Looking for observables to constrain the prompt emission mechanism in GRBs

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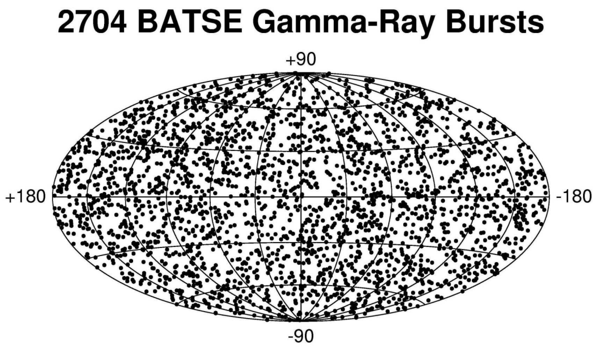
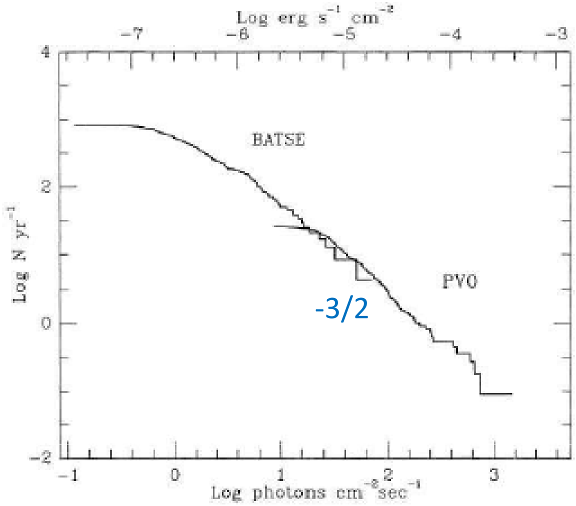
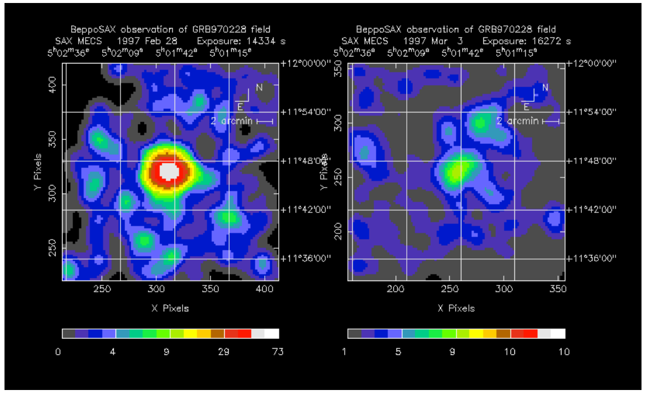
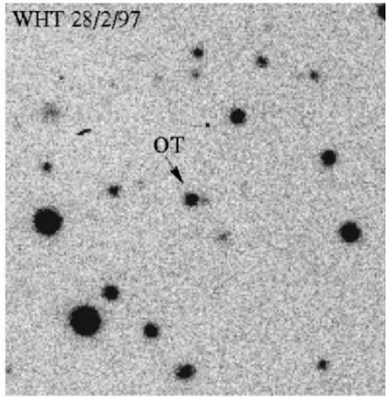
25 years since BATSE

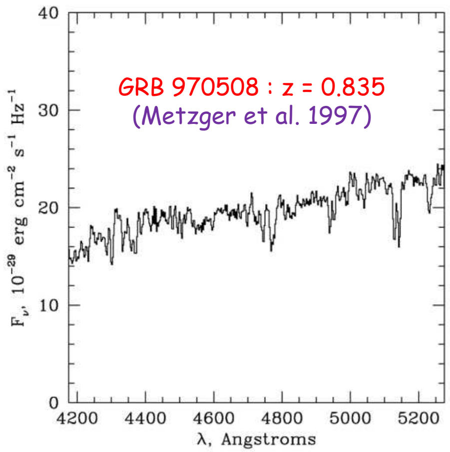




20 years since Beppo-SAX





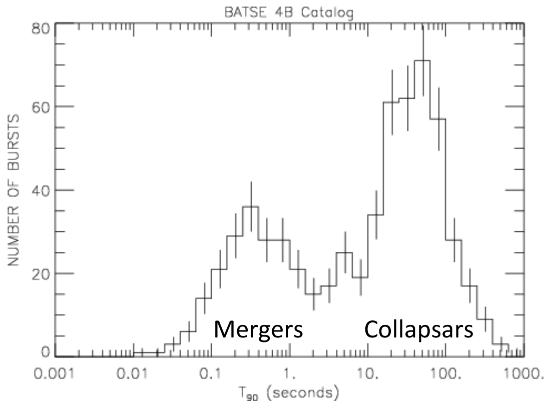


GRBs are located at cosmological distances

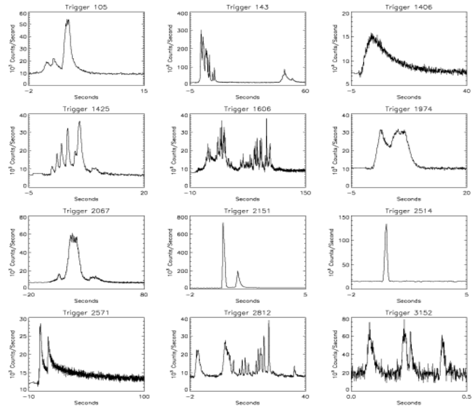
They are the brightest (EM) sources in the Universe !

