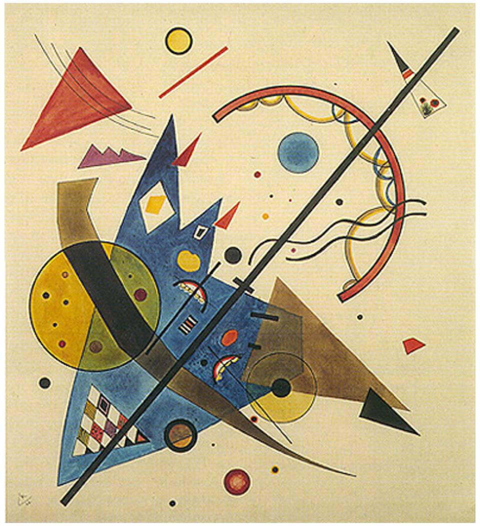
The origin of the prompt GRB spectrum

Frédéric Daigne (Institut d'Astrophysique de Paris)
with Z. Bošnjak, G. Dubus and R. Mochkovitch.



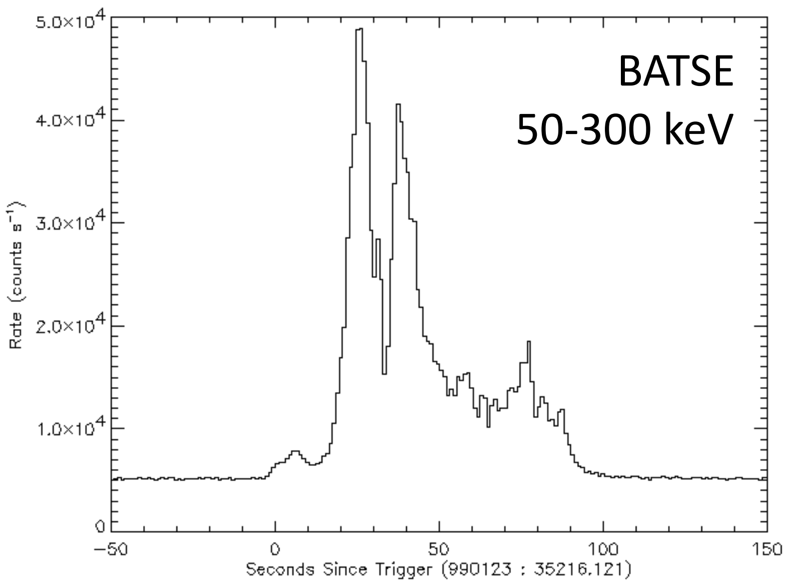
2009 Fermi Symposium – David Band session – Washington DC – November 2-5, 2009

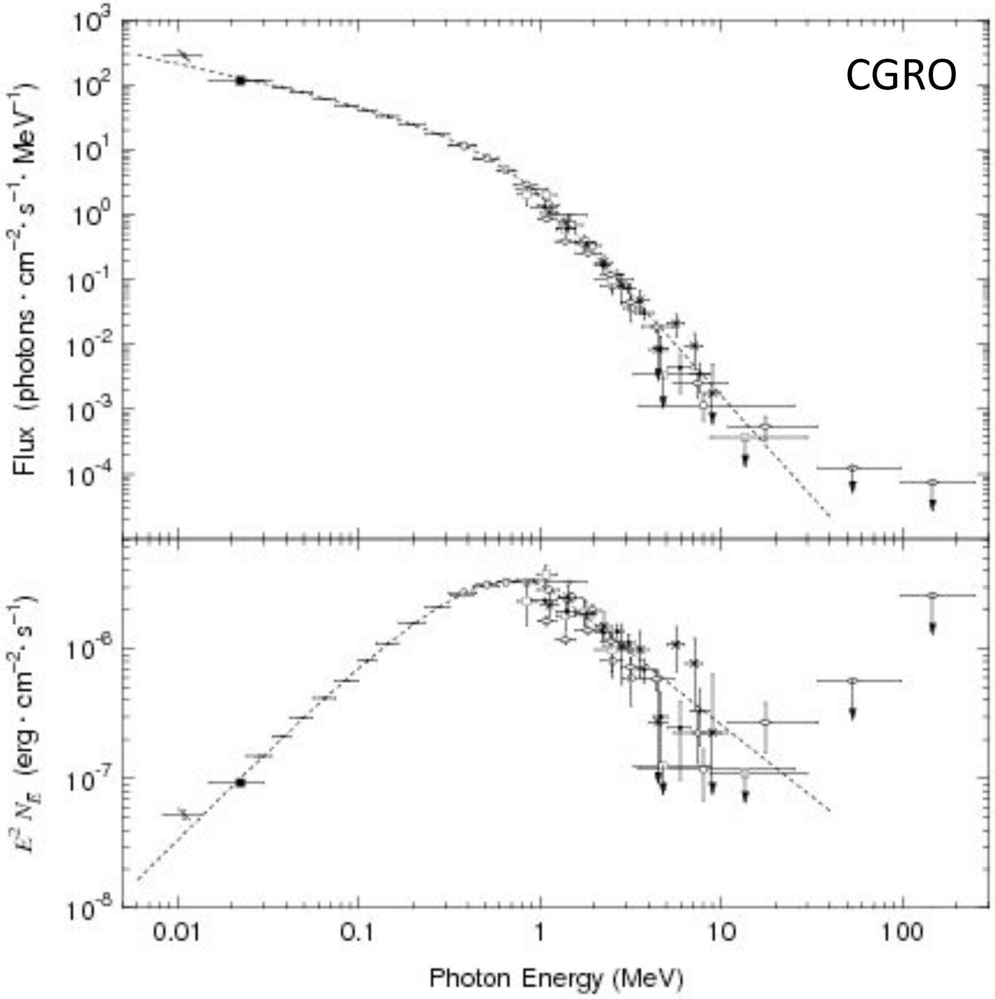
Prompt GRB emission

Pre-Fermi observations

GRB 990123 :

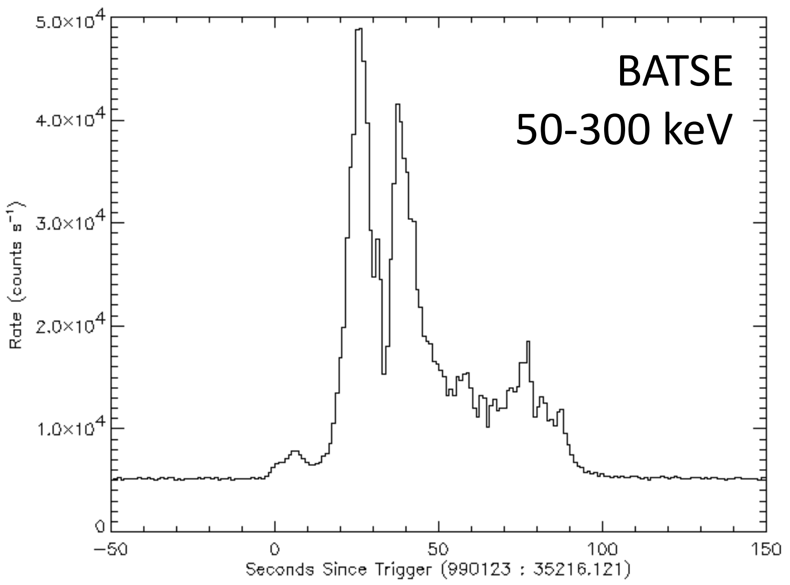
From Briggs et al. 1999





Prompt GRB emission | Pre-Fermi observations

GRB 990123 :



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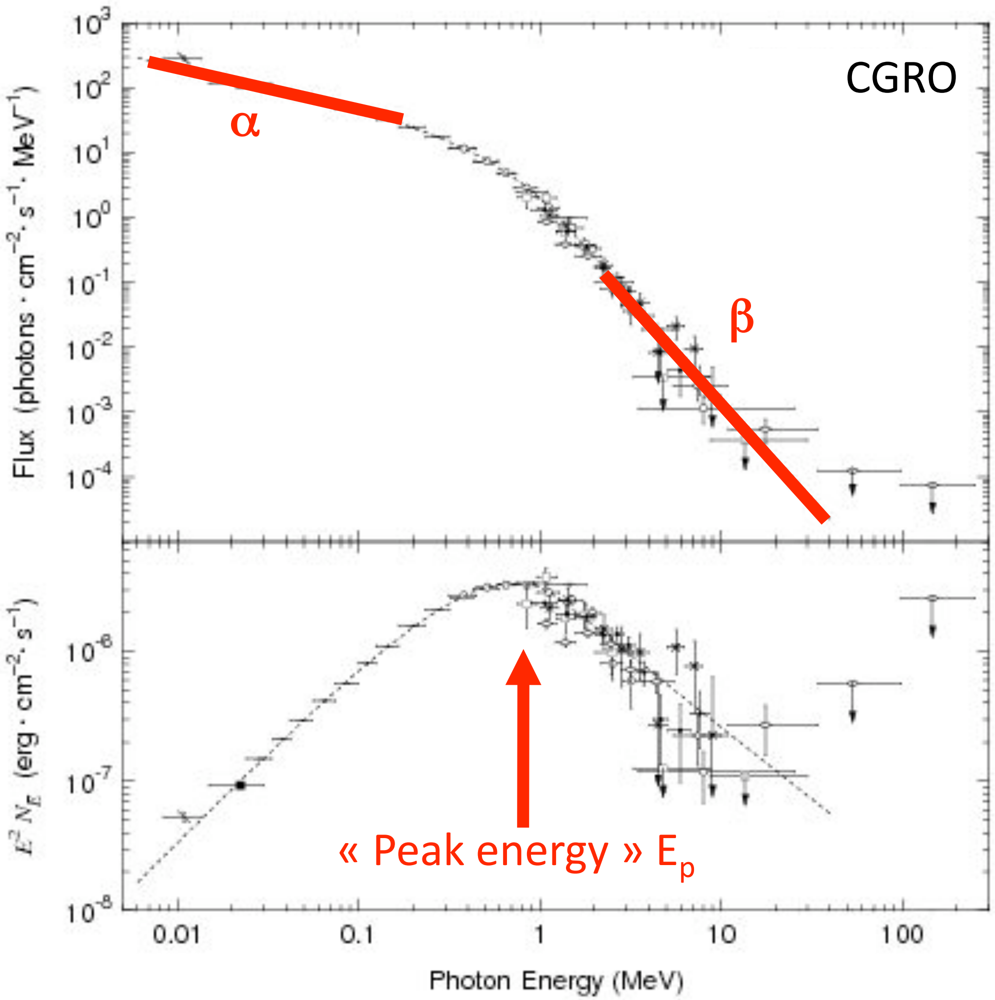

« Peak energy » E_p

4-parameters « Band spectrum » :
E_p, α, β and normalization

Band et al. 1993

Prompt GRB emission | Pre-Fermi observations

GRB 990123 :

