GRB spectral evolution in the internal shock model: confrontation with Fermi observations

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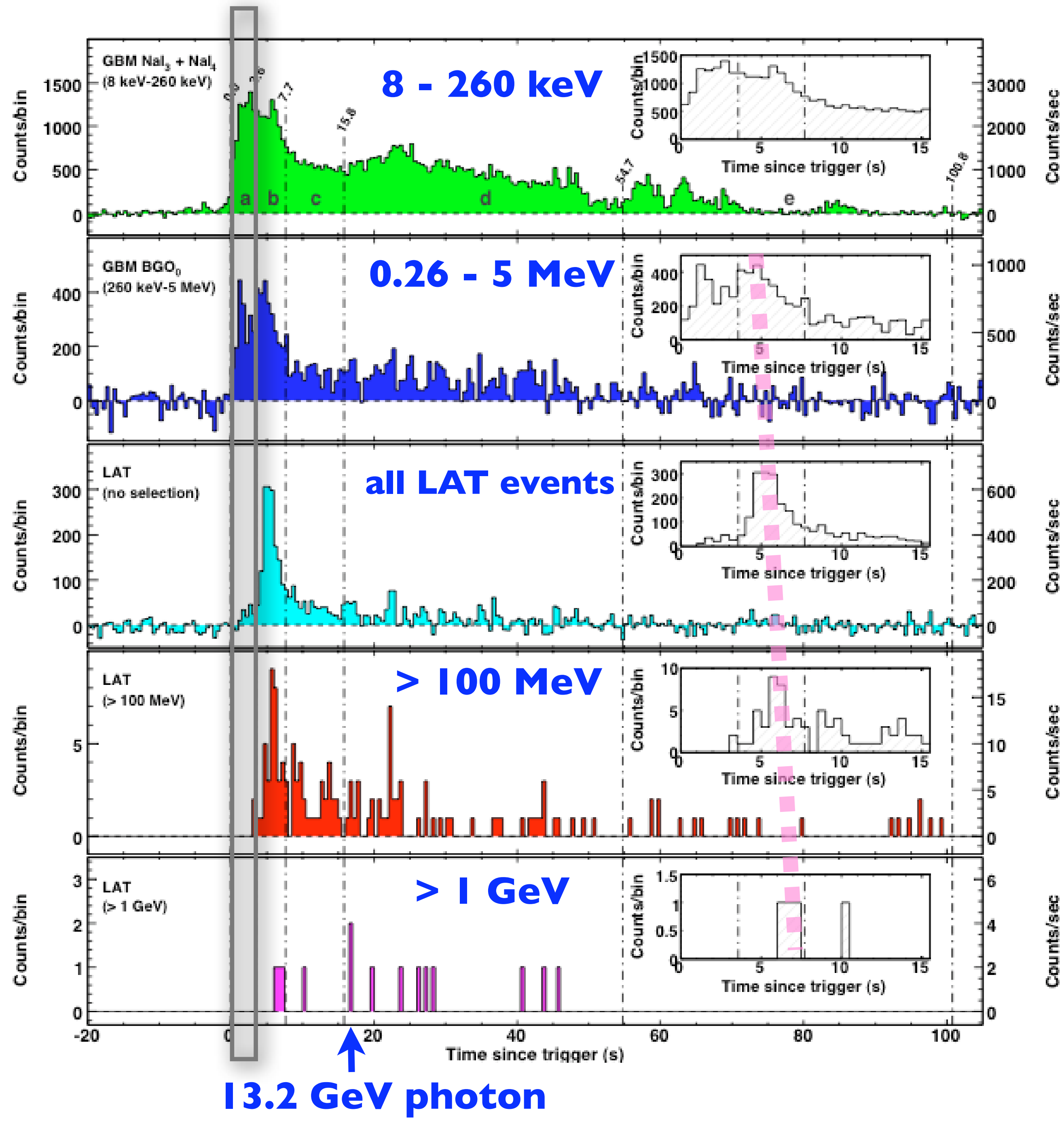
Les sursauts gamma avec Fermi, Swift et X-Shooter: situation et perspectives, Toulouse, September 2010

High energy gamma ray emission



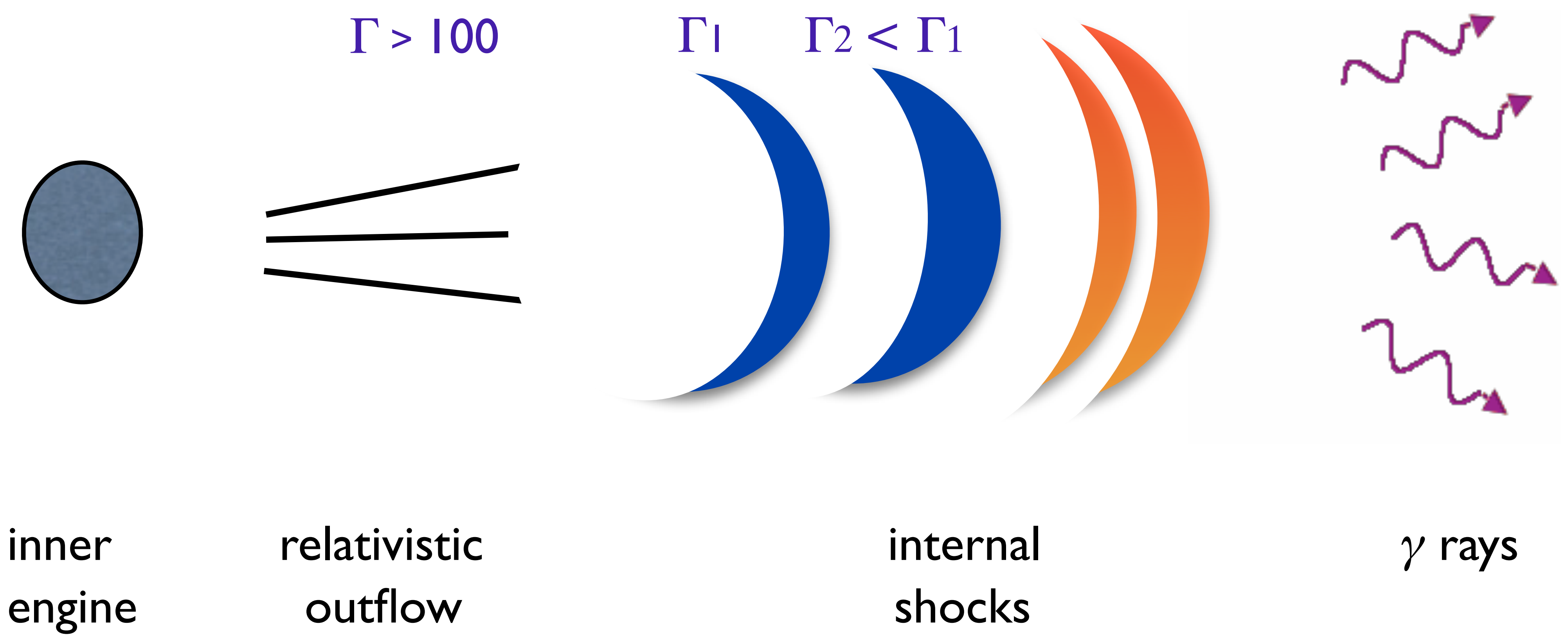
GRB 080916C
Abdo et al. 2008

Fermi observations:

- ✓ Delayed onset of high energy (>100 MeV) emission (5/11 of LAT GRBs)
- ✓ Long lived high energy emission (9/11)
- ✓ Deviation from the usual GRB spectral models: extra component (3/11)

N. Omodei
Fermi Symposium 2009

Modeling: prompt high energy emission in the framework of IS



Modeling:

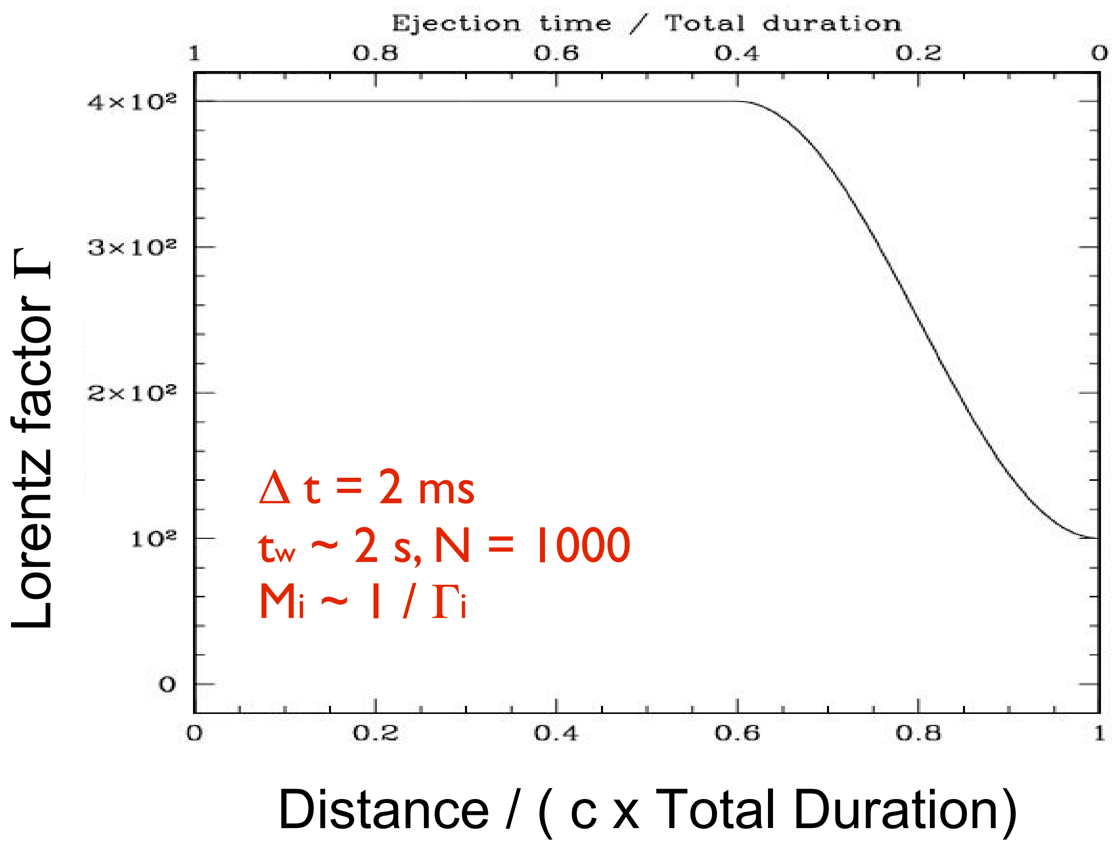
1. dynamics of internal shocks

2. radiative processes in the shocked medium

3. observed spectra and time profiles

Dynamics of the internal shocks

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



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

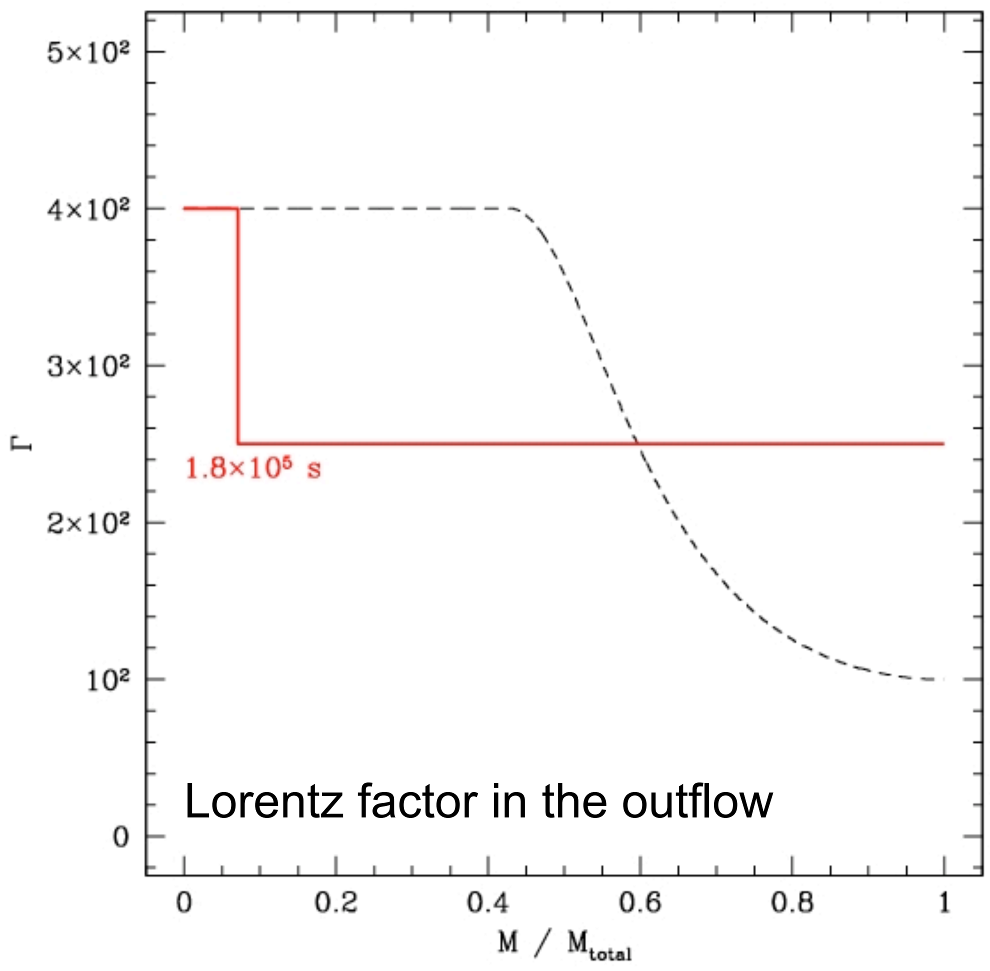
$R_{IS, end} \sim \Gamma^2 c\, t_w \sim 3 \times 10^{15}$ cm $(\Gamma/100)^2 (t_w / 10\ \mathrm{s})$

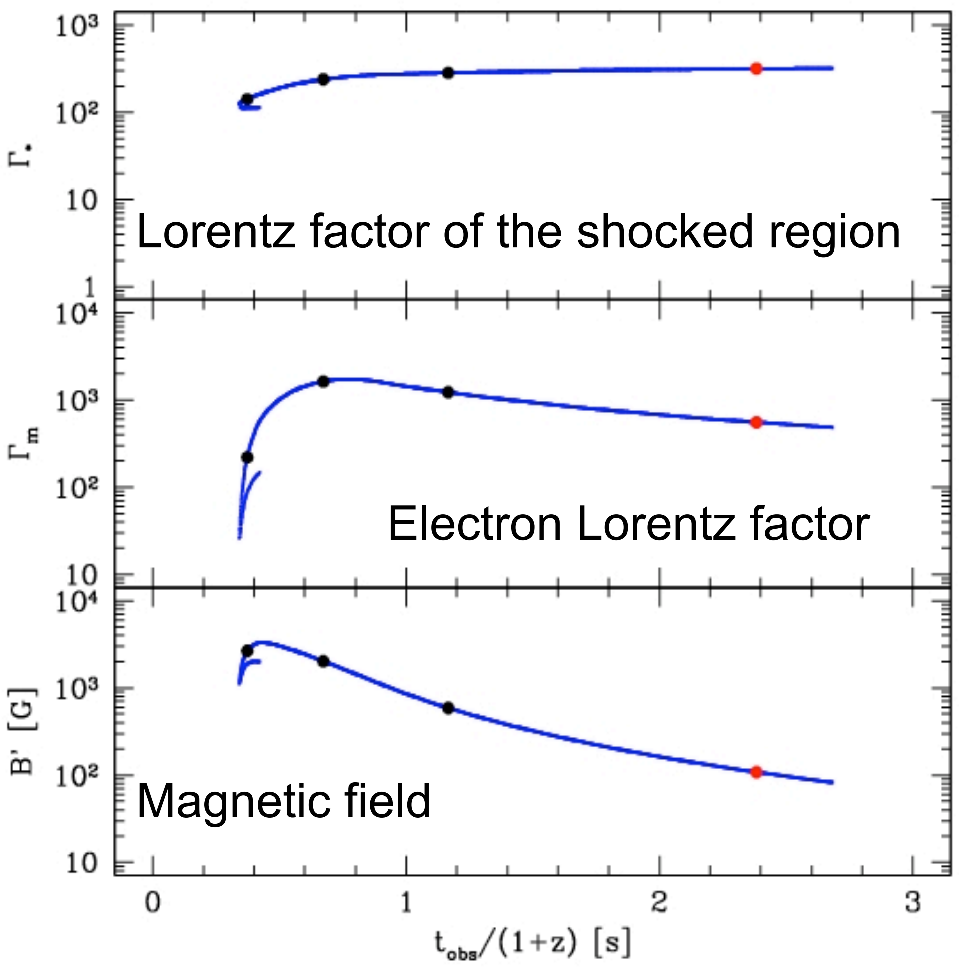
Dissipated energy: from 6% ($\Gamma_2 / \Gamma_1 = 2$) to 43 % ($\Gamma_2 / \Gamma_1 = 10$)

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

Dynamics of the internal shocks

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





Dynamics of the internal shocks

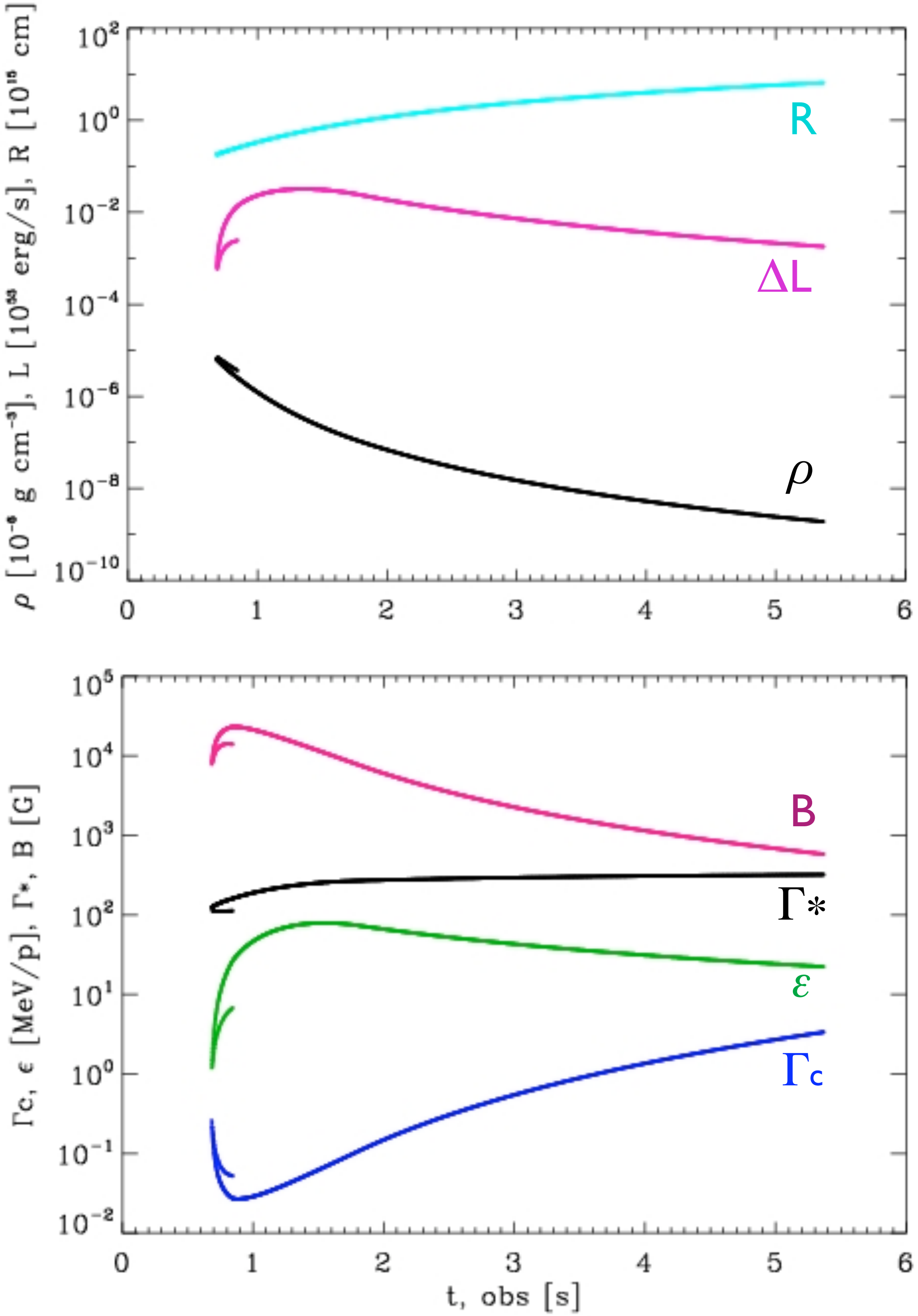
Physical conditions in the shocked medium: Lorentz factor $\Gamma*$, comoving density $\rho*$, comoving specific energy density $\varepsilon*$

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

Relativistic electron density:

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

$\zeta < 1$ of all electrons is accelerated into a powerlaw distribution with slope -p (e.g. Bykov & Meszaros 1996)



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!

Radiative processes

Assumption: instantaneous shock acceleration

* *Adiabatic cooling timescale:* $t'_{ex} = R / \Gamma^* c$ (comoving frame)
* *Radiative timescale:* t'_{rad}

$t'_{rad} \ll t'_{ex}$ 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 $n'_e(\Gamma'_e, t')$ and the photon density $n'_{\nu'}(t')$ including the following processes:

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

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

ELECTRONS:

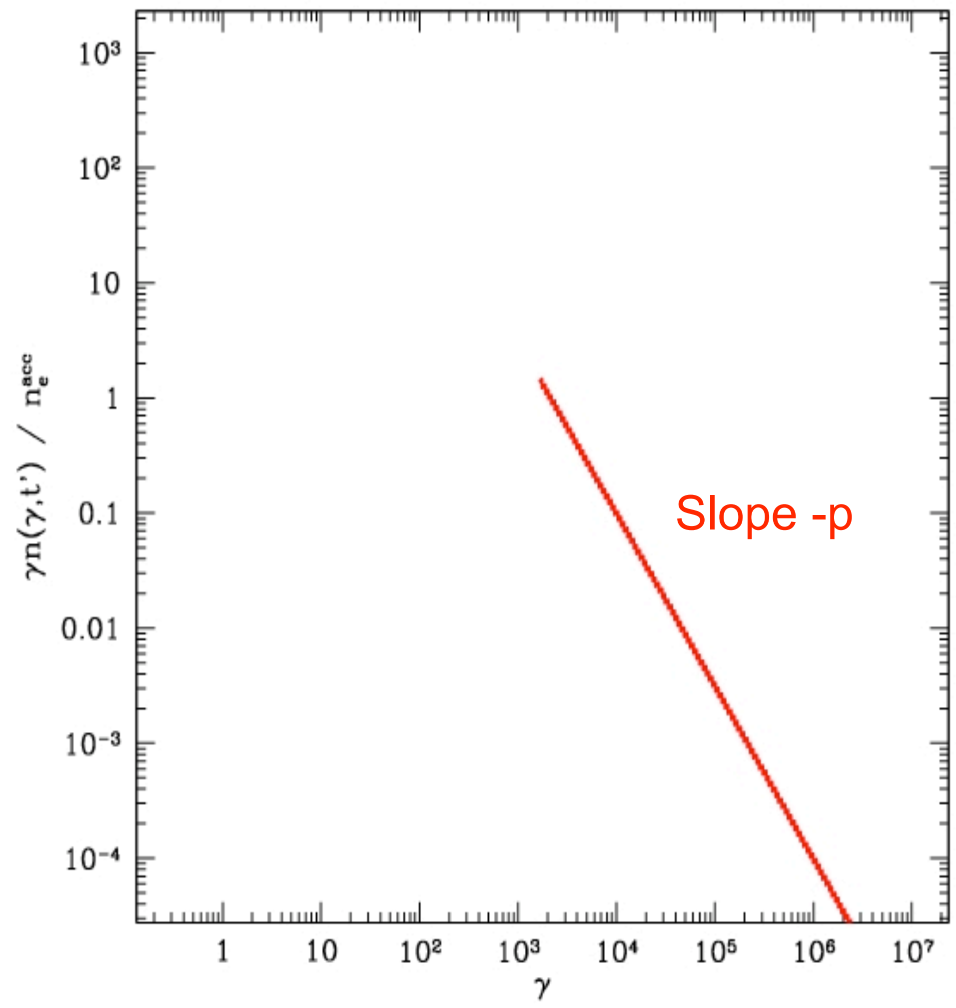
$$\frac{\partial n'}{\partial t'}(\Gamma'_e, t') = -\frac{\partial}{\partial \Gamma'_e}\left[\left(\frac{d\Gamma'_e}{dt'}\Big|_{syn+ic} + \frac{d\Gamma'_e}{dt'}\Big|_{ad}\right) n'(\Gamma'_e, t')\right]$$

