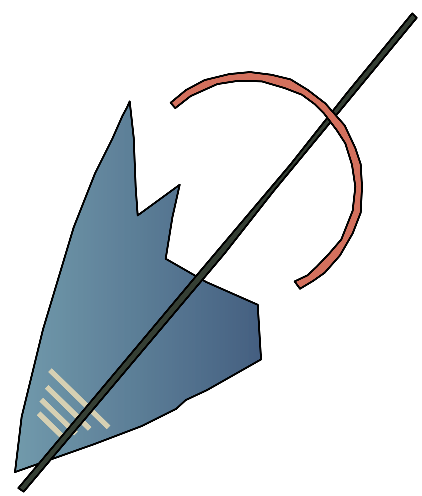
Gamma-Ray Bursts

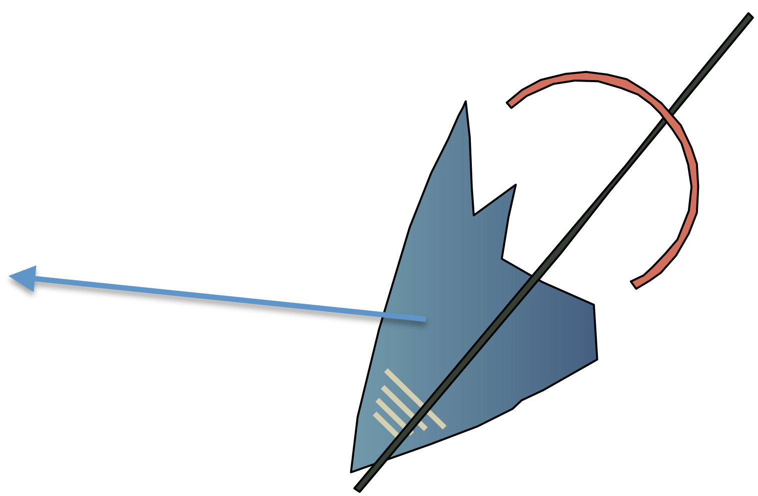
Frédéric Daigne (Institut d'Astrophysique de Paris)
daigne@iap.fr



Fourth School of Astroparticle Physics: « Gravitational Waves » – May 27 – June 1st, 2013 – OHP, France

Gamma-Ray Bursts

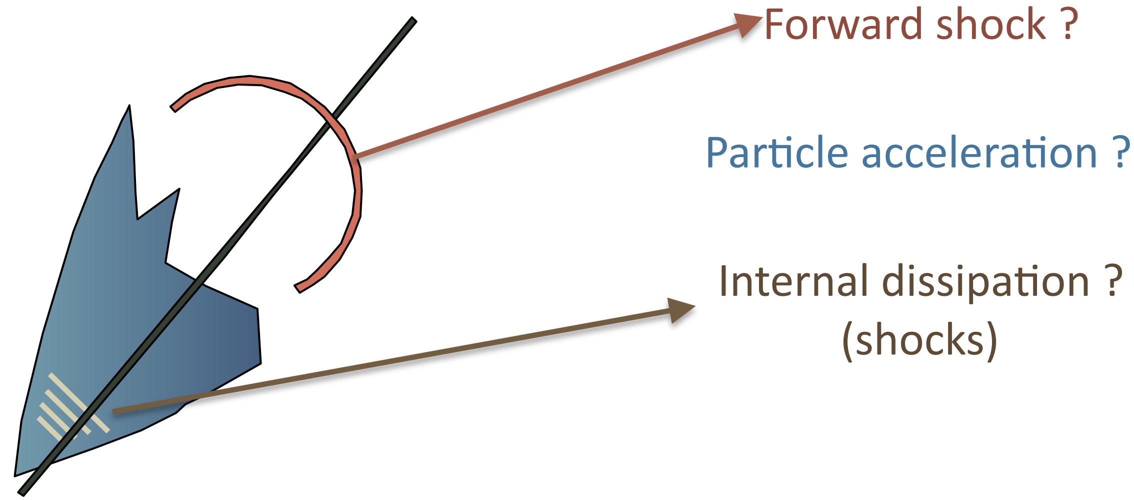
Frédéric Daigne (Institut d'Astrophysique de Paris)
daigne@iap.fr



Fourth School of Astroparticle Physics: « Gravitational Waves » – May 27 – June 1st, 2013 – OHP, France

Gamma-Ray Bursts

Frédéric Daigne (Institut d'Astrophysique de Paris)
daigne@iap.fr

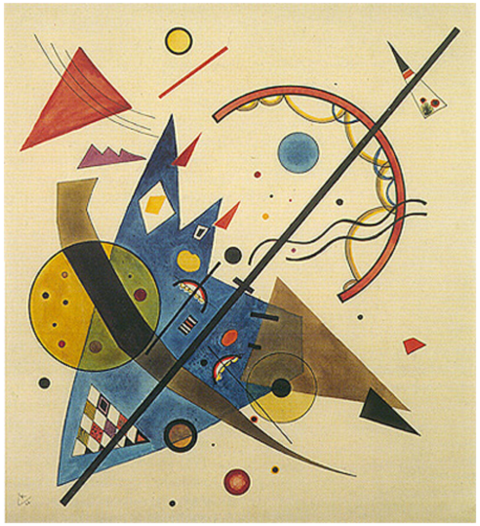


Fourth School of Astroparticle Physics: « Gravitational Waves » – May 27 – June 1st, 2013 – OHP, France

Gamma-Ray Bursts

Frédéric Daigne (Institut d'Astrophysique de Paris)
daigne@iap.fr

UPMC
PARIS UNIVERSITAS
IUF



Kandinksy – Curves and sharp angles - 1923

Fourth School of Astroparticle Physics: « Gravitational Waves » – May 27 – June 1st, 2013 – OHP, France

Outline

1) Summary of the main observations
2) Identification of progenitors
3) Minimal constraints on any GRB model
4) A « standard » scenario ?

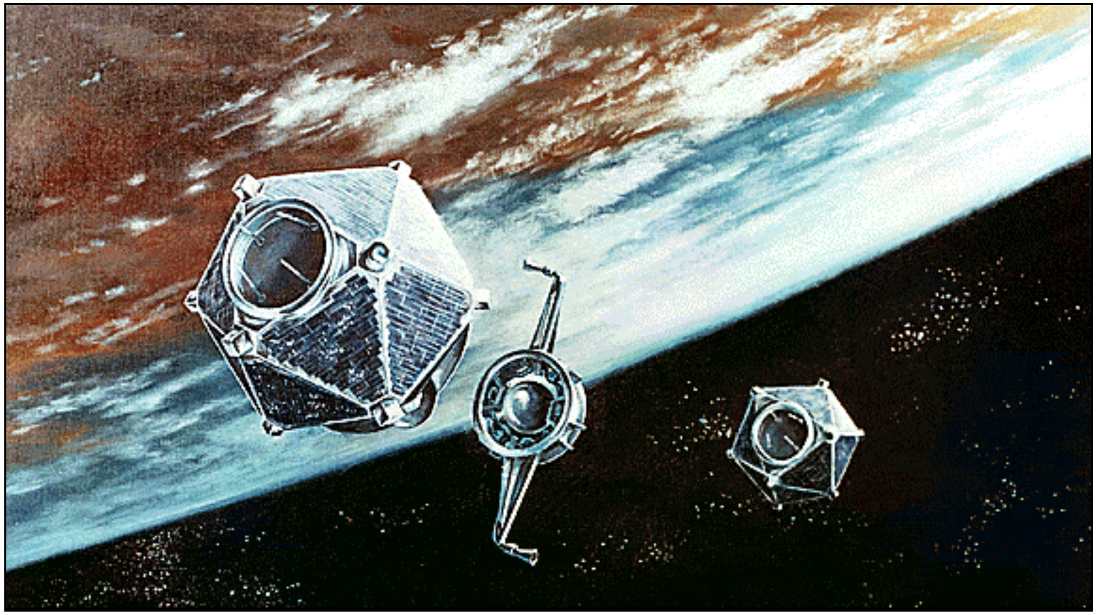
5) Central engine – Gravitational waves
6) Relativistic ejection – Jet composition ?
7) Afterglow models
8) Prompt emission models

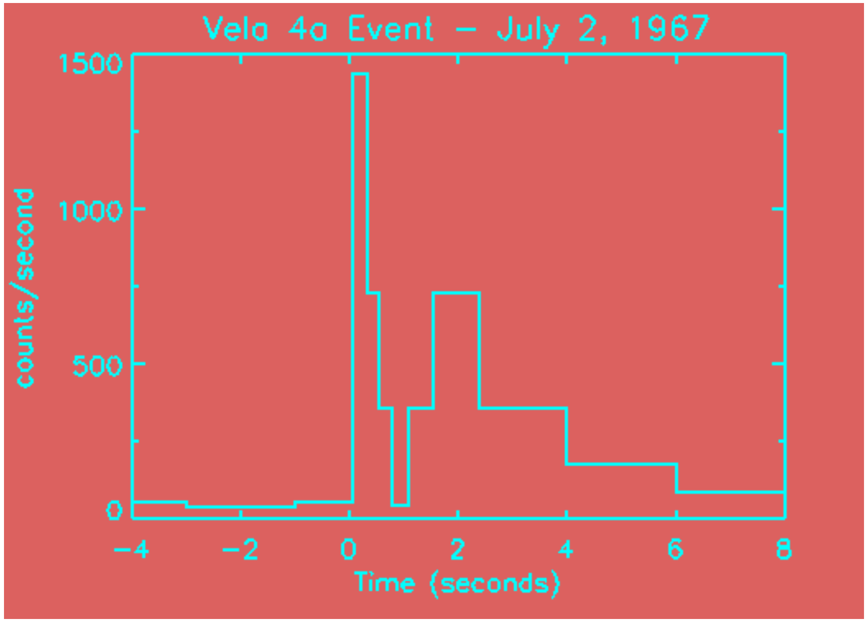
Conclusion

1– Main observations

Gamma-Ray Bursts were discovered in 1967

VELA : 3 pairs of satellites, launched in 1963, 1964 & 1965

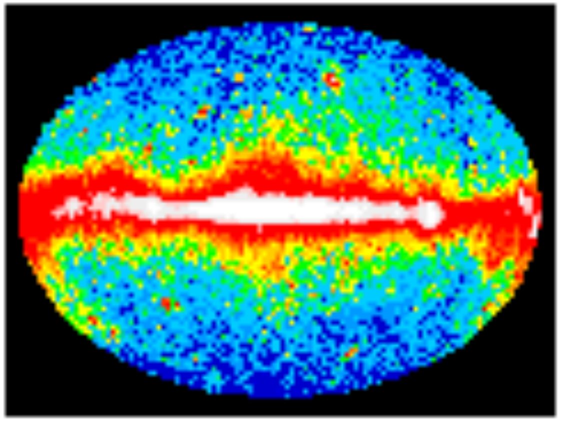


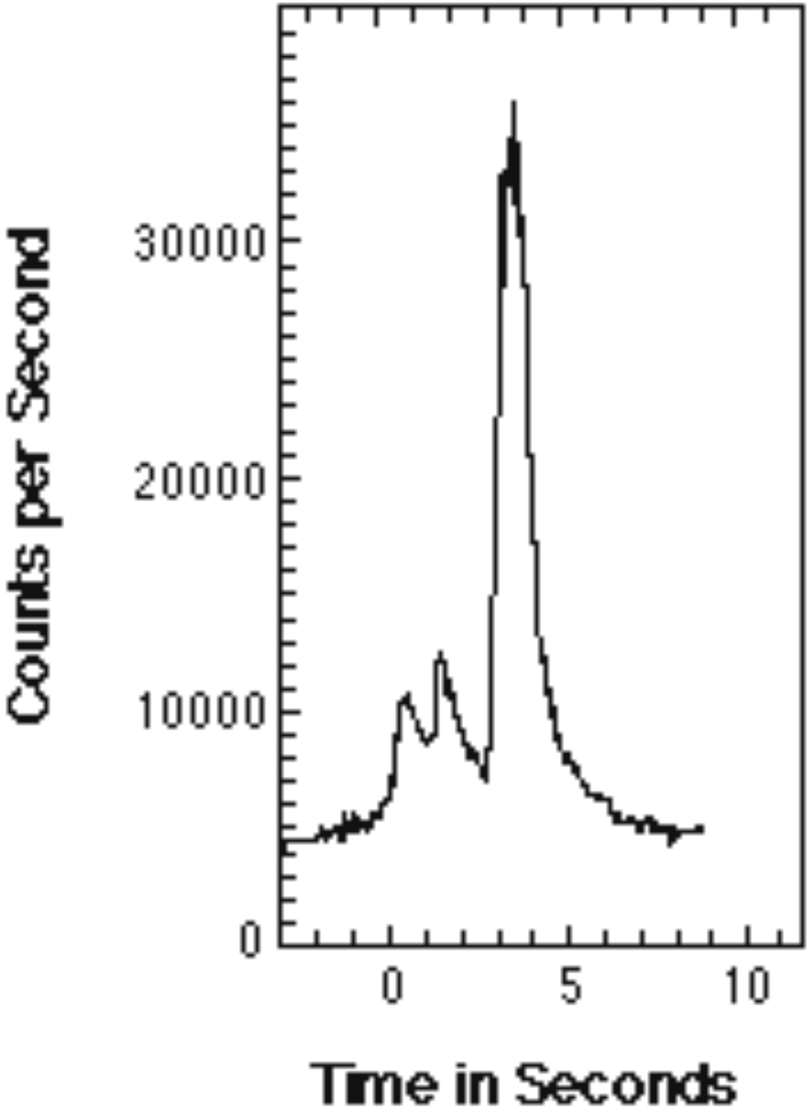


The first GRB

Discovery paper : Klebesadel et al. 1973

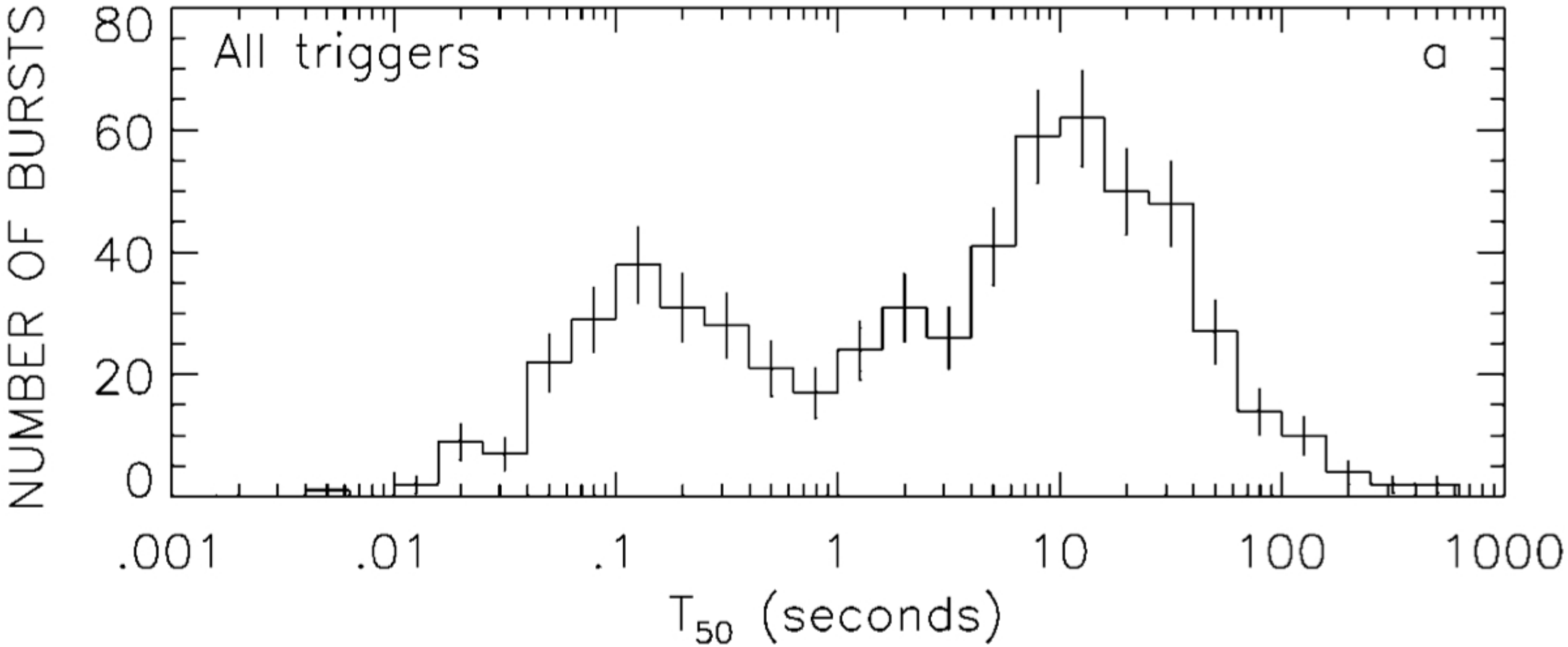
What is a Gamma-Ray Burst ?





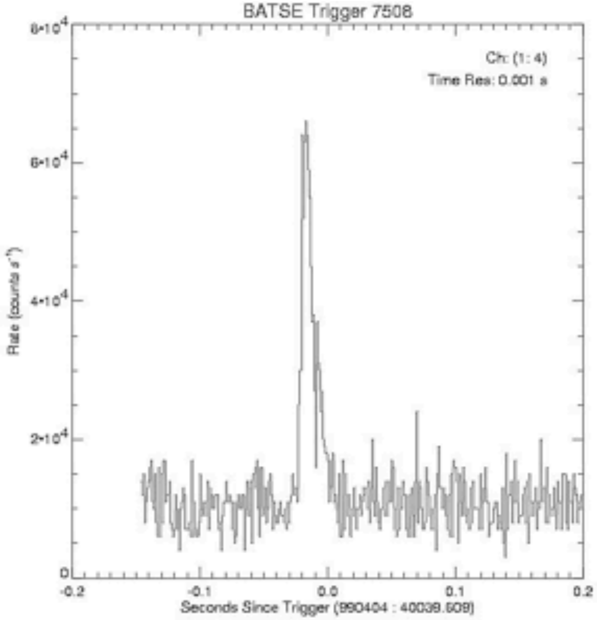
Duration: short and long bursts

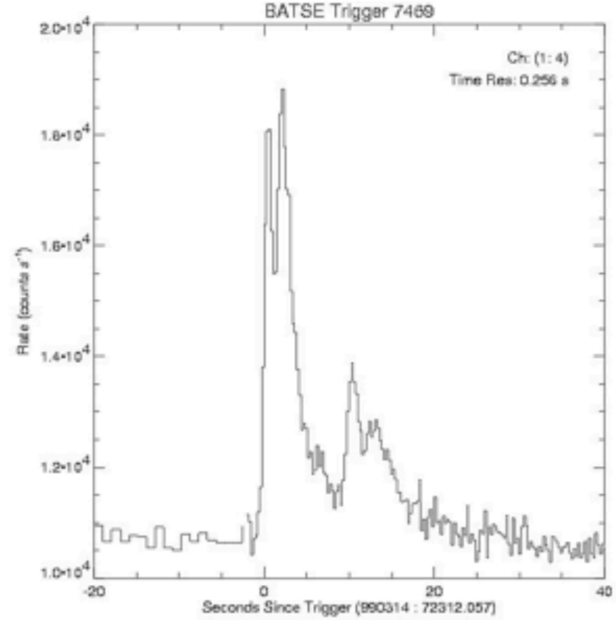
Two groups: short vs long (Kovelioutou et al. 1993)

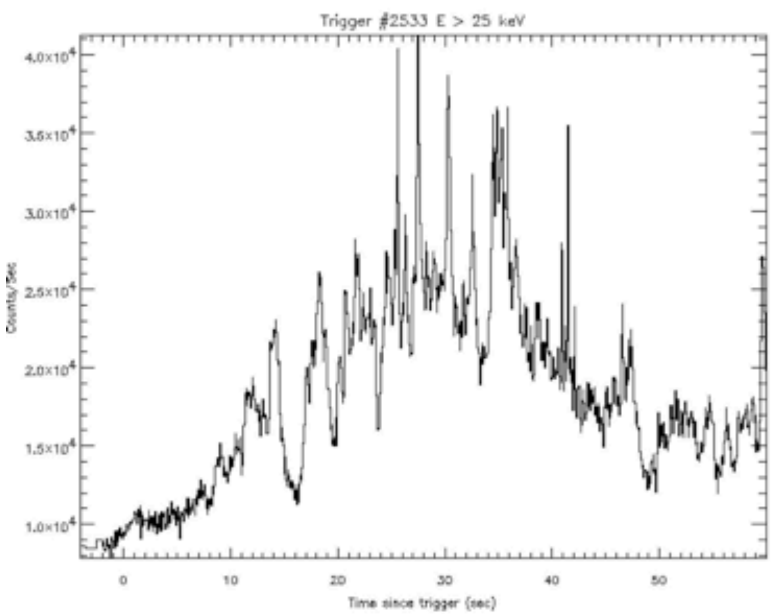


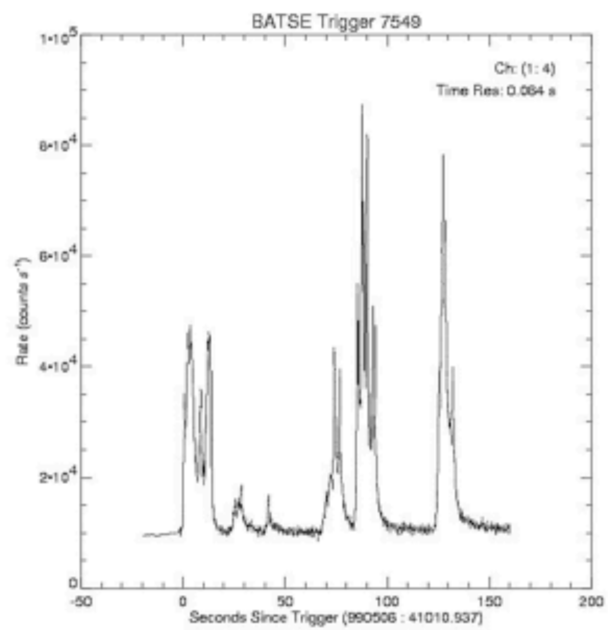
The 4th BATSE catalog (Paciesas et al. 1999)

Lightcurves: variability and diversity



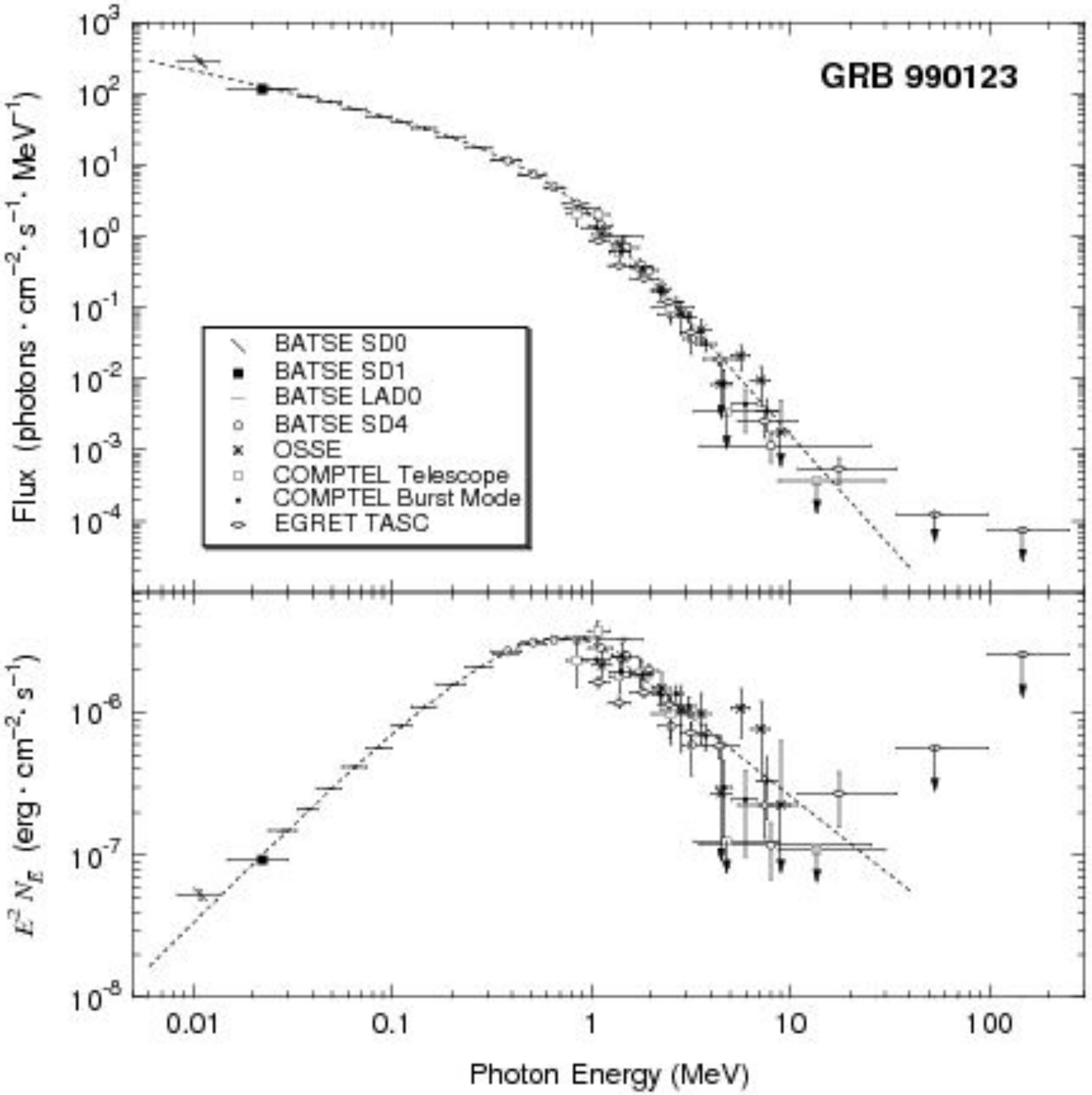






The 4th BATSE catalog (Paciesas et al. 1999)

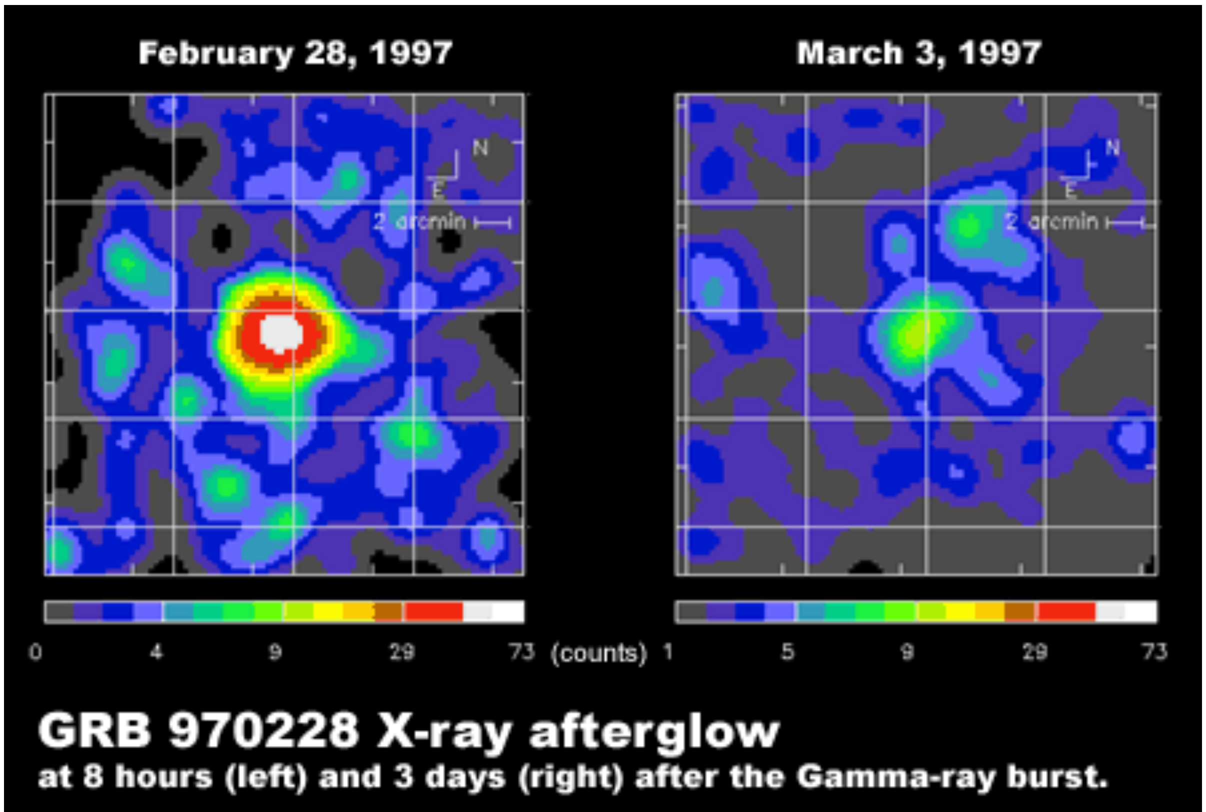
Non-thermal spectrum

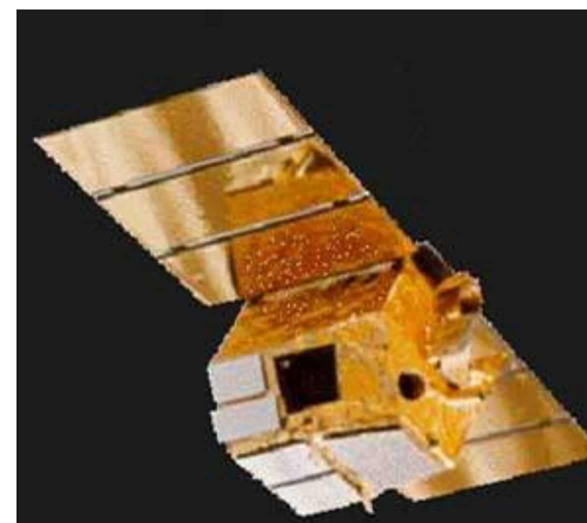


Briggs et al. 1999

Short bursts are harder than long bursts.

X-ray afterglows (Beppo-SAX, 1997)

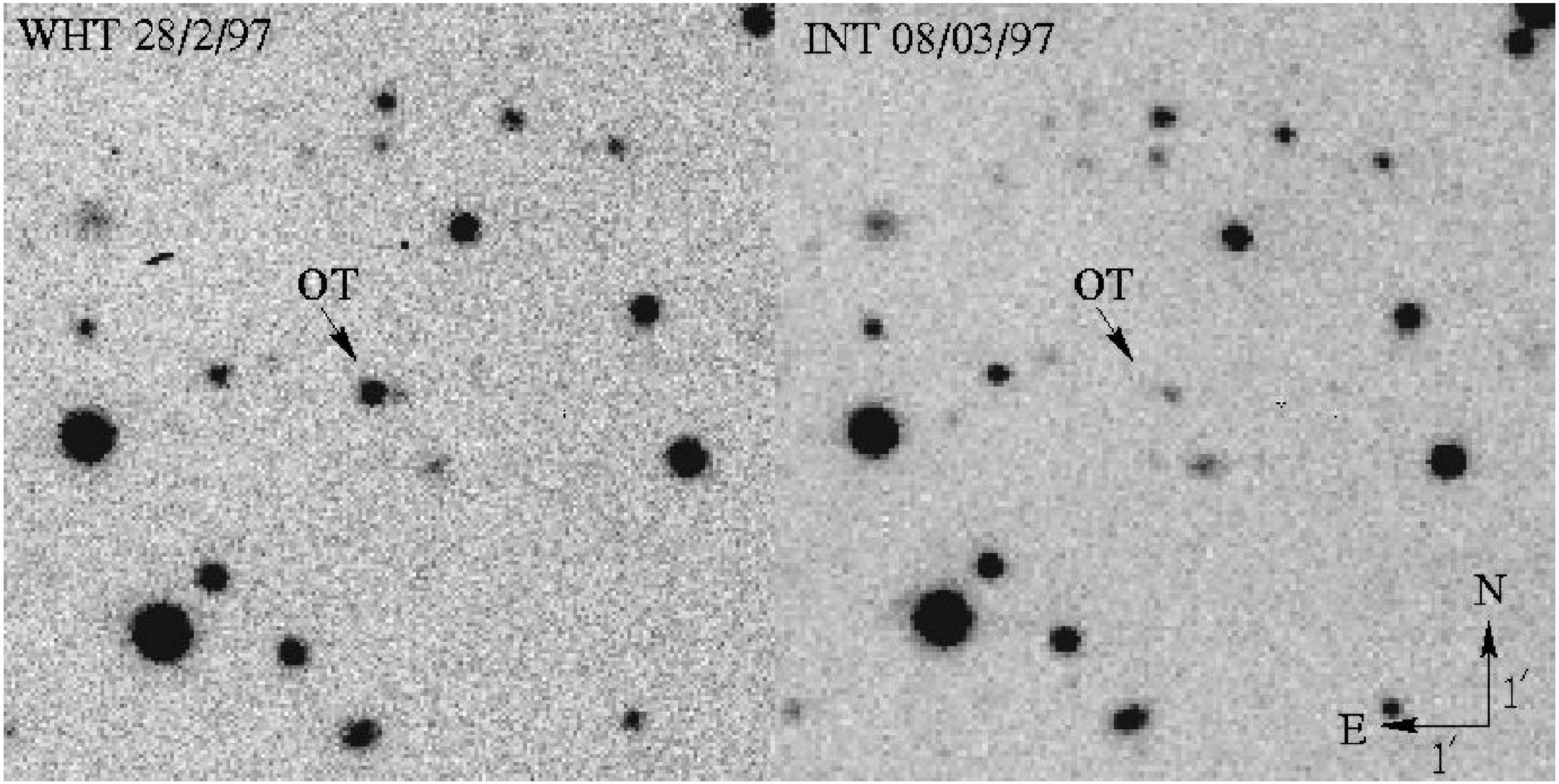




Beppo-SAX

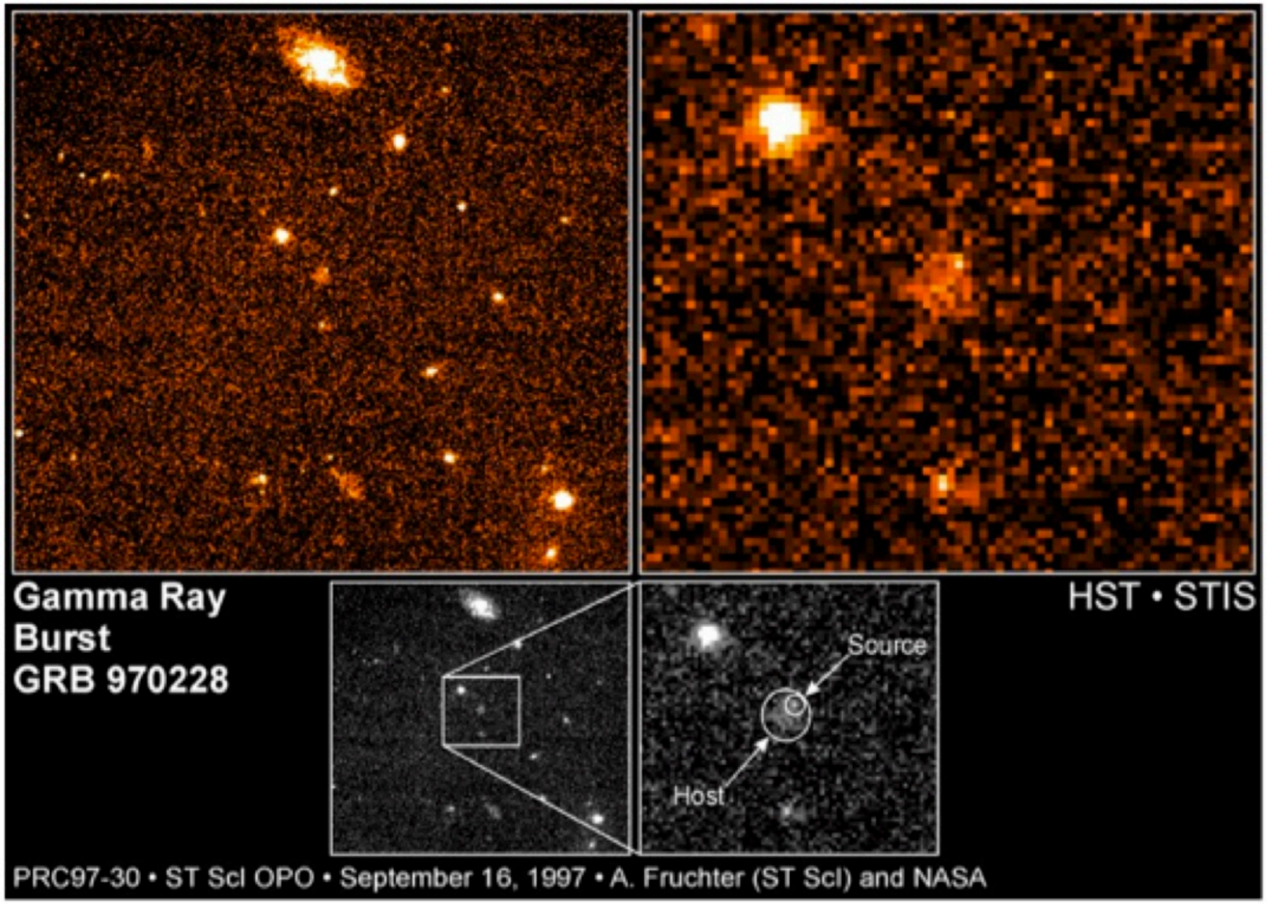
1997: the first optical afterglow

GRB 970228, van Paradijs et al.



van Paradijs et al. 1997

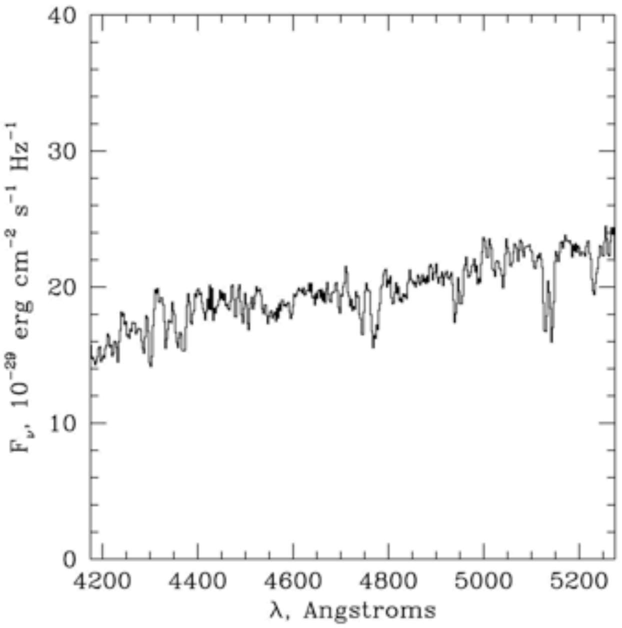
Afterglows: the host galaxy of GRB 970228



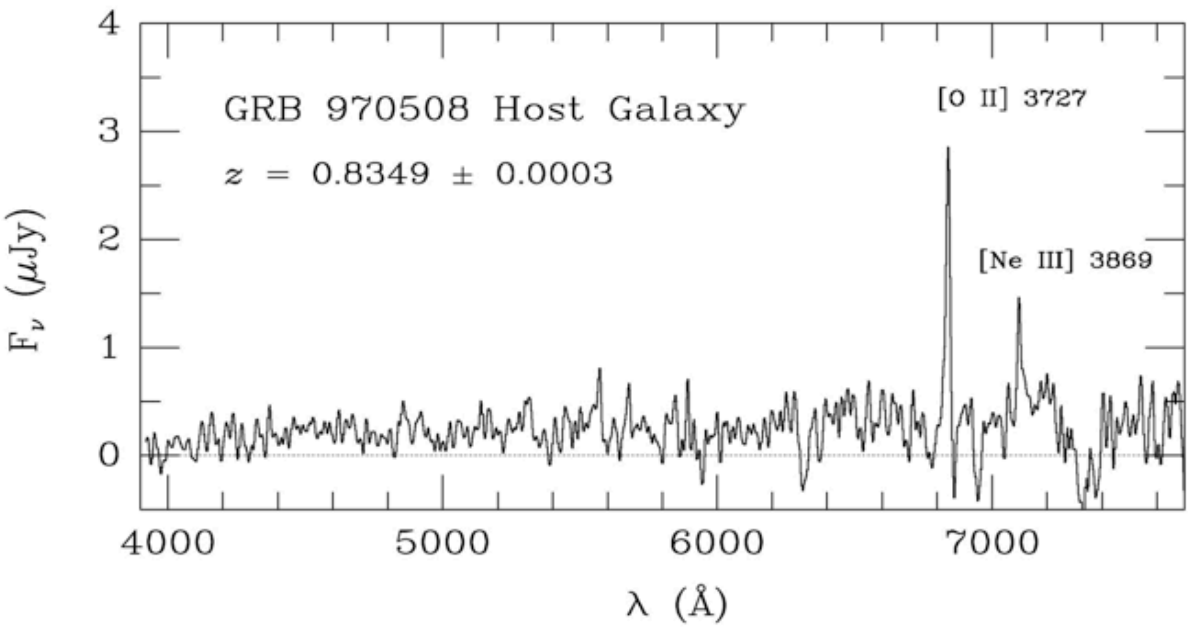
Fruchter et al. 1997

Afterglows: the first optical spectrum

GRB 970508 and its host galaxy: redshift z=0.835 !

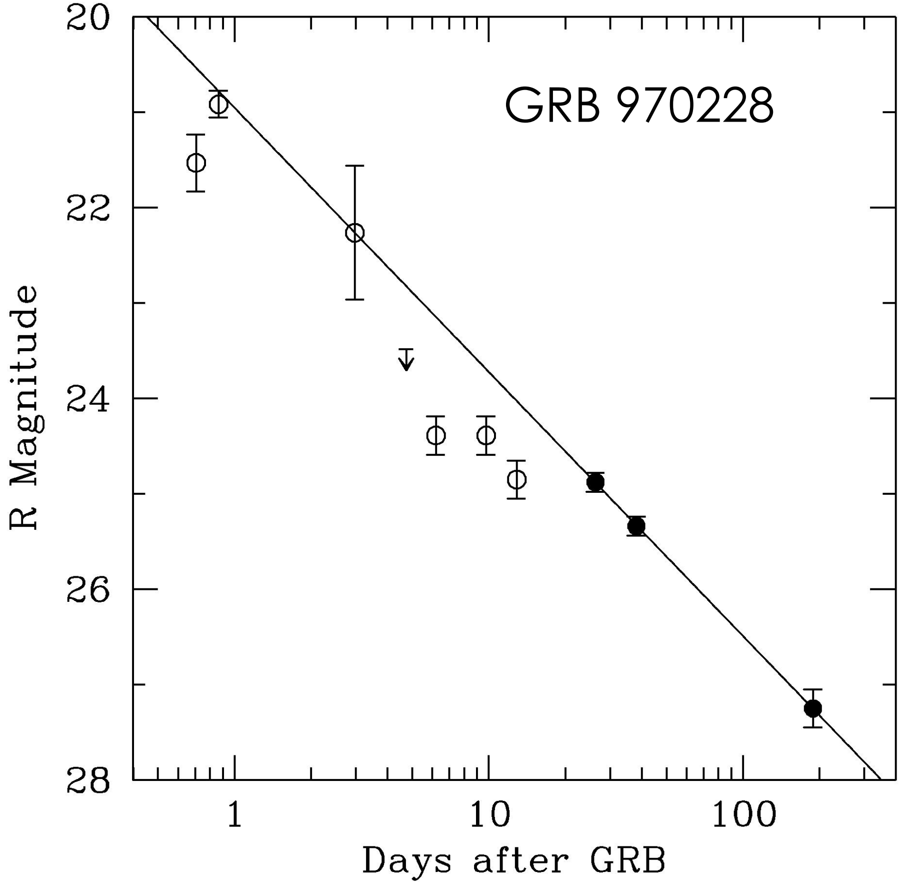


Metzger et al. 1997



Bloom et al. 1998

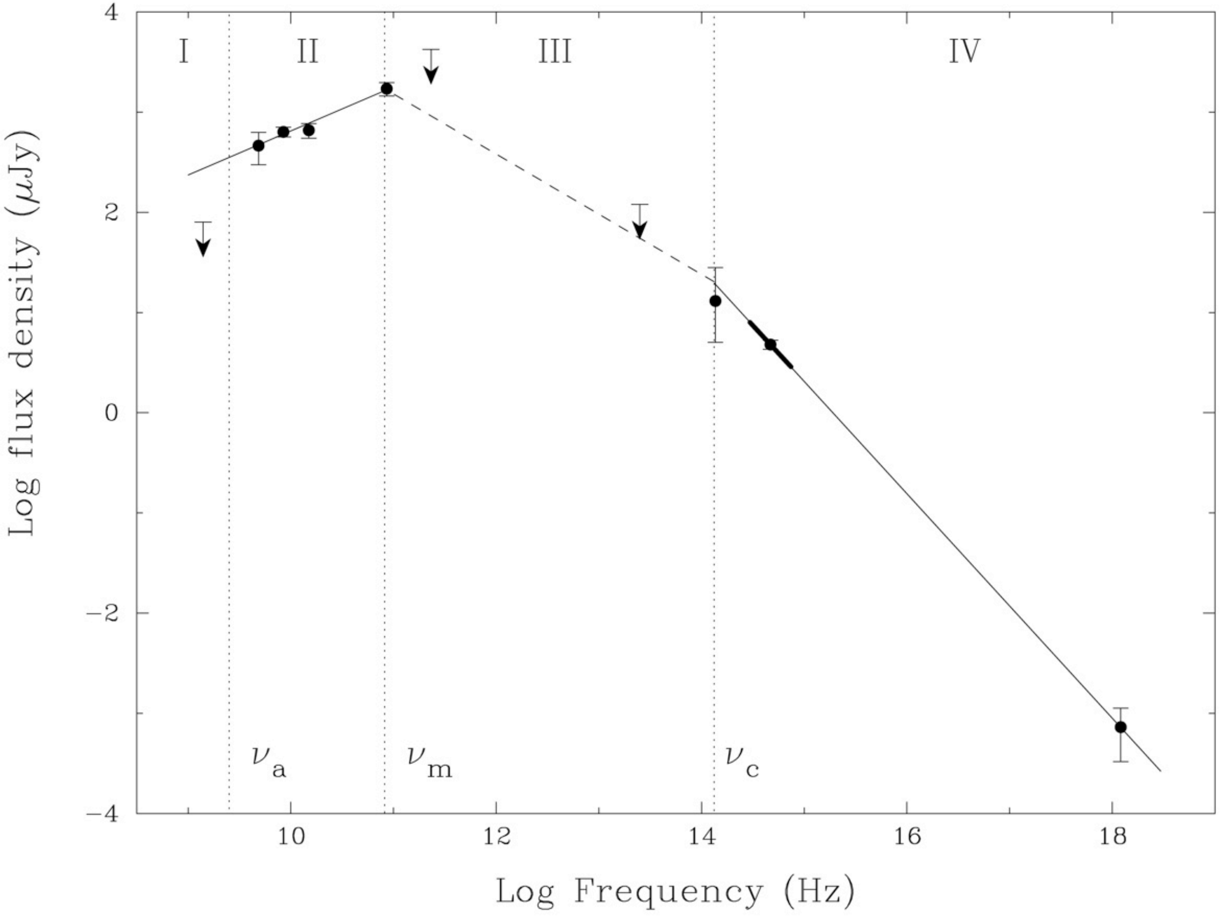
Afterglows: the first light curve



Fruchter et al. 1999

Afterglow spectrum: radio to X-rays

GRB 970508



Galama et al. 1998

Synchrotron spectrum from shock accelerated electrons ?

Reducing the number of models…

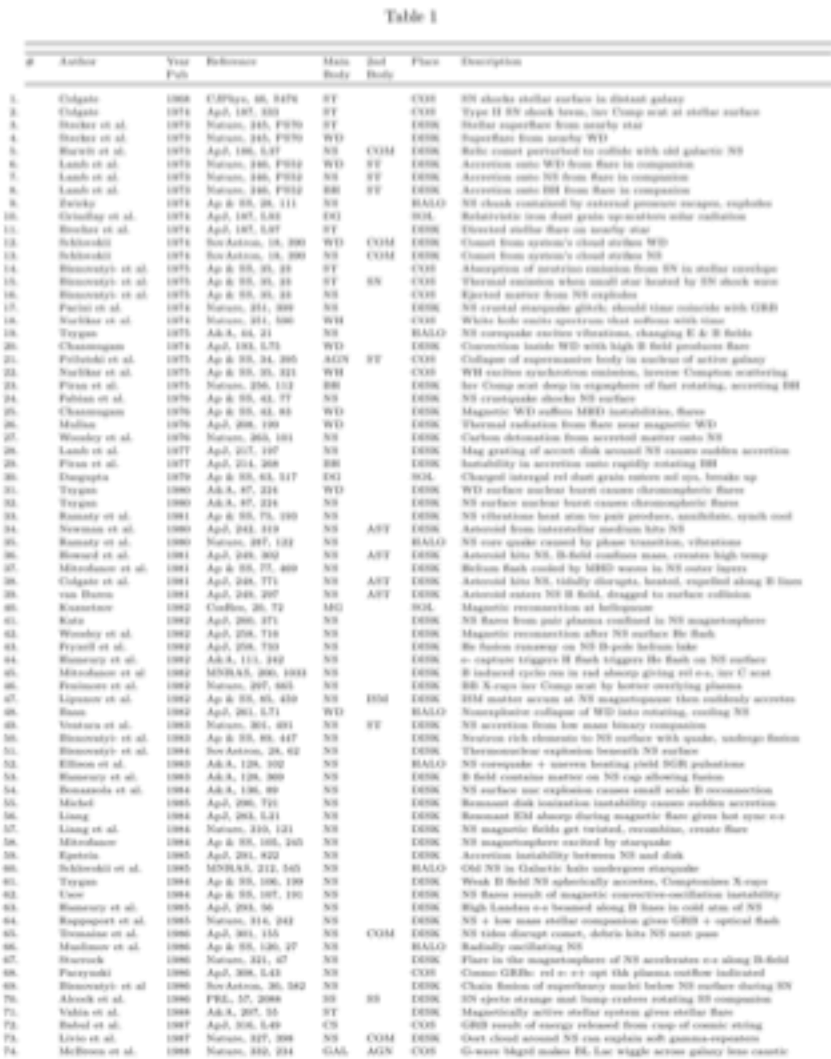


Table 1

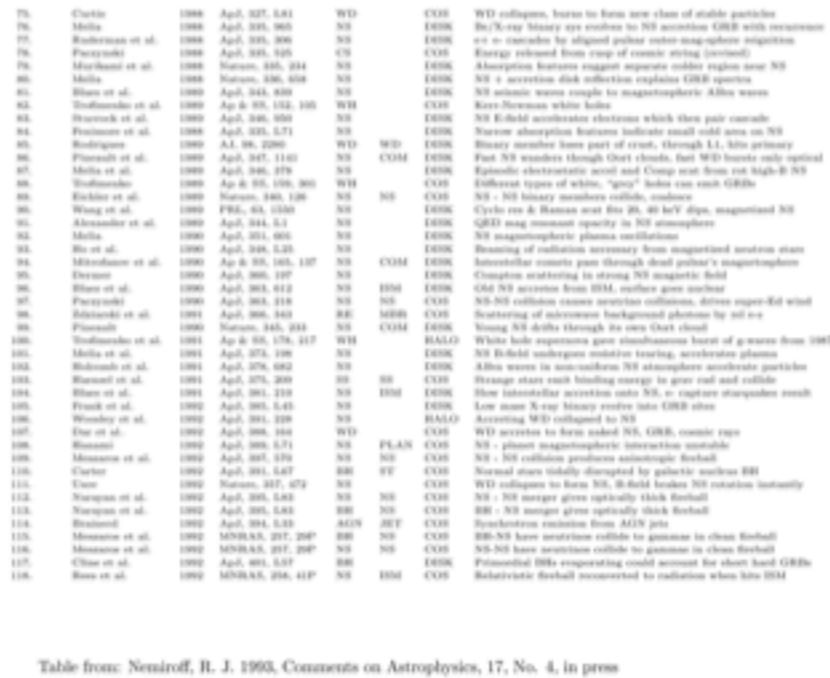
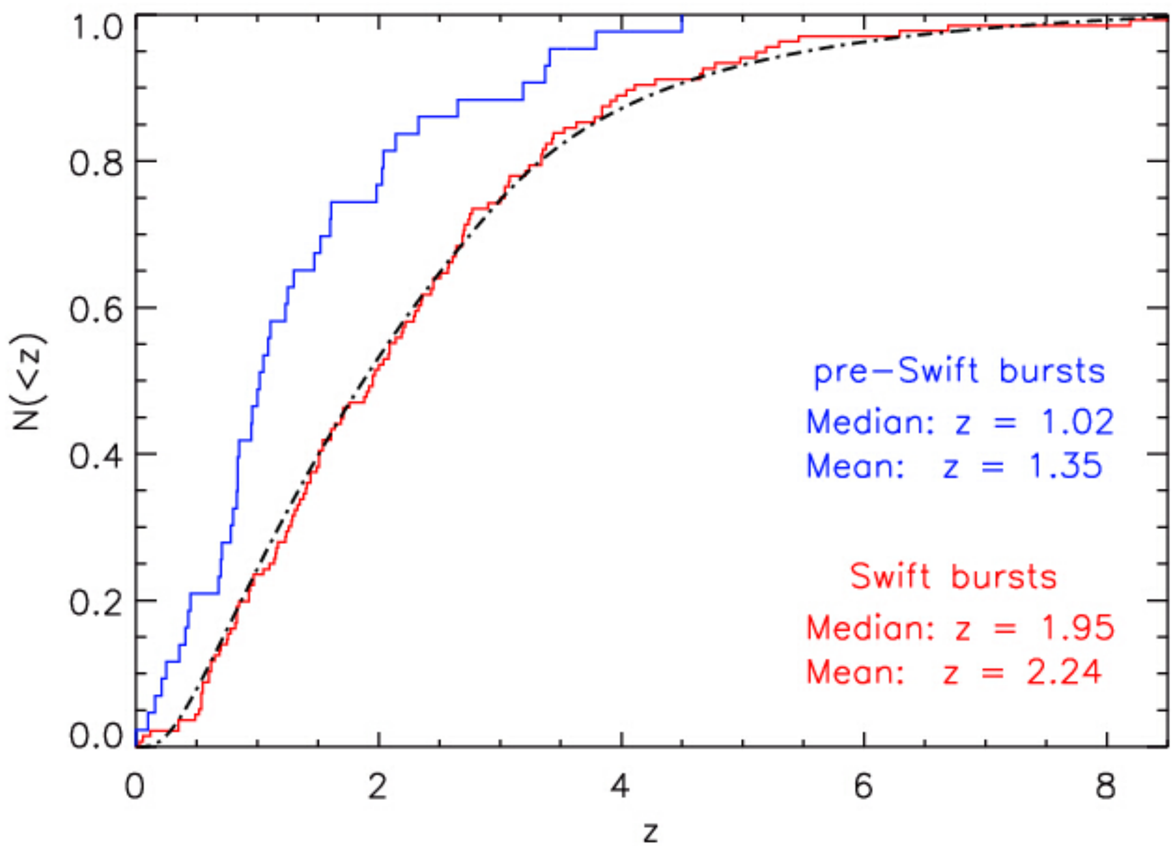


Table from: Nemiroff, R. J. 1993, Comments on Astrophysics, 17, No. 4, in press

Nemiroff 1994

An immediate consequence of the identification of the GRB distance scale: most models disappear !

GRB redshift distribution

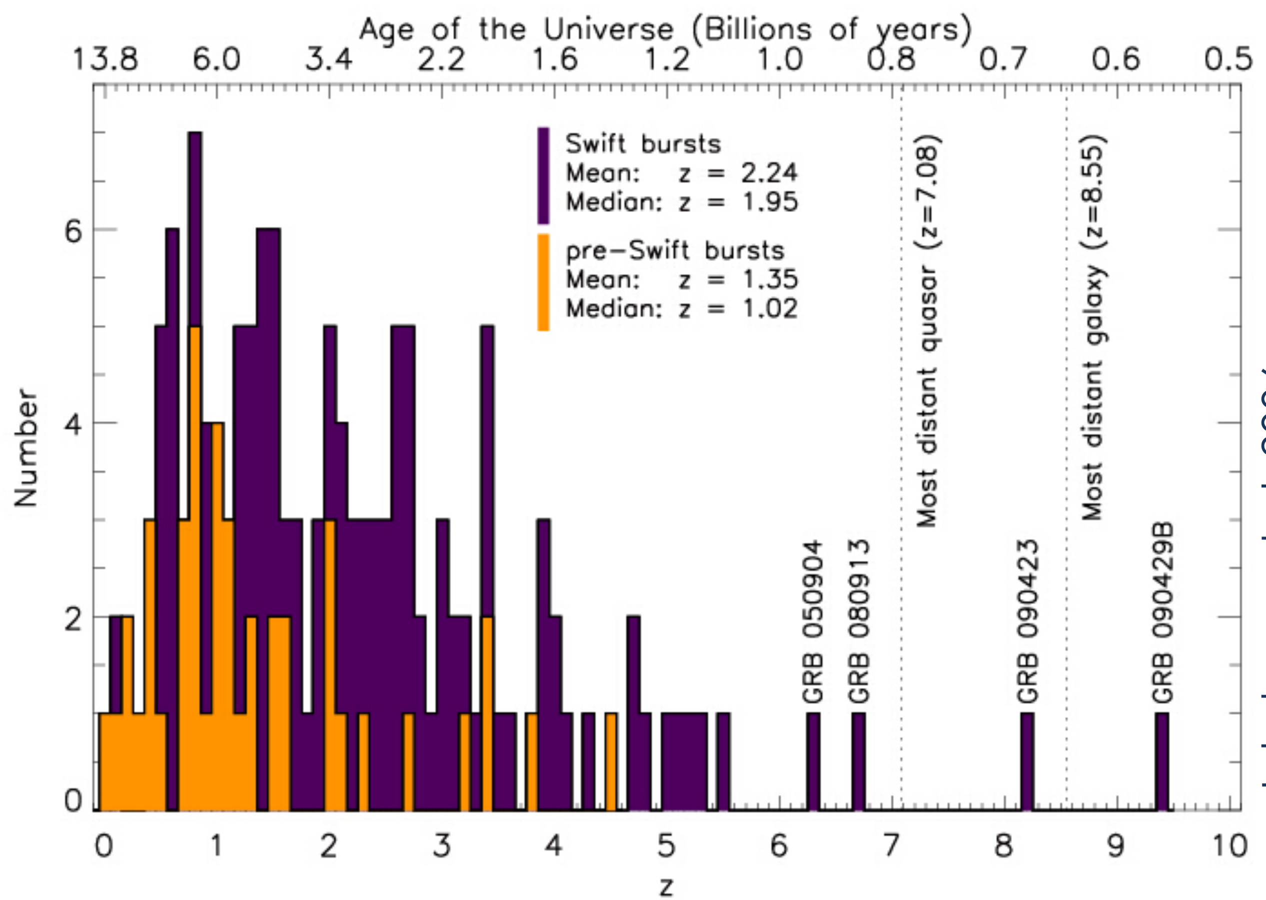


Jakobsson et al. 2006
(update November 2011)

http://raunvis.hi.is/~pja/GRBsample.html

Most GRBs in the sample are long GRBs.

