Gamma-ray burst emission models: spectral evolution in the internal shock model

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from Astrophysics to Fundamental Physics, Trieste - May 2016

Outline

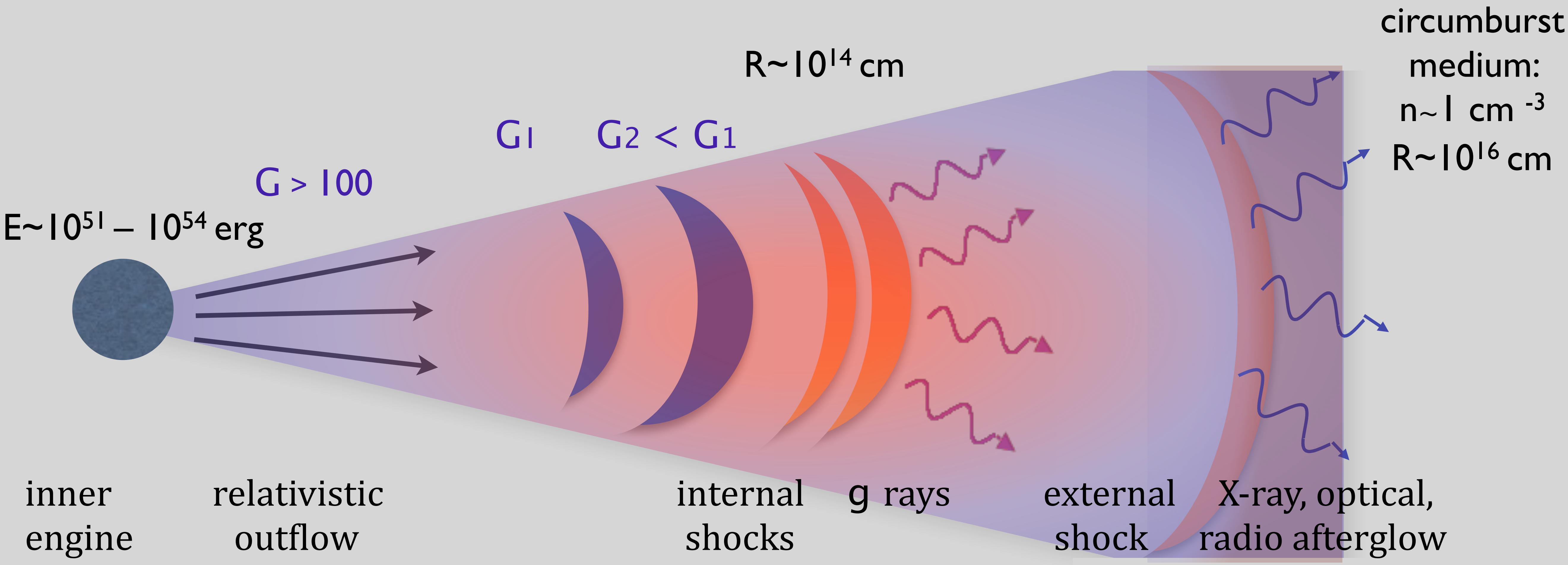
- What do we know about GRB emission?

    fireball model
    models for the prompt gamma-ray emission

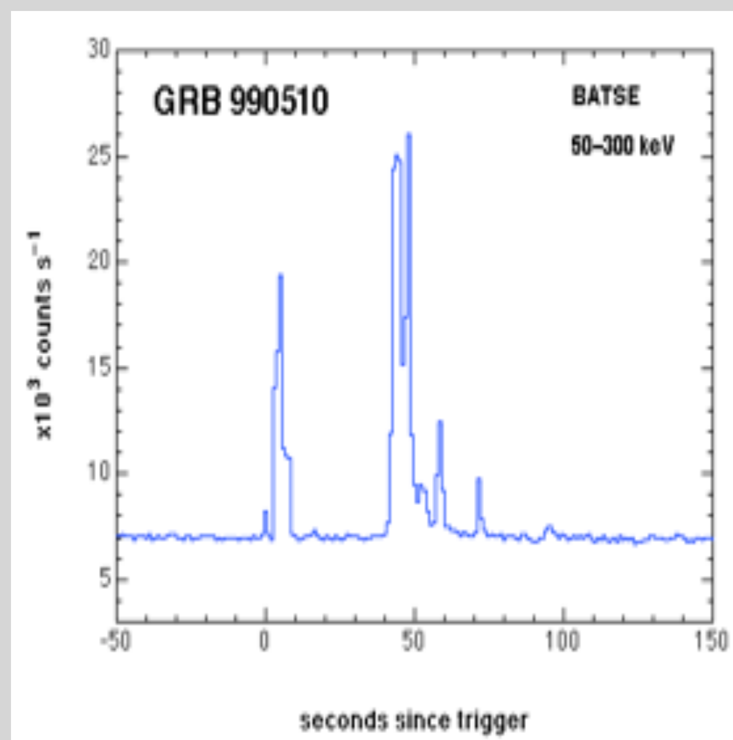
- Modeling: relativistic jets and the internal shock model

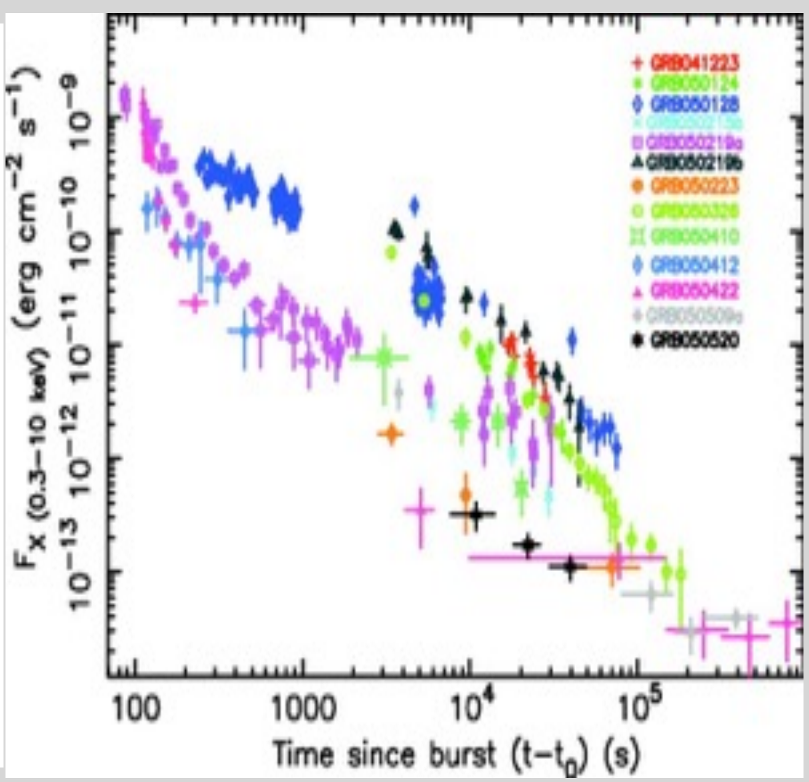
    GRB spectra and lightcurves: synchrotron/inverse Compton case
    comparison with observations

Fireball model



- ✓ ~10 ^{53} ergs in a few seconds
- ✓ variability ~ 10 ms
- ✓ relativistic motion: Γ > 100
- ✓ internal shocks: prompt emission
- ✓ external shock: afterglow





Models for the prompt gamma-ray emission

The standard GRB model:

internal dissipation within an ultra-relativistic outflow ($G \gtrsim 100$) ejected by a new-born compact source

What is the nature of the dissipation mechanism?

Models for the prompt gamma-ray emission

The standard GRB model:

internal dissipation within an ultra-relativistic outflow ($\Gamma \gtrsim 100$) ejected by a new-born compact source

What is the nature of the dissipation mechanism?

internal shocks

✓ *detailed calculations of the expected light curves and spectra are available*
(Kobayashi et al. 1997; Bošnjak et al. 2009; Asano & Meszaros 2011)

✓ *good agreement with observations*

✓ *the low energy index usually observed to be larger than -3/2 BUT solutions have been proposed*
(Derishev et al. 2009; Nakar et al. 2009; Daigne et al. 2011; Zhao et al. 2014)

Models for the prompt gamma-ray emission

The standard GRB model:

internal dissipation within an ultra-relativistic outflow (G ≳ 100) ejected by a new-born compact source

What is the nature of the dissipation mechanism?

internal shocks

thermal emission

✓ *the different sub-photospheric dissipation processes may affect the spectrum, so that it appears as non-thermal. The observed peak energy values can be reproduced*

(Thompson 1994; Rees & Meszaros 2005; Giannios & Spruit 2007; Beloborodov 2010; Toma et al. 2011; Veres et al. 2013)

Models for the prompt gamma-ray emission

The standard GRB model:

internal dissipation within an ultra-relativistic outflow ($\Gamma \gtrsim 100$) ejected by a new-born compact source

What is the nature of the dissipation mechanism?

internal shocks

thermal emission

magnetized ejecta

- ✓ *a strong initial magnetization can play a major role in acceleration of the jet*
  (Begelman & Li 1994; Vlahakis & Konigl 2003; Komissarov et al. 2009, 2010,..)

- ✓ *if the ejecta is still magnetized at large distances, magnetic reconnection can provide a new dissipation process*
  (Spruit et al. 2001; Drenkhahn & Spruit 2002; Giannios & Spruit 2002)

- ✓ *no detailed predictions for the GRB light curves and spectra*
  (preliminary calculation Zhang & Zhang 2014)

Models for the prompt gamma-ray emission

The standard GRB model:

internal dissipation within an ultra-relativistic outflow (G ≳ 100) ejected by a new-born compact source

What is the nature of the dissipation mechanism?

internal shocks

thermal emission

magnetized ejecta

The photospheric emission should be present in all scenarios, even if very weak.

Magnetic reconnection requires strong magnetization at a large distance (Giannios et al. 2008; Narayan et al. 2011). This may prevent internal shock formation and propagation

Only one of the two mechanisms should be at work!

Models for the prompt gamma-ray emission

The standard GRB model:

internal dissipation within an ultra-relativistic outflow ($\Gamma \gtrsim 100$) ejected by a new-born compact source

What is the nature of the dissipation mechanism?

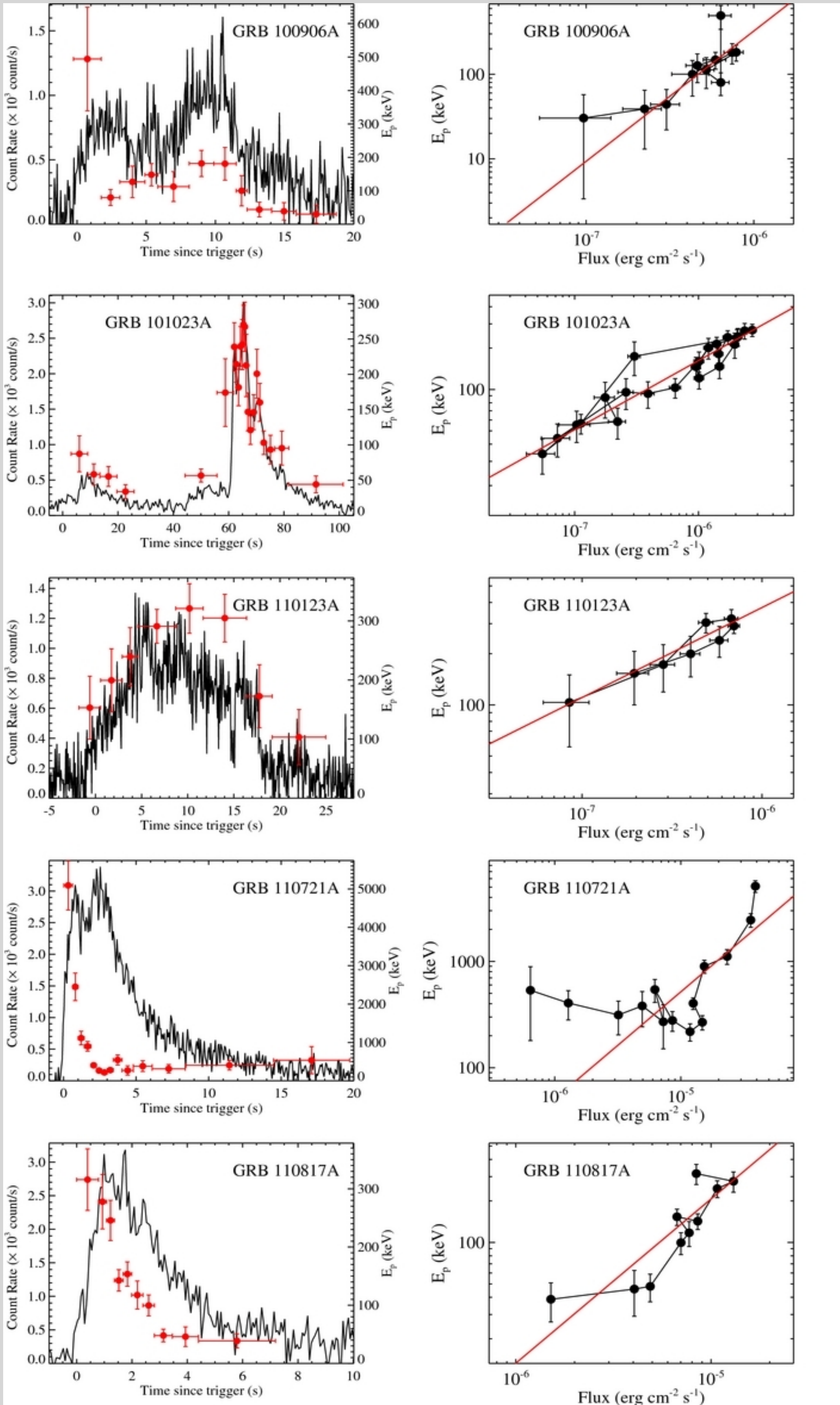
internal shocks

thermal emission

magnetized ejecta

Can the observed spectral evolution be computed?

Sub-MeV emission



Ferm/GBM observations:

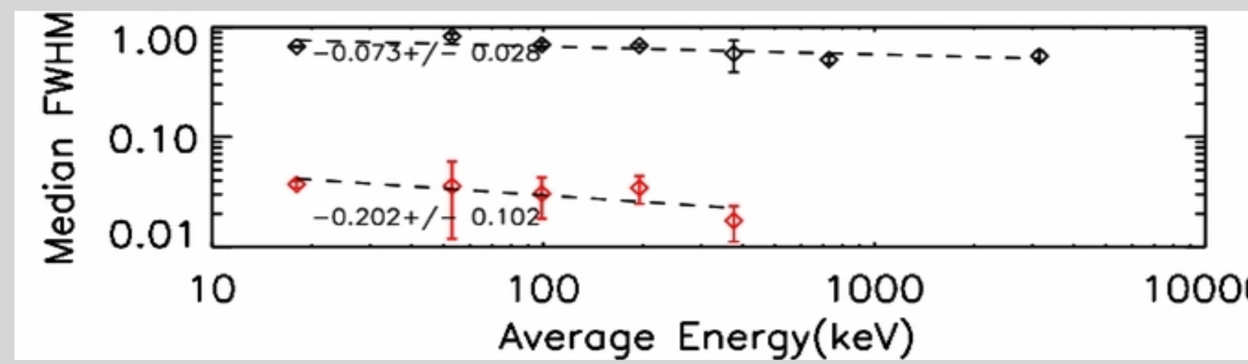
hard-to-soft evolution

hardness maximum preceding the peak of the intensity

hardness-intensity correlation: $E_{p,obs} \propto F(t)^{k}$, $k \simeq 0.4\text{-}1.2$

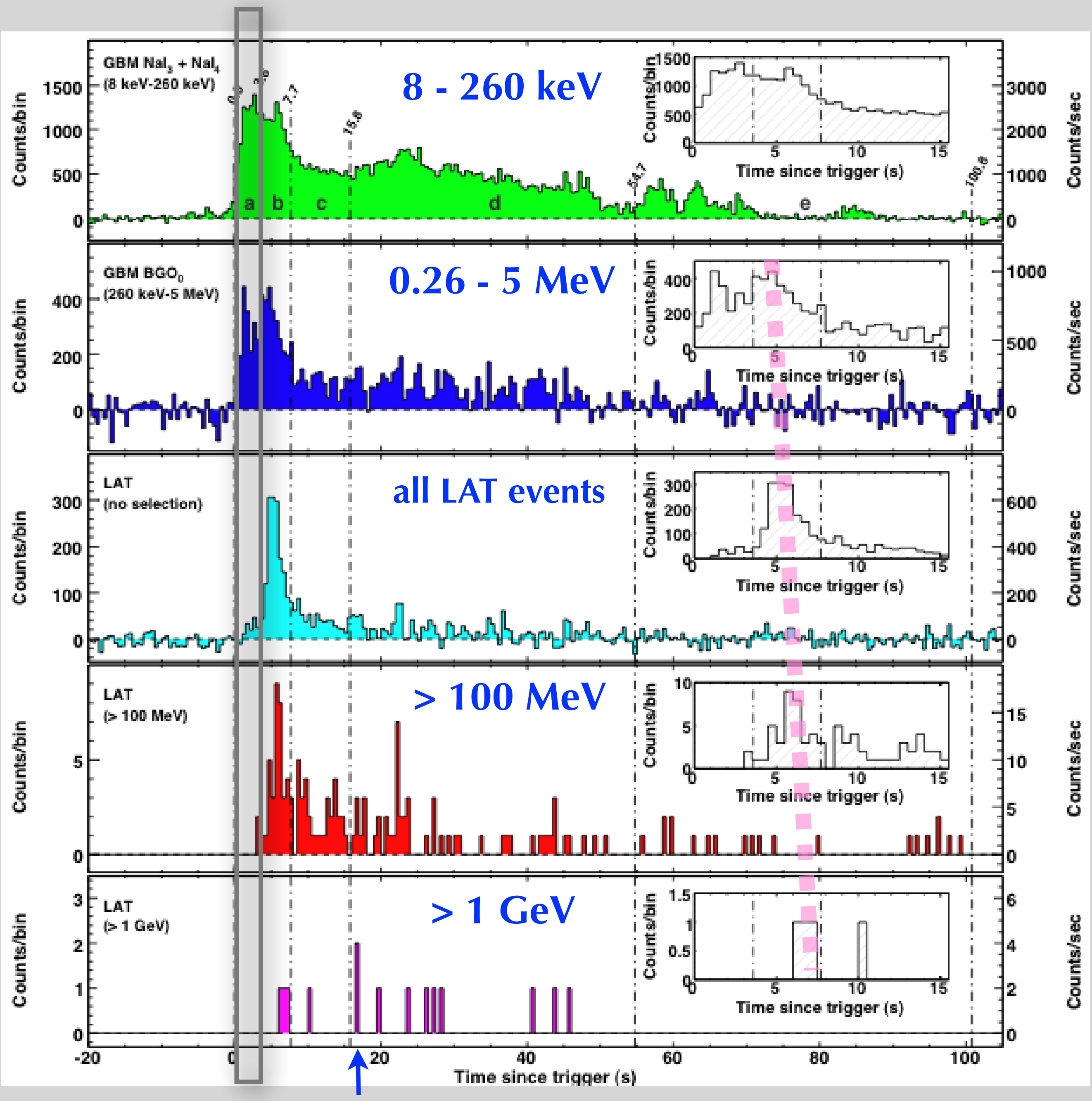
energy-dependent pulse asymmetry: $W(E_{obs}) \propto E_{obs}^{-a}$

