GRB prompt emission mechanisms

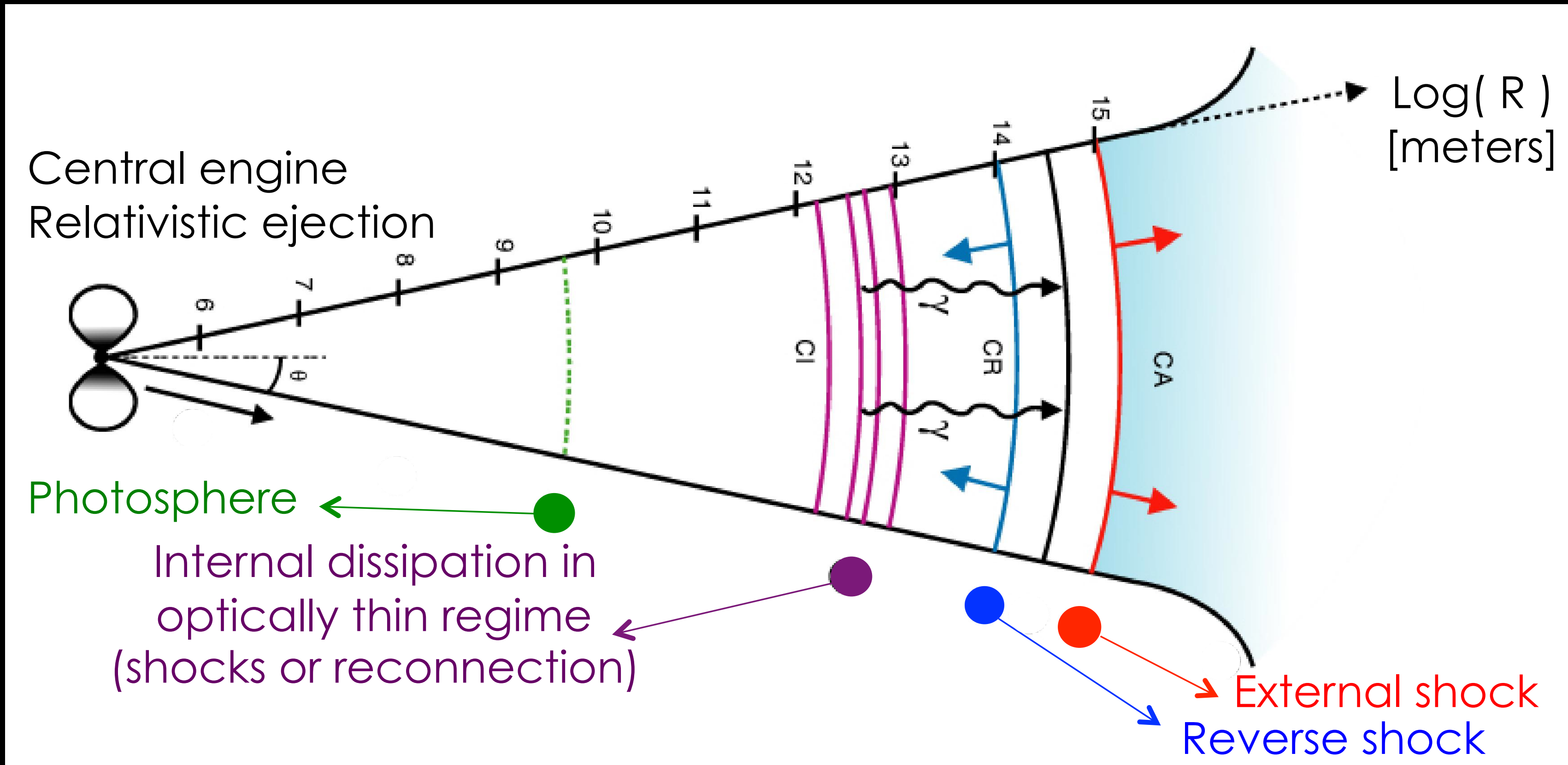
Frédéric Daigne
(Institut d'Astrophysique de Paris; Université Pierre et Marie Curie-UMPC)

with R. Mochkovitch, R. Hascoët, Z. Bosnjak

Ioffe GRB Workshop 2014 – St. Petersburg, September 22-26, 2014

Prompt emission models

Possible emission sites in GRBs



Contribution of each region ?

Dissipation mechanism ?

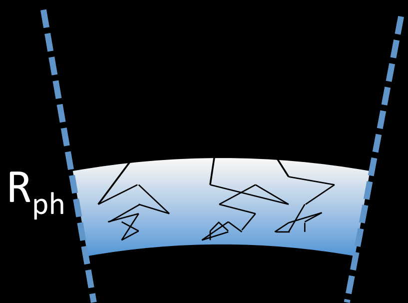
Radiative process ?

Internal dissipation: prompt

Deceleration: afterglow

Internal dissipation (1) photosphere

- PHOTOSPHERE:

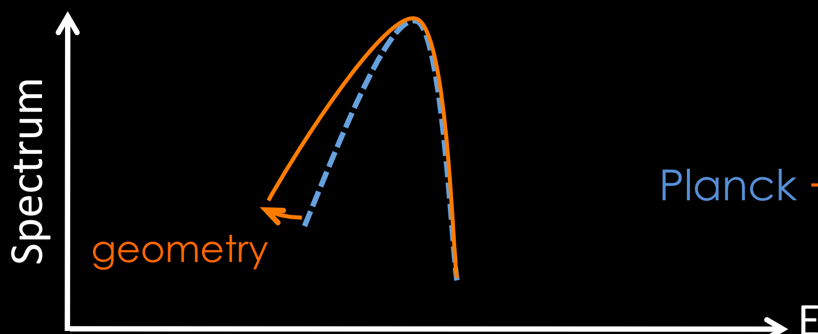


-The relativistic outflow becomes transparent

-Internal energy can be released as radiation

-Almost no theoretical uncertainties
(still: lateral geometry of the jet; initial magnetization)

-Spectrum is quasi-thermal: exp. cutoff at high-energy
PL at low-energy with $\alpha \approx +0{,}4$

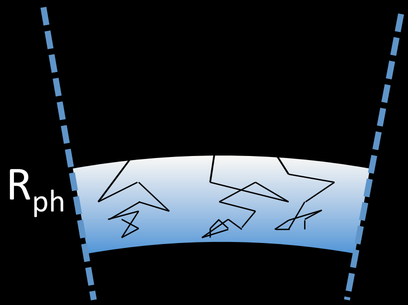


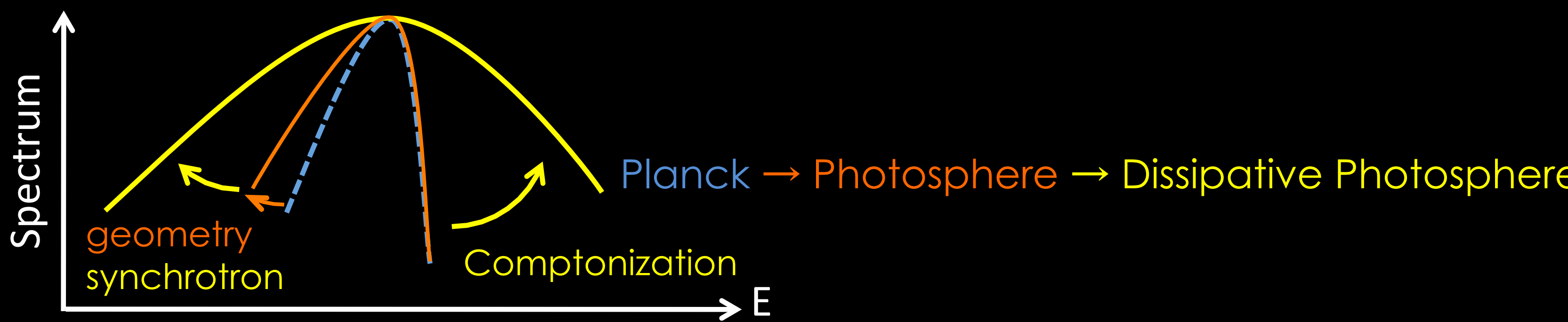
Planck → Photosphere

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

Internal dissipation (1) photosphere

- PHOTOSPHERE:
  - -The relativistic outflow becomes transparent
  - -Internal energy can be released as radiation
  - -Almost no theoretical uncertainties
  - -Spectrum is quasi-thermal





- DISSIPATIVE PHOTOSPHERE:
  - -Sub-photospheric dissipation: non-thermal electrons
  - -Large uncertainties: details of the dissipation process
    neutron heating ? internal shocks ? reconnection ? …
  - -Non thermal spectrum: Comptonization & Synchroton

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

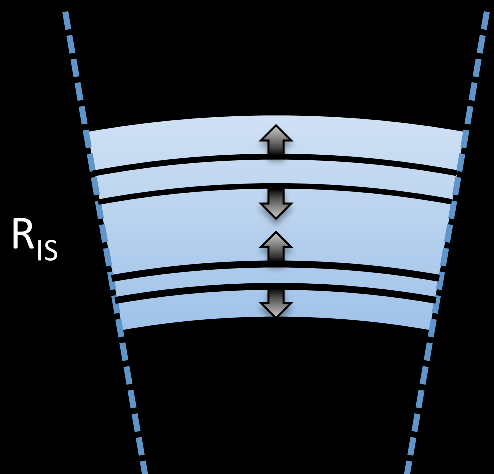
Internal dissipation (2) optically thin

Non-thermal emission can be produced above the photosphere if there are dissipation processes producing non-thermal electrons.

SSC is ruled out by *Fermi* observations – Synchrotron ?

Bosnjak & Daigne 2009 ;
Piran et al. 2009

- INTERNAL SHOCKS:



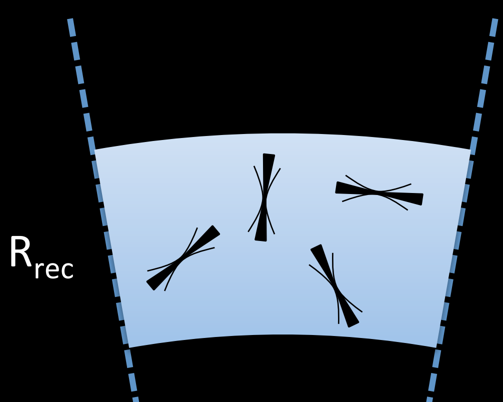
-Assumes: Variability of the central engine + low magnetization at large distance

-Large uncertainties:
microphysics (B amplification, e acceleration) ?

-Non-thermal spectrum, several components (syn, IC)

Rees & Meszaros 1994 ;
Kobayashi et al. 1997 ; Daigne & Mochkovitch 1998

- RECONNECTION:



-Assumes: Variability + large mag. at large distance

-Large uncertainties:
radius ? microphysics ?