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
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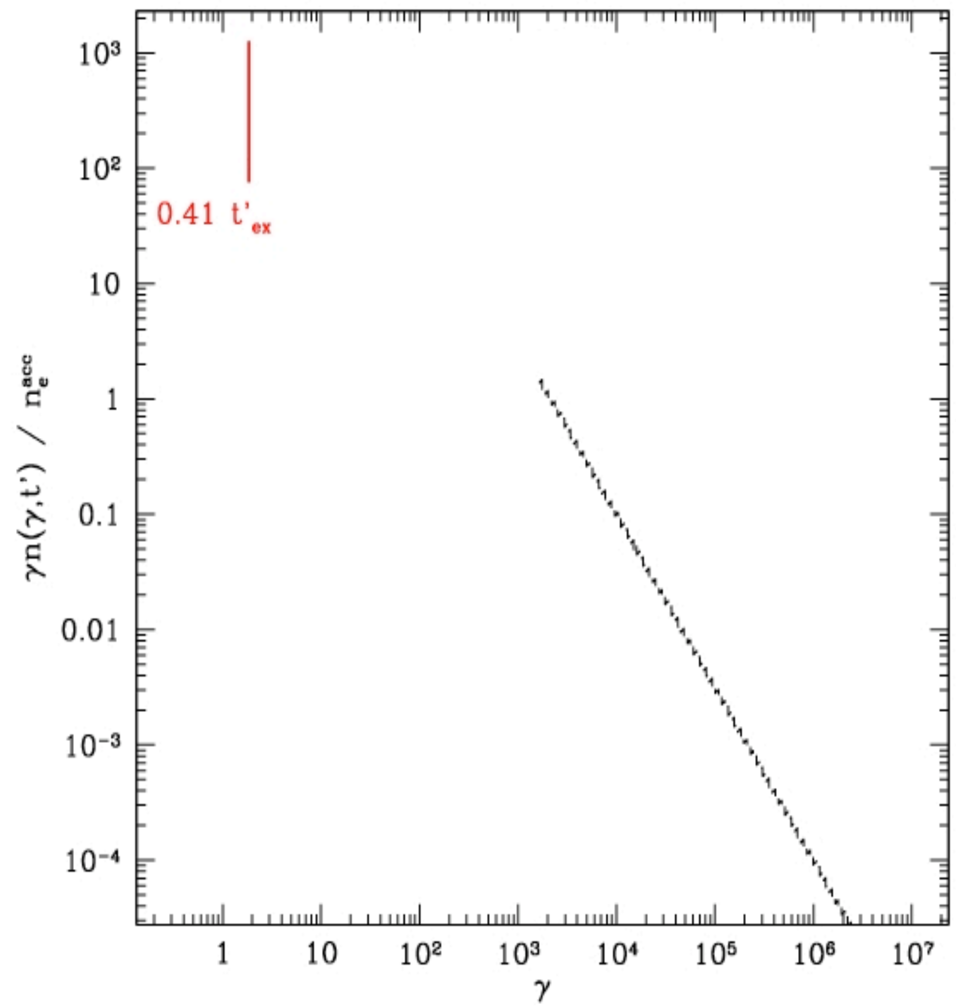
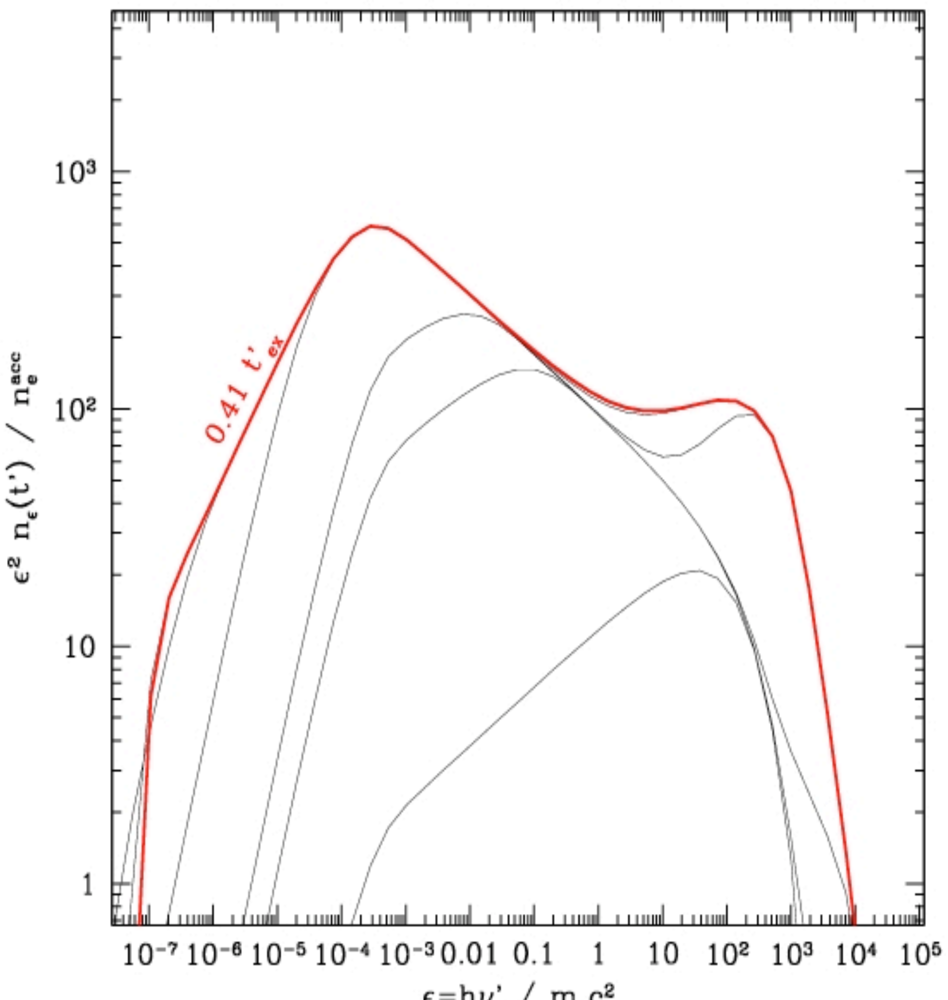


Electron distribution



Photon spectrum

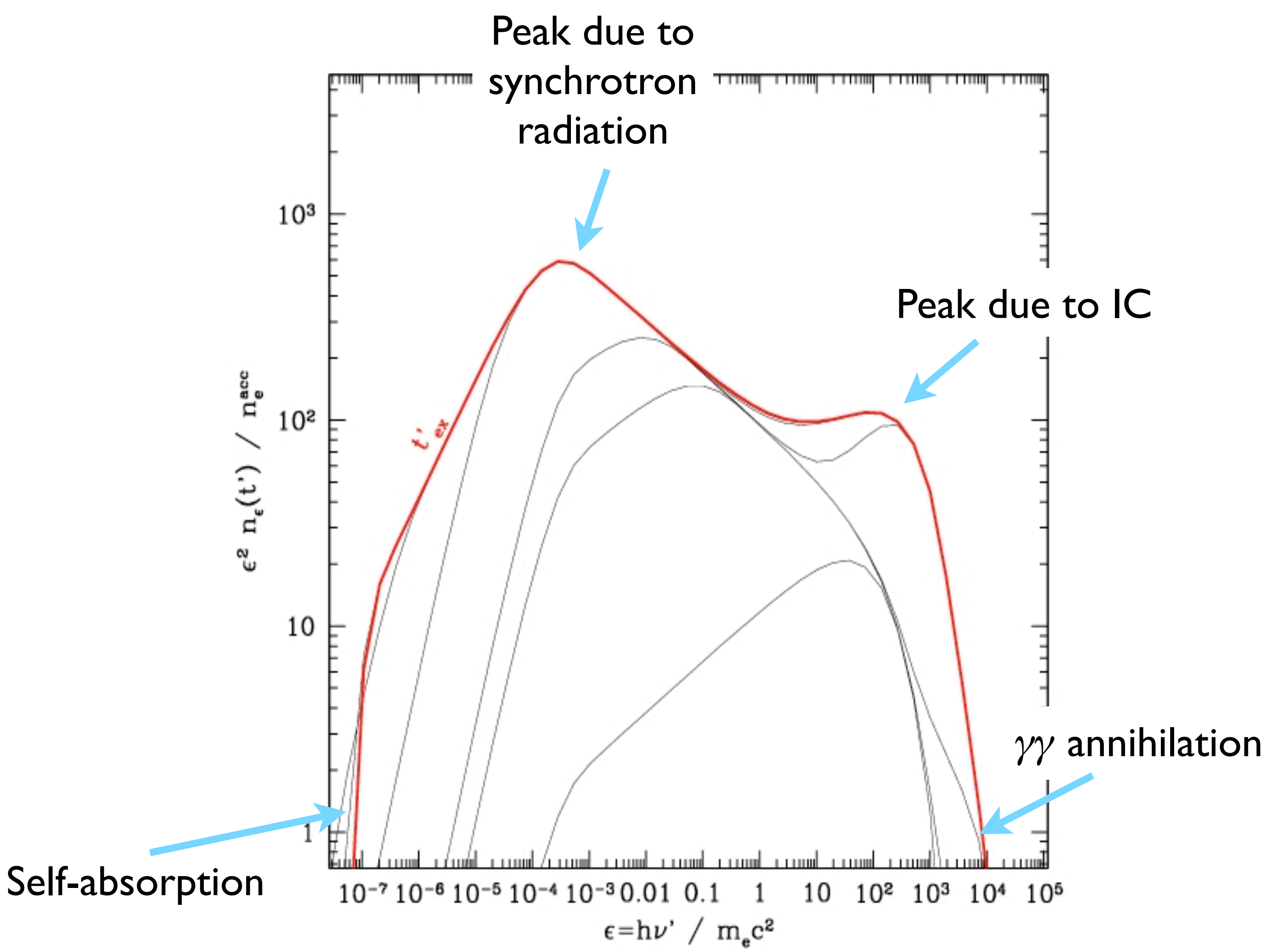
Radiative processes

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

Radiative processes

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

Comptonization parameter
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IC dominant:
low frequency synchrotron peak
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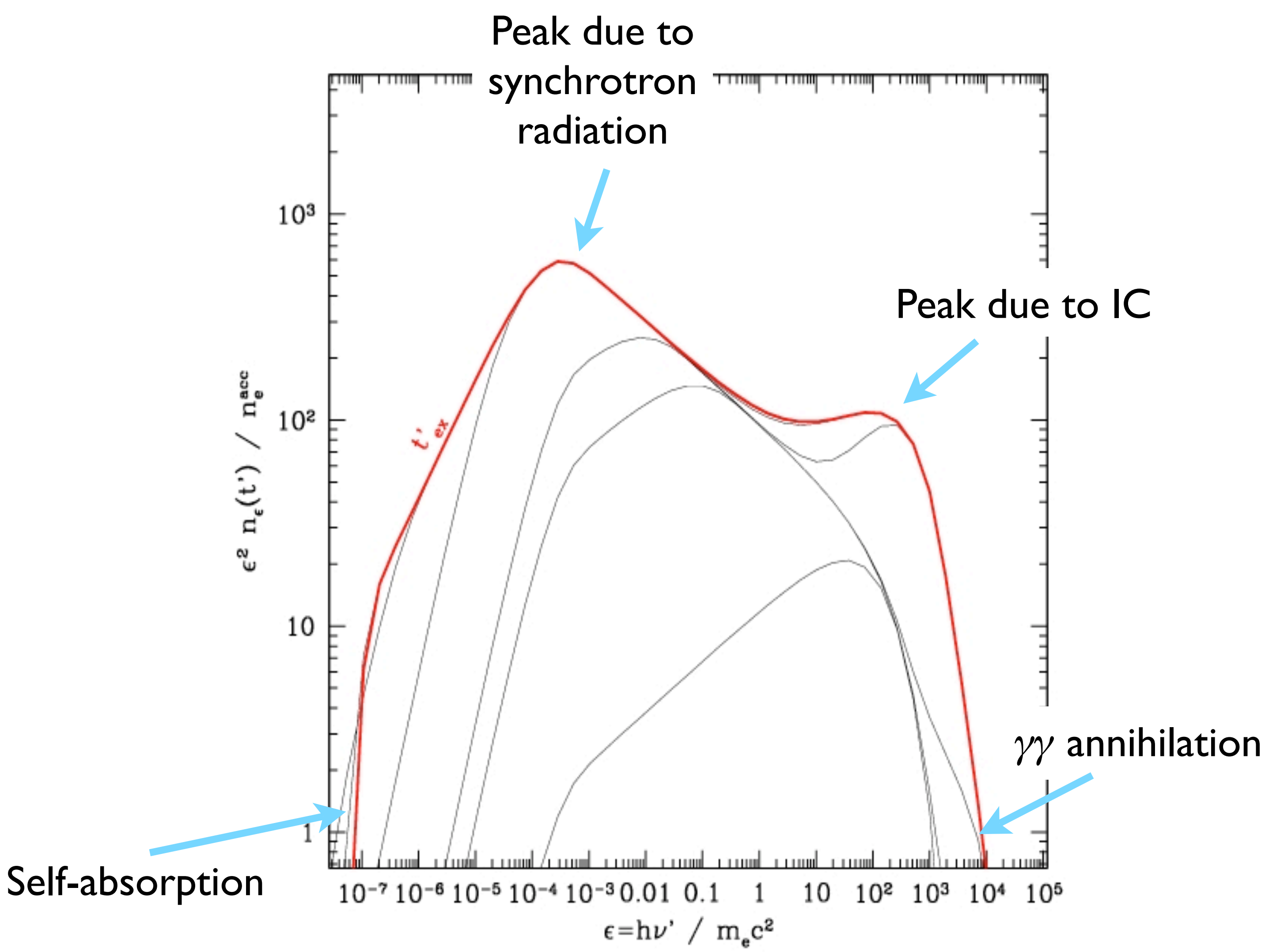


Emitted photon spectrum

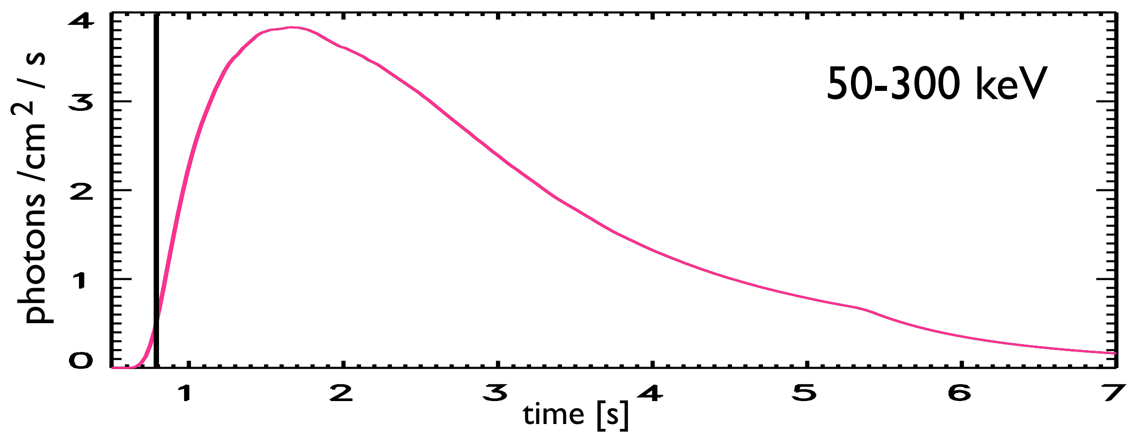
This calculation is done at all times along the propagation of each shock wave

All the contributions are added together to produce a synthetic gamma-ray burst (spectrum+lightcurve)

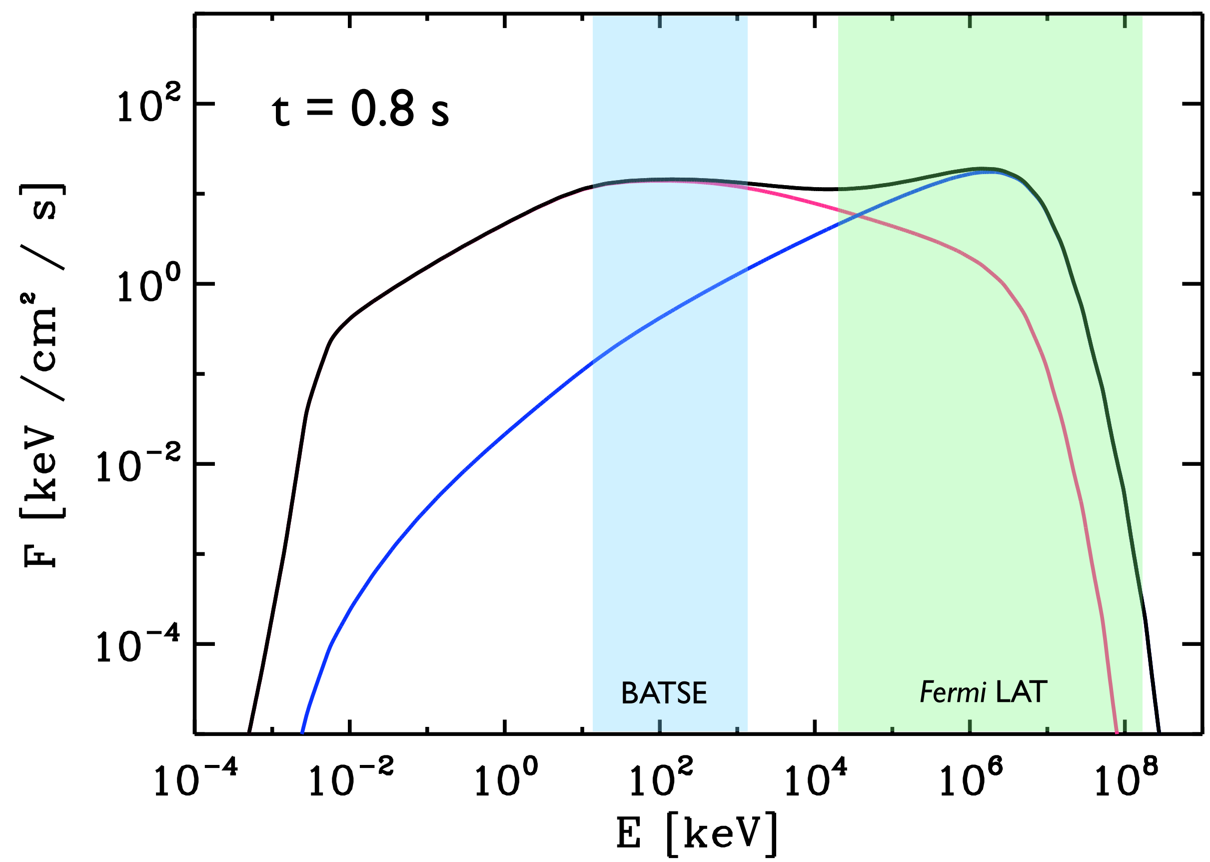
Observed spectra and time profiles

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:



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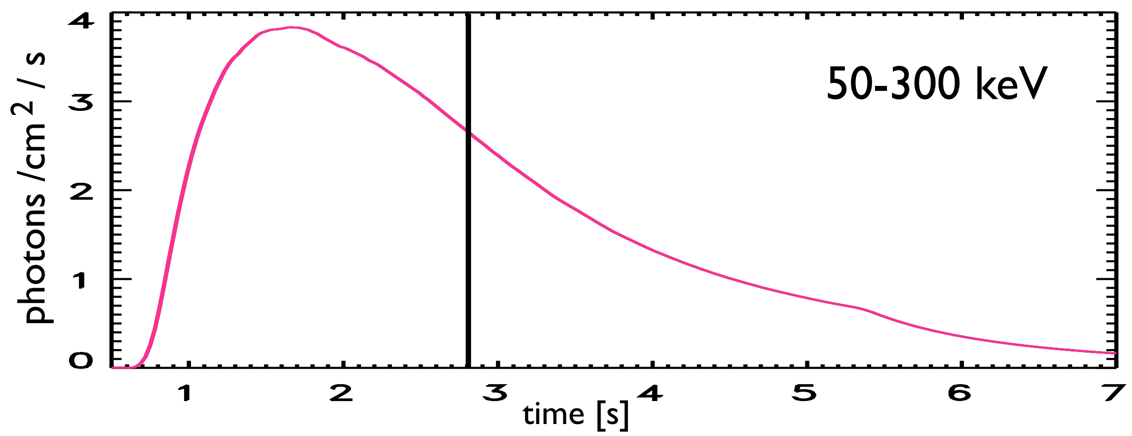
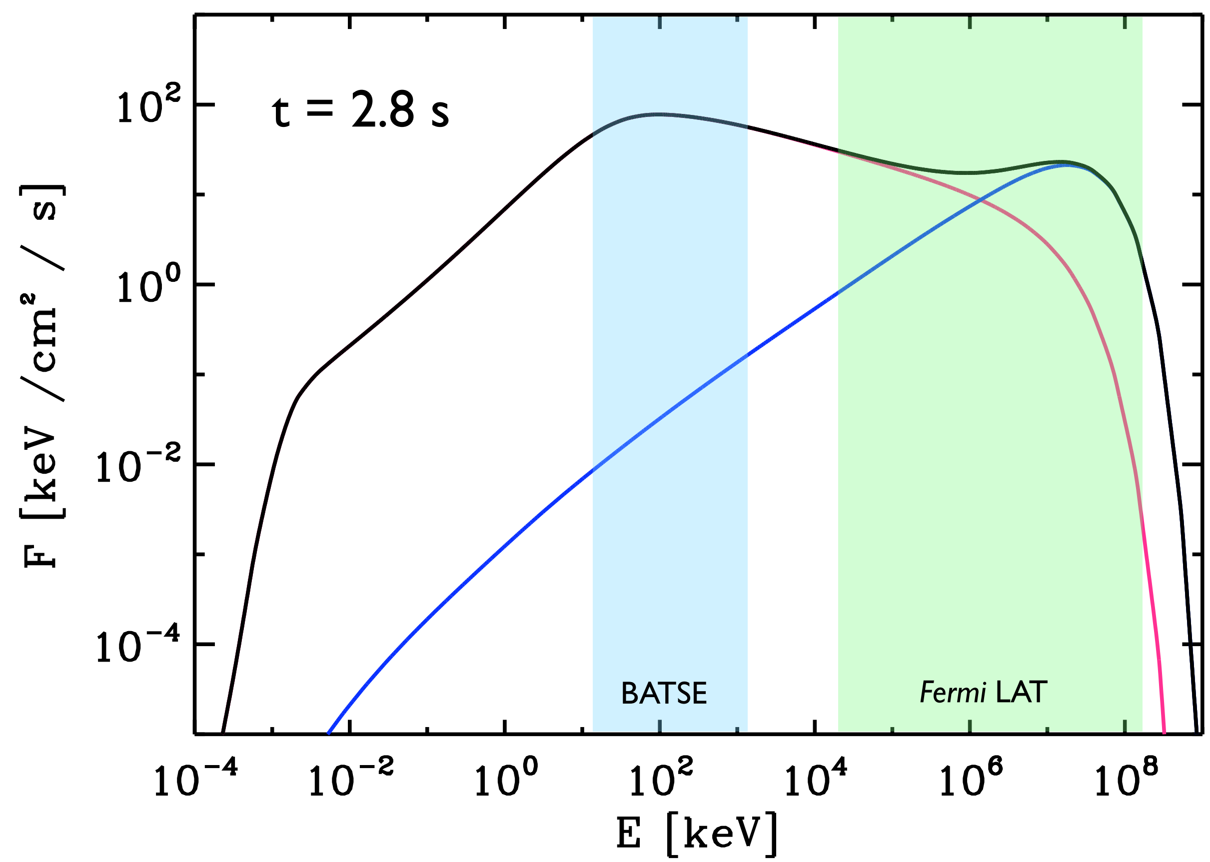
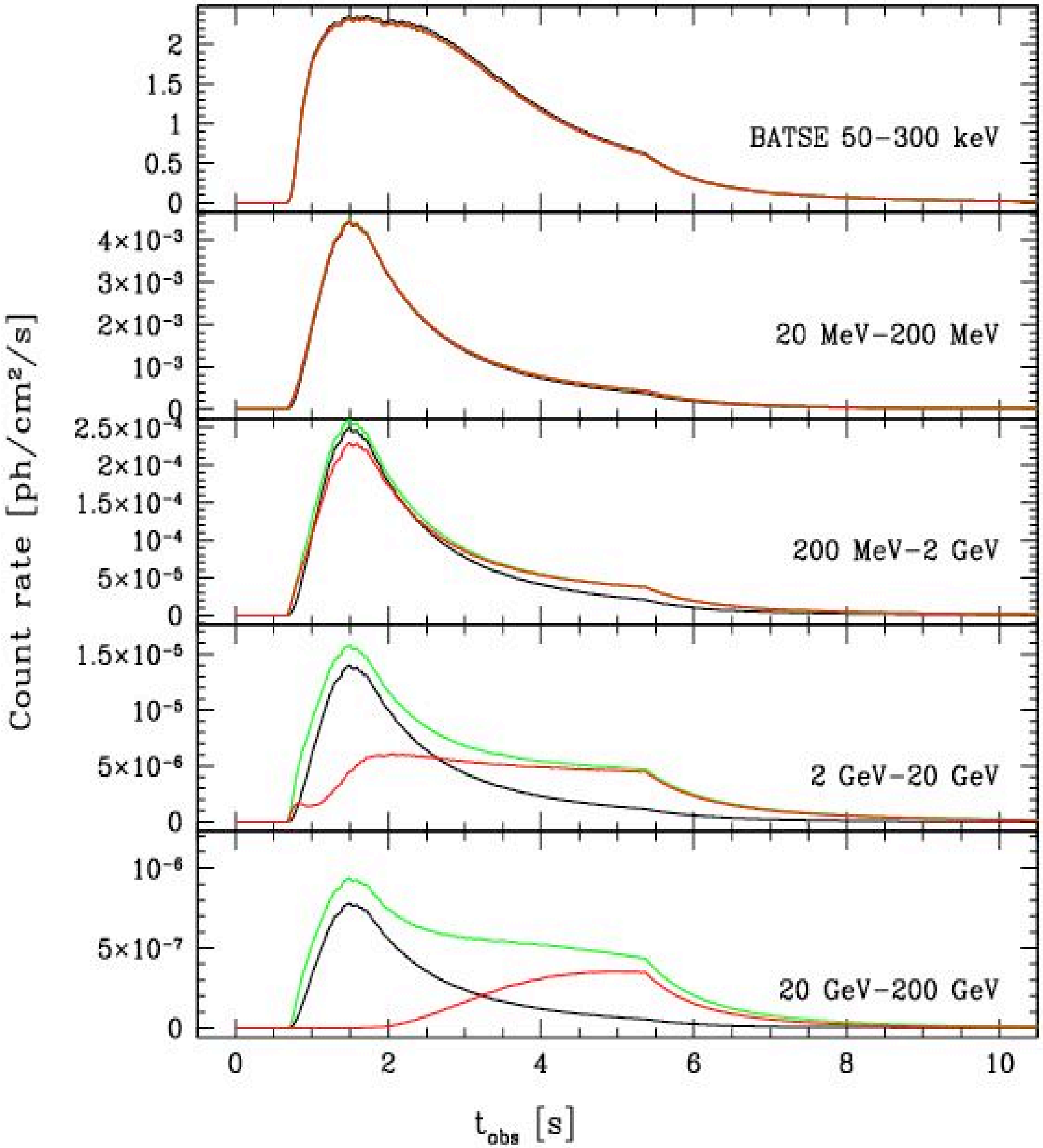


Instantaneous observed spectrum:

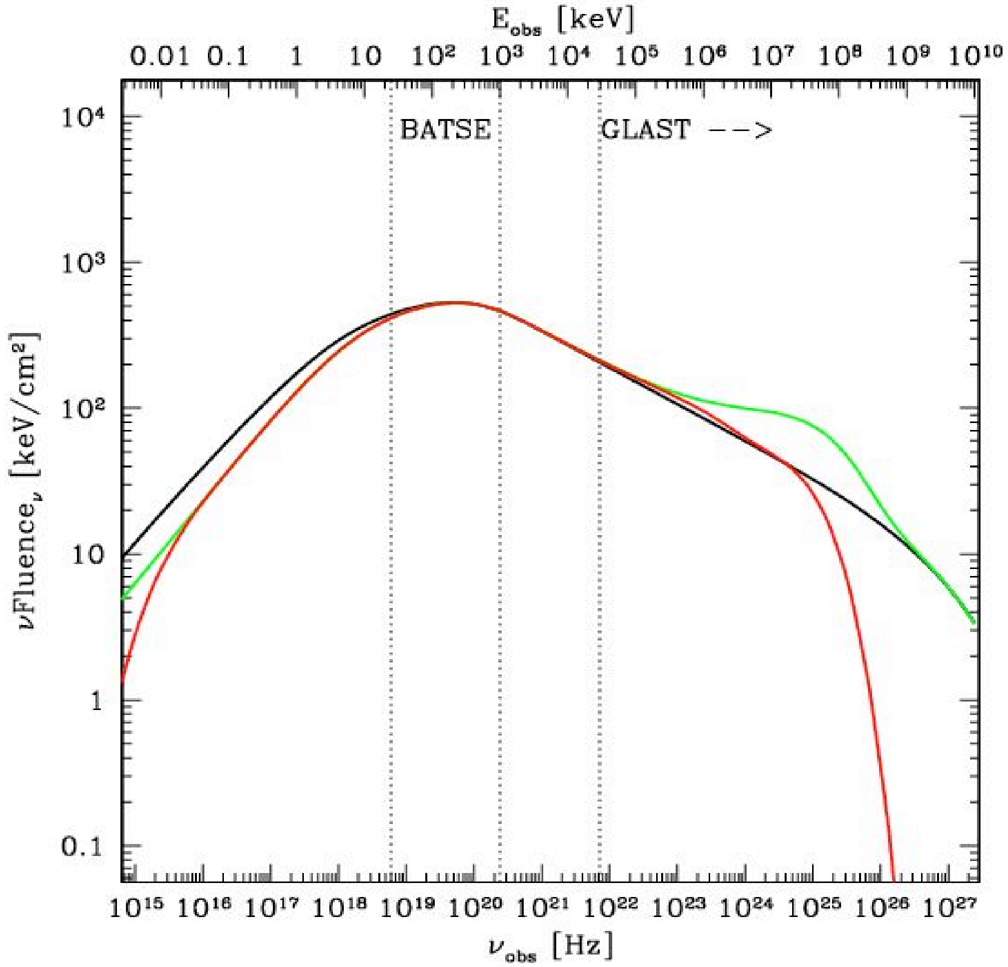
synchrotron
inverse Compton
total



Observed spectra and time profiles



synchrotron only
synchrotron + IC
synchrotron + IC + $\gamma\gamma$ annihilation
+ self absorption



time-integrated spectrum

Dominant radiative process in sub-MeV range

2 possibilities for the dominant process in the keV-MeV range

1. SYNCHROTRON

2. INVERSE COMPTON

Dominant radiative process in sub-MeV range

2 possibilities for the dominant process in the keV-MeV range

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

Dominant radiative process in sub-MeV range

2 possibilities for the dominant process in the keV-MeV range

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

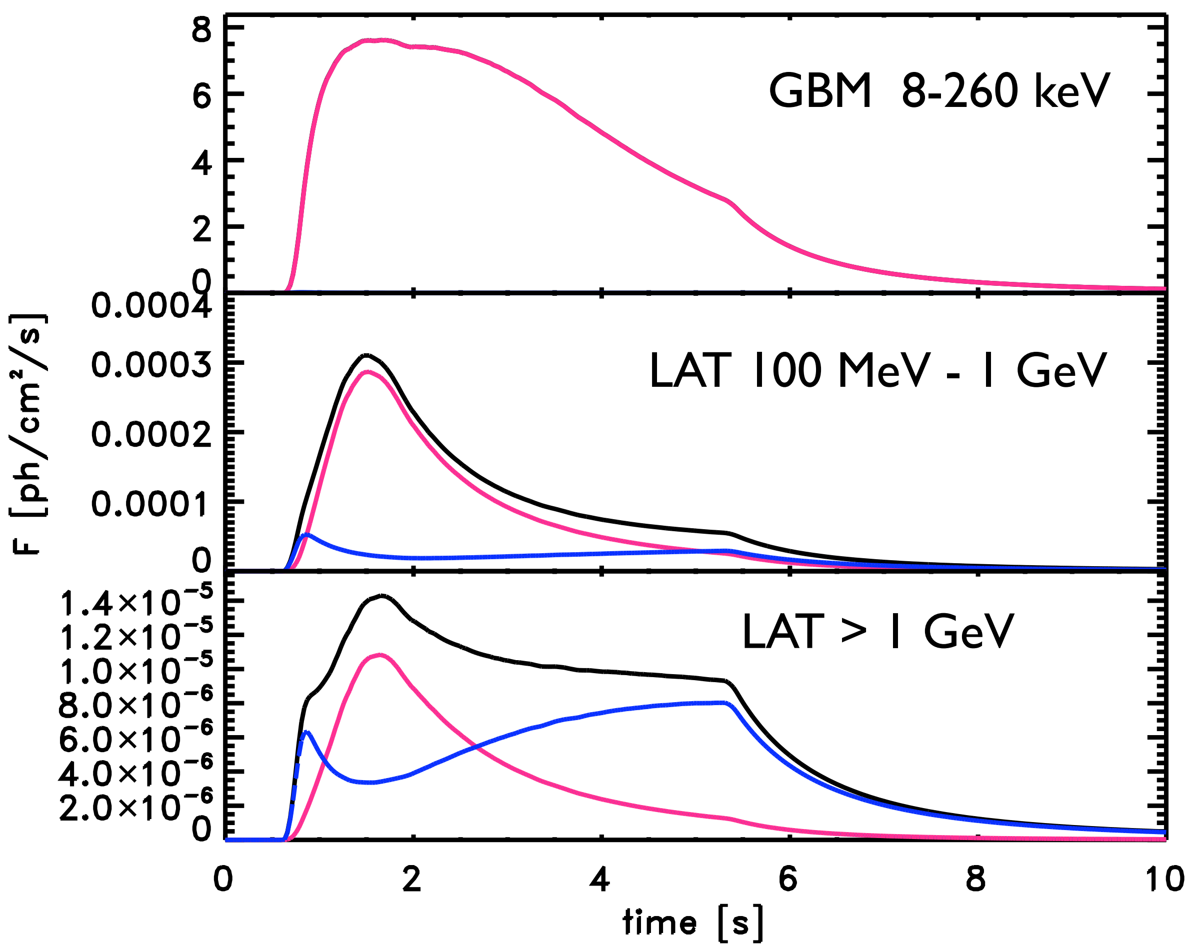
A steep electron slope ($p>3$) is required to have two well defined peaks

Dominant radiative process in sub-MeV range

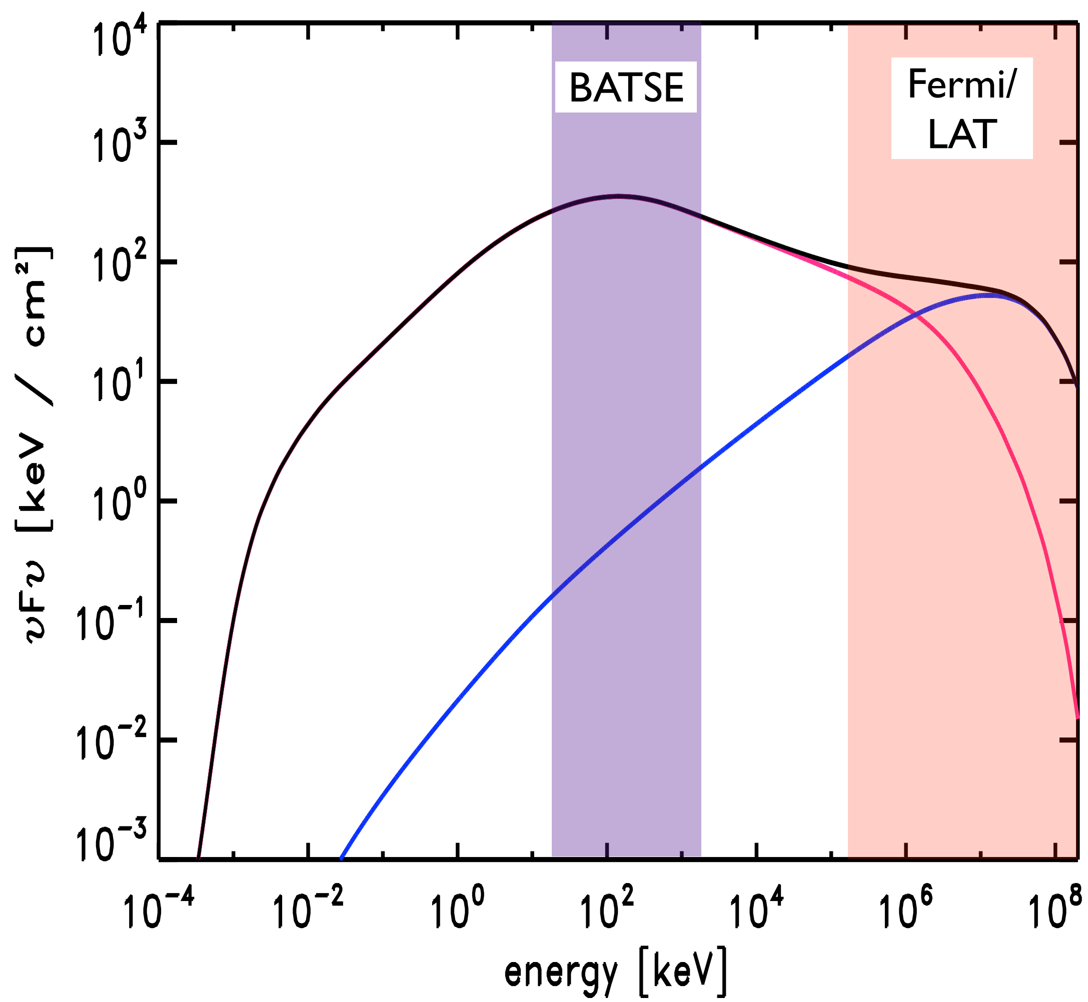
SYNCHROTRON CASE

high magnetic field

dE/dt = 5 x 10^{53} erg s^{-1}, $\varepsilon_B = \varepsilon_e = 1/3$, $\zeta = 0.003$, $p = 2.5$, $z=1$



Observed lightcurve



Observed spectrum

synchrotron
inverse Compton
total

Dominant radiative process in sub-MeV range

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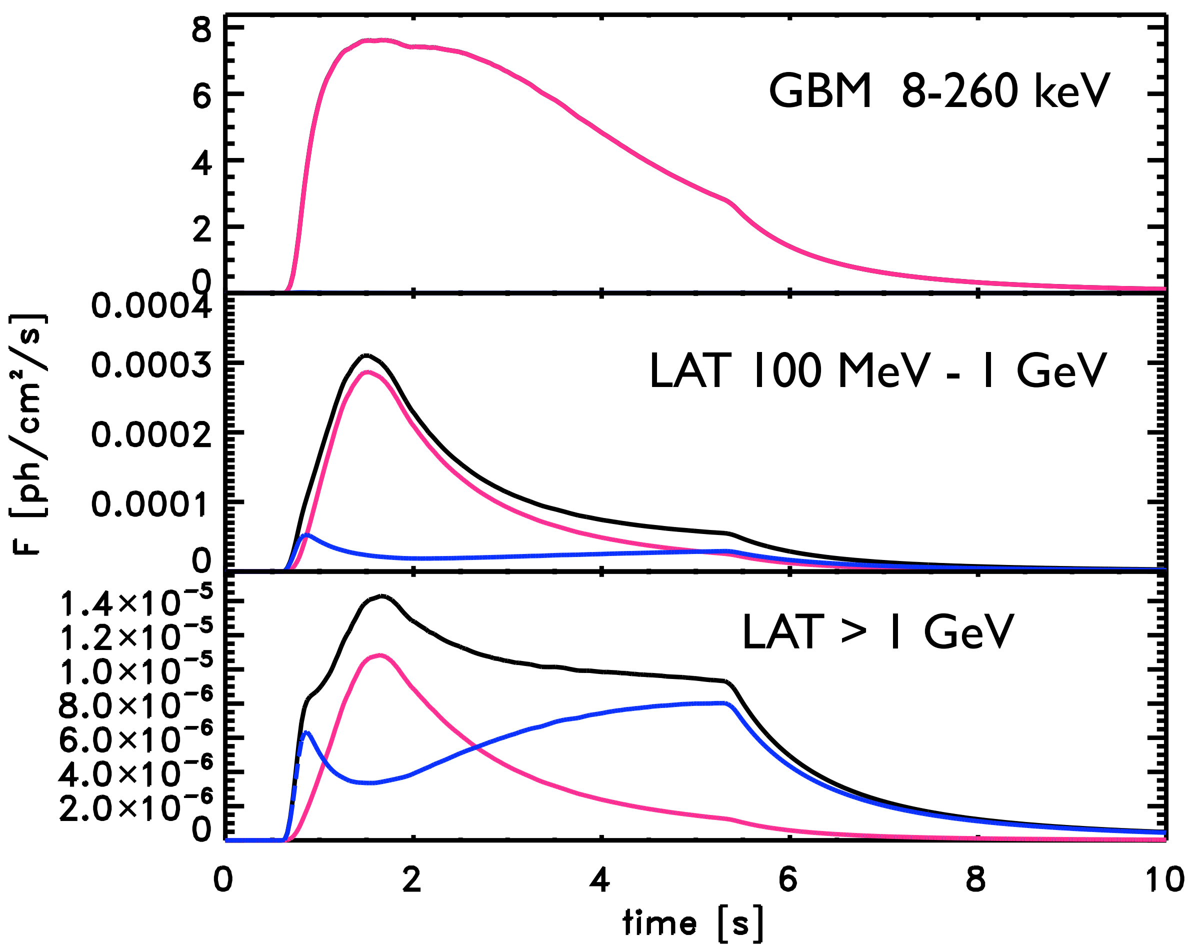
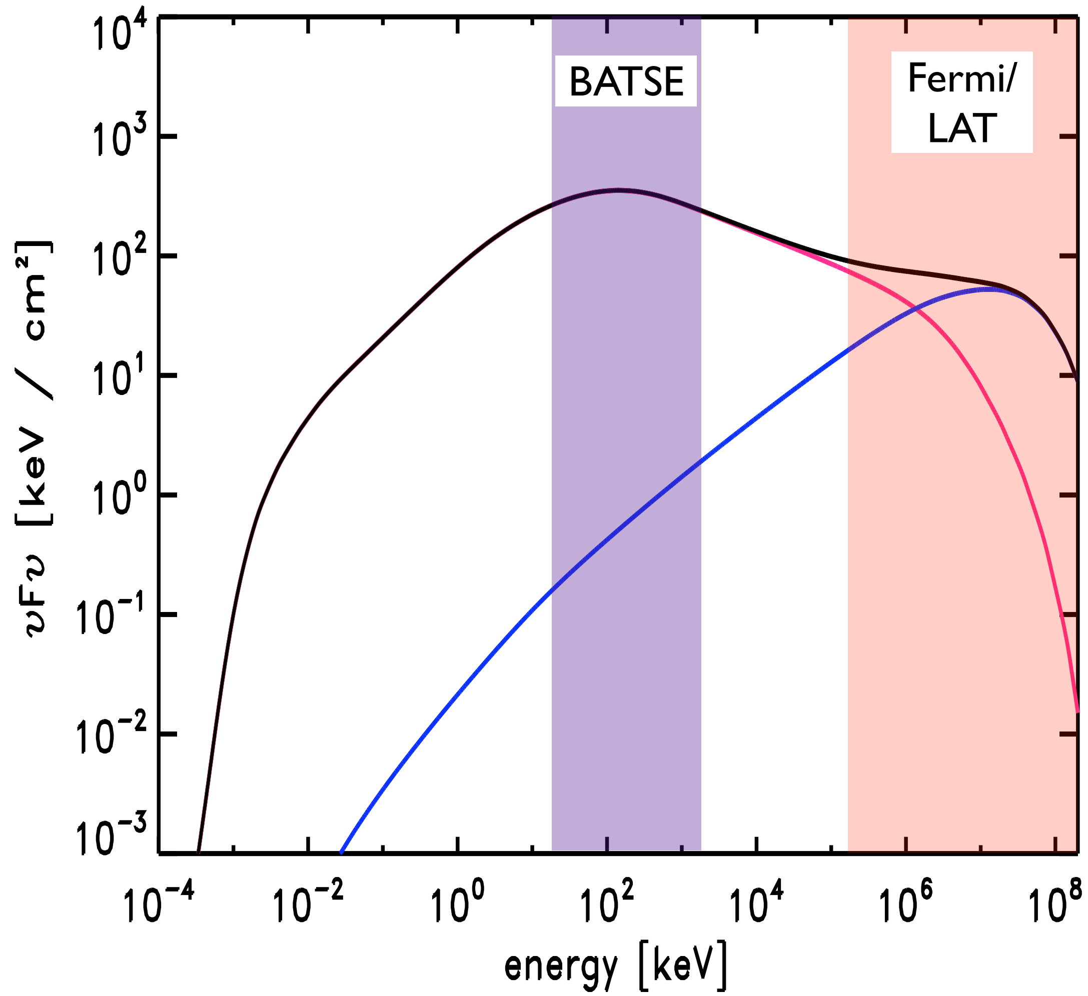


Observed lightcurve



Observed spectrum

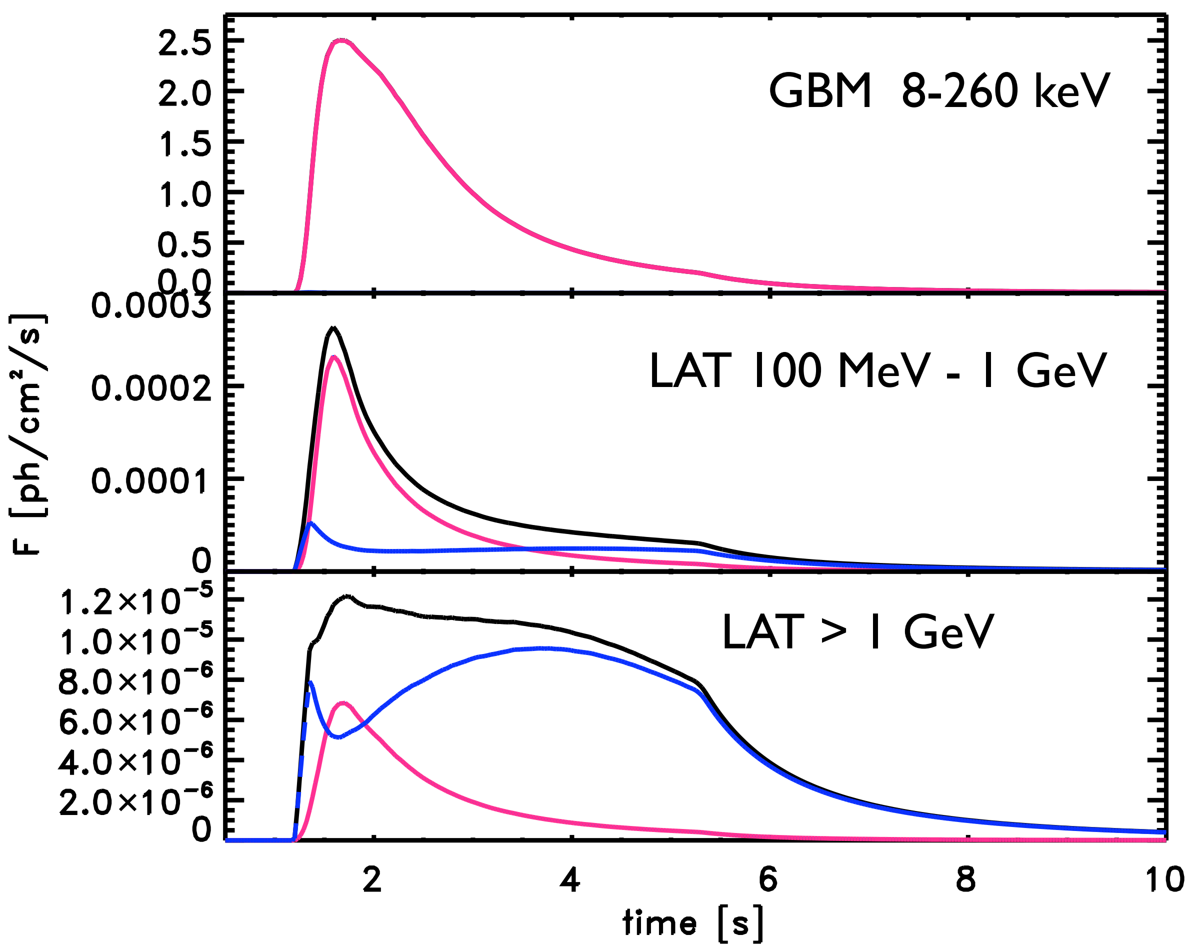
synchrotron
inverse Compton
total

Dominant radiative process in sub-MeV range

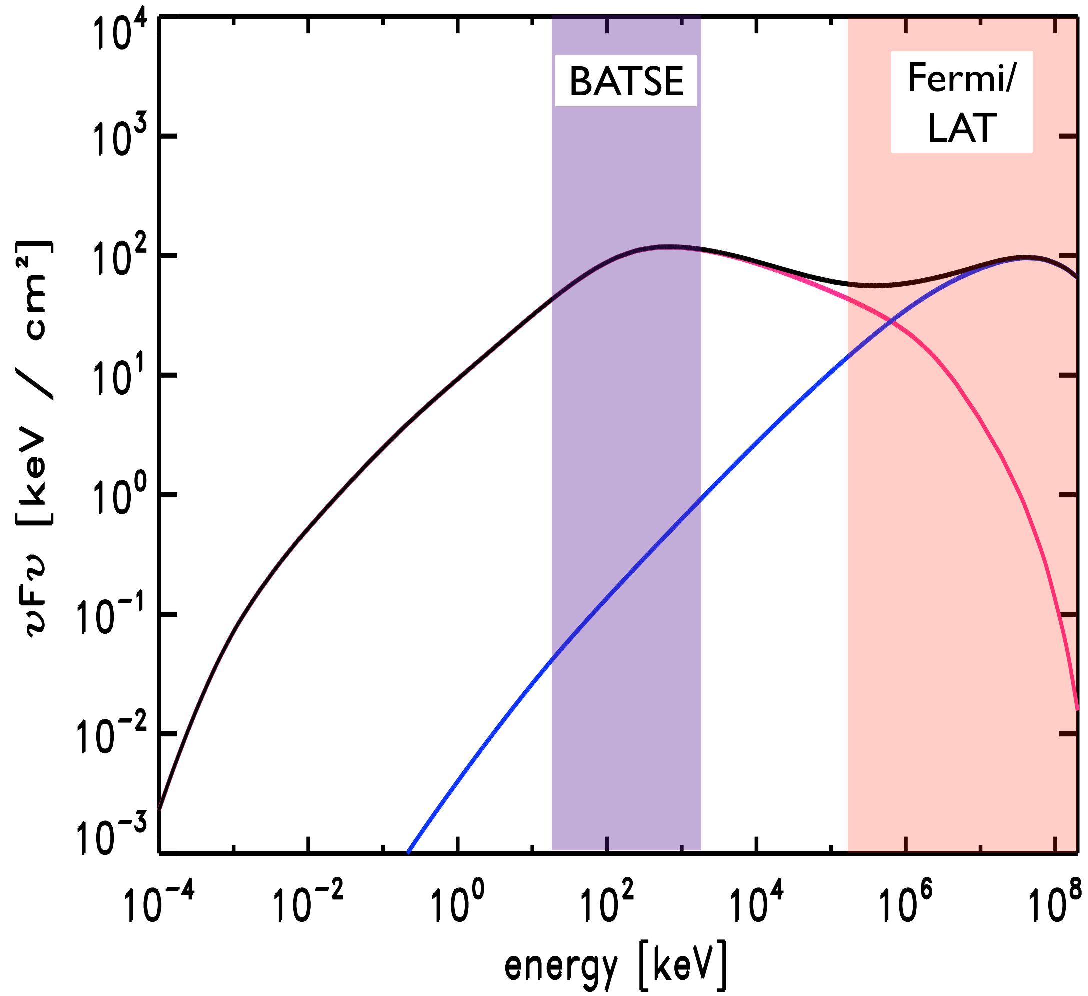
SYNCHROTRON CASE

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

Dominant radiative process in sub-MeV range

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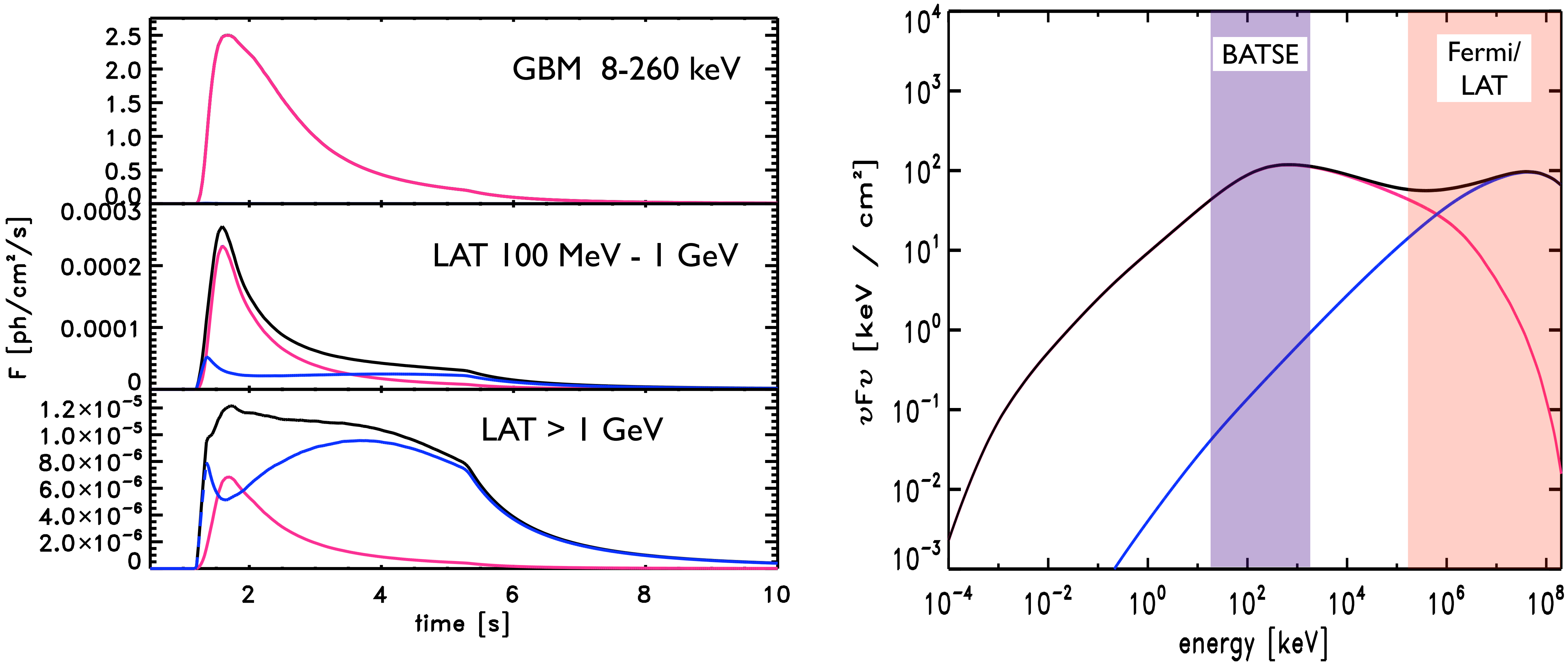
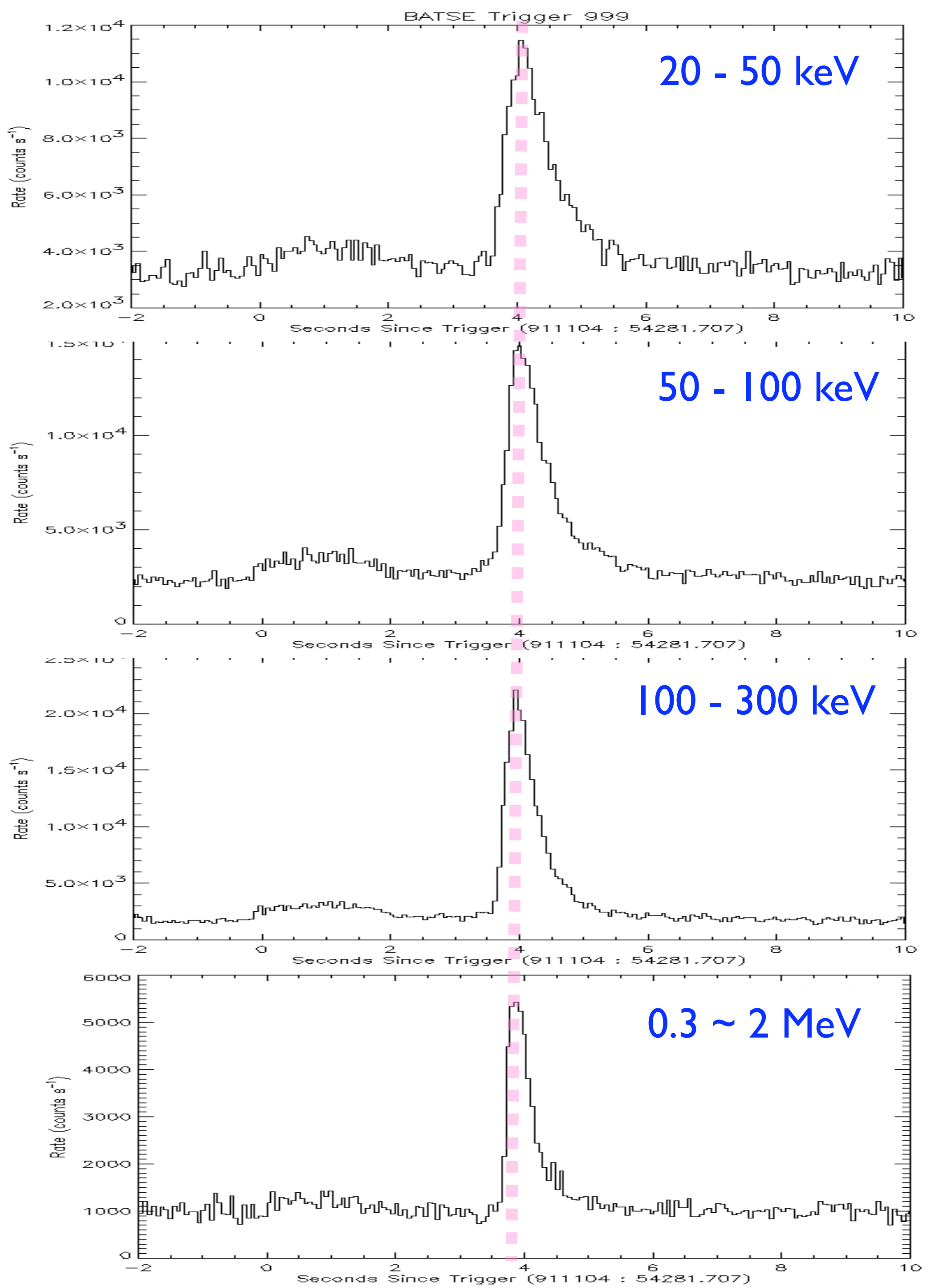