Bhat et al. 2012

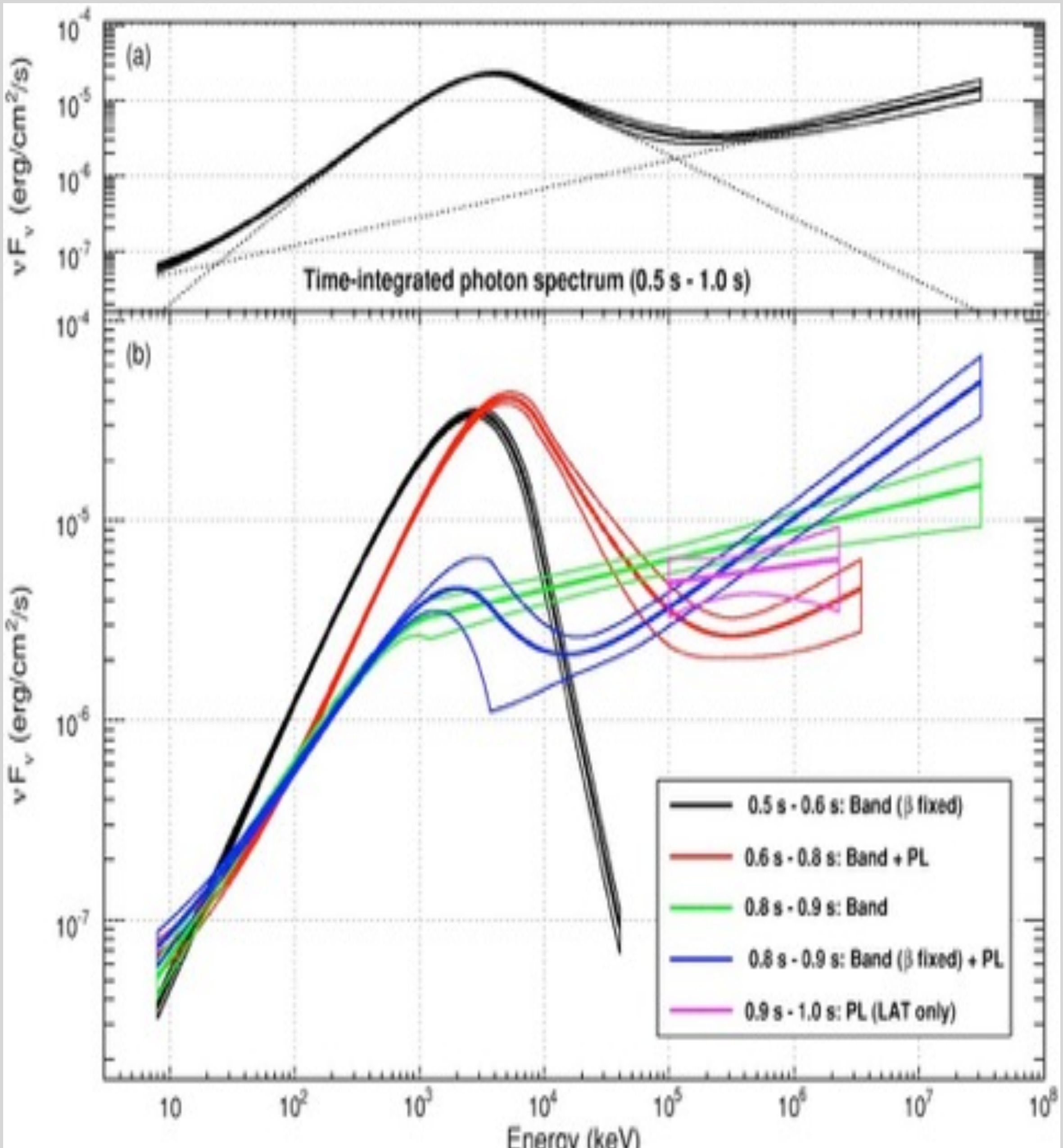


Lu et al. 2012

High energy emission



GRB 080916C
Abdo et al. 2008

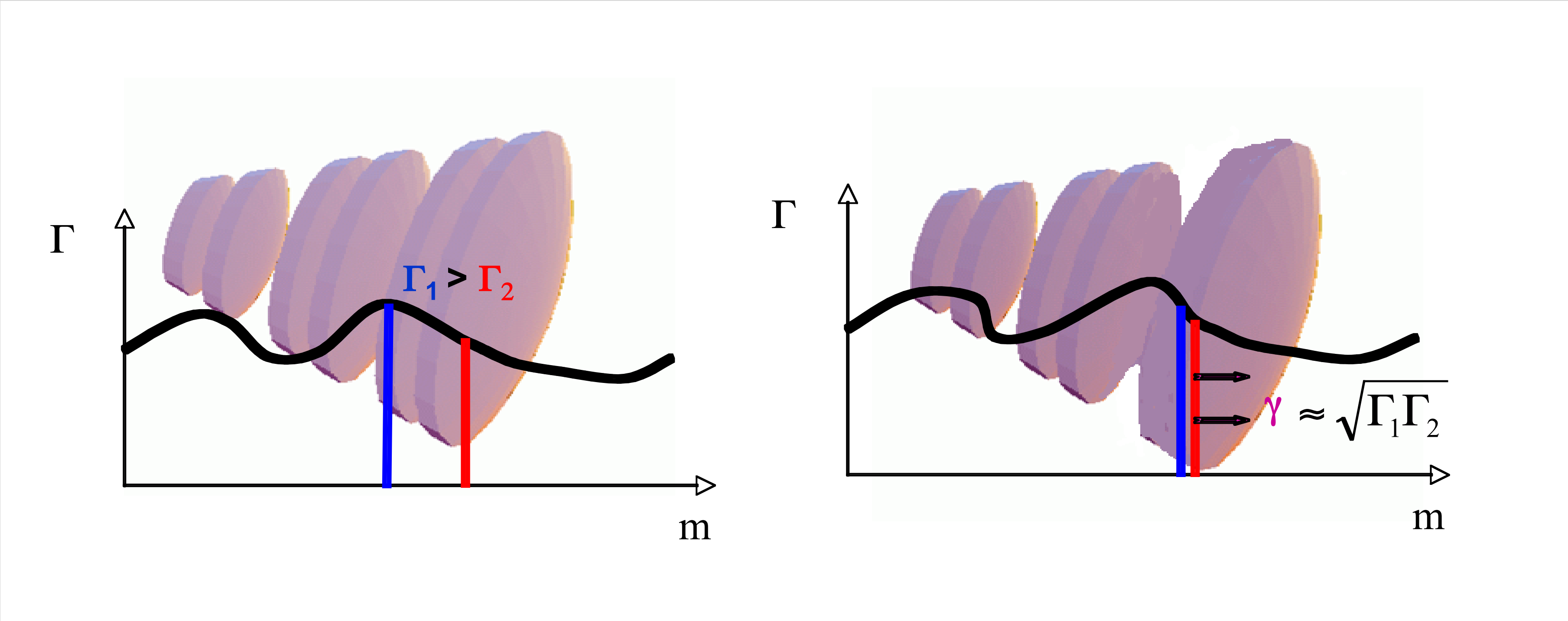


GRB 090510
Ackermann et al. 2010

Fermi/LAT observations:

- Delayed onset of high energy (>100 MeV) emission
- **Long lived** high energy emission
- Deviation from the usual GRB spectral models: **extra component**

Prompt high energy emission in the framework of internal shocks



Modeling:

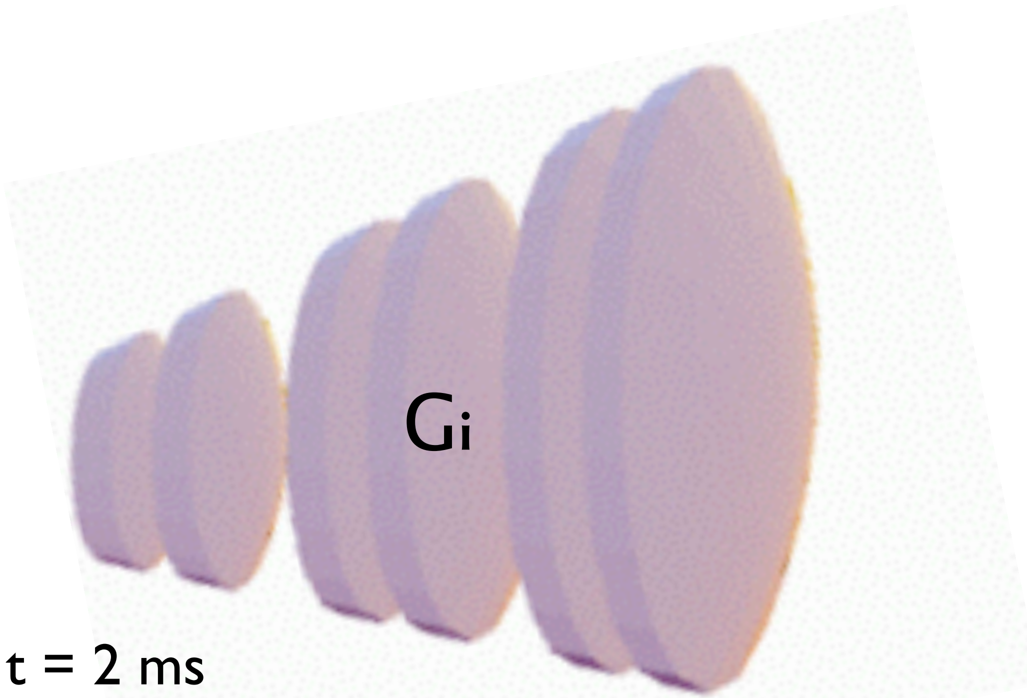
1. dynamics of internal shocks

2. radiative processes in the shocked medium

3. observed spectra and time profiles

Dynamic of internal shocks

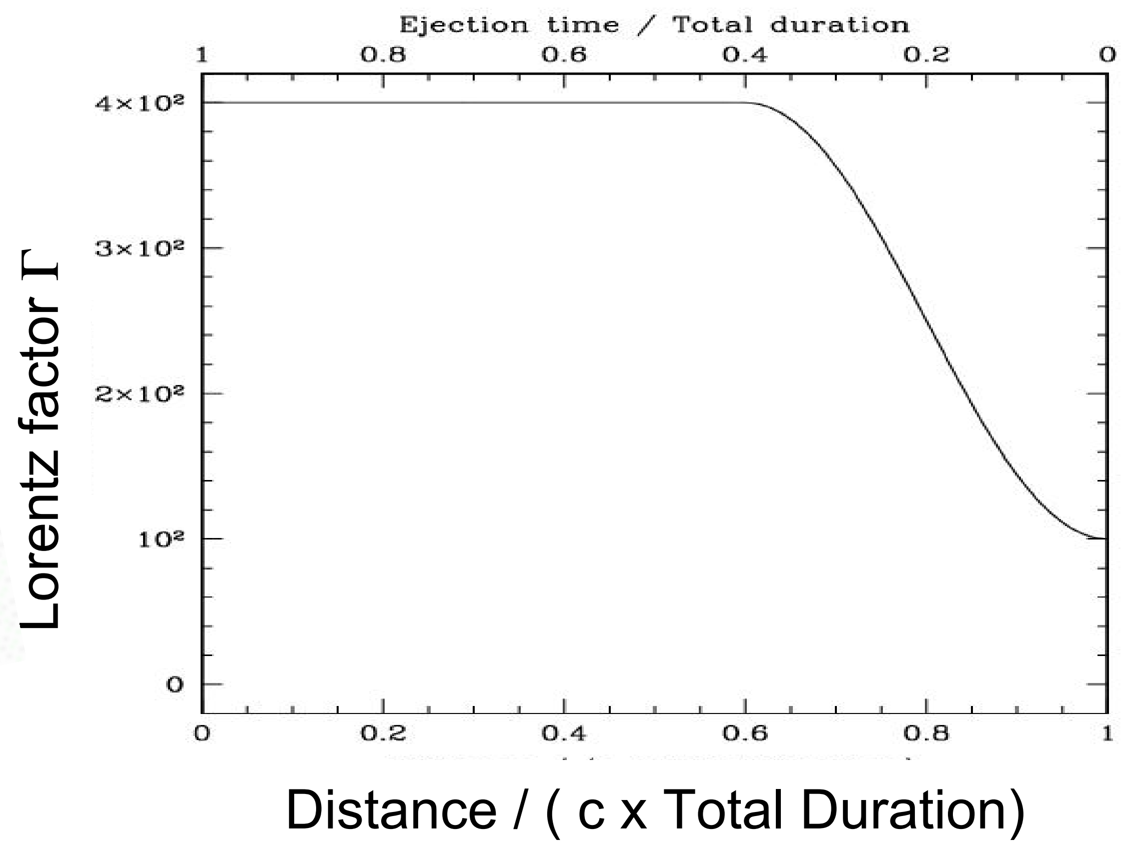
Input parameters: distribution of Lorentz factors $G(t)$, kinetic energy rate dE/dt during the relativistic ejection, total duration of the ejection phase t_w



D t = 2 ms

$t_w \sim 2$ s, N = 1000

$M_i \sim 1 / G_i$



$$R_{IS,\ start} \sim G^2 c t_{var} \sim 3 \times 10^{11}\ \mathrm{cm}\ (G/100)^2\ (t_{var}/1\ \mathrm{ms})$$

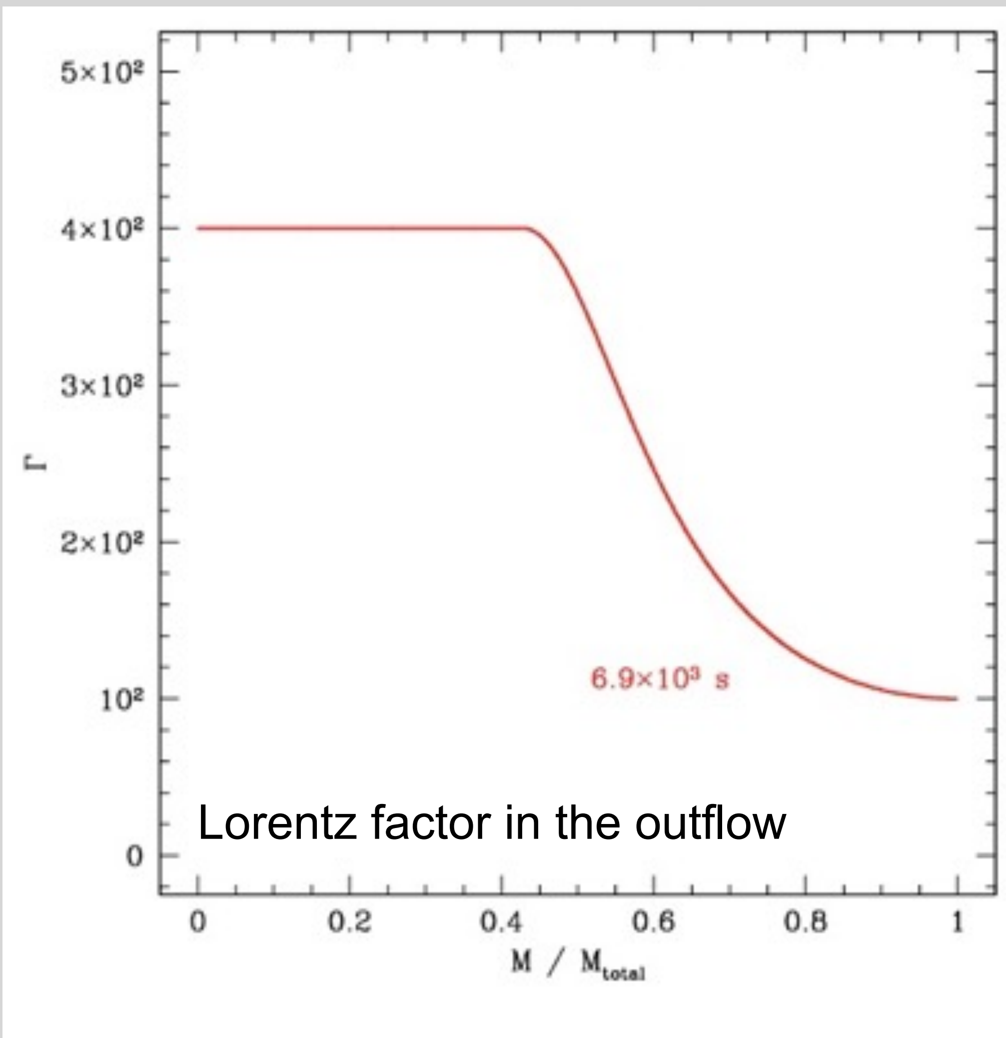
$$R_{IS,\ end} \sim G^2 c t_w \sim 3 \times 10^{15}\ \mathrm{cm}\ (G/100)^2\ (t_w/10\ \mathrm{s})$$

