Gamma-Ray Bursts

Frédéric Daigne (Institut d'Astrophysique de Paris)

Atelier OCEVU « The physics of relativistic outflows », 22-24 March, 2016, IRAP, Toulouse

Emission from relativistic outflows: the case of Gamma-Ray Bursts

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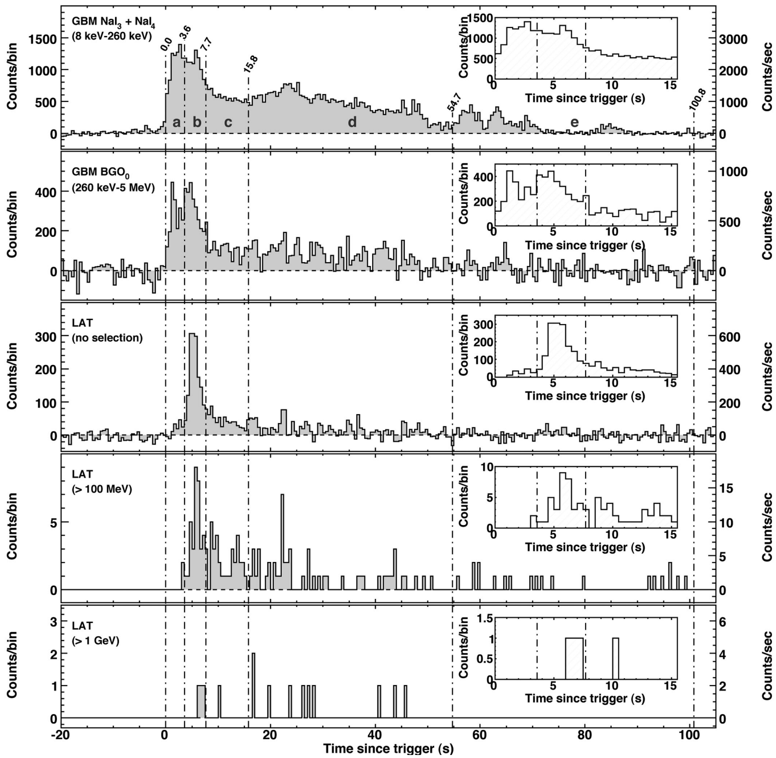
Introduction

1. GRBs: observed emission
2. Relativistic outflows in GRBs
3. Possible emission sites in GRBs
4. Modelling the emission from relativistic outflows

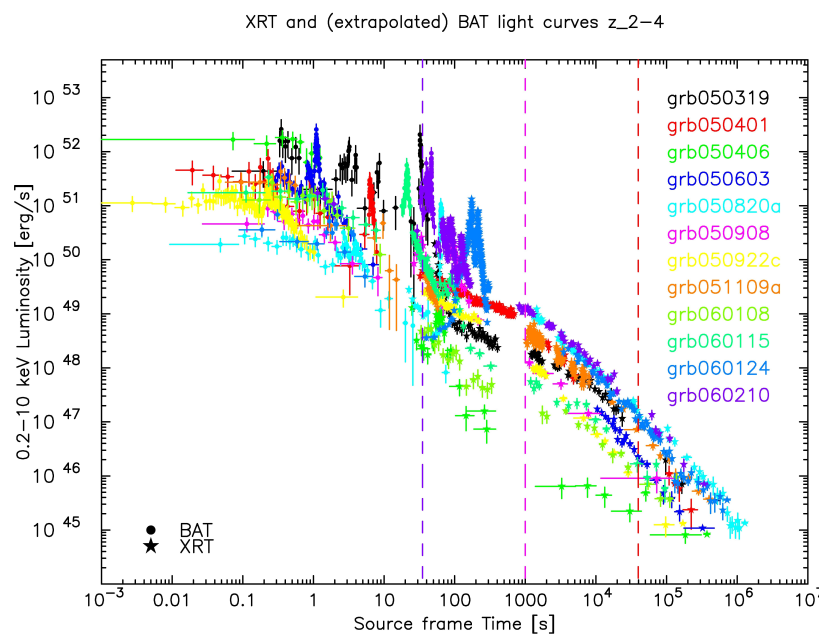
Some recent results

1. Weak photospheric emission in GRBs: constraints on magnetization
2. The origin of X-ray flares in GRB afterglows
3. Prompt GRB emission from internal shocks

GRBs: observed emission



Prompt emission keV ➞ GeV (Fermi)



X-ray afterglow (Swift)

Observed emission

Prompt GRB
(soft γ-rays)

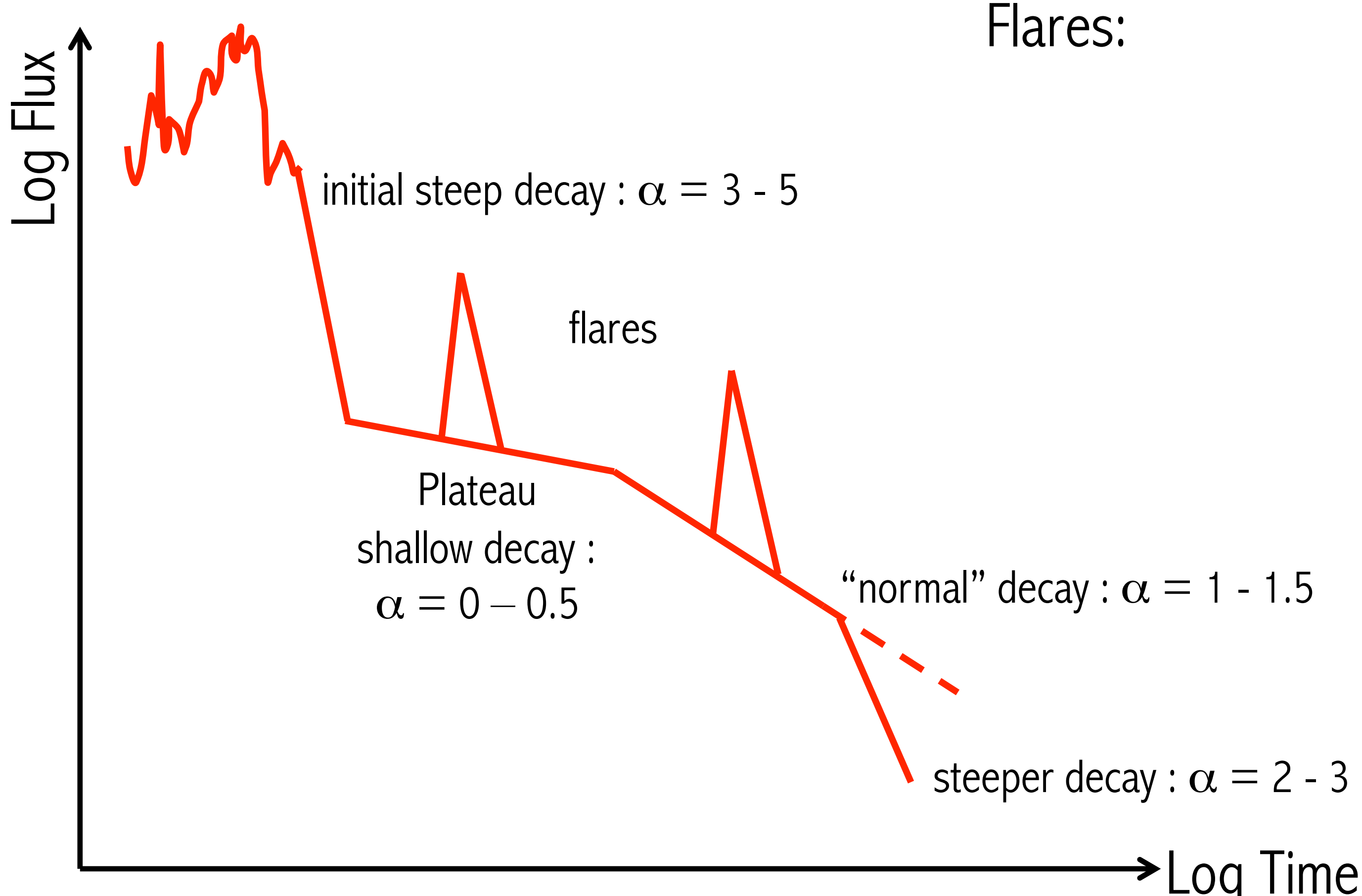
Afterglow
(X-rays)

Swift XRT:

Early steep decay: >90%

Plateau: ~60%

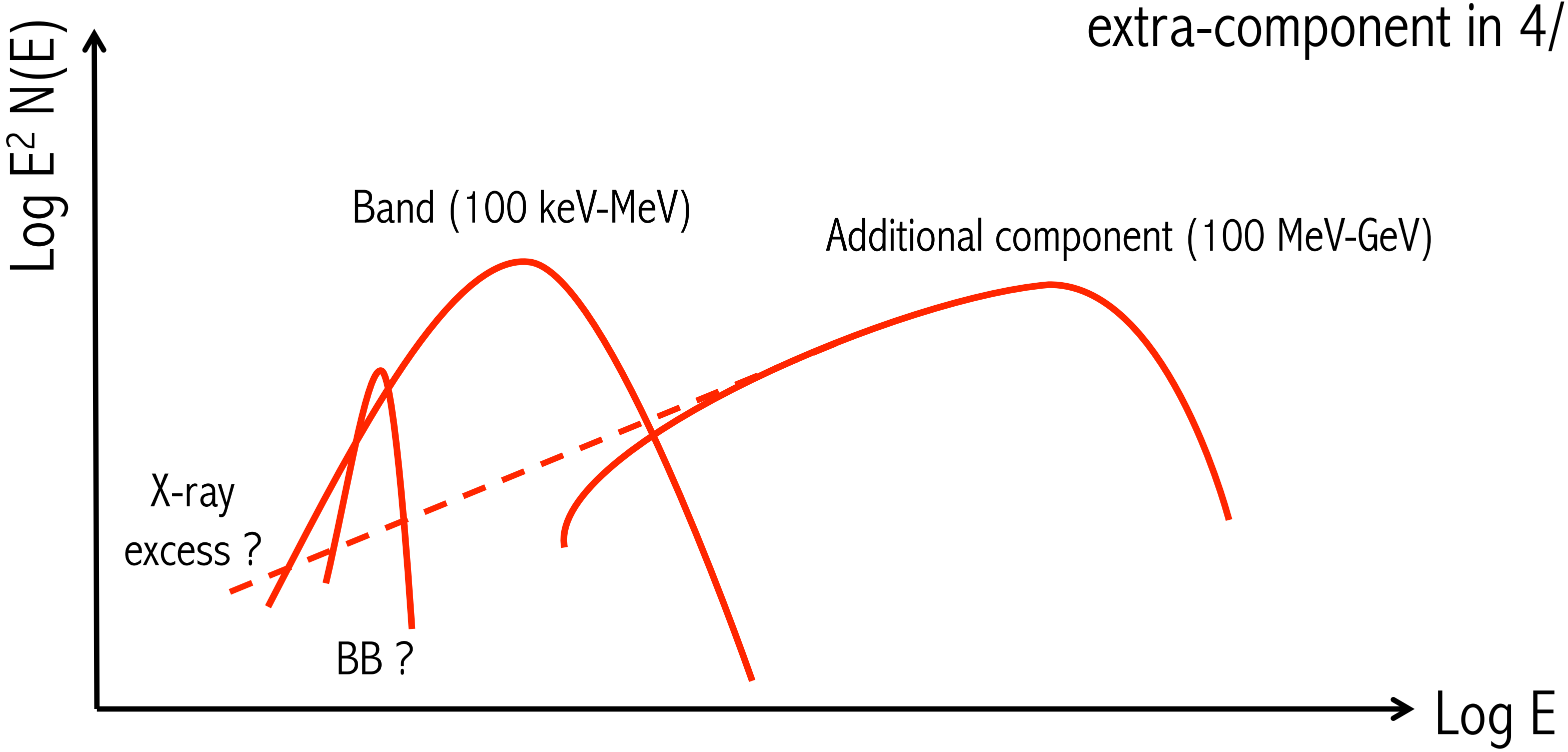
Flares: ~30%



Also: prompt optical, GeV

Also: optical, radio afterglow long-lasting Fermi/LAT emission

Observed prompt γ-ray spectrum



Fermi/GBM:
BB looked for in bright cases & found in many cases

Fermi/LAT: 1st catalog extra-component in 4/28

Relativistic outflows in GRBs

Indirect: necessary to avoid a strong $\gamma\gamma$ annihilation

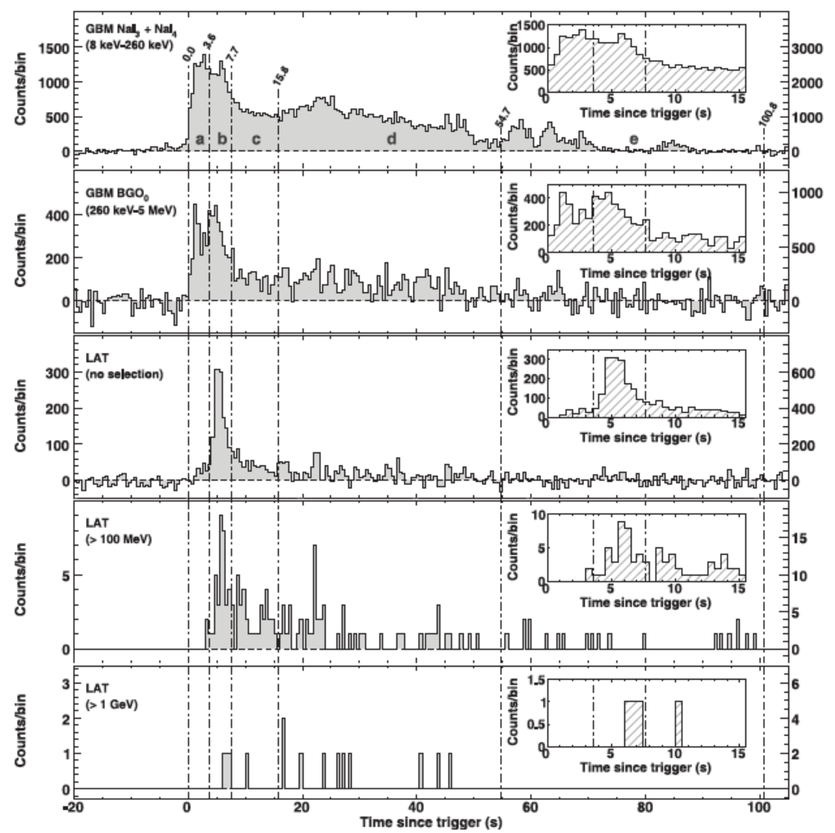
Direct (in a few cases): apparent super-luminal motion

How relativistic are GRB outflows?

Pre-Fermi (MeV range) : $\Gamma_{min} \sim$ 100-300

GeV detection by Fermi: stricter Lorentz factor constraints

- GRB 080916C: $\Gamma_{min} \geq 887$ (Abdo et al. 09)
- GRB 090510: $\Gamma_{min} \geq 1200$ (Ackerman et al. 10)

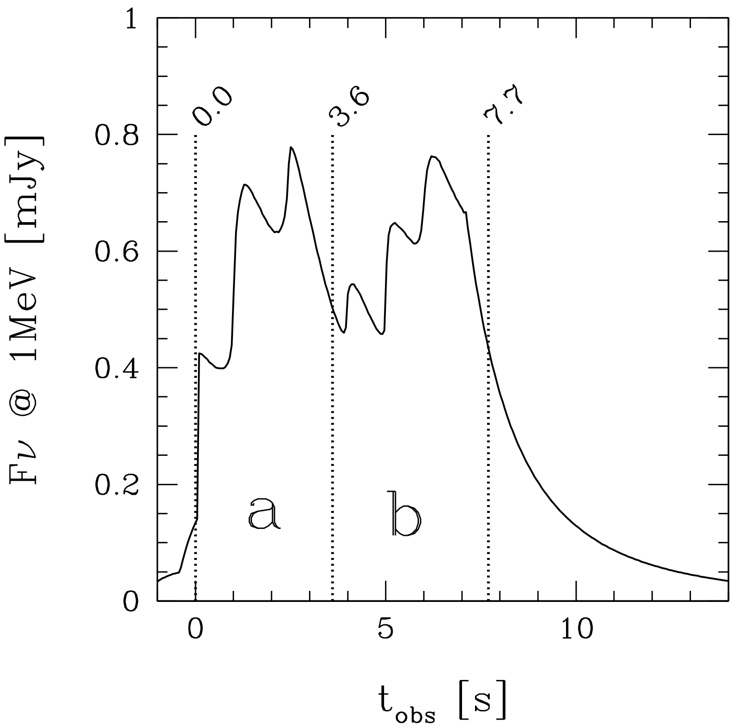


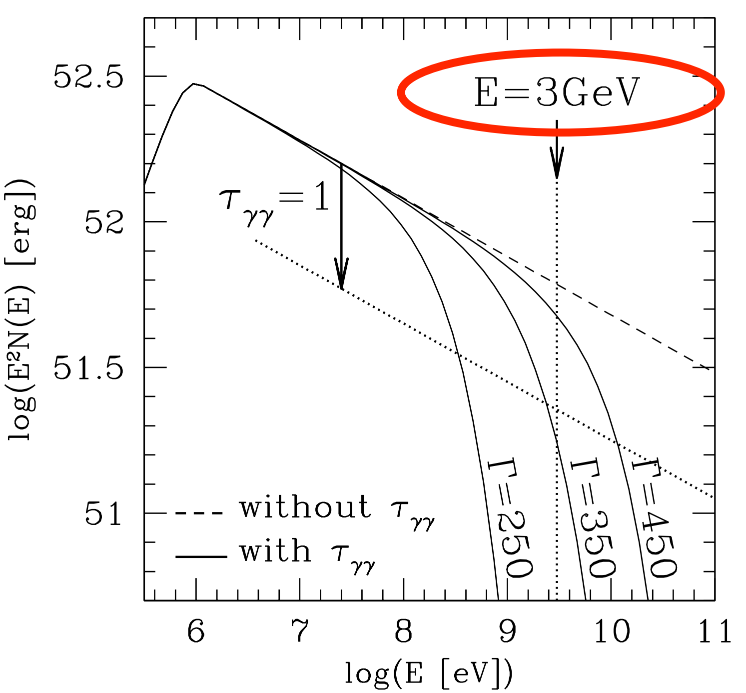
How relativistic are GRB outflows?

Detailed calculation: space/time/direction-dependent radiation field

the estimate of Γ_{min} is reduced by a factor ~ 2-3

(see Granot et al. 2008; Hascoët, FD, Mochkovitch & Vennin 2012)





Model of bins a+b in GRB 080916C : Γ_{min} ~ 360 (Hascoët et al. 2012)

instead of ~900 (Abdo et al. 2009)

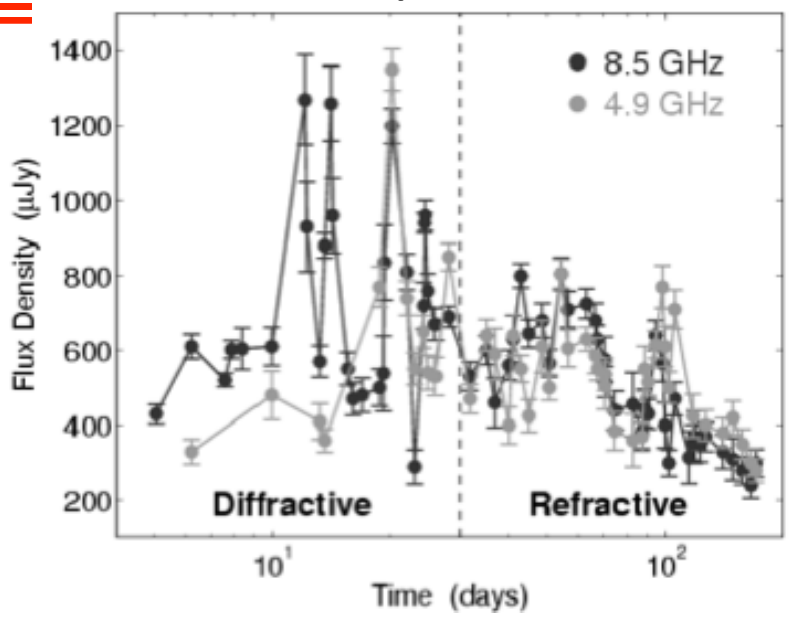
GRB 090926A: observed cutoff? See F. Piron's talk

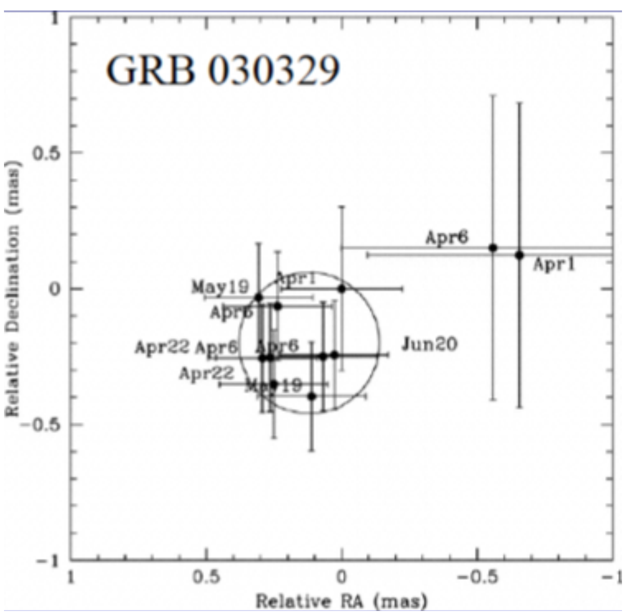
Apparent super-luminal motion in GRBs (radio afterglow)

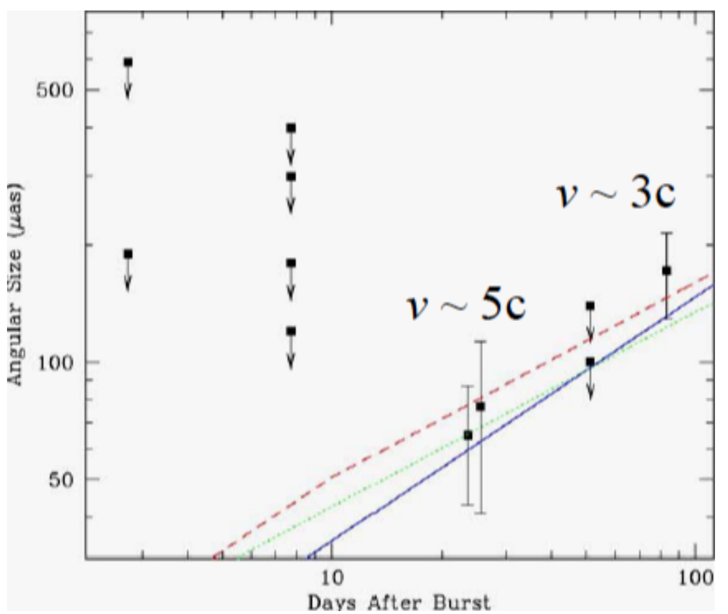
Method 1 :
Radio scintillation quenches as the source increases
Transition diffractive / refractive : estimate of the angular size