Basic observational facts

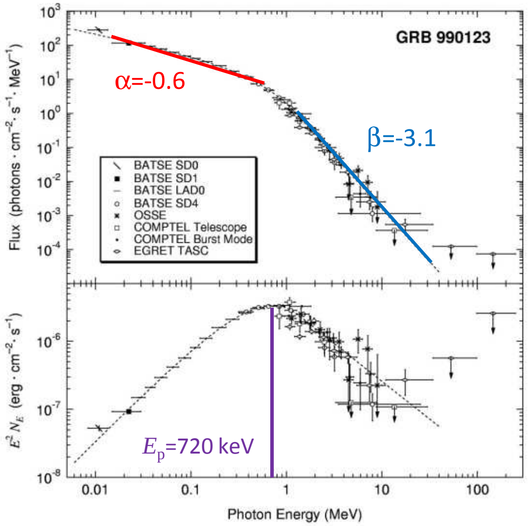
Bimodal duration distribution

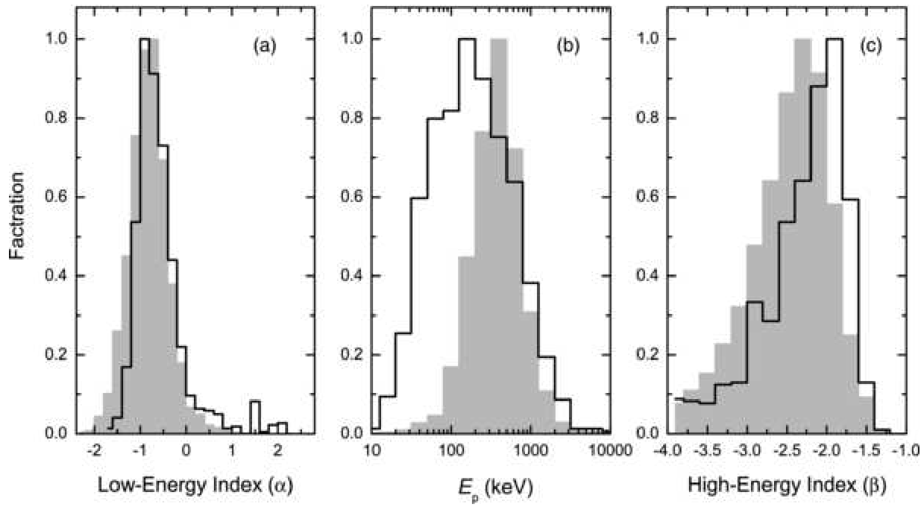


Great diversity of light curves



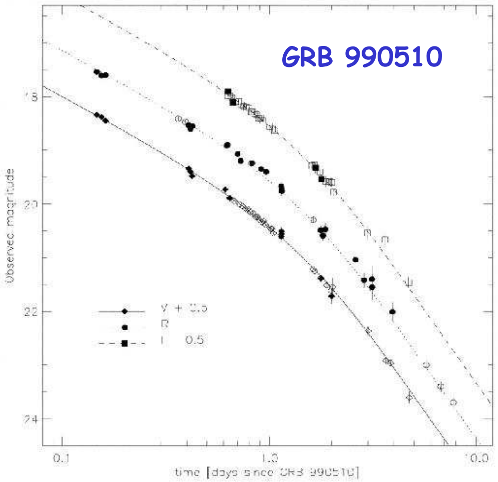
Non thermal spectra (broken power-law)





<u>Radiated energy</u>

$E_{\gamma,\mathrm{iso}}$: up to several 10^{54} ergs but **jet emission**



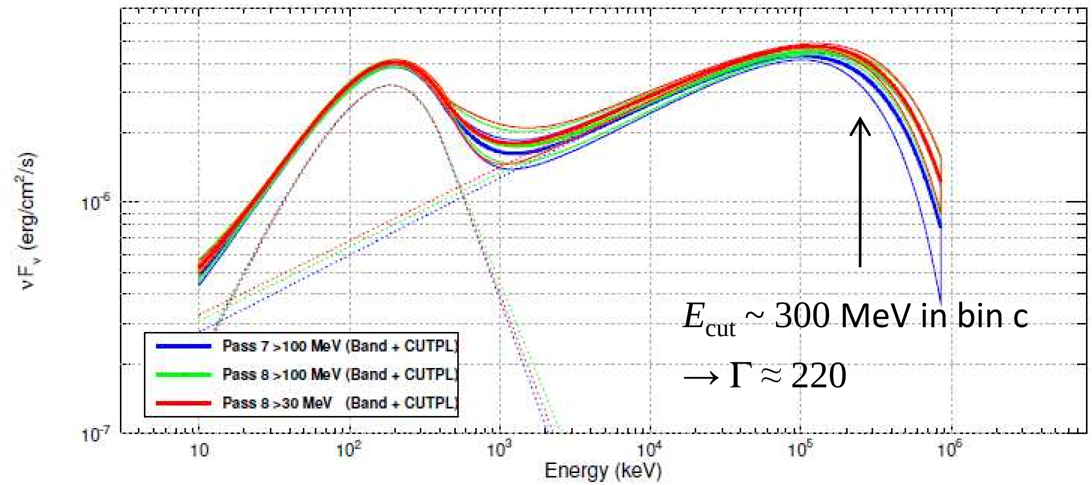
"jet break" when $1/\Gamma > \theta_j \;\rightarrow\; \theta_j \sim 0.1$ rd

