The prompt emission from gamma-ray bursts: Understanding the spectral evolution.

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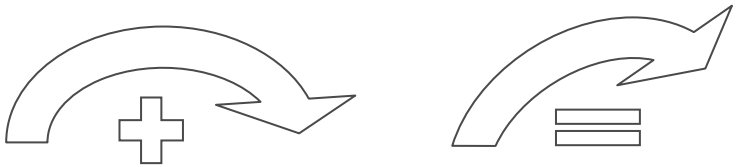
A toy model for a pulse : assume a given time evolution for :

the total radiated power L(t) ;

the peak energy $E_p(t)$ of the spectrum.

The observed lightcurve depends on the chosen energy channel : time lags appear.



Evolving power **Evolving spectrum**

In real bursts : all spectral parameters are varying (peak energy and slopes).

Observed lightcurves

Theoretical framework

Questions

General framework : *the different observed phases in gamma-ray bursts (prompt, afterglow) are associated to events in the life of an ultra-relativistic outflow produced by a newly formed compact source.*

Geometry and composition of the outflow ?
(e.g. spherical vs jet vs … ;
matter vs Poyting flux vs …)

Nature and role of the environment ?
(e.g. uniform density medium vs stellar wind vs plerion vs … ;
internal vs external mechanisms)

Energy reservoir and extraction mechanism associated to each observed phase ?
(e.g. thermal vs kinetic vs magnetic vs … energy ;
photosphere vs internal shocks vs magnetic reconnection vs …)

Microphysics and radiative processes at work ?
(e.g. shock acceleration ; magnetic field amplification ; …
synchrotron radiation vs IC vs …)

etc.

« Standard » scenario

Log(R) [meters]

⑧ « jet-break » ? : $1/\Gamma > \theta$

⑦ Forward (external) shock → afterglow ?

⑥ Contact discontinuity

⑤ Reverse shock → optical flash ?

④ Internal dissipation → prompt emission ?

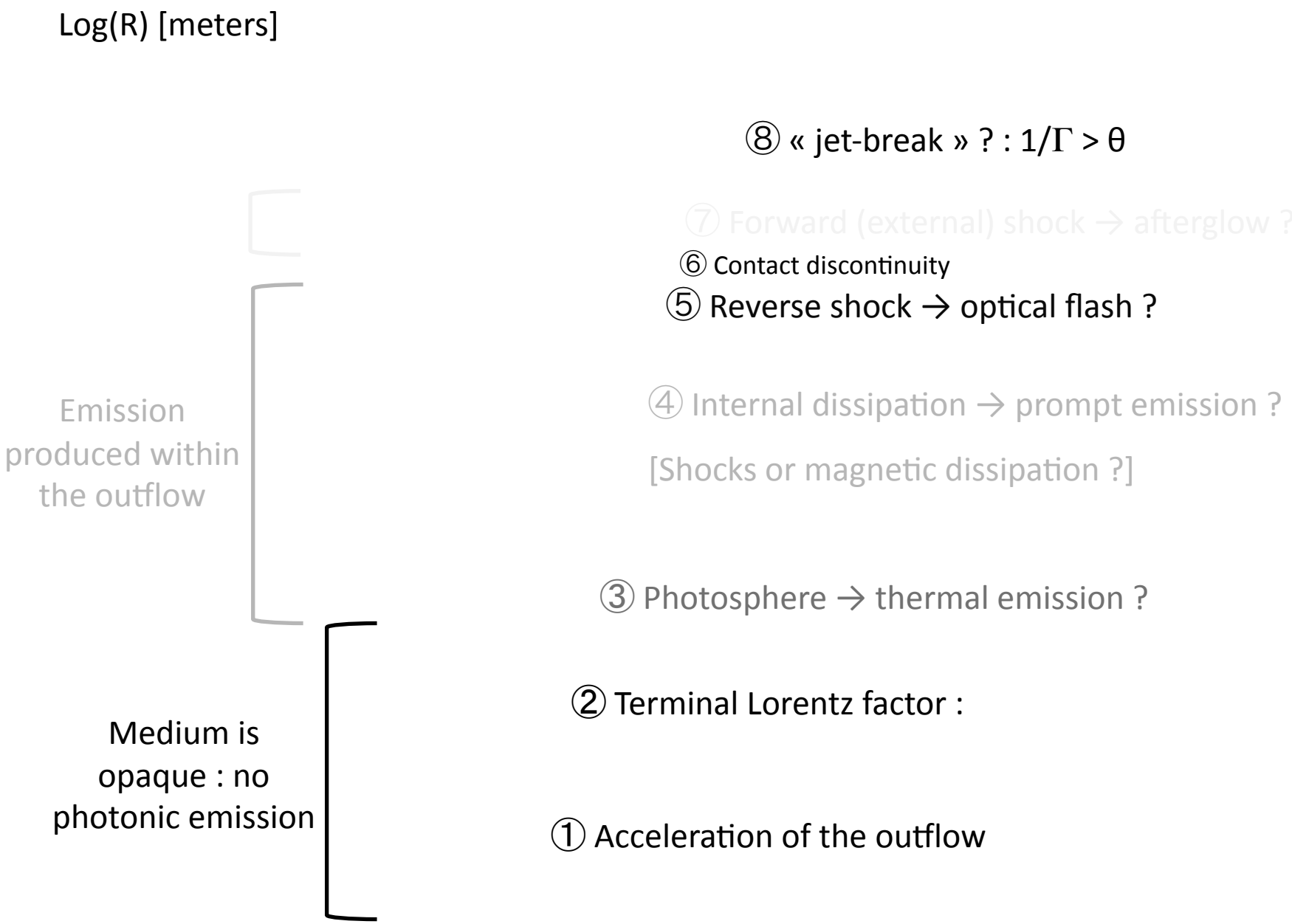
[Shocks or magnetic dissipation ?]

③ Photosphere → thermal emission ?

② Terminal Lorentz factor :

① Acceleration of the outflow

« Standard » scenario



Log(R) [meters]

Emission produced within the outflow

④ Internal dissipation → prompt emission ?

[Shocks or magnetic dissipation ?]

③ Photosphere → thermal emission ?

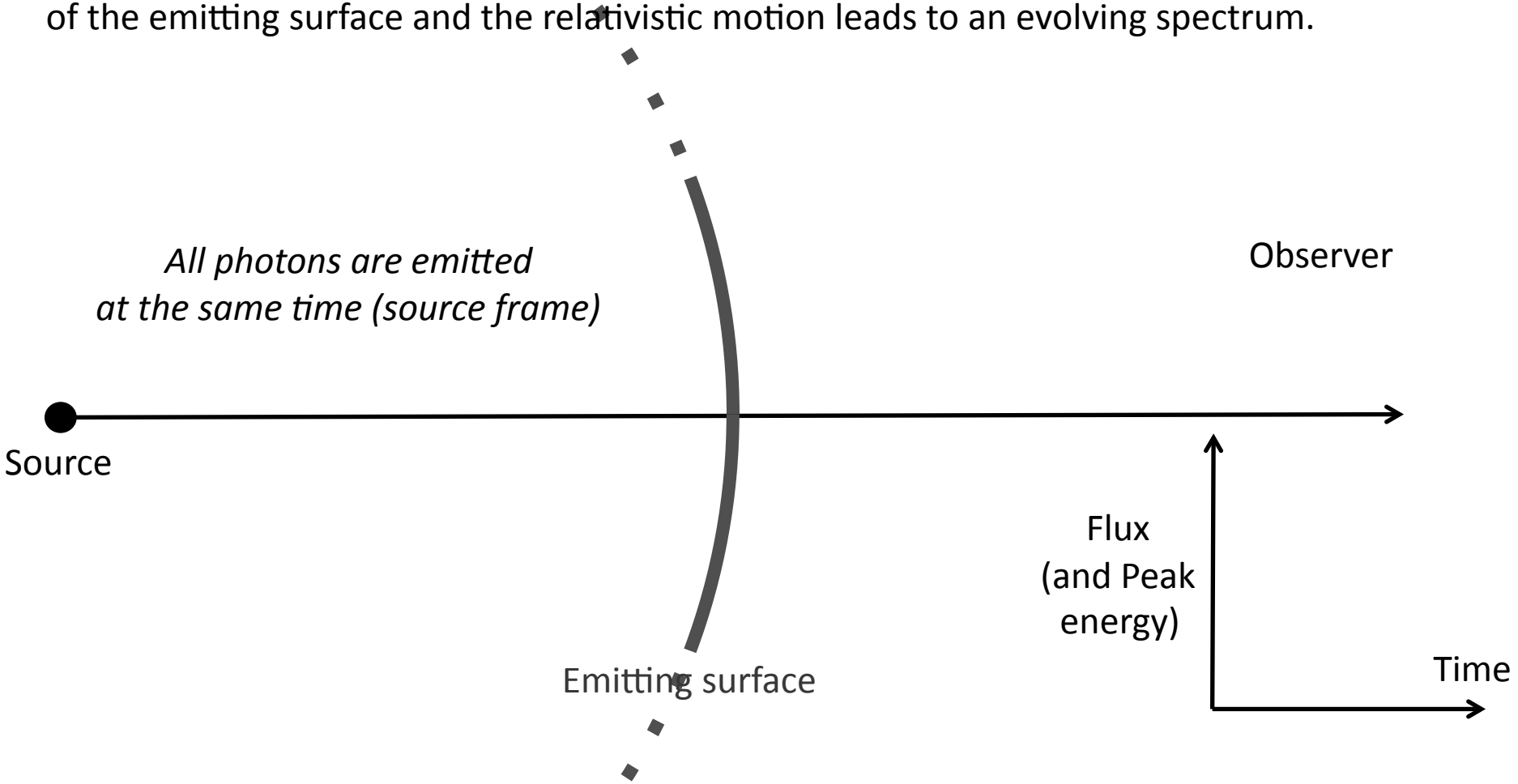
Origin of the spectral evolution

(1) Curvature effect

The prompt emission from GRBs is most probably produced in highly relativistic outflows :

High Lorentz factors are necessary to avoid $\gamma\gamma$ annihilation at high energy;
An « internal origin » of the emission is necessary to reproduce the variability.

