The Flat Decay Phase in the Early X-ray Afterglows of Swift GRBs

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Includes work from the papers:

- Granot, Königl & Piran 2006 (astro-ph/0601056)
- Granot & Kumar 2006, MNRAS, 366, L13-L16
- Eichler & Granot 2006, ApJ, 641, L5-L8
- Nousek et al. 2006, ApJ, 642, 389-400

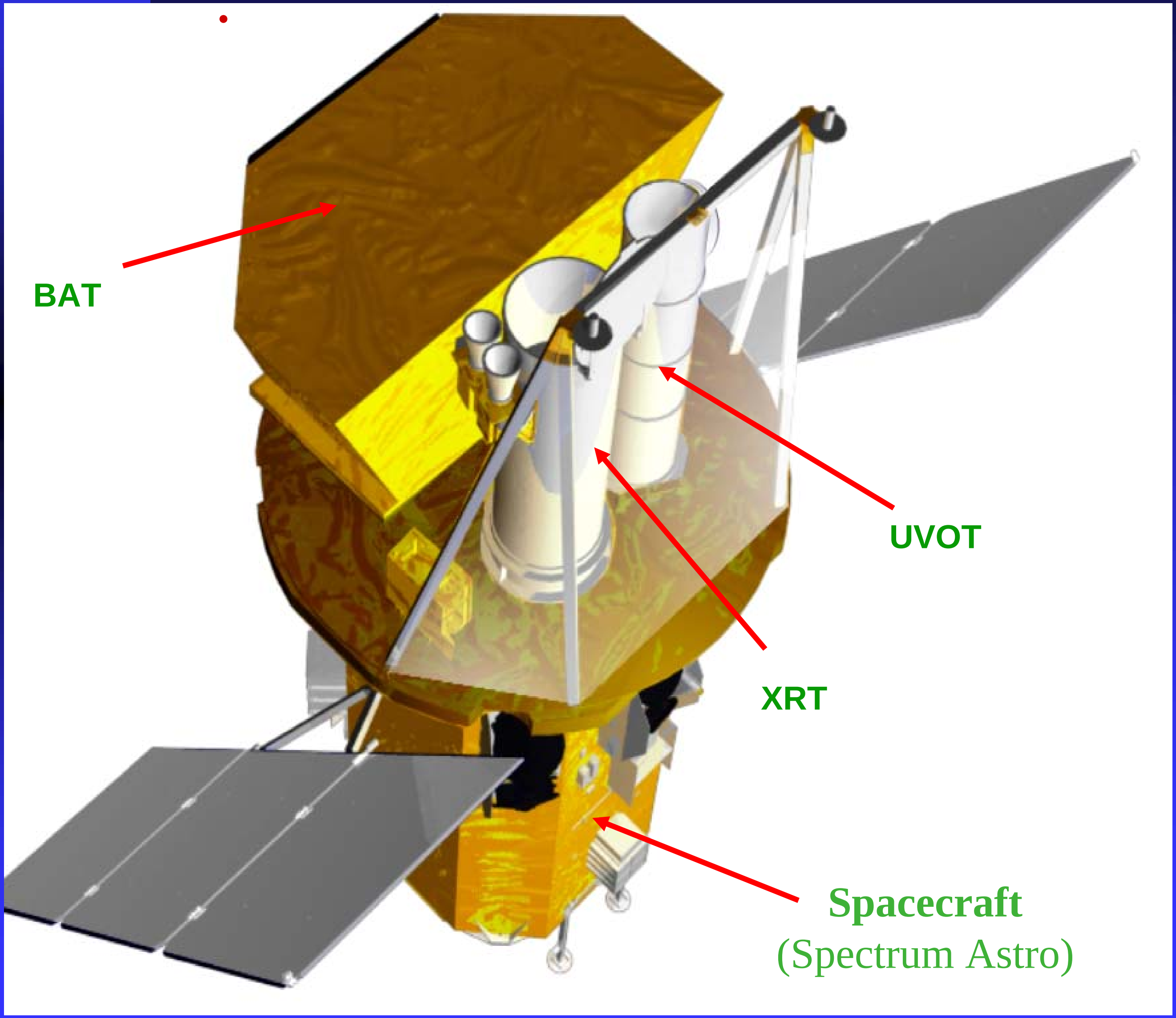
GLAST Lunch Seminar, May 25, 2006, SLAC

Outline of the Talk:

- Short description of Swift & its main findings
- Swift finds a flat decay phase in the early X-ray afterglow of many GRBs: $F_X <$ was expected
- Possible Explanations:
  - Energy injection into the afterglow shock
  - viewing angle slightly outside emitting region
  - Afterglow efficiency increases with time
  - A two component jet model
- Possible implications:
  - The efficiency of the gamma-ray emission
  - The kinetic energy in the afterglow shock
- **Conclusions**