$E_{\gamma,\mathrm{true}} =$ a few 10^{51} ergs

$E_{\mathrm{diss}} = E_{\gamma,\mathrm{true}} / f_\gamma$

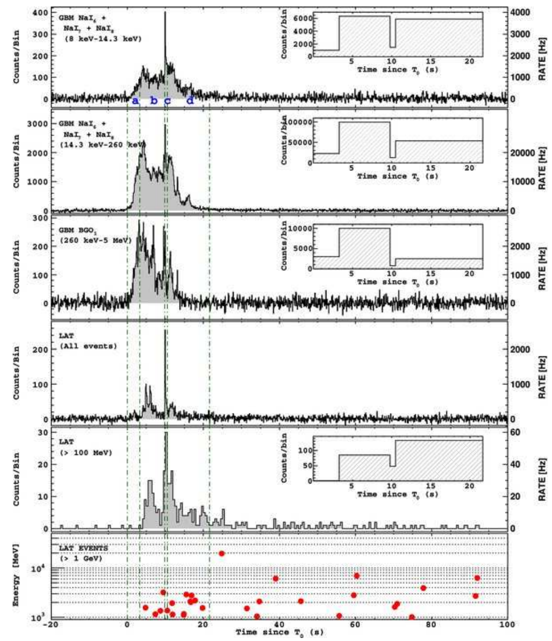
The jet must be highly relativistic to avoid $\gamma\gamma$ annihilation $\Gamma > 100$

Annihilation cut-off possibly observed in GRB 090926A



$E_{\mathrm{cut}} \sim 300$ MeV in bin c

$\rightarrow \Gamma \approx 220$

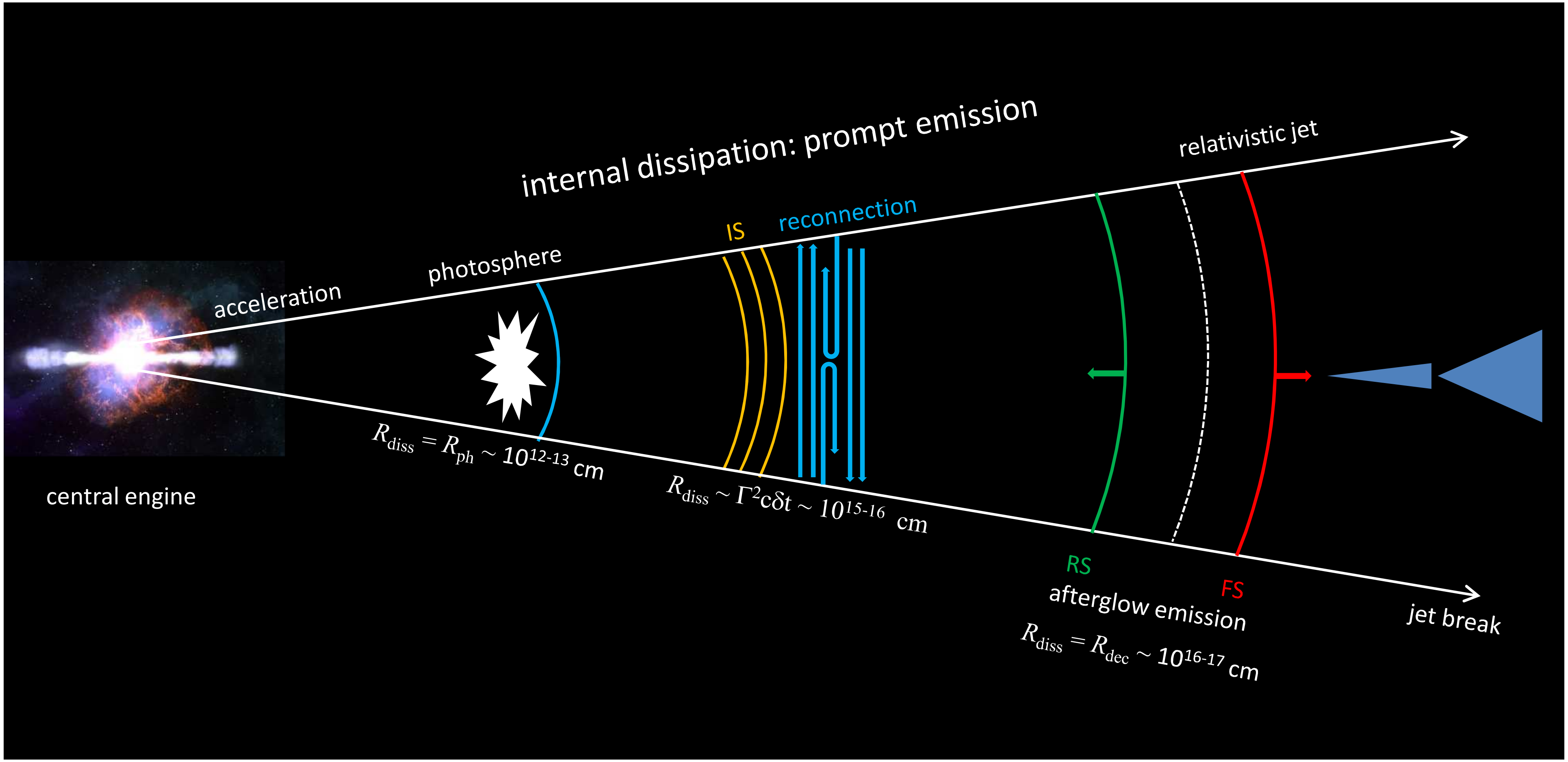


Building a prompt emission model

Ingredients:

- jet acceleration: radiative (fireball)/magnetic $\rightarrow \sigma_\infty$? ($\infty \sim \Gamma^2 c\delta t$)
- dissipation mechanism: shocks, reconnection, inelastic particle collisions
- radiative process(es): synchrotron + IC, comptonization

Three main scenarios:



Internal shocks

Simple, large set of predictions to compare with data, many in good agreement

(temporal profiles, duration-hardness relation, hard to soft evolution, etc)

But also problems:

(i) do shocks form ? $\longrightarrow$ $\sigma < 0.1$

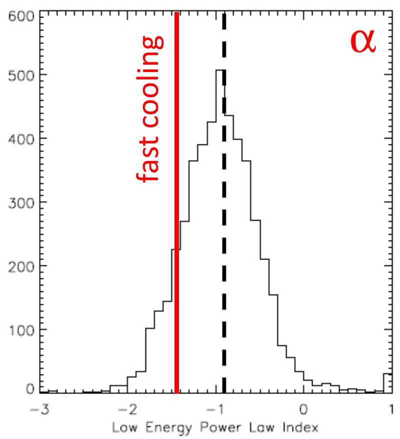
(ii) do they efficiently accelerate particles (electrons) ?

