An External Inverse-Compton Emission Model of Gamma-Ray Burst High-Energy Lags

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Abstract summary

We discuss an external inverse Compton model for the delayed high-energy emission observed in some LAT-GRBs, focusing on GRB 080916C. The delay times may be directly linked to the physical parameters of GRB progenitors in this model.

Abstract

The Fermi satellite has been reporting the detailed temporal properties of gamma-ray bursts (GRBs) in an extremely broad spectral range, 8keV - 300GeV, in particular, the unexpected delays of the GeV emission onsets behind the MeV emission of some GRBs. We focus on GRB 080916C, one of the Fermi-GRBs for which the observational analysis is fairly complete at the moment and the data of the delayed high-energy emission is quite extensive, and we show that the behavior of the high-energy emission of this burst can be explained by a model in which the prompt emission consists of two components: one is the MeV component due to the synchrotron-self-Compton radiation of electrons accelerated in the internal shock of the jet and the other is the high-energy component due to up-scattering of the photospheric X-ray emission of the expanding cocoon off the same electrons in the jet. Such an up-scattering effect could be important for other Fermi-GRBs, including short GRBs, as well. In this model, the delay times of the high-energy emission is directly linked to the physical parameters of progenitor stars of GRBs.
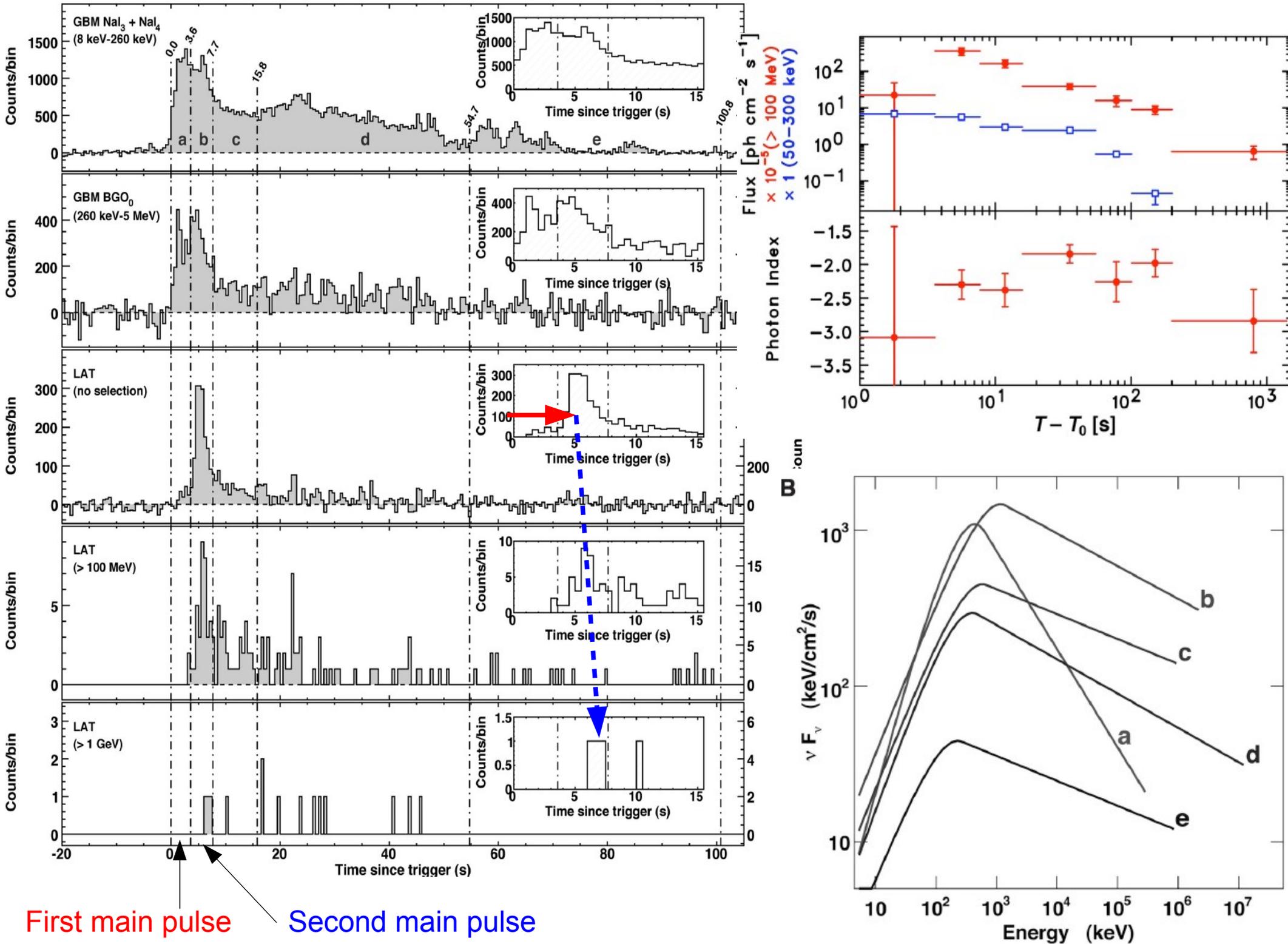
GRB High-Energy Lags