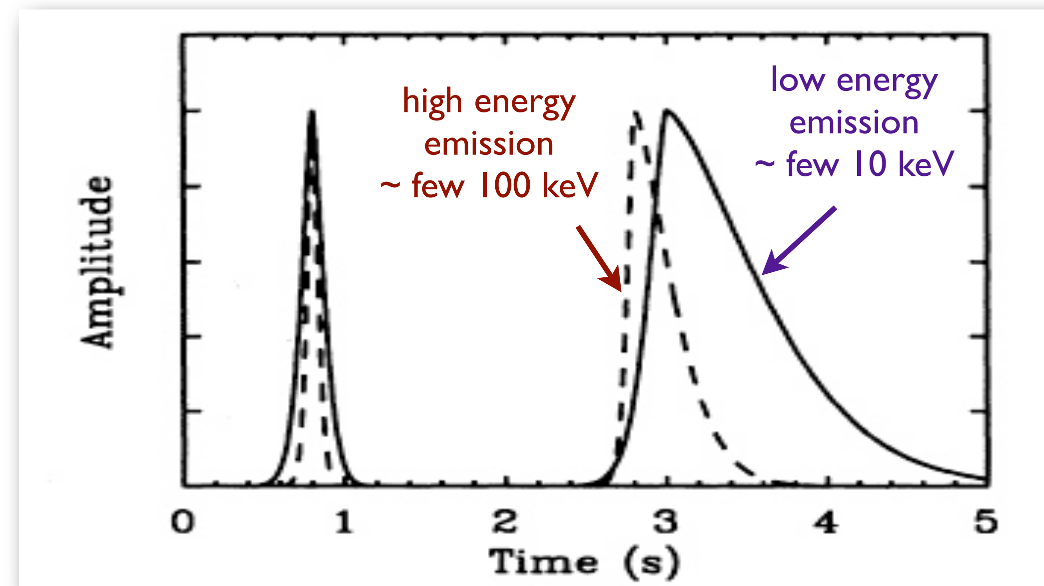
Observed lightcurve

Observed spectrum

synchrotron
inverse Compton
total

Emission processes and temporal profile: sub MeV range

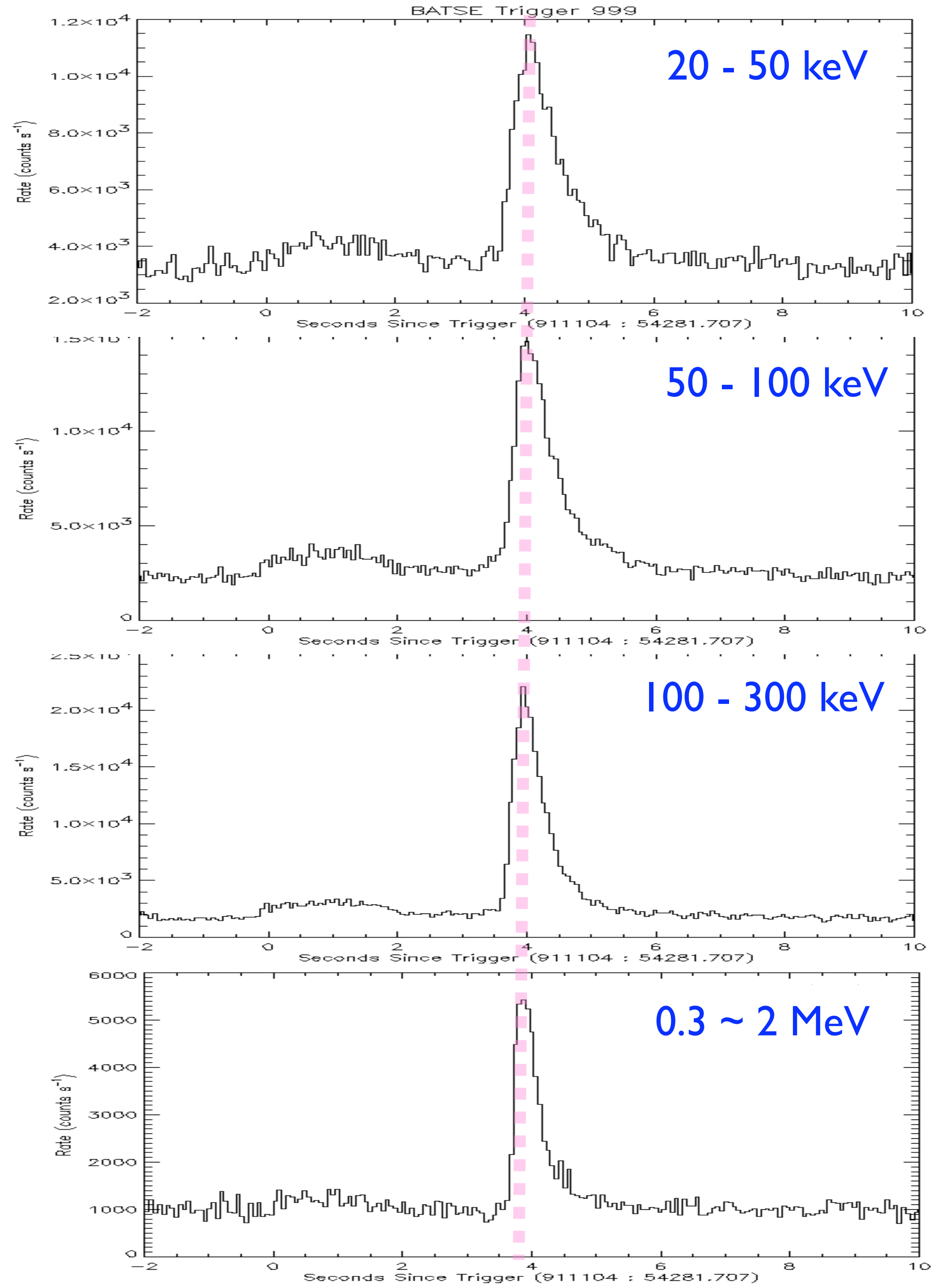


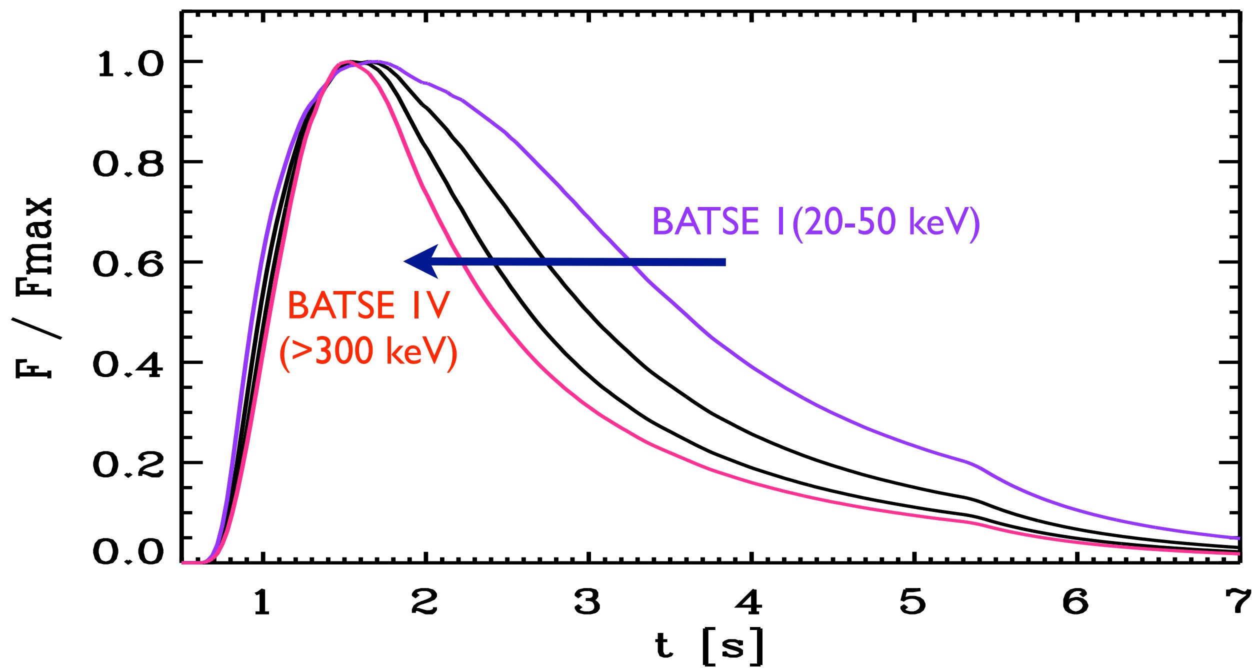


Norris et al. 1996 (BATSE GRBs):
asymmetry/energy-shift paradigm

Emission processes and temporal profile: sub MeV range

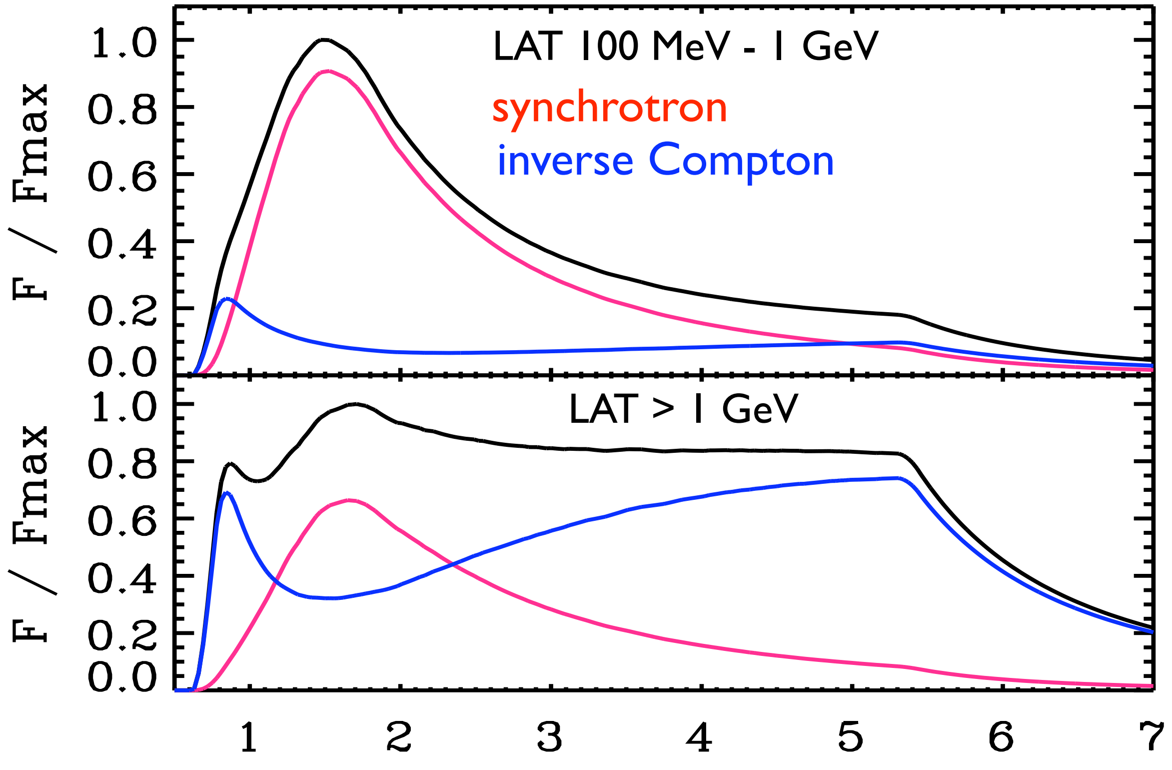
Model: synchrotron emission dominant in sub-MeV range





Emission processes and temporal profile: >100 MeV bands

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



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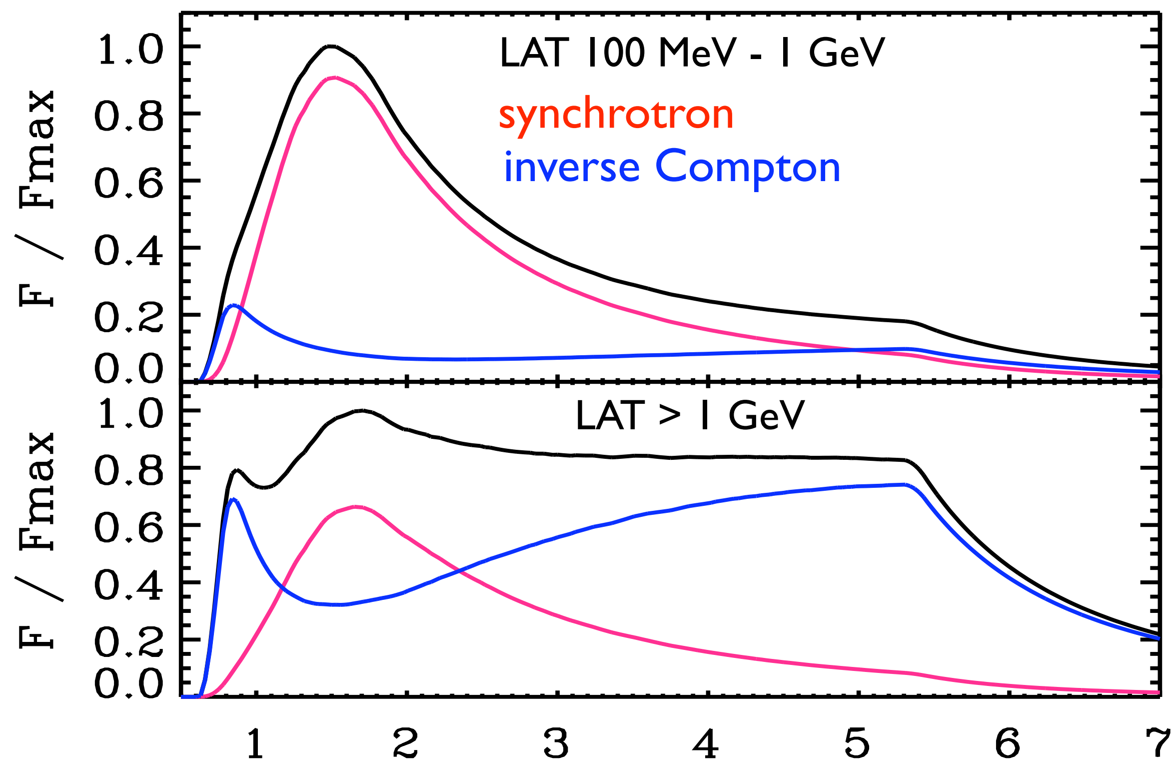

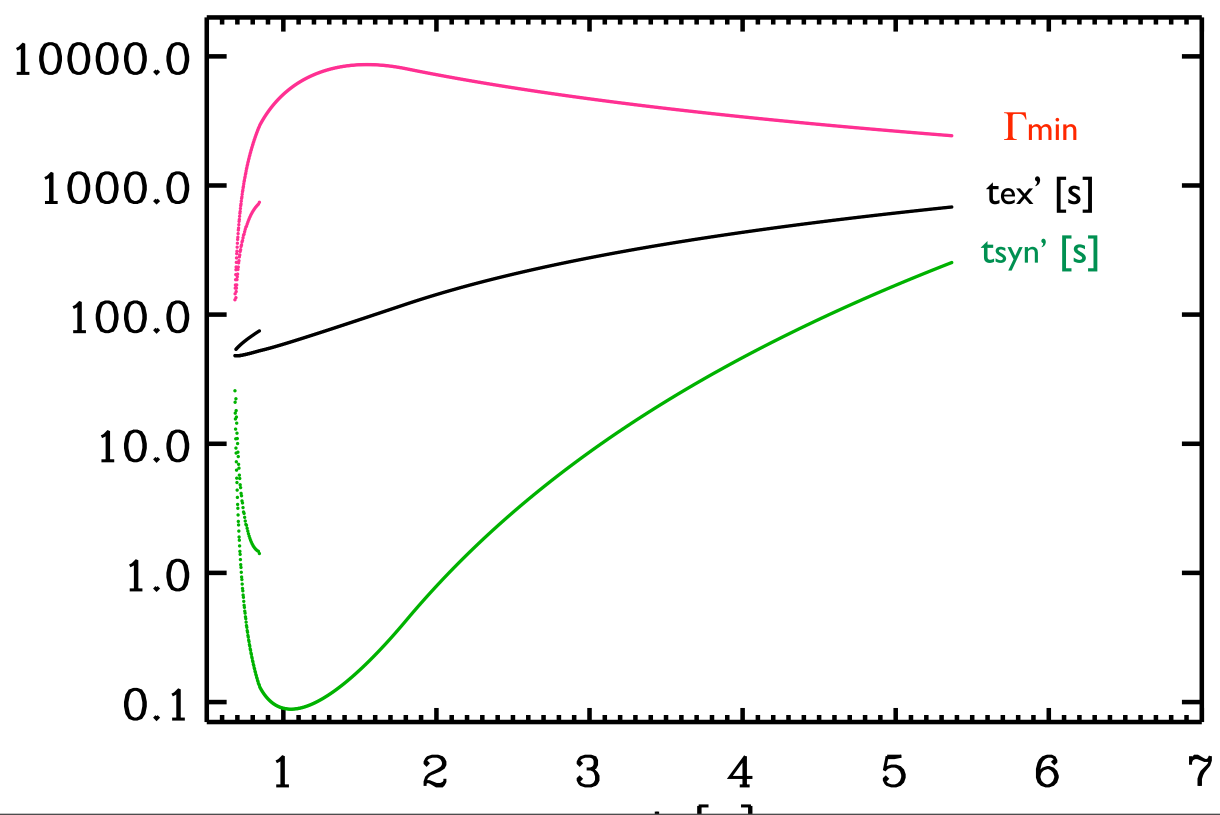

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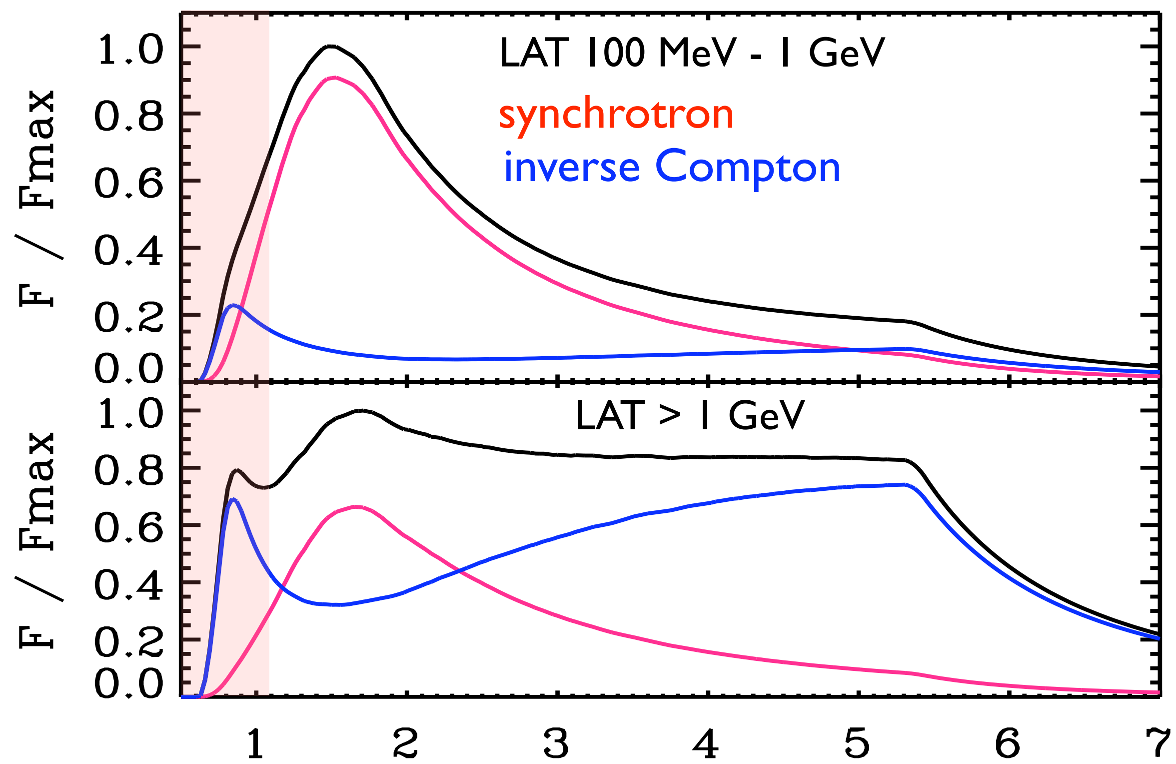
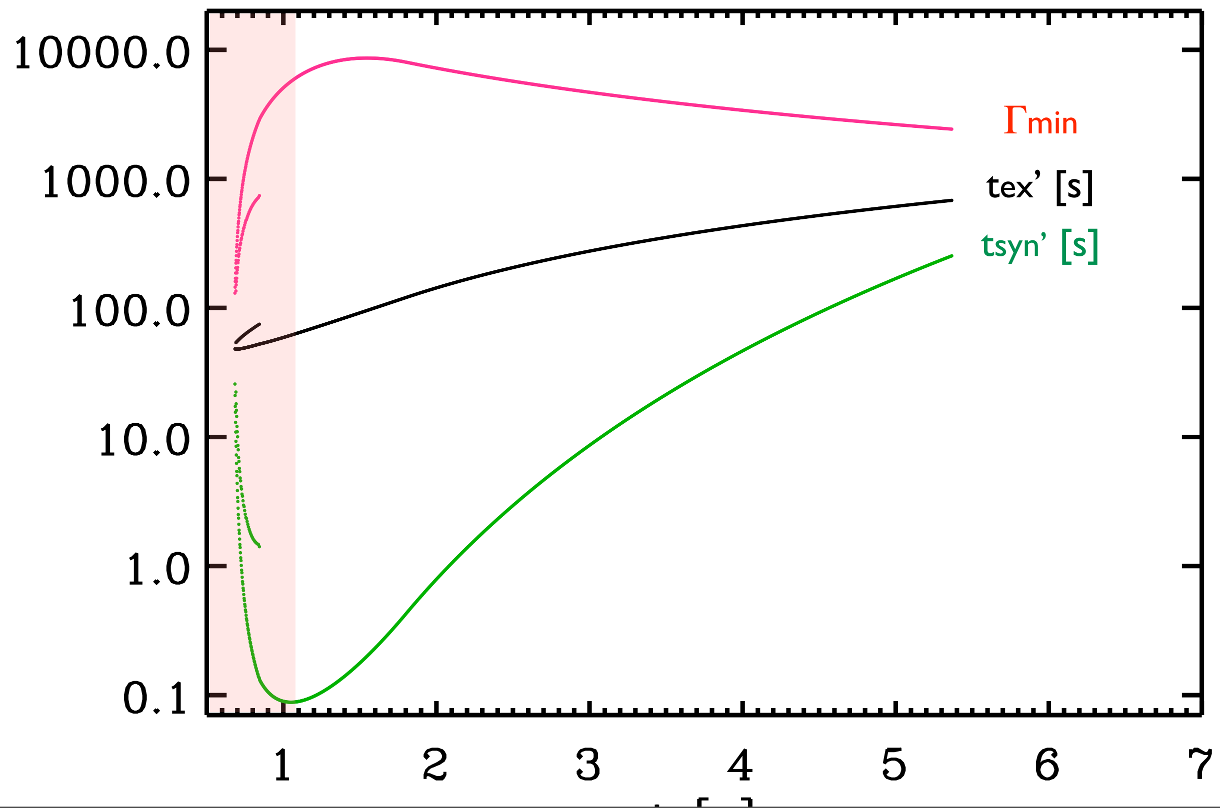




weak shock

ε^* low

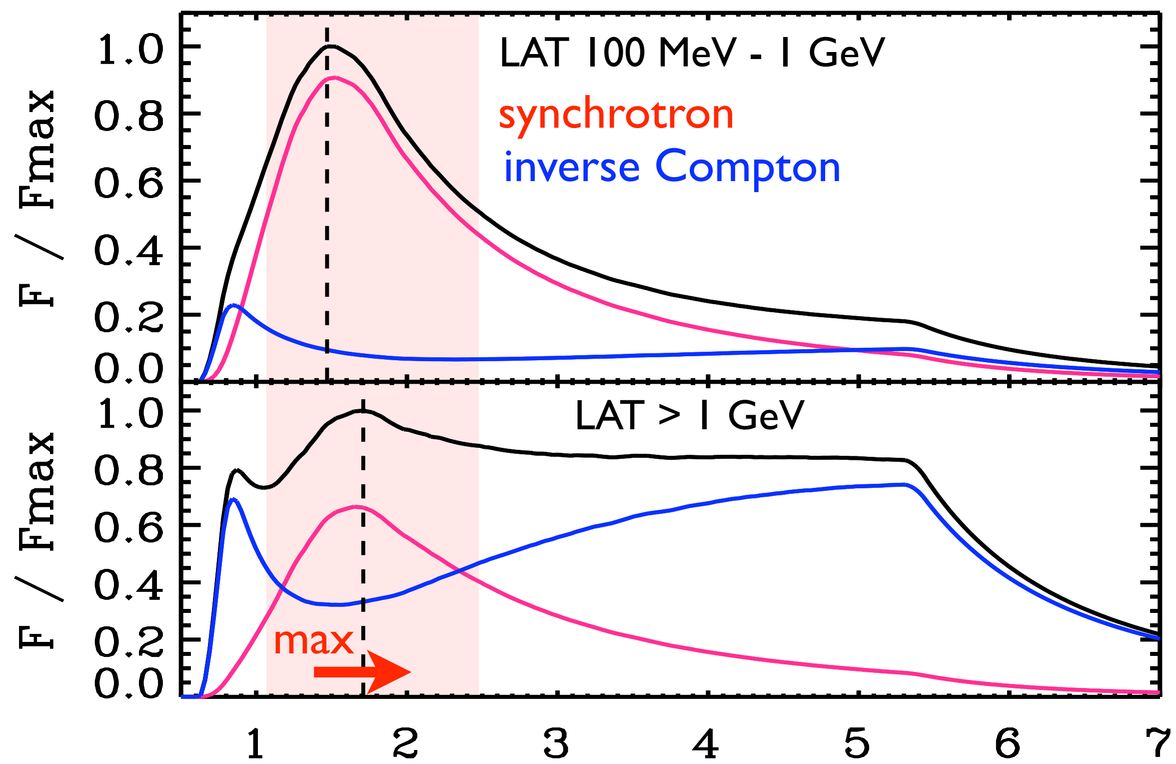
moderate $\Gamma_m \Rightarrow$ large t_{syn}'

