Gamma-ray burst spectral evolution in the internal shock model

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in collaboration with:

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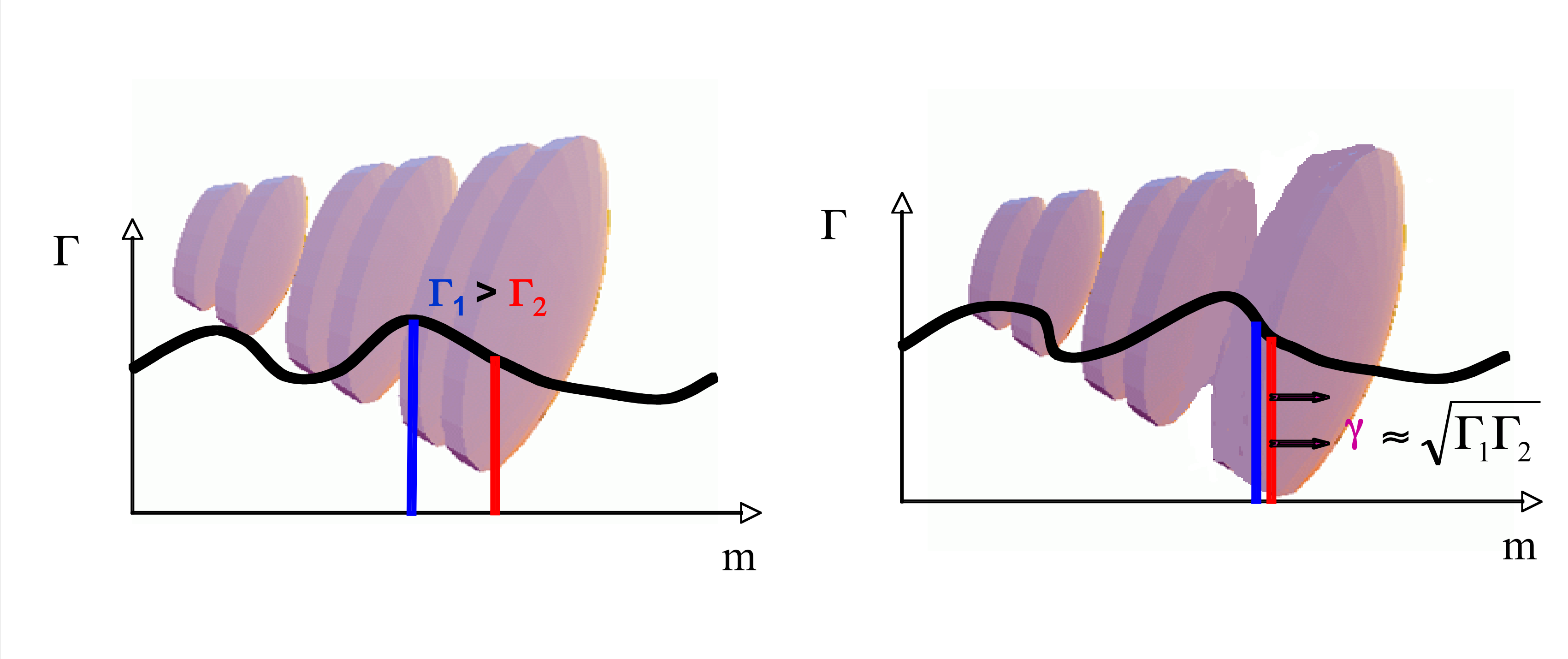
Prompt high energy emission in the framework of internal shocks



Modeling:

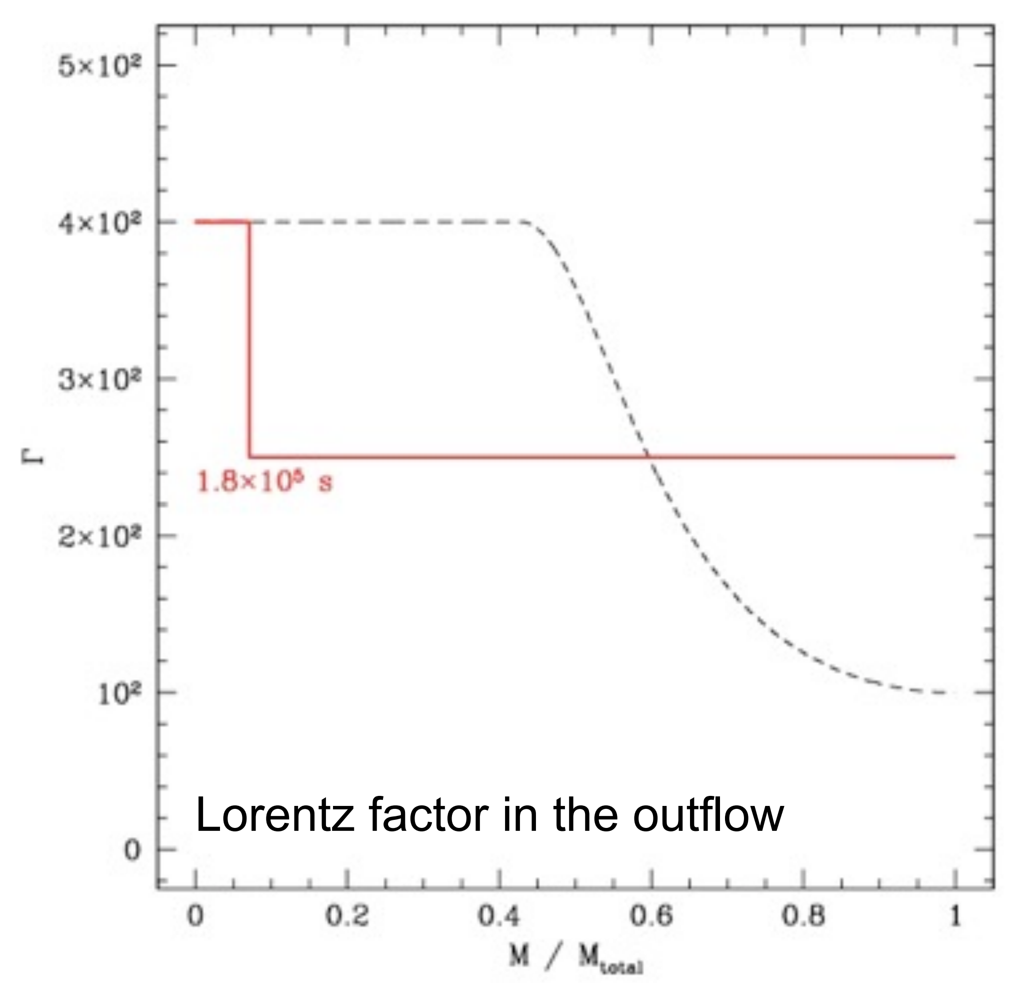
1. dynamics of internal shocks

2. radiative processes in the shocked medium

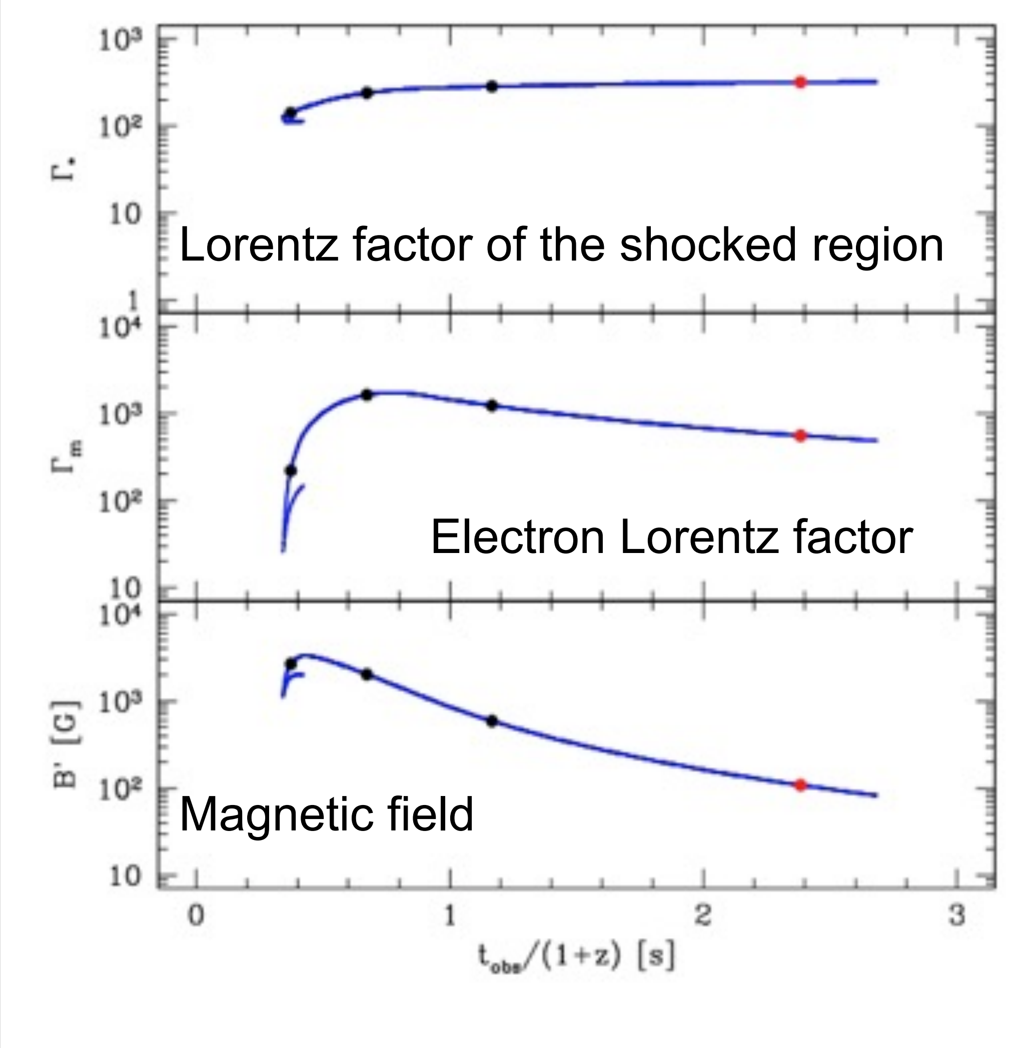
3. observed spectra and time profiles

Dynamics of the internal shocks

Physical conditions in the shocked medium: Lorentz factor Γ_*, comoving density ρ^*, comoving specific energy density ε^*



Lorentz factor in the outflow



Lorentz factor of the shocked region

Electron Lorentz factor

Magnetic field

Dissipated energy is distributed between protons, electrons (fraction ε_e) and magnetic field (fraction ε_B)