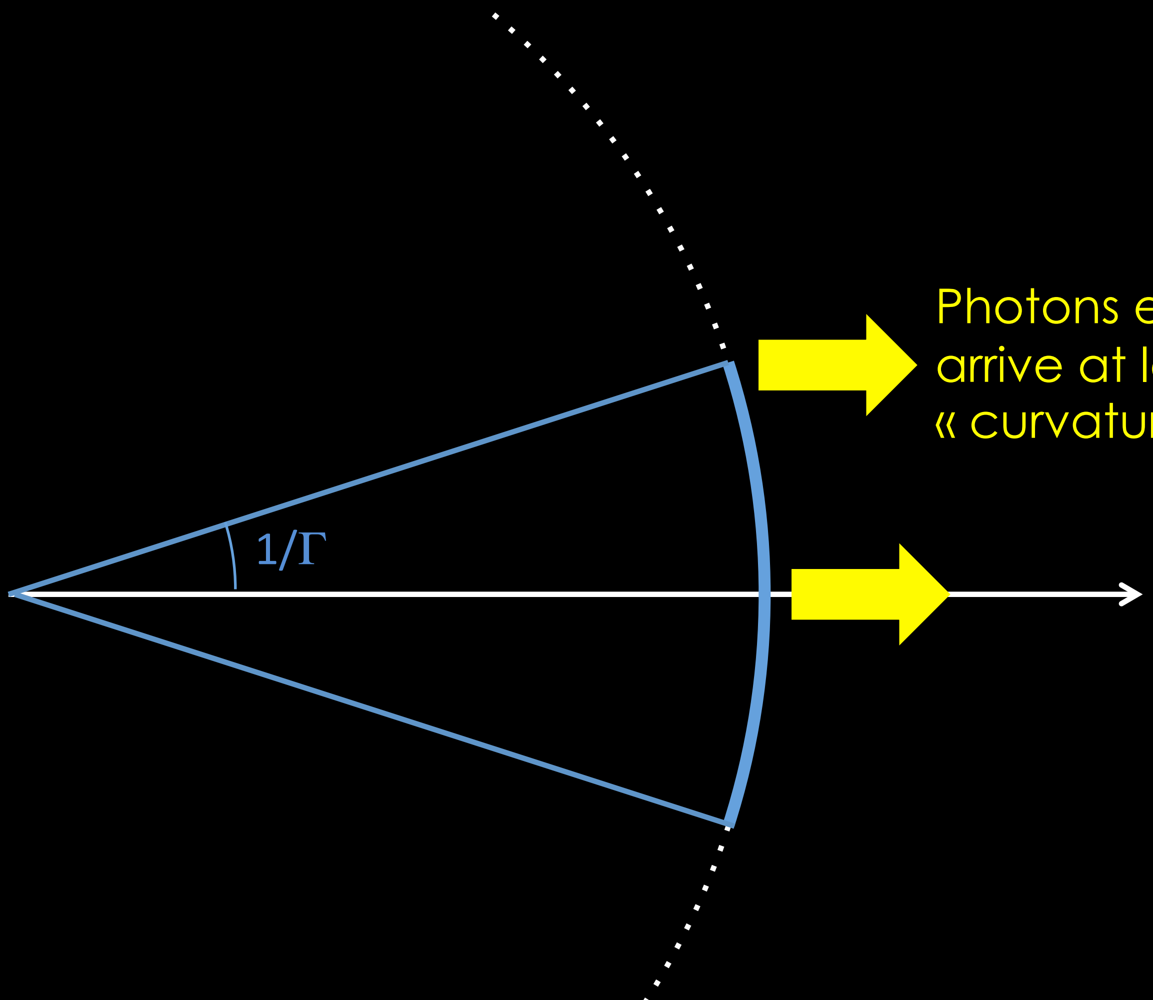
-Non-thermal spectrum

See e.g. Lyutikov & Blandford 2003 ; Zhang & Yan 2011

Models vs Observations
Prompt soft gamma-ray emission

Light curves

All possible sites for the prompt emission can reproduce the observed variable light curves, but with important differences due to very different radii.



Photons emitted at higher latitudes arrive at later times
« curvature effect » - Delay $R/\Gamma^2 c$

Light curves

- (DISSIPATIVE) PHOTOSPHERE: ✔

-Low radius: curvature effect is negligible (except for peculiar lateral distribution)

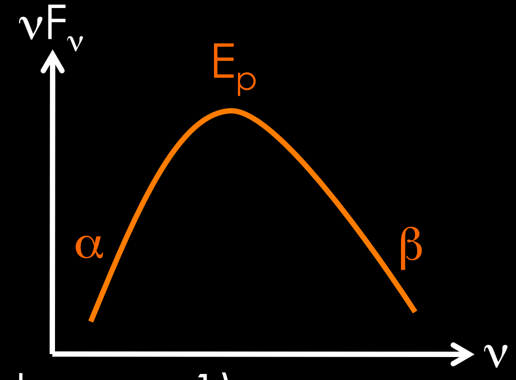
-The light curve directly traces the activity of the central engine

Light curves

- (DISSIPATIVE) PHOTOSPHERE: ✔ -Low radius: curvature effect is negligible (except for peculiar lateral distribution)
  -The light curve directly traces the activity of the central engine
- INTERNAL SHOCKS: ✔ -The light curve is also tracing the central activity
  -Additional effects: shock propagation & curvature effect
- RECONNECTION: ✔ -The light curve is also tracing the central activity
  -Additional effects: reconnection process (fast variability) & curvature effect

Open issue with observations:
continuum of variability timescales or two components ?

Spectrum (1) models



General shape ("Band") / Low-energy photon index α (obs: $\alpha \approx -1$)

- PHOTOSPHERE: ? — α too large except for peculiar lateral struct.

Time-integ. spec. ?

- DISSIPATIVE PHOTOSPH.: ✔ ? — -α correct (depends on magnetization)

- INTERNAL SHOCKS: ? — -Synchrotron only: α = -3/2 (fast cooling)

-Possible mechanisms to increase α
(a) Marginally fast cooling ;
(b) IC in KN regime ; (c) B decay

(a) Daigne et al. 11 ; Beniamini & Piran 13
(b) Derishev et al. 01 ; Bosnjak et al. 09 ; Wang et al. 09 ; Daigne et al. 11
(c) Derishev 07 ; Lemoine 13 ; Uhm & Zhang 14 ; Zhao et al. 14

- RECONNECTION: ? — -α correct ? (slow heating in turbulent acc.)

Uhm & Zhang 2014

-Spectrum is probably much too broad (multi emitters)

Spectrum (2) observations

- Should we believe the distribution of α ? the Band shape ?

  -*Fermi* bursts: multi-component spectra (2, 3 components)

  -Parameters of the "Band" component vary when the other components are taken into account

  See e.g. Guiriec et al. submitted
  Two bright *Fermi* bursts
  BB+Band+PL [GBM+LAT]

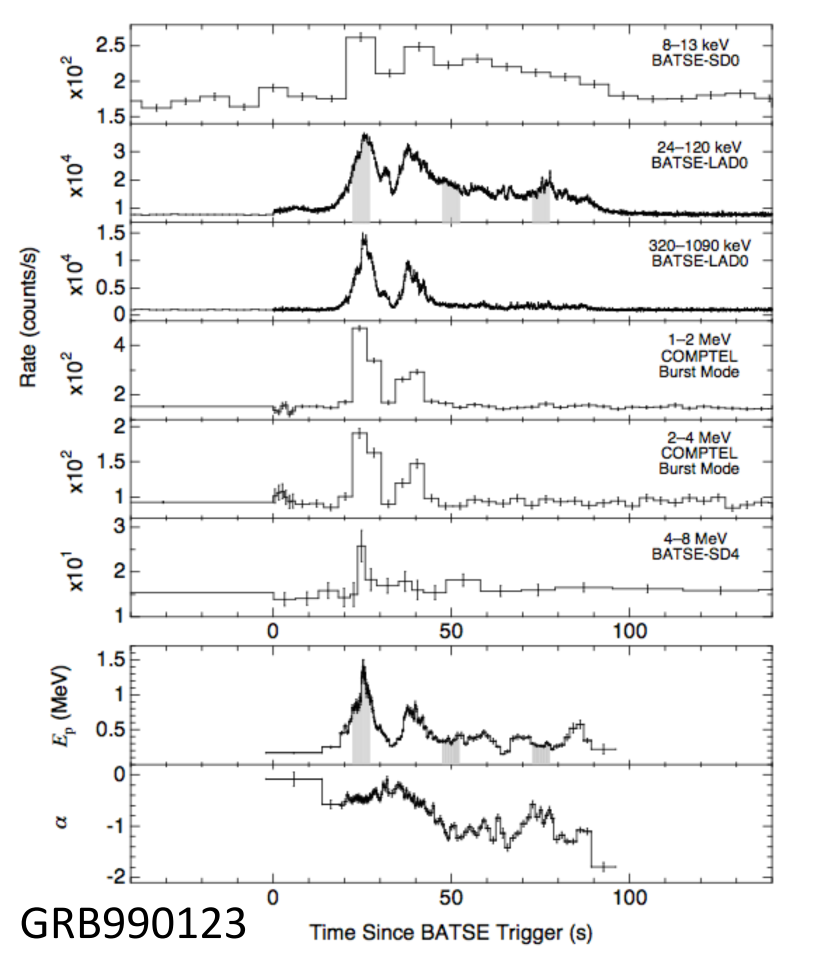
  GRB 080916C: $\alpha < -1$
  GRB 090926A: α -0.7 → -1

- Should we believe that the spectrum is so narrow around the peak ?

  -Spectral evolution in GRBs

  -Integration of a time-evolving Band function
  is not a Band function
  (it is broader)

(Briggs et al. 1999)



GRB990123

Distribution of Epeak
Spectral evolution

- E_{peak} varies a lot :

    -from a GRB to another (XRF, XRR, GRBs, short GRBs)

    -within a GRB (spectral evolution)

    -dissipative photosphere: ✔ ? (depends on the details of the heating)

    -internal shocks: ✔

    -reconnection: ?

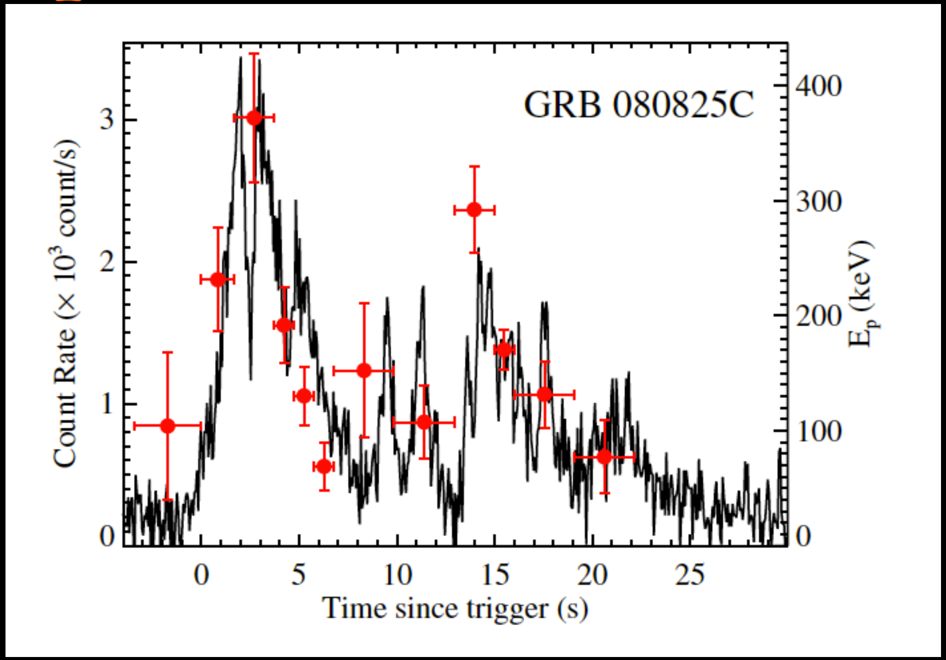
See discussion by Vurm et al. 2013 ;
Asano & Meszaros 2013 ; Gill & Thompson 2014

