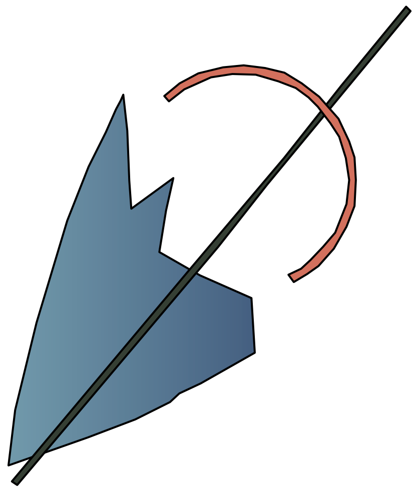
Les sursauts gamma

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



IIIème école de physique des astroparticules – 23-28 mai 2011 – Observatoire de Haute Provence

Les sursauts gamma

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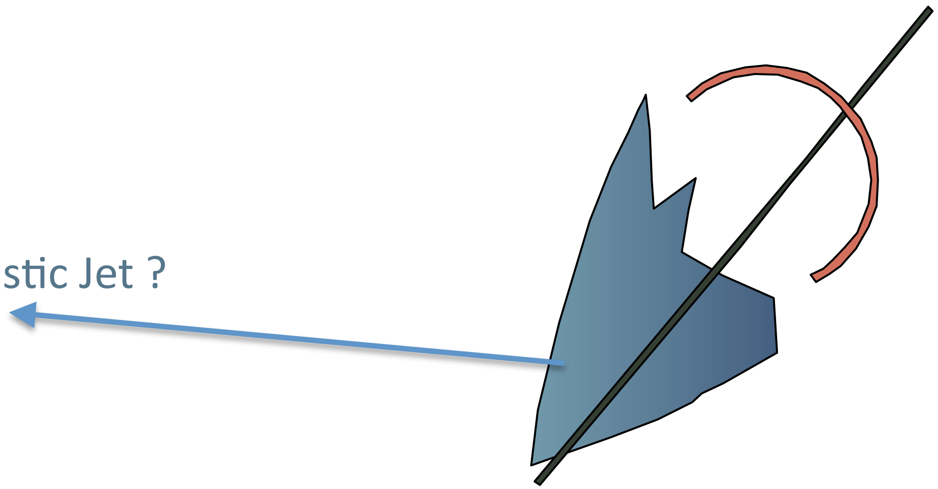
daigne@iap.fr

UPMC
PARISUNIVERSITAS

IUF



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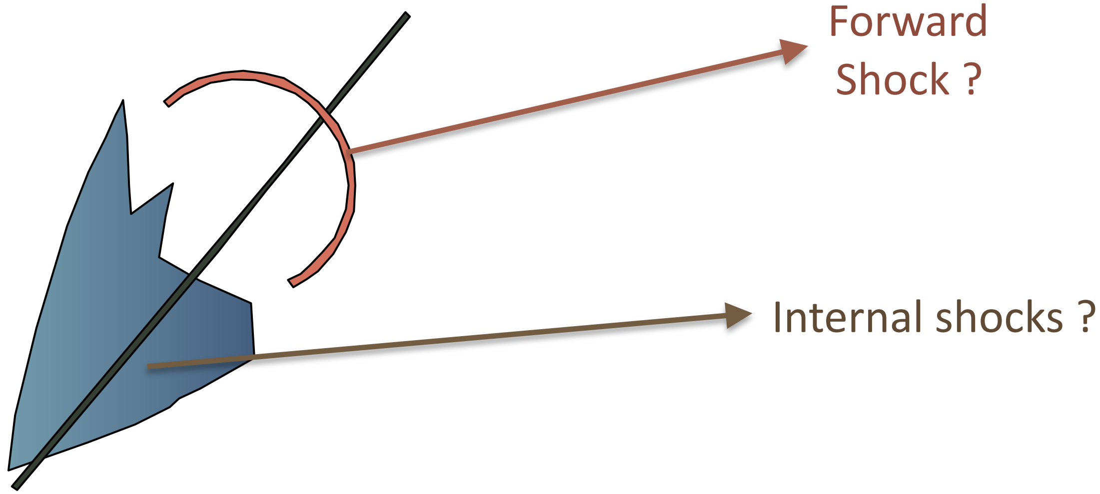

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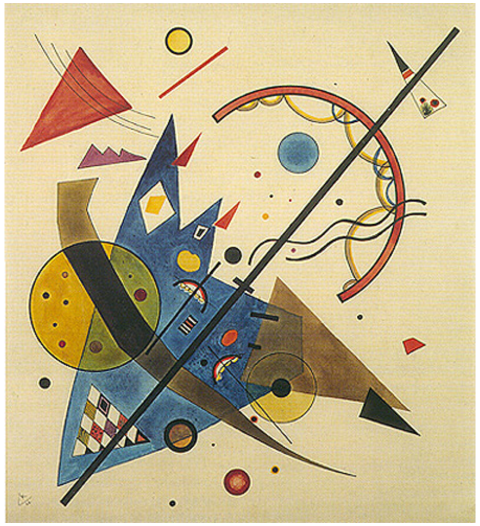

Kandinksy – Curves and sharp angles - 1923

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Les sursauts gamma

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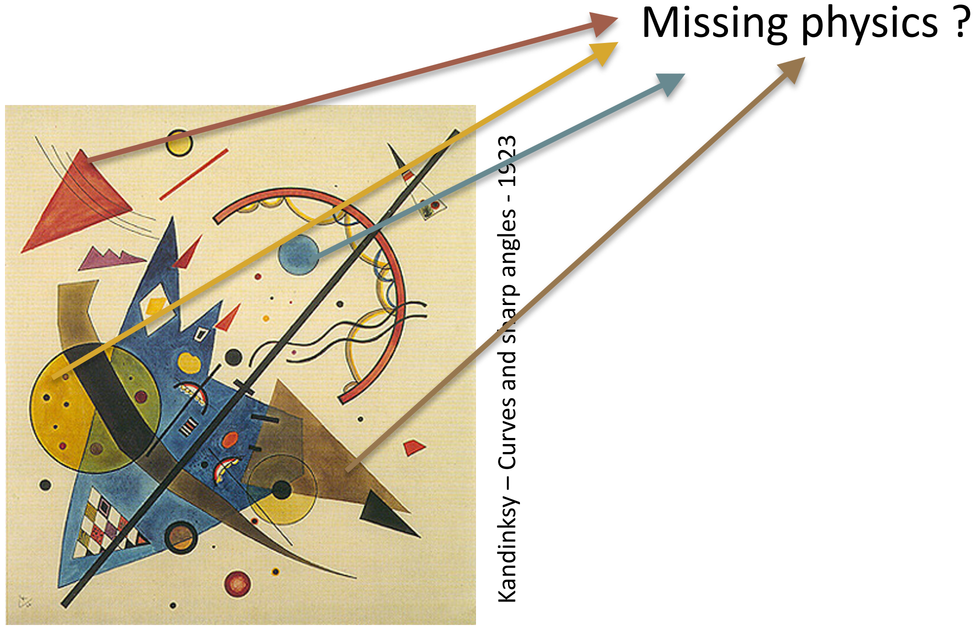


Kandinksy – Curves and sharp angles - 1923

IIIème école de physique des astroparticules – 23-28 mai 2011 – Observatoire de Haute Provence

Plan :

1) Historique – les principaux faits observationnels
2) Quelques observations récentes d'intérêt particulier
3) Les contraintes de base pour construire un modèle de sursaut gamma
4) Le scénario « standard »

5) Quelques questions sur la composition du jet
6) Le mécanisme pour l'émission du sursaut gamma proprement dit

7) En conclusion, quelques mots sur tout ce dont je n'ai pas parlé…

Historique

Principaux faits observationnels

Treaty Banning Nuclear Weapon Tests in the Atmosphere, in Outer Space and under Water Signed by the Original Parties, the Union of Soviet Socialist Republics, the United Kingdom of Great Britain and Northern Ireland and the United States of America at Moscow: 5 August 1963

The Governments of the United States of America, the United Kingdom of Great Britain and Northern Ireland, and the Union of Soviet Socialist Republics, hereinafter referred to as the "Original Parties,"

Proclaiming as their principal aim the speediest possible achievement of an agreement on general and complete disarmament under strict international control in accordance with the objectives of the United Nations which would put an end to the armaments race and eliminate the incentive to the production and testing of all kinds of weapons, including nuclear weapons,

Seeking to achieve the discontinuance of all test explosions of nuclear weapons for all time, determined to continue negotiations to this end, and desiring to put an end to the contamination of man's environment by radioactive substances,

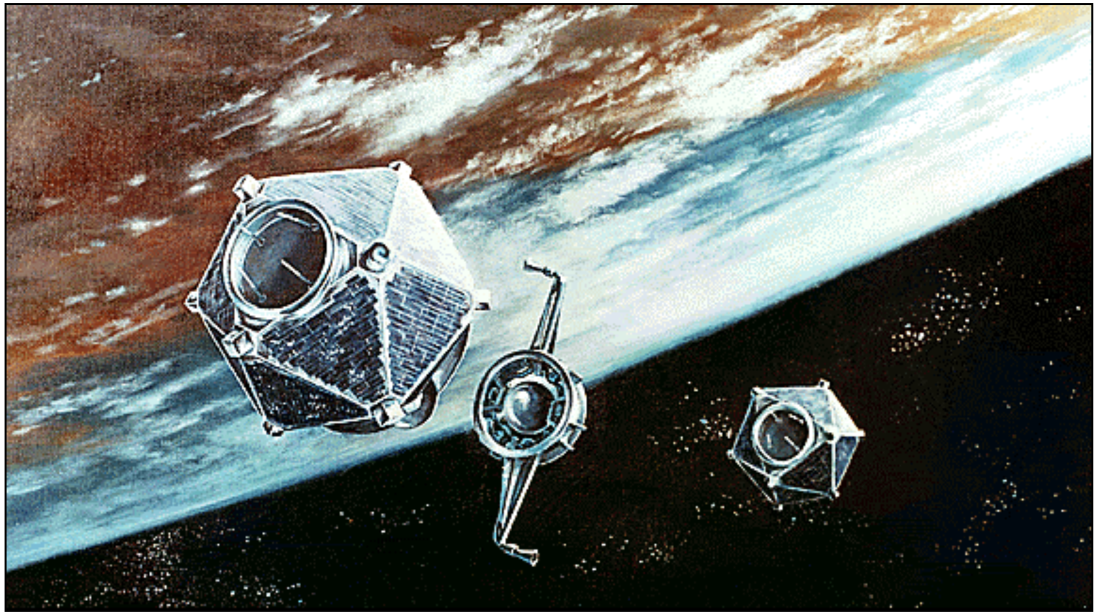
Have agreed as follows:

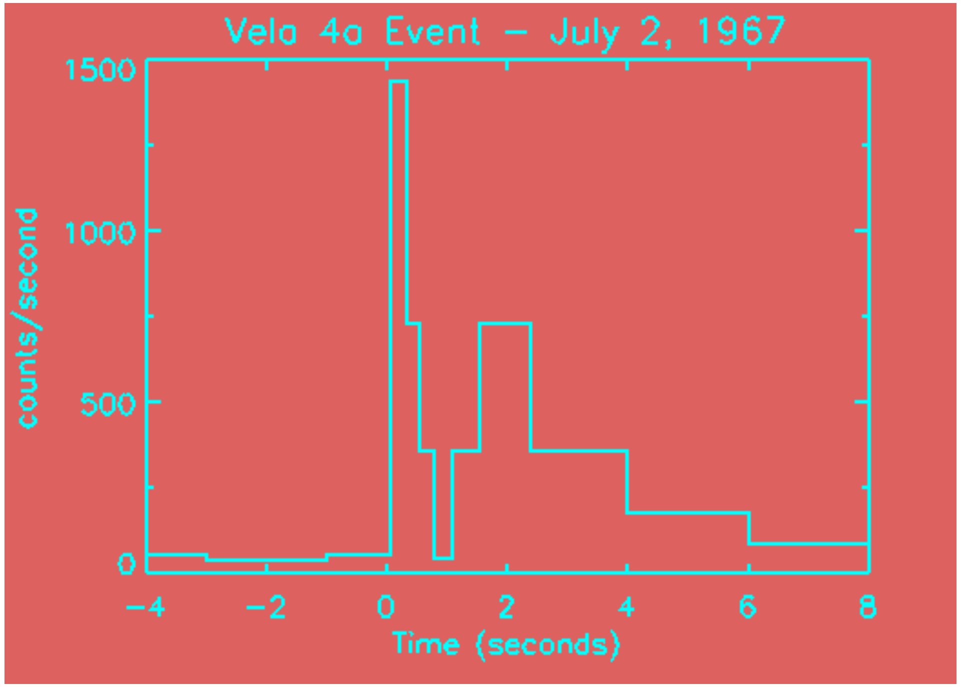
Article I

1. Each of the Parties to this Treaty undertakes to prohibit, to prevent, and not to carry out any nuclear weapon test explosion, or any other nuclear explosion, at any place under its jurisdiction or control:

(a) in the atmosphere; beyond its limits, including outer space; or under water, including territorial waters or high seas; or

Le projet « VELA » (3 paires de satellites lancés en 1963, 1964 et 1965)





The Astrophysical Journal, **182:** L85–L88, 1973 June 1

OBSERVATIONS OF GAMMA-RAY BURSTS OF COSMIC ORIGIN

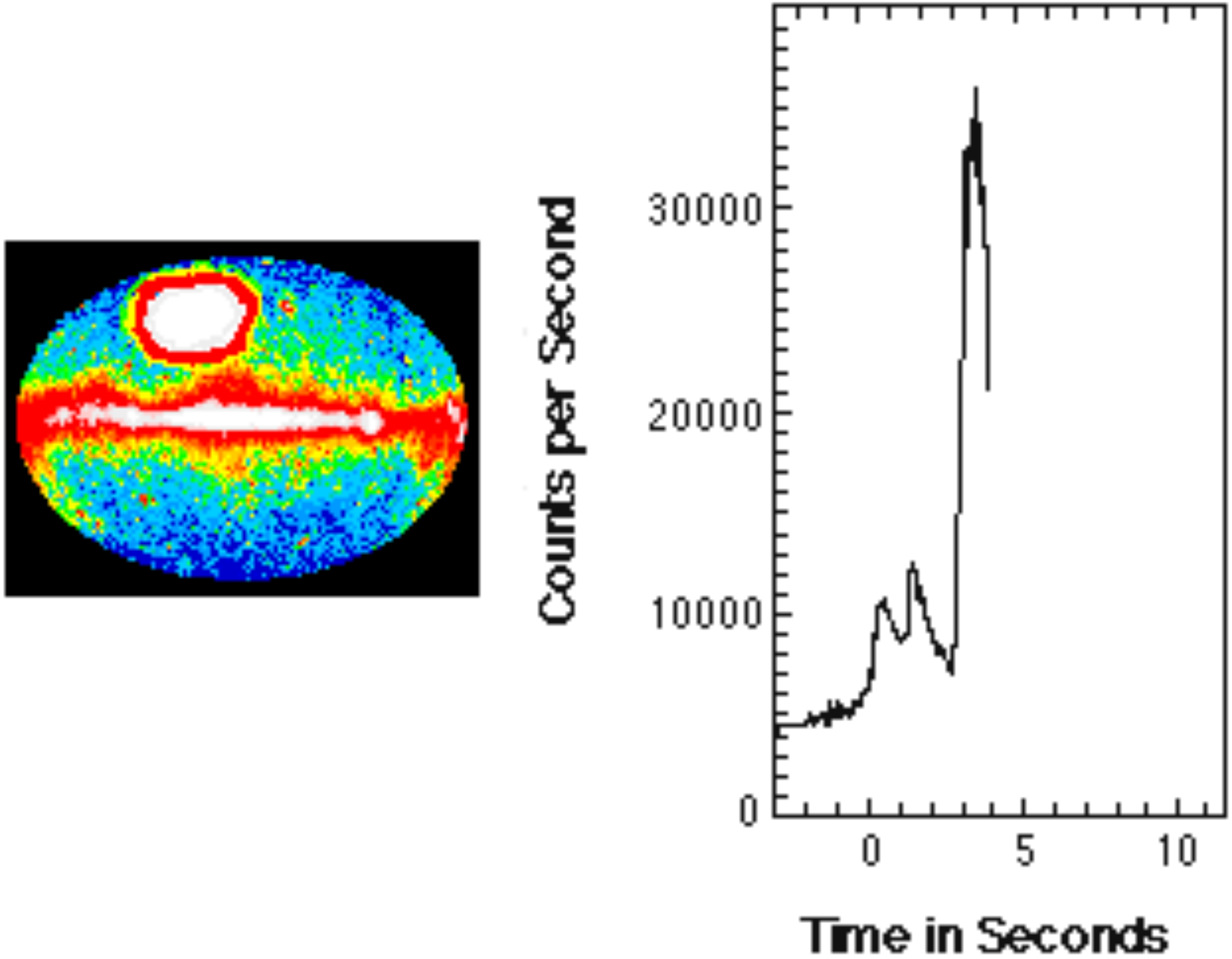
Ray W. Klebesadel, Ian B. Strong, and Roy A. Olson

University of California, Los Alamos Scientific Laboratory, Los Alamos, New Mexico
Received 1973 March 16; revised 1973 April 2

ABSTRACT

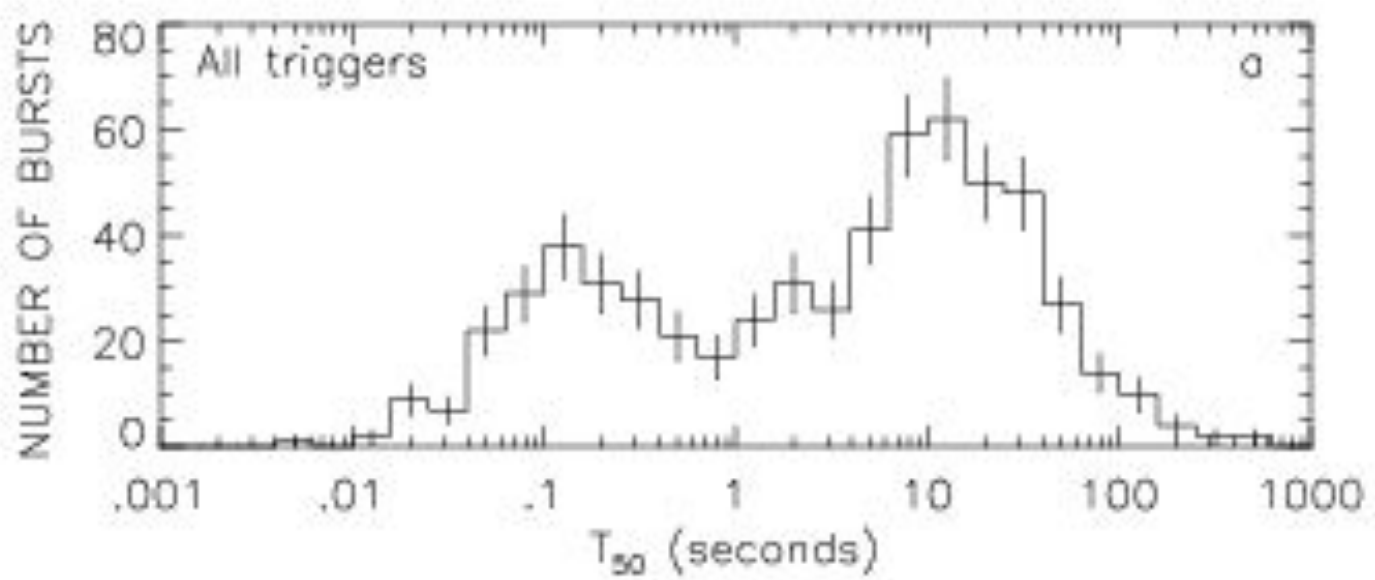
Sixteen short bursts of photons in the energy range 0.2–1.5 MeV have been observed between 1969 July and 1972 July using widely separated spacecraft. Burst durations ranged from less than 0.1 s to ~30 s, and time-integrated flux densities from $\sim 10^{-5}$ ergs cm^{-2} to $\sim 2 \times 10^{-4}$ ergs cm^{-2} in the energy range given. Significant time structure within bursts was observed. Directional information eliminates the Earth and Sun as sources.

Subject headings: gamma rays — X-rays — variable stars



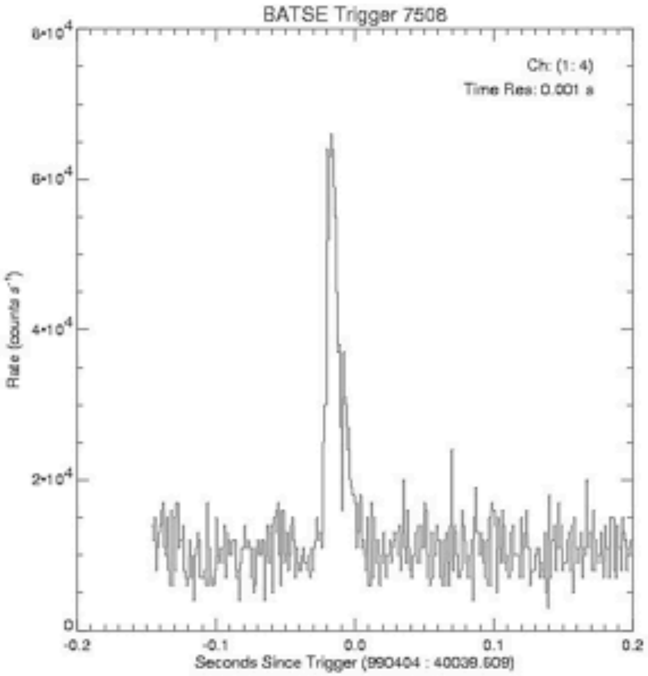
Counts per Second
30000
20000
10000
0
0
5
10
Time in Seconds

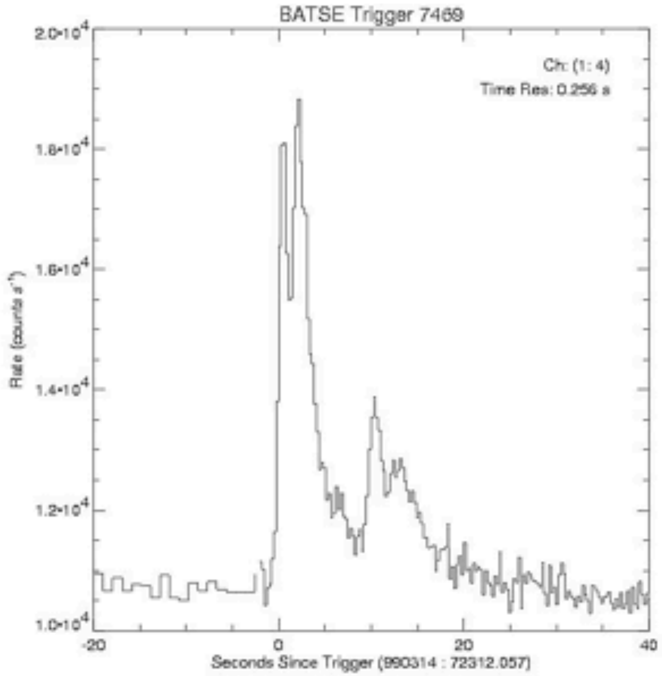
Duration

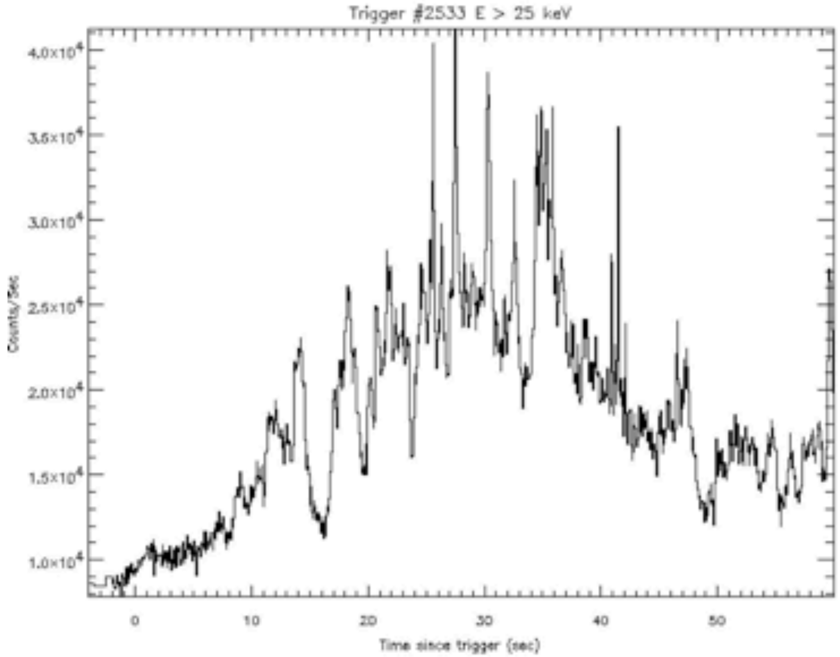


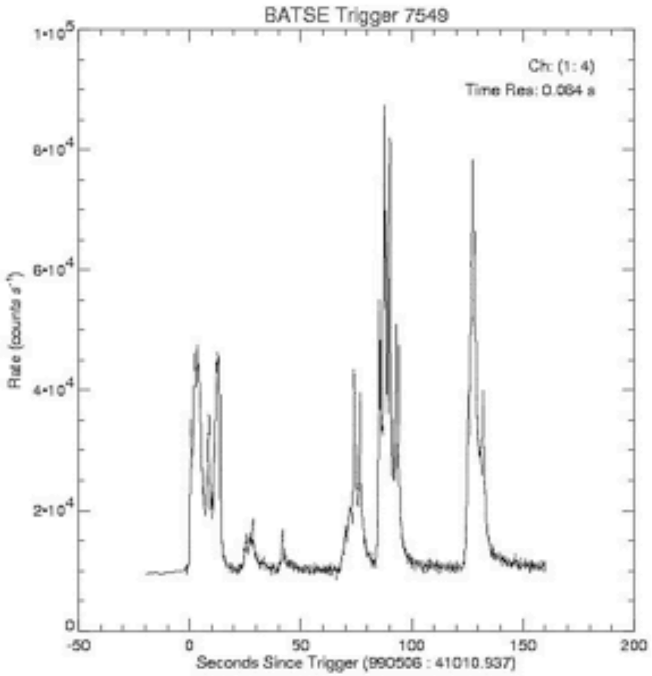
NUMBER OF BURSTS
80
60
40
20
0
All triggers
a
.001
.01
.1
1
10
100
1000
T_{50} (seconds)

Lightcurves

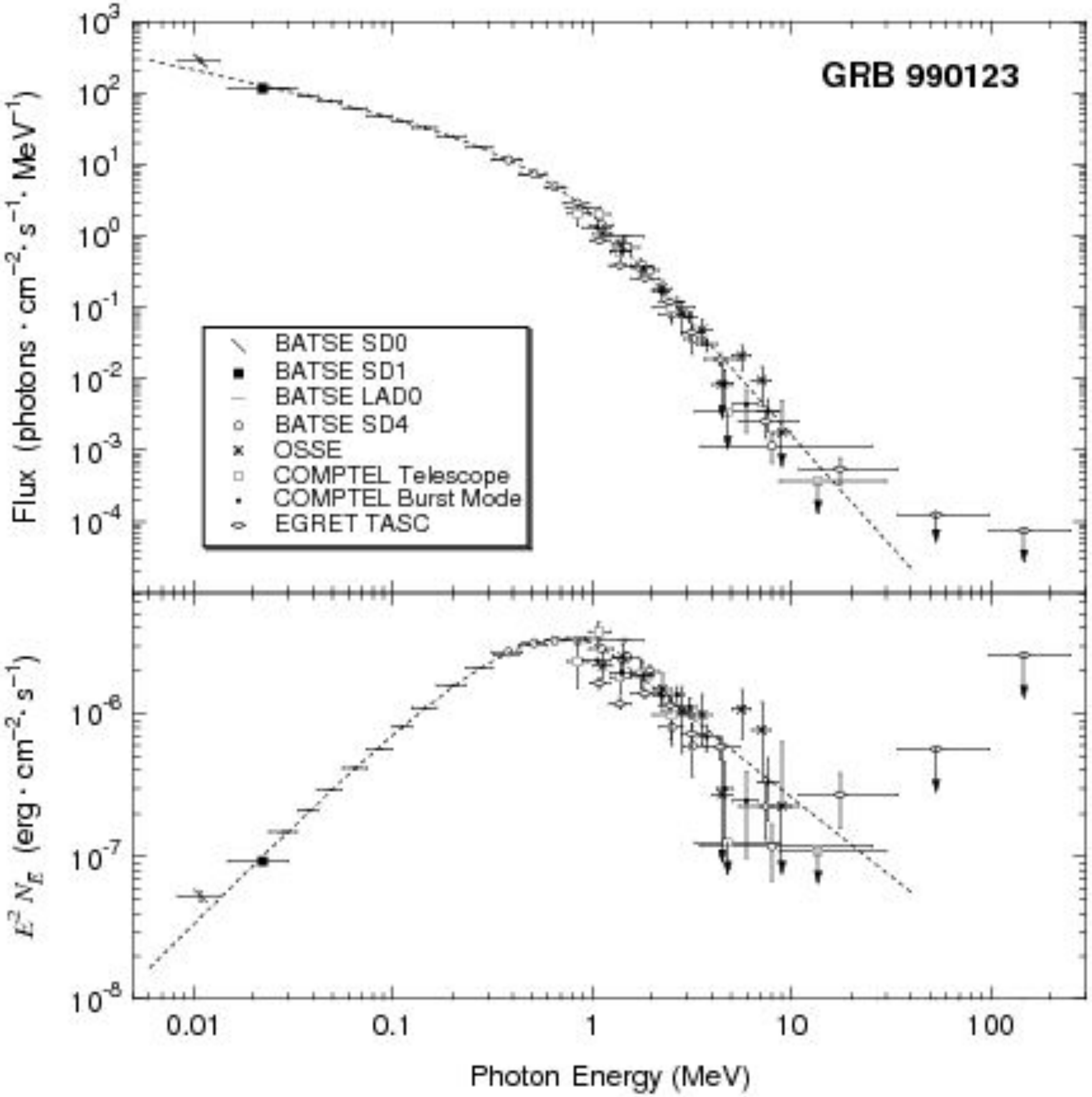






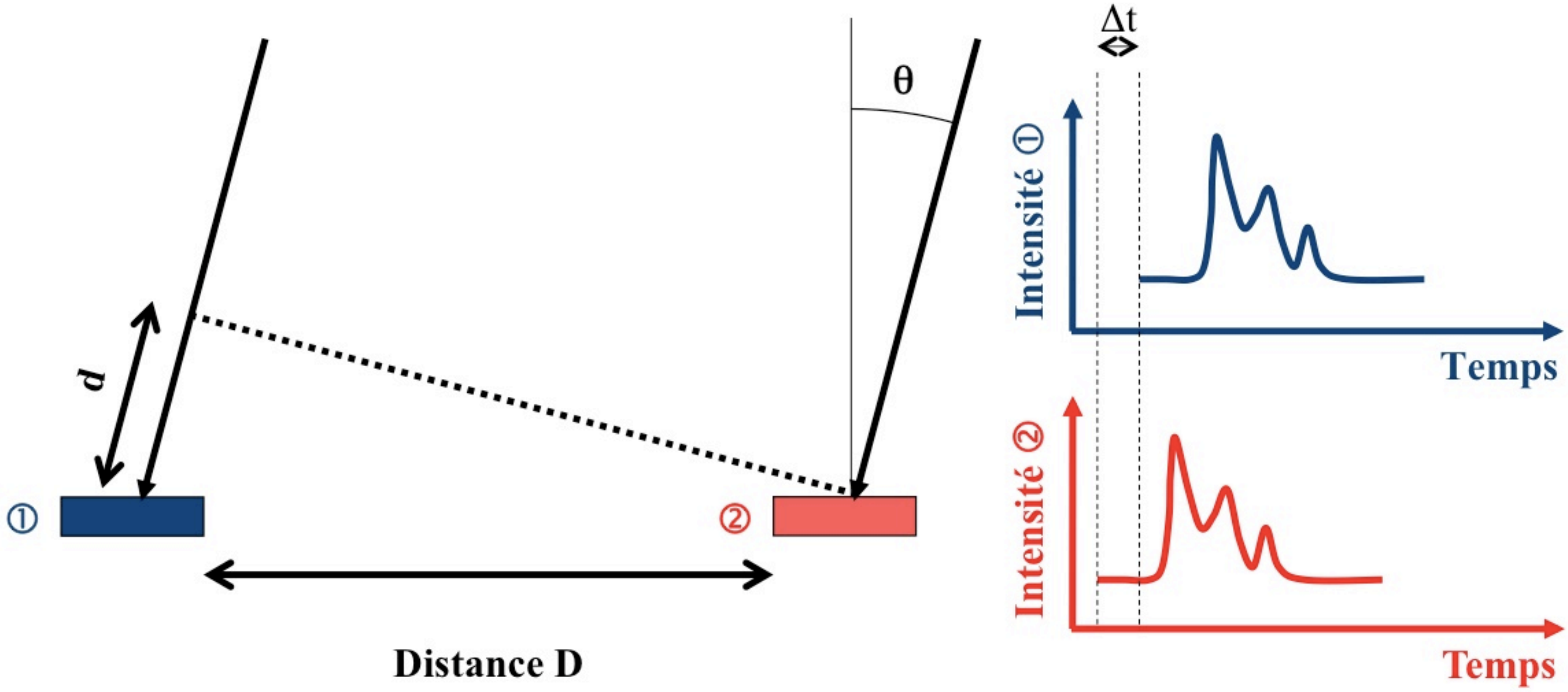


Spectrum

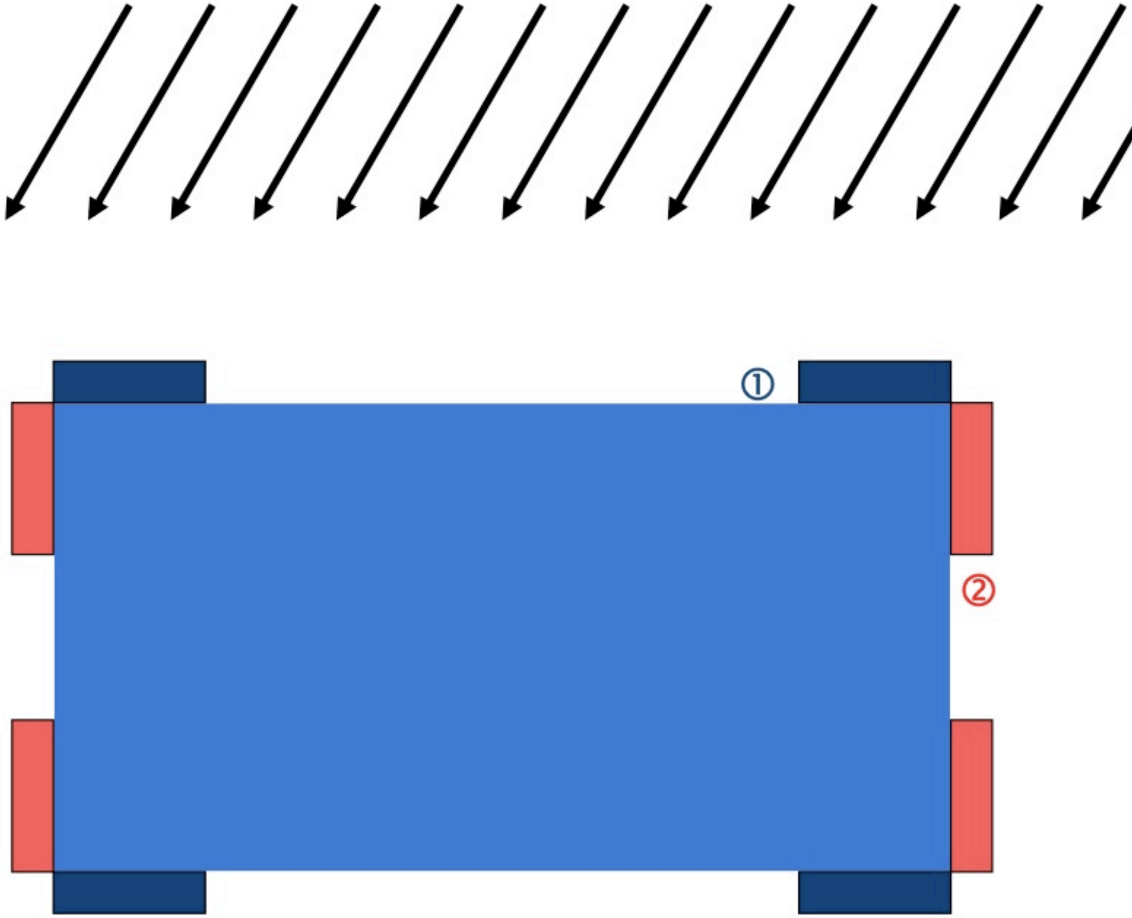


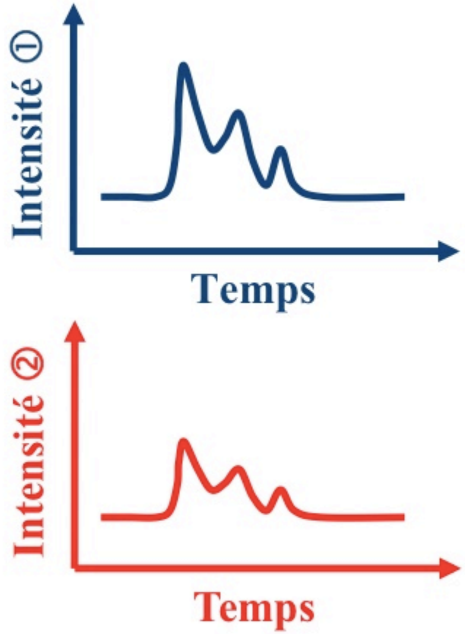
GRB 990123
BATSE SD0
BATSE SD1
BATSE LAD0
BATSE SD4
OSSE
COMPTEL Telescope
COMPTEL Burst Mode
EGRET TASC
Flux (photons · cm^{-2} · s^{-1} · MeV^{-1})
$E^2 N_E$ (erg · cm^{-2} · s^{-1})
Photon Energy (MeV)

Localization (1) IPN

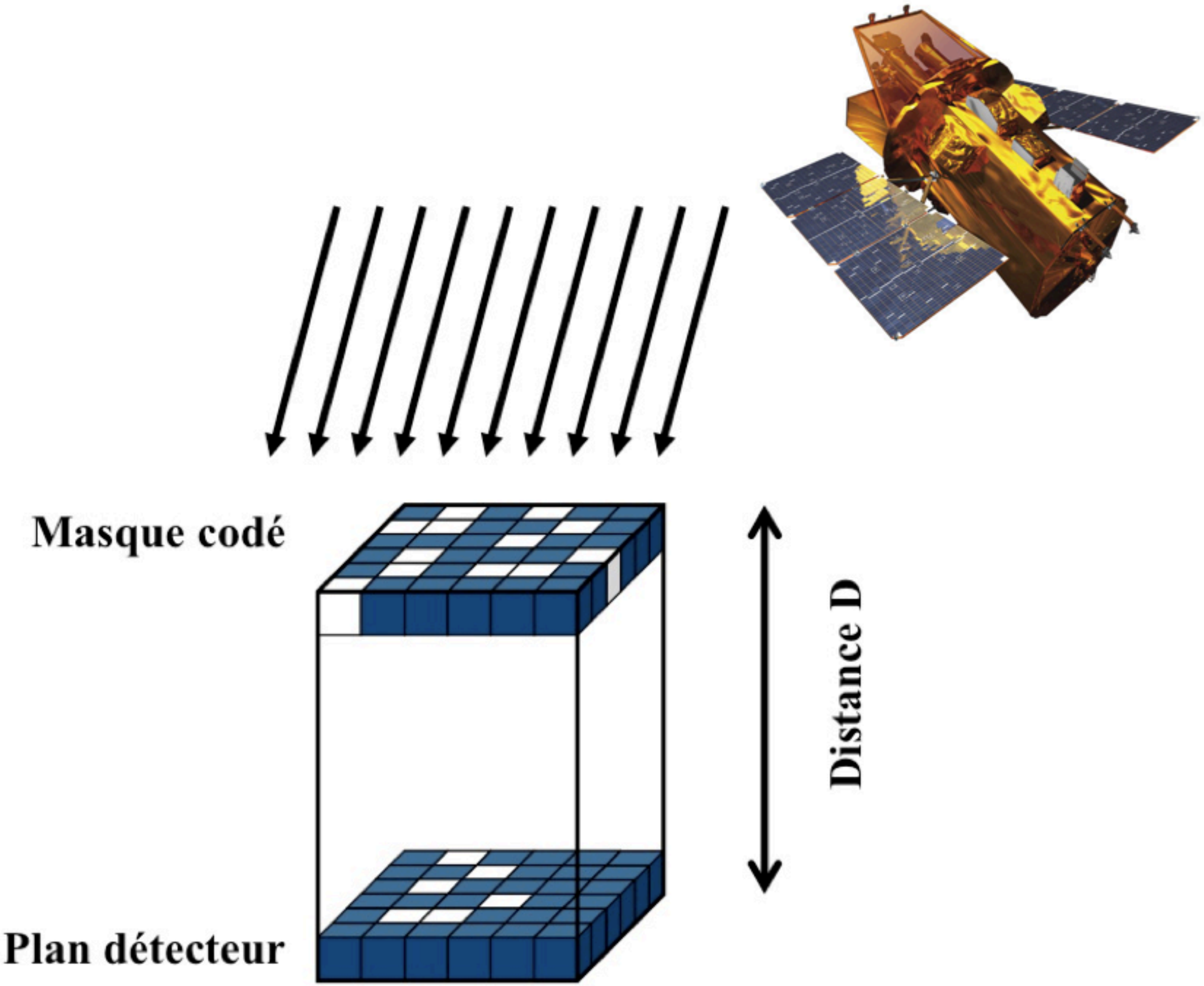


Localization (2) BATSE





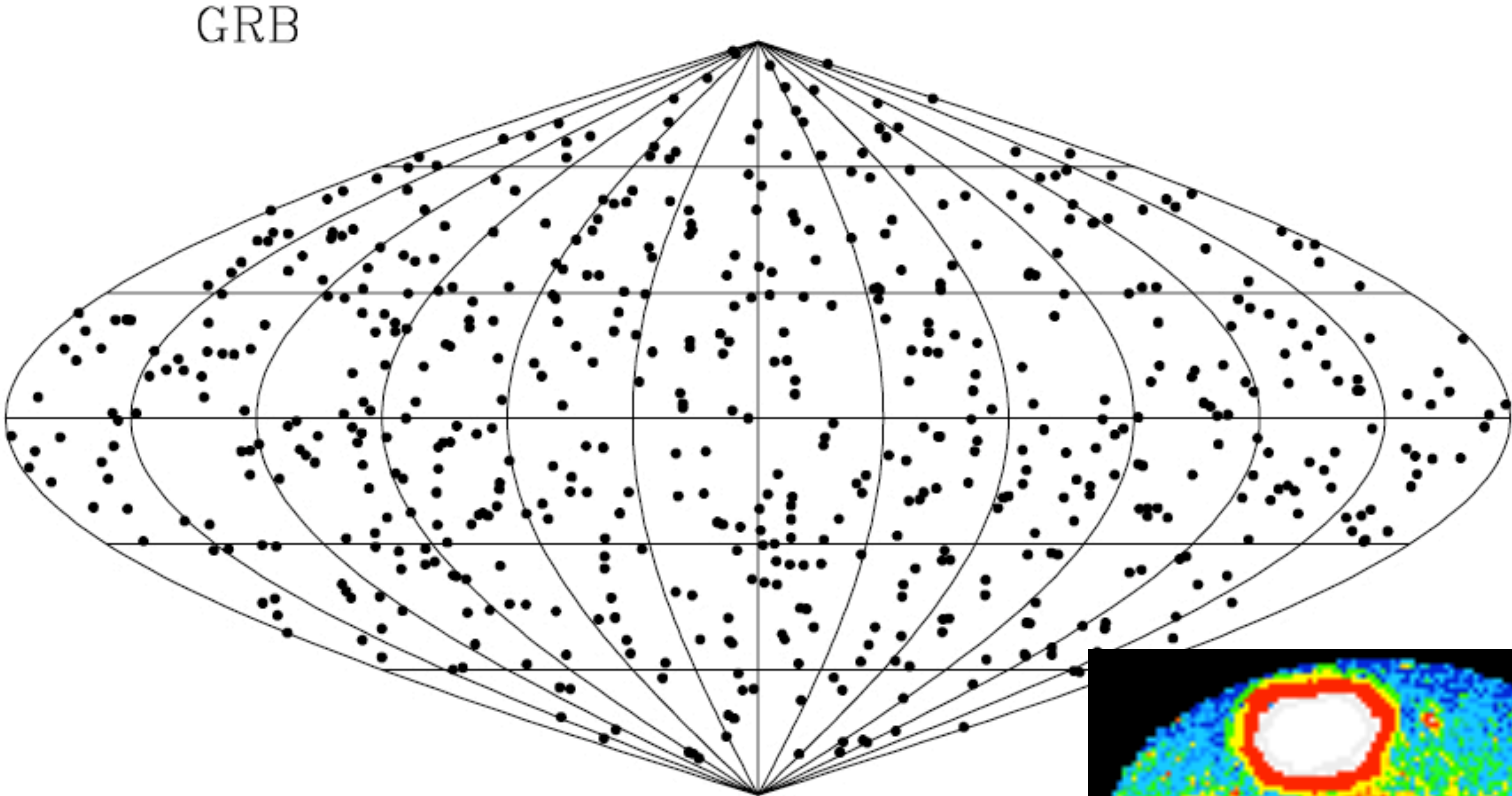
Localization (3) Swift

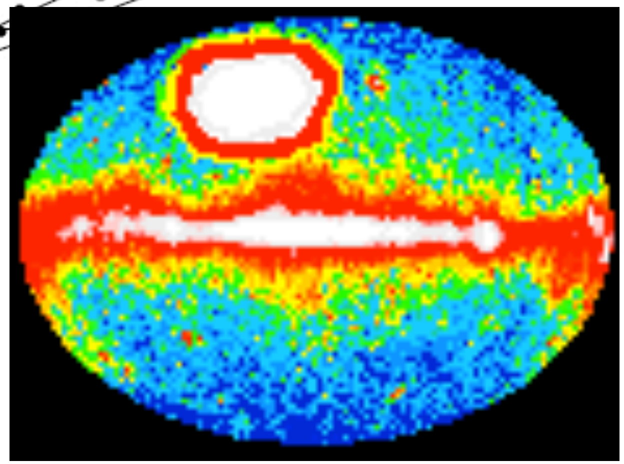


The coded mask of Swift

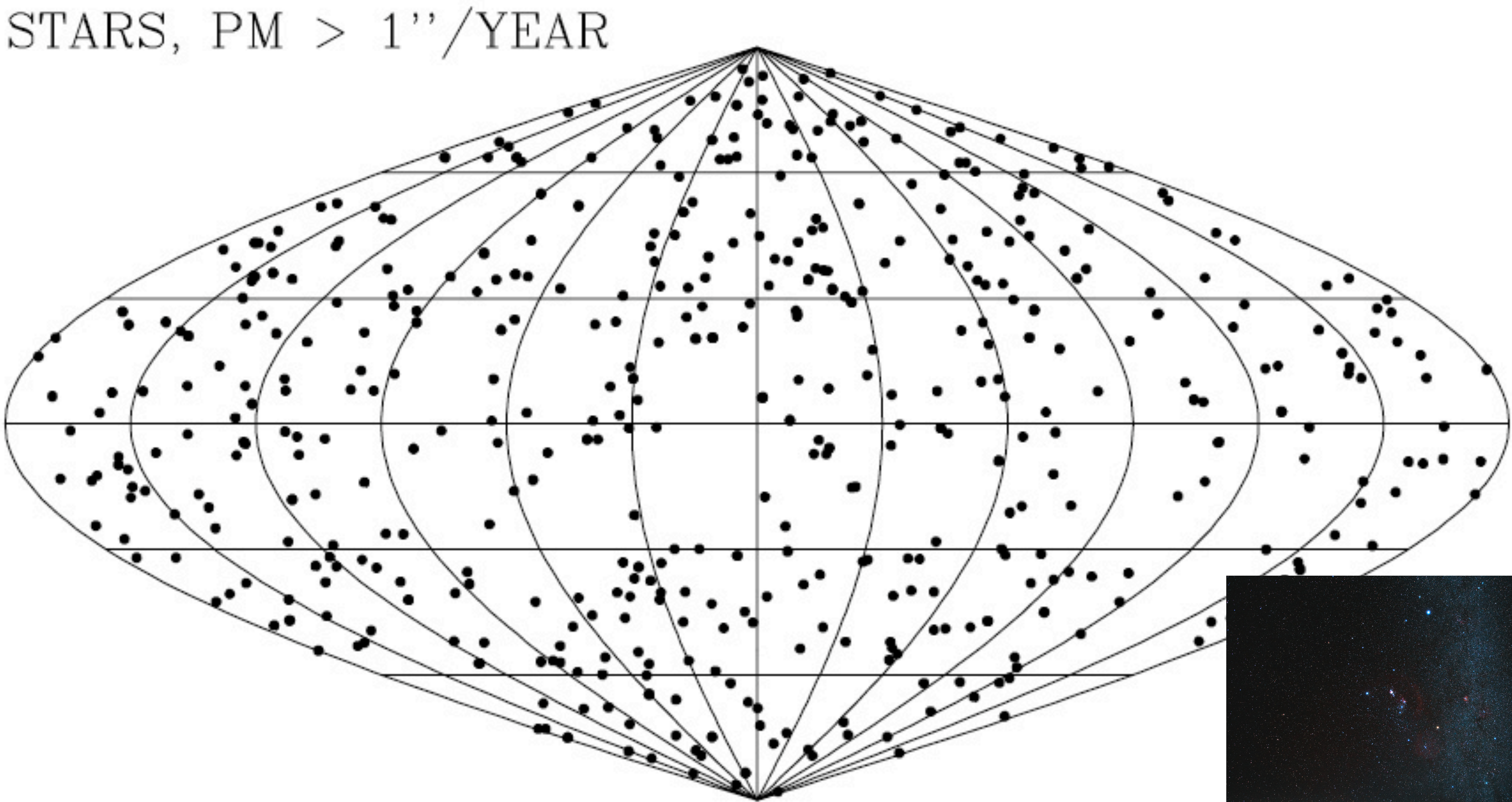
1994 : The Great Debate

GRB sky map (BATSE, 1994)

