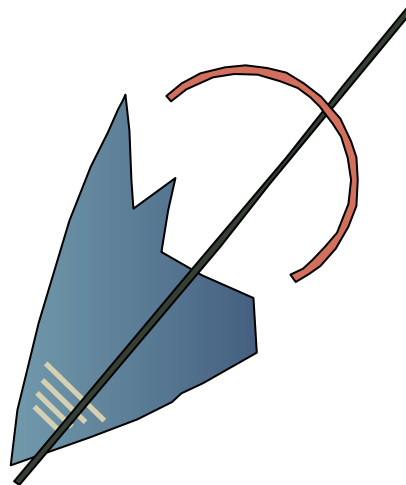


Gamma-Ray Bursts

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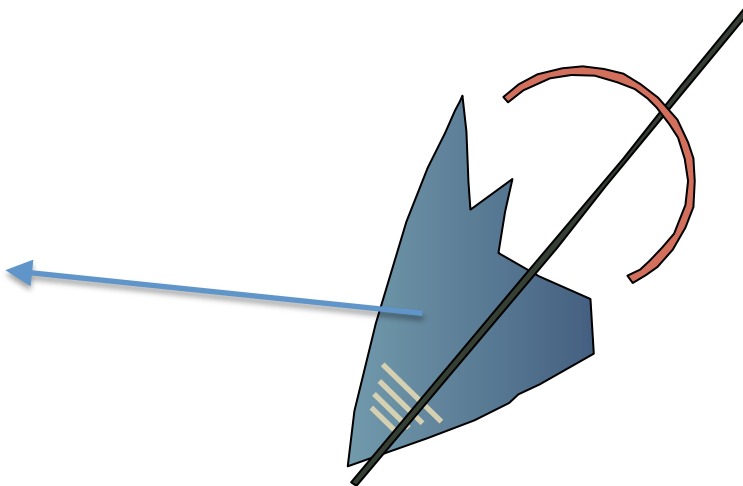


Gamma-Ray Bursts

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Relativistic Jet ?

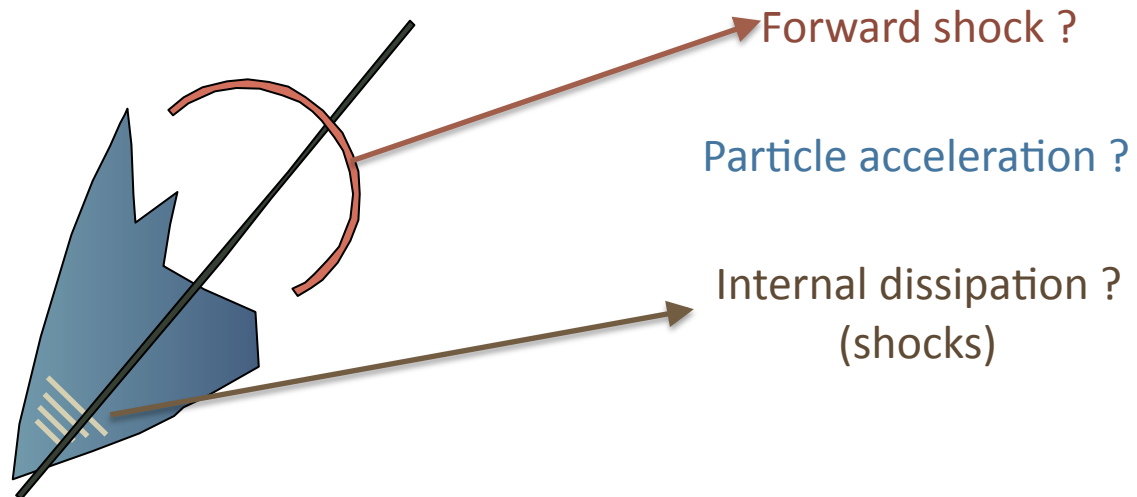


Gamma-Ray Bursts

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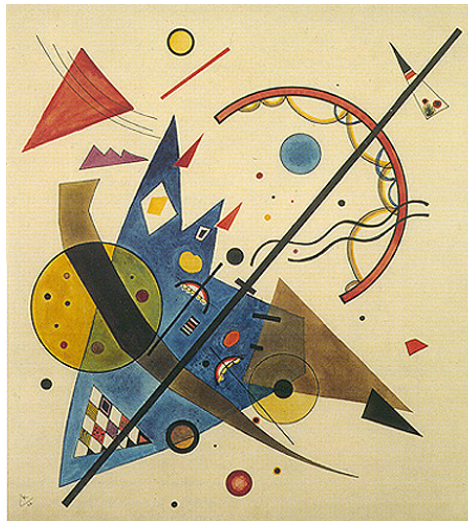


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Gamma-Ray Bursts

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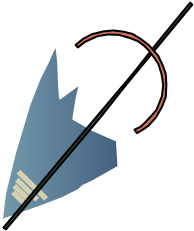
Kandinsky – Curves and sharp angles - 1923

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

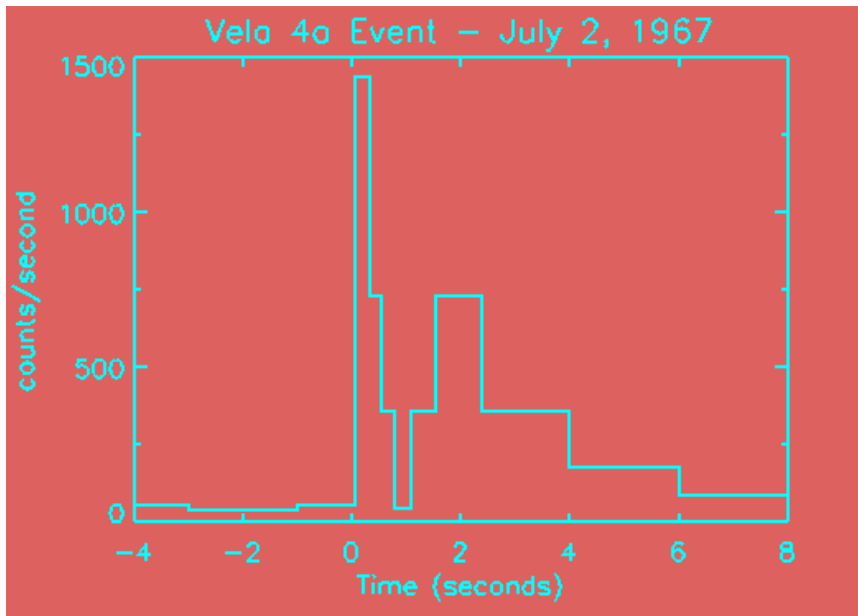
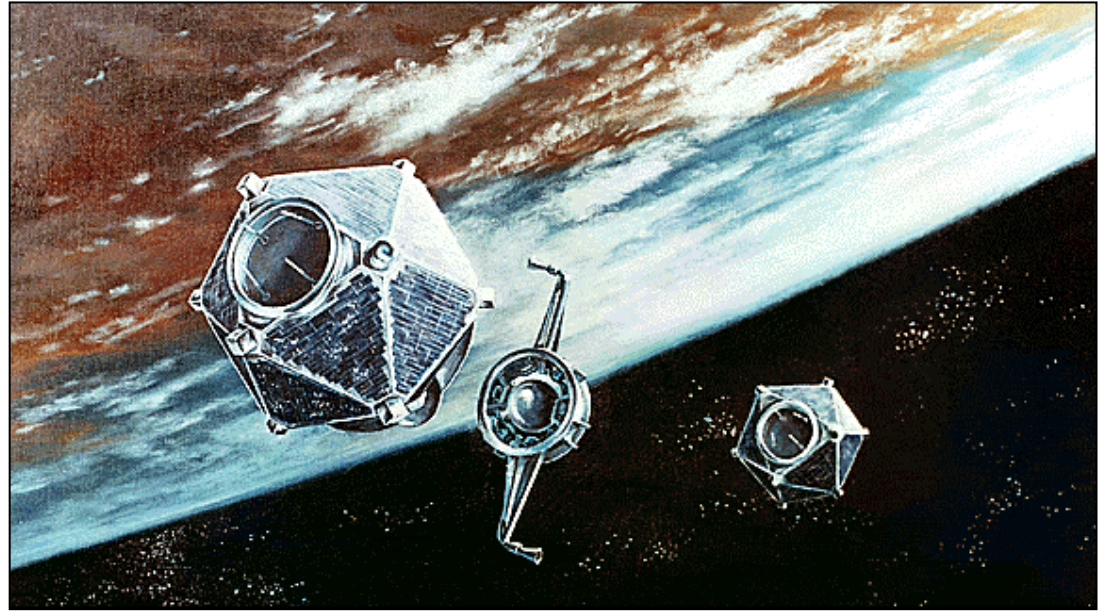
Conclusion



1– Main observations

Gamma-Ray Bursts were discovered in 1967

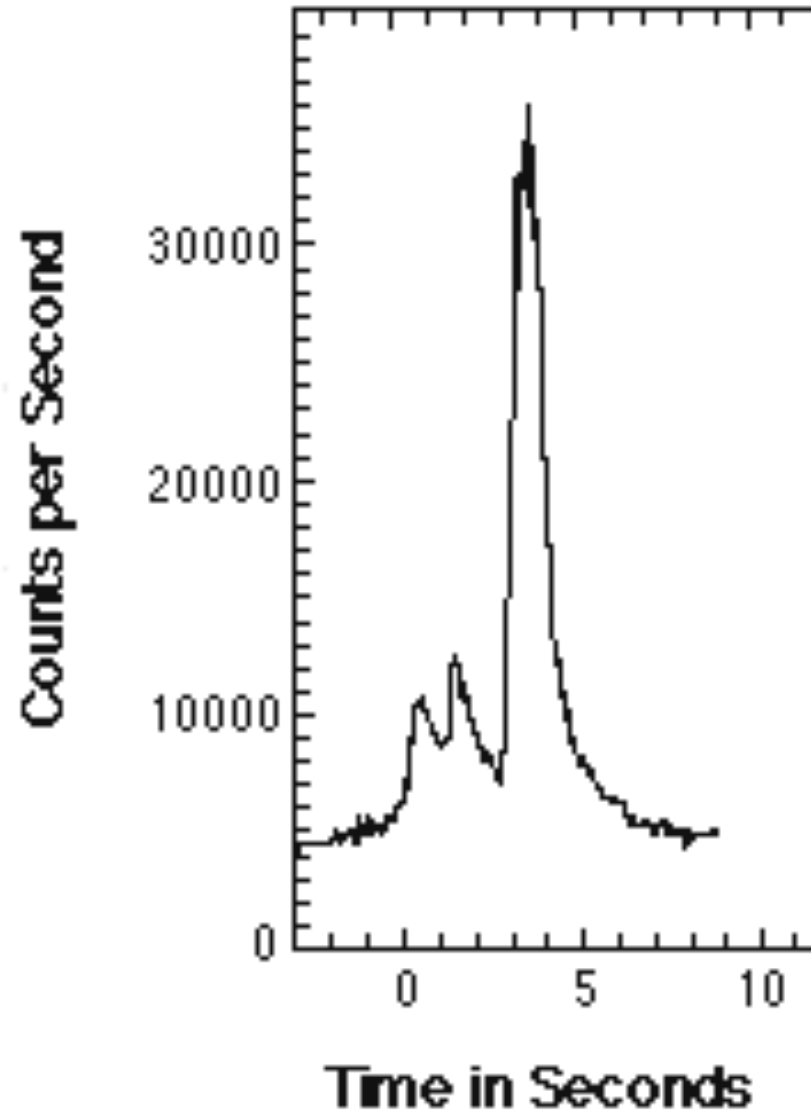
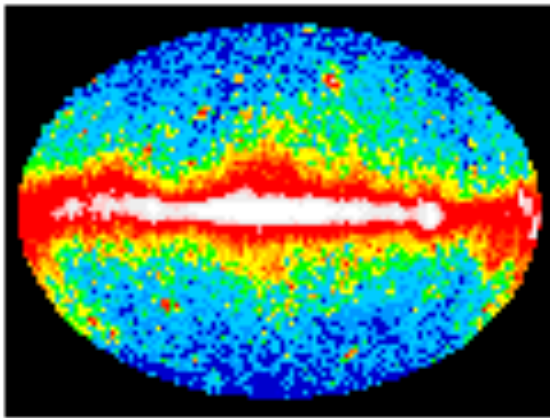
VELA : 3 pairs of satellites,
launched in 1963, 1964 & 1965



The first GRB

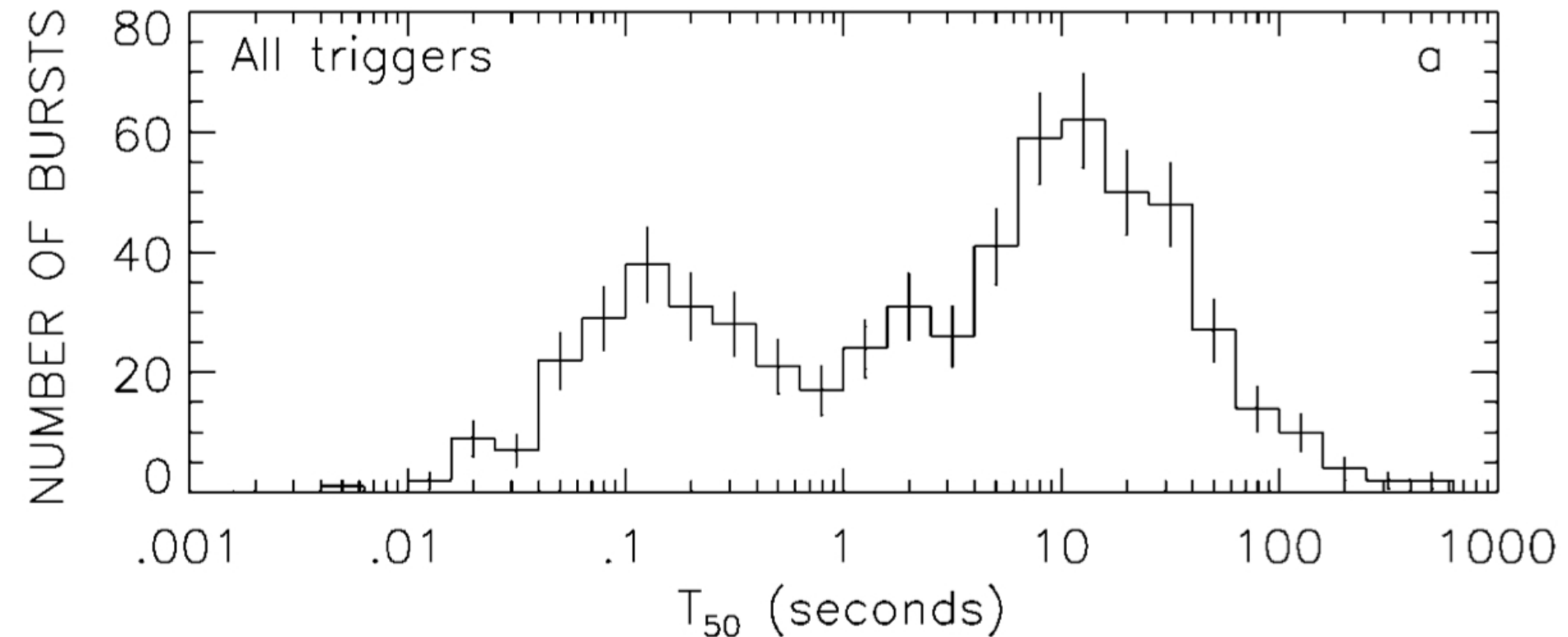
Discovery paper : [Klebesadel et al. 1973](#)

What is a Gamma-Ray Burst ?



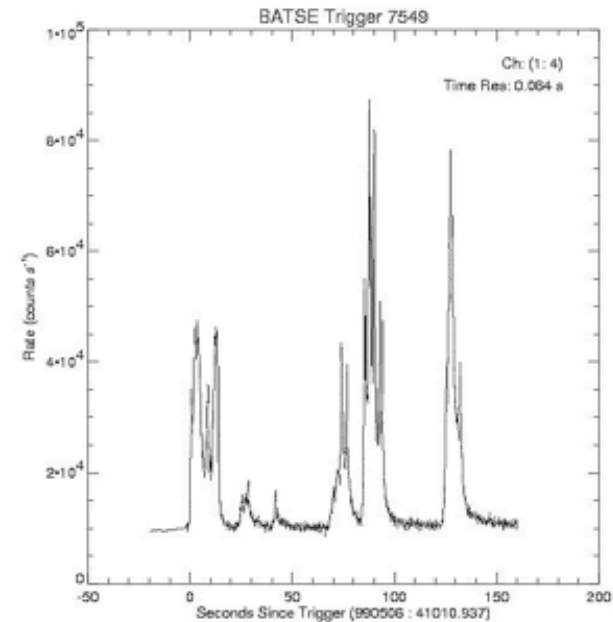
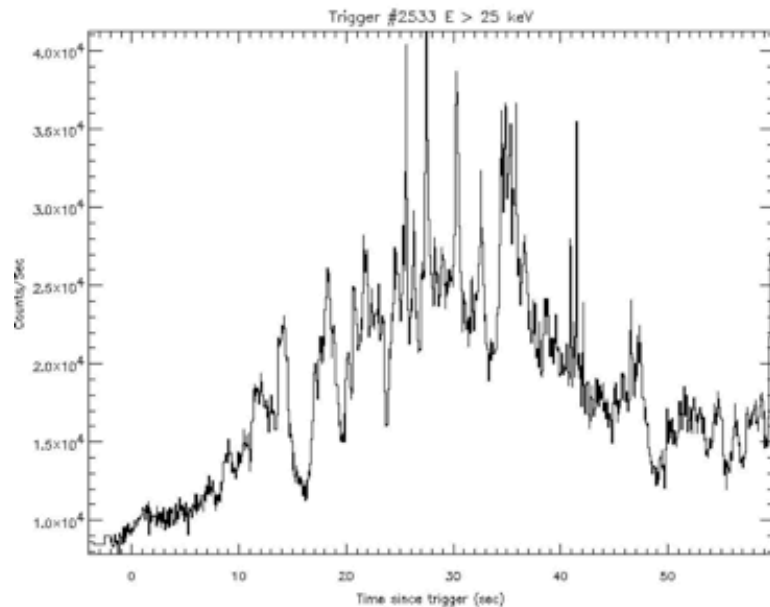
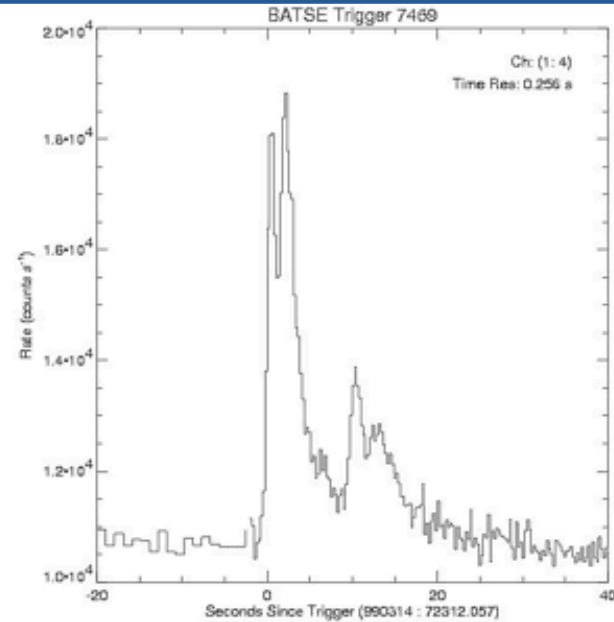
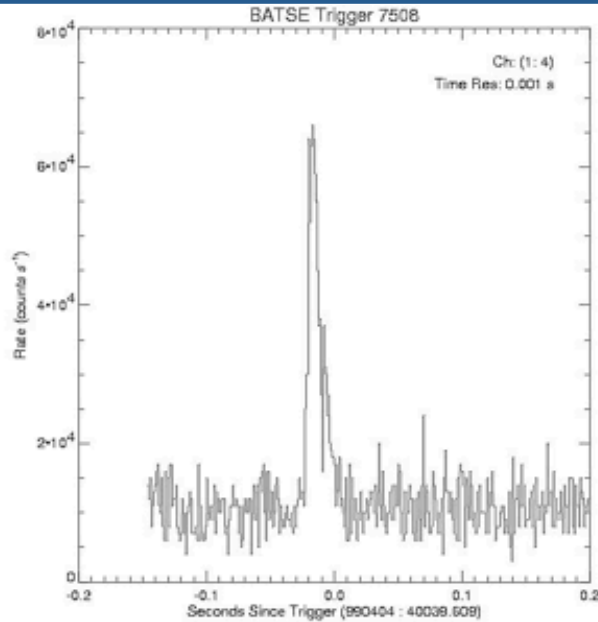
Duration: short and long bursts

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

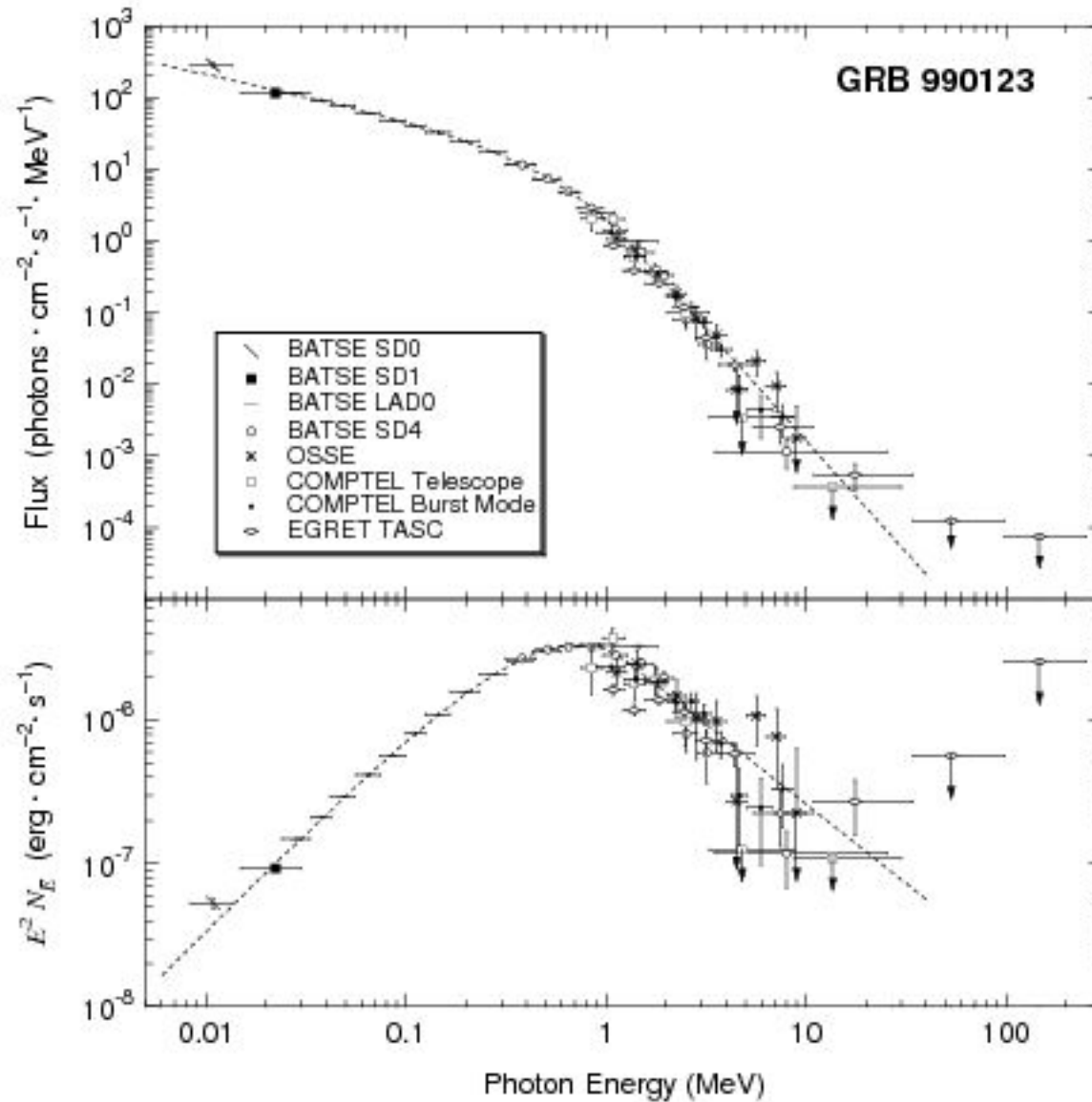


The 4th BATSE catalog (Paciesas et al. 1999)

Lightcurves: variability and diversity



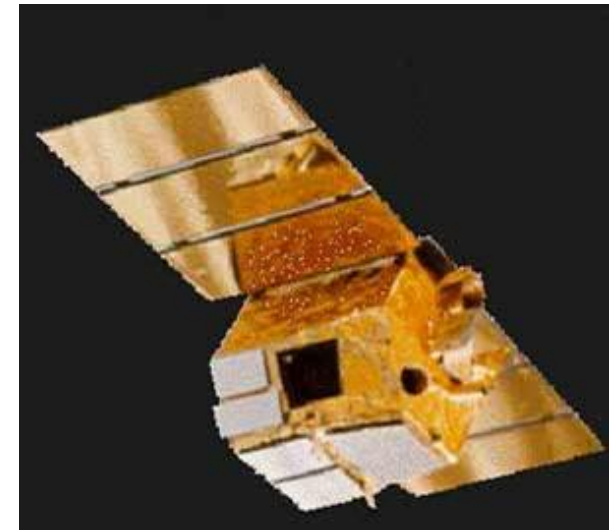
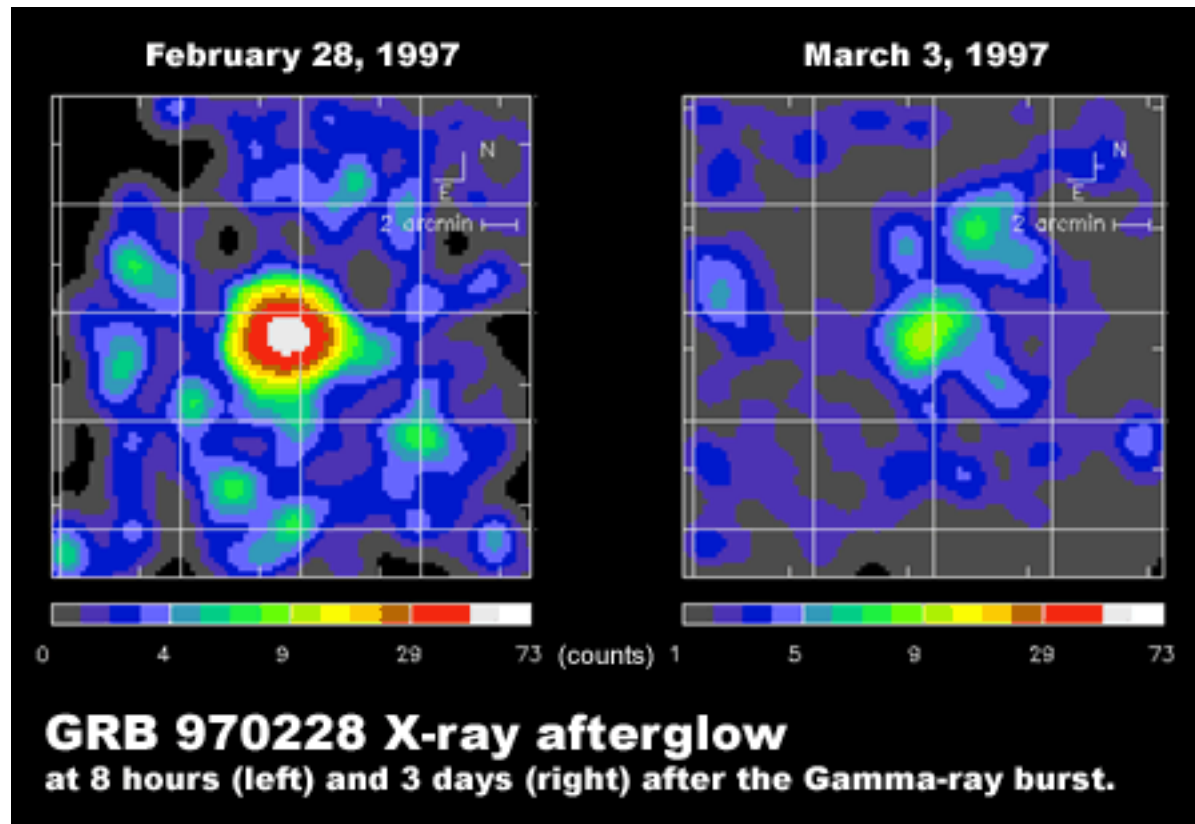
Non-thermal spectrum



Briggs et al. 1999

Short bursts are harder than long bursts.

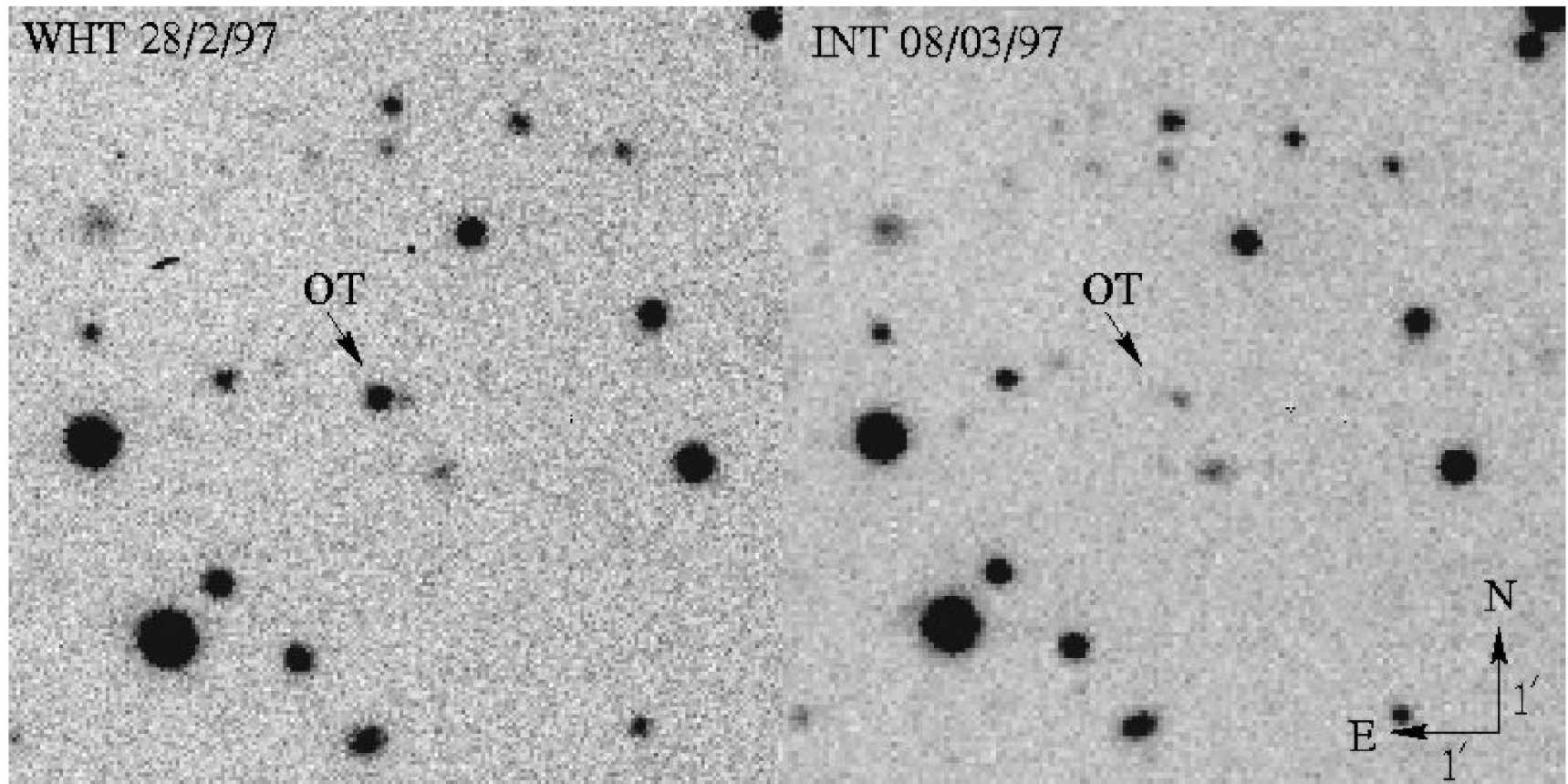
X-ray afterglows (Beppo-SAX, 1997)



Beppo-SAX

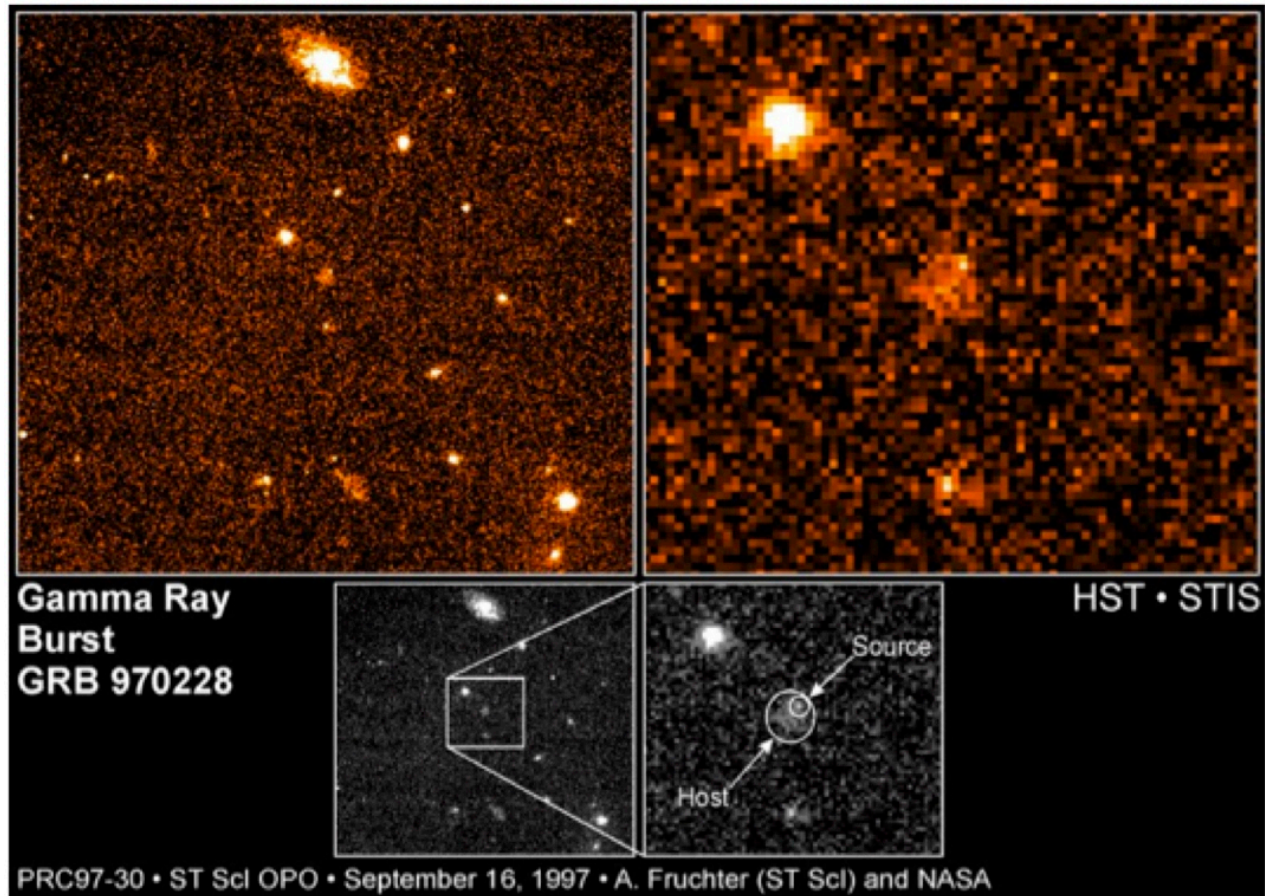
1997: the first optical afterglow

GRB 970228, van Paradijs et al.



van Paradijs et al. 1997

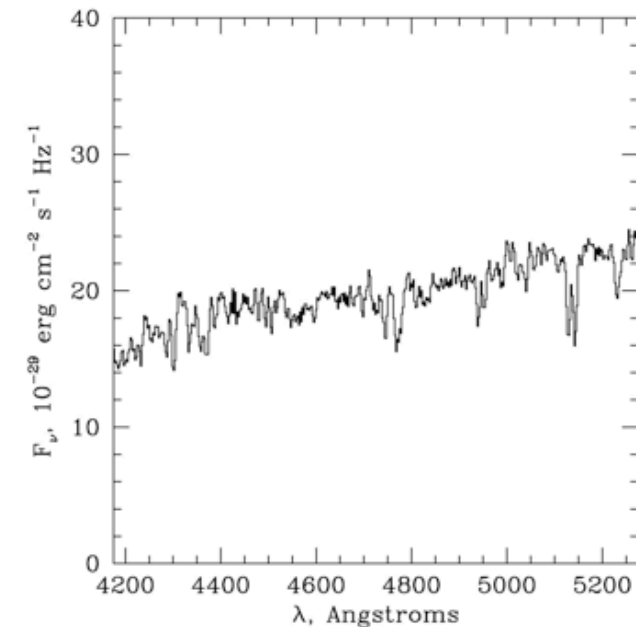
Afterglows: the host galaxy of GRB 970228



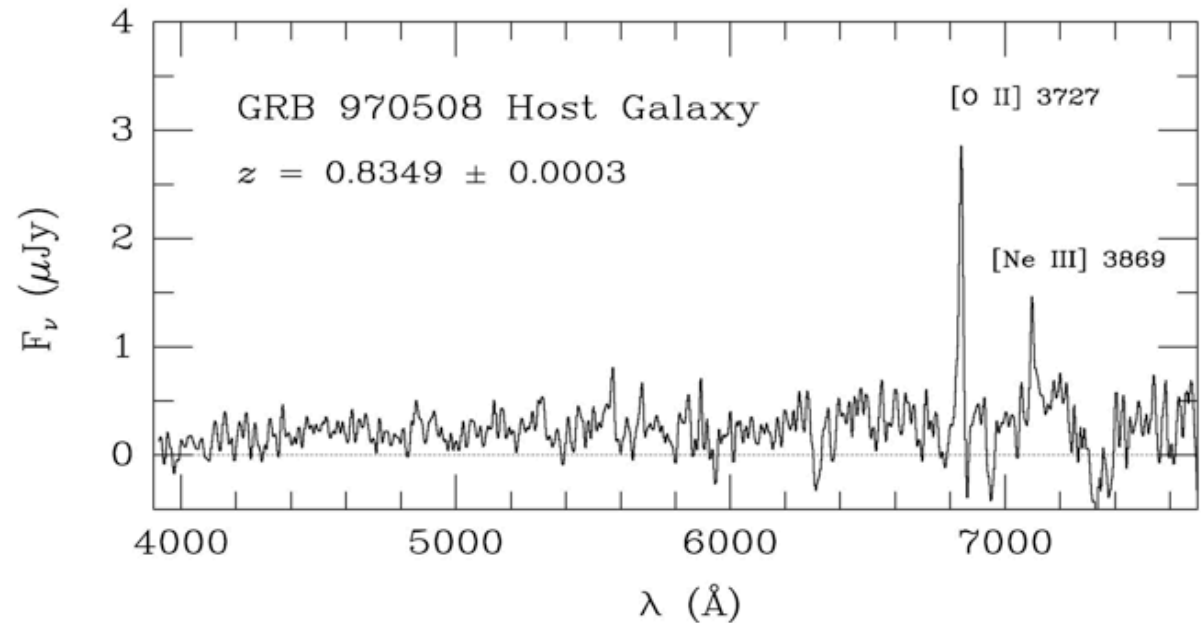
Fruchter et al. 1997

Afterglows: the first optical spectrum

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

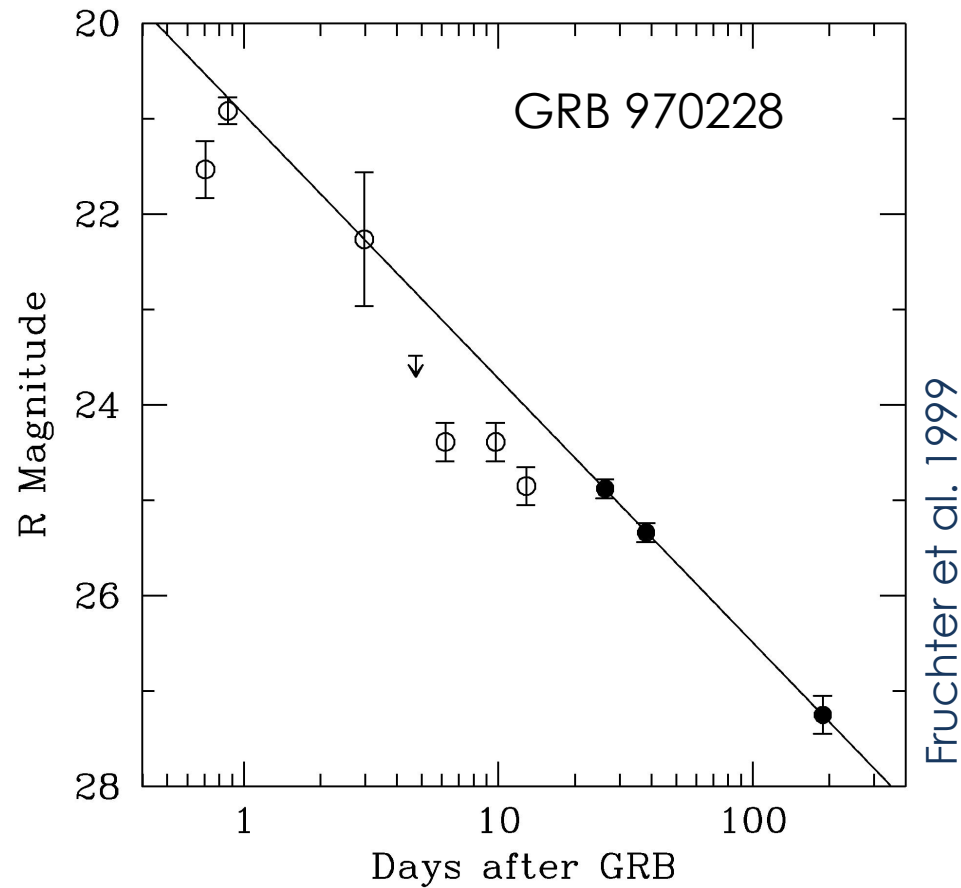


Metzger et al. 1997

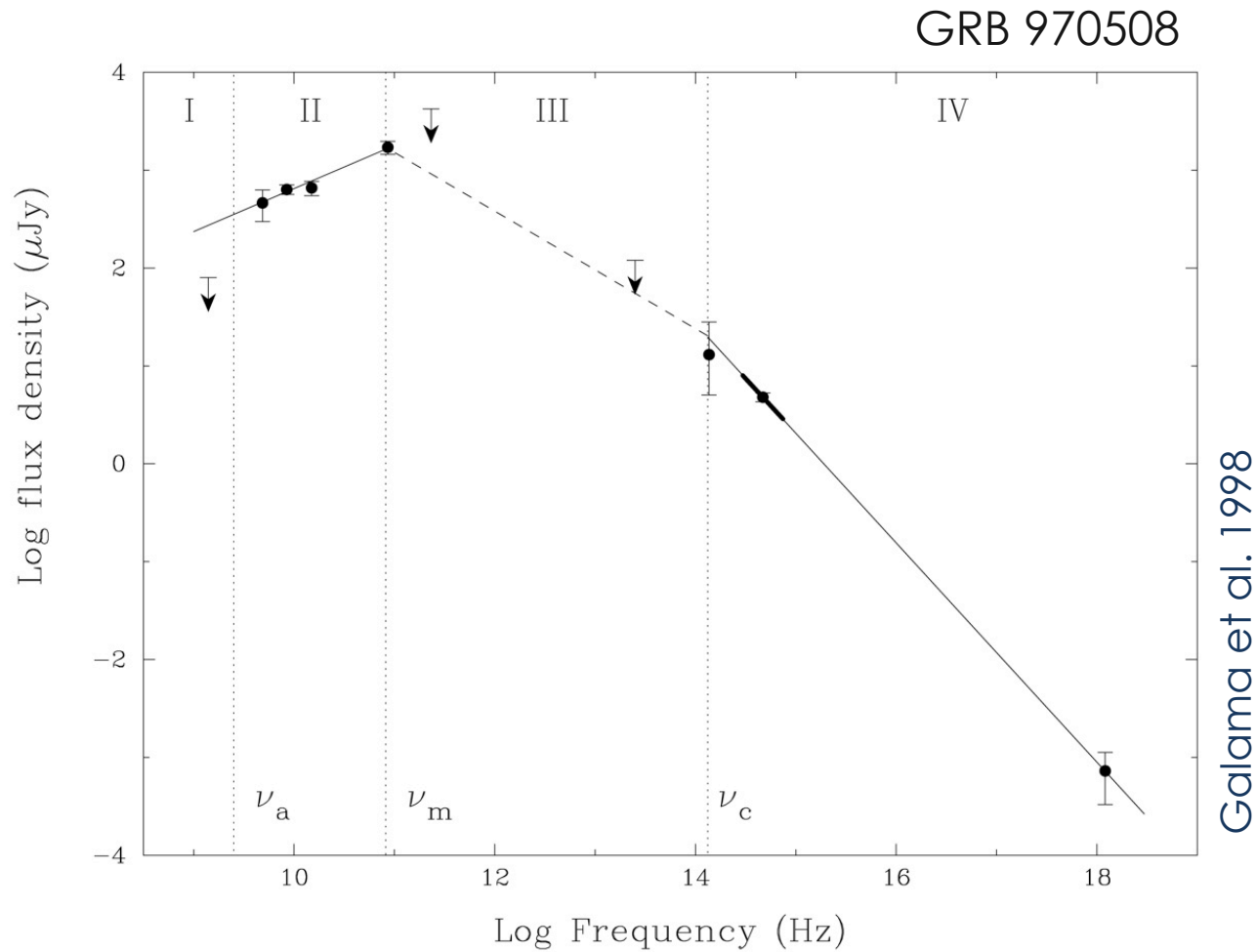


Bloom et al. 1998

Afterglows: the first light curve



Afterglow spectrum: radio to X-rays



Synchrotron spectrum from shock accelerated electrons ?

Reducing the number of models...

Table 1

#	Author	Year	Reference	Main	Ref	Place	Description
Pub	Body	Body					
1.	Chugate	1968	CSPire, 68, 3478	ST		COO	NS shock stellar surface in distant galaxy
2.	Chugate	1974	ApJ, 187, 503	ST		COO	Type II SN shock wave, low Comp out at stellar surface
3.	Stacker et al.	1975	Nature, 245, P970	ST		COO	Stellar superflares from nearby star
4.	Stacker et al.	1975	Nature, 245, P970	WD		COO	Superflares from nearby WD
5.	Burck et al.	1976	ApJ, 196, 537	N	COM		Radio count predicted to collide with old galactic NS
6.	Lamb et al.	1976	Nature, 246, P919	WD	ST	COO	Accretion onto WD from flare in companion
7.	Lamb et al.	1976	Nature, 246, P919	N	ST	COO	Accretion onto NS from flare in companion
8.	Lamb et al.	1976	Nature, 246, P919	RR	ST	COO	Accretion onto RR from flare in companion
9.	Parry	1976	Ap & SS, 35, 111	N		RAIO	NS shock contained by external pressure waves, explains
10.	Chugate et al.	1976	ApJ, 187, 510	ST		COO	Relativistic iron dust grains upstream after collision
11.	Stacker et al.	1976	ApJ, 187, 537	ST		COO	Directed stellar flare on nearby star
12.	Schlicke	1976	Sci-Astron, 18, 390	WD	COM	COO	Onset from system's cloud stellar WD
13.	Schlicke	1976	Sci-Astron, 18, 390	N	COM	COO	Onset from system's cloud stellar NS
14.	Rumery et al.	1976	Ap & SS, 35, 35	ST		COO	Absorption of neutron radiation from SN in stellar envelope
15.	Rumery et al.	1976	Ap & SS, 35, 35	ST	N	COO	Thermal emission when small star heated by SN shock wave
16.	Rumery et al.	1976	Ap & SS, 35, 35	N		COO	Stellar matter from NS explosion
17.	Pacini et al.	1976	Nature, 241, 309	N		COO	NS crustal stagnation glitch, should time coincide with GRB
18.	Sticker et al.	1976	Nature, 241, 309	WH		COO	White hole nuclei spectrum that follows with time
19.	Teggen	1976	AdA, 4, 21	N		RAIO	NS quadrupole star vibrations, changing E & B fields
20.	Chugate	1976	ApJ, 183, 175	WD		COO	Chromosphere inside WD with high B field produces flare
21.	Polubny et al.	1976	Ap & SS, 34, 205	AGN	ST	COO	Collapsar of supermassive body in nucleus of active galaxy
22.	Sticker et al.	1976	Ap & SS, 35, 321	WH		COO	WH surface synchrotron emission, inverse Compton scattering
23.	Piran et al.	1976	Nature, 256, 133	RR		COO	low Comp out deep in synchrotron of fast rotating, accreting RR
24.	Fabian et al.	1976	Ap & SS, 43, 77	N		COO	NS crustal shock NS surface
25.	Chugate	1976	Ap & SS, 43, 85	WD		COO	Magnetic WD surface MHD instabilities, flares
26.	Malin	1976	ApJ, 208, 130	WD		COO	Thermal radiation from free neutron WD
27.	Woodley et al.	1976	Nature, 265, 101	N		COO	Carbon detonation from accreted matter onto NS
28.	Lamb et al.	1977	ApJ, 217, 197	N		COO	Mag grating of accreted disk around NS causes sudden accretion
29.	Piran et al.	1977	ApJ, 214, 208	RR		COO	Instability in accretion onto rapidly rotating RR
30.	Daguerre	1979	Ap & SS, 43, 317	AGN		COO	Charged integral red dust grains return red eye, break up
31.	Teggen	1980	AdA, 47, 224	WD		COO	WD surface nuclear burst causes chromospheric flares
32.	Teggen	1980	AdA, 47, 224	N		COO	NS surface nuclear burst causes chromospheric flares
33.	Rumery et al.	1981	Ap & SS, 75, 330	N		COO	NS vibrations heat star to pair produce, annihilate, spray out
34.	Newman et al.	1980	ApJ, 243, 519	N	AST	COO	Antennae from interstellar medium into NS
35.	Rumery et al.	1980	Nature, 287, 133	N	RAIO	COO	NS core quake caused by phase transition, vibrations
36.	Rumery et al.	1981	ApJ, 249, 303	N	AST	COO	Antennae into NS, B-field confines mass, creates high temp
37.	Mitrofanov et al.	1981	Ap & SS, 77, 469	N		COO	Relativistic shock caused by MHD waves in NS outer layers
38.	Chugate et al.	1981	ApJ, 249, 771	N	AST	COO	Antennae into NS, tidally disrupted, heated, ejected along B lines
39.	van Duyn	1981	ApJ, 249, 207	N	AST	COO	Antennae enters NS B field, dragged to surface collision
40.	Konstantin	1982	Quell, 20, 72	AGN		COO	Magnetic reconnection at heliopause
41.	Kato	1982	ApJ, 260, 371	N		COO	NS flares from pair plasma confined in NS magnetosphere
42.	Woodley et al.	1982	ApJ, 258, 718	N		COO	Magnetic reconnection after NS surface B field
43.	Pyroly et al.	1982	ApJ, 258, 718	N		COO	NS fusion recovery on NS B pole before the flares
44.	Rumery et al.	1982	AdA, 113, 342	N		COO	α -capture triggers B field triggers the flares on NS surface
45.	Mitrofanov et al.	1982	MNRAS, 200, 1003	N		COO	0.5 second cycle rise in red shadow giving red eye, low C out
46.	Pyroly et al.	1982	Nature, 297, 363	N		COO	BB X-rays low Comp out by better overlying plasma
47.	Lipman et al.	1982	Ap & SS, 85, 410	N	HO	COO	RR matter accret on NS magnetosphere then outflows accretes
48.	Rumery et al.	1982	ApJ, 263, 171	WD		COO	Superficial collapse of WD into neutron, cooling NS
49.	Ward et al.	1982	Nature, 301, 401	N	ST	COO	NS accretion from low mass binary companion
50.	Rumery et al.	1983	Ap & SS, 88, 447	N		COO	Neutron rich elements to NS surface with quakes, outflows flares
51.	Rumery et al.	1984	Sci-Astron, 26, 62	N		COO	Thermomagnetic explosion beneath NS surface
52.	Ellison et al.	1983	AdA, 128, 302	N		RAIO	NS corequake + neutron heating yield GRB pulsations
53.	Rumery et al.	1983	AdA, 128, 309	N		COO	B field contains matter on NS cap allowing fusion
54.	Rumery et al.	1984	AdA, 136, 89	N		COO	NS surface core explosion causes small scale B reconnection
55.	Malin	1985	ApJ, 286, 751	N		COO	Recurrent disk instability causes sudden accretion
56.	Living	1984	ApJ, 283, 131	N		COO	Recurrent RR sharp during magnetic flare gives hot eye on
57.	Living et al.	1984	Nature, 310, 121	N		COO	NS magnetic fields get twisted, recombine, create flare
58.	Mitrofanov	1984	Ap & SS, 105, 245	N		COO	NS magnetosphere excited by starquake
59.	Eggleston	1985	ApJ, 281, 822	N		COO	Accretion instability between NS and disk
60.	Schlicke et al.	1985	MNRAS, 211, 345	N		COO	Old NS in Galactic halo undergoes starquake
61.	Teggen	1984	Ap & SS, 106, 189	N		COO	Weak B field NS spherically accretes, Comptonizes X-rays
62.	Uwe	1984	Ap & SS, 107, 193	N		COO	NS flares result of magnetic reconnection-instability
63.	Rumery et al.	1985	ApJ, 293, 96	N		COO	High Landau α -beam along B lines in cold star of NS
64.	Rappaport et al.	1985	Nature, 314, 243	N		COO	NS + low mass stellar companion gives GRB + optical flash
65.	Rumery et al.	1986	ApJ, 301, 114	N	COM	COO	NS takes through contact, debris into NS accretion
66.	Madison et al.	1986	Ap & SS, 120, 37	N		RAIO	Radially oscillating NS
67.	Sticker	1986	Nature, 321, 47	N		COO	Flare in the magnetosphere of NS accelerates α -along B-field
68.	Pyroly et al.	1986	ApJ, 308, 143	N		COO	Coma GRBs: red α - α opt 136 plasma outflow indicated
69.	Rumery et al.	1986	Sci-Astron, 28, 382	N		COO	Chain fusion of superheavy nuclei below NS surface during SN
70.	Alcock et al.	1986	PRL, 57, 2088	N	SS	COO	NS ejects strange star loop system rotating NS companion
71.	Valin et al.	1986	AdA, 207, 55	ST		COO	Magnetically active stellar system gives stellar flare
72.	Reid et al.	1987	ApJ, 308, 149	CO		COO	GRB result of energy released from core of cosmic string
73.	Living et al.	1987	Nature, 327, 399	N	COM	COO	Dark cloud around NS can explain soft gamma-ray emission
74.	McDonnell et al.	1988	Nature, 332, 234	GAS	AGN	COO	G-wave signal around NS, low wiggle across galaxy line cosmic