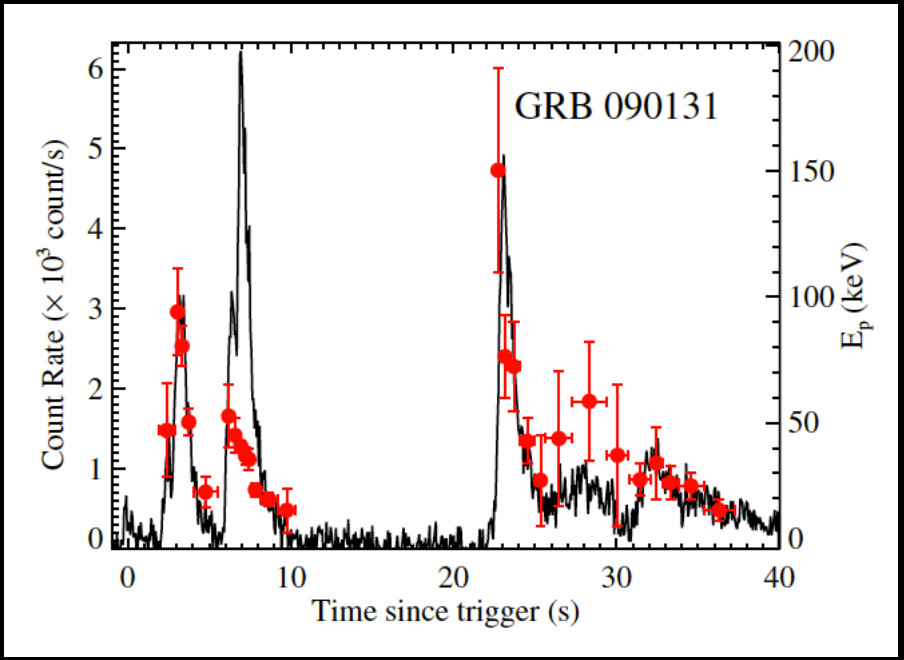
Spectral evolution

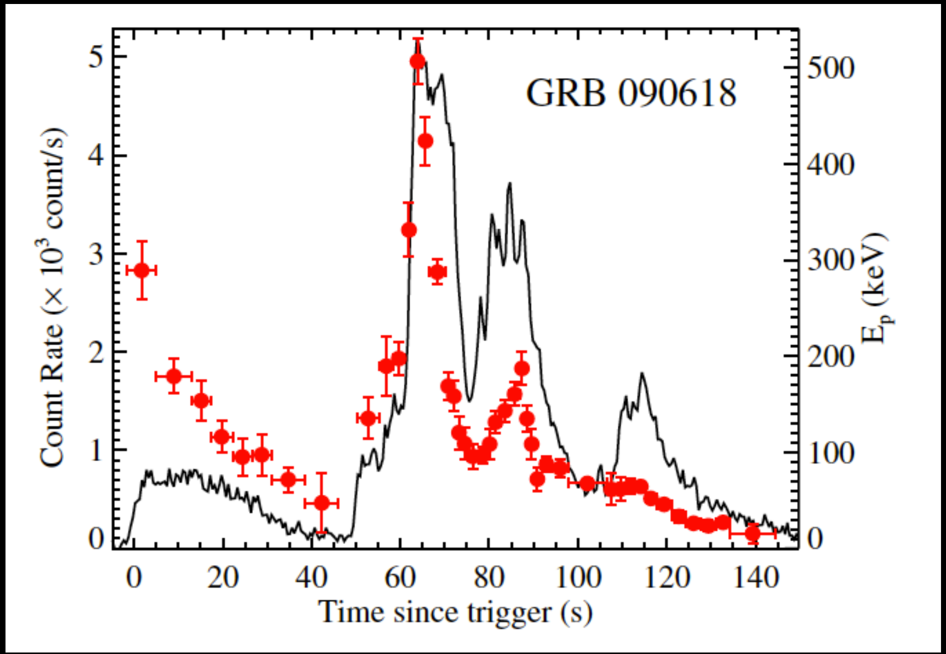
E_p evolution (intensity tracking)
Hardness Intensity correlation (HIC)
Hardness Fluence correlation (HFC)
Pulse width vs Energy ; Time lags ; etc.

- Dissipative photosphere: details of the dissipative process ?
- Internal shocks: ✔ -natural qualitative agreement ; -constraints on microphysics for a quantitative agreement — Bosnjak & Daigne 2014
- Reconnection: ?

Spectral evolution: *Fermi*-GBM bursts

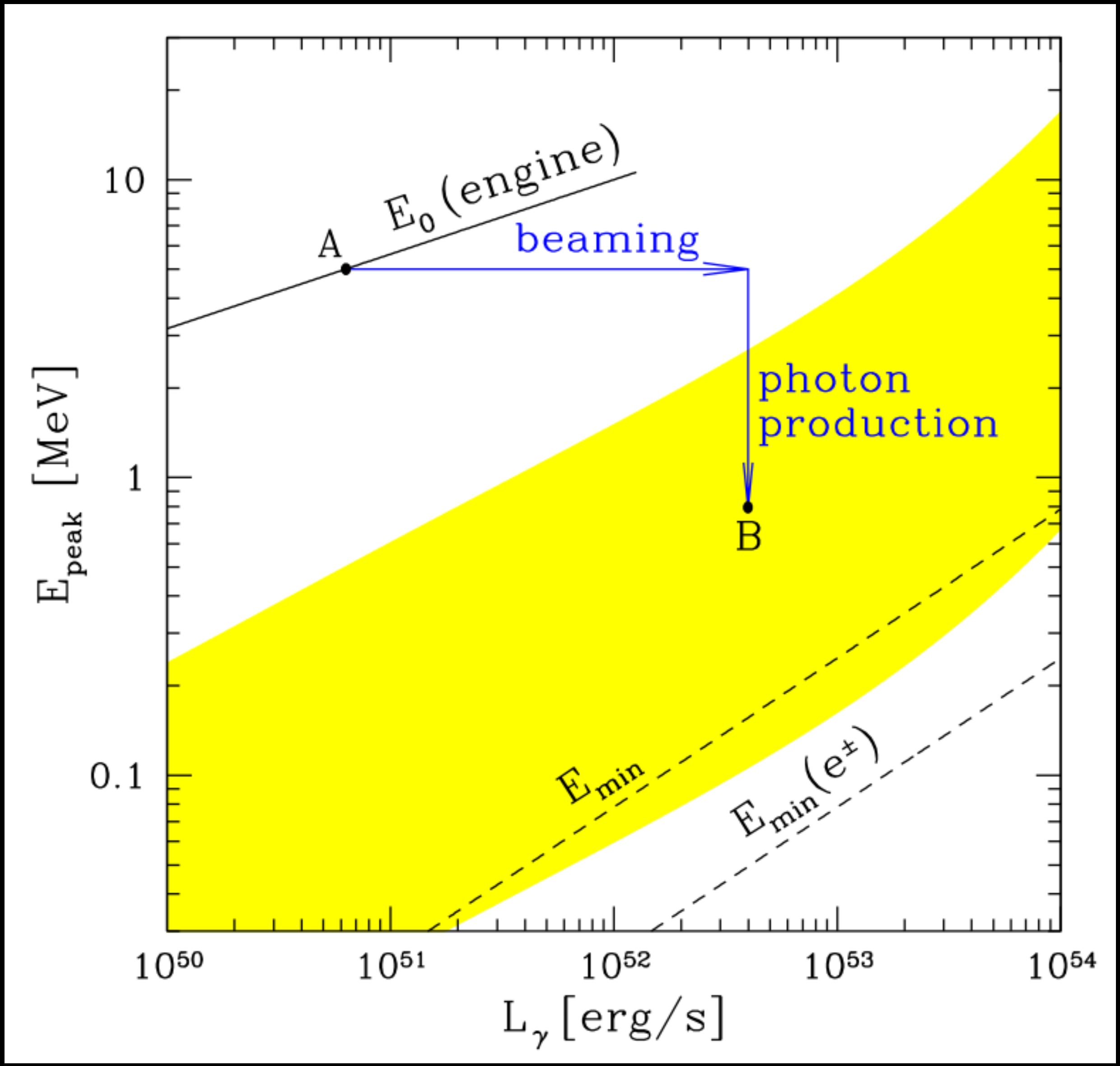






Lu et al. 2012

Dissipative photosph.: spectral evolution

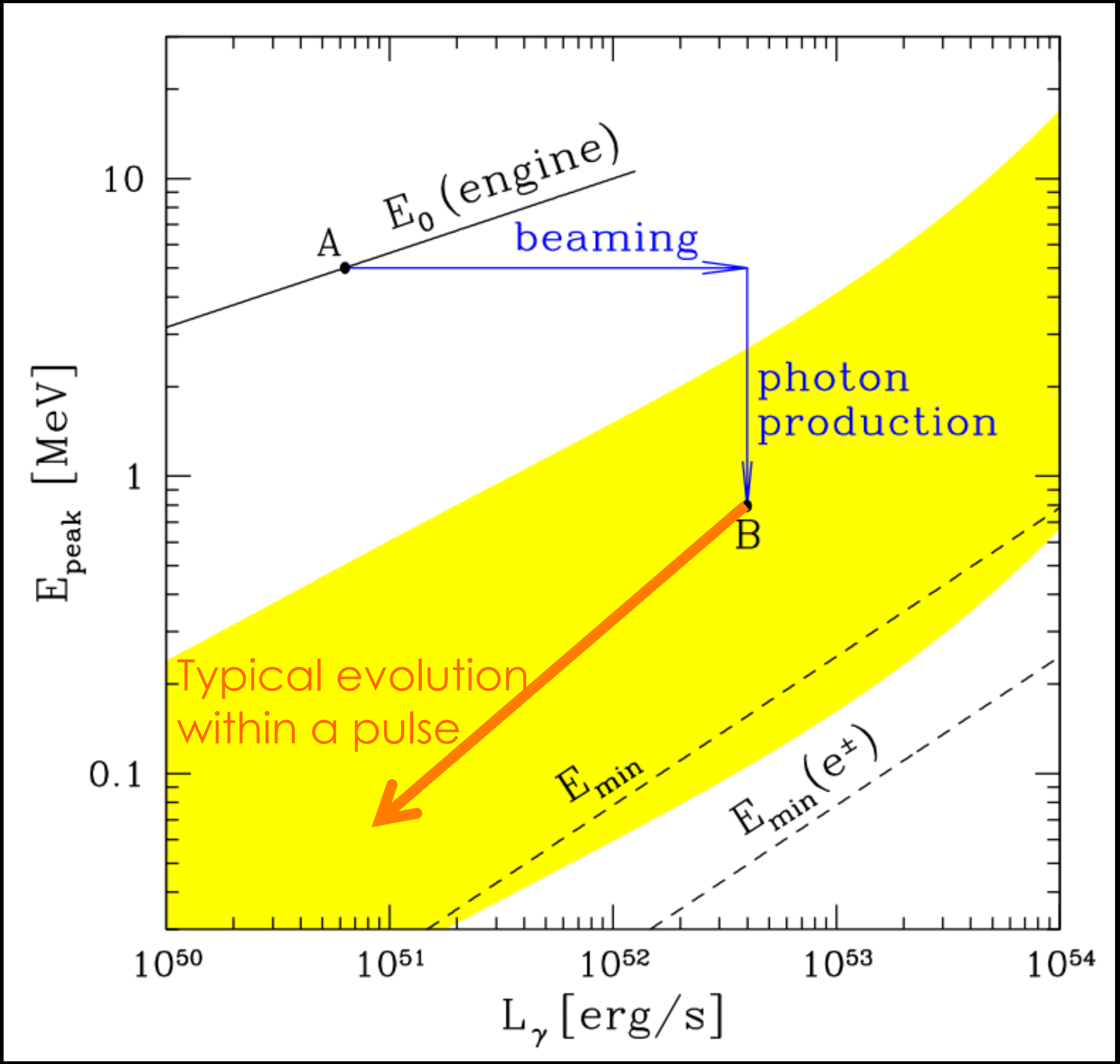


(Beloborodov 2013)

Dissipative photosph.: spectral evolution

What are the constraints on the dissipative process ?

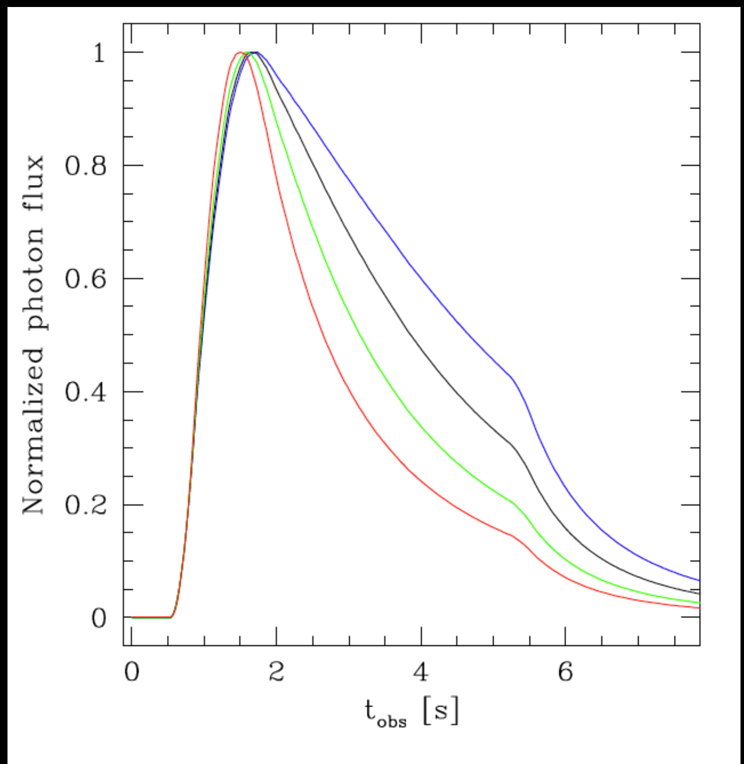
How does the dissipative process adjust its radius to the photospheric radius ?



