GRB emission mechanisms

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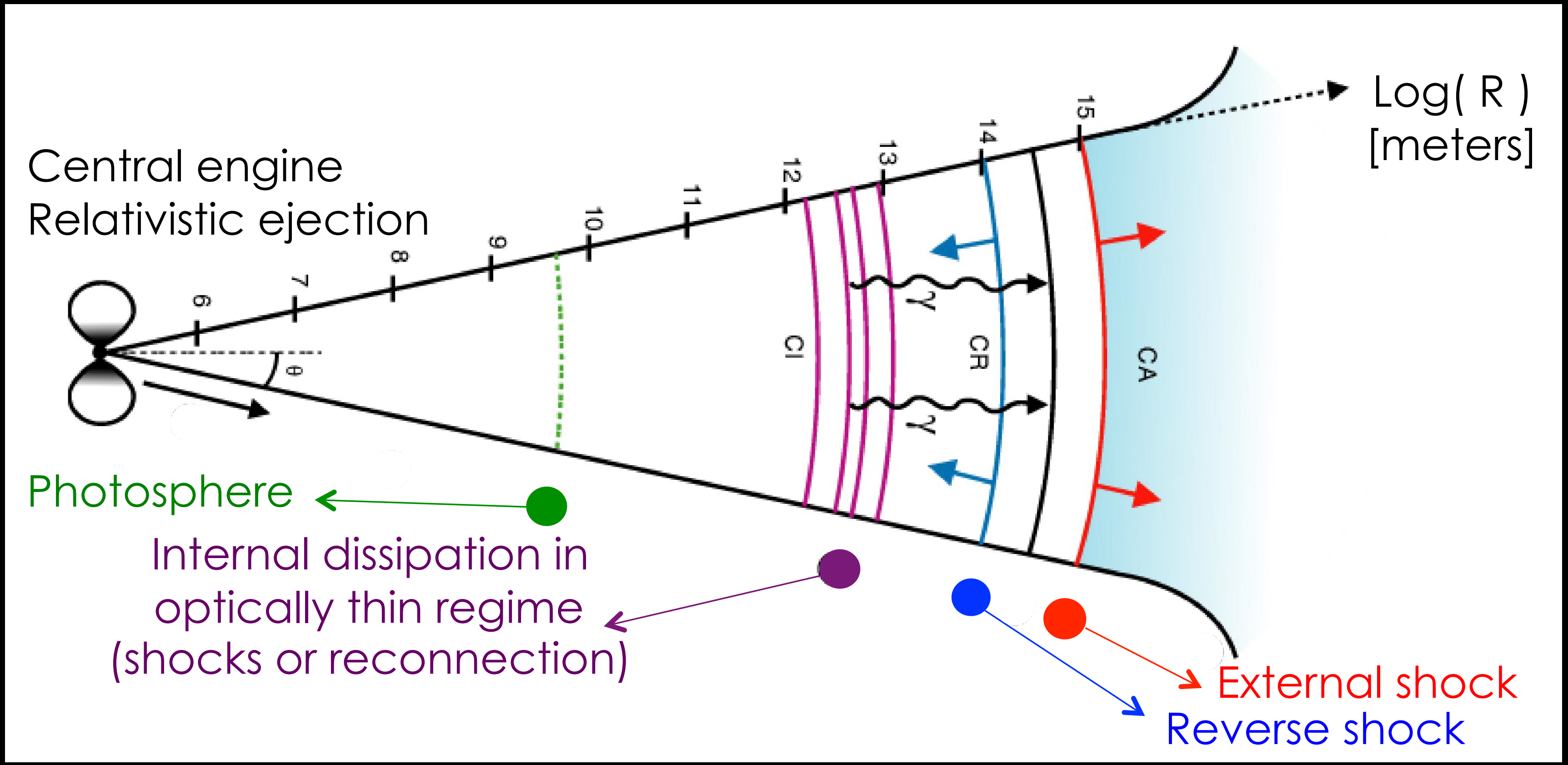
Possible emission sites in GRBs



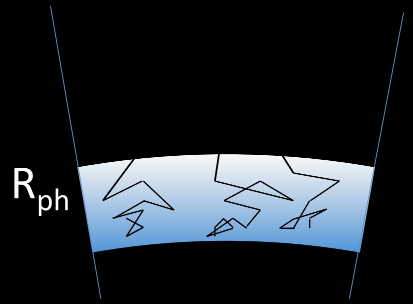
Contribution of each region ?
Dissipation mechanism ?
Radiative process ?

Internal dissipation: prompt

Deceleration: afterglow

Internal dissipation (1) photosphere

- PHOTOSPHERE:

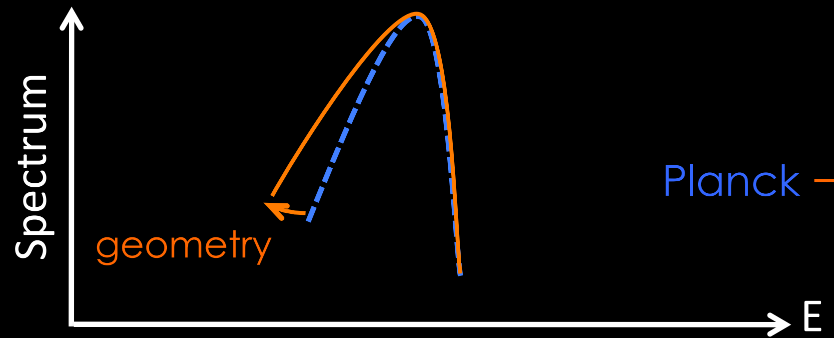


-The relativistic outflow becomes transparent

-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

Internal dissipation (1) photosphere

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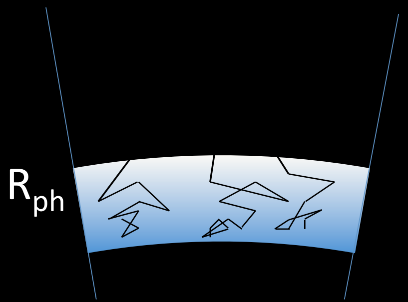
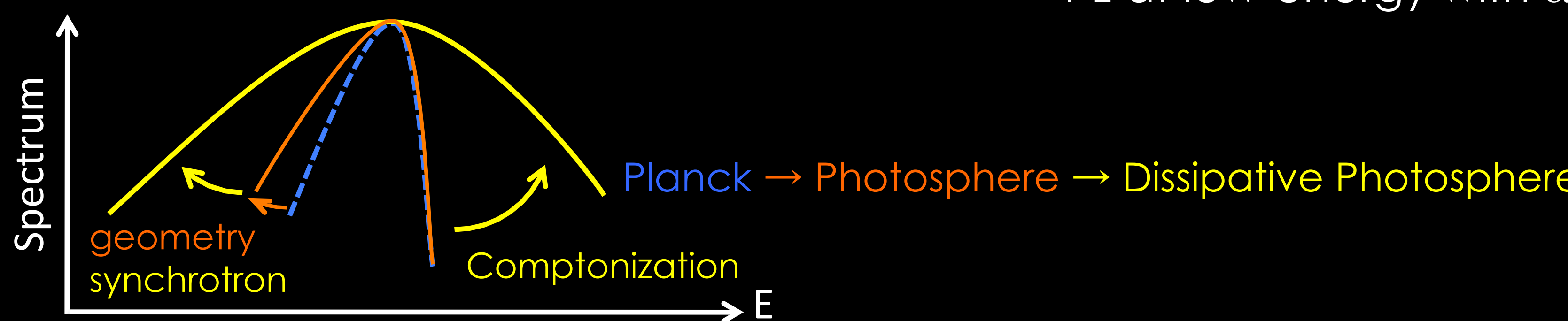




- DISSIPATIVE PHOTOSPHERE:

-Sub-photospheric dissipation: non-thermal electrons

-Large uncertainties: details of the dissipation process
neutron heating ? internal shocks ? reconnection ? …

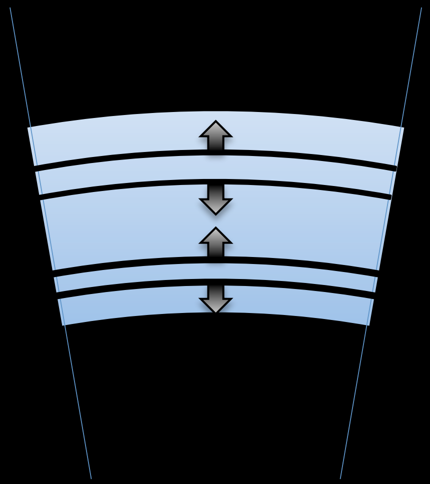
-Spectrum is non-thermal:
Comptonization: high-energy tail
Synchrotron radiation: modifies the low-energy slope

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 ?

- INTERNAL SHOCKS:



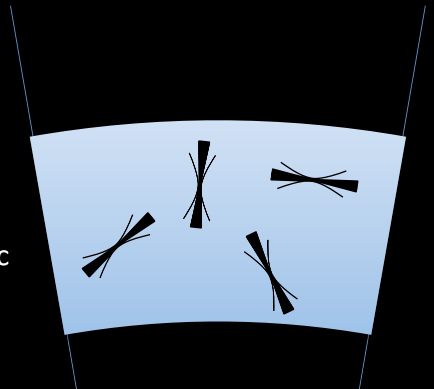
R_{IS}

-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)

- RECONNECTION:



R_{rec}

-Assumes: Variability + large mag. at large distance

-Large uncertainties: radius ? microphysics ?

-Non-thermal spectrum

Prompt soft gamma-ray emission

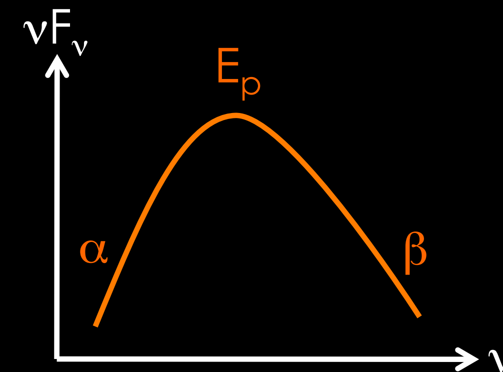
Light curves

All possible sites for the prompt emission can reproduce the observed variable light curves, but with important differences:

- (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.
  - -Instantaneous spectrum is narrow
- DISSIPATIVE PHOTOSPH.: ✔ ?
  - -α correct (depends on magnetization)
  - -Instantaneous spectrum is narrow

Time-integ. spec. ?