Method 2 :
VLBI allows to resolve the late afterglow for nearby GRBs

From the size, the apparent velocity is deduced:
superluminal apparent motion: relativistic motion







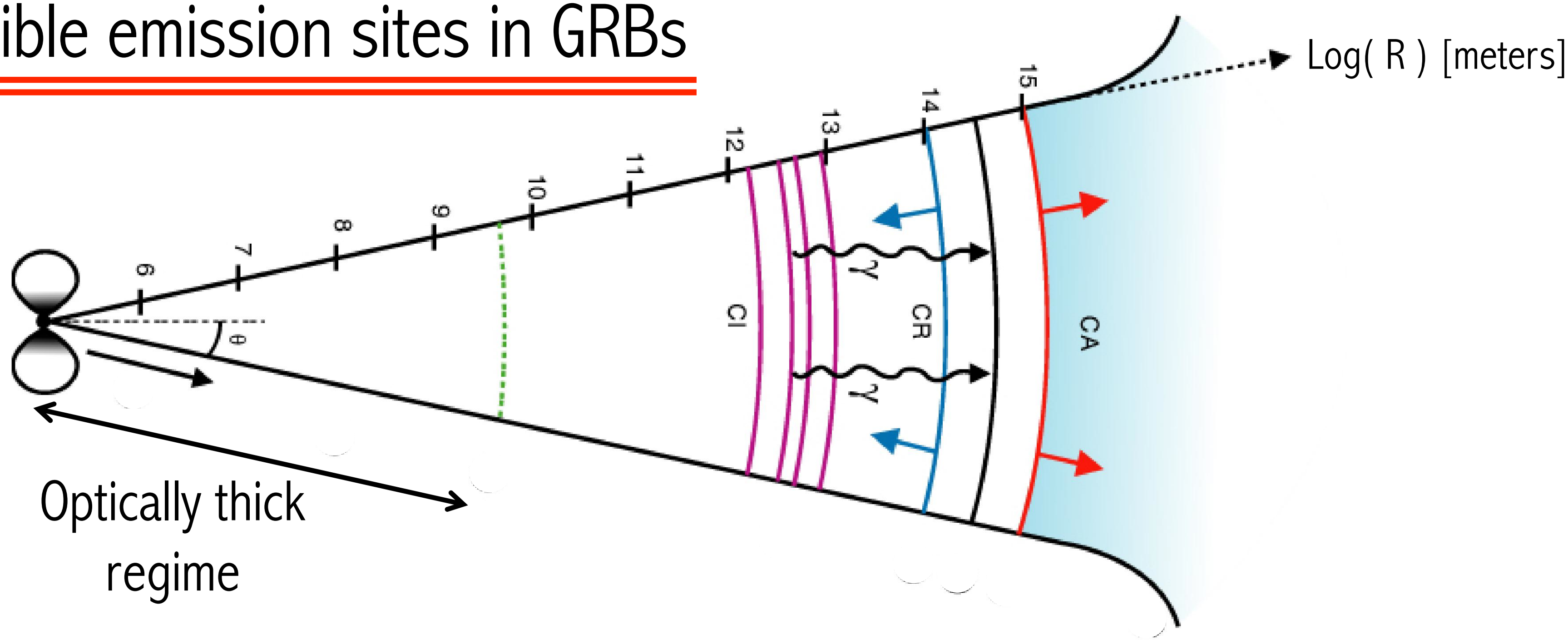
After 25 days:
65 μas (5.7 10^{17} cm)

Proper motion:
0.1 mas in 80 days

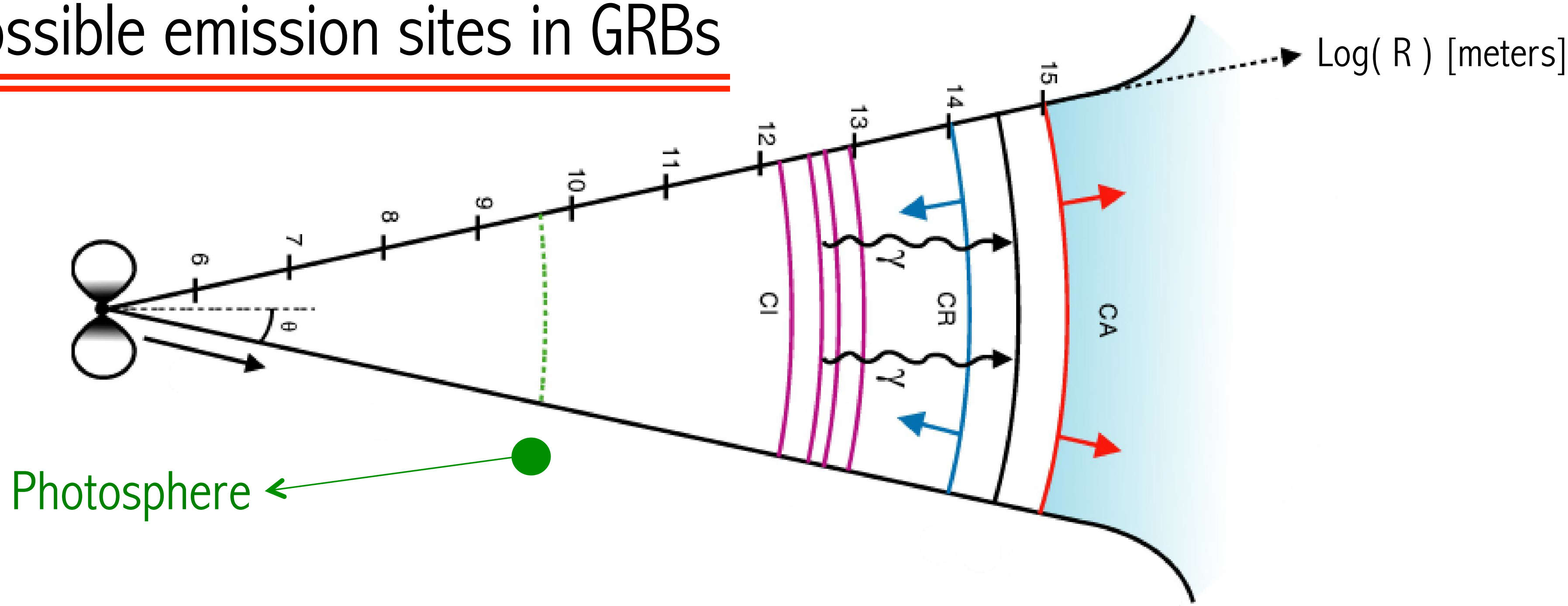
Taylor et al. 2004

GRBs: possible emission sites

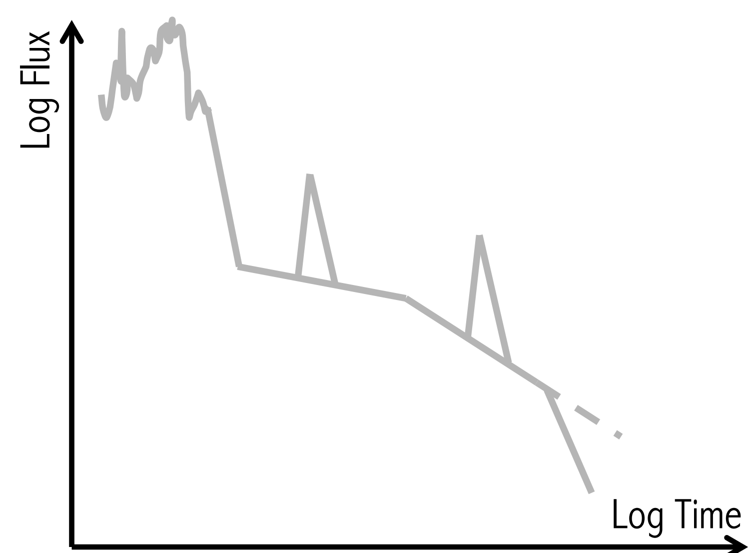
Possible emission sites in GRBs



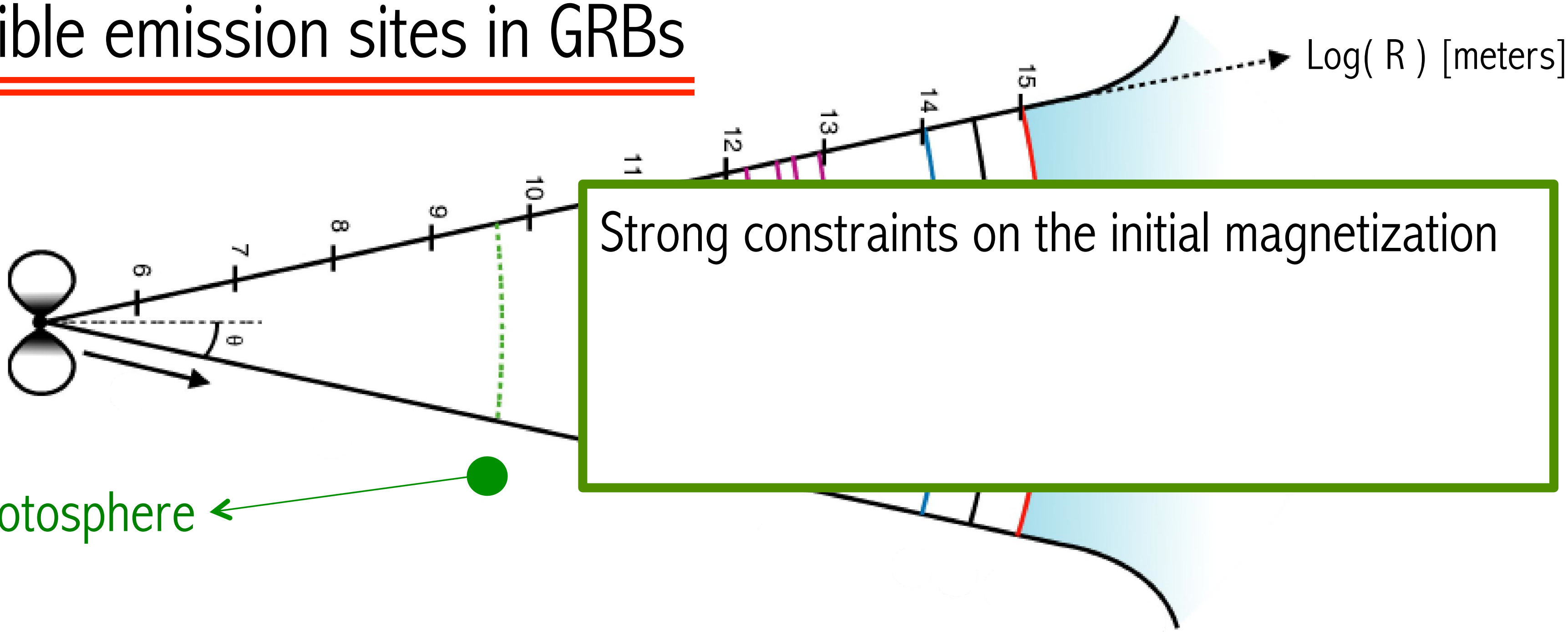
Possible emission sites in GRBs



Prompt emission: weak quasi-thermal component



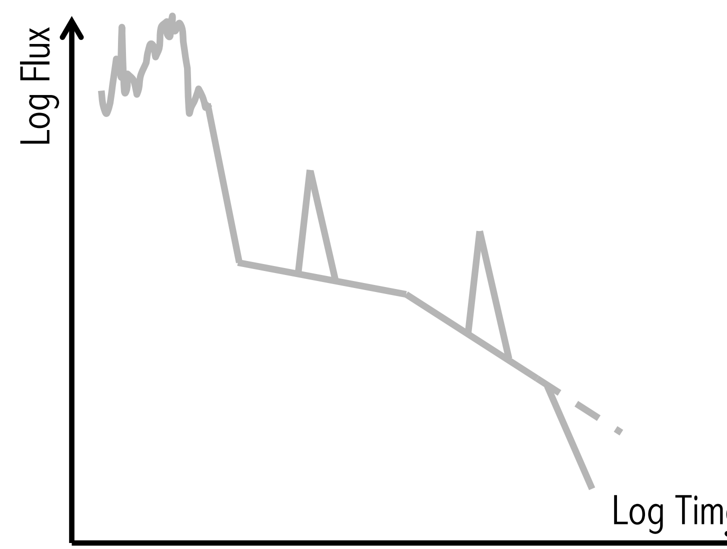
Possible emission sites in GRBs



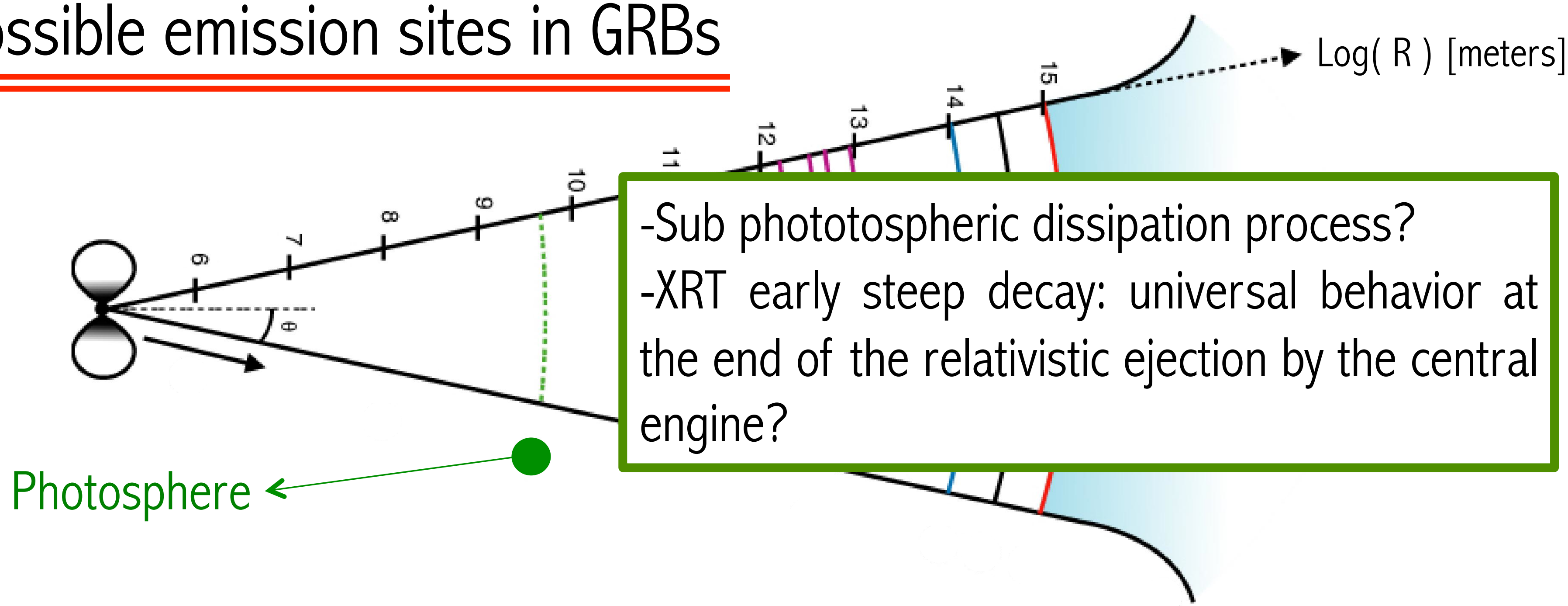
Strong constraints on the initial magnetization

Photosphere

Prompt emission: weak quasi-thermal component



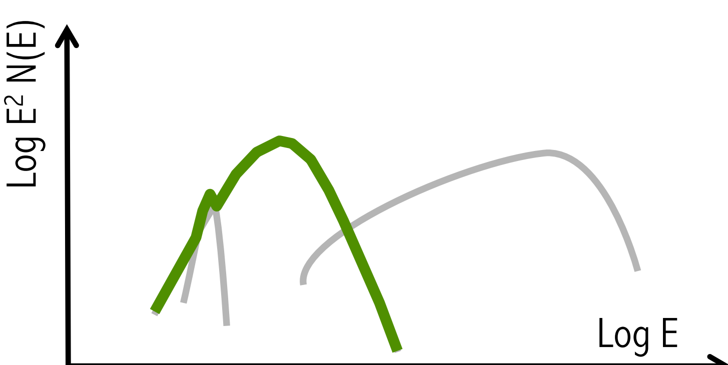
Possible emission sites in GRBs

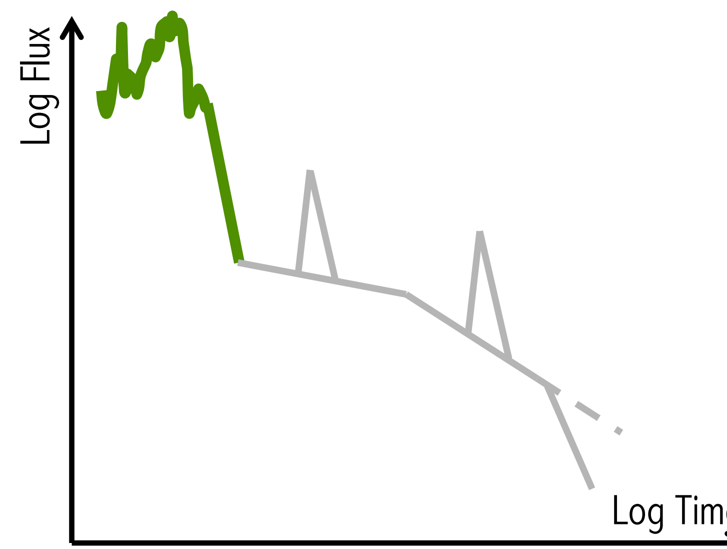


-Sub phototospheric dissipation process?

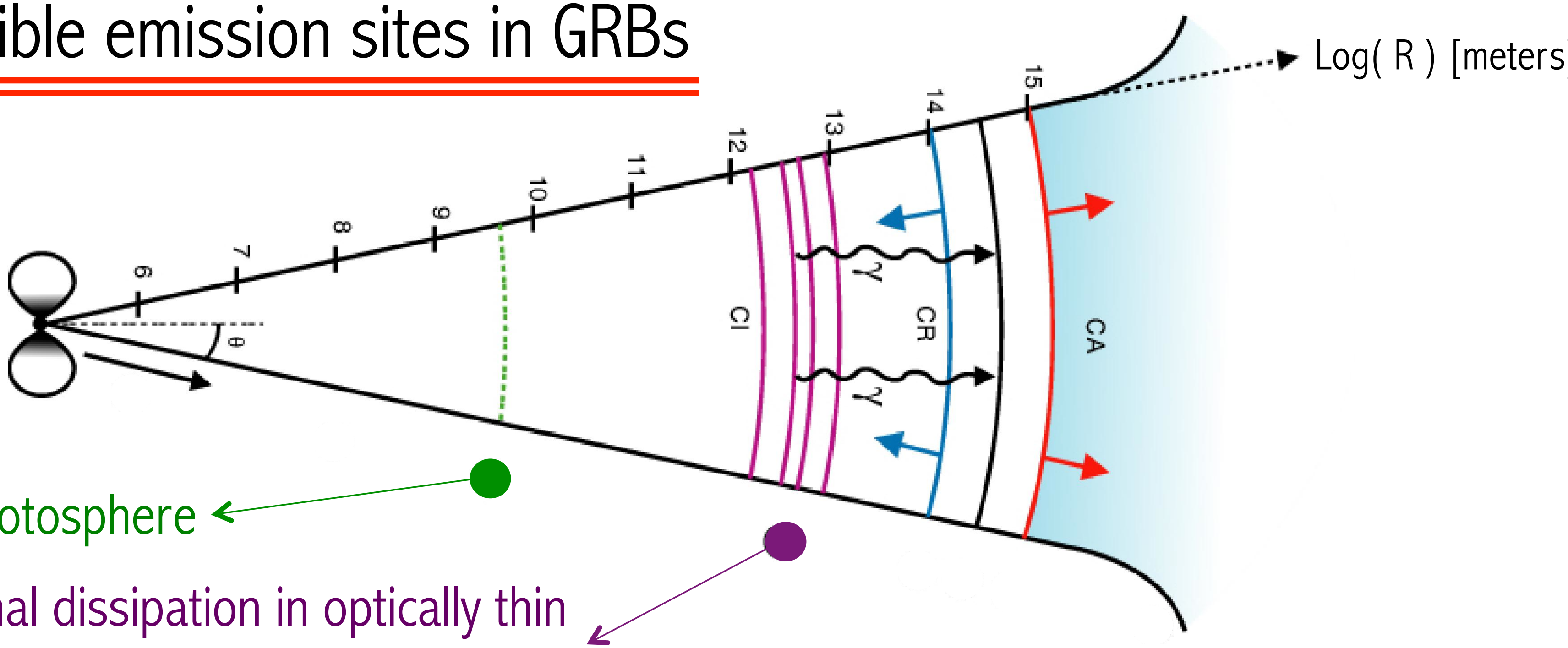
-XRT early steep decay: universal behavior at the end of the relativistic ejection by the central engine?

Prompt emission: weak quasi-thermal component or dominant non-thermal component ?





