Afterglow physics and observations

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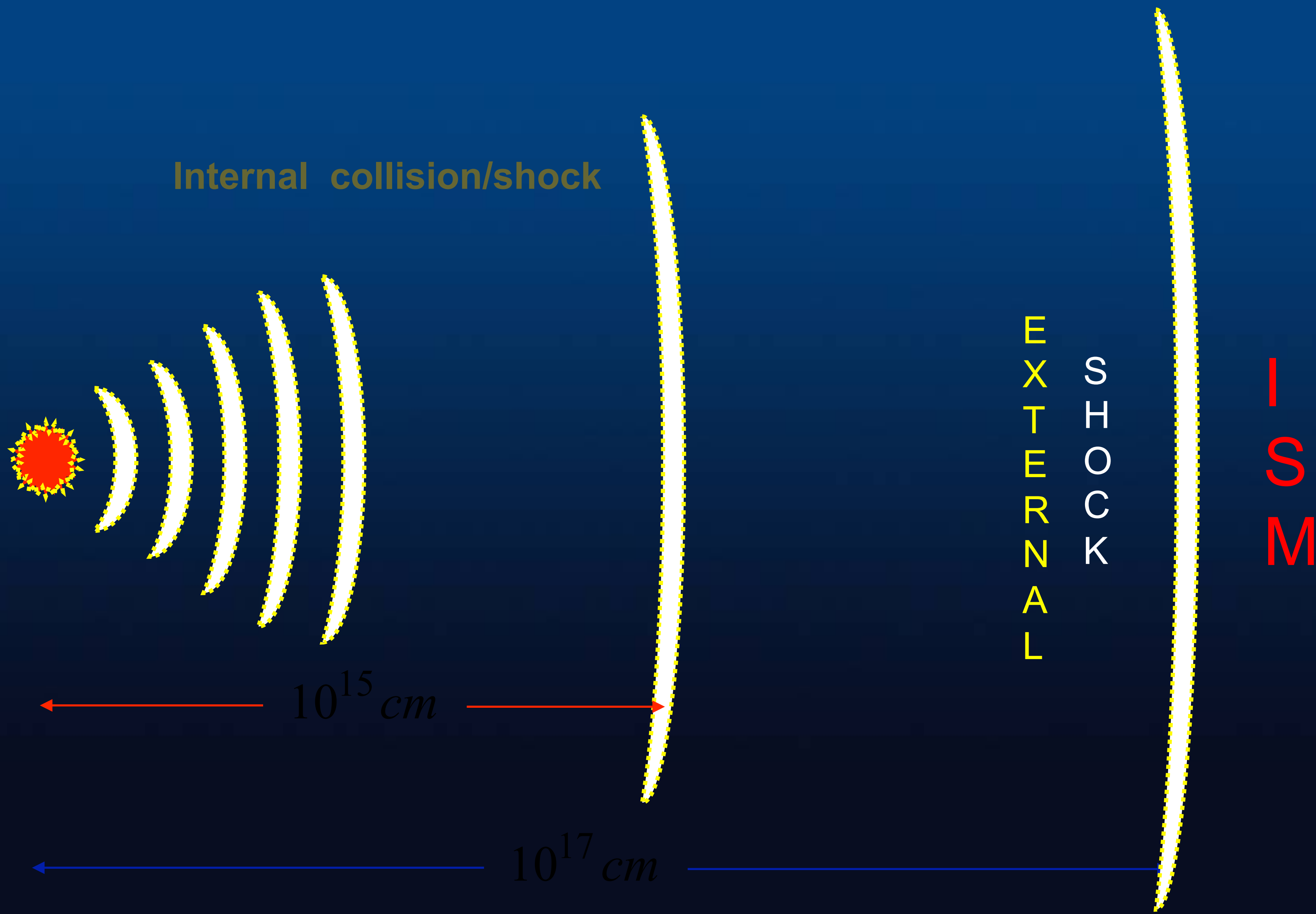
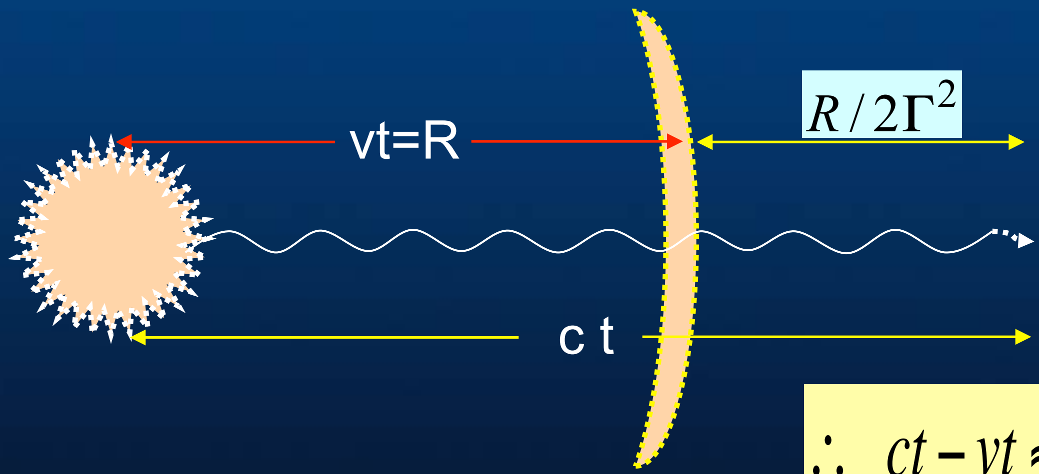
Pune, July 5, 2017

Internal-External Shock Model for GRBs



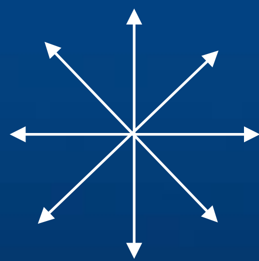
Relation between R and observer time (t_{obs})



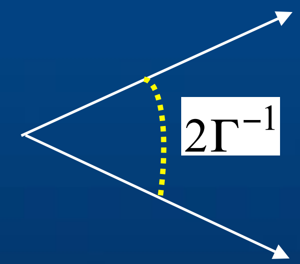
$$\therefore \quad ct - vt \approx ct/2\Gamma^2 \Rightarrow t_{obs} \approx R/(2c\Gamma^2)$$

$$v = c\sqrt{1-\Gamma^{-2}} \approx c(1-1/2\Gamma^2)$$

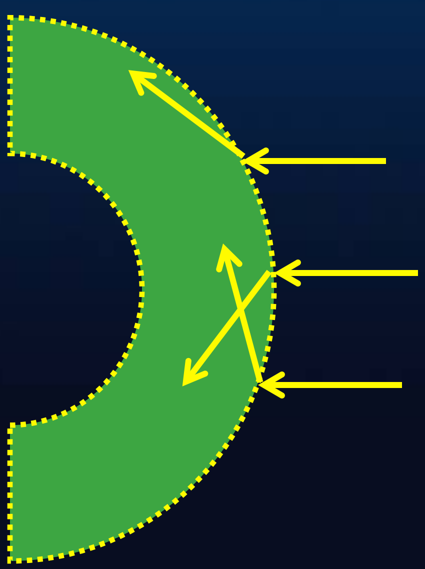
Some Relativistic Effects



$$\Gamma = \left(1 - \frac{v^2}{c^2}\right)^{-1/2}$$



Relativistic shock



Thermal energy per proton (in shock frame) = $m_p c^2 \Gamma$

(In CE frame) = $m_p c^2 \Gamma^2$

Energy conservation implies: $n R^3 m_p c^2 \Gamma^2 = E$

Using: $t_{obs} \approx R/(2c\Gamma^2)$

We find: $\Gamma = \left(\frac{E}{8nc^5 m_p}\right)^{1/8} t^{-3/8}$

External forward shock

LF and Radius:

With the previously derived relations for the LF and radius, we can find:

$$\Gamma \propto t_{obs}^{-3/8} \qquad R \propto t_{obs}^{1/4}$$

Substituting typical parameters for GRBs, we find:

$$\Gamma(t_{obs}) = 10\left(\frac{E_{53}}{n}\right)^{1/8}\left(\frac{t_{obs}}{1day}\right)^{-3/8}(1+z)^{3/8}$$

Deceleration radius (R_d)

This is the radius where roughly half of the explosion energy is imparted to the surrounding medium

$$\frac{4}{3}\pi R_d^3 n m_p c^2 \frac{\Gamma_0^2}{2} \approx \frac{E}{2}$$

← LF at R_d is smaller than Γ_0 by ~$2^{1/2}$

Γ_0 is the initial LF of the GRB jet, i.e. the LF when $r \ll R_d$

External forward shock

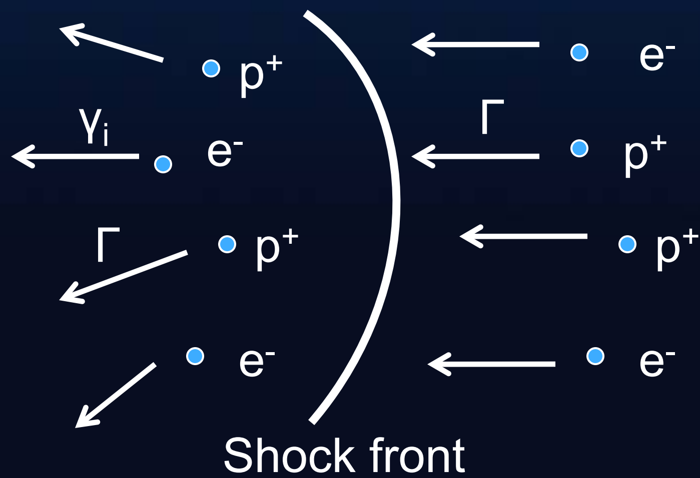
Deceleration radius (R_d)

$$\therefore R_d = \left[\frac{3}{4\pi}\frac{E}{nm_p c^2\Gamma_0^2}\right]^{1/3} = (1.2\times10^{17}cm)E_{53}^{1/3}n^{-1/3}\Gamma_{0,2}^{-2/3}$$

Observer frame deceleration time is:

$$t_d = \frac{(1+z)R_d}{2c\Gamma^2} = \frac{(1+z)R_d}{c\Gamma_0^2} = (389s)(1+z)E_{53}^{1/3}n^{-1/3}\Gamma_{0,2}^{-8/3}$$

Electron thermal LF in shocked fluid



Observationally determined to be ~0.2

$$\gamma_i \approx \boxed{\varepsilon_e}\left(\frac{p-2}{p-1}\right)\frac{m_p}{m_e}\Gamma$$

Electron distribution is:

$$\frac{dn_e}{d\gamma_e} = A\left(\frac{\gamma_e}{\gamma_i}\right)^{-p} \;;\; for\;\; \gamma_e > \gamma_i$$