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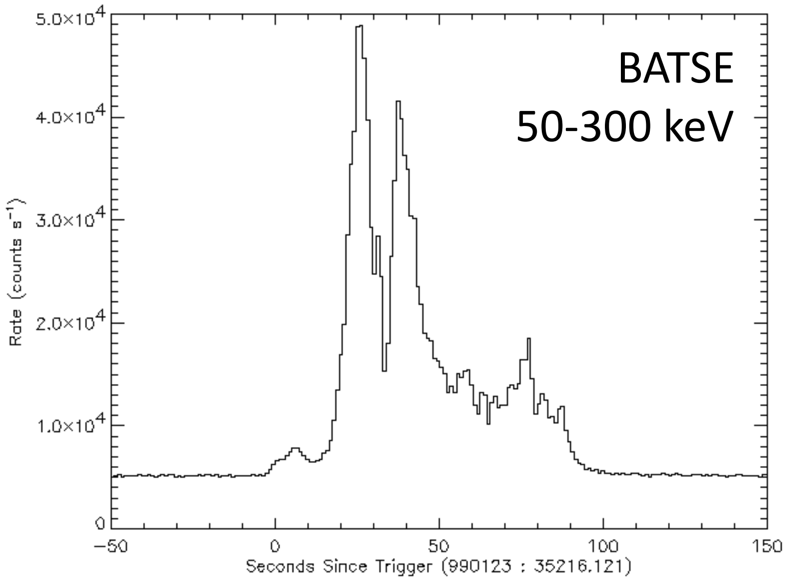
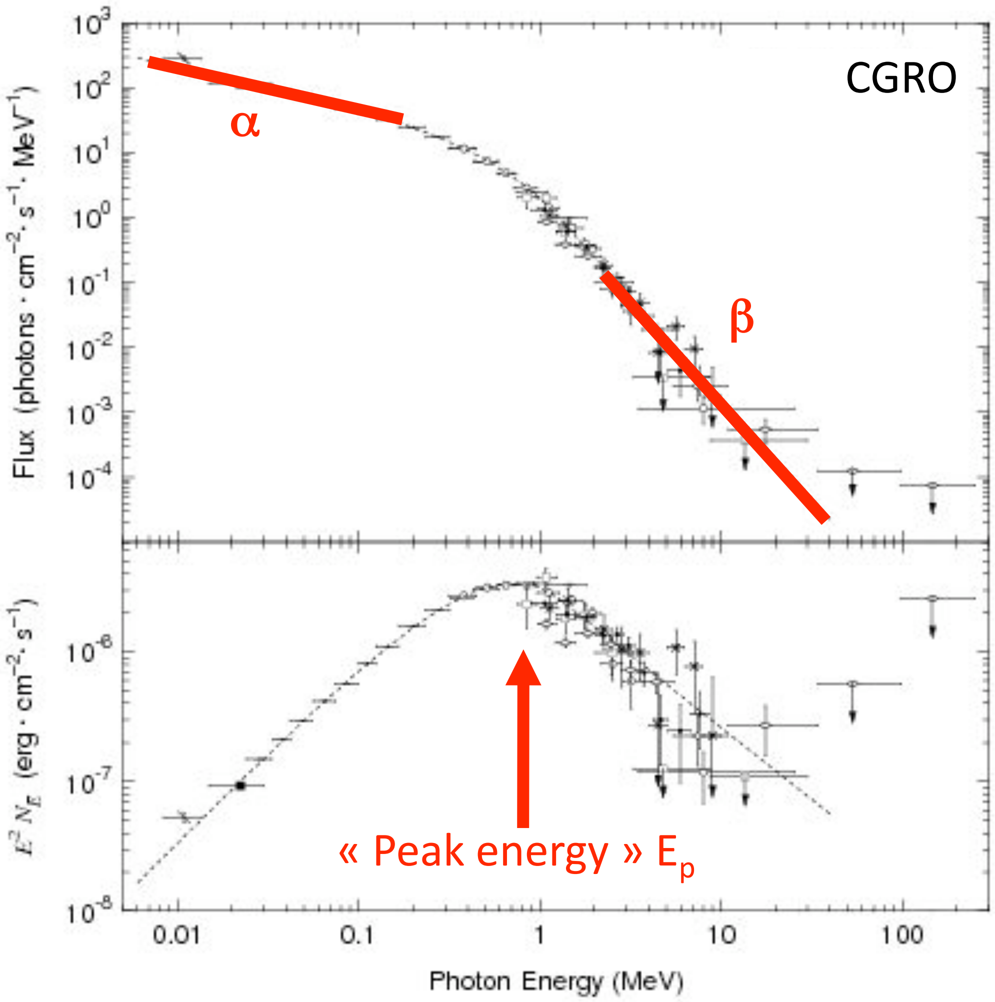
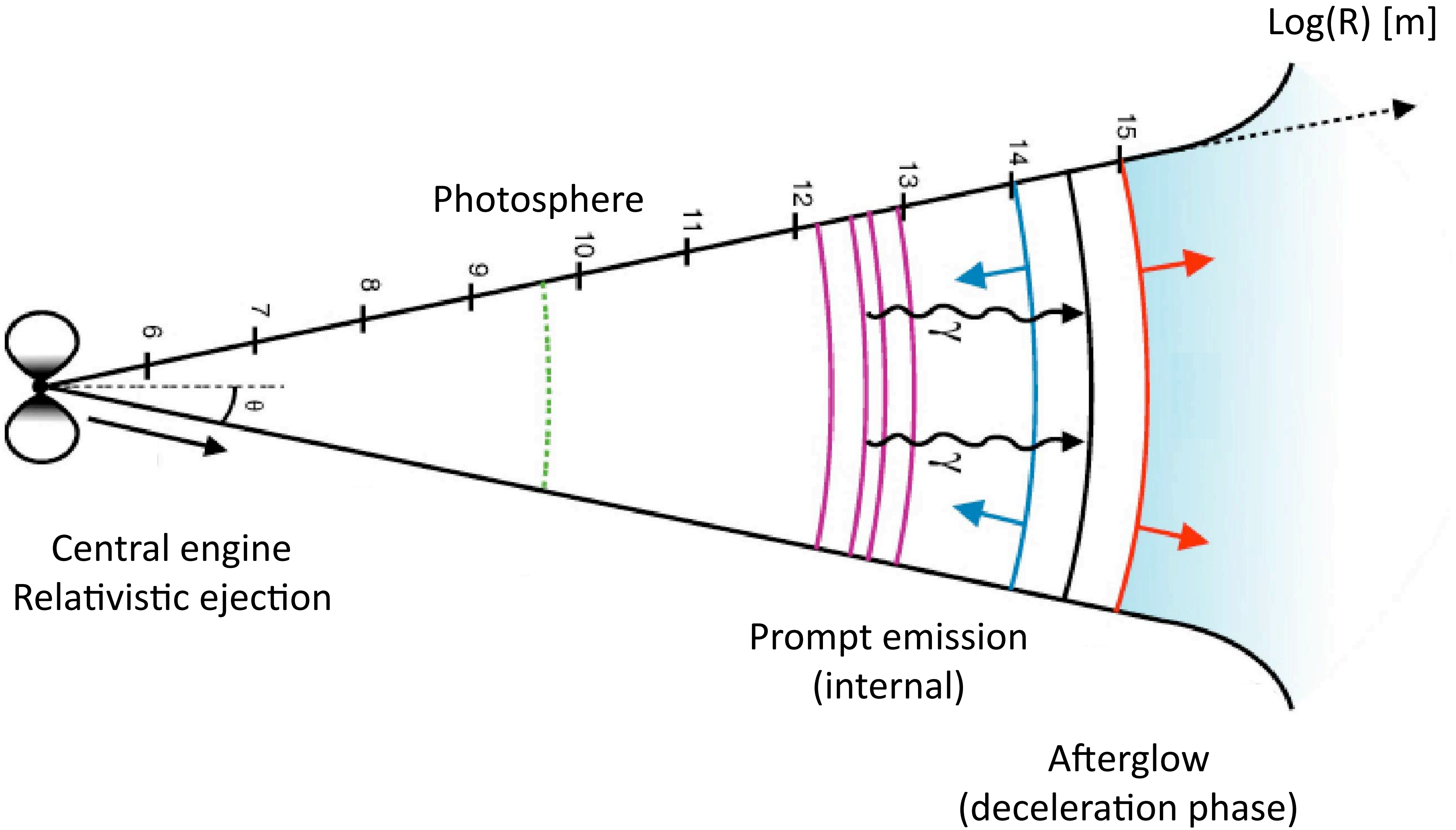




In most GRBs, the spectral parameters (E_p, α, …) evolve with time.

Scenario

Internal vs external



Photosphere

Central engine
Relativistic ejection

Prompt emission
(internal)

Afterglow
(deceleration phase)

Origin of the prompt GRB emission

Questions

Short timescale variability in the lightcurve : internal origin of the prompt GRB emission
(i.e. : emission is radiated from the relativistic outflow)

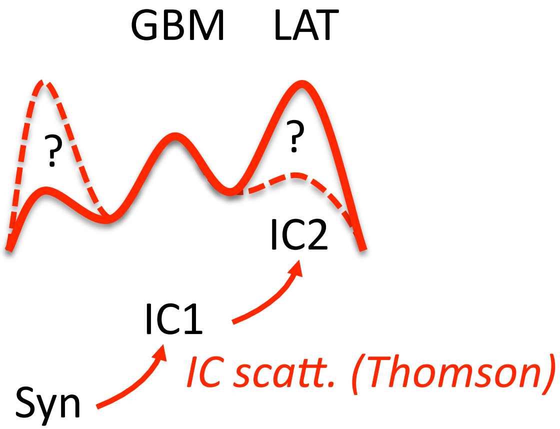
Two questions :

- physical mechanism ?
  - Internal shocks ?
  - Photosphere ?
  - Magnetic dissipation ?
- dominant radiative process ?
  - Synchrotron ?
  - SSC ?
  - Others ?

To understand many observed features (spectral evolution, « delays », …),
both questions must be considered simultaneously.

Dominant radiative process Synchrotron vs SSC

SSC :



GBM LAT

?

?

IC2

IC1

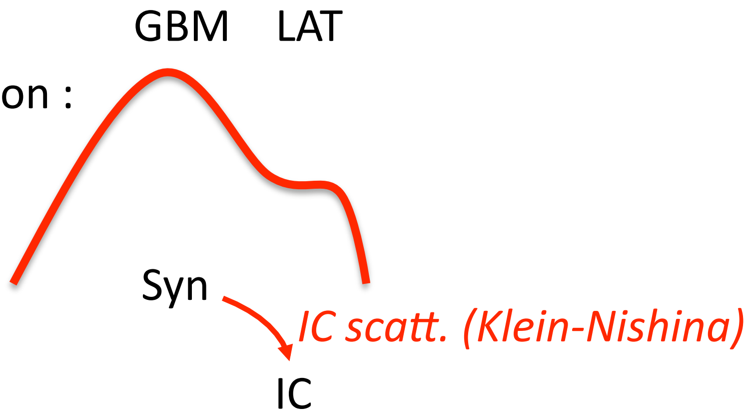
IC scatt. (Thomson)

Syn

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

-Energy crisis

Synchrotron :



GBM LAT

Syn

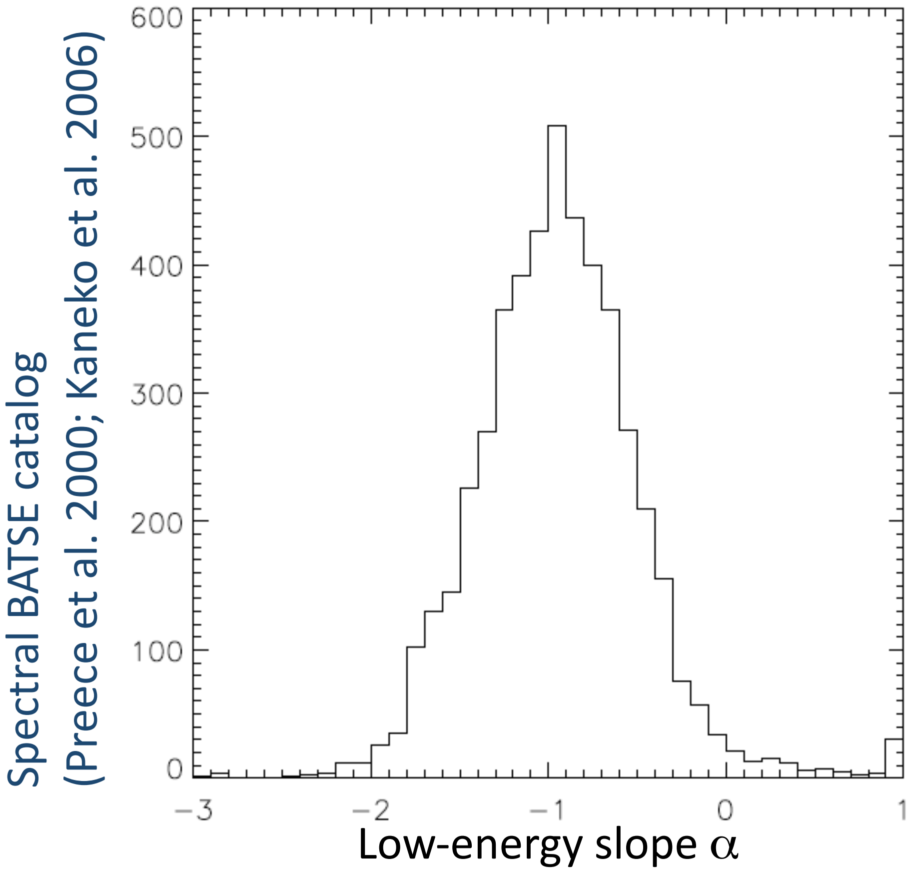
IC scatt. (Klein-Nishina)

