Gamma-Ray Bursts

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Observing the X- and Gamma-Ray Sky, Cargèse/Corsica, April 2006

1. The discovery of GRBs

2. Main properties

3. The GRB distance scale

4. The afterglow era

5. Recent results : SWIFT

6. How to produce a GRB

7. GRBs and cosmology

Introduction…

The discovery of GRBs

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

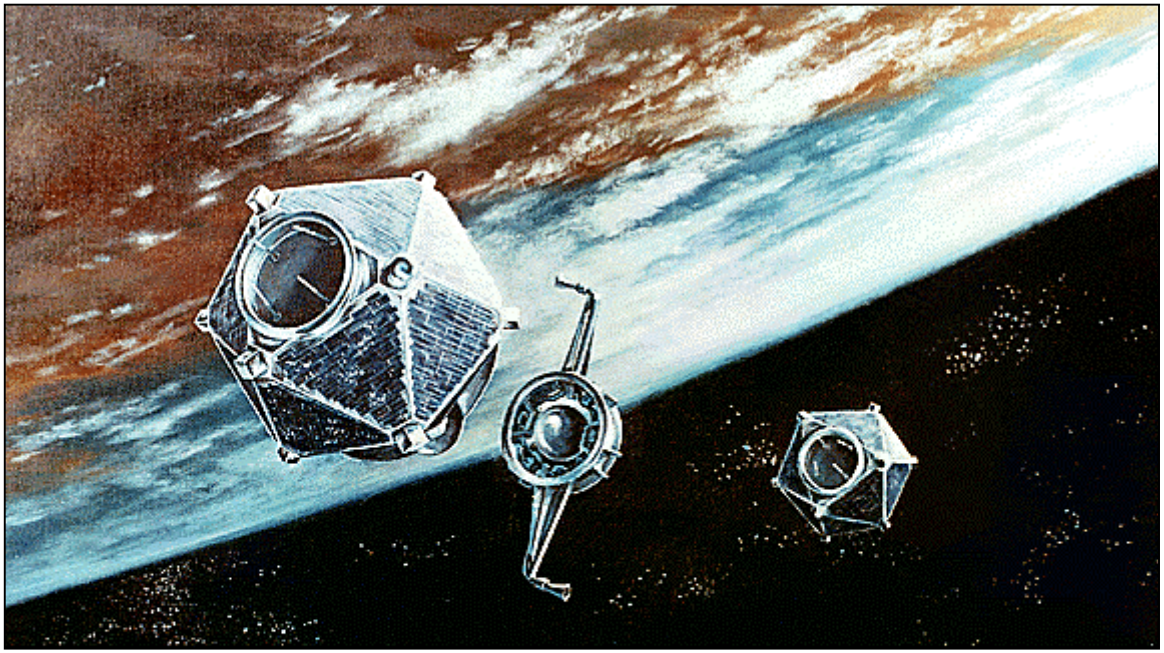
1. Each of the Parties to this Treaty undertakes to prohibit, to prevent, and not to carry out any nuclear weapon test explosion, or any other nuclear explosion, at any place under its jurisdiction or control:

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

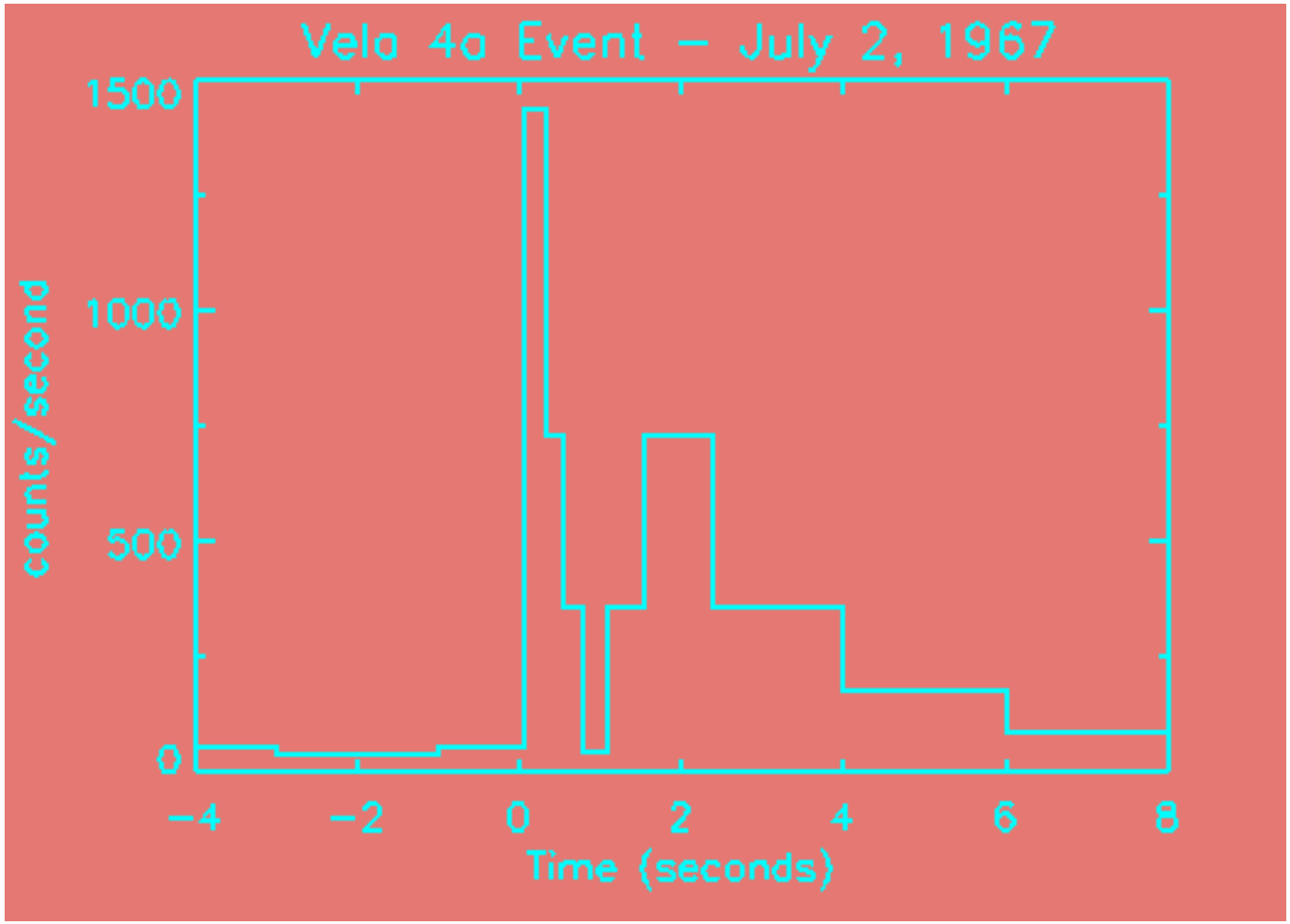
How to detect a nuclear explosion ?

Signatures :

- Seismic signals
- Very low frequency sound waves
- **Gamma-rays** → **The « VELA » program (3 pairs of satellites, launched in 1963, 1964 and 1965)**



The discovery of GRBs



The discovery of GRBs

THE ASTROPHYSICAL JOURNAL, 182:L85–L88, 1973 June 1
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OBSERVATIONS OF GAMMA-RAY BURSTS OF COSMIC ORIGIN

RAY W. KLEBESADEL, IAN B. STRONG, AND ROY A. OLSON

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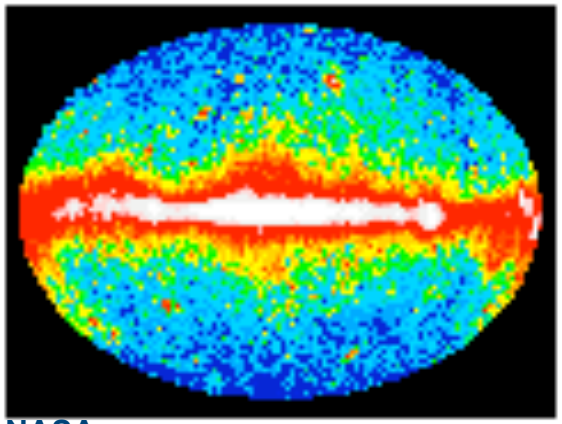
Received 1973 March 16; revised 1973 April 2

ABSTRACT

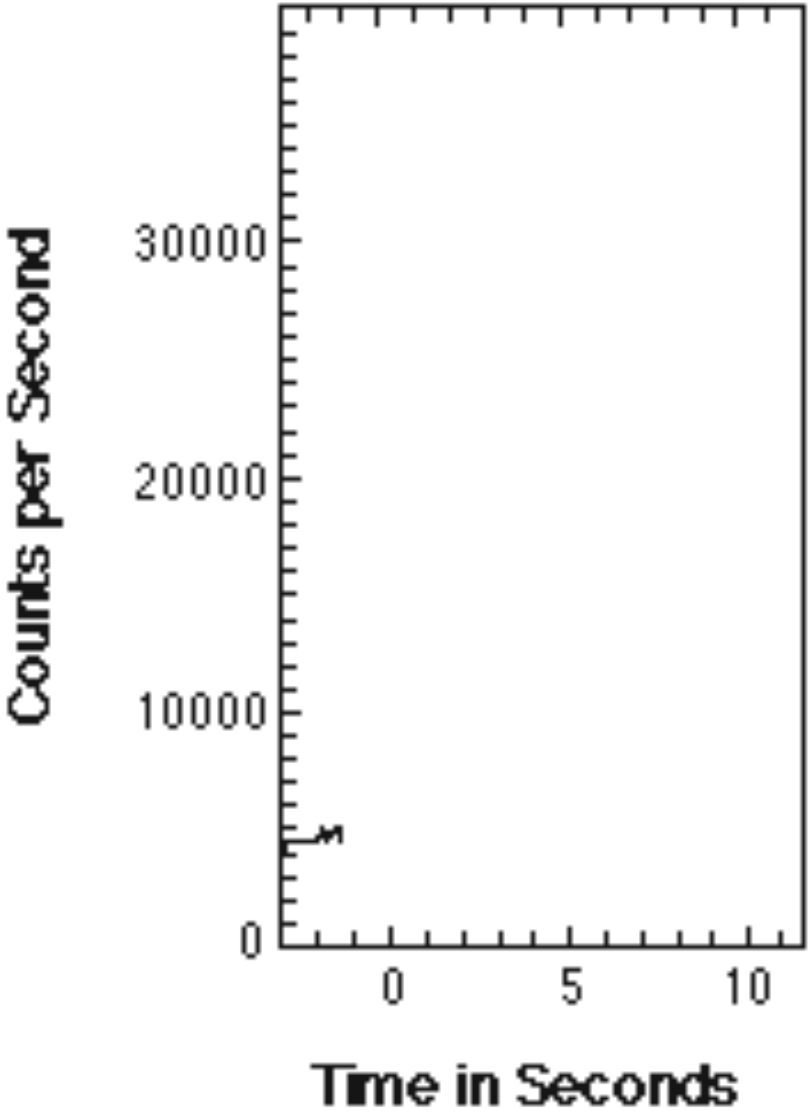
Sixteen short bursts of photons in the energy range 0.2–1.5 MeV have been observed between 1969 July and 1972 July using widely separated spacecraft. Burst durations ranged from less than 0.1 s to ~30 s, and time-integrated flux densities from $\sim 10^{-5}$ ergs cm^{-2} to $\sim 2 \times 10^{-4}$ ergs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

What is a Gamma-Ray Burst ?



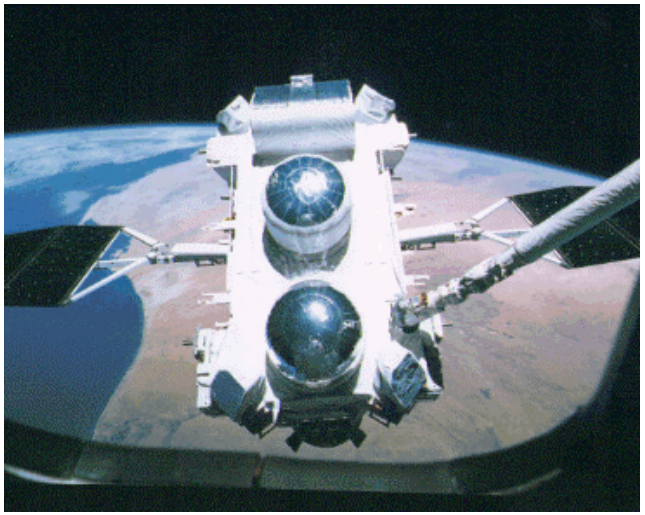
NASA

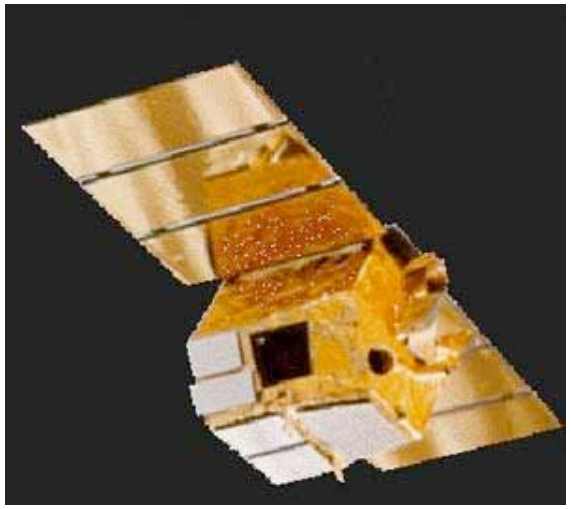


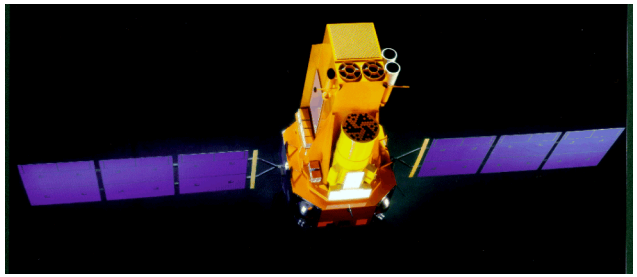
What is a Gamma-Ray Burst ?

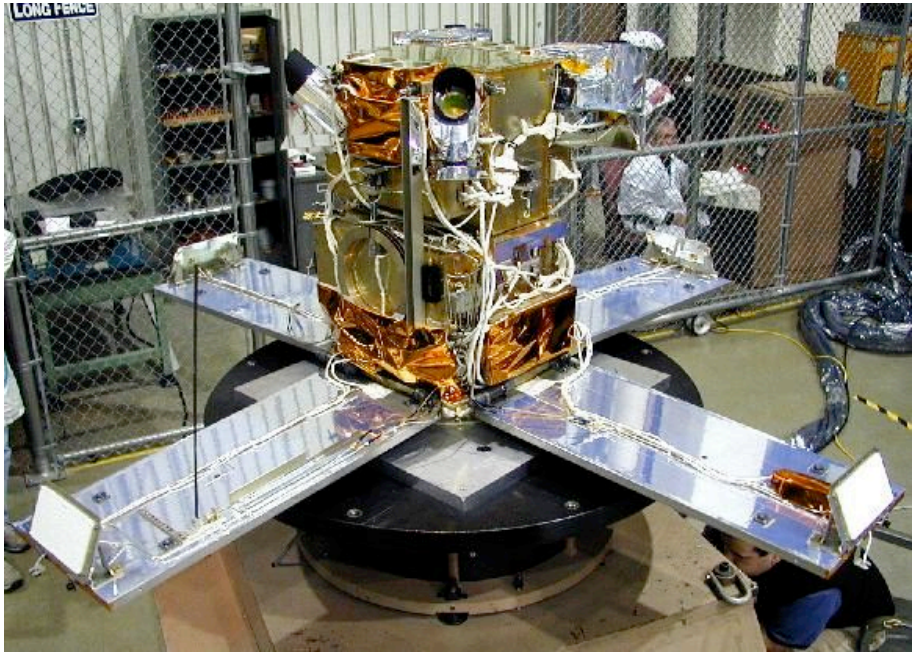
1970-1980 :	**GRBs are studied by several satellites.**
90' :	**BATSE experiment onboard CGRO**
	Beppo-SAX satellite (april 1996 – april 2002)
2000' :	**HETE-2 satellite (launch: october 2000)**
	INTEGRAL observatory (launch: october 2002)
	SWIFT satellite (launch: october 2004)

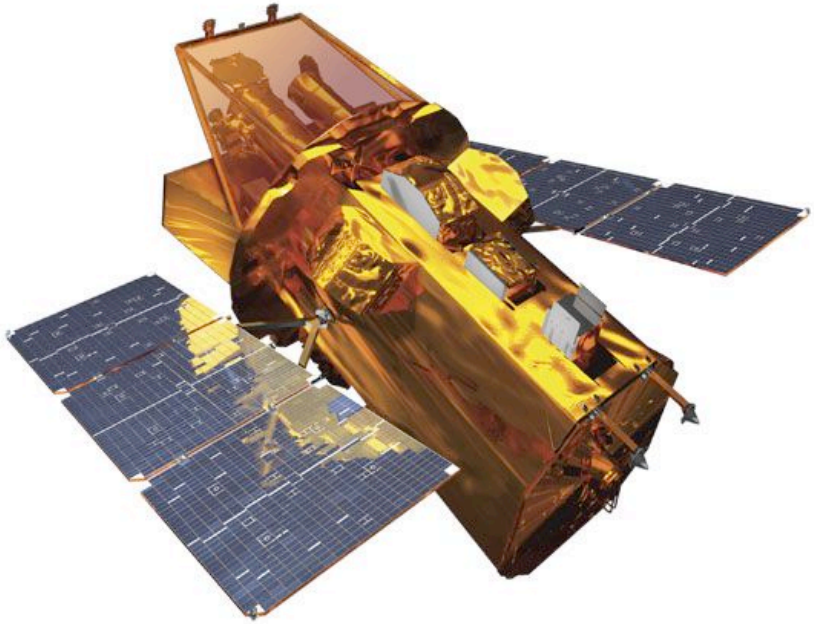
Detecting GRBs











Observations

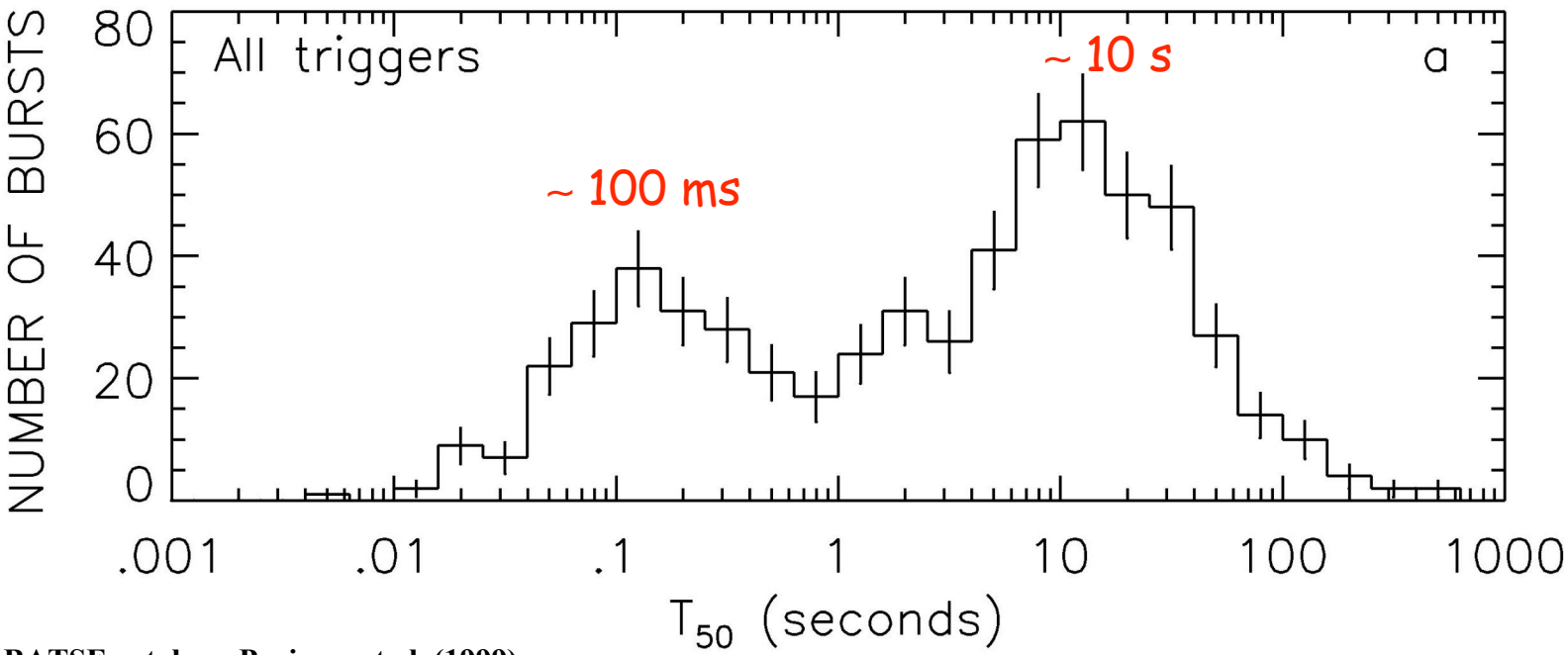
Main GRB properties

Observations : GRB rate

1991-2000 : BATSE ~ 1 GRB per day (total : 2704 GRBs)

Observations : GRB duration

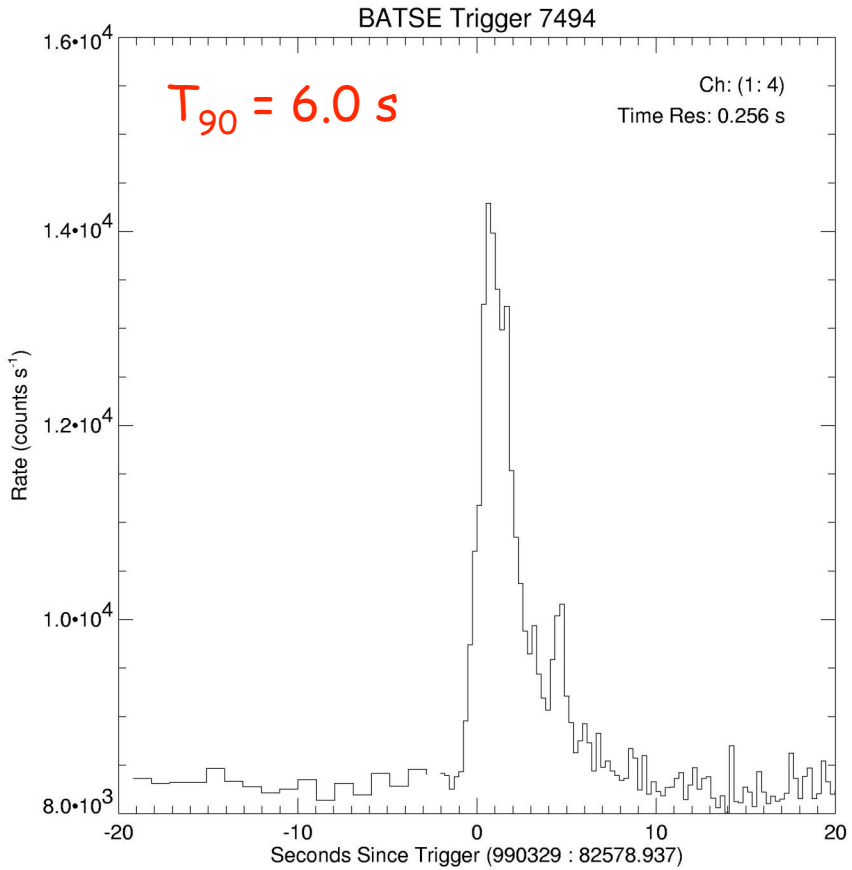
Two groups



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

Observations : time profiles

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



Observations : time profiles

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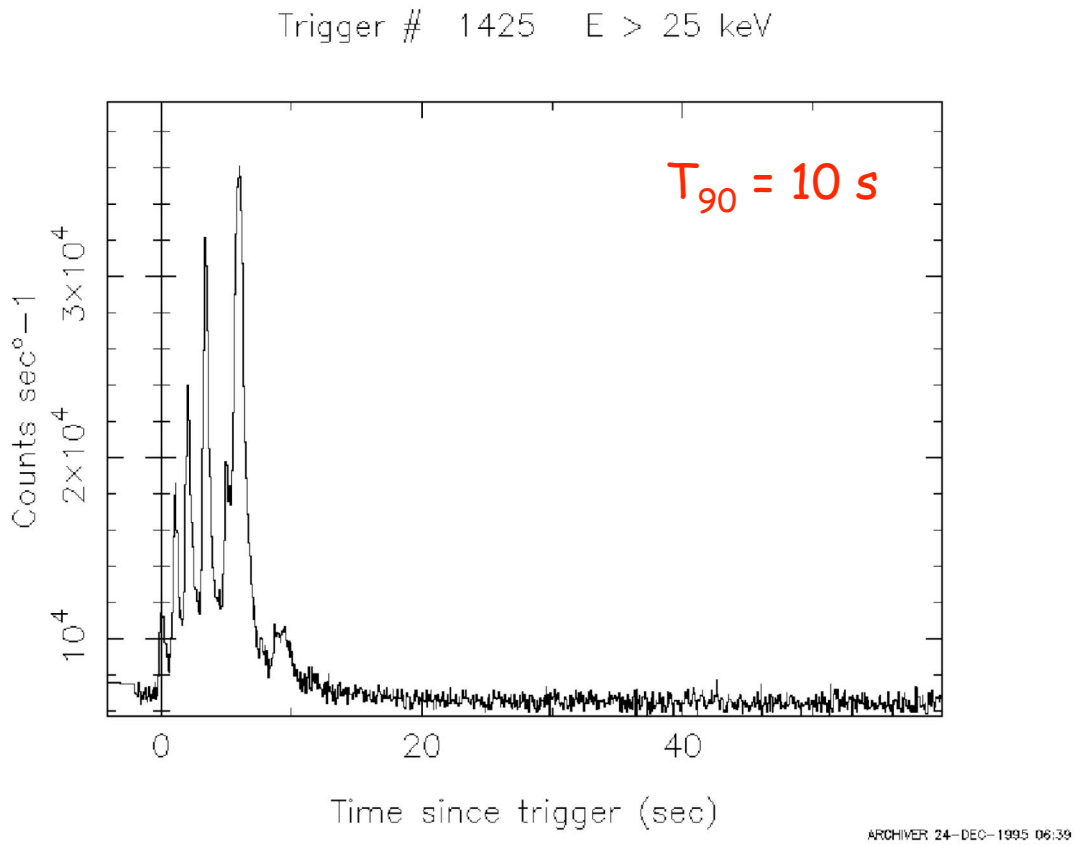

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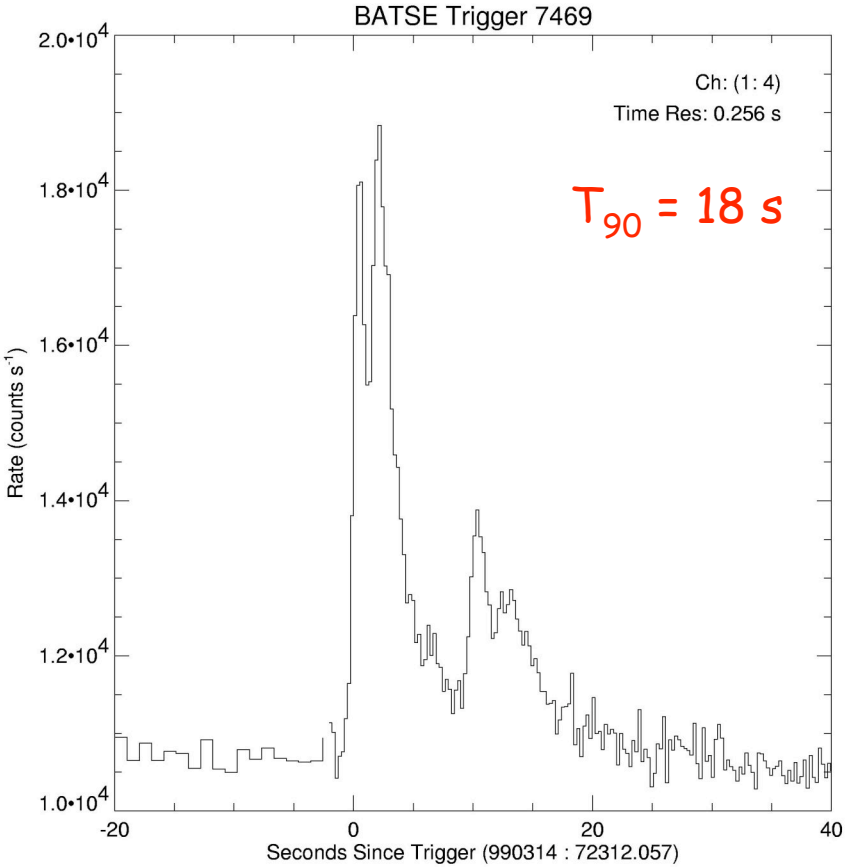