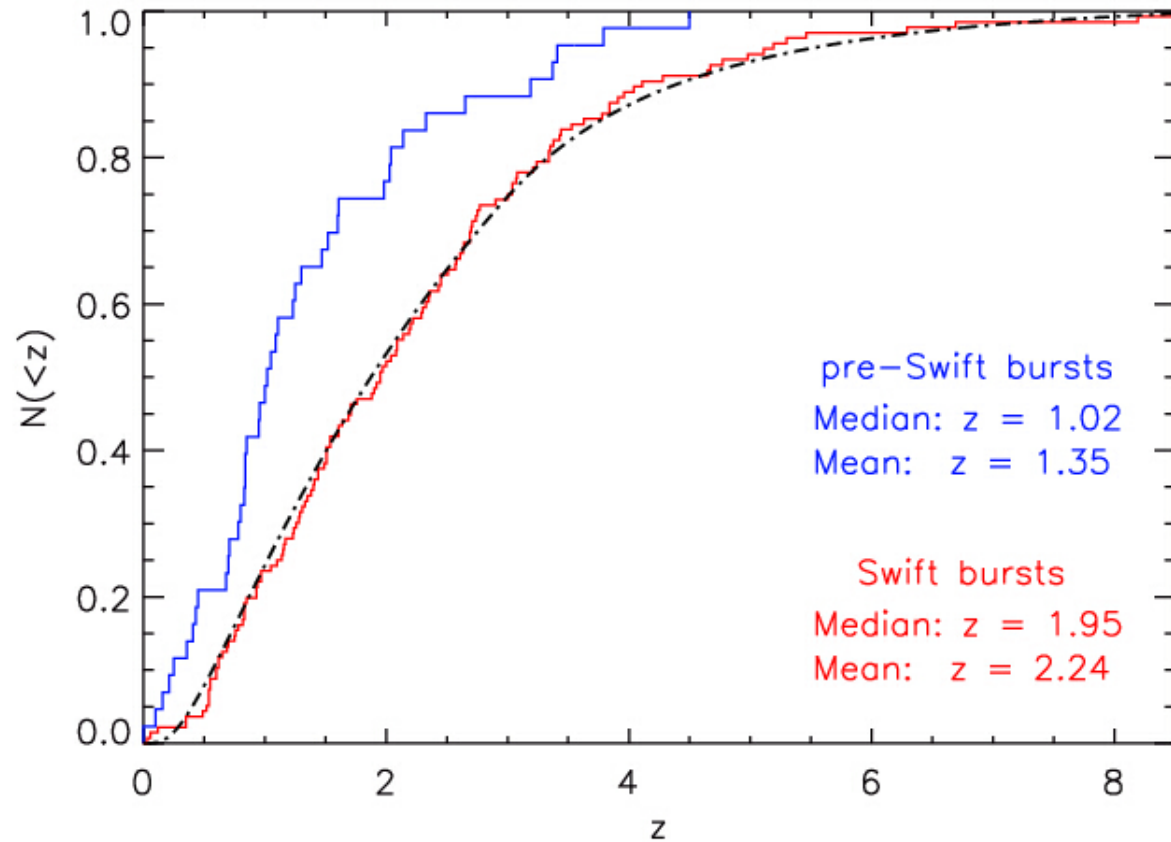
75.	Curtis	1988	ApJ, 327, 181	WD		COO	WD collapses, bursts to form new class of stable particles
76.	Molla	1988	ApJ, 333, 365	N		COO	Be/X-ray binary eye evidence to NS accretion GRB with recurrence
77.	Rumery et al.	1988	ApJ, 333, 386	N		COO	α - α cascade by aligned pulsed radio-magnetospheric emission
78.	Pyroly et al.	1988	ApJ, 335, 525	CO		COO	Energy released from core of cosmic string (revised)
79.	Mitrofanov et al.	1988	Nature, 335, 234	N		COO	Absorption features suggest separate colder regions near NS
80.	Molla	1988	Nature, 336, 458	N		COO	NS + accretion disk reflection explains GRB spectra
81.	Blum et al.	1989	ApJ, 344, 450	N		COO	NS atomic wave couple to magnetospheric Alfvén waves
82.	Trofanenko et al.	1989	Ap & SS, 154, 105	WH		COO	Kerr-Newman white holes
83.	Sticker et al.	1989	ApJ, 346, 350	N		COO	NS E-field accelerates electrons which then pair cascade
84.	Pyroly et al.	1989	ApJ, 346, 350	N		COO	Neutron absorption features indicate small cold area on NS
85.	Pyroly et al.	1989	ApJ, 325, 171	N		COO	Binary member leaves part of crust, through L1, into primary
86.	Rumery et al.	1989	ApJ, 347, 1145	N	COM	COO	Fast NS wanders through Oort clouds, fast WD bursts only optical
87.	Molla et al.	1989	ApJ, 346, 379	N		COO	Epistemic electromagnetic axial and Comp near on high-B NS
88.	Trofanenko	1989	Ap & SS, 156, 380	WH		COO	Efficient types of white, "gray" holes can exist GRBs
89.	Pyroly et al.	1989	Nature, 340, 126	N	SS	COO	NS + NS binary members collide, coalesce
90.	Wang et al.	1989	PRL, 63, 1580	N		COO	Cycle on & Raman scattering 20-40 keV dips, magnetized NS
91.	Alexander et al.	1989	ApJ, 344, 51	N		COO	GRB mag moment opacity in NS atmosphere
92.	Molla	1989	ApJ, 351, 955	N		COO	NS magnetospheric plasma oscillations
93.	Blum et al.	1989	ApJ, 348, 135	N		COO	Reaming of radiation necessary from magnetized neutron stars
94.	Mitrofanov et al.	1989	Ap & SS, 165, 137	N	COM	COO	Interstellar comets pass through dead pulsar's magnetosphere
95.	Pyroly et al.	1989	ApJ, 360, 197	N		COO	Compton scattering in strong NS magnetic field
96.	Blum et al.	1989	ApJ, 363, 612	N	HO	COO	Old NS accretion from ISM, surface goes outflow
97.	Pyroly et al.	1989	ApJ, 363, 218	N	SS	COO	NS-NS collision causes neutron collisions, drives super-Edd wind
98.	Pyroly et al.	1991	ApJ, 366, 143	RR	COO	COO	Scattering of microwave background photons by hot α -
99.	Pyroly et al.	1990	Nature, 345, 281	N	COM	COO	Young NS drifts through its own Oort cloud
100.	Trofanenko et al.	1991	ApJ, 375, 178, 217	WH		RAIO	White hole represents past simultaneous burst of gamma from 100TA
101.	Molla et al.	1991	ApJ, 373, 109	N		COO	NS B-field undergoes resistive tearing, accelerates plasma
102.	Rumery et al.	1991	ApJ, 378, 682	N		COO	Alfvén waves in non-collisional NS atmosphere accelerate particles
103.	Rumery et al.	1991	ApJ, 378, 690	N	SS	COO	Strange stars can bind energy in gamma ray and collide
104.	Blum et al.	1991	ApJ, 381, 219	N	HO	COO	Slow interstellar accretion onto NS, α -capture starquakes result
105.	Pyroly et al.	1992	ApJ, 385, 145	N		COO	Low mass X-ray binary evolve into GRB stars
106.	Woodley et al.	1992	ApJ, 381, 328	N		RAIO	Accreting WD collapsed to NS
107.	Uwe et al.	1992	ApJ, 388, 154	WD		COO	WD accretion to then faded NS, GRB, cosmic rays
108.	Rumery et al.	1992	ApJ, 390, 171	N	PLAN	COO	NS + planet magnetospheric interaction unstable
109.	Monson et al.	1992	ApJ, 387, 179	N	SS	COO	NS + NS collision produces antineutrino flash
110.	Curry	1992	ApJ, 381, 547	RR	ST	COO	Neutron stars tidally disrupted by galactic nucleus BH
111.	Uwe	1992	Nature, 357, 475	N		COO	WD collapses to form NS, B-field breaks NS rotation instantly
112.	Narayan et al.	1992	ApJ, 385, 148	N	SS	COO	NS + NS merger gives optically thick flares
113.	Narayan et al.	1992	ApJ, 393, 183	RR	N	COO	RR + NS merger gives optically thick flares
114.	Bratton	1992	ApJ, 394, 133	AGN	JET	COO	Synchrotron emission from AGN jets
115.	Monson et al.	1992	MNRAS, 257, 298	RR	N	COO	RR-NS have neutron collide to gamma in close flares
116.	Monson et al.	1992	MNRAS, 257, 298	N	SS	COO	NS-NS have neutron collide to gamma in close flares
117.	Uwe et al.	1992	ApJ, 391, 537	RR		COO	Pinpointed BHs evaporating could account for short hard GRBs
118.	Ross et al.	1992	MNRAS, 258, 41P	N	HO	COO	Relativistic flares occurred to collision when into ISM

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

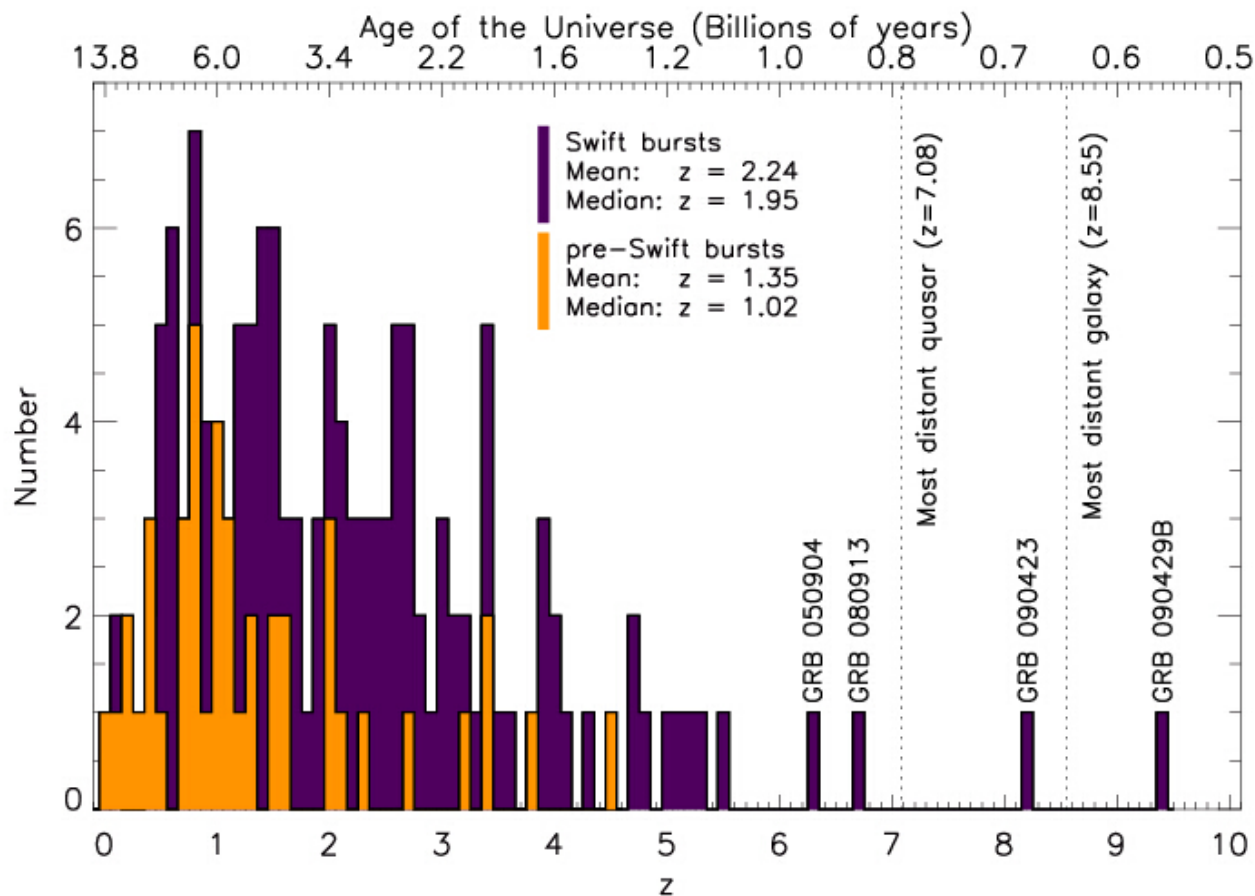


Jakobsson et al. 2006
(update November 2011)

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

Most GRBs in the sample are long GRBs.

GRB redshift distribution

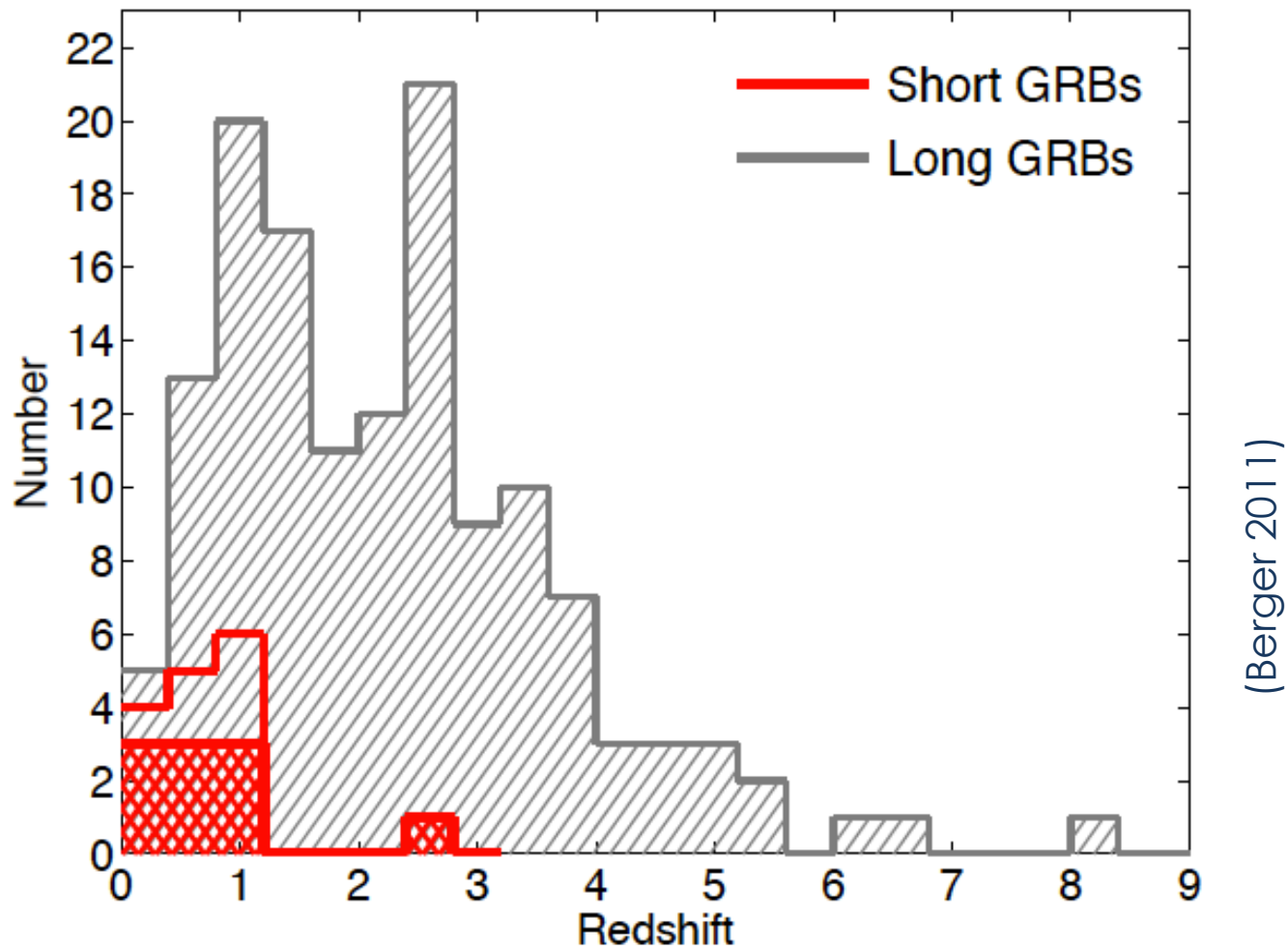


Jakobsson et al. 2006
(update November 2011)

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

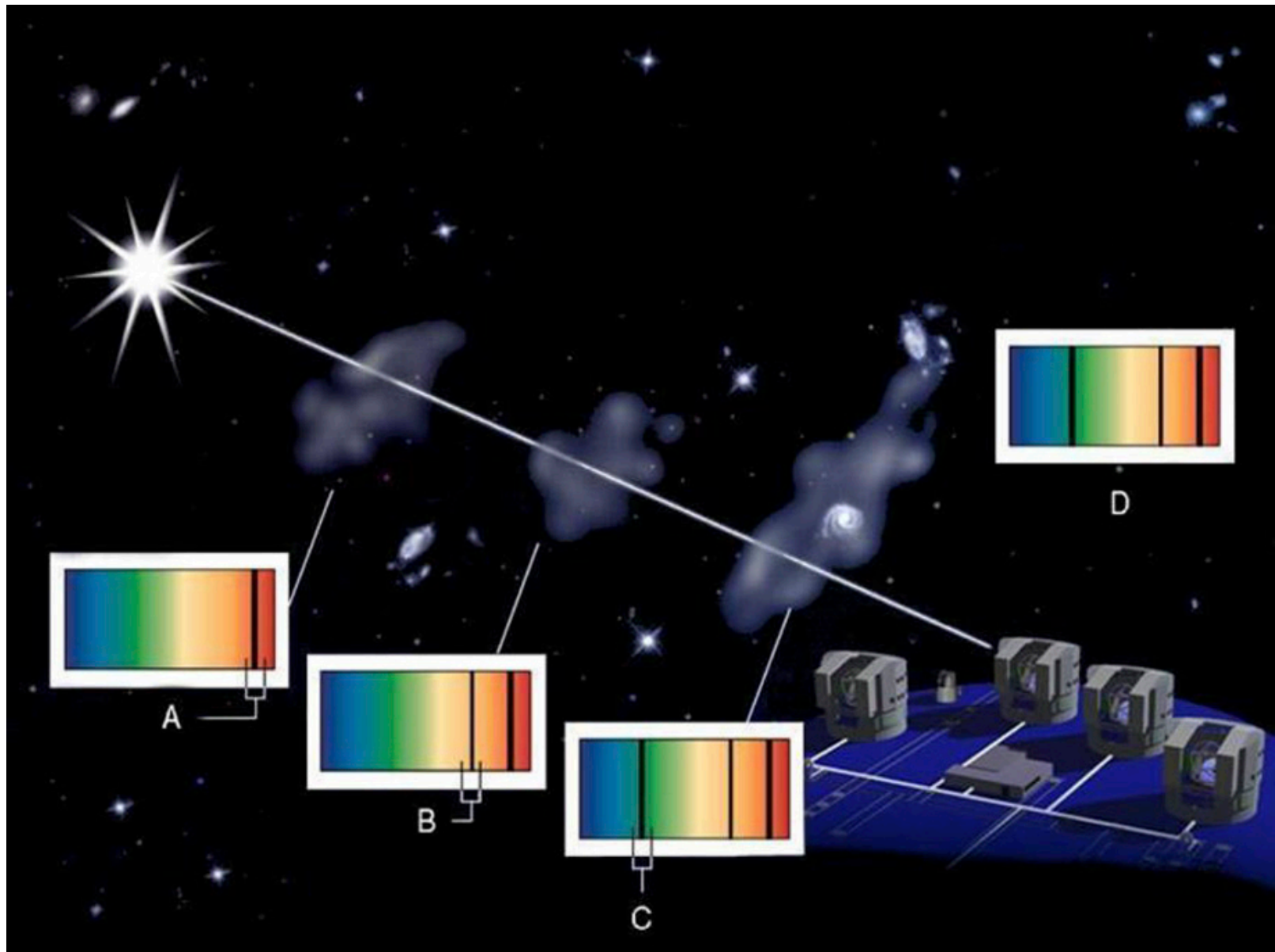
Maximum redshift : GRB 090423 at $z = 8.2$ (Universe is 630 Myr old)
GRB 090429B at $z = 9.3$ (Universe is 520 Myr old)

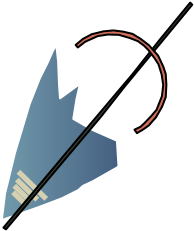
GRB redshift distribution : short GRBs



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

GRBs as a tool for cosmology





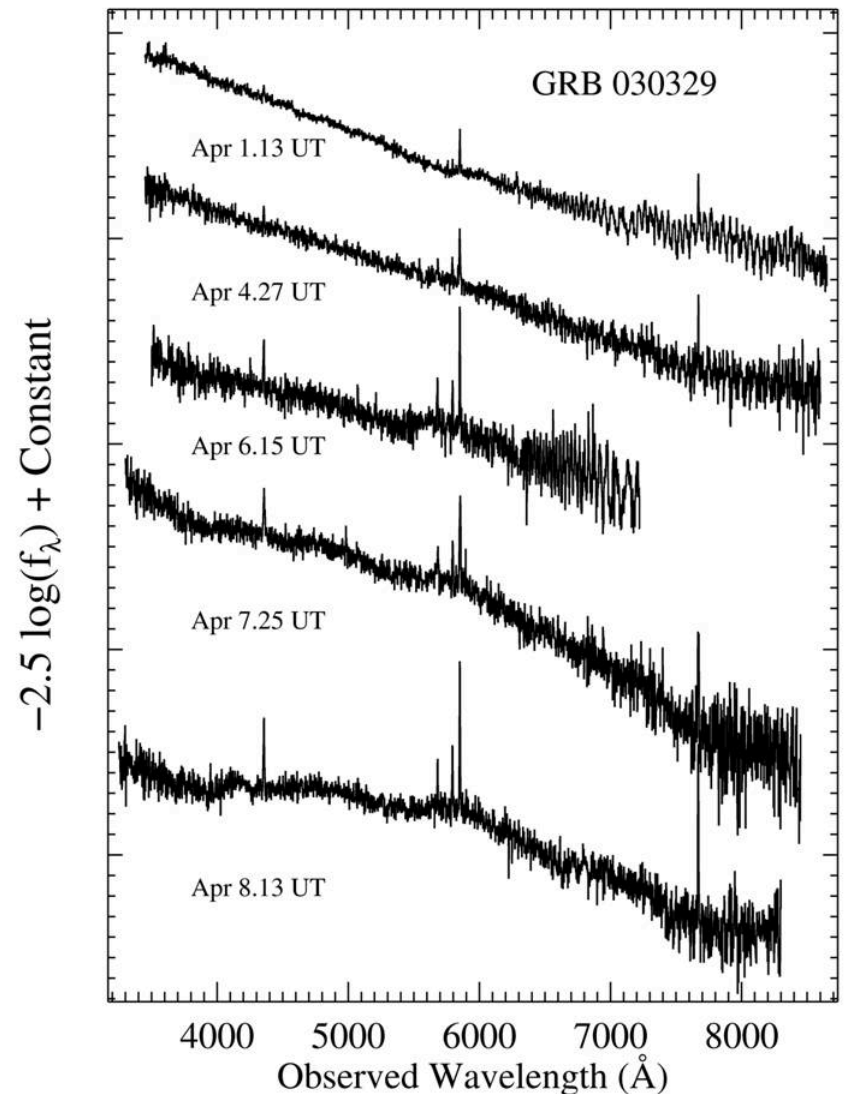
2– Identification of progenitors

Association of long GRBs with massive stars

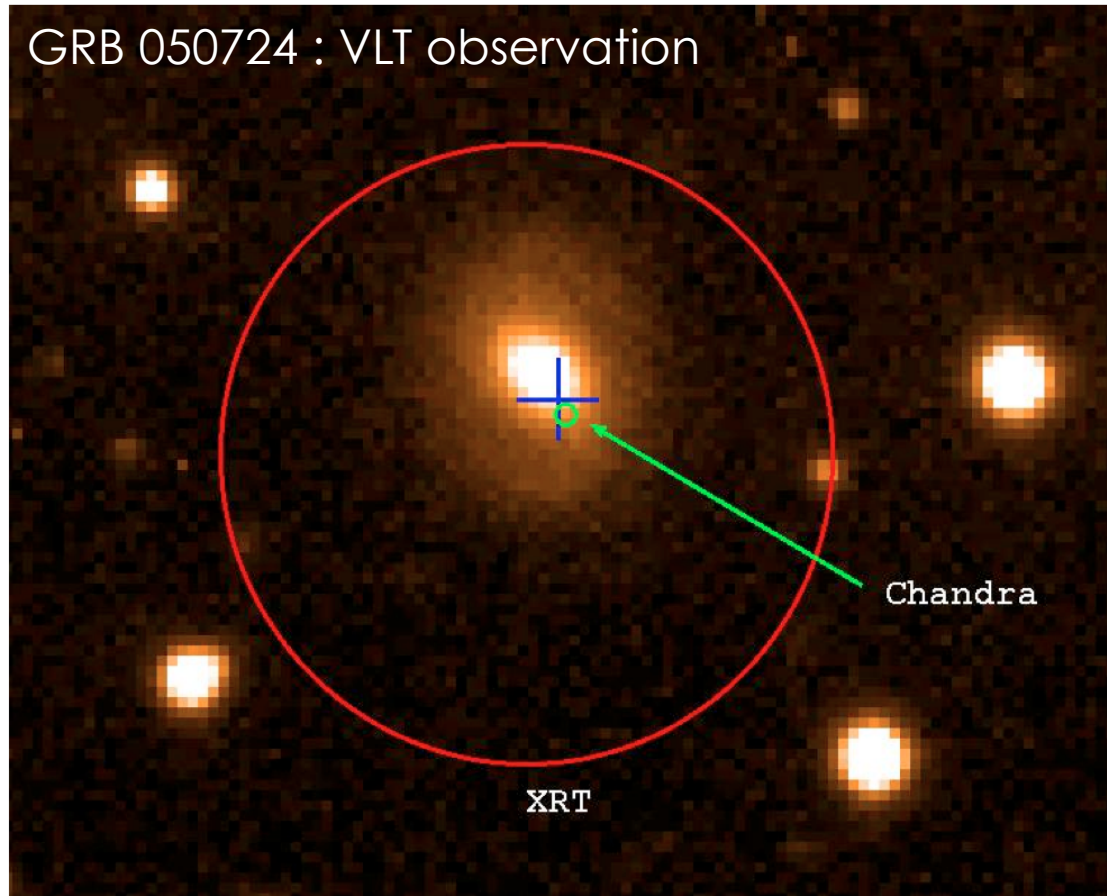
The case of GRB 030329 (HETE2) :
association with a SNIc

Several evidences for the association:

- star forming host galaxies
- afterglow location in the host galaxy
- associated SNaE



Progenitors of short GRBs : NS+NS mergers ?

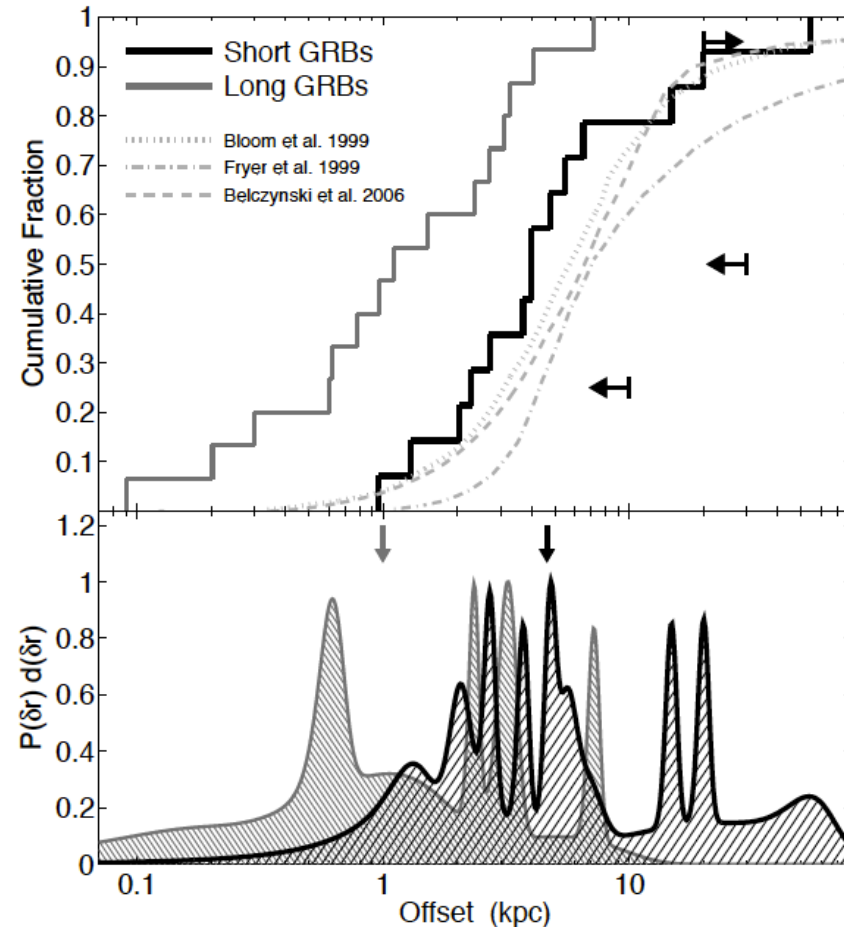


Barthelmy et al. 2005

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:

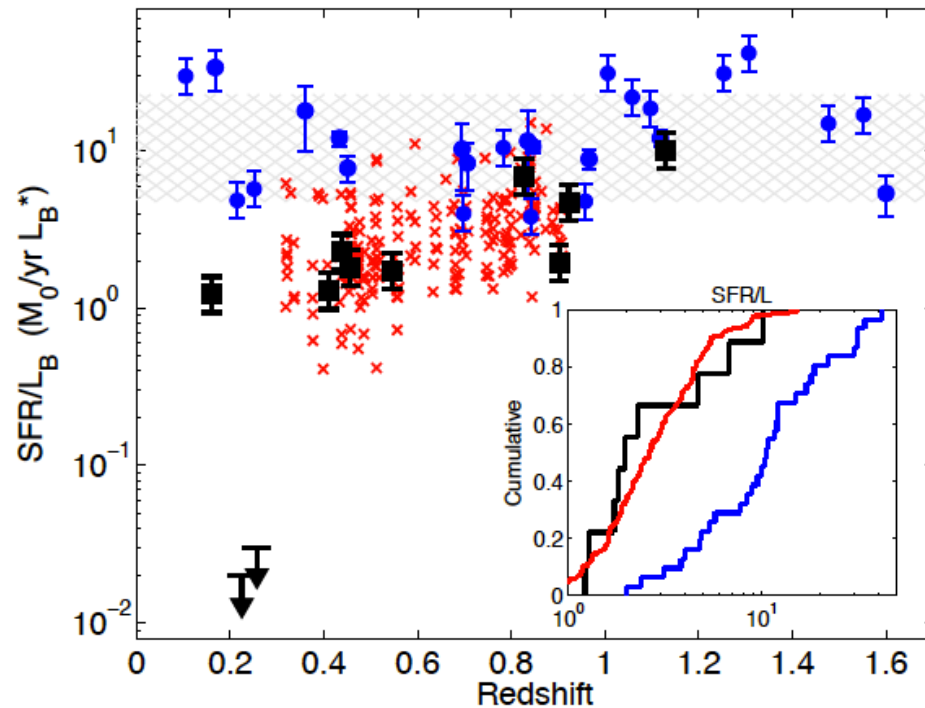
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- some are star-forming galaxies (e.g. GRB 050709; GRB 051221A; ...)

Progenitors of short GRBs : NS+NS mergers ?

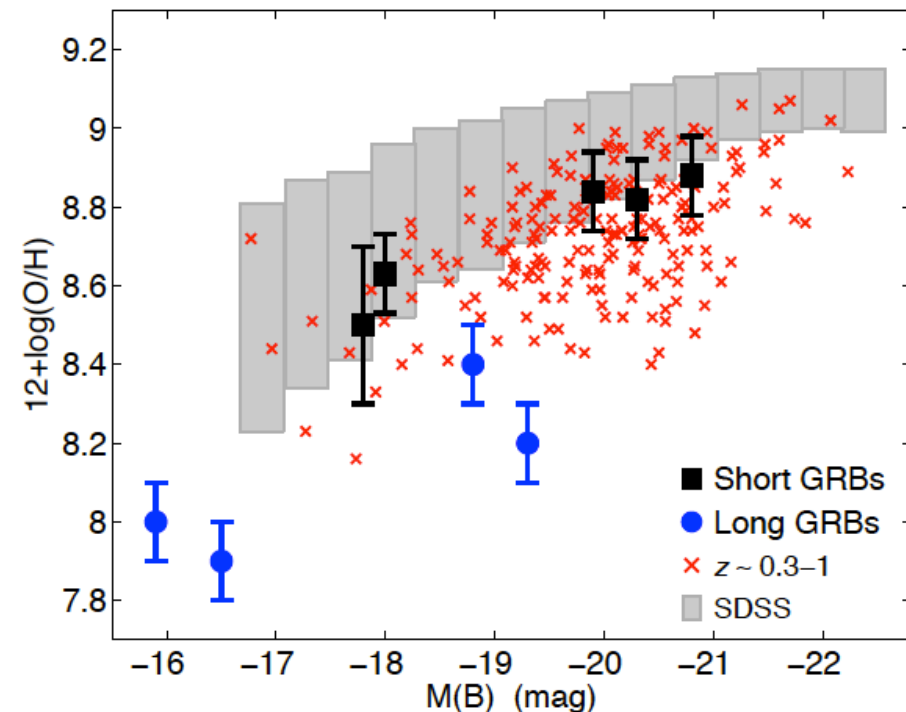
Long GRB hosts

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 :

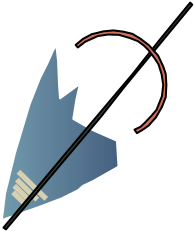
- No correlation with star formation due to long coalescence times
no preferred types of host galaxies

e.g. The Hulse-Taylor binary pulsar (PSR B1513+16) will merge in 300 Myr
- Large offsets are possible due to long coalescence times + kick velocity of NS

For $v = 100 \text{ km/s}$ and $T = 100 \text{ Myr}$, $D = v T = 10 \text{ kpc}$

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

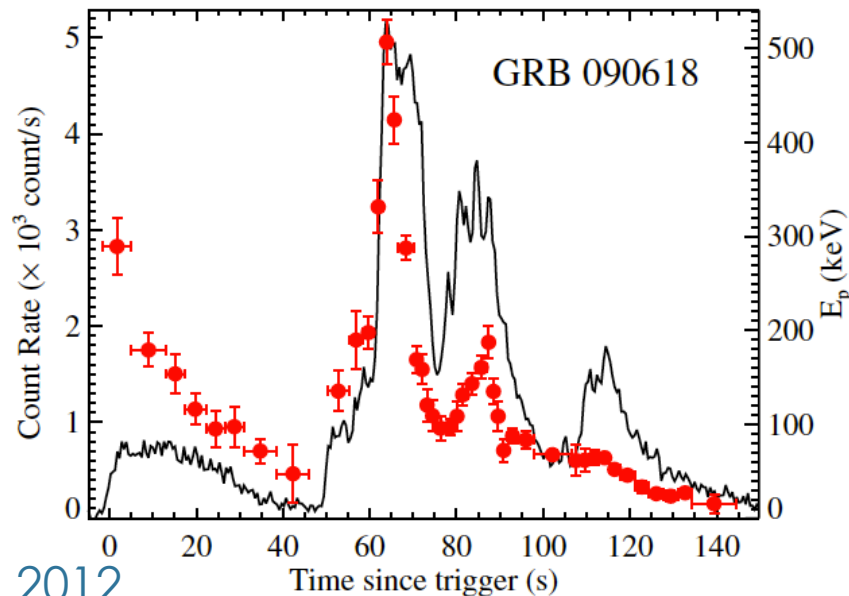
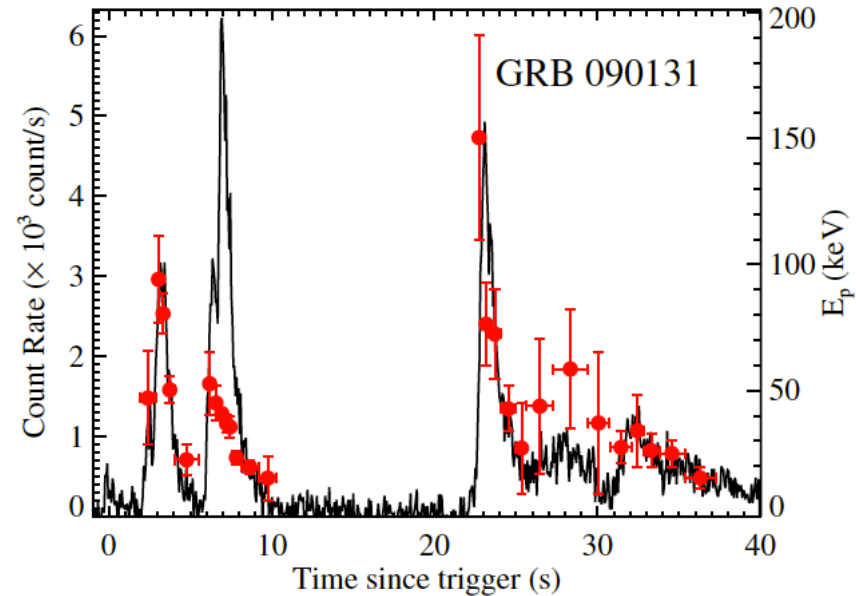
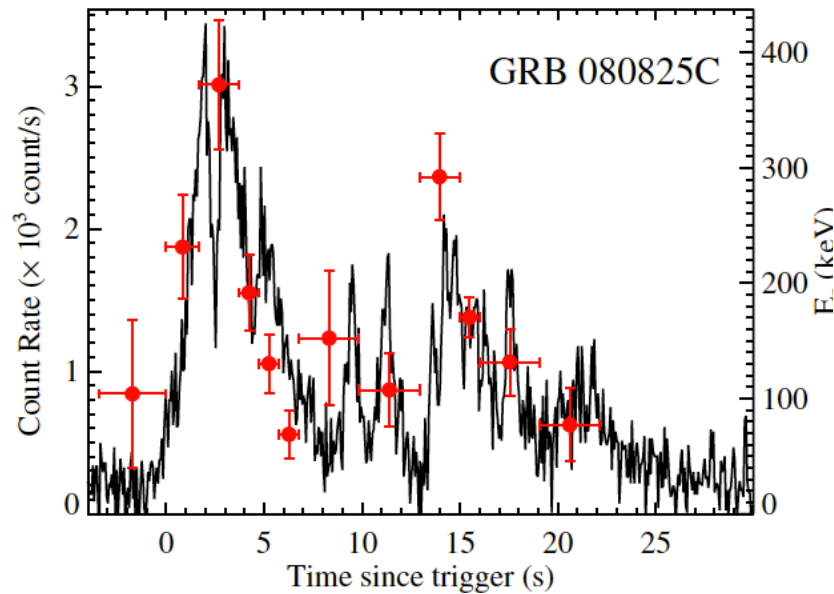
This applies to long AND short GRBs :

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

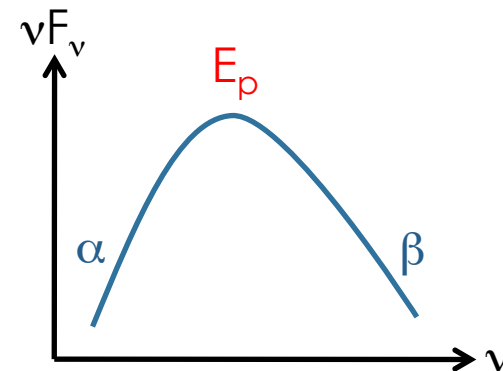
Main differences : timescales (prompt) + afterglow

Fermi: soft gamma-ray emission (GBM)

- Three examples: long GRBs



Lightcurve (photon flux, GBM)
Peak energy

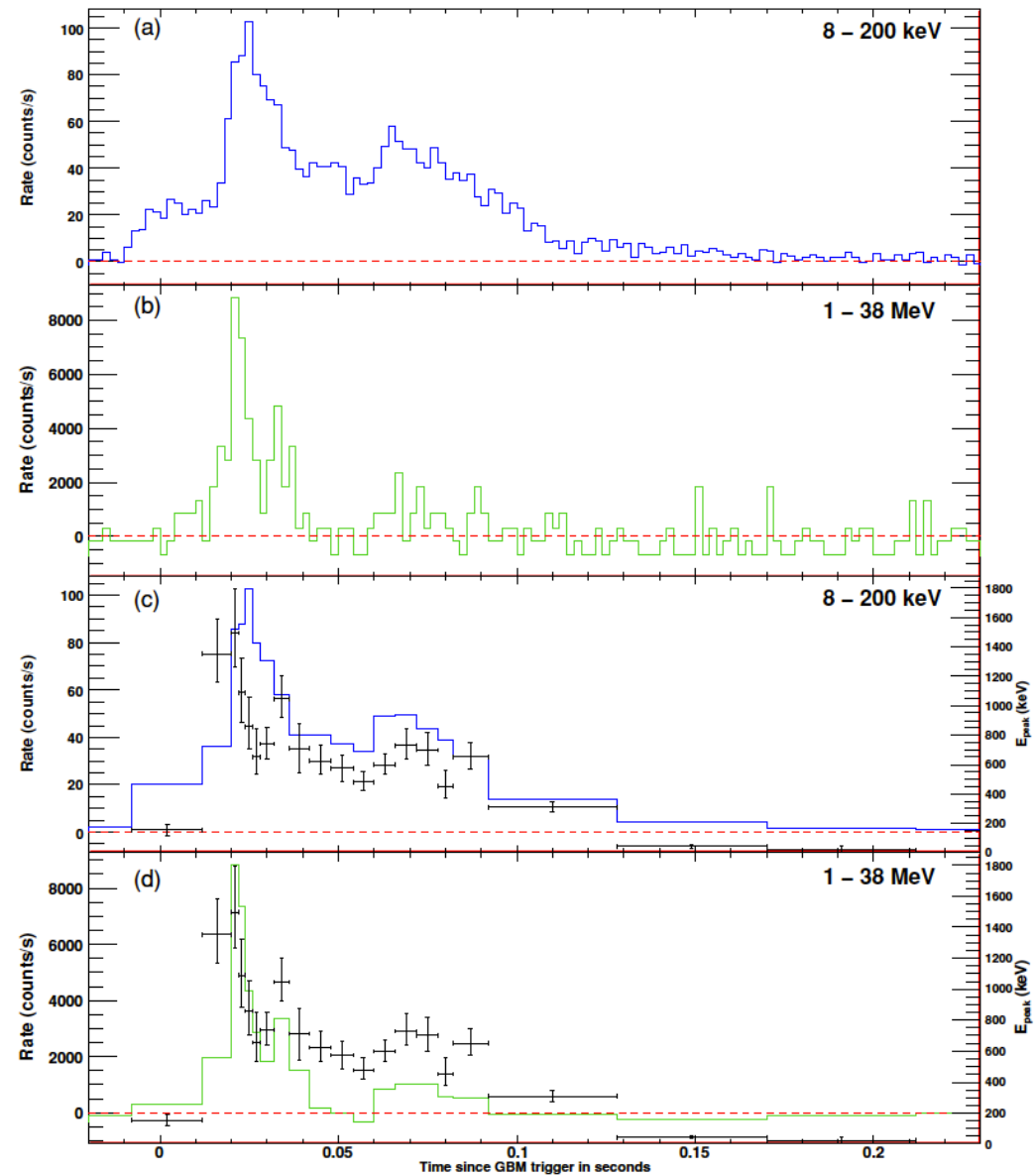


Fermi: soft gamma-ray emission (GBM)

- Another example: a short GRB

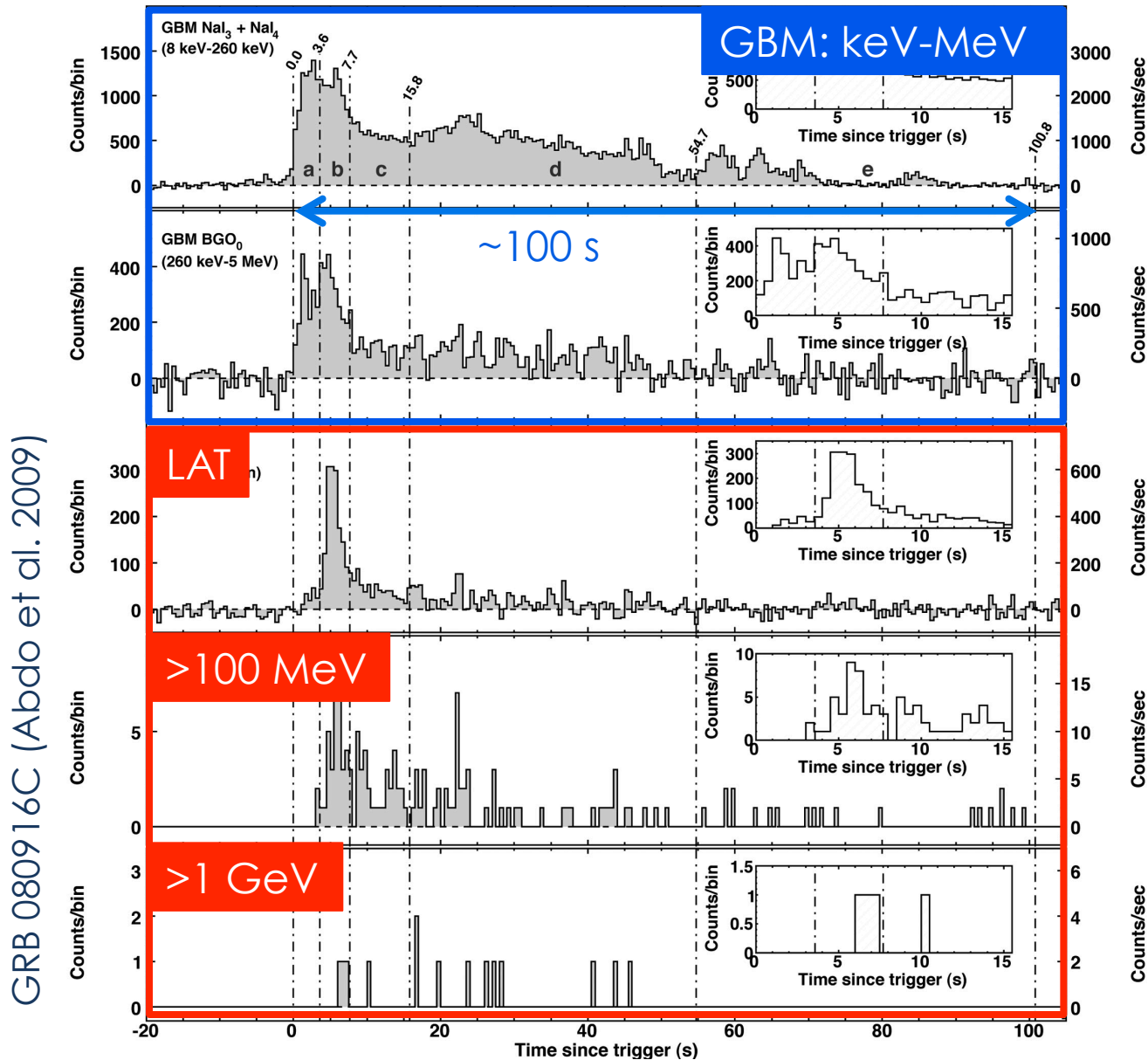
Lightcurves (photon flux, GBM)

Peak energy



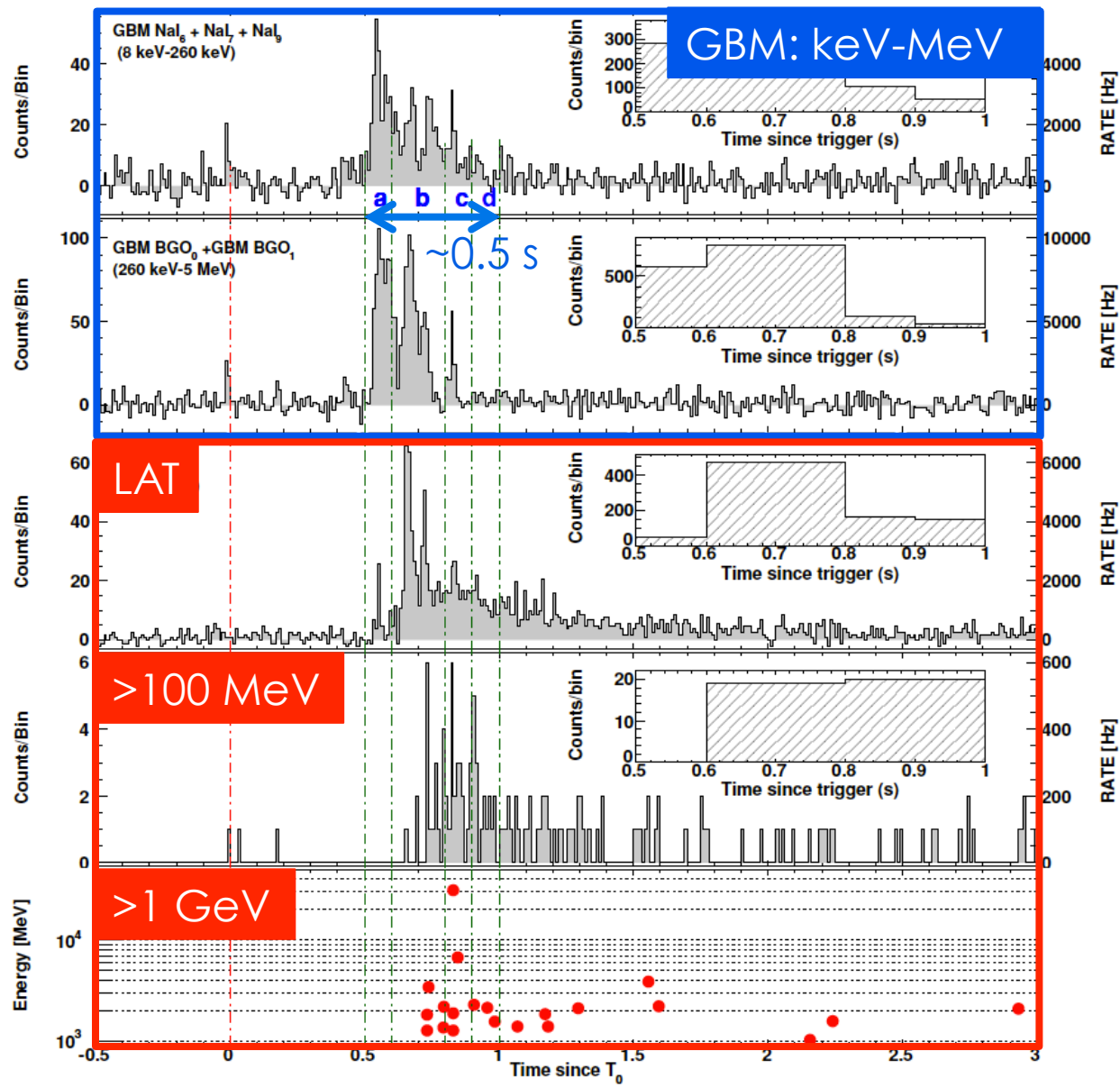
Fermi: high-energy detections (GeV)

- 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) : $\Gamma_{\min} \sim 100\text{-}300$ (see e.g. Baring & Harding 97; Lithwick & Sari 01)

➔ **GeV detection: stricter Lorentz factor constraints**

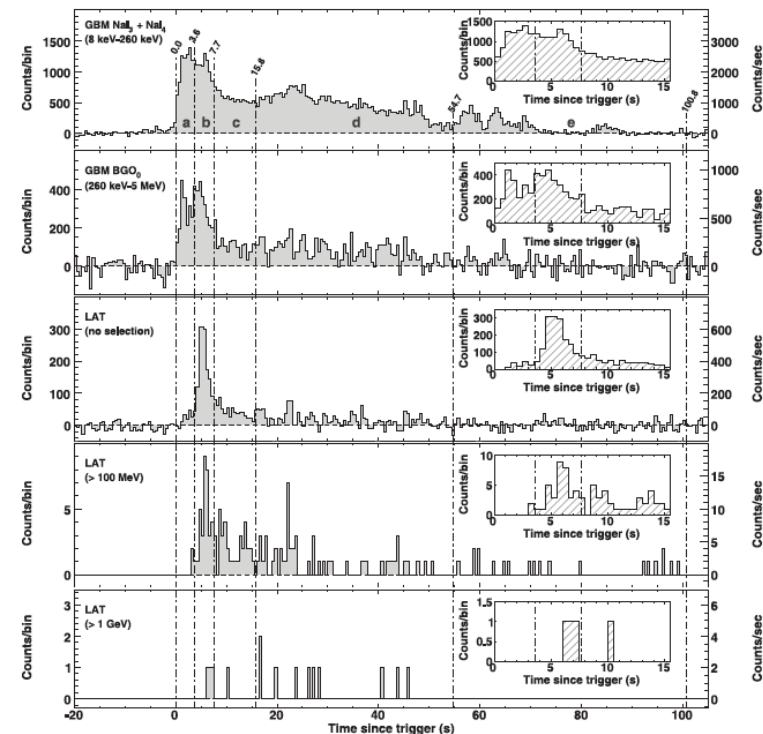
- GRB 080916C : $\Gamma_{\min} \geq 887$ (Abdo et al. 09)
- GRB 090510 : $\Gamma_{\min} \geq 1200$ (Ackerman et al. 10)

➔ 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.**

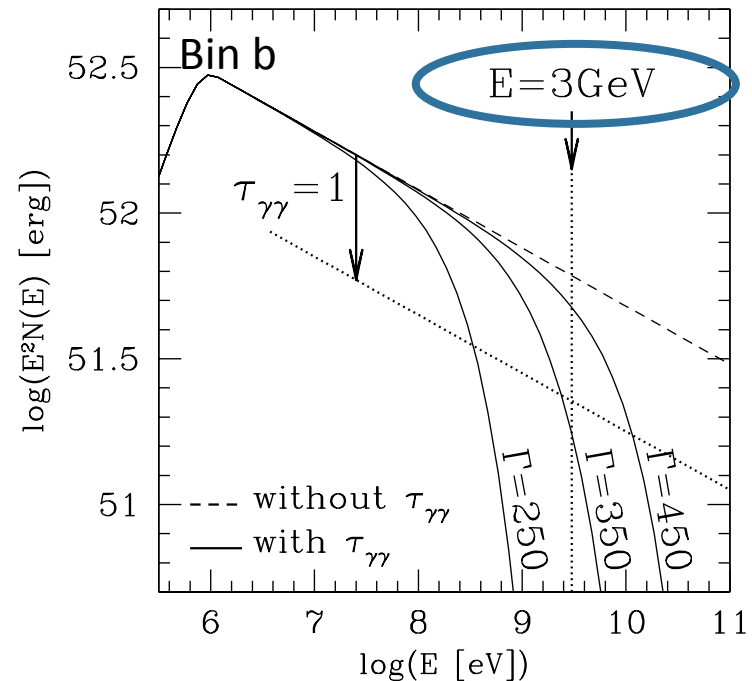
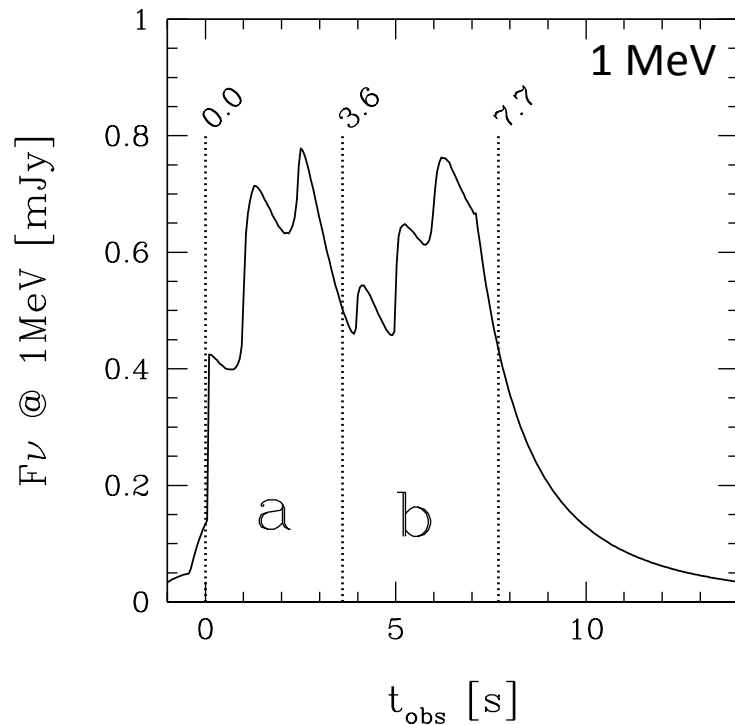


GRB 080916C (Abdo et al. 2009)

Consequences: how relativistic are GRBs ?

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

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



➡ Model of bins a+b in GRB 080916C : $\Gamma_{\min} \sim 360$ (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 $\sim 2-3$
(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 ($z = 0.01 \rightarrow 8\dots$) : Huge isotropic equivalent radiated energy E_{rad}
- Small timescales ($t_{\text{var}} = \text{ms} \rightarrow 100 \text{ s}$) : Small emitting region ($< c t_{\text{var}}$)
- 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.

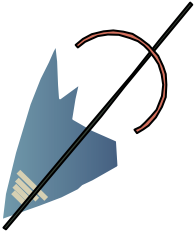
- Non photonic emission ?

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

Log(R) [meters]

Emission produced
within the external
medium

=

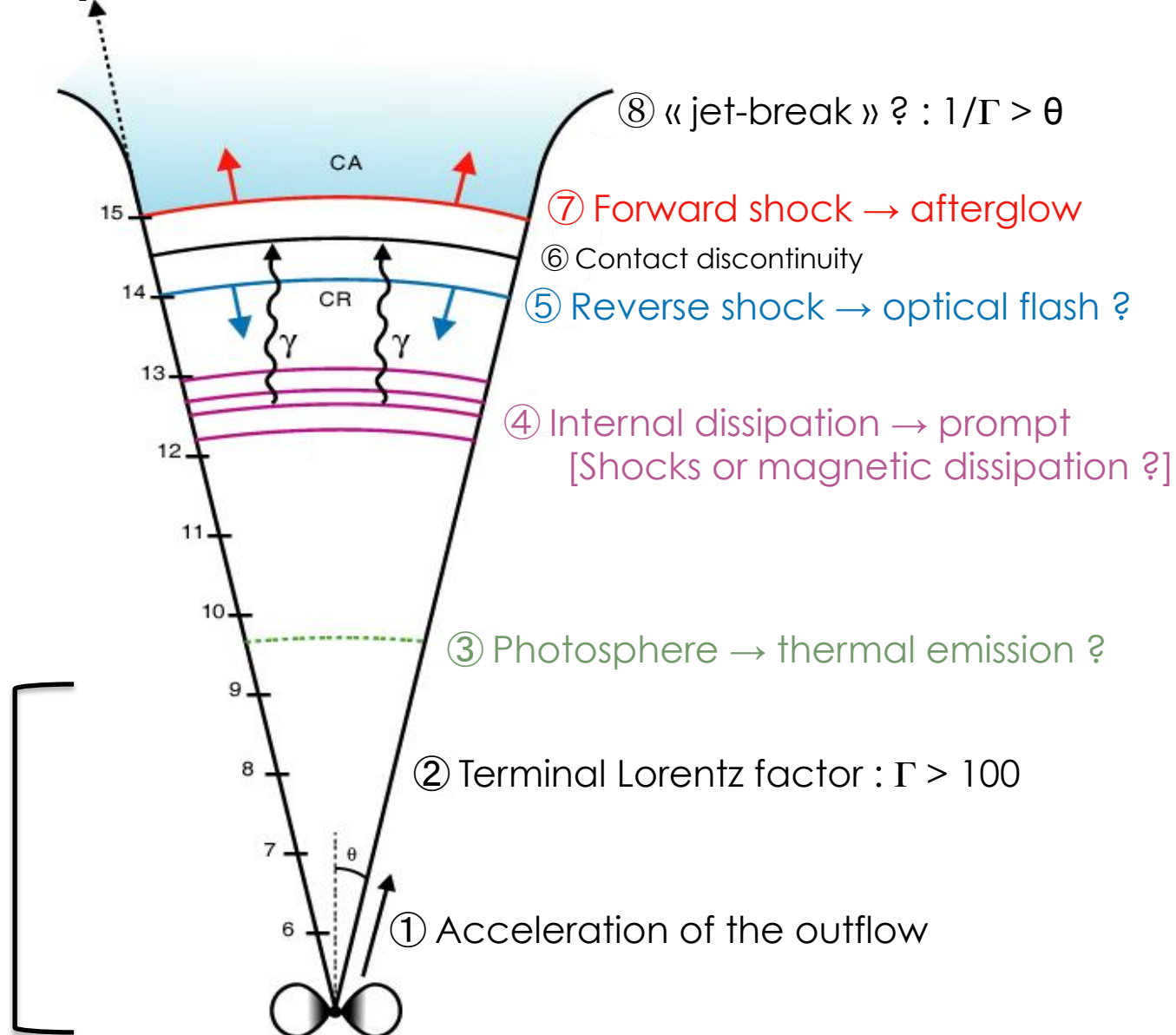
« external »

Emission produced
within the outflow

=

« internal »

Medium is opaque:
no photonic emission



Common physics in short and long GRBs ?