Even if a pulse is produced by an instantenous emission, the combination of the curvature of the emitting surface and the relativistic motion leads to an evolving spectrum.



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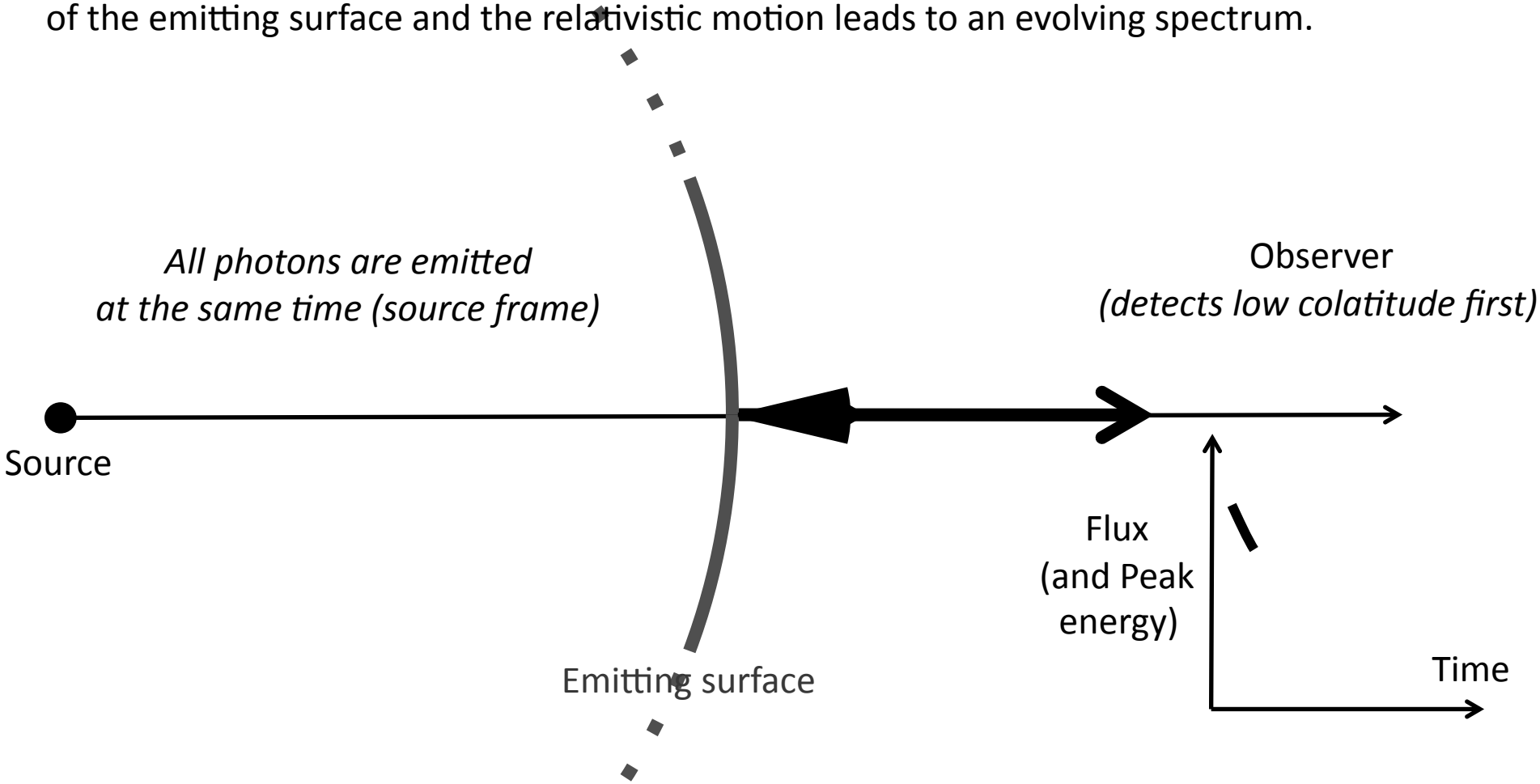

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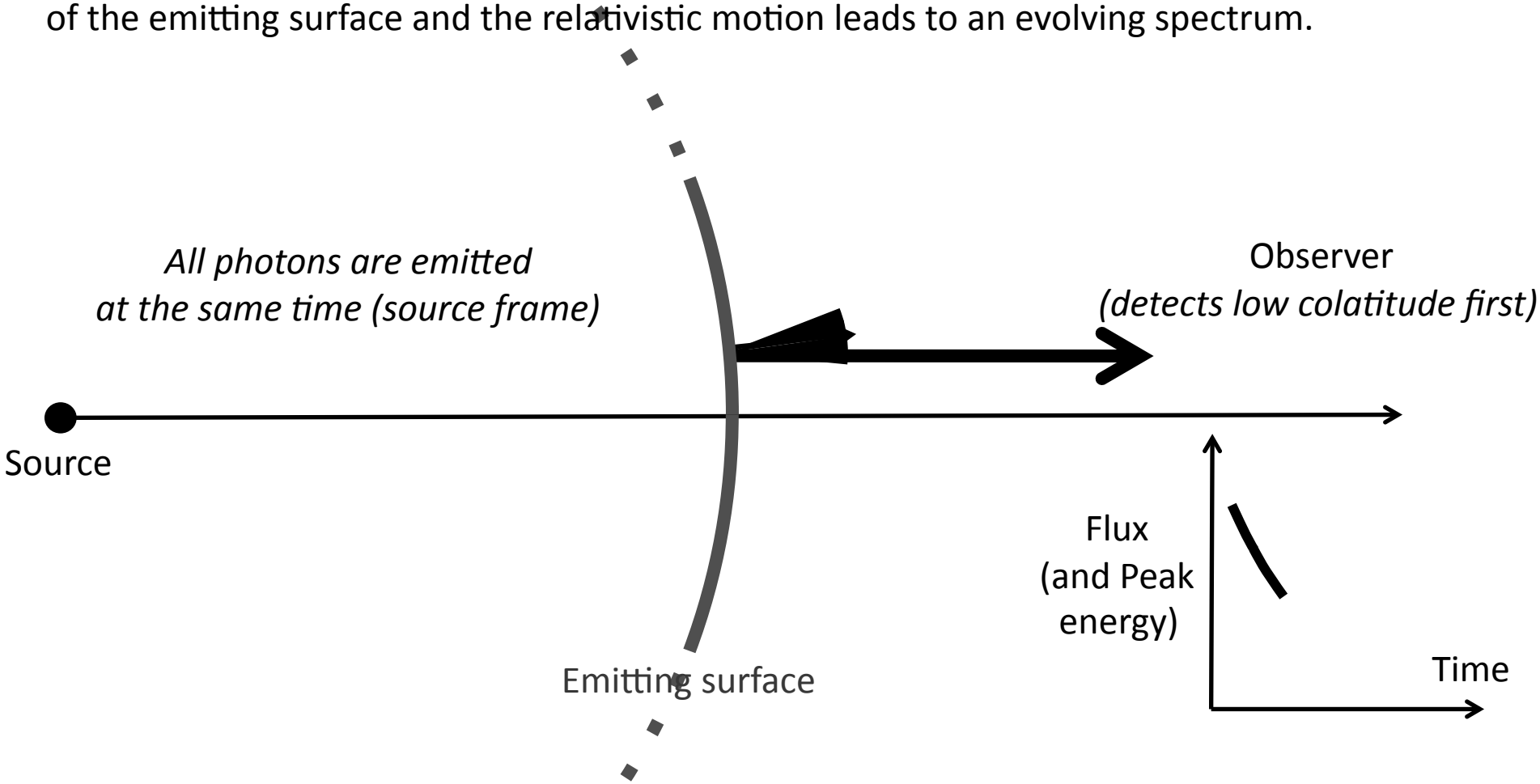

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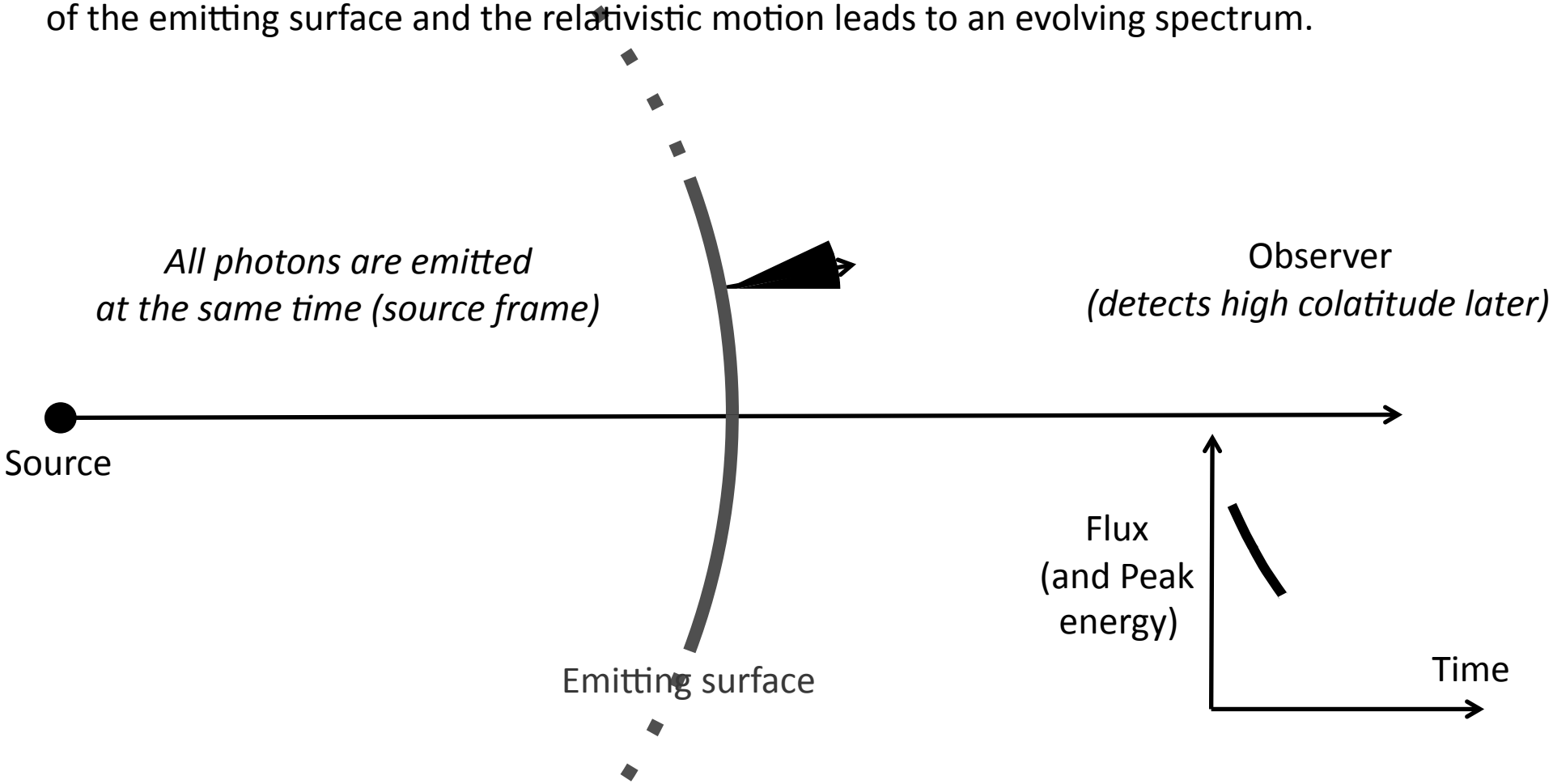