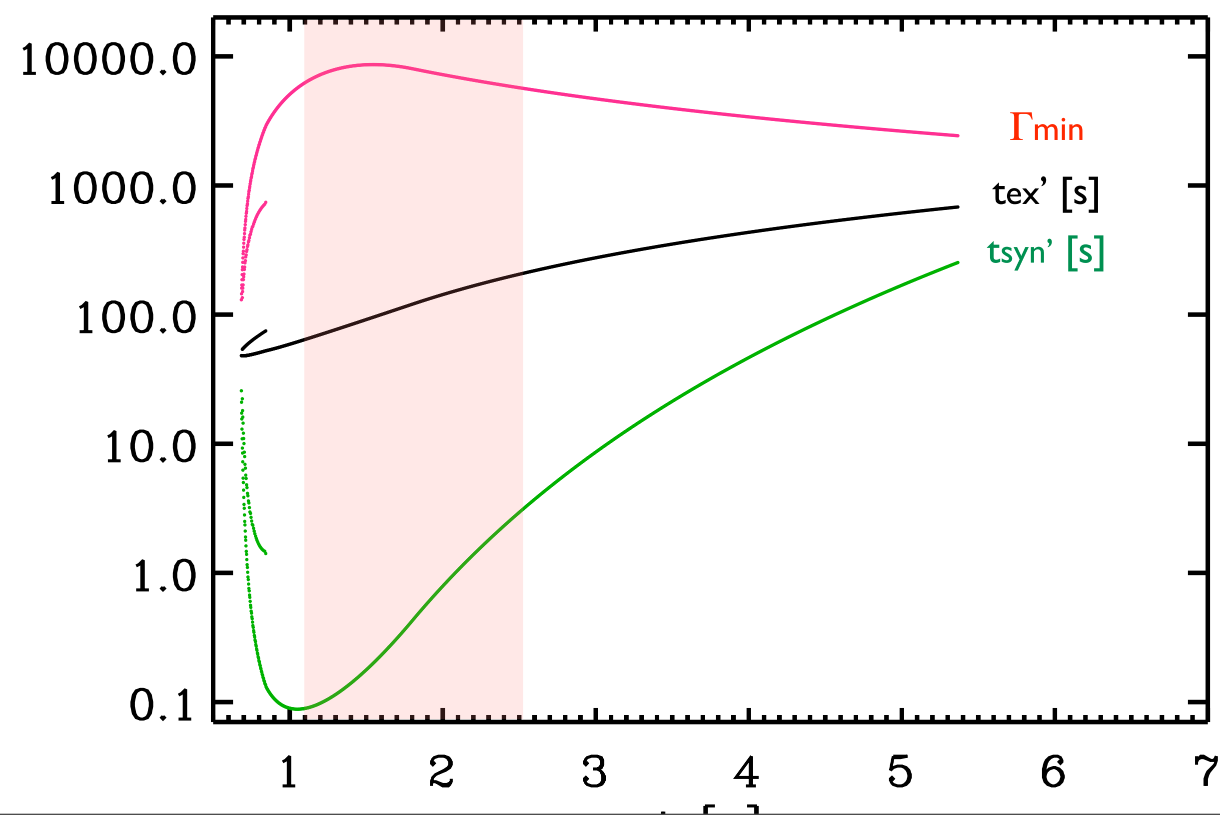
R small $\Rightarrow t_{ex}' \cong R/\Gamma^* c$ small

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

Emission processes and temporal profile

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





shock becomes stronger

Γ_m increases ⇒ t_{syn}' decreases

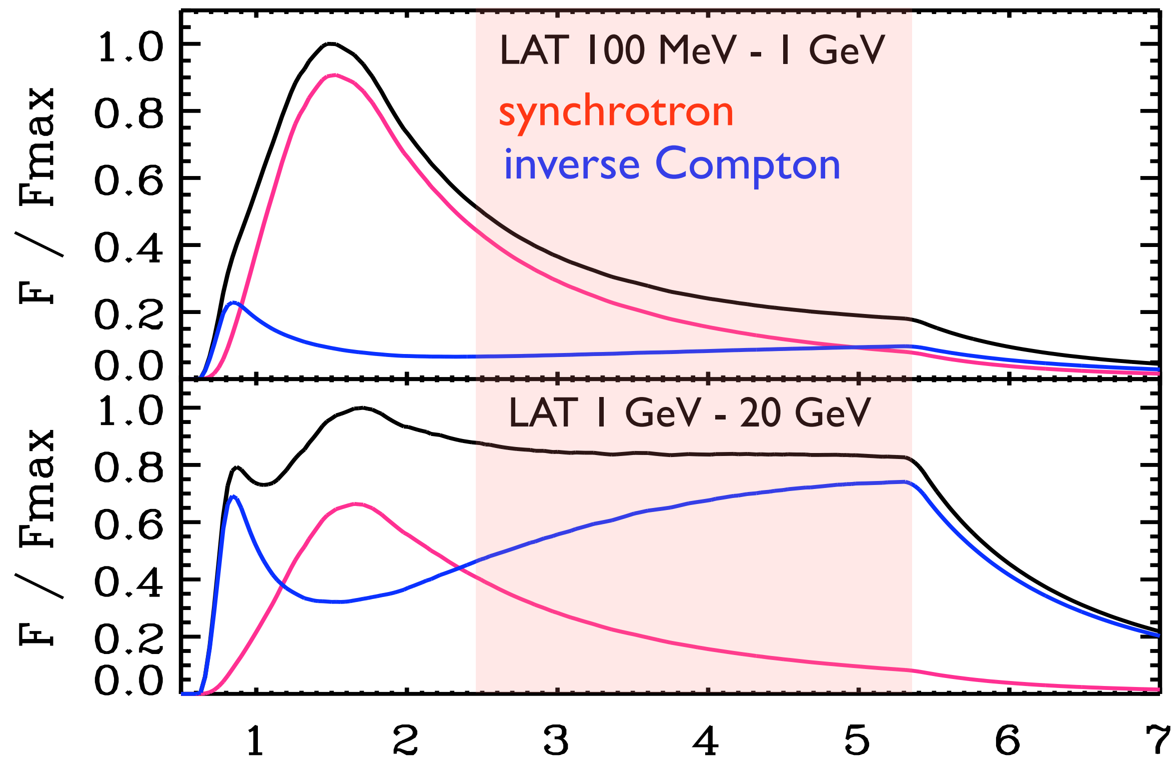
R, t_{ex}' increase

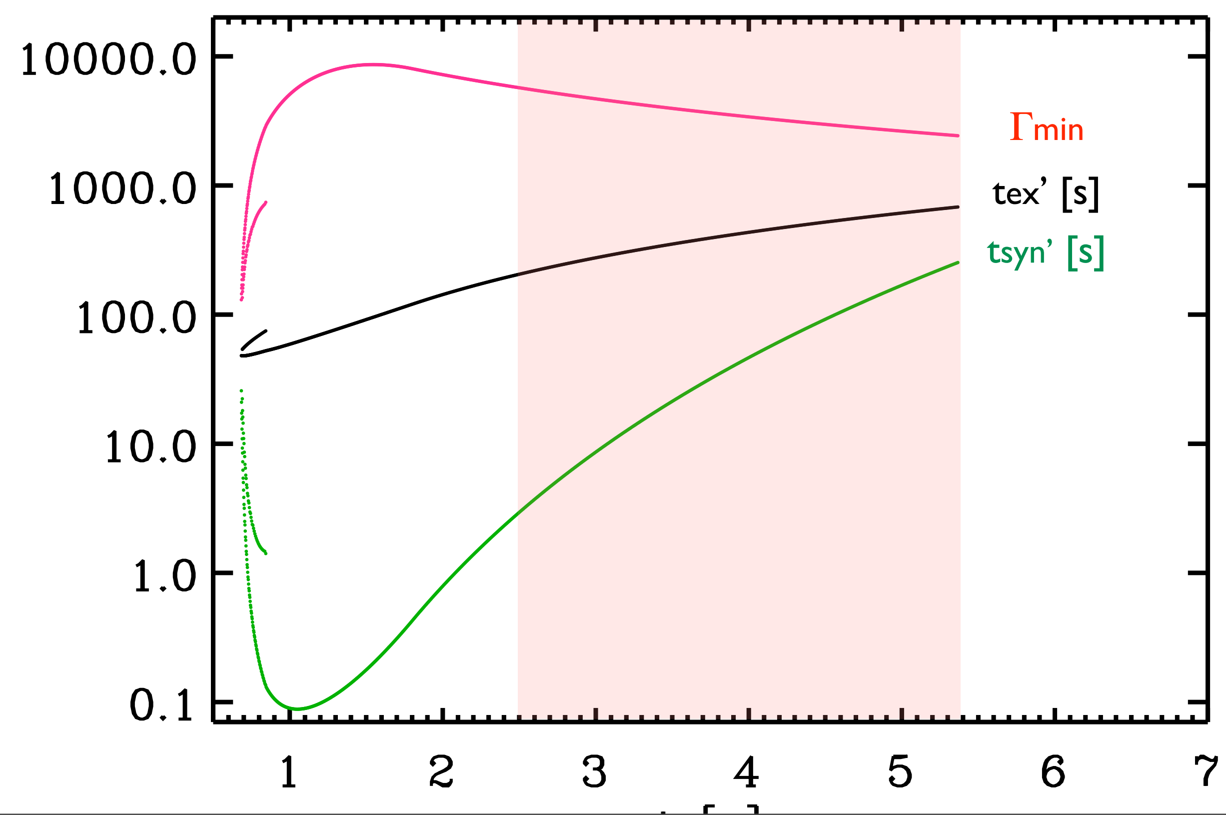
$t_{syn}' \ll t_{ex}'$ ⇒ low efficiency of IC

dominant synchrotron component

Emission processes and temporal profile

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





tail of the pulse:

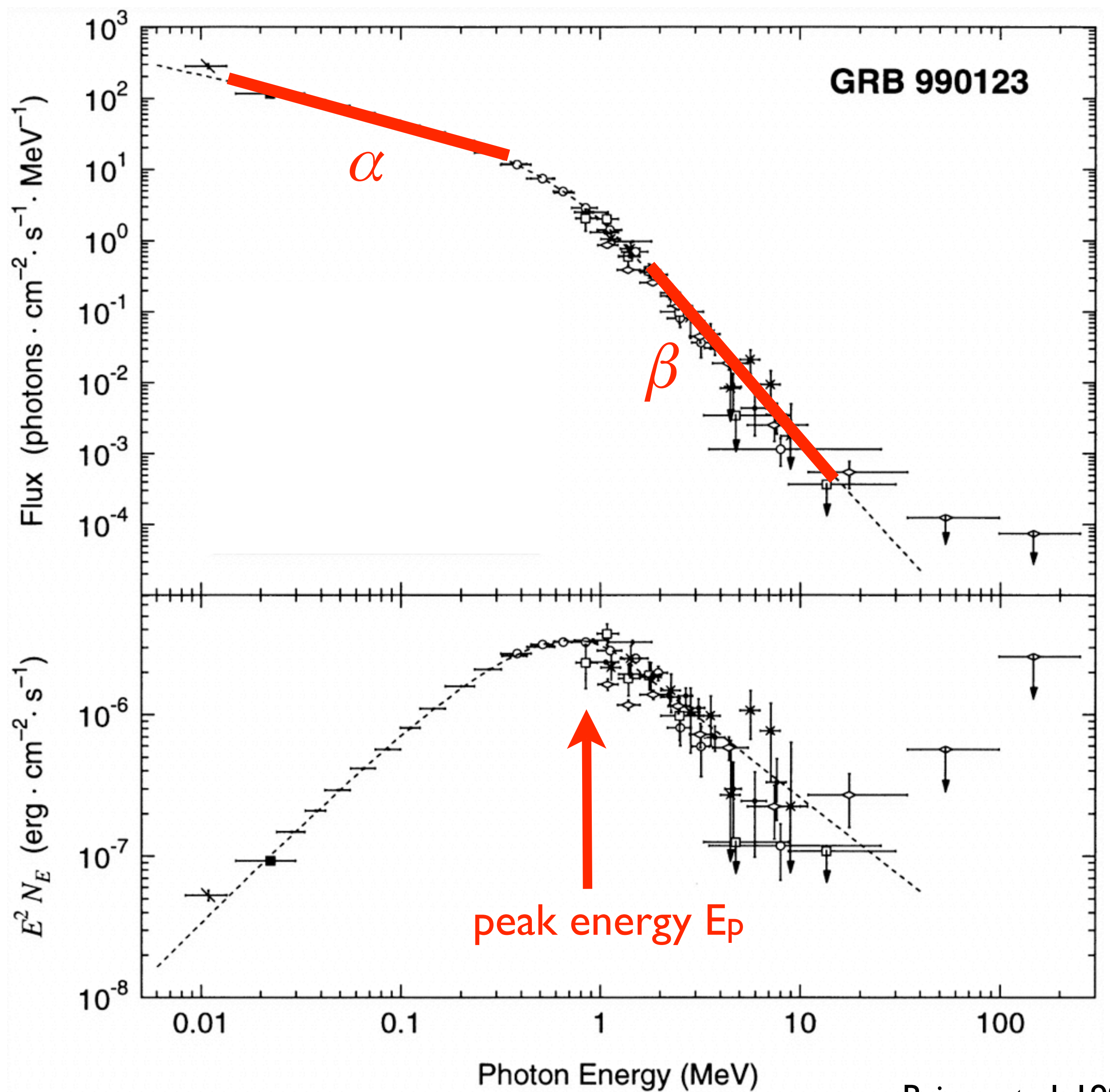
B decreases ⇒ tsyn' increases

tsyn' ≤ tex' ⇒ increased efficiency of IC

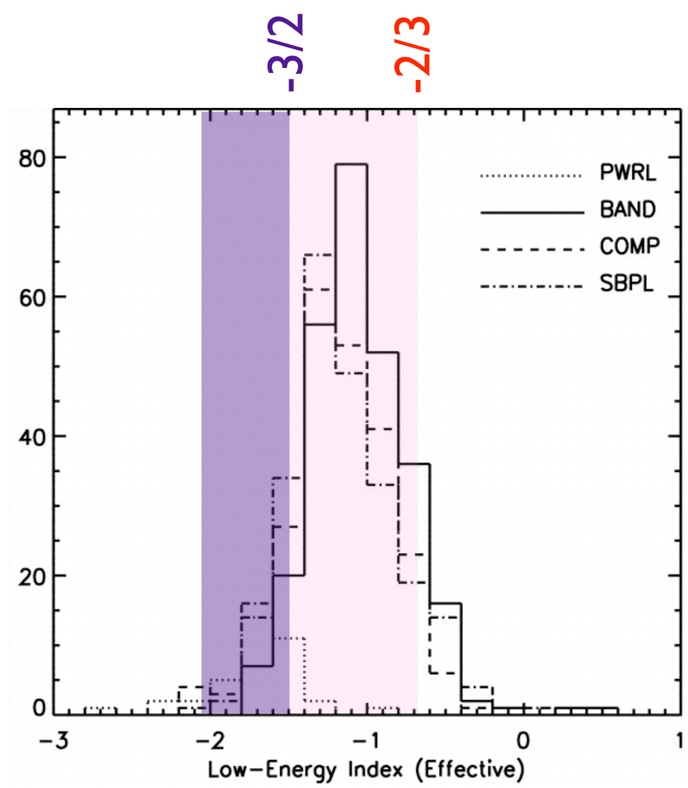
IC component dominant in GeV

Emission processes and spectral properties

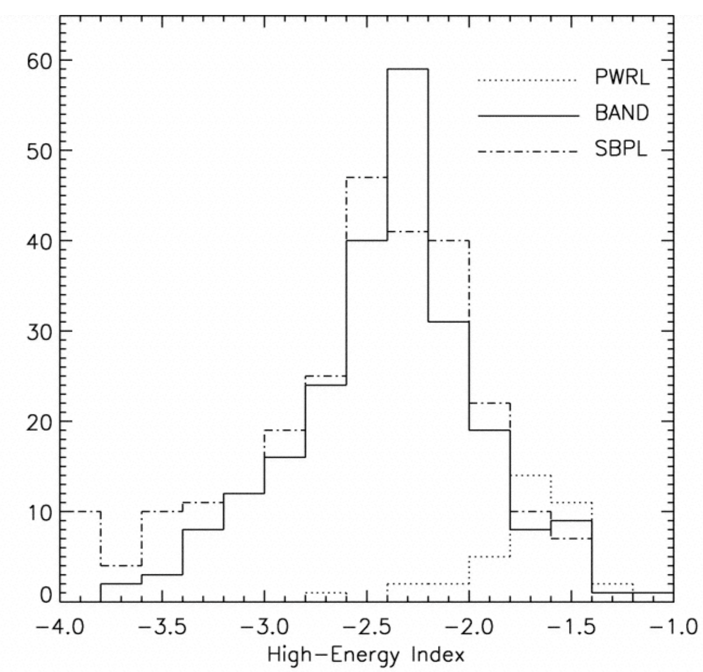
4-parameters "Band spectrum"
E_p, α, β and normalization
Band et al. 1993



Briggs et al. 1999



α = -1.02 ± 0.27



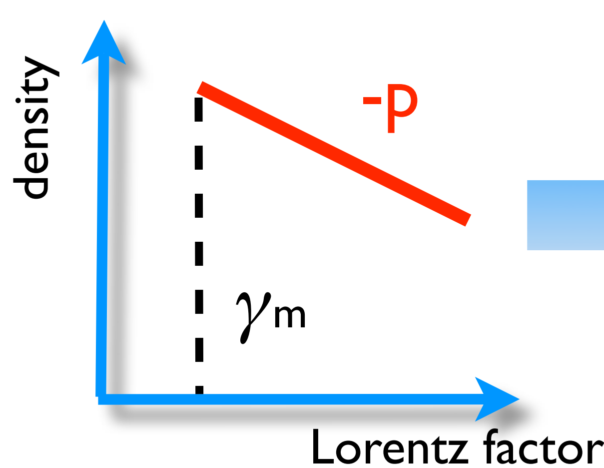
β = -2.35 ± 0.27

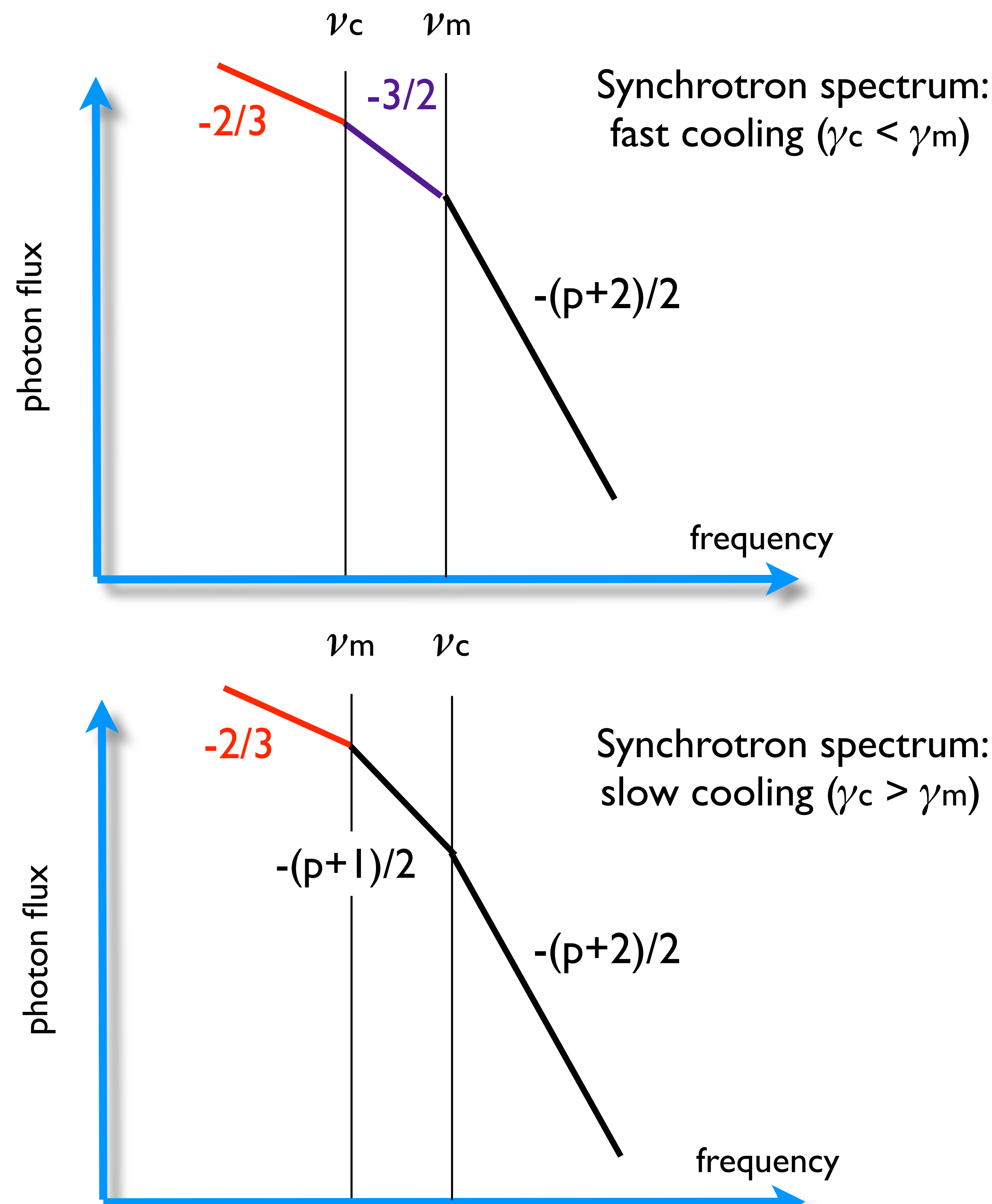
Kaneko et al. 2006

Emission processes and spectral properties

Sari, Piran & Narayan 1998

Relativistic electrons:

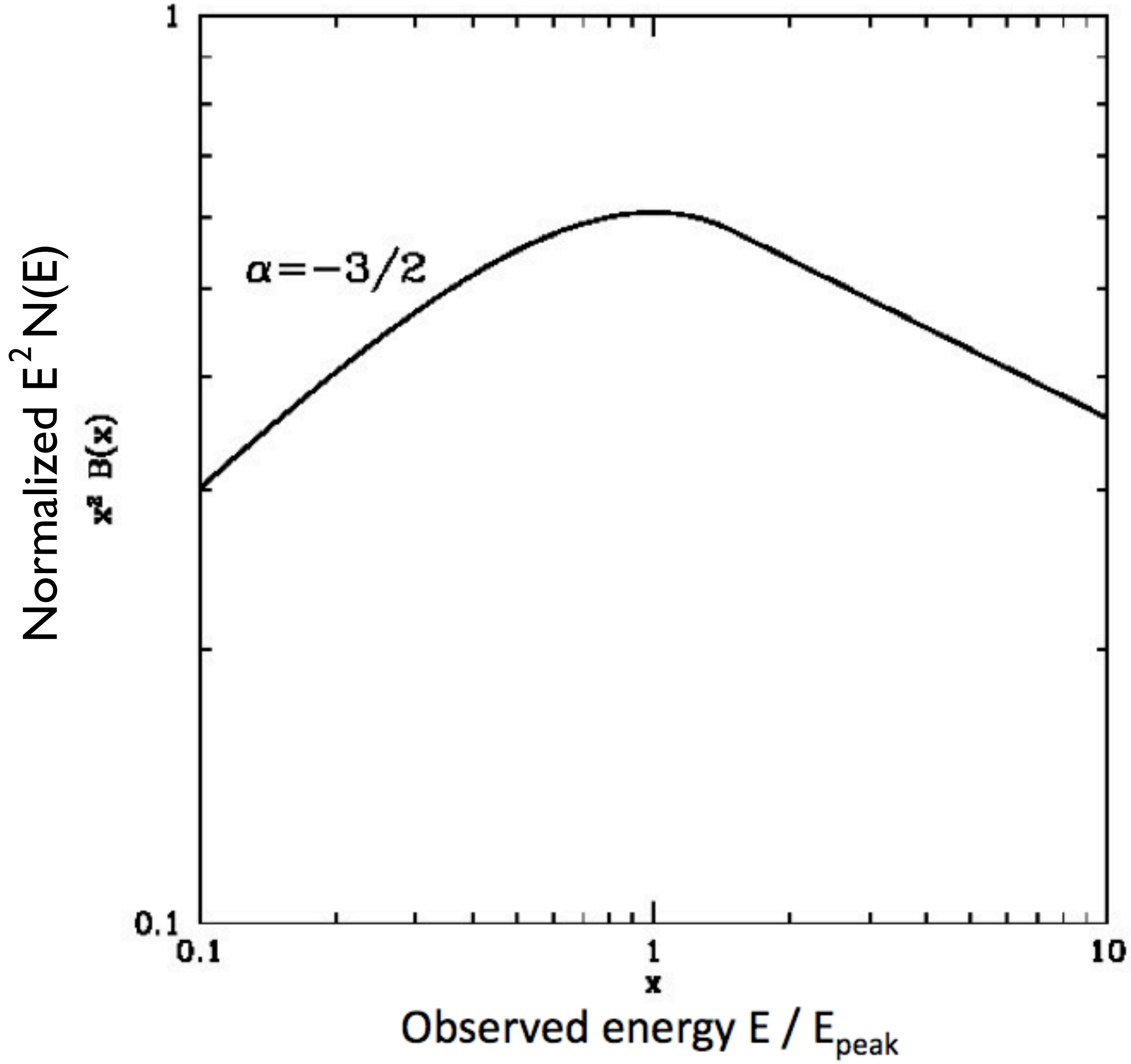




γ_m: minimum Lorentz factor at injection

γ_c: radiative timescale = dynamical timescale

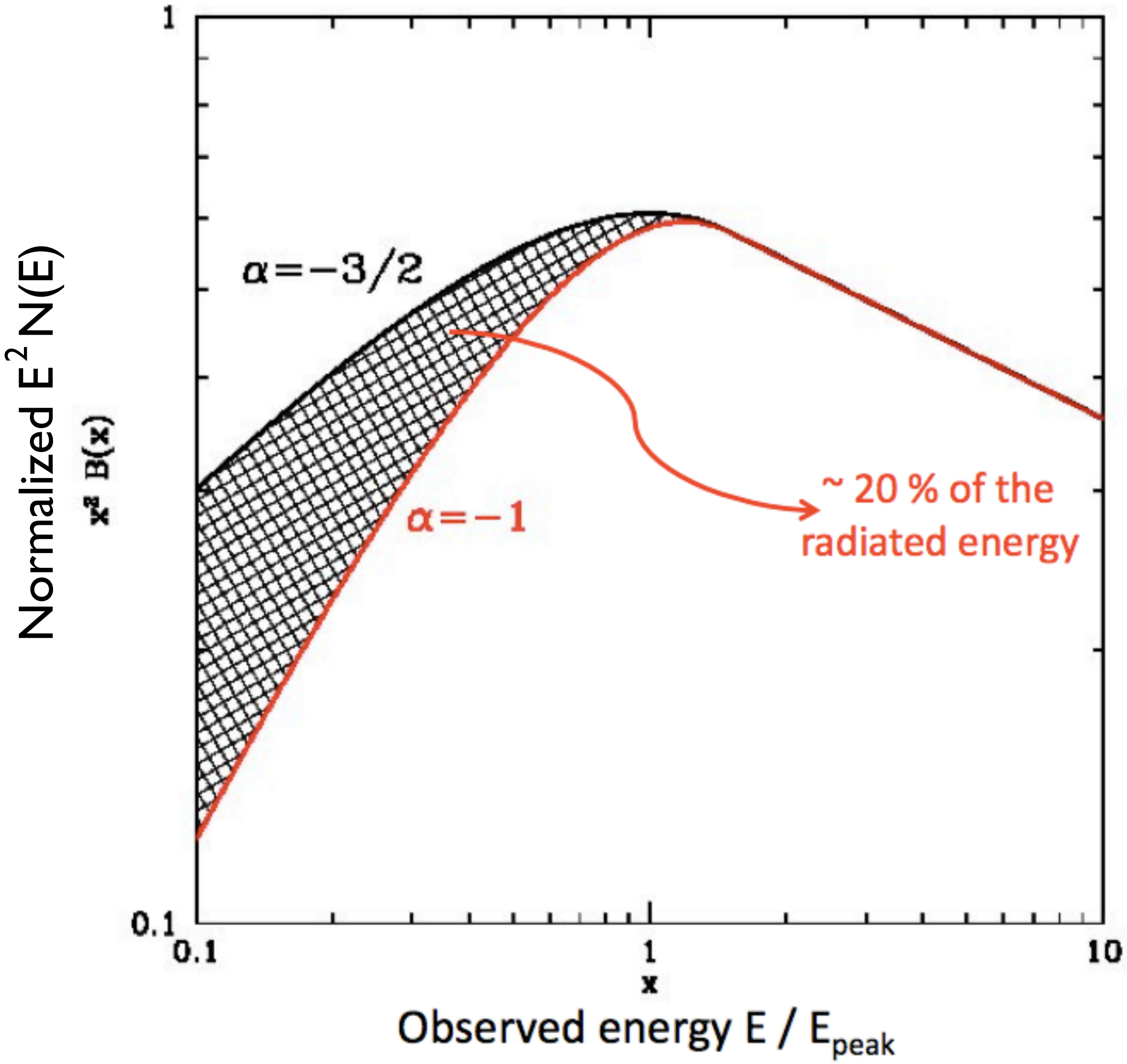
Emission processes and spectral properties