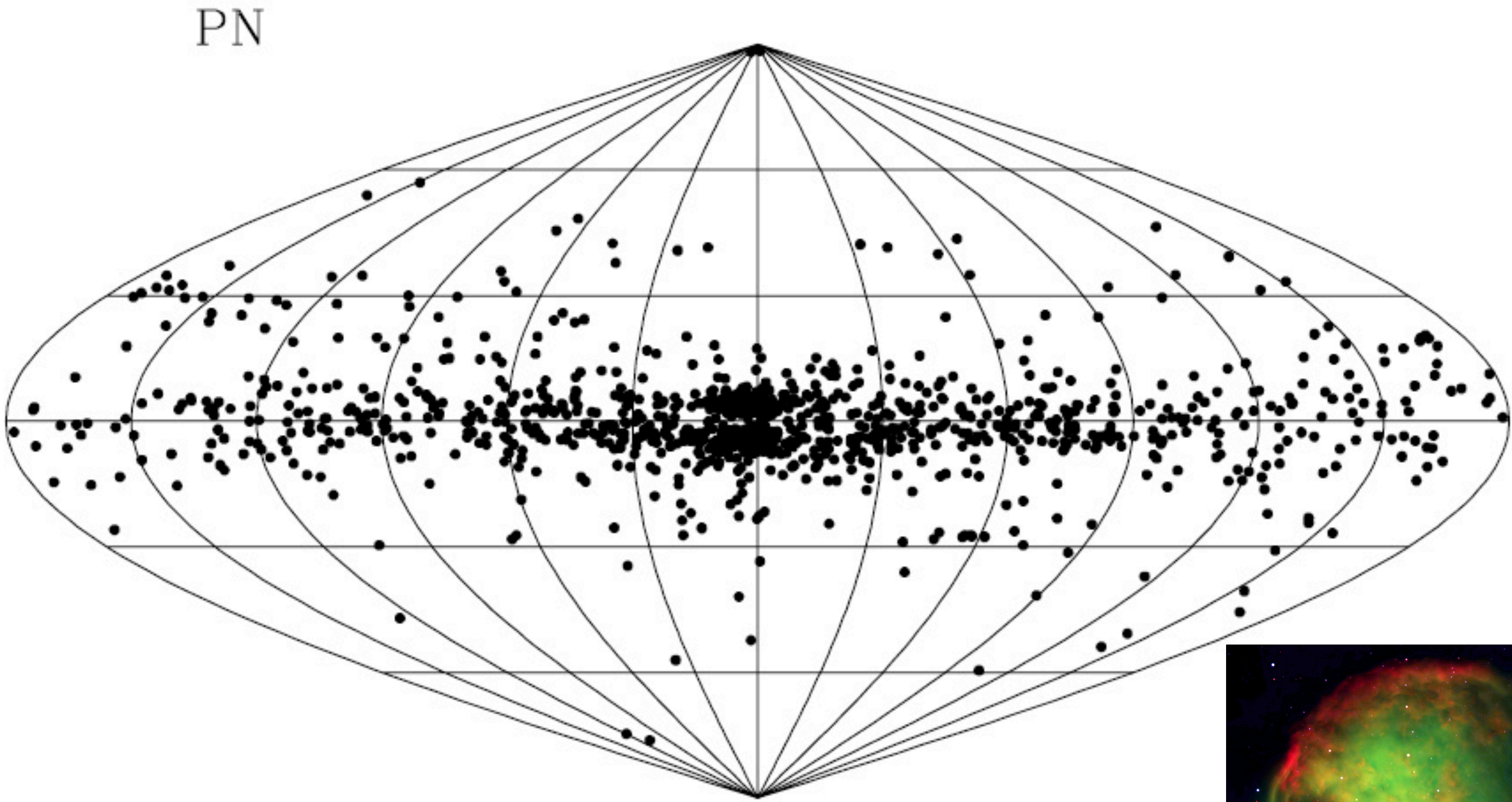


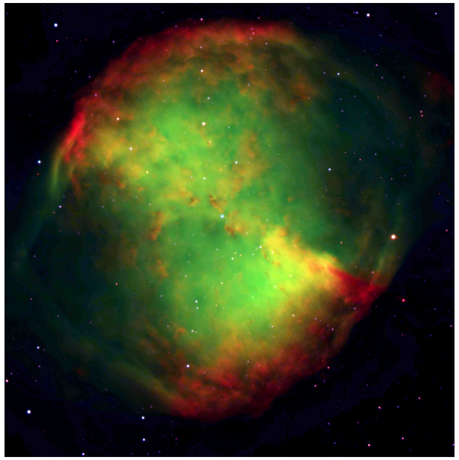


Nearby stars : isotropy + proper motion

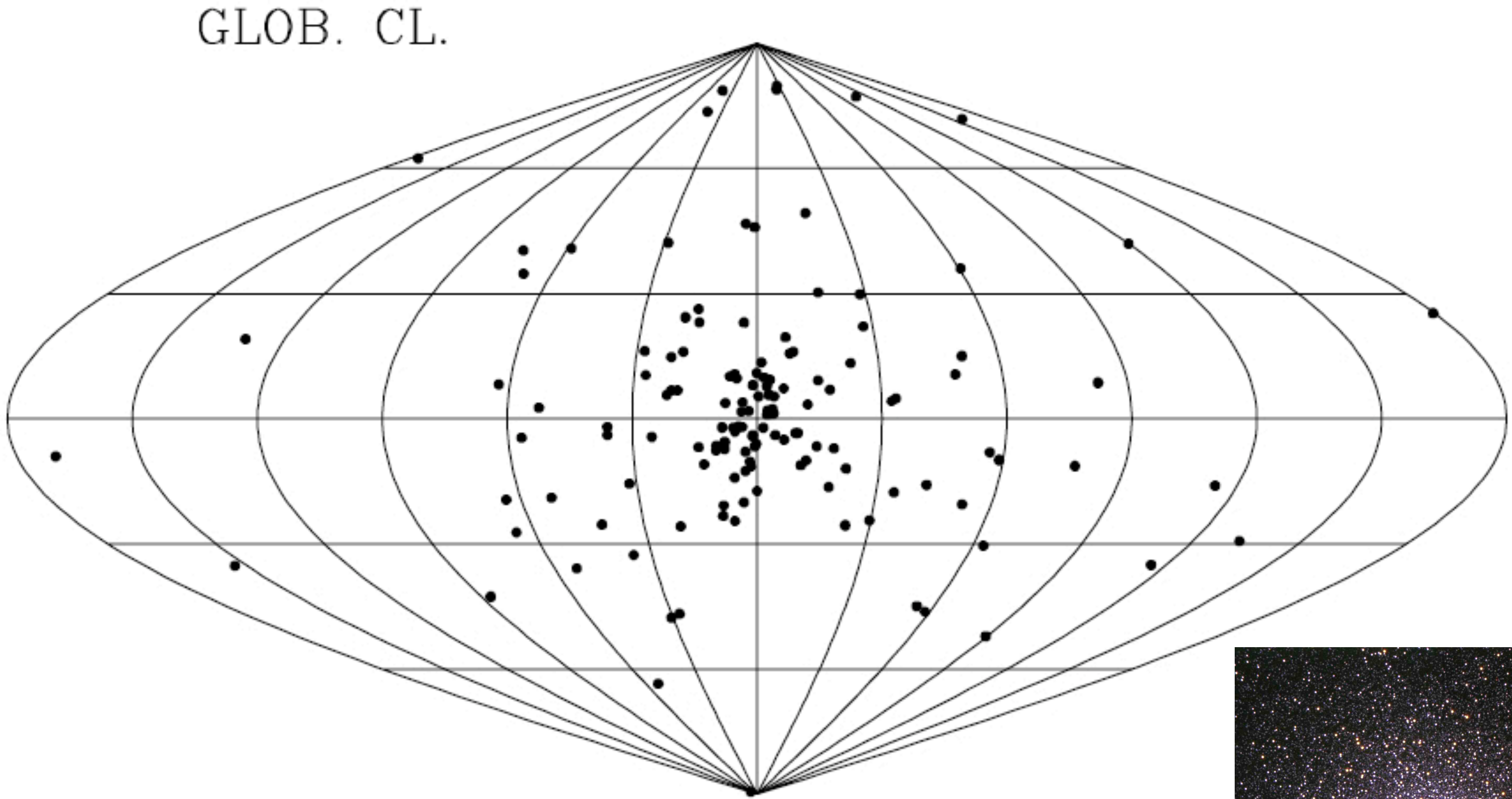


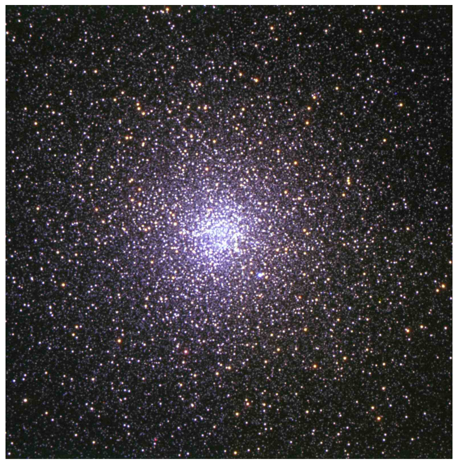
Planetary nebulae : Galactic disk



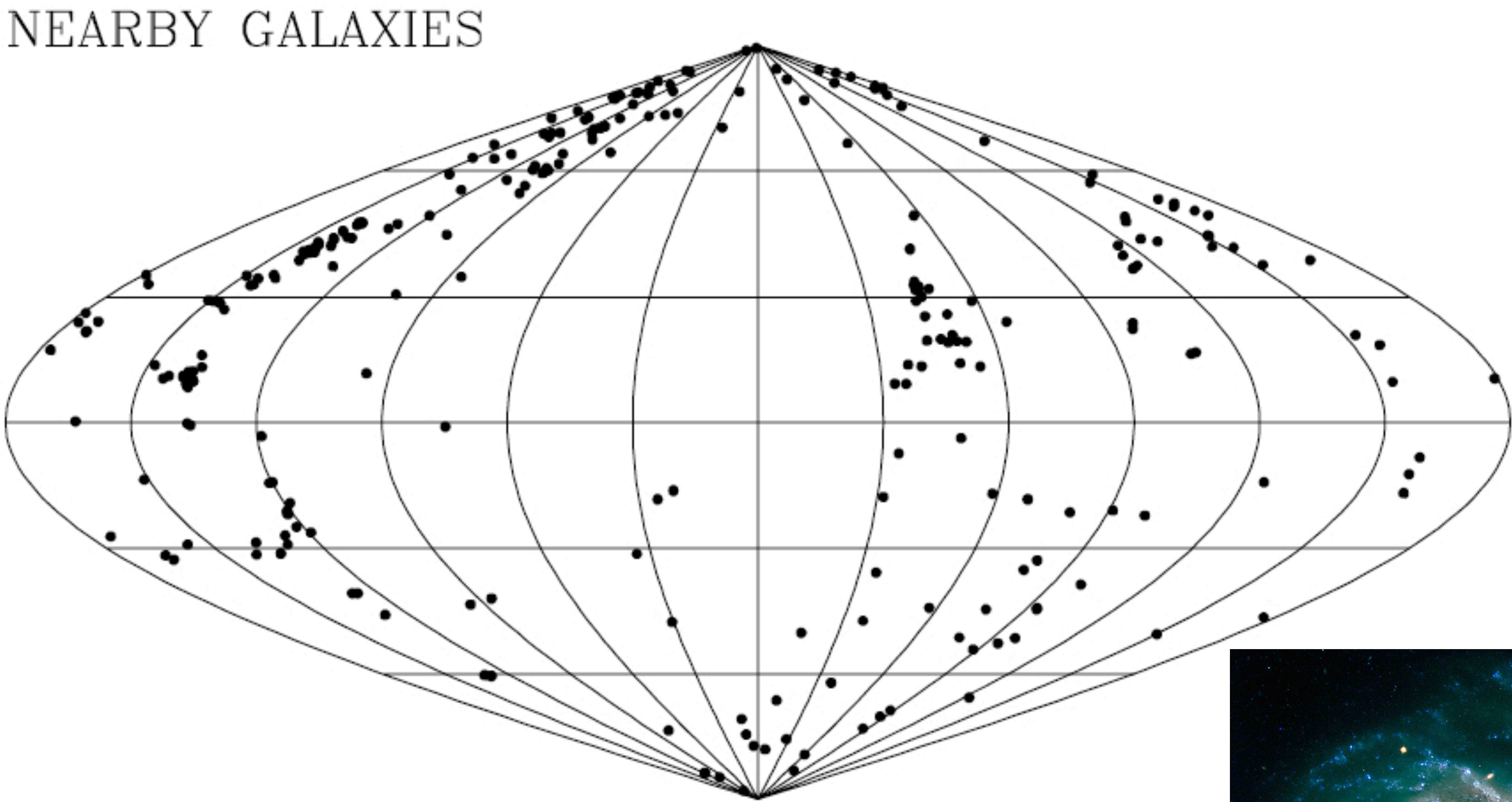


Globular clusters : ~ spherical halo – The Sun is not at the center

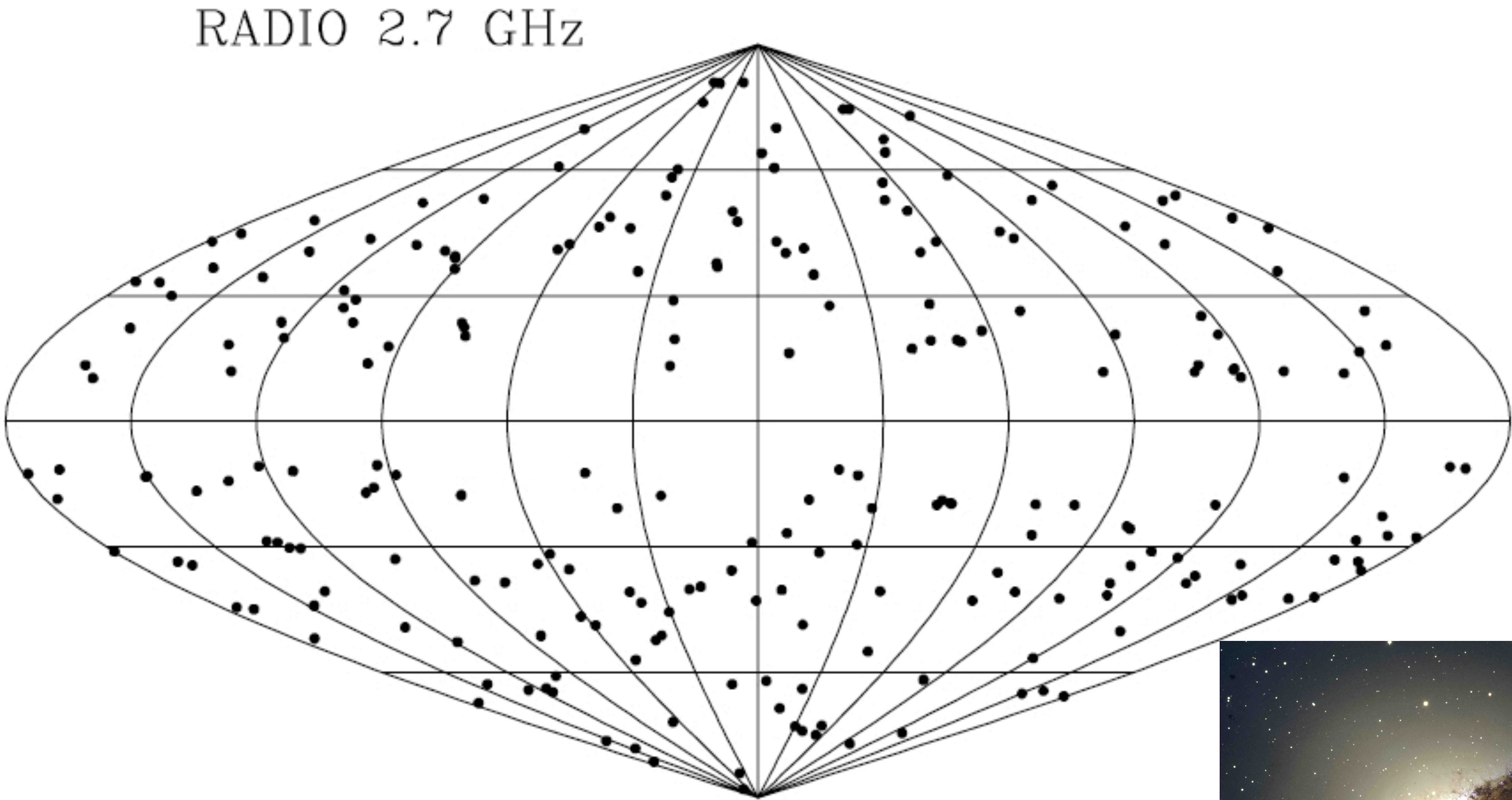


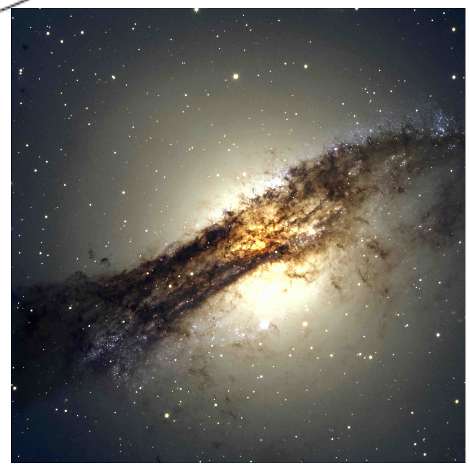


Nearby stars : large structures

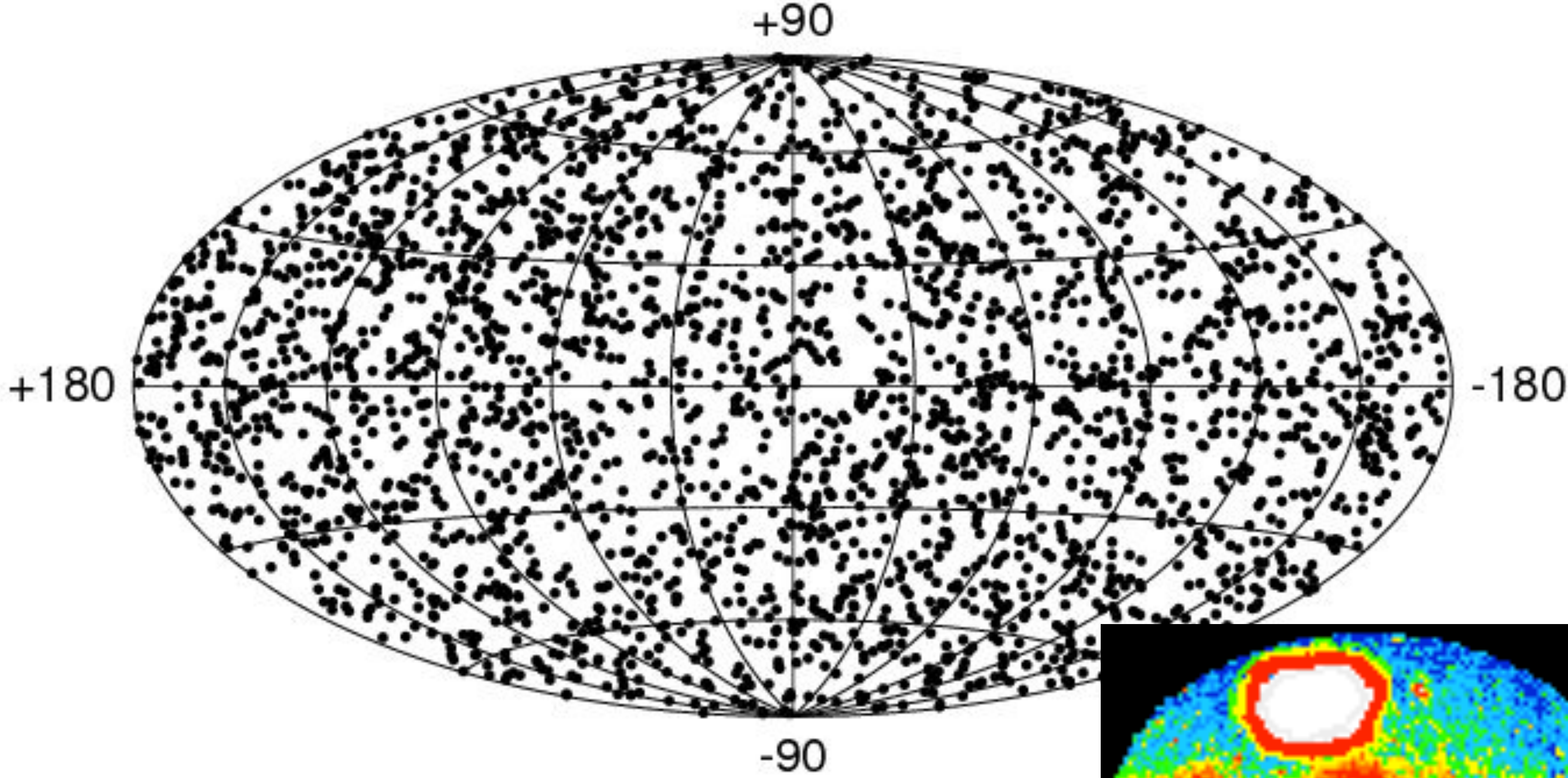


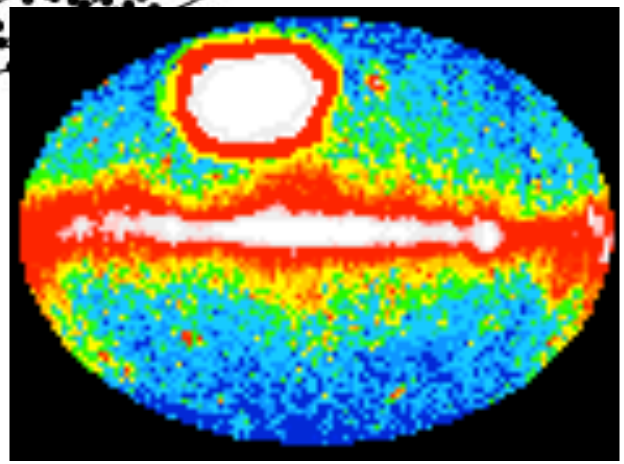
Radio-galaxies : ~ isotropy



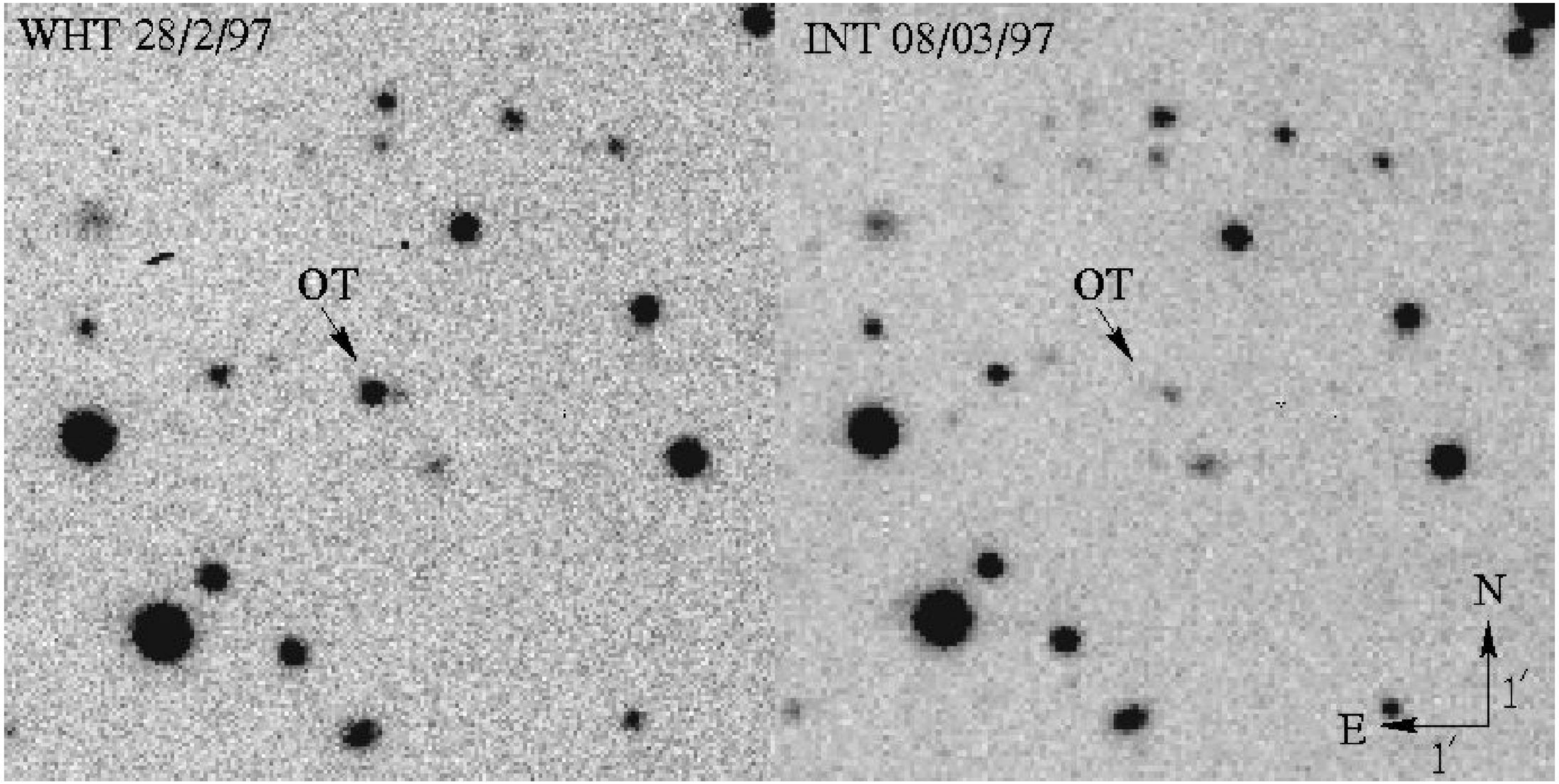


GRB sky map (BATSE final catalog)

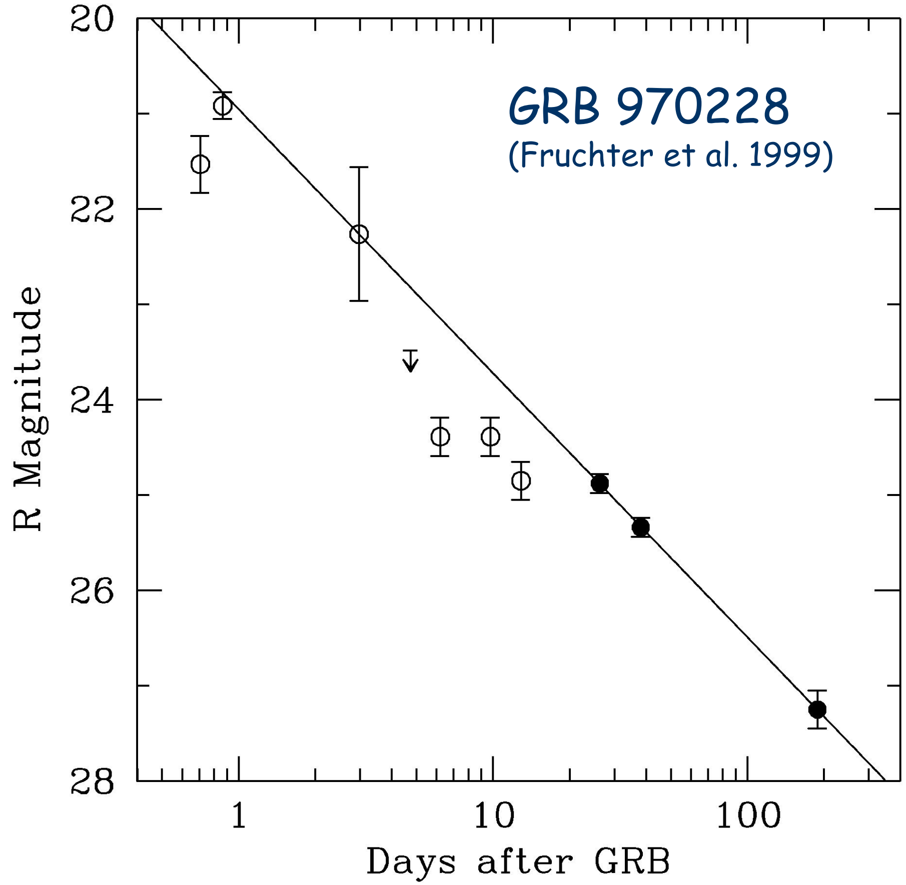




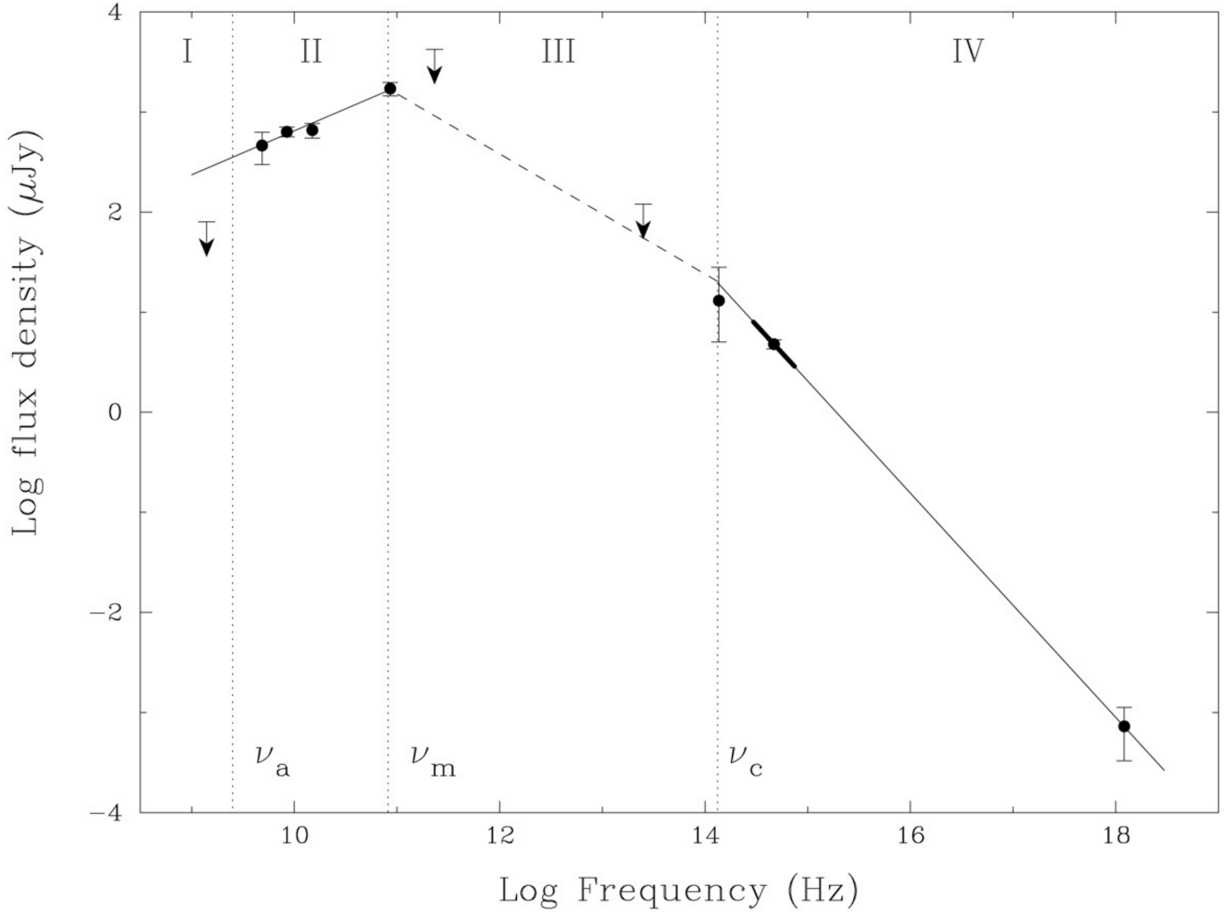
1997 : The first afterglow



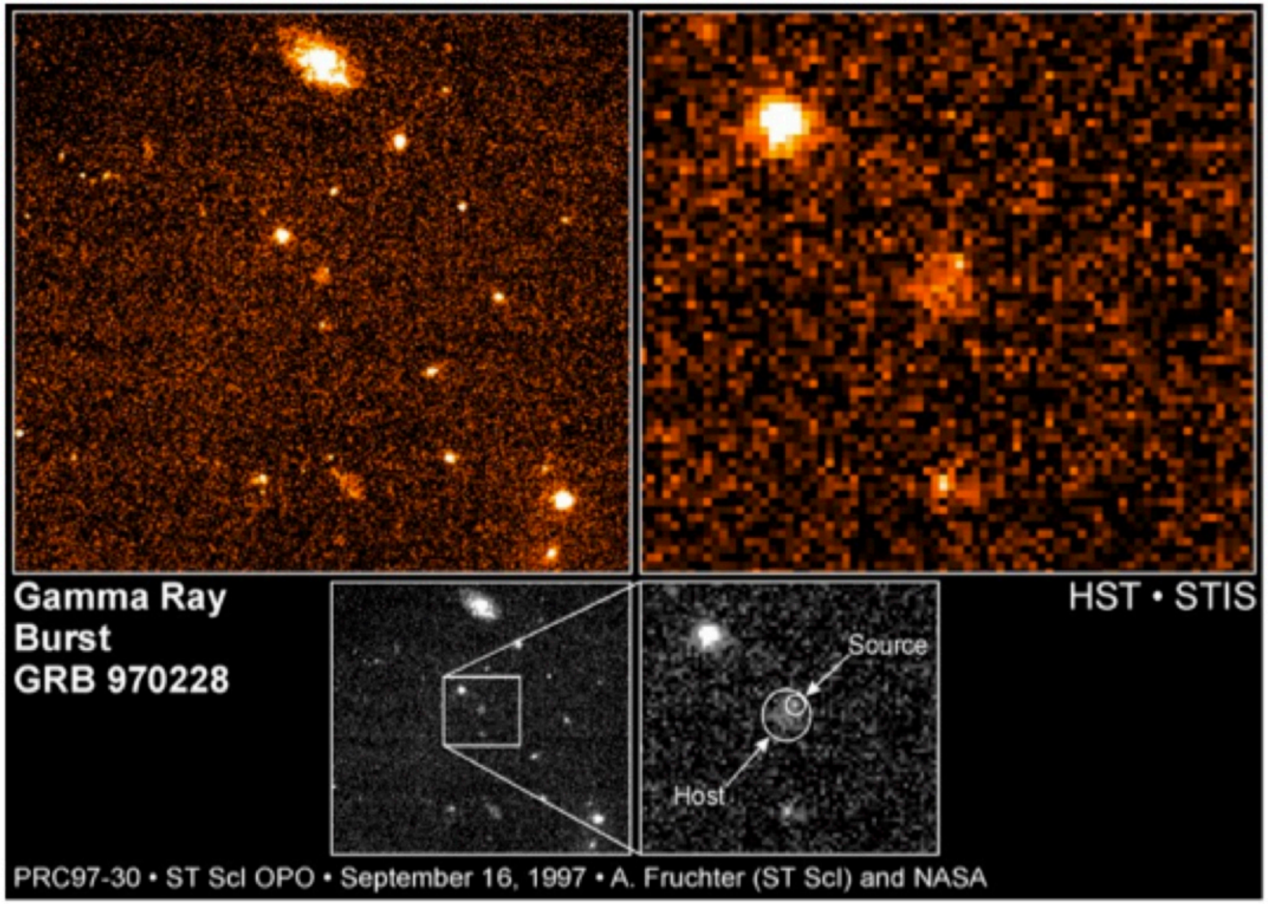
Lightcurve of the first afterglow



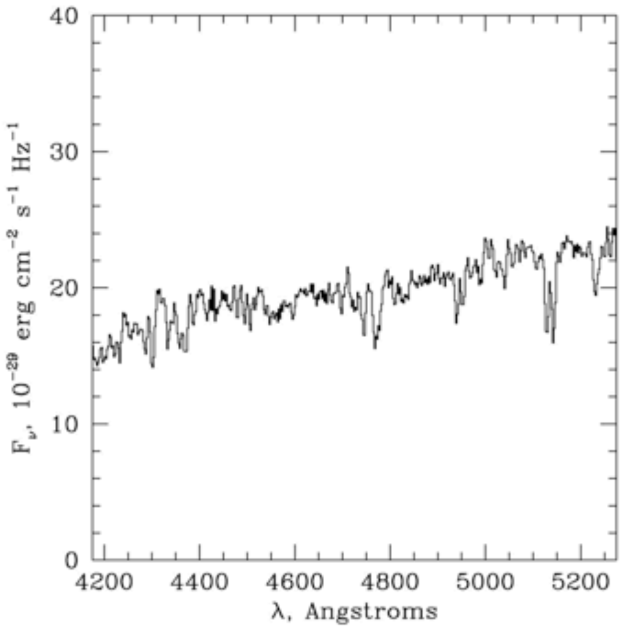
Afterglow spectrum : GRB 970508 (radio to visible)



Afterglows : the host galaxy of GRB 970228



The first spectrum of a GRB optical afterglow : GRB 970508 and its host galaxy (z=0.835)



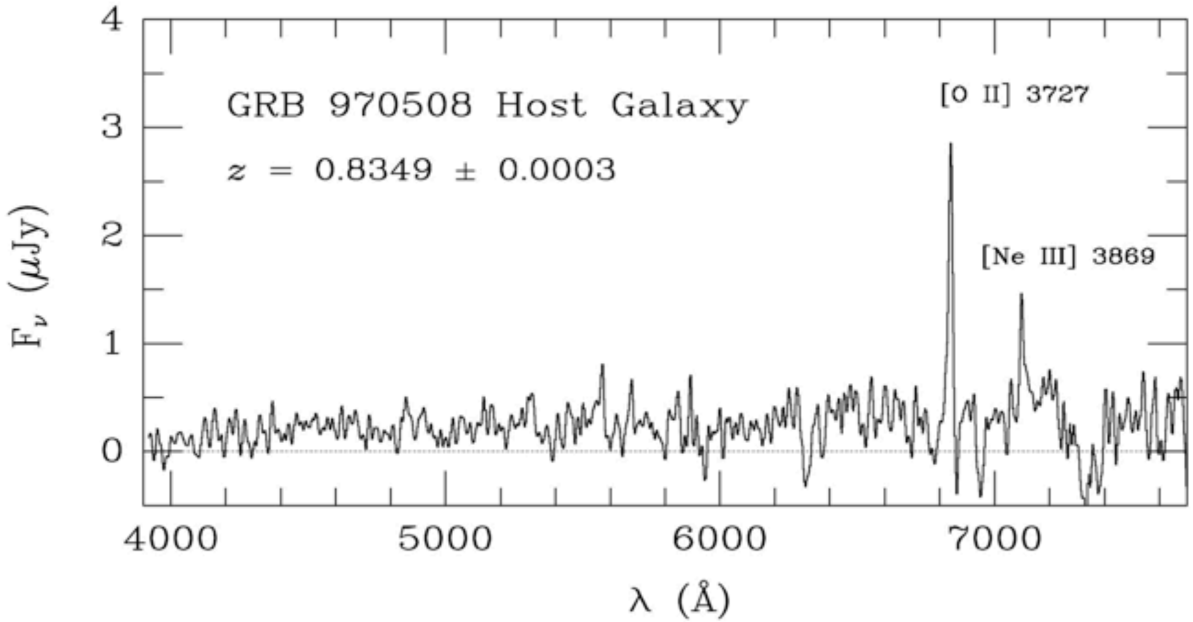
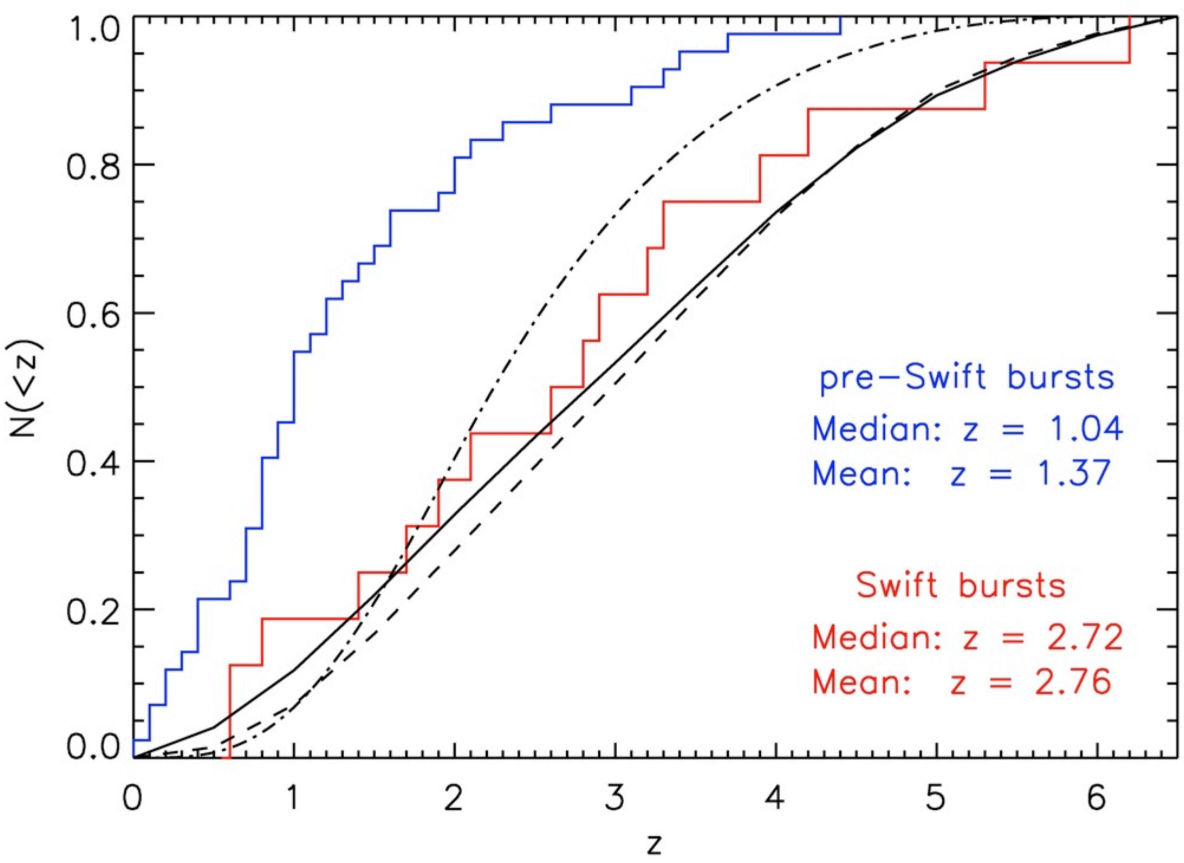


Table 1

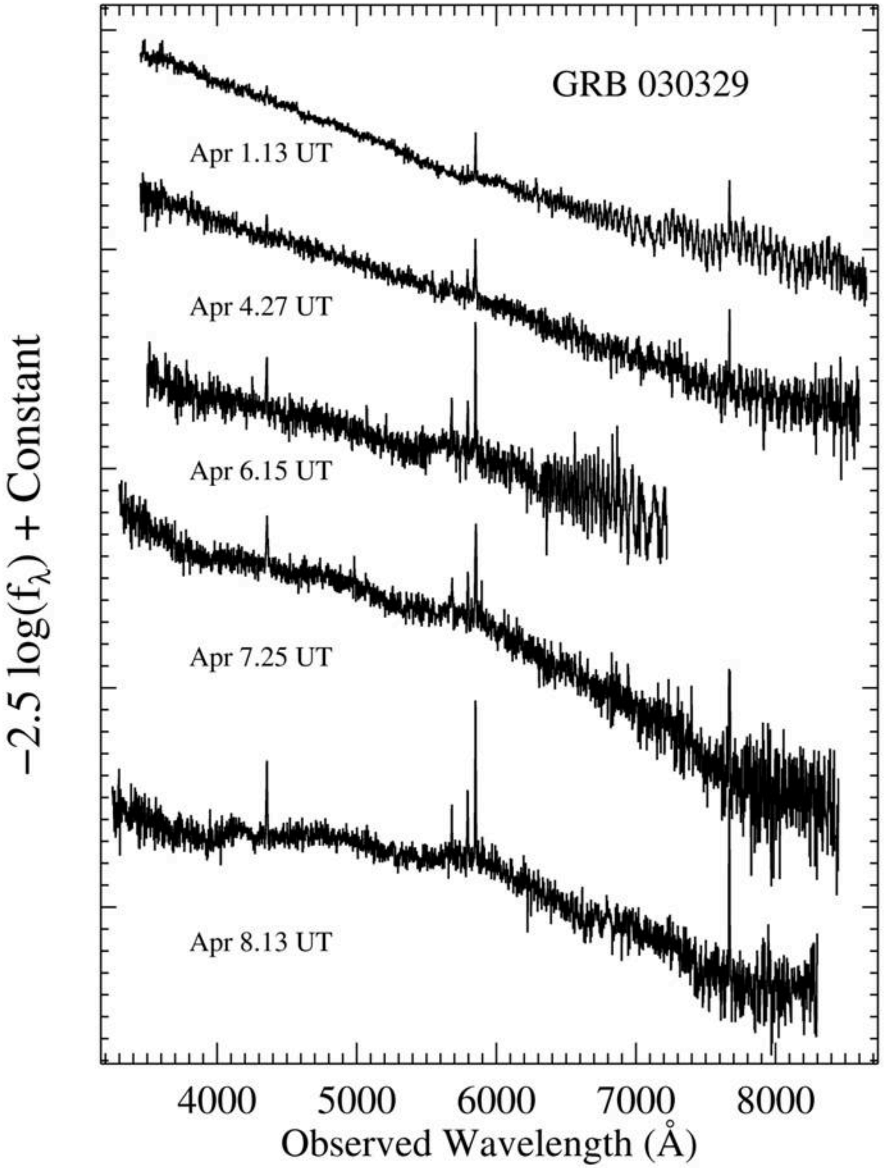
#	Author	Year Pub	Reference	Main Body	2nd Body	Place	Description
1.	Colgate	1968	CJPhys, 46, S476	ST		COS	SN shocks stellar surface in distant galaxy
2.	Colgate	1974	ApJ, 187, 333	ST		COS	Type II SN shock brem, inv Comp scat at stellar surface
3.	Stecker et al.	1973	Nature, 245, PS70	ST		DISK	Stellar superflare from nearby star
4.	Stecker et al.	1973	Nature, 245, PS70	WD		DISK	Superflare from nearby WD
5.	Harwit et al.	1973	ApJ, 186, L37	NS	COM	DISK	Relic comet perturbed to collide with old galactic NS
6.	Lamb et al.	1973	Nature, 246, PS52	WD	ST	DISK	Accretion onto WD from flare in companion
7.	Lamb et al.	1973	Nature, 246, PS52	NS	ST	DISK	Accretion onto NS from flare in companion
8.	Lamb et al.	1973	Nature, 246, PS52	BH	ST	DISK	Accretion onto BH from flare in companion
9.	Zwicky	1974	Ap & SS, 28, 111	NS		HALO	NS chunk contained by external pressure escapes, explodes
10.	Grindlay et al.	1974	ApJ, 187, L93	DG		SOL	Relativistic iron dust grain up-scatters solar radiation
11.	Brecher et al.	1974	ApJ, 187, L97	ST		DISK	Directed stellar flare on nearby star
12.	Schlovskii	1974	SovAstron, 18, 390	WD	COM	DISK	Comet from system's cloud strikes WD
13.	Schlovskii	1974	SovAstron, 18, 390	NS	COM	DISK	Comet from system's cloud strikes NS
14.	Bisnovatyi- et al.	1975	Ap & SS, 35, 23	ST		COS	Absorption of neutrino emission from SN in stellar envelope
15.	Bisnovatyi- et al.	1975	Ap & SS, 35, 23	ST	SN	COS	Thermal emission when small star heated by SN shock wave
16.	Bisnovatyi- et al.	1975	Ap & SS, 35, 23	NS		COS	Ejected matter from NS explodes
17.	Pacini et al.	1974	Nature, 251, 399	NS		DISK	NS crustal starquake glitch; should time coincide with GRB
18.	Narlikar et al.	1974	Nature, 251, 590	WH		COS	White hole emits spectrum that softens with time
19.	Tsygan	1975	A&A, 44, 21	NS		HALO	NS corequake excites vibrations, changing E & B fields
20.	Chanmugam	1974	ApJ, 193, L75	WD		DISK	Convection inside WD with high B field produces flare
21.	Prilutski et al.	1975	Ap & SS, 34, 395	AGN	ST	COS	Collapse of supermassive body in nucleus of active galaxy
22.	Narlikar et al.	1975	Ap & SS, 35, 321	WH		COS	WH excites synchrotron emission, inverse Compton scattering
23.	Piran et al.	1975	Nature, 256, 112	BH		DISK	Inv Comp scat deep in ergosphere of fast rotating, accreting BH
24.	Fabian et al.	1976	Ap & SS, 42, 77	NS		DISK	NS crustquake shocks NS surface
25.	Chanmugam	1976	Ap & SS, 42, 83	WD		DISK	Magnetic WD suffers MHD instabilities, flares
26.	Mullan	1976	ApJ, 208, 199	WD		DISK	Thermal radiation from flare near magnetic WD
27.	Woosley et al.	1976	Nature, 263, 101	NS		DISK	Carbon detonation from accreted matter onto NS
28.	Lamb et al.	1977	ApJ, 217, 197	NS		DISK	Mag grating of accret disk around NS causes sudden accretion
29.	Piran et al.	1977	ApJ, 214, 268	BH		DISK	Instability in accretion onto rapidly rotating BH
30.	Dasgupta	1979	Ap & SS, 63, 517	DG		SOL	Charged intergal rel dust grain enters sol sys, breaks up
31.	Tsygan	1980	A&A, 87, 224	WD		DISK	WD surface nuclear burst causes chromospheric flares
32.	Tsygan	1980	A&A, 87, 224	NS		DISK	NS surface nuclear burst causes chromospheric flares
33.	Ramaty et al.	1981	Ap & SS, 75, 193	NS		DISK	NS vibrations heat atm to pair produce, annihilate, synch cool
34.	Newman et al.	1980	ApJ, 242, 319	NS	AST	DISK	Asteroid from interstellar medium hits NS
35.	Ramaty et al.	1980	Nature, 287, 122	NS		HALO	NS core quake caused by phase transition, vibrations
36.	Howard et al.	1981	ApJ, 249, 302	NS	AST	DISK	Asteroid hits NS, B-field confines mass, creates high temp
37.	Mitrofanov et al.	1981	Ap & SS, 77, 469	NS		DISK	Helium flash cooled by MHD waves in NS outer layers
38.	Colgate et al.	1981	ApJ, 248, 771	NS	AST	DISK	Asteroid hits NS, tidally disrupts, heated, expelled along B lines
39.	van Buren	1981	ApJ, 249, 297	NS	AST	DISK	Asteroid enters NS B field, dragged to surface collision
40.	Kuznetsov	1982	CosRes, 20, 72	MG		SOL	Magnetic reconnection at heliopause
41.	Katz	1982	ApJ, 260, 371	NS		DISK	NS flares from pair plasma confined in NS magnetosphere
42.	Woosley et al.	1982	ApJ, 258, 716	NS		DISK	Magnetic reconnection after NS surface He flash
43.	Fryxell et al.	1982	ApJ, 258, 733	NS		DISK	He fusion runaway on NS B-pole helium lake
44.	Hameury et al.	1982	A&A, 111, 242	NS		DISK	e- capture triggers H flash triggers He flash on NS surface
45.	Mitrofanov et al	1982	MNRAS, 200, 1033	NS		DISK	B induced cyclo res in rad absorp giving rel e-s, inv C scat
46.	Fenimore et al.	1982	Nature, 297, 665	NS		DISK	BB X-rays inv Comp scat by hotter overlying plasma
47.	Lipunov et al.	1982	Ap & SS, 85, 459	NS	ISM	DISK	ISM matter accum at NS magnetopause then suddenly accretes
48.	Baan	1982	ApJ, 261, L71	WD		HALO	Nonexplosive collapse of WD into rotating, cooling NS
49.	Ventura et al.	1983	Nature, 301, 491	NS	ST	DISK	NS accretion from low mass binary companion
50.	Bisnovatyi- et al.	1983	Ap & SS, 89, 447	NS		DISK	Neutron rich elements to NS surface with quake, undergo fission
51.	Bisnovatyi- et al.	1984	SovAstron, 28, 62	NS		DISK	Thermonuclear explosion beneath NS surface
52.	Ellison et al.	1983	A&A, 128, 102	NS		HALO	NS corequake + uneven heating yield SGR pulsations
53.	Hameury et al.	1983	A&A, 128, 369	NS		DISK	B field contains matter on NS cap allowing fusion
54.	Bonazzola et al.	1984	A&A, 136, 89	NS		DISK	NS surface nuc explosion causes small scale B reconnection
55.	Michel	1985	ApJ, 290, 721	NS		DISK	Remnant disk ionization instability causes sudden accretion
56.	Liang	1984	ApJ, 283, L21	NS		DISK	Resonant EM absorp during magnetic flare gives hot sync e-s
57.	Liang et al.	1984	Nature, 310, 121	NS		DISK	NS magnetic fields get twisted, recombine, create flare
58.	Mitrofanov	1984	Ap & SS, 105, 245	NS		DISK	NS magnetosphere excited by starquake
59.	Epstein	1985	ApJ, 291, 822	NS		DISK	Accretion instability between NS and disk
60.	Schlovskii et al.	1985	MNRAS, 212, 545	NS		HALO	Old NS in Galactic halo undergoes starquake
61.	Tsygan	1984	Ap & SS, 106, 199	NS		DISK	Weak B field NS spherically accretes, Comptonizes X-rays
62.	Usov	1984	Ap & SS, 107, 191	NS		DISK	NS flares result of magnetic convective-oscillation instability
63.	Hameury et al.	1985	ApJ, 293, 56	NS		DISK	High Landau e-s beamed along B lines in cold atm of NS
64.	Rappaport et al.	1985	Nature, 314, 242	NS		DISK	NS + low mass stellar companion gives GRB + optical flash
65.	Tremaine et al.	1986	ApJ, 301, 155	NS	COM	DISK	NS tides disrupt comet, debris hits NS next pass
66.	Muslimov et al.	1986	Ap & SS, 120, 27	NS		HALO	Radially oscillating NS
67.	Sturrock	1986	Nature, 321, 47	NS		DISK	Flare in the magnetosphere of NS accelerates e-s along B-field
68.	Paczynski	1986	ApJ, 308, L43	NS		COS	Cosmo GRBs: rel e- e+ opt thk plasma outflow indicated
69.	Bisnovatyi- et al	1986	SovAstron, 30, 582	NS		DISK	Chain fission of superheavy nuclei below NS surface during SN
70.	Alcock et al.	1986	PRL, 57, 2088	SS	SS	DISK	SN ejects strange mat lump craters rotating SS companion
71.	Vahia et al.	1988	A&A, 207, 55	ST		DISK	Magnetically active stellar system gives stellar flare
72.	Babul et al.	1987	ApJ, 316, L49	CS		COS	GRB result of energy released from cusp of cosmic string
73.	Livio et al.	1987	Nature, 327, 398	NS	COM	DISK	Oort cloud around NS can explain soft gamma-repeaters
74.	McBreen et al.	1988	Nature, 332, 234	GAL	AGN	COS	G-wave bkgrd makes BL Lac wiggle across galaxy lens caustic
75.	Curtis	1988	ApJ, 327, L81	WD		COS	WD collapses, burns to form new class of stable particles
76.	Melia	1988	ApJ, 335, 965	NS		DISK	Be/X-ray binary sys evolves to NS accretion GRB with recurrence
77.	Ruderman et al.	1988	ApJ, 335, 306	NS		DISK	e+ e- cascades by aligned pulsar outer-mag-sphere reignition
78.	Paczynski	1988	ApJ, 335, 525	CS		COS	Energy released from cusp of cosmic string (revised)
79.	Murikami et al.	1988	Nature, 335, 234	NS		DISK	Absorption features suggest separate colder region near NS
80.	Melia	1988	Nature, 336, 658	NS		DISK	NS + accretion disk reflection explains GRB spectra
81.	Blaes et al.	1989	ApJ, 343, 839	NS		DISK	NS seismic waves couple to magnetospheric Alfen waves
82.	Trofimenko et al.	1989	Ap & SS, 152, 105	WH		COS	Kerr-Newman white holes
83.	Sturrock et al.	1989	ApJ, 346, 950	NS		DISK	NS E-field accelerates electrons which then pair cascade
84.	Fenimore et al.	1988	ApJ, 335, L71	NS		DISK	Narrow absorption features indicate small cold area on NS
85.	Rodrigues	1989	AJ, 98, 2280	WD	WD	DISK	Binary member loses part of crust, through L1, hits primary
86.	Pineault et al.	1989	ApJ, 347, 1141	NS	COM	DISK	Fast NS wanders through Oort clouds, fast WD bursts only optical
87.	Melia et al.	1989	ApJ, 346, 378	NS		DISK	Episodic electrostatic accel and Comp scat from rot high-B NS
88.	Trofimenko	1989	Ap & SS, 159, 301	WH		COS	Different types of white, "grey" holes can emit GRBs
89.	Eichler et al.	1989	Nature, 340, 126	NS	NS	COS	NS - NS binary members collide, coalesce
90.	Wang et al.	1989	PRL, 63, 1550	NS		DISK	Cyclo res & Raman scat fits 20, 40 keV dips, magnetized NS
91.	Alexander et al.	1989	ApJ, 344, L1	NS		DISK	QED mag resonant opacity in NS atmosphere
92.	Melia	1990	ApJ, 351, 601	NS		DISK	NS magnetospheric plasma oscillations
93.	Ho et al.	1990	ApJ, 348, L25	NS		DISK	Beaming of radiation necessary from magnetized neutron stars
94.	Mitrofanov et al.	1990	Ap & SS, 165, 137	NS	COM	DISK	Interstellar comets pass through dead pulsar's magnetosphere
95.	Dermer	1990	ApJ, 360, 197	NS		DISK	Compton scattering in strong NS magnetic field
96.	Blaes et al.	1990	ApJ, 363, 612	NS	ISM	DISK	Old NS accretes from ISM, surface goes nuclear
97.	Paczynski	1990	ApJ, 363, 218	NS	NS	COS	NS-NS collision causes neutrino collisions, drives super-Ed wind
98.	Zdziarski et al.	1991	ApJ, 366, 343	RE	MBR	COS	Scattering of microwave background photons by rel e-s
99.	Pineault	1990	Nature, 345, 233	NS	COM	DISK	Young NS drifts through its own Oort cloud
100.	Trofimenko et al.	1991	Ap & SS, 178, 217	WH		HALO	White hole supernova gave simultaneous burst of g-waves from 1987A
101.	Melia et al.	1991	ApJ, 373, 198	NS		DISK	NS B-field undergoes resistive tearing, accelerates plasma
102.	Holcomb et al.	1991	ApJ, 378, 682	NS		DISK	Alfen waves in non-uniform NS atmosphere accelerate particles
103.	Haensel et al.	1991	ApJ, 375, 209	SS	SS	COS	Strange stars emit binding energy in grav rad and collide
104.	Blaes et al.	1991	ApJ, 381, 210	NS	ISM	DISK	Slow interstellar accretion onto NS, e- capture starquakes result
105.	Frank et al.	1992	ApJ, 385, L45	NS		DISK	Low mass X-ray binary evolve into GRB sites
106.	Woosley et al.	1992	ApJ, 391, 228	NS		HALO	Accreting WD collapses to NS
107.	Dar et al.	1992	ApJ, 388, 164	WD		COS	WD accretes to form naked NS, GRB, cosmic rays
108.	Hanami	1992	ApJ, 389, L71	NS	PLAN	COS	NS - planet magnetospheric interaction unstable
109.	Meszaros et al.	1992	ApJ, 397, 570	NS	NS	COS	NS - NS collision produces anisotropic fireball
110.	Carter	1992	ApJ, 391, L67	BH	ST	COS	Normal stars tidally disrupted by galactic nucleus BH
111.	Usov	1992	Nature, 357, 472	NS		COS	WD collapses to form NS, B-field brakes NS rotation instantly
112.	Narayan et al.	1992	ApJ, 395, L83	NS	NS	COS	NS - NS merger gives optically thick fireball
113.	Narayan et al.	1992	ApJ, 395, L83	BH	NS	COS	BH - NS merger gives optically thick fireball
114.	Brainerd	1992	ApJ, 394, L33	AGN	JET	COS	Synchrotron emission from AGN jets
115.	Meszaros et al.	1992	MNRAS, 257, 29P	BH	NS	COS	BH-NS have neutrinos collide to gammas in clean fireball
116.	Meszaros et al.	1992	MNRAS, 257, 29P	NS	NS	COS	NS-NS have neutrinos collide to gammas in clean fireball
117.	Cline et al.	1992	ApJ, 401, L57	BH		DISK	Primordial BHs evaporating could account for short hard GRBs
118.	Rees et al.	1992	MNRAS, 258, 41P	NS	ISM	COS	Relativistic fireball reconverted to radiation when hits ISM

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

Redshift distribution



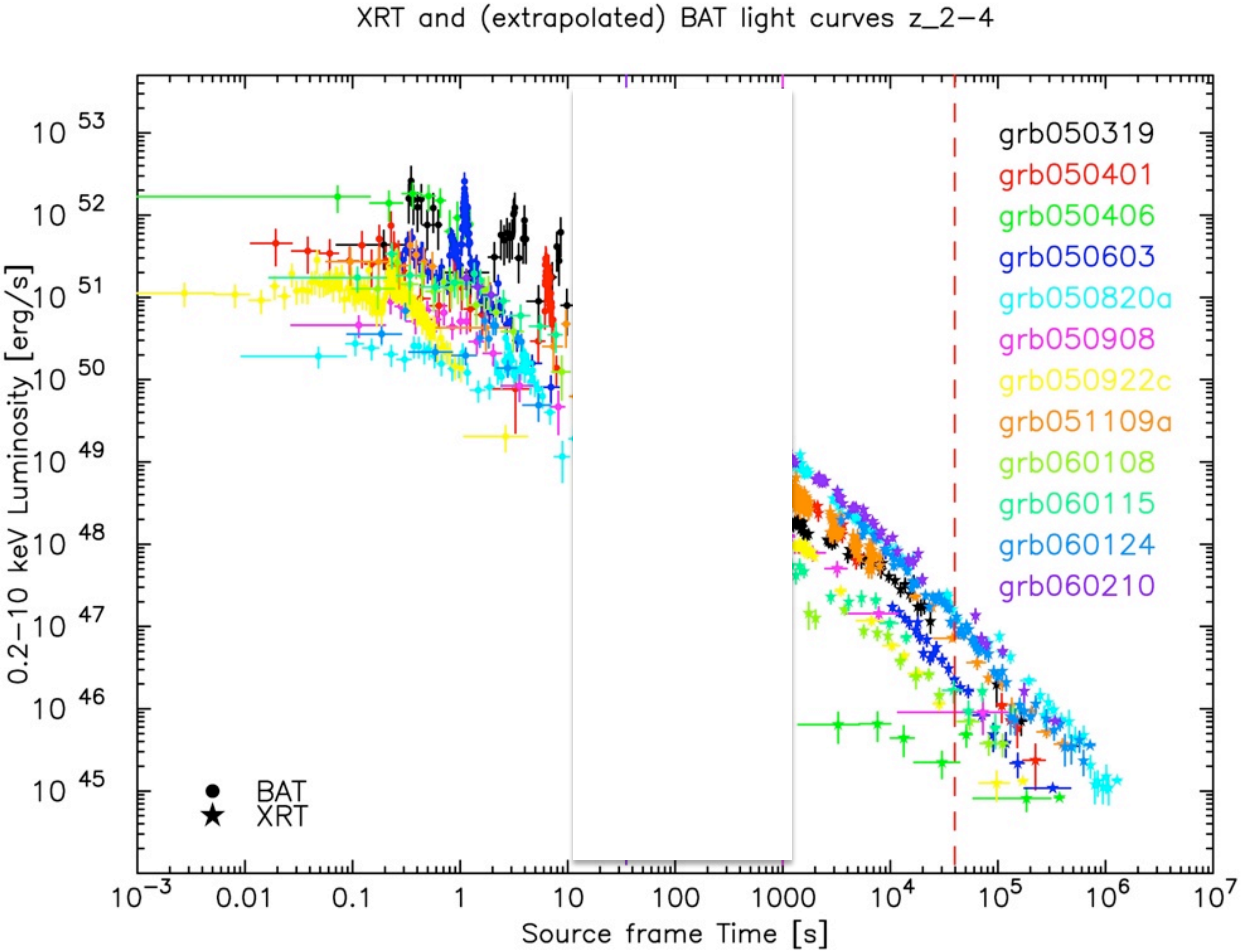
Association of long GRBs with massive stars :
the case of GRB 030329 (HETE2)



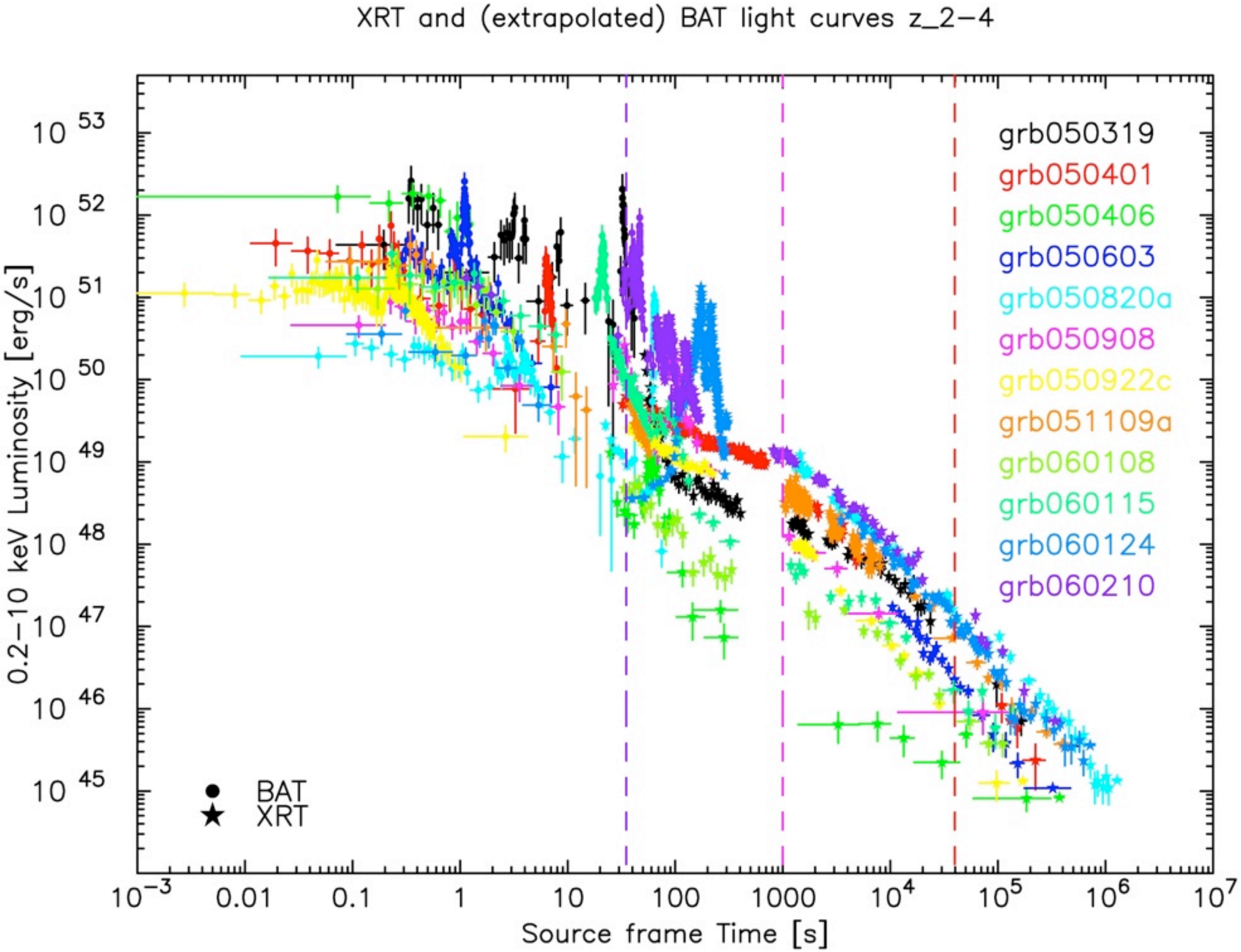
Quelques observations récentes :

Swift puis Fermi viennent compliquer la situation…

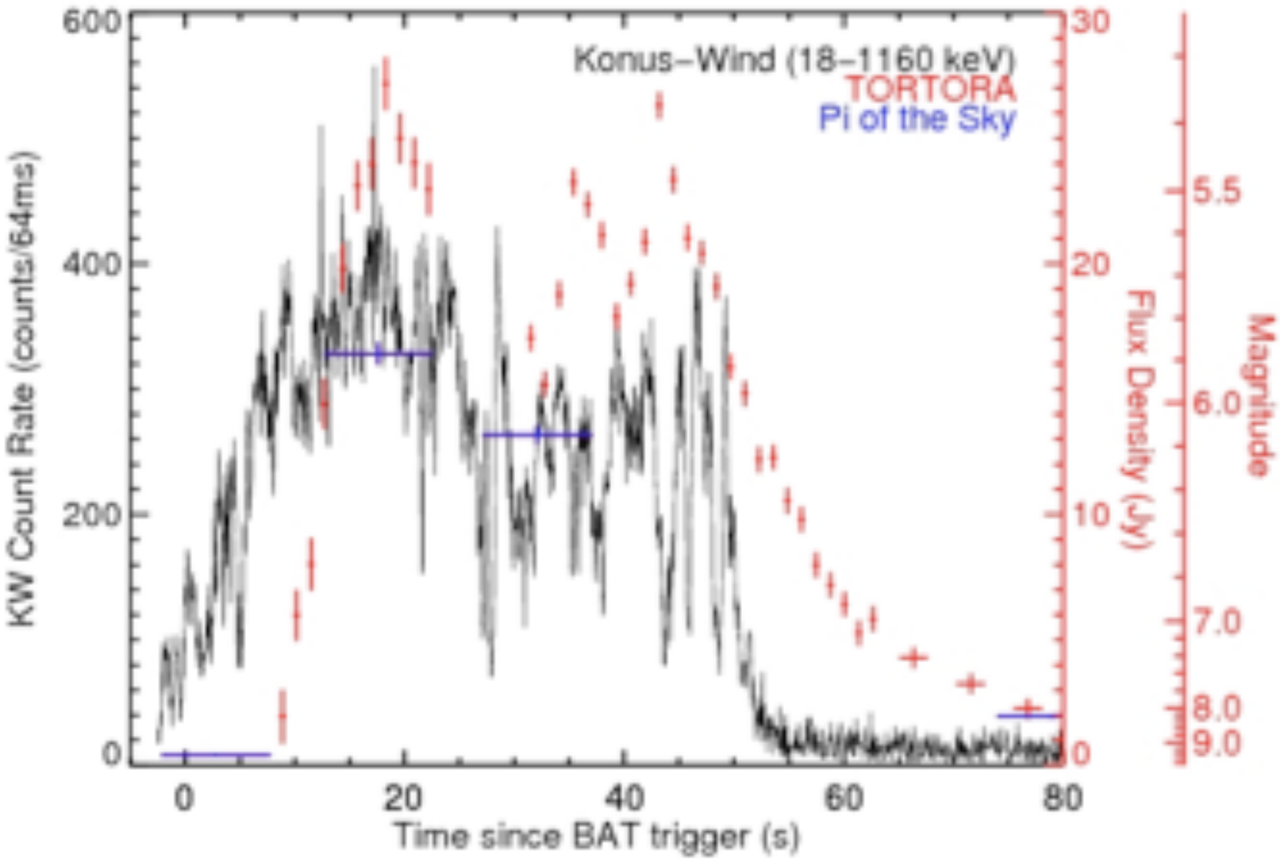
Swift: les rémanences ne sont plus ce qu'elles étaient.



