Bulk Comptonization GRB Model and its Relation to the Fermi GRB Spectra

A. Mastichiadis, DK 2009
DK, A. Mastichiadis, M. Georaganopoulos 2007
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DK, M. Georganopoulos, A. Mastichiadis 2002

Major GRB Facts/Issues

- GRB involve relativistic blast waves (Ress & Meszaros)
- This guarantees that most of the energy of the swept-up matter is stored in relativistic protons (accelerated or not; electrons carry ~1/2000 of available energy).

PROBLEMS:

- Protons do not lose energy to radiation easily.
- The observed luminosity peaks at E~1 MeV in the lab frame! (Despite the blast wave LF of order 100-1000).

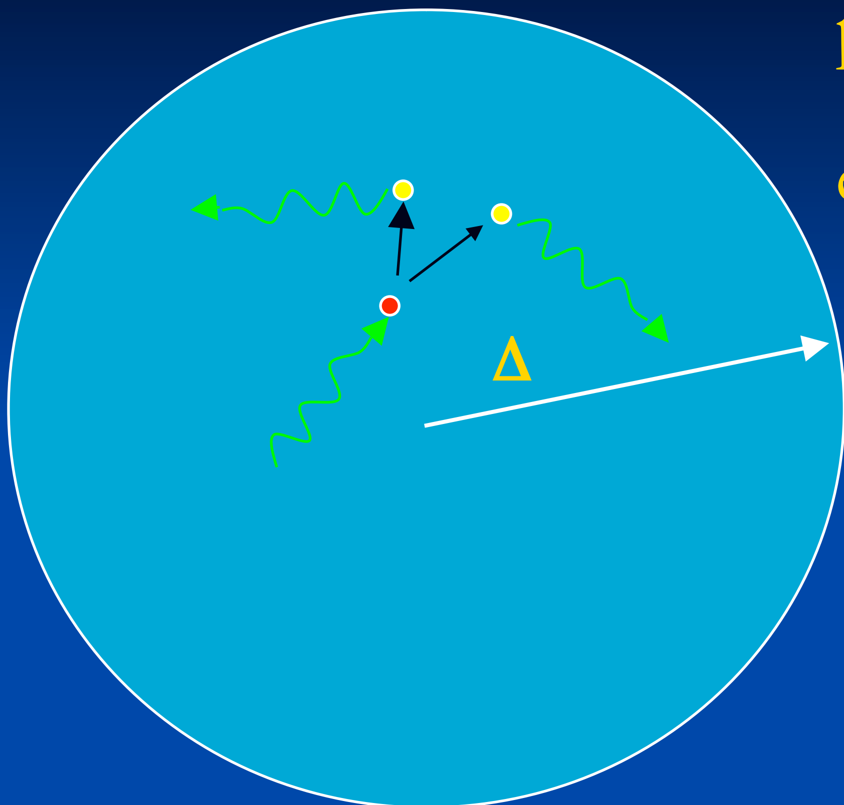
- There are (at least) two outstanding issues with the prompt GRB emission (Piran 2004):
  - A. Dissipation of the RBW free energy. Energy stored in relativistic p’s or B-field. Sweeping of ambient protons stores significant amount of energy in p’s anyway. Necessary to store energy in non-radiant form, but hard to extract when needed.
  - B. The presence of E_{peak} ~0.1 – 1.0 MeV. If prompt emission is synchrotron by relativistic electrons of Loretnz factor (LF) same as shock $E_p \sim \Gamma^4$, much too strong to account for the observations.

- We have proposed a model that can resolve both these issues simultaneously. The model relies:
  - 1. On a radiative instability of a relativistic proton plasma with B-fields due to the internally produced sychrotron radiation (Kirk & Mastichiadis 1992).
  - 2. On the amplification of the instability by relativistic motion and scattering of the internally produced radiation by upstream located matter, a 'mirror' (Kazanas & Mastichiadis 1999).

THE INSTABILITY

- Assume the presence of a plasma "blob" of size R, containing a relativistic proton population of form $n_p(\gamma_p) = n_o \gamma_p^{-\beta}$.

- Consider the possibility of e^+e^- pair production through the process $p\gamma \rightarrow e^+e^-$ of the relativistic protons of Lorentz factor γ_p with the synchrotron photons emitted by the e^+e^- pair with Lorentz factor $\gamma_e = \gamma_p$.



$p\gamma \longrightarrow e^+e^-$

$eB \longrightarrow B\gamma$

In the blast frame the width of the shock $\Delta \sim R/\Gamma$ is comparable to its observed lateral width thereby considering all processes taking place in a spherical volume of radius Δ

- The instability involves 2 thresholds:

  1. A kinematic one for the reaction $p\,\gamma \rightarrow e^-\,e^+$

  $$b\,\Gamma^5 > 2\,m_e\,c^2$$

  (the prompt phase ends when this condition is not satisfied)

  2. A dynamic one: At least one of the synchrotron photons must be able to reproduce before escaping the plasma volume. This leads to the following condition for the plasma column density (note similarity with atomic bombs!)

  $$\sigma_{p\gamma}\,R\,n \gtrsim b\,\Gamma \quad \text{or} \quad \sigma_{p\gamma}\,R\,n\,\Gamma^4 \gtrsim 2$$

Similarity of GRB/Nuclear Piles-Bombs

- The similarity of GRB to a "Nuclear Pile" is more than incidental:
- 1. They both contain lots of free energy stored in:
  - Nuclear Binding Energy (nuclear pile)
  - Relativistic Protons or Magnetic Field (GRB)

  2. The energy can be released explosively once certain condition on the fuel column density (and not mass) is fulfilled (Note: no particle acceleration required!!).

- The energy of the synchrotron photons is $E_s = \gamma_e^2 b$ (where $b = B/B_{cr}$ is the magnetic field in units of the critical one). For the $p\gamma \rightarrow e^+e^-$, $Be \rightarrow \gamma$ reaction network to to be self-contained $\gamma_p E_s = \gamma_p^3 b \simeq 2$ (all energies measured in units of the electron rest mass $m_e c^2$). The proton distribution must therefore exceed the kinematic threshold

$$\gamma_p \geq \left(\frac{2}{b}\right)^{1/3} \tag{1}$$

- The "blob" will be "critical" if at least one of the synchrotron photons pair-produces before escape. Since each electron emits $\mathcal{N} \simeq \gamma_e/\gamma_e^2\, b = 1/\gamma_e\, b$ photons, the optical depth of the "blob" to the $p\gamma \to e^+e^-$ reaction must be $\tau_{p\gamma} > 1/\mathcal{N} = \gamma_e\, b$, which leads to the dynamic threshold

$$n_o \gamma_p^{-(\beta-1)} \sigma_{p\gamma} R \geq \frac{\gamma_p^2 b}{\gamma_p} = \gamma_e\, b \tag{2}$$

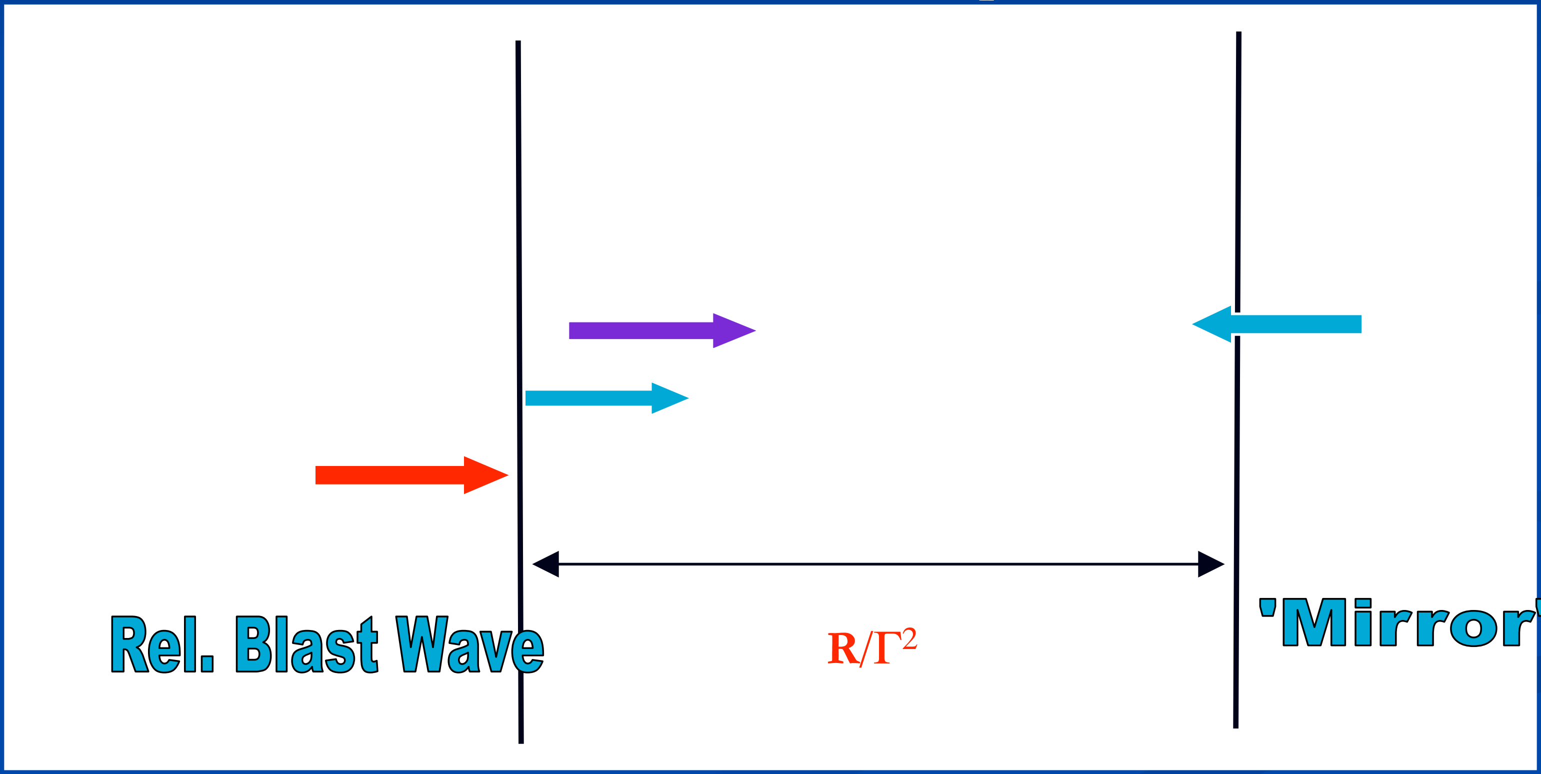
- Taking into account the kinematic constraint the dynamic constraint reads

$$n_o \geq n_{\text{crit}} = \left(\frac{2}{3}\beta - 1\right) b^{1-\beta/3} \tag{3}$$