Dynamics of the internal shocks

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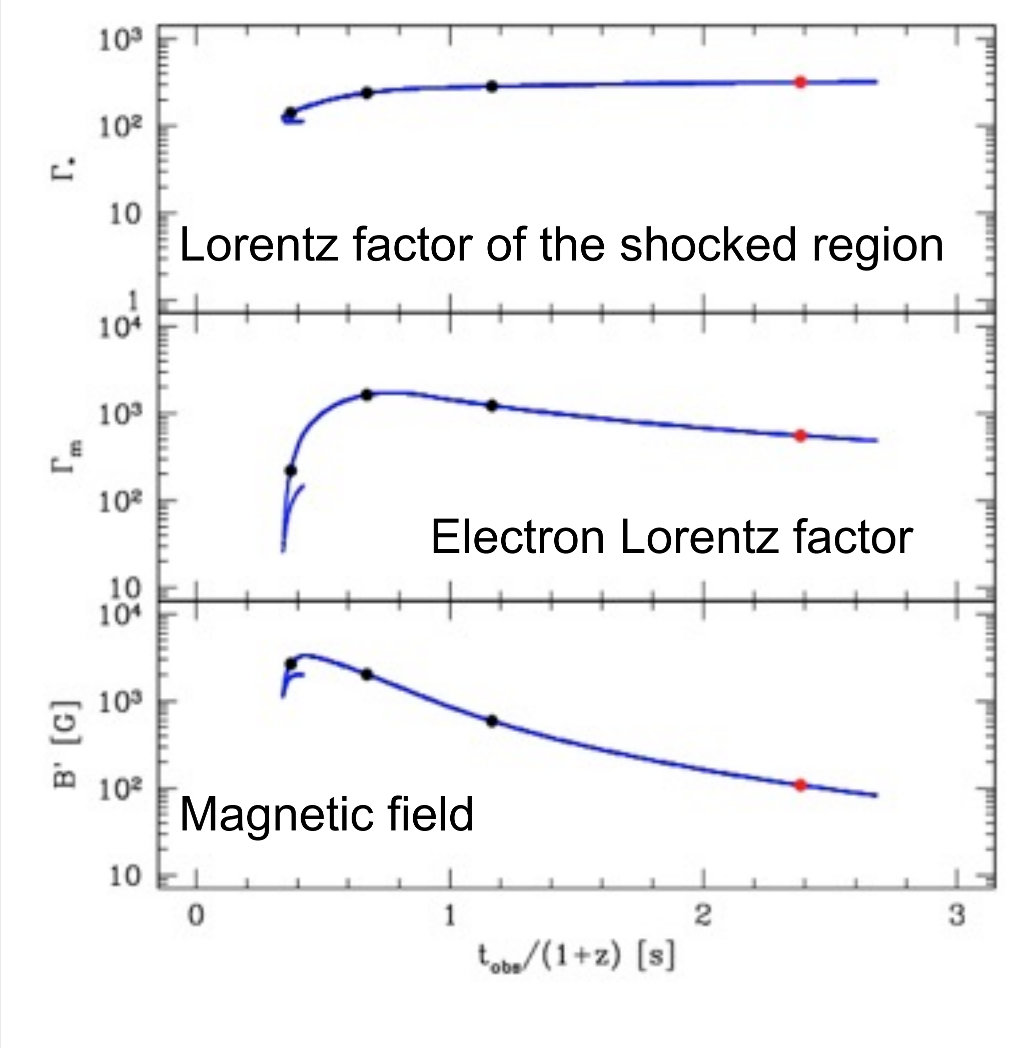

Lorentz factor of the shocked region

Electron Lorentz factor

Magnetic field

Relativistic electron density:

$$n'(\Gamma_e, t'=0) \propto \Gamma_e^{-p} \qquad \Gamma_e \geq \Gamma_m$$

$\xi < 1$ of all electrons is accelerated

Dissipated energy is distributed between protons, electrons (fraction ε_e) and magnetic field (fraction ε_B)

Radiative processes

Assumption: instantaneous shock acceleration

Adiabatic cooling timescale: $t`_{ex} = R / \Gamma^* c$ (comoving frame)
Radiative timescale: $t`_{rad}$

$t`_{rad} << t`_{ex}$ high radiative efficiency

Electron and photon distributions evolve strongly with time!

The present version of the code follows the time evolution of the electron density and the photon density including the following processes:

- adiabatic cooling (spherical expansion)
- synchrotron
- inverse Compton
- synchrotron self-absorption
- $\gamma\gamma$ annihilation

Not included:
* emission from secondary leptons
* IC in optically thick regime (Comptonisation)

ELECTRONS:

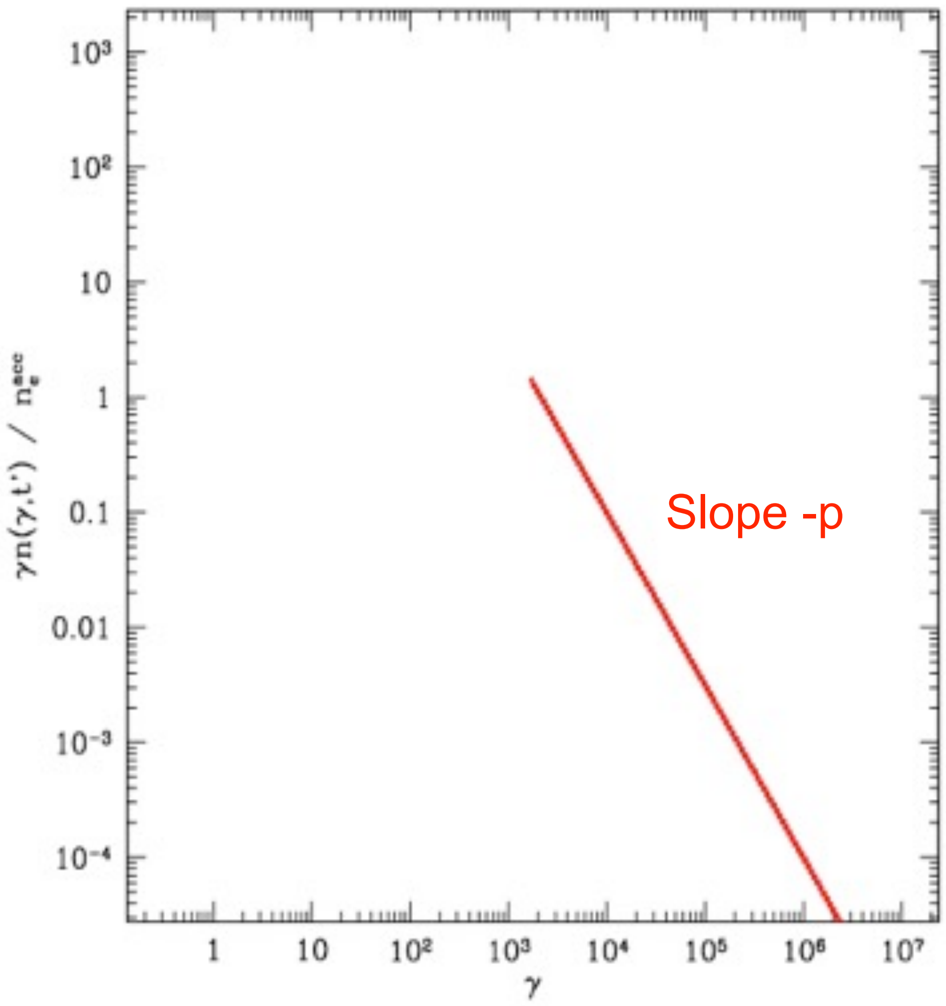
$$\frac{\partial n'}{\partial t'}(\Gamma'_e, t') = -\frac{\partial}{\partial \Gamma'_e}\left[\left(\frac{d\Gamma'_e}{dt'}\bigg|_{syn+ic} + \frac{d\Gamma'_e}{dt'}\bigg|_{ad}\right) n'(\Gamma'_e, t')\right]$$

PHOTONS:

$$\frac{\partial n'_\nu}{\partial t'} = \int n'(\Gamma'_e, t') P_{syn+ic}(\Gamma'_e) d\Gamma'_e - c n'_\nu \int n'(\Gamma'_e, t') \sigma_{abs}(\Gamma'_e, \nu) d\Gamma'_e - c n'_\nu \int_{\nu' > \frac{(m_e c^2)^2}{h^2 \nu}} n'_{\nu'}(t') \sigma_{\gamma\gamma}(\nu, \nu') d\nu'$$

Radiative processes

Radiation: the time evolution of electrons and photons in the comoving frame is solved (time-dependent radiative code)



Electron distribution

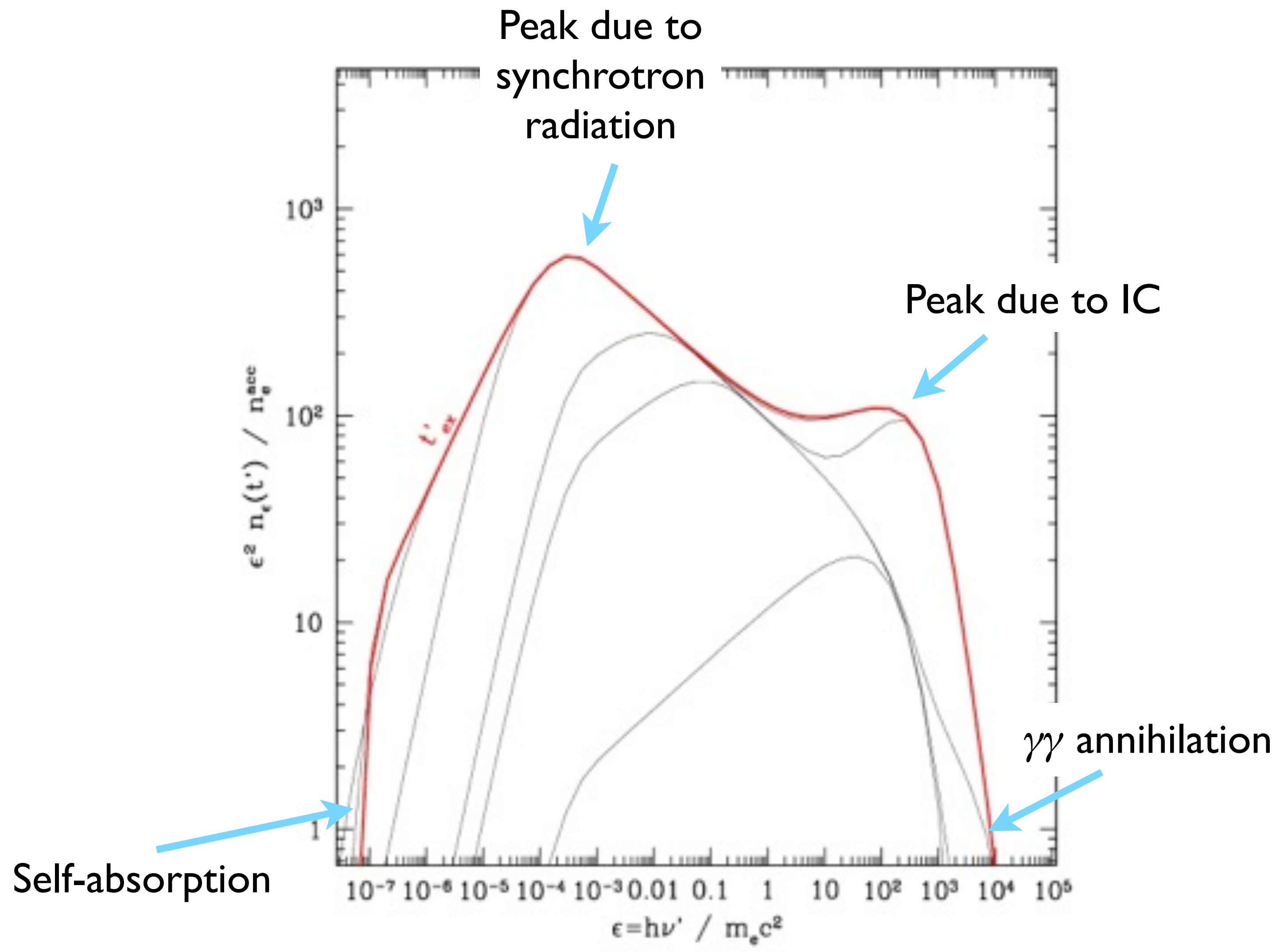
Radiative processes

Radiation: the time evolution of electrons and photons in the comoving frame is solved (time-dependent radiative code)

