GeV-TeV emission from inverse-Compton scattering processes in GRBs

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GRB-shock acceleration

- Protons-

  shock acceleration $\sim 10^{20}\,\mathrm{eV}$ (e.g. Waxman 1995; Vietri 1995)

  photo-meson process:

  (e.g. Waxman & Bahcall 1997; Bottcher & Dermer 1998)

  $$\gamma + p \rightarrow \Delta^{+} \rightarrow \pi^{0} + p \qquad \pi^{0} \rightarrow \gamma + \gamma$$

  proton synchrotron radiation

  (e.g. Vietri 1997; Totani 1998)

- Electrons-

  Shock acceleration: ~10 TeV

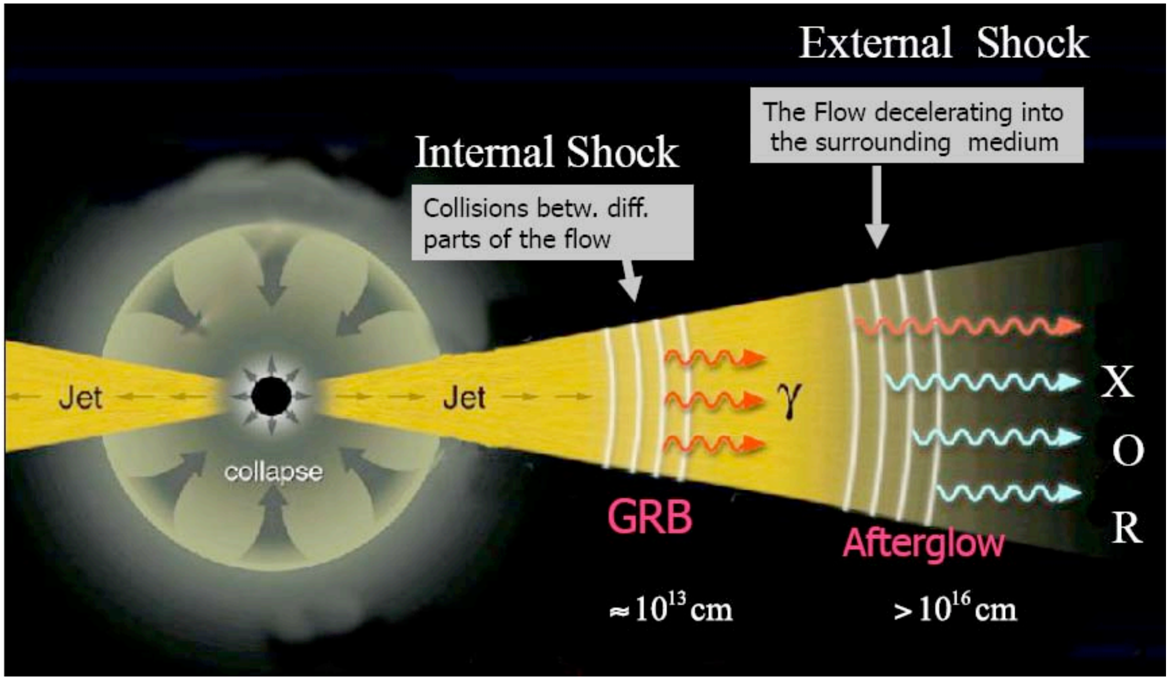
  $$t_{cool} \sim t_{acc} \Rightarrow \gamma_{e,Max} \leq 10^{7}$$

  X-ray afterglows $\rightarrow \gamma_{e,Max} > 10^{5}$

  e.g. Li & Waxman 2006

  Leptonic inverse Compton scattering

Inverse-Compton scattering in GRB shocks



Credit P. Meszaros

Internal shock IC: e.g. Pilla & Loeb 1998; Razzaque et al. 2004

External shock IC

- reverse shock IC: e.g. Meszaros , et al. 94; Wang et al. 01; Granot & Guetta 03
- forward shock IC: e.g.Meszaros & Rees 94; Dermer et al. 00; Zhang & Meszaros 01