Different progenitors \Rightarrow 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 ?
- similar central engines (BH+torus) ?
- similar mechanism for the relativistic ejection ?

Yes

Probably

Not necessarily

- similar jet composition ?
- similar energy extraction process ?

Not necessarily

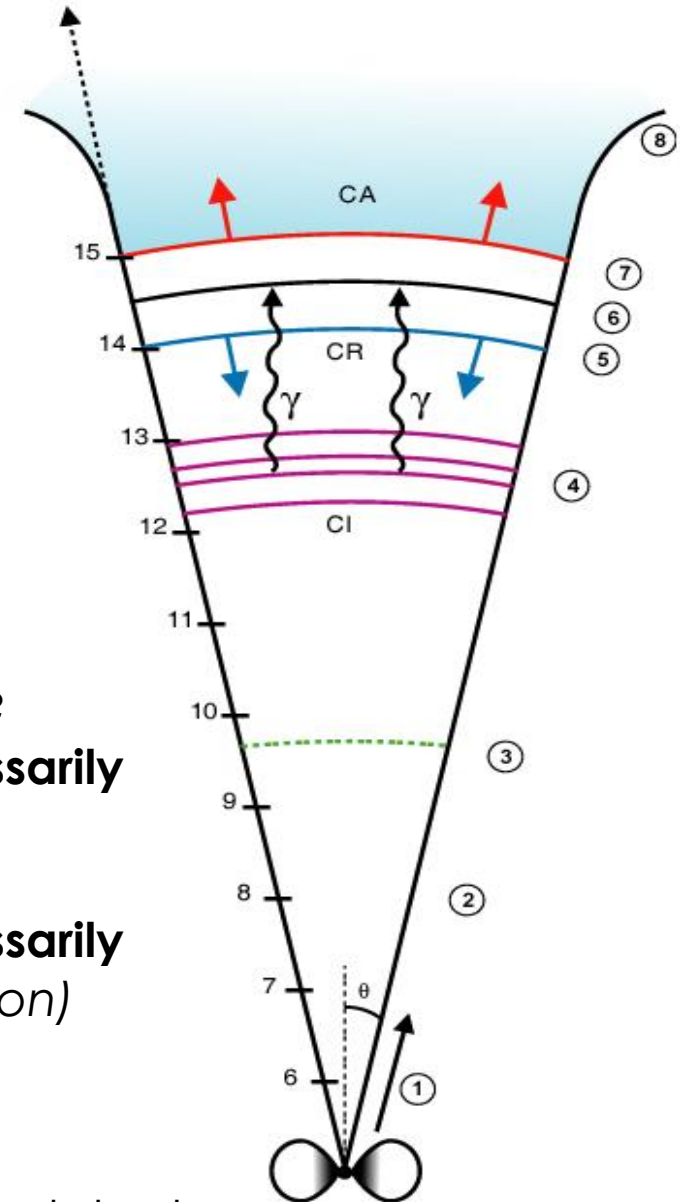
(depends on the answer of the previous question)

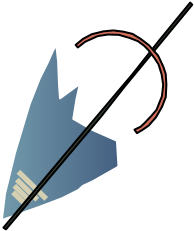
- similar radiative processes ?

Probably

■ Gravitational waves ?

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

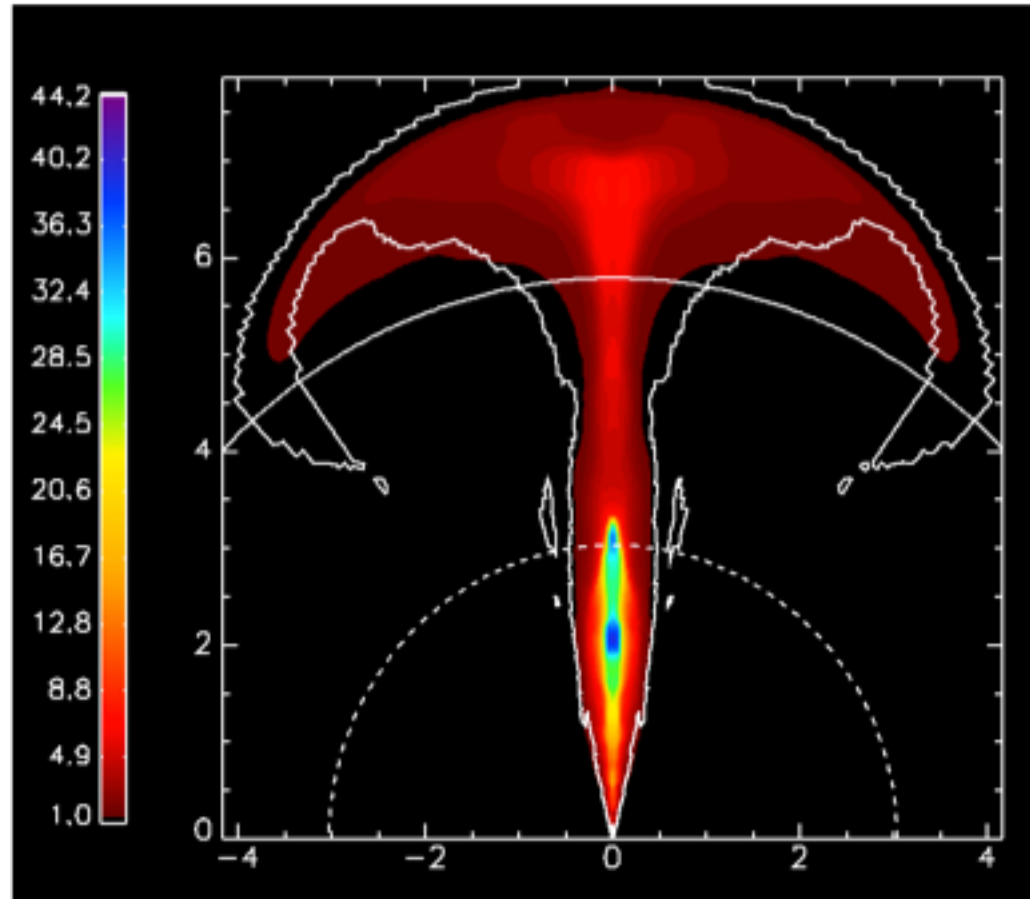
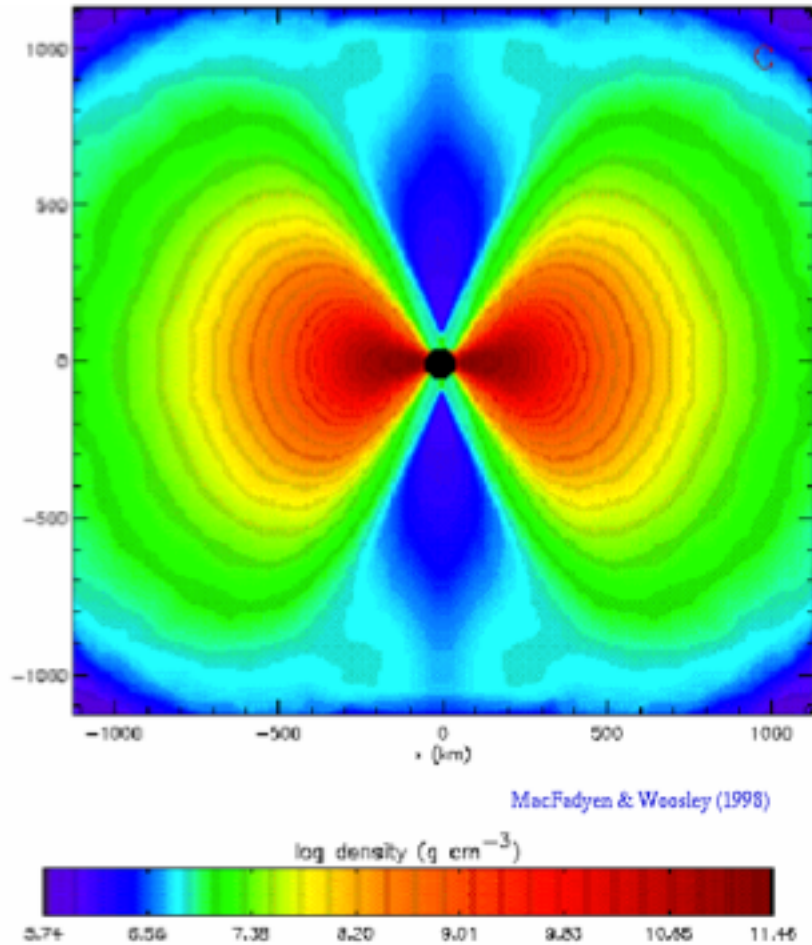




5– Central engine Gravitational waves

Central engines (1) Long GRBs

Long GRBs : collapsars (Paczynski, Woosley, ...)

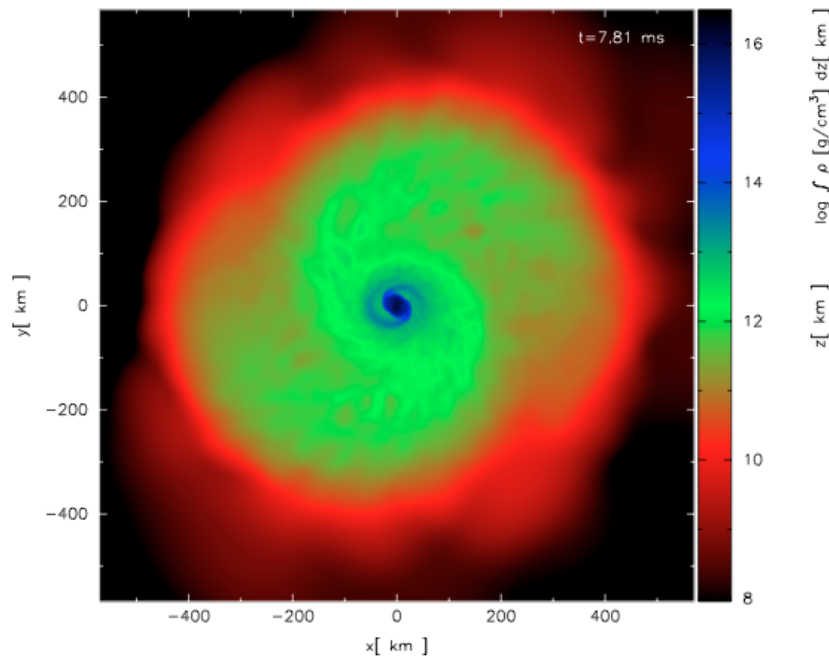


Escaping the star ?

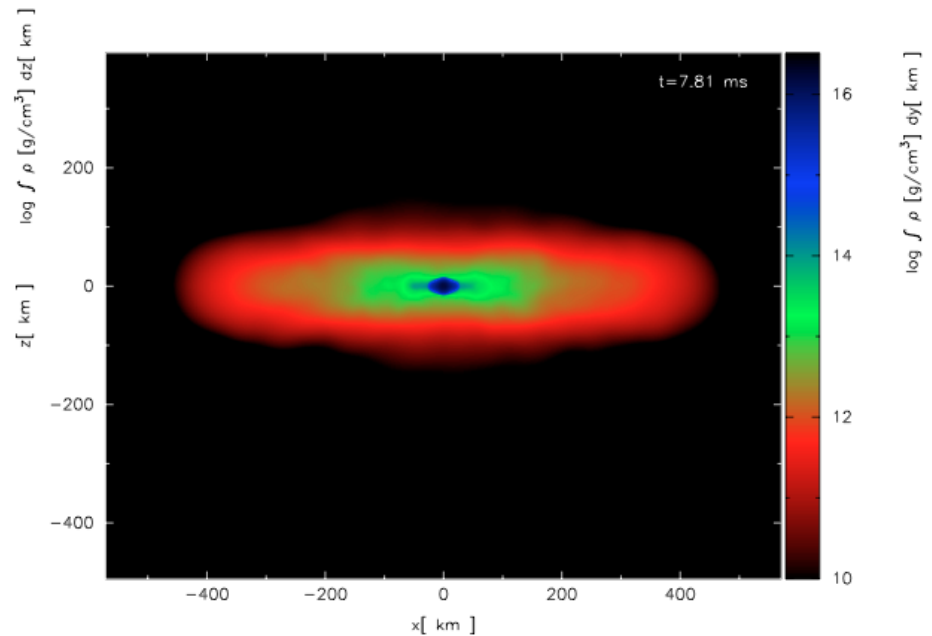
(MacFadyen et al.)

Central engines (2) Short GRBs

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



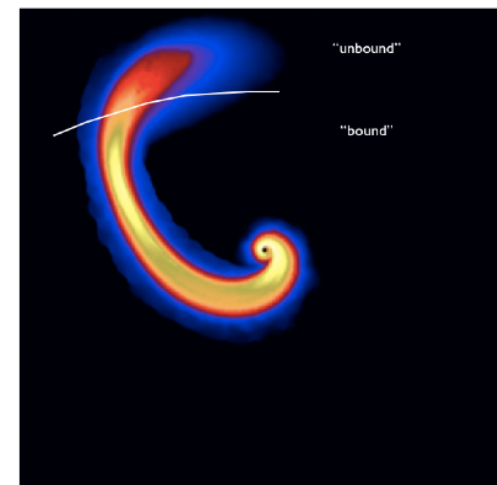
(Rosswog et al.)



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.

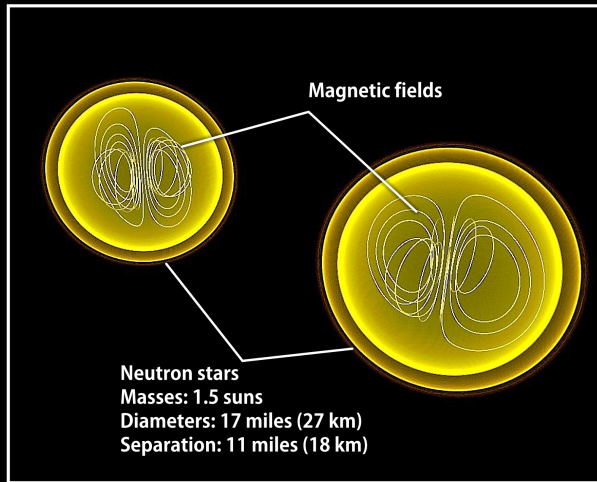


Central engines (2) Short GRBs

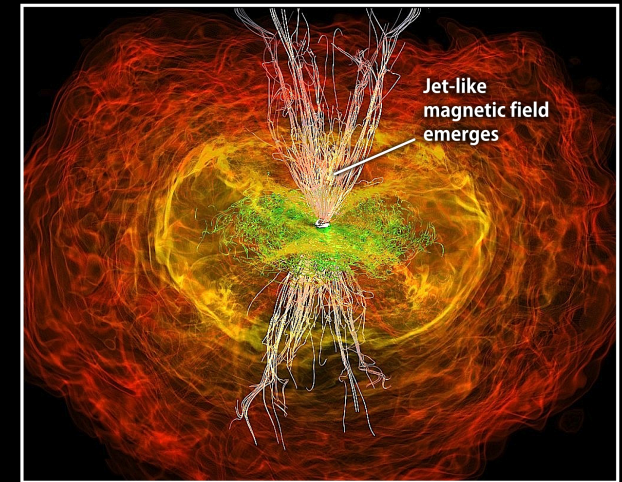
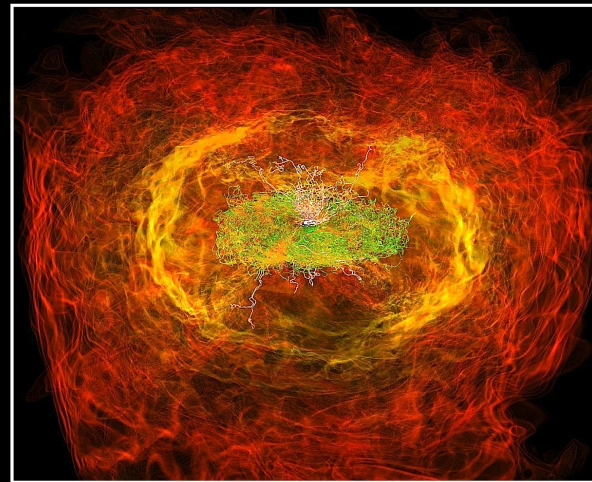
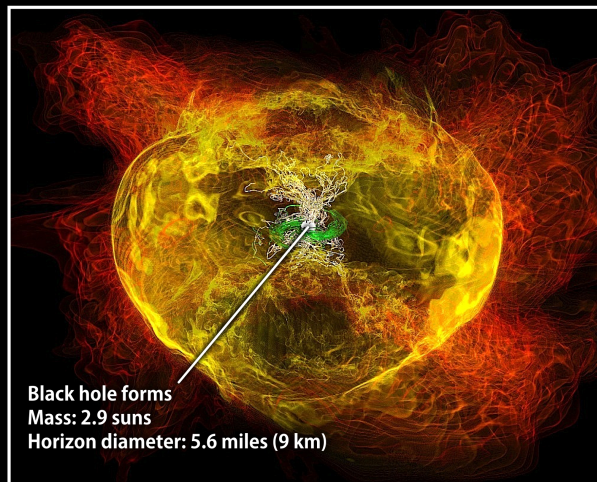
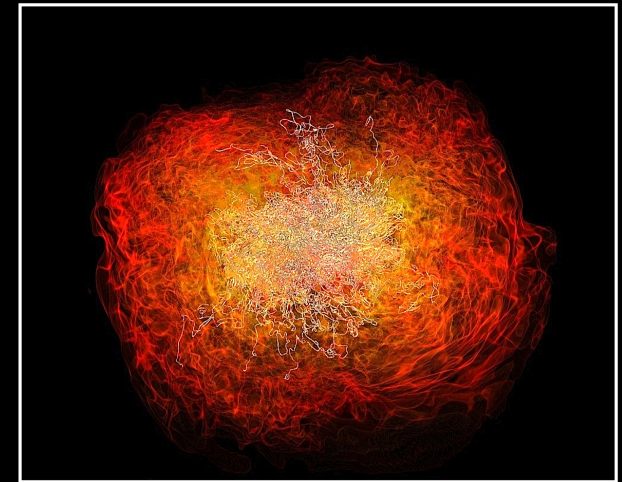
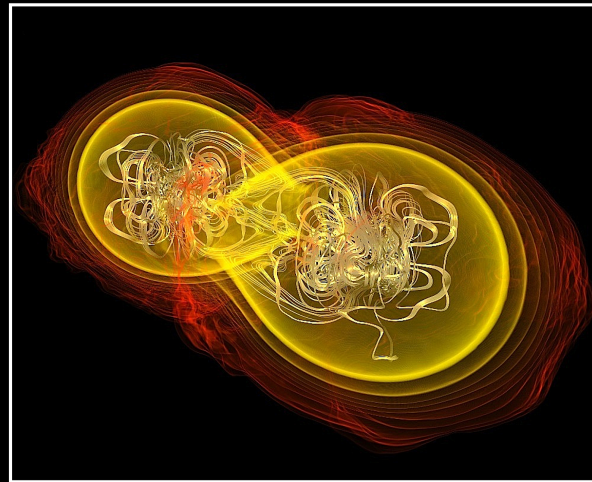
Short GRBs : NS+NS or NS+BH mergers ?

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

Rezzolla et al. 2011



Simulation begins

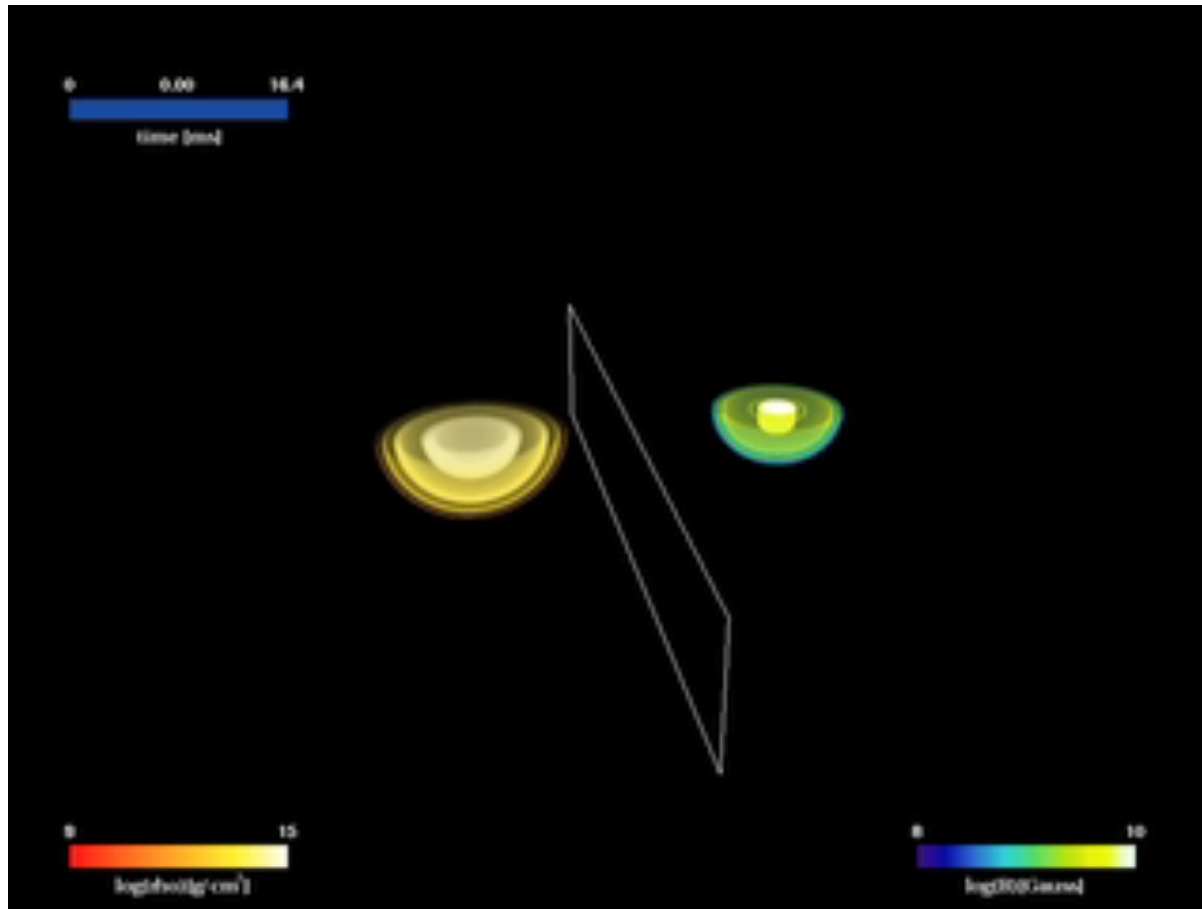


Central engines (2) Short GRBs

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

Rezzolla et al. 2011

Duration of the simulation : ~ 16 ms



Density

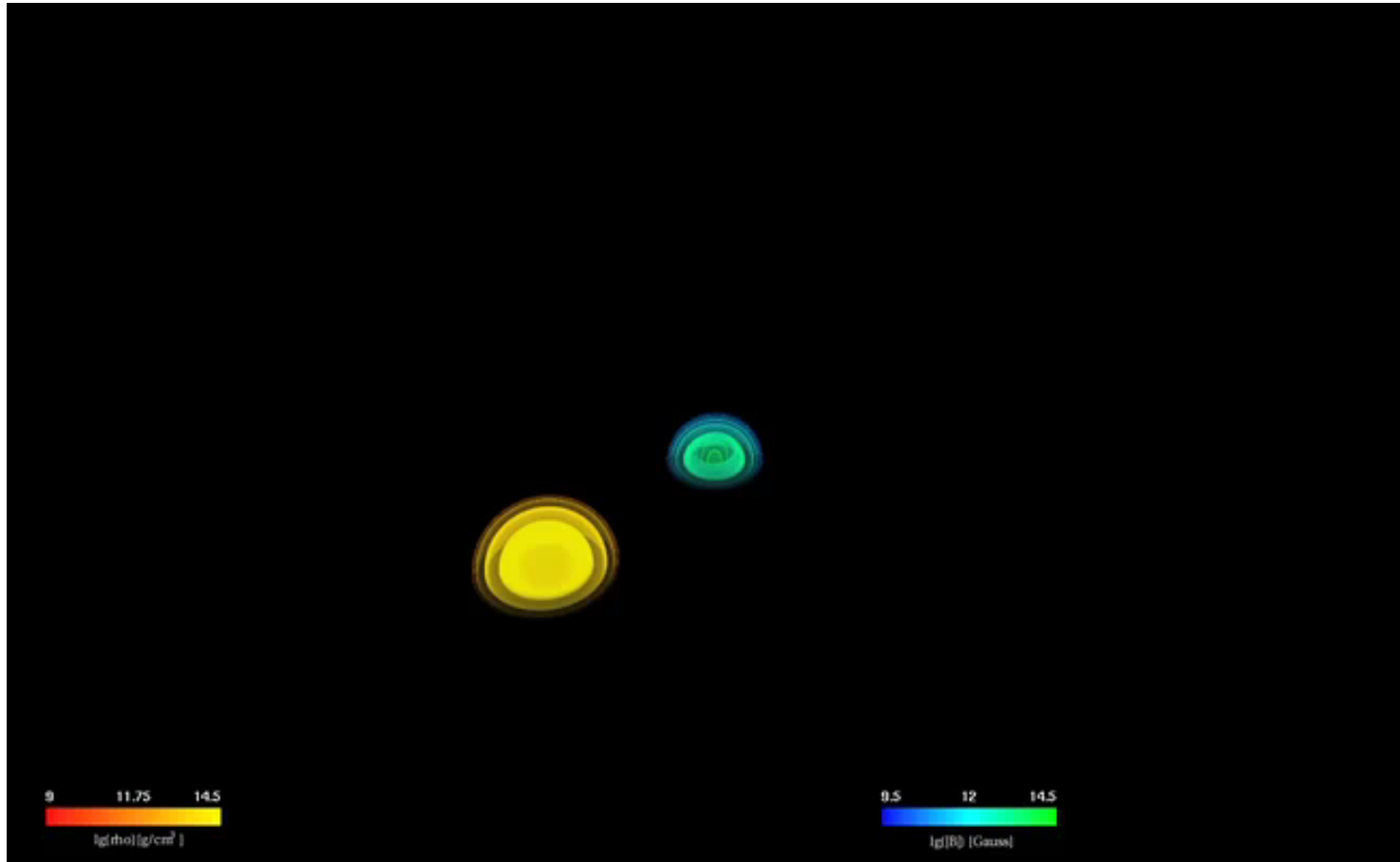
B-field

Central engines (2) Short GRBs

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

Rezzolla et al. 2011

Duration of the simulation : ~ 26 ms



Density

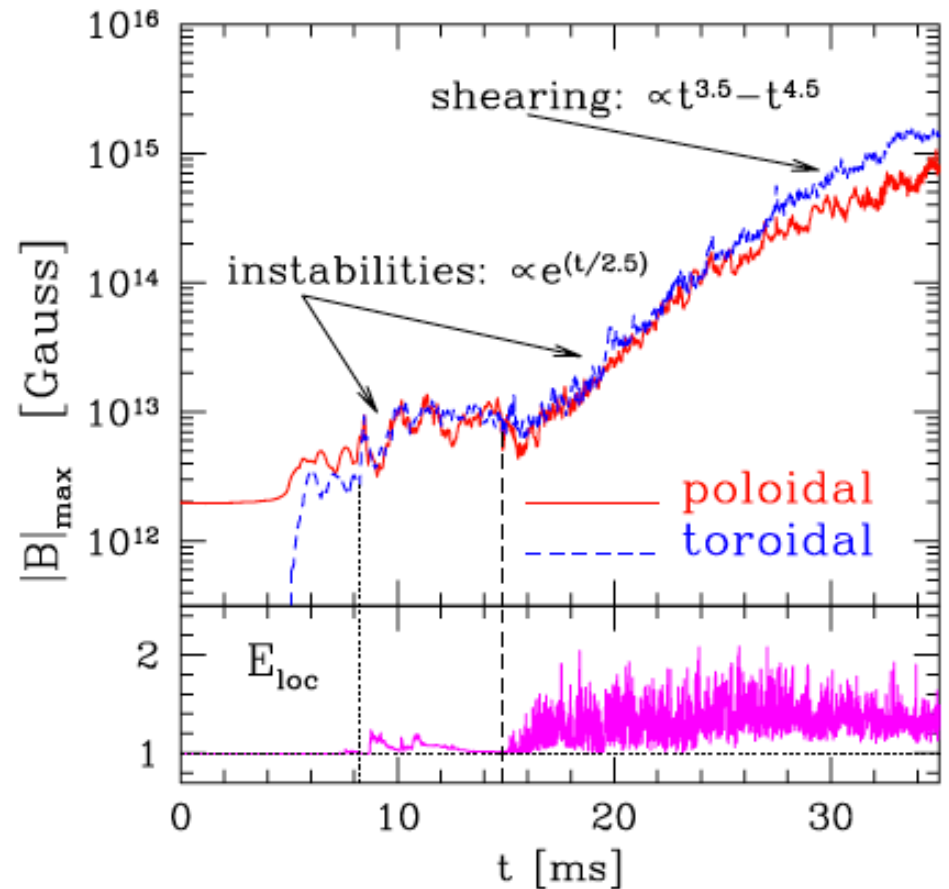
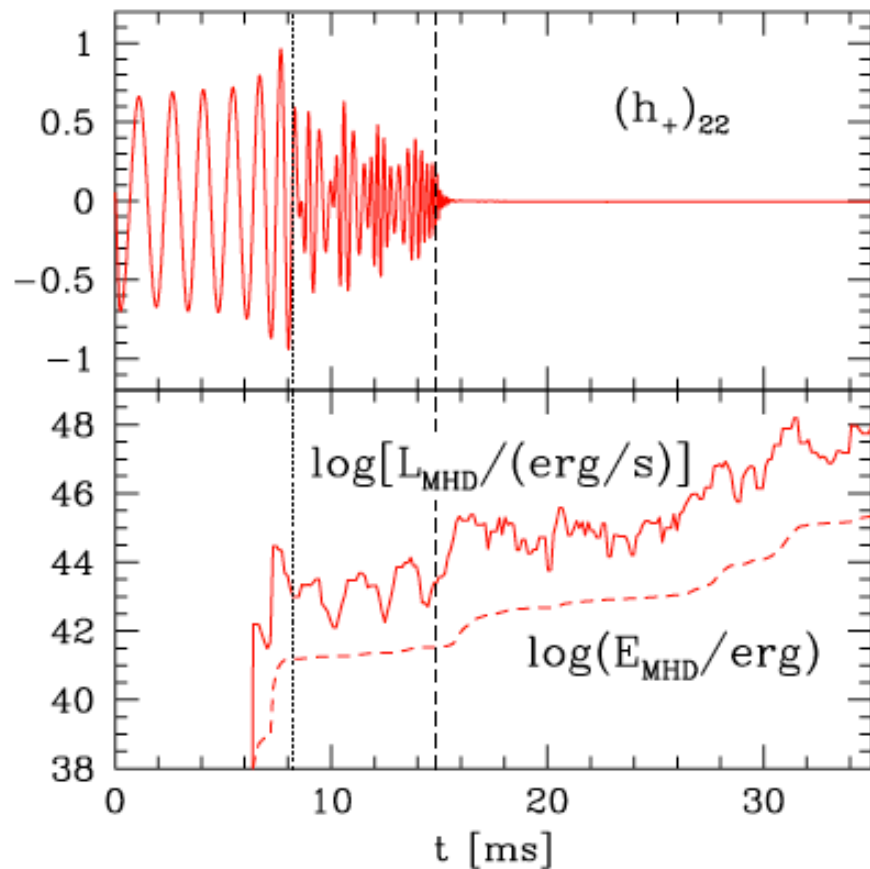
B-field

Central engines (2) Short GRBs

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

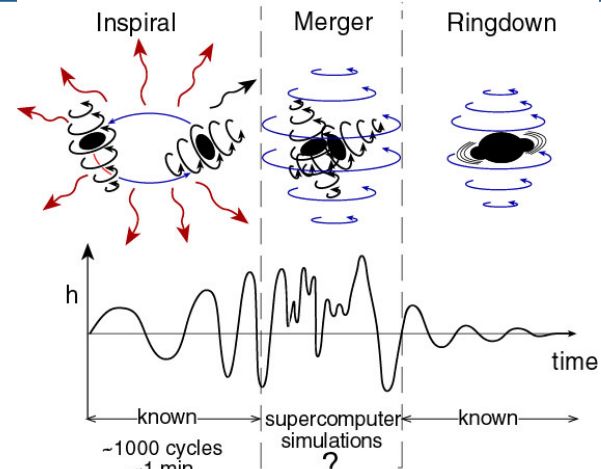
Rezzolla et al. 2011

GW emission and MHD power



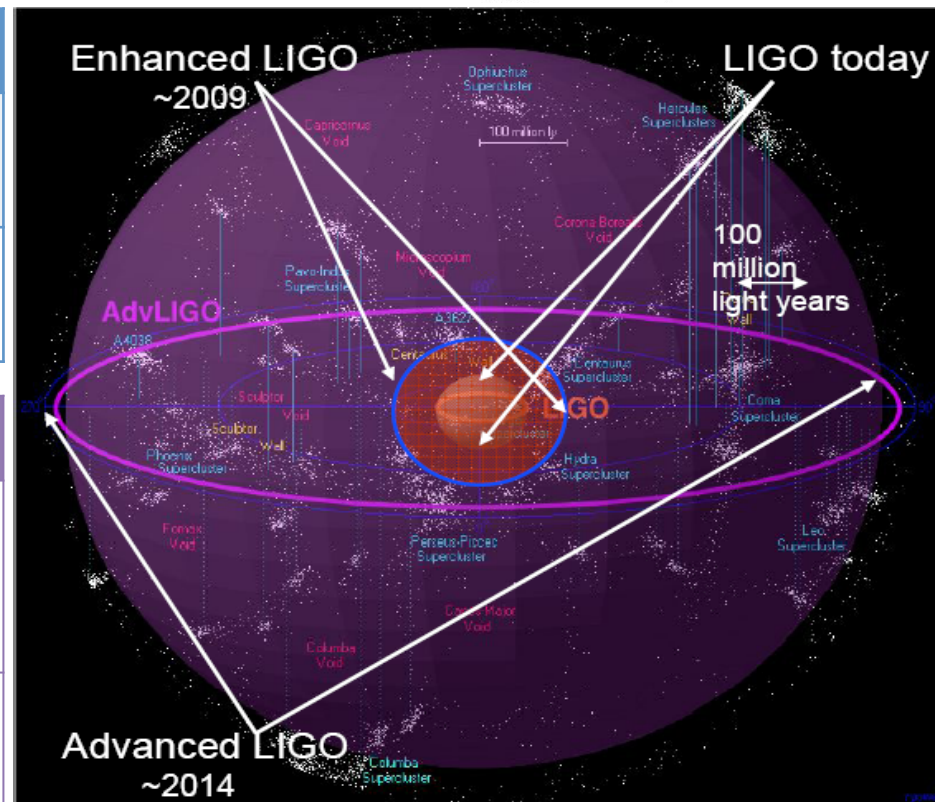
Mergers: GW emission

- 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 ?



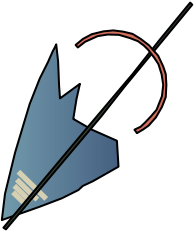
	NS/NS	NS/BH
LIGO I/ Virgo	15 Mpc	30 Mpc
Ad LIGO/ Ad Virgo	200 Mpc	420 Mpc

	NS/NS	NS/BH
LIGO I/ Virgo	0.02 yr^{-1} ($2\text{e-}4 - 0.2$)	0.004 yr^{-1} ($7\text{e-}5 - 0.1$)
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 $\theta_{\text{jet}}=30^\circ$ and efficiency 80 % \Rightarrow 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

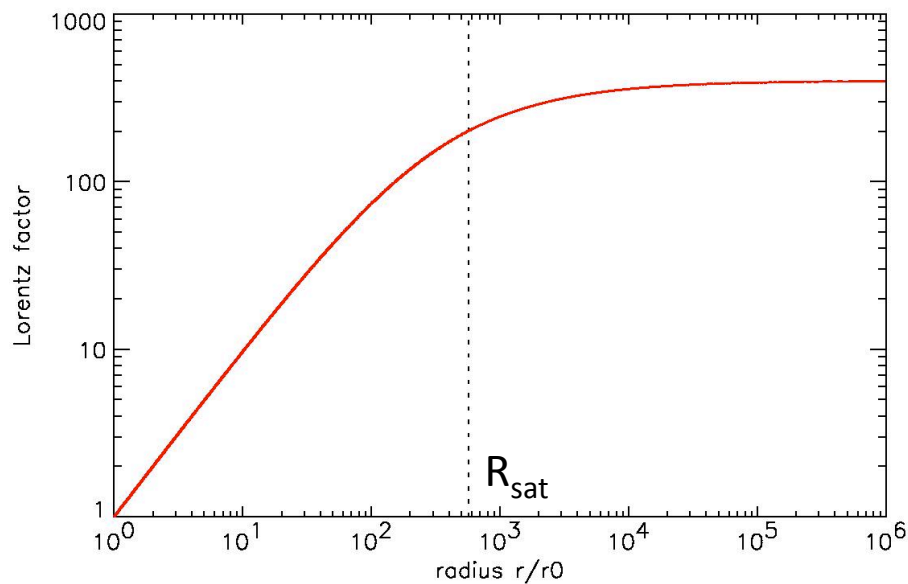
Jet composition

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.

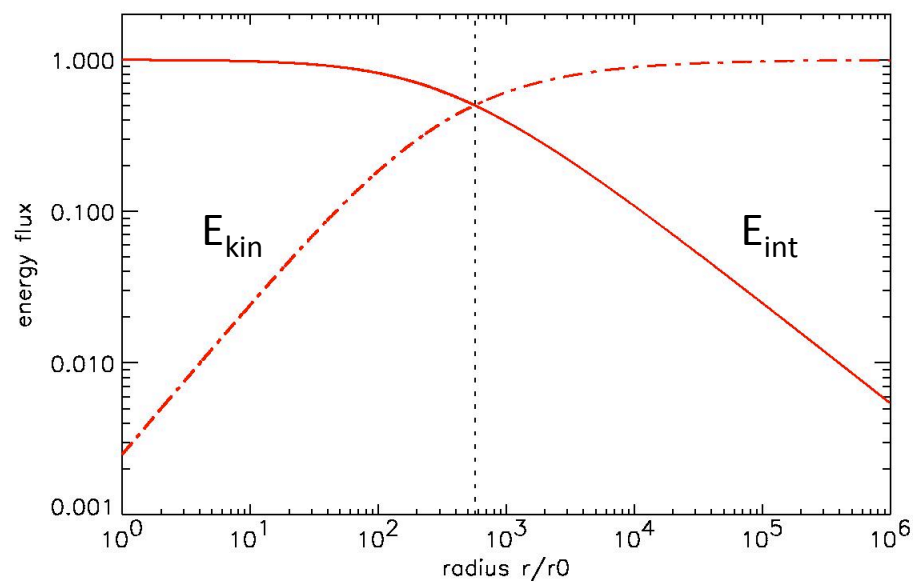
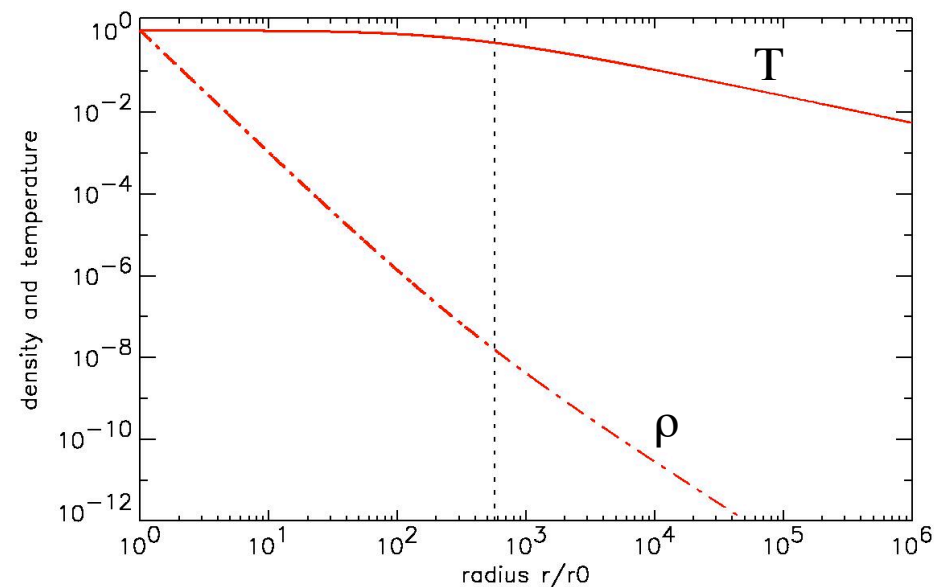
- Paczynski 1986; Goodman 1986
- Energy (E_0) injected in matter (M_0) very close to the central engine (R_0)
- Adiabatic expansion and hydrodynamical acceleration
- If $E_0 \gg M_0 c^2$: relativistic motion ($G_\infty \approx E_0 / M_0 c^2$ for 100% efficiency).
- No magnetic fields
- No gradual energy 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.

$$R_0 \sim \text{a few } GM / c^2 \sim 100 \text{ km}$$
$$R_{\text{sat}} \sim \Gamma_{\infty} R_0 \sim 10\,000 \text{ km for } \Gamma=100$$



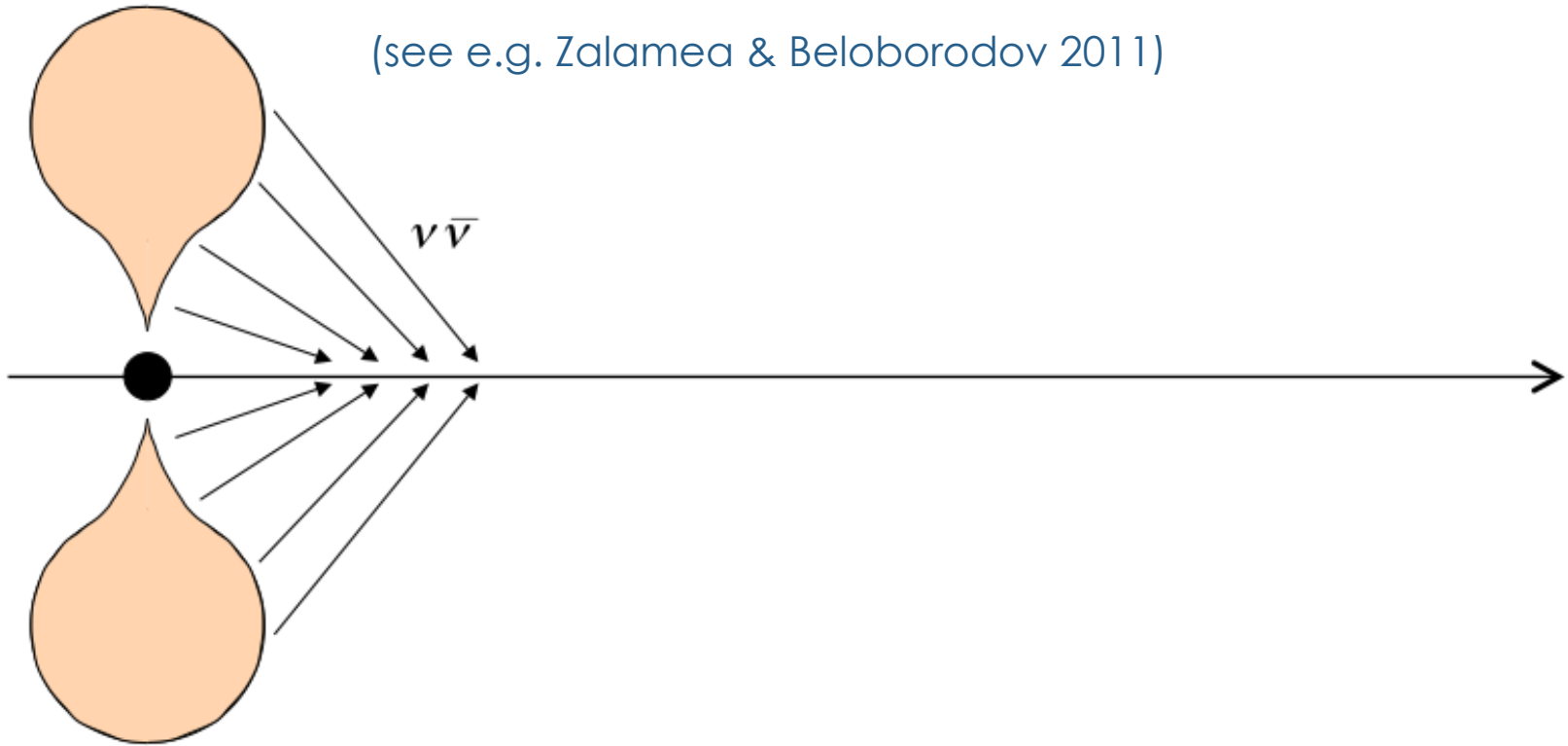
Relativistic ejection : neutrinos ?

Baryonic pollution ?

Efficiency may be an issue, especially for long GRBs.

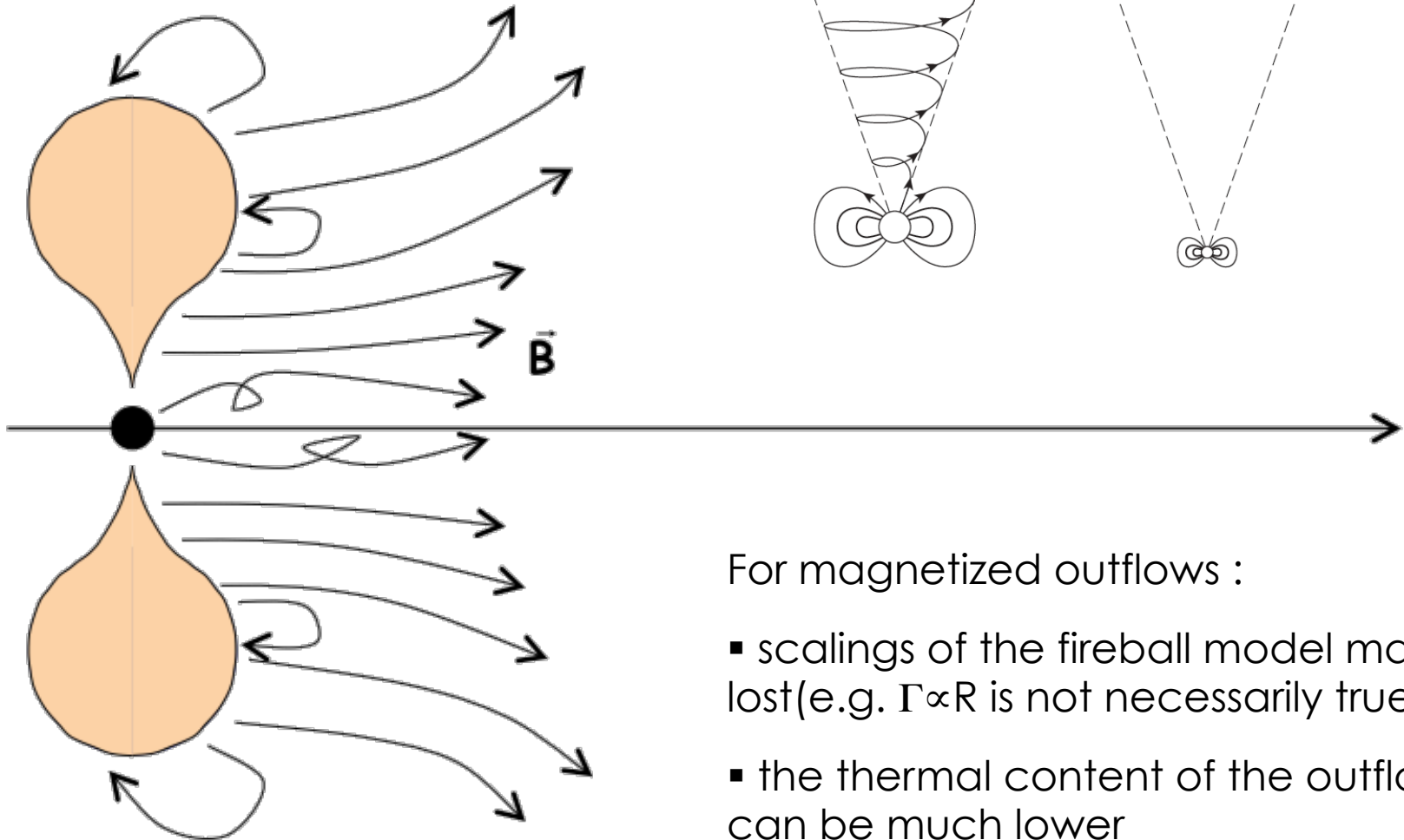
It is a promising mechanism for short GRBs.

(see e.g. Zalamea & Beloborodov 2011)



Relativistic ejection : magnetic field ?

Baryonic pollution ?
Initial/final magnetization ?
Beaming ?



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

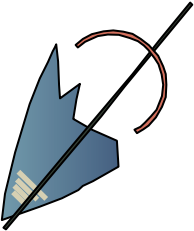
- A thick accretion disk orbiting a stellar mass black hole ?
- Differences:
 - Black hole: mass, spin
 - Disk: mass, reservoir
 - Close environment
 - Other ? (magnetization, ...)
- Is there an alternative to BH+disk ? Magnetars ? Something more exotic ?

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 ?

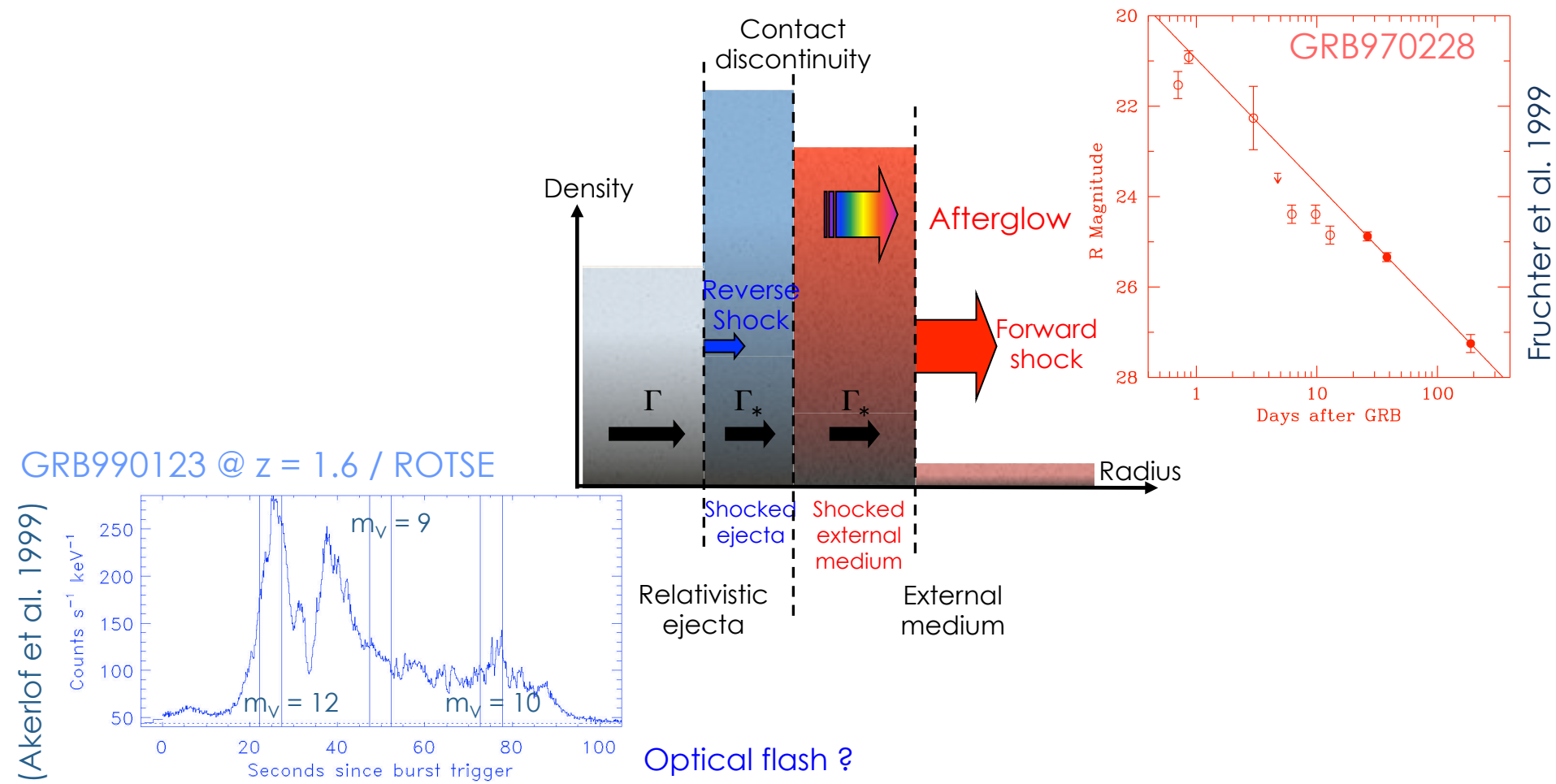


7– Afterglow models

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)



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 :

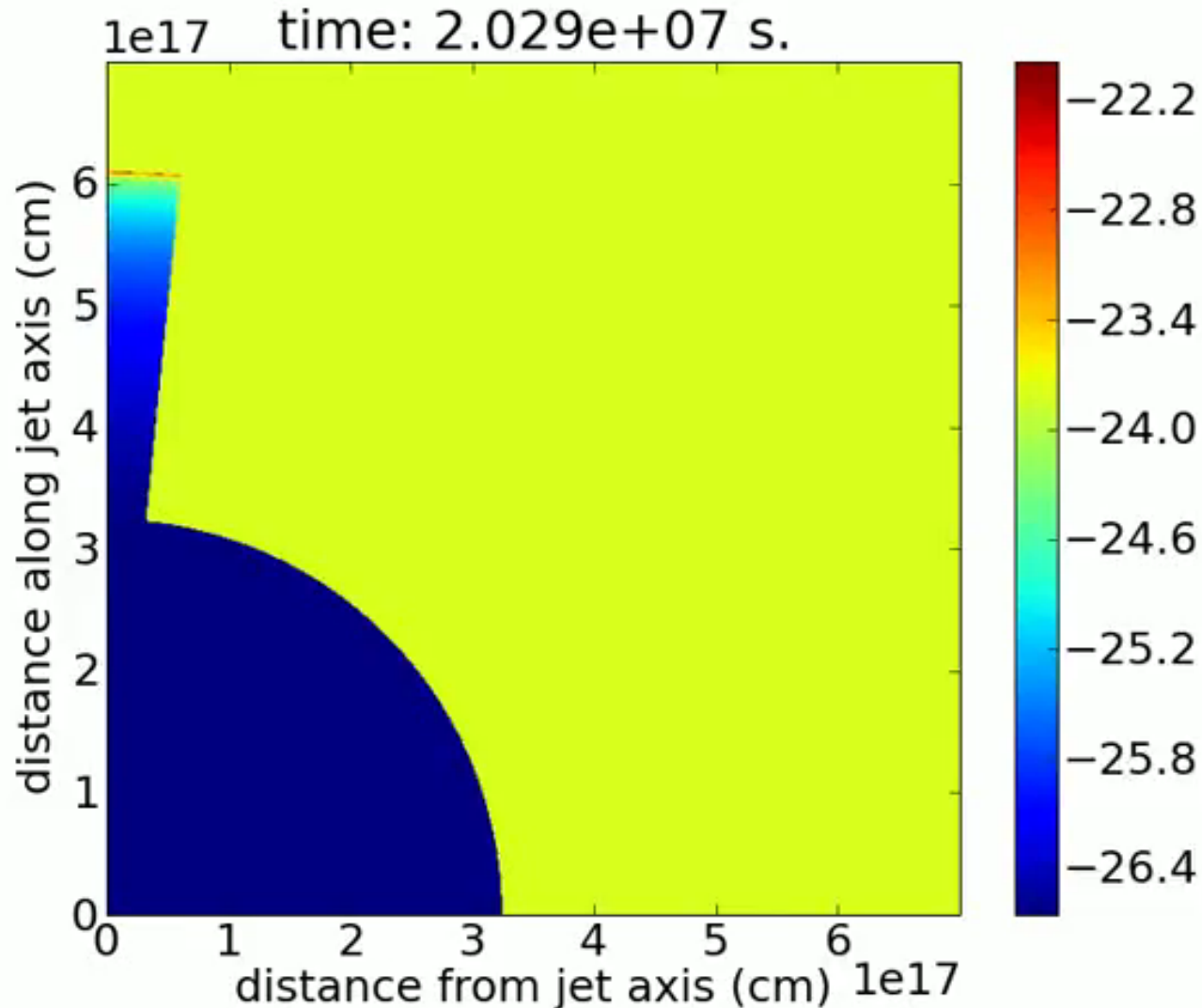
- Dynamics : Blandford & McKee 1976
- Microphysics : ϵ_e , p , ϵ_B = **main unknown**
- Synchrotron radiation : Sari, Piran, Narayan 1998

Two important regimes: Slow cooling with $t(\text{syn}) \gg t(\text{dyn})$
Fast cooling with $t(\text{syn}) \ll t(\text{dyn})$

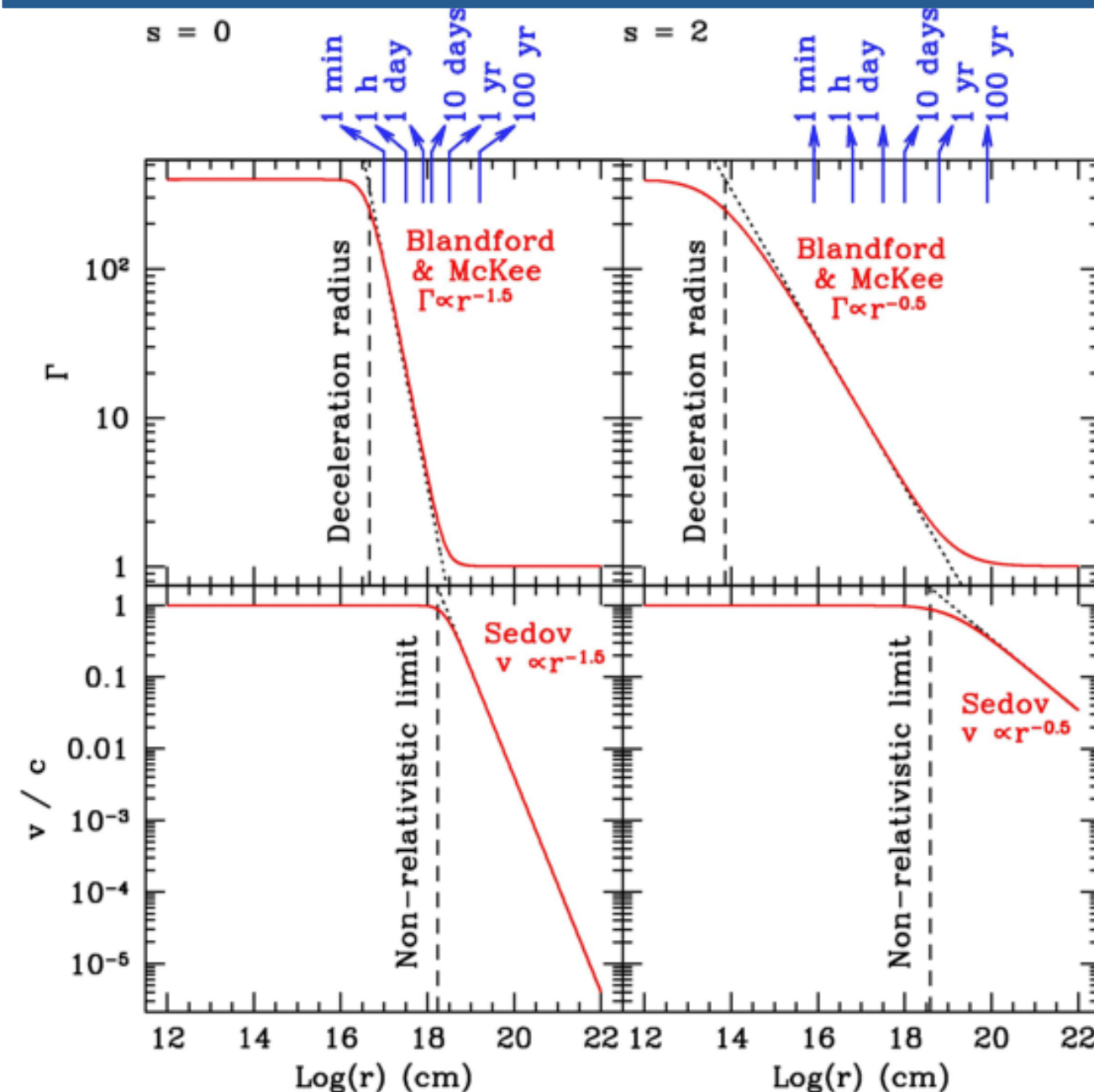
- Effect of a stellar wind : Chevalier & Li 2000
- Jet vs spherical outflow : Rhoads 1997

Forward (external) shock model

A recent simulation by van Eerten et al.