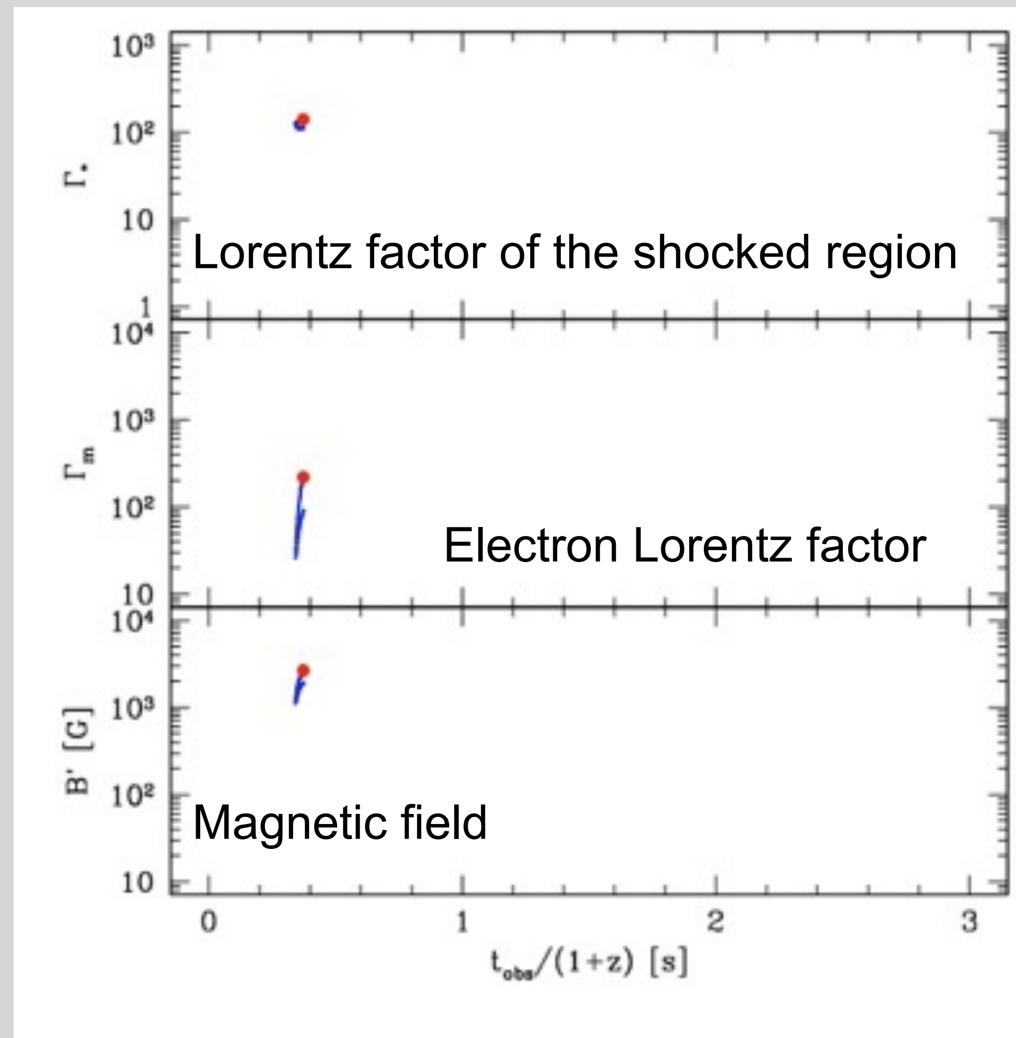
Dissipated energy: from 6% ($G_2 / G_1 = 2$) to 43 % ($G_2 / G_1 = 10$)

Daigne & Mochkovitch 2000: the simplified approach for dynamics has been confirmed by comparison with a full hydrodynamical calculation

Dynamics of the internal shocks

Physical conditions in the shocked medium: Lorentz factor G*, comoving density r*, comoving specific energy density e*





Dissipated energy is distributed between protons, electrons (fraction e_e) and magnetic field (fraction e_B)

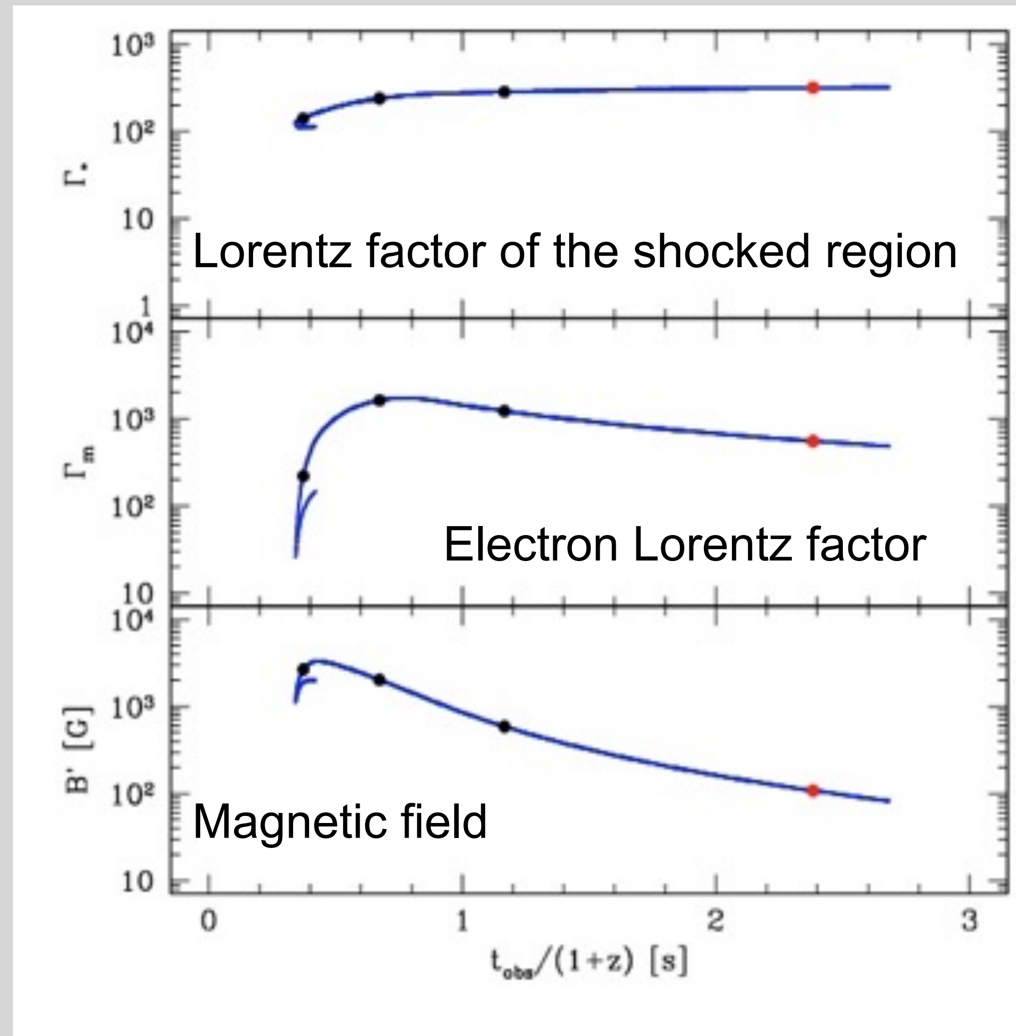
Dynamics of the internal shocks

Physical conditions in the shocked medium: Lorentz factor G*,
comoving density r*, comoving specific energy density e*

Relativistic electron density:

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

z < 1 of all electrons is accelerated



Dissipated energy is distributed between protons, electrons (fraction e_e) and magnetic field (fraction e_B)

Radiative processes

Assumption: instantaneous shock acceleration

Adiabatic cooling timescale: t\`ex = R / G* 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
- gg annihilation

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

ELECTRONS:

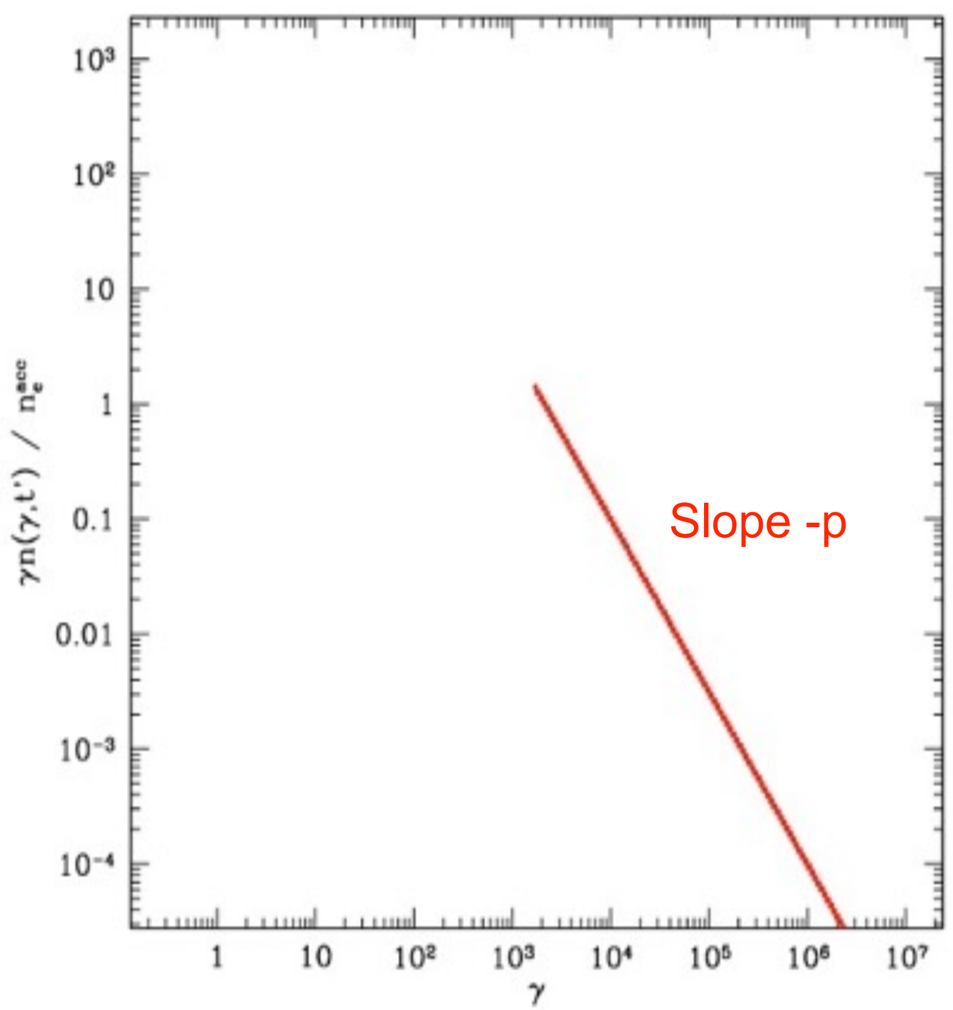
$$\frac{\partial n'}{\partial t'}(\Gamma'_e, t') = -\frac{\partial}{\partial \Gamma'_e}\left[\left(\frac{d\Gamma'_e}{dt'}\bigg|_{syn+ic} + \frac{d\Gamma'_e}{dt'}\bigg|_{ad}\right) n'(\Gamma'_e, t')\right]$$

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

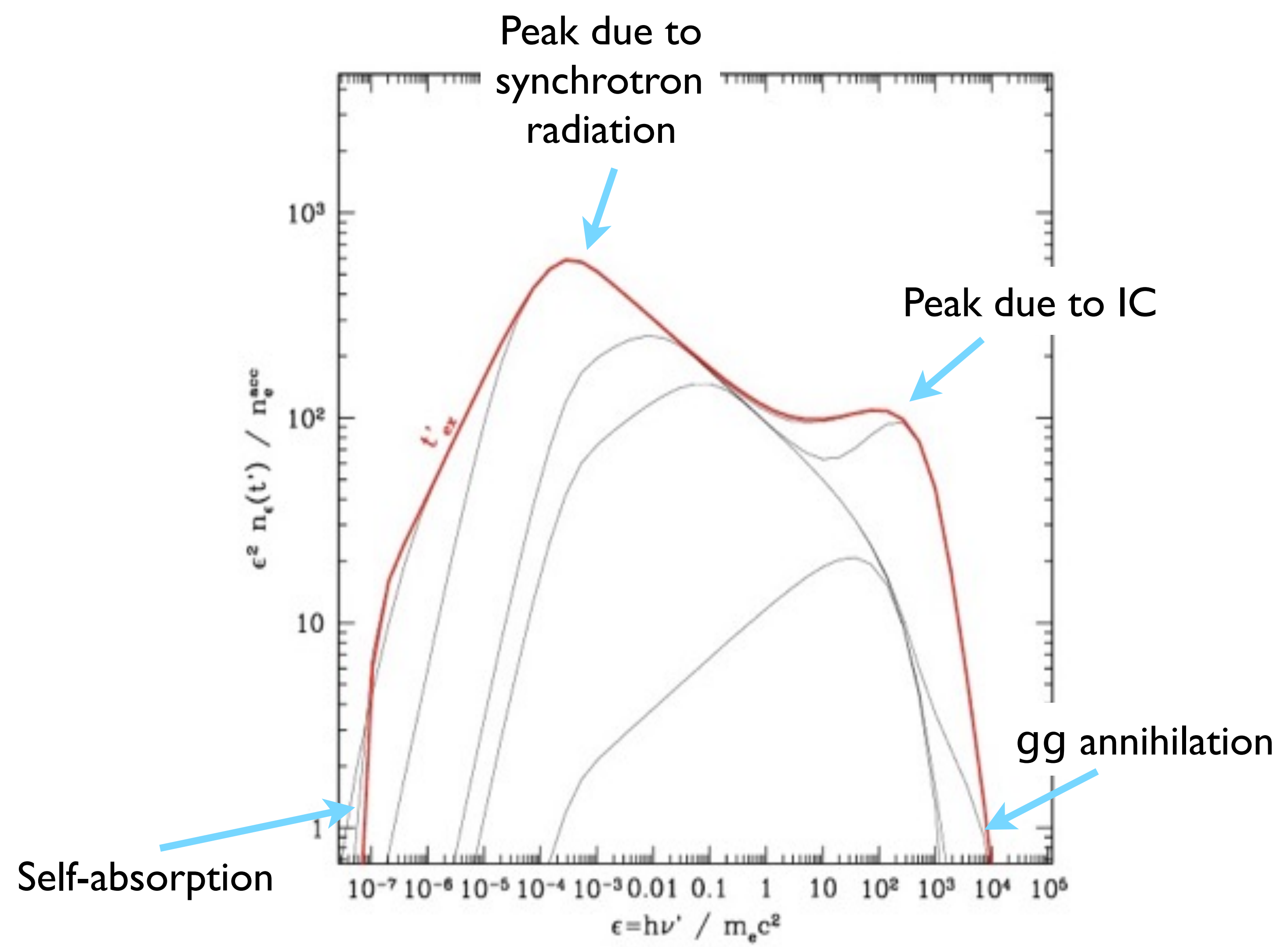
Radiative processes

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



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)

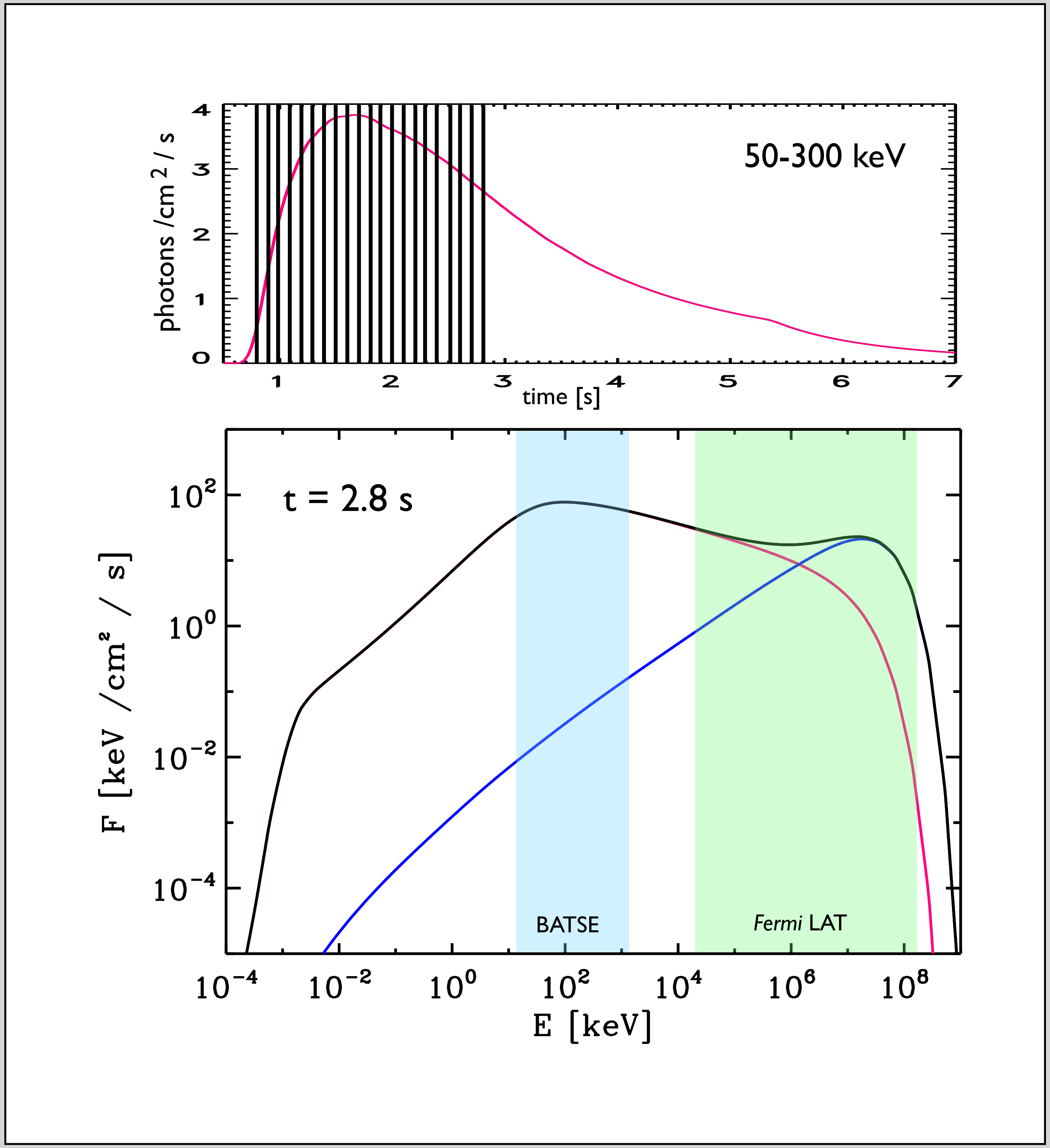
Observed spectra and time profiles

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



Dominant radiative process in sub-MeV range?