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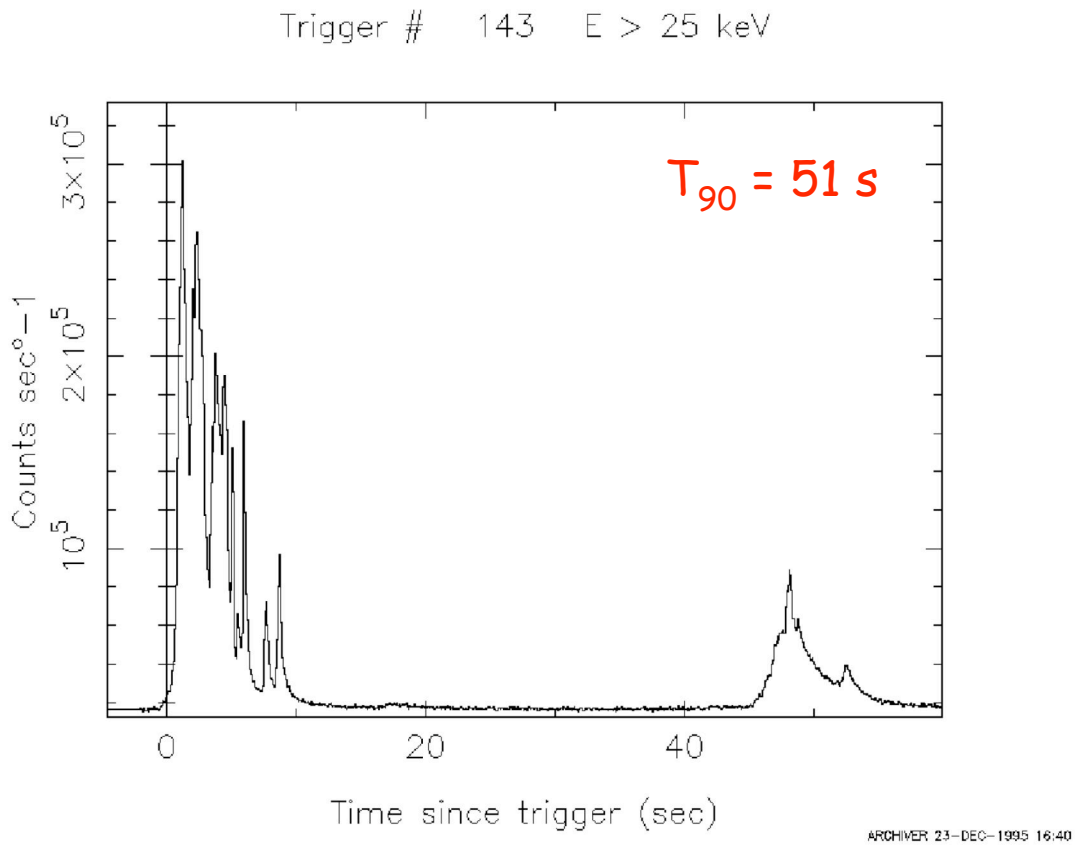
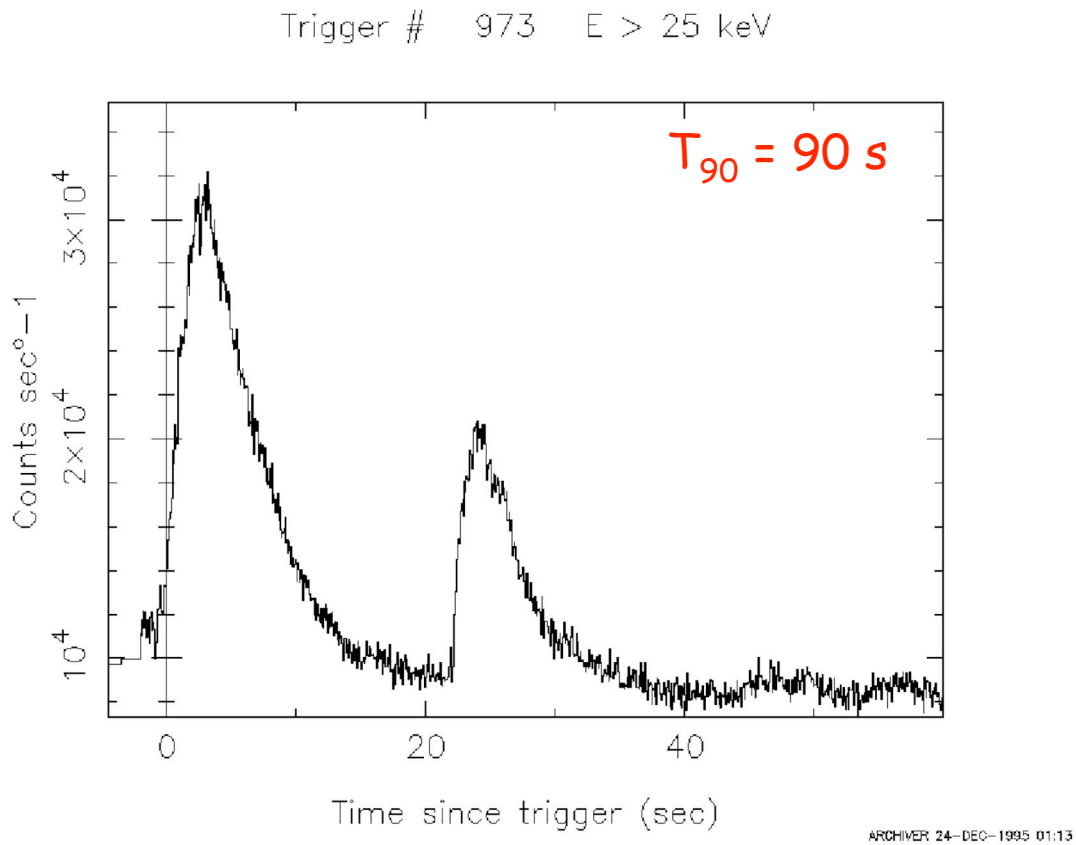


Observations : time profiles

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



Observations : time profiles

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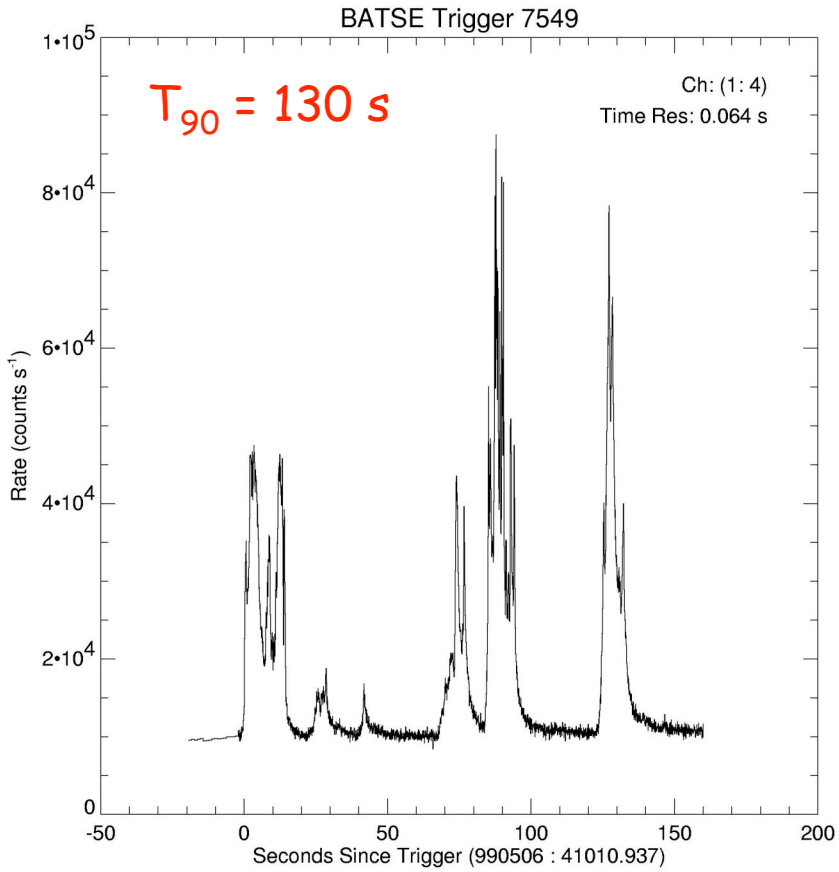
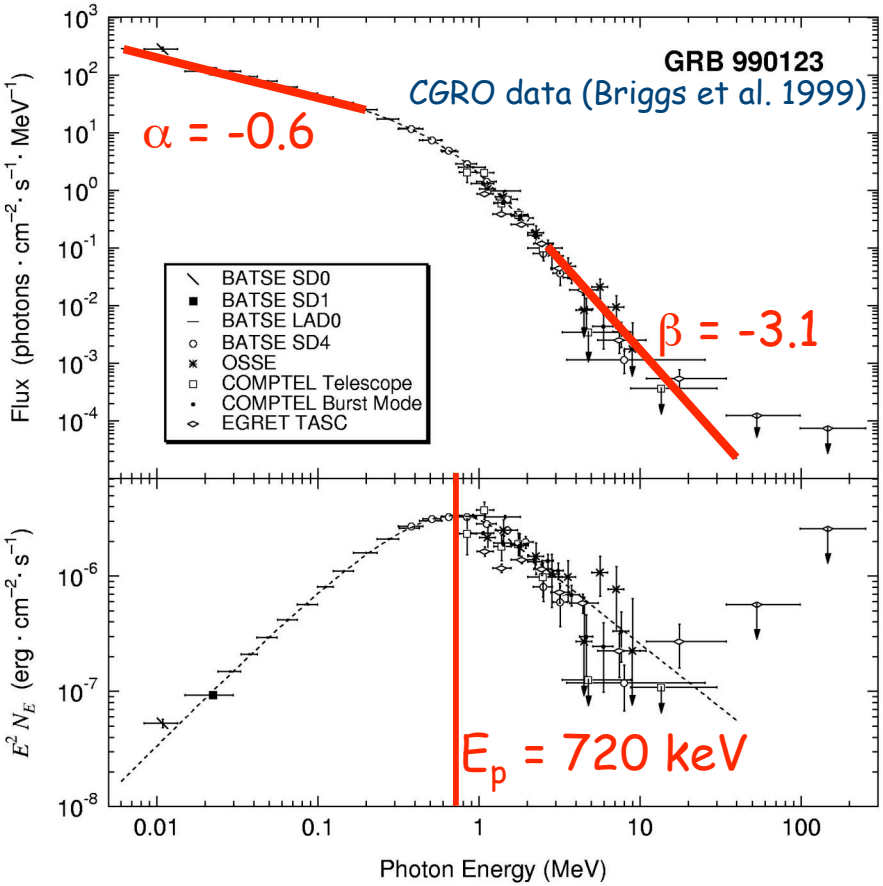
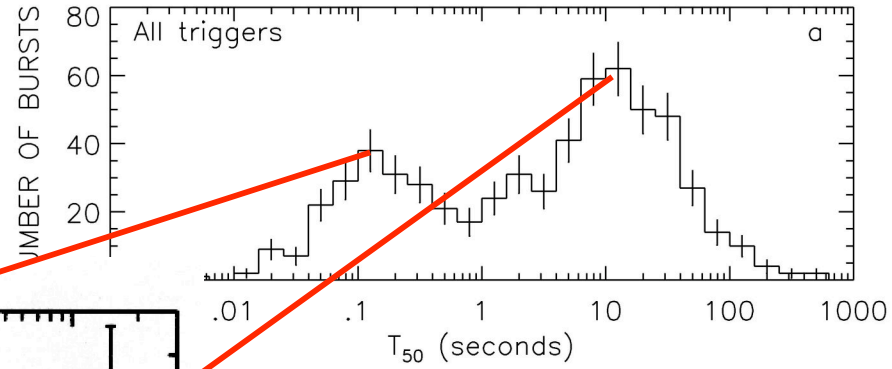
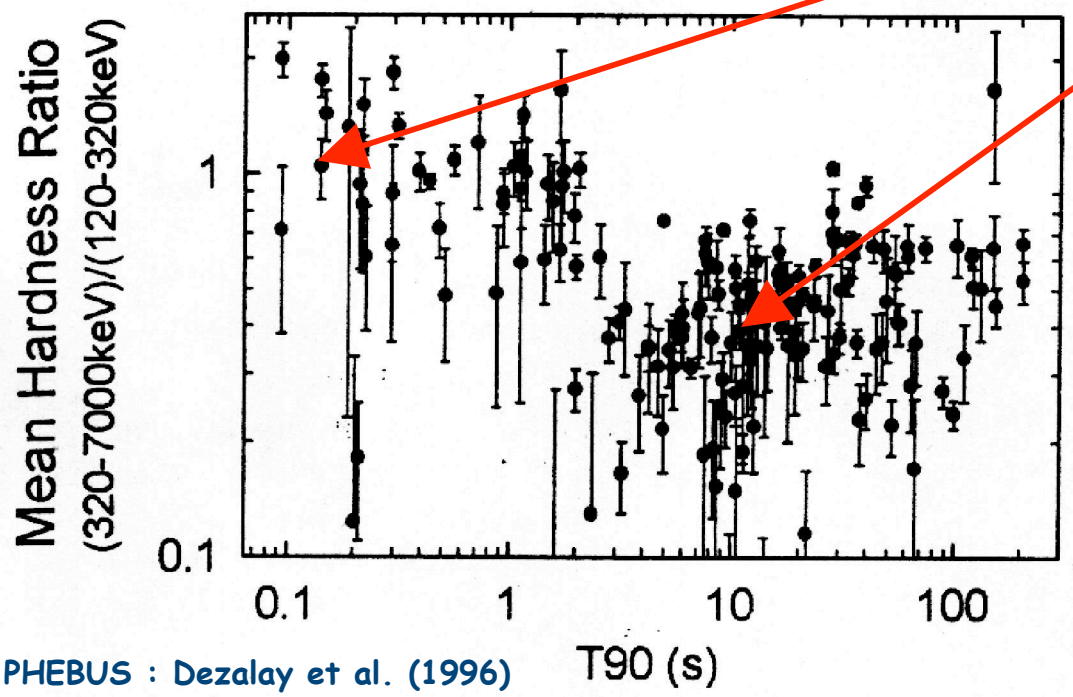


Observations : spectrum



Obs : spectrum vs time profile

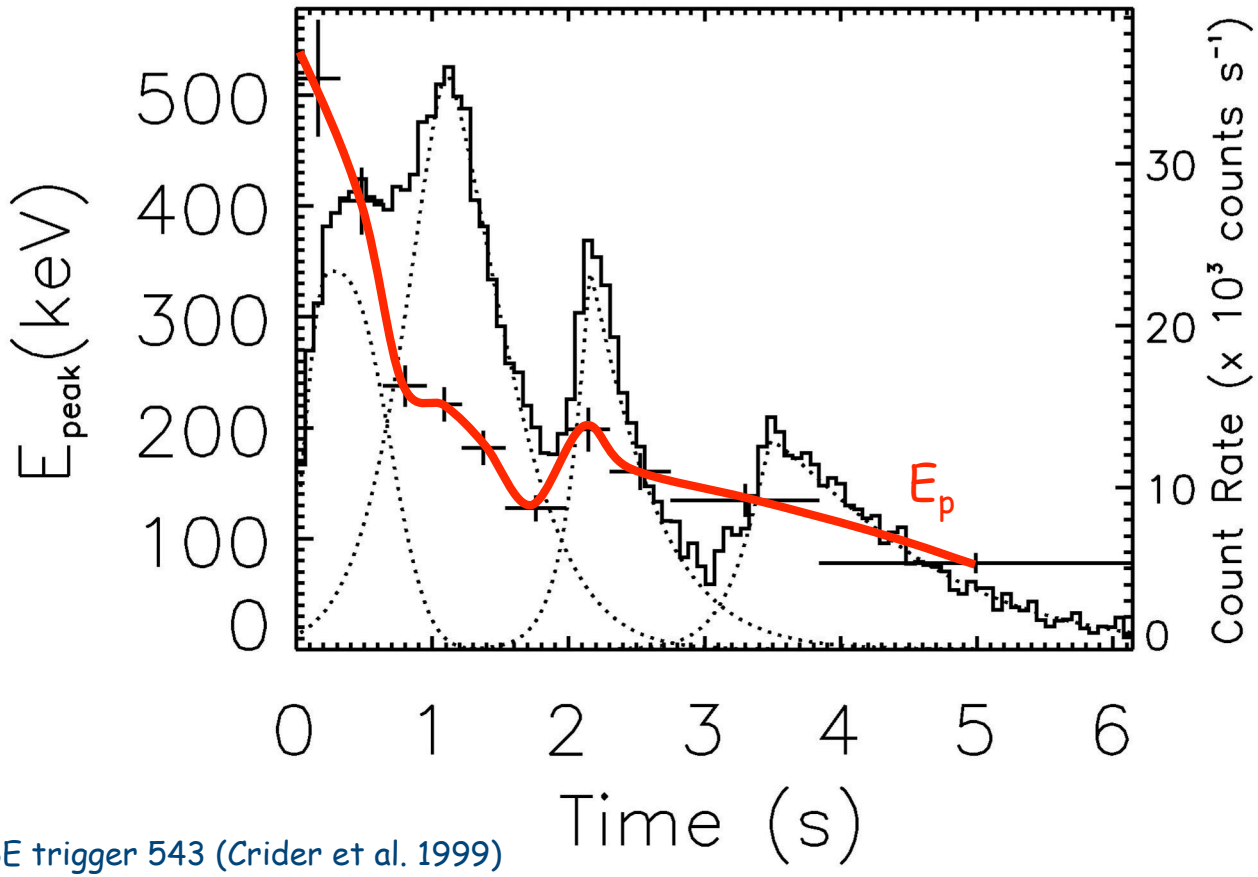




PHEBUS : Dezalay et al. (1996)

short/hard
vs
long/soft

Obs : spectrum vs time profile



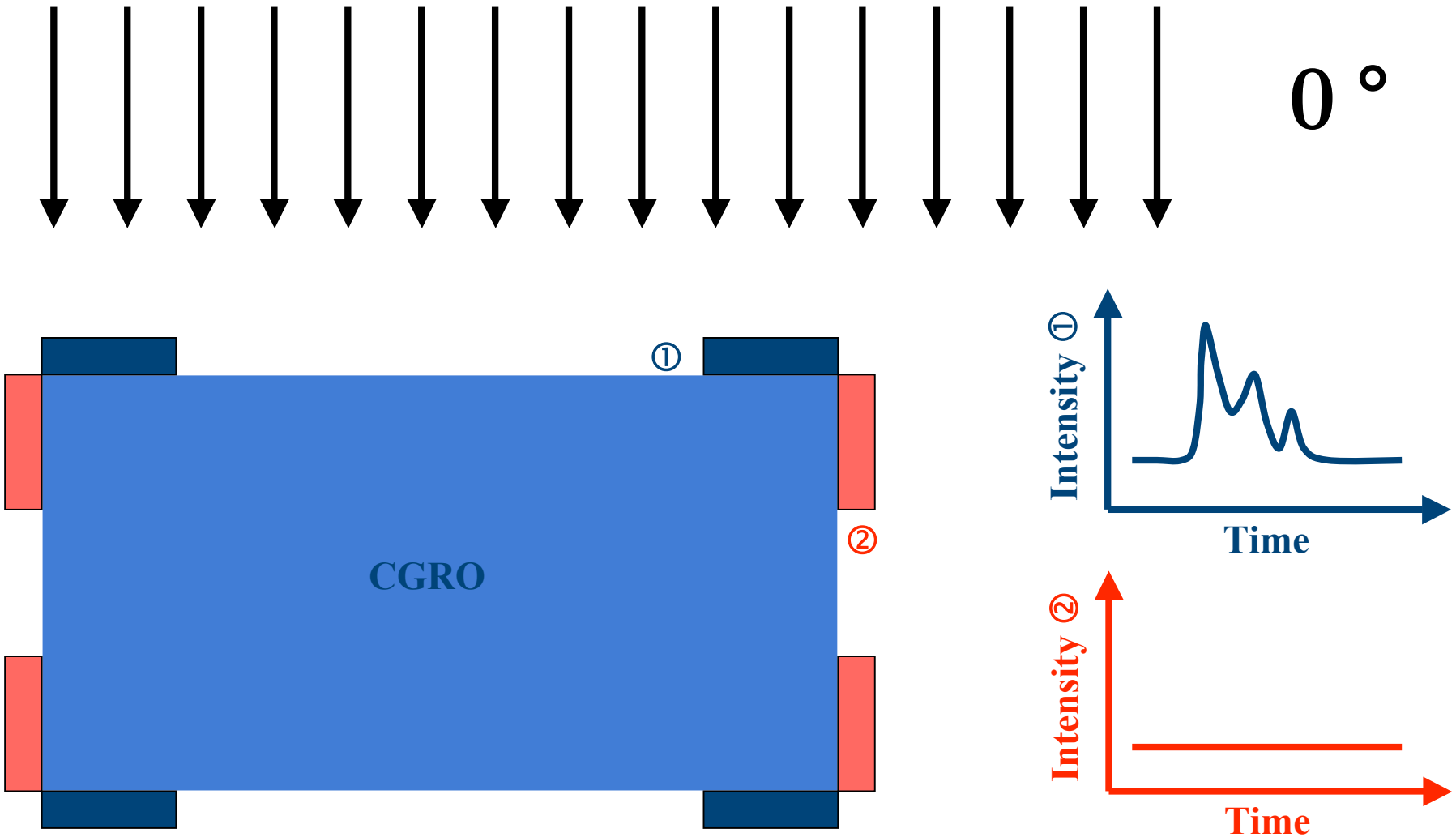
BATSE trigger 543 (Crider et al. 1999)

The GRB distance scale

... a question for 30 years

GRB localization

BATSE : comparison between count rates in different detectors.



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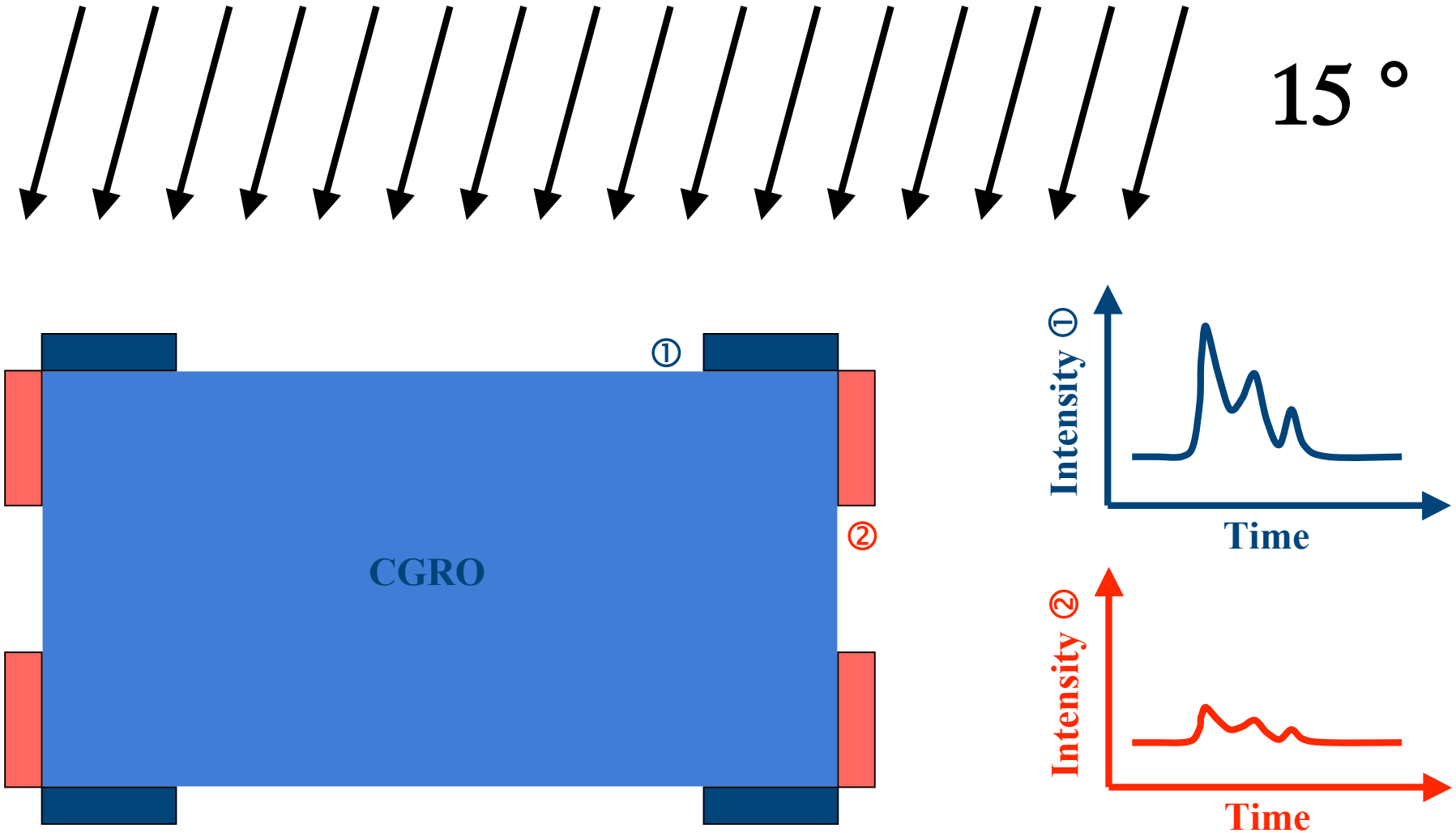

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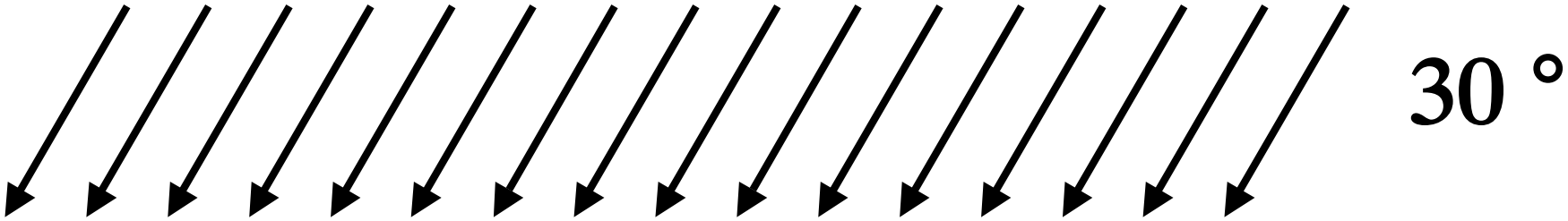

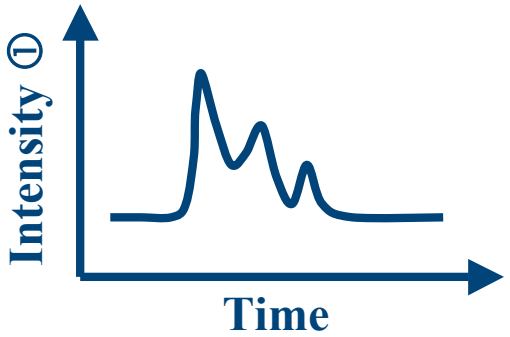

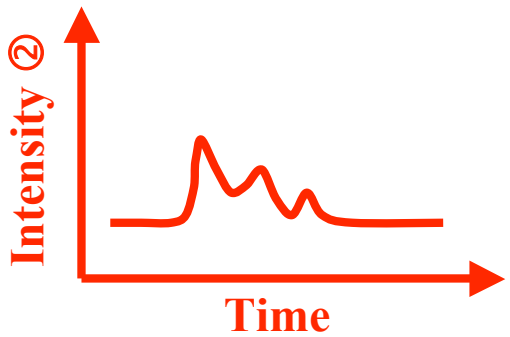

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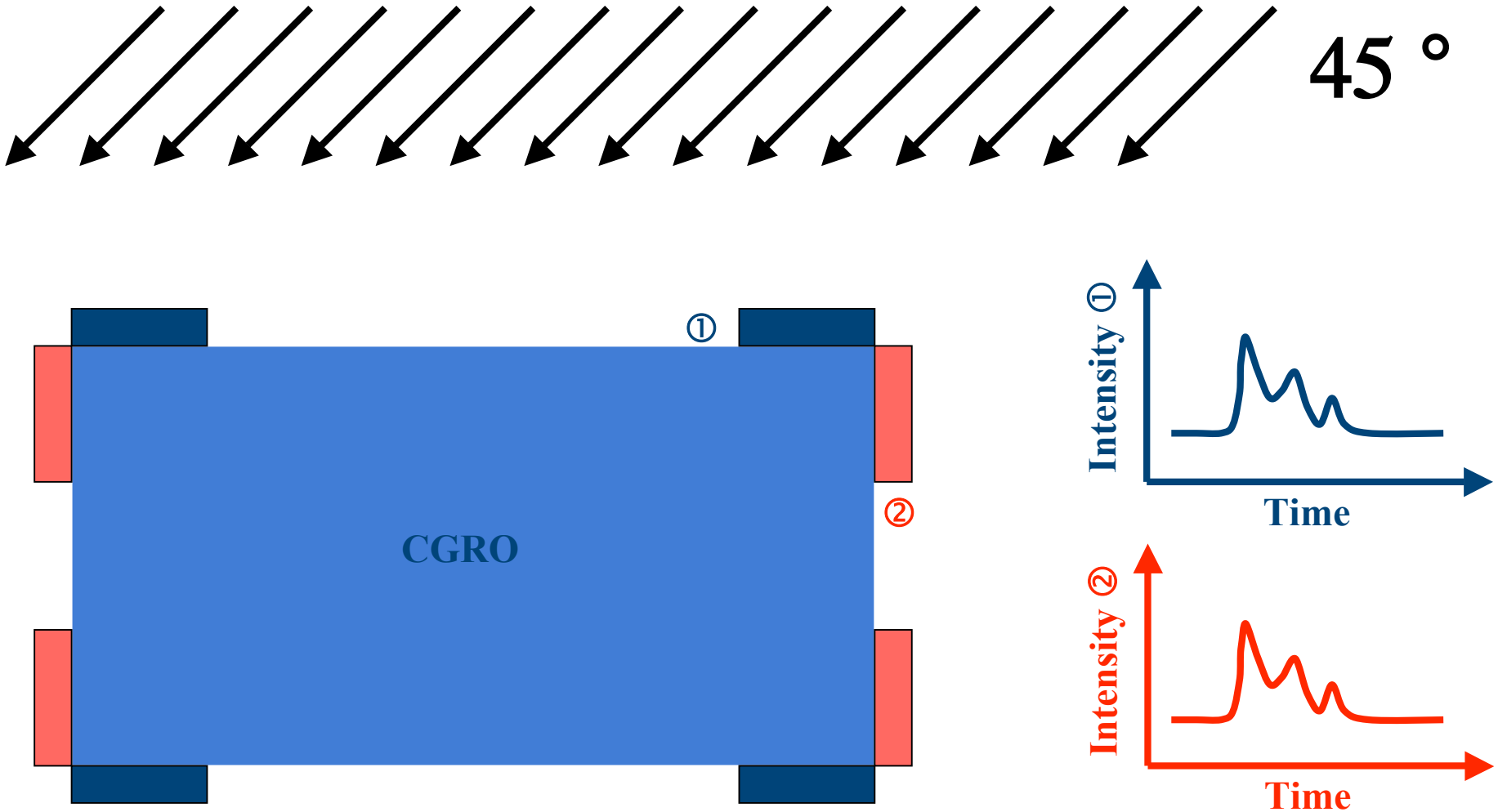