IC

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

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

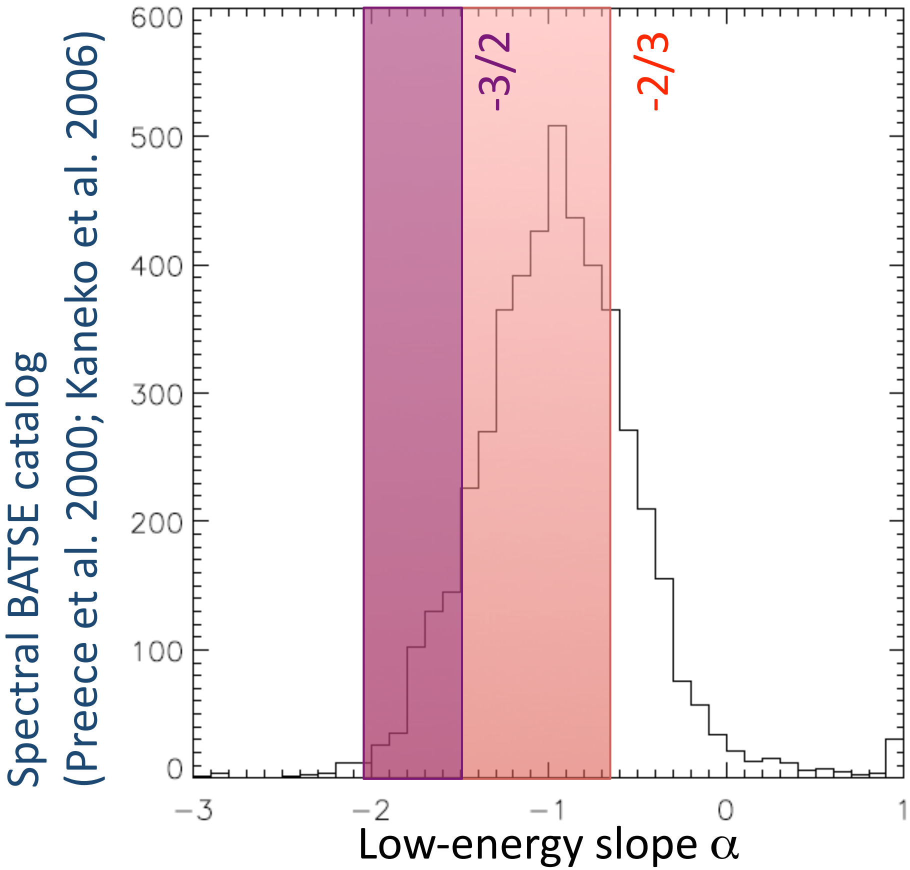
Synchrotron radiation | The low-energy spectral slope α



Synchrotron radiation | The low-energy spectral slope α

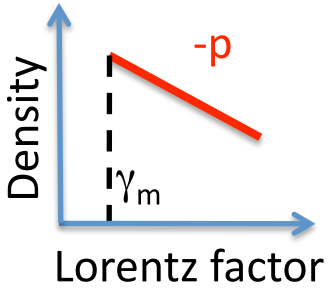
γ_m : minimum Lorentz factor at injection
γ_c : radiative timescale = dynamical timescale

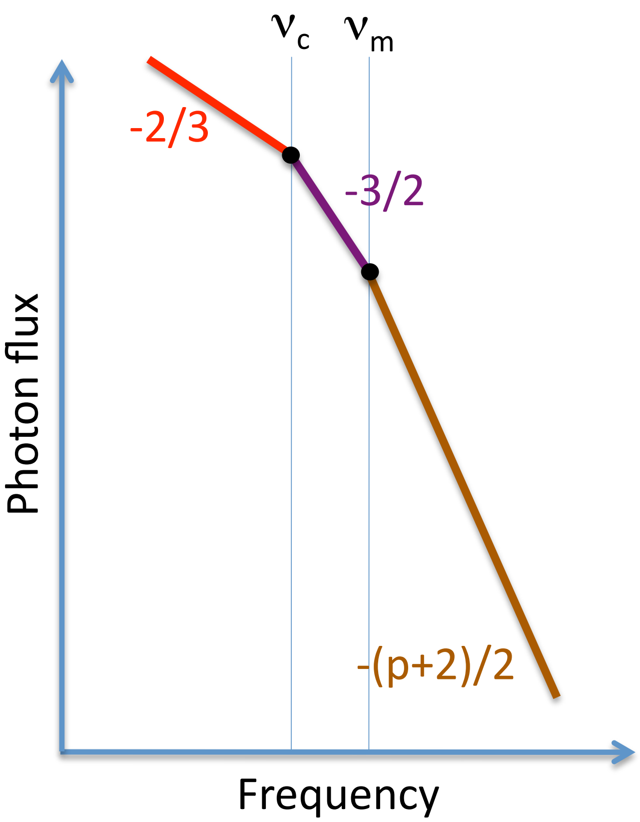
Synchrotron frequencies : $\gamma_m \leftrightarrow \nu_m$ and $\gamma_c \leftrightarrow \nu_c$



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

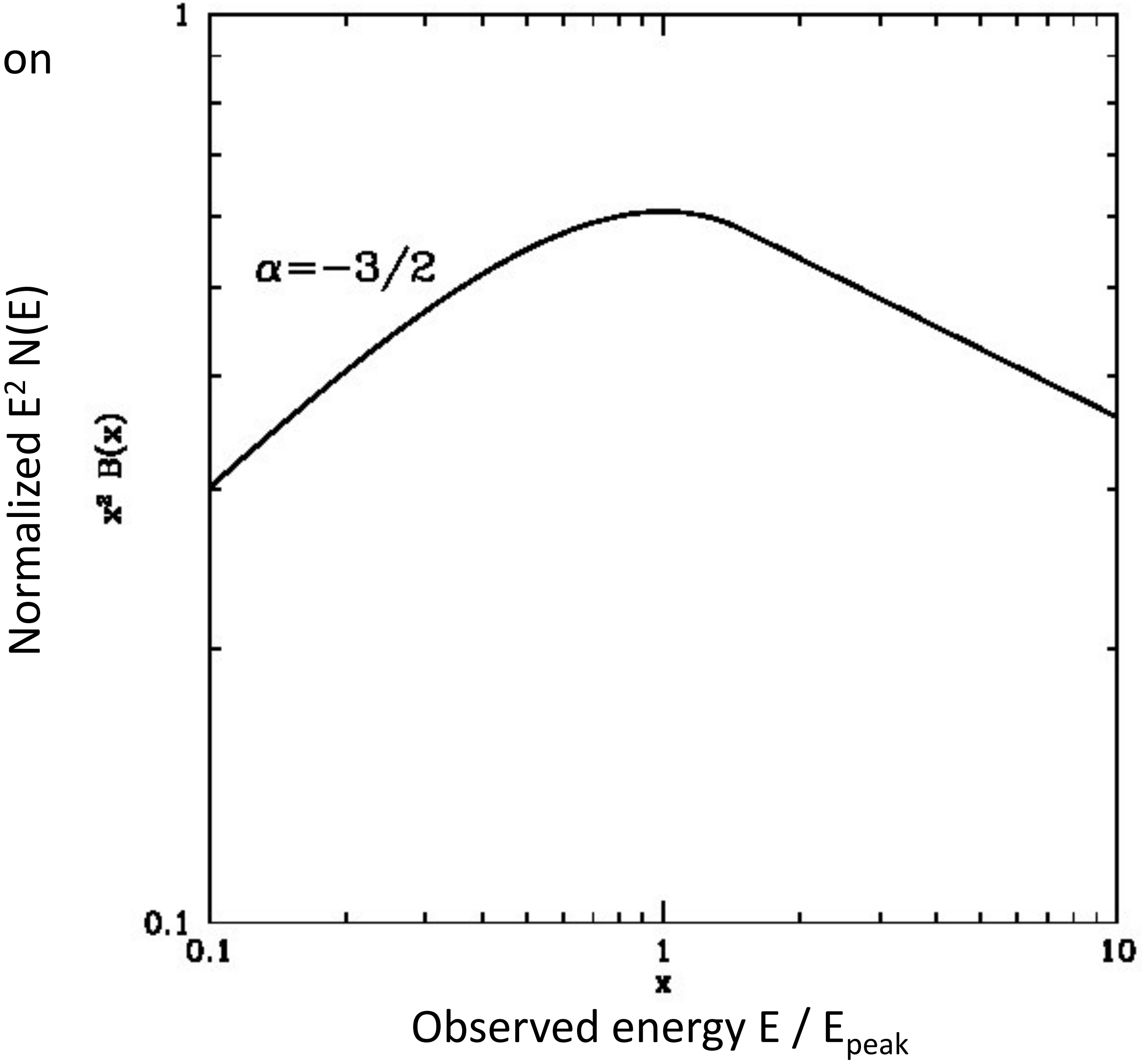
Relativistic electrons :