2 possibilities:

1. SYNCHROTRON

High Γ_m requires that only a fraction of the electrons is accelerated (<10%)

High B: no IC component at high energy

Low B: IC component at high energy

2. INVERSE COMPTON

All electrons are accelerated

Synchrotron component at low energy

Second inverse Compton peak at high energy

Piran et al. 2008: crisis for the GRB energy budget

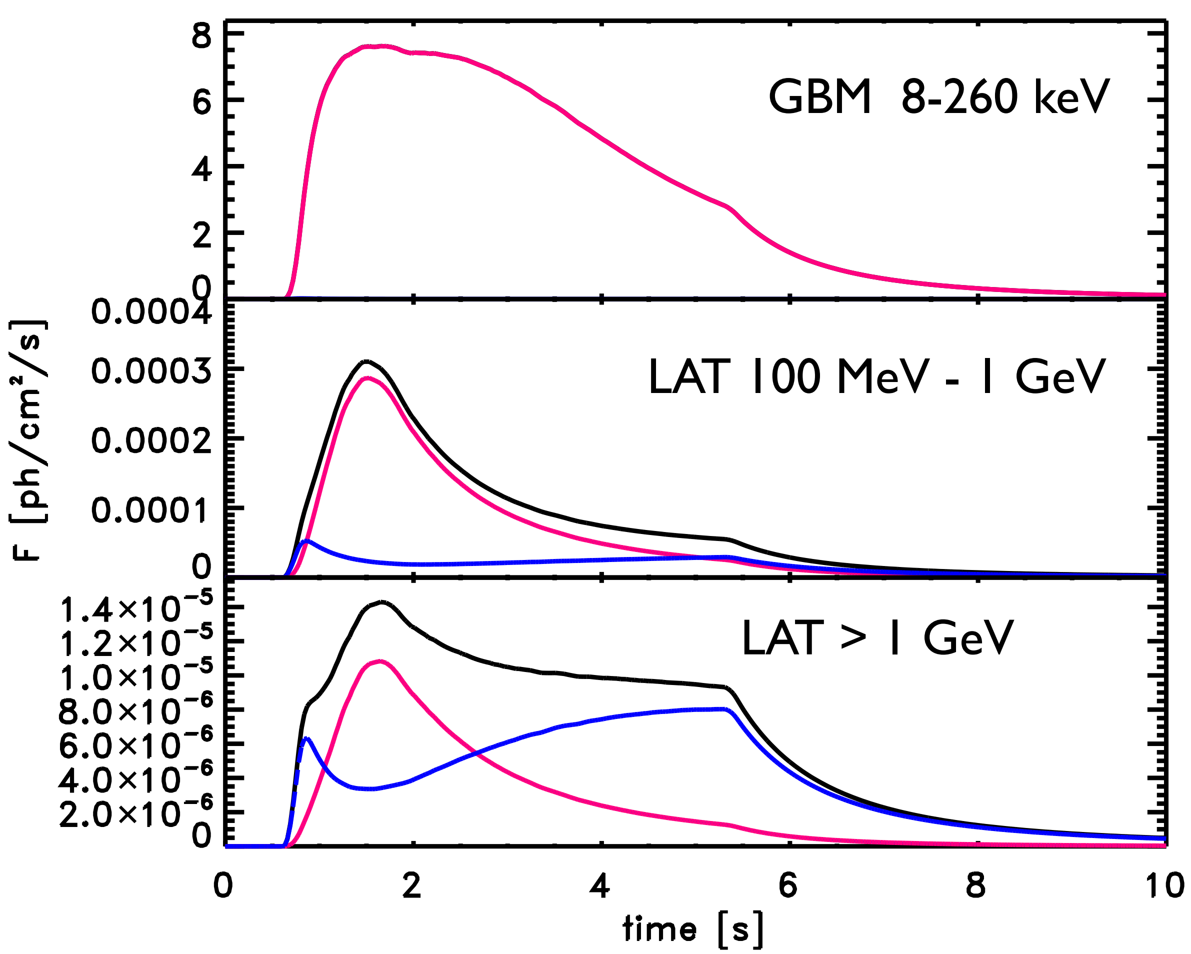
A steep electron slope (p>3) is required to have two well defined peaks

Dominant radiative process in sub-MeV range?

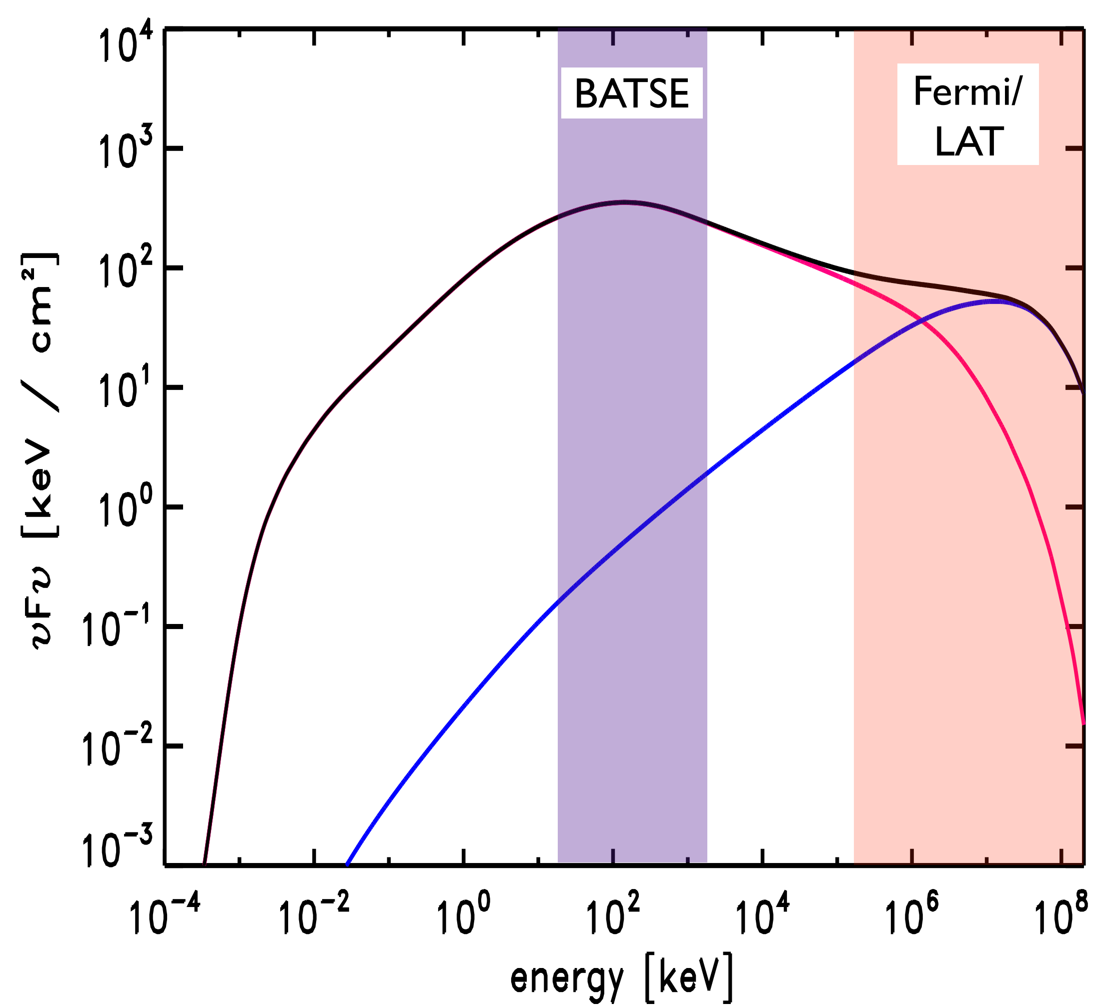
SYNCHROTRON CASE (A)

high magnetic field

$dE/dt = 5 \times 10^{53}$ erg s^{-1}, $e_B = e_e = 1/3$, $z = 0.003$, $p = 2.5$,
$z=1$



Observed lightcurve



Observed spectrum

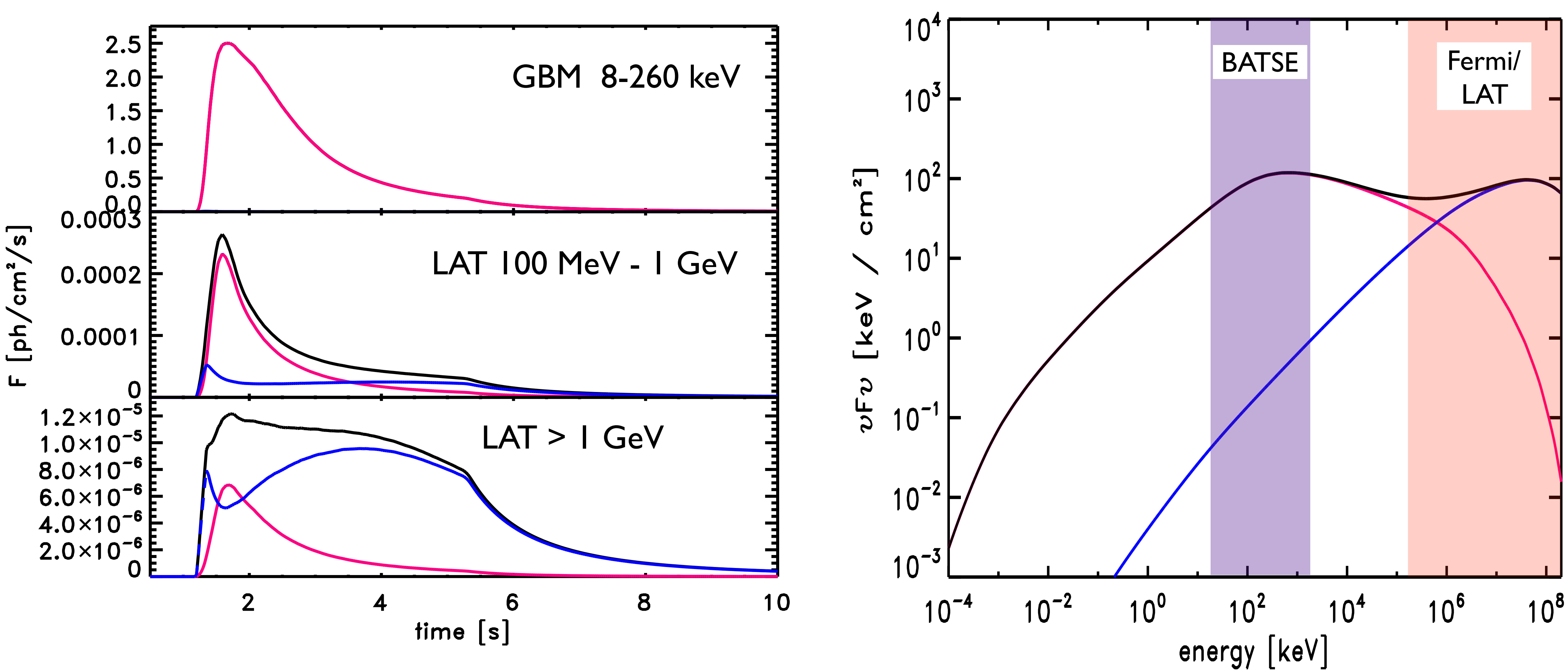
synchrotron
inverse Compton
total

Dominant radiative process in sub-MeV range?

SYNCHROTRON CASE (B)

low magnetic field

$dE/dt = 5 \times 10^{53}$ erg s^{-1}, $e_B = 0.003$, $e_e = 1/3$, $z = 0.003$, $p = 2.5$, $z=1$