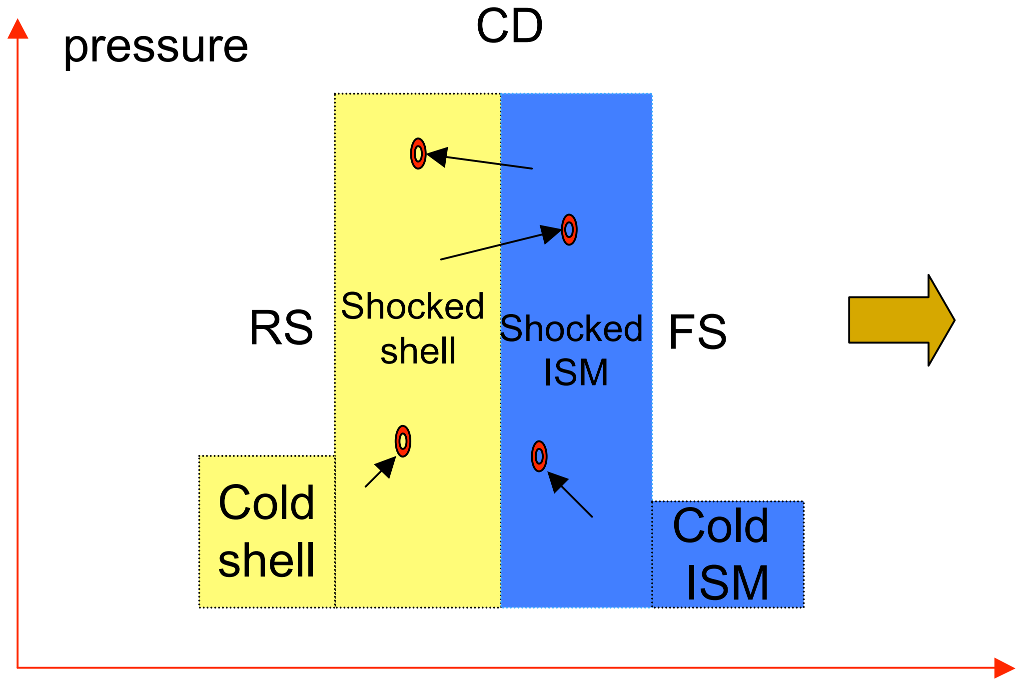
I will include…

- VHE photons from GRB early external shocks--very early afterglow phase
- VHE photons related to X-ray flares: X-ray flares photons are IC scattered by electrons in afterglow shocks

1. IC emission from very **early external shocks**

(Wang, Dai & Lu 2001 ApJ,556, 1010)