- INTERNAL SHOCKS: ?
  - -Synchrotron only: α = -3/2 (fast cooling)
  - -Possible mechanisms to increase α IC in KN regime ; B decay in shocked region
  - -Other process ?
  - -Spectrum is too broad around the peak ?
- RECONNECTION: ?
  - -α correct ? (slow heating in turbulent acc.)
  - -Spectrum is probably much too broad (multi emitters)

Spectrum (2) observations

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

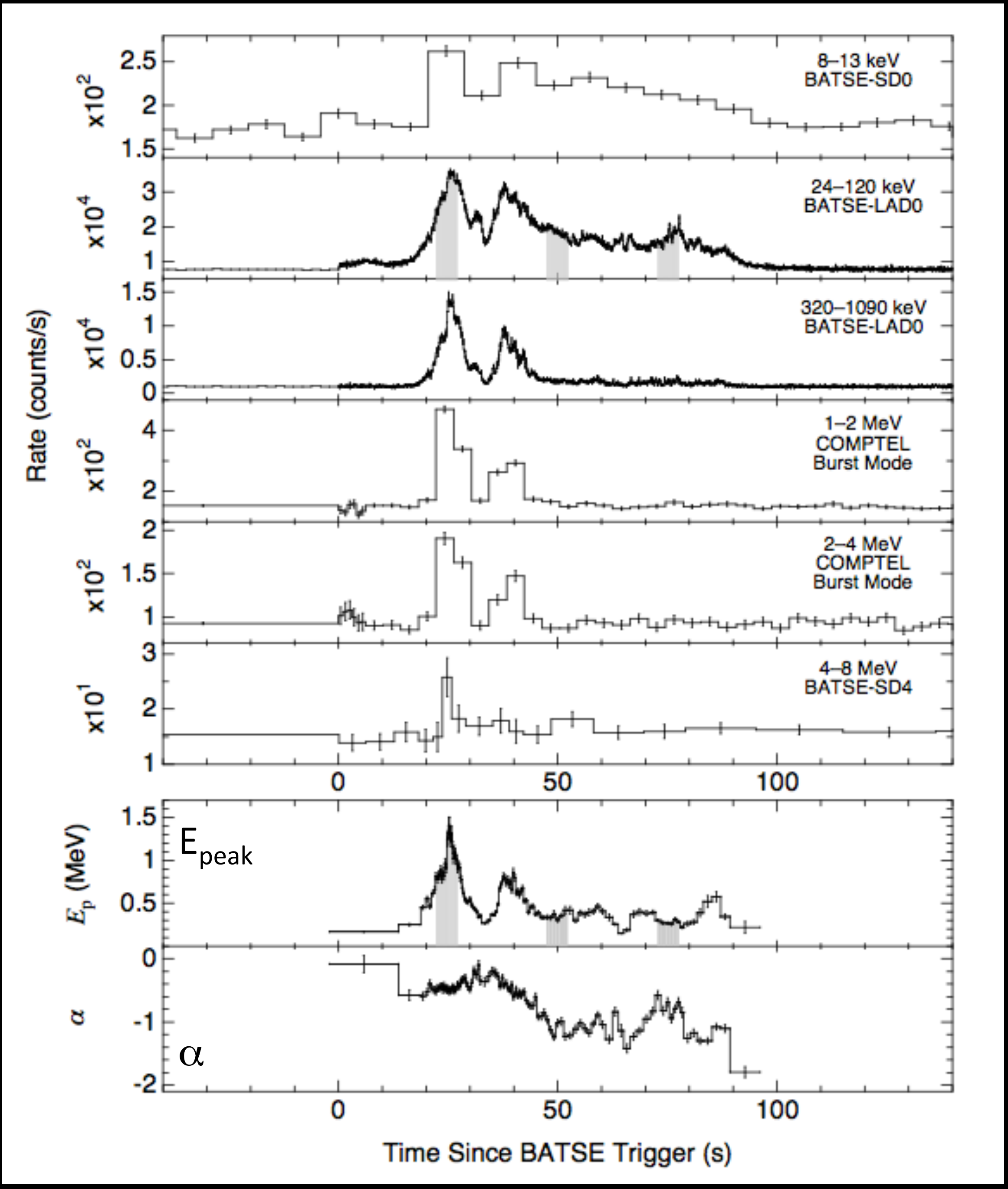
  -*Fermi* bursts: multi-component spectra (2, 3 components)

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

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

  -Spectral evolution in GRBs

GRB 990123



(Briggs et al. 1999)

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

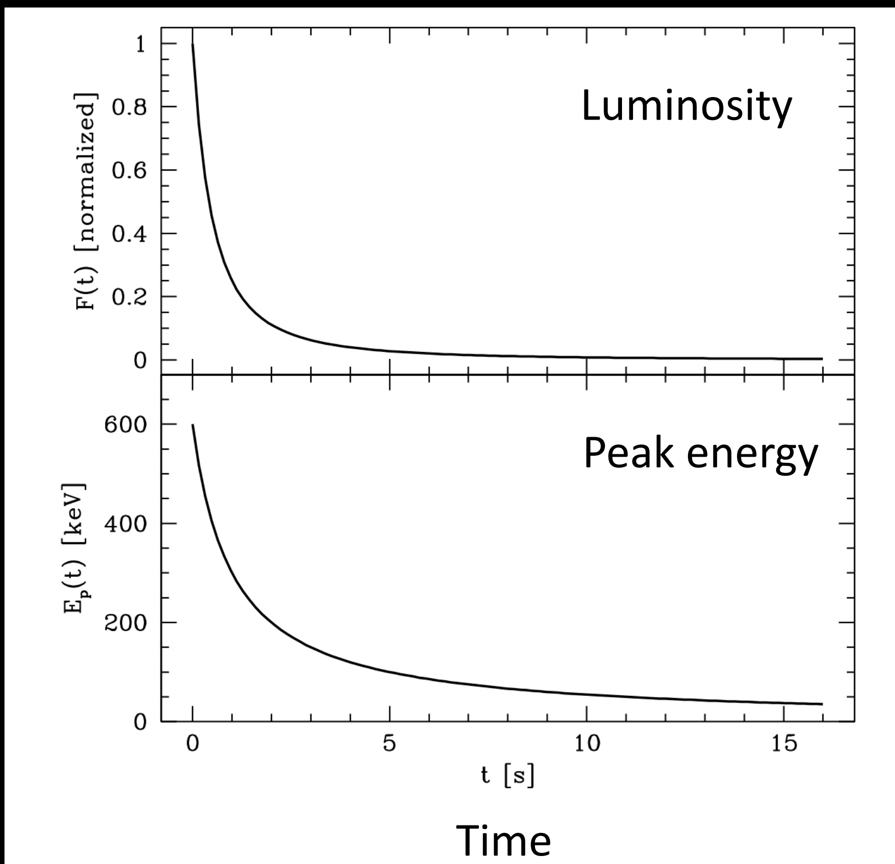
- Should we believe that the spectrum is narrow around the peak ?

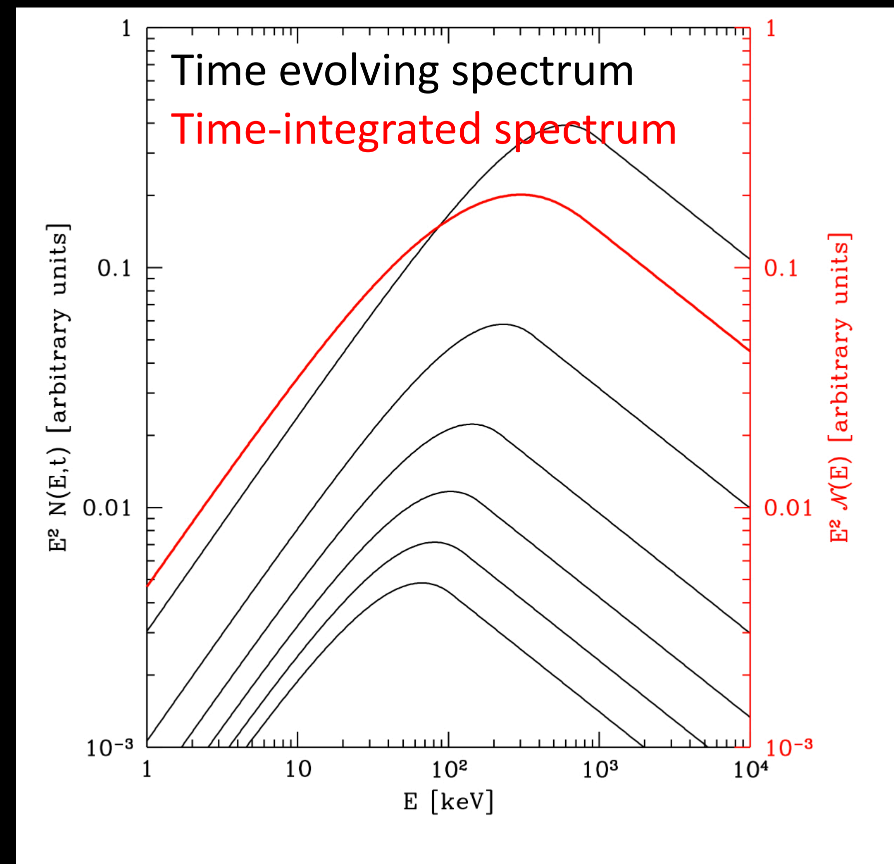
  -Spectral evolution in GRBs

  -The integration of a time-evolving Band function is <u>not</u> a Band function (it is broader)