Swift Observatory

launched: November 20, 2004



Orbit

600 km x 28˚ inclination

Data Downlinks

TDRSS rapid (2 kbps)
ASI Malindi gnd station

Operations

Ops Center @ Penn State
Science Center @ GSFC

BAT

New CdZnTe detector
~100 GRBs/yr

XRT

Arcsec GRB positions
CCD spectroscopy

UVOT

Sub-arcsec positions
Grism spectroscopy

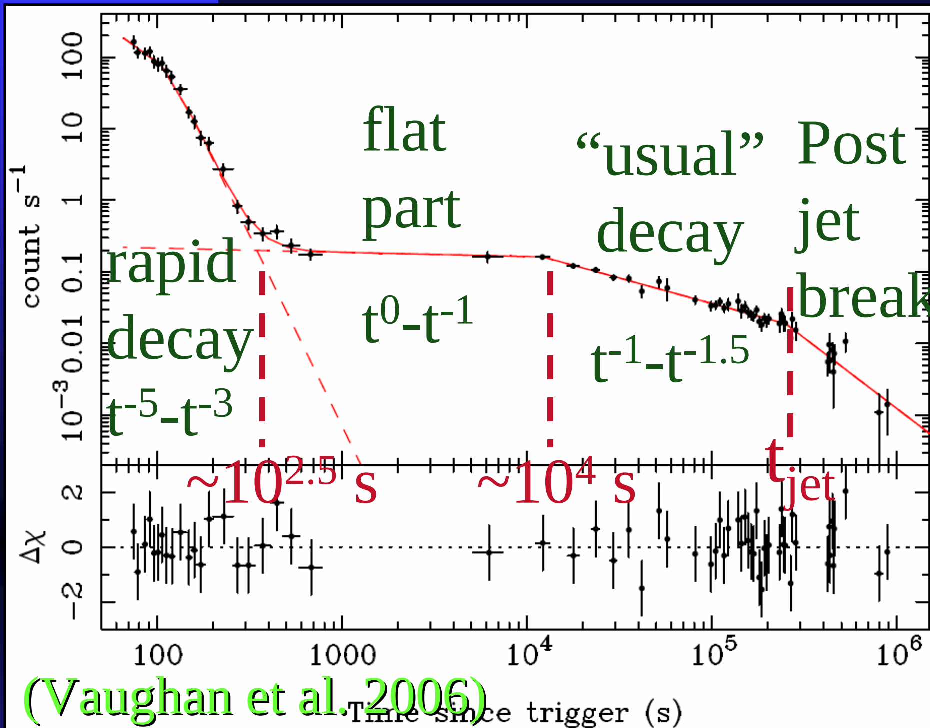
Spacecraft

Autonomous slews 20-75s

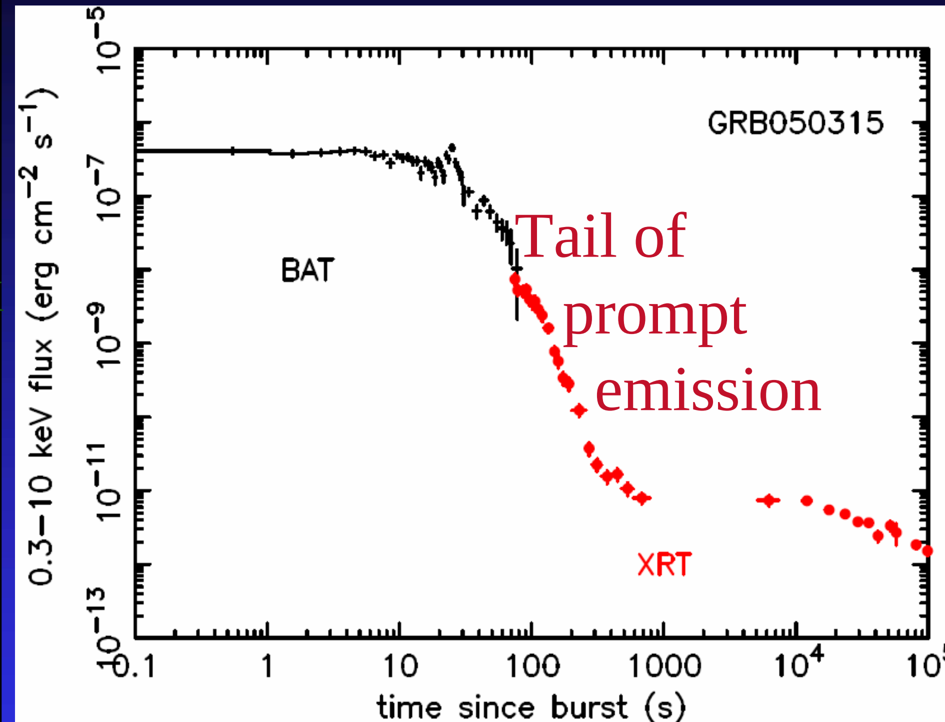
Swift's Main Discoveries so far:

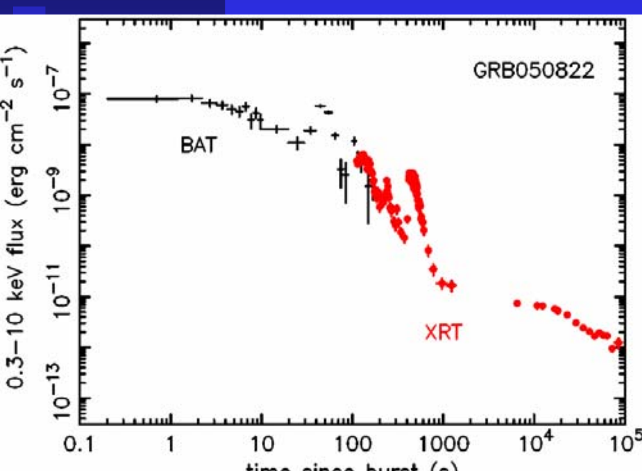
- Short-hard GRBs
  - First detection of their afterglows
  - redshifts ($z \sim 0.2$-0.7) $\Rightarrow$ energy & event rate
  - Host galaxies (different from long-soft GRBs)
  - Constraints on contemporaneous supernova
- Early afterglow emission
  - Flat decay phase in many X-ray light curves
  - X-ray flares in many cases
  - Dim early optical emission (reverse shock)
- GRBs at high redshifts ($z = 6.29$) $\Rightarrow$ cosmology
- Resolved rise time of SGR 1806-20 giant flare

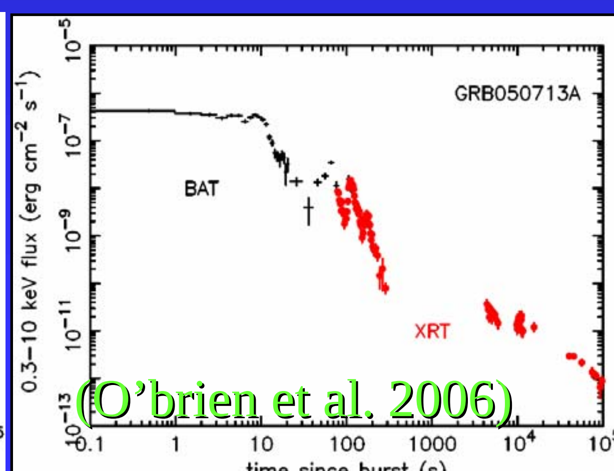
Early X-ray Afterglows from Swift:



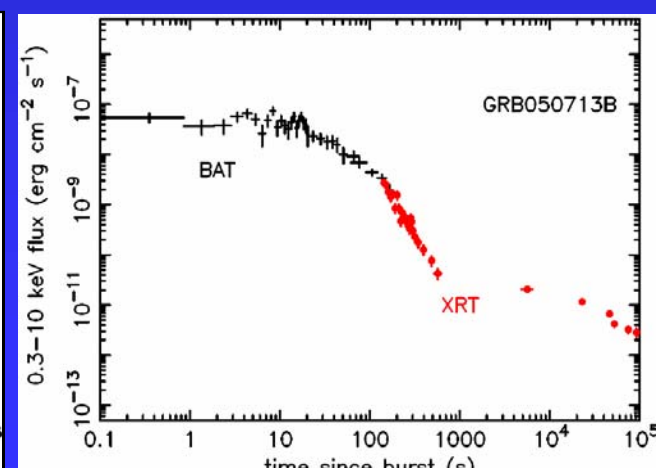
(Vaughan et al. 2006)