The low-energy spectral slope α

Band function
α = -1.5
β = -2.25

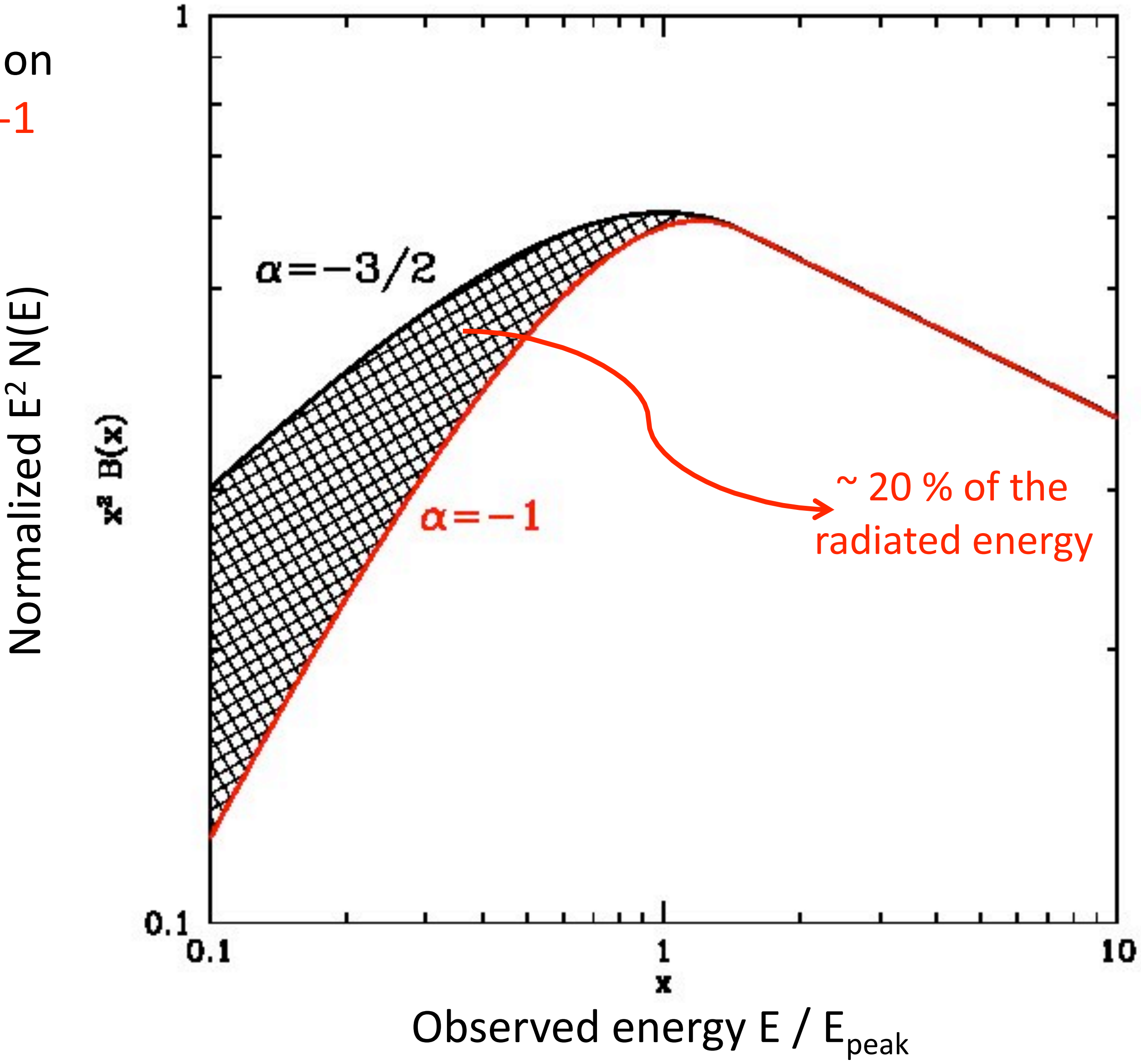


Synchrotron radiation | The low-energy spectral slope α

Band function

$\alpha = -1.5 \rightarrow -1$

$\beta = -2.25$



Synchrotron radiation | The low-energy spectral slope α

Band function

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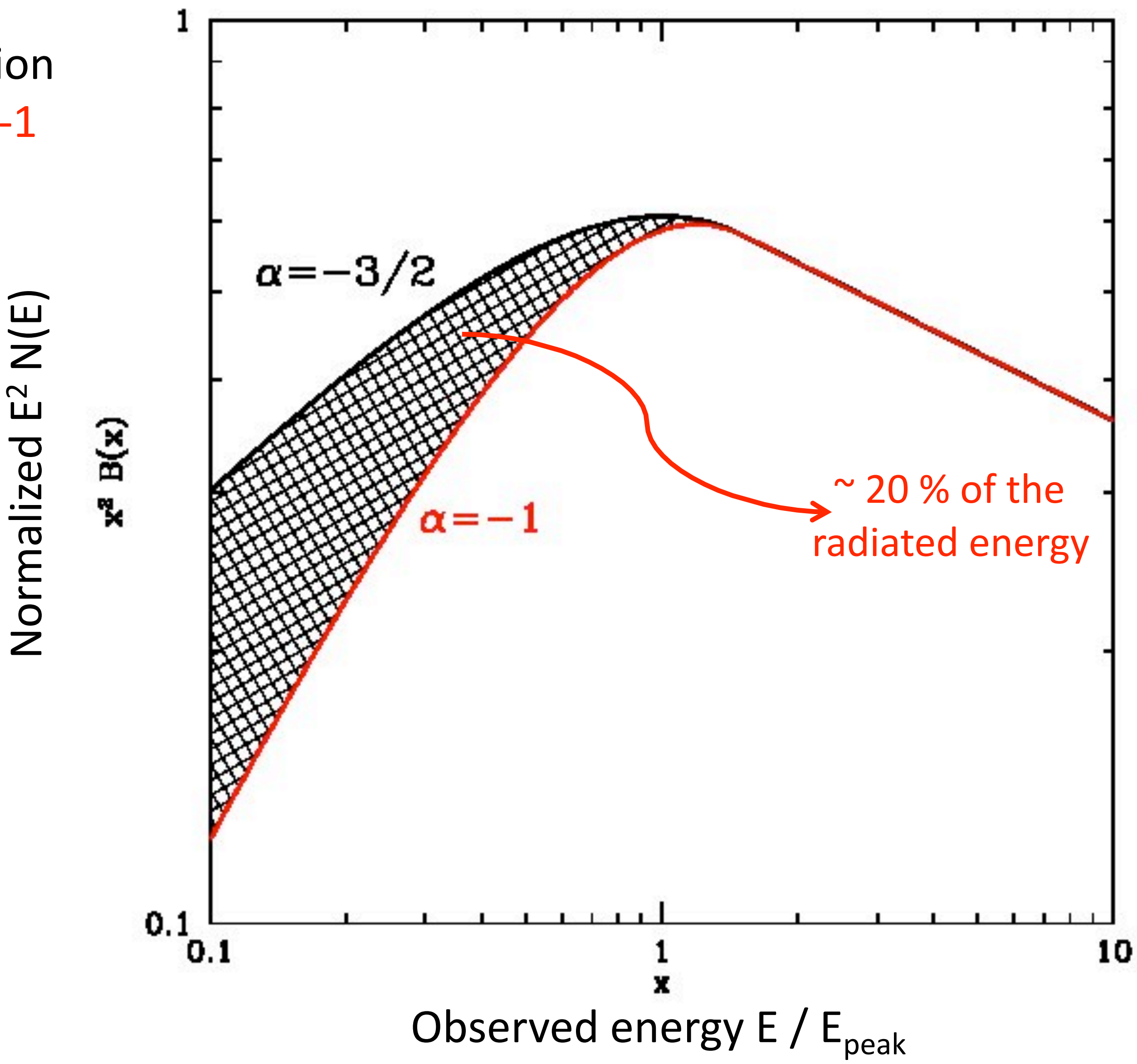


~ 20 % of the radiated energy

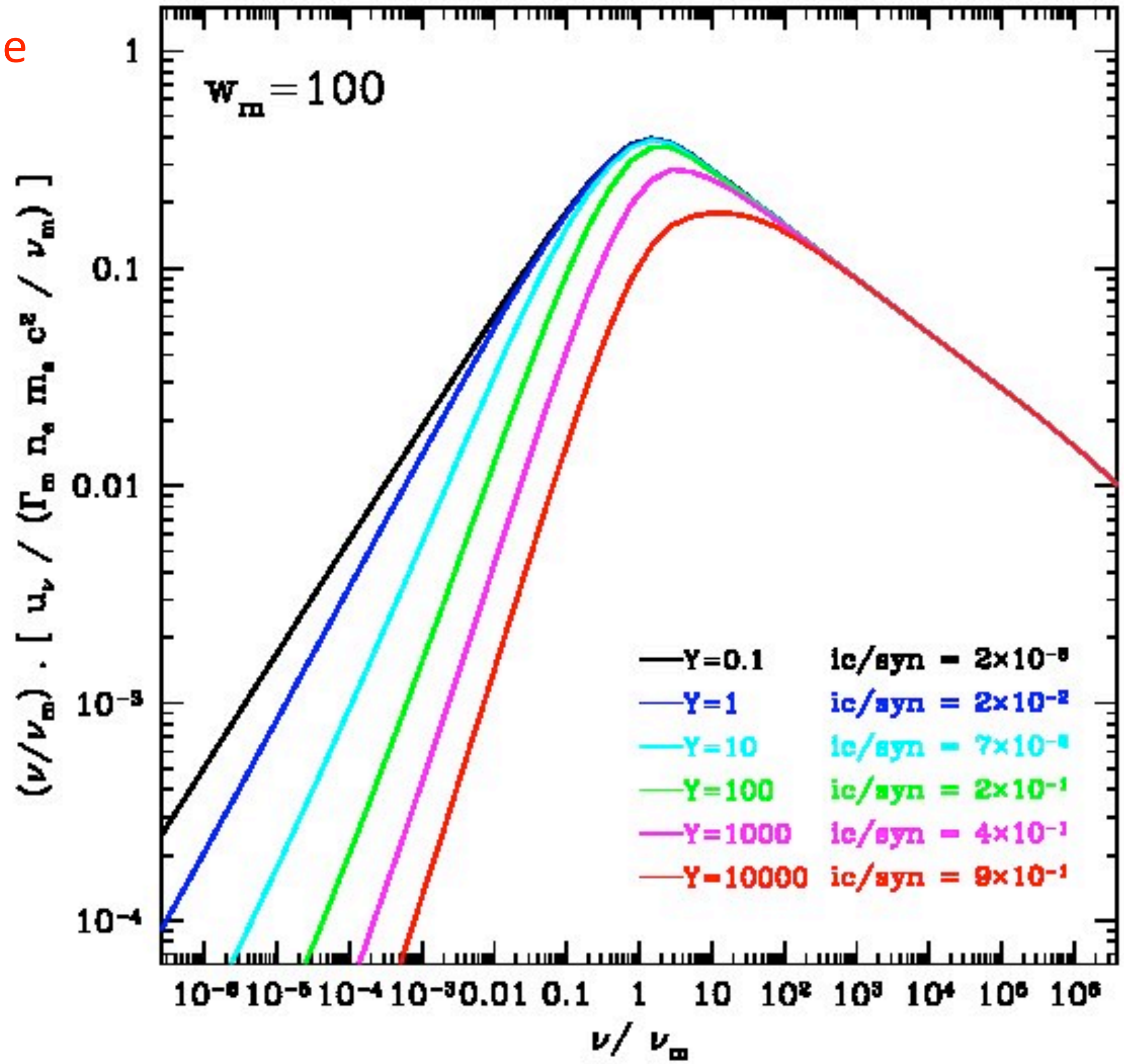
Inverse Compton in Klein-Nishina regime has an impact on the synchrotron slope α

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

Synchrotron radiation | The low-energy spectral slope α

Example

Normalized νF_ν



Frequency

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

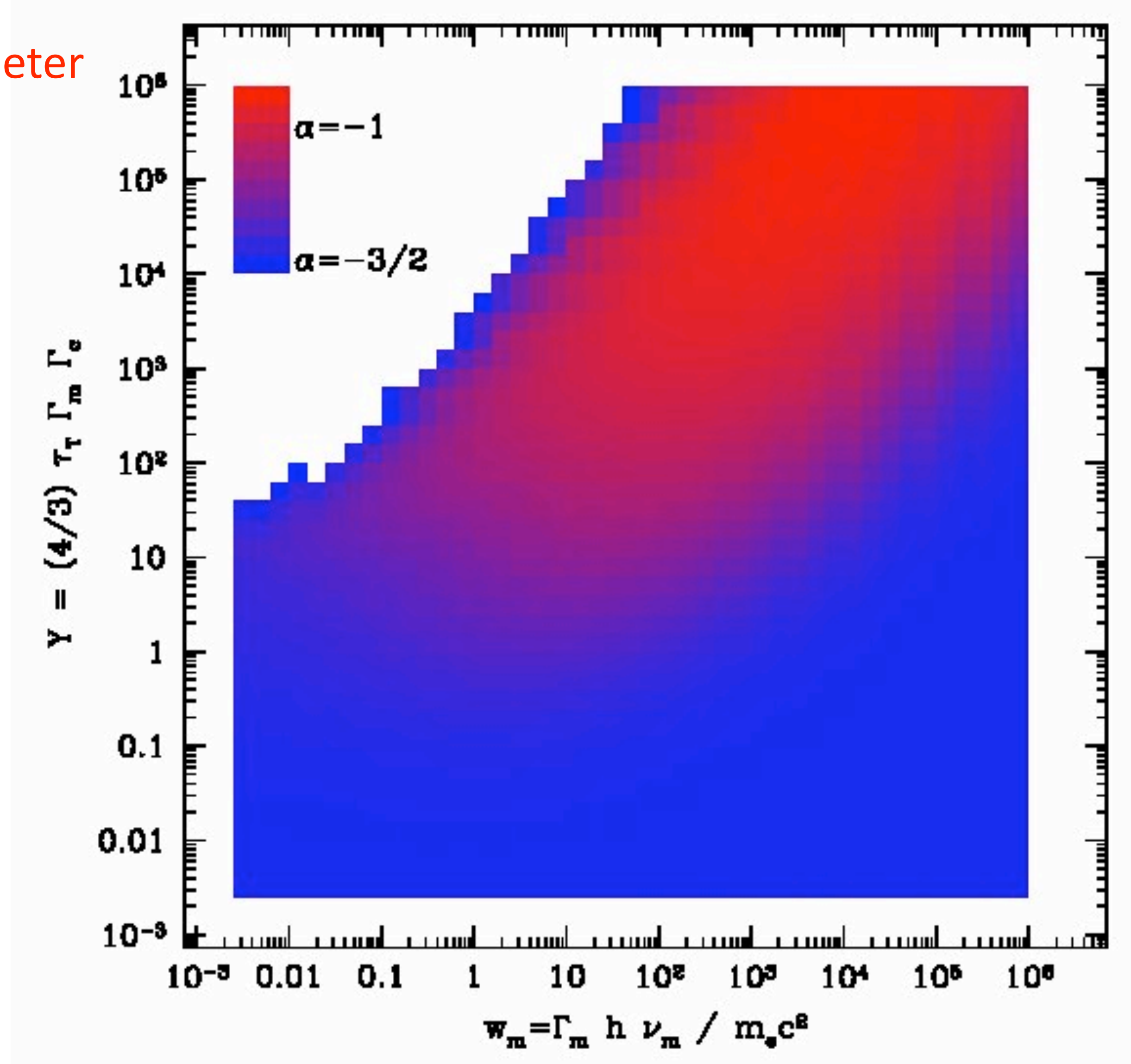
$$Y = \frac{4}{3} \tau_{\rm T} \Gamma_{\rm m} \Gamma_{\rm c} \simeq \frac{\epsilon_{\rm e}}{\epsilon_{\rm B}}$$