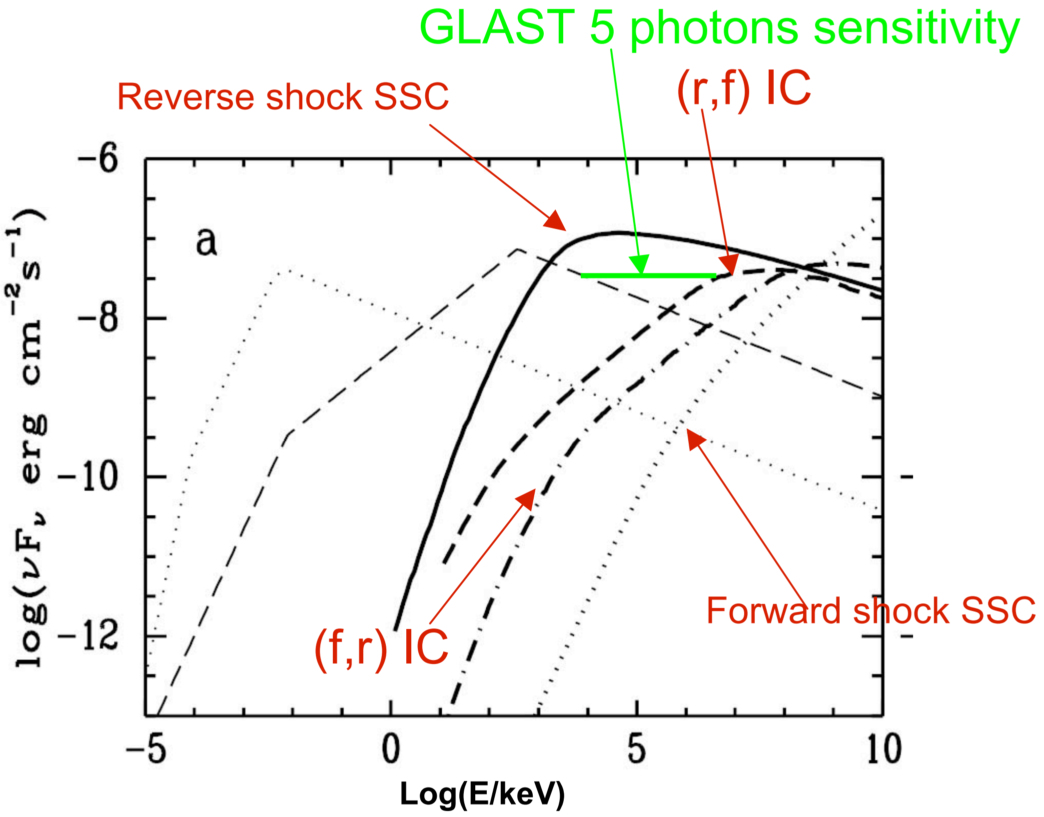
At deceleration radius, T_obs~10-100 s
Forward shock---Reverse shock structure is developed



Four IC processes

1) (rr)
2) (ff)
3) (fr)
4) (rf)

Energy spectra--- $\nu f_\nu - \nu$ **(Wang, Dai & Lu 2001 ApJ,556, 1010)**



GLAST 5 photons sensitivity

Reverse shock SSC

(r,f) IC

(f,r) IC

Forward shock SSC

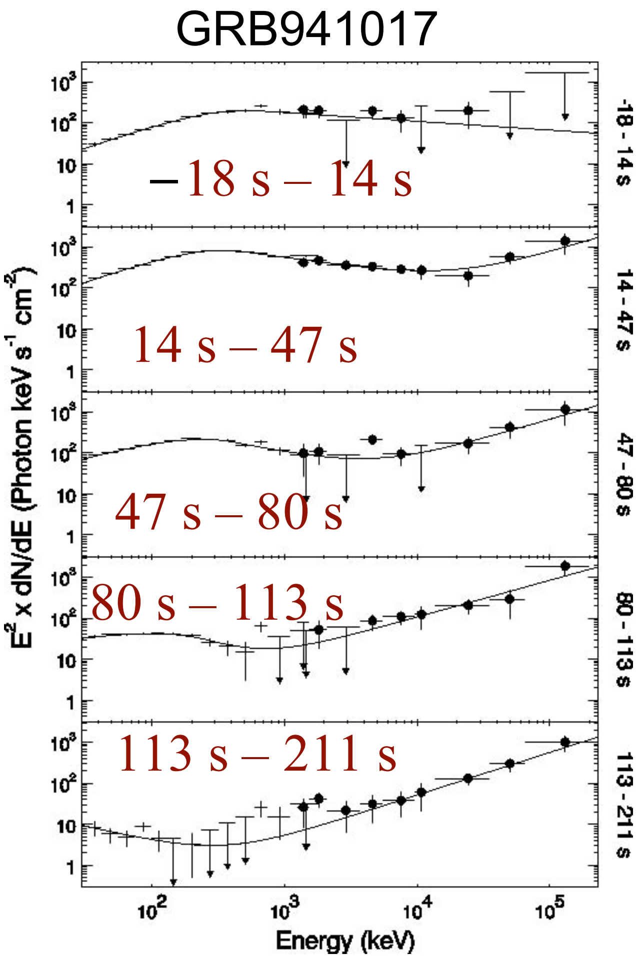
$$f_\nu^{IC} = 3\Delta r'\sigma_T \int_{\gamma_{\min}}^{\gamma_{\max}} d\gamma N(\gamma) \int_0^1 dx g(x) f_\nu(x)$$