External forward shock

Magnetic field in shocked fluid

The thermal energy density for shocked fluid is given by

$$\boxed{4n\Gamma}\,\boxed{m_p c^2 \Gamma} = 4 n m_p c^2 \Gamma^2$$

Proton number density for shocked fluid

Energy per proton

It is assumed that the energy density in magnetic fields in the shocked fluid is some fraction, ε_B, of the thermal energy density:

$$\frac{B'^2}{8\pi} = \varepsilon_B 4 n m_p c^2 \Gamma^2 \Rightarrow B' \propto \Gamma$$

$$B' = \sqrt{32\pi\varepsilon_B n m_p c^2 \Gamma^2} = (225\,Gauss)\,\varepsilon_B^{1/2} n^{3/8} E_{53}^{1/8} t_{obs}^{-3/8} (1+z)^{3/8}$$

External forward shock

Observed synchrotron frequency

$$\nu_i = \nu_i'\Gamma = \frac{qB'\gamma_i^2\Gamma}{2\pi m_e c} \propto \Gamma^4 \propto t_{obs}^{-3/2}$$

$$\nu_i = (9.9\times 10^{24}\,Hz)\,\varepsilon_e^2\,\varepsilon_B^{1/2}\,E_{53}^{1/2}\,t_{obs}^{-3/2}(1+z)^{1/2}$$

For $t_{obs} = 10^2\,s,\ \varepsilon_B \approx 10^{-4},\ \varepsilon_e \approx 0.1$ **we find:** $\nu_i = (9.9\times 10^{17}\,Hz) \approx 5\,keV$

Observed flux at ν_i

Total number of swept-up electrons

$$f_i = \boxed{\frac{\sigma_T}{6\pi}B'^2\gamma_i^2 c}\,(\nu_i')^{-1}\,\frac{\boxed{\frac{4}{3}\pi R^3 n}\,\boxed{\Gamma}}{4\pi\, d_L^2/(1+z)}$$

Transforming from co-moving frame to lab frame

Total synchrotron power for one electron in co-moving frame

External forward shock

Observed flux at ν_i

$$f_i \propto n R^3 \Gamma^2$$

← Which is time independent – from energy conservation

$$f_i = (0.3\,Jy)\, E_{53} \varepsilon_B^{1/2} n^{1/2} d_{L,28}^{-2} (1+z)$$

Cooling of electrons

Electrons cool down with time due to loss of energy to synchrotron radiation and Inverse Compton (IC) scatterings.

Let us define a characteristic LF for electrons, γ_c, such that electrons of this LF lose their energy in a time available since the explosion began.

$$\frac{d(m_e c^2 \gamma_e)}{dt'} = -\frac{\sigma_T}{6\pi} B'^2 \gamma_e^2 c (1+Y)$$

← Y is Compton-Y parameter

Co-moving frame time is: $t' \approx \frac{t}{\Gamma} \approx \frac{R}{c\Gamma}$

$$\therefore \gamma_c \approx \frac{6\pi\, m_e c^2 \Gamma}{\sigma_T B'^2 R (1+Y)} \propto \frac{1}{\Gamma R} \propto t_{obs}^{1/8}$$

External forward shock

Cooling frequency (ν_c)

It is defined to be the synchrotron frequency corresponding to electron LF = γ_c

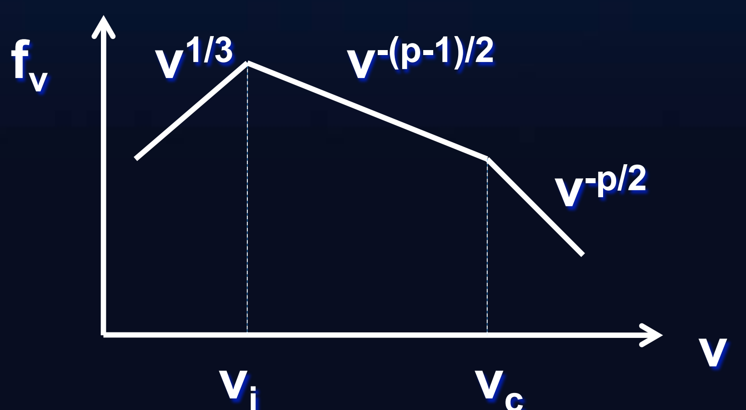
$$\therefore \nu_c = \frac{qB'\gamma_c^2\Gamma}{2\pi m_e c} \propto \Gamma^2\gamma_c^2 \propto \frac{1}{R^2} \propto t_{obs}^{-1/2}$$

$$\nu_c = (1.1\times 10^{14}\,Hz)\,\varepsilon_B^{-3/2} n^{-1} E_{53}^{-1/2} t_{obs}^{-1/2} (1+z)^{-1/2} (1+Y)^{-2}$$

The electron energy distribution is modified due to cooling:

$$\frac{dn_e}{d\gamma_e} \propto \gamma_e^{-p-1}\ ;\ for\ \ \gamma_e > \gamma_i\ \&\ \gamma_c$$

The synchrotron spectrum is:



External forward shock

The observed flux in a fixed observer energy band (ν), for $\nu > \nu_i$ and ν_c

$$f_\nu = f_i(\nu_i/\nu_c)^{\frac{p-1}{2}}(\nu_c/\nu)^{\frac{p}{2}} = f_i \nu_c^{1/2} \nu_i^{\frac{p-1}{2}} \nu^{-p/2}$$

Substituting for f_i, ν_i and ν_c we find that the flux is:

$$f_\nu \propto t_{obs}^{-\frac{3p-2}{4}} \nu^{-\frac{p}{2}} \equiv t_{obs}^{-\alpha} \nu^{-\beta}$$

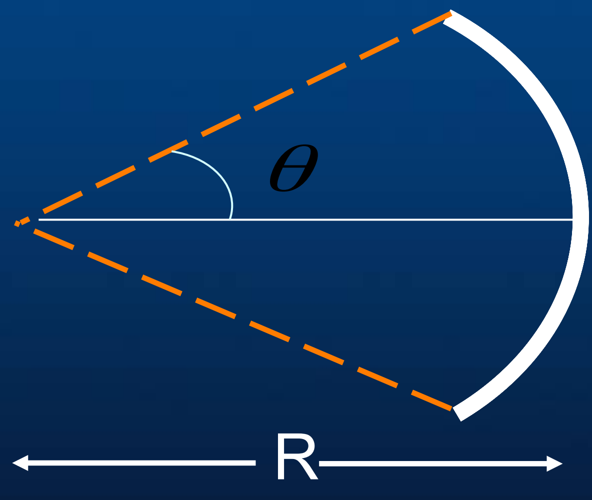
Closure relation: $\alpha = (3\beta - 1)/2$

Moreover, we find the flux (for parameters of Fermi GRBs):

$$f_\nu = (0.2\, mJy)\, E_{55}^{\frac{p+2}{4}}\, \varepsilon_e^{p-1}\, \varepsilon_{B,-2}^{\frac{p-2}{4}}\, t_1^{-\frac{3p-2}{4}}\, \nu_8^{-\frac{p}{2}} (1+Y)^{-1} (1+z)^{\frac{p+2}{4}}\, d_{L,28}^{-2}$$

Note that the observed flux is independent of n and extremely weakly dependent on ε_B!

Jet dynamics



$$\delta\theta = \frac{\delta t c_s}{R\gamma}$$

$$\delta t c_s = \delta R / \sqrt{3}$$

$$\theta = \theta_0 + \delta\theta \approx \theta_0 + \frac{1}{\sqrt{3}\gamma}$$

For appreciable change to jet angle, $\delta\theta = \theta_0$, requires: $\gamma \approx \theta_0^{-1} / 3^{1/2}$

Using dynamics discussed before $\Rightarrow \theta_0 \approx 5.2^\circ \left(n_0 / E_{iso,52}\right)^{1/8} \left(t_{jet} / 1day\right)^{3/8}$

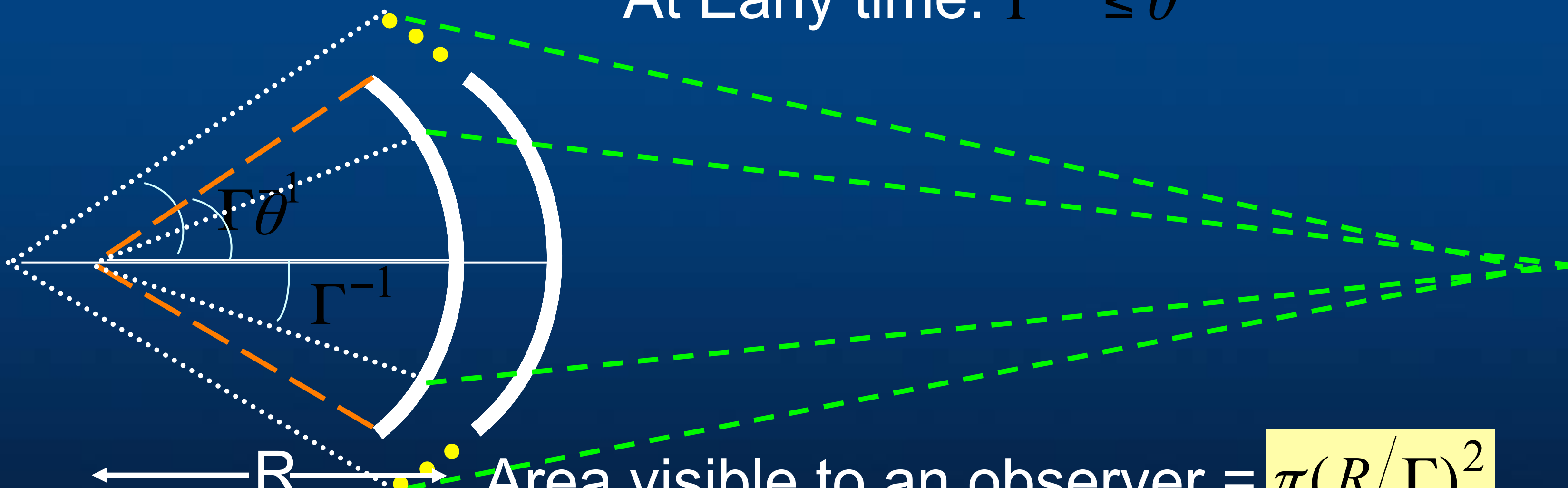
At late times, after the jet break: $\theta \approx \gamma^{-1} / \sqrt{3}$

Effect of Relativistic jet on Light-curve

(Rhoads 1999, Sari et al. 1999, Kumar & Panaitescu 2000)