Forward (external) shock model



Relativistic ejecta :

$$\Gamma_0 = 400$$

$$E_0 = 10^{53} \text{ erg}$$

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

External medium :

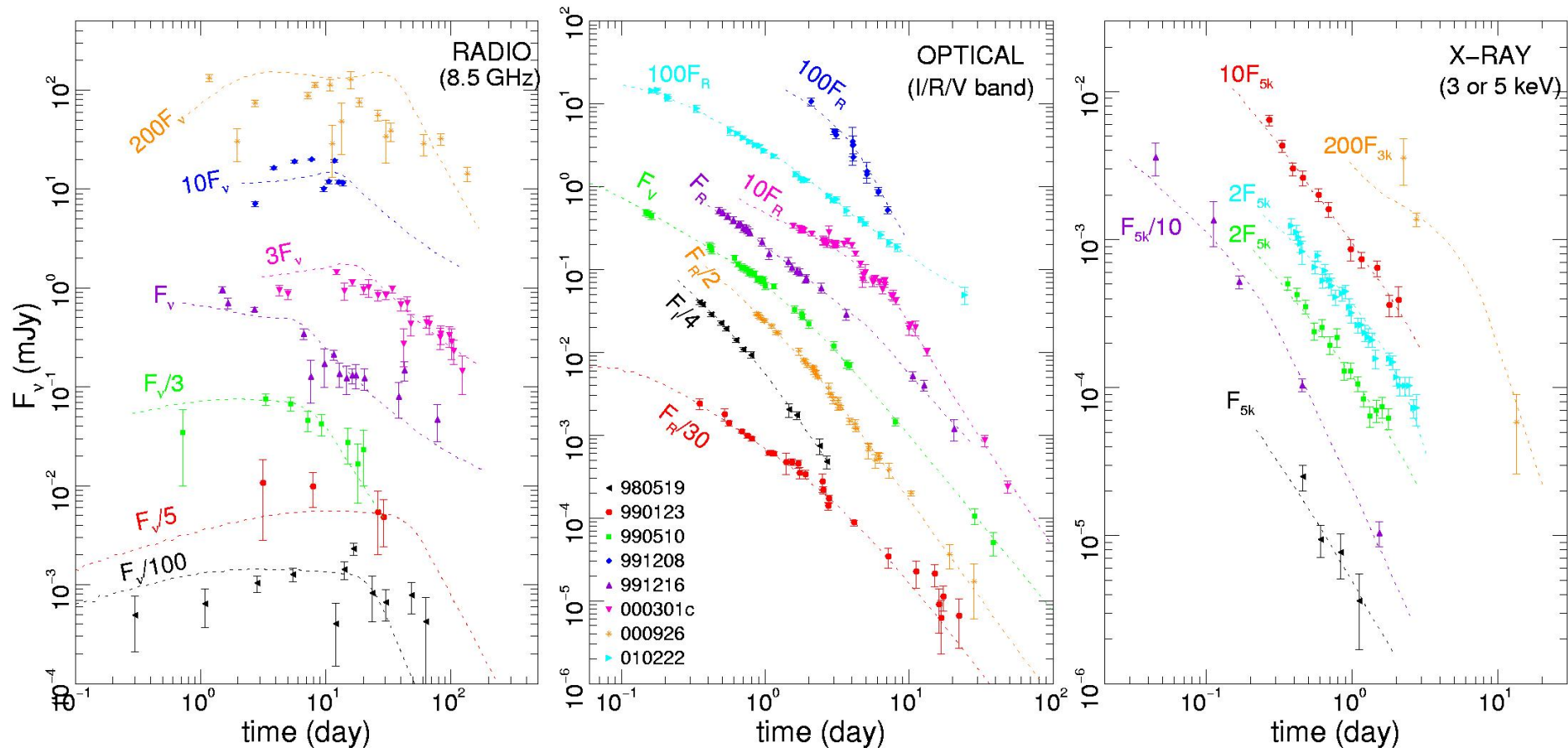
Uniform ($s=0$): $n = 1 \text{ cm}^{-3}$

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

Pre-Swift status: nice fits to observations

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

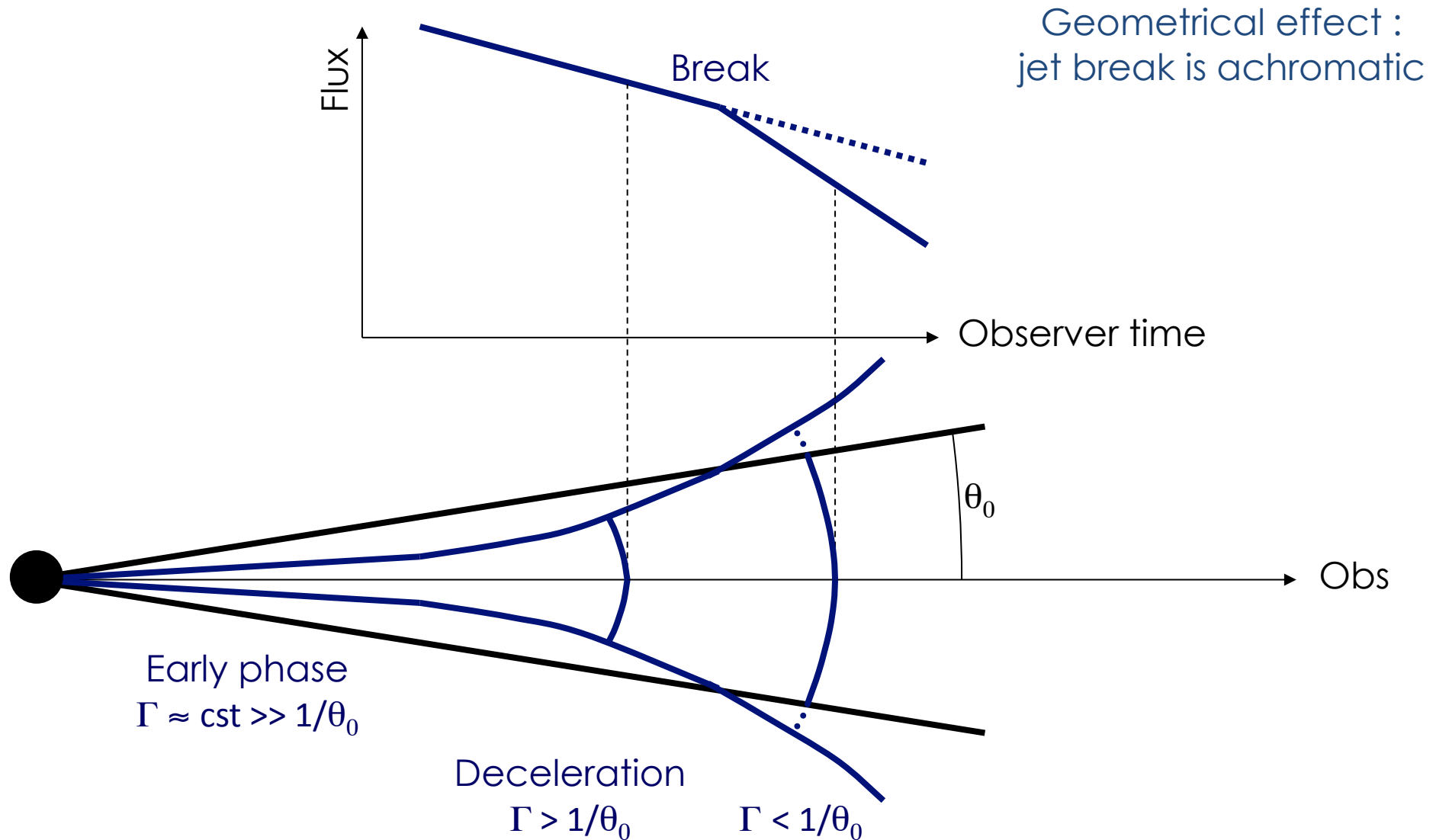
Some problems? (external density, p slope, ...)



(Panaitescu & Kumar 2001)

Jet breaks

(Rhoads 1997)



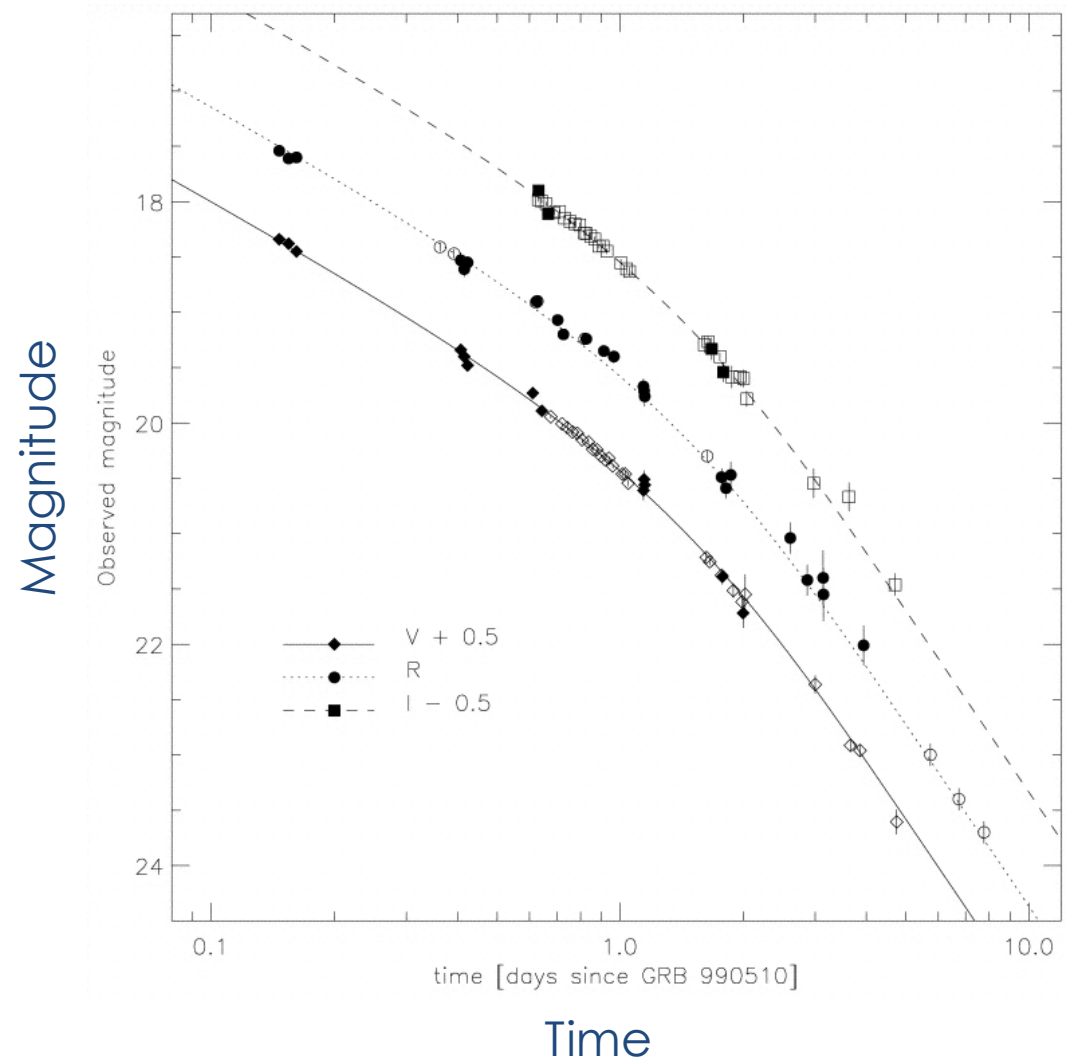
Pre-Swift status: jet breaks

GRB 990510

(Harrison et al. 1999)

$E_{\gamma, \text{true}} \sim 10^{51}$ 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.

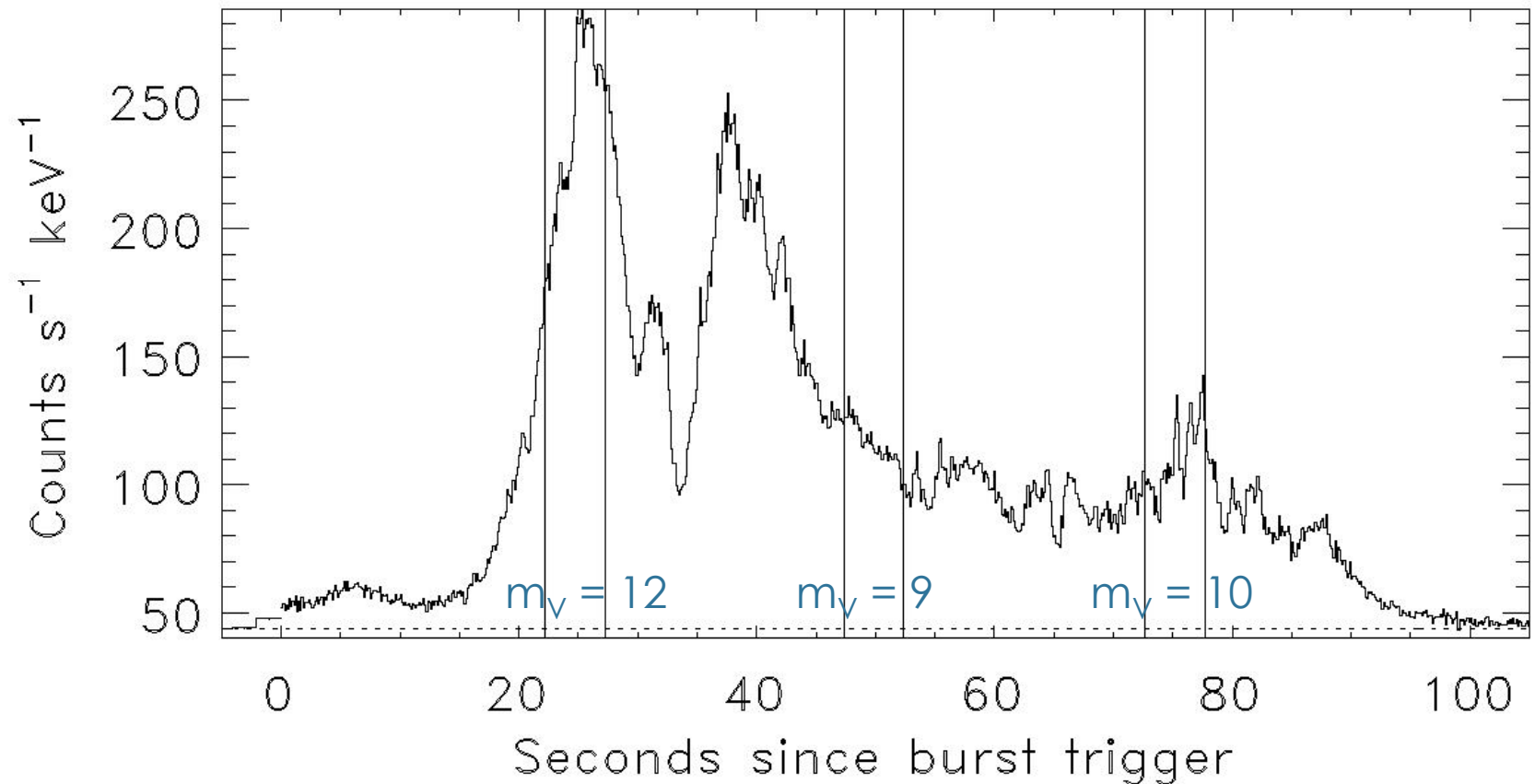
Reverse shock

- 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)



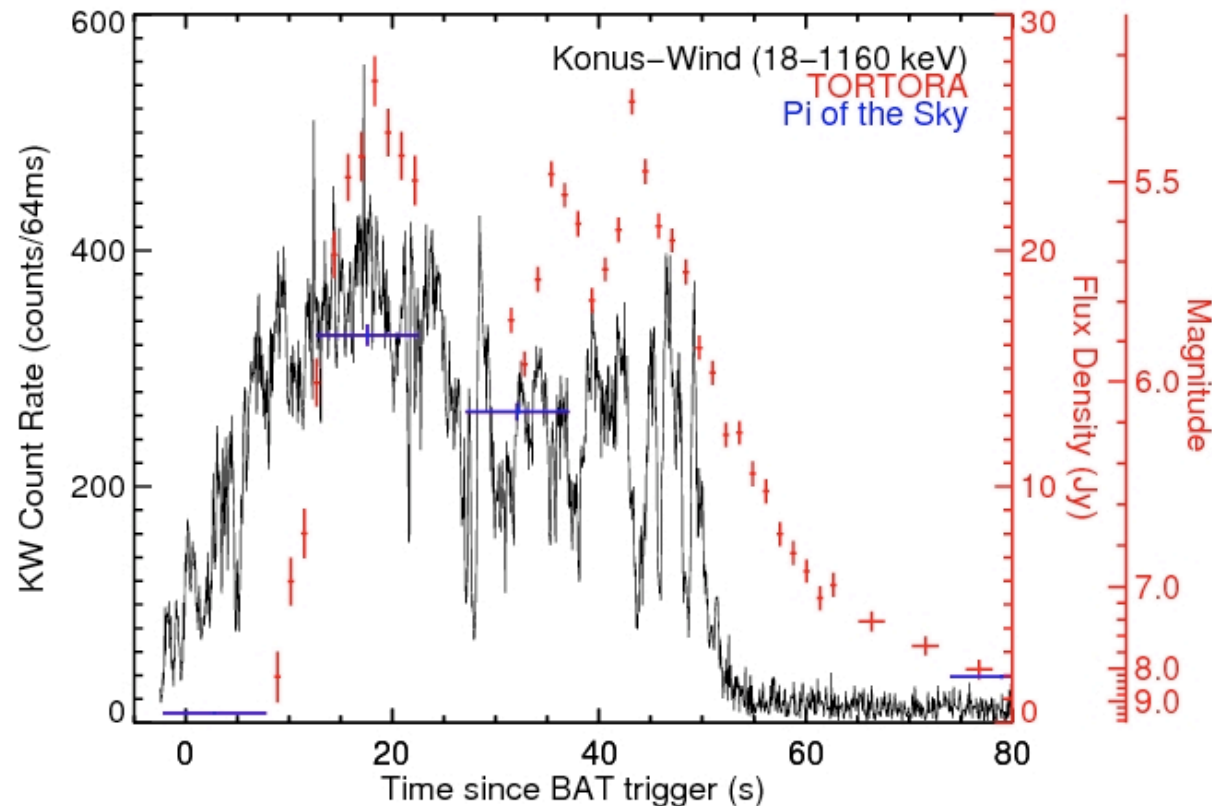
The *Swift* era

- Many more afterglows
- Observations start earlier : 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 @ $z = 0.937$

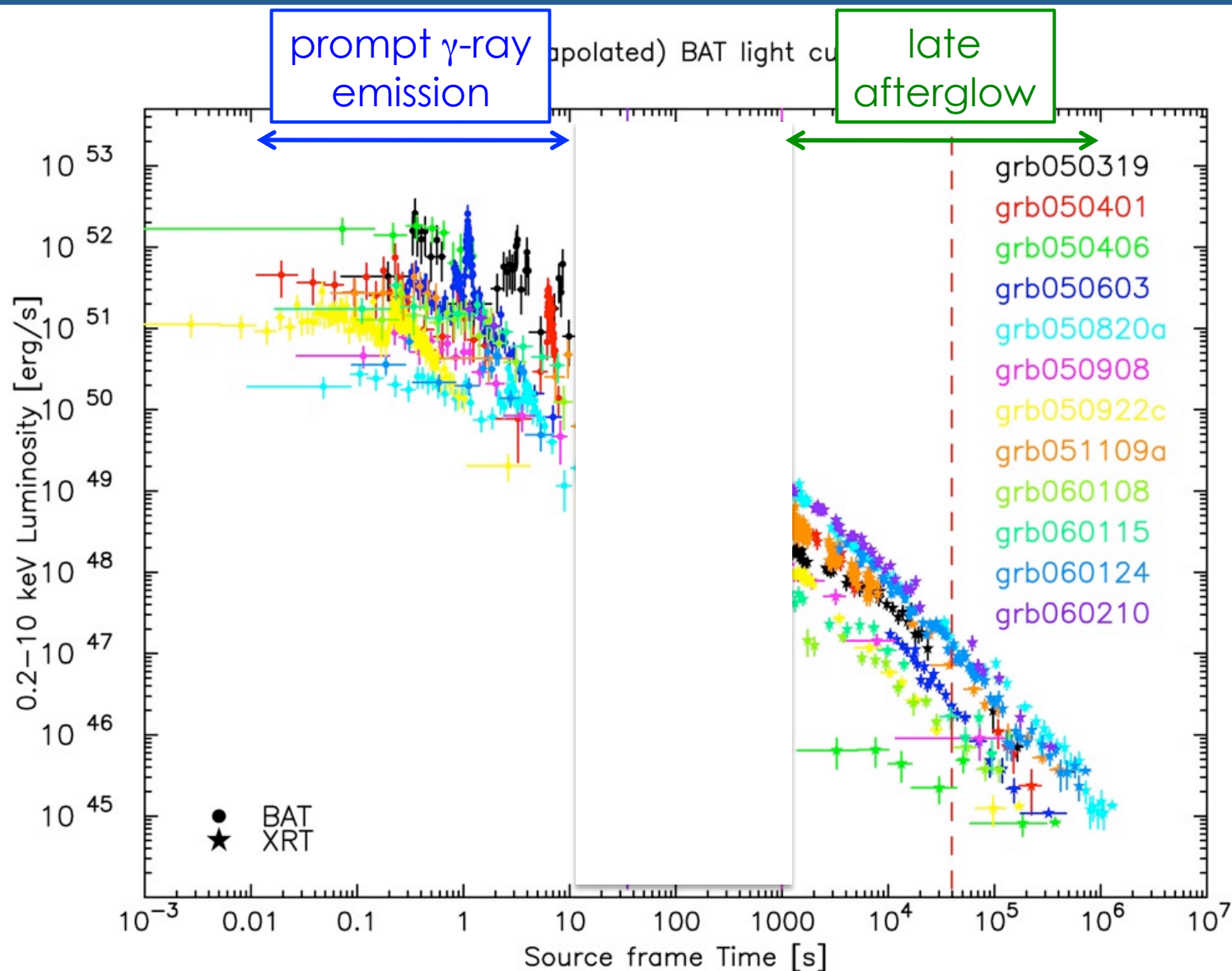


(Racusin et al. 2008)

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

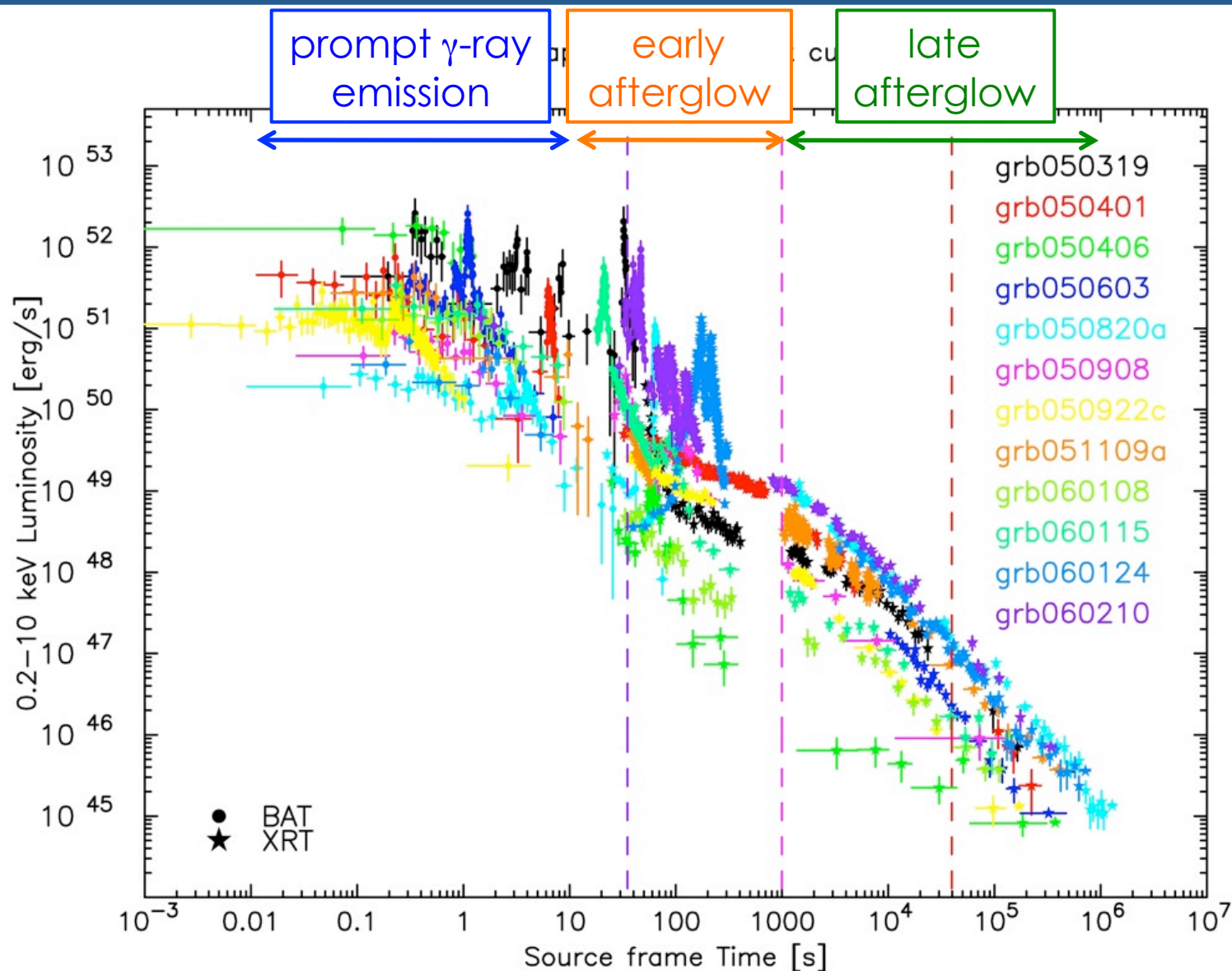
Swift observations: afterglow

X-rays



Swift observations: afterglow

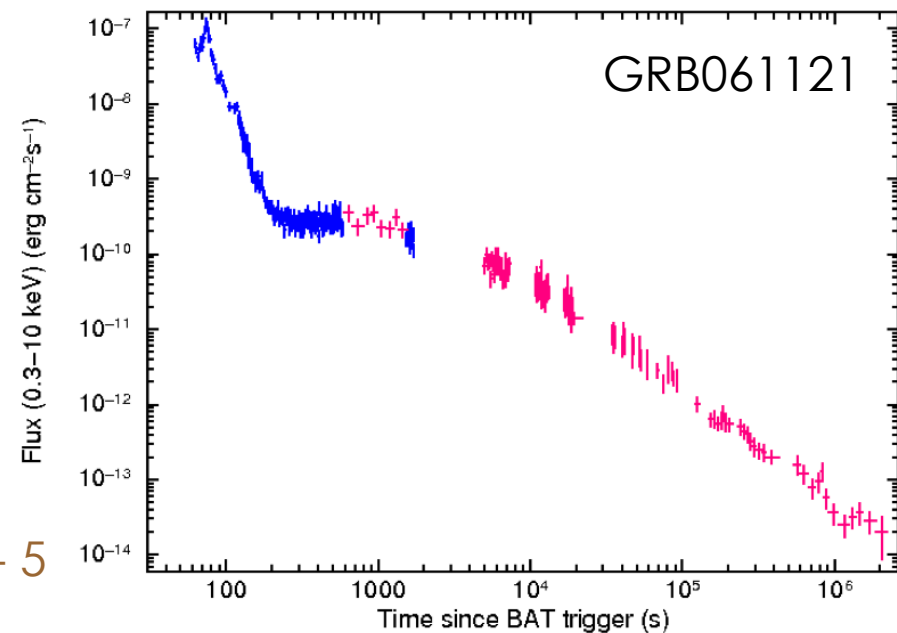
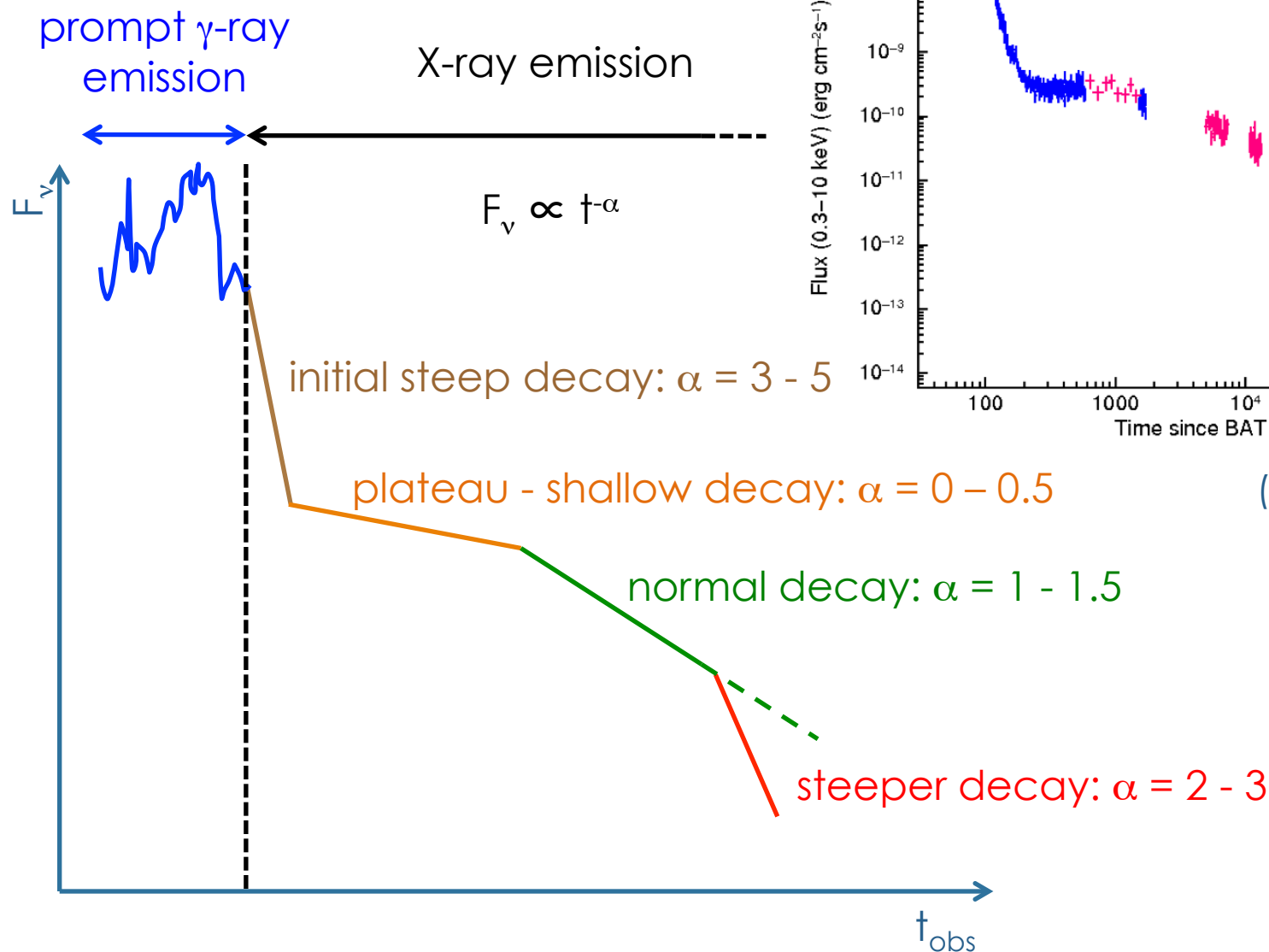
X-rays



(Mangano et al. 2007)

Swift: (1) Afterglow lightcurve

- « Canonical » lightcurve:

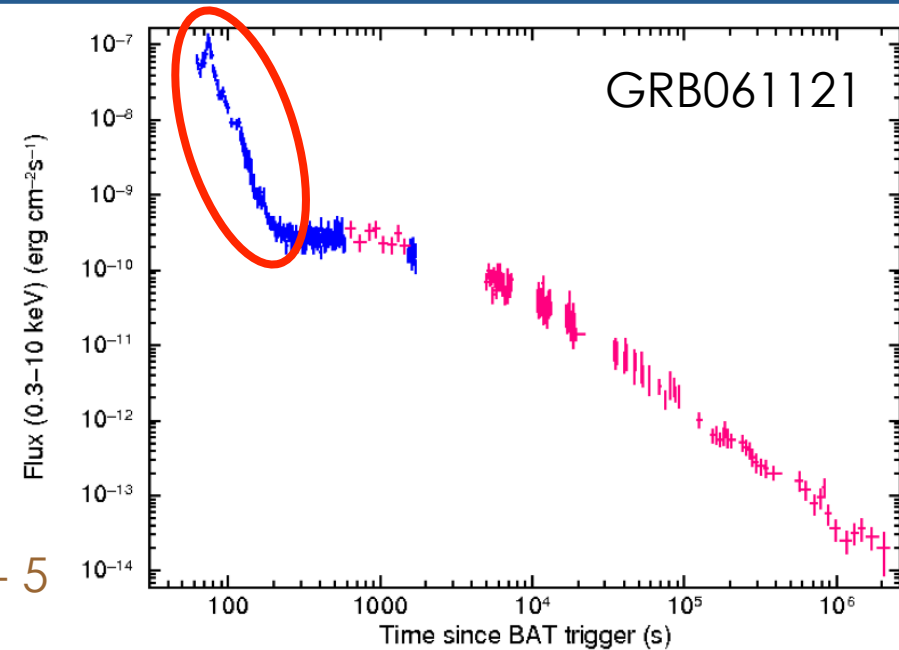
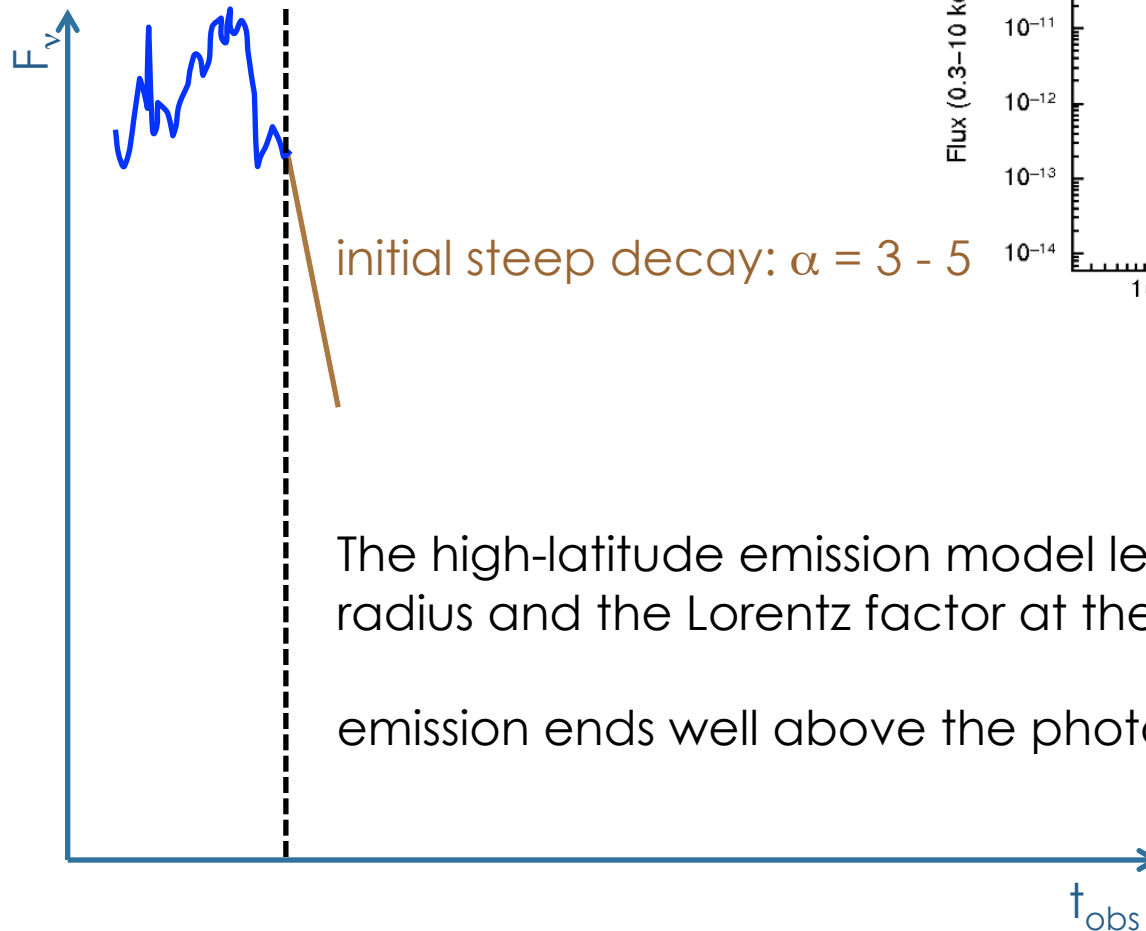


(Page et al. 2007)

(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)

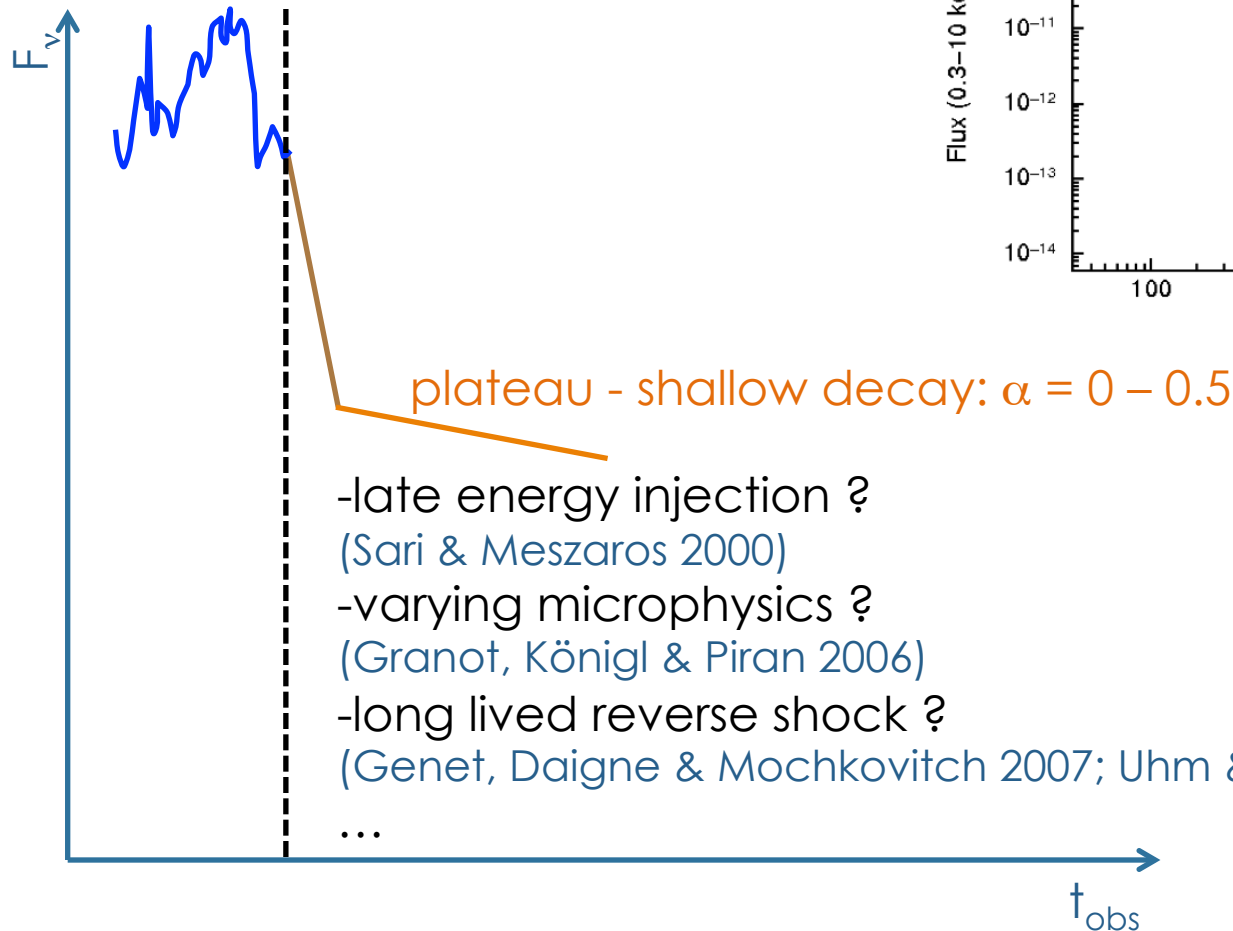


(Page et al. 2007)

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.



-late energy injection ?

(Sari & Meszaros 2000)

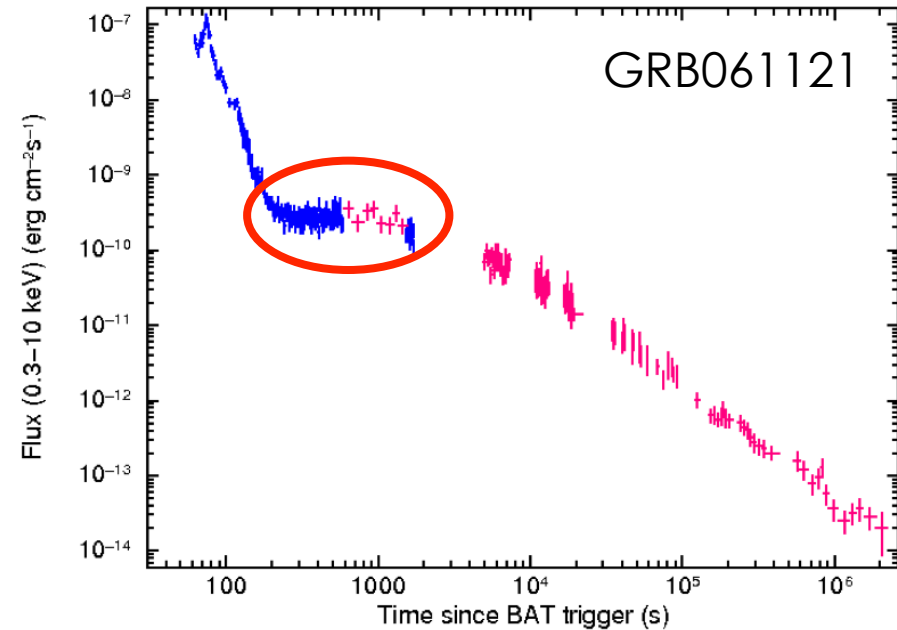
-varying microphysics ?

(Granot, Königl & Piran 2006)

-long lived reverse shock ?

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

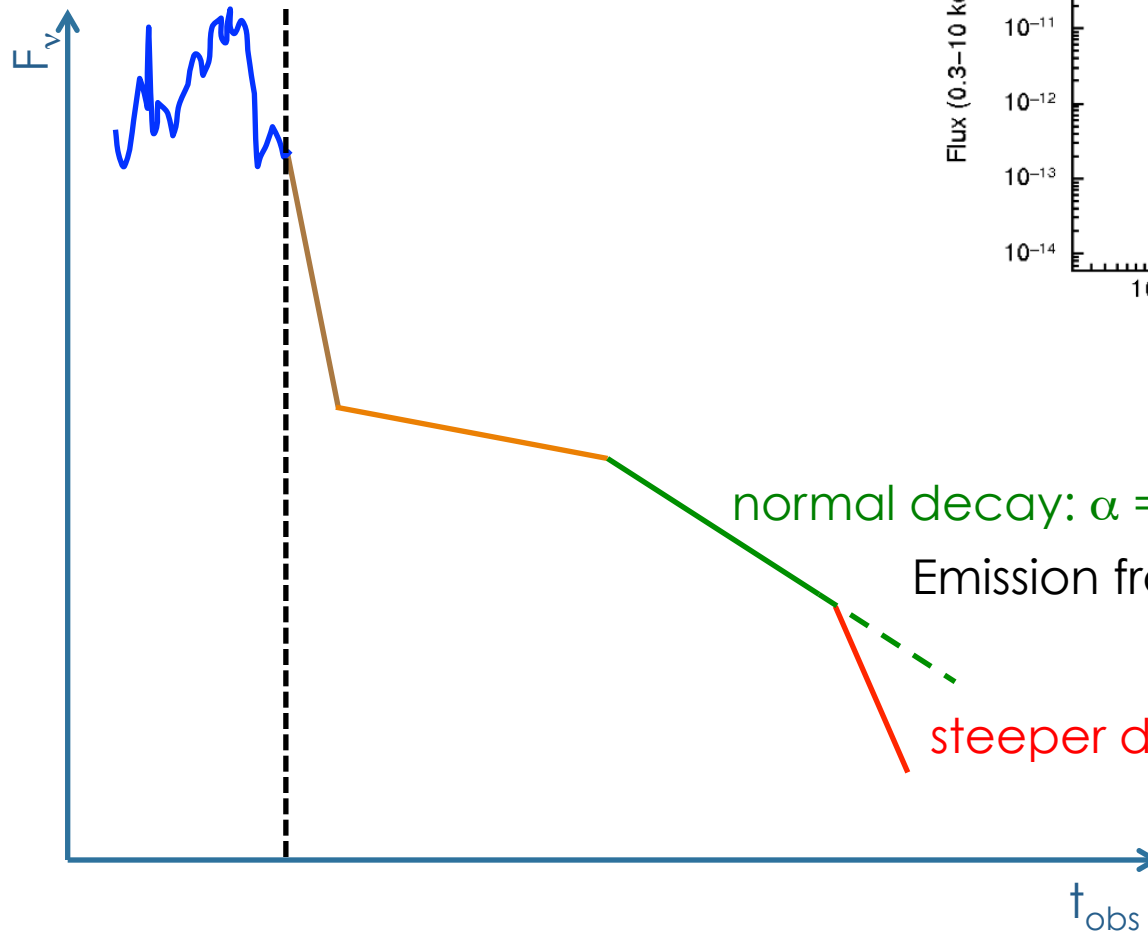
...



(Page et al. 2007)

Swift: (1) Afterglow lightcurve

- « Normal » afterglow:

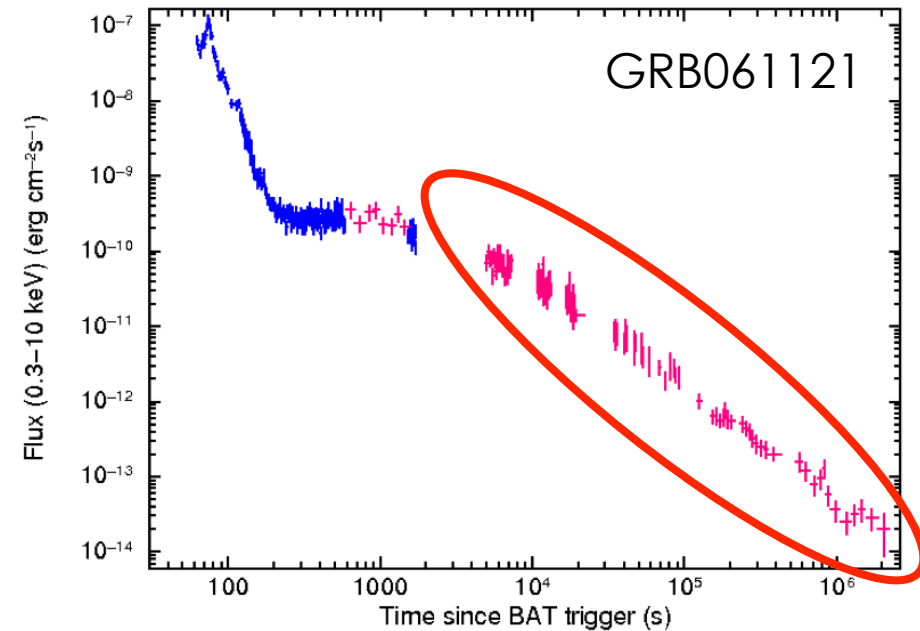


normal decay: $\alpha = 1 - 1.5$

Emission from the forward shock ?

steeper decay: $\alpha = 2 - 3$

Jet break ?