a) $E = 10^{53} erg, \xi_e = 0.6, \xi_B = 0.01, p = 2.5, n = 1;$

At sub-GeV to GeV energies, the SSC of reverse shock is dominant; at higher energies, the Combined IC or SSC of forward shock becomes increasingly dominated

See also Wang, Dai & Lu 2001, ApJ,546, L33

One interesting GeV burst



Gonzalez et al. 03: **Hadronic model**

Leptonic IC model:

Granot & Guetta 03
Pe’er & Waxman 04
Wang X Y et al. 05, A&A, 439,957

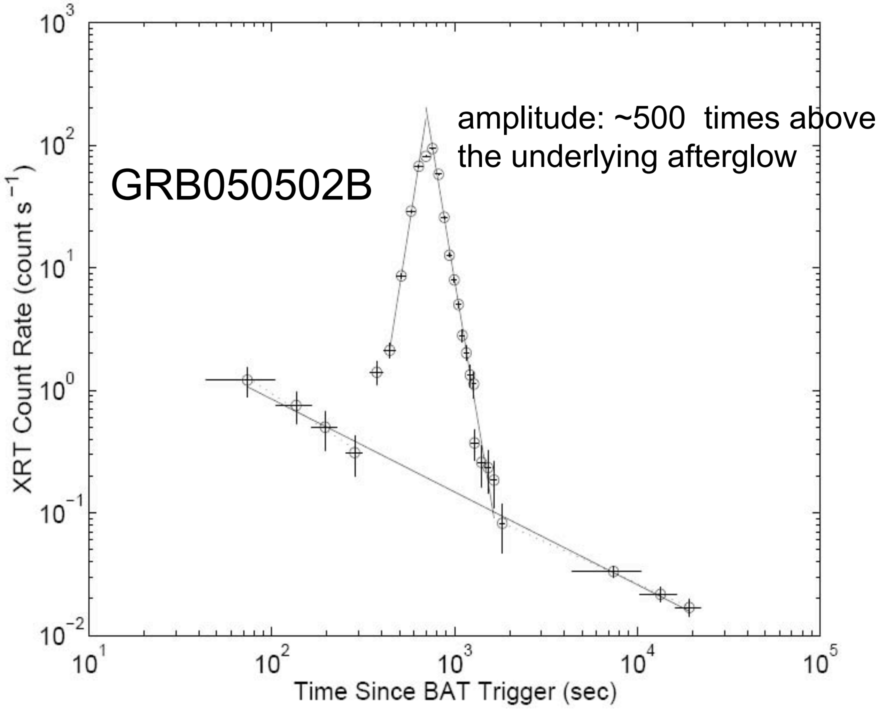
2. VHE photons from x-ray flare-blast wave interaction

X-ray flares: late-time central engine activity

- ~30%-50% early afterglow have x-ray flares, Swift discovery
- Most striking flare GRB050502B discovered by Swift
- Flare light curves: rapid rise and decay

  $\delta t / t \quad << 1$
- Afterglow decay consistent with a single power-law before and after the flare