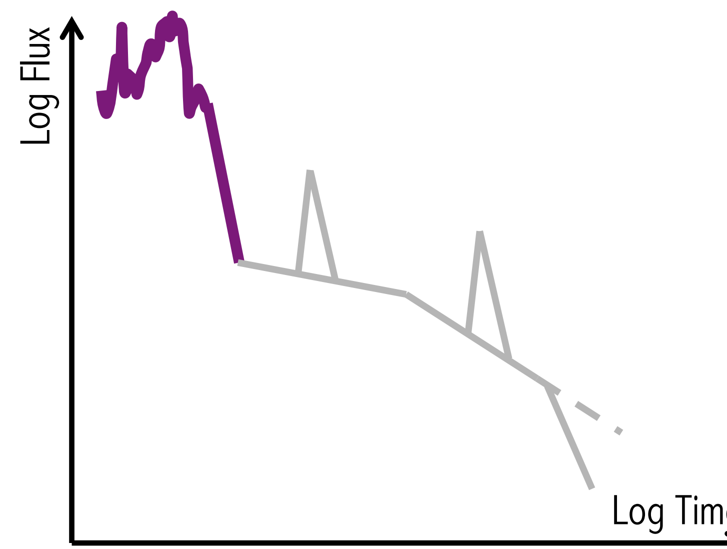
Possible emission sites in GRBs



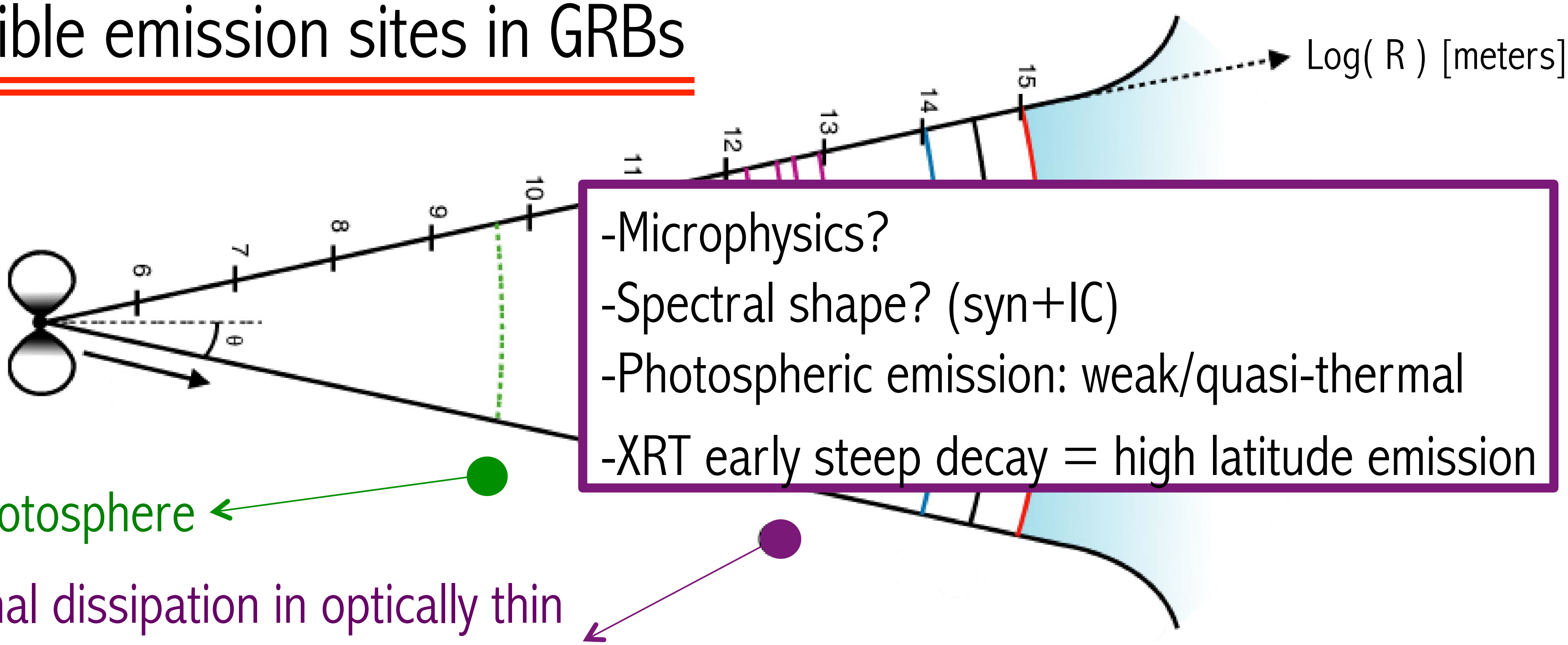
Photosphere

Internal dissipation in optically thin regime (shocks or reconnection)

Prompt emission: dominant non-thermal component?



Possible emission sites in GRBs

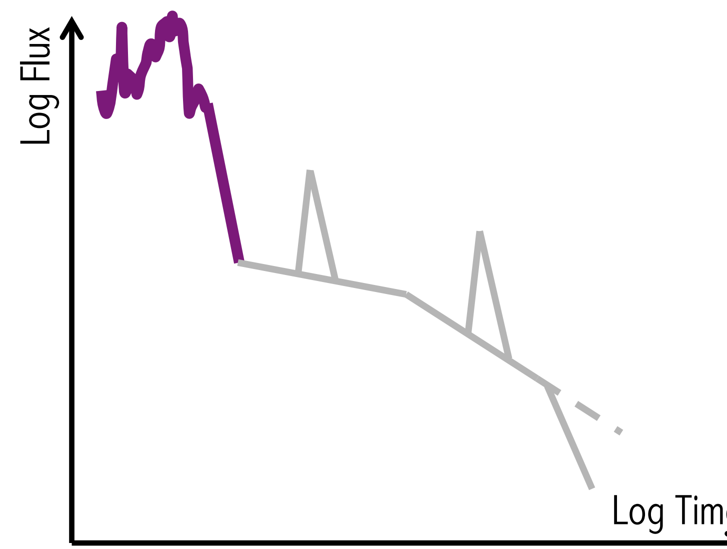


- -Microphysics?
- -Spectral shape? (syn+IC)
- -Photospheric emission: weak/quasi-thermal
- -XRT early steep decay = high latitude emission

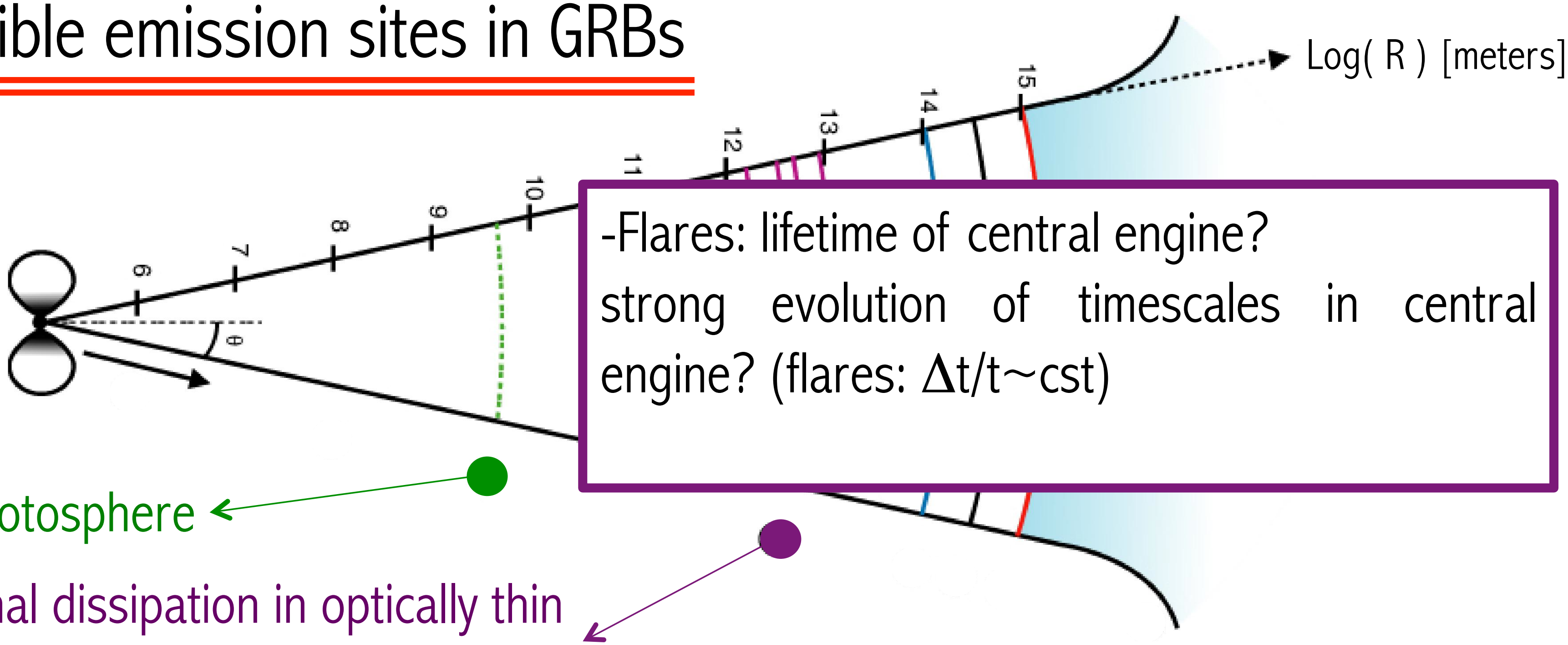
Photosphere

Internal dissipation in optically thin regime (shocks or reconnection)

Prompt emission: dominant non-thermal component?
+additional component ?



Possible emission sites in GRBs



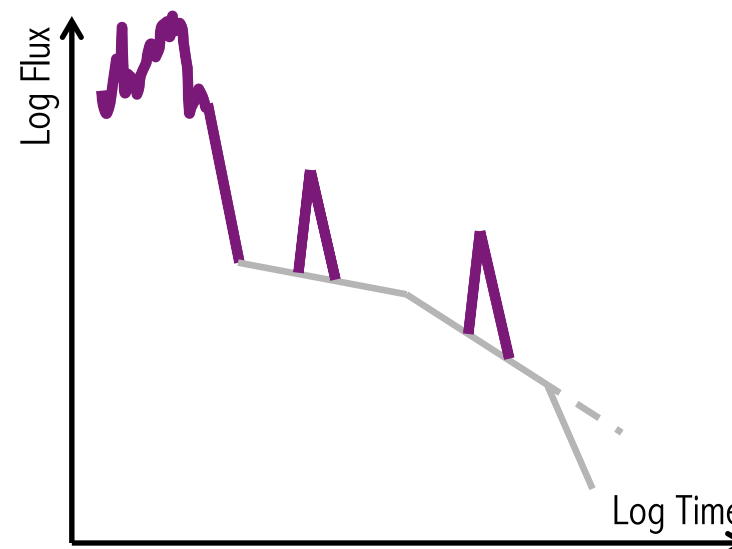
-Flares: lifetime of central engine?
strong evolution of timescales in central engine? (flares: $\Delta t/t \sim cst$)

Photosphere

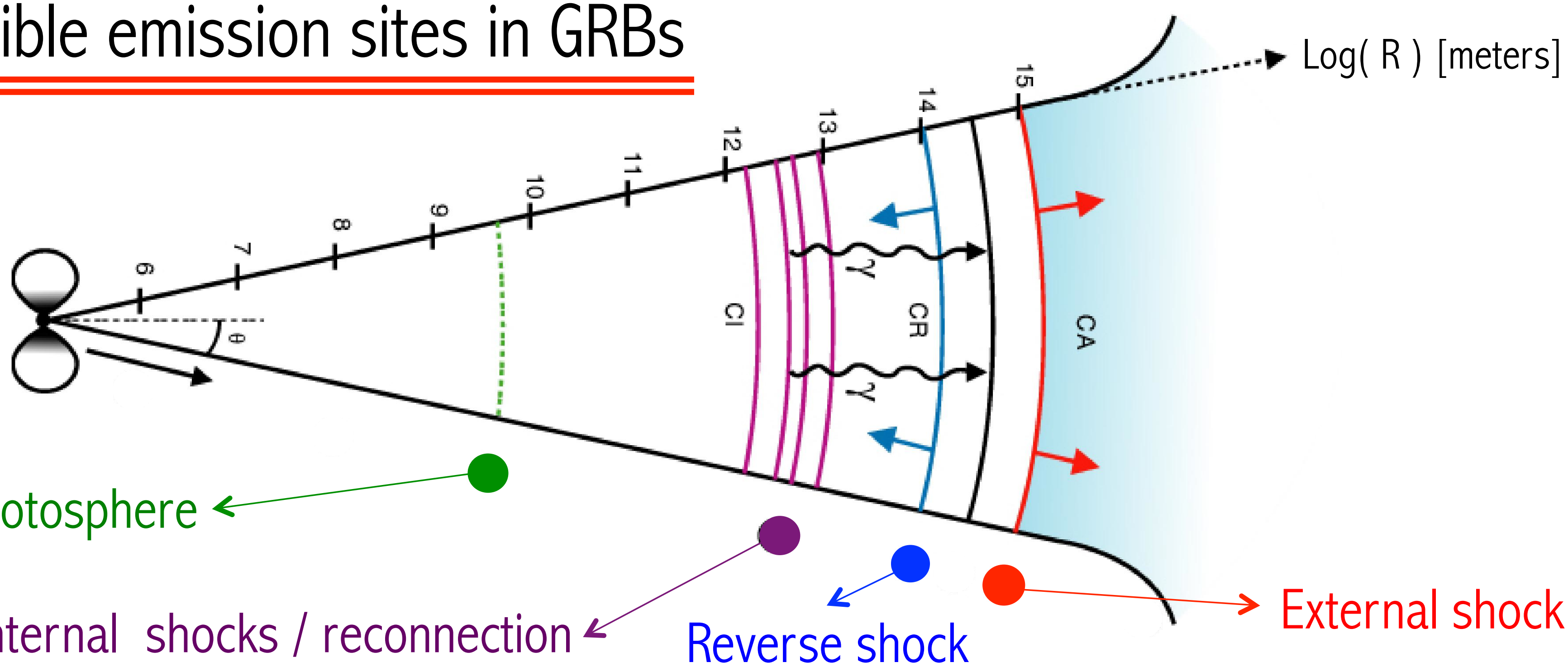
Internal dissipation in optically thin regime (shocks or reconnection)

Prompt emission: dominant non-thermal component?
+additional component ?

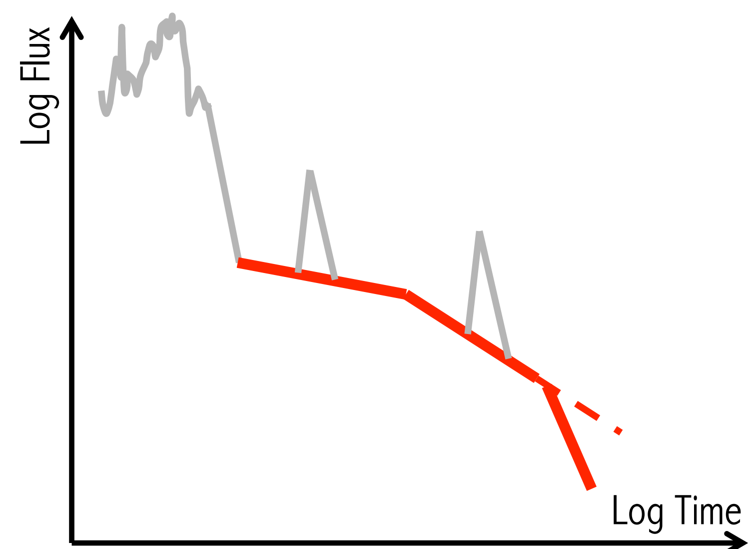
Afterglow: flares?



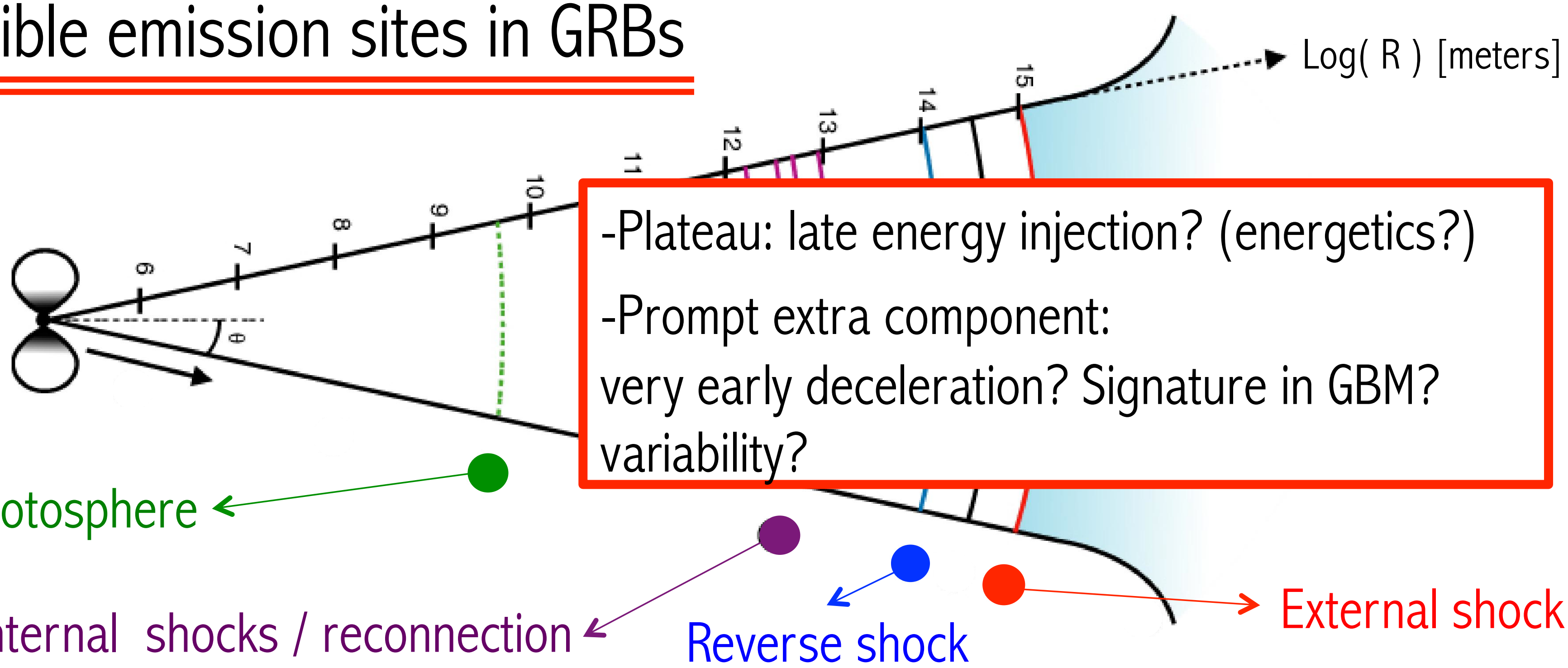
Possible emission sites in GRBs



RS:Prompt optical & FS: Afterglow



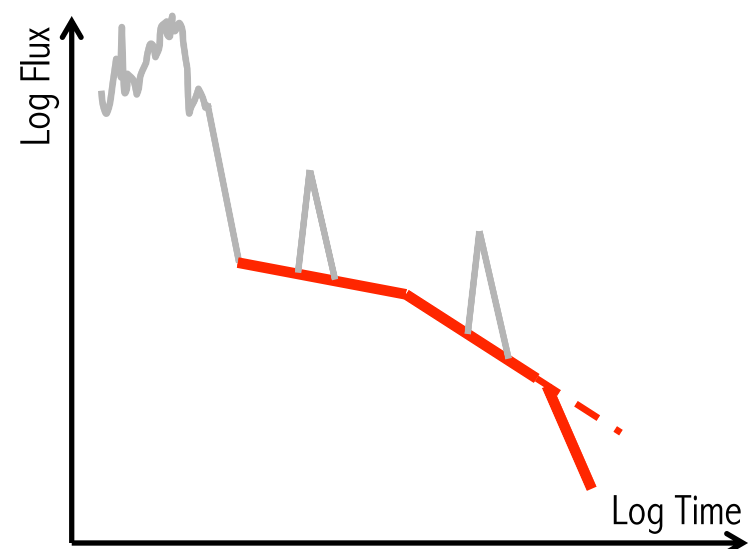
Possible emission sites in GRBs



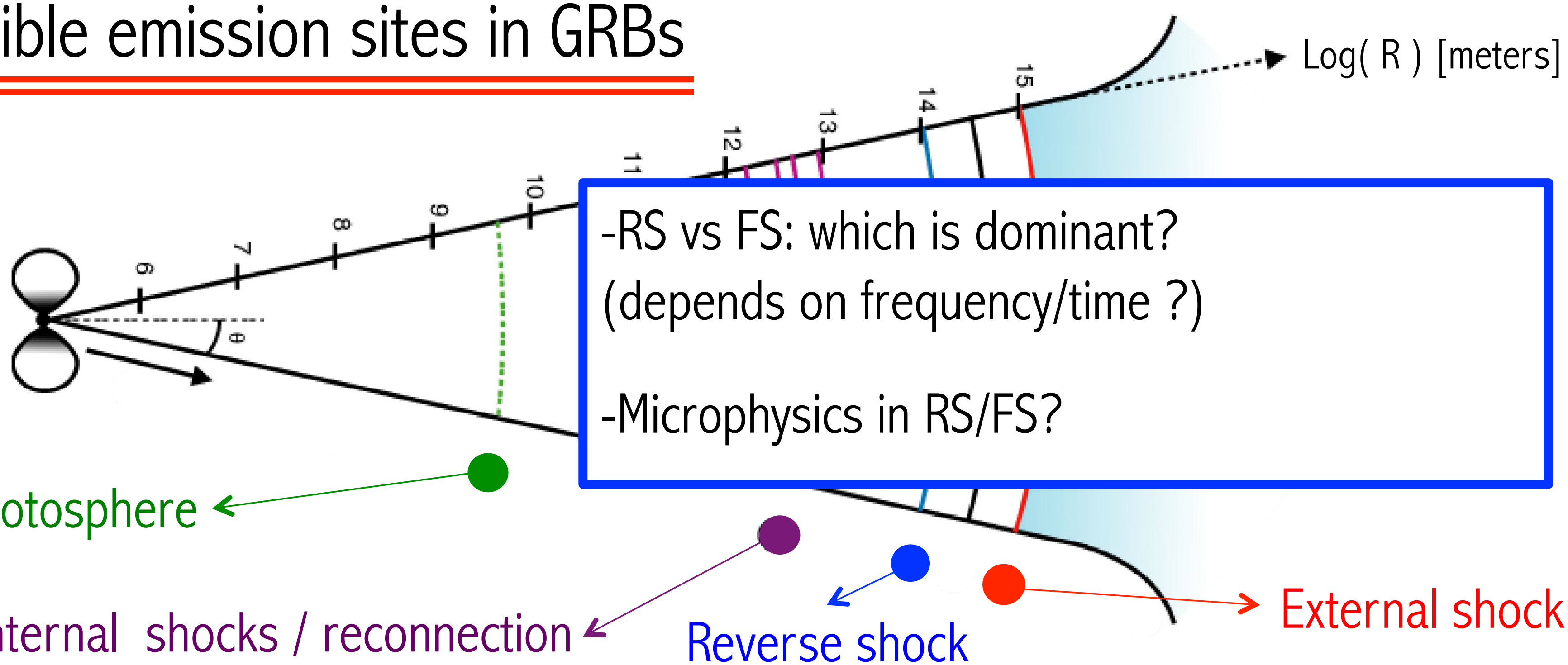
-Plateau: late energy injection? (energetics?)

-Prompt extra component:
very early deceleration? Signature in GBM? variability?

RS:Prompt optical & FS: Afterglow
+prompt additional component?



