The physical origin of the GRB prompt emission

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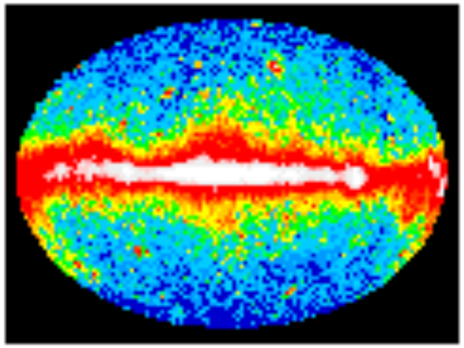
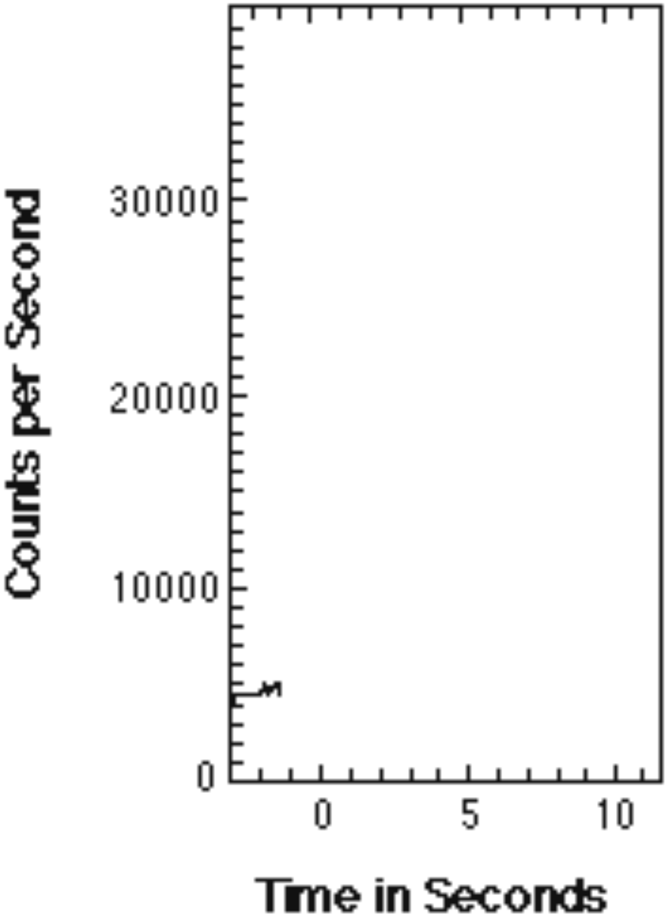
Probing quantum spacetime with Astrophysical Sources: the CTA era and beyond – Paris – 20 November 2017

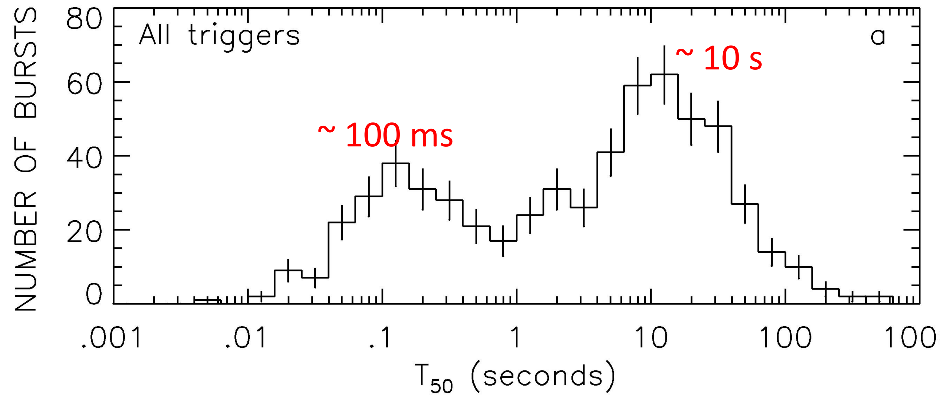
GRBs: observations





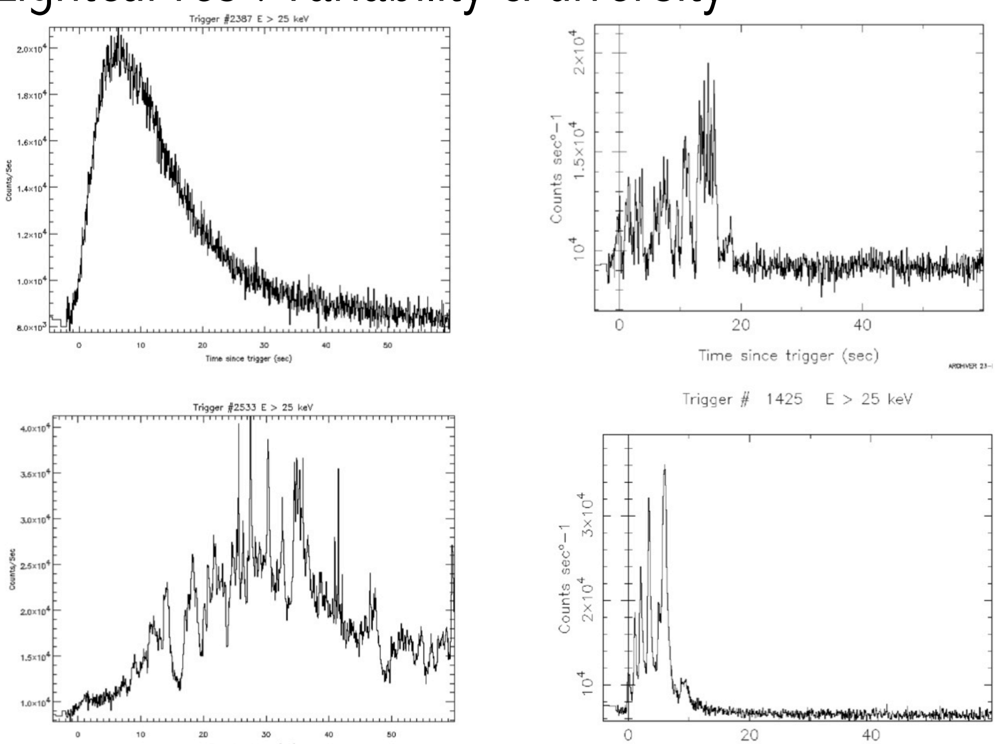
Gamma-ray bursts: prompt emission

- Apparent rate:
  ~ 1 GRB / day
- Duration: two groups

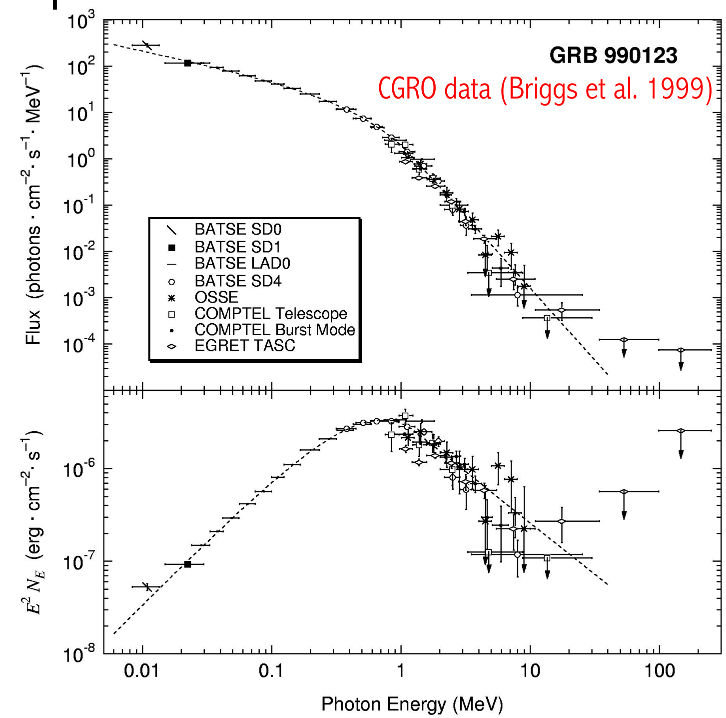


CGRO/BATSE

- Lightcurves : variability & diversity



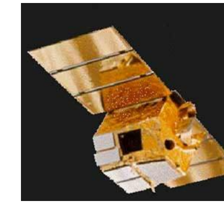
- Spectrum: non-thermal



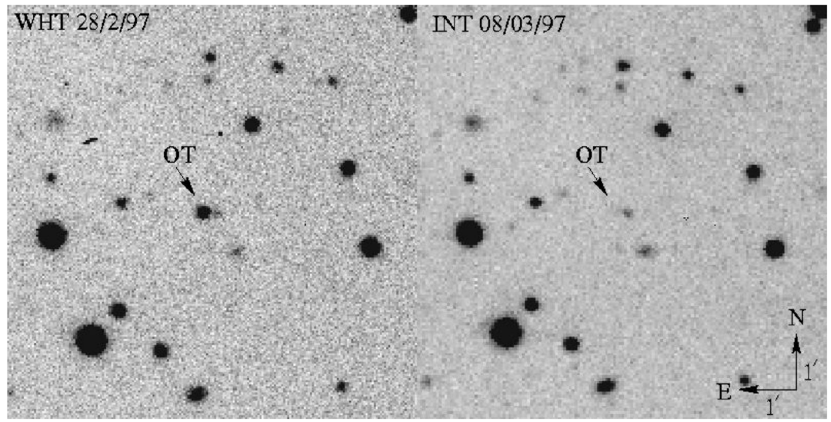
- Peak energy: keV → MeV

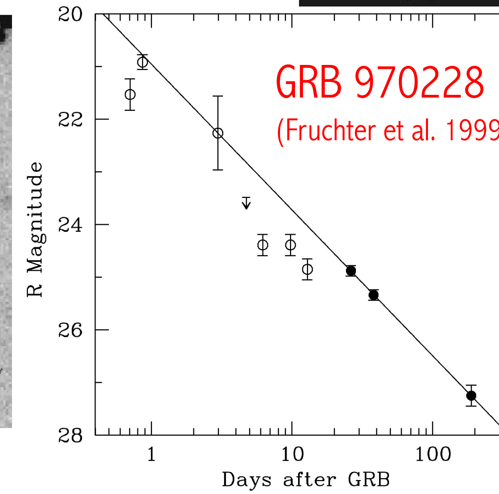
Gamma-ray bursts: afterglow

Beppo-SAX

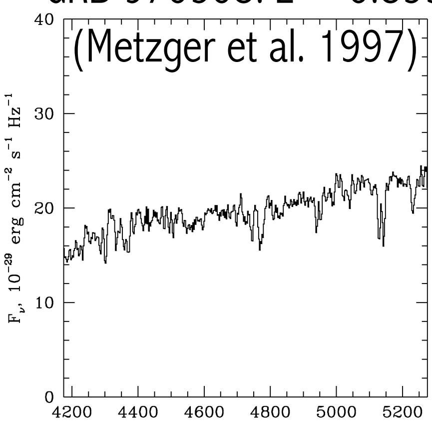


- Flux: power-law decay
- Non-thermal spectrum
- Spectral evolution: X-rays $\longrightarrow$ V $\longrightarrow$ radio
- Redshift & host galaxy
- High redshift ($z_{max,obs} > 9$): huge luminosities! $E_{iso,\gamma} \sim 10^{51} - 10^{54}$ erg