X-ray flares occur inside the deceleration radius of the afterglow shock

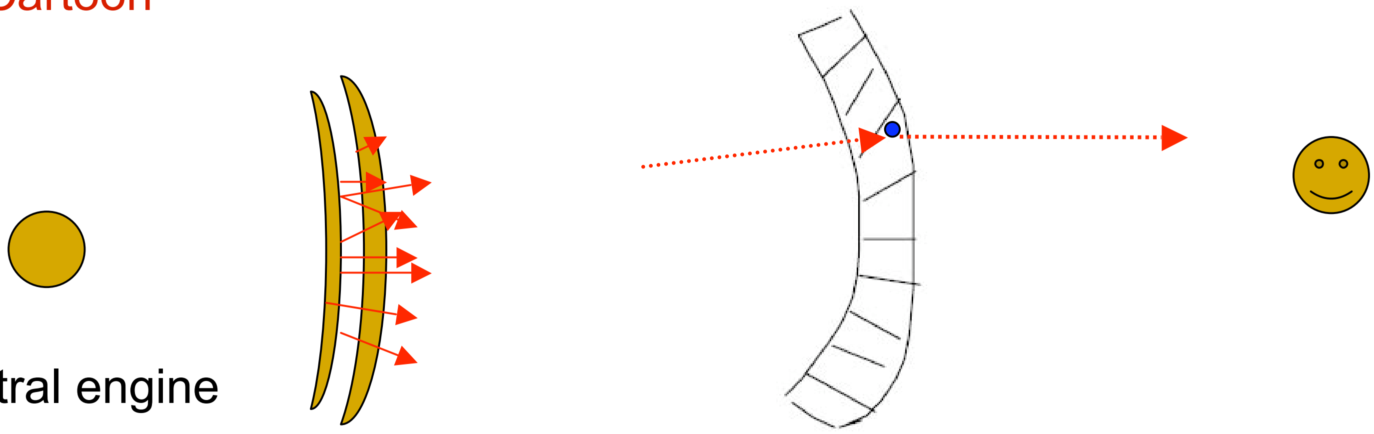


Burrows et al. 2005
Falcone et al. 2006

IC between X-ray flare photons and afterglow electrons (Wang, Li & Meszaros 2006)

X-ray flare photons illuminate the afterglow shock electrons from inside

Cartoon



Cnetral engine

X-ray flare photons

Forward shock region

also see Fan & Piran 2006: unseen UV photons

Flare photons is the dominant cooling source of afterglow electrons

- Flare photons is the dominant cooling source for electrons in the afterglow jet

$$U'_X = D^2 F_X/(\Gamma^2 R^2 c) \quad > \quad B^2/8\pi$$

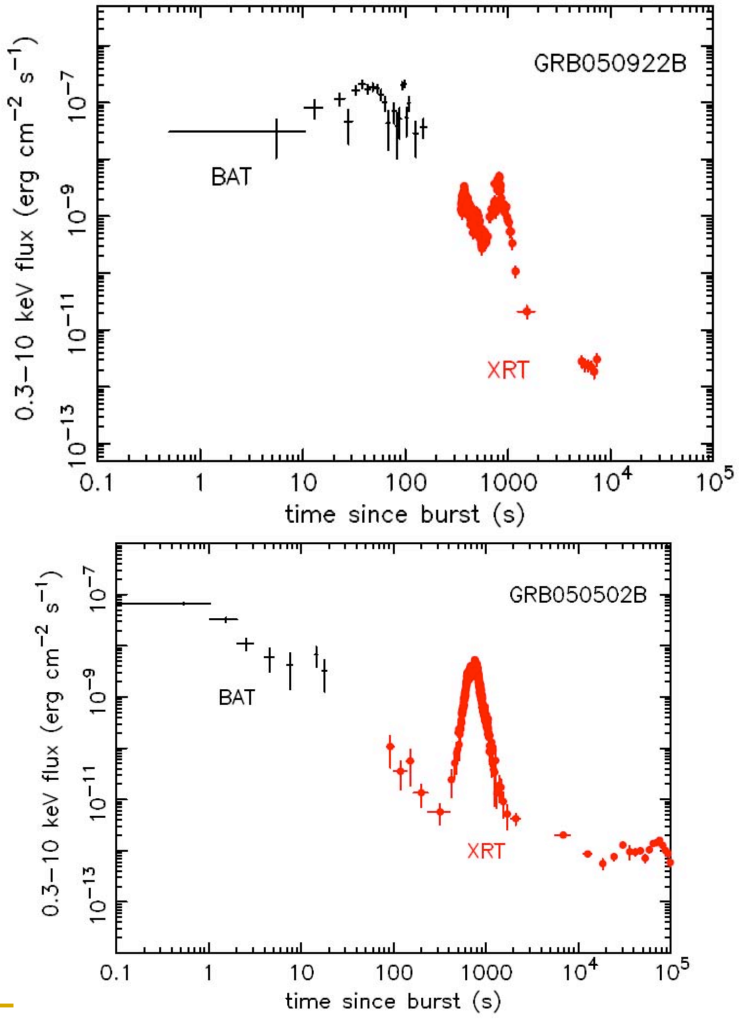
$$F_X \;>\; 10^{-10}\epsilon_{B,-2}E_{52}t_3^{-1}D_{28}^{-2}\,\mathrm{ergcm^{-2}s^{-1}}$$