$b\Gamma^{6+1}$ ~ 100 GeV photons

$b\Gamma^{4+1}$ ~ 1 MeV photons

$b\Gamma^{2+1}$ ~ 10 eV O-UV photons



• The combined process of the proton - photon - electron instability with upstream mirroring enhances the the "blob" synchrotron photons energy by Γ^2. This modifies the kinematic threshold to (Kazanas & Mastichiadis 1999),

$$\gamma_{\rm crit} = \left(\frac{2}{b\,\Gamma^2}\right)^{1/3} \qquad (4)$$

• The most stringent condition is to assume that $\gamma_{\rm crit} = \Gamma$, i.e. that the ONLY relativistic protons present are those produced by the shock thermalization. If the ambient and co-moving densities are respectively n, $n_{\rm co}$ ($n_{\rm co} \simeq n\,\Gamma$) and $\Delta_{\rm co} \simeq R/\Gamma$ the comoving thickness of the blast wave, the kinematic and dynamic thresholds respectively are

$$\Gamma^5 b \simeq 2 \quad \text{and} \quad \sigma_{p\gamma}\, n\, R = \sigma_{p\gamma}\, n_{\rm co}\, \Delta_{\rm co} \geq b\Gamma \qquad (5)$$

- The combined constraint will therefore be

$$n\,\sigma_{p\gamma}\,R\,\Gamma^4 \geq 2 \qquad (6)$$

where R the shock radius. With $\sigma_{p\gamma} \simeq 5\,10^{-27}$ cm^2 and values for n, R typical for those used in GRBs $n = 1\,n_0$ cm^{-3} $\quad R \simeq 10^{16}\,R_{16}$ cm, the combined constraints reduce to

$$\Gamma \gtrsim 380\,(n_0\,R_{16})^{-1/4} \qquad (7)$$

values consitent with those thought to apply to GRBs.

- For magnetic field in equipartition, the value of the blast wave Lorentz factor derived from the kinematic threshold is

$$\Gamma \gtrsim 235\,(\Theta\,R_{16})^{1/5}\,E_{51}^{-1/10} \qquad (8)$$

where Θ is the opening angle of the blast wave (in units of π) and E_{51} its total energy (in

THE SPECTRA

- Behind the forward shock, all particles (including the secondary e^+e^-–pairs) have originally Lorentz factor Γ (in the blast wave rest frame).

No accelerated population is invoked !!

- The electrons cool on time scales shorter than the light crossing time to produce a population of "cold" electrons of significant Thompson depth.

- The main process for photon production is synchrotron radiation.

- The main process of energy loss for the relativistic electrons (i.e. of energy $\Gamma m_e c^2$) is IC on "reflected" synchrotron photons.

- The "reflected" synchrotron photons also scatter on the "cold" electrons, a process that can impart on them significant luminosity.

- Synchrotron and Self–Compton radiation at frequencies

$$\nu_S \simeq b\,\Gamma^2 \qquad \nu_{SSC} \simeq b\,\Gamma^4 \tag{9}$$

- IC of “reflected” synchrotron photons by “cold” electrons at frequency

$$\nu_{c,IC} \simeq b\,\Gamma^4 \tag{10}$$

- IC of “reflected” synchrotron photons by relativistic electrons at frequency

$$\nu_{r,IC} \simeq b\,\Gamma^6 \tag{11}$$

• In the Lab Frame these frequencies will then have the following values (taking into consideration that $\Gamma^5 b \simeq 2$):

$$\nu_S \simeq b\,\Gamma^3 \simeq \frac{2}{\Gamma^2} \quad (\mathrm{O-UV}) \qquad (12)$$

$$\nu_{SSC} \simeq b\,\Gamma^5 \simeq 2 \quad (1\ \mathrm{MeV}) \qquad (13)$$

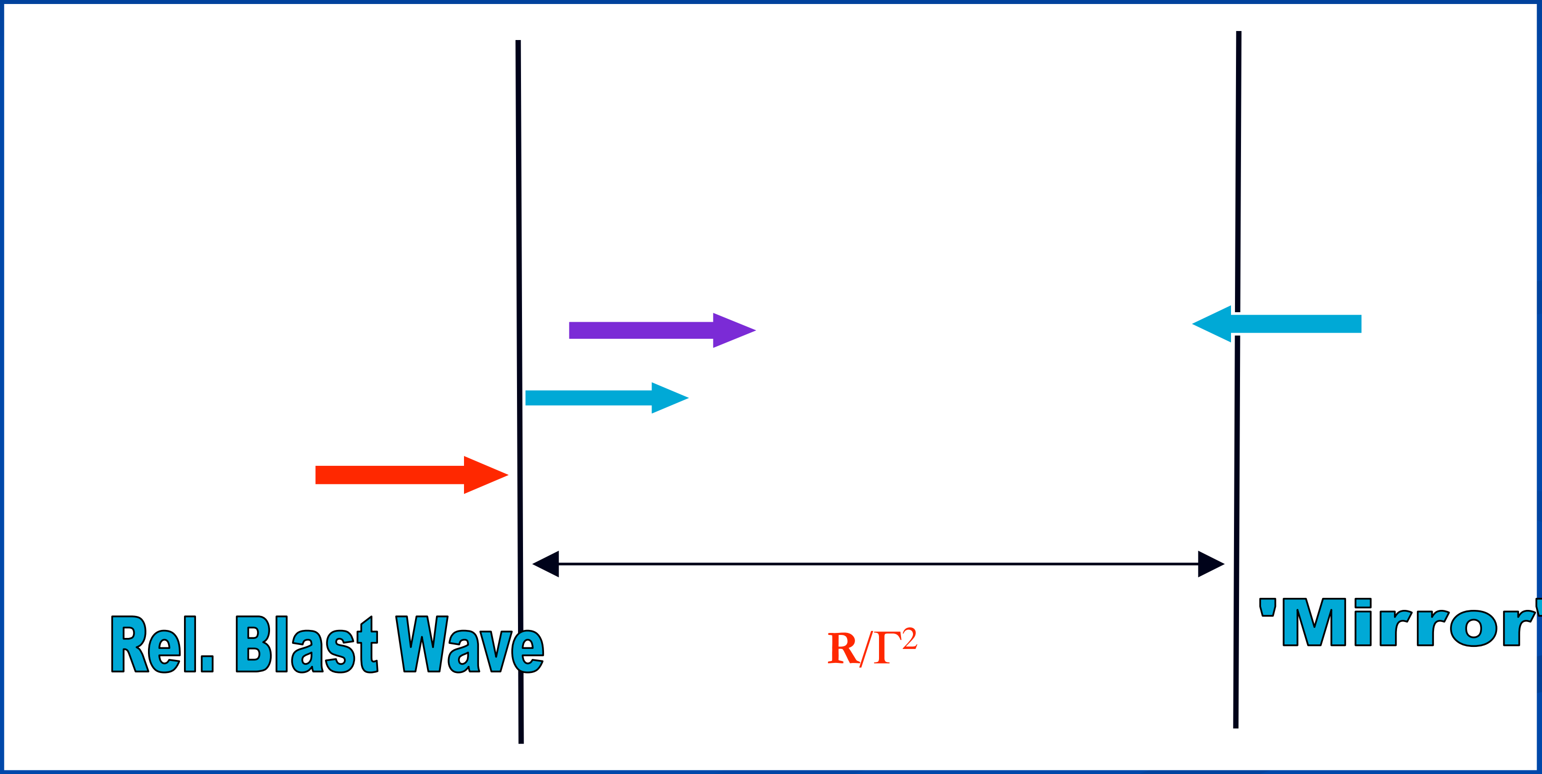
$$\nu_{c,IC} \simeq b\,\Gamma^5 \simeq 2 \quad (1\ \mathrm{MeV}) \qquad (14)$$

$$\nu_{r,IC} \simeq b\,\Gamma^7 \simeq \Gamma^2 \quad (10\ \mathrm{GeV}) \qquad (15)$$

BC SSC → $\mathrm{Min}(m_e c^2\, \Gamma^{1+1},\, b\Gamma^{6+1})$ ~ 100 GeV photons

BC RS → $b\Gamma^{4+1}$ ~ 1 MeV photons (GBM photons are due to BC)

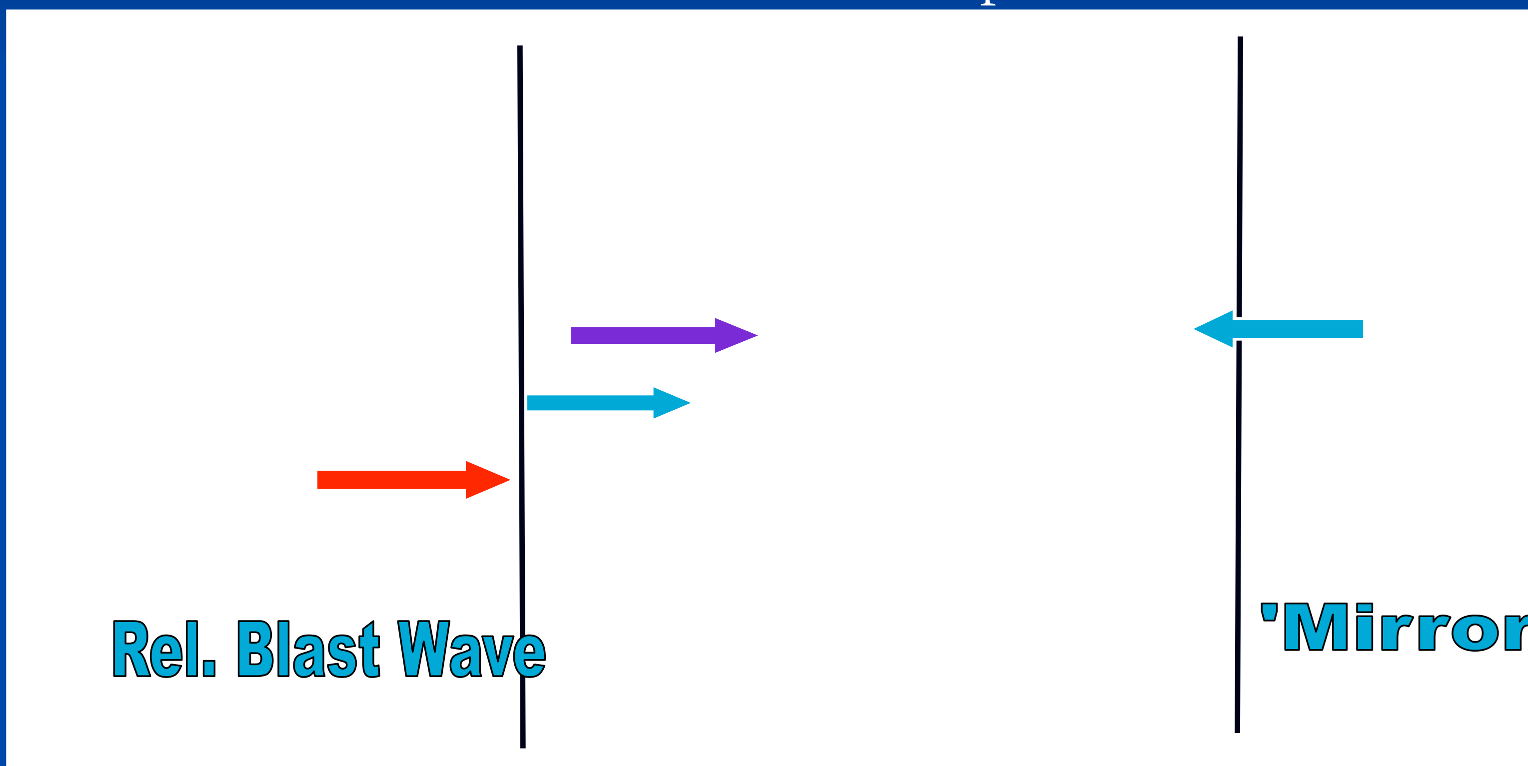
Syn. → $b\Gamma^{2+1}$ ~ 10 eV O-UV photons



$b\Gamma^{6+1}$ $\sim$ 100 GeV photons

$b\Gamma^{4+1}$ $\sim$ 1 MeV photons

$b\Gamma^{2+1}$ $\sim$ 10 eV O-UV photons



- We have modeled this process numerically. We assume the presence of scattering medium at $R \sim 10^{16}$ cm and of finite radial extent.
- We follow the evolution of the proton, electron and photon distribution by solving the corresponding kinetic equations.
- We obtain the spectra as a function of time for the prompt GRB emission.
- The time scales are given in units of the comoving blob crossing time $\Delta_{co}/c \sim R / \Gamma^2 c \sim 2\ R_{16}/\Gamma_{2.6}$ sec.