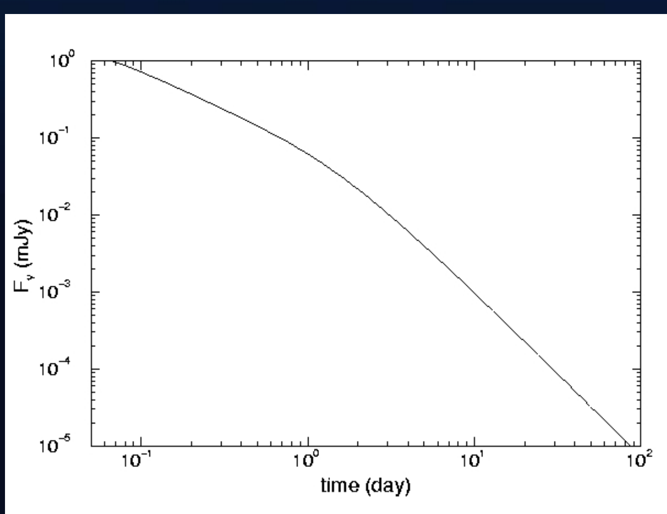
At Late time: $\Gamma^{-1} \geq \theta$

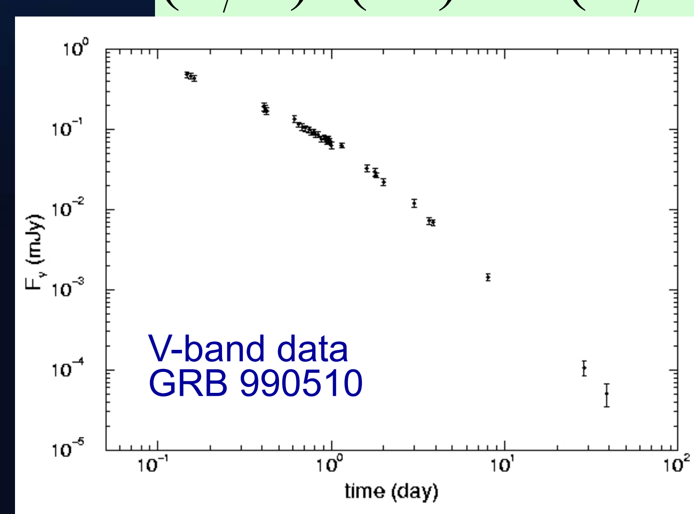
At Early time: $\Gamma^{-1} \leq \theta$



Area visible to an observer = $\pi(R/\Gamma)^2$

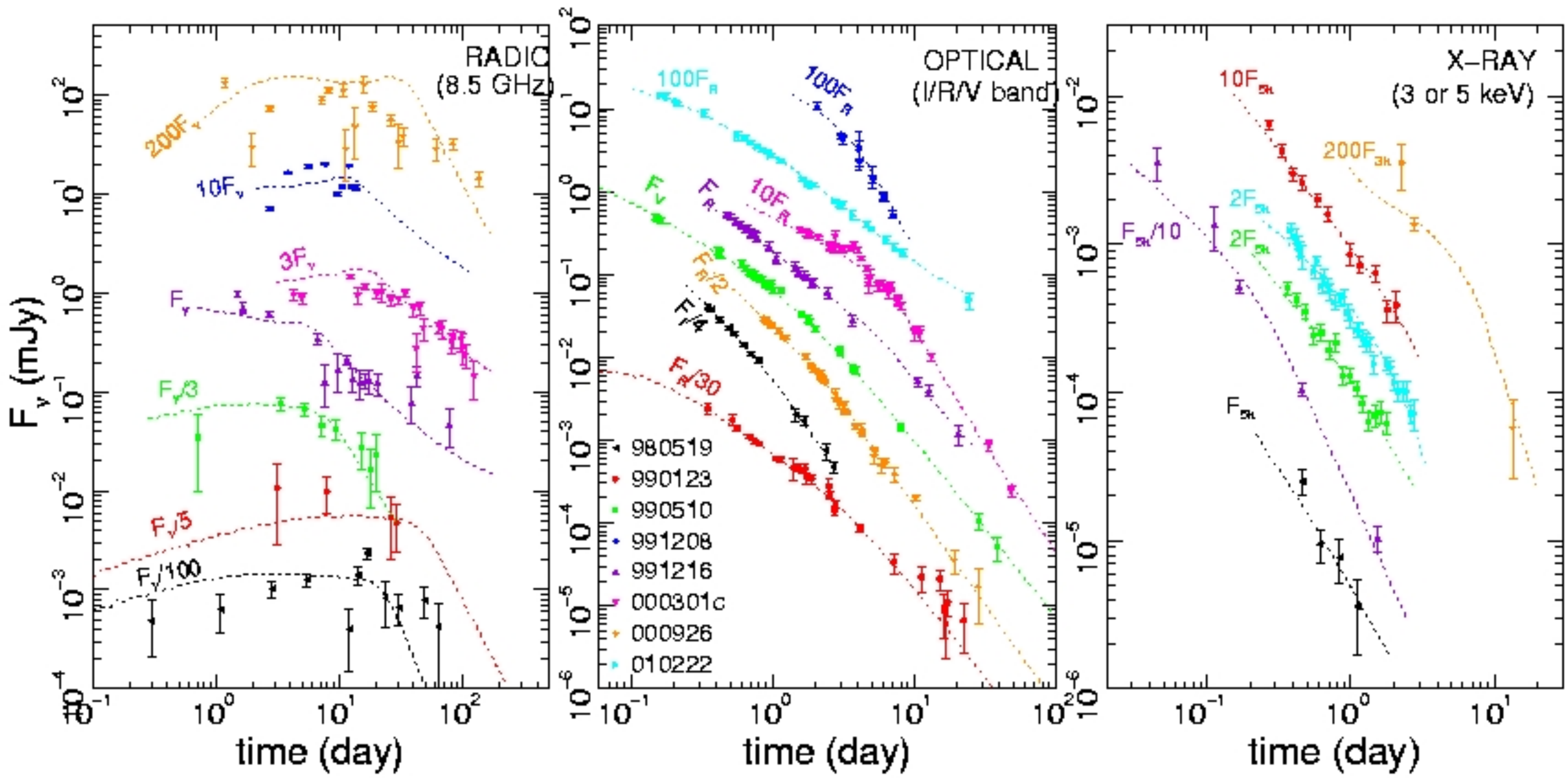
Area visible to an observer = $\pi(R\theta)^2 \propto (R/\Gamma)^2(\theta\Gamma)^2 \propto (R/\Gamma)^2\, t^{-3/4}$





Afterglow theory: synchrotron radiation in external shock

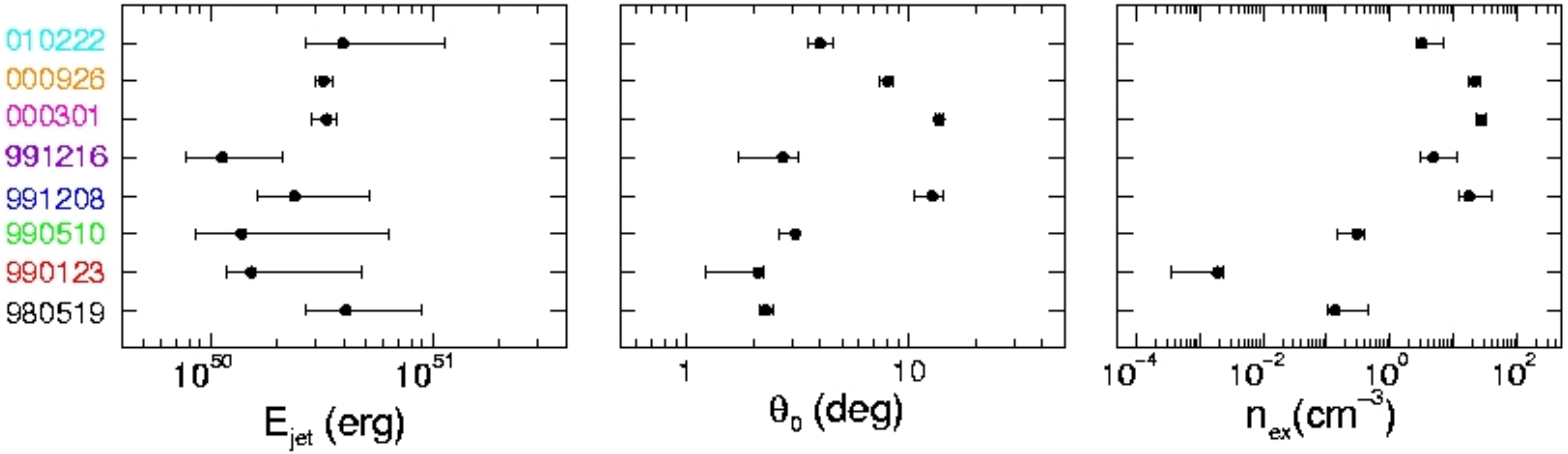
Panaitescu & Kumar (2001)



Late time afterglow data (t> 5 hrs) is well described by this model

The true amount of energy release in these explosions is determined by modeling of multi-wavelength afterglow data, and is found to be on average ~10^{51} erg.

Energy in Relativistic Ejecta, Jet Opening **Angle** and ISM **Density**



(Panaitescu & Kumar, 2002)

ε_e and ε_B

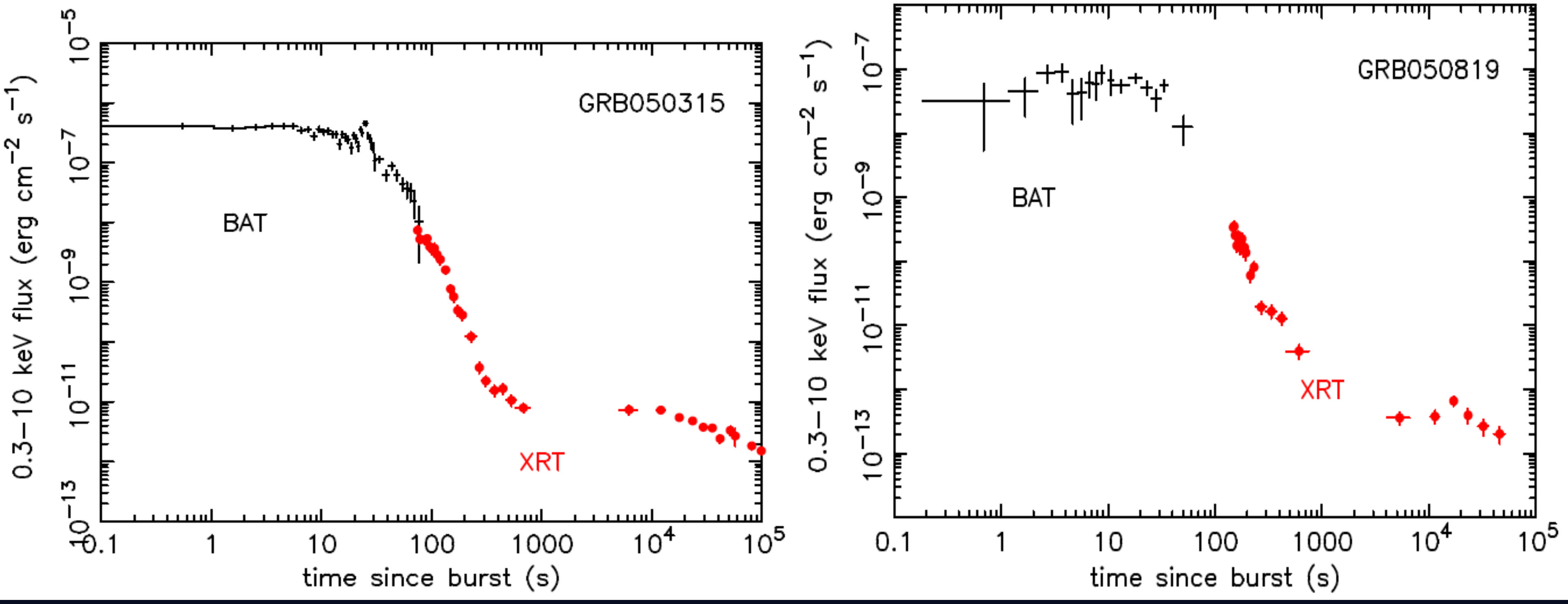
The launch of Swift satellite – 11/20/04 – was a major milestone in the study of GRBs

INTEGRAL satellite – Oct 17, 2002 launch – has discovered many GRBs and contributed much to our knowledge of these bursts.

