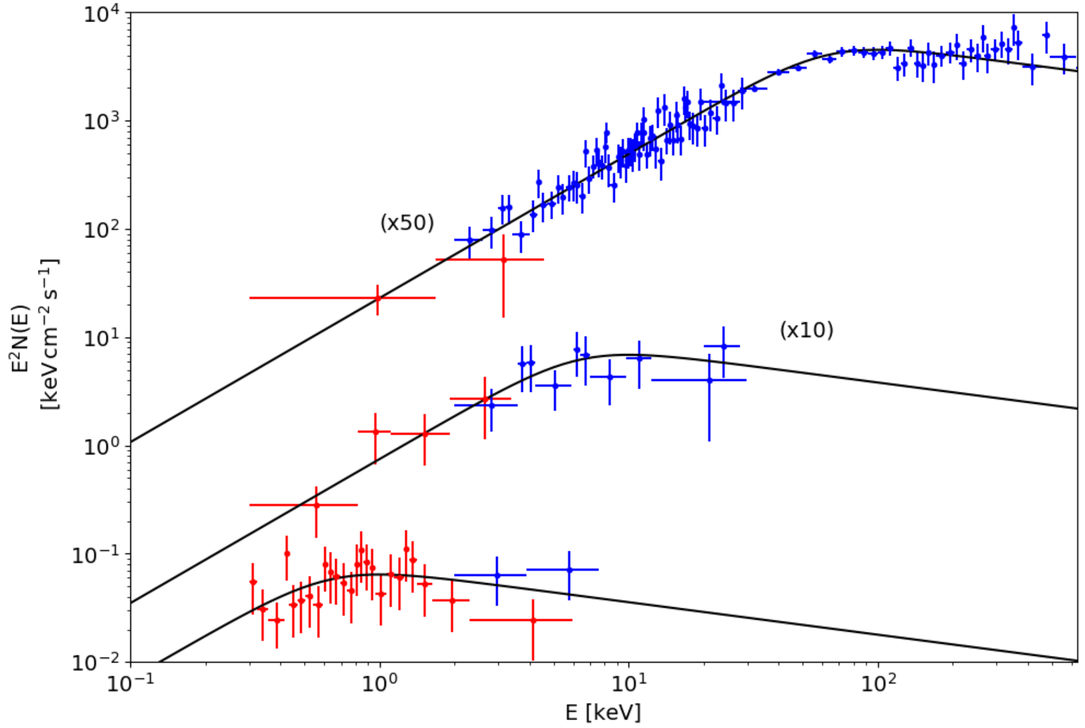
IC becomes important

Large radii are required, i.e. R~10^{16}-10^{17} cm

Incompatible with variability time scale requirements: $R/2c\Gamma^2 < 1$ sec

What about protons?

(Ghisellini et al. 2020)

$$t_{\mathrm{cool,S,p}} = t^{\mathrm{obs}}_{\mathrm{cool,S,e}} \left(\frac{m_\mathrm{p}}{m_\mathrm{e}}\right)^{5/2}$$

The steep decay observed by THESEUS