Modelling the prompt emission from Gamma-Ray Bursts

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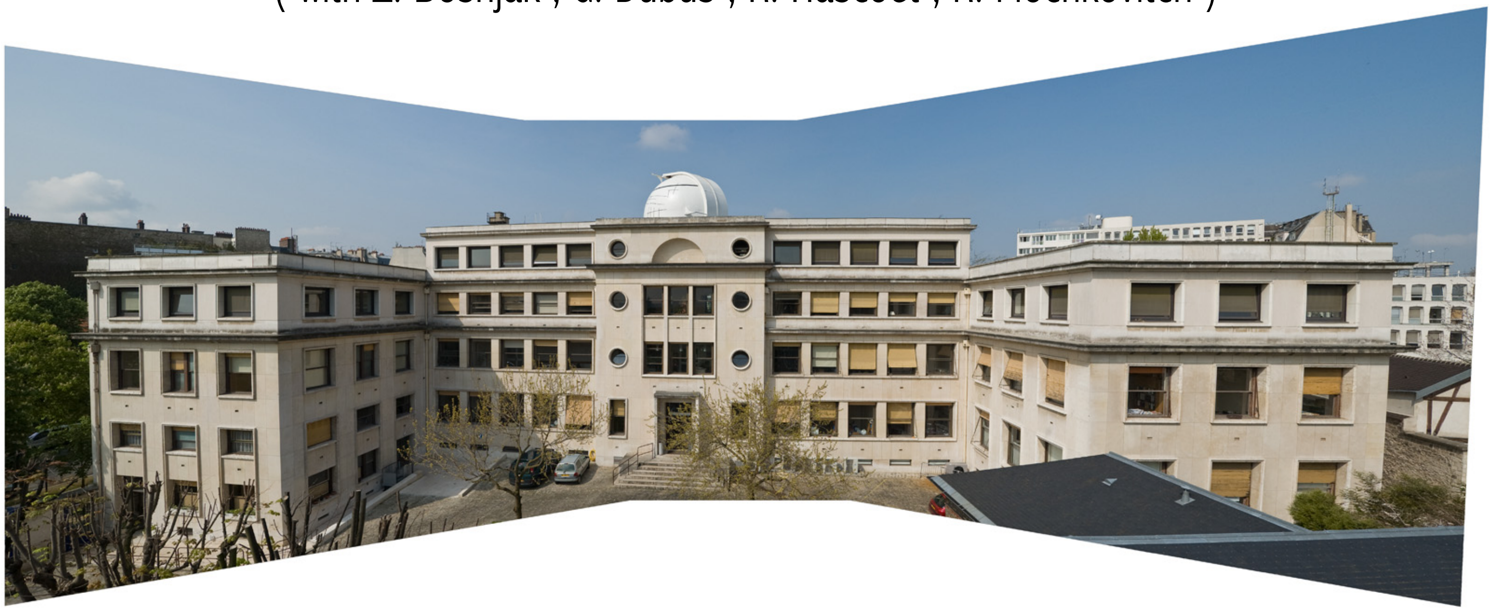
(with Z. Bosnjak ; G. Dubus ; R. Hascoët ; R. Mochkovitch)



Gamma-Ray Bursts 2010 Conference – November 1-4, 2010 – Annapolis, MD

General framework

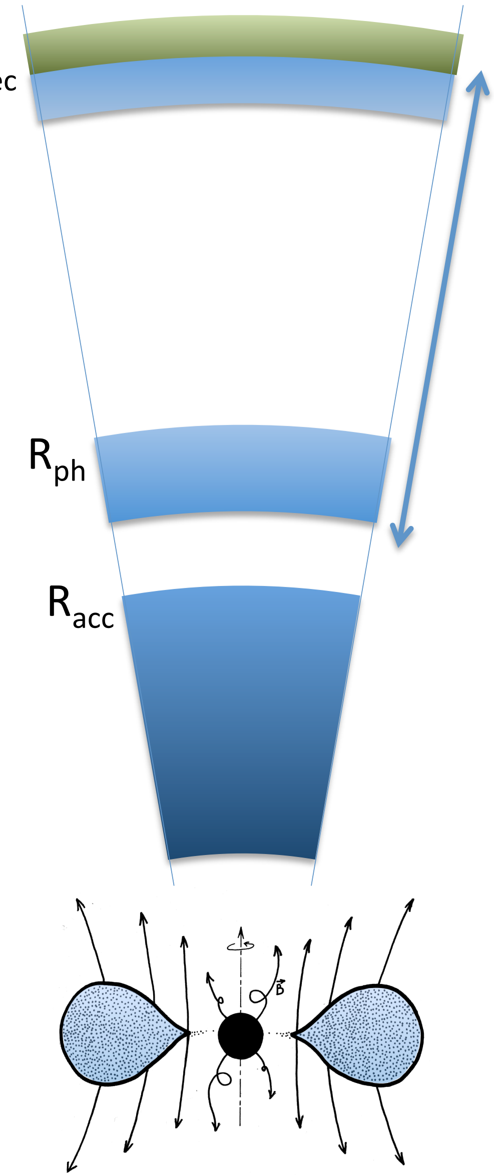
Deceleration by the circumburst medium

Outflow becomes transparent for its own radiation

Acceleration of the outflow

Energy release by the central source

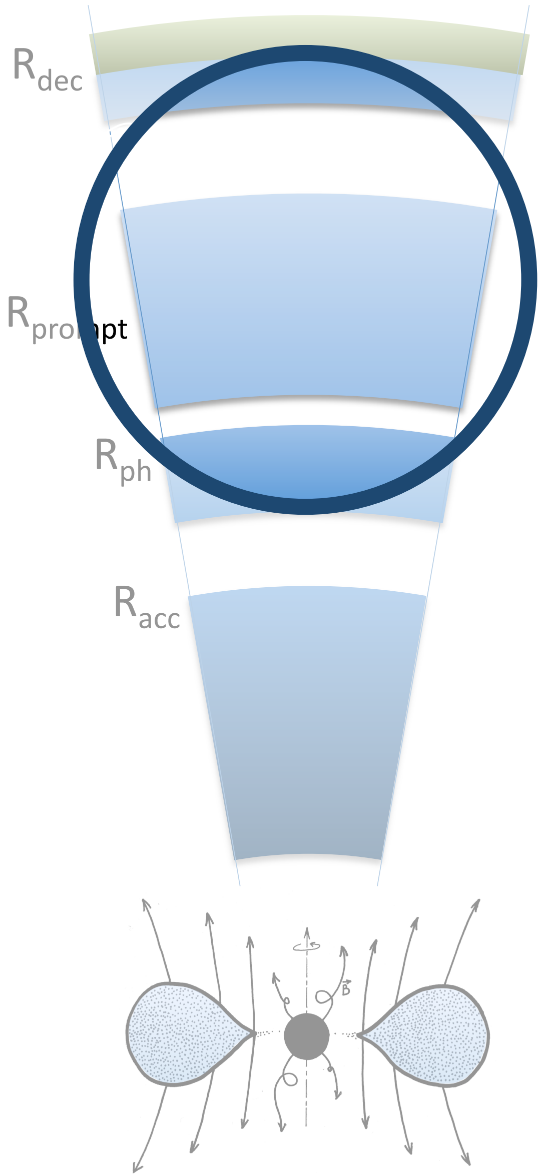
(activity lasts Δt_{engine})



Prompt emission

R_{prompt} ?

Prompt emission: questions



Energy reservoir & extraction mechanism ?

Microphysics ?

Radiative processes ?

Matter dominated vs magnetic outflow ?

Thermal emission ?
Shock waves ?
Reconnection ?

Synchrotron ? IC ? …

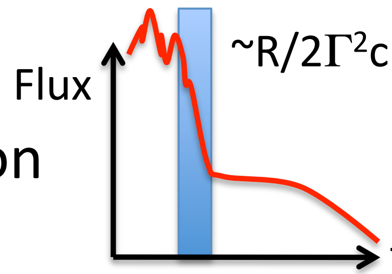
Prompt: constraints ?

- Magnetization : Polarization measurements in γ-rays still difficult
  (see however Willis et al. 05; Kalemci et al. 07; McGlinn et al. 07; Götz et al. 09; McGlinn et al. 09)

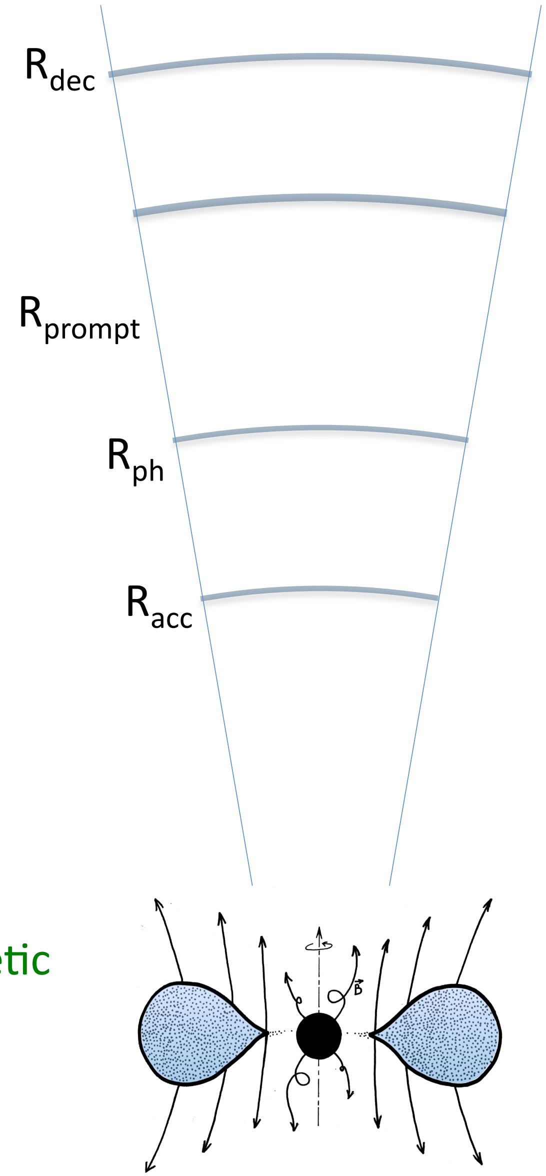
- Lorentz factor : high values to avoid a strong $\gamma\gamma$ annihilation
  -pre-Fermi era: $\Gamma > 50-100$
  -Fermi: Γ may be much larger – e.g. GRB 080916C: $\Gamma \sim 900$
  (Abdo et al. 2010)
  -More realistic estimates reduce Γ_{min} by at least a factor ~ 2-3
  (Granot et al. 08 ; Bosnjak et al 09 ; Aoi et al. 10 ; Zou et al. 10)

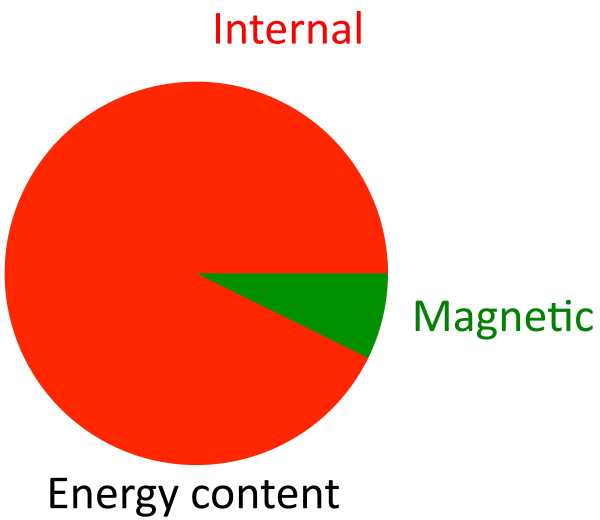
see Poster 2.07 by R. Hascoët et al. : $\Gamma \sim$ 300-400 in GRB 080916C

- Radius : estimate from early X-ray steep decay (Swift/XRT)
  -high latitude emission? $R > 6.10^{15}\,(\Gamma/100)^2$ cm
  (Lyutikov 06; Lazzati & Begelman 06; Kumar et al. 07; Genet & Granot 09)
  -measure the radius at the end of the prompt emission
  -effect of comoving anistropy ?
  (Lyutikov 06; Beloborodov, Daigne, Mochkovitch & Uhm 10) – see talk by M. Medvedev



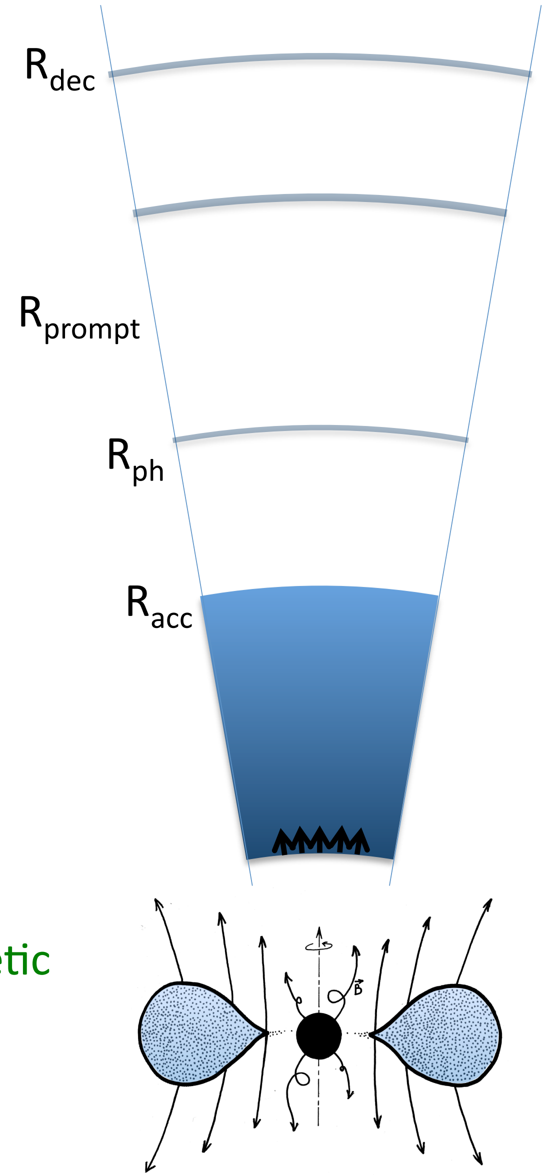
Standard fireball scenario



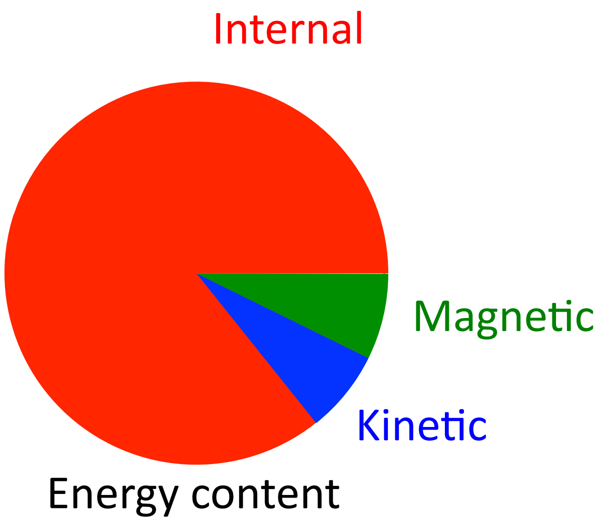


Initial energy release :
negligible magnetization

Standard fireball scenario



Acceleration :
adiabatic expansion



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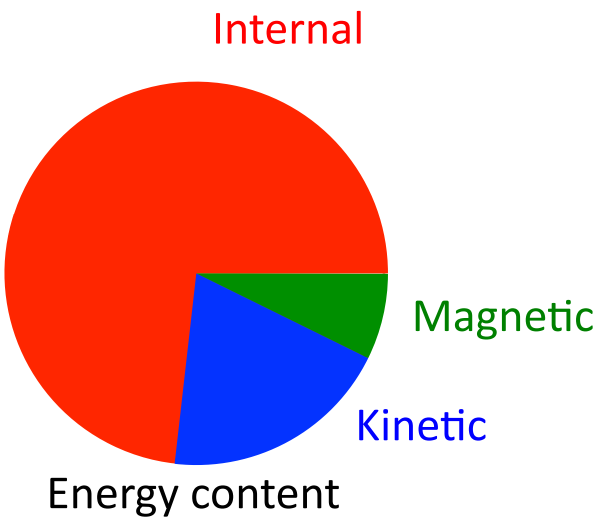

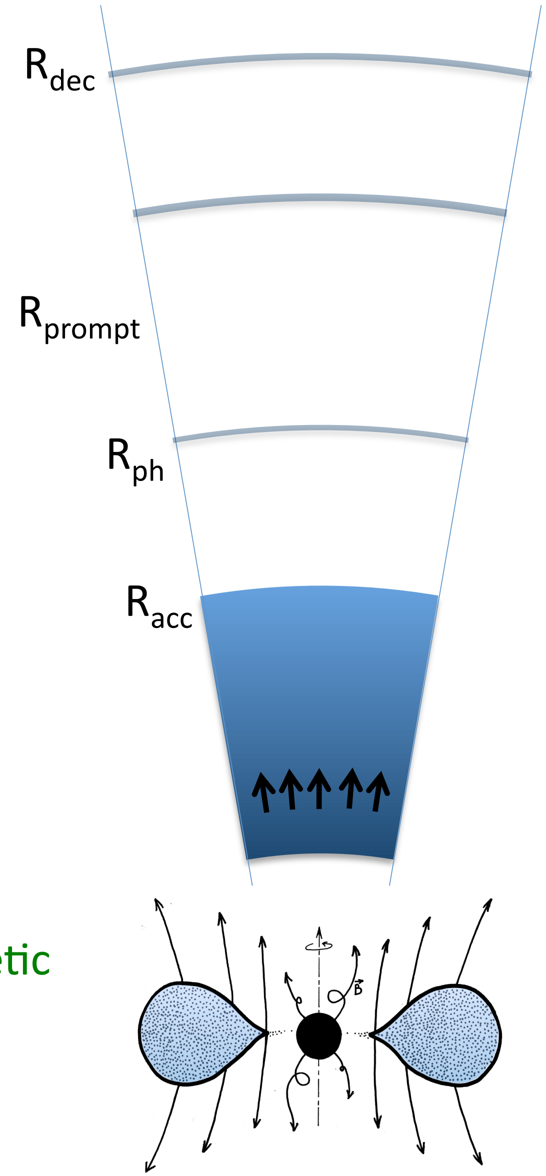

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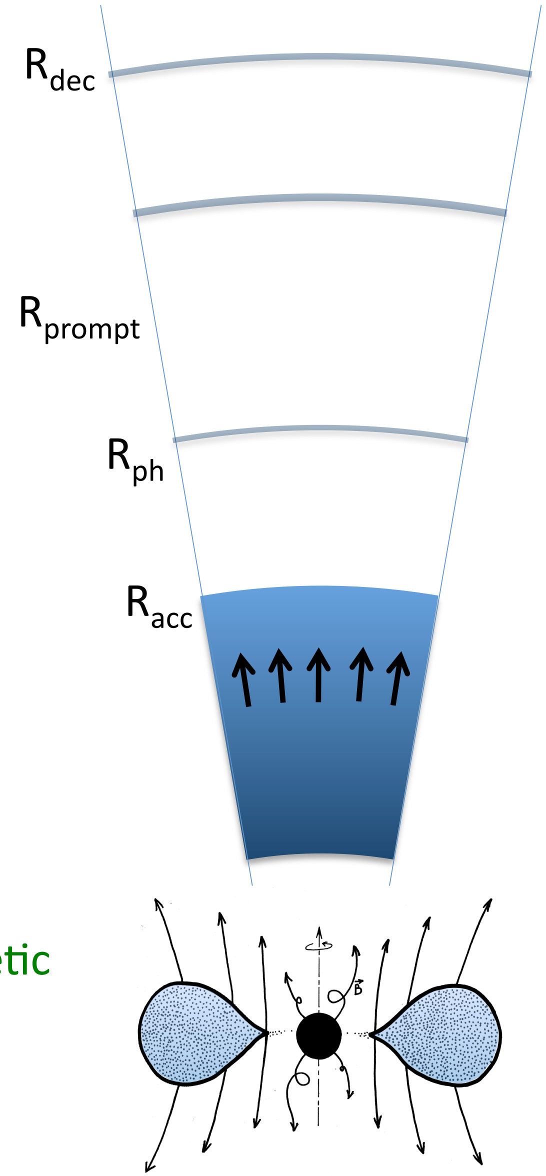