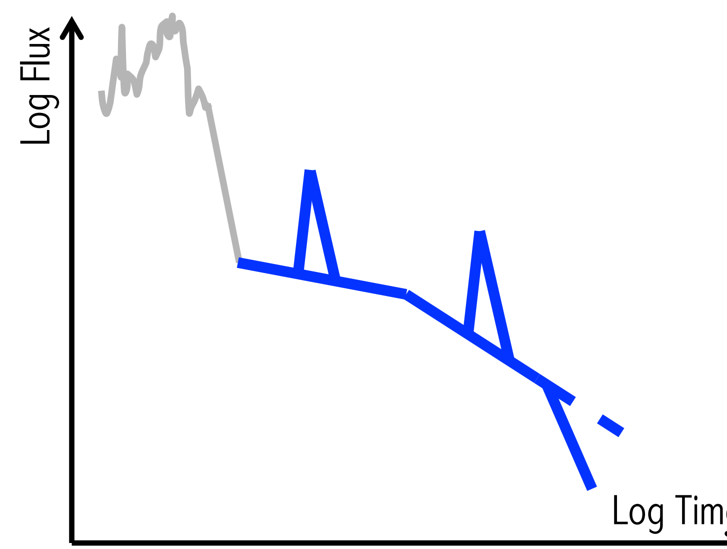
Possible emission sites in GRBs



-RS vs FS: which is dominant?
(depends on frequency/time ?)

-Microphysics in RS/FS?

Long lived RS: (early ?) afterglow ?



Modelling the emission from relativistic outflows

Relativistic jets:

Modelling the emission from relativistic jets involves many steps:

- Dynamics
- Microphysics: magnetic field? Particle acceleration? Etc.
- Emission in the comoving frame?
- Emission in the observer frame (time delays, relativistic Doppler boosting, etc.)

Emission can be produced in several sites:

- Photosphere
- Internal shocks
- Reconnection
- External shock

Relativistic jets: dynamics (1)

In the most general case, dynamics of relativistic jets is complicated…
(3D relativistic MHD ?)

In many cases, a simplified solution is possible :

- MHD? Not in the case of a non-magnetized outflow or a passive field
- Fluid? If the kinetic energy is dominant, a ballistic approach is possible (interacting shells, e.g. internal shock model for GRBs)
- 3D/complex geometry?
  - If the Lorentz factor is very large, global geometry is not important ($1/\Gamma \ll$ jet opening angle)
  - If the Lorentz factor is very large, lateral expansion is negligible ($c_s/\Gamma \ll c$)
- Interaction with ambient medium/deceleration?
  May be neglected when computing emission with an internal origin emitted well below the deceleration radius

Relativistic jets: dynamics (2)

Usually, the initial conditions are not well known, especially due to the poor understanding of the physics of the relativistic ejection.

- Mass flux ?
- Energy flux ?
- Lorentz factor ?
- Magnetization / field geometry ?

Relativistic jets: microphysics

It remains difficult to couple a dynamical calculation with a realistic microphysics. In addition, despite some recent progress, the relevant microphysics is not well understood (shock acceleration / reconnection).

This part is usually highly parametrized (e.g. “equipartition parameters”, etc.)

Relativistic jets: emission in the comoving frame

In the most general case, emission in the comoving frame is also complicated…
(time-dependent radiative transfer with non-thermal particles)

- Many process: synchrotron, IC, $\gamma\gamma$, etc.
- Leptons: primary electrons + secondary pairs due to $\gamma\gamma$
- Contributions from hadrons?
- Two regimes:
  - radiatively efficient: radiative timescale $\ll$ dynamical timescale
    = particle cool immediately where they are accelerated, transport in the jet is not important
  - radiatively inefficient: radiative timescale $\gg$ dynamical timescale
- Optical depth? Optically thin vs optically thick (comptonization ?)
  - calculation is more complicated in the second case (multi-scatterings)
- Geometry of the photon field (important for IC, $\gamma\gamma$, etc.) ?

Etc.

Relativistic jets: emission in the observer frame

- Integration over equal-arrival time surface (curvature of the emitting surface ?)
- Doppler effect
- (cosmological effects / interaction with ambient photon field, etc.)

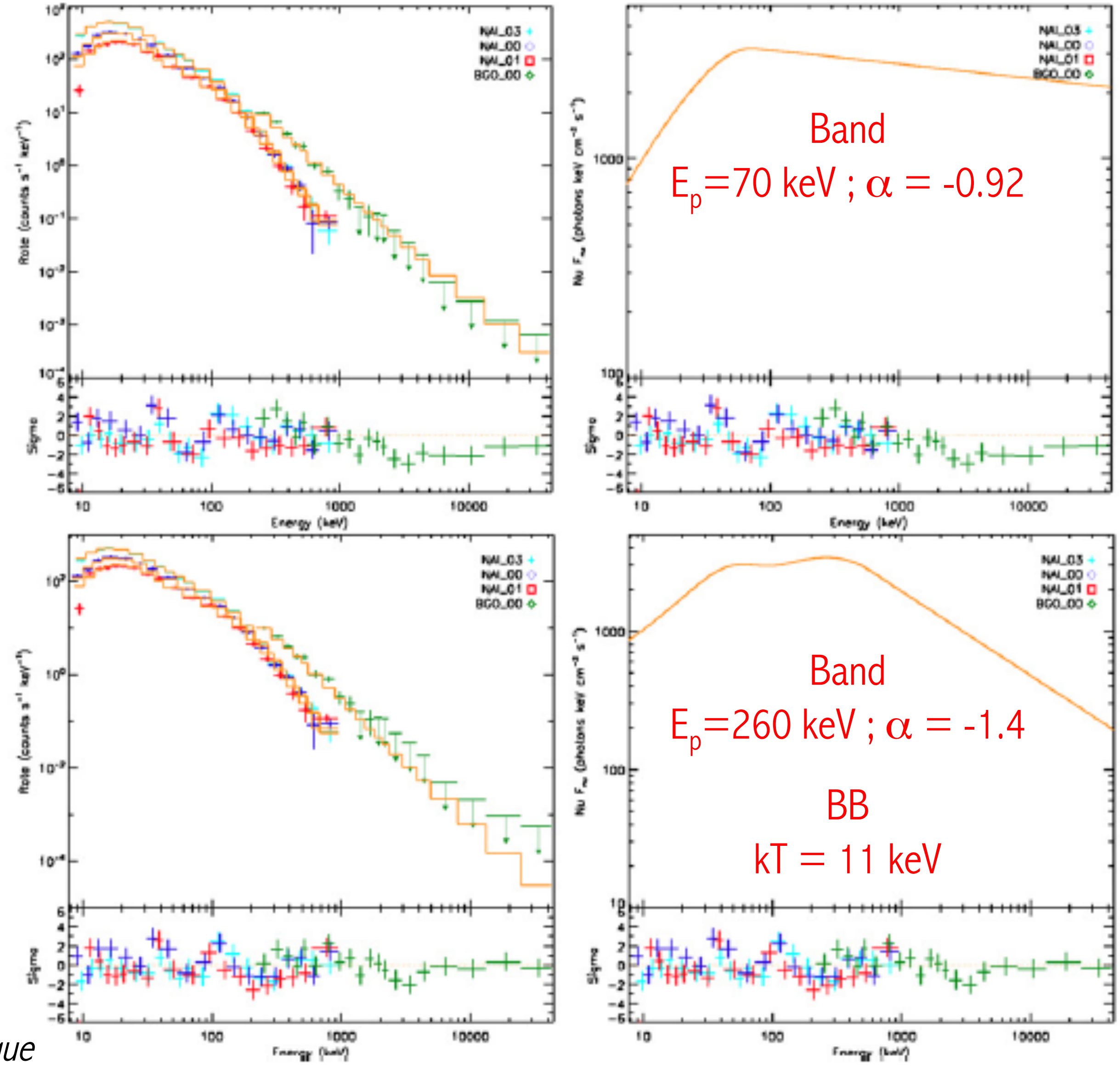
Complexity: multi-zones interactions

e.g. photons emitted in a zone are scattered by accelerated electrons in another zone

Weak quasi-thermal photospheric emission: constraints on the magnetization

Weak quasi-thermal components in GRB spectra?

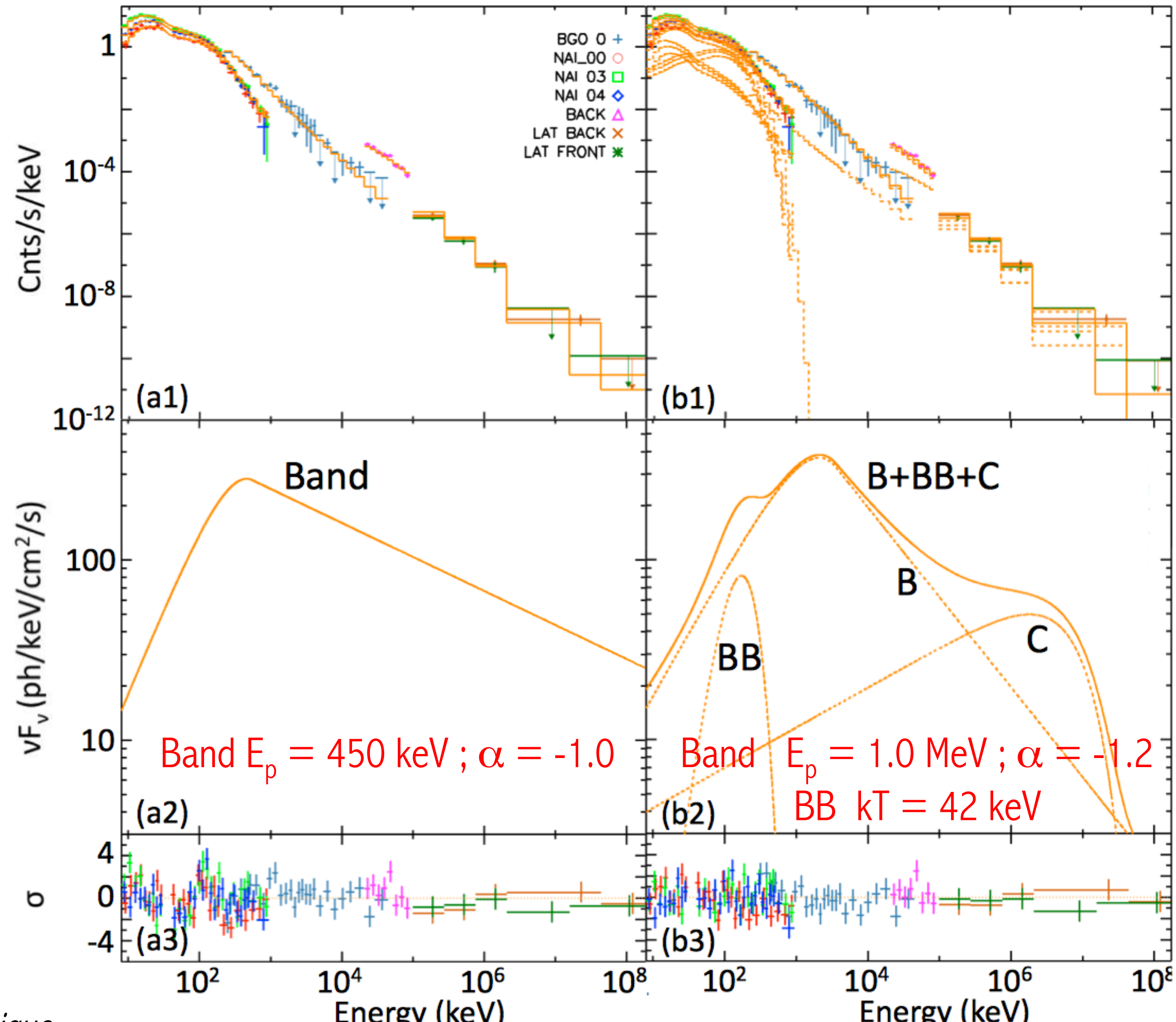
e.g. GRB 120323A (short GRB) Guiriec [FD] et al. 2013



Warning:
spectral analysis based
on forward folding technique

Weak quasi-thermal components in GRB spectra?

e.g. GRB 080916C (long GRB) Guiriec [FD] et al. 2015



Warning:
spectral analysis based
on forward folding technique

Weak quasi-thermal components in GRB spectra?

Non dissipative photosphere in magnetized outflows:

- Initial geometry is not specified
- Beyond R_{sph}, the flow is radial (opening angle θ)
- Total injected power in the flow: $\dot{E}$
  - -fraction ε_{th} is thermal
  - -fraction $1-\varepsilon_{th}$ is magnetic
- Acceleration is complete at $R_{sat} > R_{sph}$
- The final magnetization (above R_{sat}) is σ
- Photospheric emission occurs at R_{ph}
- Non-thermal emission occurs above R_{ph} with efficiency f_{NT}

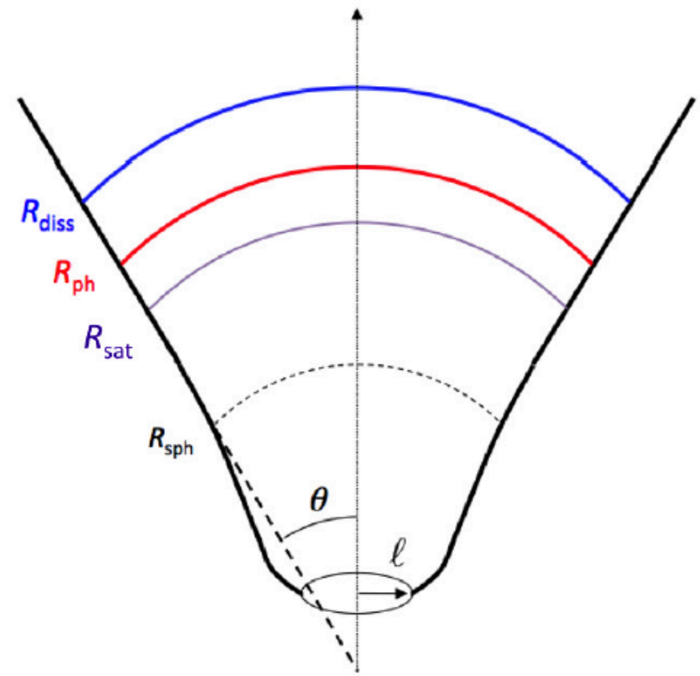


Fig. 1. Schematic view of the problem geometry. The flow emerges from the central engine through a "circular opening" of radius ℓ. Beyond a radius R_{sph} it expands radially within a cone of half opening θ. The acceleration is completed at R_{sat}. The photosphere is located at R_{ph} and dissipation of kinetic and/or magnetic energy takes place at R_{diss}.

Three main parameters: ε_{th}, σ, f_{NT}

Inversion method described by Pe'er et al. 2007

$R_0, R_{ph}, \Gamma = F(\text{data} ; \varepsilon_{th}, \sigma, f_{NT} ; z)$

Hascoet, Daigne & Mochkovitch 2013

Weak quasi-thermal components in GRB spectra?

Three main parameters: ε_{th}, σ, f_{NT}

$$R_0 \simeq \left[\frac{D_L \mathcal{R}}{2(1+z)^2}\left(\frac{\phi}{1-\phi}\right)^{3/2}\right] \times \left[\frac{f_{NT}}{\epsilon_T}\right]^{3/2},$$

Inversion method described by Pe'er et al. 2007

$$\Gamma \simeq \left[\frac{\sigma_T}{m_p c^3}\frac{(1+z)^2 D_L F_{BB}}{\phi}\frac{1-\phi}{\phi}\right]^{\frac{1}{4}} \times \left[(1+\sigma)\, f_{NT}\right]^{-1/4},$$

$$R_{ph} \simeq \left[\frac{\sigma_T}{16 m_p c^3}\frac{D_L^5 F_{BB} \mathcal{R}^3}{(1+z)^6}\frac{1-\phi}{\phi}\right]^{\frac{1}{4}} \times \left[(1+\sigma)\, f_{NT}\right]^{-1/4},$$

$$\phi = F_{BB}/F_{tot} \qquad \mathcal{R} = \left(\frac{F_{BB}}{\sigma T_{BB}^4}\right)^{1/2}.$$

R_0, R_{ph}, $\Gamma = F(\text{data}\ ;\ \varepsilon_{th}, \sigma, f_{NT}\ ;\ z)$

Different scenarios:

-Thermal acceleration (standard fireball): $\varepsilon_{th}=1$ & $\sigma=0$ and $f_{NT} <10\%$ (internal shocks)

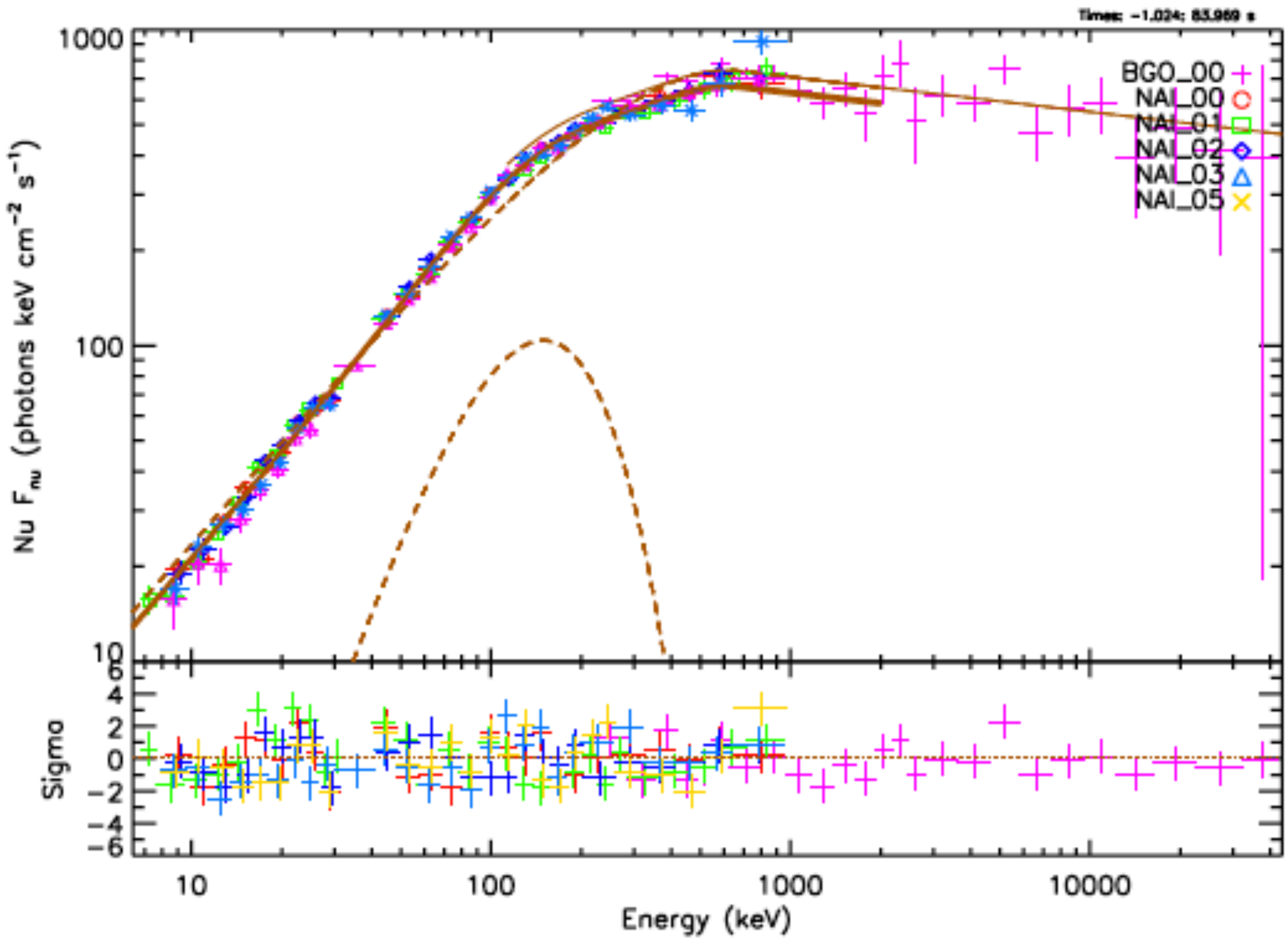
-Magnetized outflows: $\varepsilon_{th}<1$

-efficient acceleration: $\sigma < 0.1\text{-}1$ and $f_{NT} <10\%$ (internal shocks)

-mag. outflow at large distance: $\sigma > 1$ and $f_{NT} >30\%$ (reconnection)

Exemple: GRB 100724B

Thermal component is weak (4% of total)



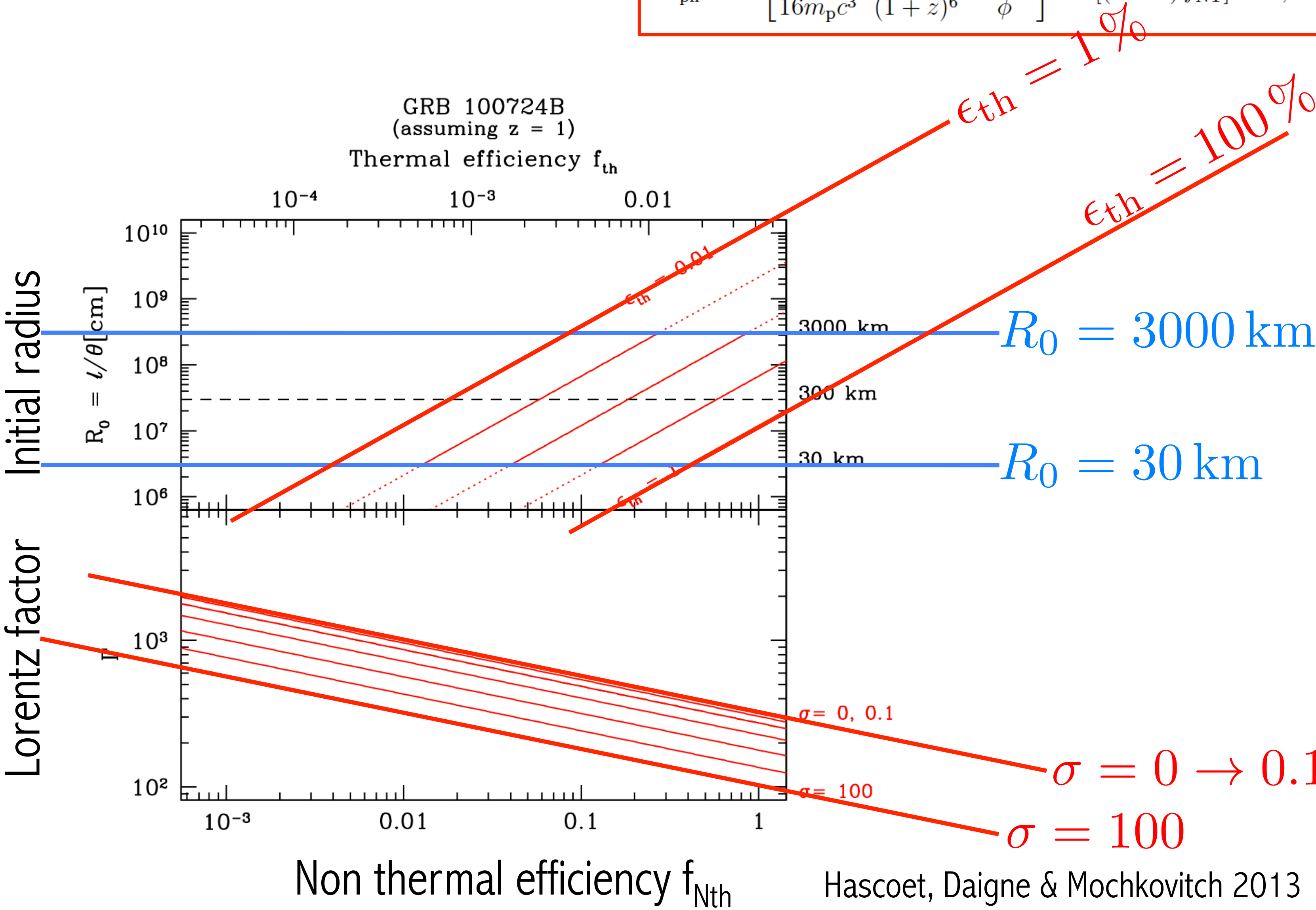
Guiriec [FD] et al. (2011)