The Fermi satellite provides an unparalleled broad energy coverage with good temporal resolution, and it is accumulating a steady stream of new data on the high-energy emission of GRBs. One of new important properties is that some GRBs show delayed onsets of high-energy ($\varepsilon > 100$ MeV) emission behind onsets of $\varepsilon <\sim 1$ MeV emission.

GRB 080916C: notable example

(i) Time-resolved spectra are well fitted by a broken-power-law (so-called Band) function

(ii) HE ($\varepsilon > 100$MeV) emission delayed by ~ 5 sec behind MeV emission ($\varepsilon <\sim 1$ MeV)

(iii) The emission onset times shift towards later times in higher energy bands

(iv) HE emission lasts much longer than MeV emission

(v) Redshift z ~ 4.35, $E_{\gamma,iso}$ ~ 8.8e+54 erg (largest so far)

(Abdo et al. 2009)

GBM NaI$_3$ + NaI$_4$ (8 keV–260 keV)

GBM BGO$_0$ (260 keV–5 MeV)

LAT (no selection)

LAT (> 100 MeV)

LAT (> 1 GeV)

First main pulse   Second main pulse

Flux [ph cm^{-2} s^{-1}]
× 10^{-5} (> 100 MeV)
× 1 (50–300 keV)

Photon Index

$T - T_0$ [s]

B

νF_ν (keV/cm^2/s)

Energy (keV)

Property (i): Single or Double spectral component?

Time-resolved spectra can be fitted by double-broken-power-law (so-called Band) functions.
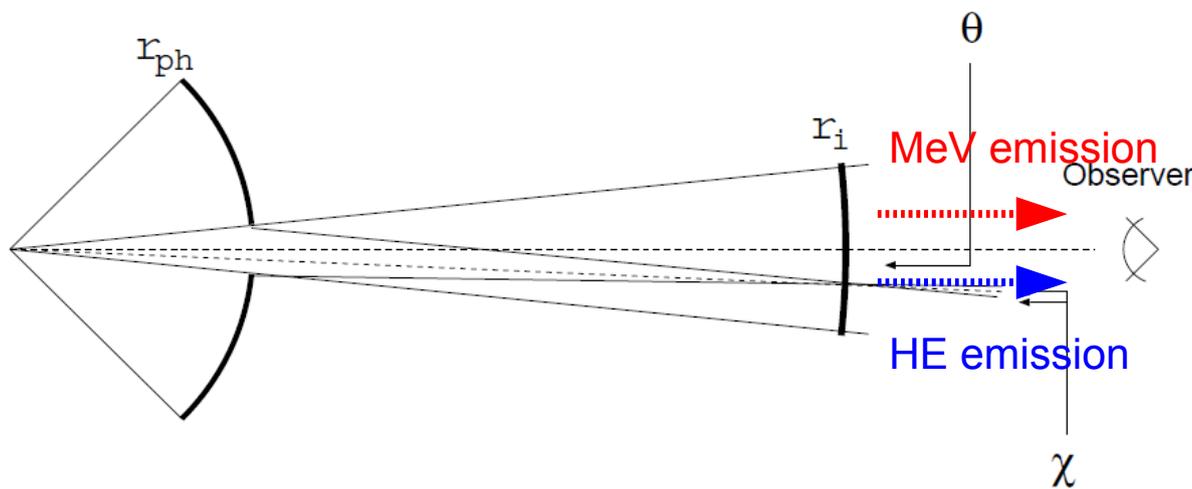
Single emission component?

- This seems at odds with the property (iii). The emission after the MeV flux peak could be the high-latitude emission, so that the emission has to be systematically harder in the high-latitude region.

Two emission components?

- MeV component + Delayed HE component.
- The latter could be due to hadronic effects (cf. Razzaque et al. 2009, Asano et al. 2009)
- We focus on the leptonic process as the latter component

Property (ii): Delayed Onset of HE emission

We consider an external inverse Compton radiation as the HE component, i.e., up-scattering of delayed soft photons off the electrons accelerated in the jet which emits the MeV component.


