How may GLAST Help Solve some GRB Mysteries Raised by *Swift*

Jonathan Granot

KIPAC @ Stanford

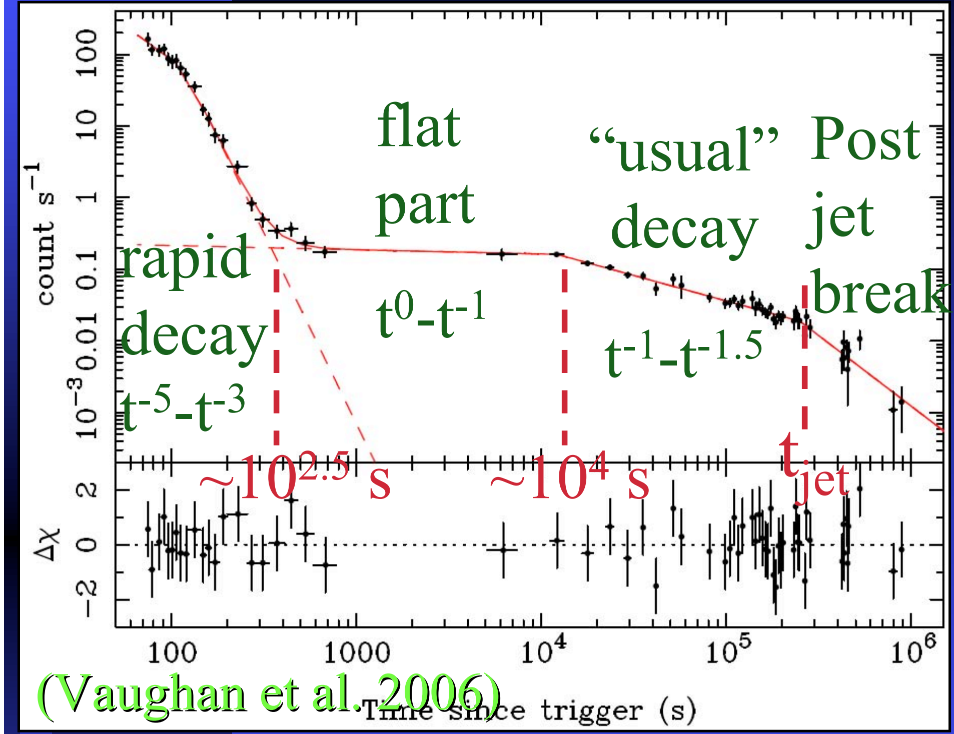
Collaborators: **J. Cohen-Tanugi, E. do Couto e Silva**
A. Königl, T. Piran, P. Kumar, D. Eichler,
E. Ramirez-Ruiz, C. Kouveliotou, …

First GLAST Symposium, February 7, 2007, Stanford

Outline of the Talk:

- Early X-ray afterglow of Swift GRBs: flat decay phase
  - brief outline of possible explanations & implications
  - **GLAST** could test the models & effect implications
- X-ray flares: from same mechanism as prompt GRB?
  - **GLAST** could probe emission site & mechanism
- Opacity effects in prompt GRB emission / X-ray flares
  - Time dependence: helps distinguish between models & effects shape of high-energy cutoff in spectrum
  - Results applicable to impulsive relativistic sources
- **Conclusions**

Early X-ray Afterglows from Swift:



rapid decay t^{-5}-t^{-3}

flat part t^0-t^{-1}

"usual" decay t^{-1}-$t^{-1.5}$

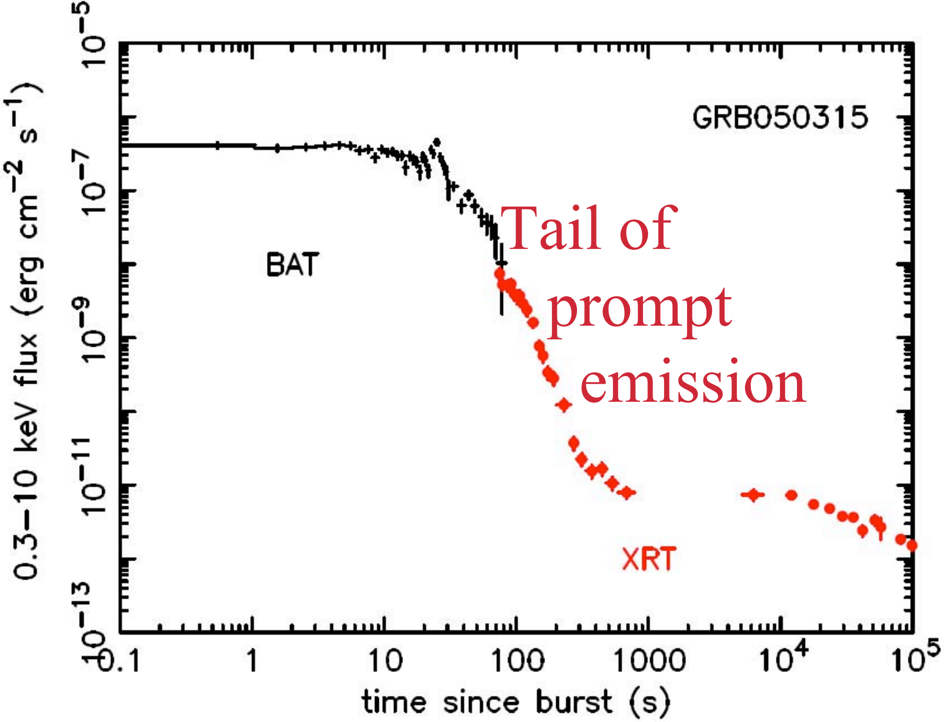
Post jet break

~$10^{2.5}$ s

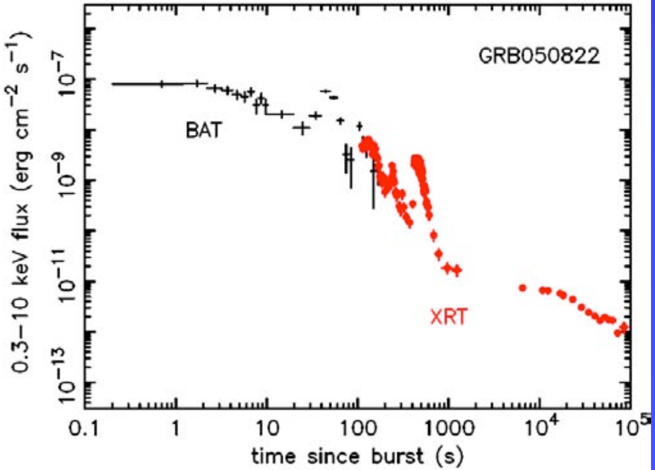
~10^4 s

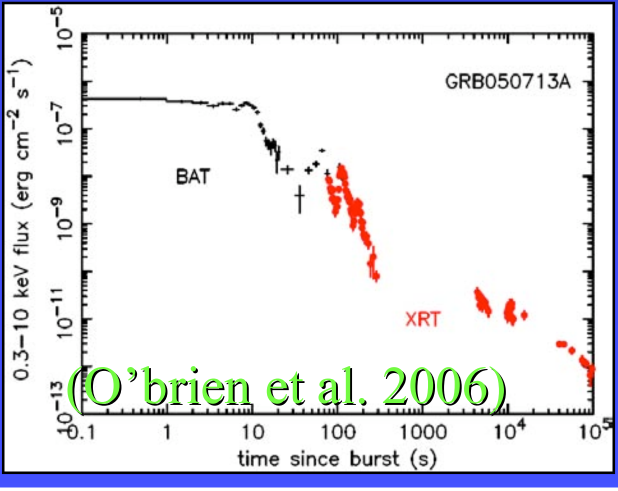
t_{jet}

(Vaughan et al. 2006)

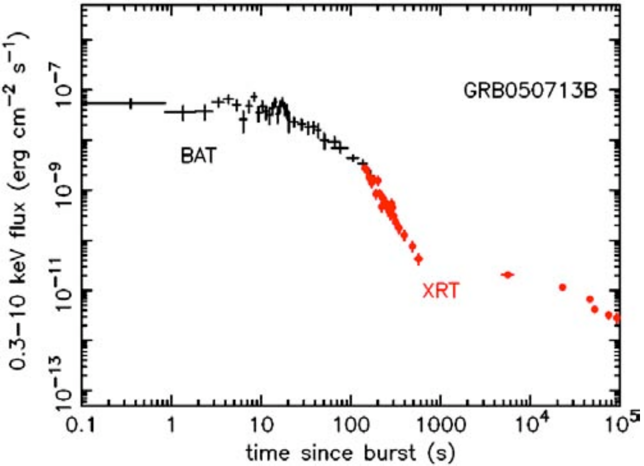


Tail of prompt emission



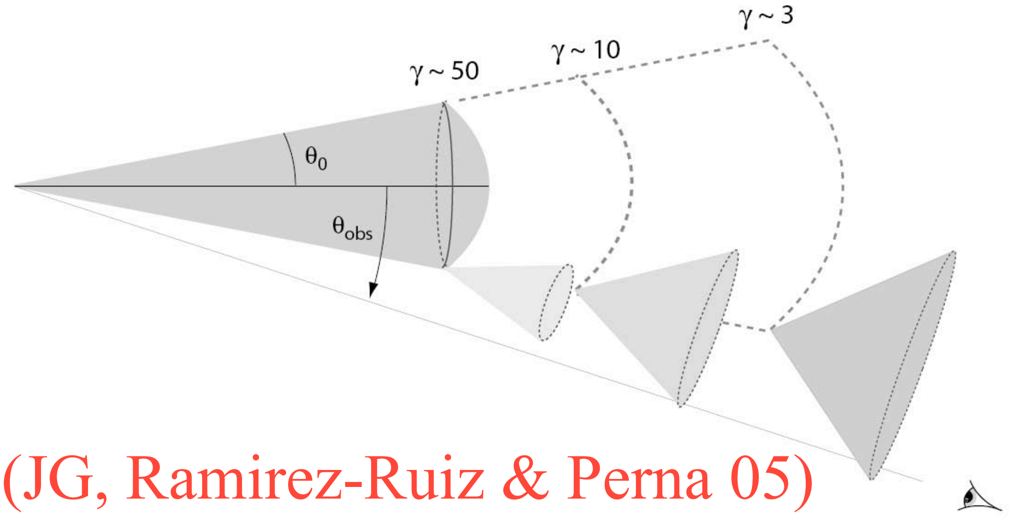


(O'brien et al. 2006)