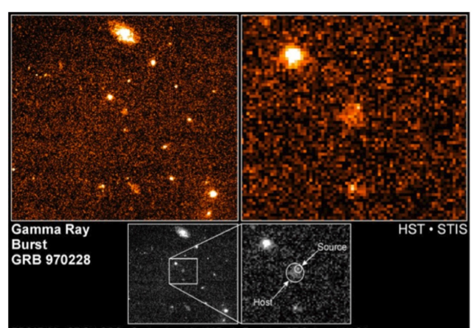


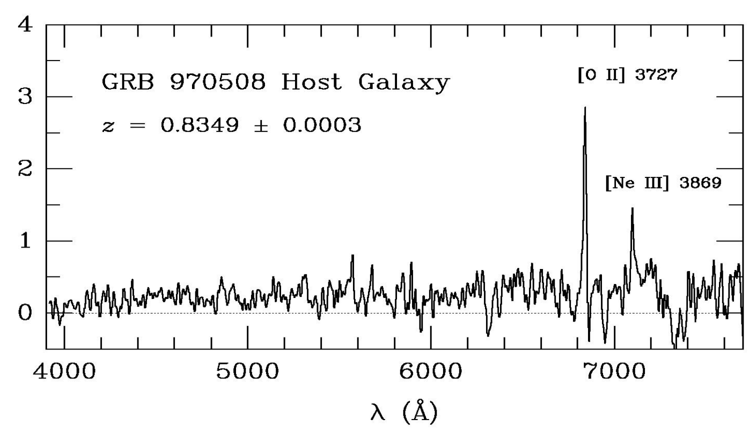


GRB 970508: z = 0.835

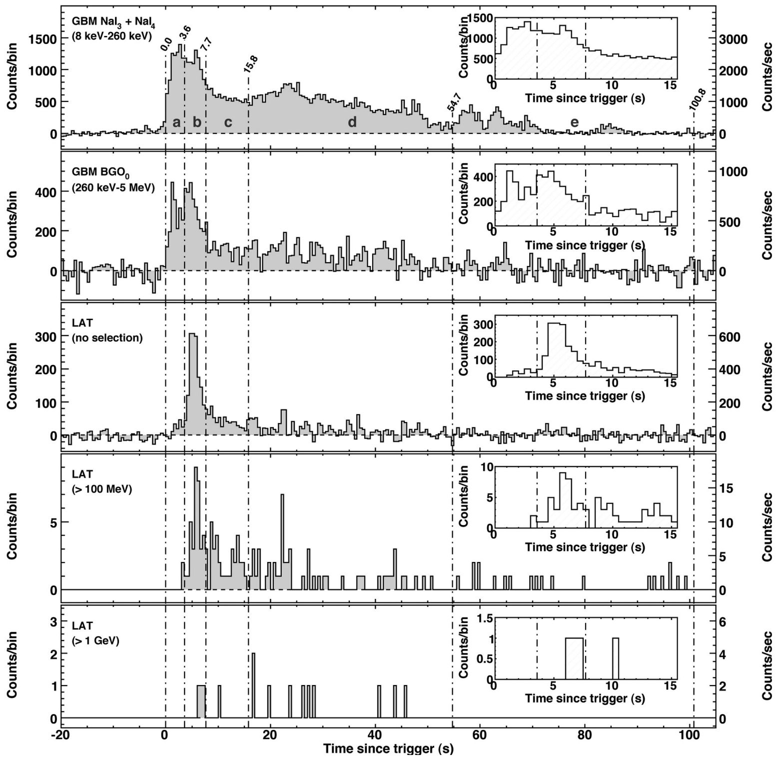


Fruchter et al. 1997

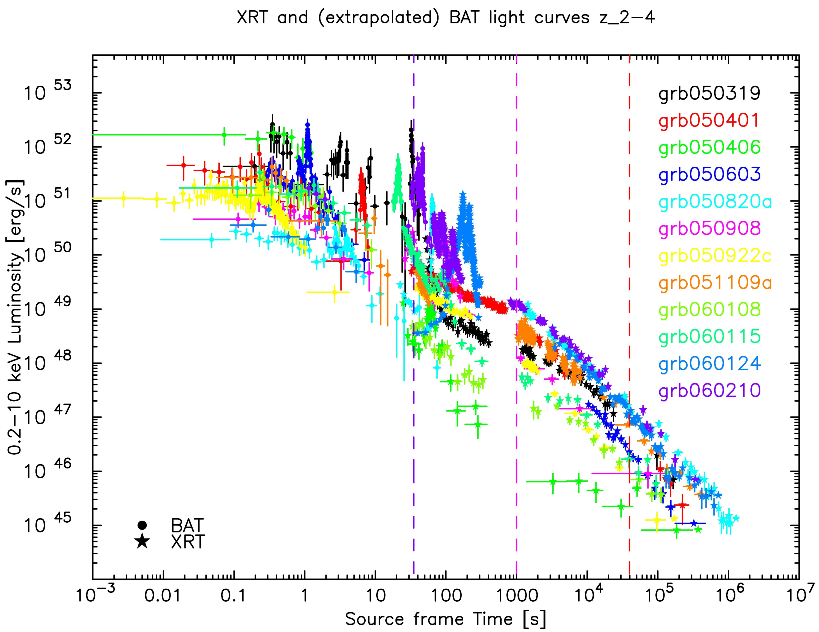




GRBs: Swift & Fermi observations

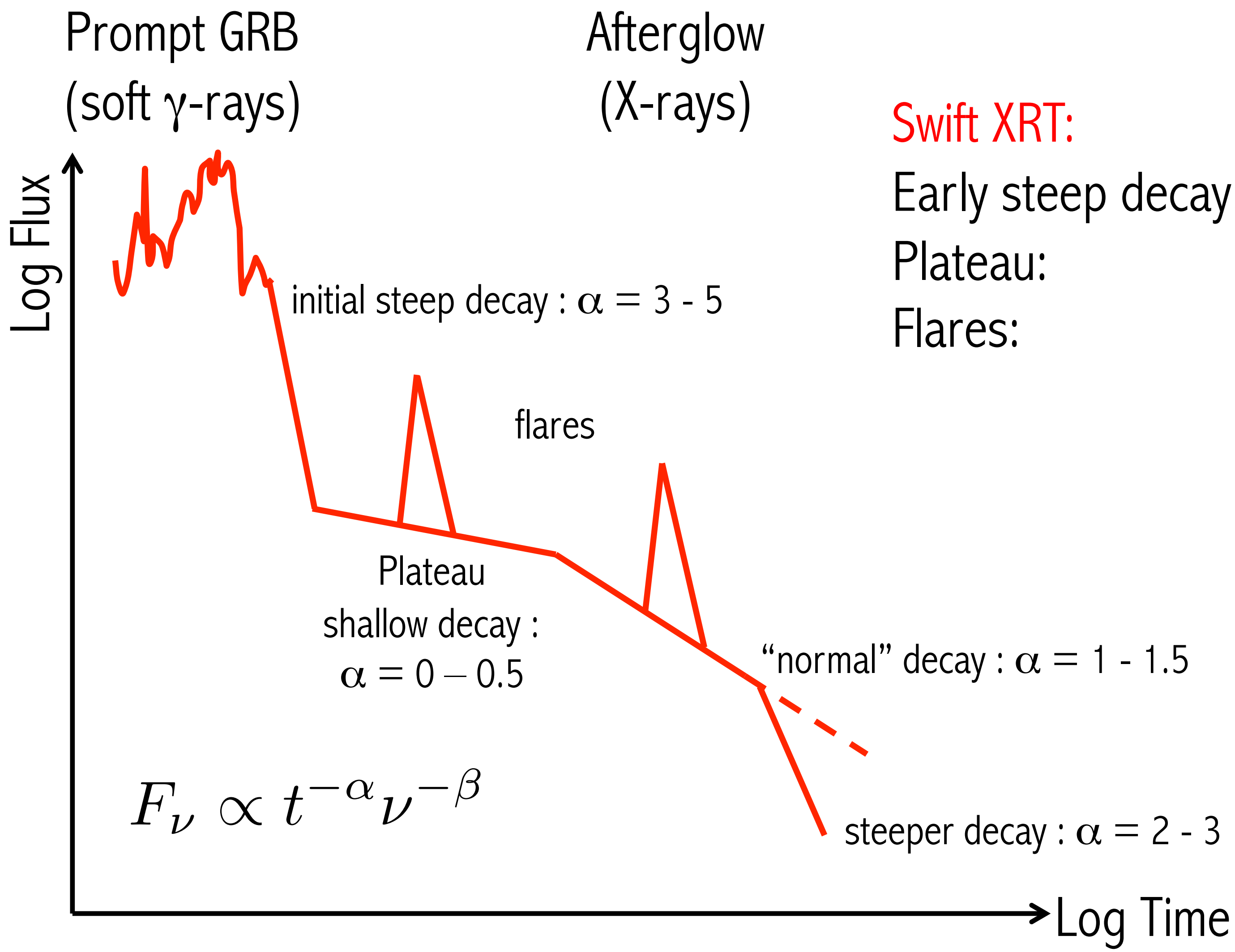


Prompt emission keV ➞ GeV (Fermi)



X-ray afterglow (Swift)

Observed emission: prompt $\longrightarrow$ afterglow



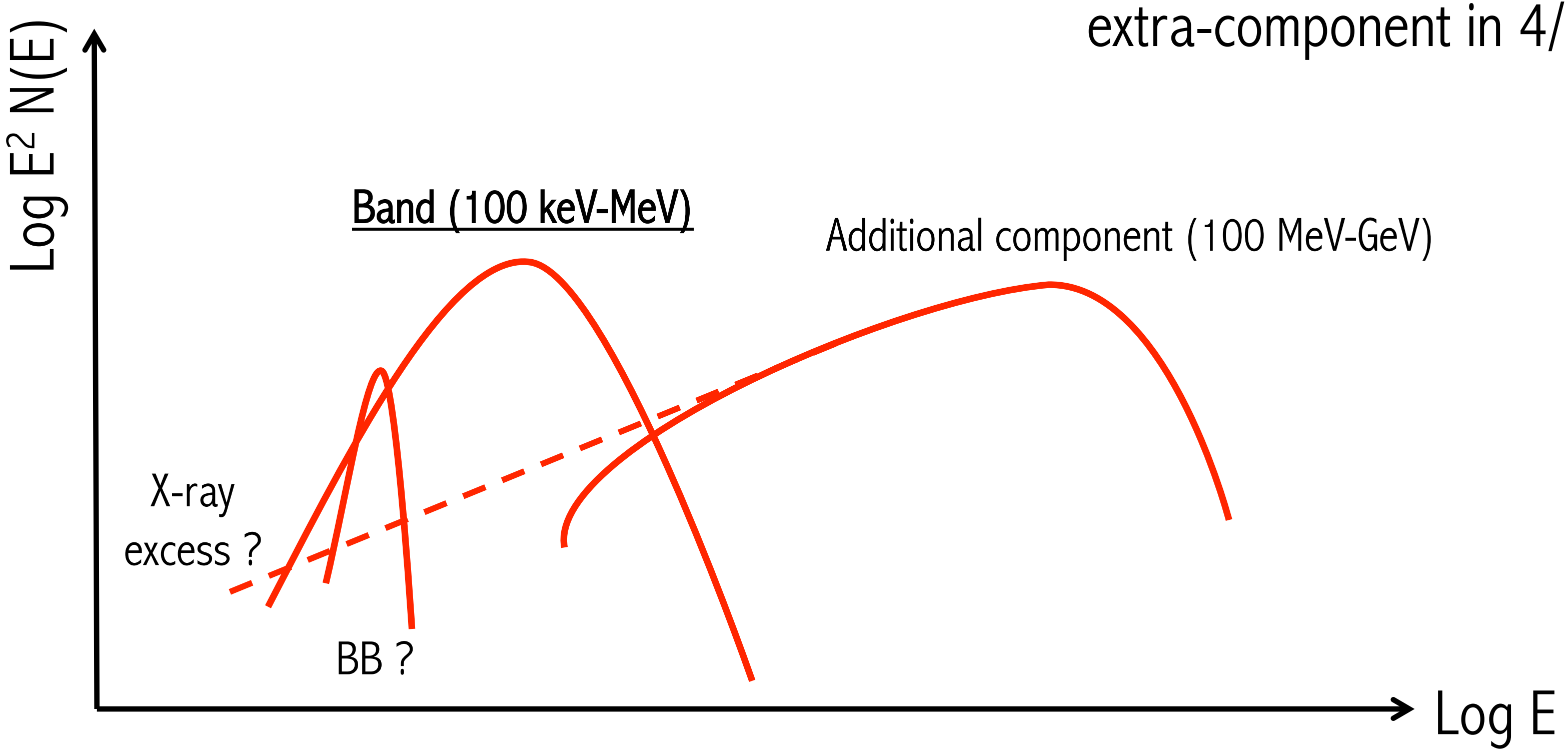
Swift XRT:

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

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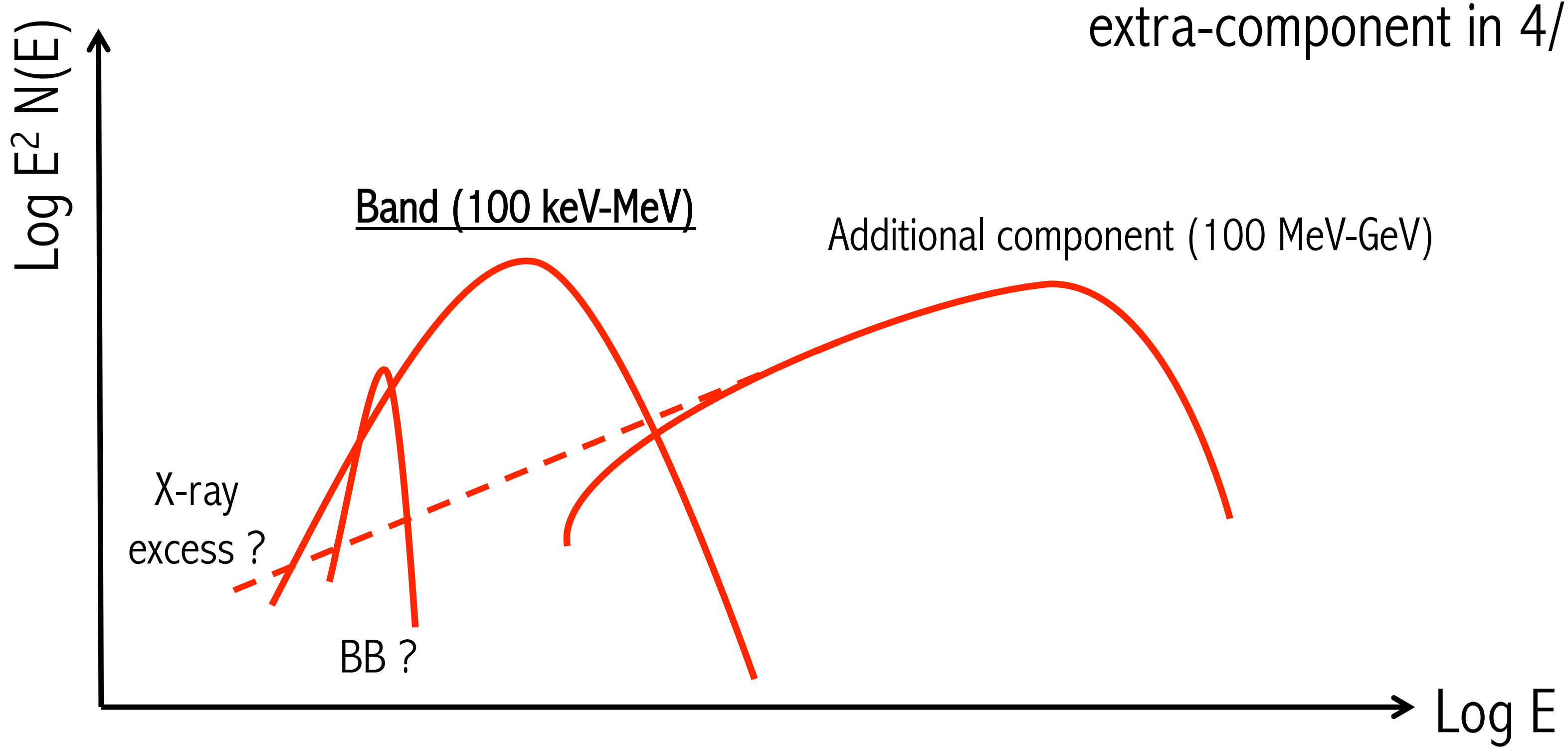
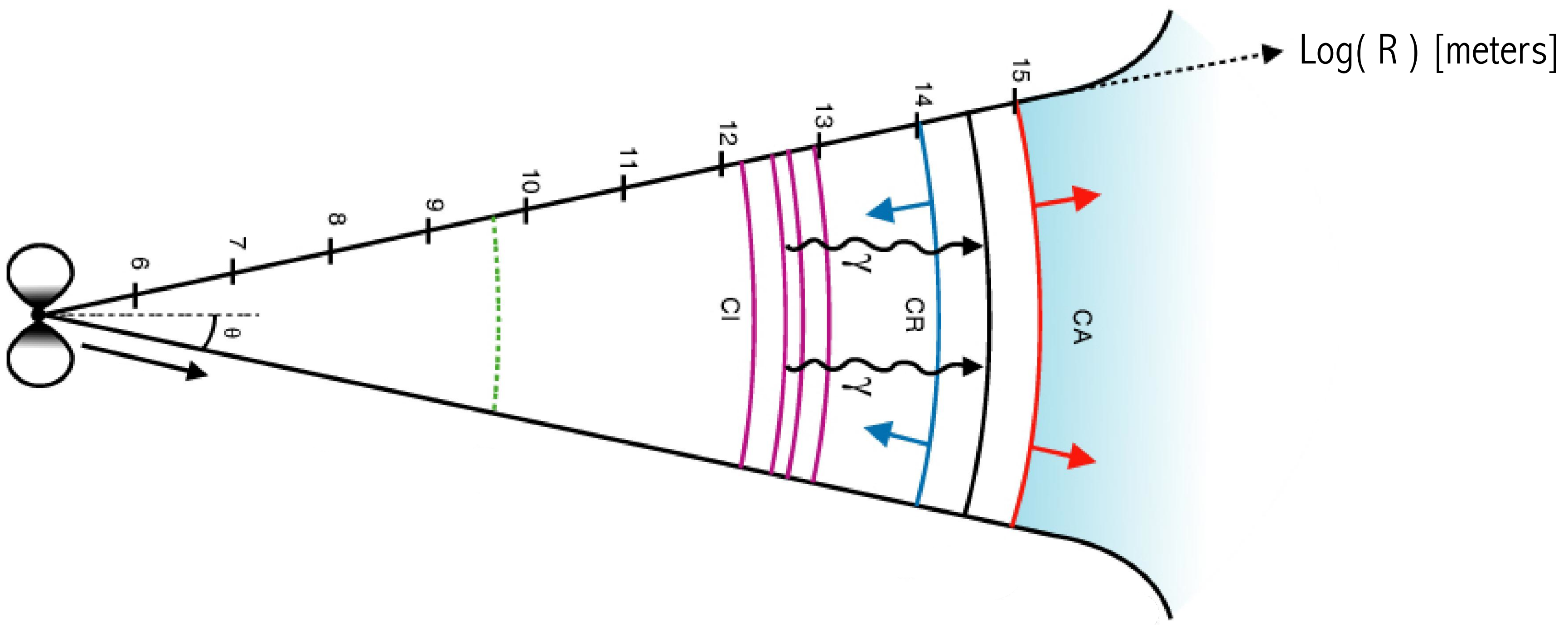


LIV tests: are these components produced at the same location/time?