Pulse

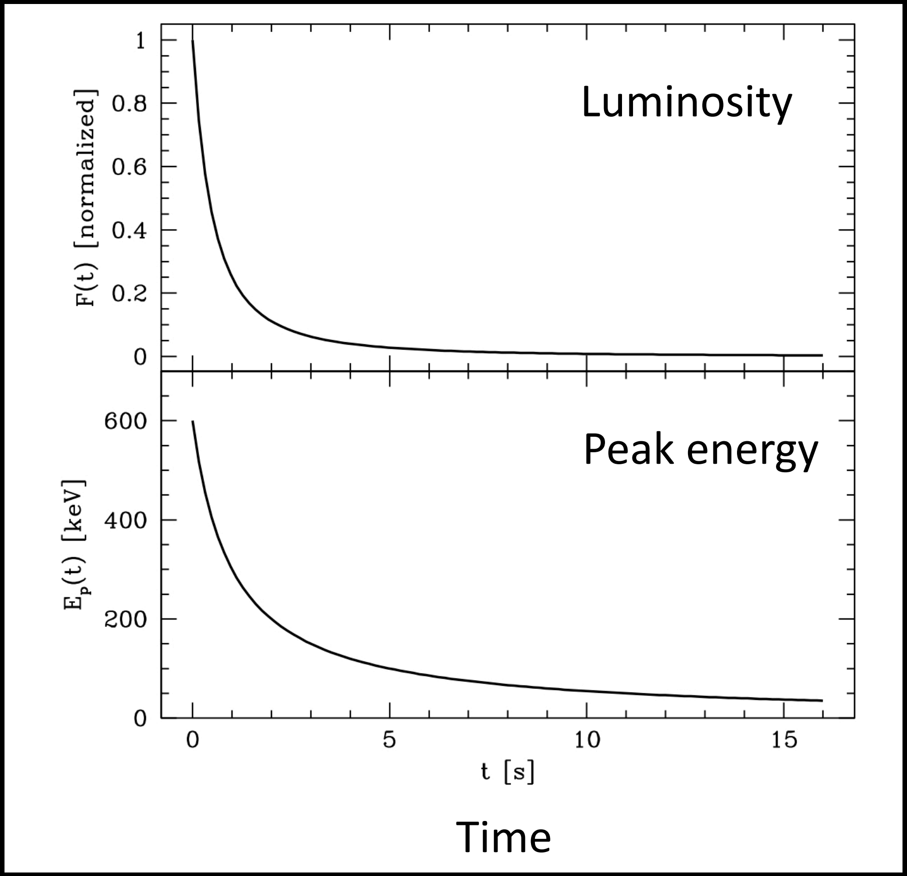
Typical pulse decay

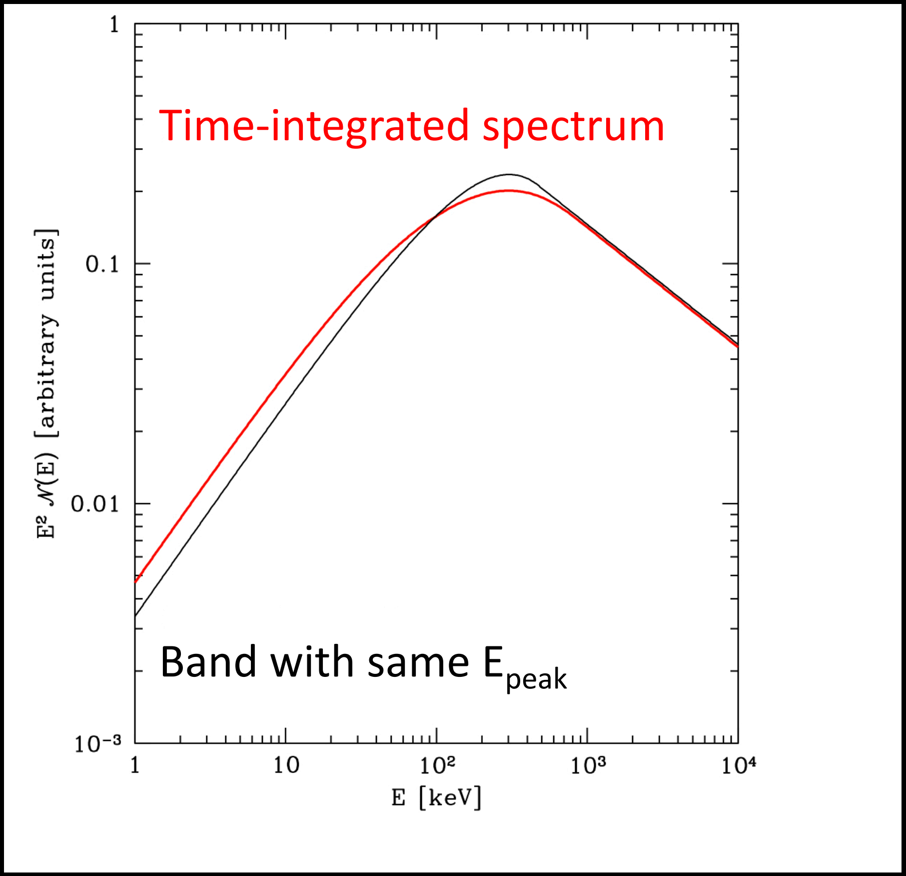




Pulse

Typical pulse decay





The integration of a time-evolving Band function is <u>not</u> a Band function.

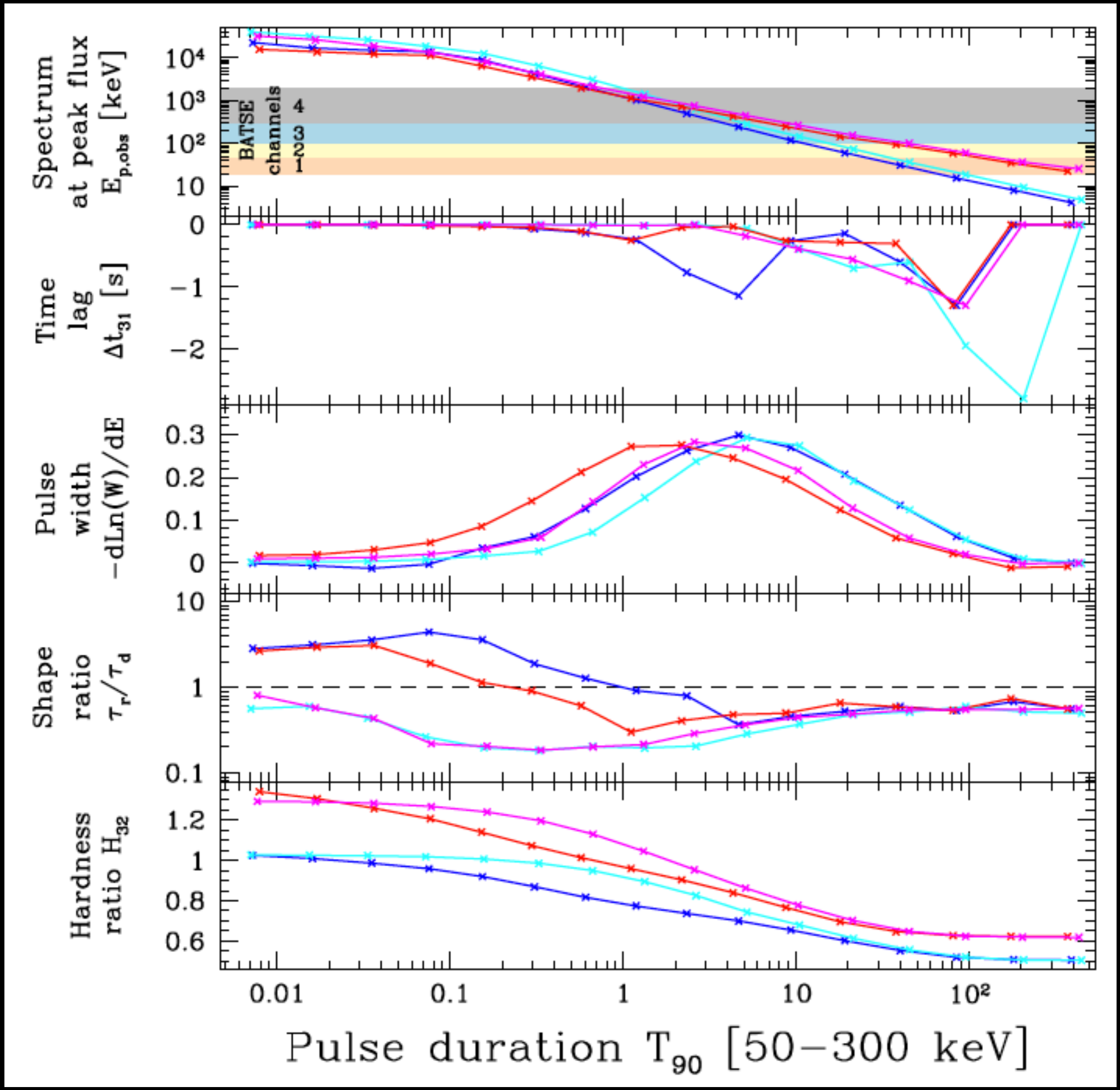
Distribution of Epeak
Hardness-Duration correlation

- 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: ?
- Short bursts have usually higher peak energies
  - -dissipative photosphere: change in properties of central engine ?
  - -internal shocks: natural explanation ✔
  - -reconnection: ?

Hardness-Duration in internal shocks

Effect of duration:

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



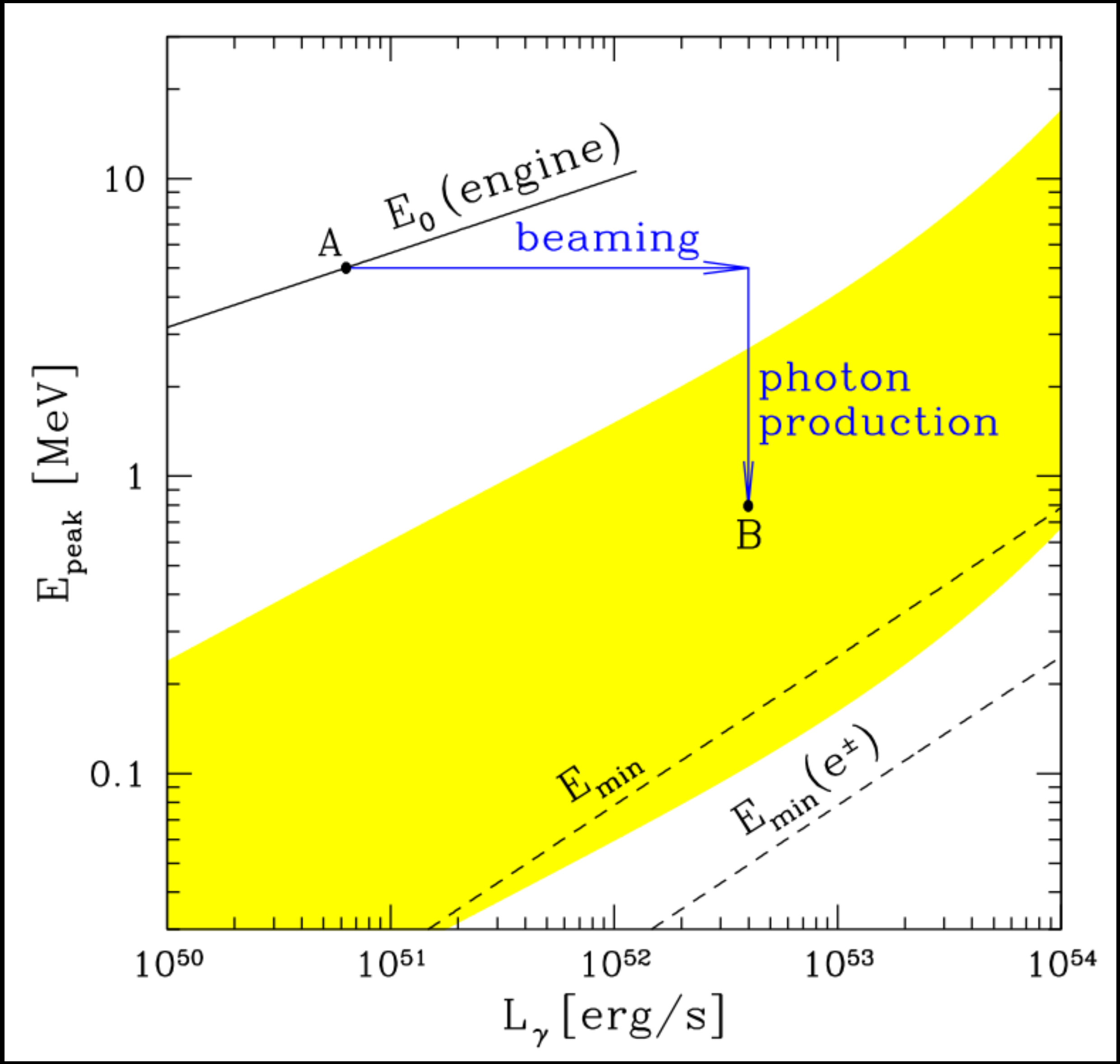
Pulse calculation: the only varying parameter is the duration (Bosnjak & Daigne submitted)

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
- Reconnection: ?