Possible **Explanations** for Early Flat Decay

- **Energy injection** into afterglow: (Nousek et al. 06)
  - **I.** Continuous relativistic wind $L \propto t^{-0.5}$ (magnetar?)
  - **II.** Slower material ejected during the prompt GRB gradually catches up the decelerating afterglow shock
- Afterglow efficiency increases with time (varying shock micro-physics parameters; JG, Königl & Piran 06)
- Observer outside emitting region (JG & Eichler 06)

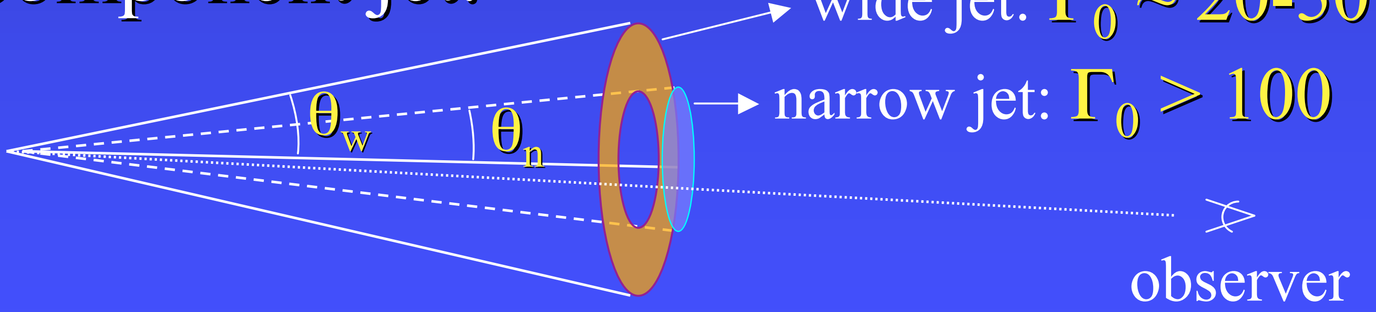


(JG, Ramirez-Ruiz & Perna 05)

Possible **Explanations** for Early Flat Decay

- **Energy injection** into afterglow: (Nousek et al. 06)
  - **I.** Continuous relativistic wind $L \propto t^{-0.5}$ (magnetar?)
  - **II.** Slower material ejected during the prompt GRB gradually catches up the decelerating afterglow shock
- Afterglow efficiency increases with time (varying shock micro-physics parameters; JG, Königl & Piran 06)
- Observer outside emitting region (JG & Eichler 06)
- Two component jet:

(JG, Königl & Piran 06)



