Gamma-Ray Bursts

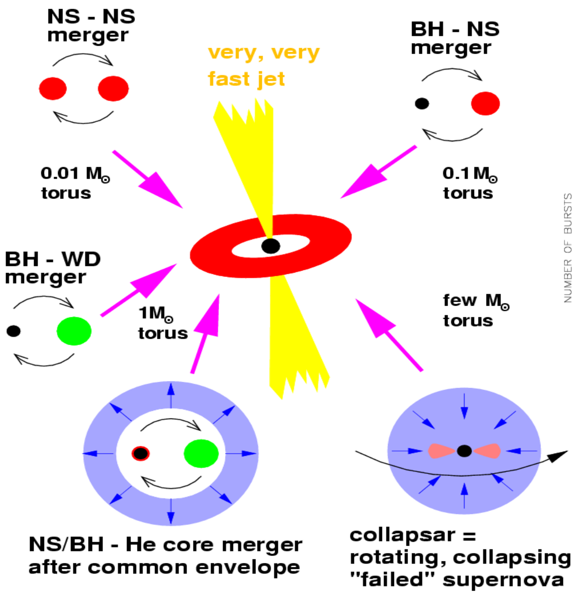
Recent developments based on Fermi and Swift Observations

Peter Mészáros,
Pennsylvania State University

IAP Nov. 2010

GRB: standard paradigm

Hyperaccreting Black Holes

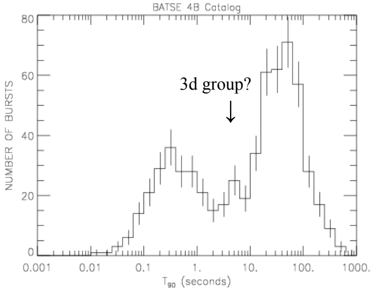


M. Ruffert, H.-Th. Janka, 1998

Bimodal distribution of t_γ duration

←↓**Short**

(t_q< 2 s)

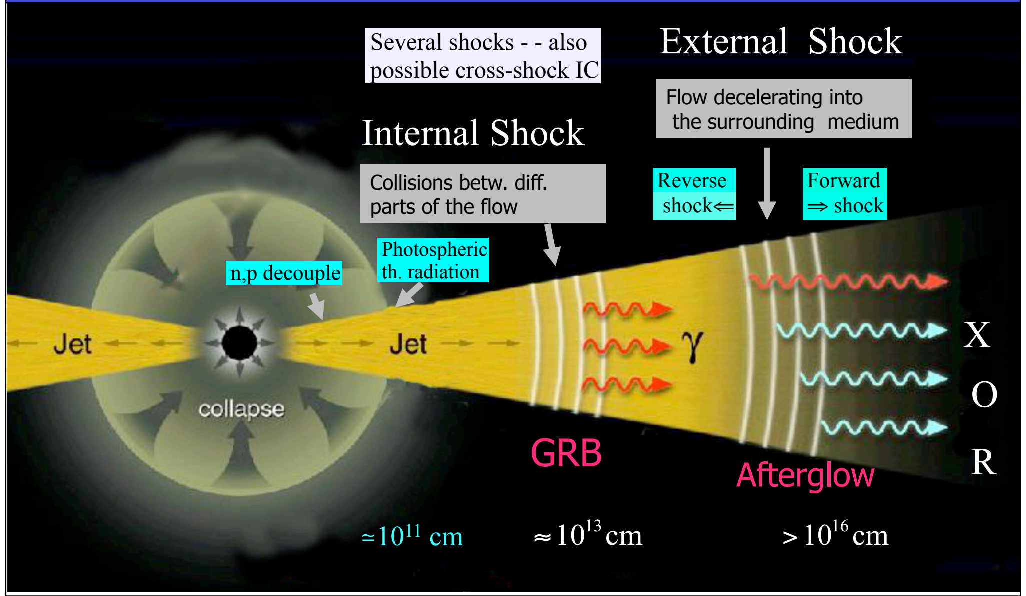


3d group?
↓

→↑**Long**

(t_g >2 s)

Fireball Shock Model of GRBs



Several shocks - - also possible cross-shock IC

External Shock

Flow decelerating into the surrounding medium

Internal Shock

Collisions betw. diff. parts of the flow

Reverse shock⇐

Forward ⇒ shock

n,p decouple

Photospheric th. radiation

γ

X

O

R

GRB

Afterglow

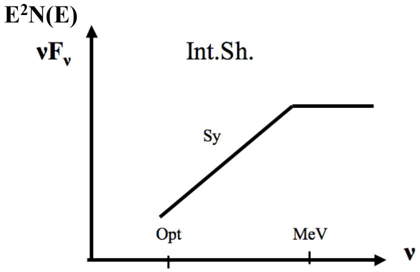
$\simeq 10^{11}$ cm

$\approx 10^{13}$ cm

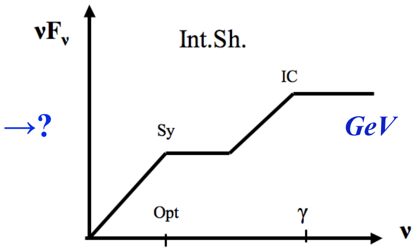
$> 10^{16}$ cm

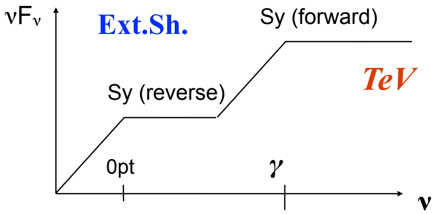
Standard GRB shock *leptonic* EM rad'n:

shock Fermi acc. of e^- → synchrotron and inv.Compton



Or →?





- **GRB 990123** ⟶ bright (9th mag) **prompt opt. transient** (Akerlof etal 99) .
  – 1st 10 min: decay steeper than forw.sh.
- →Interpreted as **reverse shock** ....
- Several more examples (but not ubiquitous)

(Less) standard GRB *hadronic* radiation: UHE CR, ν , γ

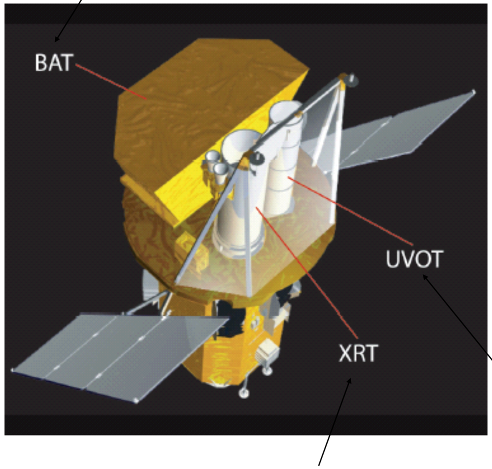
- If protons present in (baryonic) jet → p^+ Fermi accelerated (as are e^-)
- $\mathbf{p,\gamma \rightarrow \pi^{\pm} \rightarrow \mu^{\pm}, \nu_\mu \rightarrow e^{\pm}, \nu_e, \nu_\mu}$ (**Δ**-res.: $E_p E_\gamma \sim 0.3$ GeV^2 in jet frame)
- → $E\nu_{,br} \sim 10^{14}$ **eV** for MeV γs (int. shock)
- → $E\nu_{,br} \sim 10^{18}$ **eV** for 100 eV γs (ext. rev. sh.) **: ICECUBE**
- **→π^0 →2γ →** γγ cascade **: GLAST, ACTs..**
- Test hadronic content of jets (are they pure MHD/$e^\pm$, or baryonic …?)
- Also (if dense): $\mathbf{p,\gamma \rightarrow \pi^{\pm} \rightarrow \mu^{\pm}, \nu_\mu \rightarrow e^{\pm}, \nu_e, \nu_\mu}$
- **$E_\gamma \sim$ GeV (internal shock) ; $E_\gamma \sim$ TeV (ext shock/IGM)**
- **→ photon cut-off: diagnostic for int. vs. ext-rev shock**

So far:

- Seen (for sure) only EM radiation (lots)
- Are these photons ***leptonic*** or ***hadronic*** origin?
- ***Answer:***
- X-ray to radio ⇒ surely leptonic
- MeV: probably leptonic (but...)
- GeV: debated
- ***But ..... one of few UHECR candidate sources!***

SWIFT

BAT: Energy Range: 15-150kev
FoV: 2.0 sr
Burst Detection Rate: 100 bursts/yr



Three instruments

Gamma-ray, X-ray and optical/UV

Slew time: 20-70 s !

>95% of triggers yield XRT det
>50% triggers yield UVOT det.

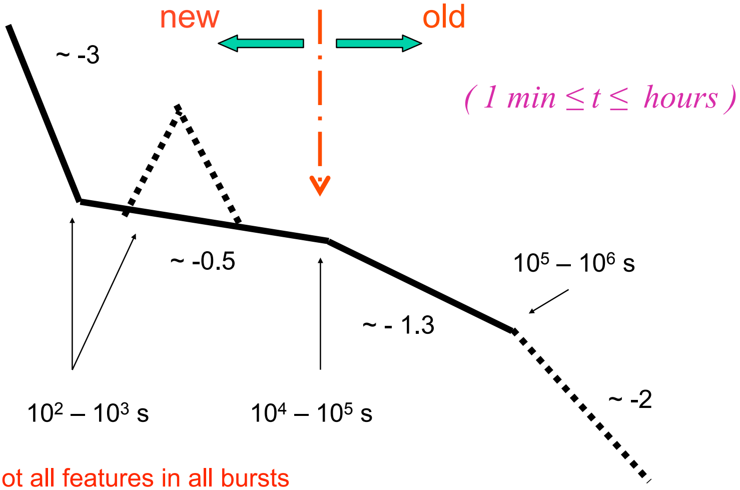
UVOT: Wavelength Range: 170-650nm

XRT: Energy Range: 0.2-10 keV

Launched Nov 04

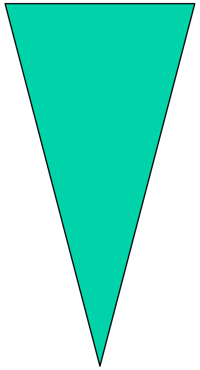
Mission Operations Center: @ PSU
(Bristol Res. Park)

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



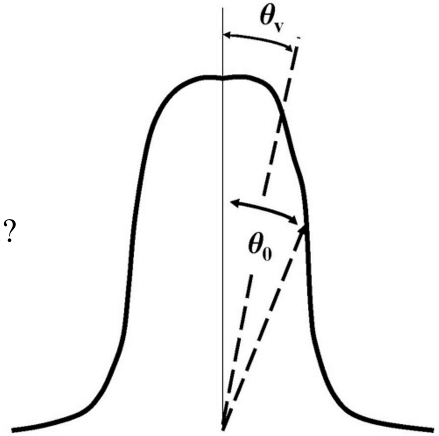
BUT: not all features in all bursts

Jet Structure



Top-hat (monolithic)

or →..?



Quasi-Universal Structured Gaussian

A burning issue:
Jet Structure ?

z=0.937

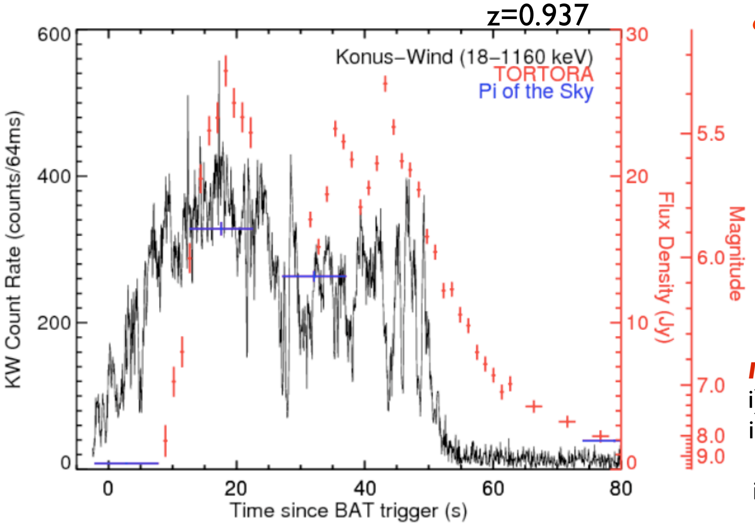


Figure 1 | Prompt Emission Light Curve. The Konus-Wind background-subtracted γ-ray lightcurve (black), shown relative to the *Swift* BAT trigger time, T_0. Optical data from "Pi of the sky" (blue) and TORTORA (red) are superimposed for comparison. The optical emission

GRB 080319B

A prompt "naked eye" optical GRB

Racusin et al, 08
Nature 455:183

γ, opt prompt l.c. appear similar → same emission region, e.g. "internal" shock; but rad. mechanism?