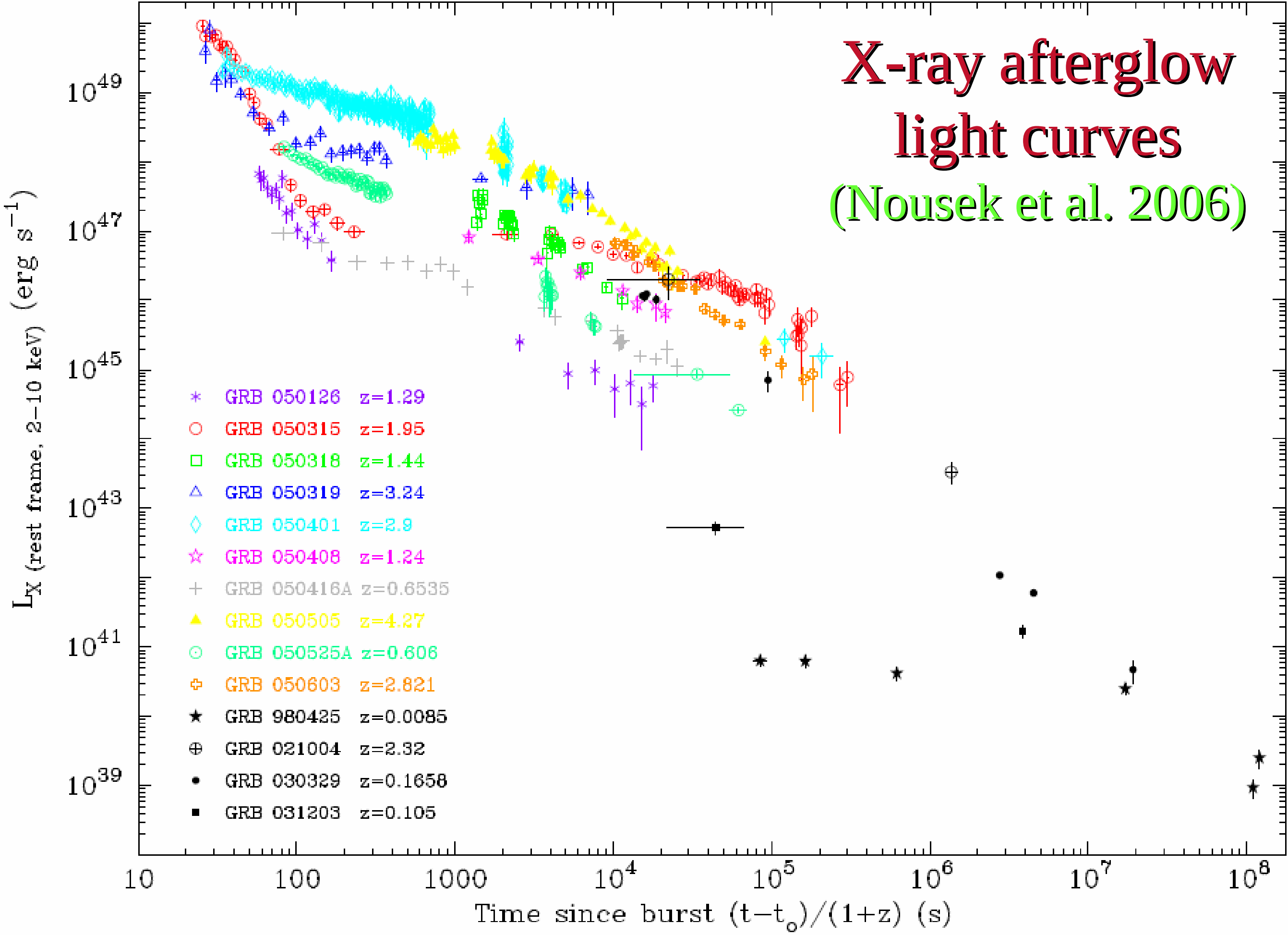


(O'brien et al. 2006)



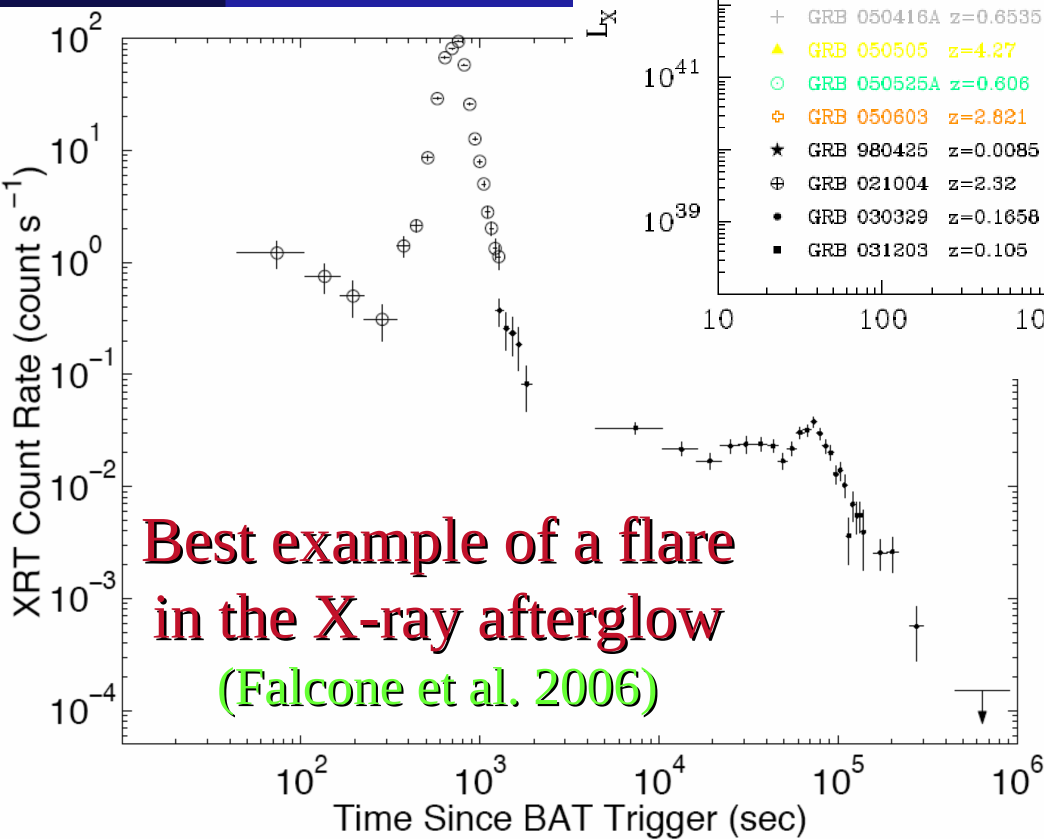
X-ray afterglow light curves

(Nousek et al. 2006)



Best example of a flare in the X-ray afterglow

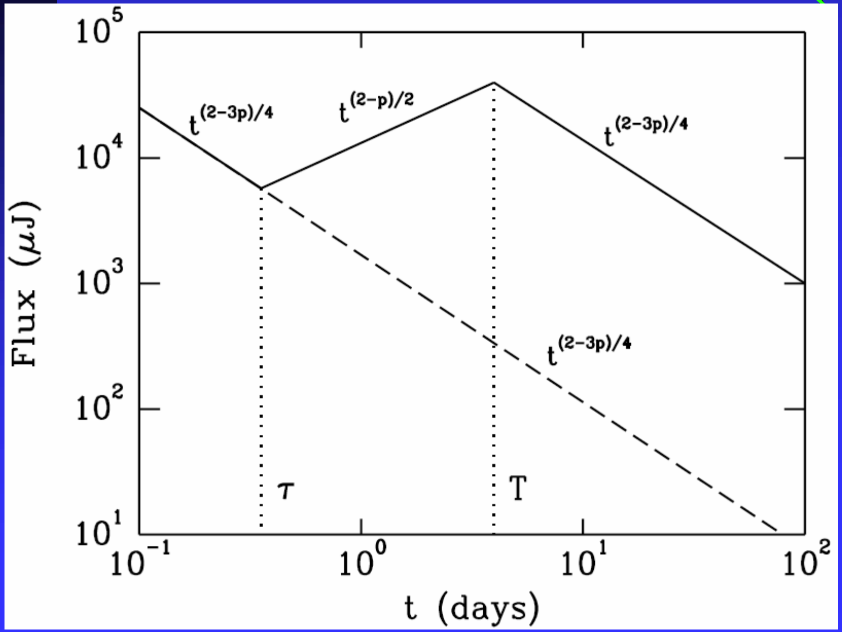
(Falcone et al. 2006)