(Beloborodov 2013)

Internal shocks: spectral evolution

Example of a simulated pulse
(internal shocks with full radiative calculation)

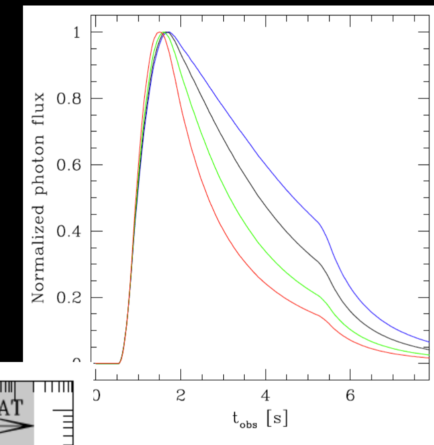


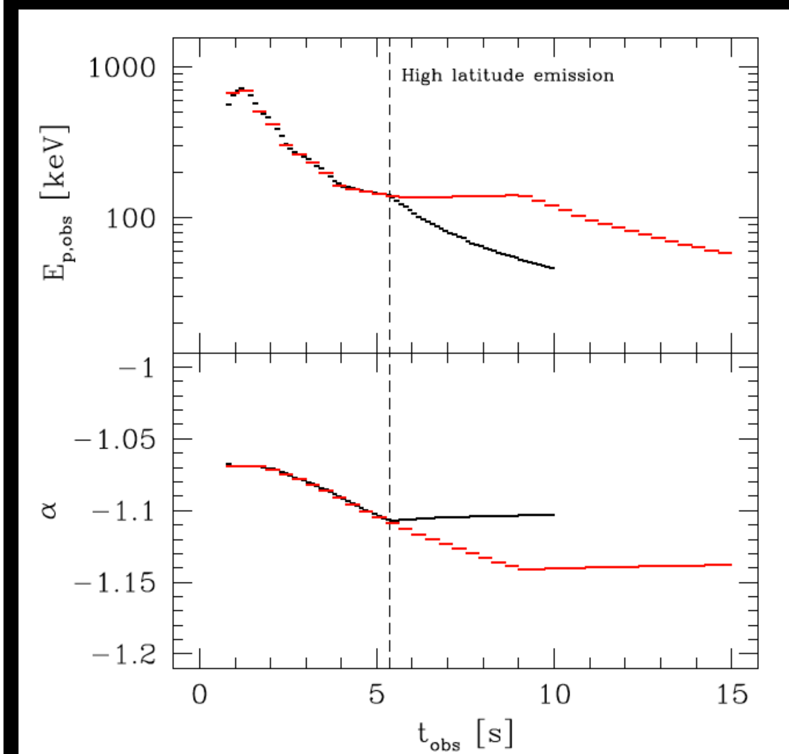
Light curve in BATSE range :
channels 1 (blue) to 4 (red)

(Bosnjak & Daigne 2014)

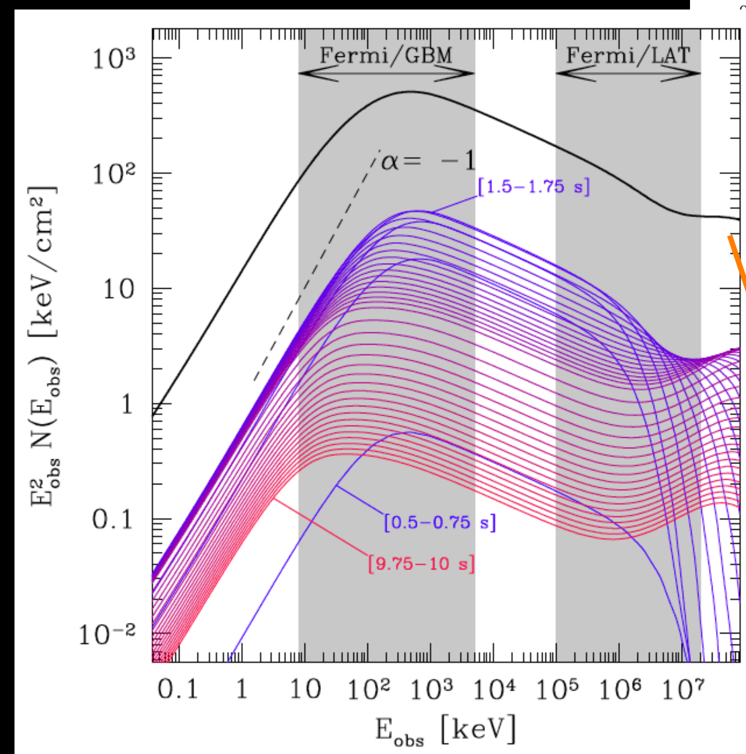
Internal shocks: spectral evolution

Example of a simulated pulse
(internal shocks with full radiative calculation)





Evolution of E_{peak} and α



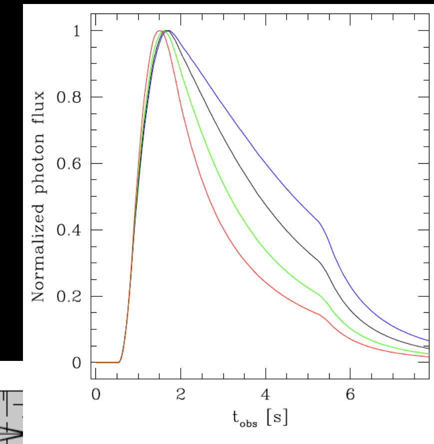
Time-evolving spectrum

Additional PL component with index ~-2 ?

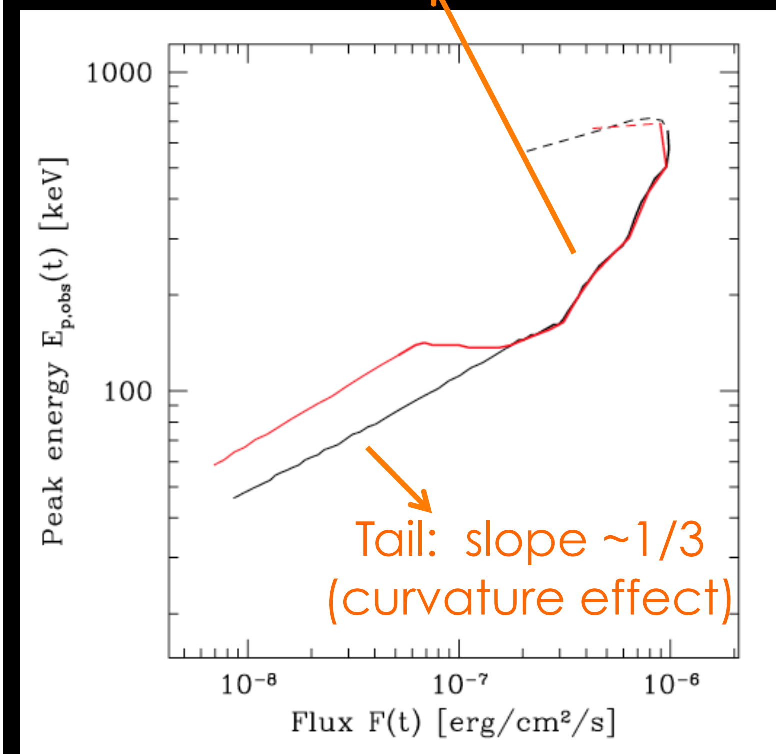
(Bosnjak & Daigne 2014 ; see also Asano & Meszaros)

Internal shocks: spectral evolution

Example of a simulated pulse
(internal shocks with full radiative calculation)

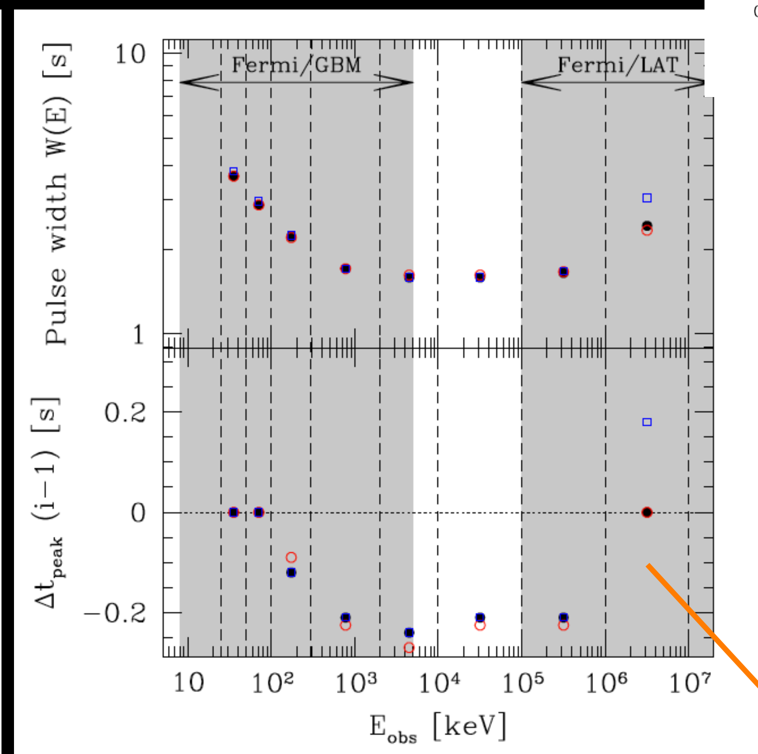


Slope ~1-1.5 fixed by shock propagation



Tail: slope ~1/3 (curvature effect)

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



Pulse width and time lags

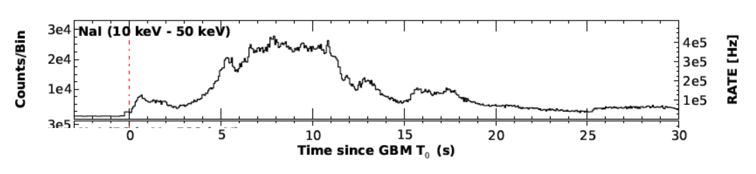
$$W(E) \propto E^{-a}$$
$$a \simeq 0.2 - 0.3$$

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

(Bosnjak & Daigne 2014 ; see also Asano & Meszaros)