Interpret prompt as:

i) optical: synchrotron
ii) MeV: 1 st ord. SSC
and
iii) predict 2nd order IC @ ~100 GeV

(there are also differing opinions)

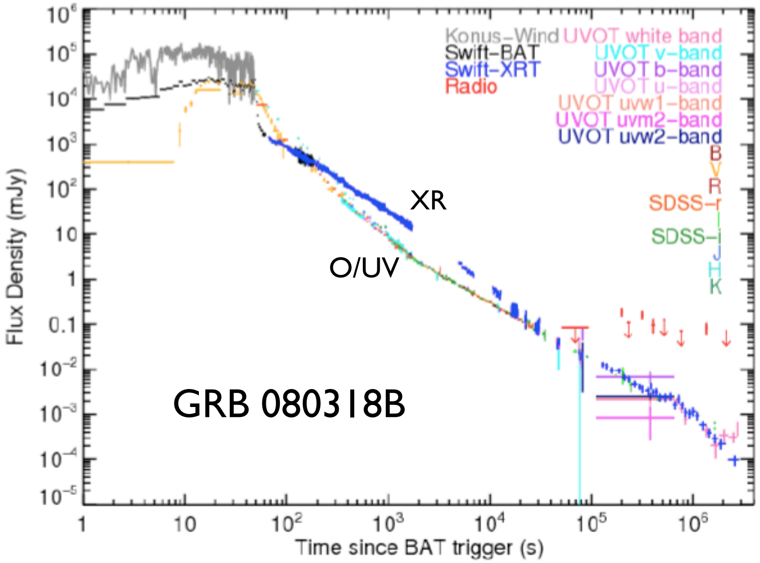


Figure 2 | **Composite Light Curve**. Broadband light curve of GRB 080319B, including radio, NIR, optical, UV, X-ray and γ-ray flux densities. The UV/optical/NIR data are normalized to the UVOT v-band in the interval between T_0+500 s and T_0+500 ks. The *Swift*-BAT data are extrapolated down into the XRT bandpass (0.3-10 keV) for direct comparison with the XRT data. The combined X-ray and BAT data are scaled up by a factor of 45, and the Konus-Wind data are scaled up by a factor of 10^4 for comparison with the optical flux densities. This figure

Hei08

GRB 080319B

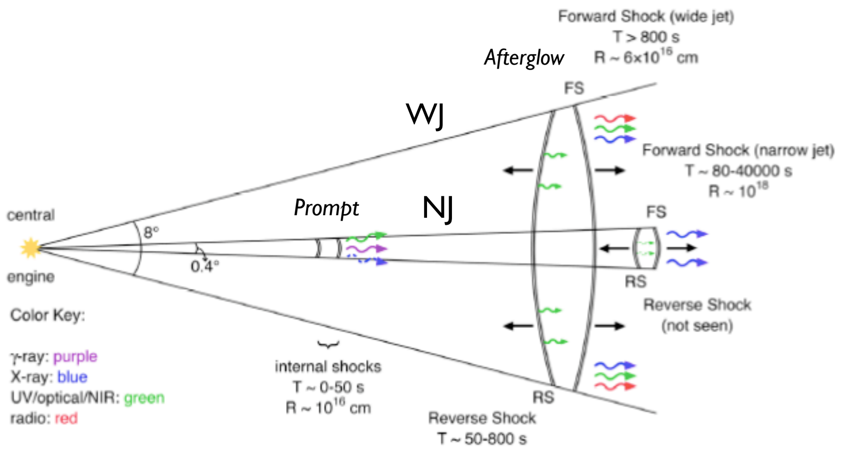


Figure 4 | Schematic of Two-Component Jet Model. Summary diagram showing spectral and temporal elements of our two-component jet model. The prompt γ-ray emission is due to the internal shocks in the narrow jet, and the afterglow is a result of the forward and reverse shocks from both the narrow and wide jets. The reverse shock from the narrow jet is too faint to detect compared to the bright wide jet reverse shock and the prompt emission. If X-ray observations had begun earlier, we would have detected X-ray emission during the prompt

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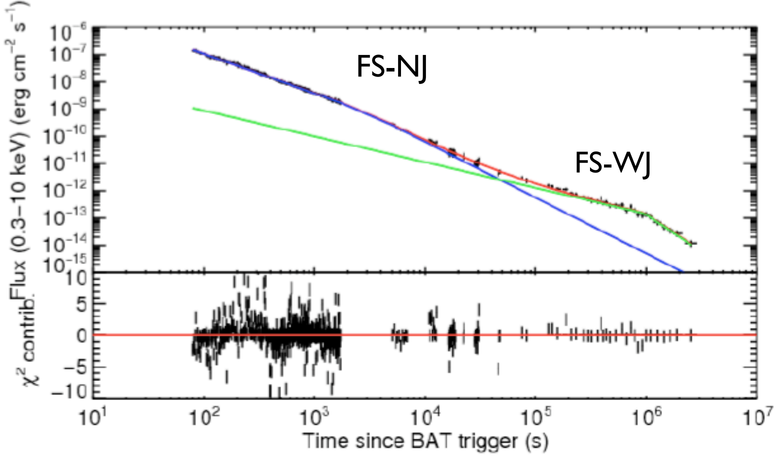
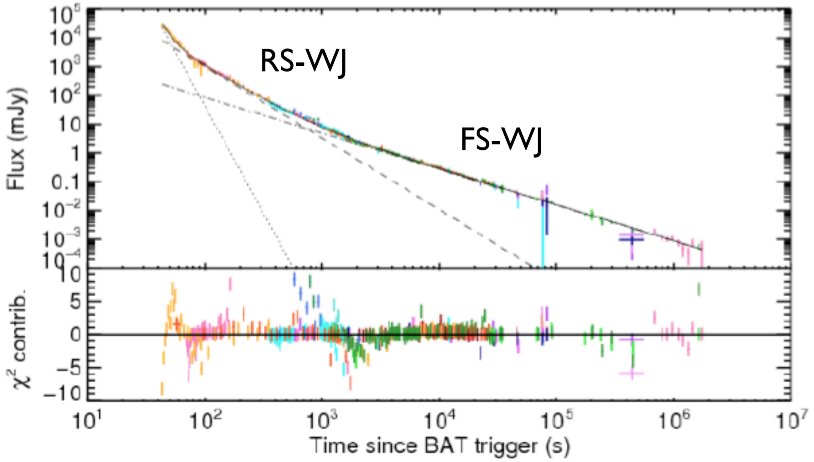
080319B X-Ray 2-jet fit

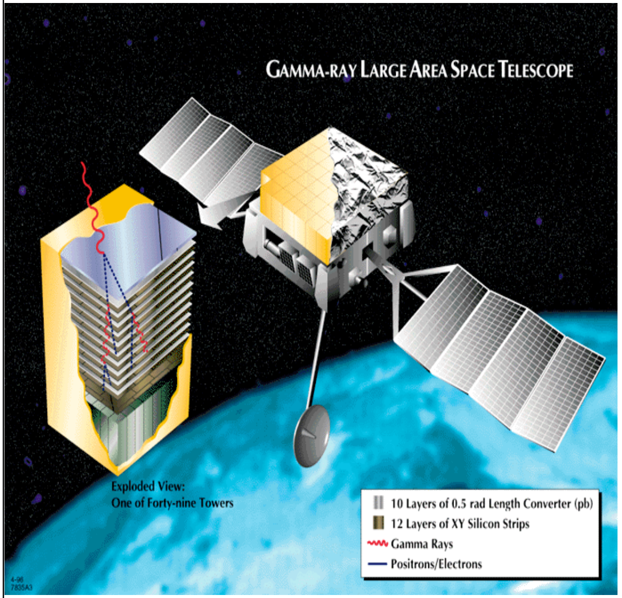


Supplementary Figure 7 | Two-Component Jet Model fit to X-ray Afterglow. The X-ray afterglow is best described by the superposition of two broken power-laws, which is consistent with the narrow and wide jets of a two-component jet expanding into a stratified wind environment. The narrow jet dominates the first ~40 ks of the afterglow as indicated by the blue line, which shows the fit to the narrow jet component. After the narrow jet break decays, the wide jet dominates as indicated by the green line fit to late afterglow. The red line shows the superposition of both components and the overall fit to the X-ray light curve.

080319B optical 2-jet fit



Supplementary Figure 6 | Three-Spectral Component Fit to the Decaying Optical Transient Following the peak of the prompt optical flash, the optical transient light curve displays three distinct components that dominate in the intervals t<50s, 50s<t<800s, and t>800s. The initial decay of the bright optical flash is a power-law with α_1=6.5±0.9 (dotted line). This is superimposed on a power-law with decay index α_2=2.49±0.09 (dashed line) that dominates in the middle time interval and a third power-law with α_3=1.25±0.02 (dot-dashed line)



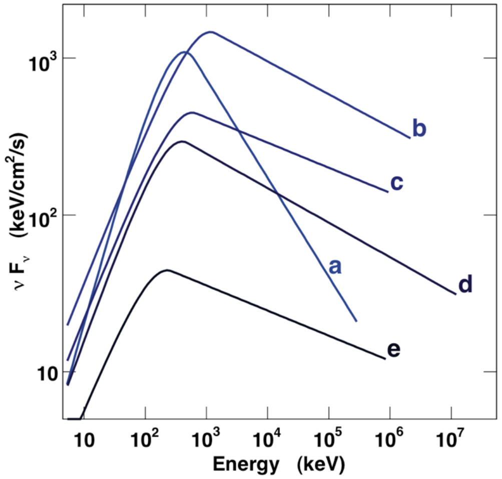
Also on Fermi : **GBM** (~BATSE range) ;
12 NaI: 10keV-3 MeV; 2 BGO: 150 keV-30 MeV

Fermi

- Launched June 11 2008
- **LAT**: Pair-conv.modules + calorimeter
- 20 MeV-300 GeV,
  $\Delta E/E \sim 10\%$@1 GeV
- FoV = 2.5 sr (2xEgret), ang.res. $\theta \sim 30" - 5'$ (10GeV)
- Sensit. $\sim 2.10^{-9}$ ph/cm^2/s
  (2 yr; > 50xEgret)
- GBM: FoV 4π,
  10keV-30MeV
- 2.5 ton , 518 W
- det ~300 GRB/yr (GBM); simult. w. Swift : 30/yr; LAT: 1-2/month

GRB 080916C

Spectrum : up to ~10 GeV!



- "Band" (broken power-law) fits, joint GBM/LAT, in ***all*** time intervals
- "Soft-to-hard", to "soft-peak-hard-slope" evolution
- ***Long***-lived (10^3 s) GeV afterglow
- ***No*** evidence for ***2nd*** spectr. comp.

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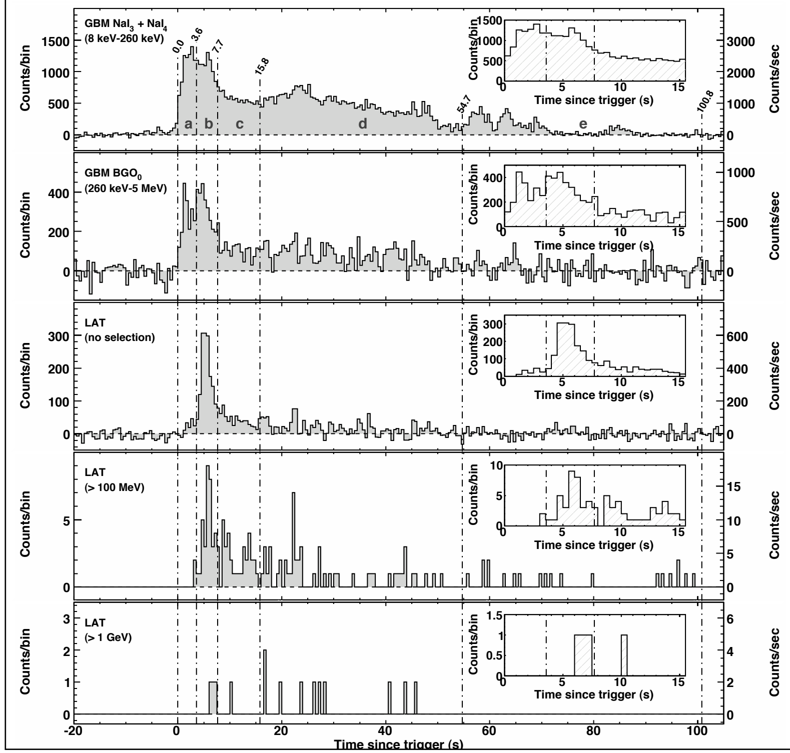


GRB 080916c

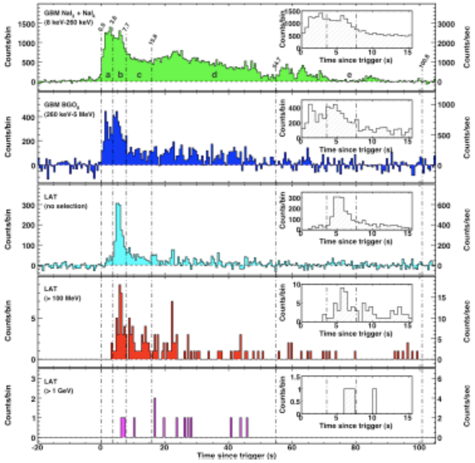
Light-curve
E↓

Abdo, A. and
Fermi coll., 09,
Sci. 323:1688

Note :
GeV photons
←“lag”
behind MeV!