Swift provided an almost continuous coverage for afterglow radiation. And that led to a number of important discoveries (which has made the afterglow theory much more complicated).

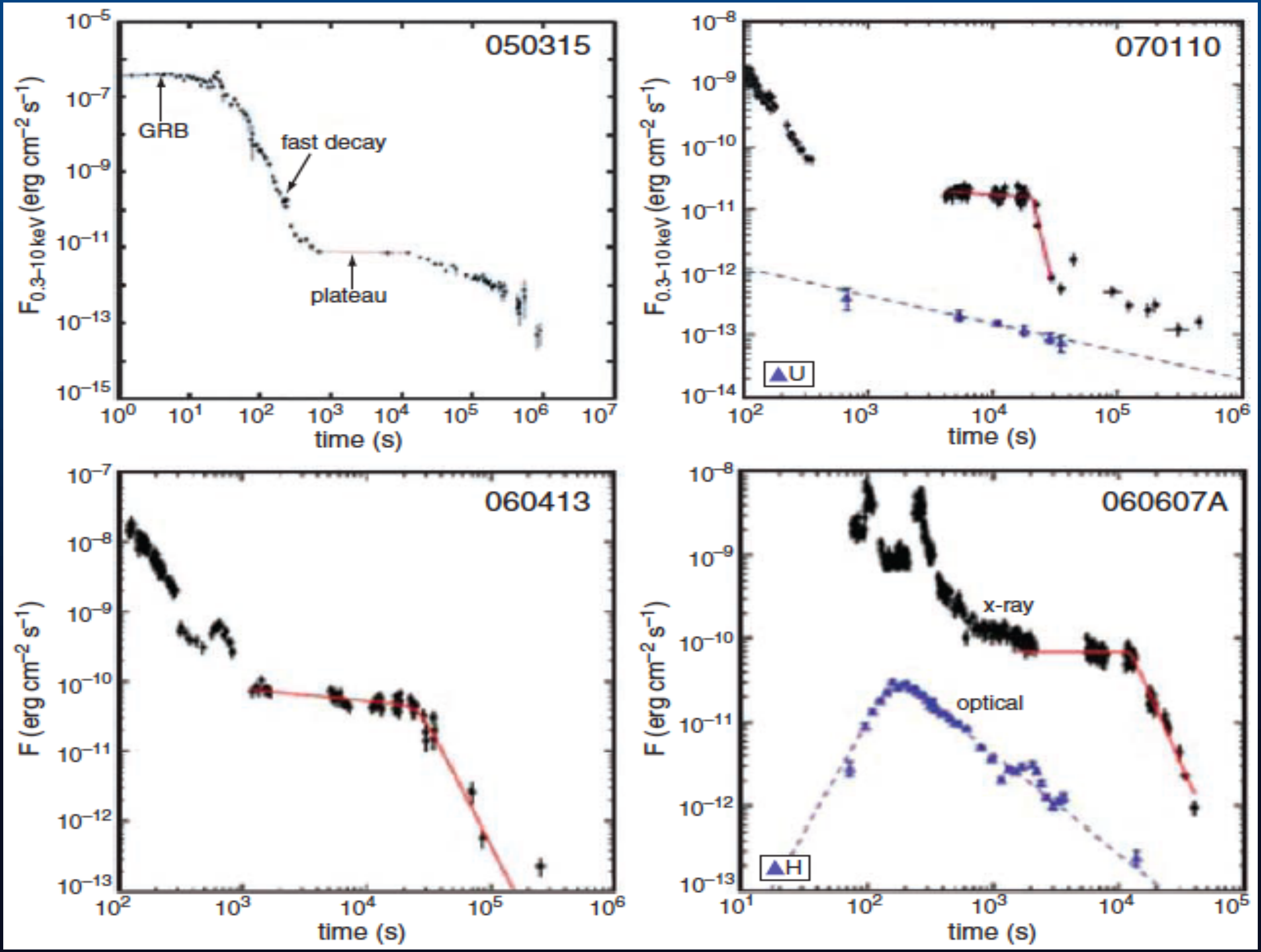
1. Steep decline of X-ray afterglow lightcurve

O'Brien et al., 2006



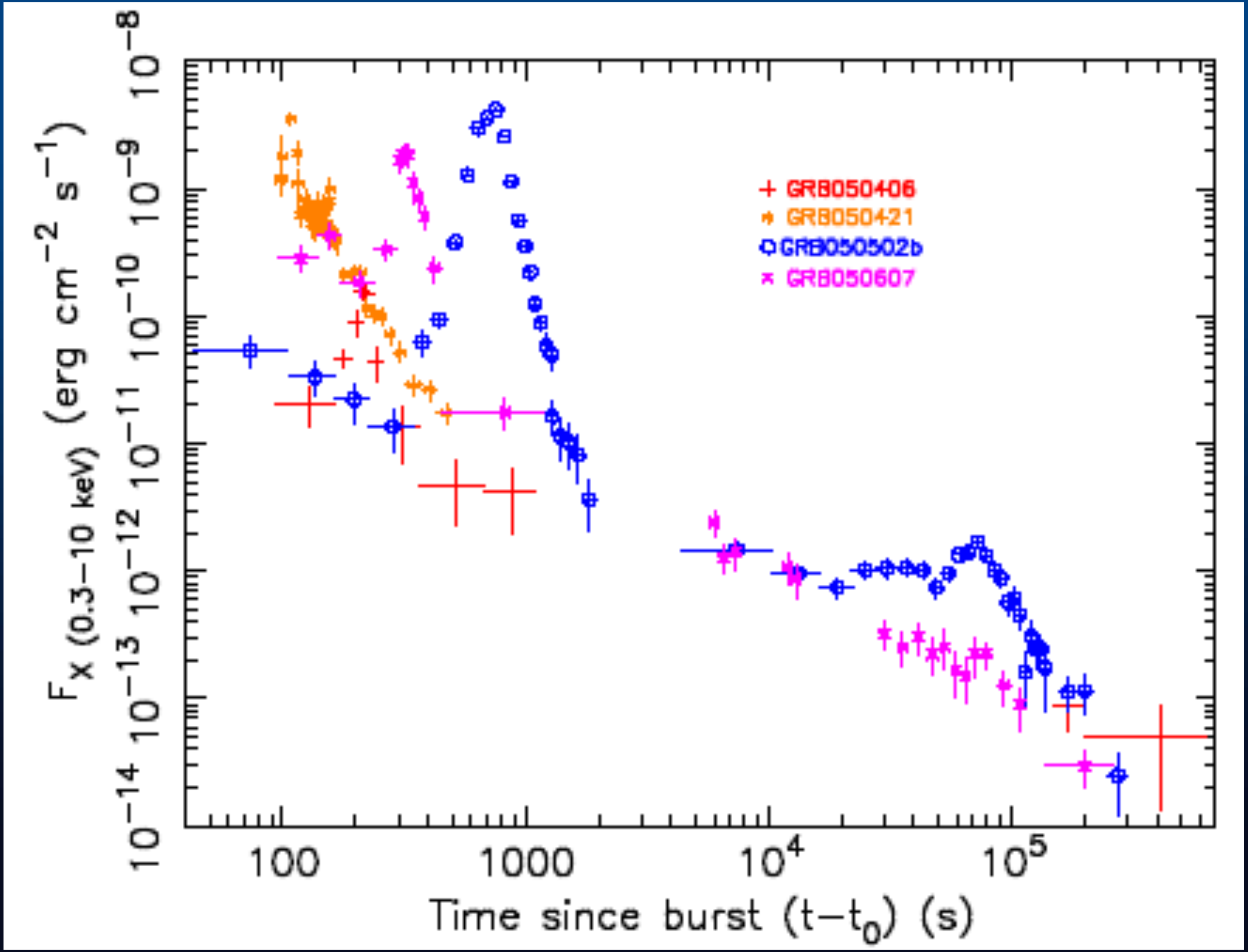
2. Plateau in the X-ray AG lightcurves (but no plateau in optical)

Liang et al. 2007



3. Flares in X-ray afterglows (0.3-10 keV), i.e. engine reactivation

Nousek et al. 2005



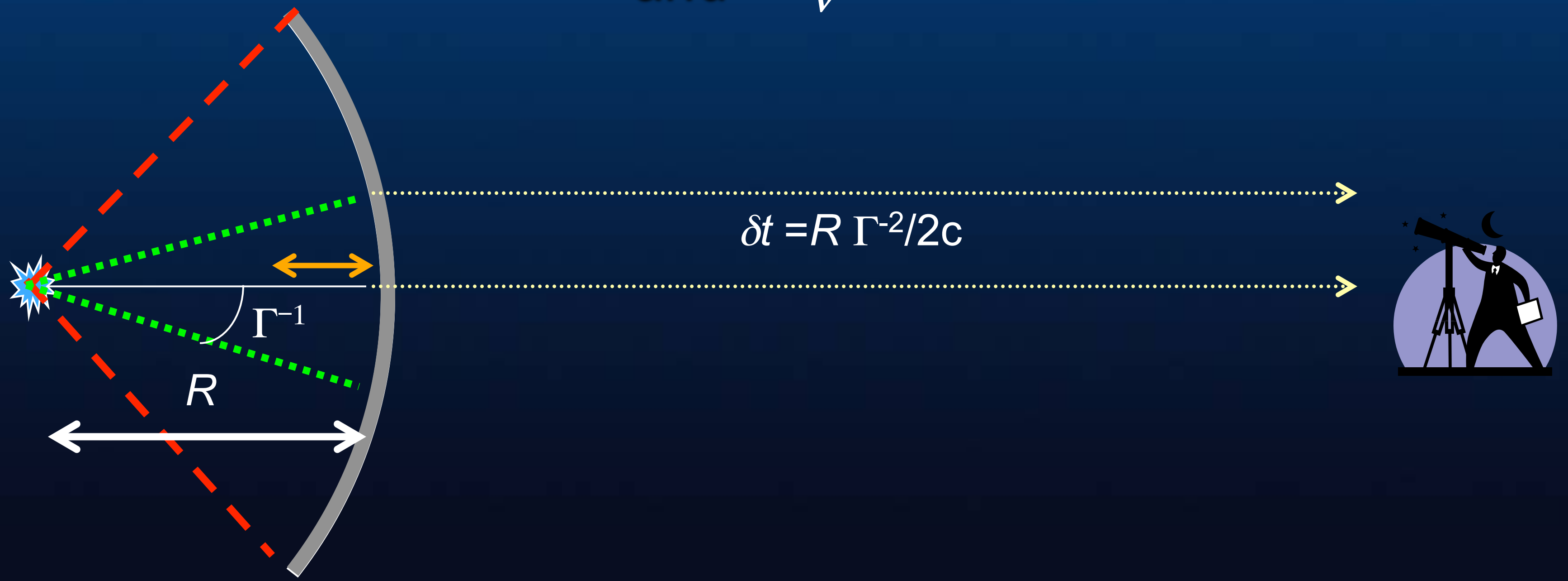
Because of smearing due to curvature dt/t ~ 1 in FS. Many of the flares have dt/t << 1 which suggests late time engine activity.