Band function

α = - 1.5
β = - 2.25

Emission processes and spectral properties



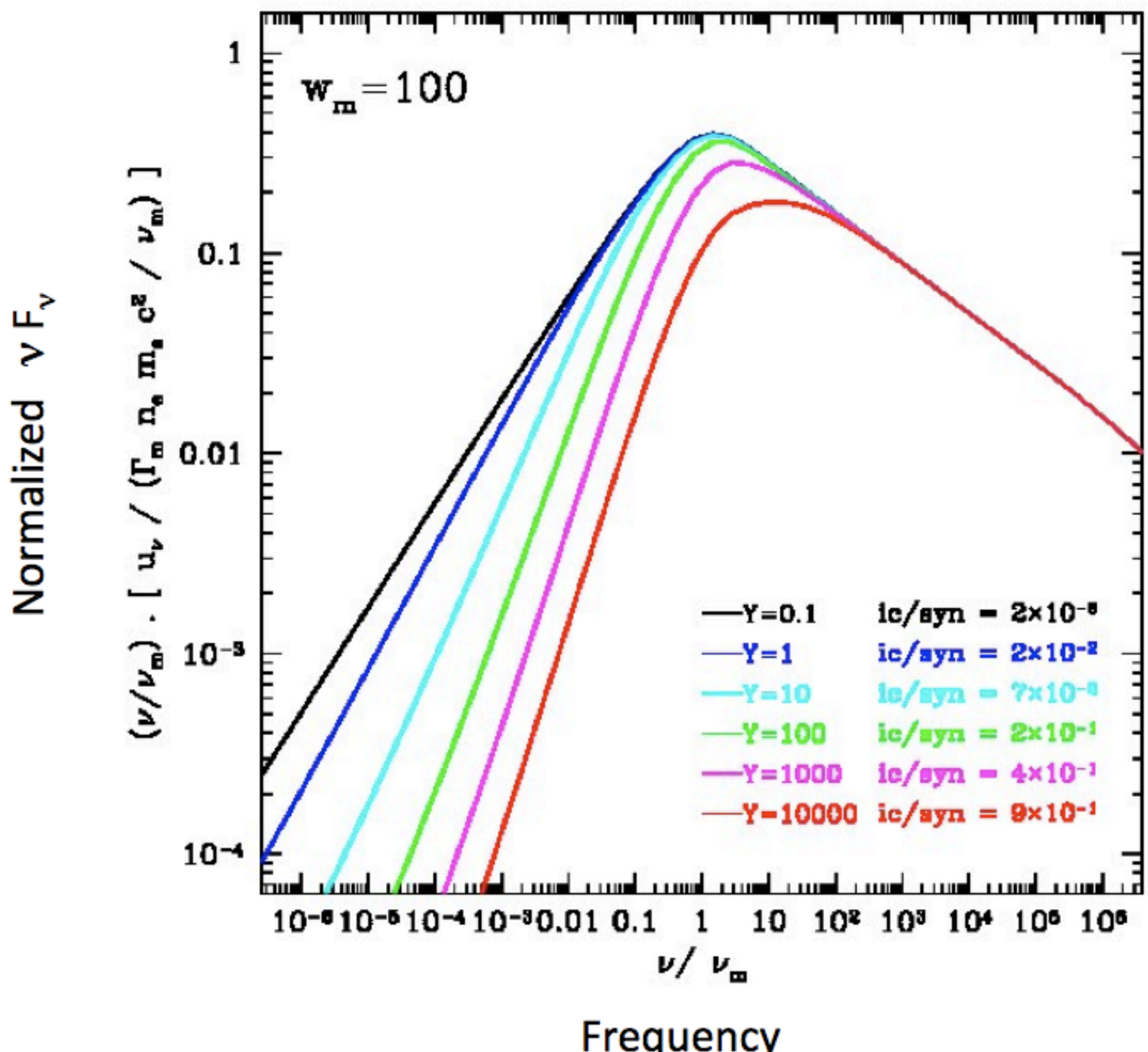
Band function

α = - 1.5 → -1

β = - 2.25

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

Emission processes and 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

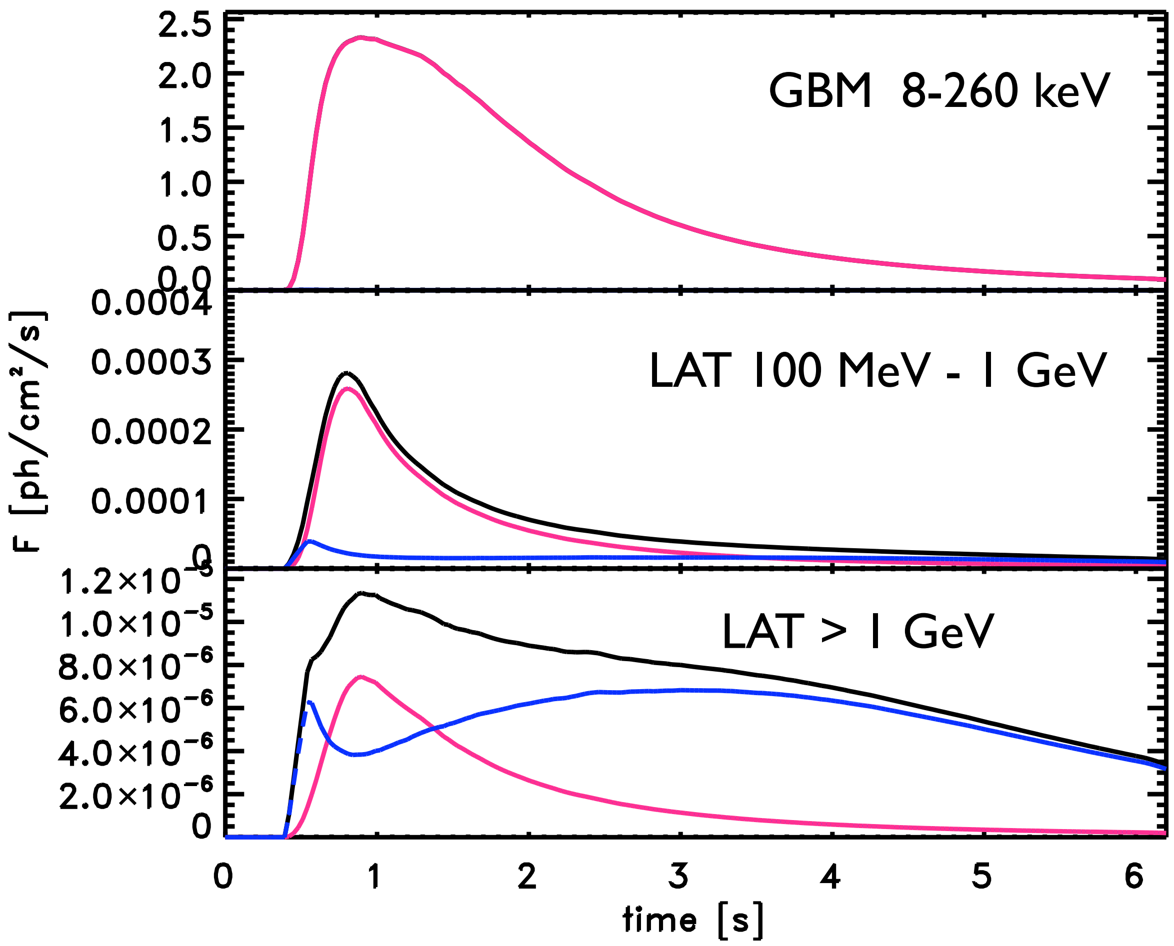
Exact calculation with synchrotron + IC only
(no adiabatic cooling, synchrotron self-absorption, $\gamma\gamma$ annihilation)

Emission processes and spectral properties

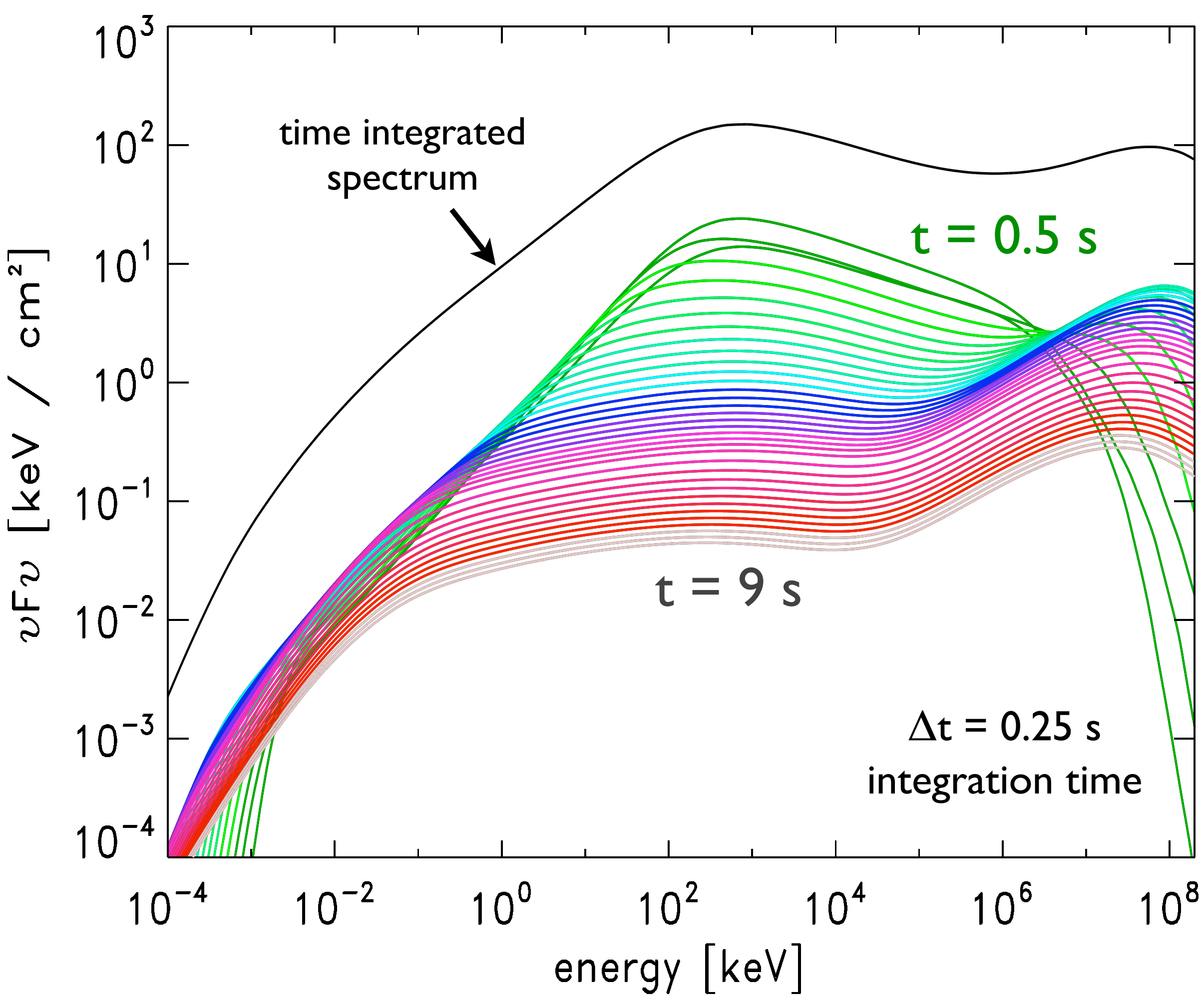
SYNCHROTRON CASE

low magnetic field

dE/dt = 5 x 10^{53} erg s^{-1}, ε_B = 0.0005, ε_e = 1/3, ζ = 0.002, p = 2.5, z=1



Observed lightcurve



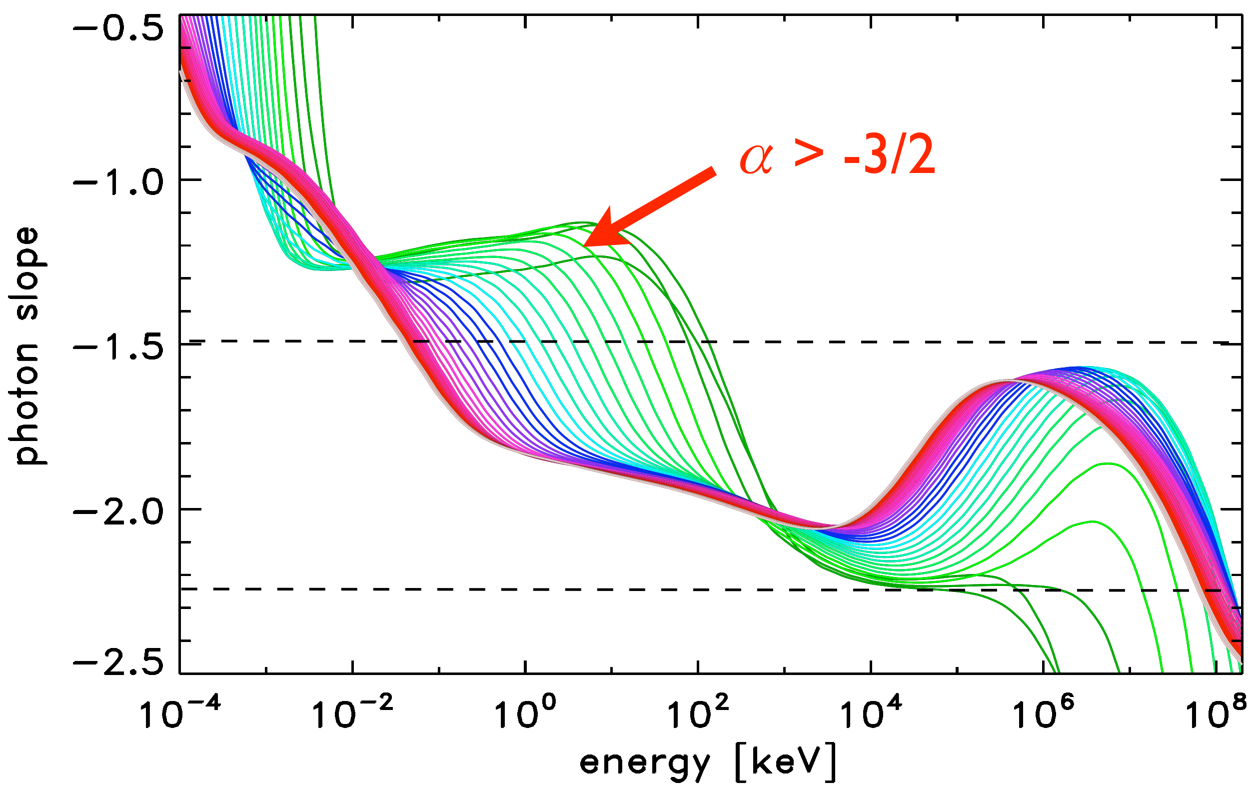
Time resolved spectra

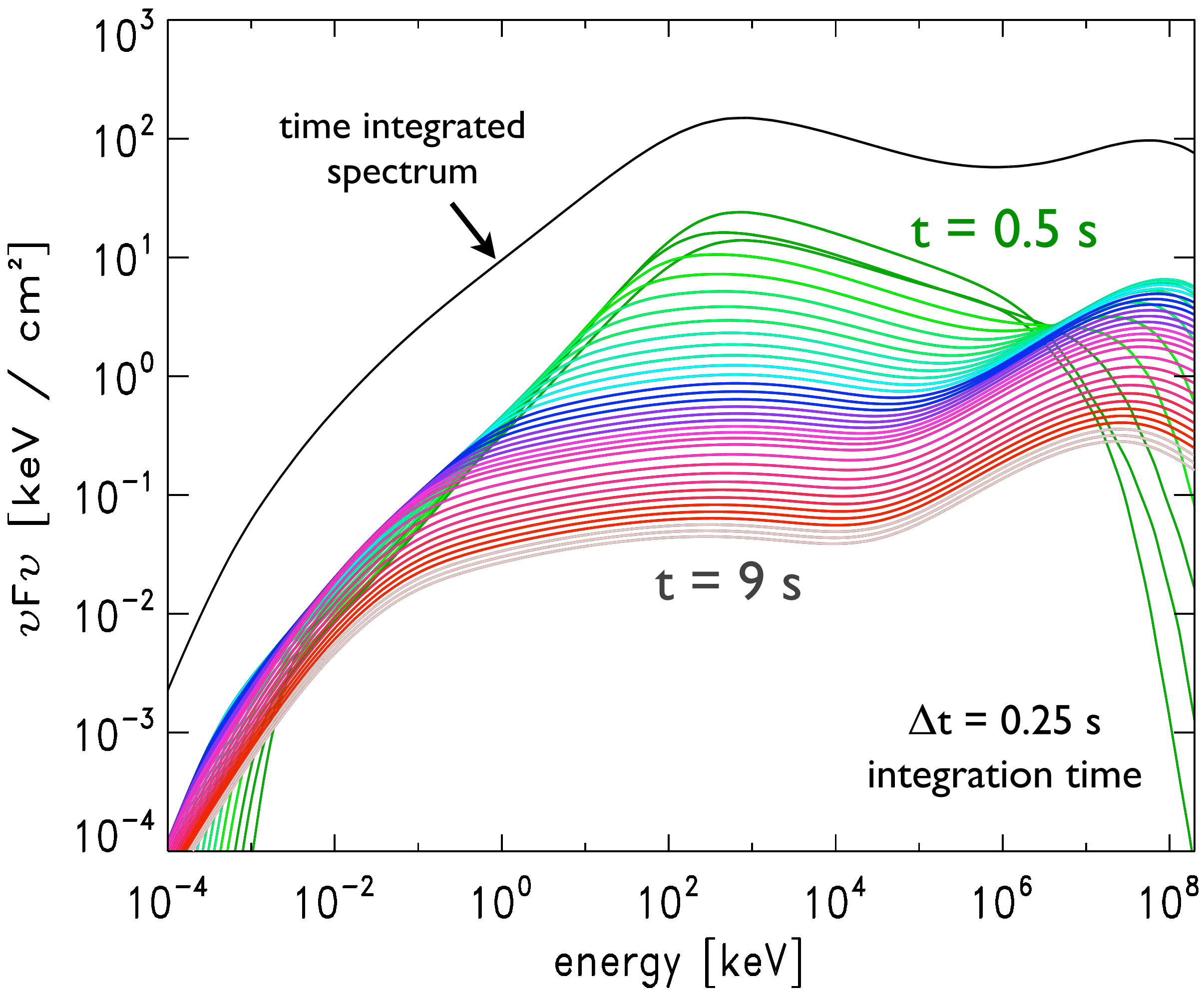
Emission processes and spectral properties

SYNCHROTRON CASE

low magnetic field

dE/dt = 5 x 10^{53} erg s^{-1}, ε_B = 0.0005, ε_e = 1/3, ζ = 0.002, p = 2.5, z=1



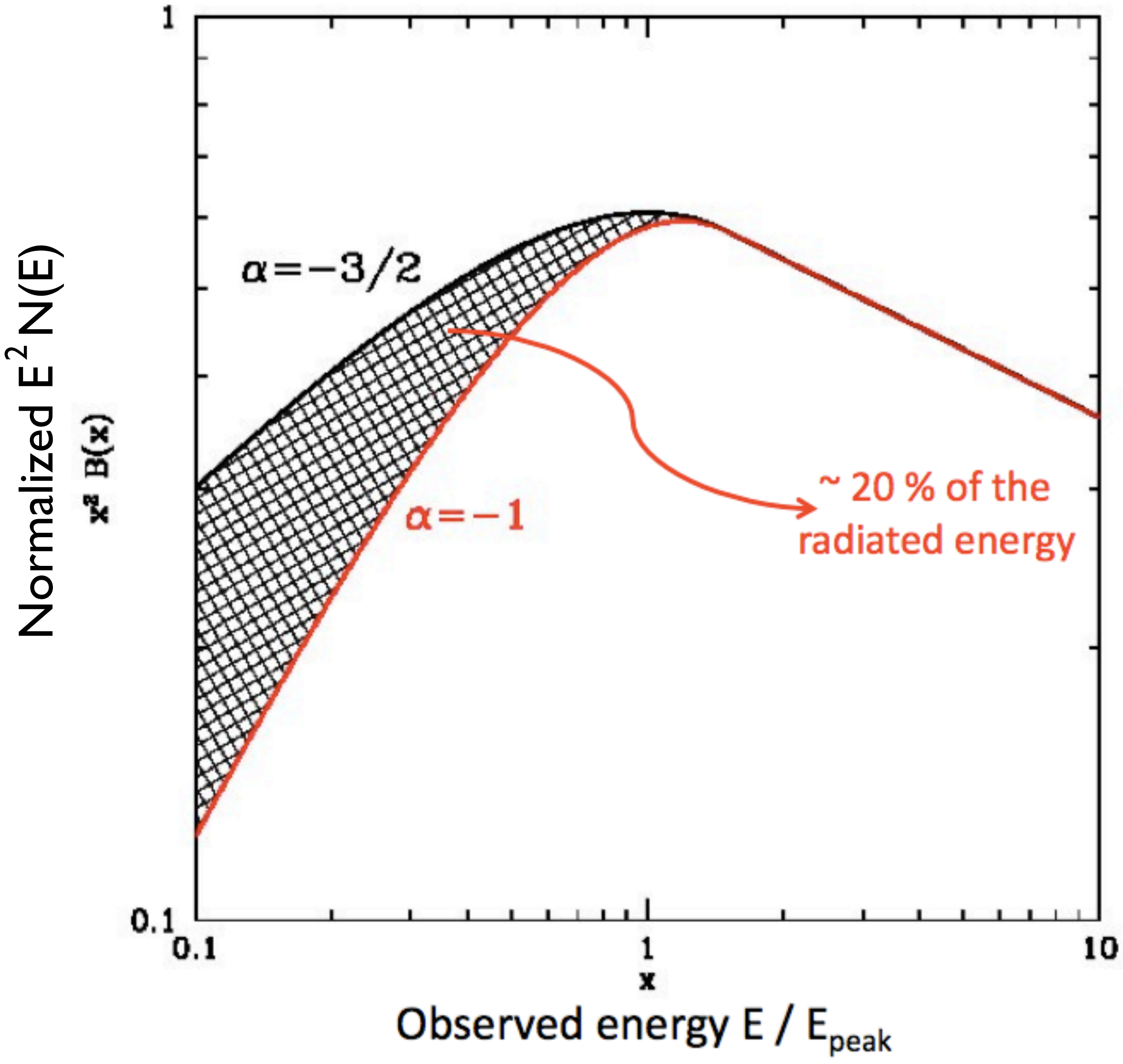


α = -3/2

low energy spectral slope of the fast cooling synchrotron spectrum

Time resolved spectra

Emission processes and spectral properties



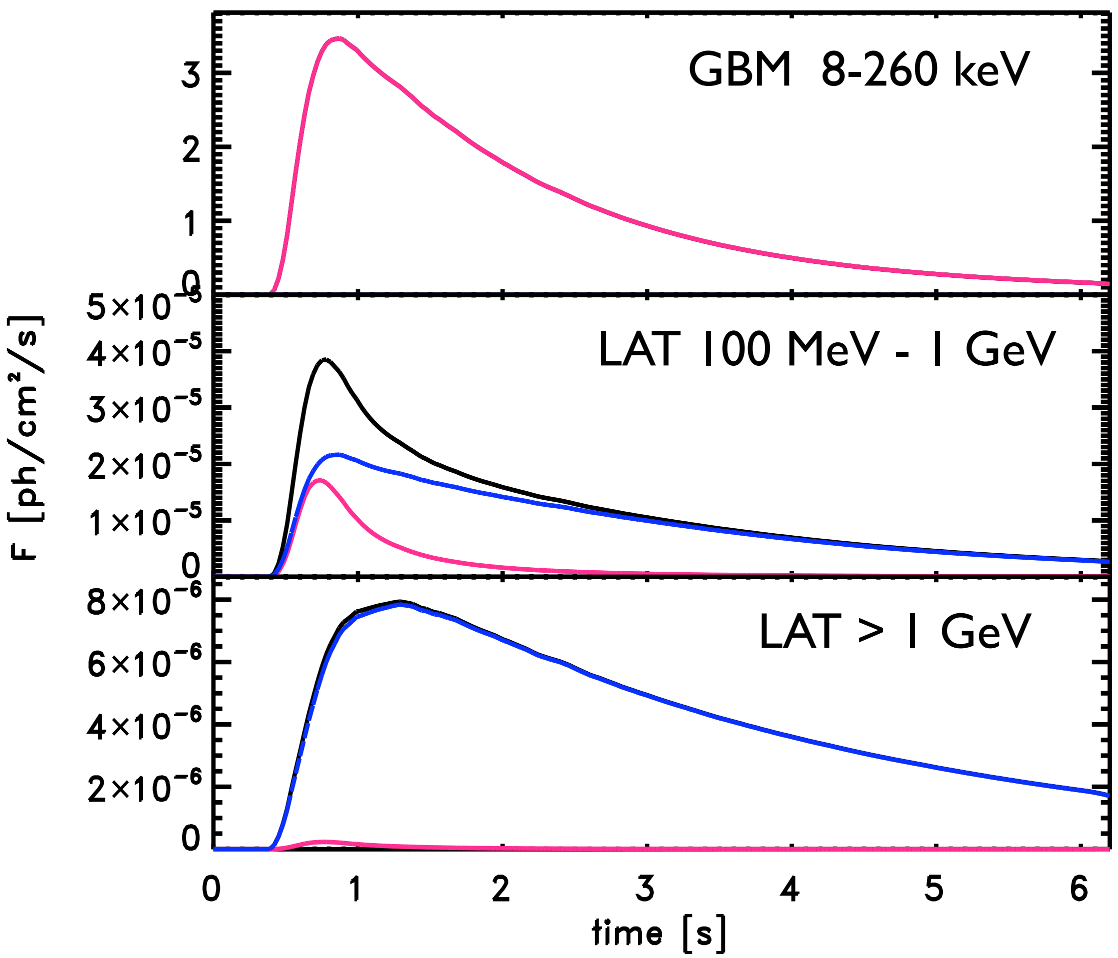
Spectral peak energy is also affected by IC scatterings!