Log Density (g/cm³) at Time = 17.000 s

Just after jet breakout

r_{ph}

θ

r_i

MeV emission

Observer

HE emission

χ

Cocoon (= thermal bubble of wasted jet energy)

Jet

Progenitor star

Seed photons?
- Jet breakout X-rays? - No. This is prior to the MeV emission.
- Cocoon X-rays? - Yes! This is energetic and may be delayed.
- Supernova shock breakout? - This is behind the cocoon.

r (10^9 cm)

Hydrodynamical simulation by Morsony et al. 2007
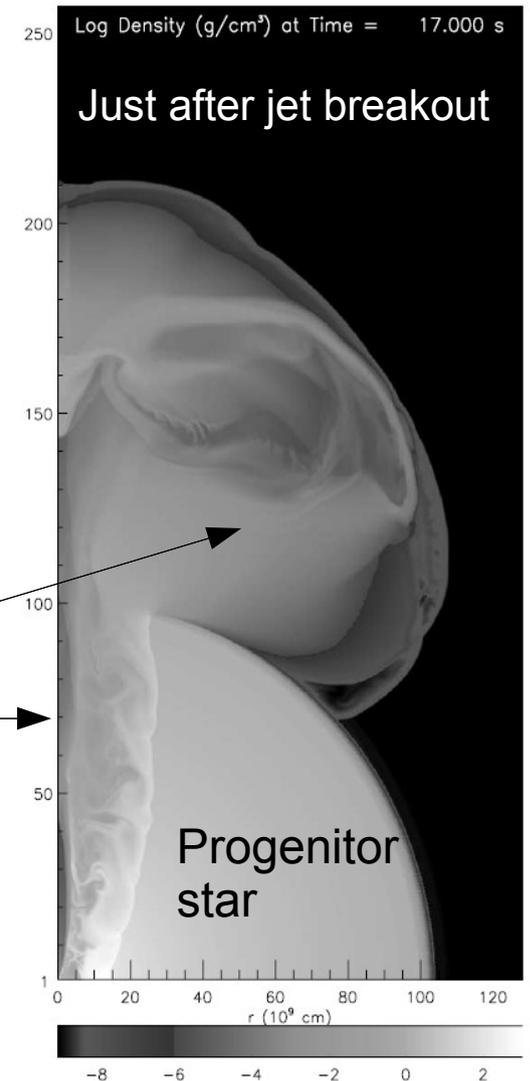
Jet Emission Onset & Cocoon Emission Onset

The 1st MeV pulse produced by an internal shock in the jet is observed at

$$t \simeq \Delta t_i \equiv \frac{r_i}{2c\Gamma_j^2}(1+z), \quad \sim 2 \text{ sec}$$ (This is trigger time)

[Inferred from the observed pulse width]

The cocoon expands after the jet breakout as predicted in the standard fireball model (Ramirez-Ruiz et al. 2002). The photosphere radius is

$$r_{\rm ph} \simeq \left[\frac{E_c \sigma_T}{2\pi(1-\cos\theta_c)\Gamma_c m_p c^2} \right]^{1/2} \simeq 2.1 \times 10^{14} \text{ cm } E_{c,52}^{1/2} \left(\frac{\Gamma_c}{50} \right)^{-1/2},$$
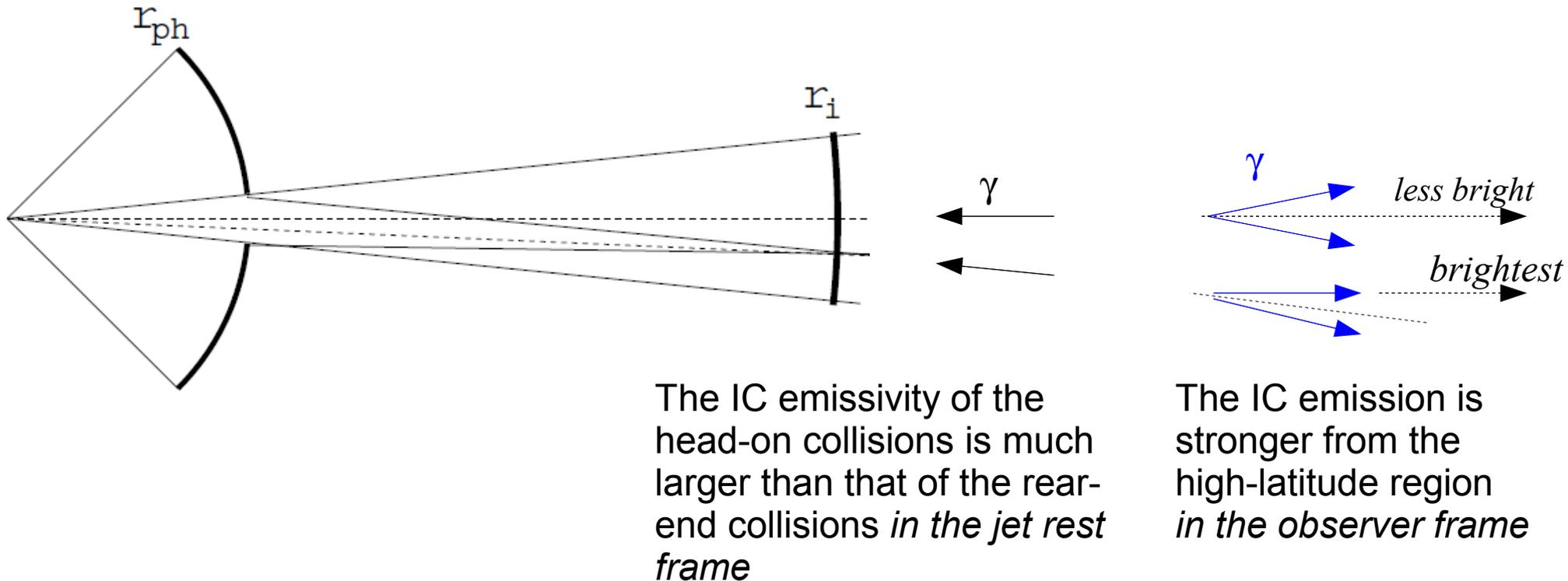
The cocoon photospheric emission (and up-scattered cocoon emission) is observed at