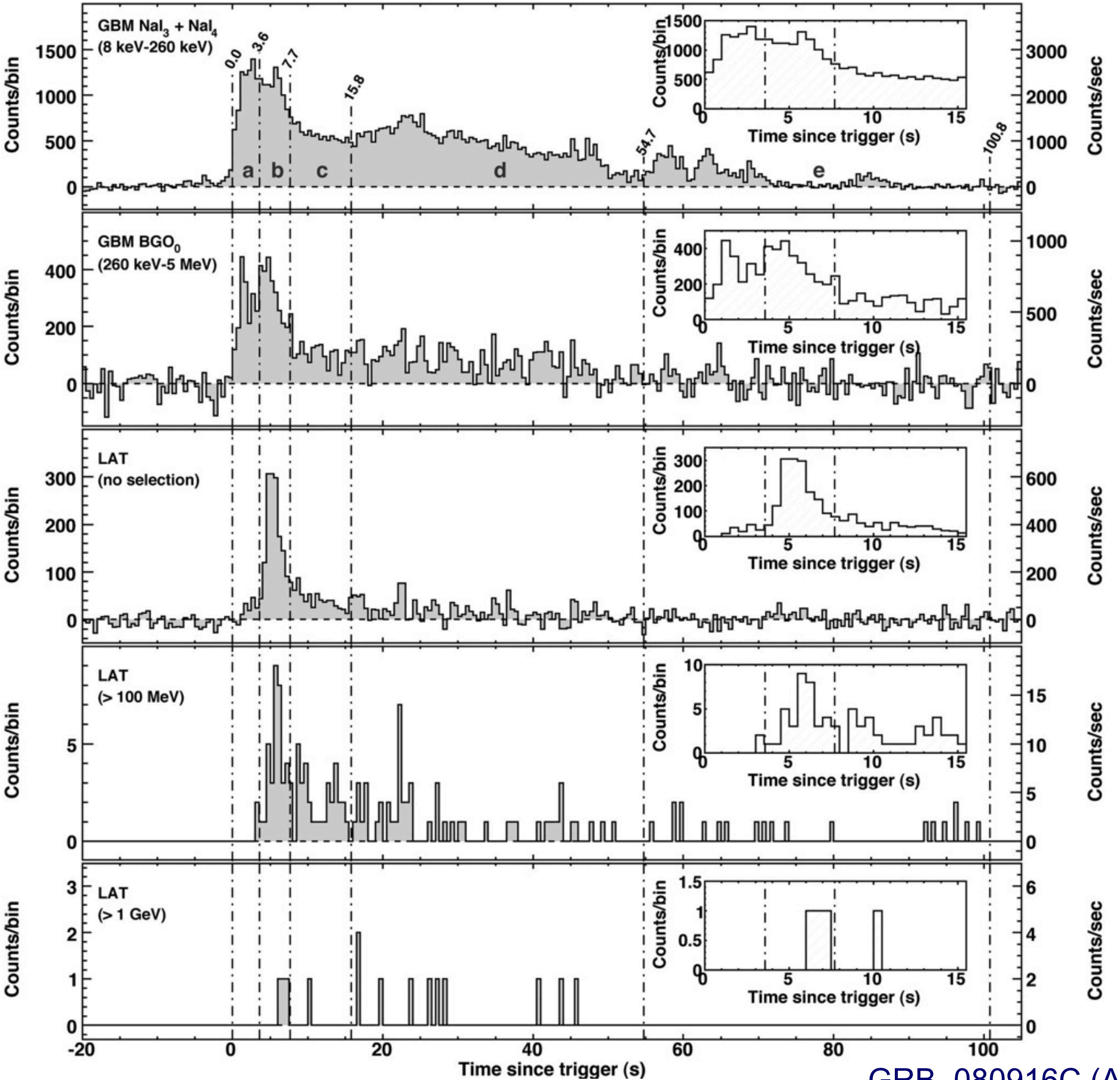
Swift: les rémanences ne sont plus ce qu'elles étaient.



Un cas extrême d’émission « prompte » dans le visible :
the naked eye burst



Fermi-LAT détecte des « monstres » jusqu'au GeV



GRB 080916C (Abdo et al. 2009)

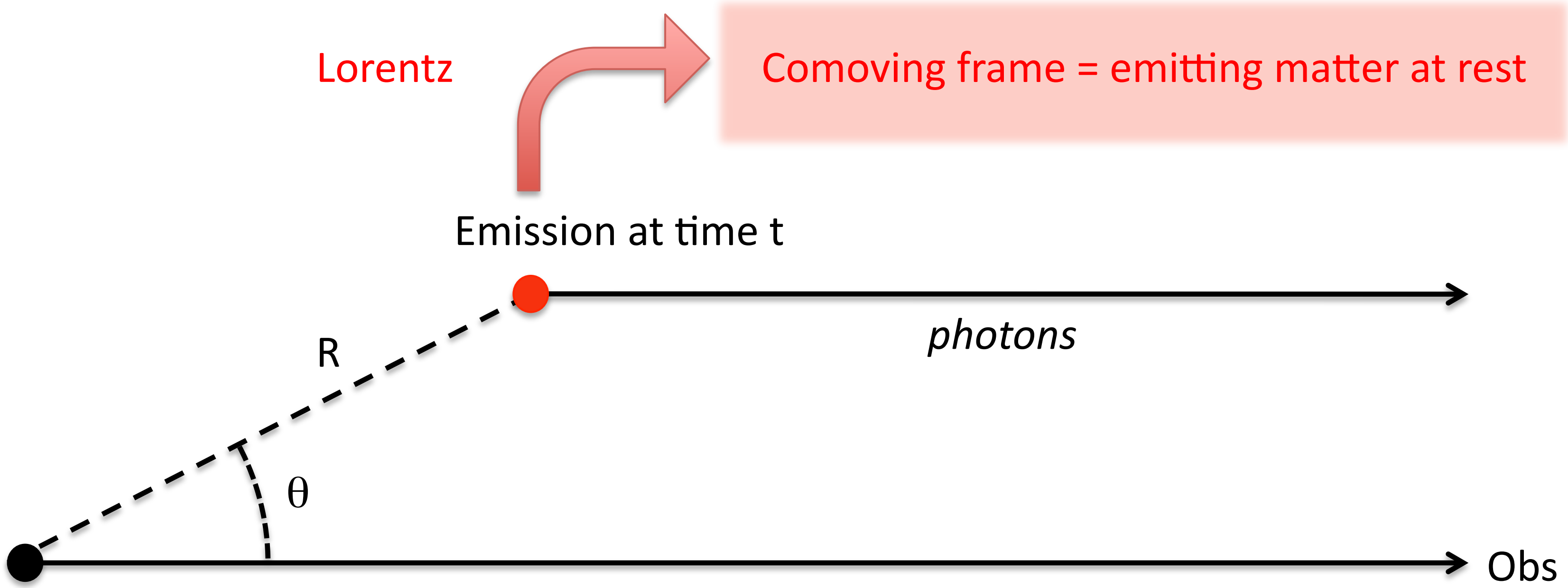
Construire un modèle physique

des sursauts gamma

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

General framework : *the different observed phases 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.*

Hopefully, the evolution of the relativistic jet can be understood without knowing the details of the central engine (central source + acceleration mechanism).



Central source
Source frame (or fixed frame or lab frame) : source at rest

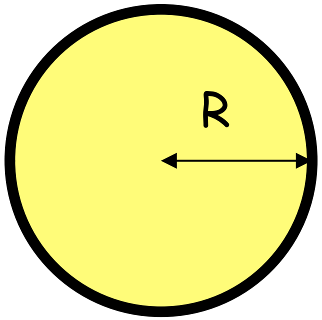
Light propagation
+ Cosmology

Observer frame :

Reception at time
$t_{obs} / (1+z) = t - (R/c)\cos\theta$

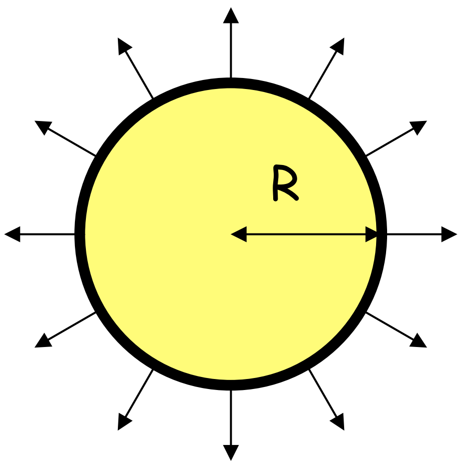
Using the convention

$(t=0 ; R=0) \rightarrow t_{obs} = 0$



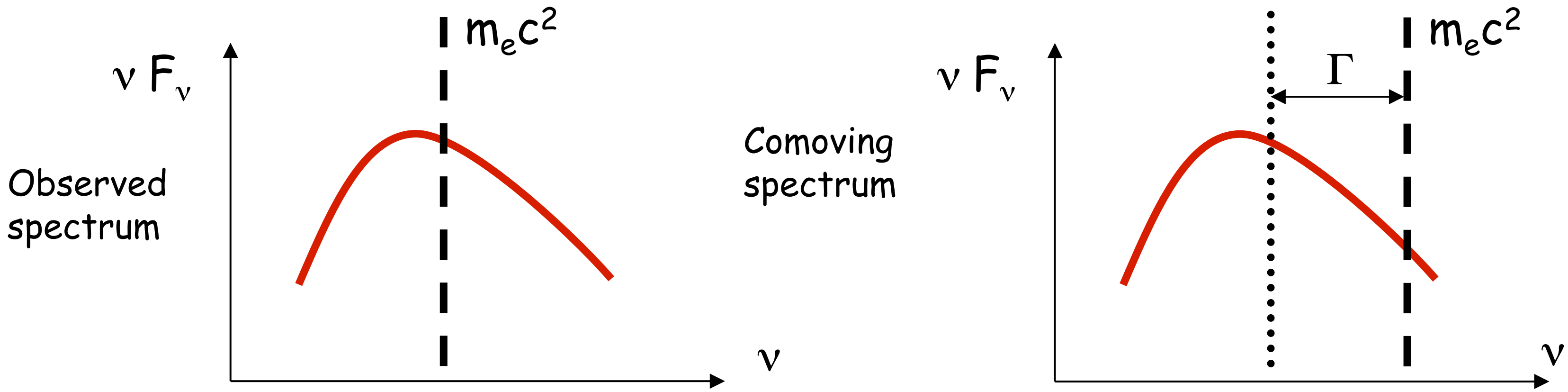
Source size : $R \leq c\, t_{var}$

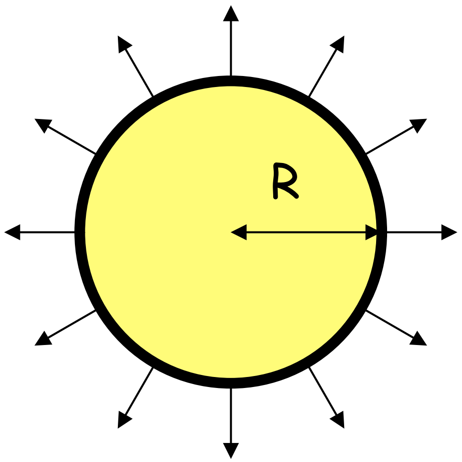
Opacity $\tau_{\gamma\gamma} \rightarrow e^+e^-$: $\tau_{\gamma\gamma}$ is very large



Expanding source : Lorentz factor Γ

(i) in the comoving frame of the emitting material, the photon energy is divided by Γ, therefore less photons are above the threshold for pair creation.

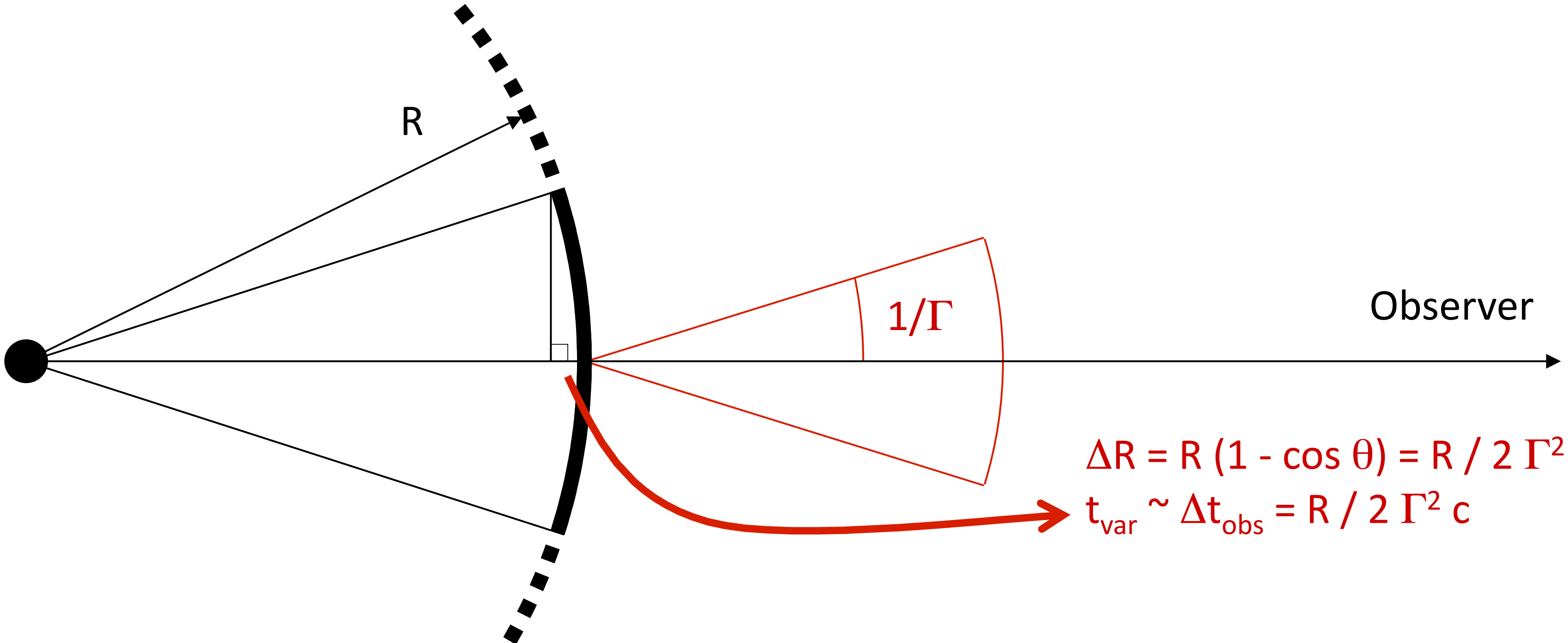


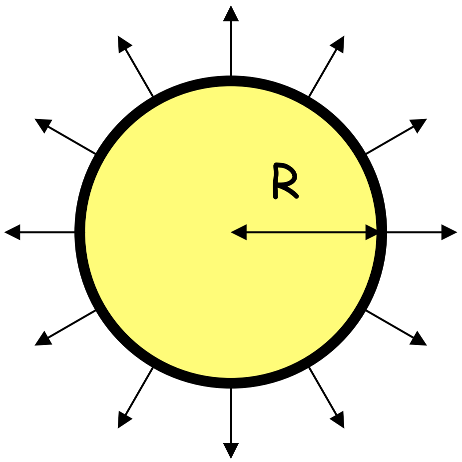


Expanding source : Lorentz factor Γ

(i) in the comoving frame of the emitting material, the photon energy is divided by Γ, therefore less photons are above the threshold for pair creation.

(ii) because of the relativistic beaming, the size of the emitting region can be multiplied by Γ^2.





Expanding source : Lorentz factor Γ

(i) in the comoving frame of the emitting material, the photon energy is divided by Γ, therefore less photons are above the threshold for pair creation.

(ii) because of the relativistic beaming, the size of the emitting region can be multiplied by Γ^2.

For large Lorentz factors (typically 100 or above), $\tau_{\gamma\gamma} < 1$.

See for instance Lithwick & Sari 2001.

Do Fermi-LAT observations really imply very large Lorentz factors in GRB outflows ?

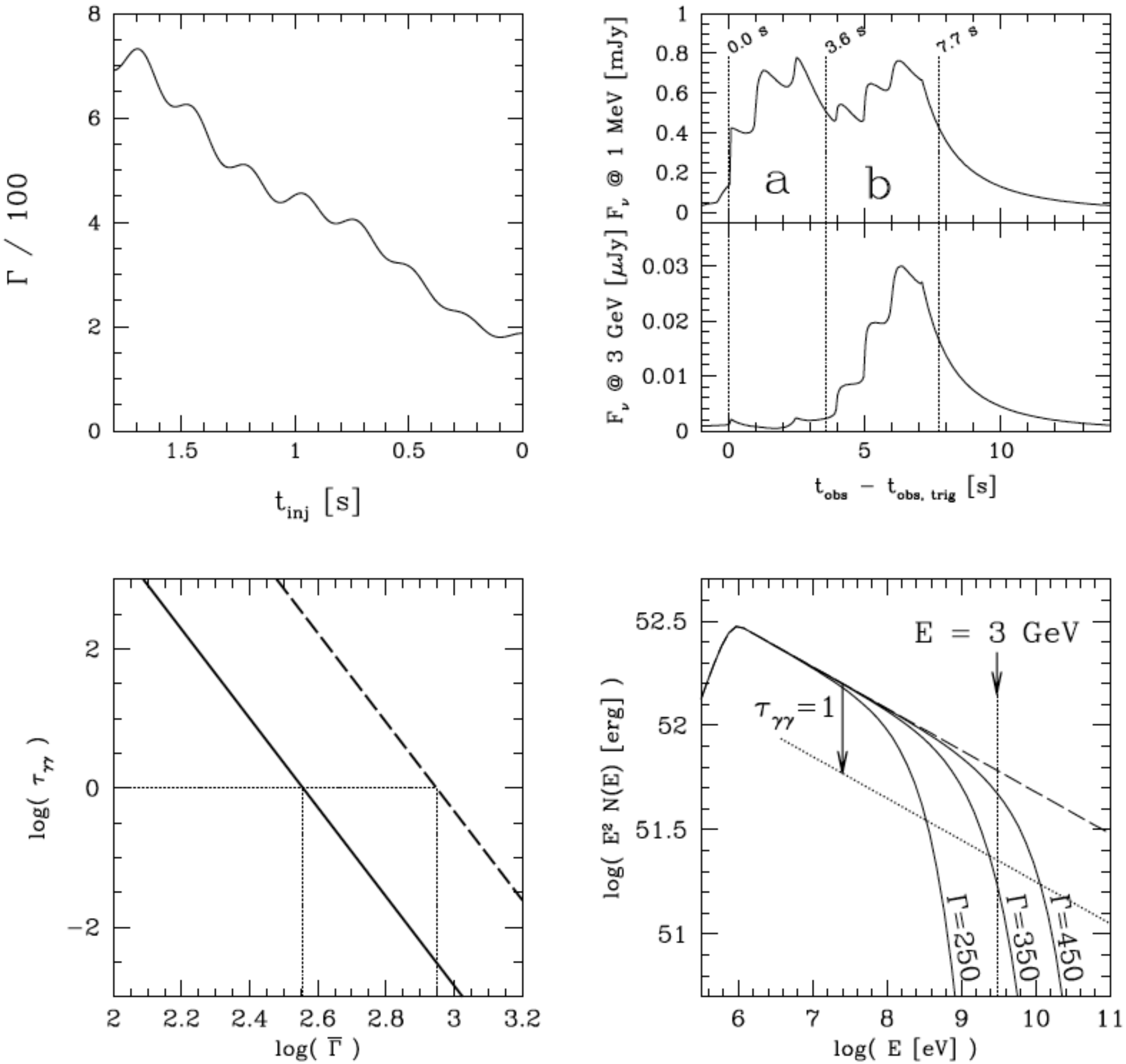
Fermi collaboration :	Γ = 887 in GRB 080916C	(Abdo et al. 2009)
	Γ ~ 1000 in GRB 090902B	(Abdo et al. 2009)
	Γ = 1200 in GRB 090510	(Ackermann et al. 2010)
	Γ = 720 in GRB 090926A	(Ackermann et al. 2011)

These estimates are based on single zone models.

A detailed calculation taking into account a time, space and direction dependent radiation field leads to a reduction by a factor ~ 2.5

If in addition GeV and MeV photons are not produced at the same place, the constraint is even weaker.

see Granot & Cohen-Tanugi 2008 ;
Hascoët, Daigne, Mochkovitch and Vennin to be submitted



Hascoët et al. 2011

General framework : *the different observed phases 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.*

- 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 associated to each observed phase ?
(e.g. thermal vs kinetic vs magnetic vs … energy ;
photosphere vs internal shocks vs magnetic reconnection vs …)

- Microphysics and radiative processes at work ?
(e.g. shock acceleration ; magnetic field amplification ; …
synchrotron radiation vs IC vs …)

- etc.

- Large similarities in the emission from short and long GRBs

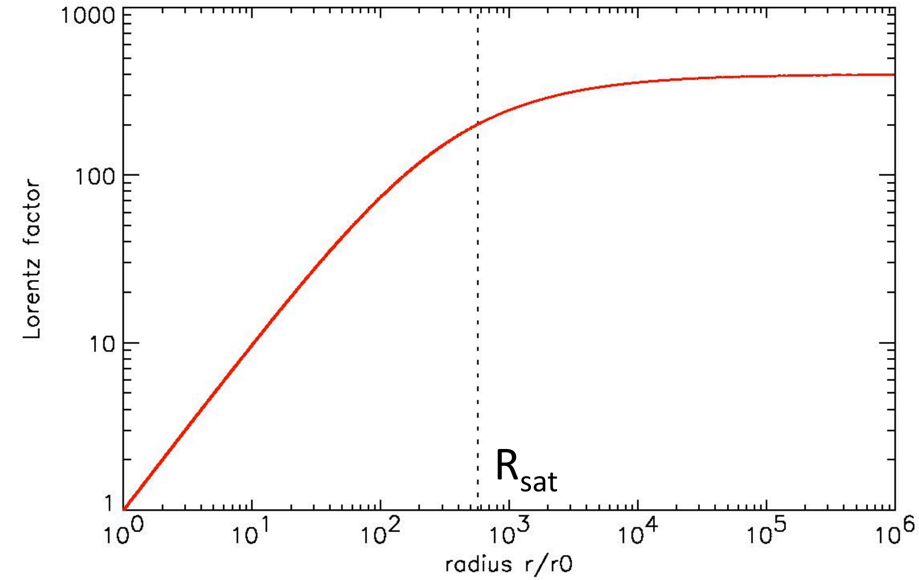
Frequent assumption : *short and long GRBs are due to different progenitors leading to the same succession of events : formation of a compact object and ejection of a relativistic outflow. Differences in the two classes of bursts (prompt/afterglow) are then due to different initial/boundary conditions (energetics and lifetime of the central engine, circumburst environment, …*

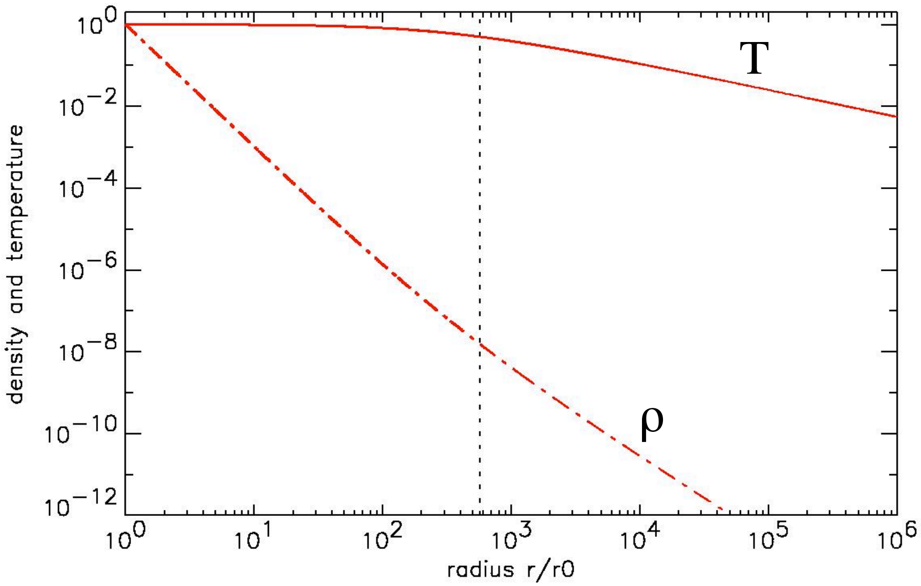
The physics of relativistic ejections by a compact source is complicated and not well understood… The fireball model is a useful toy model but one should recall that the real jet evolution could be rather different, especially if the magnetic field plays a dominant role in the acceleration mechanism.

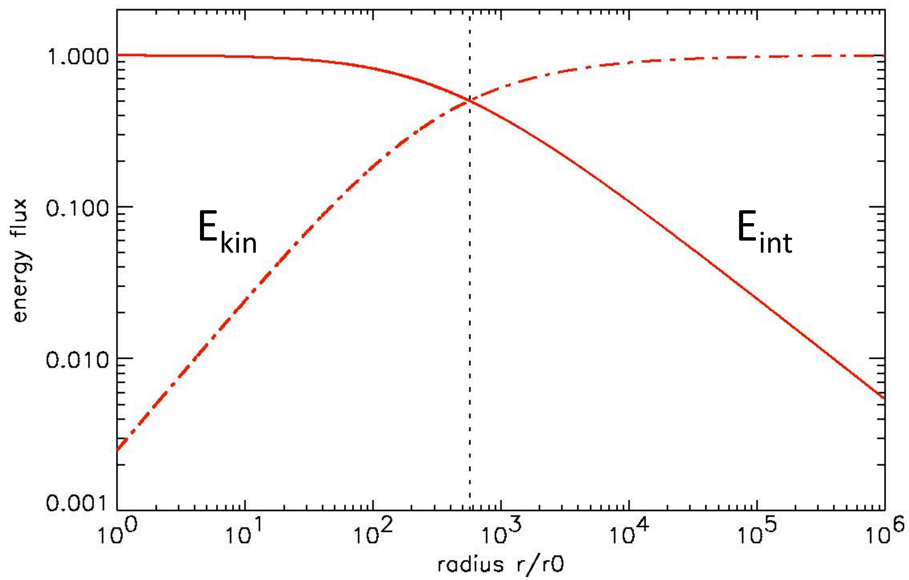
- Paczynski 1986; Goodman 1986
- Energy (E_0) injected in matter (M_0) very close to the central engine (R_0)
- Adiabatic expansion and hydrodynamical acceleration
- If $E_0 \gg M_0 c^2$: relativistic motion ($\Gamma_\infty \simeq E_0 / M_0 c^2$ for 100% efficiency).

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

Fireballs


Lorentz factor
1000
100
10
1
R_sat
10^0 10^1 10^2 10^3 10^4 10^5 10^6
radius r/r0


density and temperature
10^0
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
T
ρ
10^0 10^1 10^2 10^3 10^4 10^5 10^6
radius r/r0


energy flux
1.000
0.100
0.010
0.001
E_{kin}
E_{int}
10^0 10^1 10^2 10^3 10^4 10^5 10^6
radius r/r0

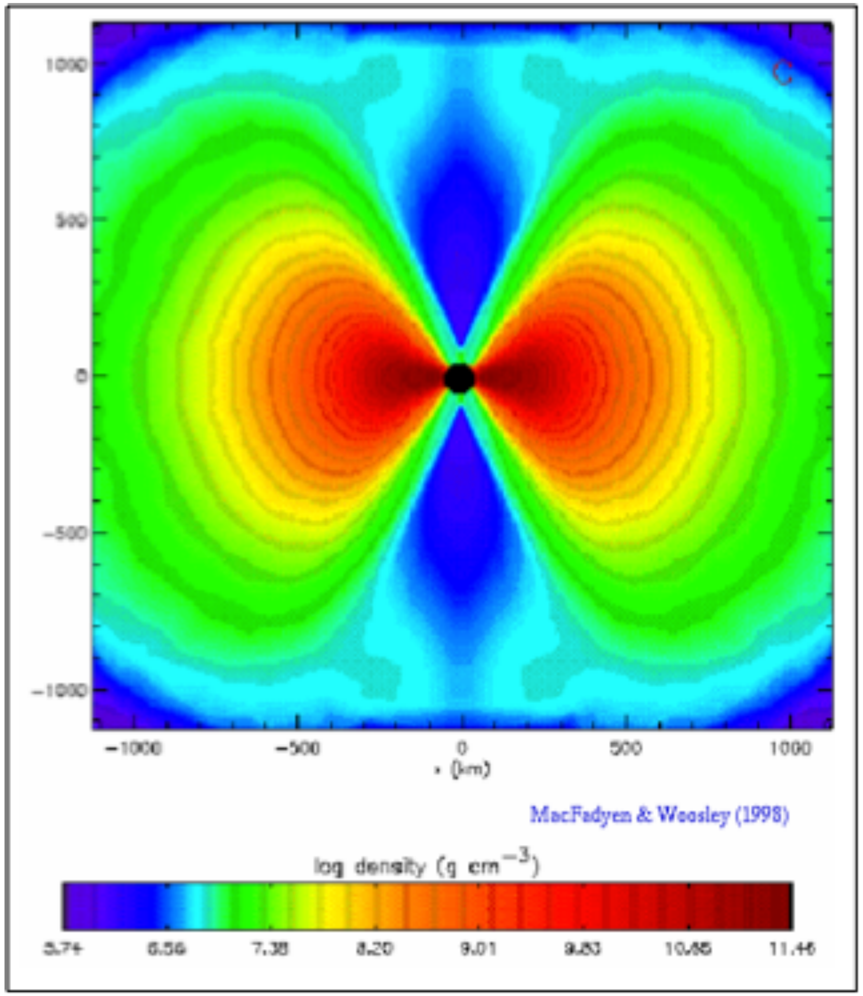
- Acceleration radius (or *saturation* radius) :

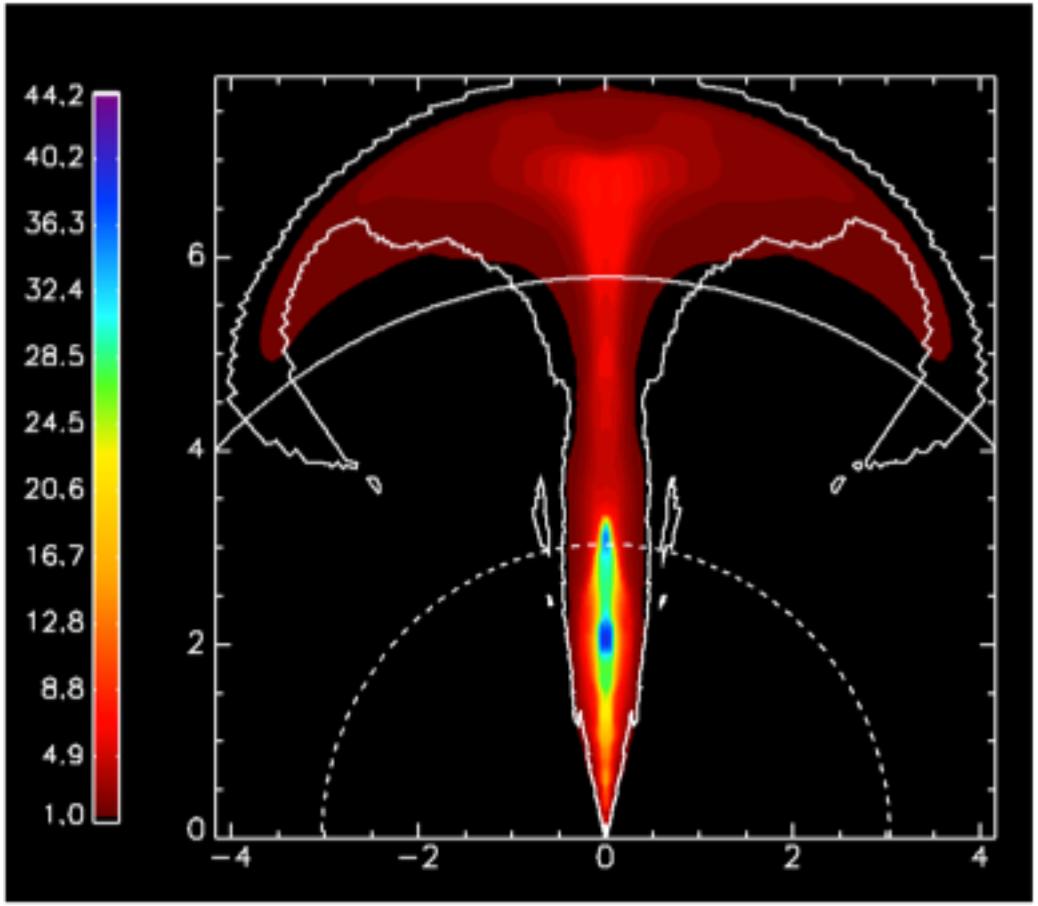
$$R_{\rm acc} \simeq R_0 \Gamma_\infty \simeq 3 \times 10^8 \left(\frac{\Gamma_\infty}{100} \right) \, {\rm cm}$$

- Spreading radius :

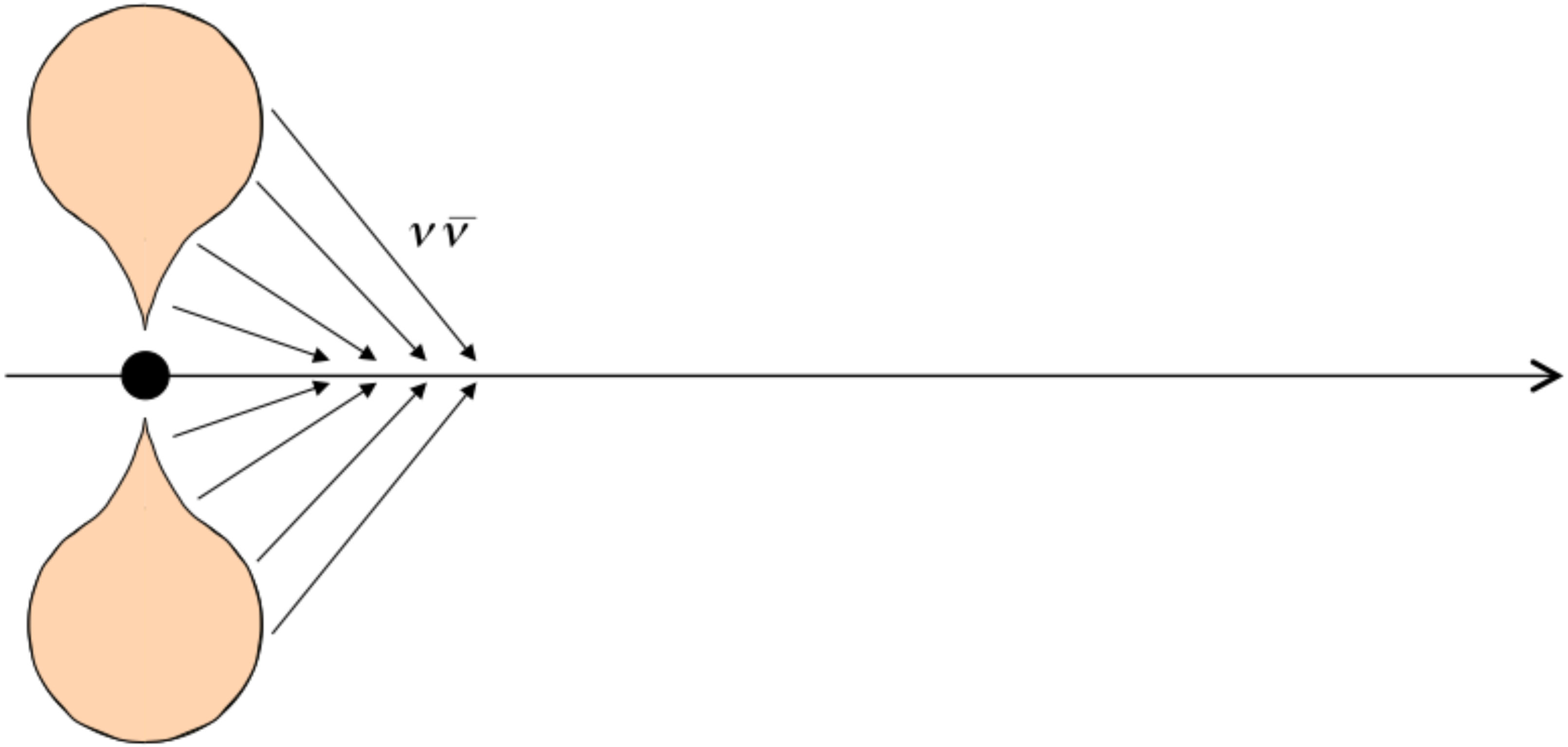
$$R_{\rm spread} \simeq \Gamma_\infty^2 \Delta_0 \simeq 3 \times 10^{15} \left(\frac{\Gamma_\infty}{100} \right)^2 \left(\frac{\Delta_0 / c}{10\,{\rm s}} \right) \, {\rm cm}$$

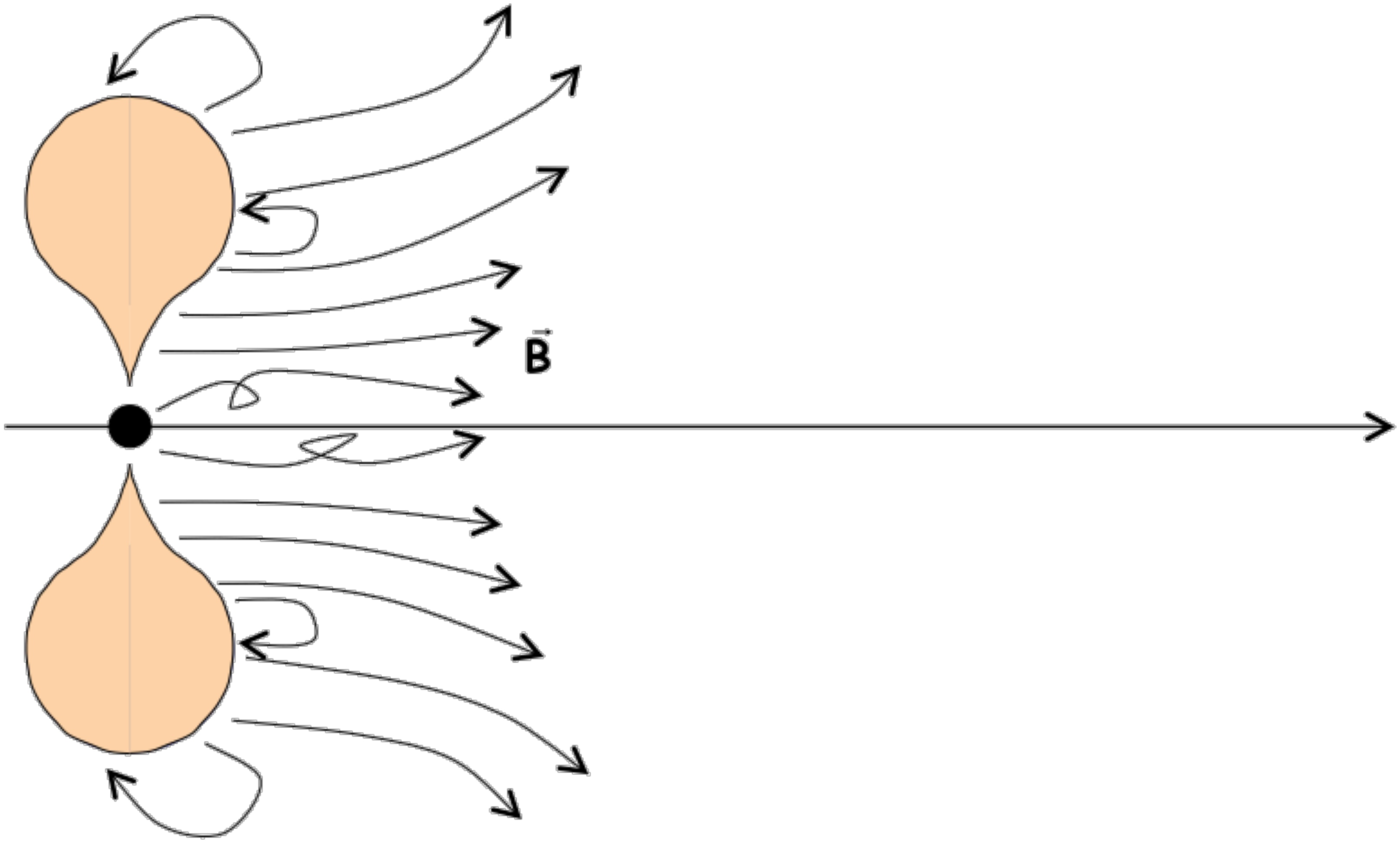
- Long GRBs : collapsar

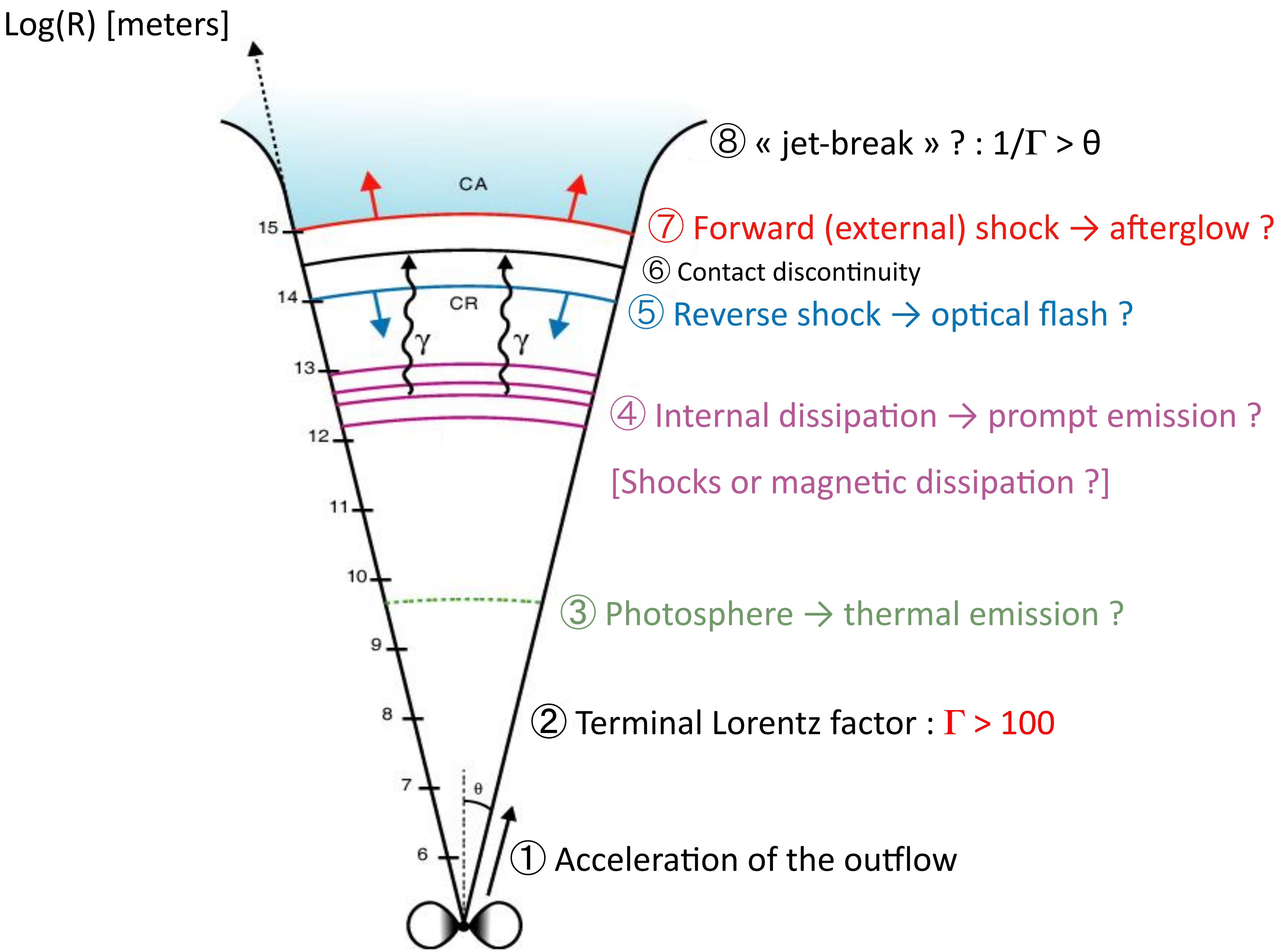


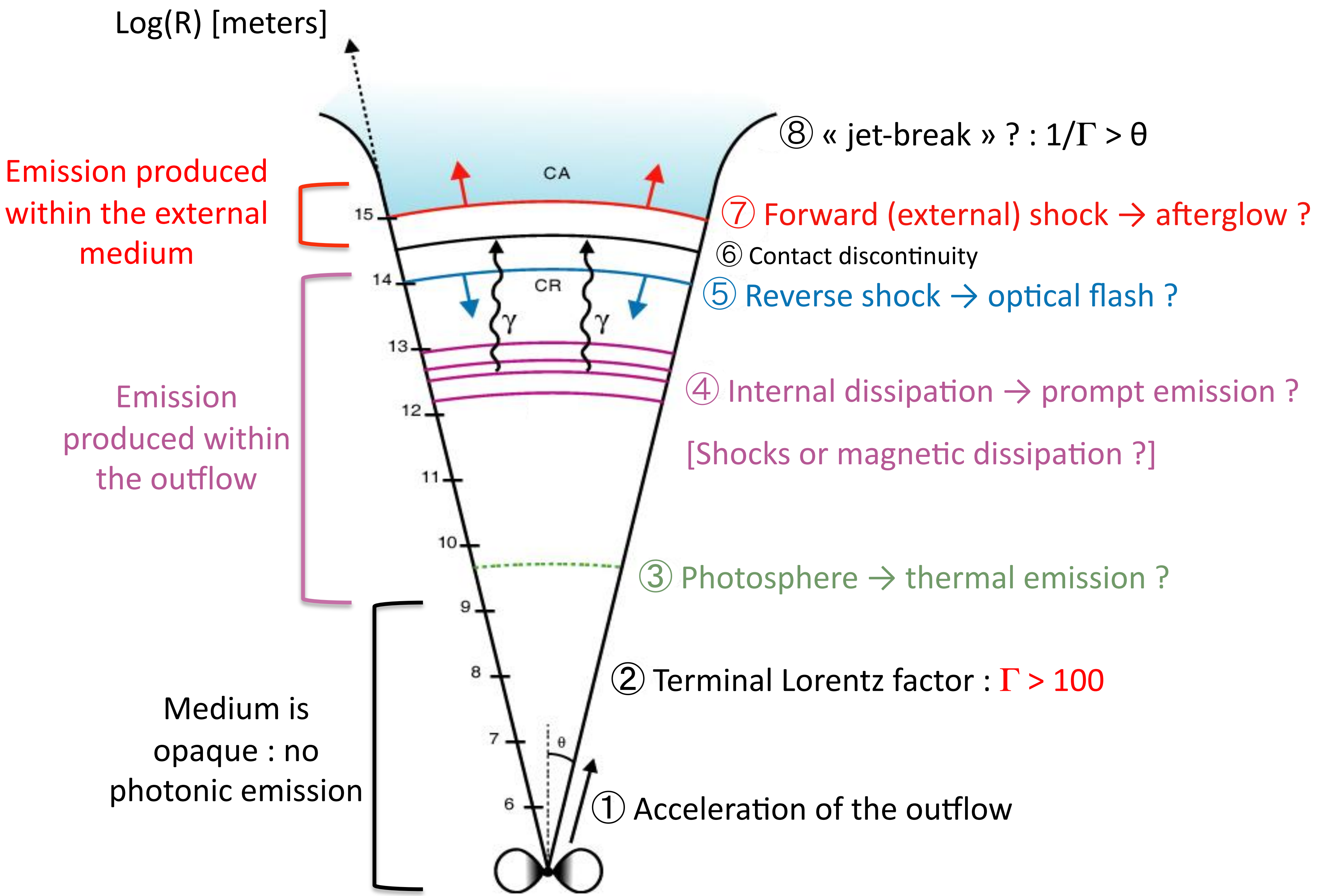


- Short GRBs : NS+NS or NS+BH merger ?