Exemple: GRB 100724B

$$R_0 \simeq \left[\frac{D_L \mathcal{R}}{2(1+z)^2}\left(\frac{\phi}{1-\phi}\right)^{3/2}\right] \times \left[\frac{f_{NT}}{\epsilon_T}\right]^{3/2},$$

$$\Gamma \simeq \left[\frac{\sigma_T}{m_p c^3}\frac{(1+z)^2 D_L F_{BB}}{\phi}\frac{1-\phi}{\phi}\right]^{\frac{1}{4}} \times \left[(1+\sigma)\, f_{NT}\right]^{-1/4},$$

$$R_{ph} \simeq \left[\frac{\sigma_T}{16 m_p c^3}\frac{D_L^5 F_{BB} \mathcal{R}^3}{(1+z)^6}\frac{1-\phi}{\phi}\right]^{\frac{1}{4}} \times \left[(1+\sigma)\, f_{NT}\right]^{-1/4},$$

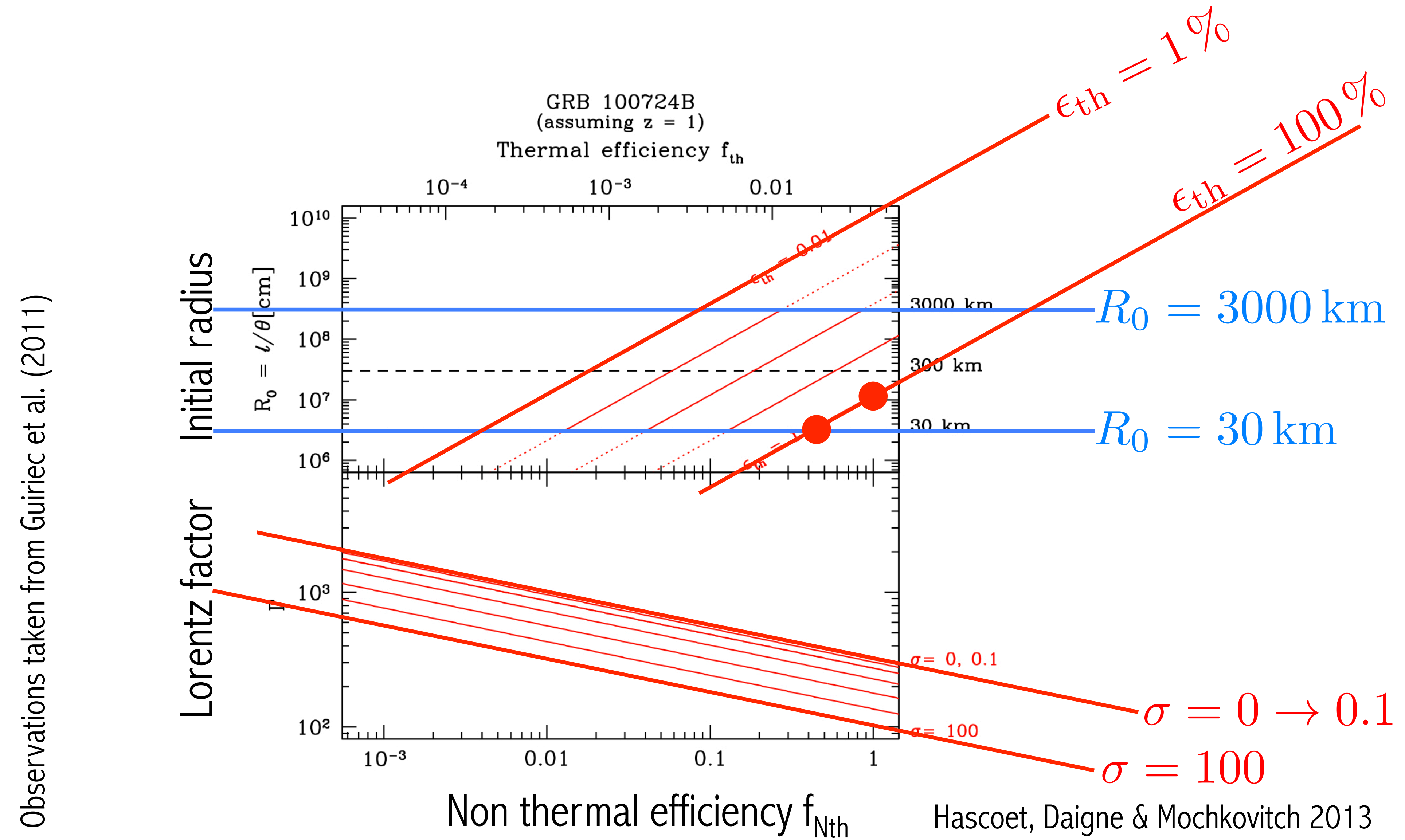


Observations taken from Guiriec et al. (2011)

Hascoet, Daigne & Mochkovitch 2013

Exemple: GRB 100724B

- Incompatible with the standard fireball, except for a very low R_0 + very high non-thermal efficiency



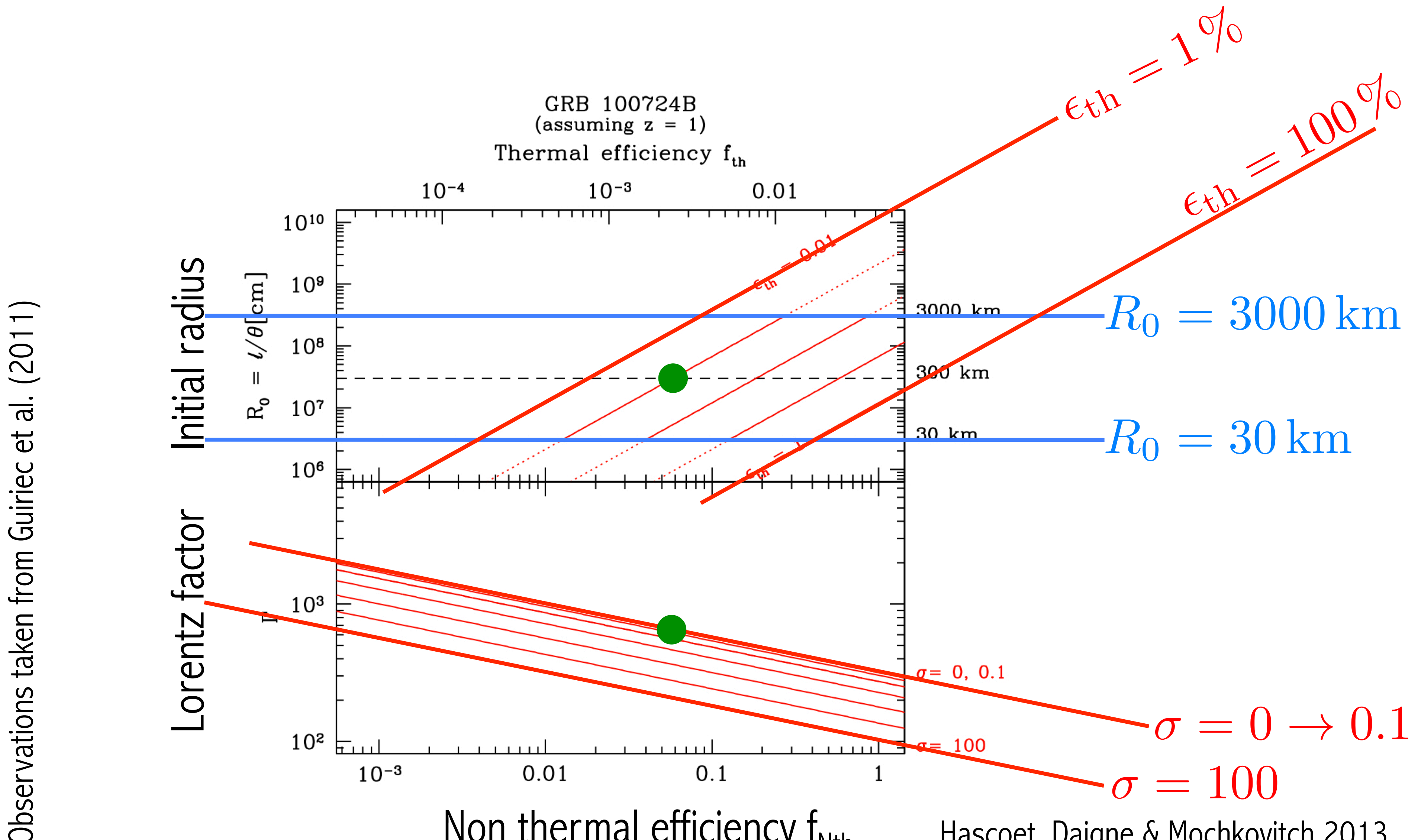
Hascoet, Daigne & Mochkovitch 2013

Exemple: GRB 100724B

ε_{th} must be small to have a low non-thermal efficiency compatible with internal shocks (here: f_{NTh}~6% and Γ~670)

$\epsilon_{th} = 0.03$
$\sigma \ll 1$

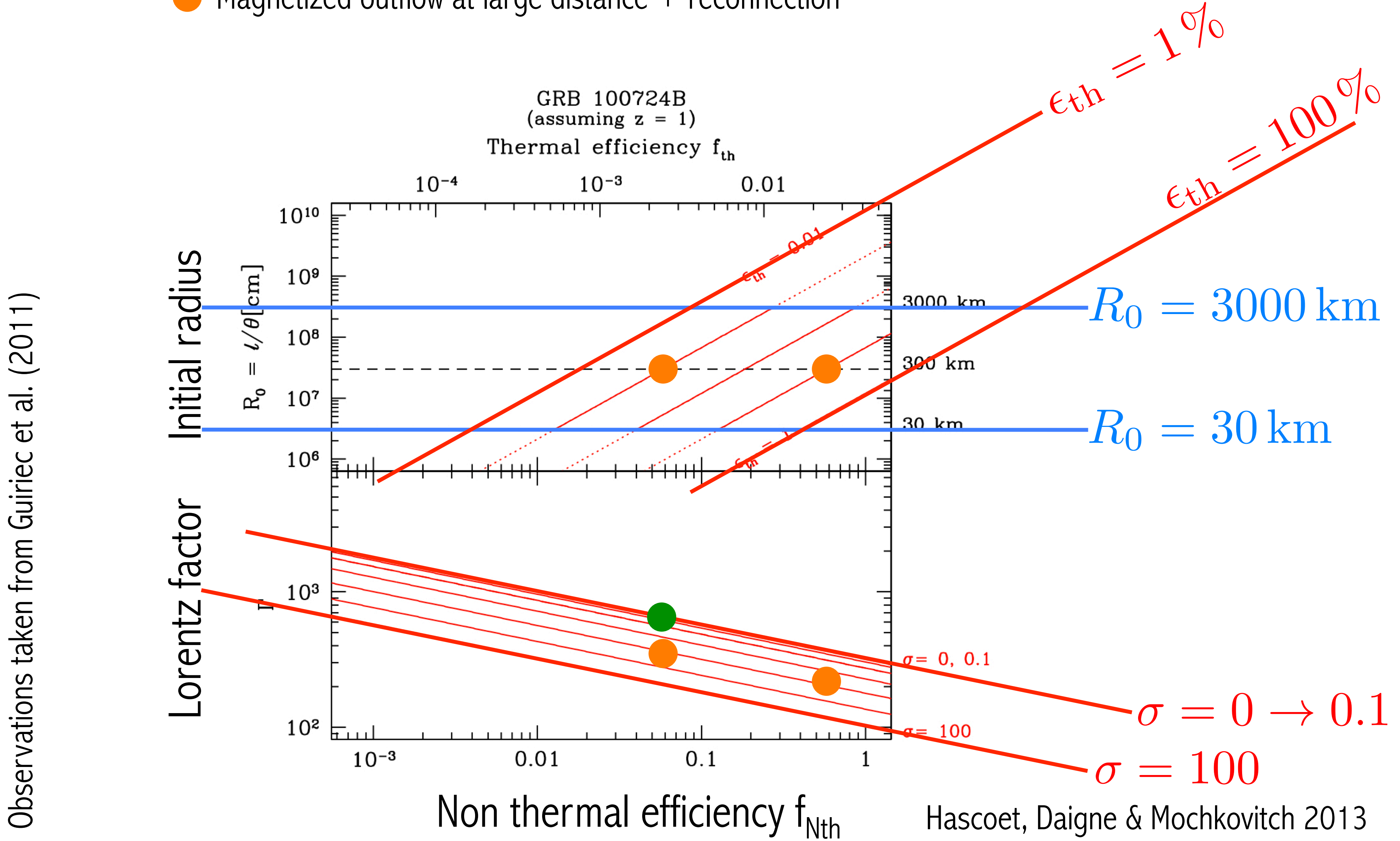
● Efficient magnetic acceleration + internal shocks



Hascoet, Daigne & Mochkovitch 2013

Exemple: GRB 100724B

- Efficient magnetic acceleration + internal shocks
- Magnetized outflow at large distance + reconnection



Hascoet, Daigne & Mochkovitch 2013

Other exemples and summary

- Most GRBs have a weak photosphere and are not compatible with the standard fireball : $\varepsilon_{th} < 1\%$ (Daigne & Mochkovitch 2002)

- Exemples: GRB100724B (long)
  - -non compatible with a standard fireball
  - -compatible with
    - efficient mag. acceleration + internal shocks ($\varepsilon_{th} < 1\text{-}10\%$)
    - or magnetized outflow + reconnection (but low efficiency or $\varepsilon_{th} > 30\%$)

  (Guiriec et al. 2011; Hascoet et al. 2013)

  GRB120323A (short) : similar conclusions, but allowing a larger $\varepsilon_{th} > 50\%$

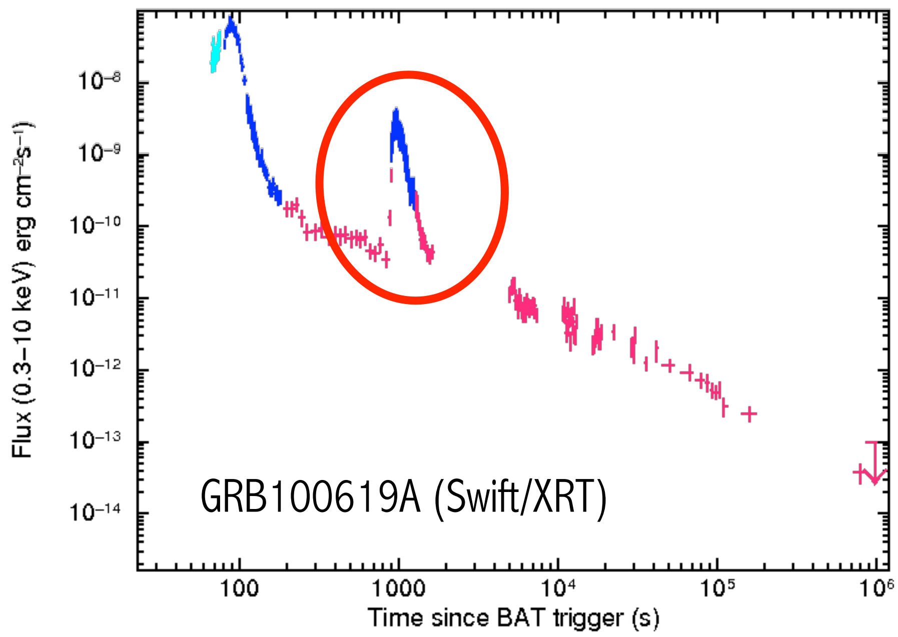
  GRB 090902B: only case compatible with standard fireball

- It implies a large initial magnetization in GRB outflows:

  What is the magnetization σ at large distance?

  Internal dissipation by shocks or reconnection?

X-ray flares produced by a long-lived RS: consequences for the structure of the relativistic ejecta



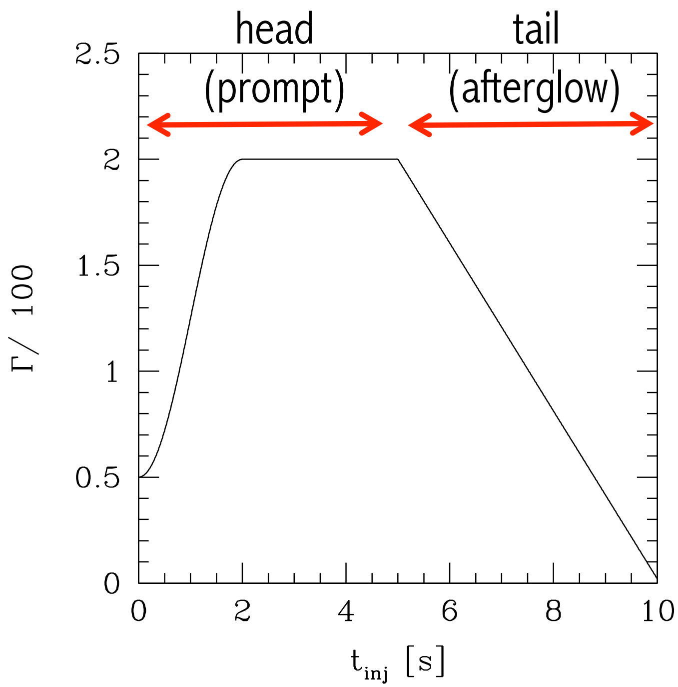
Afterglow from a long-lived RS:

Genet, Daigne & Mochkovitch 2007 ; Uhm & Beloborodov 2007

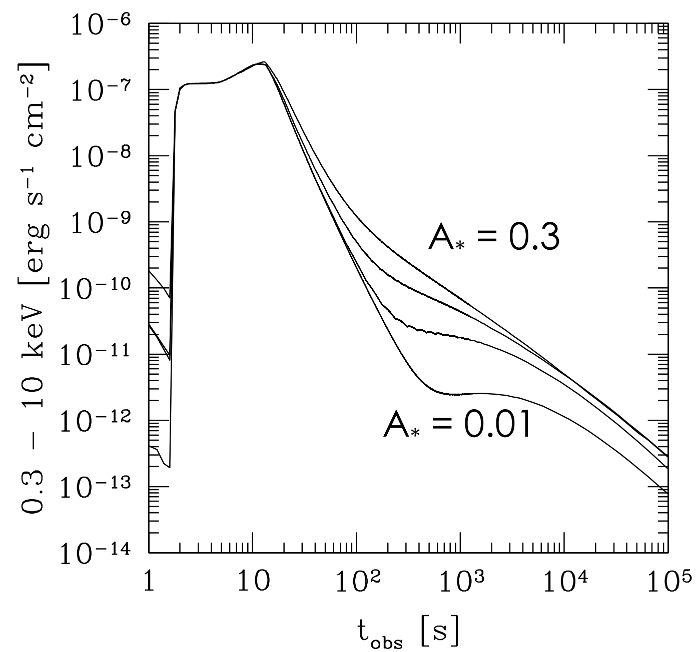
Afterglow from a long-lived RS

-long lived reverse shock: constraint on the initial Lorentz factor in the ejecta
(Rees & Meszaros 98 ; Sari & Meszaros 00 ; Genet [FD] & Mochkovitch 07 ; Uhm & Beloborodov 07)

-dominant RS emission: constraint on microphysics RS vs FS (ε_e, ε_B)
(Genet [FD] et al. 07 ; Uhm & Beloborodov 07 ; Uhm [FD] et al. 11)



Initial Lorentz factor distribution



X-ray light-curves

$E_{kin,iso} = 2.10^{54}$ ergs ; z = 1
wind density profile $\rho(r) = A_* A_0 r^{-2}$ with $A_0 = 5\ 10^{-11}$ g cm^{-1}

Afterglow from a long-lived RS

-long lived reverse shock: constraint on the initial Lorentz factor in the ejecta

-dominant RS emission: constraint on microphysics RS vs FS (ε_e, ε_B)

-No need for late energy injection to reproduce plateaus

-Large diversity of lightcurves is expected (internal structure of the ejecta)

(Uhm [FD] et al. 2012)