wide jet: $\Gamma_0 \sim 20\text{-}50$

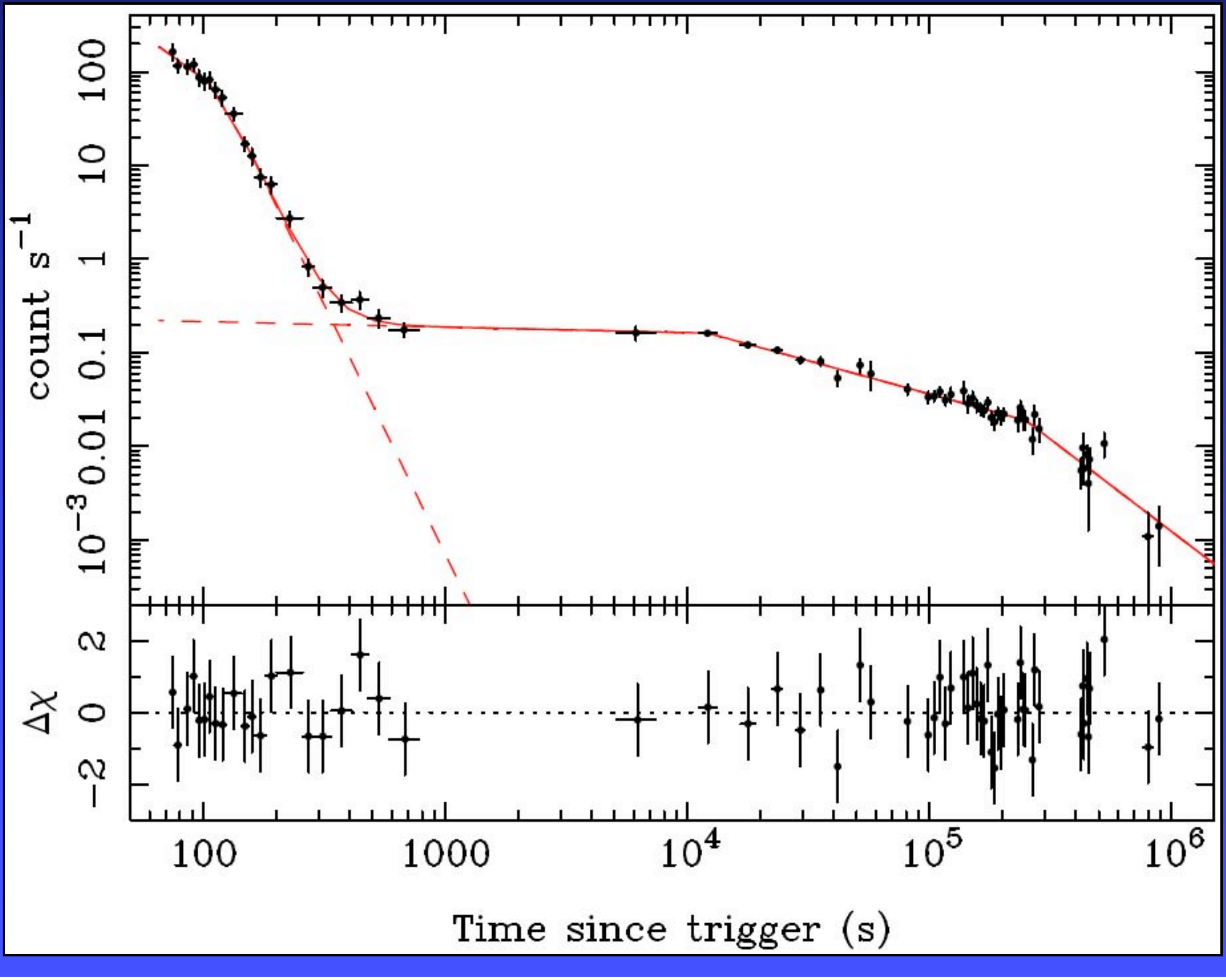
narrow jet: $\Gamma_0 > 100$

observer

$t_{dec} \propto \Gamma_0^{-2(4-k)/(3-4)}$ for $\rho_{ext} \propto r^{-k} \Rightarrow t_{dec,n} \ll t_{dec,w}$

Implications for γ-ray Efficiency

- $\varepsilon_\gamma = E_\gamma/E_0$, $\varepsilon_\gamma/(1-\varepsilon_\gamma) = \kappa f$; $\kappa = E_\gamma/E_k(t)$, $f = E_k(t)/E_{k,0}$
- $\kappa \sim 1$ from the X-ray afterglow flux at $t = 10$ hr