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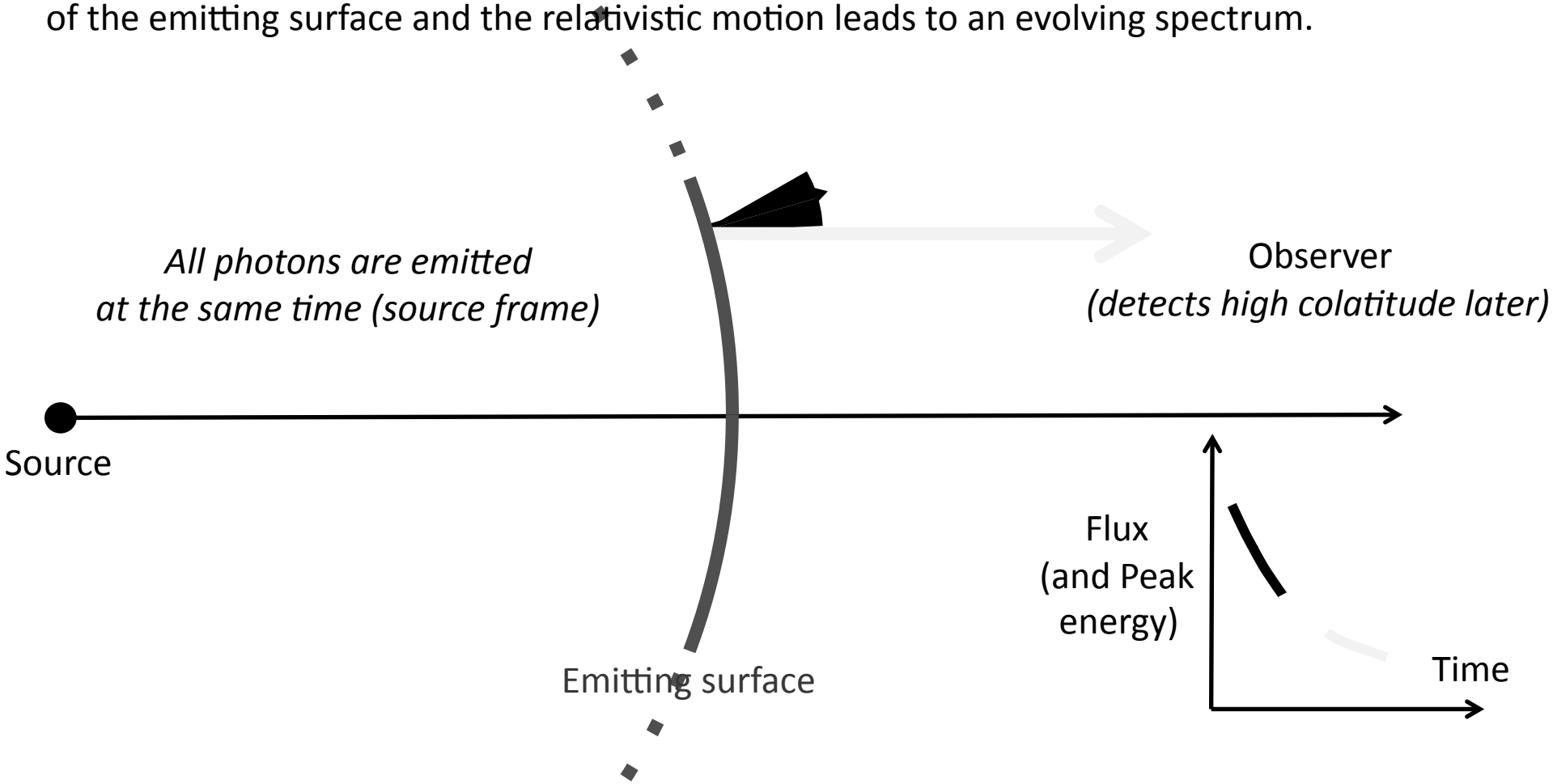

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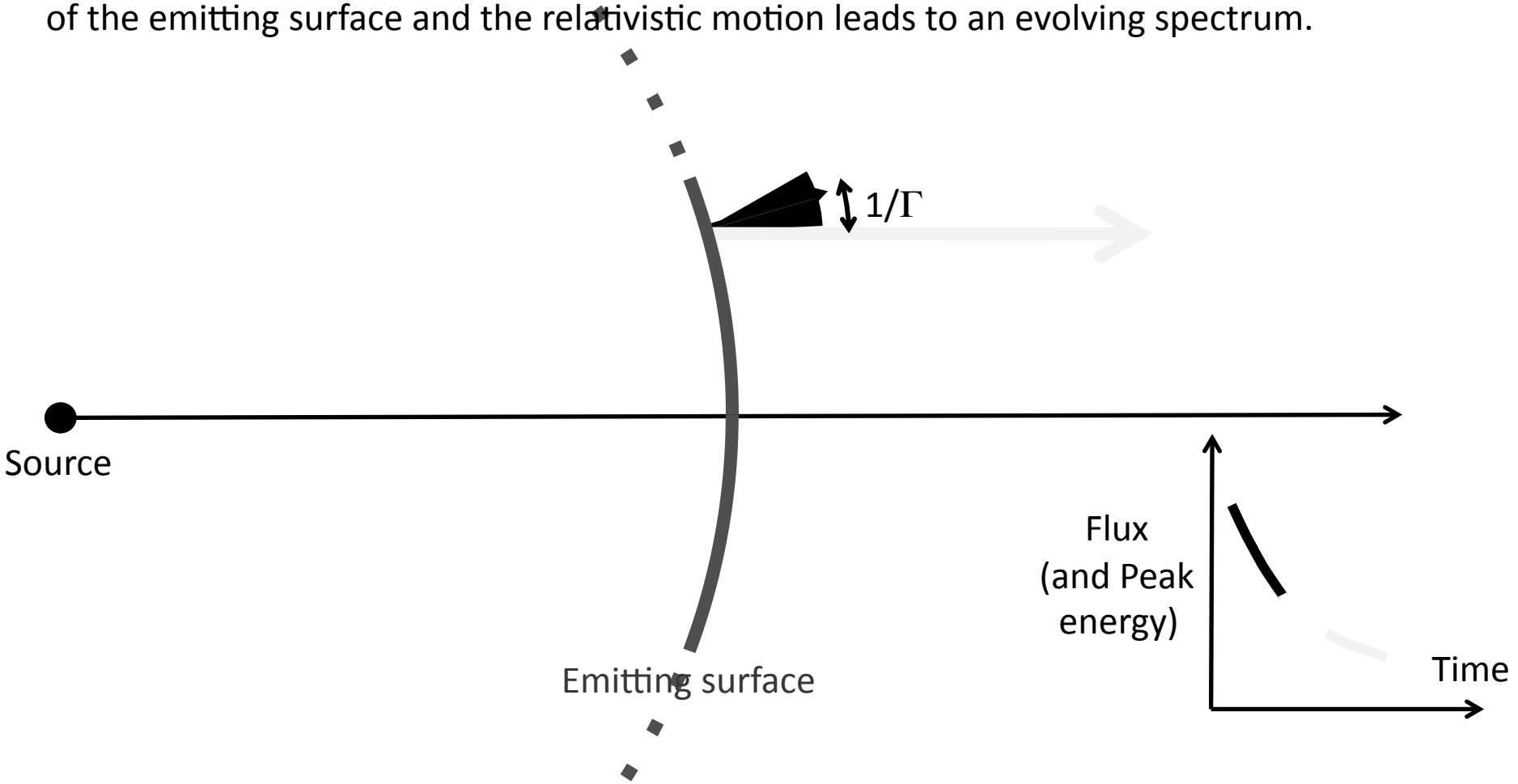