GRB redshift distribution

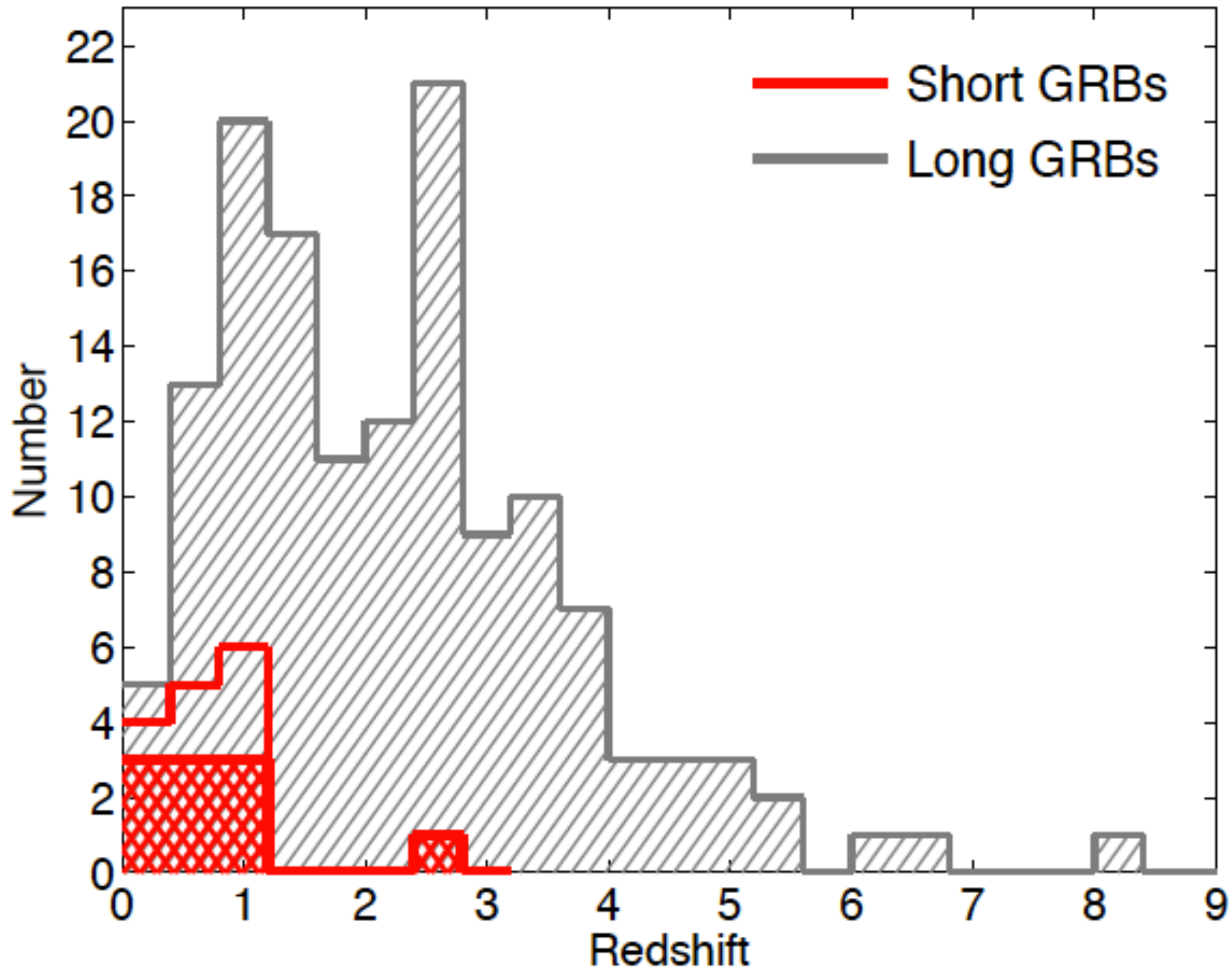


Jakobsson et al. 2006
(update November 2011)

http://raunvis.hi.is/~pja/GRBsample.html

Maximum redshift : GRB 090423 at z = 8.2 (Universe is 630 Myr old)
GRB 090429B at z = 9.3 (Universe is 520 Myr old)

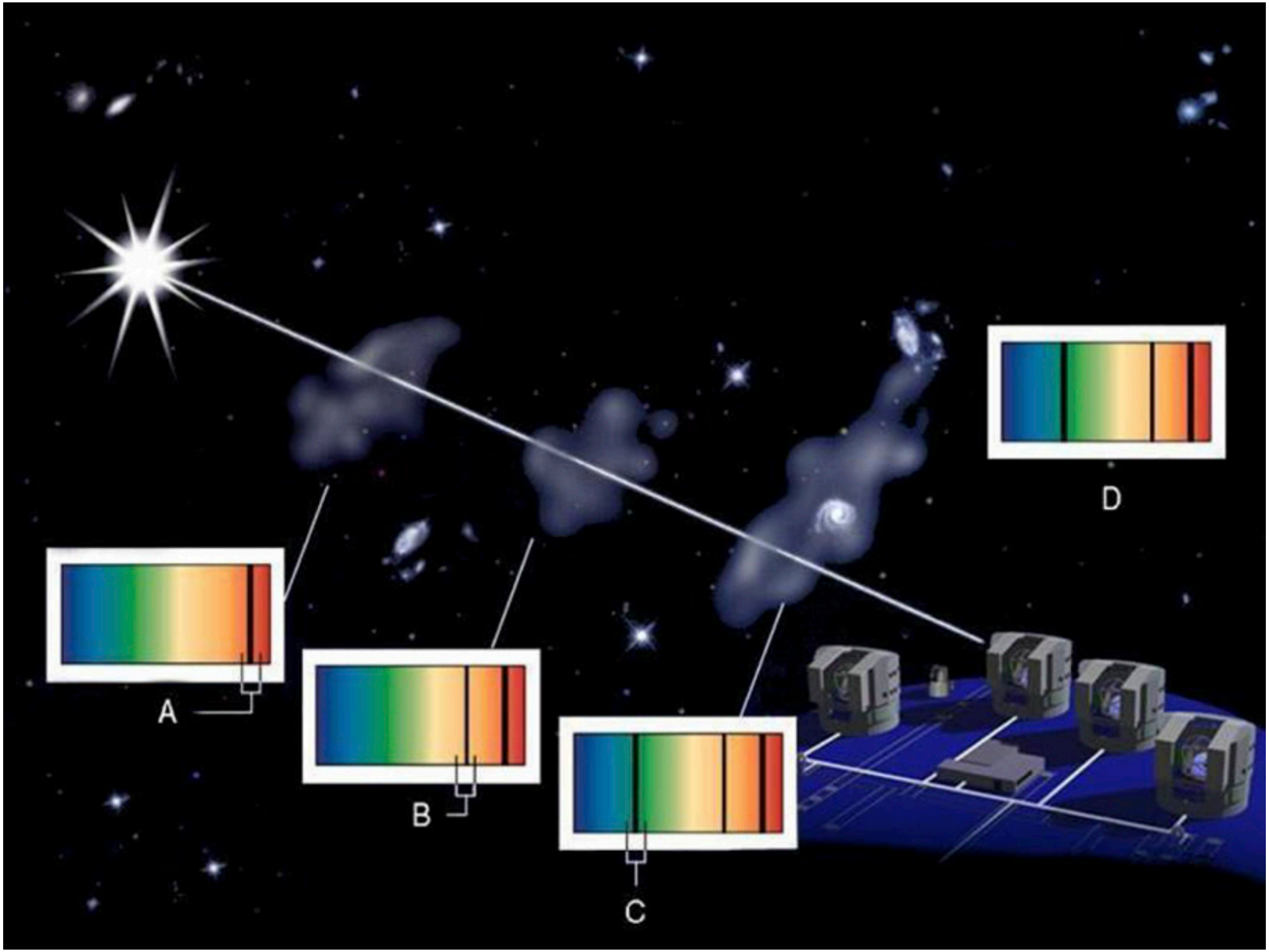
GRB redshift distribution : short GRBs



(Berger 2011)

Short GRBs have usually a lower redshift (typical : z ~ 0.5)
Possible high z short GRBs ?
(warning: duration measurements can be affected by z)

GRBs as a tool for cosmology



2– Identification of progenitors

Association of long GRBs with massive stars

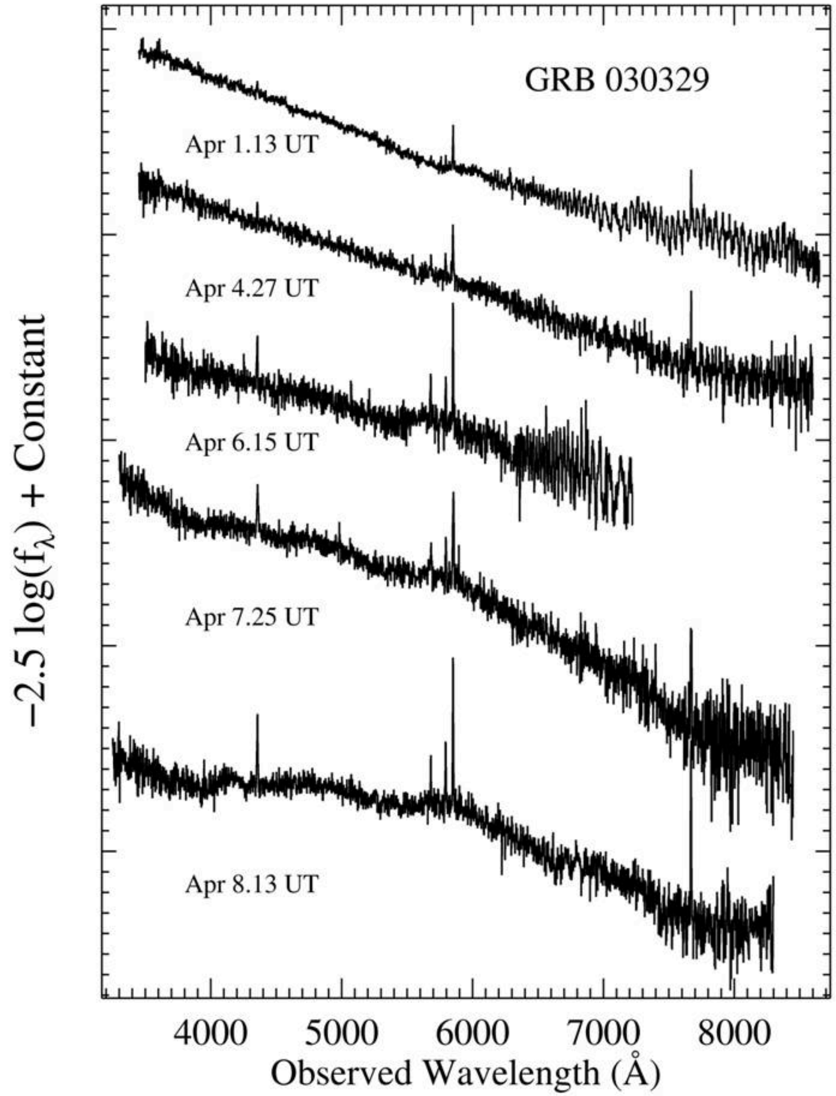
The case of GRB 030329 (HETE2) :
association with a SNIc

Several evidences for the association:

- star forming host galaxies

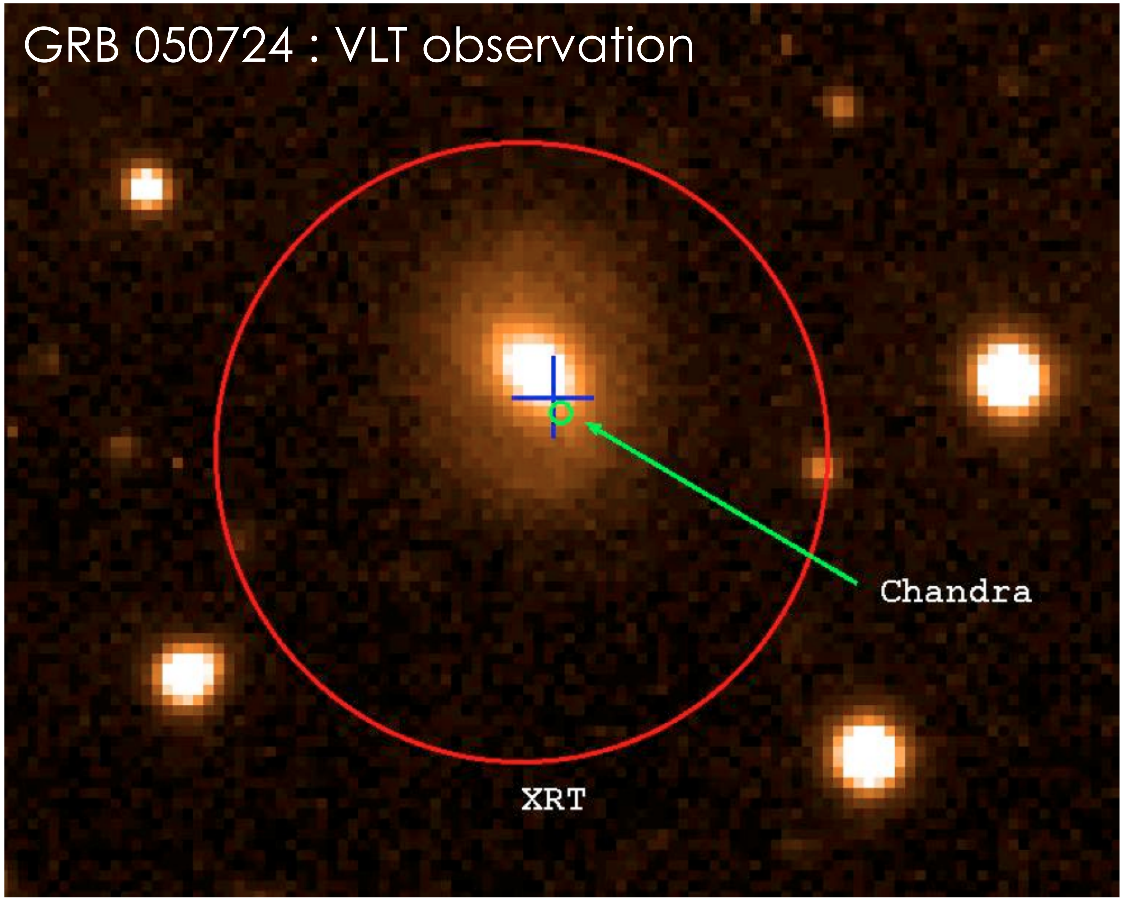
- afterglow location in the host galaxy

- associated SNae



Stanek et al. 2003

Progenitors of short GRBs : NS+NS mergers ?

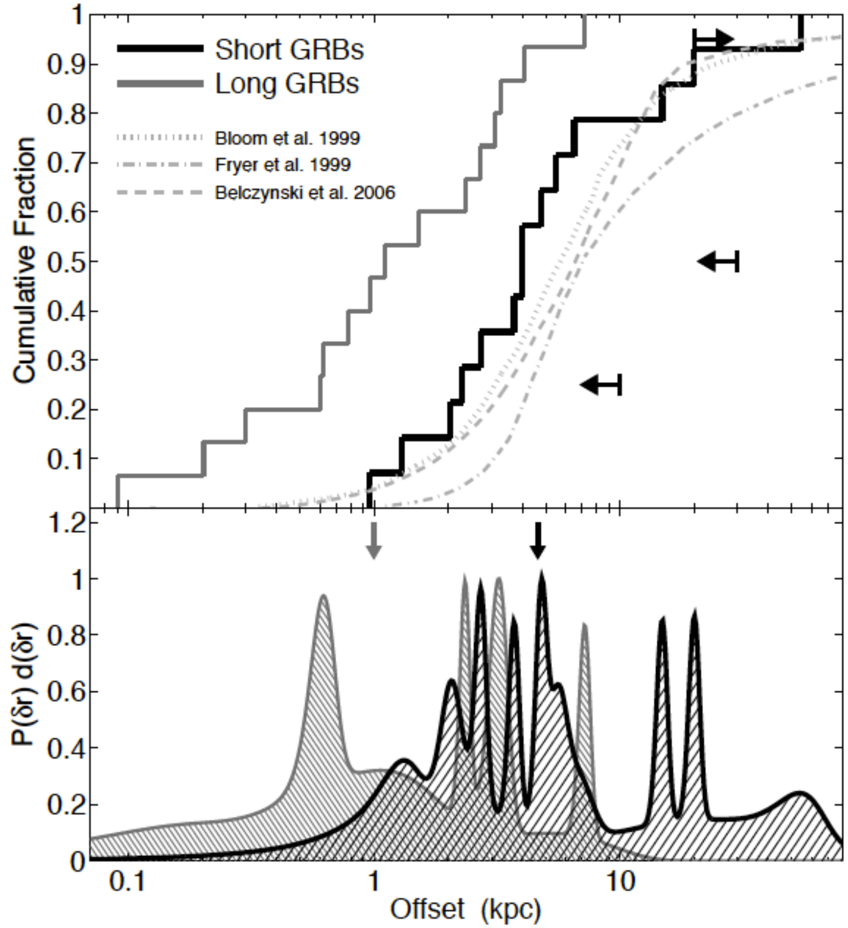


Barthelmy et al. 2005

Only a few host galaxies of short GRBs are identified:

- some are elliptical galaxies (e.g. GRB 050509B; GRB 050724; …)
  sometimes the afterglow has a large offset
- some are star-forming galaxies (e.g. GRB 050709; GRB 051221A; …)

Progenitors of short GRBs : NS+NS mergers ?



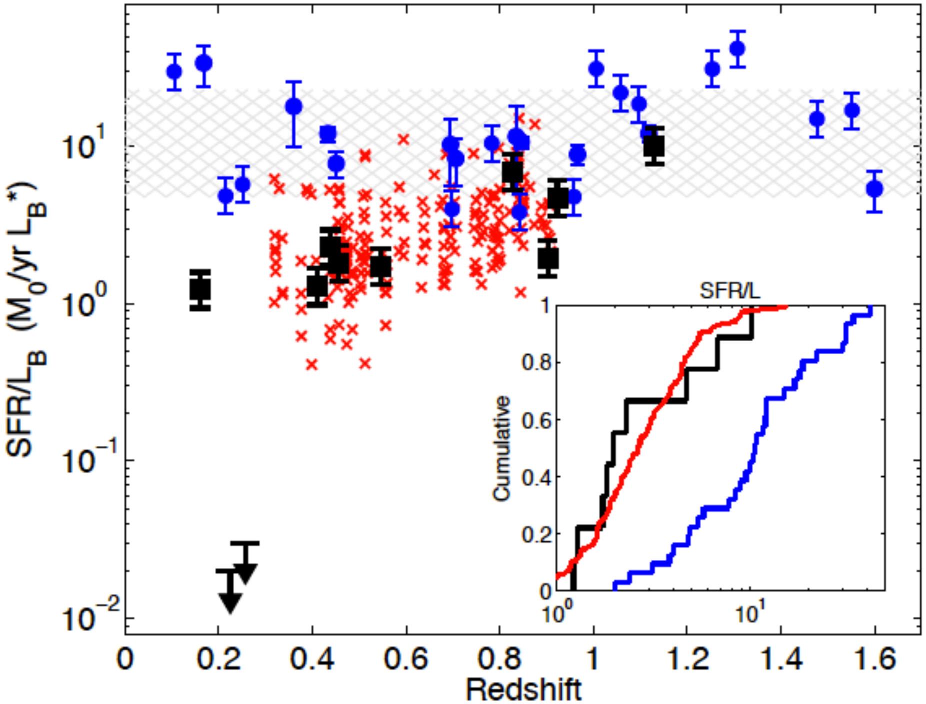
Berger 2011

Only a few host galaxies of short GRBs are identified:

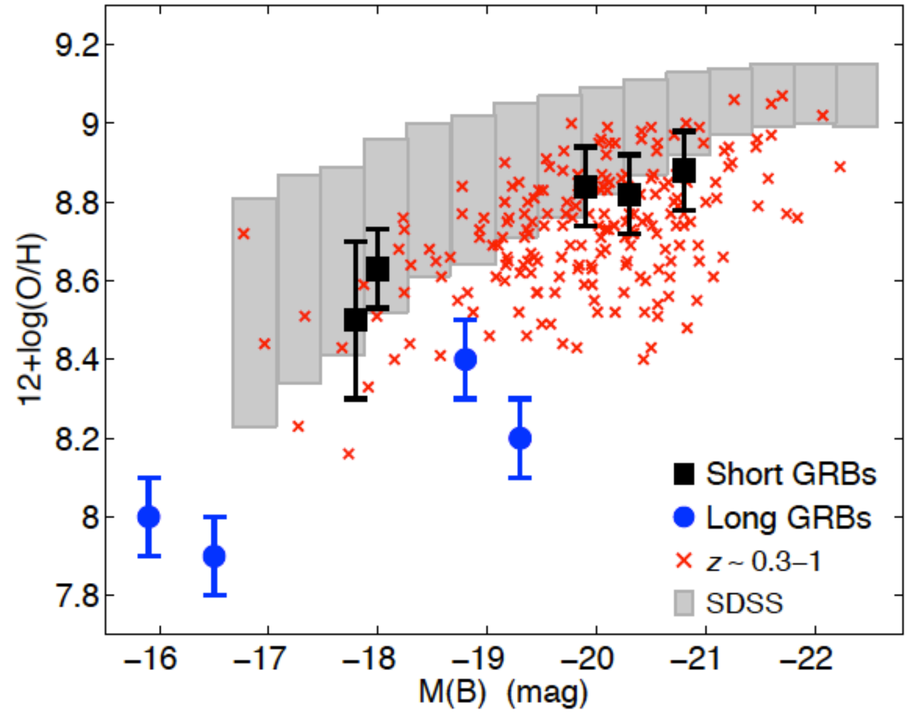
- some are elliptical galaxies (e.g. GRB 050509B; GRB 050724; ...)
  sometimes the afterglow has a large offset
- some are star-forming galaxies (e.g. GRB 050709; GRB 051221A; ...)

Progenitors of short GRBs : NS+NS mergers ?

Long GRB hosts
Short GRB hosts
Field galaxies (GOODS-N survey)



(Berger 2011)



Only a few host galaxies of short GRBs are identified:

- some are elliptical galaxies (e.g. GRB 050509B; GRB 050724; …)
  sometimes the afterglow has a large offset
- some are star-forming galaxies (e.g. GRB 050709; GRB 051221A; …)

In the future : association with gravitational waves ?

Progenitors of short GRBs : NS+NS mergers ?

Expected signatures for NS+NS (or BH+NS) mergers :

- No correlation with star formation due to long coalescence times
  no prefered types of host galaxies

  e.g. The Hulse-Taylor binary pulsar (PSR B1913+16) will merge in 300 Myr

- Large offsets are possible due to long coalescence times + kick velocity of NS

  For v = 100 km/s and T = 100 Myr, D = v T = 10 kpc

  Observed pulsar velocities in the Milky Way : as high as 1000 km/s
  bimodal 300 and 700 km/s

- Low density environments are possible, if associated to large offsets

- Gravitational waves

3– Minimal constraints on any GRB model

Minimum requirements for GRB models

- Cosmological distances ($z = 0.01 \rightarrow 8\ldots$) : Huge isotropic equivalent radiated energy L_{rad}, E_{rad}
- Small timescales (t_{var} = ms $\rightarrow$ 100 s) : Small emitting region (< c t_{var})
- Non-thermal spectrum : Relativistic outflow ($\Gamma > 100$?)

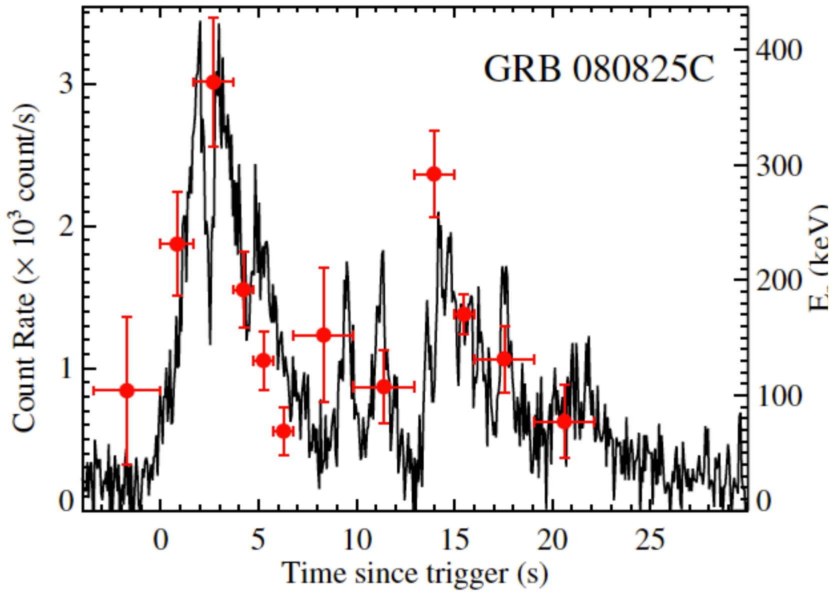
This applies to long AND short GRBs :

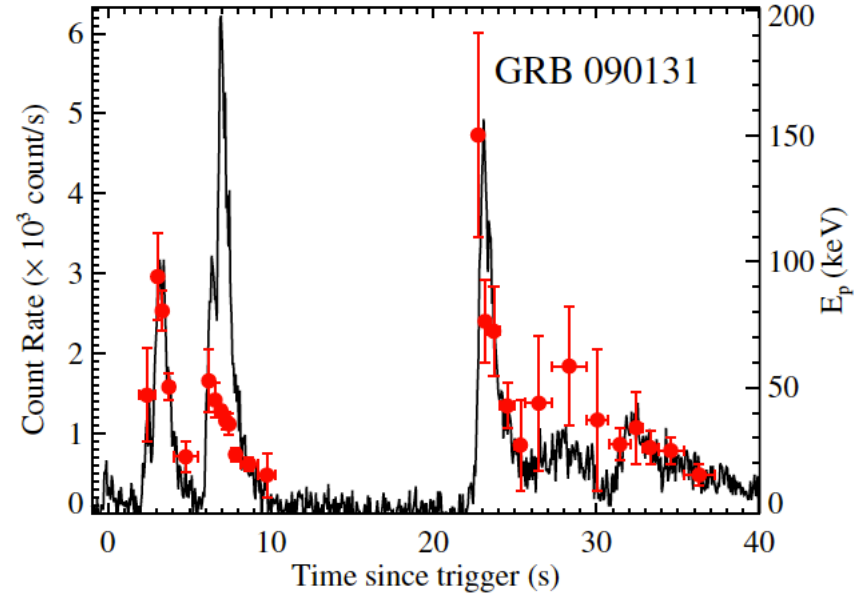
- comparable power L_{rad} : E_{rad}(short) < E_{rad}(long) because of duration
- comparable peak energies (if not higher for short GRBs)
- similar lightcurves (all timescales are compressed in short GRBs)

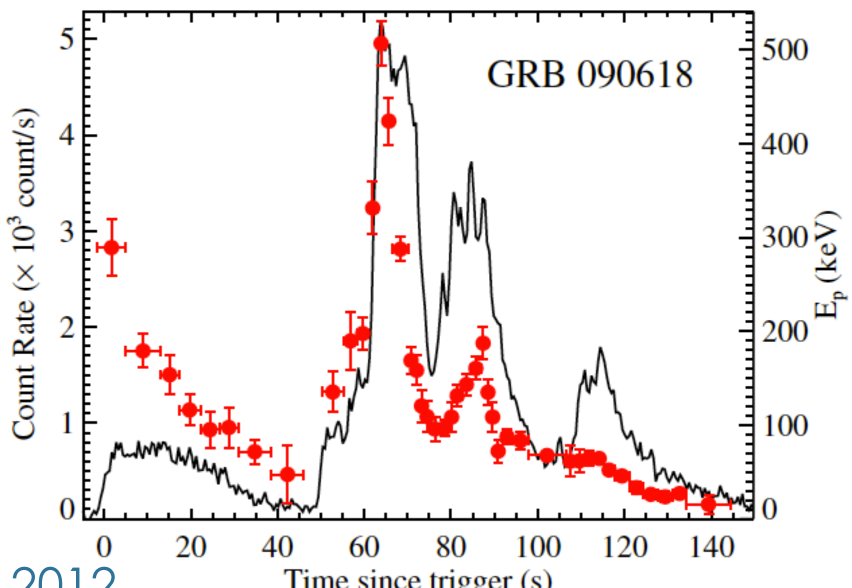
Main differences : timescales (prompt) + afterglow

Fermi: soft gamma-ray emission (GBM)

- Three examples: long GRBs



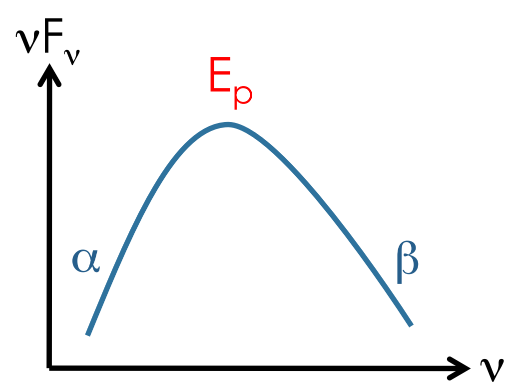




Lu et al. 2012

Lightcurve (photon flux, GBM)

Peak energy

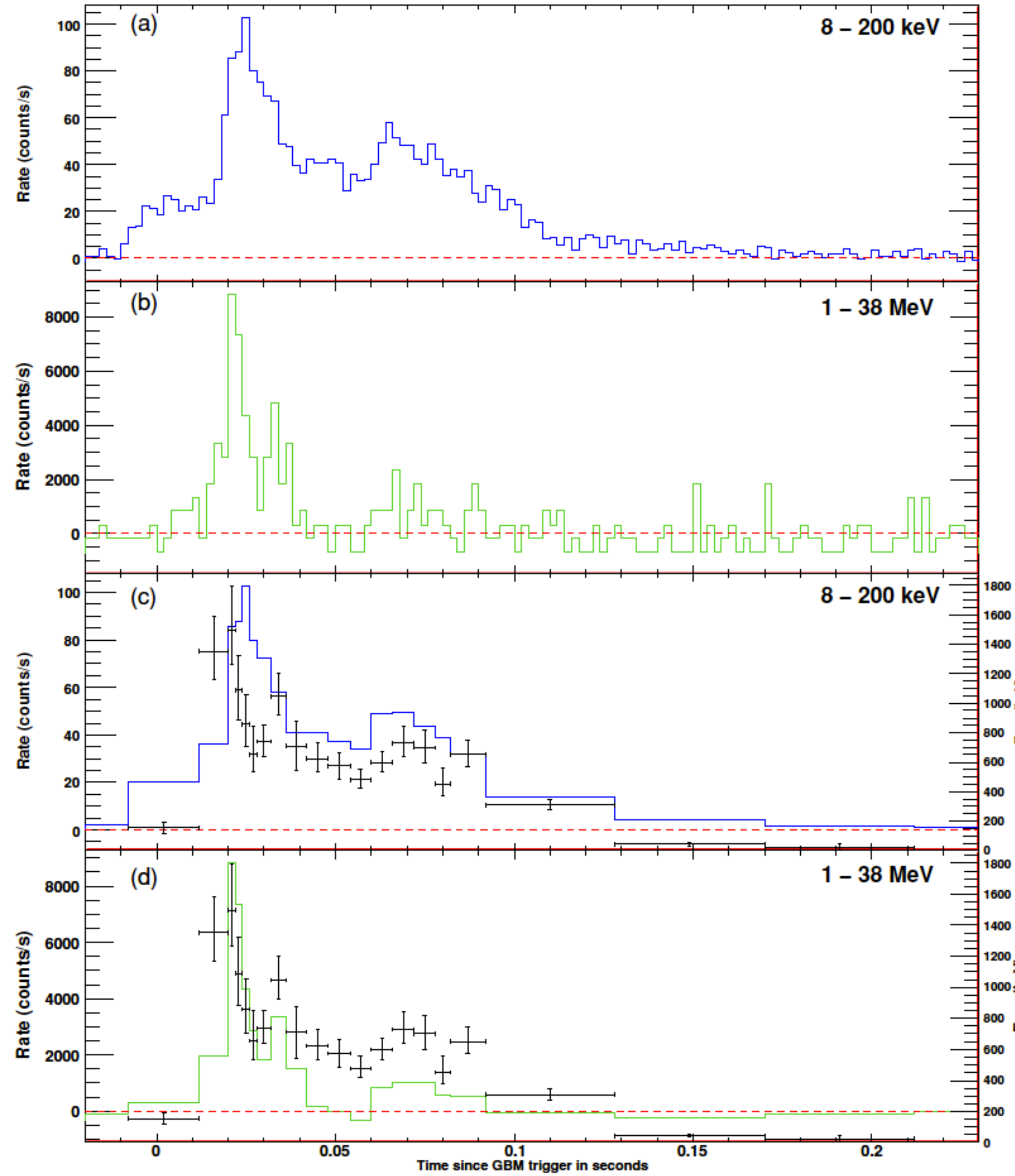


Fermi: soft gamma-ray emission (GBM)

- Another example: a short GRB

Lightcurves (photon flux, GBM)

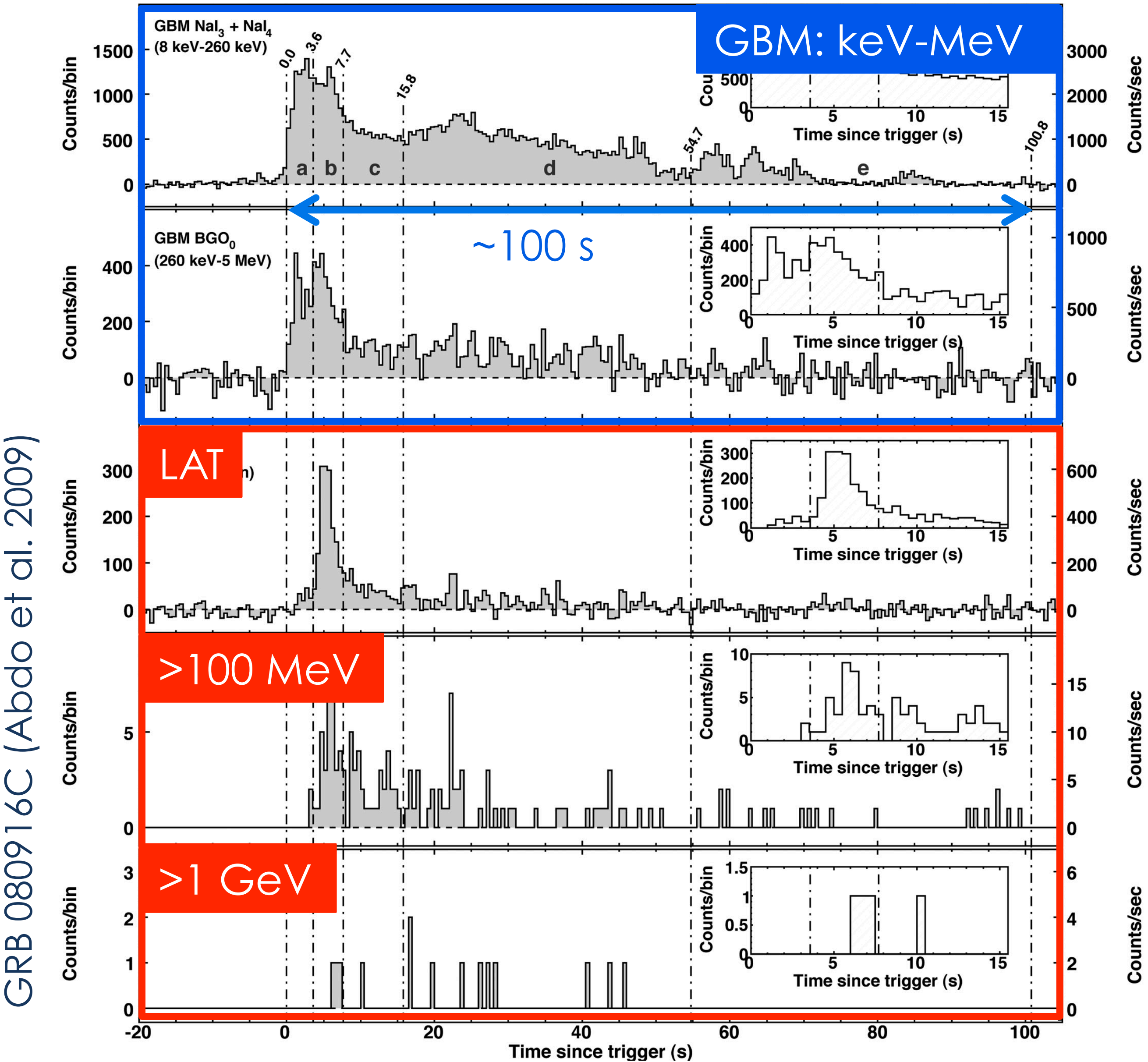
Peak energy



Guiriec et al. 2010

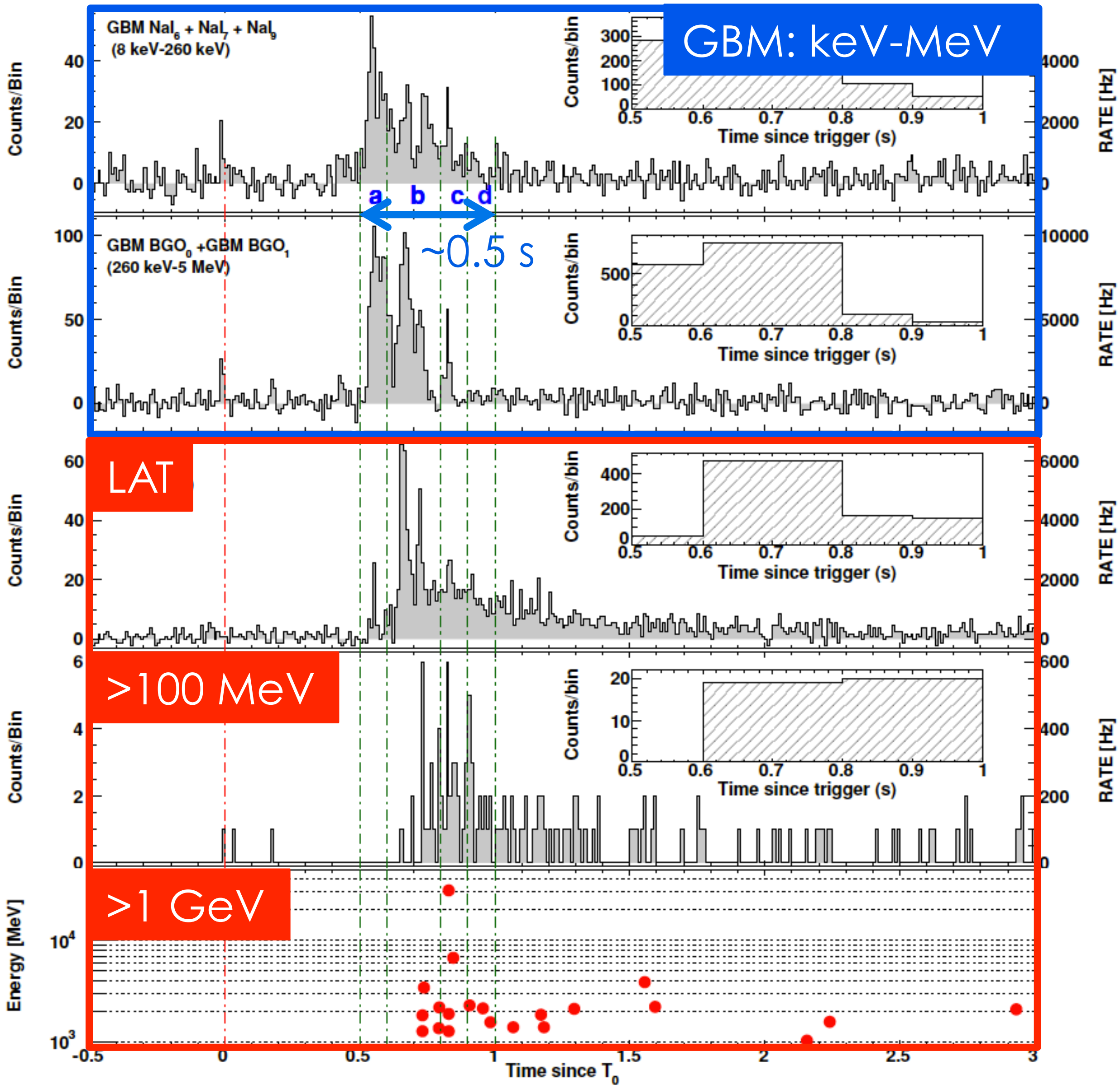
Fermi: high-energy detections (GeV)

- An example: GRB 080916C



Fermi: high-energy detections (GeV)

- Another example: GRB 090510 (short GRB)



Consequences: how relativistic are GRBs ?

$\gamma\gamma$ opacity constraint: $\tau_{\gamma\gamma}(E_{max}) < 1$ leads to a minimum Lorentz factor
pre-Fermi (MeV range) : Γ_{min} ~ 100-300 (see e.g. Baring & Harding 97; Lithwick & Sari 01)

GeV detection: stricter Lorentz factor constraints

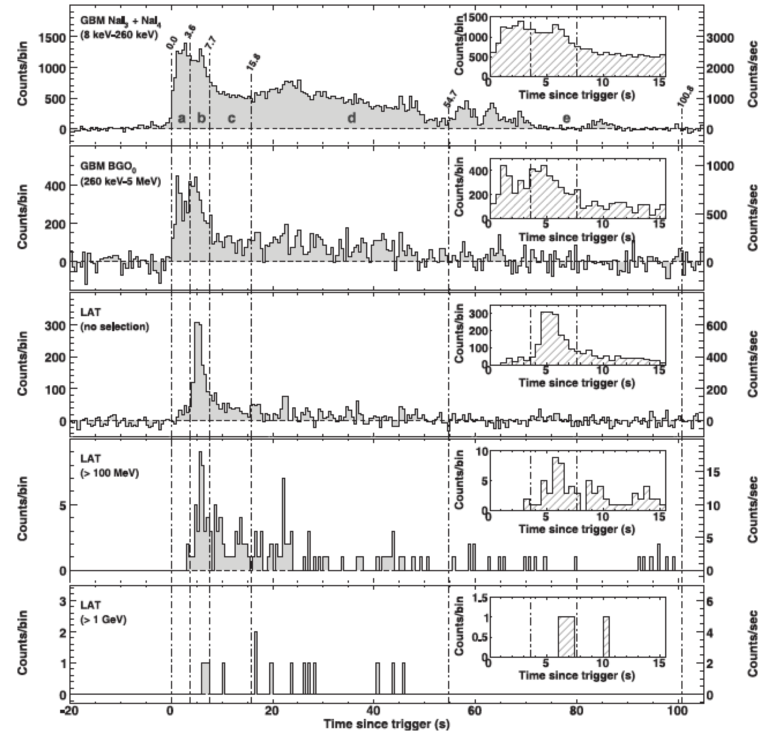
- GRB 080916C : $\Gamma_{min} \geq 887$ (Abdo et al. 09)
- GRB 090510 : $\Gamma_{min} \geq 1200$ (Ackerman et al. 10)

Such values of the Lorentz factor :

-are challenging for most models of the central engine ;

-have strong consequences on the GRB scenario (photospheric radius, deceleration radius, …).

However, these estimates are based on simplified single zone models.

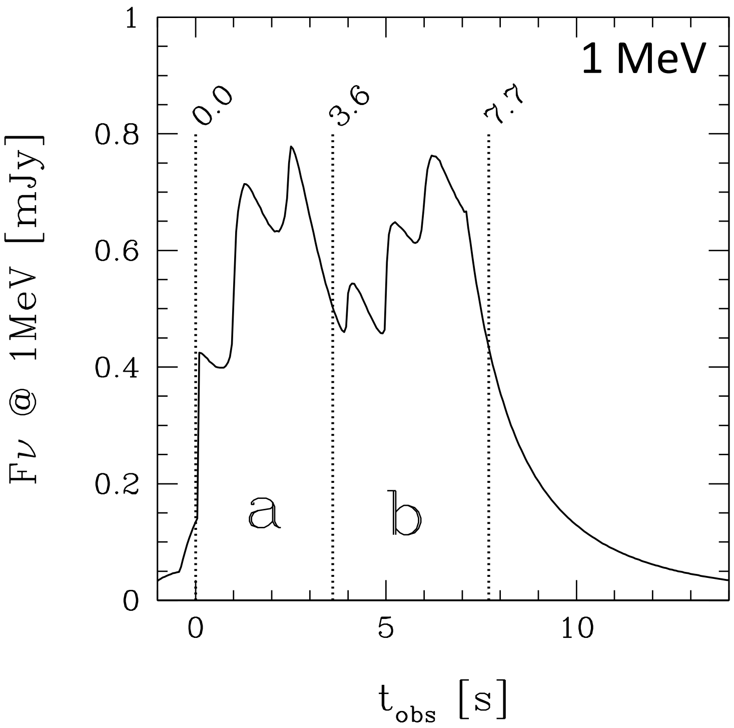


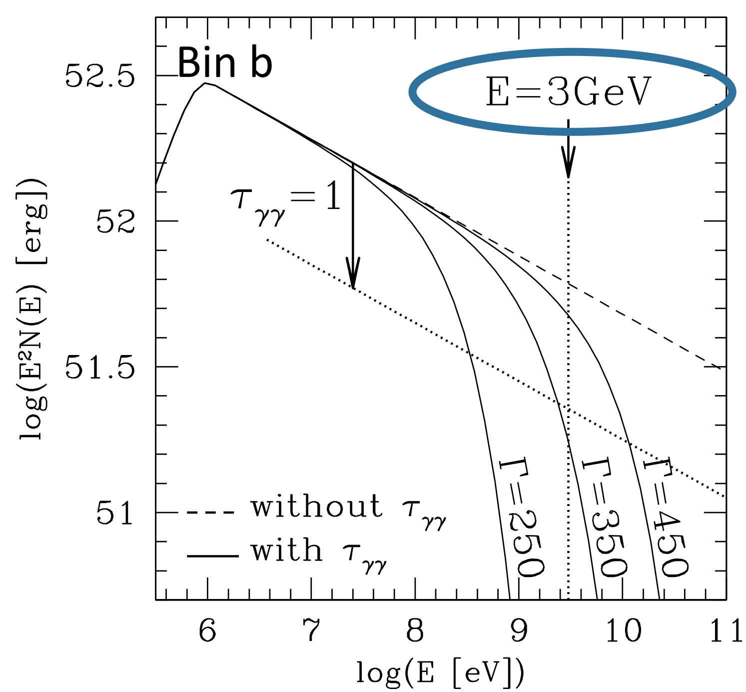
GRB 080916C (Abdo et al. 2009)

Consequences: how relativistic are GRBs ?

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

➡ the estimate of Γ_{min} is reduced by a factor ~ 2-3
(see Granot et al. 2008; Hascoët, Daigne, Mochkovitch & Vennin 2012)





➡ Model of bins a+b in GRB 080916C : Γ_{min} ~ 360 (Hascoët et al. 2012)
instead of ~900 (Abdo et al. 2009)

Consequences: how relativistic are GRBs ?

- **Detailed calculation : space/time/direction-dependant radiation field**

→ the estimate of Γ_{min} is reduced by a factor ~ 2-3
(see Granot et al. 2008; Hascoët, Daigne, Mochkovitch & Vennin 2012)

- **If the GeV and the MeV emission are not produced at the same place : the constraint is even further reduced.** (see also Zhao et al. 2011; Zou et al. 2011)

Minimum requirements for GRB models

- Cosmological distances ($z = 0.01 \rightarrow 8\ldots$) : Huge isotropic equivalent radiated energy E_{rad}
- Small timescales (t_{var} = ms $\rightarrow$ 100 s) : Small emitting region ($< c\ t_{var}$)
- Non-thermal spectrum : Relativistic outflow ($\Gamma > 100$)

General framework :

-the different observed stages in gamma-ray bursts (prompt, afterglow) are associated to events in the life of a ultra-relativistic outflow produced by a newly formed compact source.

-short and long GRBs differ by their progenitors and environment.

Minimum requirements for GRB models

General framework :

-the different observed stages in gamma-ray bursts (prompt, afterglow) are associated to events in the life of a ultra-relativistic outflow produced by a newly formed compact source.

-short and long GRBs differ by their progenitors and environment.

- Geometry and composition of the outflow ? *(e.g. spherical vs jet vs … ; matter vs Poyting flux vs …)*
- Nature and role of the environment ? *(e.g. uniform density medium vs stellar wind vs plerion vs … ; internal vs external mechanisms)*
- Energy reservoir and extraction mechanism in each observed phase ? *(e.g. thermal vs kinetic vs magnetic ; photosphere vs shocks vs magnetic reconnection)*
- Microphysics and radiative processes at work ? *(e.g. shock acceleration ; magnetic field amplification ; … synchrotron radiation vs IC vs …)*

Minimum requirements for GRB models

General framework :

-the different observed stages in gamma-ray bursts (prompt, afterglow) are associated to events in the life of a ultra-relativistic outflow produced by a newly formed compact source.

-short and long GRBs differ by their progenitors and environment.

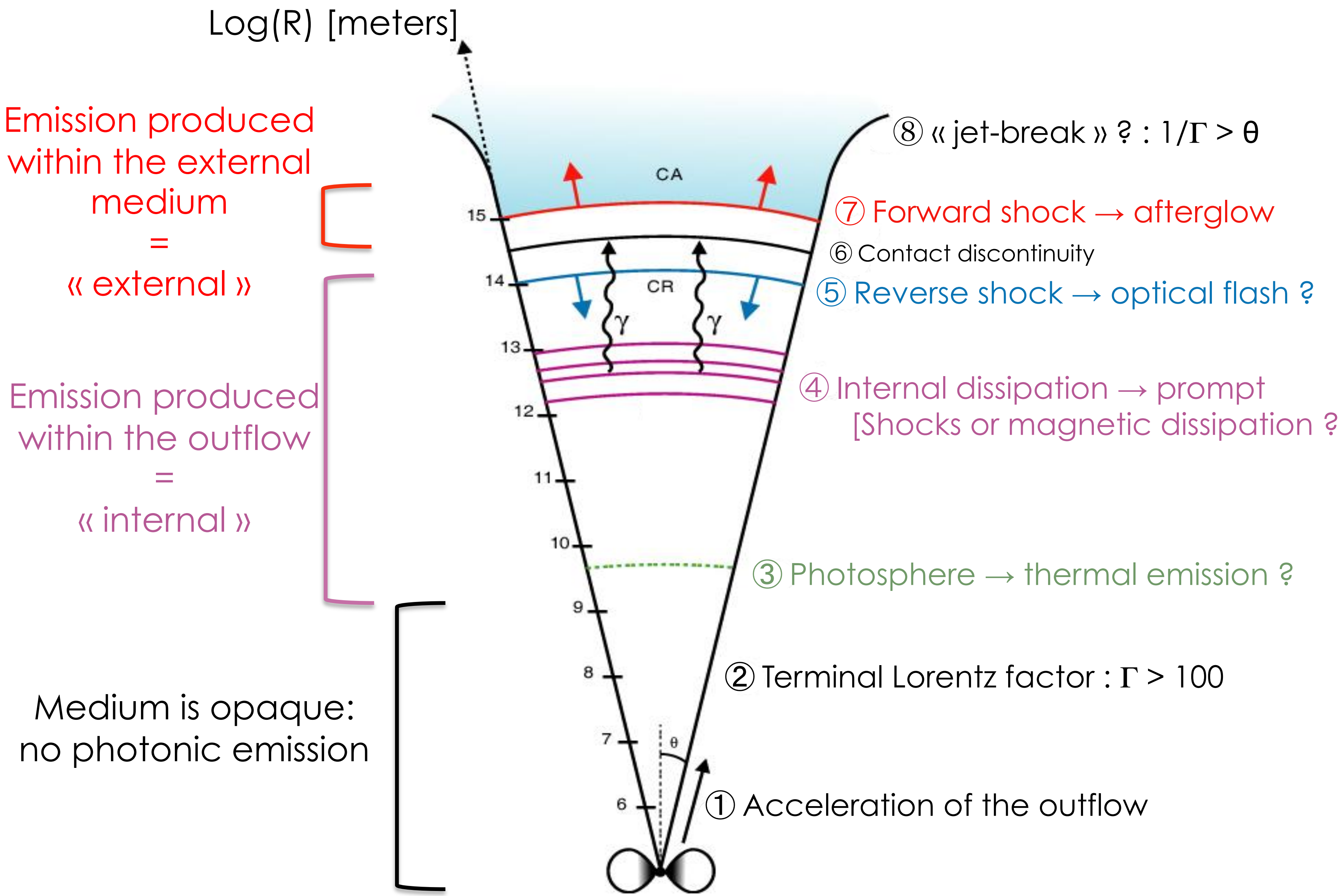
- Non photonic emission ?

  HE neutrinos from the relativistic outflow ?
  (signature of the composition & particle acceleration process)

  Gravitational waves & neutrinos from the central source ?
  (signatures of the progenitors & relativistic ejection process)

4– A « standard » scenario ?

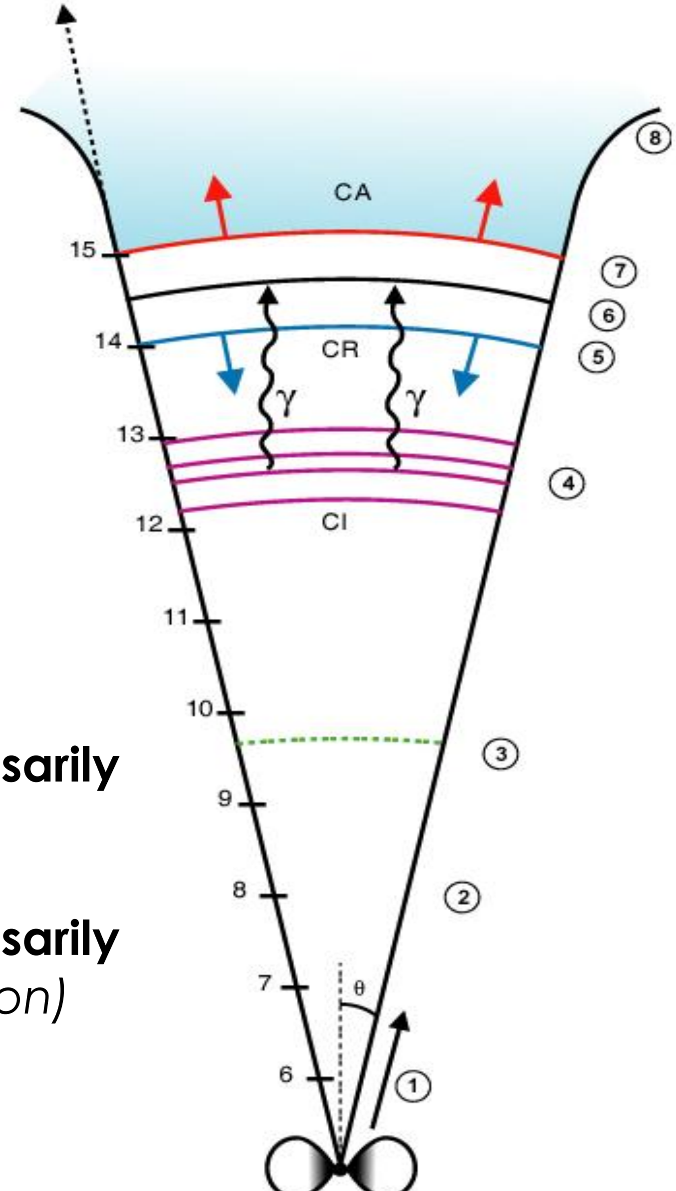
« Standard » scenario



Common physics in short and long GRBs ?

Different progenitors ⇒ different environments

- **Afterglow :**
  - if the environment of short GRBs is less dense
  - - deceleration starts at later times
  - - afterglow is fainter
  - if the relativistic ejection is different
  - - beaming may be different ?