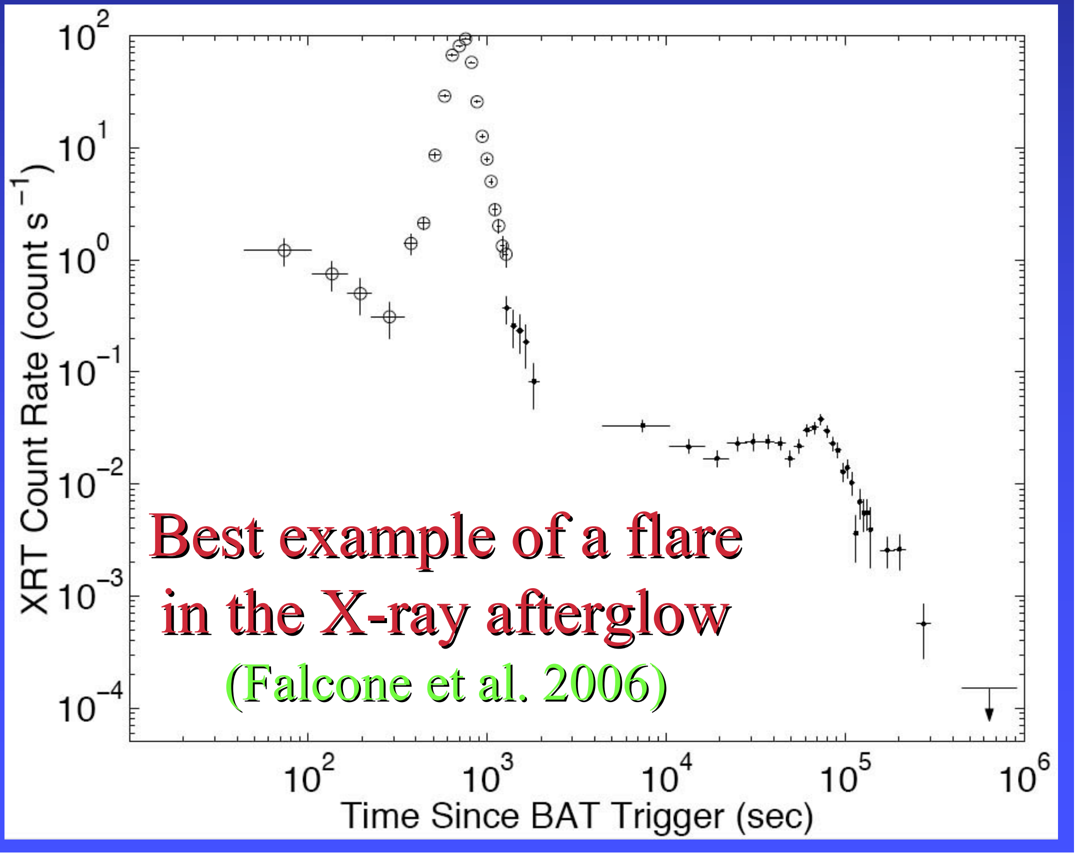


Implications for γ-ray Efficiency

- $\epsilon_\gamma = E_\gamma/E_0$, $\epsilon_\gamma/(1-\epsilon_\gamma) = \kappa f$; $\kappa = E_\gamma/E_k(t)$, $f = E_k(t)/E_{k,0}$
- $\kappa \sim 1$ from the X-ray afterglow flux at $t = 10$ hr
- $f \gtrsim 10$ if flat decay is **energy injection**: $\boldsymbol{\epsilon_\gamma \gtrsim 0.9}$
- If the flat decay phase is due to an increase in the afterglow efficiency then $f \sim 1$ & $\epsilon_\gamma \sim 0.5$
- If also $E_k(t = 10\ \mathrm{hr})$ is underestimated (e.g., $\xi_e \sim 0.1$ instead of 1) then possibly $\kappa \sim 0.1$ & $\epsilon_\gamma \sim 0.1$
- ⇒ a typical afterglow kinetic energy $\gtrsim 10^{52}$ erg ($\gtrsim 10^{53}$ erg) for a uniform (structured) jet
- **GLAST** might find a larger $\mathbf{E_\gamma}$ ⇒ higher $\boldsymbol{\epsilon_\gamma}$
- Models differ in **GLAST** range (SSC componet)

X-ray Flares

- Temporal & spectral properties similar to prompt GRB
- The emission site & mechanism is similarly uncertain
- **GLAST** observations can help solve such questions (SSC component, opacity effects)



Best example of a flare in the X-ray afterglow

(Falcone et al. 2006)

Pair Opacity: Time Dependence

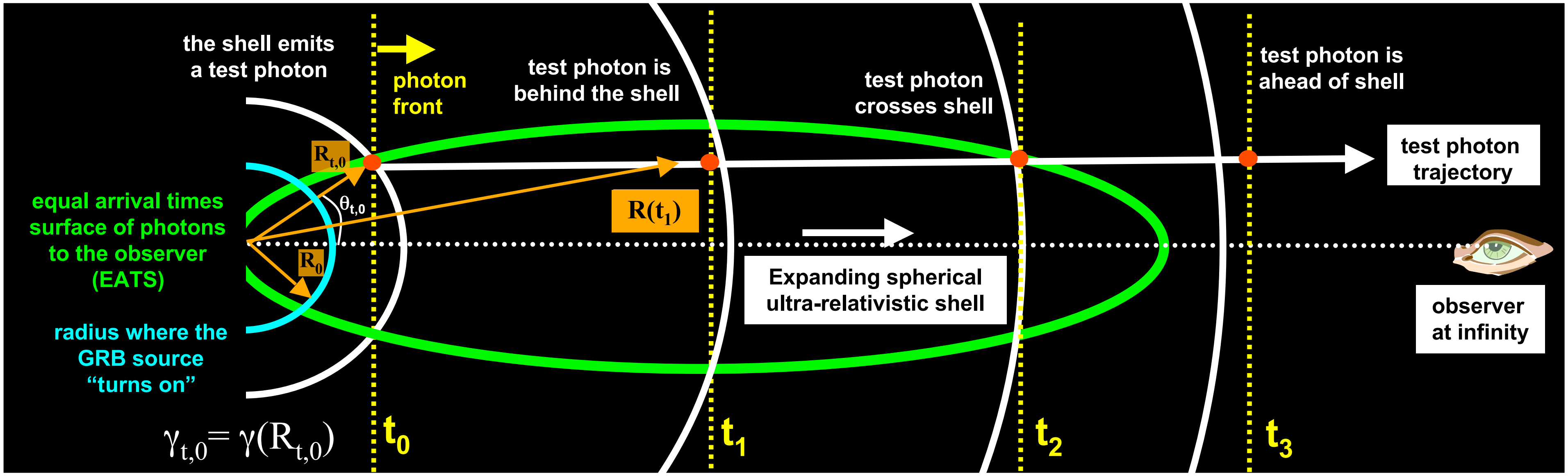
work in progress, with J. Cohen-Tanugi & E. do Couto e Silva