Dissipative photosph.: spectral evolution

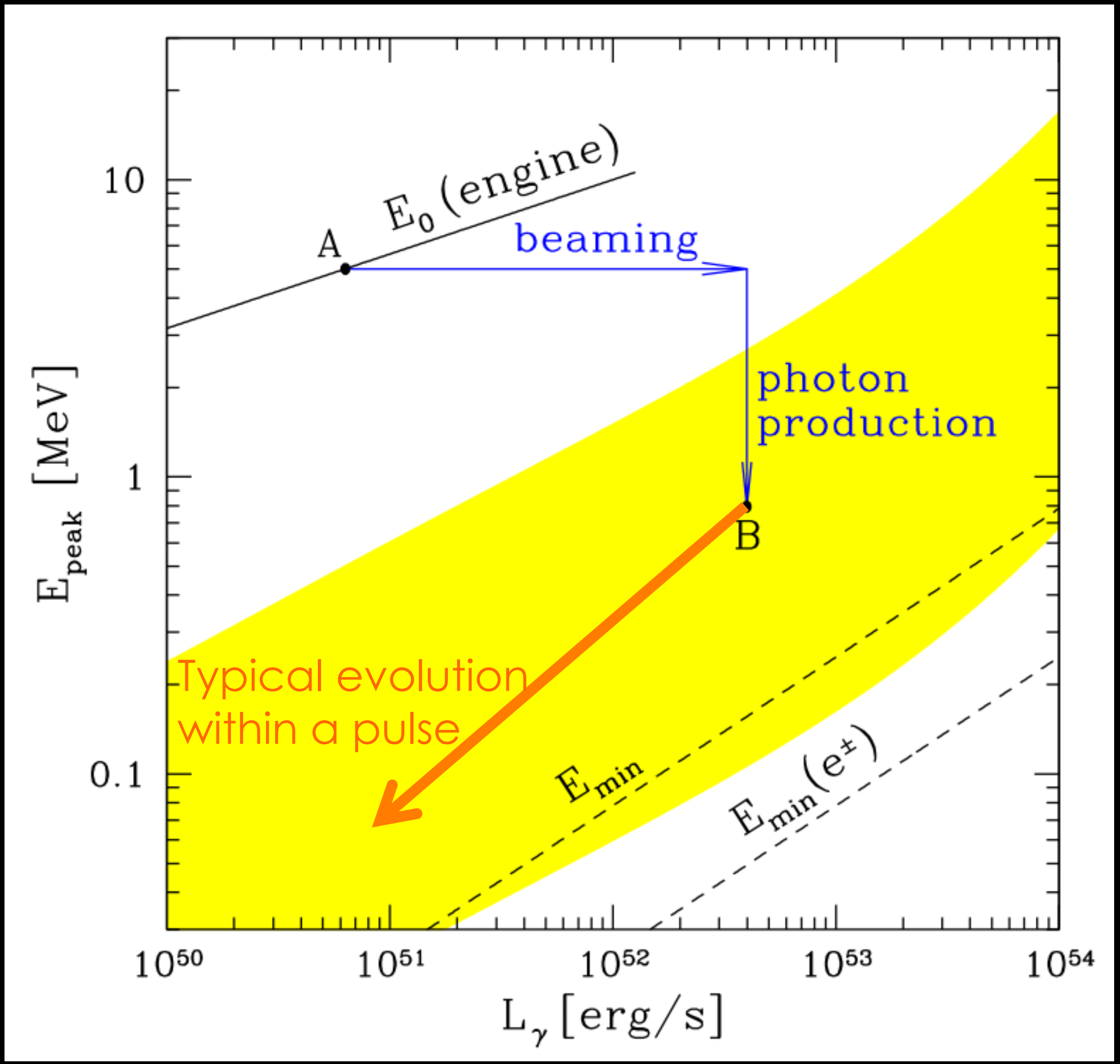


(Beloborodov 2013)

Dissipative photosph.: spectral evolution

What are the constraints on the dissipative process ?

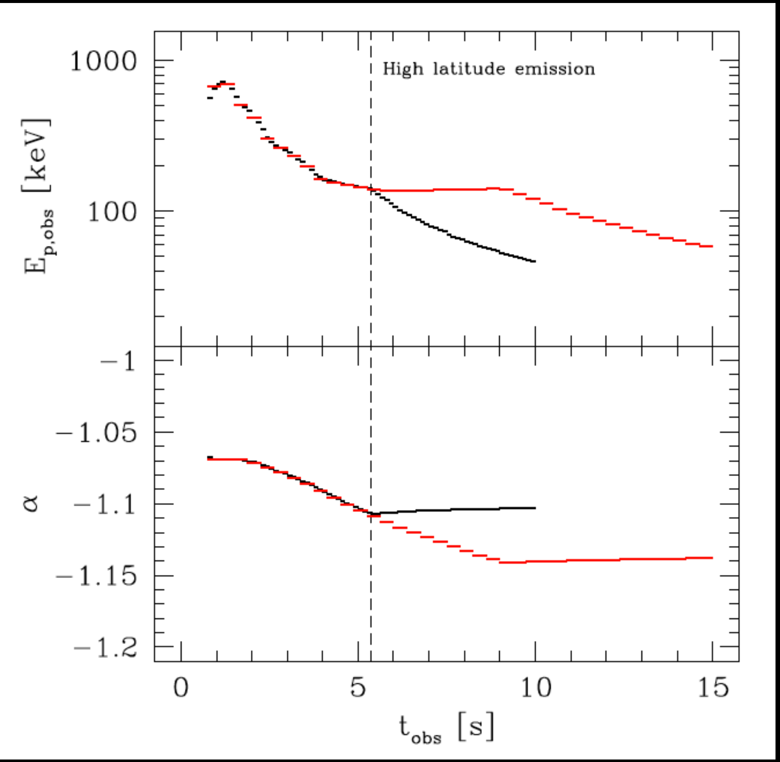
How does the dissipative process adjust its radius to the photospheric radius ?



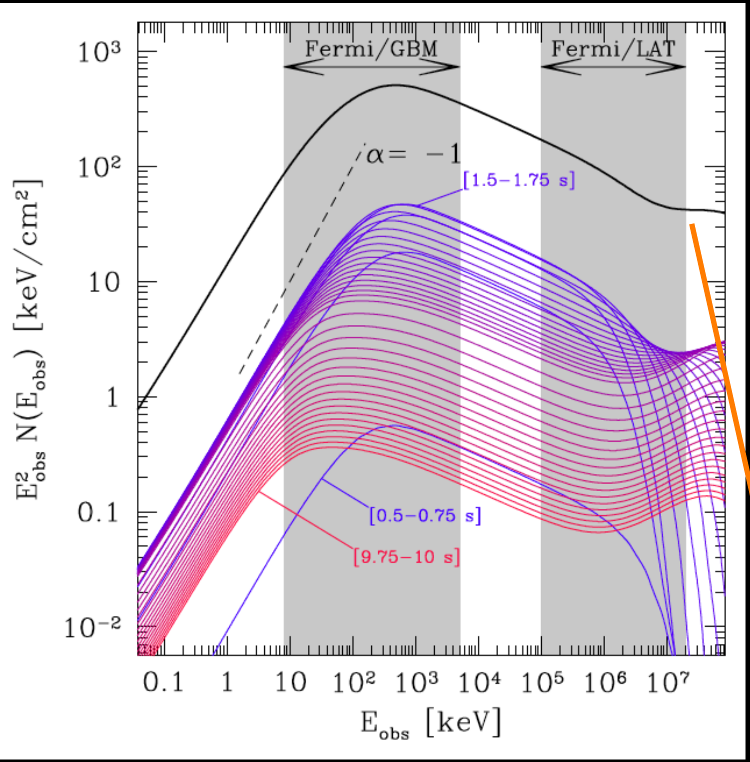
(Beloborodov 2013)

Internal shocks: spectral evolution

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



Evolution of E_{peak} and α



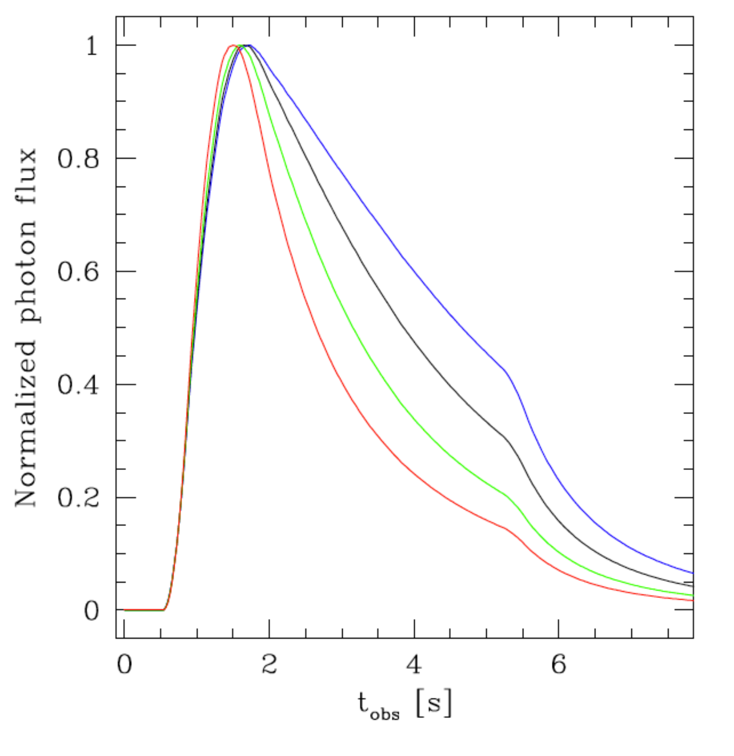
Time-evolving spectrum

Additional PL component with index ~-2 ?

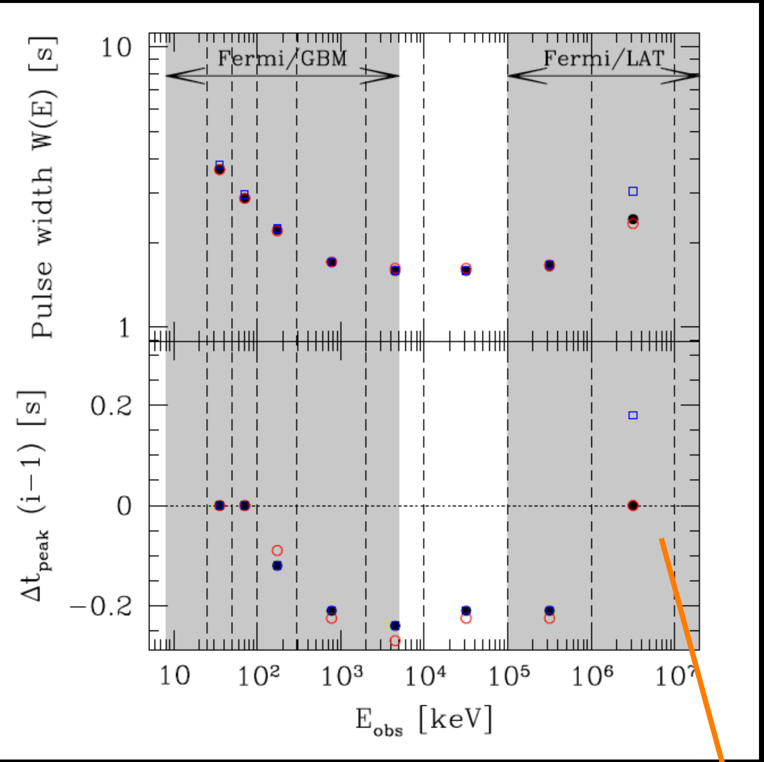
(Bosnjak & Daigne submitted ; see also Asano & Meszaros)

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)



Pulse width and time lags

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

Delayed onset ? $\gamma\gamma$?
(Hascoet et al. 2012)

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

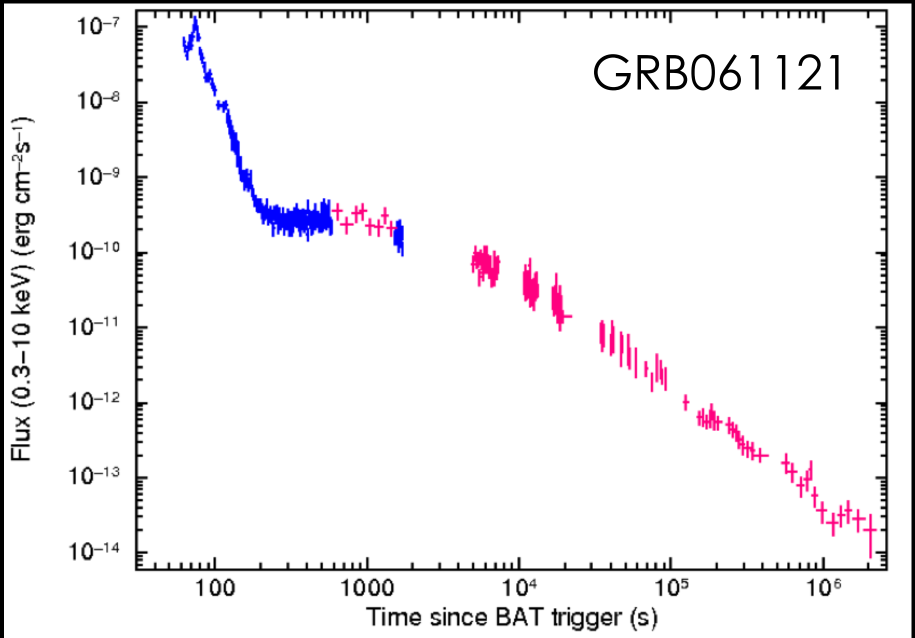
The end of the prompt emission: X-ray early steep decay