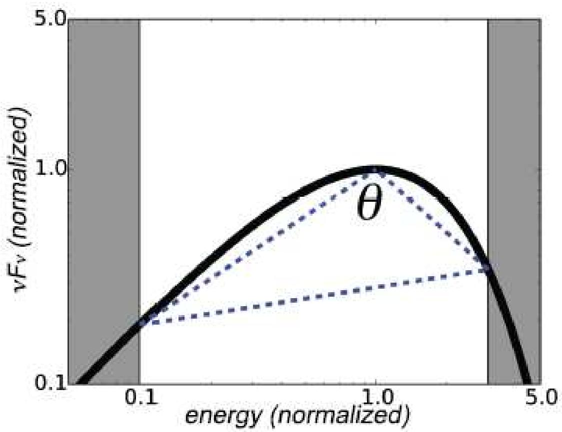
multiple crossings of the shock $\longrightarrow$ narrow window in parameter space $[\sigma\ ,\ \beta_{sh}\gamma_{sh}]$

(Sironi, Petropoulou & Giannios 2015, but see next talk by TP)

(iii) if (i) and (ii) can be satisfied is the resulting spectrum OK ?

synchrotron (+ IC) $\longrightarrow$ problems with the spectral shape ?





synchrotron spectrum too broad ?

Reconnection

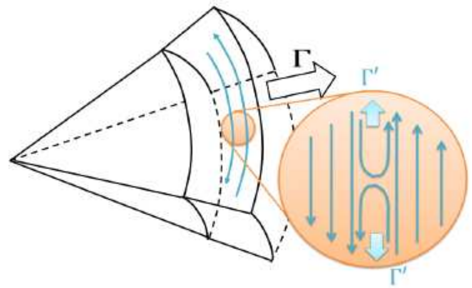
Expected in a magnetized ejecta $\sigma > 1$

Particle acceleration can operate efficiently

Radiation process: synchrotron $\longrightarrow$ same problems as for internal shocks ?

α slope: can electrons receive energy while they radiate ? No

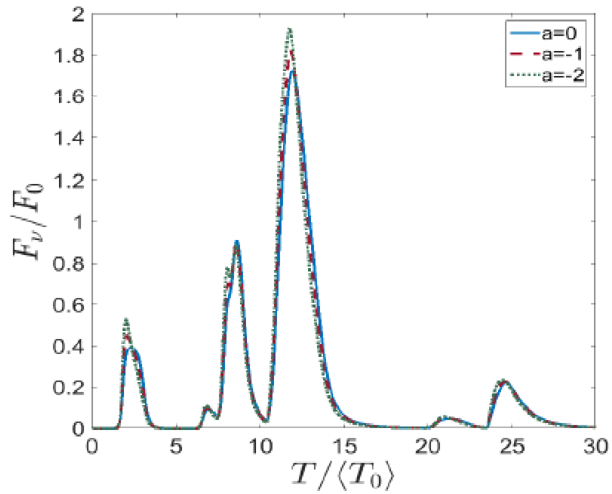
broadening of the spectrum bv motions from reconnection ?



Model phenomenology

Few studies (Beniamini & Granot, 2015, ICMART)

Light curve

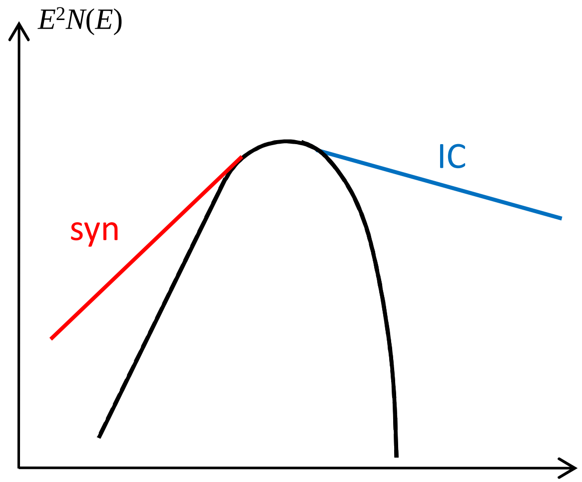


Concerns about spectrum shape ?

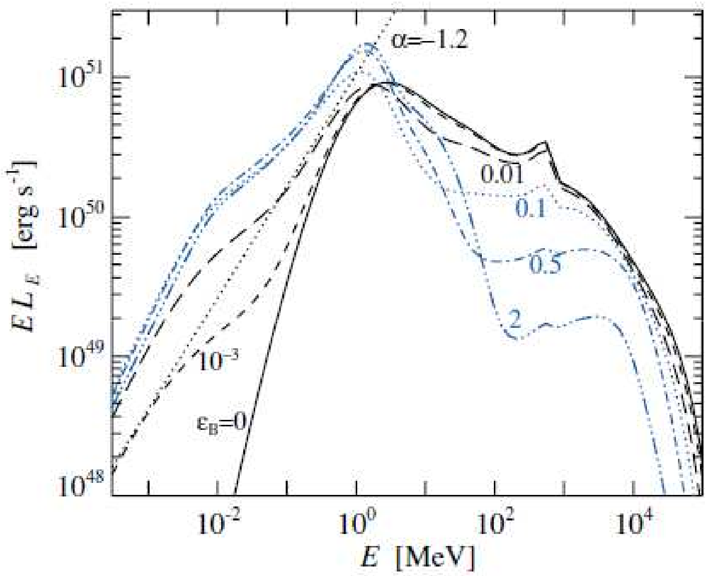
Dissipative photosphere

Sub-photospheric dissipation must transform a quasi blackbody (α = +1 , β = -∞) into a smoothly broken power-law (α = -1 , β = -2.5)   (Band fonction)