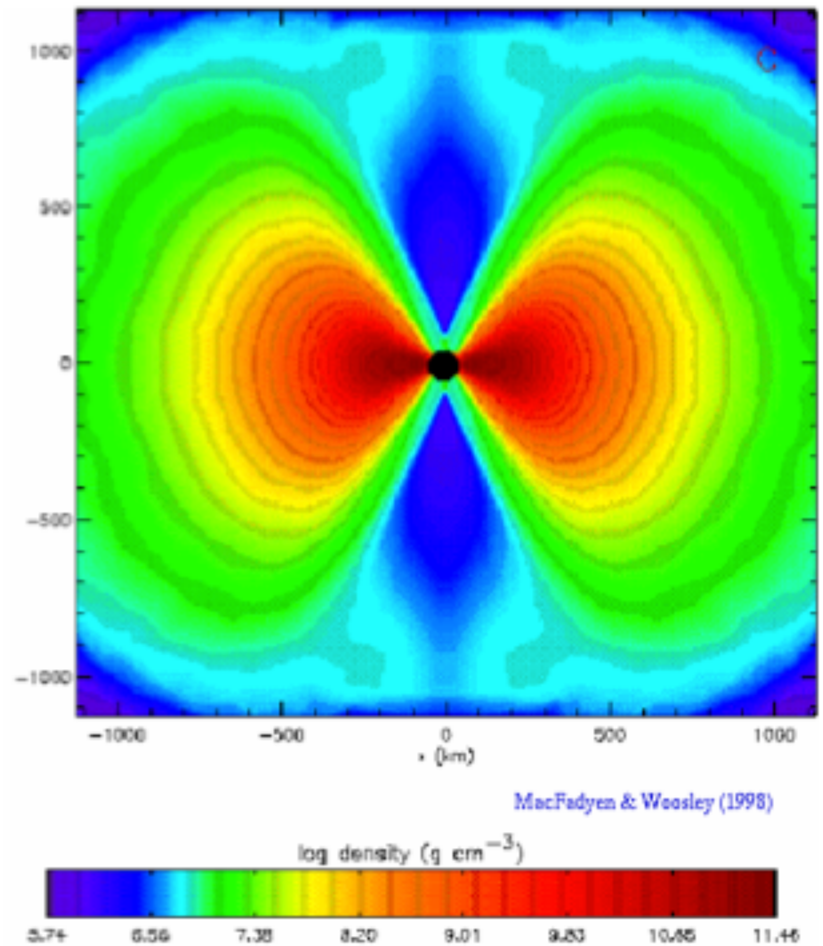
- **Prompt :**
  - - different initial events ? **Yes**
  - - similar central engines (BH+torus) ? **Probably**
  - - similar mechanism for the relativistic ejection ? **Not necessarily**
  - - similar jet composition ?
    similar energy extraction process ? **Not necessarily**
    (depends on the answer of the previous question)
  - - similar radiative processes ? **Probably**

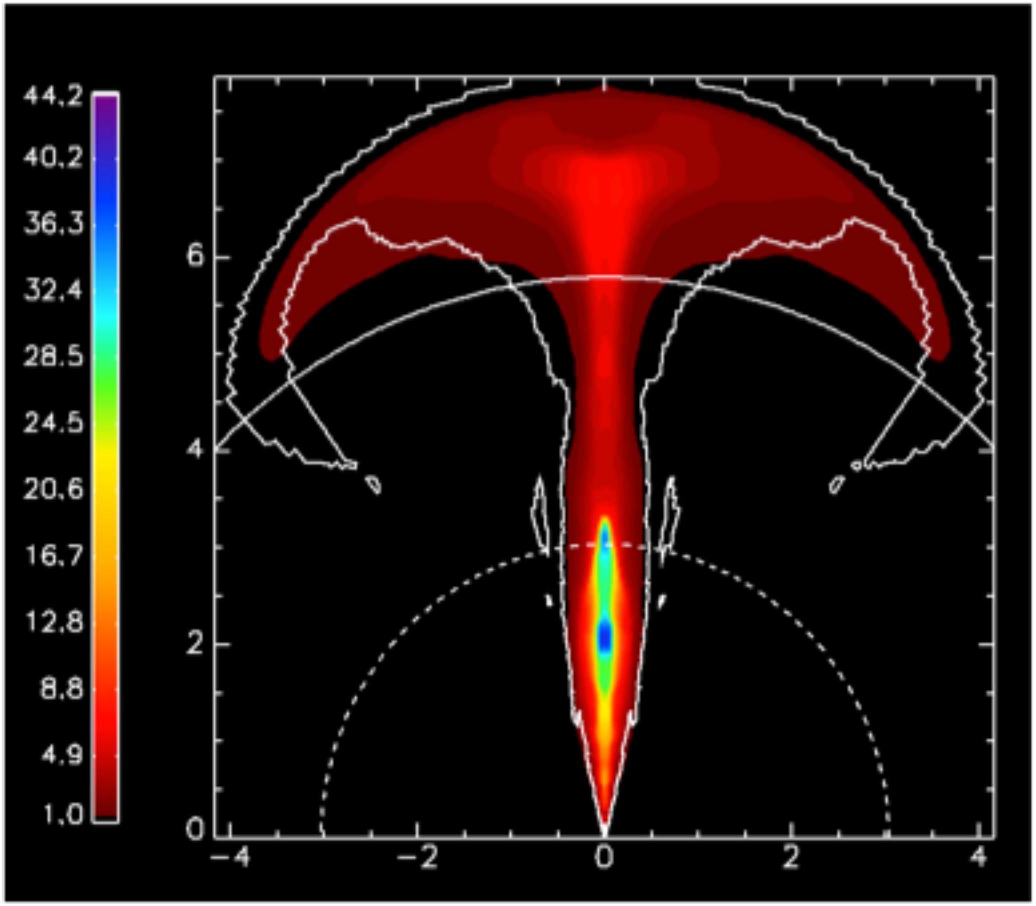
- **Gravitational waves ?**
  - - long GRBs ? Collapsars emit GW but difficult to detect
  - - short GRBs ? Expected detections if associated with mergers

5– Central engine
Gravitational waves

Central engines (1) Long GRBs

Long GRBs : collapsars (Paczynski, Woosley, …)



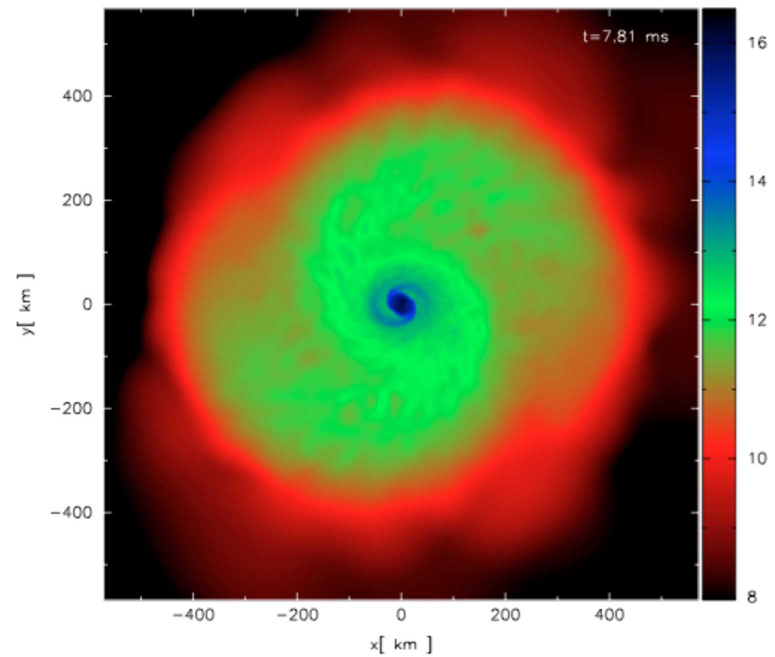


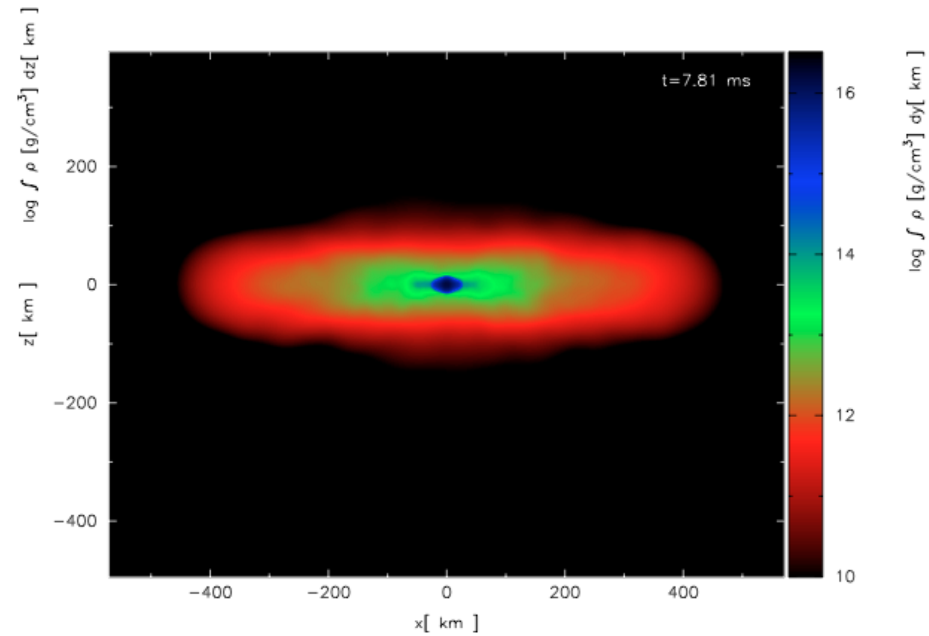
Escaping the star ?

(MacFadyen et al.)

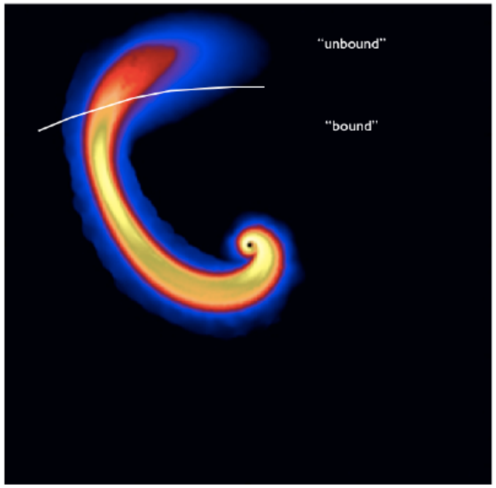
Central engines (2) Short GRBs

Short GRBs : NS+NS or NS+BH mergers ?





(Rosswog et al.)



Many simulations :

GR or Newtonian ?

B-field ?

Detailed EOS or not

Neutrinos ?

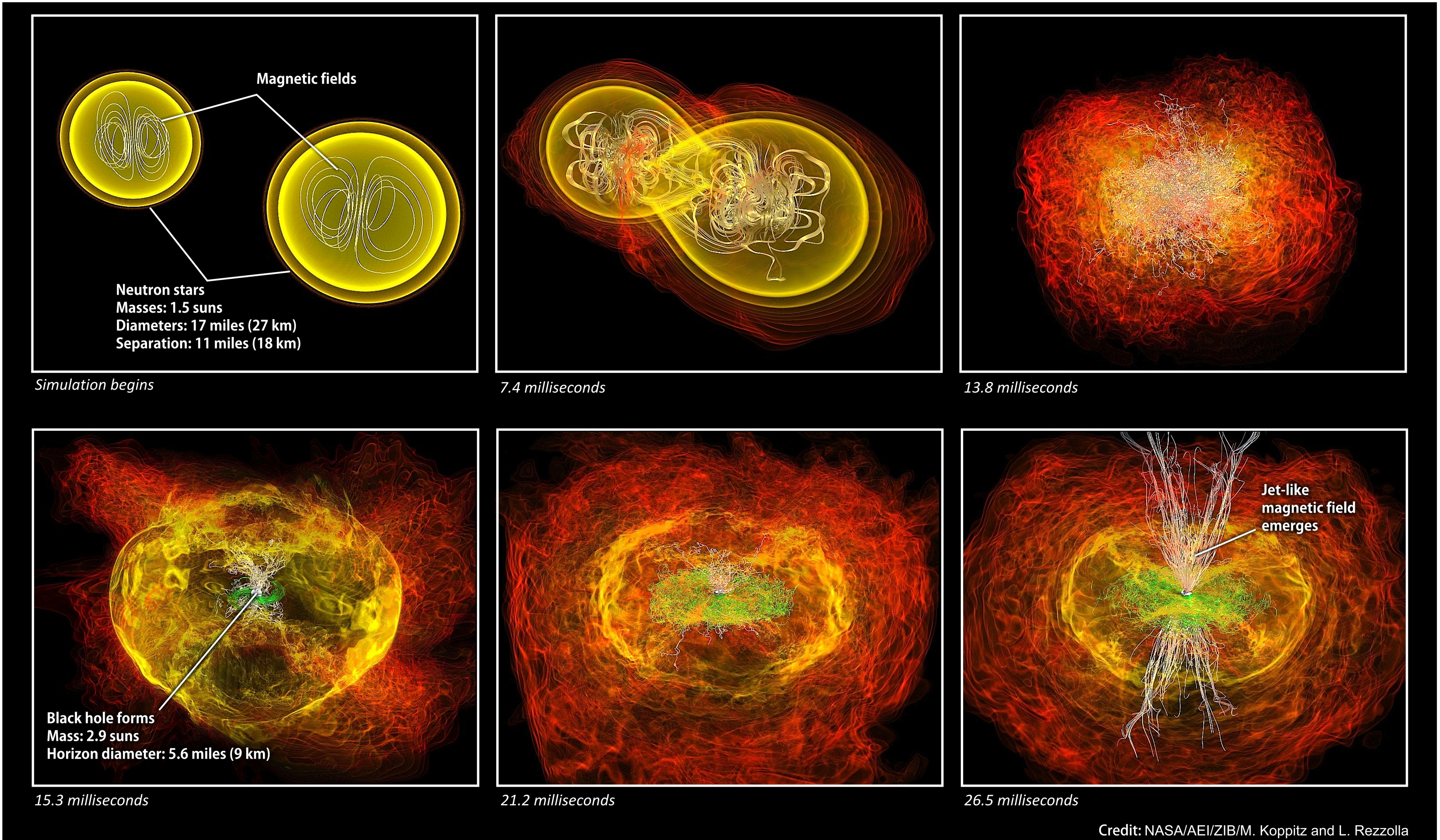
Shibata et al. ; Baiotti et al. ;Janka et al. ;
Rosswog et al. ; Rezzolla et al. ; etc.

Central engines (2) Short GRBs

Short GRBs : NS+NS or NS+BH mergers ?

Color = Log(density) – Lines = B-field

Rezzolla et al. 2011

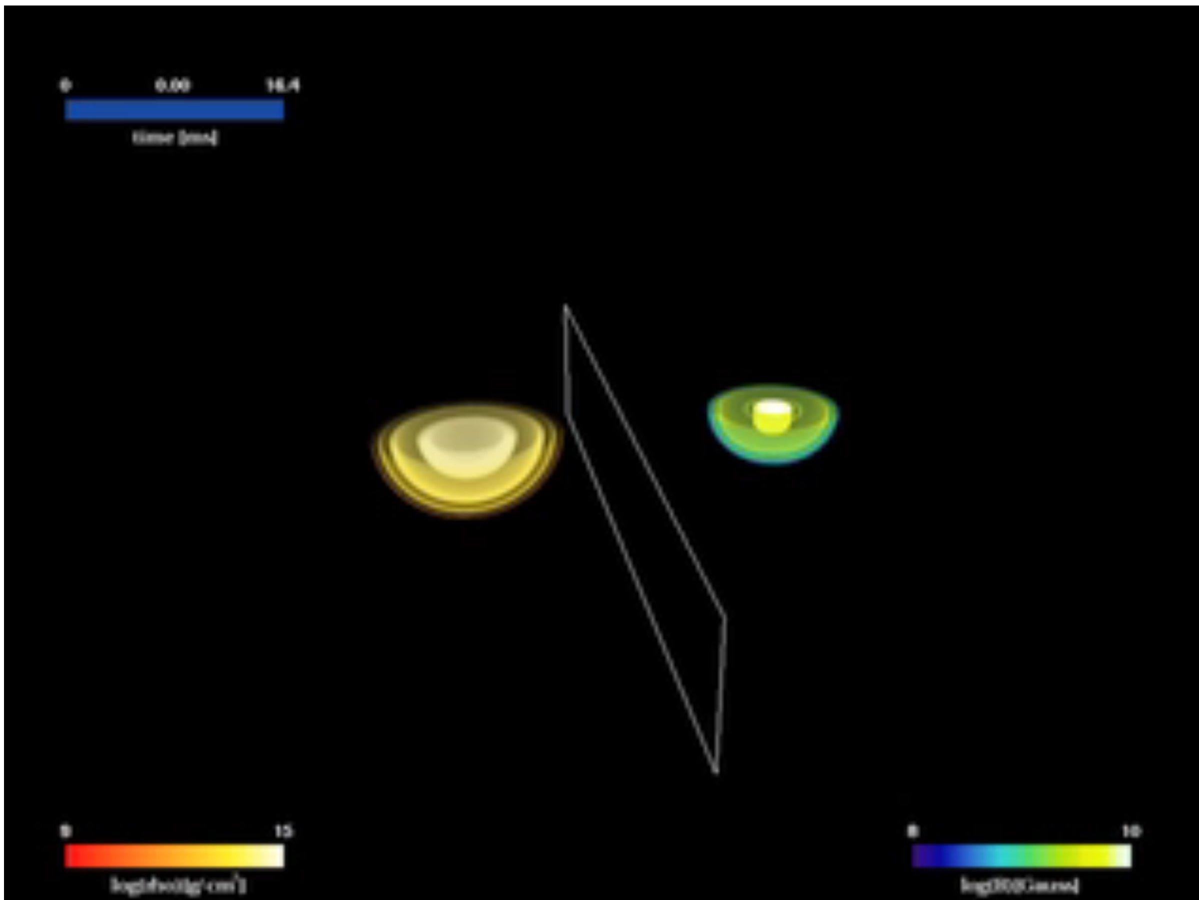


Central engines (2) Short GRBs

Short GRBs : NS+NS or NS+BH mergers ?

Rezzolla et al. 2011

Duration of the simulation : ~ 16 ms



Density

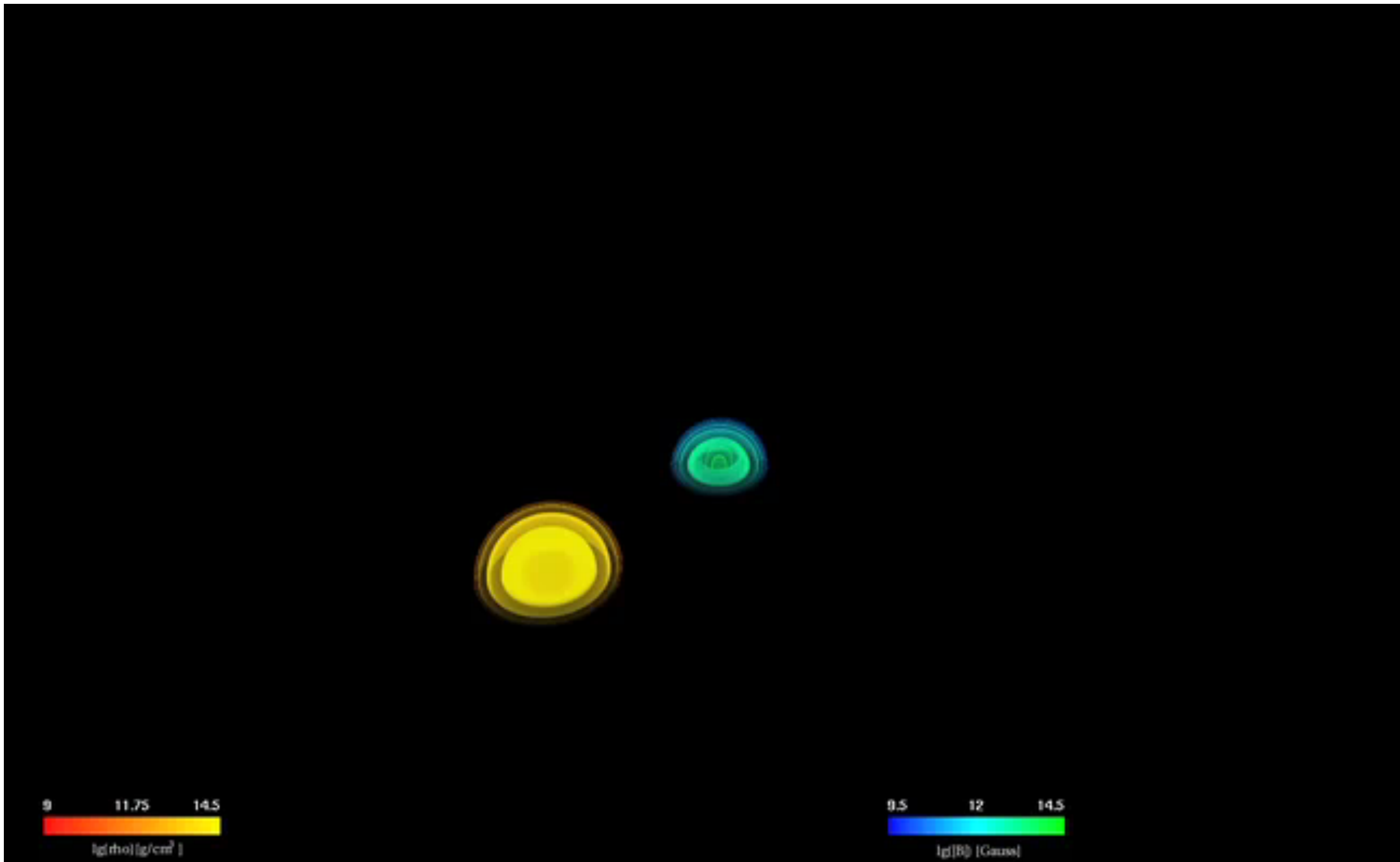
B-field

Central engines (2) Short GRBs

Short GRBs : NS+NS or NS+BH mergers ?

Rezzolla et al. 2011

Duration of the simulation : ~ 26 ms



Density

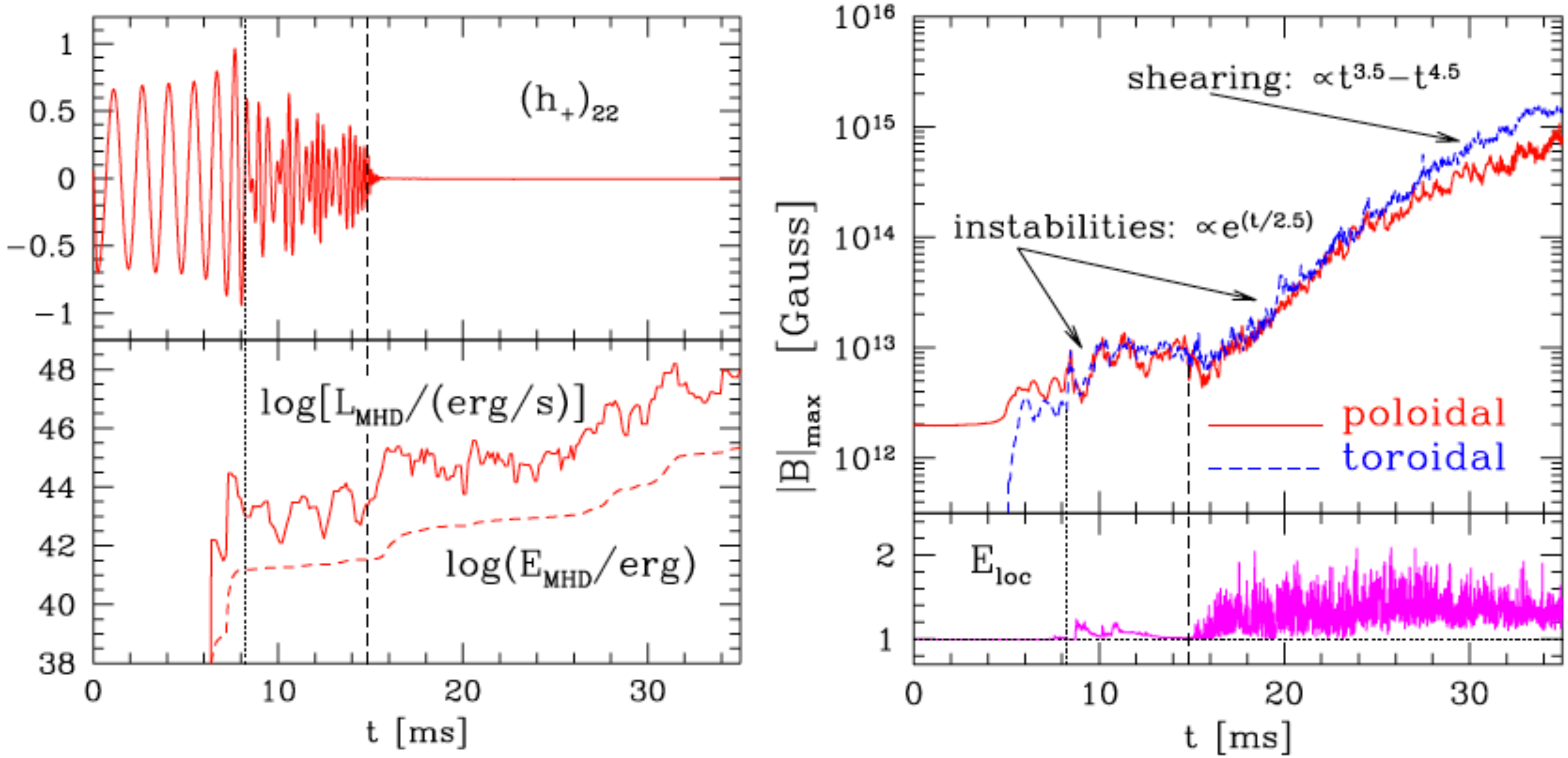
B-field

Central engines (2) Short GRBs

Short GRBs : NS+NS or NS+BH mergers ?

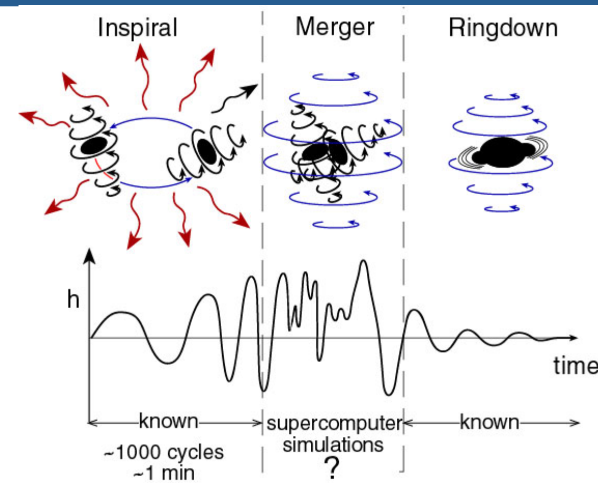
Rezzolla et al. 2011

GW emission and MHD power



Mergers: GW emission

- Inspiral : expected signal is well known
- Merger : more uncertain, needs complex simulations
- Ringdown : expected signal is well known

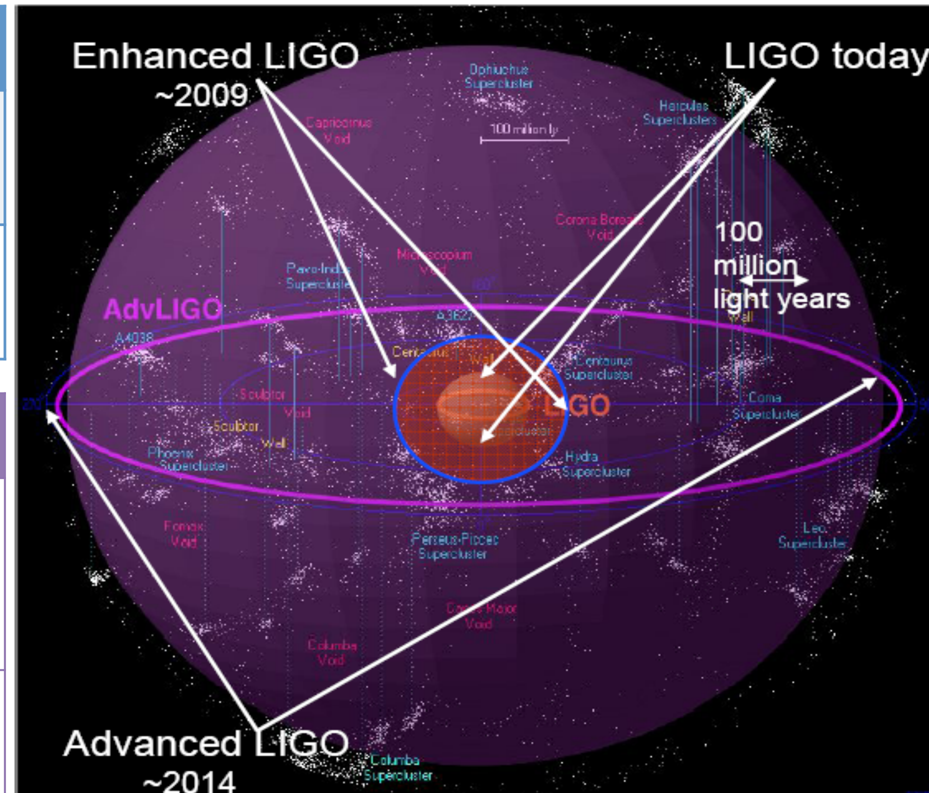


- Merger rate ? uncertain, even in the Milky Way
  (see Abadie et al. 2010)

- Detection rates ?

	NS/NS	NS/BH
LIGO I/ Virgo	15 Mpc	30 Mpc
Ad LIGO/ Ad Virgo	200 Mpc	420 Mpc

	NS/NS	NS/BH
LIGO I/ Virgo	$0.02\ yr^{-1}$ (2e-4 – 0.2)	$0.004\ yr^{-1}$ (7e-5 – 0.1)
Ad LIGO/ Ad Virgo	$40\ yr^{-1}$ (0.4 – 400)	$10\ yr^{-1}$ (0.2 – 300)



GW - Short GRB association ?

- GW : detection is uncertain
- Short GRBs (assuming they are associated to mergers) :

- Fraction of mergers ?	Probably high to reproduce the observed rate
- Orientation ?	Depends on the jet beaming ? *(Expected large* *but not well constrained by observations)*
- Gamma-ray detection ?	Depends on available instruments *e.g. GBM more efficient than Swift for short GRBs*
- Afterglow detection ?	Depends on available instruments *Compared to long GRBs:* *localization is more difficult (less photons)* *afterglows are usually fainter*

- Final result is highly uncertain…
  [optimistic θ_{jet}=30° and efficiency 80 % ➡ 10% of GW detection rate]
- **Keeping the capability to detect GRBs in space while GW detectors are operating is crucial (Swift, Fermi, SVOM ?)**

6– Relativistic ejection

Jet composition

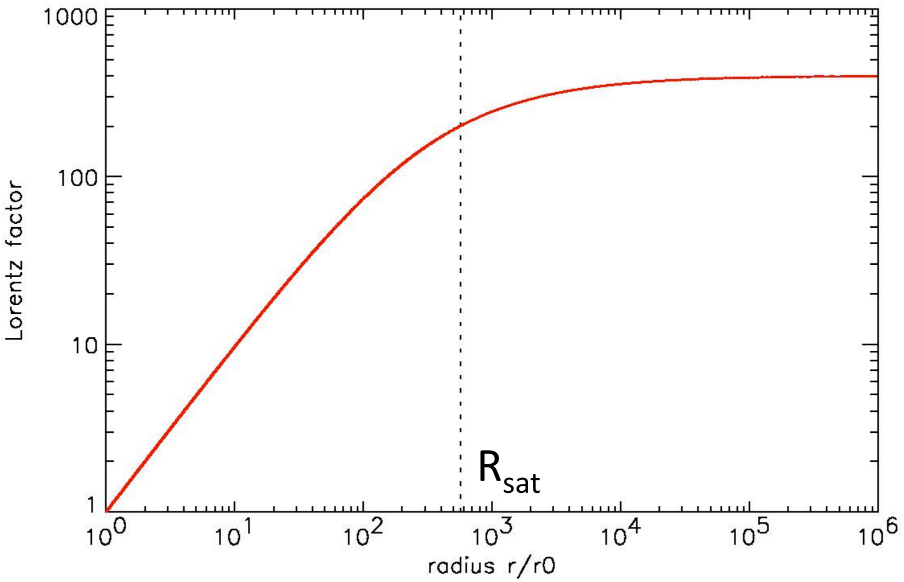
Fireballs: thermal acceleration

The physics of relativistic ejections by a compact source is complicated and not well understood… The fireball model is a useful toy model but one should recall that the real jet evolution could be rather different, especially if the magnetic field plays a dominant role in the acceleration mechanism.

- Paczynski 1986; Goodman 1986
- Energy (E_0) injected in matter (M_0) very close to the central engine (R_0)
- Adiabatic expansion and hydrodynamical acceleration
- If $E_0 \gg M_0 c^2$: relativistic motion ($G_\infty \simeq E_0 / M_0 c^2$ for 100% efficiency).

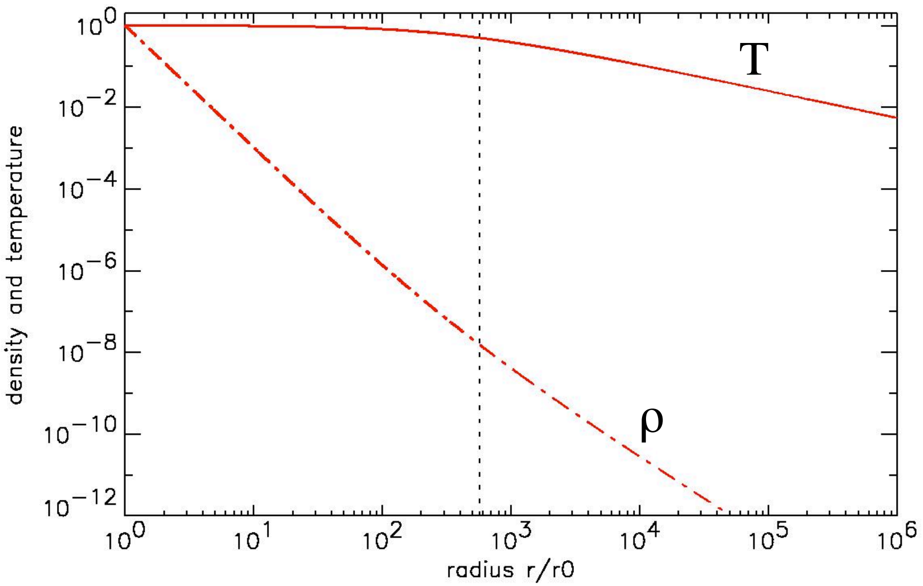
- No magnetic fields
- No gradual energy injection
- No complex composition (e.g. neutrons + protons)
- No dense external medium (e.g. collapsing progenitor star, …)
- No collimation
- …

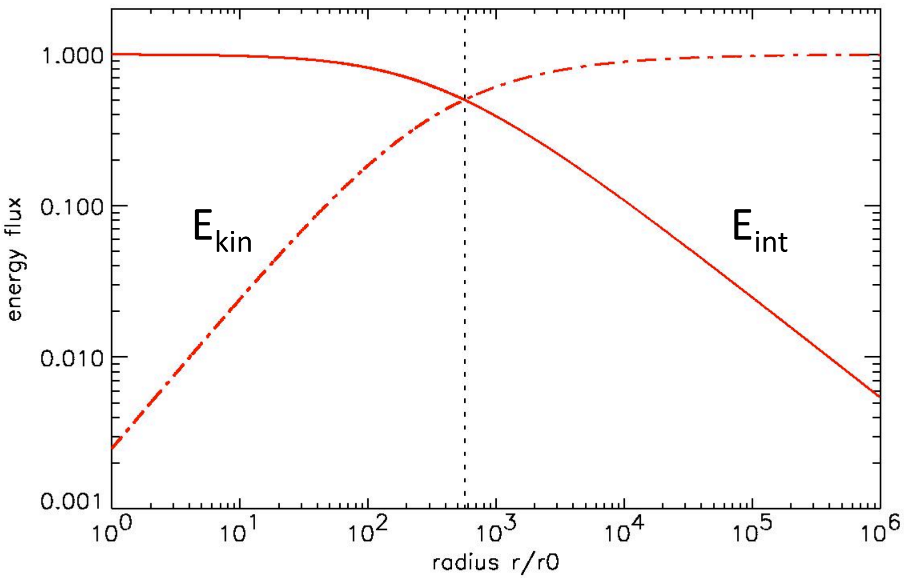
Fireballs: thermal acceleration



A toy model for GRB outflows : thermal acceleration.

R_0 ~ a few GM / c^2 ~ 100 km
R_{sat} ~ Γ_∞ R_0 ~10 000 km for Γ=100





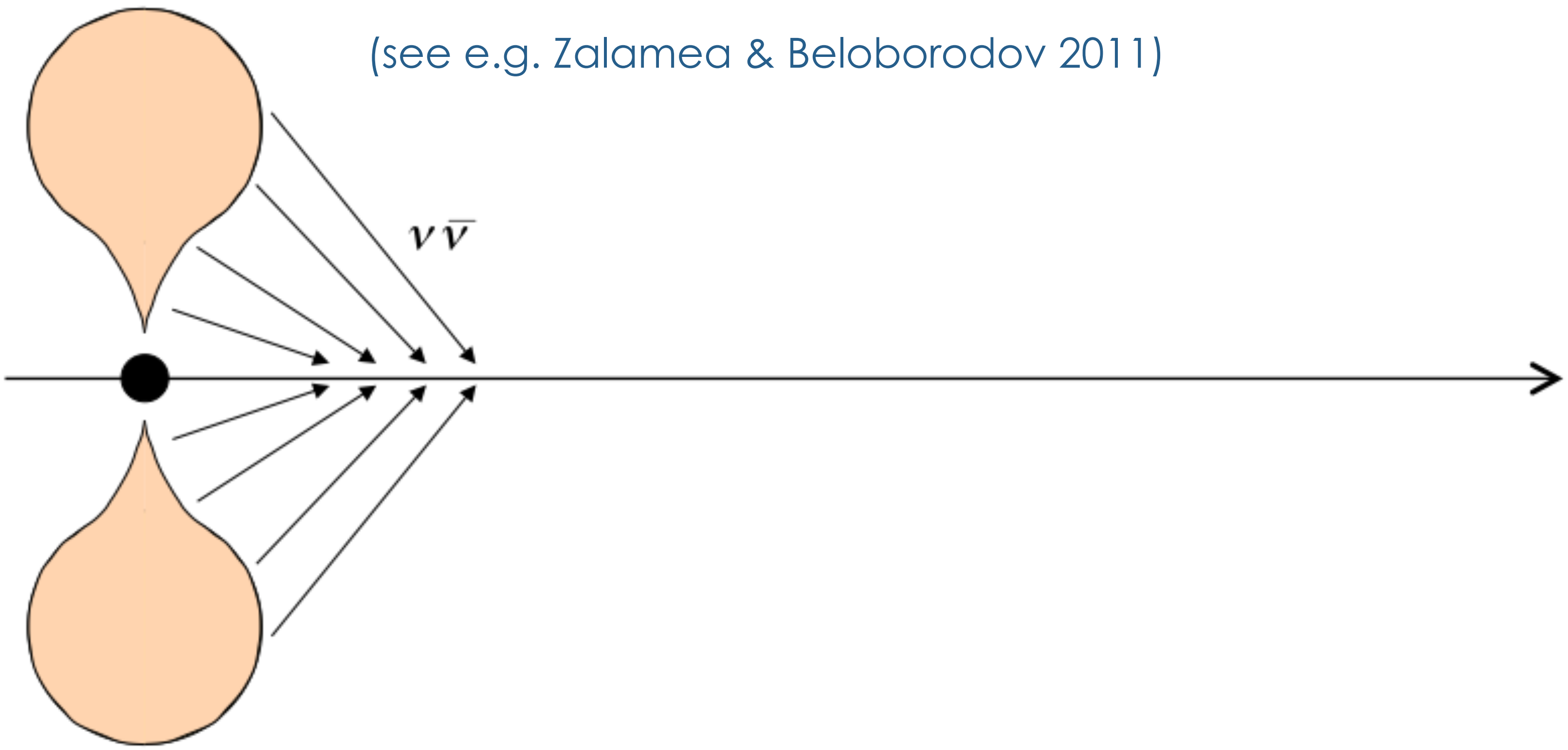
Relativistic ejection : neutrinos ?

Baryonic pollution ?

Efficiency may be an issue, especially for long GRBs.

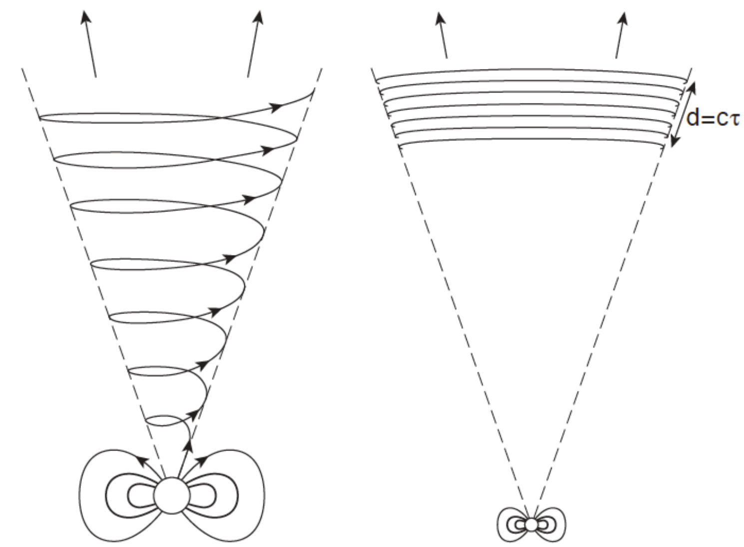
It is a promising mechanism for short GRBs.

(see e.g. Zalamea & Beloborodov 2011)

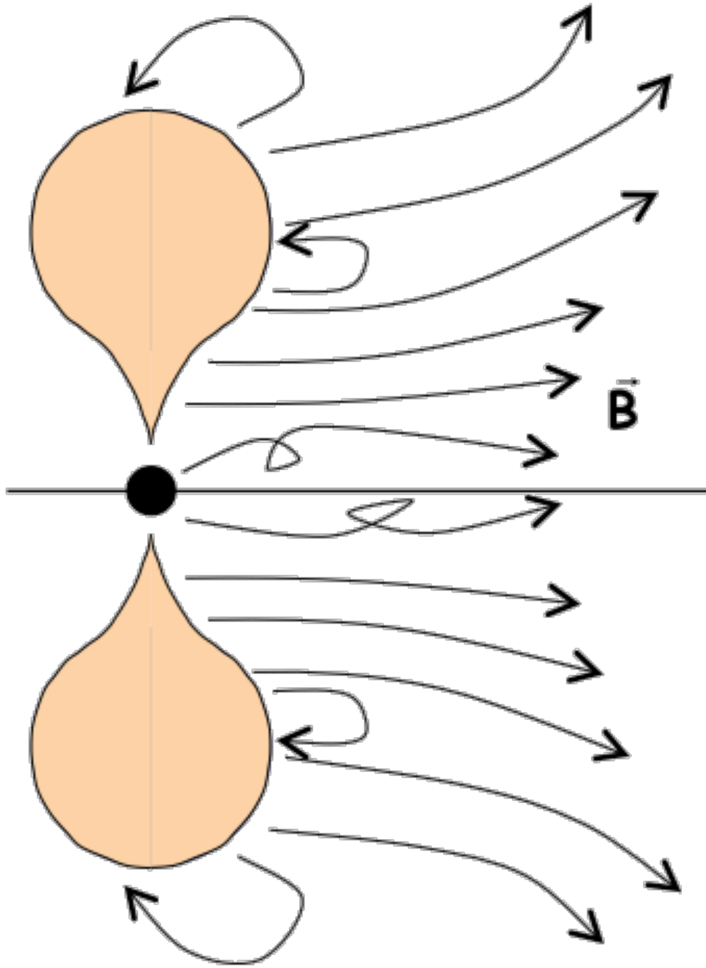


Relativistic ejection : magnetic field ?

Baryonic pollution ?
Initial/final magnetization ?
Beaming ?



Spruit et al. 2001



For magnetized outflows :

- scalings of the fireball model may be lost(e.g. $\Gamma \propto R$ is not necessarily true)
- the thermal content of the outflow can be much lower

Short vs long GRBs: summary

Short and long GRBs have different progenitors

- Long GRBs: collapsars (conditions ? Mass, rotation, binarity, …)
- Short GRBs: mergers ?

Short and long GRBs may have similar central engines

- A thick accretion disk orbiting a stellar mass black hole ?
- Differences:
  - Black hole: mass, spin
  - Disk: mass, reservoir
  - Close environment
  - Other ? (magnetization, …)
- Is there an alternative to BH+disk ? Magnetars ? Something more exotic ?

Short and long GRBs should have different environments

- Collapsars: star forming region (high density) + stellar wind ?
- Mergers: low density environment ?

Is the ejection mechanism the same ?

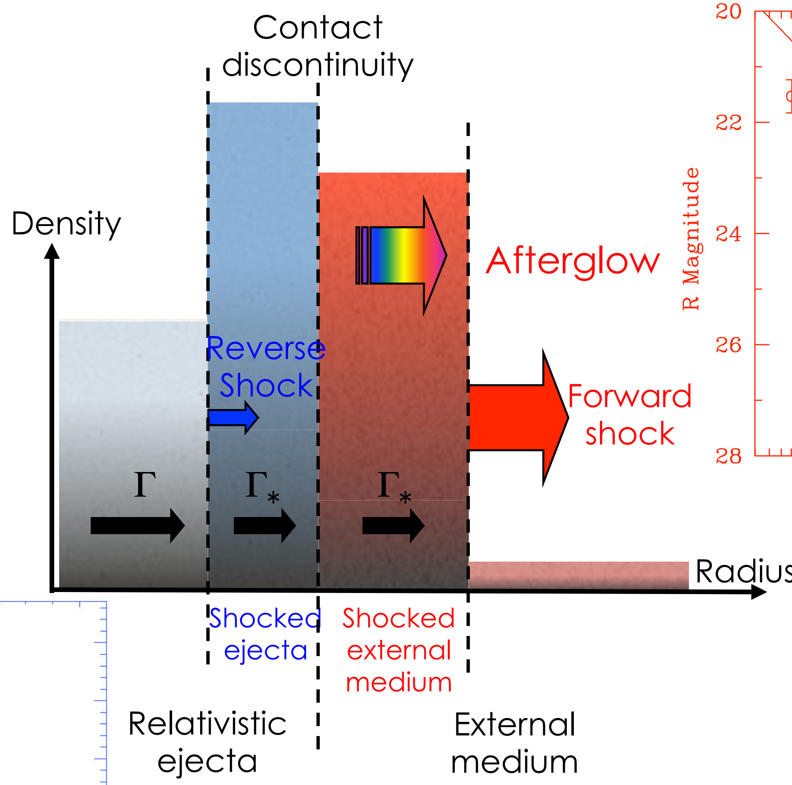
- Thermal or magnetic ? This leads to different jet composition
- Final Lorentz factor ? Final magnetization ?
- Opening angle ?

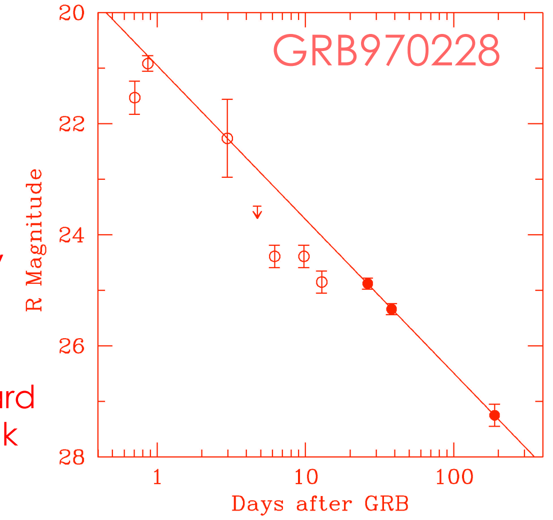
7– Afterglow models

Afterglow model

The afterglow is associated to the forward (external) shock.

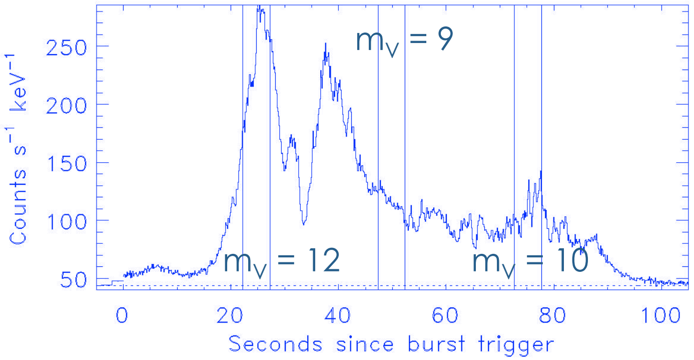
- model: relativistic blast wave (Blandford & McKee 76) + synchrotron (Sari et al. 98
- main uncertainty: **microphysics (acceleration at ultra-relativistic shocks)**
- predicted lightcurves: simple powerlaws (fit well with pre-*Swift* data)





Fruchter et al. 1999

GRB990123 @ z = 1.6 / ROTSE



(Akerlof et al. 1999)

Optical flash ?

Forward (external) shock model

*The **afterglow** is usually interpreted as the signature of the deceleration of the relativistic outflow by the external medium.*

Forward shock :

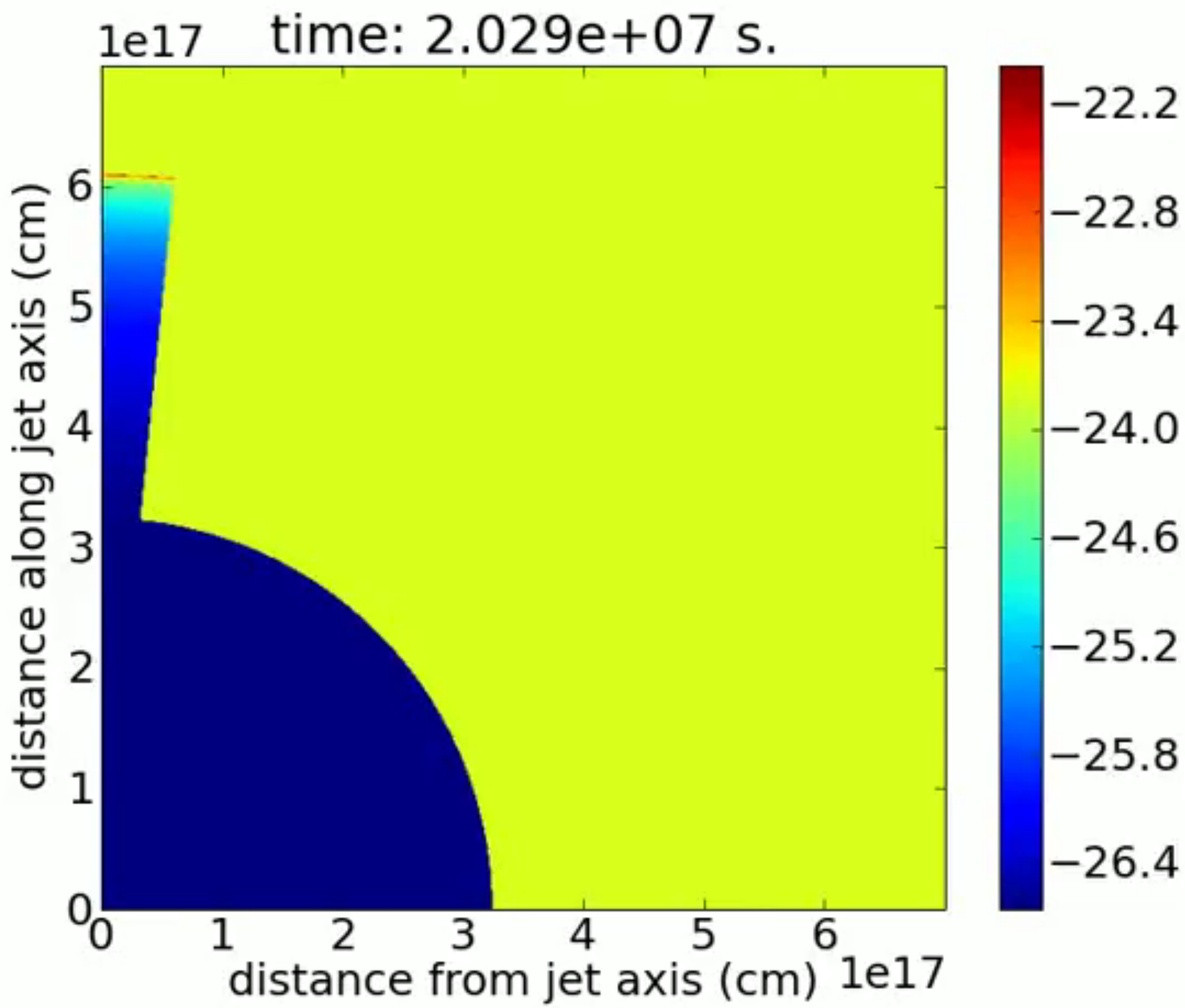
- Dynamics : Blandford & McKee 1976
- Microphysics : ε_e, p, ε_B **= main unknown**
- Synchrotron radiation : Sari, Piran, Narayan 1998

  Two important regimes: Slow cooling with t(syn) >> t(dyn)
  Fast cooling with t(syn) << t(dyn)

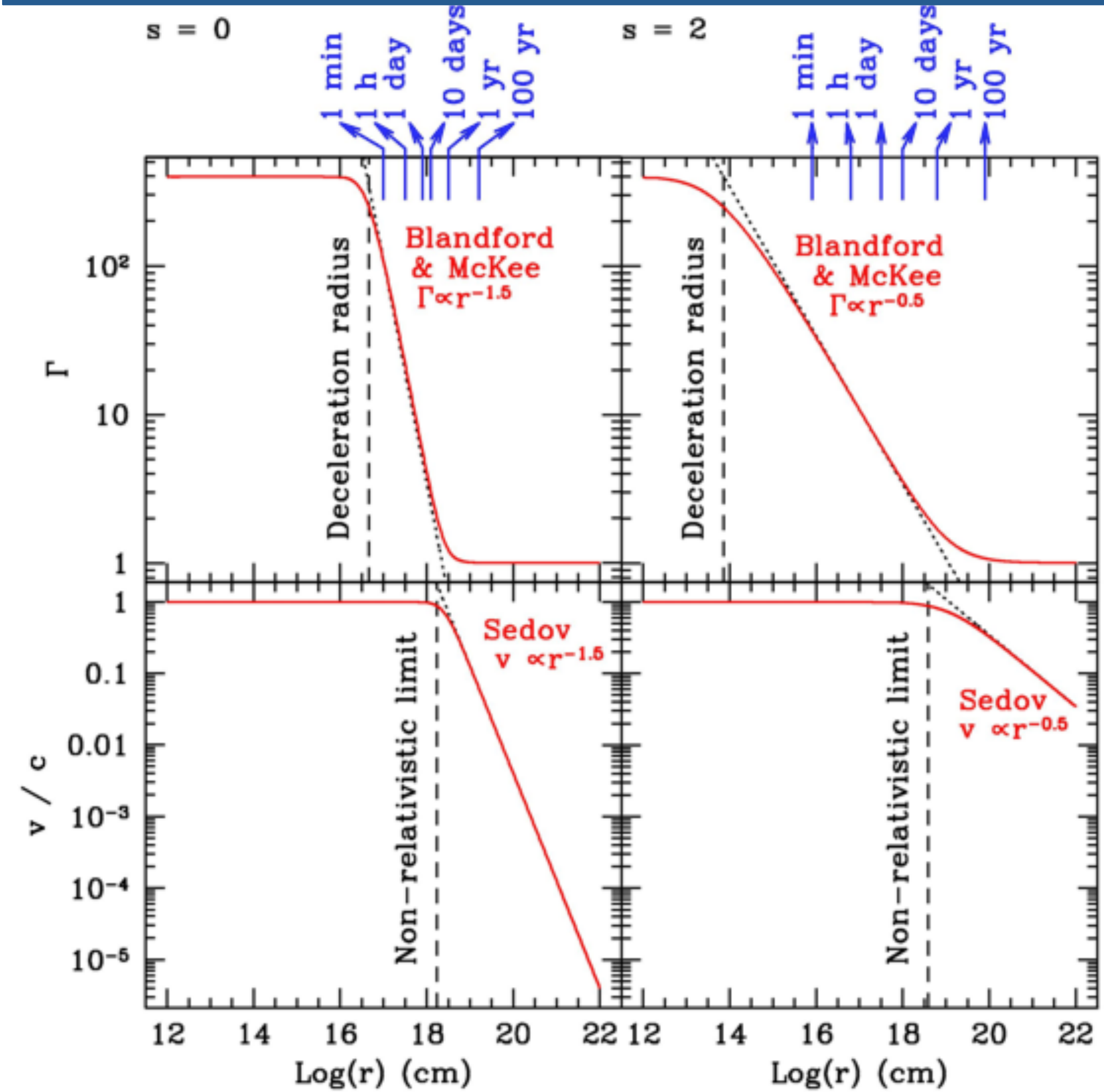
- Effect of a stellar wind : Chevalier & Li 2000
- Jet vs spherical outflow : Rhoads 1997

Forward (external) shock model

A recent simulation by van Eerten et al.