Fastest decay of LCs (High latitude emission)

(Kumar & Panaitescu 2000)

If we turn-off emission instantaneously at radius R, observers will see the flux decay over $\delta t \approx R/2c\Gamma^2$

and $f_\nu \propto t^{-2-\beta} \nu^{-\beta}$ ***at later times***



This seems to explain the fast decay of X-ray lightcurve as shown by a number of people – Tagliaferri et al. (2005), Zhang et al. (2009), Genet & Granot (2009) …..

High energy photons (>100 MeV) from GRBs

Fermi

8 KeV to 300 GeV

6/11/2008

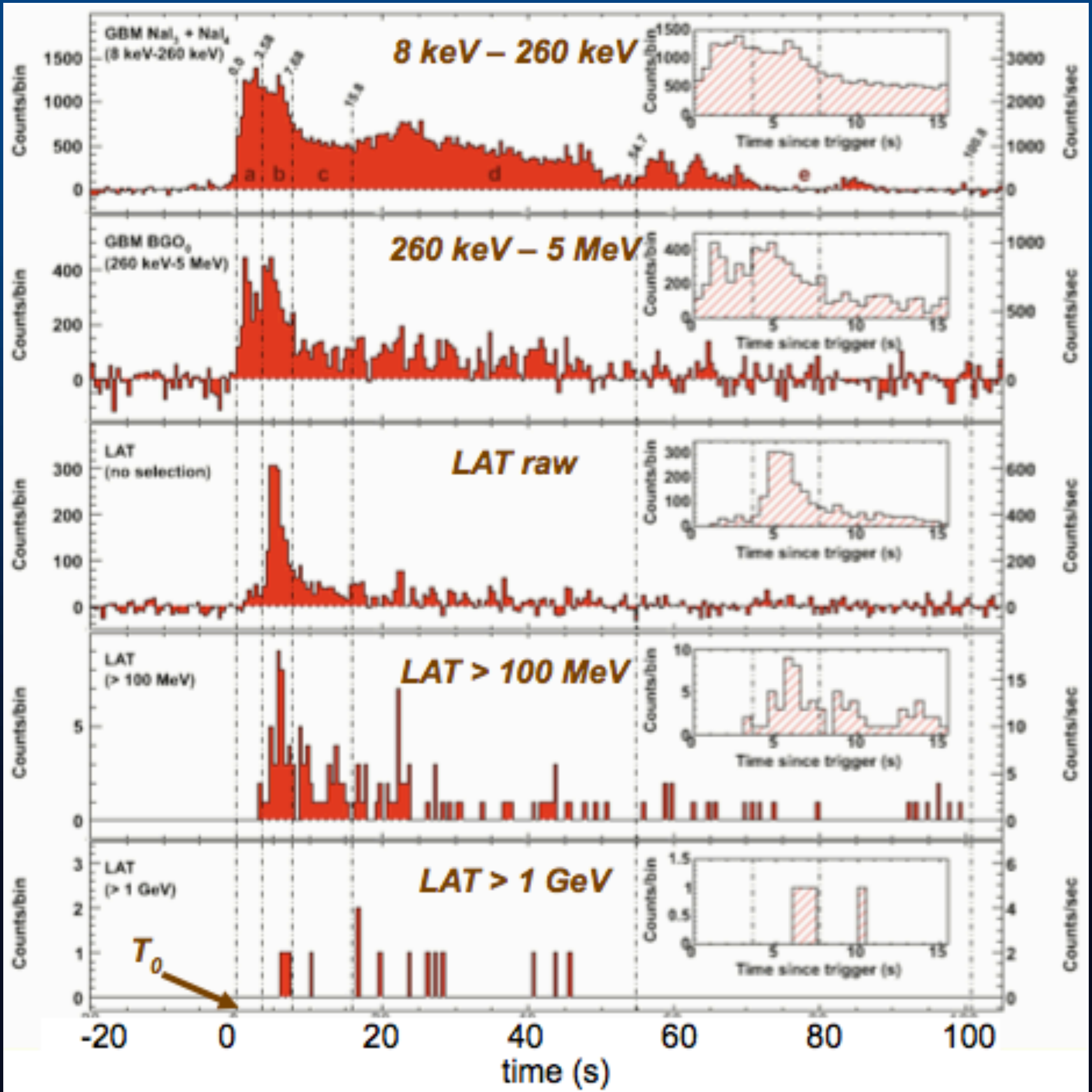
How are γ-rays generated?

One of the goals for Fermi is to understand γ-ray burst prompt radiation mechanism by observing high energy photons from GRBs.

Let us see how Fermi has done…

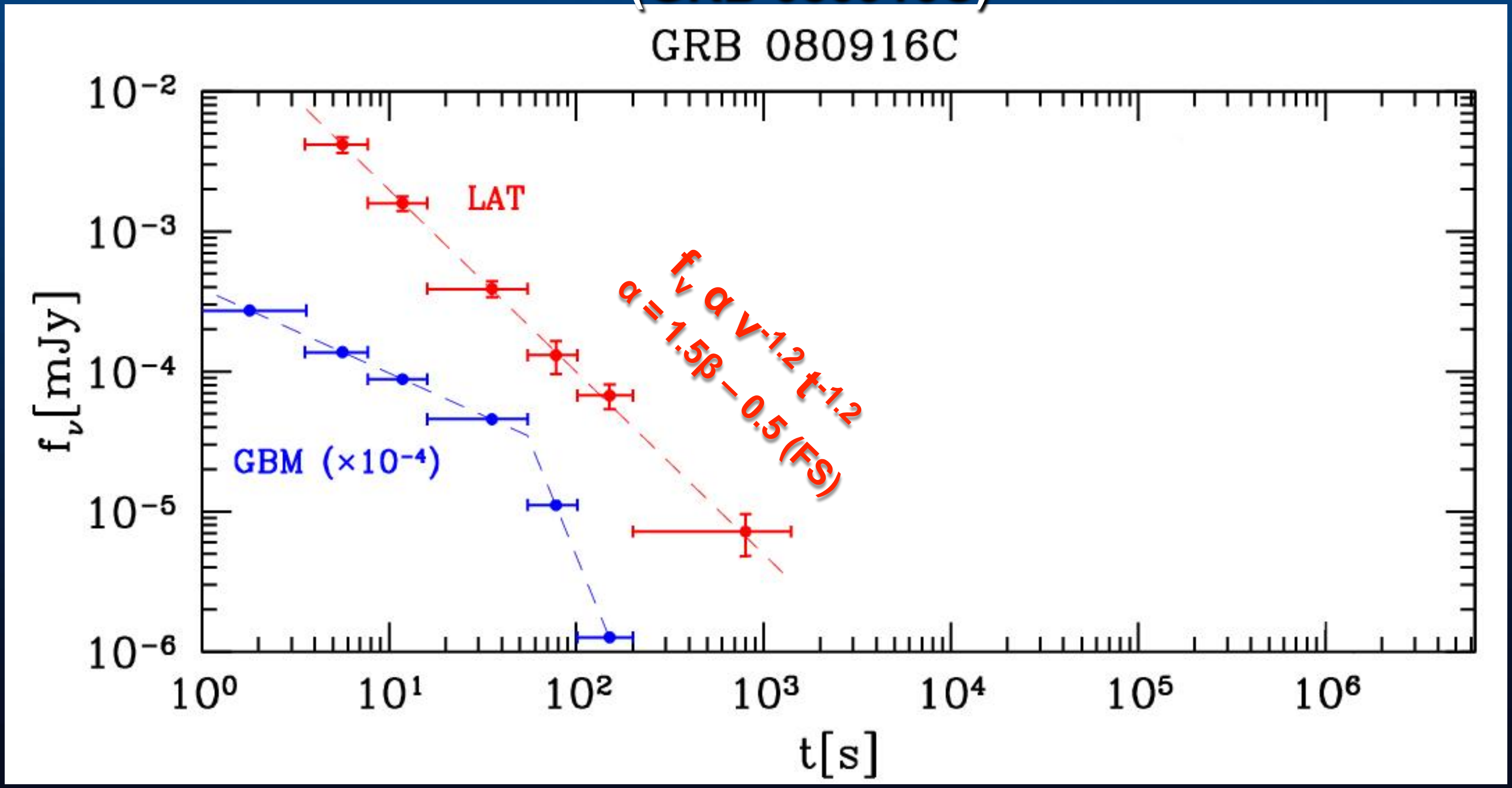
Delayed high energy emission; Abdo et al. (2009)