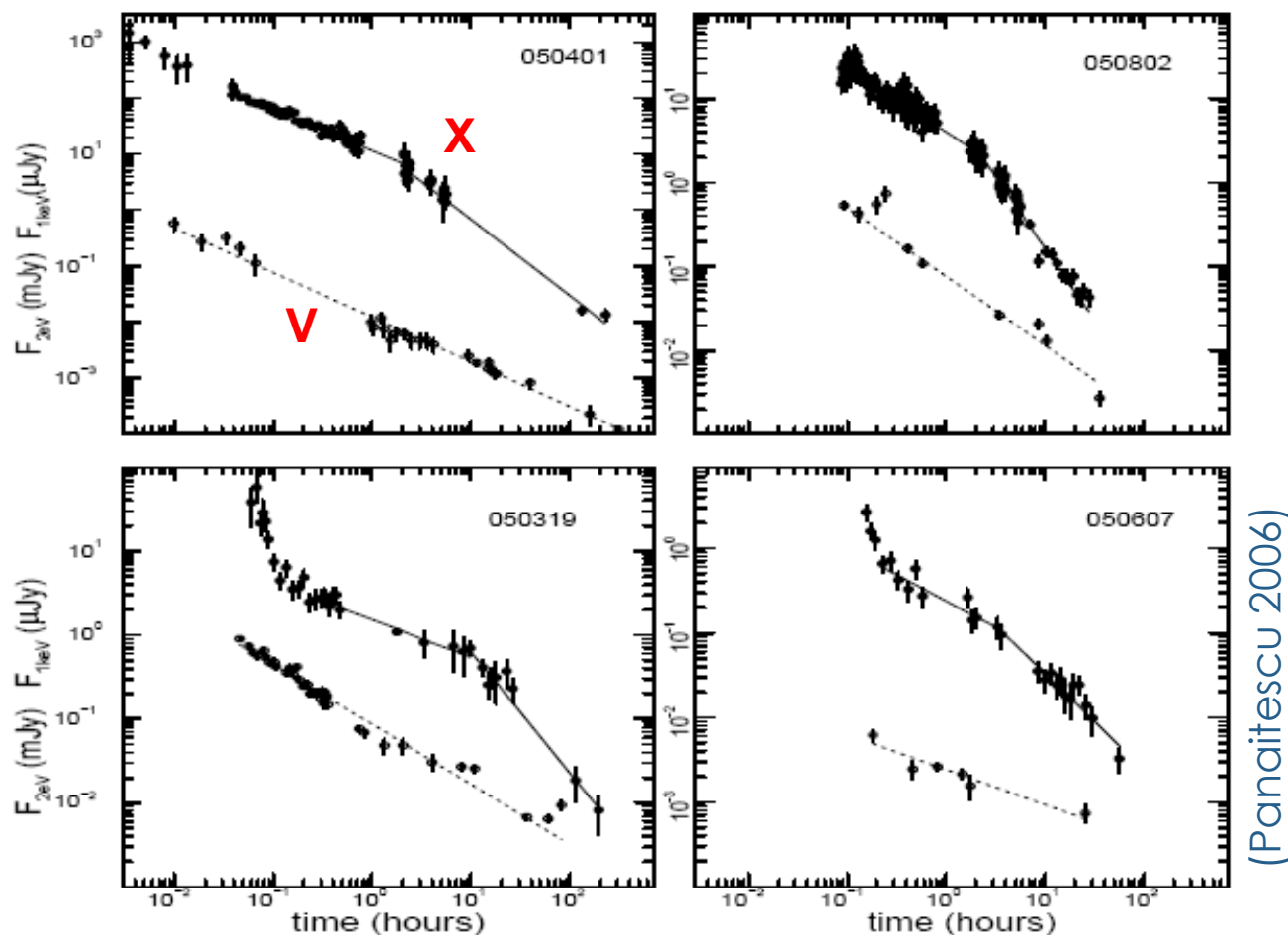


(Page et al. 2007)

Swift: (2) Chromatic breaks

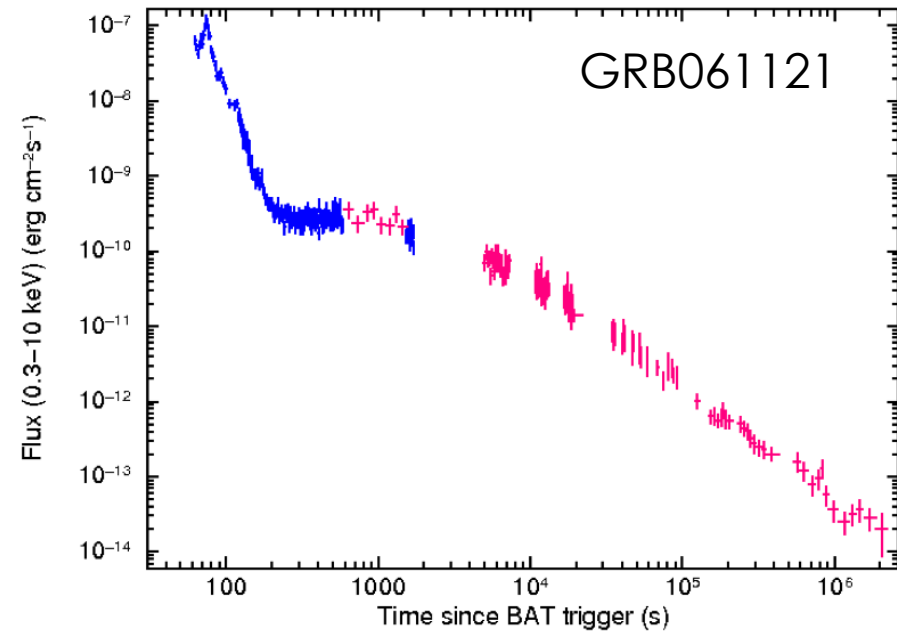
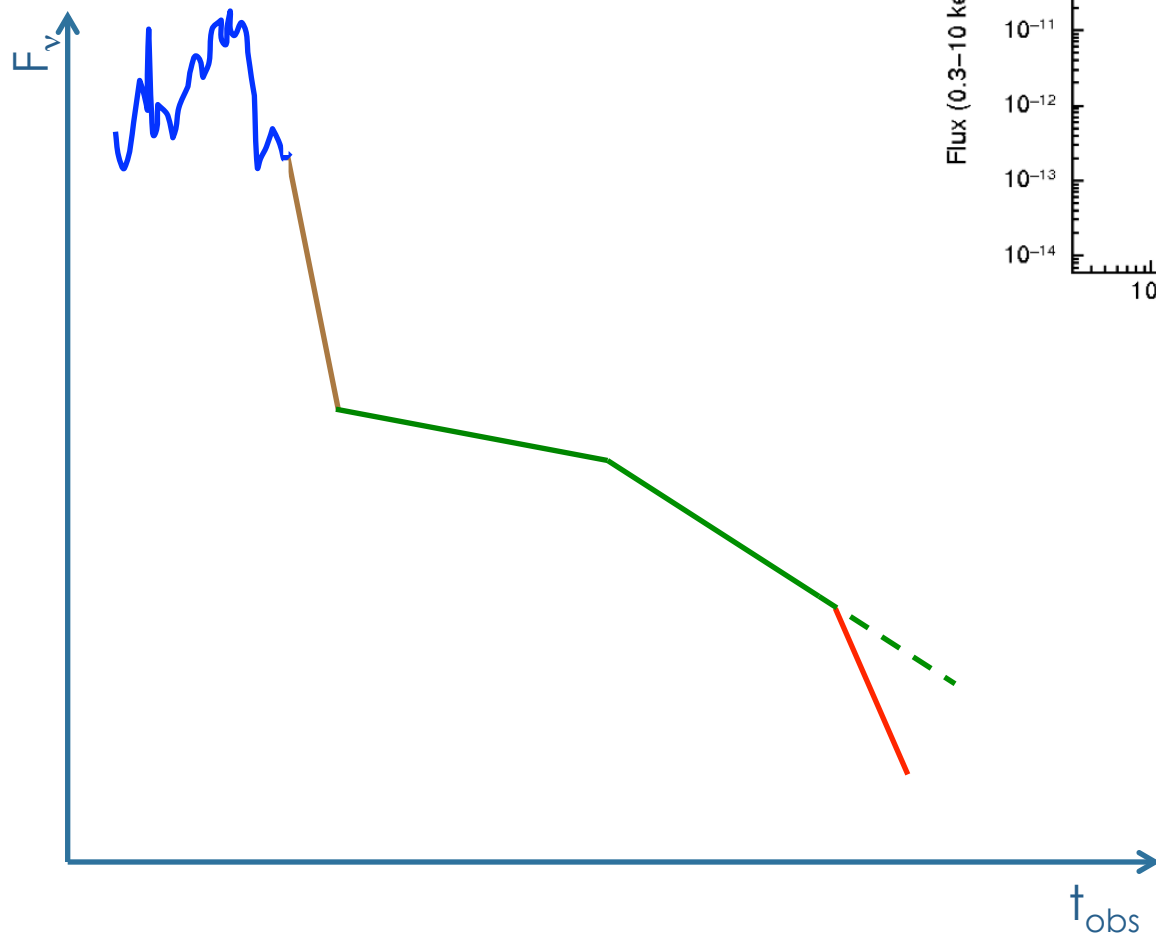
- X-rays vs optical: chromatic breaks

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



- Forward shock: evolving microphysics ? (Panaiteescu 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)

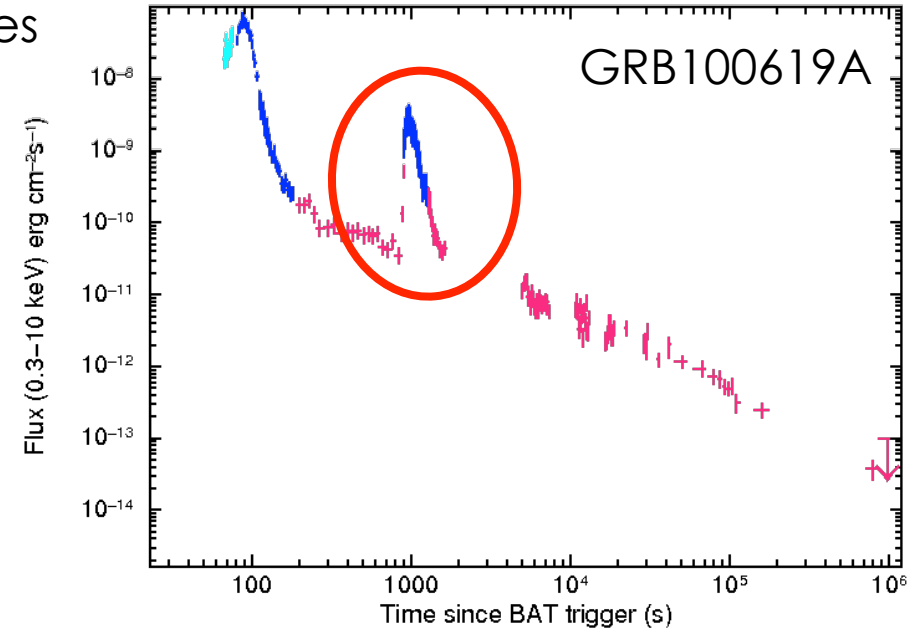
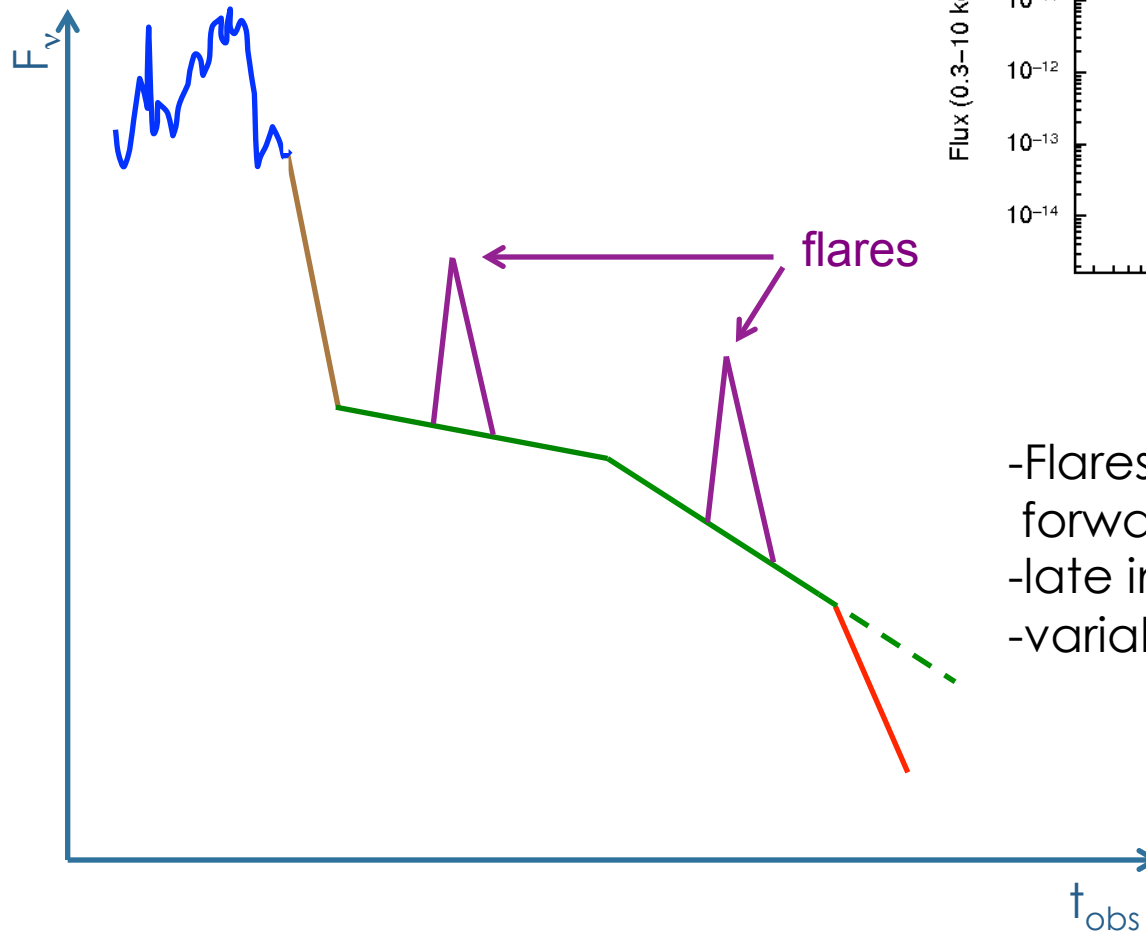
Swift: (3) Flares



(Swift XRT catalog)

Swift: (3) Flares

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

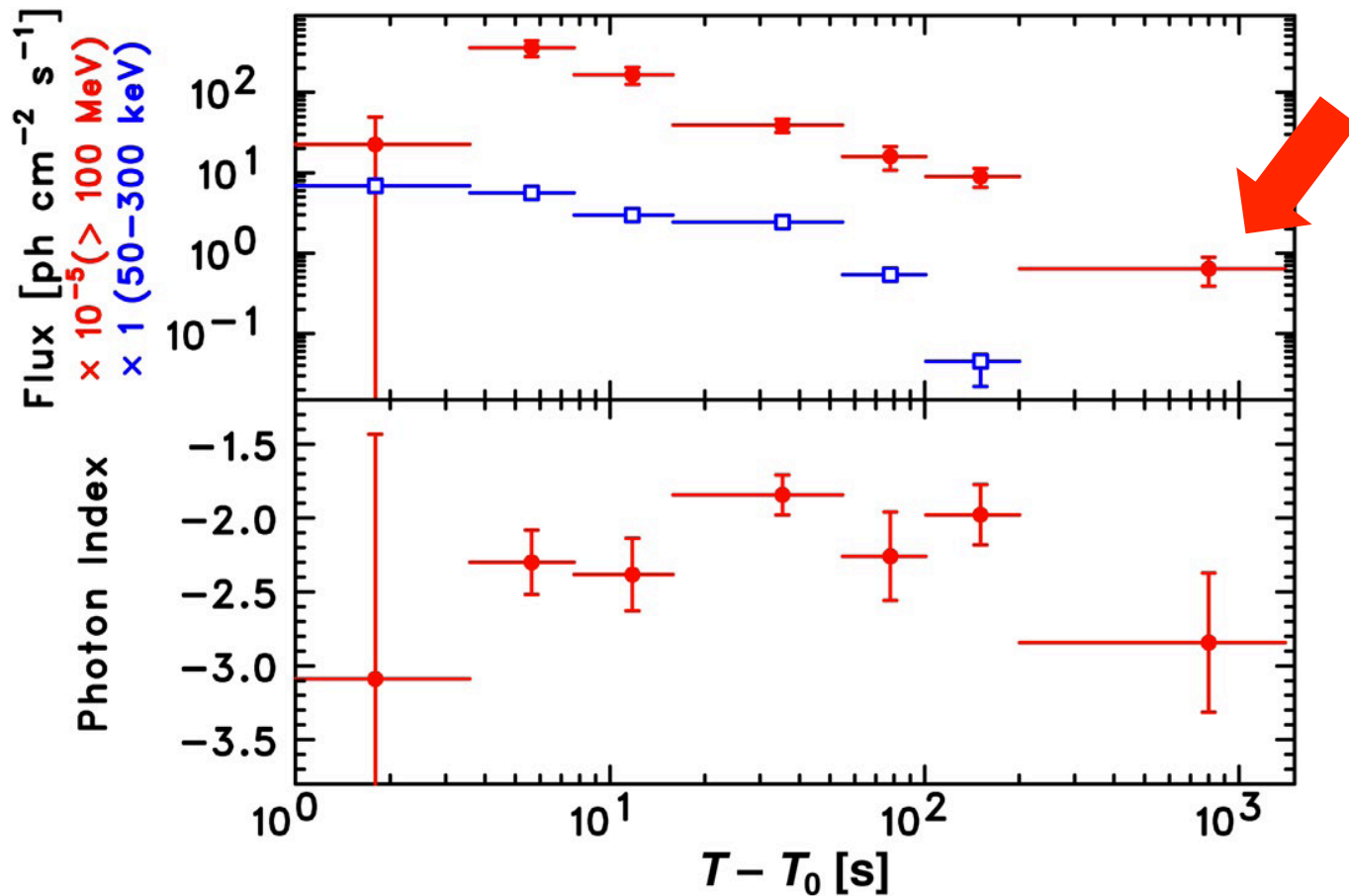


(Swift XRT catalog)

- 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)

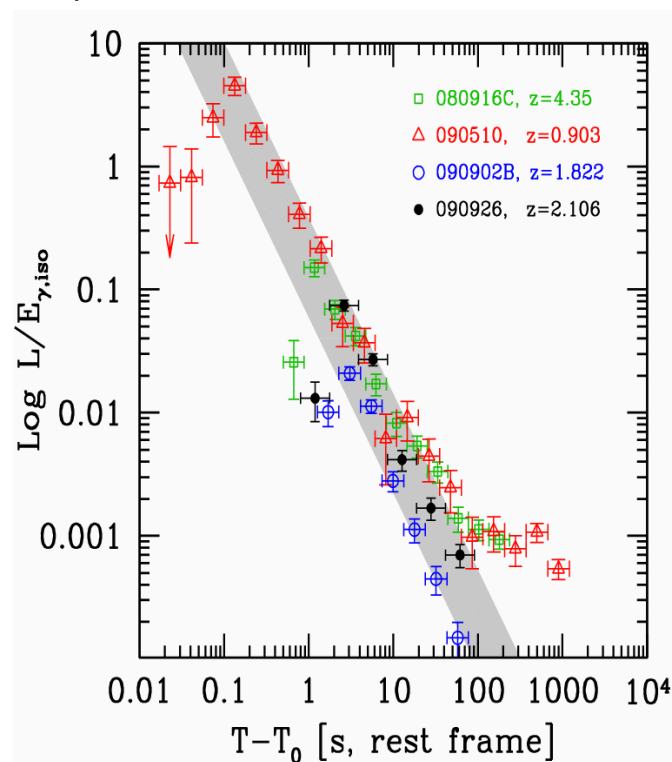
Observing the long lasting emission associated with a « standard » early afterglow may help in distinguishing between afterglow models

Long lasting emission

- High-energy afterglow ?

- **An intriguing 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 intriguing 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)

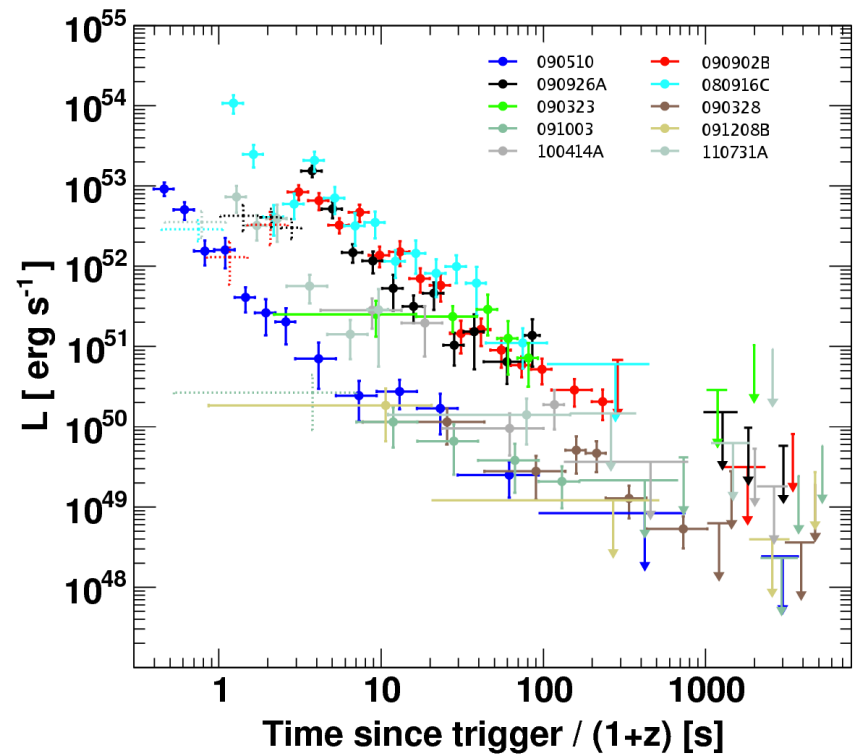
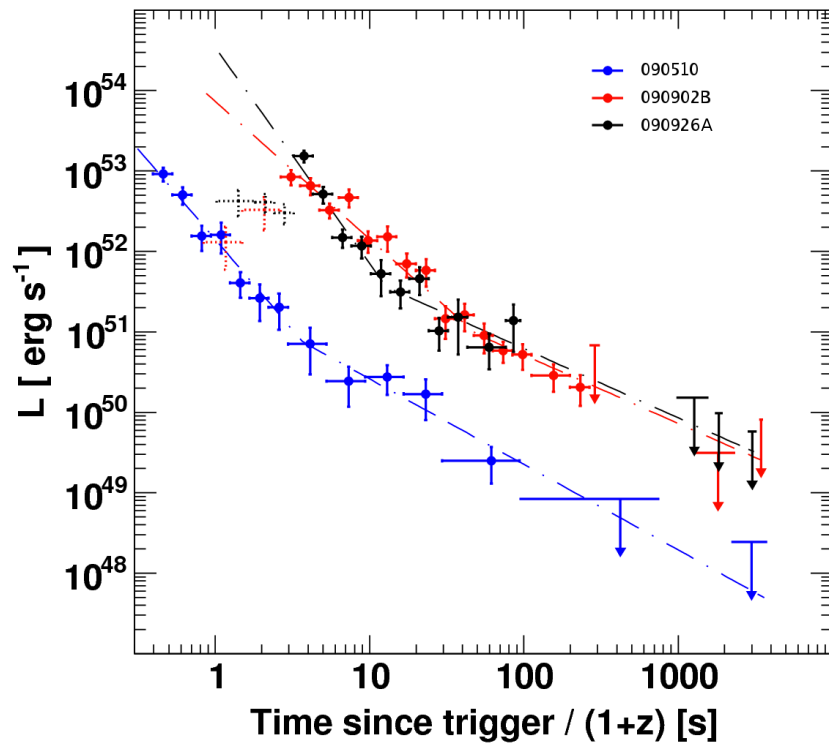
- needs very low density and magnetization in the external medium (Kumar & Barniol Duran 2009)

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 ?



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 ($T_{90} < 2\text{s}$) with an early XRT observation before May 2012 :

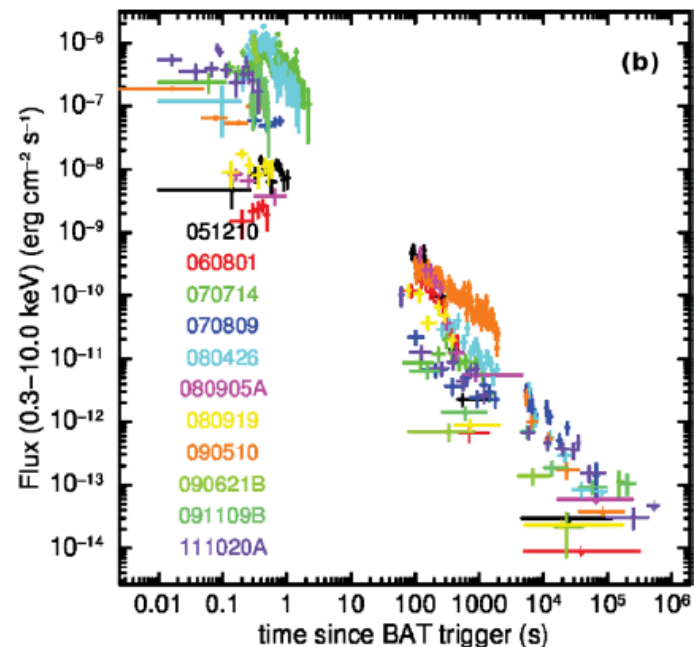
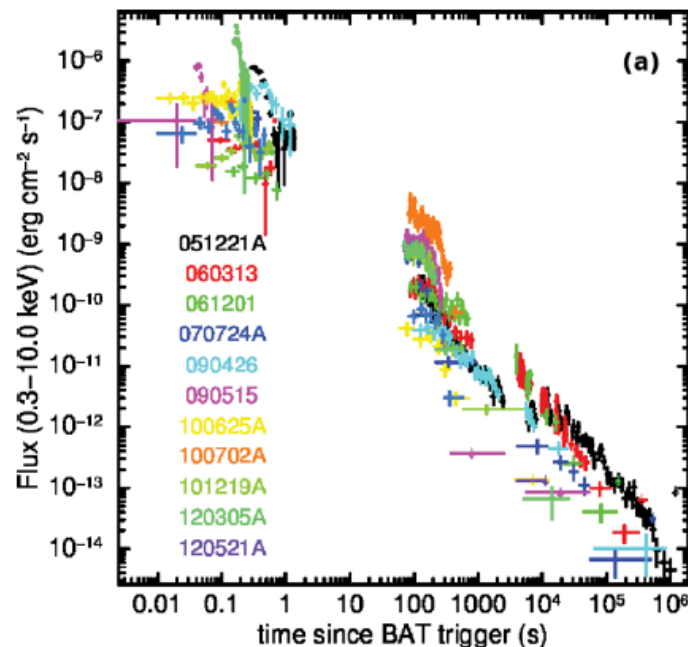
- 43 events
- 10 with a redshift ($z = 0.111$ to 2.6)
 - 13 have an identified host galaxy
 - 18 have $T_{90} > 0.5\text{ s}$ [to compare to typical duration = 100 ms]
 - only 5 have $T_{90} < 0.1\text{ s}$ [to compare to typical duration = 100 ms]

= long short GRBs

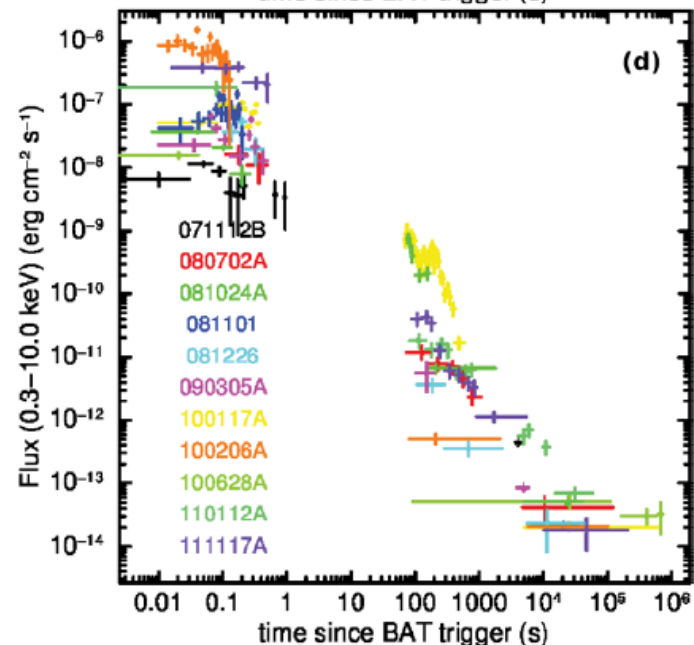
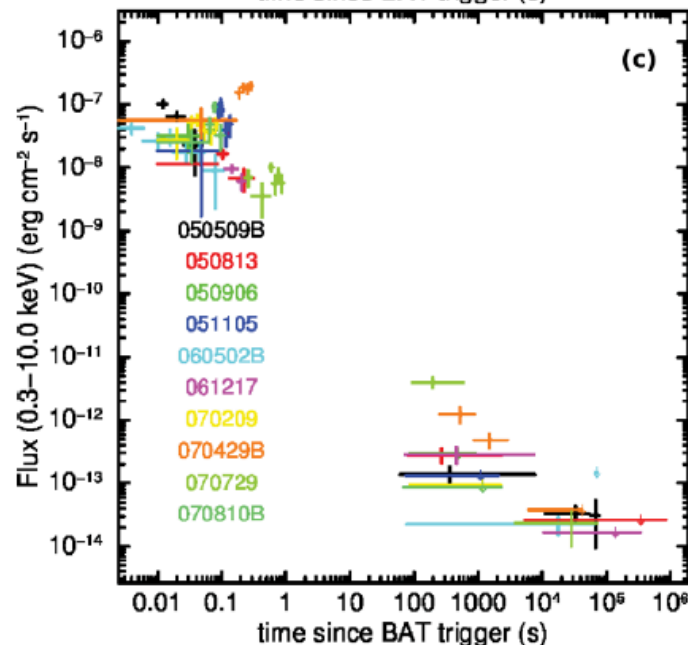
The case of short GRBs

X-rays

Some have bright AG with breaks (plateaus,...)

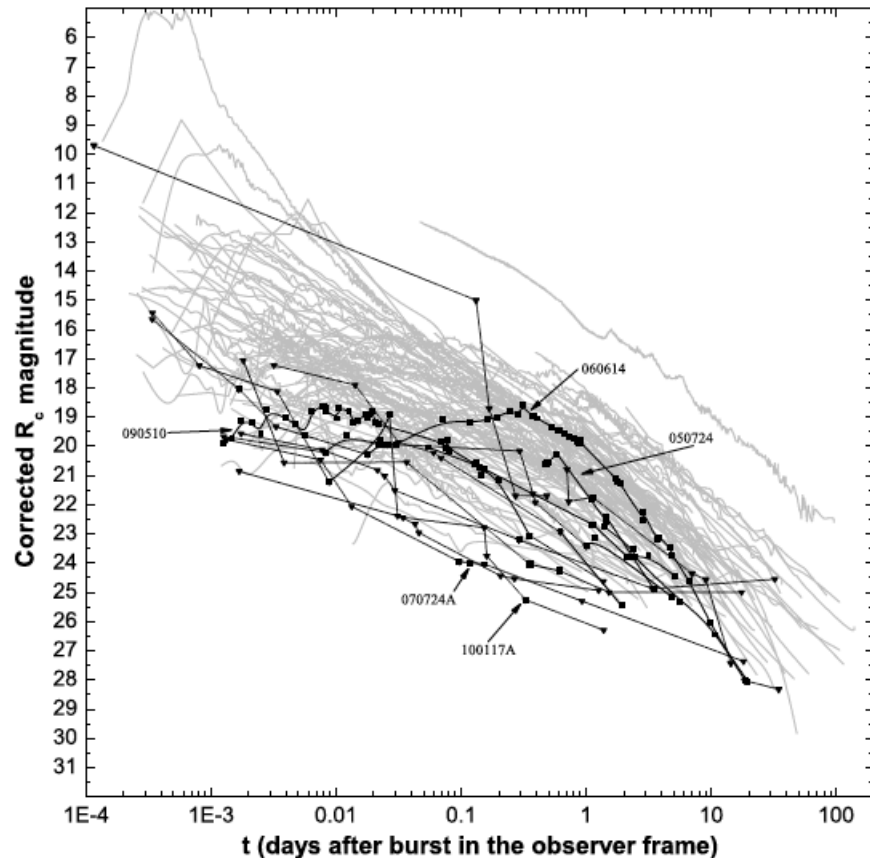


Some have very faint AG

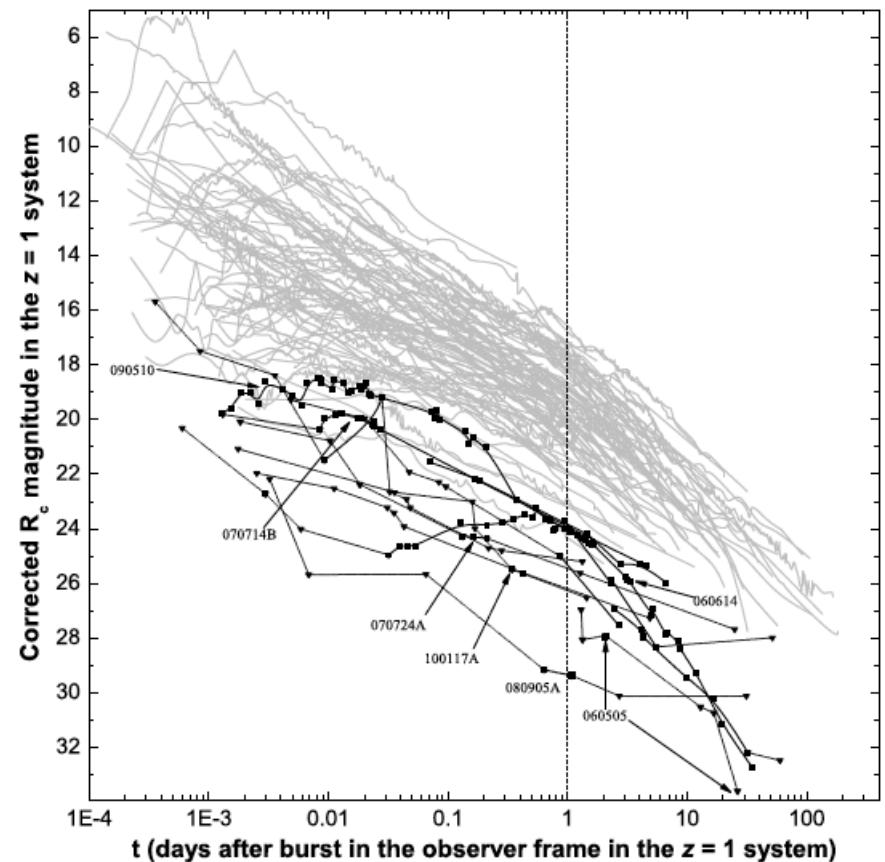


The case of short GRBs

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



Observer frame



Rest frame

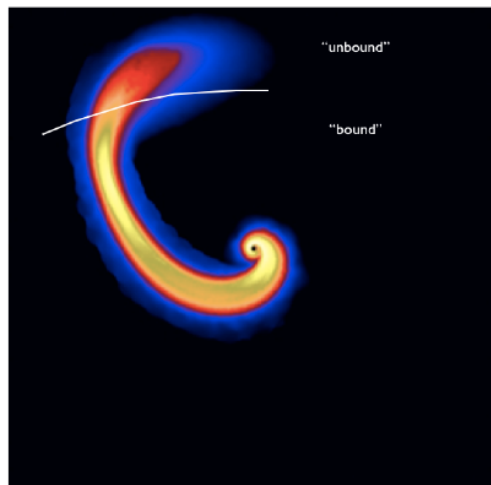
A new puzzle : extended soft X-ray tail

- Some short GRBs have a long X-ray tail

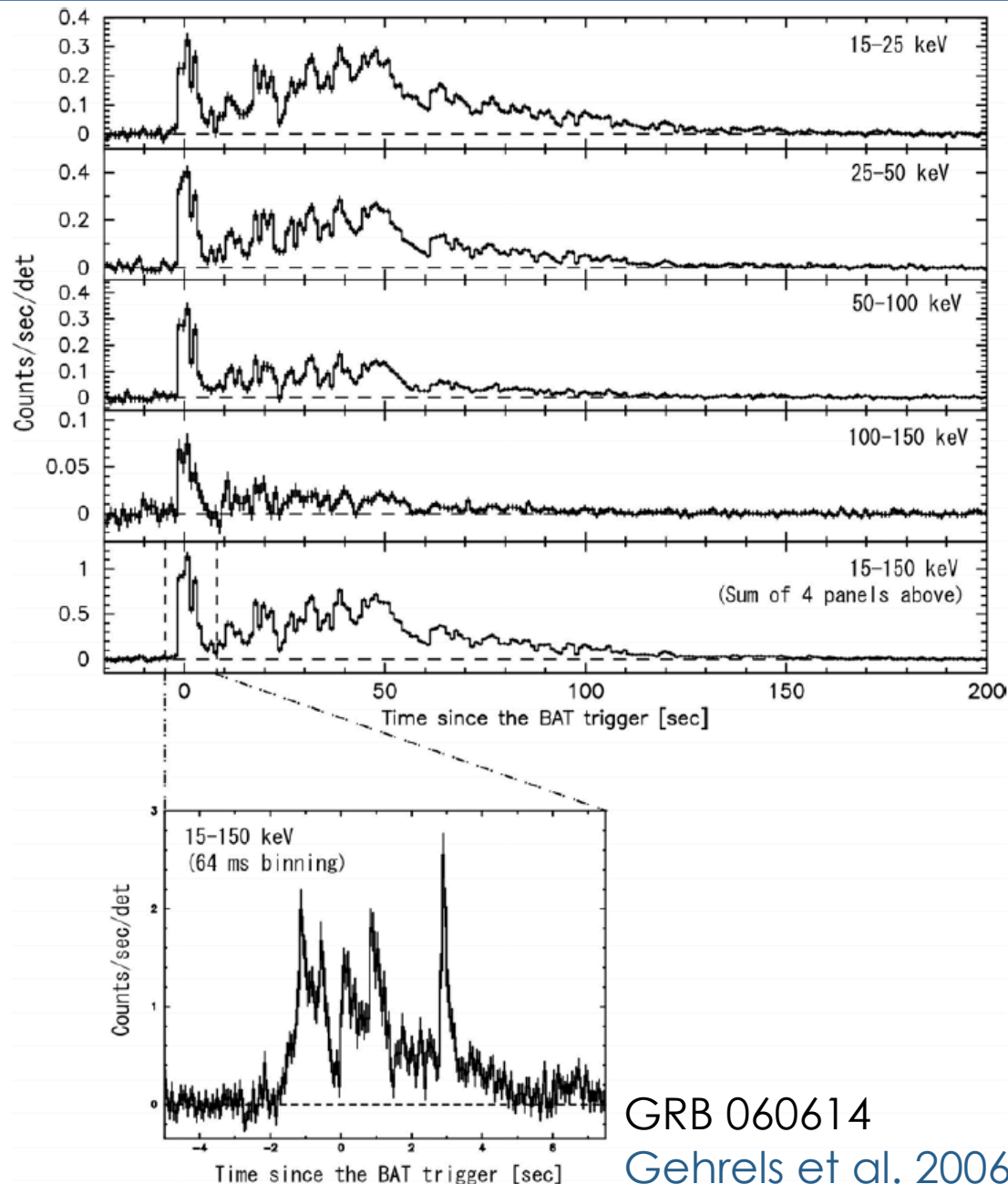
Prompt or afterglow ?

Prompt is preferred (variability)

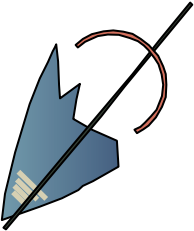
In the merger scenario :
tidal trails ? Enough mass ?



- Observed in 1/3 of Rowlinson's sample



GRB 060614
Gehrels et al. 2006

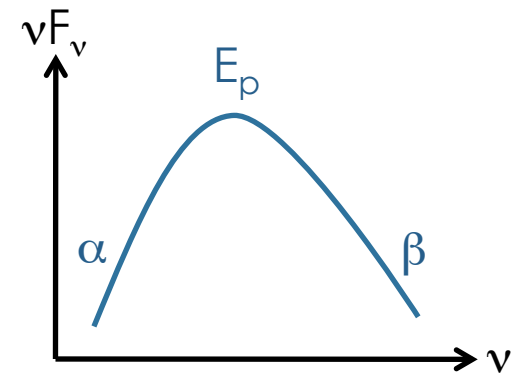


8– Prompt emission models

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.

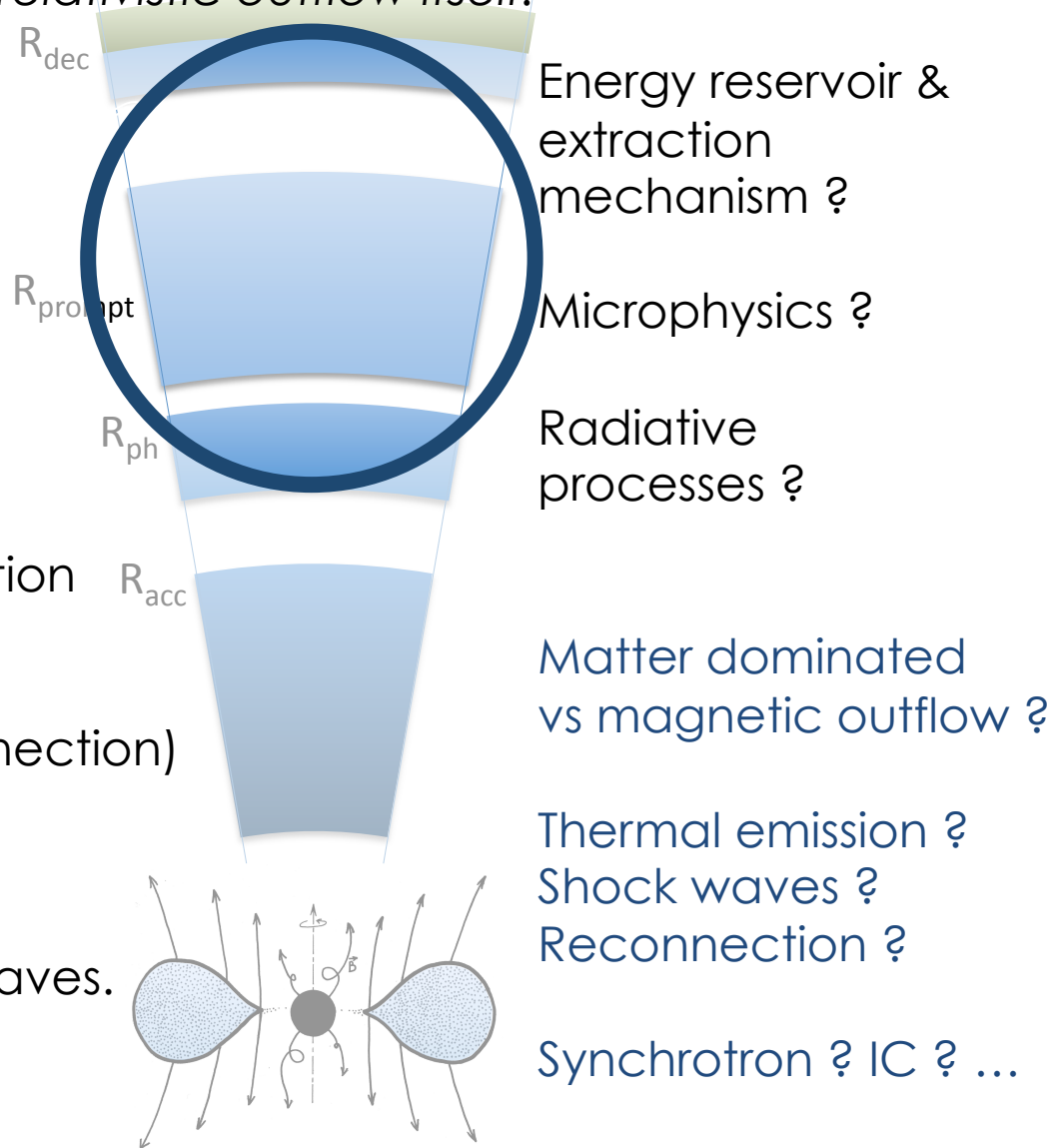
Prompt emission

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 :

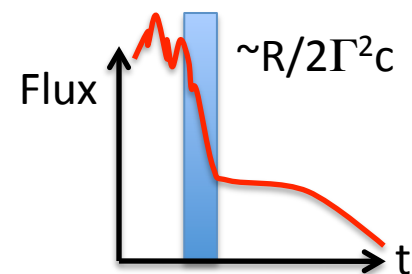
- Thermal energy
Photospheric emission
- Kinetic energy
Internal shocks + shock acceleration
- Magnetic energy
Magnetic dissipation (e.g. reconnection)

Note that a large magnetization probably exclude internal shock waves.



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** :
 - $R_{\text{prompt,start}} < 6 \cdot 10^{11} (\Gamma/100)^2 \text{ cm}$ (short time scale variability)
 - $R_{\text{prompt,end}} > 6 \cdot 10^{15} (\Gamma/100)^2 \text{ cm}$ (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: $R_{\text{prompt}} < R_{\text{dec}}$

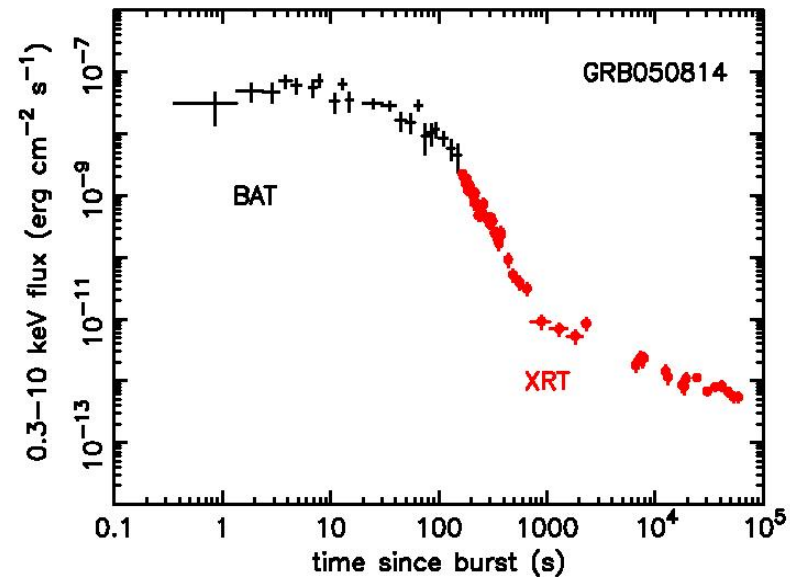


Prompt emission: The End

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).

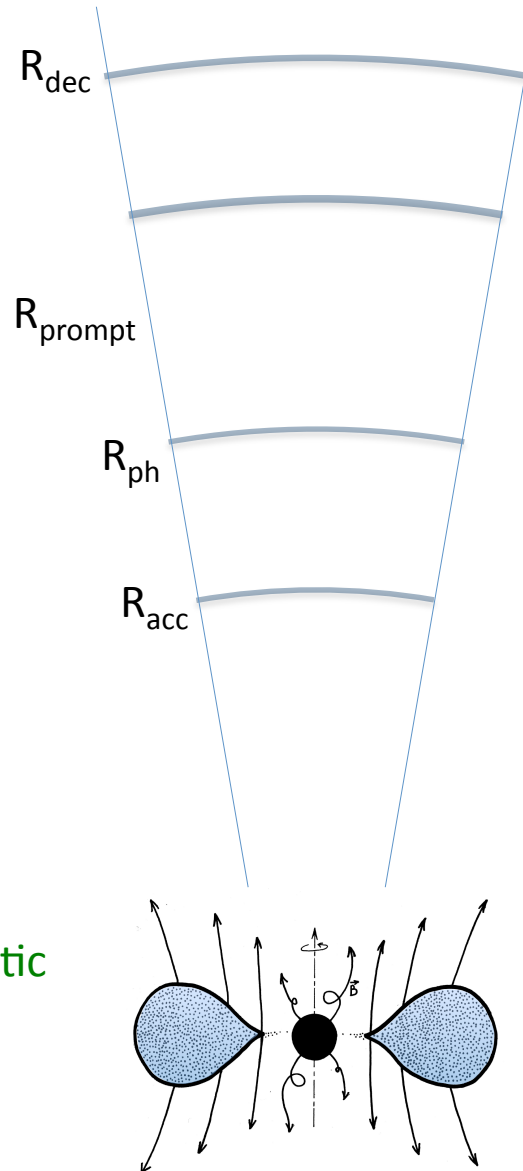
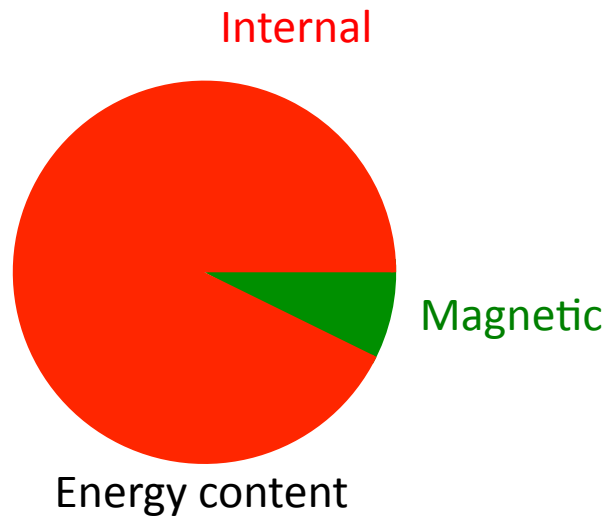
- Bolometric flux decays as t_{obs}^{-3}
(or steeper if anisotropic emission, [Beloborodov, Daigne et al. 2010](#))
- Predict a X-ray tail at the end of the prompt (Kumar & Panaitescu 2002)
- Observed by Swift ?
- Constrains the radius at the end of the prompt emission

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



Standard fireball

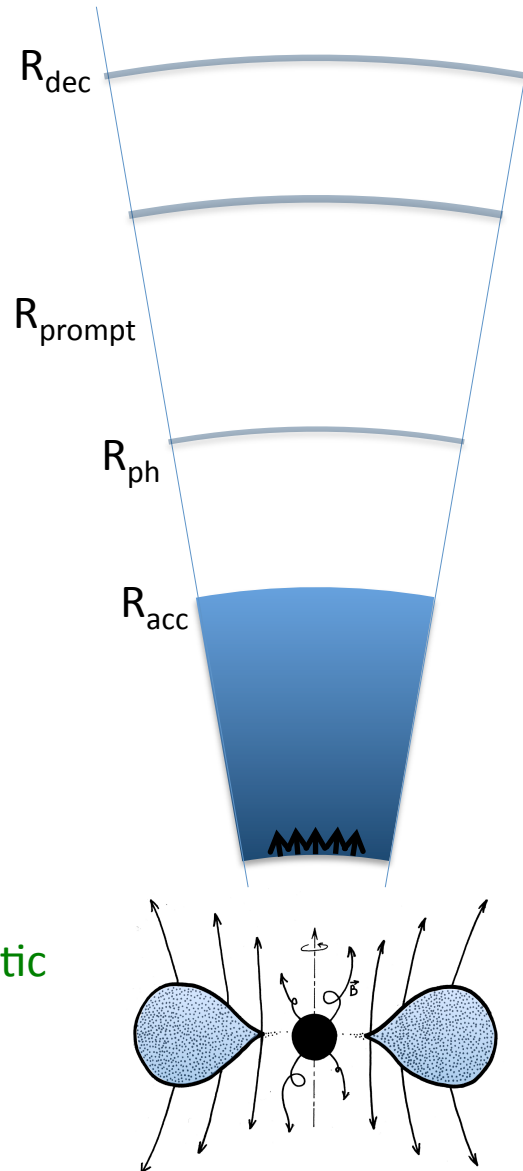
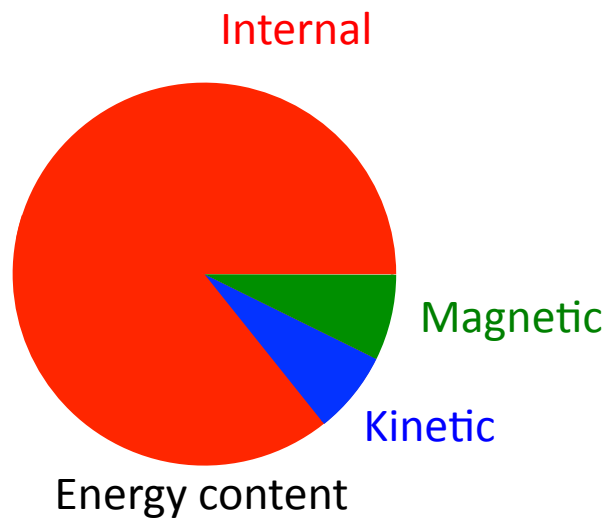
Or weakly magnetized fireballs



Initial energy release :
negligible magnetization

Standard fireball

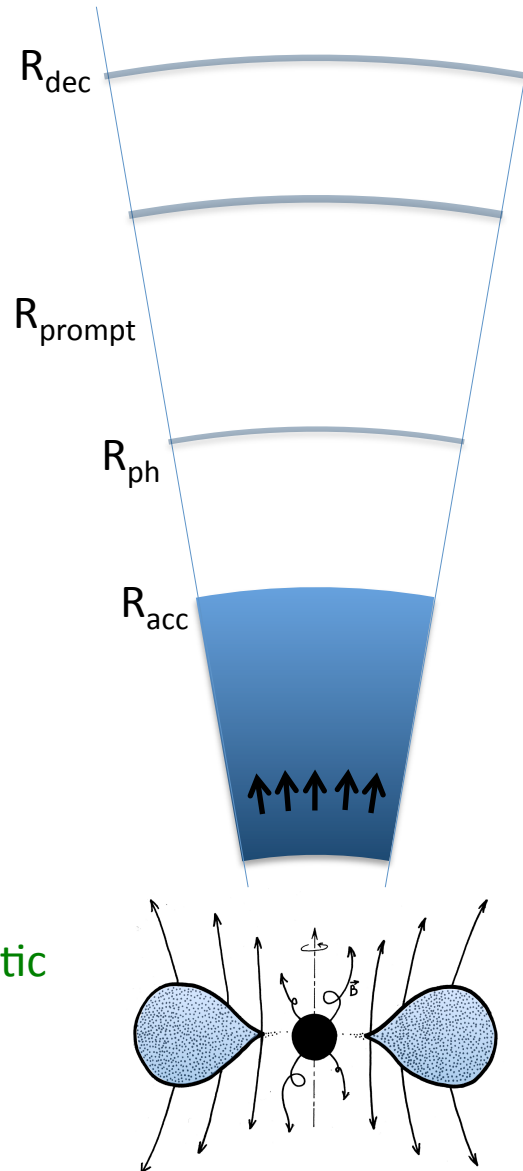
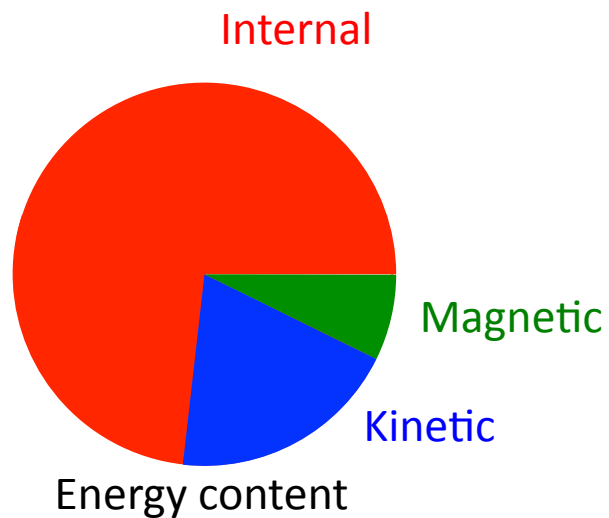
Or weakly magnetized fireballs



Acceleration :
adiabatic expansion

Standard fireball

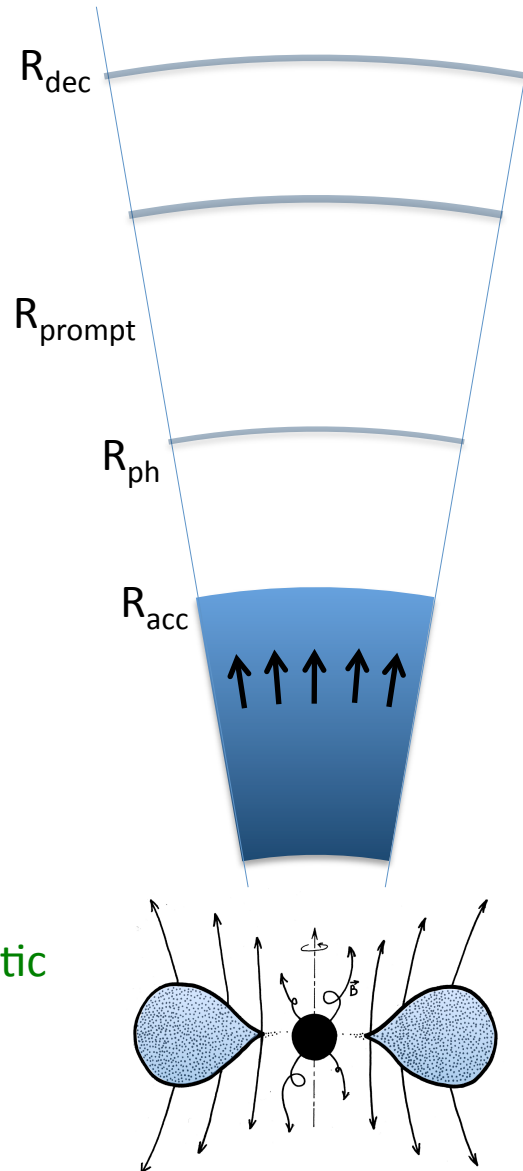
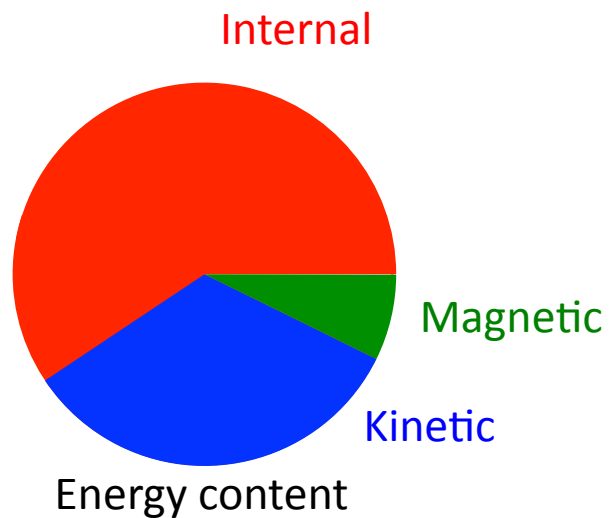
Or weakly magnetized fireballs



Acceleration :
adiabatic expansion

Standard fireball

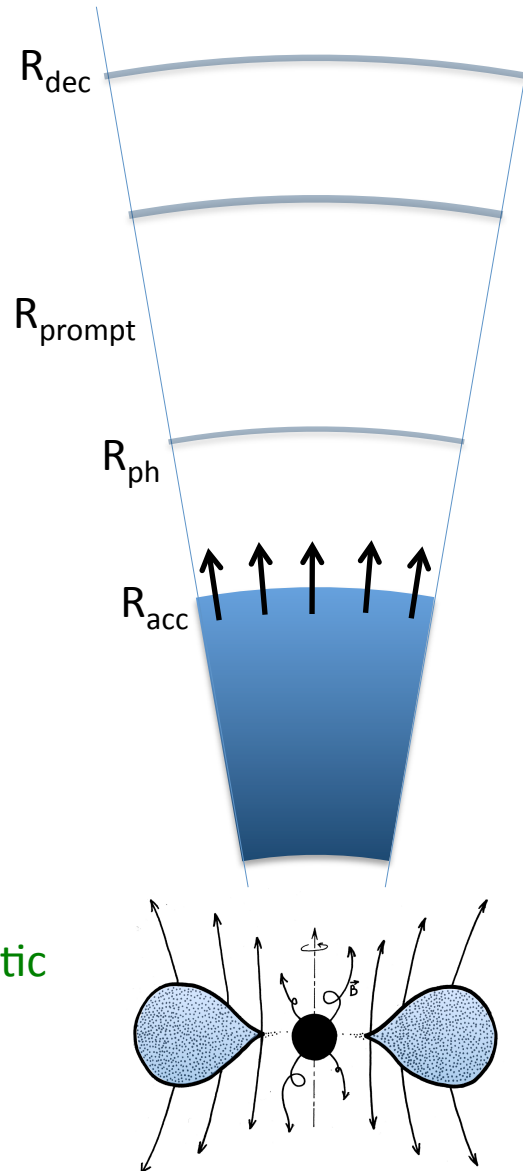
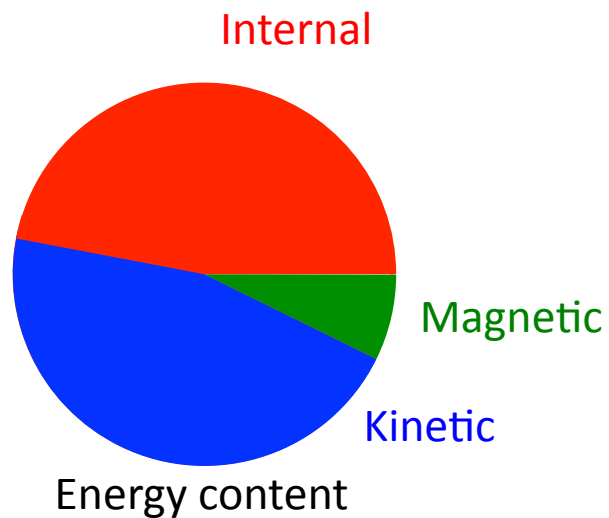
Or weakly magnetized fireballs