The kinetic equations are solved on the **RBW rest frame** with **pair production, synchrotron, IC losses, escape** in a spherical geometry of **radius R/Γ** and proton **density $n = n_0\,\Gamma$**. The protons are assumed to be injected at energy $E_p = m_p c^2\,\Gamma$. These are the following:

- Protons

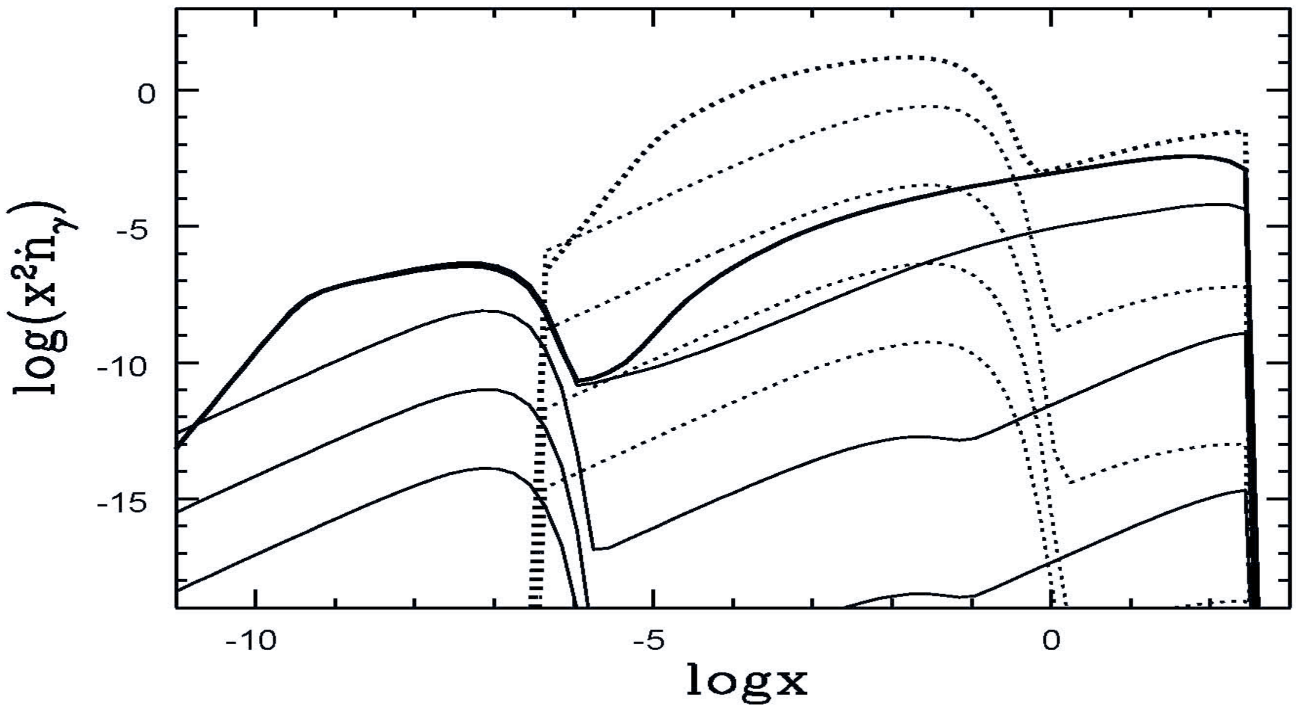
$$\frac{\partial n_p}{\partial t} + L_p^{BH} + H(t - t_{crit}) L_p^{BH;R} = 0 \qquad (9)$$

- Electrons

$$\frac{\partial n_e}{\partial t} + L_e^{syn} + L_e^{ics} + H(t - t_{crit}) L_e^{ics;R} = Q_e^{BH} + H(t - t_{crit}) Q_e^{BH;R} + Q_e^{\gamma\gamma} + H(t - t_{crit}) Q_e^{\gamma\gamma;R}$$

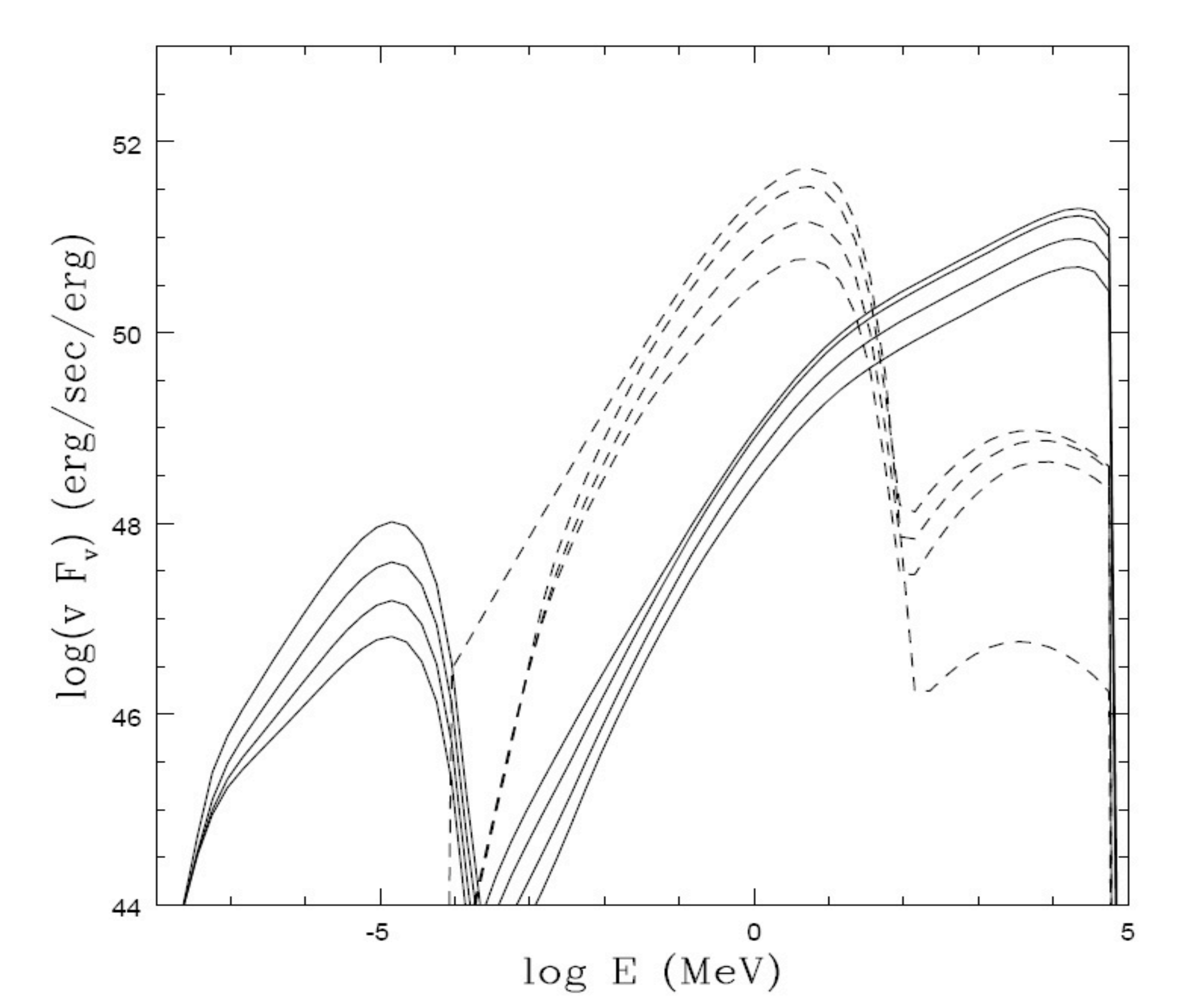
- Photons

$$\frac{\partial n_\gamma}{\partial t} + \frac{n_\gamma}{t_{cr}} + L_\gamma^{\gamma\gamma} + L_\gamma^{ssa} = Q_\gamma^{syn} + Q_\gamma^{ics} + H(t - t_{crit}) Q_\gamma^{ics;R} \qquad (11)$$



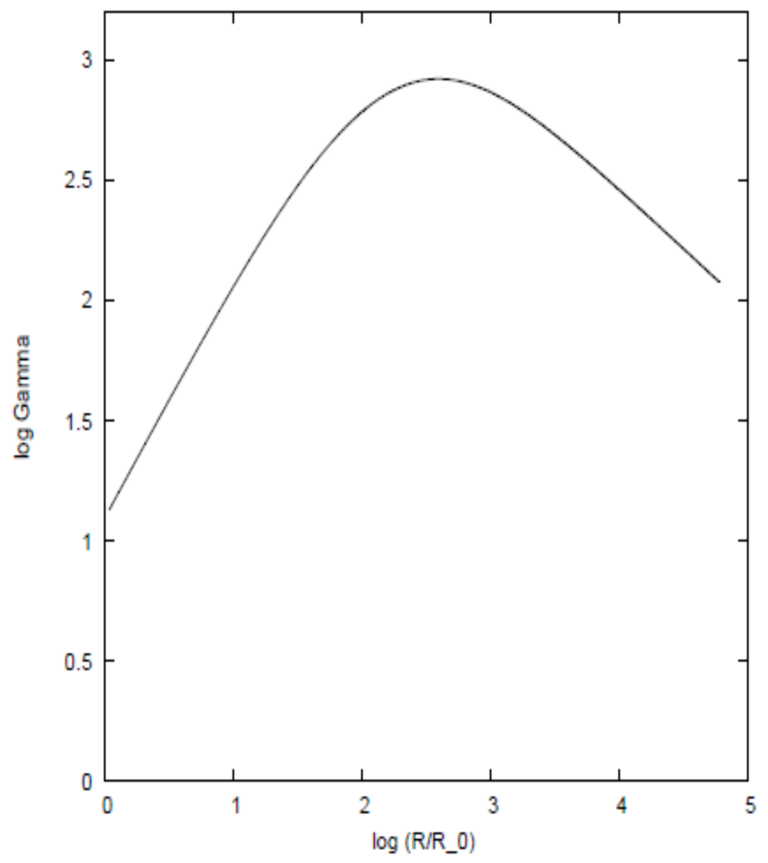
0
-5
-10
-15
$\log(x^2\dot{n}_\gamma)$
-10
-5
0
logx