Forward (external) shock model



Relativistic ejecta :

Γ_0 = 400

$E_0 = 10^{53}$ erg

$M_0 = E_0/\Gamma_0 c^2 = 1.4\ 10^{-4}\ M_\odot$

External medium :

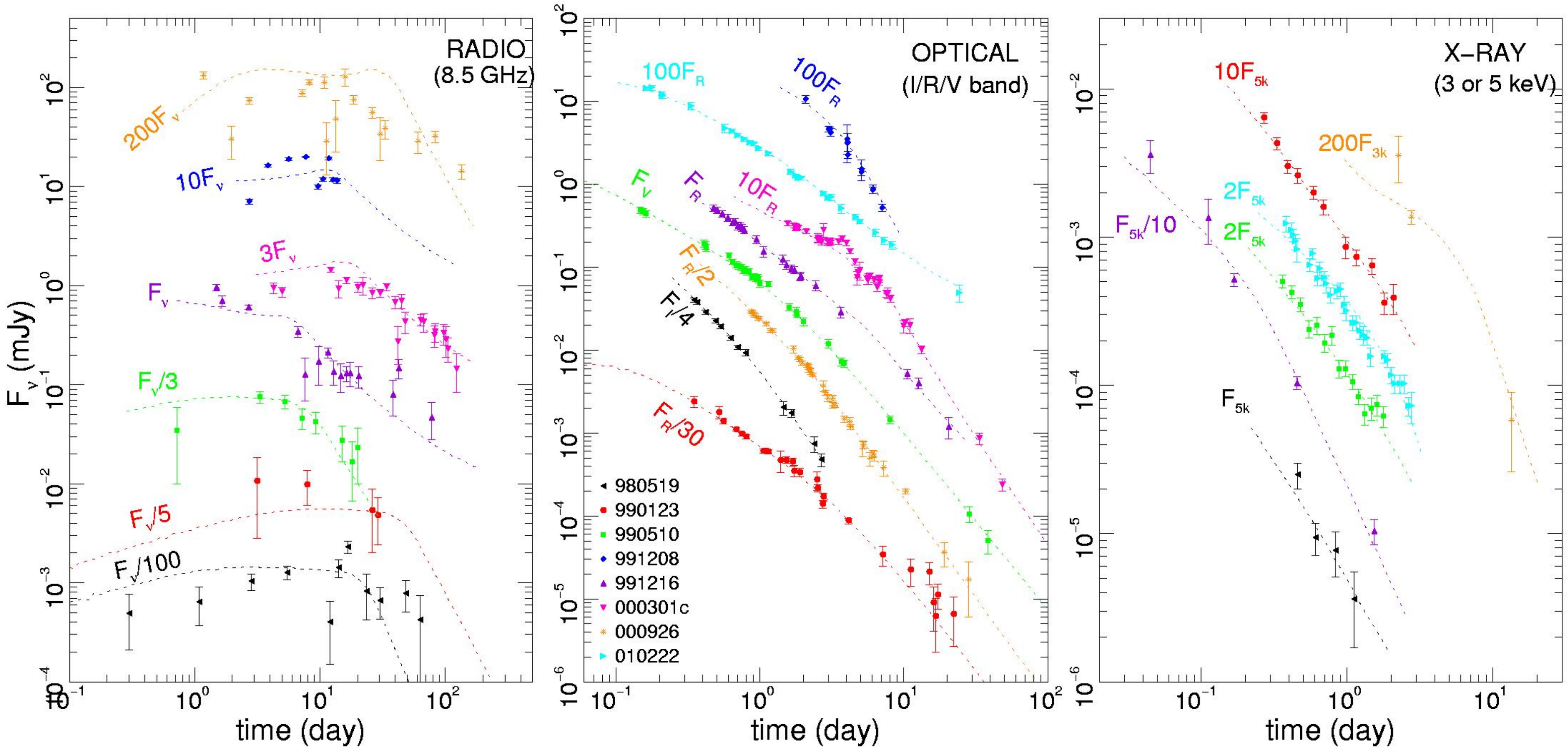
Uniform (s=0): n = 1 cm^{-3}

Stellar wind (s=2): $A_* = 1$

Pre-*Swift* status: nice fits to observations

Pre-Swift era : very promising results (multi-wavelength fits)

Some problems? (external density, p slope, ...)

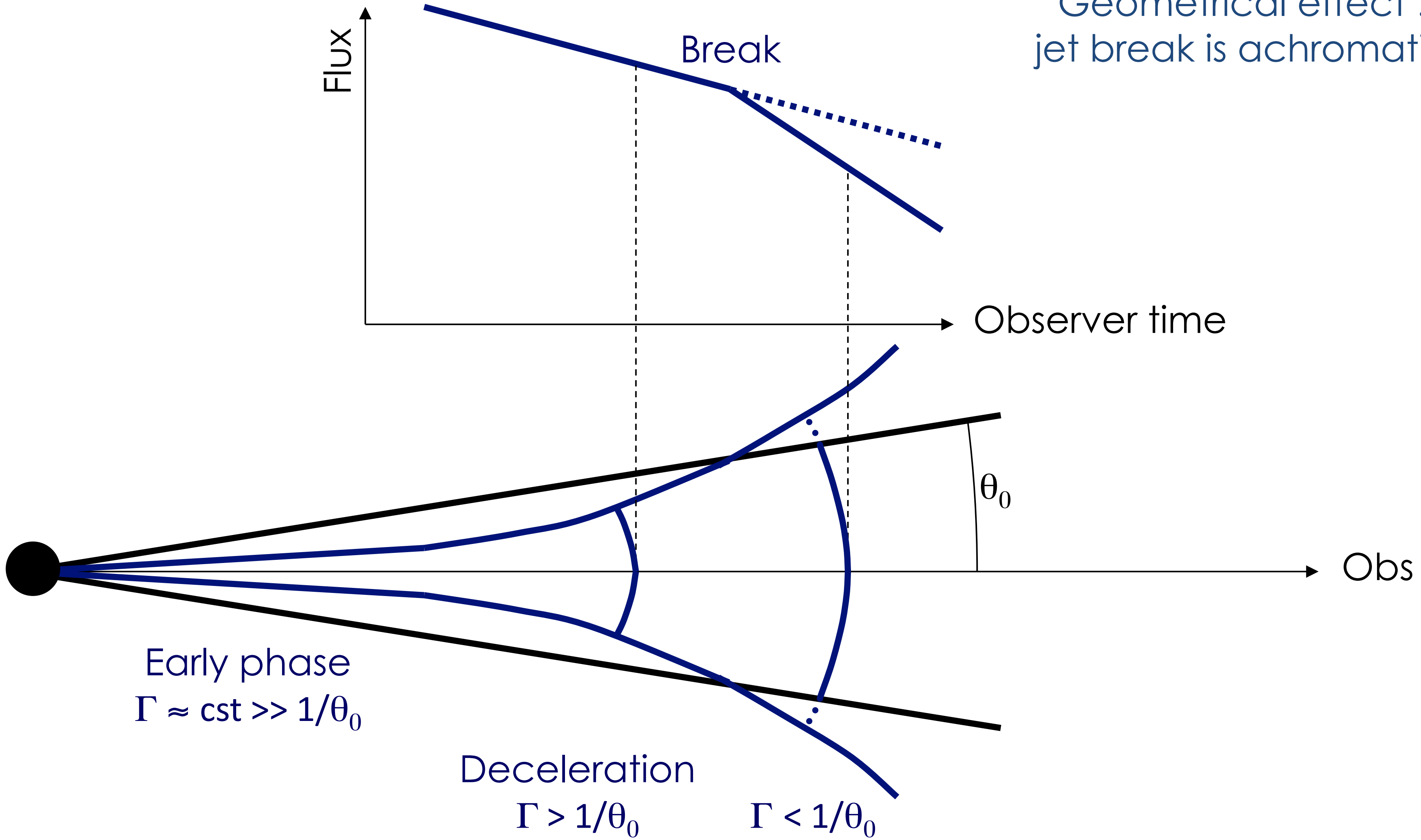


(Panaitescu & Kumar 2001)

Jet breaks

(Rhoads 1997)

Geometrical effect :
jet break is achromatic



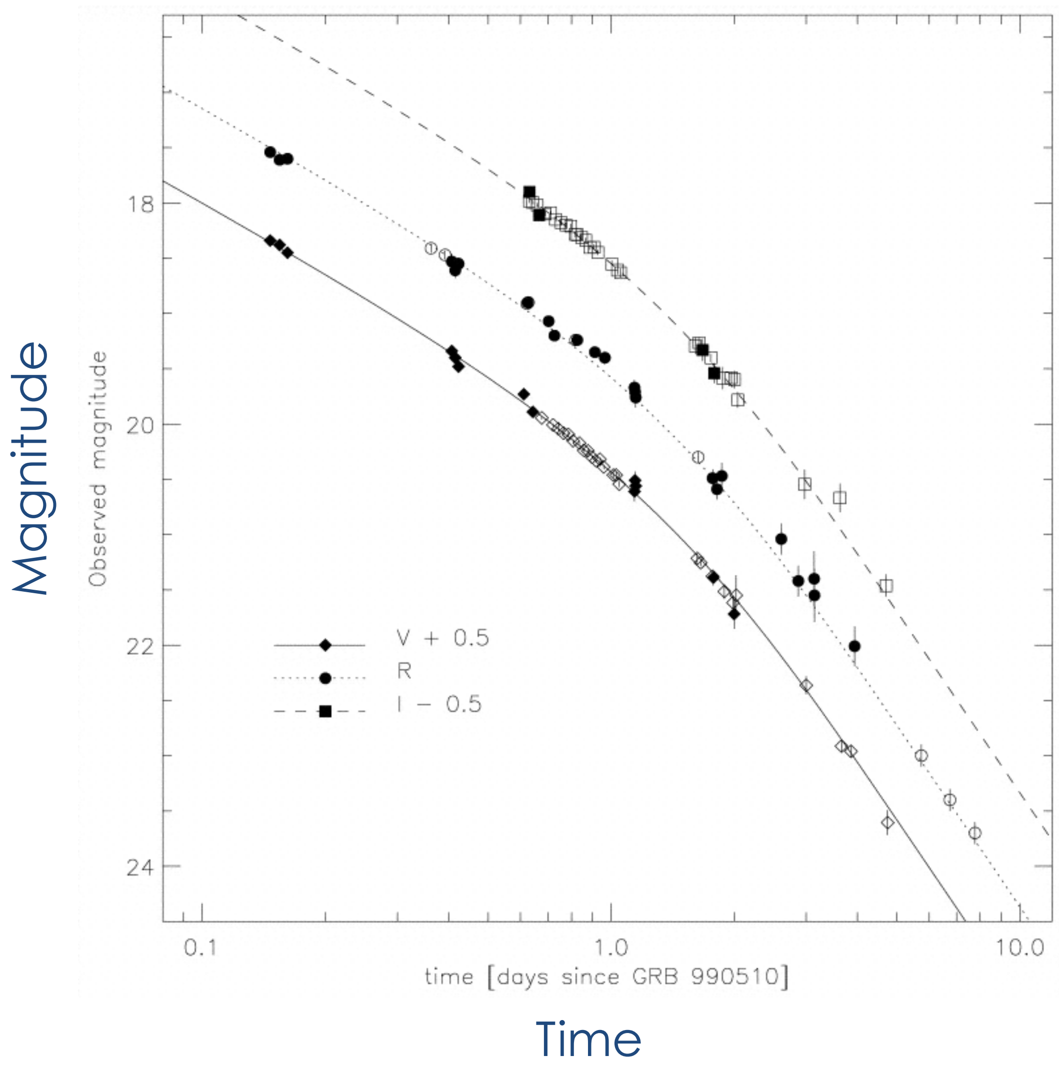
Pre-*Swift* status: jet breaks

GRB 990510

(Harrison et al. 1999)

$E_{\gamma,true} \sim 10^{51}$ erg ?

(Frail et al. 1999)



Forward (external) shock model

Possible additional effects :

- Pre pair-enrichment of the circumburst medium by the prompt gamma-ray flash : delay of the deceleration and different prediction for the early afterglow.
- Detailed calculation of the electron cooling
- Structured jets (= angular structure)
- Inhomogeneities in the circumburst medium : low amplitude variability
- Realistic environments : structured medium due to the interaction between stellar winds and ISM ?
- Orphan afterglows ?
- Counter-jet ?

…

Reverse shock

Due to the interaction with the surrounding medium, a reverse shock propagates within the ejecta. It is usually believed to contribute to the prompt emission (optical flash) and/or the early afterglow.

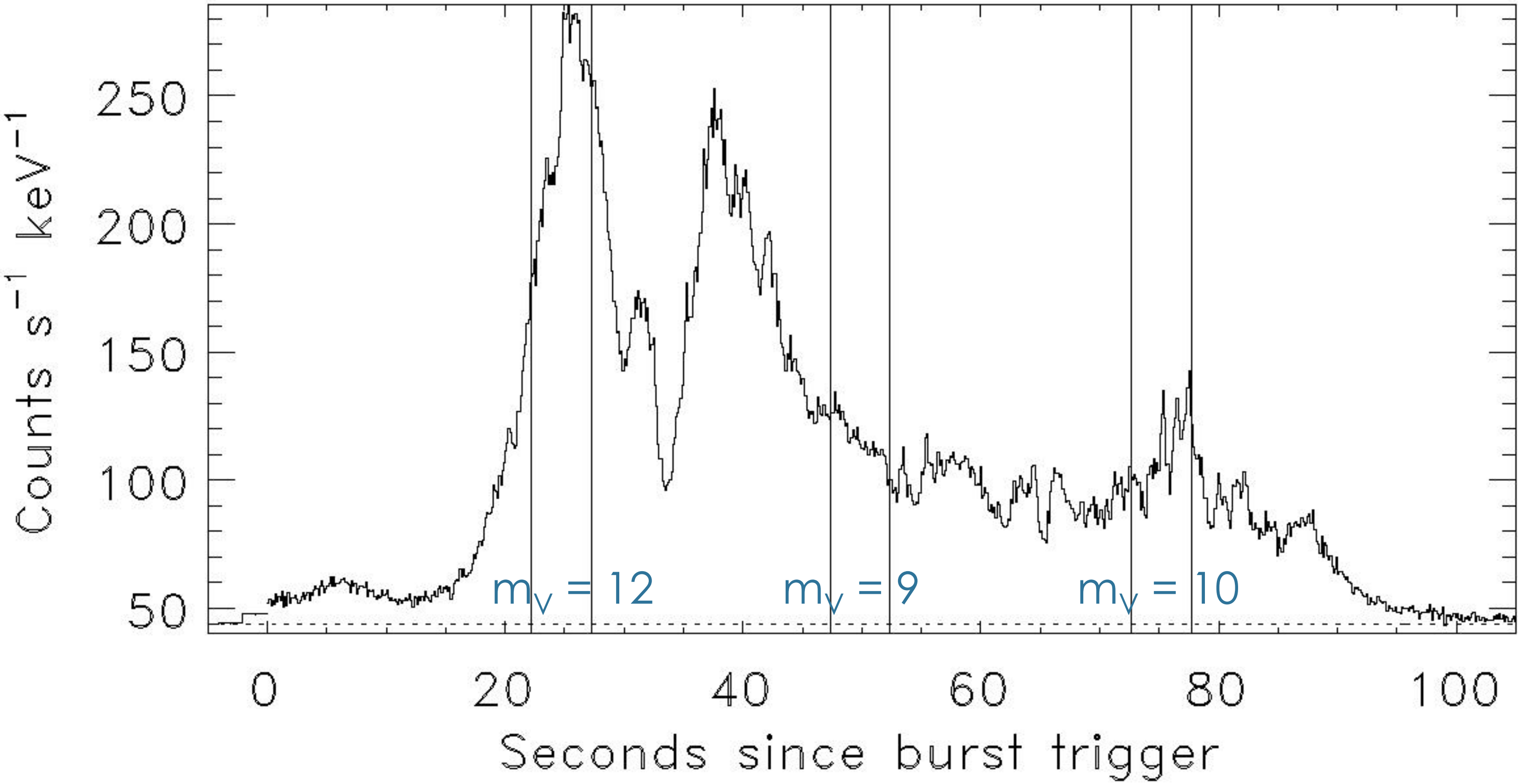
Reverse shock

- Theory is also well established for non magnetized outflows
- Main parameter : width of the relativistic shell
- Emission is also governed by synchrotron radiation
- Microphysics **= main unknown**

Pre-*Swift* status: reverse shock

- Optical flash like in GRB 990123 ? Problem : such optical flashes are rare (Sari & Piran 1999)

GRB990123 / ROTSE (Akerlof et al. 1999)



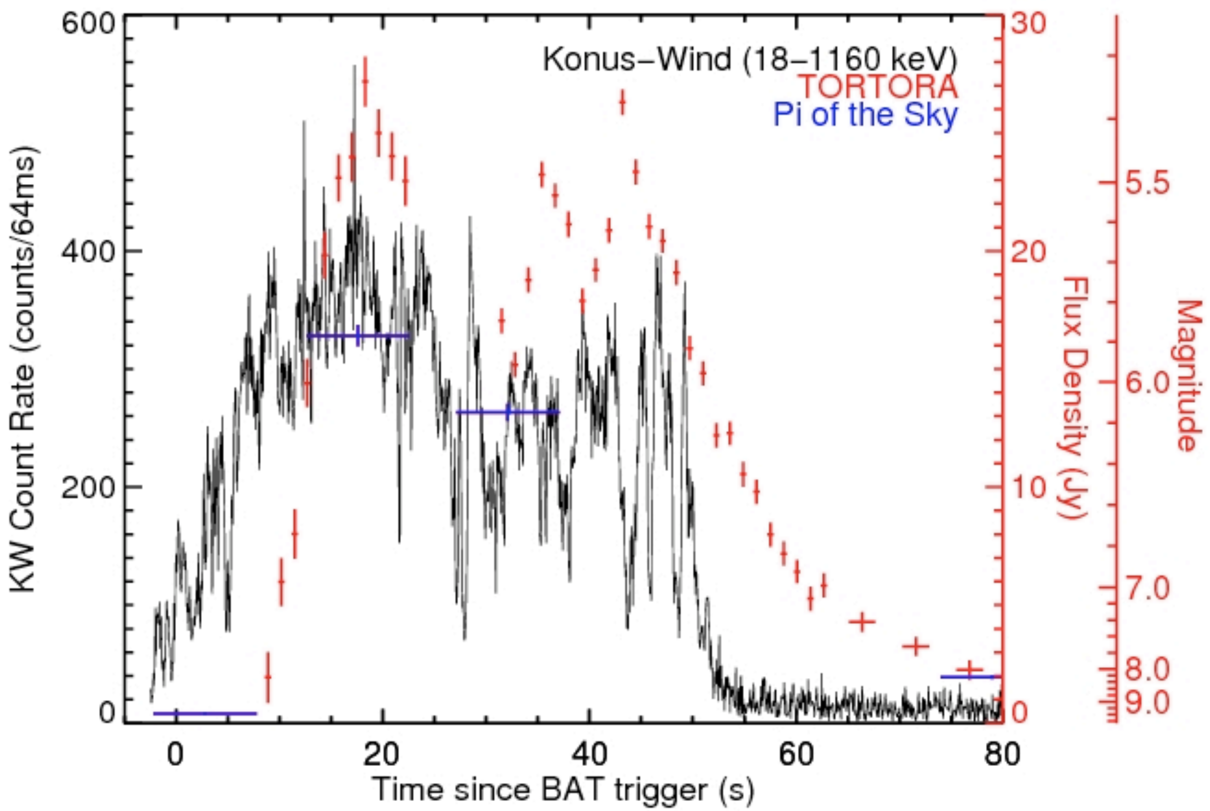
The *Swift* era

- Many more afterglows
- Observations start ealier : continuity from prompt to afterglow
- Simultaneous X-ray/optical observations in many cases

- **Forward shock = afterglow : many unexpected problems !**
- **Reverse shock = prompt optical flash : may be not…**

Swift observations: prompt optical emission

GRB 080319B @ z = 0.937

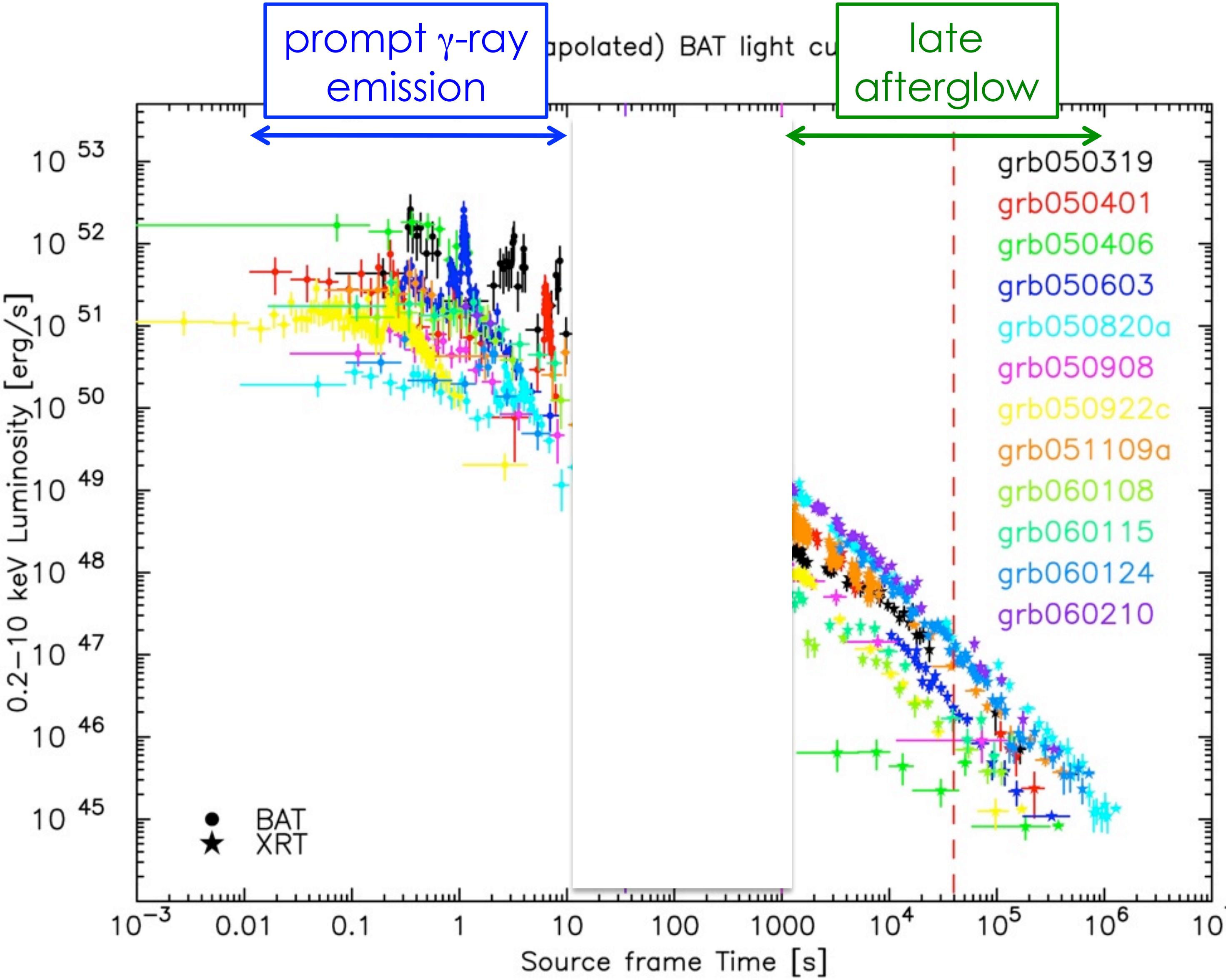


(Racusin et al. 2008)

-This optical flash is too variable to be explained by the reverse shock
-Internal shocks ?

Swift observations: afterglow

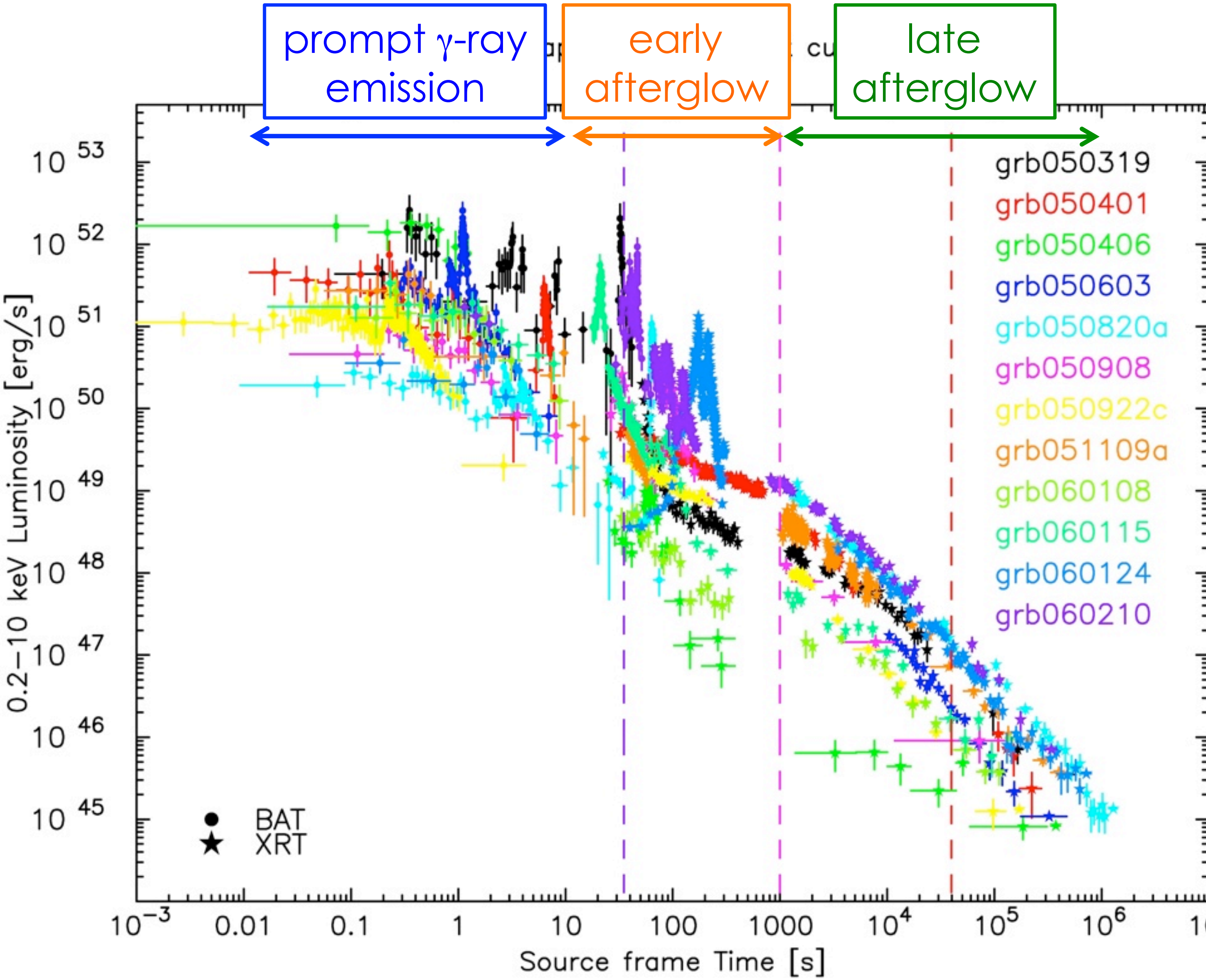
X-rays



(Mangano et al. 2007)

Swift observations: afterglow

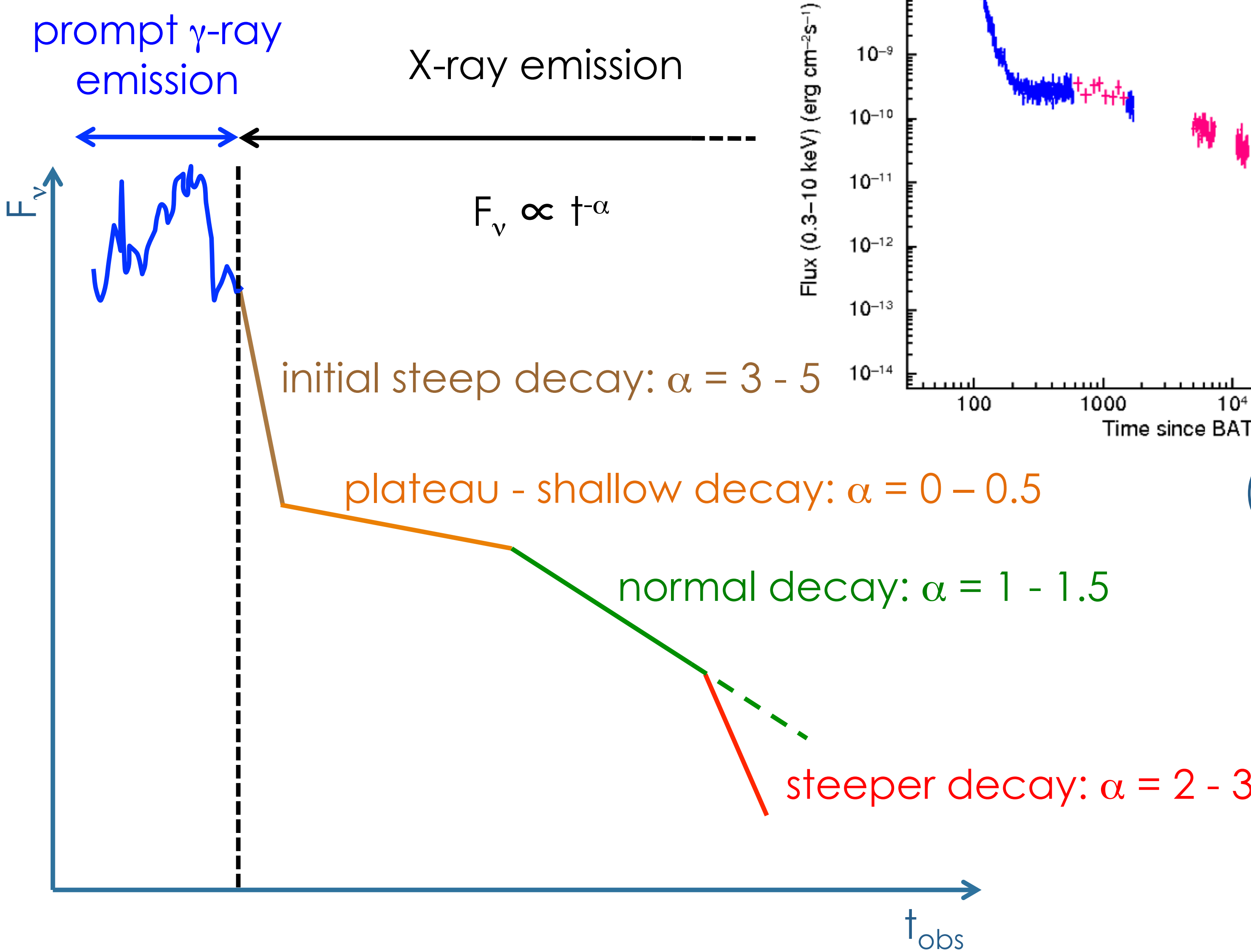
X-rays

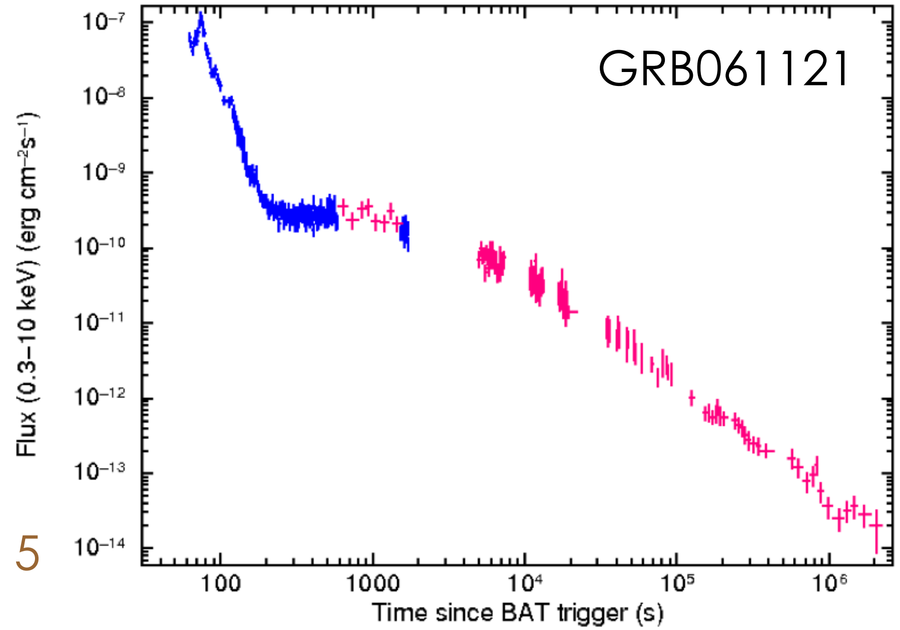


(Mangano et al. 2007)

Swift: (1) Afterglow lightcurve

- « Canonical » lightcurve:



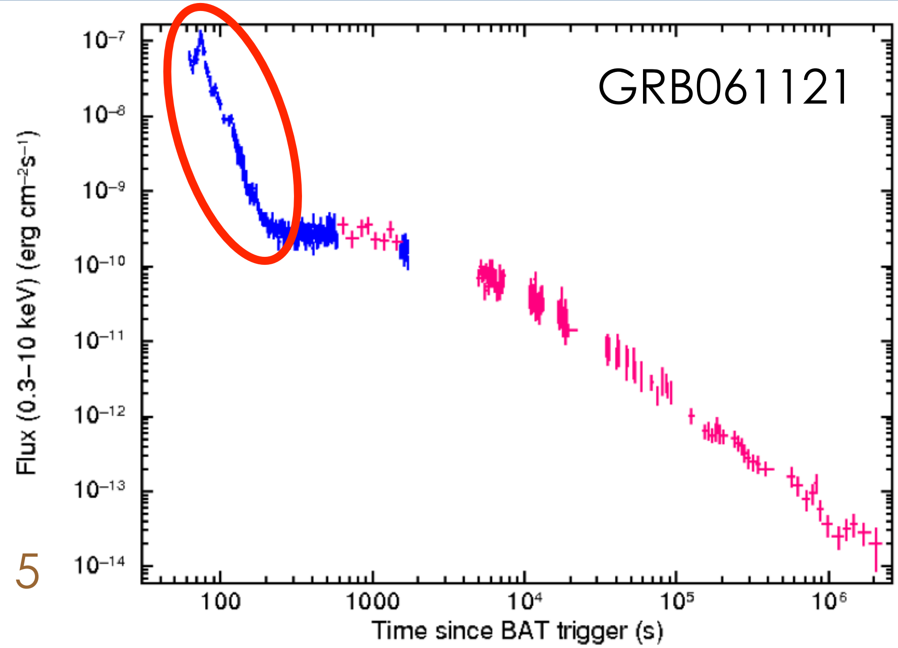


(Page et al. 2007)

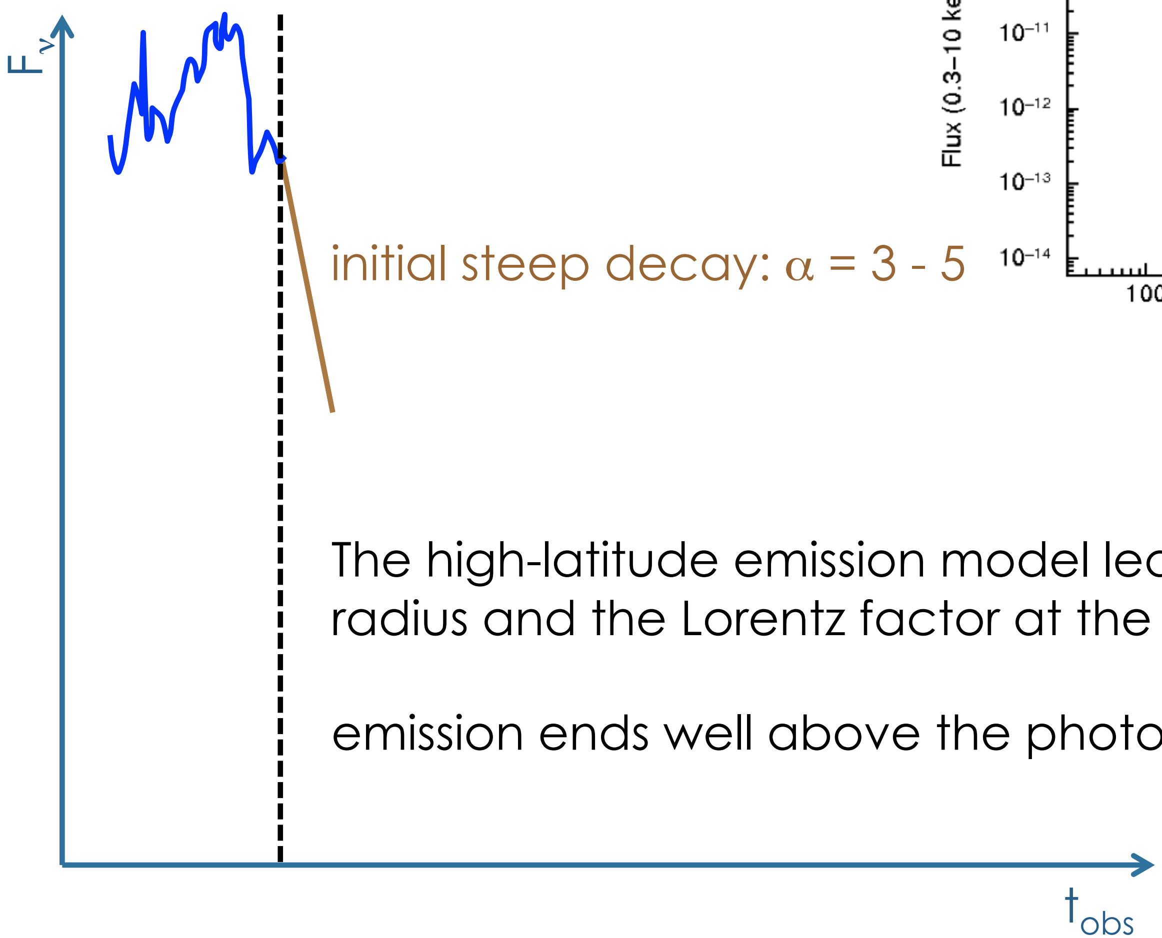
(Nousek et al. 2006, O'Brien et al. 2006)

Swift: (1) Afterglow lightcurve

- Initial steep decay:
  high-latitude emission at the end of the prompt phase ?
  (expected: Kumar & Panaitescu 2000)



(Page et al. 2007)

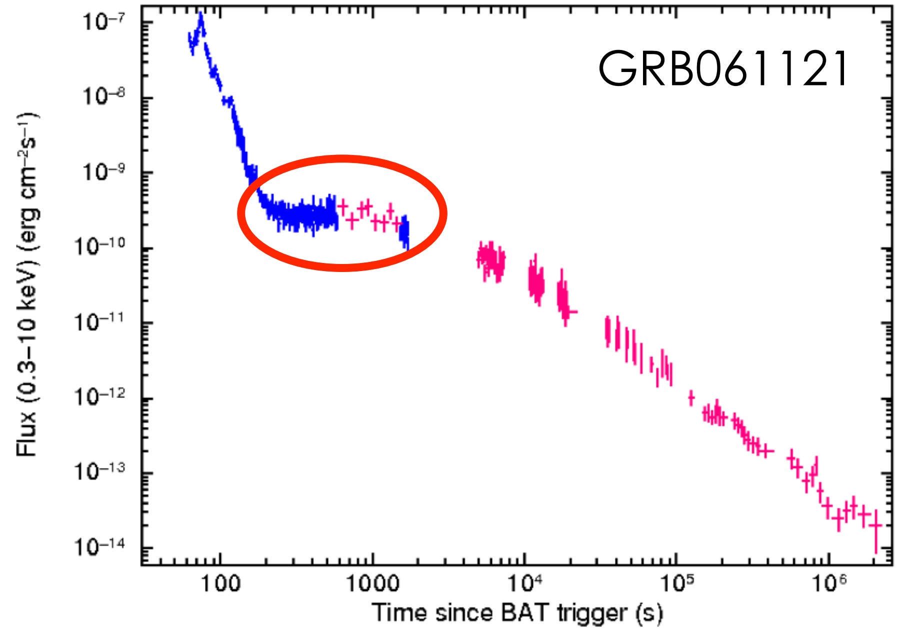


The high-latitude emission model leads to a constraint on the radius and the Lorentz factor at the end of the prompt phase:

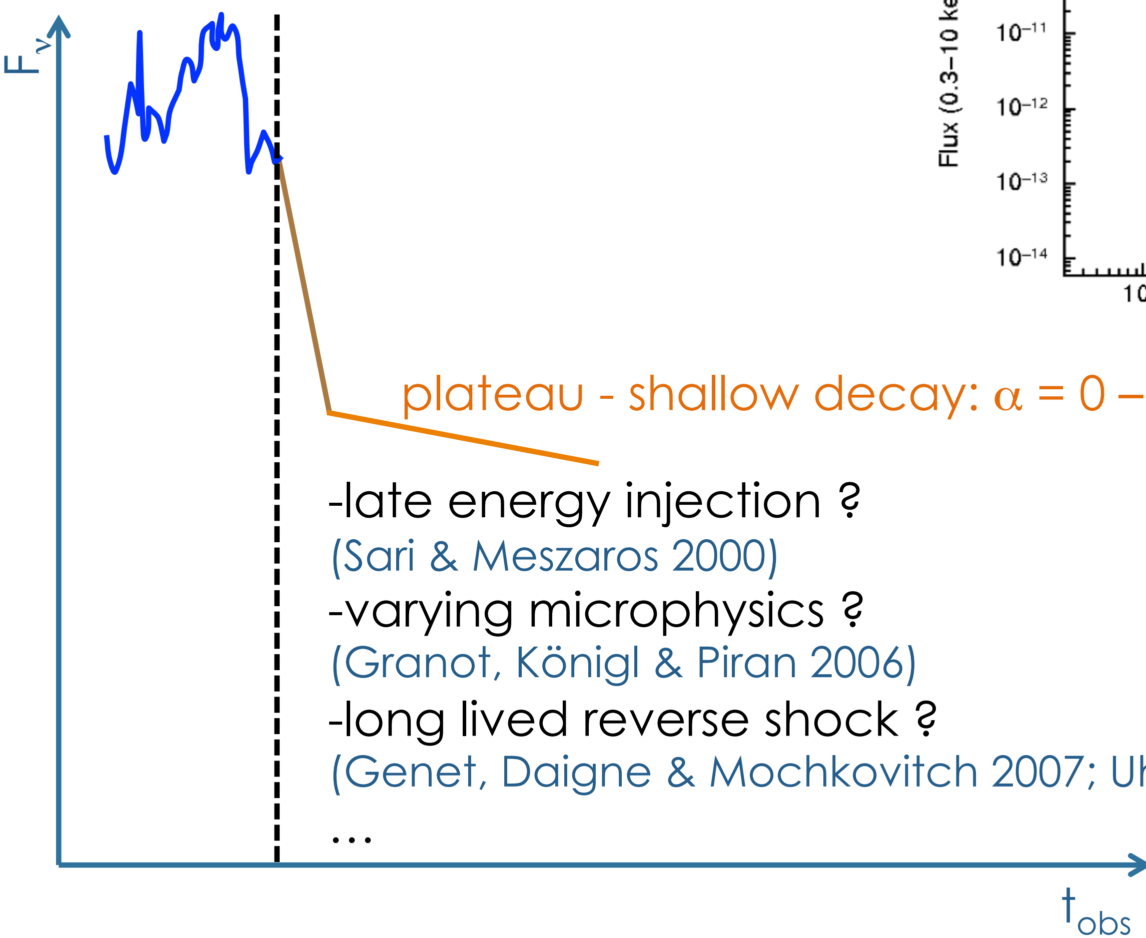
emission ends well above the photosphere.

Swift: (1) Afterglow lightcurve

- Plateau: **unexpected !**
  Difficult to reconcile with the standard model.



(Page et al. 2007)

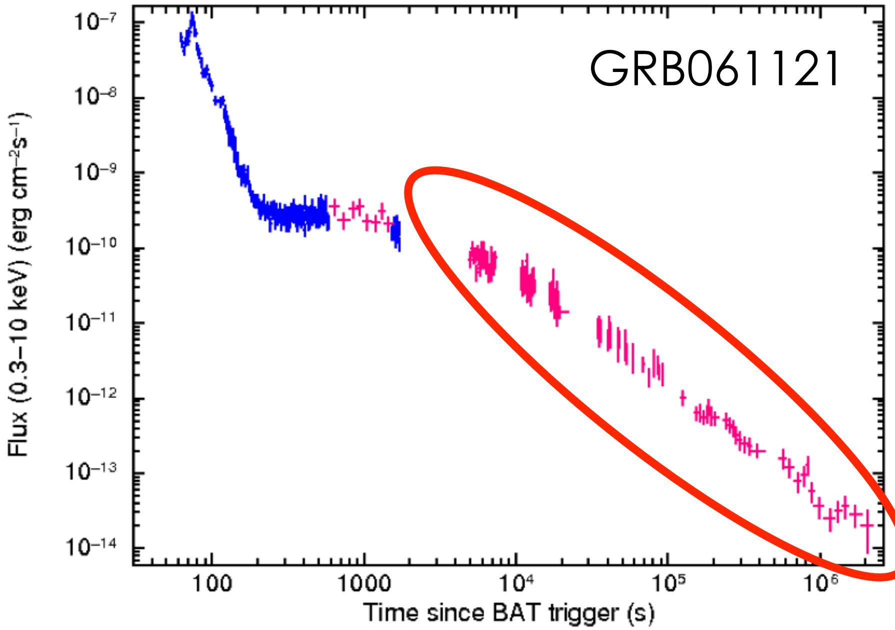


plateau - shallow decay: $\alpha = 0 - 0.5$

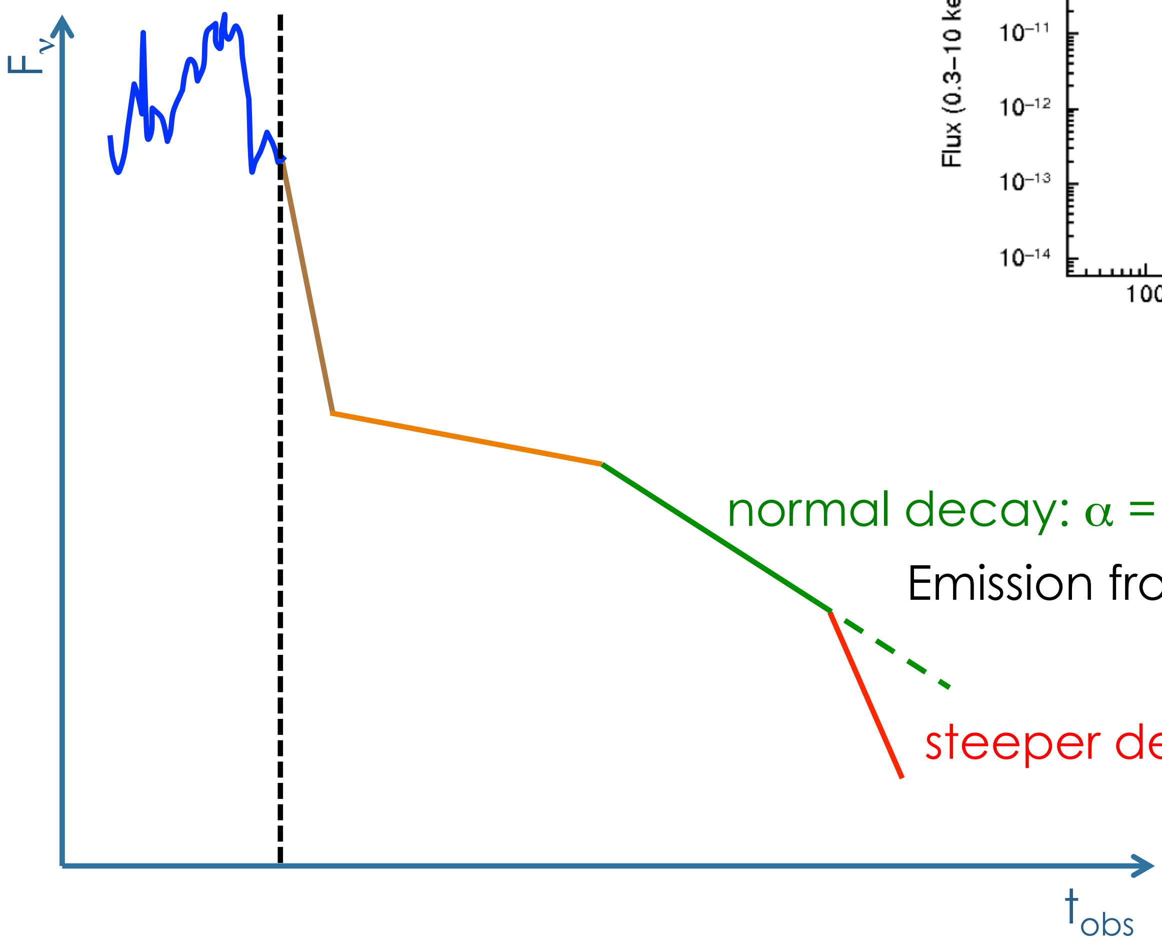
-late energy injection ?
(Sari & Meszaros 2000)
-varying microphysics ?
(Granot, Königl & Piran 2006)
-long lived reverse shock ?
(Genet, Daigne & Mochkovitch 2007; Uhm & Beloborodov 2007)
...

Swift: (1) Afterglow lightcurve

- « Normal » afterglow:



(Page et al. 2007)



normal decay: α = 1 - 1.5

Emission from the forward shock ?

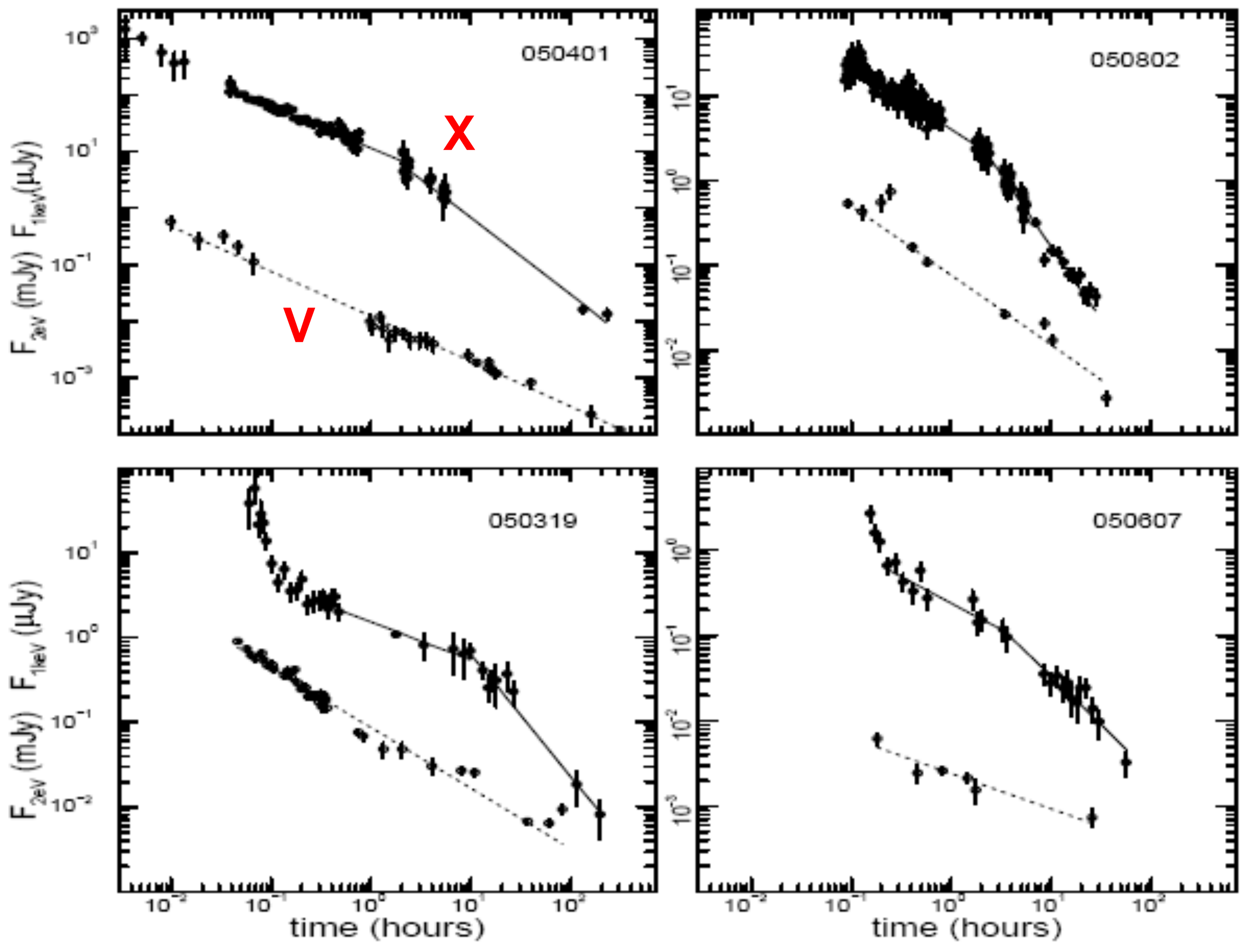
steeper decay: α = 2 - 3

Jet break ?