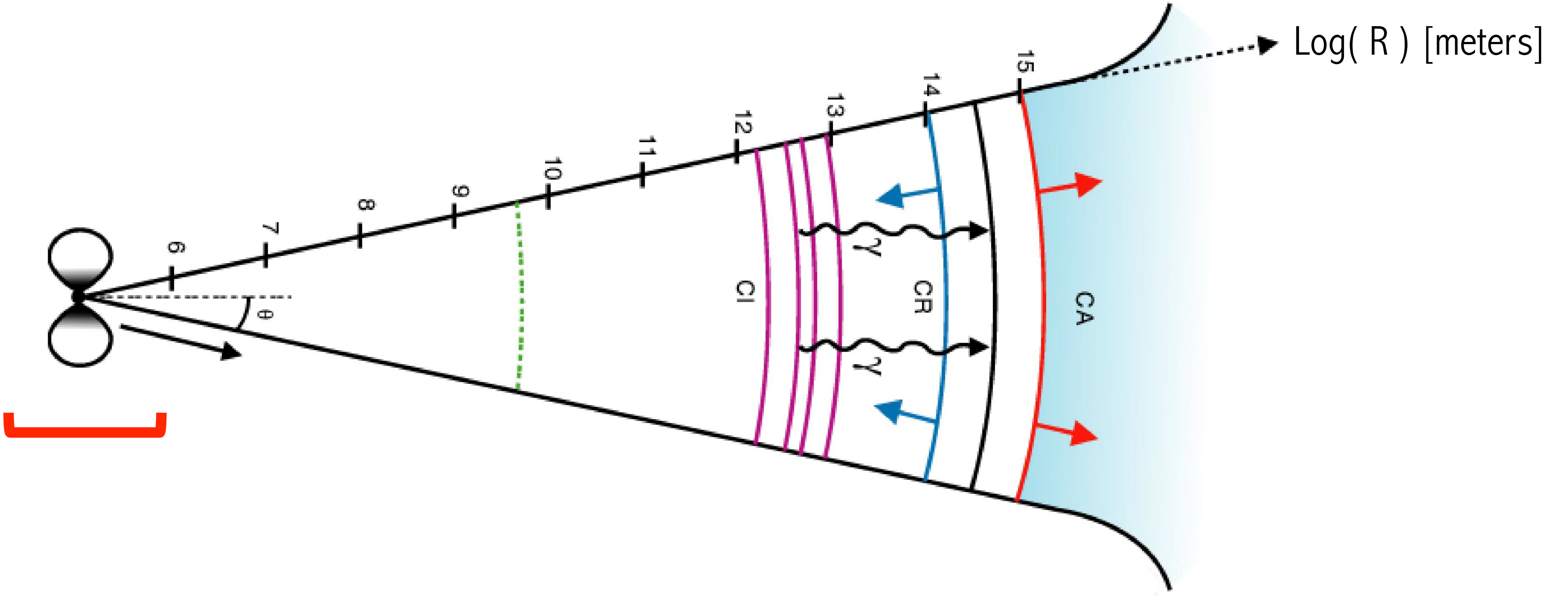
GRB physics



GRB physics

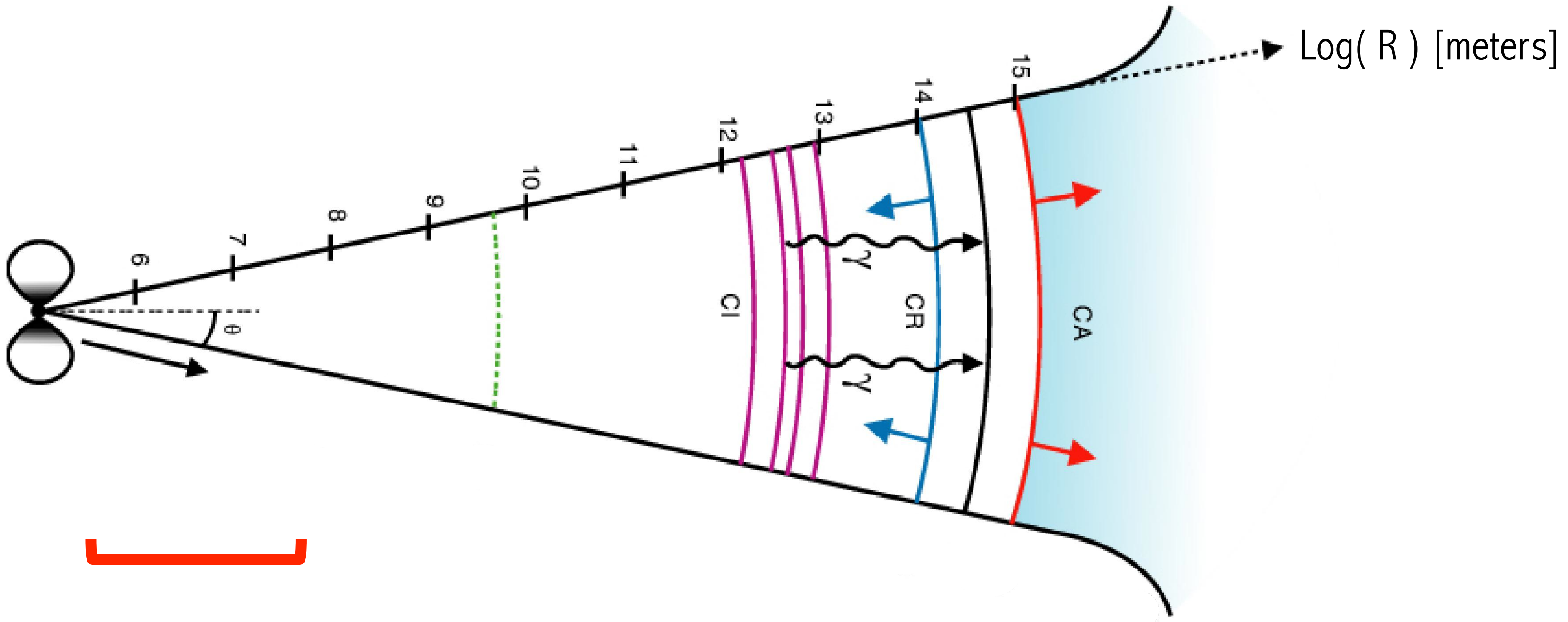
- Cosmological distance: huge radiated energy ($E_{iso,\gamma} \sim 10^{50}$-$10^{55}$ erg)
- Variability + energetics: violent formation of a stellar mass BH

Long GRBs: collapse of a massive star
Short GRBs: NS+NS(/BH ?)merger(?) [GRB170817/GW170817A]



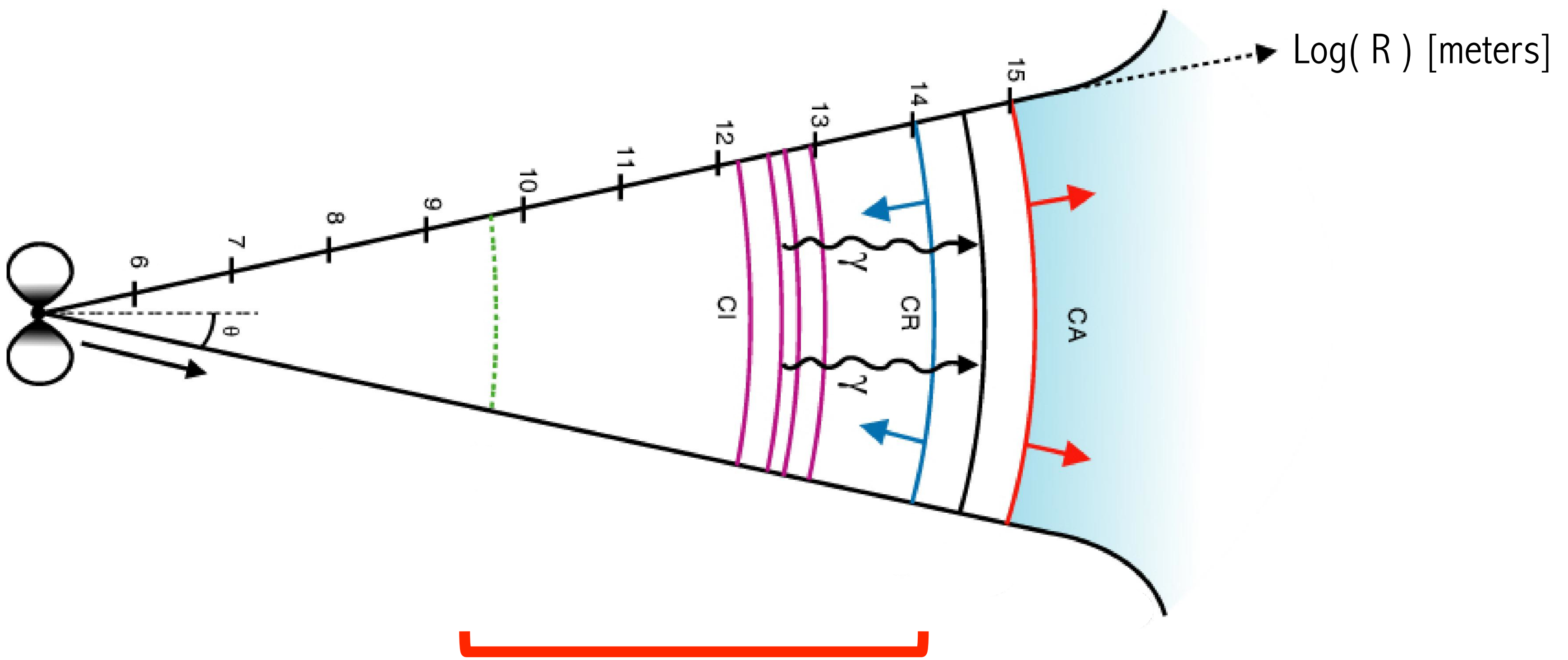
GRB physics

- Variability + energetics + gamma-ray spectrum: relativistic ejection



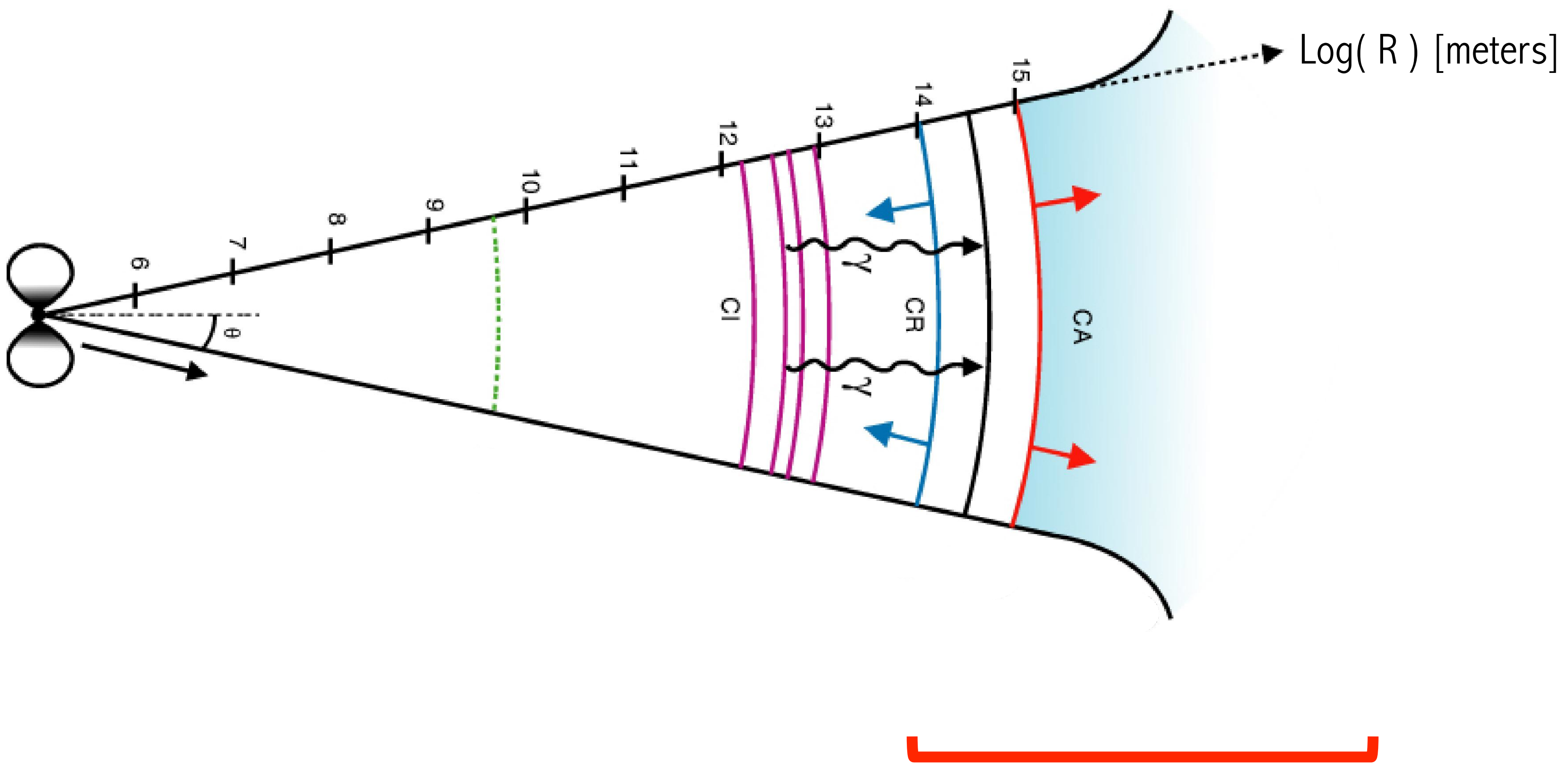
GRB physics

- Variability + energetics + gamma-ray spectrum: relativistic ejection
- Prompt keV-MeV emission: internal origin in the ejecta



GRB physics

- Variability + energetics + gamma-ray spectrum: relativistic ejection
- Prompt keV-MeV emission: internal origin in the ejecta
- Afterglow: deceleration by ambient medium



Relativistic outflows in GRBs

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

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

Other indirect methods: rise of the afterglow, etc.

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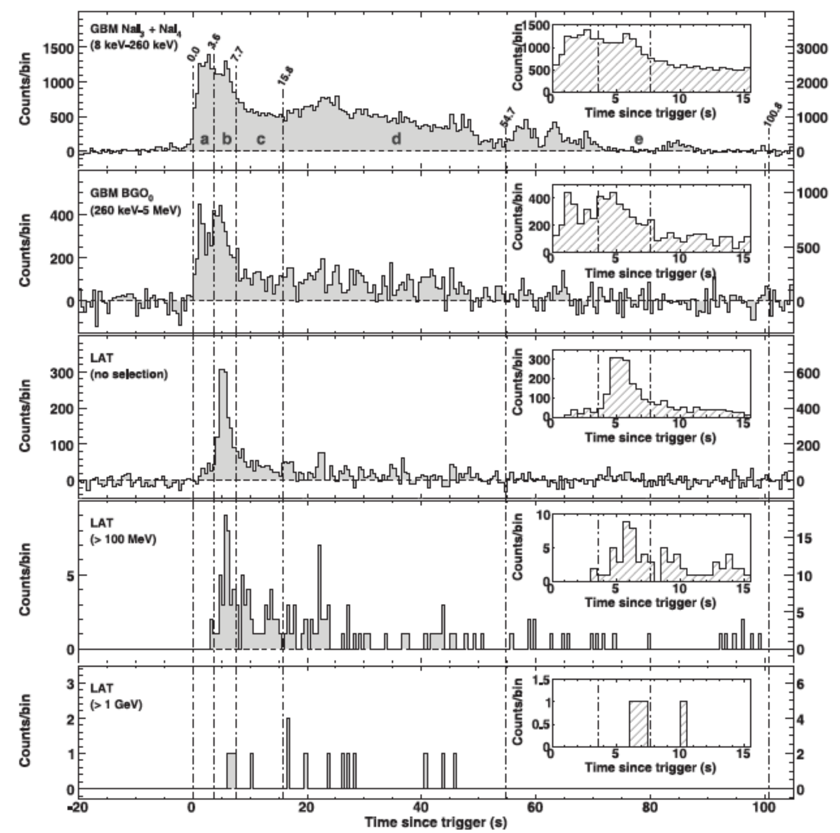
How relativistic are GRB outflows?