$$t \simeq \Delta t_c \equiv \frac{r_{\rm ph}}{2c\Gamma_c^2}(1+z) \simeq 7.5 \text{ s } E_{c,52}^{1/2} \left(\frac{\Gamma_c}{50} \right)^{-5/2},$$

The delay timescale is $\Delta t_c - \Delta t_i$. The observed delay ~ 5 sec constrains the physical parameters of the cocoon.

Property (iii): High-energy lag within the 2nd pulse

Inverse Compton scattering of photons coming from the rear by electrons in the jet is stronger in the high latitude region for the observer.

The IC emissivity of the head-on collisions is much larger than that of the rear-end collisions *in the jet rest frame*

The IC emission is stronger from the high-latitude region *in the observer frame*

The pulse peak of the EIC emission lags behind those of synchrotron and SSC emission, which are isotropic in the jet rest frame, on the angular spreading timescale $\sim r_i/(2c\Gamma^2)$ (cf. Aharonian & Atoyan 1981, Wang & Meszaros 2006, Fan et al. 2008)

Property (iv): Long-lived HE emission

The photospheric emission of the cocoon is short-lived, so that the up-scattered cocoon (UC) emission is also short-lived. The duration is estimated as the expansion timescale

$$\frac{r_{\mathrm{ph}}}{2c\Gamma_c^2}(1+z) \simeq 7.5 \text{ s } E_{c,52}^{1/2}\left(\frac{\Gamma_c}{50}\right)^{-5/2},$$

It is natural that the HE emission in later times is related to the afterglow, i.e., produced by the external shock which propagates in the ambient medium. This possibility is studied by Kumar & Barniol Duran (2009) (see also Ghirlanda et al. 2009, Ghisellini et al. 2009 for other LAT-GRBs).

The rise of the HE emission ($\sim t^6$) is too steep for the external shock to produce it. Thus at least the first part of the HE emission should be related to the prompt emission.

Photospheric Emission of the Cocoon

The comoving temperature of the cocoon can be estimated by fireball model. The photospheric emission is expected to have a quasi-thermal spectrum (because of possible internal shocks at r < r$_{ph}$) (Pe'er, Meszaros & Rees 2006):

$$F_\varepsilon^{co} = F_{\varepsilon_{ph}}^{co} \times \begin{cases} \left(\dfrac{\varepsilon}{\varepsilon_{ph}^{co}}\right)^2 & \text{for } \varepsilon < \varepsilon_{ph}^{co}, \\[2em] \left(\dfrac{\varepsilon}{\varepsilon_{ph}^{co}}\right)^\beta & \text{for } \varepsilon_{ph}^{co} < \varepsilon < \varepsilon_{cut}^{co}, \end{cases}$$

where ε_{ph}^{co} and $F_{\varepsilon_{ph}}^{co}$ are given by

$$\varepsilon_{ph}^{co} \simeq 2.82\, kT'_{ph} \frac{2\Gamma_c}{1+z} \simeq 1.2 \text{ keV } E_{c,52}^{-1/12} r_{*,11}^{-1/12} \left(\frac{\Gamma_c}{50}\right)$$

$$\begin{aligned} F_{\varepsilon_{ph}}^{co} &\simeq \frac{(1+z)^3}{d_L^2} \frac{2\pi(\nu_{ph}^{co})^2}{c^2} kT'_{ph}\Gamma_c \left(\frac{r_{ph}}{\Gamma_c}\right)^2 \\ &\simeq 31 \text{ keV cm}^{-2}\text{ s}^{-1}\text{ keV}^{-1}\, E_{c,52}^{3/4} r_{*,11}^{-1/4}, \end{aligned}$$