Testing different assumptions on the relativistic e- distribution

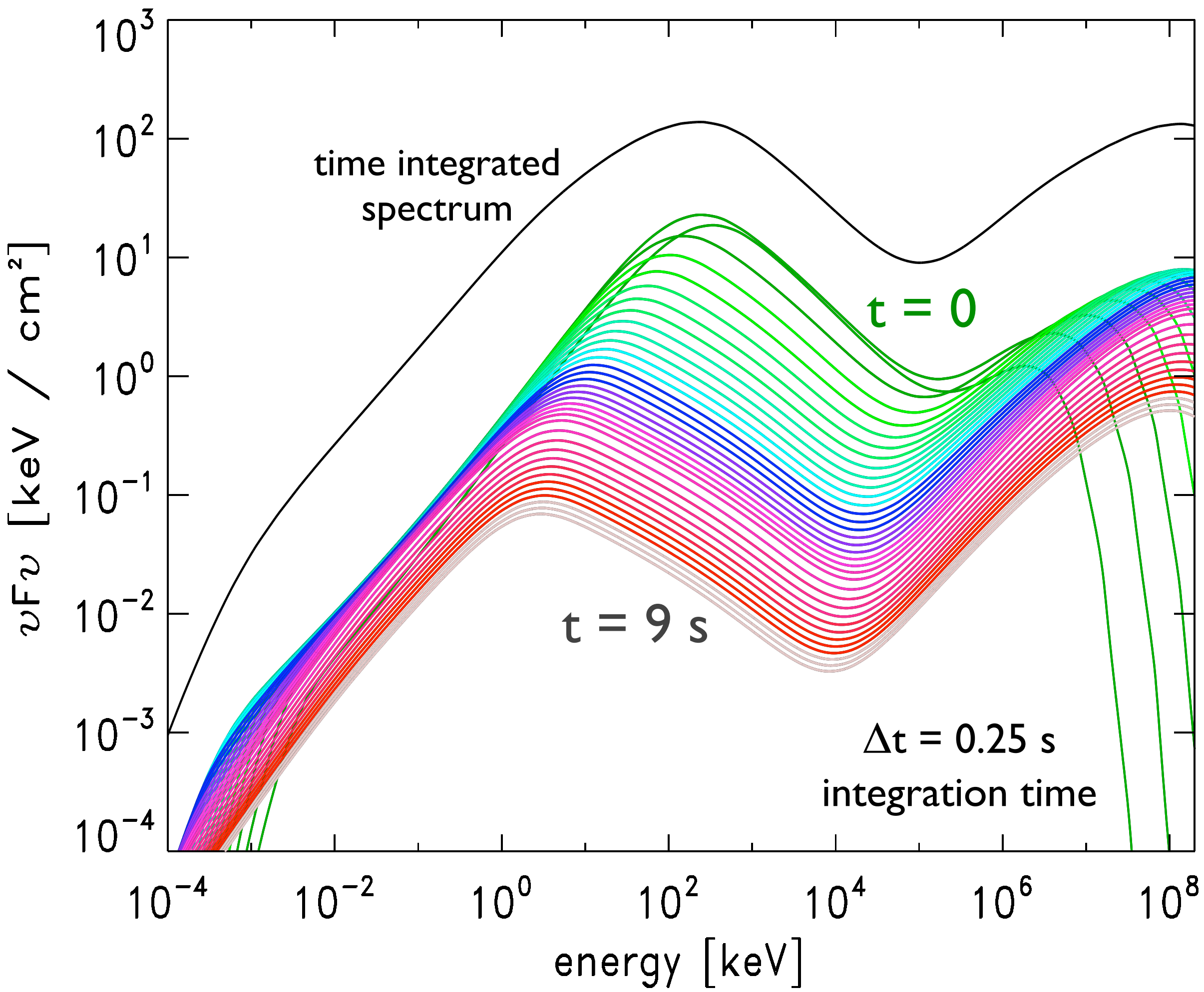
SYNCHROTRON CASE

low magnetic field with ζ varying and a steep slope p of the e- distribution

dE/dt = 5 x 10^{53} erg s^{-1}, $\varepsilon_B = 0.0005$, $\varepsilon_e = 1/3$, $\zeta_{max} = 0.0025$, p = 3.5, z=1



Observed lightcurves



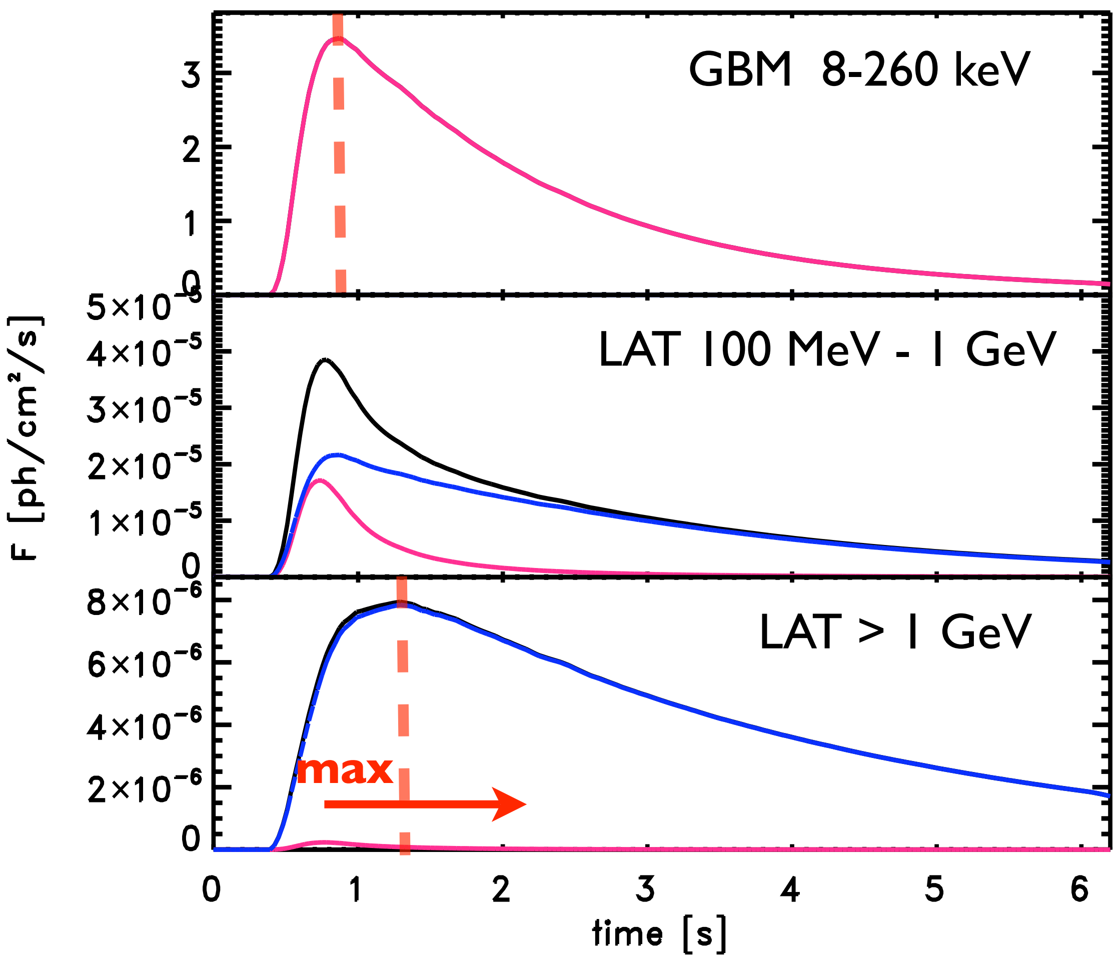
Time resolved spectra

Testing different assumptions on the relativistic e- distribution

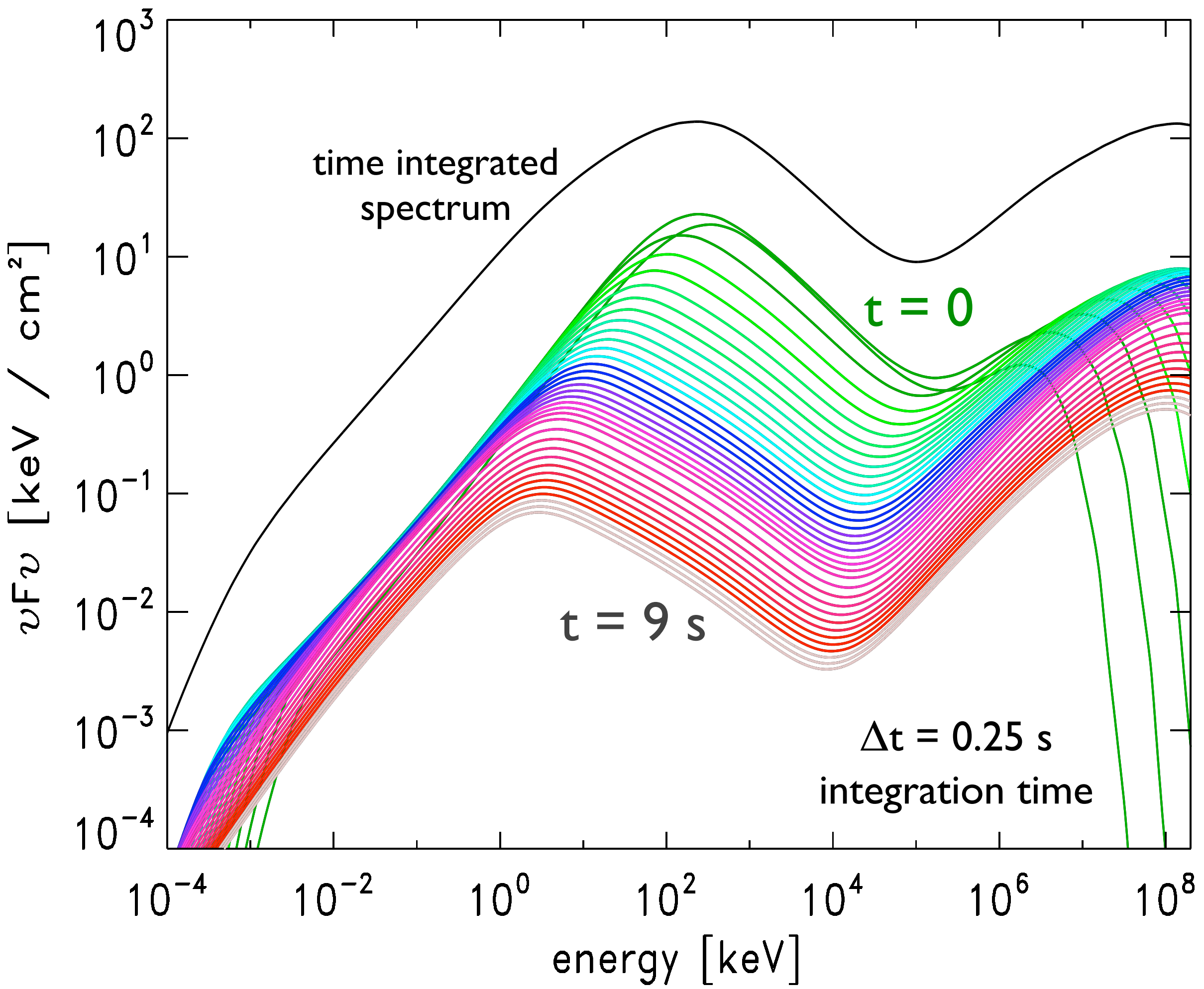
SYNCHROTRON CASE

low magnetic field with ζ varying and a steep slope p of the e- distribution

dE/dt = 5 x 10^{53} erg s^{-1}, ε_B = 0.0005, ε_e = 1/3, ζ_{max} = 0.0025, p = 3.5, z=1



Observed lightcurves



Time resolved spectra

Testing different assumptions on the relativistic e- distribution

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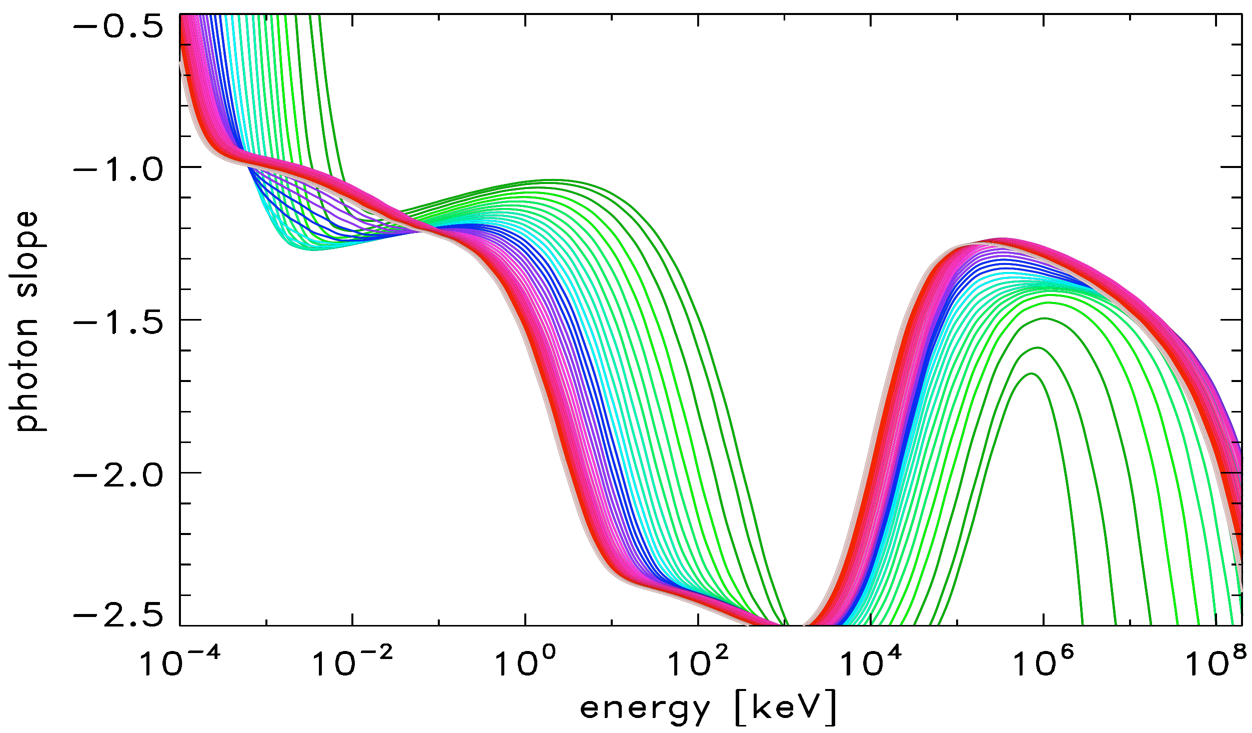

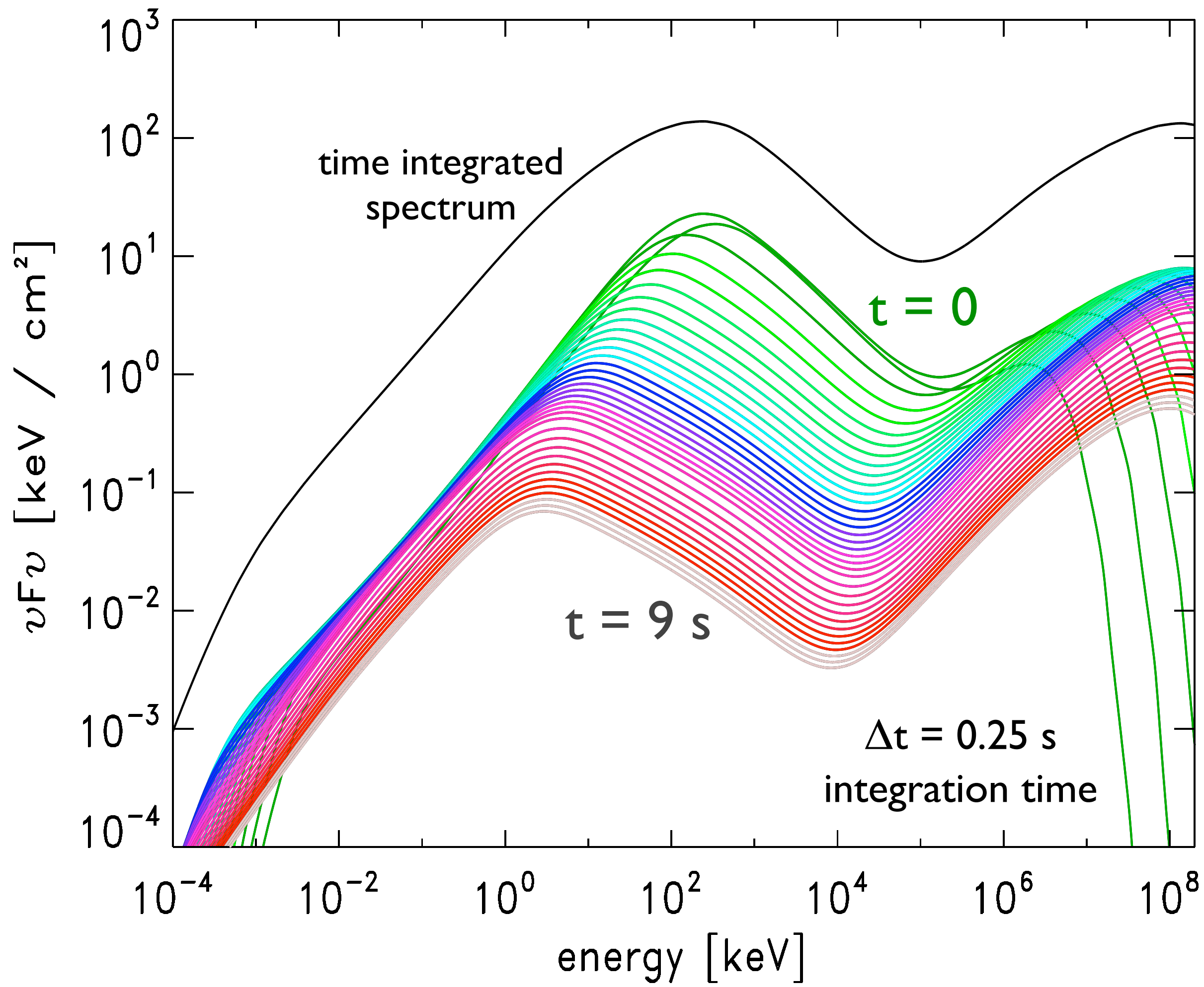

Time resolved spectra

Testing different assumptions on the relativistic e- distribution

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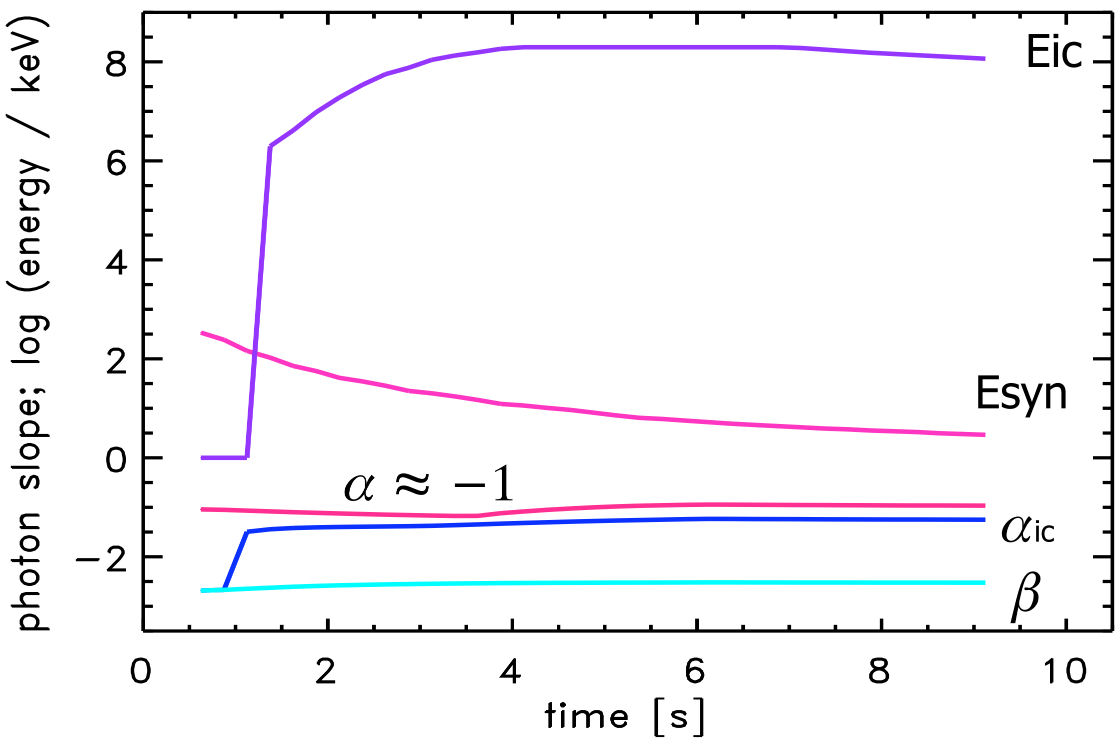
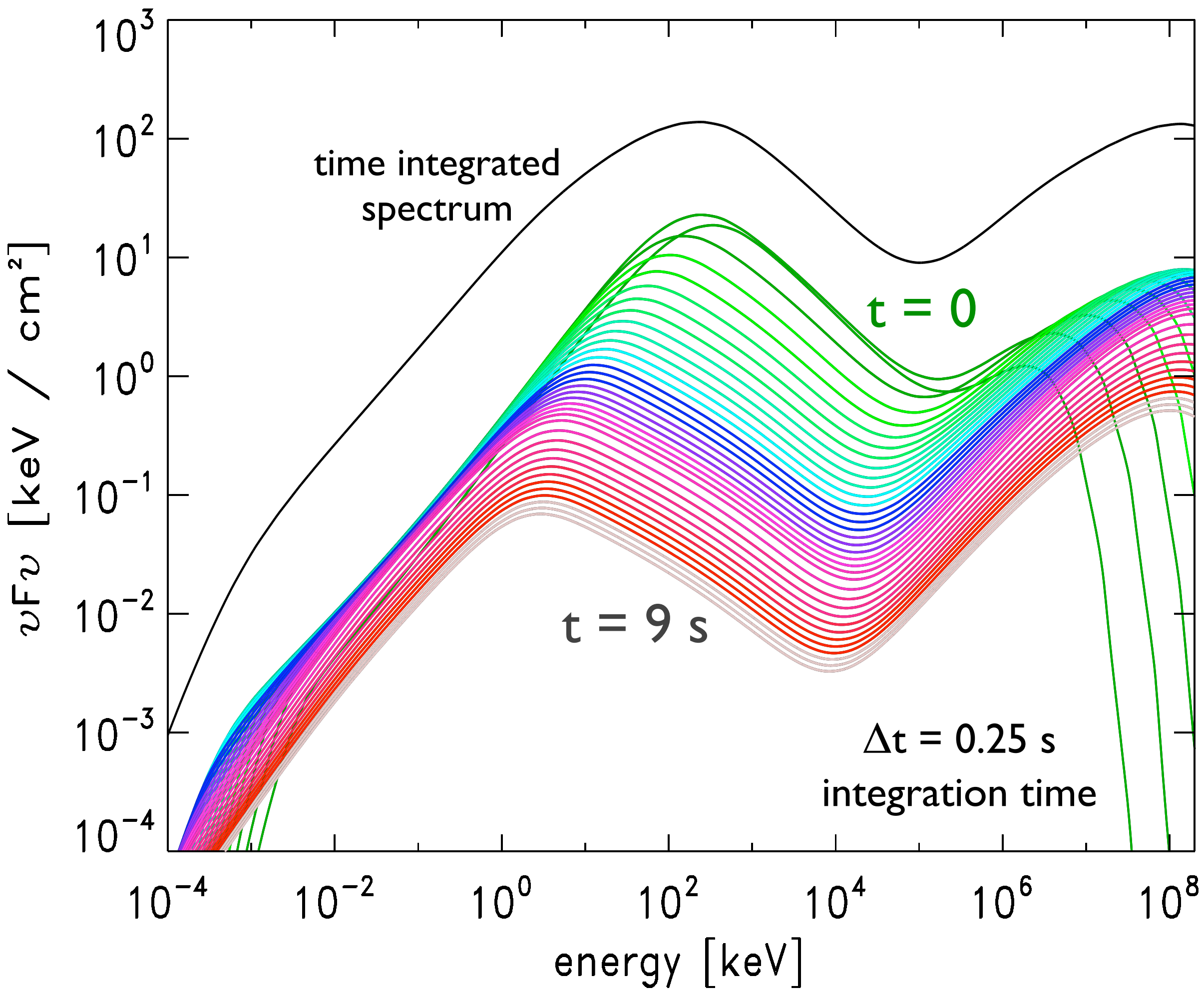
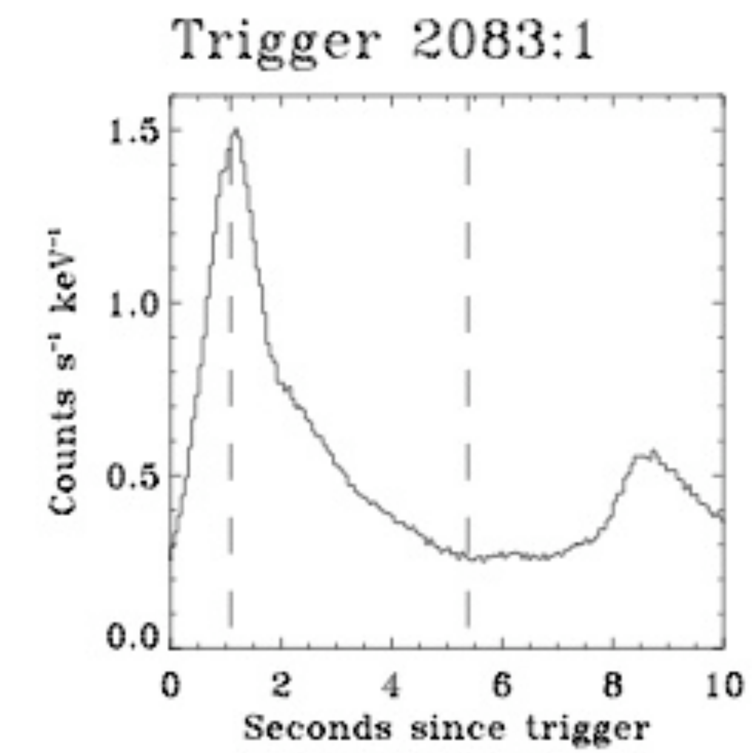