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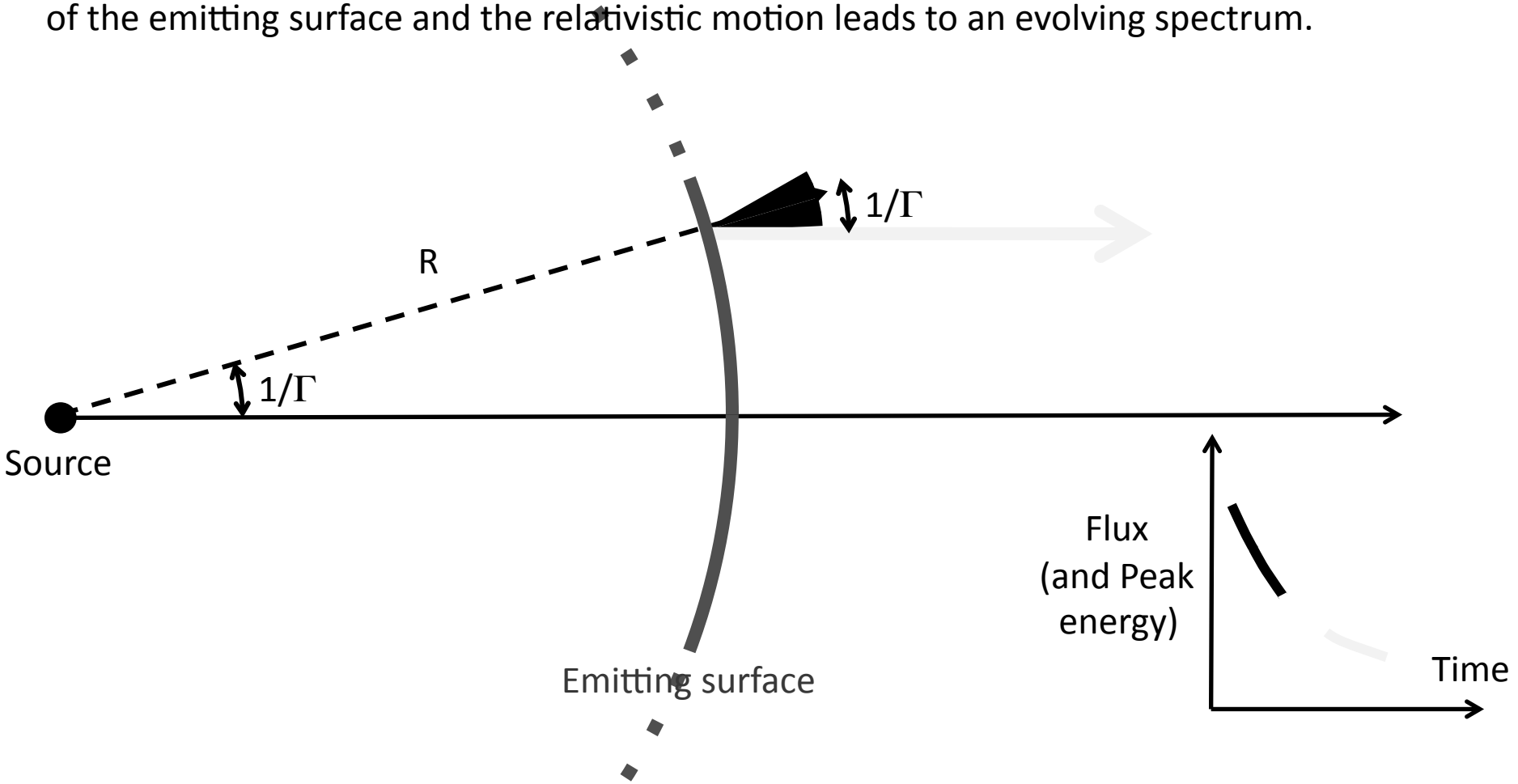

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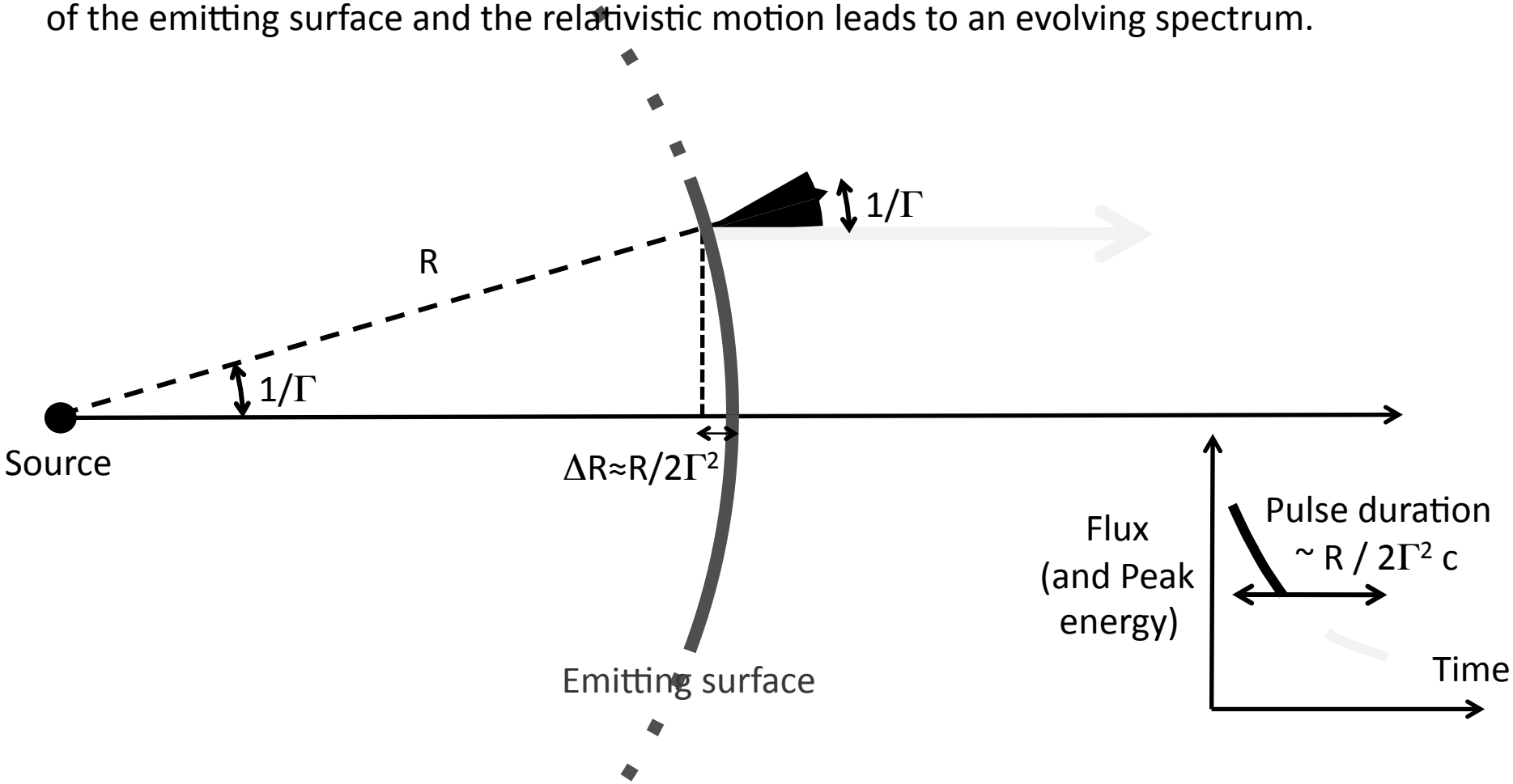


The curvature effects predicts a steep spectral evolution which usually disagrees with observations in GRB pulses (e.g. Fenimore et al. 1996).

The time evolution can be governed by an intrinsic timescale related to the mechanism which extracts the energy from the outflow.

To reproduce the shortest timescale variability (and also to avoid an energy crisis), the radiation processes responsible for the emission must occur on even shorter timescales (« fast cooling regime »).

(see e.g. Sari & Piran 1995)

Energy reservoir / extraction mechanism : different possibilities discussed in the litterature :

Thermal energy / photospheric emission
Kinetic energy / internal shocks
Magnetic energy / reconnection

To understand the spectral evolution, it is necessary to model both the extraction mechanism and the associated **radiated processes**.

(potential problem: many uncertainties regarding the microphysics : shock acceleration, etc.)

Dominant radiative process

GBM LAT

SSC :

? ?

IC2

IC1

Syn

GBM LAT

Synchrotron :

Syn

IC

Synchrotron vs SSC

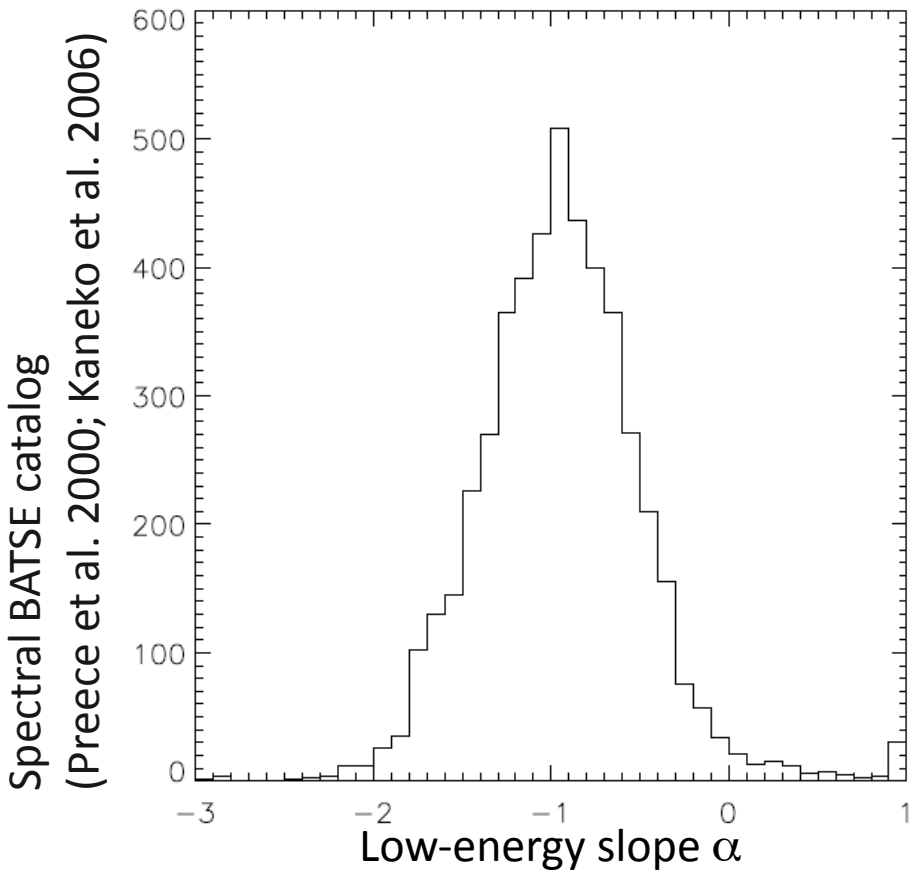
-Where is the strong IC2 component ?
or the strong syn component ?