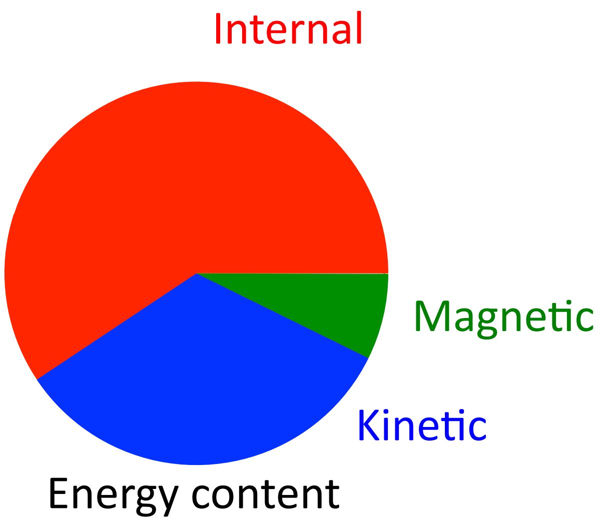

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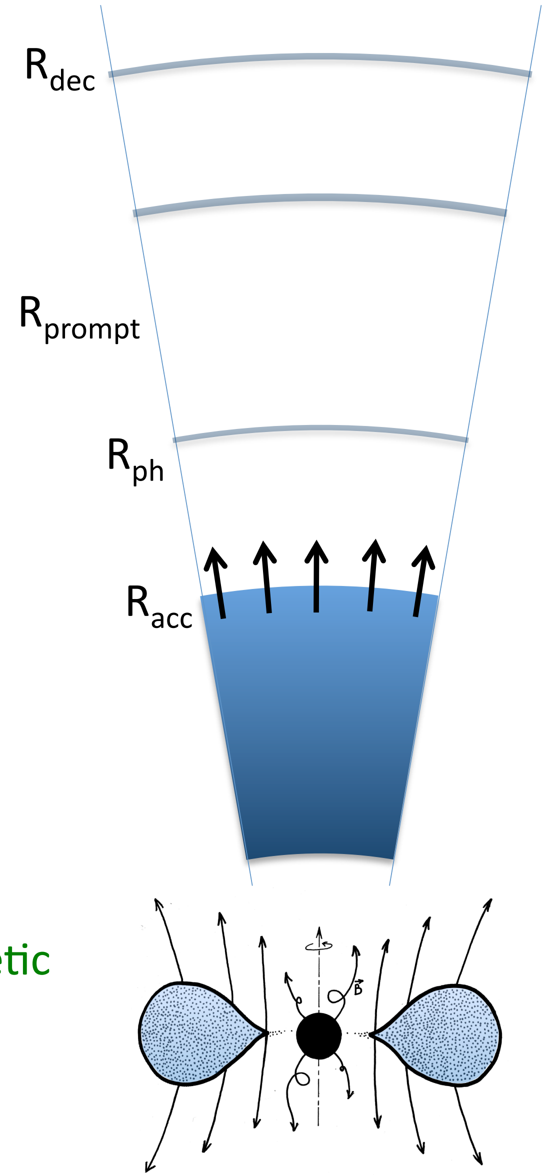

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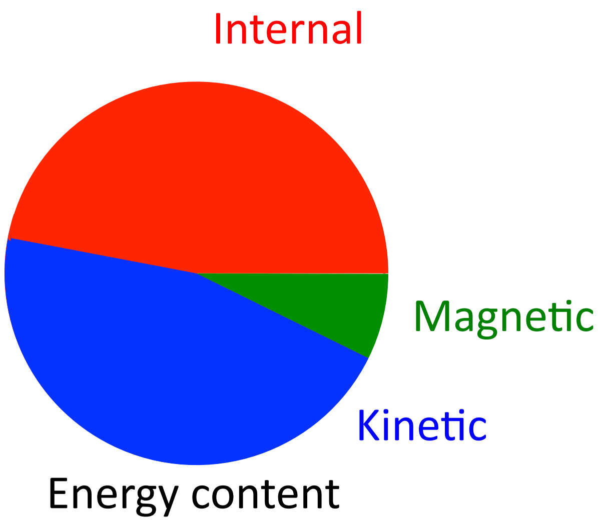

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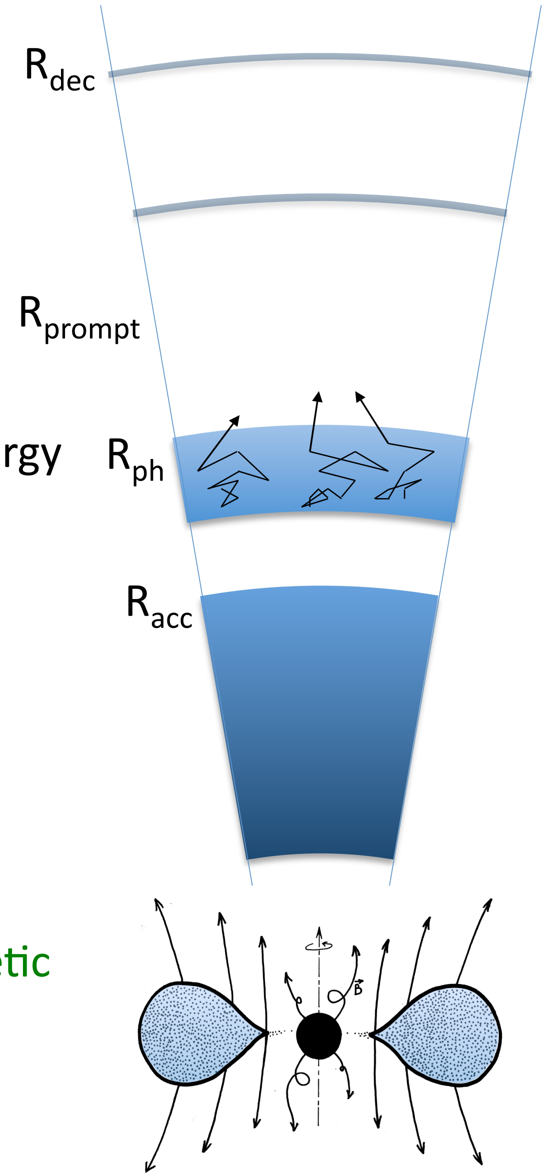
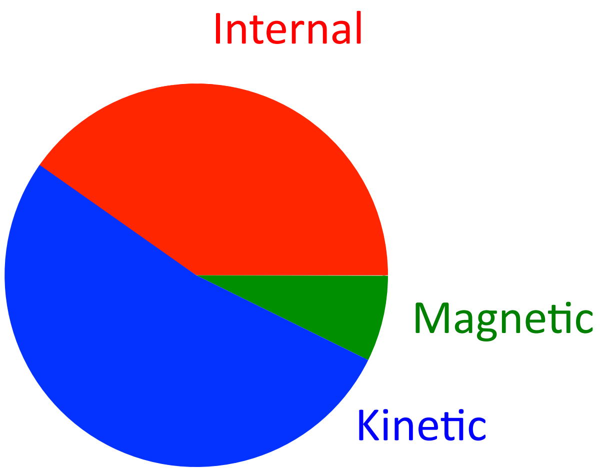
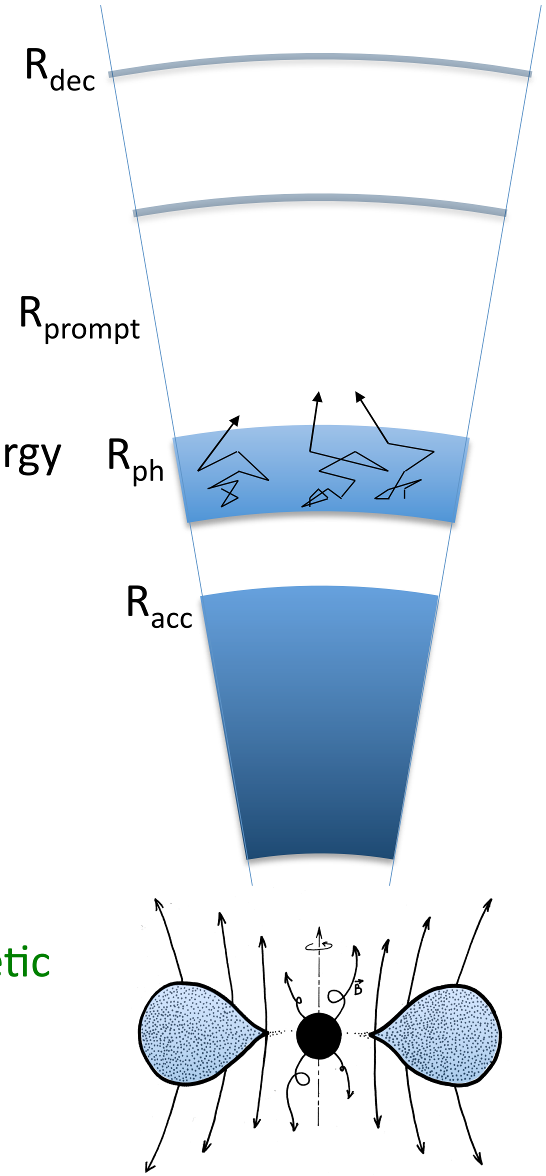


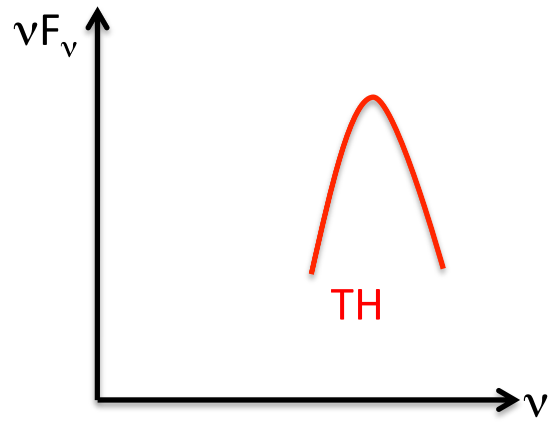
Photosphere : internal energy can be radiated.



Energy content

Standard fireball scenario





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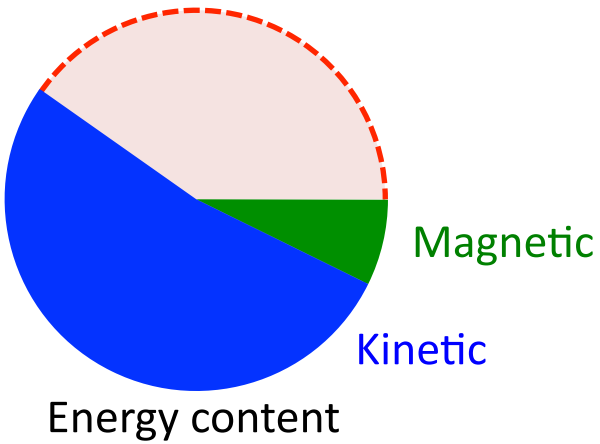
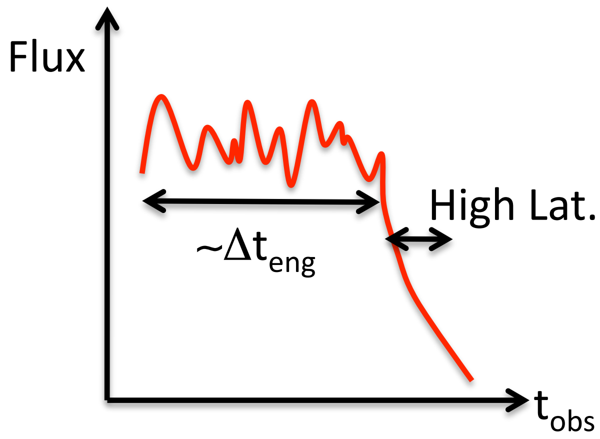
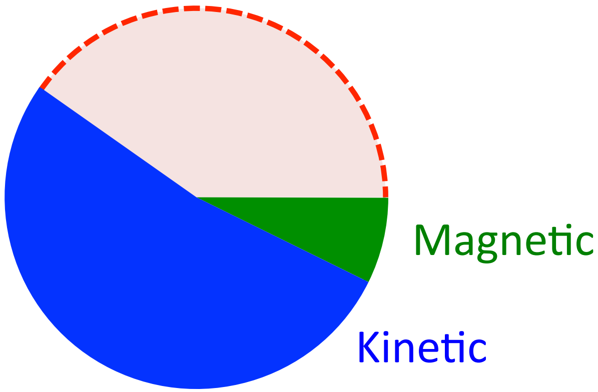




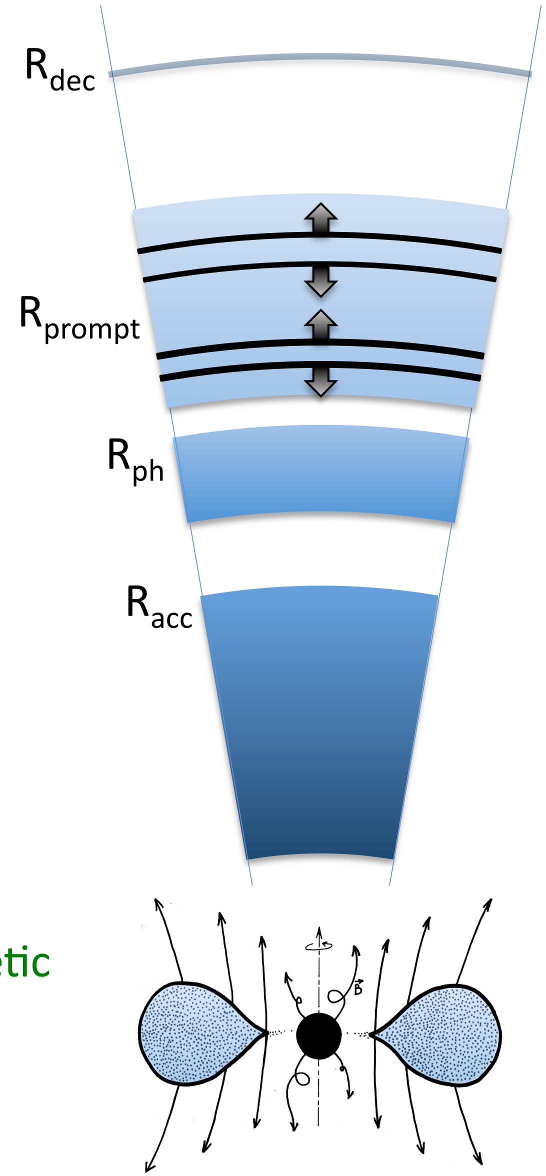
Standard fireball scenario

Non-thermal emission :
Internal shocks

A fraction of the kinetic energy is radiated



Energy content



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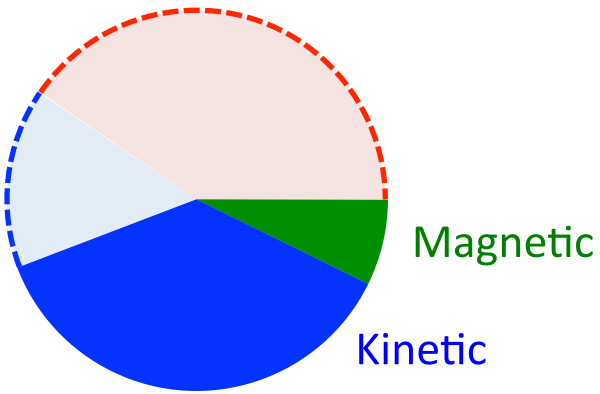
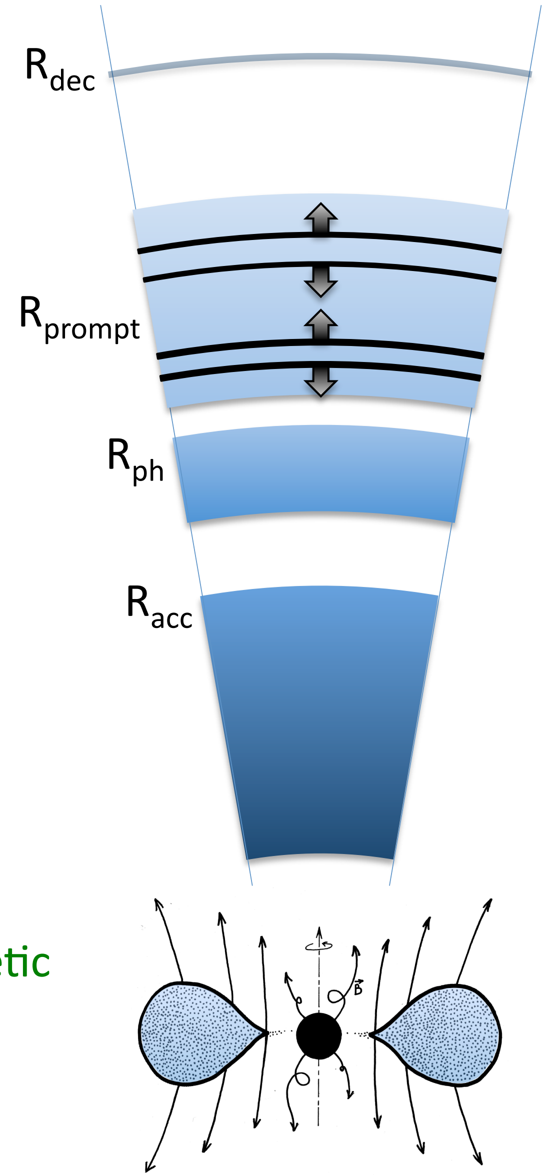
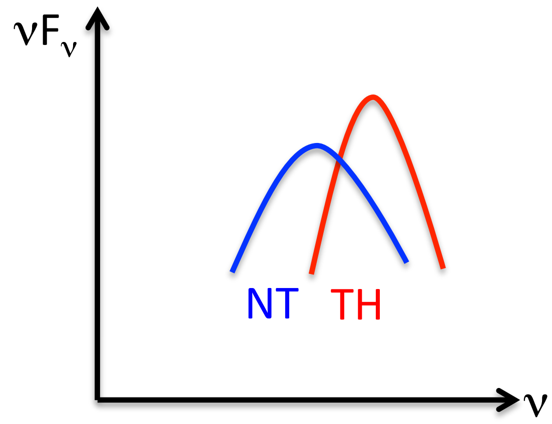
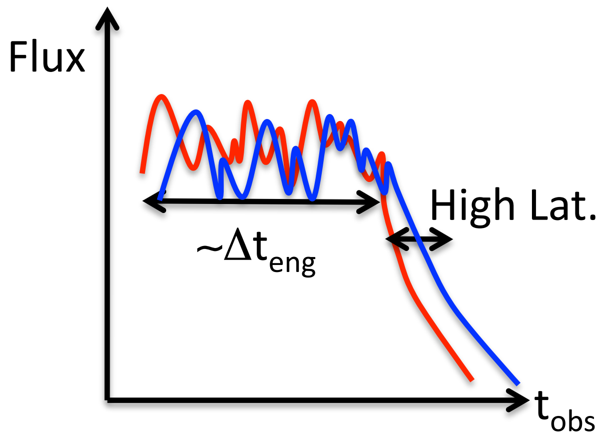


Energy content







Standard fireball scenario

Photosphere + internal shocks

- Photospheric emission : well understood
  - very efficient
  - may be more complicated than blackbody (HLE, comptonization, …)

(Paczynski 86; Goodman 86; Shemi & Piran 90; Meszaros & Rees 00; Meszaros et al. 02; Daigne & Mochkovitch 02; Zhang & Meszaros 02; Rees & Meszaros 05; Pe'er et al. 06, 07, 08, 10; Ioka et al. 07; Beloborodov 10; Toma et al. 10; …)

- Internal shocks : more uncertain
  - low efficiency (less than 10 % ?)