Comptonization parameter
$Y = L_{ic} / L_{syn}$

IC dominant:
low frequency synchrotron peak
Thomson regime

Synchrotron dominant:
high frequency synchrotron peak
Klein-Nishina regime



Peak due to synchrotron radiation

Peak due to IC

$\gamma\gamma$ annihilation

Self-absorption

Emitted photon spectrum

This calculation is done at all times along the propagation of each shock wave
All the contributions are added together to produce a synthetic gamma-ray burst (spectrum+lightcurve)

Observed spectra and time profiles

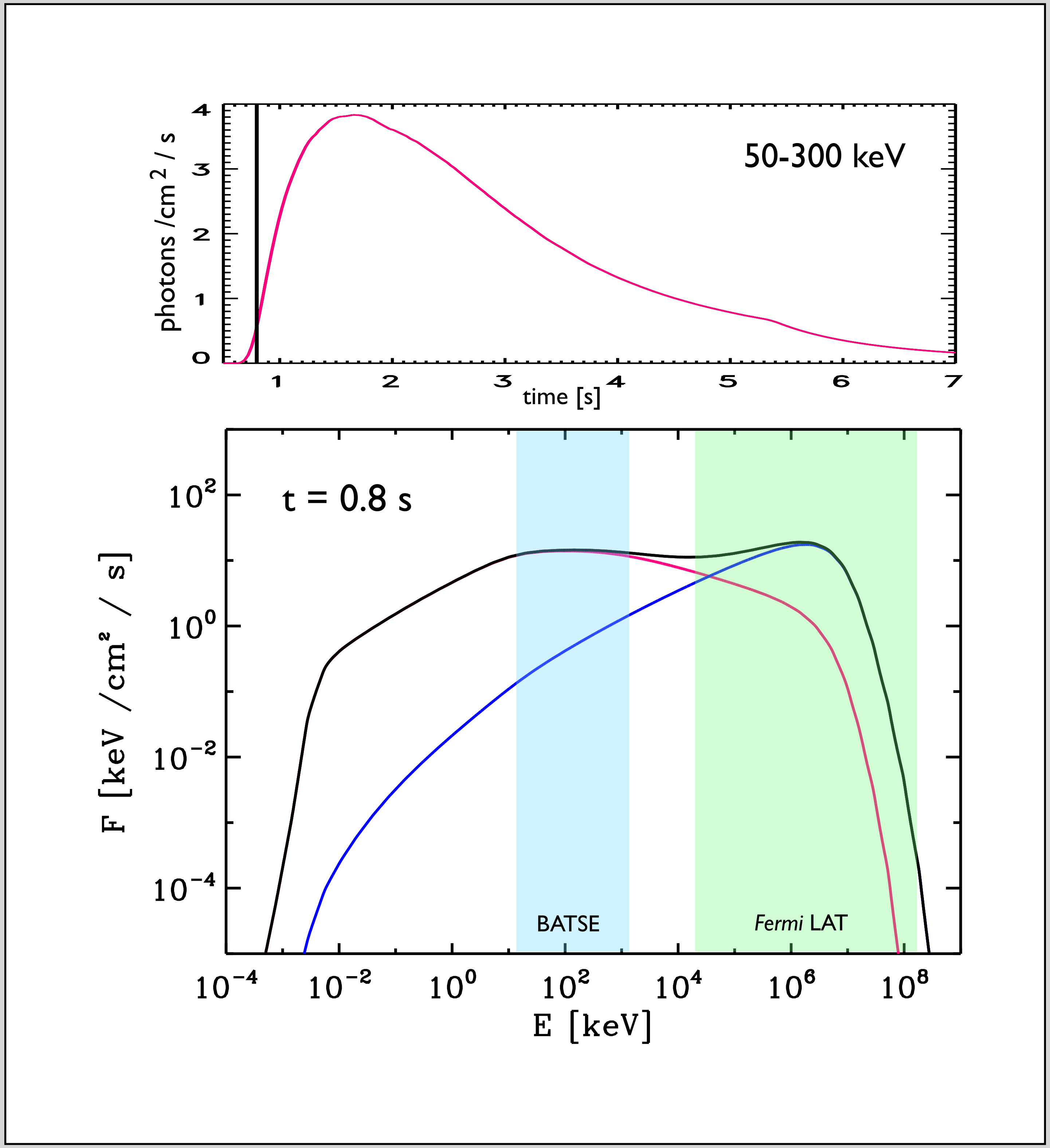
The observed spectra and the light curves are computed from the comoving emission by integration over equal-arrival time surfaces.

relativistic effects (Doppler factor)

geometry (curvature of the emitting surface)

cosmological effect (redshifts)

Instantaneous observed spectrum:



synchrotron
inverse Compton
total

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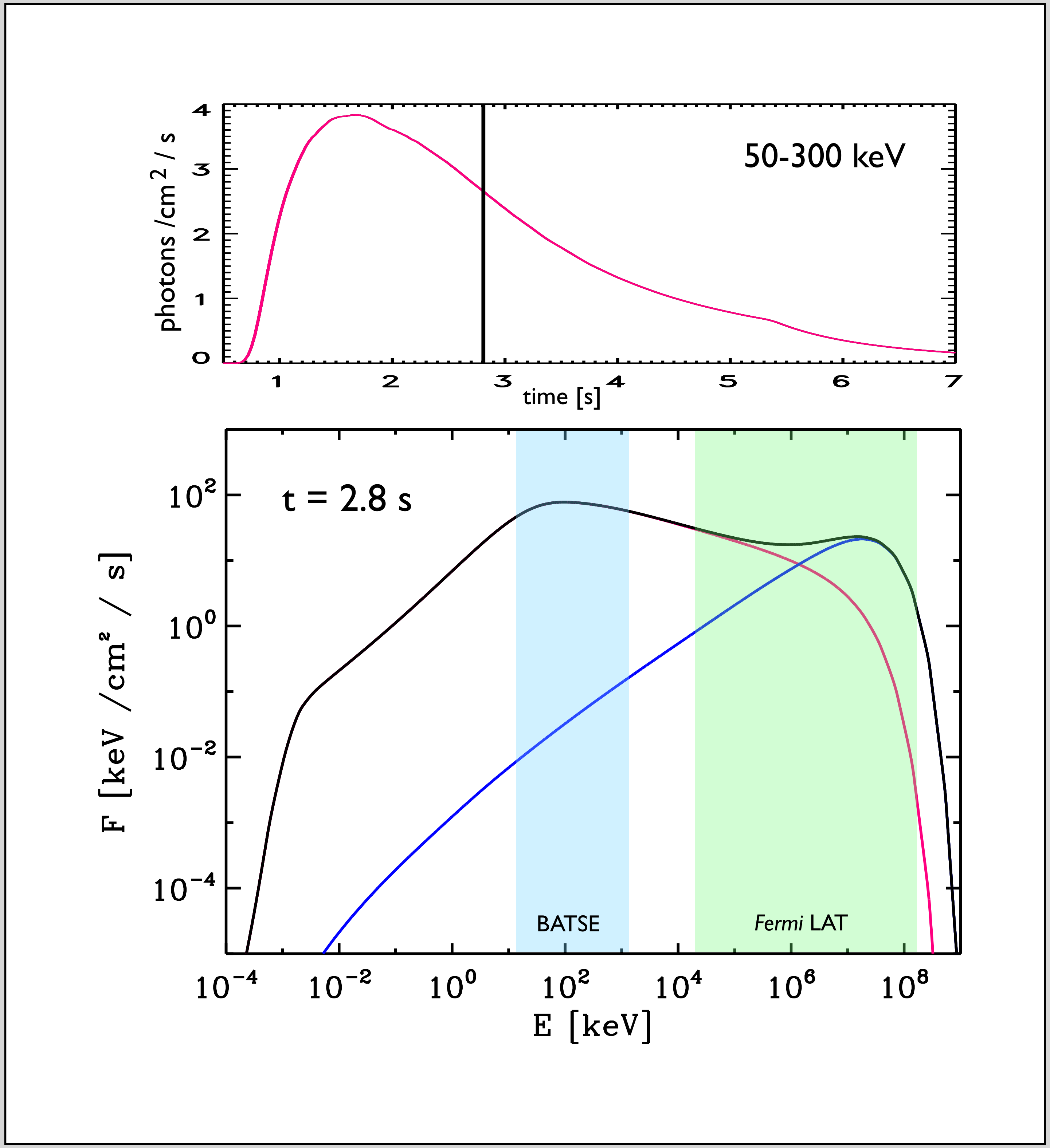