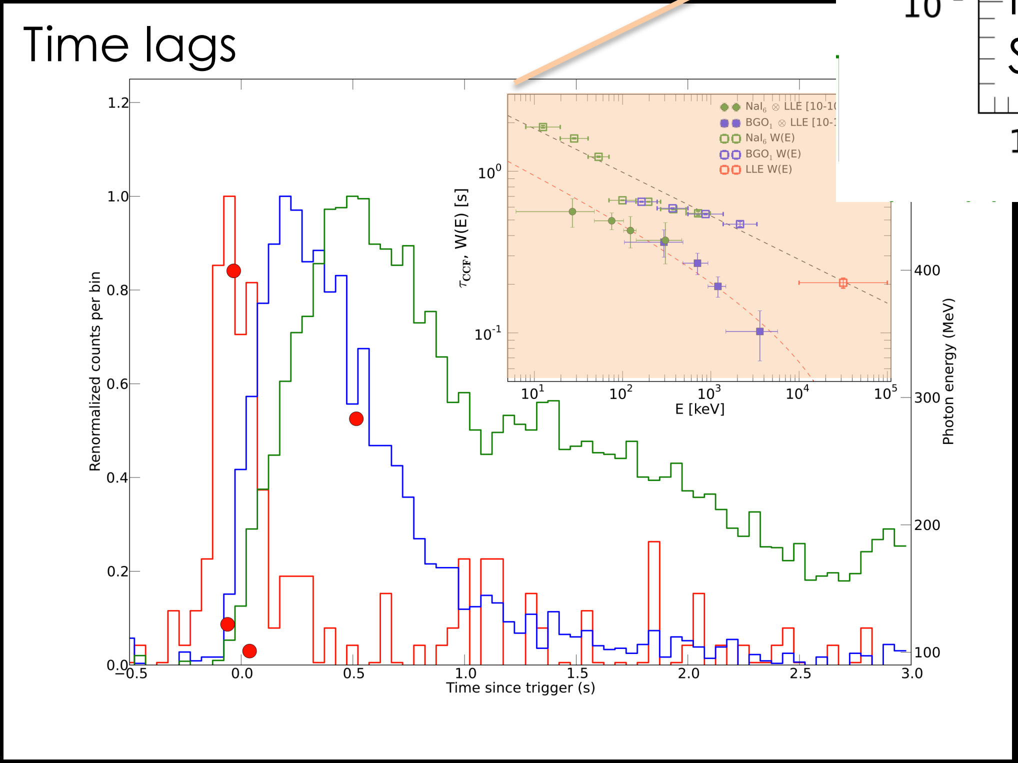
GRB 130427A

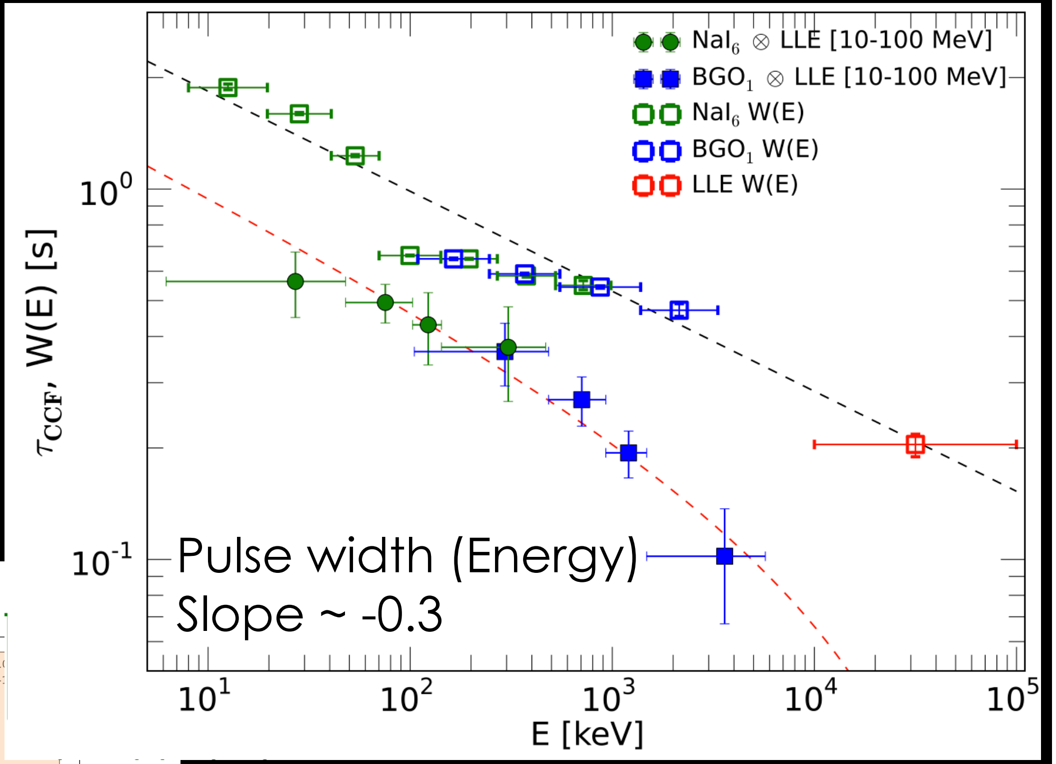
Good agreement with internal shock scenario

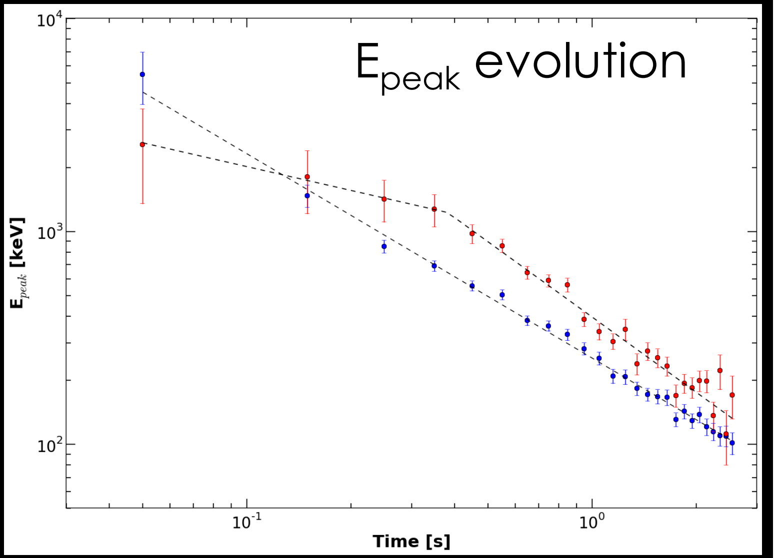


The first 3 s

Time lags







Preece et al. 2013, see also Piron's talk

Not shown: hardness-intensity correlation slope 1.4

Distribution of Epeak
Hardness-Duration correlation

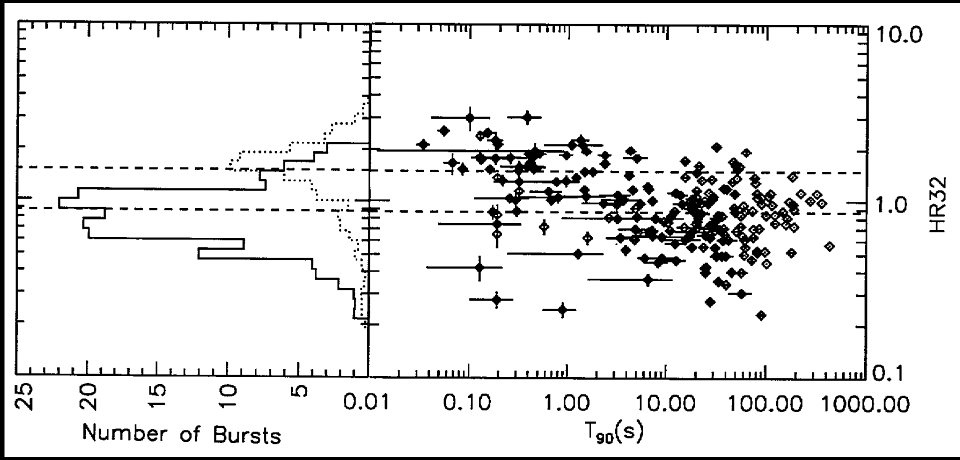
- Short bursts have usually higher peak energies

See also Sakamoto's talk

-dissipative photosphere: change in properties of central engine ?

-internal shocks: natural explanation ✔

-reconnection: ?

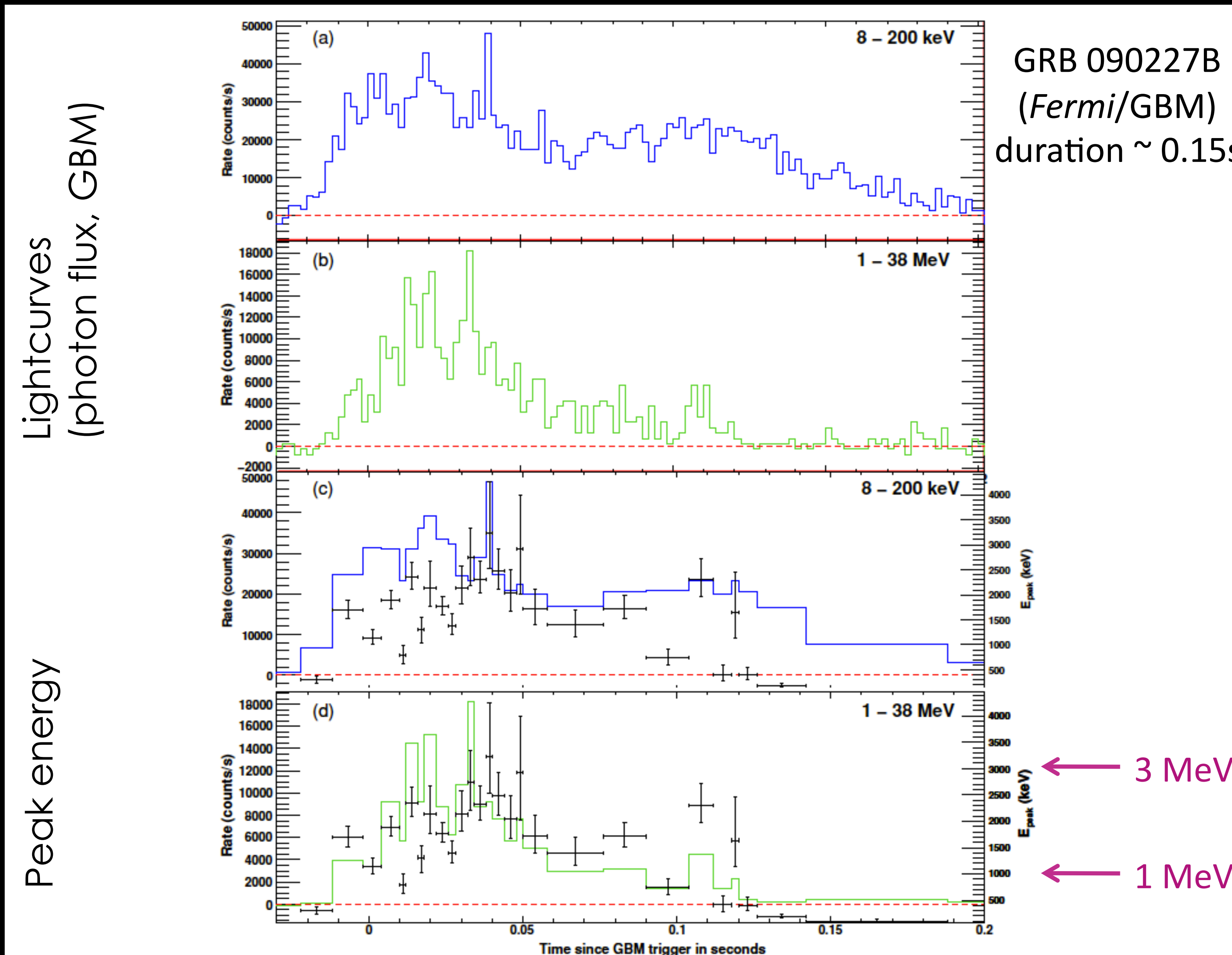


Kouveliotou et al. 1993

A short GRB seen by *Fermi*/GBM

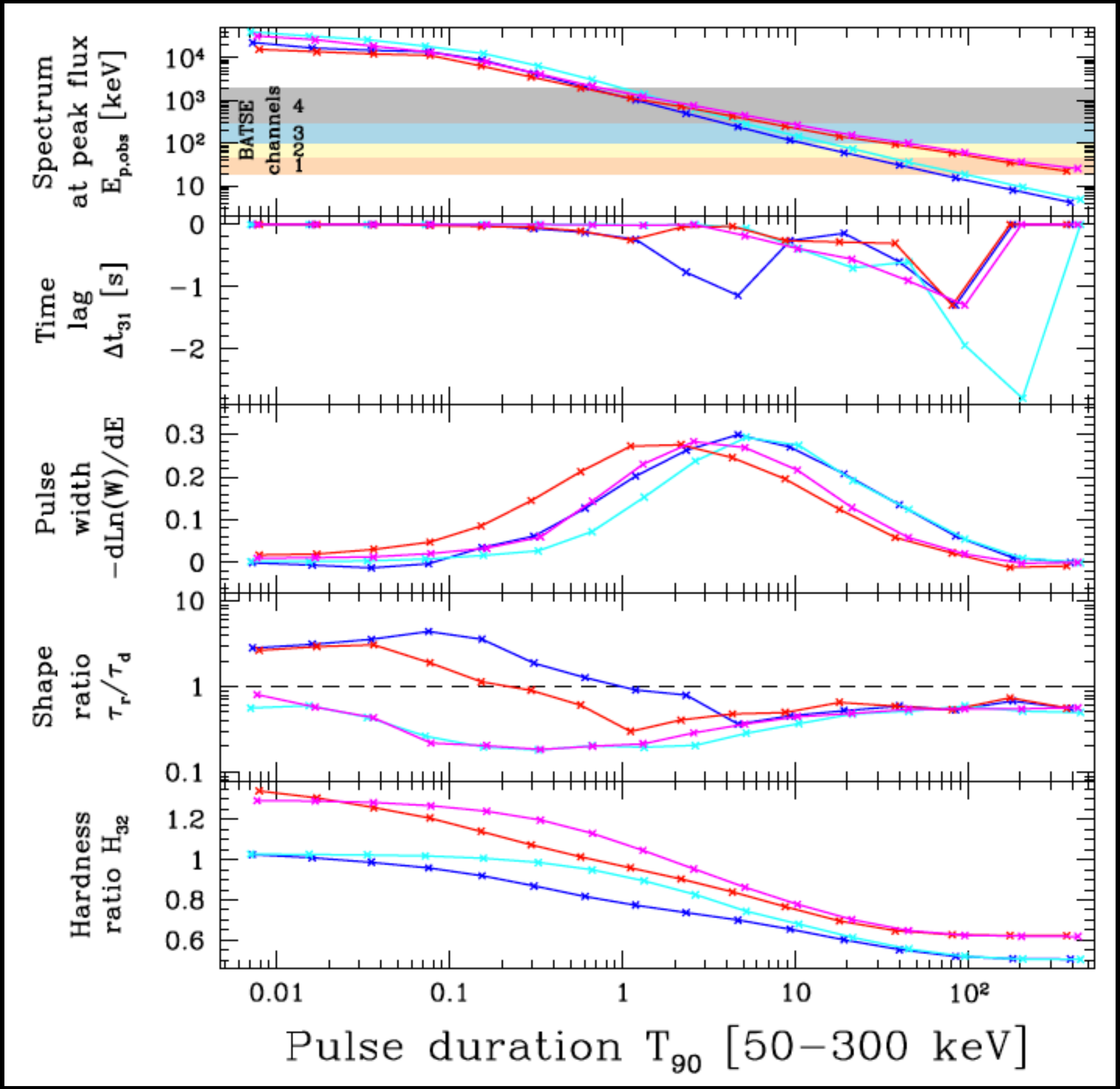
Lightcurves (photon flux, GBM)