-Observed correlations between prompt and plateau properties can be reproduced

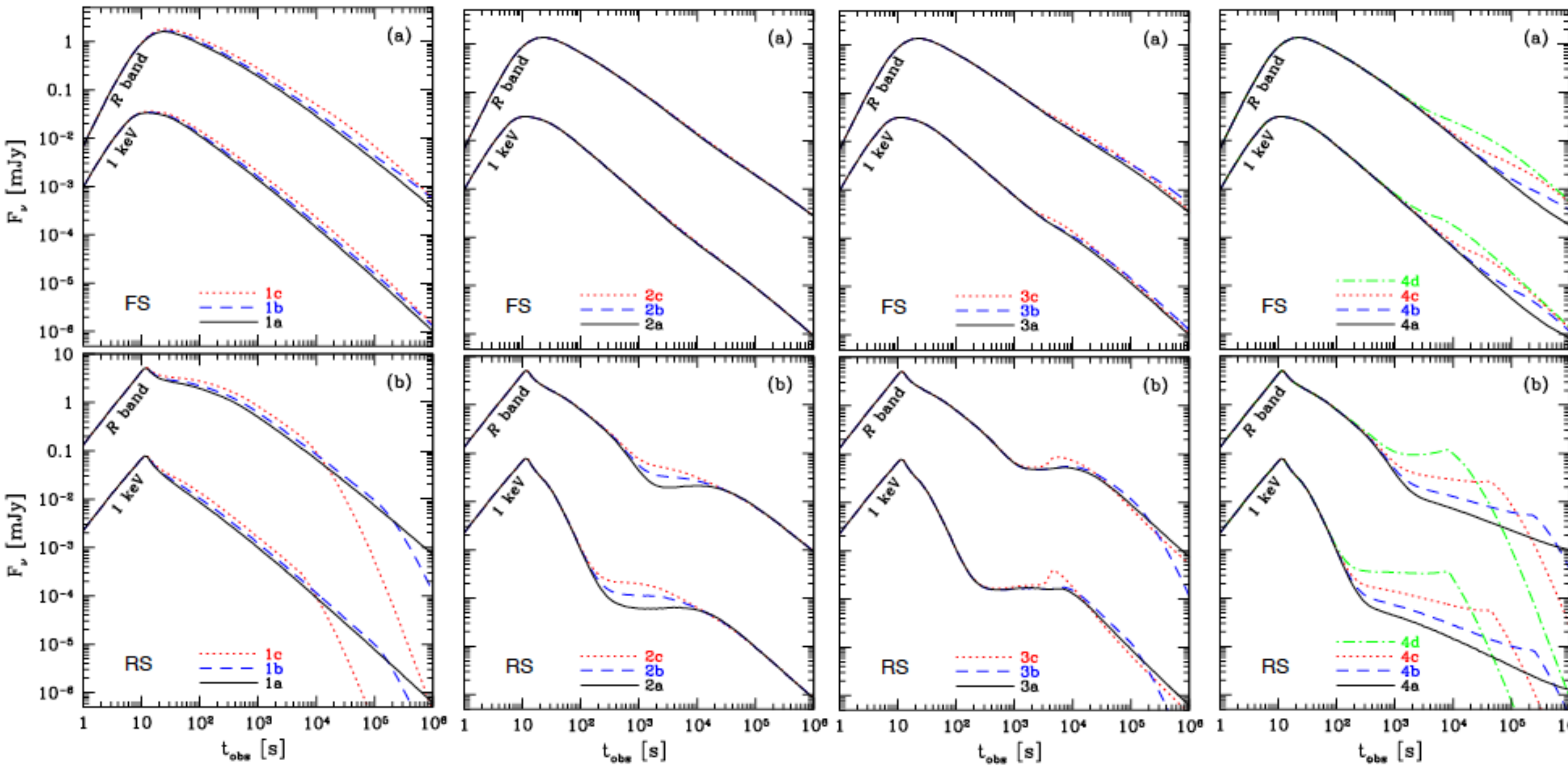
(Hascoët [FD] et al. 2013)

-No need for late activity of the central engine to reproduce flares

(Hascoët [FD] et al. arXiv:1503.08333)

Long-lived RS afterglow: diversity

Top: FS (very low sensitivity to the internal structure of the ejecta)



Bottom: RS

External medium: uniform 1 cm^{-3}

Relativistic ejecta: constant 10^{53} erg/s for 10 s – Source at z = 1

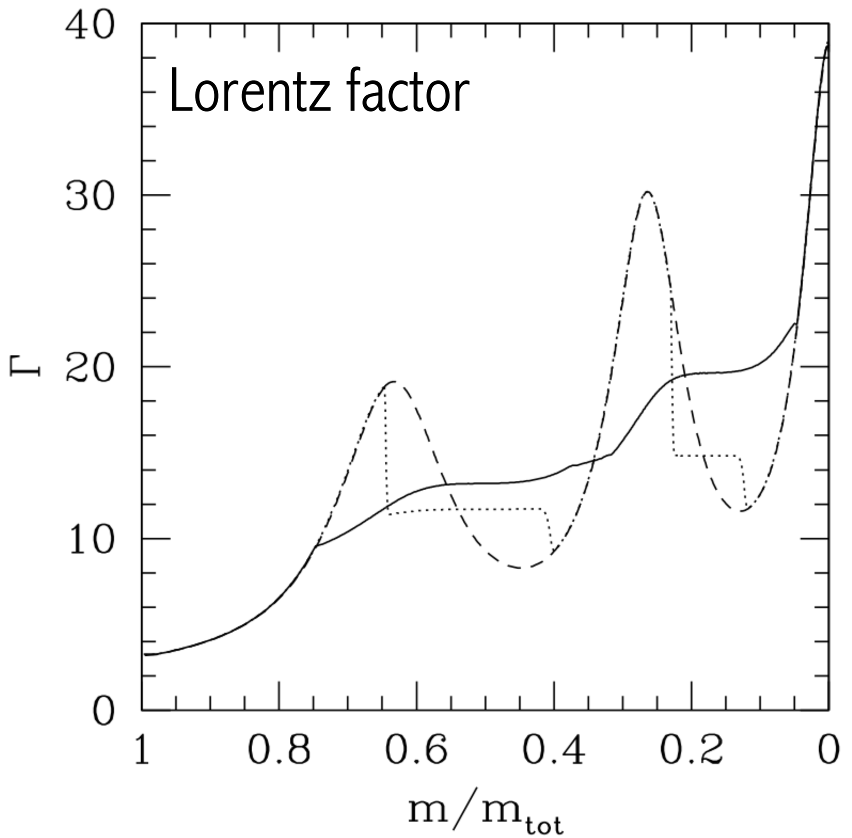
FS: $\varepsilon_e = 10^{-2}$; $\varepsilon_B = 10^{-4}$; p = 2.3 ; RS: $\varepsilon_e = 10^{-1}$; $\varepsilon_B = 10^{-2}$; p = 2.3

Uhm [FD] et al. 2011

Each case corresponds to a different initial distribution of the Lorentz factor

X-ray flares

-propagation of the reverse shock in a structured outflow
-a signature of internal shocks?



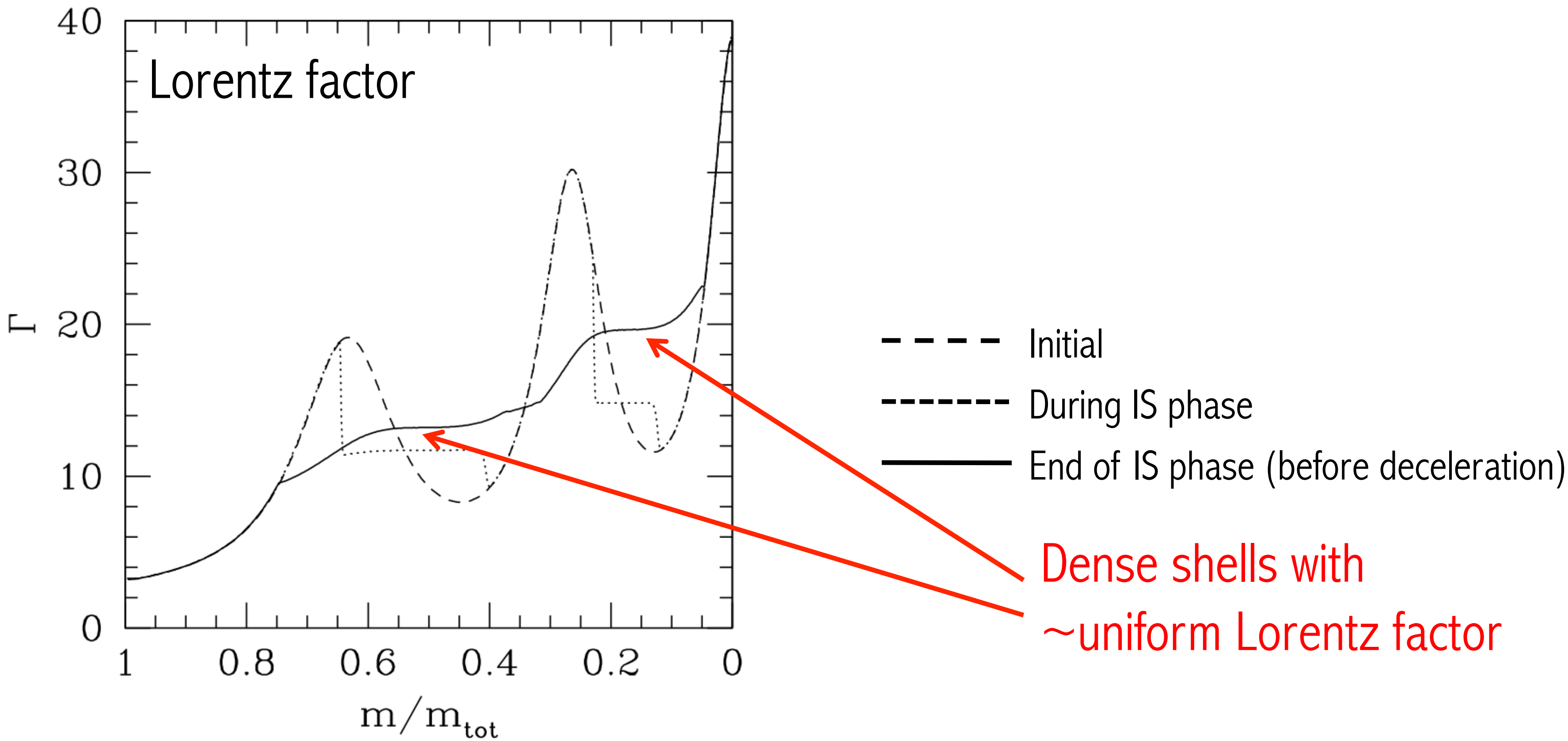
An exemple of the distribution of Lorentz factor in the ejecta: (relativistic hydro simulation)

- - - - Initial
------- During IS phase
——— End of IS phase (before deceleration)

Hascoët et al. astro-ph/1503.08333

X-ray flares

-propagation of the reverse shock in a structured outflow
-a signature of internal shocks?



Hascoët et al. astro-ph/1503.08333

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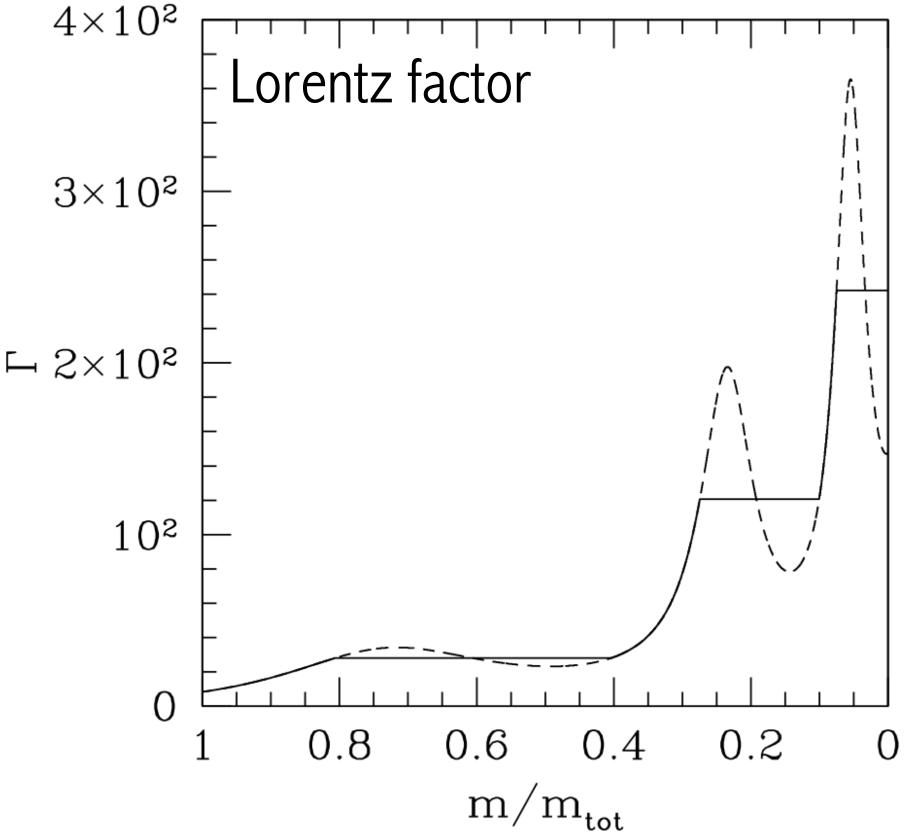

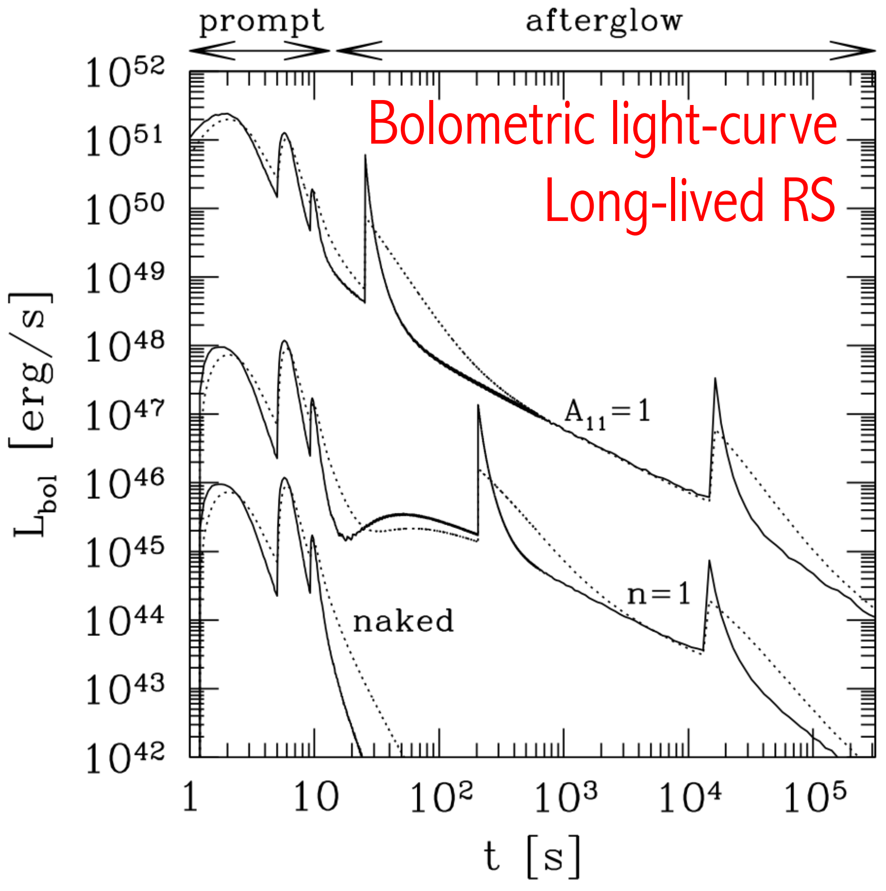

Hascoët et al. astro-ph/1503.08333

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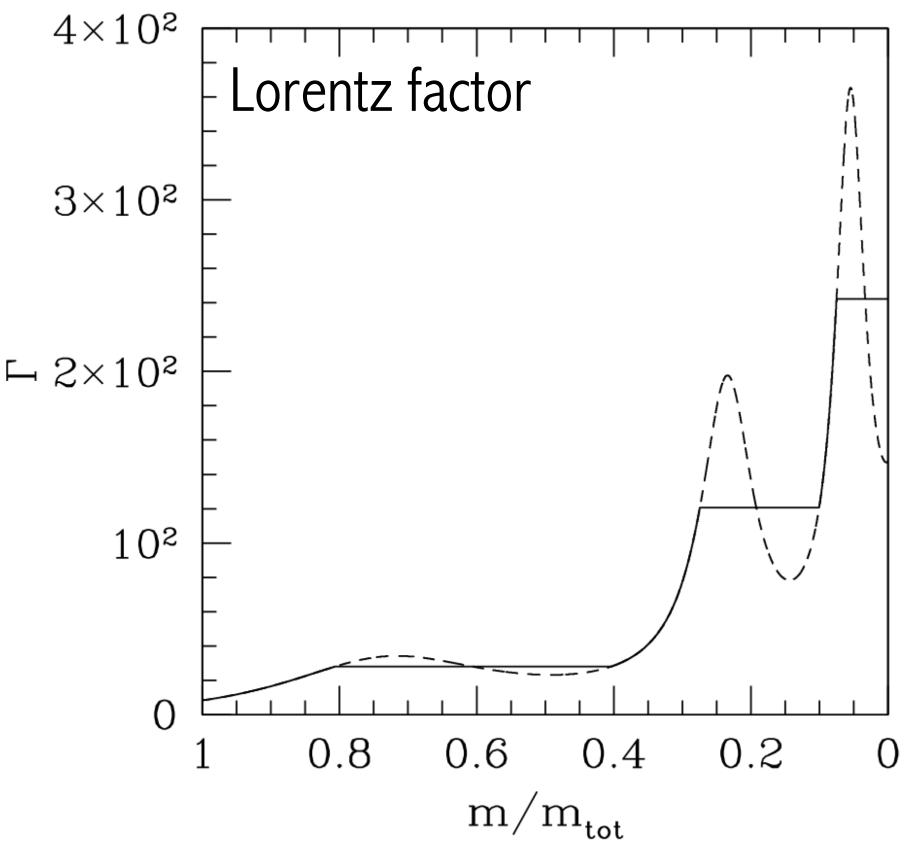
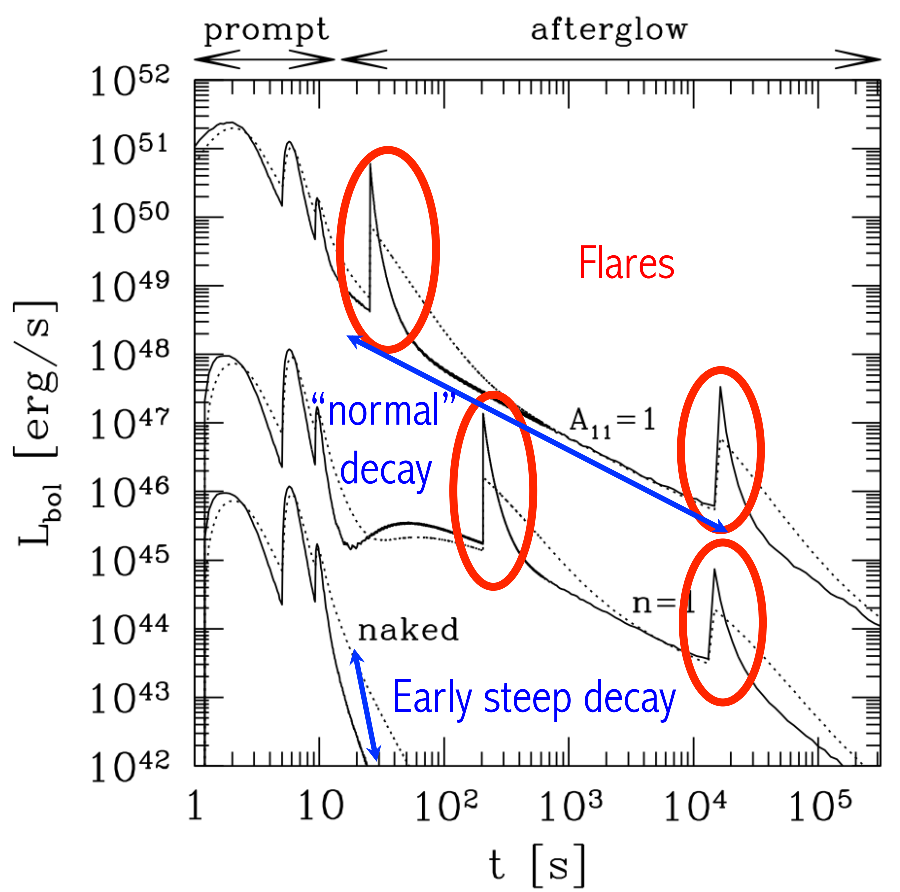




Flares are produced when the RS crosses a dense shell formed in the IS phase

Hascoët et al. astro-ph/1503.08333

X-ray flares

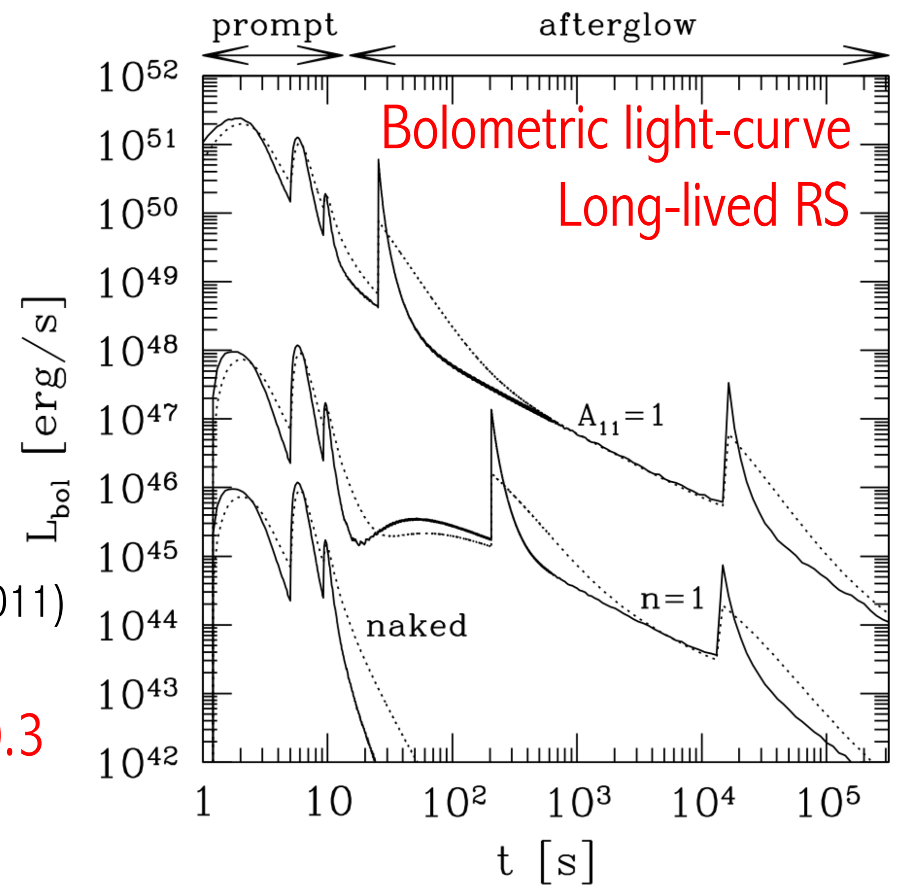
-propagation of the reverse shock in a structured outflow
-a signature of internal shocks?