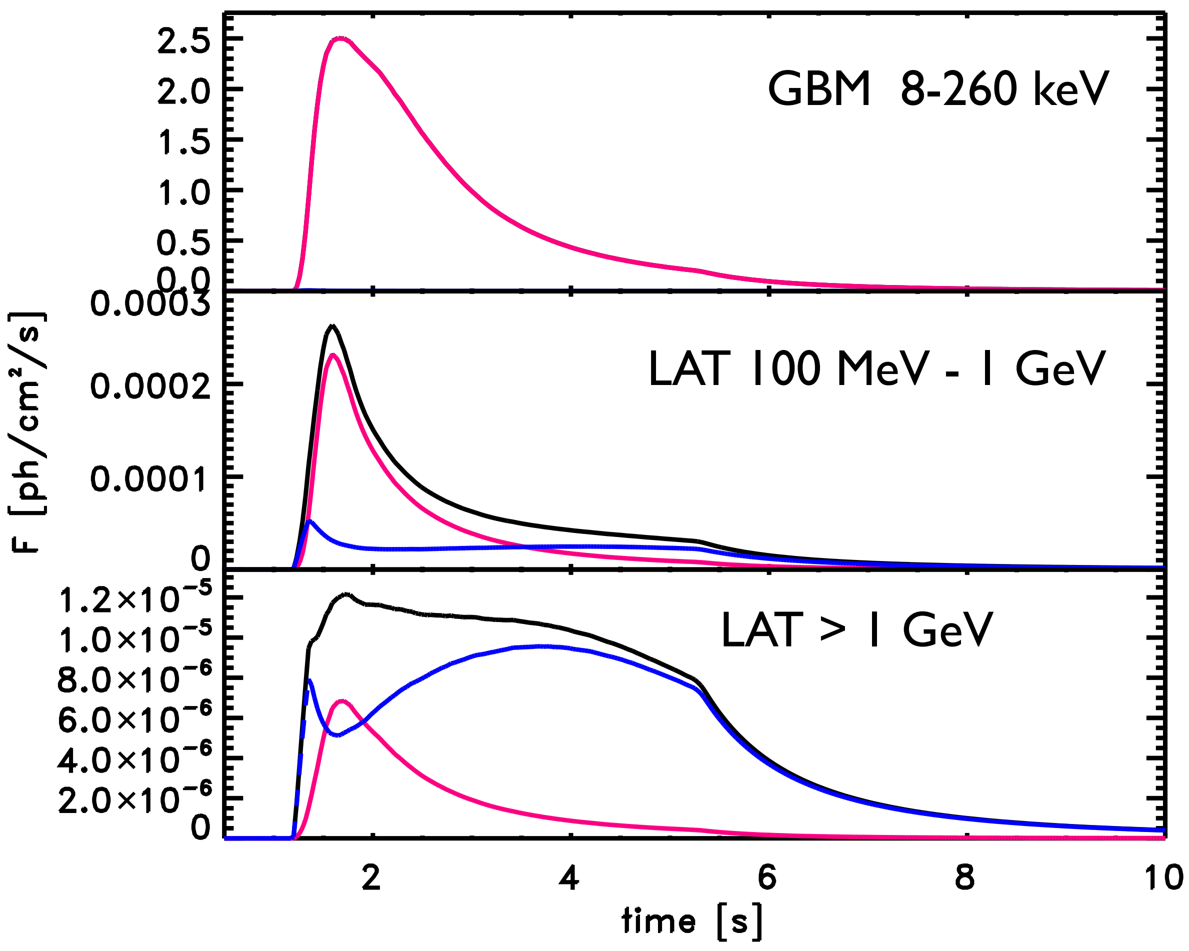
synchrotron
inverse Compton
total

Dominant radiative process in sub-MeV range?

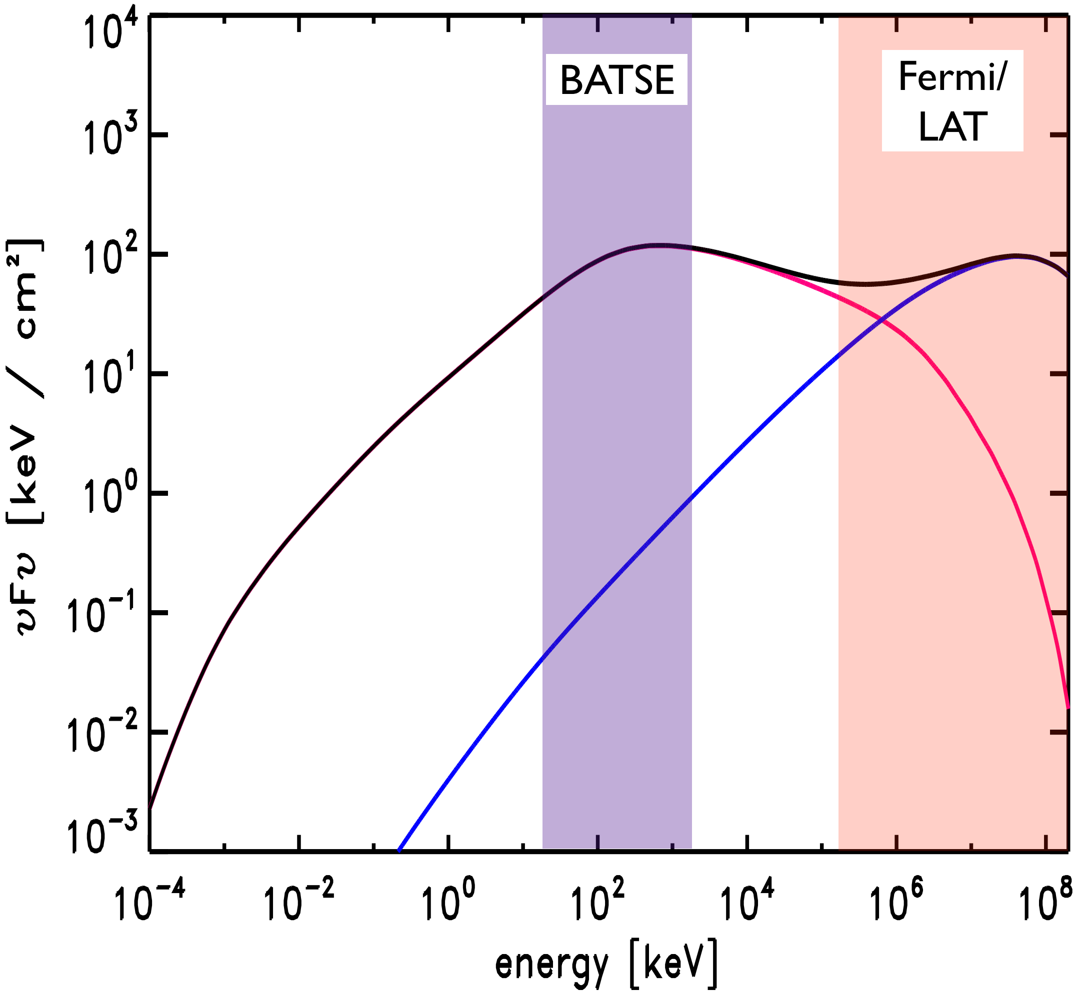
SYNCHROTRON CASE (B)

low magnetic field

dE/dt = 5 x 10^{53} erg s^{-1}, ε_B = 0.003, ε_e = 1/3, ζ = 0.003, p = 2.5, z=1



Observed lightcurve

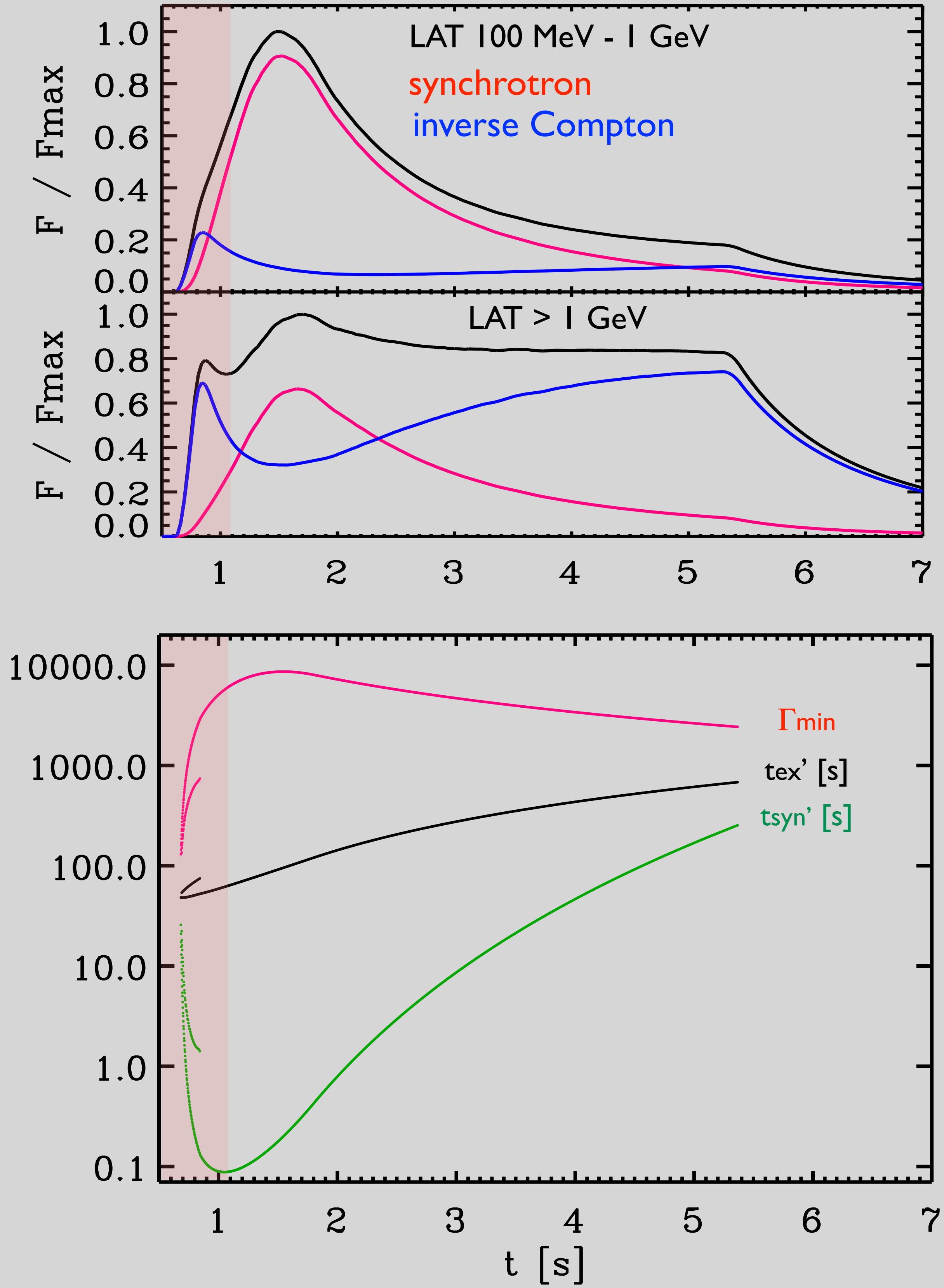


Observed spectrum

synchrotron
inverse Compton
total

Temporal profiles: > 100 MeV bands

Model: in LAT (>100 MeV) energy bands both components present, synchrotron + IC



weak shock

ε^* low

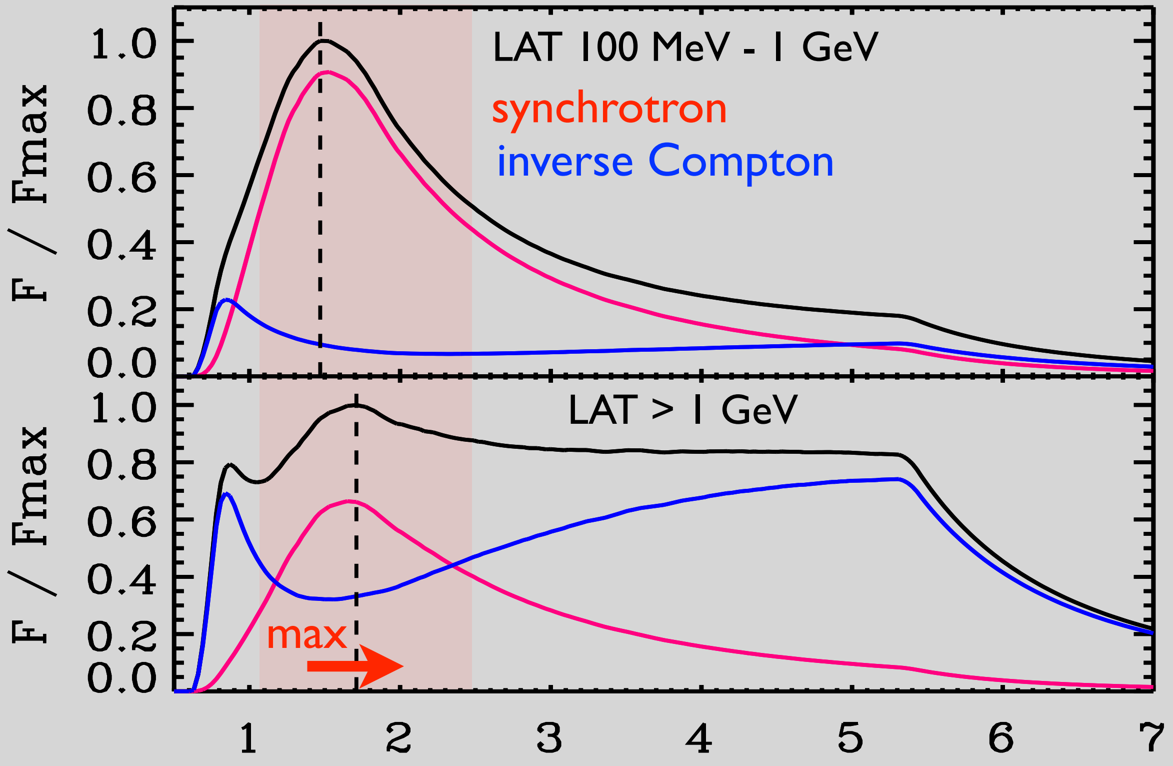
moderate $\Gamma_m \Rightarrow$ large t_{syn}'