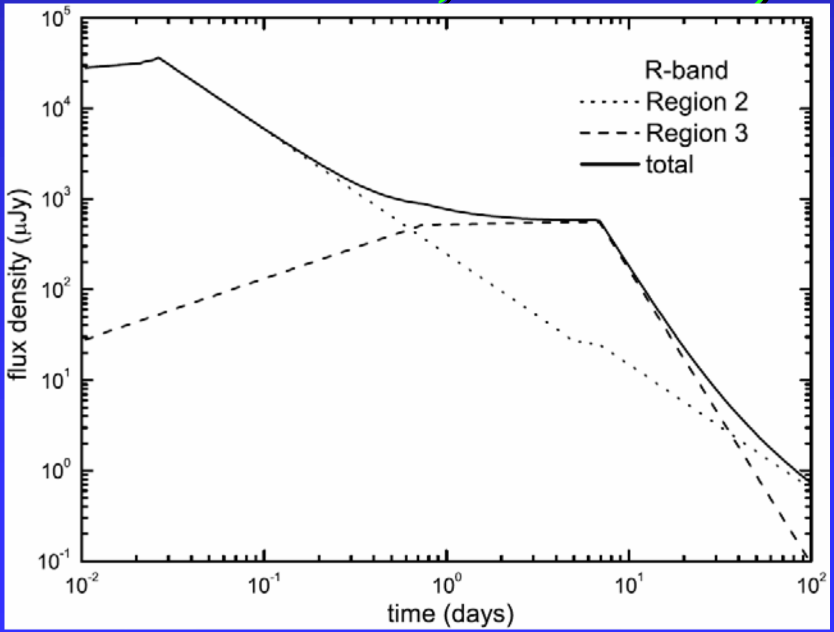


Possible Explanations for Early Flat Decay

1. Energy Injection into the Afterglow Shock

- **Type I**: continuous relativistic wind:
  - The source must remain active for up to a few hours with $L \propto \sim t^{-0.5}$
  - might be possible for a magnetar (Usov 1992) where $L \propto t^{0} \rightarrow t^{-2}$ (Dai & Lu 1998; Dai 2004)





- The magnetar model is able to reproduce the right energy scale and time scale

$$E \approx 5\times10^{52}\left(\frac{\Omega}{10^{4}\,\mathrm{s}^{-1}}\right)^{2}\mathrm{erg}$$

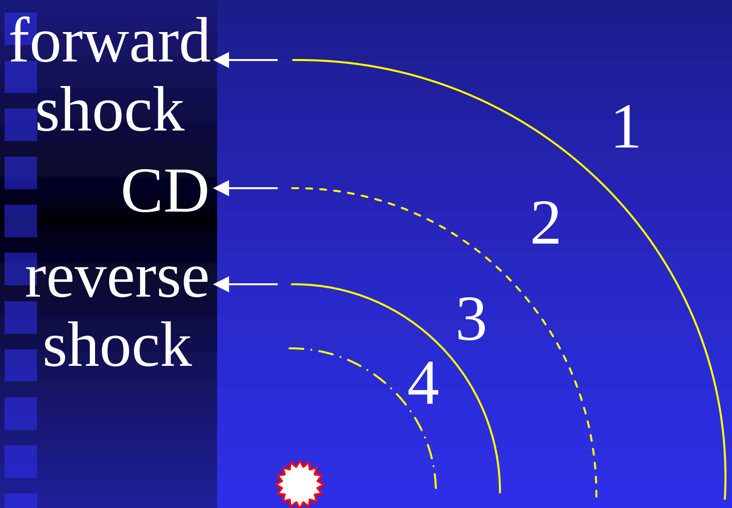
$$\tau \approx 20\left(\frac{\Omega}{10^{4}\,\mathrm{s}^{-1}}\right)^{-2}\left(\frac{B}{3\times10^{15}\,\mathrm{G}}\right)^{-2}\mathrm{s}$$

- It has many potential problems:
  - How to launch a collimated relativistic jet
  - What sets the GRB duration & energy
  - Hard to explain the observed diversity
  - How to avoid collapse into a black hole

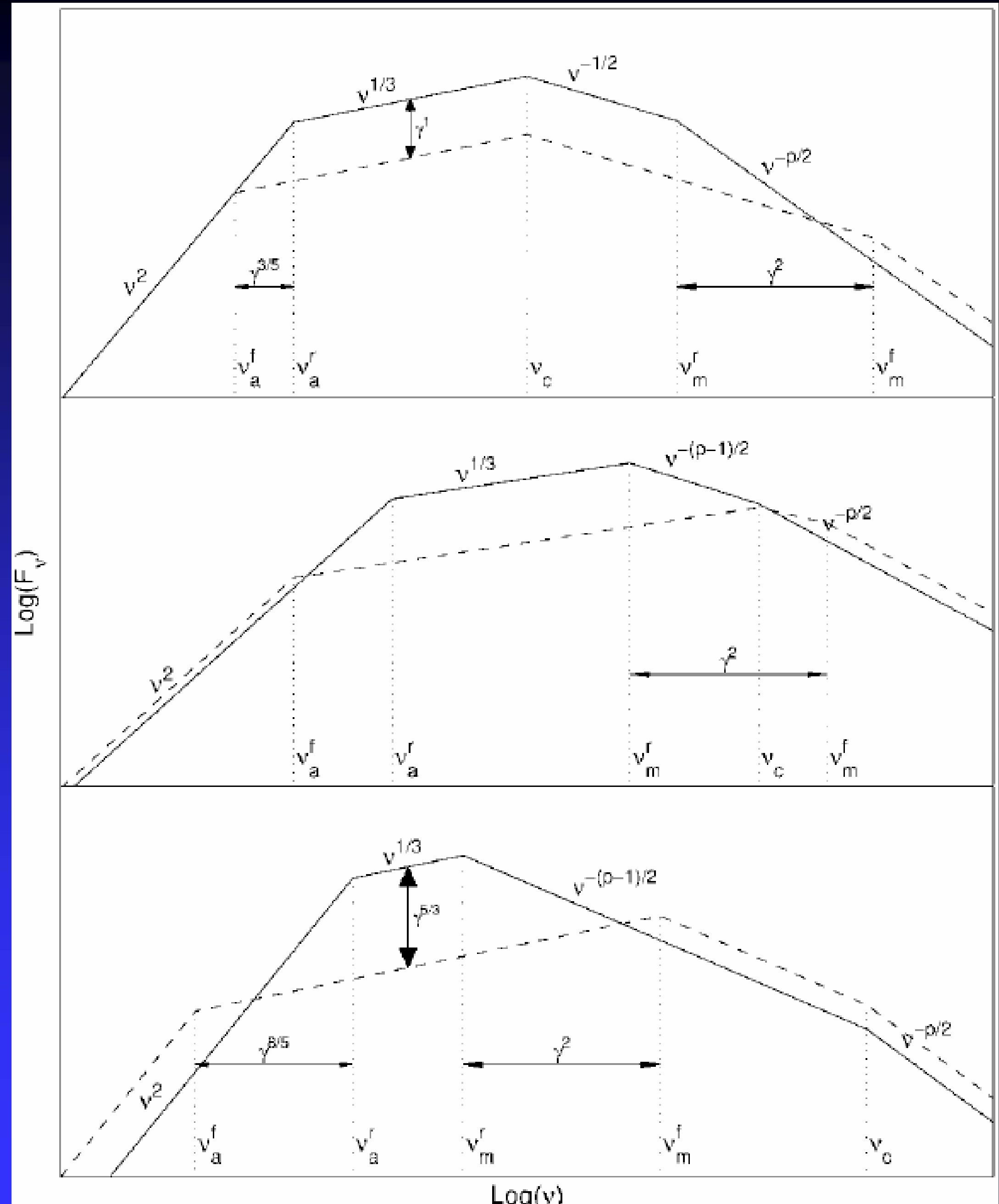
Type II Energy Injection:

- The outflow is ejected within the duration of the GRB (typically tens of seconds)
- It naturally has some spread in Lorentz factors
- The outflow naturally sorts itself out in order of increasing velocity - faster ahead of slower
- Slower outflow takes longer to catch up with the afterglow shock & deposit its energy
- $\Rightarrow$ gradual energy injection (Sari & Mészáros '00) until the slower outflow that carries most of the energy catches up with the afterglow shock

- has predictions for the evolution of the broad band spectrum & the light curves