Curves: different circumburst medium

Wind	10^{11} g/cm	(L_{bol})
Uniform	1 cm^{-3}	(L_{bol} divided par 10^3)
Naked burst		(L_{bol} divided by 10^5)

------- Isotropic emission

——— Anisotropic synchrotron emission in the comoving frame (Beloborodov [FD] et al. 2011)



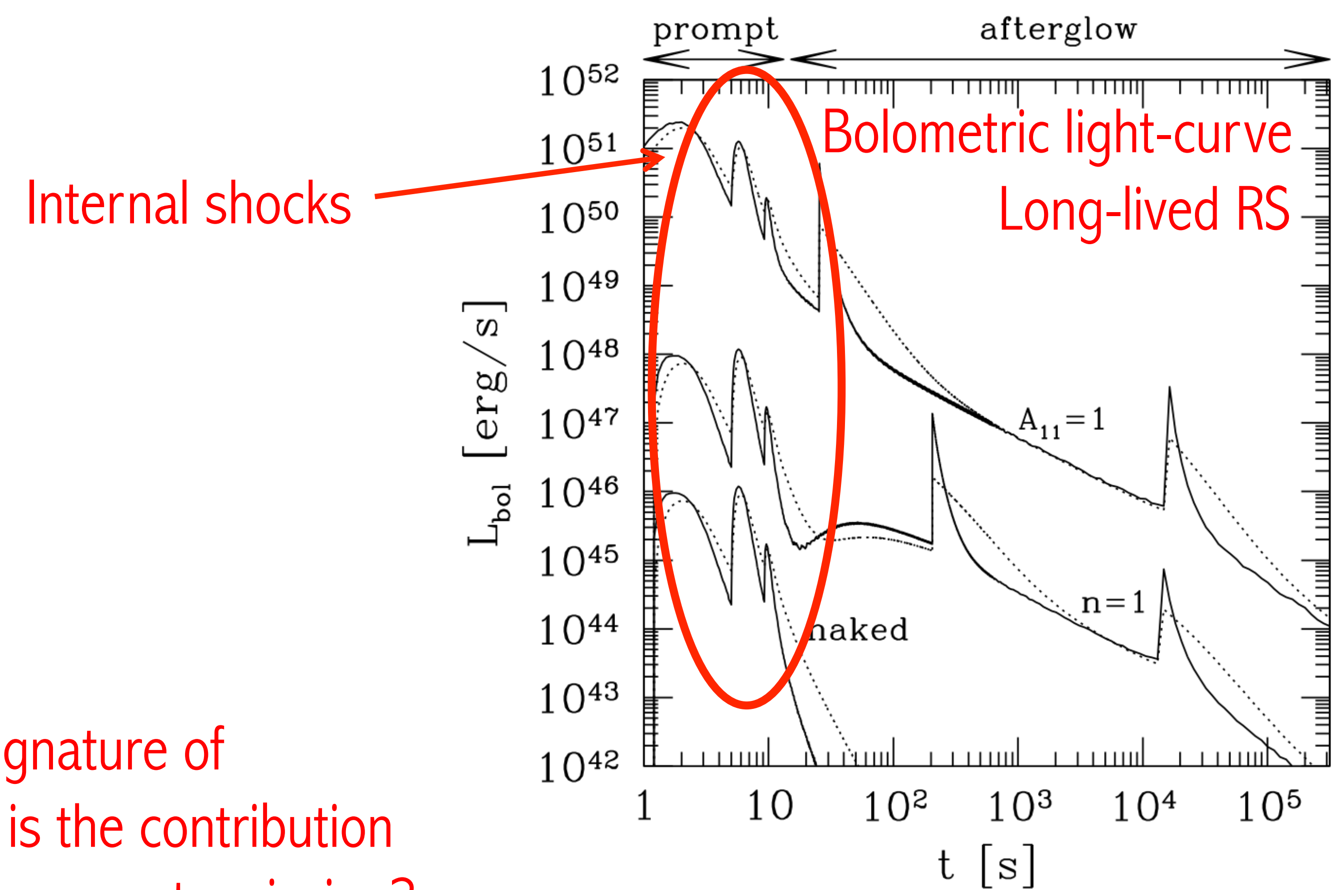
Flares: Fast rise/Steep decay with $\Delta t/t \sim 0.1\text{-}0.3$
(no need for a long-lived central engine)

Hascoët et al. astro-ph/1503.08333

Needs hydro simulation + radiative calculation for validation

X-ray flares

-propagation of the reverse shock in a structured outflow
-a signature of internal shocks?



If X-ray flares are a signature of internal shocks, what is the contribution of these shocks to the prompt emission?

Sub-photospheric dissipation or direct emission?

Prompt gamma-ray emission from internal shocks?

How to distinguish between the proposed mechanisms for the prompt emission?

-Lighcurves: OK for all scenarios

-Spectrum

-Spectral evolution

Spectrum

Main difficulty to model the prompt GRB with internal shocks: spectral shape

- -depends on a complex microphysics
- -observational constraints not always clear?

Spectrum

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Low-energy photon index in fast cooling synchrotron spectrum?

-3/2 : pure fast cooling synchrotron

$\sim$ -1 : fast cooling synchrotron + inverse Compton in KN regime

(Derishev et al. 01 ; Bosnjak et al. 09 ; Wang et al. 09 ; Daigne et al. 11)

-2/3 : marginally fast cooling synchrotron (Daigne et al. 11 ; Beniamini & Piran 13)

-1 $\rightarrow$ -0.5 : fast cooling synchrotron + IC in decaying magnetic field

(Derishev 07 ; Lemoine 13 ; Uhm & Zhang 14 ; Zhao et al. 14)

Spectrum

Main difficulty to model the prompt GRB with internal shocks: spectral shape

-depends on a complex microphysics

-observational constraints not always clear?

- Band vs Band+BB: different low-energy photon index? Compatible with (modified) fast cooling synchrotron?

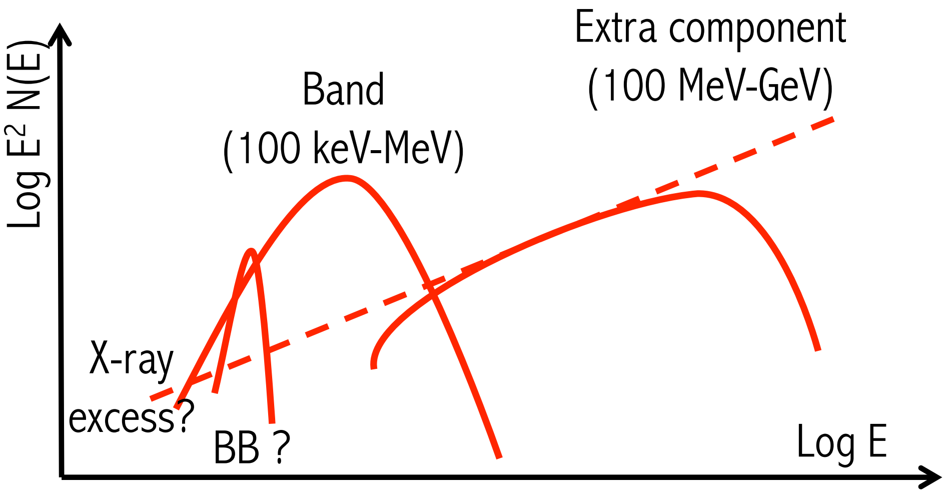
  e.g. GRB120323A α=-0.92 → -1.4 Guiriec [FD] et al. 2013

  GRB 080916C α=-1.0 → -1.2 Guiriec [FD] et al. 2015

  etc.

- Inconsistency between time-integrated and time-resolved analysis?

- Shape of the extra-component in LAT is not well constrained. Is the X-ray excess real?



Spectrum

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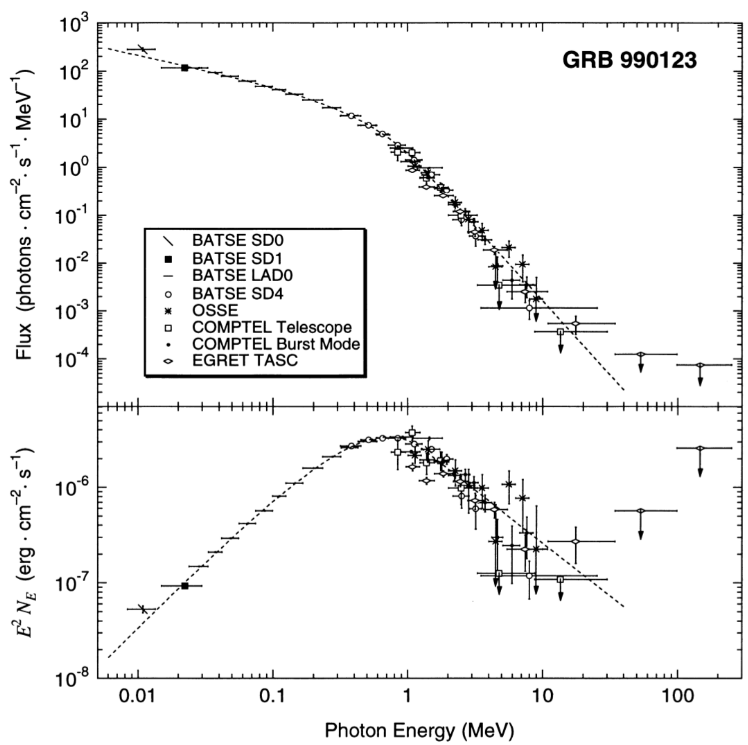
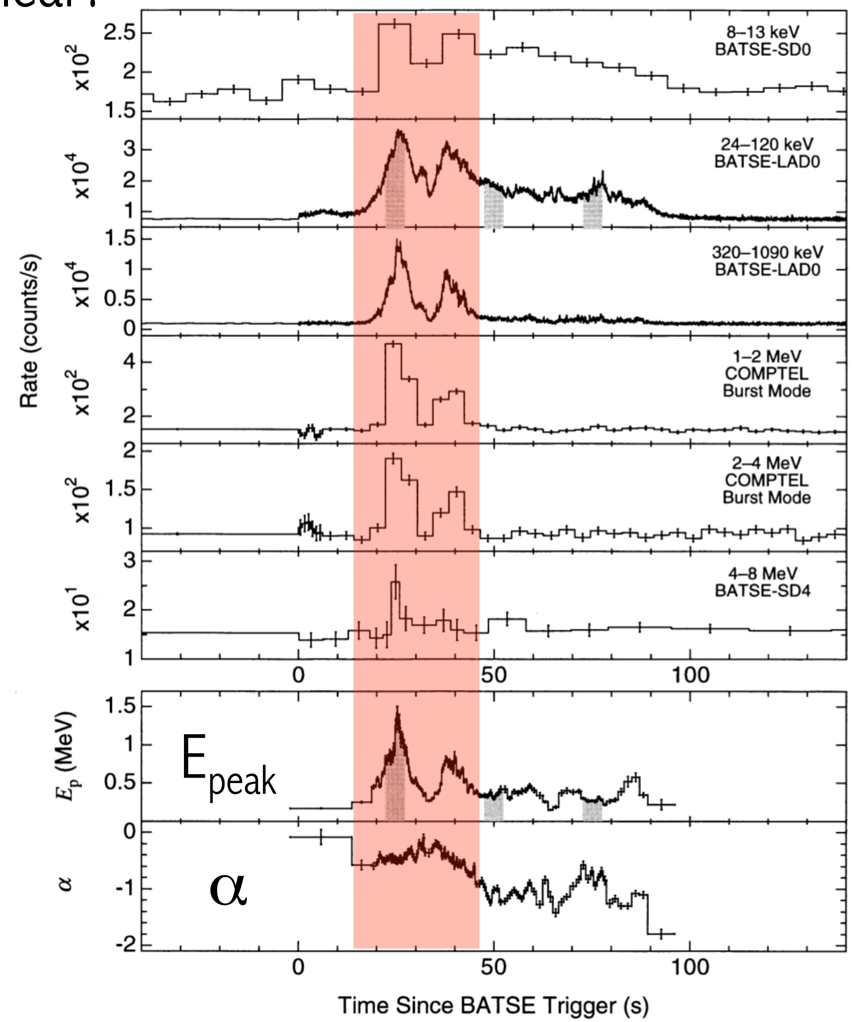
e.g. GRB 990123 (Briggs et al. 2000)





Band function used both in time-integrated/resolved analysis

Spectrum

Main difficulty to model the prompt GRB with internal shocks: spectral shape

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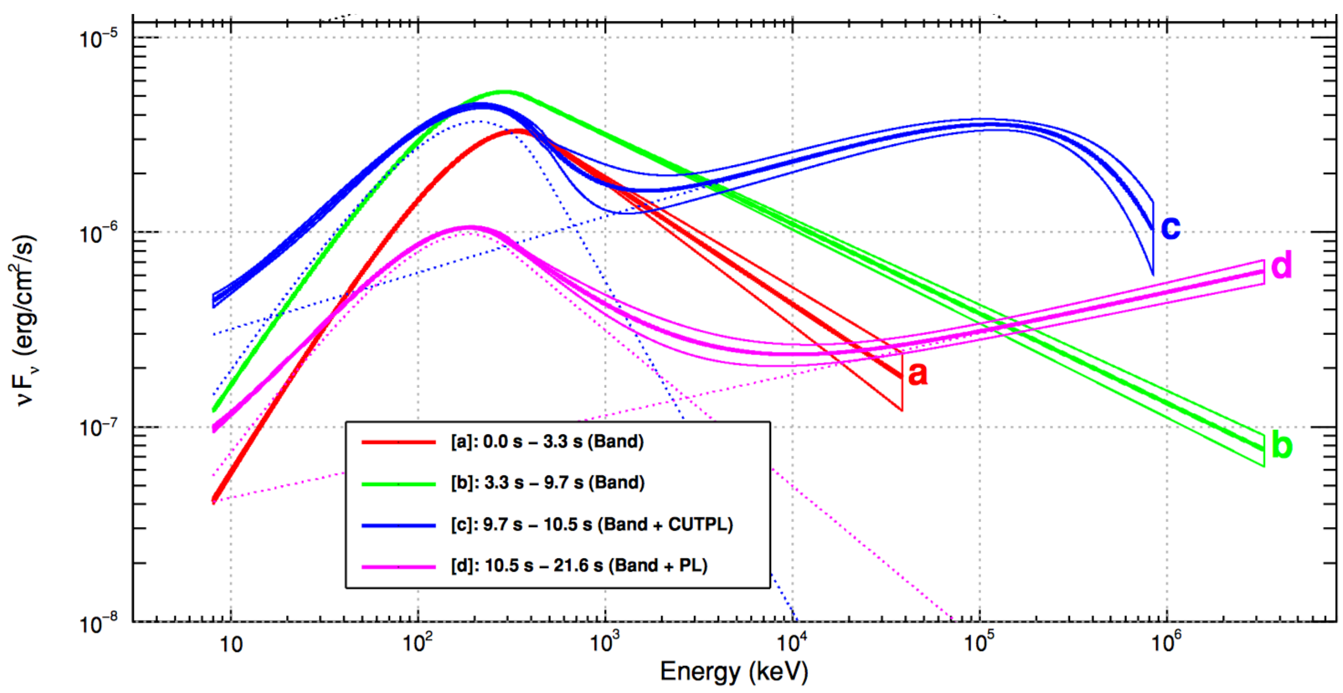
- -observational constraints not always clear?

e.g. New analysis of GRB090926A with Pass 8 (LAT photons × 2.4) : see F. Piron's talk



Ackermann et al. 2011: Band (steep α) + PL (with cutoff in bin c) – X-ray excess

Spectrum

Main difficulty to model the prompt GRB with internal shocks: spectral shape

-depends on a complex microphysics

-observational constraints not always clear?

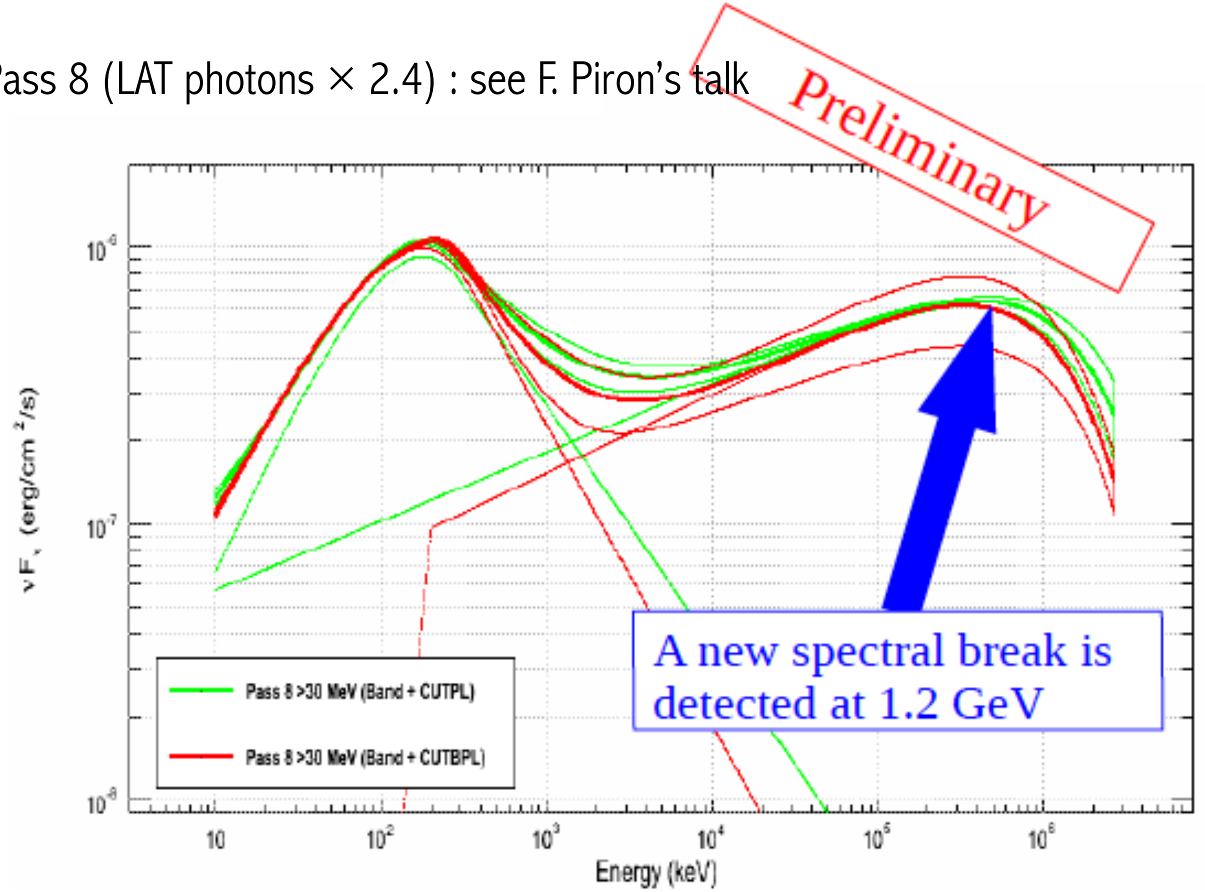
e.g. New analysis of GRB090926A with Pass 8 (LAT photons × 2.4) : see F. Piron's talk

Band + broken PL + cutoff in bins c and d

-X-ray excess disappears

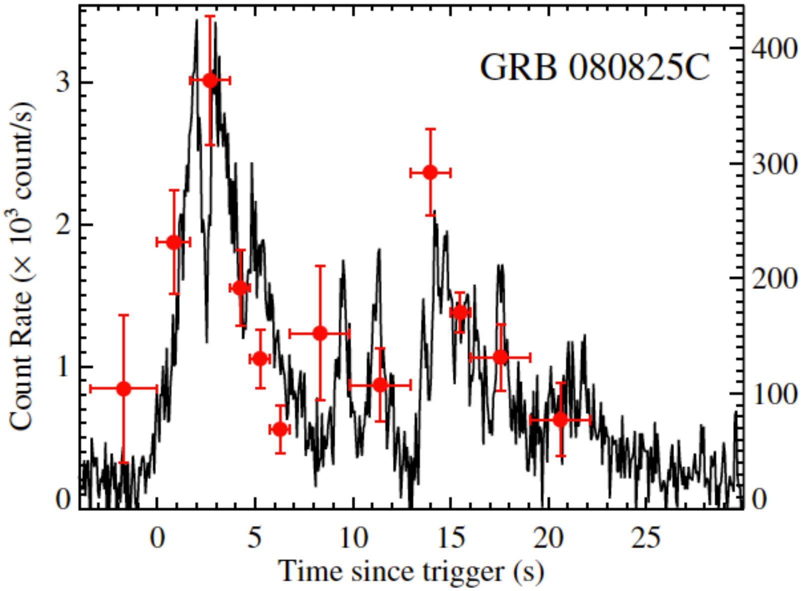
-Band ($\alpha \rightarrow$ -1)

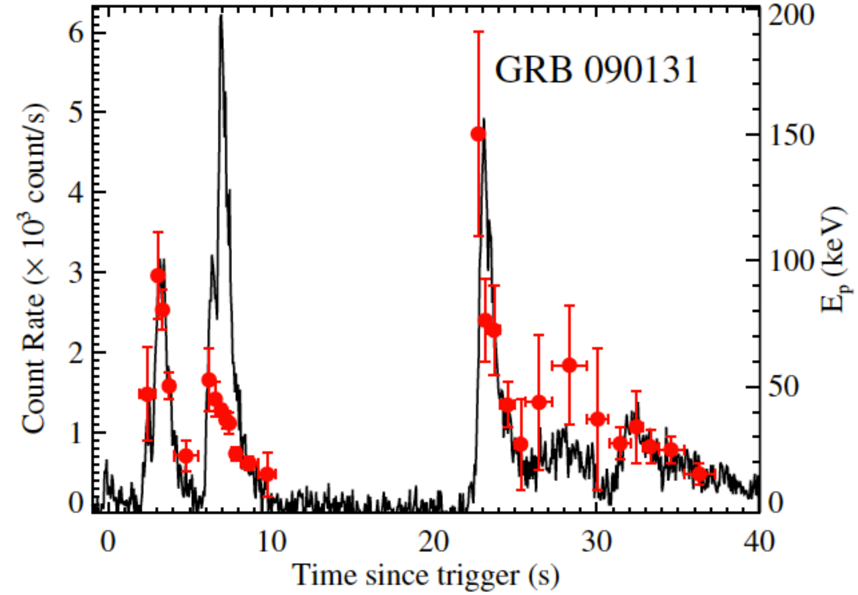
Syn+IC with KN/γγ ?