GRB localization

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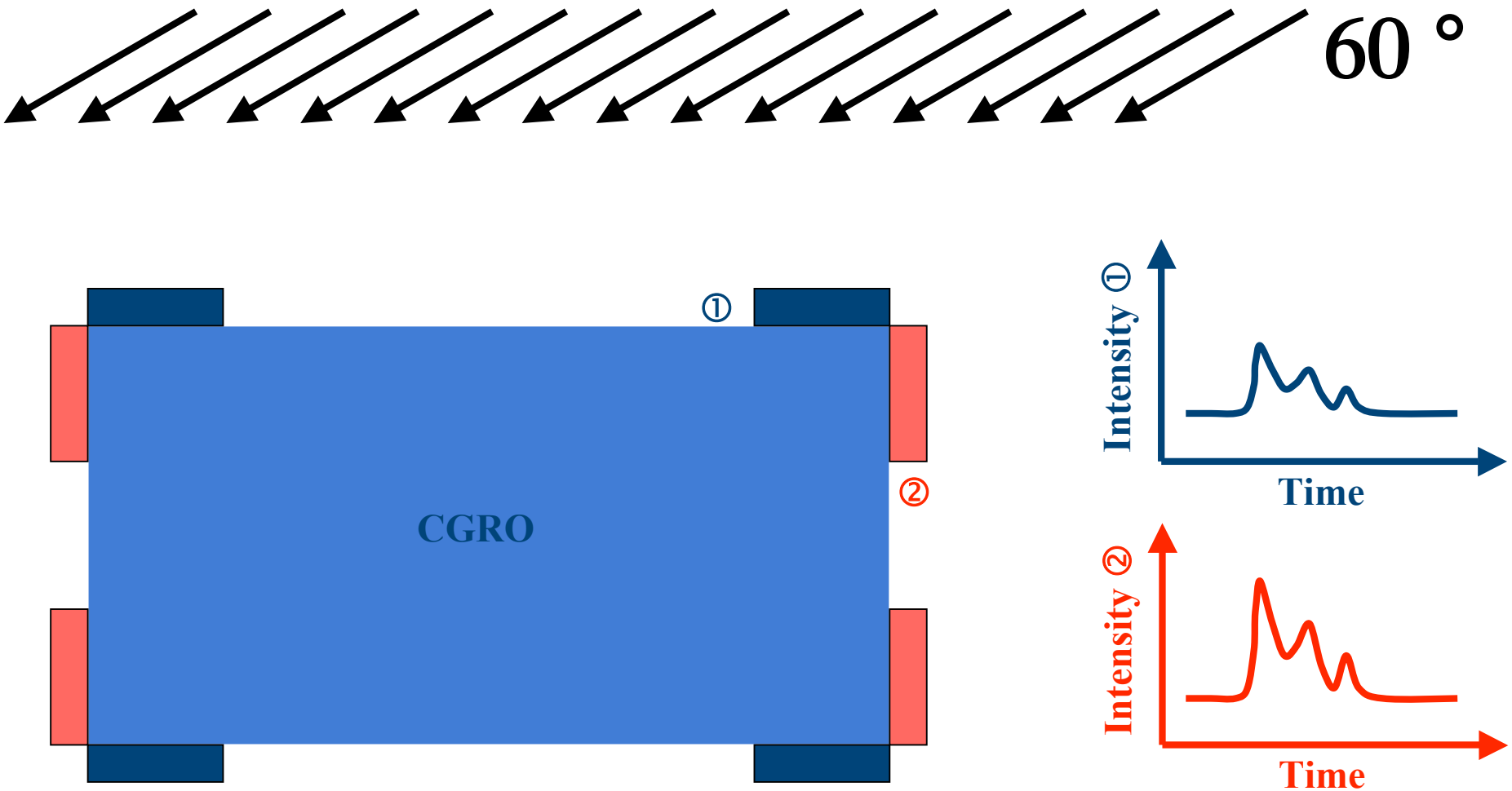

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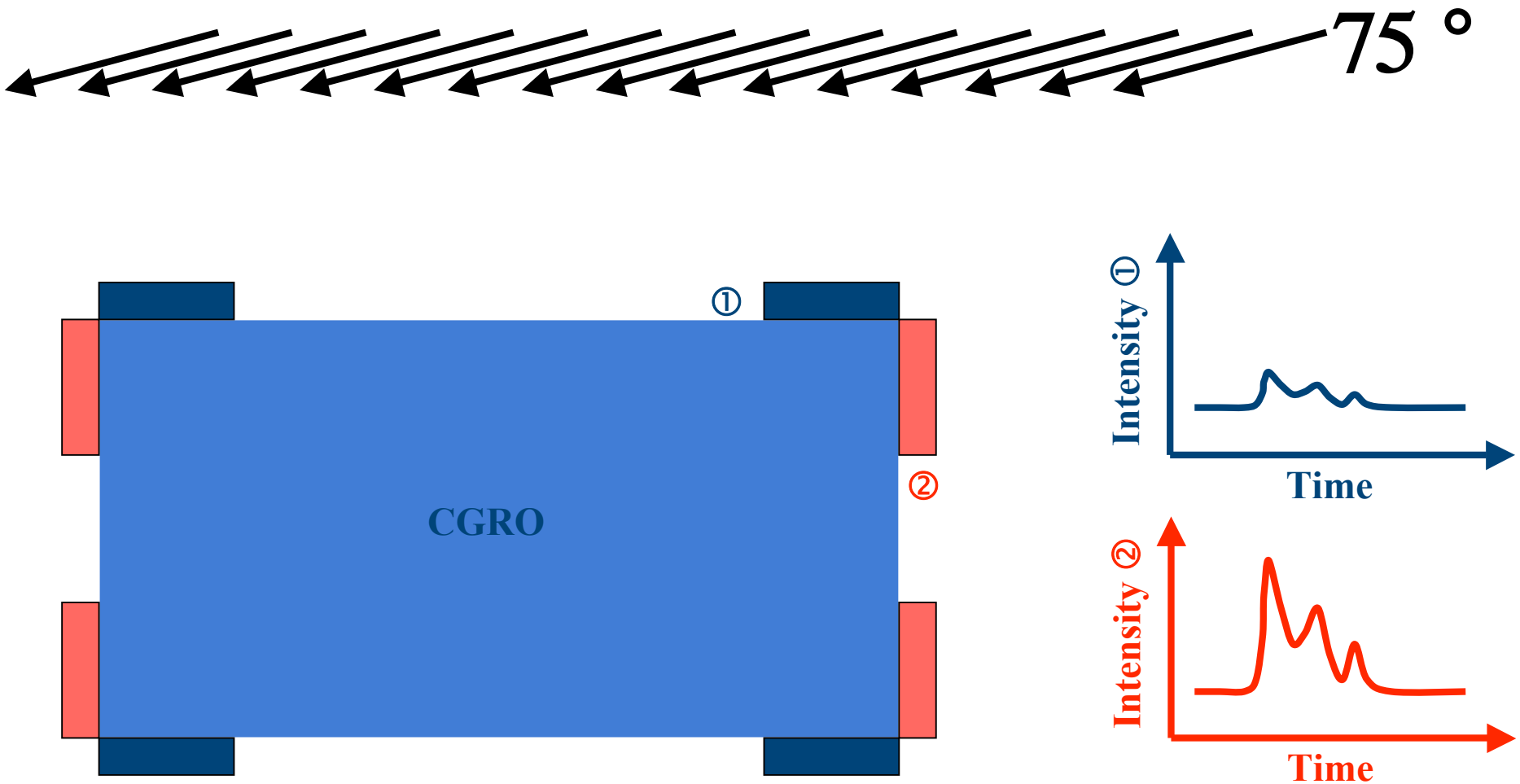

GRB localization

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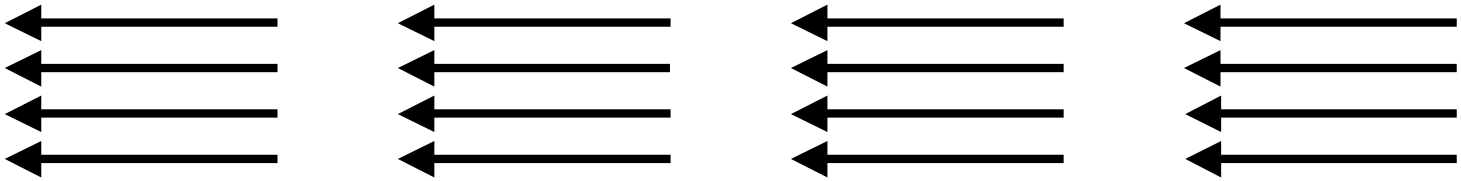
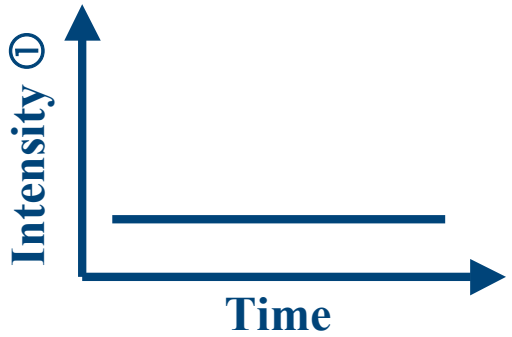
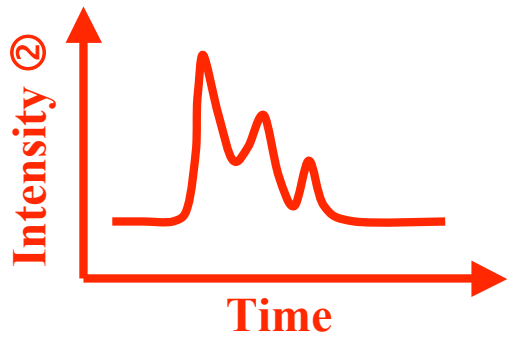


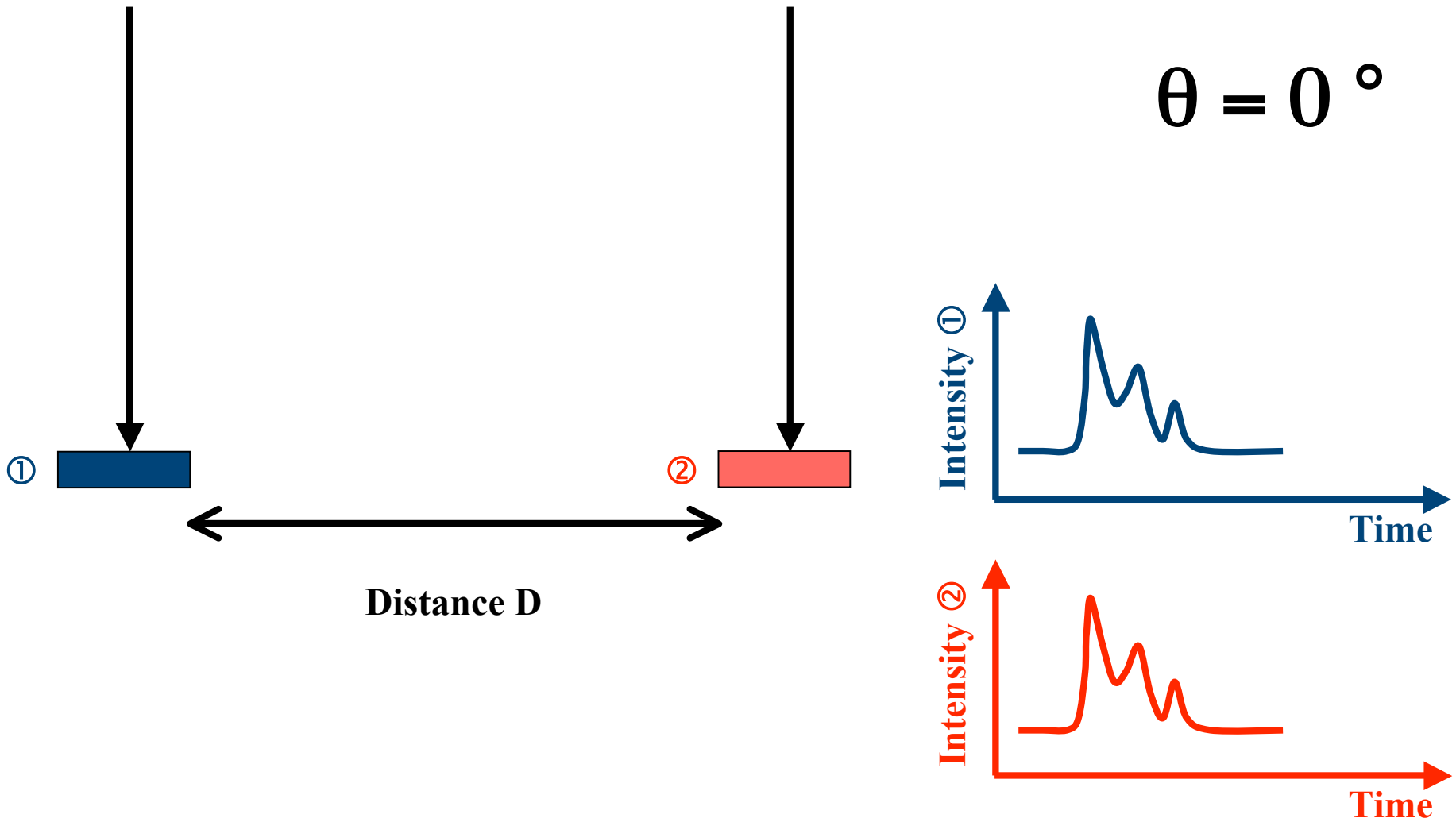
90 °





GRB localization

IPN : difference in arrival times for several satellites.



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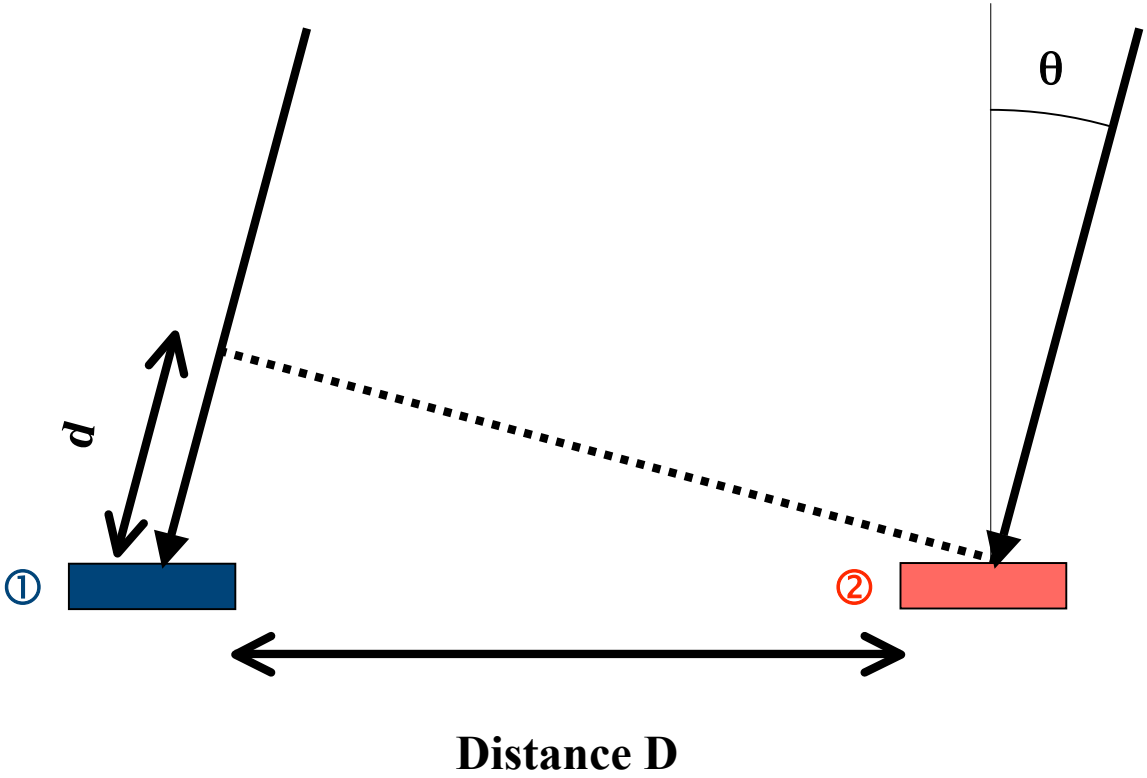
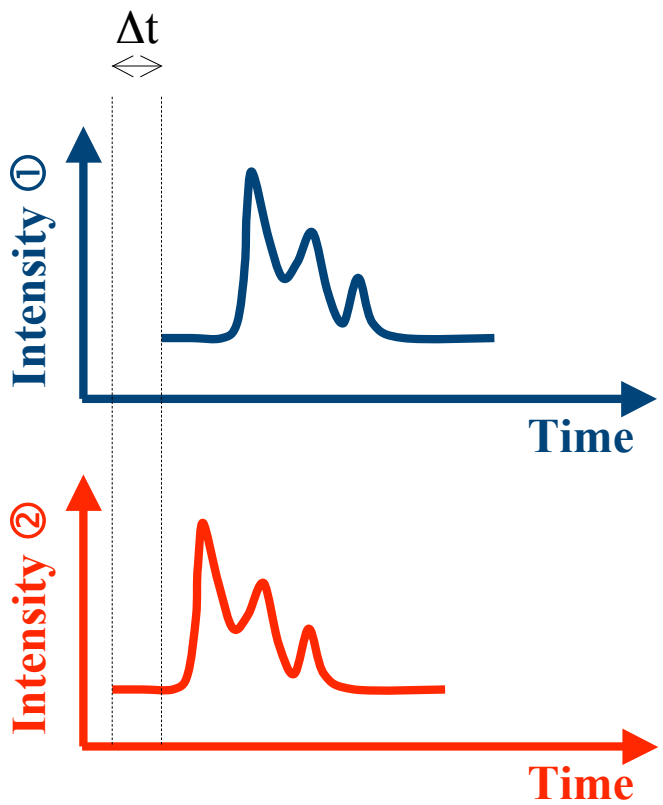


$\theta = 15\,°$



$\Delta t = d / c = (D/c) \sin \theta$

$D/c = 33 \text{ ns } (D / 10 \text{ m}) = 500 \text{ s } (D / 1 \text{ UA})$

GRB localization

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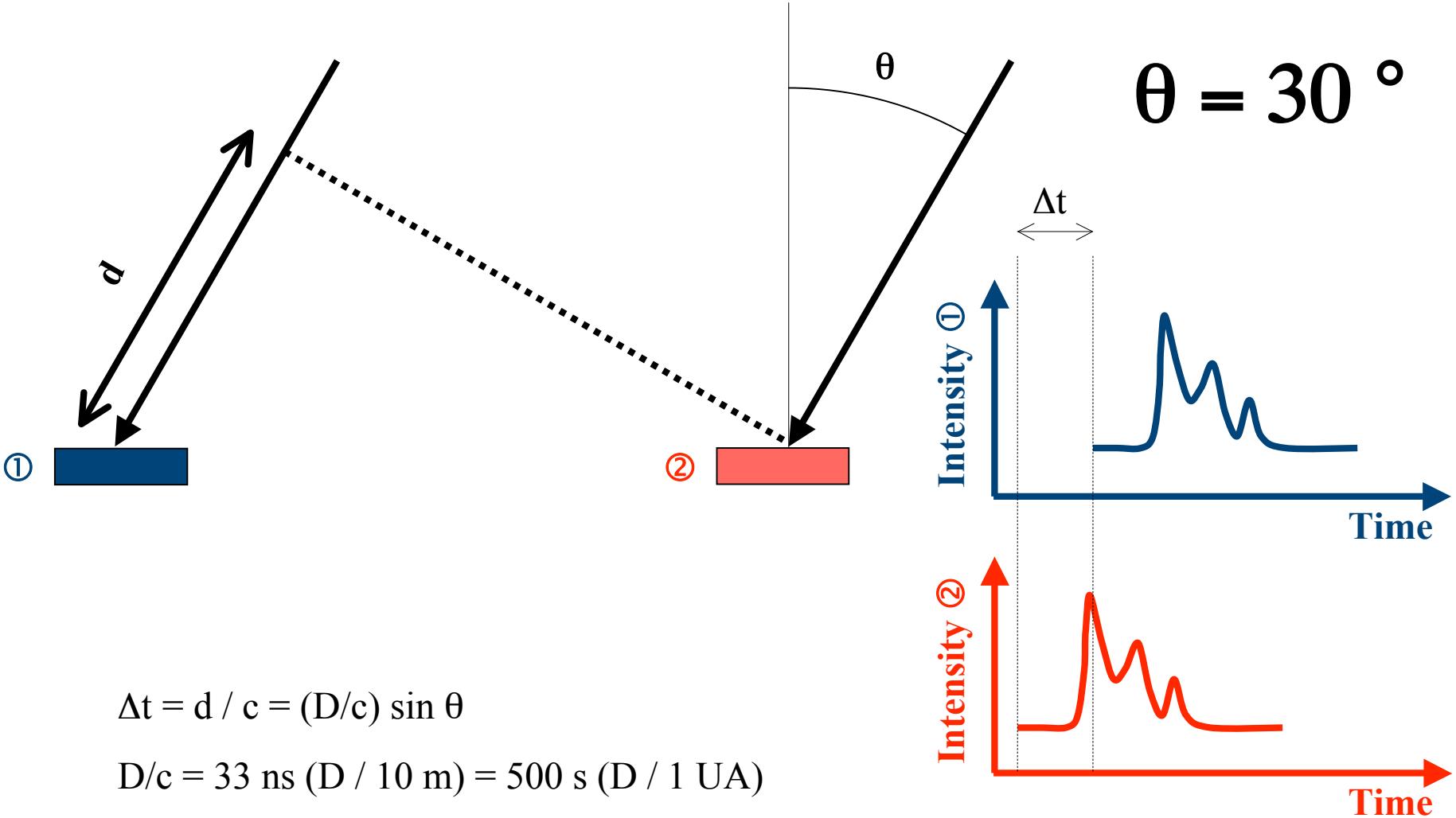

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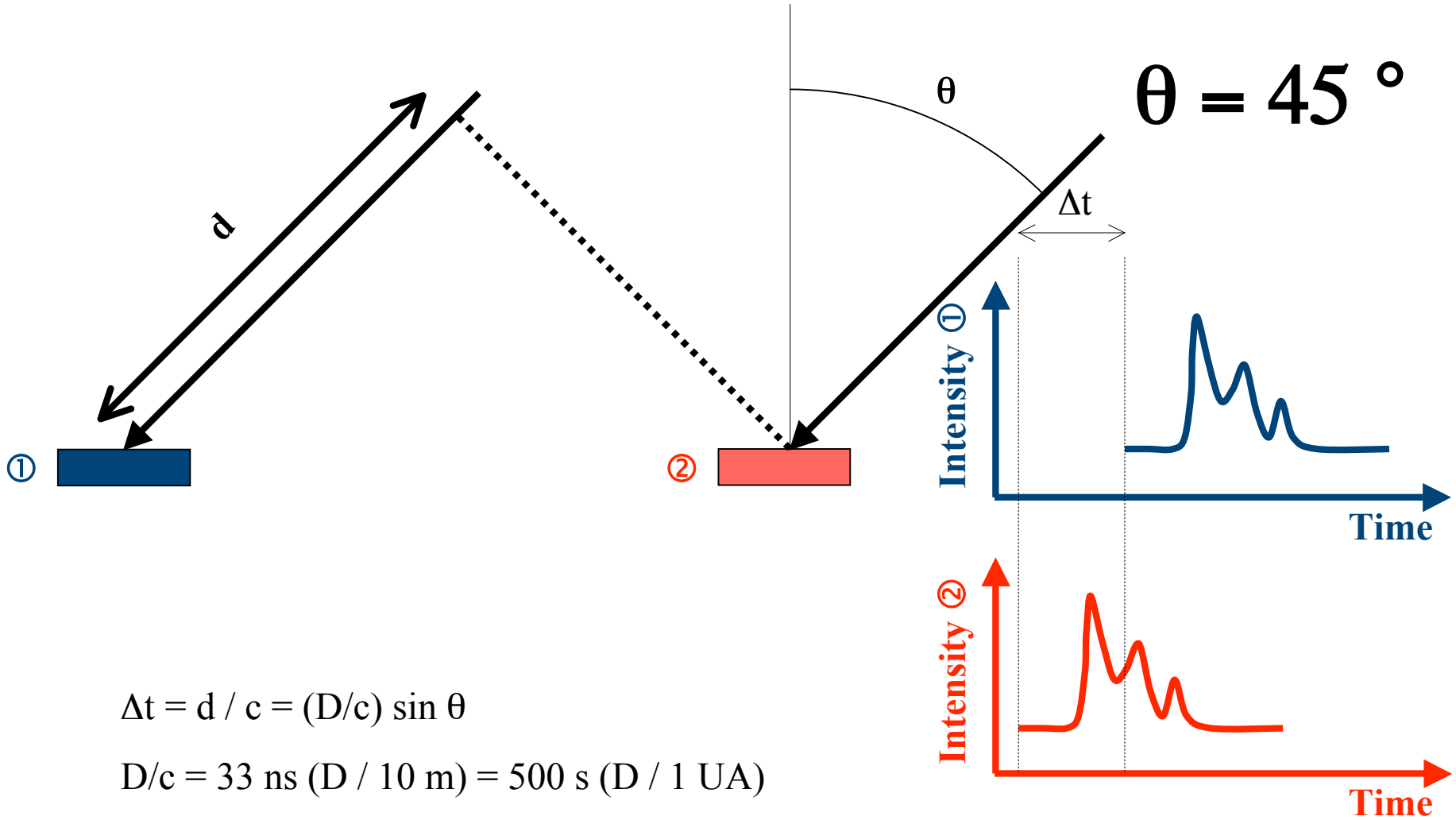

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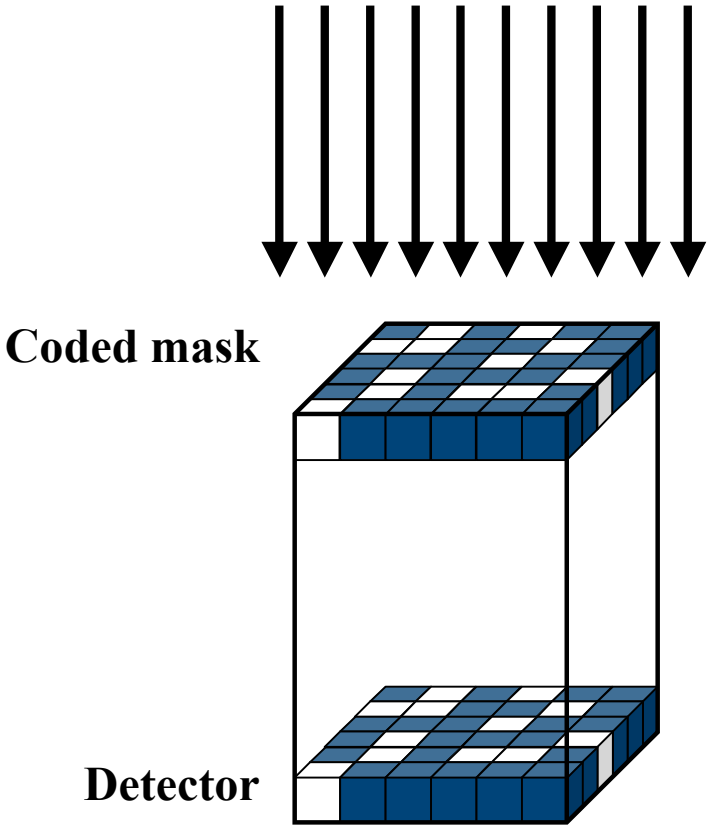
GRB localization