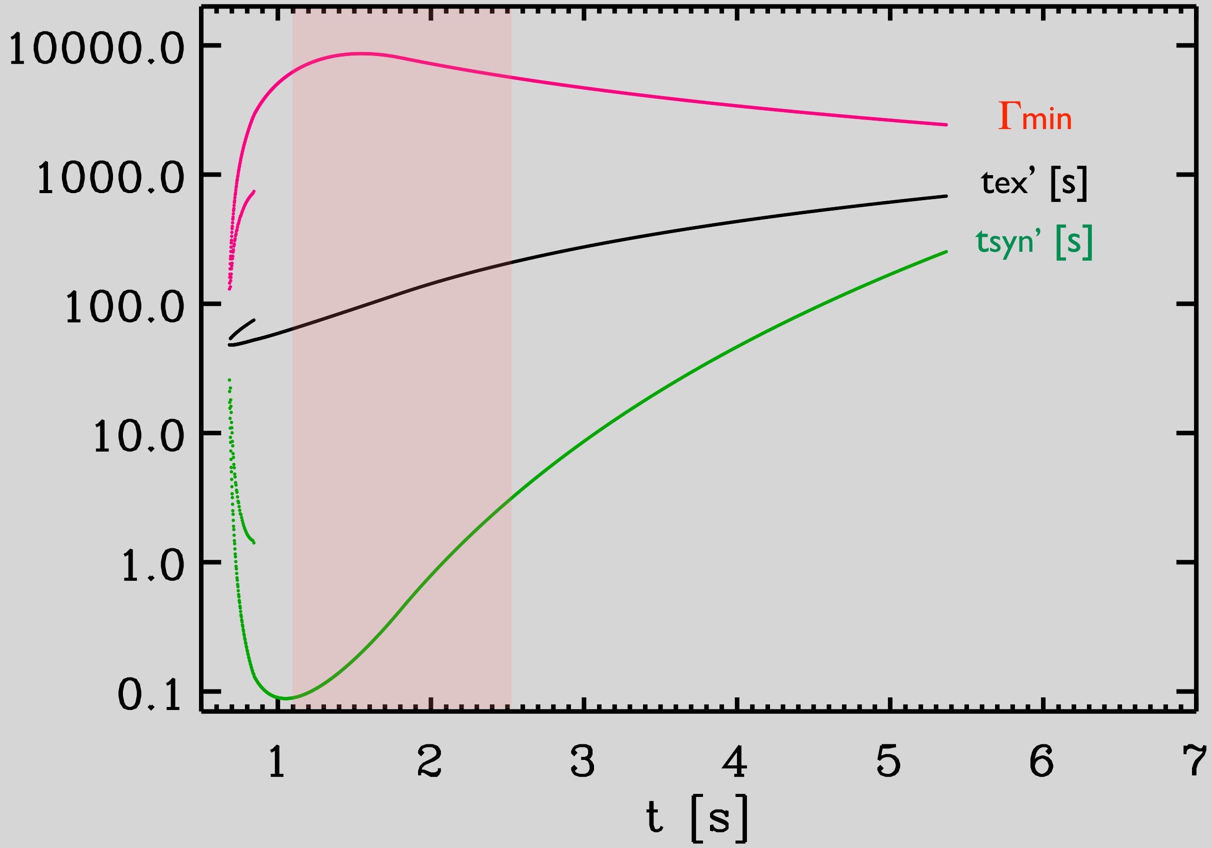
R small $\Rightarrow t_{ex}' \cong R/\Gamma^* c$ small

$t_{syn}' \leq t_{ex}' \Rightarrow$ large efficiency of IC

Temporal profiles: > 100 MeV bands

Model: in LAT (>100 MeV) energy bands both components present, synchrotron + IC



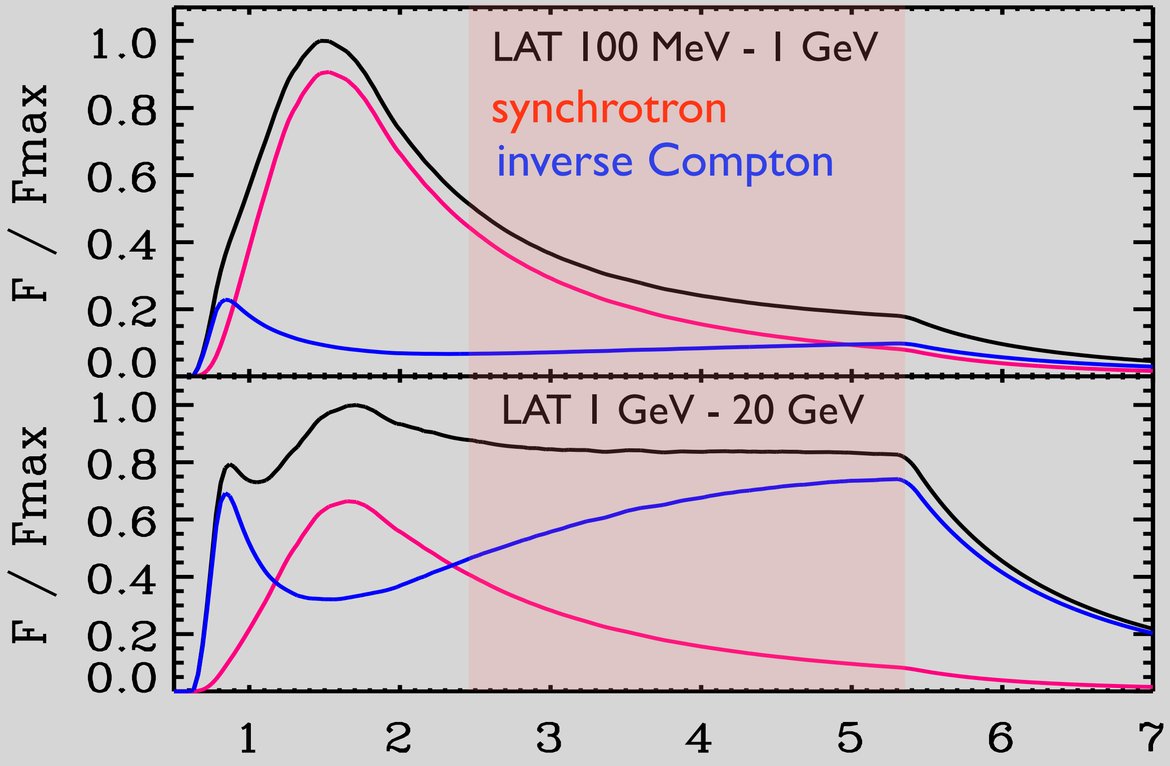


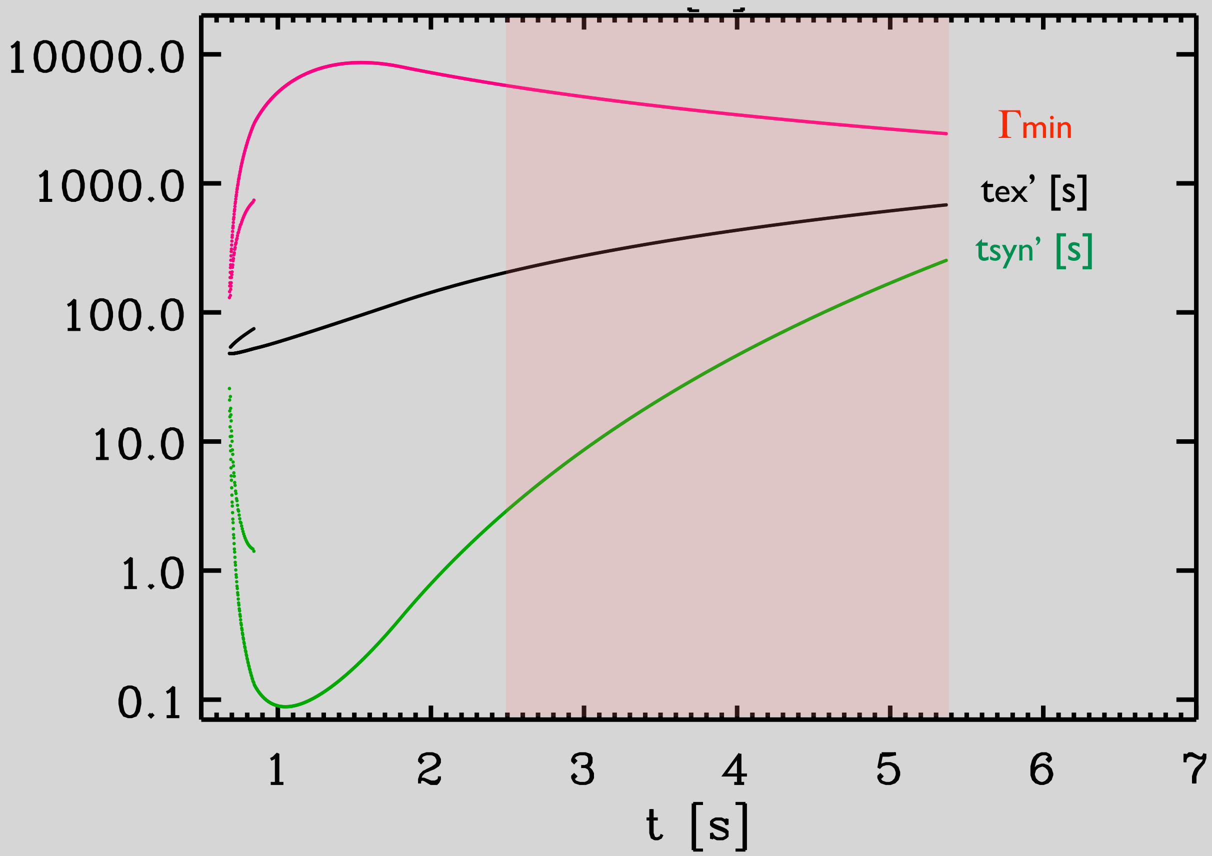
shock becomes stronger
Γm increases ⇒ tsyn' decreases
R, tex' increase
tsyn' << tex' ⇒ low efficiency of IC