Swift: (2) Chromatic breaks

- X-rays vs optical: chromatic breaks

  Achromatic breaks are rare : where are the jet breaks ? (Burrows & Racusin 2007)

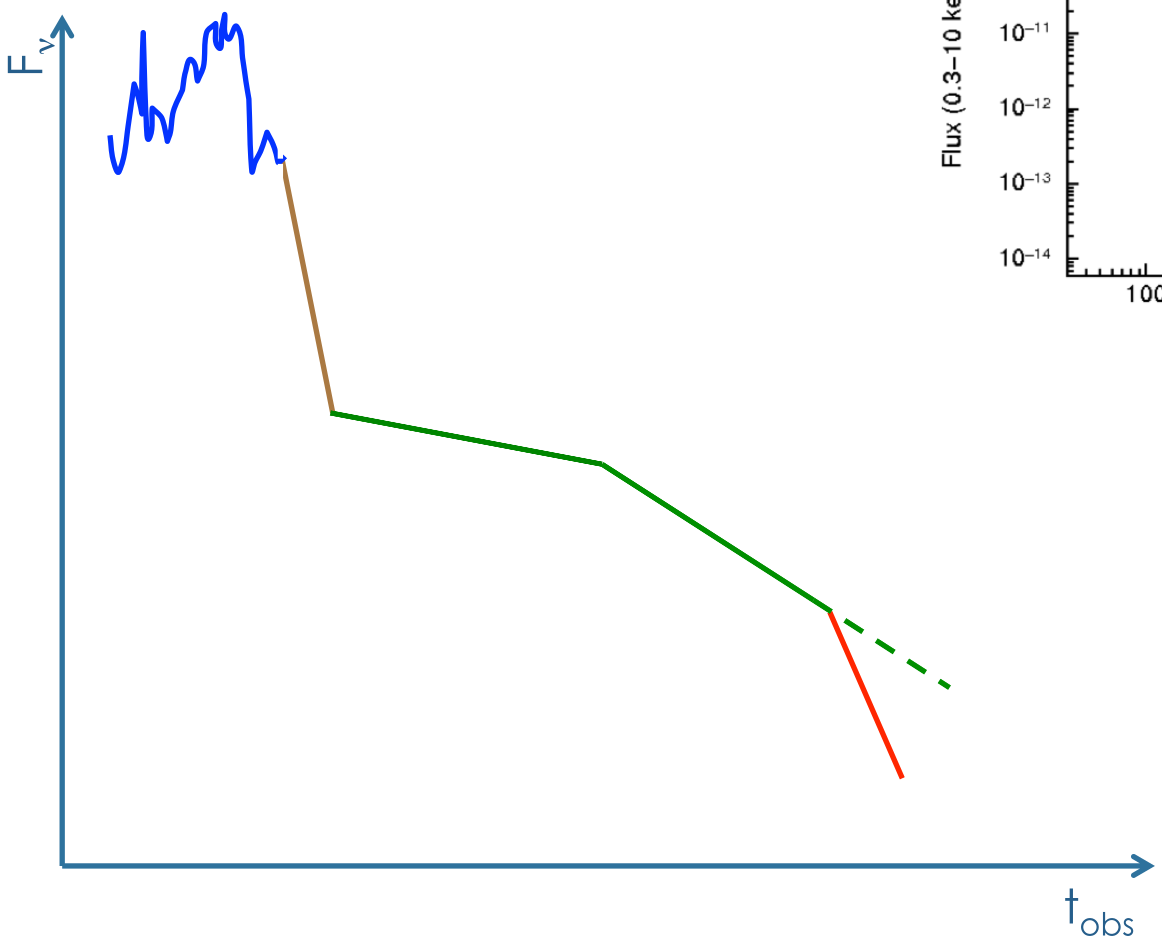


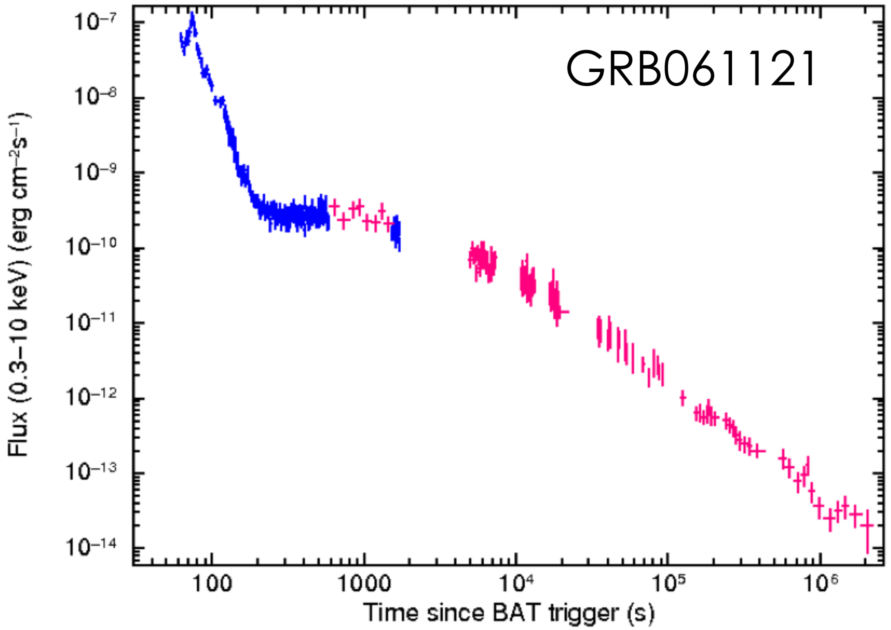
(Panaitescu 2006)

- Forward shock: evolving microphysics ? (Panaitescu 2006)
- Long-lived reverse shock: slow vs fast cooling e^- / Late jet break due to anisotropy

  (Genet, Daigne & Mochkovitch 2007; Beloborodov, Daigne, Mochkovitch & Uhm 2011)

Swift: (3) Flares

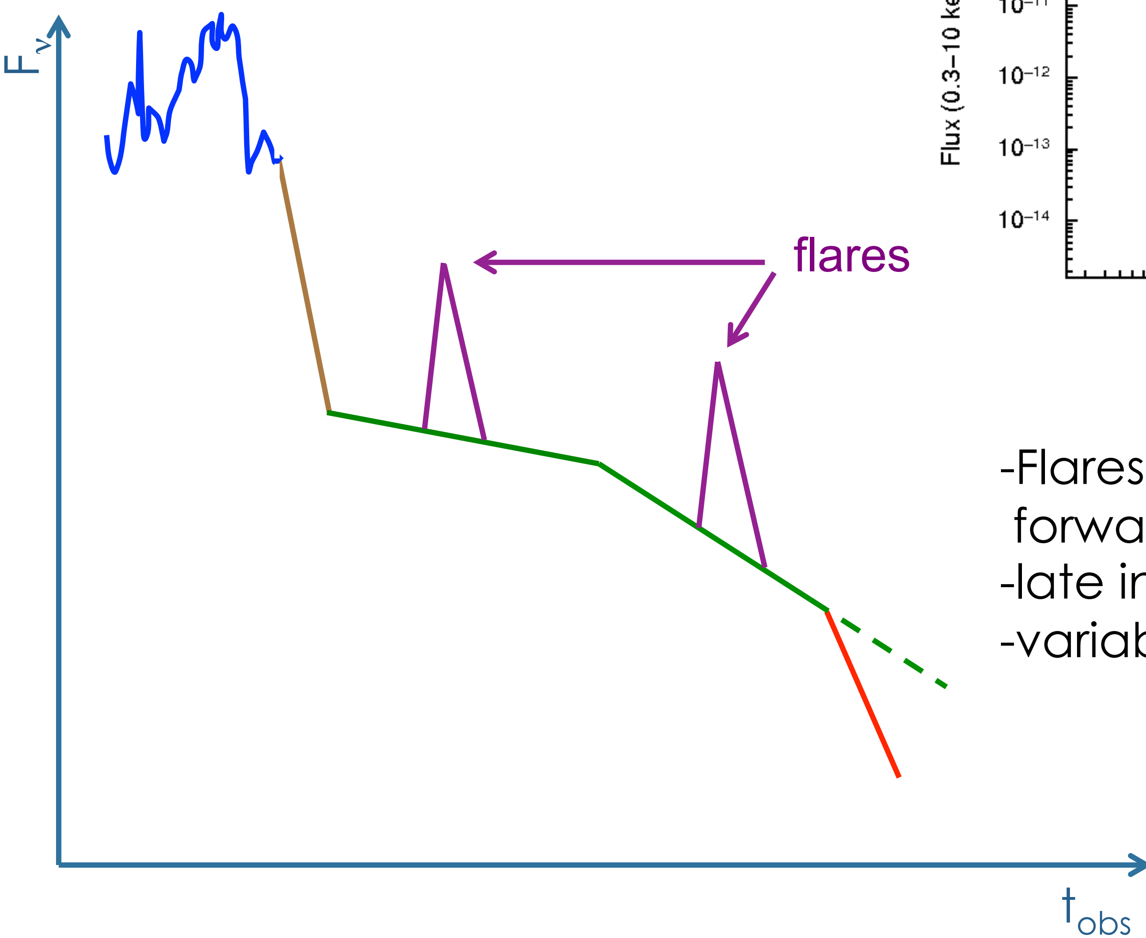


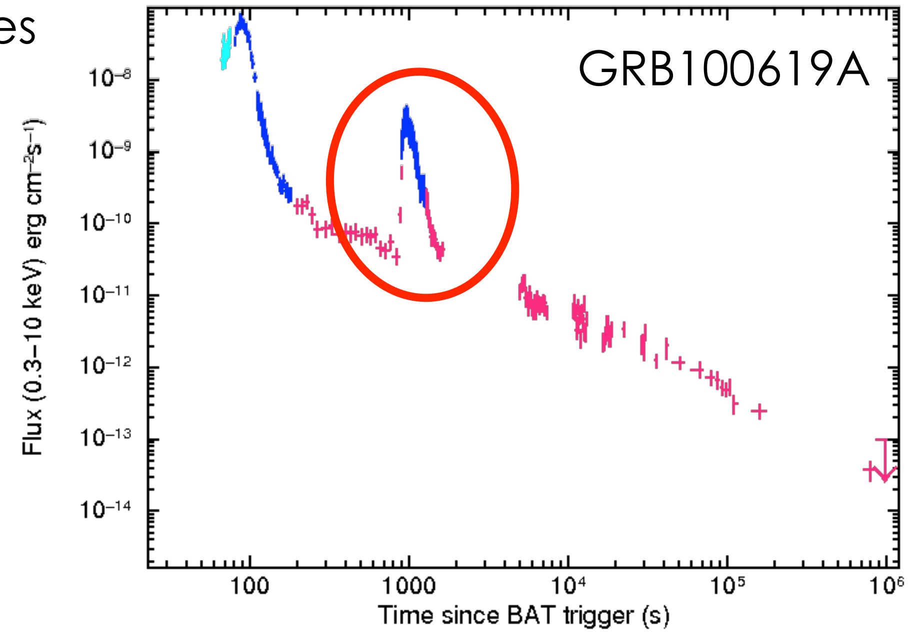


(Swift XRT catalog)

Swift: (3) Flares

- X-ray flares are found at early or late times
  $\Delta t/t \sim 0.1$



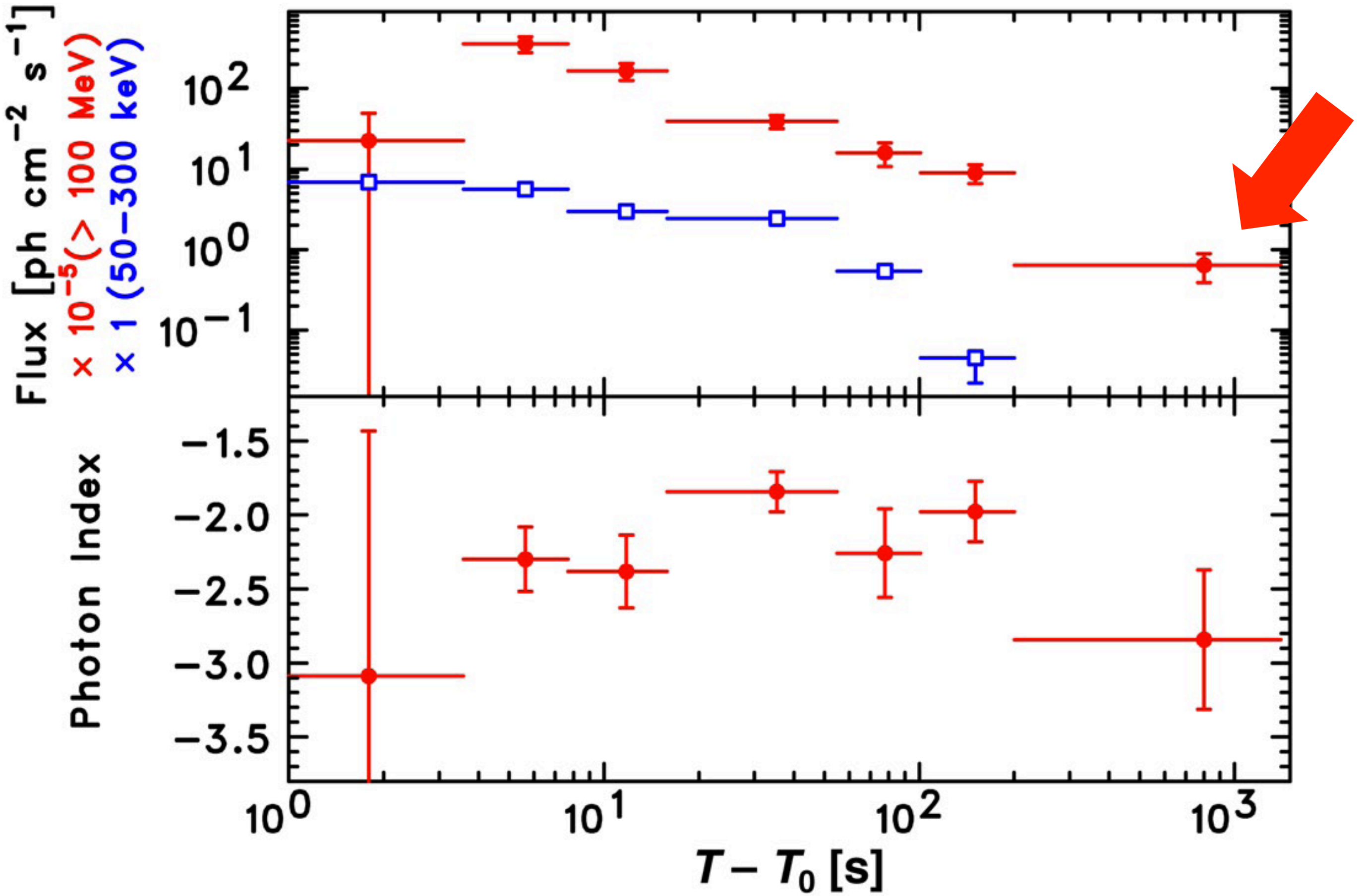


(Swift XRT catalog)

-Flares cannot be explained by the forward shock
-late internal shocks ?
-variability in the reverse shock ?

Fermi: long lasting emission in the LAT

- A long lasting emission is detected in many cases in the LAT after the end of the GBM emission : high-energy afterglow ?



GRB 080916C (Abdo et al. 2009)

- See also T90 (LAT) vs T90 (GBM) (1st LAT GRB catalog)

Long lasting emission

- **The long lasting emission detected by the LAT is difficult to explain with GRB prompt emission models**

- **High-energy afterglow ?**

  Problem: no simultaneous observations of the early X-ray afterglow by Swift

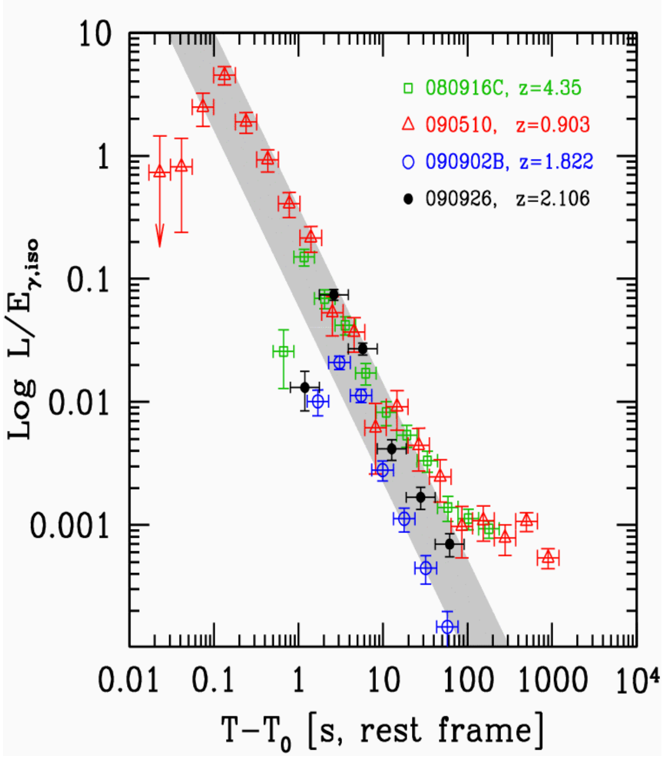
  Where is the X-ray early steep decay ?
  (in the high latitude emission scenario: prompt/afterglow transition)

  Observing the long lasting emission associated with a « standard » early afterglow may help in distinguishing between afterglow models

Long lasting emission

- High-energy afterglow ?

- **An intringuing possibility: may the whole GeV emission be due to the external shock ?**
(Kumar & Barniol Duran 2009, 2010 ; Gao et al. 2009 ; Corsi, Guetta & Piro 2010 ; de Pasquale 2010; Ghisellini et al. 2010 ; Ghirlanda et al. 2010 ; ...)



Ghisellini et al. 2010

Long lasting emission

- High-energy afterglow ?

- **An intringuing possibility: may the whole GeV emission be due to the external shock ?**

(Kumar & Barniol Duran 2009, 2010 ; Gao et al. 2009 ; Corsi, Guetta & Piro 2010 ; de Pasquale 2010; Ghisellini et al. 2010 ; Ghirlanda et al. 2010 ; …)

- **Possible issues with the forward shock model for the long lasting LAT emission:**

-afterglow must be in radiative regime pair enrichment ?
(see e.g. Beloborodov 2002)– works only for bright GRBs ?
– alternative model for LAT emission (Beloborodov et al. 2013)

-needs $\Gamma > 1000$ (independent from $\gamma\gamma$ constraint)

-exceeds maximum energy of synchrotron ?
(Piran & Nakar 2010)

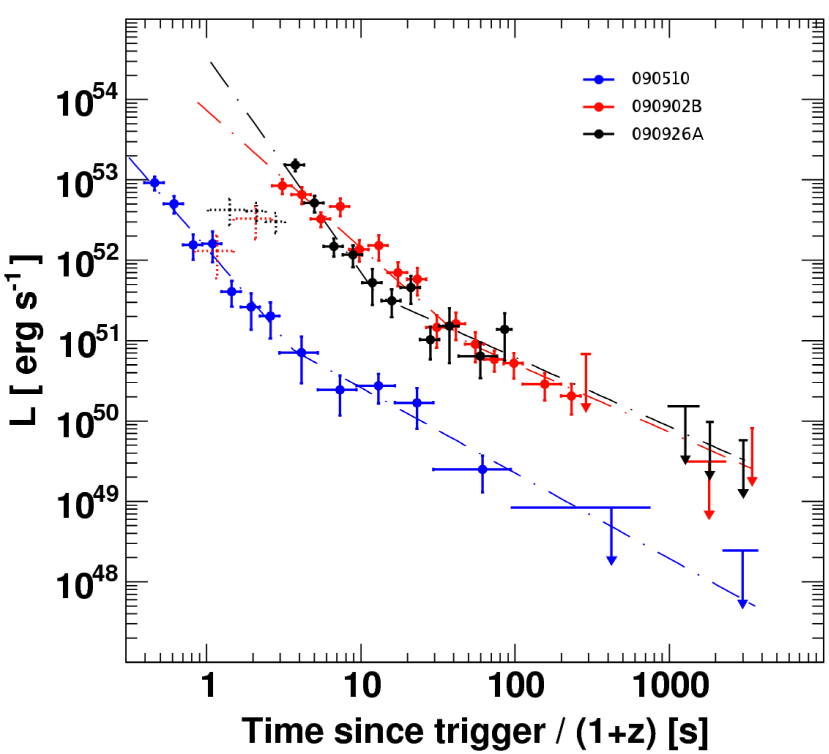
-needs very low density and magnetization in the external medium (Kumar & Barniol Duran 2009)

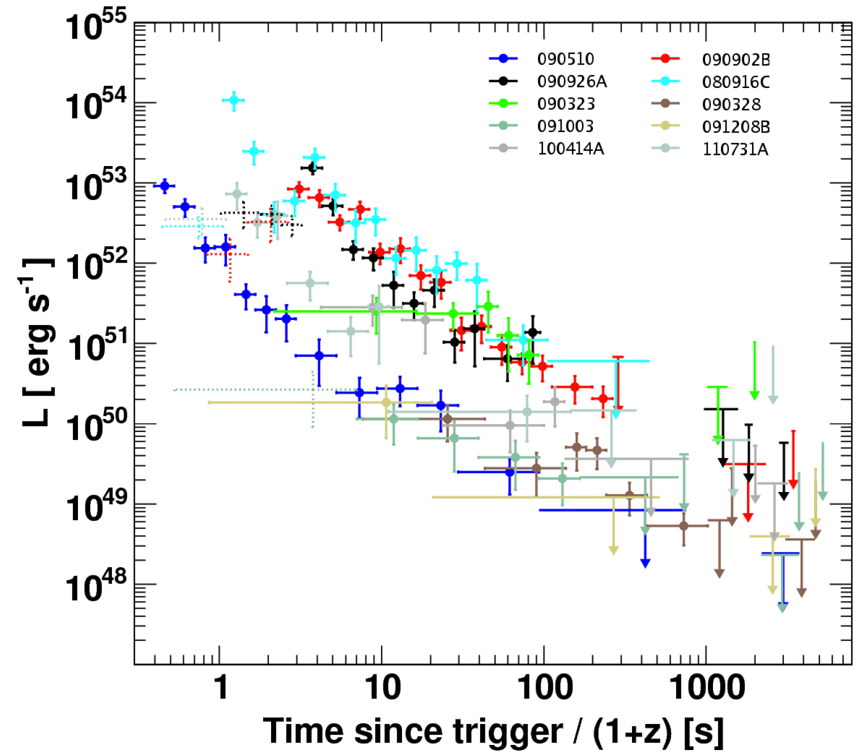
] Solved by taking into account a realistic microphysics at the shock ? (Lemoine 2012)

- **A possible test ?** Variability in GeV lightcurve

Long lasting emission

- Prompt to afterglow transition ?





First Fermi LAT GRB Catalog (2013)

GRB afterglow models

- **Standard scenario:** Forward (external) shock
- **Dynamics is known:** analytic + simulations
- **Microphysics is unknown:** ε_e, ε_B, …
- **Radiation can be easily computed:** synchrotron dominant

- ***Swift*:** many new unexpected features (plateaus, flares, chromatic breaks, …)
- ***Fermi***: long lasting emission in the LAT
- **No clear signature for the jet opening angle (especially for short GRBs)** : search for orphan afterglows ?

Current ideas:

- **Playing with the dynamics ?**
  - Late energy injection: energy crisis ? (plateaus)
  - Large Lorentz factors ? (LAT emission)
  - Long-lived central engine ?(plateaus or flares)
- **Playing with the microphysics ?**
  - Varying microphysics ? (plateaus, chromatic breaks)
  - Inefficient early forward shock ? (plateaus, flares, … : long lived RS model)
- **Mixing internal and external emission ?**
  - e.g. scatterings of prompt photons by shock accelerated e^- at FS

The case of short GRBs

- Small sample, e.g. recent study by Rowlinson et al. 2013

All Swift short GRBs (T_{90}<2s) with an early XRT observation before May 2012 :

43 events → 10 with a redshift (z = 0.111 to 2.6)
→ 13 have an identified host galaxy
→ 18 have T_{90} > 0.5 s [to compare to typical duration = 100 ms]
→ only 5 have T_{90} < 0.1 s [to compare to typical duration = 100 ms]

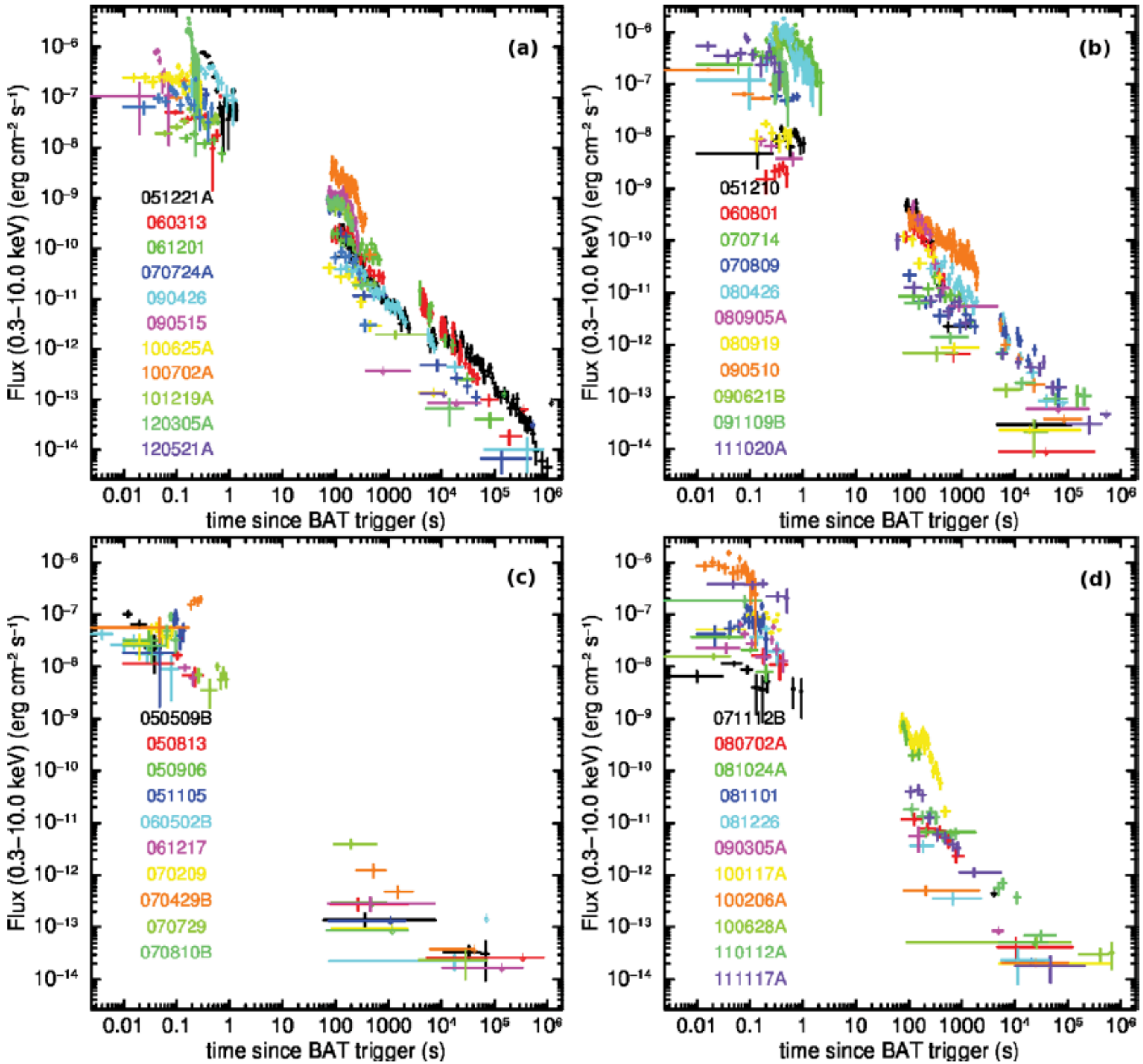
= long short GRBs

The case of short GRBs

X-rays

Some have bright AG with breaks (plateaus,…)

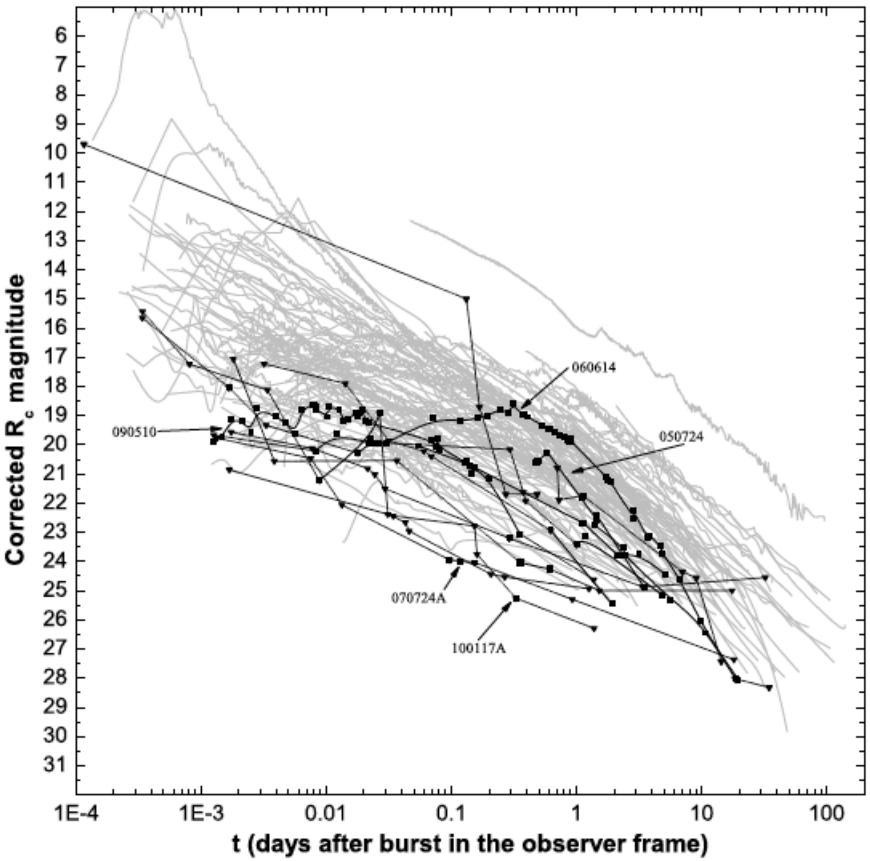
Some have very faint AG



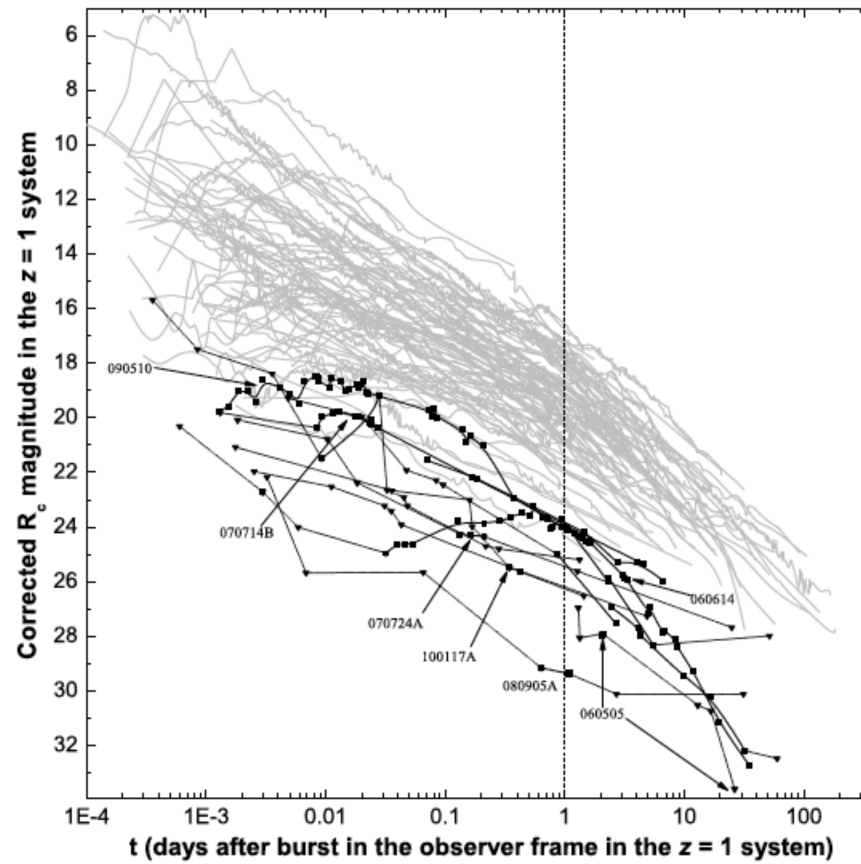
Rowlinson et al. 2013

The case of short GRBs

Optical : faint afterglows, compatible with lower E_{kin} + lower external density



Observer frame



Rest frame

Kann et al. 2011

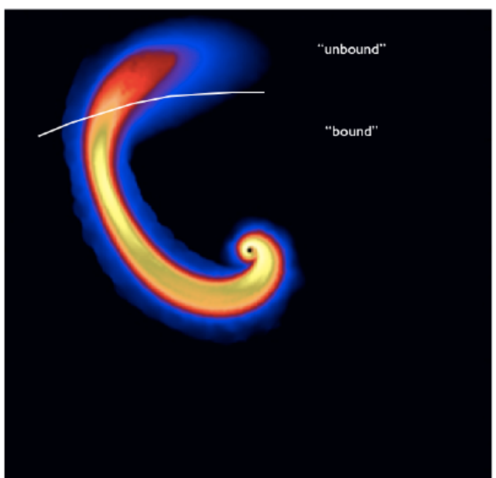
A new puzzle : extended soft X-ray tail

- Some short GRBs have a long X-ray tail

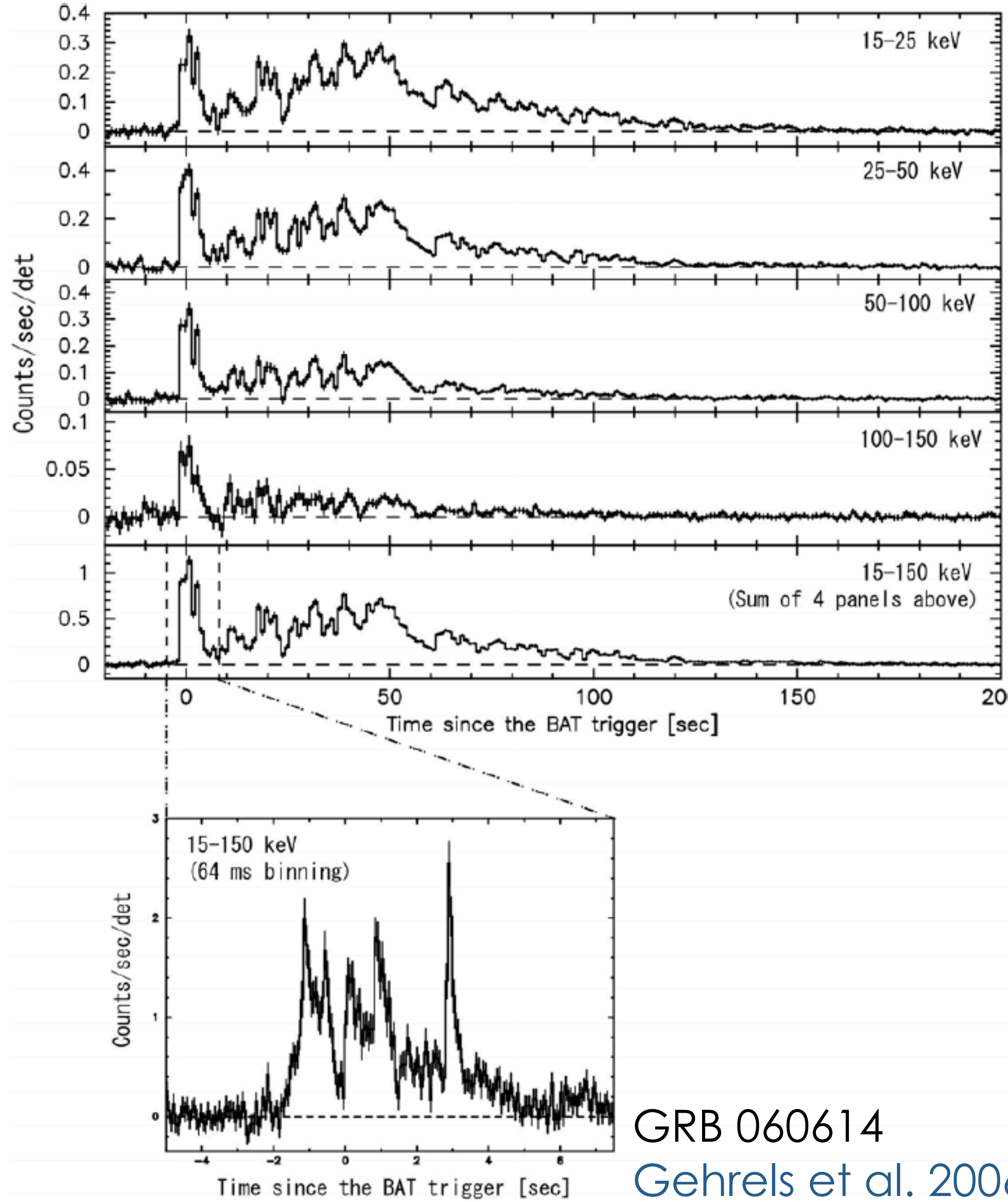
Prompt or afterglow ?

Prompt is preferred (variability)

In the merger scenario : tidal trails ? Enough mass ?



- Observed in 1/3 of Rowlinson'sample

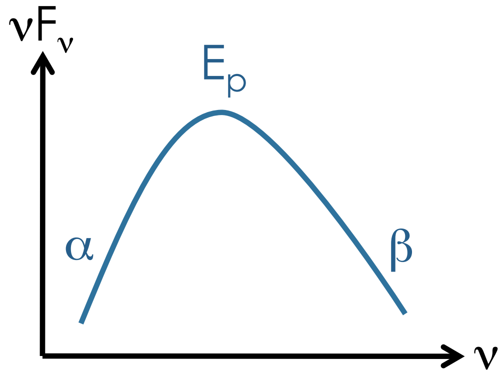


GRB 060614
Gehrels et al. 2006

8– Prompt emission models

Pre-*Fermi* status

- BATSE catalog : more than 2500 GRBs observed between 25 keV and 1 MeV
- Above 1 MeV : only rare and incomplete detections by EGRET
- Below 25 keV : -detections in X-rays (Beppo-SAX, HETE2)
  -a few detections in the optical (1st GRB : GRB 990123)



- Lightcurves are well characterized
- Spectrum is non thermal and fit by the « Band » function
- Spectral evolution is observed

- No strong differences between short and long GRBs, except for timescales
  Short GRBs are usually harder.

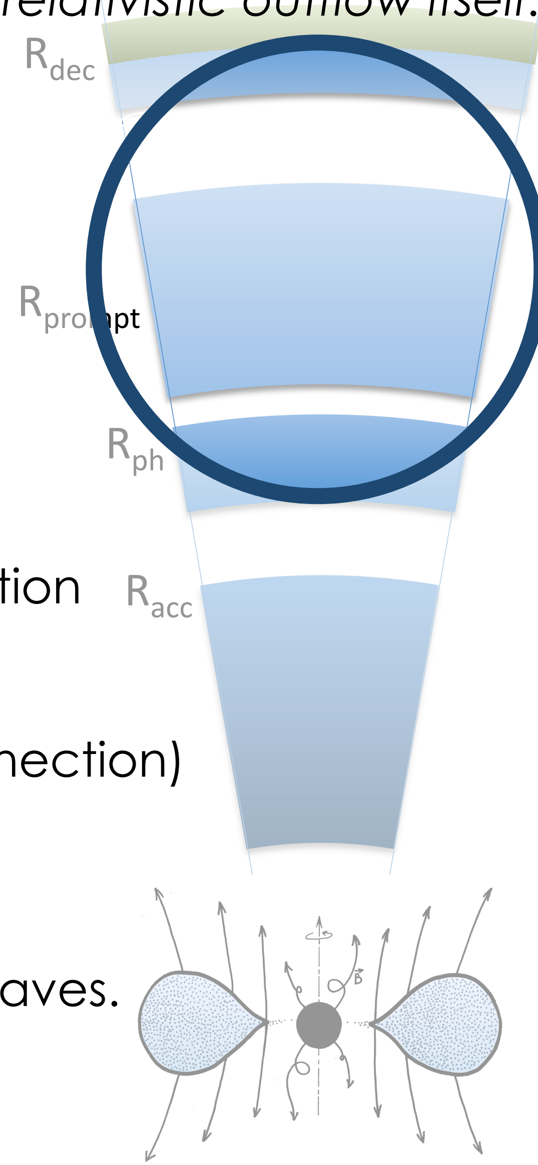
Prompt emission

*Short timescale variability is difficult to explain with the external shock. Therefore, the **prompt** emission must have an internal origin, i.e. be produced from dissipative processes within the relativistic outflow itself.*

Possible energy reservoirs and extraction mechanisms :

- Thermal energy
  Photospheric emission
- Kinetic energy
  Internal shocks + shock acceleration
- Magnetic energy
  Magnetic dissipation (e.g. reconnection)

Note that a large magnetization probably exclude internal shock waves.



Energy reservoir & extraction mechanism ?

Microphysics ?

Radiative processes ?

Matter dominated vs magnetic outflow ?

Thermal emission ?
Shock waves ?
Reconnection ?

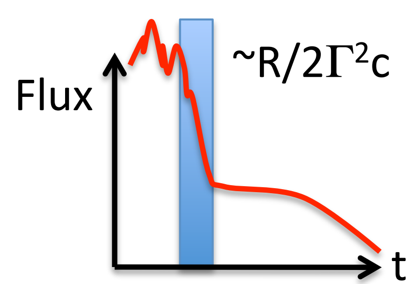
Synchrotron ? IC ? …

Prompt emission

- 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 ; Aoi et al. 10 ; Zou et al. 10 ; Hascoët et al. 2011)

- Radius :
  -$R_{prompt,start} < 6.10^{11}\ (\Gamma/100)^2$ cm (short time scale variability)
  -$R_{prompt,end} > 6.10^{15}\ (\Gamma/100)^2$ cm (early X-ray steep decay, *Swift*/XRT)
  (Lyutikov 06; Lazzati & Begelman 06; Kumar et al. 07; Genet & Granot 09, Hascoët, Daigne & Mochkovitch 12)
  -another constraint: $R_{prompt} < R_{dec}$

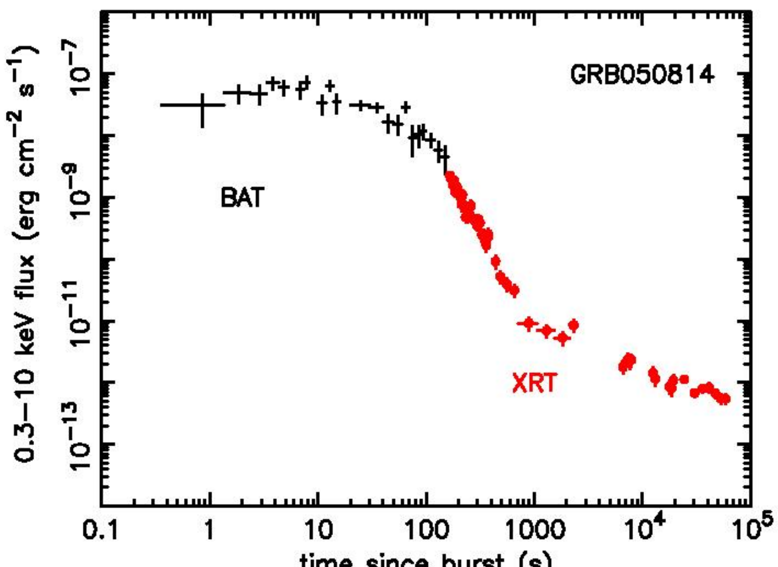


Prompt emission: The End

Due to the curvature of the emitting surface, the « internal » activity of the outflow should not stop instantaneously : the observed flux decays as the observer detects photons emitted at larger (co-)latitudes (these photons are less and less Doppler-boosted).

- Bolometric flux decays as t_{obs}^{-3}
  (or steeper if anisotropic emission, Beloborodov, Daigne et al. 2010)
- Predict a X-ray tail at the end of the prompt (Kumar & Panaitescu 2002)
- Observed by Swift ?
- Constrains the radius at the end of the prompt emission

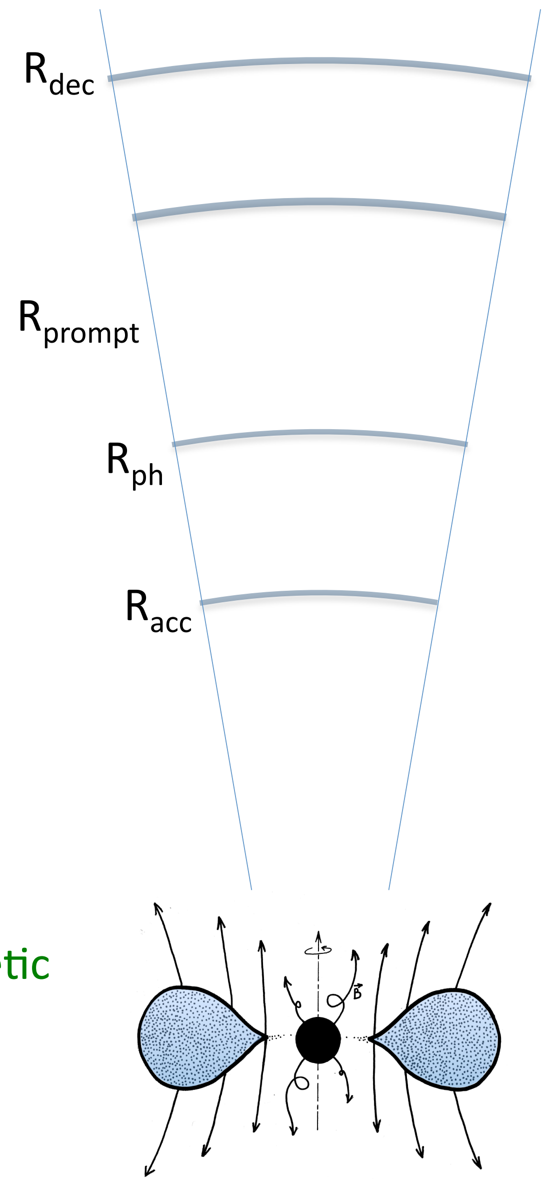
$$R_\gamma \simeq R_* = 6 \times 10^{15}\,(t_{\rm burst}/10\ {\rm s})\,(\Gamma/100)^2\ {\rm cm}.$$

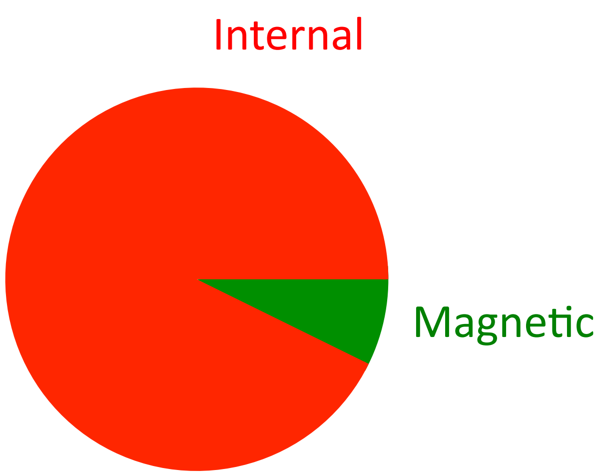


O'Brien et al.

Standard fireball

Or weakly magnetized fireballs



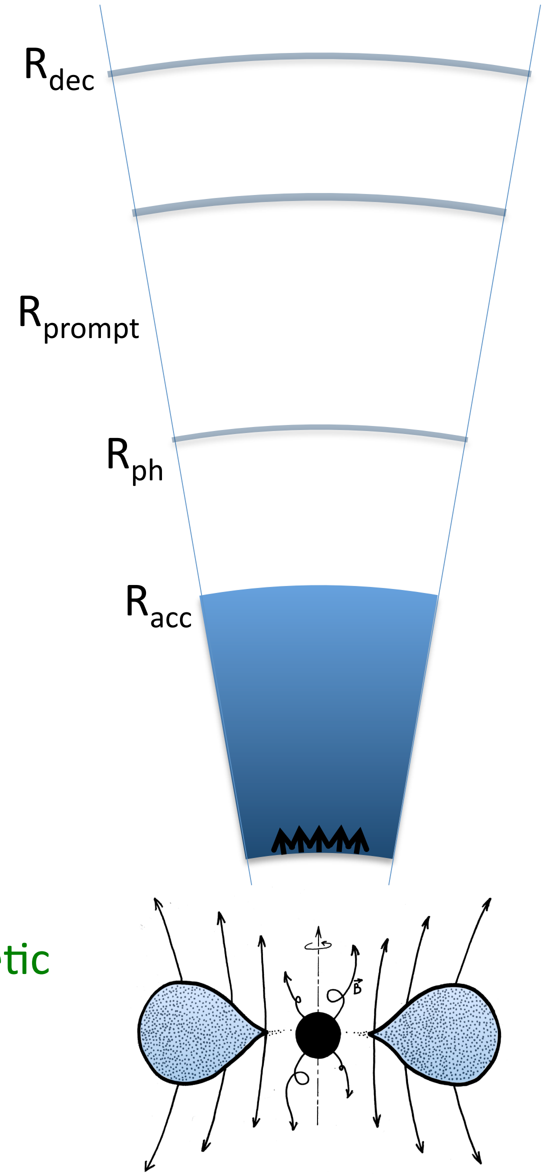


Energy content

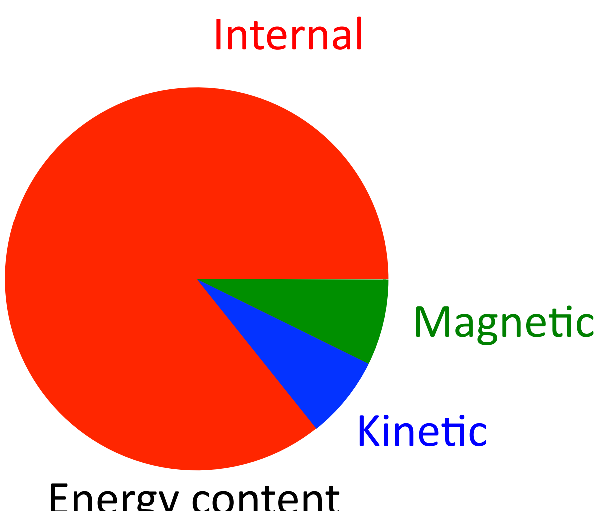
Initial energy release :
negligible magnetization

Standard fireball

Or weakly magnetized fireballs

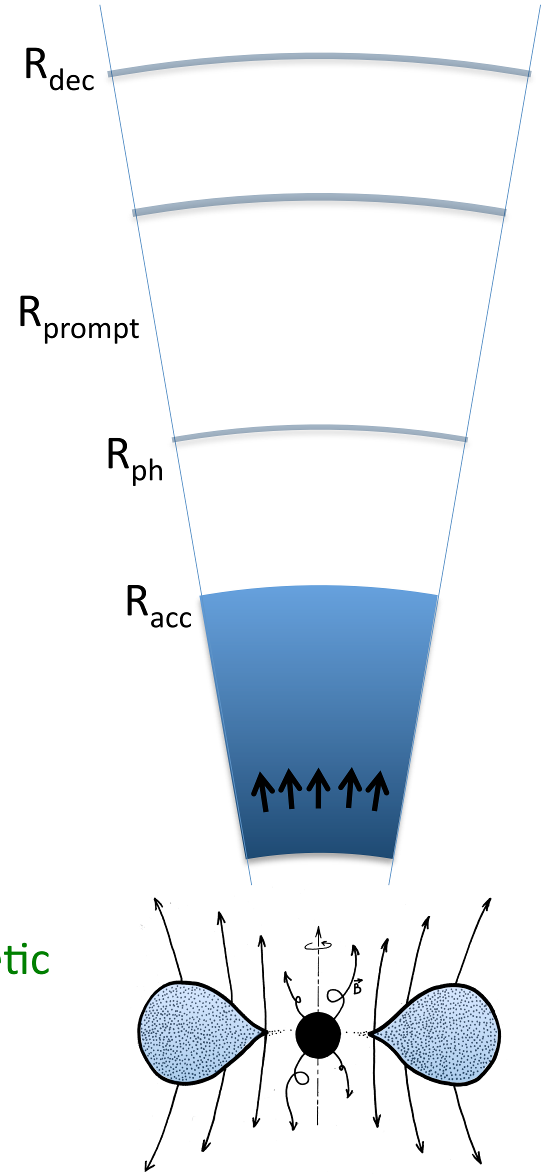


Acceleration :
adiabatic expansion

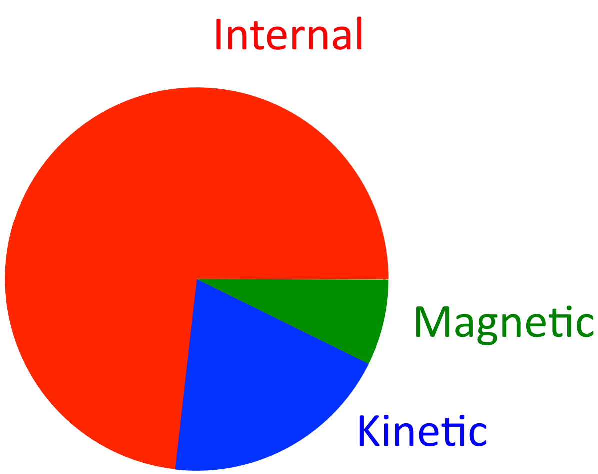


Standard fireball

Or weakly magnetized fireballs



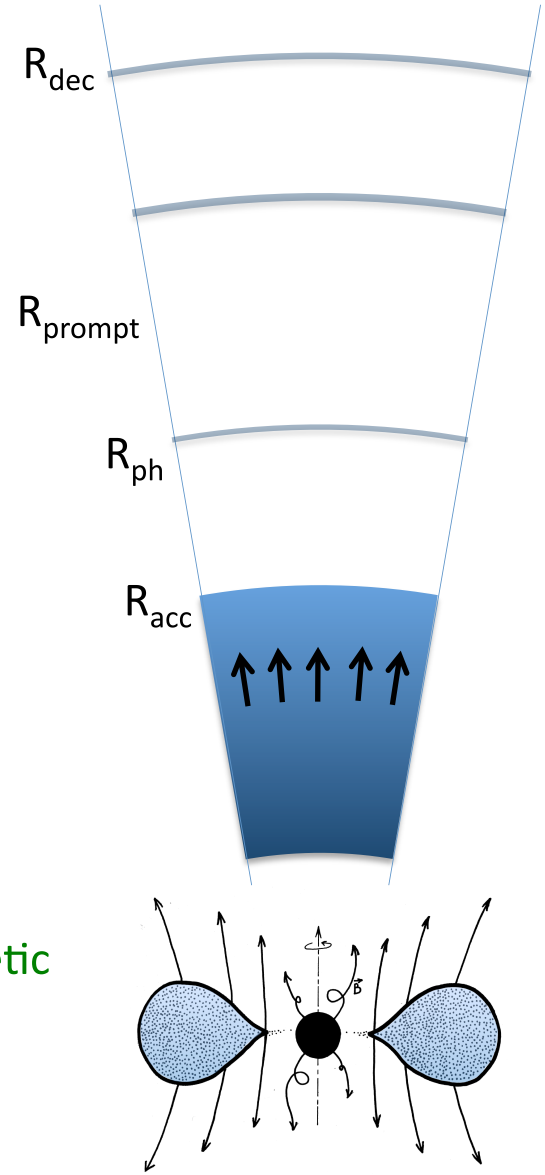
Acceleration :
adiabatic expansion



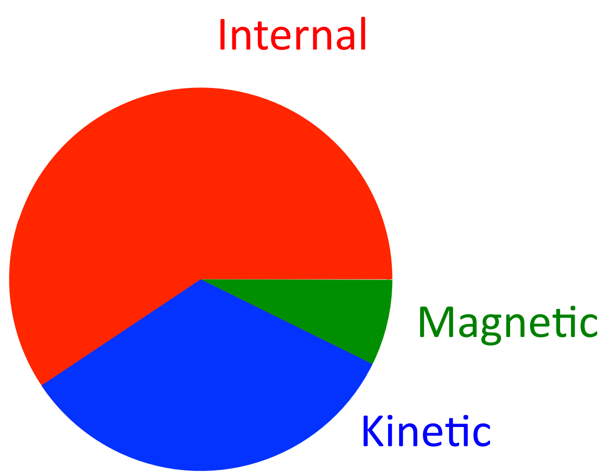
Energy content

Standard fireball

Or weakly magnetized fireballs



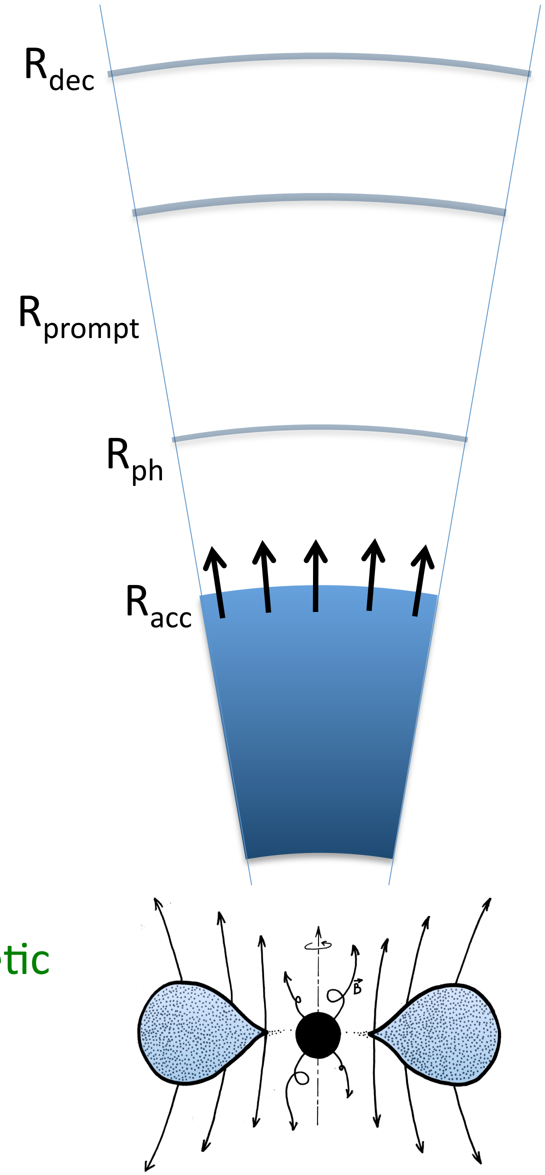
Acceleration : adiabatic expansion



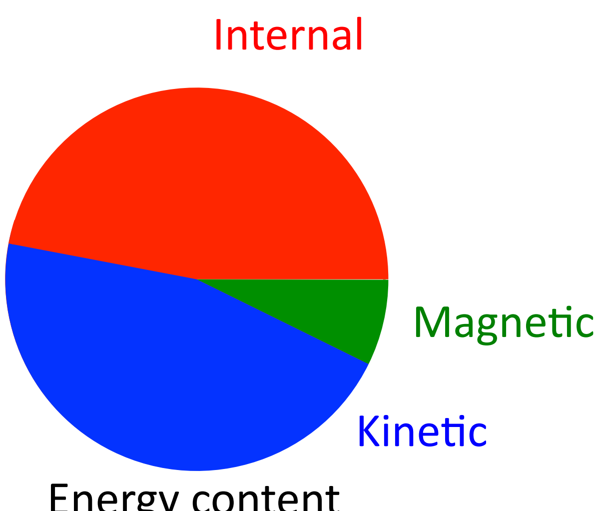
Energy content

Standard fireball

Or weakly magnetized fireballs

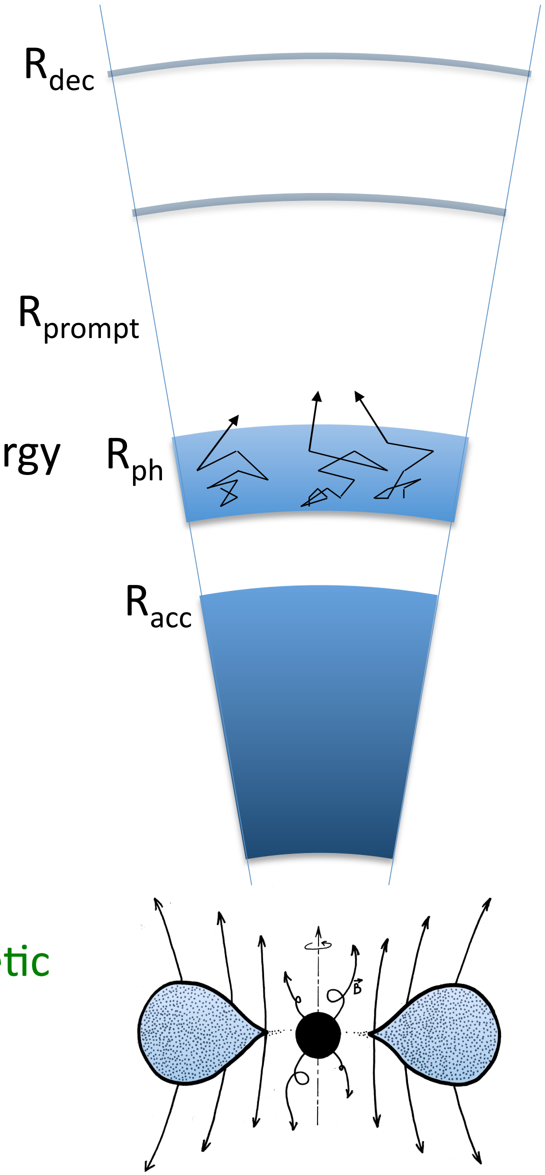


Acceleration :
adiabatic expansion

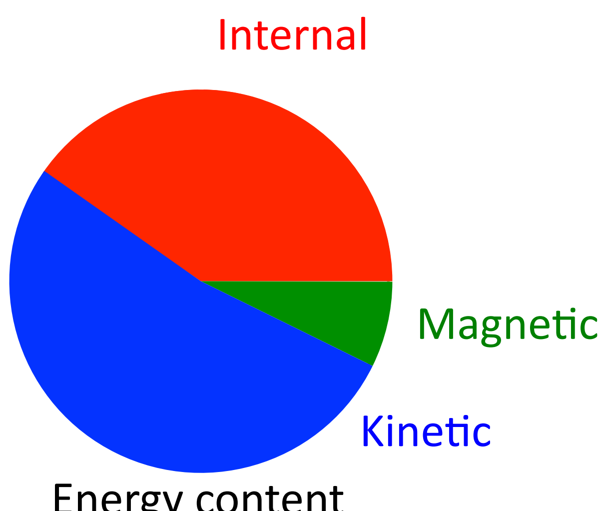


Standard fireball

Or weakly magnetized fireballs



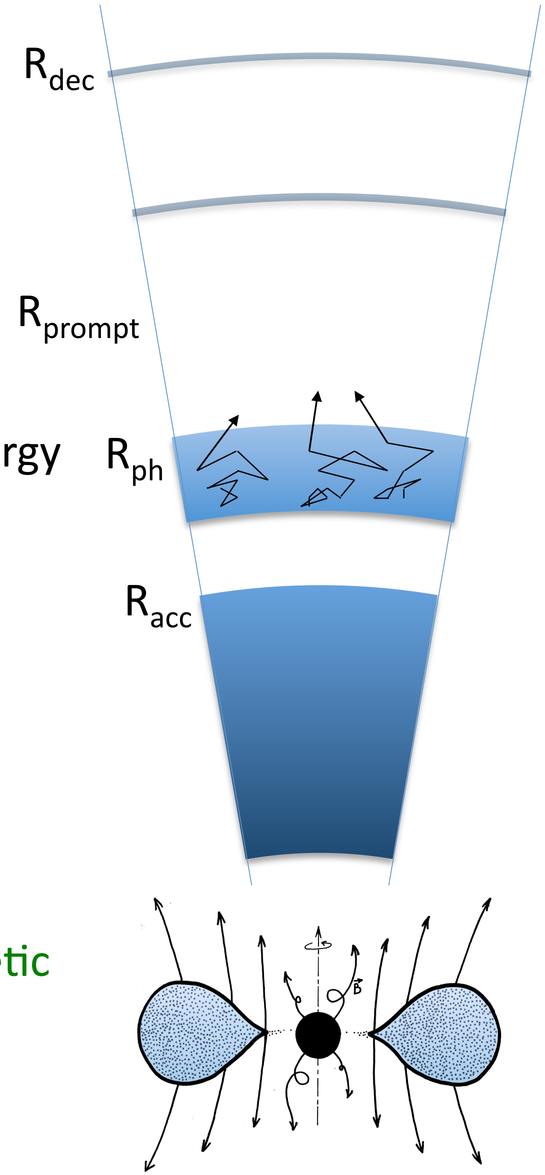
Photosphere : internal energy can be radiated.