GRB 080916C



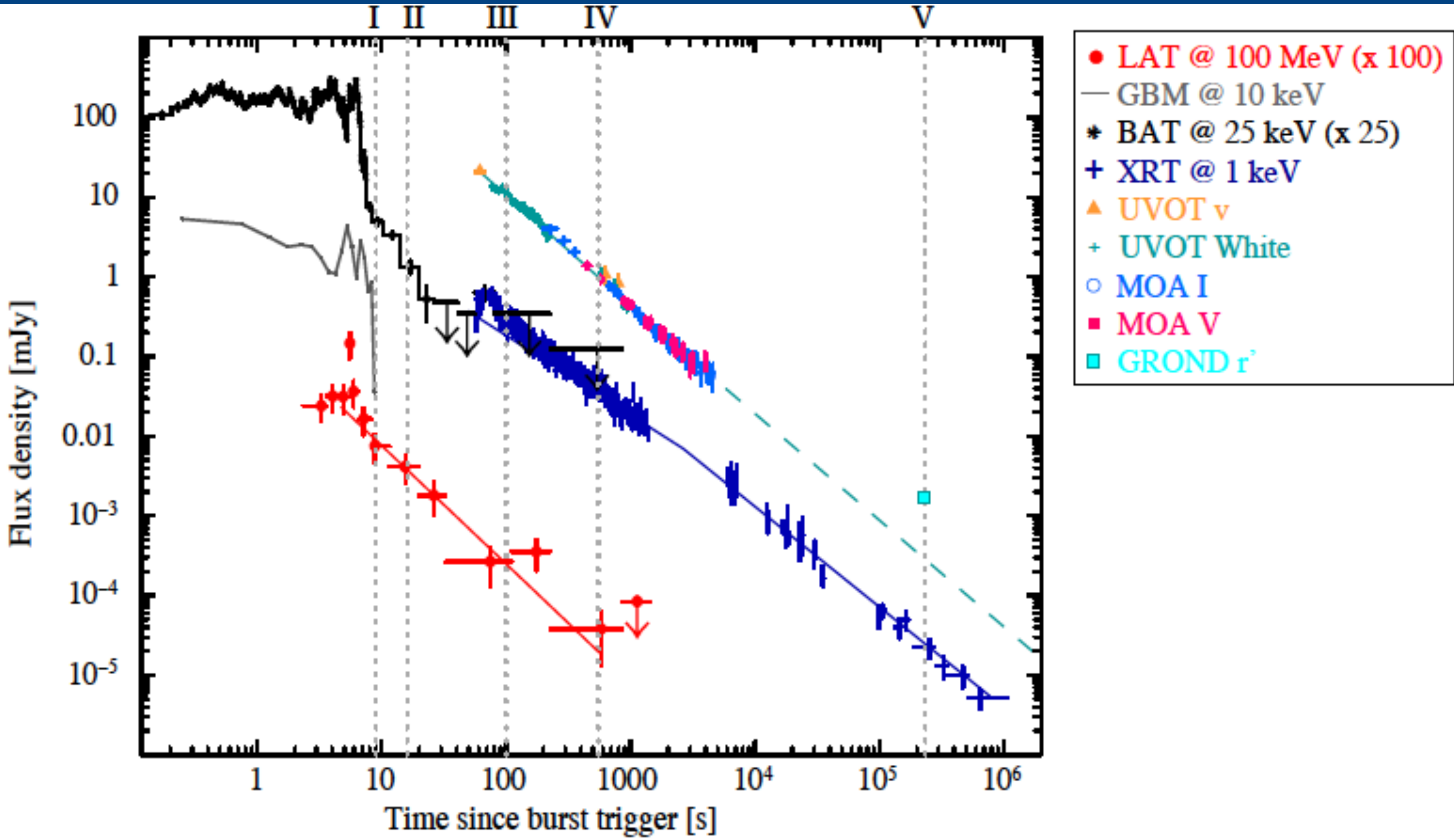
Long lived lightcurve for >10^2MeV (Abdo et al. 2009)

(GRB 080916C)



Abdo et al. 2009

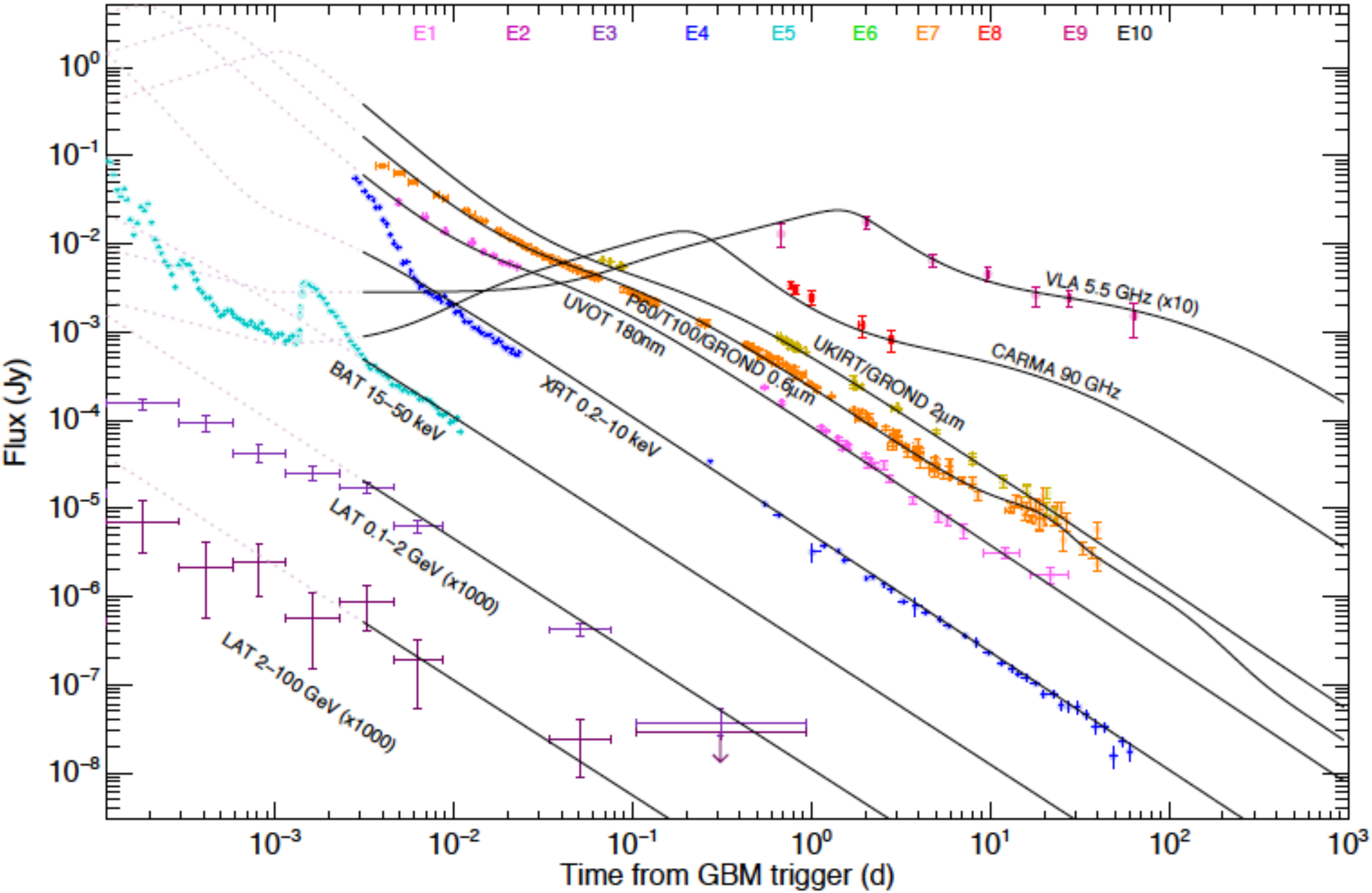
GRB 110731A (Ackermann et al. 2013)



GRB 130427A (Perley et al. arXiv:1307.4401)

MeV duration (T_{90}) = 138s, LAT duration (T_{GeV}) > 4.3×10^3s; T_{GeV}/T_{90} > 31

Highest energy photon (95 GeV) detected 242s after T_0; z=0.34; $E_{\gamma,iso}$= 7.8×10^{53}erg



Origin of high energy photons (>100 MeV)

Prompt phase: high energy photons during this phase might have a separate origin than photons that come afterwards if rapid fluctuations and correlation with MeV lightcurve is established.

- Hadronic processes: proton synchrotron, photo-meson …

  Bottcher and Dermer, 1998; Totani, 1998; Aharonian, 2000; Mucke et al., 2003; Reimer et al., 2004; Gupta and Zhang, 2007b; Asano et al., 2009; Fan and Piran, 2008; Razzaque et al. 2010; Asano and Meszaros, 2012; Crumley and Kumar, 2013….

  Inefficient process – typically requires several order more energy than we see in the MeV band (unless Γ were to be small, of order a few hundred, which few people believe is the case for Fermi/LAT bursts), e.g. Razzaque et al. 2010, Crumley & Kumar 2013.

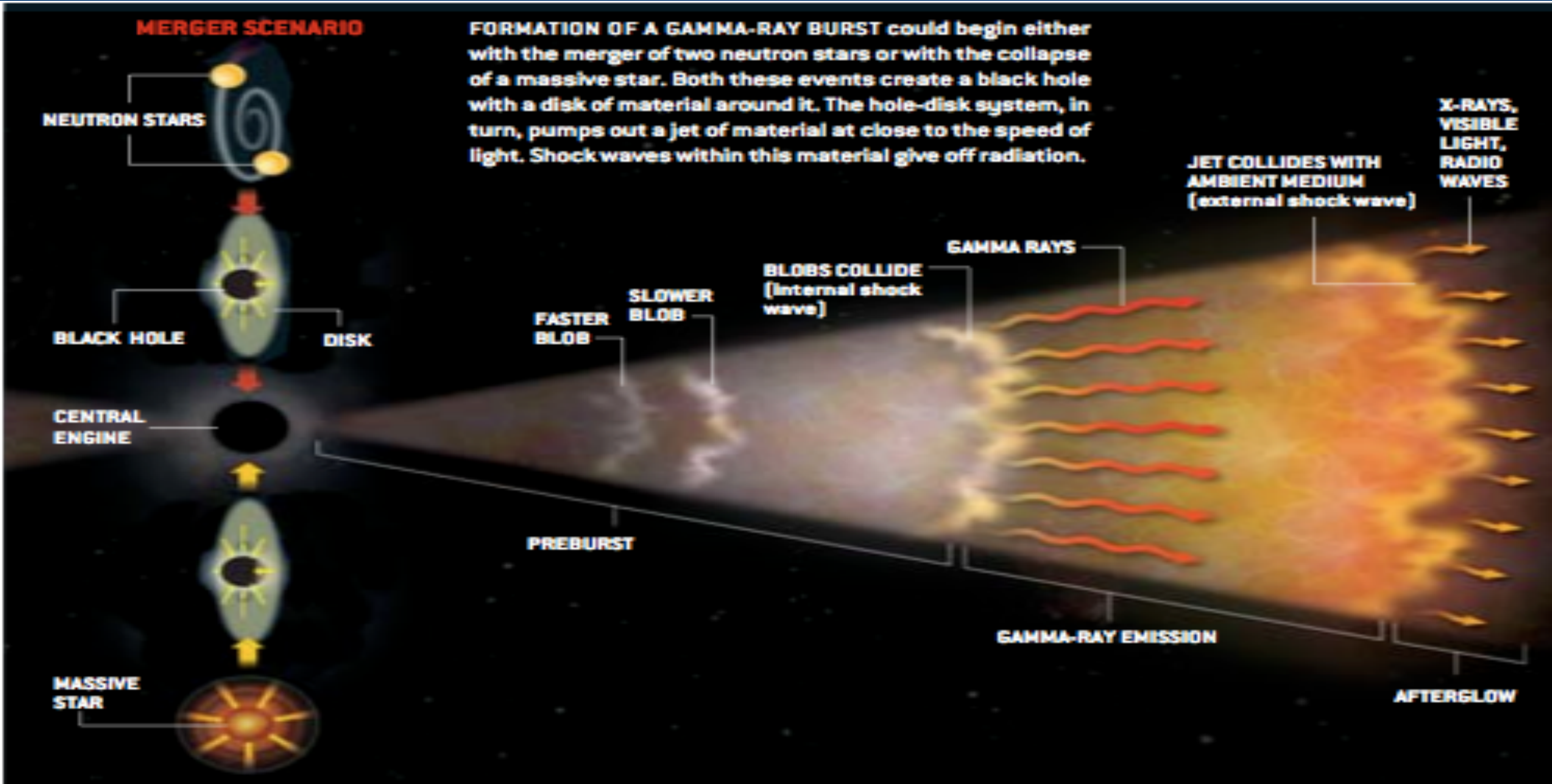
- Internal shock and SSC: e.g. Bosnjak et al. 2009, Daigne et al. 2011