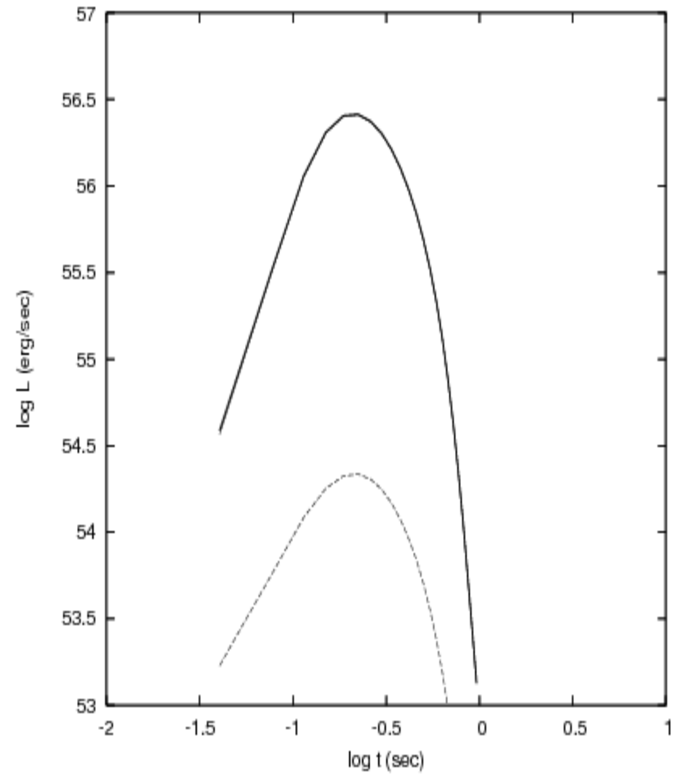
Prompt GRB Spectra (Mastichiadis & Kazanas 2006)



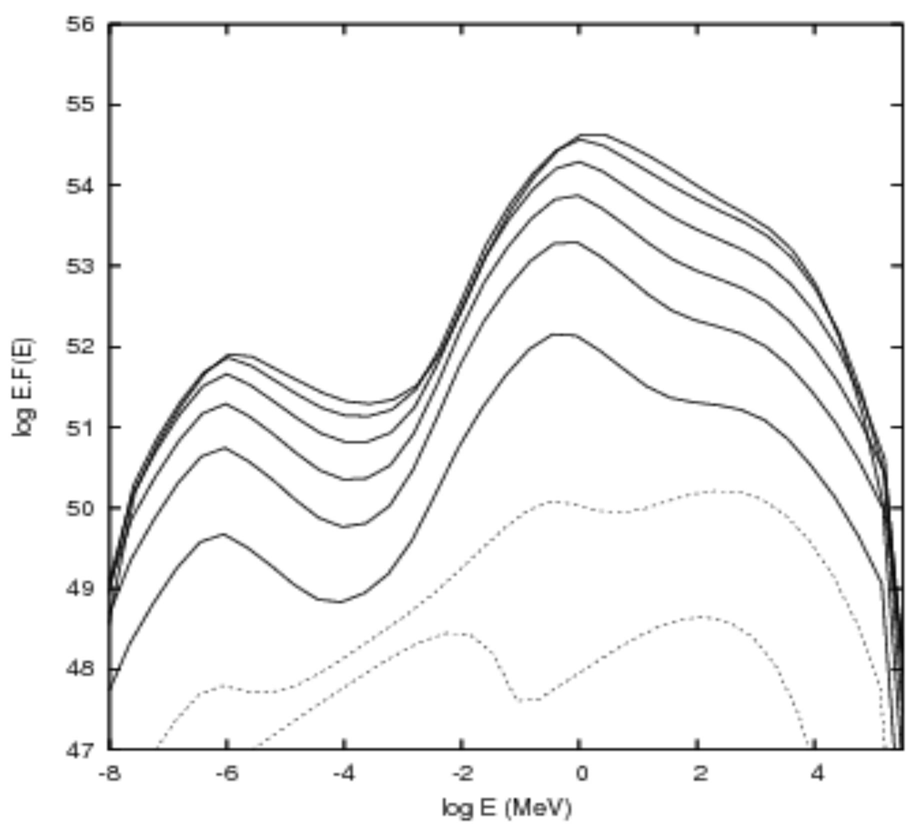
- We have also modeled the propagation of a relativistic blast wave through the wind of a WR star (that presumably collapses to produce the relativistic outflow that produces the GRB).
- In this case we also follow the development of the blast wave LF and the radiative feedback on it.
- In this scenario the "mirror" necessary for the model to work is provided by the pre-supernova star wind, the length scales smaller, $R_0 \sim 10^{13}$ cm and the GRB is a "short GRB".

Evolution of the LF and the luminosity

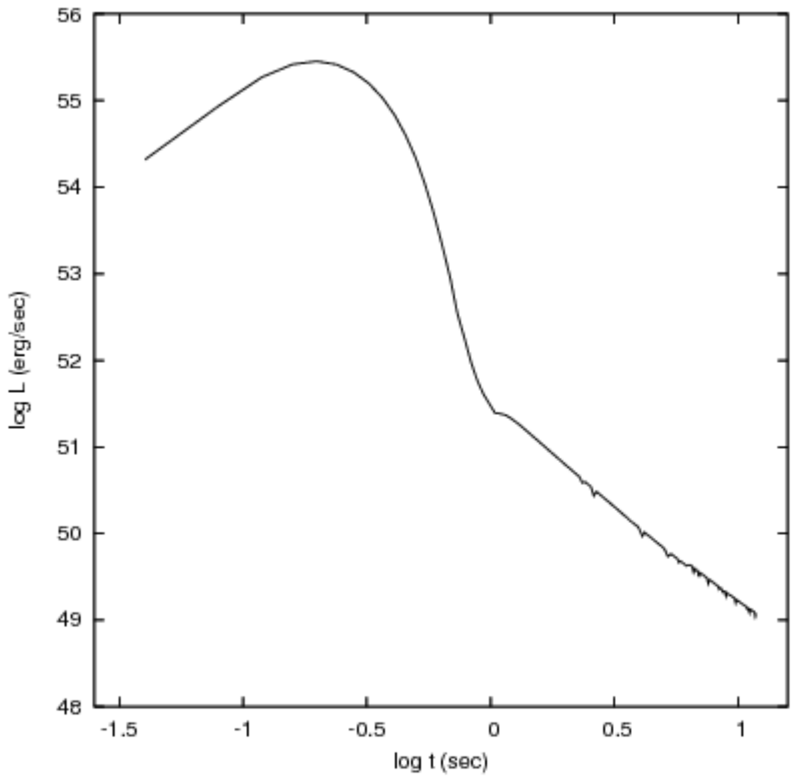




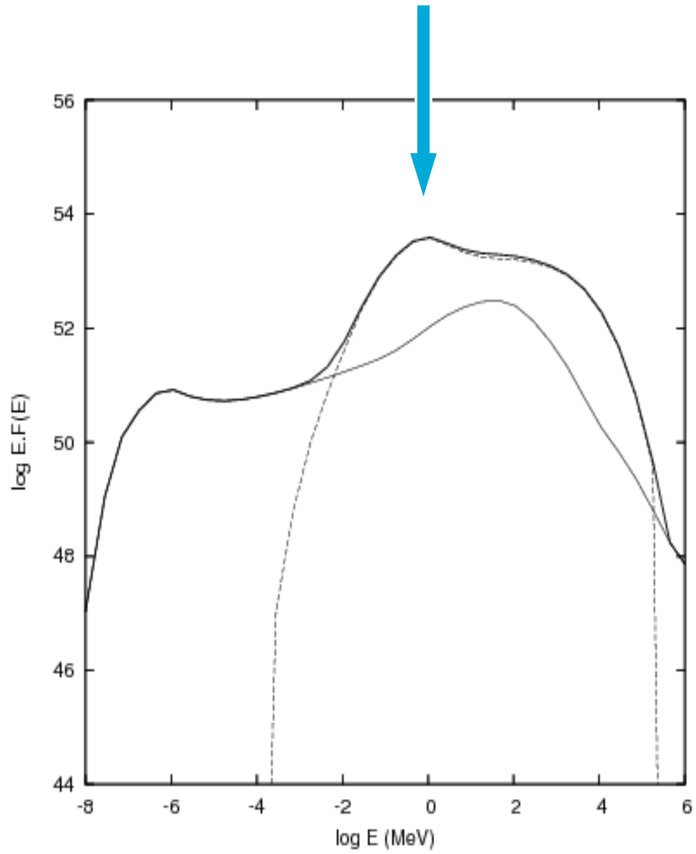
Evolution of Spectra with Time (ε_B~1)

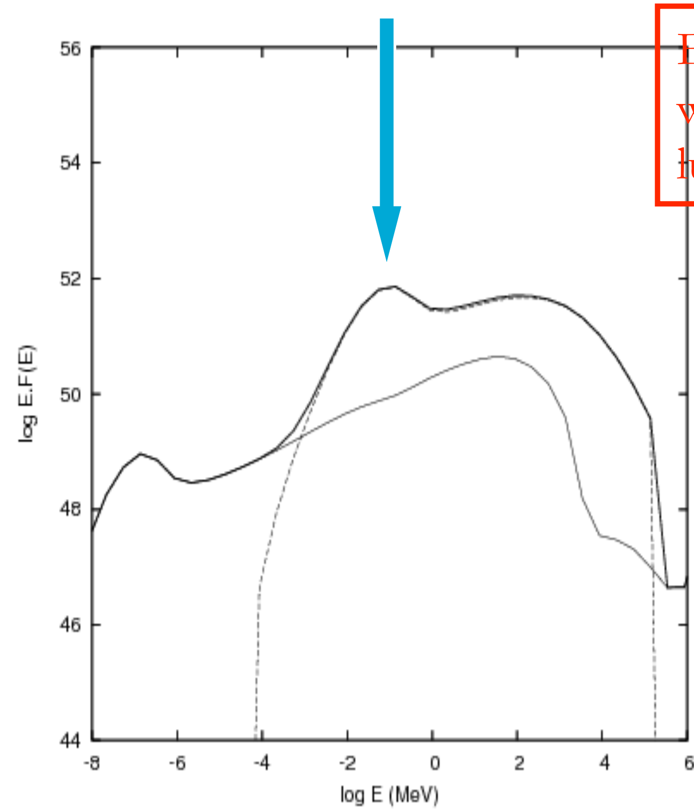


Evolution of Luminosity with Time ($\varepsilon_B \sim 1$)