$\nu\bar{\nu}$


B


Log(R) [meters]
CA
CR
γ
γ
15
14
13
12
11
10
9
8
7
6
θ
⑧ « jet-break » ? : 1/Γ > θ
⑦ Forward (external) shock → afterglow ?
⑥ Contact discontinuity
⑤ Reverse shock → optical flash ?
④ Internal dissipation → prompt emission ?
[Shocks or magnetic dissipation ?]
③ Photosphere → thermal emission ?
② Terminal Lorentz factor : Γ > 100
① Acceleration of the outflow


Log(R) [meters]
Emission produced within the external medium
Emission produced within the outflow
Medium is opaque : no photonic emission
CA
CR
γ
γ
15
14
13
12
11
10
9
8
7
6
θ
⑧ « jet-break » ? : 1/Γ > θ
⑦ Forward (external) shock → afterglow ?
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④ Internal dissipation → prompt emission ?
[Shocks or magnetic dissipation ?]
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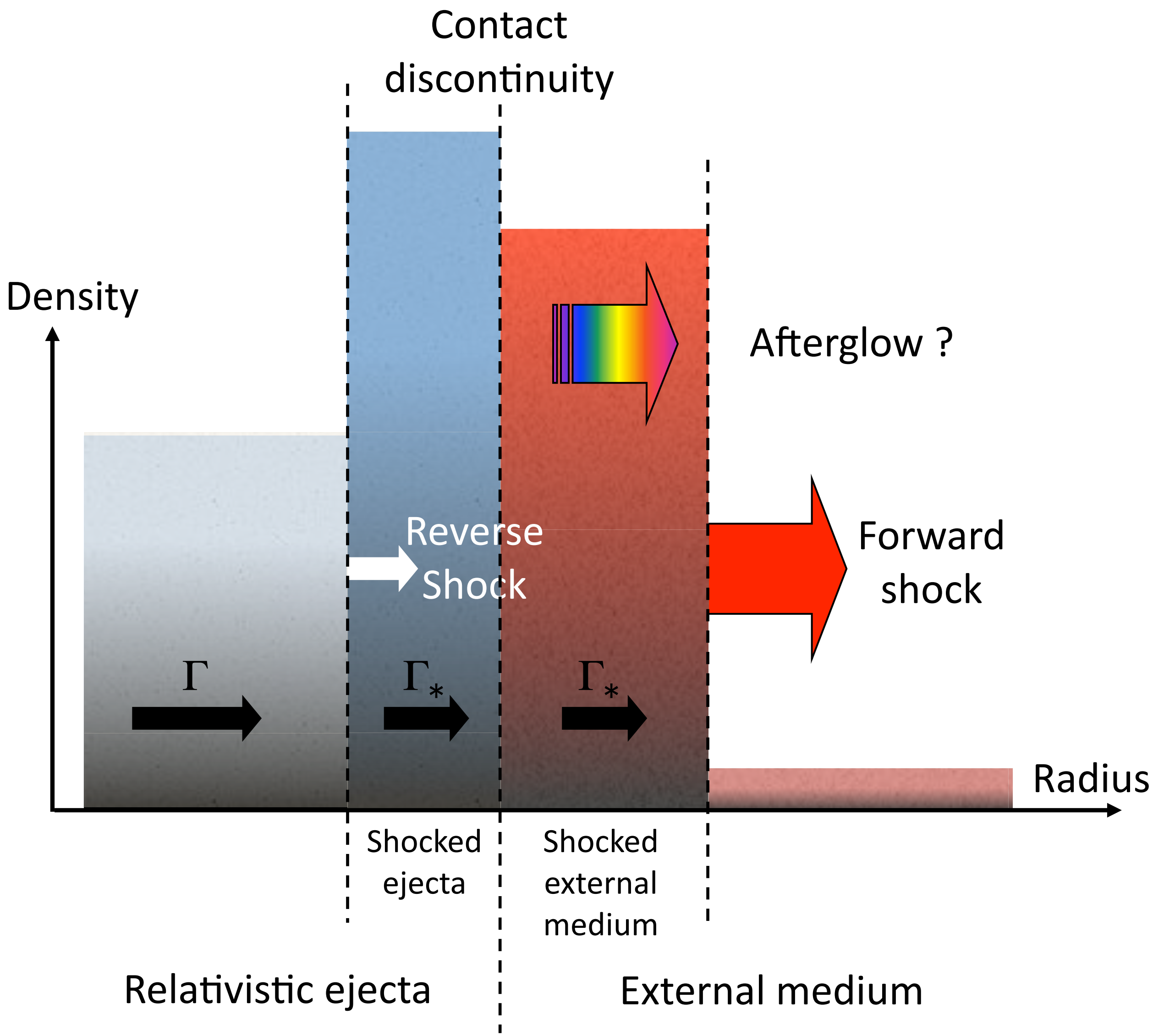
② Terminal Lorentz factor : Γ > 100
① Acceleration of the outflow

Effect of the external medium (1) | Forward (external shock)

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



Effect of the external medium (1) — Forward (external shock)

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

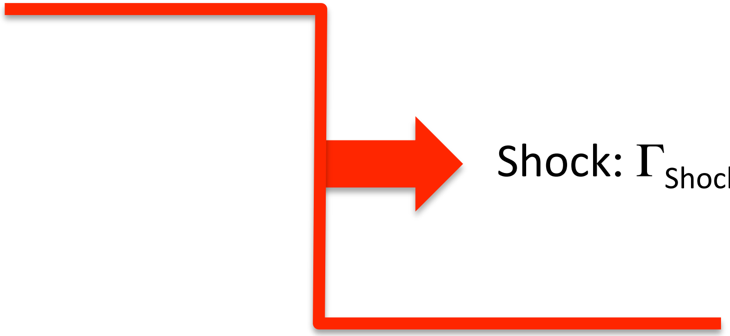
Forward shock :

- Dynamics : Blandford & McKee 1976
- Microphysics : ε_e, p, ε_B
- Synchrotron radiation : Sari, Piran, Narayan 1998
- Effect of a stellar wind : Chevalier & Li 2000
- Jet vs spherical outflow : Rhoads 1997

Effect of the external medium (1) — Forward (external shock)

Strong shock in ultra-relativistic limit : « Rankine Hugoniot » jump conditions

Shocked region:
$\rho_* ; P_* ; \Gamma_* \gg 1$

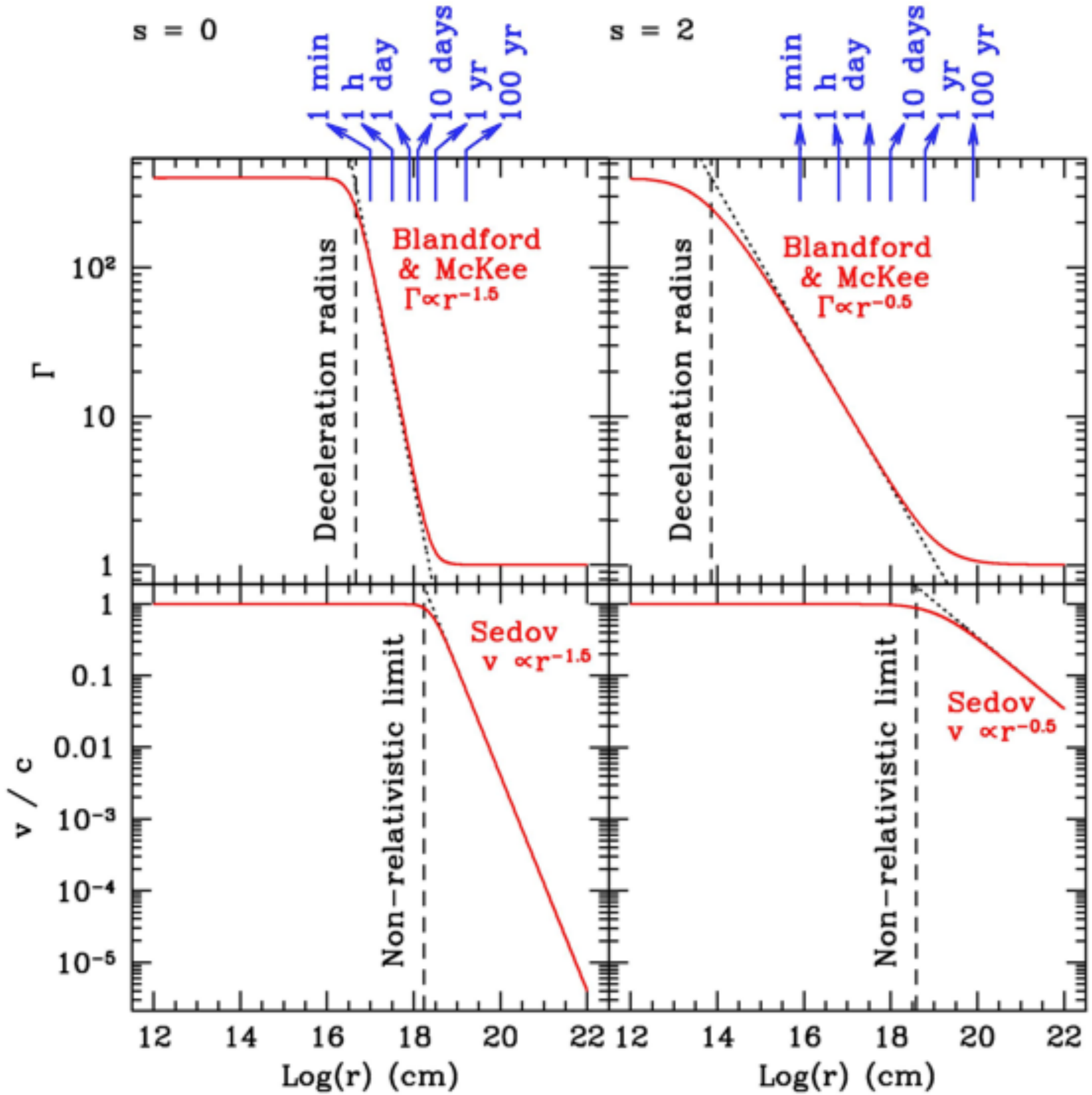


Shock: $\Gamma_{\text{Shock}} \gg 1$

Unshocked region:
$\rho ; P \ll \rho c^2 ; v=0$

$$
\begin{aligned}
\varepsilon_* &\simeq \Gamma_* c^2 , \\
\rho_* &\simeq 4\Gamma_* \rho , \\
\Gamma_{\text{Shock}} &\simeq \sqrt{2}\Gamma_* ,
\end{aligned}
$$

Effect of the external medium (1) | Forward (external shock)



Relativistic ejecta :

Γ_0 = 400

E_0 = 10^{53} erg

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

External medium :

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

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

Effect of the external medium (1) | Forward (external shock)

- Deceleration radius :

$$\rho_{\rm ext} = \frac{A}{R^s} \qquad R_{\rm dec} \simeq \left(\frac{3-s}{4\pi}\,\frac{E_0}{A\Gamma_0^2 c^2}\right)^{\frac{1}{3-s}}$$

- Uniform medium : s = 0 ; A = n m_p

$$R_{\rm dec} \simeq 1.2\times10^{17}\,{\rm cm}\left(\frac{E_0}{10^{53}\,{\rm erg}}\right)^{\frac{1}{3}}\left(\frac{n}{1\,{\rm cm}^{-3}}\right)^{-\frac{1}{3}}\left(\frac{\Gamma_0}{100}\right)^{-\frac{2}{3}}$$

- Stellar wind : s = 2 ; A = $A_* \times 5\times10^{11}$ g.cm^{-1}

$$R_{\rm dec} \simeq 1.8\times10^{16}\,{\rm cm}\left(\frac{E_0}{10^{53}\,{\rm erg}}\right)\left(\frac{A_*}{0.1}\right)^{-1}\left(\frac{\Gamma_0}{100}\right)^{-2}$$

Standard parametrization of microphysics in shocks (magnetic field amplification ; particle acceleration)

$$u_* \left[\mathrm{erg.cm^{-3}}\right] = \rho_* \epsilon_*$$

- Magnetic field :

$$u_\mathrm{B} \left[\mathrm{erg.cm^{-3}}\right] = \frac{B^2}{8\pi} = \epsilon_\mathrm{B} u_*$$

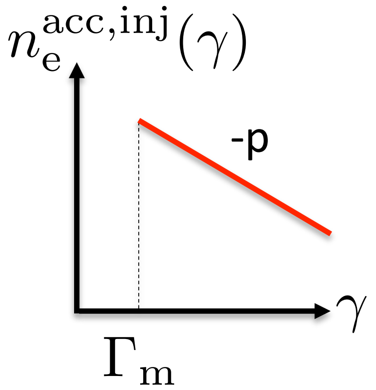
$$B = \sqrt{8\pi \epsilon_\mathrm{B} \rho_* \epsilon_*}$$

- Shock-accelerated electrons :

$$u_\mathrm{e}^\mathrm{acc} \left[\mathrm{erg.cm^{-3}}\right] = \epsilon_\mathrm{e} u_*$$

$$n_\mathrm{e}^\mathrm{acc} \left[\mathrm{e^-.cm^{-3}}\right] = \zeta \frac{\rho_*}{m_\mathrm{p}}$$

$$n_\mathrm{e}^\mathrm{acc,inj}(\gamma) = (p-1)\frac{n_\mathrm{e}^\mathrm{acc}}{\Gamma_\mathrm{m}} \left(\frac{\gamma}{\Gamma_\mathrm{m}}\right)^{-p} \text{ for } \gamma \geq \Gamma_\mathrm{m}$$



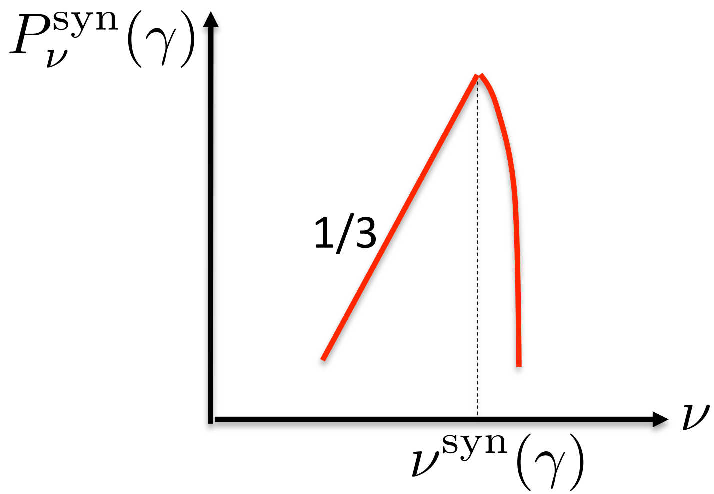
$$\Gamma_\mathrm{m} = \frac{p-2}{p-1}\frac{\epsilon_\mathrm{e}}{\zeta}\frac{m_\mathrm{p}}{m_\mathrm{e}}\frac{\epsilon_*}{c^2}$$

Synchrotron radiation (A) Single electron

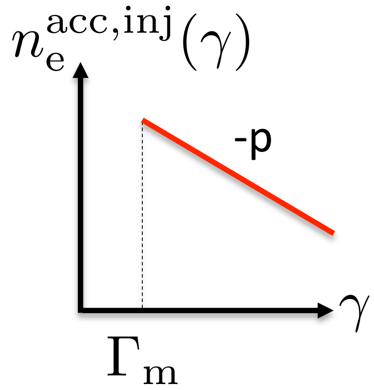
- Power : $$P^{\rm syn}(\gamma) = \frac{\sigma_{\rm T} c}{6\pi} B^2 \gamma^2$$

- Spectrum : $$\nu^{\rm syn}(\gamma) = \frac{e}{2\pi m_{\rm e} c} B \gamma^2$$

$$P_\nu^{\rm syn}(\gamma) = \frac{P^{\rm syn}(\gamma)}{\nu^{\rm syn}(\gamma)} \Phi\left(\frac{\nu}{\nu^{\rm syn}}\right) \simeq \frac{\sigma_{\rm T} m_{\rm e} c^2}{3e} B \times \begin{cases} \frac{4}{3}\left(\frac{\nu}{\nu^{\rm syn}}\right)^{1/3} & \text{if } \nu \leq \nu^{\rm syn}(\gamma) \\ 0 & \text{otherwise} \end{cases}$$



Synchrotron radiation (B) Power-law distribution of electrons

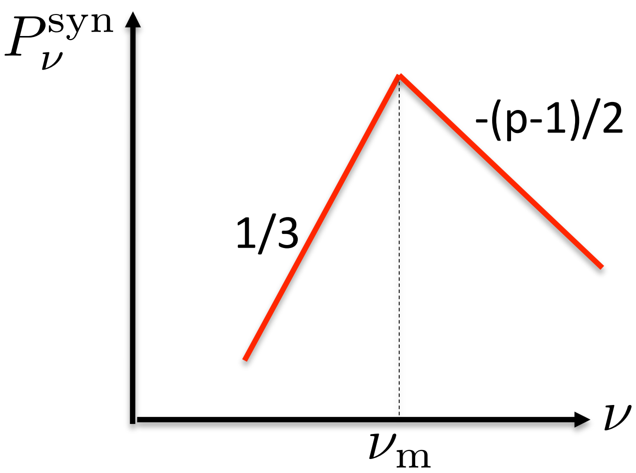


- Electron distribution :

$$n_e^{acc,inj}(\gamma) = (p-1)\frac{n_e^{acc}}{\Gamma_m}\left(\frac{\gamma}{\Gamma_m}\right)^{-p} \text{ for } \gamma \geq \Gamma_m$$

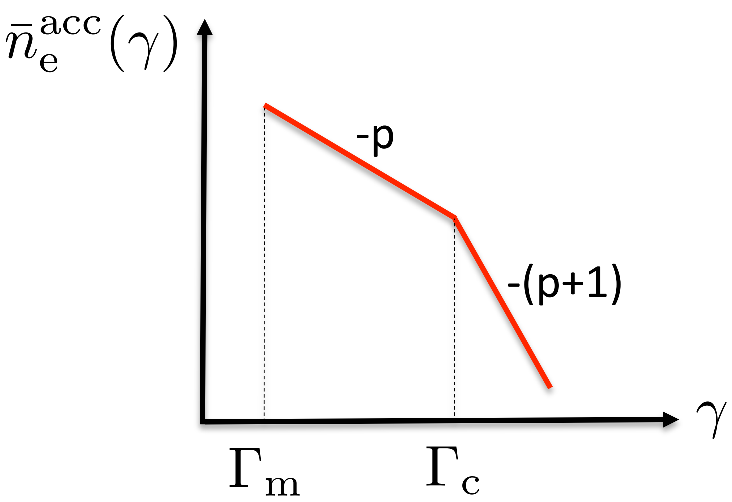
- Spectrum : $\nu_m = \nu_{syn}(\Gamma_m)$

$$P_\nu^{syn} \simeq \frac{3}{4}\frac{p-1}{p-\frac{1}{3}}\frac{\sigma_T m_e c^2}{3e} B n_e^{acc} \times \begin{cases} \left(\frac{\nu}{\nu_m}\right)^{1/3} & \text{for } \nu \leq \nu_m \\ \left(\frac{\nu}{\nu_m}\right)^{-\frac{p-1}{2}} & \text{for } \nu \geq \nu_m \end{cases}$$

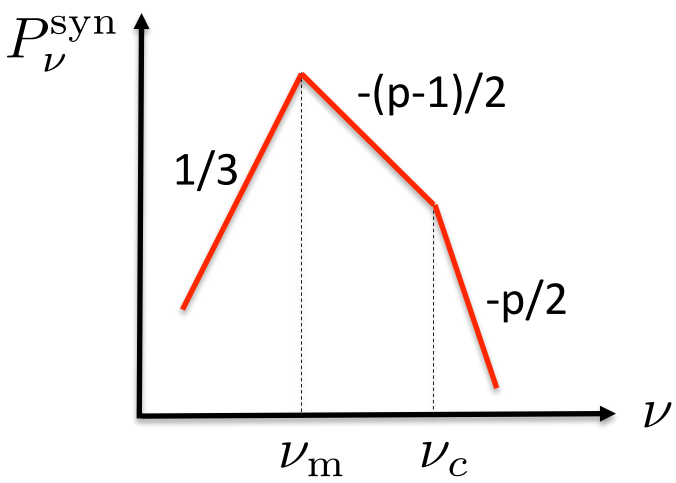


Competition between synchrotron radiation and adiabatic cooling :
Sari, Piran, Narayan 1998

- Dynamical timescale = adiabatic cooling timescale : $t_{\rm dyn}$
- Critical Lorentz factor : $$\Gamma_{\rm c} = \frac{6\pi m_{\rm e} c}{\sigma_{\rm T}} \frac{1}{B^2 t_{\rm dyn}}$$
- Cooling frequency : $$\nu_{\rm c} = \nu_{\rm syn}\left(\Gamma_{\rm c}\right)$$
- Spectrum :



Slow cooling
$\Gamma_c \gg \Gamma_{\rm m}$

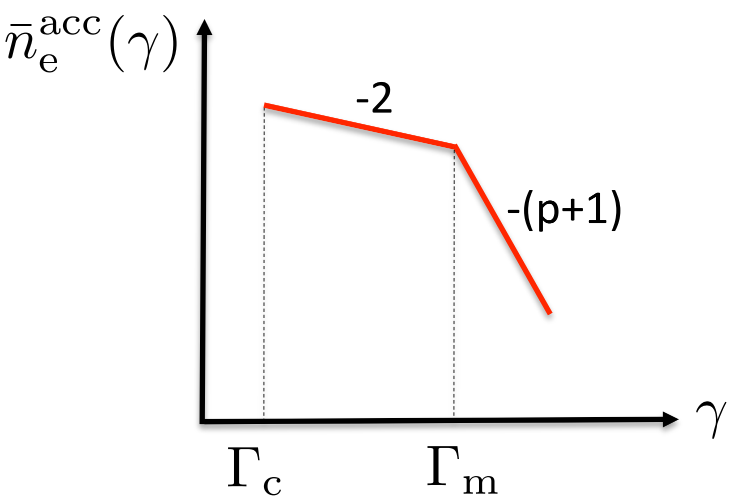


Only high-energy electrons radiate effiently

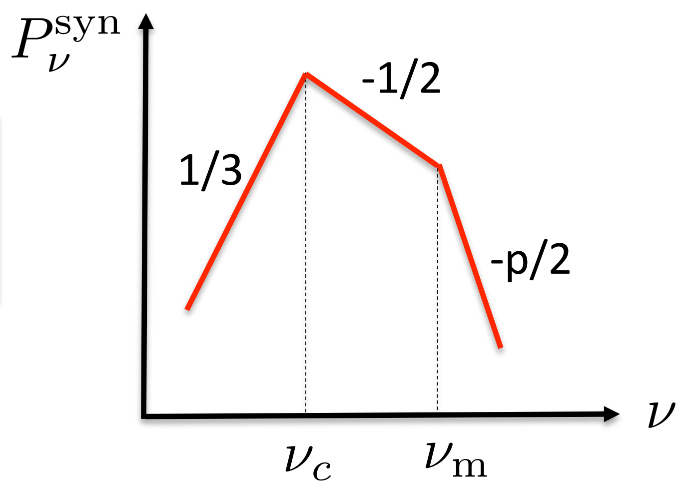
Effect of the external medium (1) | Forward (external shock)

Competition between synchrotron radiation and adiabatic cooling :
Sari, Piran, Narayan 1998

- Dynamical timescale = adiabatic cooling timescale : t_{dyn}
- Critical Lorentz factor : $$\Gamma_{\mathrm{c}} = \frac{6\pi m_{\mathrm{e}} c}{\sigma_{\mathrm{T}}} \frac{1}{B^2 t_{\mathrm{dyn}}}$$
- Cooling frequency : $$\nu_{\mathrm{c}} = \nu_{\mathrm{syn}}\left(\Gamma_{\mathrm{c}}\right)$$
- Spectrum :



Fast cooling
$\Gamma_c \ll \Gamma_{\mathrm{m}}$



All electrons radiate effiently

Effect of the external medium (1) — Forward (external shock)

Observed lightcurves at a given frequency :

- Observed flux (**fast** cooling regime) :

$$F_{\nu_{\rm obs}} = \underbrace{\{\text{num. factor}\} \frac{N_{\rm e}}{4\pi D^2}\Gamma \frac{\sigma_{\rm T} m_{\rm e} c^2}{3e} B'}_{F_{\nu_{\rm obs},max}} \times \begin{cases} \left(\frac{\nu_{\rm obs}}{\Gamma\nu'_{\rm c}}\right)^{1/3} & \nu_{\rm obs} \ll \Gamma\nu'_{\rm c} \\ \left(\frac{\nu_{\rm obs}}{\Gamma\nu'_{\rm c}}\right)^{-1/2} & \Gamma\nu'_{\rm c} \ll \nu_{\rm obs} \ll \Gamma\nu'_{\rm m} \\ \left(\frac{\nu'_{\rm m}}{\nu'_{\rm c}}\right)^{-1/2} \left(\frac{\nu_{\rm obs}}{\Gamma\nu'_{\rm m}}\right)^{-p/2} & \Gamma\nu'_{\rm m} \ll \nu_{\rm obs} \end{cases}$$

- Observed flux (**slow** cooling regime) :

$$F_{\nu_{\rm obs}} = \underbrace{\{\text{num. factor}\} \frac{N_{\rm e}}{4\pi D^2}\Gamma \frac{\sigma_{\rm T} m_{\rm e} c^2}{3e} B'}_{F_{\nu_{\rm obs},max}} \times \begin{cases} \left(\frac{\nu_{\rm obs}}{\Gamma\nu'_{\rm m}}\right)^{1/3} & \nu_{\rm obs} \ll \Gamma\nu'_{\rm m} \\ \left(\frac{\nu_{\rm obs}}{\Gamma\nu'_{\rm m}}\right)^{-(p-1)/2} & \Gamma\nu'_{\rm m} \ll \nu_{\rm obs} \ll \Gamma\nu'_{\rm c} \\ \left(\frac{\nu'_{\rm c}}{\nu'_{\rm m}}\right)^{-(p-1)/2} \left(\frac{\nu_{\rm obs}}{\Gamma\nu'_{\rm c}}\right)^{-p/2} & \Gamma\nu'_{\rm m} \ll \nu_{\rm obs} \end{cases}$$

- Principle :

(1) Compute $F_{\nu_{\rm obs},max}$, $\nu_{\rm m,obs} = \Gamma\nu'_{\rm m}$ and $\nu_{\rm c,obs} = \Gamma\nu'_{\rm c}$ as function of $t_{\rm obs}$

(2) Deduce the observed flux at a given frequency from formulae above

Observed lightcurves at a given frequency :

- An example of such a calculation for s=0 (uniform medium) and s=2 (stellar wind)

Panaitescu & Kumar 2000

- Additional effects :

- Synchrotron self-absorption (radio)
- Inverse Compton scattering (high-energy + electron cooling, see e.g. Sari & Esin 2001)
- Precise calculation using a full integration over equal-arrival time surfaces

- Late time evolution :

jet break – non relativistic regime

APPENDIX B

HOMOGENEOUS EXTERNAL MEDIUM ($s = 0$)

By substituting the equations for the break frequencies and equation (64) in equations (65) and (66) and taking into account the above correction factors for the remnant curvature, the following fluxes are obtained:

$$F_\nu \overset{(1)}{=} 0.3 D_{28}^{-2} (Y_r + 1)^{-1} n_{*,0}^{-1/2} \varepsilon_{B,-1}^{-1/2} \nu_{9.7}^{2} T_{d,-1} \text{ mJy} , \quad \text{(B1)}$$

$$F_\nu \overset{(2)}{=} 10 D_{28}^{-2} (Y_r + 1)^{2/3} E_{53}^{7/6} n_{*,0}^{5/6} \varepsilon_{B,-2} \nu_{14.6}^{1/3} T_{d,-2}^{1/6} \text{ mJy} , \quad \text{(B2)}$$

$$F_\nu \overset{(3)}{=} 40 D_{28}^{-2} (Y_r + 1)^{-1} E_{53}^{3/4} \varepsilon_{B,-1}^{-1/4} \nu_{14.6}^{-1/2} T_{d,-2}^{-1/4} \text{ mJy} , \quad \text{(B3)}$$

$$F_\nu \overset{(4)}{=} 10^{2.1-0.6p} D_{28}^{-2} (Y_r + 1)^{-1} E_{53}^{(p+2)/4} \varepsilon_{e,-1}^{p-1} \varepsilon_{B,-1}^{(p-2)/4} \nu_{14.6}^{-(p/2)} T_d^{-[(3p-2)/4]} \text{ mJy} , \quad \text{(B4)}$$

$$F_\nu \overset{(5)}{=} 30 D_{28}^{-2} E_{53}^{1/2} n_{*,0}^{-1/2} \varepsilon_{e,-1} \nu_{9.7}^{2} T_{d,1}^{1/2} \text{ mJy} , \quad \text{(B5)}$$

$$F_\nu \overset{(6)}{=} 1 D_{28}^{-2} E_{53}^{5/6} n_{*,0}^{1/2} \varepsilon_{e,-1}^{-2/3} \varepsilon_{B,-4}^{1/3} \nu_{14.6}^{1/3} T_{d,-2}^{1/2} \text{ mJy} , \quad \text{(B6)}$$

$$F_\nu \overset{(7)}{=} 10^{2.1-1.3p} D_{28}^{-2} E_{53}^{(p+3)/4} n_{*,0}^{1/2} \varepsilon_{e,-1}^{p-1} \varepsilon_{B,-4}^{(p+1)/4} \nu_{14.6}^{-[(p-1)/2]} T_d^{-[(3/4)(p-1)]} \text{ mJy} , \quad \text{(B7)}$$

$$F_\nu \overset{(8)}{=} 10^{2.4-0.8p} D_{28}^{-2} E_{53}^{(p+2)/4} \varepsilon_{e,-1}^{p-1} \varepsilon_{B,-2}^{(p-2)/4} \nu_{14.6}^{-(p/2)} T_d^{-[(3p-2)/4]} \text{ mJy} , \quad \text{(B8)}$$

$$F_\nu \overset{(8a)}{=} 10^{(2p^2-7.7p+0.8)/(4-p)} D_{28}^{-2} \left(E_{53}^{(1/4)(12-p^2)} n_{*,0}^{-(1/2)(p-2)} \varepsilon_{e,-1}^{(p-1)(3-p)} \varepsilon_{B,-4}^{(1/4)(-p^2+2p+4)}\right)^{1/(4-p)} \nu_{17.3}^{-(p/2)} T_{d,-1}^{-(3p/4)+[1/(4-p)]} \text{ mJy} \quad (2 < p < 3) . \quad \text{(B9)}$$

The case given in equation (B9) and labeled (8a) corresponds to the same frequency ordering as for case (8), but the cooling break ν_c evolution (eq. [45]) is determined by the IC losses; i.e., $T_r < T < T_y$ and $Y_a > 1$.

APPENDIX C

WIND EXTERNAL MEDIUM ($s = 2$)

Following the same exercise as above and using the relevant equations, the following results can be obtained for the wind model:

$$F_\nu \overset{(1)}{=} 0.03 D_{28}^{-2} (Y_r + 1)^{-1} E_{53} A_*^{-2} \varepsilon_{e,-1}^{-1} \varepsilon_{B,-2}^{-1} \nu_{9.7}^{2} T_{d,-1}^{2} \text{ mJy} , \quad \text{(C1)}$$

$$F_\nu \overset{(2)}{=} 70 D_{28}^{-2} (Y_r + 1)^{2/3} E_{53}^{1/3} A_*^{5/3} \varepsilon_{B,-2} \nu_{12}^{1/3} T_{d,-1}^{-2/3} \text{ mJy} , \quad \text{(C2)}$$

$$F_\nu \overset{(5)}{=} 0.07 D_{28}^{-2} E_{53} A_*^{-1} \varepsilon_{e,-1} \nu_{9.7}^{2} T_{d,-1}^{1} \text{ mJy} , \quad \text{(C3)}$$

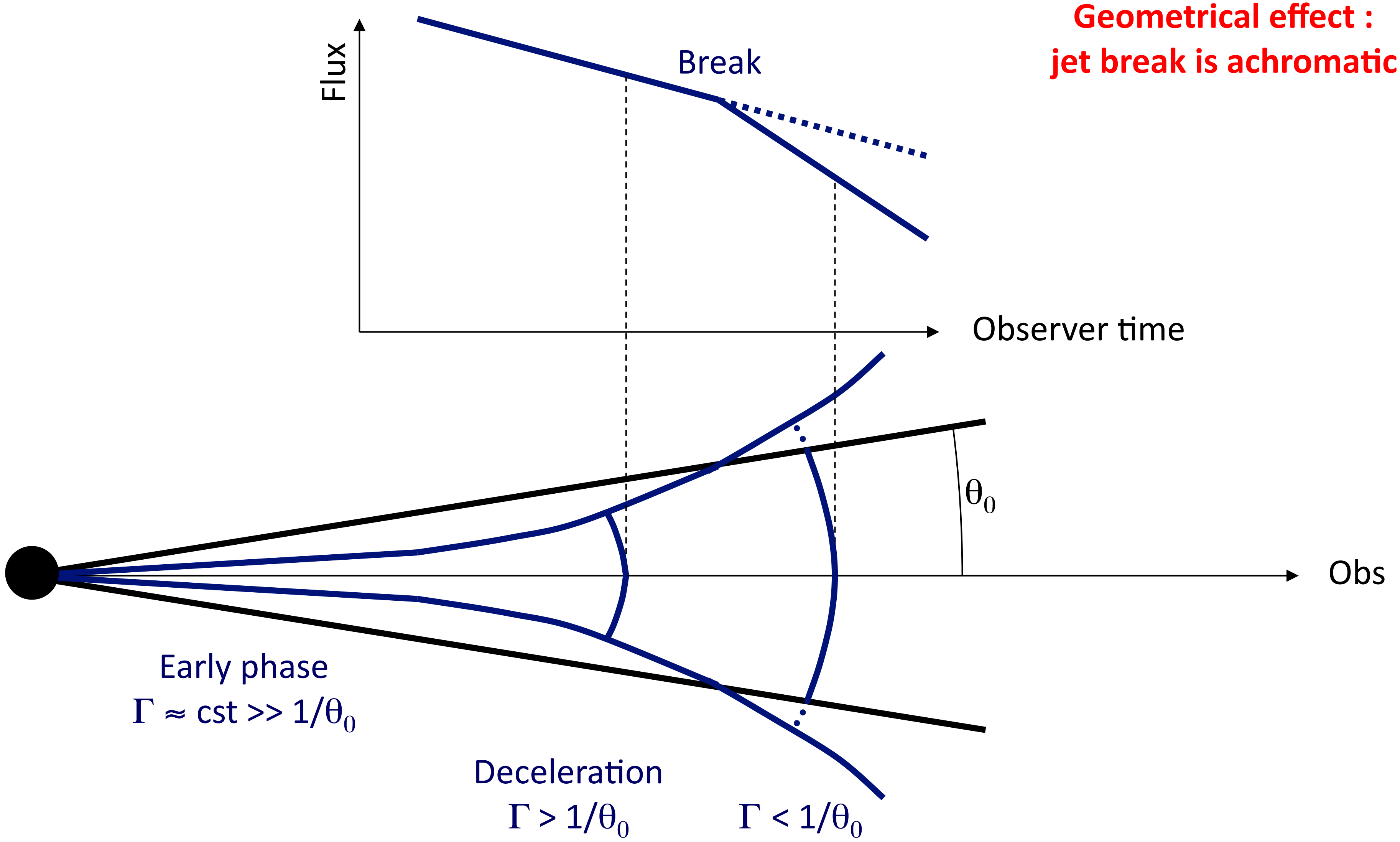
$$F_\nu \overset{(6)}{=} 9 D_{28}^{-2} E_{53}^{1/3} A_* \varepsilon_{e,-1}^{-2/3} \varepsilon_{B,-3}^{1/3} \nu_{12}^{1/3} T_d^{0} \text{ mJy} , \quad \text{(C4)}$$

$$F_\nu \overset{(7)}{=} 10^{2.3-1.2p} D_{28}^{-2} E_{53}^{(p+1)/4} A_* \varepsilon_{e,-1}^{p-1} \varepsilon_{B,-4}^{(p+1)/4} \nu_{14.6}^{-[(p-1)/2]} T_d^{-[(3p-1)/4]} \text{ mJy} , \quad \text{(C5)}$$

$$F_\nu \overset{(8a)}{=} 10^{(1.9p^2-8.6p+5.4)/(4-p)} D_{28}^{-2} E_{53}^{(p+2)/4} \left(A_*^{-(p-2)} \varepsilon_{e,-1}^{(p-1)(3-p)} \varepsilon_{B,-4}^{(1/4)(-p^2+2p+4)}\right)^{1/(4-p)} \nu_{17.3}^{-(p/2)} T_{d,-1}^{-(3p/4)+[p/[2(4-p)]]} \text{ mJy} \quad (2 < p < 3) . \quad \text{(C6)}$$

Jet break :
(Rhoads 1997)

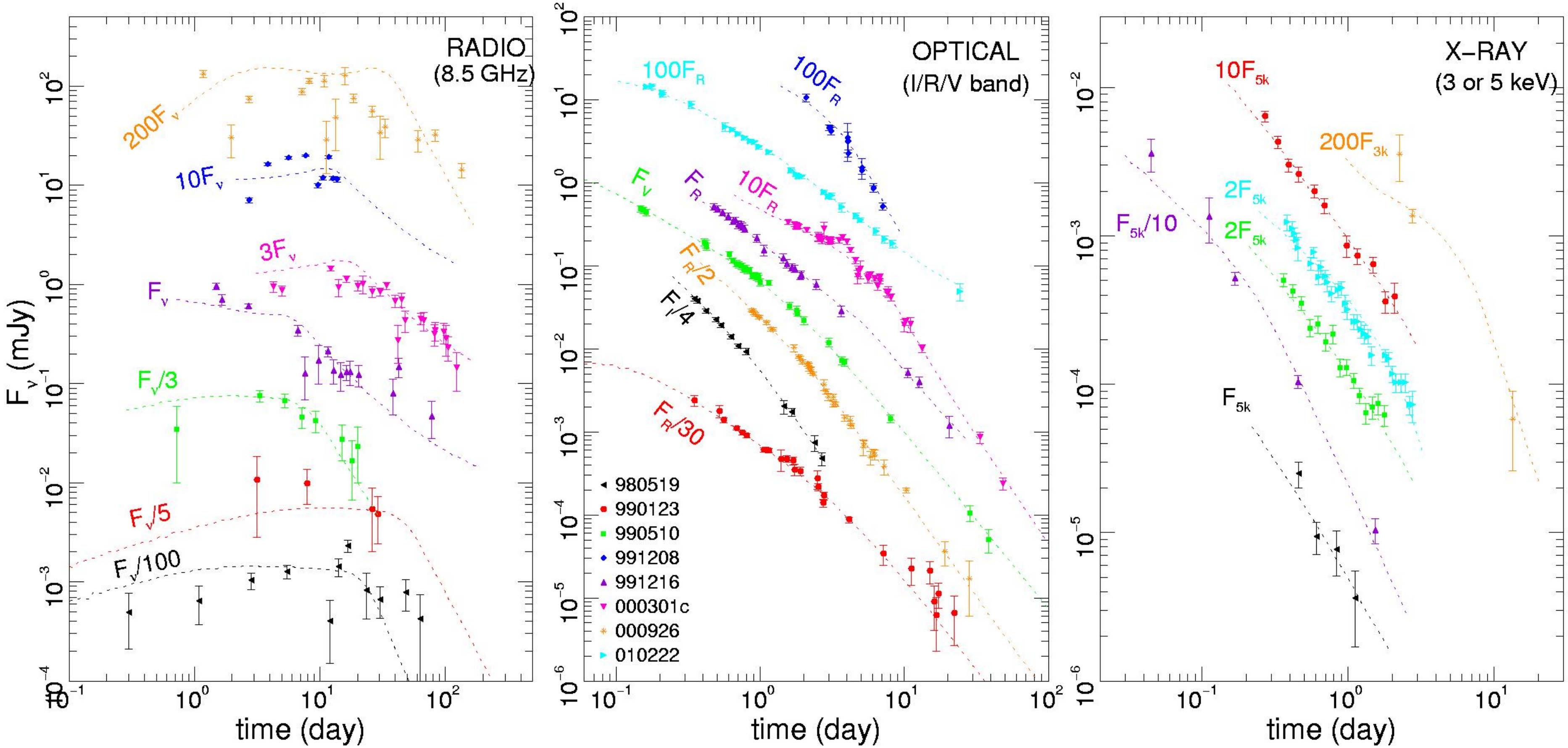
Geometrical effect : jet break is achromatic



Confronting the forward shock model to afterglow observations

- Pre-Swift era : very promising results (multi-wavelength fits) but already some problems

- Nice fits :



(Panaitescu & Kumar 2001)

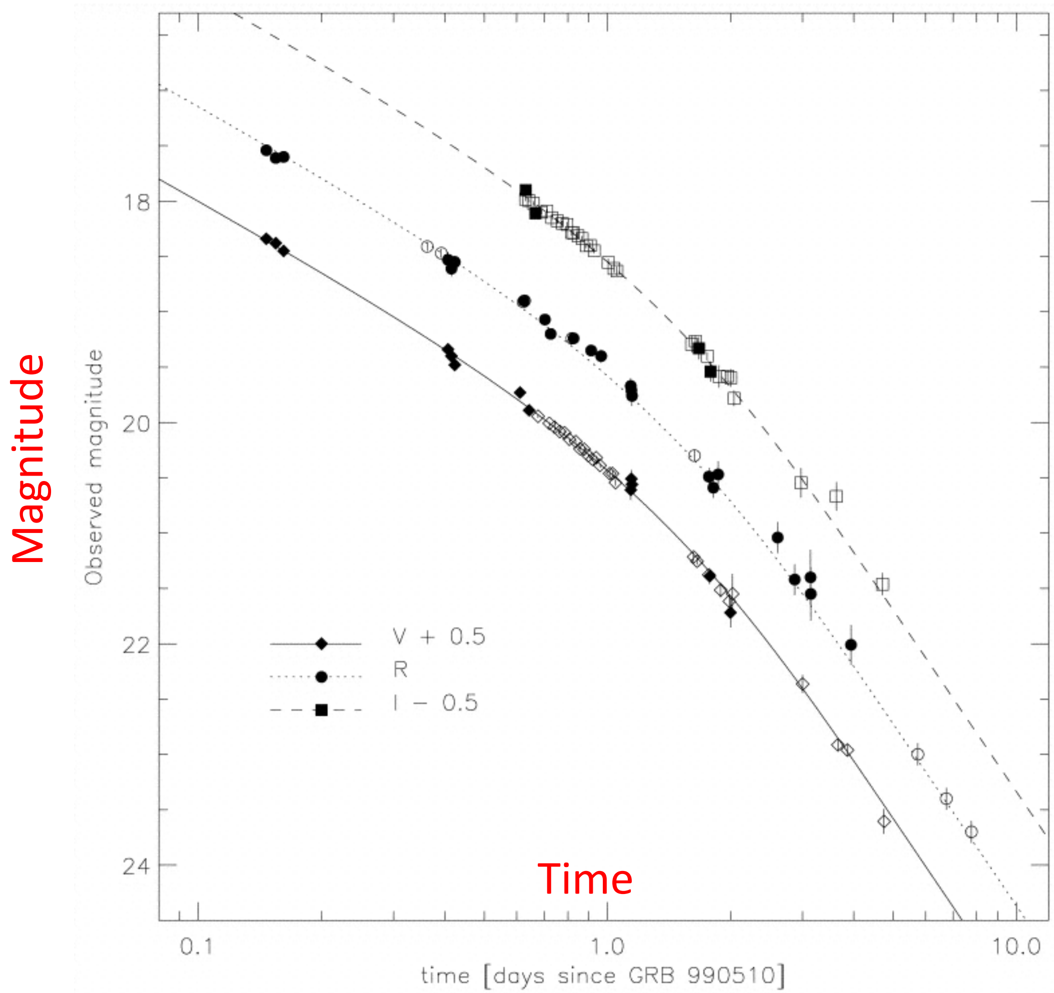
Confronting the forward shock model to afterglow observations

- Pre-Swift era : very promising results (multi-wavelength fits) but already some problems

- Nice jet breaks :

GRB 990510

Harrison et al. 1999



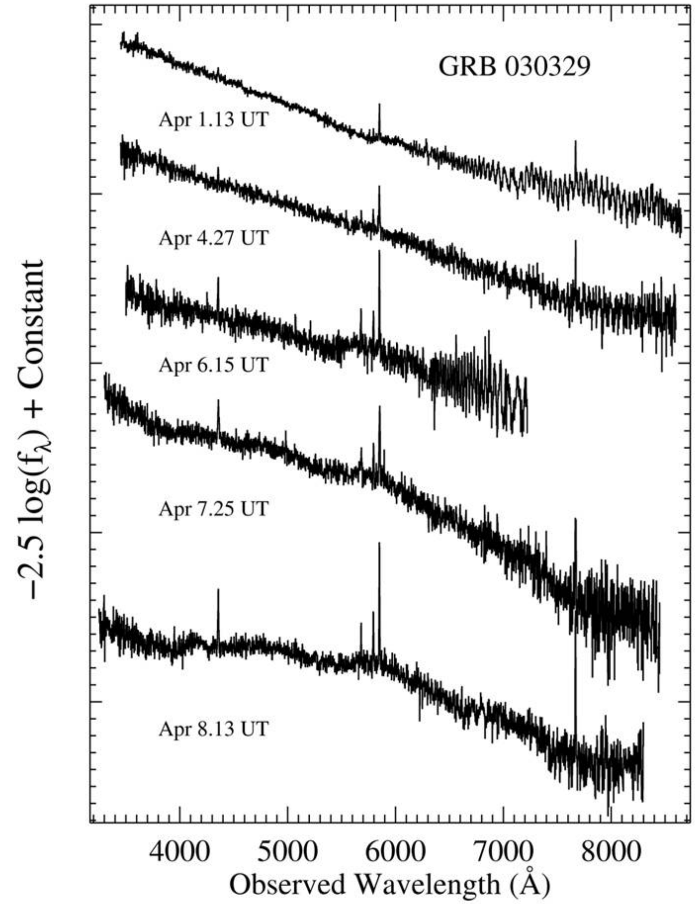
Confronting the forward shock model to afterglow observations

- Pre-Swift era : very promising results (multi-wavelength fits) but already some problems

- Potential problem : a low density uniform medium is usually found when a stellar wind or high density medium is expected for long bursts…
(Chevalier, Li & Fransson 2004)

n ~ 0.01 – 10 cm^{-3}
(Panaitescu & Kumar 2001)

e.g. GRB030329 : uniform medium with n ~ 2 cm^{-3} !
(Berger et al. 2003)



Effect of the external medium (1) | Forward (external shock)

Confronting the forward shock model to afterglow observations

- Pre-Swift era : very promising results (multi-wavelength fits) but already some problems

- Potential problem : the slope of the electron distribution is found to be $p < 2$ in many cases whereas shock acceleration theory would predict $2 < p < 2.5$?

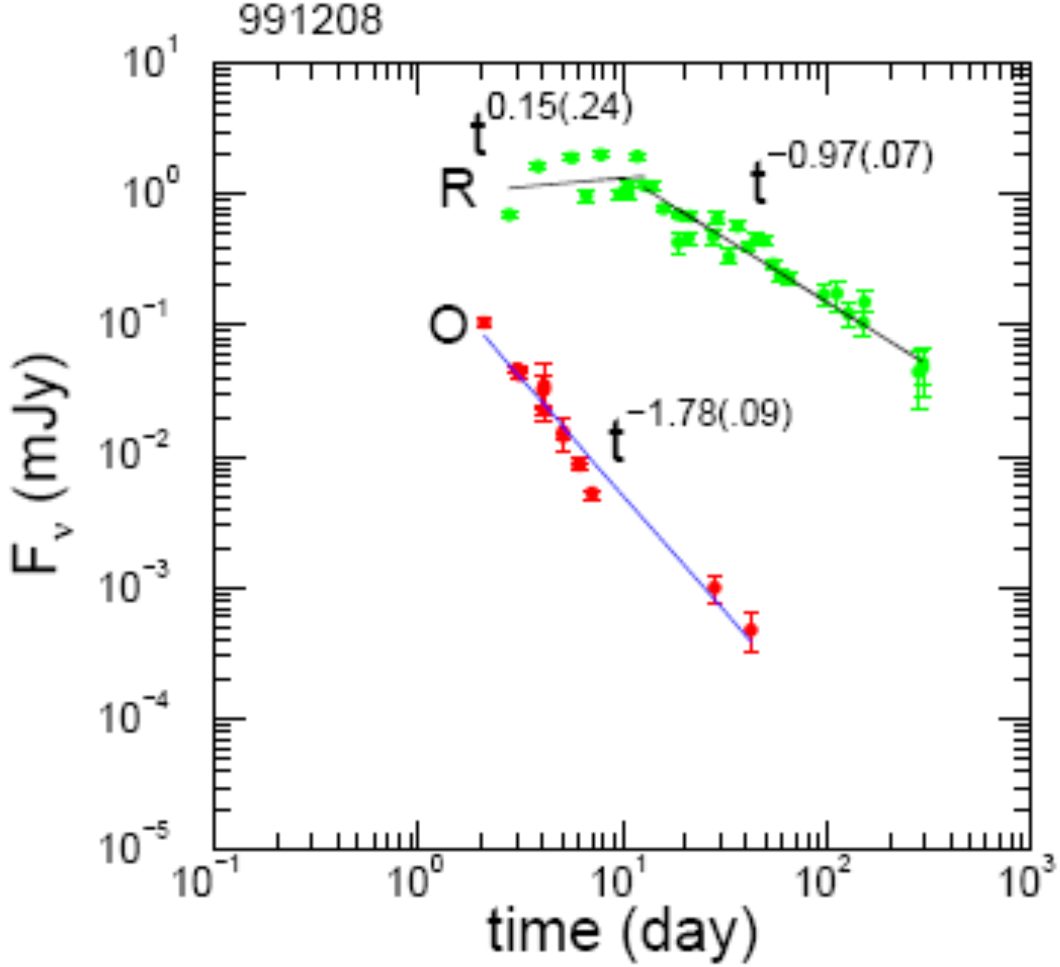
$p \sim 1.4 - 2.8$ (Panaitescu & Kumar 2001)

Confronting the forward shock model to afterglow observations

- Pre-Swift era : very promising results (multi-wavelength fits) but already some problems

- Potential problem : the radio afterglow temporal decay is often in contradiction with the theory.

(Panaitescu & Kumar 2004)



Confronting the forward shock model to afterglow observations

- Pre-Swift era : very promising results (multi-wavelength fits) but already some problems

- Swift era : new problems, especially with the early afterglow…

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 (N_e ?)
- 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 ?

…

Effect of the external medium (2) — 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.

- For a uniform shell : reverse shock is short-lived

- If $R_{spread} << R_{dec}$ (=thin shell =low-density external medium)

- RS is non-relativistic
- RS crosses the relativistic shell at R_{dec}

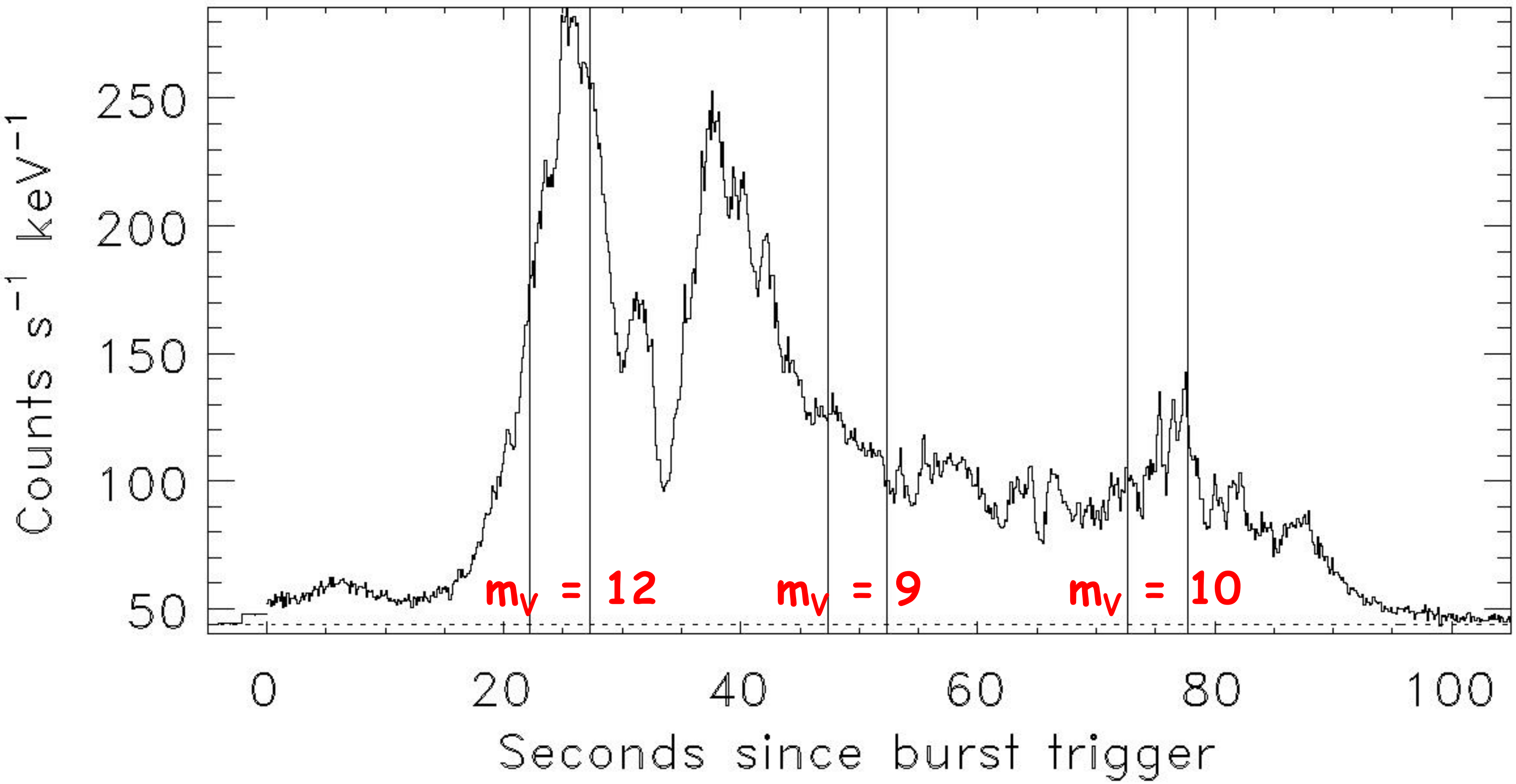
- If $R_{spread} >> R_{dec}$ (=thick shell=high-density external medium)

- RS is initially non-relativistic
- RS becomes ultra-relativistic at $R_{\mathrm{N}} \simeq \left(R_{\mathrm{dec}}^{3-s} R_{\mathrm{spread}}^{-1}\right)^{\frac{1}{2-s}}$
- RS crosses the relativistic shell at $R_{\mathrm{cross}} \simeq \left(R_{\mathrm{dec}}^{3-s} R_{\mathrm{spread}}\right)^{\frac{1}{4-s}}$

- Optical flash like in GRB 990123 ? (Sari & Piran 1999)

Problem : such optical flashes are rare

GRB990123 / ROTSE (Akerlof et al. 1999)



Effect of the external medium (2) | Reverse shock

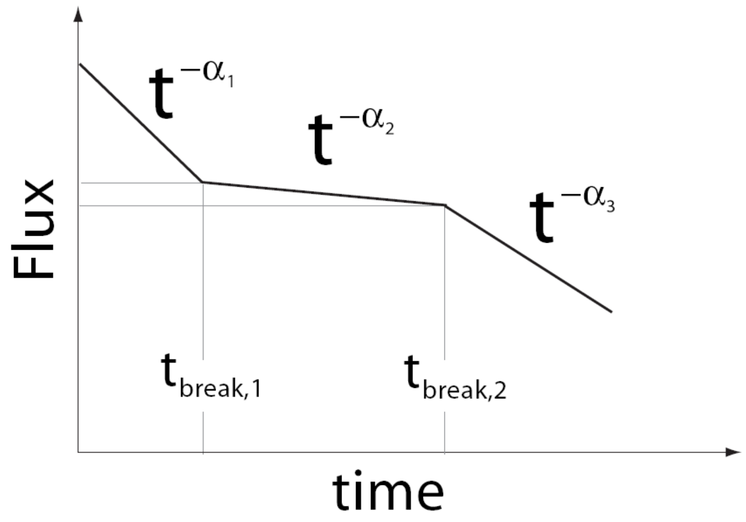
- When discussing the Reverse Shock, one often forgets that this shock wave is more similar to Internal Shocks tha to the Forward Shock.

- RS microphysics parameters = IS microphysics parameters ≠ FS microphysics parameters

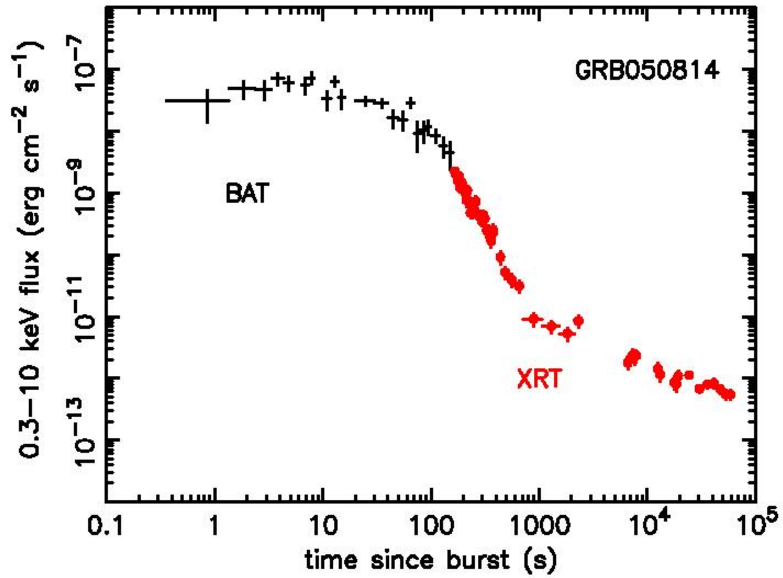
- IS contribute mostly in gamma-rays, why RS should produce optical ?

- If the outflow is variable, RS can be much more complicated than this simple picture, and can even be long-lived…

- X-ray plateaux (Swift)



Nousek et al. 2006



O'Brien et al.

- X-ray plateaux (Swift)

This plateau cannot be reproduced by the simplest version of the external shock model.

Most discussed possibility : late energy injection (Sari & Meszaros 2000)

→ **Efficiency crisis ?**

This scenario requires to add a large amount of energy to the FS.
(Panaitescu et al. 2006)

It is not really consistent with internal shocks (requires > 90 % efficiency !)

→ **Models of the central engine ?**

Effect of the external medium (3) | Problems with afterglow theory…

- Where are the jet breaks ?

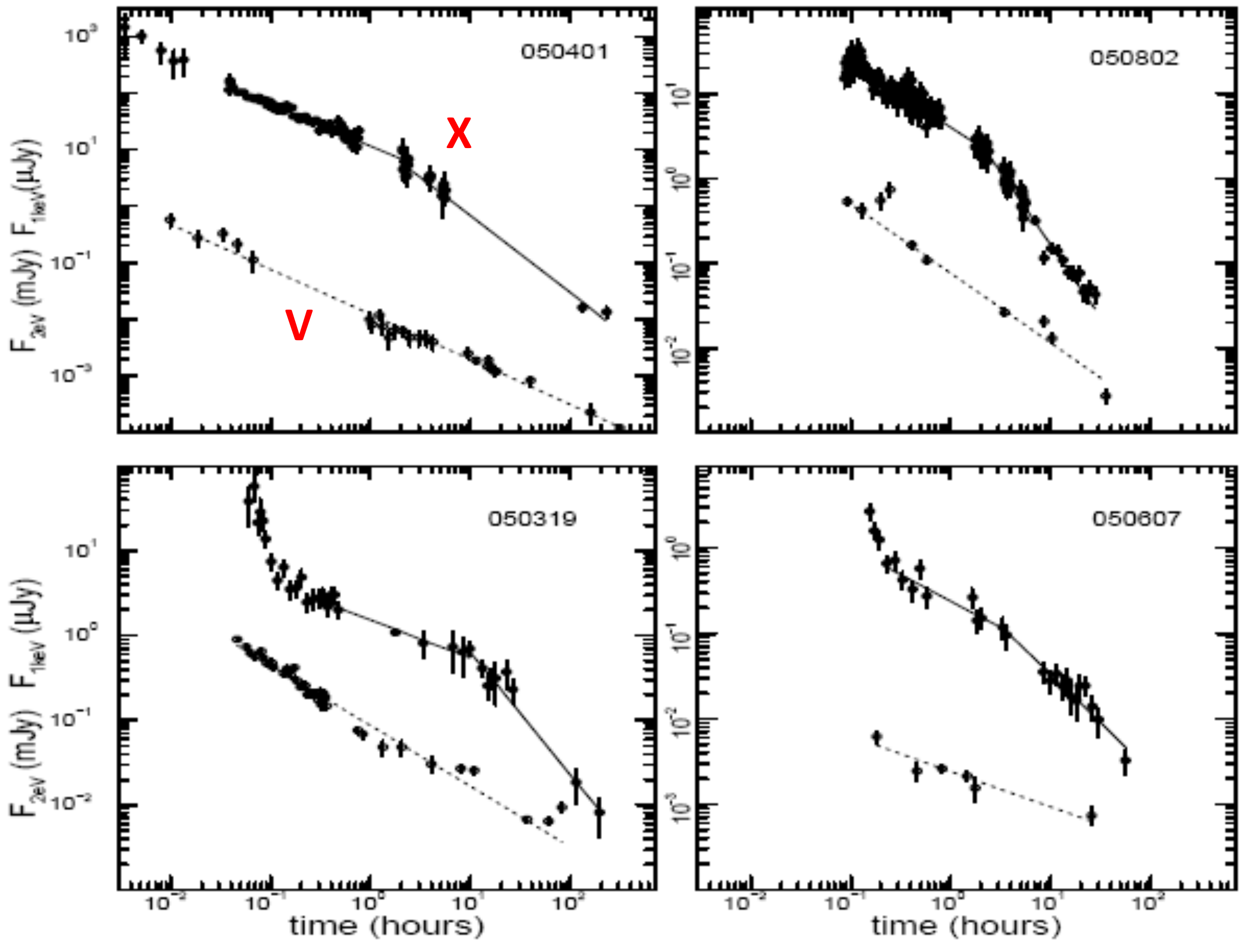
(Burrows & Racusin 2007)

Real achromatic breaks are rare in the Swift era…

- What are chromatic breaks ?

(Panaitescu 2006)

Difficult to explain
in FS model
(varying microphysics ?)

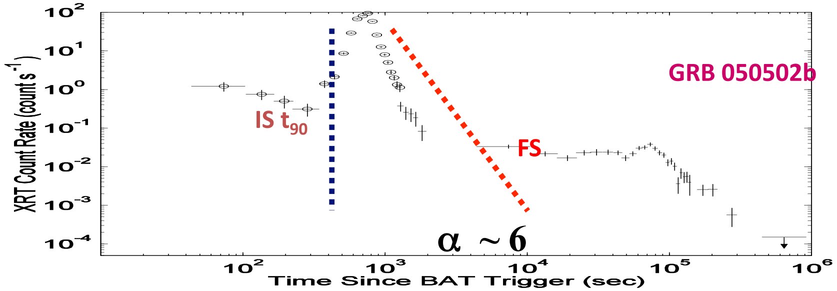


- X-ray flares (Swift)
(Burrows et al. 2006)

Usually interpreted as late time activity of the central engine.

Forward shock : rise and decay are too steep.