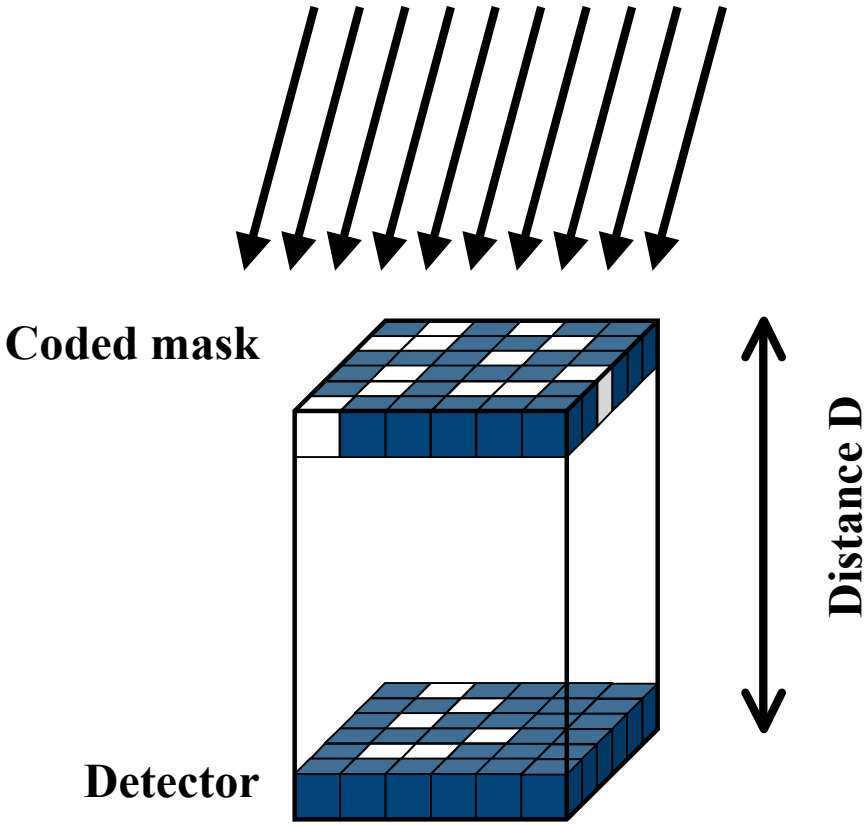
Beppo-SAX / HETE-2 / INTEGRAL / SWIFT : coded mask



$\theta = 0\,°$

GRB localization

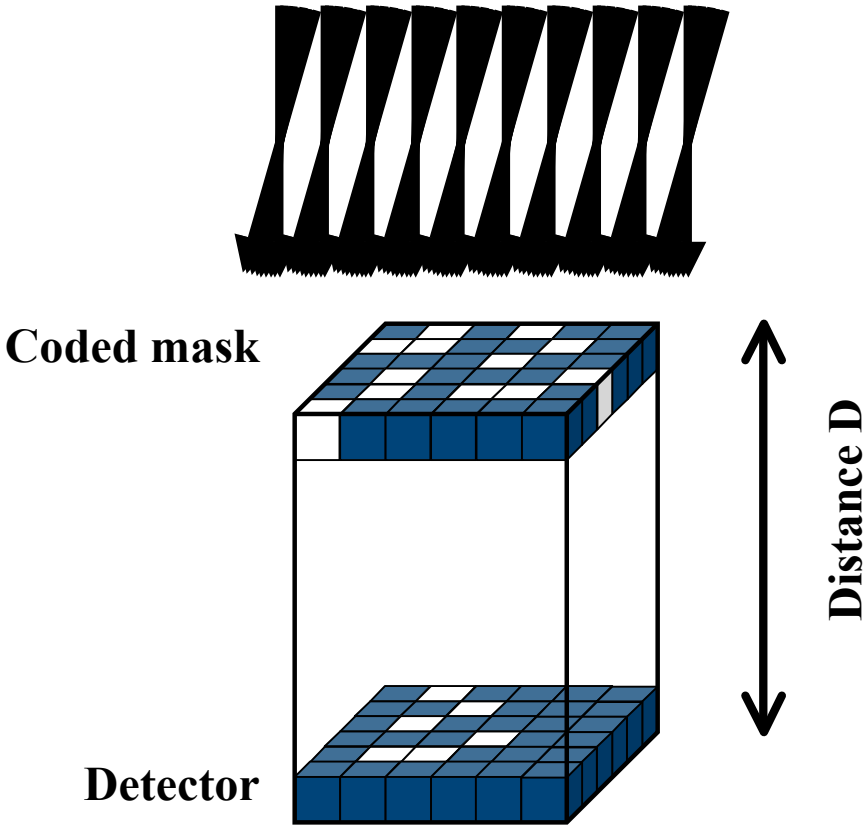
Beppo-SAX / HETE-2 / INTEGRAL / SWIFT : coded mask



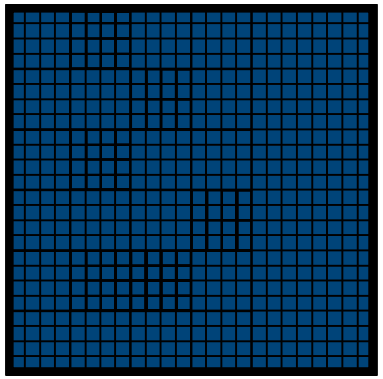
$\theta = 15\,°$

GRB localization

Beppo-SAX / HETE-2 / INTEGRAL / SWIFT : coded mask



$\theta = 0.5°$



The SWIFT coded mask

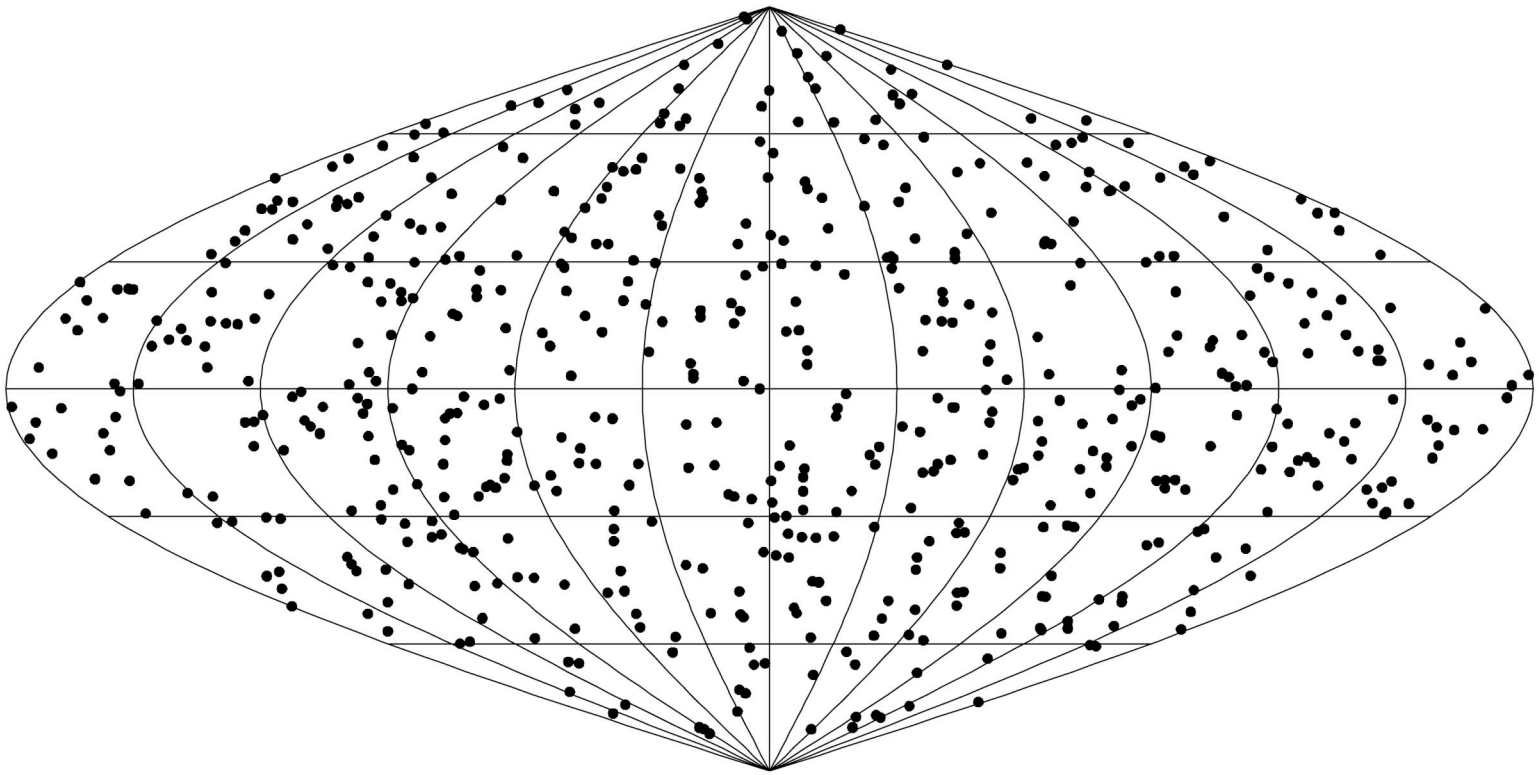
GRB localization

BATSE = a few degrees

IPN = better than one arc minute but slow

Beppo SAX / HETE-2 / INTEGRAL / SWIFT = a few arc minutes

Distribution of locations



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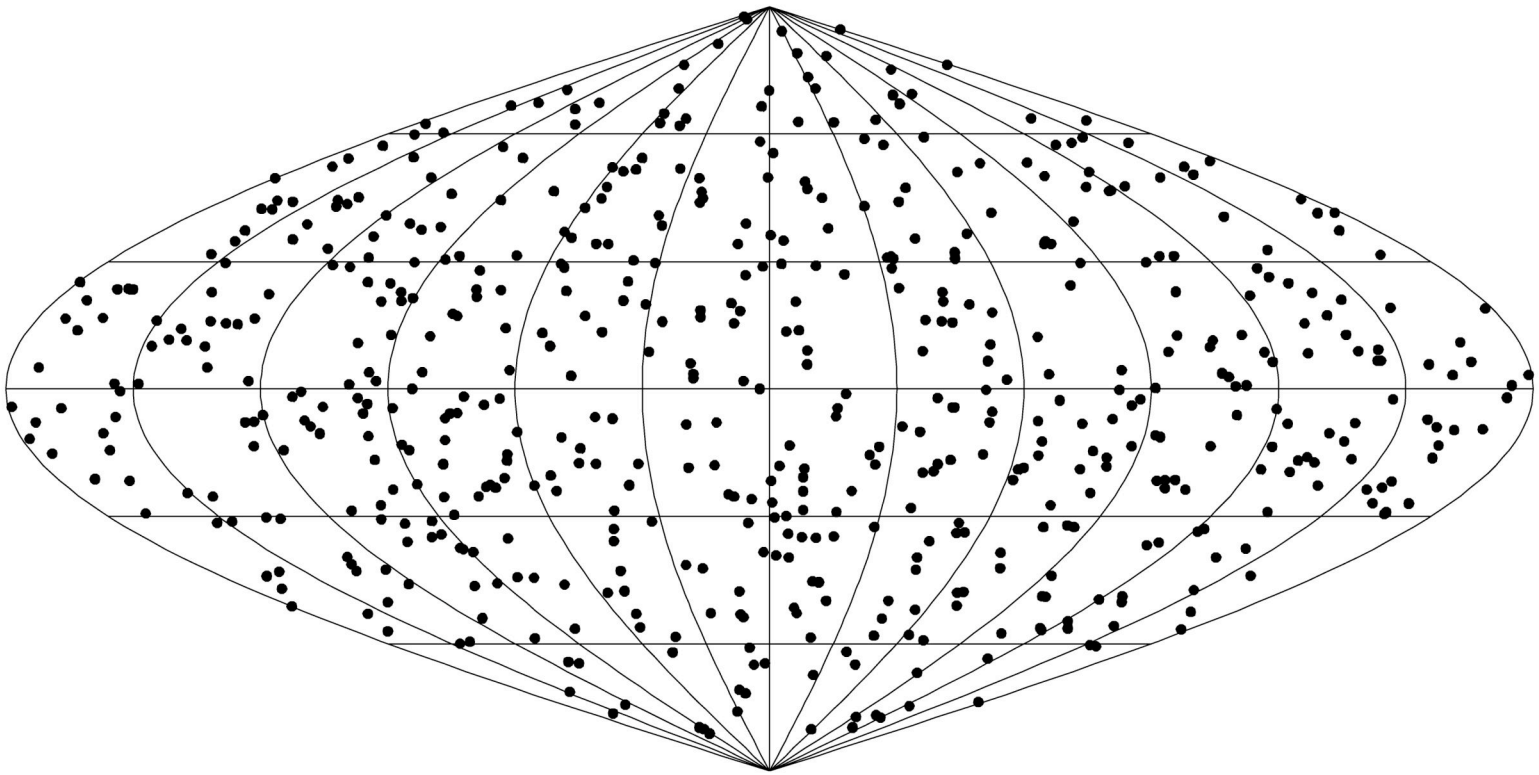
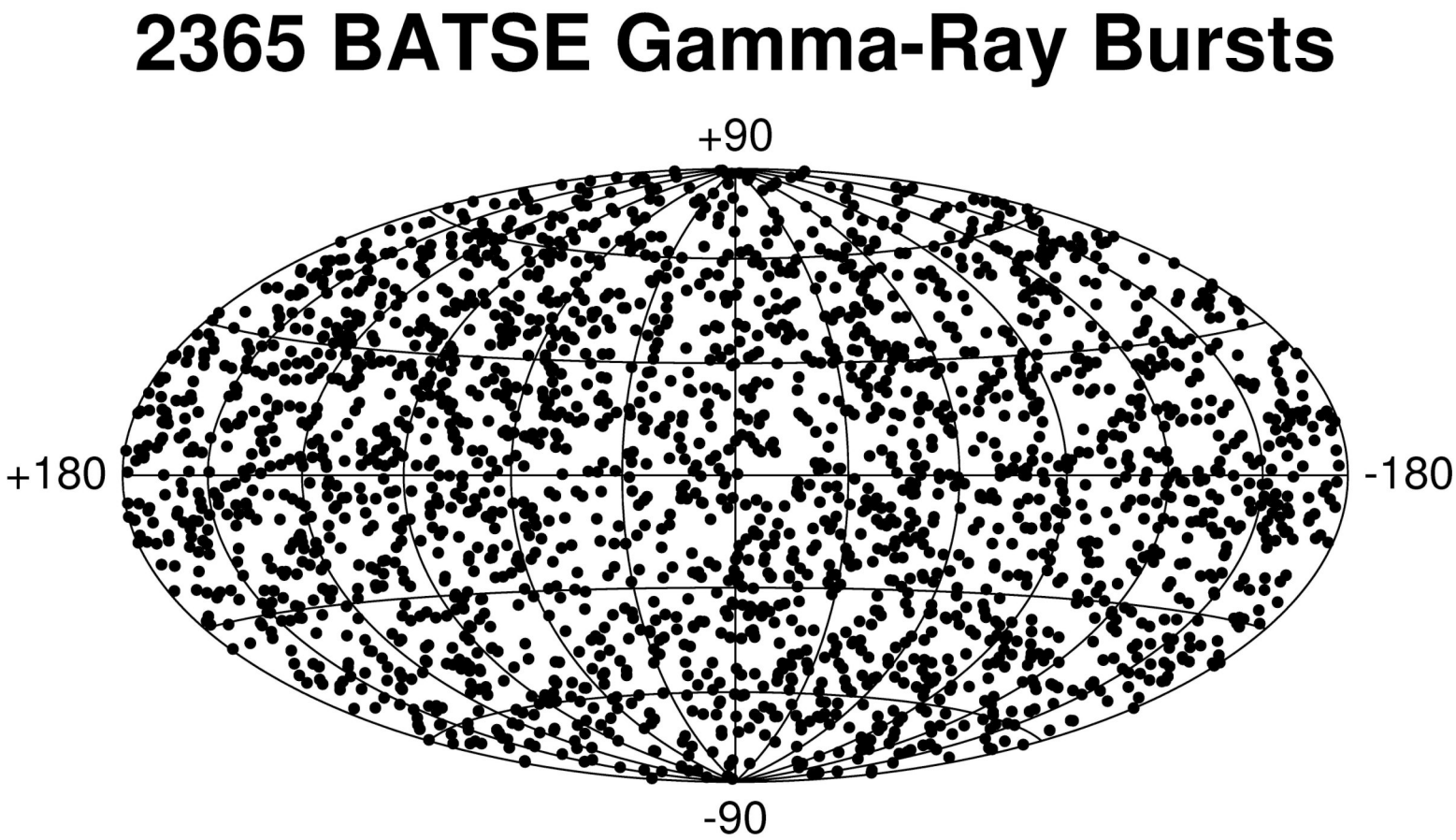


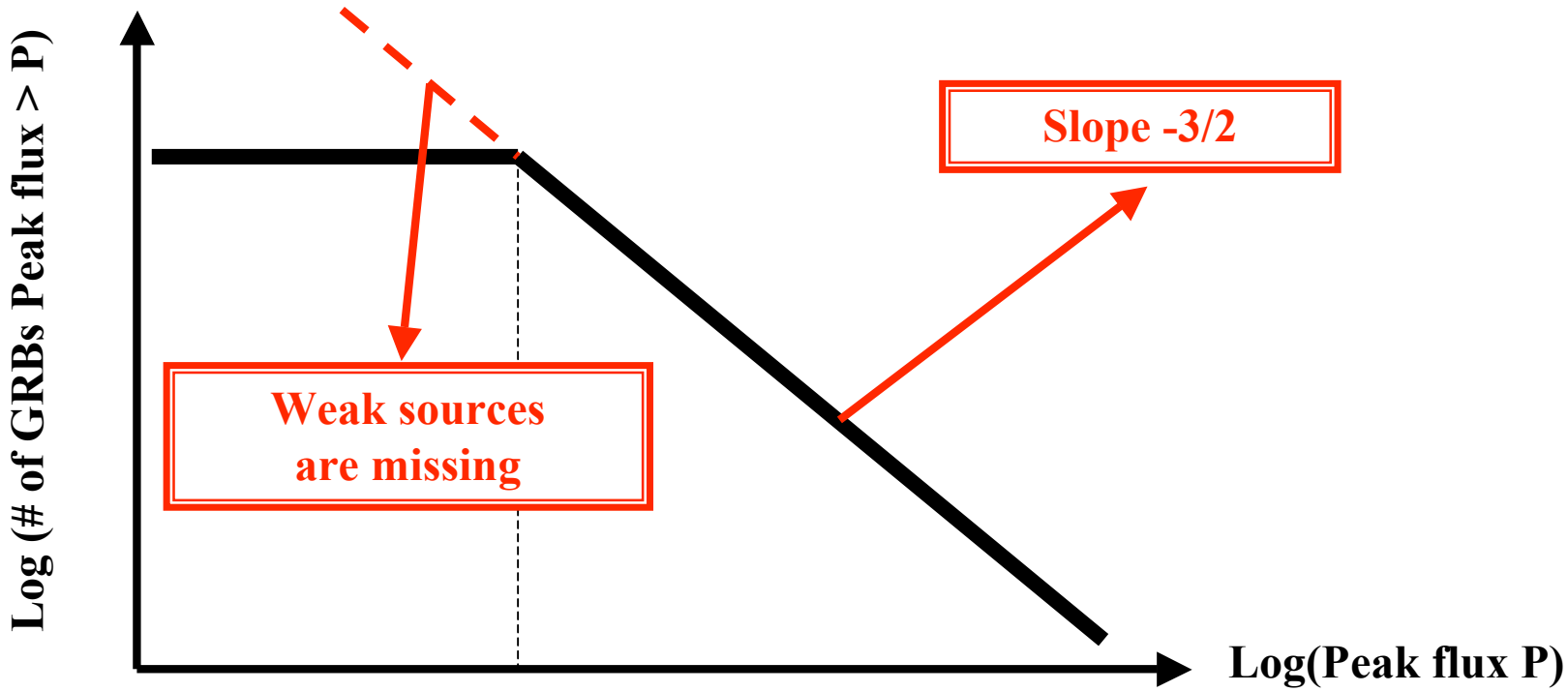
[illegible]

Distribution of locations



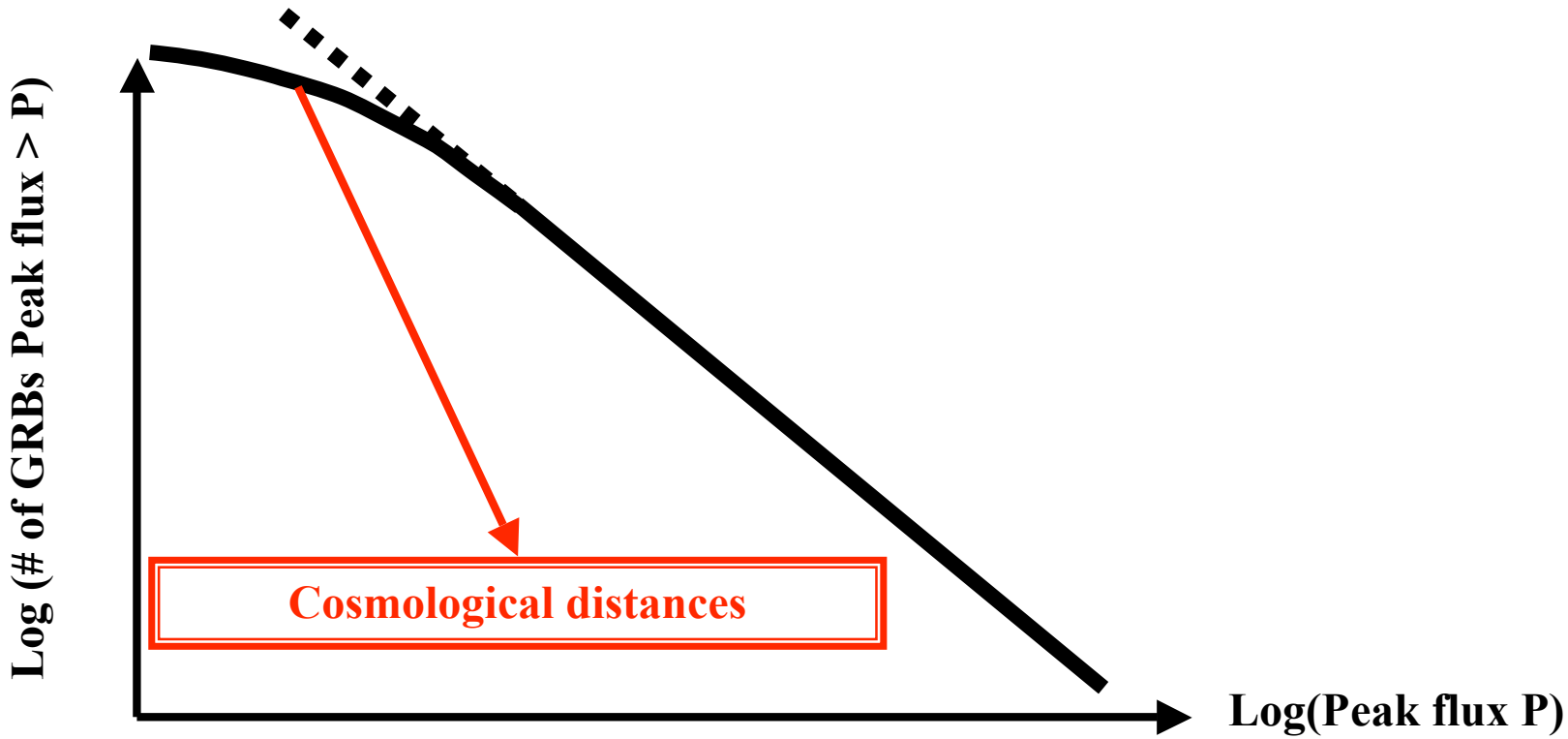
Distribution of peak flux

❶ Uniformly distributed sources within a sphere



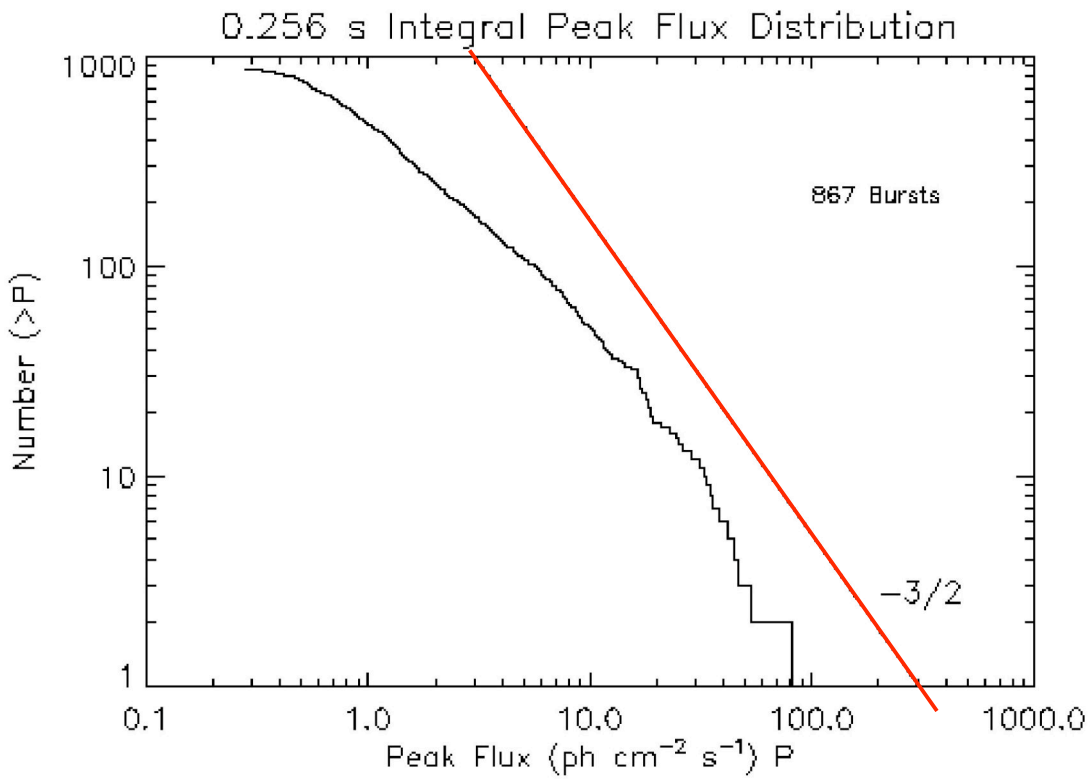
Distribution of peak flux

❷ Cosmological sources



Distribution of peak flux

Observed log N – log P diagram :



Great debate (1995) : the distance scale to GRBs

cf. Great debate (1920) : the scale of the Universe
H. Shapley vs H.D. Curtis

H. Shapley : spiral nebulae = gaz nebulae inside a big single Galaxy.
H.D. Curtis : spiral nebulae = other galaxies like the Milky Way.