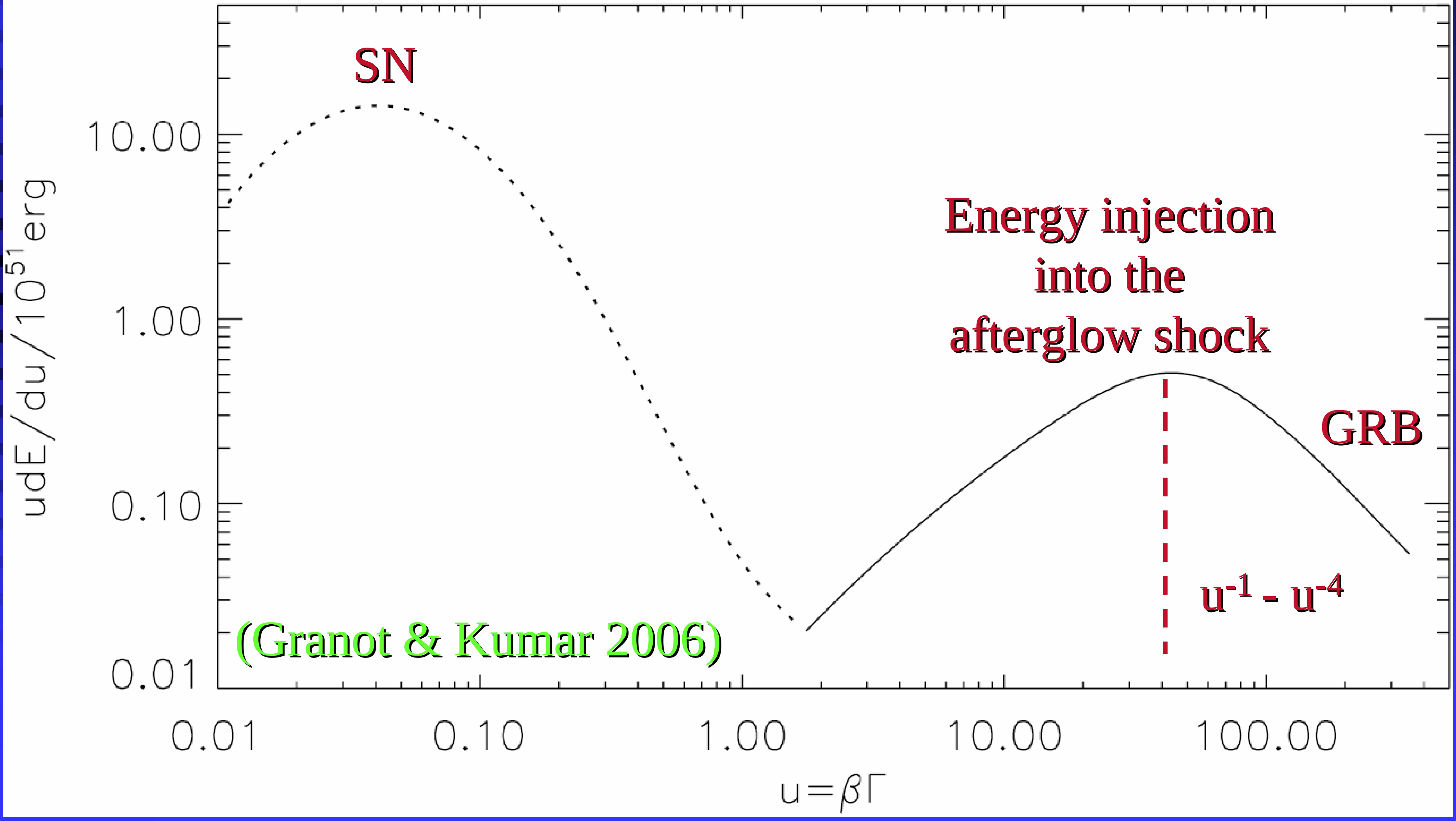
1. Unperturbed ext. medium
2. Shocked external medium
3. Shocked ejecta
4. Freely expanding ejecta



(Sari & Mészáros 2000)

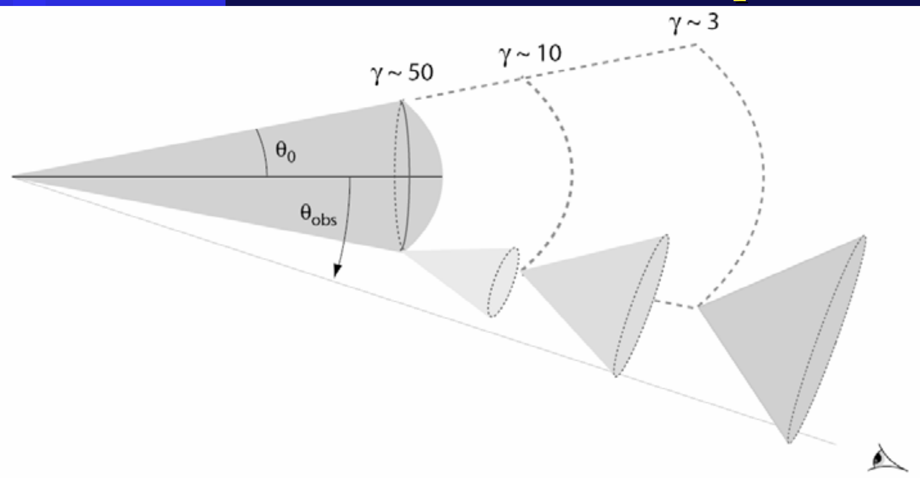
Implications of Type II Energy Injection:

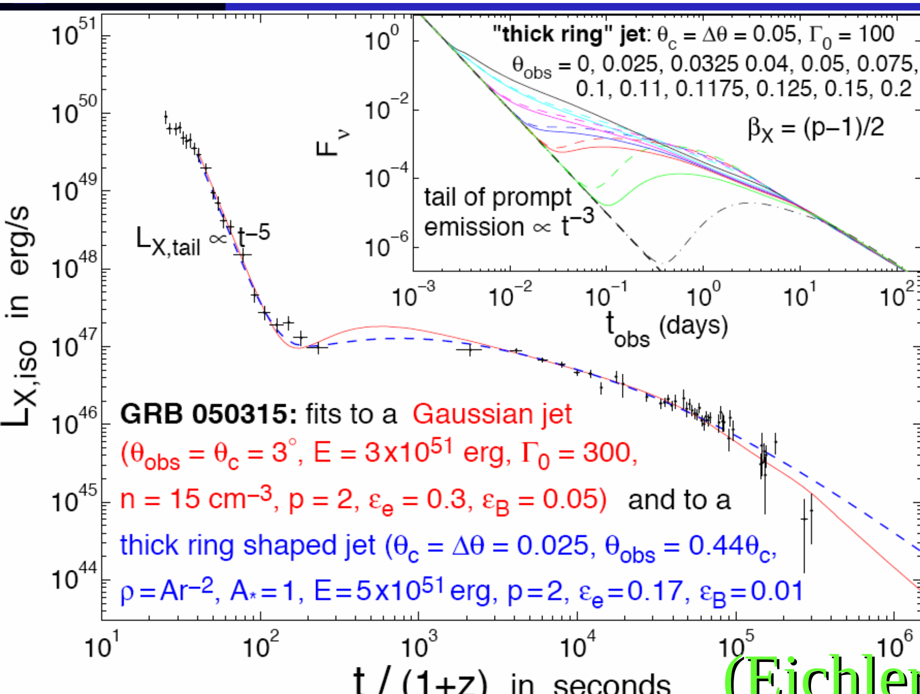
Distribution of energy with ejecta 4-velocity