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

Synchrotron radiation | The low-energy spectral slope α

Parameter space

Thomson Y parameter



Klein-Nishina parameter

w_m : importance of KN

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

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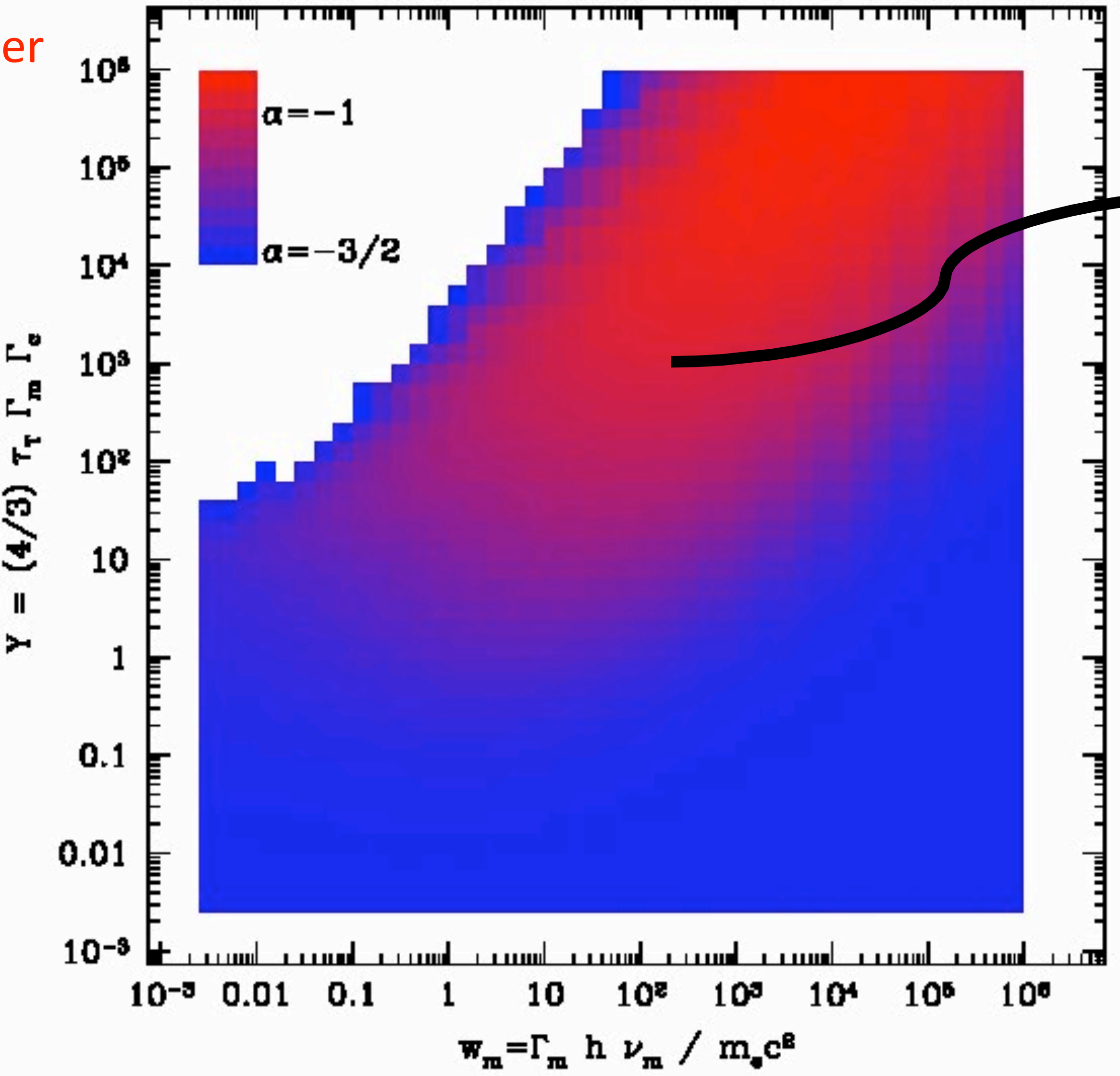
Synchrotron radiation | The low-energy spectral slope α

Parameter space



Thomson Y parameter

Klein-Nishina parameter

Steep slopes α = -1
can be obtained
in fast cooling regime

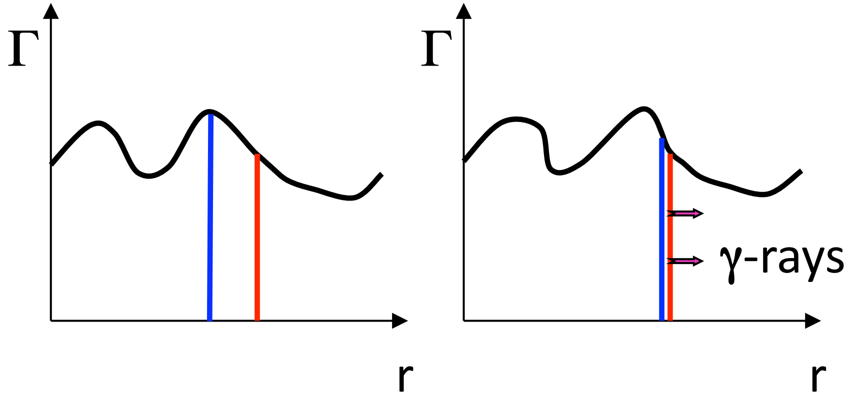
L_{ic}/L_{syn} ~ 0.1-1
in this region

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

Origin of the prompt GRB spectrum | Internal shocks

To go further, one needs a physical model for the emission region.

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



Detailed model :

(Bošnjak, Daigne & Dubus 09)

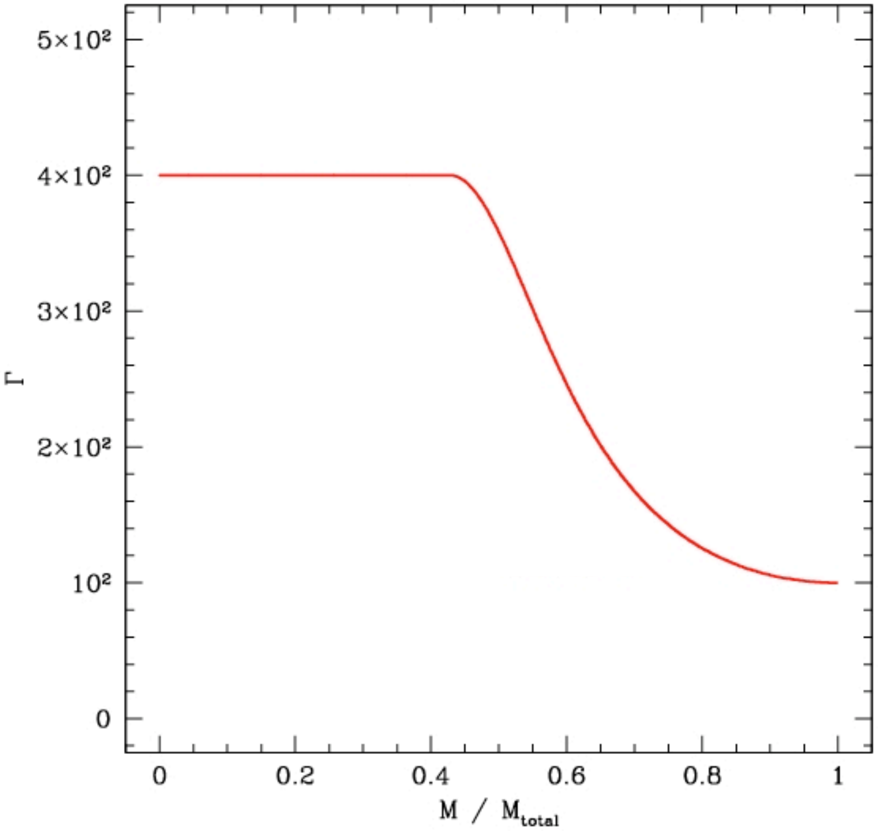
– Dynamics :	multi-shell approximation
– Microphysics :	magnetic field (ε_B) ; non-thermal population of electrons (ε_e,ζ,p)
– Radiation :	solve time evolution of electrons and photons in the comoving frame of each shocked region (adiabatic cool.; synchrotron; syn. self-absorption; IC; $\gamma\gamma \rightarrow e^+e^-$)
– Observed GRB :	integration over equal-arrival time surfaces

Detailed model

Example

A single pulse burst (as a building block for more complex GRBs)

- Initial distribution of Lorentz factor :

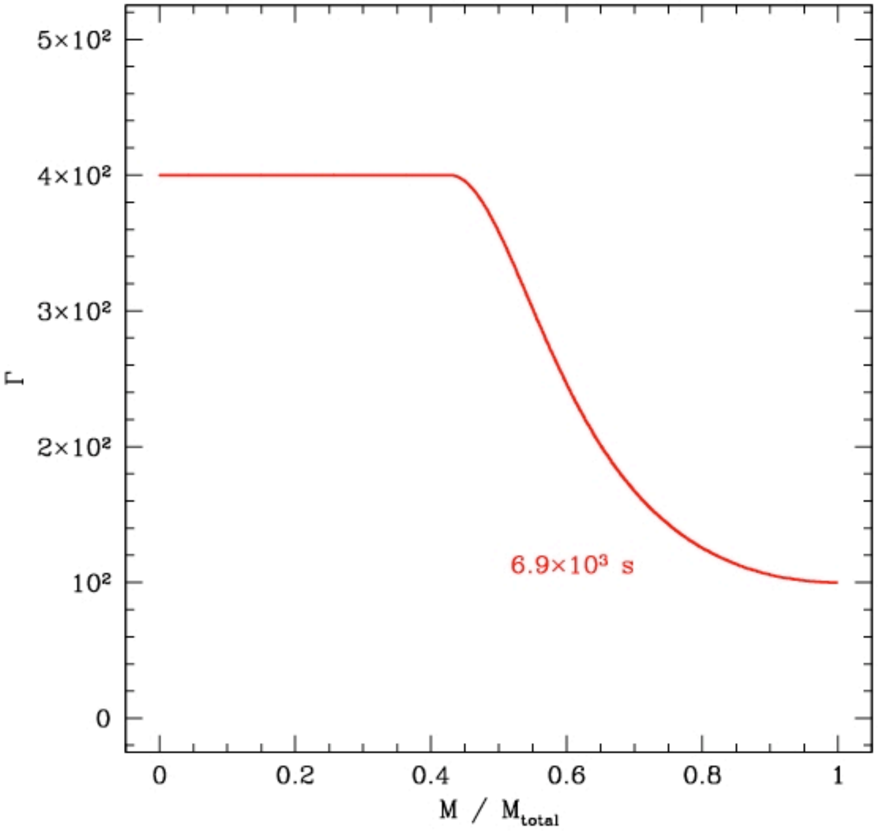


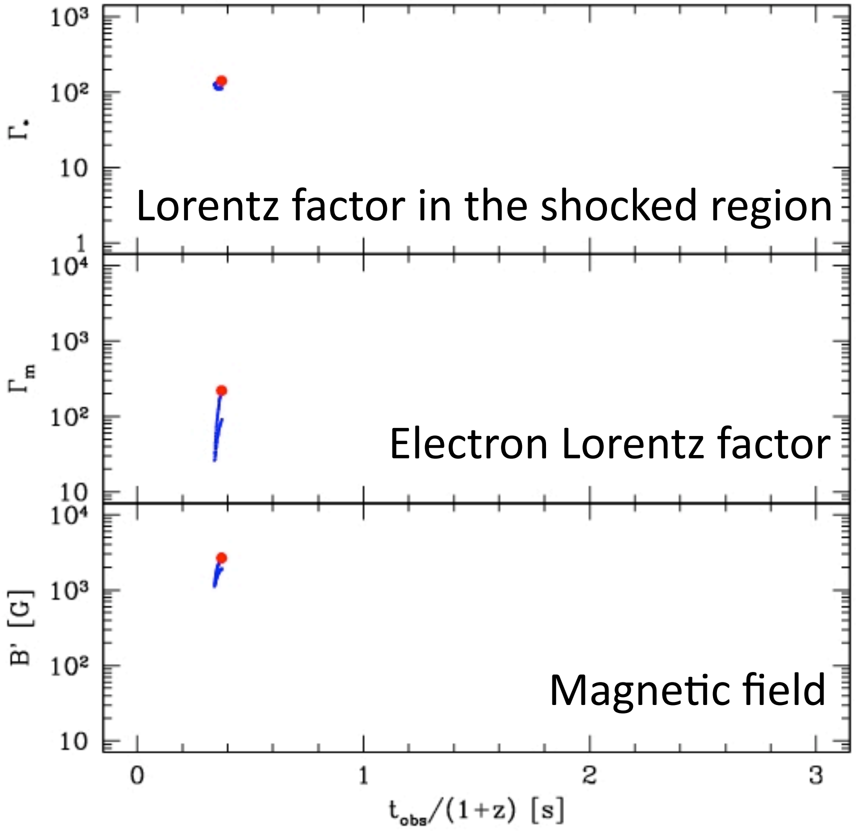
- Ejection lasts for $t_w = 2$s
- Constant energy injection rate : $L_{kin} = 2\times10^{52}$ erg/s