(Daigne & Mochkovitch 98 ; see however Beloborodov 00; Kobayashi & Sari 01)

  - microphysics ?
  - spectrum may have several components

(Rees & Meszaros 94 ; Paczynski & Xu 94; Kobayashi et al. 97 ; Daigne & Mochkovitch 98, 00, 03 ; Meszaros & Rees 00; Pe'er et al. 06; Bosnjak, Daigne & Dubus 09 ; …)

- Main uncertainties in this scenario :

  microphysics in shocks : particle acceleration, field amplification, …

Standard fireball scenario

Photosphere + internal shocks

- *Photospheric component is dominant* except if
  - internal shocks have a large efficiency
  - $R_{ph} >> R_{acc}$ (i.e. very small size R_0 at the base of the outflow)

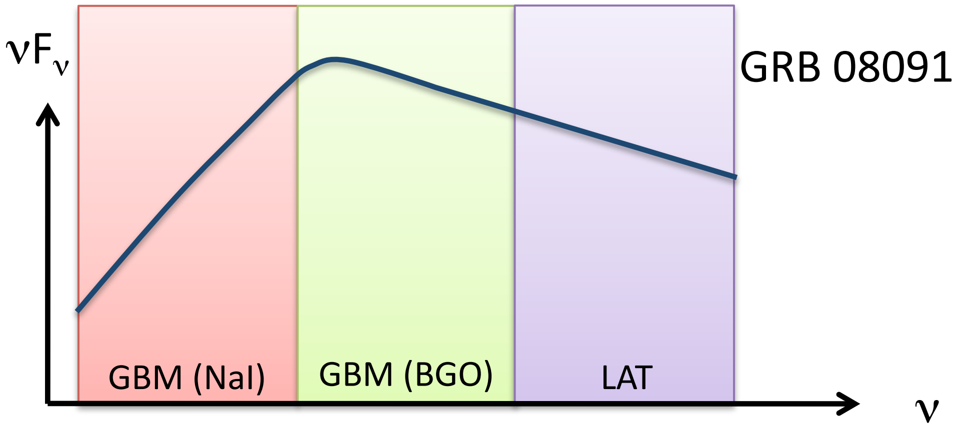
(Daigne & Mochkovitch 02)

- This is very difficult to reconcile with observations :
  - BATSE spectroscopic catalog (Preece et al. 00; Kaneko et al. 06)
  - indirect analysis of GRB 080916C (Zhang & Pe'er 09)
  - Fermi observations of GRB 100724B (Guiriec et al. 10)
  - most Fermi bursts show a strong dominant component (Band) + some weaker additional components at low and/or high energy

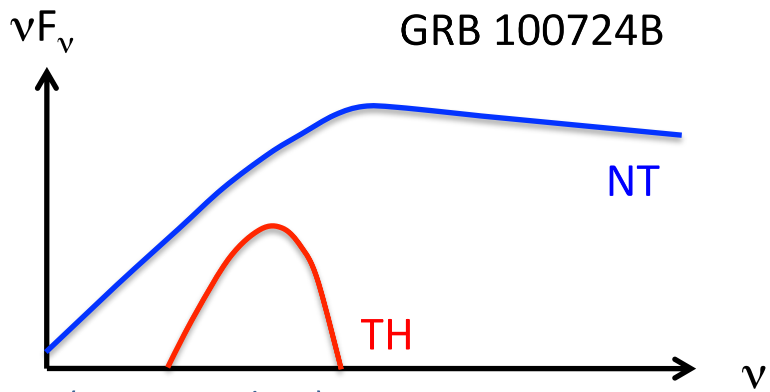
(see analysis by Zhang, B.-B. et al. 2010)

Standard fireball scenario

- Fermi observations :

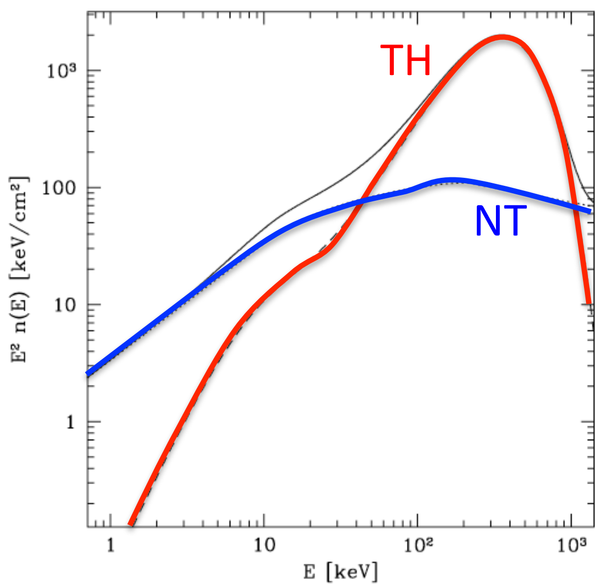


(Abdo et al. 08)

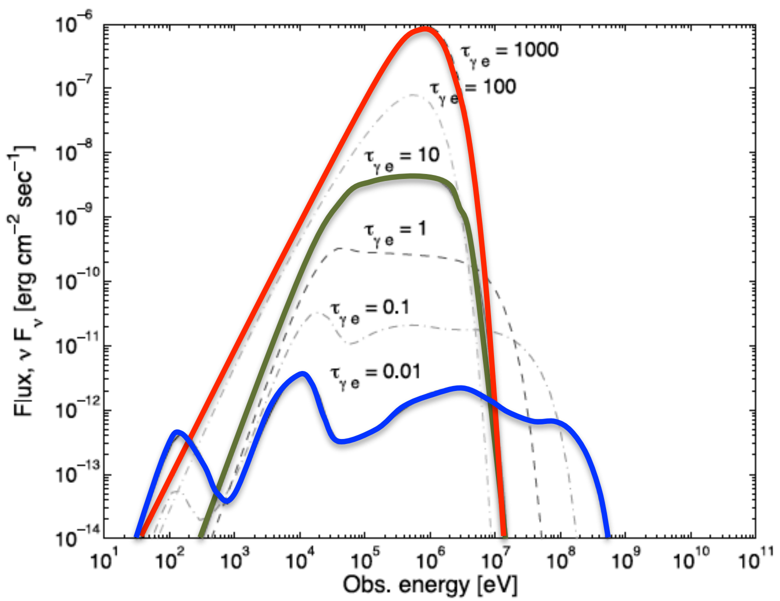


(Guiriec et al. 10)

- Model :



(Daigne & Mochkovitch 02)



(Pe'er et al. 06)

Standard fireball scenario

Photosphere + internal shocks

- It remains the possibility that the main spectral component (Band) has a photospheric origin, if the spectral shape is affected by additional processes.

(Ryde et al. 10; Pe'er et al. 10 (GRB 090902B) ; Toma et al. 10; Beloborodov et al. 10)

Magnetized outflows

A new ingredient : the magnetic field

- Passive field : B does not play a role for the dynamics
- Active field : B does have an influence on the dynamics

(Usov 92; Thompson 94; Meszaros & Rees 97; Spruit et al. 01; Daigne & Drenkhahn 02;

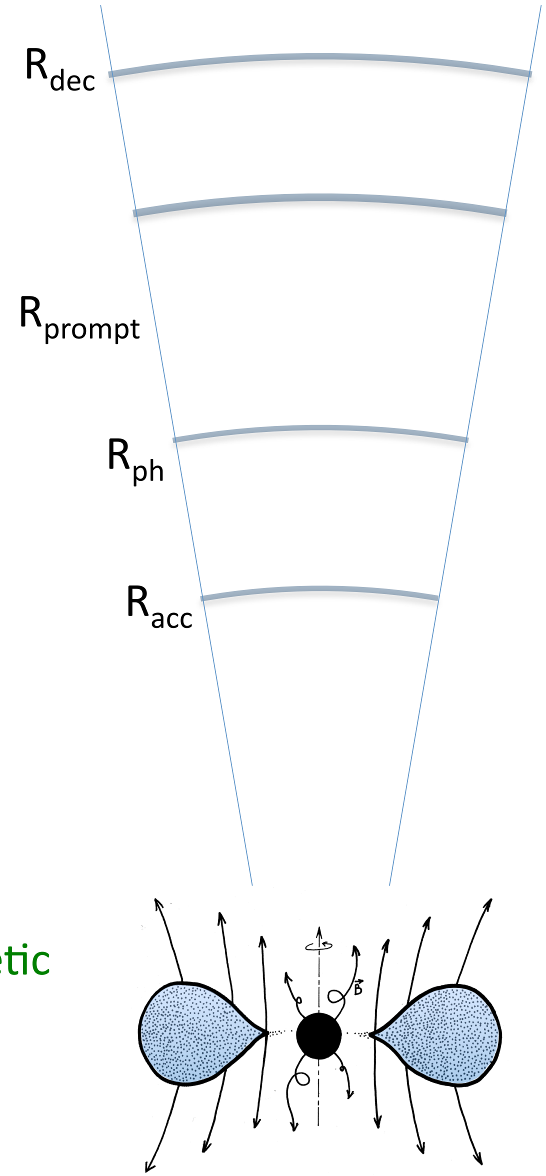
Vlahakis & Königl 03; Giannios & Spruit 06; …)

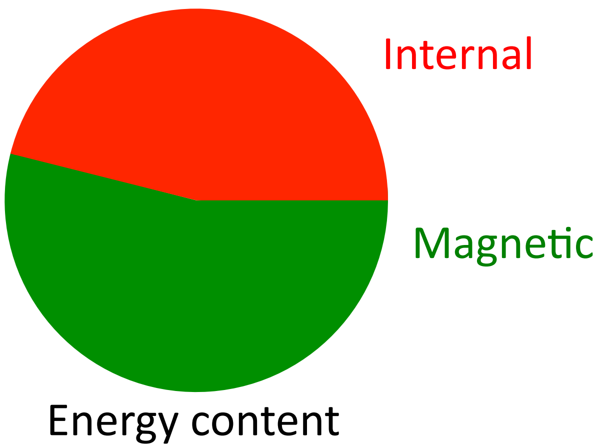
Magnetization : $\sigma = \dfrac{\text{Poynting flux}}{\text{Power carried by matter (internal + kinetic)}}$

- An extreme version : the initial energy release is purely magnetic ($\sigma = \infty$) – no photospheric emission in this case

(Blandford & Lyutikov 03)

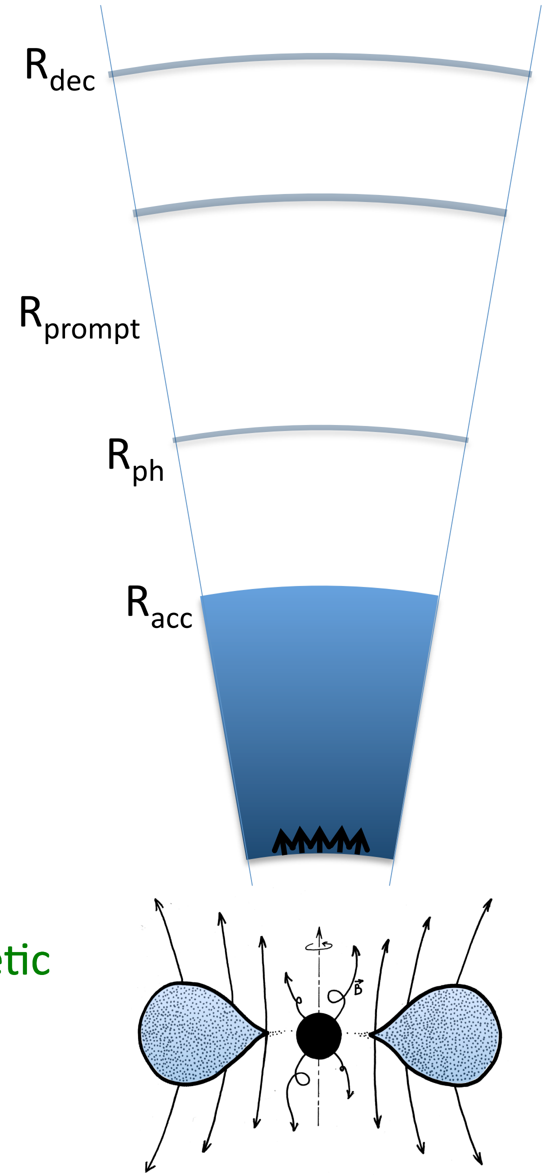
Magnetized outflows (1) passive field



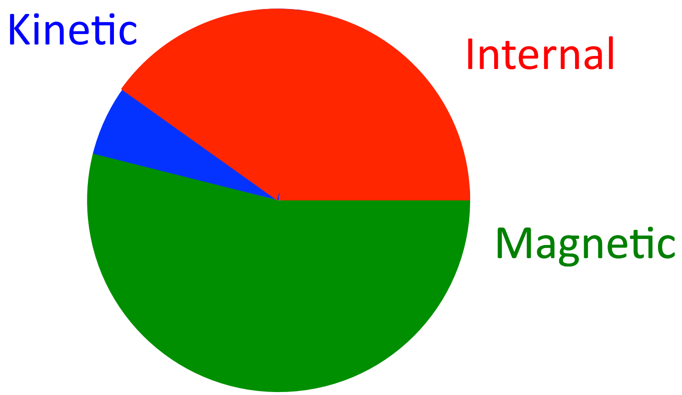


Large magnetization

Magnetized outflows (1) passive field

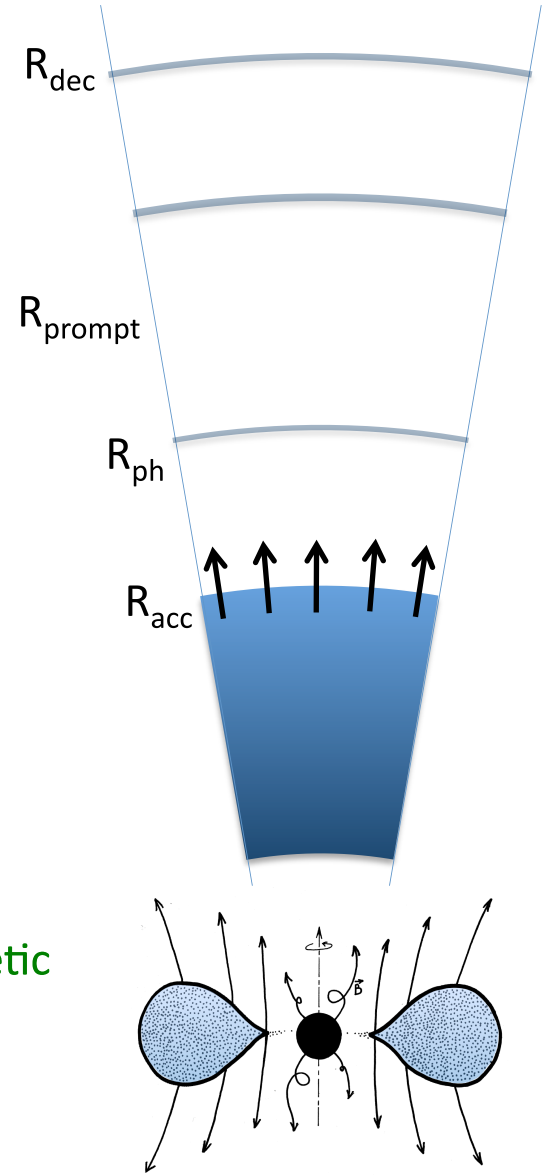


Acceleration :
adiabatic expansion



Energy content

Magnetized outflows (1) passive field



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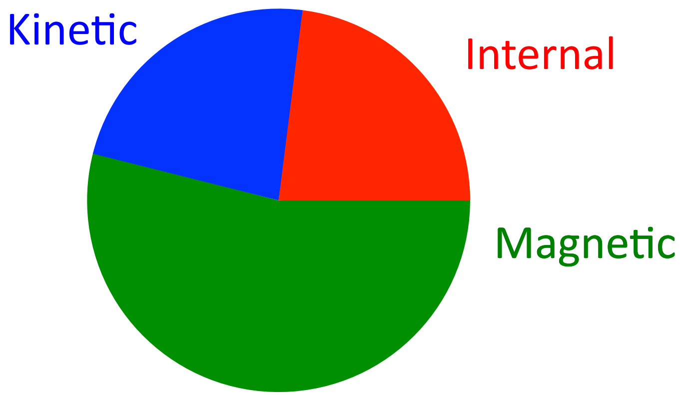
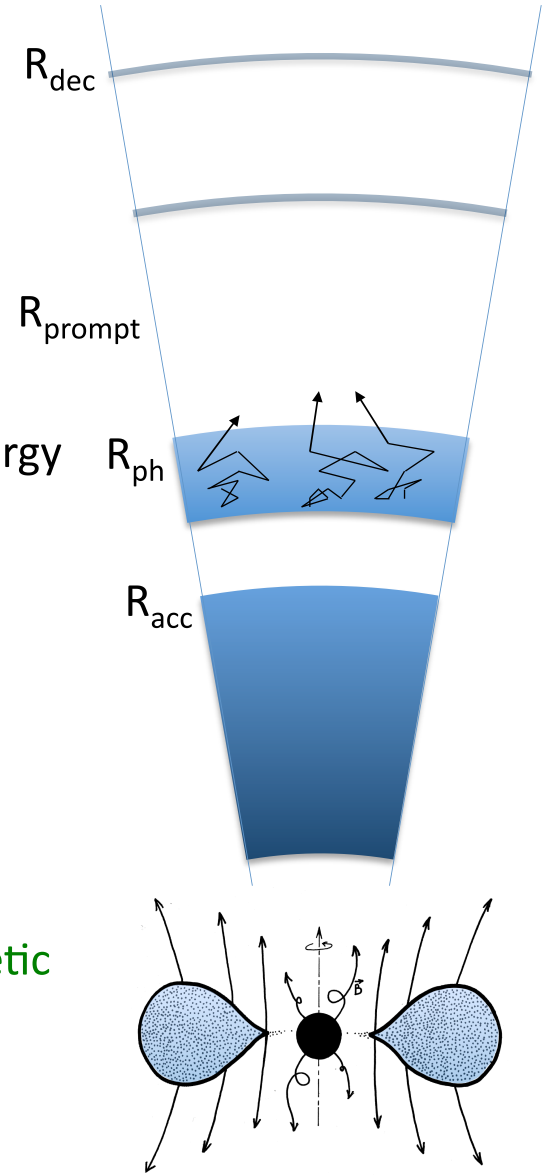
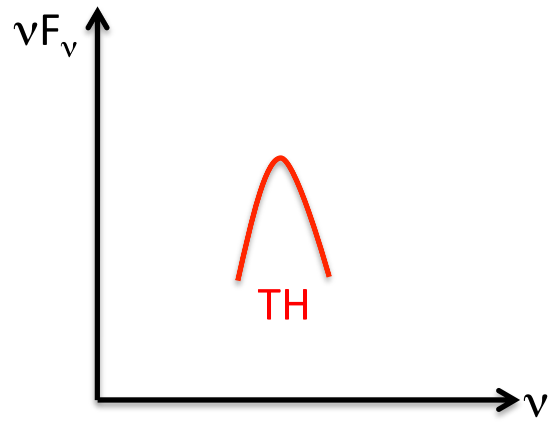


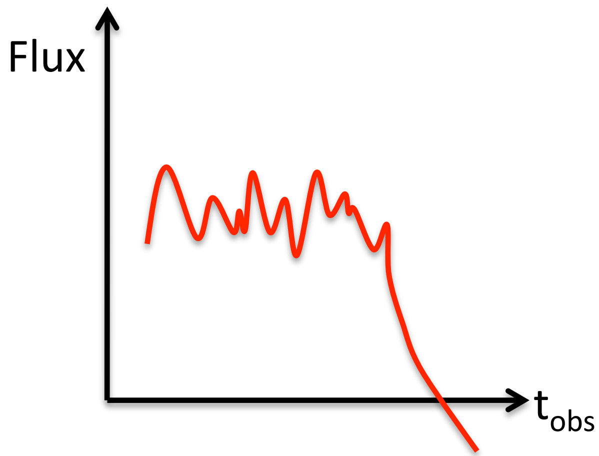
Energy content

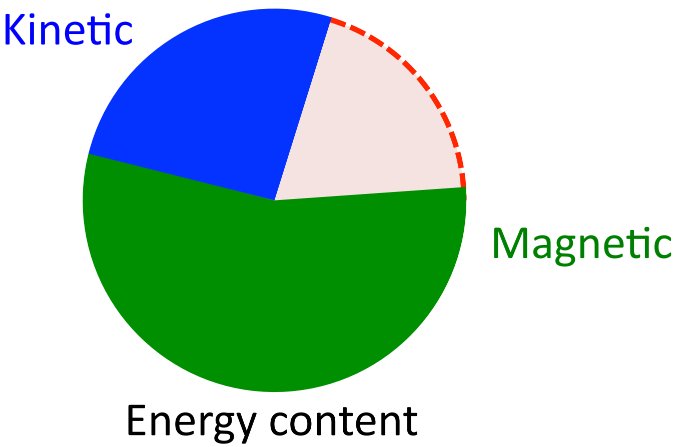
Magnetized outflows (1) passive field



Photosphere : internal energy can be radiated.