- Flare photons make the afterglow electrons fast-cooling

$$F_X \;>\; 10^{-10}\epsilon_{B,-2}E_{52}t_3^{-1}D_{28}^{-2}\,\mathrm{ergcm^{-2}s^{-1}}$$

$$\gamma_m \gtrsim \gamma_c$$

$$F_X > 3\times10^{-10}E_{52}^{1/2}\epsilon_{e,-1}^{-1}n_0^{-1/2}t_3^{-1/2}D_{28}^{-2}\mathrm{ergcm^{-2}s^{-1}}$$



O'Brien et al. 2006

IC GeV flare fluence-An estimate

- So most energy of the newly shock electrons will be lost into IC emission

$$0.1 < \delta t/t < 1 \qquad \Psi = 10^{-7} - 10^{-6}\epsilon_{e,-1}E_{52}D_{28}^{-2}\,\mathrm{erg\,cm^{-2}}$$

$$\varepsilon_{IC,p} \simeq 2\gamma_m^2\varepsilon_X \simeq 3\epsilon_{e,-1}^2 E_{52}^{1/4} n_0^{-1/4} t_3^{-3/4}\left(\frac{\varepsilon_X}{1\mathrm{keV}}\right)\mathrm{GeV}$$

X-ray flare peak energy

Klein-Nishina suppression is unimportant below TeV

νF_ν 1/2 and $-(p-2)/2$ before and after the break at $\varepsilon_{IC,p}$

Klein-Nishina cutoff $\gamma_e < \gamma_{e,M} = \Gamma m_e c^2/\varepsilon_X$

$$\varepsilon_{IC,M} = 2\gamma_{e,M}^2(\varepsilon_X/\Gamma)\Gamma = 0.4E_{52}^{1/4}n_0^{-1/4}t_3^{-3/4}\left(\frac{\varepsilon_X}{1\mathrm{keV}}\right)^{-1}\ \mathrm{TeV}$$

$$\tau_{\gamma\gamma} \simeq 0.1\sigma_T\frac{U'_X}{\varepsilon_X/\Gamma}(\Gamma c\delta t) = 0.3F_{X,-9}n_0^{1/2}t_3^{1/2}E_{52}^{-1/2}D_{28}^2\left(\frac{\delta t}{t}\right)\left(\frac{\varepsilon_X}{1\mathrm{keV}}\right)^{-1}$$

Magic, Milagro, HESS, etc.