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

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)

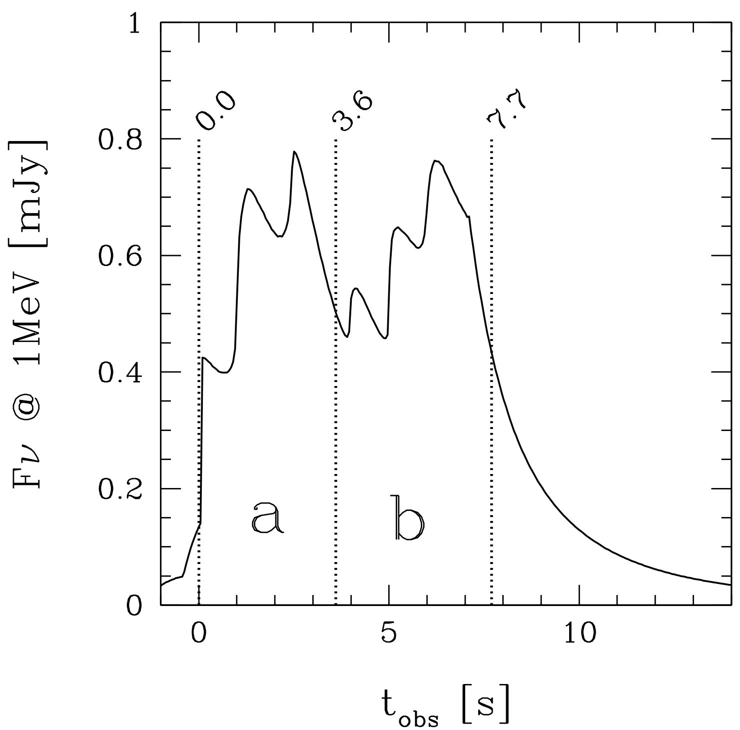


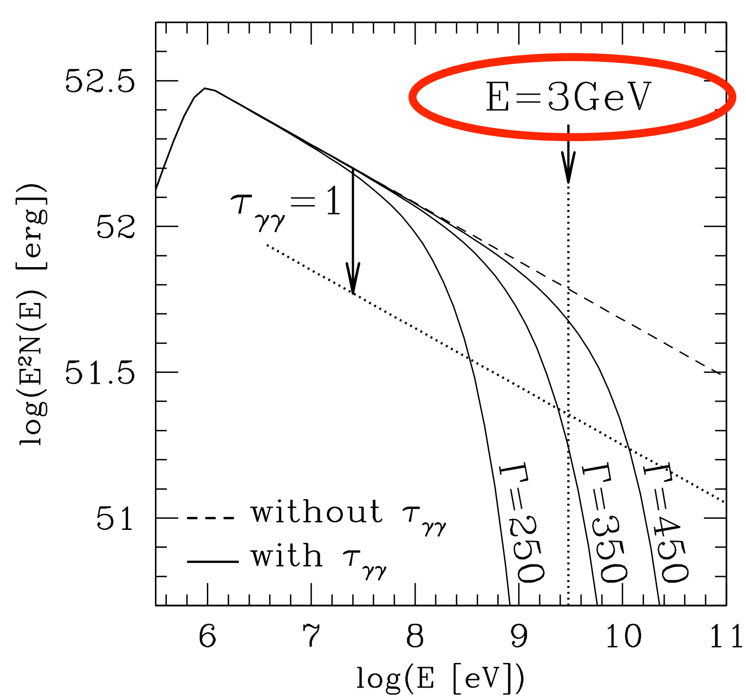
How relativistic are GRB outflows?

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

the estimate of $\Gamma_{\min}$ is reduced by a factor ~ 2-3

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





GRB 080916C : $\Gamma_{\min} \sim 360$

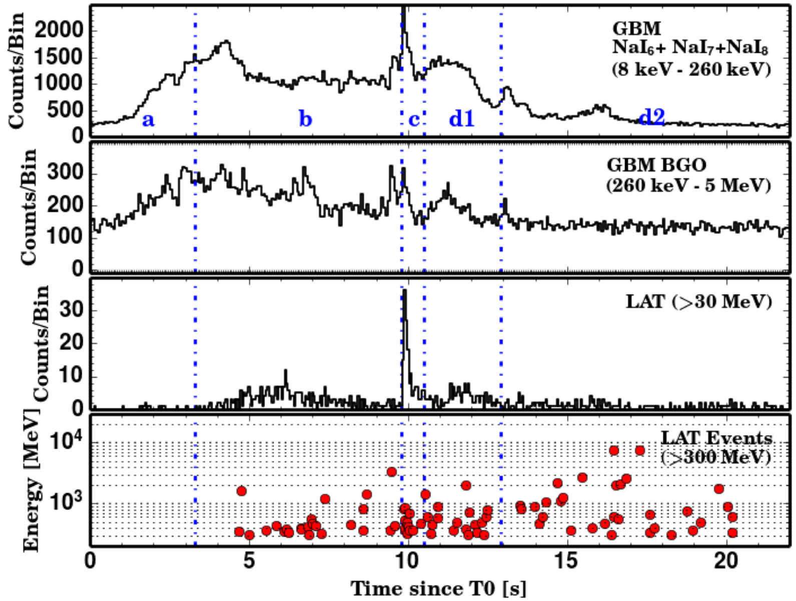
instead of ~900

(Hascoët, Daigne, Mochkovitch & Vennin, 2012)

(Abdo et al. 2009)

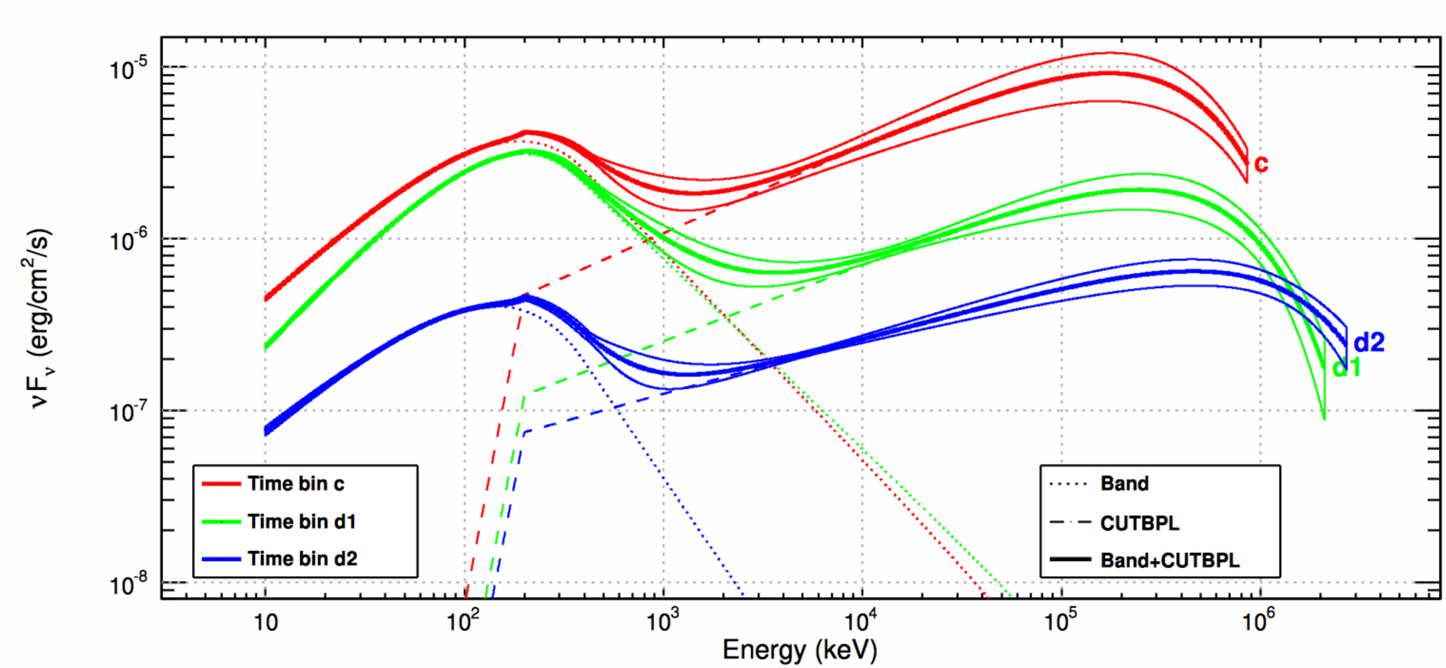
First observation of the γγ cutoff ?

- GRB 090926A (Fermi-LAT):
  first observed cutoff at high-energy
  (Ackermann et al. 2011)



- New analysis and interpretation:

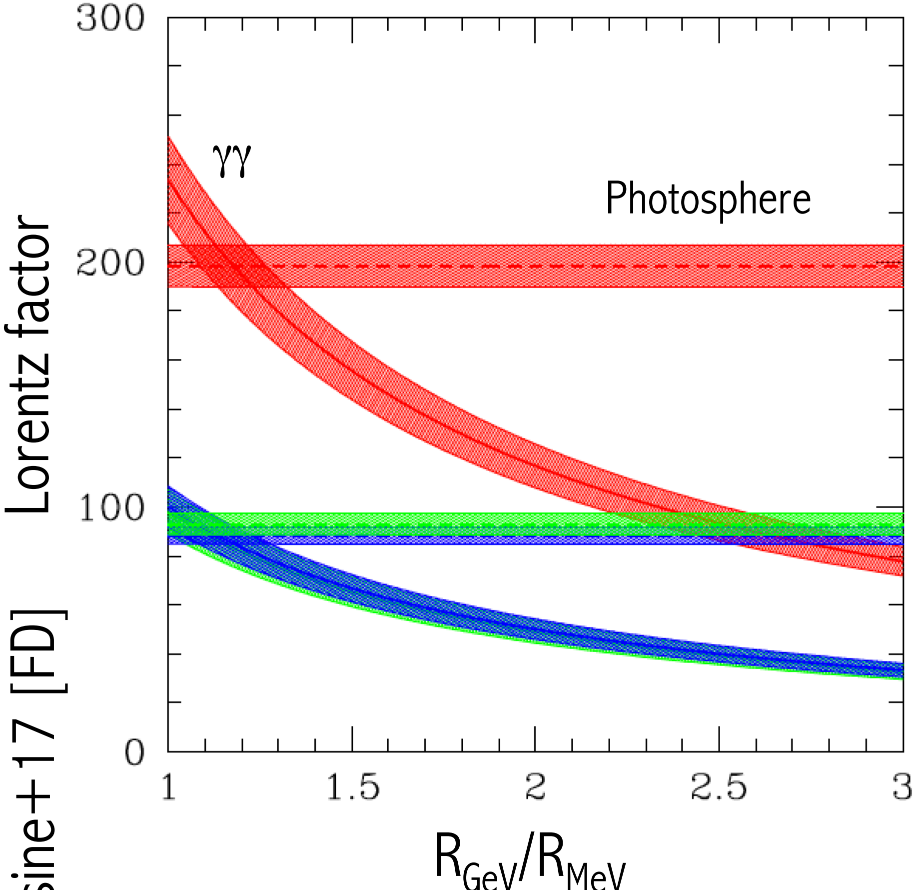
  - Path 8: 447 ⟶ 1088 evts in LAT (× 2.4)
  - cutoff is *better* detected, in *several* time bins

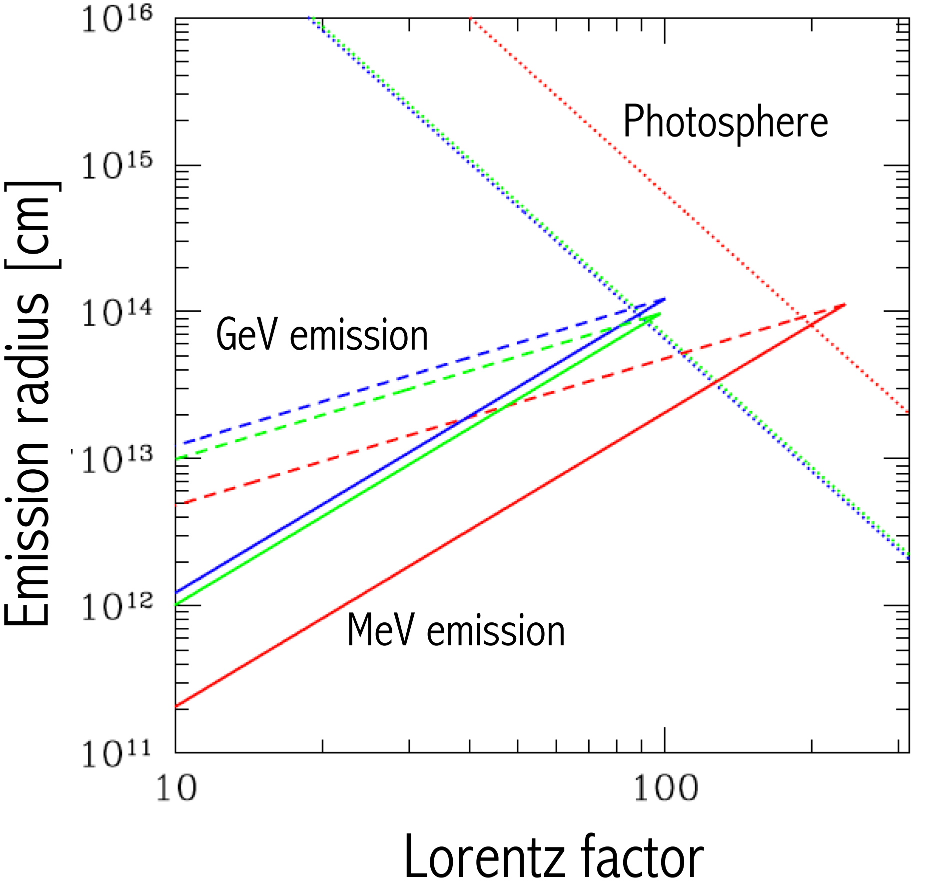


Yassine+17 [FD]

First observation of the $\gamma\gamma$ cutoff ?

- GRB 090926A (Fermi-LAT): first observed cutoff at high-energy (Ackermann et al. 2011)
- New analysis and interpretation: cutoff detected in several bins, **strong constraint on Lorentz factor and emission radius**!