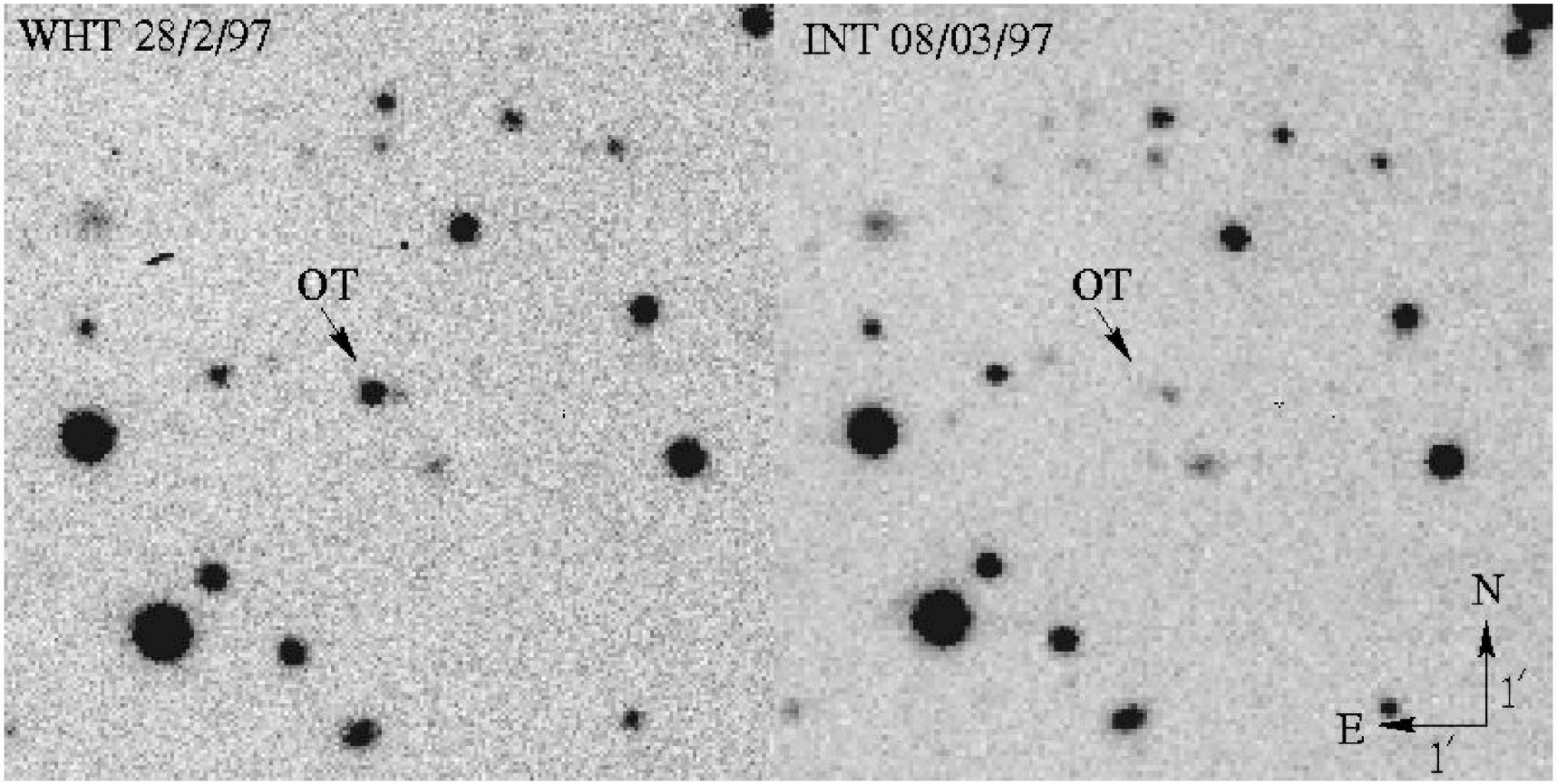
Solved in the mid-20' by Hubble (cepheids in M31).

1995 : B. Paczynski vs D. Lamb,
(moderator: M. Rees)

D. Lamb : galactic « super-halo »
B. Paczynski : cosmological GRBs

Solved in 1997 by Beppo-SAX : first optical counterpart.

1997 : the answer

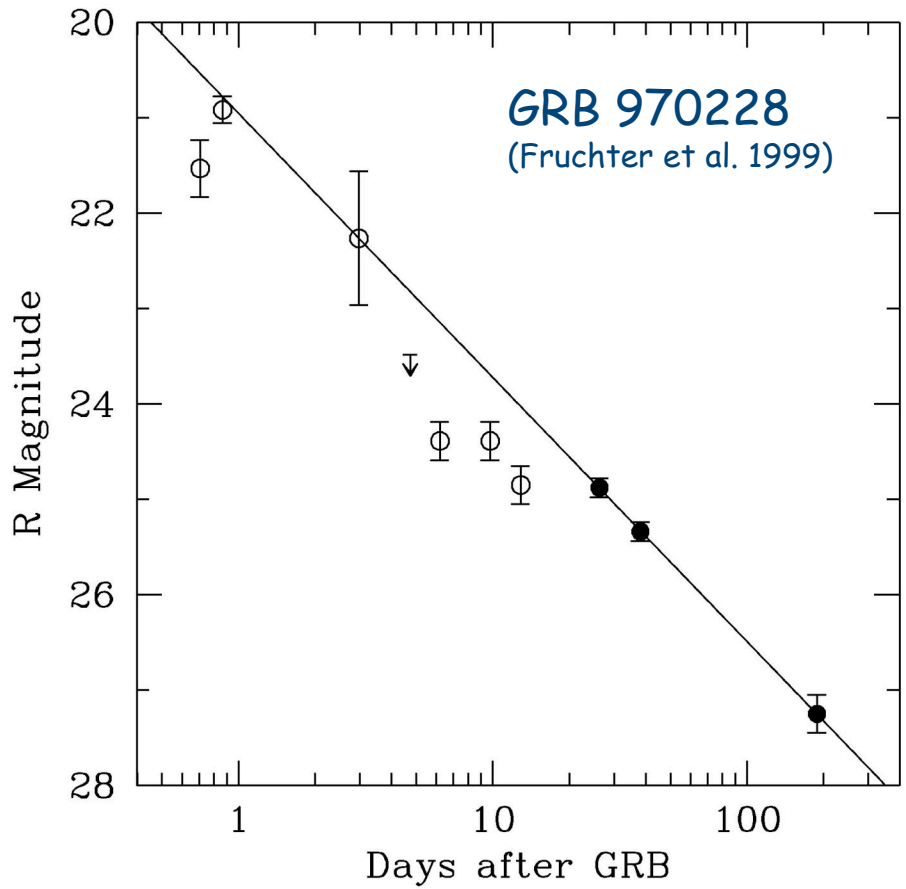


1997 : afterglows

GRB afterglows :

→ fast temporal decay

→ spectral evolution :
X , visible, radio



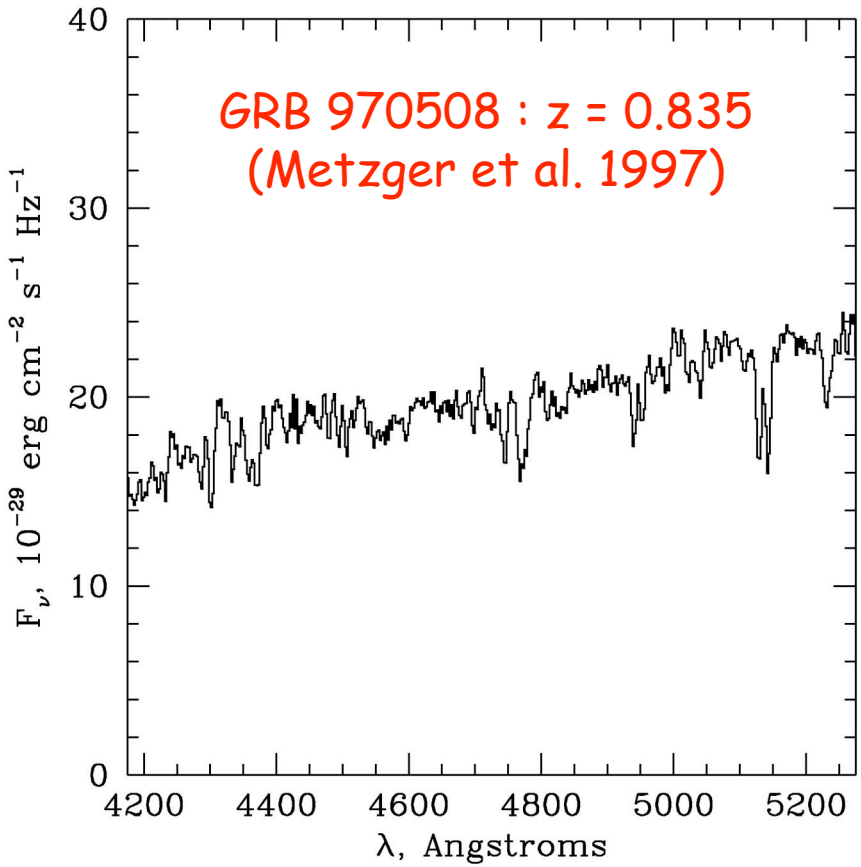
1997 : afterglows

First optical counterpart : **GRB 970228**

Second optical counterpart : **GRB 970508 → spectrum.**

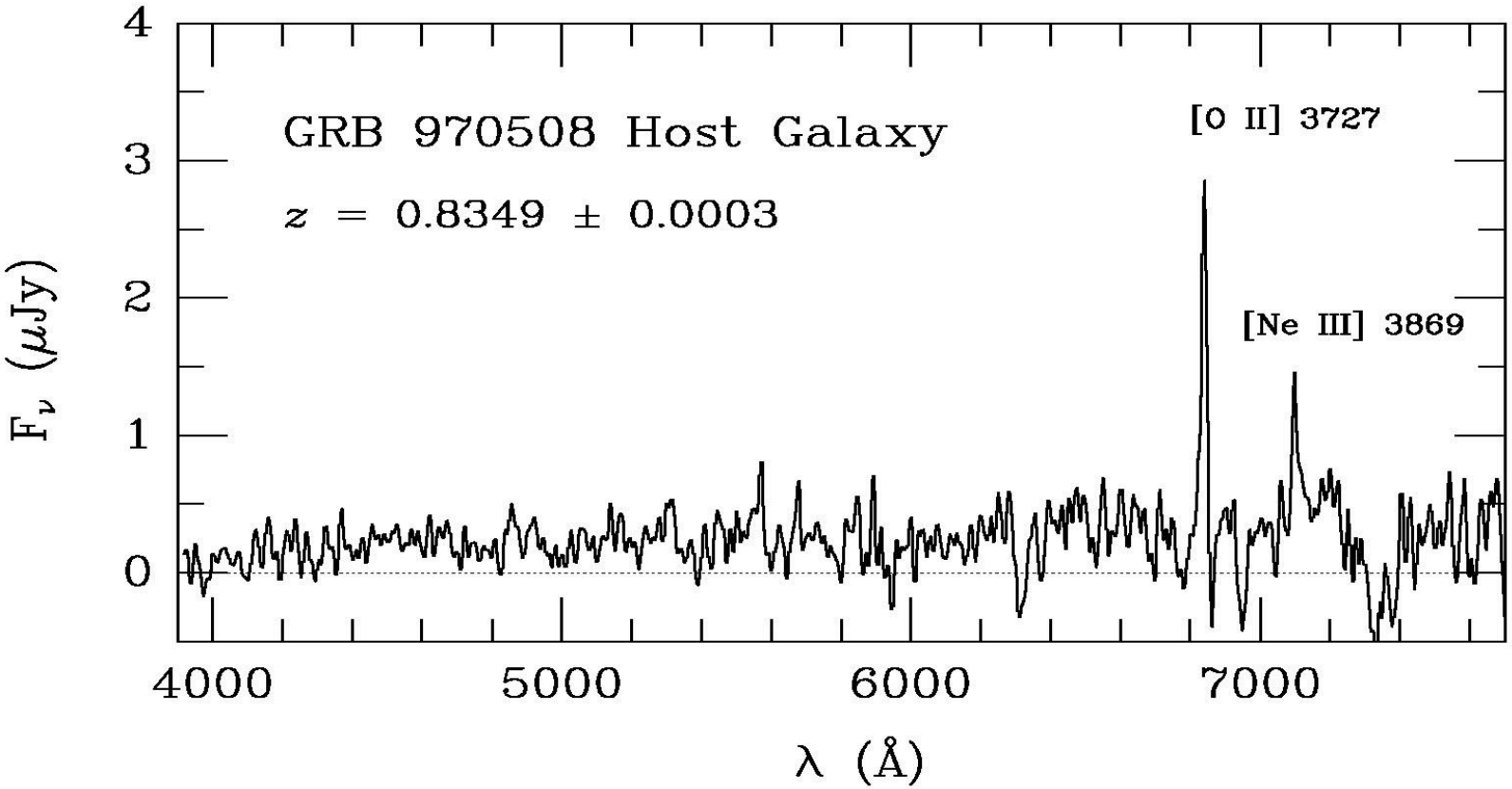
Identification of redshifted absorption lines : cosmological origin !

1997 : afterglows



This GRB was emitted when the Universe was 6.5 Gyr old only !

1997 : afterglows



Host galaxy : same redshift ! (mission lines)

GRBs are cosmological !

1997	GRB	970228	970508	970828	971214		
		0.695	0.835	[illegible]	[illegible]		
1998			980703				
	z		[illegible]				
1999	GRB	990123	[illegible]	[illegible]	990712	991208	991216
	z	1.60	1.61[illegible]		0.434	0.706	1.02
2000	GRB	000131	000301C	000[illegible]	[illegible]	[illegible]0926	
	z	4.5	2.03	1.118			
2001	GRB	010222	010921	011121	011211		
	z	1.477	0.36	0.36	2.14		
2002	GRB	020405	020813	021004	021211		
	z	0.69	1.25	2.3	1.01		
2003	GRB	030226	030323	030328	030329	030429	031203
	z	1.98	3.37	1.52	0.168	2.65	0.105
2004	GRB	040701	040924	041006			
	z	0.215	0.859	0.716			

Redshift z = 4.5 :
the Universe is 1.4 Gyr old !

Long GRBs only !

Consequences

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
[redacted]							Stellar superflare from nearby star
[redacted]							Superflare from nearby WD
[redacted]							Relic comet perturbed to collide with old galactic NS
[redacted]							Accretion onto WD from flare in companion
[redacted]							Accretion onto NS from flare in companion
[redacted]							Accretion onto BH from flare in companion
[redacted]							NS chunk contained by external pressure escapes, explodes
[redacted]							Relativistic iron dust grain up-scatters solar radiation
[redacted]							Directed stellar flare on nearby star
[redacted]							Comet from system's cloud strikes WD
[redacted]							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
[redacted]							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
[redacted]							NS corequake excites vibrations, changing E & B fields
[redacted]							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
[redacted]							Inv Comp scat deep in ergosphere of fast rotating, accreting BH
[redacted]							NS crustquake shocks NS surface
[redacted]							Magnetic WD suffers MHD instabilities, flares
[redacted]							Thermal radiation from flare near magnetic WD
[redacted]							Carbon detonation from accreted matter onto NS
[redacted]							Mag grating of accret disk around NS causes sudden accretion
[redacted]							Instability in accretion onto rapidly rotating BH
[redacted]							Charged intergal rel dust grain enters sol sys, breaks up
[redacted]							WD surface nuclear burst causes chromospheric flares
[redacted]							NS surface nuclear burst causes chromospheric flares
[redacted]							NS vibrations heat atm to pair produce, annihilate, synch cool
[redacted]							Asteroid from interstellar medium hits NS
[redacted]							NS core quake caused by phase transition, vibrations
[redacted]							Asteroid hits NS, B-field confines mass, creates high temp
[redacted]							Helium flash cooled by MHD waves in NS outer layers
[redacted]							Asteroid hits NS, tidally disrupts, heated, expelled along B lines
[redacted]							Asteroid enters NS B field, dragged to surface collision
[redacted]							Magnetic reconnection at heliopause
[redacted]							NS flares from pair plasma confined in NS magnetosphere
[redacted]							Magnetic reconnection after NS surface He flash
[redacted]							He fusion runaway on NS B-pole helium lake
[redacted]							e- capture triggers H flash triggers He flash on NS surface
[redacted]							B induced cyclo res in rad absorp giving rel e-s, inv C scat
[redacted]							BB X-rays inv Comp scat by hotter overlying plasma
[redacted]							ISM matter accum at NS magnetopause then suddenly accretes
[redacted]							Nonexplosive collapse of WD into rotating, cooling NS
[redacted]							NS accretion from low mass binary companion
[redacted]							Neutron rich elements to NS surface with quake, undergo fission
[redacted]							Thermonuclear explosion beneath NS surface
[redacted]							NS corequake + uneven heating yield SGR pulsations
[redacted]							B field contains matter on NS cap allowing fusion
[redacted]							NS surface nuc explosion causes small scale B reconnection
[redacted]							Remnant disk ionization instability causes sudden accretion
[redacted]							Resonant EM absorp during magnetic flare gives hot sync e-s
[redacted]							NS magnetic fields get twisted, recombine, create flare
[redacted]							NS magnetosphere excited by starquake
[redacted]							Accretion instability between NS and disk
[redacted]							Old NS in Galactic halo undergoes starquake
[redacted]							Weak B field NS spherically accretes, Comptonizes X-rays
[redacted]							NS flares result of magnetic convective-oscillation instability
[redacted]							High Landau e-s beamed along B lines in cold atm of NS
[redacted]							NS + low mass stellar companion gives GRB + optical flash
[redacted]							NS tides disrupt comet, debris hits NS next pass
[redacted]							Radially oscillating NS
[redacted]							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
[redacted]							Chain fission of superheavy nuclei below NS surface during SN
[redacted]							SN ejects strange mat lump craters rotating SS companion
[redacted]							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
[redacted]							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
[redacted]							Be/X-ray binary sys evolves to NS accretion GRB with recurrence
[redacted]							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)
[redacted]							Absorption features suggest separate colder region near NS
[redacted]							NS + accretion disk reflection explains GRB spectra
[redacted]							NS seismic waves couple to magnetospheric Alfen waves
82.	Trofimenko et al.	1989	Ap & SS, 152, 105	WH		COS	Kerr-Newman white holes
[redacted]							NS E-field accelerates electrons which then pair cascade
[redacted]							Narrow absorption features indicate small cold area on NS
[redacted]							Binary member loses part of crust, through L1, hits primary
[redacted]							Fast NS wanders though Oort clouds, fast WD bursts only optical
[redacted]							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
[redacted]							Cyclo res & Raman scat fits 20, 40 keV dips, magnetized NS
[redacted]							QED mag resonant opacity in NS atmosphere
[redacted]							NS magnetospheric plasma oscillations
[redacted]							Beaming of radiation necessary from magnetized neutron stars
[redacted]							Interstellar comets pass through dead pulsar's magnetosphere
[redacted]							Compton scattering in strong NS magnetic field
[redacted]							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
[redacted]							Young NS drifts through its own Oort cloud
[redacted]							White hole supernova gave simultaneous burst of g-waves from 1987A
[redacted]							NS B-field undergoes resistive tearing, accelerates plasma
[redacted]							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
[redacted]							Slow interstellar accretion onto NS, e- capture starquakes result
[redacted]							Low mass X-ray binary evolve into GRB sites
[redacted]							Accreting WD collapsed 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
[redacted]							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

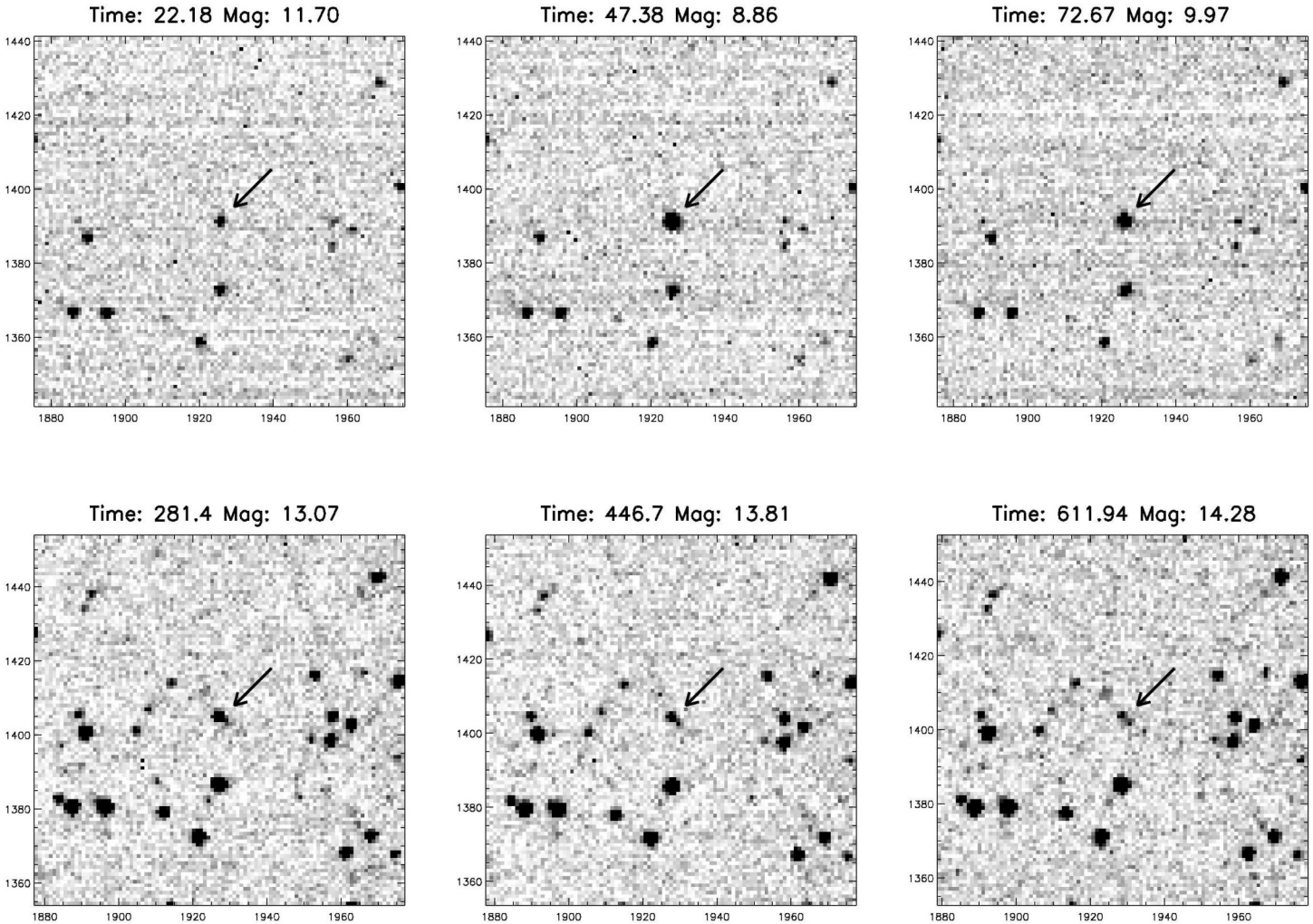
Nemiroff 1994

« the afterglow era »

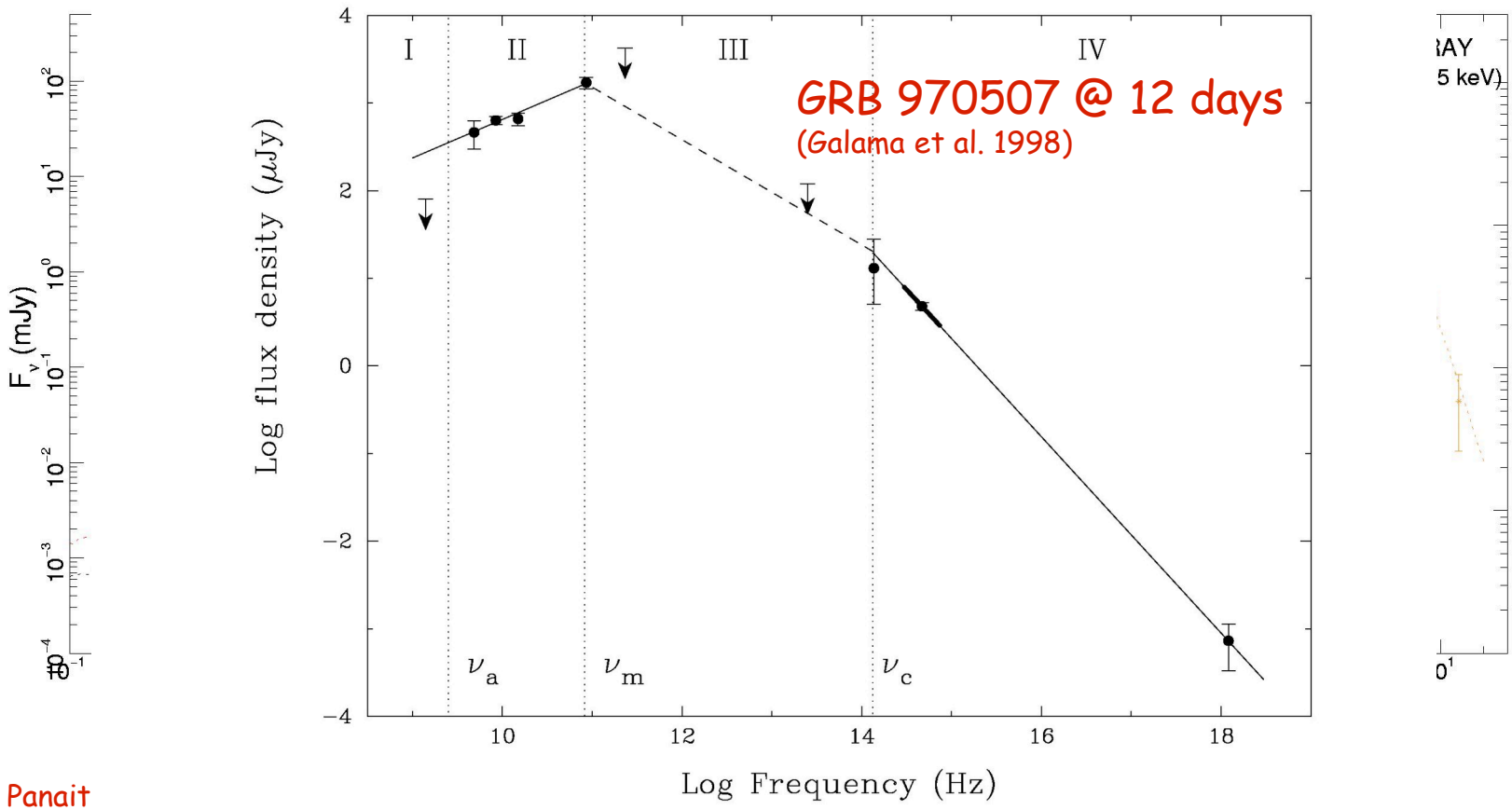
More observations

GRB 990123 : optical flash

GRB 990123 : optical flash

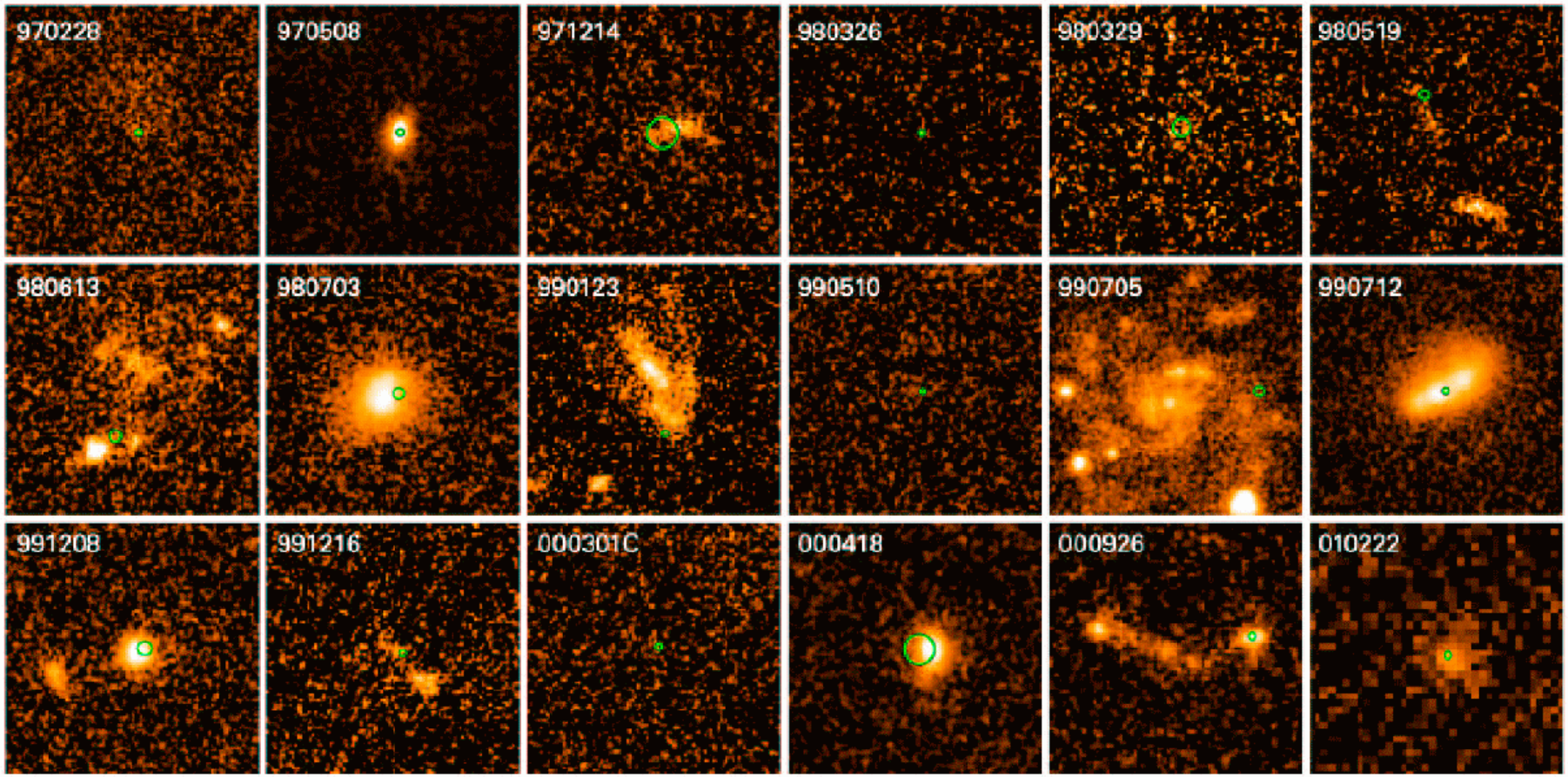


Afterglows : light curve and spectrum



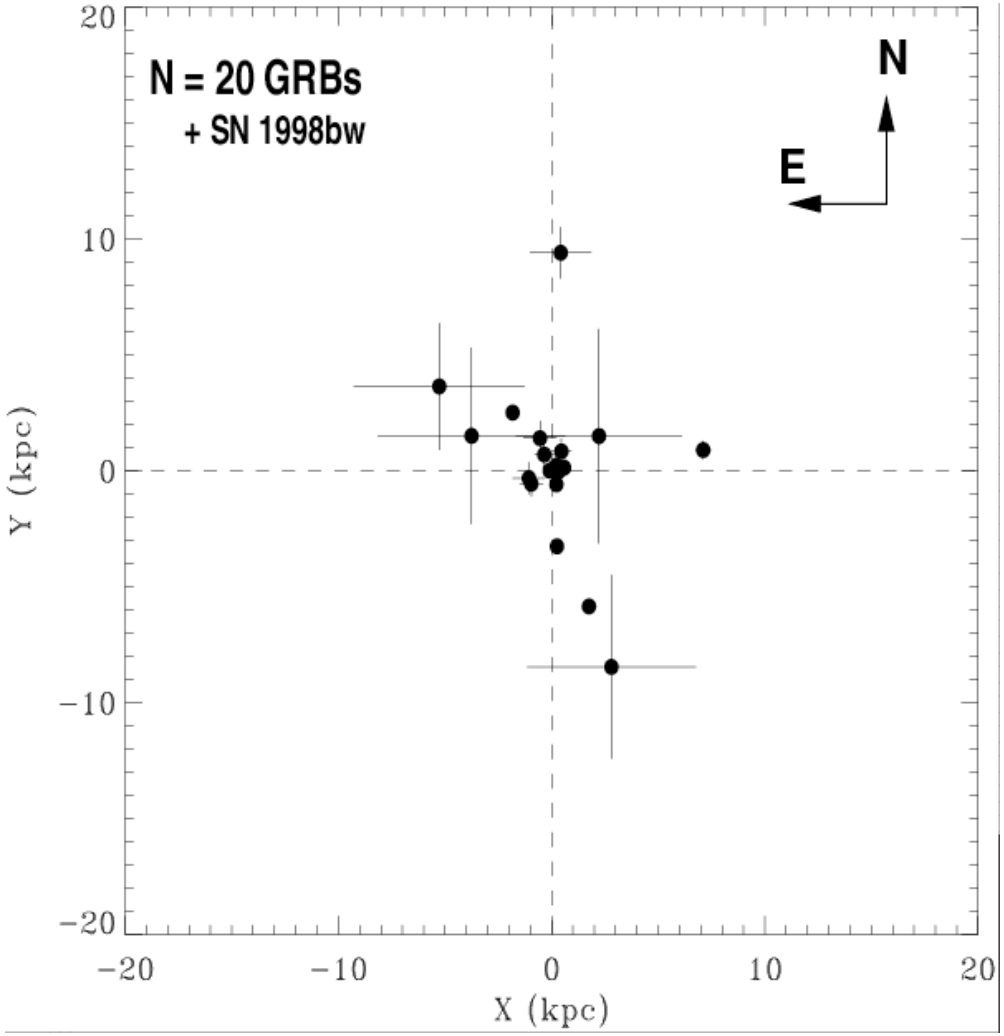
Panait

GRB host galaxies



(Vreeswijk P., PhD thesis, 2001)