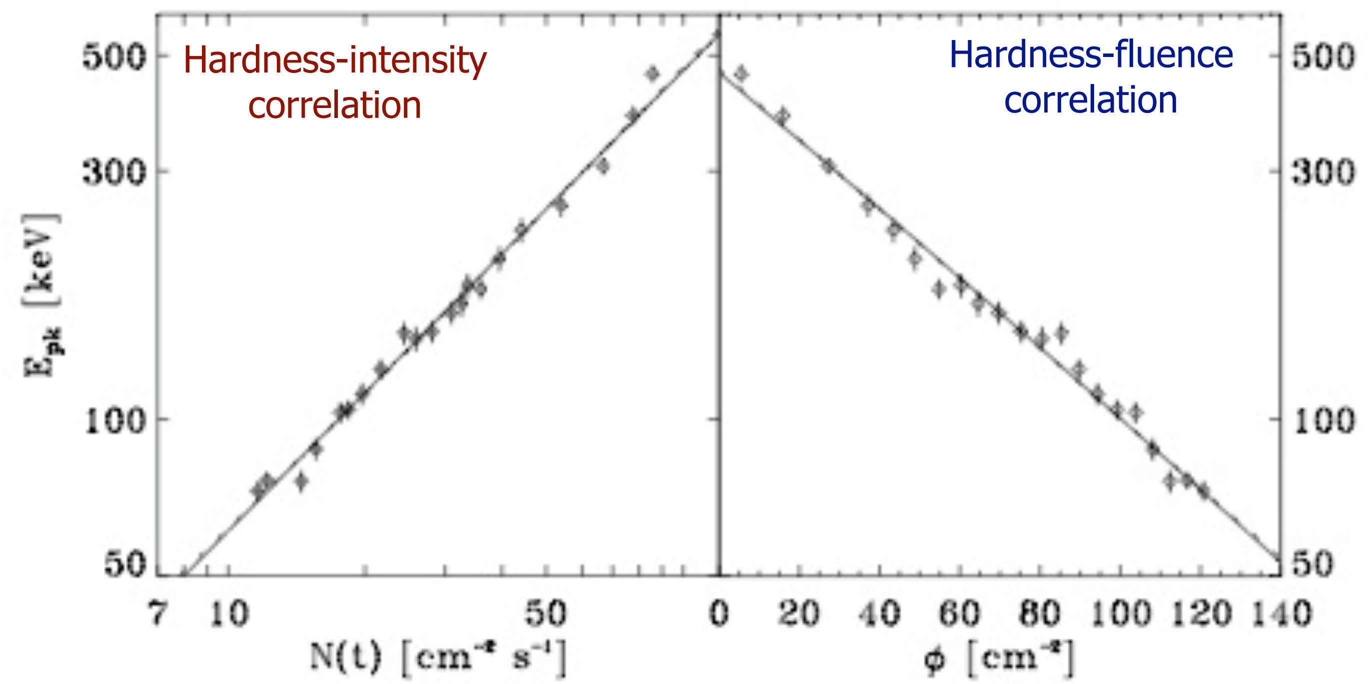


Time resolved spectra

Spectral and temporal behavior: HIC & HFC



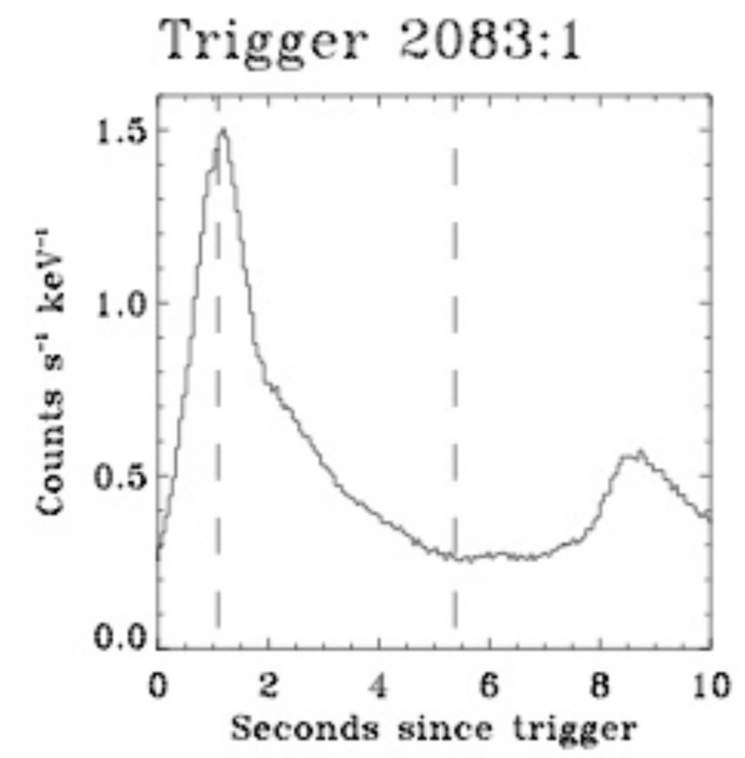
Kargatis 1995
Liang & Kargatis 1996
Ryde & Svensson 2002



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

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

Spectral and temporal behavior: HIC & HFC



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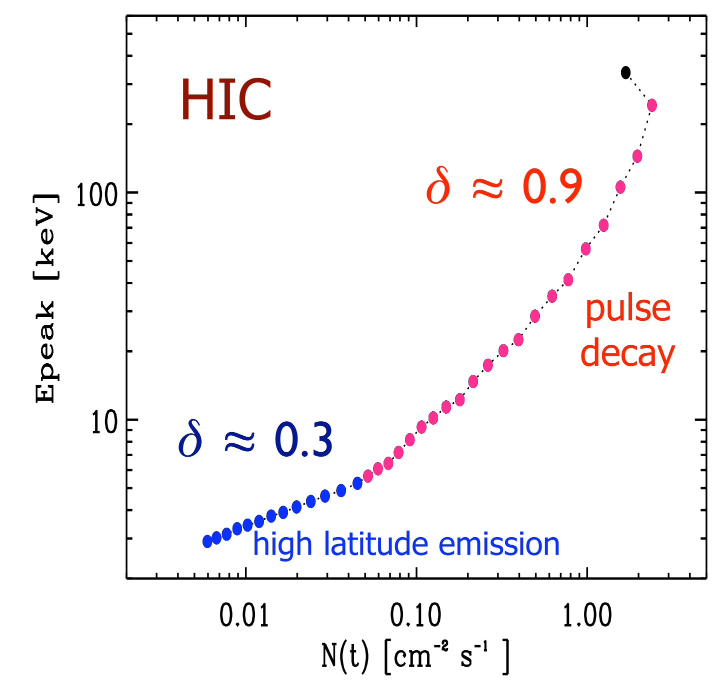
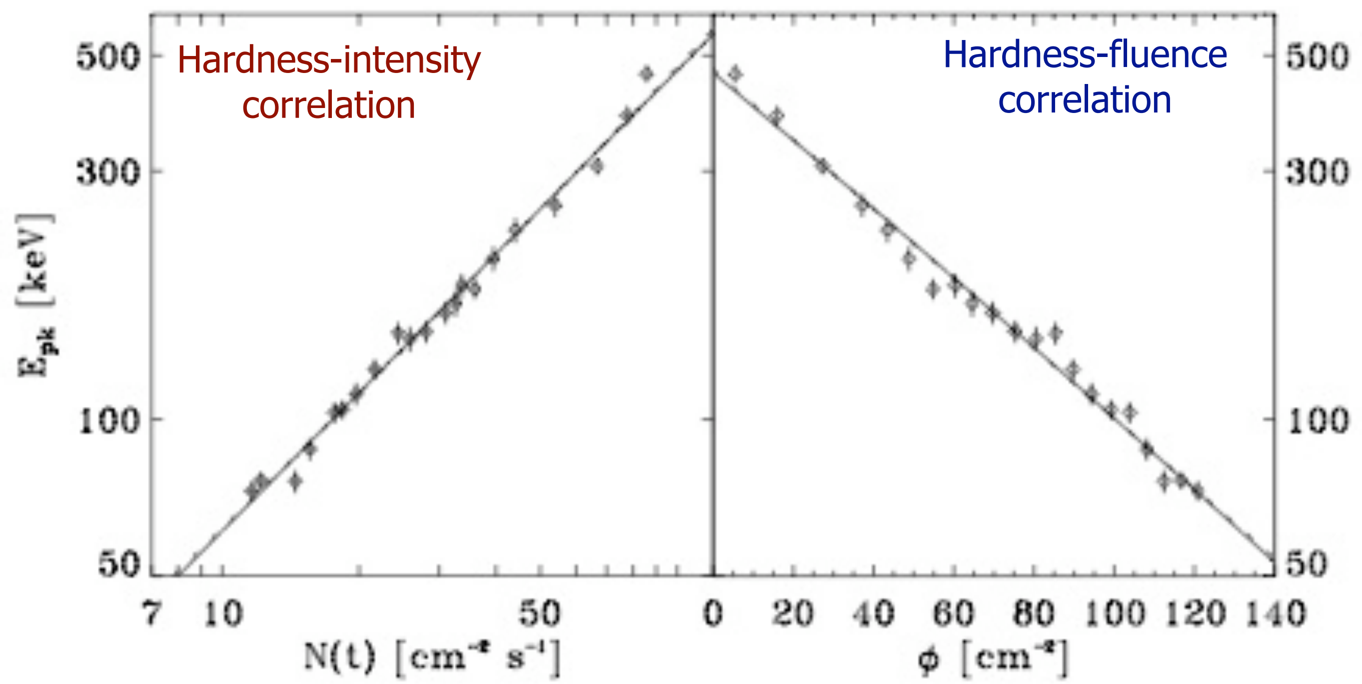
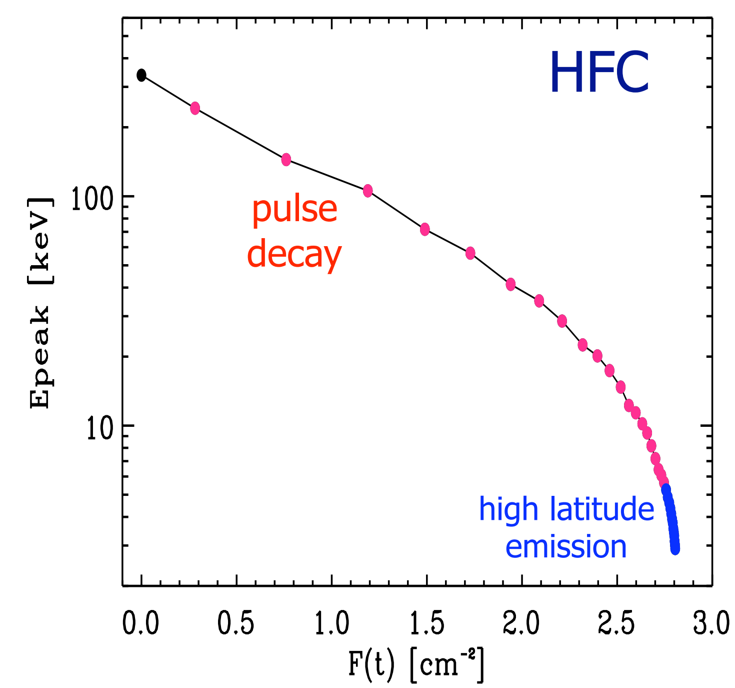






$$E_{\rm pk}(N) = E_{\rm pk,\,0}(N/N_0)^{\delta}$$

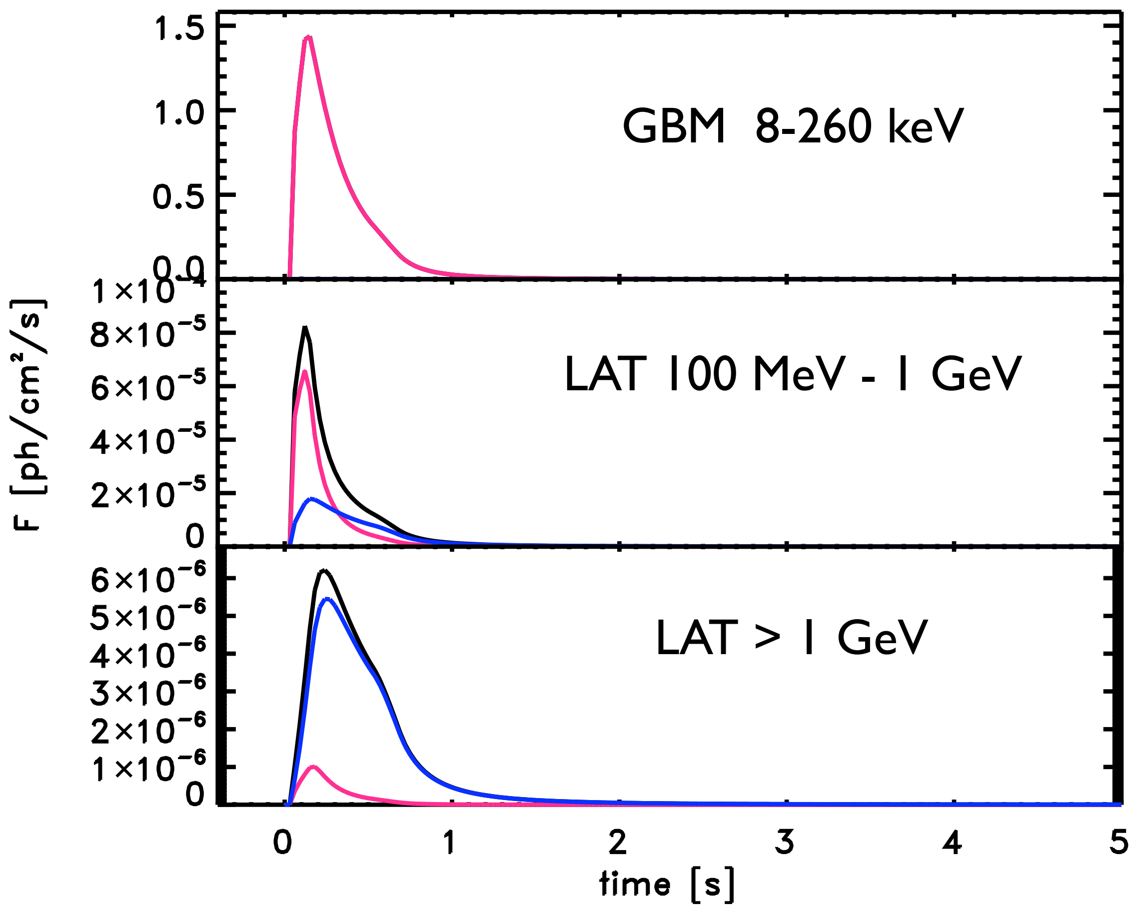
$$E_{\rm pk}(\Phi) = E_{\rm pk,\,max}\, e^{-\Phi/\Phi_0}$$

Modeling of short pulses, multi-peaked bursts...

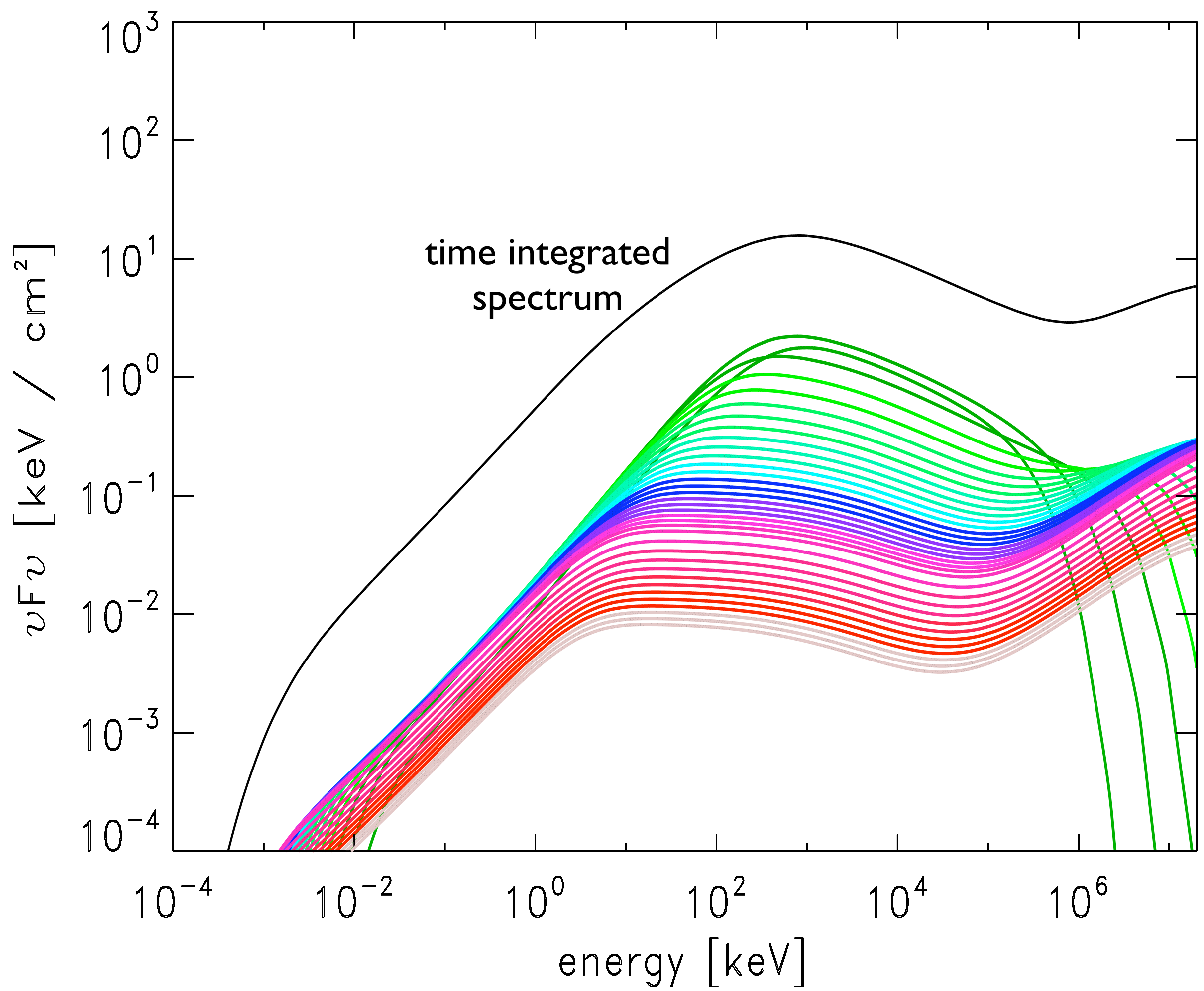
Short GRBs are expected to be harder in our model:

$R_{is} \sim c\, t_{var}\, \Gamma^2 \Rightarrow$ closer to the source if the burst evolves on a shorter time scale

The equipartition B is stronger and E_{syn} is larger in the dissipation region

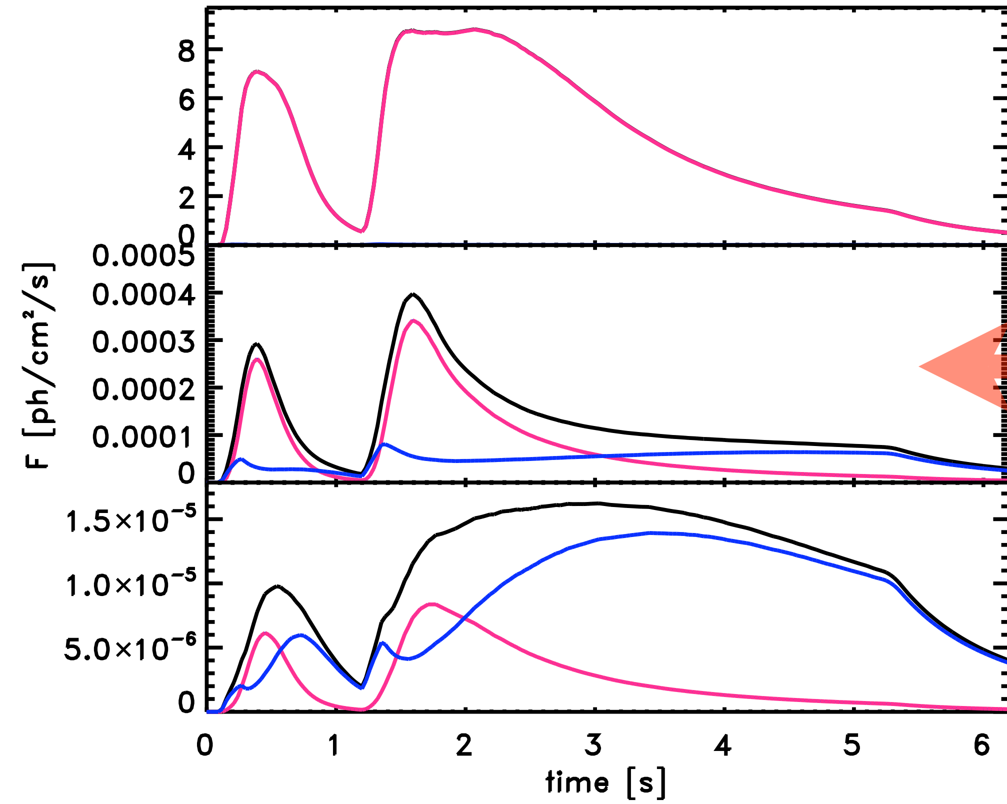


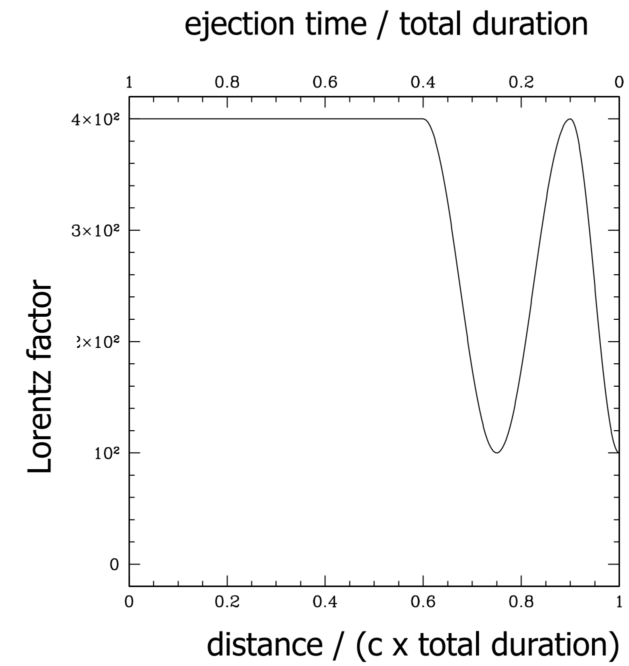
Observed lightcurve

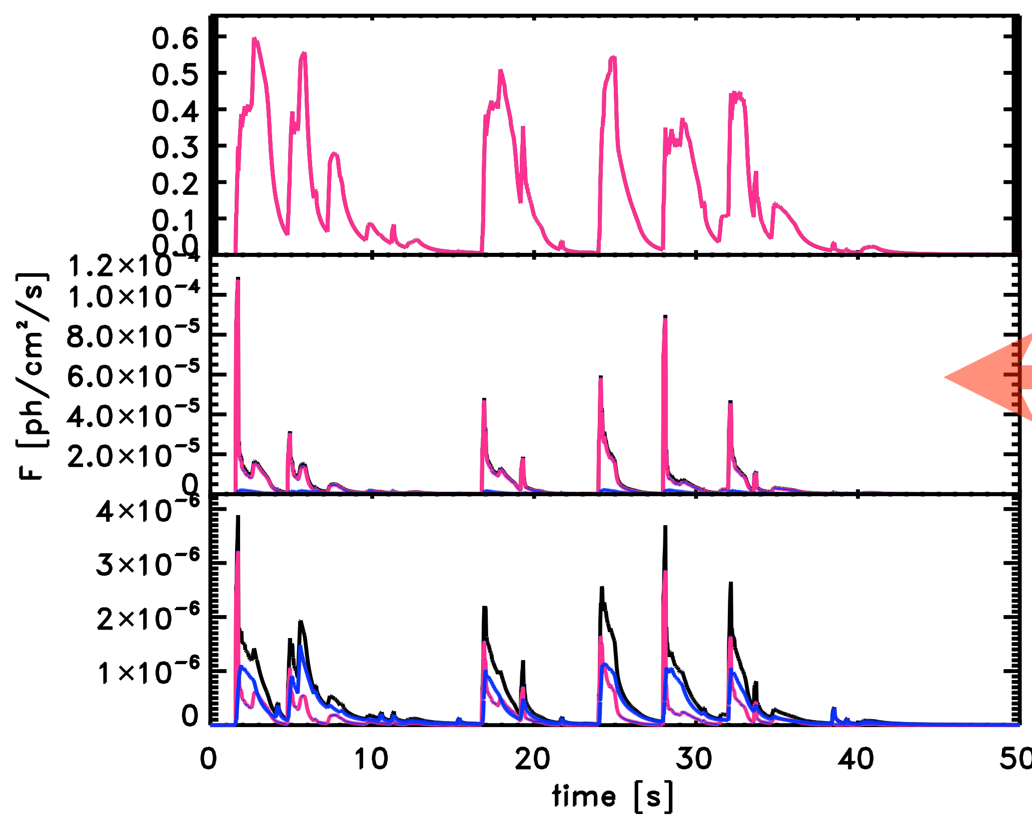


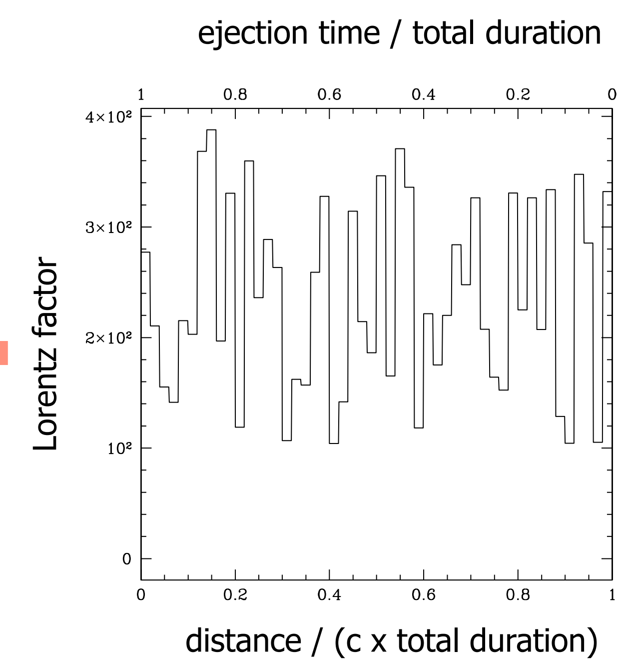
Time resolved spectra

Modeling of short pulses, multi-peaked bursts...









synchrotron
inverse Compton
total

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: *"synchrotron case"* (where the dominant process in Fermi-GBM range is synchrotron radiation) and *"inverse Compton case"* (where the synchrotron component peaks at low energy and dominant process in GBM range is inverse Compton)

Fermi GRB observations favor the "synchrotron case". We investigated the effect of the different radiation processes on spectral parameters and light curve properties. We are currently modeling in detail the broad-band spectra of Fermi GRBs