Peak energy



Guiriec et al. 2010

Hardness-Duration in internal shocks



Effect of duration:

- -hardness-duration correlation
- -lags become short and tend to zero
- -pulses become more symmetric

Pulse calculation: the only varying parameter is the duration (Bosnjak & Daigne 2014)

The end of the prompt emission: X-ray early steep decay

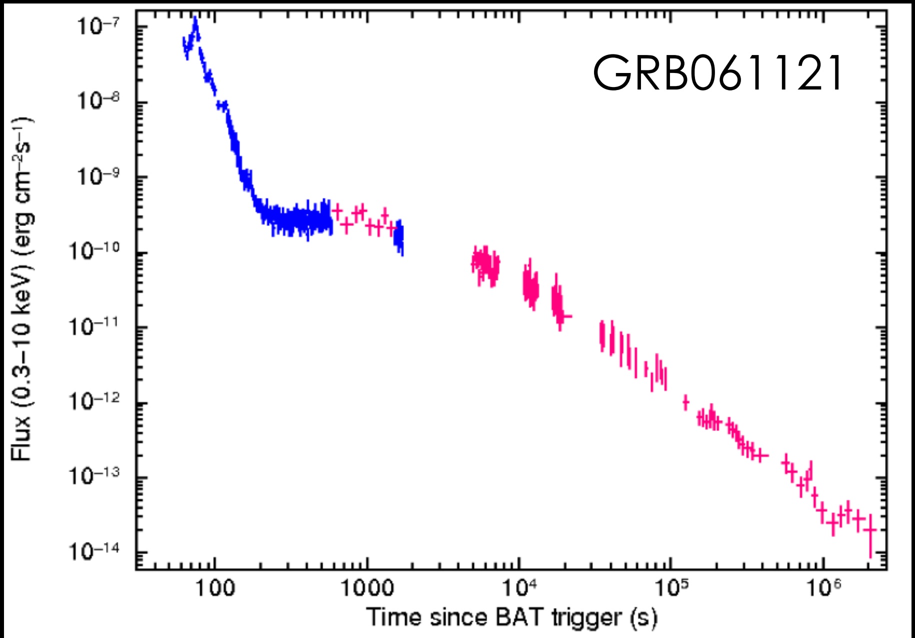
- A natural explanation: high-latitude emission from the prompt (fits well XRT data)

See Willingale's talk

-(Dissipative) photosphere: ✗ (radius is too small)

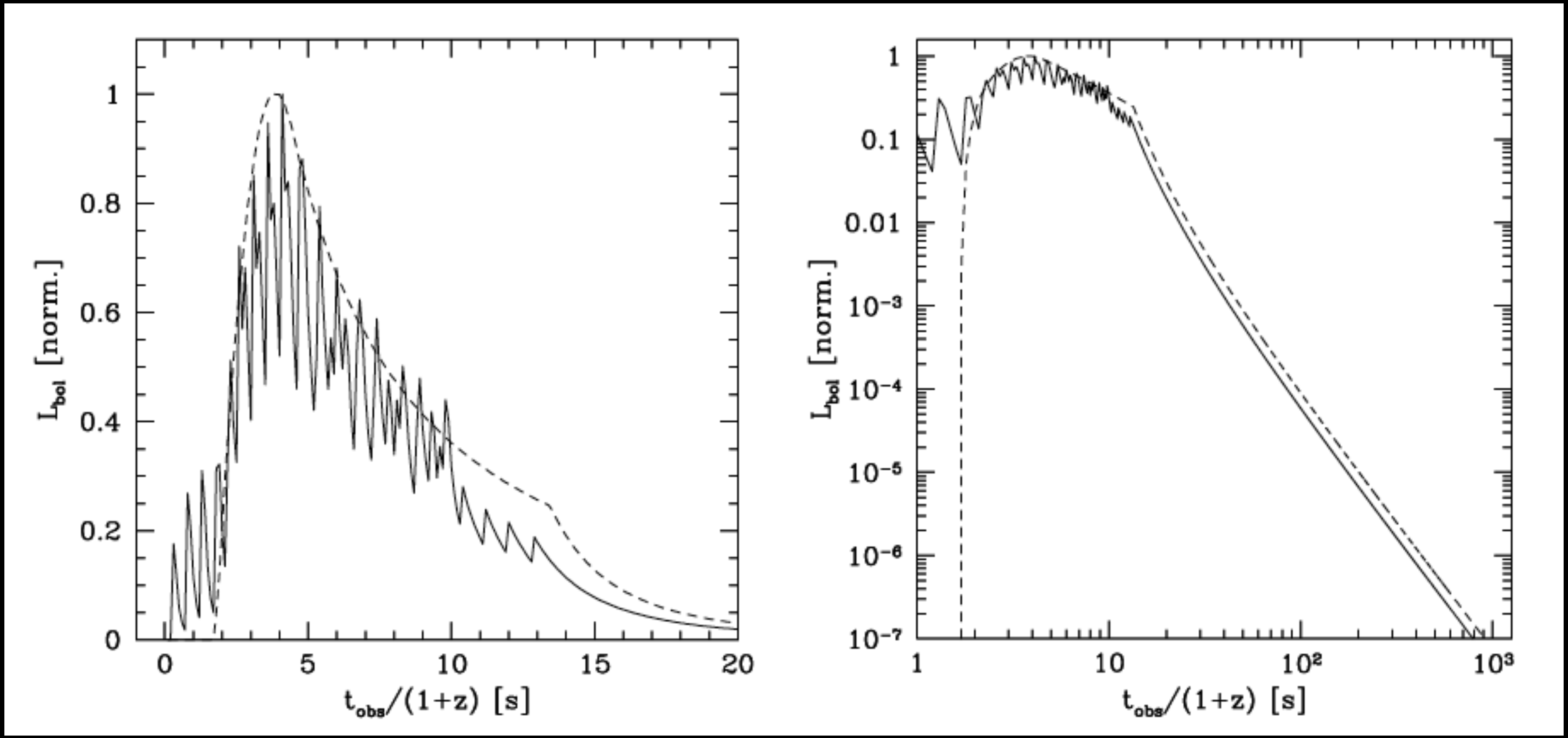
-Internal shocks: ✓ (final radius of the order of Γ^2 c t_{burst})

-Reconnection: ✓? (final radius ?)



(Page et al. 2007)

High-latitude emission in internal shocks



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

(Hascoët et al. 2012)

The end of the prompt emission: X-ray early steep decay

- A natural explanation: high-latitude emission from the prompt (fits well XRT data)

  -(Dissipative) photosphere: ✗ (radius is too small)

  -Internal shocks: ✔

  -Reconnection: ✔ ?

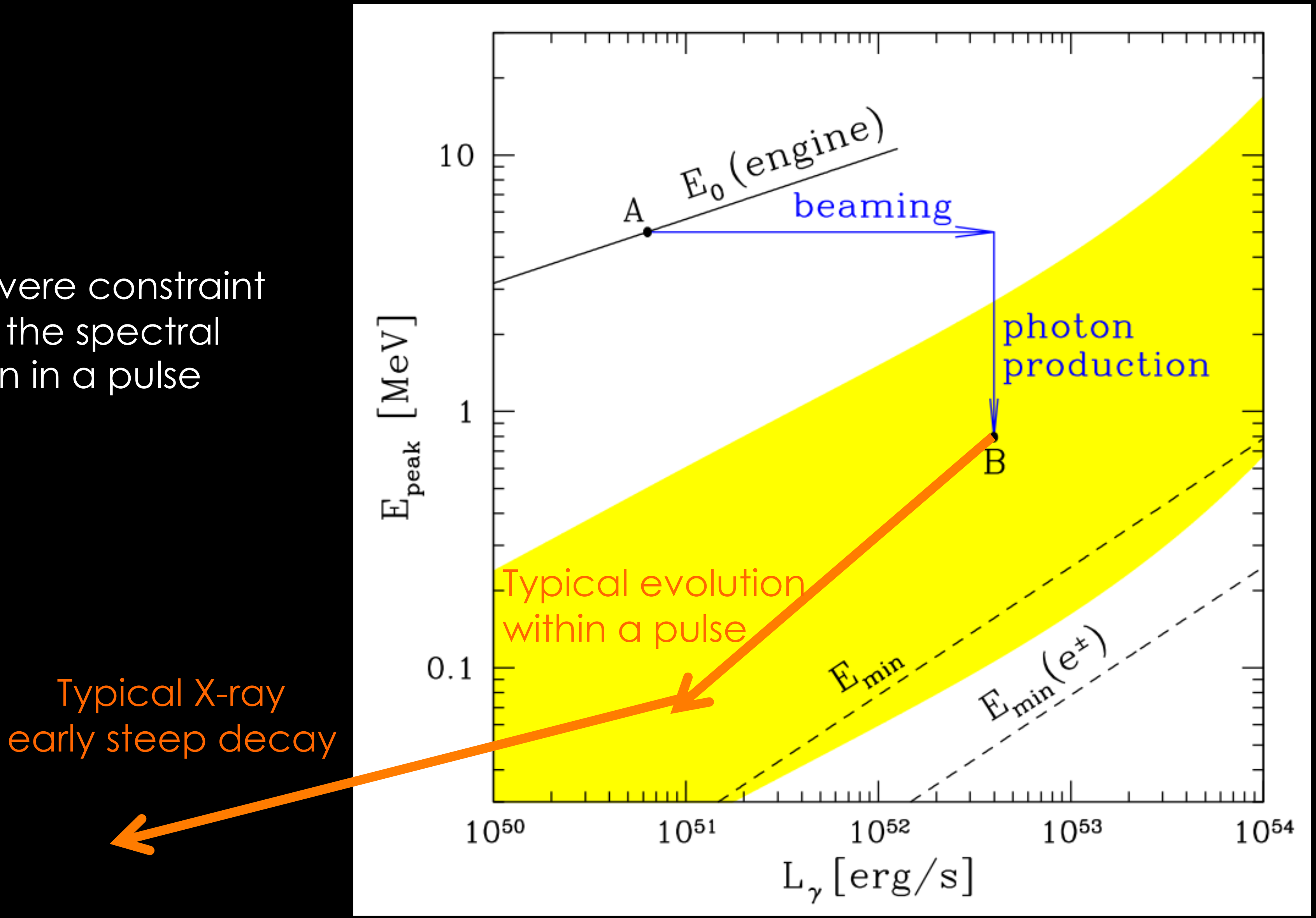
- Alternative explanation: late evolution of the central engine

  - Photosphere: ? (inefficient ?)

  - Dissipative photosphere: ? (constraints on dissipative process ?)