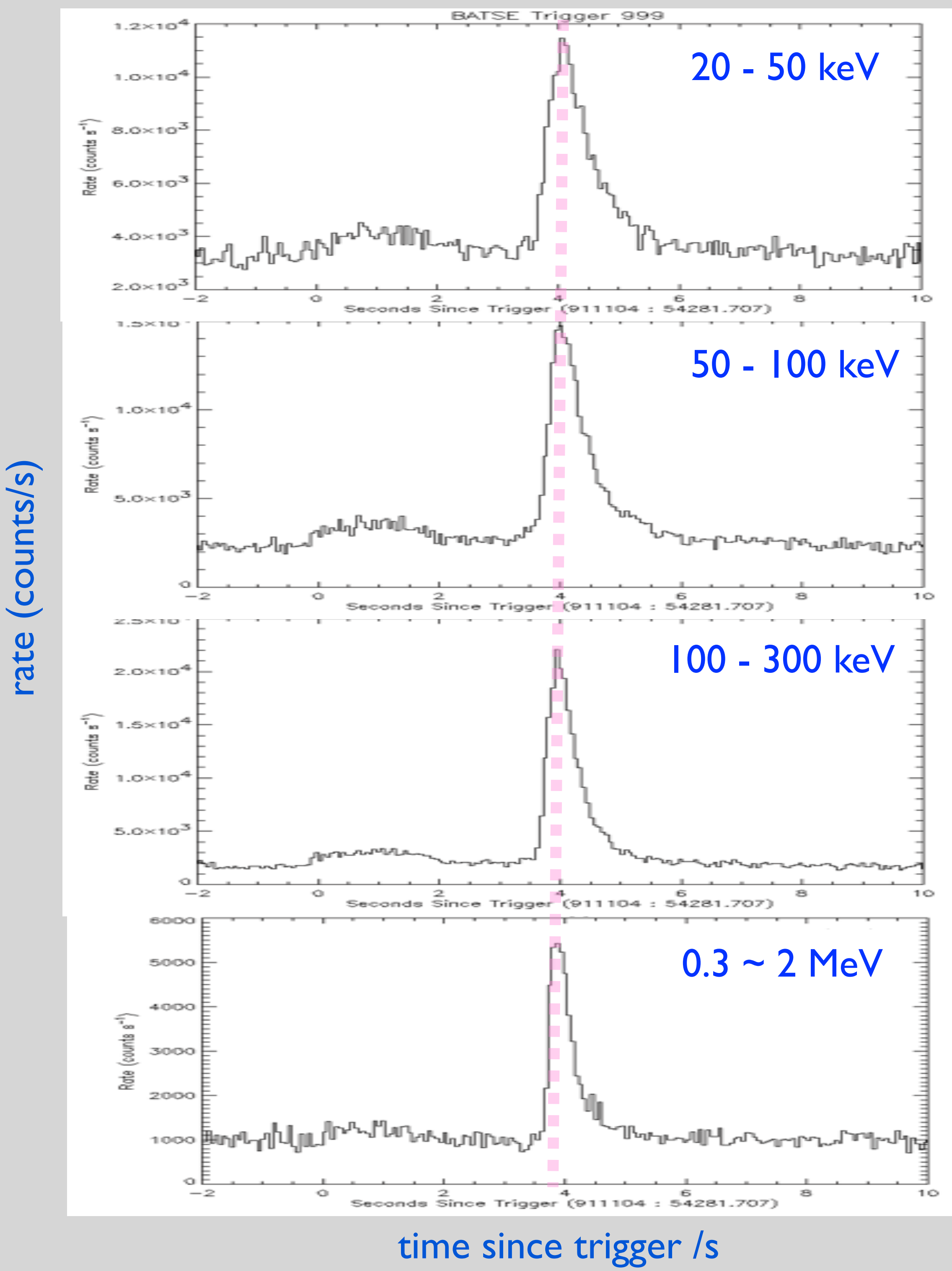
Observed lightcurve

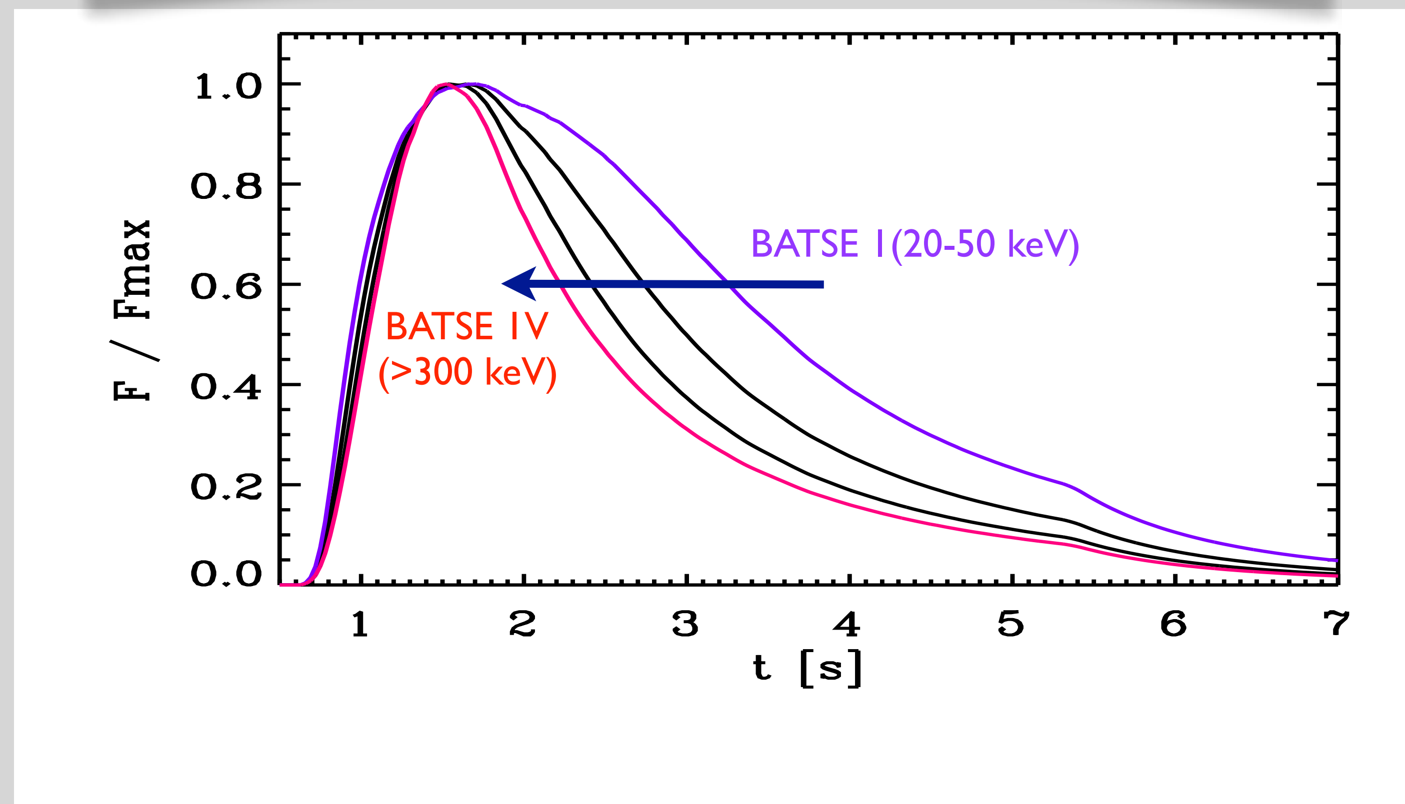
Observed spectrum

synchrotron
inverse Compton
total

Temporal profiles: sub-MeV range

Model: dominant synchrotron emission in sub-MeV range



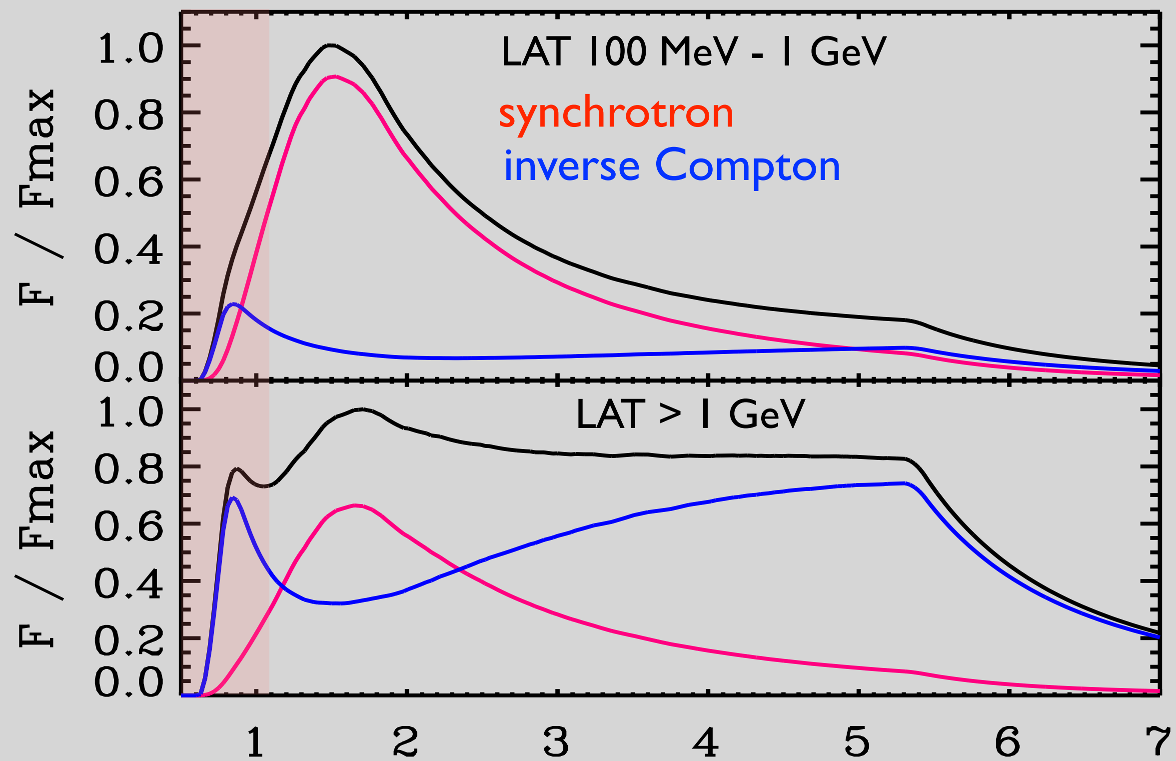


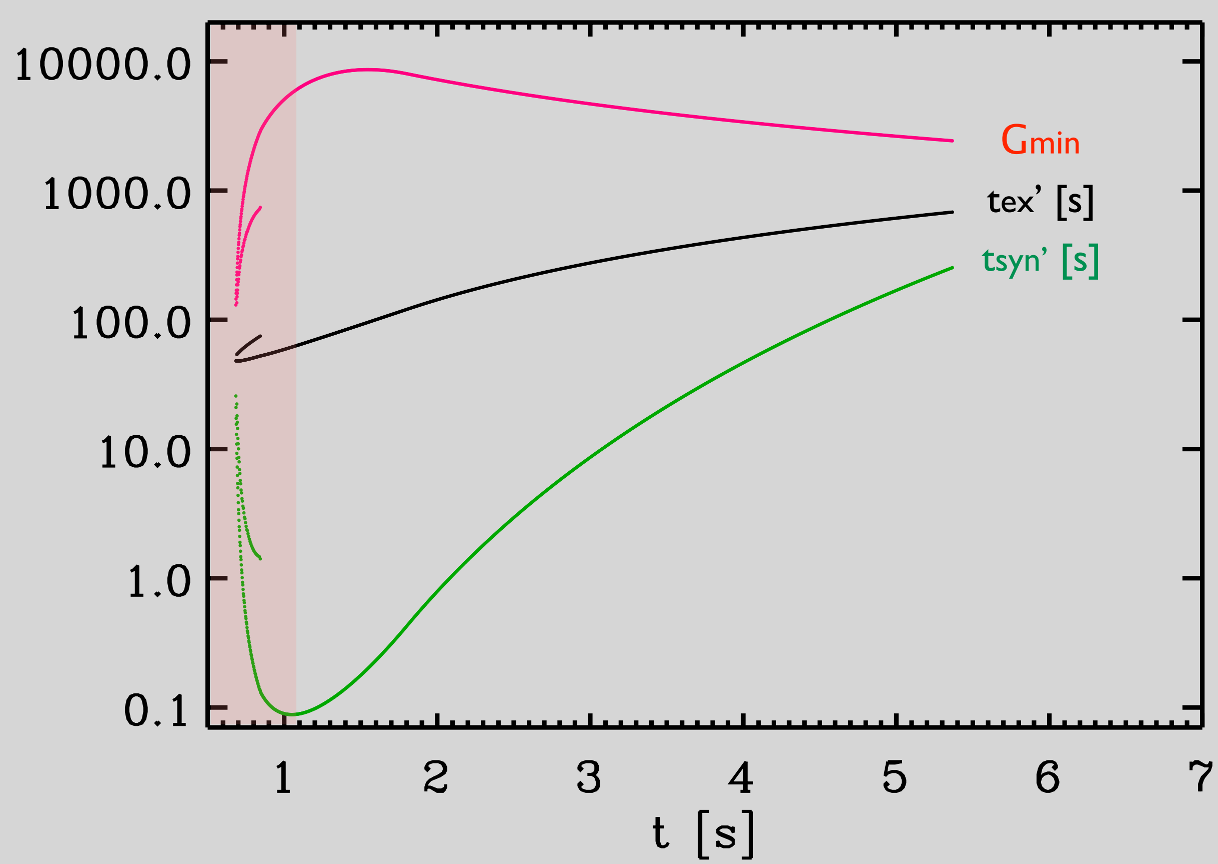
$W(E) \sim E^{-a}$ $\quad a \simeq 0.40$

Fenimore et al 1995
Norris et al 1996
Bissaldi et al. 2011

Temporal profiles: > 100 MeV bands

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





weak shock

e* low

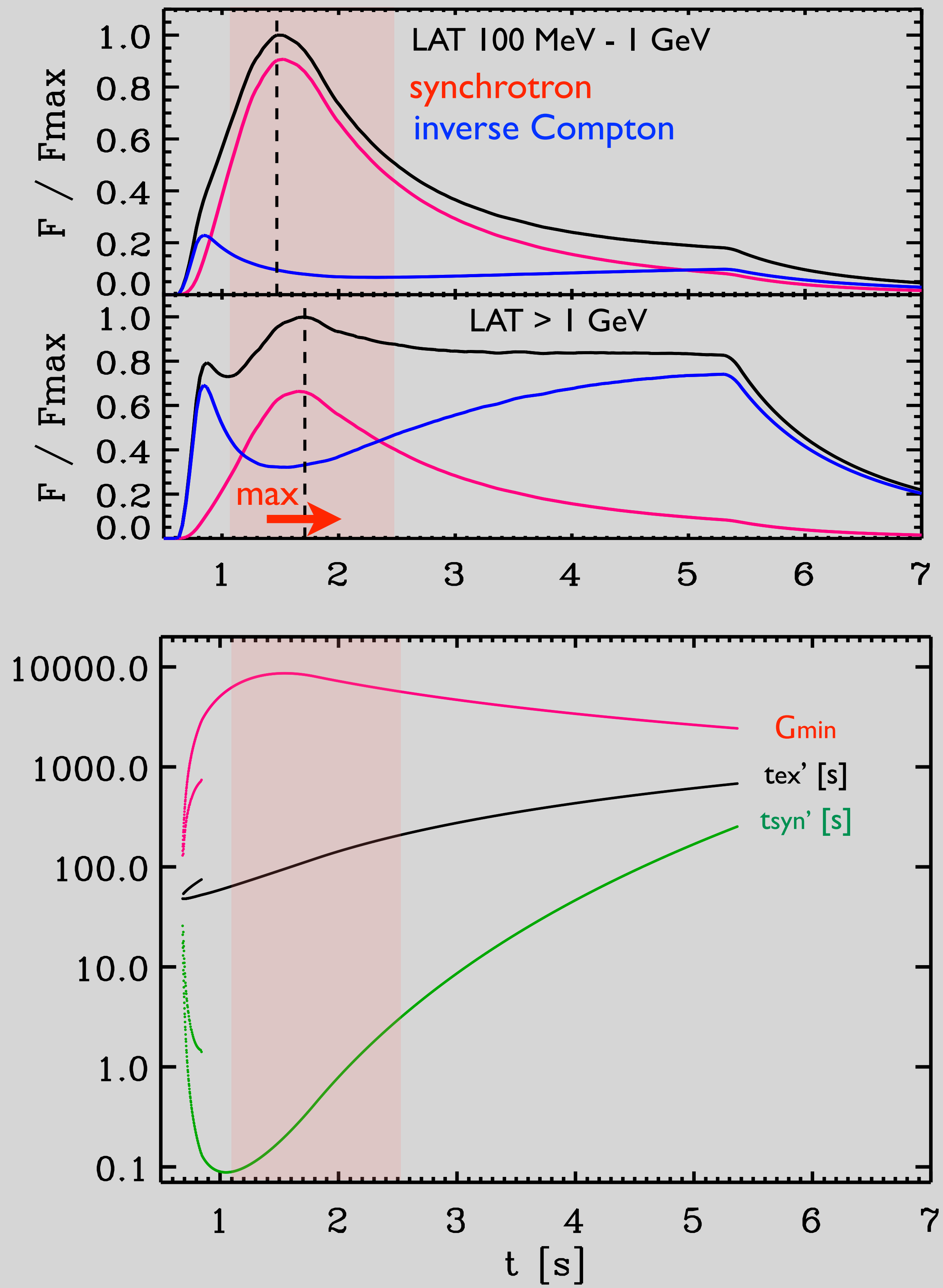
moderate Gm ⇒ large tsyn'

R small ⇒ tex' ≅ R/G*c small

tsyn' ≤ tex' ⇒ large efficiency of IC

Temporal profiles: > 100 MeV bands

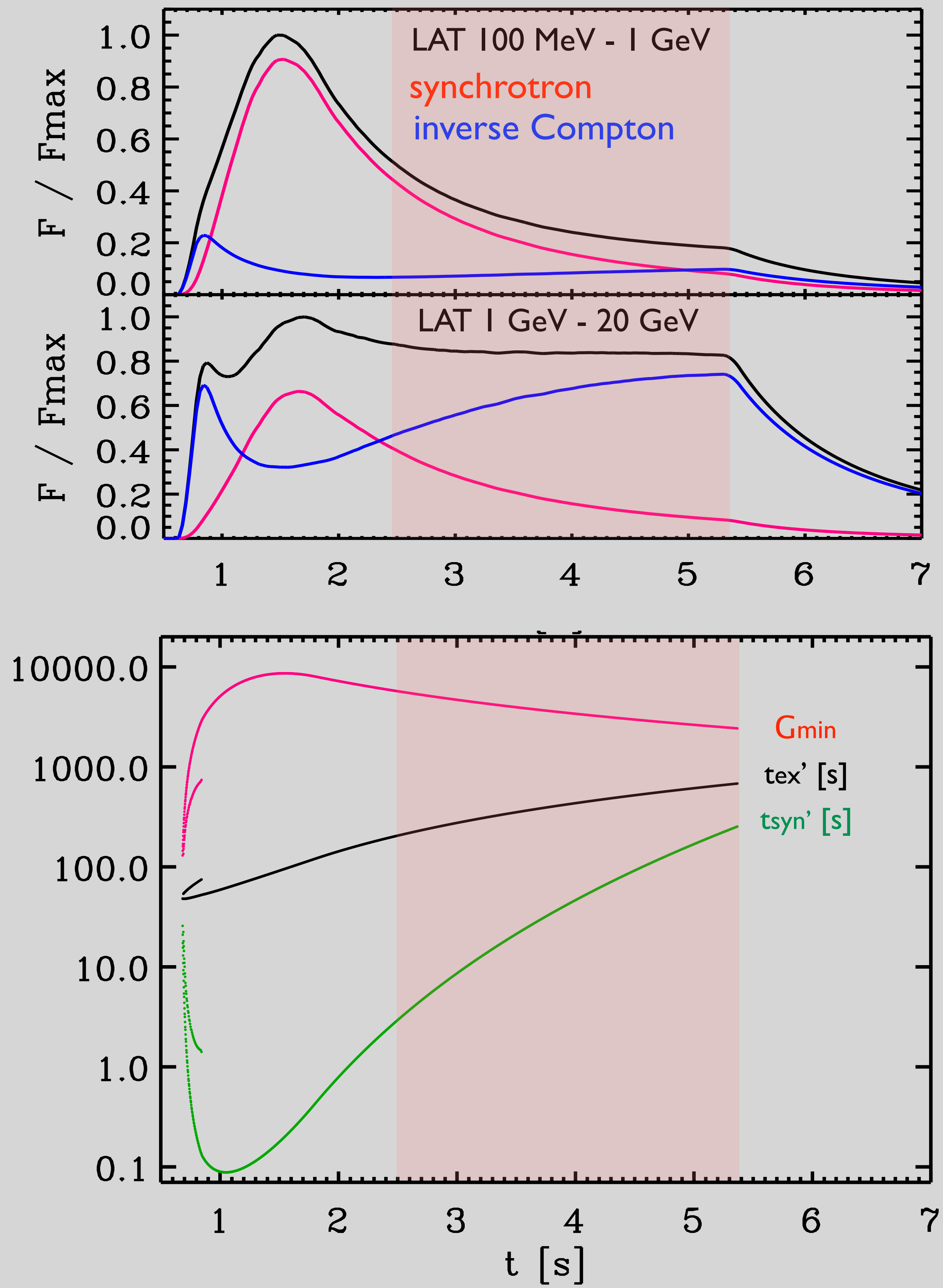
Model: in LAT (>100 MeV) energy bands both components present, synchrotron + IC