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

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

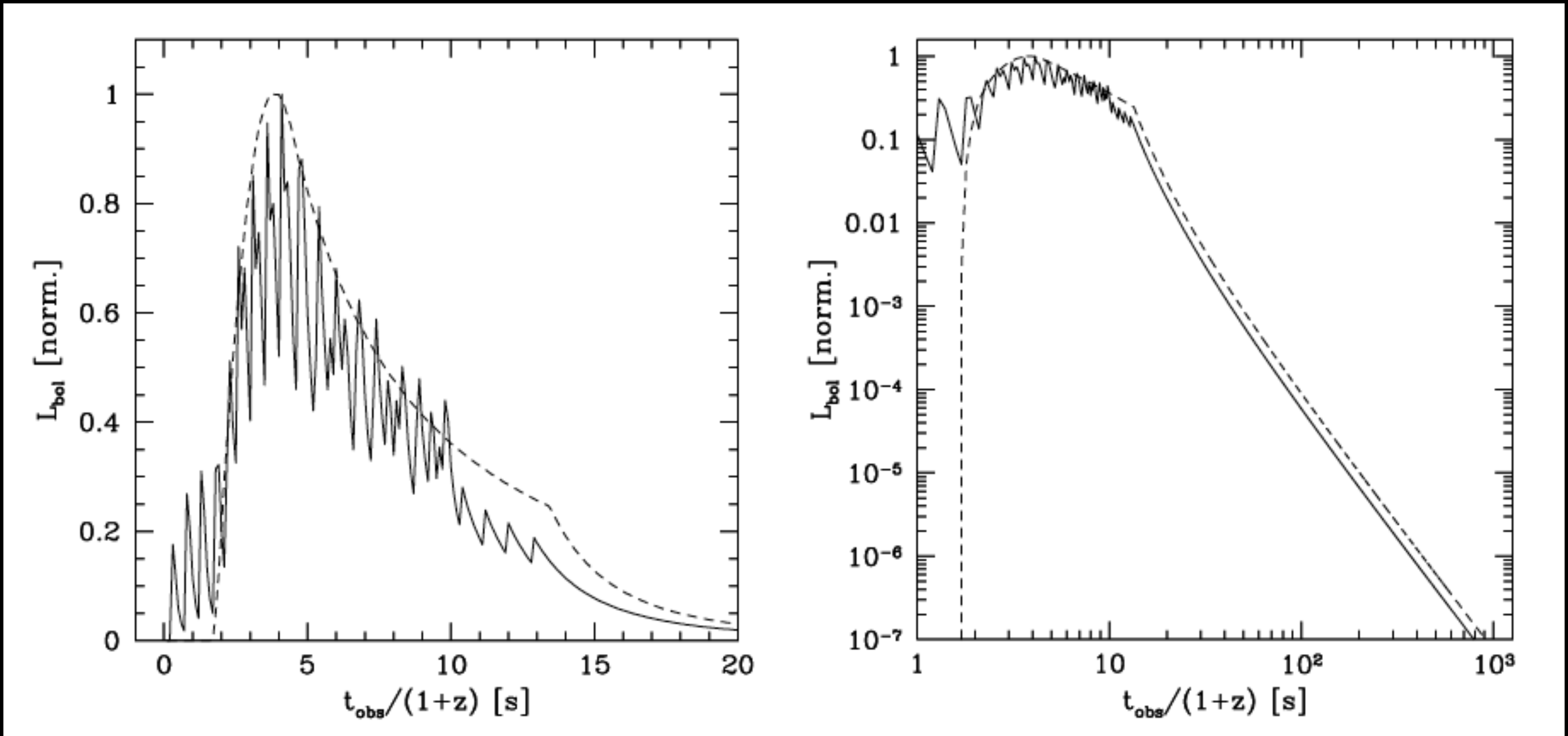
  -Internal shocks: ✔ (final radius of the order of Γ^2 c t_{burst})

  -Reconnection: ✔ ? (final radius ?)



(Page et al. 2007)

High-latitude emission in internal shocks



(Hascoët et al. 2012)

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

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

  -Internal shocks: ✔

  -Reconnection: ✔ ?

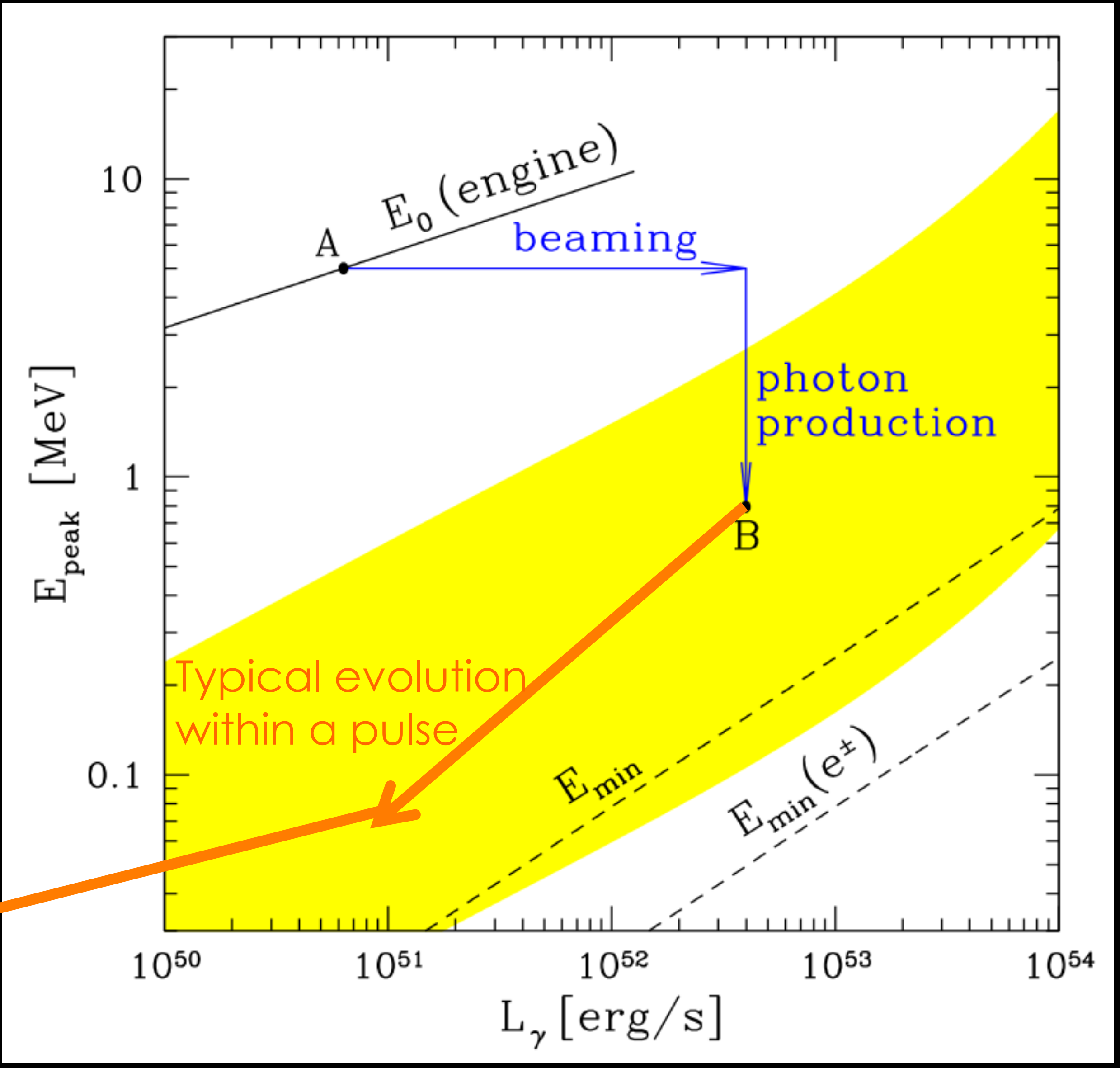
- Alternative explanation: late evolution of the central engine

  - 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



Typical X-ray early steep decay

(Beloborodov 2013)

Electron acceleration in intern. shocks ?

Microphysics is the main source of uncertainties in internal shocks. It is sometimes proposed that they play only a dynamical role, without associated emission.

- Acceleration is difficult (PIC simulations, …) :

  However, if electron acceleration does not work in the mildly relativistic regime, then:

  Major crisis !

  -no emission from internal shocks, even in non GRB sources

  -no emission from the reverse shock

  -no emission from the late forward shock

- Shock acceleration leads to Maxwellian+Power-law tail: one should detect the Maxwellian !

  Same question should be asked for the Forward and Reverse Shock

  Small ε_e(Maxwell) / ε_e(PL) ?

Dissipative photosphere: emission above the photosphere ?

- Several possible dissipation process have no reasons to stop close to the photosphere:

  e.g. internal shocks, reconnection

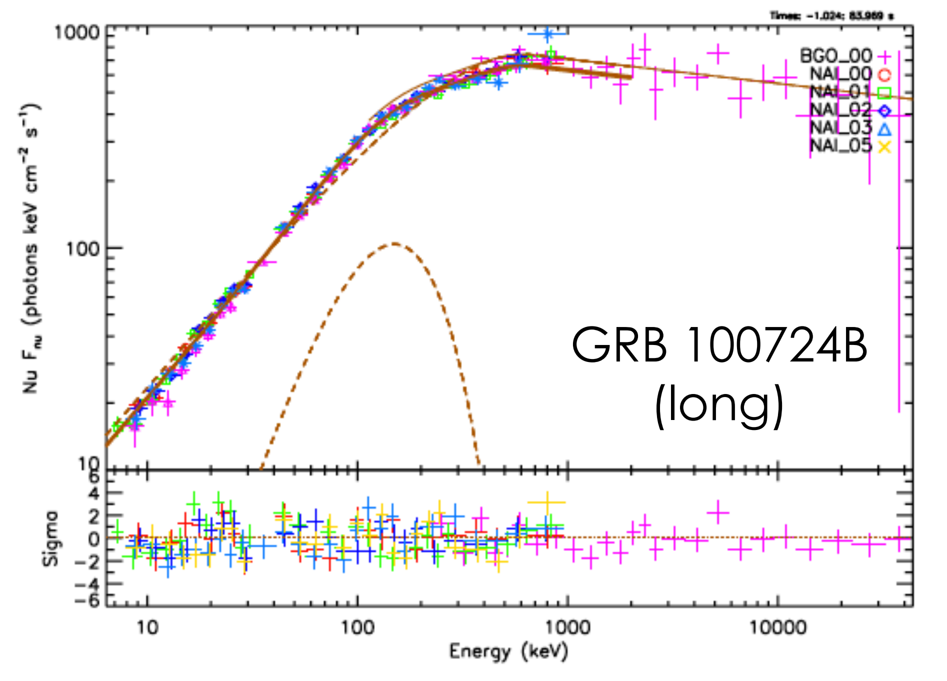
- Hidden component in the spectrum ?

  No detection: constraints on the dissipation efficiency ?