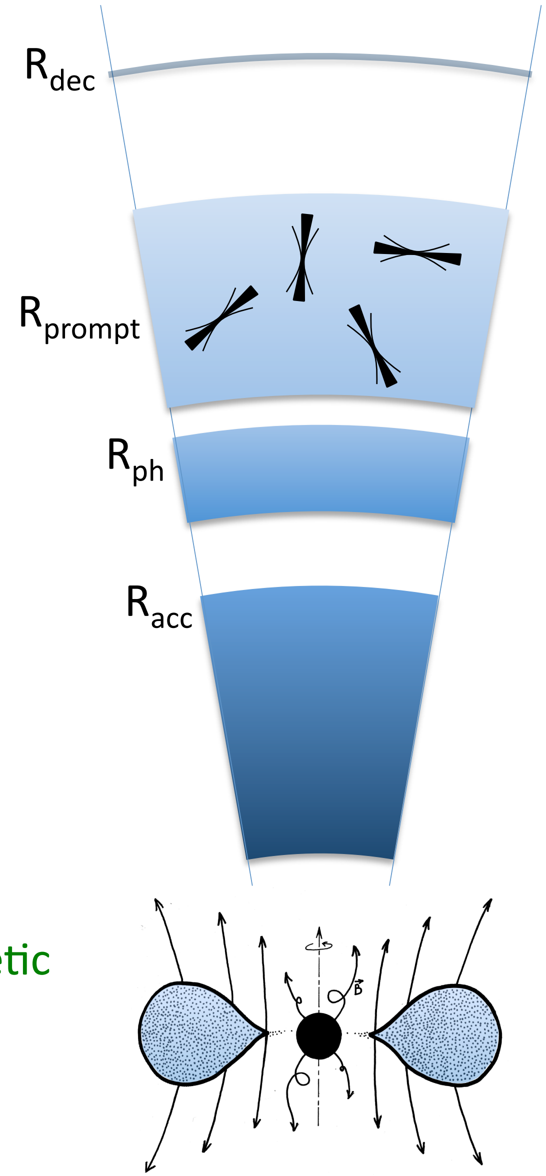


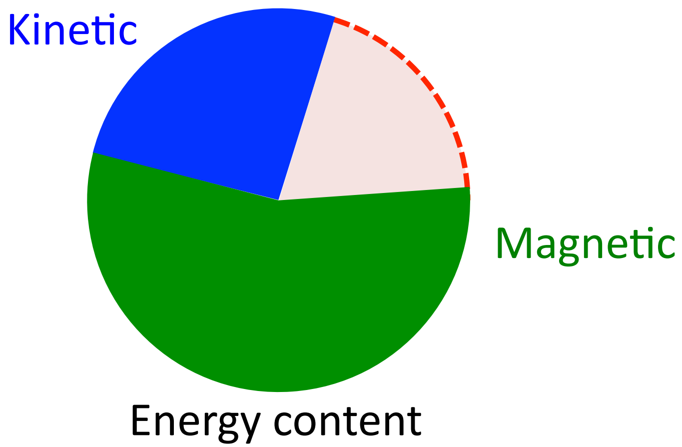




Magnetized outflows (1) passive field

Non-thermal emission :
Internal shocks
or magnetic dissipation





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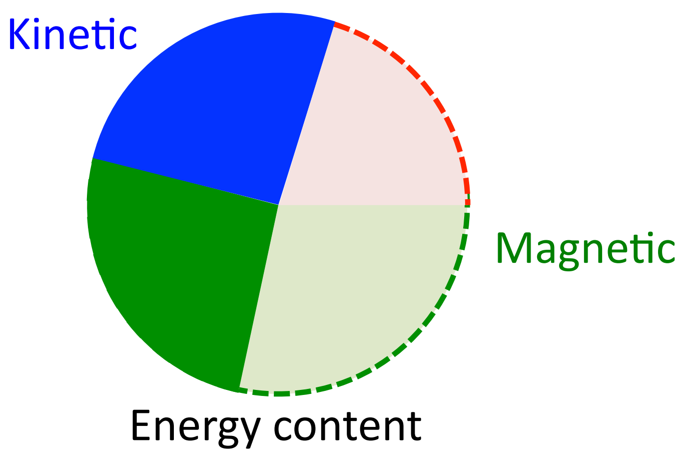
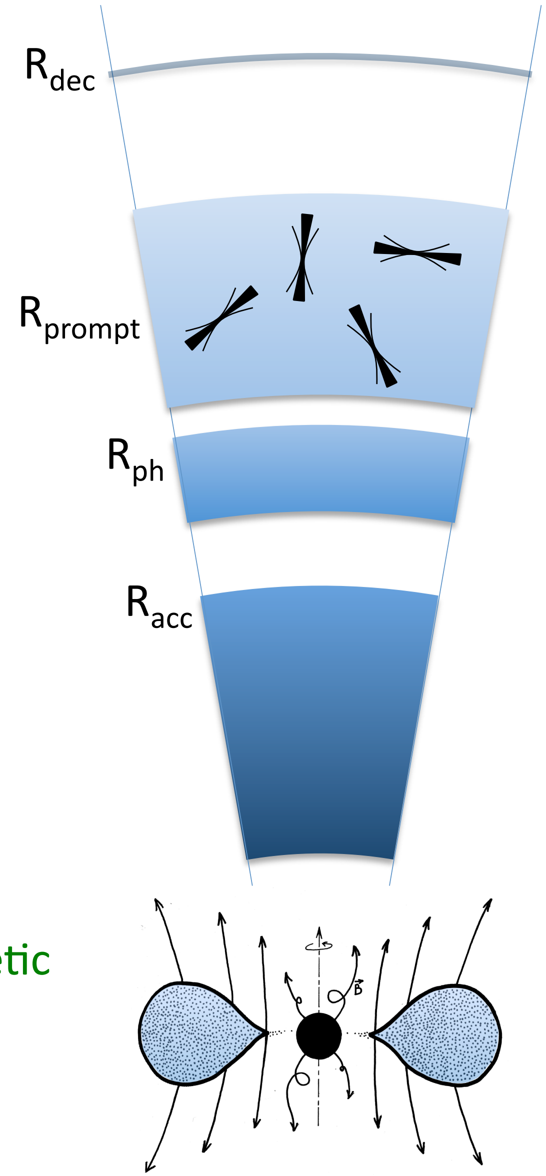
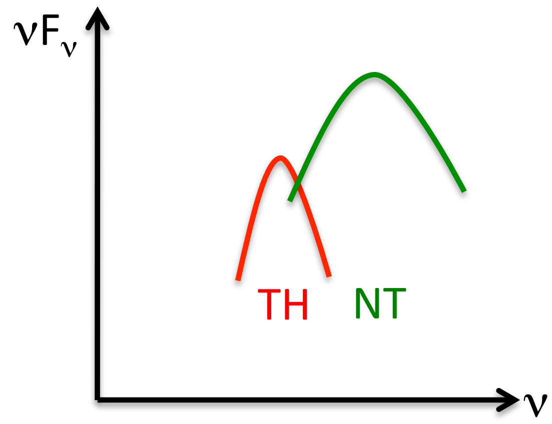
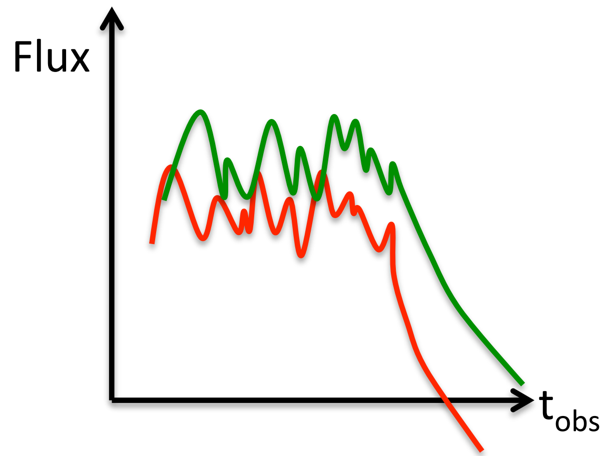








Magnetized outflows (1) passive field

Photosphere + Magnetic dissipation at late times

- weak thermal component + dominant non-thermal component

- is it possible to reconcile this scenario with large Lorentz factors ?

- Main uncertainties in this scenario :
  - physics of the magnetic dissipation process / associated emission
  - efficiency ?

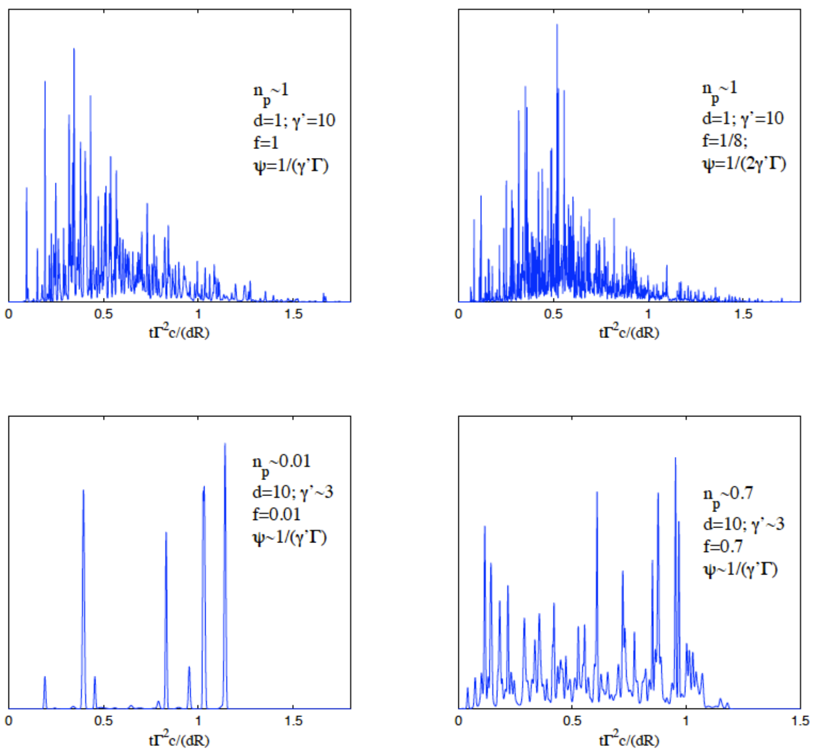
(Thomson 94 ; Spruit et al. 01 ; Drenkhahn & Daigne 02 ; Giannios 06 ; Giannios & Spruit 07 ; Giannios 08 ; …)

  - critical magnetization to suppress shocks (existence of IS/RS) ?

(Zhang & Kobayashi 05; Giannios, Mimica & Aloy 08)

Magnetized outflows (1) passive field

- Some estimates using a simple geometrical description of the dissipation (« fundamental relativistic emitters ») : lightcurves are too symmetric ? (Lyutikov 06; Kumar & Narayan 09; Lazar, Nakar & Piran 09)



Lazar, Nakar & Piran 09

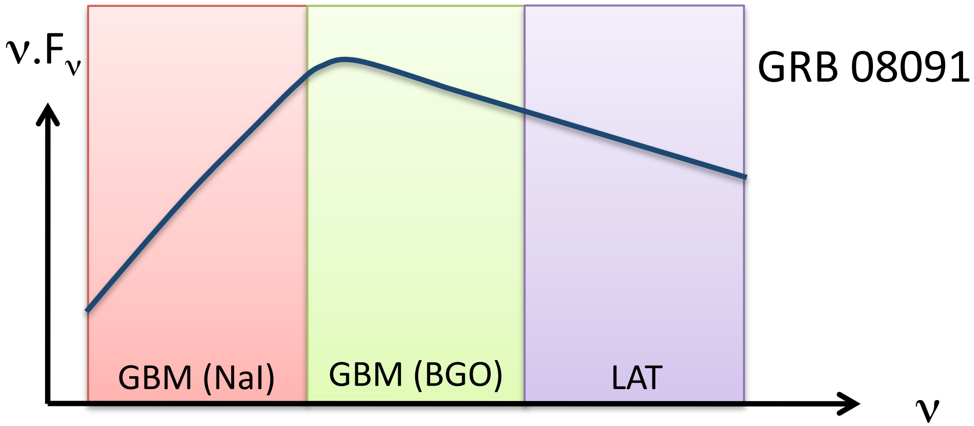
Magnetized outflows (1) passive field

- Some estimates using a simple parametrization of the dissipation
  - efficiency may be high
  - spectrum may have several strong components
  (contradiction with Fermi-LAT observations ?)

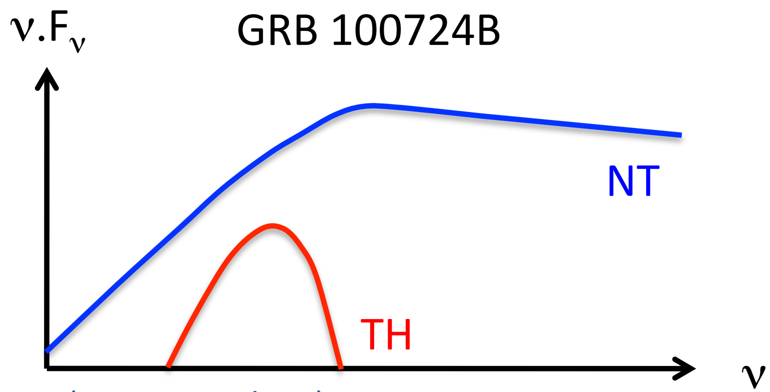
(Giannios 08)

Magnetized outflows (1) passive field

- Fermi observations :

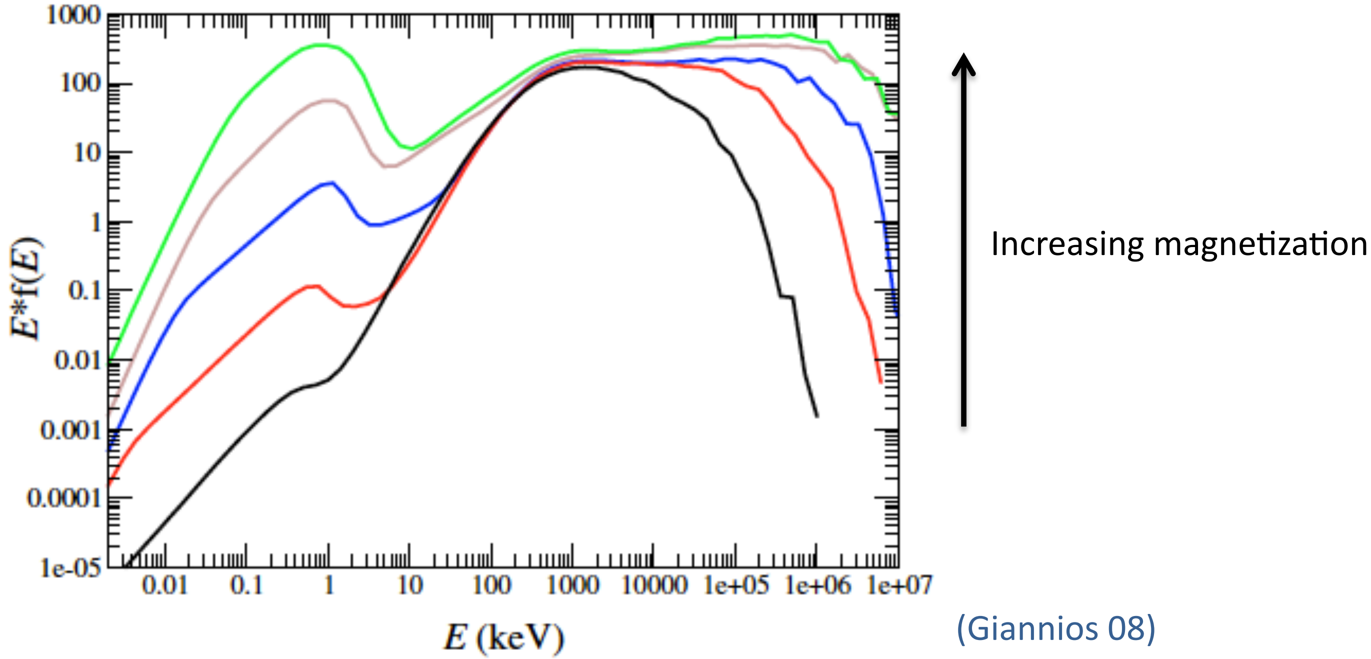


(Abdo et al. 08)



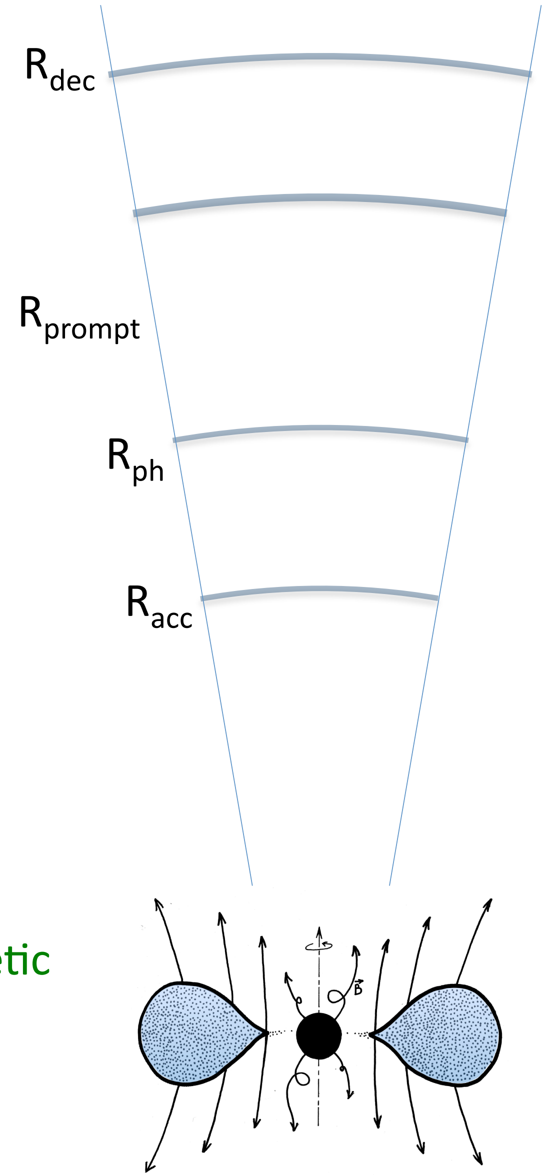
(Guiriec et al. 10)

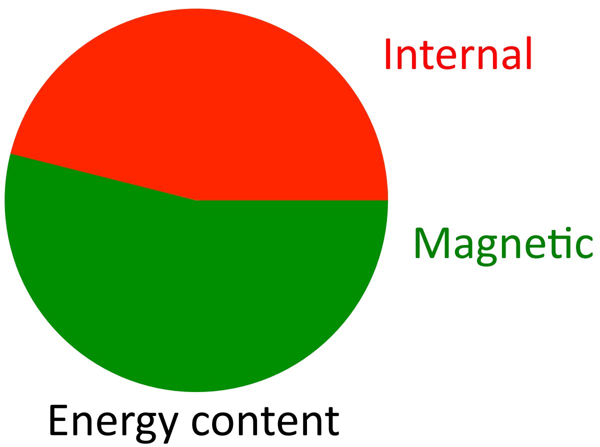
- Model :



(Giannios 08)