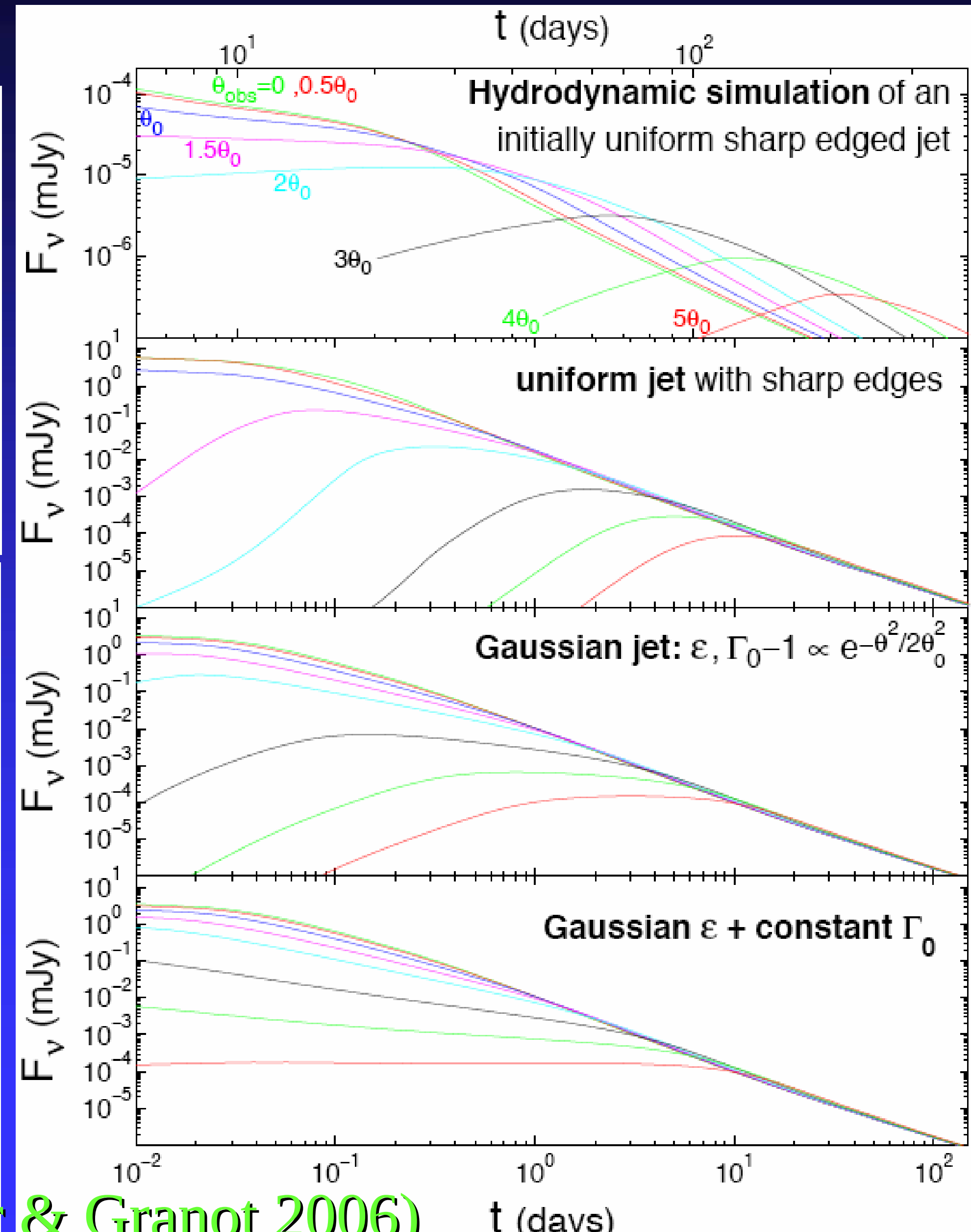


2. Viewing angle outside the emitting region

- Smaller F, f, E_{peak}?







(Eichler & Granot 2006)

Implications of viewing angle interpretation:

- If the regions of prominent **gamma-ray** and **afterglow** emission **coincide**, then a smaller typical photon energy, fluence and peak flux are expected: X-ray flashes (Yamazaki et al. '02, 03, 04)
- This does **not show up** in the **data**: it might suggest that **these two regions do not coincide**
- Along some lines of sight there is a bright gamma-ray emission but dim afterglow emission ⇒ high gamma-ray efficiency and/or low afterglow efficiency

3. Increase in afterglow Efficiency:

(Granot, Königl & Piran 2006)

- The energy in the afterglow shock is constant
- The emission is from along our line of sight
- The afterglow efficiency initially increases with time, due to a change in one or more of:
  - ε_e = fraction of energy in relativistic electrons
  - ε_B = fraction of energy in the magnetic field
  - ξ_e = fraction of electrons that are relativistic
- The shock microphysics parameters eventually saturate at some asymptotic values
- This may have interesting implications for relativistic collisionless shocks

Inferring the Kinetic Energy:

$$F_{\nu>\max(\nu_m,\nu_c)} \propto \xi_e^{2-p}(1+Y)^{-1}\varepsilon_e^{p-1}\varepsilon_B^{(p-2)/4}E_{k,iso}^{(p+2)/4}t^{(2-3p)/4}\nu^{-p/2}$$

$$E_{k,iso} \propto \xi_e^{4(p-2)/(p+2)}(1+Y)^{4/(p+2)}\varepsilon_e^{-4(p-1)/(p+2)}\varepsilon_B^{-(p-2)/(p+2)}$$

- Flux independent of external density ($\nu > \nu_m,\nu_c$)
- Weak dependence on ε_B which is very uncertain
- $E_{k,iso}$ inferred from F_X(10hr) pre-*Swift* (for $\xi_e=1$)

Problems with this method:

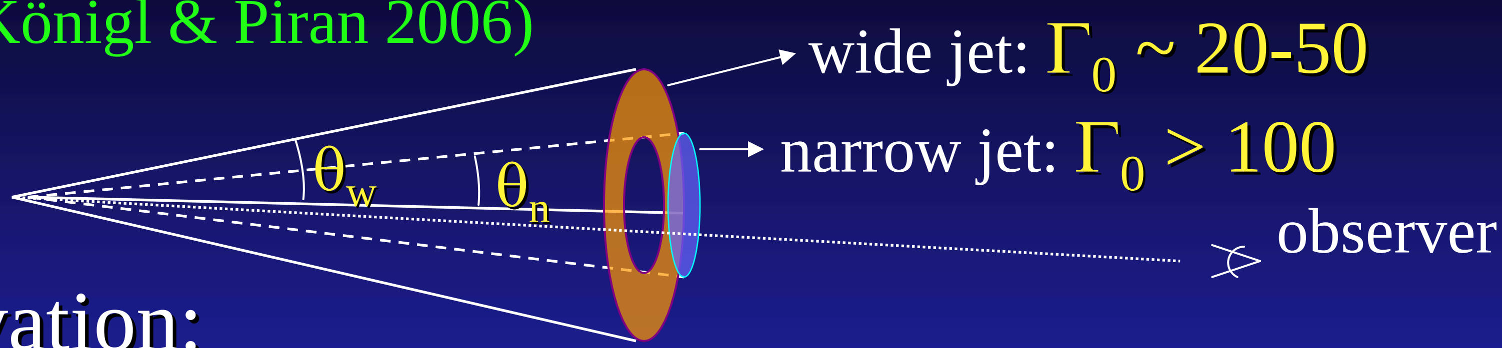
- Typically $\varepsilon_B \ll \varepsilon_e \Rightarrow (1+Y) \sim (\varepsilon_e/\varepsilon_B)^{1/2}$, $F_\nu \propto (\varepsilon_e)^{-2(2p-3)/(p+2)}(\varepsilon_B)^{-p/(p+2)}$ (larger ε-dependence)
- There is a degeneracy: the observed F_ν is not effected by $(E,n) \rightarrow (E,n)/\xi_e$, $(\varepsilon_e,\varepsilon_B) \rightarrow \xi_e(\varepsilon_e,\varepsilon_B)$ for $m_e/m_p < \xi_e \leq 1$ (Eichler & Waxman 2005)