Afterglow: external shock synchrotron, IC in forward or reverse shock of prompt radiation or afterglow photons; IC of CMB photons by $e^{\pm}$ in IGM; pair enrichment of external medium and IC…

Dermer et al., 2000; Zhang and Meszaros, 2001; Wang et al. 2001; Granot and Guetta, 2003; Gupta and Zhang, 2007b; Fan and Piran, 2008; Zou et al., 2009; Meszaros and Rees 1994; Beloborodov 2005; Fan et al., 200; Dai and Lu 2002; Dai et al. 2002; Wang et al. 2004; Murase et al. 2009; Beloborodov 2013….

Kumar & Barniol Duran (2009) and Ghisellini, Ghirlanda & Nava (2010) showed that high energy γ-ray radiation from GRBs, after the prompt phase, are produced in the external-forward shock via the synchrotron process. The reasoning for this will be described in the next several slides.

Gehrels, Piro & Leonard: Scientific American, Dec 2002



Flux above ν_c is independent of density and almost independent of ε_B

- Consider GRB circumstellar medium density profile: $\rho \propto r^{-s}$
- Blast wave dynamics follows from energy conserv $\Gamma \propto r^{-(3-s)/2}$
- Observer frame elapsed time: $t_{obs} \approx \frac{r}{2c\Gamma^2} \propto r^{4-s}$
- Comoving magnetic field in shocked fluid: $B'^2 \propto \varepsilon_B \rho \Gamma^2$
- Synchrotron characteristic frequency: $\nu_m \propto B' \gamma_m^2 \Gamma \propto \varepsilon_B^{1/2} t_{obs}^{-3/2}$
- Observed flux at ν_m: $f_{\nu_m} \propto \varepsilon_B^{1/2} r^{-s/2}$
- Synchrotron cooling frequency: $\nu_c \propto \varepsilon_B^{-3/2} r^{(3s-4)/2}$

$\therefore$ **Observed flux at ν:**

$$f_\nu = f_{\nu_m} \left(\frac{\nu_m}{\nu_c}\right)^{(p-1)/2} \left(\frac{\nu_c}{\nu}\right)^{p/2} \propto \varepsilon_B^{(p-2)/4} t_{obs}^{-(3p-2)/4}$$

The flux from the external shock above the cooling frequency is given by:

$$f_\nu = \frac{0.2\ \mathrm{mJy}\ E_{55}^{(p+2)/4}\ \varepsilon_e^{p-1}\ \varepsilon_B^{(p-2)/4}(1+z)^{(p+2)/4}}{d_{L28}^{2}(t/10s)^{(3p-2)/4}\ \nu_8^{p/2}\ (1+Y)}$$

Y << 1 due to Klein-Nishina effect for electrons radiating 10^2MeV photons.

Note that the flux does not depend on the external medium density or stratification, and has a very weak dependence on ε_B.

The expected decline of the >100 MeV lightcurve according to the external shock model is $t^{-(3p-2)/4}$. For p=2.2 the expected decline is $t^{-1.1}$ which is in agreement with Fermi/LAT observations.

Temporal decay index in Fermi/LAT band; Ackermann et al. 2013

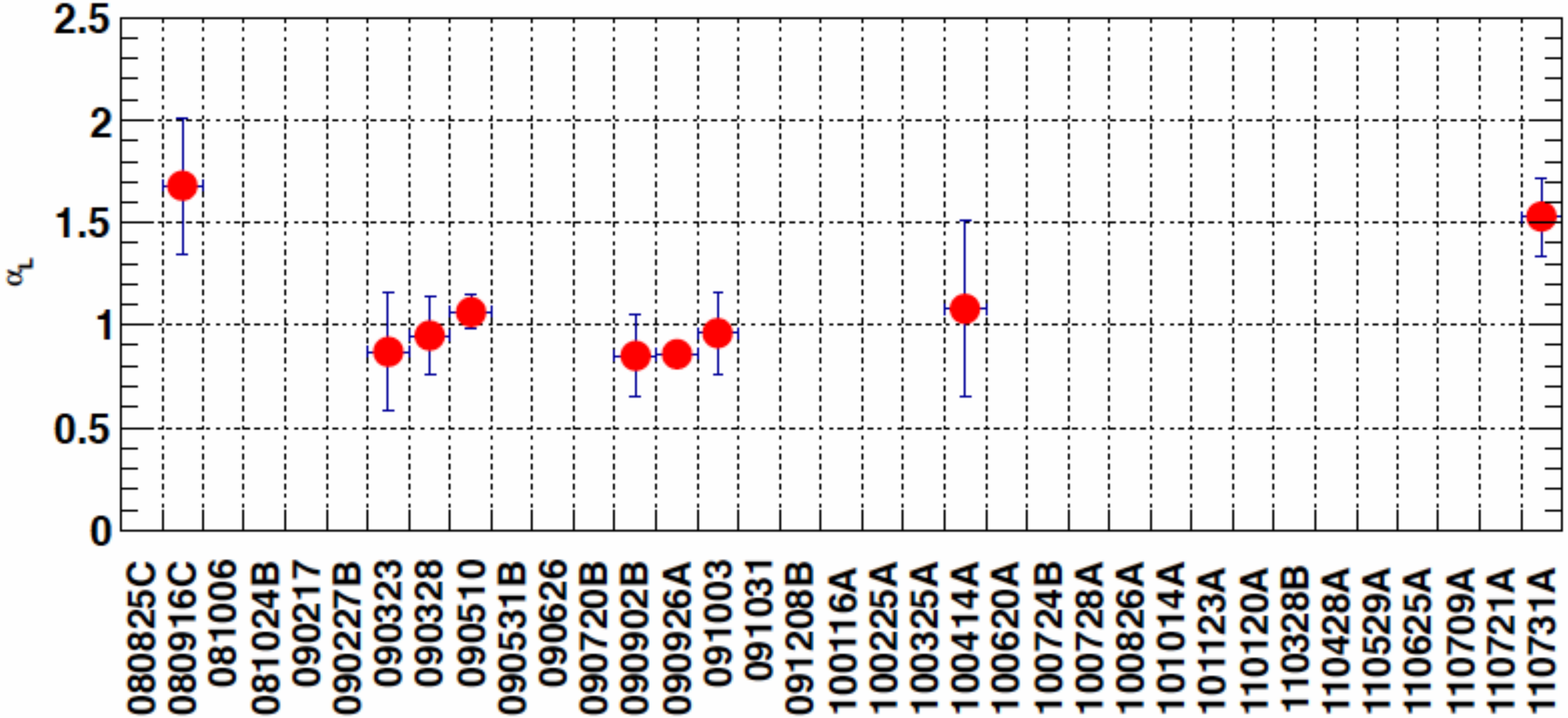


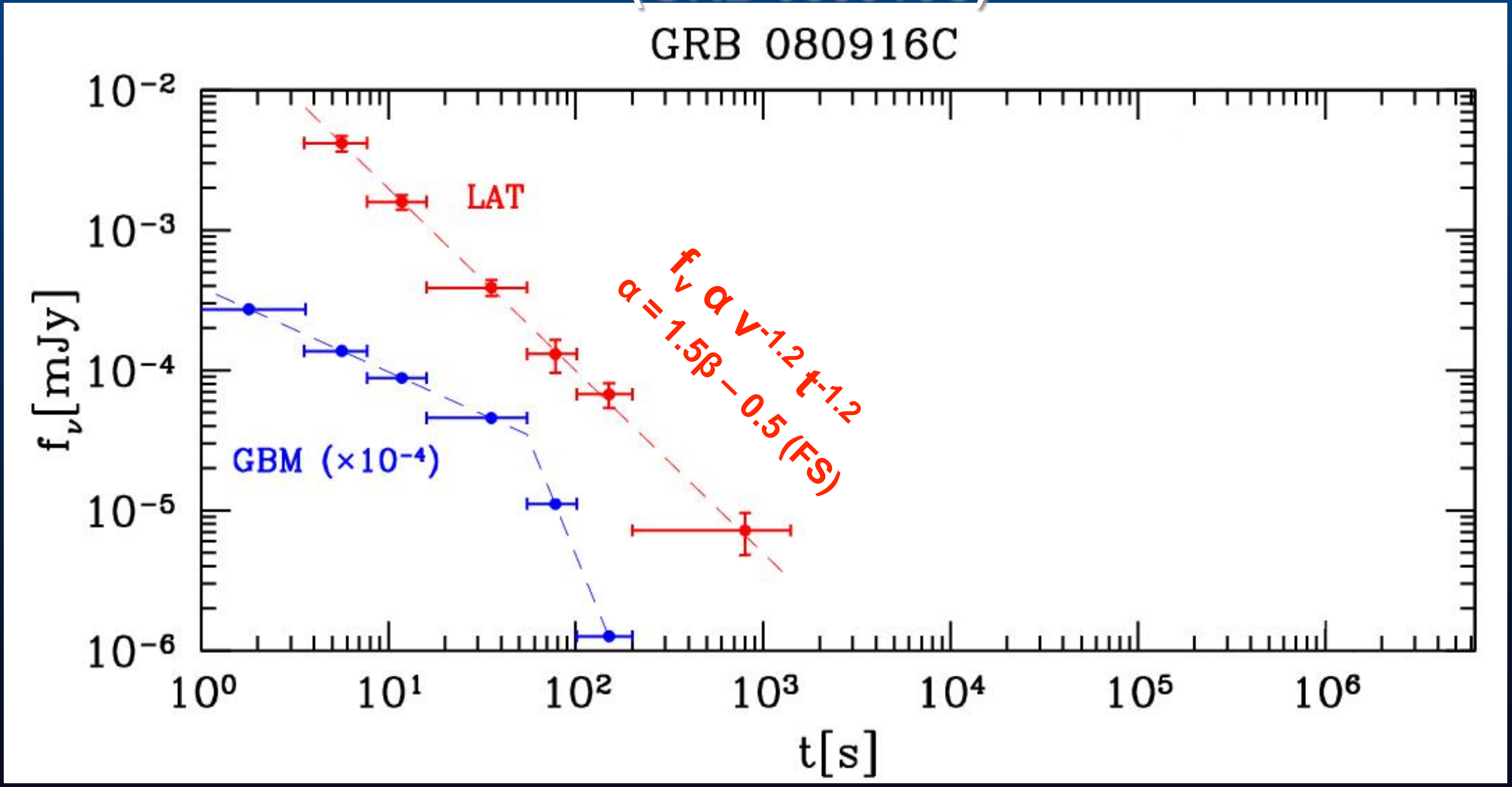
Table of expected and observed 100 MeV flux

	z	$E_{\gamma,54}$	Time (observer frame in s)	Expected flux♪ from ES in nJy	Observed flux (nJy)
080916C	4.3	8.8	150	50	67
090510	0.9	0.11	100	9	14
090902B	1.8	3.6	50	300	220
110731A	2.83	0.6	100	8	~5
130427A	0.34	0.78	600	48	~40