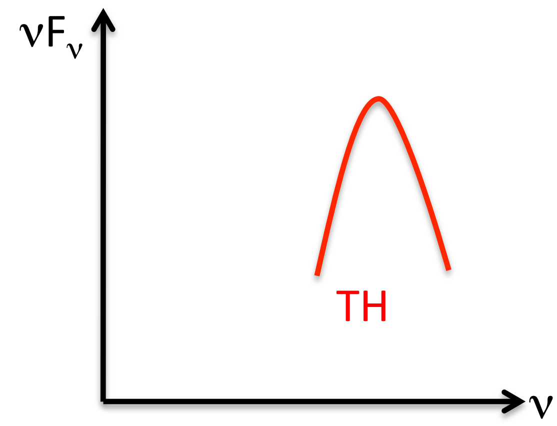


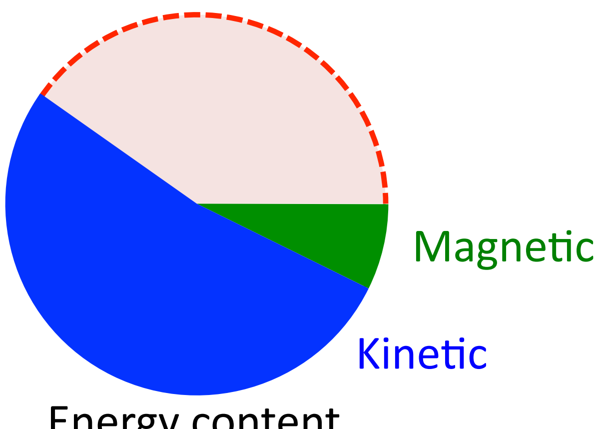
Standard fireball

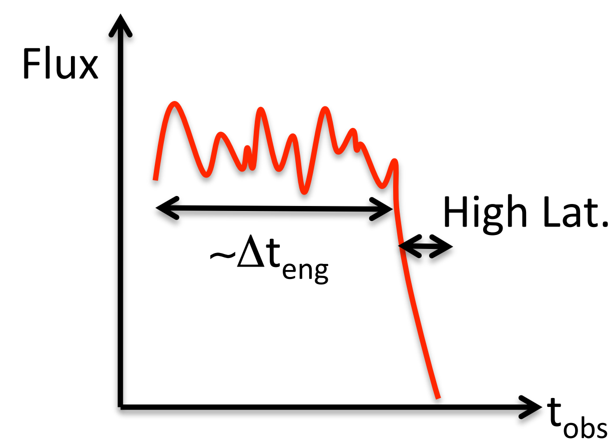
Or weakly magnetized fireballs

Photosphere : internal energy can be radiated.







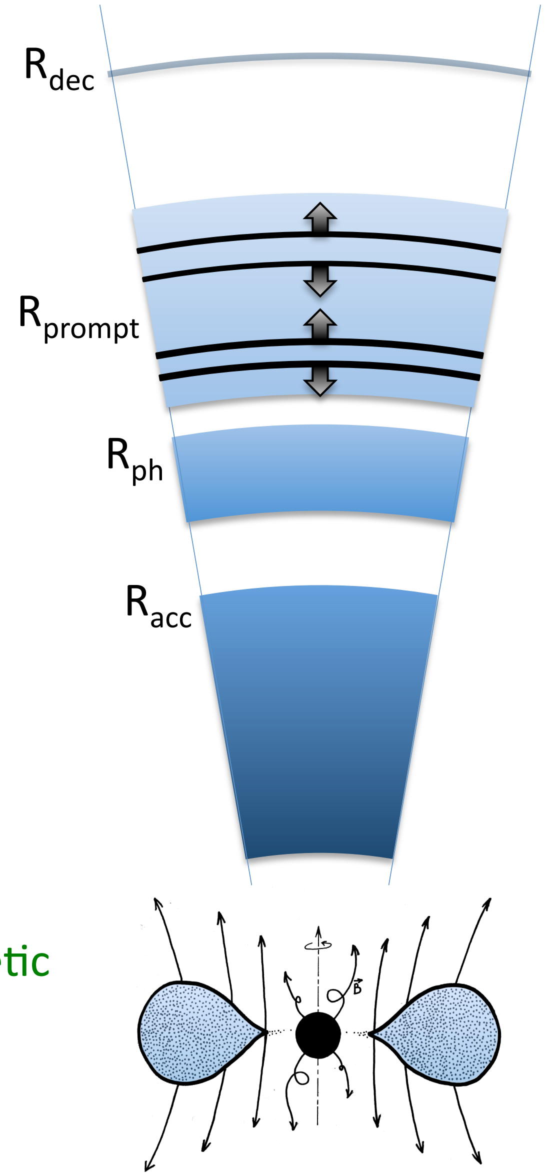


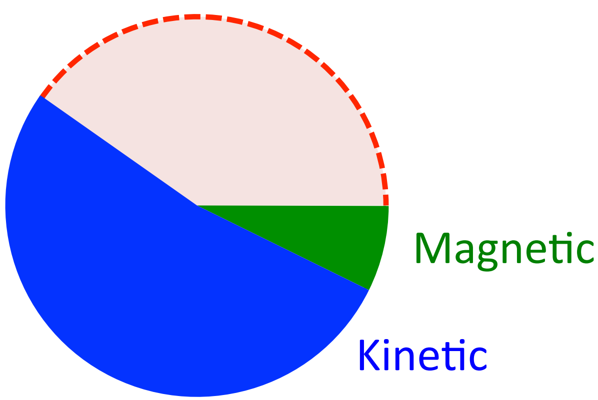
Standard fireball

Or weakly magnetized fireballs

Non-thermal emission :
Internal shocks

A fraction of the kinetic energy is radiated





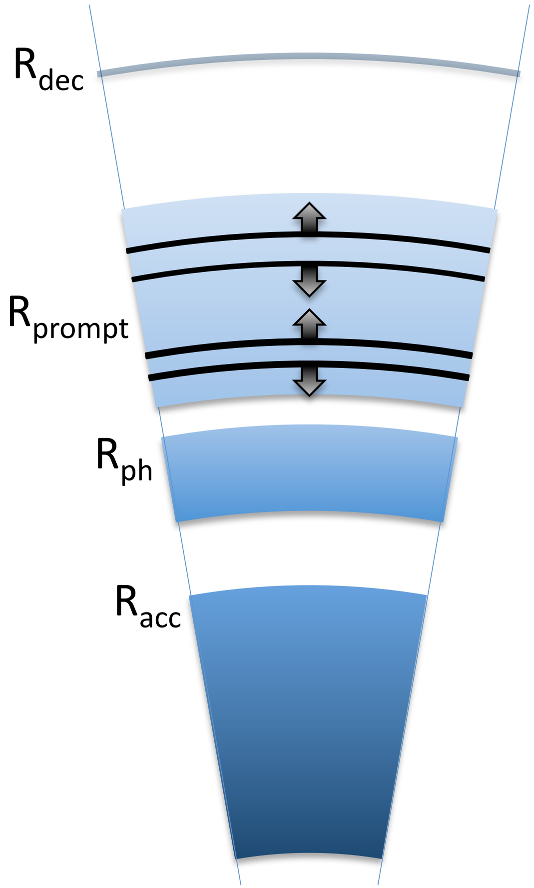
Energy content

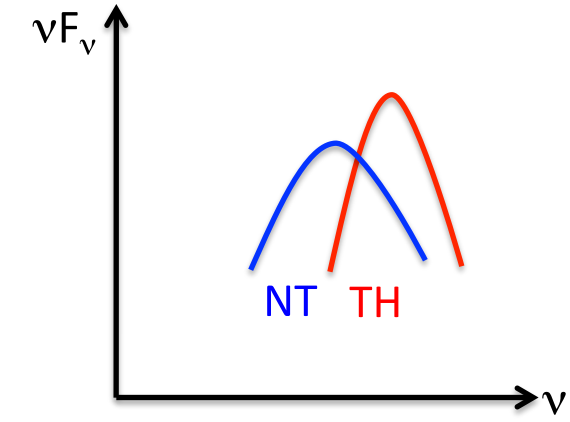
Standard fireball

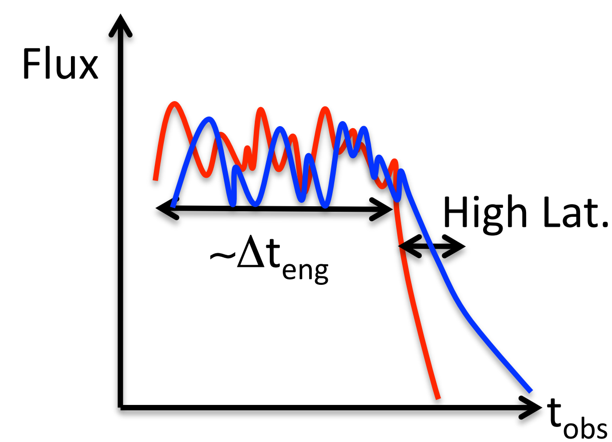
Or weakly magnetized fireballs

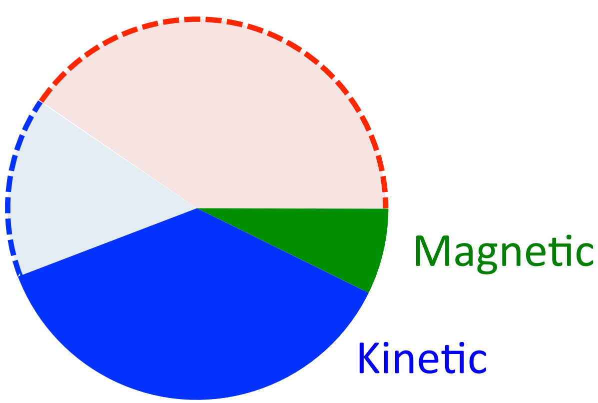
Non-thermal emission :
Internal shocks

A fraction of the kinetic energy is radiated

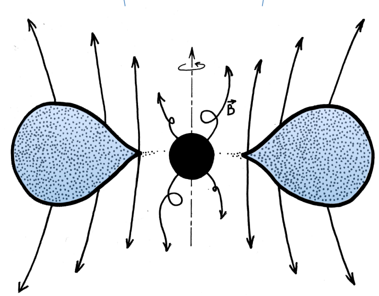






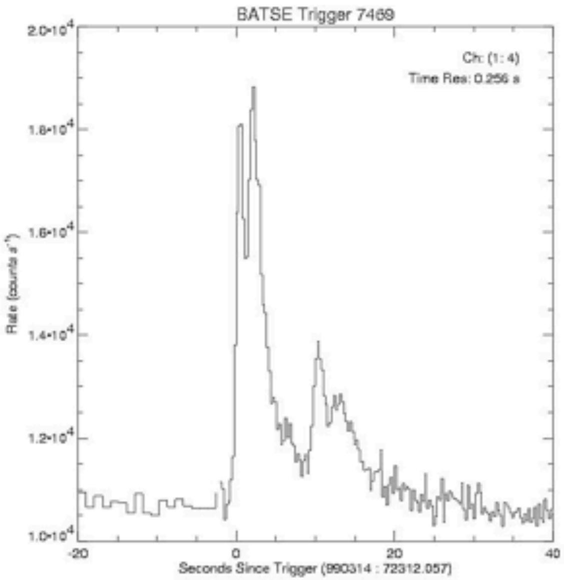


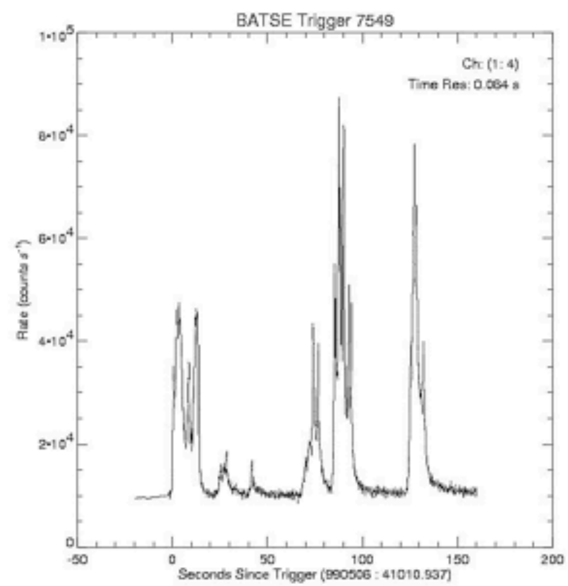
Energy content

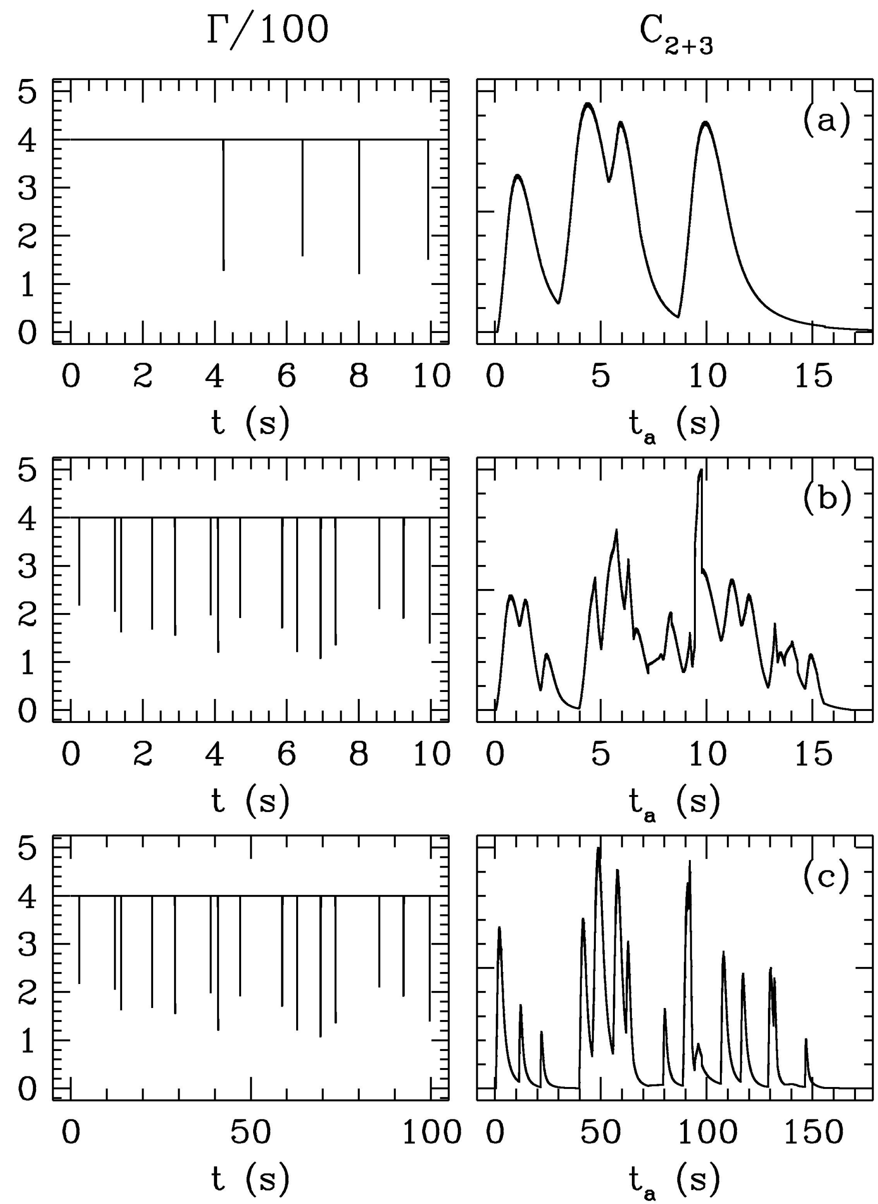


Internal shocks

- Lightcurves, spectral evolution ….





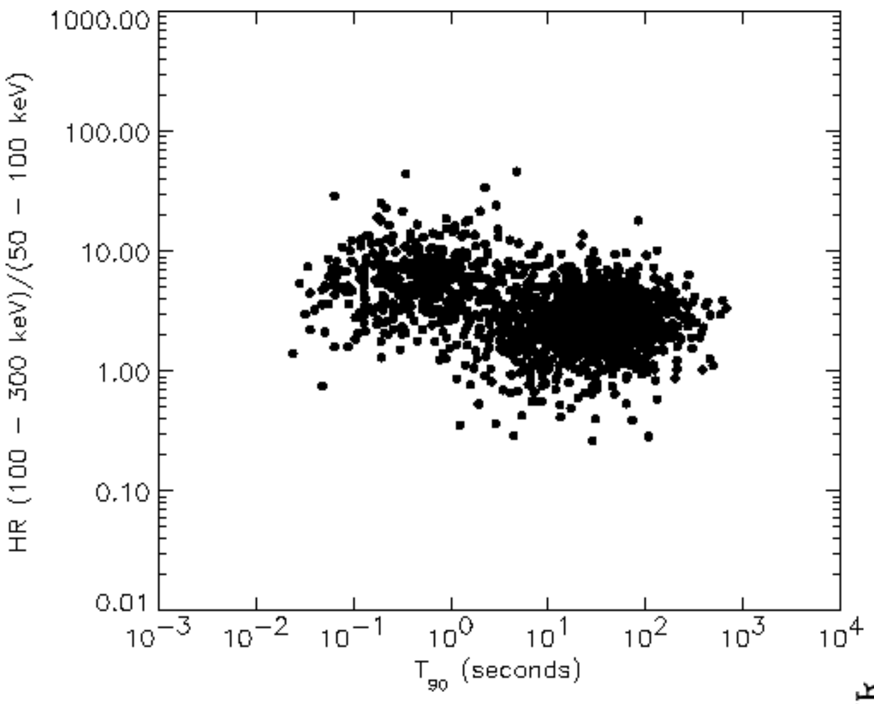


BATSE catalog

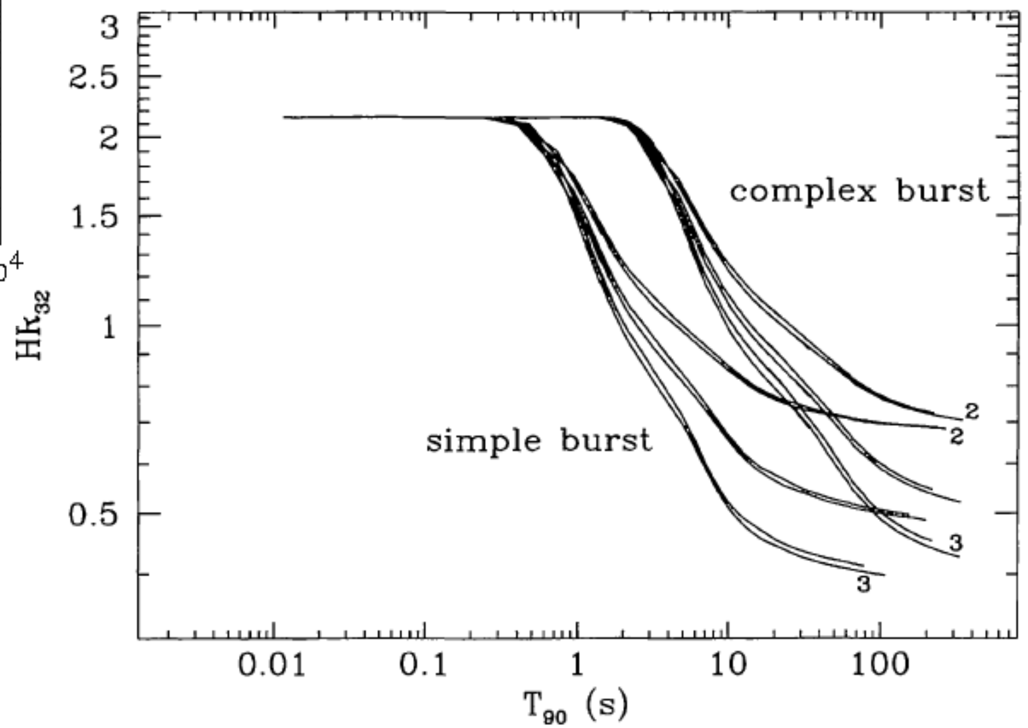
Daigne & Mochkovitch 1998

Internal shocks

- Hardness-Duration



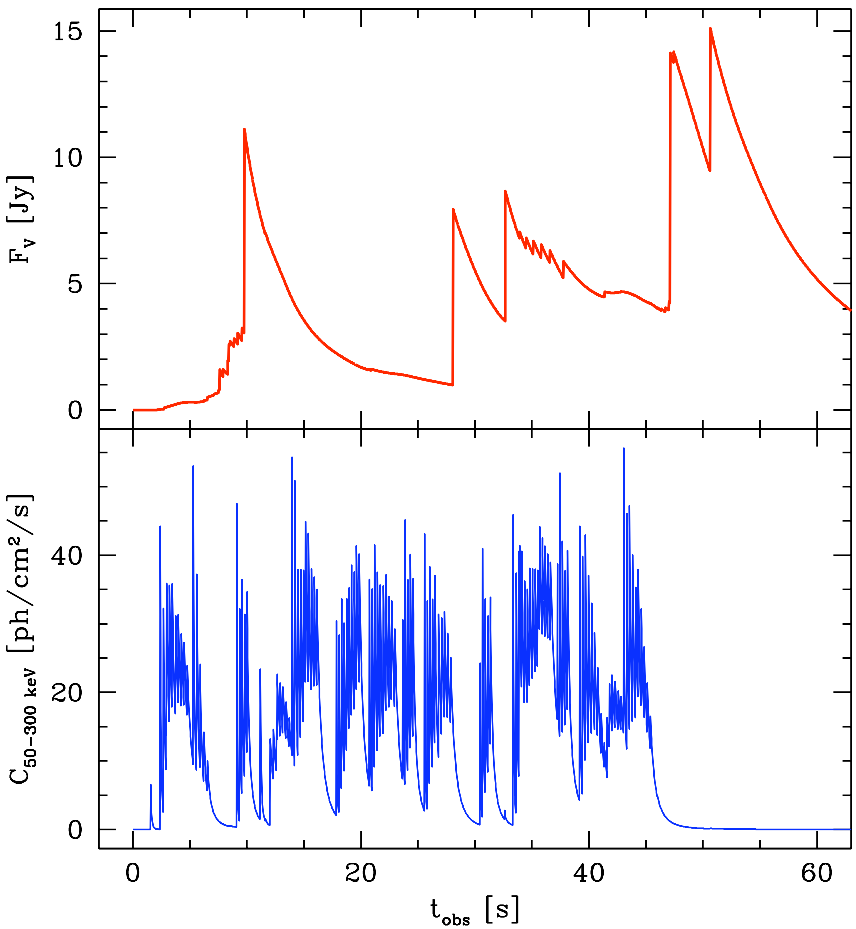
Kouveliotou et al. 1993



Daigne & Mochkovitch 1998

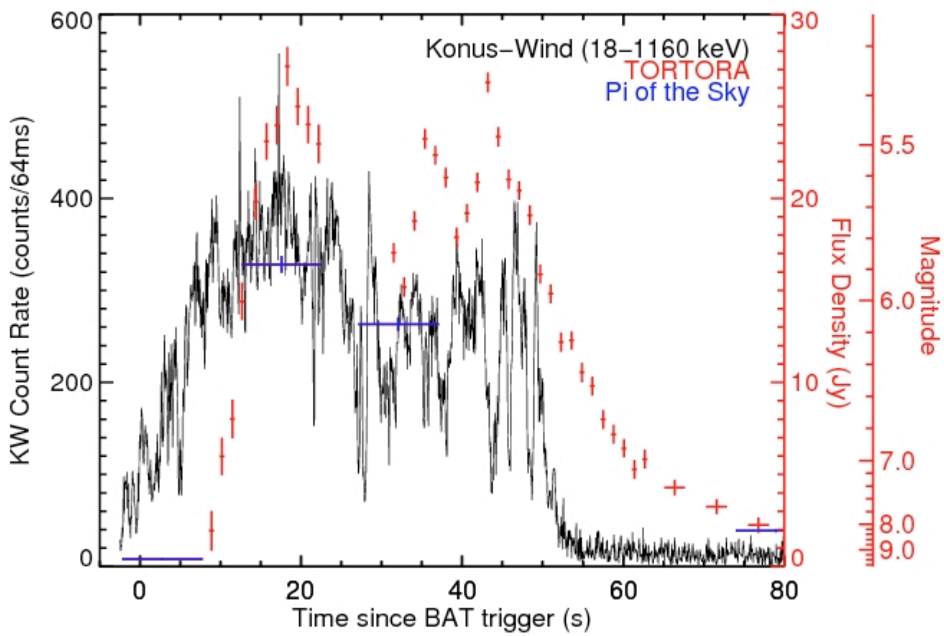
Internal shocks

- Prompt optical emission



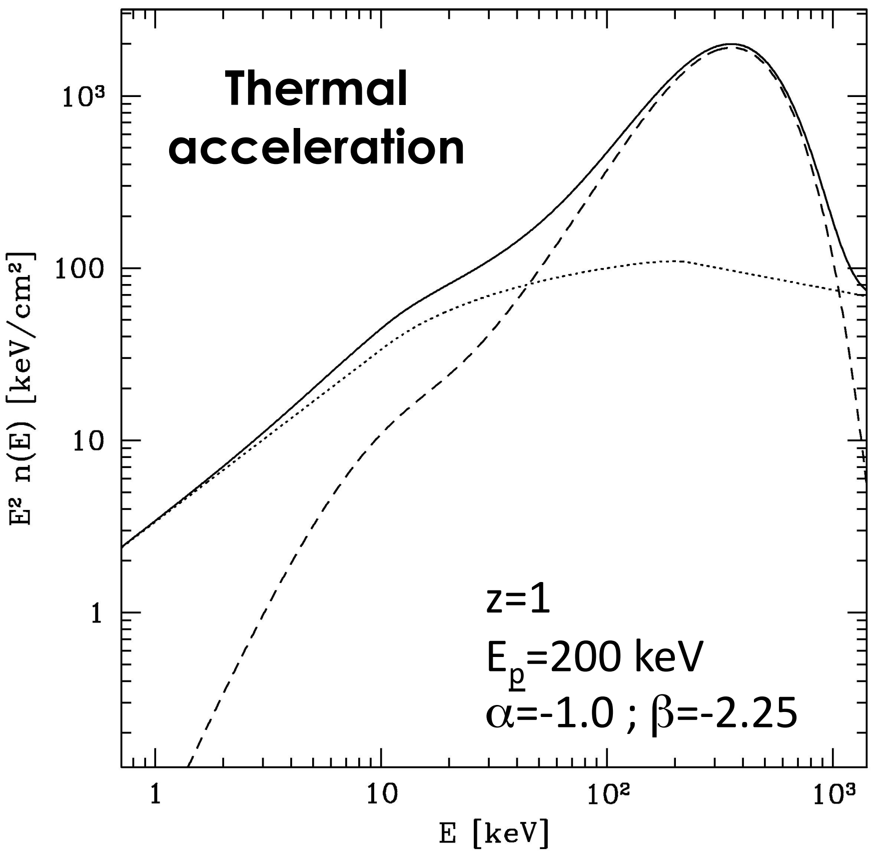
(Hascoët et al. 2011;
see also Li & Waxman 2008)

GRB 080319B @ z = 0.937



(Racusin et al. 2008)

Spectrum : photosphere + internal shocks



(Daigne & Mochkovitch 2002)

Standard fireball: prompt emission

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, magnetic field, ...

Standard fireball: prompt emission

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)
  - New *Fermi* results

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

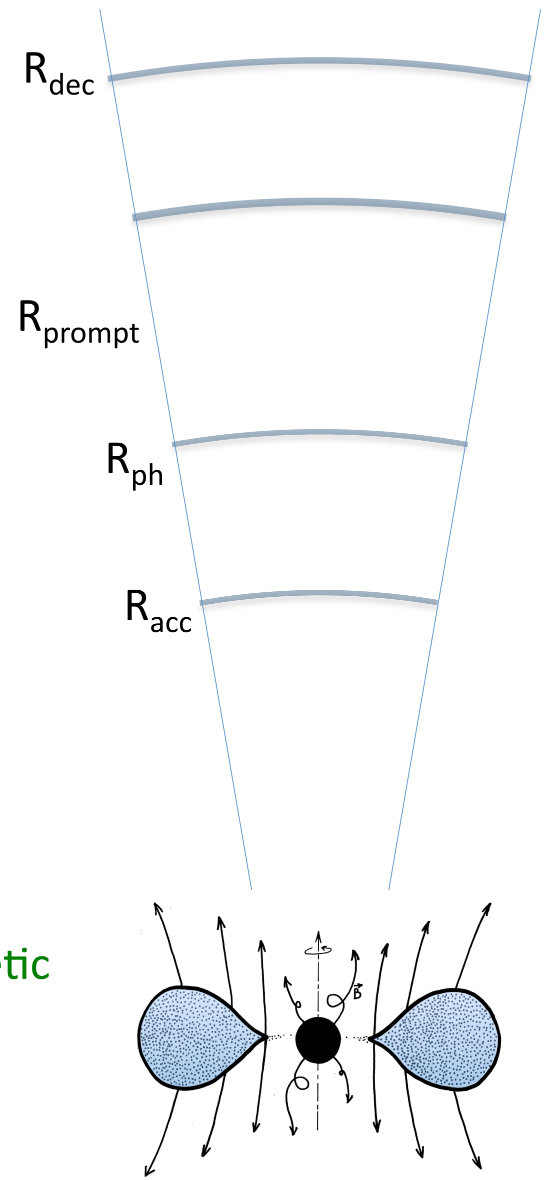
(Usov 92; Thompson 94; Meszaros & Rees 97; Spruit et al. 01; Daigne & Drenkhahn 02; Vlahakis & Königl 03; Giannios & Spruit 06; ...)

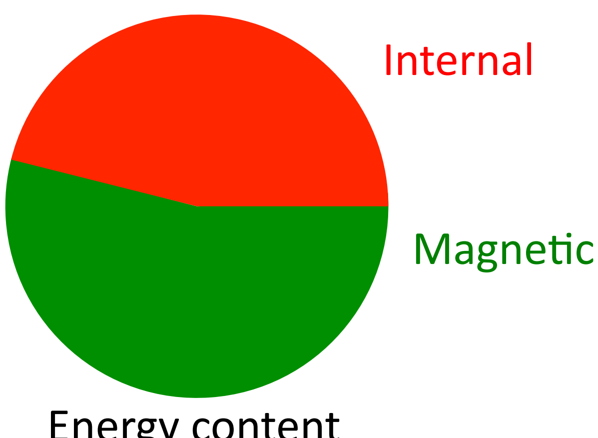
Magnetization : $$\sigma = \frac{\text{Poynting flux}}{\text{Power carried by matter (internal + kinetic)}}$$

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

(Blandford & Lyutikov 03)

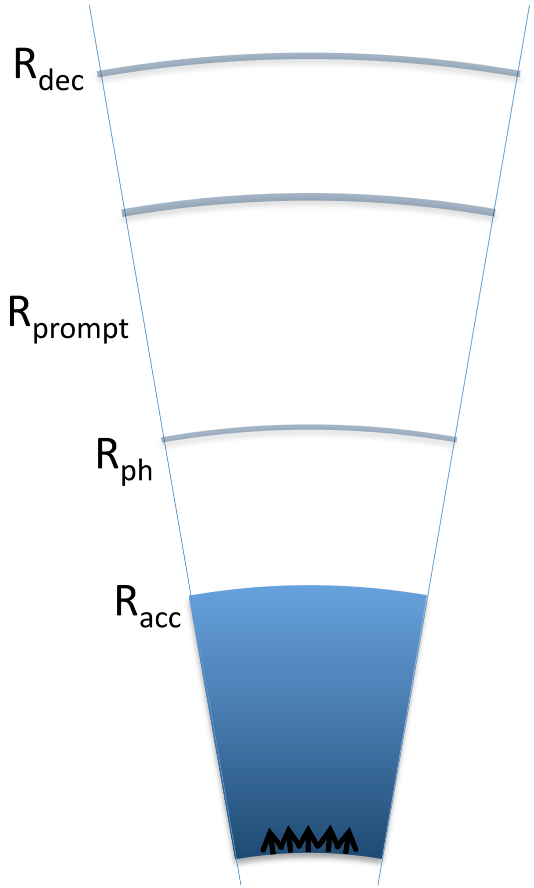
Passive field

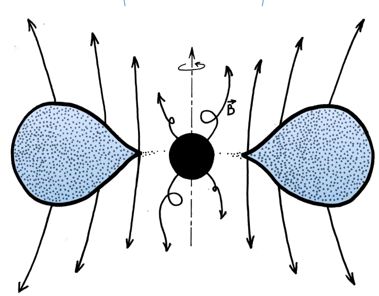




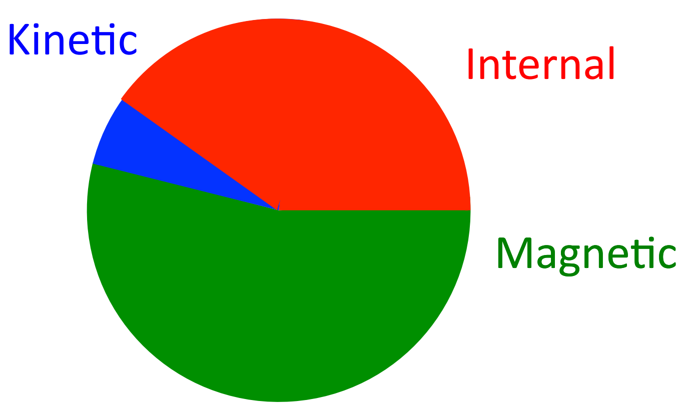
Large magnetization

Passive field



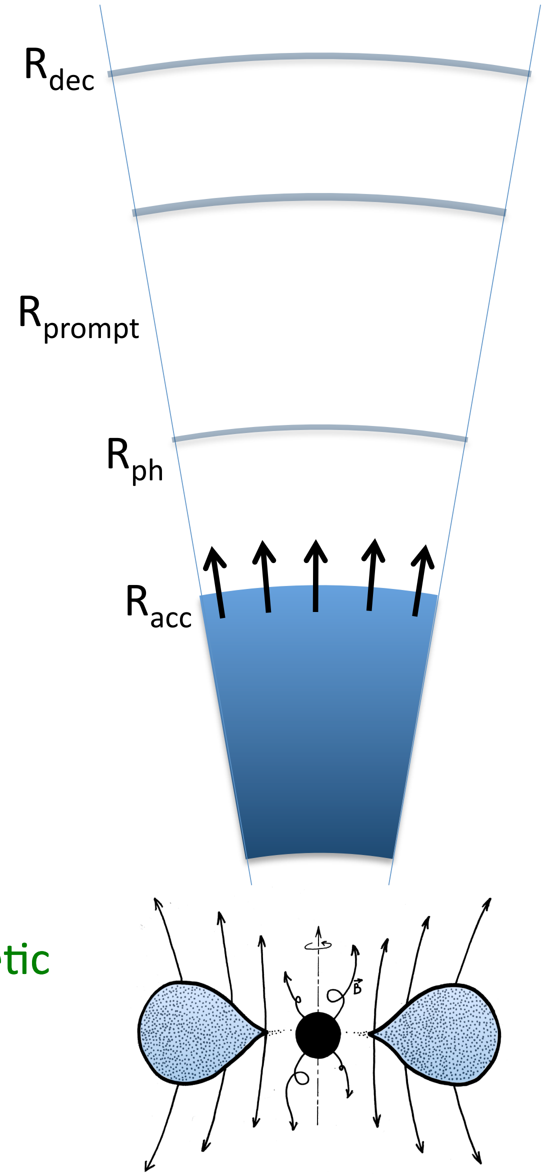


Acceleration : adiabatic expansion

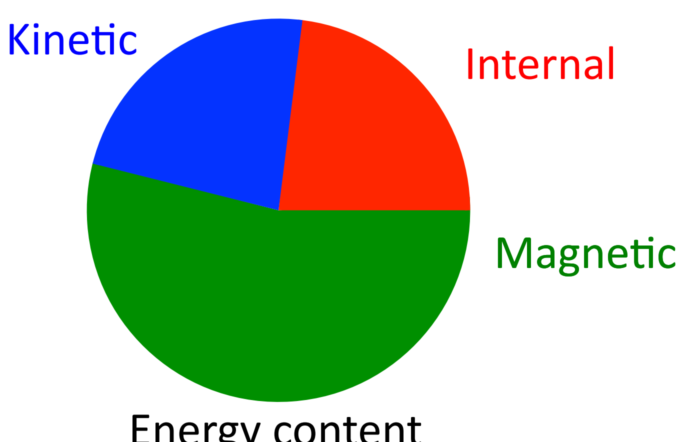


Energy content

Passive field

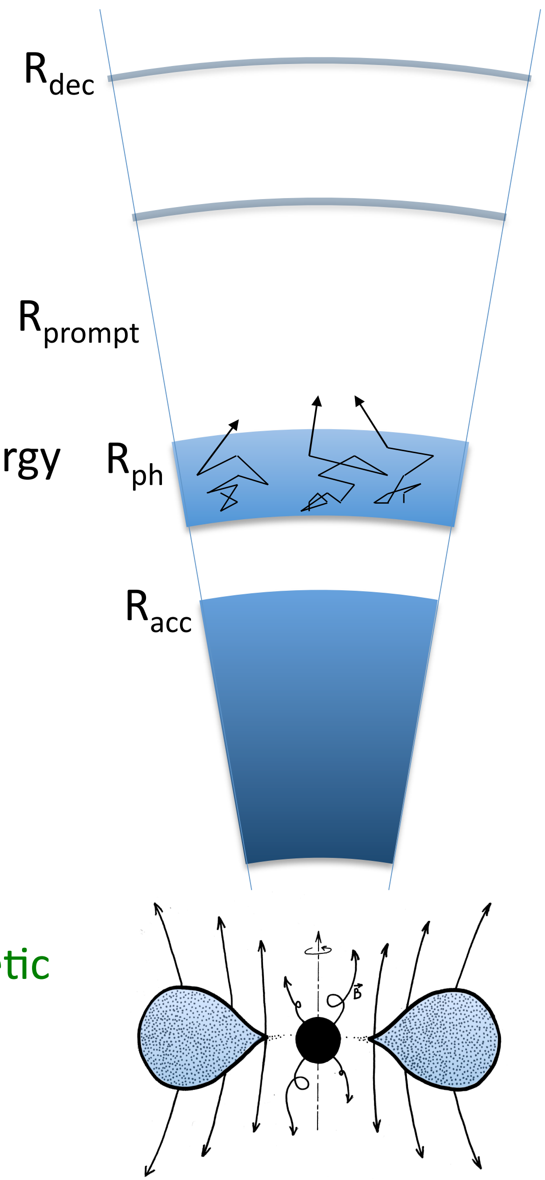


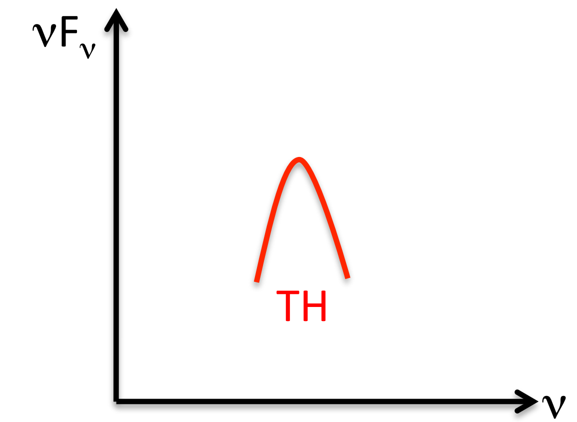
Acceleration :
adiabatic expansion

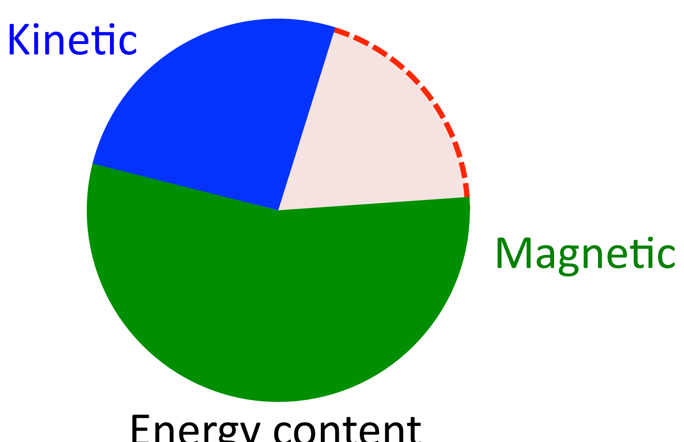


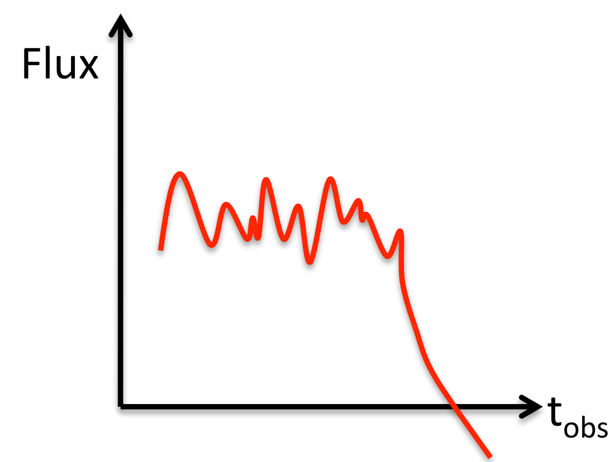
Passive field

Photosphere : internal energy can be radiated.





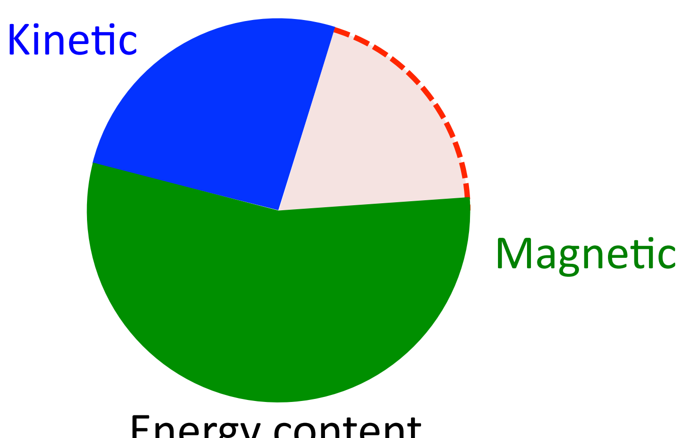


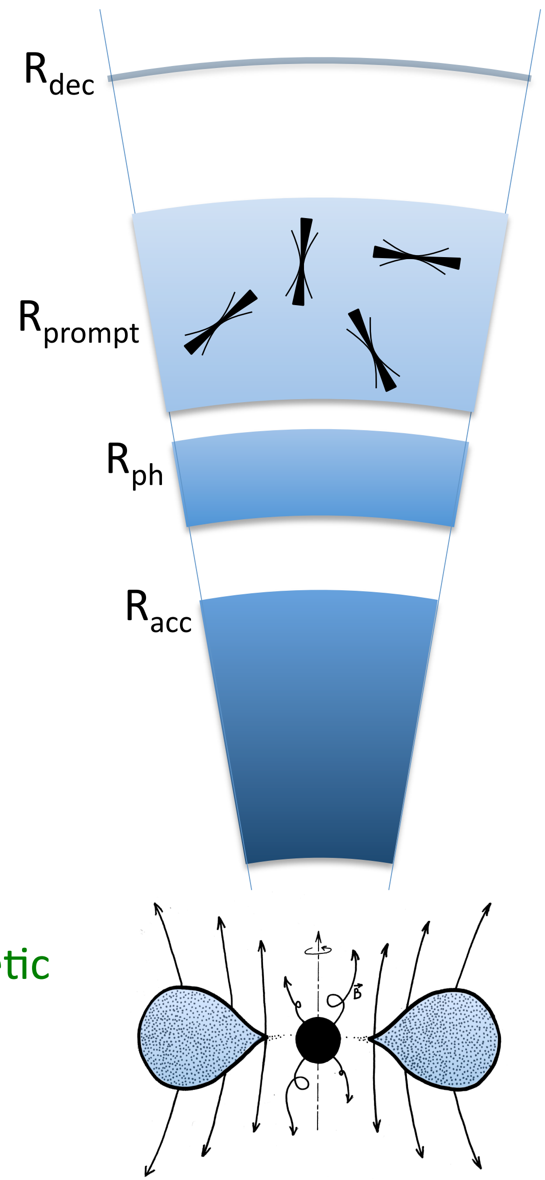


Passive field

Non-thermal emission :
Internal shocks
or <u>magnetic dissipation</u>

Note: magnetic dissipation can occur below the photosphere

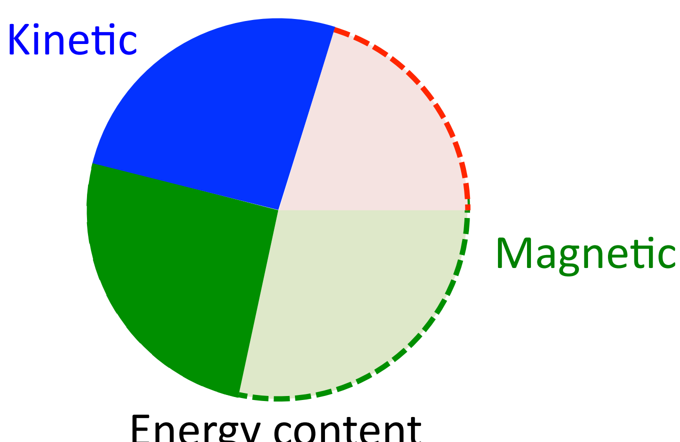


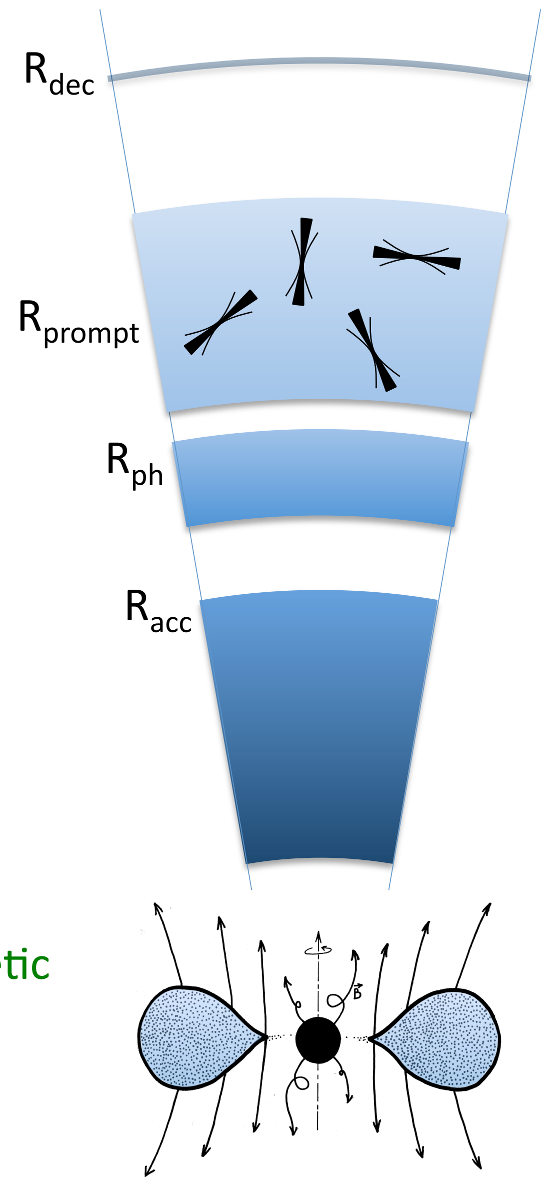


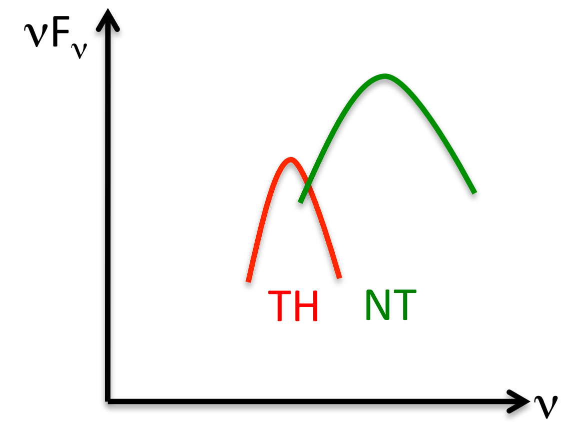
Passive field

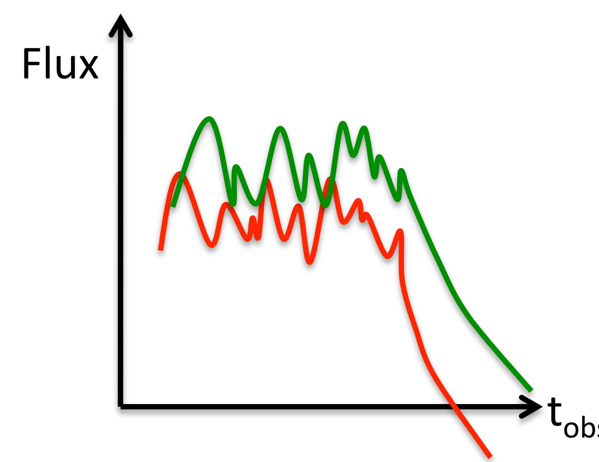
Non-thermal emission :
Internal shocks
or <u>magnetic dissipation</u>

Note: magnetic dissipation can occur below the photosphere

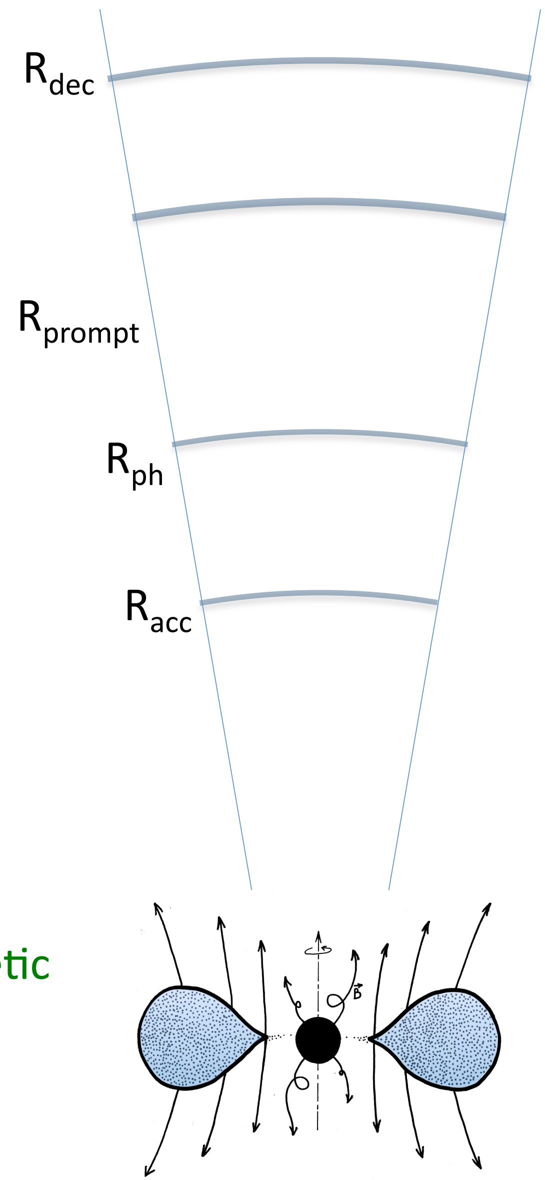


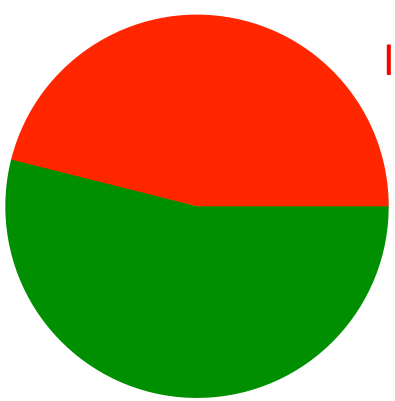






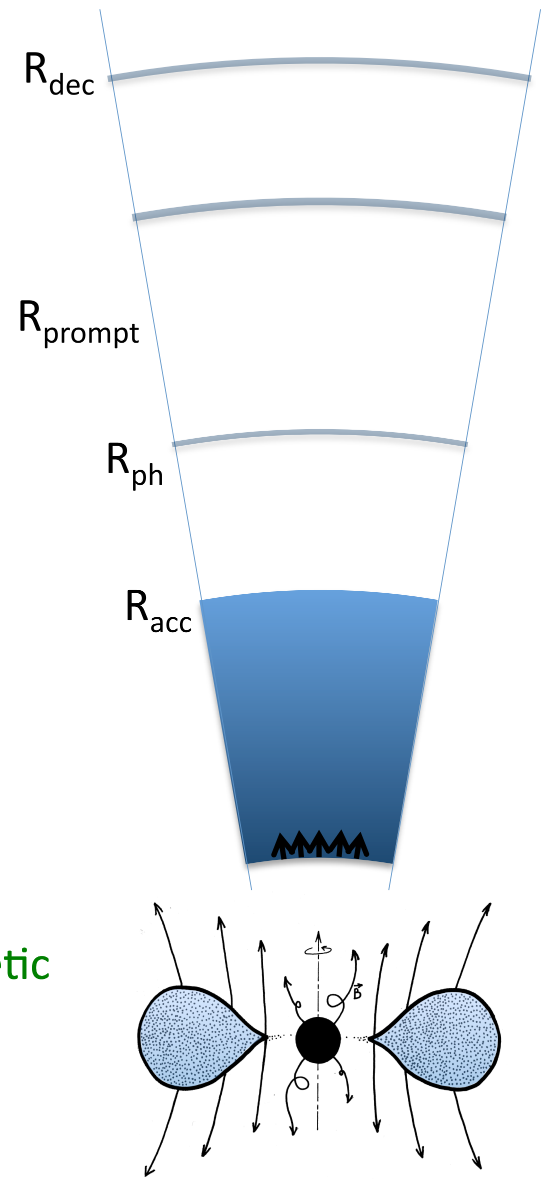
Active field



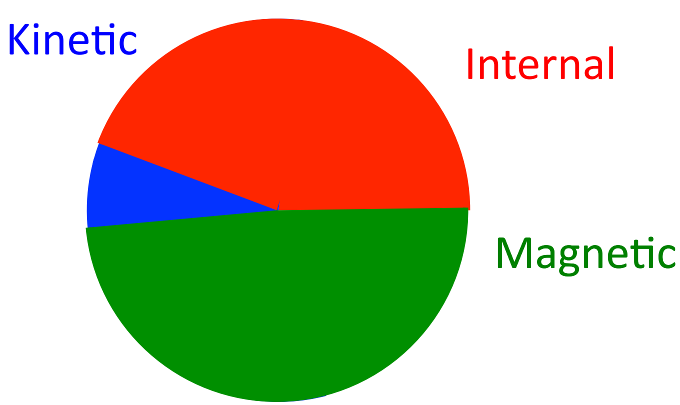


Large magnetization

Active field

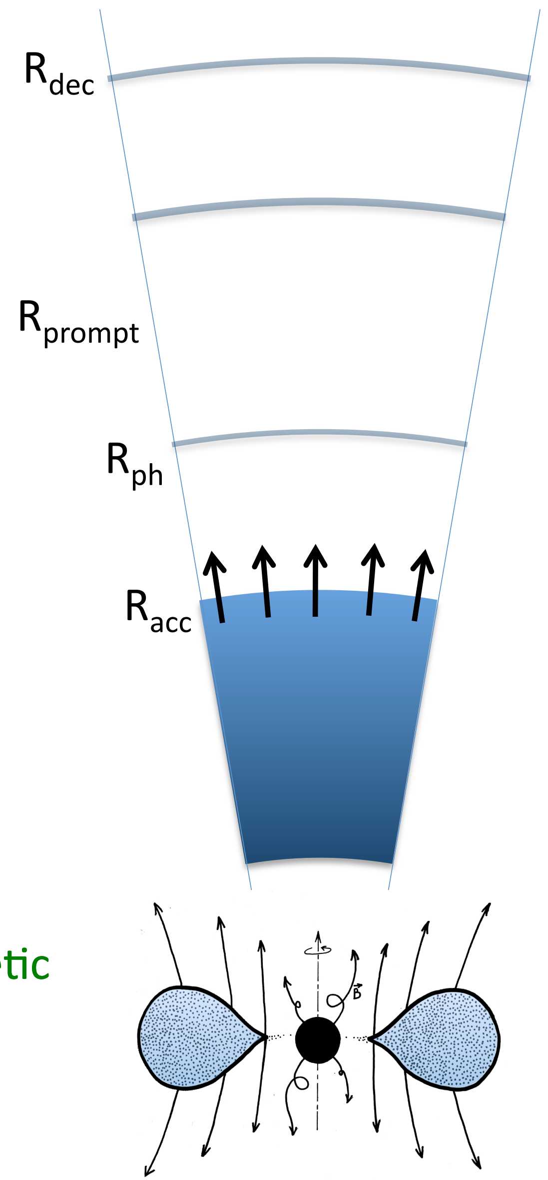


Magnetic acceleration

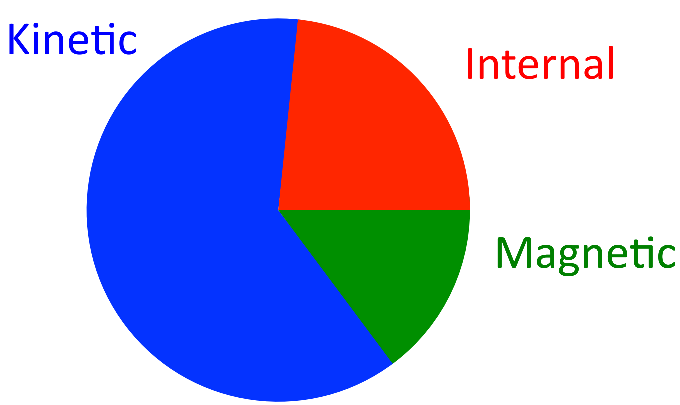


Energy content

Active field

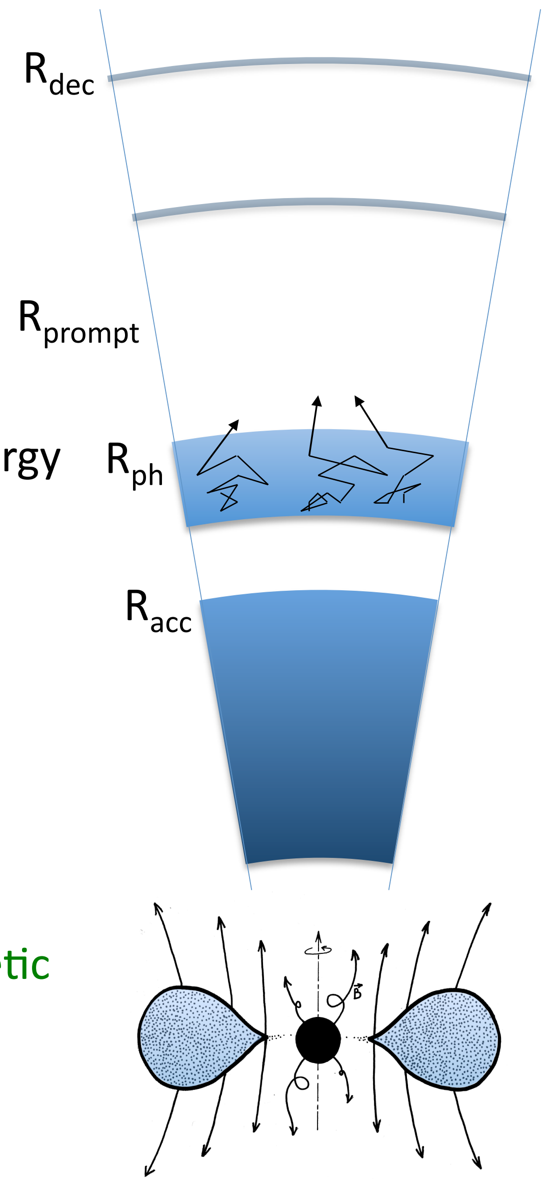


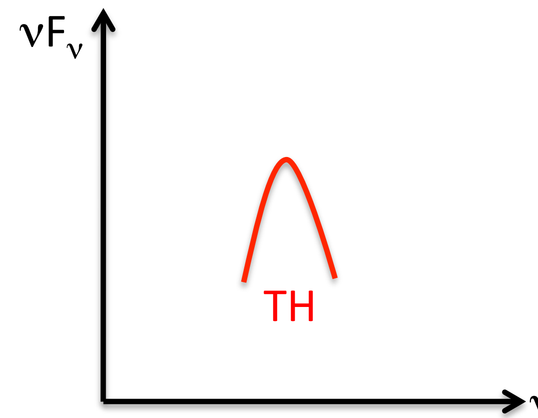
Magnetic acceleration



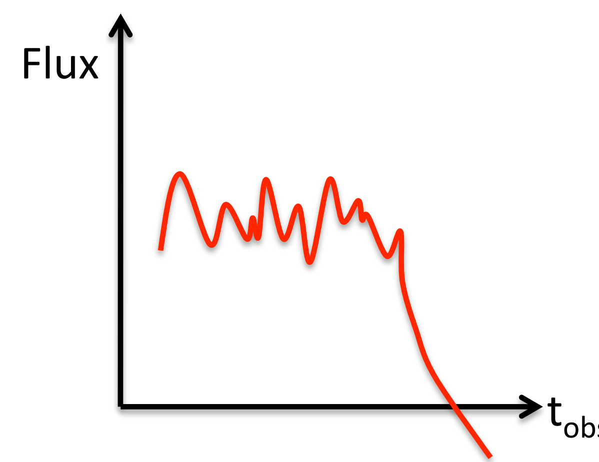
Energy content

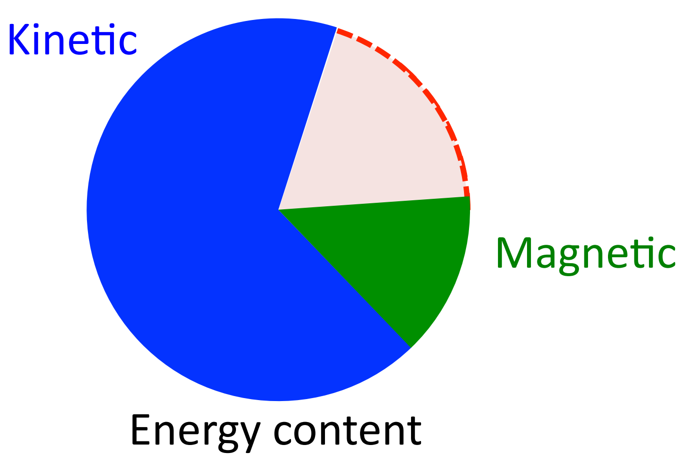
Active field





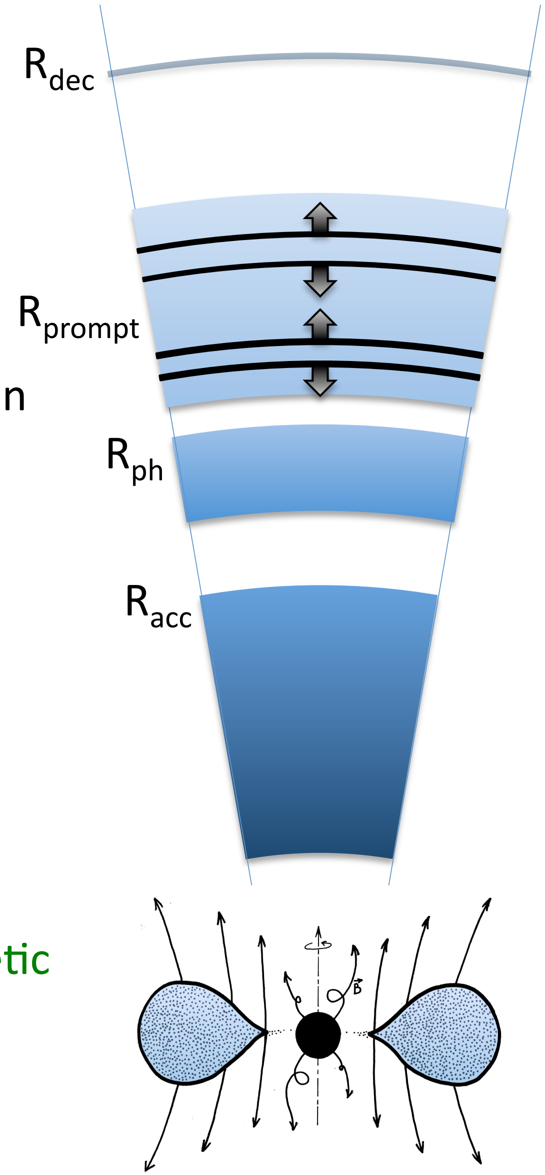
Photosphere : internal energy can be radiated.