Dissipative ph.: X-ray early steep decay

More severe constraint than for the spectral evolution in a pulse

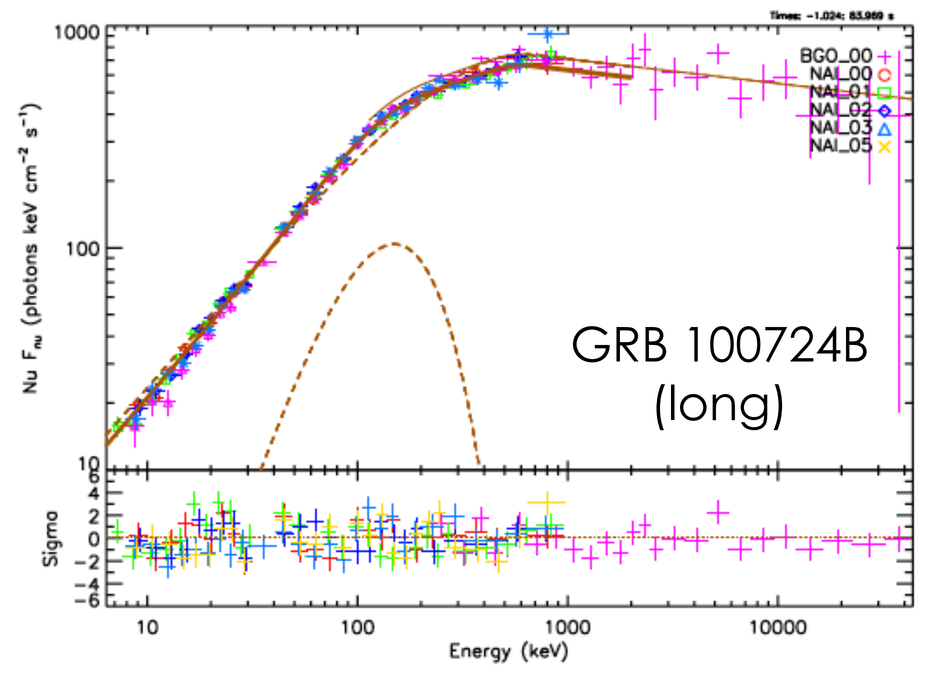


(Beloborodov 2013)

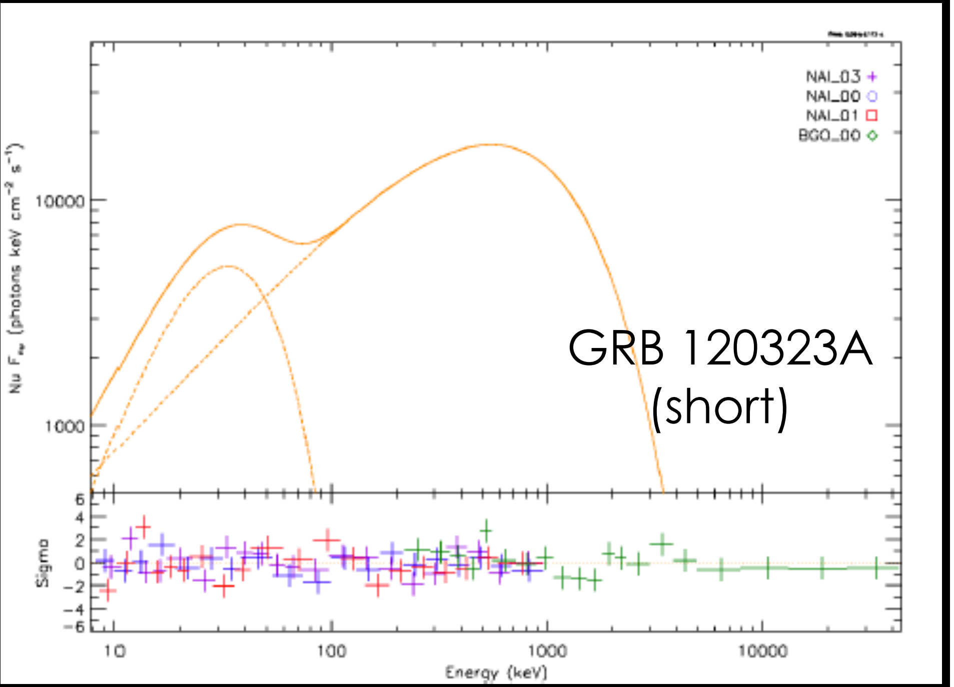
Photosphere+internal shocks/reconn.

In the optical thin scenario (internal shocks or reconnection), photospheric emission is expected, with a brightness depending on the composition of the jet.

- GBM observations: weak photospheric emission is detected ?



Guiriec et al. (2011)



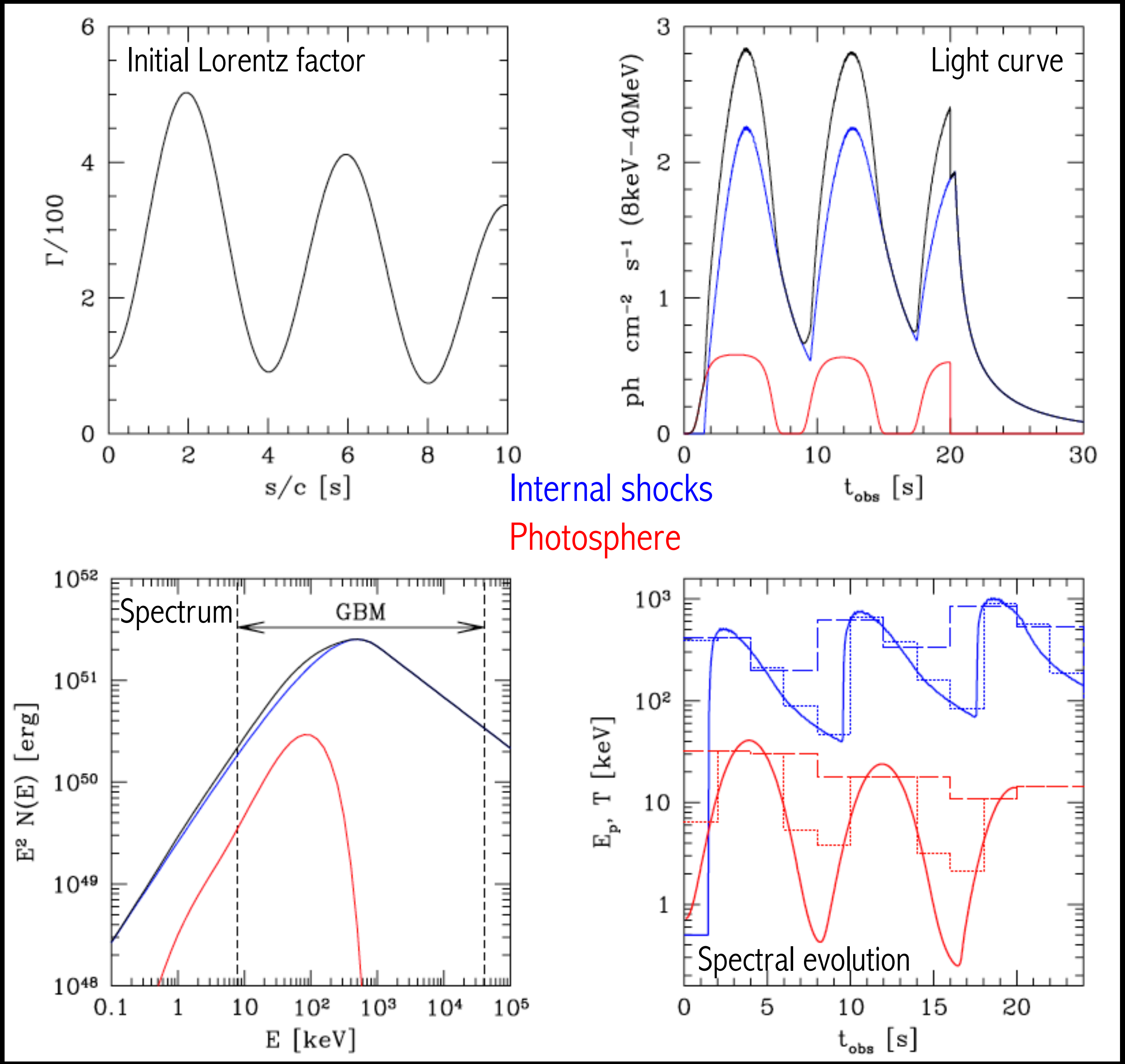
Guiriec et al. (2013)

- Favors magnetic acceleration, with a range of magnetization in the GRB population, with a hint for a lower magnetization in short GRBs

Daigne & Mochkovitch 2002 ; Zhang & Pe'er 2009 ; Zhang et al. 2011 ; Hascoët et al. 2013 ; Gao & Zhang 2014

Photosphere + internal shocks

Hascoët, Daigne & Mochkovitch 2013



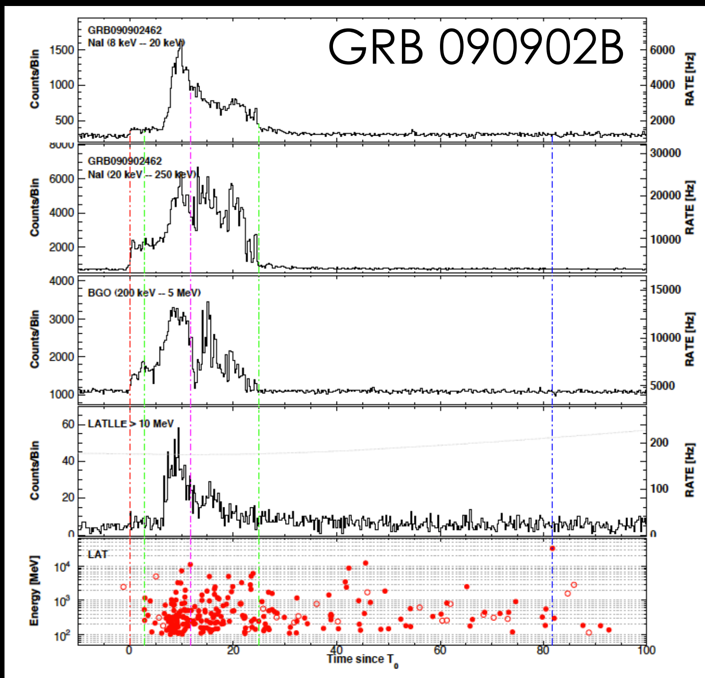
Models vs Observations
Prompt GeV emission
Prompt optical emission

Prompt GeV emission

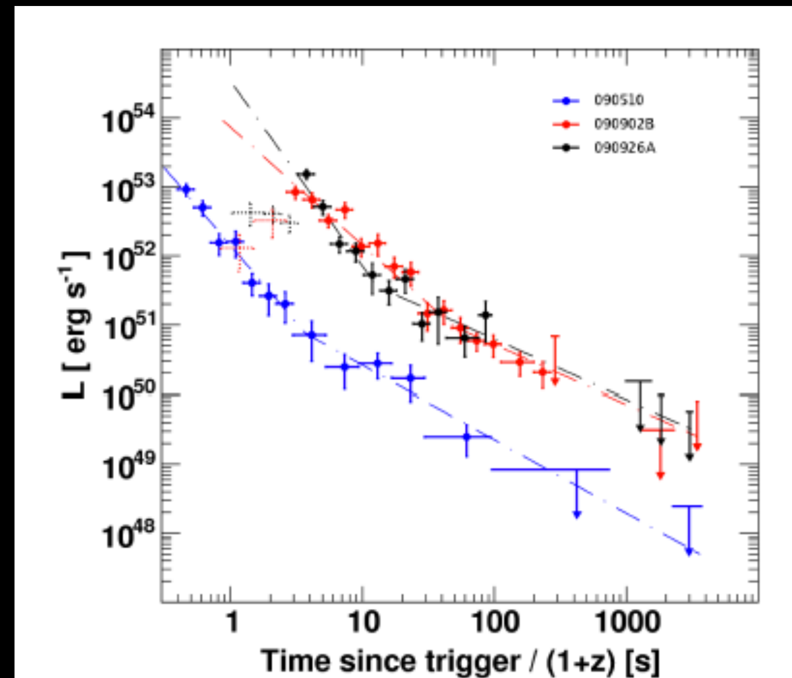
- There is probably a prompt variable component in the LAT, different from the long lasting emission (external origin)

See Piron's talk & Tavani's talk

(1st GRB LAT catalog)