Evolution of Luminosity with Time ($\varepsilon_B \sim 0.01$)



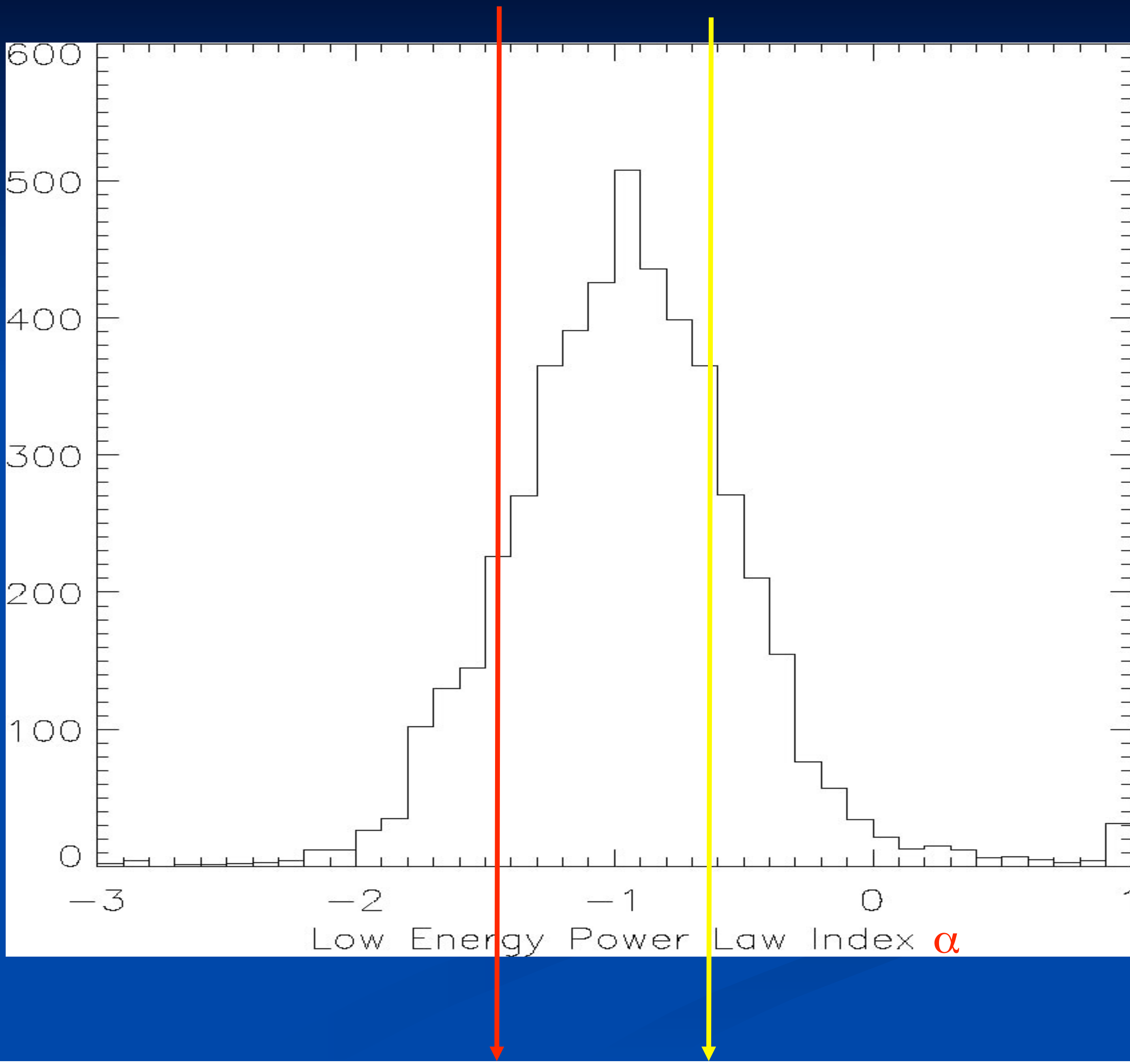


Ep decreases with decreasing luminosity

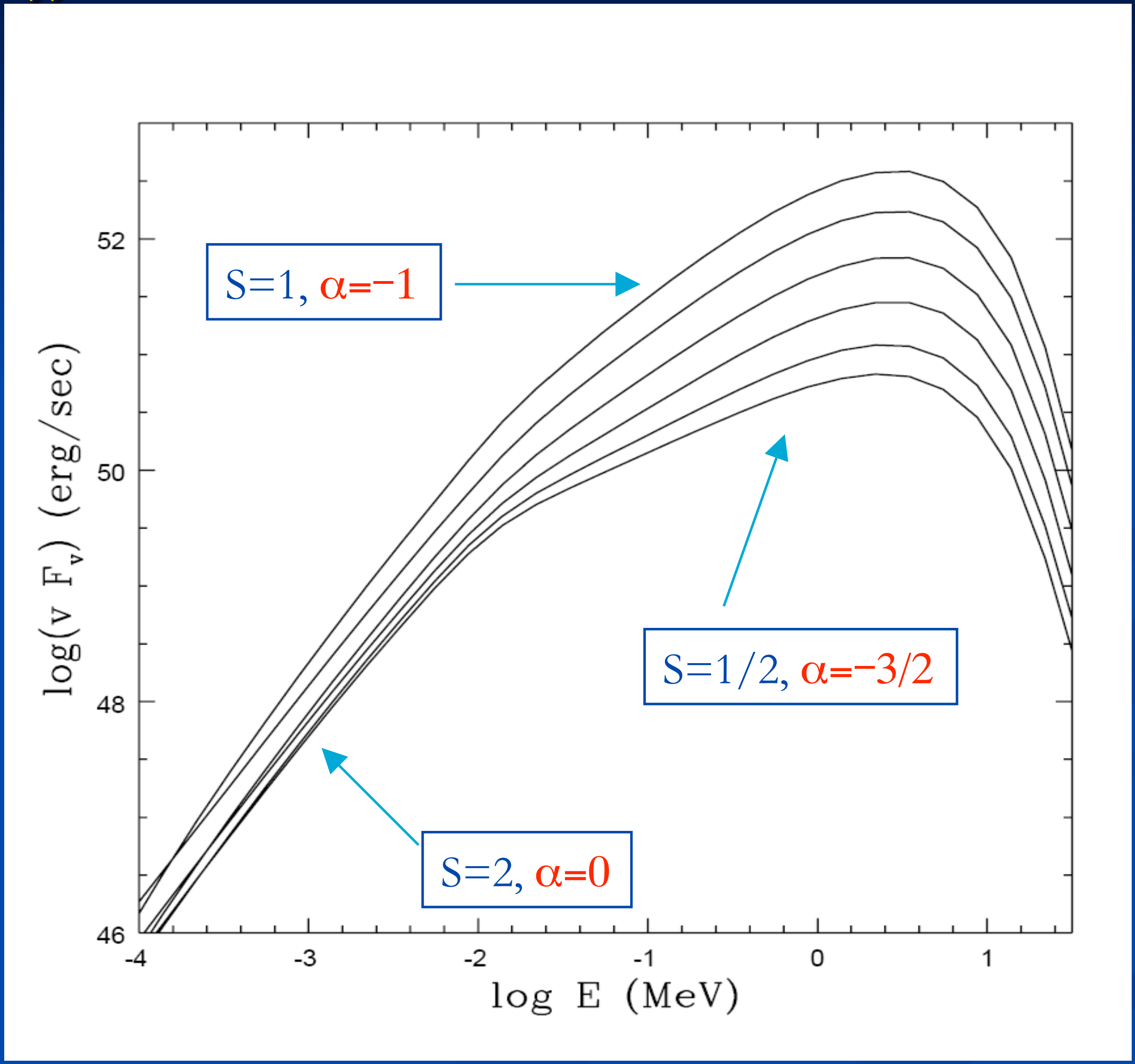
Conclusions

- The "nuclear pile" GRB model provides an over all satisfactory description of several GRB features, including the dissipation process, Ep and the Fermi observations.
- Provides an operational definition of the GRB prompt phase.
- No particle acceleration necessary to account for most of prompt observations (but it is not forbidden!).
- GBM photons due to bulk Comptonization (=> possibility of high polarization ~100%).
- It can produce "short GRB" even in situations that do not involve neutron star mergers.
- Exploration of the parameter space and attempt to systematize GRB phenomenology within this model is currently at work.

Distribution of LE indices



The spectra of doubly scattered component (Mastichiadis & DK (2005))