♪We have taken energy in blast wave = $3E_\gamma$, $\epsilon_e=0.2$, $p=2.4$, $\epsilon_B=10^{-5}$

Long lived lightcurve for >10^2MeV (Abdo et al. 2009)

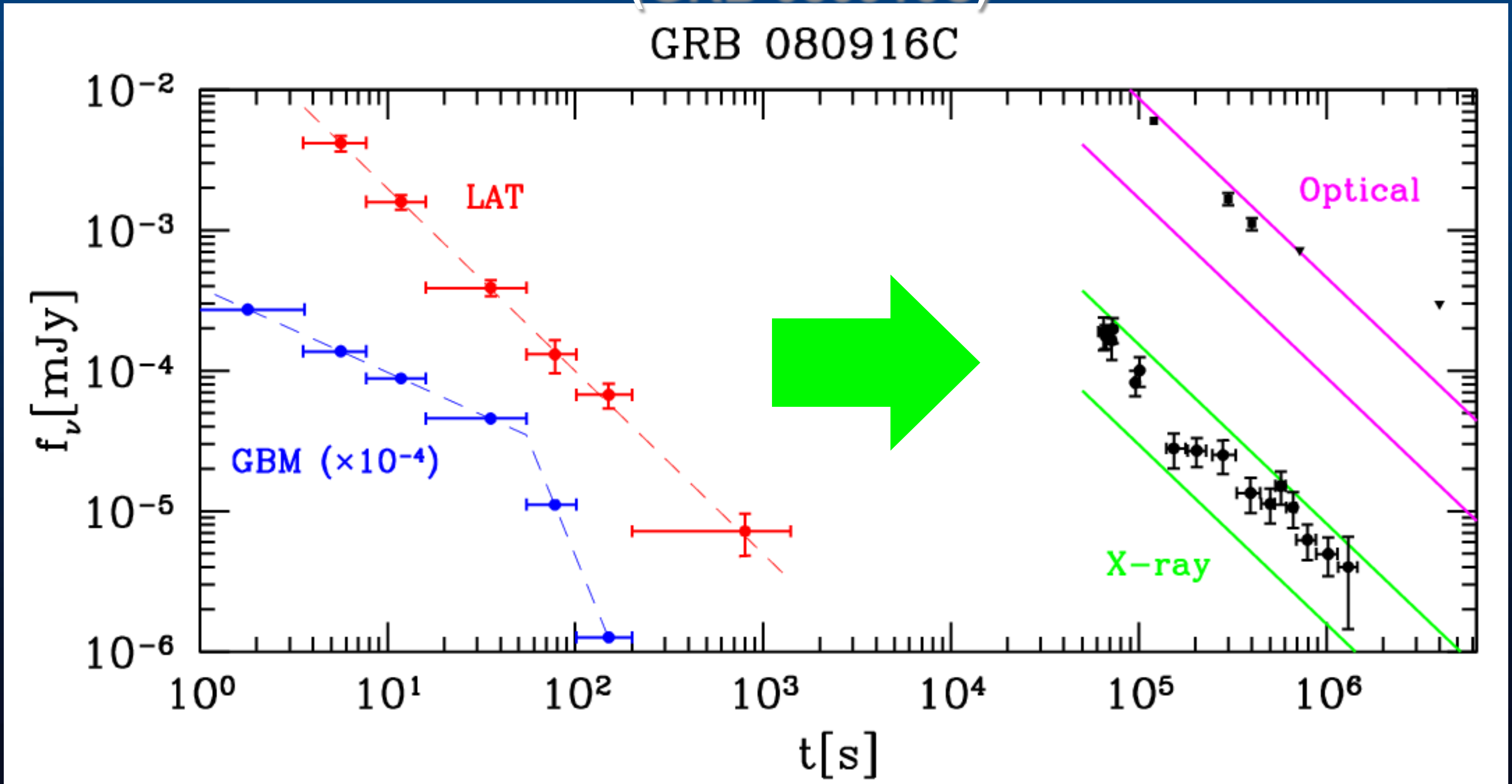
(GRB 080916C)



Abdo et al. 2009

Long lived lightcurve for >10^2MeV (Abdo et al. 2009)

>10^2MeV data ⇒ expected ES flux in the X-ray and optical band (GRB 080916C)



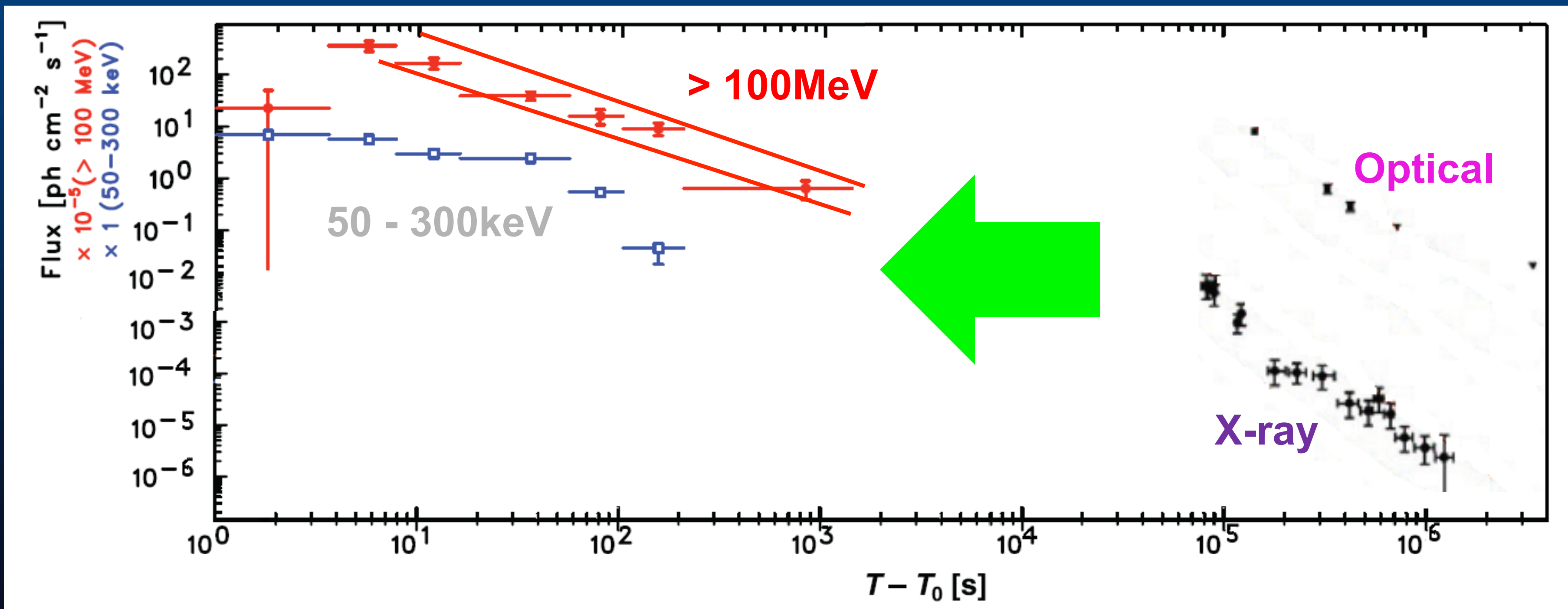
Kumar & Barniol Duran (2009)

Abdo et al. 2009, Greiner et al. 2009, Evans et al. 2009

We can then compare it with the available X-ray and optical data.

Or we can go in the reverse direction…

Assuming that the late (>1day) X-ray and optical flux are from ES, calculate the expected flux at 100 MeV at early times



Kumar & Barniol Duran (2009)

Abdo et al. 2009, Greiner et al. 2009, Evans et al. 2009

And that compares well with the available Fermi data.

A Brief Summary

- ★ The expected flux between 100 MeV and ~10 GeV due to synchrotron emission in external shock is within a factor 2 of the observed flux (as long as electrons are accelerated as per Fermi mechanism).

The predicted flux is independent of ISM density and ϵ_B. And hence the flux predictions are robust.

- ★ An alternate mechanism to explain the >100 MeV flux observed by Fermi/LAT would have to make a more compelling case than the external shock model.

What about 10 GeV – 95 GeV photons detected from GRB 130427A?

Could these be produced by the synchrotron process?

- ★ **Highest energy photon (95 GeV) was detected 242s after the trigger ($z=0.34$, $E_{\gamma,iso}= 7.8\times10^{53}$erg) when $\Gamma \sim 10^2$.**

- ★ **Highest possible energy for synchrotron photons is when electrons lose half their energy in one Larmor time**

  (Because electrons gain energy by a factor ~2 in shock acceleration in ~ a few Larmor time)

- ★ **Larmor time =** $\dfrac{m_e \gamma_e c}{qB}$ **Synchrotron loss rate** $= \dfrac{\sigma_T B^2 \gamma_e^2 c}{6\pi}$

$$\text{Larmor time} \times \boxed{\begin{array}{c}\text{Synchrotron}\\ \text{loss rate}\end{array}} < m_e \gamma_e c^2$$

$$\Longrightarrow \quad \nu_{max} = \frac{q \gamma_e^2 \Gamma B}{2\pi m_e c} < \frac{9 m_e c^3 \Gamma}{16\pi q^2} = 50\ \Gamma\ \text{MeV} \lesssim 10\text{GeV}$$

>10GeV photons might be due to IC in external shock, however, perhaps the above limit could be violated by inhomogeneous B.

Summary

- ☆ *Life before Swift was launched was simple (afterglow lightcures were easy to understand). However, the behavior of multi-wavelength afterglow data since the launch of Swift has turned out to be a lot more complicated than we had expected. We understand some basic features but there are many things we don't understand!*

- ☆ *High energy photons (>100 MeV), after the prompt phase, are produced by the simplest possible mechanism one could imagine, i.e. synchrotron in external shock. However, it is unclear how >10 GeV photons are produced.*