dominant synchrotron component

Temporal profiles: > 100 MeV bands

Model: in LAT (>100 MeV) energy bands both components present, synchrotron + IC



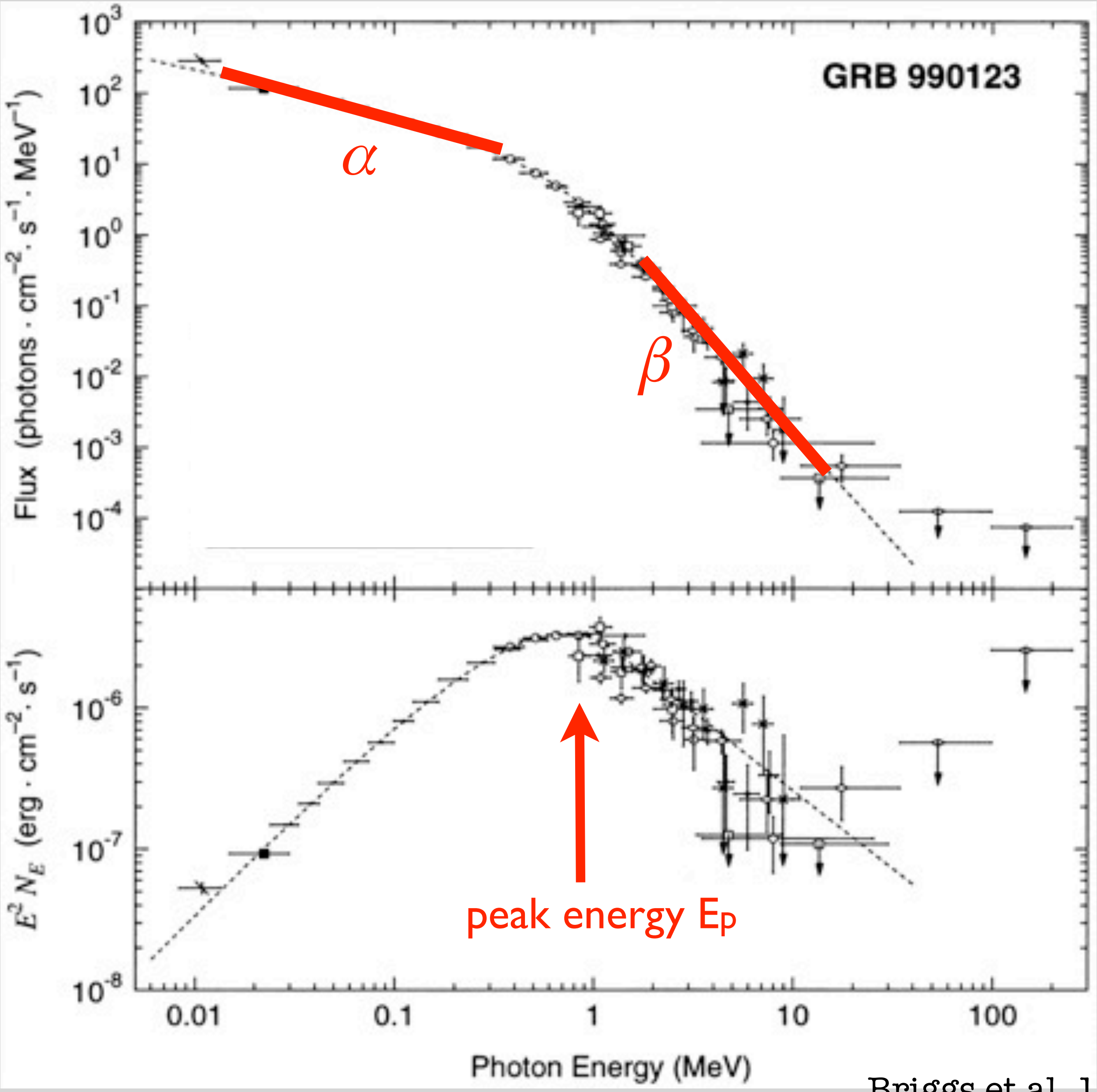


tail of the pulse:
B decreases ⇒ tsyn' increases
tsyn' ≤ tex' ⇒ increased efficiency of IC

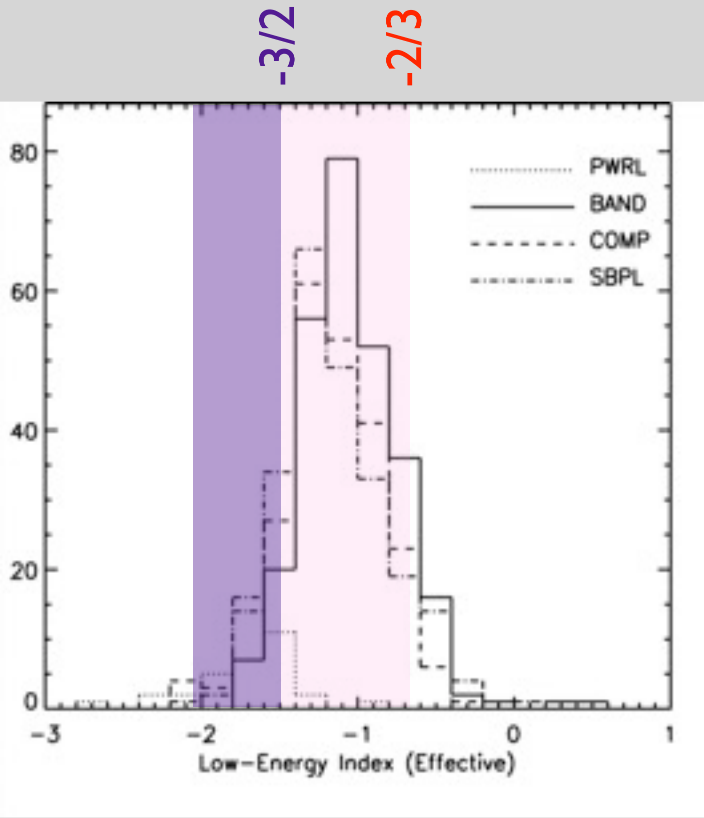
IC component dominant in GeV

Spectral properties

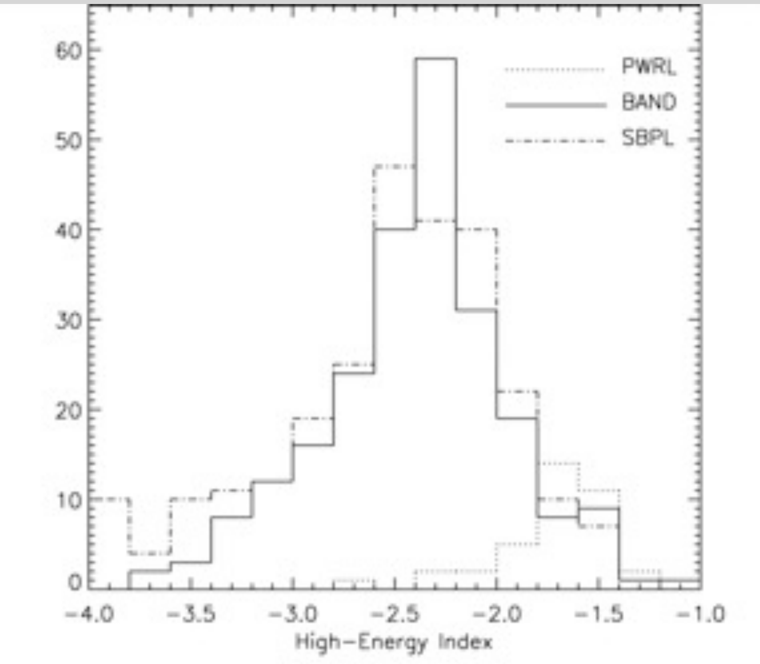
4-parameters “Band spectrum”
E_p, α, β and normalization
Band et al. 1993