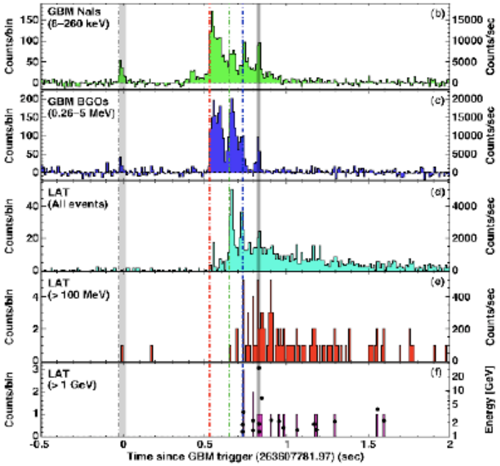
HE delayed onset in long and short GRBs

GRB 080916C
Abdo et al. 2009, Science 323, 1688



- **The first LAT peak coincide with the second GBM peak**
- **Delay in HE onset: ~4-5 s**

GRB 090510
Abdo et al. 2009, Nature 462, 331



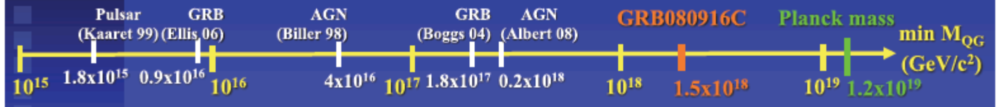
- **The first few GBM peaks are missing in the LAT but later peaks coincide**
- **Delay in HE onset: 0.1-0.2 s**

Limits on Lorentz Invariance Violation

- Some QG models violate Lorentz invariance: $v_{ph}(E_{ph}) \neq c$

$$c^2 p_{ph}^2 = E_{ph}^2 \left[1 + \frac{E_{ph}}{M_{QG,1}c^2} + \left(\frac{E_{ph}}{M_{QG,2}c^2} \right)^2 + \ldots \right] \quad , \quad v_{ph} = \frac{\partial E_{ph}}{\partial p_{ph}} \approx c \left[1 - \frac{1+n}{2} \left(\frac{E_{ph}}{M_{QG,n}c^2} \right)^n \right]$$

- A high-energy photon E_h would arrive after (or possibly before in some models) a low-energy photon E_l emitted together
- GRB080916C: highest energy photon (13 GeV) arrived 16.5 s after low-energy photons started arriving (=the GRB trigger)
  ⇒ a conservative lower limit: $M_{QG,1} > (1.50 \pm 0.20) \times 10^{18}$ GeV/c^2



$$\Delta t = \frac{(1+n)}{2H_0} \frac{E_h^n - E_l^n}{(M_{QG,n}c^2)^n} \int_0^z \frac{(1+z')^n}{\sqrt{\Omega_m(1+z')^3 + \Omega_\Lambda}} dz'$$

(Jacob & Piran 2008)

Sci. 323:1688, 2009

n = 1,2 for linear and quadratic Lorentz invariance violation, respectively

GRB090510: L.I.V

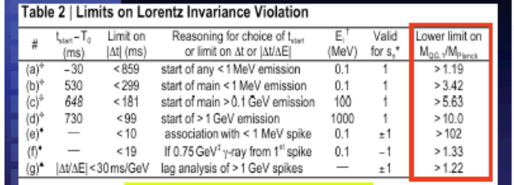
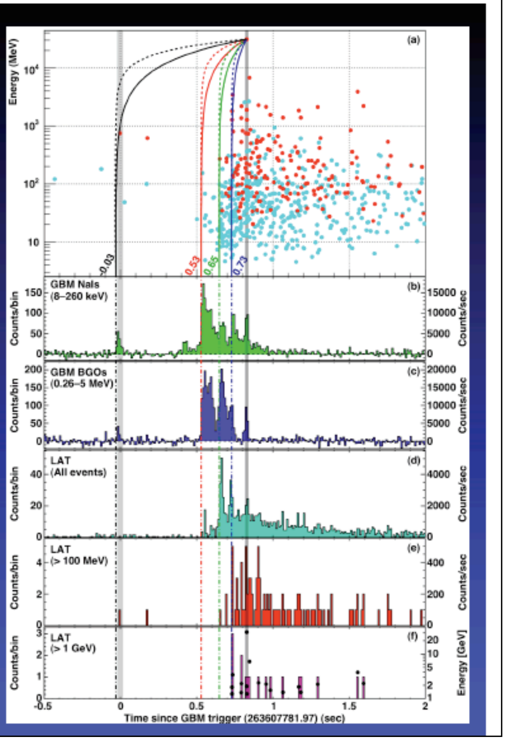


Table 2 | Limits on Lorentz Invariance Violation

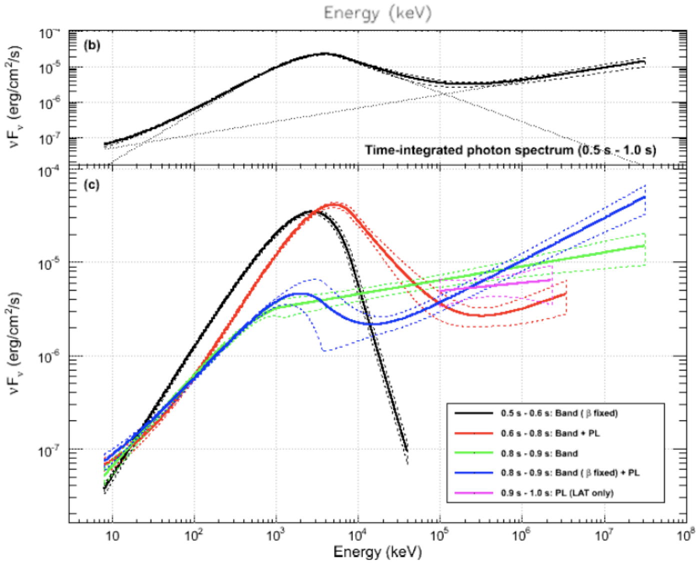
#	$t_{start} - T_0$ (ms)	Limit on $\lvert\Delta t\rvert$ (ms)	Reasoning for choice of t_{start} or limit on Δt or $\lvert\Delta t/\Delta E\rvert$	E_l[†] (MeV)	Valid for s_n*	Lower limit on $M_{QG,1}/M_{Planck}$
(a)$^{\diamond}$	−30	< 859	start of any < 1 MeV emission	0.1	1	> 1.19
(b)$^{\diamond}$	530	< 299	start of main < 1 MeV emission	0.1	1	> 3.42
(c)$^{\diamond}$	648	< 181	start of main > 0.1 GeV emission	100	1	> 5.63
(d)$^{\diamond}$	730	< 99	start of > 1 GeV emission	1000	1	> 10.0
(e)$^{\bullet}$	—	< 10	association with < 1 MeV spike	0.1	±1	> 102
(f)$^{\bullet}$	—	< 19	If 0.75 GeV[‡] γ-ray from 1st spike	0.1	−1	> 1.33
(g)$^{\blacktriangle}$	$\lvert\Delta t/\Delta E\rvert < 30$ ms/GeV		lag analysis of > 1 GeV spikes	—	±1	> 1.22

[Nat., 462:331, 2009]

- All of our lower limits on $M_{QG,1}$ are above M_{Planck}
- a-e based on 31 GeV γ-ray
- a-d assume that $t_{em} \geq t_{strat}$
  t_{strat} = emission onset time
- e,f association with a specific low-energy spike
- g sharpness of HE spikes



GRB 090510



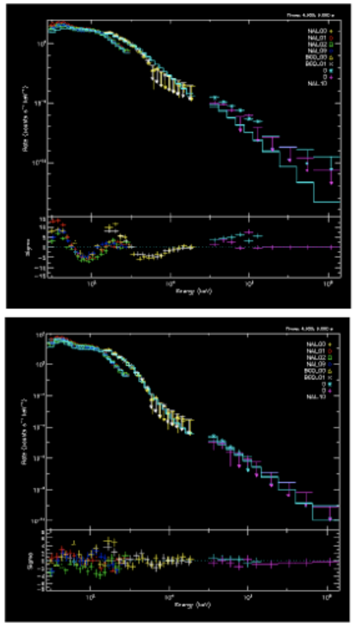
Spectrum:
clear 2nd
comp (5σ)

(unlike in
0809916C &
some others. which
show pure Band)

Abdo, et al. 09
(LAT/GBM coll.)
Nature, 462:331

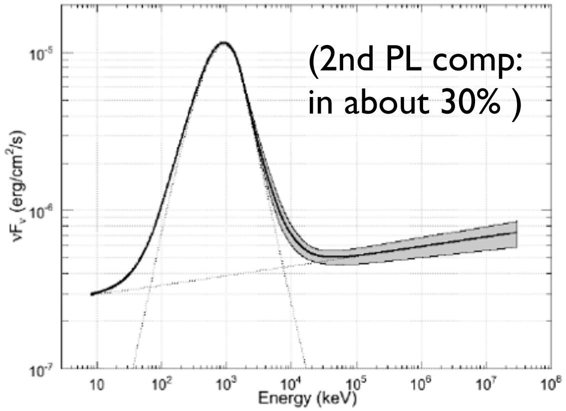
Extra power-law component

GRB 090902B



- **Interval b (T0 + 4.6 s to 9.6 s):**
  Δ CSTAT = 3165, (≥ 1000 for GBM only)
- **This is the first time a low-energy extension of the power-law component has been seen**

Abdo, A. A. et al., ApJL 706, 138 (2009)



(2nd PL comp:
in about 30%)

Theoretical Issues:

- Is the single component Band spectrum up to GeV due to internal or external shocks?
- Is it of purely leptonic, hadronic or mixed?
- Besides delay providing QG upper limits (based on zero intra-source GeV-MeV delay): what are astrophysical causes of delay?
- Is 2nd component a ≠ rad.mech. from 1st?

Plethora of Models

- Radiative $e^{\pm}$ ext. shock (Ghisellini et al)
- Unmag. adiab. ext. shock (Kumar & Barniol)
- Critique thereof (Piran & Nakar)
- Klein-Nishina IC ext. shock (Wang, He, ..)
- Structured adiab. ext. shock (Corsi et al)
- Cocoon int. shock upscattering (Toma et al)
- Photosp. int. shock upscattering (Toma et al)
- Critique phot & magn. outflow (Zhang, Pe'er)
- Hadronic models (Razzaque et al, Asano et al)

Radiative ext. shock model

Ghisellini et al, 0910.2459

- GeV light curves *roughly* $F_E \sim t^{-1.5}$ for most LAT obs.
- Spectrum *roughly* $F_E \sim E^{-1}$, not strongly evolving
- Argue it is external shock, with $L \sim t^{-10/7}$ as expected for \`radiative' f'balls $\Gamma \sim r^{-3} \sim t^{-3/7}$
- To make 'radiative', need \`enrich' ISM with $e^{\pm}$
- Argue pair-dominated f'ball obtained from backscatt. of $E>0.5$ MeV photons by ext. medium, → cascade
- External shock (afterglow) delay: explain GeV from MeV delay (MeV prompt is something else (?))

- Problem: $r \gtrsim 10^{16}$ cm needed, where $n_{\pm} \lesssim n_p$ (e.g. '01 ApJ 554,660)

Adiabatic Unmag. Ext. Shock

Kumar & Barniol-Duran, MNRAS, arXiv.0905.2417, 0910.5726

- t>4 s at >100 MeV, $E>E_c, E_m$ (sync.) ⇒sp. indep. of Γ, n
- Interpret $F_E \sim t^{-1.2\pm0.2}$ ⇒ adiabatic ext. shock
- Get ε_B, n from argument that ES at t<50 s should not dominate spec. at <500 keV (of unspec. origin)
- →ES params. from >0.1 GeV predict XR, O ✓

Problems:

1) densities extremely low (<halo?)
2) In SNR, evidence for B >> B_{compr}
3) Adiabaticity reliant on low n cond

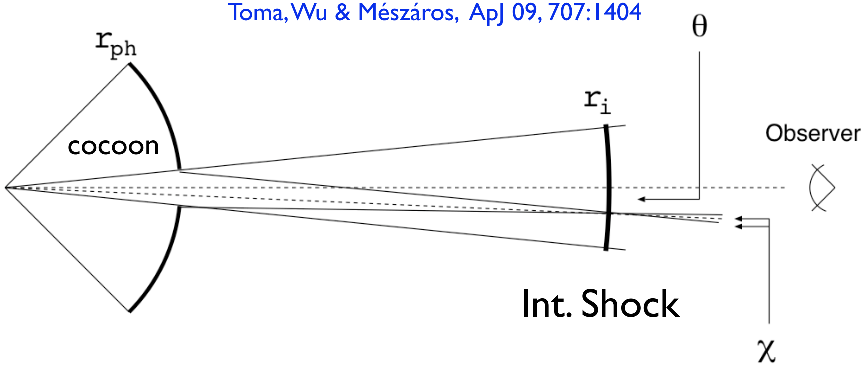
KN adiabatic ES model

Wang, He et al, 0911.4189 (also He et al in prep.)

- KN effects influence IC emission through Y parameter
- Calc. $Y(\gamma_L)$, where $\nu_L(\gamma_L)$= 0.1GeV; also calc. $Y(\gamma_c)$, $Y(\gamma_m)$
- At t $\lesssim$10 s, $Y(\gamma_L) \lesssim 1$ (SSC weak: KN) → 0.1 GeV SY ***(strong)***
- but $Y(\gamma_c, \gamma_m) >> 1$ → SSC strong (not KN) → X, O Sy ***weak***
- $Y(\gamma_L)$ incr. in time (less KN, strong IC) → SY @ GeV gets weaker → GeV light curve ***steeper*** than simple $t^{-1.2}$ adiab. decay
- Early ***steep*** LAT decay (SY modified by SSC w. decr. KN), followed by ***flatter*** decay (SY w/o SSC)
- Argue Kumar's late X not steep enough & early LAT too flat , while KN can make LC in LAT & X steeper, as seen

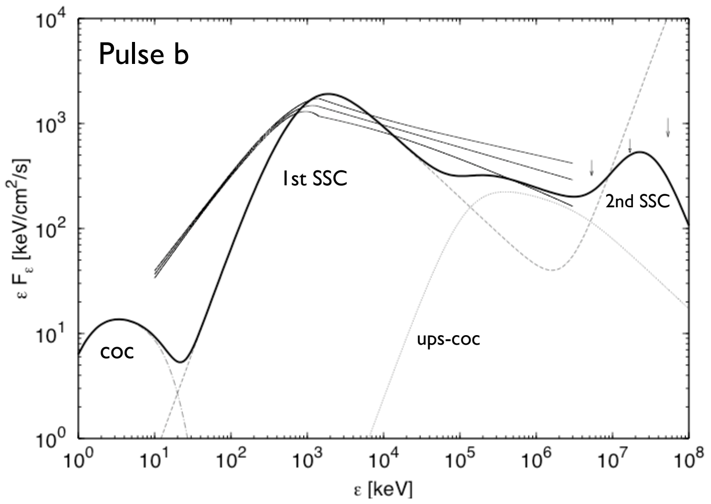
Time lags and Band spectrum: A Cocoon + IS Upscattering model

Toma, Wu & Mészáros, ApJ 09, 707:1404



- Assume jet emits synchrotron in optical, and 1st ord SSC is in MeV
- Cocoon emits soft XR, jet upscatters this to ~0.3 GeV; time lag ~3s

Cocoon + jet IS upscatt



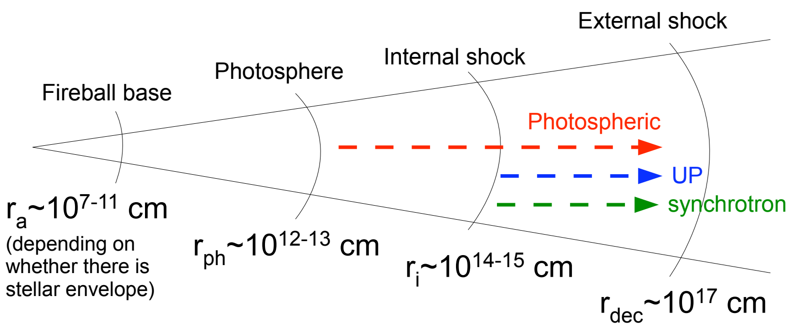
- L_{55}=1.1, Γ_3=0.93, Δt_j=2.3 s, γ_m=400, γ_c=390, τ_T=3.5x10^{-4}, , ε_B=10-5, ε_e=0.4

Data: courtesy of Fermi GBM/LAT coll.