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
- $f \gtrsim 10$ if the early flat decay phase is interpreted as energy injection into afterglow shock: $\varepsilon_\gamma \gtrsim 0.9$
- Such high efficiencies are very hard to produce
- If the flat decay phase is due to an increase in the afterglow efficiency then $f \sim 1$ & $\varepsilon_\gamma \sim 0.5$
- If also $E_k(t = 10\ \mathrm{hr})$ is underestimated (e.g., $\xi_e \sim 0.1$ instead of 1) then possibly $\kappa \sim 0.1$ & $\varepsilon_\gamma \sim 0.1$
- ⇒ a typical afterglow kinetic energy $\gtrsim 10^{52}$ erg ($\gtrsim 10^{53}$ erg) for a uniform (structured) jet

4. A Two Component Jet:

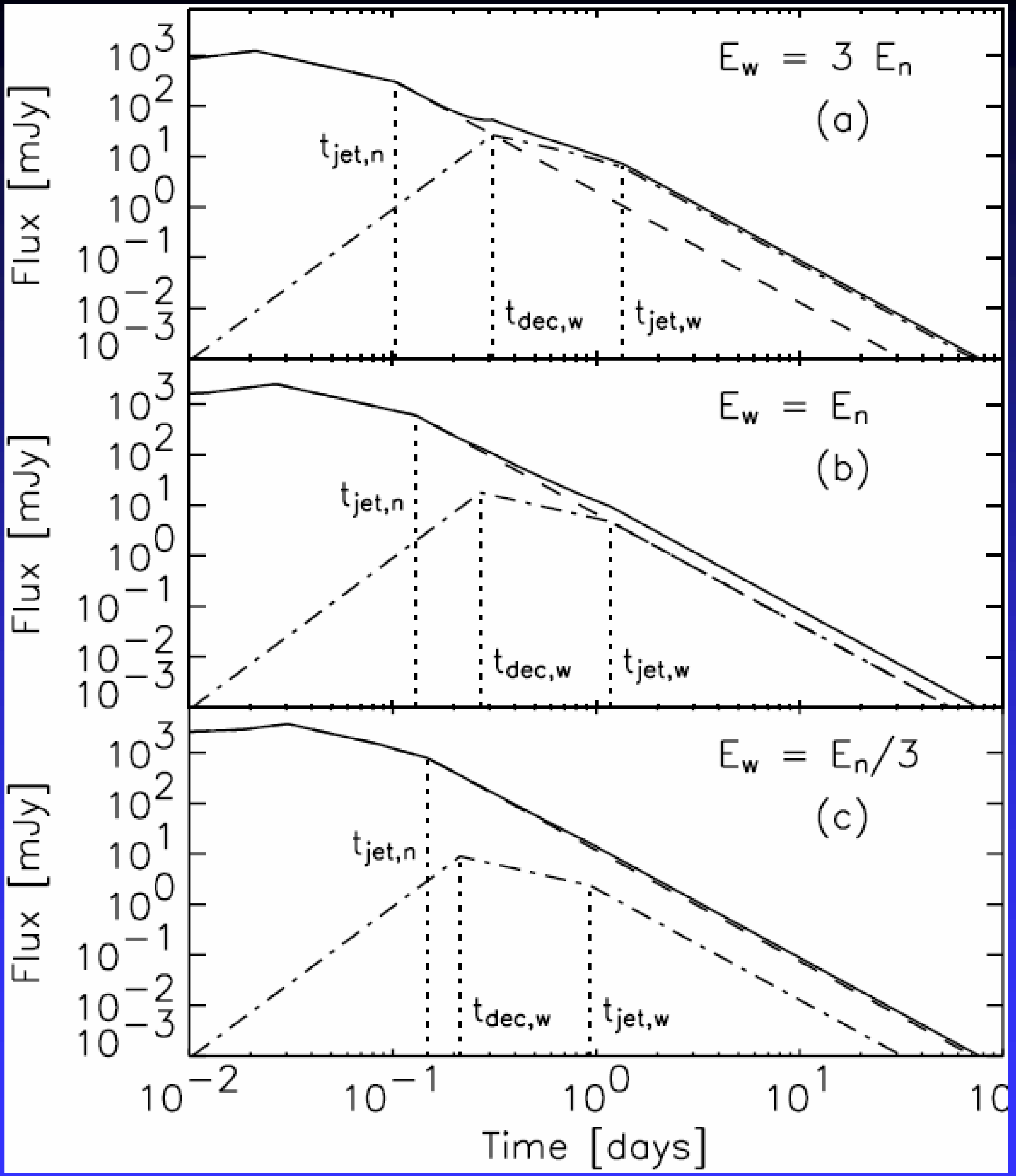
(Granot, Königl & Piran 2006)



- Motivation:
  - In the collapsar model the wide jet is produced by the cocoon (Ramirez-Ruiz et al. 2002)
  - Neutron decoupling in a hydromagnetically driven neutron rich jet (Vlahakis et al. 2003)
- $t_{dec} \propto \Gamma_0^{-2(4-k)/(3-4)}$ for $\rho_{ext} \propto r^{-k} \Rightarrow t_{dec,n} \ll t_{dec,w}$
- $E_{iso,w} < E_{iso,n}$ & $E_w > E_n \Rightarrow$ lowers the required γ-ray efficiency ε_γ (Peng, Königl & Granot 2005)

Afterglow light curves for a two component jet:

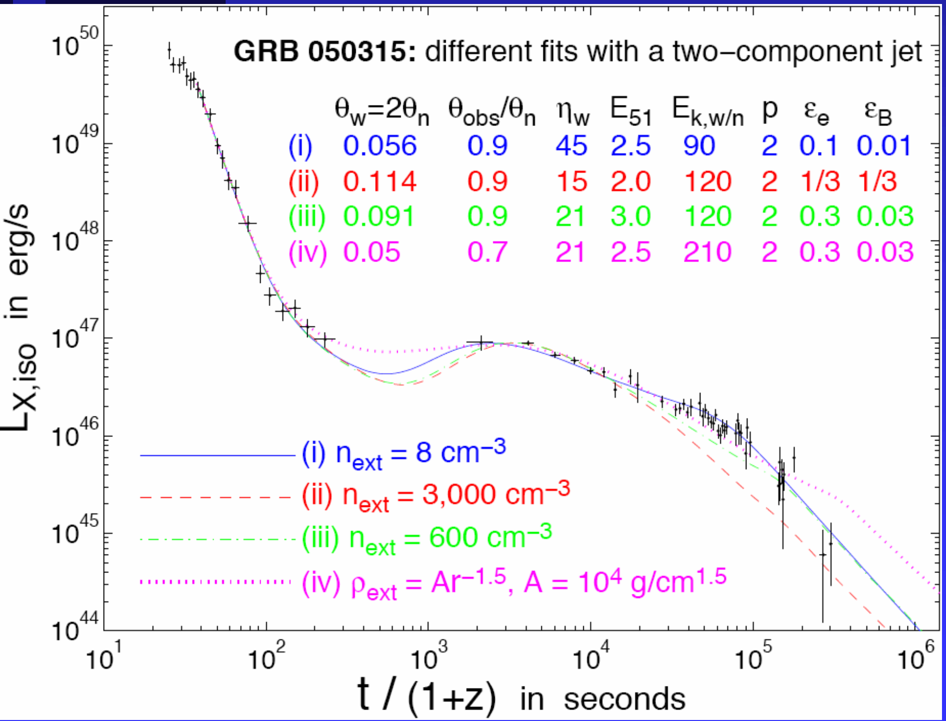
- $E_w > E_n$ is required for the wide jet to dominate the flux at late times
- $E_{iso,w} < E_{iso,n}$ is in order to lower the required ε_γ