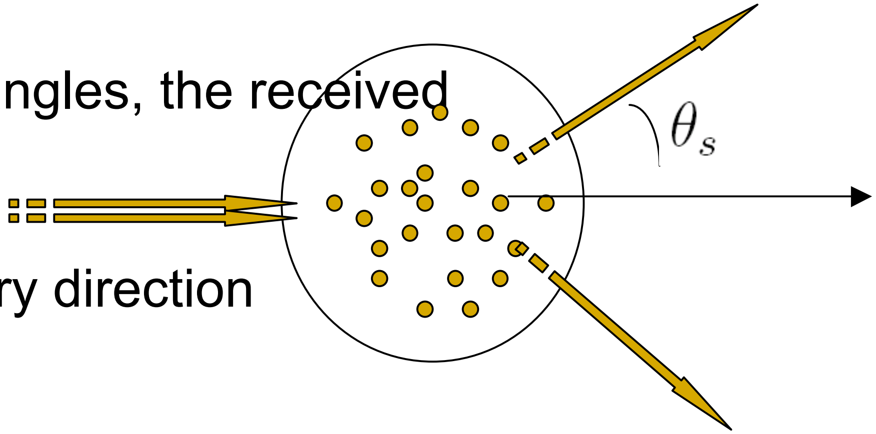
But at high redshift, the infrared background absorption will be important

Anisotropic IC scattering effect

- Effect: decrease the power along the seed photon beam direction, but increase larger angle emission, about a half within $2/\Gamma$ (Wang, Li & Meszaros 2006)

e.g. Ghisellini 1978; Brunetti 2000; Fan & Piran 2006

- If $\theta_j \gg 1/\Gamma$, when integrated over angles, the received IC fluence will not be reduced.



- Suppose the sphere geometry: every direction has the same fluence.

The IC fluence will not change

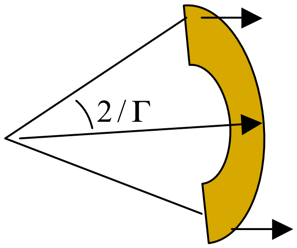
Temporal behavior of the IC emission

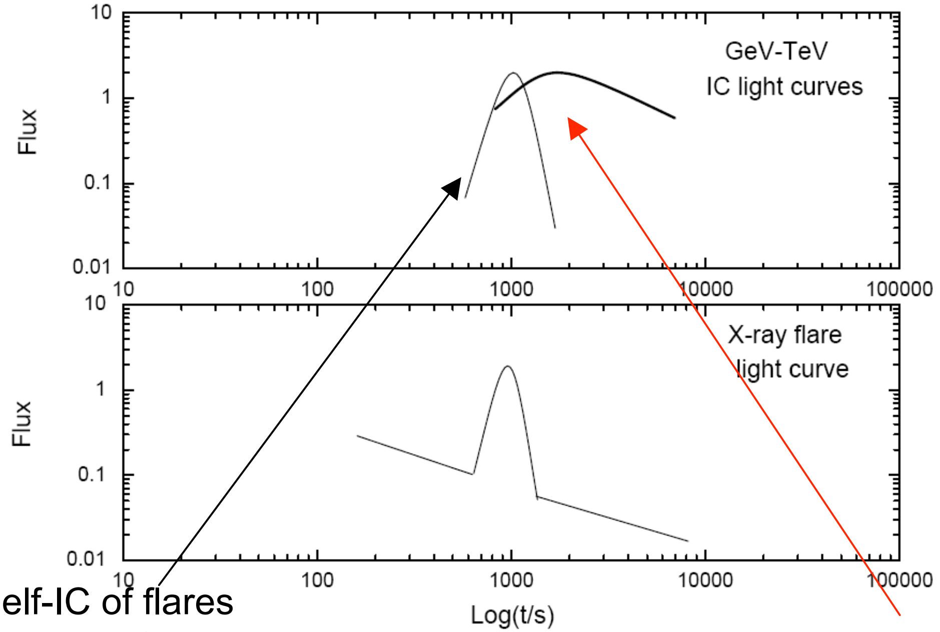
- Not correlated with the X-ray flare light curves. IC emission will be lengthened by the afterglow shock angular spreading time and the anisotropic IC effect

IC photons emitted in the cone from $1/\Gamma$ to $2/\Gamma$

$$t_{obs} \sim \frac{R}{2\Gamma^2} + \frac{R\theta^2}{2} = \frac{R}{\Gamma^2} = 2t_{XRF}$$