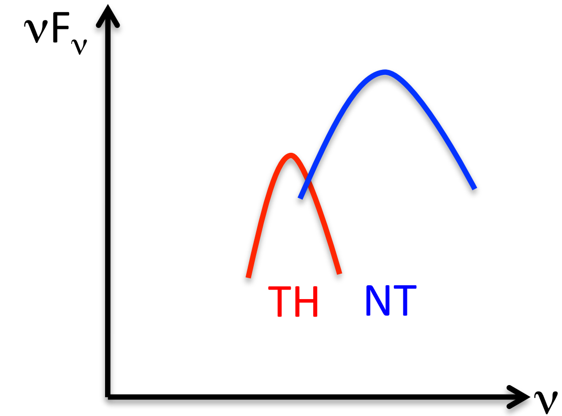


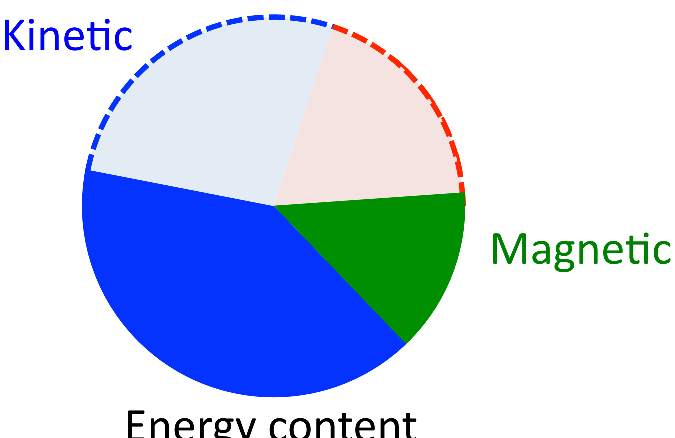


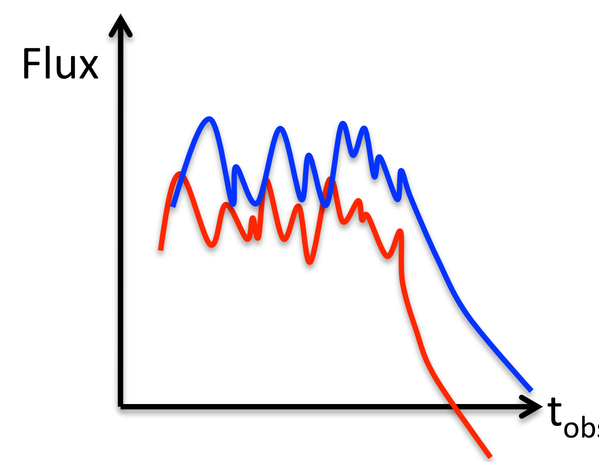
Active field

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









Magnetized outflows

- **Allows a weak thermal photospheric component**

- Large uncertainties on the acceleration mechanism
  - Contribution of the magnetization ?
  - Needs an external confinement ?
  - High or low final magnetization ?
  - etc.

  (Spruit et al. 01; Daigne & Drenkhahn 02; Spruit & Drenkhahn 02; Giannios & Spruit 06; Tchekhovskoy, Narayan & McKinney 10 ; Granot et al. 10; etc)

- If there is significant magnetic dissipation :
  - Gradual or not ?
  - Below or above the photosphere ?
  - Large uncertainties in reconnection physics…

  - If not: minimal magnetization to suppress shocks ?

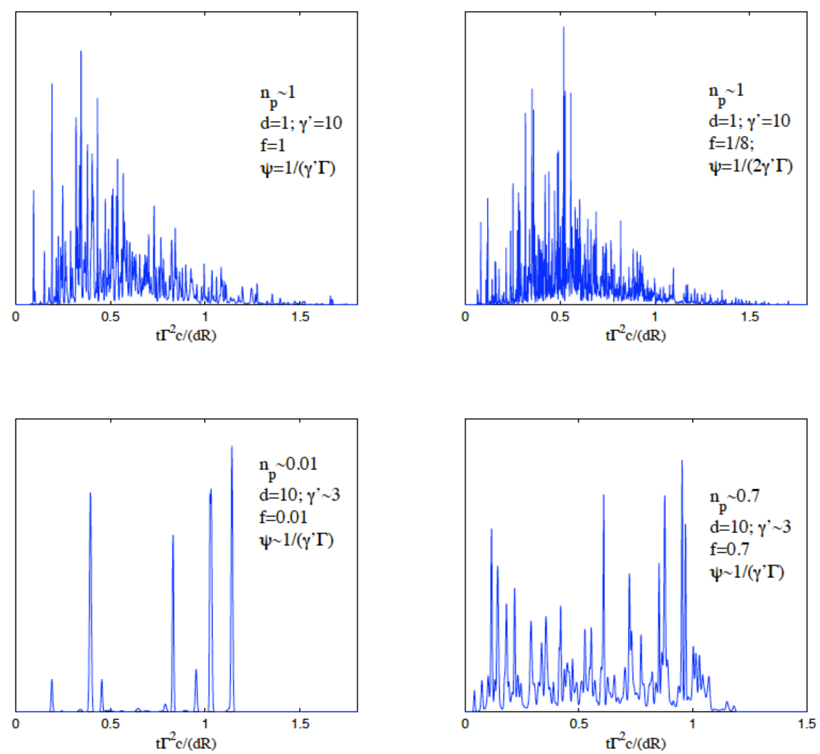
  (Zhang & Kobayashi 05; Giannios, Mimica & Aloy 08)

- Several scenarios:
  - Gradual dissipation below the photosphere (e.g. Spruit & Giannios, …)
  - Shock-triggered reconnection – ICMART (Zhang)
  - Etc.
- **High efficiency seems possible – Multi-component spectra are expected**

Relativistic emitters

« fundamental relativistic emitters » : lightcurves are too symmetric ?

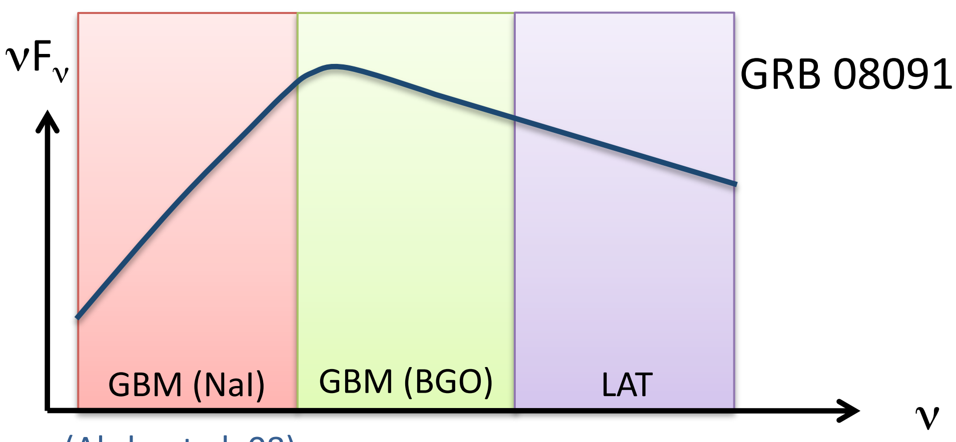
(Lyutikov 06; Kumar & Narayan 09; Lazar, Nakar & Piran 09)



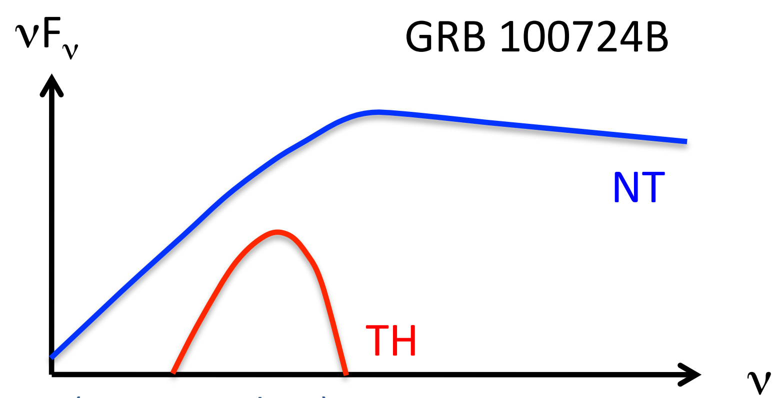
Lazar, Nakar & Piran 09

Standard fireball: prompt emission

- Fermi observations :

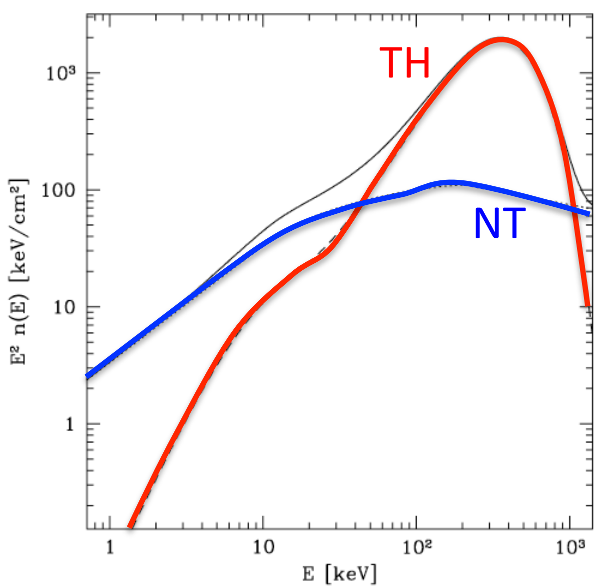


(Abdo et al. 08)

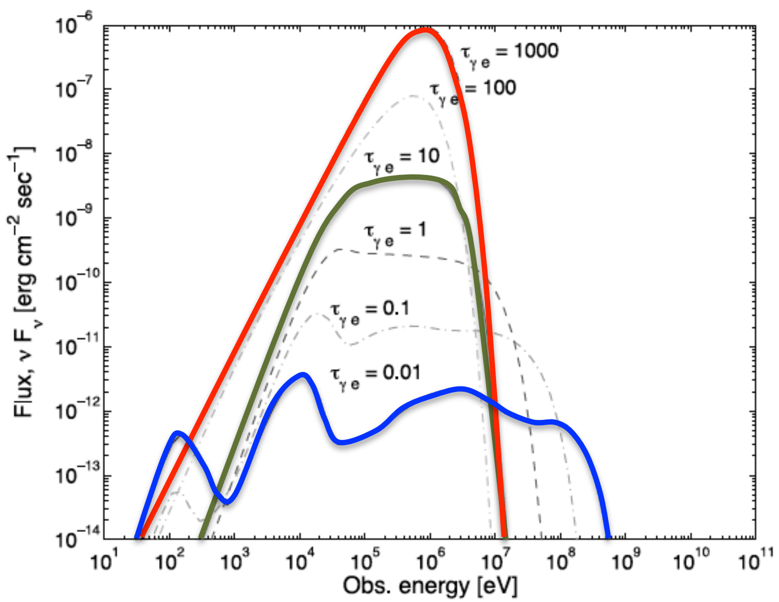


(Guiriec et al. 10)

- Model :



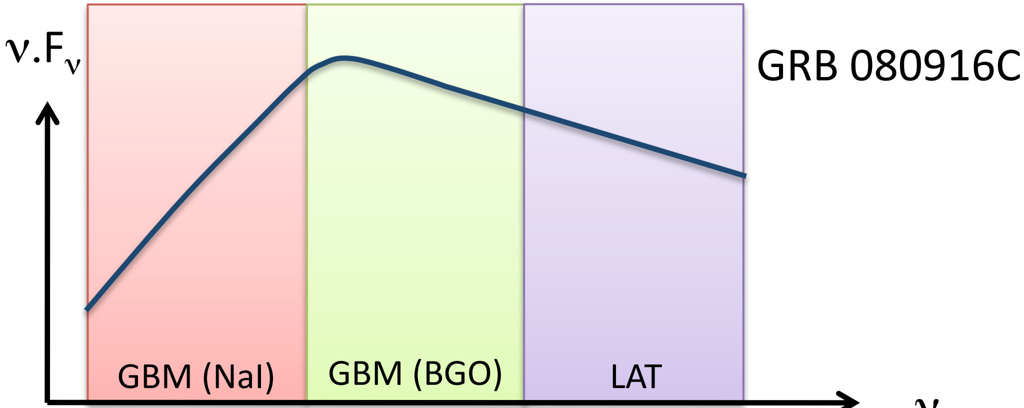
(Daigne & Mochkovitch 02)



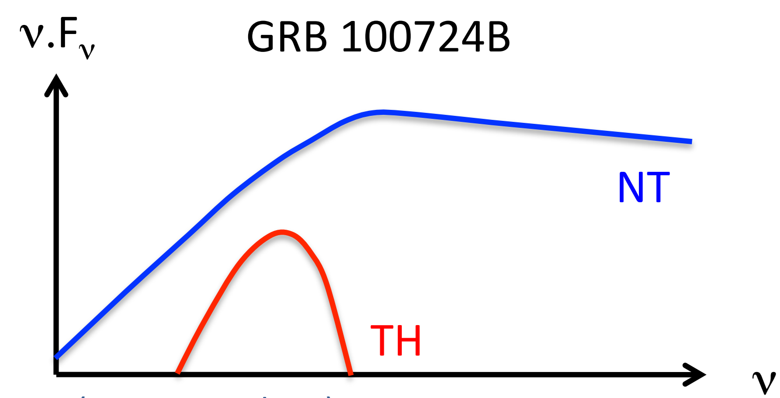
(Pe'er et al. 06)

Magnetized outflows: prompt emission

- Fermi observations :

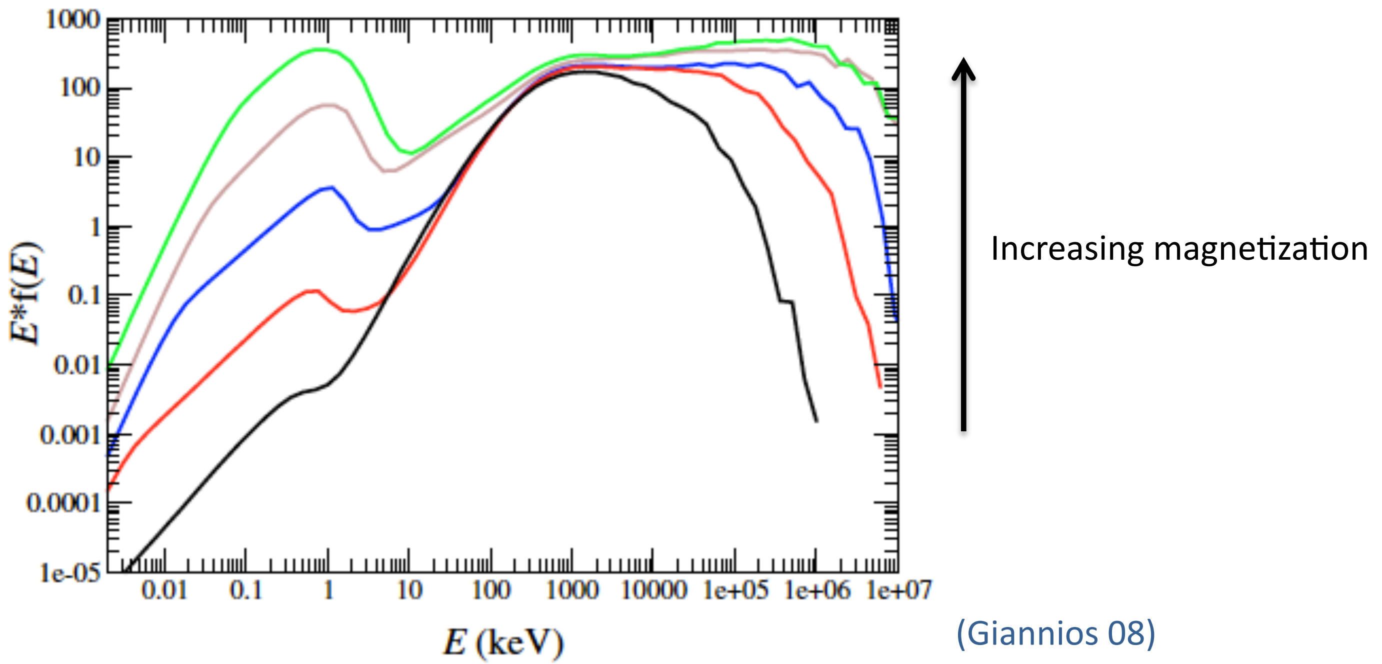


(Abdo et al. 08)



(Guiriec et al. 10)

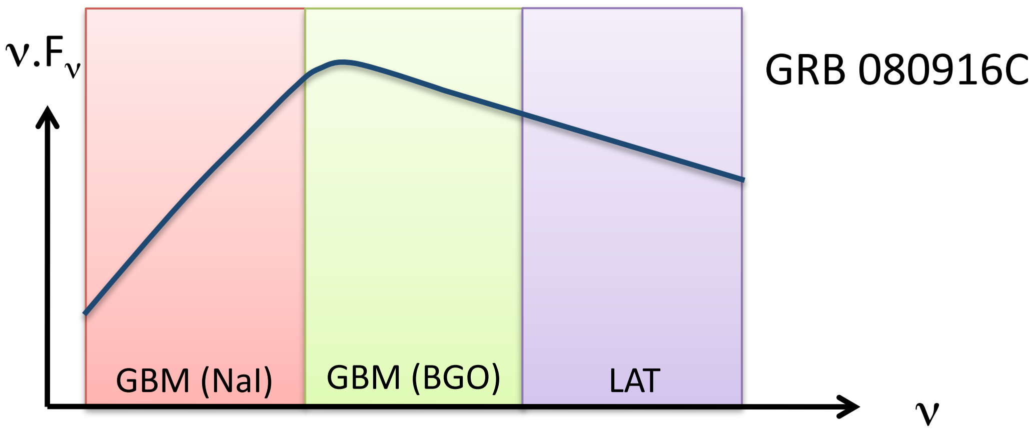
- Model : gradual sub photospheric magnetic dissipation



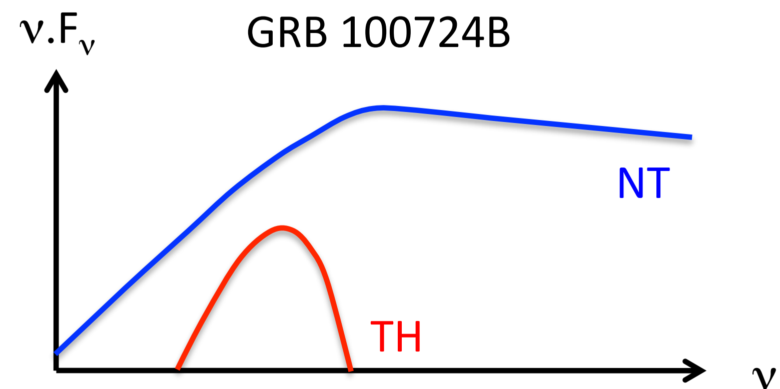
(Giannios 08)

Magnetized outflows: prompt emission

- Fermi observations :

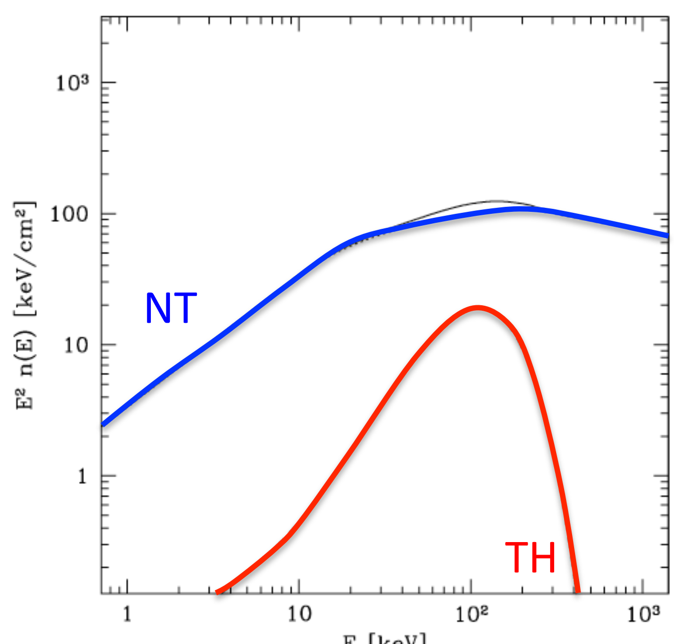


(Abdo et al. 08)



(Guiriec et al. 10)

- Model : efficient magnetic acceleration + internal shocks



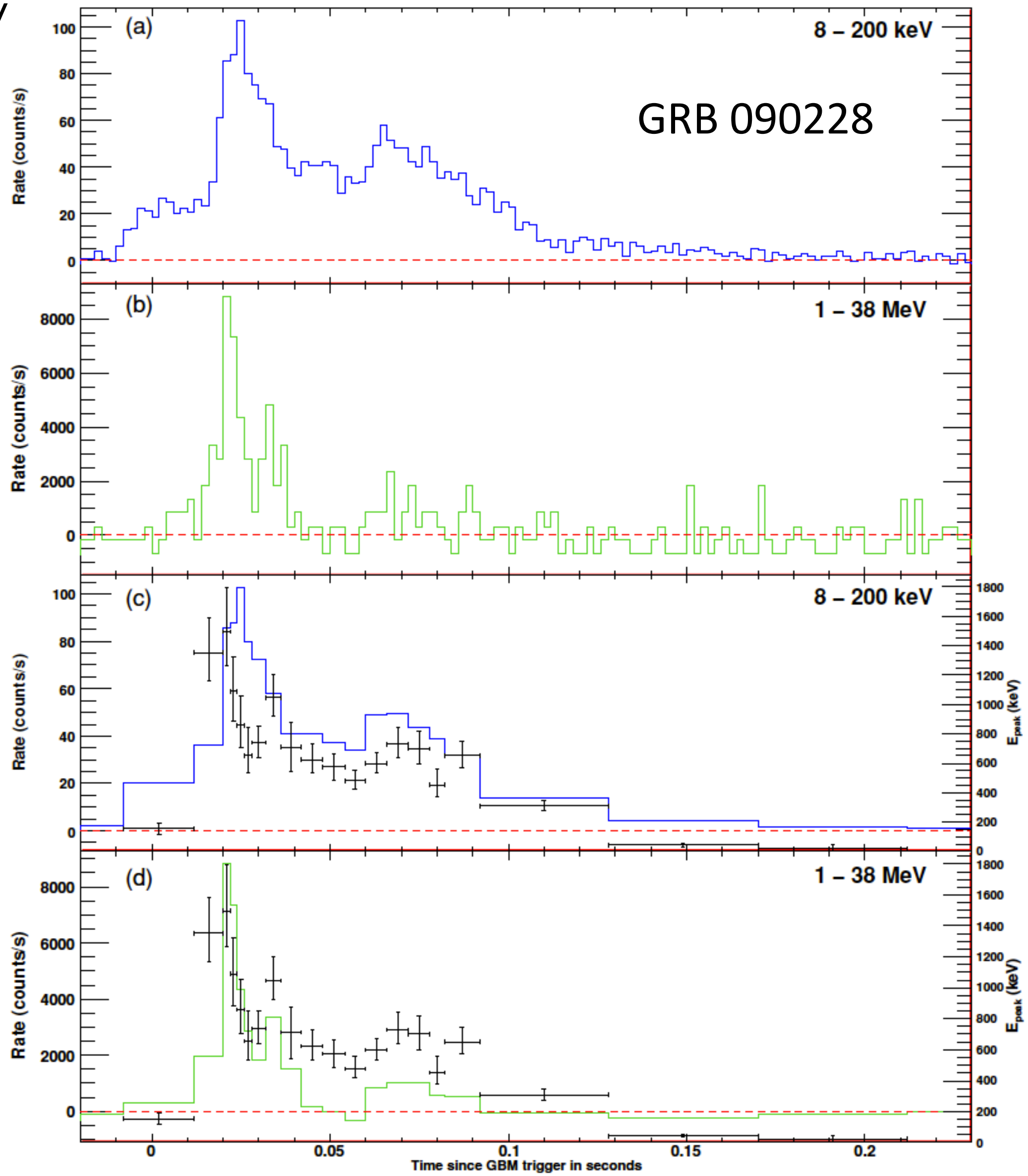
(Daigne & Mochkovitch 02)

How to distinguish between models ?

New observations (especially by Fermi)…

Fermi: (1) low-energy emission

- Fermi-GBM : from 8 keV to ~30 MeV
- Rate ~ 250 GRB/year
- Improved description of spectrum, even for short GRBs
- Deviation from « Band » function ?



Guiriec et al. 2010

Fermi: (2) high-energy detections (GeV)

- Fermi-LAT : ~ 10 GRBs / year (to compare to GBM : ~ 250 GRBs / year)
- In 3 years: 28 GRBs detected above 100 MeV
- 4 brightest bursts : « hyper-energetic events »

GRB	z	$E_{\gamma,iso}$	Group	Refs
080916C	4.35	$8.8\ 10^{54}$ erg	long	Abdo et al. (2009a)
090510	0.9	$1.1\ 10^{53}$ erg	short	Ackermann et al. (2010)
090902B	1.8	$3.6\ 10^{54}$ erg	long	Abdo et al. (2009b)
090926A	2.1	$2.2\ 10^{54}$ erg	long	Ackermann et al. (2011)

(1st LAT GRB catalog, 2013)

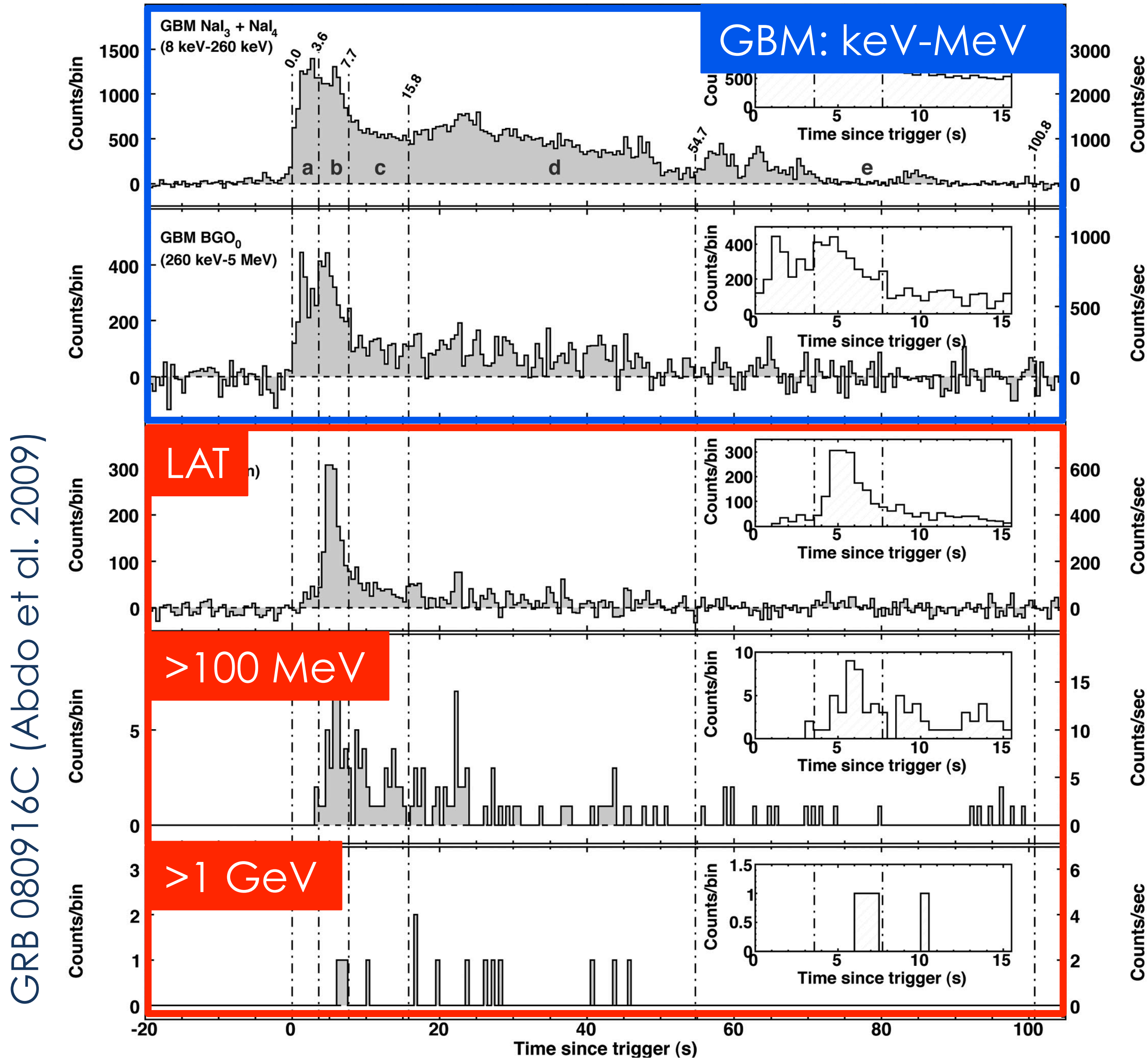
- Low detection rate by the LAT :
  - **no bright new component in the LAT range**

    Fluence(LAT)/Fluence(GBM) ~ 0.1 in LAT long GRBs
    [> 1 in LAT short GRBs but 2 events only]
  - rate below pre-launch estimate (Band et al. 09)
  - **need for a cutoff at ~ 100 MeV in most GRBs ?**

    (e.g. Le & Dermer 09 ; Granot et al. 10 ; Guetta et al. 11 ; Beniamini et al. 11 ; Ackermann et al. 12)
  - constraints from new LLE analysis ?

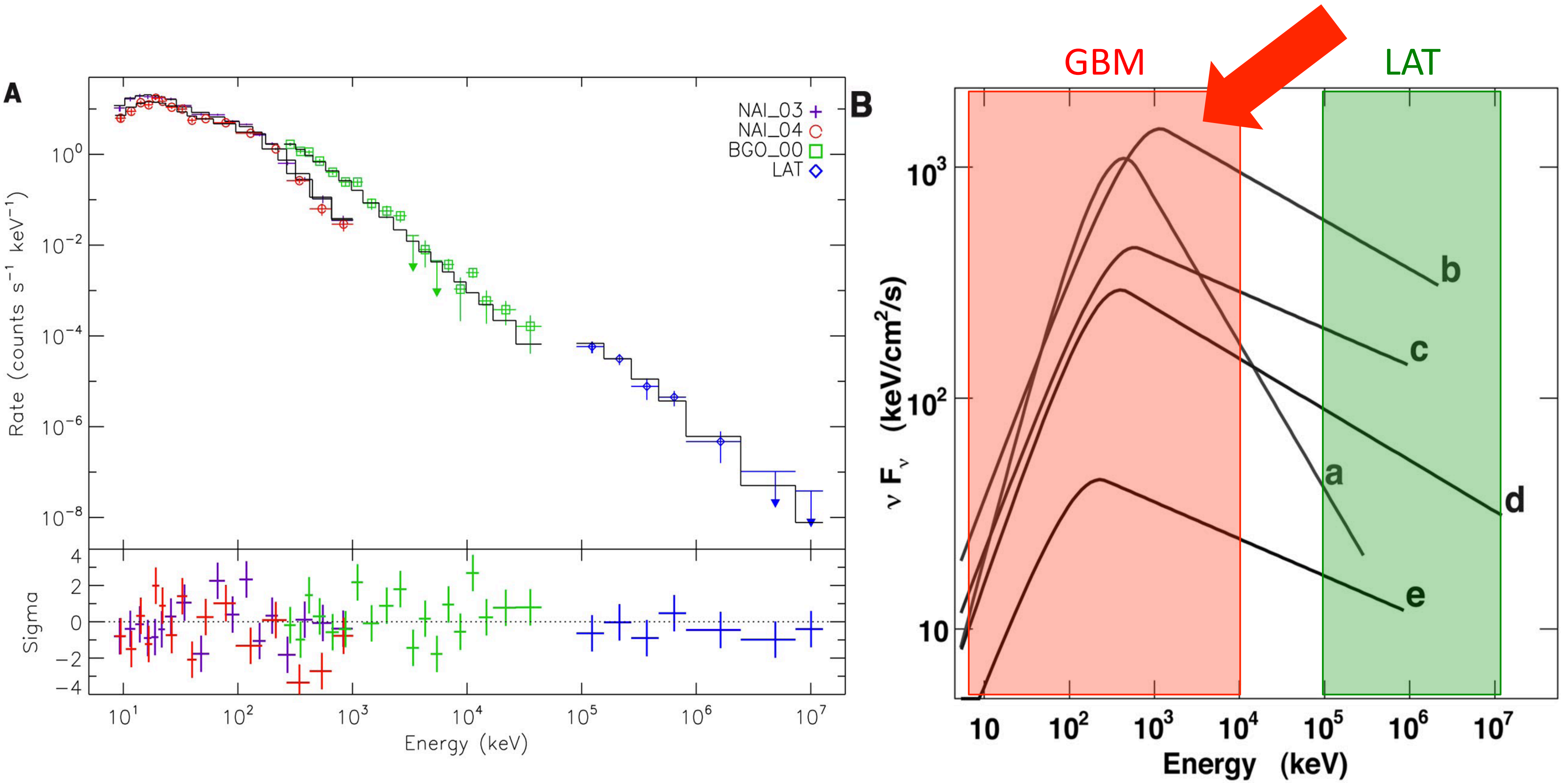
Fermi: (2) high-energy detections (GeV)

- An example: GRB 080916C



Fermi: dominant spectral component

- The main component already known in the keV-MeV range is dominant :



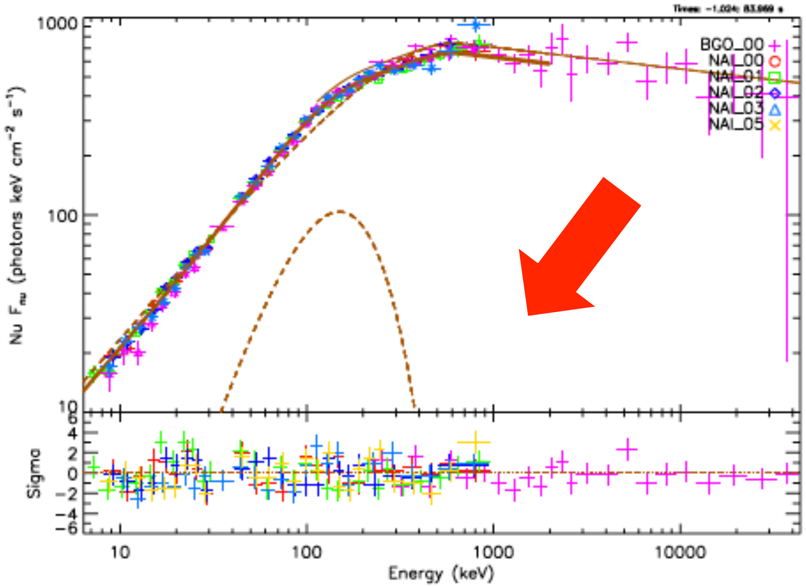
GRB 080916C (Abdo et al. 2009)

- This component is usually reasonnably well described by the Band function

A weak/soft photospheric component ?

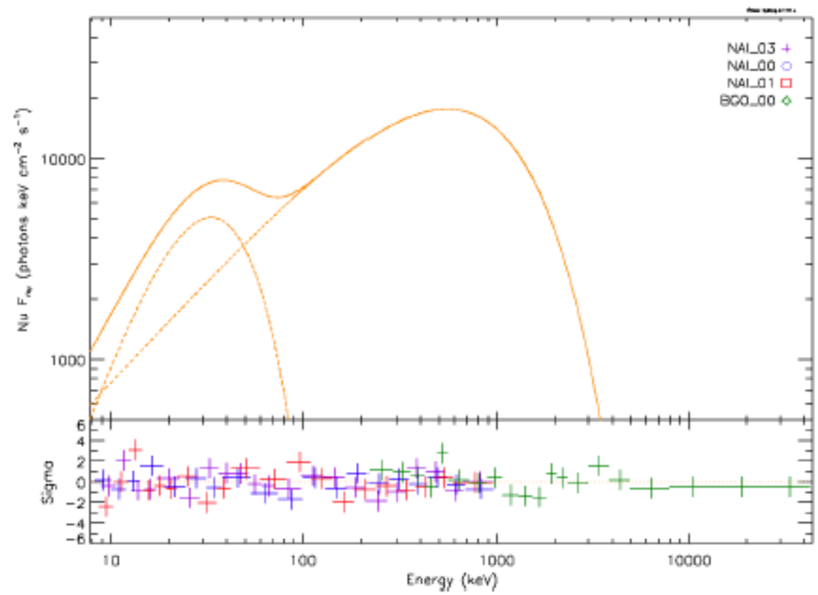
- In a few cases : evidence for an additional weak/soft component in GBM:

GRB 100724B



(Guiriec et al. (FD) 2011)

GRB 120323A



(Guiriec, Daigne, et al. 2013)

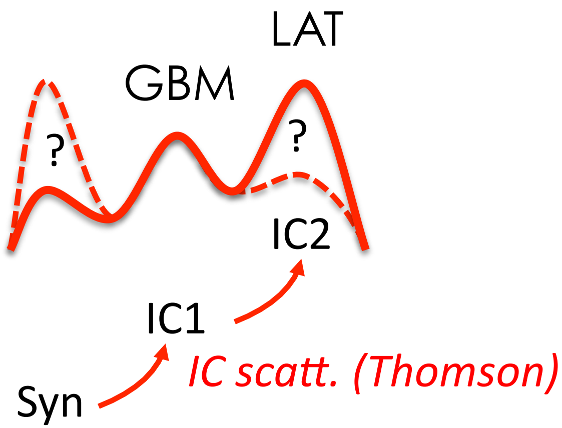
-See also other GBM bursts : GRB 110721A (Axelsson et al. 2012)
GRB 081207, GRB 110920, …
(McGlynn, Ryde, GRB 2012 Conference, Munich, May 2012)

-GRB 090902B: strong BB ? (Ryde et al. 2010) – Such cases seem really rare

Dominant radiative process ?

- Dominant radiative process: synchrotron vs SSC ? (non photospheric models)

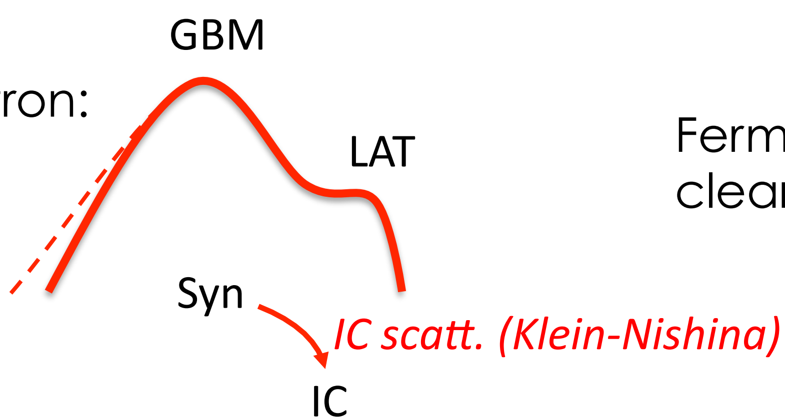
SSC:



-Where is the strong IC2 component ?
or the strong syn component ?

-Energy crisis

Synchrotron:



Fermi-LAT detection rate and observations clearly favor the synchrotron process.

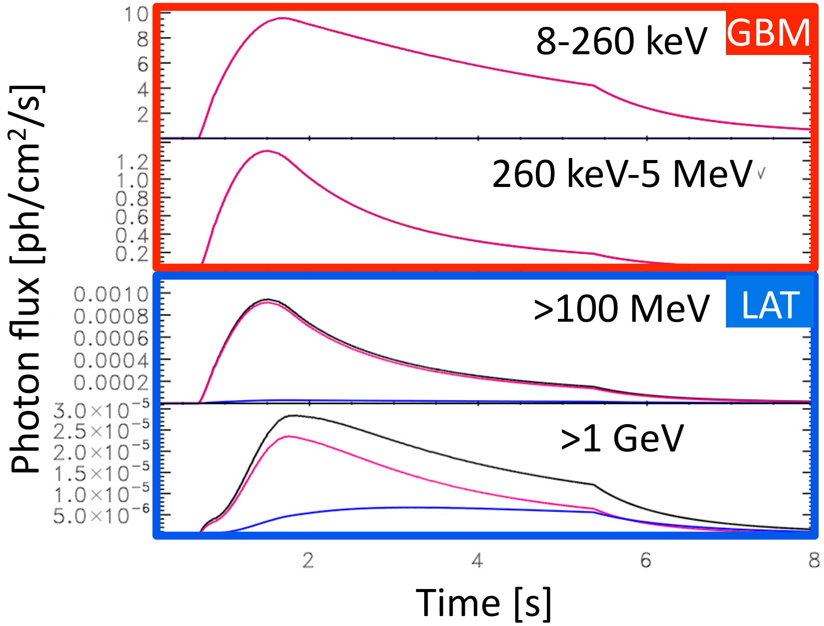
(see e.g. Bošnjak, Daigne & Dubus 09; Piran, Sari & Zou 09)

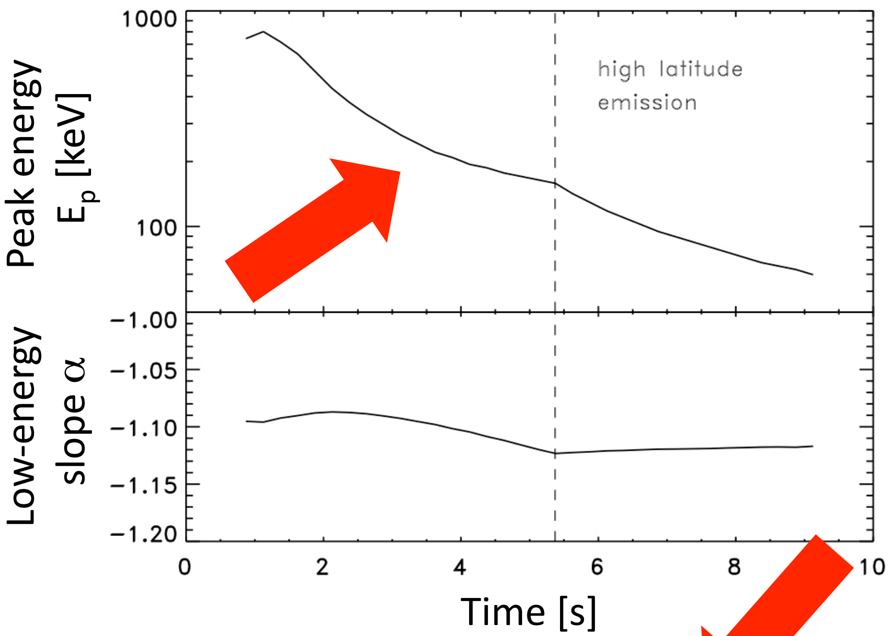
- Synchrotron + IC scatterings in KN regime : low-energy slope $\alpha \sim -3/2 \rightarrow -1$

(Derishev et al. 2001; Bosnjak et al. 2009 ; Nakar et al. 2009 ; Daigne et al. 2011)

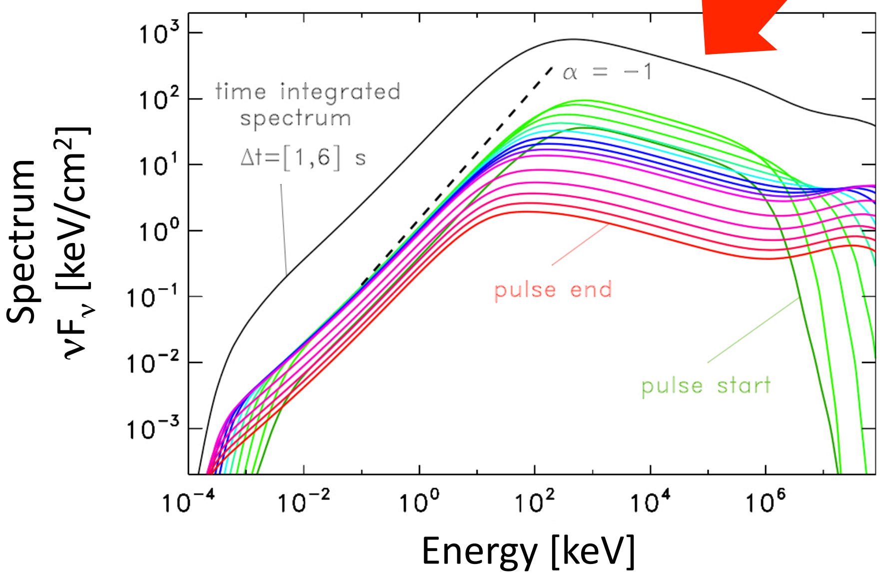
Dominant radiative process ?

- Internal shocks + dominant synchrotron + IC scattering in KN regime





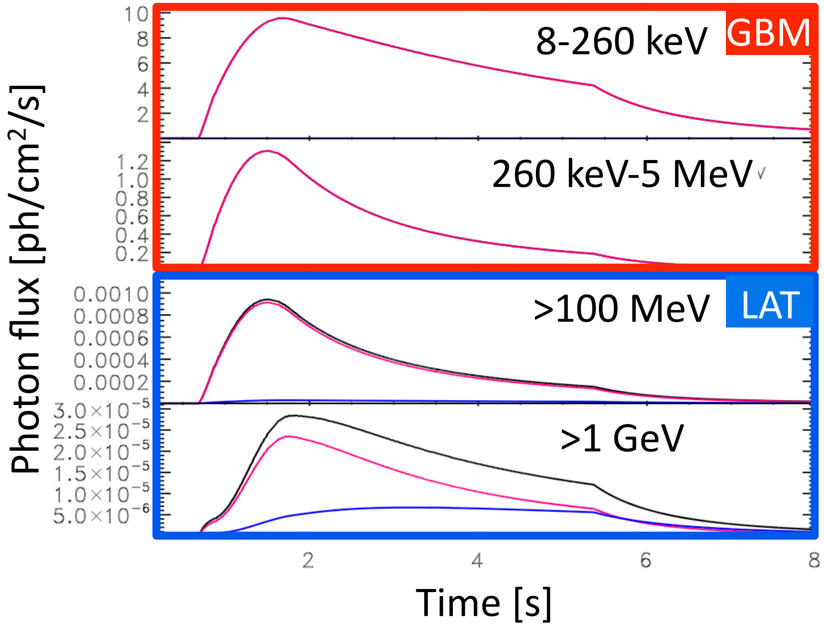
Spectral evolution in a pulse: both E_p and α evolve

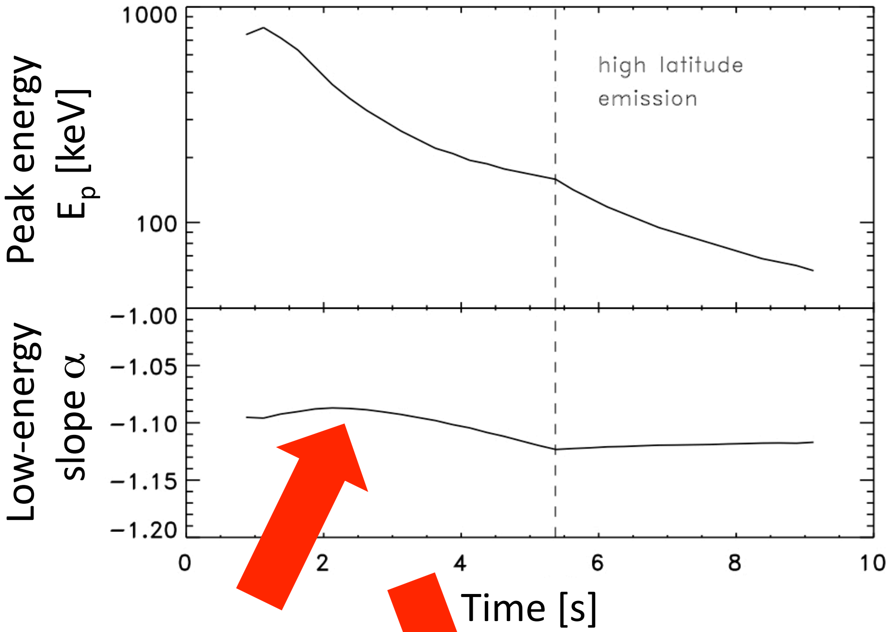


Example taken from
Bošnjak & Daigne 2013 in preparation

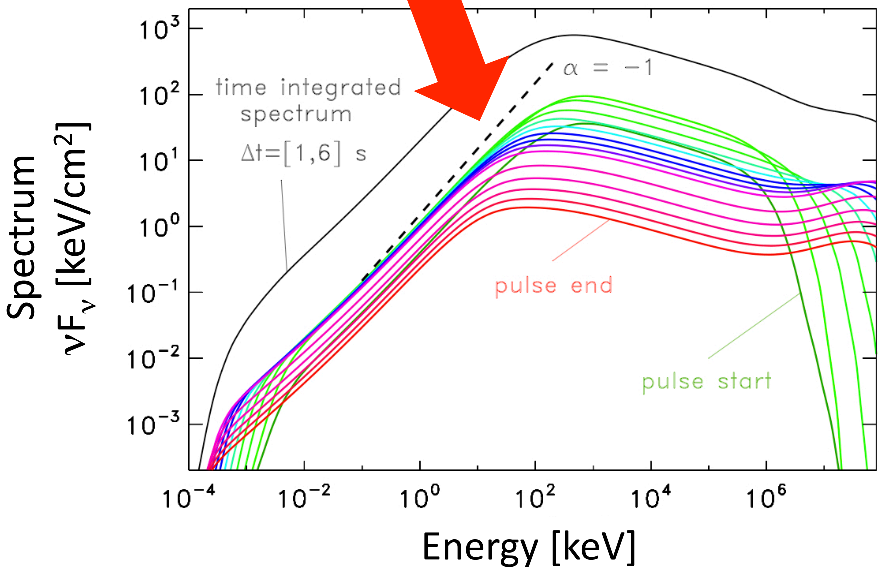
Dominant radiative process ?