shock becomes stronger
Gm 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

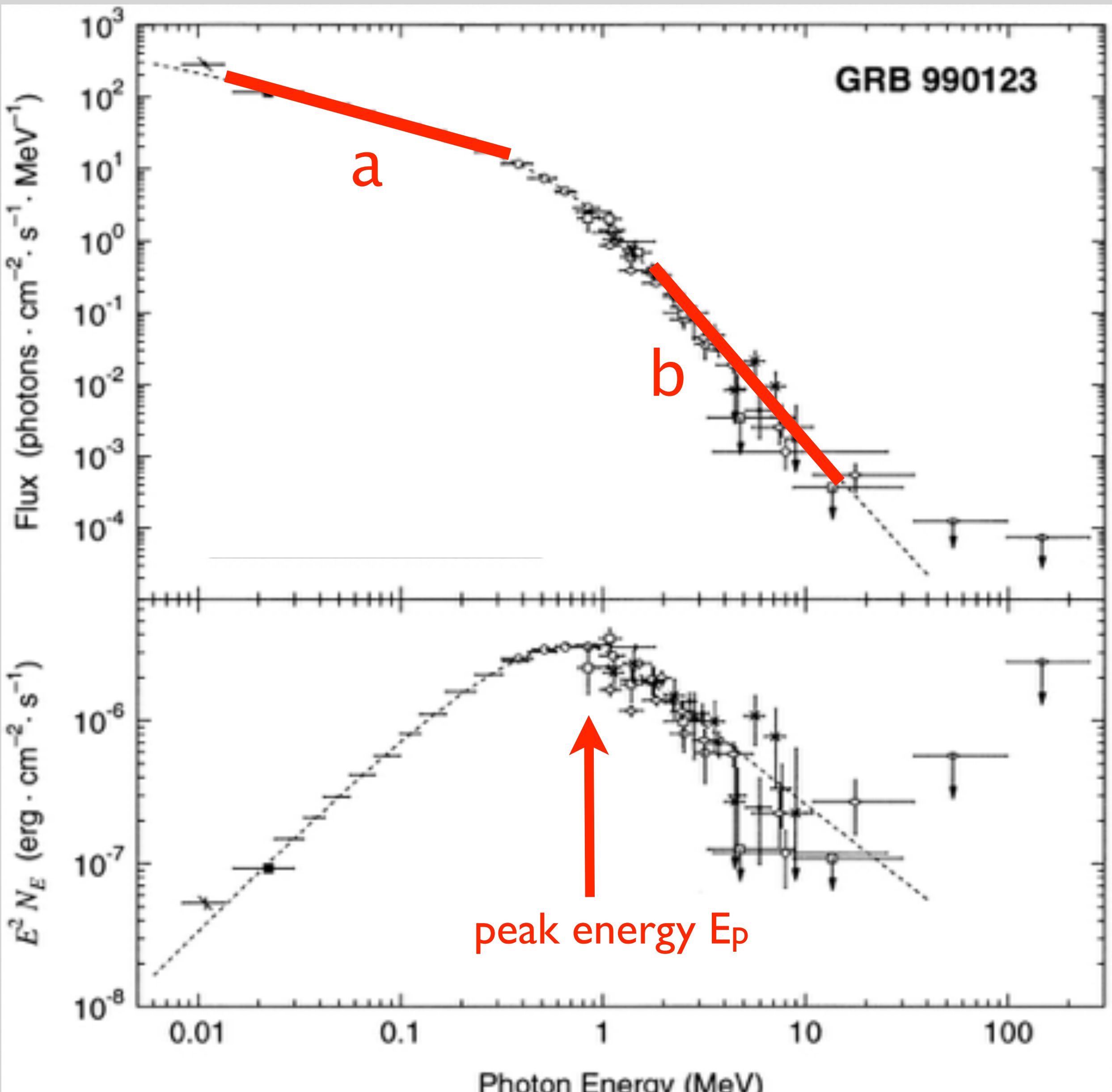
IC component dominant in GeV

Spectral properties

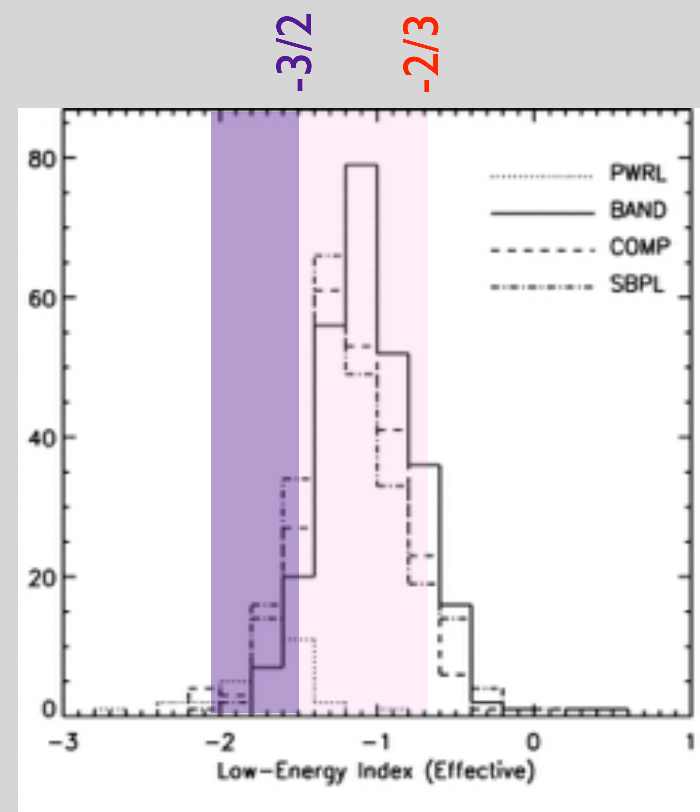
4-parameters “Band spectrum”

E_p, a, b and normalization

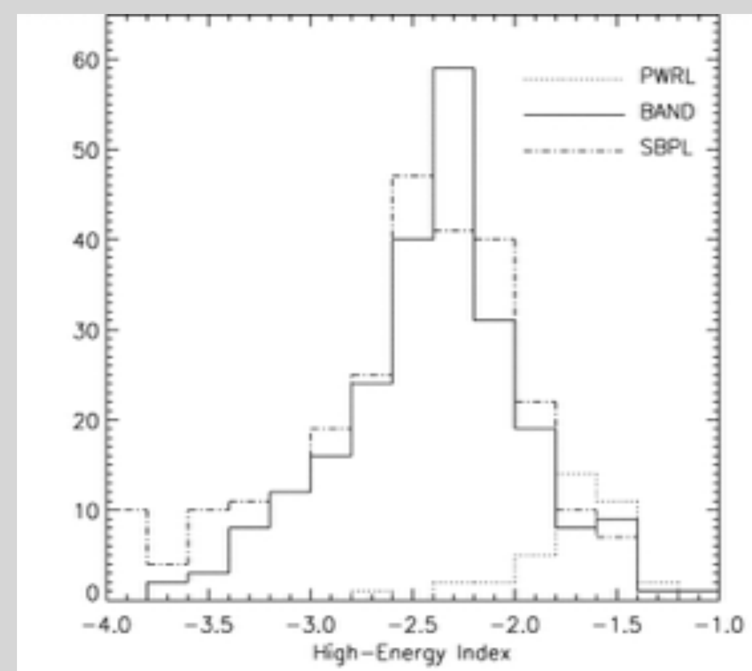
Band et al. 1993



Briggs et al. 1999



a = -1.02 ± 0.27



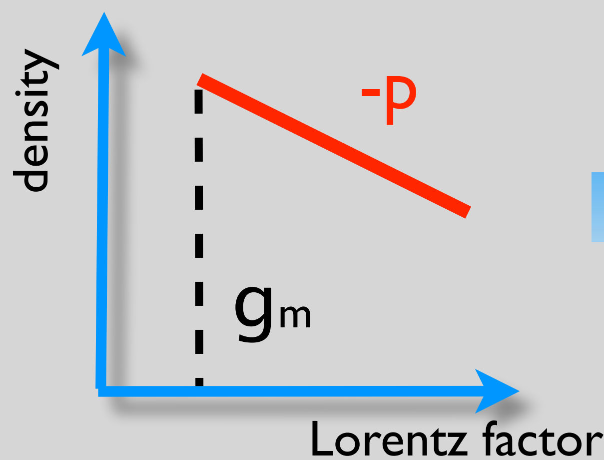
b = -2.35 ± 0.27

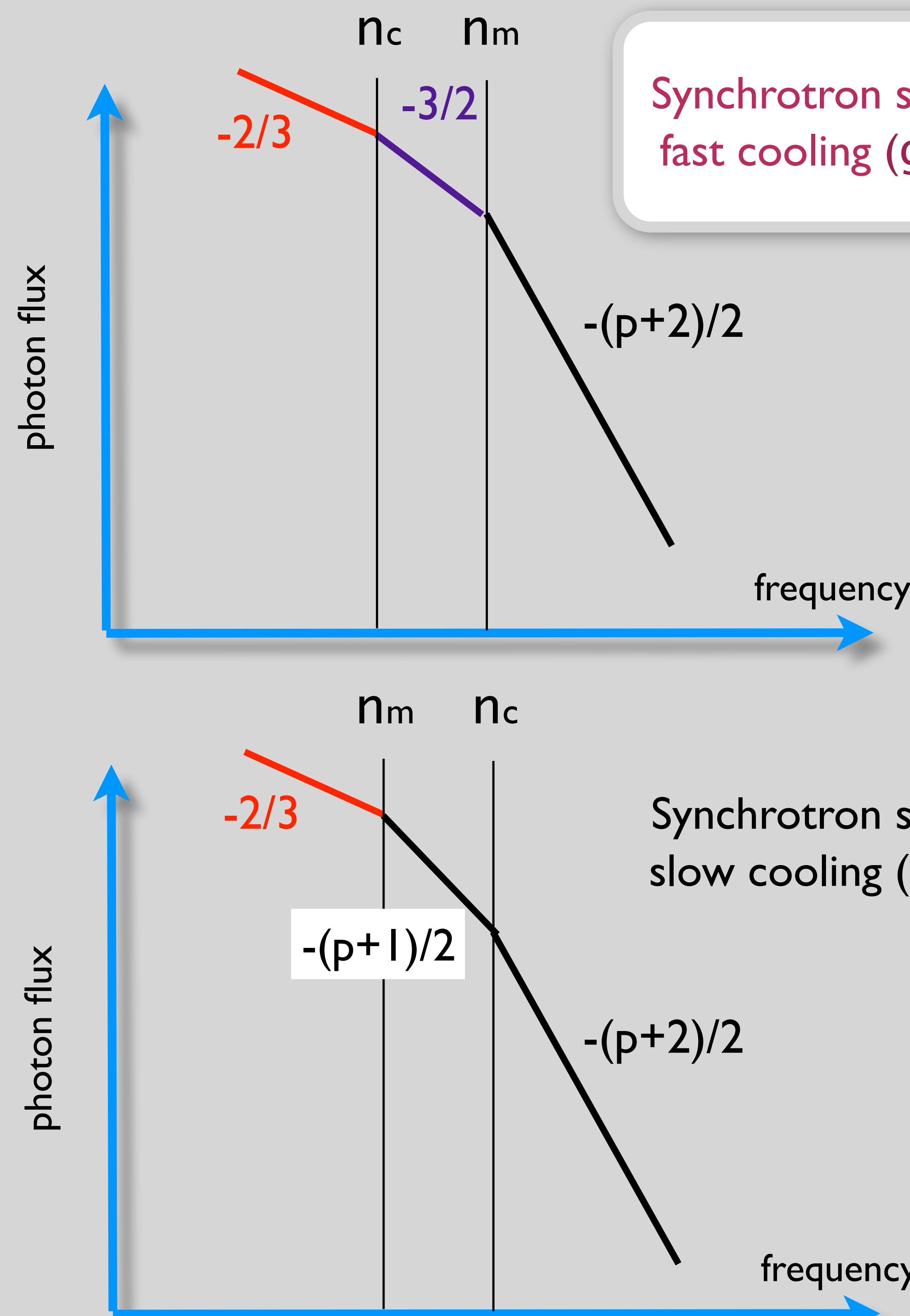
Kaneko et al. 2006

Spectral properties

Sari, Piran & Narayan 1998

Relativistic electrons:





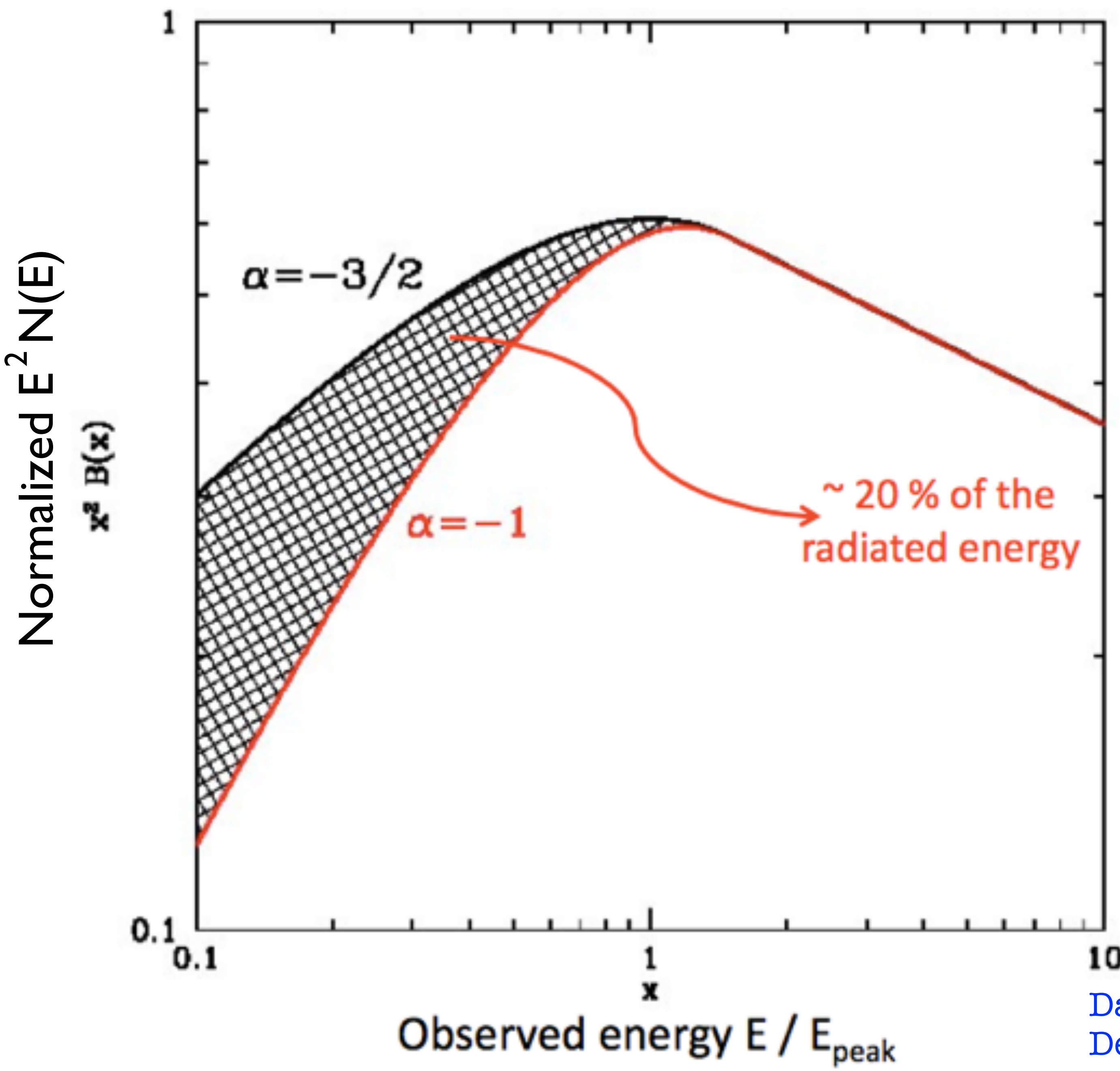
Synchrotron spectrum:
fast cooling ($g_c < g_m$)