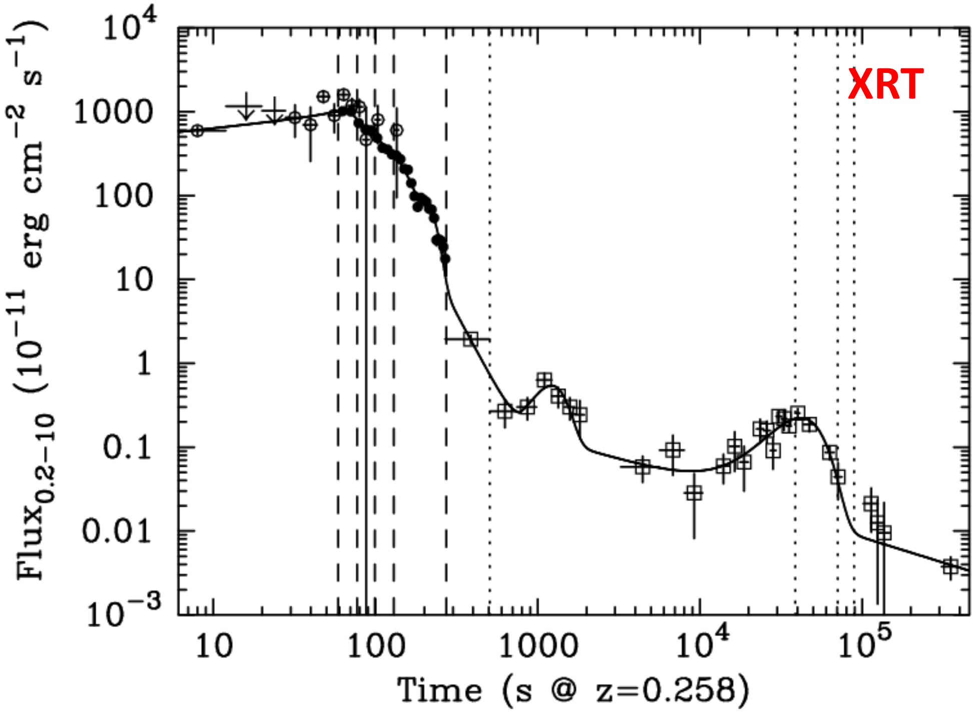
Internal shocks : duration seems very long.



(Burrows et al; Falcone et al, 2005)

- Short GRB afterglows are also complex (plateau, soft bumps, …)

Requirements such as late energy injection could be even more difficult for short burst central engines.



e.g. GRB 050724
(Campana et al. 2006)

- Proposed solutions in the standard FS model are not fully satisfactory

- Constraints on the central engine
- Constraints on the energy budget

- Other possibilities :

Two components (Ghisellini et al. 2007)

Long-lived reverse shocks (Uhm & Beloborodov 2007 ; Genet, Daigne & Mochkovitch 2007)

Requirements :

- FS is radiatively inefficient

(problems with shock acceleration/magnetic field amplification in ultra relativistic shocks ?)

- Tail of low Lorentz factor material

Effect of the external medium (3)

- A possible test to distinguish between the models : the high energy afterglow

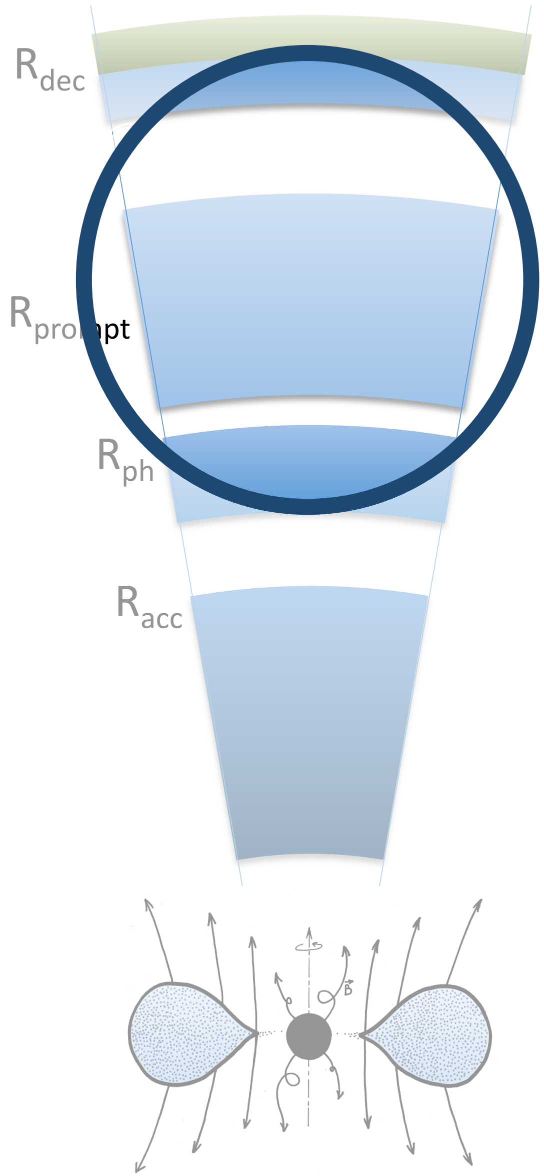
- Fermi : long lasting emission is seen in a few LAT GRBs

but …

there are no cases with a simultaneous multi-wavelength Swift-like observation…

« Internal processes » Energy reservoir and extraction mechanism

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.*



Energy reservoir & extraction mechanism ?

Microphysics ?

Radiative processes ?

Matter dominated vs magnetic outflow ?

Thermal emission ?
Shock waves ?
Reconnection ?

Synchrotron ? IC ? …

Possible energy reservoirs and extraction mechanisms :

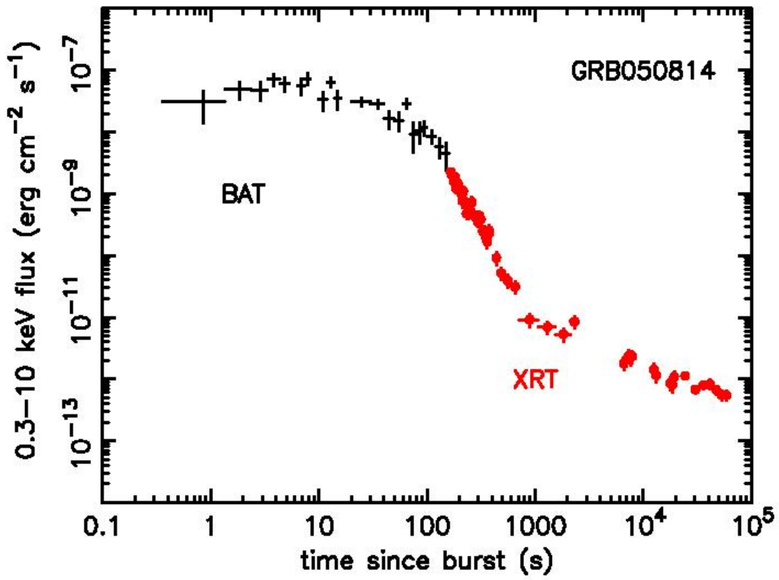
- Thermal energy
  Photospheric emission
- Kinetic energy
  Internal shocks + shock acceleration
- Magnetic energy
  Magnetic dissipation (e.g. reconnection)

Note that a large magnetization probably exclude internal shock waves.

Prompt emission (1) : The End ? | High (co-)latitude emission

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).

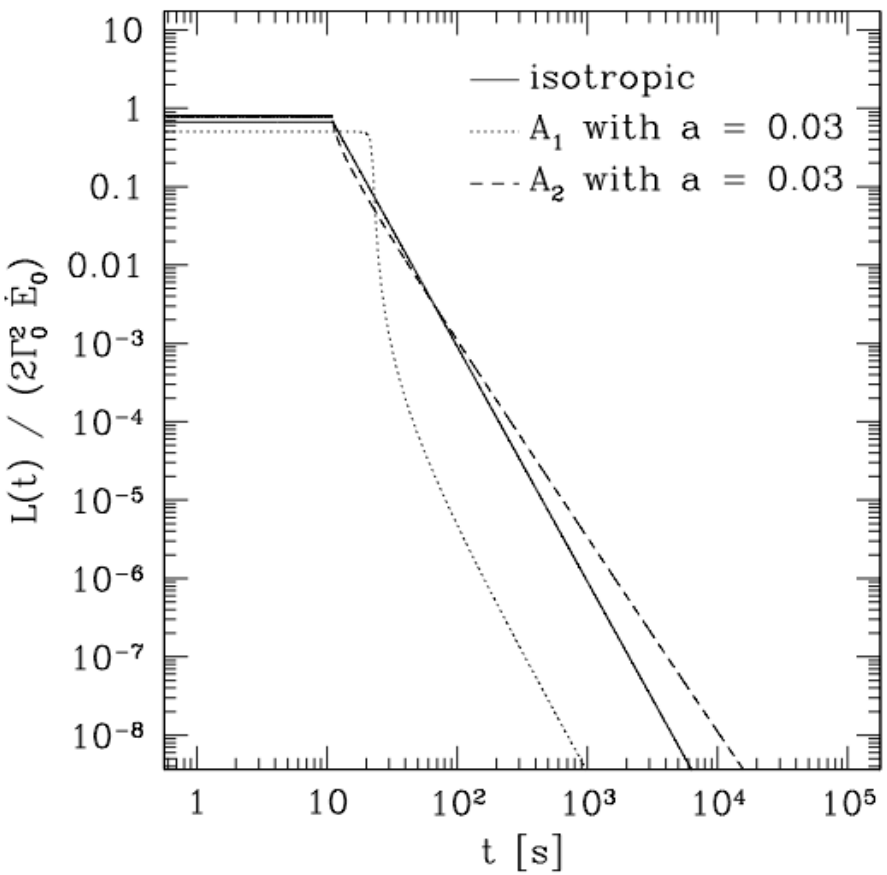
- Bolometric flux decays as t_{obs}^{-3}
- Predict a X-ray tail at the end of the prompt (Kumar & Panaitescu 2002)
- Observed by Swift ?   Too steep decay ?



O'Brien et al.

High (co-)latitude emission

- Anisotropic emission in the comoving frame ?



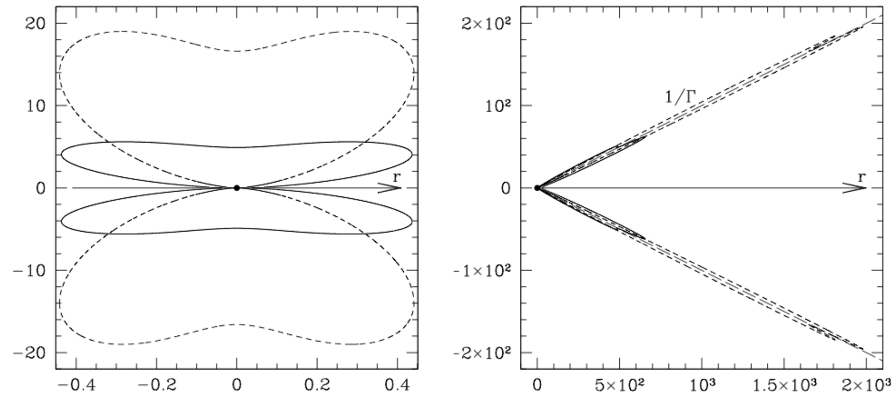


Figure 1. Diagram of angular distribution of radiation $A_1(\theta)$ (electrons accelerated preferentially along **B**) measured in the source rest frame (left) and transformed to the observer frame (right). Solid curves correspond to $a = 0.1$ and dashed to $a = 0.03$. Rotation of the shown curve about the horizontal axis gives the 3-dimensional diagram.

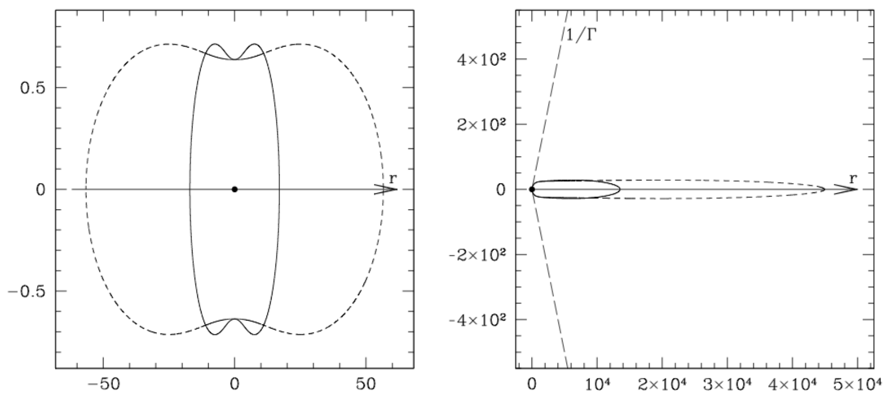


Figure 2. Same as in Figure 1 but for the angular distribution $A_2(\theta)$ (electrons accelerated preferentially perpendicular to **B**).

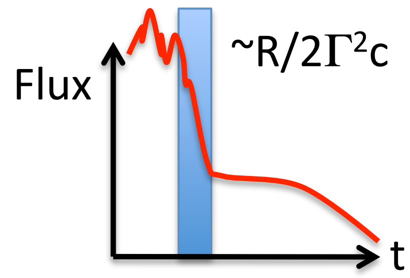
Beloborodov, Daigne, Mochkovitch & Uhm 2010

Prompt emission — Constraints ?

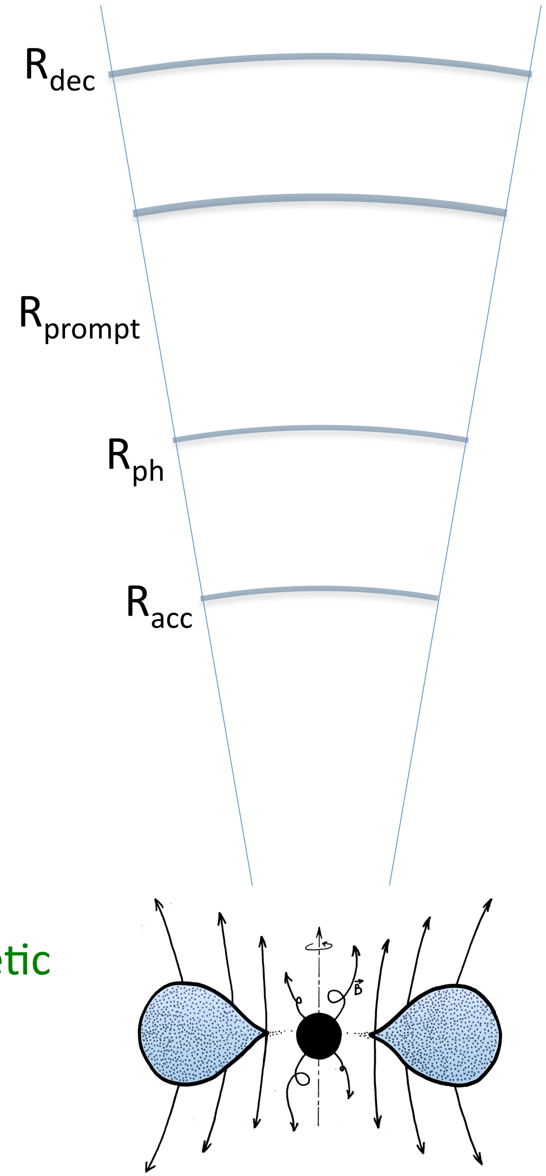
- Magnetization : Polarization measurements in γ-rays still difficult
  (see however Willis et al. 05; Kalemci et al. 07; McGlinn et al. 07; Götz et al. 09; McGlinn et al. 09)

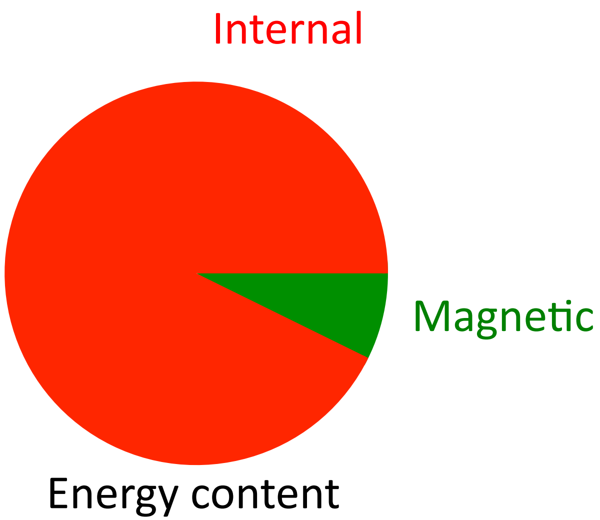
- Lorentz factor : high values to avoid a strong $\gamma\gamma$ annihilation
  - -pre-Fermi era: $\Gamma > 50-100$
  - -Fermi: Γ may be much larger – e.g. GRB 080916C: $\Gamma \sim 900$ (Abdo et al. 2010)
  - -More realistic estimates reduce Γ_{min} by at least a factor ~ 2-3
  (Granot et al. 08 ; Aoi et al. 10 ; Zou et al. 10 ; Hascoët et al. 2011)

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

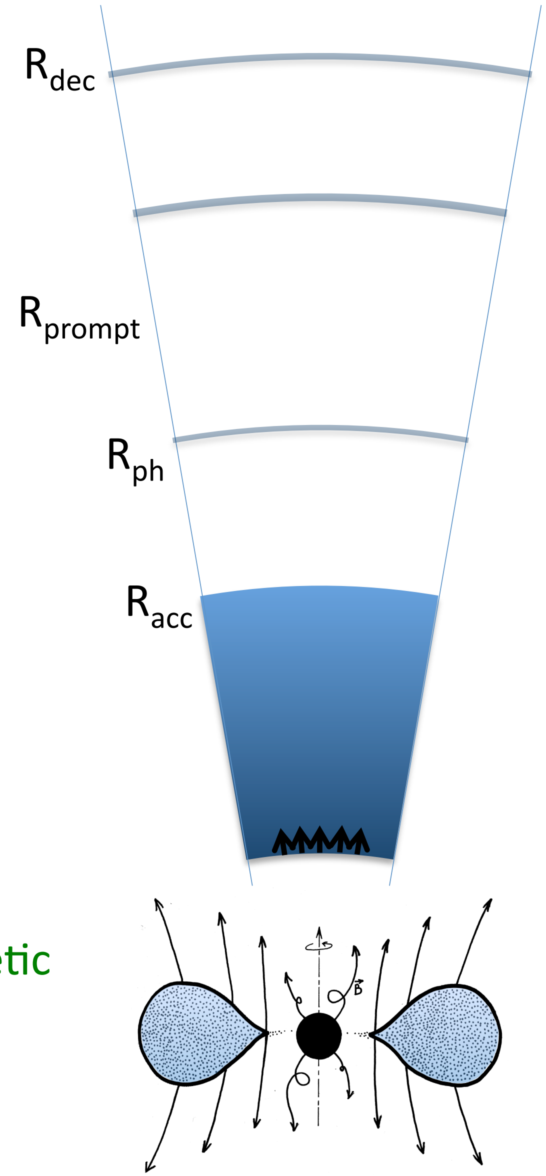


Standard « fireball »

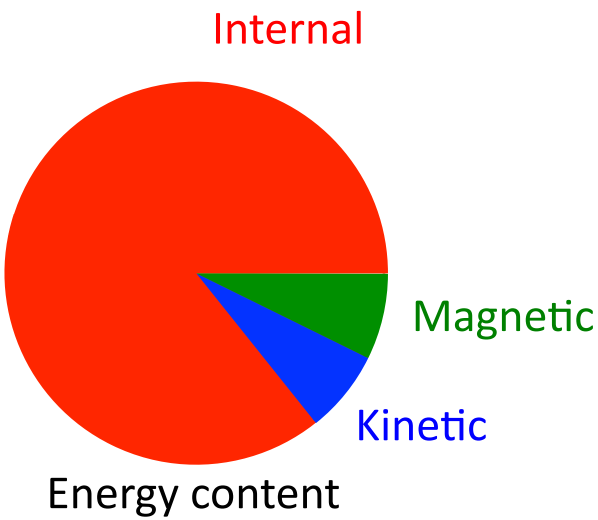


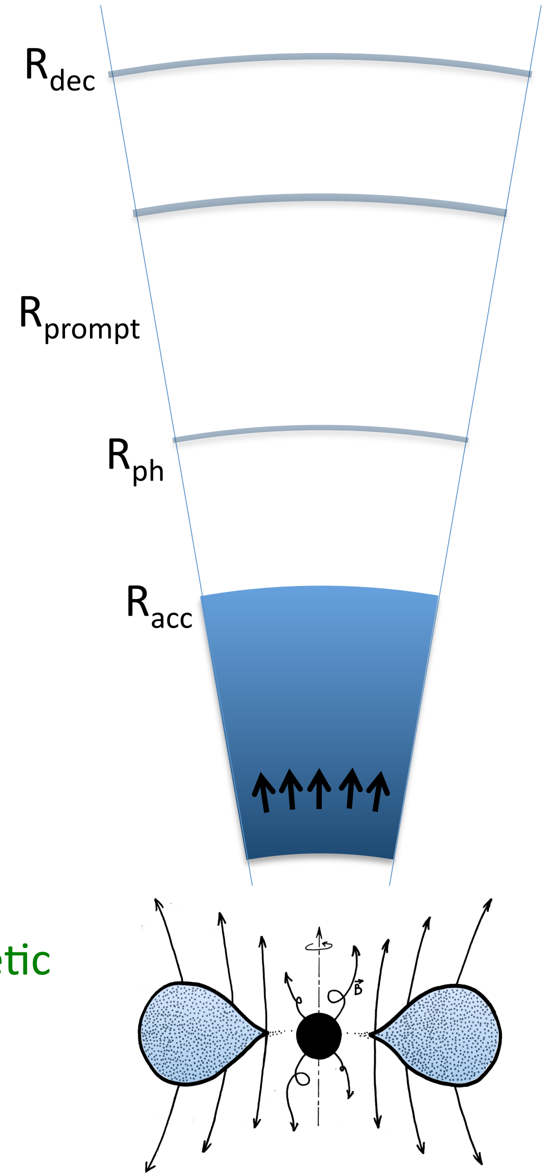


Initial energy release :
negligible magnetization

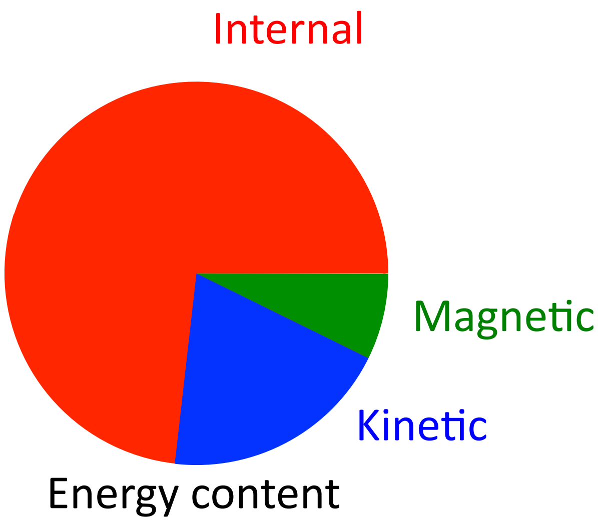


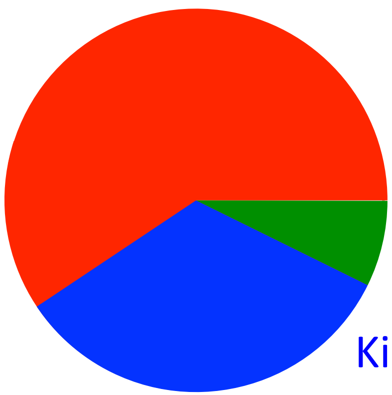
Acceleration :
adiabatic expansion

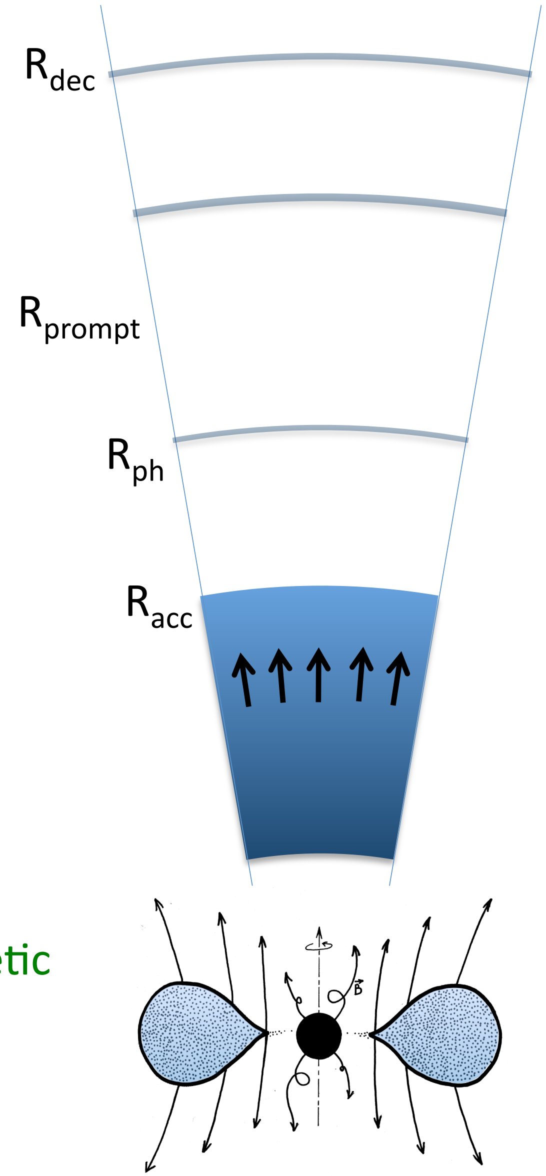




Acceleration :
adiabatic expansion

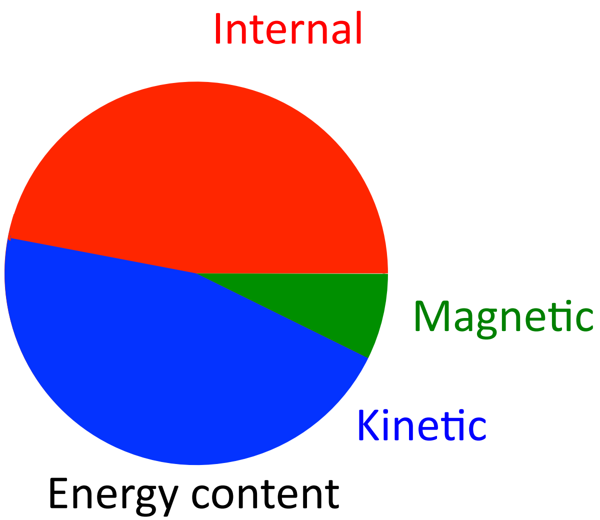


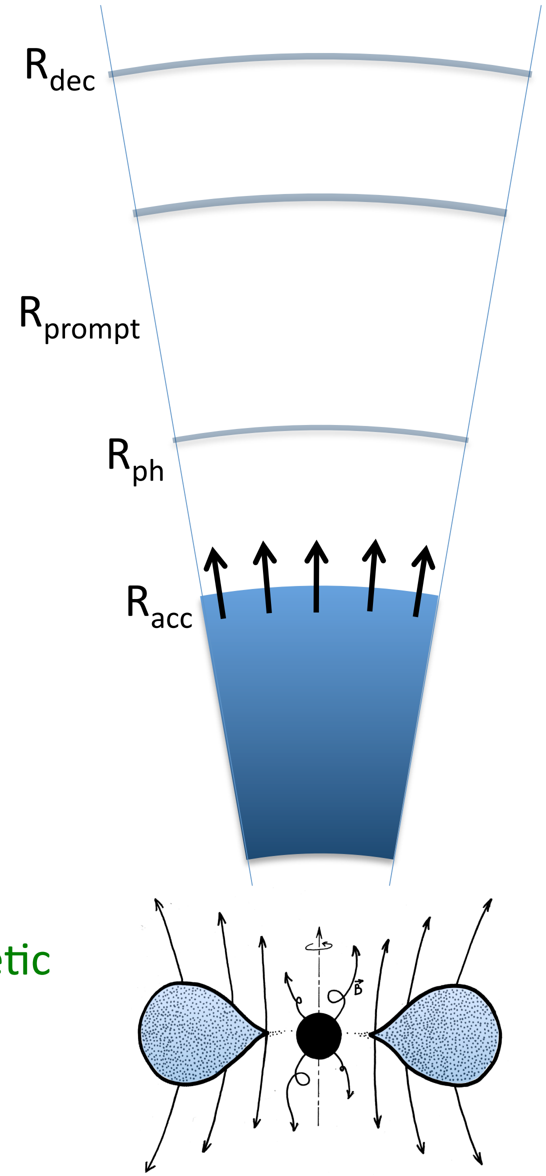




Acceleration :
adiabatic expansion

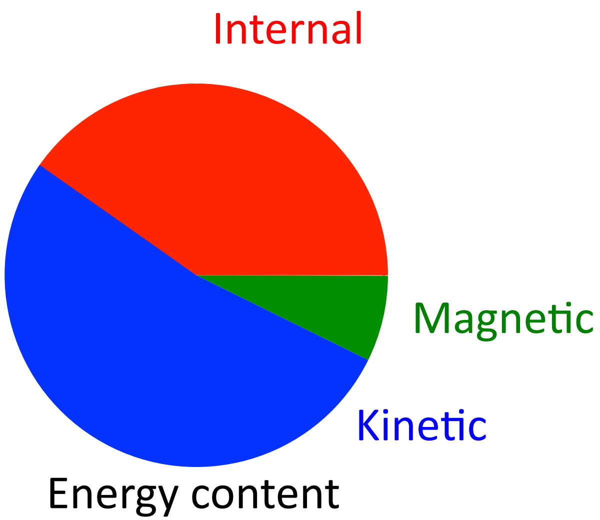
Prompt emission | Standard « fireball »

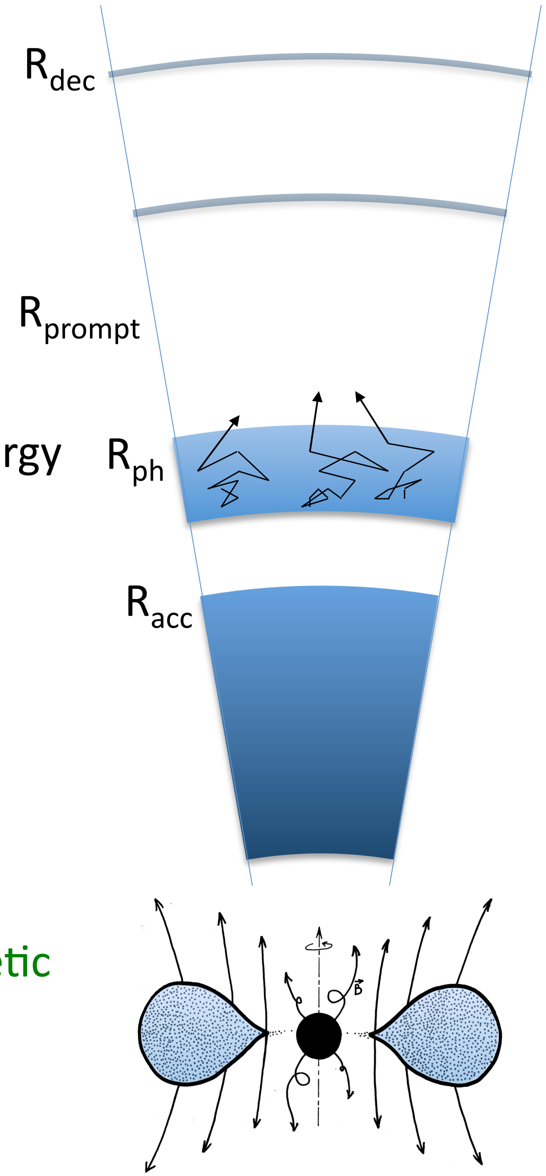




Acceleration :
adiabatic expansion

Photosphere : internal energy can be radiated.





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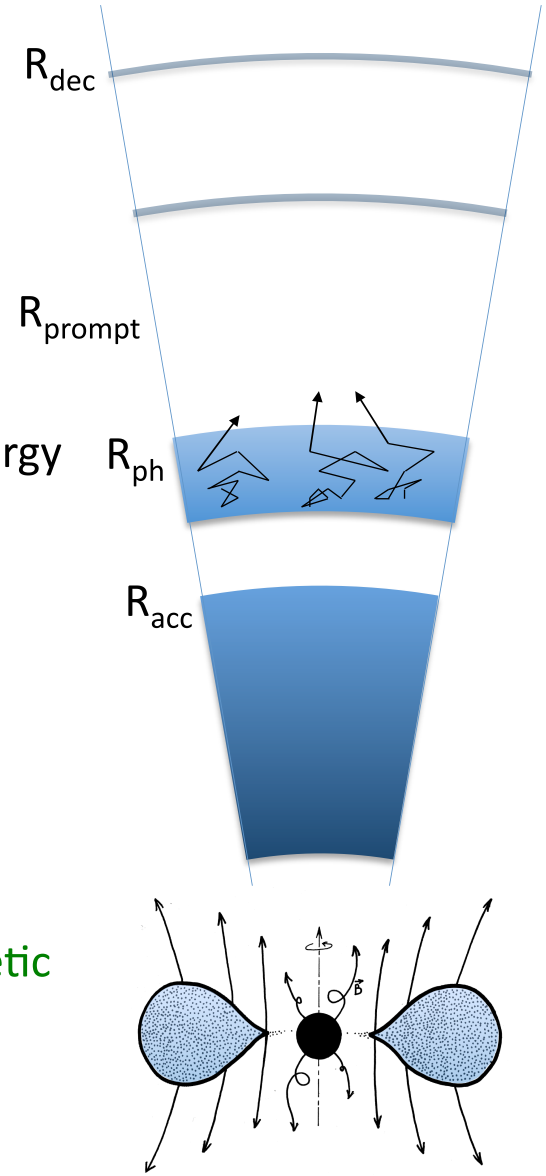
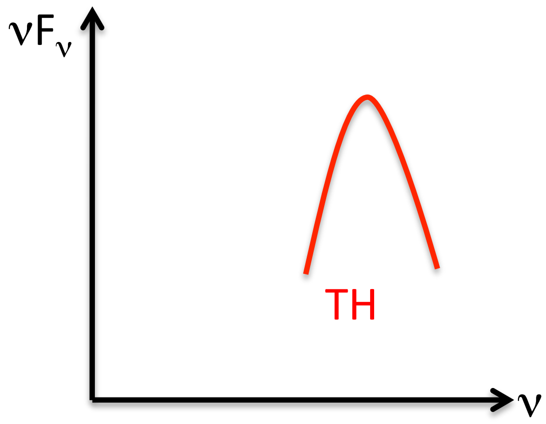
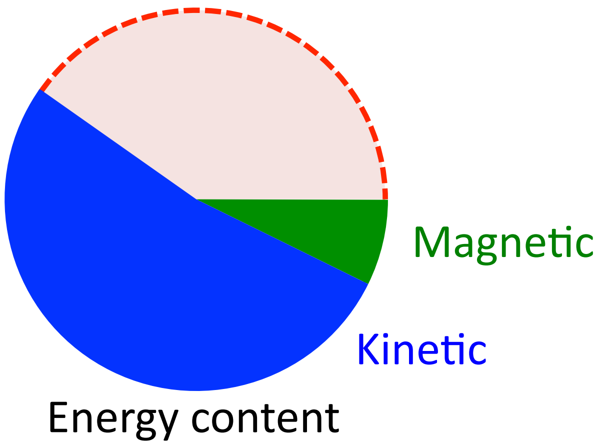
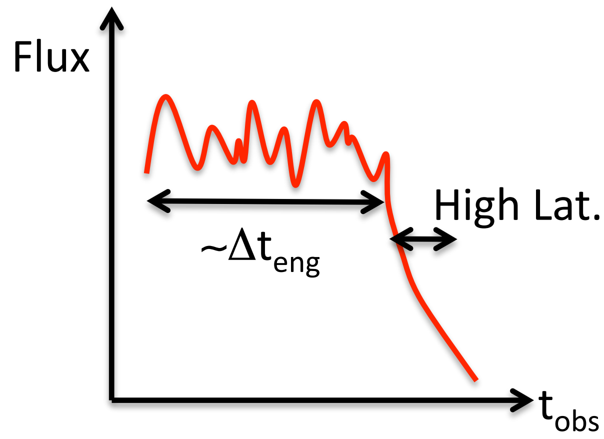




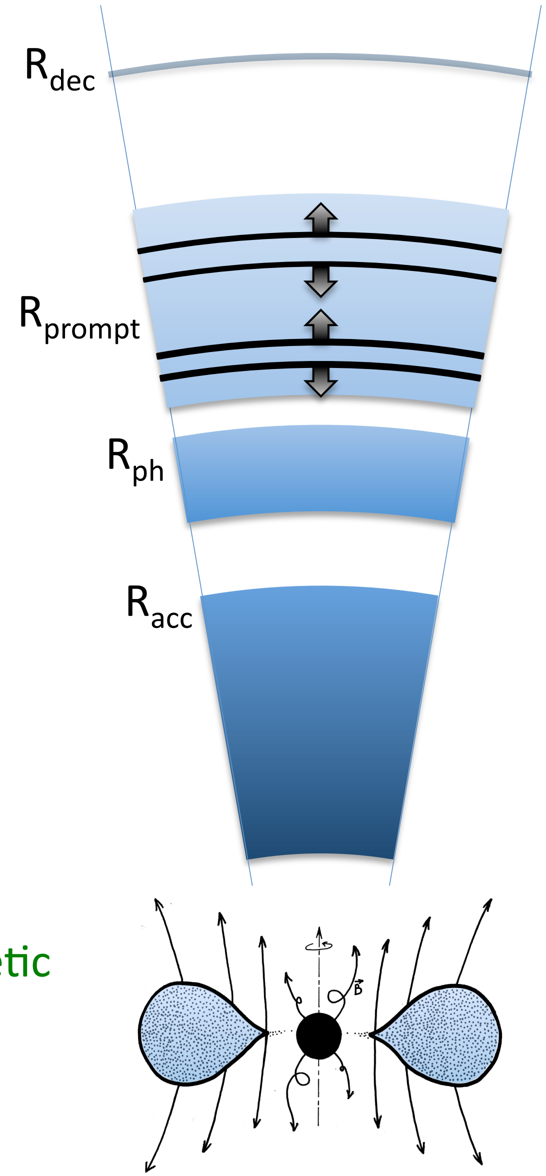


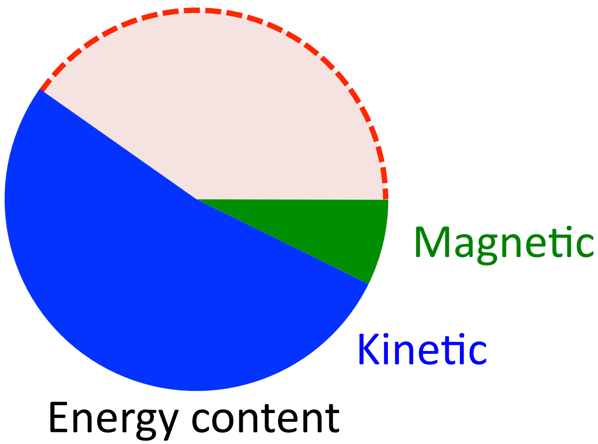


Prompt emission | Standard « fireball »

Non-thermal emission :
Internal shocks

A fraction of the kinetic energy is radiated





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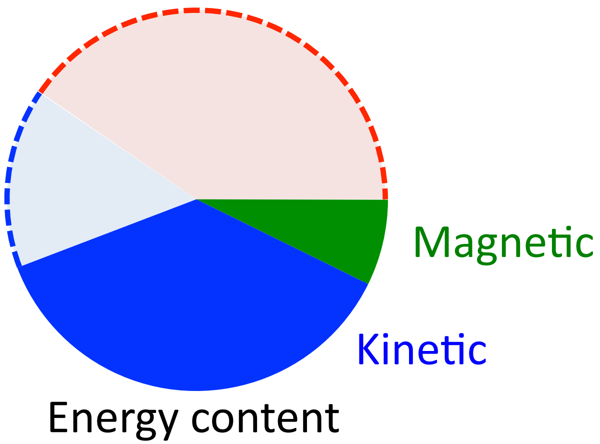
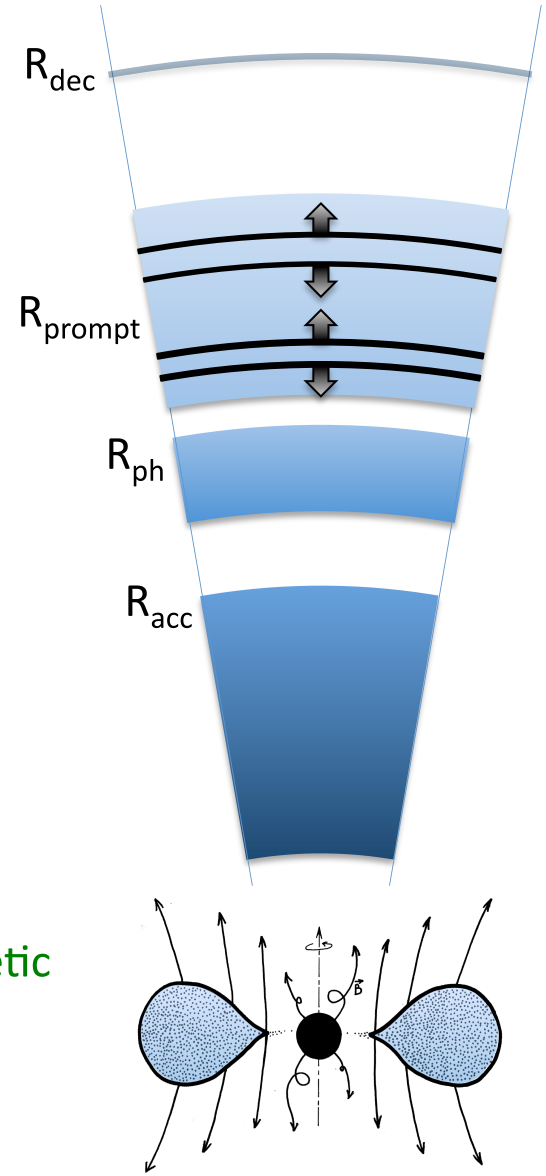
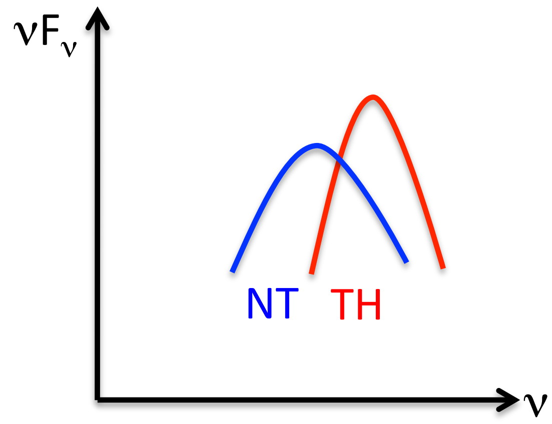
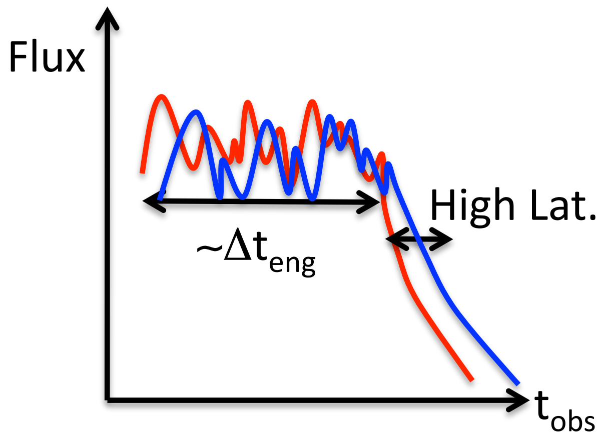








At the photosphere, the outflow becomes transparent for its own radiation. If its internal energy content has not be entirely converted into kinetic energy, it can be radiated.

Fireball model :

- Above R_{sat}, opacity is dominated by Thomson diffusion on ambient electrons
- Photospheric radius :

$$R_{\rm ph} \simeq 5.9 \times 10^{12} \left(\frac{\dot{E}}{10^{52}\,{\rm erg.s^{-1}}} \right) \left(\frac{\Gamma_0}{100} \right)^{-3} \,{\rm cm}$$

- Temperature and luminosity at the photosphere :

$$kT_{\rm ph} \simeq kT_0 \left(\frac{R_{\rm ph}}{R_{\rm sat}} \right)^{-2/3}$$

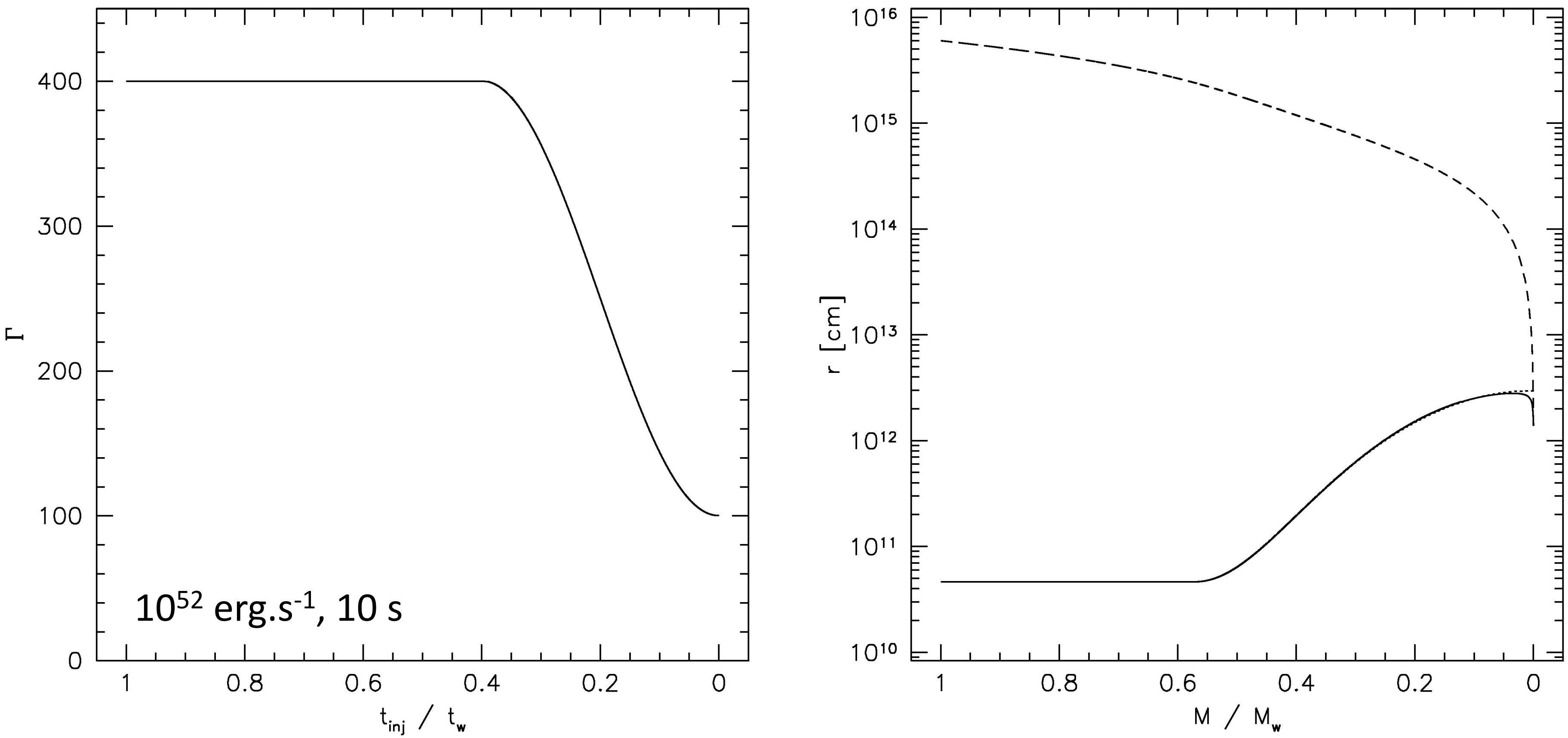
$$kT_0 \simeq 1.3 \left(\frac{\dot{E}}{10^{52}\,{\rm erg.s^{-1}}} \right)^{1/4} \left(\frac{M_{\rm BH}}{10\,M_\odot} \right)^{-1/2} \,{\rm MeV}$$

$$L_{\rm ph} \simeq \dot{E} \left(\frac{R_{\rm ph}}{R_{\rm sat}} \right)^{-2/3}$$

$$R_{\rm sat} \simeq 9 \times 10^{8} \left(\frac{M_{\rm BH}}{10\,M_\odot} \right) \left(\frac{\Gamma_0}{100} \right) \,{\rm cm}$$

At the photosphere, the outflow becomes transparent for its own radiation. If its internal energy content has not be entirely converted into kinetic energy, it can be radiated.

- If the outflow is variable, each region has its own photospheric radius, … : the photospheric emission is variable and trace the history of the relativistic ejection.



Daigne & Mochkovitch 2002

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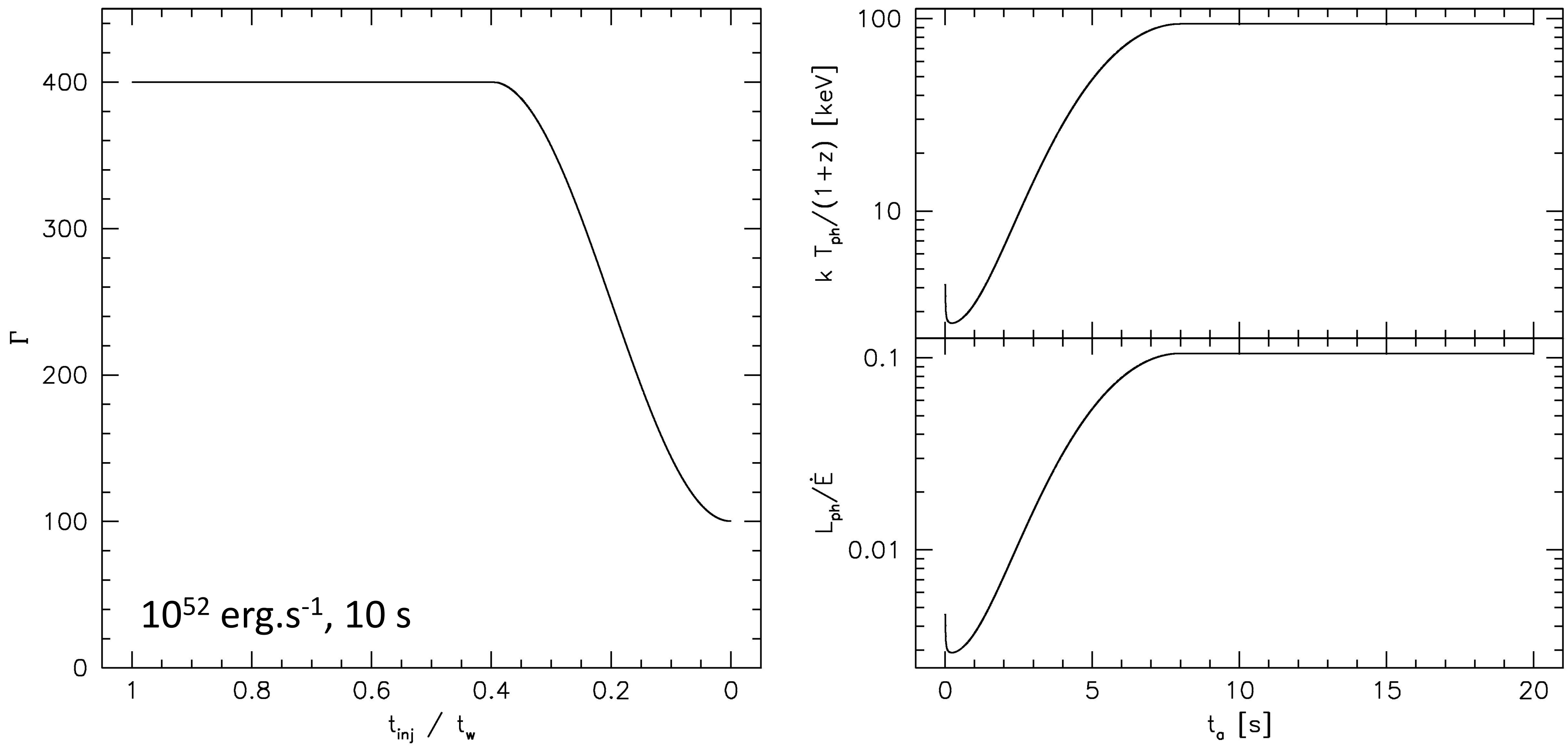

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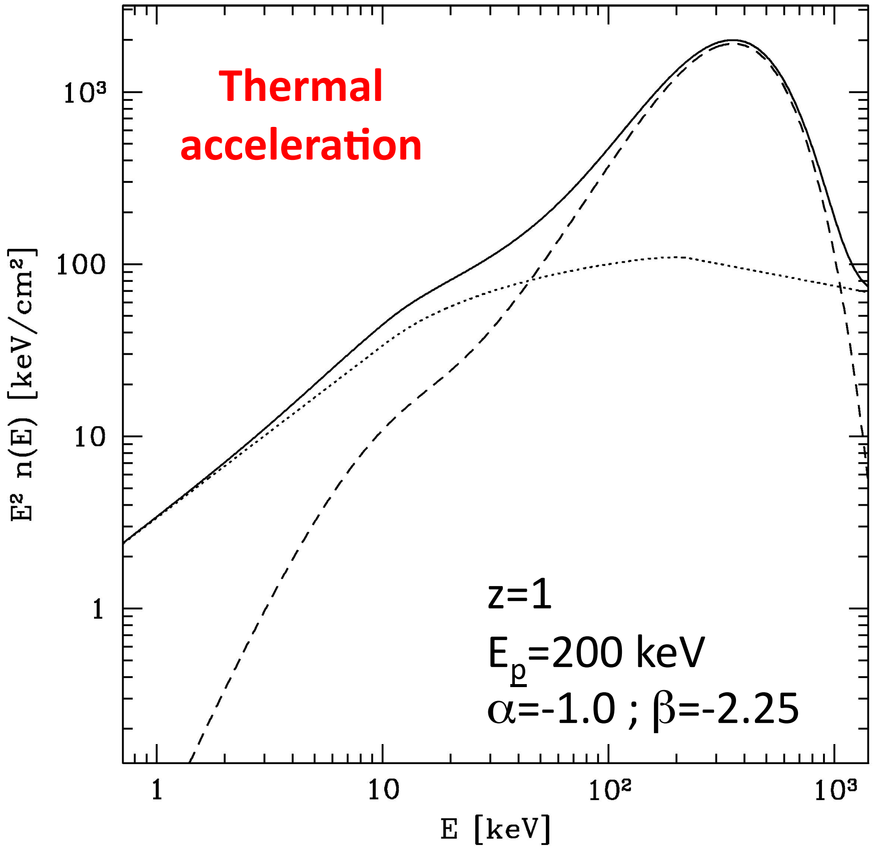


(Daigne & Mochkovitch 2002)

Prompt emission (3) — Internal shocks

The central engine is expected to be highly variable on different timescales (dynamical time → accretion time). Therefore, the ejected mass flux and energy flux should also vary on similar timescales : different regions in the outflow have initially different Lorentz factors. This leads to the formation of shock waves (« internal shocks », Rees & Meszaros 1994).

- As relative velocities are small (ultra-relativistic outflow), internal shocks form at large distance from the central source : usually $R_{is} > R_{ph}$.

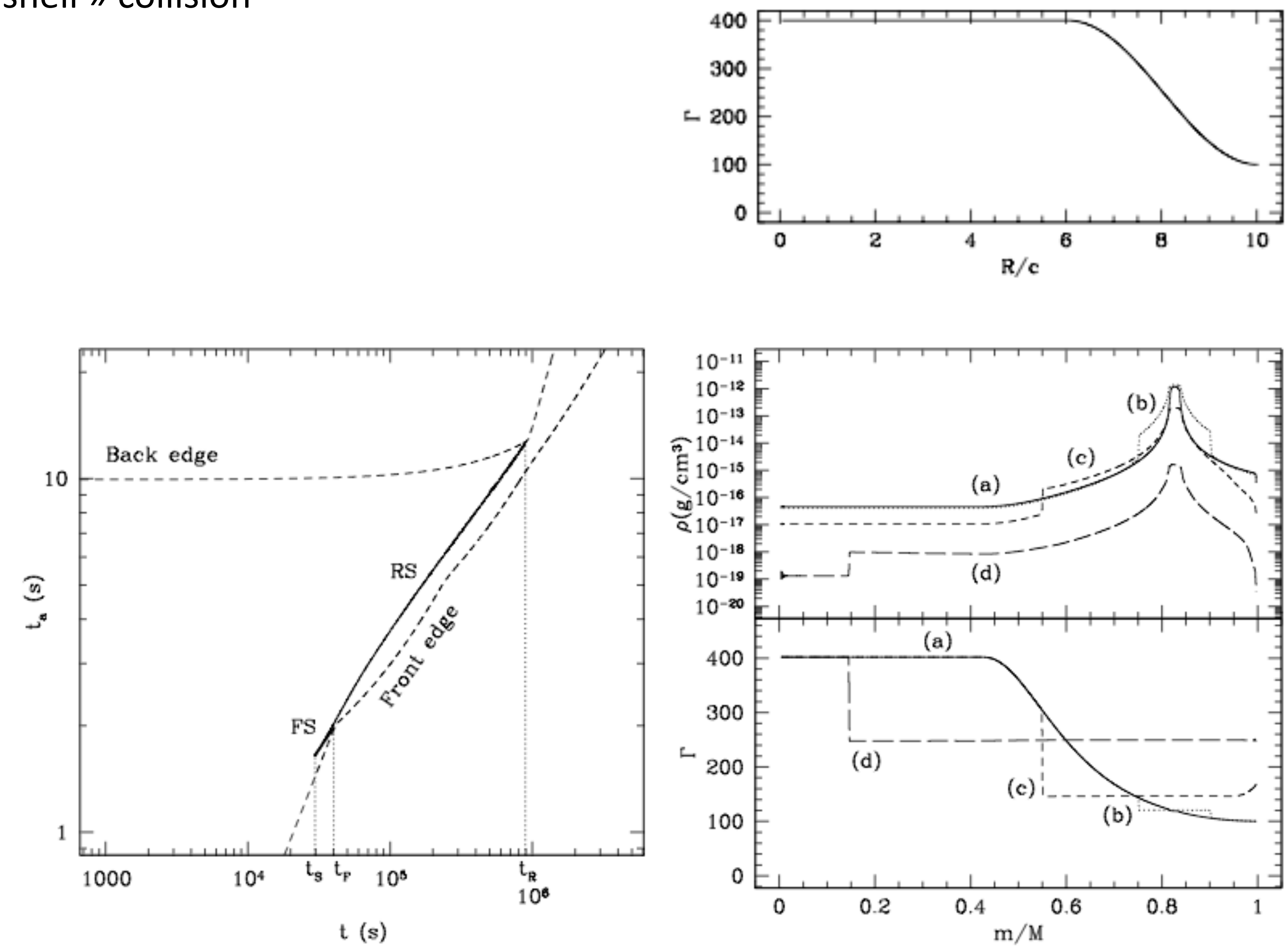
- The observed variability in the lightcurve is a miror of the central engine activity.