- Above some photon energy ε_1, $\tau_{\gamma\gamma} > 1$ at the source & the spectrum cuts off exponentially
- Lack of such a cutoff up to an observed photon energy $\varepsilon_{max} \Rightarrow \gamma \gtrsim 100[L_{0,52}(\varepsilon_{max})^{\alpha}/R_{13}]^{1/2(1+\alpha)}$ where $\varepsilon = E_{ph}/m_ec^2$, $L_\varepsilon = L_0\varepsilon^{-\alpha}$
- In some models the emission is impulsive (e.g. internal shocks), rather than quasi-steady state
- Initially there is no photon field & the opacity builds-up with time $\Rightarrow$ even $\varepsilon > \varepsilon_1$(steady state) photons can initially escape, as long as $\varepsilon_1(t) > \varepsilon$
- $\Rightarrow$ a distinct temporal & spectral signature

Simple (yet rich) Semi-Analytic Model

- Ultra-relativistic ($\gamma \gg 1$) spherical thin ($\Delta \ll R/\gamma^2$) shell emits in a finite interval $R_0 \leq R \leq R_0 + \Delta R$
- Isotropic emission in the shell co-moving frame
- For simplicity $\gamma^2 \propto R^{-m}$, $L'_{\varepsilon'} \propto (\varepsilon')^{-\alpha} R^b$ is assumed while the formalism is more general
- The thin shell approximation is valid for GRB internal shocks (fast cooling: thin cooling layer)
- The photon field is calculated at all space & time
- The pair-production optical depth is integrated along the trajectory of each photon

Calculating the $\gamma\gamma \rightarrow e^+e^-$ Optical Depth



$$\boxed{\tau_{\gamma\gamma}(R_{t,0},\theta_{t,0},\varepsilon_t) = \tau_0(R_{t,0},\varepsilon_t)\cdot F(\gamma_{t,0}\theta_{t,0})}$$

$F(\gamma_{t,0}\theta_{t,0})$ is a double integral on the positions of the two photons, after several changes of variables

$$\boxed{\tau_{\gamma\gamma}(R_{t,0},\theta_{t,0},\varepsilon_t) = \int ds \int d\varepsilon_i \int d\Omega_i \sigma^*\left[\chi(\varepsilon_t,\varepsilon_i,\mu_{t,i})\right](1-\mu_{t,i})\frac{dn_i}{d\varepsilon_i d\Omega_i}}$$

s = path length along test photon trajectory

$\theta_{t,0}$ = initial angle between the test photon direction and the radial direction

$\mu_{t,i}$ = cosine of the angle between the directions of the two photons

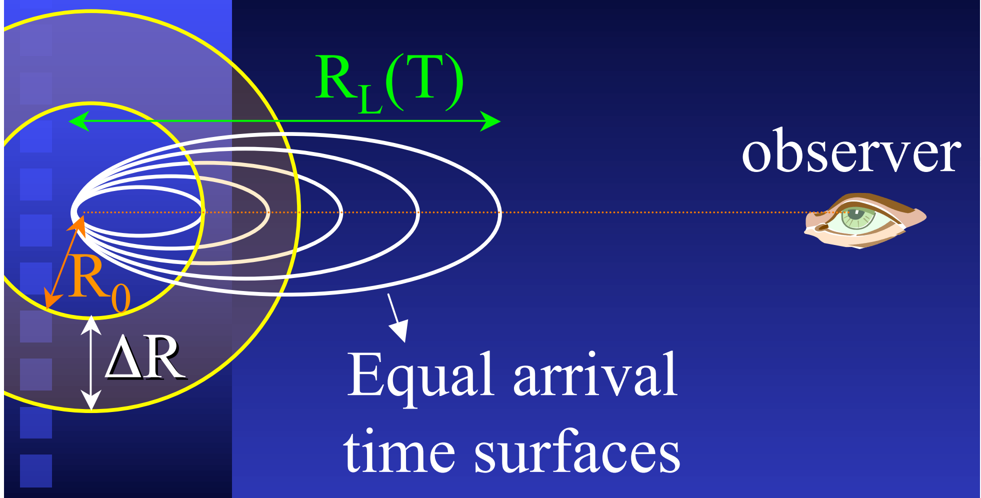
χ = center of momentum energy of photons in units of $m_e c^2$