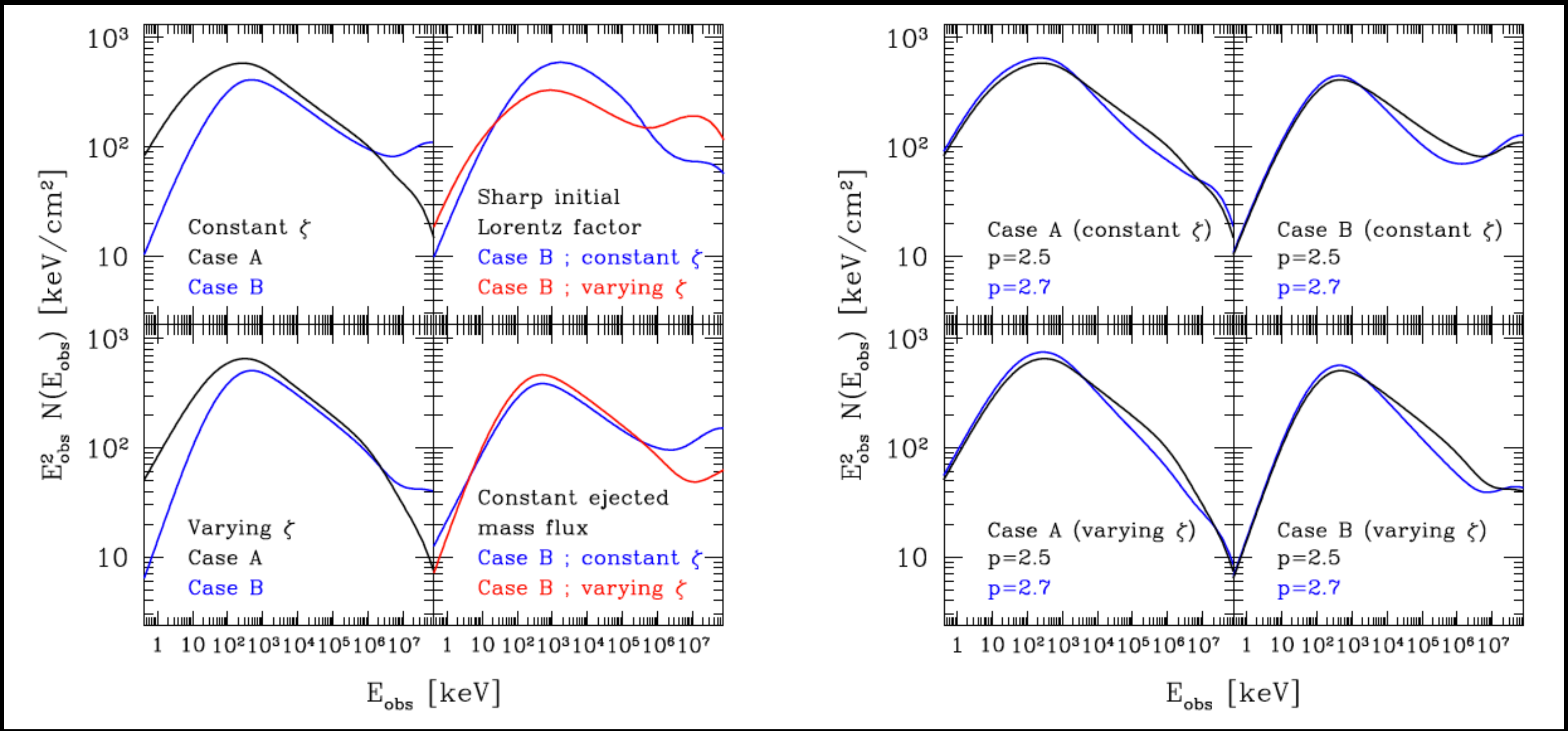


$t_{var} < 100$ ms



- Strong constraint on the emission radius from γγ opacity
  - (Dissipative) photosphere: ✗ Additional process is needed ✔ (e.g. scattering mechanism proposed by Beloborodov et al.)
  - Internal shocks: ✔ (IC)
  - Reconnection: ?

Prompt GeV emission in internal shocks

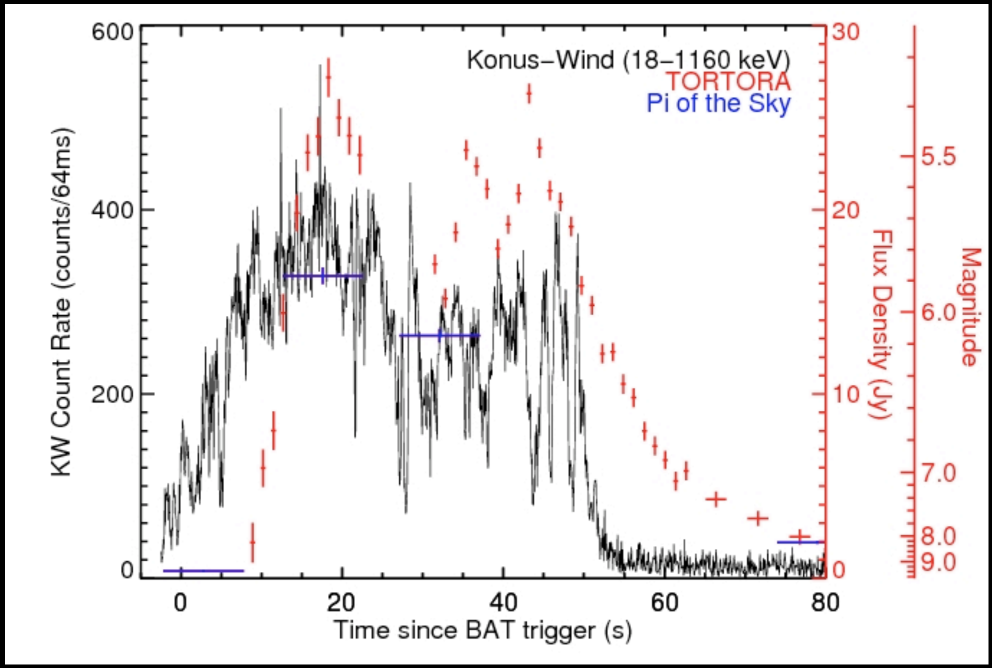


(Bosnjak & Daigne 2014 ; see also Asano & Meszaros)

Prompt optical emission

- The prompt optical emission can change a lot from a burst to another
- In optical bright burst, the optical emission is probably variable: internal origin

GRB 080319B @ z = 0.937

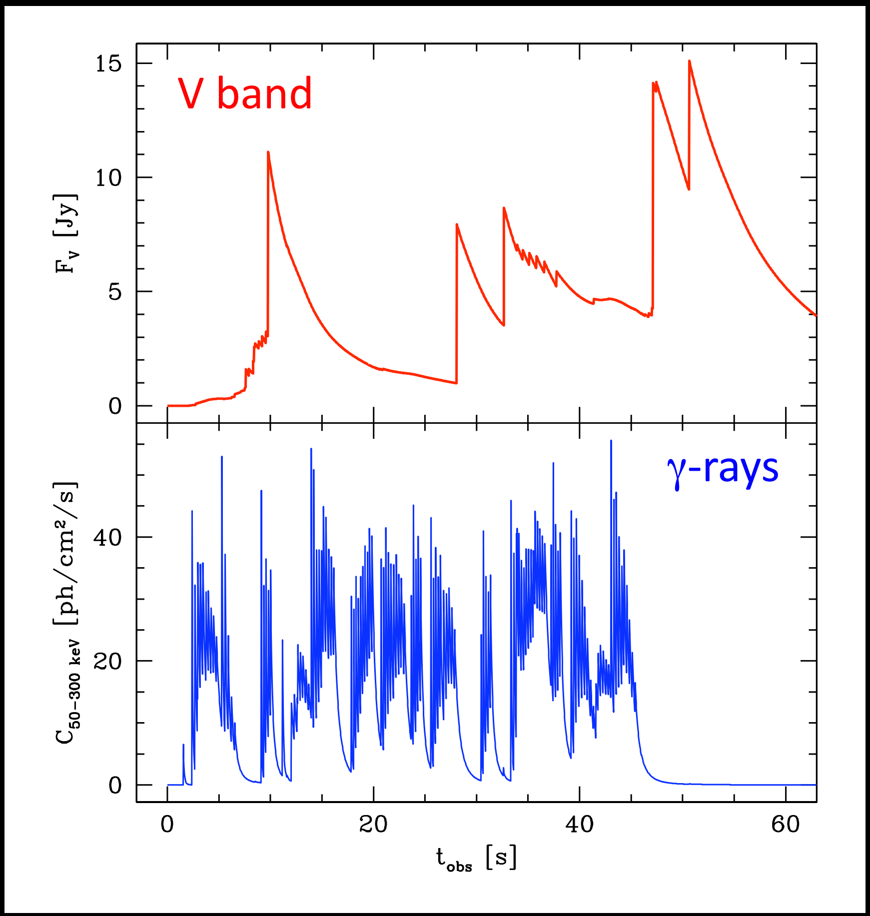


(Racusin et al. 2008)

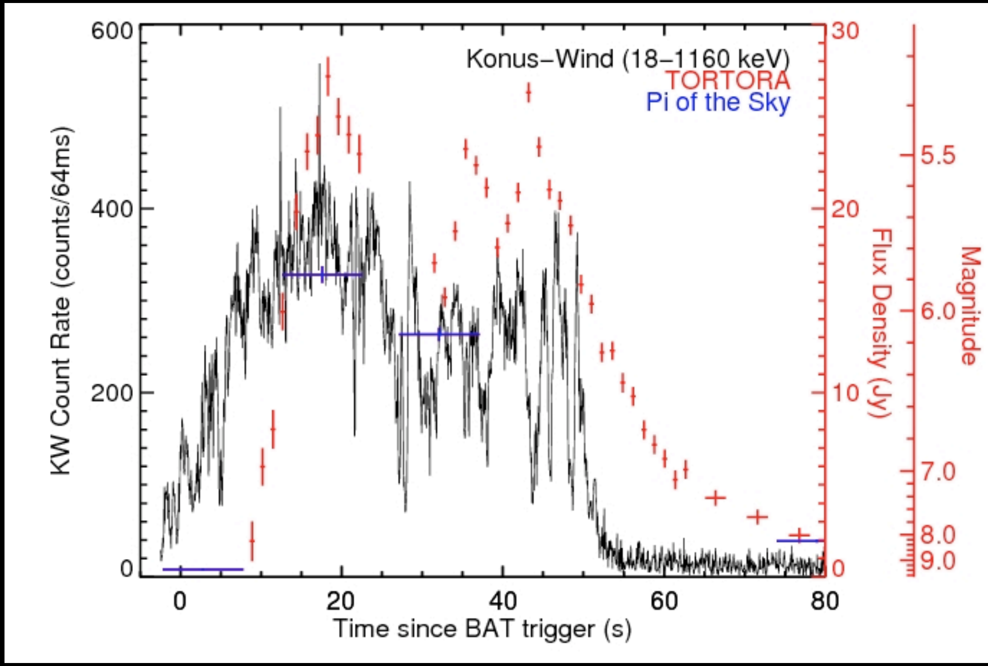
- Strong constraint on the radius from the synchrotron self-absorption

  - (Dissipative) photosphere: ✗ Additional process is needed ✔ (e.g. mechanism proposed by Beloborodov et al.)
  - Internal shocks: ✔ (late collisions)
  - Reconnection: ?

Optical emission from internal shocks



(Hascoët et al. 2011)



(Racusin et al. 2008)

Summary

Summary

Understanding the physical origin of the GRB emission is difficult, especially for the prompt emission.

- Dissipative photospheres are promising, however:

  - strong constraints on the unknown dissipation process
  - "complicated" model: different mechanisms for different components in the prompt (soft γ-rays, optical, GeV)

- Reconnection above the photosphere looks promising, however:

  - uncertainties both on the dynamics and the microphysics
  - difficult to conclude without any predictions for the spectrum
  - potential problem with the spectral shape (broadening by multi-emitters)

- Internal shocks can produce emission from optical to GeV. The model can be explored in details (spectral evolution, etc.). Results are promising, however:

  - large uncertainties on the microphysics
  - is there a problem with α ? With the efficiency ?
  - is there a problem with the general shape of the spectrum ? (too broad ?)

- Obsevations: a better description of the spectral properties is needed (issues with the present method of analysis, based on the Band model)