- Dynamics :

Kobayashi et al. 1997 (discrete « shells ») ;
Daigne & Mochkovitch 1998 (discretization of a continuous outflow) ;
Daigne & Mochkovitch 2000 (1D relativistic hydro)

- Radiation : Daigne & Mochkovitch 1998 ; Bosnjak, Daigne & Dubus 2009

- Hydro : « two shell » collision



Daigne & Mochkovitch 2000

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- Radius of internal shocks :

$$R_{\rm is} \simeq \Gamma_0^2 c t_{\rm var} \simeq \left(3\times 10^{13} \to 3\times 10^{16}\right) \left(\frac{\Gamma_0}{300}\right)^2 \left(\frac{t_{\rm var}}{10\,{\rm ms} \to 10\,{\rm s}}\right)\ {\rm cm}$$

- Efficiency of internal shocks : $f_{\rm IS} \simeq f_{\rm dyn} \times \epsilon_{\rm e} \times f_{\rm rad}$ Max 10 % ?

$f_{\rm dyn}$ → 10-40 % ?

$\epsilon_{\rm e}$ → 0.1 – 1/3 ?

$f_{\rm rad}$ → 1 ?

Prompt emission (3) — Internal shocks

The central engine is expected to be highly variable on different timescales (dynamical time → accretion time). Therefore, the ejected mass flux and energy flux should also vary on similar timescales : different regions in the outflow have initially different Lorentz factors. This leads to the formation of shock waves (« internal shocks », Rees & Meszaros 1994).

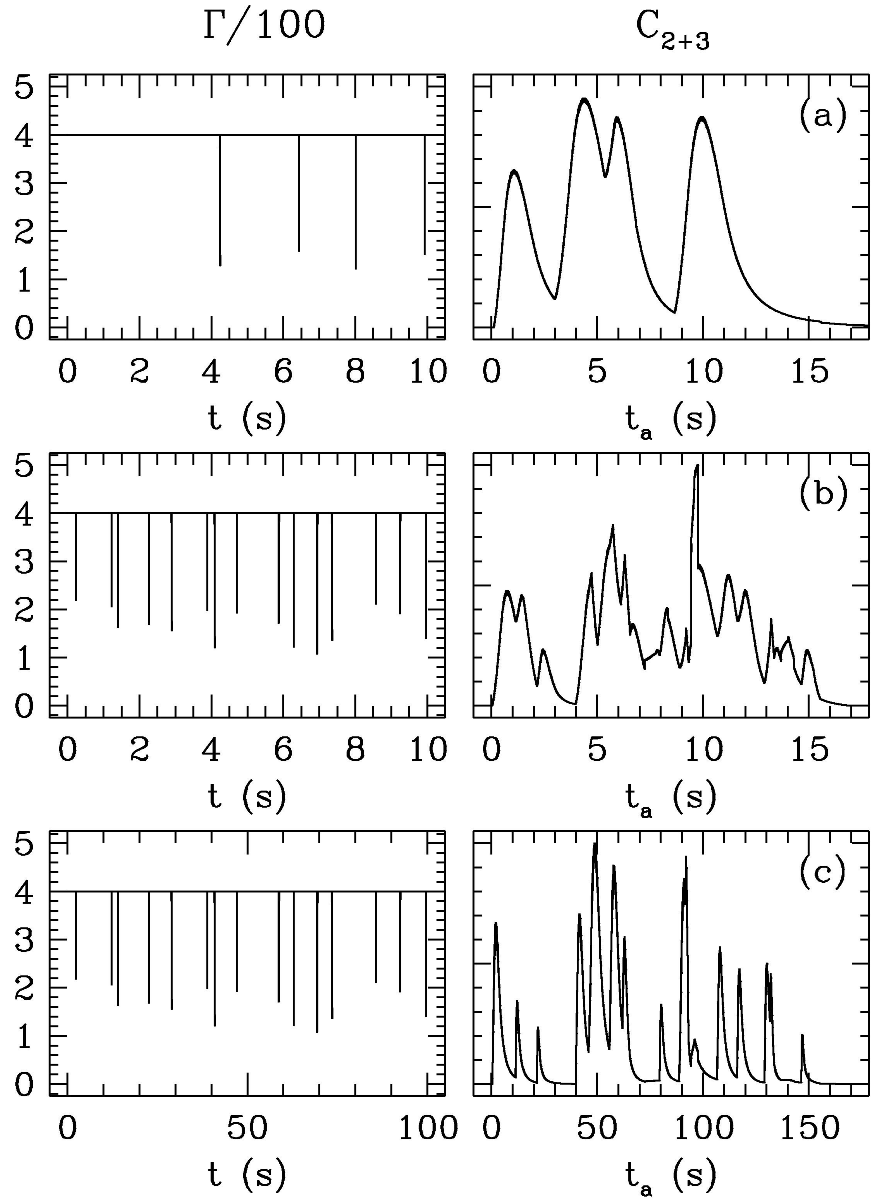
- Radiative processes : syn vs IC ?

Synchrotron radiation is favored but problem with slope α…

Nice features of the model :

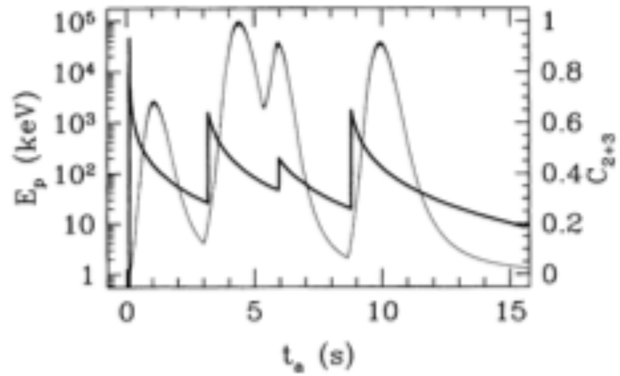
- Variability in lightcurves
- Spectral evolution (pulse width, time lags, HIC, HFC, …)
- GRB diversity (XRFs, XRRs, …)

- Lightcurves

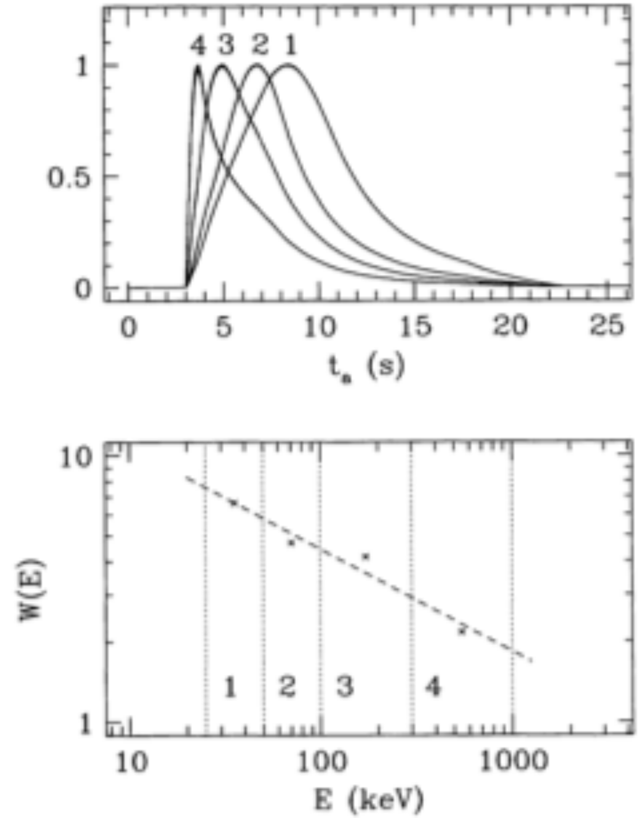


Daigne & Mochkovitch 1998

- Spectral evolution



- Pulse



Prompt emission (3) | Internal shocks

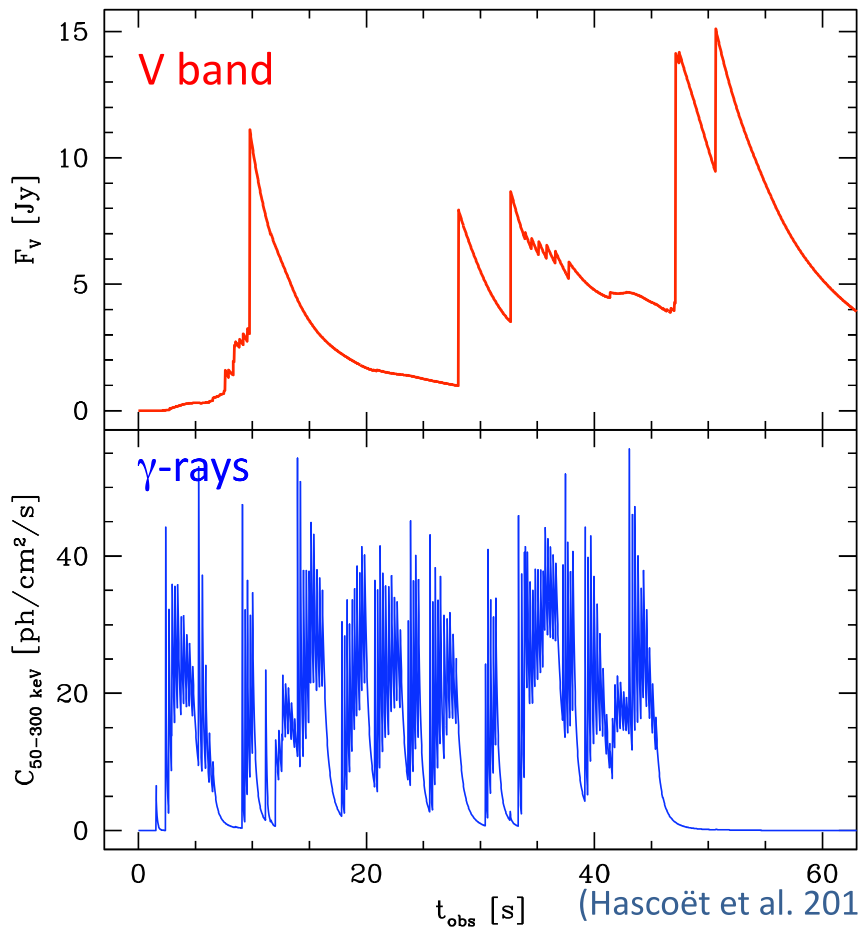
Prompt optical emission

- Variable prompt optical emission is expected from internal shocks

(see e.g. D. Götz et al. on GRB 041219A)

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

(Li & Waxman 2008 ;
Hascoët et al. 2011 in preparation)



(Hascoët et al. 2011)

Photosphere + internal shocks

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

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

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

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

  - microphysics ?
  - spectrum may have several components

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

- Main uncertainties in this scenario :
  microphysics in shocks : particle acceleration, field amplification, …

Photosphere + internal shocks

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

(Daigne & Mochkovitch 02)

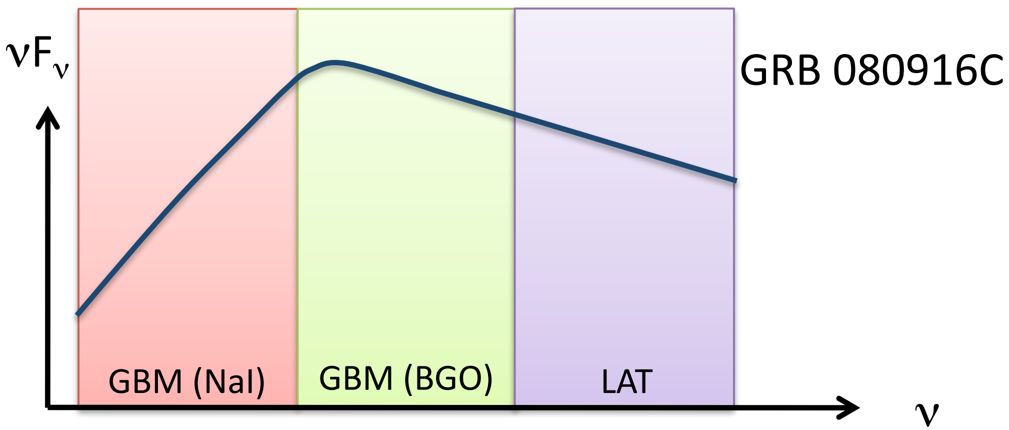
- This is very difficult to reconcile with observations :
  - BATSE spectroscopic catalog (Preece et al. 00; Kaneko et al. 06)
  - indirect analysis of GRB 080916C (Zhang & Pe'er 09)
  - Fermi observations of GRB 100724B (Guiriec et al. 10)
  - most Fermi bursts show a strong dominant component (Band)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

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

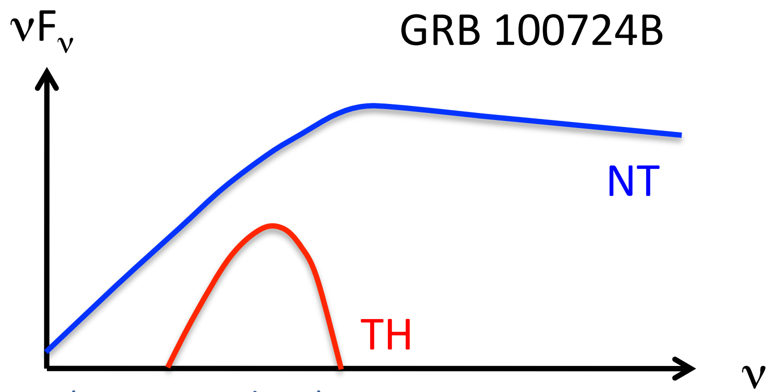
- It remains the possibility that the main spectral component (Band) has a photospheric origin, if the spectral shape is affected by additional processes.

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

- Fermi observations :

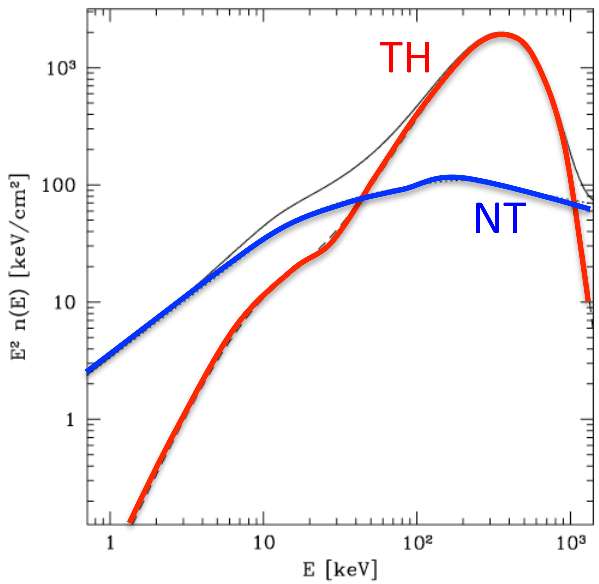


(Abdo et al. 08)

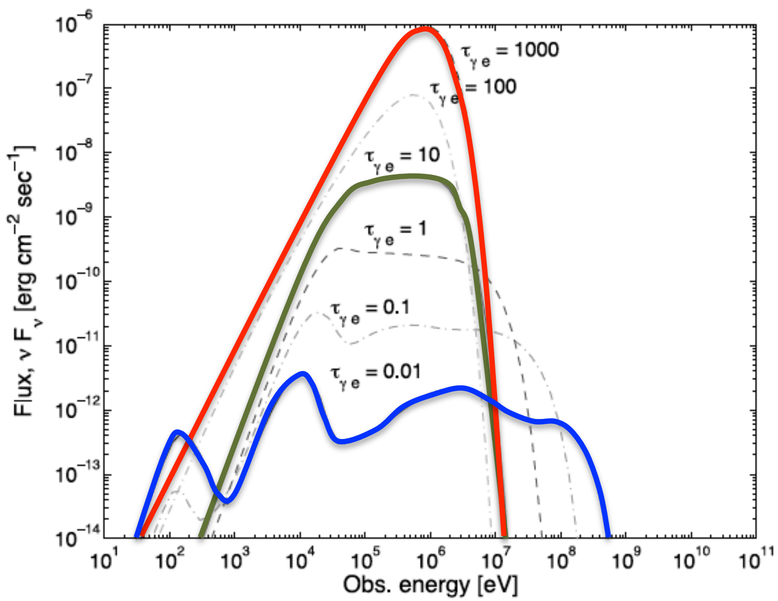


(Guiriec et al. 10)

- Model :



(Daigne & Mochkovitch 02)



(Pe'er et al. 06)

A new ingredient : the magnetic field

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

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

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

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

(Blandford & Lyutikov 03)

At the photosphere, the outflow becomes transparent for its own radiation. If its internal energy content has not be entirely converted into kinetic energy, it can be radiated.

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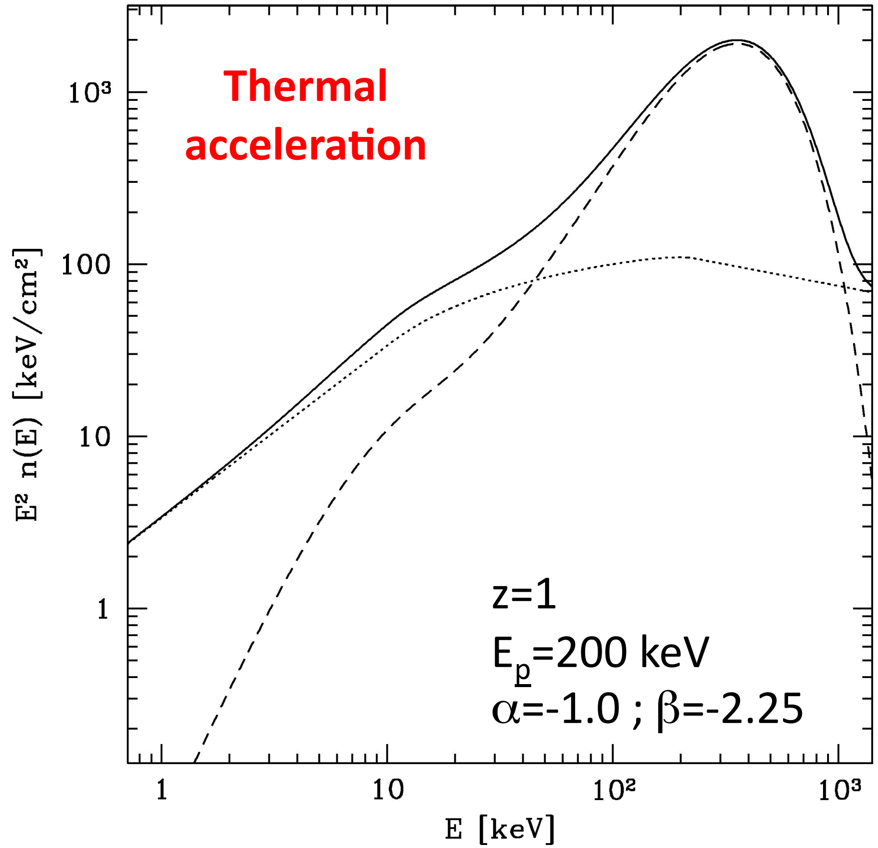

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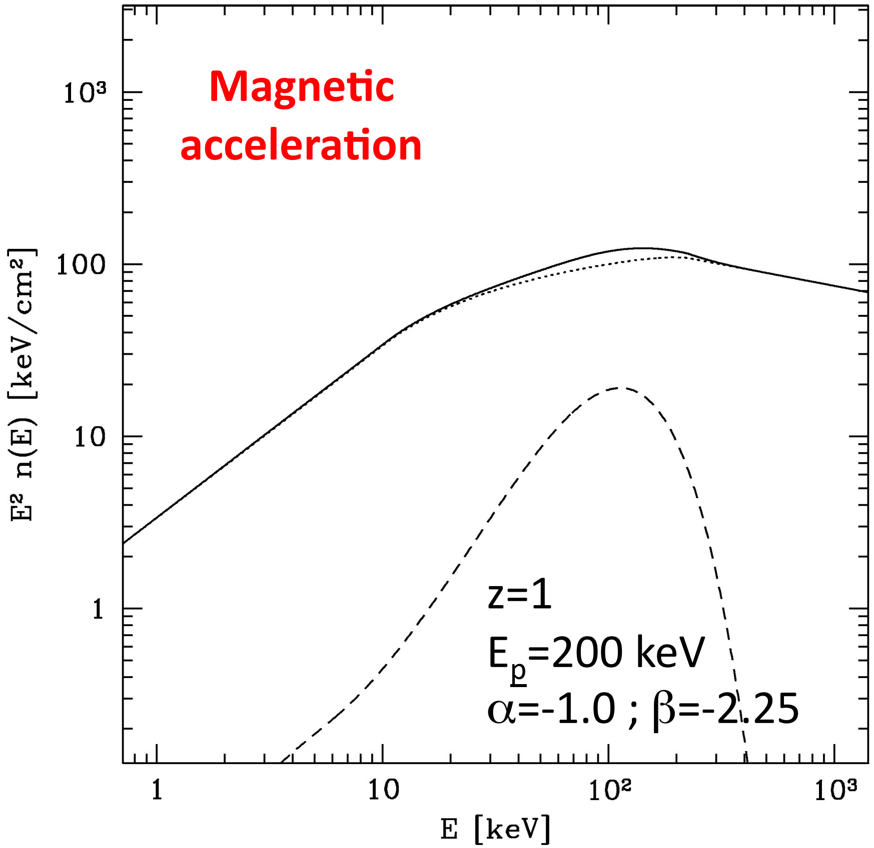
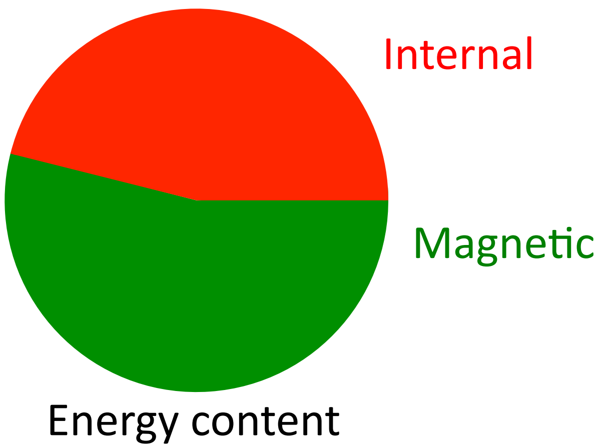
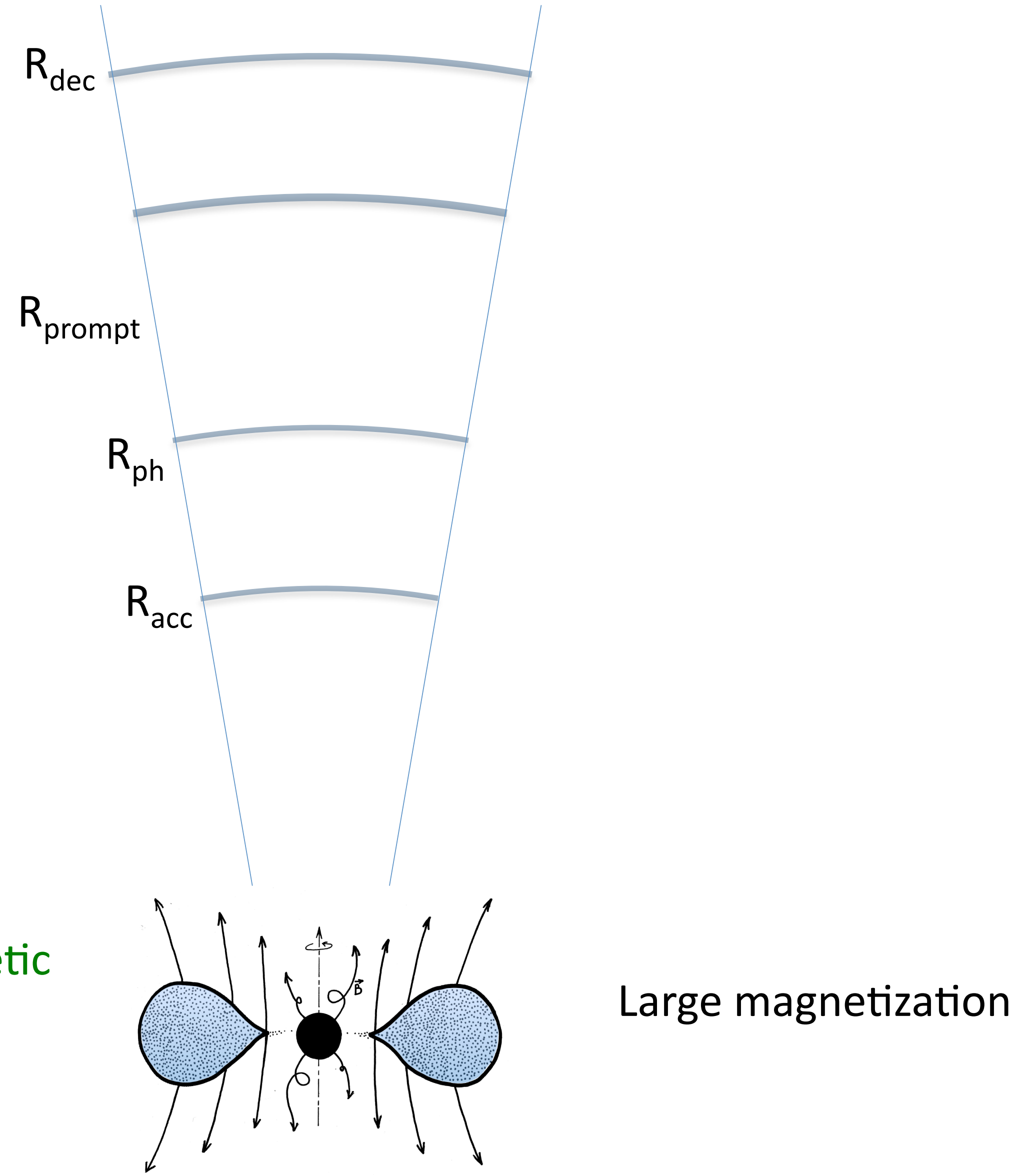
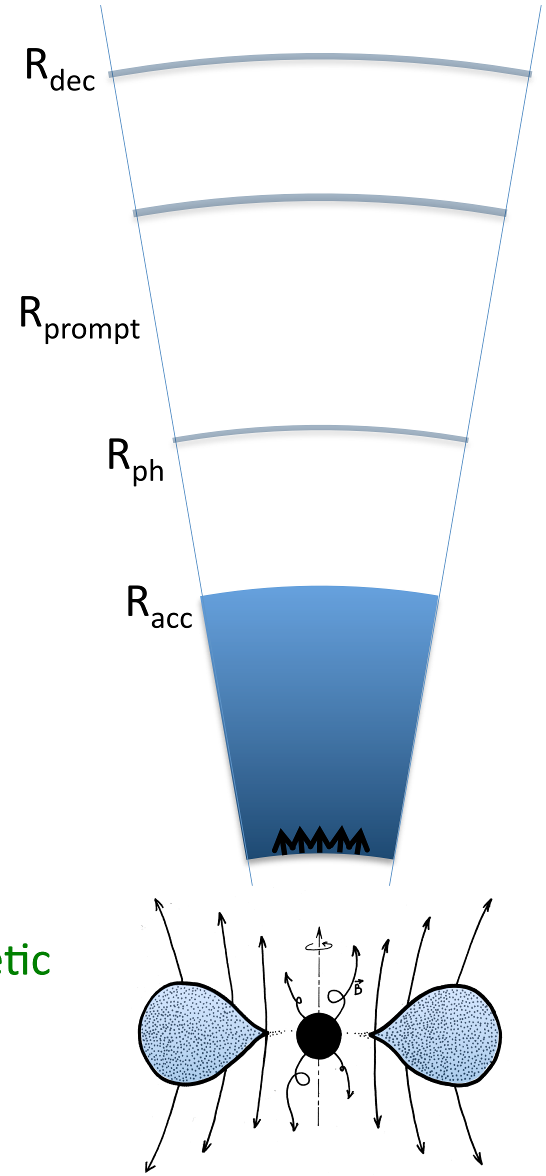


(Daigne & Mochkovitch 2002)

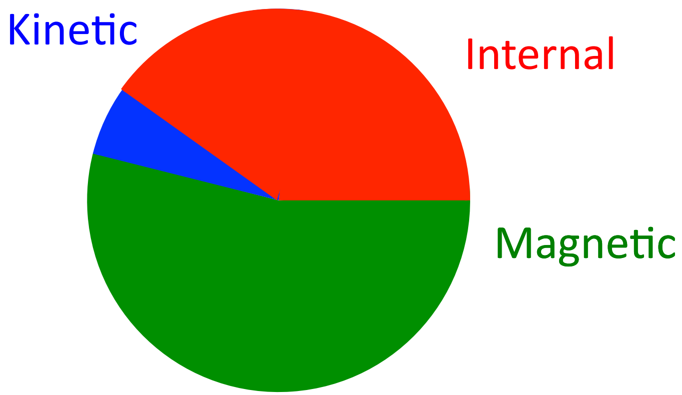
Prompt emission | **Magnetized outflows : passive fields**



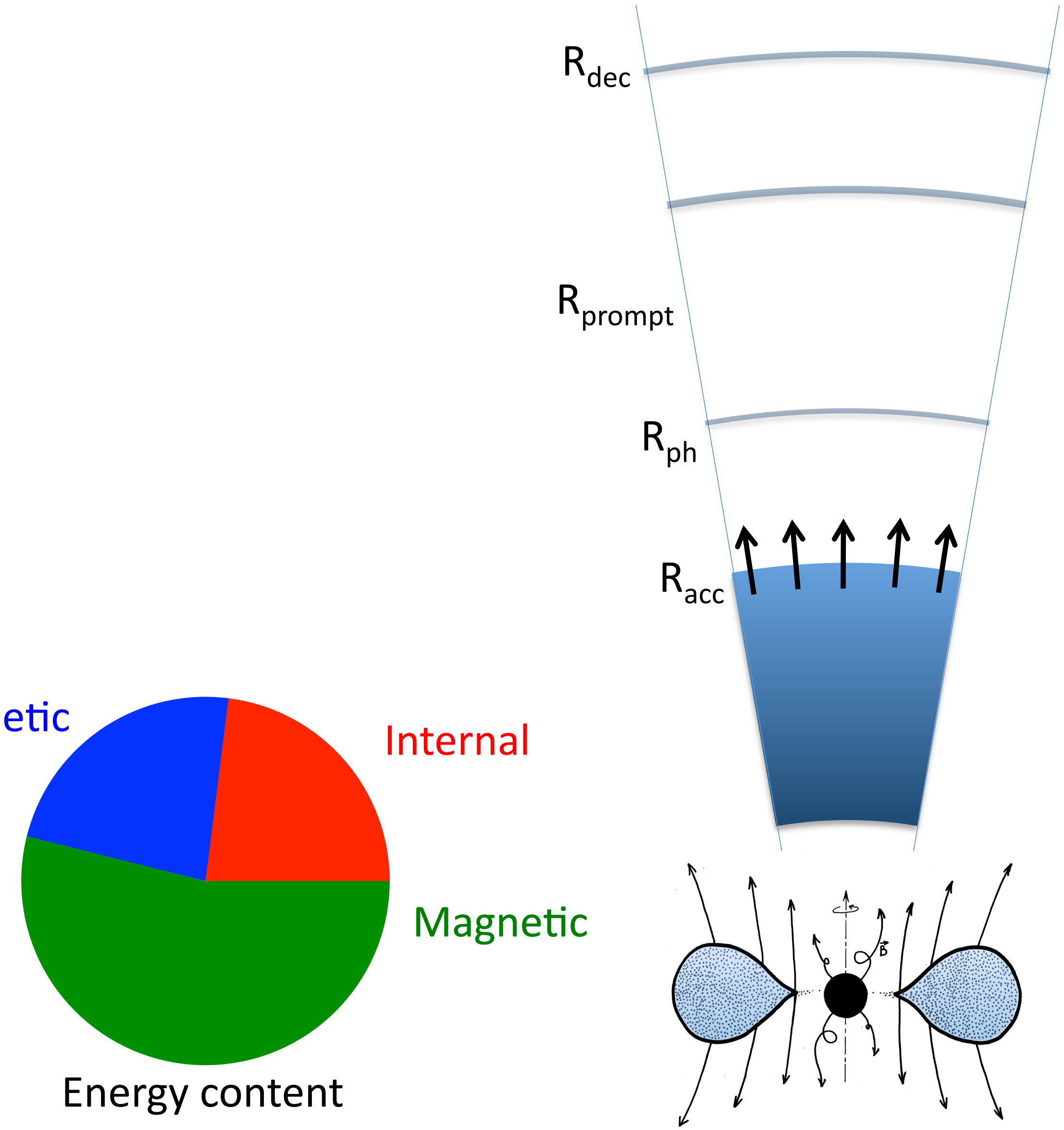




Acceleration :
adiabatic expansion

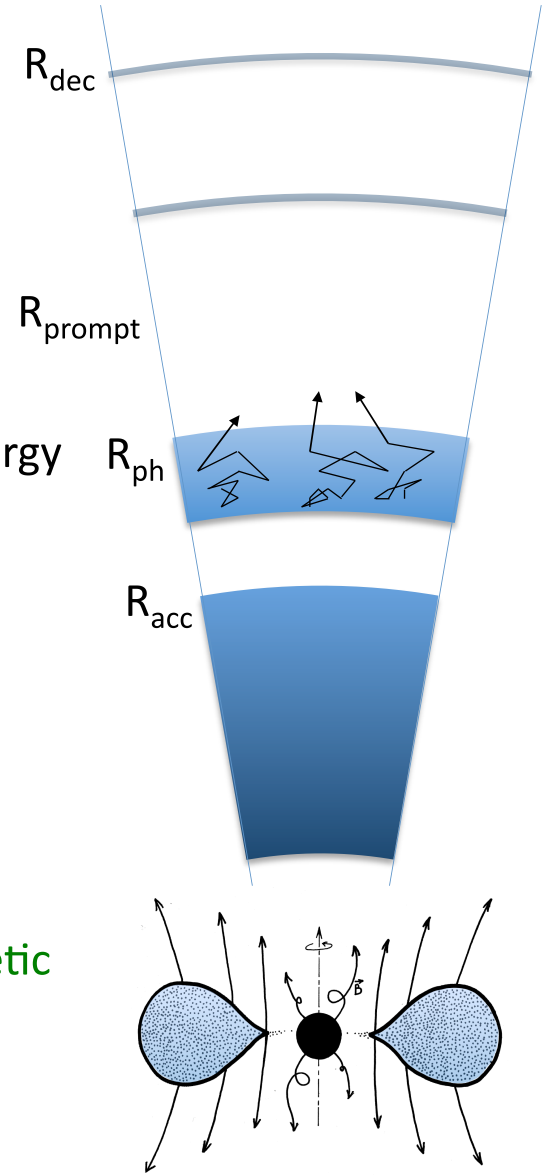


Energy content



Acceleration :
adiabatic expansion

Magnetized outflows : passive fields



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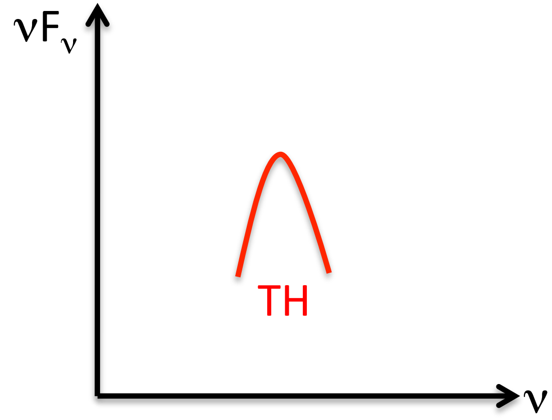
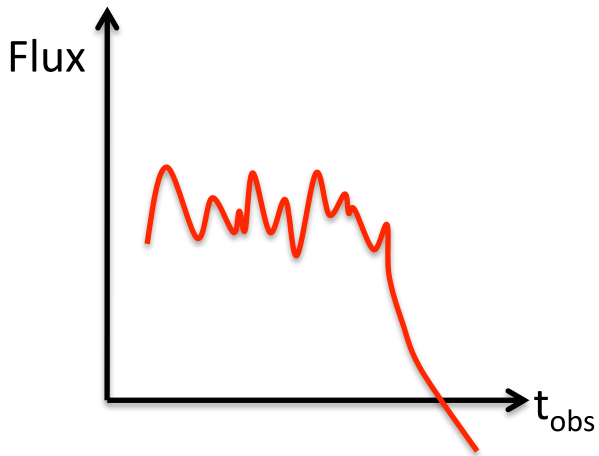
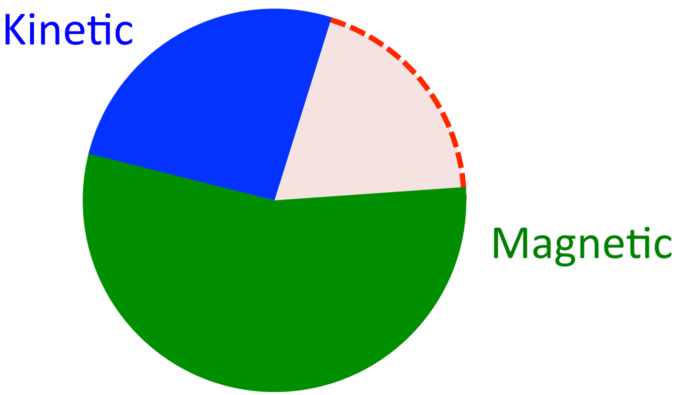
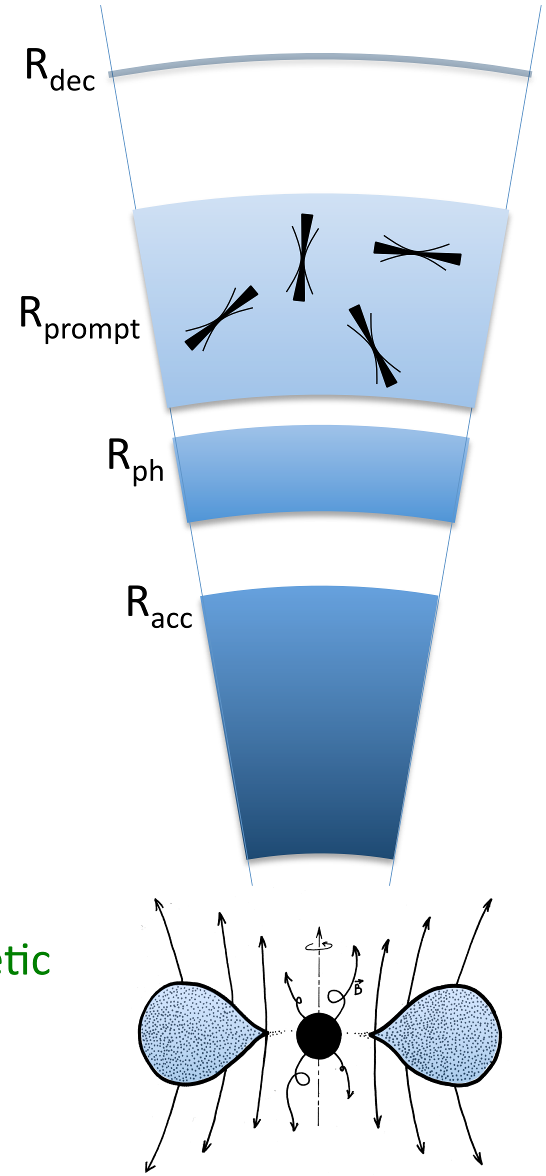




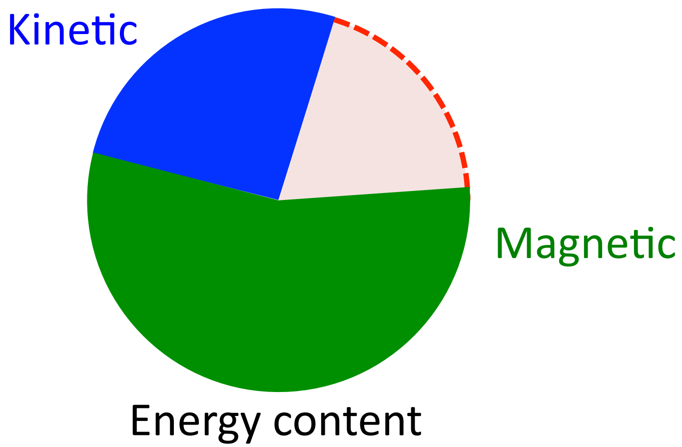


Energy content

Prompt emission | Magnetized outflows : passive fields



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



Prompt emission | Magnetized outflows : passive fields

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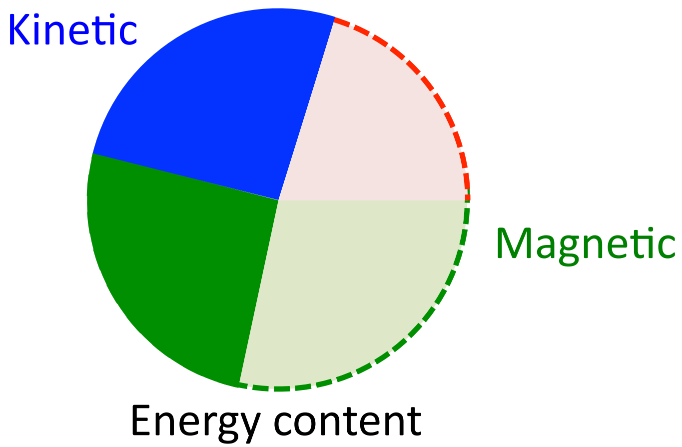
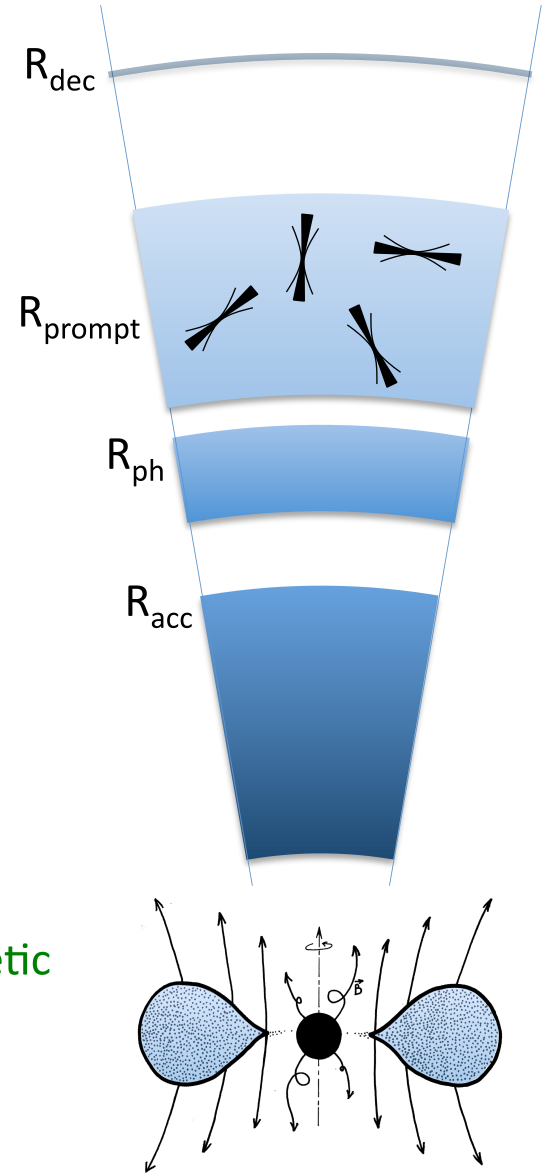
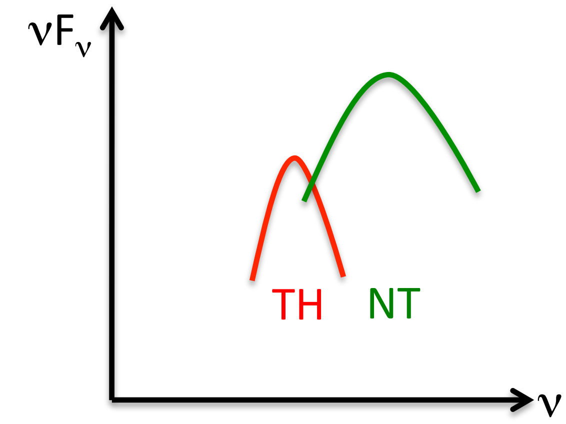
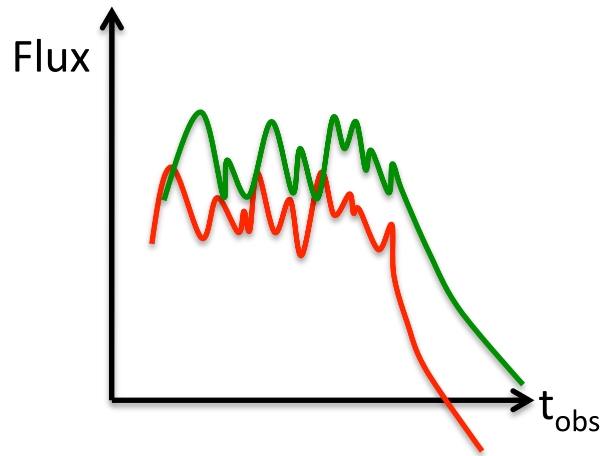








Photosphere + Magnetic dissipation at late times

- weak thermal component + dominant non-thermal component

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

- Main uncertainties in this scenario :

  - physics of the magnetic dissipation process / associated emission

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

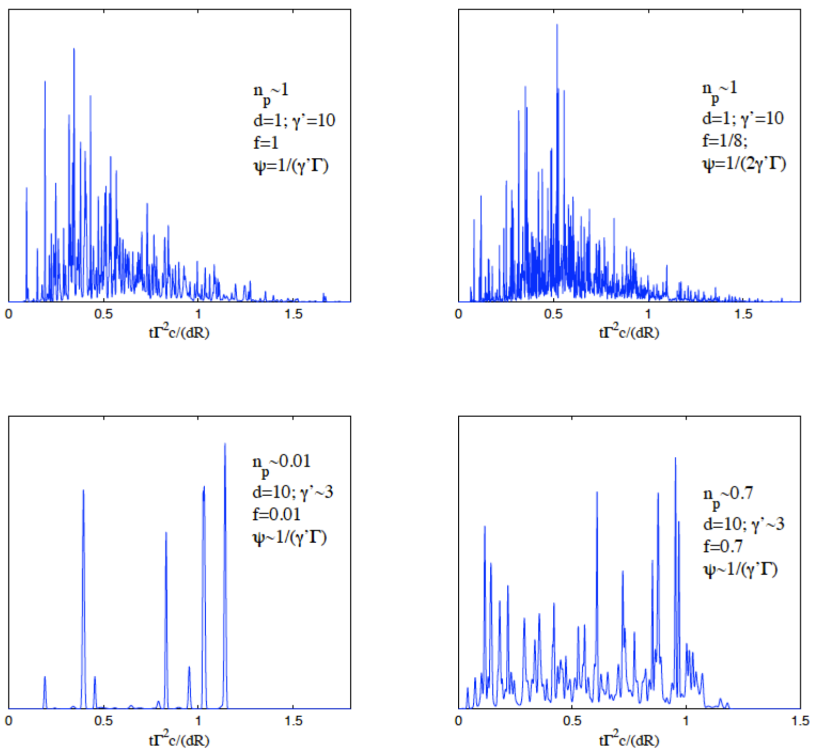
  - critical magnetization to suppress shocks (existence of IS/RS) ? (Zhang & Kobayashi 05; Giannios, Mimica & Aloy 08)

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

(Giannios 08)

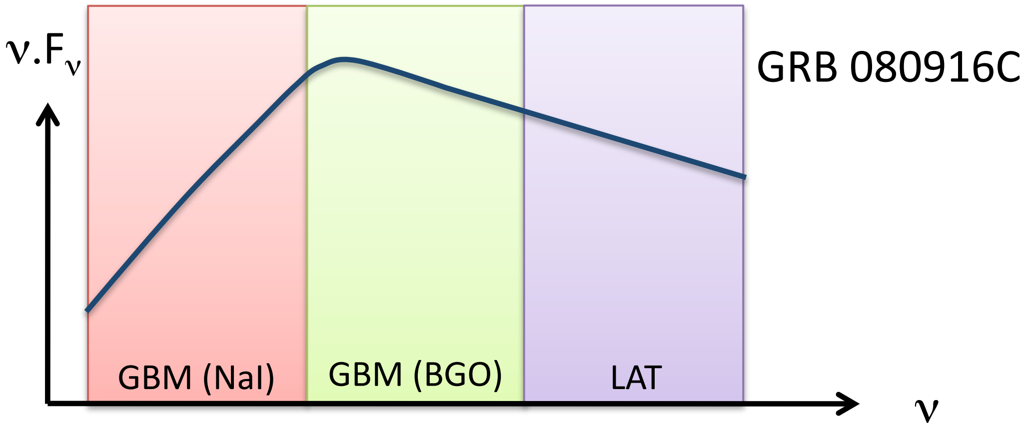
- Some estimates using a simple geometrical description of the dissipation (« fundamental relativistic emitters ») : lightcurves are too symmetric ?

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

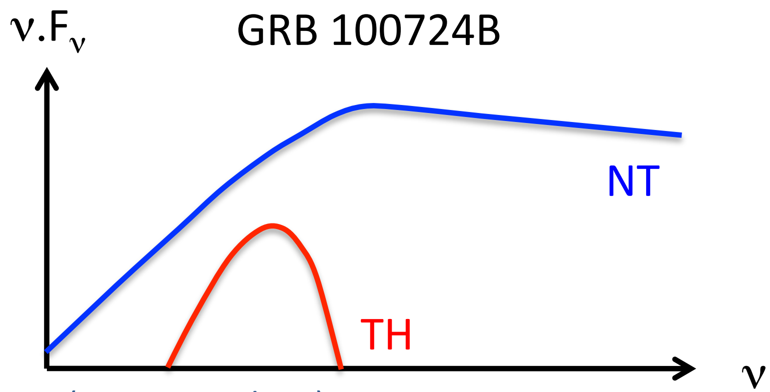


Lazar, Nakar & Piran 09

- Fermi observations :

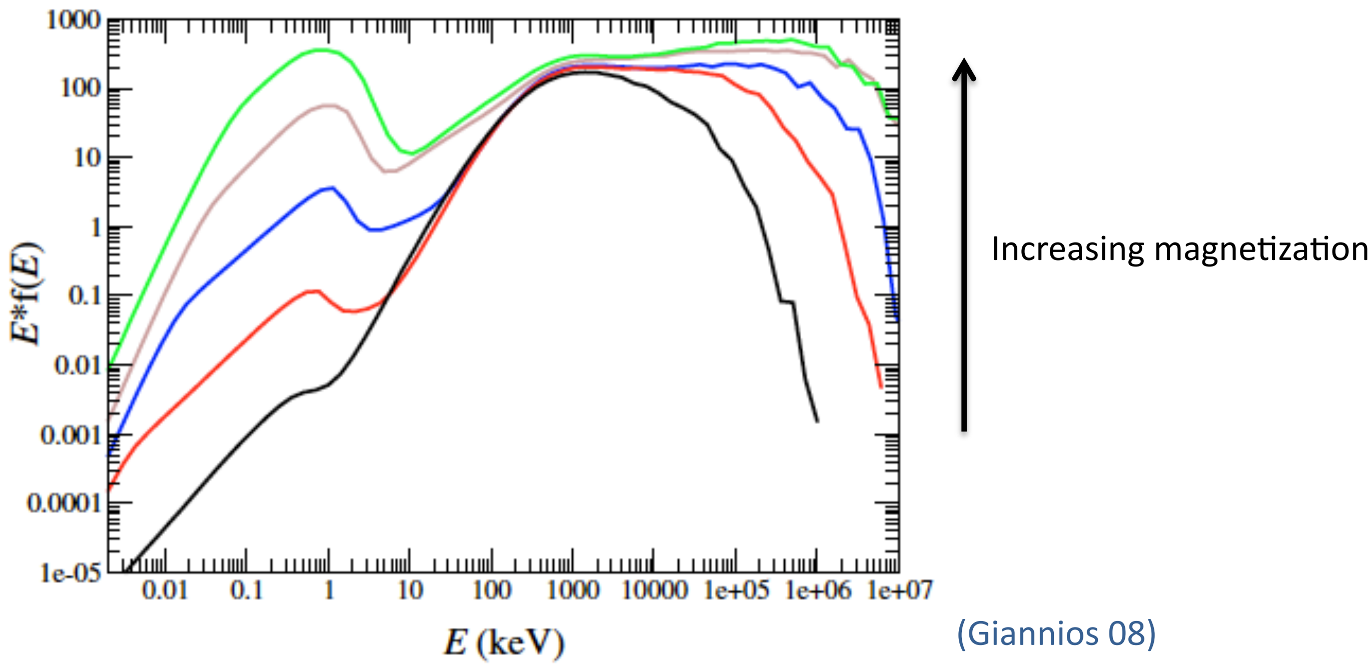


(Abdo et al. 08)

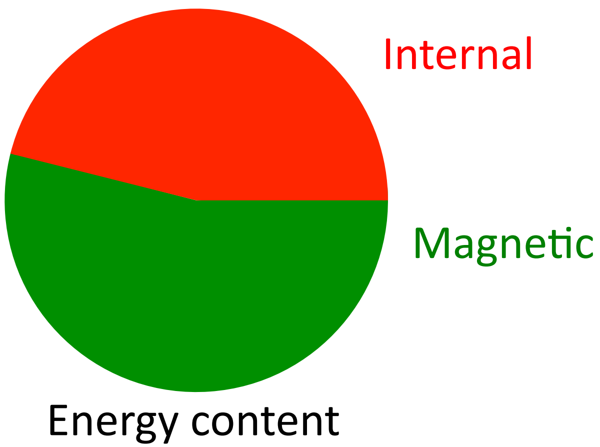


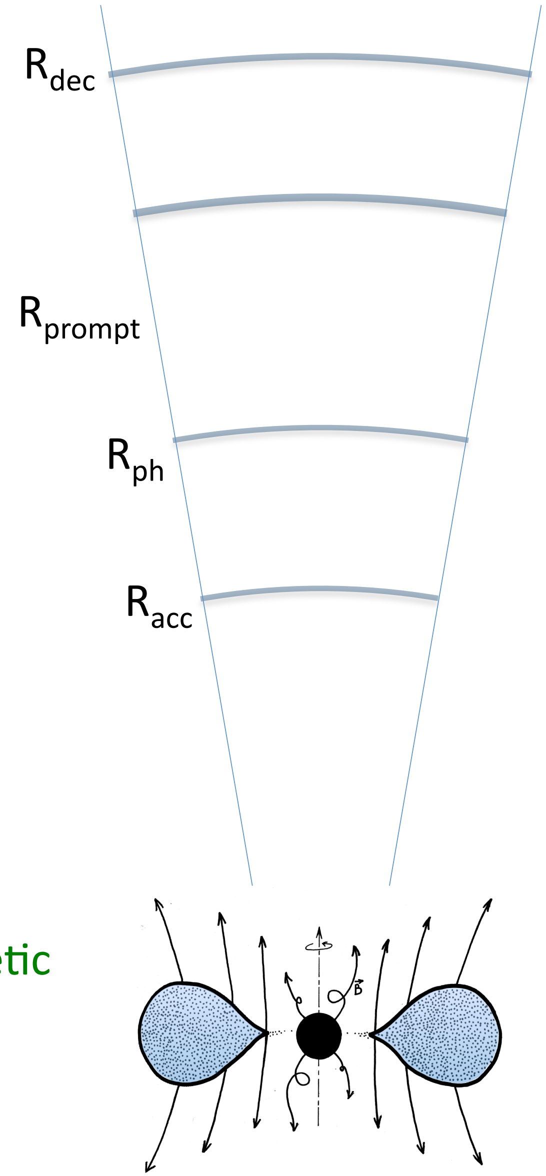
(Guiriec et al. 10)

- Model :



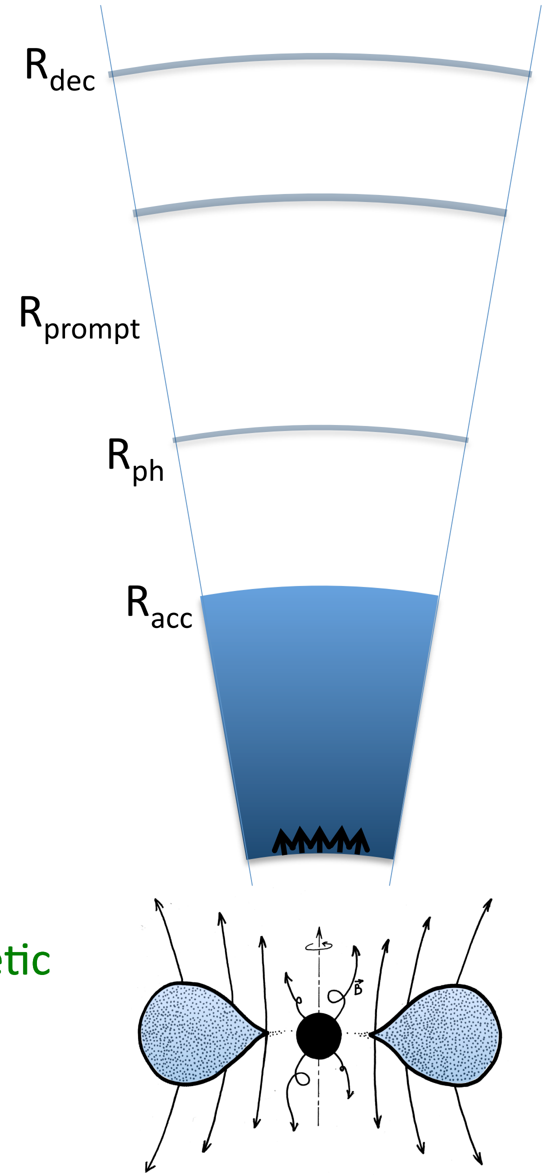
(Giannios 08)



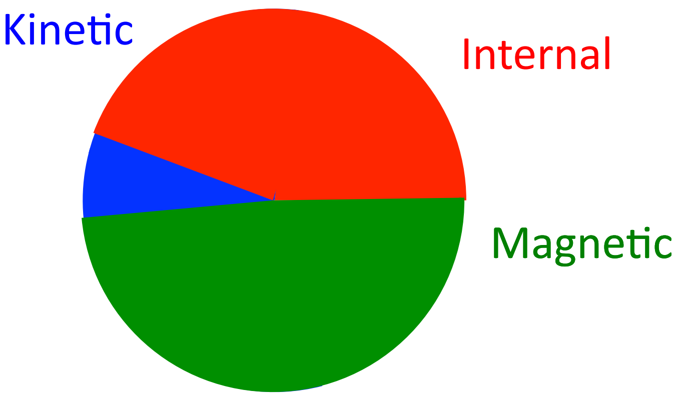


Large magnetization

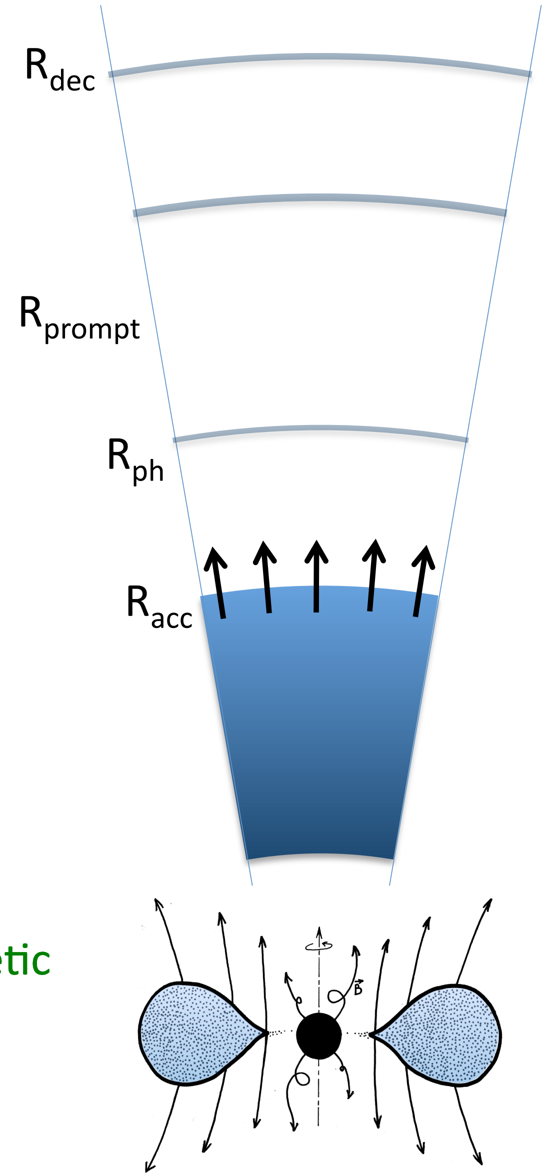
Prompt emission | Magnetized outflows : active fields



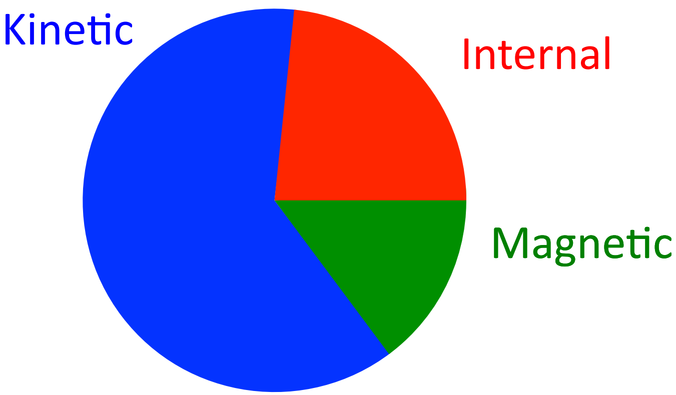
Magnetic acceleration



Energy content

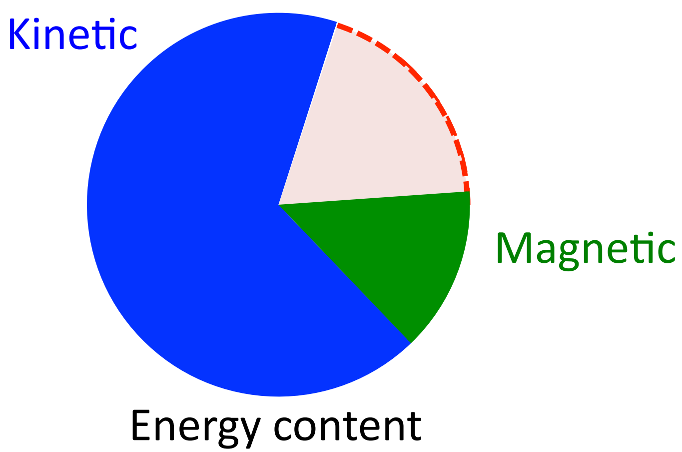


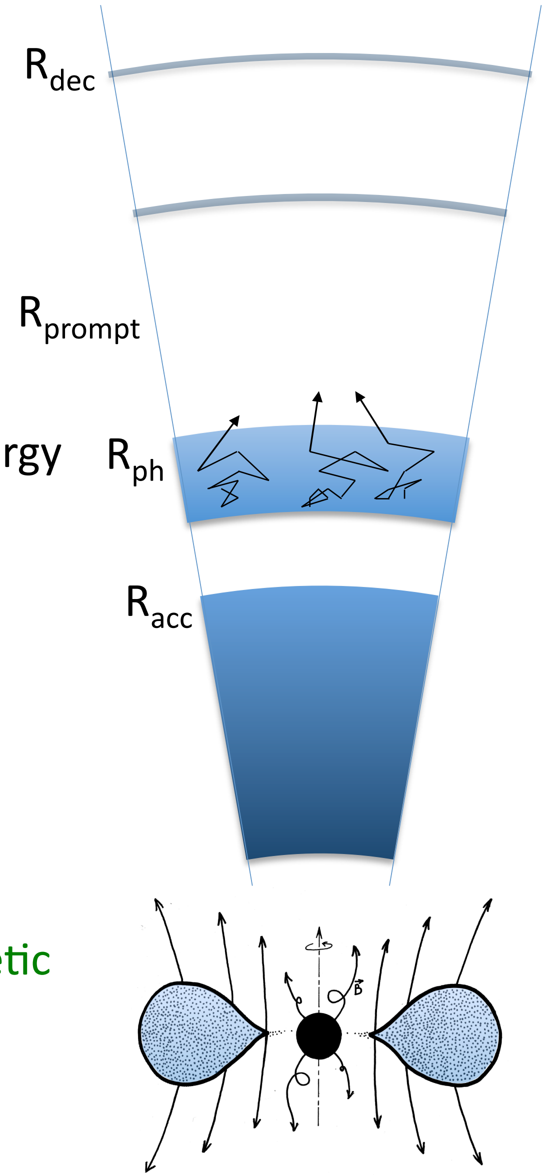
Magnetic acceleration

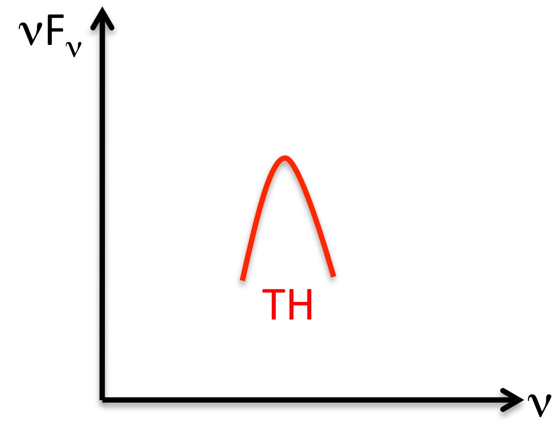


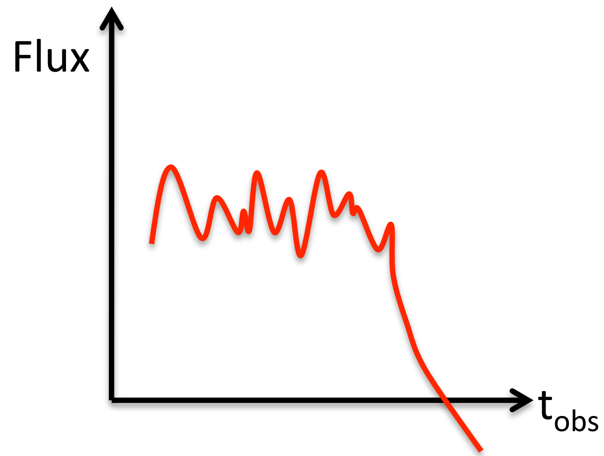
Energy content

Photosphere : internal energy can be radiated.