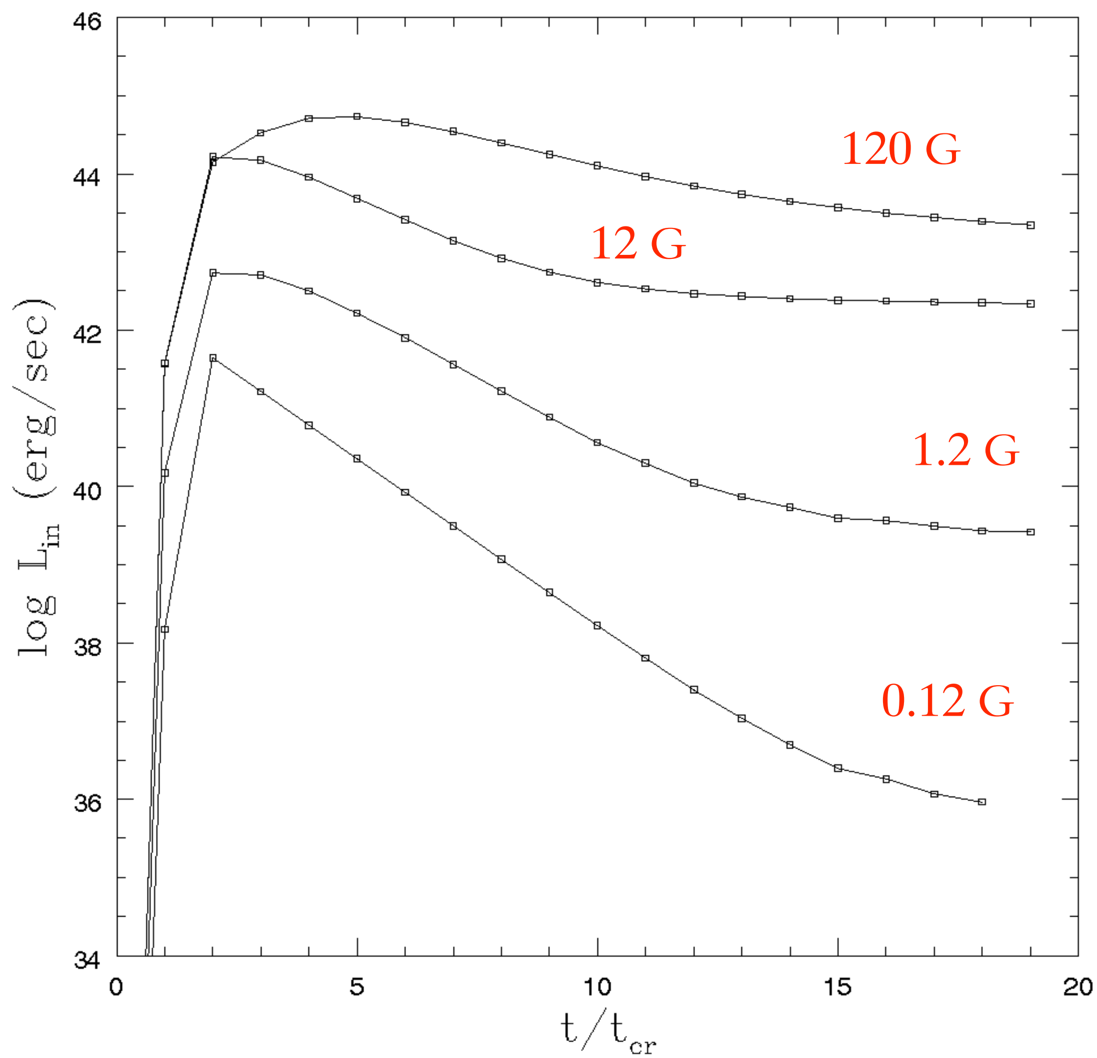
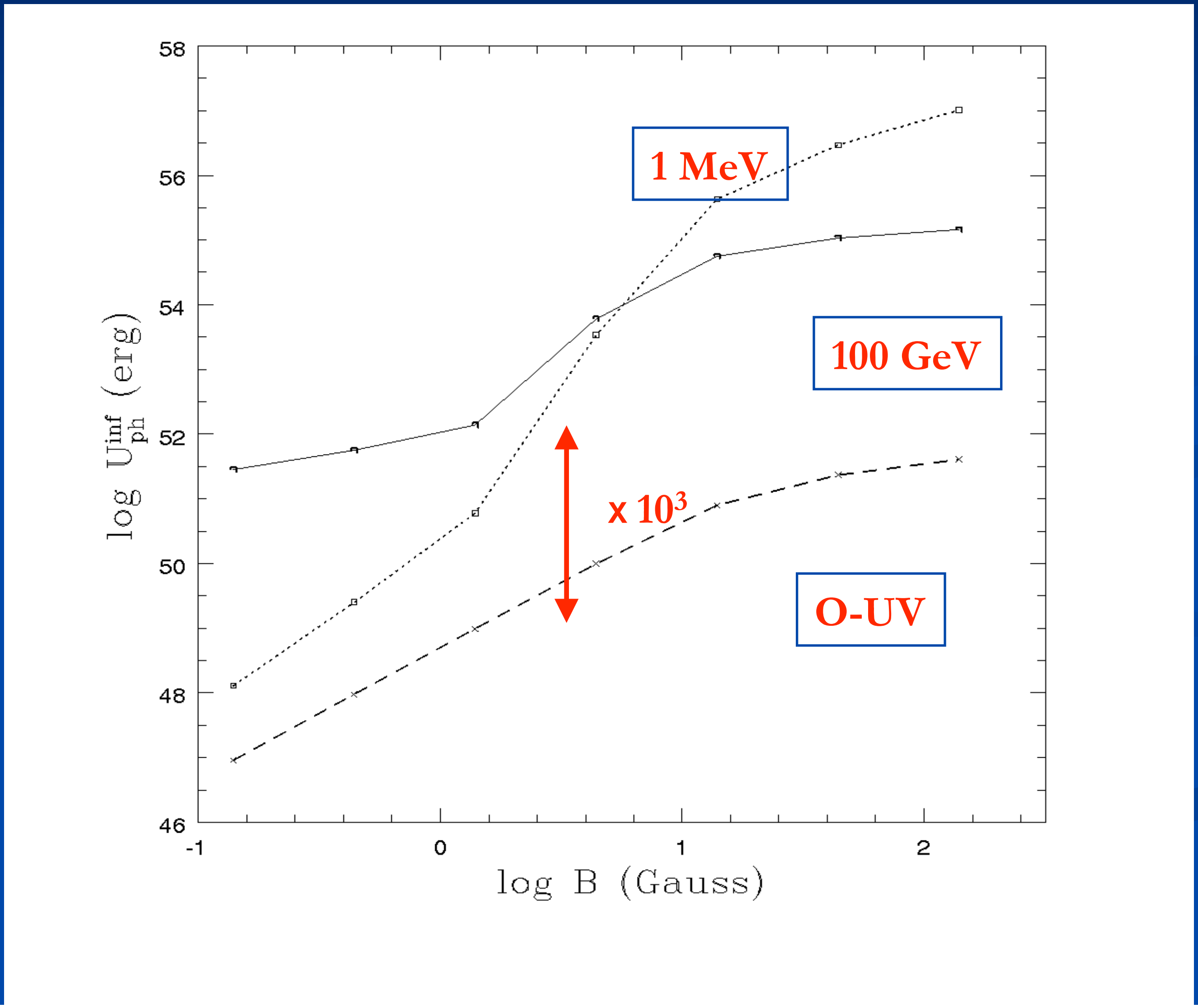
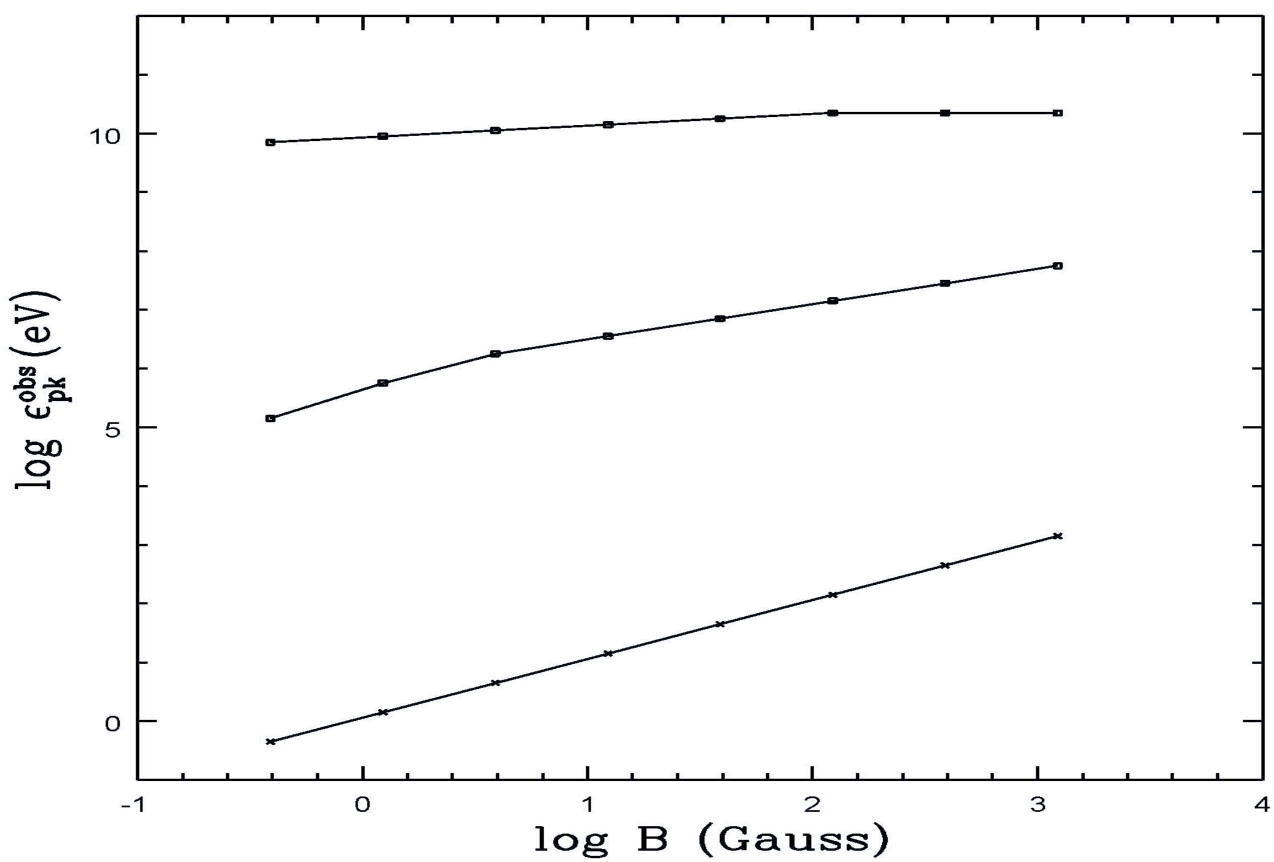


Fig. 6.l Plot of the photon luminosity evolution as this is measured in the comoving frame in the EE case where $n_p = n_e = 10^4$ cm^{-3} while B varies (bottom to top) from 0.12 G to 120 G by increments of a factor of 10. The rest of the parameters are as stated in the text. Time is measured in blob crossing times and the value t = 0 has been set at the instant when the RBW enters the reflection zone.

E_{iso} of the three different spectral components as a function of B for Γ=400 and n_p=10^5 cm^{-3}. x 10^3 denotes the relative γ-ray – O-UV normalization of GRB 990123, 041219a.