-Energy crisis

Fermi-LAT detection rate and observations clearly favor the process.

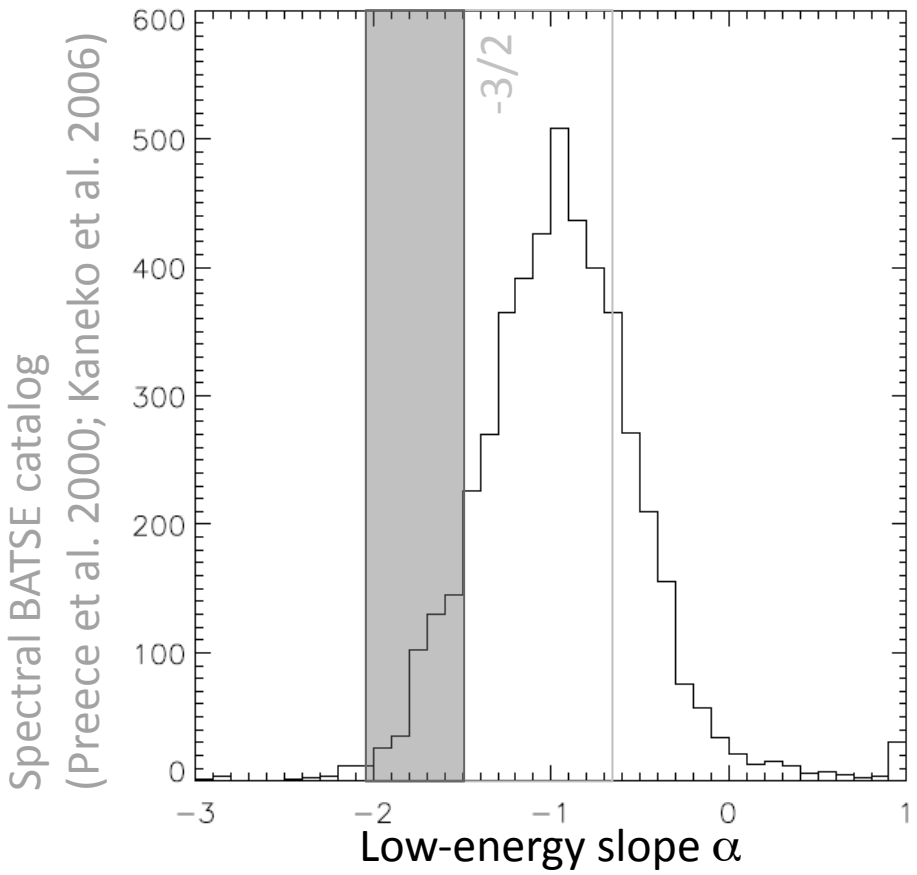
(see e.g. Bošnjak, Daigne & Dubus 09; Piran, Sari & Zou 09)

The low-energy spectral slope α



Synchrotron radiation

The low-energy spectral slope α



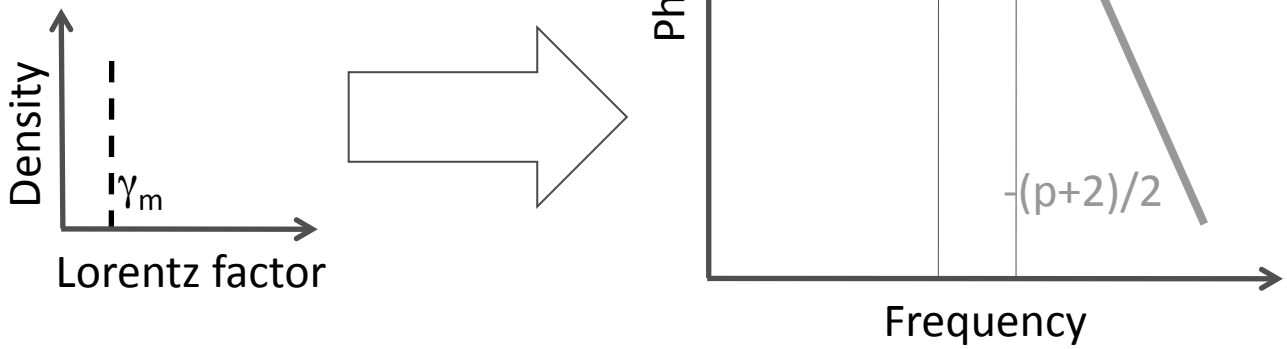
γ_m : minimum Lorentz factor at injection

γ_c : radiative timescale = dynamical timescale

Synchrotron frequencies : $\gamma_m \leftrightarrow \nu_m$ and $\gamma_c \leftrightarrow \nu_c$

Synchrotron spectrum : fast cooling ($\gamma_c < \gamma_m$)

Relativistic electrons :



Synchrotron radiation

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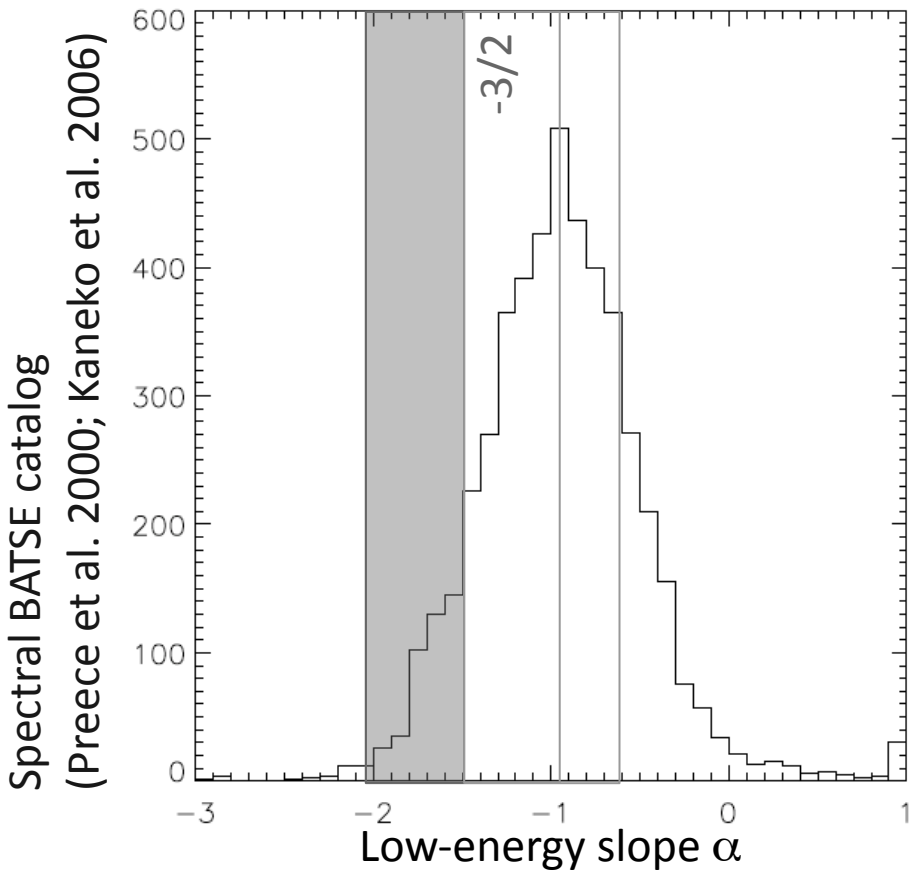
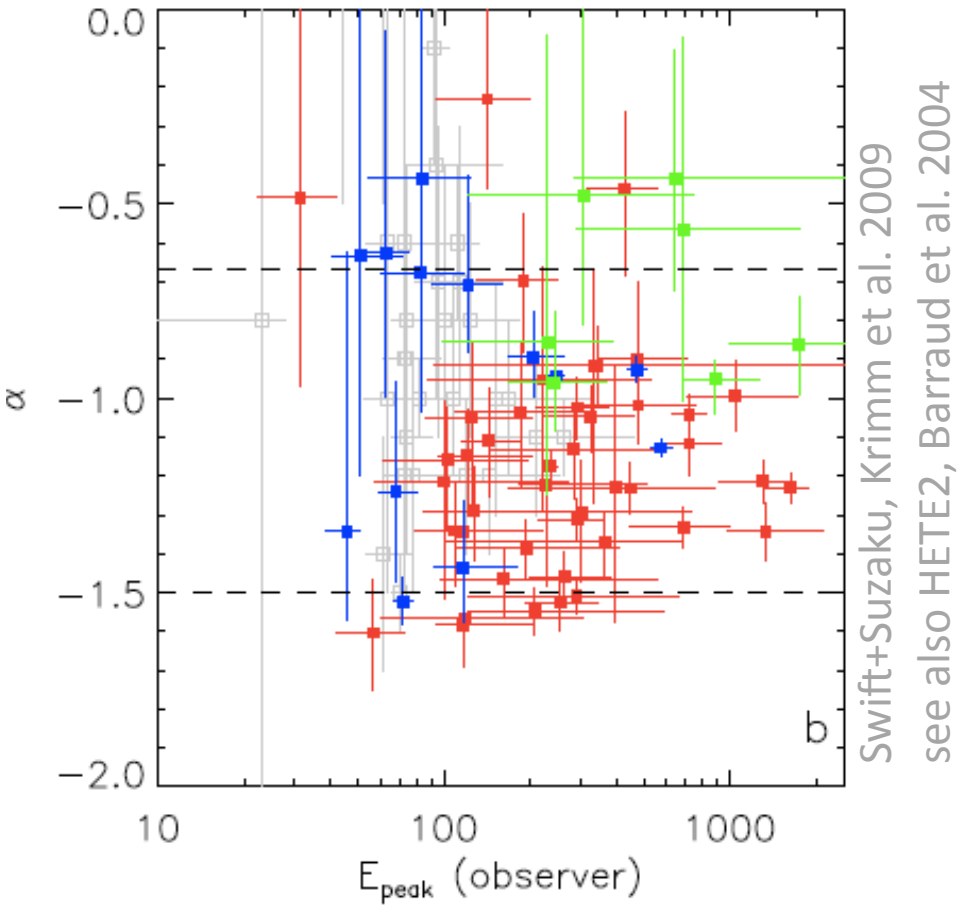