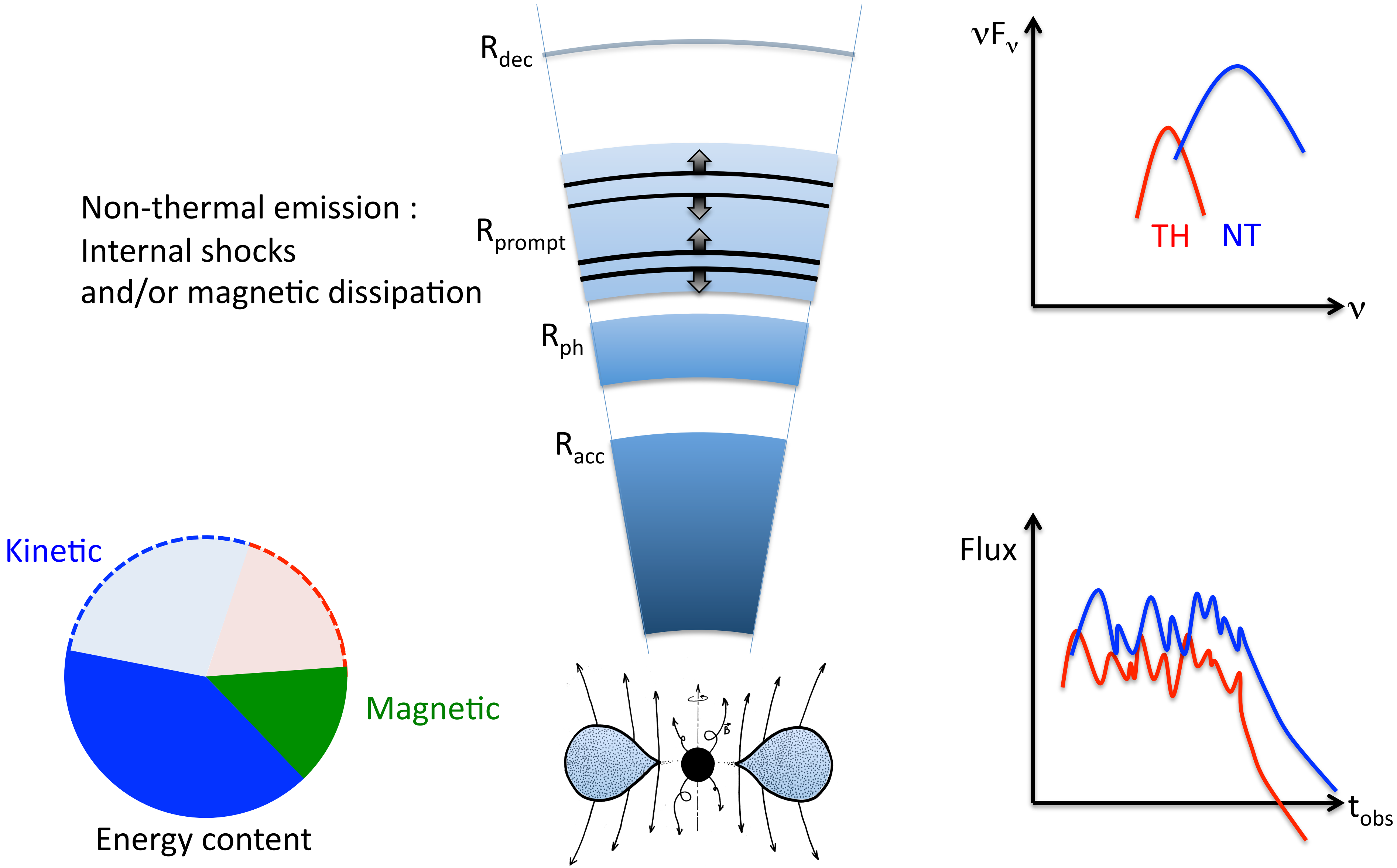






Magnetized outflows : active fields

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



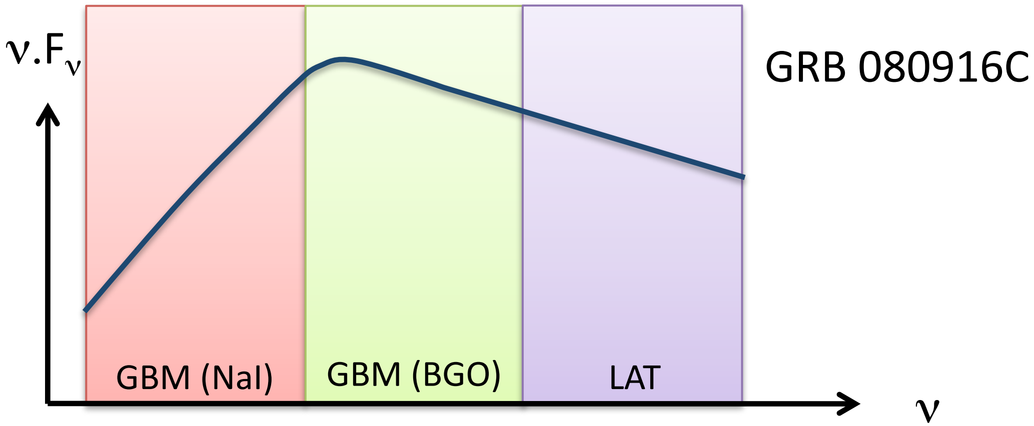
Efficient magnetic acceleration : (photosphere) + internal shocks

- Large Lorentz factors can be reached

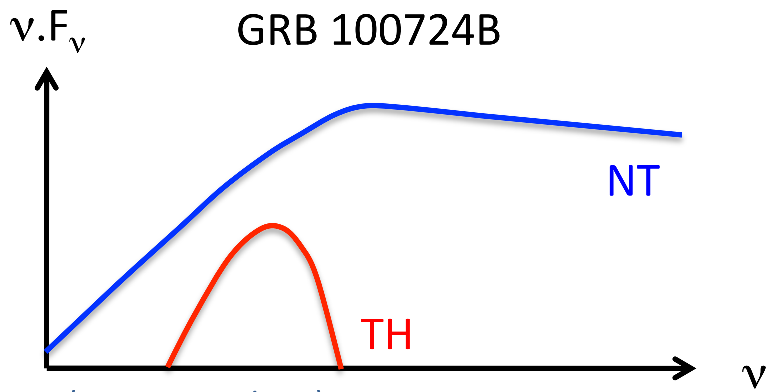
- *Above the acceleration radius, the outflow is very similar to a standard fireball, except that it is colder*.
  - non-thermal emission is dominant, in agreement with observations
  - a weak thermal component may be seen
  - diversity is possible depending on the initial magnetization

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

- Fermi observations :



(Abdo et al. 08)



(Guiriec et al. 10)

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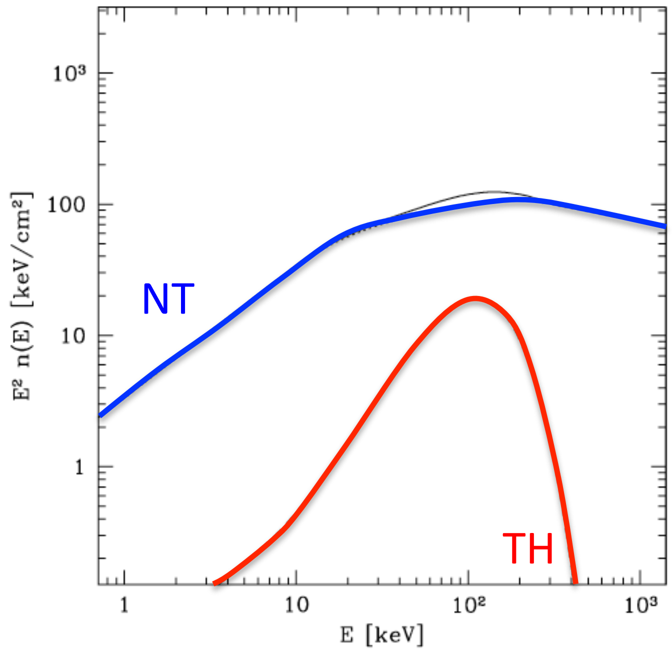
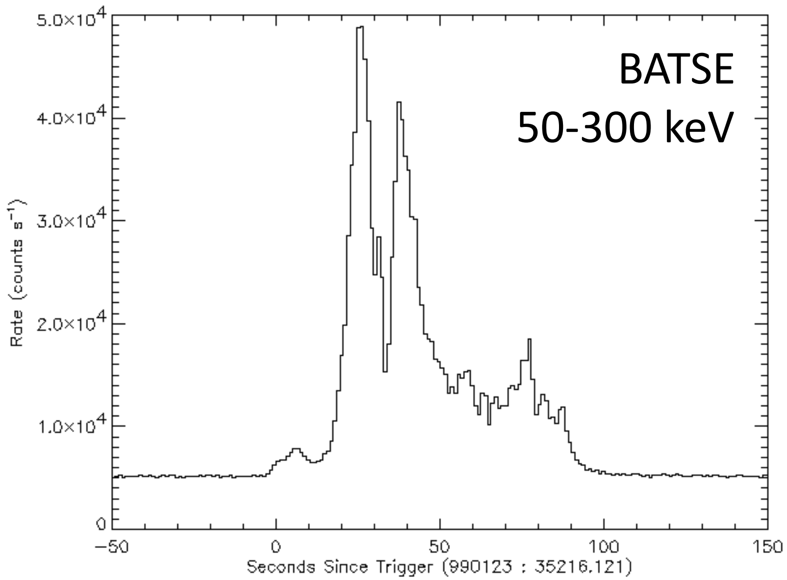
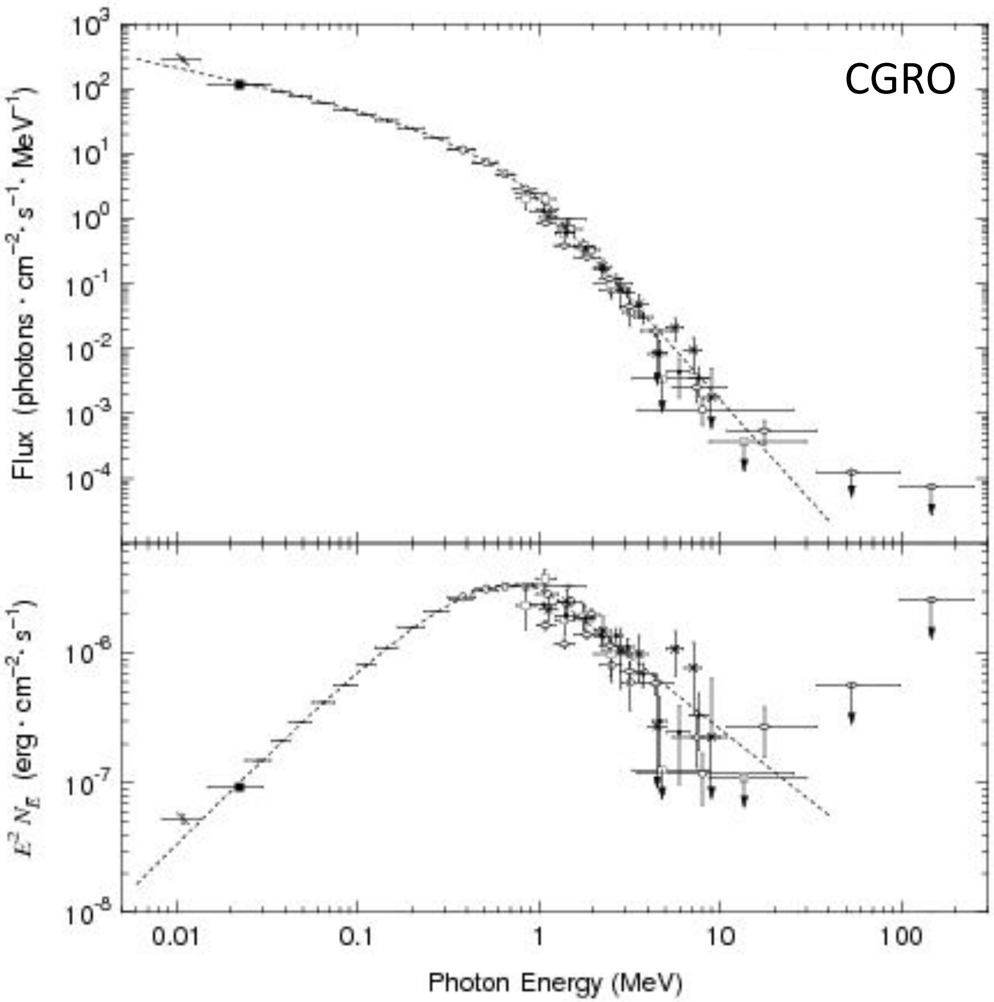


(Daigne & Mochkovitch 02)

GRB 990123 :

From Briggs et al. 1999

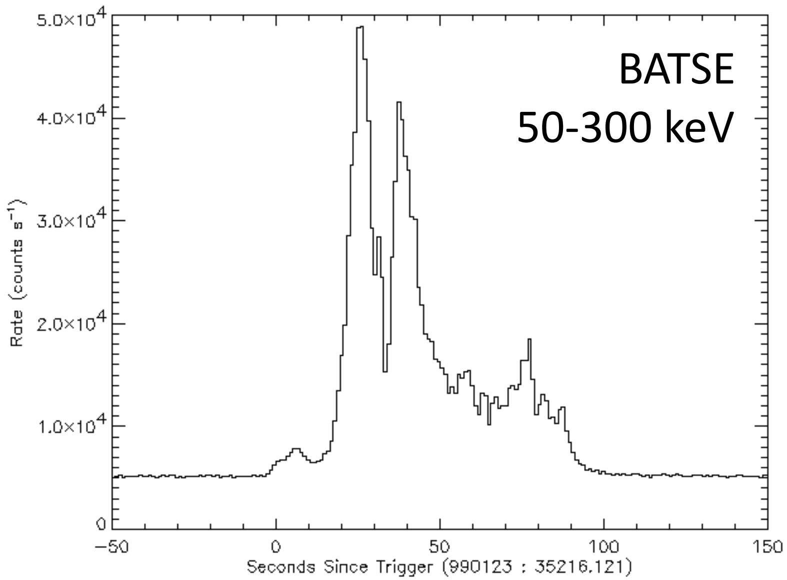


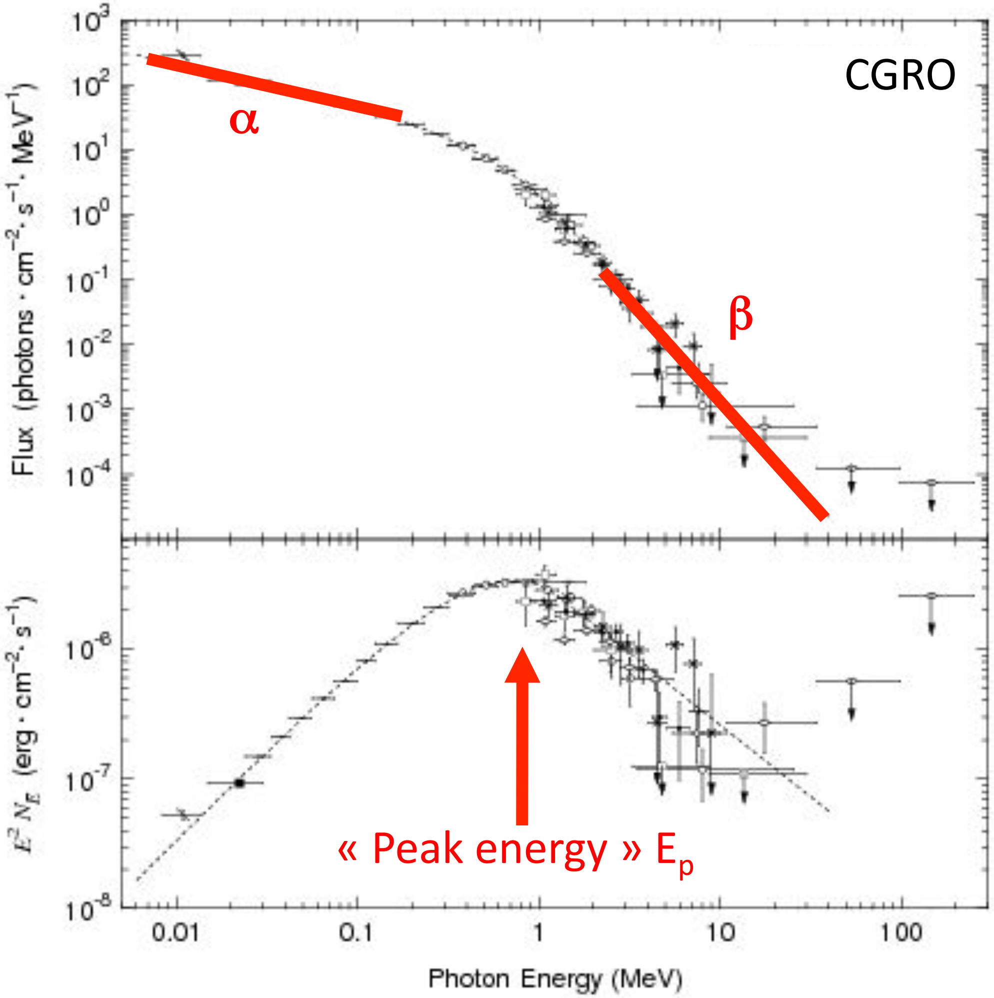


Prompt emission (4) | Radiative processes

GRB 990123 :

From Briggs et al. 1999





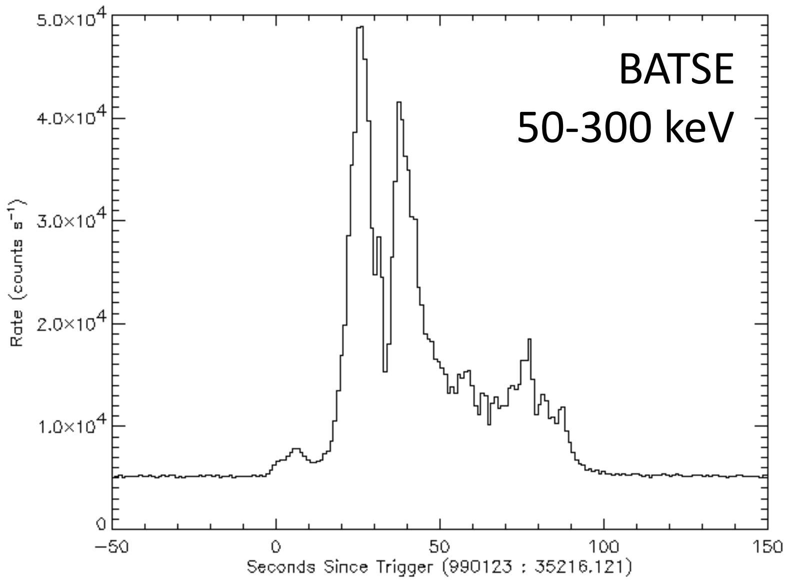
4-parameters « Band spectrum » :
E_p, α, β and normalization

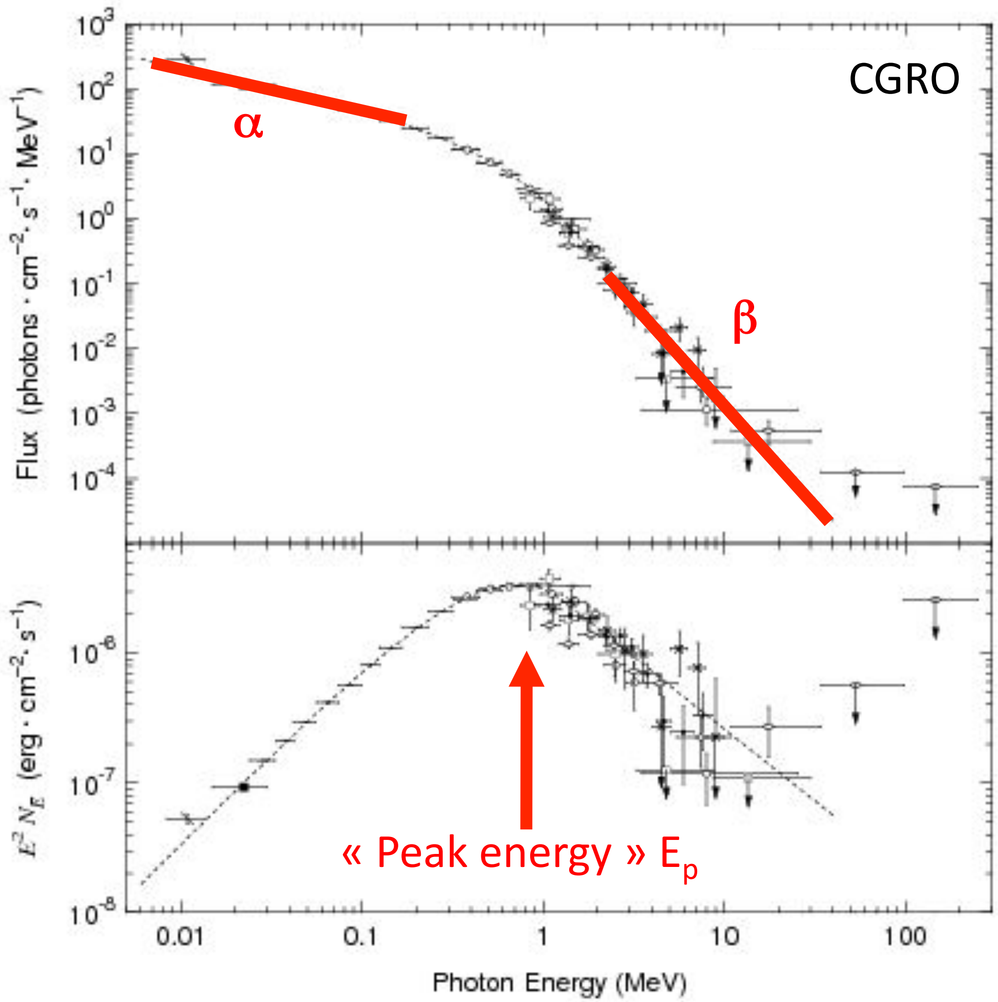
Band et al. 1993

Prompt emission (4) | Radiative processes

GRB 990123 :

From Briggs et al. 1999





In most GRBs, the spectral parameters (E_p, α, …) evolve with time.

Prompt emission (4) — Radiative processes

Short timescale variability in the lightcurve : internal origin of the prompt GRB emission (i.e. : emission is radiated from the relativistic outflow)

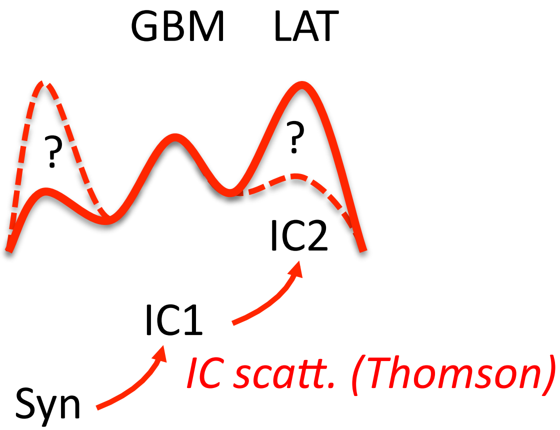
Two questions :

- physical mechanism ?
  - Internal shocks ?
  - Photosphere ?
  - Magnetic dissipation ?
- dominant radiative process ?
  - Synchrotron ?
  - SSC ?
  - Others ?

To understand many observed features (spectral evolution, « delays », …), both questions must be considered simultaneously.

Prompt emission (4) — Radiative processes

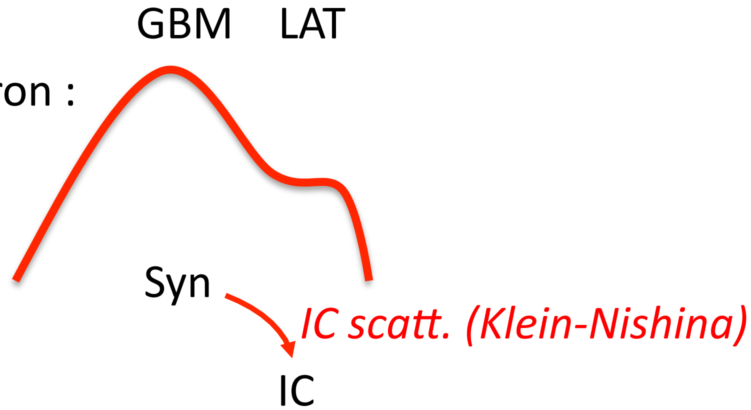
SSC :



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

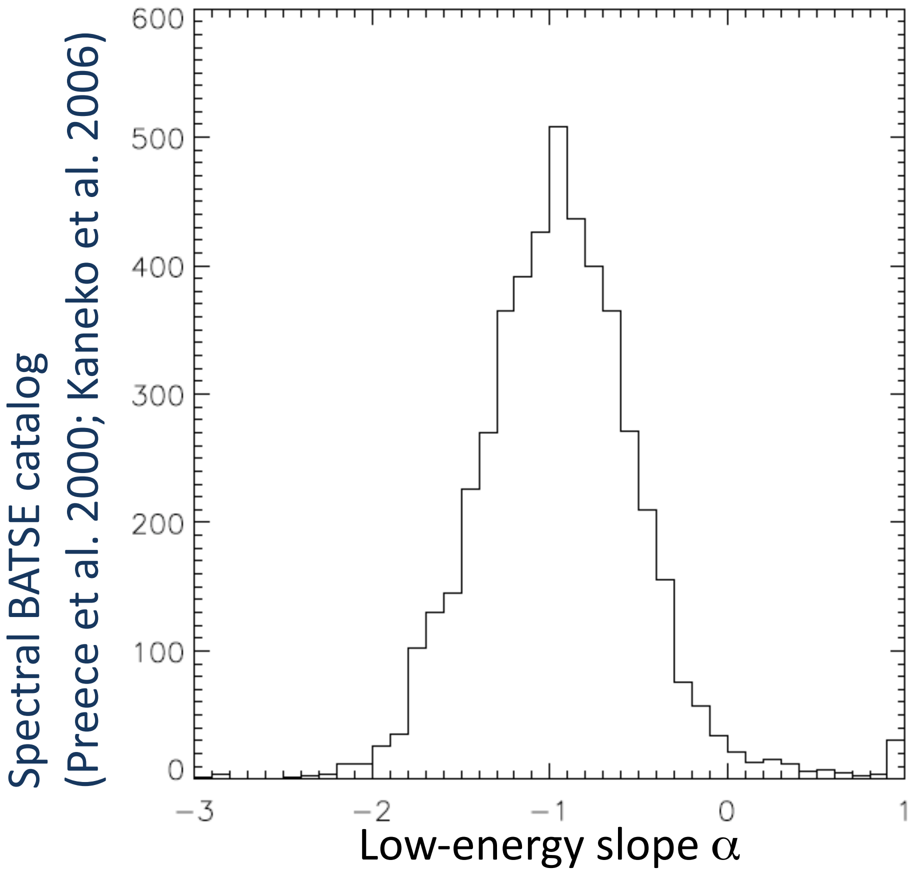
-Energy crisis

Synchrotron :

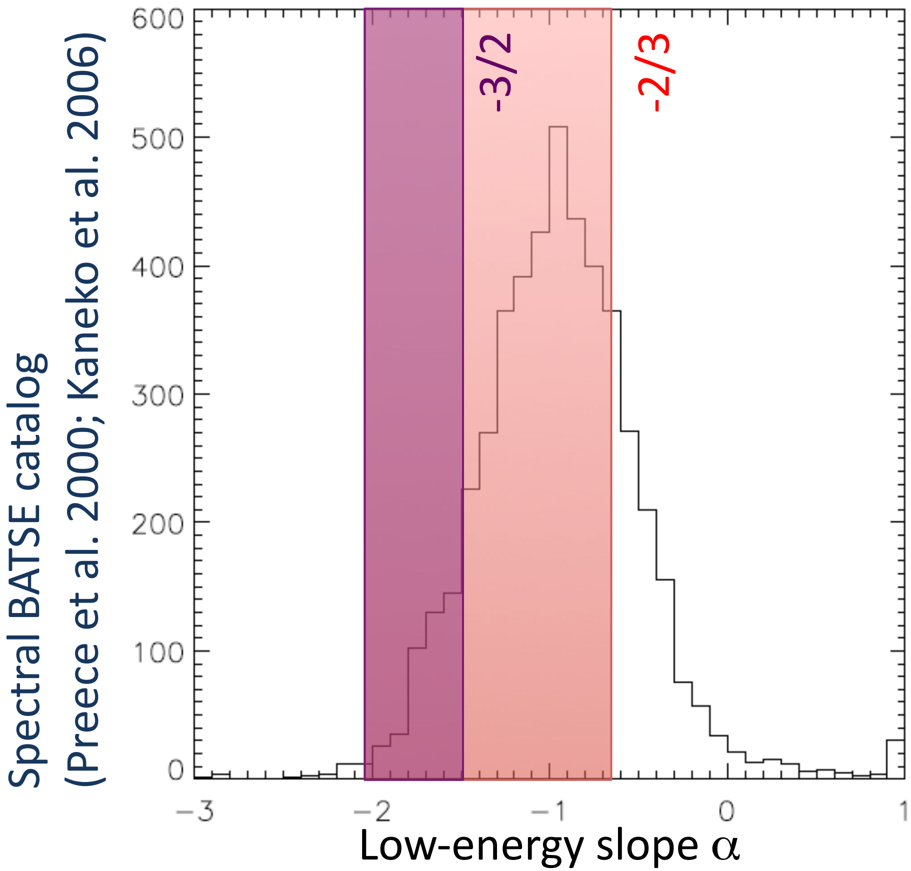


Fermi-LAT detection rate and observations clearly favor the synchrotron process.

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


Spectral BATSE catalog
(Preece et al. 2000; Kaneko et al. 2006)
600
500
400
300
200
100
0
−3
−2
−1
0
1
Low-energy slope α

Prompt emission (4) — Radiative processes



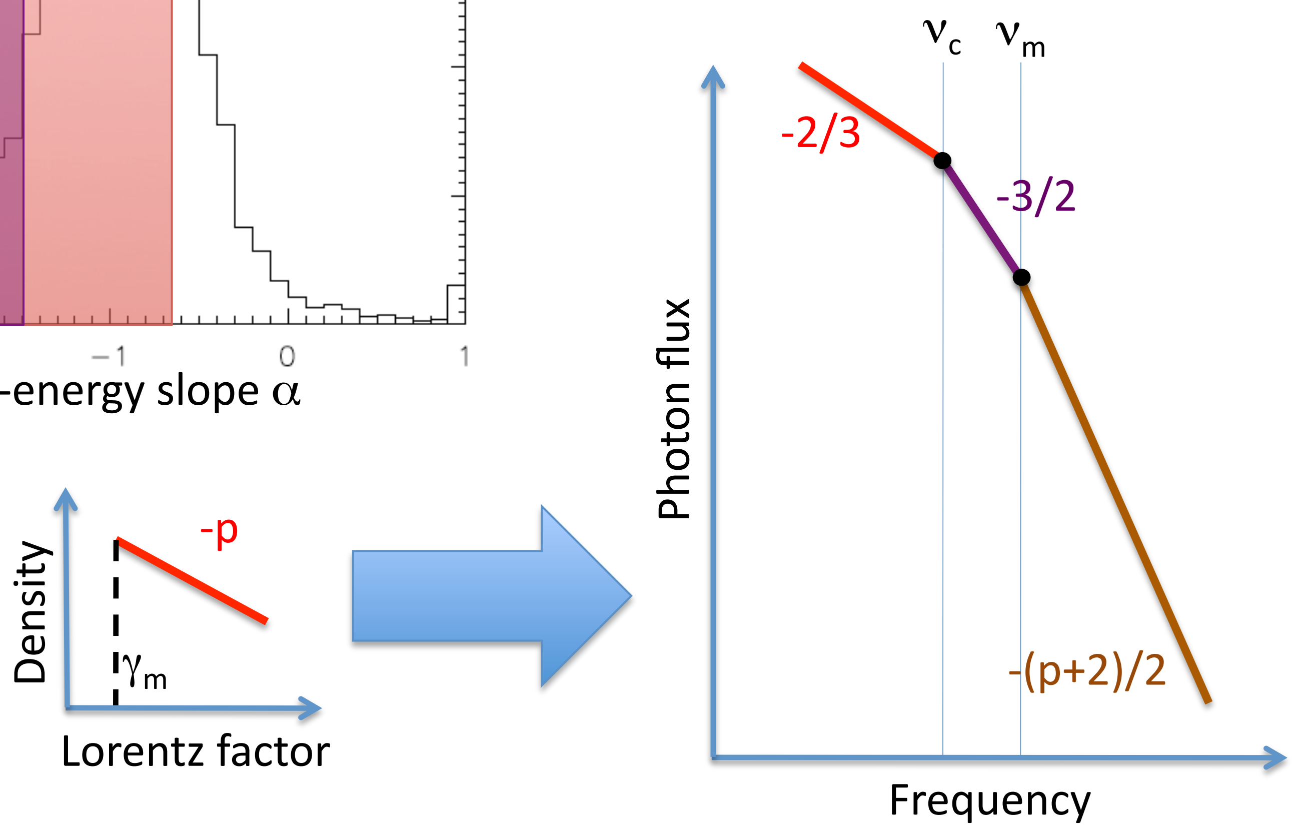
γ_m : minimum Lorentz factor at injection

γ_c : radiative timescale = dynamical timescale

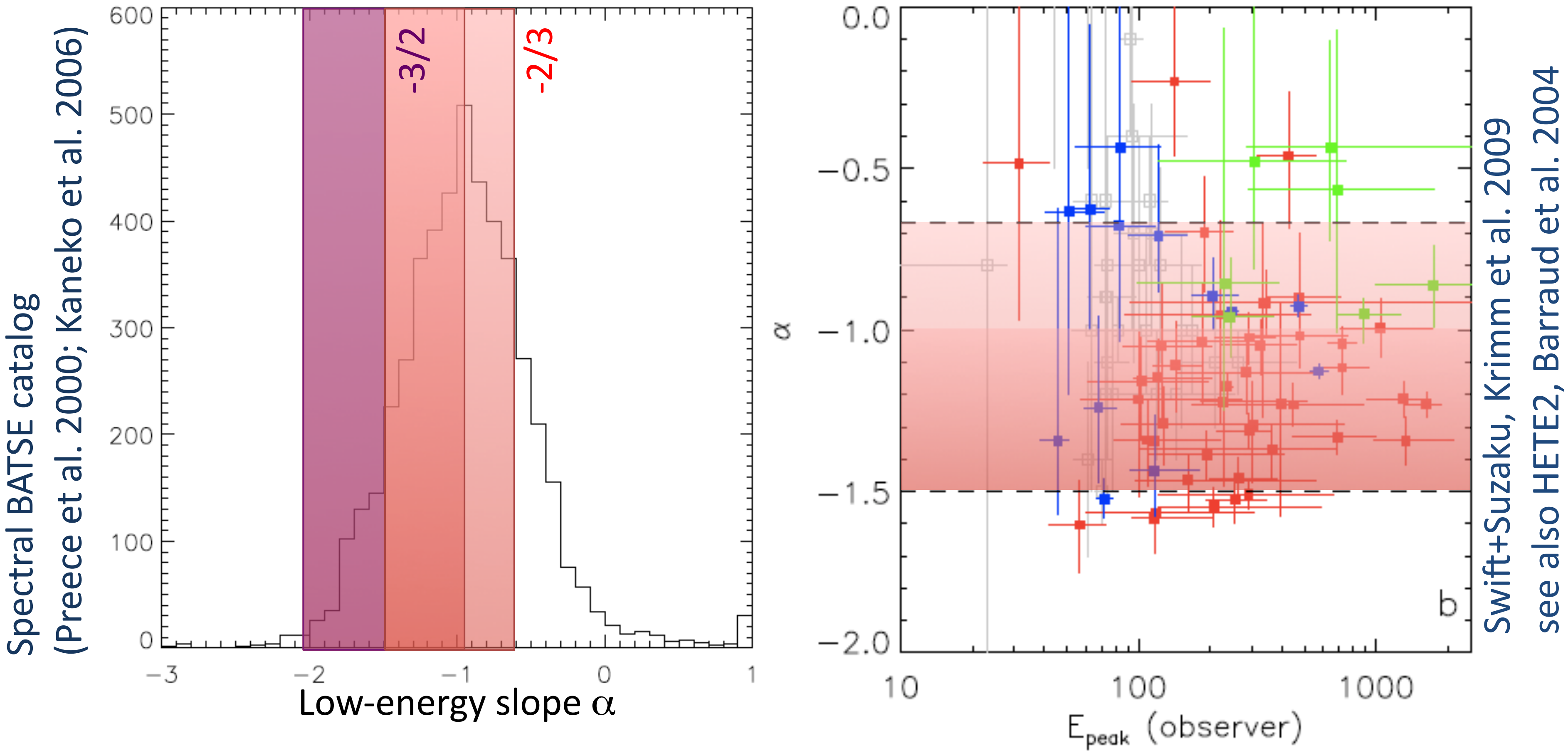
Synchrotron frequencies : $\gamma_m \leftrightarrow \nu_m$ and $\gamma_c \leftrightarrow \nu_c$

Synchrotron spectrum : fast cooling ($\gamma_c < \gamma_m$)

Relativistic electrons :



Prompt emission (4) — Radiative processes

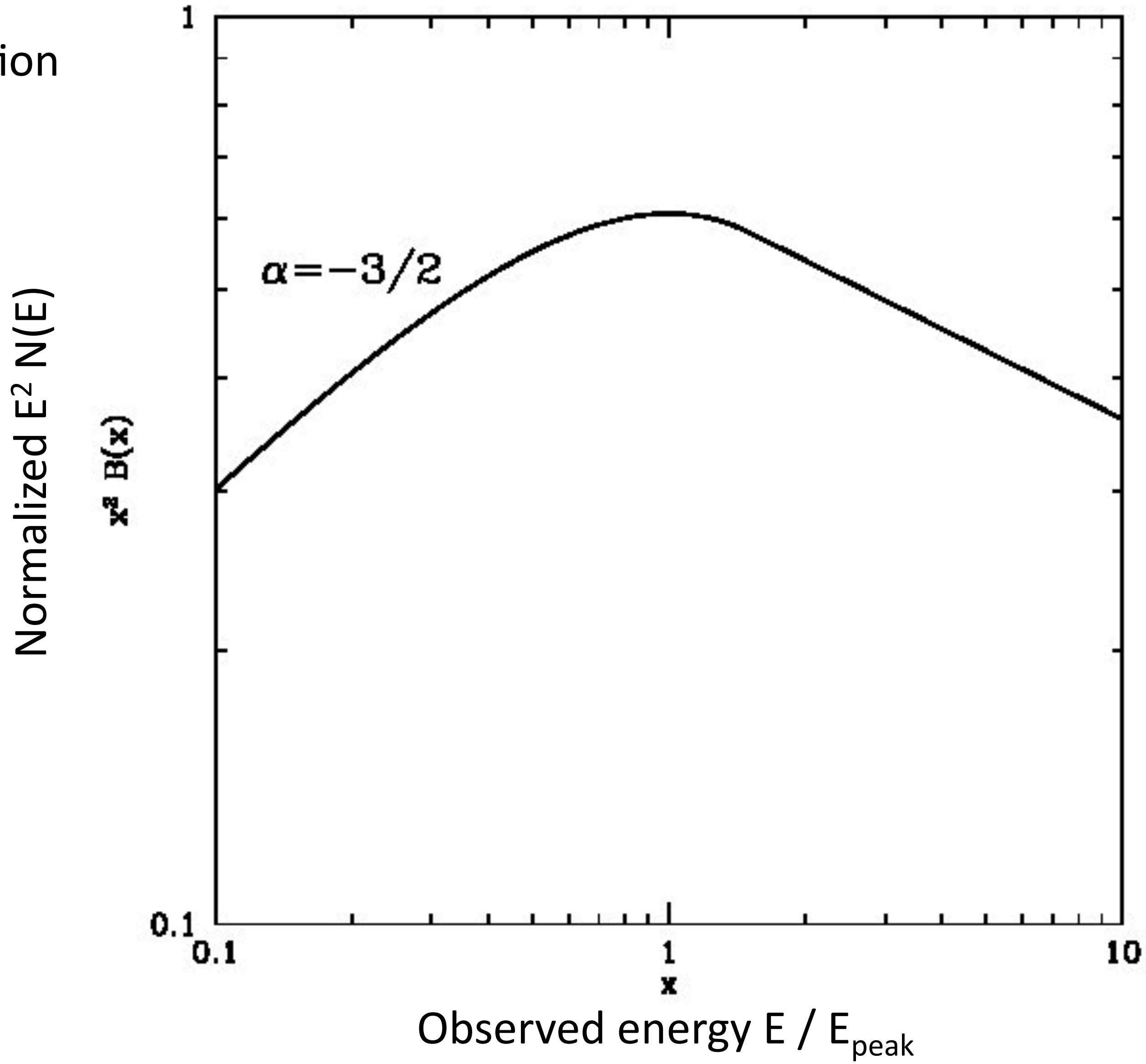


Is it possible to reconcile the synchrotron process in fast cooling regime with $-3/2 < \alpha < -1$?

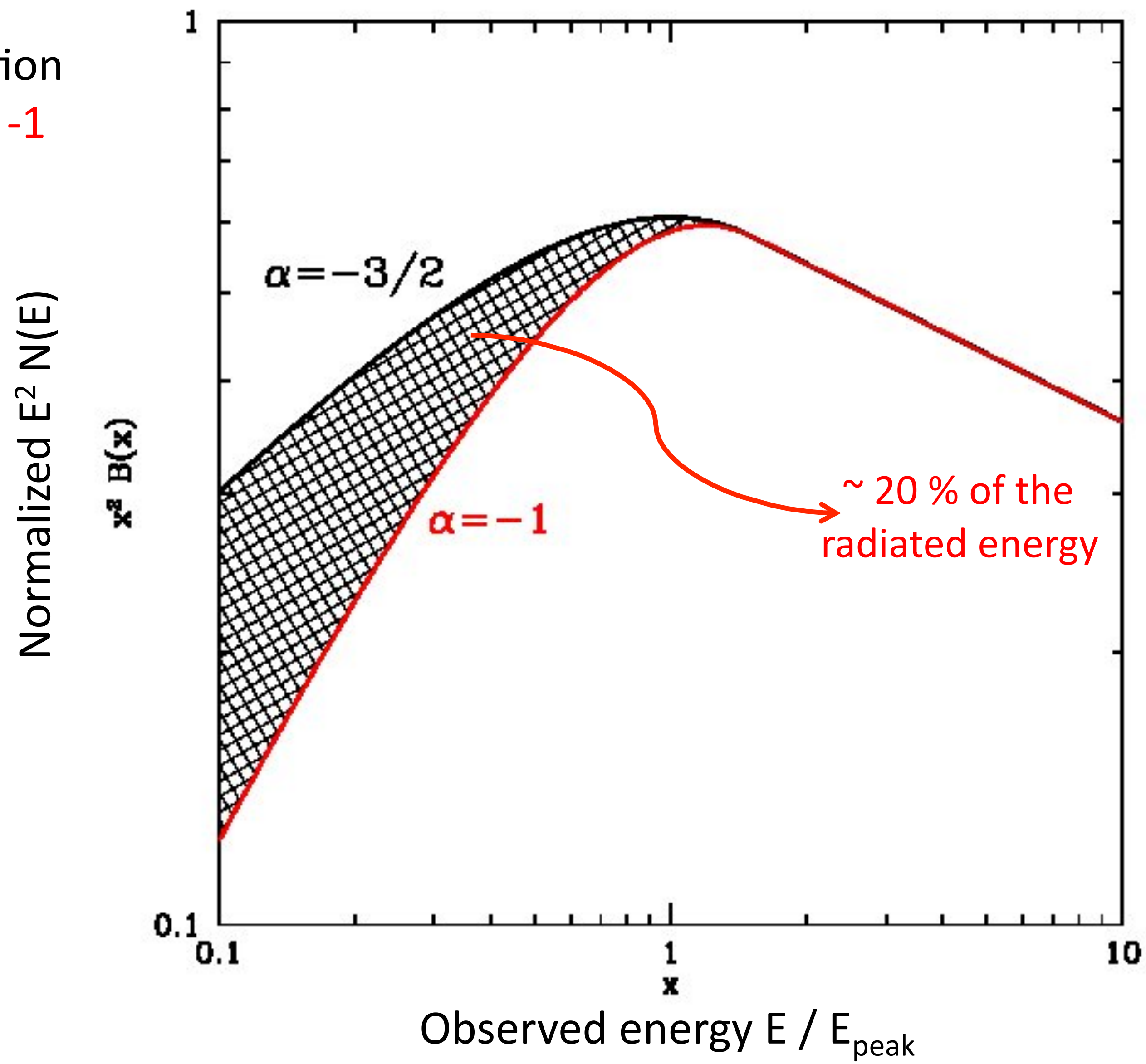
Band function

α = -1.5

β = -2.25



Band function
α = -1.5 → -1
β = -2.25



Band function

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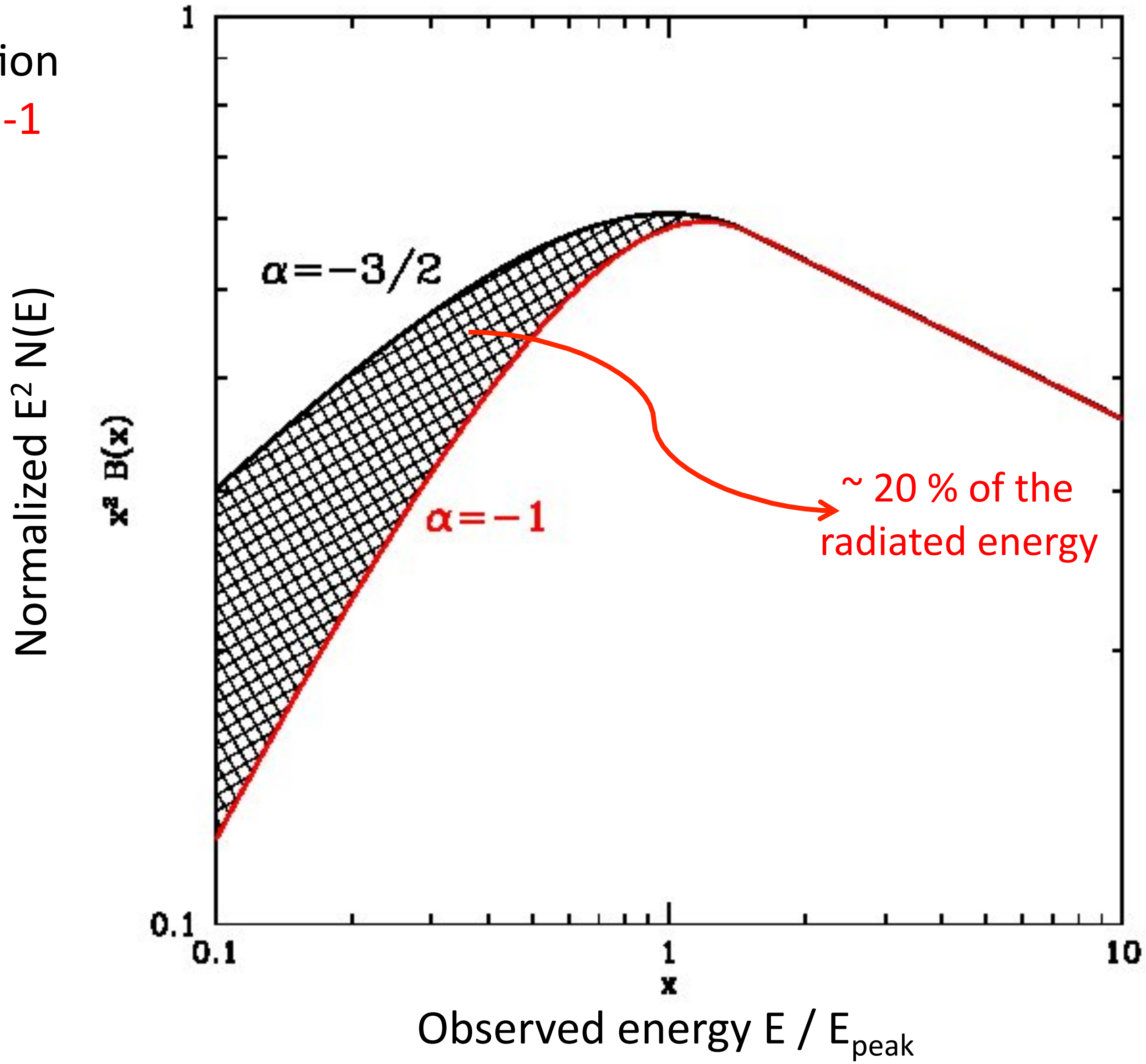


Inverse Compton in Klein-Nishina regime has an impact on the synchrotron slope α

(see Derishev et al. 01 ; Bošnjak, Daigne & Dubus 09 ; Nakar, Ando & Sari 09)

Inverse Compton in Klein-Nishina regime has an impact on the synchrotron slope α

(see Derishev et al. 01 ; Bošnjak, Daigne & Dubus 09 ; Nakar, Ando & Sari 09)

- Thomson regime : ($w_m < 1$)

