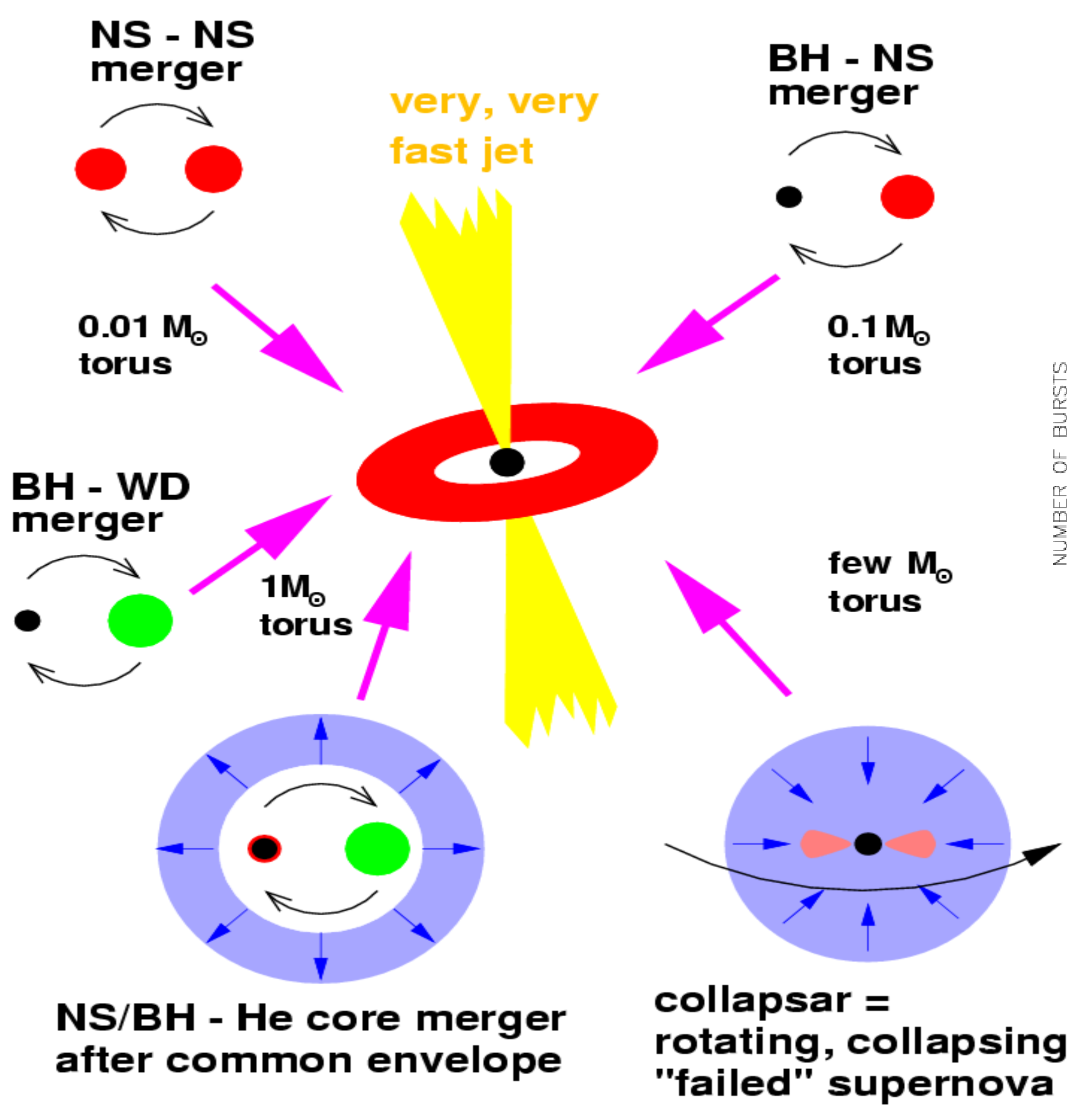
Models of Early Afterglows in the light of Swift

Peter Mészáros
Pennsylvania State University

GRB: standard paradigm

Hyperaccreting Black Holes

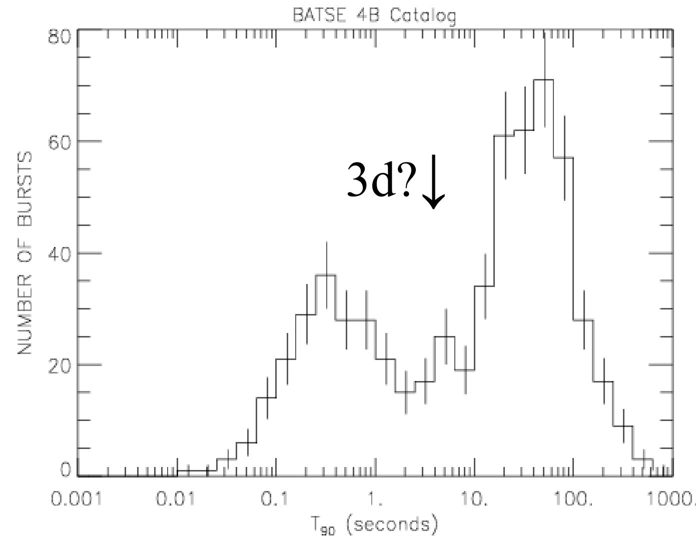


M. Ruffert, H.-Th. Janka, 1998

Bimodal distribution of t_γ duration

← ↓**Short**

(t_g< 2 s)



← ↑**Long**

(t_g >2 s)

Relativistic Outflows

- Energy-impulse tensor : $T_{ik} = w\, u_i\, u_k + p\, g_{ik}$,
  $\mathbf{u}^i$: 4-velocity, $\mathbf{g}_{ik}$= metric, $g_{11}=g_{22}=g_{33}=-g_{00}=1$, others 0;
  ultra-rel. enthalpy: $w = 4p \propto n^{4/3}$; w, p, n : in comoving-frame
- 1-D motion : $u^i=(\gamma,u,0,0)$, where $\mathbf{u = \Gamma\, (v/c)}$,
  v = 3-velocity, **A**= outflow channel cross section :
- Impulse flux
  energy flux
  particle number flux

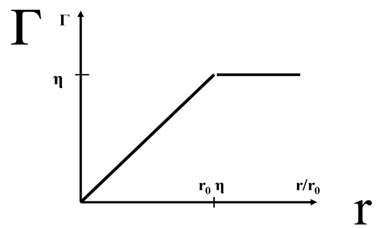
Impulse flux	$Q=(w\, u^2 + p)\, A$
energy flux	$L= wu\, \Gamma\, c\, A$
particle number flux	$J= n\, u\, A$

- Isentropic flow : **L, J constant** →

  $w\, \Gamma\, /n = \text{constant}$ (relativistic Bernoulli equation);
  for ultra-rel. equ. of state $p \propto w \propto n^{4/3}$, and cross section $A \propto r^2$

→ $n \propto 1 / r^2\, \Gamma$ comoving density drops
→ $\Gamma \propto r$ "bulk" Lorentz factor initially grows with **r**.

- But, eventually saturates,
  $\Gamma \rightarrow E_j/M_j c^2$ ~ constant



Shock formation

- Collisionless shocks (rarefied gas)
- "Internal" shock waves: where ?

  If two gas shells ejected with $\Delta \Gamma = \Gamma_1 - \Gamma_2 \sim \Gamma$, starting at time intervals $\Delta t \sim t_v$,, they collide at r_{is} ,

$$r_{is} \sim 2\, c\, \Delta t\, \Gamma^2 \sim 2\, c\, t_v\, \Gamma^2 \sim 10^{12}\, t_{-3}\, \Gamma_2^2 \text{ cm}$$

(internal shock)

[Alternative picture: magnetic dissipation, reconnection]

- "External shock": merged ejected shells coast out to r_{es}, where they have swept up enough enough external matter to slow down, $E=(4p/3) r_{es}^3\, n_{ext}\, m_p\, c^2\, \Gamma^2$,

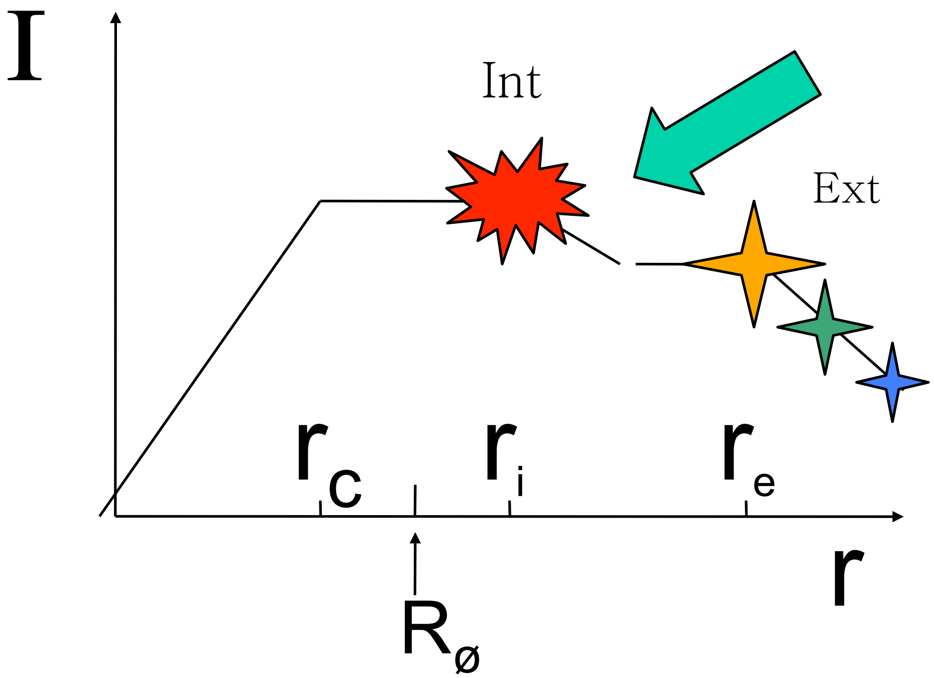
$$r_{es} \sim (3E/4p n_{ext} m_p c^2)^{1/3}\, \Gamma^{-2/3} \sim 3.10^{16} (E_{51}/n_O)^{1/3}\, \Gamma_2^{-2/3} \text{ cm}$$

(external shock)

Internal & External Shocks

in optically thin medium :

LONG-TERM BEHAVIOR



- **Internal** shocks (or other, e.g. magnetic dissipation) at radius $r_i \sim 10^{12}$cm

  →**γ-rays** (***burst***, t_γ ~sec)
- **External** shocks at $r_e \sim 10^{16}$cm;

  progressively decelerate, get **weaker and redder** in time (Rees & Meszaros 92)
- Decreasing Doppler boost: → roughly, expect **radio** @ ~1 week , **optical** @ ~1 day (Paczynski, & Rhoads 93, Katz 94)
- PREDICTION :

  Full quantitative theory of:
- External ***forward*** shock spectrum

  softens in time:

  X-ray, optical, radio …

  →**long fading afterglow**

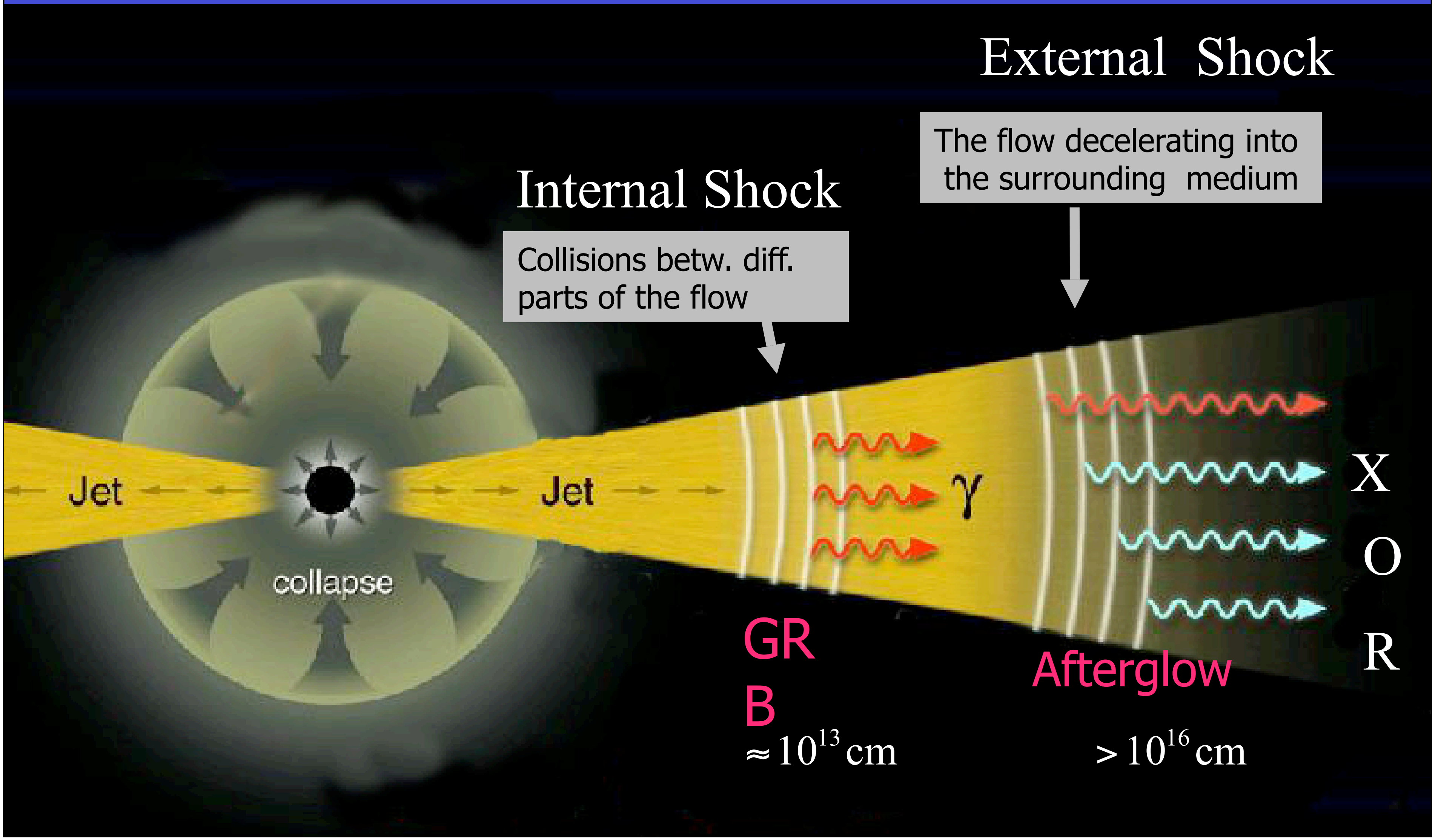
  (t ~ min, hr, day, month)
- External ***reverse*** shock (less relativistic, cooler, denser):

  Prompt **Optical → quick fading**

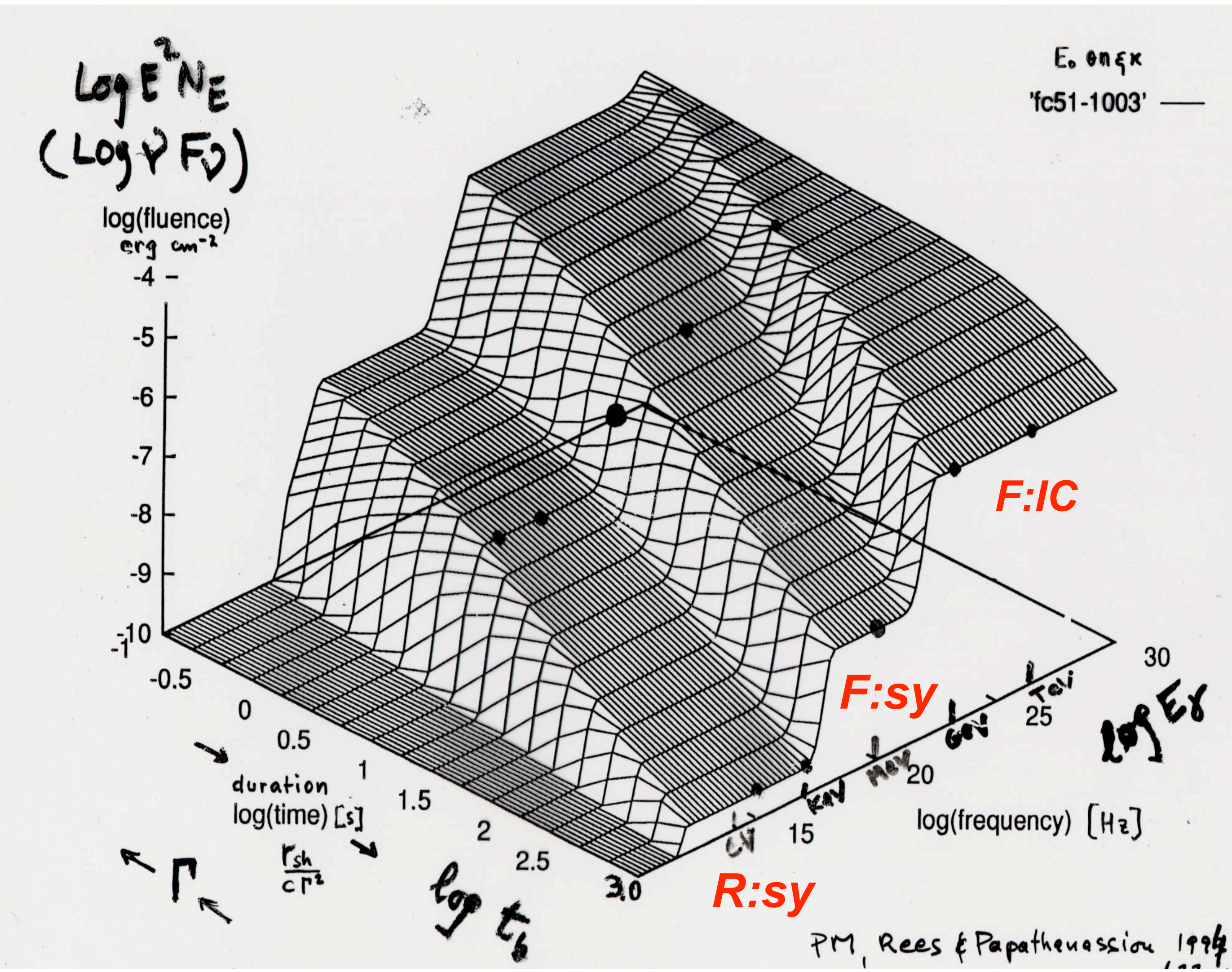
  (t ~ mins)

  (Meszaros & Rees 1997 ApJ 476,232)

Fireball Model: long GRBs



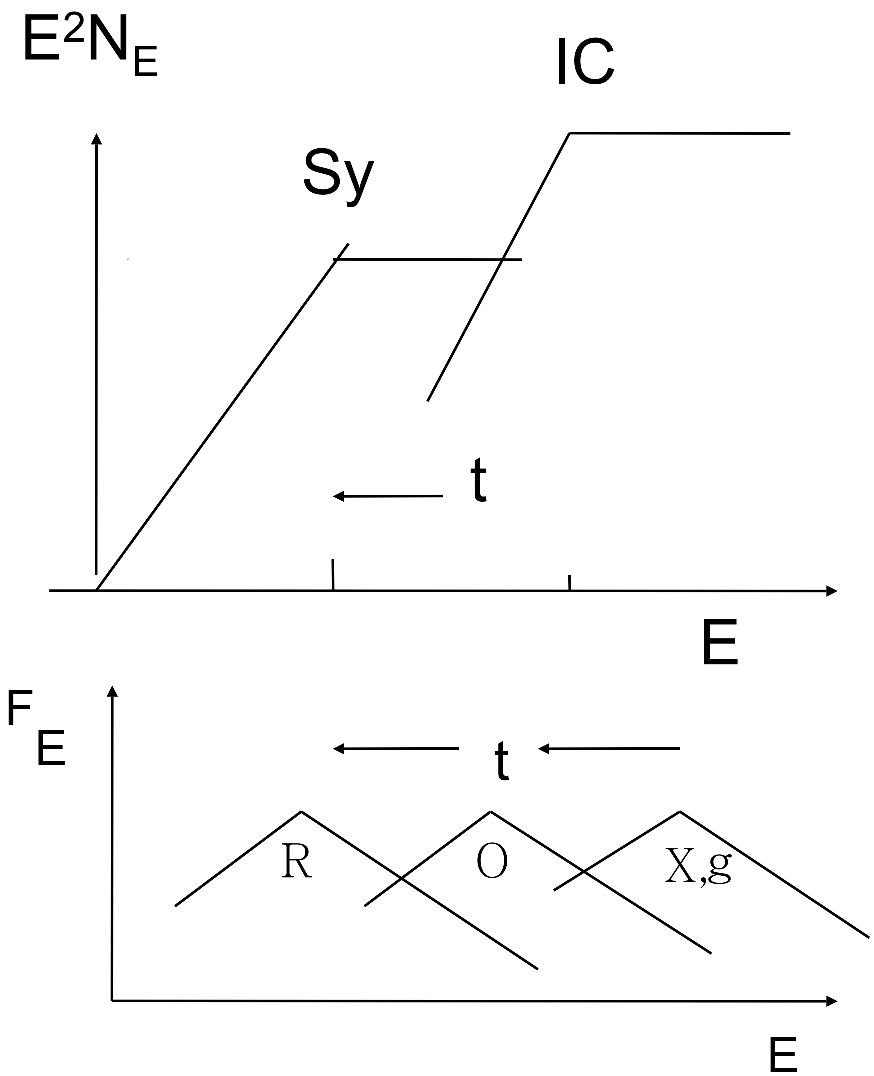
Standard External Forw. & Rev. Shock Synchroton & IC spectrum



Lower energy:
Synchrotron
(reverse: eV,
forward: MeV)

Higher energy:
Inv. Compton
(forward: GeV)

Shock Photon Spectrum



- **Non-thermal** power law spectrum, both in int. and ext. shocks, due to
- **Synchrotron**, peak at ~200 keV (or ~ eV?)
- **Inv. Compton**, peak ~ GeV (or ~200 keV ?
- Sy peak location, ratio Sy/IC dep. on $\mathbf{B_{sh}}$, $\boldsymbol{\gamma_{e,m}}$
- Peak **softens** with time
- Ratio Sy/IC **decr** w. time

SWIFT: New Results

- **> 90** new **afterglows** localized since launch
- **Redshifts** for **>18** long GRB and **4** short GRB
- **$\langle z_{long} \rangle \sim 2.4\text{-}2.8$**, which is 2x Beppo-Sax distance