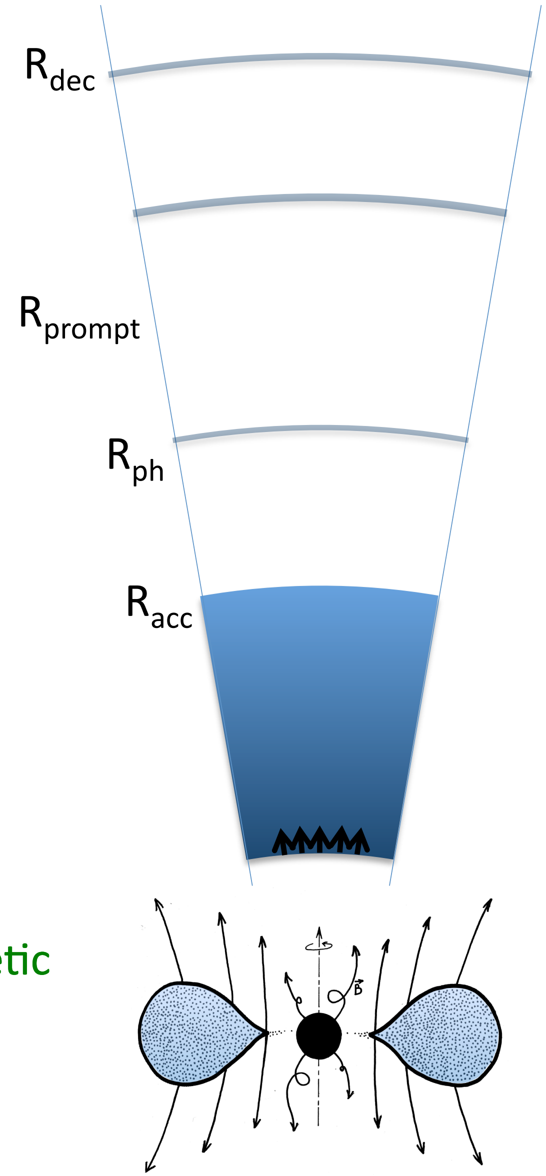
Magnetized outflows (2) active field



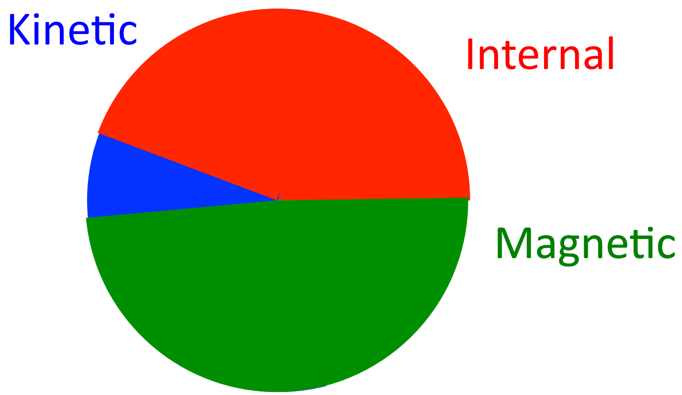


Large magnetization

Magnetized outflows (2) active field

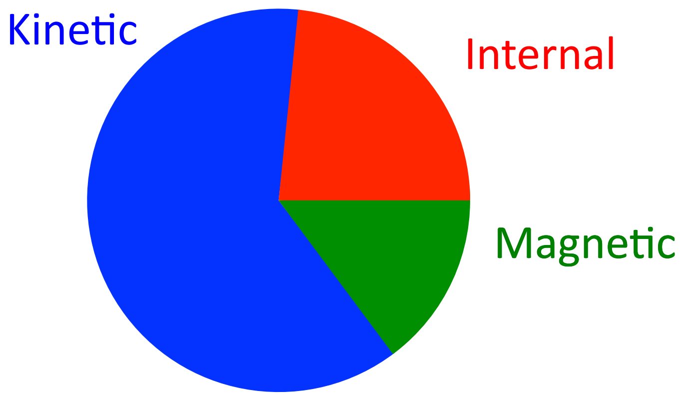


Magnetic acceleration



Energy content

Magnetized outflows (2) active field



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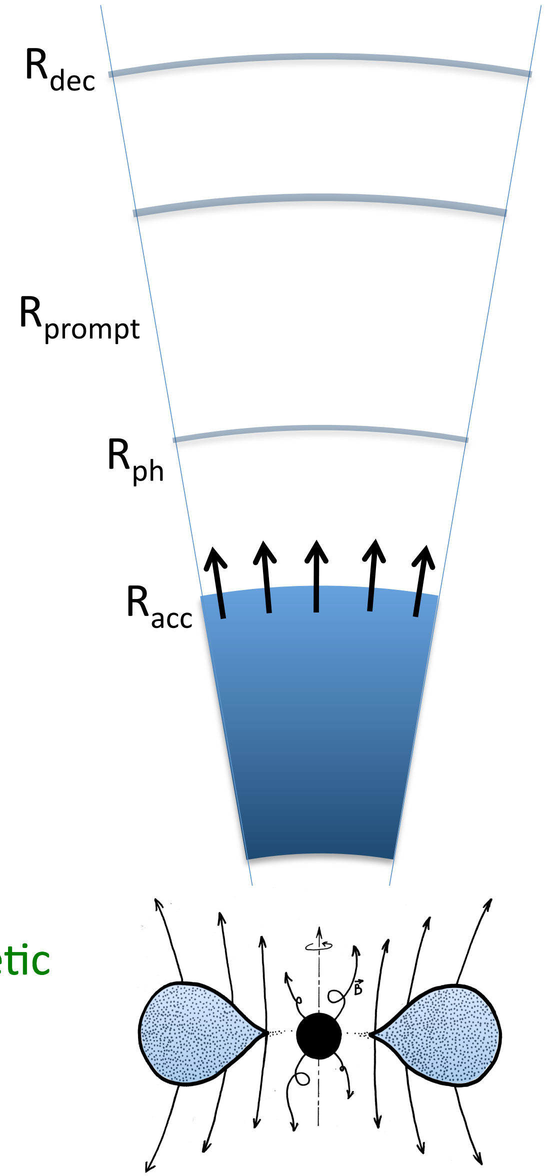
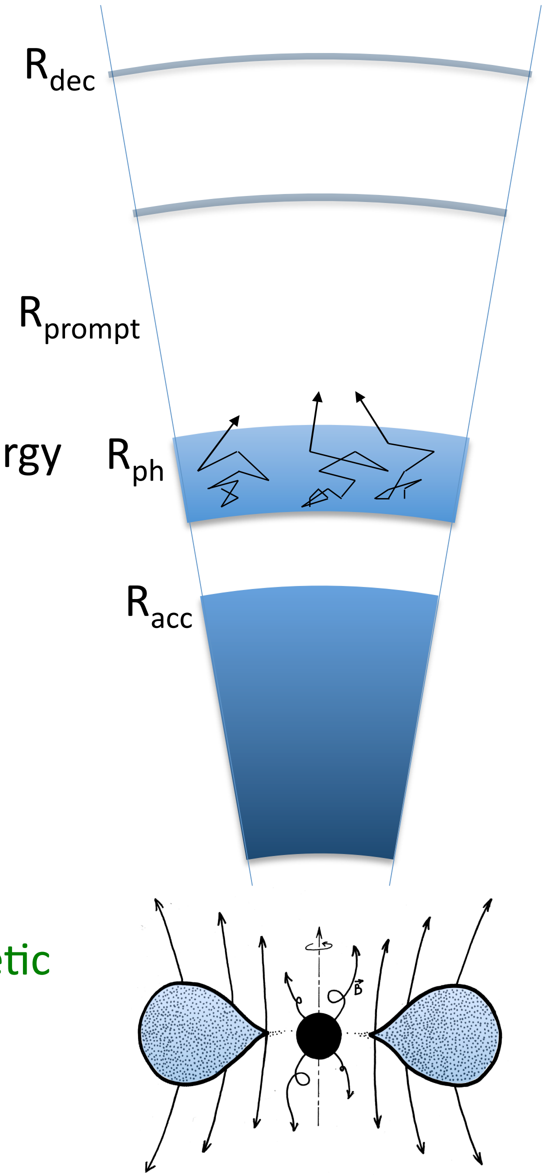
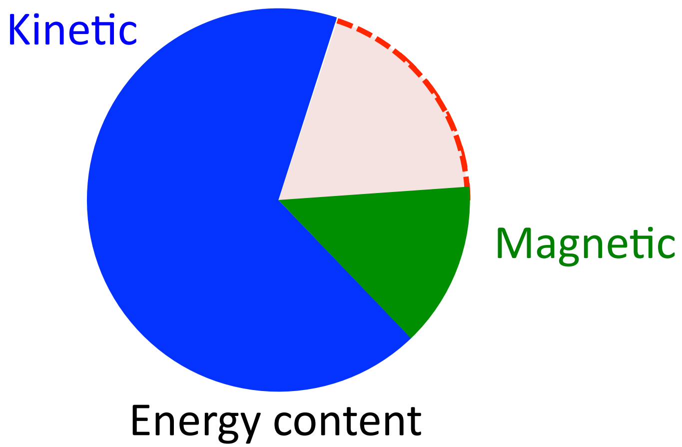


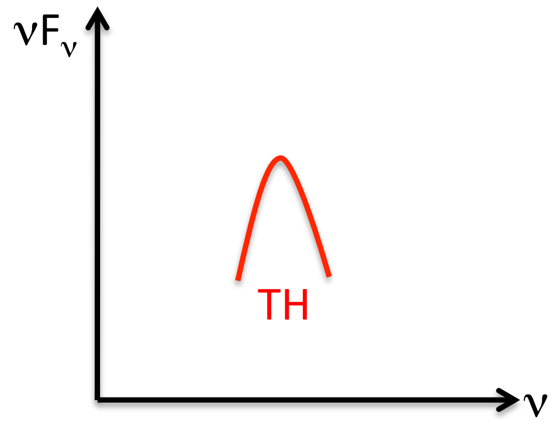
Magnetic acceleration

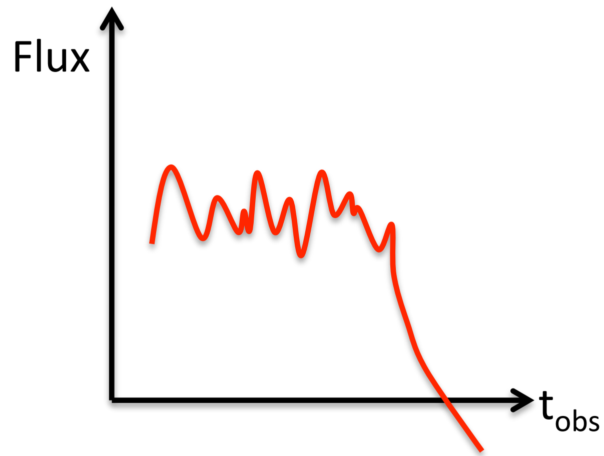
Magnetized outflows (2) active field



Photosphere : internal energy can be radiated.

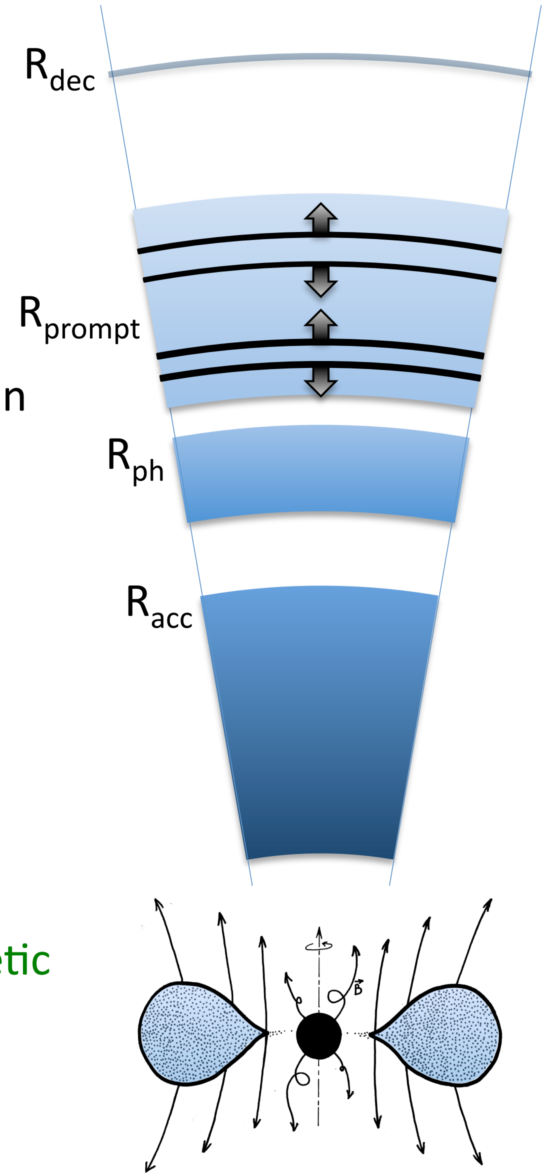


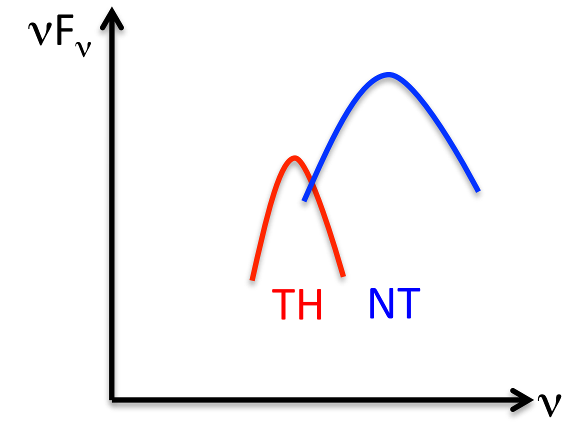


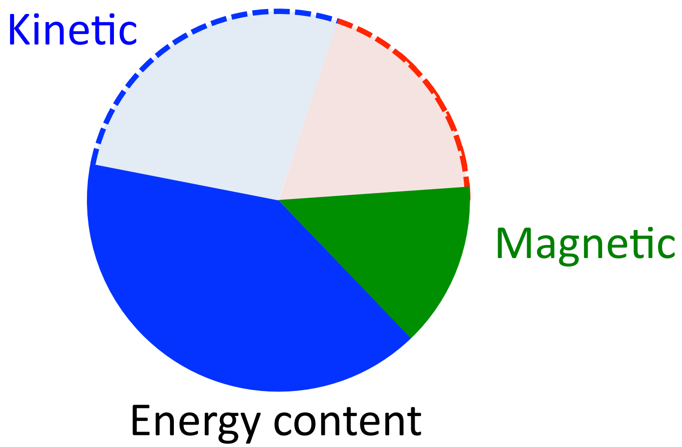


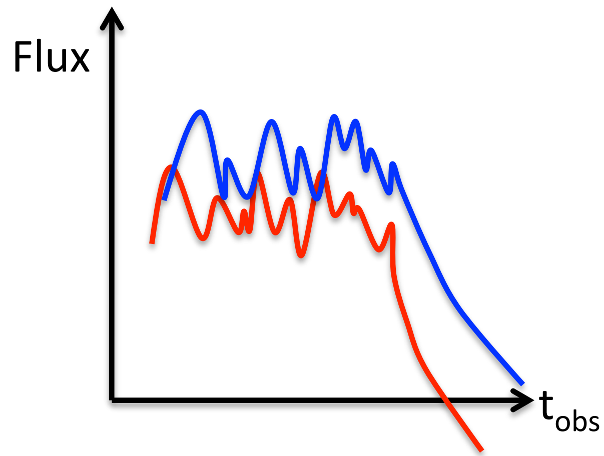
Magnetized outflows (2) active field

Non-thermal emission :
Internal shocks
and/or magnetic dissipation









Magnetized outflows (2) active field

Efficient magnetic acceleration : (photosphere) + internal shocks

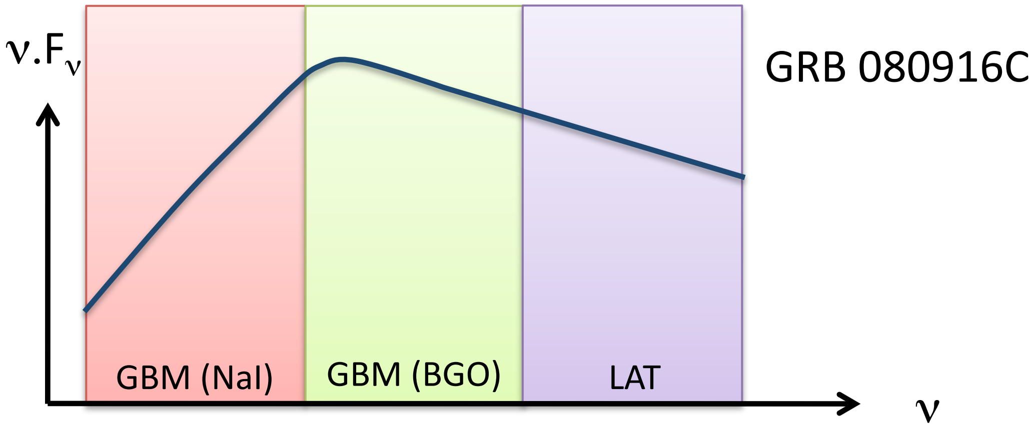
- Large Lorentz factors can be reached

- *Above the acceleration radius, the outflow is very similar to a standard fireball, except that it is colder*.
  - non-thermal emission is dominant, in agreement with observations
  - a weak thermal component may be seen
  - diversity is possible depending on the initial magnetization

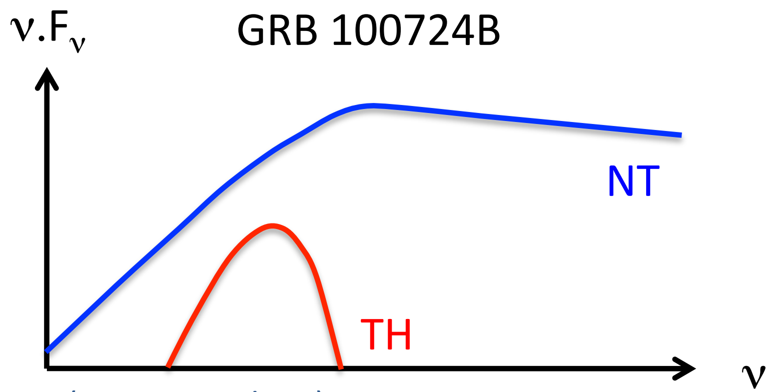
- Main uncertainties in this scenario :
  - identification of a « magnetic acceleration » mechanism
    (Spruit et al. 01; Daigne & Drenkhahn 02; Spruit & Drenkhahn 02; Giannios & Spruit 06; Granot et al. 10; etc)
  - same uncertainties as in the standard fireball model (microphysics)

Magnetized outflows (2) active field

- Fermi observations :

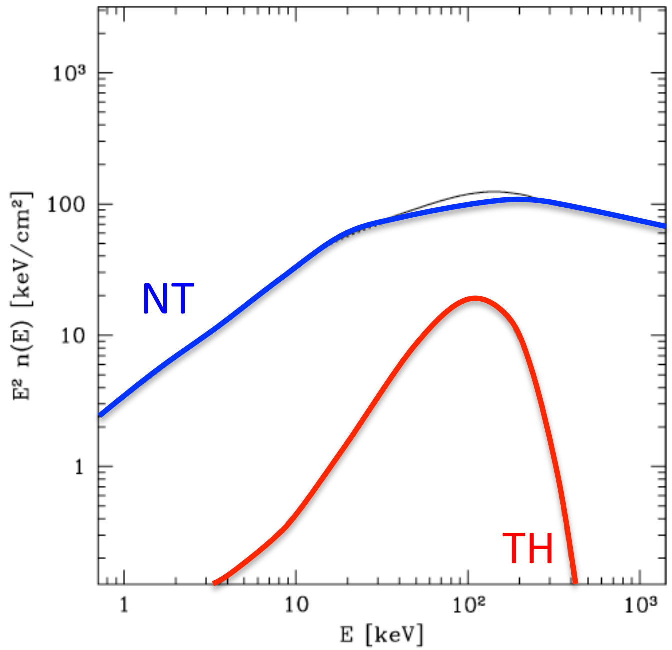


(Abdo et al. 08)



(Guiriec et al. 10)

- Model :



(Daigne & Mochkovitch 02)

Summary (1)

- *The standard fireball scenario overpredicts the thermal photospheric emission, in contradiction with observations.*

  However, mechanisms have been proposed that affect the photospheric emission, which could appear as a « Band » spectrum.

see talks by A. Pe'er, K. Toma, A. Beloborodov

see poster 2.10 by R. Mochkovitch, R. Hascoët and F. Daigne

Summary (1)

- *The standard fireball scenario overpredicts the thermal photospheric emission, in contradiction with observations.*

- *Magnetized outflows produce weaker photospheric emission.*

  Several scenarii are possible, depending on the existence of mechanisms to dissipate the magnetic energy and/or of mechanisms to convert magnetic energy into kinetic energy.

  Depending on the magnetization above the photosphere, prompt emission can be associated to internal shock or magnetic dissipation.

  Intermediate scenarii are possible.

see next talk by B. Zhang

Internal shocks + synchrotron

A possible scenario :

- The outflow is initially highly magnetized

- Most of the magnetic energy is converted into kinetic energy

- Above the acceleration radius, the outflow looks like a « standard fireball », with a low magnetization, except that it is much colder.

- The prompt non-thermal emission is due to internal shocks above the photosphere.