Internal shock emission of the jet

The emission radius is estimated to be

$$r_i \simeq 2c\Gamma_j^2 \frac{\Delta t_i}{1+z} \simeq 2.2 \times 10^{16} \text{ cm } \Gamma_{j,3}^2 \left(\frac{\Delta t}{2 \text{ s}}\right).$$

In the internal shock model, synchrotron emission flux peaks at

$$\varepsilon_m \simeq \frac{3heB'}{4\pi m_e c} \gamma_m^2 \frac{2\Gamma_j}{1+z}$$

$$\simeq 2.7 \text{ eV } L_{55}^{1/2}\Gamma_{j,3}^{-2} \left(\frac{\Delta t_i}{2 \text{ s}}\right)^{-1} \theta_p^{5/2} \left(\frac{\epsilon_B}{10^{-5}}\right)^{1/2} \left(\frac{\epsilon_e}{0.4}\right)^2,$$

1st-order synchrotron self-Compton (SSC) emission is

$$\varepsilon_m^{SC} \simeq 4\gamma_m^2 \varepsilon_m$$

$$\simeq 1.7 \text{ MeV } L_{55}^{1/2}\Gamma_{j,3}^{-2} \left(\frac{\Delta t_i}{2 \text{ s}}\right)^{-1} \theta_p^{9/2} \left(\frac{\epsilon_B}{10^{-5}}\right)^{1/2} \left(\frac{\epsilon_e}{0.4}\right)^4,$$

$$F_{\varepsilon_c}^{SC} \simeq \tau F_{\varepsilon_c}$$

$$\simeq 3.4 \text{ keV cm}^{-2} \text{ s}^{-1} \text{ keV}^{-1} L_{55}^{5/2}\Gamma_{j,3}^{-8} \left(\frac{\Delta t_i}{2 \text{ s}}\right)^{-1} \theta_p^{1/2} \left(\frac{\epsilon_B}{10^{-5}}\right)^{1/2}.$$

This is consistent with the MeV component of the 2nd main pulse (interval b).

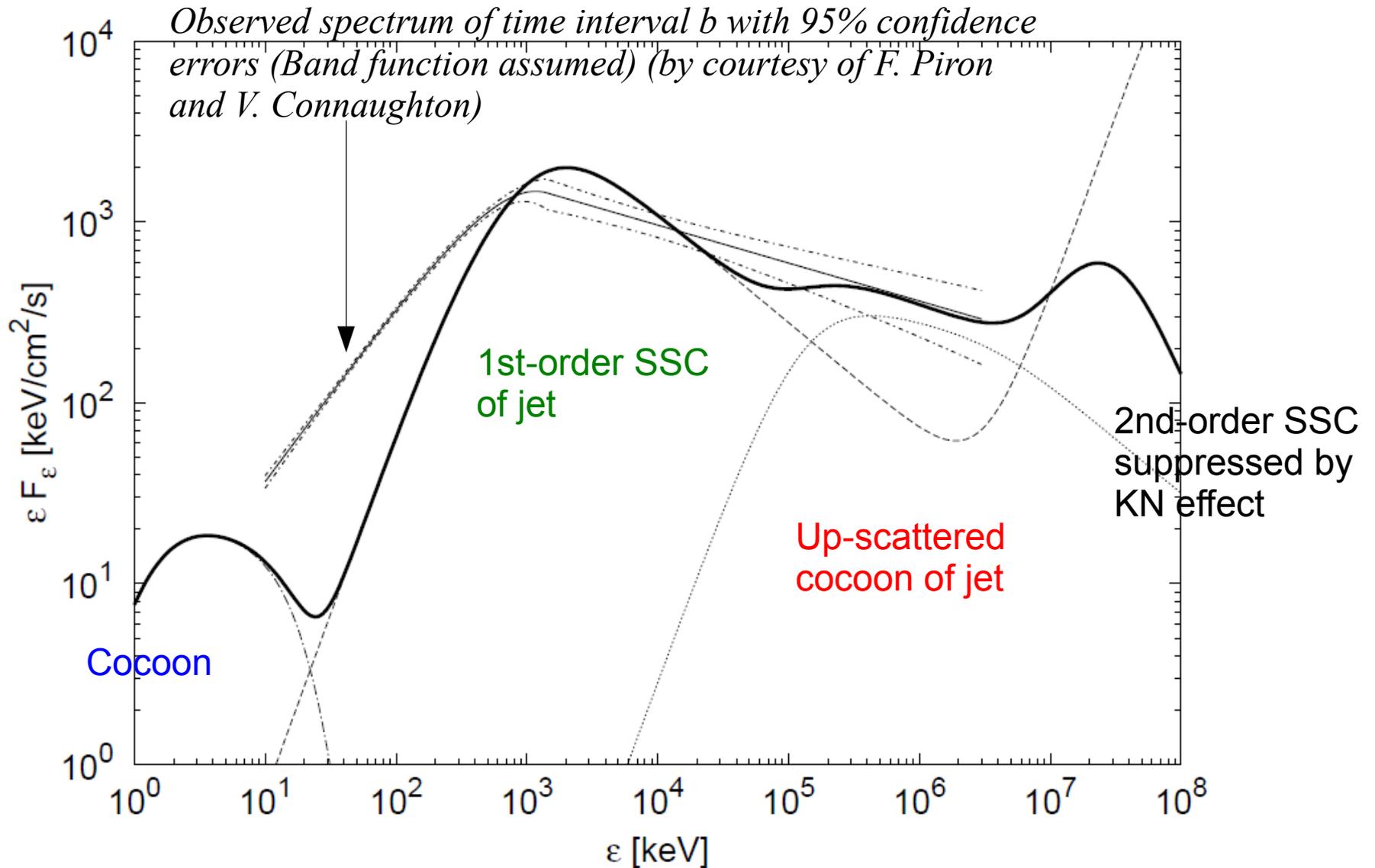# Up-Scattered cocoon (UC) emission of the jet