Briggs et al. 1999



α = -1.02 ± 0.27



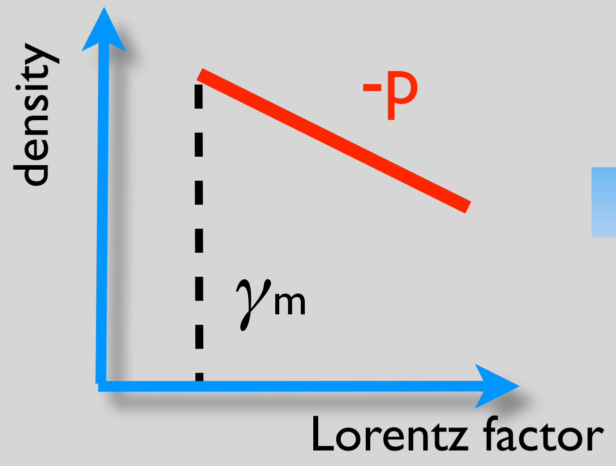
β = -2.35 ± 0.27

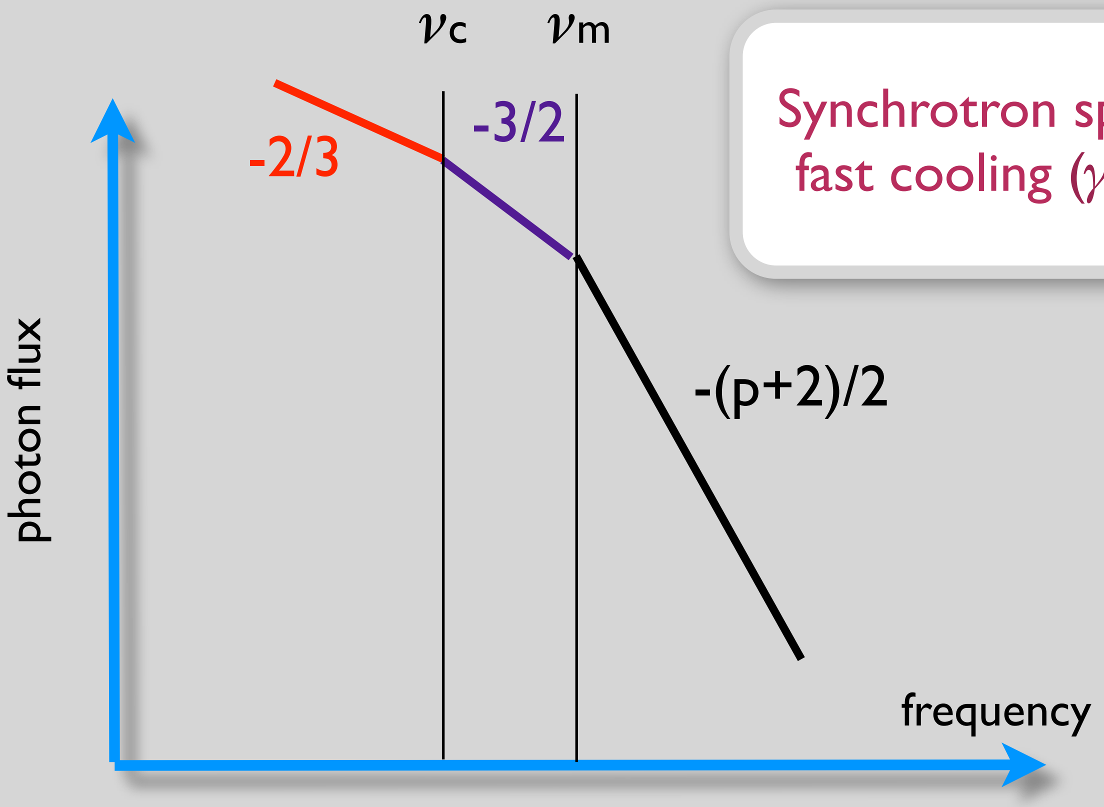
Kaneko et al. 2006

Spectral properties

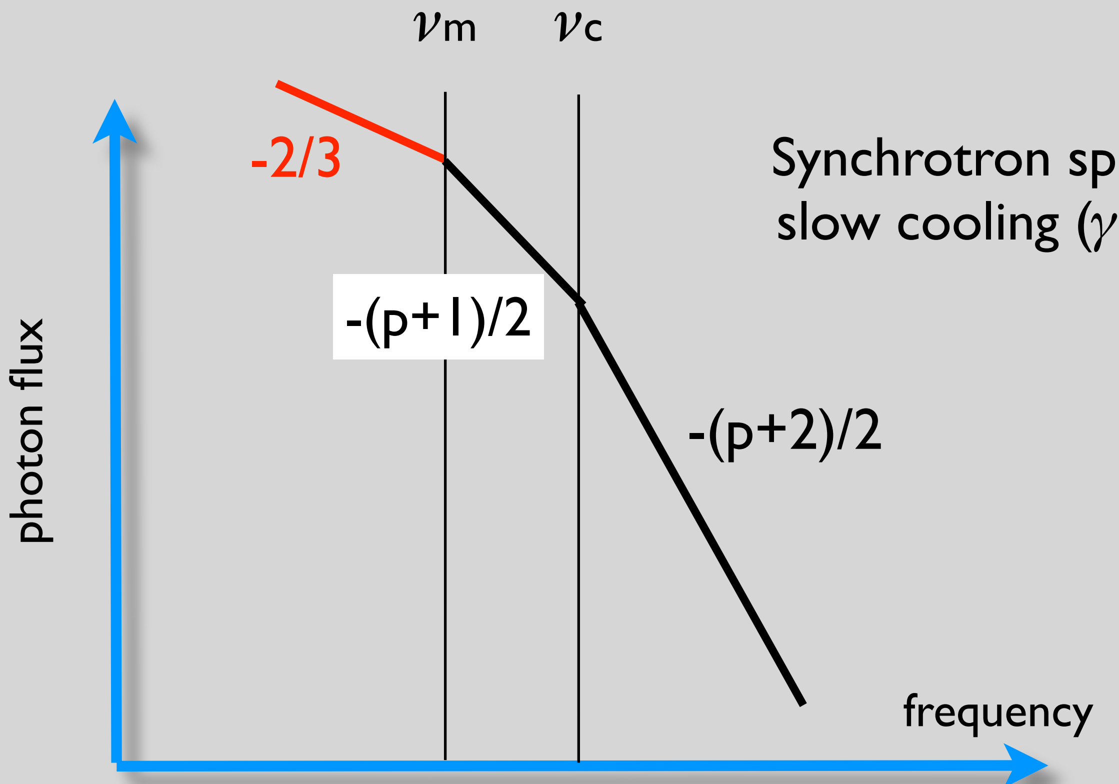
Sari, Piran & Narayan 1998

Relativistic electrons:





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

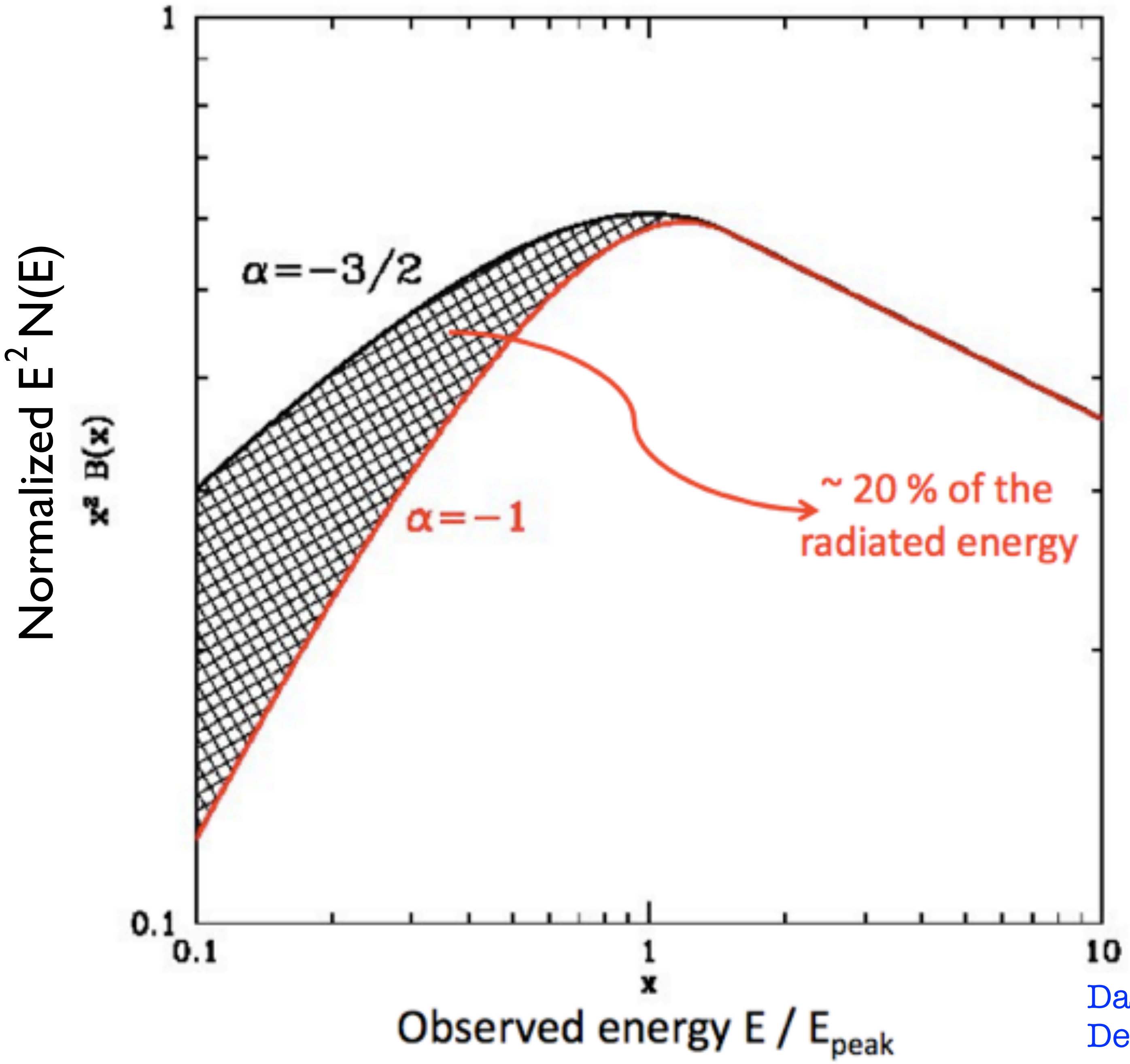


Synchrotron spectrum: slow cooling ($\gamma_c > \gamma_m$)

γ_m: minimum Lorentz factor at injection

γ_c: radiative timescale = dynamical timescale

Spectral properties



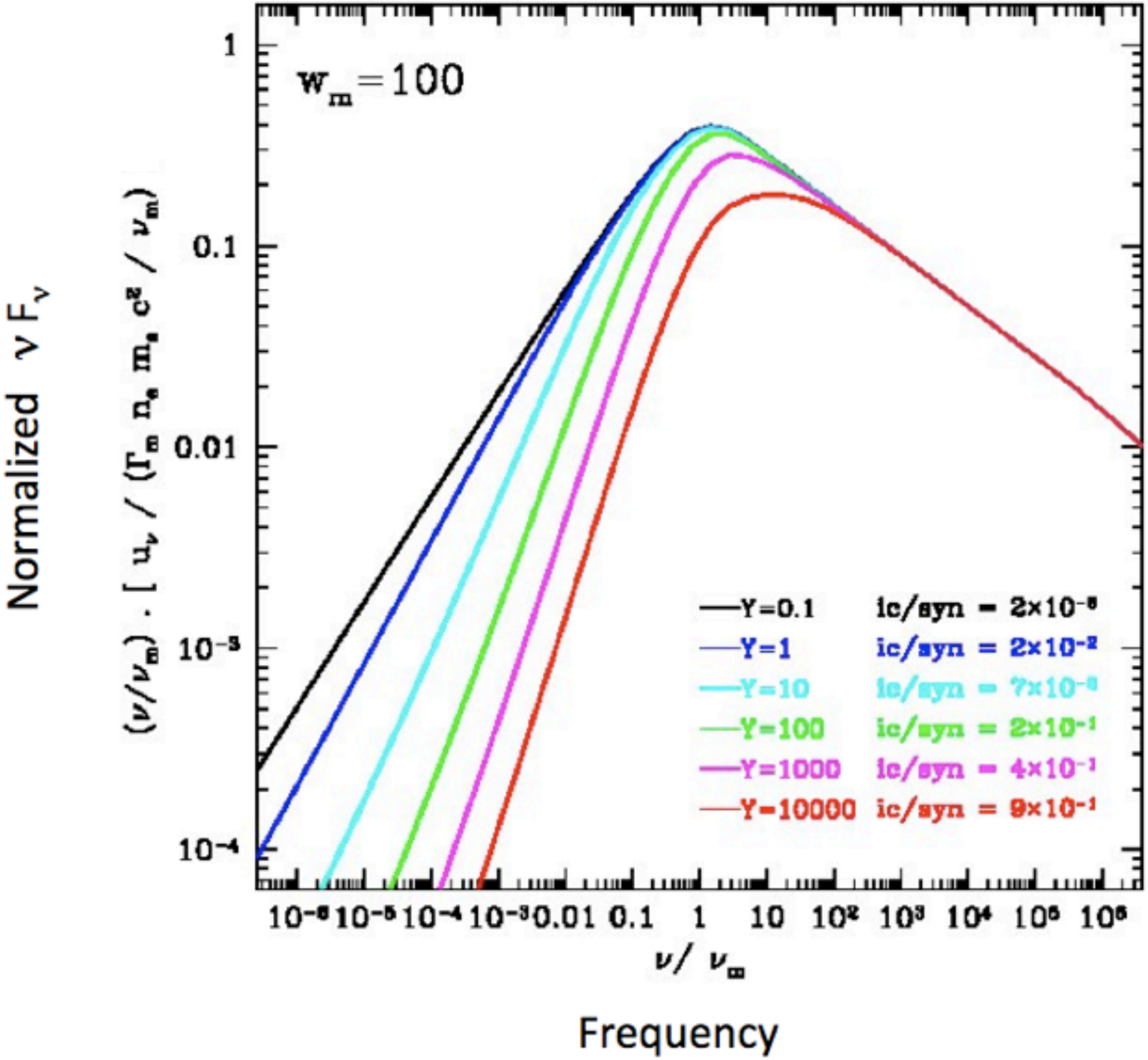
Band function

α = - 1.5 $\rightarrow$ -1
β = - 2.25

Daigne, Bosnjak & Dubus 2011
Derishev 2001

Inverse Compton scatterings in Klein-Nishina regime have an impact on the synchrotron slope