Photosphere + IS model

Toma, Wu, Mészáros, arX:1002.2634

Photosphere and internal shock of the GRB jet



Fireball base

Photosphere

Internal shock

External shock

Photospheric

UP

synchrotron

$r_a \sim 10^{7\text{-}11}$ cm

(depending on
whether there is
stellar envelope)

$r_{ph} \sim 10^{12\text{-}13}$ cm

$r_i \sim 10^{14\text{-}15}$ cm

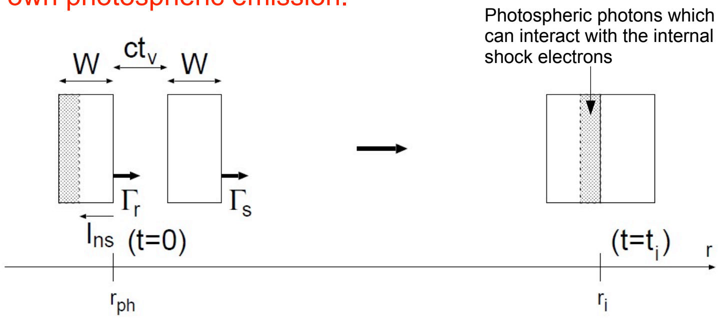
$r_{dec} \sim 10^{17}$ cm

- Photosphere: prompt, variable MeV
- IS occur at $r \gtrsim 10^{15}$ cm (high Γ) : Sy=XR, IC(UP)=GeV

Phot-IS model, cont.

Temporal properties: a simple two-shell collision

The electrons in the internal shock of two given shells can upscatter their own photospheric emission.


Photospheric photons which can interact with the internal shock electrons

$$l_{ns} = c(1-\beta_r)t_i = \frac{1-\beta_r}{\beta_r-\beta_s}ct_v \approx \frac{\Gamma_s^2}{\Gamma_r^2}ct_v.$$

$< W/2$: efficient scattering regime

(The case of $W \sim ct_v$ is included.)

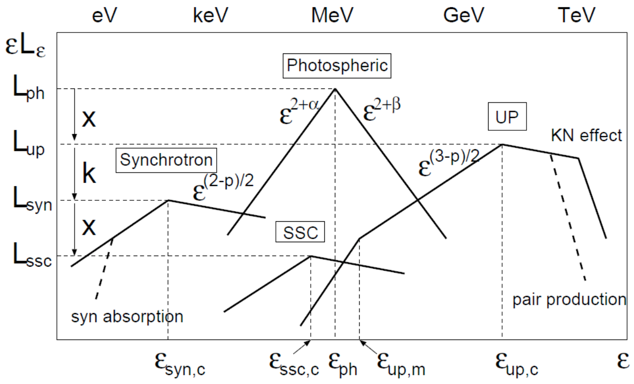
$$t_{delay} = (W + ct_v + l_{ns})/c \sim W/c.$$

~ (pulse duration of the photospheric emission) ~ 0.01-0.1 s

This kinematic delay could explain the observed high-energy delays of short GRBs. For long GRBs, we will propose alternative explanation.

Phot-IS model, cont.

Broadband spectrum for the high baryon load case



$$x \simeq \frac{\epsilon_d \epsilon_e}{(\eta/\eta_*)^{8/3}} \left(\frac{\gamma_c}{\gamma_m}\right)^{2-p}.$$

$$k \equiv \frac{L_{\rm syn}}{L_{\rm up}} = \frac{U'_B}{U'_{\rm ph}} = \frac{\epsilon_d \epsilon_B}{(\eta/\eta_*)^{8/3}},$$

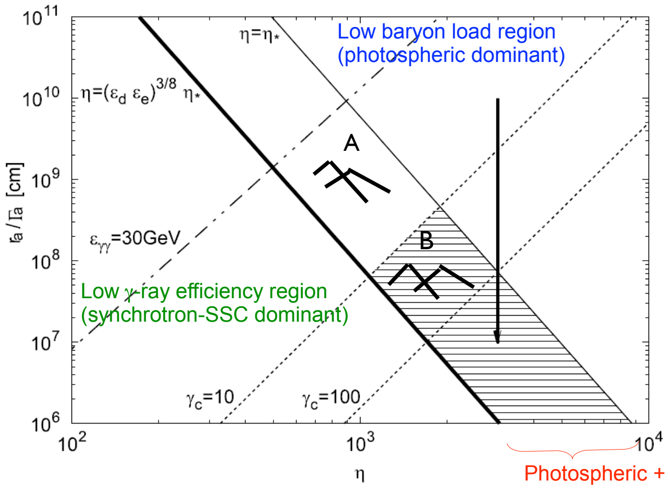
$$L_{\rm up} = L\epsilon_d\epsilon_e \left(\frac{\gamma_c}{\gamma_m}\right)^{2-p}$$

$$\varepsilon_{\rm up,c} = \varepsilon_{\rm ph}\gamma_c^2$$

This figure does not take into account the secondary emission by the e+e- pairs created by the high-energy absorption (and the cascade process), which could make the UP, synchrotron, and SSC emission appear as a broad component. To derive a more

Photosphere-IS model, cont.

Constraints on parameters for distinct, bright UP emission



Photospheric + UP dominant

$L_{54} = 1$

$t_{v,-2} = 1$

$\epsilon_d = 0.2$

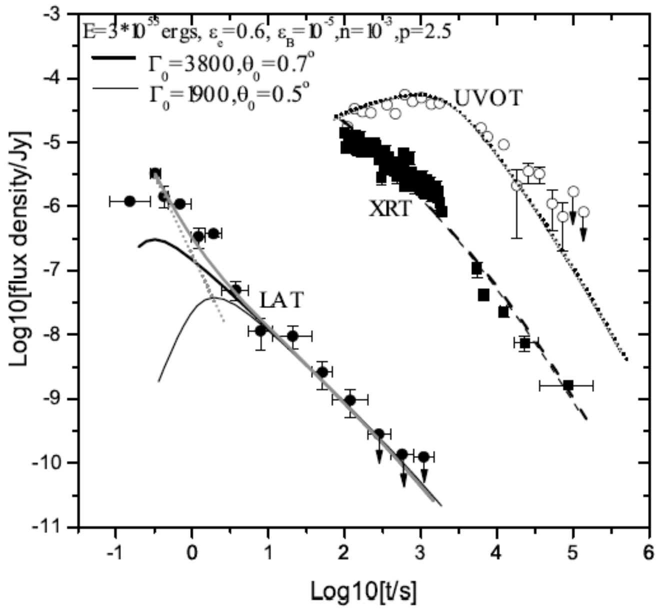
$\epsilon_e = 0.3$

A: Phot., UP
merged
(080916C)

B: Phot.. UP
distinct
(090902B)

A distinct, bright UP emission does not need a strong fine tuning of the physical parameters, but the appropriate parameter ranges are limited, which is consistent with the fact that not all the LAT GRBs have a distinct high-energy component.

Adiab. IS+ES : GRB 090510



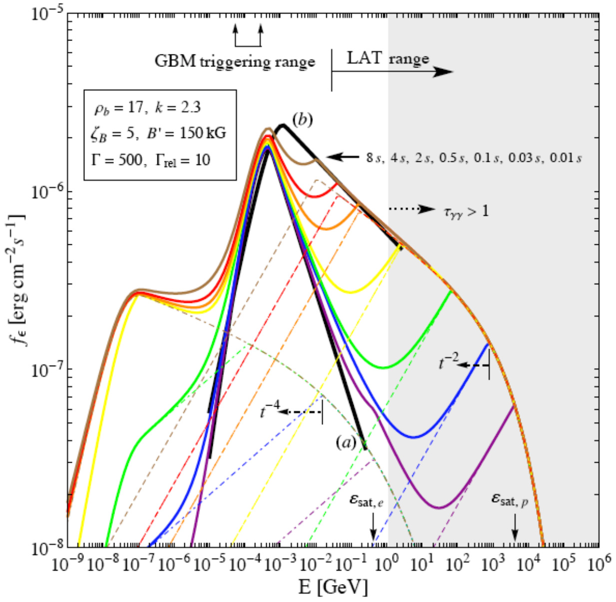
Haoning He, et al, arXiv:1009.1432

- Adiab. forward shock (afterglow) is OK, but only after t~3 s
- Previous to that, GeV must be due to prompt (e.g. IS) component
- Ext n_0~10^{-3}-10^{-6} cm^{-3} and B_0 ~7μG (if ony amplif.) - but unlikely B fir this n_0
- May still require B amplificat. in shock

Mészáros

Hadronic models:

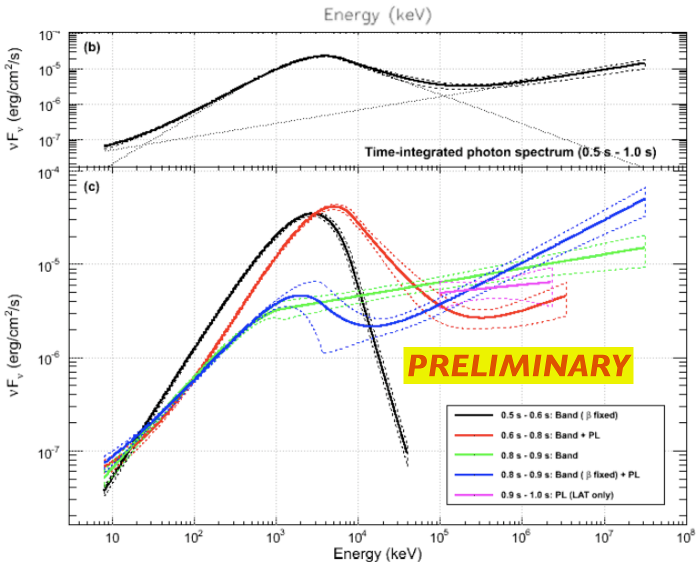
Proton Sy model, ***080916C***



Razzaque, Dermer, Finke,
arXiv:0908.0513

- GBM range: produced by primary e$^-$ sy (dark line, 1st pulse)
- LAT range: p$^+$ sy (2nd pulse,color curves), moving down in energy and up in flux with incr. time
- 2nd gen'tn e$^-$ sy comp. (from γγ) appears in KeV to MeV range

GRB 090510



Short burst
LAT/GBM,
shows lags

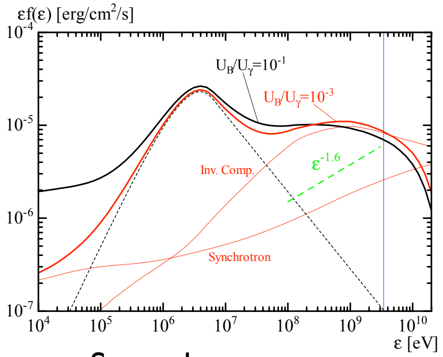
Abdo, et al. 09
(LAT/GBM coll.)
Nature, 462:331

Spectrum:
clear 2nd
comp (5σ)

(ApJ, subm.)

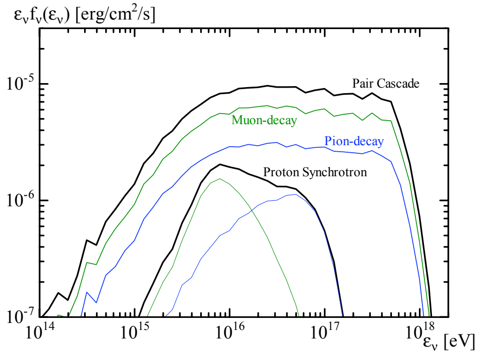
Hadronic model of extra comp:

GRB 090510



Asano, Guierec, Mészáros, 09
ApJL, 705:L191

Secondaries from photomeson cascades ✔
(but: need $L_{p,iso}$~10^{55} erg/s !)