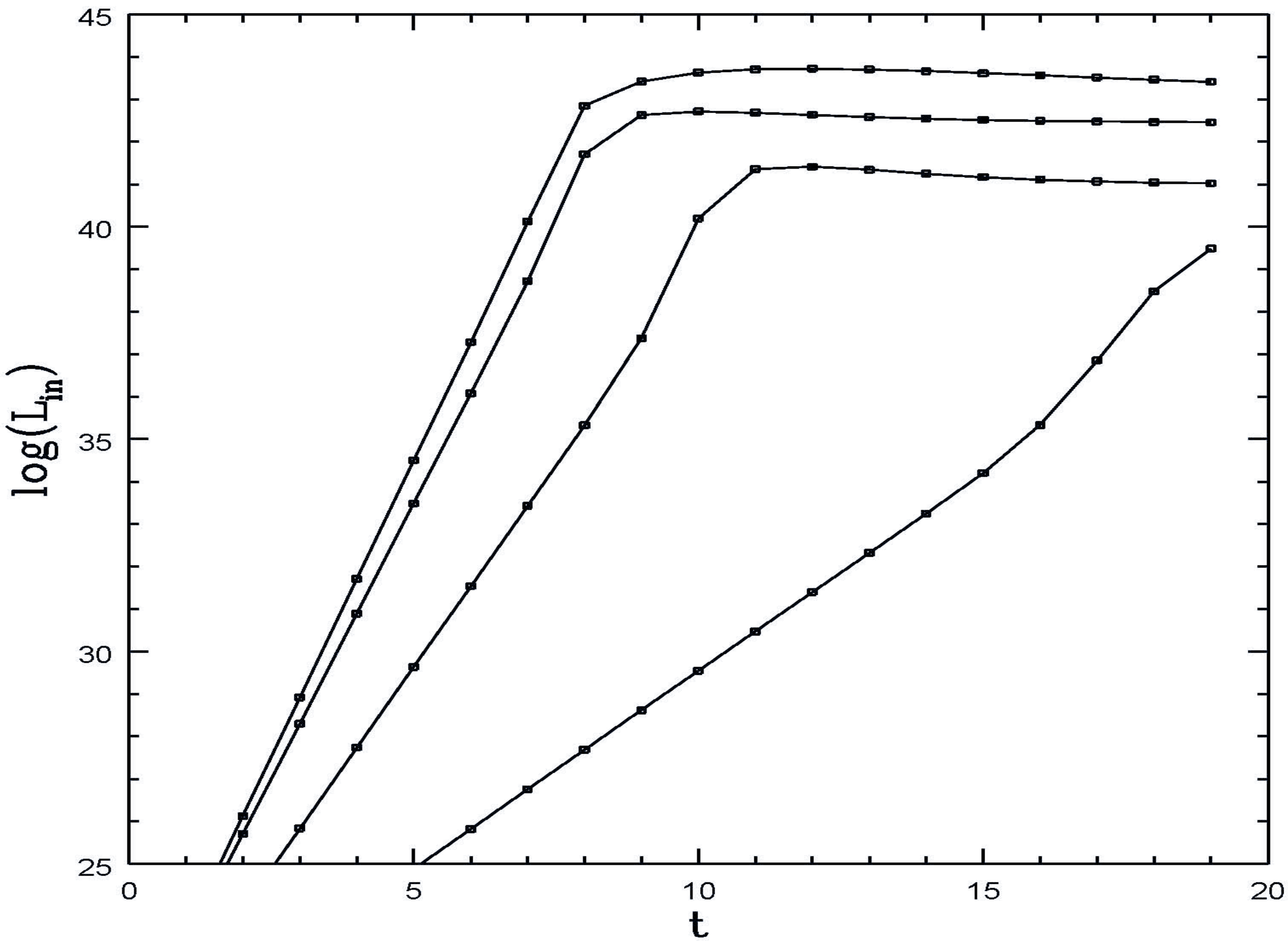


E_{peak} as a function of the magnetic field B

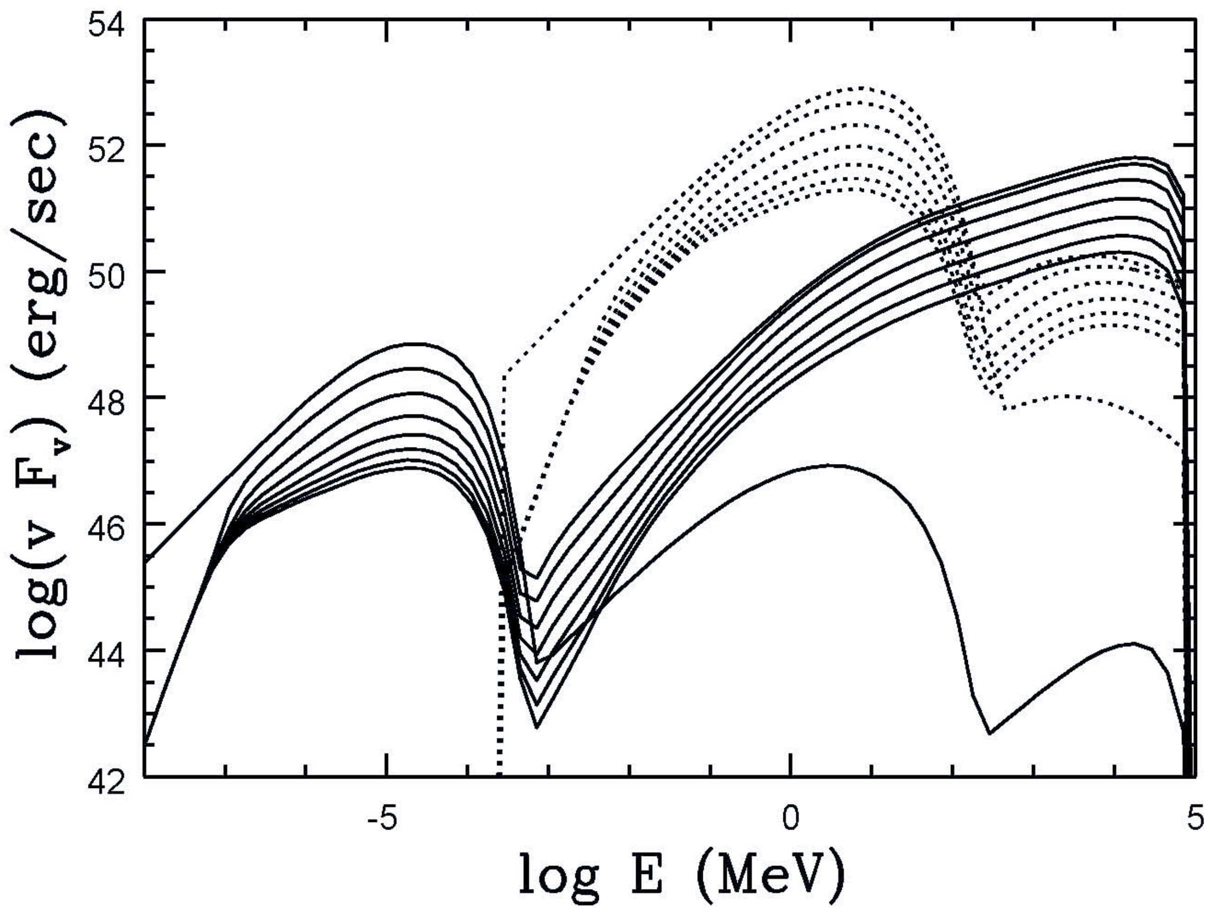


Variations

- If the "mirror" is in relative motion to the RBW then the kinematic threshold is modified to $b\,\Gamma^3\,\Gamma^2_{rel} \sim 2$; Γ_{rel} is the relative LF between the RBW and the "mirror".
- The value of E_{peak} is again ~ 1 MeV, however the synchrotron and IC peaks are higher and lower by Γ^2_{rel} than Γ^2.
- In the presence of accelerated particles the threshold condition is satisfied even for $\Gamma < (2/b)^{1/5}$. This may explain the time evolution of GRB941017 (Gonzalez et al. 04)
- GRB flux is likely to be highly polarized (GRB 031206, Coburn & Boggs 03).
- This model applicable to internal shock model (photons from downstream shell instead of "mirror").



45
40
35
30
25
0
5
10
15
20
t
log(L_in)



54
52
50
48
46
44
42
-5
0
5
log(ν F$_ν$) (erg/sec)
log E (MeV)

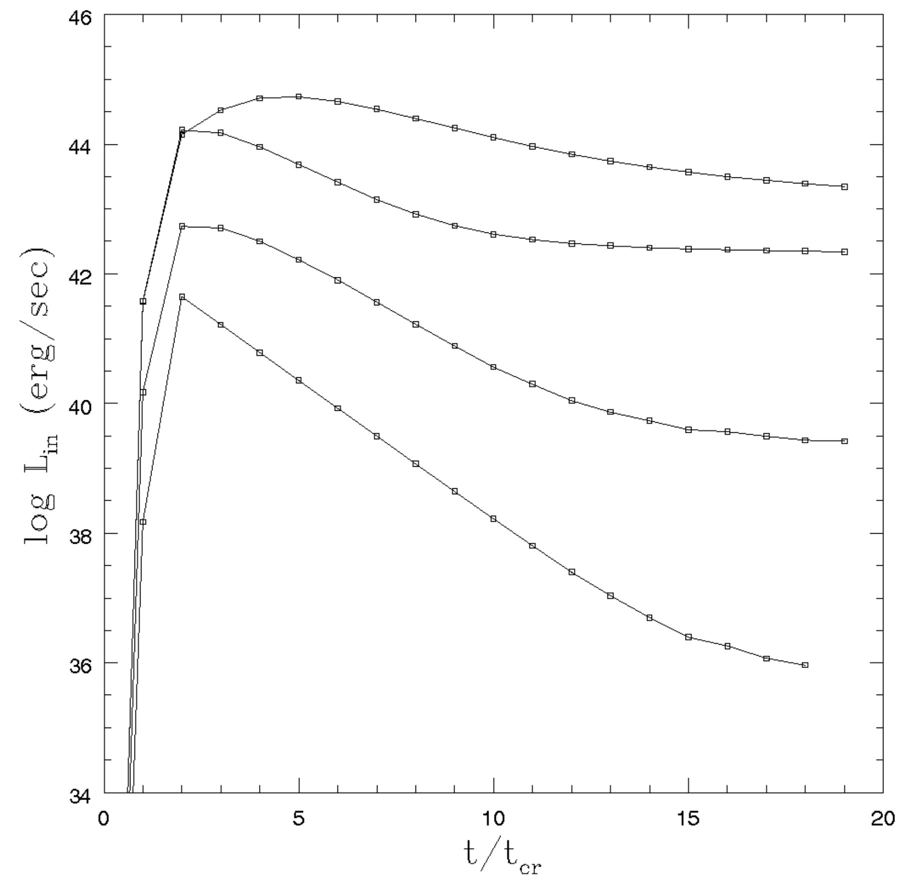
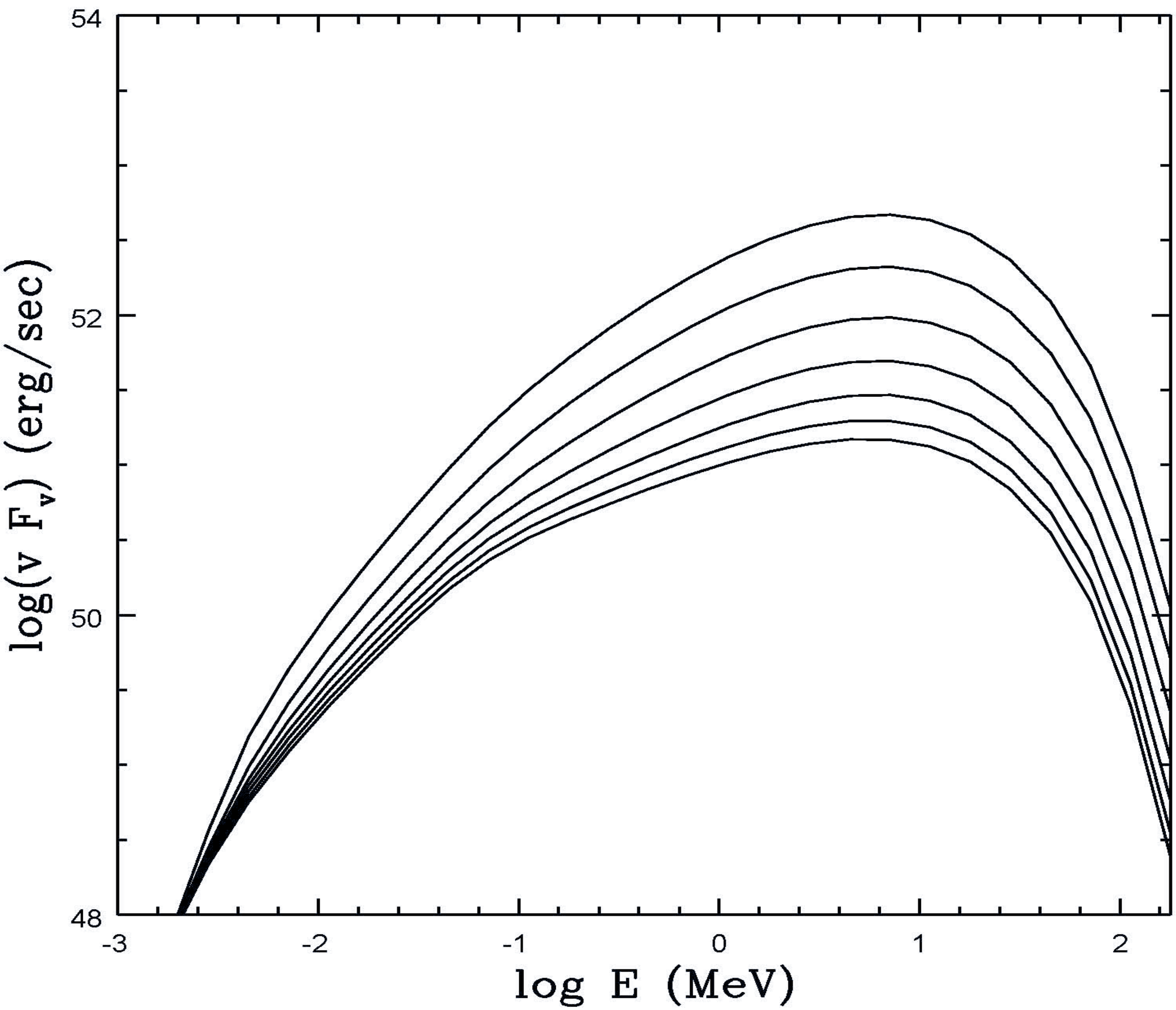