The electrons which emit the 1st-order SSC can naturally up-scatter the cocoon emission to the > 100MeV energy range.

$$\varepsilon_m^{\mathrm{UC}} = 2\gamma_m^2 \varepsilon_{\mathrm{ph}}^{\mathrm{co}} \frac{\xi(\theta)}{1 + \Gamma_j^2 \theta^2}$$

$$\simeq 160 \text{ MeV} \left[\frac{4q}{(1+q)^2}\right] \left(\frac{\gamma_m}{400}\right)^2 \left(\frac{\varepsilon_{\mathrm{ph}}^{\mathrm{co}}}{1 \text{ keV}}\right),$$

$$\varepsilon_m^{\mathrm{UC}} F_{\varepsilon m}^{\mathrm{UC}} = 3\tau \gamma_m \gamma_c \varepsilon_{\mathrm{ph}}^{\mathrm{co}} F_{\varepsilon_{\mathrm{ph}}}^{\mathrm{co}} \frac{\xi^2(\theta)}{[1 + \Gamma_j^2 \theta^2]^3}$$

$$\simeq 580 \text{ keV cm}^{-2} \text{ s}^{-1} \left[\frac{40q^2}{(1+q)^5}\right]$$

$$\times \left(\frac{\tau}{4 \times 10^{-4}}\right) \left(\frac{\gamma_m}{400}\right) \left(\frac{\gamma_c}{400}\right) \left(\frac{\varepsilon_{\mathrm{ph}}^{\mathrm{co}} F_{\varepsilon_{\mathrm{ph}}}^{\mathrm{co}}}{30 \text{ keVcm}^{-2}\text{s}^{-1}}\right),$$