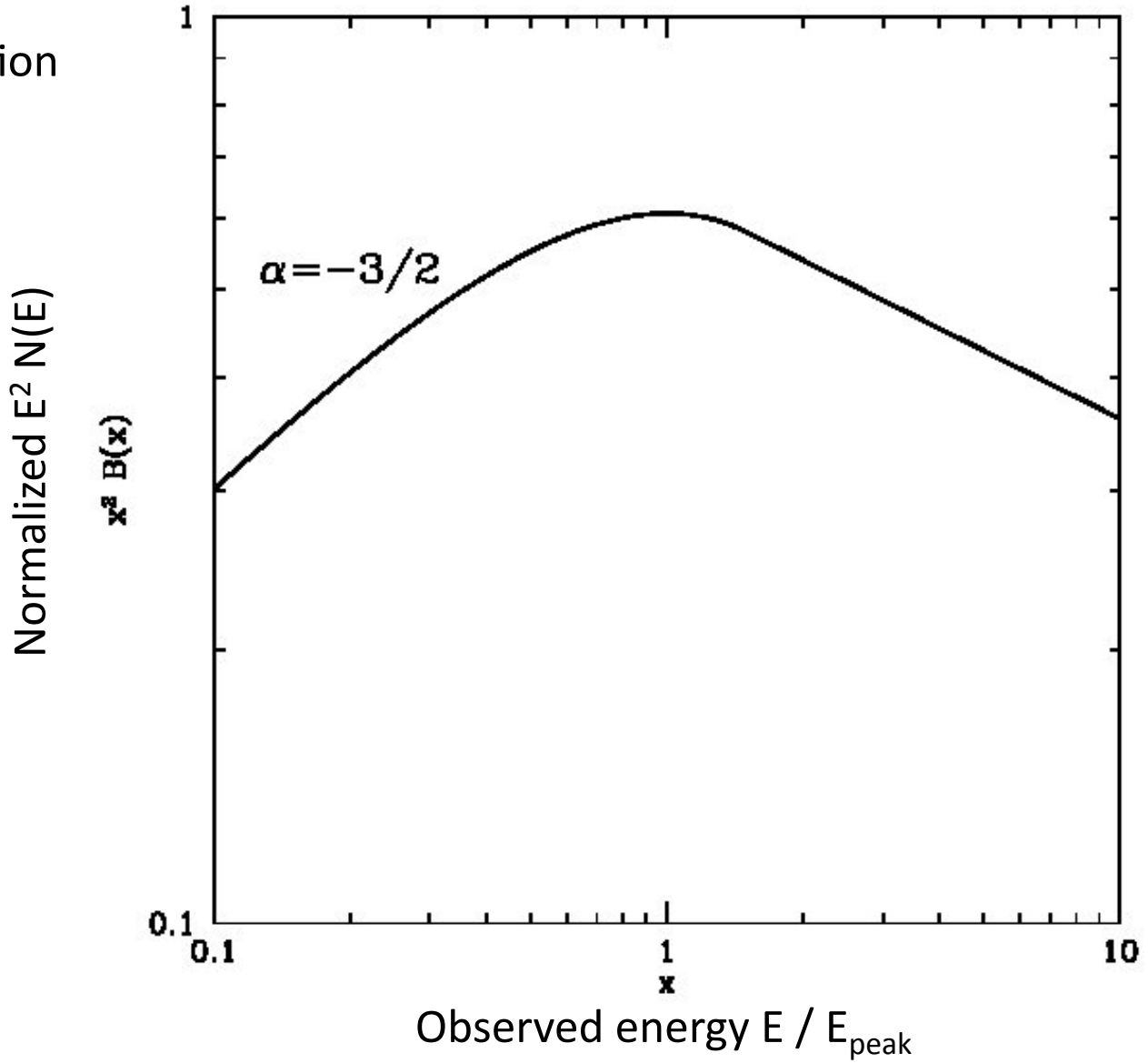
Swift+Suzaku, Krimm et al. 2009
see also HETE2, Barraud et al. 2004

The low-energy spectral slope α

Band function

α = -1.5

β = -2.25



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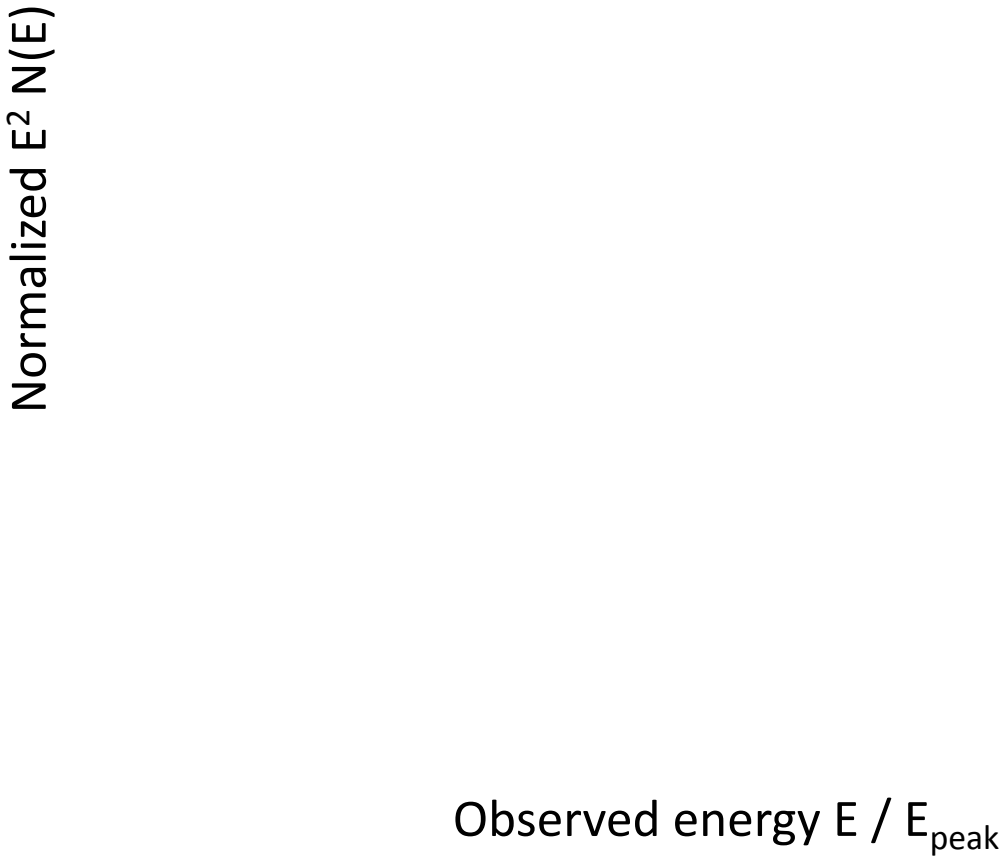

Band function

α = -1.5

β = -2.25

Observed energy E / E_{peak}

(see Derishev et al. 01 ; Bošnjak, Daigne & Dubus 09 ; Nakar, Ando & Sari 09)

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Thomson regime :
($w_m < 1$)

$$\frac{L_{\rm ic}}{L_{\rm syn}} \sim Y = \frac{4}{3}\tau_{\rm T}\Gamma_{\rm m}\Gamma_{\rm c} \simeq \frac{\epsilon_{\rm e}}{\epsilon_{\rm B}}$$

Klein-Nishina regime :
($w_m > 1$)

$$\frac{L_{\rm ic}}{L_{\rm syn}} \sim Y \times f(w_{\rm m}) \quad \text{with} \quad f(w) \ll 1 \text{ for } w \gg 1$$

Klein-Nishina parameter : $w_{\rm m} = \Gamma_{\rm m}\frac{h\nu'_{\rm m}}{m_{\rm e}c^2}$

w_m : importance of KN

$$w_{\rm m} = \Gamma_{\rm m} \frac{h\nu'_{\rm m}}{m_{\rm e}c^2}$$

Y : importance of IC vs syn

$$Y = \frac{4}{3}\tau_{\rm T}\Gamma_{\rm m}\Gamma_{\rm c} \simeq \frac{\epsilon_{\rm e}}{\epsilon_{\rm B}}$$