- at high energy: dissipative process → energetic électrons → IC on thermal photons
- at low energy: additional synchrotron contribution



Planck → Band



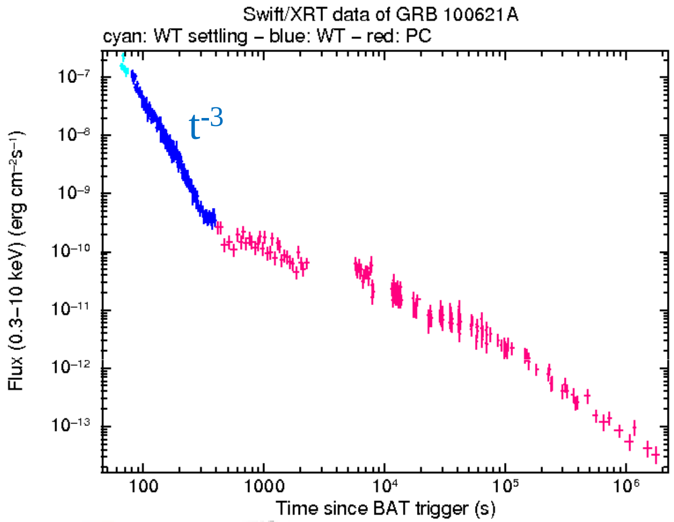
Vurm, Beloborodov & Potanen, 2011

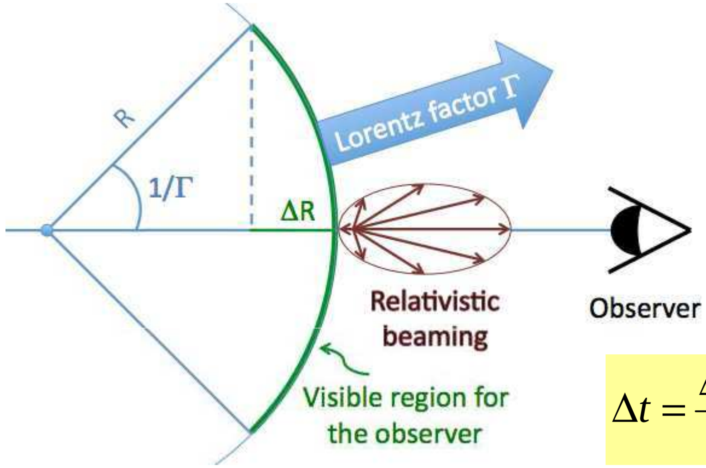
But dissipation process to be specified
and should operate in a variety of regimes: standard GRBs, XRFs

Looking for observables: R_{diss}, presence of shocks/degree of magnetization, radiation processes

R_{diss} : “early steep decay”, prompt optical emission

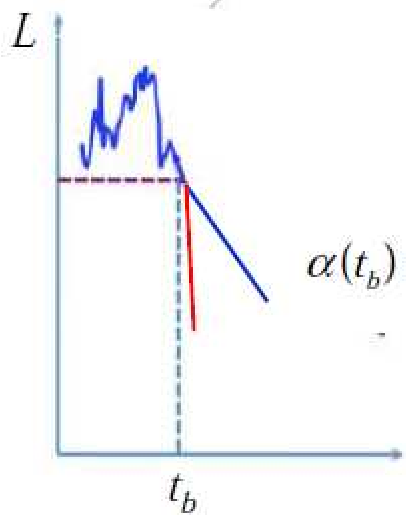
<u>ESD: the geometrical interpretation</u>





$$\Delta t = \frac{\Delta R}{c} = \frac{R}{2c\Gamma^2}$$

$$L(t) \sim \frac{1}{\left(1+\frac{t-t_b}{\Delta t}\right)^3}$$



$$\alpha(t_b) = \left.\frac{d\mathrm{Log}L}{d\mathrm{Log}t}\right|_{t_b} = -3\frac{t_b}{\Delta t}$$

The geometrical interprétation works only if

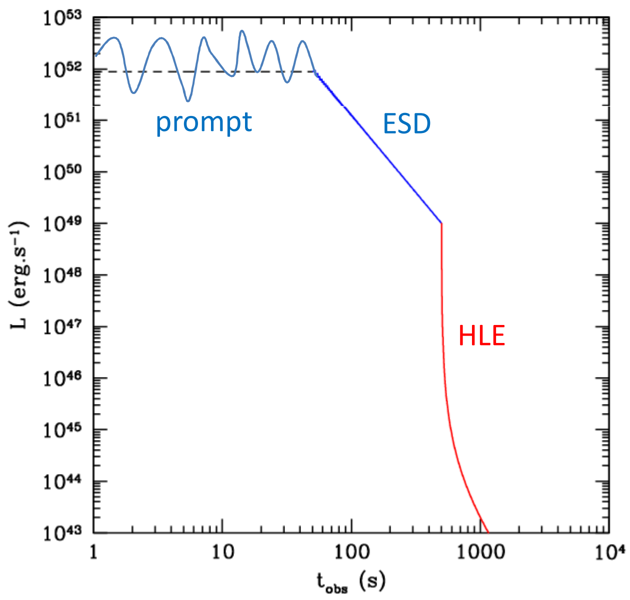
$\Delta t \sim t_b$ i.e.

$R \sim 2c\Gamma^2 t_b = 6\ 10^{14}\,\Gamma_2^{\,2}\, t_b(\mathrm{s})$ cm (IS, reconnection?)

ESD: an effective behavior of the central engine ?

Is it possible ? What does it tell us about the source extinction ?