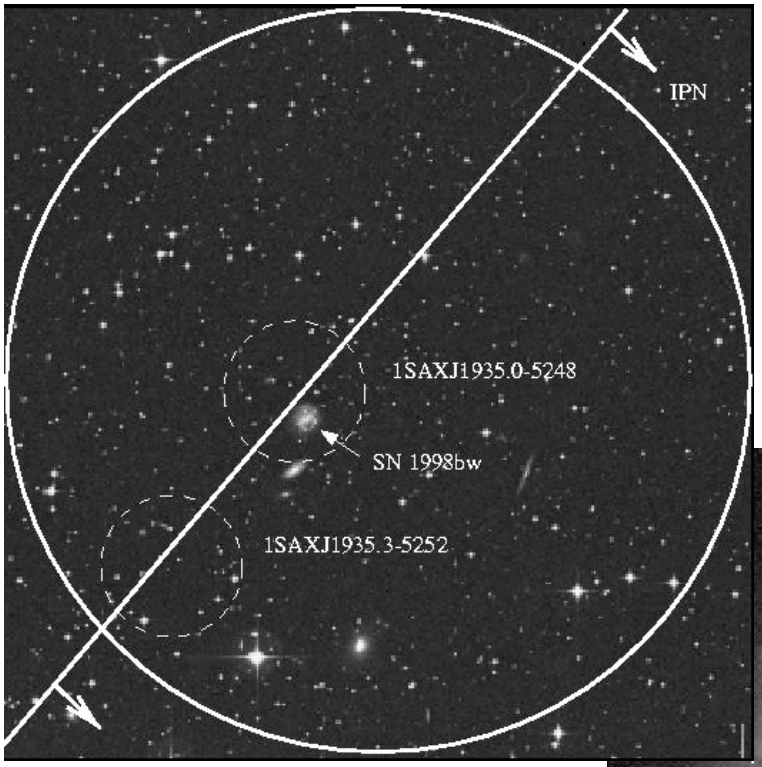
GRB location in the host



Central regions.

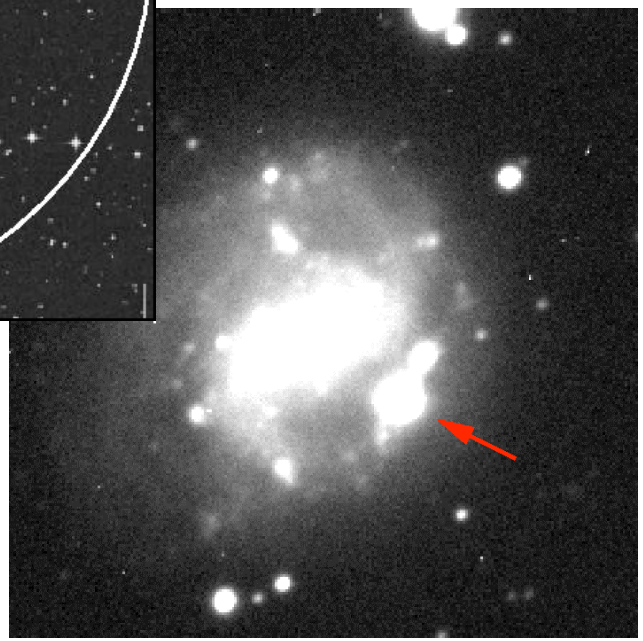
Bloom et al. 2002

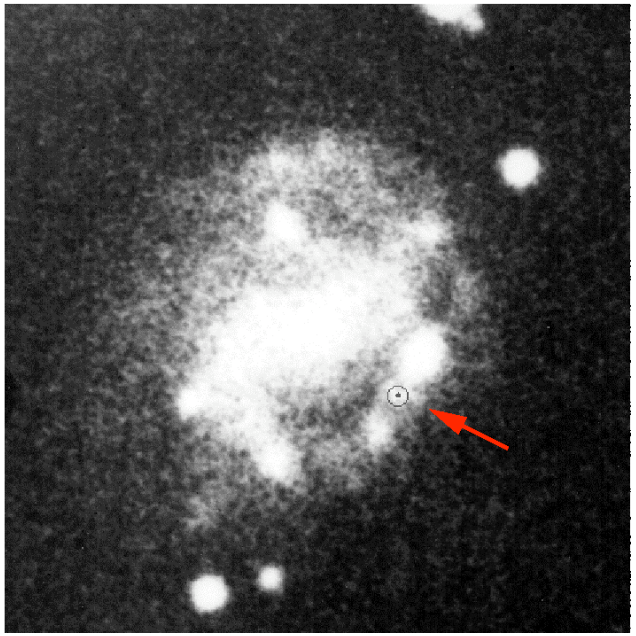
GRB 980425 / SN 1998bw



z = 0.008

A very energetic supernova associated with a weak GRB.

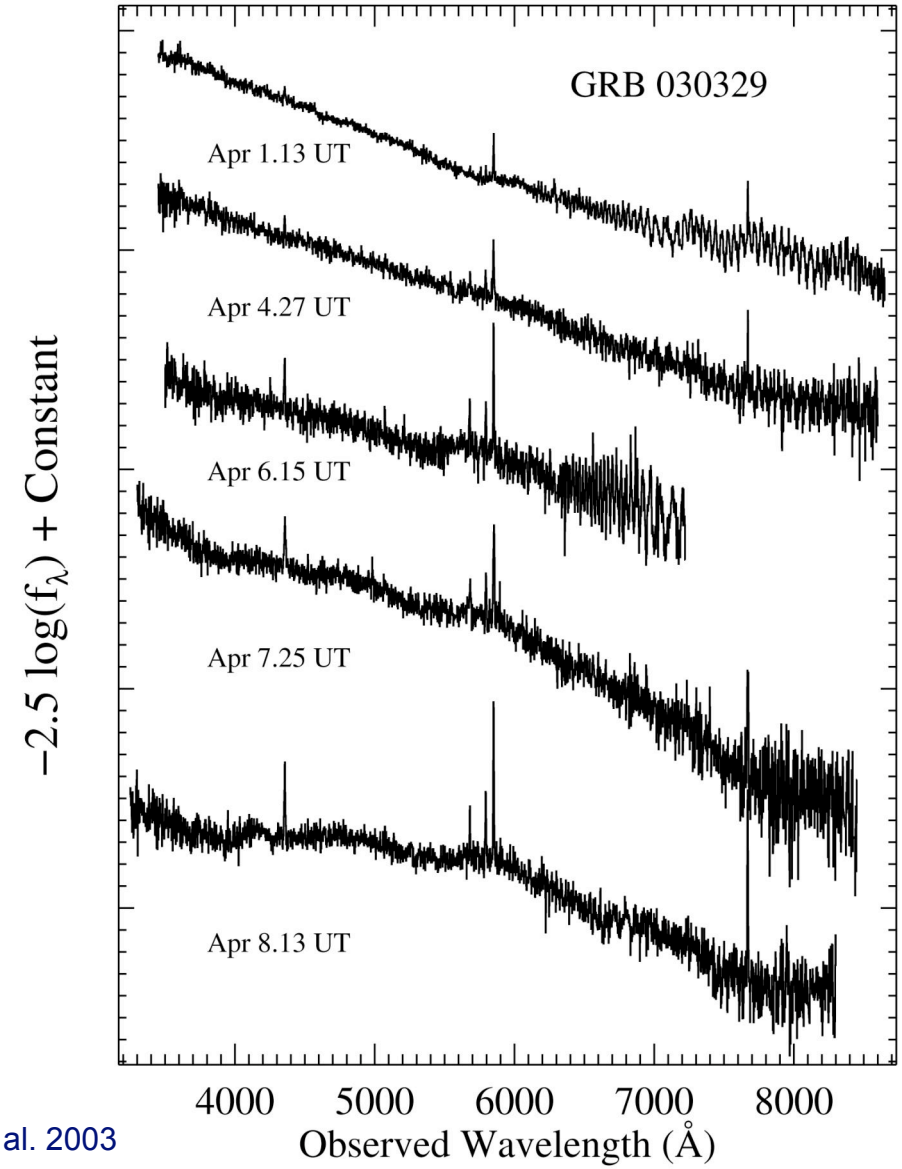




Galama et al. 1998

(NTT)

GRB 030329 / Type Ic SN



Stanek et al. 2003

(Discovery by HETE-2)

A « standard » energetic cosmological GRB (z=0.17) associated with a type Ic SN.

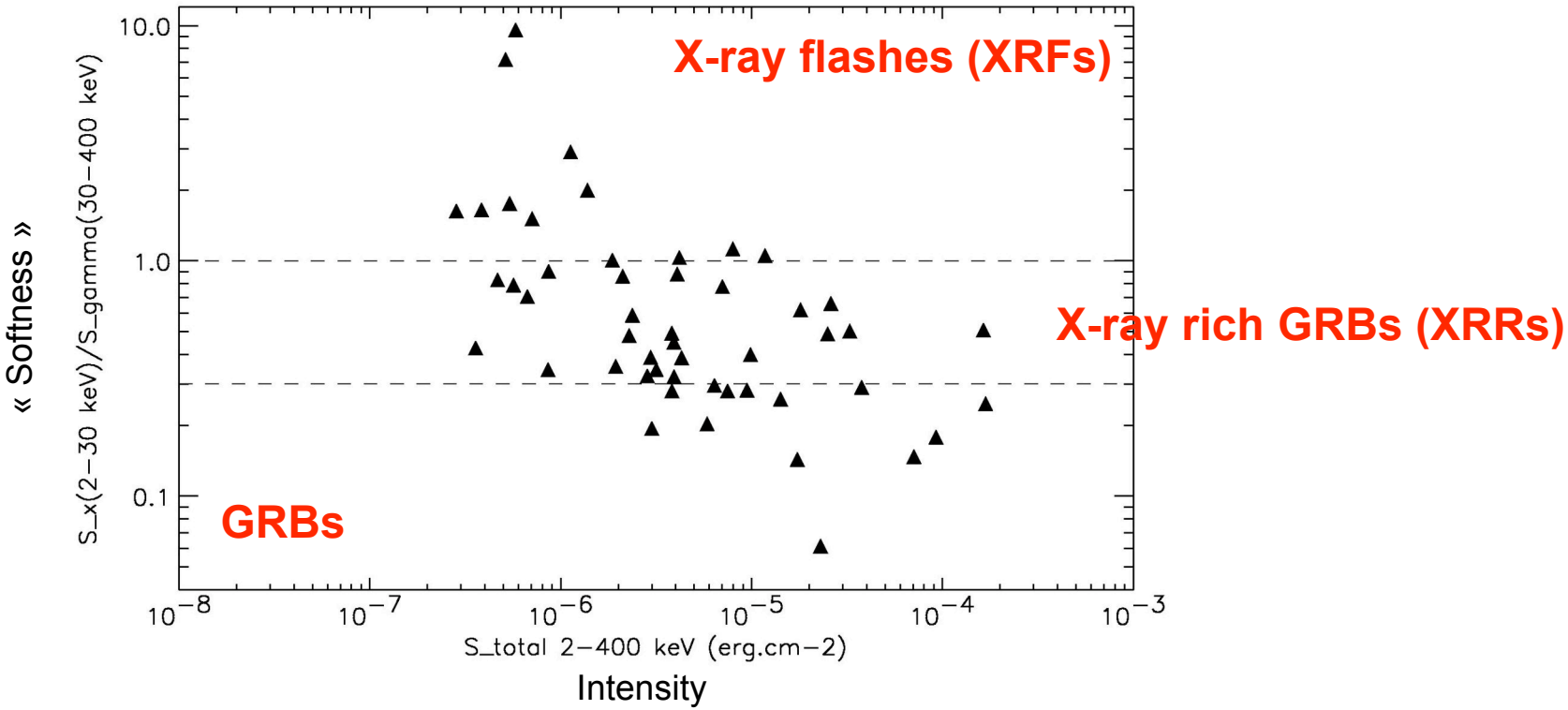
A least a fraction of long GRBs are associated with supernovae.

Soft GRBs

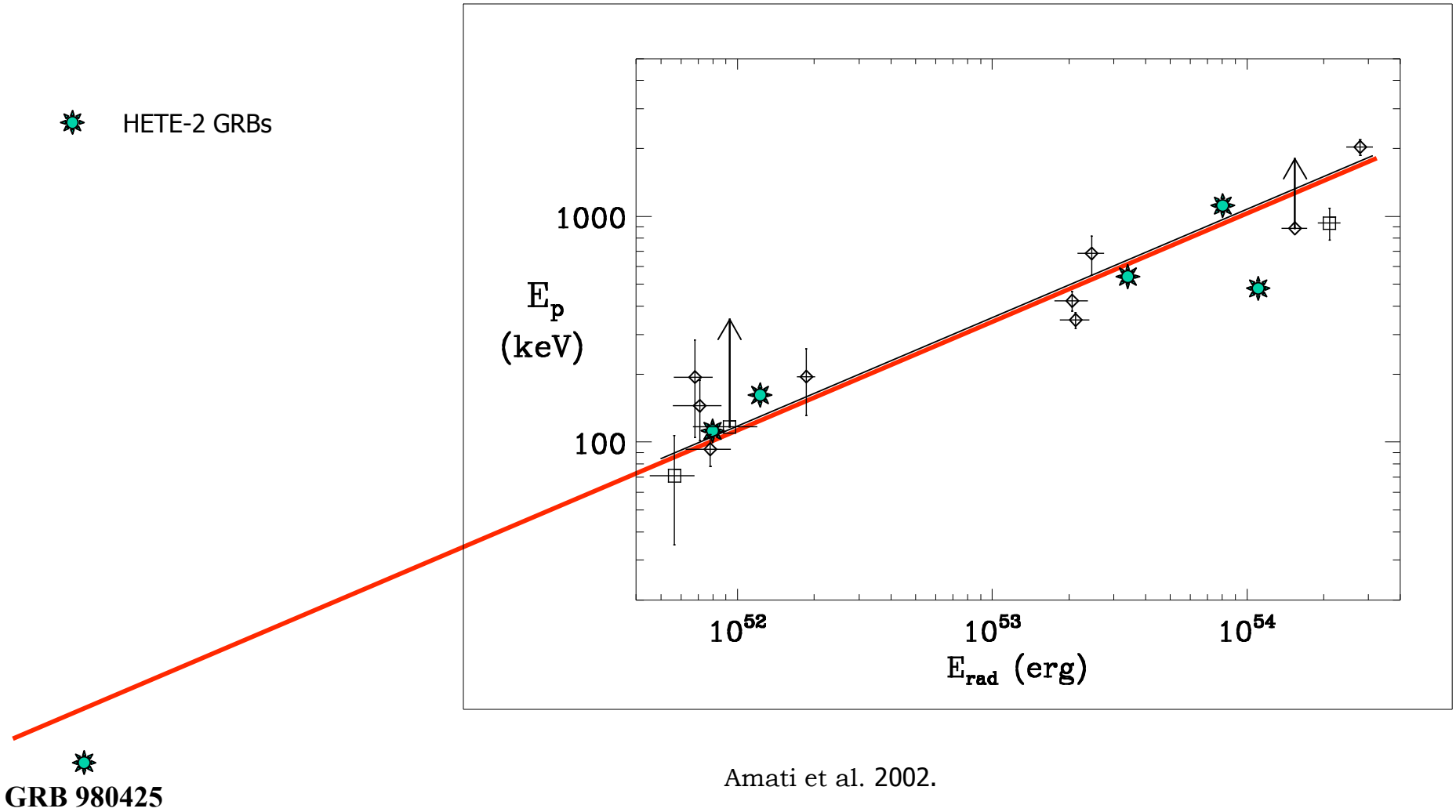
HETE-2 has confirmed the existence of soft or very soft GRBs :
(GINGA, BeppoSAX) : X-ray rich GRBs and X-ray Flashes.

(Barraud et al. 2002)

Same properties (variability, duration, …) BUT softer emission.



Amati relation



Amati et al. 2002.

GRB rate

Assume a constant efficiency for GRB production by stars :

1 GRB (pointing towards us) for 10^6 supernovae

i.e. 1 GRB (pointing towards us) per 50 Myr per galaxy.

Correction for the beaming factor :

1 GRB per 2000 supernovae

i.e. 1 GRB per 100 000 yr per galaxy.

Only a small fraction of massive stars produce GRBs.

Recent results

... SWIFT !

Afterglow detections

Localizations : better, faster

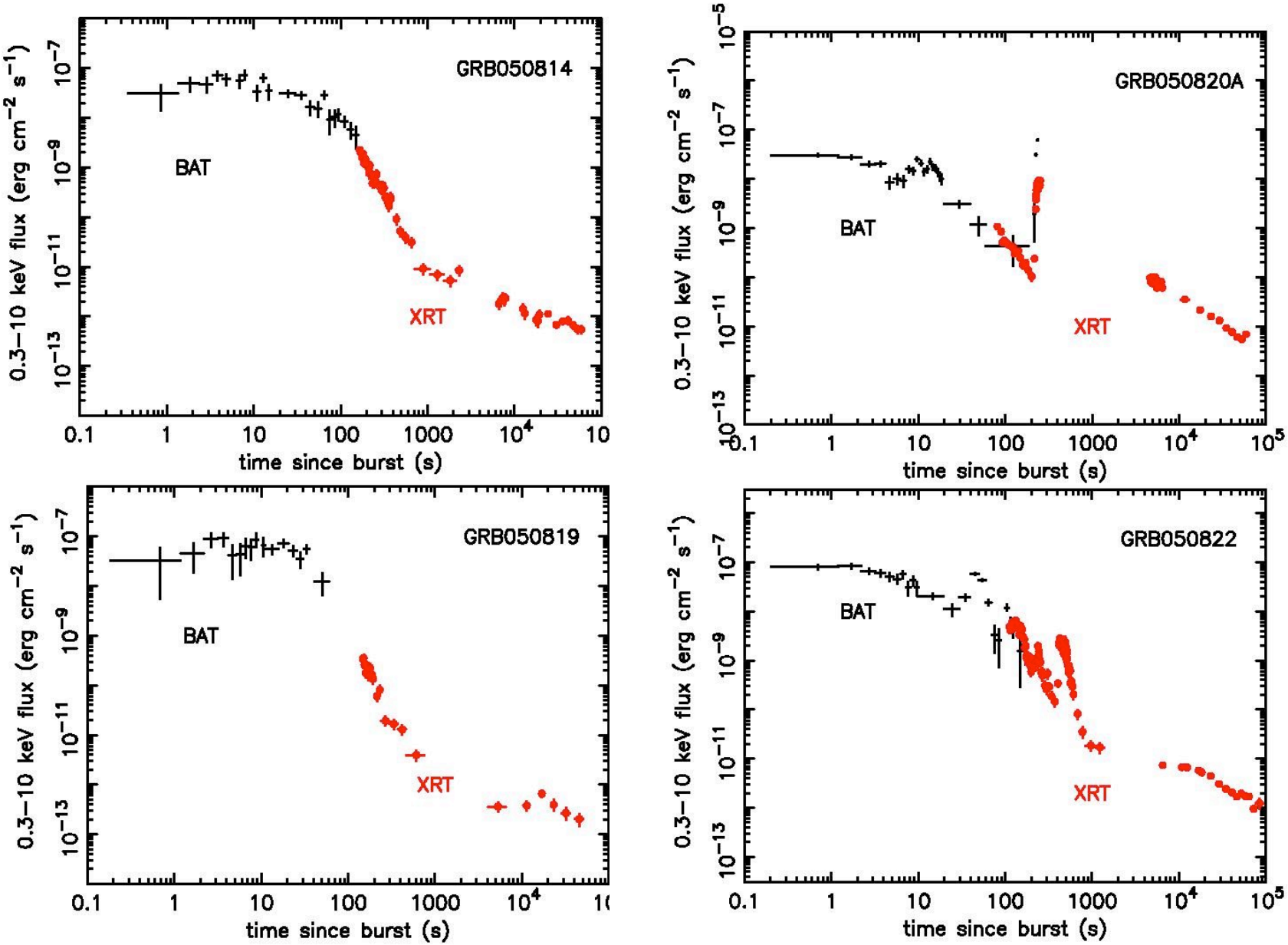
Since january 2005 :

INTEGRAL :	14 GRBs (2' to 3') and 1 redshift.
HETE-2 :	11 GRBs (2' to 15') and 3 redshifts.
SWIFT :	110 GRBs (2' to 4') and 29 redshifts !

The afterglow is detected at earlier epoch :
Unexpected complexity of the GRB to afterglow transition.

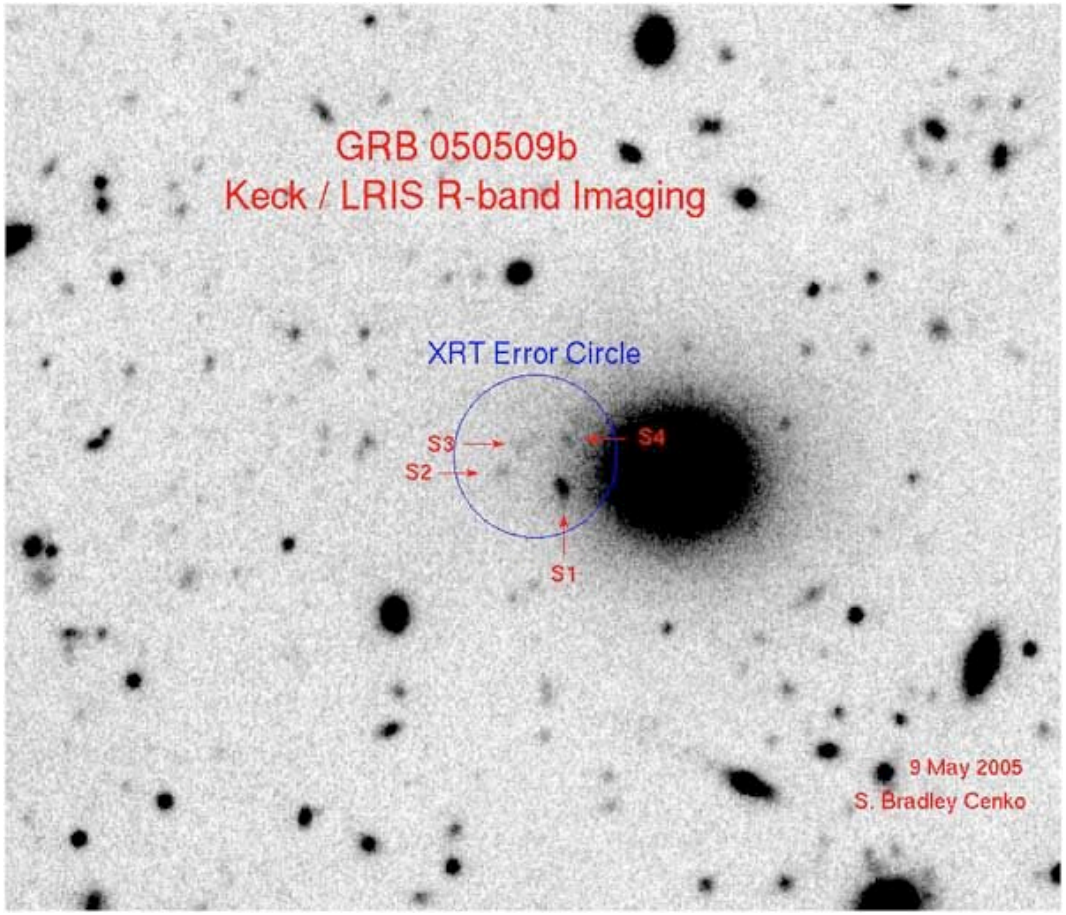
Most distant GRB : z = 6.29 (the Universe is 750 Myr old).