Acceleration :
adiabatic expansion

Standard fireball

Or weakly magnetized fireballs

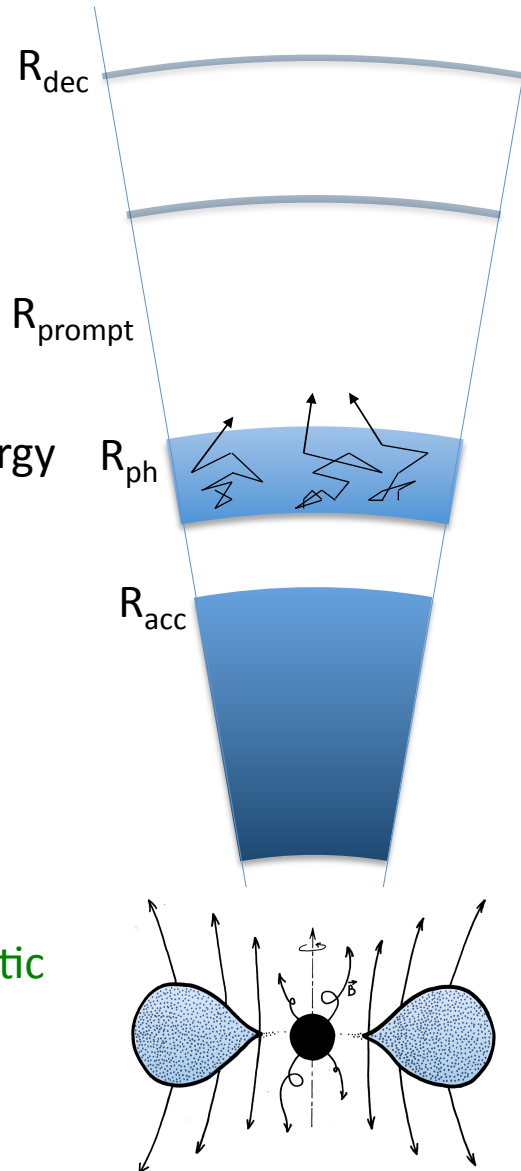
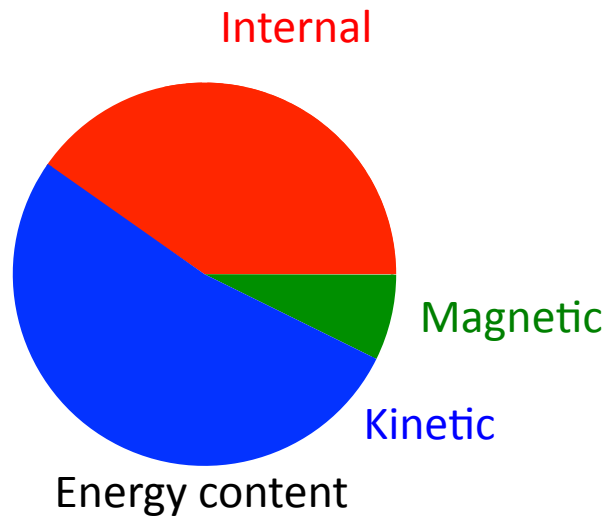


Acceleration :
adiabatic expansion

Standard fireball

Or weakly magnetized fireballs

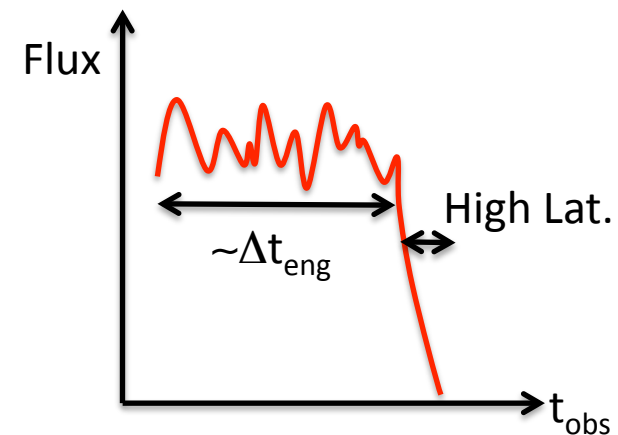
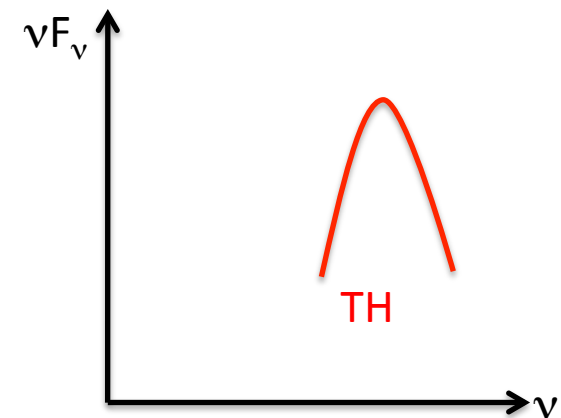
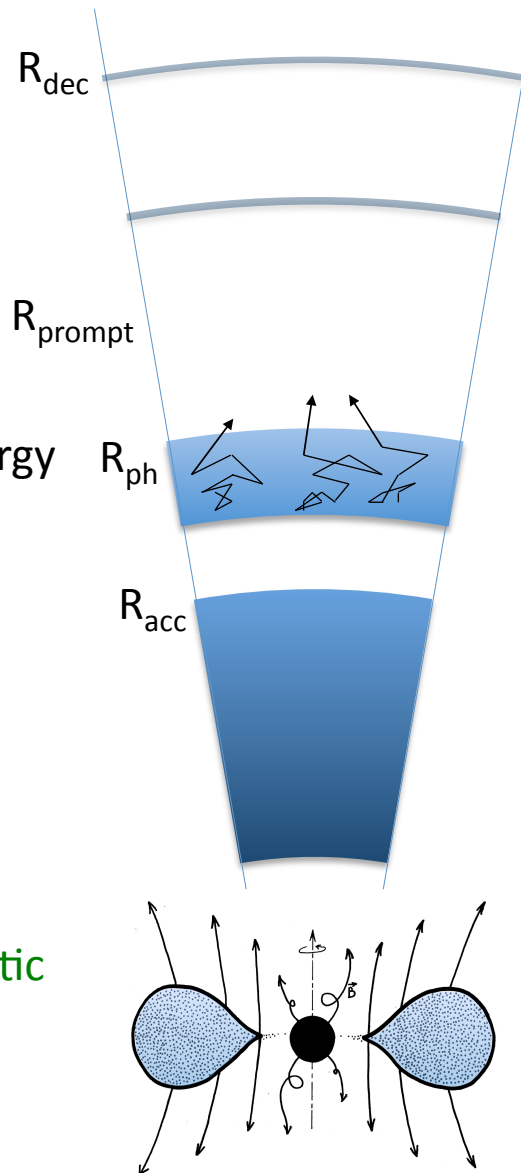
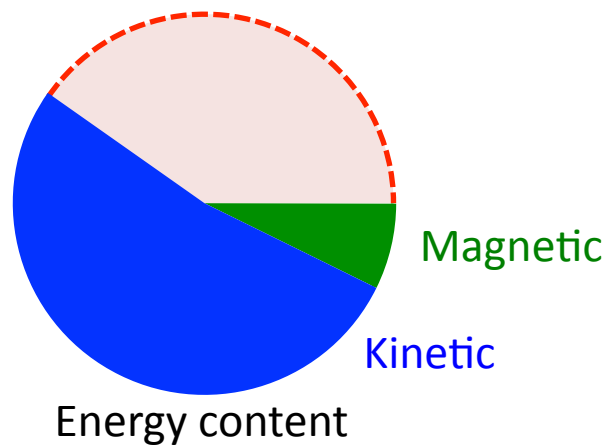
Photosphere : internal energy
can be radiated.



Standard fireball

Or weakly magnetized fireballs

Photosphere : internal energy
can be radiated.

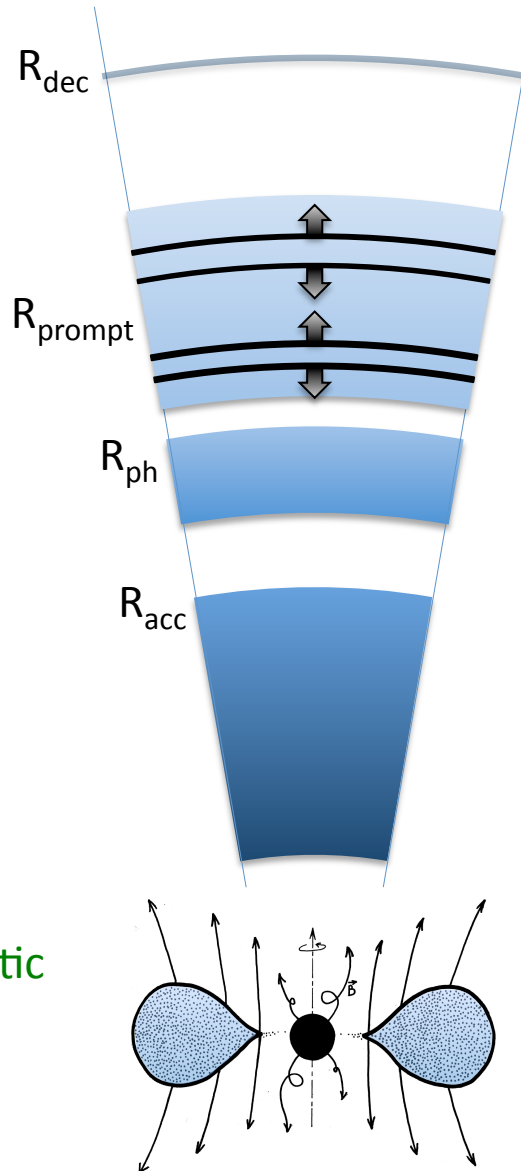
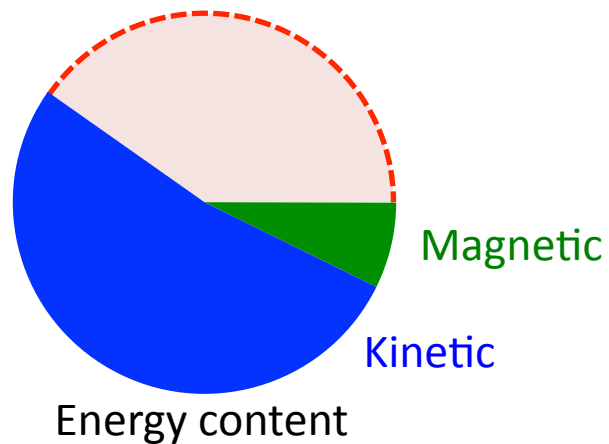


Standard fireball

Or weakly magnetized fireballs

Non-thermal emission :
Internal shocks

A fraction of the kinetic
energy is radiated

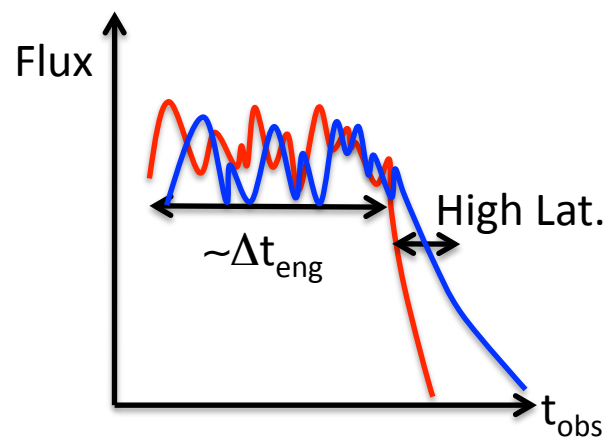
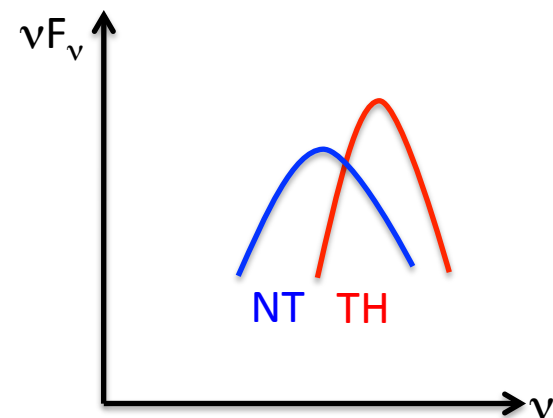
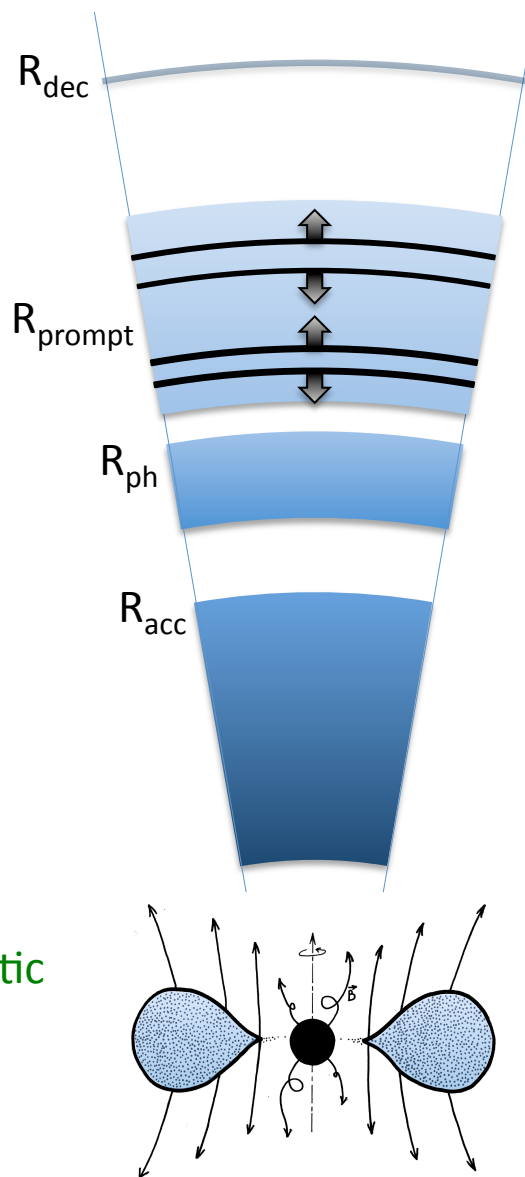
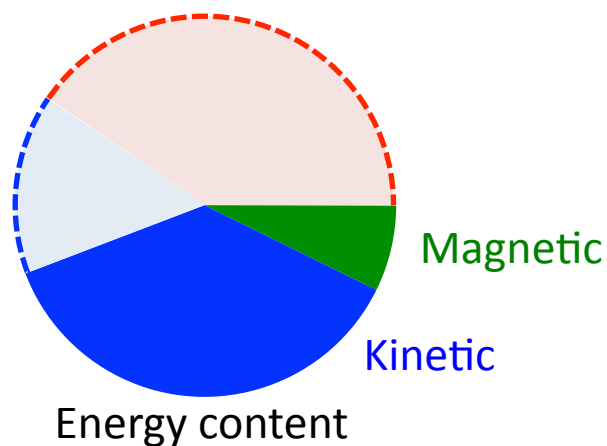


Standard fireball

Or weakly magnetized fireballs

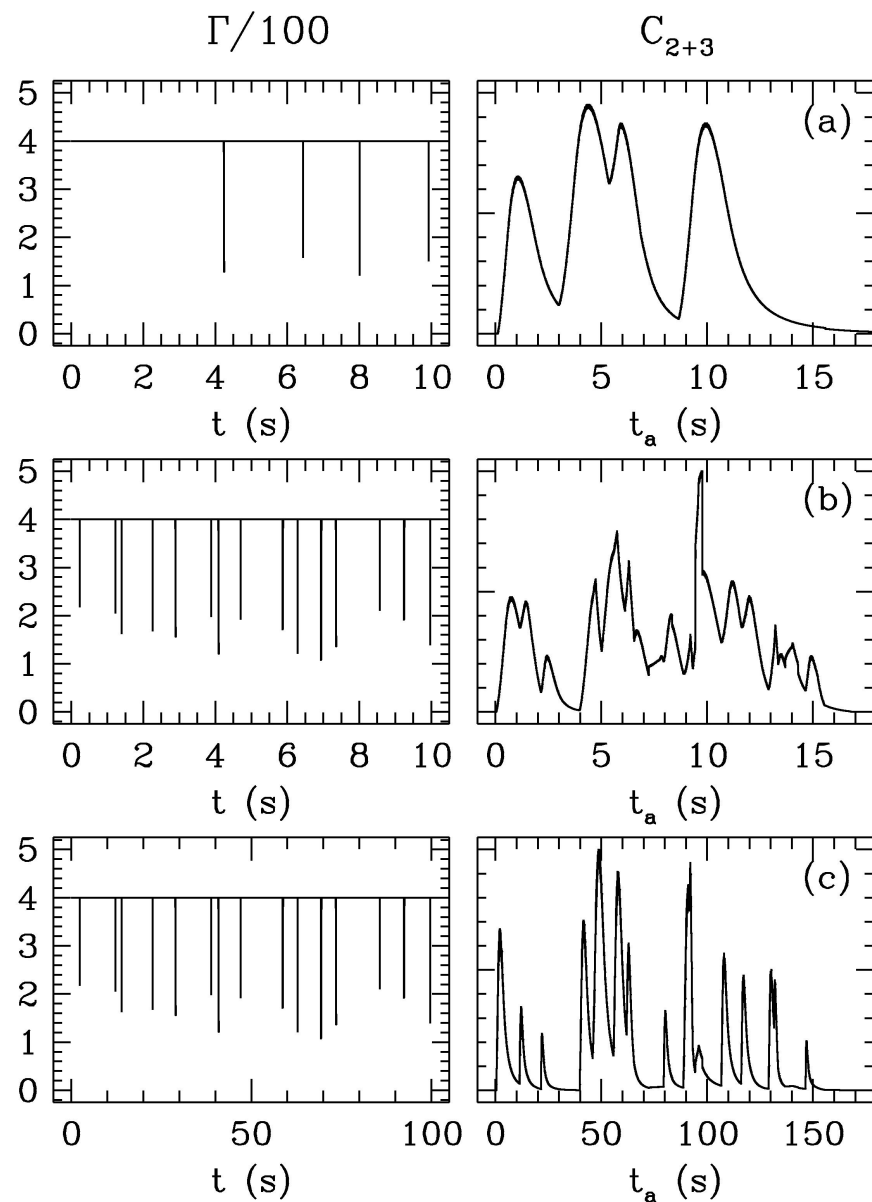
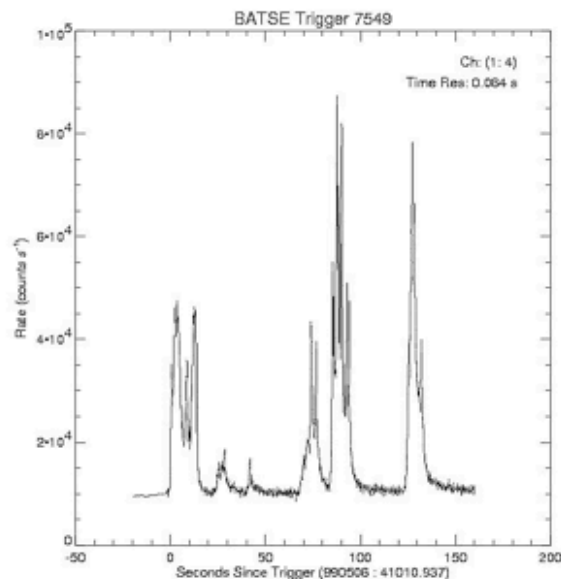
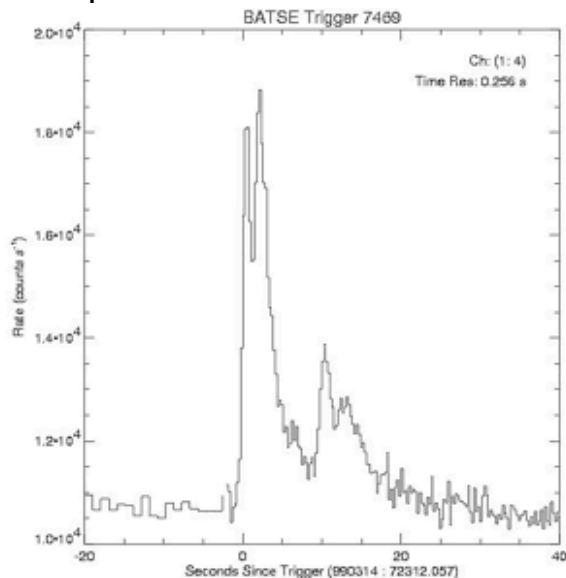
Non-thermal emission :
Internal shocks

A fraction of the kinetic
energy is radiated



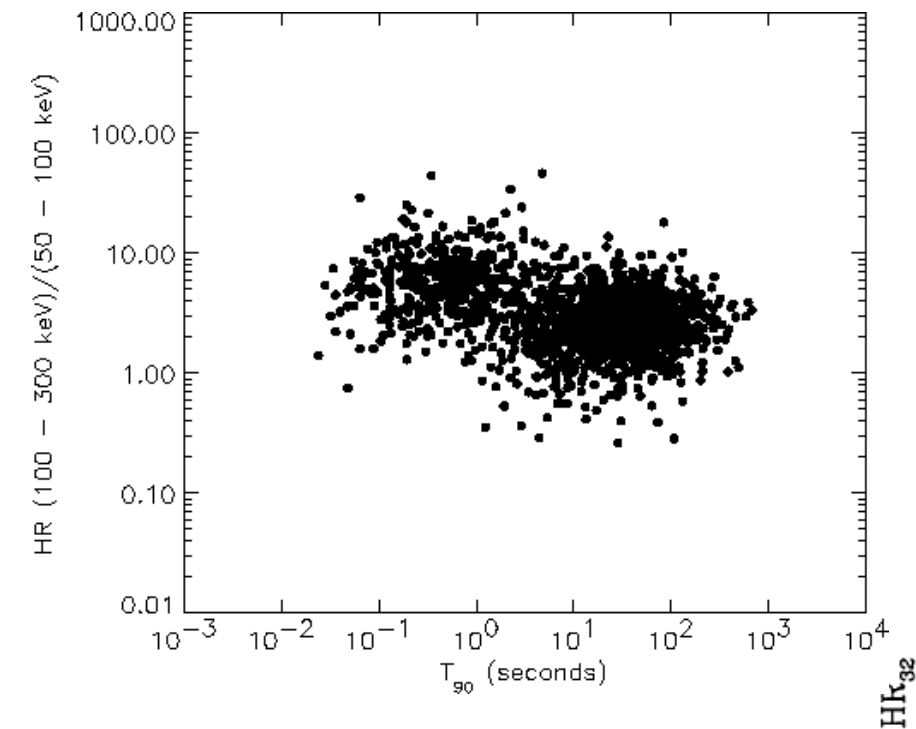
Internal shocks

- Lightcurves, spectral evolution

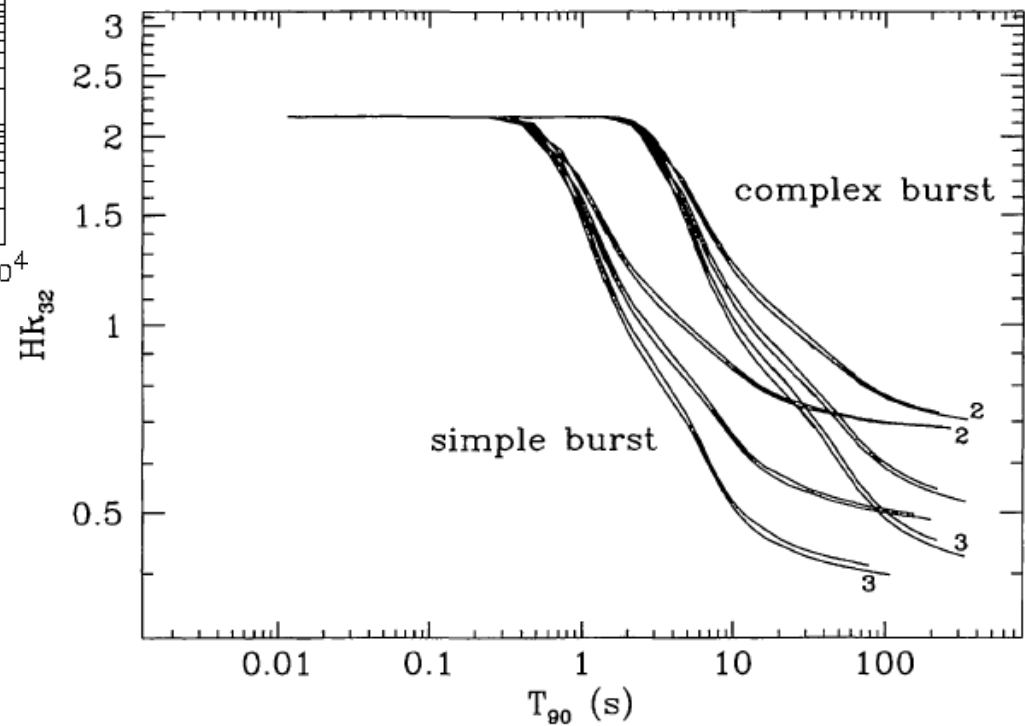


Internal shocks

■ Hardness-Duration



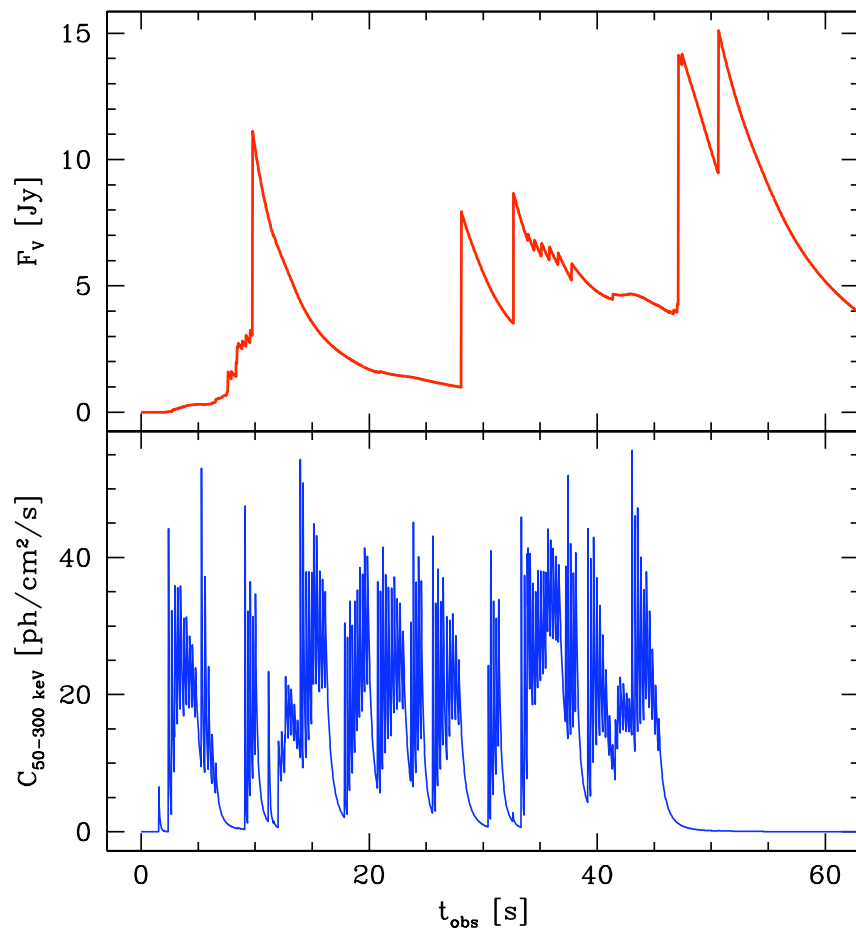
Kouveliotou et al. 1993



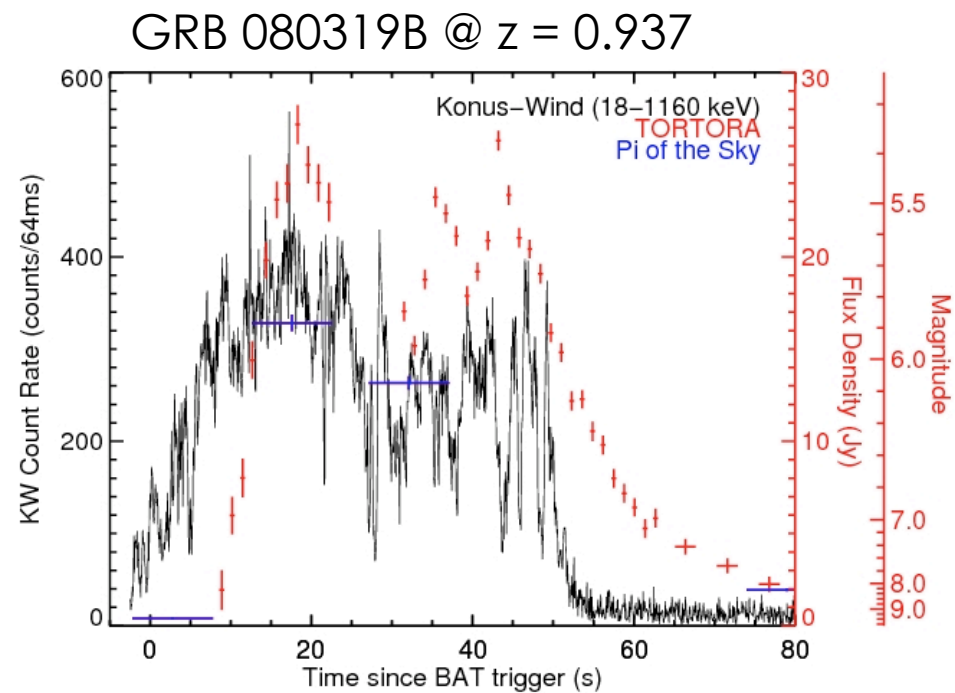
Daigne & Mochkovitch 1998

Internal shocks

- Prompt optical emission

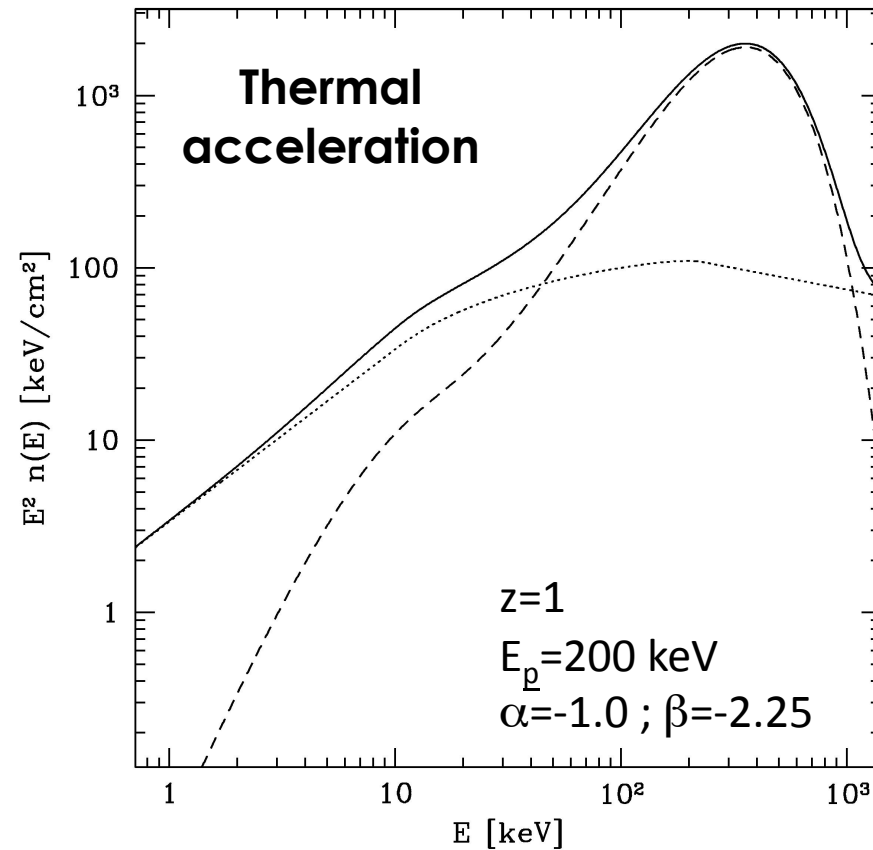


(Hascoët et al. 2011;
see also Li & Waxman 2008)



(Racusin et al. 2008)

Spectrum : photosphere + internal shocks



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
 - $R_{\text{ph}} \gg R_{\text{acc}}$ (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

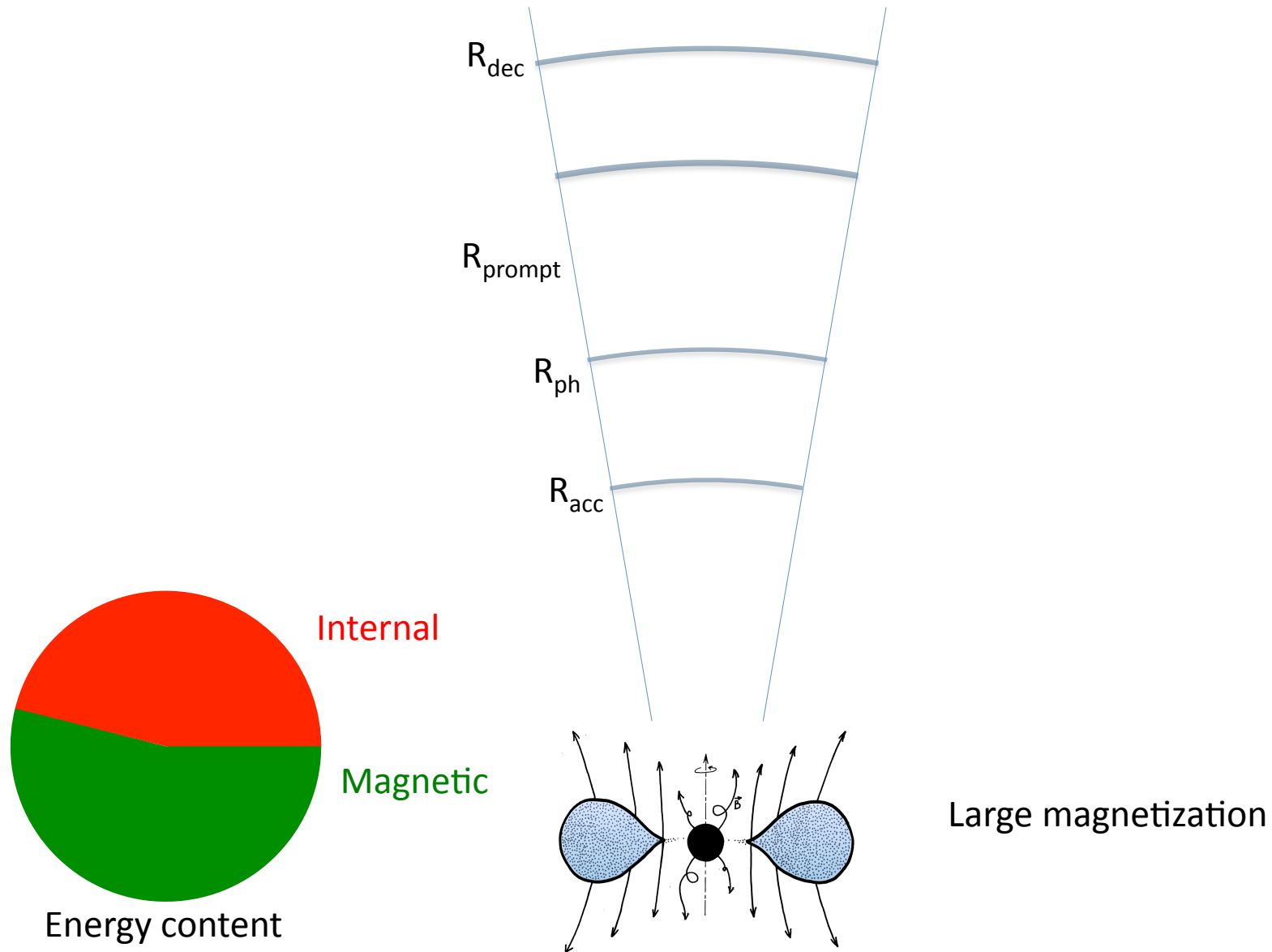
A new ingredient : the magnetic field

- 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; ...)

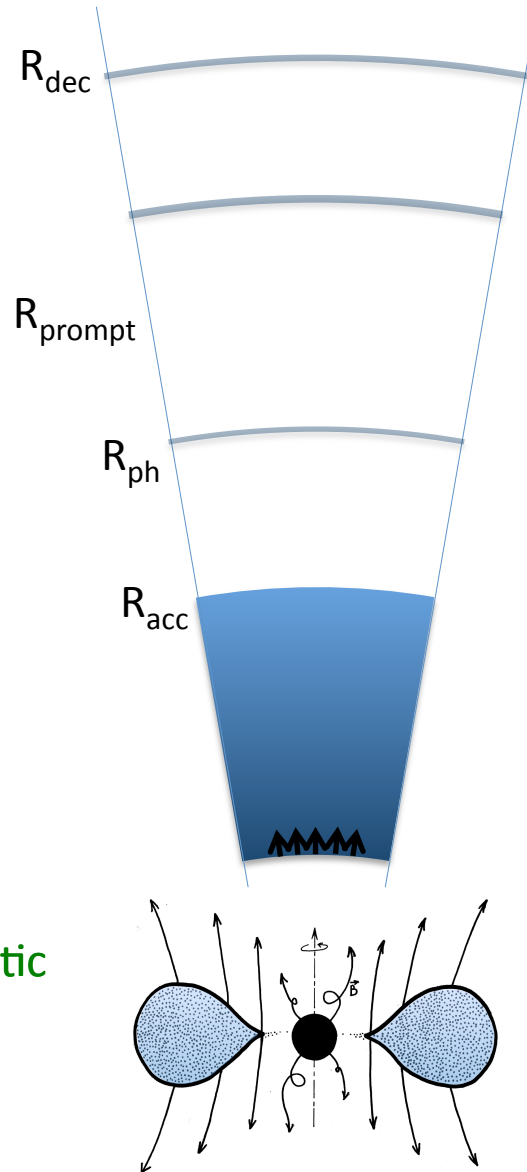
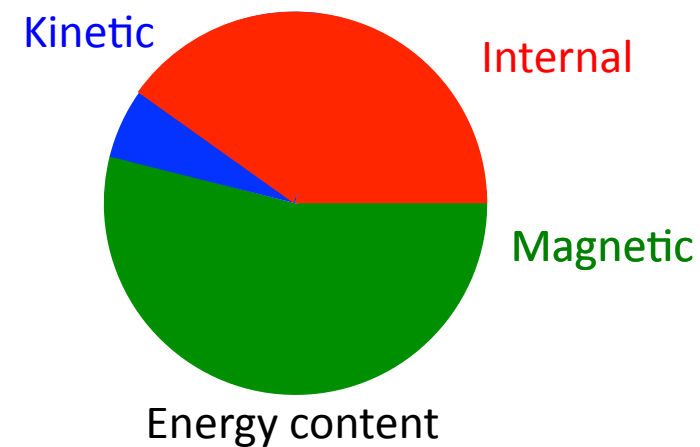
$$\text{Magnetization : } \sigma = \frac{\text{Poynting flux}}{\text{Power carried by matter (internal + kinetic)}}$$

- An extreme version : the initial energy release is purely magnetic
($\sigma = \infty$) – no photospheric emission in this case
(Blandford & Lyutikov 03)

Passive field

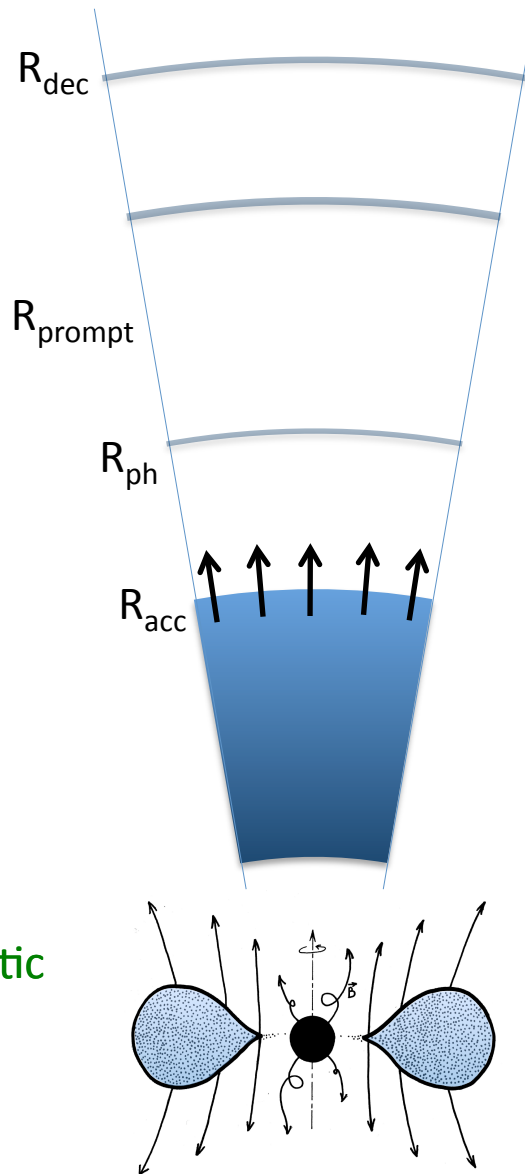
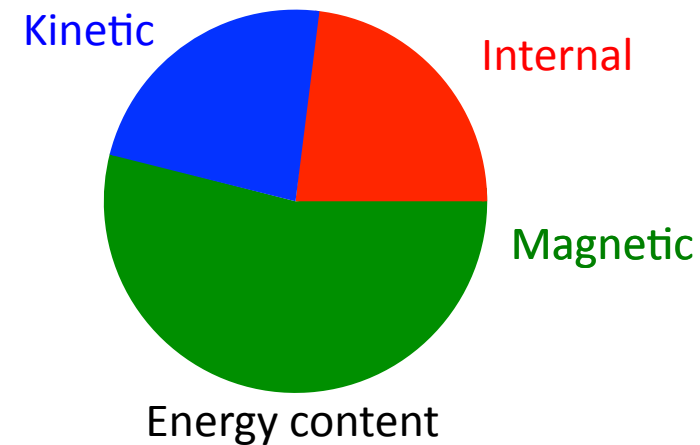


Passive field



Acceleration :
adiabatic expansion

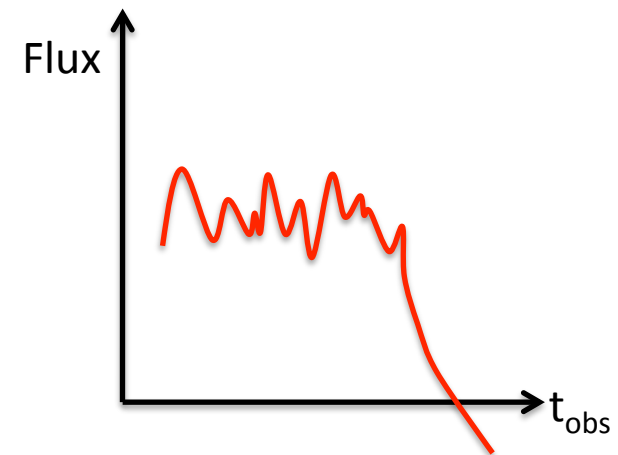
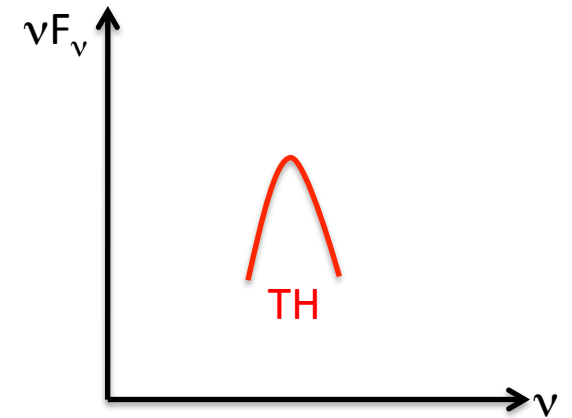
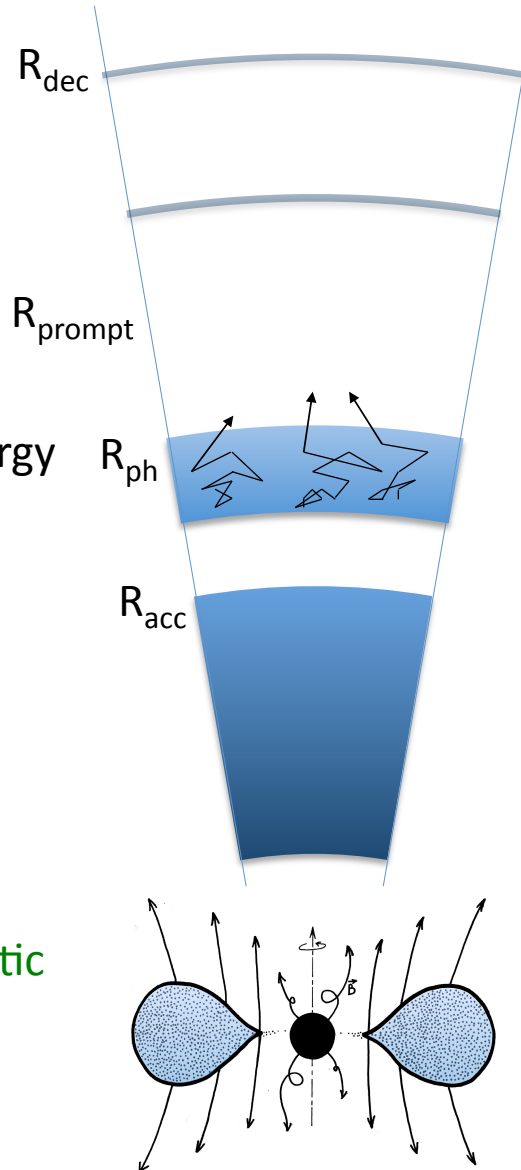
Passive field



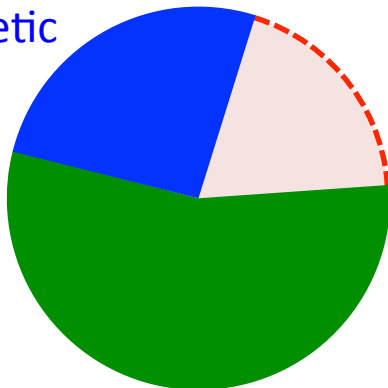
Acceleration :
adiabatic expansion

Passive field

Photosphere : internal energy
can be radiated.



Kinetic



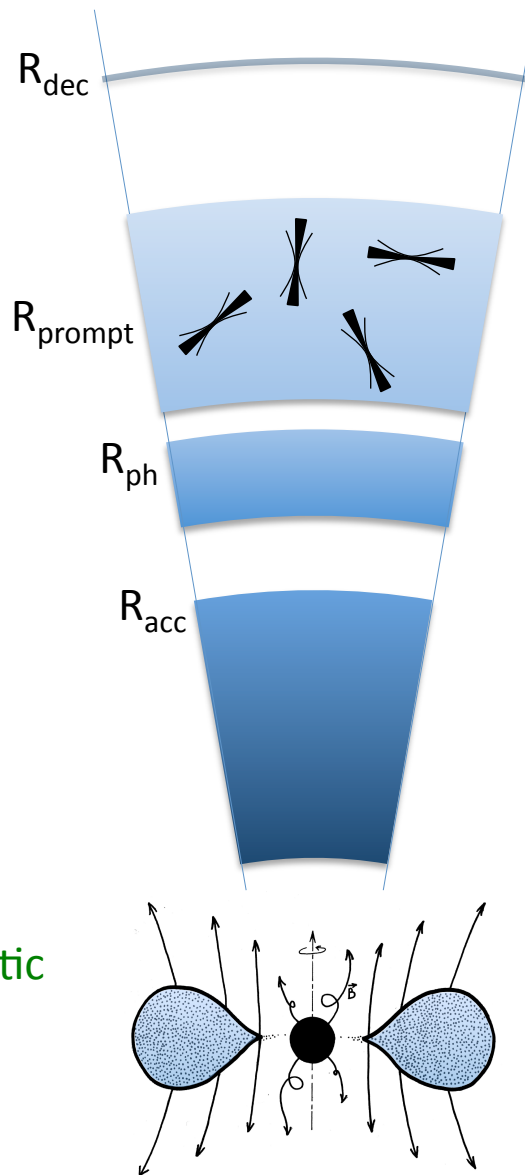
Energy content

Magnetic

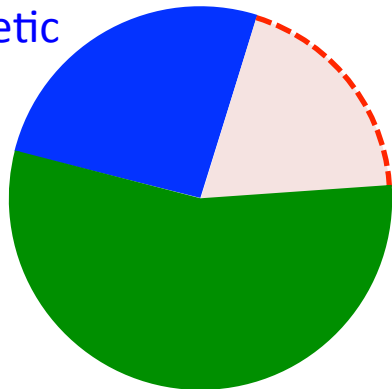
Passive field

Non-thermal emission :
Internal shocks
or magnetic dissipation

*Note: magnetic dissipation
can occur below the
photosphere*



Kinetic



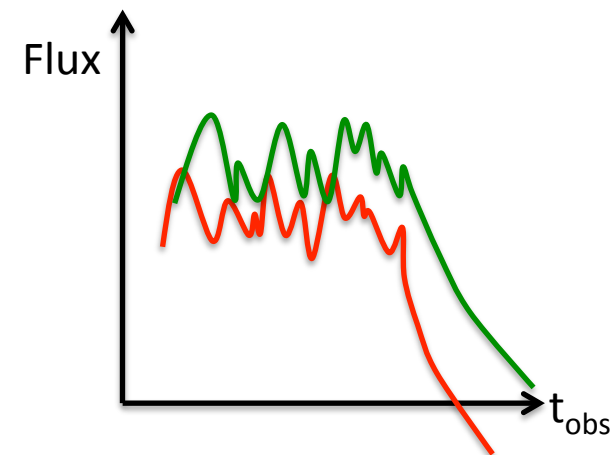
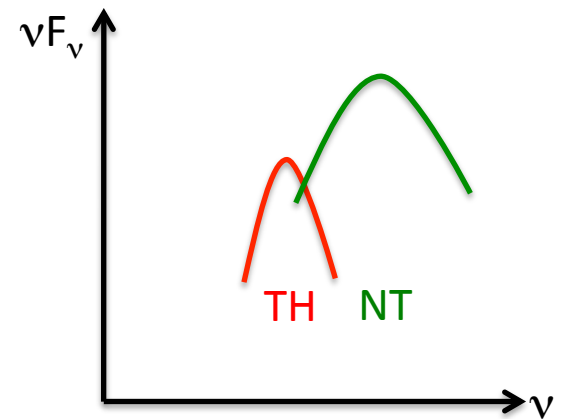
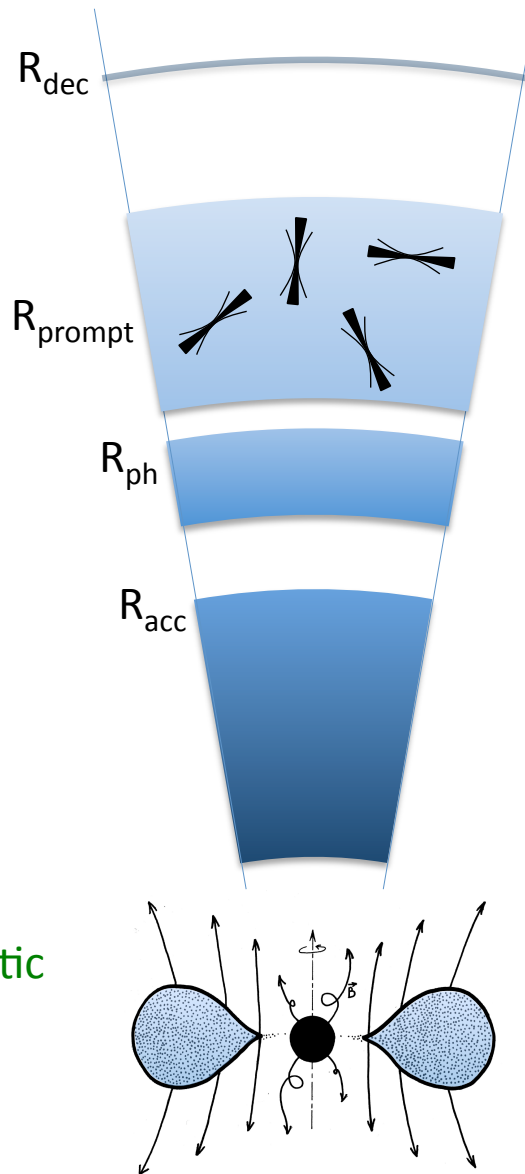
Magnetic

Energy content

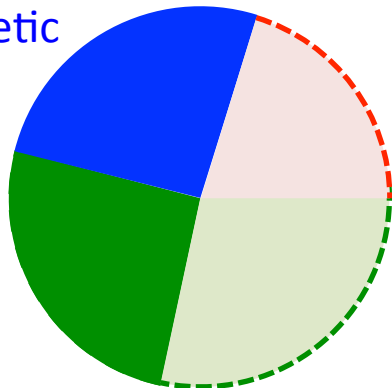
Passive field

Non-thermal emission :
Internal shocks
or magnetic dissipation

*Note: magnetic dissipation
can occur below the
photosphere*



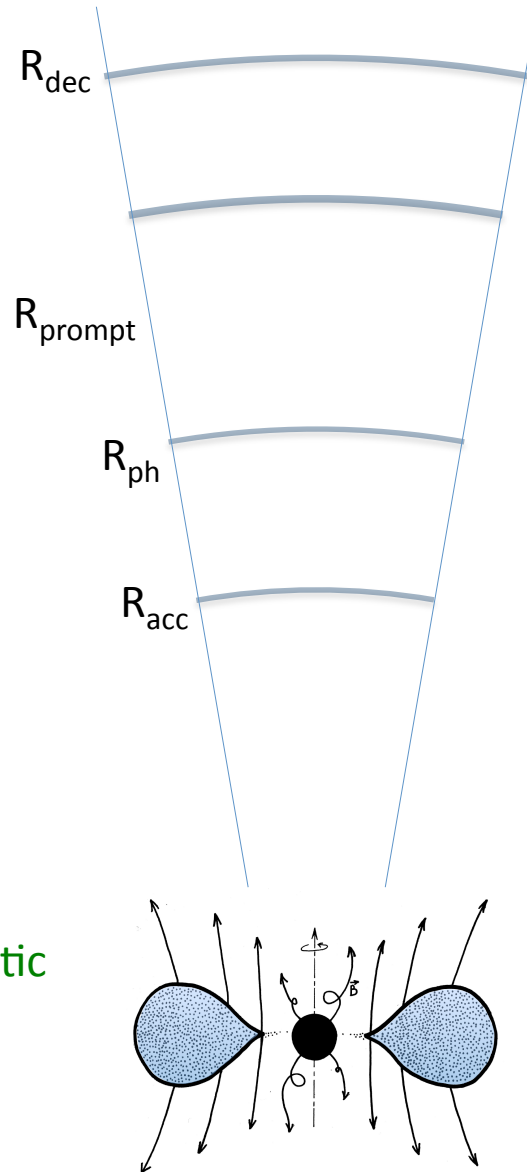
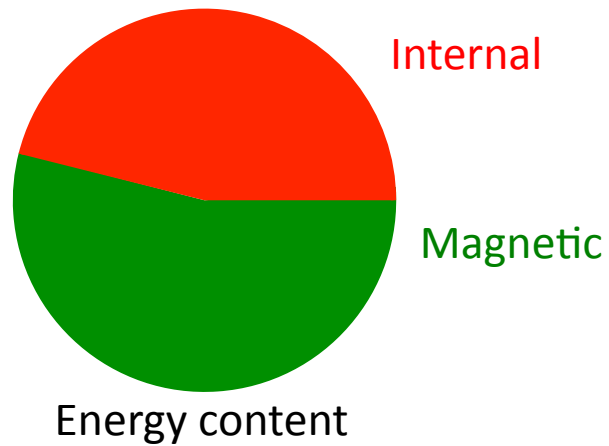
Kinetic