- Observed behavior: $L \propto \left(\frac{t}{t_0}\right)^{-3}$, $E_p \propto L^{\alpha}$ with $\alpha \sim 1/3$
- Define $\varepsilon_{rad} = \left(\frac{L}{\dot{E}}\right)$ radiative efficiency of subphotospheric heating ($\dot{E}$ injected power in jet)
- Compute the evolution of Γ and $R_{\rm ph}$ that reproduce the observed behavior



$$R_{ph} \approx 5\,10^{13}\, \varepsilon_{rad}^{-2/5} L_{52}^{1/10}\ \mathrm{cm}$$

$$\Gamma \approx 65\, \varepsilon_{rad}^{-1/5} L_{52}^{3/10}$$

Reasonable evolution:
as L decreases by a factor 1000
$R_{\rm ph}$ decreases by 2 and Γ by 10

Some questions and one interesting feature

- Questions

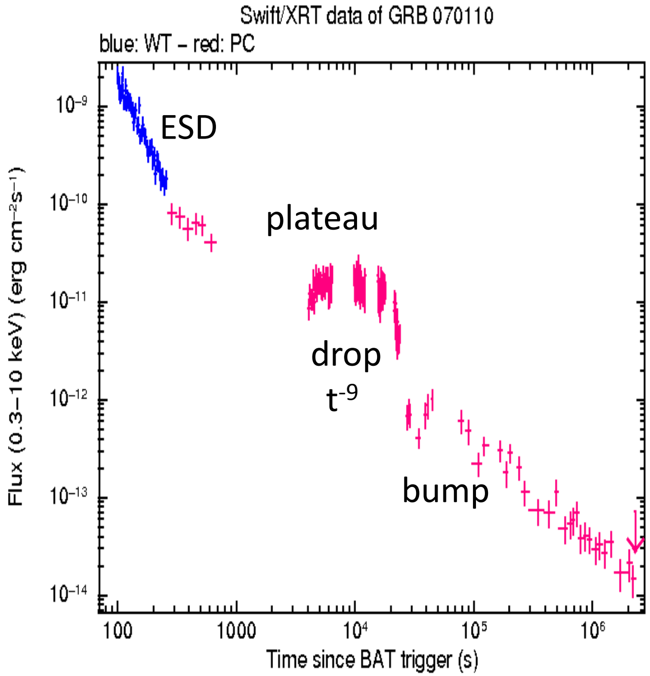
  (i) which sub-photospheric dissipation process ? ($\varepsilon_{rad} \sim 0.1 - 1$)

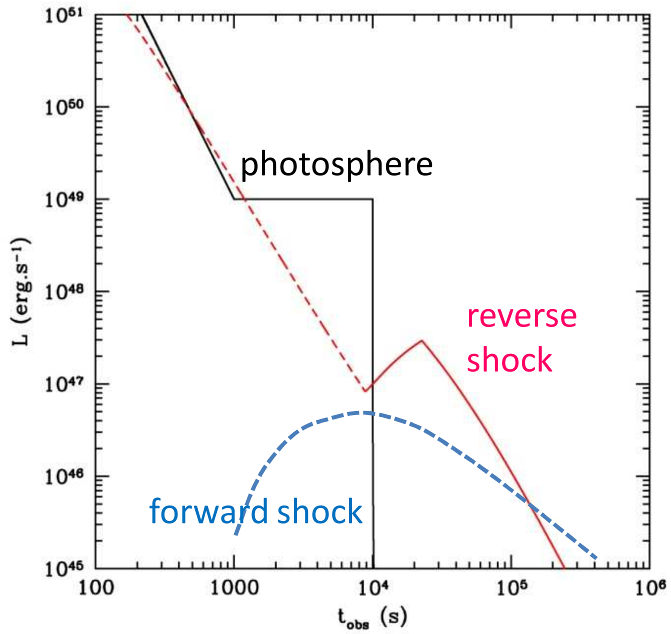
  (should operate over a large range of luminosity)

  (ii) why is the ESD more regular than the prompt phase ?

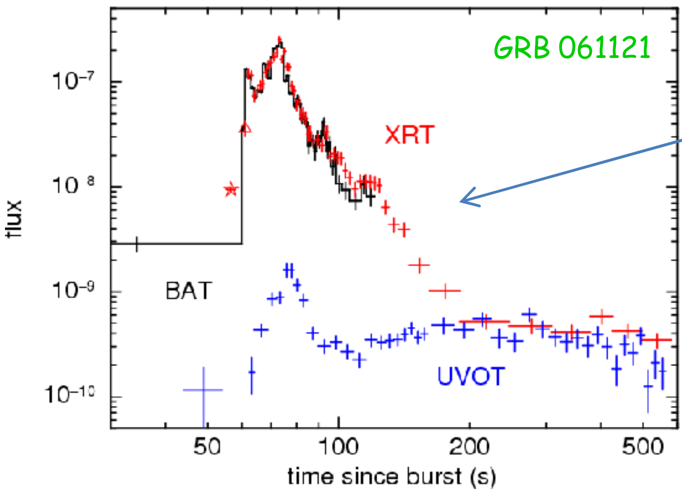
  (why such a diversity of prompt light curves and a generic behavior for the ESD ?)