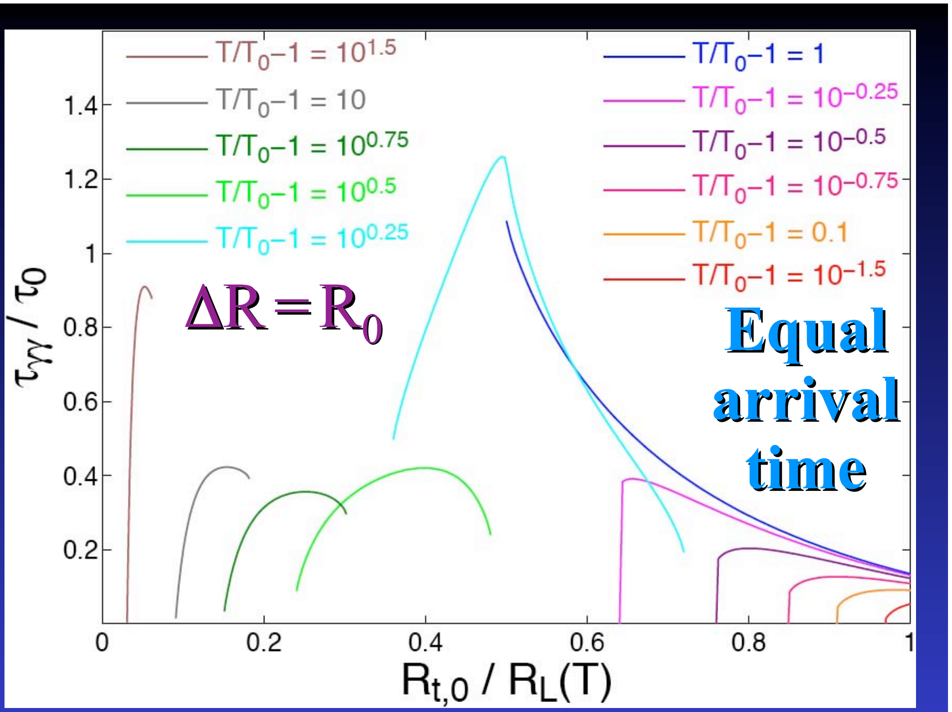
Ω_i = solid angle of the photons that can potentially interact with the test photon

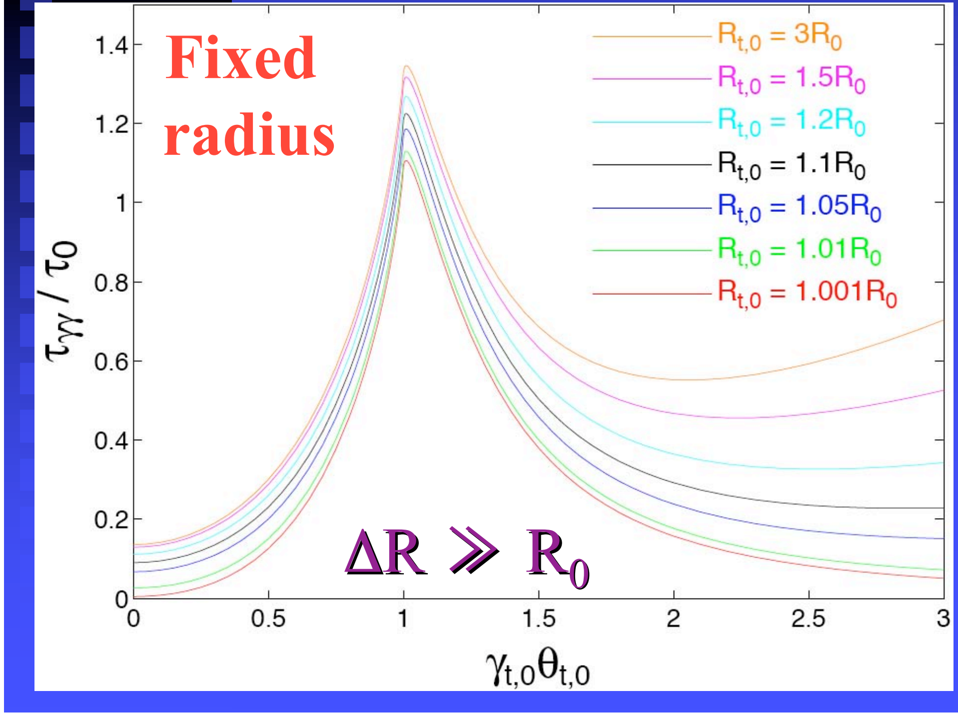
n_i = number density of these photons

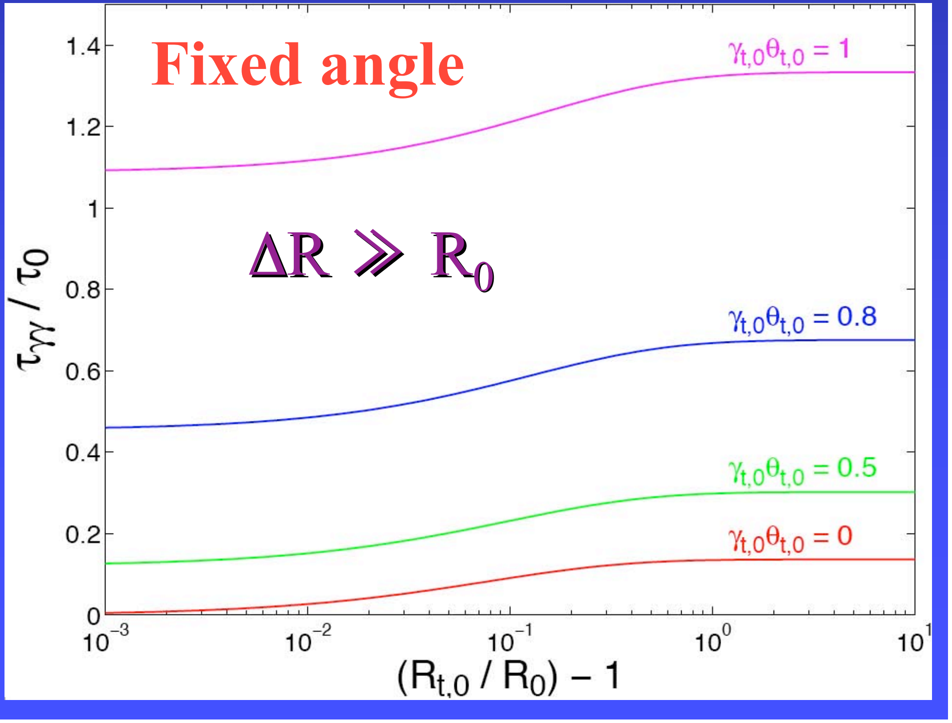
σ^* = the cross section for pair production