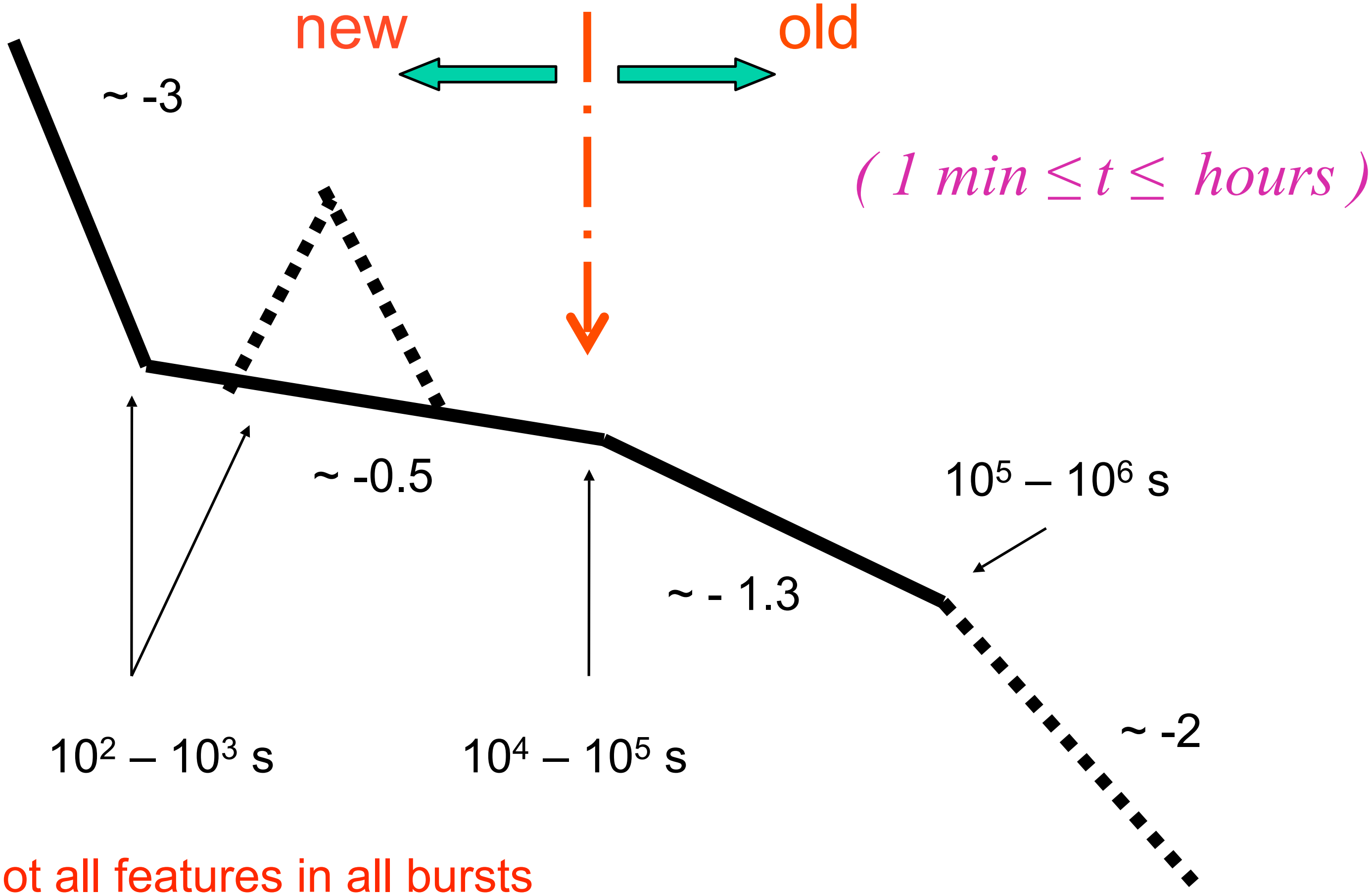
  (i.e. significantly ***fainter & redder***, than Beppo-Sax afterglows!)
- **$\langle z_{short} \rangle \sim 0.1\text{-}0.7$**; $L_{short} \sim 10^{-2} L_{long}$; compact merger
- **XR light curves** (10^2s-10^4s): new features

  (both long and short) - **steep + shallow decay, flares**

→ evidence for ***continued activity?***

In the period ***1 min < t < hrs***, new features show up, which ***may*** be natural extensions of the standard burst & AG model (or ..?)

New features seen by Swift : A Generic X-ray Lightcurve



BUT: not all features in all bursts

Afterglow: when does it start?

- standard interpretation: AG starts at

  $t_{dec} \sim (3/4)\,(r_{dec}/2\,c\,\Gamma^2)\,(1+z)$

  $\sim (3/8\,c\,\Gamma^2)(3E/4\pi\,n\,m_p\,c^2\,\Gamma^2)^{1/3}\,(1+z)$

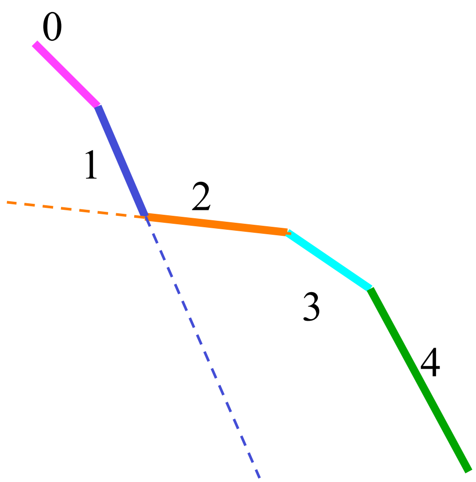
  $\sim 10^2\,(E_{52}/n_0)^{1/3}\,\Gamma_2^{-8/3}\,(1+z)$ s

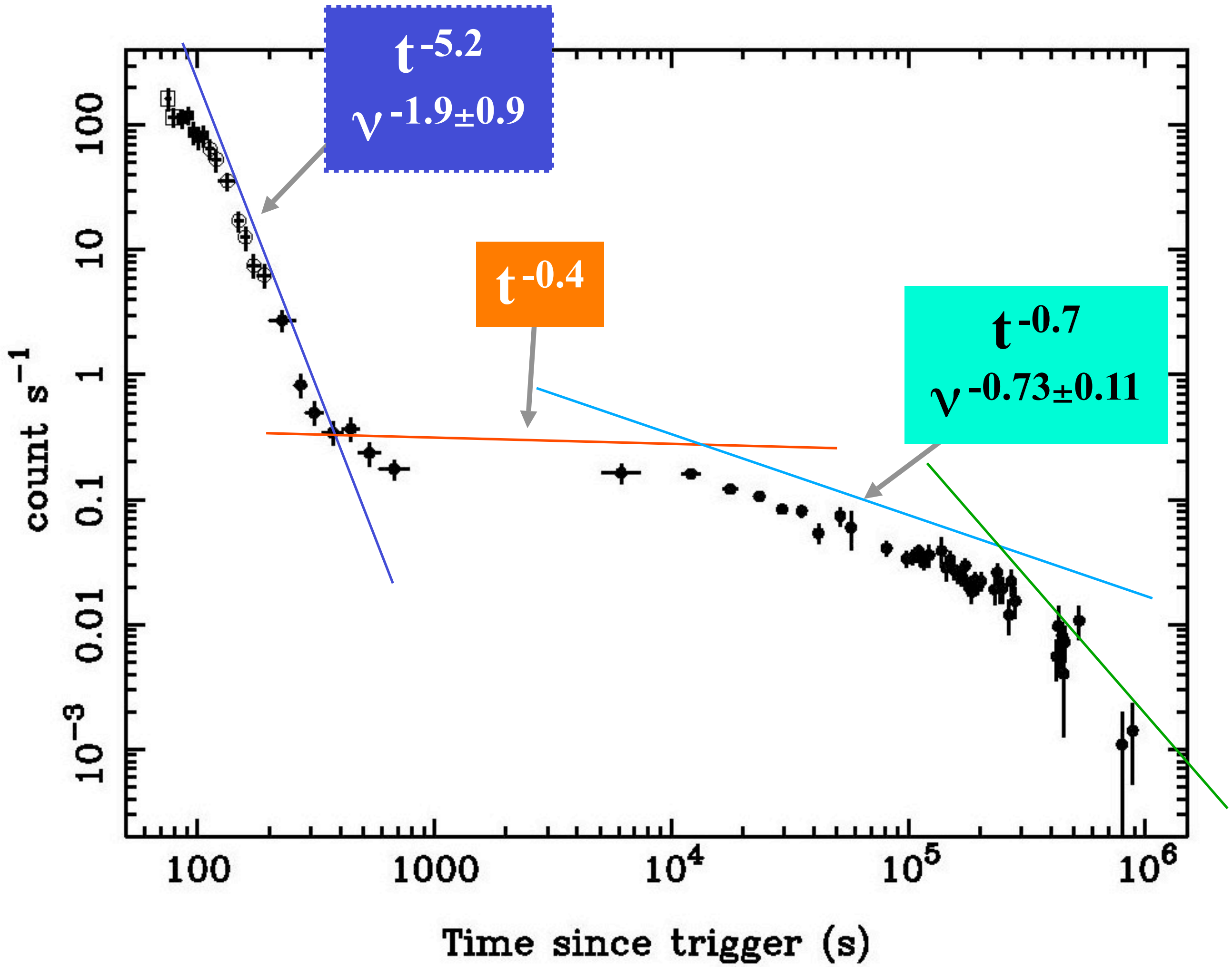
- But, for prompt duration $T=T_\gamma=T_{outflow} \sim T90$

  - "Thin shell": $T < t_{dec} \rightarrow$ AG start at t_{dec} above
  - "Thick shell": $T > t_{dec} \rightarrow$ AG start at $T \sim T_\gamma \sim T90$

Example : GRB 050315

Vaughn et al. 2005



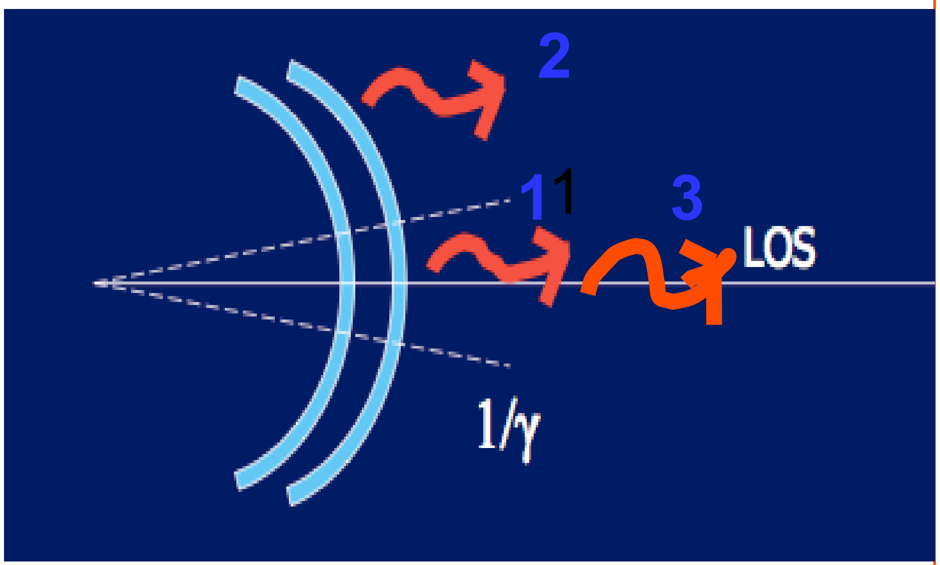


Initial steep drop:
$F_x \propto (t-t_0)^{-\alpha}$

- Very early jet break? (jet too narrow)
- Patchy jet (spike)? (same … probability?)
- Cocoon radiation? Possible (Pe'er, et al, 06 in prep.)
- Current bet: ***tail end of GRB*** (**high latitude** emission) : radiation from outside main beam, $\theta > \Gamma^{-1}$
  - *arrives at* $t \sim R\theta^2/2c$ *later than from* $\theta \sim 0$,
  - *is softer by* $D \sim t^{-1}$ (Nousek et al 05, Zhang et al 05, Panaitescu et al 05))
- expect $\alpha = 2 + \beta$, where $F \sim t^{\alpha}\nu^{\beta}$ (Kumar, Panaitescu 00)

  ~ OK , generally; departures may be understood

Initial rapid decay: **High latitude emission**



Radiation Components:

- **1** : Prompt γ-rays (GRB) from l.o.s. angles $\theta < \Gamma^{-1}$
- **2** : tail-end of GRB, from high latitude emission : γ-rays emited promptly, but from angles $\theta > \Gamma^{-1}$; arrive at time **$t \sim R\theta^2/2c$** later than from $\theta \sim 0$, and is softer by **$D \sim t^{-1}$**; expect

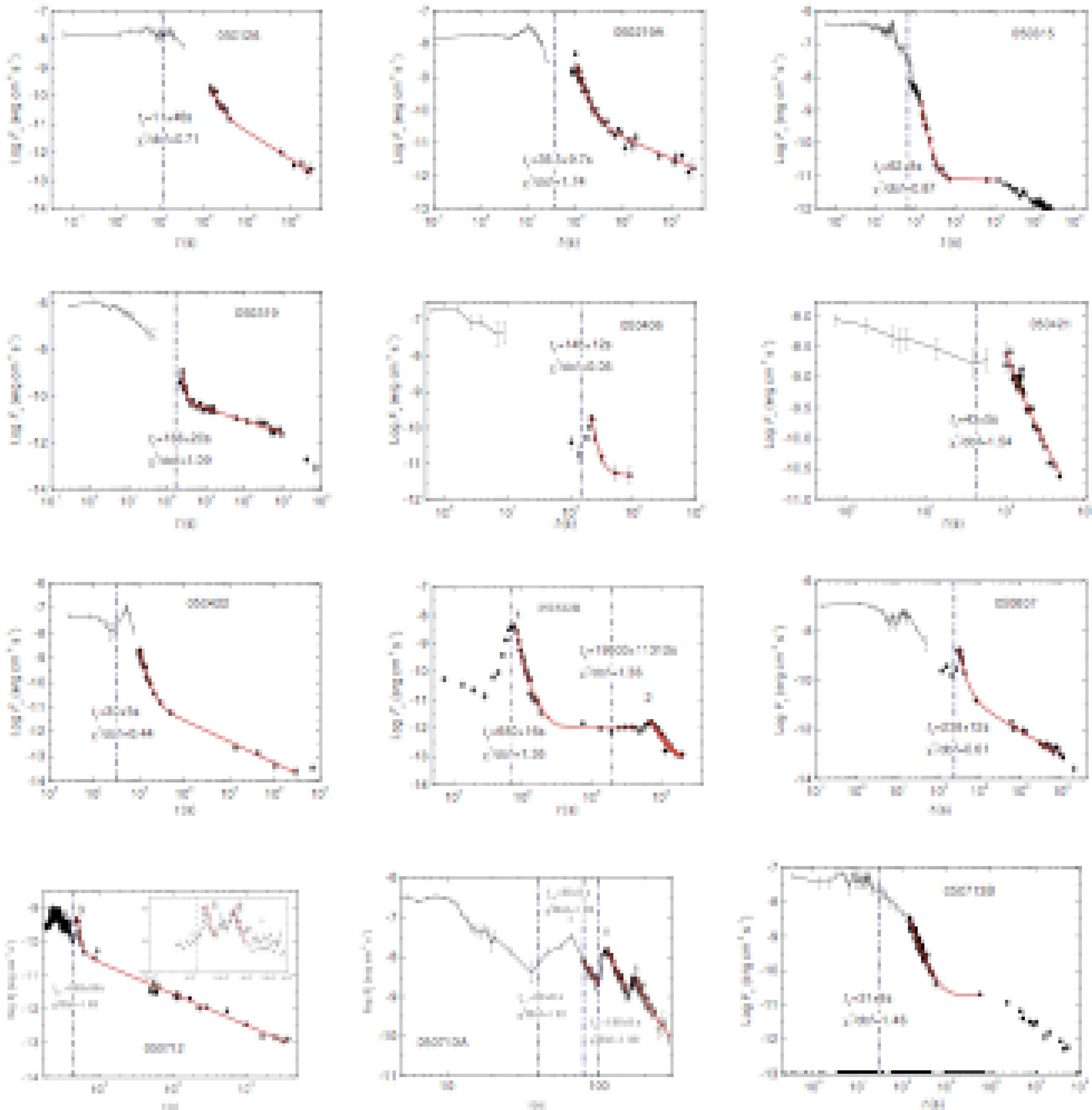
  $\alpha = 2 + \beta$, ~ OK
- **3** : afterglow, from forward shock at l.o.s.angles $\theta < \Gamma^{-1}$; later than (or partially overlap with) high latitude comp. (**2**)

High latitude …

- Time slope α depends on choice of t_0

  $\rightarrow$ can fit t_0 such that slope is satisfied

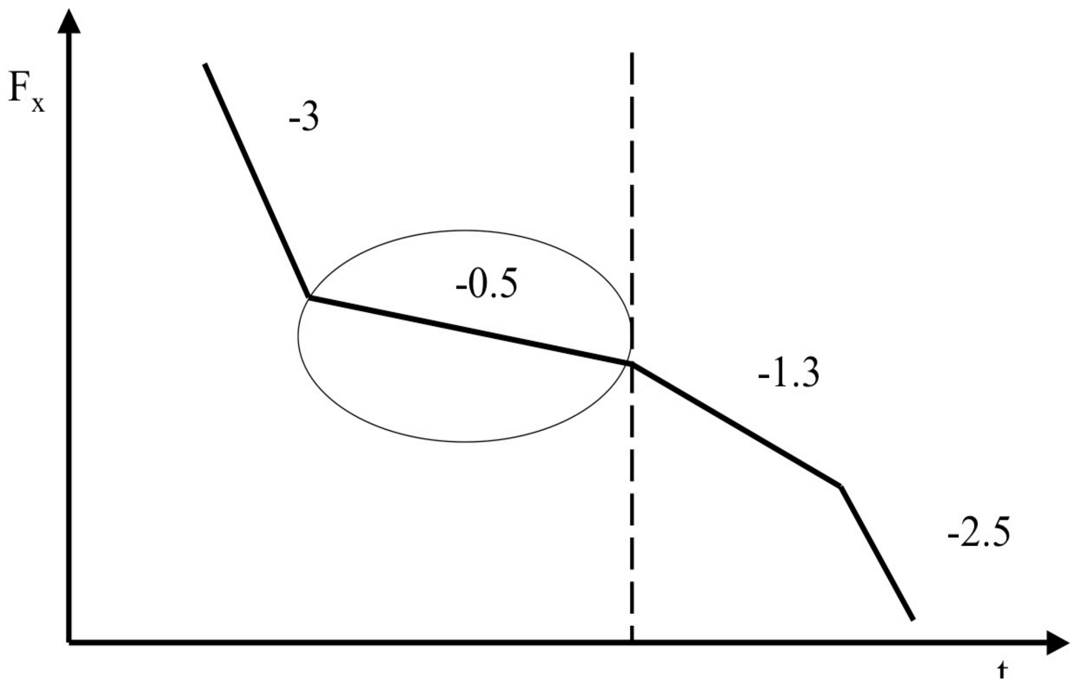
  i.e., determine t_{dec} ? (Liang et al astroph/0602142)
- When $T > t_{dec}$ (and also when $T < t_{dec}$) can have an admixture of (a) afterglow (l.o.s) $\theta<\Gamma^{-1}$, and (b) high latitude $\theta>\Gamma^{-1}$ components. Generally $\beta_{prompt} < \beta_{steep}$, so can accommodate steeper decays than $2+\beta_{prompt}$ (O'Brien et al, 05)
- Flares: t_0 fit can give pulse ejection time by engine (Liang et al 06)
- Structured jet: for on-beam viewing jet shape has little effect, but off-beam can get shallower slope (Dyks et al aph/0511699)
- From initial steep decay slope, t_0 constraints suggest $t_0 \sim t_{trigger}$, may infer prompt emission radius R_γ (Lazzati, Begelman aph/0511658)



Retrofit:

The t_0 which fits the steep decay slope generally agrees with the onset of the rising segment of the last peak before the decay

Liang, et al aph/0602142



Shallow decay

- Slope $0.3 \leq \alpha \leq 1$:

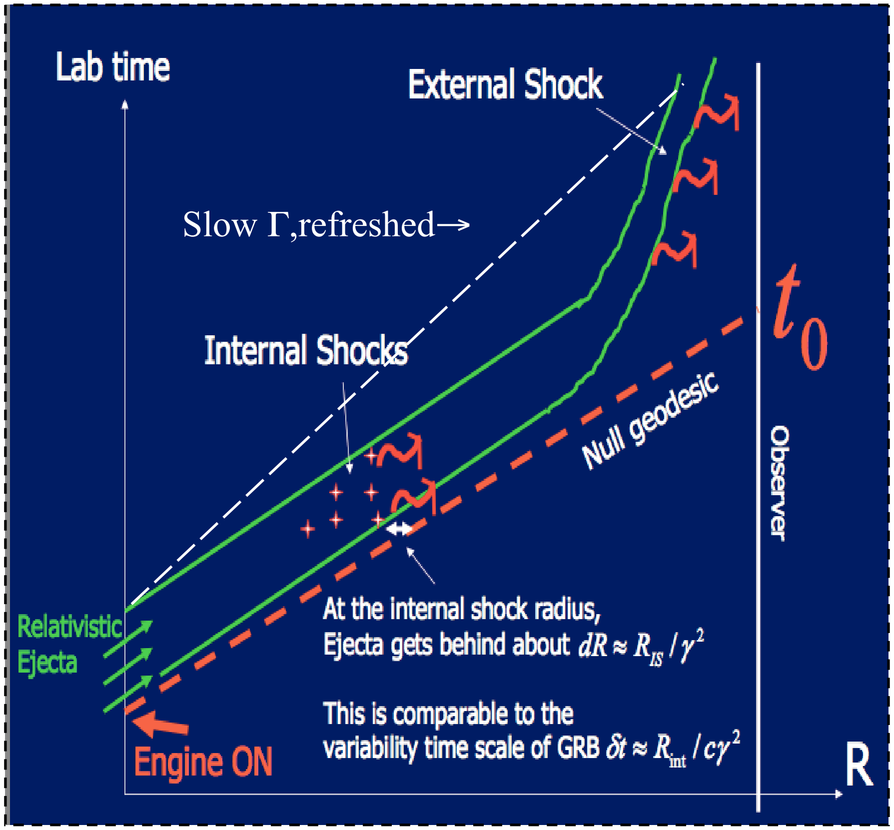
likely due to ***"refreshed shock"*** …

I.e. the forward afterglow shock receives continued reinforcement from late-arriving ejecta

NOTE: late ***arriving***, but not necessarily late ***ejected!***

(Rees-Meszaros 98, Panaitescu, PM, MJR 98, Kumar-Piran 00, Sari-Meszaros 00, Nousek et al 05, Zhang et al 05, Granot-Kumar 05)

Shallow decay ($0.2 \leq \alpha \leq 1$)



- Probably due to **refreshed shocks,** due ***either*** to:
- ***Long*** duration ejection ($t \sim t_{flat}$) ; ***or***
- ***Short*** duration ejection ($t \sim t_\gamma$), but with range of Γ, e.g. $M(\Gamma) \sim \Gamma^{-s}$, $E(\Gamma) \sim \Gamma^{-s+1}$, for $\rho \sim r^{-g}$ ext. medium :

e.g. FS: $\alpha=[-4-4s+g+sg+\beta(24-7g+sg)]/[2(7+s-2g)]$

Rees+PM, 98 ApJ 496, L1 ; Sari +PM, 00, ApJ 535, L33 ; Zhang +PM 01, ApJ 552, L35

Note : Fit to Swift data ⇒ Γ distrib. may be a broken power law

(Granot, Kumar astro-ph/0511049)

Refreshed (shallow decay)

- Note : $E_{Xshallow} \leq E_{\gamma prompt}$ [O'Brien, et al, 06].