Early X-ray afterglow



O' Brian et al. 2005

Short GRBs

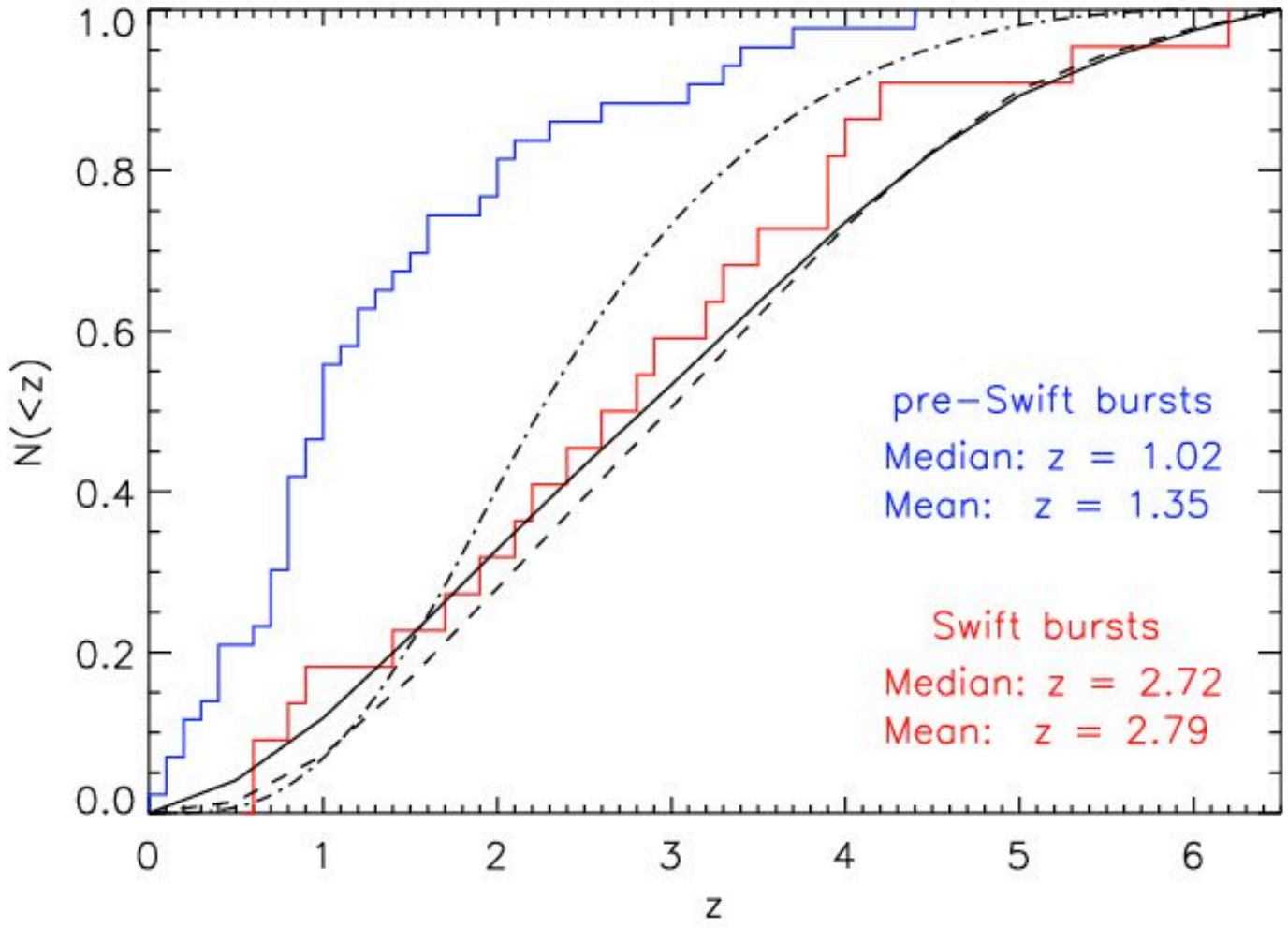


First redshift of a short GRB ! **z = 0,266**

(SWIFT+HETE-2 : 3 short GRB afterglows)

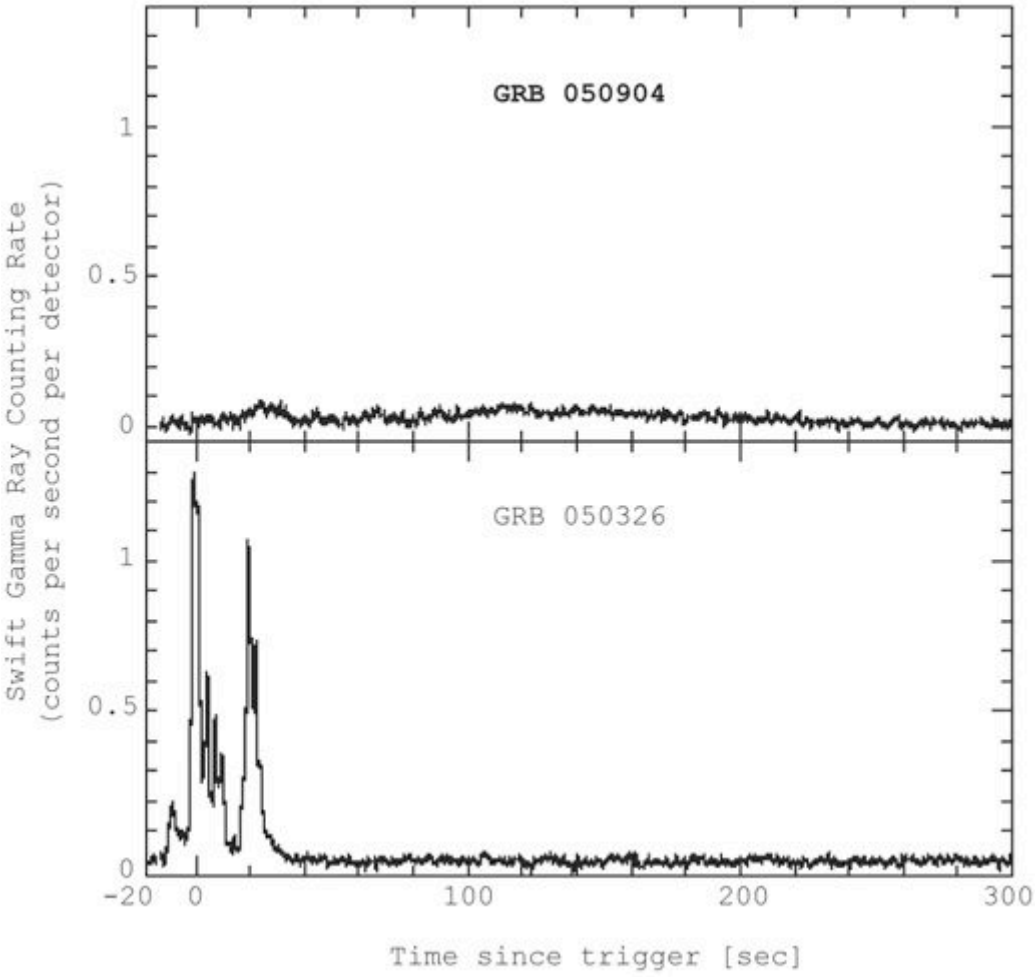
Elliptical host galaxy + afterglow far from the center: **NS+NS mergers ?**

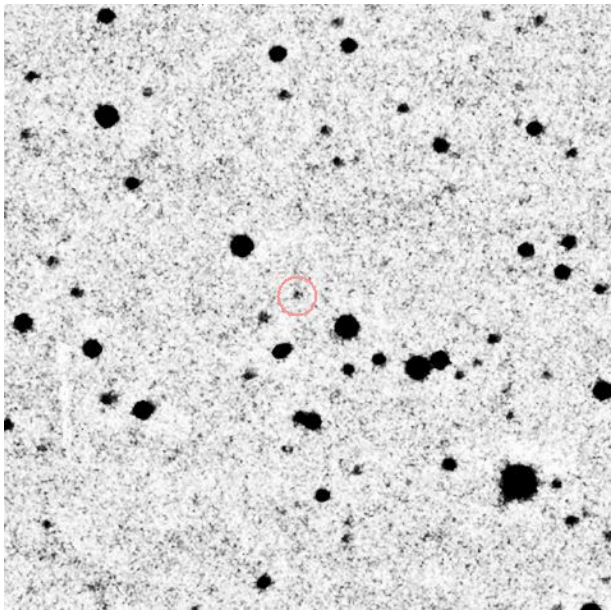
Redshift distribution



Jakobsson et al. 2005

GRB 050904 at z = 6.29 !



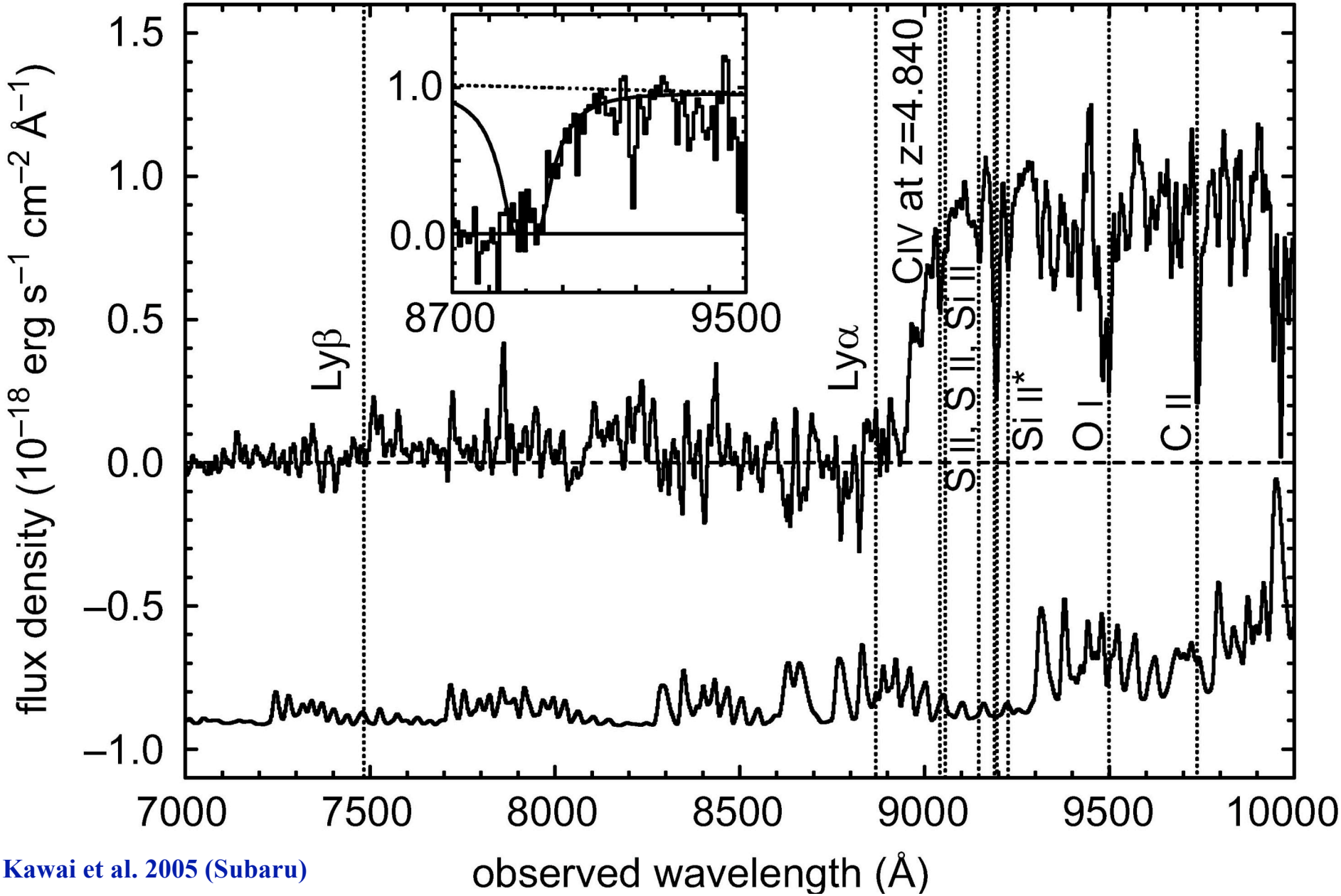


TAROT detection :
86 s after the burst : I~16

(Quasar : z = 6.37, I=23.3)

Timescales are multiplied by 1+z = 7.3 ! **(T_{90}>200 s)**

GRB 050904 at z = 6.29 !



Kawai et al. 2005 (Subaru)

Models...

How to produce a GRB

Energetics

Isotropic equivalent energy :

$$E_{\gamma,iso} = 10^{51} \rightarrow 10^{54} \text{ erg}\ldots$$

True energy :

(correction for the beaming factor)

$$E_{\gamma} \approx 10^{51} \text{ erg}$$

(Frail et al. 2001)

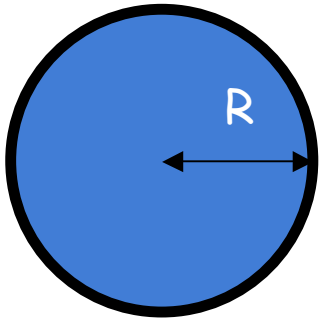
GRB : energy radiated in gamma-rays ~ SN : kinetic energy !

Compactness problem

Energy radiated in γ-rays : $E_\gamma = f_\Omega \, 10^{51}$ erg

Variability : $t_{var} \leq 10$ ms

Beaming



Source size : $R \leq c \, t_{var} \leq 3000$ km

Opacity $\tau_{\gamma\gamma} \rightarrow e^+e^-$: $\tau_{\gamma\gamma} \approx f_{\gamma\gamma} \, E_\gamma \, \sigma_T / 4\pi R^2 m_e c^2$

$\tau_{\gamma\gamma} \geq 7 \, 10^{14} \, f_\Omega \, f_{\gamma\gamma}$

Fraction of photons above the pair production threshold (10^{-3} – 10^{-2}).

Problem :

non-thermal spectrum

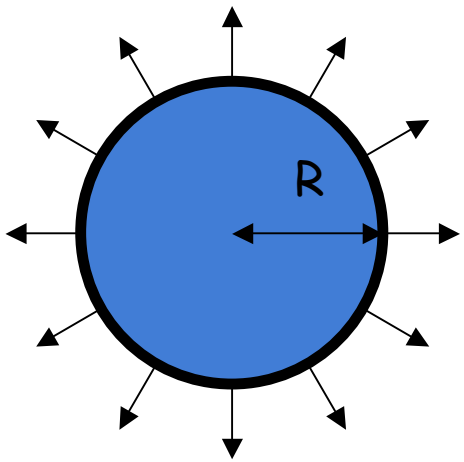
⇒ optically thin medium

Relativistic motion

Energy radiated in γ-rays : $E_\gamma = f_\Omega \, 10^{51}$ erg

Variability : $t_{var} \leq 10$ ms

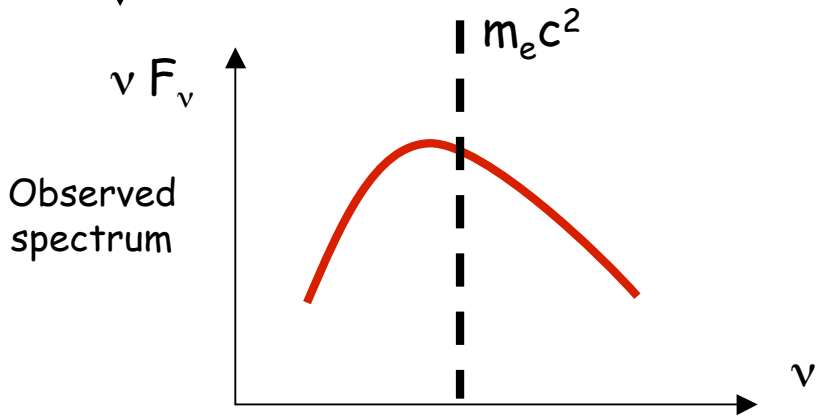
Beaming

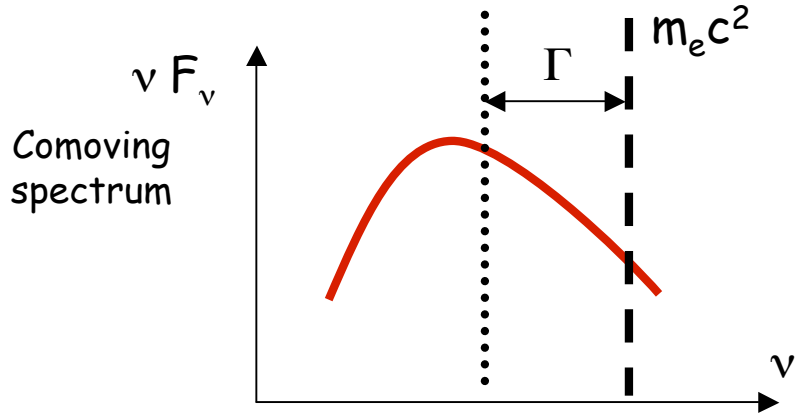


Expanding source : Lorentz factor Γ

(i) in the comoving frame of the emitting material, the photon energy is divided by Γ, the fraction $f_{\gamma\gamma}$ is divided by $\Gamma^{2\beta+2}$.

High energy slope

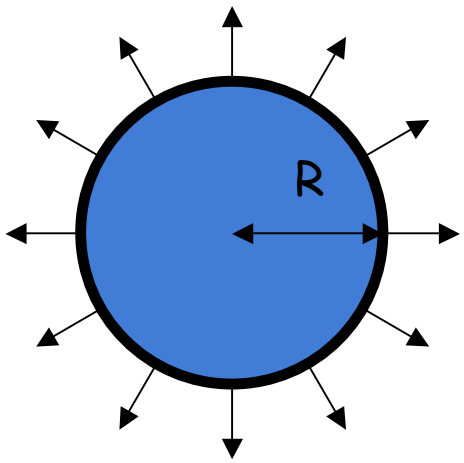




Relativistic motion

Energy radiated in γ-rays : $E_\gamma = f_\Omega \, 10^{51}$ erg

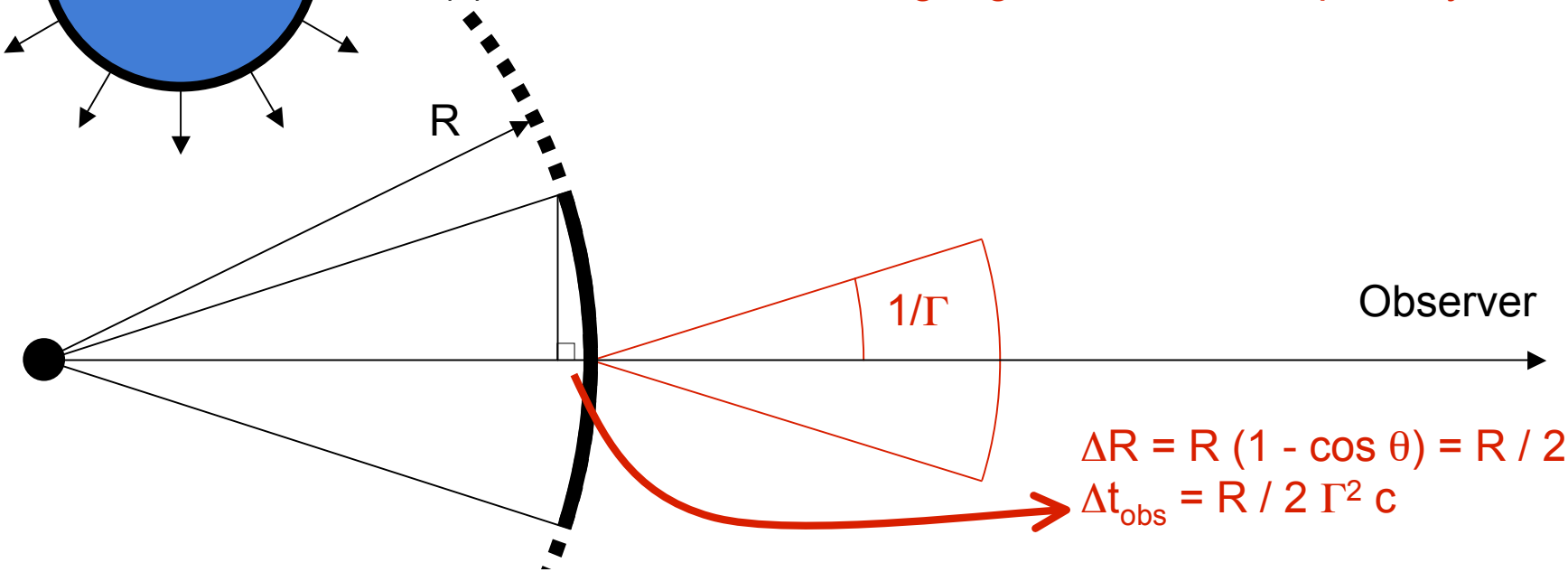
Variability : $t_{var} \leq 10$ ms



Expanding source : Lorentz factor Γ

(i) in the comoving frame of the emitting material, the photon energy is divided by Γ, the fraction $f_{\gamma\gamma}$ is divided by $\Gamma^{2\beta+2}$.

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



$\Delta R = R\,(1 - \cos\theta) = R / 2\,\Gamma^2$

$\Delta t_{obs} = R / 2\,\Gamma^2\,c$

1. The discovery of GRBs

2. Main properties

3. The GRB distance scale

4. The afterglow era

5. Recent results : SWIFT

6. **How to produce a GRB**

7. **GRBs and cosmology**

Minimal requirements for a GRB model

Cosmological distance

Isotropic equivalent energy : $E_{\gamma,iso} = 10^{51} \rightarrow 10^{54}$ erg…

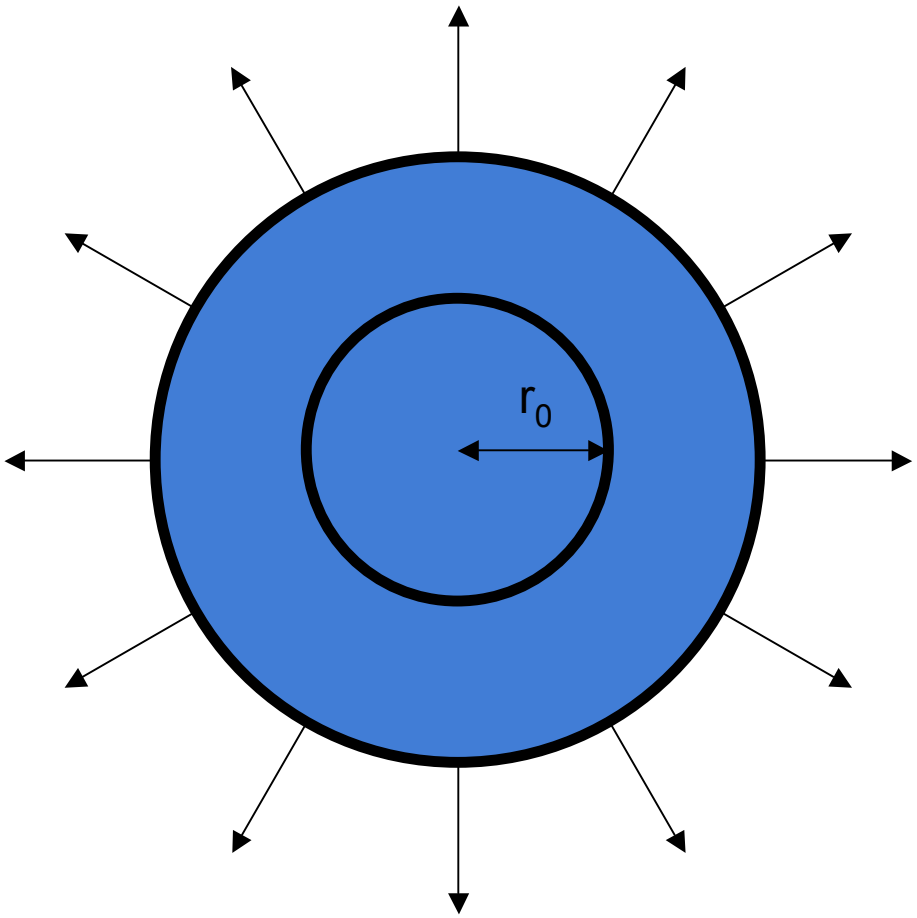
[True energy : $E_{\gamma} \approx 10^{51}$ erg]

Minimum Lorentz factor (to solve the « compactness problem ») : $\Gamma > 100$…

Variability timescales/Duration : a few ms to a few 100 s

Rate : ~1 GRB (pointing towards us) for 10^6 supernovae

Fireballs



Energy E released in volume r_0

Mass : $Mc^2 << E$

Hydrodynamics

1D – Spherical symmetry – Adiabatic : Newtonian

Mass conservation :

$$\frac{\partial \rho}{\partial t} + \frac{1}{r^2}\frac{\partial (r^2 \rho v)}{\partial r} = 0$$

Momentum conservation :

$$\frac{\partial (\rho v)}{\partial t} + \frac{1}{r^2}\frac{\partial (r^2 \rho v^2)}{\partial r} = -\frac{\partial P}{\partial r}$$

Energy conservation :

$$\frac{\partial \left(\frac{1}{2}\rho v^2 + \rho\varepsilon\right)}{\partial t} + \frac{1}{r^2}\frac{\partial \left(r^2 (\frac{1}{2}\rho v^2 + \rho\varepsilon + P) v\right)}{\partial r} = 0$$

E.O.S. : $\varepsilon = \frac{1}{\gamma - 1}\frac{P}{\rho}$

Hydrodynamics

1D – Spherical symmetry – Adiabatic : Special relativity

Mass conservation :

$$\frac{\partial(\rho\Gamma)}{\partial t} + \frac{1}{r^2}\frac{\partial(r^2\rho\Gamma v)}{\partial r} = 0$$

Momentum conservation :

$$\frac{\partial(\rho h\Gamma^2 v)}{\partial t} + \frac{1}{r^2}\frac{\partial(r^2\rho h\Gamma^2 v^2)}{\partial r} = -\frac{\partial P}{\partial r}$$

Energy conservation :

$$\frac{\partial(\rho h\Gamma^2 - P - \rho\Gamma)}{\partial t} + \frac{1}{r^2}\frac{\partial\left(r^2(\rho h\Gamma^2 - \rho\Gamma)v\right)}{\partial r} = 0$$

E.O.S. : $\varepsilon = \frac{1}{\gamma - 1}\frac{P}{\rho}$ **Lorentz factor :** $\Gamma = \frac{1}{\sqrt{1 - v^2}}$ **Specific enthalpy :** $h = 1 + \varepsilon + \frac{P}{\rho}$

Hydrodynamics

1D – Spherical symmetry – Adiabatic : Special relativity

Retarded time : $s = t - r$

$$\frac{\partial}{\partial r} \rightarrow \frac{\partial}{\partial r} - \frac{\partial}{\partial s} \qquad \frac{\partial}{\partial t} \rightarrow \frac{\partial}{\partial s}$$

$$\frac{\partial q}{\partial t} + \frac{1}{r^2}\frac{\partial (r^2 q v)}{\partial r} \rightarrow \frac{\partial \big(q(1-v)\big)}{\partial s} + \frac{1}{r^2}\frac{\partial (r^2 q v)}{\partial r}$$

Hydrodynamics

1D – Spherical symmetry – Adiabatic : Special relativity

Mass conservation :

$$\frac{\partial(\rho\Gamma(1-v))}{\partial s} + \frac{1}{r^2}\frac{\partial(r^2\rho\Gamma v)}{\partial r} = 0$$

Momentum conservation :

$$\frac{\partial(\rho h\Gamma^2 v(1-v))}{\partial s} + \frac{1}{r^2}\frac{\partial(r^2\rho h\Gamma^2 v^2)}{\partial r} = -\frac{\partial P}{\partial r} + \frac{\partial P}{\partial s}$$

Energy conservation :

$$\frac{\partial\left(P^{1/\gamma}\Gamma(1-v)\right)}{\partial s} + \frac{1}{r^2}\frac{\partial\left(r^2(P^{1/\gamma}\Gamma)v\right)}{\partial r} = 0$$

E.O.S. : $\varepsilon = \frac{1}{\gamma-1}\frac{P}{\rho}$ **Lorentz factor :** $\Gamma = \frac{1}{\sqrt{1-v^2}}$ **Specific enthalpy :** $h = 1 + \varepsilon + \frac{P}{\rho}$

Hydrodynamics

High Lorentz factor : $$v \approx 1 - \frac{1}{2\Gamma^2}$$

Mass conservation : $$\frac{\partial(\rho\Gamma(1-v))}{\partial s} + \frac{1}{r^2}\frac{\partial(r^2\rho\Gamma v)}{\partial r} = 0$$

$$\rho\Gamma(1-v) \approx \frac{\rho}{2\Gamma} << \rho\Gamma v \approx \rho\Gamma$$

Therefore : $$\frac{1}{r^2}\frac{\partial(r^2\rho\Gamma v)}{\partial r} \approx 0$$ **for small radii.**

Same calculations for energy-momentum conservation.