Results: optical depth



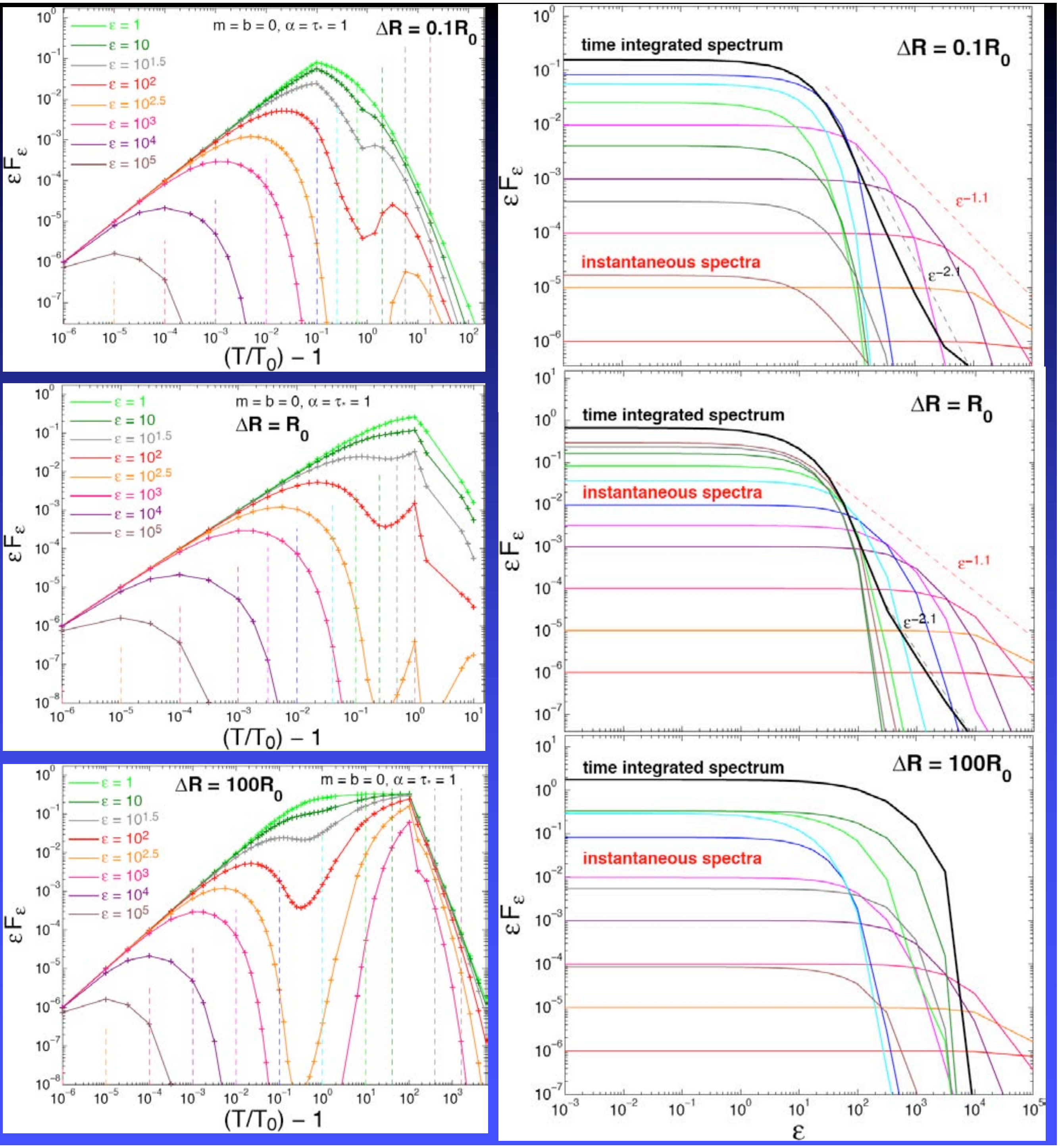






Light Curves & Spectra

The power law tail is more pronounced for larger ΔR / R_0



Conclusions:

- High energy spectral components in the **GLAST** range may help pin down the origin of the early shallow decay phase, as well as the emission mechanism in the prompt GRB & X-ray flares
- Opacity build-up in impulsive relativistic sources
  - **Power law high-energy tail** instead of the exponential cutoff in steady state models
  - Photons above the spectral break would arrive mainly near the onset of spikes in light curve