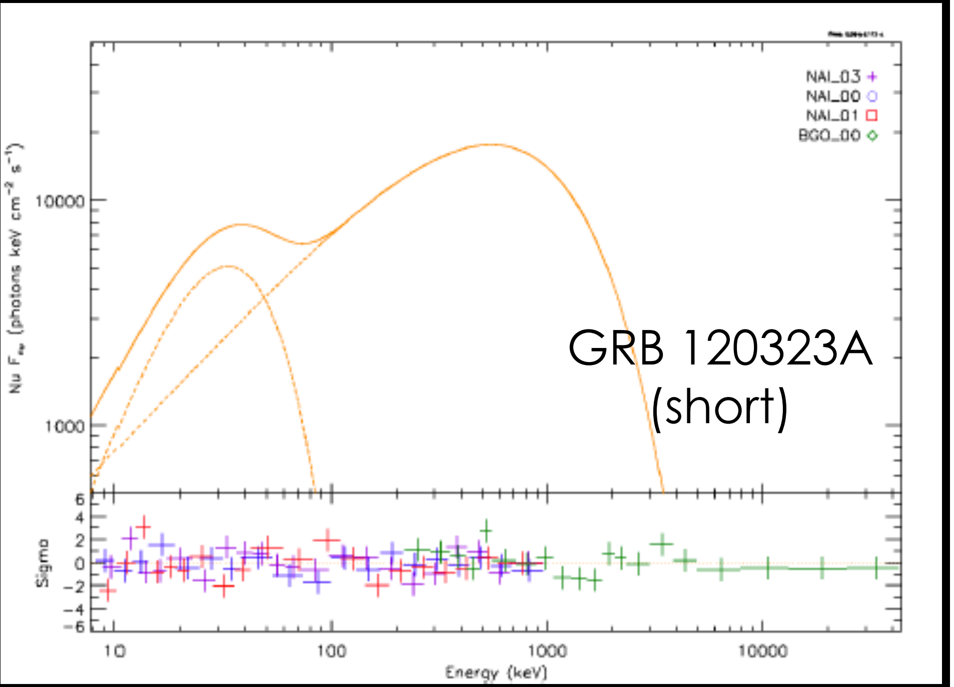
Photosphere+internal shocks/reconn.

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 ?



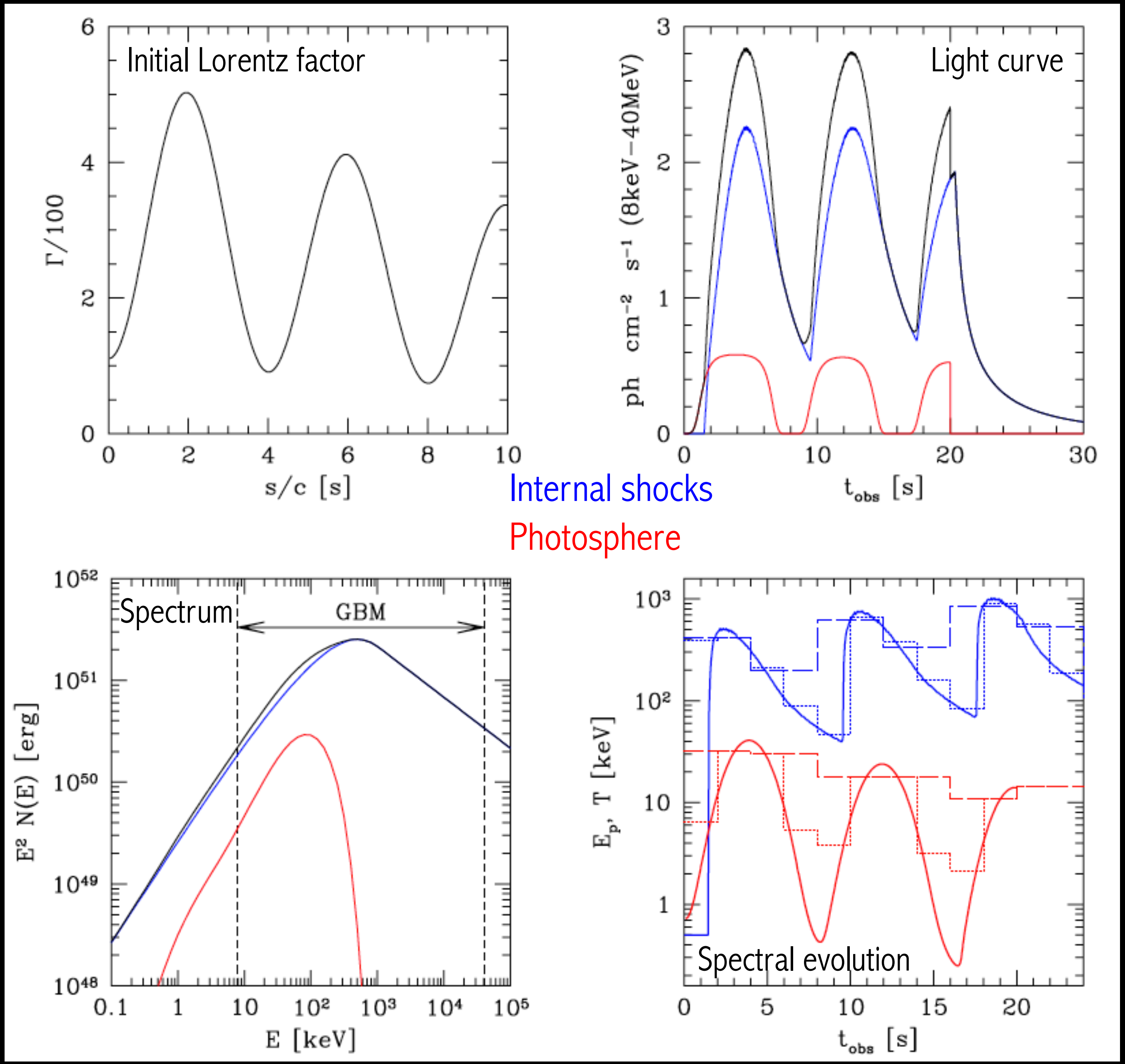
Guiriec et al. (2011)



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

Photosphere + internal shocks



Hascoet, Daigne & Mochkovitch 2013

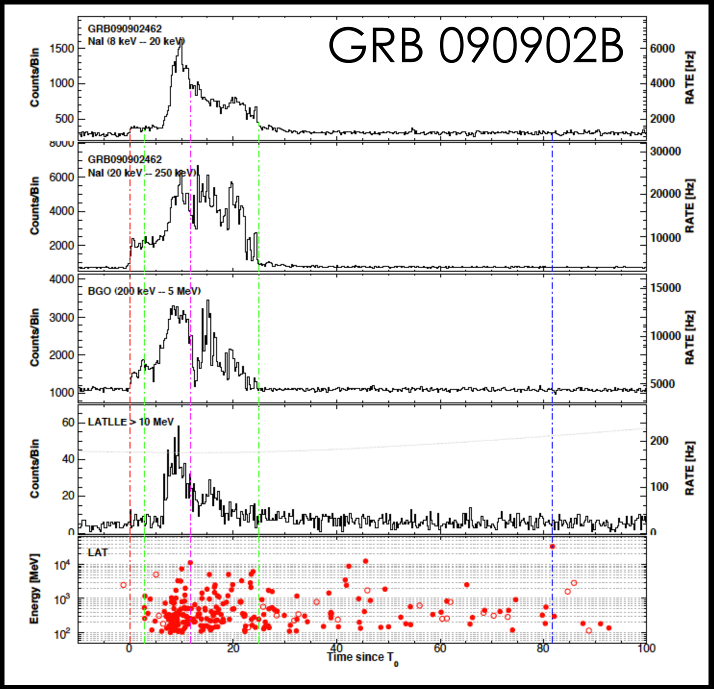
Prompt GeV emission

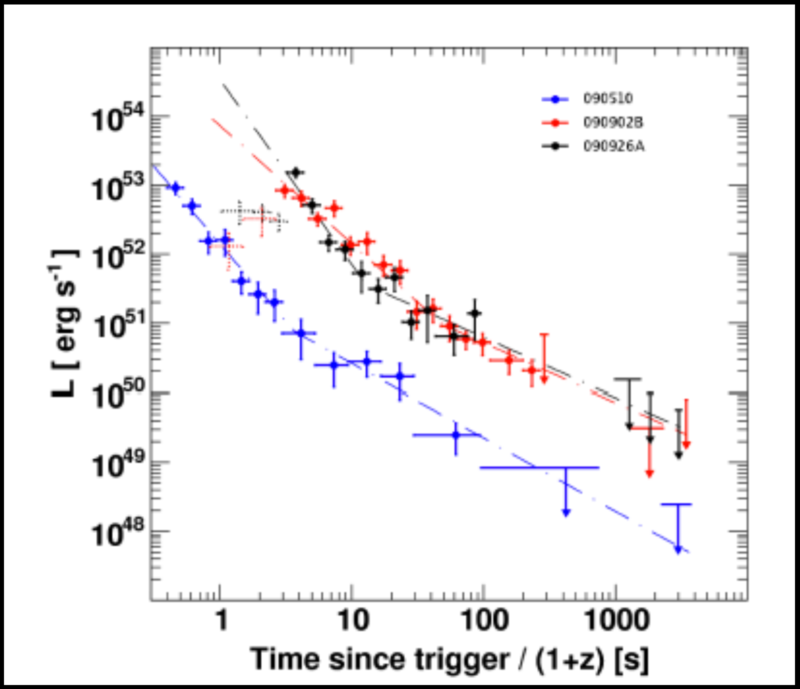
Prompt optical emission

Prompt GeV emission (LAT)

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

(1st GRB LAT catalog)