Normalized νF_ν

Frequency

Exact calculation with synchrotron + IC only (no adiabatic cooling; syn. self-abs; $\gamma\gamma$ annihilation, …)

w_m : importance of KN

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Thomson Y parameter

Klein-Nishina parameter

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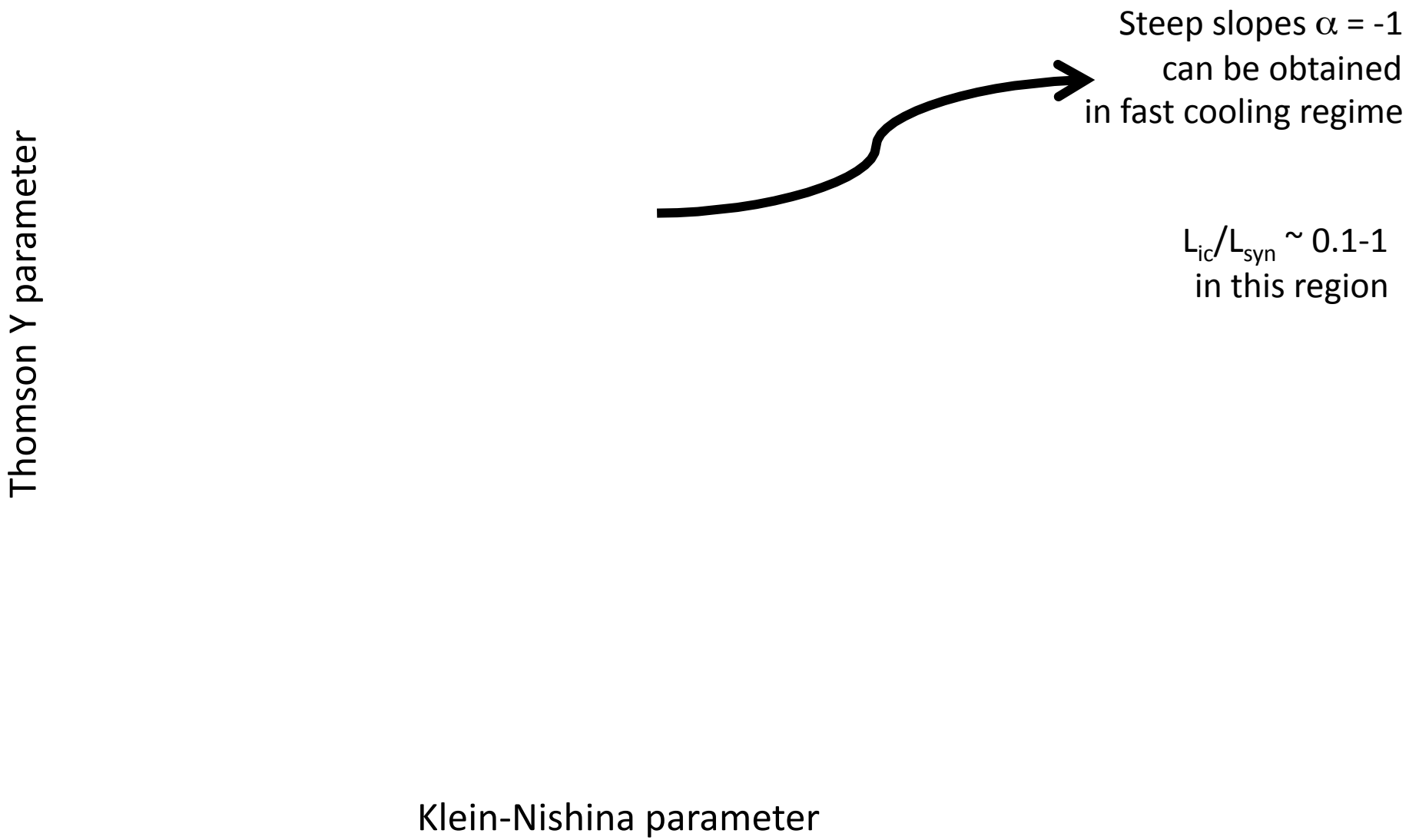
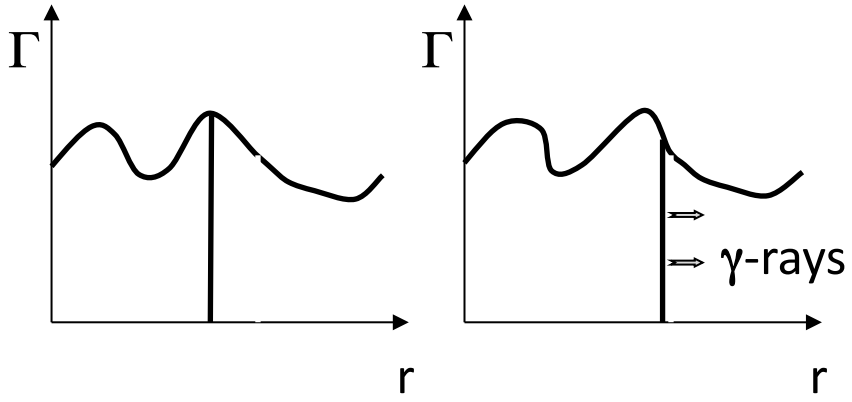


Exact calculation with synchrotron + IC only (no adiabatic cooling; syn. self-abs; $\gamma\gamma$ annihilation, …)

If the dominant radiative process at work is indeed synchrotron radiation, then spectral evolution is expected if the physical conditions (magnetic field, electron acceleration) vary in the emitting regions.

If IC plays also a role, it can introduce an additional spectral evolution between high and soft gamma-rays if the relative intensity of the two processes vary.

An often discussed possibility : internal shocks (Rees & Meszaros 1994)

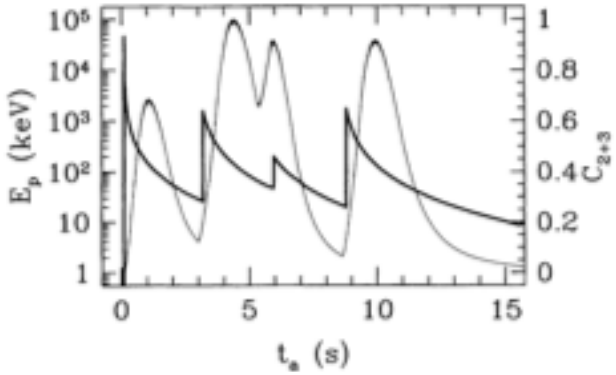


Origin of the spectral evolution

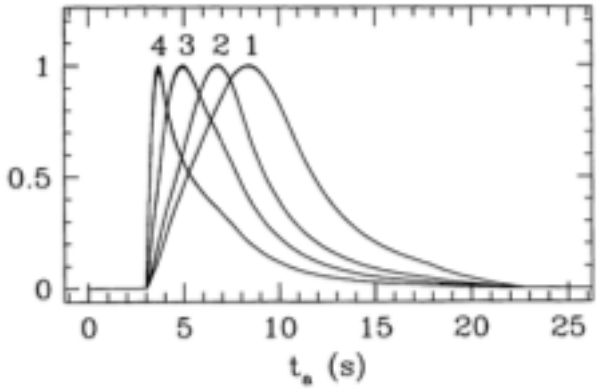
Internal shocks

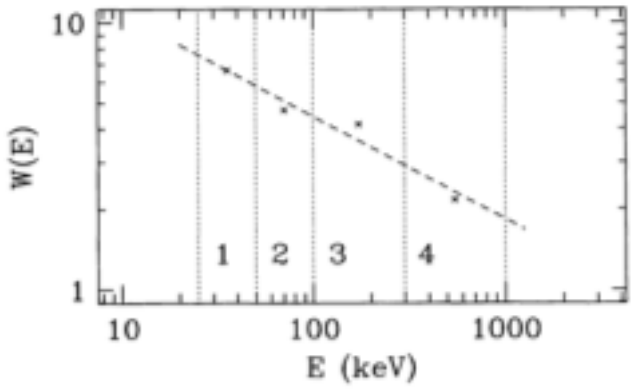
Lightcurves

Spectral evolution



Pulse

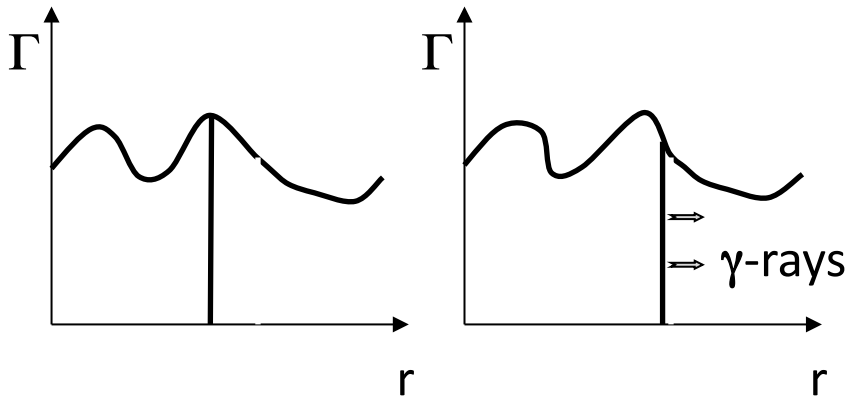




Daigne & Mochkovitch 1998

Hydro : « two shell » collision

Daigne & Mochkovitch 2000



(Bošnjak, Daigne & Dubus 09)

Fraction of accelerated electrons

Dynamics : multi-shell approximation

Microphysics : magnetic field (ε_B) ; non-thermal population of electrons (ε_e,ζ,p)

Radiation : solve time evolution of electrons and photons in the comoving frame of each shocked region
(adiabatic cool.; synchrotron; syn. self-absorption; IC; $\gamma\gamma \rightarrow e^+e^-$)

Observed GRB : integration over equal-arrival time surfaces

(as a building block for more complex GRBs)

Initial distribution of Lorentz factor :

Ejection lasts for $t_w = 2s$

Constant energy injection rate : $L_{kin} = 2 \times 10^{52}$ erg/s

(as a building block for more complex GRBs)

Dynamical evolution :

Lorentz factor in the shocked region

Electron Lorentz factor

Magnetic field

Constant microphysics parameters : $\varepsilon_e=\varepsilon_B=1/3$; $\zeta = 0.01$; $p=2.5$

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Examples : a single pulse burst

EBL not included

$\zeta = 10^{-3}$

Full calculation with all processes (adiabatic cooling; sync; sync self-abs; IC; $\gamma\gamma$ annihilation)

Dynamics : ejection $\Gamma(t)=100\rightarrow400$; duration = 1 s ; kinetic energy injection rate $L_{kin} = 10^{54}$ erg