where we approximate the emission as instantaneous from the infinitely thin shell. The angle parameter q = $(\Gamma\theta)^2$ represents that the UC emission flux is zero at θ = 0 and peaks at θ ~ 1/Γ (i.e., brighter in the high-latitude region).
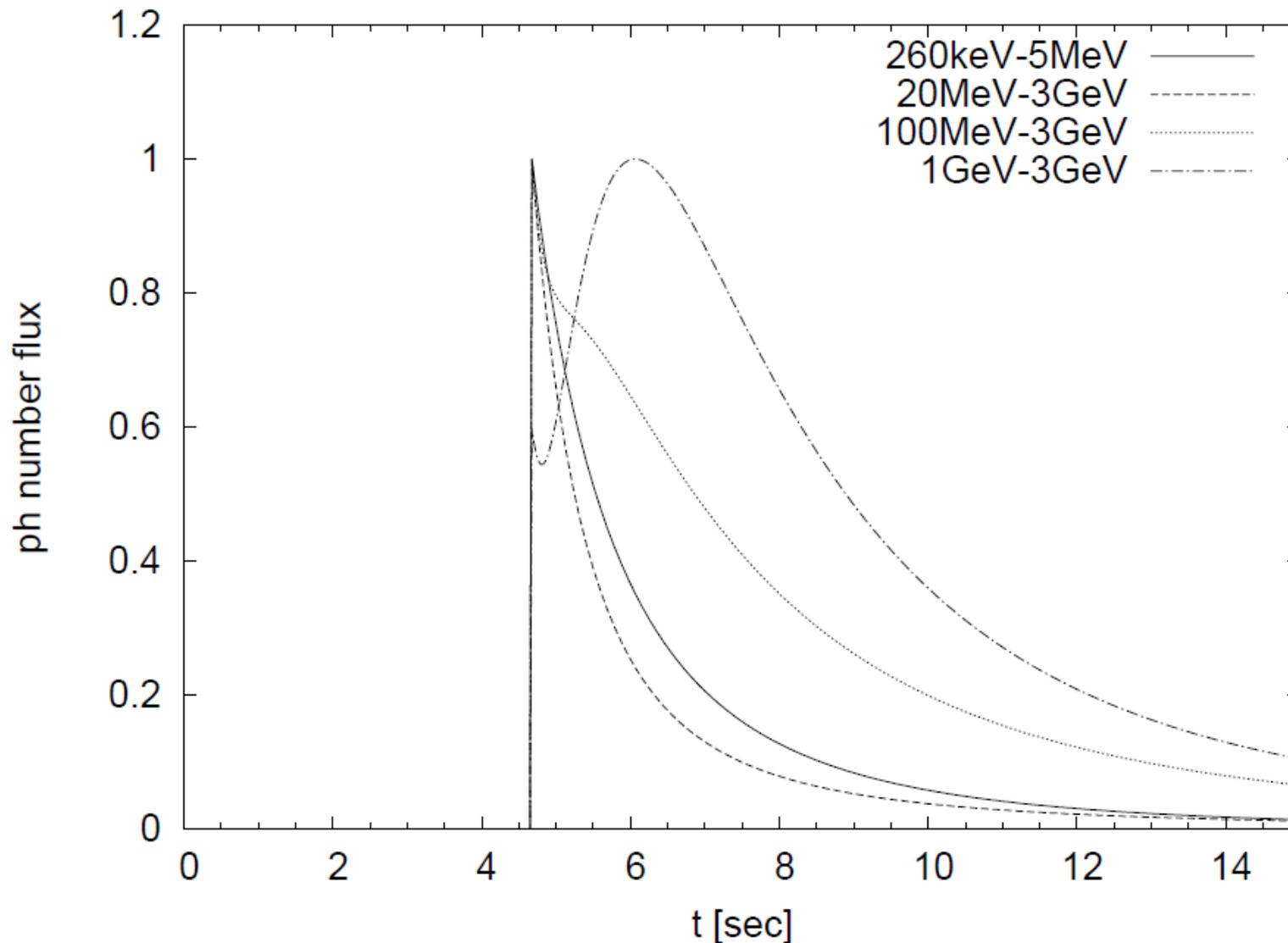
Spectrum of the 2nd pulse

Observed spectrum of time interval b with 95% confidence errors (Band function assumed) (by courtesy of F. Piron and V. Connaughton)

1st-order SSC of jet

2nd-order SSC suppressed by KN effect

Up-scattered cocoon of jet

Cocoon

$\varepsilon F_\varepsilon$ [keV/cm^2/s]

ε [keV]