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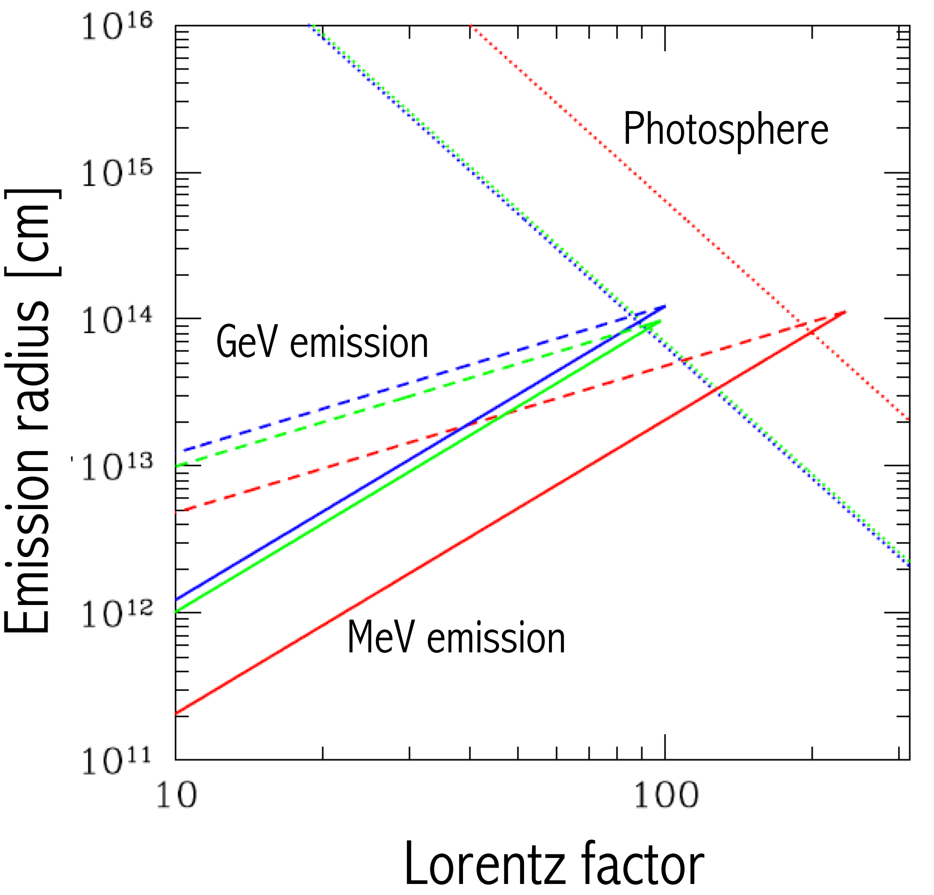
Lorentz factor ~ 230 to 100

Emission radius ~ 10^{14} cm

Photospheric radius ~5 10^{13} cm

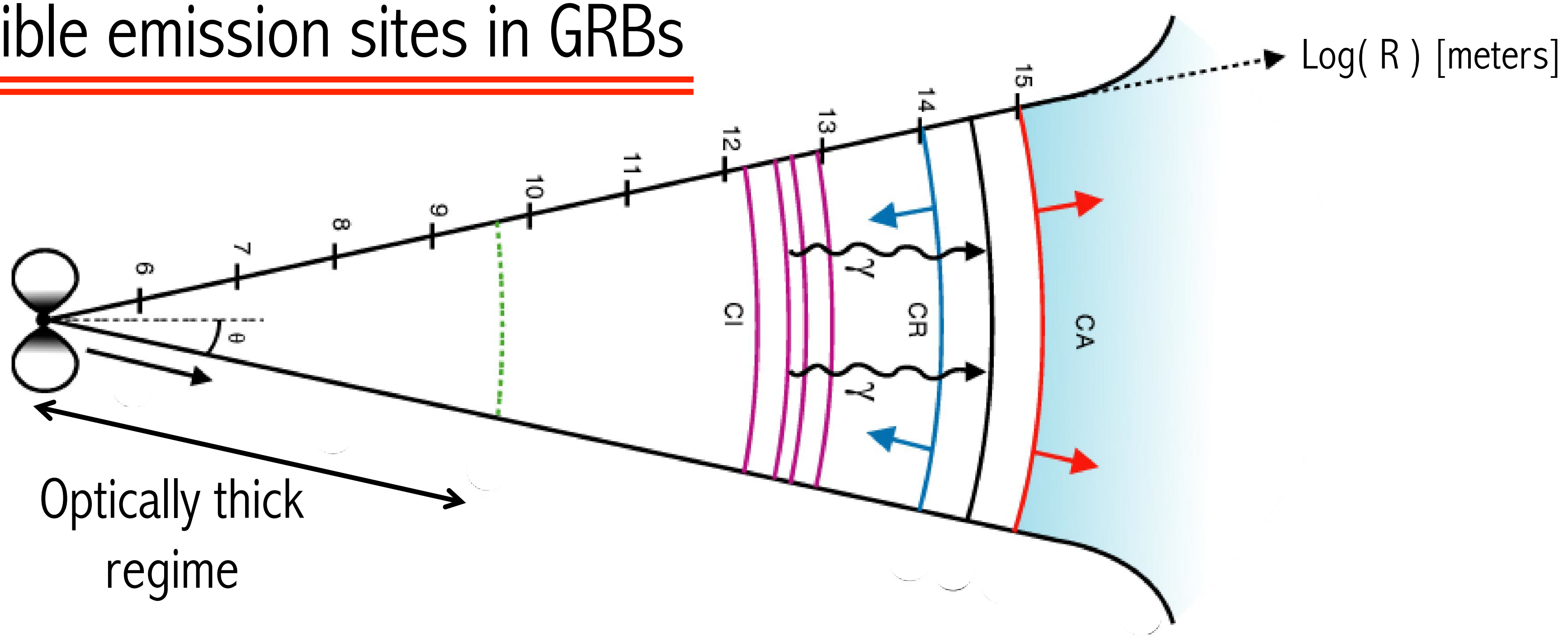
Compatible with « standard scenario » (internal shocks above the photosphere)



Yassine, Piron, Daigne & Mochkovitch, to be submitted

Prompt GRB emission: possible emission sites

Possible emission sites in GRBs



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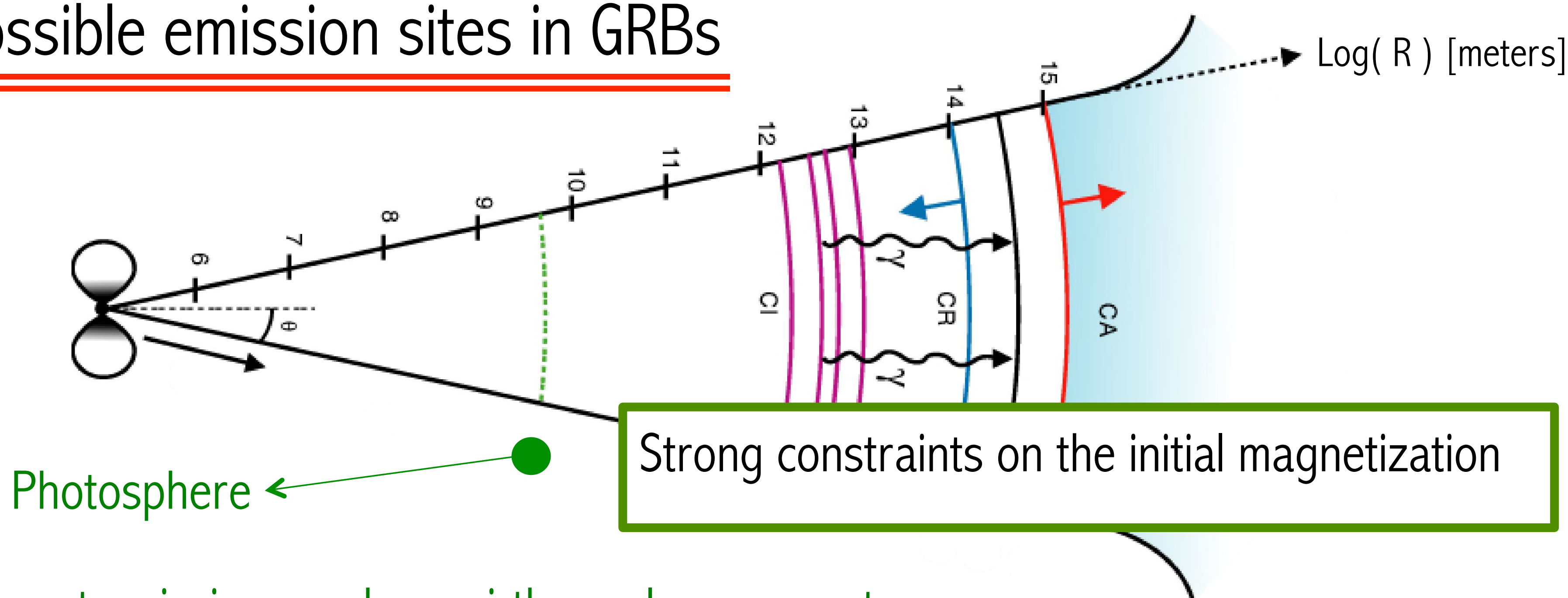
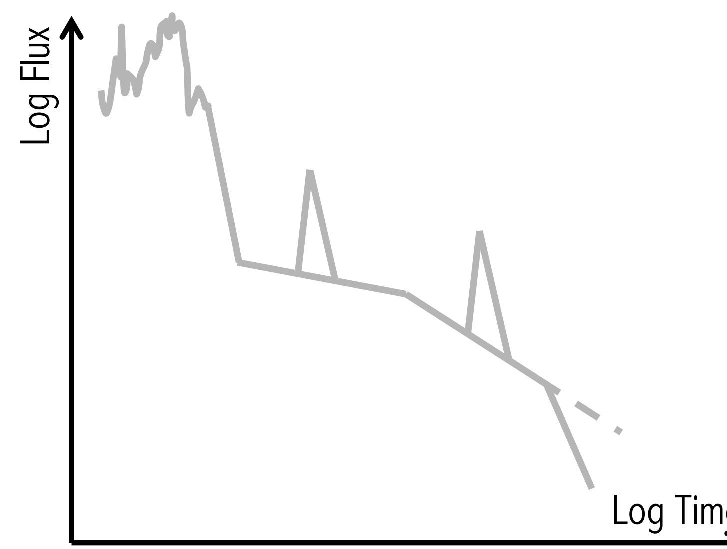


Strong constraints on the initial magnetization

Prompt emission: weak quasi-thermal component

→ main spectral component produced at larger radius (shocks or reconnection)

Goodman 1986; Paczynski 1986;
Daigne & Mochkovitch 2002;
see also Beloborodov 2011; Lundman et al. 2013;
Deng & Zhang 2014



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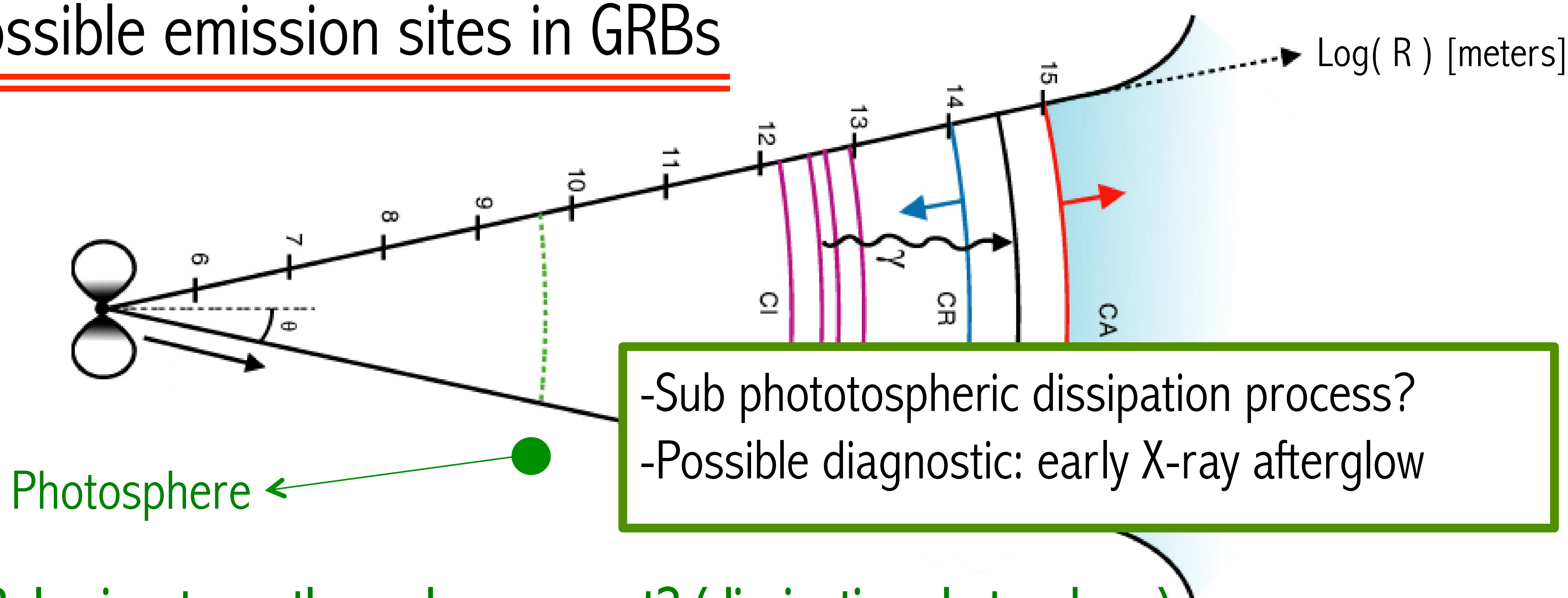


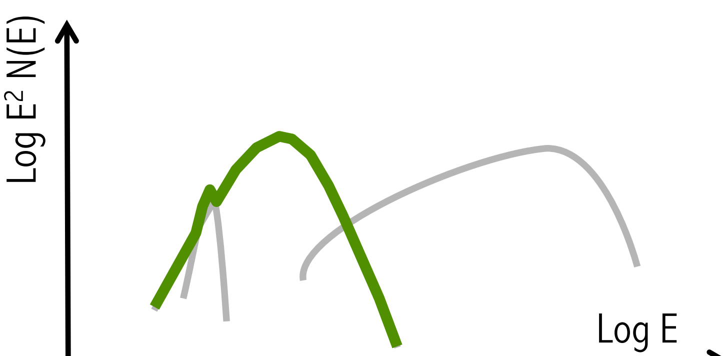
-Sub phototospheric dissipation process?