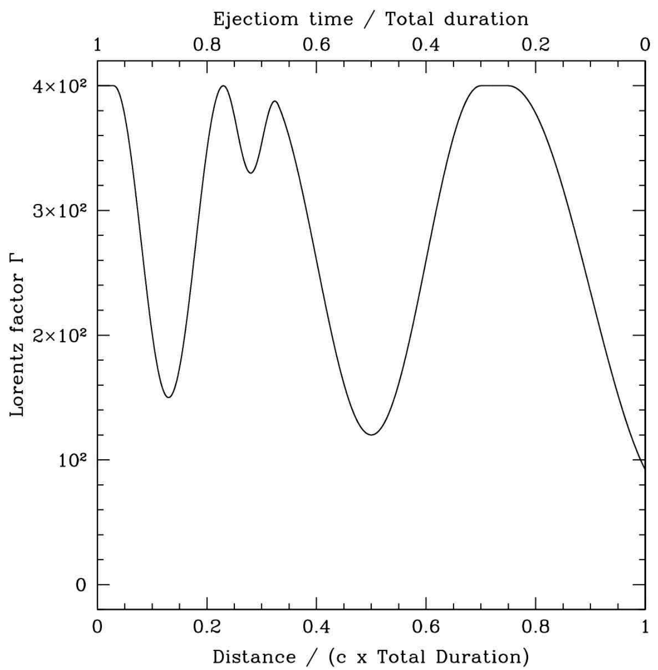
- *Observed soft gamma-rays are emitted by synchrotron radiation from electrons accelerated to large Lorentz factors in these shocks.*

Internal shocks + synchrotron

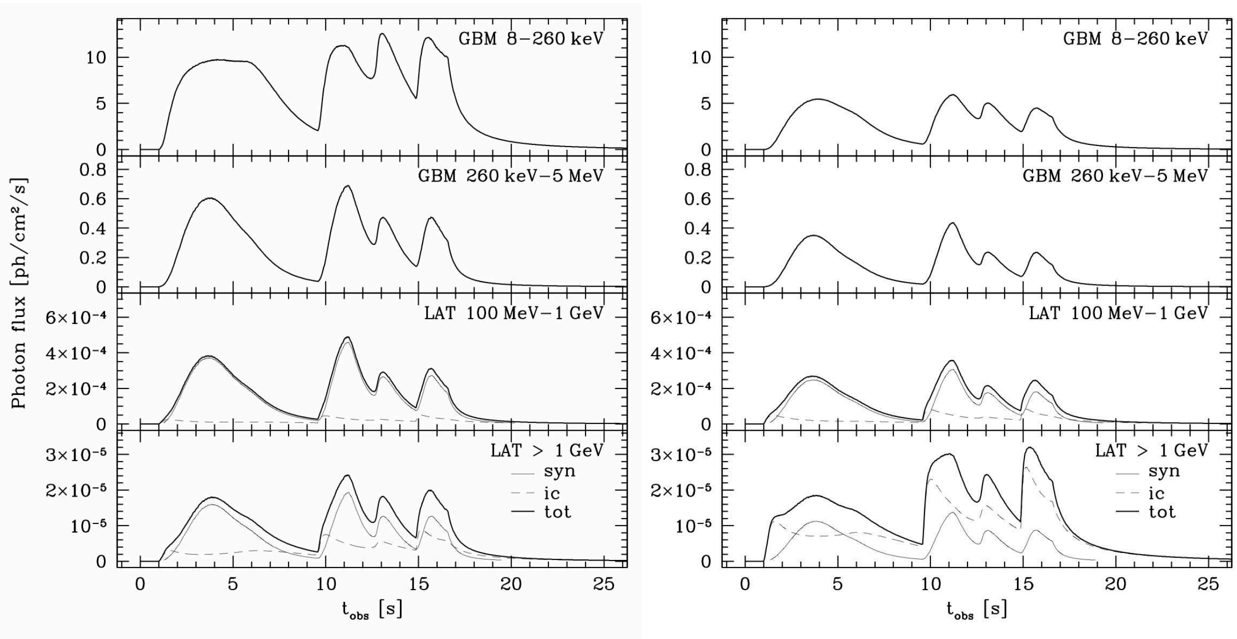
(1) Lightcurves :

- Variability is directly associated to the variability of the central engine and/or additional variability during the early propagation of the outflow

(see Lazzati et al. 2010)



Initial Lorentz factor



Lightcurves (for two sets of microphysics parameters)

(Bosnjak, Daigne & Dubus 2009)

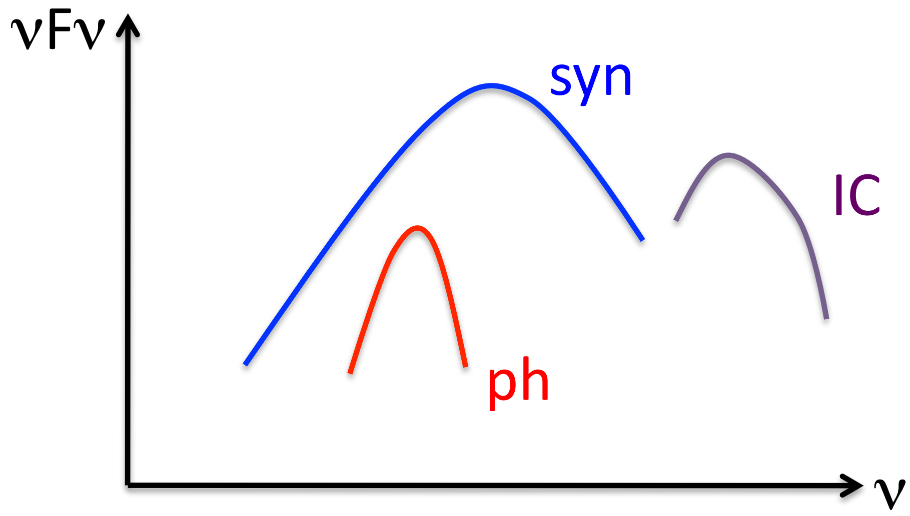
Internal shocks + synchrotron

(2) Spectrum :

- The non-thermal component is dominant

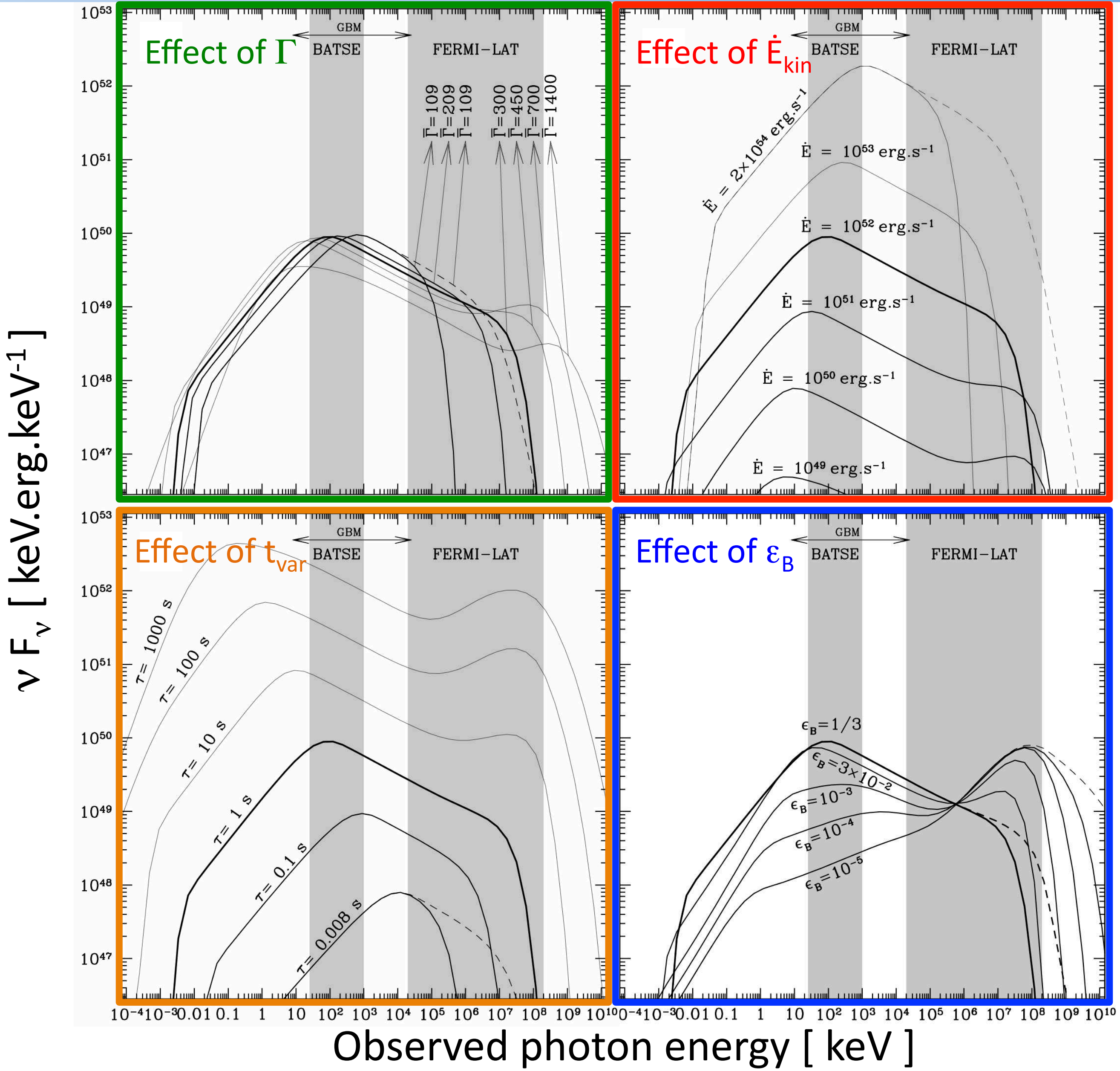
- Synchrotron emission in γ-rays : electrons have high Lorentz factors. Without any fine tuning (like in SSC models), the spectrum has one clear dominant component (IC limited by KN corrections)

(Bosnjak et al. 2009; Zou et al. 2009; Piran et al. 2009)



Internal shocks + synchrotron

(2) Spectrum :



(Bosnjak, Daigne & Dubus 2009)

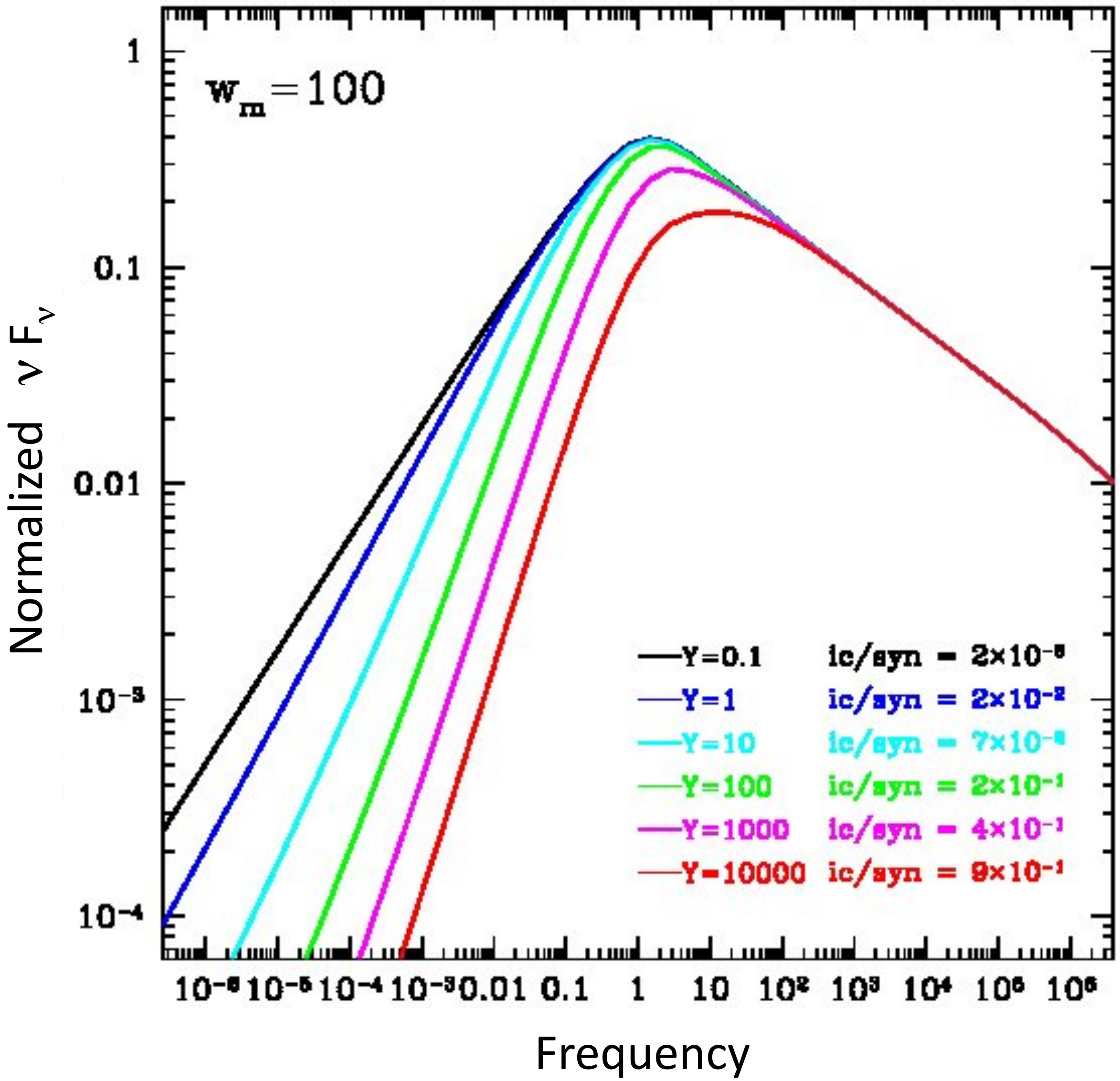
Internal shocks + synchrotron

(2) Spectrum :
low-energy slope α

Effect of IC scatterings in KN regime :

$$\boxed{-3/2 < \alpha < -1}$$

(Derishev et al. 01 ; Bosnjak et al. 09 ; Nakar et al. 09 ; Daigne et al. 10)

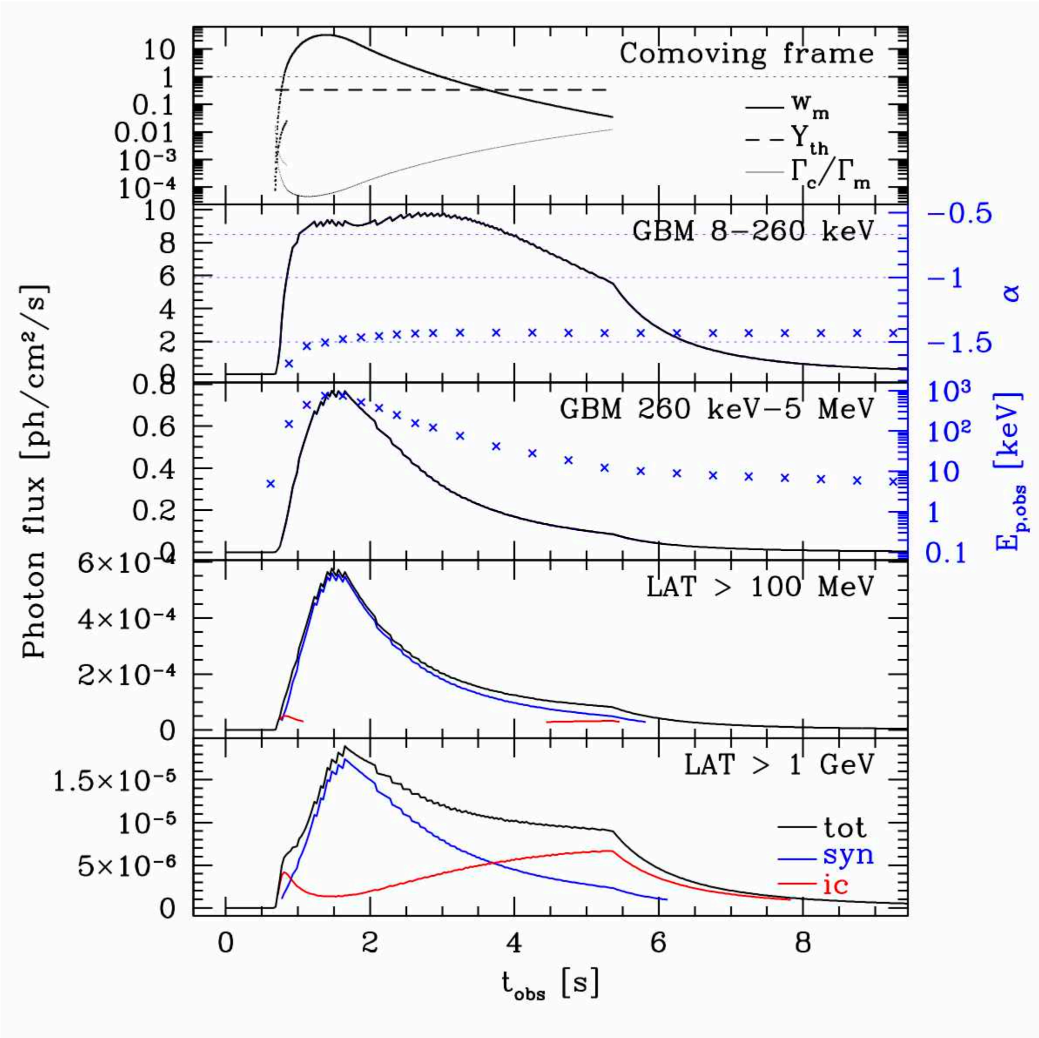


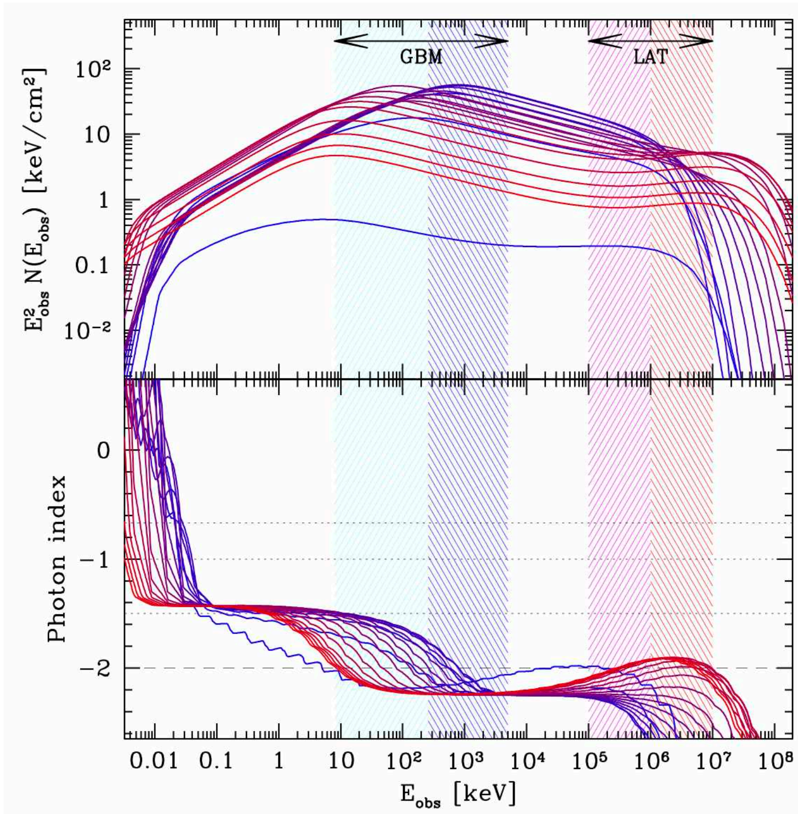
(Daigne, Bosnjak & Dubus 2010)

Internal shocks + synchrotron

(2) Spectrum :
low-energy slope α

Example of a single pulse with α = -3/2 (fast cooling synchrotron – weak IC)