Time delay relative to the flare time



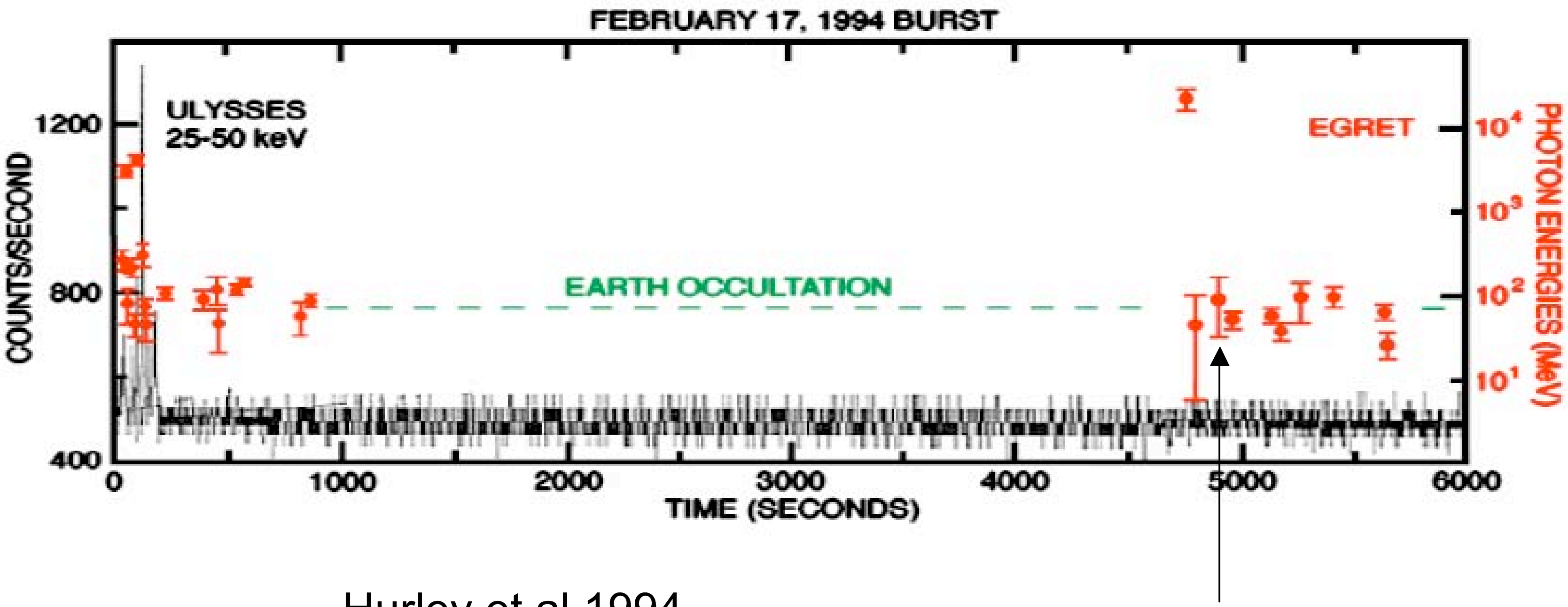


Self-IC of flares
Wang, Li & Meszaros 2006
also see Galli et al. poster

GLAST might be able to distinguish them

Delayed GeV emission ---GRB940217

EGRET on board Compton



Hurley et al.1994

Was there a delayed X-ray flare ?

See also Zhang & Meszaros 2001
Wei & Fan 2007

Summary

$\left\{ \begin{array}{l} \text{IC in early external shocks} \\ \text{IC of x-ray flares} \end{array} \right.$

Both are promising VHE photon sources for GLAST

- What could GLAST tell us?

- Origin of GeV photons (both prompt and delayed): Spectral and temporal properties
- Maximum energy of the shock accelerated electrons : $\varepsilon_{e,Max} > ?$
- Magnetic field in the shocks: $L_{IC} / L_{syn} = U_{ph} / U_B$
- ...