- Photospheric models easily produce "Internal Plateaus"





Prompt optical emission



Diversity of behaviors but in some cases:

optical flux highly correlated with X,γ

If same emission radius R_e for all and synchrotron process

$\longrightarrow$ condition on R_e to avoid self-absorption

$$R_e \geq 10^{14}\Gamma_{300}^{3/4} B_3^{1/4} \text{ cm}$$

(Shen & Zhang, 2009)

$\longrightarrow$ seems uncompatible with photospheric models

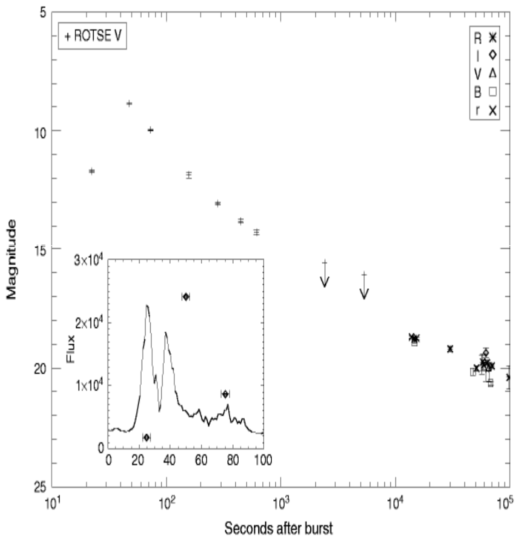
Presence of shocks

If shocks are present $\longrightarrow$ constraint on the magnetization

when shocks develop $\sigma \lesssim 0.1$ (from the origin or due to decay?)

Several possible contributions from the reverse shock have been proposed:

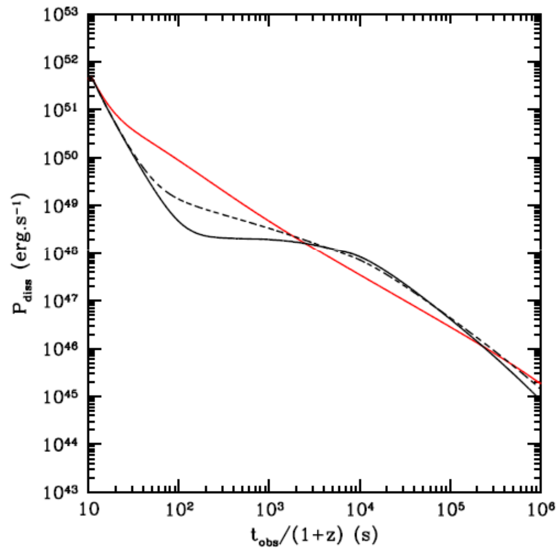
Optical flash in GRB 990123



high Γ ejecta (short-lived RS)

Sari & Piran, 1999

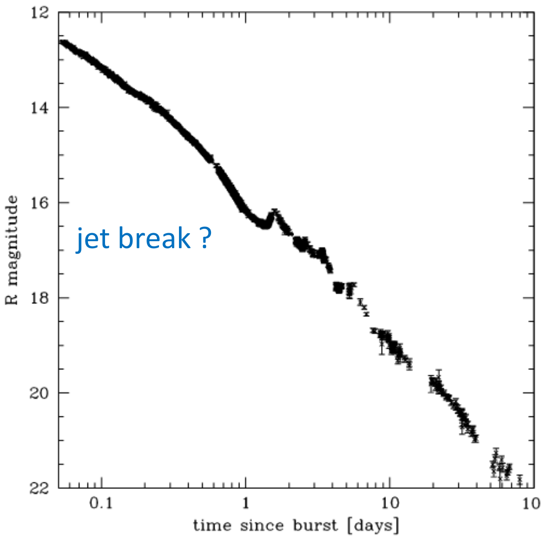
Plateaus in the early afterglow

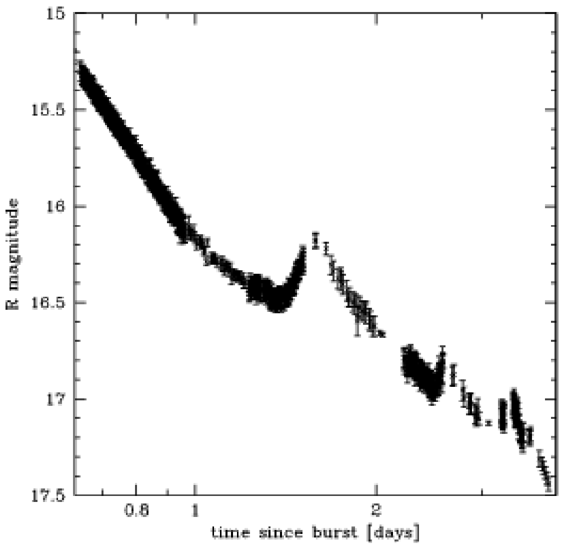


ejecta with a low Γ tail (long-lived RS)

GDM 2007

Bumps in the optical afterglow light curve of GRB 030329: evidence of previous internal shocks ?





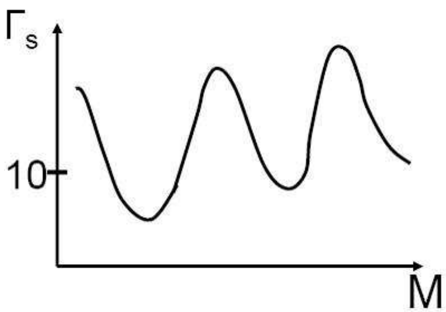
$$\frac{t_{rise}}{t_{bump}} \approx 0.3$$

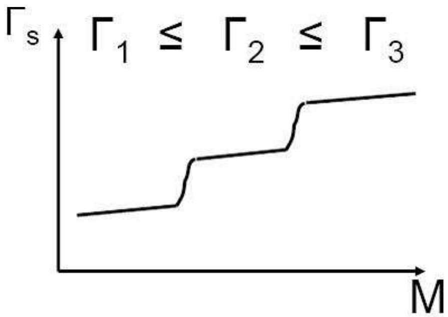
- density clumps in ISM
- "patchy shell"
- narrow and wide jets

"refreshed shell model" $\longrightarrow$ addition of energy to the forward shock from an initially slower shell
(Granot, Nakar & Piran, 2003)

But works only for a very narrow distribution of Γ in the slow material

$$\Gamma \propto t^{-3/8} \;\; (t^{-1/4}) \rightarrow \frac{\Delta\Gamma}{\Gamma} \lesssim 0.1 \text{ to have } \frac{t_{rise}}{t_{bump}} \approx 0.3$$





IS are just the right machine to do that !