But in order for refreshed shock to dominate the afterglow, energy input in refreshed component needs exceed that in prompt

- $\Rightarrow$ *either* - rad'n. effic. $\varepsilon_\gamma > \varepsilon_x$ (eg prompt is Poynting dominated ?..)

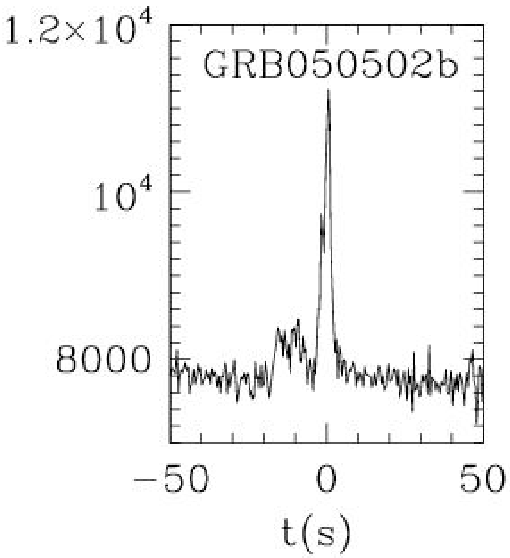
  or - fraction of refreshed shock energy **undetected** (IR? GeV?…)

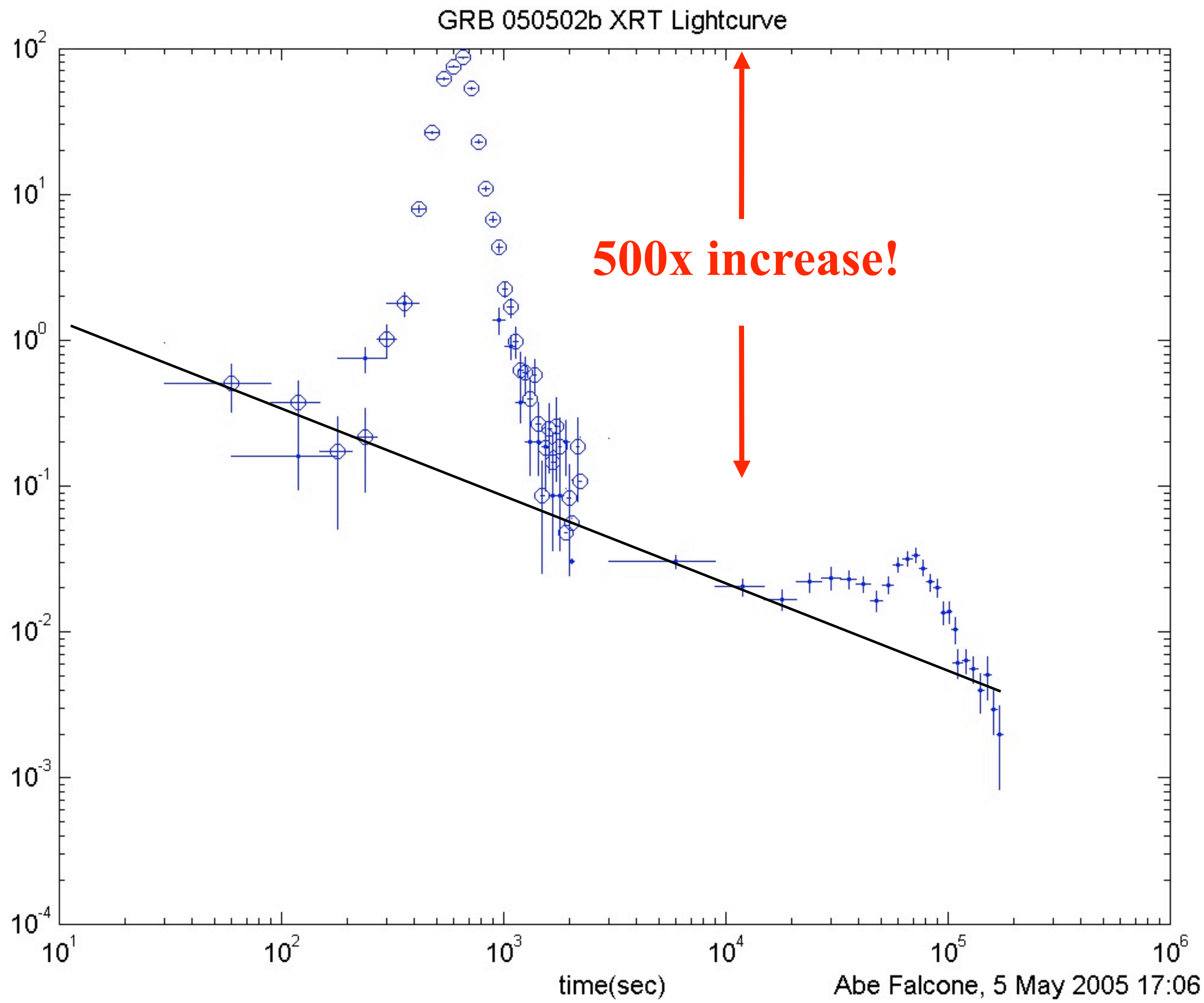
  or - preactivity evacuates cavity, or

  fraction of energy into electrons $\propto t^{1/2}$ (Ioka et al, astro-ph/0511749

- Alternative : shallow decay due to emission from anisotropic jet lines of sight just outside sharp edge of main bright jet (Eichler-Granot astroph/0509857)
- Other possibilities:
  - E_{kin} underestimated (also in BATSE), so ε_γ is reasonable relative to ε_X
  - Two-component jet (narrow-fast/broad-slow) (Granot, et al, astroph/0601056)

Giant X-ray Flare: GRB050502b





GRB Fluence:
8E-7 ergs/cm^2

Flare Fluence:
9E-7 ergs/cm^2

Burrows et al. 2005, Science; Falcone et al. 2005, ApJ

XR Flares

- Main puzzles: - large energy $E_{xfl} \leq 0.1\text{-}1\ E_{\gamma prompt}$
  - steep rise/decay $F \propto (t-t_0)^{\alpha}$, $\alpha \sim \pm 3\text{-}6$
- Possible causes:
  - refreshed (forward) shocks (rise & decay too shallow)
  - reverse IC component (one shot affair- where is forward?)
  - interaction with external matter (rise/decay slope?)
  - ➡ continued central engine activity, e.g. internal shocks, dissipation (difficult for central engine, but address temp. slope, total energy - less problematic than others ?)

XR Flare triggers?

- Gravitational instability → disk fragmentation → lumpy accretion

  (Perna, Armitage, B.Zhang)

- MHD accretion- magnetic tension (“springy”) → lumpy accretion

  (Proga & Begelman, Fan, Proga &B.Zhang)

- Short bursts: BH-NS disr (SPH GR numerical)

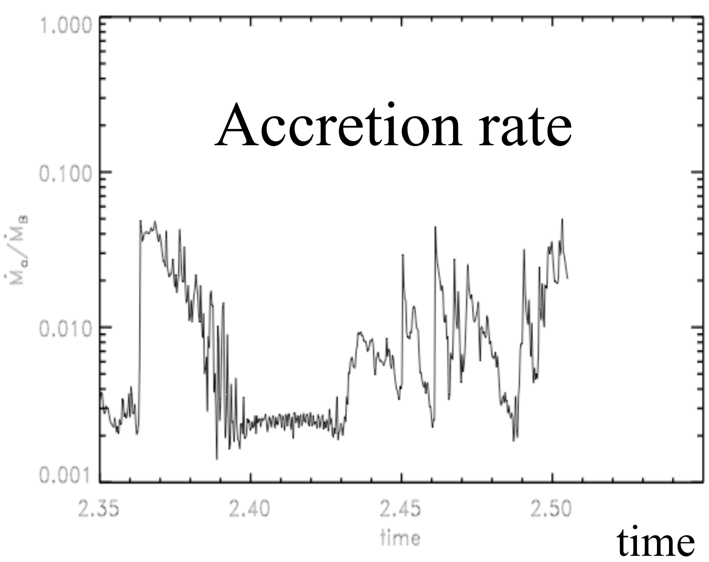
  → prompt accretion + extended tail

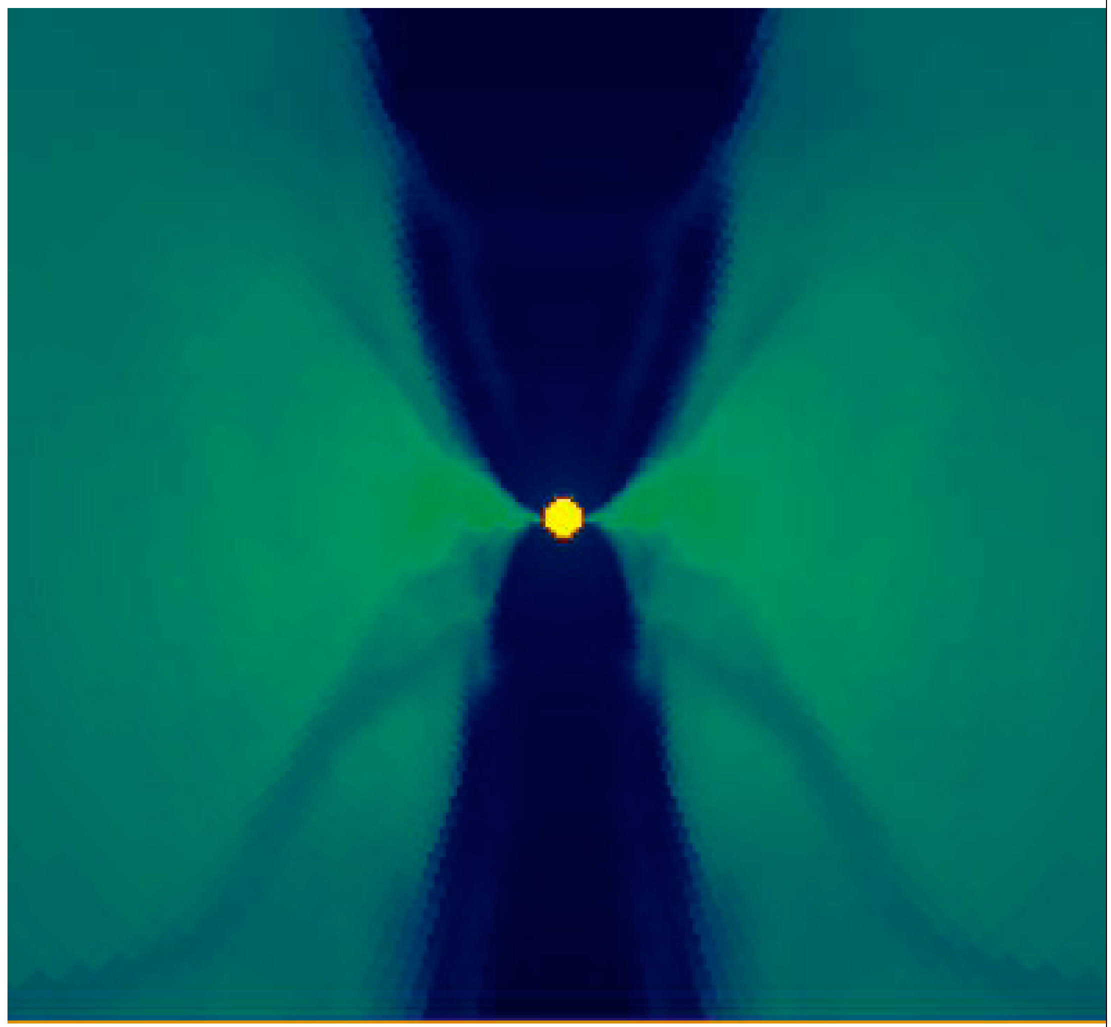
  → delayed lumpy accretion

  (Davies, et al 05; Lee et al 00, Rosswog et al 04; Laguna, Rasio 05)

MHD accretion?