Detailed model | Example

A single pulse burst (as a building block for more complex GRBs)

- Dynamical evolution :



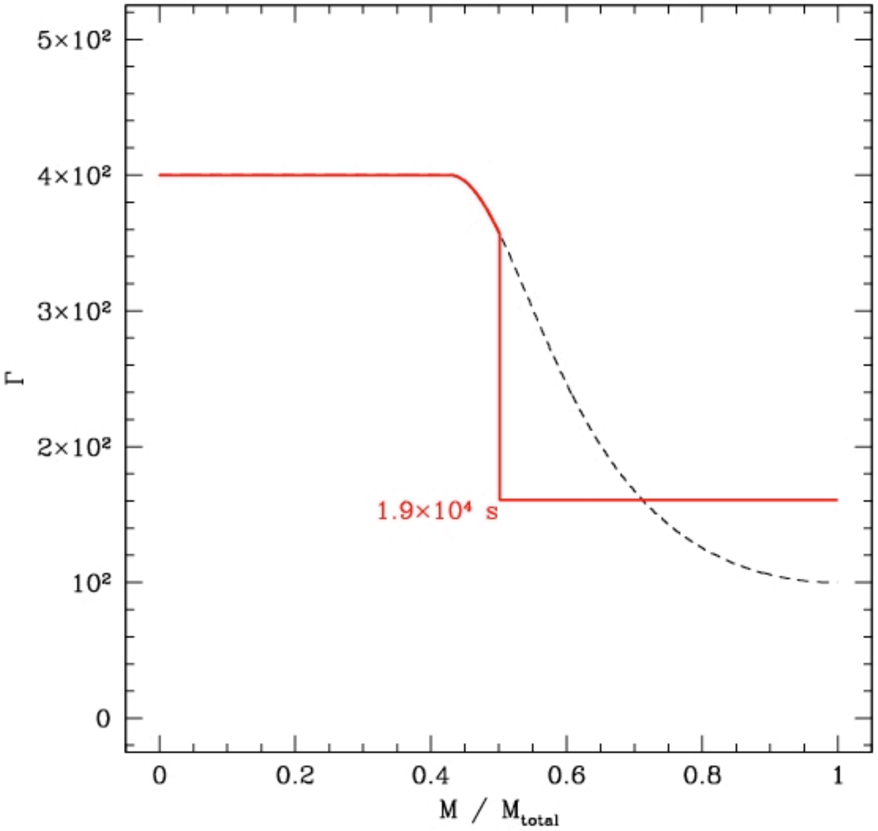


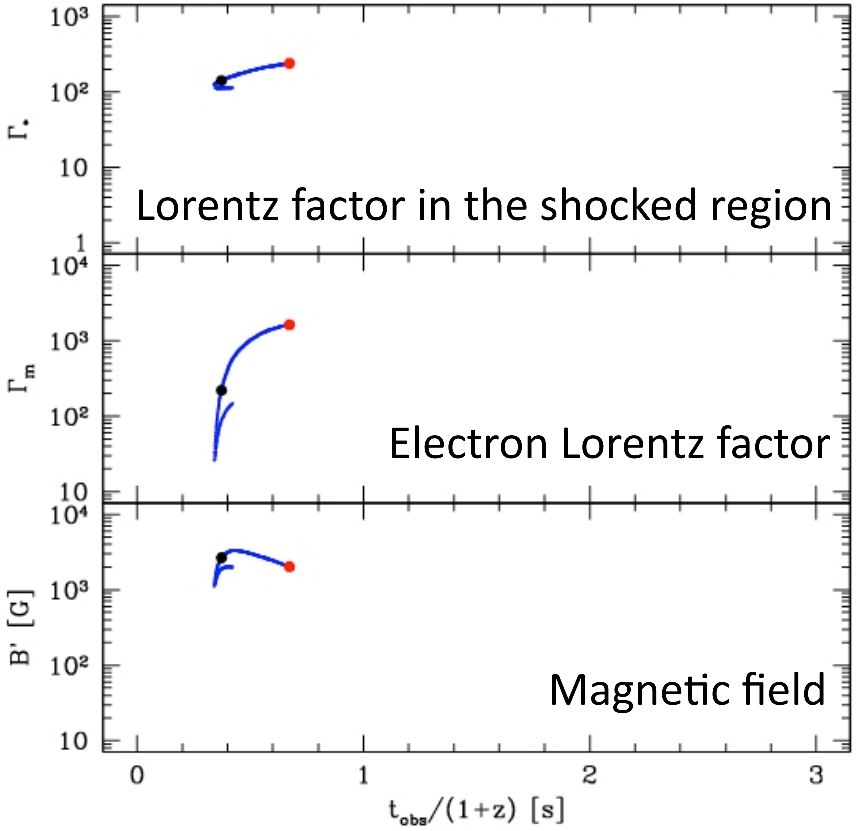
- Constant microphysics parameters : $\varepsilon_e=\varepsilon_B=1/3$; $\zeta = 0.01$; $p=2.5$

Detailed model | Example

A single pulse burst (as a building block for more complex GRBs)

- Dynamical evolution :





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Detailed model

Example

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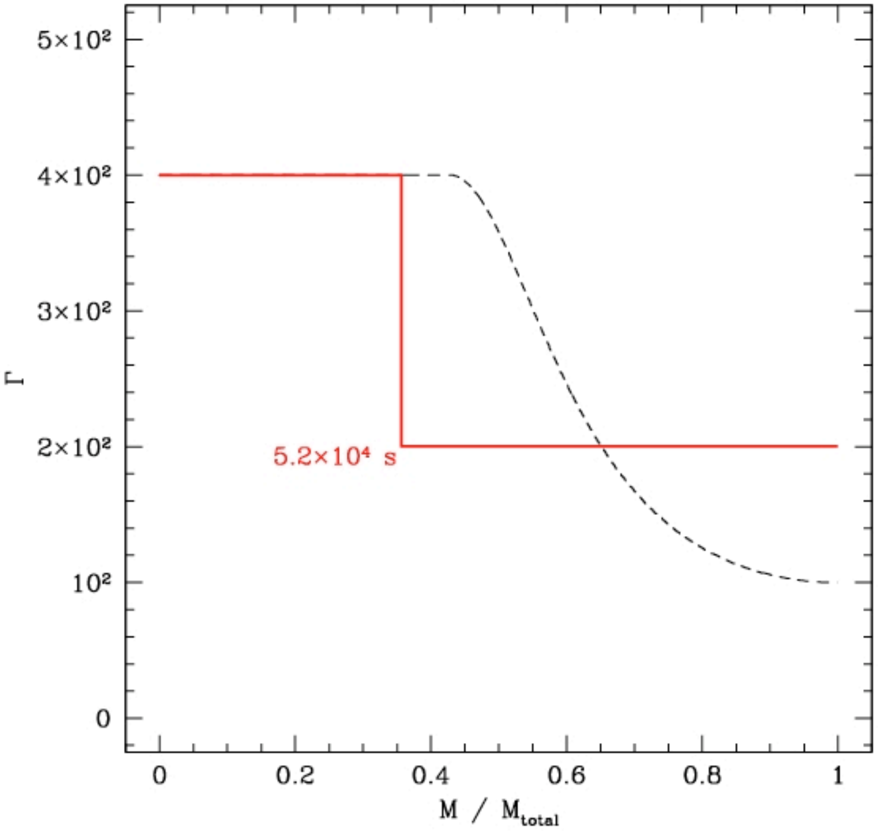

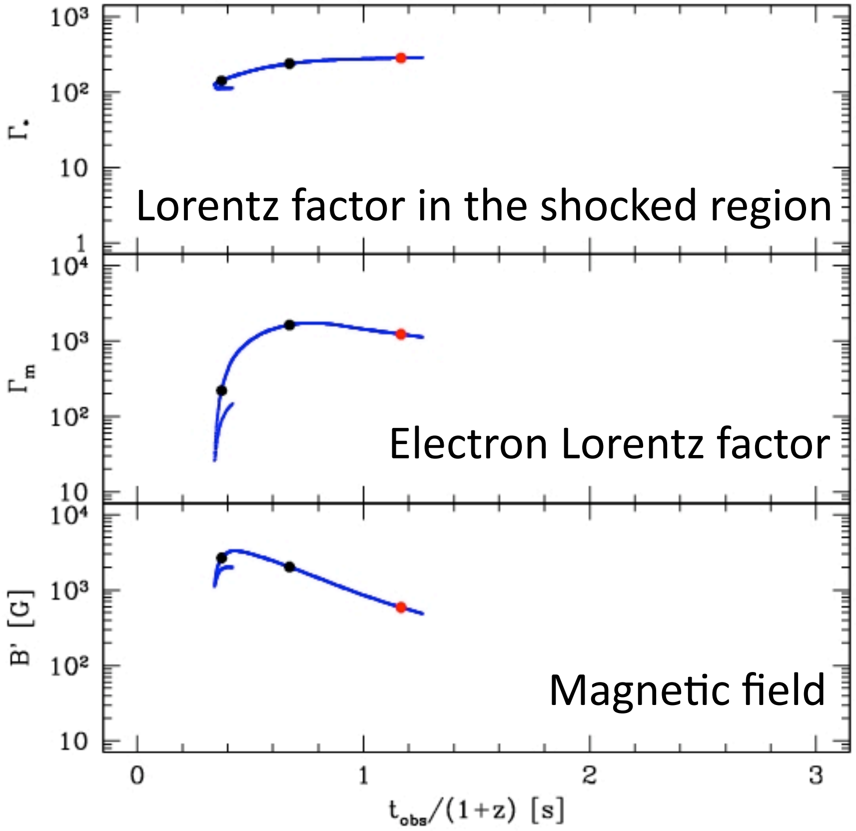

Lorentz factor in the shocked region

Electron Lorentz factor

Magnetic field

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

Detailed model | Example

A single pulse burst (as a building block for more complex GRBs)