- **Internal shocks + dominant synchrotron + IC scattering in KN regime**





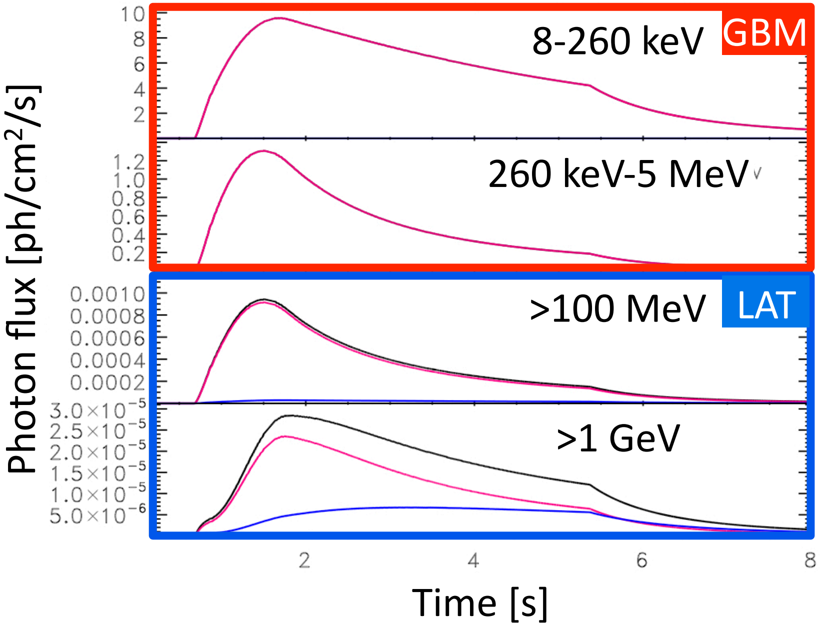
Fast cooling synchrotron:
α can be steeper than -3/2
(here α ~ -1.1)

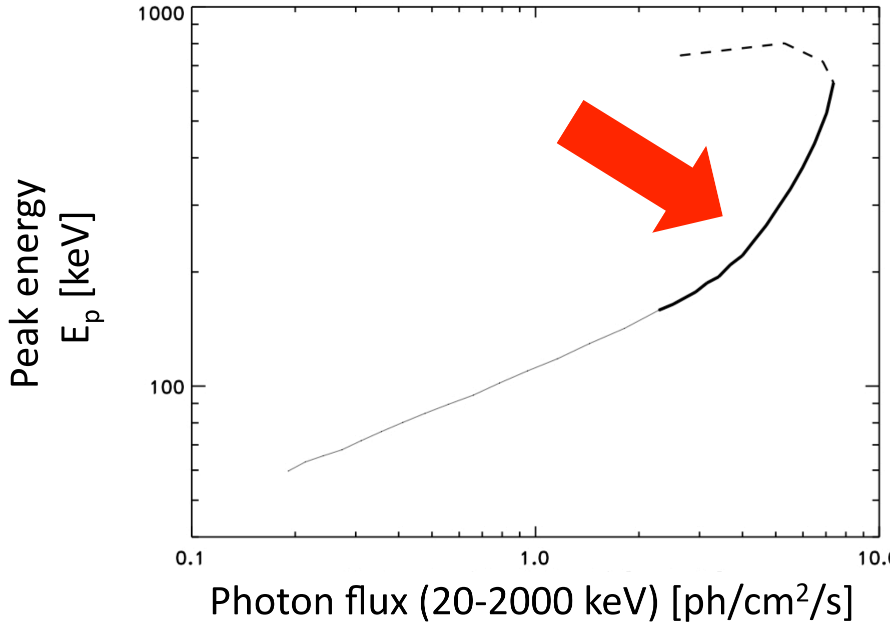


Example taken from
Bošnjak & Daigne 2013 in preparation

Dominant radiative process ?

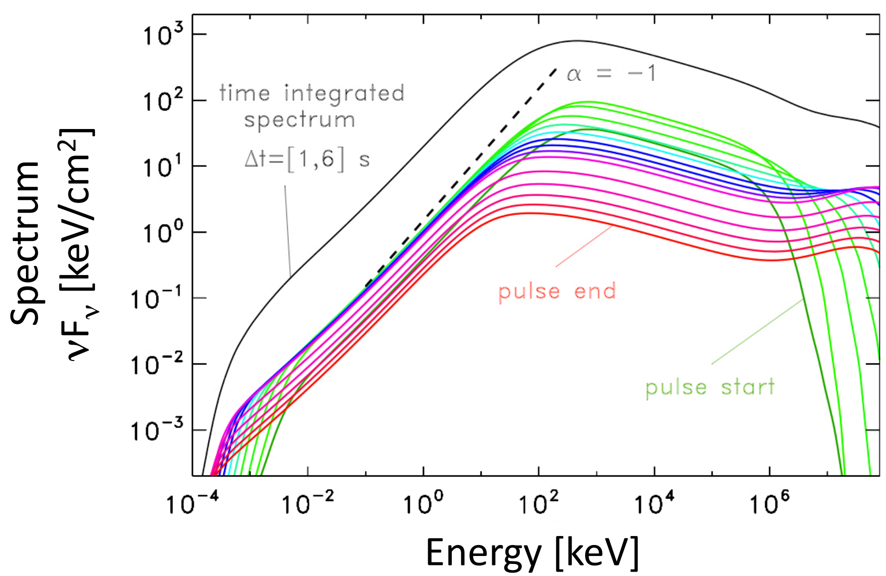
- Internal shocks + dominant synchrotron + IC scattering in KN regime





Spectral evolution in a pulse:
Hardness-intensity correlation

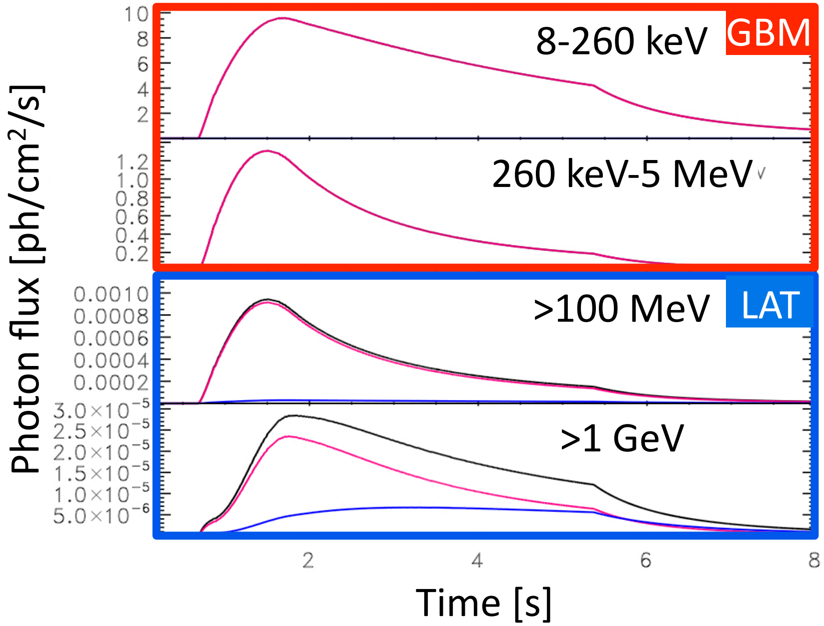
(HIC slope in agreement with BATSE results : e.g. Ryde & Svensson 02)

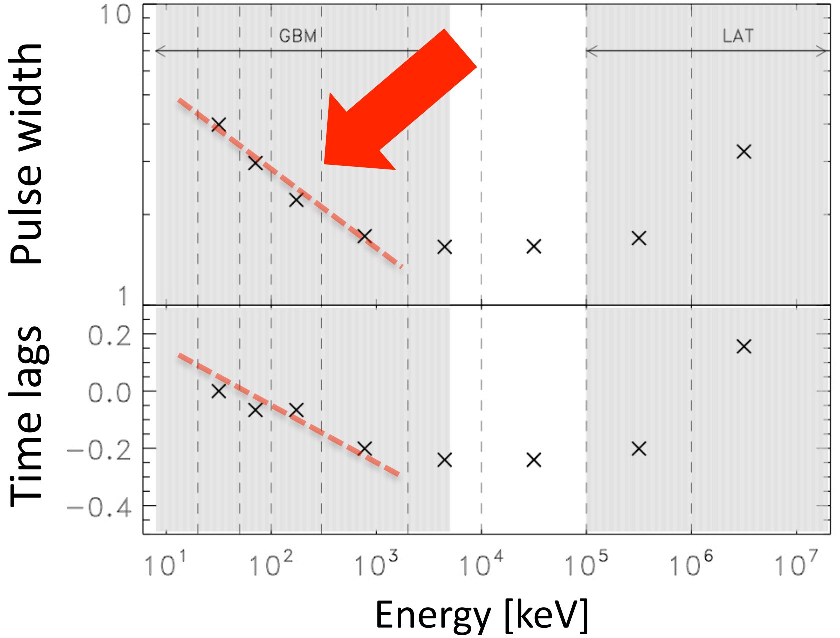


Example taken from
Bošnjak & Daigne 2013 in preparation

Dominant radiative process ?

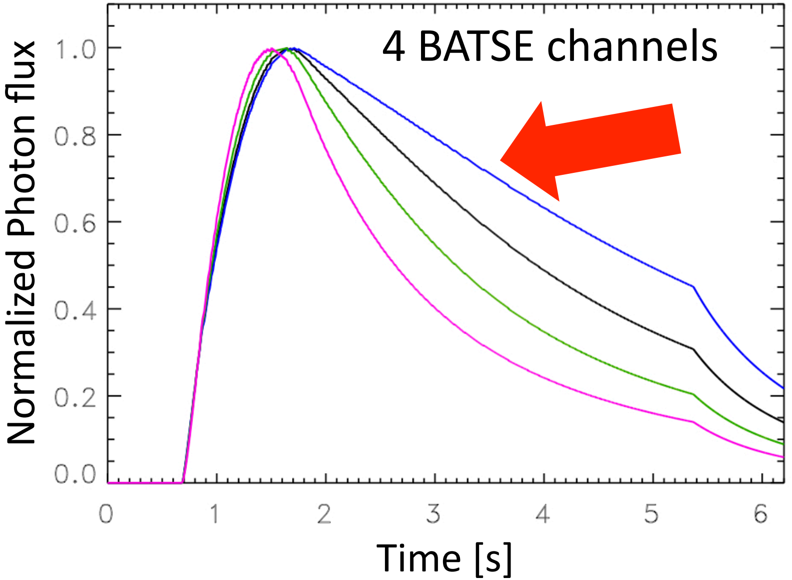
- Internal shocks + dominant synchrotron + IC scattering in KN regime





Spectral evolution in a pulse:
BATSE/GBM range: hard to soft evolution

Time lags : channel 4 peaks earlier
Pulse width : channel 4 is narrower
(slope in agreement with BATSE results : e.g. Norris et al. 96)



Example taken from
Bošnjak & Daigne 2013 in preparation

Dominant radiative process ?

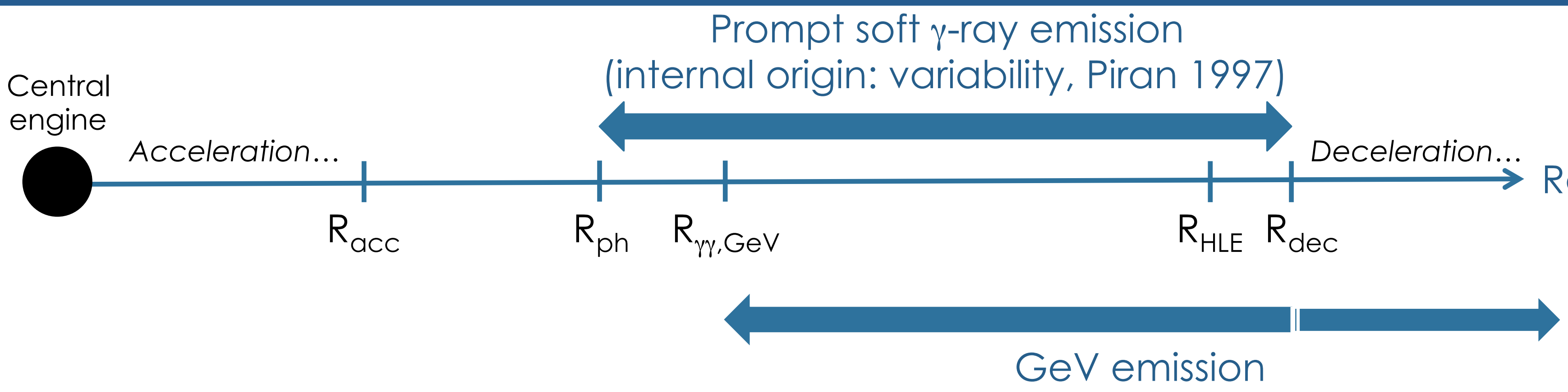
- **Internal shocks + dominant synchrotron + IC scattering in KN regime**

- **Works well BUT**

Is the microphysics realistic ?
(e.g. low ε_B, low fraction of accelerated electrons)

mildly relativistic shocks
from the plasma scale to the dynamical scale…

Origin of the prompt emission ?



Standard fireball is excluded

First possibility: all the soft γ-ray emission is produced at the photosphere
(Pe'er ; Giannios ; Beloborodov ; Lazzati ; etc.)

– Sub-photospheric dissipation is needed

– GeV emission needs another mechanism

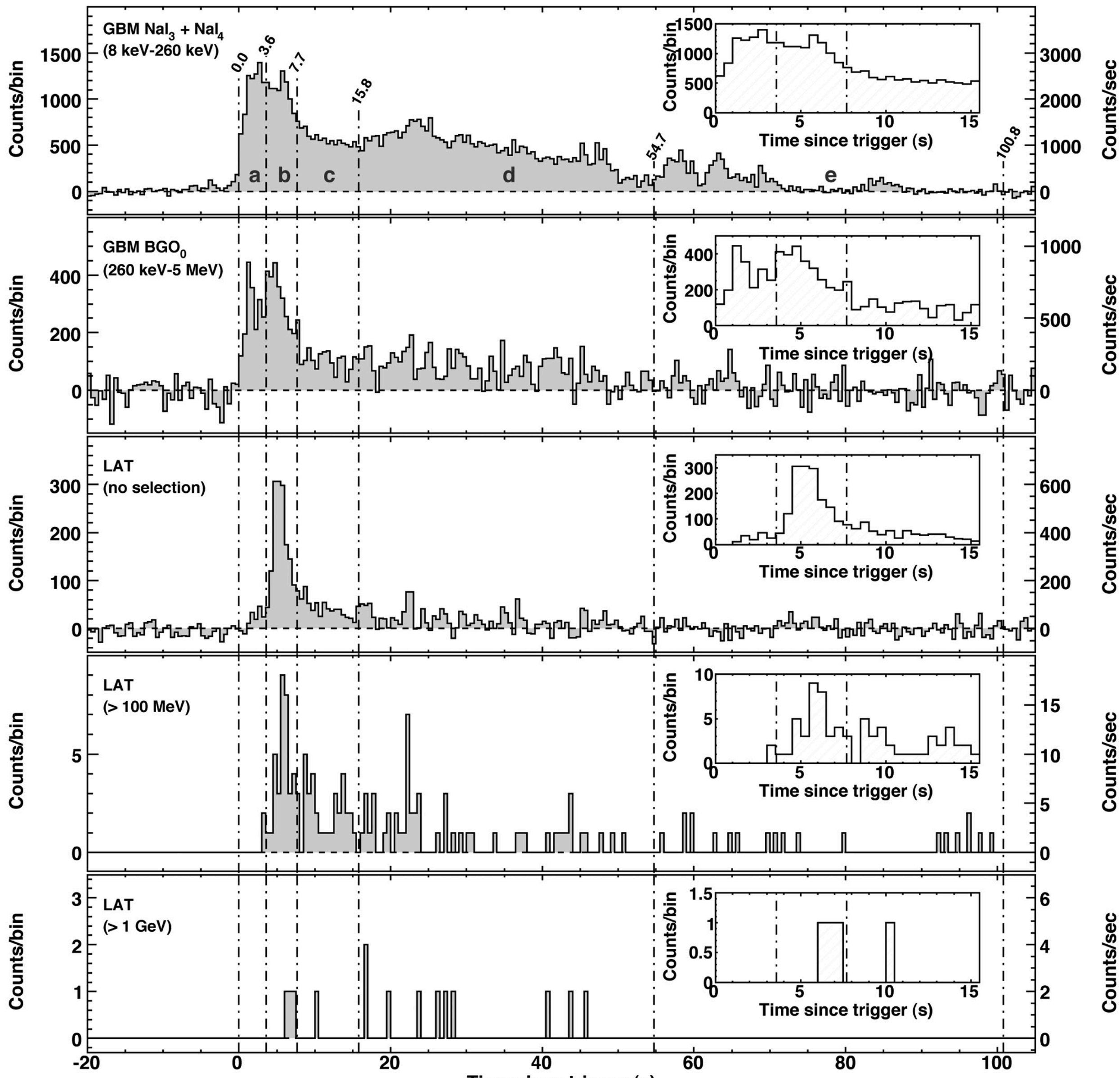
– Early steep decay in X-rays can't be due to the prompt high-latitude emission
(Hascoët, Daigne & Mochkovitch 2012

Second possibility: - soft/weak BB component : photosphere
(Daigne & Mochkovitch 2002 ; Hascoët, Daigne & Mochkovitch 2012)

- main component (MeV → GeV) :
internal shocks or magn. Reconnection
(Rees & Meszaros 1994; Kobayashi et al. 1997;
Daigne & Mochkovitch 1998; ICMART Zhang et Yan 2011; …)

Fermi: delayed onset of the GeV emission

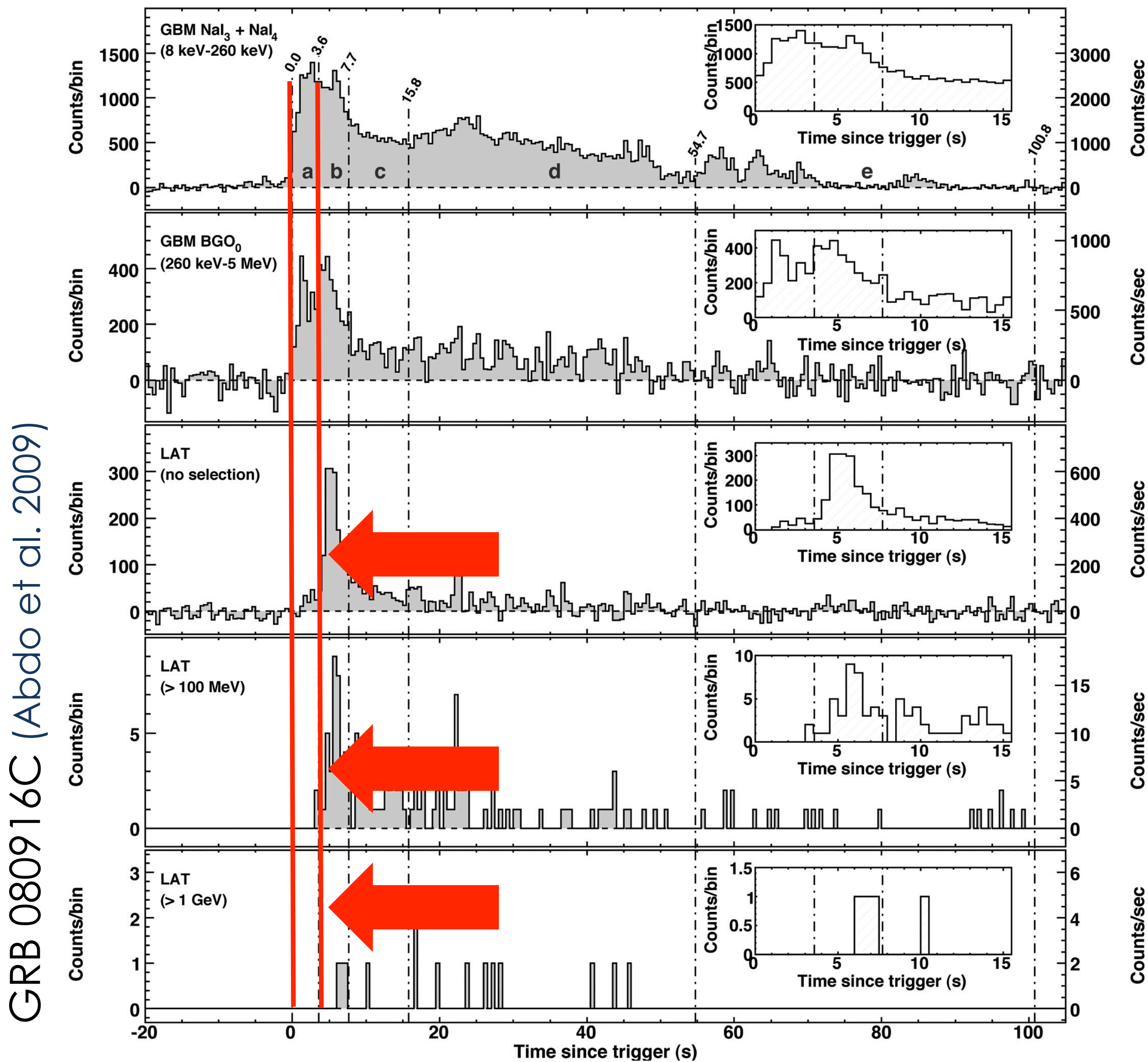
- In several cases, there is a delayed onset of the GeV component:



GRB 080916C (Abdo et al. 2009)

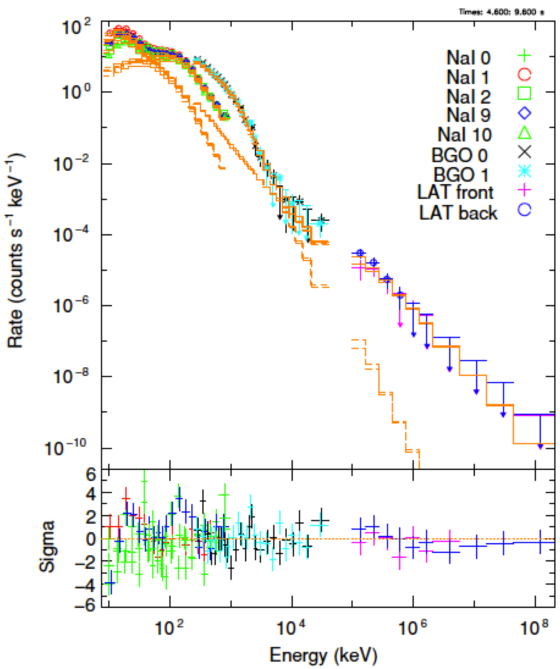
Fermi: delayed onset of the GeV emission

- In several cases, there is a delayed onset of the GeV component:

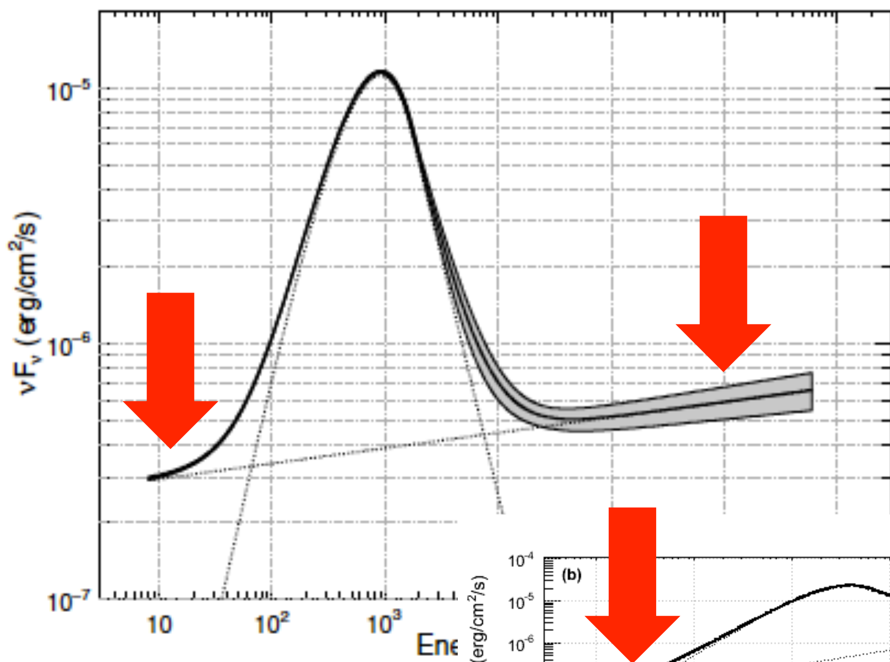


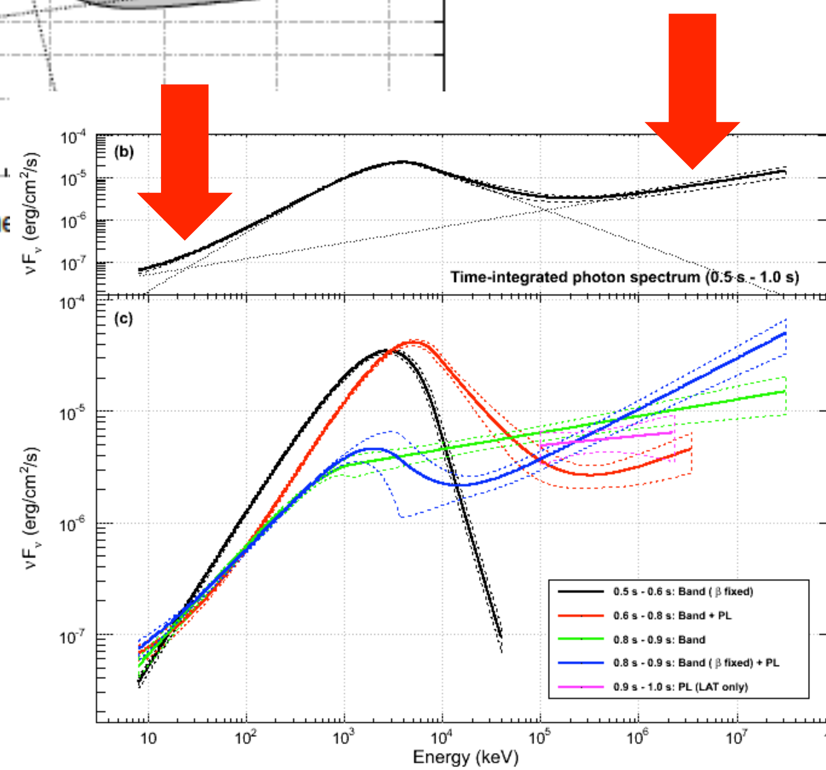
Fermi: additional spectral components

- In some cases, an additional component is seen at high energy



GRB 090902B (Abdo et al. 2009)

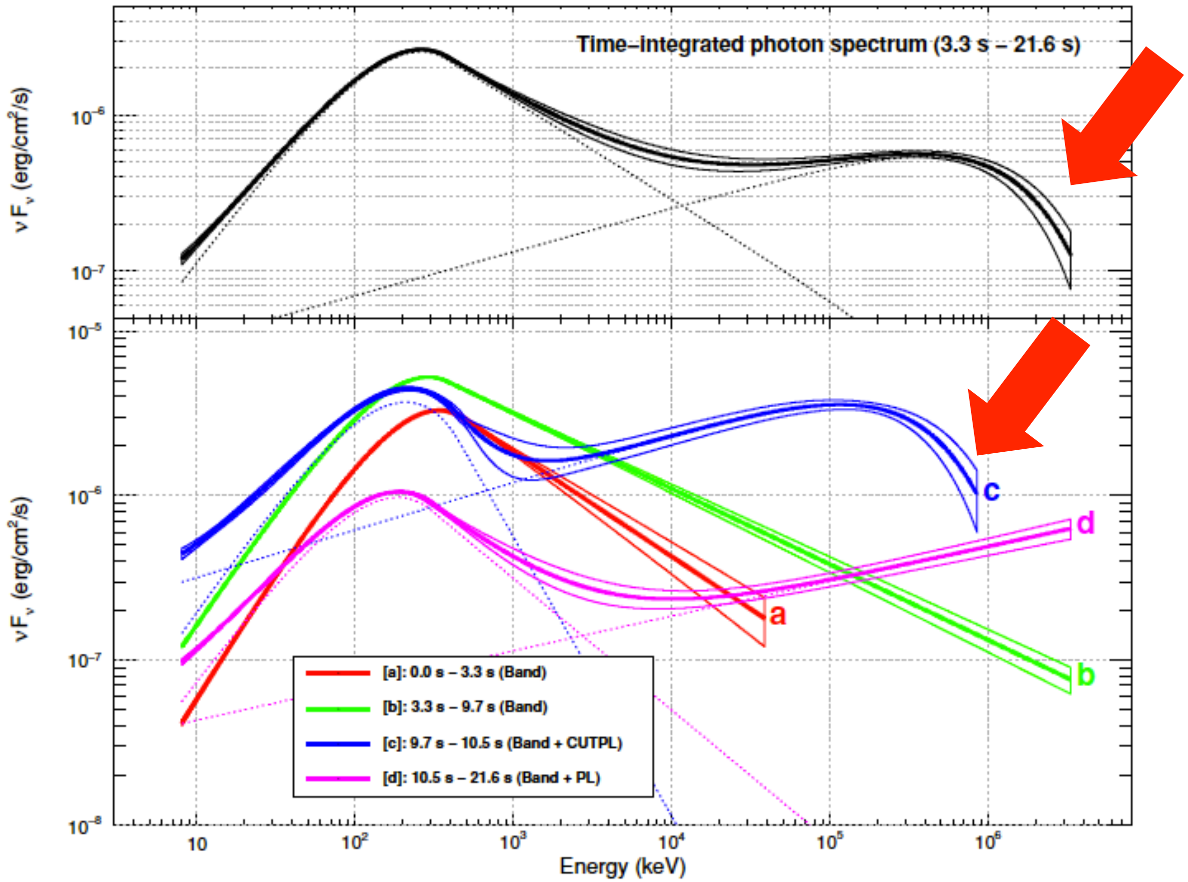




GRB 090510 (Abdo et al. 2009)

Fermi: cutoff at high energy ?

- Except in one case, there is no clear signature for a cutoff at high energy

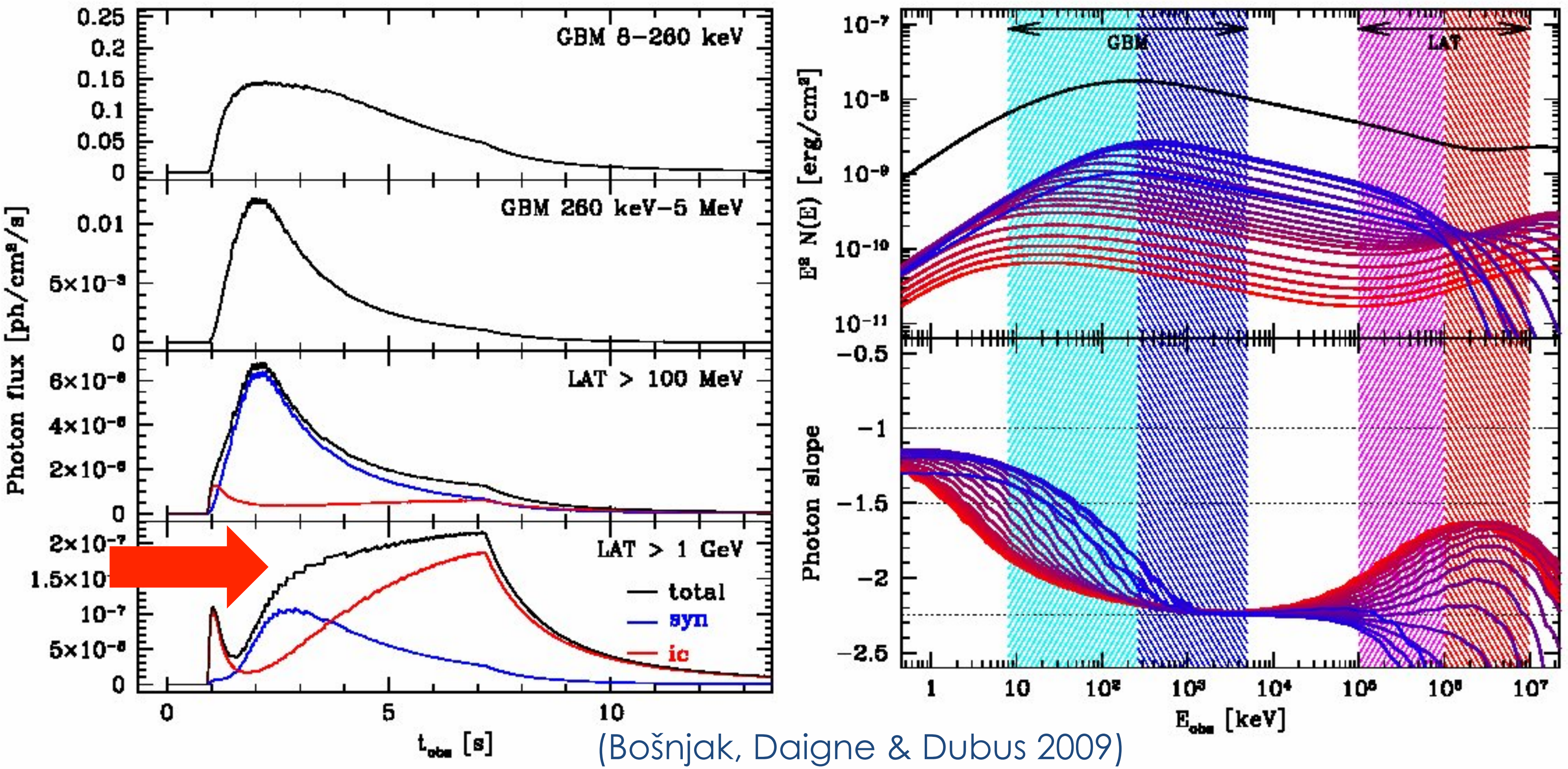


GRB 090926A (Ackermann et al. 2011)

- In GRB 090926A, the spectral shape of the cutoff cannot be well characterized:
  - $\gamma\gamma$ opacity (shape depends on the time interval) ?
  - intrinsic curvature of the HE component ?

GeV delayed onset & additional components

- **Intrinsic spectral evolution ?** (e.g. emergence of an IC component : leptonic scenario with low magnetic field)

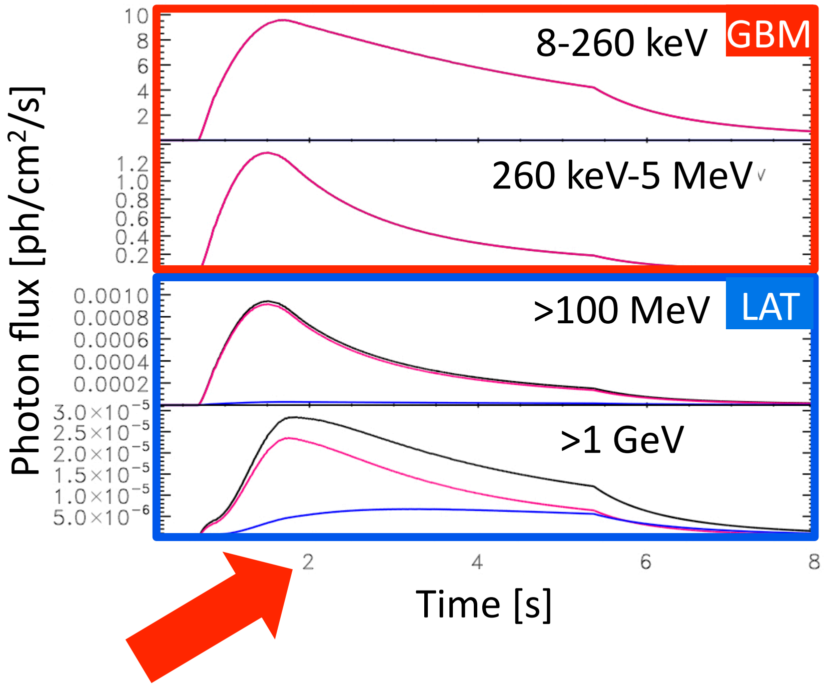


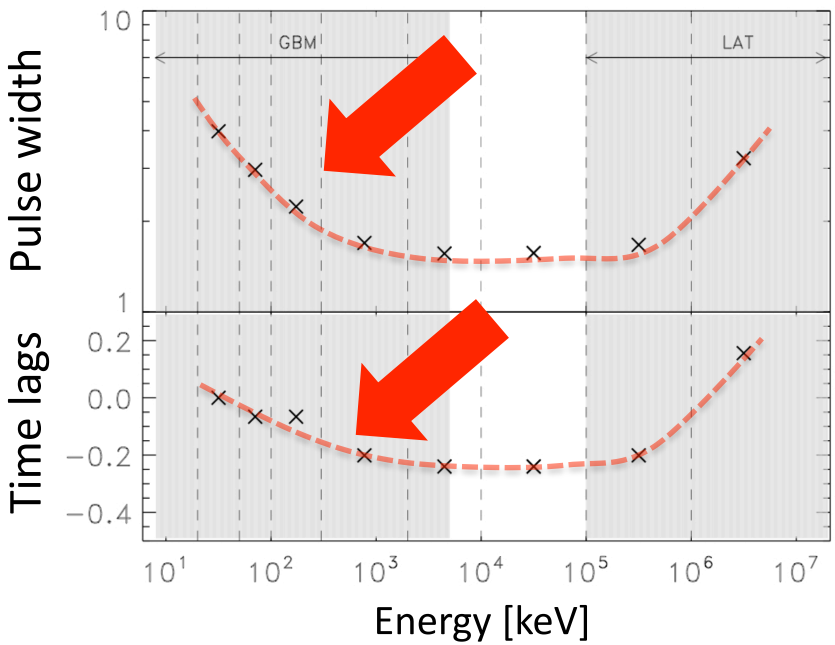
(Bošnjak, Daigne & Dubus 2009)

It seems difficult to have a delay > typical pulse duration in this scenario (see also Asano & Meszaros 2012)

GeV delayed onset & additional components

- **Intrinsic spectral evolution ?** (e.g. emergence of an IC component : leptonic scenario with low magnetic field)



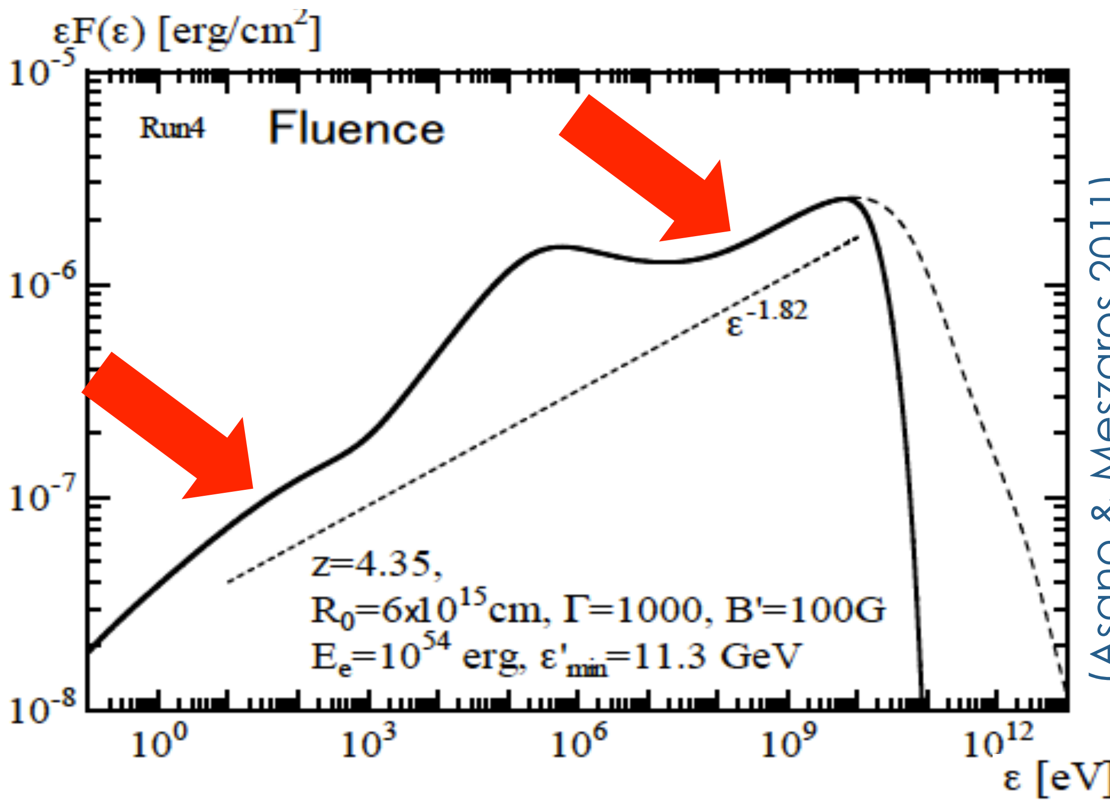


Example taken from
Bošnjak & Daigne 2013 in preparation

Different spectral evolution in GBM NaI/BGO and LAT
(see Foley et al. 11)

GeV delayed onset & additional components

- **Intrinsic spectral evolution ?** (e.g. emergence of an IC component : leptonic scenario with low magnetic field)



(Asano & Meszaros 2011)

Similar conclusions about the extra leptonic component are obtained by Asano & Meszaros 2011

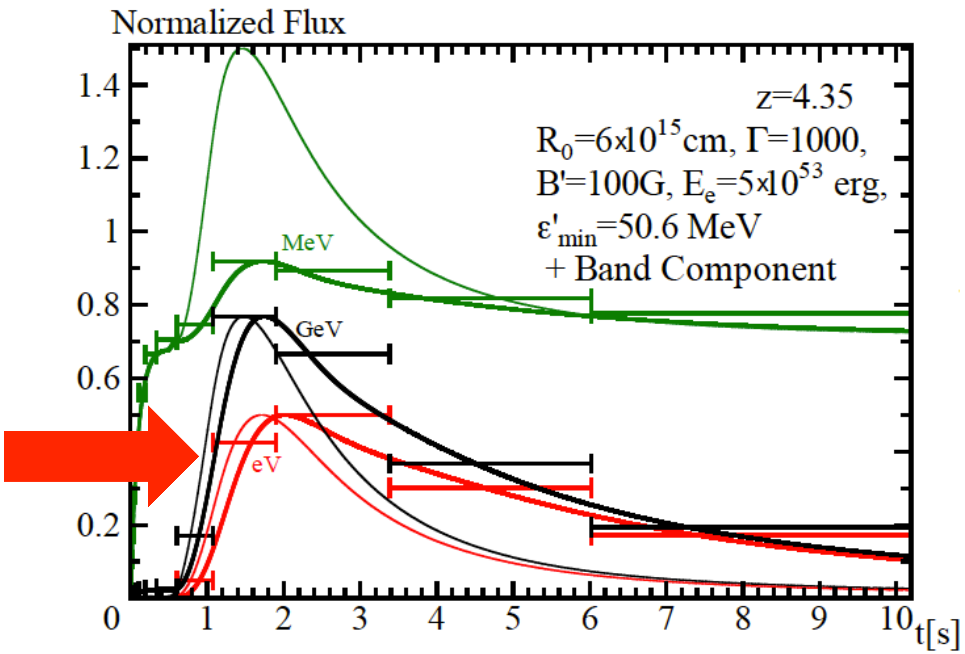
In addition, their results show that the late synchroton emission may explain the X-ray excess.

GeV delayed onset & additional components

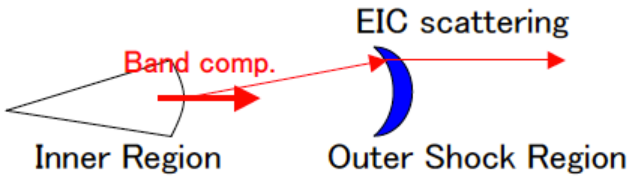
- Intrinsic spectral evolution (leptonic scenario with low B : IC component)

- **External inverse Compton**

-seed photons = jet cocoon, photosphere, …
-relativistic electrons = internal shocks
(Toma et al. 2009; Toma et al. 2011 ; …)



Thick: Fully-beamed approximation
Thin dashed: Isotropic approximation



(Asano & Meszaros 2011)

This model shows naturally several components in the spectrum.
Problem : energy budget (needs a large number of accelerated e^-)

GeV delayed onset & additional components

- Intrinsic spectral evolution (leptonic scenario with low B : IC component)
- External inverse Compton

- **Emergence of a hadronic component ?** -delay = proton acceleration
  -GeV emission = p synchrotron or hadronic cascade

  (Bötcher & Dermer 1998 ; Gupta & Zhang 2007 ; Asano & Inoue 2007 ; Asano, Inoue & Meszaros 2009 ; ...)

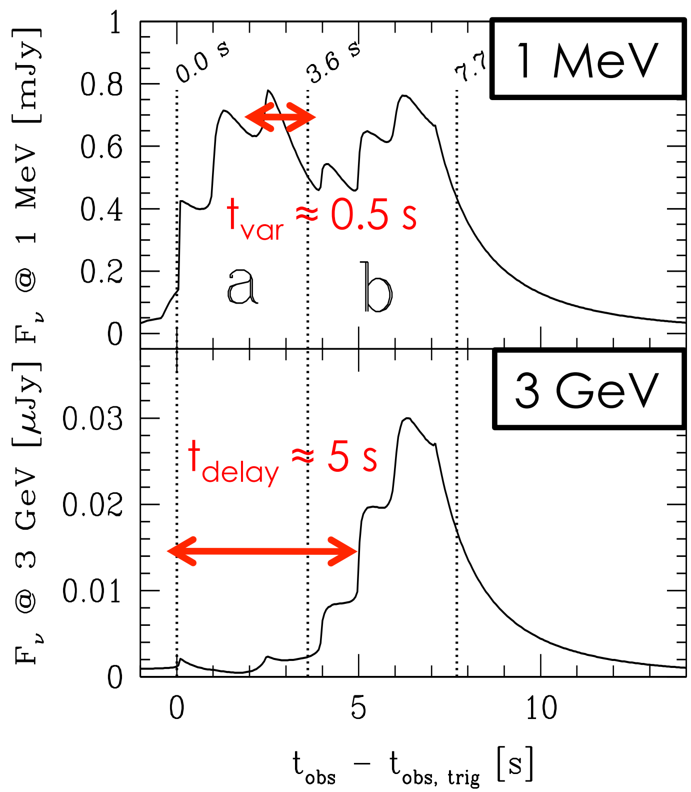
This scenario can produce larger delays

However :

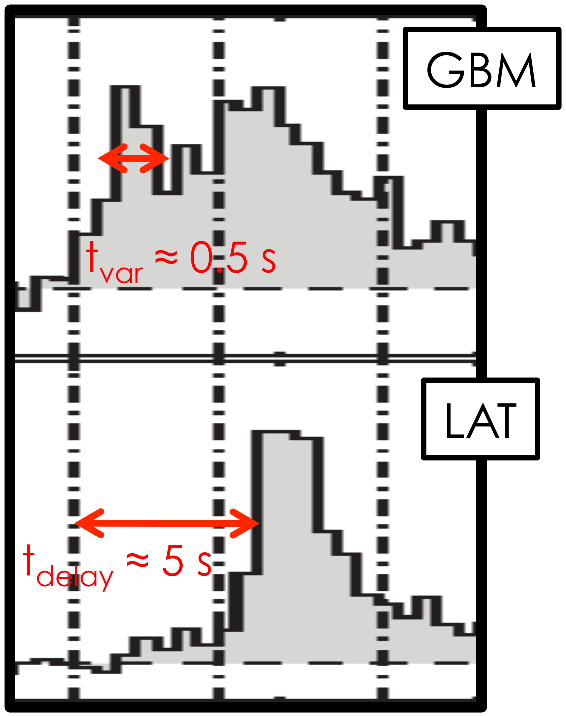
efficiency is low and these models require a huge energy injected in protons.
(see e.g. Asano & Meszaros 2012)

Delayed onset of the GeV emission

- Intrinsic spectral evolution (leptonic scenario with low B : IC component)
- External inverse Compton
- Emergence of a hadronic component
- **Delay : opacity effect ?** (Granot et al. 08 ; Hascoët, Daigne, Mochkovitch & Vennin 12)



GRB 080916C bins a+b : model



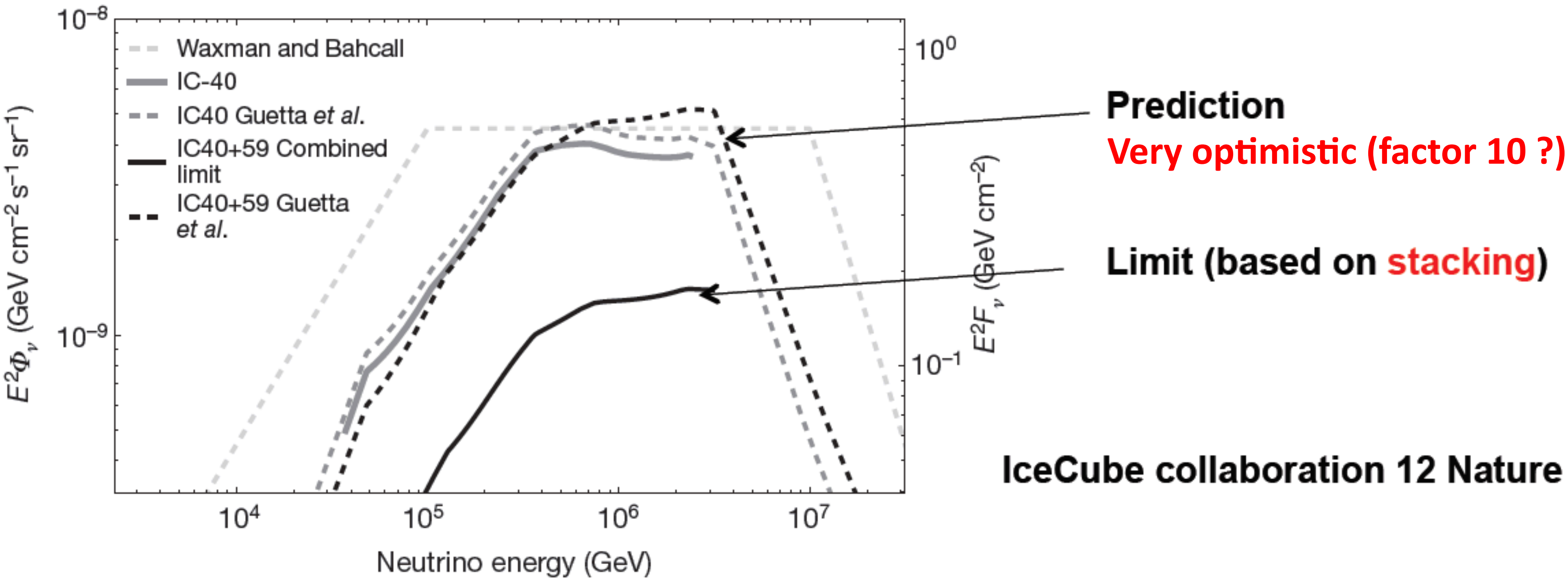
Fermi observations (Abdo et al. 2009)

-Delays larger than the variability timescale can be reproduced.
-see also Bosnjak & Kumar 2011:
delay due to opacity effects in magnetized jets.

Hadronic component ?

- Another test: HE neutrinos

$$p+\gamma / p \rightarrow N\pi + X \qquad \pi^{\pm} \rightarrow \nu_{\mu} + \bar{\nu}_{\mu} + \nu_{e}(\bar{\nu}_{e}) + e^{\pm}$$



IceCube collaboration 12 Nature

(Taken from Murase 2013)

- ICECUBE can eliminate very optimistic models
- With a larger integration time (>10 yr), more realistic models could be tested

GRB prompt emission models

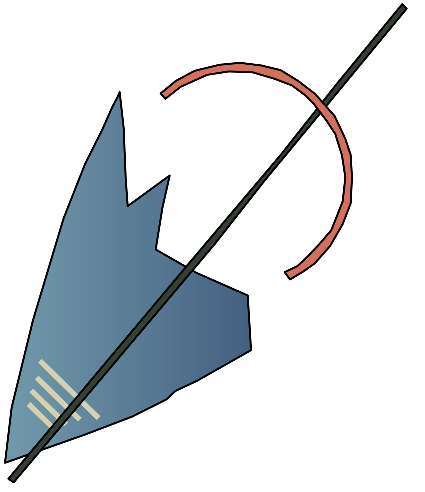
- **Is there a standard scenario ?**
- **Three main possibilities :** photosphere
  internal shocks
  reconnection
- **With several variants…**
- **Some variants have been eliminated**
(standard fireball, SSC spectrum, …)

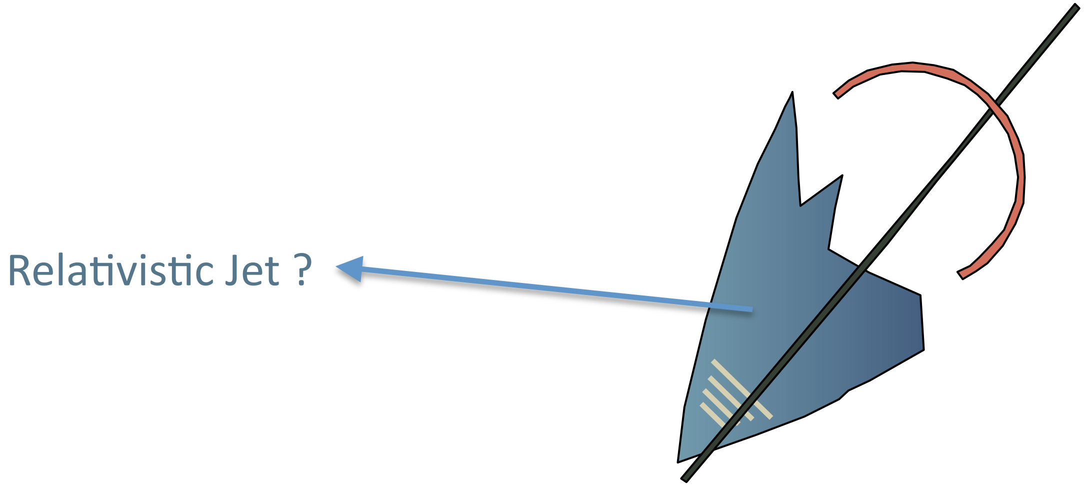
- **Large theoretical uncertainties in each of these three scenarios**

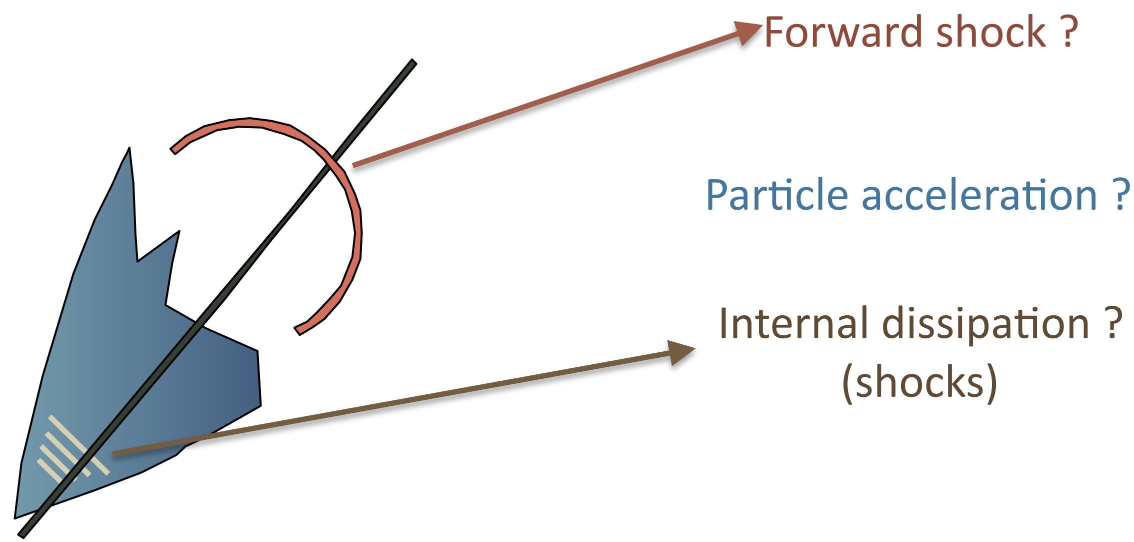
Main uncertainties:

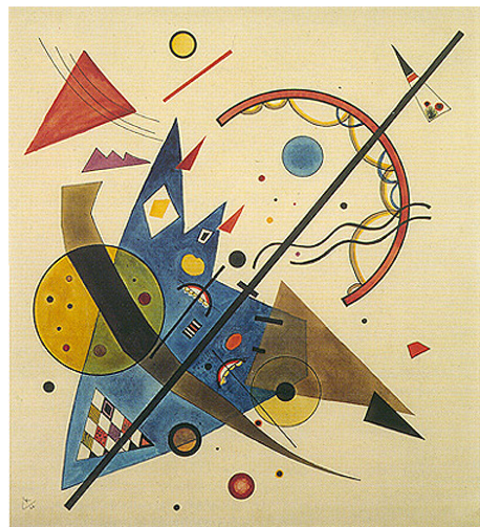
- Jet acceleration
- Microphysics (shock acceleration, reconnection, …)

Conclusion




Relativistic Jet ?


Forward shock ?
Particle acceleration ?
Internal dissipation ?
(shocks)



Kandinksy – Curves and sharp angles - 1923

Missing physics ?

Kandinksy – Curves and sharp angles - 1923

or missing observations…

Post Swift/Fermi era ?

CTA ; SVOM

+ multi-wavelength/messenger context,
including gravitational waves