(Proga & Begelman 03)





Main Possible Explanations of long GRB afterglow new features

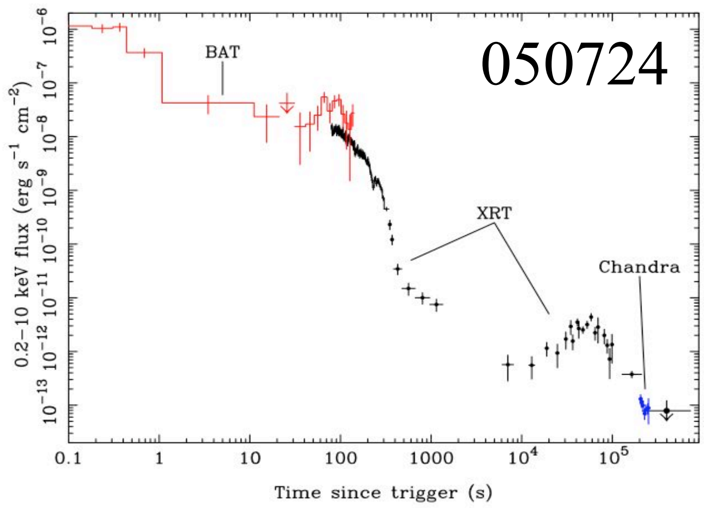
- ***Initial drop:*** likely due to **tail end of GRB** (high latitude emission) : rad'n from $\theta > \Gamma^{-1}$ arrives at **$t \sim R\theta^2/2c$** later than from $\theta \sim 0$, is softer by $D \sim t^{-1}$; expect $\alpha = 2 + \beta$, ~ OK
- ***Shallow decay:*** probably "refreshed shocks", ***either*** from ***Long**er* ejection ($t \sim t_{flat}$) ; ***or Short*** ejection ($t \sim t_\gamma$), but with range of Γ, e.g. $M(\Gamma) \sim \Gamma^{-s}$, $E(\Gamma) \sim \Gamma^{-s+1}$
- ***Flares:*** likely due to continued central engine activity : main constraints: very sharp rise and decline ($t^{\pm 3} \longleftrightarrow t^{\pm 6}$)
- ***But:*** remains work in progress- depending also on new observations

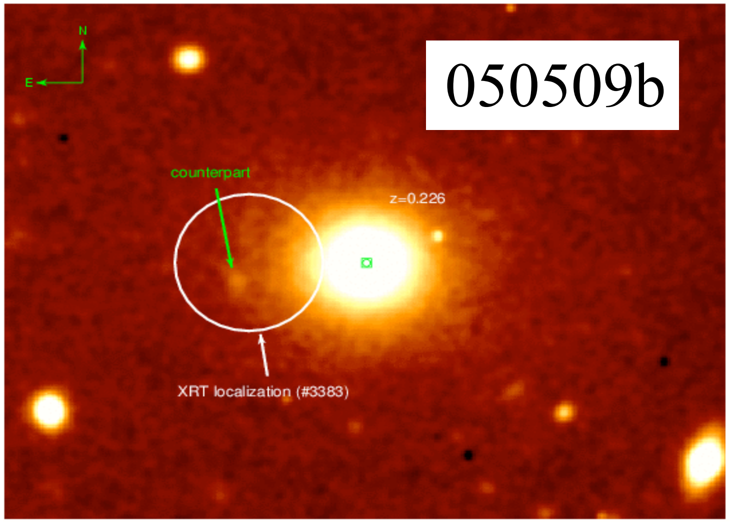
Short & Long Afterglows

- ***Big question: are they the same?***
- 0th order answer: looks like **yes**
  - initial steep decay ✓
  - XR flares ✓
  - “normal forward shock” decay ✓
  - jet break ✓
- But: 1st order **differences** are interesting
  - Avg. kin. energy/solid angle x100 smaller
  - Avg. jet angle x2 larger than in long bursts

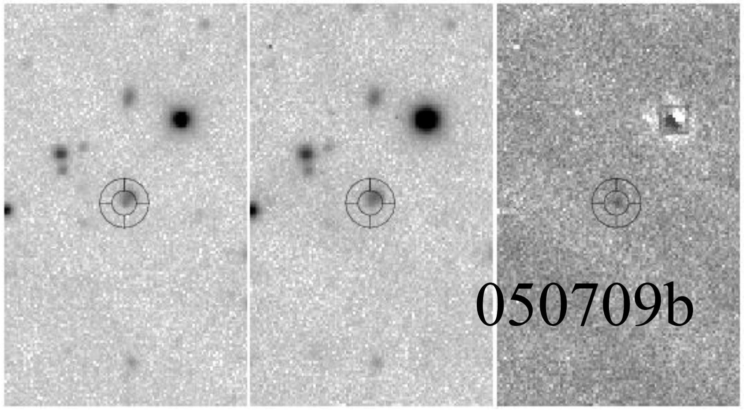
(Fox et al 05, Panaitescu 05)

Short Bursts





- ***Hosts:*** **E , Irr , SFR**
  (compat. W. NS merg, ✓
  but: some SGR, other?)
- ***Redshift :*** < 0.1 to ~ 0.7
- ***XR, OT, RT:*** yes (mostly)
- ***XR l.c.:*** similar to long bursts?
  (XR bumps too- late engine?)



SHB afterglow fits

- So far, > 11 shb afterglows, 5-6 hosts (D. Fox talk, Nature 05)
- AG fits for **050709** (Irr), **050724** (E) (Panaitescu, aph/0511588)

Using fluxes and break times, standard ag model:

$$\Gamma = 6.5\,(E_{50}/n_0)^{1/8}\, t_d^{-3/8}\ , \quad \theta_j = \Gamma(t_b)^{-1}$$

$$\rightarrow \quad \boldsymbol{\theta_j = 9^o\,(n_0/E_{50})^{1/8}\, t_{bd}^{\ 3/8}\ ,}$$

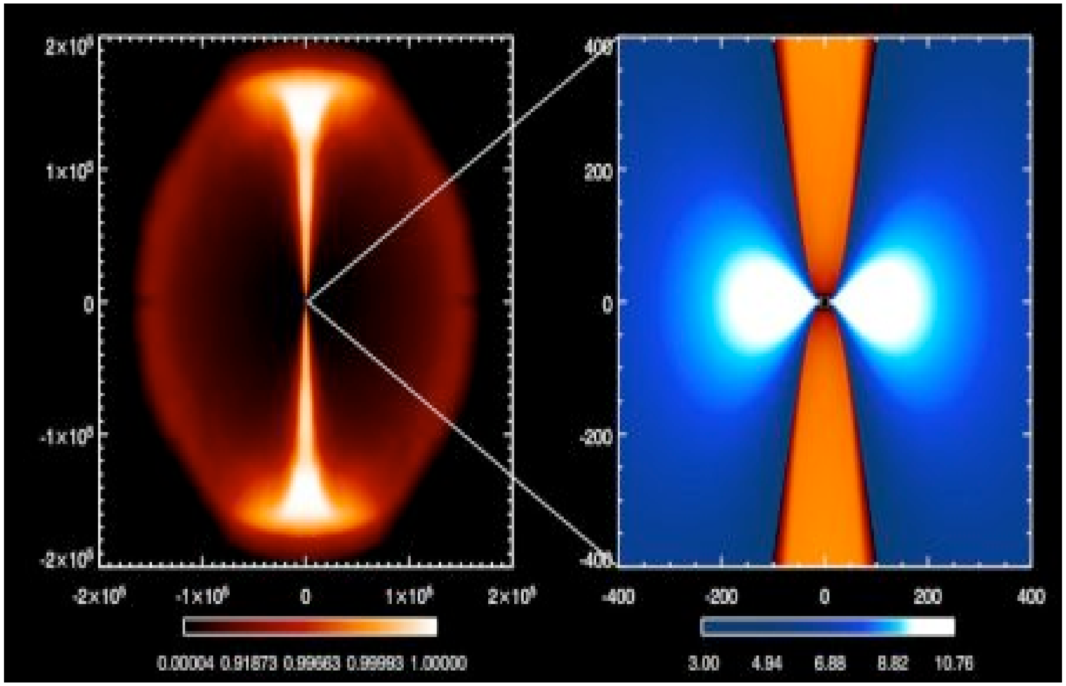
$$\boldsymbol{E_j = \pi\theta_j^2 E \sim 10^{49}\, n_0^{\ 1/4}\,(E_{50}\, t_{bd})^{3/4}\ \mathrm{erg}}$$

High /low dens. soln's: 050709 : $\theta_j > 6^o$, $10^{-4} < n < 10^{-1}$ cm^{-3} , E~3-300 x 10^{50} erg/s

$\theta_j > 2^o$, $n < 10^{-5}$ cm^{-3} , E~2-10 x 10^{49} erg/sr

050724 : $\theta_j > 8^o$, $10^{-1} < n < 10^{3}$ cm^{-3} , E~1-50 x 10^{49} erg/sr

- ***but:*** GRB 050724 (Grupe et al, 06, in prep.) Chandra late obs.: **no** break seen.
- ***while:*** GRB 051221A : Swift + 2 Chandra obs. : well defined jet break appears @ 4 days ⇒ $\theta_j \sim 7^o$, $E_j \sim 2.\ 10^{49}$ erg



Short burst paradigm:

NS-NS or **NS-BH**

merger

↓

BH + accretion

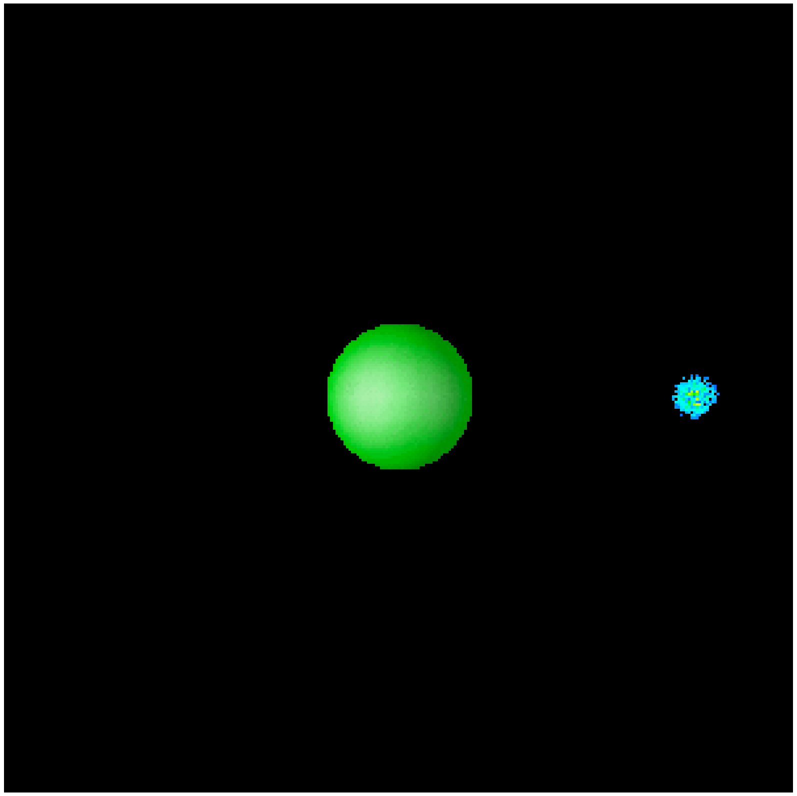
- Paradigm seems compatible with hosts, and (for Kerr BH-NS) some simulations suggest extended activity & flares ⇒