If IS were present $\rightarrow \sigma < 0.1$ at r_{IS}

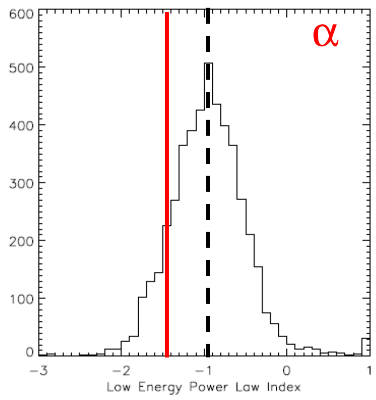
Radiation processes

Problems with synchrotron ?

Low energy spectral index α (curvature around the peak)

Efficiency $\longrightarrow$ “fast cooling” $\alpha = -3/2$ (too soft)

IC + marginally fast cooling regime (slow cooling $\alpha = -2/3$)
Continuous injection of energy in the radiating electrons } can improve

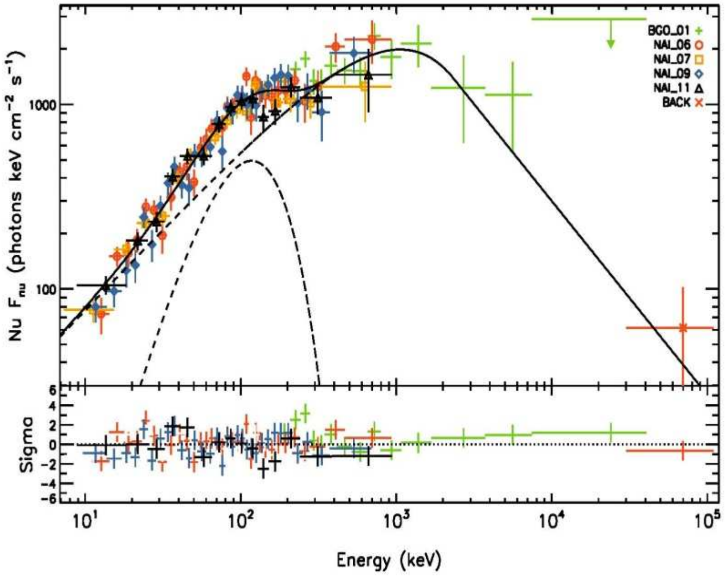


Are the problems severe enough to abandon synchrotron ?

Dissipative photosphere $\alpha = +0.8$ (too hard) $\longrightarrow$ synchrotron contribution at low energy ?

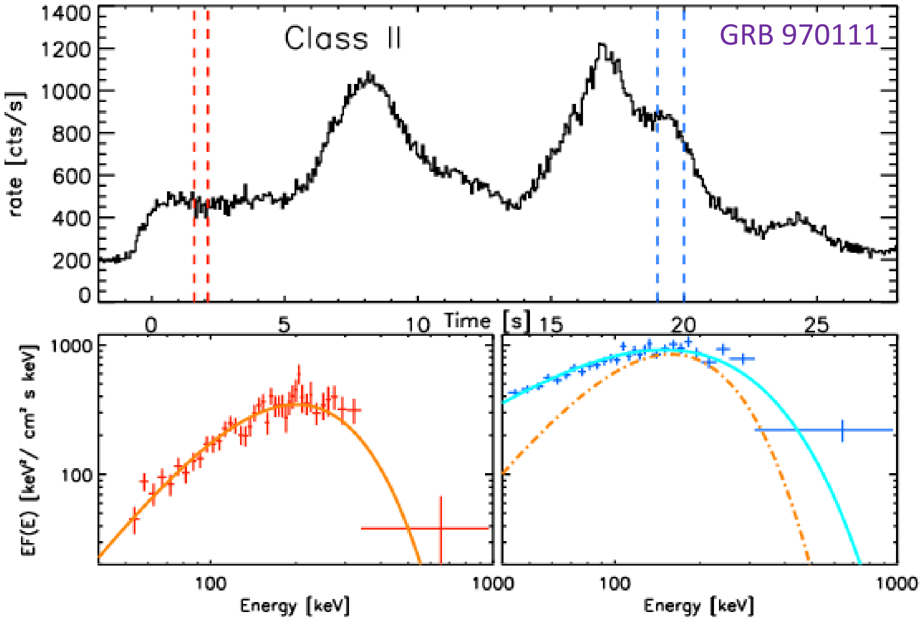
Thermal photospheric component ?

Naturally expected in IS, reconnection models
Some observational evidences but needs more good data



Flow initially magnetized ($\varepsilon_{th} \lesssim 0.3$) at the origin otherwise blackbody component would be too bright

Pure thermal emission during part of prompt phase



Easy to account with IS with Γ rising outwards in part of the jet

Reconnection initially do not operate ?

Comptonization: subphotospheric dissipation processes initially inactive ?

Conclusion

Looking for observables to constrain the prompt emission mechanism in GRBs

Unfortunately, partial pieces of evidence only, not fully conclusive

Varying weight on each, depending on one's own prejudice…

My preference: ESD robust diagnostic of $R_{\rm diss}$ ("it's so simple, it should be true"; FA)

$R_{\rm diss} \sim c\Gamma^2\tau$ $\rightarrow$ internal shocks, reconnection if $R_{\rm rec} \sim c\Gamma^2\tau$

Radiation process then should be synchrotron + IC + photospheric quasi blackbody component ultimately consistent with low energy spectral index ?

Evidences for shocks ?

if indeed present $\rightarrow$ $\sigma \lesssim 0.1$ where the shocks take place
but still compatible with reconnection if other parts of the jet are highly magnetized

Progress needed observationally: more good quality spectra over a broad energy range
and new theoretical developments