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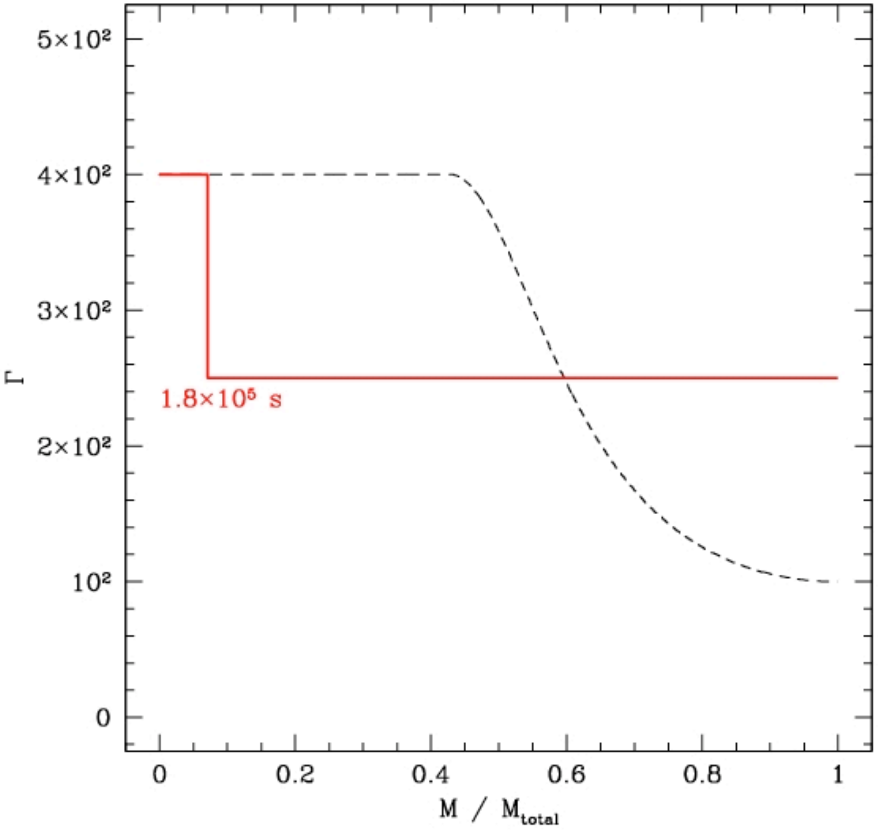
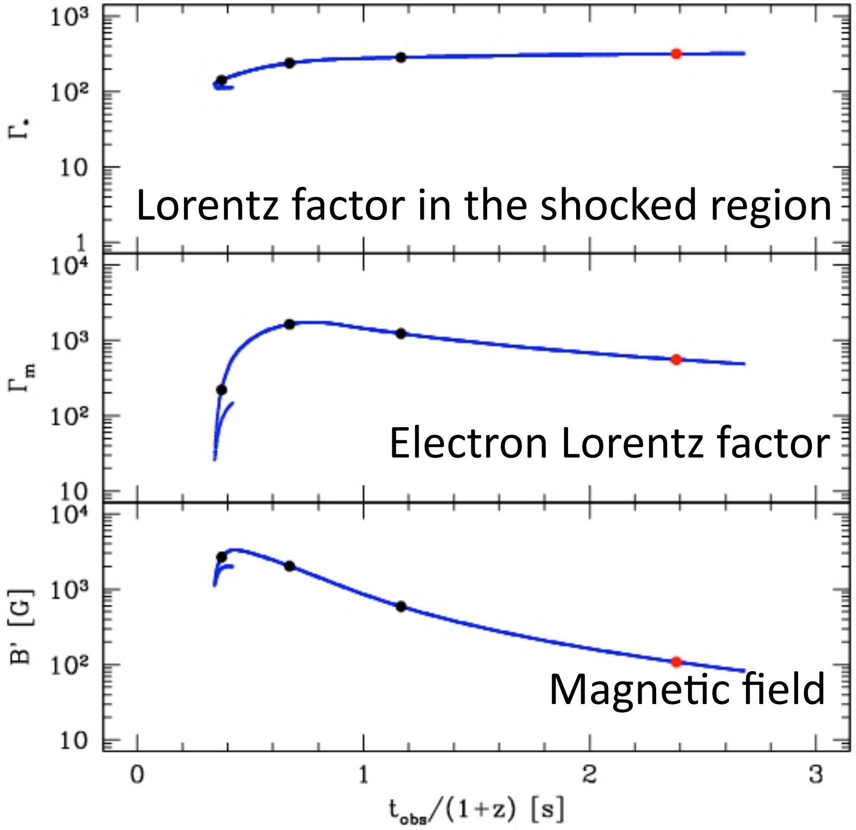




Lorentz factor in the shocked region

Electron Lorentz factor

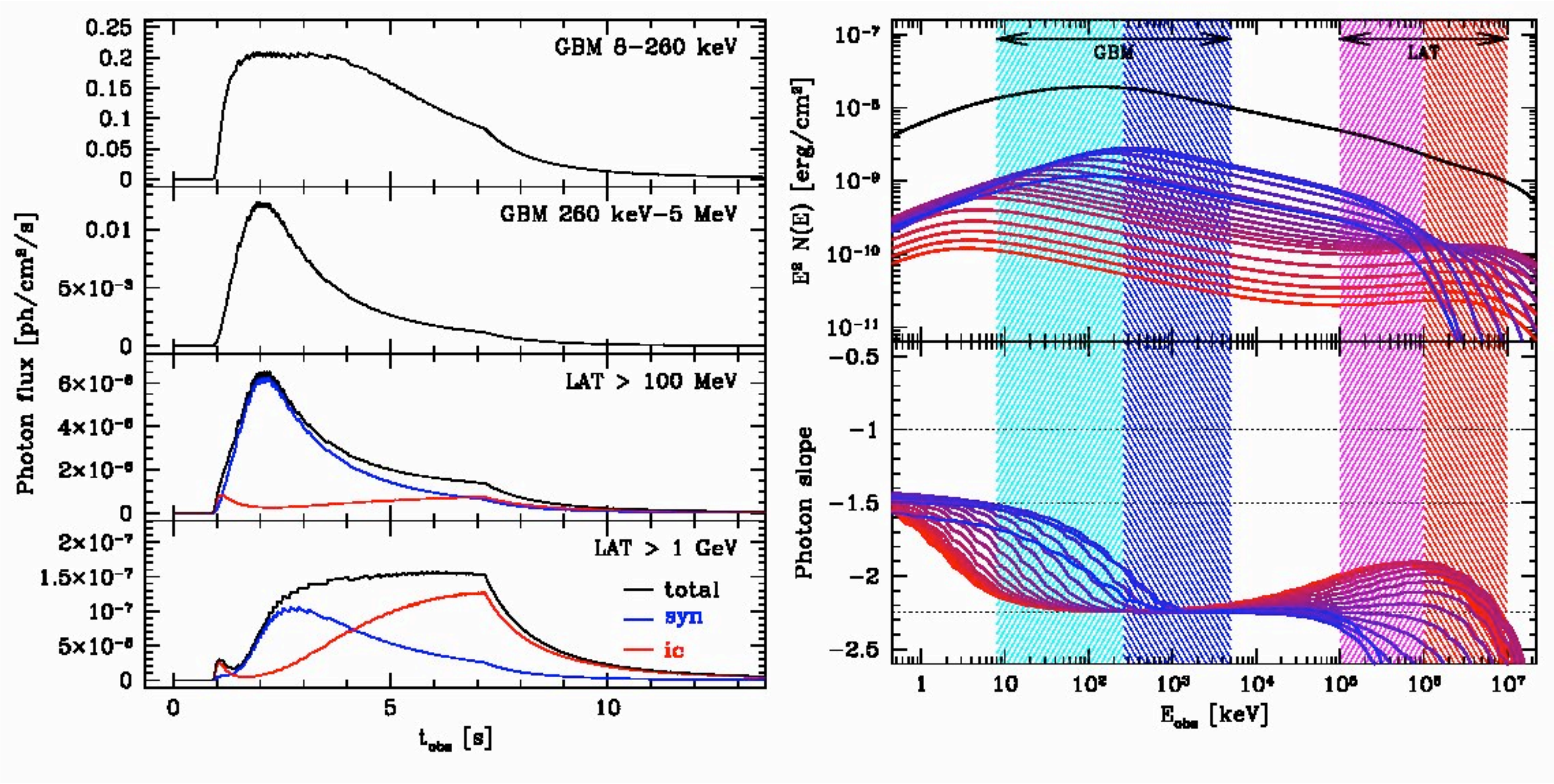
Magnetic field

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

Synchrotron radiation in internal shocks | Examples : a single pulse burst

EBL not included

$\varepsilon_B = \varepsilon_e = 0.1$ $\zeta = 10^{-3}$



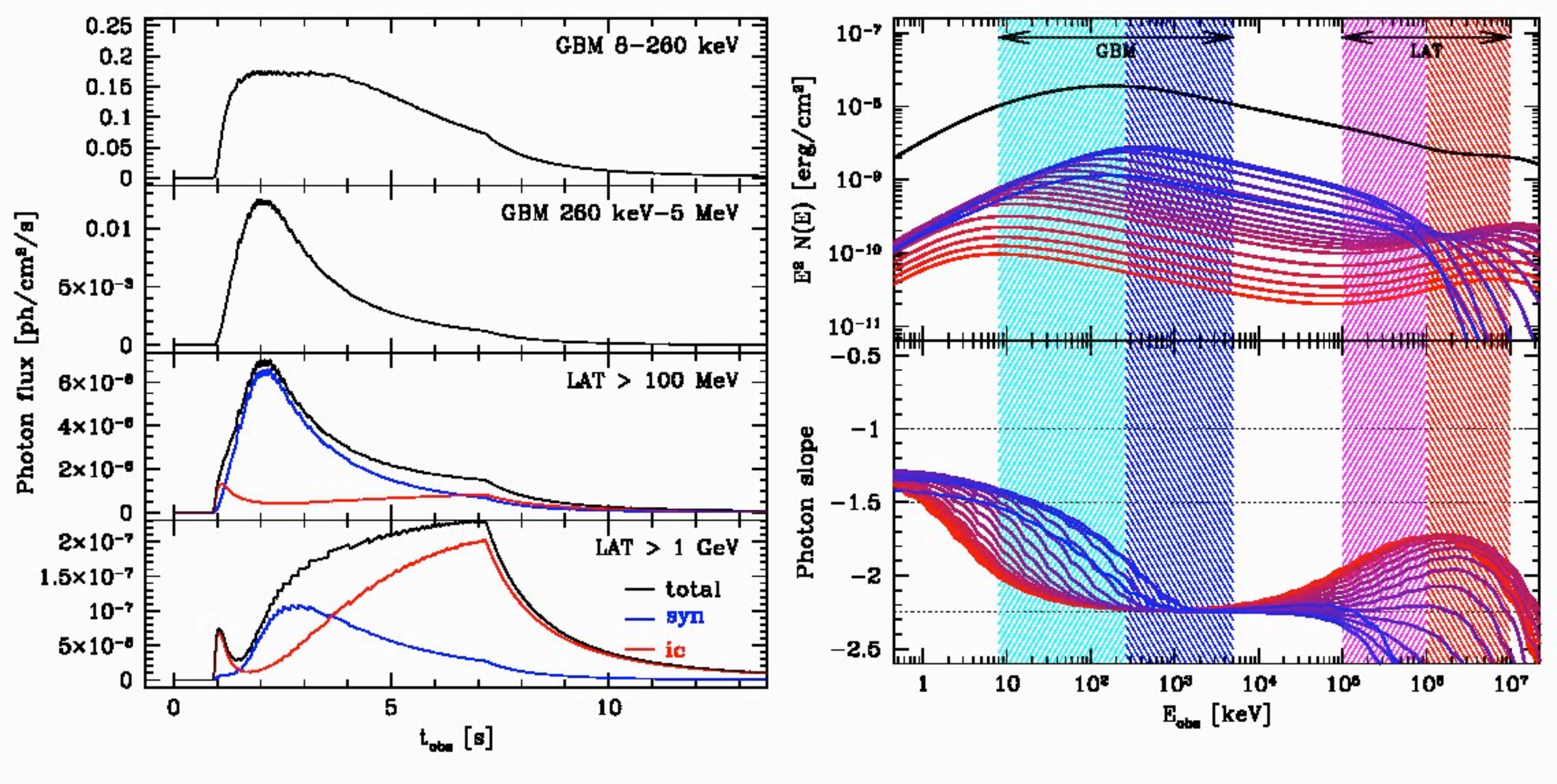
Full calculation with all processes (adiabatic cooling; sync; sync self-abs; IC; $\gamma\gamma$ annihilation)