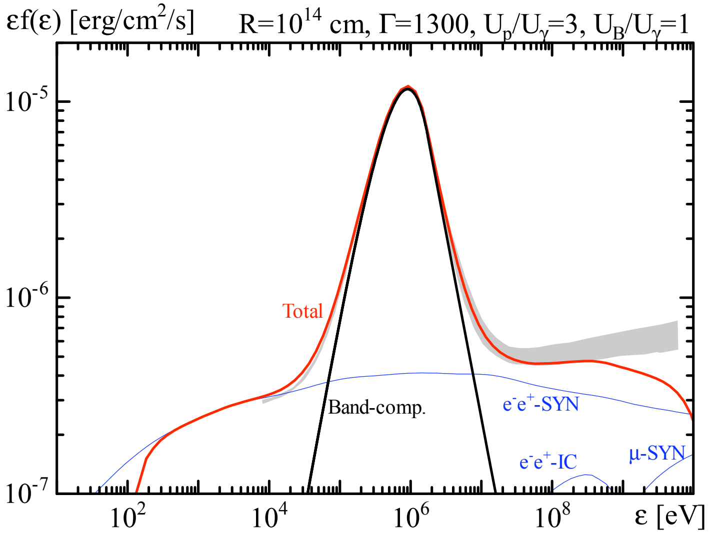
Secondary photons ↑

Secondary neutrinos →

(not detectable, for this burst)

[Other hadron model in pep: 090902B, Asano, Inoue, Mészáros, 10]

Hadronic model: **090902B**



Asano, Inoue,
Mészáros, 2010,
ApJL (in press)
arXiv:1009.5178

Hadronic model: ***080319B***

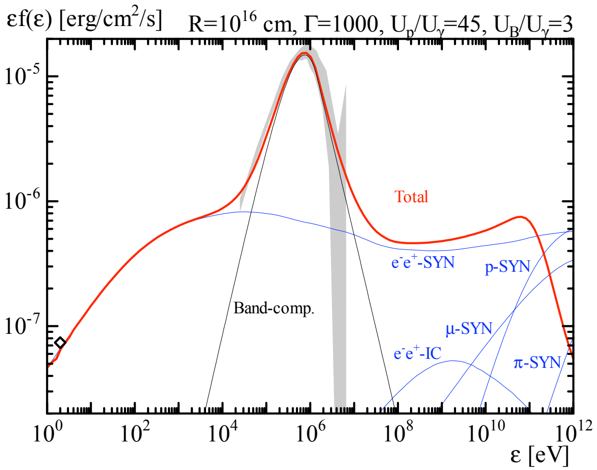


Fig. 2.— Model spectrum for parameters listed at the top as thick red curve compared with observations of GRB 080319B, for which the gray shaded area represents the spectrum measured between T_0+12 s and T_0+22s by Swift/BAT and Konus-Wind. The contemporaneous optical flux observed by “Pi of the Sky” is the black diamond. The best-fit Band component is shown separately as the thin black curve. Individual contributions of synchrotron and inverse Compton from secondary electron-positron pairs, as well as muon synchrotron and proton synchrotron are denoted by thin blue curves as labelled, not including the effects of $\gamma\gamma$ absorption or synchrotron self-absorption.

Asano, Inoue, Mészáros, 2010, ApJL (in press) arXiv:1009.5178

Some general issues on prompt & high energy emission

- Radiation mechanism?
- Electron distribution?
- Role of turbulence?
- Poynting - how much? ...

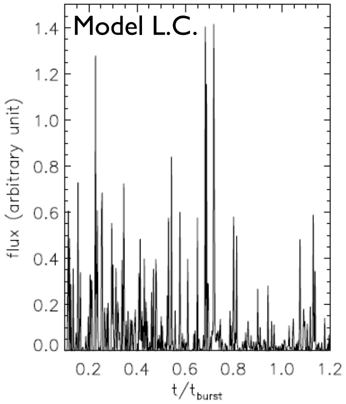
Relativistic turbulent model

Narayan-Kumar 09, MN 394:L117, K-N 09, MN 395:472; Lazar et al 09, ApJ 695:L10

- Objections to IS model (unchanged since ~1999):
  i) fast cool →spectrum $F_\nu \sim \nu^{-1/2}$;
  ii) Acell. all e- → ν_{pk} below MeV;
  iii) Low rad. efficiency;
- Propose: relativistic eddys of γ_t in frame of bulk Γ
- Shock radius R, shell size $r \sim R/\Gamma$ in shell frame
- Max. size of eddy in eddy frame : $r_e \sim r/\gamma_t \sim R/\Gamma\ \gamma_t$
- Expect eddys to move ballistically for r_e, collide w. another eddy and change directions, etc., γ_t times

Relat. Turb., cont.

- Eddy changes directions γ_t times, cum. change ~radian over its lifetime
- Eddy visible when its light cone intersects observer LOS
- Calculate no. of eddies, conclude have: $t_{burst} \sim R/\Gamma^2 c$, $t_{var} \sim R/\Gamma^2 \gamma_t^2 c$, and $n_{pulse} \sim \gamma_t^2$, →

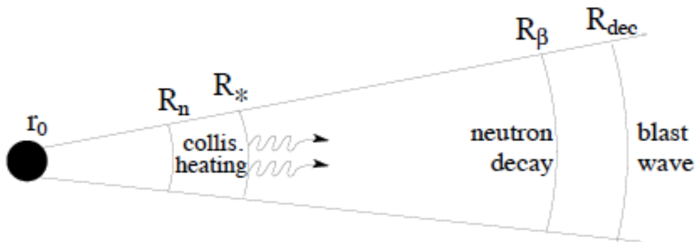


Possible problem : after each "causal time" (change direction) → would also shock → thermalize, $\gamma_t \rightarrow$unity, after only a few changes of direction (instead of γ_t changes); Can isotropic turbulence survive as relativistic for any time?

(e.g. Zhang, MacFadyen, Wang 2009, ApJ 692:L40)

“Thermal” component?

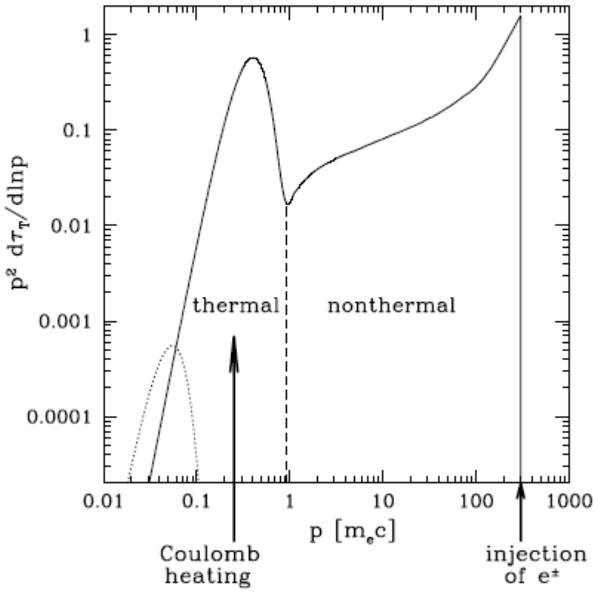
p-n collisional dissipation



Beloborodov, ’10, MN 407:1033

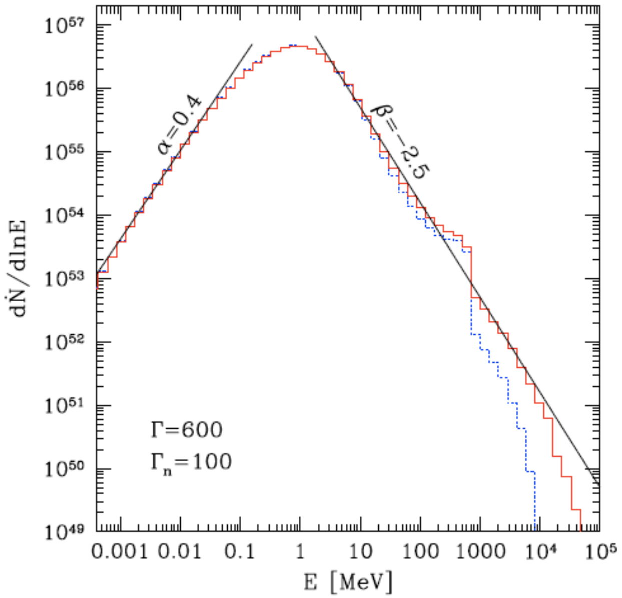
- Long history: Derishev-Kocharovsky 89, Bahcall-Meszaros 00, Rossi et al 04, etc
- Either p-n decoupling or internal colls. → relative p-n streaming, inelastic colls.
- Highly effective dissipation (involves baryons directly)- can get >50% efficiency
- Sub-photospheric dissipation can give strong photospheric component

p-n dissip. → $e^{\pm}$ p-distr.



- n-p collision lead to $\pi^{\pm}$, π^0, leading to $e^{\pm}$ and γs
- The $e^{\pm}$ and γs quickly thermalize to produce an observer frame photospheric peak at ~ 0.2-0.5 MeV
- Some of the $e^{\pm}$ are Coulomb heated by protons into a higher energy non-thermal distribution

p-n diss. →e±→γ-spectrum



- The result is a thermal peak at the ~MeV Band peak, plus
- a high energy tail due to the non-thermal $e^{\pm}$, whose slope is comparable to that of the observed Fermi bursts with a “single Band” spectrum
- The “second” higher energy component (when observed) must be explained with something else

MHD / Poynting jets?

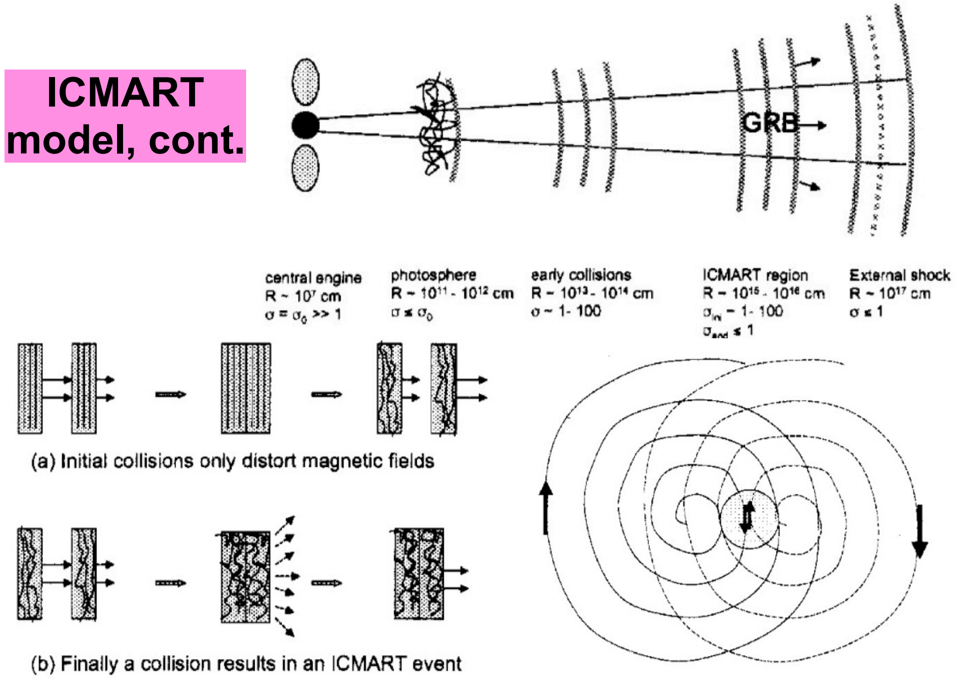
ICMART model

("Internal Collision Magnetic Reconnection Transient")

Zhang, Yan, arXiv:1011.1197

- Int. coll. w. $1 \lesssim \sigma \lesssim 100$, where $\sigma = B'^2/4\pi\rho' c^2$ (MHD)
- Magn. reconn. in intern. shock (aided by turbulence)
- Accel e^- : direct (recon.) or stochast. (turb.) → rad: SY
- Need reconn. over $\lambda_{par} \leq 10^4$ cm lengths , envisage blobs w. same directions spiral but staggered, have ↓↑ regions of B_{perp} →turb. resist. →reconn. (early colls. distort B, at large r much distort., recon)

ICMART model, cont.



(a) Initial collisions only distort magnetic fields

(b) Finally a collision results in an ICMART event

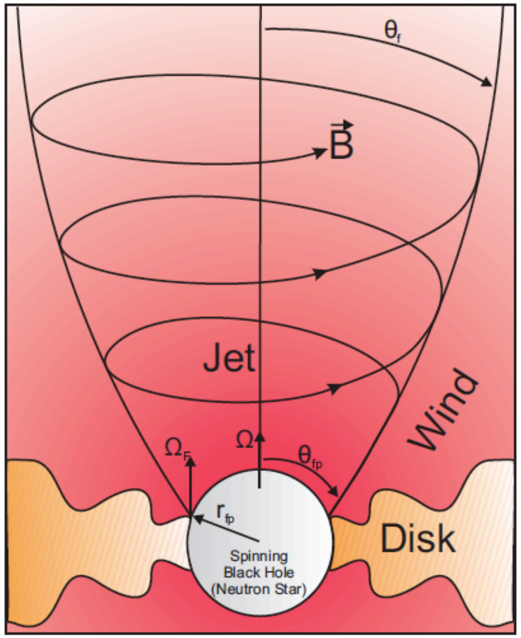
ICMART model, cont.