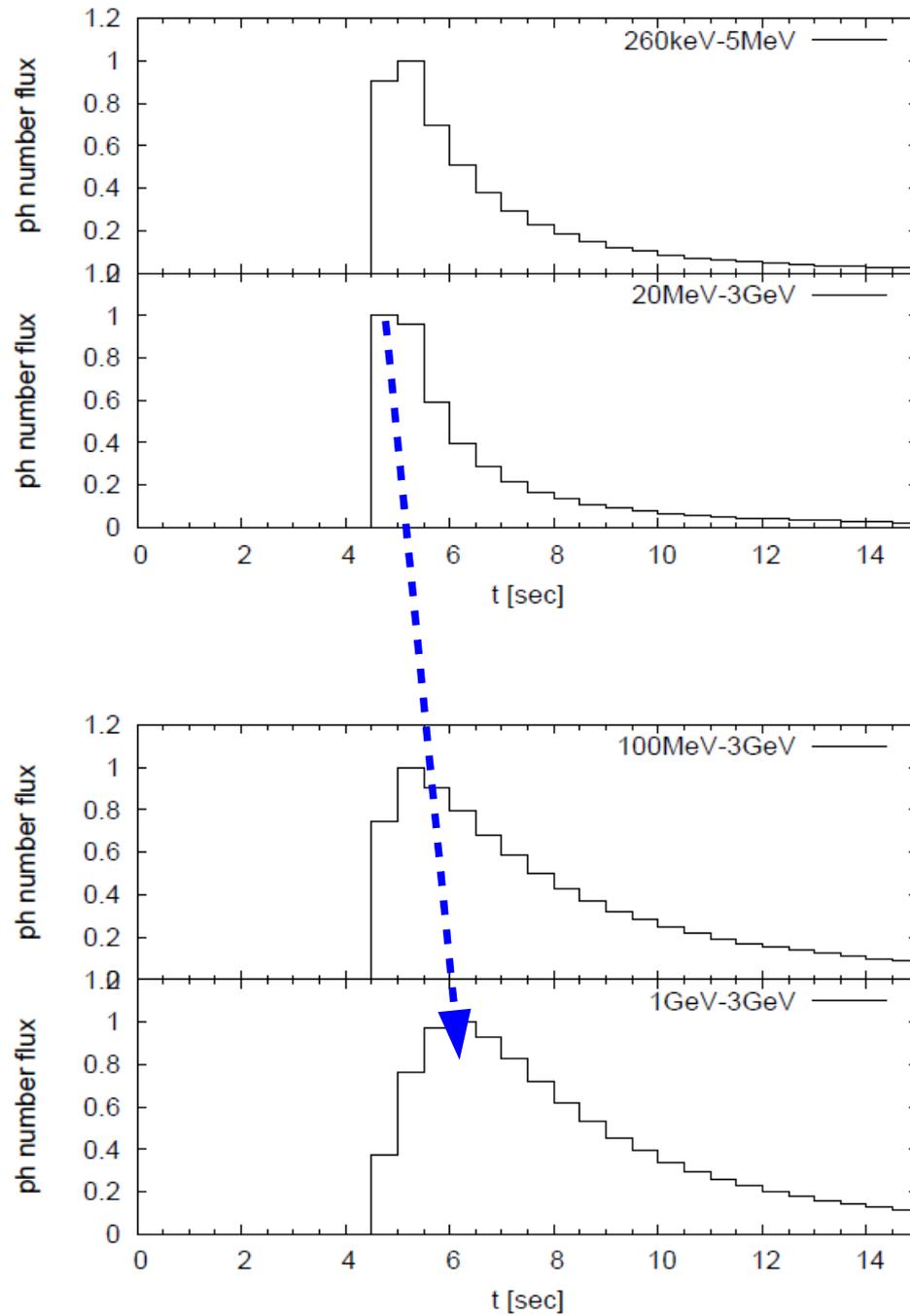$E_{c,52} = 1.0, \quad \Gamma_c = 52, \quad r_{*,11} = 2.5,$ \quad [cocoon parameters]

$L_{55} = 1.1, \quad \Gamma_{j,3} = 0.93, \quad \Delta t_i = 2.3 \text{ s}, \quad \epsilon_B = 10^{-5}, \quad \epsilon_e = 0.4,$ \quad [jet parameters]

Multi-band Light Curve

The GeV flux peak lags behind the lower-energy flux peak by angular spreading timescale. (For different parameters, the >100MeV flux peak also lags.)

Multi-band Light Curve in larger time-bins

Summary and Discussion

- We discuss an external inverse Compton model for the delayed high-energy emission of GRB 080916C, where the seed photons are assumed to be from an expanding cocoon.

- In this model, the delayed onset of the HE emission (property ii) is due to the delayed optical-thinning of the cocoon, and the HE lag within the 2nd pulse (property iii) is due to the anisotropy of the seed photon field in the jet rest frame.

- This model naturally explains the steep rise of the HE emission, which cannot be reproduced by external shock emission (cf. Kumar & Barniol Duran 2009, Ghisellini et al. 2009)

- Although we have focused on GRB 080916C, our model is generic. The EIC effect could be important for the bursts in which the MeV component is produced by the SSC radiation. If this model is correct, the delay times of the HE emission of GRBs may be directly linked to the physical parameters of the progenitor stars and the cocoons of GRBs.To investigate the seed photons for short GRBs would be an interesting approach to their progenitor.

- This model predicts bright synchrotron emission in the optical band, like "naked-eye GRB" 080319B, and soft X-ray excess due to cocoon emission in GeV-bright GRBs, like recent LAT-GRB 090902B.

- The photospheric emission of jet could be too bright (Zhang & Pe'er 2009, Lazzati et al. 2009). It is possible that the MeV component is from the jet photosphere while the HE component is still UC emission. Alternative possibility is the jet dominated by magnetic energy.