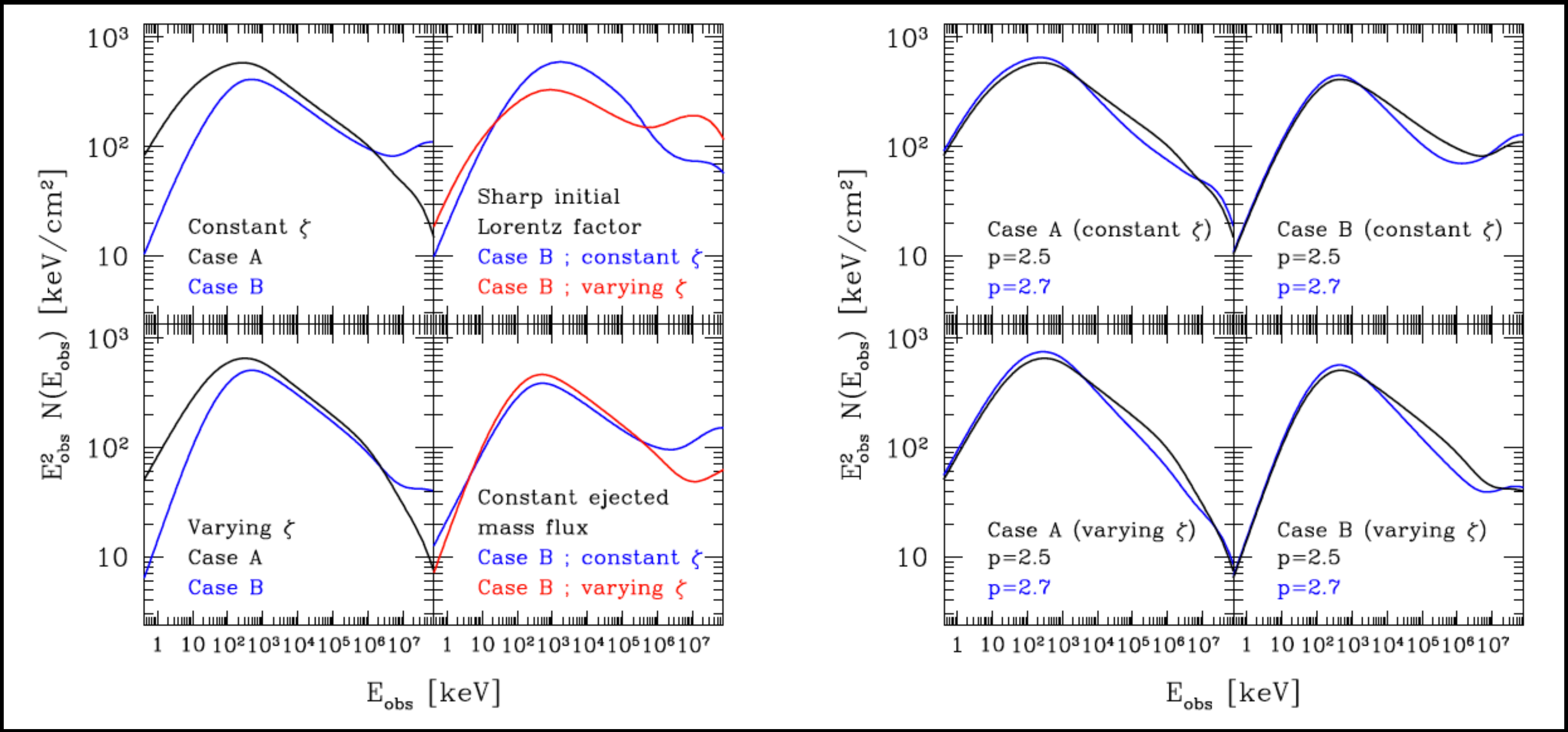




$t_{var} < 100$ ms

- 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

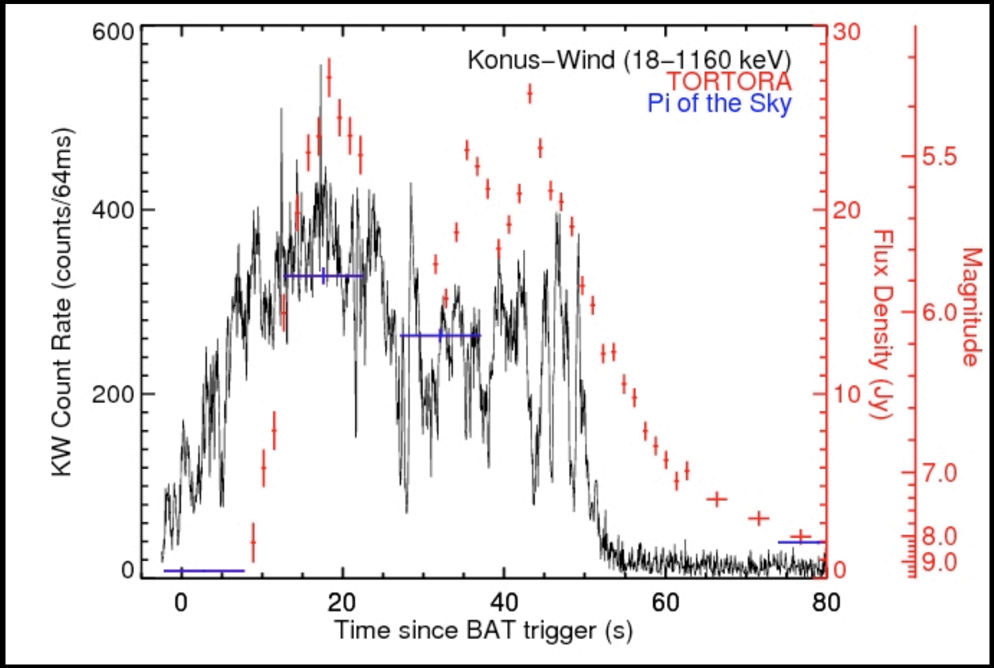


(Bosnjak & Daigne submitted ; see also Asano & Meszaros)

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

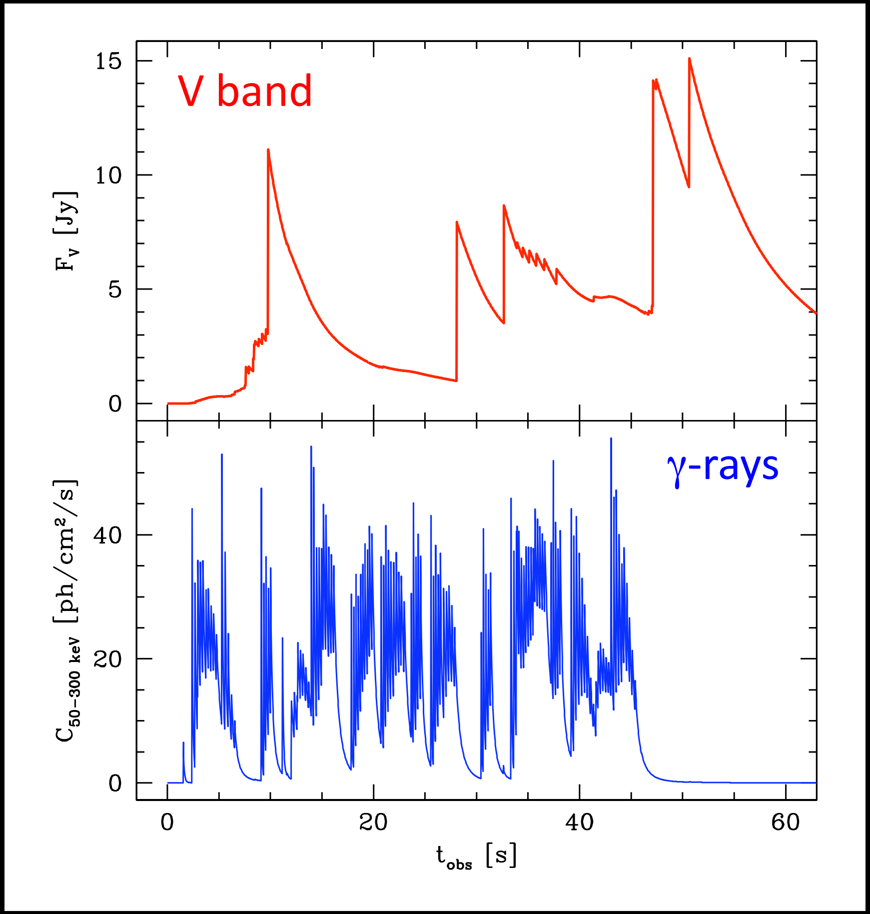
  - (Dissipative) photosphere: ✗

    Additional process is needed ✔ (e.g. mechanism proposed by Beloborodov et al.)

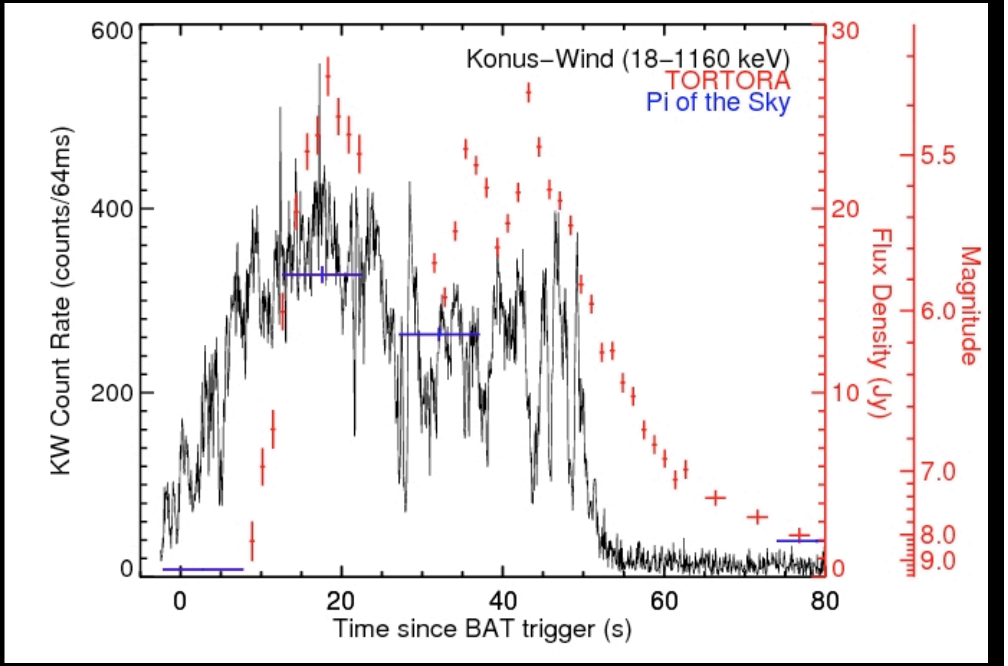
  - Internal shocks: ✔ (late collisions)

  - Reconnection: ?

Optical emission from internal shocks



(Hascoët et al. 2011)



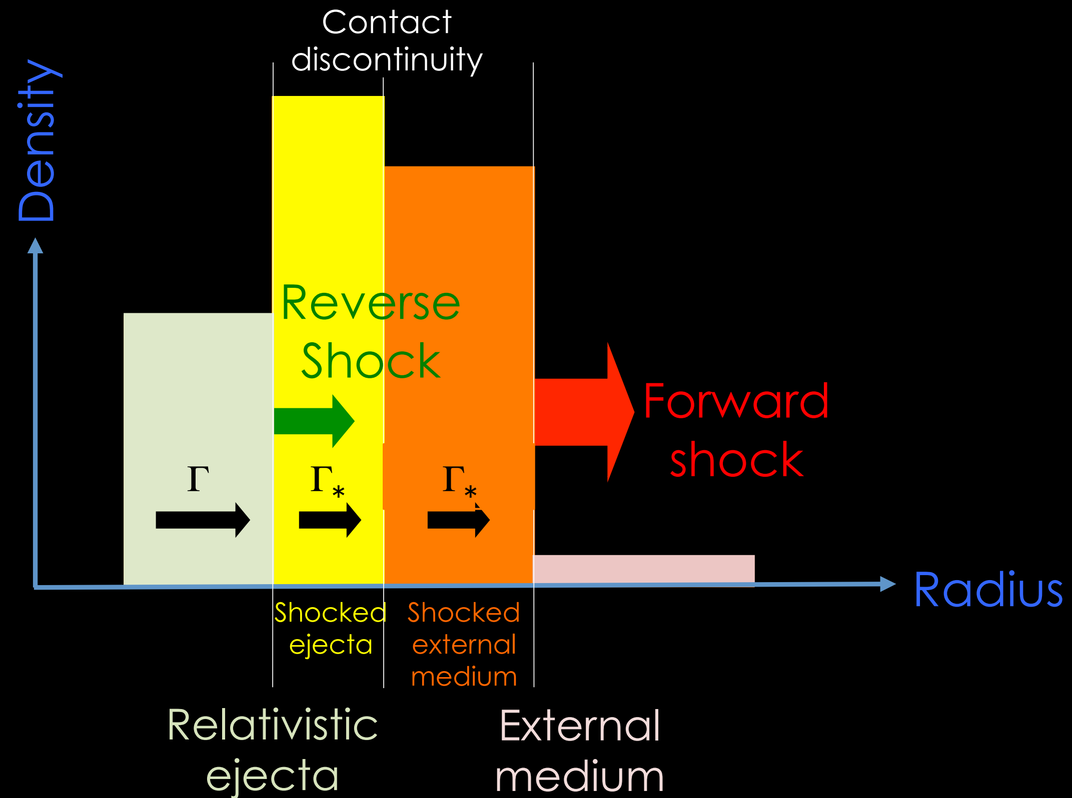
(Racusin et al. 2008)