Magnetic

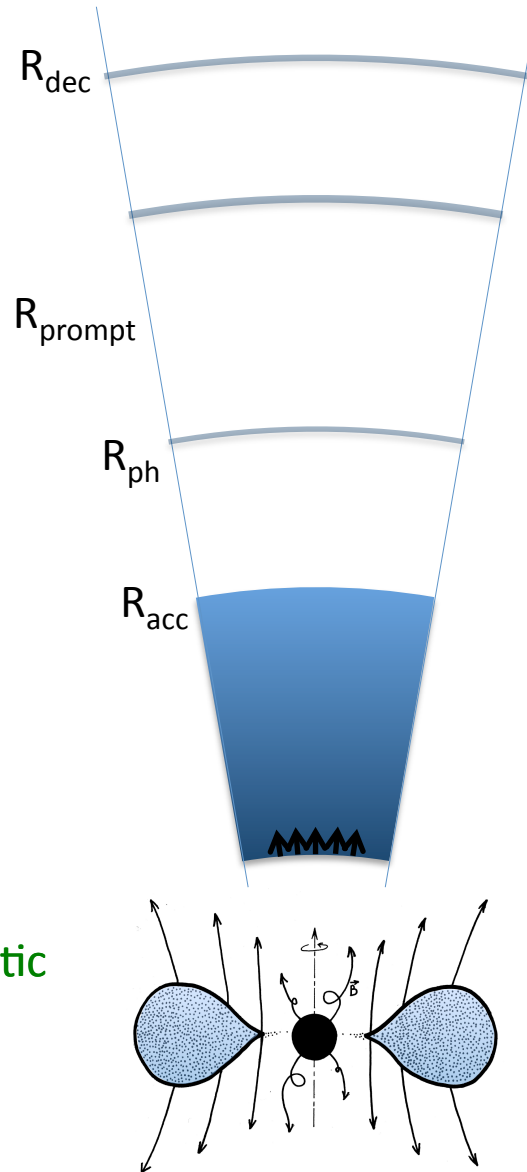
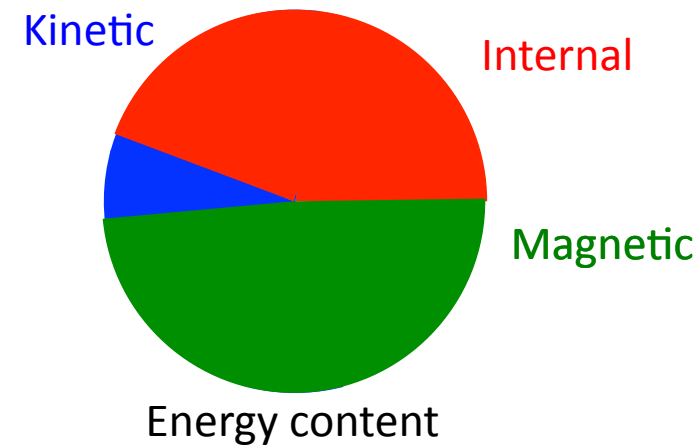
Energy content

Active field



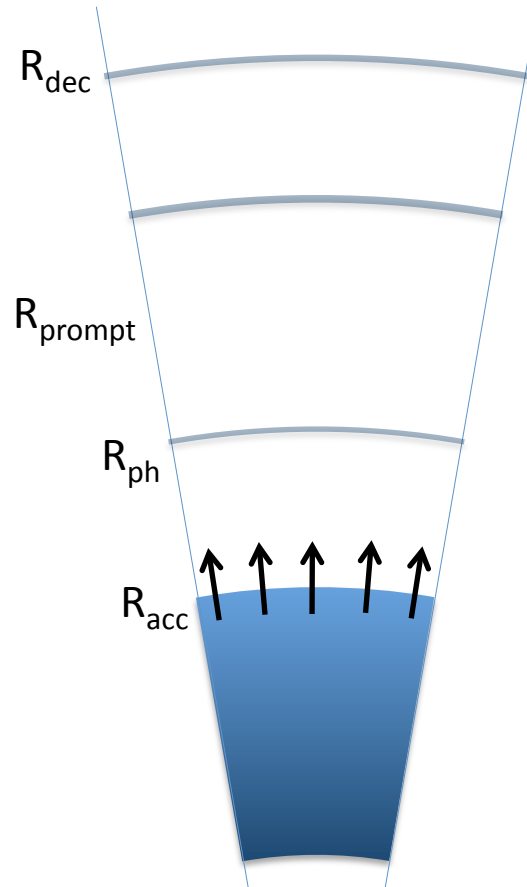
Large magnetization

Active field

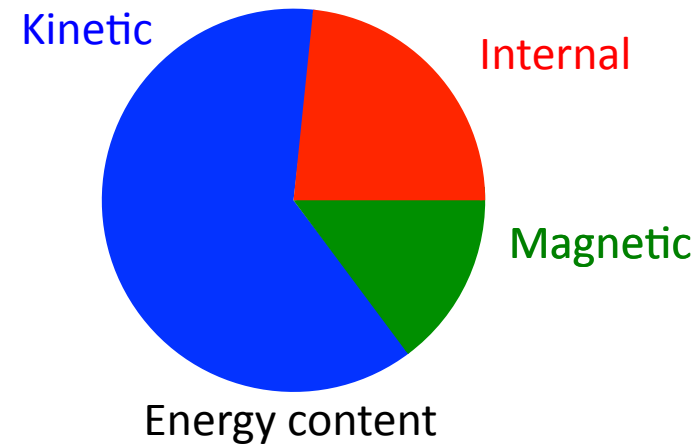
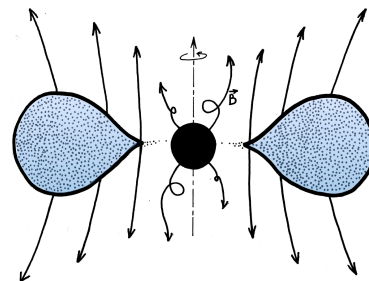


Magnetic acceleration

Active field

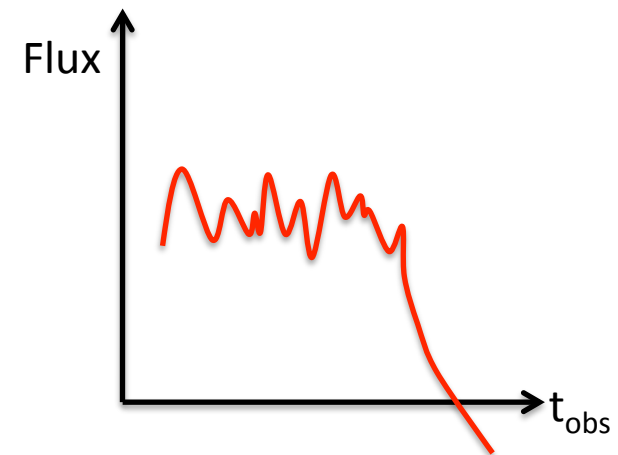
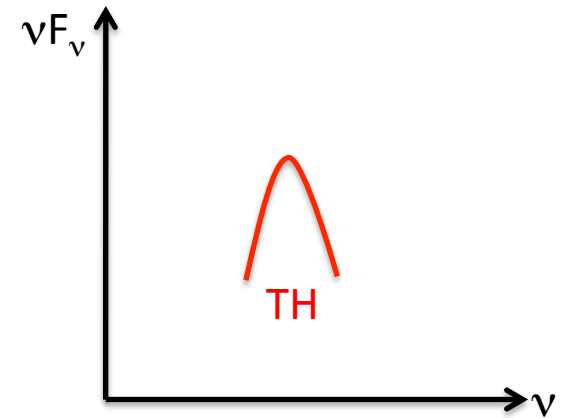
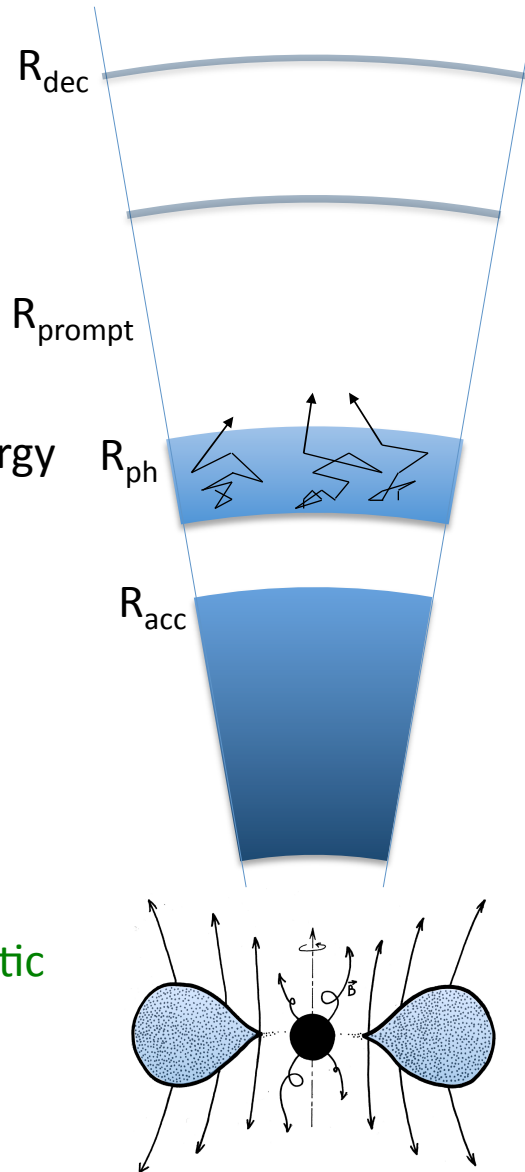


Magnetic acceleration

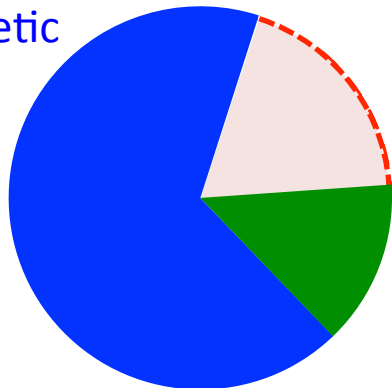


Active field

Photosphere : internal energy
can be radiated.



Kinetic

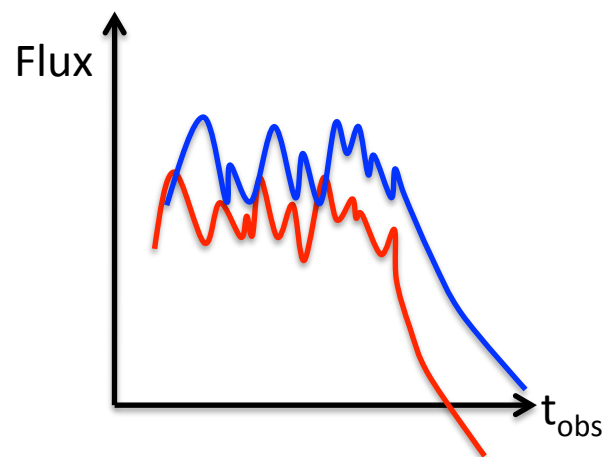
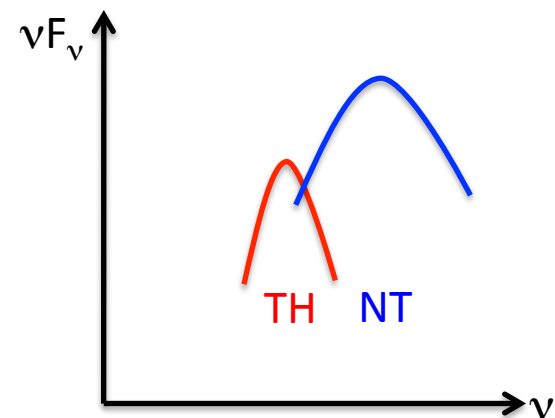
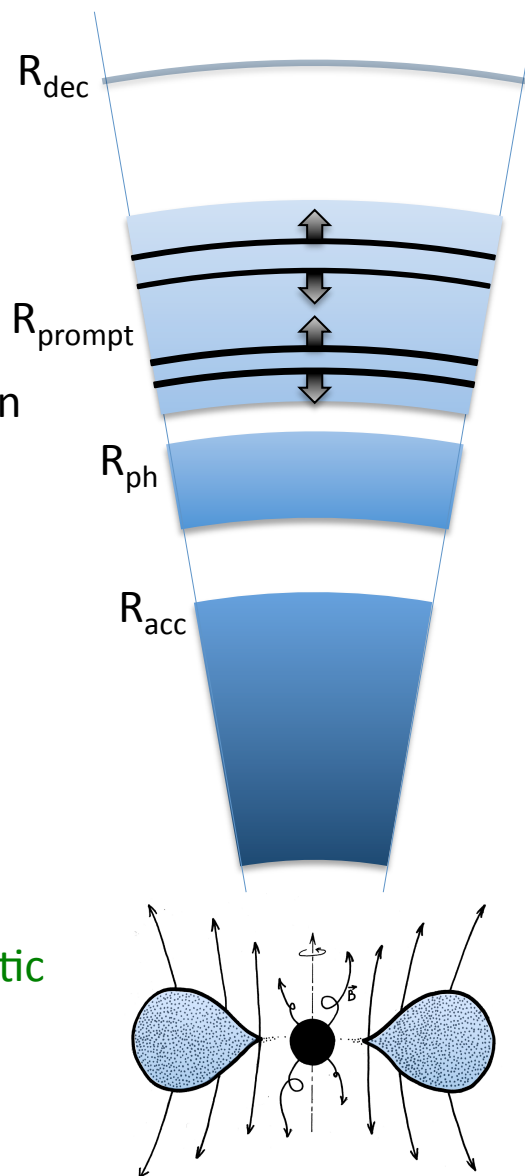


Magnetic

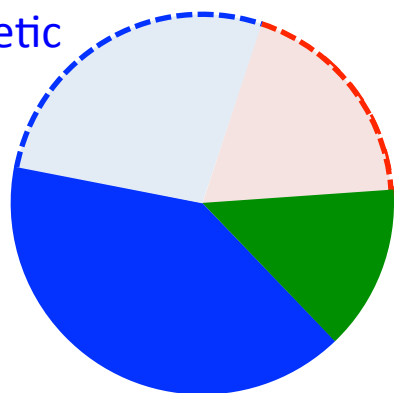
Energy content

Active field

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



Kinetic



Magnetic

Energy content

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)

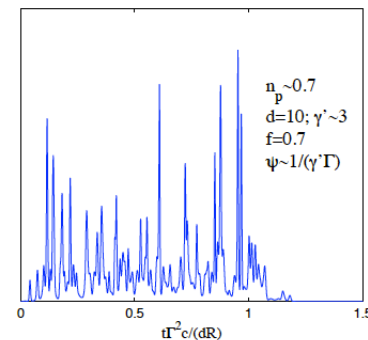
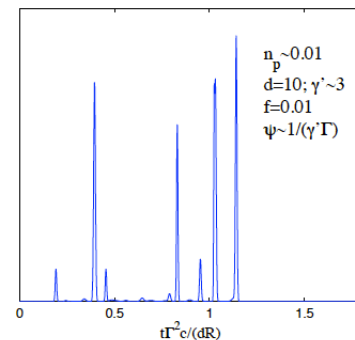
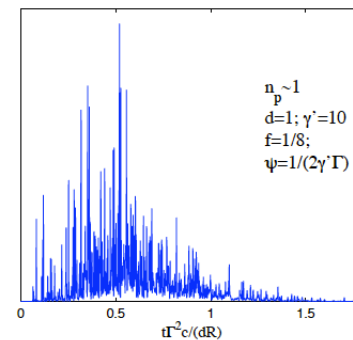
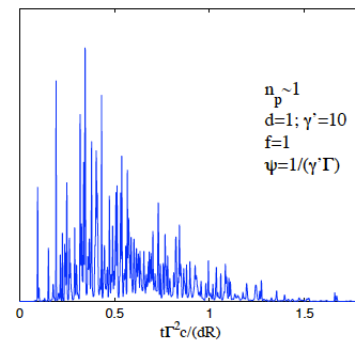
- Several scenarios:
 - Gradual dissipation below the photosphere (e.g. Spruit & Giannios, ...)
 - Shock-triggered reconnection – ICMART (Zhang)
 - Etc.

- **High efficiency seems possible – Multi-component spectra are expected**

Relativistic emitters

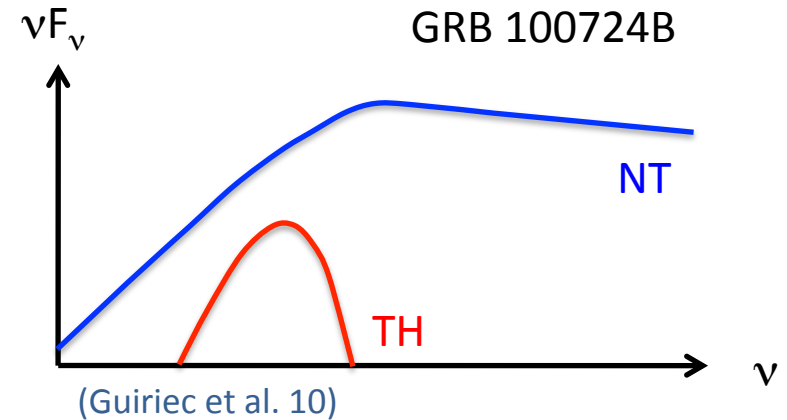
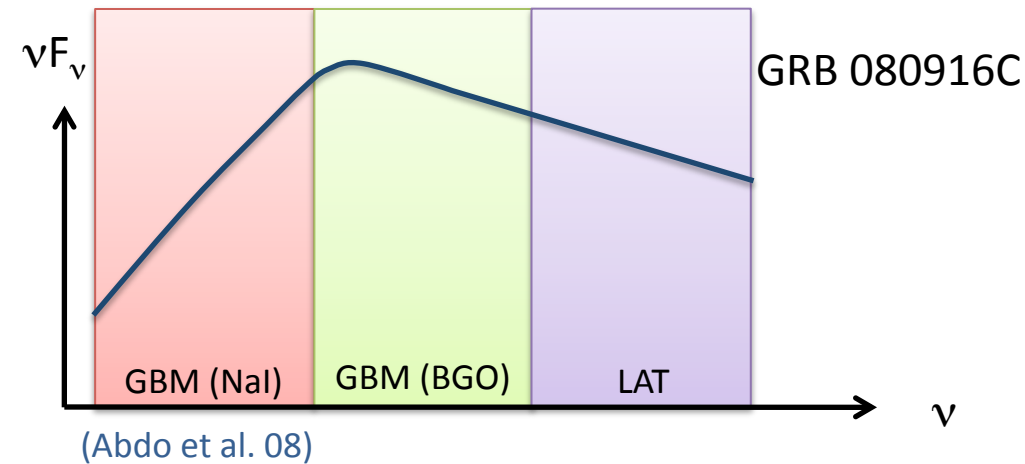
« fundamental relativistic emitters » : lightcurves are too symmetric ?

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

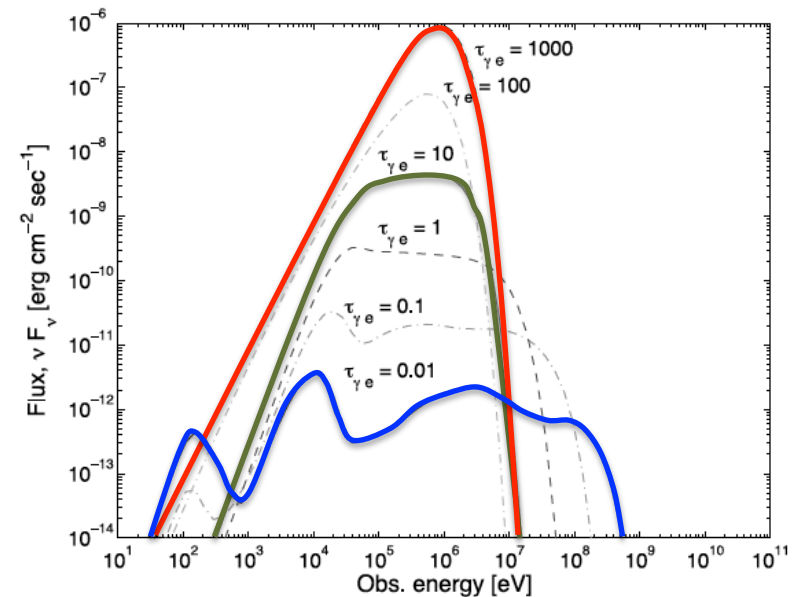
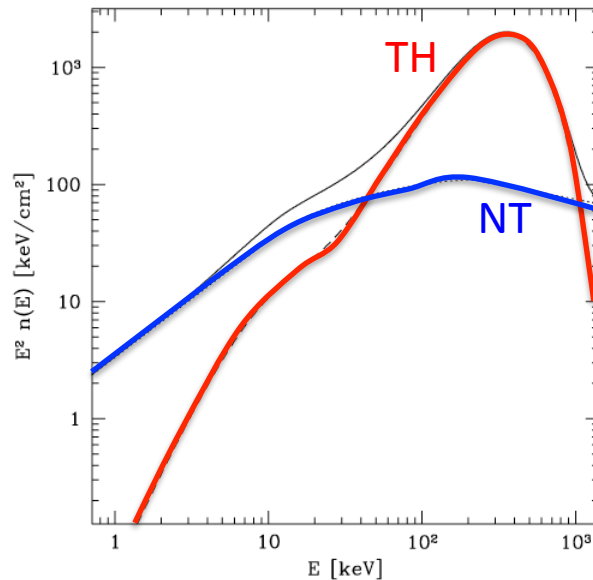


Standard fireball: prompt emission

● Fermi observations :

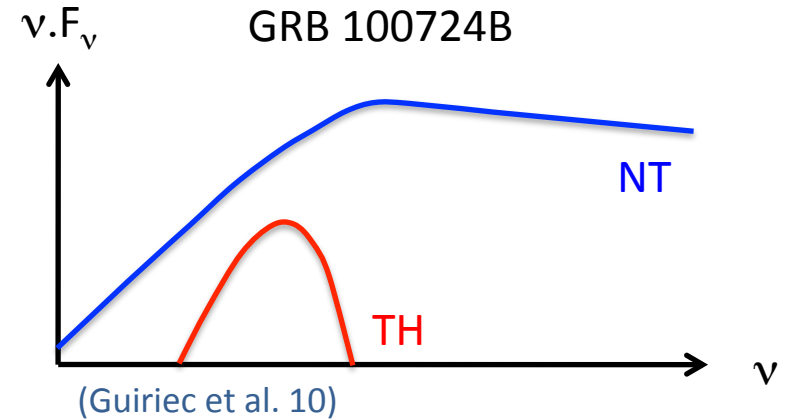
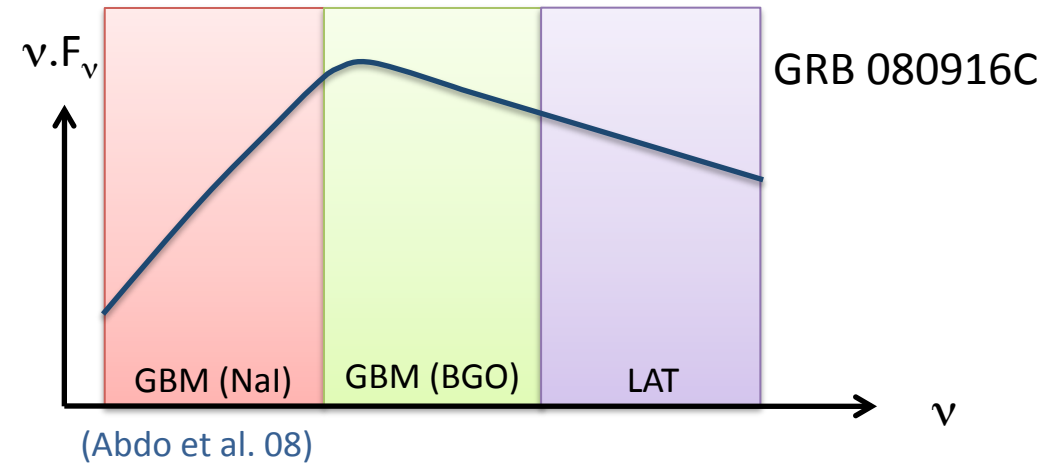


● Model :

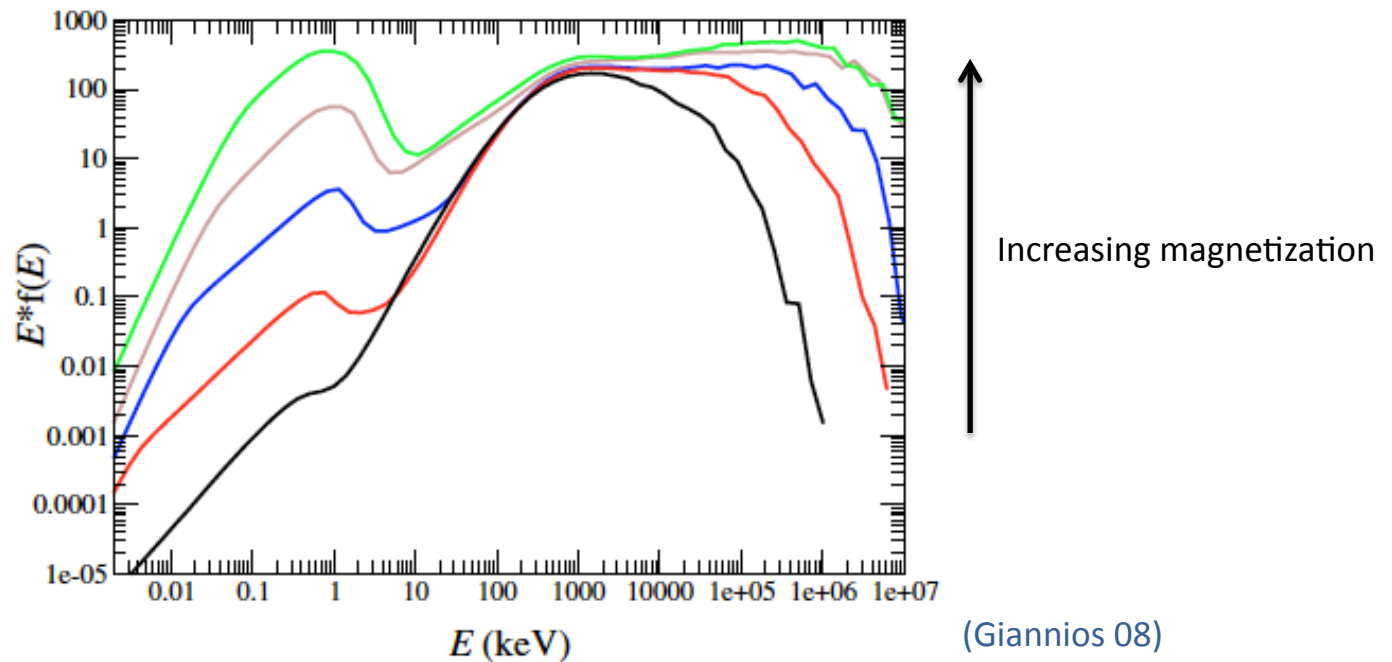


Magnetized outflows: prompt emission

● Fermi observations :

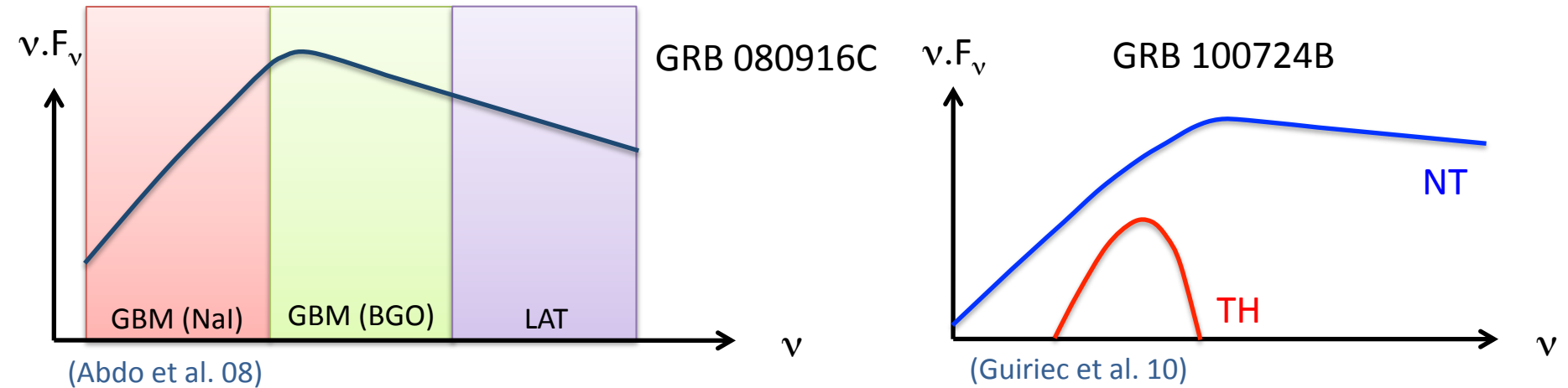


● Model : gradual
sub photospheric
magnetic dissipation

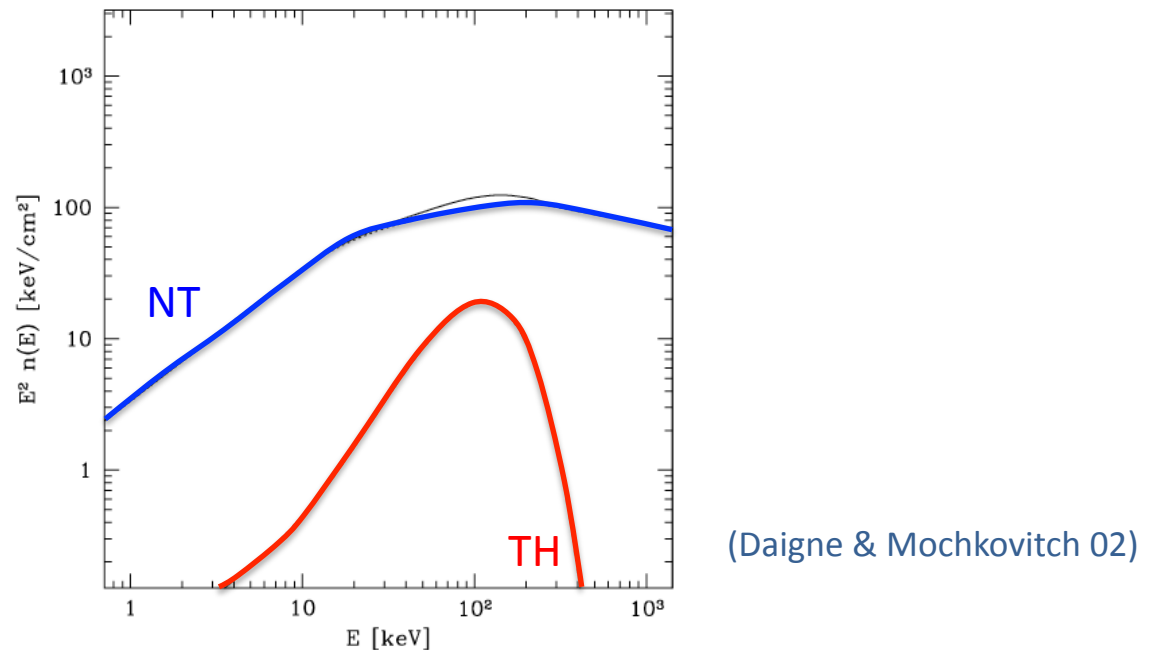


Magnetized outflows: prompt emission

● Fermi observations :



● Model : efficient magnetic acceleration + internal shocks

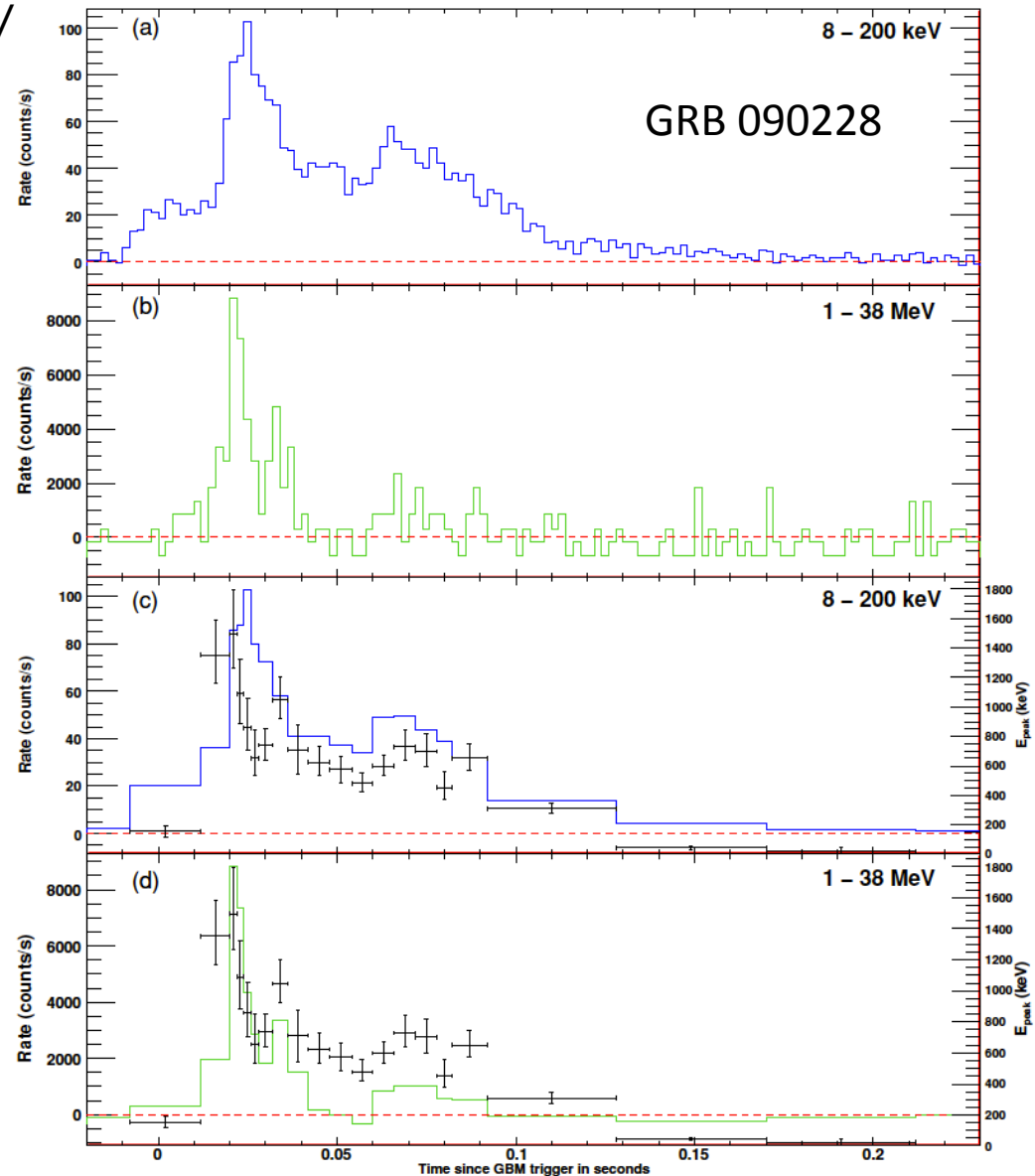


How to distinguish between models ?

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 ?



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

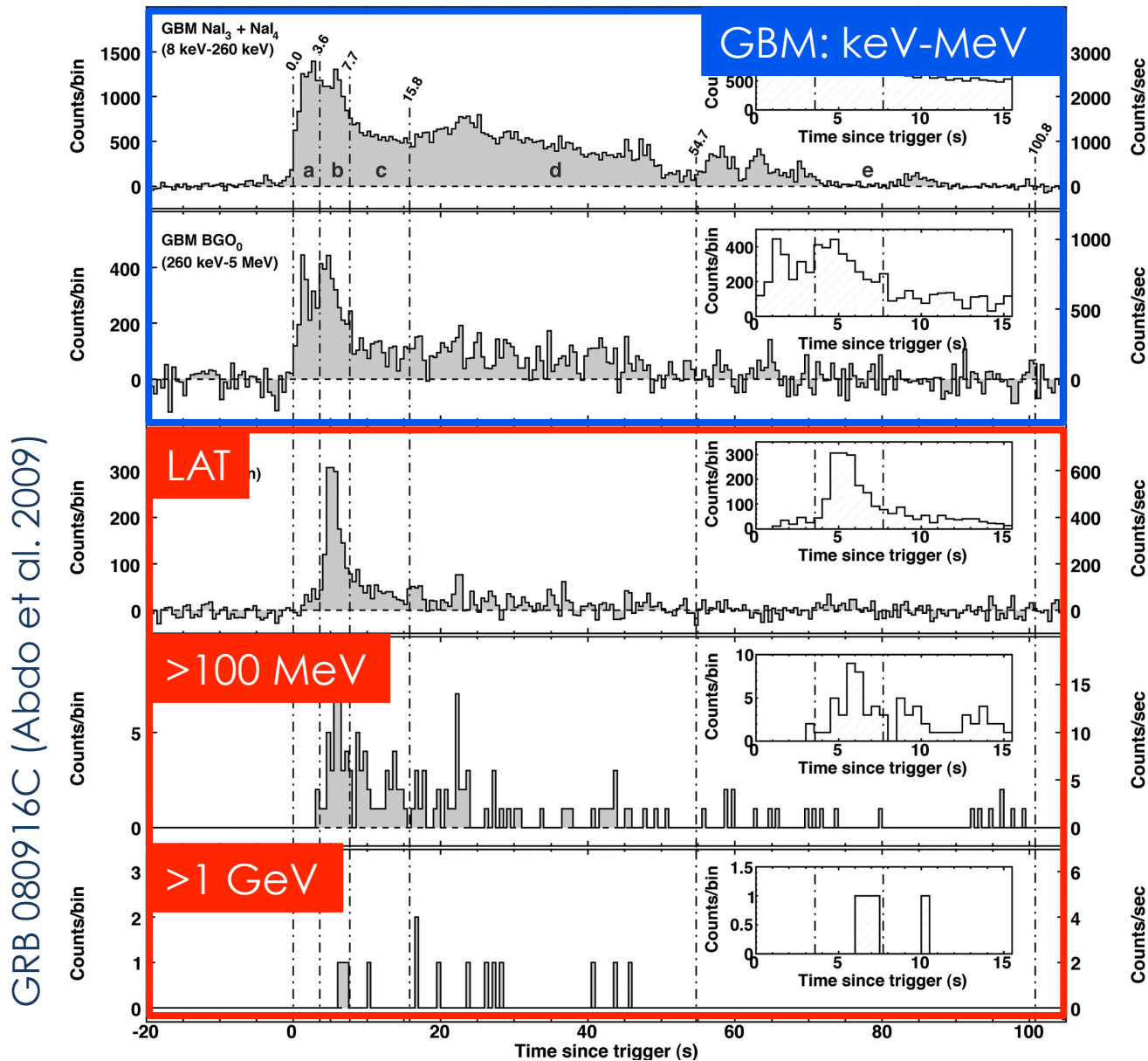
- Fermi-LAT : ~ 10 GRBs / year (to compare to GBM : ~ 250 GRBs / year)
- In 3 years: 28 GRBs detected above 100 MeV
- 4 brightest bursts : « hyper-energetic events »

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

- 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 ?

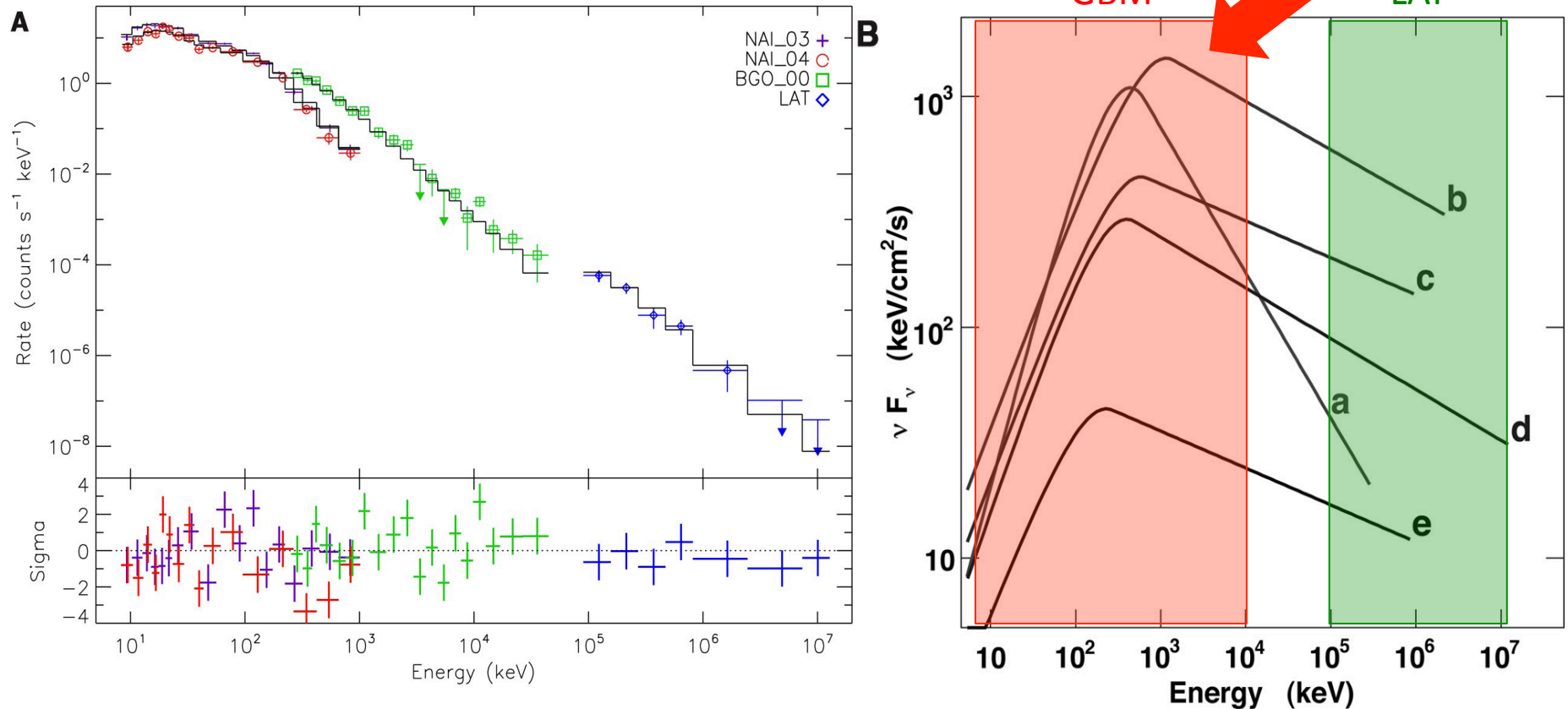
Fermi: (2) high-energy detections (GeV)

- An example: GRB 080916C



Fermi: dominant spectral component

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



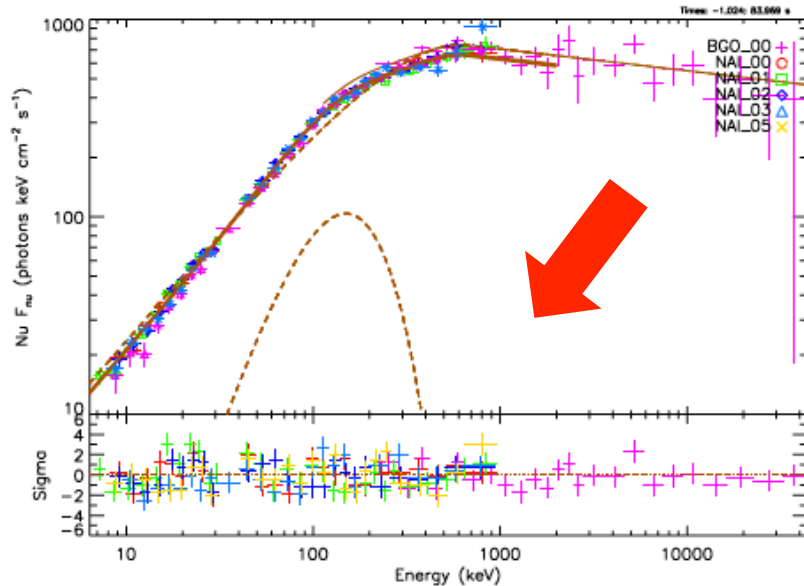
GRB 080916C (Abdo et al. 2009)

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

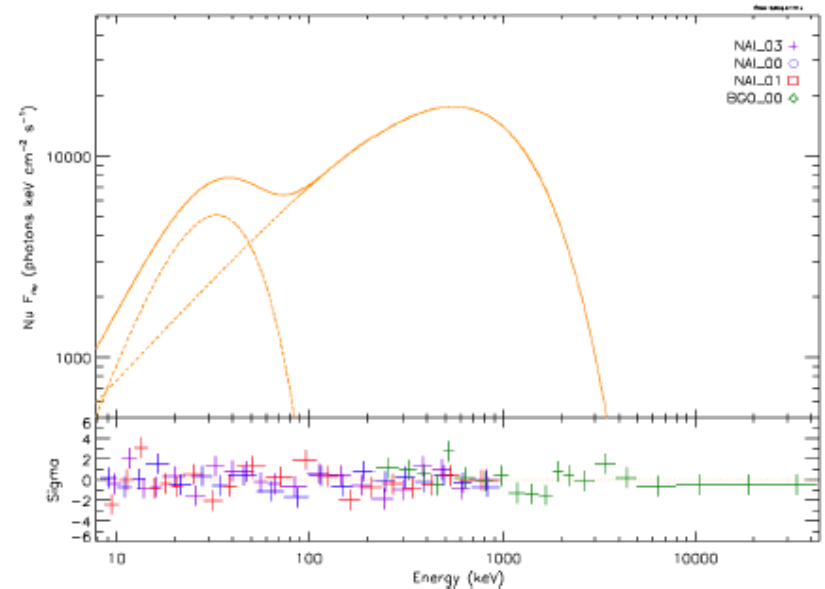
A weak/soft photospheric component ?

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

GRB 100724B



GRB 120323A



-See also other GBM bursts : GRB 110721A ([Axelsson et al. 2012](#))

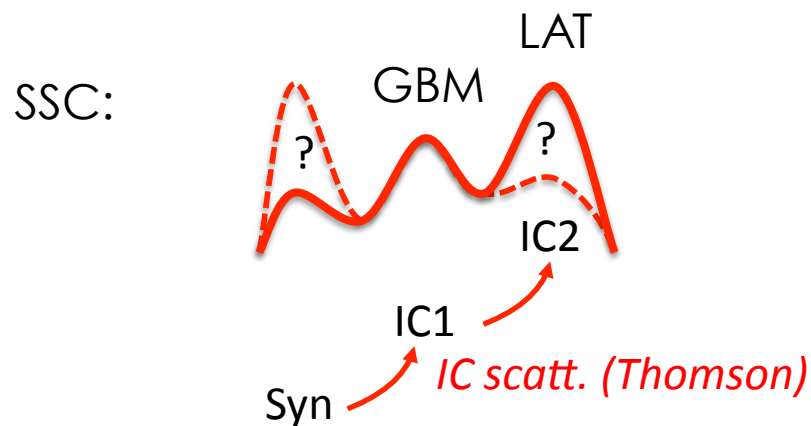
GRB 081207, GRB 110920, ...

(McGlynn, Ryde, GRB 2012 Conference, Munich, May 2012)

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

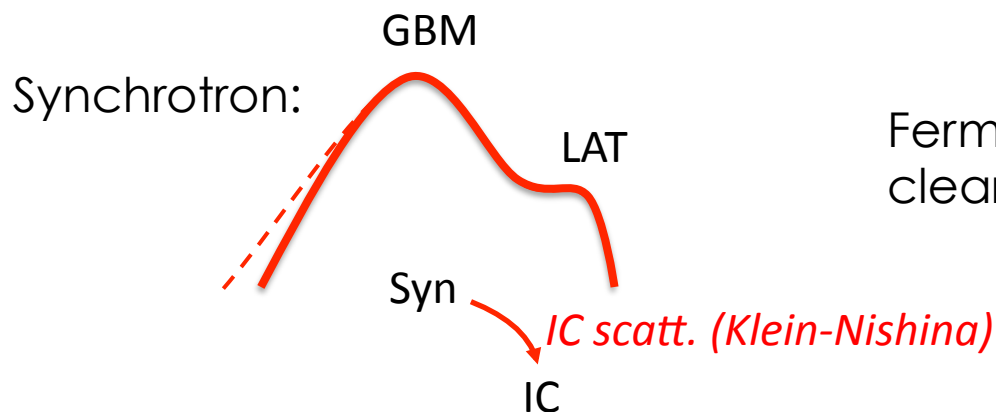
Dominant radiative process ?

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



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

-Energy crisis



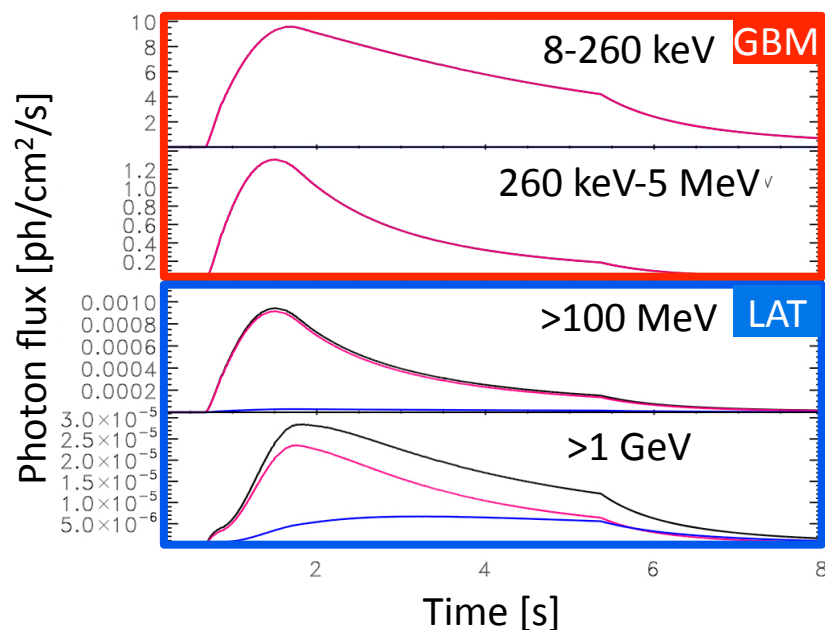
Fermi-LAT detection rate and observations
clearly favor the **synchrotron** process.

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

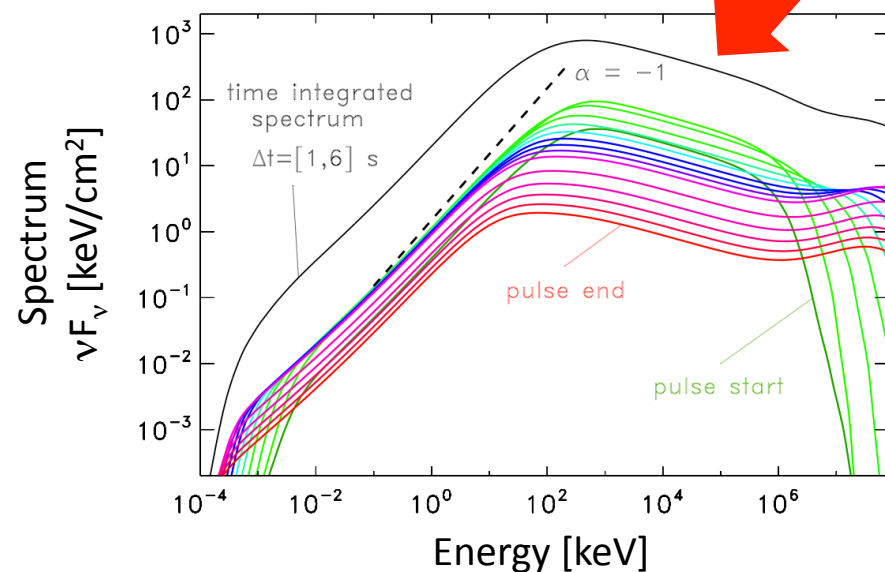
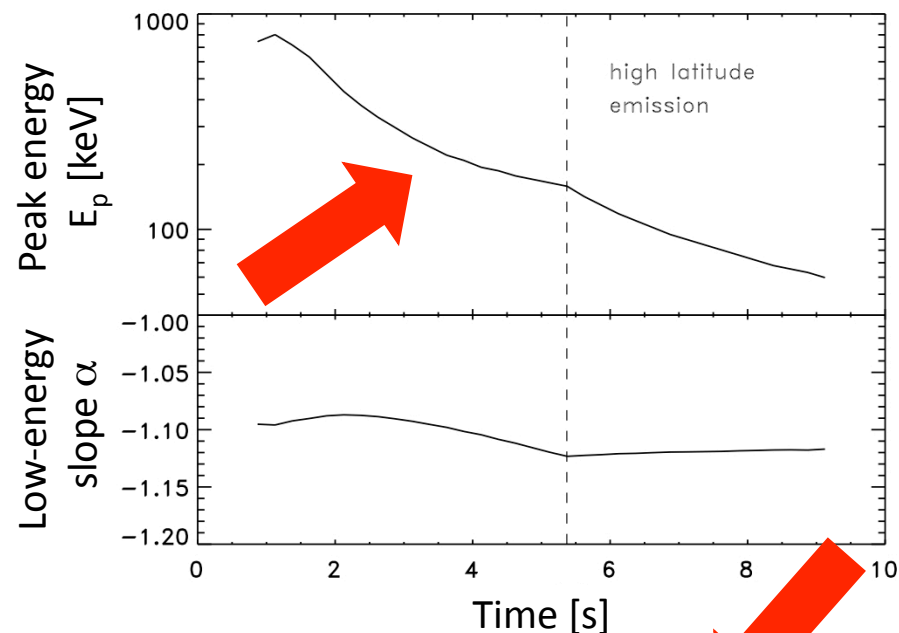
- Synchrotron + IC scatterings in KN regime : low-energy slope $\alpha \sim -3/2 \rightarrow -1$
(Derishev et al. 2001; Bosnjak et al. 2009 ; Nakar et al. 2009 ; Daigne et al. 2011)

Dominant radiative process ?

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

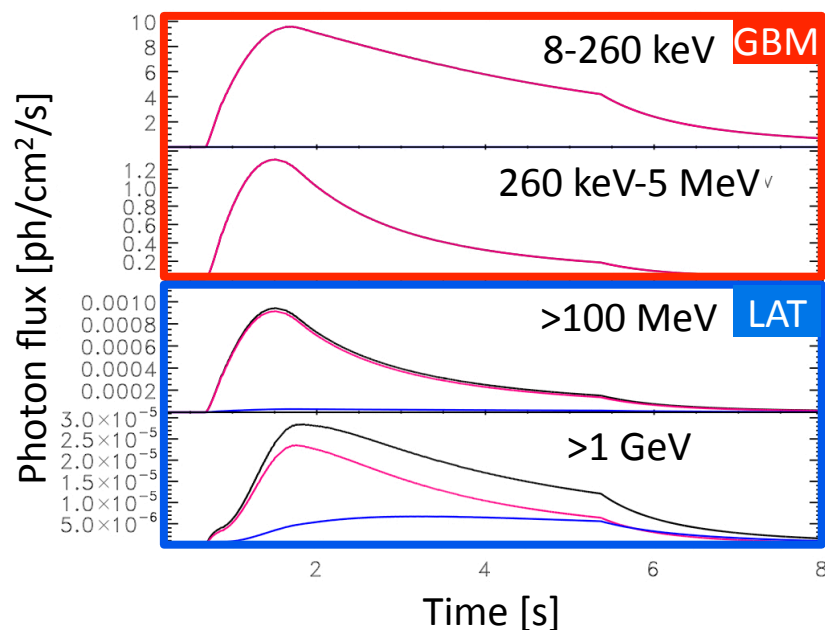


**Spectral evolution in a pulse:
both E_p and α evolve**

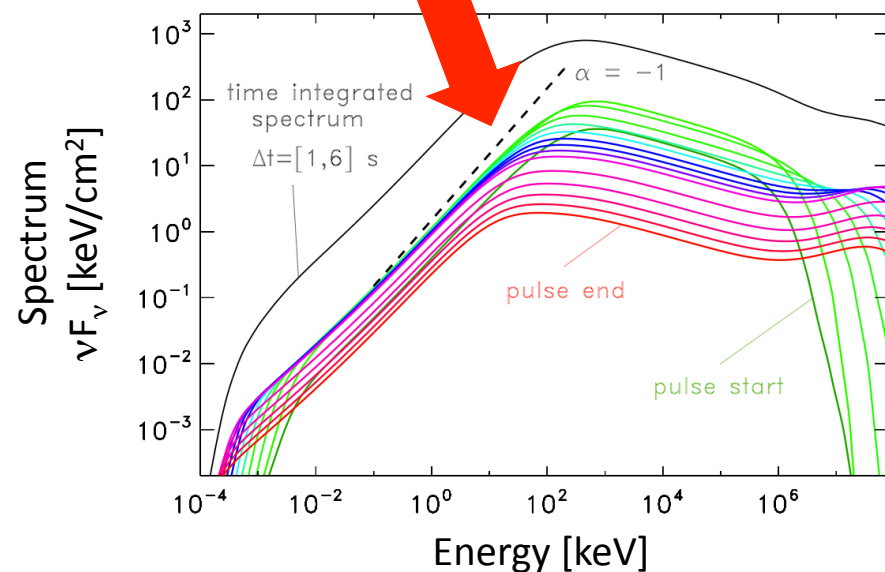
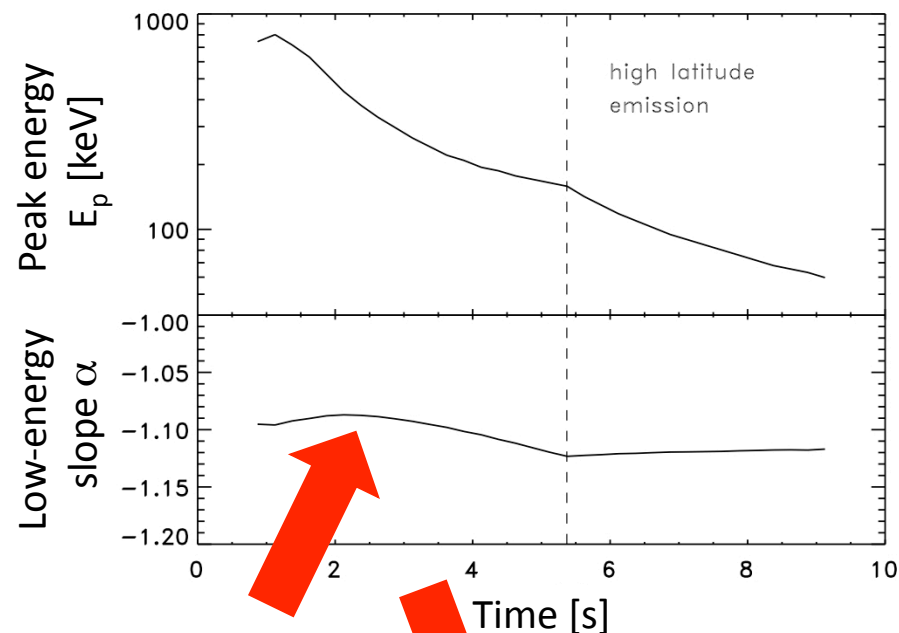


Dominant radiative process ?