- Reconnect at r$\gtrsim 10^{15}$ cm, there $\sigma_f \gtrsim 1$, Y$\lesssim 1$, no IC
- $n_{e,p} \sim 1/(1+\sigma_i) << n_e$ (bar. models)→weak photo.
- n_p also << than baryon model, →no hadr. comp.
- E_{pk} drops during pulse, hard to soft evol.
- Reverse shock possible, at late stage $\sigma_f \sim 1$.
- Two variabilities: 1) Centr. eng., ii) Recon./turb.
- *Solve: i) low effic.; ii) fast coolg sp. ; iii) electron excess; iv) no bright photosph. (need* $\sigma < 3x10^3$ *)*

(Other recent MHD model: Granot et al arXiv:1004.0959 - dynamics mainly)

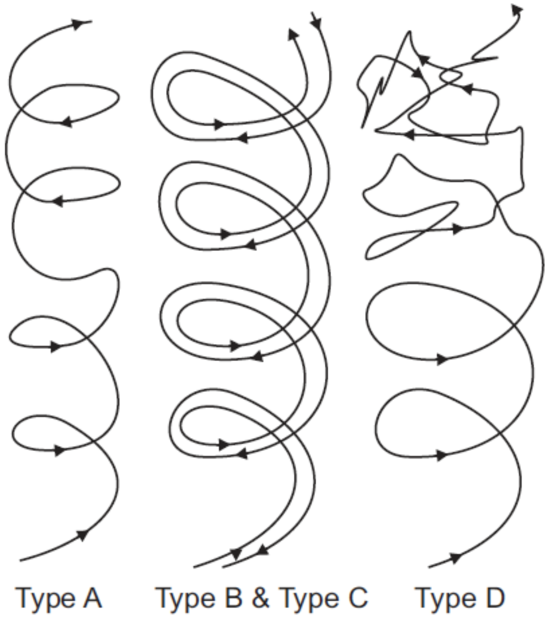
An MHD jet “reconnection switch” model

McKinney & Uzdensky, arXiv:1011.1904



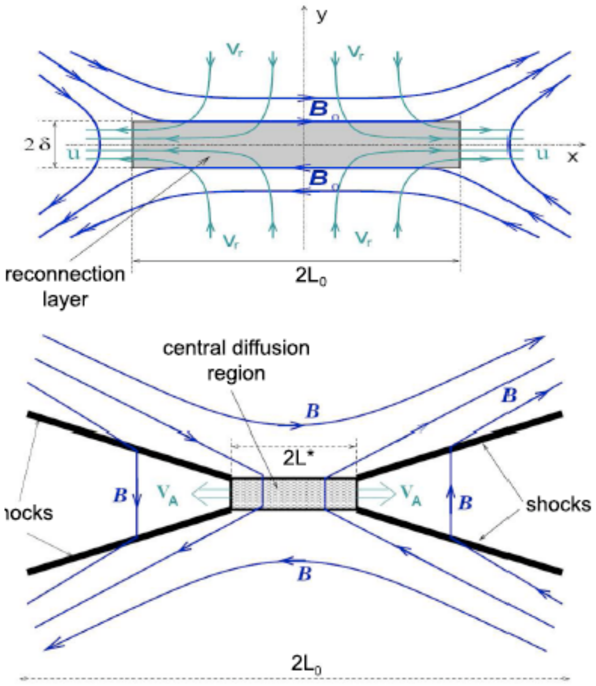
- Fast rot. collapsar→BH +disk →homopolar field (aligned rotator)
- Or, aligned rot. magnetar
- Reconnection in principle not easy (same polarity)

From axisym. homopolar to striped

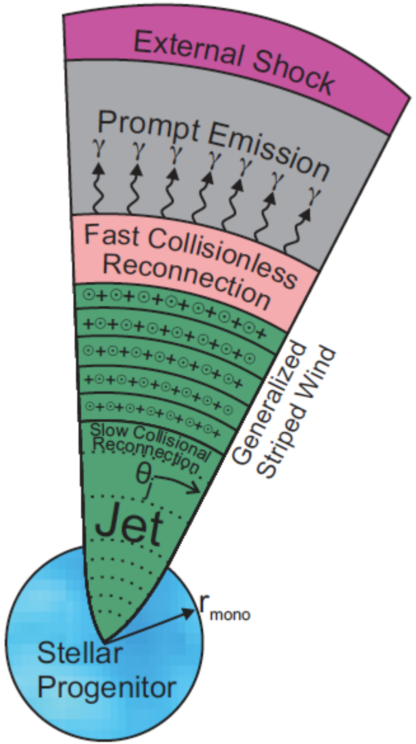


- Invoke various instabilities, dynamo effects
- Also entrainment of surrounding turbulent stellar envelope material
- Highly uncertain

Reconn. Switch



- When density drops low enough, switch from
- slow (Sweet-Parker, i.e. Spitzer resist.) reconnection to
- fast (Petschek, i.e. anomalous resist.) reconnection; occurs on fraction of Alfven timescale, beyond scatt. photosphere
- In this regime, not too diff. from Spruit et al (2001)

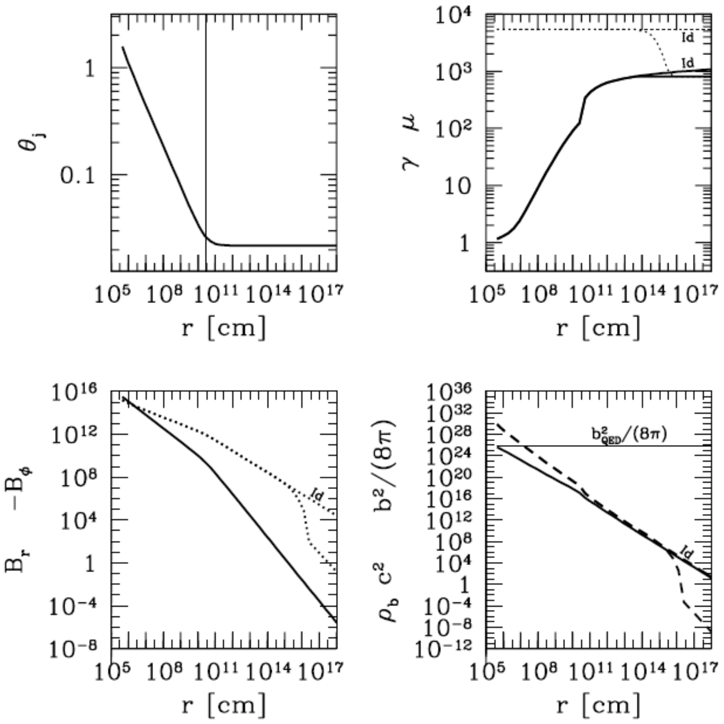


GRB "reconnection switch" mode

McKinney & Uzdensky, arXiv:1011.1904

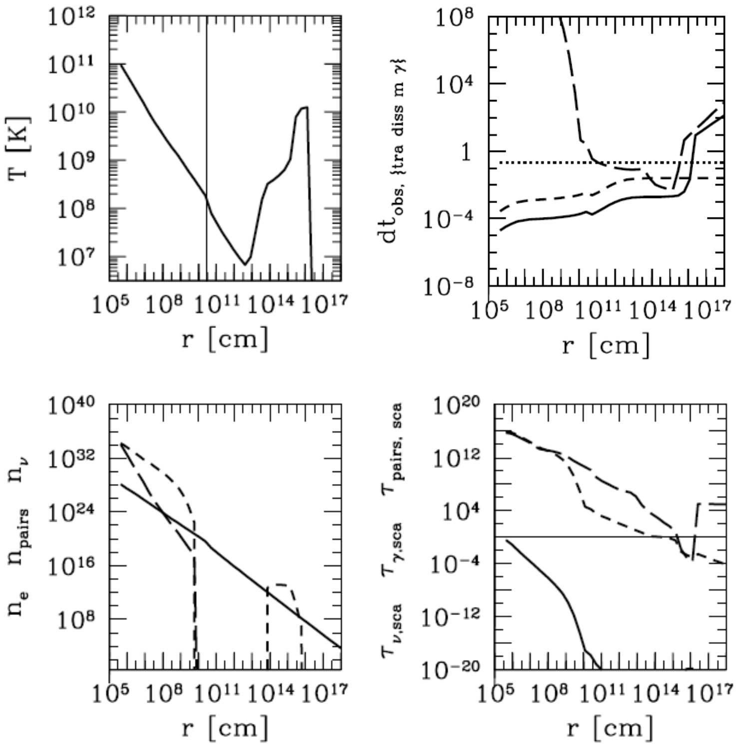
- Tangling →reversing of field lines leads:
- first (high density), to slow collisional reconnect/dissipation
- higher up (low density), to fast collisionless reconnection→ prompt emission

Jet structure and phys. quantities



- Ideally, if all works right, get:
- Lorentz factor
- Jet angle
- Diissip at radius r~10^{16} cm
- prompt emiss.
- Usual afterglow
- But spectrum? Time variability?...

Jet structure and phys. quants., II



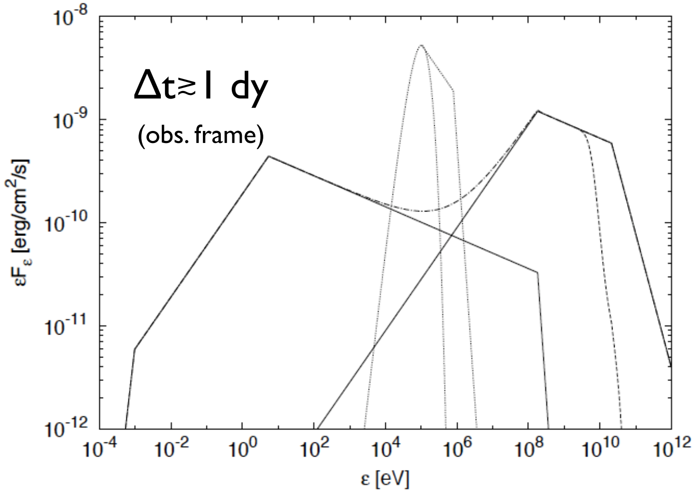
- Pair density and scatt. opt. depth remain large (slow dissip) out to $r \sim 10^{16}$ cm
- Fiducial variab. times are small enough (but wildly uncertain) at dissip radius

Pop. III GRBs?

Mészáros & Rees, 2010, ApJ 715:967

- z~20 pop.III stars 300-1000 $M_\odot$ →collapsar
- Accr. too cool for ν-cool → BZ, Poynting jet
- $L \sim 10^{52} \beta_1^{-1} R_{12}^{-3/2} M_3^{3/2}$ erg, $t_{ac} \sim 10^5 (1+z/20)$ s
- If mostly B, e± → emission is leptonic,
- pair annih. photosphere: $\Delta t_{prompt} \sim 10^5([1+z]/20)$s
  $E_{an}^{ob} \sim 50$ keV (20/1+z) peak + PL (IC)
- External shock (indep. of ext. density):
  $E_{sy}^{ob} \sim 2.5$ keV(20/1+z) , $E_{ssc}^{ob} \sim 75$ GeV (20/1+z)
- Flux : $F \sim 10^{-7}$ erg cm^{-2}s^{-1} $\eta_{-1} \Omega_3^{-1} \beta_1^{-1} R_{12}^{-3/2} M_3^{3/2}$

Pop. III GRBs: afterglow



$\Delta t \gtrsim 1$ dy

(obs. frame)

Toma, Sakamoto & Mészáros, ApJ (in press) arXiV:1008.1269

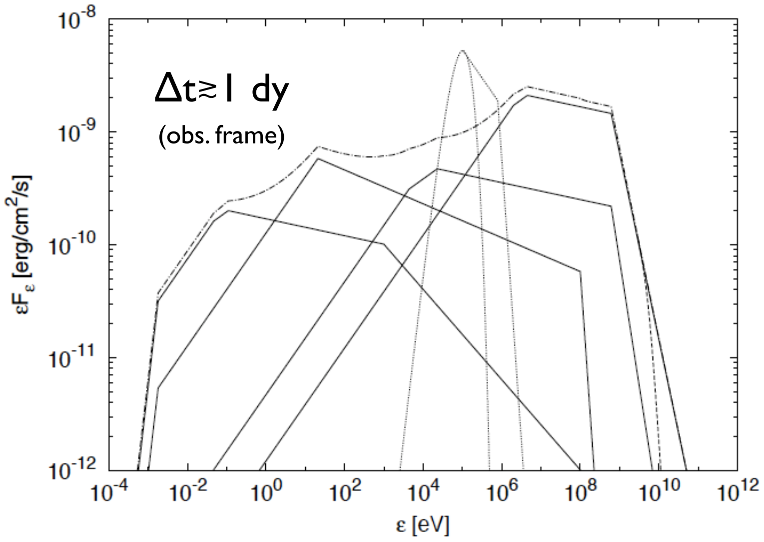
Case ***without*** internal pair formation, $n_0 \sim 1 \mathrm{cm}^{-3}$,only EBL, $z=20$

Mainly Near-IR, XR, GeV

$\nu F_\nu \lesssim 10^{-9}\ \varepsilon_{e-1}\ t_{a5}^{-1}\ d_{L,20}^{-2}$ erg cm^{-2} s^{-1}

Detectable only with image trigger (v. gradual)

Pop III GRB afterglow

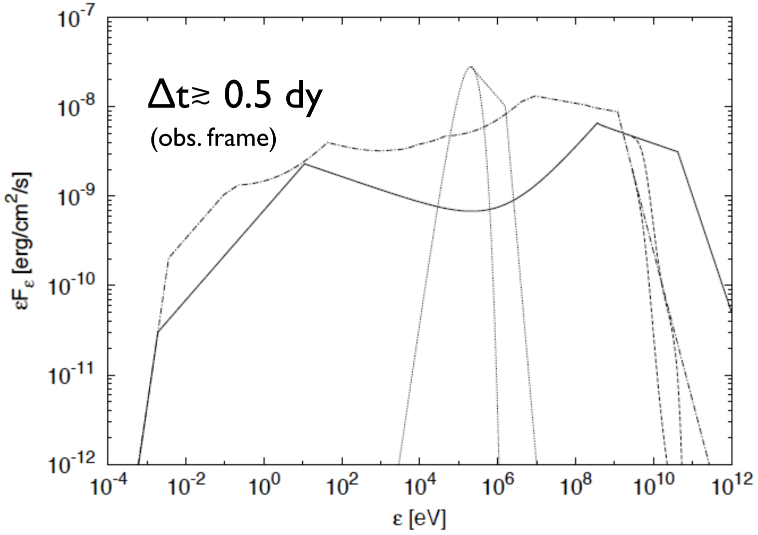


Case ***with*** pair formation & 1st gen. cascade, $n_0 \sim 10^2$ cm^{-3} EBL only, z=20

Weaker IR but stronger O than in no pair case, XR, softer GeV

arXiV:1008.1269

Late Pop III GRB afterglow



$\Delta t \gtrsim 0.5$ dy

(obs. frame)

z=10

Solid: no pairs
Dashed: pairs

Some issues with high-z:

- GRB 090423, ***z=8.2***, T90=13 s (***1.4 s*** in RF)
- GRB 080913, ***z=6.7***, T90=8 s (**<*1 s*** in RF)
- Both appear "***short***" in RF, yet they are difficult to explain with ***compact merger*** at that z; likelier due to ***massive star collapse***
- In disagreement with statistics at low z
- Are high z GRB progenitors ≠ ? and how?
- Is increasingly low metallicity causing this?