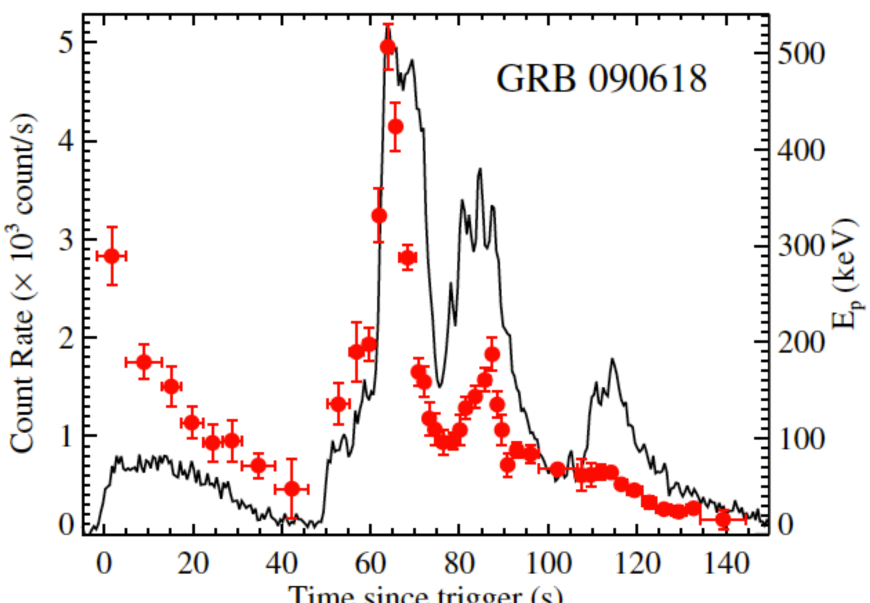


Yassine, Piron, Daigne & Mochkovitch, Fermi Symposium 2015

Spectral evolution



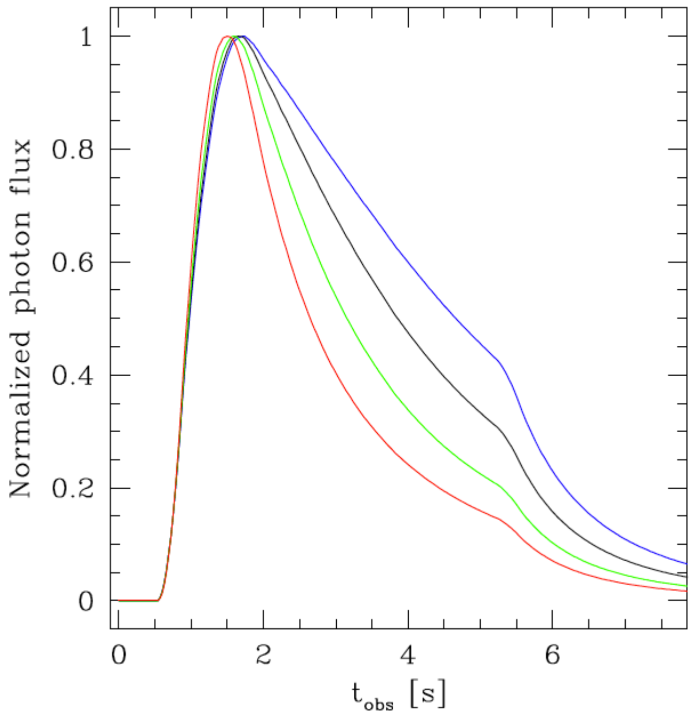




GBM bursts — Li et al. 2012

Spectral evolution

Example of a simulated GRB pulse produced by internal shocks
(full simulation: dynamics+radiation)



Light curve in BATSE range :
channels 1 (blue) to 4 (red)

Bosnjak & Daigne 2014

Spectral evolution

Example of a simulated GRB pulse produced by internal shocks
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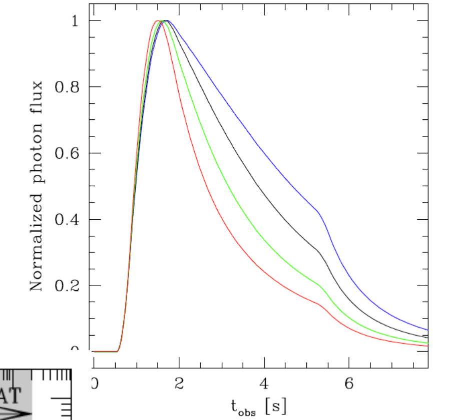
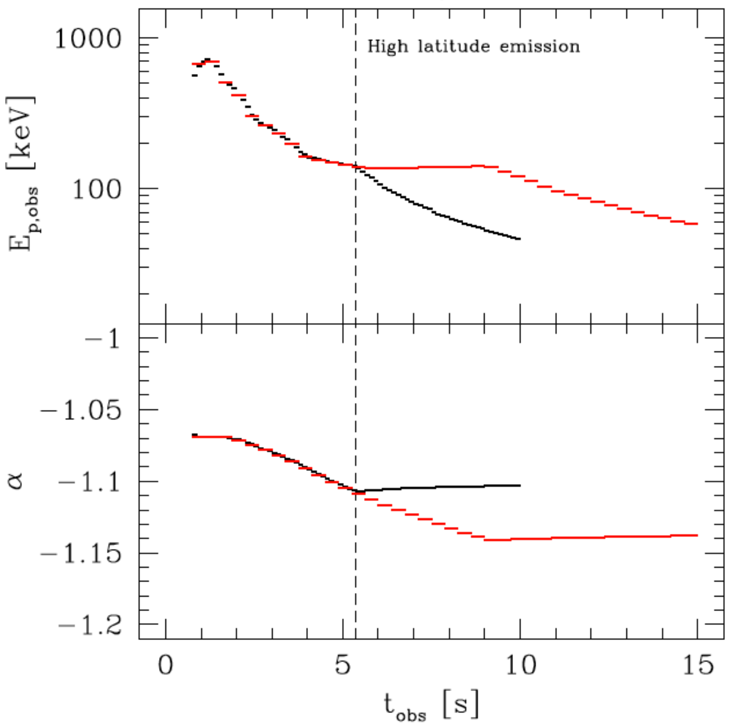
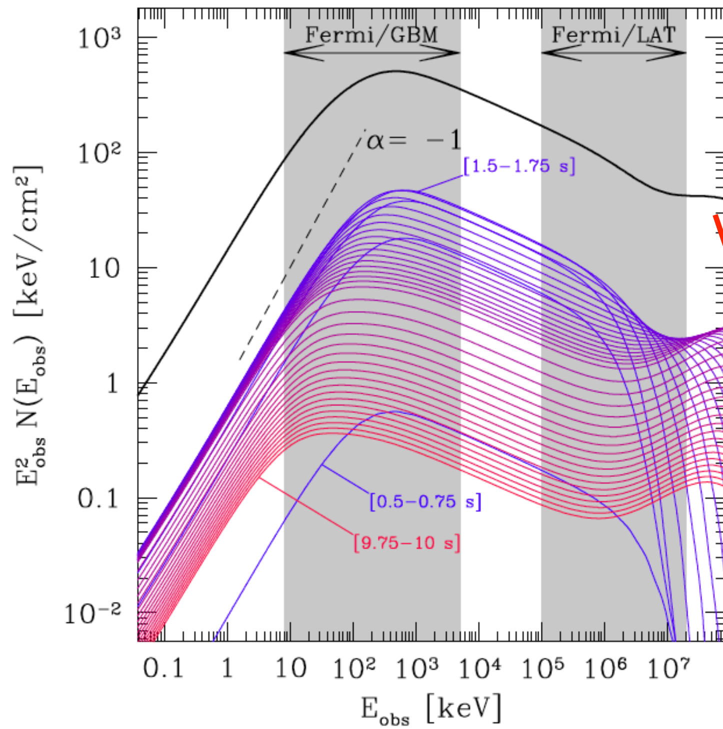


Evolution of E_{peak} and α



Time-evolving spectrum



Extra component

Bosnjak & Daigne 2014

Spectral evolution

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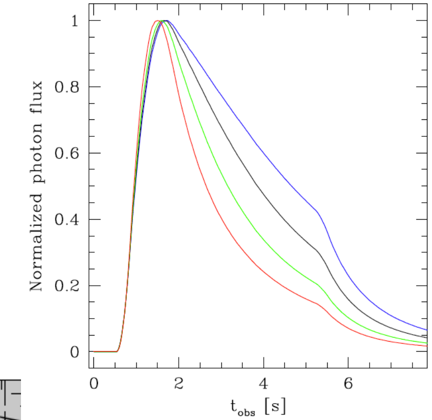
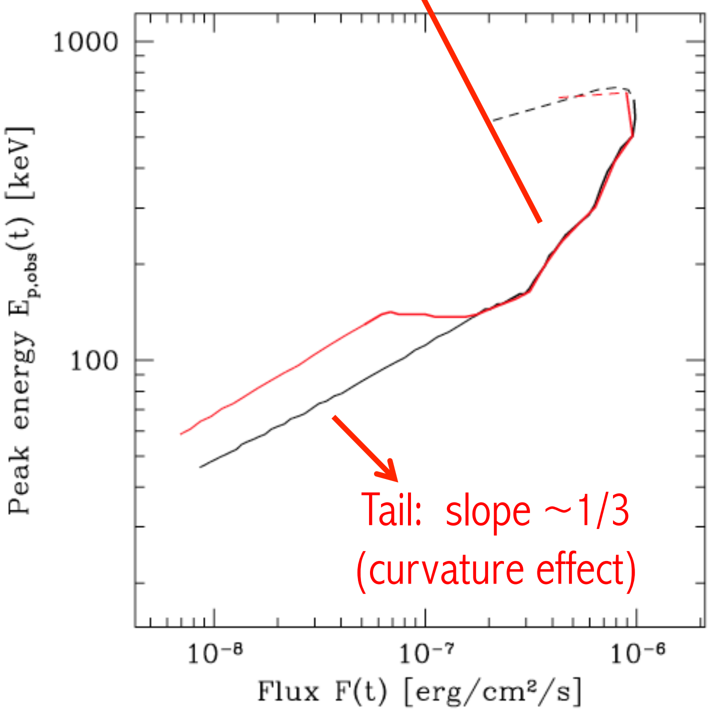
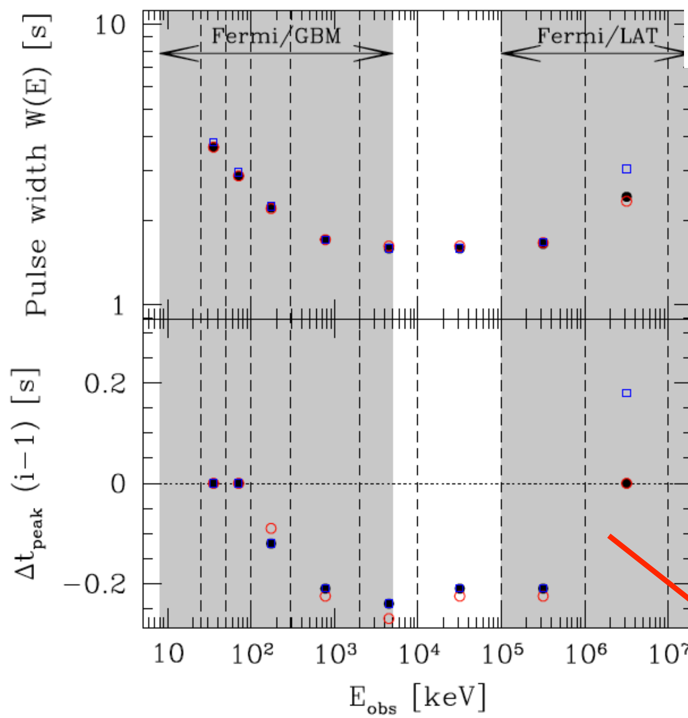


Slope ~1-1.5 fixed by shock propagation



Tail: slope ~1/3
(curvature effect)

Hardness-Intensity Correlation



Pulse width and time lags

$$W(E) \propto E^{-a}$$

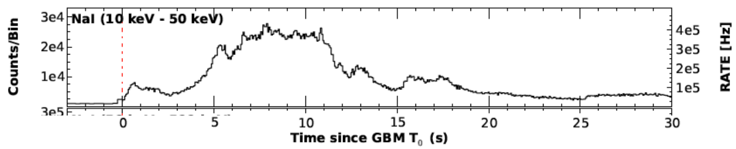
$$a \simeq 0.2 - 0.3$$

Delayed onset ? γγ ?
(Hascoet et al. 2012)

Bosnjak & Daigne 2014

Spectral evolution

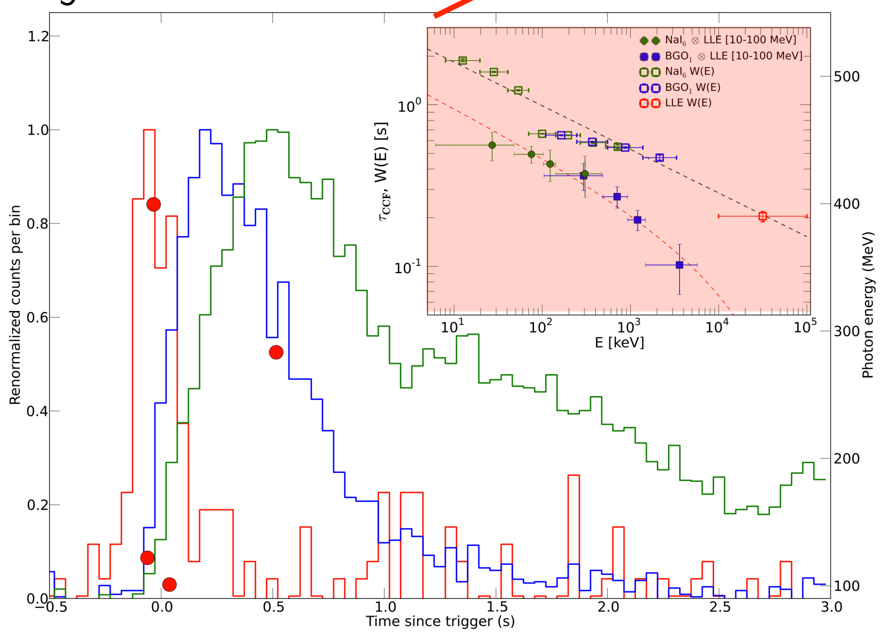
GRB 130427A

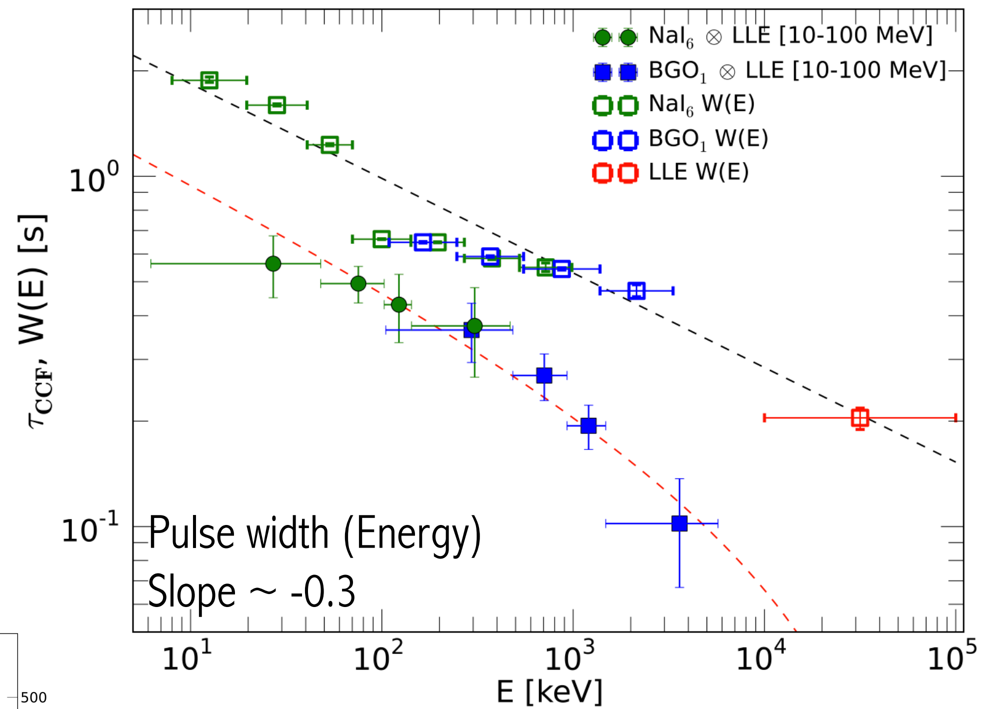


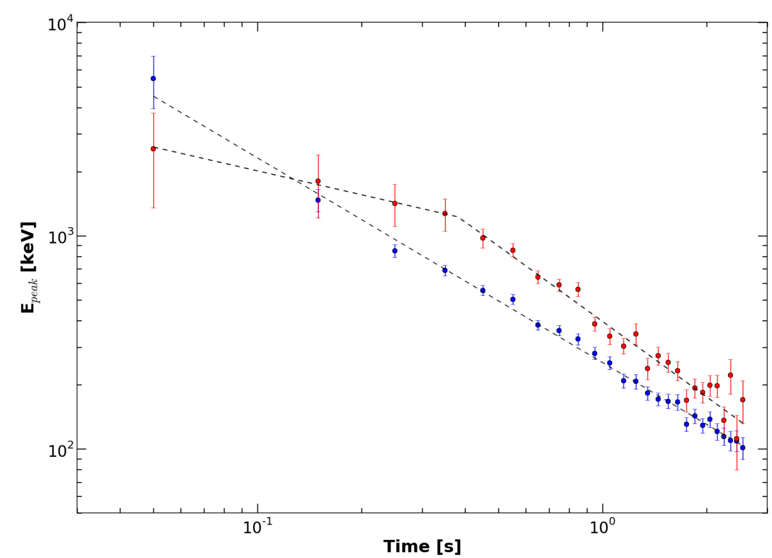
The first 3 s

zoom

Time lags



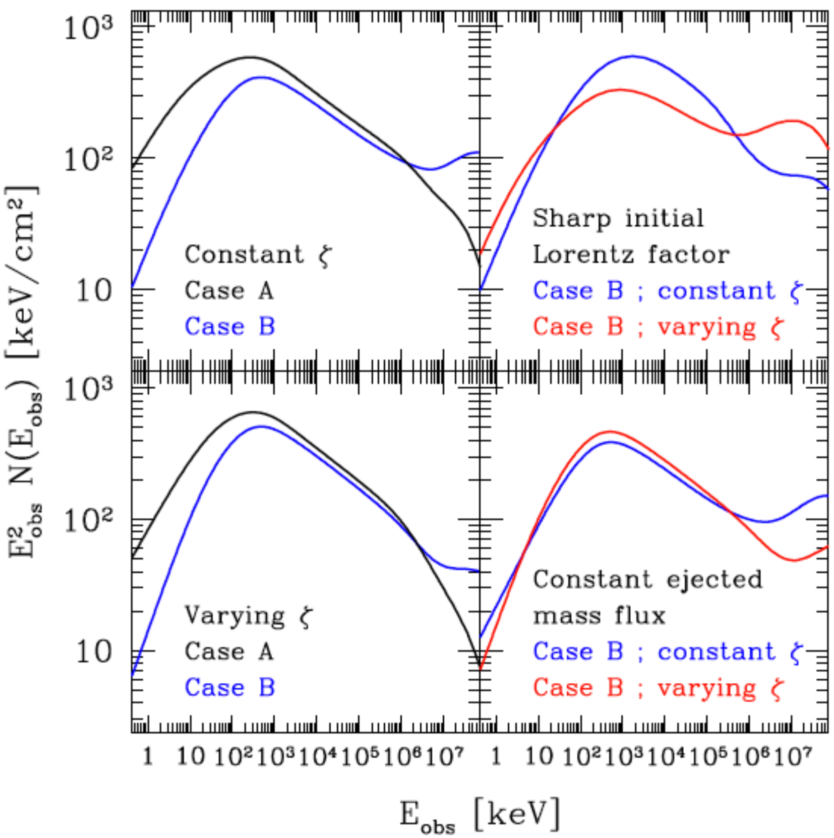


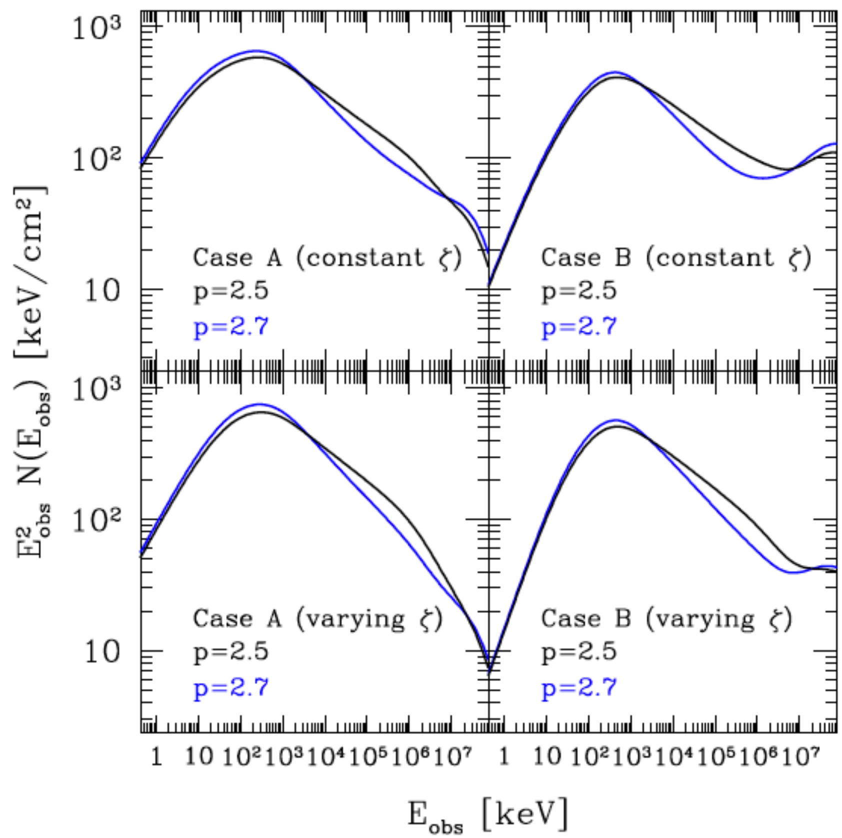


Preece et a.l. 2014

Not shown: hardness-intensity correlation slope 1.4

Prompt GeV emission from internal shocks





Bosnjak & Daigne 2014 ; see also Asano & Meszaros.

Summary

Summary

In the scenario where the prompt GRB emission is produced above the photosphere:

- The weak quasi-thermal photospheric emission implies a high magnetization at the base of the relativistic outflow.

- Then, depending on the magnetization at large distance, internal dissipation responsible of the prompt emission can be either shocks or reconnection.

- When deceleration by the external medium starts, the reverse shock may have an important contribution to the afterglow emission (constraints on Lorentz factor + microphysics). It can explain the complexity/diversity of the afterglow light-curves without strong assumptions for the central engine lifetime/energetics.

- In this scenario, X-ray flares can be a signature of previous internal shocks.

- Then internal shocks may be responsible for the prompt emission, under some strong constraints on the microphysics.