Synchrotron spectrum:
slow cooling ($g_c > g_m$)

g_m: minimum Lorentz factor at injection

g_c: radiative timescale = dynamical timescale

Spectral properties



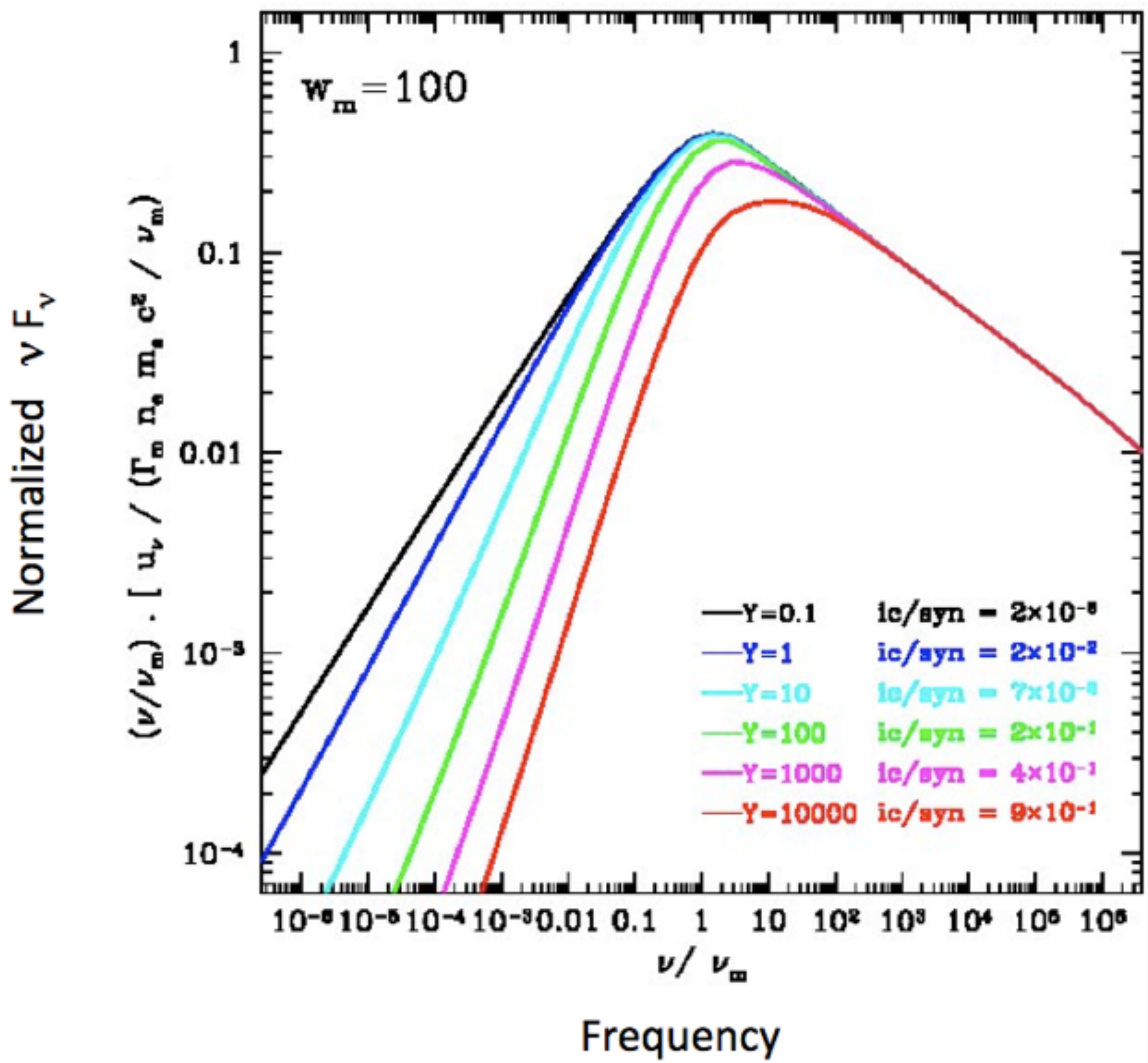
Band function

a = - 1.5 → -1
b = - 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

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

Y : importance of IC vs syn

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

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

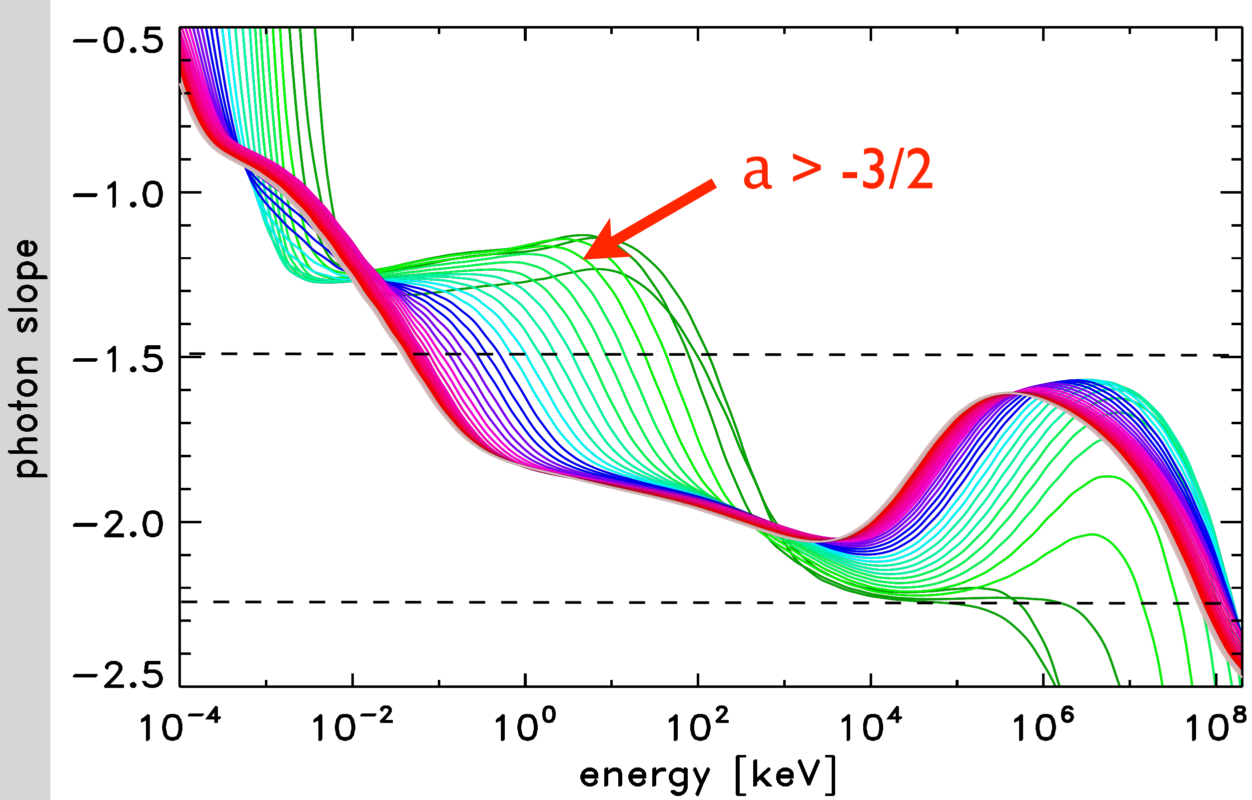
Exact calculation with synchrotron + IC only
(no adiabatic cooling, synchrotron self-absorption, $\gamma\gamma$ annihilation)

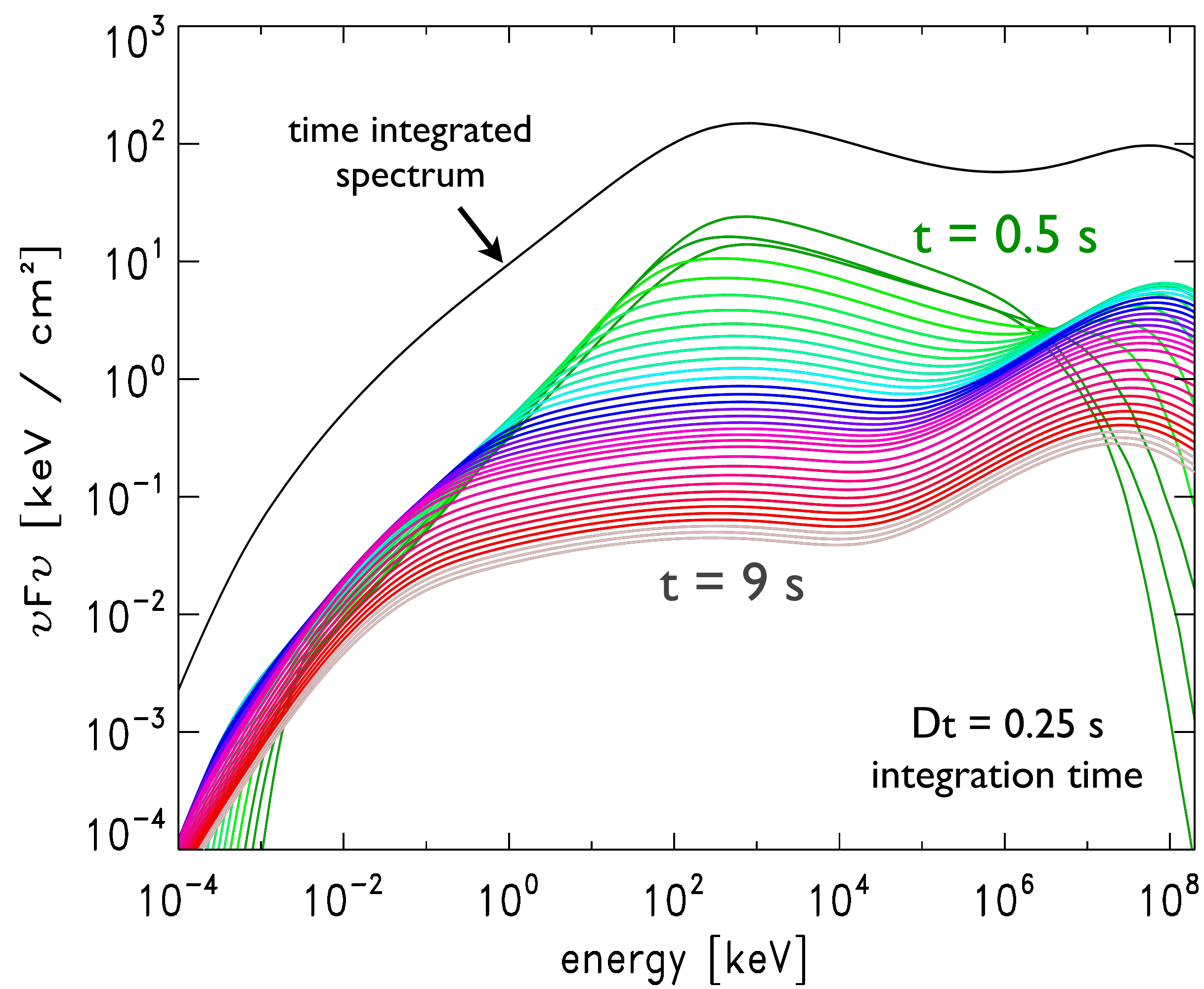
Spectral properties

SYNCHROTRON CASE (B)