simulation

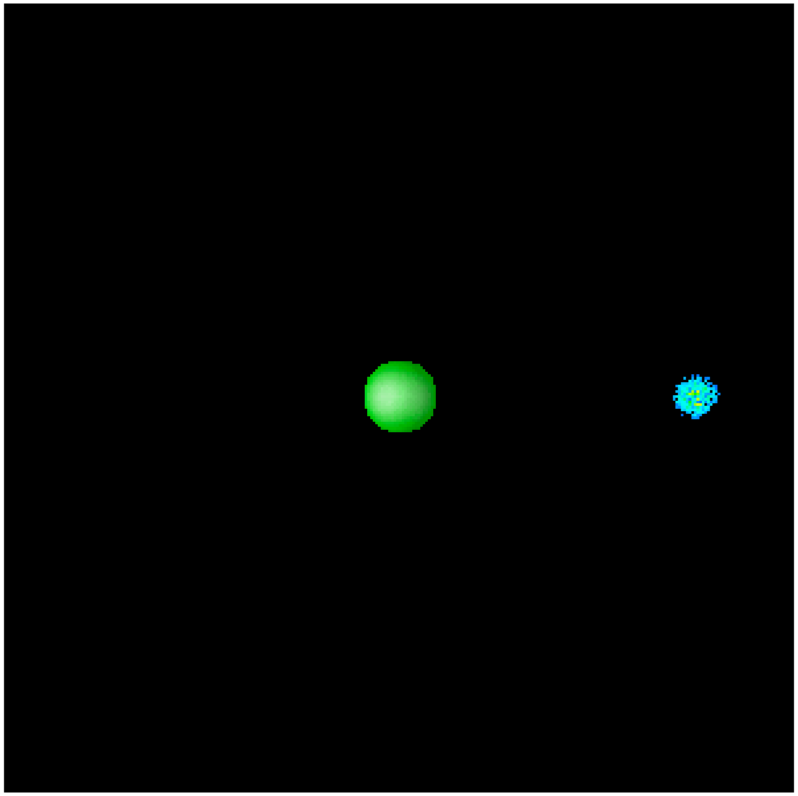
Laguna, Rasio 06;
(Preliminary)

BH-NS merger?

(Laguna & Rasio '06)

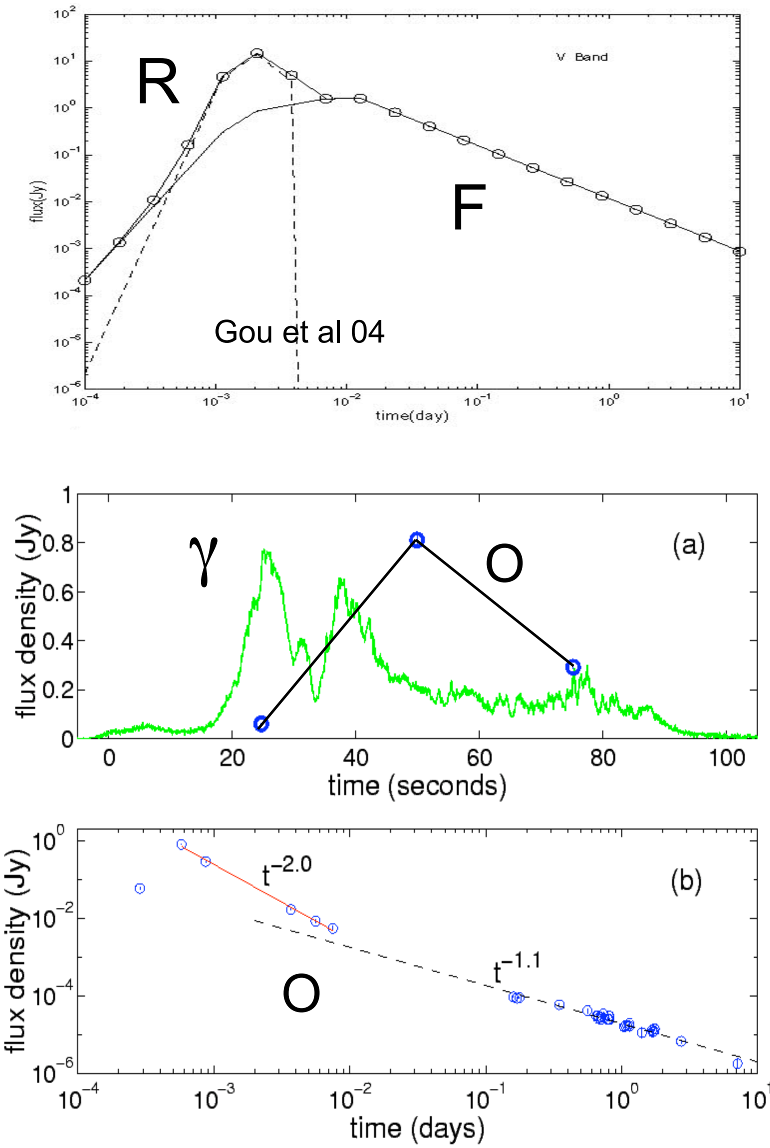


Schwarz.BH-NS



Kerr-proBH-NS

Prompt **optical** *afterglows*

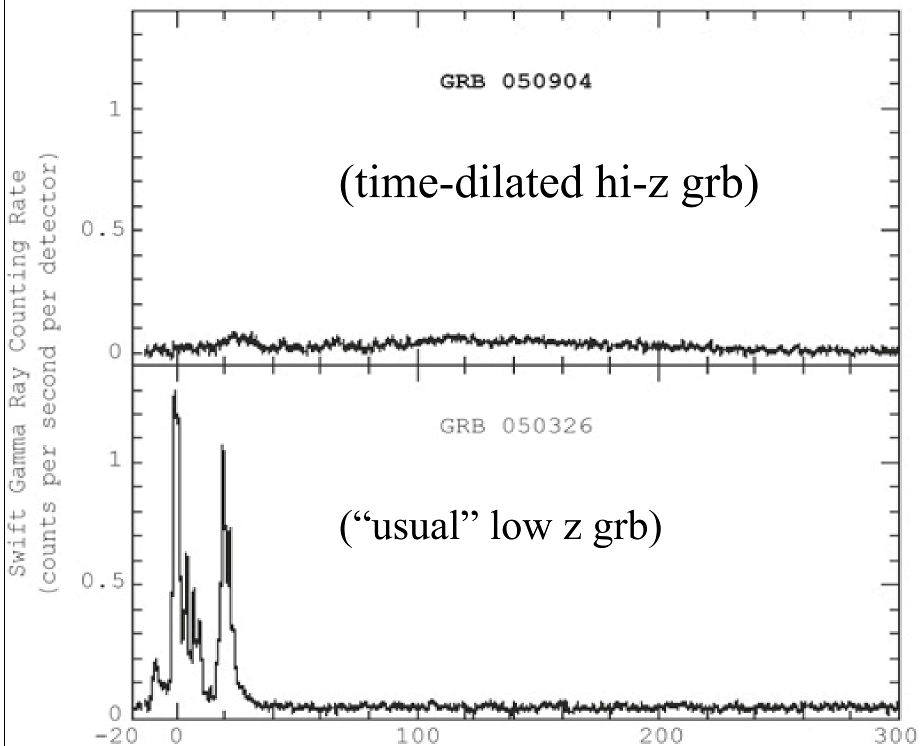


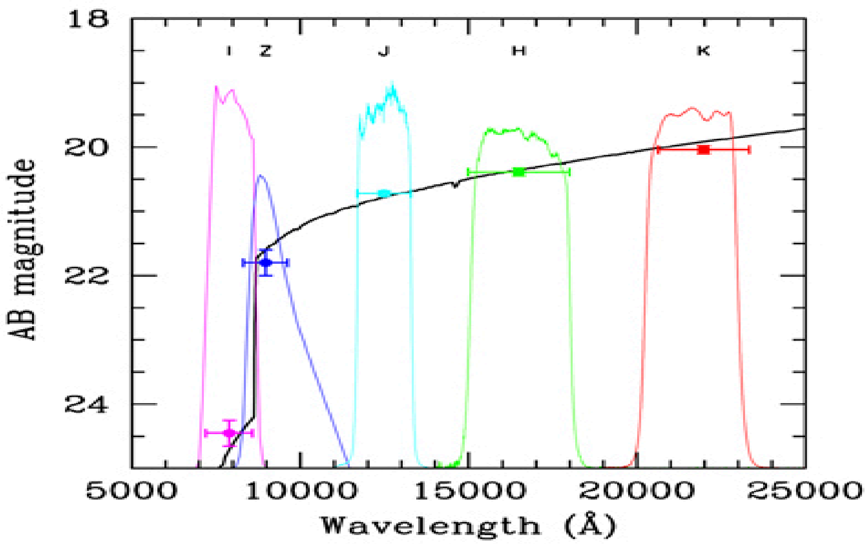
- ⇐ expected behavior: reverse shock causes prompt (10's of sec) bright ($m_V \geq 9$) optical flash, decaying much faster than long-lasting forward shock optical afterglow (Mészáros-Rees 97)
- First seen in GRB 990123

  ⇐ Rotse (Akerlof et al 99), and few other bursts, but ***rare*** : why?
- Could be that
  - rev.shock hi-mag→suppress?
  - pair formation →***spec. to IR ?***
  - rev. shock rel. →***spec. to UV ?***
- Latest :

  GRB 050904 (z=6.29)

  shows **prompt bright opt flash !**





Most distant

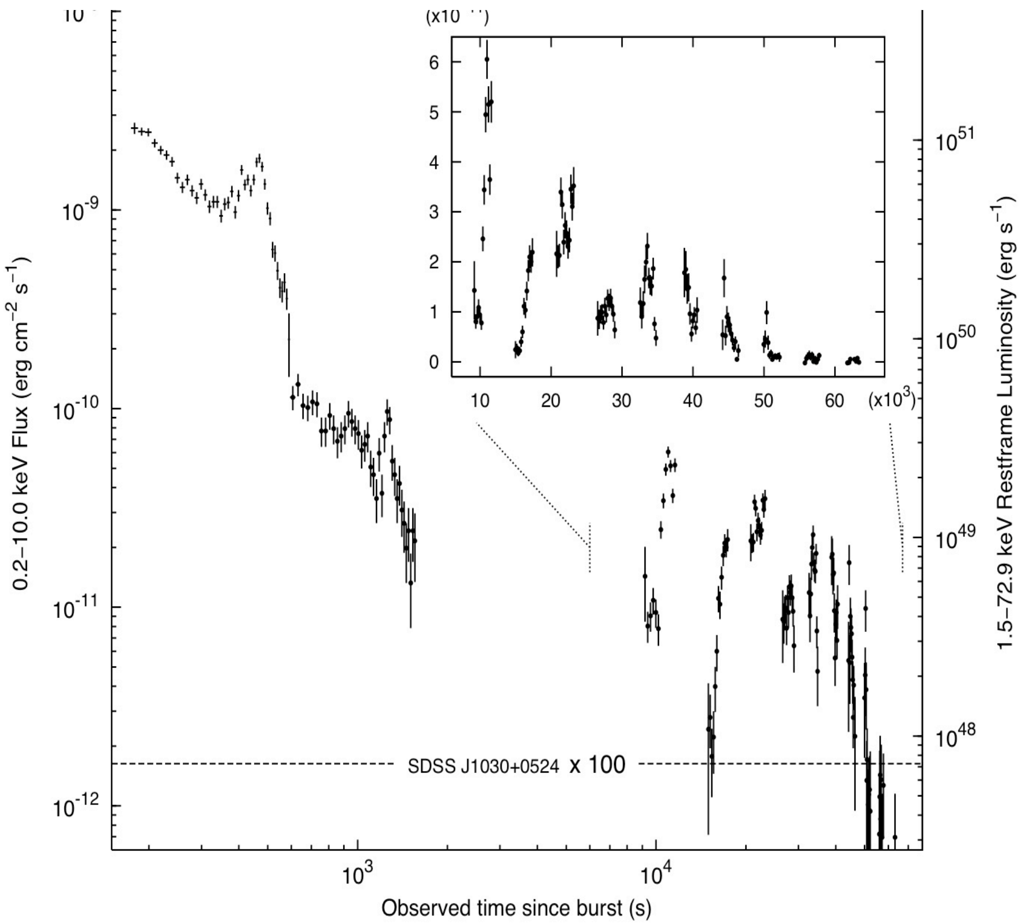
long burst from

Swift **(z=6.29):**

GRB050904

- Discovered/localized by ***Swift***
  BAT, XRT, UVOT
- Prompt ground I,R band **TAROT, P60** upper limits,
- Detection J=17 mag **FUN/SOAR**
  ← ***photometric z >6***
- Spectroscopy **Subaru** 8.5 m
  @ t=3.5 day : ***z = 6.29 !***