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

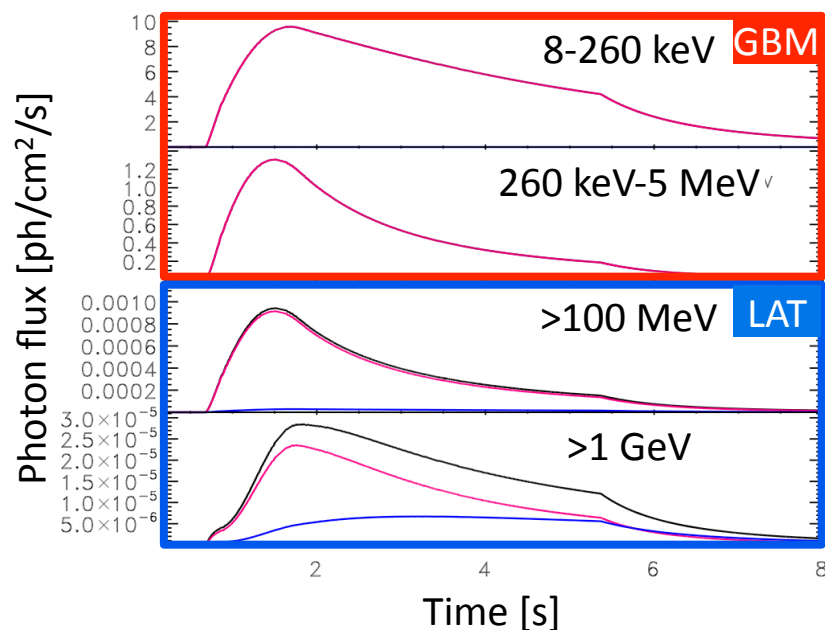


Fast cooling synchrotron:
 α can be steeper than $-3/2$
(here $\alpha \sim -1.1$)



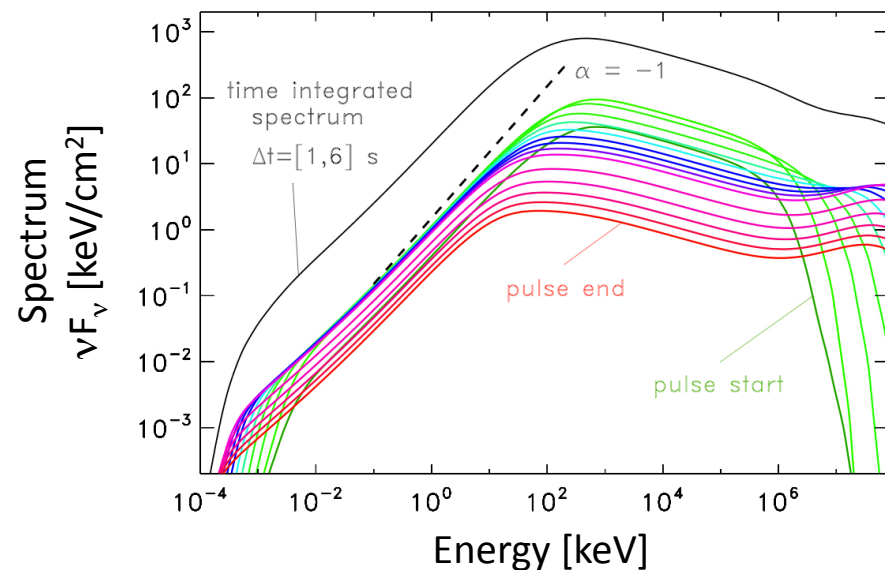
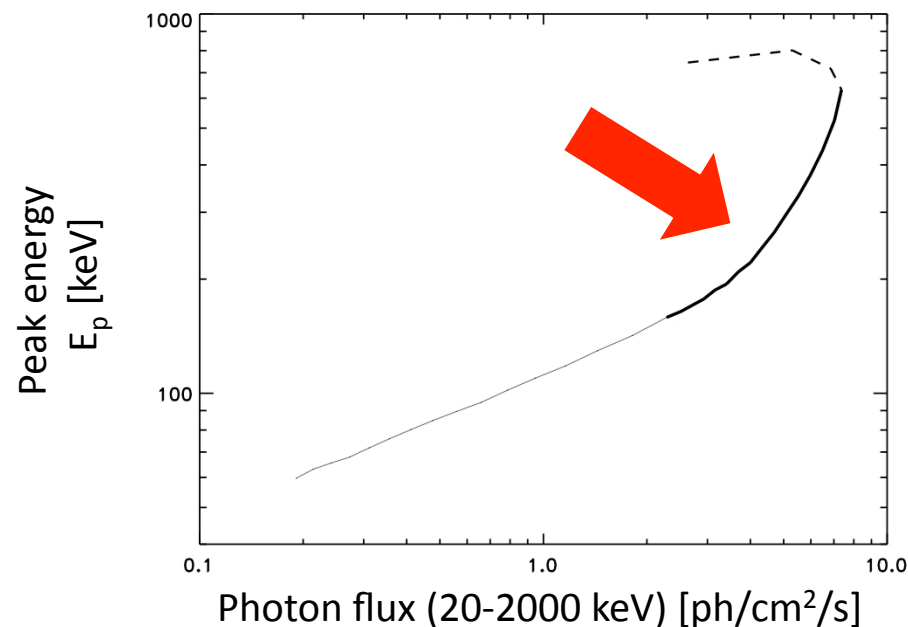
Dominant radiative process ?

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



Spectral evolution in a pulse: Hardness-intensity correlation

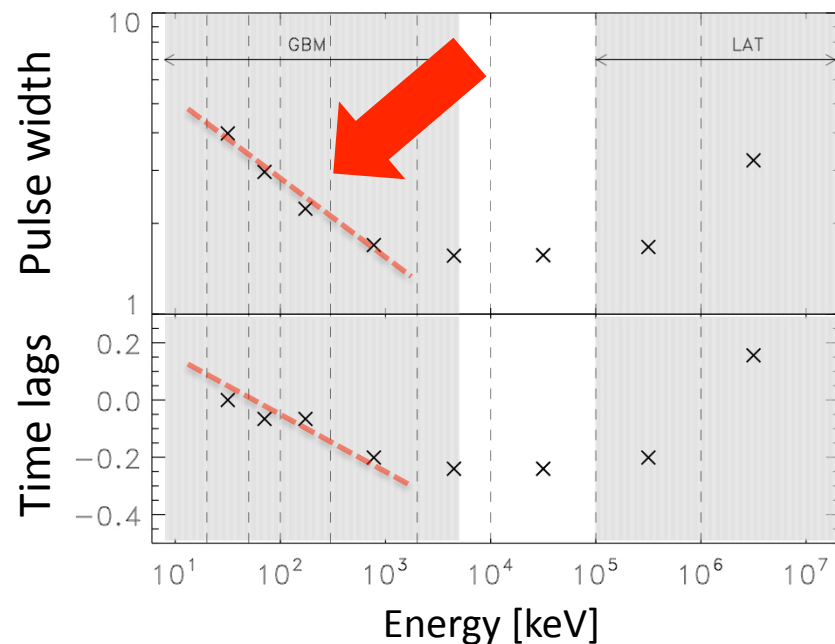
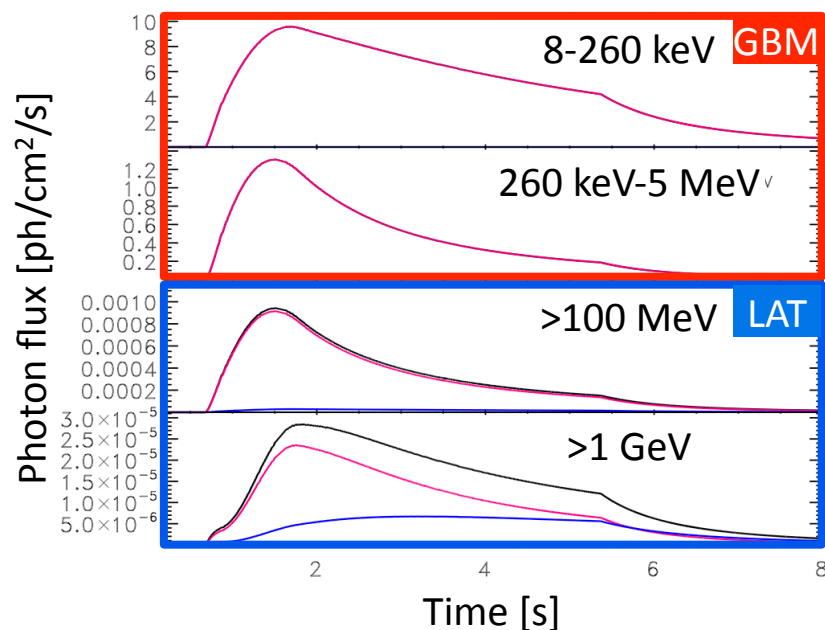
(HIC slope in agreement with
BATSE results : e.g. Ryde & Svensson 02)



Example taken from
Bošnjak & Daigne 2013 in preparation

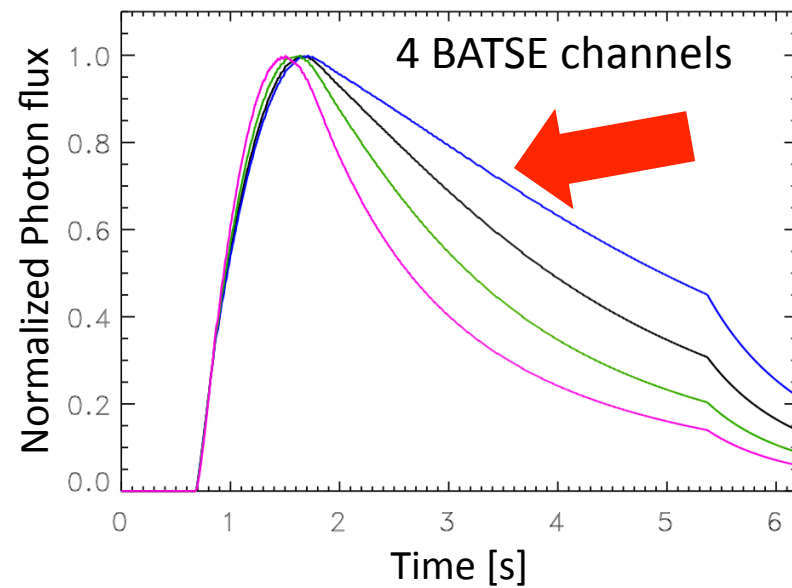
Dominant radiative process ?

- 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 ?

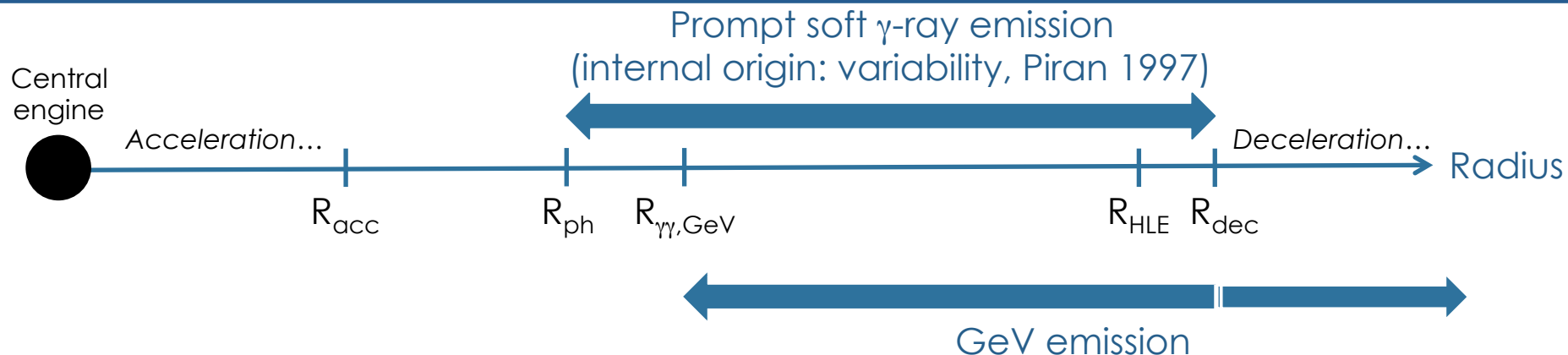
- Internal shocks + dominant synchrotron + IC scattering in KN regime
- Works well BUT

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)

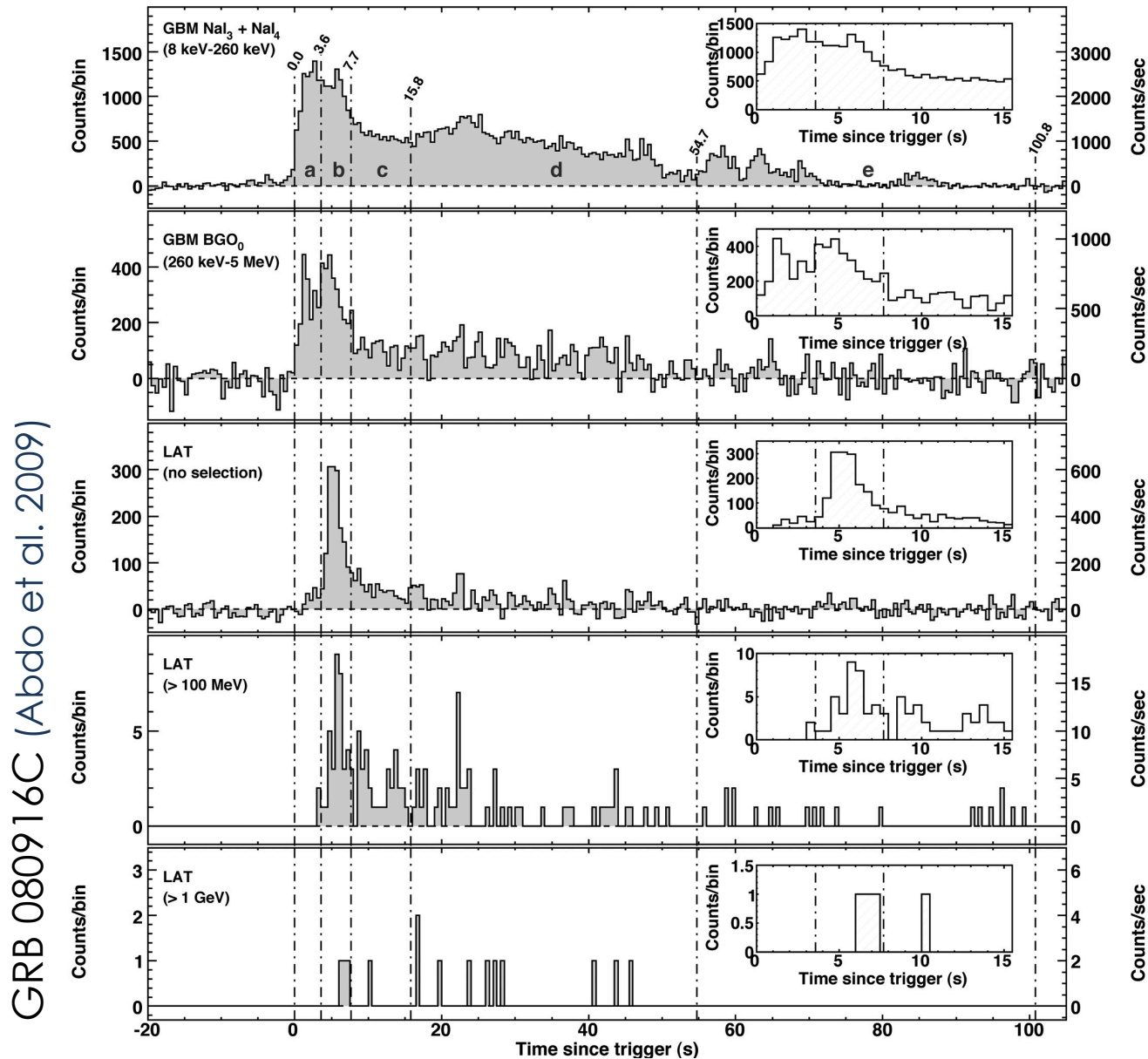
- main component (MeV \rightarrow GeV) : internal shocks or magn. Reconnection

(Rees & Meszaros 1994; Kobayashi et al. 1997;

Daigne & Mochkovitch 1998; ICMART Zhang et Yan 2011; ...)

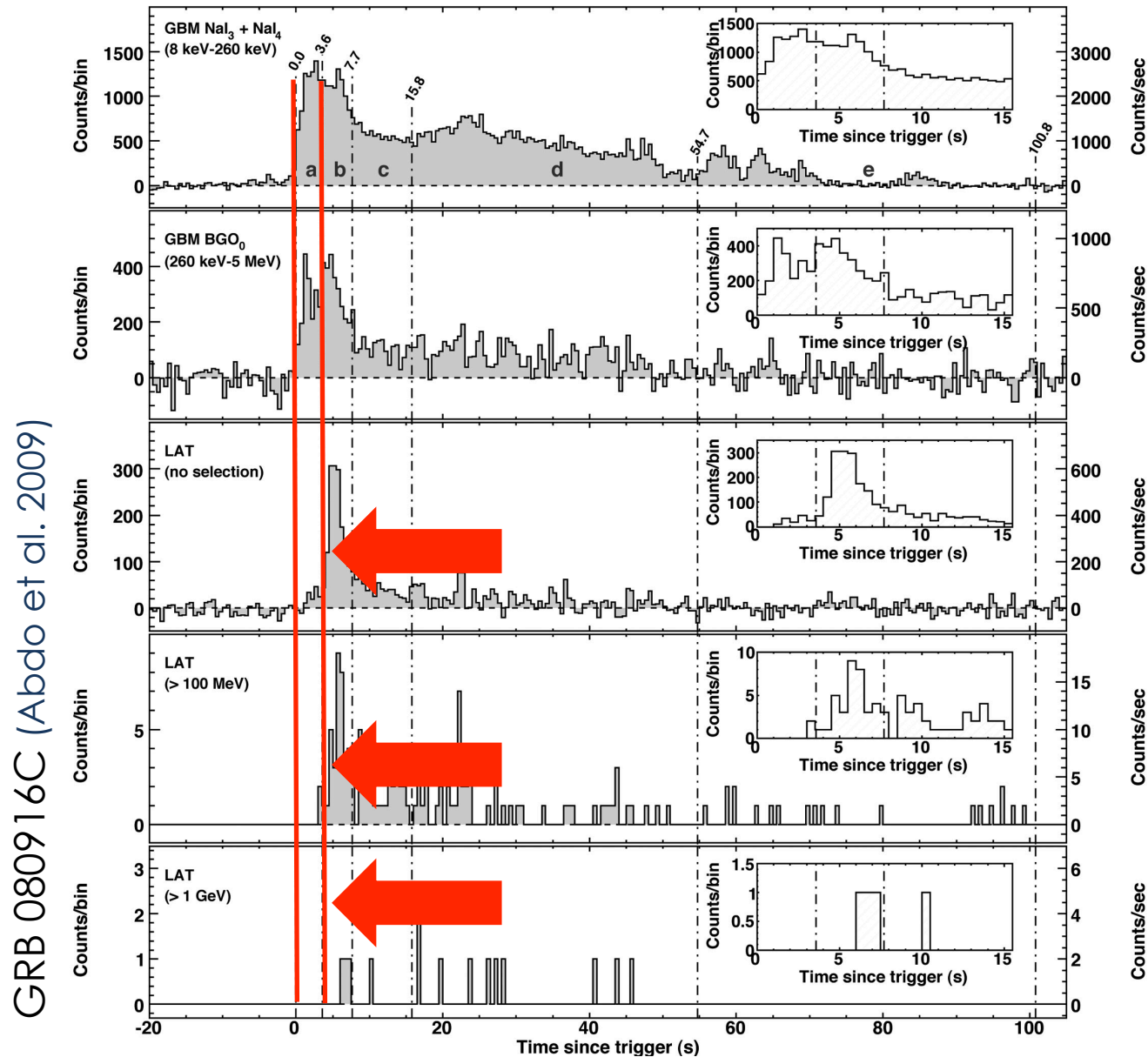
Fermi: delayed onset of the GeV emission

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



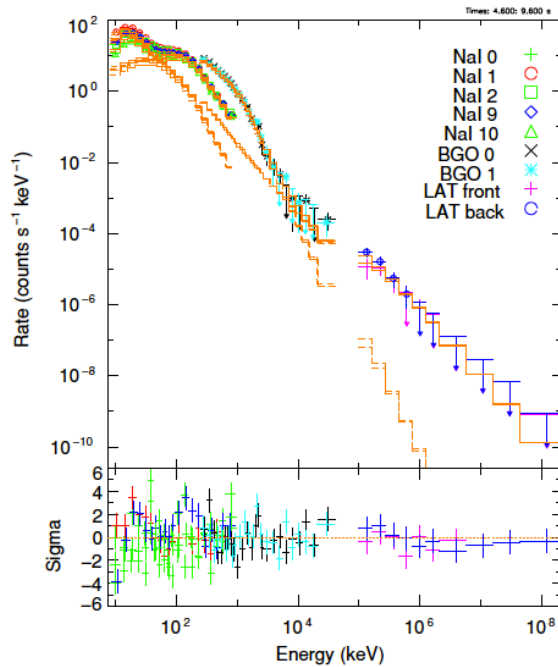
Fermi: delayed onset of the GeV emission

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

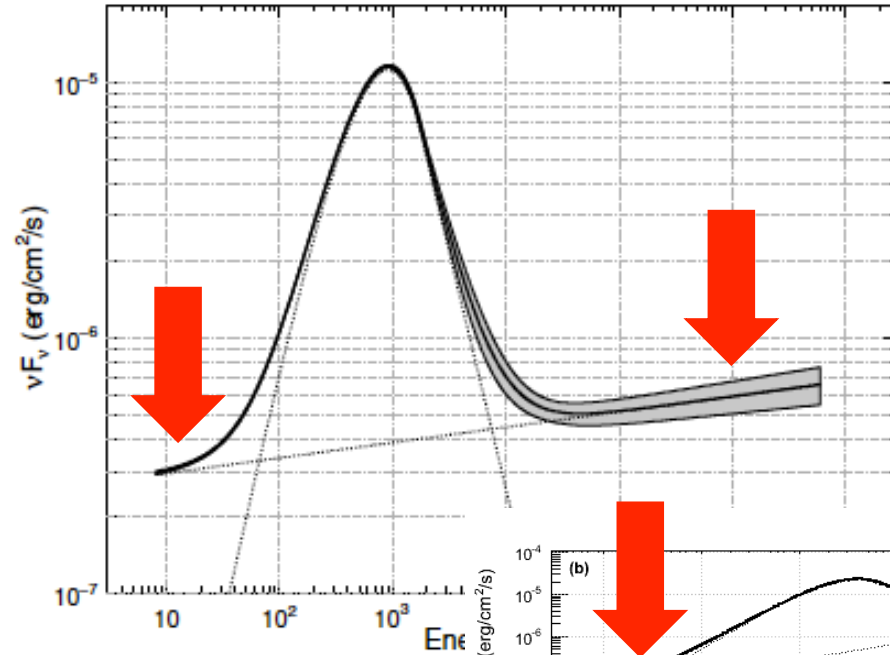


Fermi: additional spectral components

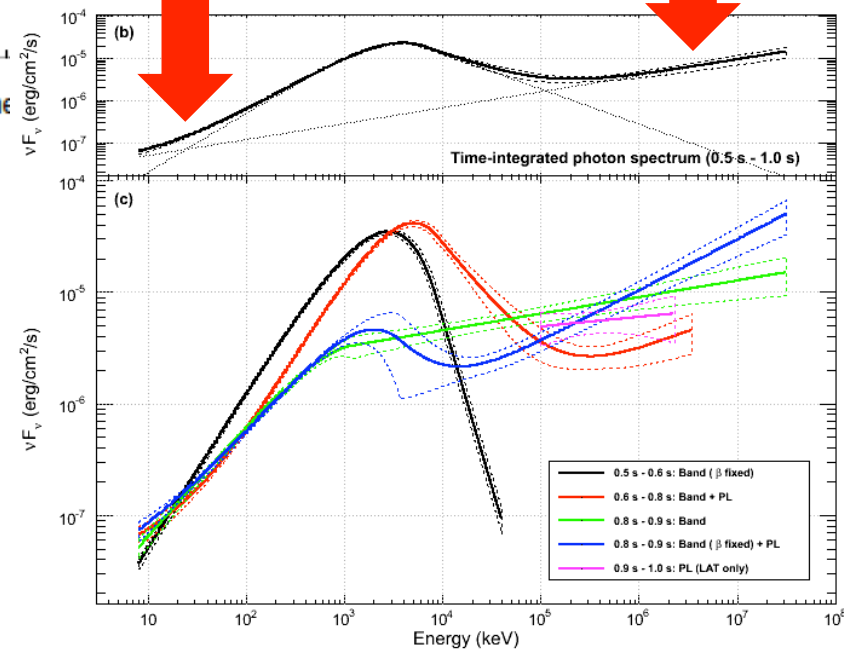
- In some cases, an additional component is seen at high energy



GRB 090902B (Abdo et al. 2009)

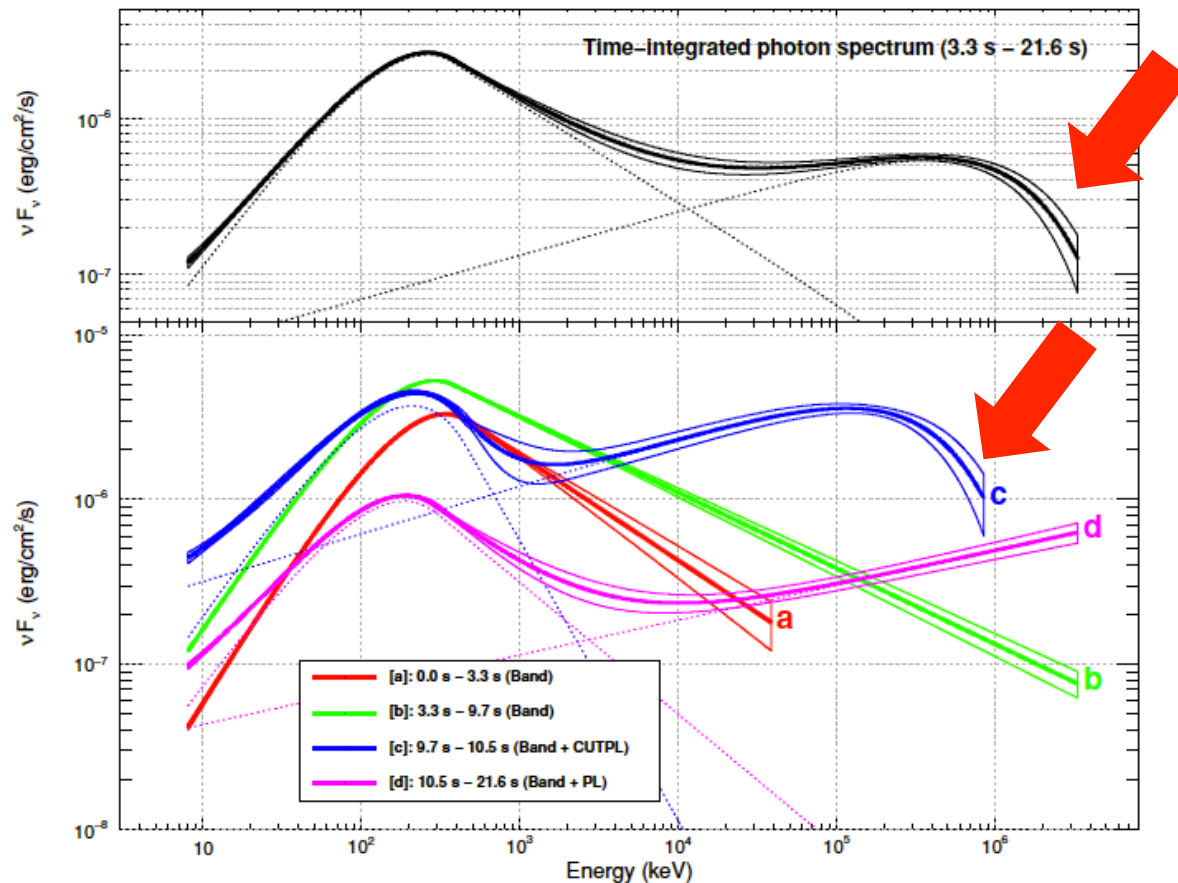


GRB 090510 (Abdo et al. 2009)



Fermi: cutoff at high energy ?

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

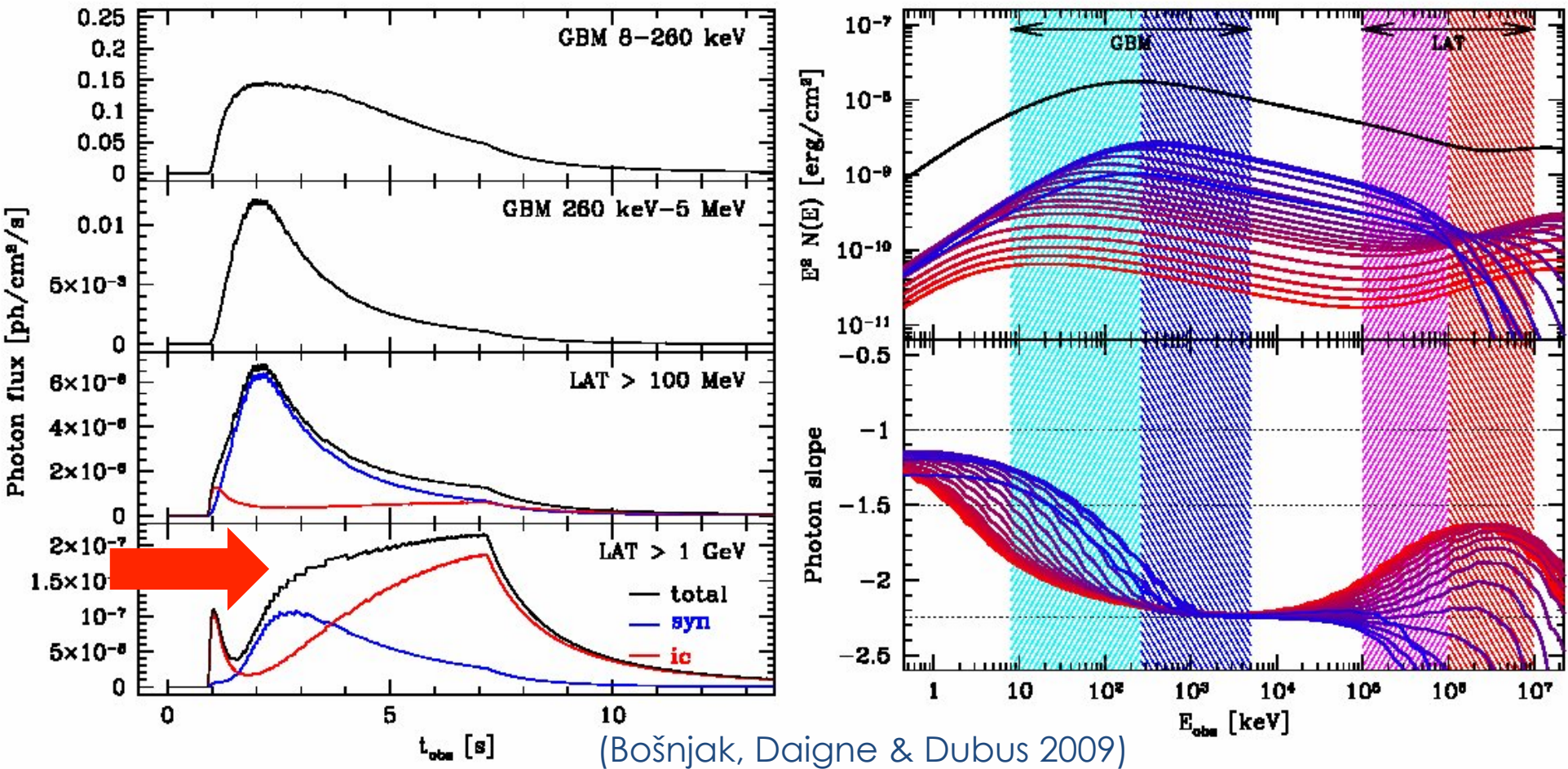


GRB 090926A (Ackermann et al. 2011)

- 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

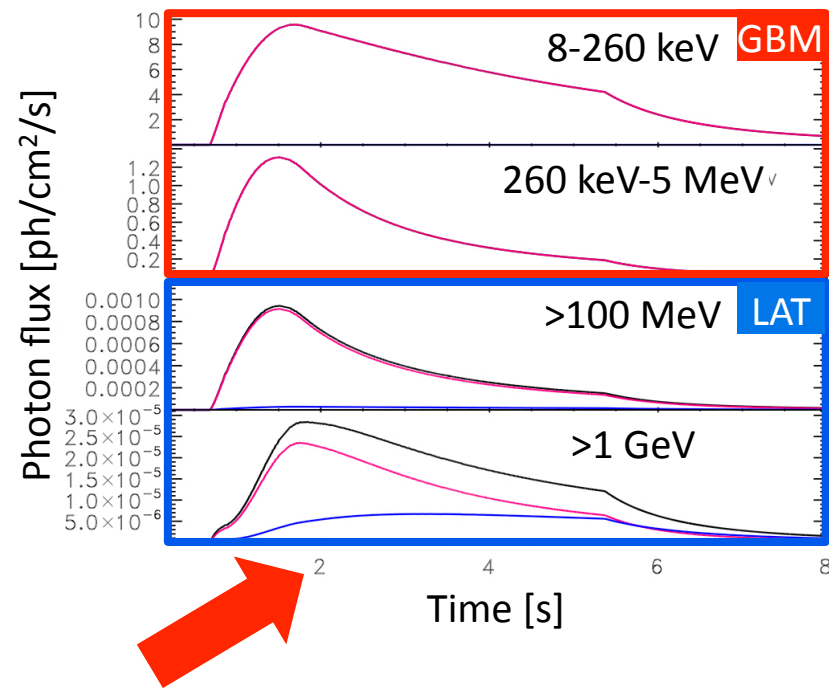
- **Intrinsic spectral evolution ?** (e.g. emergence of an IC component : leptonic scenario with low magnetic field)



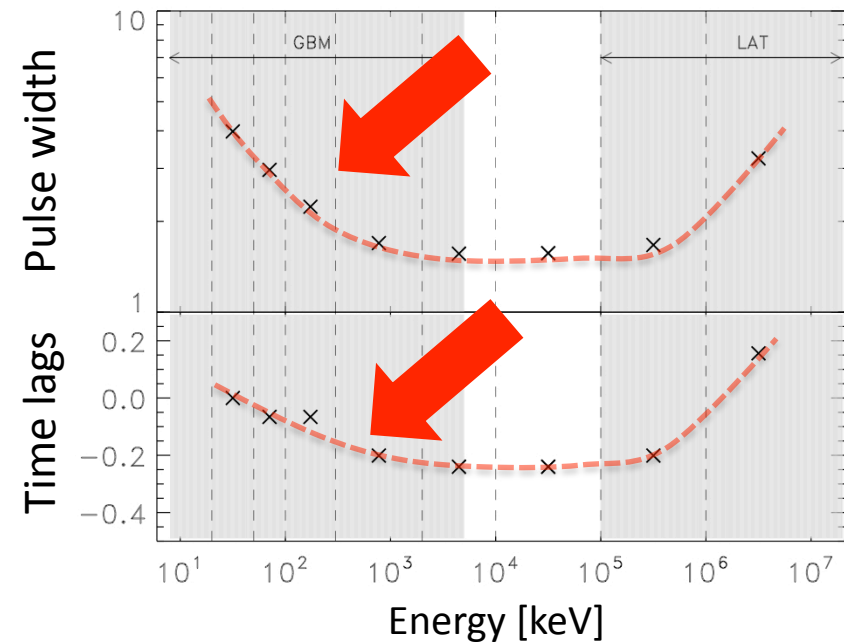
It seems difficult to have a delay > typical pulse duration in this scenario (see also Asano & Meszaros 2012)

GeV delayed onset & additional components

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



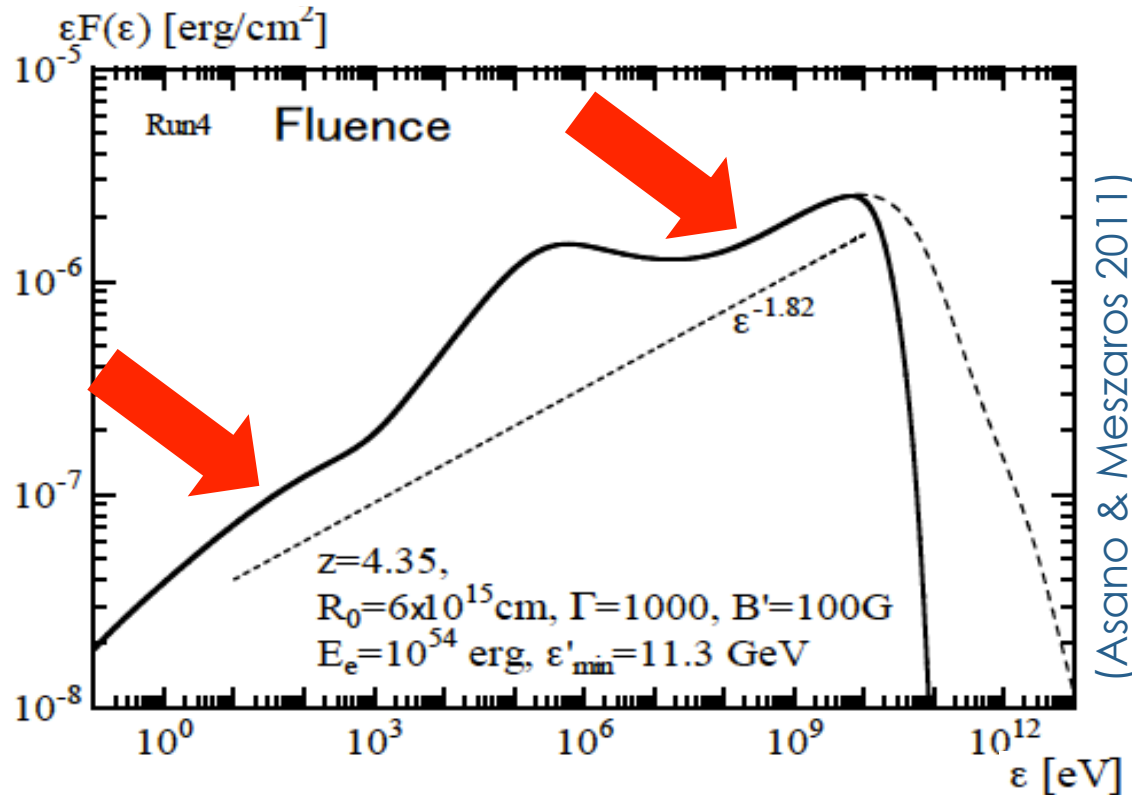
Example taken from
Bošnjak & Daigne 2013 in preparation



**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)

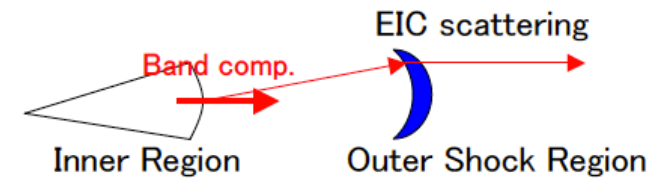
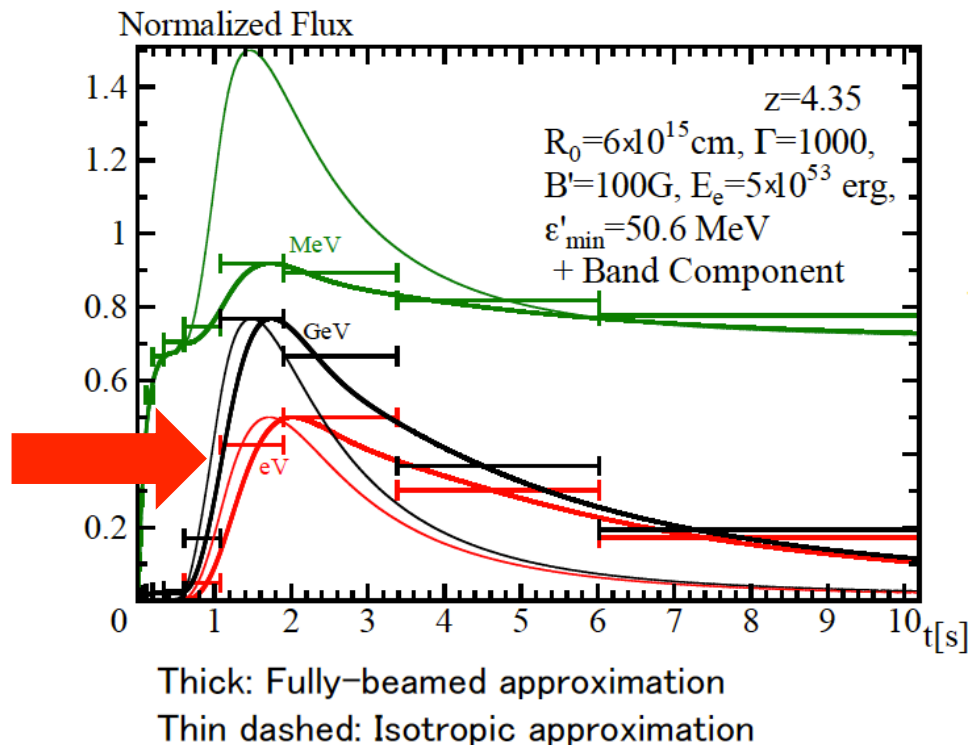


Similar conclusions about the extra leptonic component are obtained by [Asano & Meszaros 2011](#)

In addition, their results show that the late synchrotron 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 ; ...)



(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 ; ...)

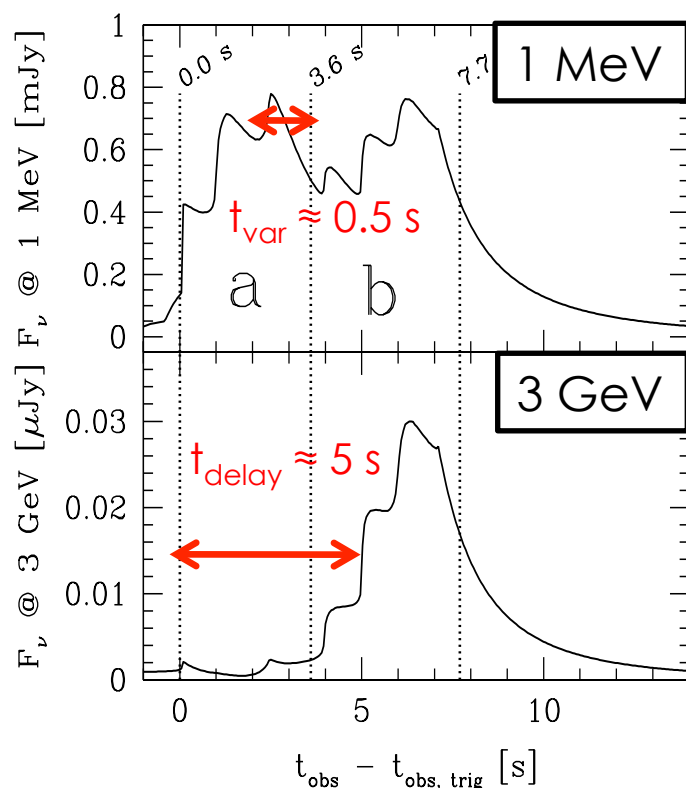
This scenario can produce larger delays

However :

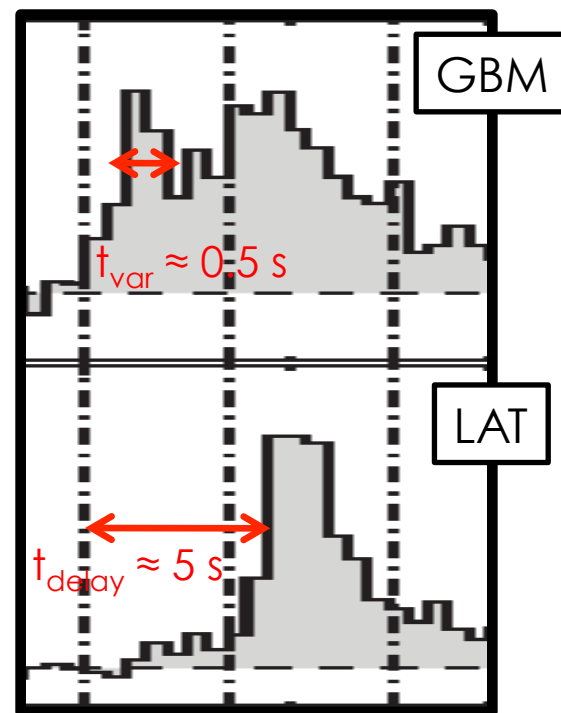
efficiency is low and these models require a huge energy injected in protons.
(see e.g. Asano & Meszaros 2012)

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



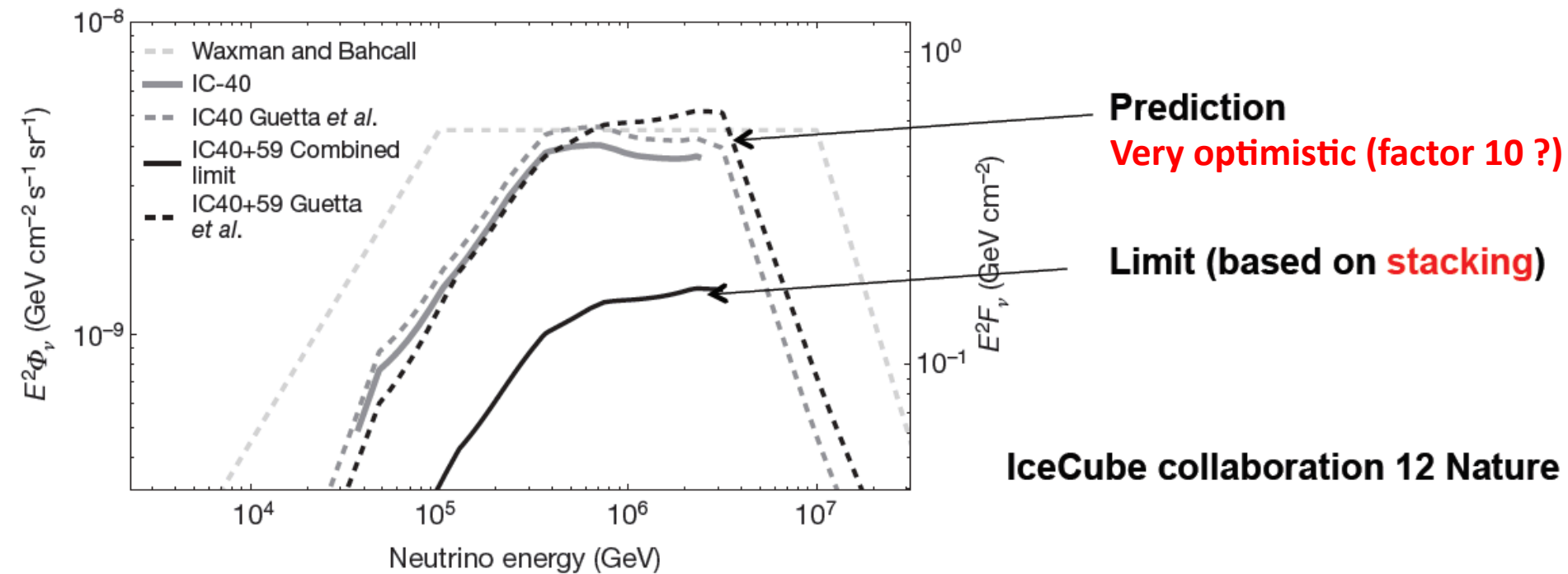
Fermi observations (Abdo et al. 2009)

- 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

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



(Taken from Murase 2013)

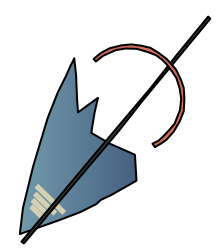
- ICECUBE can eliminate very optimistic models
- With a larger integration time (>10 yr), more realistic models could be tested

GRB prompt emission models

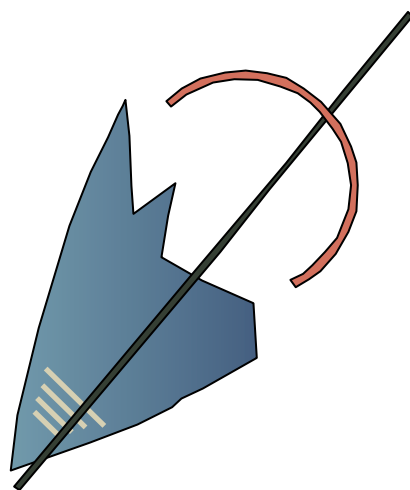
- Is there a standard scenario ?
- Three main possibilities :
 - photosphere
 - internal shocks
 - reconnection
- With several variants...
- Some variants have been eliminated
(standard fireball, SSC spectrum, ...)
- Large theoretical uncertainties in each of these three scenarios

Main uncertainties:

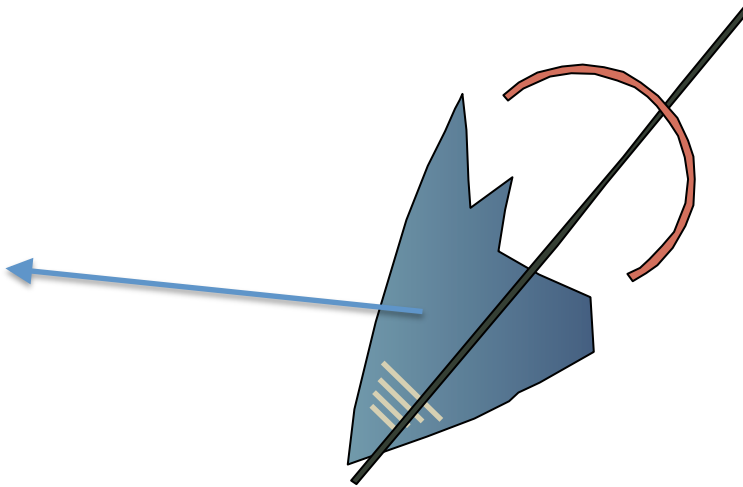
- Jet acceleration
- Microphysics (shock acceleration, reconnection, ...)

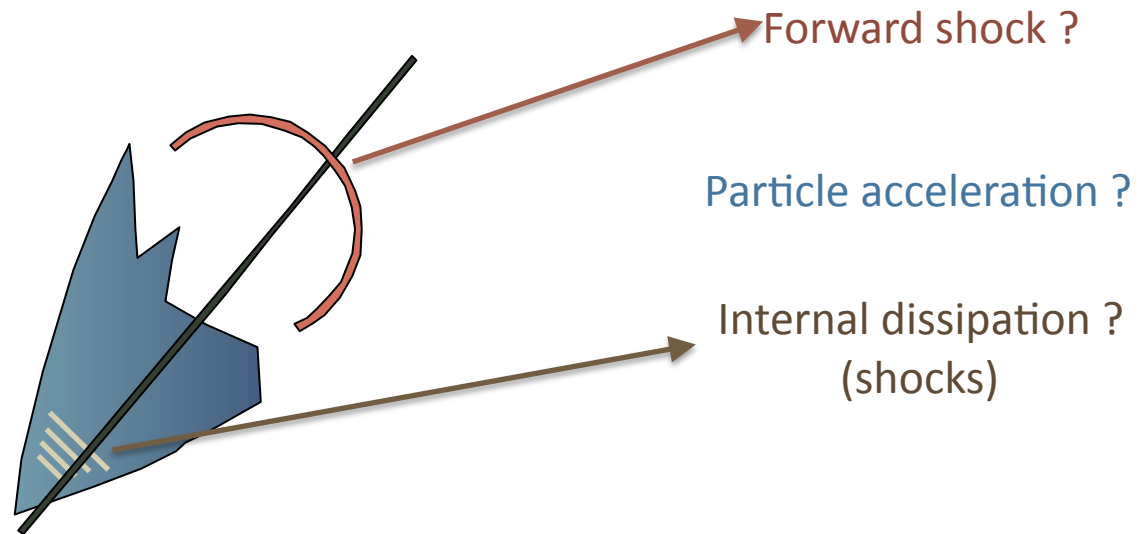


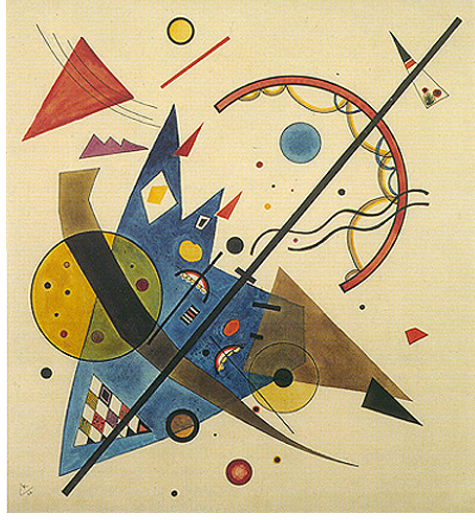
Conclusion



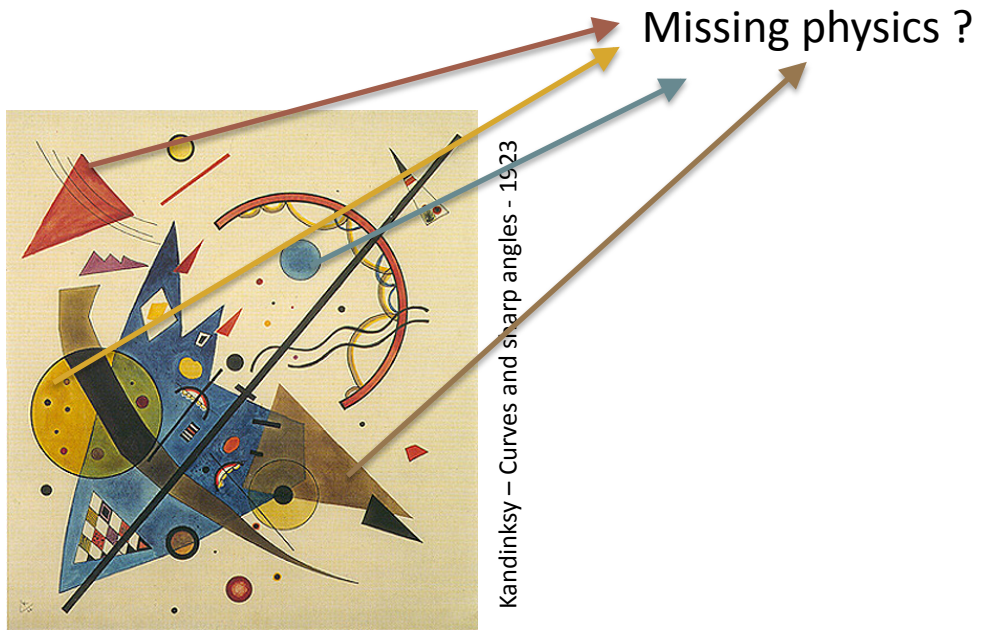
Relativistic Jet ?







Kandinsky – Curves and sharp angles - 1923



or missing observations...

Post Swift/Fermi era ?

CTA ; SVOM

*+ multi-wavelength/messenger context,
including gravitational waves*