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

Synchrotron radiation in internal shocks | Examples : a single pulse burst

EBL not included

$\varepsilon_B = \varepsilon_e/10 = 0.01$ $\zeta = 5\times10^{-4}$



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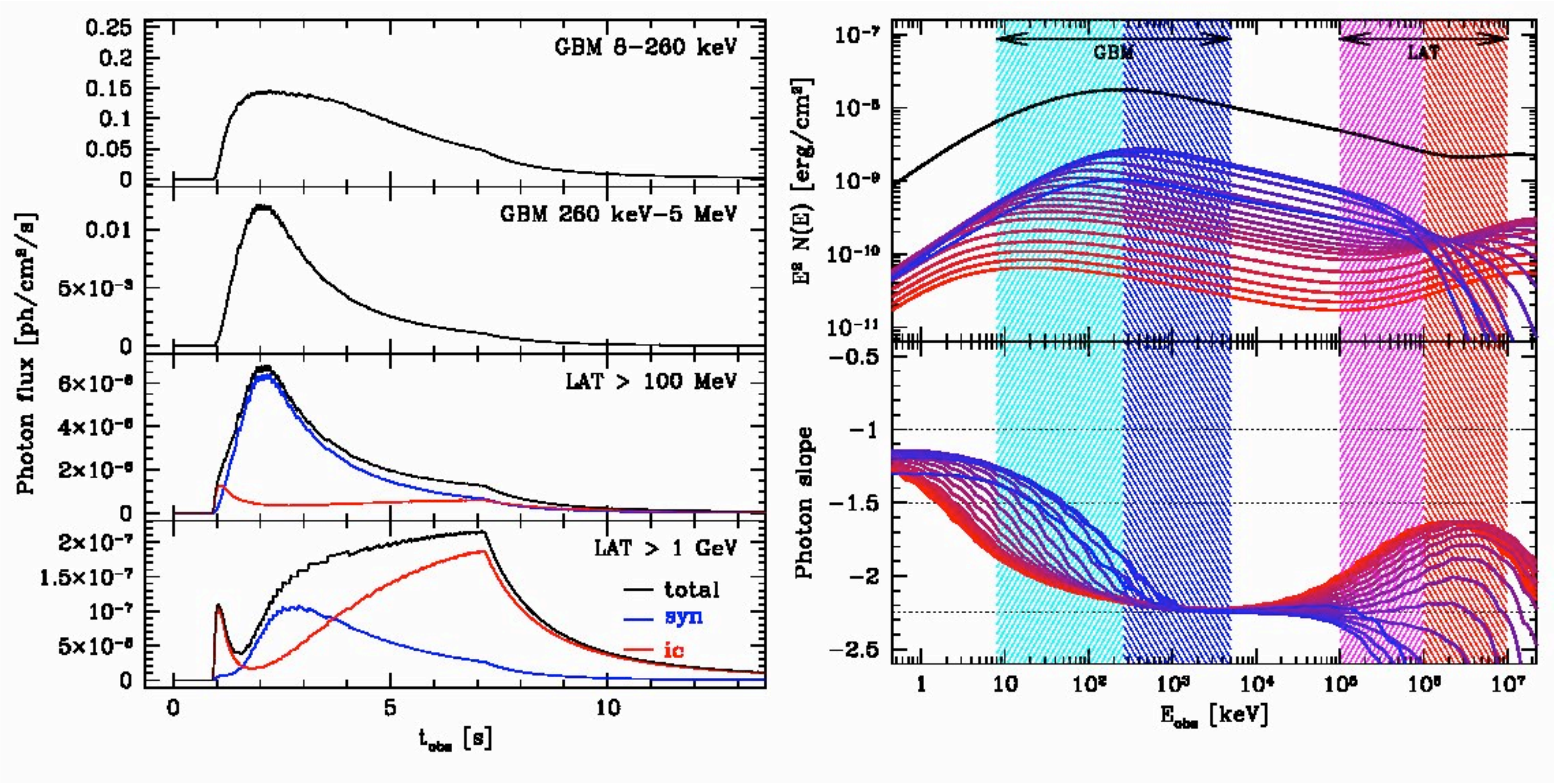
Synchrotron radiation in internal shocks

Examples : a single pulse burst

EBL not included

$\varepsilon_B = \varepsilon_e/100 = 0.001$

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



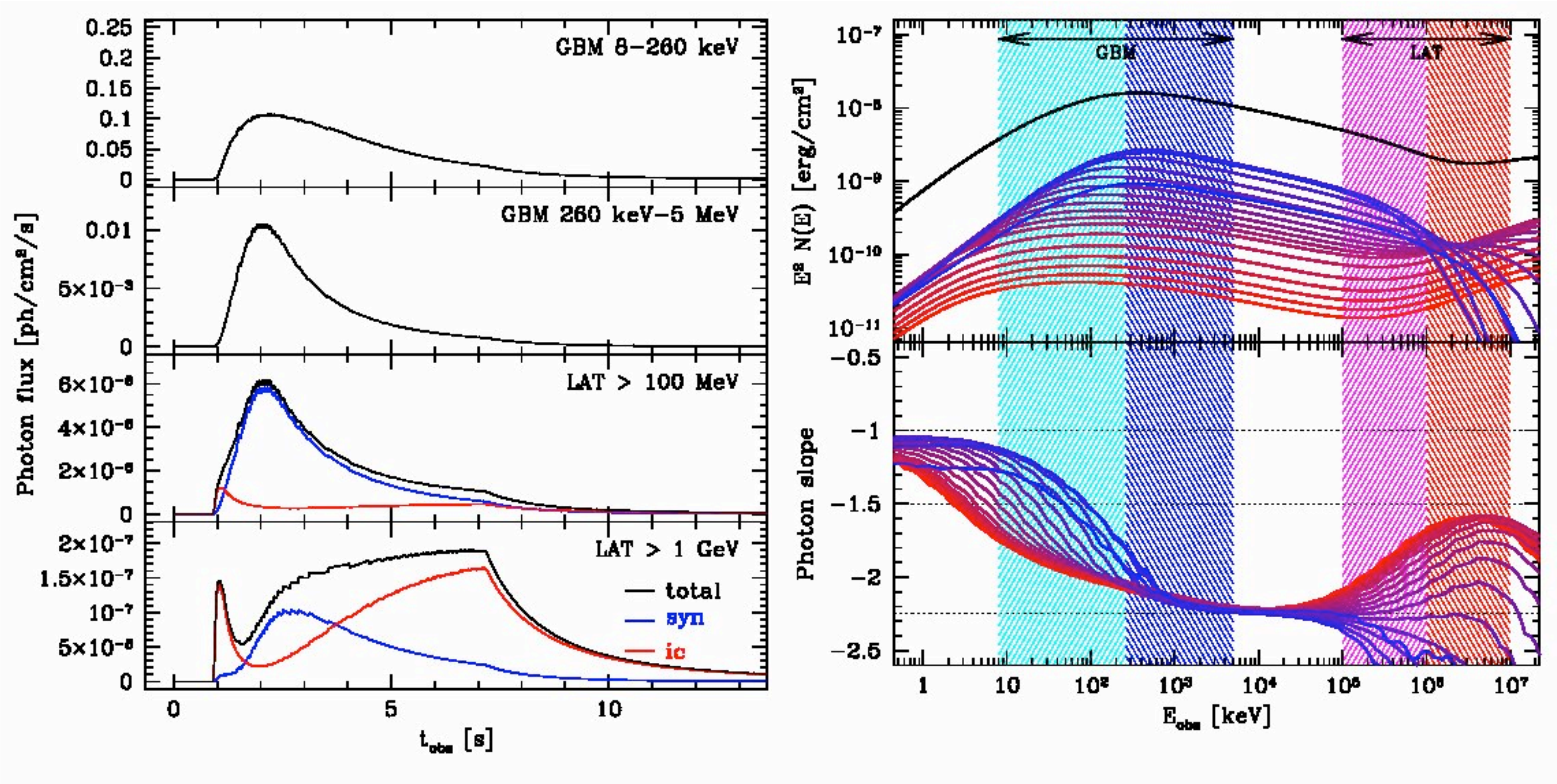
Full calculation with all processes (adiabatic cooling; sync; sync self-abs; IC; γγ annihilation)

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

$\varepsilon_B = \varepsilon_e/1000 = 0.0001$ $\zeta = 2\times10^{-4}$



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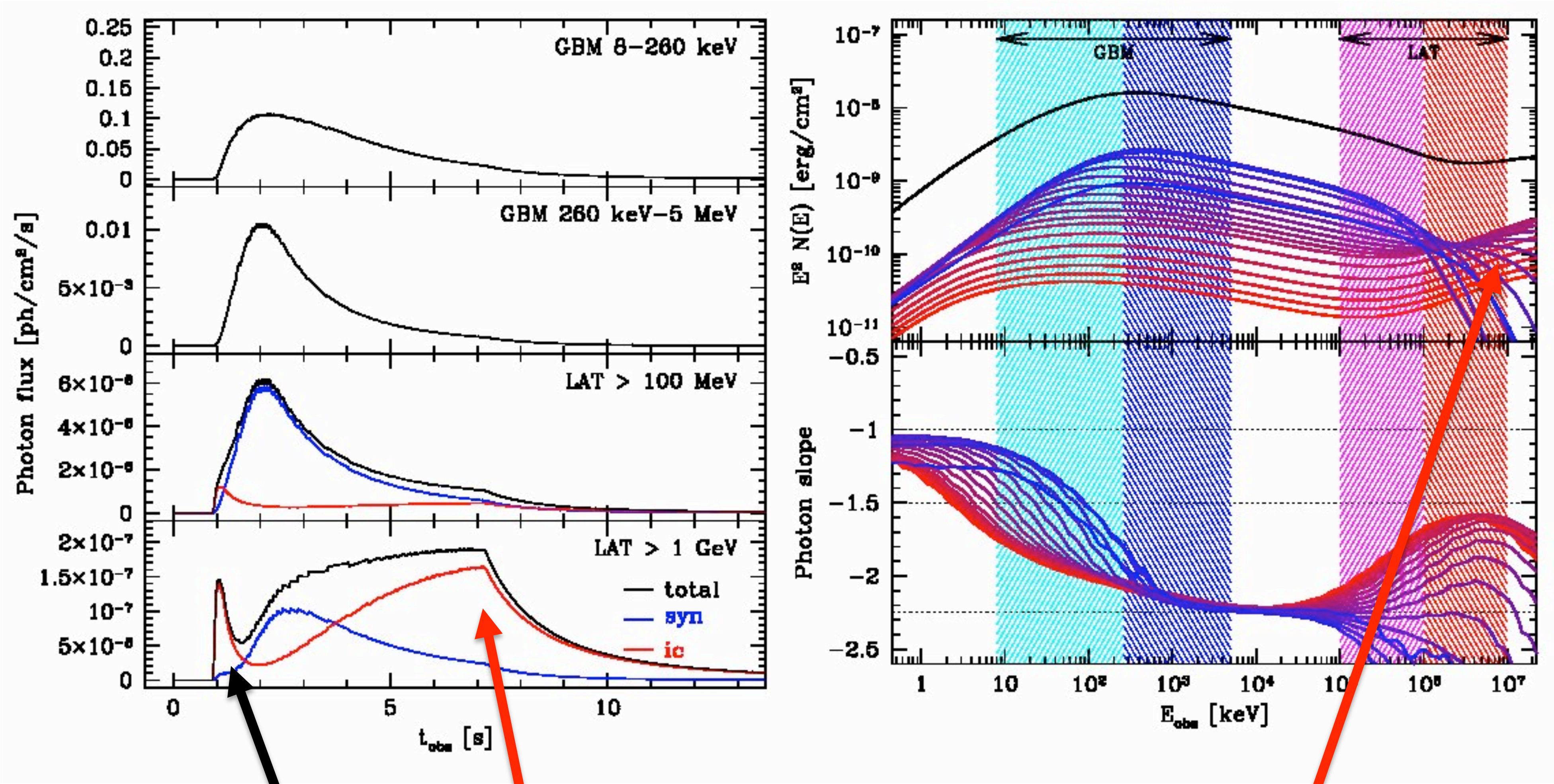
Synchrotron radiation in internal shocks

Examples : a single pulse burst

EBL not included



Delayed GeV emission

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

Variable additional
component at high-energy

Summary

- Fermi/LAT observations (rate + HE spectrum of detected GRBs) :
  - synchrotron is favored
  - SSC seems in contradiction with observations

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

- IC scatterings in KN regime can affect the synchrotron slope : $-3/2 \leq \alpha \leq -1$
  - this can reconcile the synchrotron process with observations
  - spectra with $-1 \leq \alpha \leq -2/3$?

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

- Shock acceleration physics in mildly relativistic regime ? (low ζ ; low ε_B)
  Are microphysics parameters constant ? (may change spectral evolution)

- Internal shocks : spectral evolution is expected (Bosnjak, Daigne & Dubus 2009)
  - delayed GeV emission
  - variable additional power-law component at high-energy
    (but component below 50 keV ?)

- Work in progress :
  - detailed modelling of LAT bursts
  - test of observed hardness-intensity and hardness-fluence correlations