GRB 050904 as an XR beacon



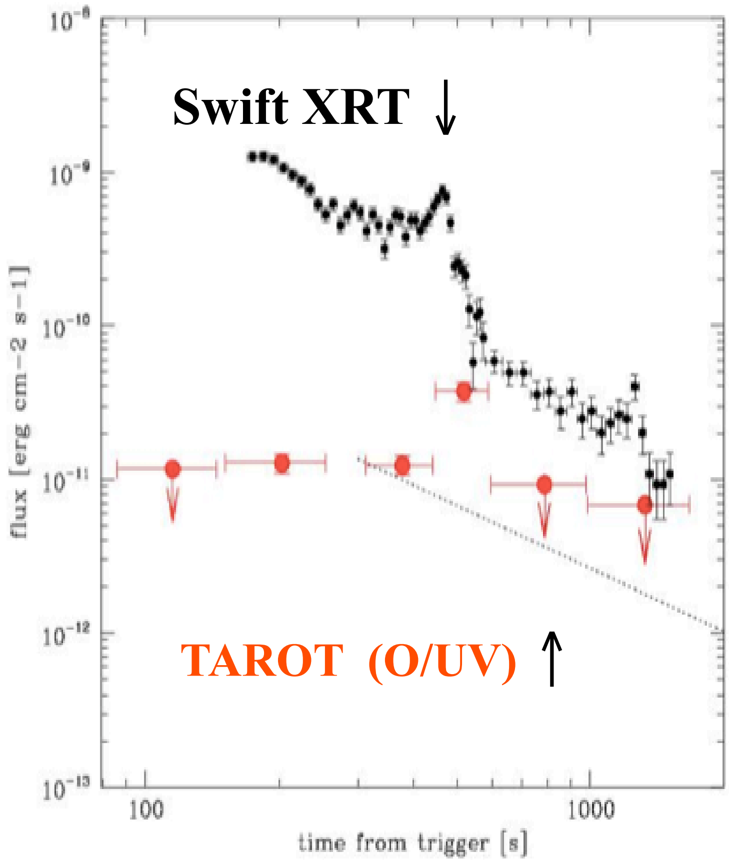
- At a redshift **z=6.29**

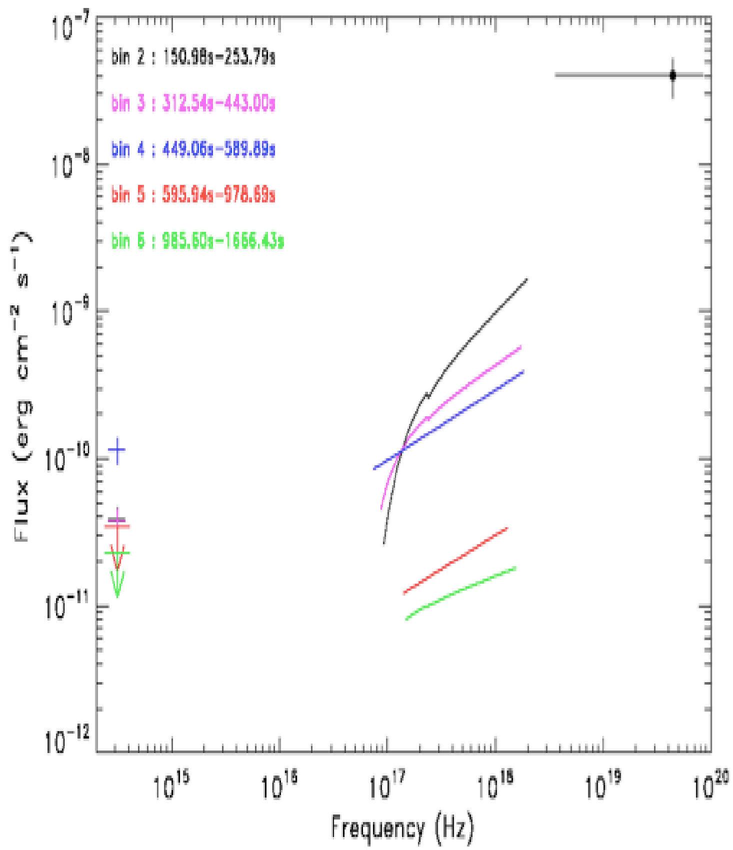
  (~reionization; most distant known known QSR: z~ 6.4)
- GRB 050904 X-ray flux ***exceeded*** that of the brightest known X-ray QSO

  SDSS J0130+0524,

  by up to x**10^5 ,** for **days**

← SDSS J0130 (multiplied by 100)





- Prompt O/UV flash as bright as 990123 (~ 9th mag!) at same z (rev. shock..)
- E_{iso} ~ 10^{54} erg, similarly very high ;decay similarly steep (~ t^{-3})
- Observed at 800-1000 nm by TAROT (25 cm tel.!) [Boer et al, astro-ph/0510381]

Why 050904 and 990123 ?

- Need high $E_{iso} \sim 10^{54}$ erg ? (or small beam?)
- If reverse shock rest frame spectrum in UV (relativistic reverse shock?)

  → ground detection @ O/IR: need high z

  (or else need enough rest-frame spectrum extending redwards of Lyα, so not absorbed)
- Need burst with strong flares (weak "smooth" afterglow component)?
- Other non-obs. or weak flash: pair formation, or weak field in ejecta → rest-frame spectrum shifted to IR?

Origin of prompt O-flash

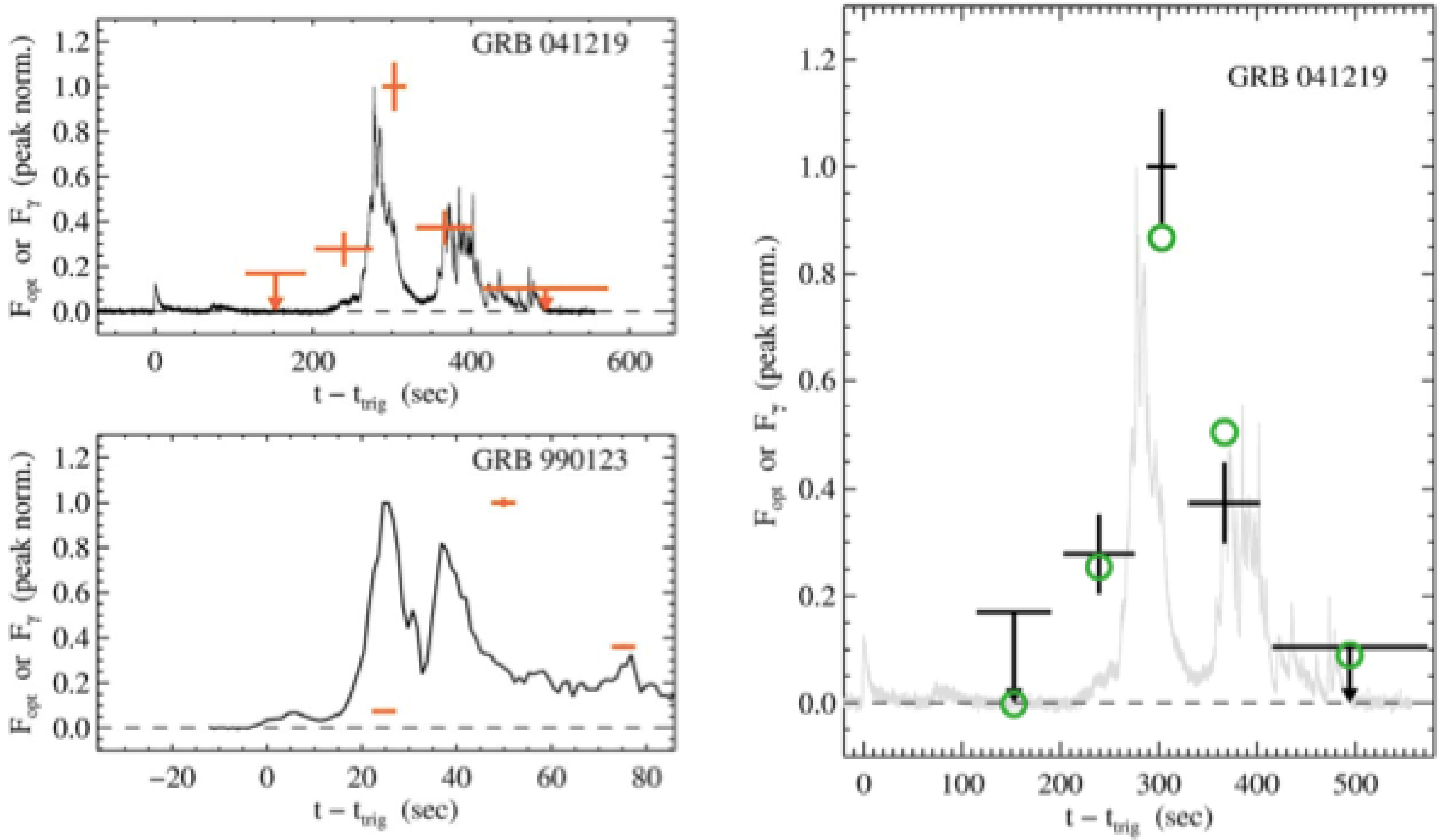
- 4 prompt optical flashes have been measured while the gamma-rays were still in progress
- in some (GRB 050904, Boer et al, astro-ph/0510381; also GRB 041219, Vestrand et al, astroph/0503521)

  - prompt optical l.c. correlates with gamma-rays

  ⇒ emission from the same region? (e.g. internal shock?)
- in others (GRB 050401, Rykoff et al astroph/0508495, GRB 990123, Akerloff et al 00)

  - prompt optical l.c. does NOT correlate with gamma-rays

  ⇒ emission from different region ? (e.g. reverse shock?)



Vestrand et al, 06, aph/0503521

Conclusions

- Swift is significantly expanding our view & understanding of afterglows
- New early XR, O features appear to be understandable within context of standard afterglow model, with (not quite mastered) extensions

  Understanding of new XR "smooth" features is reasonable, but fluid dynamics remains controversial - and MHD may play a large role.
- XR flares are significant challenge, also for progenitor, central engine
- Relation of early XRT, UVOT to BAT flux levels pose challenges to prompt GRB gamma-ray mechanisms (efficiencies, etc..)
- Commonality & differences between short and long GRB afterglow features will yield important clues, need much further work

  (diff. due to lower E_{iso}, broader θ_{jet}, E vs. Irr, Sp hosts?)
- Information on long and short GRB jet breaks (collimation) not very extensive yet, possibly due to higher avg. z and lower fluxes?
- O/UV late afterglows largely support forward shock AG interpretation
- Prompt O/IR flash detection may hold vital clues (rareness? reverse shock interpretation? other..?)
- Potential for high-z IGM probing, SFR mapping appears poised for transition from wish to actual data to be modeled $\rightarrow$ cosmology.