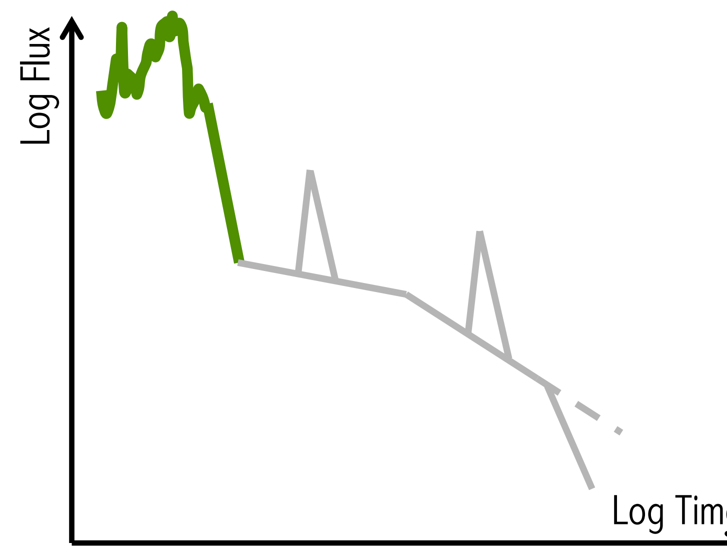
-Possible diagnostic: early X-ray afterglow

OR dominant non-thermal component? (dissipative photosphere)

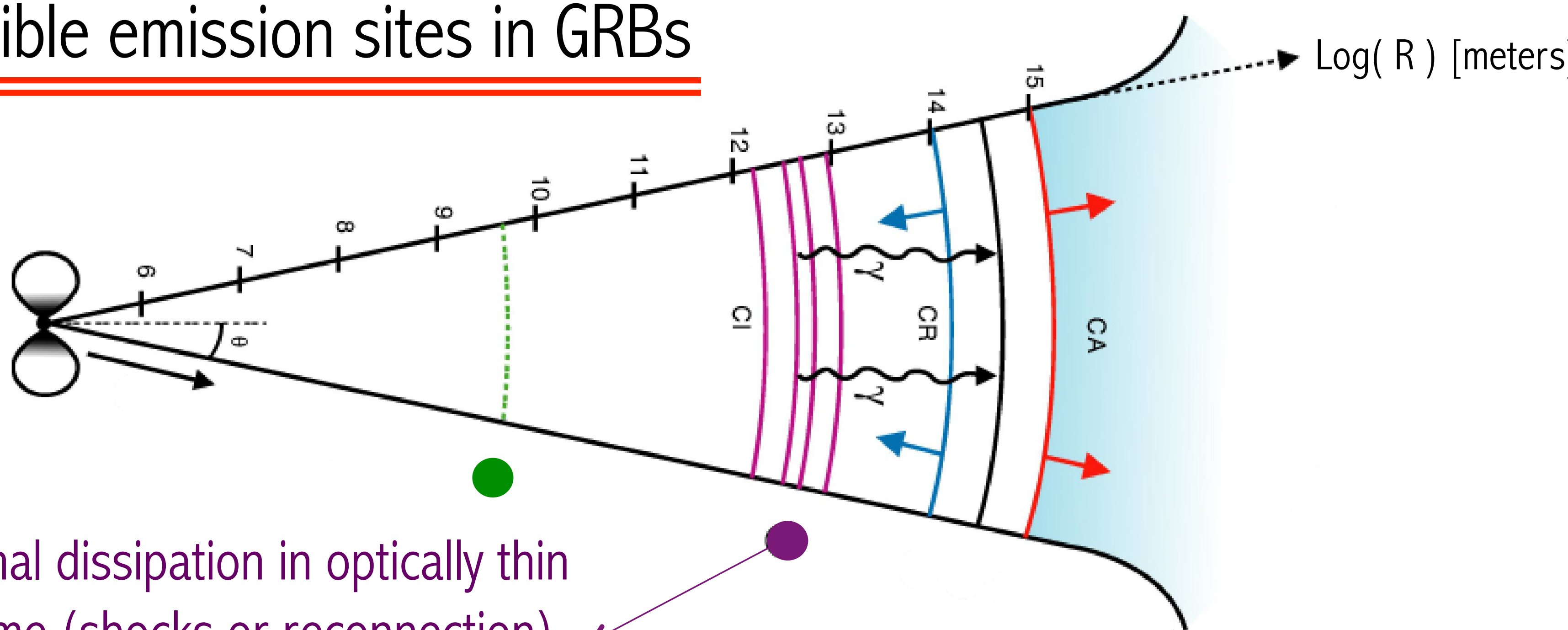
Additional component: larger radius

Rees & Meszaros 2005; Pe'er et al. 2006; Beloborodov 2010; Vurm et al. 2011





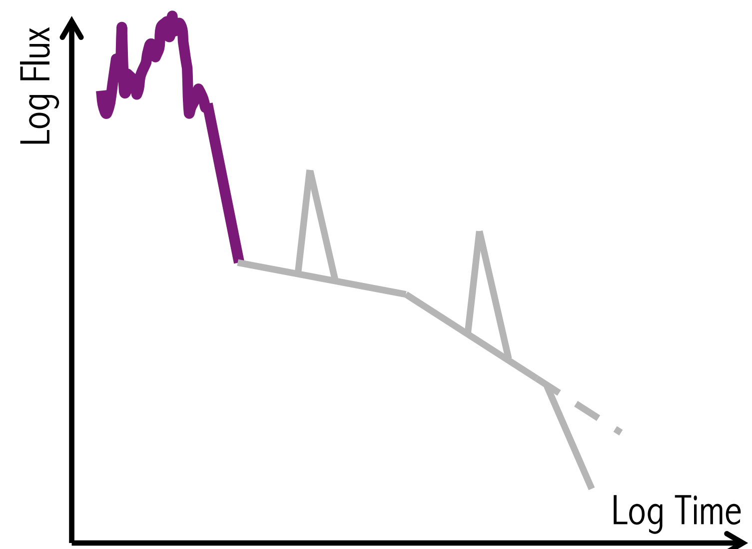
Possible emission sites in GRBs



Internal dissipation in optically thin regime (shocks or reconnection)

Prompt emission: dominant non-thermal component?

Rees & Meszaros 1994;
Kobayashi et al. 1997; Daigne & Mochkovitch 1998
Lyutikov & Blandford 2003 ; Zhang & Yan 2011



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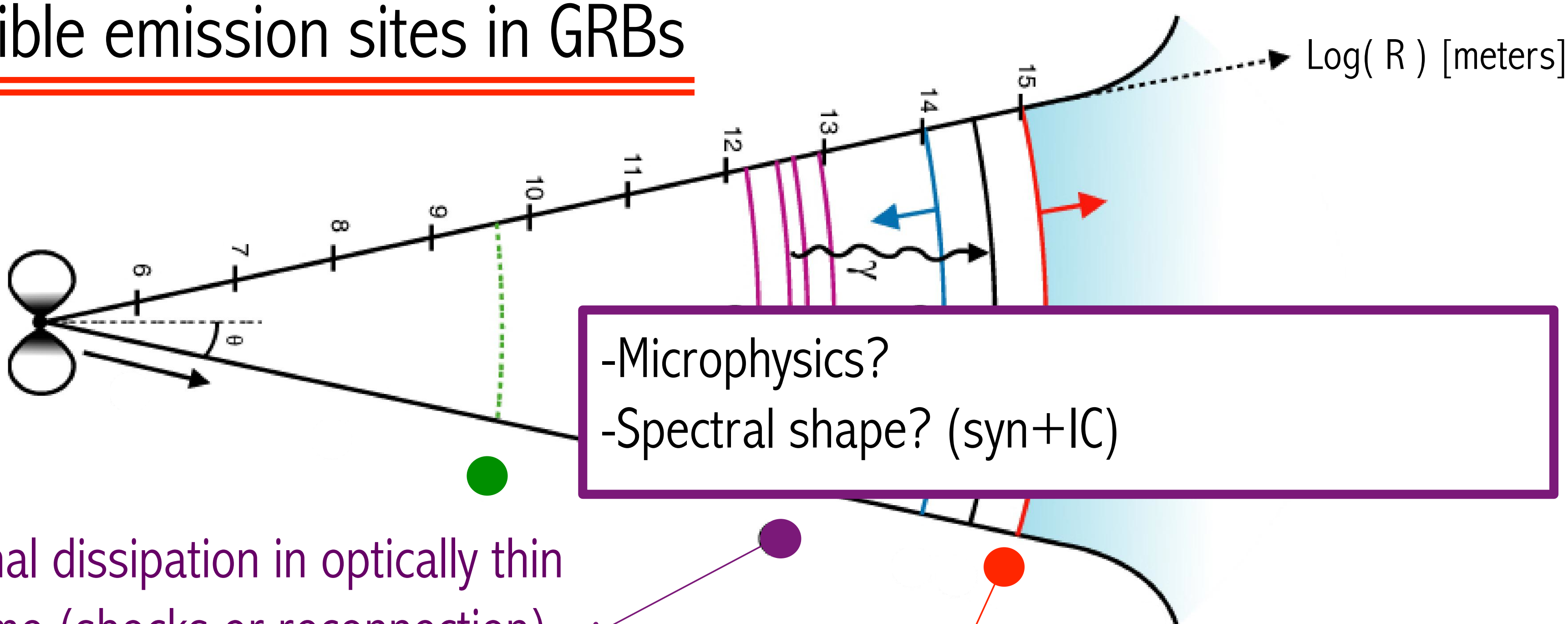
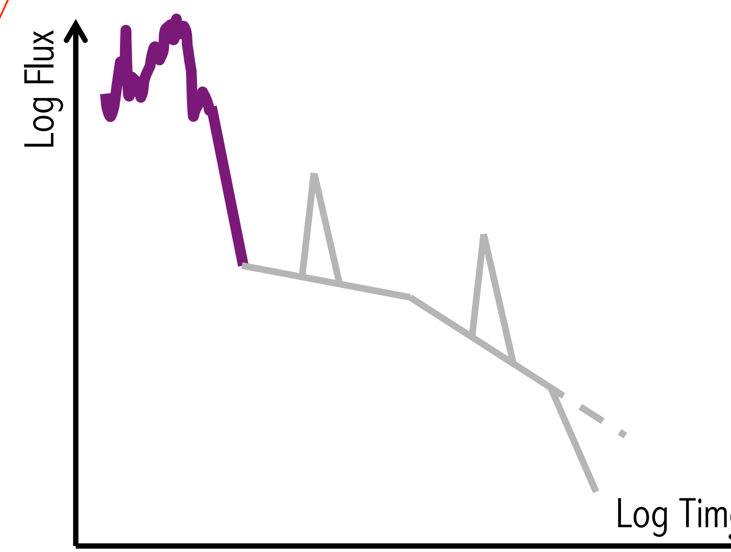


-Microphysics?
-Spectral shape? (syn+IC)

Internal dissipation in optically thin regime (shocks or reconnection)

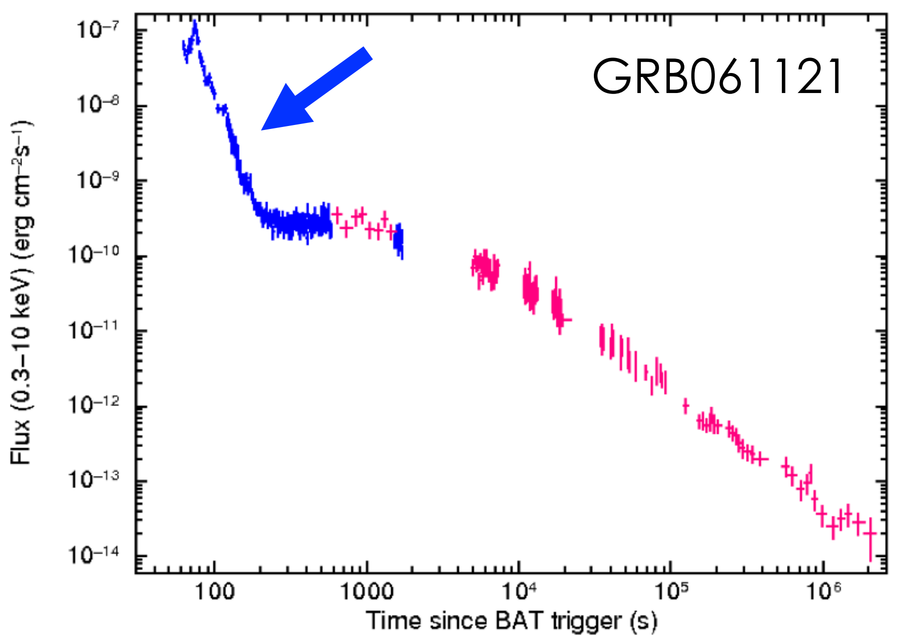
Prompt emission: dominant non-thermal component?
+additional component?

(or external origin?)
BUT -very early dec?
-variability?



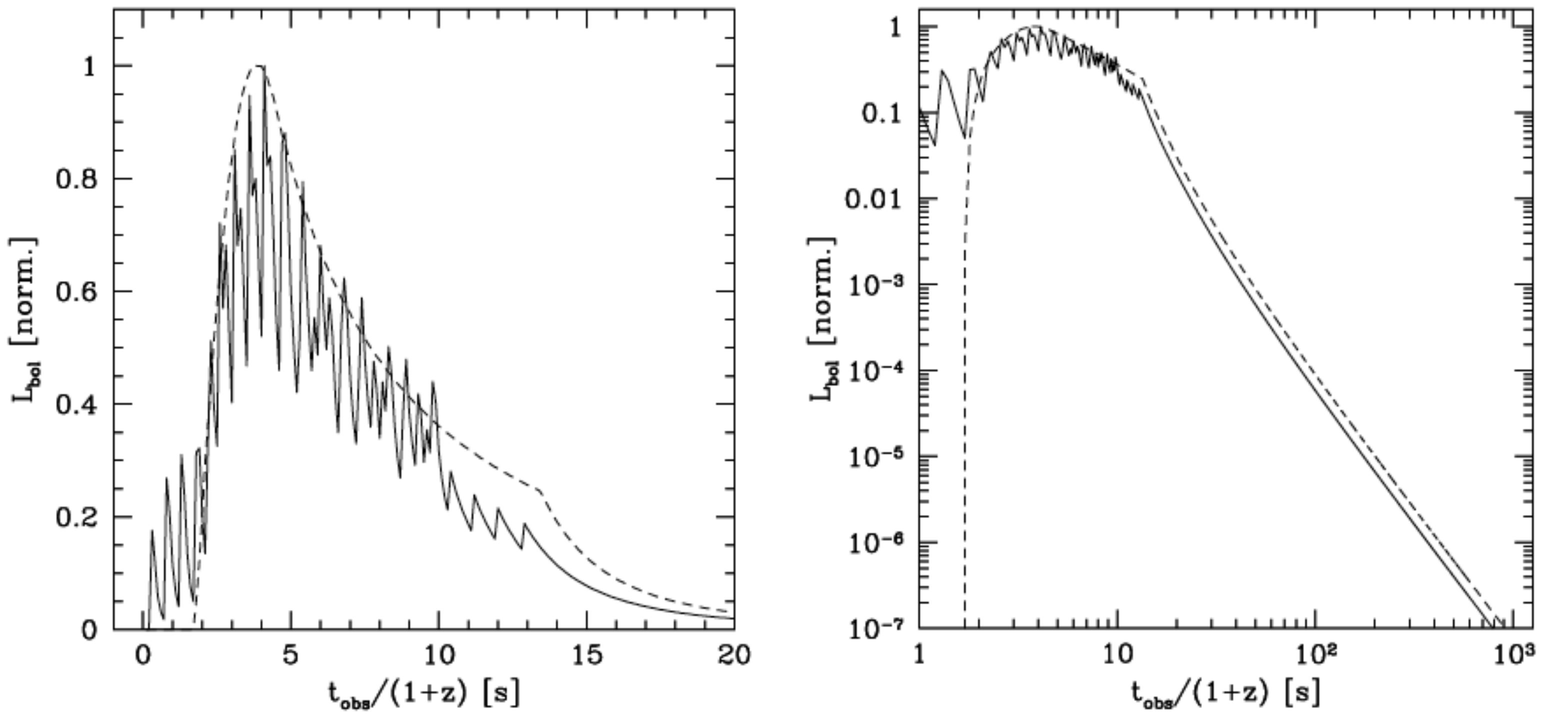
An argument against dissipative photospheric models: Early steep decay in the X-ray afterglow

Swift BAT+XRT



(Page et al. 2007)

High latitude emission at the end of the prompt phase



Final radius of the order of Γ^2 c t_{burst}

High-latitude emission interpretation of the early steep decay:
-Compatible with internal shocks or reconnection.
-Incompatible with photospheric models (decay: intrinsic source evolution).