Examples : a single pulse burst

EBL not included

$\zeta = 10^{-3}$

0-10 s

Full calculation with all processes (adiabatic cooling; sync; sync self-abs; IC; $\gamma\gamma$ annihilation)

Dynamics : ejection $\Gamma(t)=100\rightarrow400$; duration = 1 s ; kinetic energy injection rate $L_{kin} = 10^{54}$ erg

Examples : a single pulse burst

$\zeta = 10^{-3}$

Every 0.5 s blue →

Full calculation with all processes (adiabatic cooling; sync; sync self-abs; IC; $\gamma\gamma$ annihilation)

Dynamics : ejection $\Gamma(t)=100\rightarrow400$; duration = 1 s ; kinetic energy injection rate $L_{kin} = 10^{54}$ erg

$\zeta = 10^{-3}$

Peak energy ~ 300 keV

Full calculation with all processes (adiabatic cooling; sync; sync self-abs; IC; $\gamma\gamma$ annihilation)

Dynamics : ejection $\Gamma(t)=100\rightarrow400$; duration = 1 s ; kinetic energy injection rate $L_{kin} = 10^{54}$ erg

Examples : a single pulse burst

EBL not included

$\zeta = 5\times10^{-4}$

Full calculation with all processes (adiabatic cooling; sync; sync self-abs; IC; $\gamma\gamma$ annihilation)

Dynamics : ejection $\Gamma(t)=100\rightarrow400$; duration = 1 s ; kinetic energy injection rate $L_{kin} = 10^{54}$ erg

Examples : a single pulse burst

EBL not included

$\zeta = 3\times10^{-4}$

Full calculation with all processes (adiabatic cooling; sync; sync self-abs; IC; $\gamma\gamma$ annihilation)

Dynamics : ejection $\Gamma(t)=100\rightarrow400$; duration = 1 s ; kinetic energy injection rate $L_{kin} = 10^{54}$ erg

Examples : a single pulse burst

EBL not included

$\zeta = 2\times10^{-4}$

Full calculation with all processes (adiabatic cooling; sync; sync self-abs; IC; $\gamma\gamma$ annihilation)

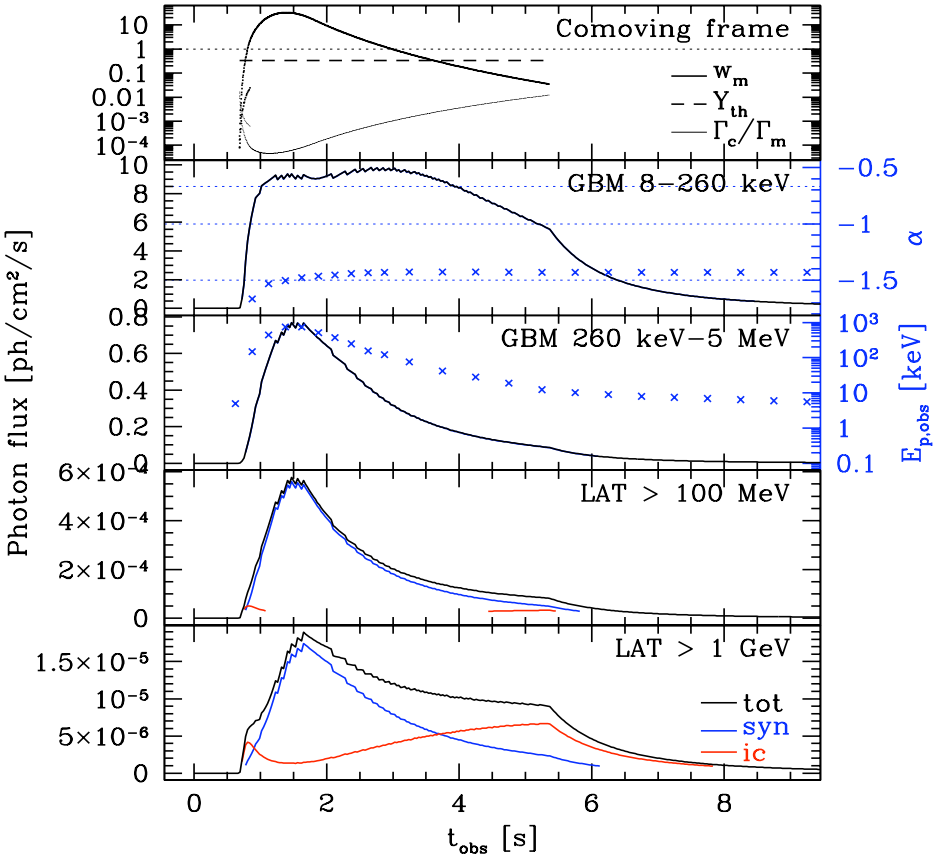
Dynamics : ejection $\Gamma(t)=100\rightarrow400$; duration = 1 s ; kinetic energy injection rate $L_{kin} = 10^{54}$ erg

EBL not included

This feature is suppressed
for more rapid variations of $\Gamma(t)$

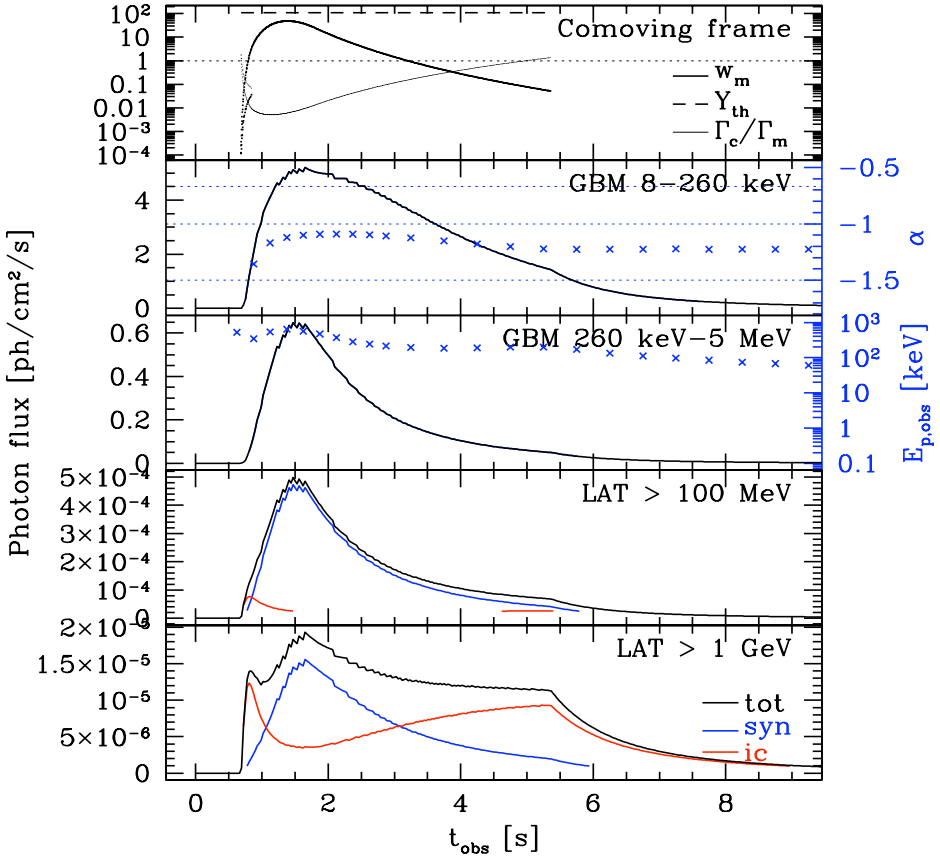
Another example :

Same burst with different microphysics parameters ε_B=1/3 or ε_B=0.001



ε_B=1/3 ; ζ = 0.003

E_p ~ 800 keV at the pulse peak



ε_B=0.001 ; ζ = 0.001

E_p ~ 700 keV at the pulse peak

Summary

Fermi/LAT observations (rate + HE spectrum of detected GRBs) :

- SSC seems in contradiction with observations

(Bosnjak, Daigne & Dubus 2009 ; Piran, Sari & Zou 2009)

- this can reconcile the synchrotron process with most observations
- spectra with $-1 \leq \alpha \leq -2/3$? (marginally fast cooling regime ?)
- spectra with $\alpha \geq -2/3$: real problem ?

(Bosnjak, Daigne & Dubus 2009 ; Nakar, Ando & Sari 2009 ; Daigne et al. in preparation)

Summary

Shock acceleration physics in mildly relativistic regime ? (low ζ ; low ε_B)

Are microphysics parameters constant ? (may change spectral evolution)

The observed spectral evolution puts some constraints on this still uncertain physics

(Daigne & Mochkovitch 2003 ; Bosnjak, Daigne & Dubus in preparation)

If only a fraction of electrons are accelerated in a « non-thermal » distribution, can we detect the « thermal » electron component ?

(Giannios & Spitkovsky 2009)

Summary

(Bosnjak, Daigne & Dubus 2009)

(origin of the additional component below 50 keV ?)

- where is the photospheric component ? (magnetic acceleration ?)
- what causes the long-lasting GeV emission ? (afterglow ?)

Work in progress :

- Discussion of correlations between spectral parameters and luminosity (Amati relation, lag-luminosity correlation, …) in the internal shock framework (see also Daigne & Mochkovitch 2003 ; Barraud et al. 2005)
- Discussion of short GRBs (why are they harder with negligible lags ?)
- Detailed modeling of Fermi-LAT bursts
- Constraints on the minimum bulk Lorentz factor

(see Granot et al. 2008)

Intrinsic time delays (ms → s) can have several origins :

Curvature of the emitting surface ;

Intrinsic evolution of the spectrum related to the extraction mechanism in the outflow (for instance softening during shock propagation in internal shocks) ;

Competition between different radiative processes (for instance synchrotron vs IC).

The spectral evolution is a key observation to understand the physics of GRB relativistic outflows. Thanks to an unprecedented spectral coverage, Fermi offers great opportunities to make progress in this field.