Fig. 6.l Plot of the photon luminosity evolution as this is measured in the comoving frame in the EE case where $n_p = n_e = 10^4 cm^{i\ 3}$ while B varies (bottom to top) from 0.12 G to 120 G by increments of a factor of 10. The rest of the parameters are as stated in the text. Time is measured in blob crossing times and the value t = 0 has been set at the instant when the RBW enters the re° ection zone.



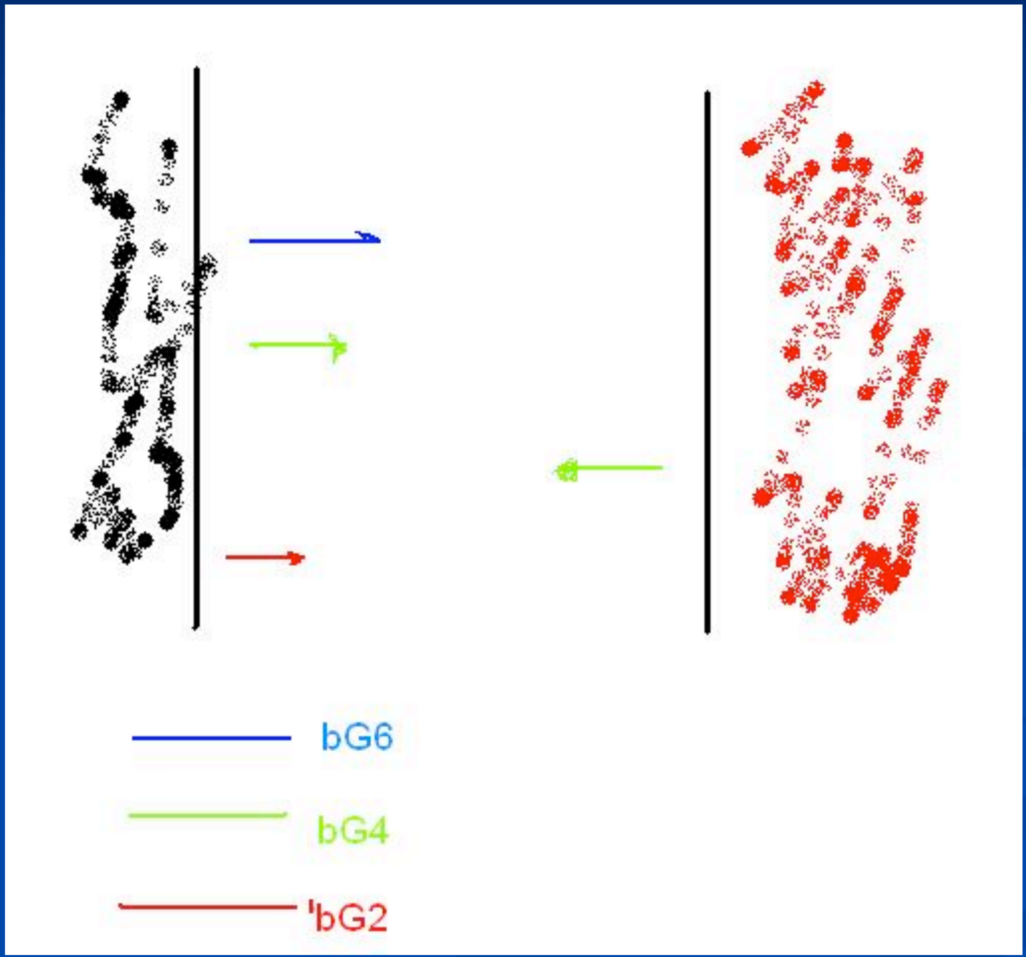
54
52
50
48
-3
-2
-1
0
1
2
log(ν F_ν) (erg/sec)
log E (MeV)

Then ....

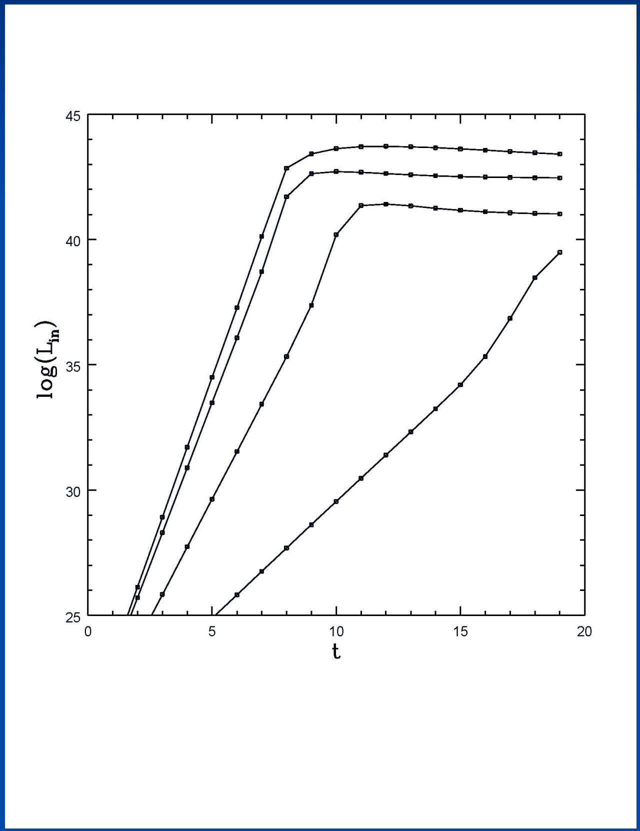
¾p° R n » b¡ or ¾p° R n¡⁴ » 2

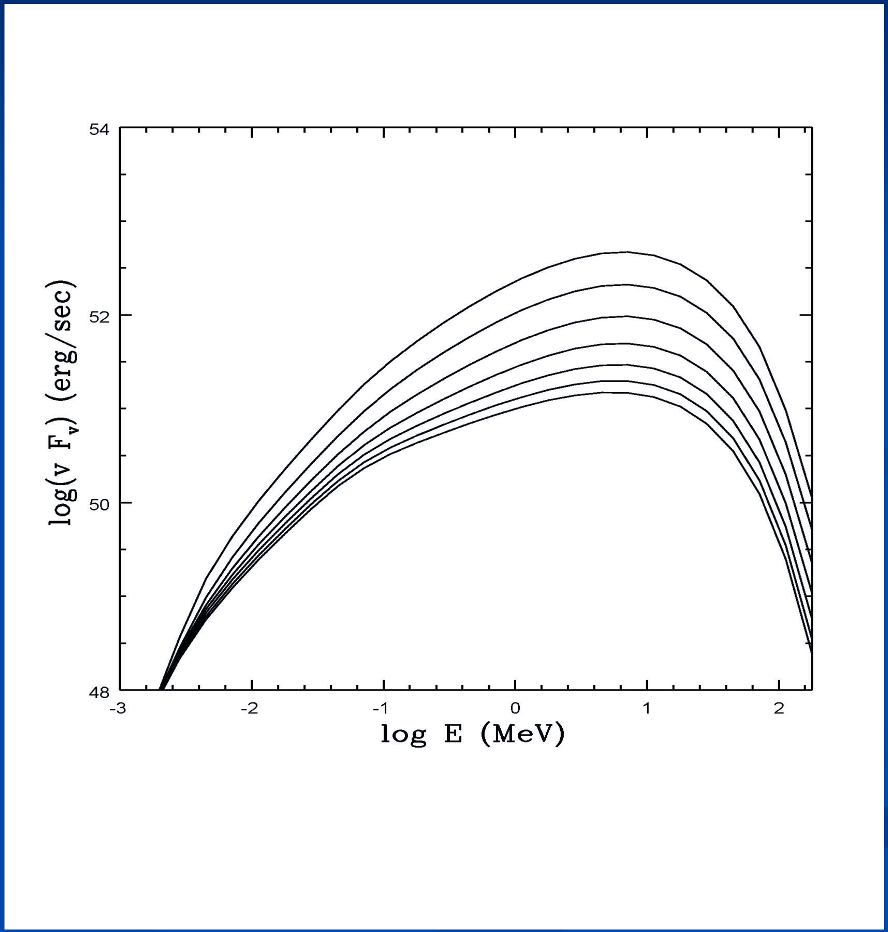
e N ' ° c=b° c 2 = 1=b° c

Shock – Mirror Geometry



formation region, generally not much different than the





$$\text{¡}^{5}b \gtrsim 2 \text{ or } \text{¡} \gtrsim \mu\, \frac{2}{b}\, ¶^{1=5} :$$