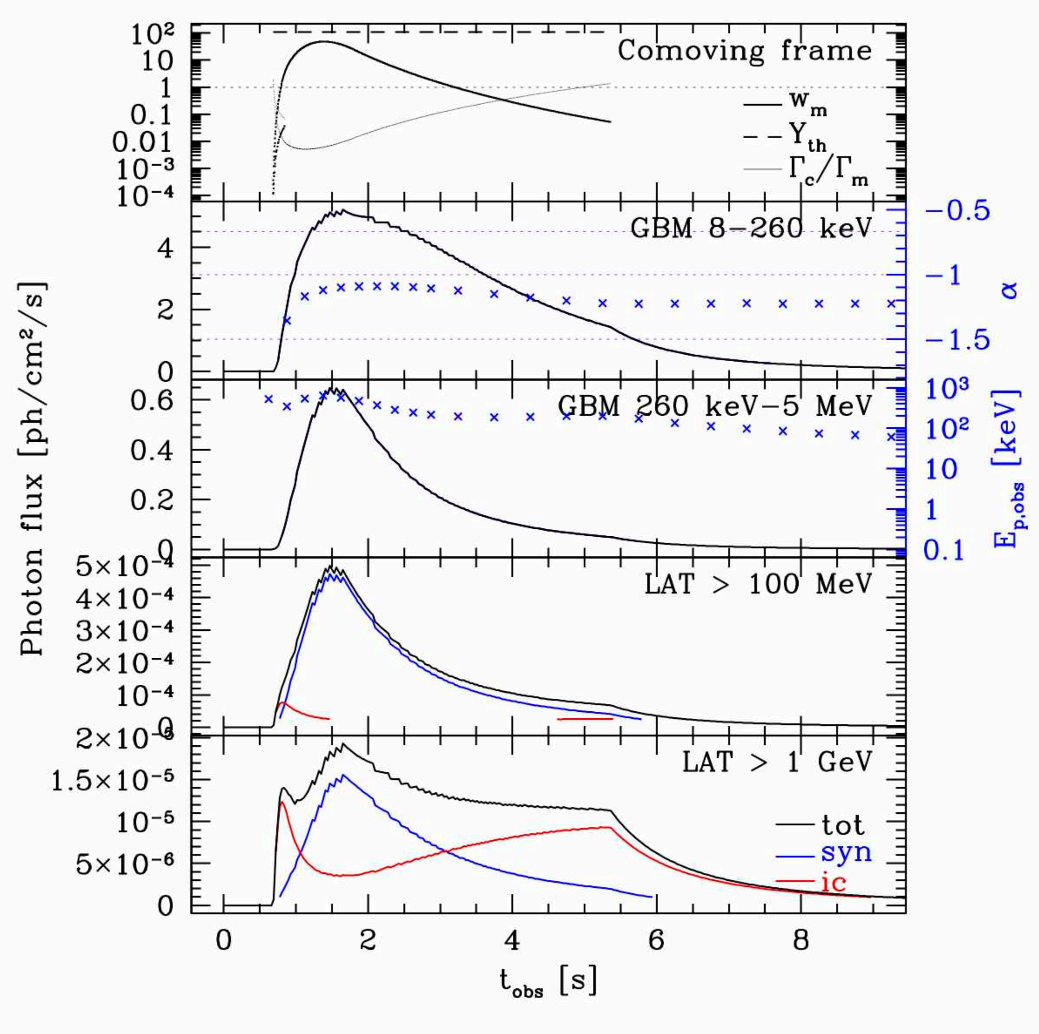


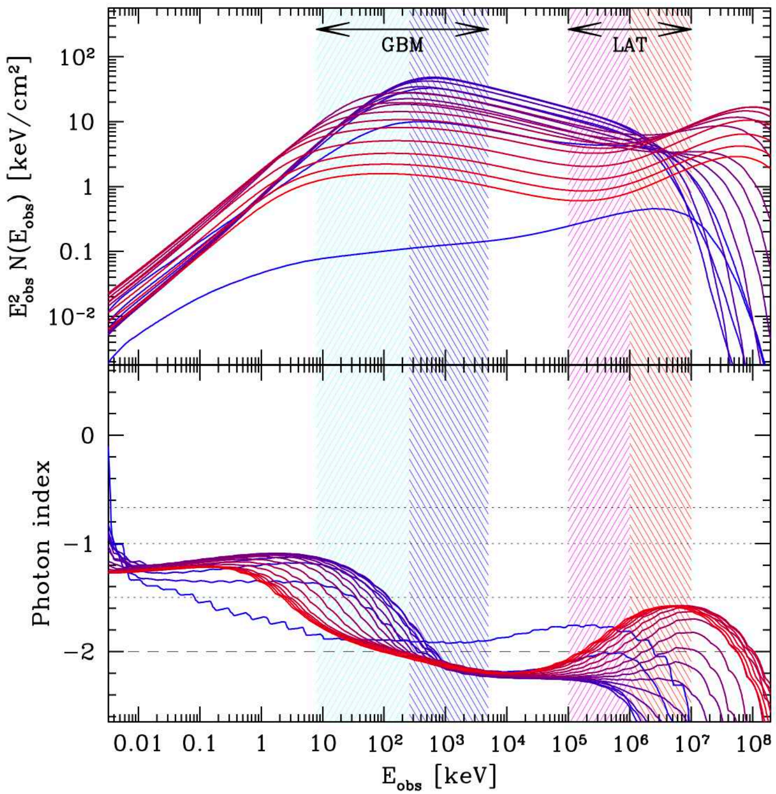
(Daigne, Bosnjak & Dubus 2010)

Internal shocks + synchrotron

(2) Spectrum :
low-energy slope α

Example of a single pulse with $-3/2 < \alpha \rightarrow -1$ (fast cooling synchrotron + IC in KN regime)



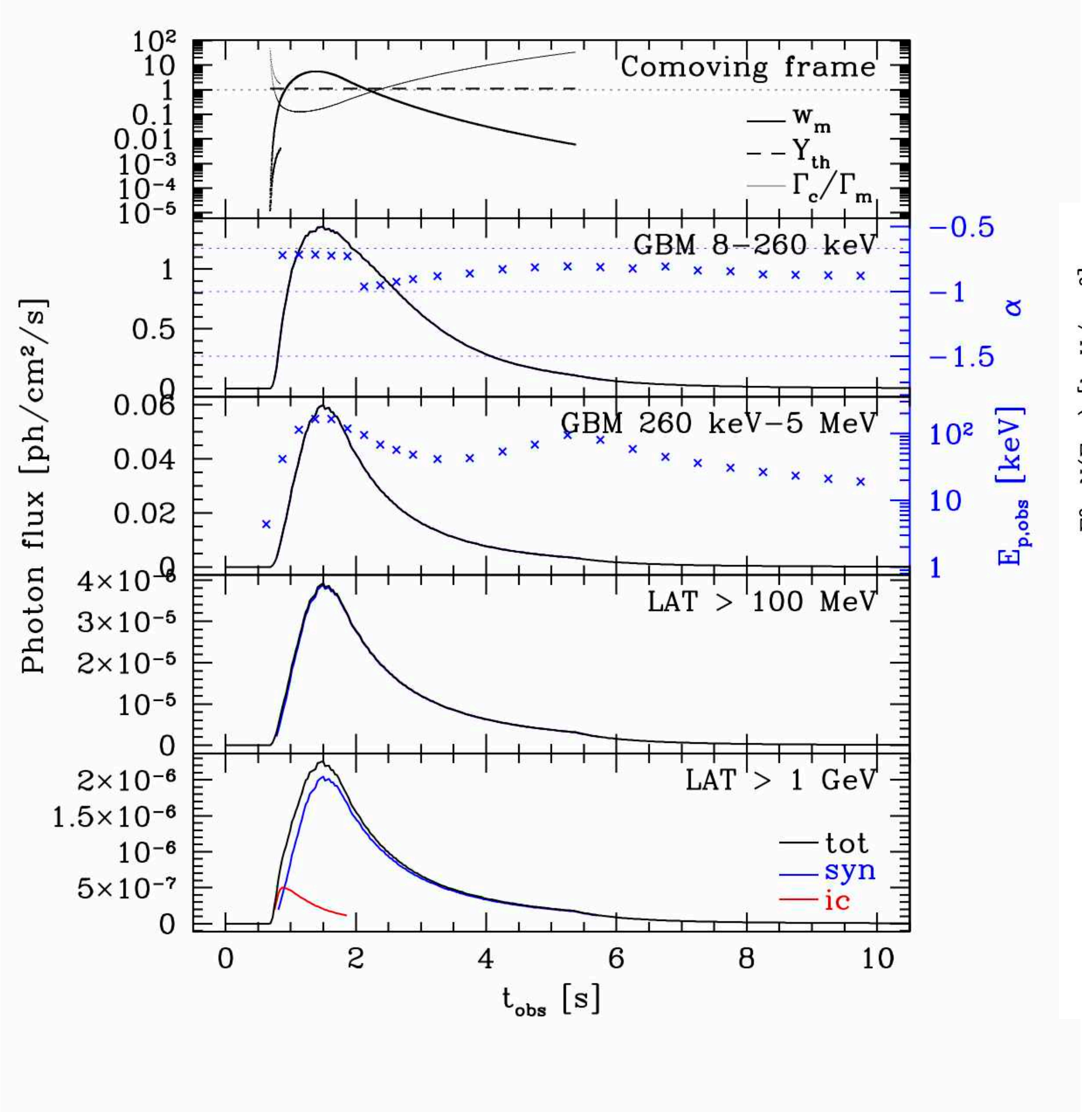


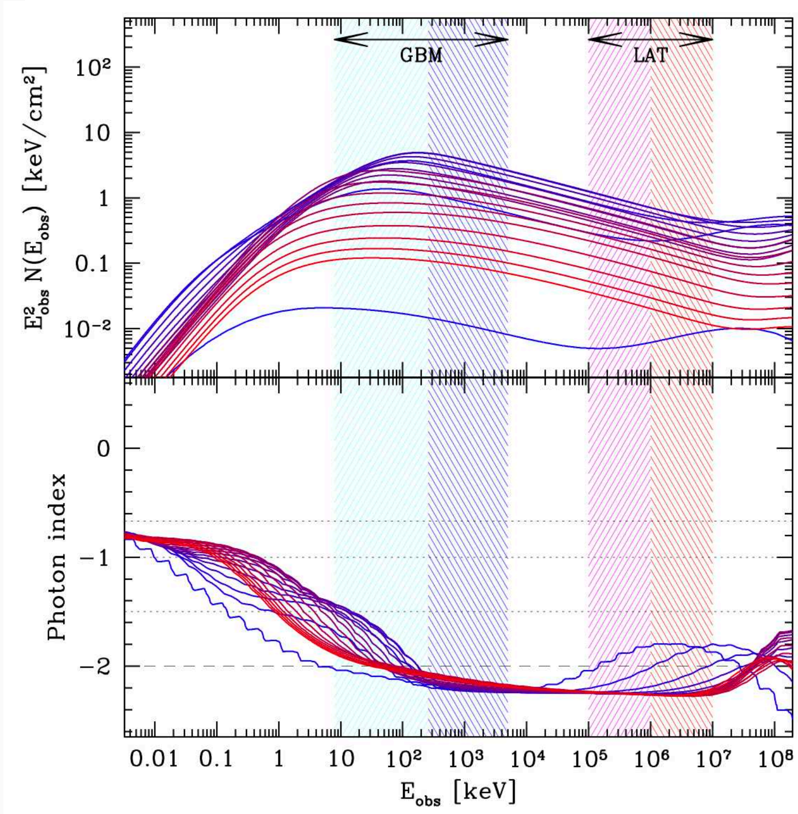
(Daigne, Bosnjak & Dubus 2010)

Internal shocks + synchrotron

(2) Spectrum :
low-energy slope α

Example of a single pulse with $-1 < \alpha \rightarrow -2/3$ (marginaly fast cooling synchrotron)





(Daigne, Bosnjak & Dubus 2010)

Internal shocks + synchrotron

(2) Spectrum :
low-energy slope α

- Fast cooling synchrotron : $\alpha = -3/2 \rightarrow -1$

(Derishev 01; Bosnjak et al. 09; Nakar et al. 09; Daigne, Bosnjak & Dubus 10)

- « Marginaly fast cooling » synchrotron : $\alpha \rightarrow$ *-2/3*

*(*this regime is possible only in a small region of the parameter space)

(Daigne, Bonsjak & Dubus 10)

- *Some GRBs show* α *> -2/3*
  - which fraction ? (depends on instrument ?)
  - is α well measured ? (Ryde & Pe'er 09; GRB 100724B, Guiriec et al. 10)
  - can the photospheric emission be dominant in some time bins ?

(Daigne & Mochkovitch 03)

Internal shocks + synchrotron

(3) Spectral evolution :

● *Most general properties in the soft γ-ray range (BATSE, Beppo-SAX, HETE2, Swift, Fermi/GBM) can be reproduced :*

-hardness-duration relation: short GRBs have larger Epeak due to smaller variability timescales.

(Daigne & Mochkovitch 1998; see GBM analysis of 3 short GRBs by Guiriec et al. 2010)

-spectral evolution: a pulse is produced by the propagation of one shock wave. Its shape and spectral evolution is related to the evolution of the physical conditions in the shocked material.

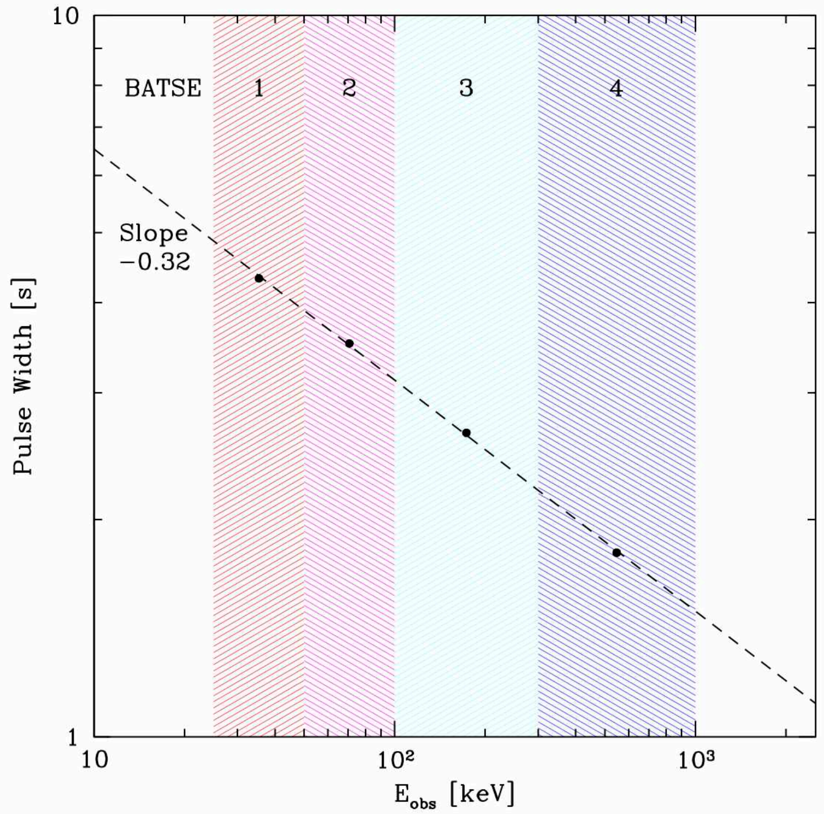
(Daigne & Mochkovitch 1998, 2002; Bosnjak, Daigne & Dubus 2009)

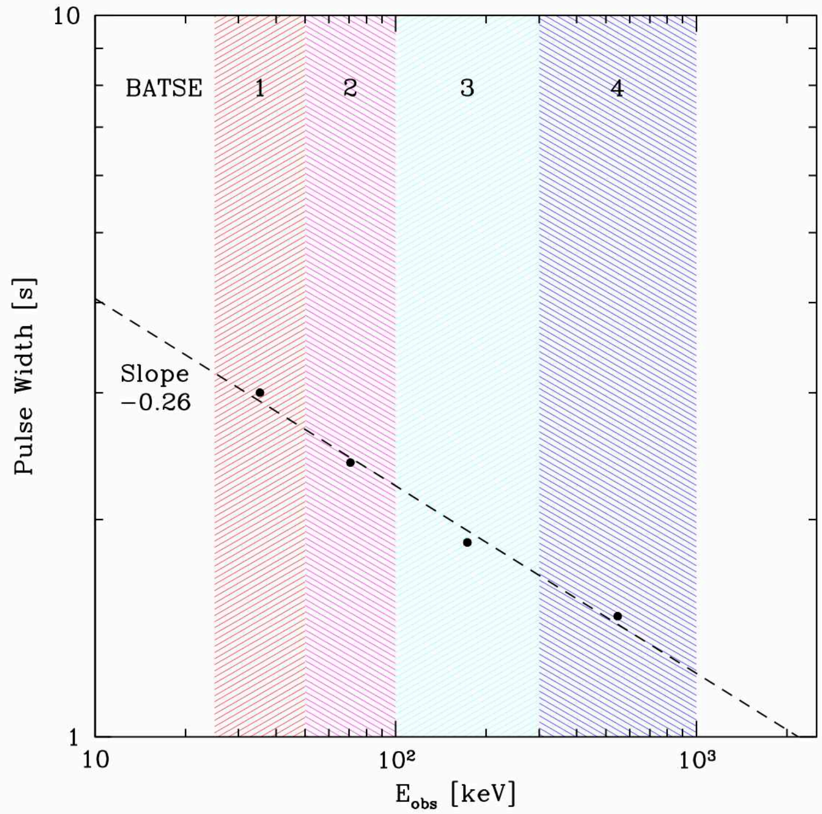
See Poster 2.01 by Z. Bosnjak et al.

Internal shocks + synchrotron

(3) Spectral evolution :

- Example : evolution of pulse shape in 4 BATSE channels





(other properties : time-lags, HIC, HFC, …)

cf. BATSE/Swift/GBM results
(Fenimore et al. 95, Norris et al. 96, …)
(Sakamoto's talk; Bissaldi's talk)

Internal shocks + synchrotron

(4) Diversity in the GRB population :

- Diversity is expected :

-cosmic GRBs :	*ultra-relativistic / ultra-energetic*
-soft GRBs (XRR, XRF) :	*lower baryonic pollution / smoother flow*
-weak GRBs :	*mildly relativistic / mildly-energetic*

- Amati-like relation is expected, however with some dispersion

(Barraud et al. 2005; Daigne & Mochkovitch 2007)

(detailed modeling needs some input : physics of central engine, microphysics in shocks)

Internal shocks + synchrotron

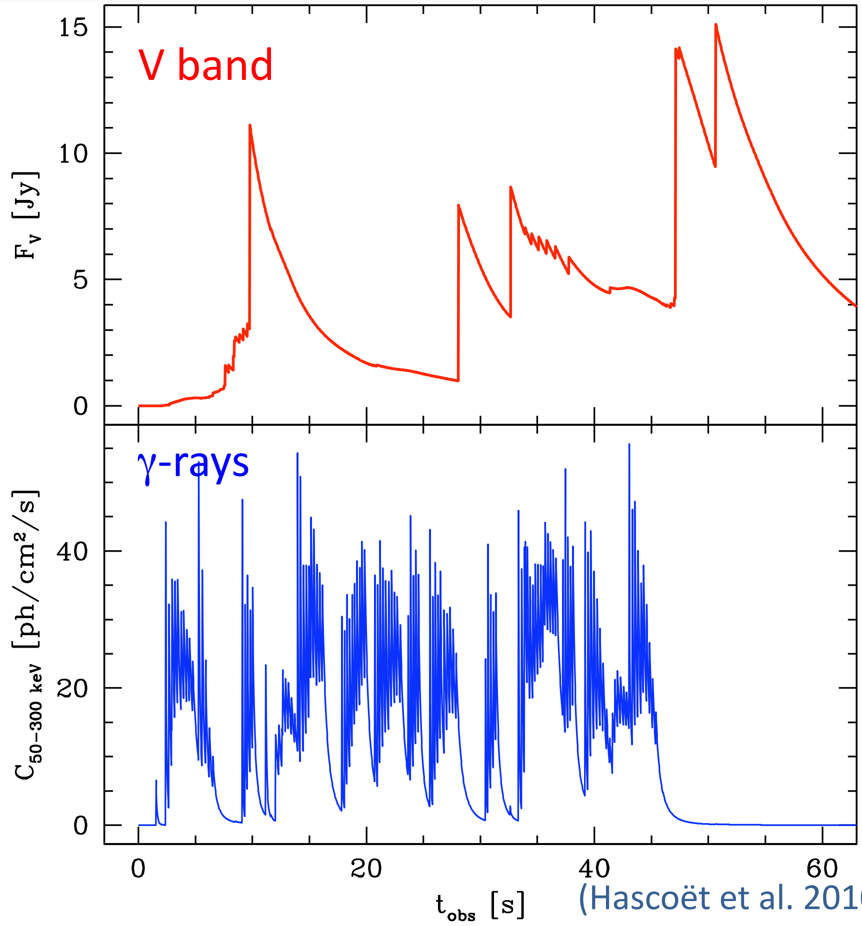
(5) Prompt optical emission :

- Variable prompt optical emission is expected from internal shocks

See Poster 8.01 by D. Götz et al. on GRB 041219A

- Bright prompt optical emission (like in the naked-eye burst) is expected for highly variable outflows.

(Li & Waxman 2008 ; Hascoët et al. 2010, in preparation)



(Hascoët et al. 2010)

Internal shocks + synchrotron

(6) Prompt high-energy emission : origin of GeV emission ?

- It has been proposed that GeV photons could have an external origin

  (Kumar & Barniol-Duran 10 ; Ghisellini et al. 10)

  - Limit below a few GeV from the forward shock ?

    (Piran & Nakar 10 ; Kumar & Barniol-Duran 10)

  - Variability ?

- High-energy photons could have an hadronic origin : energetics ?

  (Asano 09; Razzaque 09)

- In the *internal shock + synchrotron scenario*, a variable high-energy component is expected (IC with variable efficiency) – It can delay the GeV emission by a duration comparable with the pulse duration.