Spectral properties



w_m : importance of KN

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

Y : importance of IC vs syn

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

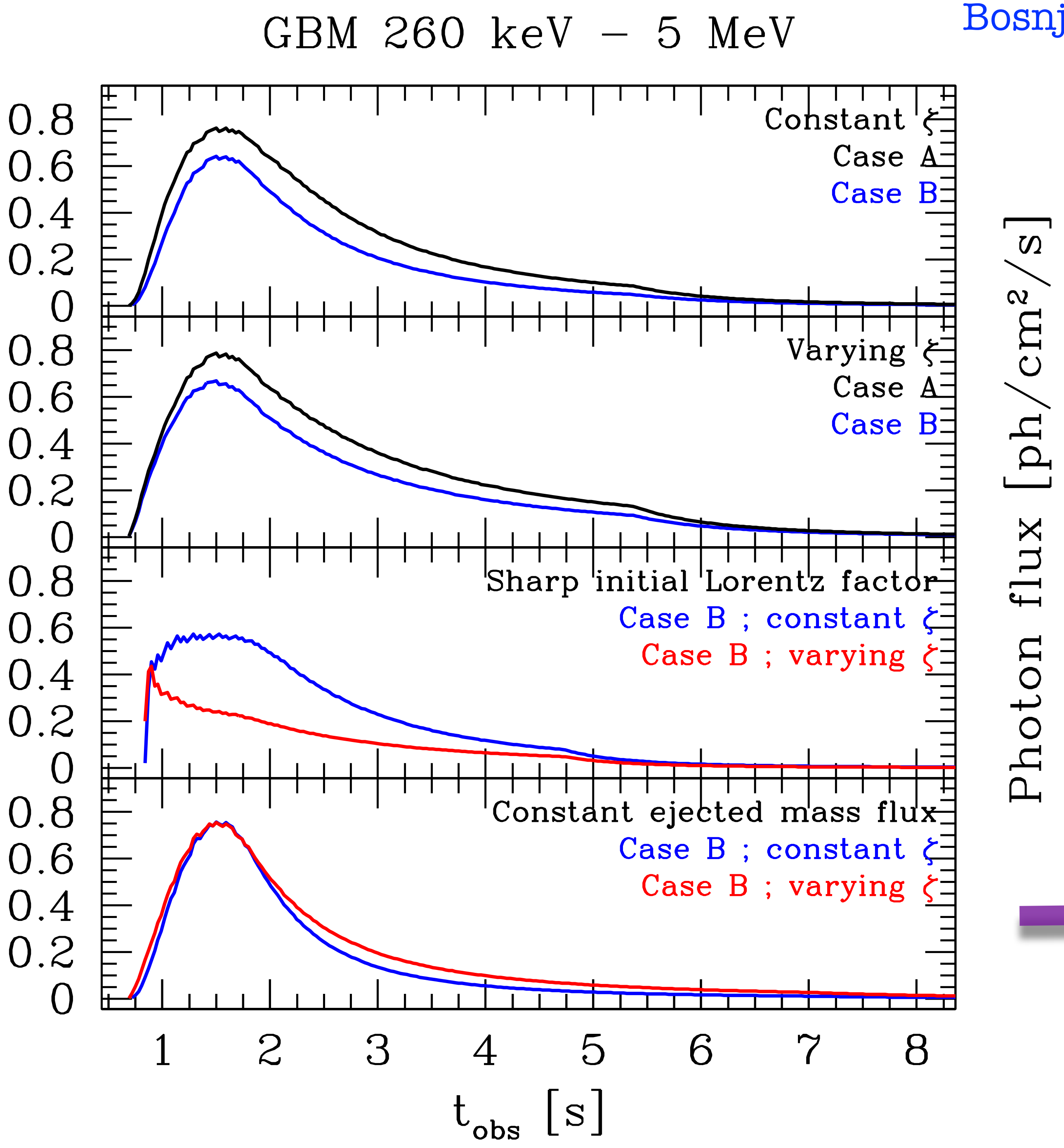
Thomson regime: the electron cooling rate due to IC scatterings remains proportional to γ^2 as for the synchrotron power

KN regime: the electron cooling rate due to IC depends on γ

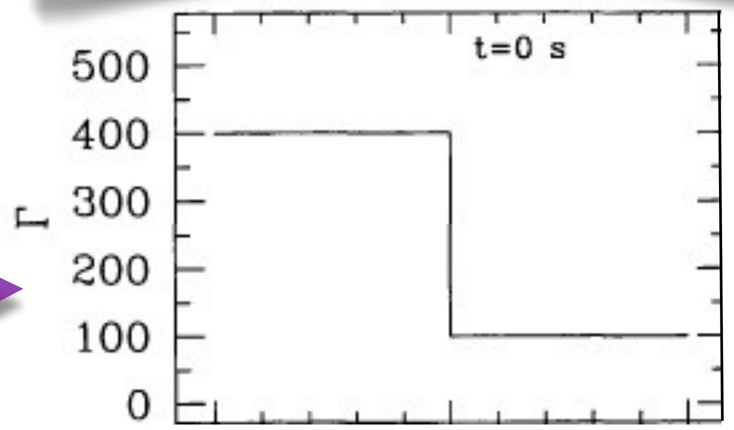
Exact calculation with synchrotron + IC only
(no adiabatic cooling, synchrotron self-absorption, $\gamma\gamma$ annihilation)

High energy emission: light curves

Bosnjak & Daigne 2014



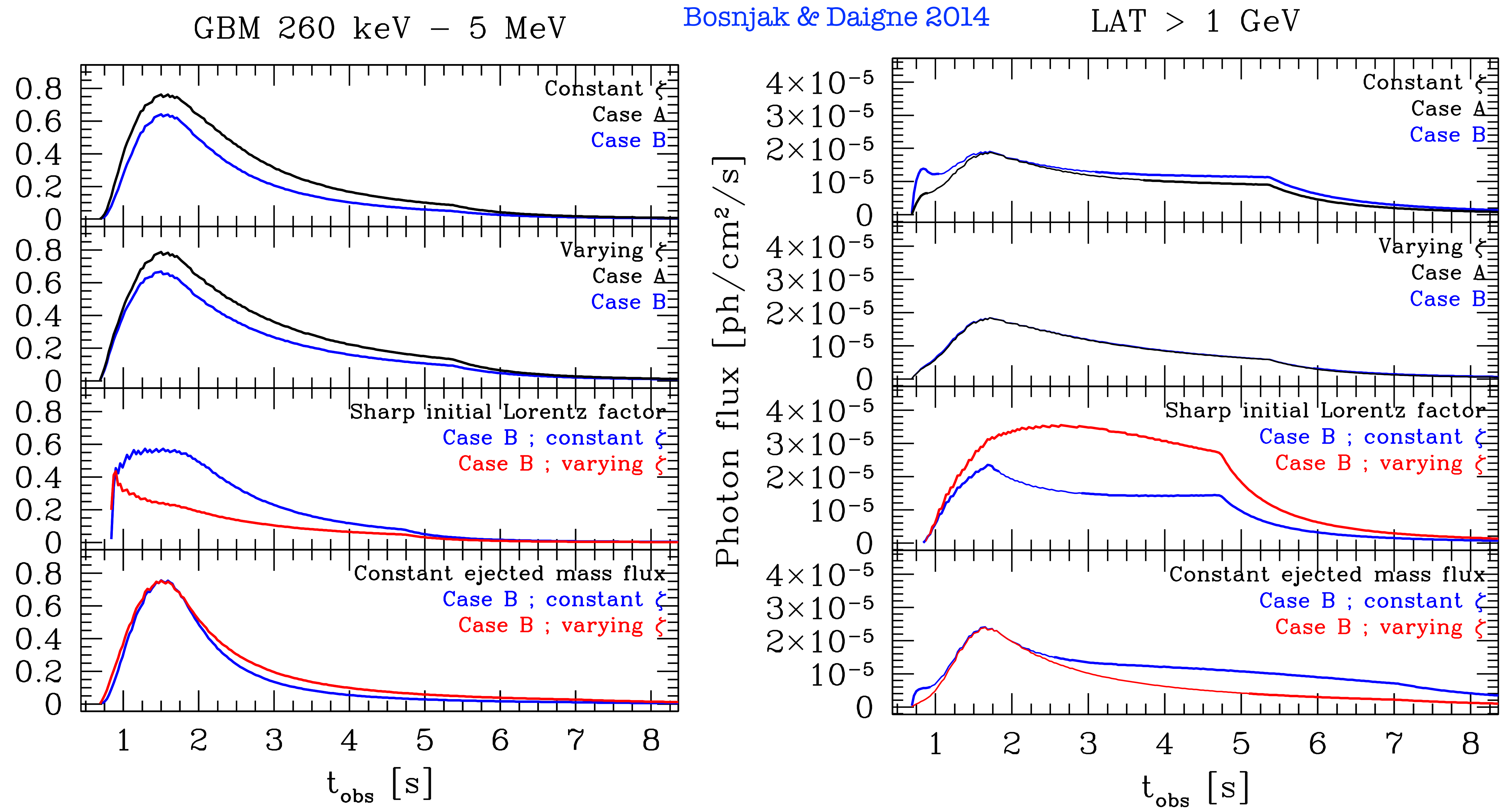
‘Sharp’ initial Lorentz factor:



Constant ejected mass flux:
dE/dt ∝ Γ

t_{obs} [s]

High energy emission: light curves



Summary

We developed modeling tools to compute the GRB prompt emission from internal shocks in a time-dependent way in different spectral bands, including the high-energy gamma rays

The exploration of the parameter space shows that we can expect two classes of broad-band spectra, which correspond to different physical conditions in the shocked region: the **"synchrotron case"** (where the dominant process in Fermi-GBM range is synchrotron radiation) and the **"inverse Compton case"** (where the synchrotron component peaks at low energy and the dominant process in the GBM range is inverse Compton)

Fermi GRB observations favor the **"synchrotron case", with inverse Compton scatterings occurring in Klein-Nishina regime. This scenario qualitatively reproduces the observed spectral evolution (HIC, HFC). We constrain the parameters of the model (p, ε_B, ζ) in order to have a quantitative agreement**

Further developments: currently **incorporating a more realistic scenario for the physical conditions in the shocked plasma and making predictions for the CTA observatory**