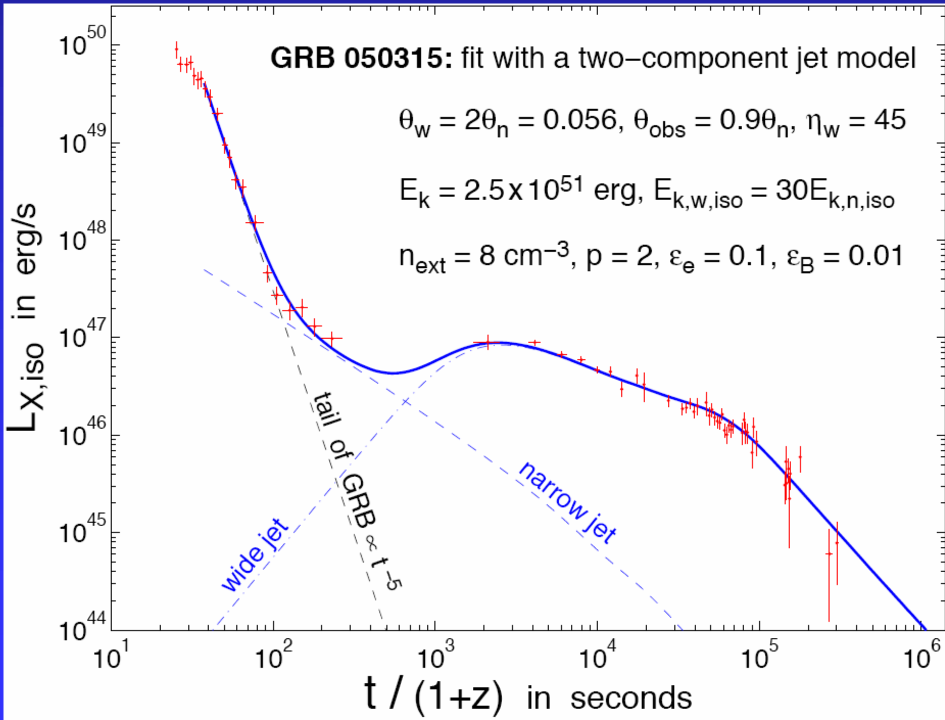


(Peng, Königl & Granot 2005)

Two component jet: Explaining the flat decay

- The X-ray afterglow of GRB 050315 requires that $f = E_{iso,w}/E_{iso,n} \gtrsim 30$ and more generally $f > 1$ so that the required gamma-ray efficiency is not lowered
- $E_w/E_n \gtrsim 100$ is challenging for theoretical models

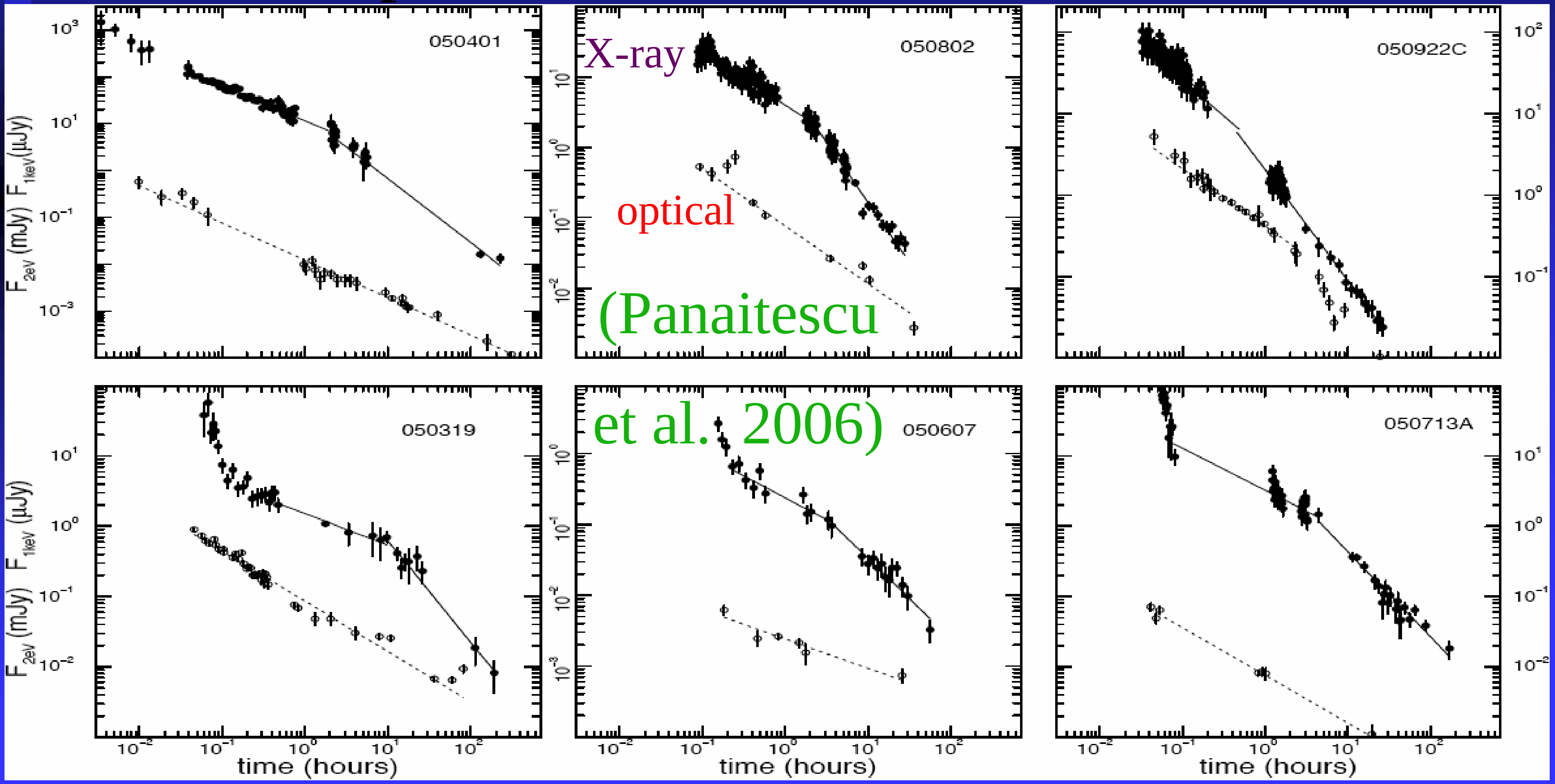




(Granot, Königl & Piran 2006)

Simultaneous Optical light curves

- The optical light curves do not show a similar flat decay phase or a similar steepening at its end
- This is problematic for most models



Conclusions:

- There are different possible explanations for the early flat decay phase in the X-ray afterglows
- the different explanations may potentially be distinguished via multi-wavelength observations
- There are potentially interesting implications for
  - The gamma-ray efficiency
  - The afterglow kinetic energy
  - Collisionless relativistic shocks
- A lot of work still remain to be done