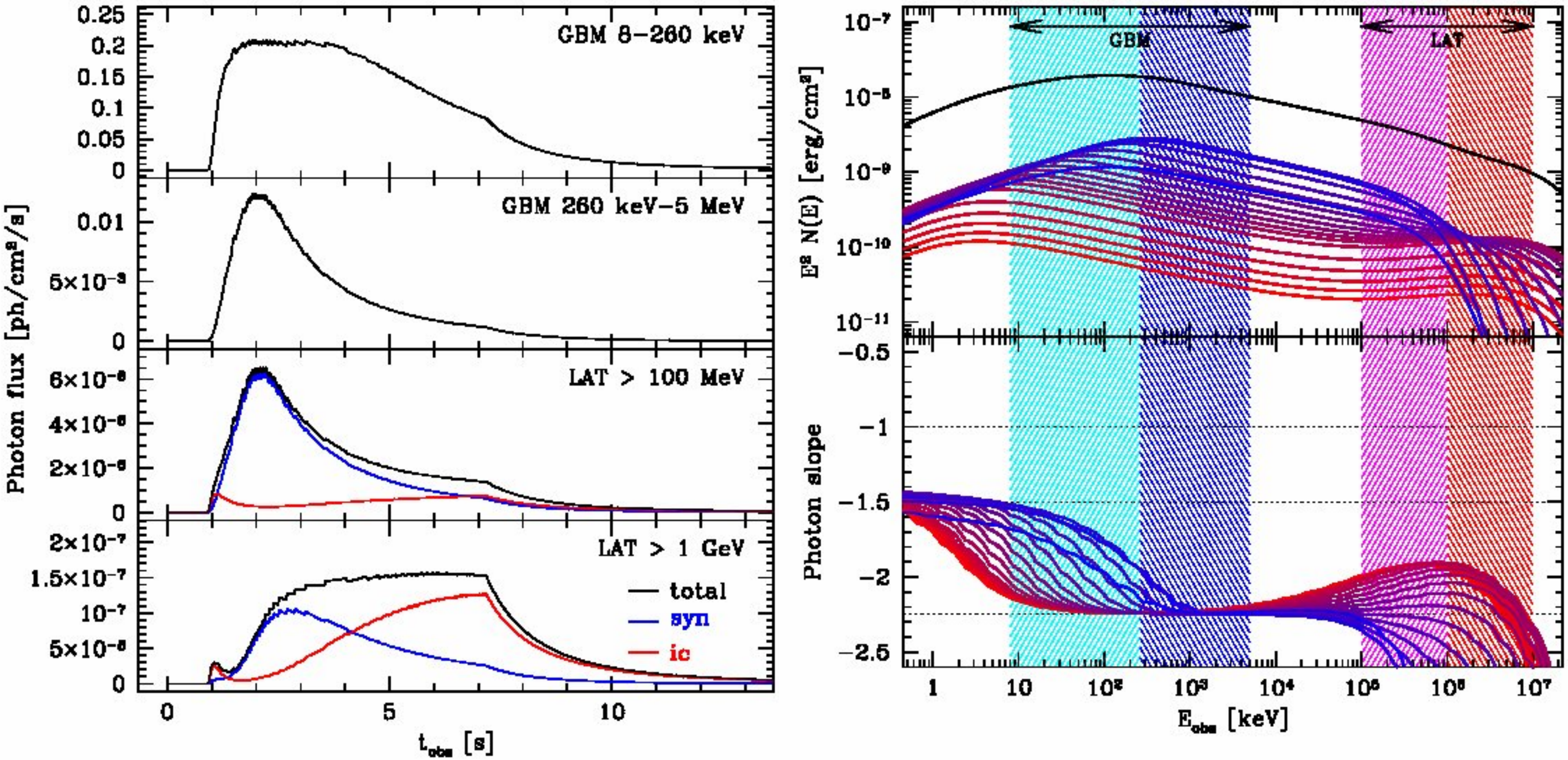
  (Bosnjak, Daigne & Dubus 2009)

Internal shocks + synchrotron

(6) Prompt high-energy emission

Example of a single pulse with different sets of microphysics parameters

$\epsilon_B = \epsilon_e = 0.1$ $\zeta = 10^{-3}$

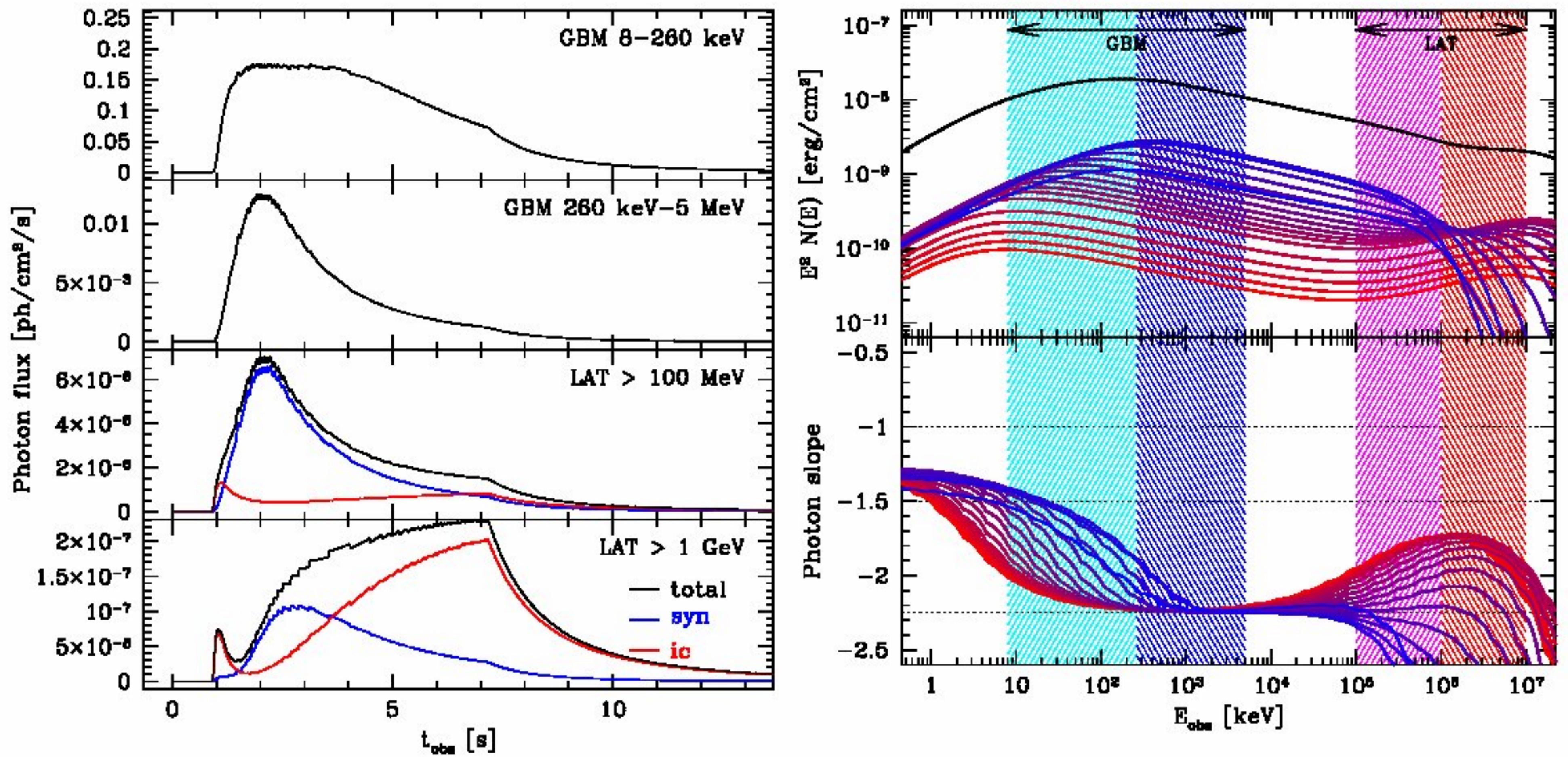


Internal shocks + synchrotron

(6) Prompt high-energy emission

Example of a single pulse with different sets of microphysics parameters

$\varepsilon_B = \varepsilon_e/10 = 0.01$ $\zeta = 5\times10^{-4}$

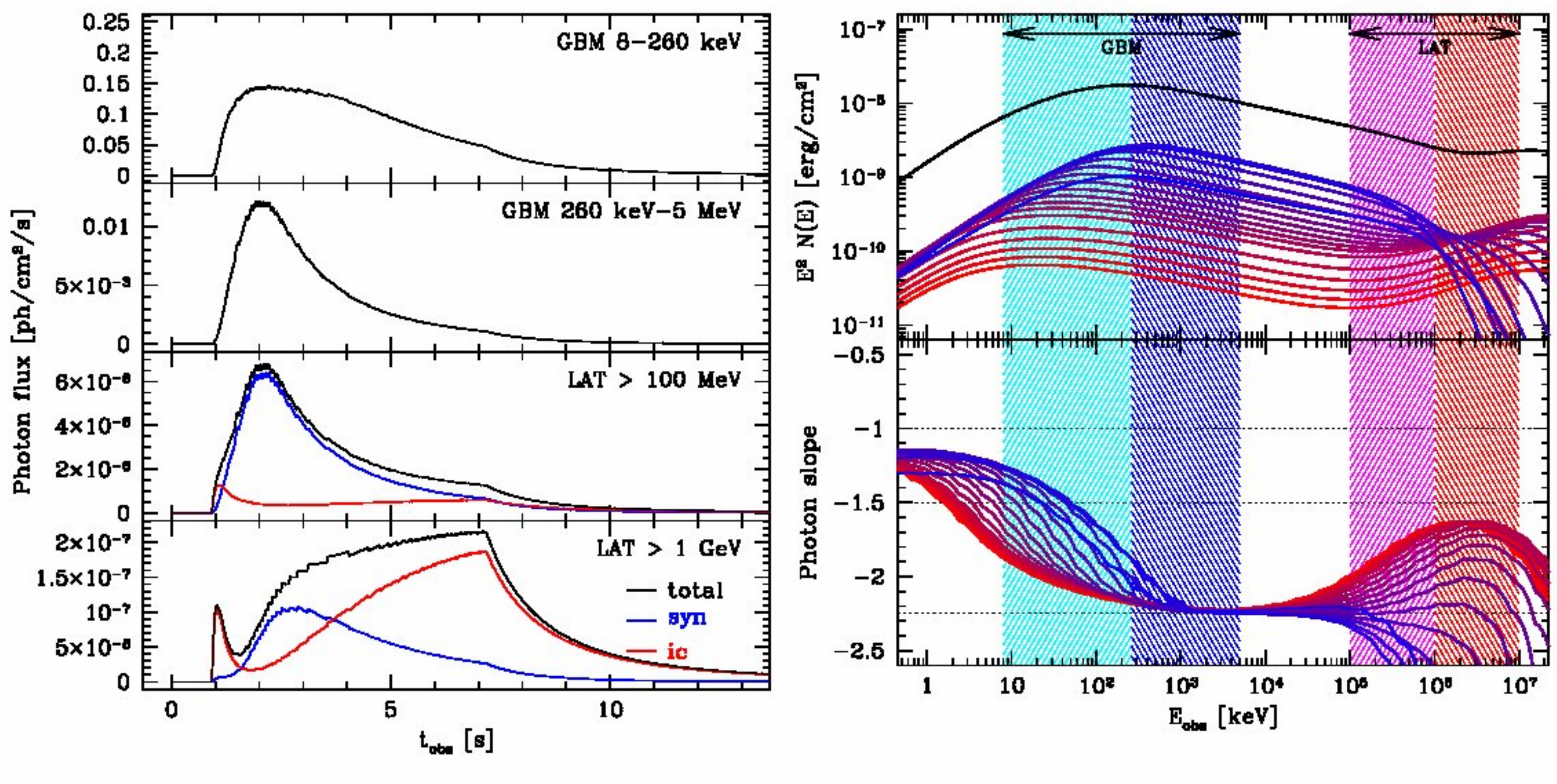


Internal shocks + synchrotron

(6) Prompt high-energy emission

Example of a single pulse with different sets of microphysics parameters

$\varepsilon_B = \varepsilon_e/100 = 0.001$ $\zeta = 3\times10^{-4}$

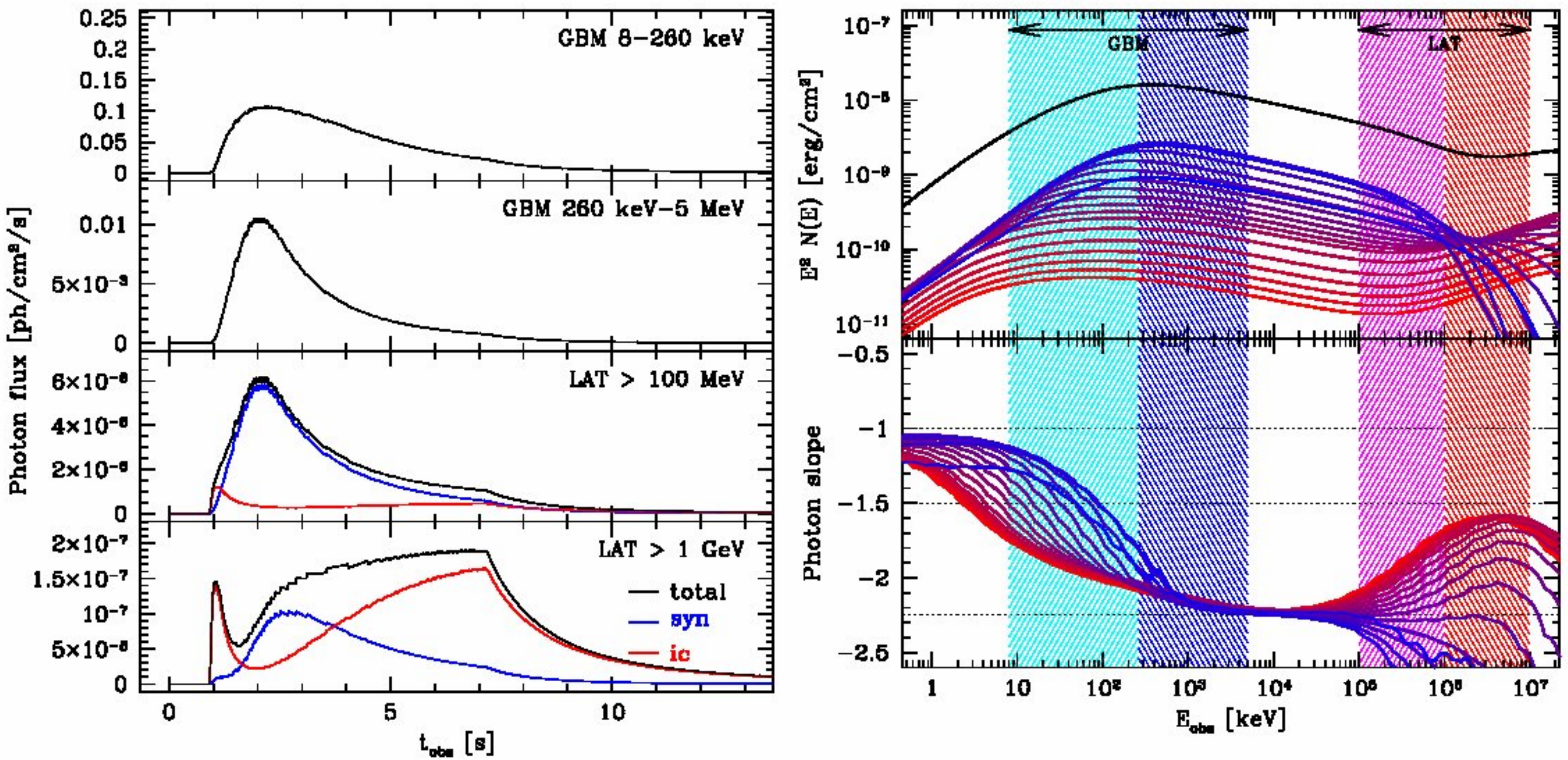


Internal shocks + synchrotron

(6) Prompt high-energy emission

Example of a single pulse with different sets of microphysics parameters

$\varepsilon_B = \varepsilon_e/1000 = 0.0001$ $\zeta = 2\times10^{-4}$

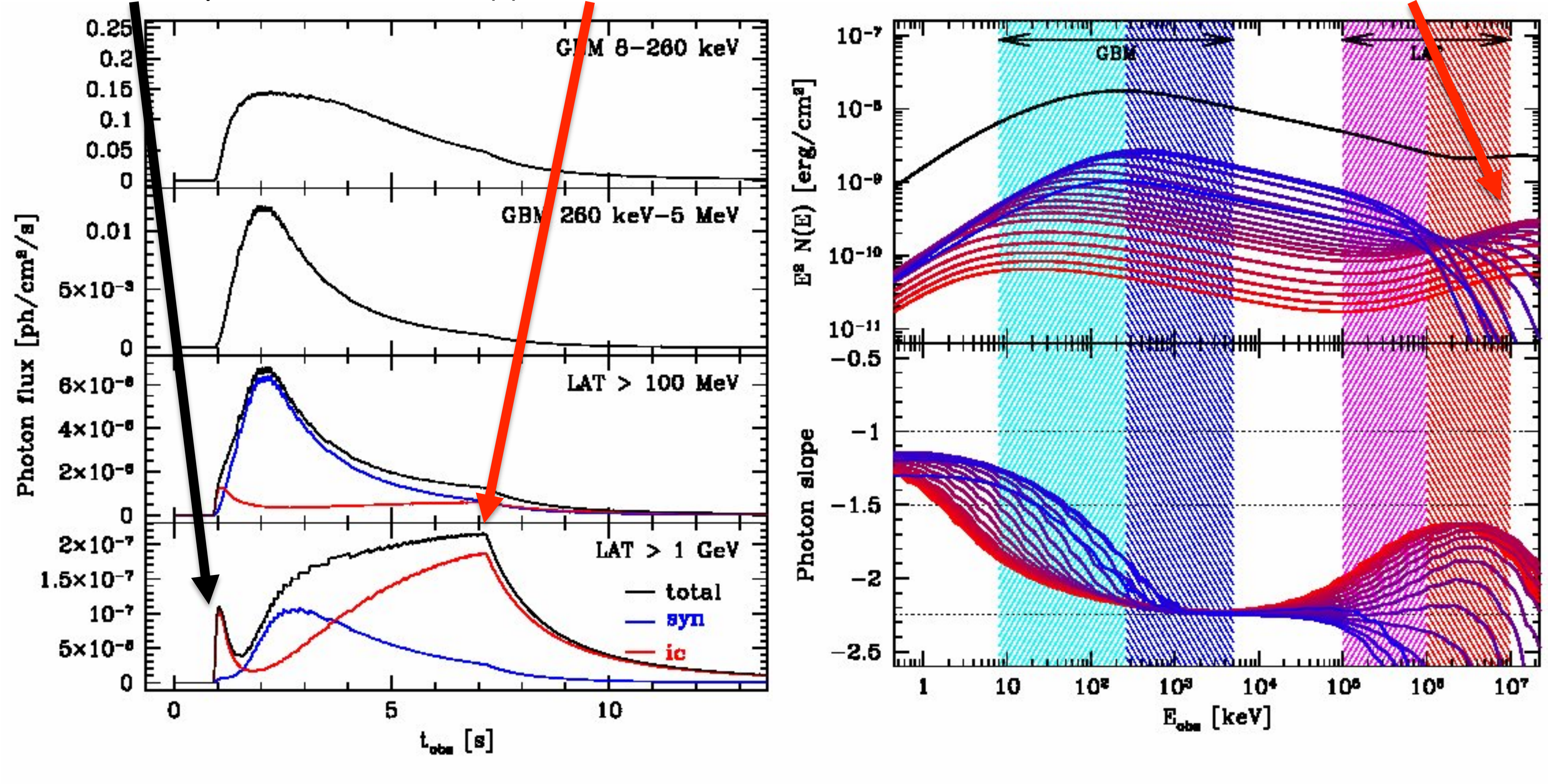


Internal shocks + synchrotron

This feature can be suppressed for more rapid variations of Γ(t)

Delayed GeV emission

Variable additional component at high-energy



Summary (2)

The scenario where the prompt GRB emission is due to *internal shocks* in a *magnetically accelerated outflow* has several interesting qualities :

- The photospheric emission can be very weak
(ratio thermal/non-thermal depends on initial magnetization)

- The soft gamma-ray properties are reasonnably well reproduced (spectral shape/slope, lightcurve, pulse shape, spectral evolution, …)

- The diversity of the GRB population can be explained
(low-luminosity GRBs, XRR, XRF, …)

- Variable prompt optical emission is expected
(it can be very bright for highly variable outflows)

- A variable component at high-energy emission (LAT) is expected
(synchrotron in soft γ-rays remains dominant in most cases)