Afterglow

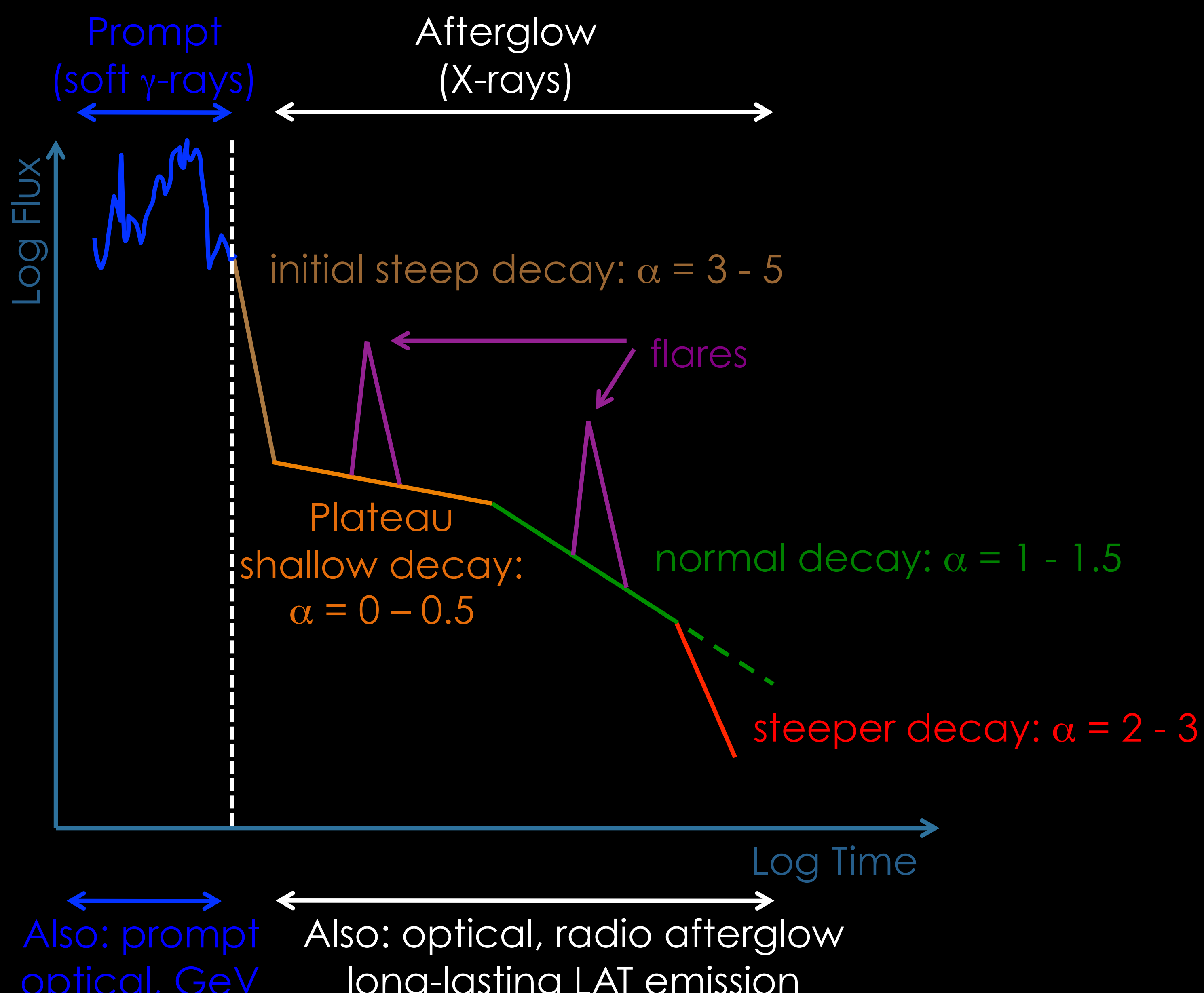
Deceleration: emission sites

- FORWARD SHOCK: -Dynamics is well understood
  -Main uncertainty: microphysics (but also: external medium)
- REVERSE SHOCK: -Assumes low magnetization at large distance
  -Main uncertainty: microphysics

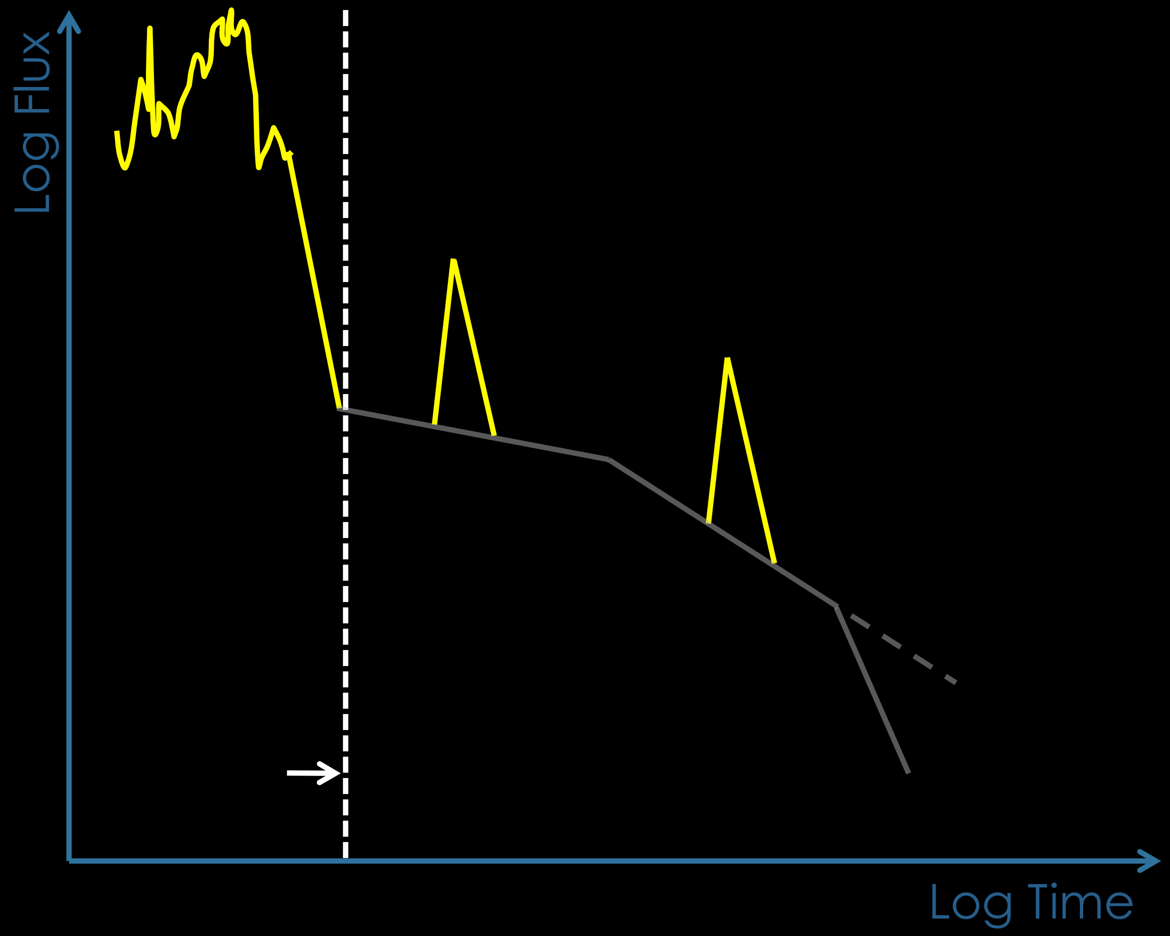
In both cases: non-thermal radiation from shock-accelerated electrons



GRB emission

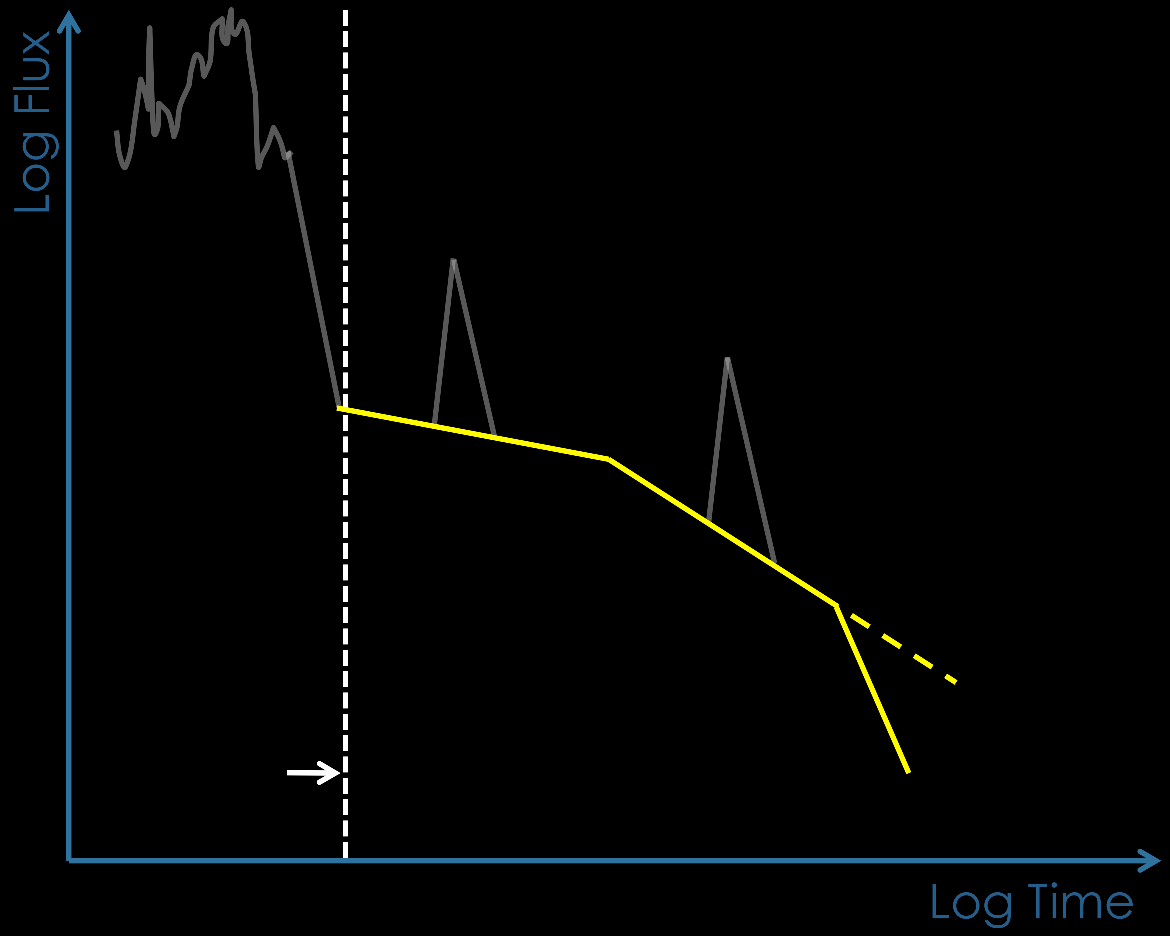


GRB emission: « standard » model



Internal origin

GRB emission: « standard » model



External origin

Some issues with afterglow theory

- Early X-ray afterglow: plateaus
  - FS: - late activity of the central engine ? ✗ (energy crisis)
    - varying microphysics ?
  - RS: OK if long lasting RS due to low-Γ tail

  Requires: - inefficient radiation from FS (acceleration in UR regime ?) ?
  - comparable efficiency prompt/RS (internal shocks ?) ✔?
- Variability in optical afterglows: bumps (e.g. GRB 030329)
  - FS: - density clumps ✗
    - Refreshed shocks ? ✔? (requires very low $\Delta\Gamma/\Gamma$: post IS ?)
  - RS: OK if long lasting RS due to low-Γ tail (same constraints as above)
- Variability in X-ray afterglows: flares
  - FS: - impossible ✗
    - Requires late prompt emission ?
  - RS: OK if long lasting RS due to low-Γ tail ✔?

  Requires: - over-densities in ejecta (a signature from internal shocks ?)

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:

  - 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)