Hascoët, Daigne & Mochkovitch (2012)

Prompt gamma-ray emission from internal shocks?

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

-Lighcurves: OK for all scenarios

-Spectrum

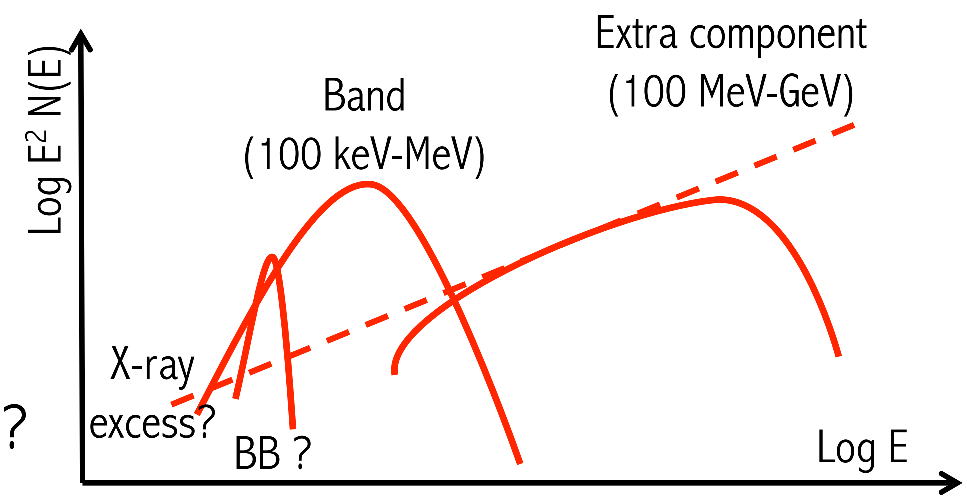
-Spectral evolution

Spectrum

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

-depends on a complex microphysics

-observational constraints not always clear?



Low-energy photon index in fast cooling synchrotron spectrum?

-3/2 : pure fast cooling synchrotron

~ -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)

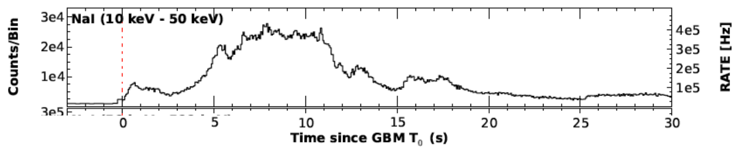
-1 → -0.5 : fast cooling synchrotron + IC in decaying magnetic field

(Derishev 07 ; Lemoine 13 ; Uhm & Zhang 14 ; Zhao et al. 14, Daigne & Bosnjak in preparation)

X-ray excess?

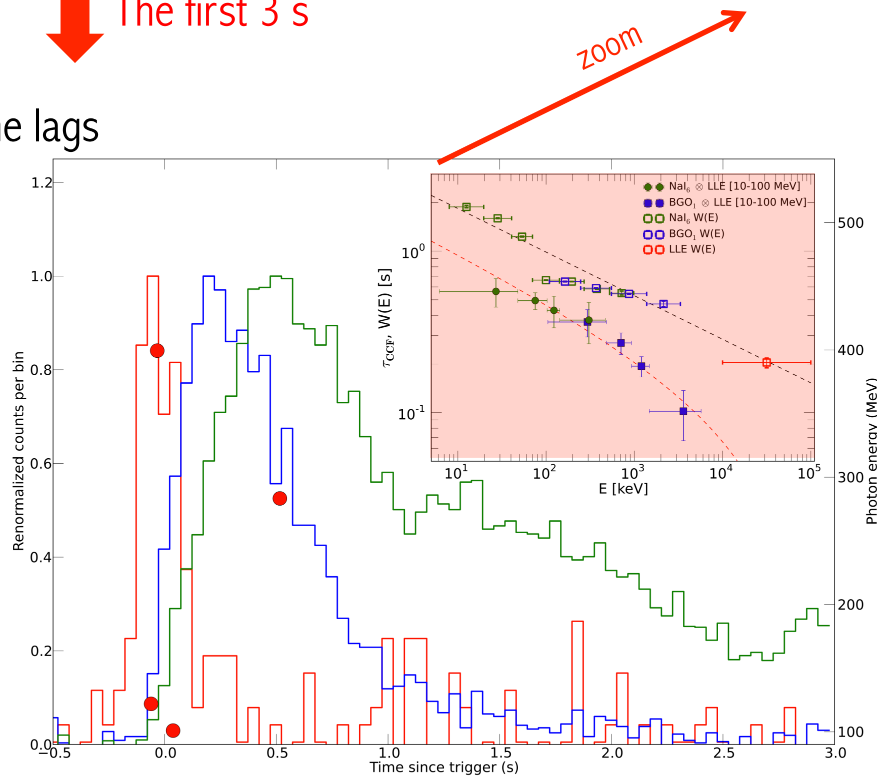
Spectral evolution

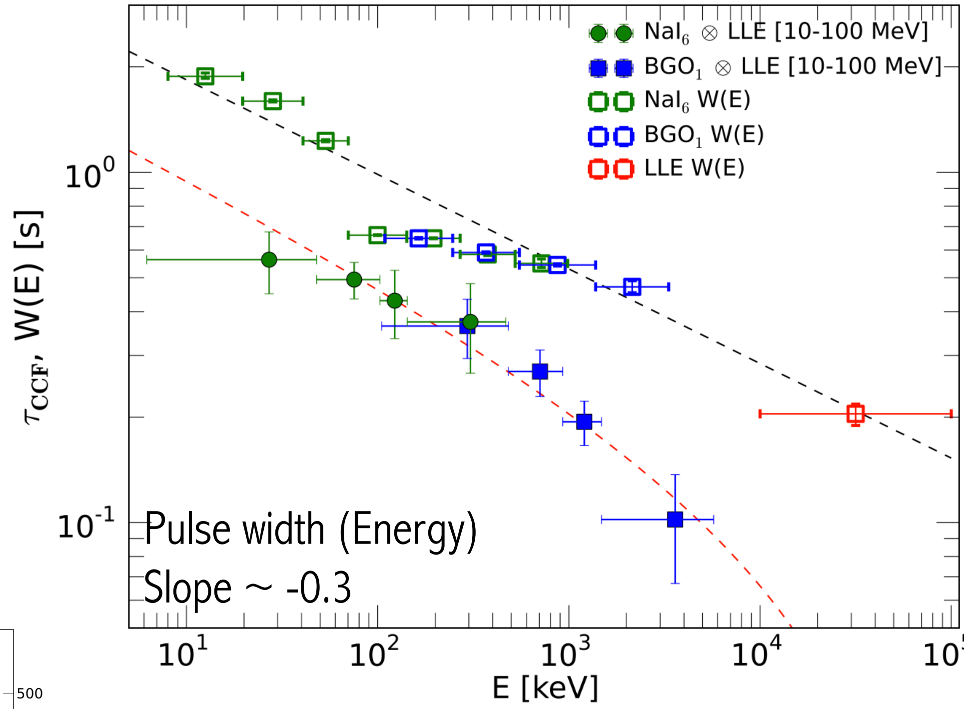
GRB 130427A

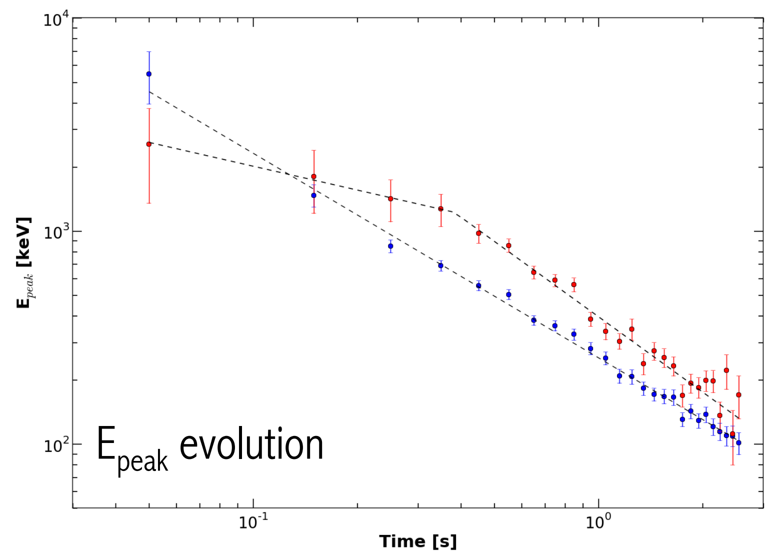


The first 3 s

Time lags





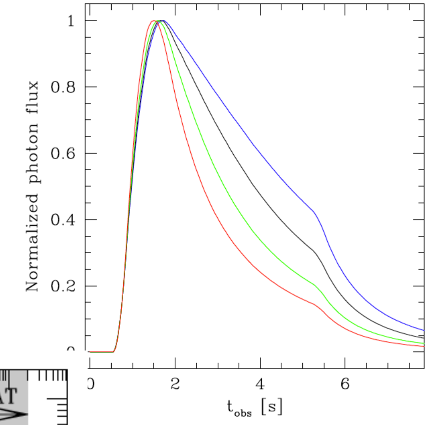


Preece et al. 2014

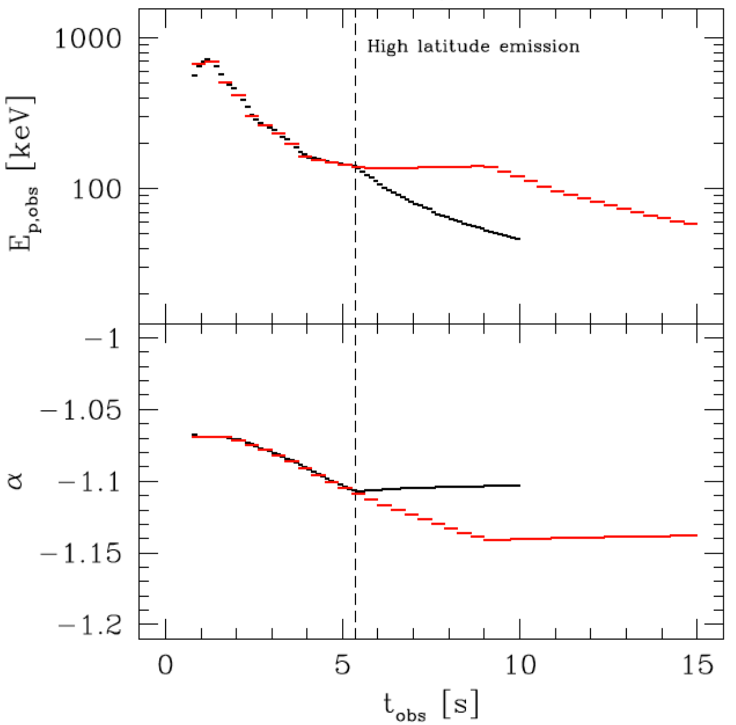
Not shown: hardness-intensity correlation slope 1.4

Spectral evolution

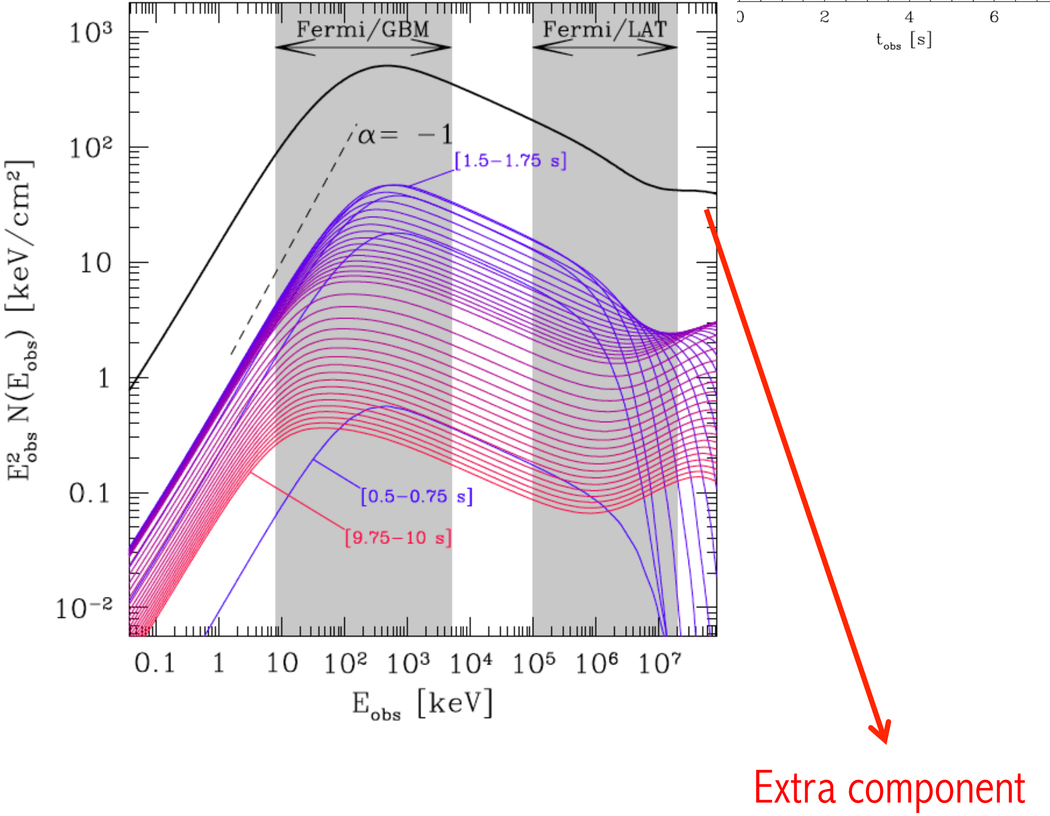
Example of a simulated GRB pulse produced by internal shocks (full simulation: dynamics+radiation)