low magnetic field

dE/dt = 5 x 10 erg s, e_B = 0.003, e_e = 1/3, z = 0.003, p = 2.5, z=1





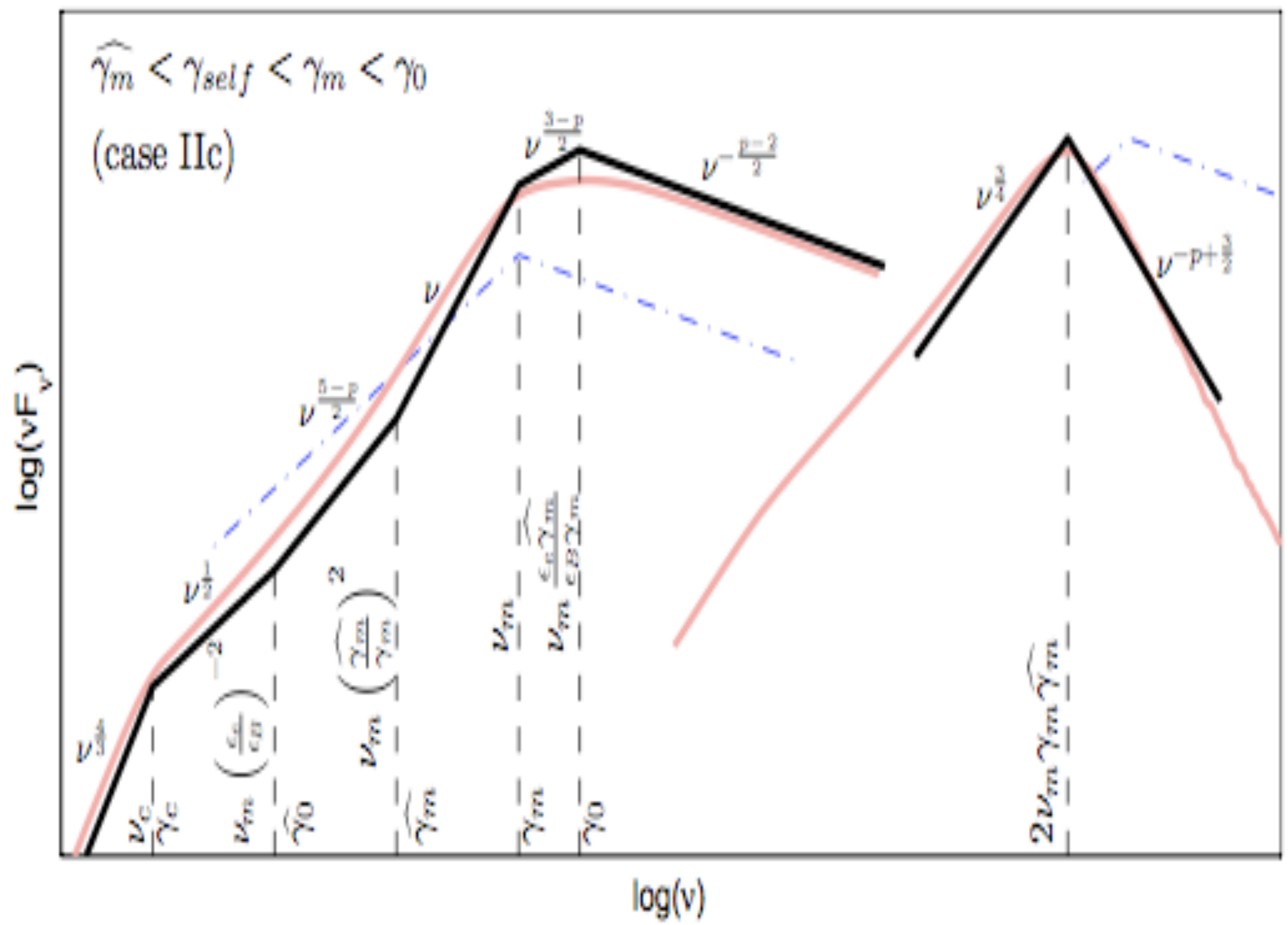
Time resolved spectra

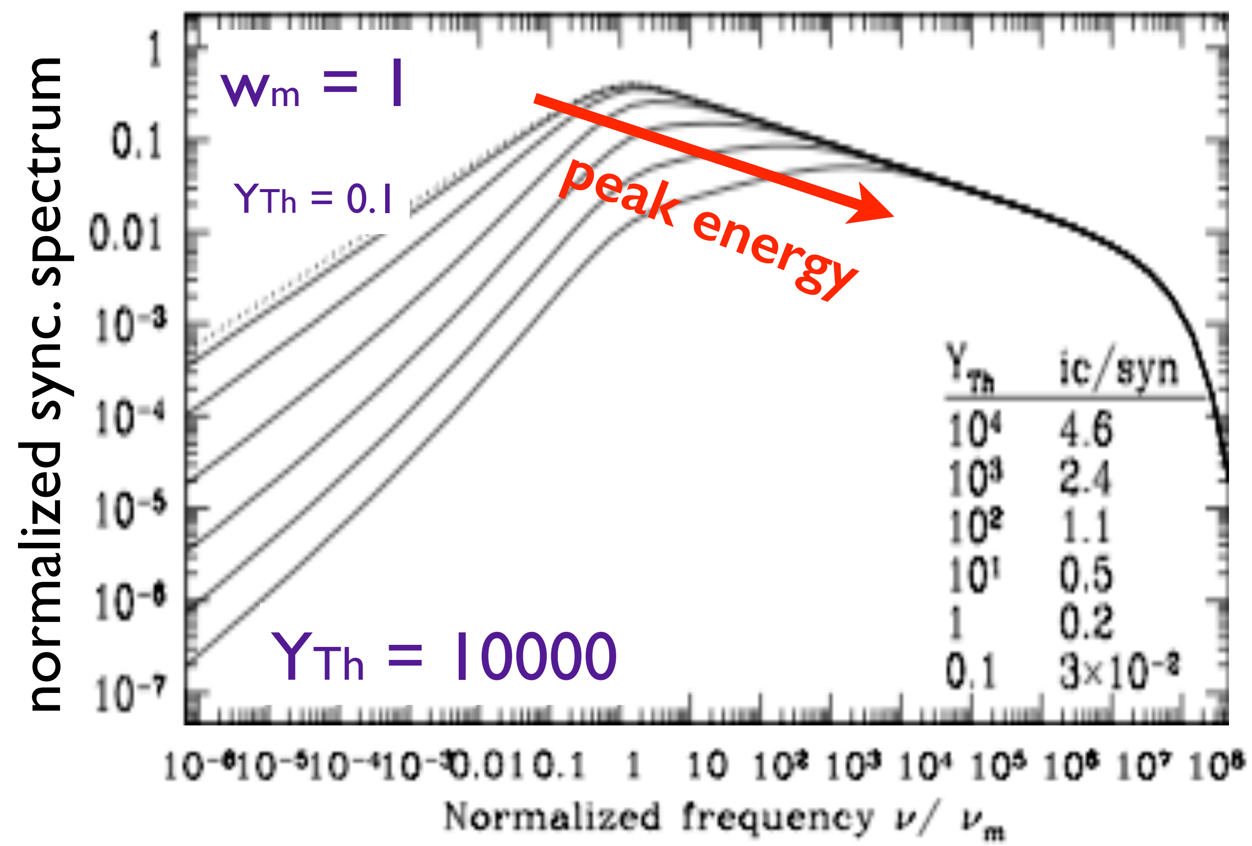
a = -3/2

low energy spectral slope
of the fast cooling synchrotron
spectrum

Spectral/temporal behavior

Spectral peak energy is affected by inverse Compton scatterings



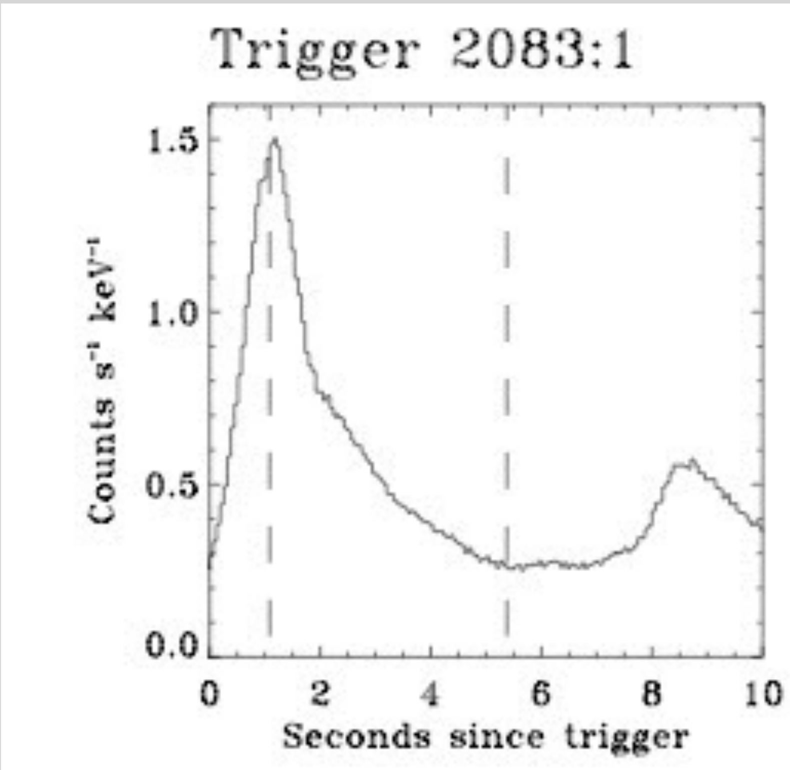


Nakar, Ando & Sari 2009

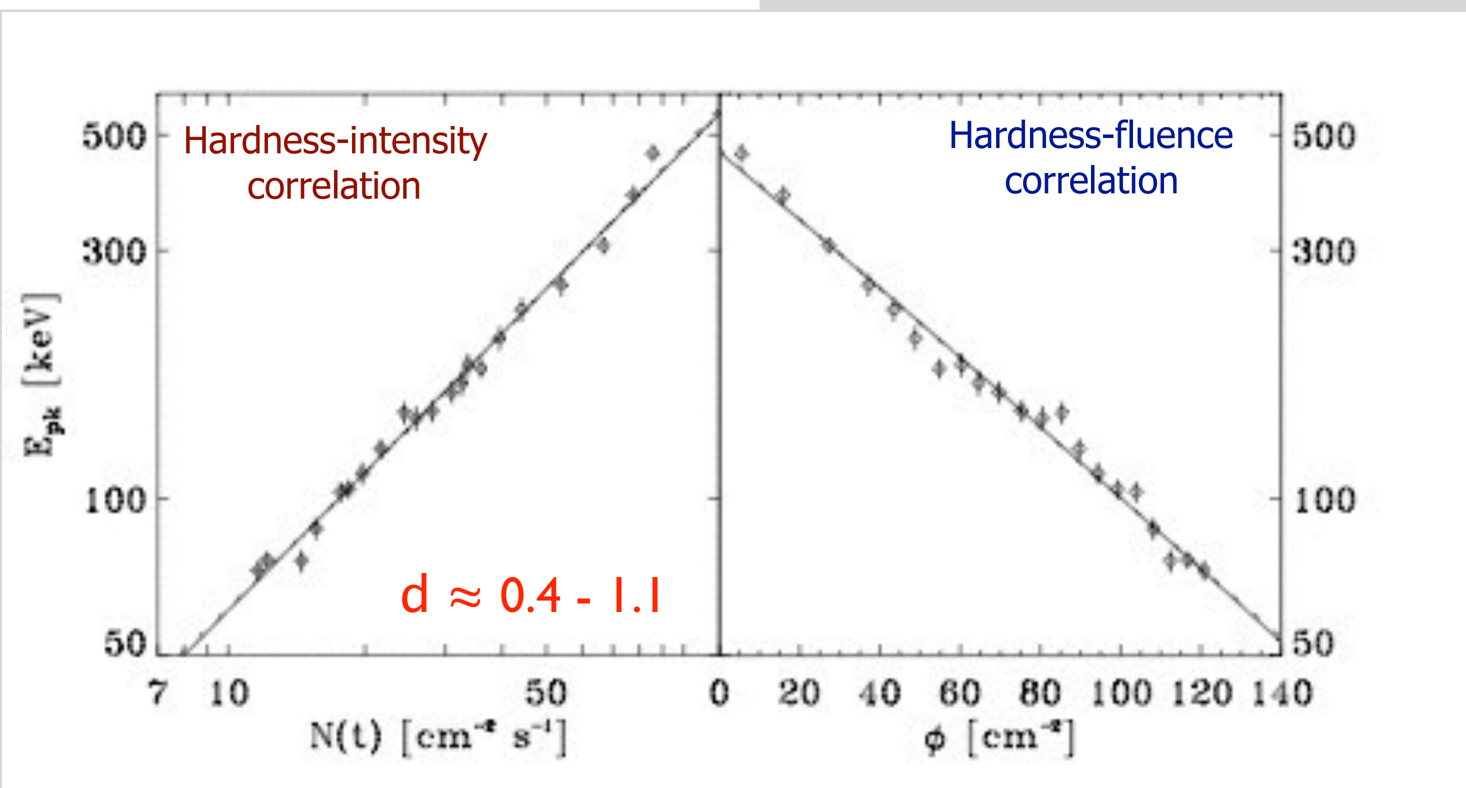
Daigne, Bosnjak & Dubus 2011

Numerical simulations show that this problem can be solved by a steeper slope of the relativistic electron distribution ($p > 2.7$-2.8) responsible for the emission is adopted (Bosnjak & Daigne 2014).

Hardness-intensity (HIC) & hardness-fluence (HFC) correlations



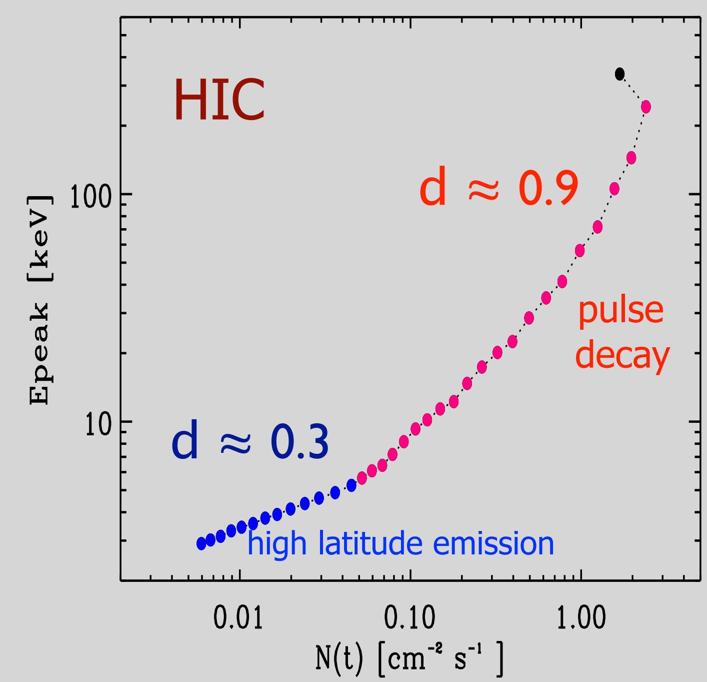
Kargatis 1995
Liang & Kargatis 1996
Ryde & Svensson 2002

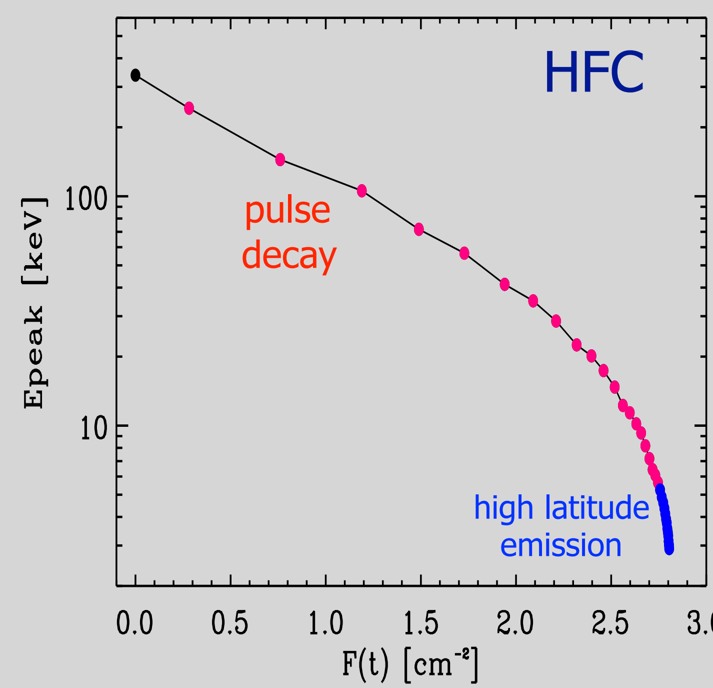


$$E_{pk}(N) = E_{pk,\,0}(N/N_0)^{\delta}$$

$$E_{pk}(\Phi) = E_{pk,\,max}\, e^{-\Phi/\Phi_0}$$

Bosnjak & Daigne 2014



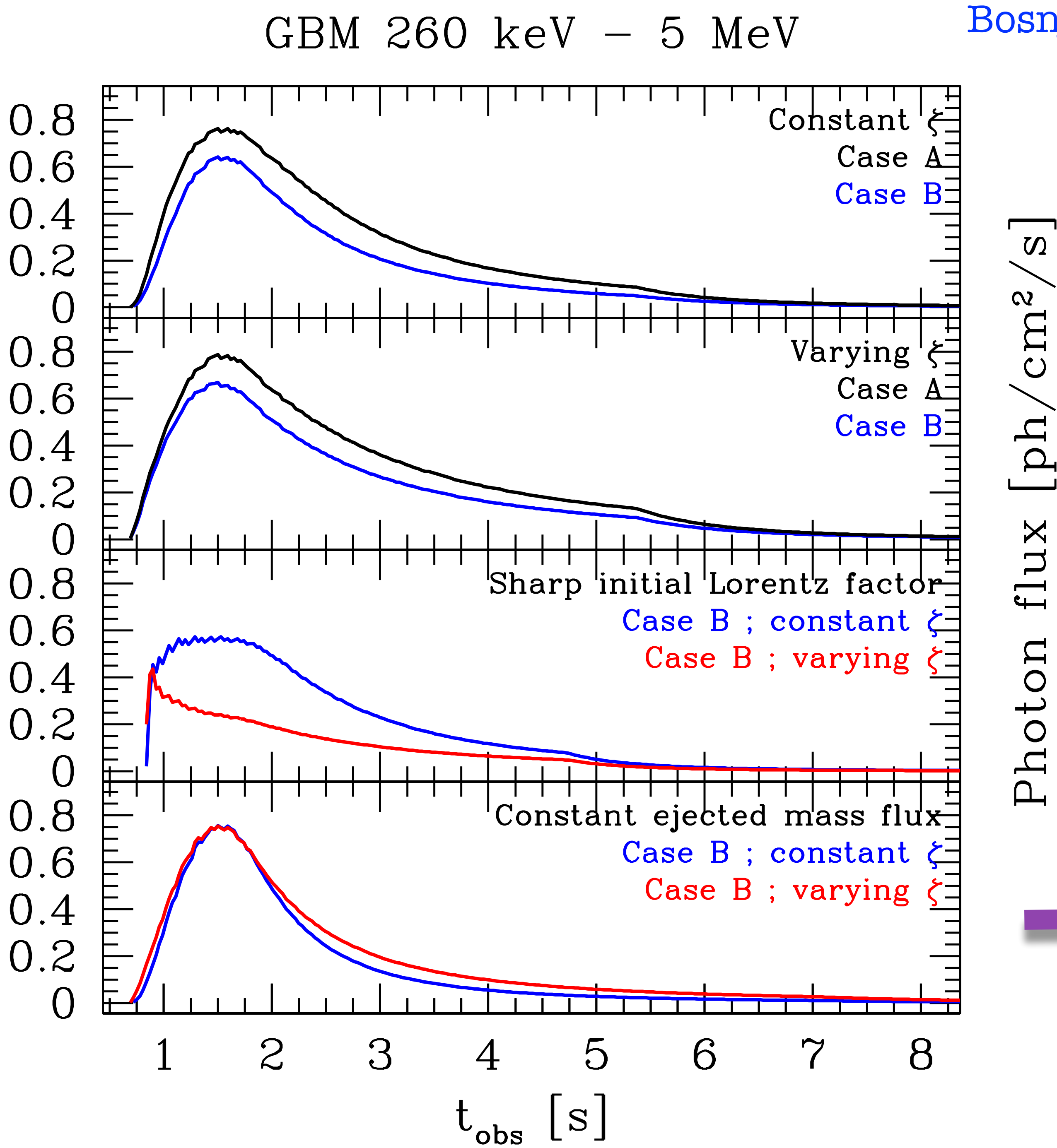


HLE: $E_p \propto 1/\, t_{obs}$

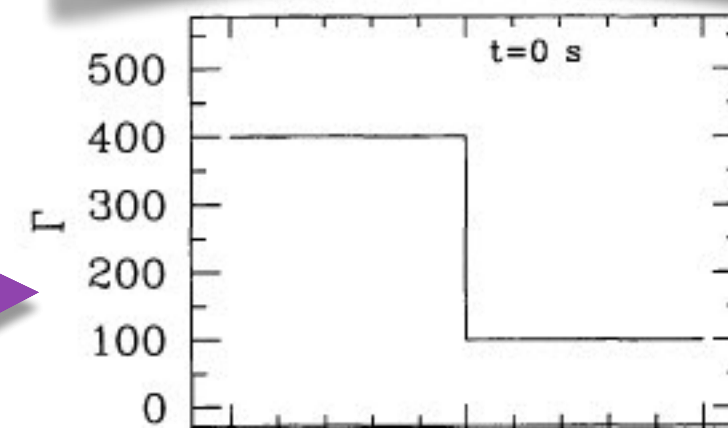
$F_{bol} \propto 1/\, t_{obs}^3$

High energy emission: light curves

Bosnjak & Daigne 2014



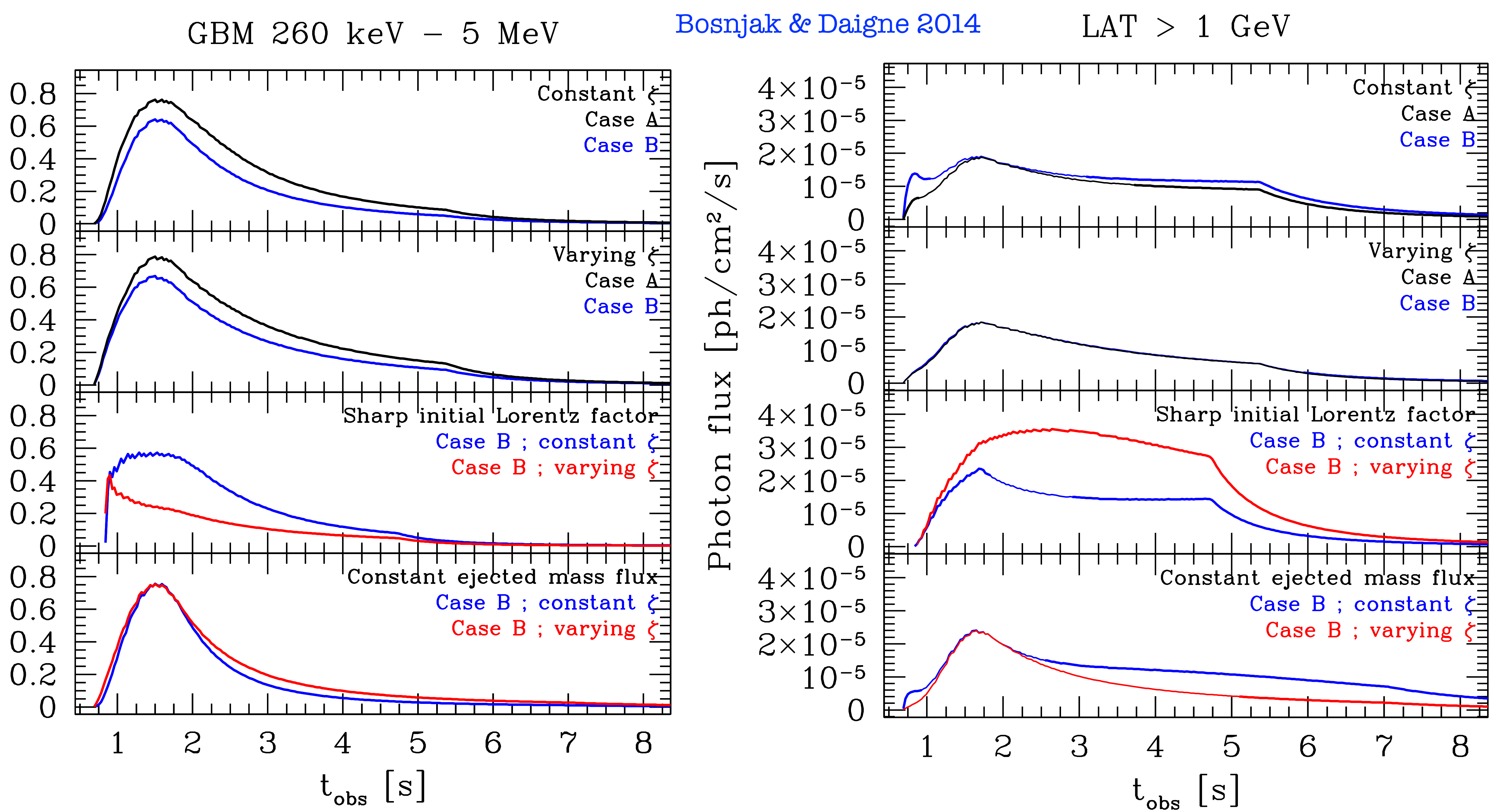
'Sharp' initial Lorentz factor:



Constant ejected mass flux:
dE/dt ∝ G

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 favour 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, e_B, z) in order to have a quantitative agreement**

Further developments: we are currently **modeling the GRBs observed by Fermi using these numerical tools, and making predictions on future HE observations**