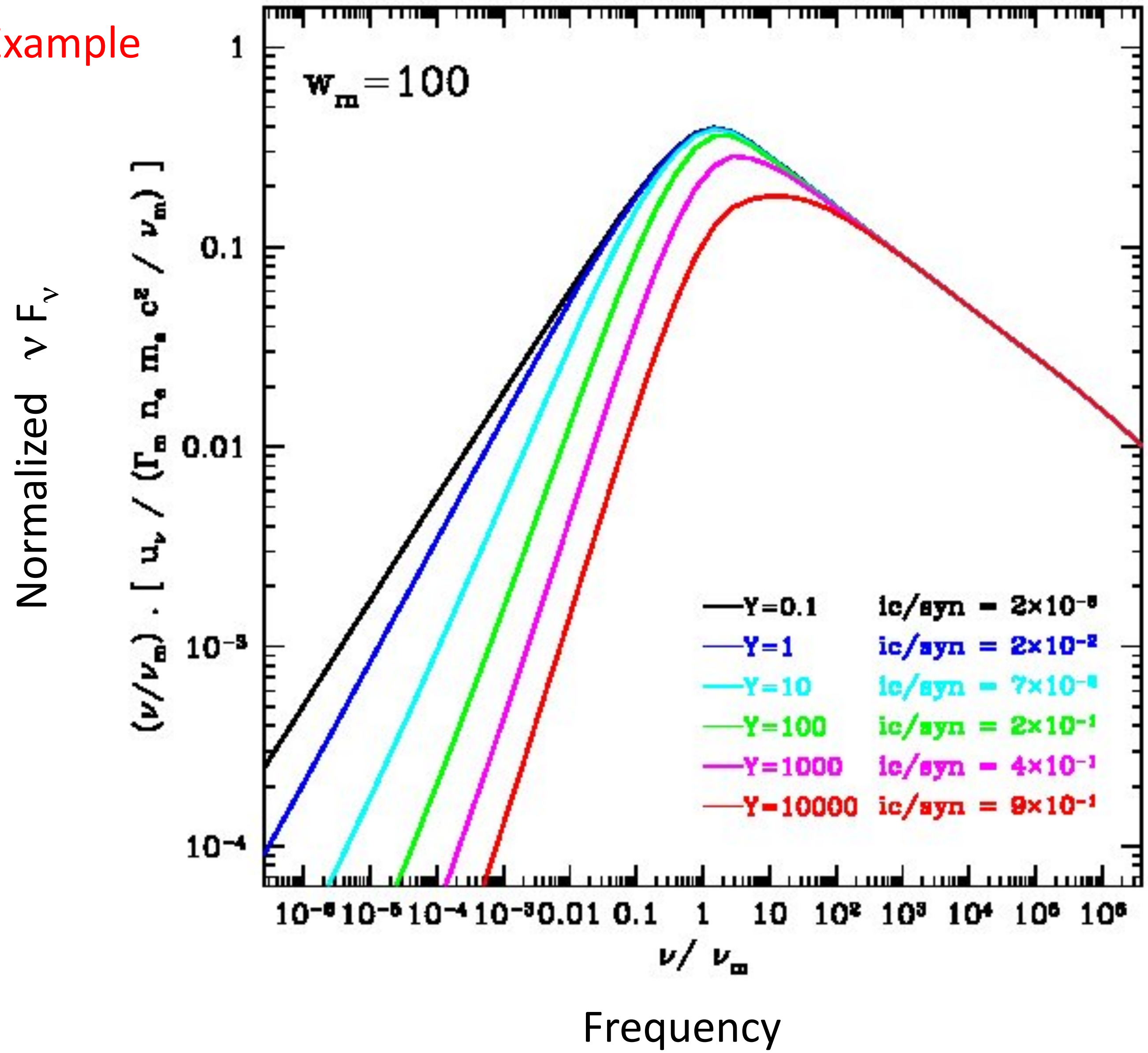
$$\frac{L_{\mathrm{ic}}}{L_{\mathrm{syn}}} \sim Y = \frac{4}{3}\tau_{\mathrm{T}}\Gamma_{\mathrm{m}}\Gamma_{\mathrm{c}} \simeq \frac{\epsilon_{\mathrm{e}}}{\epsilon_{\mathrm{B}}}$$

- Klein-Nishina regime : ($w_m > 1$)

$$\frac{L_{\mathrm{ic}}}{L_{\mathrm{syn}}} \sim Y \times f(w_{\mathrm{m}}) \quad \text{with} \quad f(w) \ll 1 \text{ for } w \gg 1$$

- Klein-Nishina parameter : $w_{\mathrm{m}} = \Gamma_{\mathrm{m}} \dfrac{h\nu'_{\mathrm{m}}}{m_{\mathrm{e}}c^2}$

Example



w_m : importance of KN

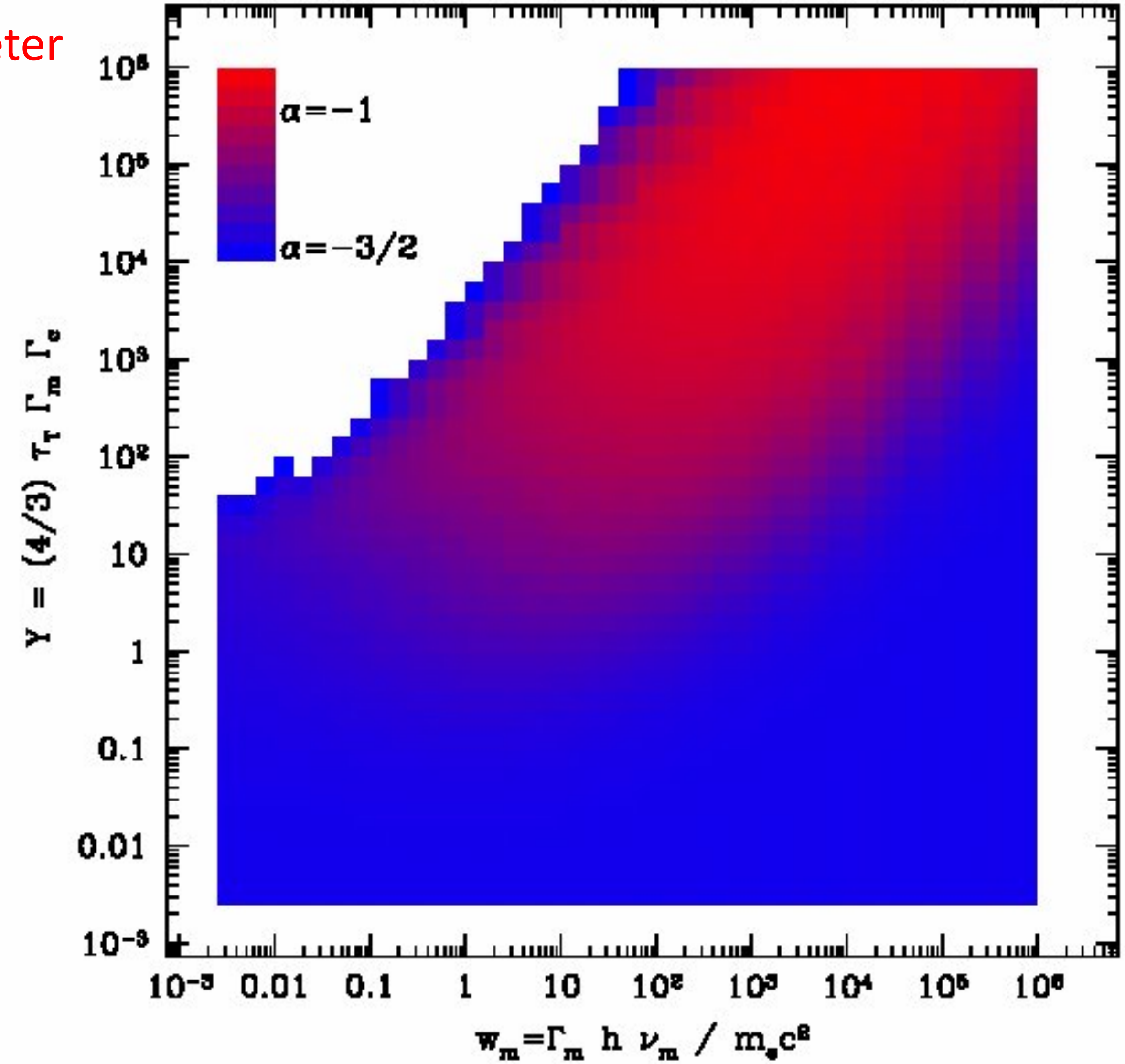
$$w_{\rm m} = \Gamma_{\rm m} \frac{h\nu'_{\rm m}}{m_{\rm e}c^2}$$

Y : importance of IC vs syn

$$Y = \frac{4}{3}\tau_{\rm T}\Gamma_{\rm m}\Gamma_{\rm c} \simeq \frac{\epsilon_{\rm e}}{\epsilon_{\rm B}}$$

Exact calculation with synchrotron + IC only (no adiabatic cooling; syn. self-abs; γγ annihilation, …)

Parameter space



Thomson Y parameter

Klein-Nishina parameter

w_m : importance of KN

$$w_{\rm m} = \Gamma_{\rm m} \frac{h\nu'_{\rm m}}{m_{\rm e}c^2}$$

Y : importance of IC vs syn

$$Y = \frac{4}{3}\tau_{\rm T}\Gamma_{\rm m}\Gamma_{\rm c} \simeq \frac{\epsilon_{\rm e}}{\epsilon_{\rm B}}$$

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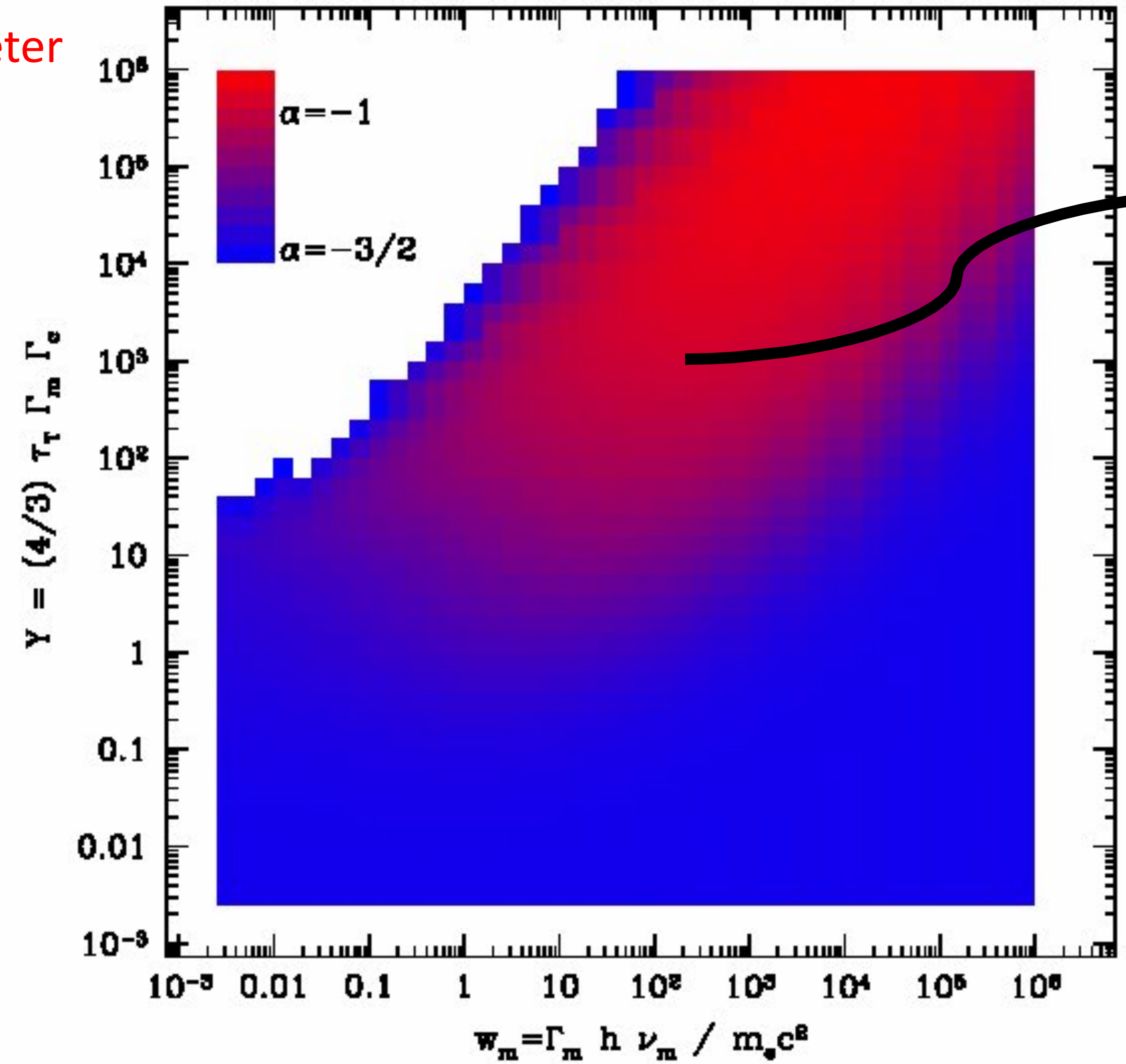


Thomson Y parameter

Klein-Nishina parameter

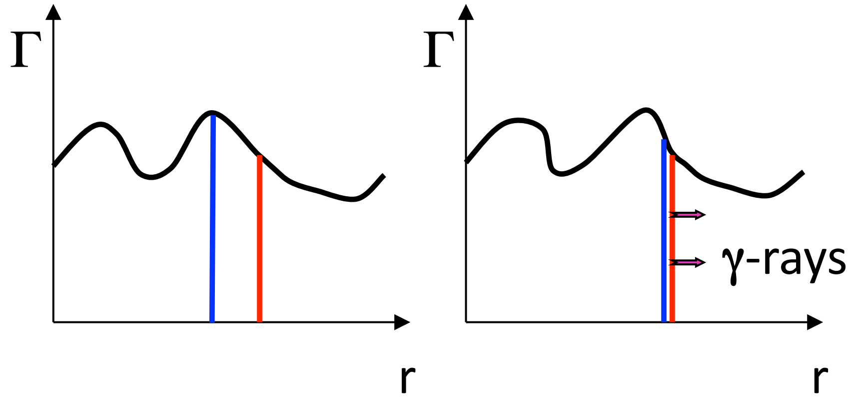
Steep slopes α = -1 can be obtained in fast cooling regime

L_{ic}/L_{syn} ~ 0.1-1 in this region

Exact calculation with synchrotron + IC only (no adiabatic cooling; syn. self-abs; γγ annihilation, …)

To go further, one needs a physical model for the emission region.

Internal shocks ?



Detailed model :

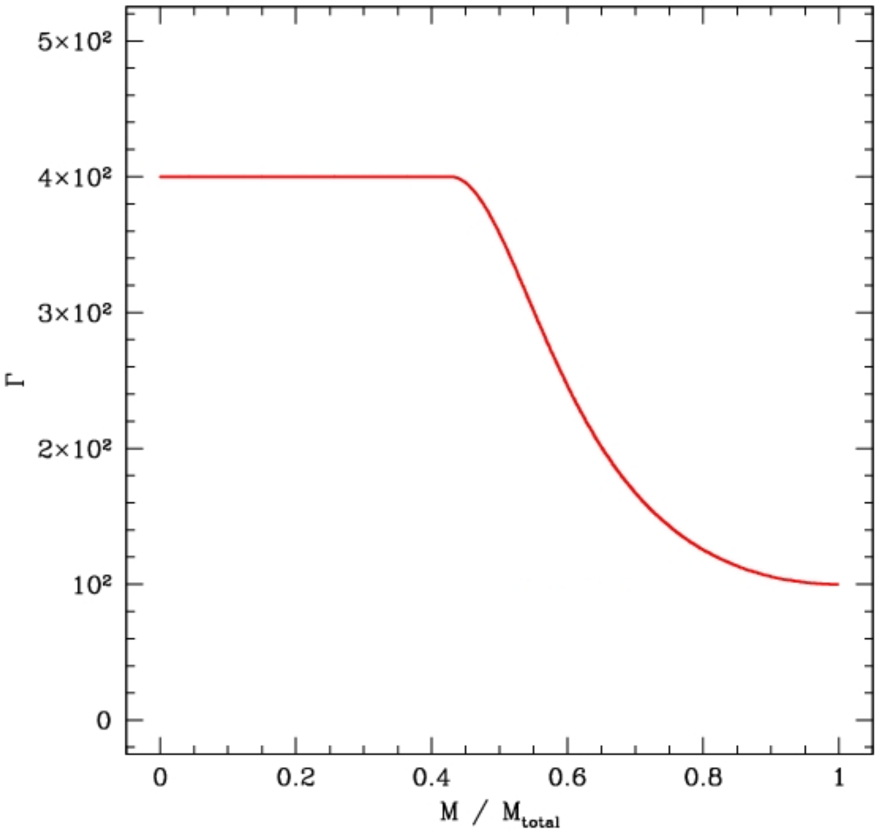
(Bošnjak, Daigne & Dubus 09)

Fraction of accelerated electrons

- Dynamics : multi-shell approximation
- Microphysics : magnetic field (ε_B) ; non-thermal population of electrons (ε_e,ζ,p)
- Radiation : solve time evolution of electrons and photons in the comoving frame of each shocked region (adiabatic cool.; synchrotron; syn. self-absorption; IC; $\gamma\gamma \rightarrow e^+e^-$)
- Observed GRB : integration over equal-arrival time surfaces

A single pulse burst (as a building block for more complex GRBs)

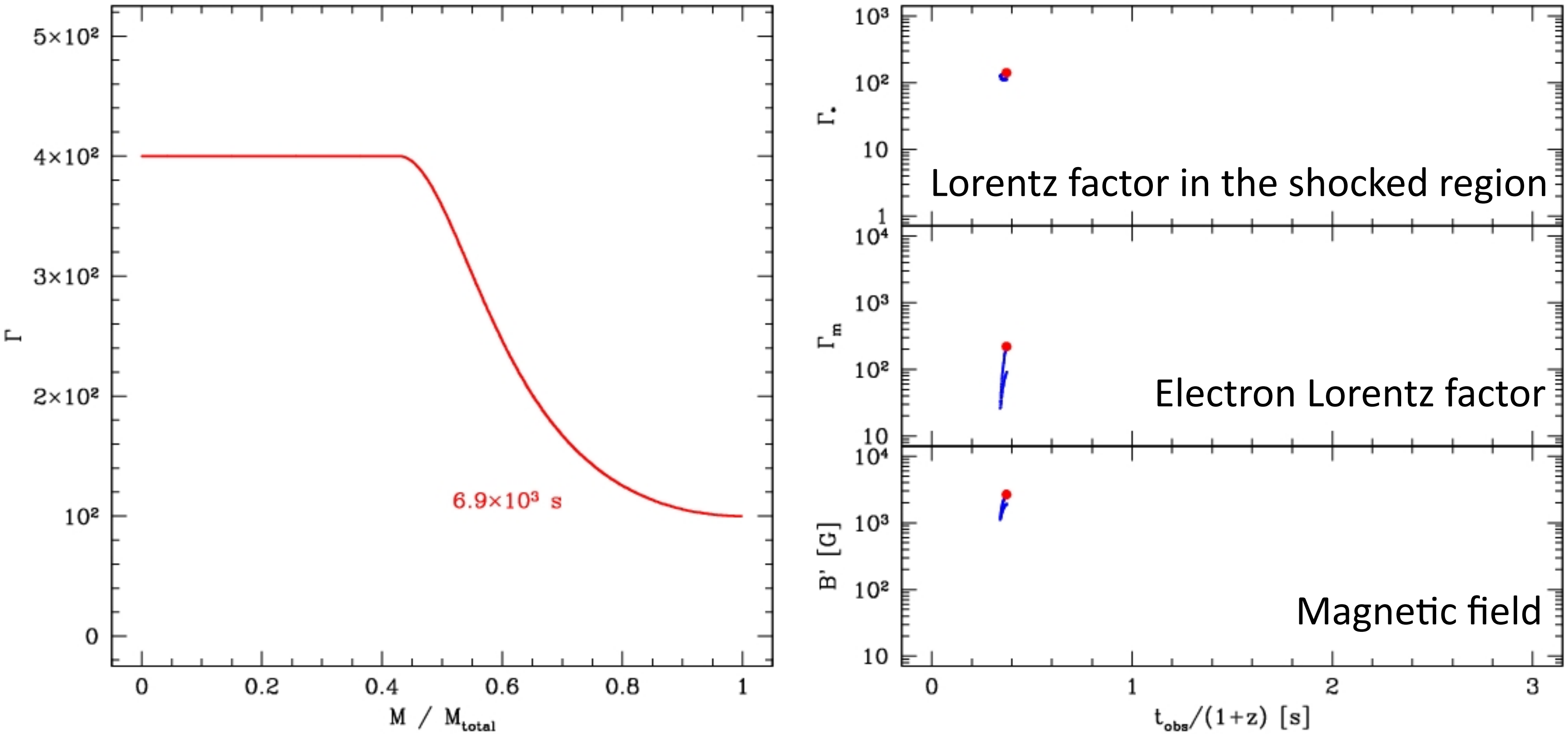
– Initial distribution of Lorentz factor :



– Ejection lasts for $t_w = 2s$
– Constant energy injection rate : $L_{kin} = 2\times10^{52}$ erg/s

A single pulse burst (as a building block for more complex GRBs)

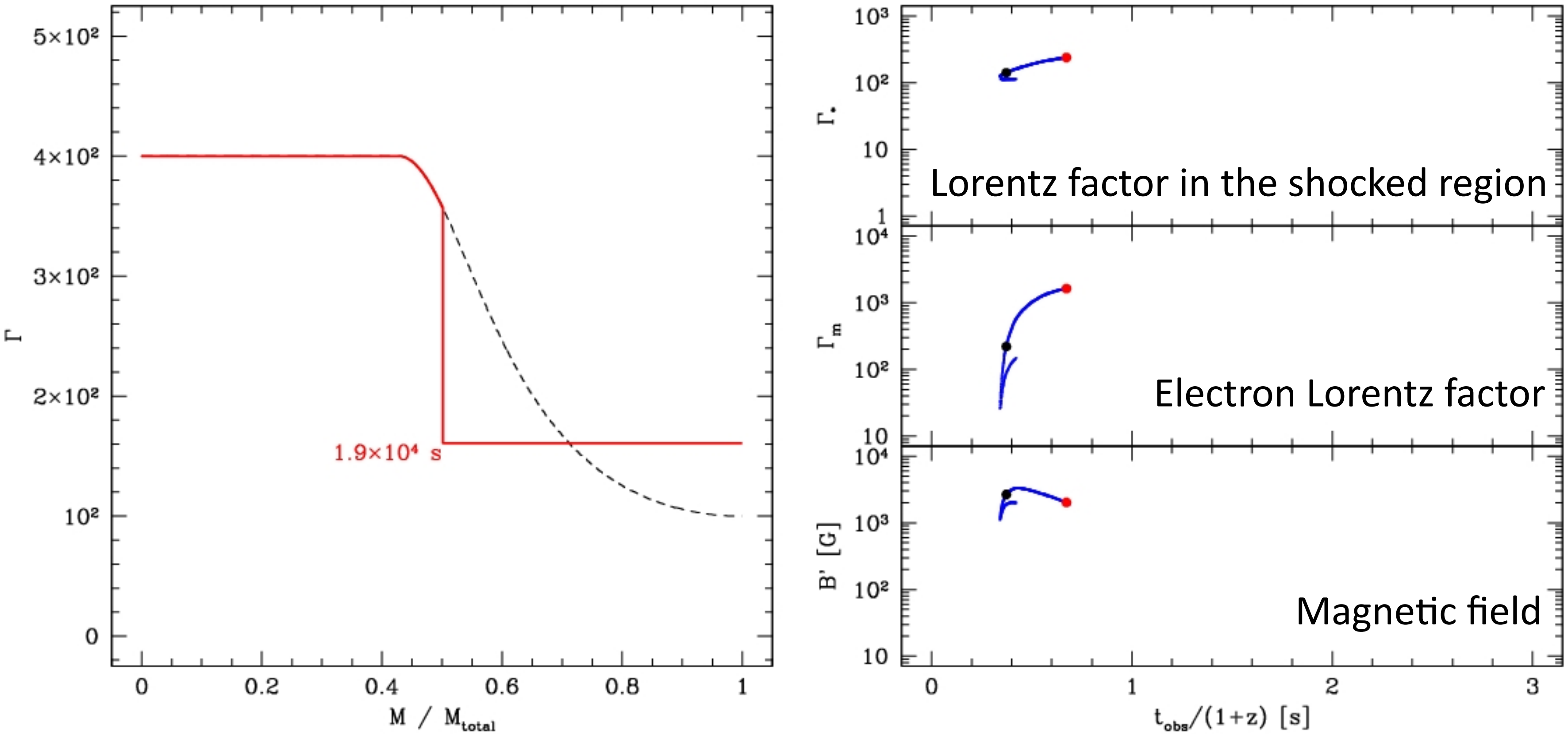
– Dynamical evolution :



– Constant microphysics parameters : $\varepsilon_e = \varepsilon_B = 1/3$; $\zeta = 0.01$; $p=2.5$

A single pulse burst (as a building block for more complex GRBs)

– Dynamical evolution :



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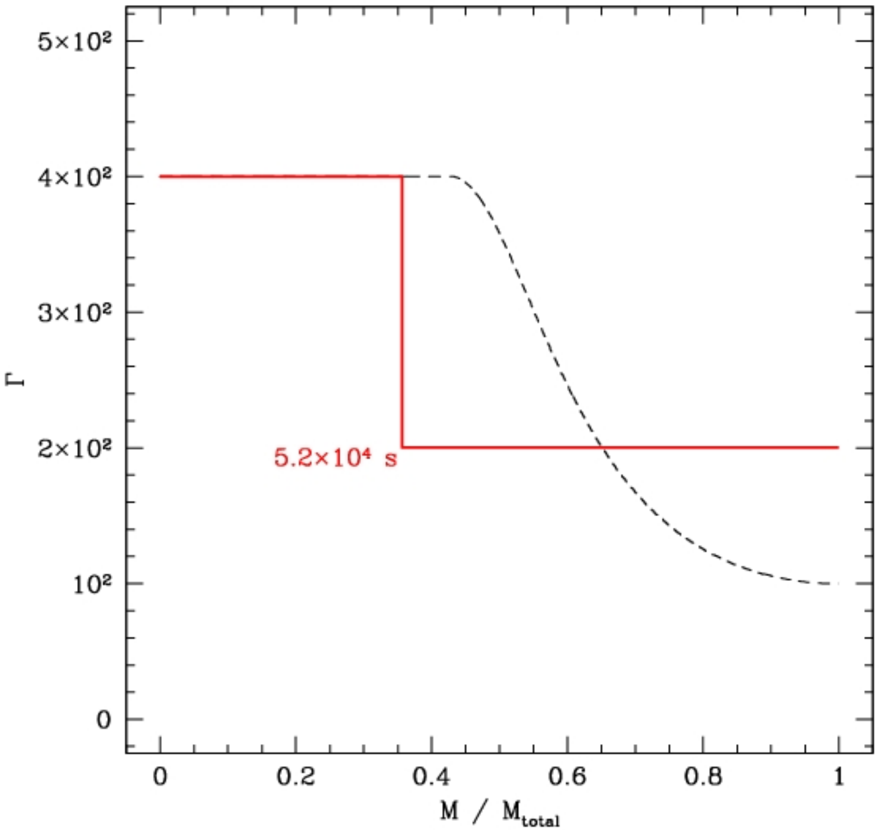

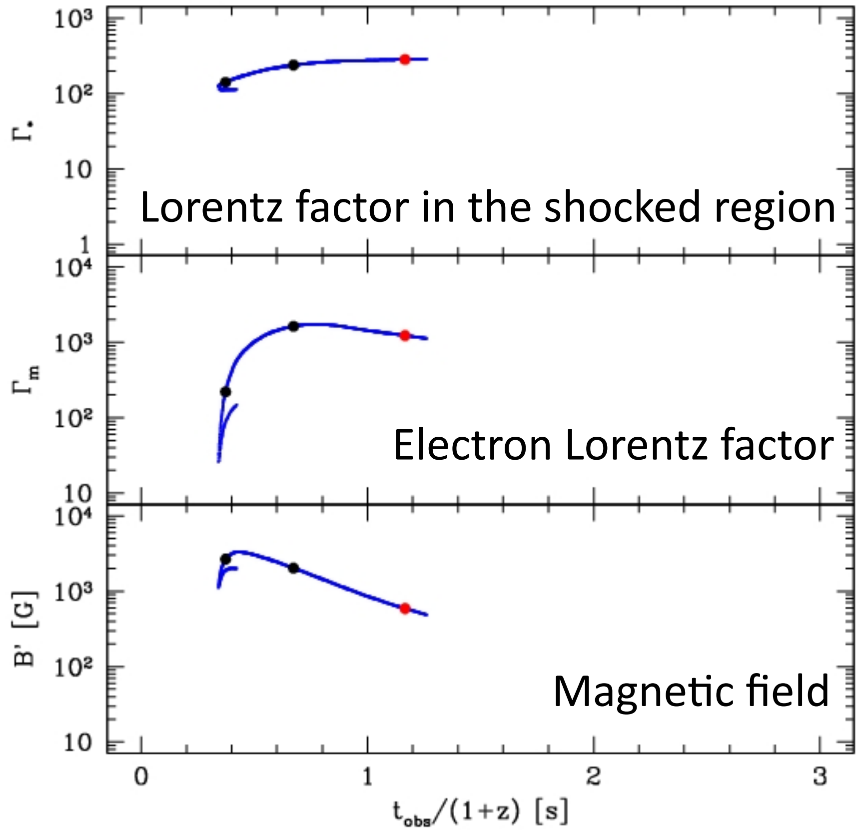

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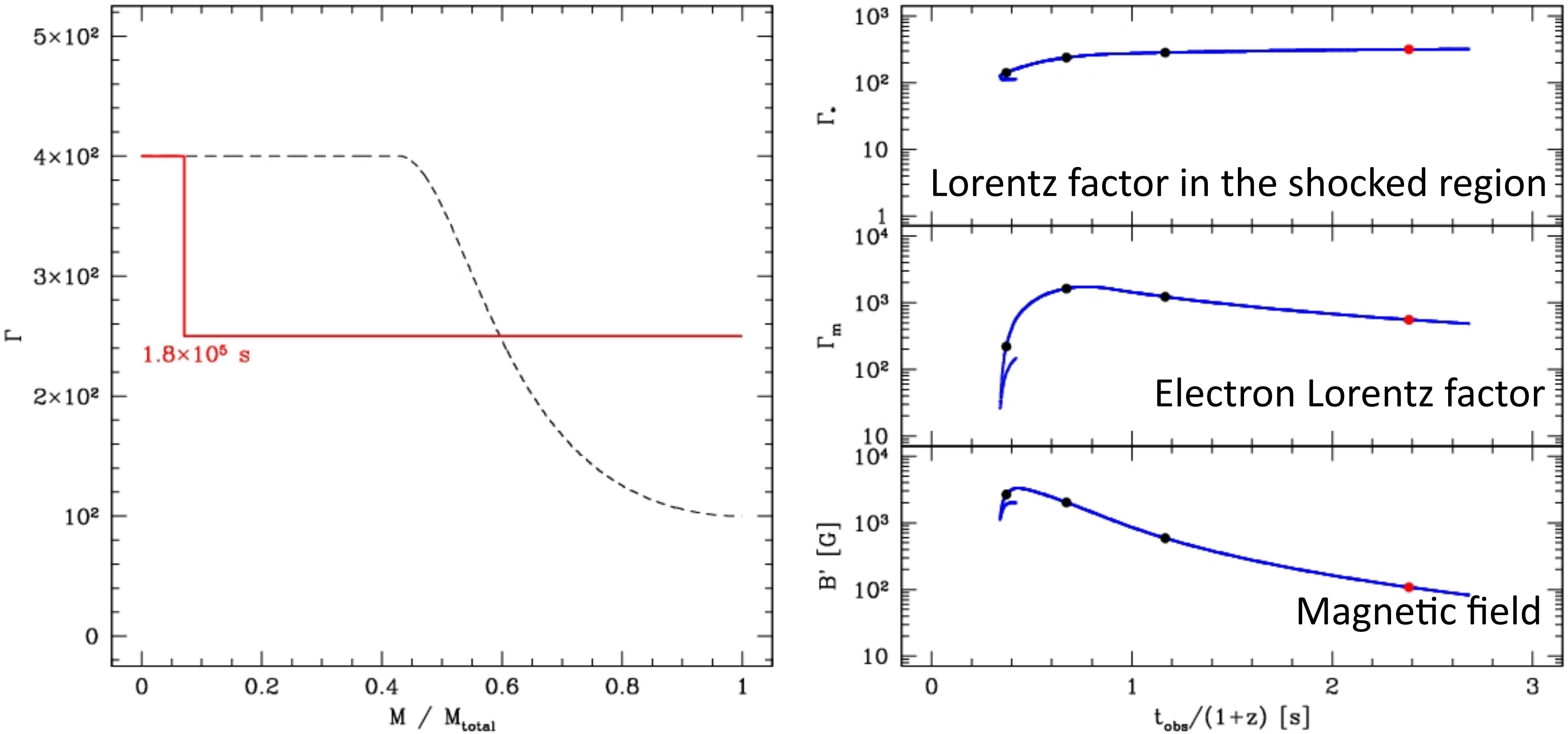
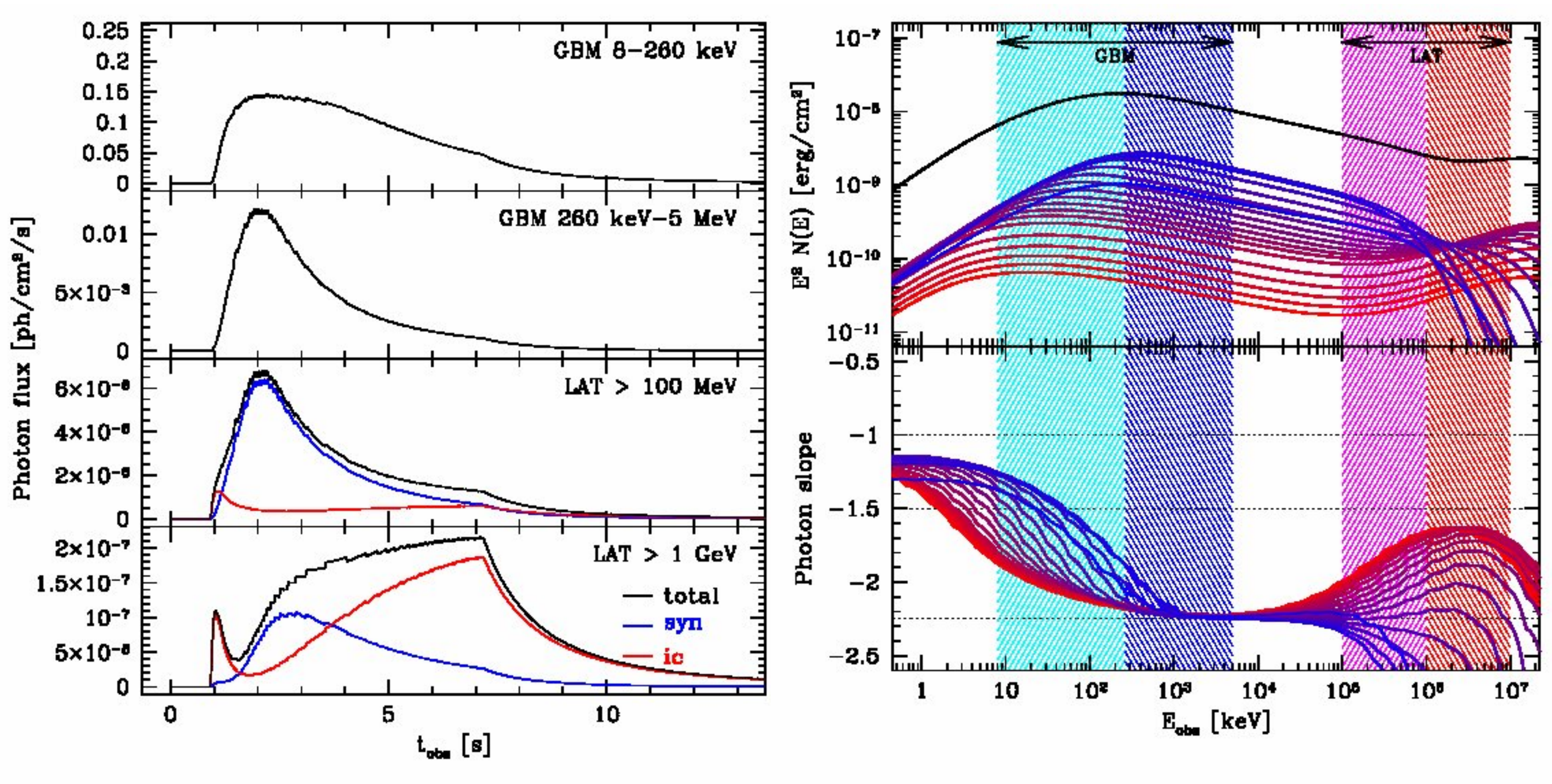


– Constant microphysics parameters : $\varepsilon_e = \varepsilon_B = 1/3$; $\zeta = 0.01$; $p = 2.5$

Prompt emission (4) — Radiative processes in internal shocks

EBL not included

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

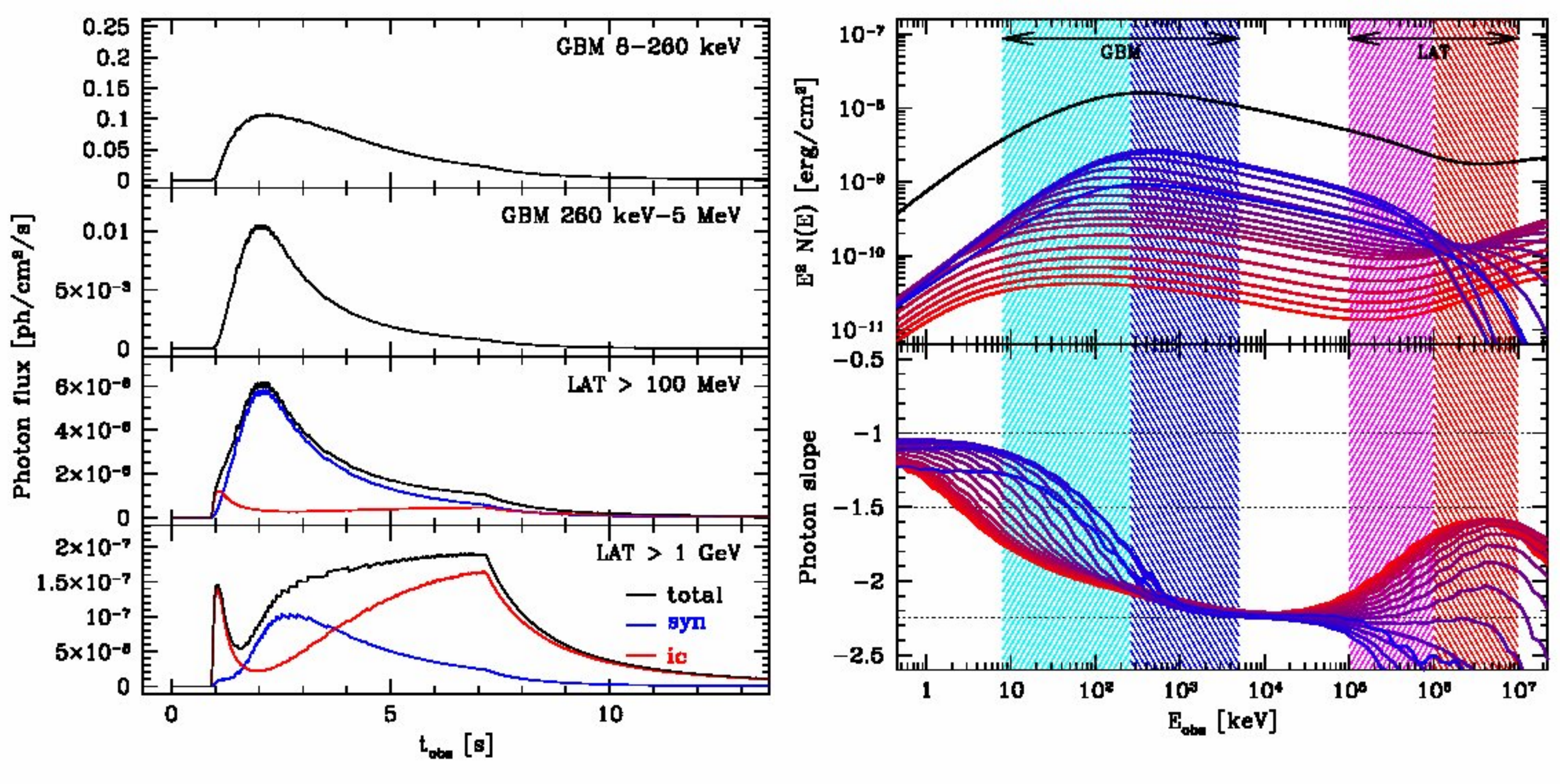


Full calculation with all processes (adiabatic cooling; sync; sync self-abs; IC; γγ annihilation)

Dynamics : ejection $\Gamma(t)$=100→400 ; duration = 1 s ; kinetic energy injection rate $L_{kin} = 10^{54}$ erg

EBL not included

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

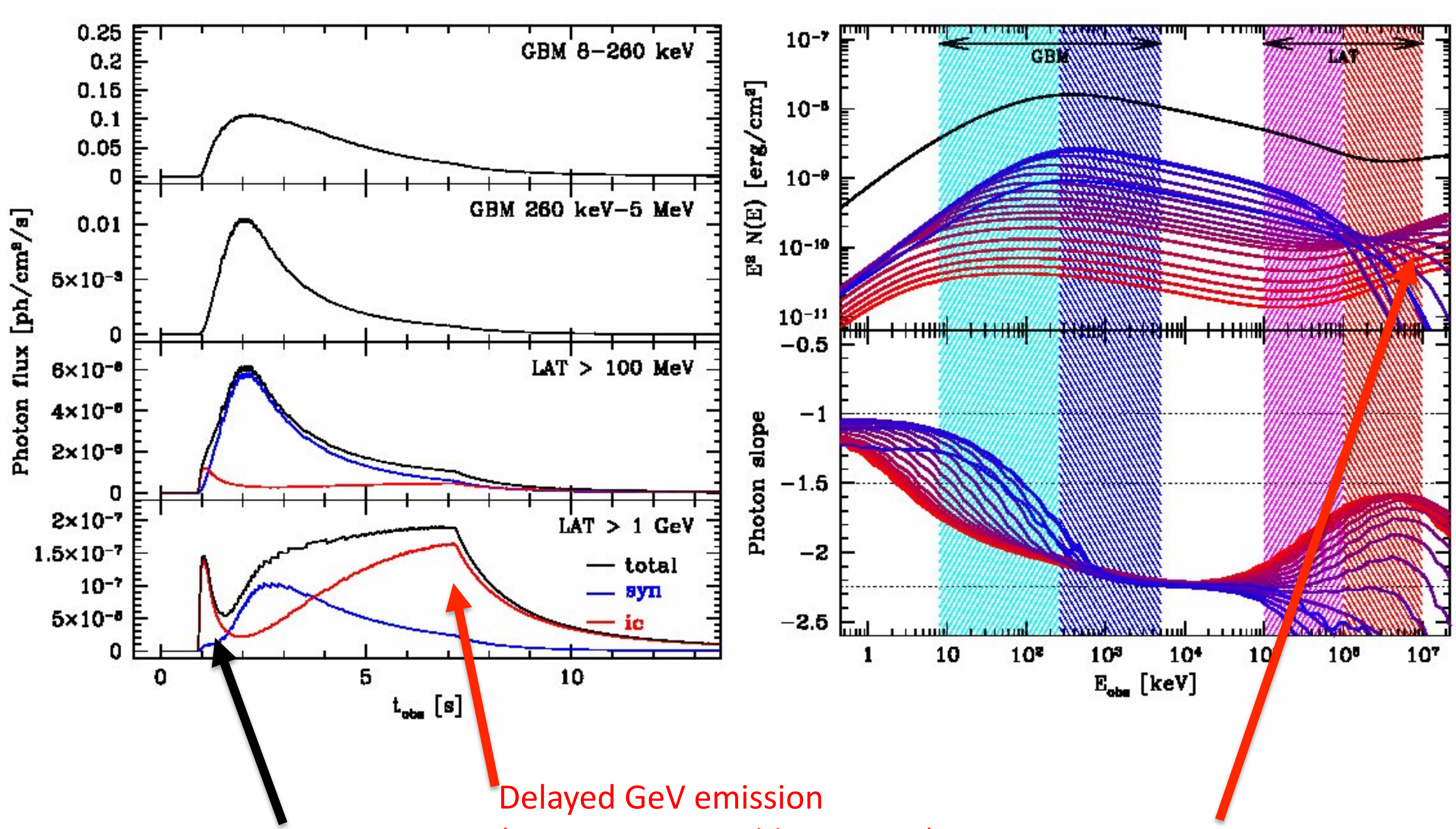


Full calculation with all processes (adiabatic cooling; sync; sync self-abs; IC; $\gamma\gamma$ annihilation)

Dynamics : ejection $\Gamma(t)$=100→400 ; duration = 1 s ; kinetic energy injection rate $L_{kin} = 10^{54}$ erg

Prompt emission (4) — Radiative processes in internal shocks

EBL not included



This feature is suppressed for more rapid variations of $\Gamma(t)$

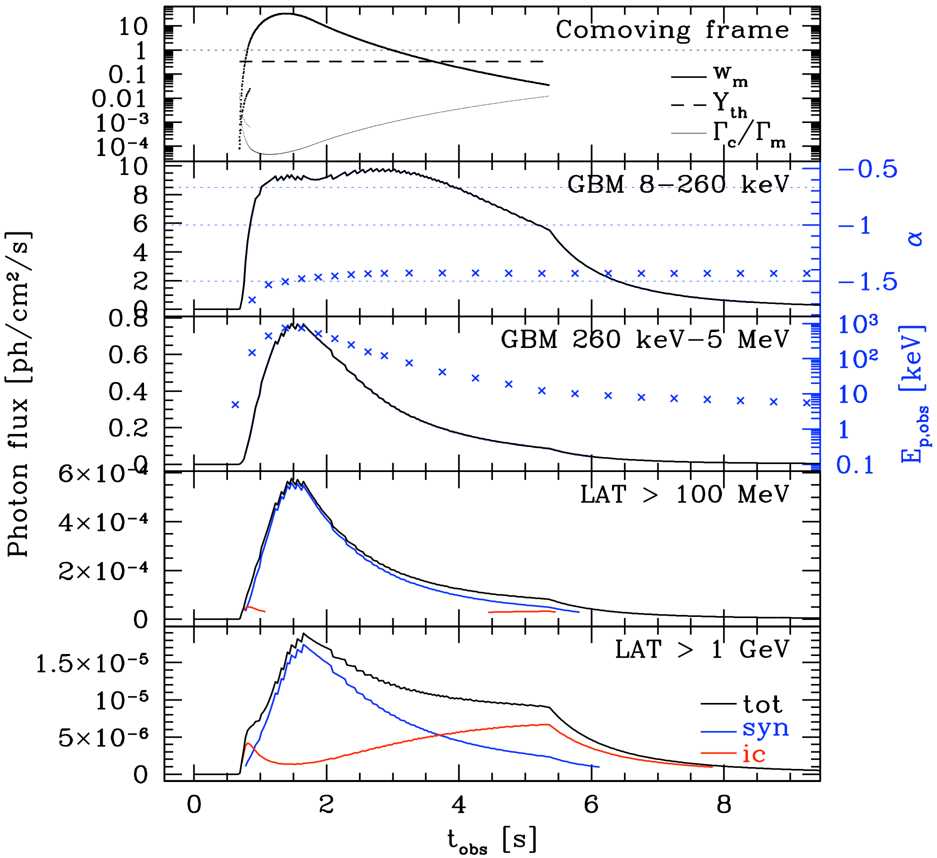
Delayed GeV emission (can operate in addition to $\gamma\gamma$)

Variable additional component at high-energy

Prompt emission (4) | Radiative processes in internal shocks

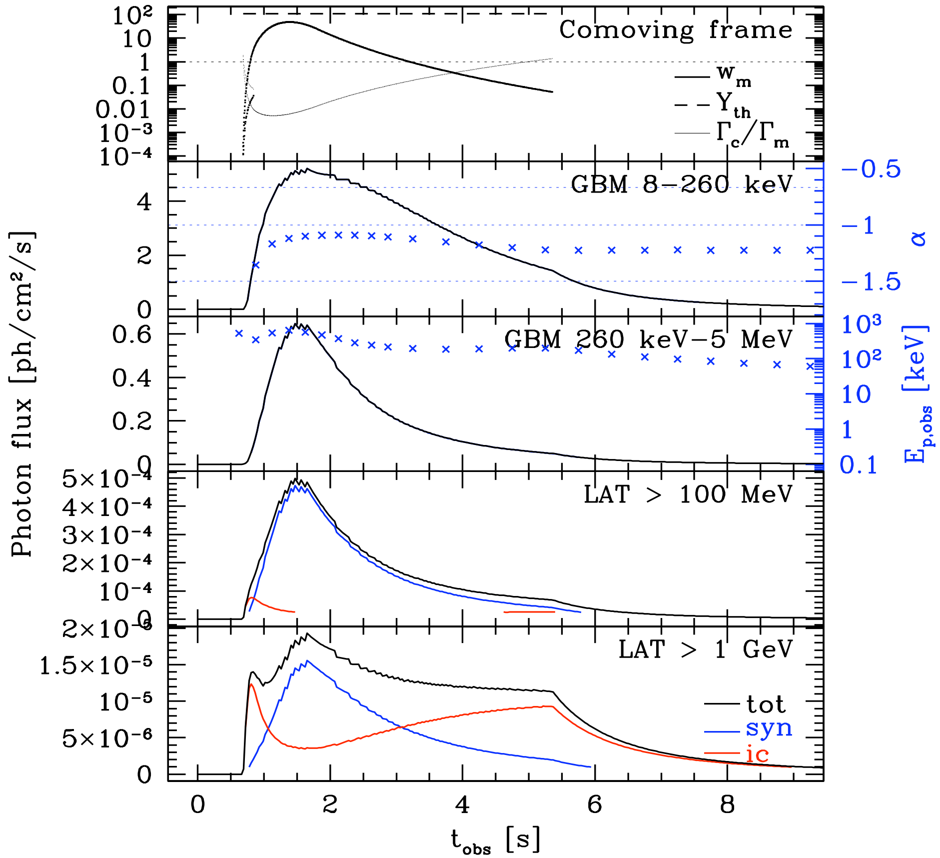
Another example :

Same burst with different microphysics parameters ε_B=1/3 or ε_B=0.001



ε_B=1/3 ; ζ = 0.003

E_p ~ 800 keV at the pulse peak



ε_B=0.001 ; ζ = 0.001

E_p ~ 700 keV at the pulse peak

Prompt emission (4) — Radiative processes in internal shocks

- Fermi/LAT observations (rate + HE spectrum of detected GRBs) :
  - synchrotron is favored
  - SSC seems in contradiction with observations

  (Bosnjak, Daigne & Dubus 2009 ; Piran, Sari & Zou 2009)

- IC scatterings in KN regime can affect the synchrotron slope : $-3/2 \leq \alpha \leq -1$
  - this can reconcile the synchrotron process with most observations
  - spectra with $-1 \leq \alpha \leq -2/3$? (marginally fast cooling regime ?)
  - spectra with $\alpha \geq -2/3$: real problem ?

  (Bosnjak, Daigne & Dubus 2009 ; Nakar, Ando & Sari 2009 ; Daigne, Bosnjak & Dubus 2011)

- Shock acceleration physics in mildly relativistic regime ? (low ζ ; low ε_B)
  Are microphysics parameters constant ? (may change spectral evolution)

  If only a fraction of electrons are accelerated, can we detect the « thermal » electron component ? (additional component seen in some Fermi bursts ?)

  (Daigne et al. in preparation)

- Internal shocks : spectral evolution is expected
  - delayed GeV emission
  - variable additional power-law component at high-energy
    (additional component below 50 keV ?)

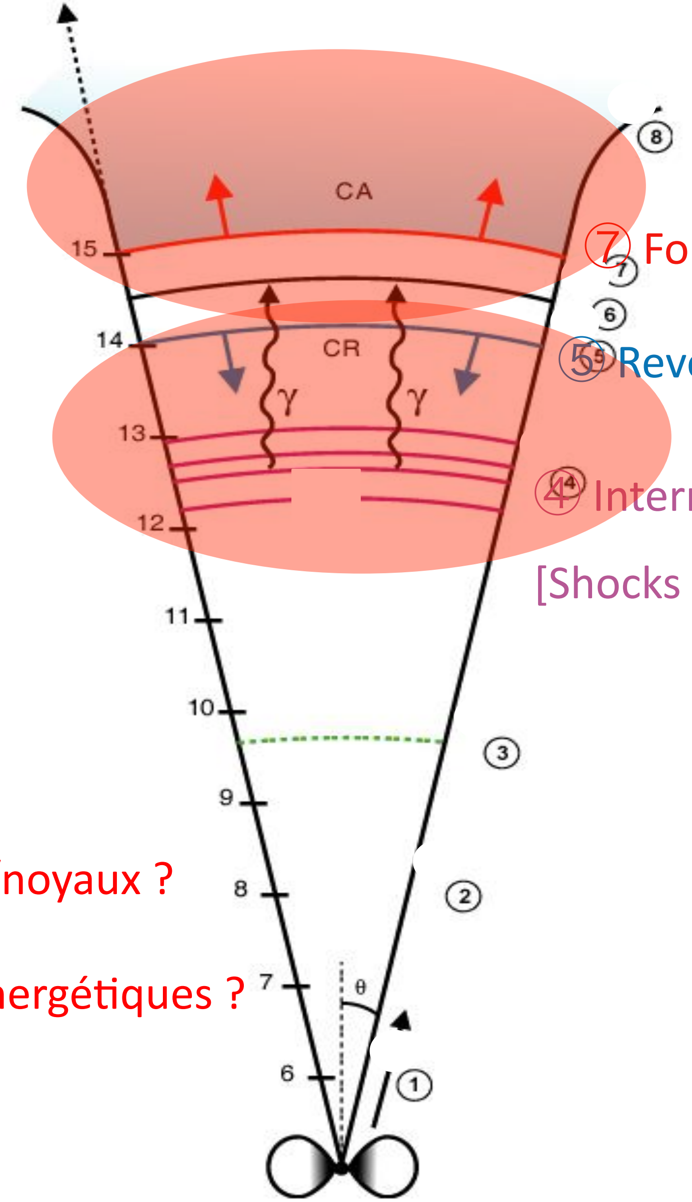
  - photospheric component (magnetic acceleration ?)

- Work in progress :
  - detailed modelling of LAT bursts
  - test of observed hardness-intensity and hardness-fluence correlations

- Measuring the physical conditions in the relativistic outflow ?
(Lorentz factor, radius, magnetic field, etc.)

En guise de conclusion | Tout ce dont je n’ai pas parlé…

Les sursauts gamma comme accélérateurs cosmiques



⑦ Forward (external) shock → afterglow ?

⑤ Reverse shock → optical flash ?

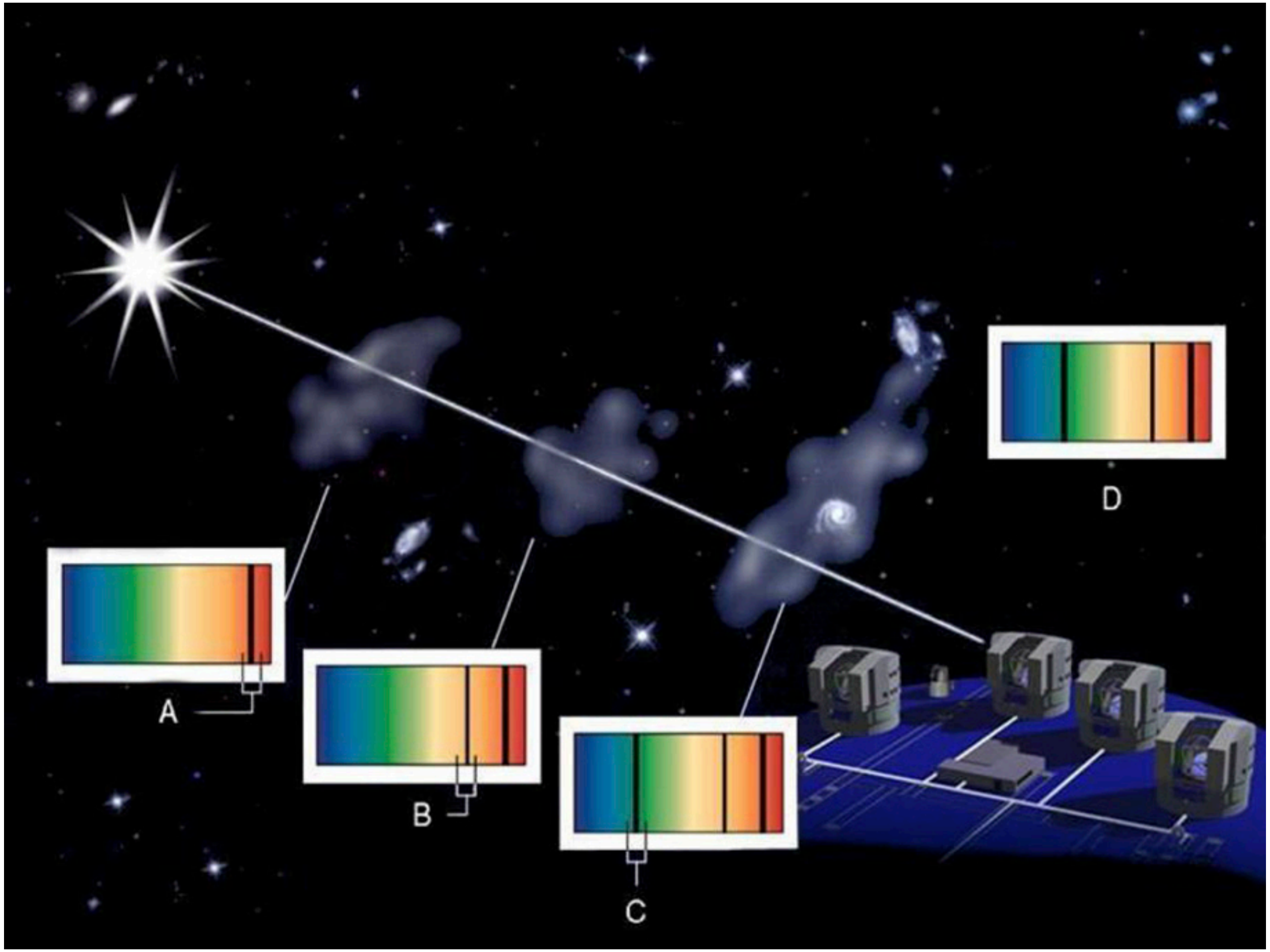
④ Internal dissipation → prompt emission ?

[Shocks or magnetic dissipation ?]

Accélération de protons/noyaux ?

Emission de neutrinos énergétiques ?

Les sursauts gamma comme sondes de l'Univers lointain



Tout ce dont je n'ai pas parlé…

Et beaucoup d'autres choses…

3) Radiative processes in internal shocks : origin of the Band spectrum ?
High-energy emission ?

The standard picture (fireball + IS-RS-FS) can explain many features observed in prompt GRBs and afterglows.

This scenario is however facing many difficulties with Swift (early afterglow) and Fermi (high-energy emission) data…

- Self-consistent treatment of all emission phases (prompt, afterglow)
-More realistic assumptions (ejecta; environment) ?
-Microphysics ?
-Missing ingredients ?