Evolution of E_{peak} and α



Time-evolving spectrum



Bosnjak & Daigne 2014

Spectral evolution

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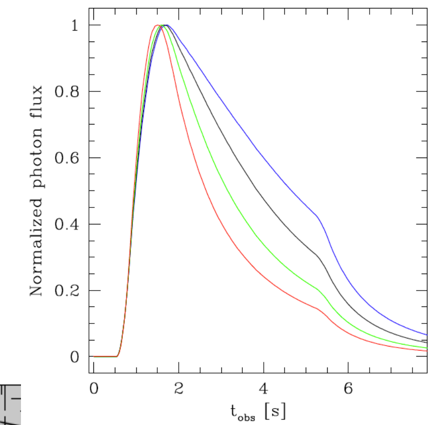
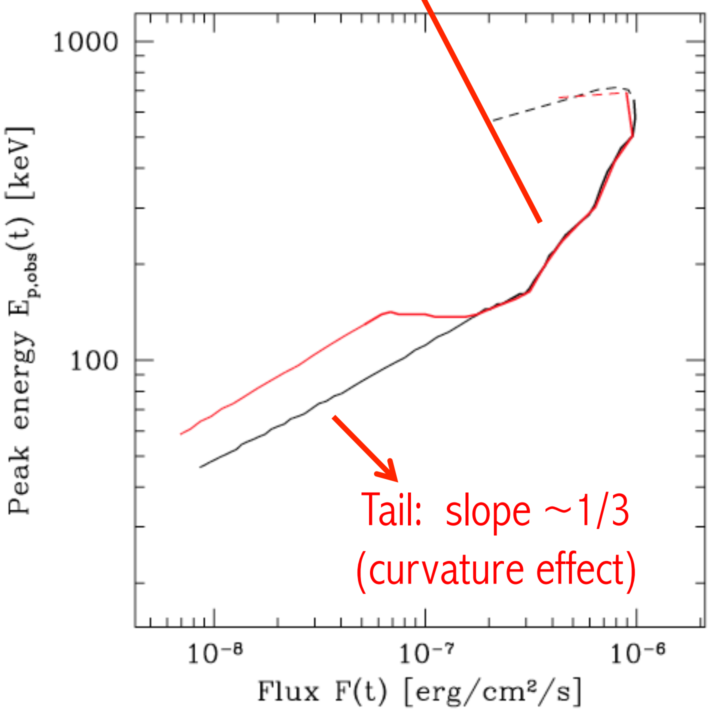
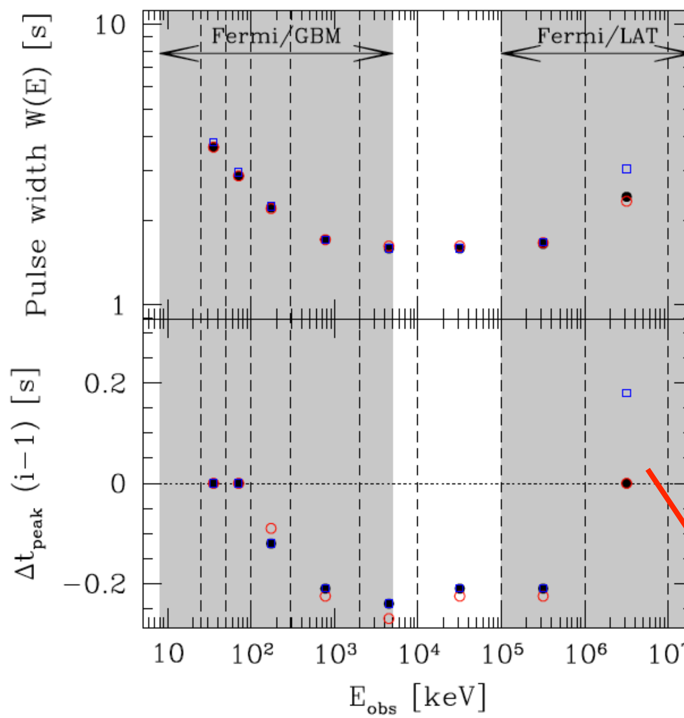


Slope ~1-1.5 fixed by shock propagation



Tail: slope ~1/3
(curvature effect)

Hardness-Intensity Correlation



Pulse width and time lags

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

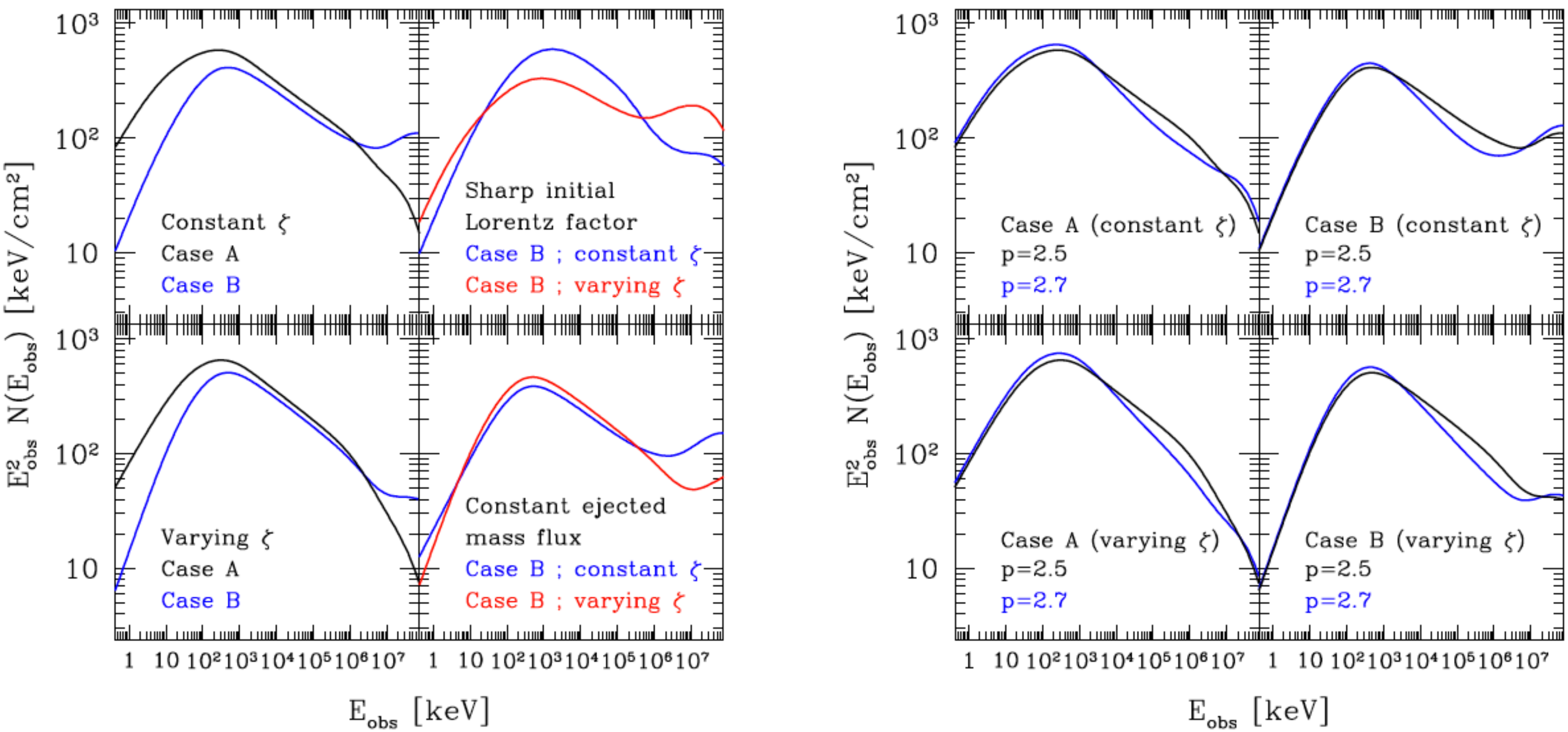
$$a \simeq 0.2 - 0.3$$

Delayed onset ? γγ ?

Bosnjak & Daigne 2014

(Hascoet [Daigne] et al. 2012)

Prompt GeV emission from internal shocks



Bosnjak & Daigne 2014 ; see also Asano & Meszaros.

Summary

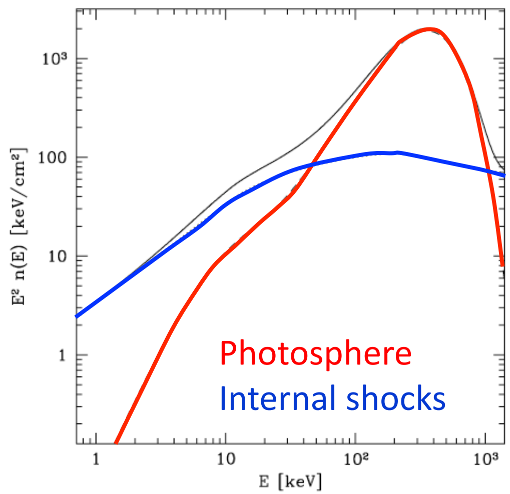
- Prompt keV-MeV emission:
  - agreement on the general theoretical scenario (relativistic ejecta, internal origin)
  - clear evidence for relativistic motion
  - BUT: debate on the internal dissipation mechanism/radiation process (dissipative photosphere, internal shocks, reconnection)
- Prompt emission > 100 MeV:
  - internal or external origin?
  - arguments for an internal component:
    - short timescale variability
    - transition at $t_{end,GBM}$?
  - internal origin:
    - IC at same location/time than the keV-MeV emission? Not in the dissipative photosphere scenario.
    - expected intrinsic delays/spectral evolution

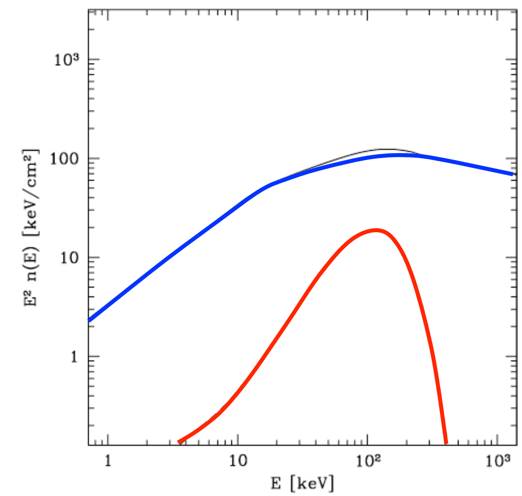
Weak quasi-thermal photospheric emission: constraints on the magnetization

Weak quasi-thermal components in GRB spectra?

Daigne & Mohckovitch 2002

Low initial magnetization

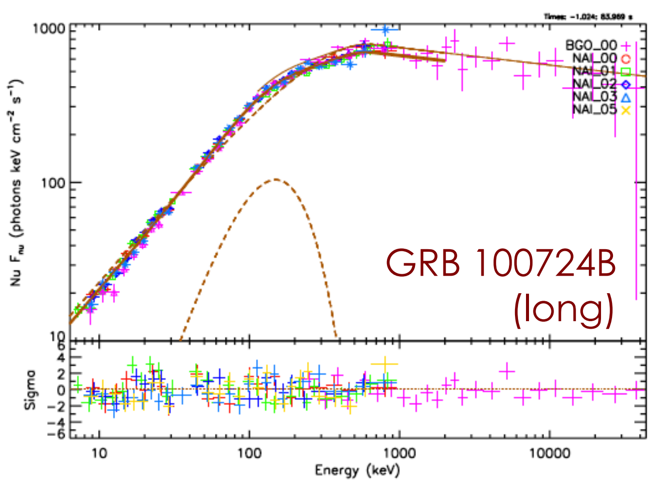


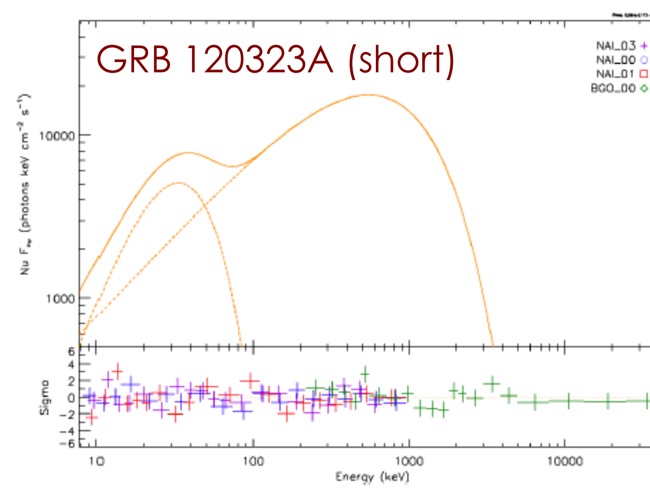


High initial magnetization

Expected case

Guiriec [FD] et al. 2011





Guiriec [FD] et al. 2013

Warning: spectral analysis based on forward folding technique

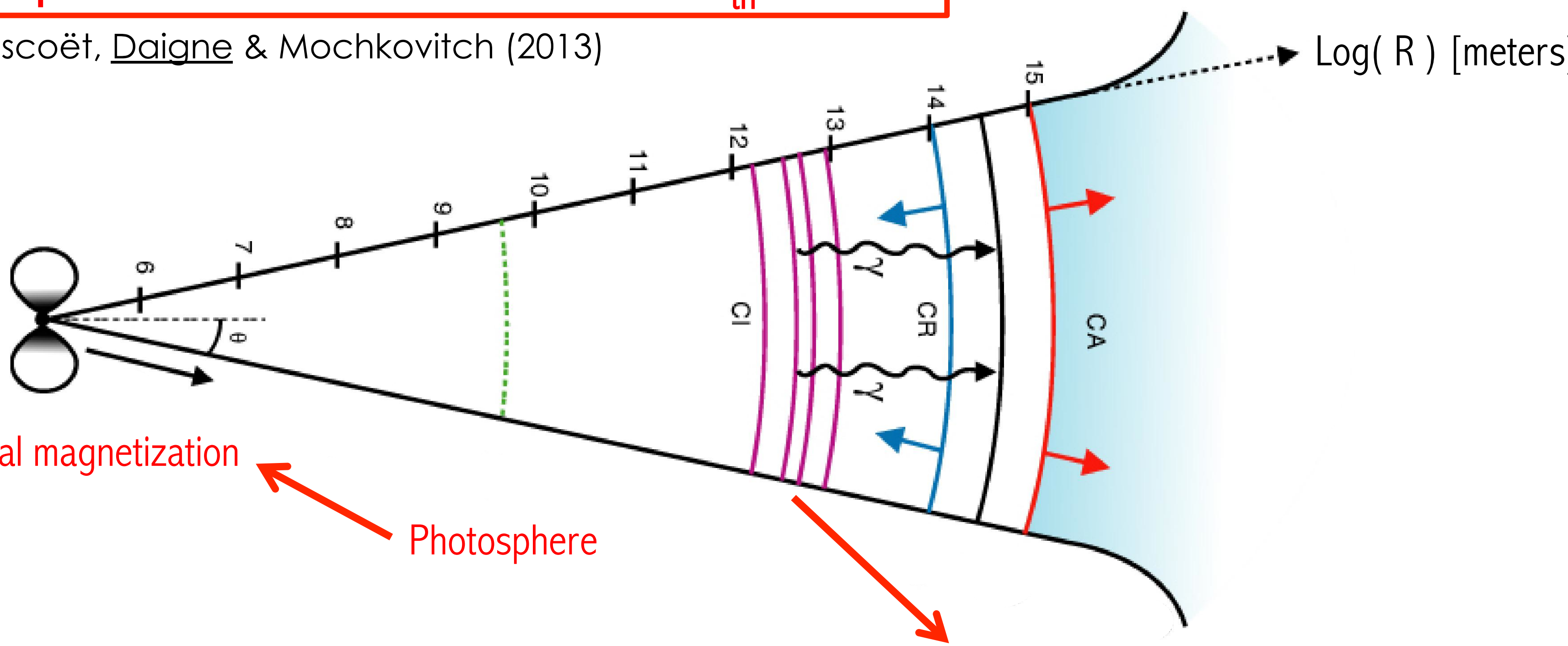
Other cases: Guiriec [<u>Daigne</u>] et al. 2015ab

Constraints on magnetization in GRB outflows

Detection: thermal/non-thermal ratio puts a constraint on the initial magnetization.

Most GRBs have a weak photosphere and are not compatible with the standard fireball : $\varepsilon_{th} < 1\%$

Hascoët, Daigne & Mochkovitch (2013)



What is the magnetization σ at large distance?

Internal dissipation by shocks or reconnection?

Daigne & Mochkovitch 2002; Zhang & Pe'er 2009;
Zhang et al. 201; Hascoët et al. 2013; Gao & Zhang 2014