Other recent theoretical papers

(won’t have time to discuss, sorry)

- Acceleration of high-σ relativistic flow: Granot et al, arXiv:1004.0959
- Dynamics of strongly magn. ejecta in GRB: Lyutikov, arXiv:1004.2429
- Accel. of UHECR in blazars & GRB: Dermer, Razzaque, preprint
- Leptonic & hadronic model GRB 090510, Razzaque et al, preprint
- Ruffini, Izzo, et al, 2010, GRB080916C & 090902B (see talk later)
- Very High Γ models (low+high baryon): Ioka, 2010, arXiv:1006.3073
- Pe’er, et al, 2010, phot. thermal+non-thermal, arXiv:1007.2228

Prospects & Perspectives

- Swift and Fermi have greatly expanded and deepened our probing into the GRB physics
- Jet structure is essential, and being probed; also the role and existence/absence of reverse shocks
- Prompt emission mechanisms are being challenged: new factors may play role - pairs, hadrons, magnetic fields, photospheres, turbulence, reconnection,...
- Debate whether magnetic fields play larger role than previously assumed - quantitative magnetic models remain sketchy; so do turbulent/reconnection models. They warrant continued attention, together with pair, photosphere, cocoon, leptonic and hadronic models

more back-up slides

GRB: *basic numbers*

- Rate: ~ 1/day inside a Hubble radius
- Distance: $0.1 \leq z \leq$ **8.2 !** → $D \sim 10^{28}$ cm
- Fluence: $\sim 10^{-4} - 10^{-7}$ erg/cm^2

  $$F = \int flux.dt \sim 1 \text{ ph/cm}^2 \ (\gamma\text{-rays !})$$

- Energy output: $10^{53} (\Omega/4\pi) D^2_{28.5} F_{-5}$ erg

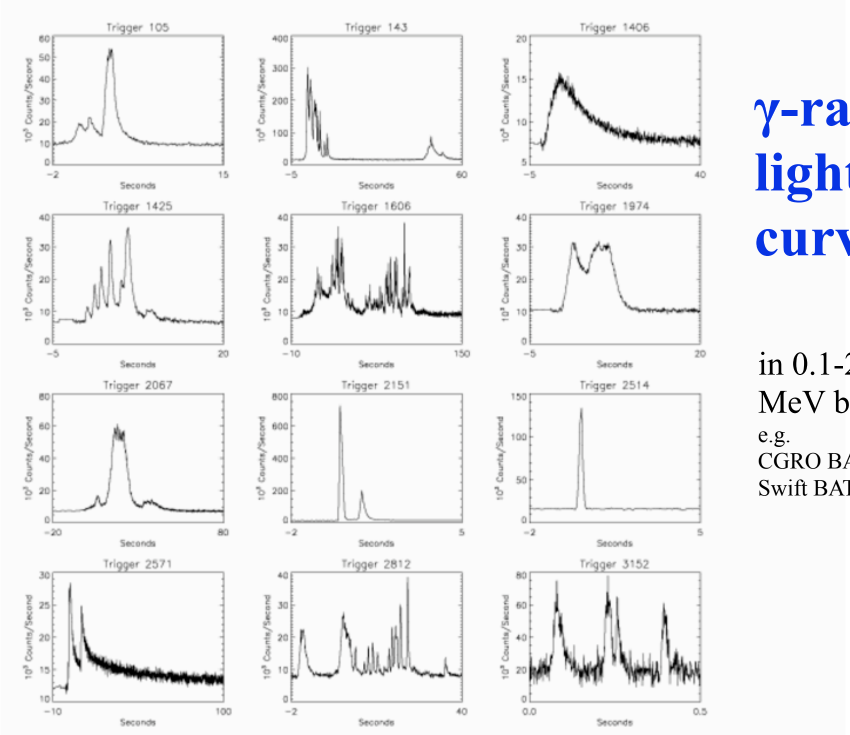
  but, jet: $(\Omega_j/4\pi) \sim 10^{-2}$ → $E_{\gamma,tot} \sim 10^{51}$ erg

  → $E_{\gamma,tot} \sim L_{\Theta}$ in 10^{10} year ~ L_{gal} in 1 year

- Rate[GRB (γ−obs)] $\sim 10^{-6}(2\pi/\ \Omega)$ /yr/gal →1/day ($z \leq 3$)

  but Rate [GRB (uncollimated)] ~ 10^{-4} /yr/gal,

  while Rate [SN (core collapse] ~ 10^{-2}/yr/gal, or 10^{7} /yr ~ 1/s (z **<**3)



γ-ray light-curves

in 0.1-2 MeV band,
e.g.
CGRO BATSE,
Swift BAT

Explosion → FIREBALL

- $E_{\gamma} \sim 10^{51}\,\Omega_{-2}\,D^2_{28.5}\,F_{-5}$ erg
- $R_0 \sim c\,t_0 \sim 10^7\,t_{-3}$ cm

→ ***Huge energy in very small volume***

- $\tau_{\gamma\gamma} \sim (E_\gamma/R^3_0 m_e c^2)\sigma_T R_0 >> 1$

→ ***Fireball:*** ***$e^{\pm},\gamma,p$ relativistic gas***

- $L_\gamma \sim E_\gamma/t_0 >> L_{Edd}$ → expanding (v~c) fireball

(Cavallo & Rees, 1978 MN 183:359)

- Observe $E_\gamma > 10$ GeV …but

  $\gamma\gamma \to e^{\pm}$, degrade 10 GeV →0.5 MeV?

  $E_\gamma E_t > 2(m_e c^2)^2/(1-\cos\Theta) \sim 4(m_e c^2)^2/\Theta^2$

→ *Ultrarelativistic* flow → **$\Gamma \geq \Theta^{-1} \sim 10^2$**

(Fenimore etal 93; Baring & Harding 94)

Ô→

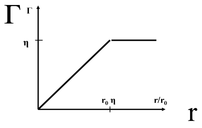
Relativistic Outflows

- Energy-impulse tensor : $\mathbf{T_{ik} = w\, u_i\, u_k + p\, g_{ik}}$,
  $\mathbf{u^i}$: 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 $\mathbf{u = \Gamma\, (v/c)}$,
  $\mathbf{v}$ = 3-velocity, **A**= outflow channel cross section :
- Impulse flux $\mathbf{Q=(w\, u^2 +p)\, A}$
  energy flux $\mathbf{L= wu\, \Gamma\, c\, A}$
  particle number flux $\mathbf{J= n\, u\, A}$
- Isentropic flow : **L, J constant** →
  $\mathbf{w\, \Gamma\, /n = constant}$ (*relativistic Bernoulli equation)*;
  for ultra-rel. equ. of state $p \propto \mathbf{w} \propto n^{4/3}$, and cross section $A \propto r^2$

→ $\mathbf{n \propto 1 / r^2\, \Gamma}$ comoving density drops

→ $\mathbf{\Gamma \propto r}$ "bulk" Lorentz factor initially grows with **r**.

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



$\Gamma \propto r \;\;\rightarrow\;\; \Gamma \sim const.$

Shock formation

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

  If two gas shells ejected with $\Delta \boldsymbol{\Gamma} = \boldsymbol{\Gamma}_1 - \boldsymbol{\Gamma}_2 \sim \boldsymbol{\Gamma}$, 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, $E=(4p/3) r_{es}^{3}\, n_{ext}\, m_p\, c^2\, \boldsymbol{\Gamma}^{2}$,

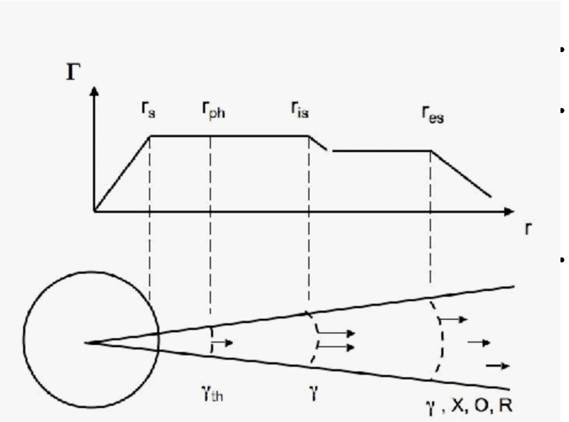
$$r_{es} \sim (3E/4p n_{ext} m_p c^2)^{1/3}\, \Gamma^{-2/3} \sim 3.10^{16} (E_{51}/n_0)^{1/3}\, \Gamma_2^{-2/3} \text{ cm}$$

(external shock)

Internal & External Shocks

in optically thin medium :

LONG-TERM BEHAVIOR



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

  →**γ-rays** (***burst***, t_γ~sec)
- **External** shocks at r_e ~10^{16}cm; progressively decelerate, get **weaker and redder** in time (Rees & Meszaros 92)
- Decreasing Doppler boost: → roughly, expect **radio** @ ~1 week , **optica**l @ ~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**

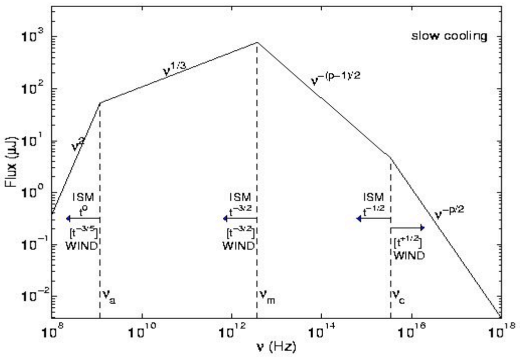
  (t ~ min, hr, day, month)
- External ***reverse*** shock (less relativistic, cooler, denser):

  Prompt Optical → quick fading

  (t ~ mins)

  (Meszaros & Rees 1997 ApJ 476,232)

Snapshot (leptonic) Afterglow Fits



Sari, Piran, Narayan ’98 ApJ(Let) 497:L17)

Break frequency decreases in time (at rate dep. on whether ext medium homog. or wind (e.g. $n \propto r^{-2}$)

- Simplest case: $t_{cool}(\gamma_m) > t_{exp}$, where $N(\gamma) \propto \gamma^{-p}$ for $\gamma > \gamma_m$ (i.e. $\gamma_{c(ool)} > \gamma_m$)
- 3 breaks: $\nu_{a(bs)}$, ν_m, ν_c
- $F_\nu \propto \nu^2 \ (\nu^{5/2})$; $\nu < \nu_a$;

  $\propto \nu^{1/3}$; $\nu_a < \nu < \nu_m$;

  $\propto \nu^{-(p-1)/2}$; $\nu_m < \nu < \nu_c$

  $\propto \nu^{-p/2}$; $\nu > \nu_c$

(Mészáros, Rees & Wijers ’98 ApJ 499:301)

Collapsar & SN :

a direct link - but always ?

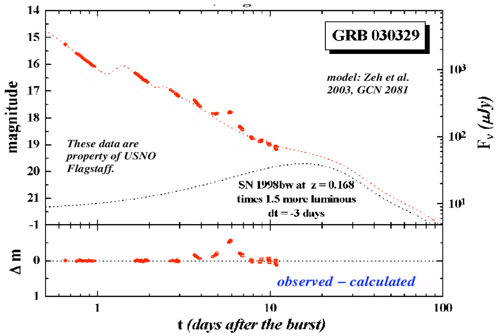
- Core collapse of star w. M_t~30 M_{sun}
  → BH + disk (if fast rot.core)
  → jet (MHD? baryonic? high Γ,
  + SNR envelope ejecta (always?)
- 3D hydro simulations (Newtonian SR) show that baryonic jet w. high Γ can be formed/escape
- SNR: convincing observations, e.g. late l.c. hump, reddening, prompt XR flash of shock outbreak, etc.; and ..
- ***Direct*** observational (spectroscopic) detections of GRB/ccSN

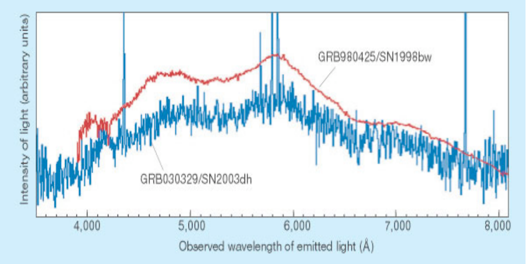
Collapsar & SN ANIMATION

Credit: Derek Fox
& NASA

Collapsar & ccSN :

GRB 030329 - SN 2003dh & others since





- 2nd Nearest “unequivocal” cosmological GRB: **z=0.17**
- **GRB-SN association**: **“strong”**
- Fluence:10^{-4} erg cm^{-2} ,

  among highest in BATSE,

  but t_γ~30s, nearby; $E_{g,iso}$~$10^{50.5}$erg: ~typical,
- $E_{SN2003dh,iso}$ ~$10^{52.3}$ erg

  ~ $E_{SN1998bw,iso}$ («grb980425)

  $v_{sn,ej}$~0.1c (→ “hypernova”)
- GRB-SN simultaneous? at most:

  < 2 days off-set (from opt. lightcurve)

  (→ i.e. not a “supra-nova”)
- But: might be 2-stage (<2 day delay) *- NS-BH collapse ?

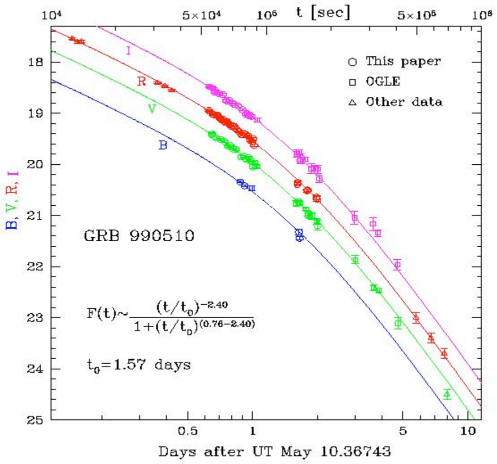
  → ν predictions may test this !
- Some others:

  GRB 031203/SN2003lw;

  - GRB 060218/SN2006aj; ...

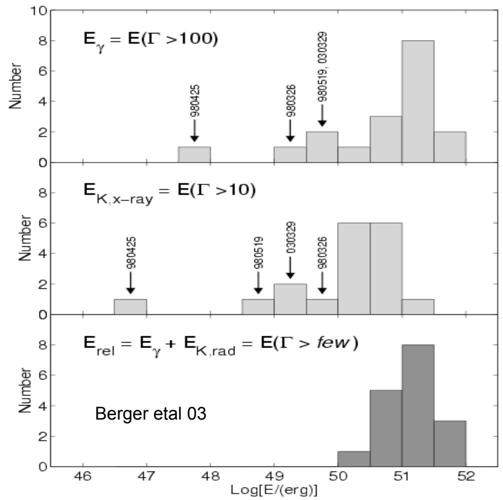
Mészáros, L’Aqu05

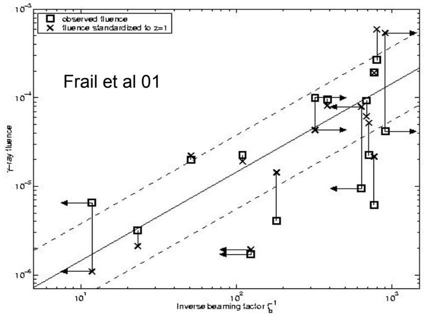
Light curve break: Jet Edge Effects



- Monochromatic break in light curve time power law behavior
- expect $\Gamma \propto t^{-3/8}$, as long as $\vartheta_{\text{light cone}}$ $\sim\Gamma^{-1} < \vartheta_{\text{jet}}$, (spherical approx is valid)
- "see" jet edge at $\Gamma \sim \vartheta_{\text{jet}}^{-1}$
- Before edge, $F_\nu \propto (r/\Gamma)^2 . I_\nu$
- After edge, $F_\nu \propto (r\,\vartheta_{\text{jet}})^2 . I_\nu$,
  $\rightarrow F_\nu$ steeper by $\Gamma^2 \propto t^{-3/4}$
- After edge, also side exp.
  $\rightarrow$ further steepen $F_\nu \propto t^{-p}$

Jet Collimation & Energetics

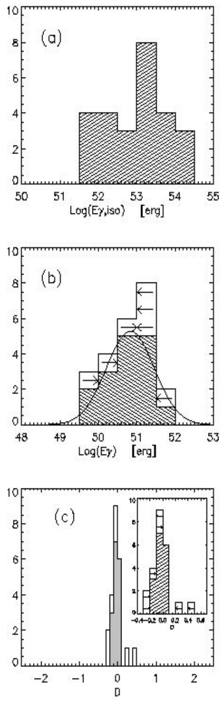




- ↑ Jet angle inv. corr. w. $L_{\gamma(iso)}$
- ← $L_{\gamma(corr)}$ ~ **const.**
- Collim. corr.: $(4\pi/2\Delta\Omega_j) \sim 10^{-2}$
- → $\mathbf{E_{total} = E_\gamma + E_{kin} \sim}$ **const.**

(→ quasi-standard candle ?)

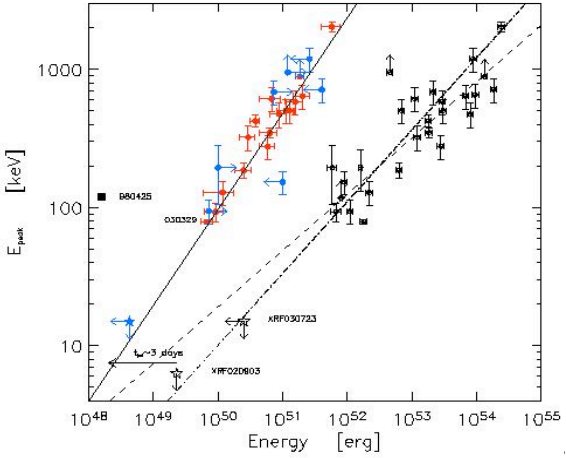
Mészáros, L'Aqu05



Amati: $E_{pk} \propto E_{iso}^{1/2}$

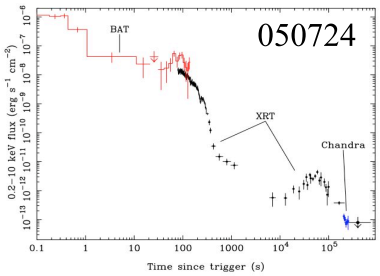
Ghirlanda: $E_{pk} \propto E_j^{0.7}$

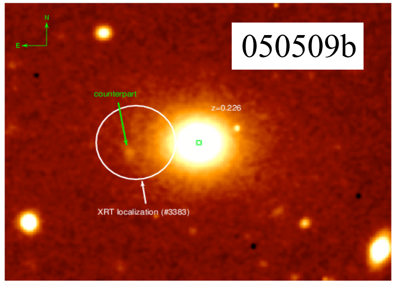
(Phenomenological: but start having reasonable interpretations; e.g. photospheric models)

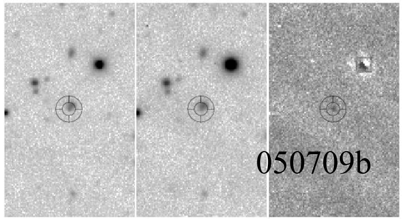


s, L'Aqu05

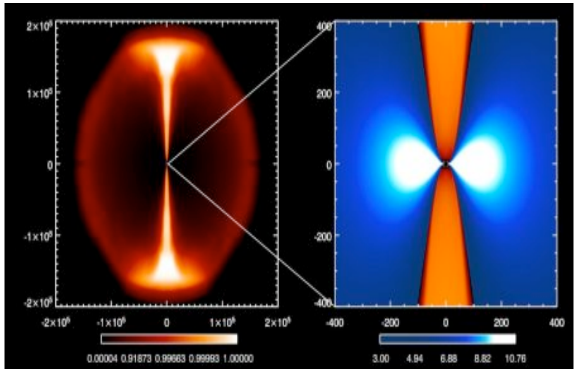
Short Bursts







- ***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?)



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)

ES Sy shock model critique

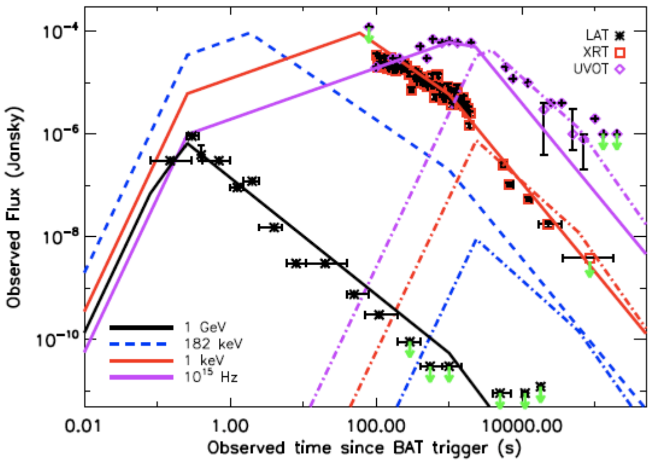
Piran-Nakar, 1003.5919

- Late photons (E >10 GeV, t > 100 s) ***cannot*** arise from ES Synchrotron (from general accel + sy constraints) → must be ≠ process
- few mJy IR flux from RS → quench GeV emiss. (by IC), unless B is amplified in shock
- If no amplification → need $B_{ext} \geq 100\ \mu G$ (adiabatic; (unless n_{ext} very low, $n<10^{-6}$) - or B higher for radiative
- If ES Sy model is true,
  → no late >10 GeV phot (t>100 s), and
  → no simult.. < mJy IR flux should be observed

– Other recent ES Sy critique: Zhuo Li, 1004.0791, argue need $5n_0^{5/8}$ mG $<B_u<10^2\ n_0^{3/8}$ mG → upstr. preamplification

ES shock model: 090510

Corsi, Guetta, Piro, arXiv:0911.4453

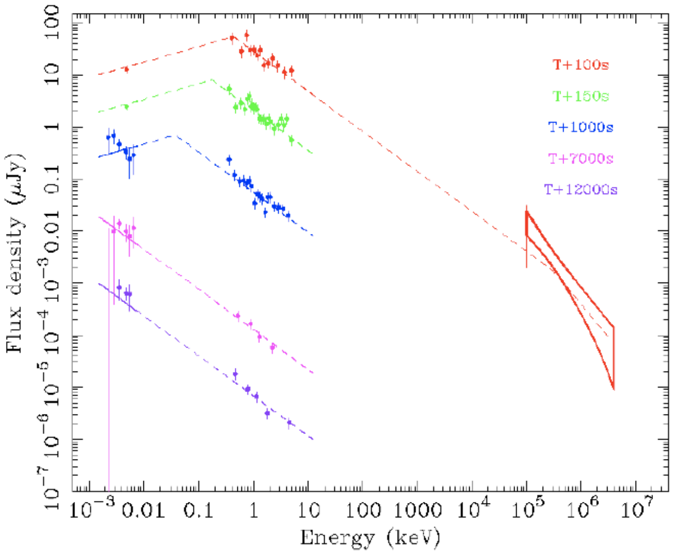


- ES: fit LAT, X, O, Γ_n~10^4, $E_{iso,n}$~$4x10^{53}$, ε_e~$3x10^{-3}$, p~2.3, n~10^{-6}, $\theta_{j,n}$~0.12°
- IS: fit GBM, BAT, Γw~300, $E_{iso,w}$~$1.7x10^{53}$, ε_e~$3x10^{-3}$, p~2.7, $\theta_{j,w}$~0.64°

Or, another IS + ES model: De Pasquale et al ’09, next slide

IS-ES shock model: 090510

De Pasquale + Fermi/Swift team, 2010, ApJ 709:146



- Early ***LAT, XRT*** due to ***IS*** , and ***O*** rise could be due to onset of simple ***FS***
- Or, ***FS*** may produce full spectrum from ***O thru GeV***, but temporal behavior → structured jet

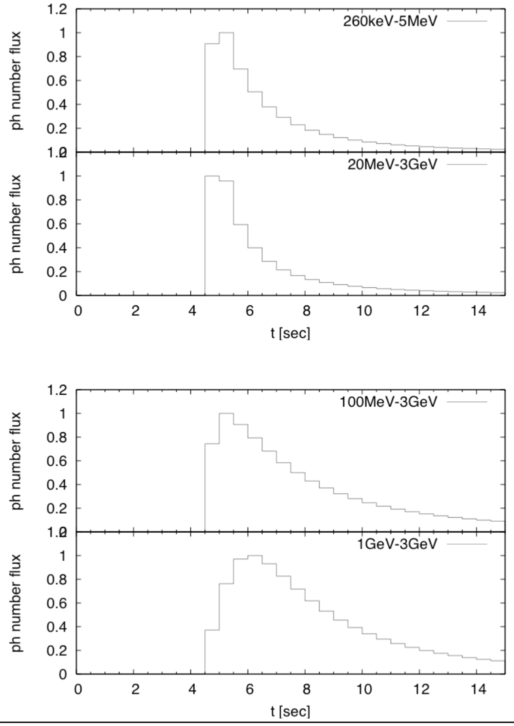
Photosp. critique: mag. outflow?

Zhang & Pe'er , 09, ApJ 700:L65

- Argue (based on $r_a \sim ct_{var}$ and assuming 080916c Band is ES Sy) that phot. radius r_{ph} is too low (below $\tau_{\gamma\gamma} \sim 1$), and T_{ph} too low to be MeV; also object to thermal spectrum
- Hence conclude outflow probably Poynting, or at least much more baryon-poor than usual baryonic fireball
- However, assumed "traditional" r_{ph} and its T_{ph}; this is different, if include additional $e^{\pm}$ and use more recent numerical simulations of jet/phot/cocoon, e.g.Morsony 09.
- The latter was used in the Toma et al phot+IS model, where T_{ph} ~ MeV (i.e. GBM), without invoking Poynting, and IS-UP provides LAT, either as Band or Band+PL
- ***However***: latest Pe'er et al (arXiv.1007.2228) likes phot!

Cocoon + IS Upscattering model

Photon time lags



- photon arrival time in different energy bands
- GeV band: delayed 2-3 s, due to geometry (source photons come from high latitude cocoon)