Fireballs

To check later : width Δ~cst

Then :

$$\Gamma = \frac{1}{\sqrt{1 - v^2}}$$

Mass conservation : $$\left(4\pi R^2 \Delta\right) \times \Gamma \rho = M = cst$$

Energy conservation : $$\left(4\pi R^2 \Delta\right) \times \left(\Gamma \rho\right) \times \left(h\Gamma - \cancel{\frac{P}{\rho\Gamma}}\right) = E = cst$$

$$h = 1 + \varepsilon + \frac{P}{\rho}$$

Adiabatic motion : $$\frac{P}{\rho^\gamma} = cst$$

Fireballs

To check later : width Δ~cst

Mass conservation : $$R^2 \Gamma \rho = \text{cst}$$

Energy conservation : $$h\Gamma = \text{cst}$$

Adiabatic motion : $$\frac{P}{\rho^\gamma} = \text{cst}$$

Energy-dominated phase : $$h \approx \frac{\gamma}{\gamma - 1}\frac{P}{\rho}$$

Then : $$\Gamma \propto R$$

$$\rho \propto R^{-3} \qquad P \propto R^{-4}$$ **(for** $\gamma = 4/3$ **)**

Fireballs

To check later : width Δ~cst

Mass conservation : $R^2 \Gamma \rho = \text{cst}$

Energy conservation : $h\Gamma = \text{cst}$

Adiabatic motion : $\dfrac{P}{\rho^\gamma} = \text{cst}$

Energy-dominated phase : $\Gamma \propto R$ $\rho \propto R^{-3}$ $P \propto R^{-4}$

Matter-dominated phase : $h \approx 1$

Then : $\Gamma = \text{cst}$

$\rho \propto R^{-2}$ $P \propto R^{-2\gamma}$

Fireballs

Energy-dominated phase : $\Gamma \propto R \qquad \rho \propto R^{-3} \qquad P \propto R^{-4}$

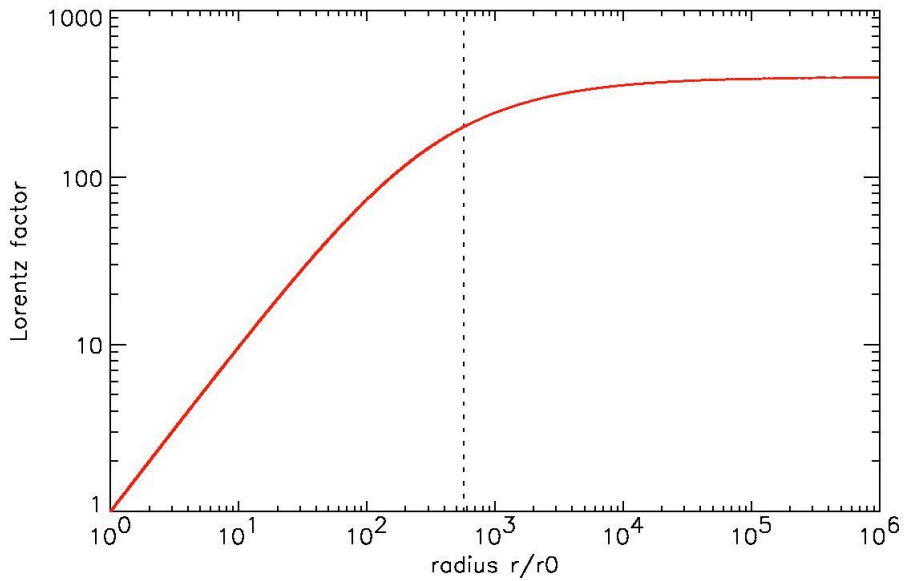
Matter-dominated phase : $\Gamma = \mathrm{cst} \qquad \rho \propto R^{-2} \qquad P \propto R^{-2\gamma}$

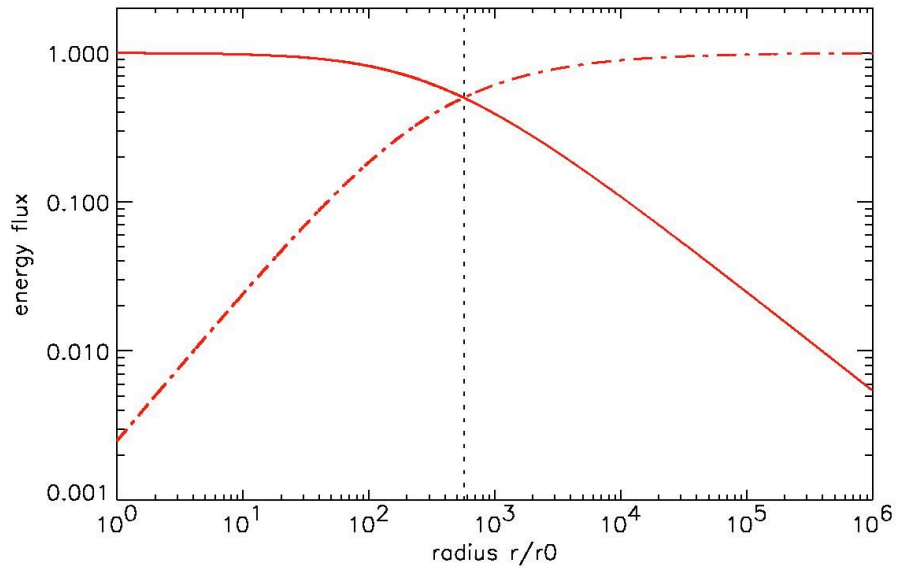
Terminal Lorentz factor : $\Gamma_\infty = h_0 \Gamma_0$

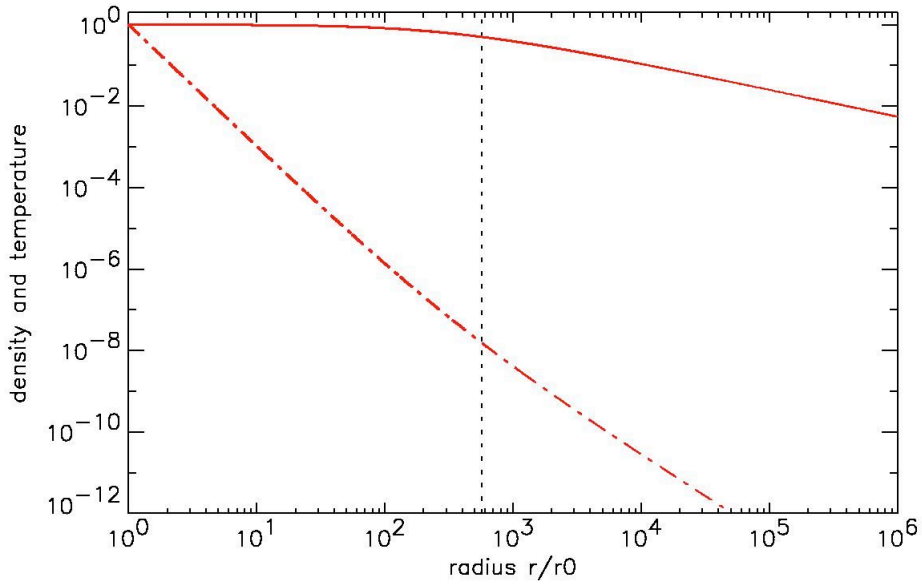
End of acceleration : $R_{acc} = R_0 \dfrac{\Gamma_\infty}{\Gamma_0}$

Constant width : $R << \Delta_0 \dfrac{\Gamma^2{}_\infty}{\Gamma_0}$

Fireballs







$$R_0 \approx \frac{6GM}{c^2} \approx 9\times10^6\,\mu_1\ \mathrm{cm}$$

$$R_{acc} \approx 9\times10^8\,\mu_1\left(\frac{\Gamma_\infty}{100}\right)\mathrm{cm}$$

$$R_{spread} \approx 3\times10^{14}\left(\frac{\Gamma_\infty}{100}\right)^2\left(\frac{\Delta/c}{1\,\mathrm{s}}\right)\mathrm{cm}$$

Fireballs

Initial temperature : $$kT'_0 \approx 1.8\left(\frac{\dot{E}}{10^{52}\,\mathrm{erg/s}}\right)^{1/4}\left(\frac{R_0}{90\mathrm{km}}\right)^{-1/2}\mathrm{MeV}$$

		$R < R_{acc}$	$R > R_{acc}$
Temperature (comoving frame) :	$T' \approx (3P/a)^{1/4}$	$T' \propto R^{-1}$	$T' \propto R^{-\gamma/2}$
Temperature (source frame) :	$T = \Gamma T'$	$T \approx \mathrm{cst}$	$T \propto R^{-\gamma/2}$

Transparent to pairs : $T' < 20\,\mathrm{keV}$ **(usually :** $R < R_{acc}$ **)**

The fireball cannot be purely leptonic (thermal spectrum) : baryonic pollution !

Fireballs : summary

Acceleration :

$$R_{acc} \approx 9 \times 10^{8} \mu_1 \left(\frac{\Gamma_\infty}{100} \right) \text{cm}$$

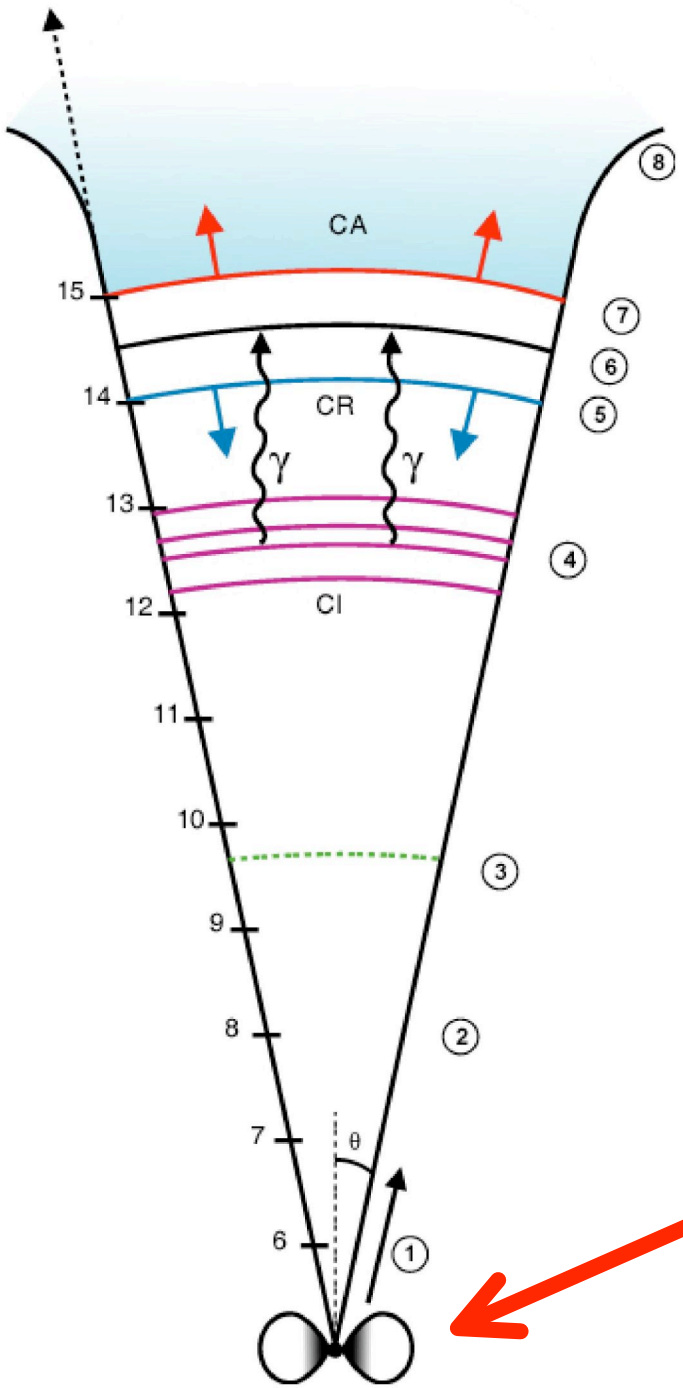
Transparency :

$$R_{ph} \approx 6 \times 10^{12} \text{cm} \left(\frac{\dot{E}}{10^{52} \text{erg/s}} \right) \left(\frac{\Gamma_\infty}{100} \right)^{-3}$$

Spreading :

$$R_{spread} \approx 3 \times 10^{14} \left(\frac{\Gamma_\infty}{100} \right)^{2} \left(\frac{\Delta / c}{1 \text{ s}} \right) \text{cm}$$

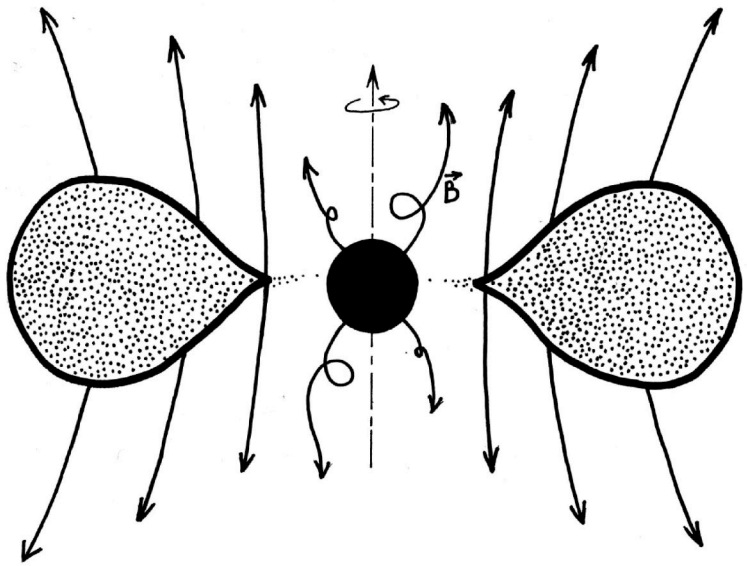
Scenario



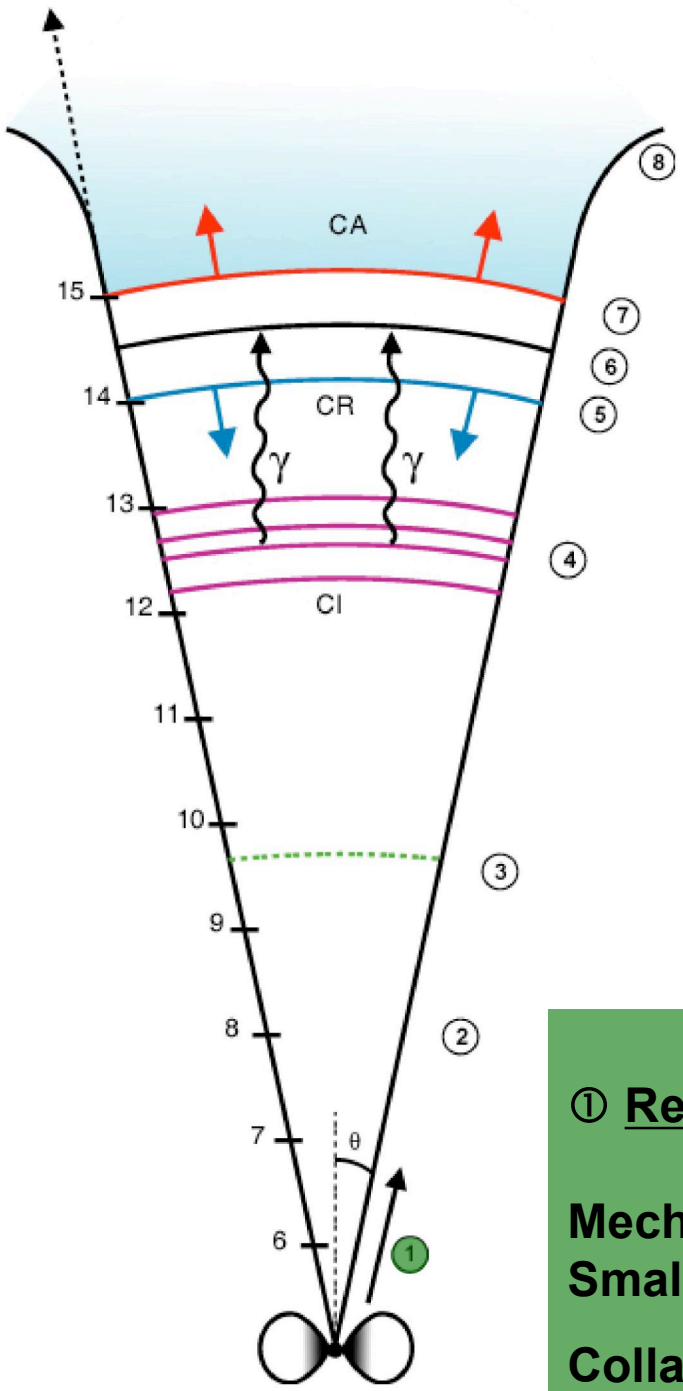
Initial event :

Formation of a stellar mass black hole surrounded by a thick accretion disk.

(collapsar, coalescence ?)



Scenario

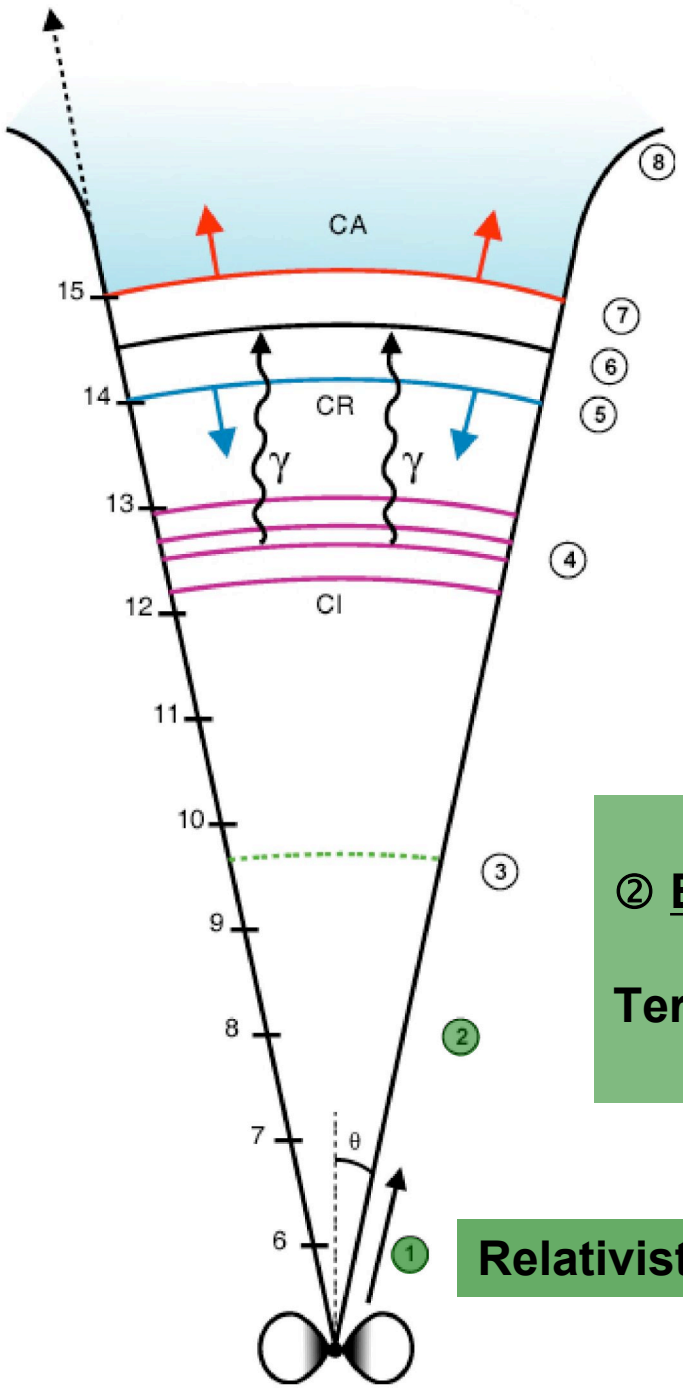


① **<u>Relativistic ejection :</u>**

Mechanism ?
Small bayonic pollution ?

Collapsars : how to escape the infalling star ?

Scenario

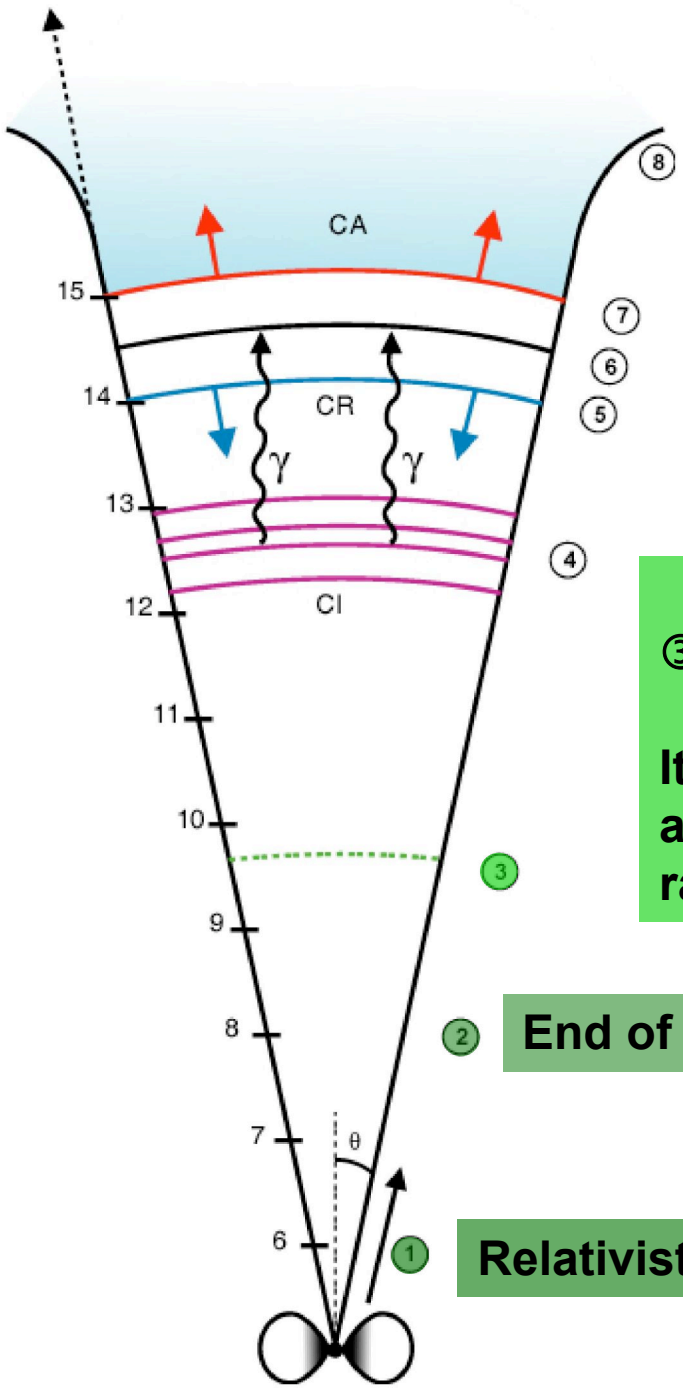


② **<u>End of the acceleration phase:</u>**

Terminal Lorentz factor $\Gamma \geq 100$!

Relativistic ejection

Scenario



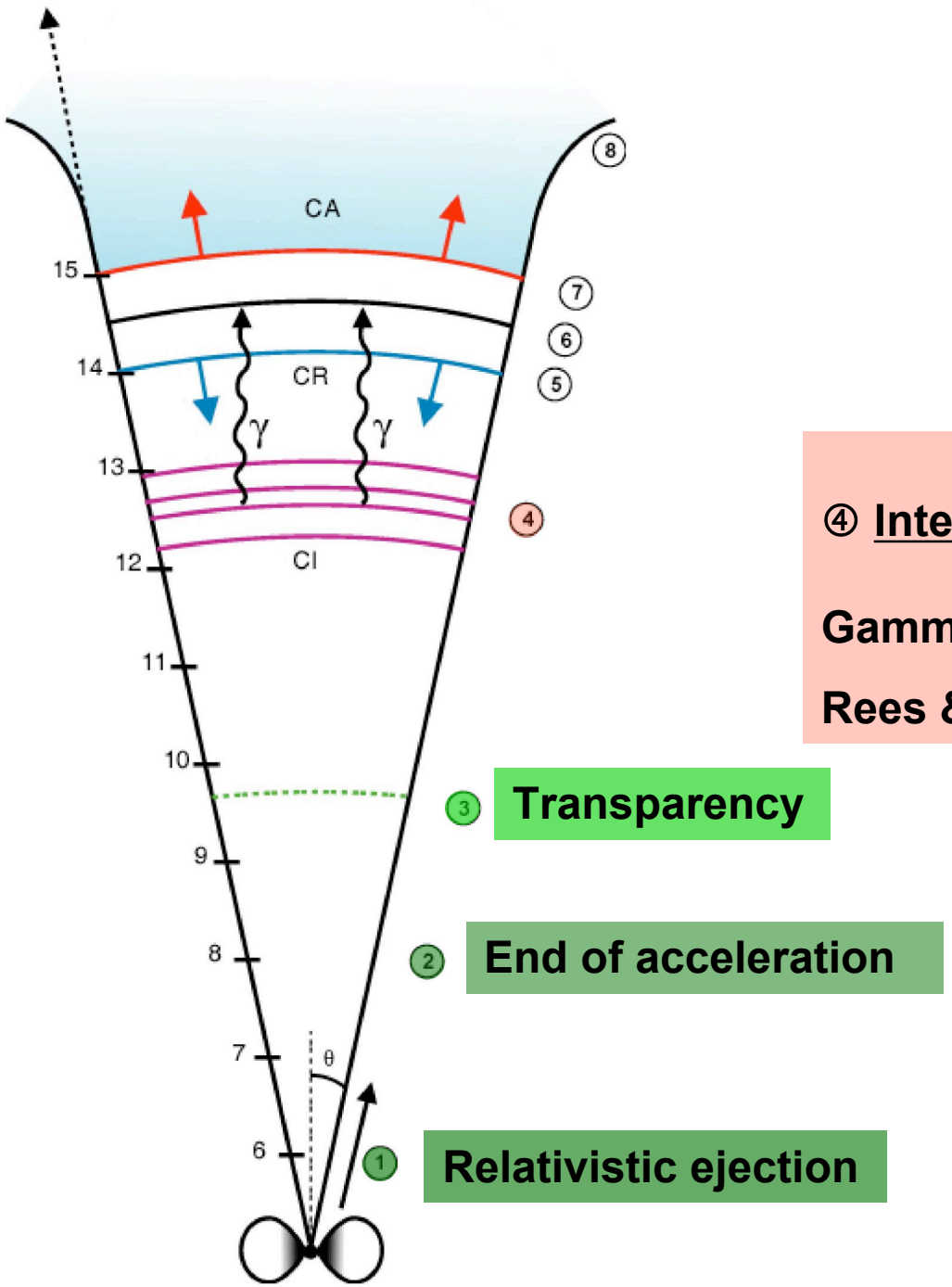
③ **Transparency :**

It is now possible for the ejecta to convert a fraction of its kinetic energy into radiation.

End of acceleration

Relativistic ejection

Scenario



Transparency

End of acceleration

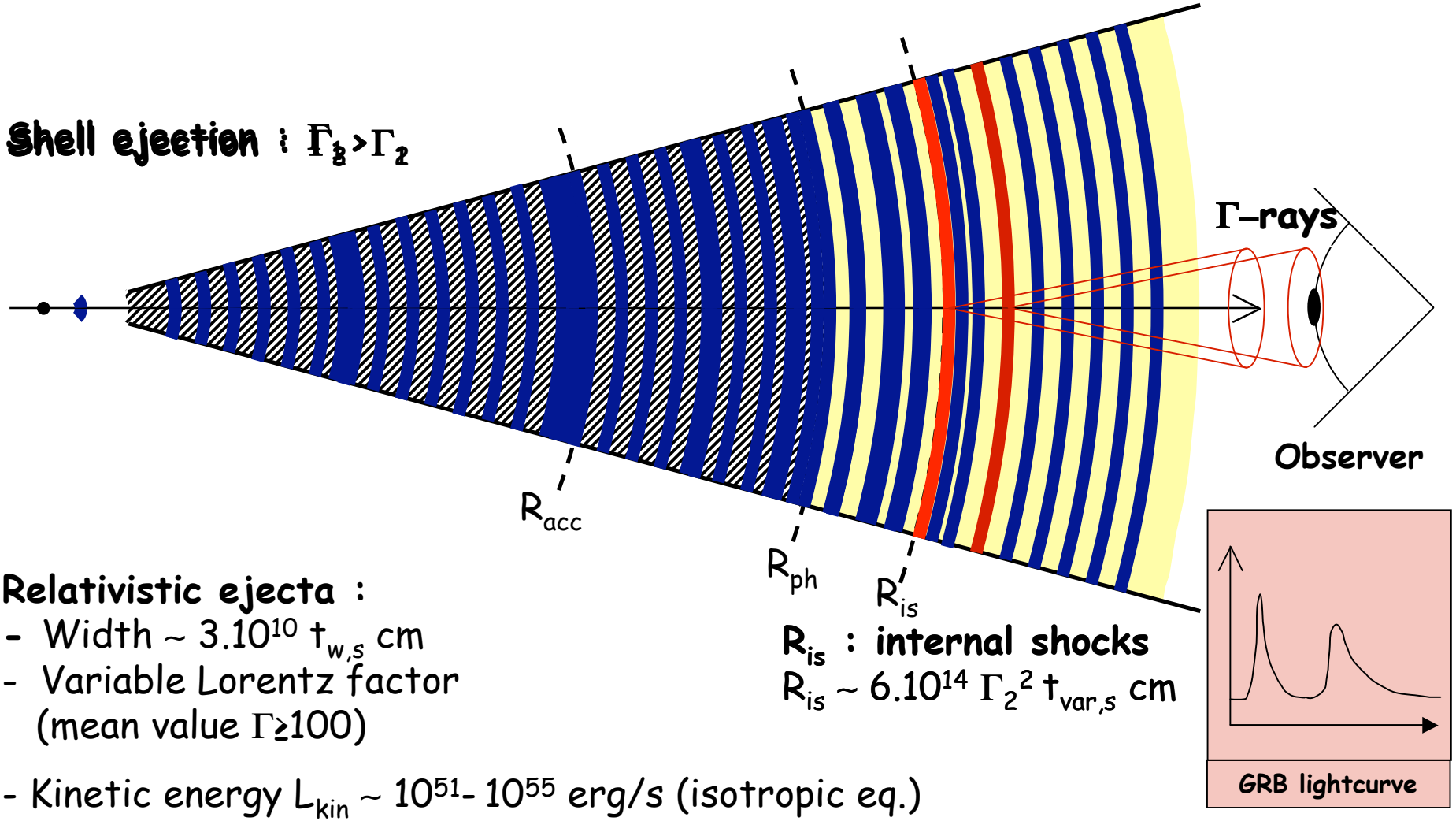
Relativistic ejection

④ **Internal shocks :**

Gamma-ray emission = GRB.

Rees & Meszaros 1994

Internal shocks



Relativistic ejecta :

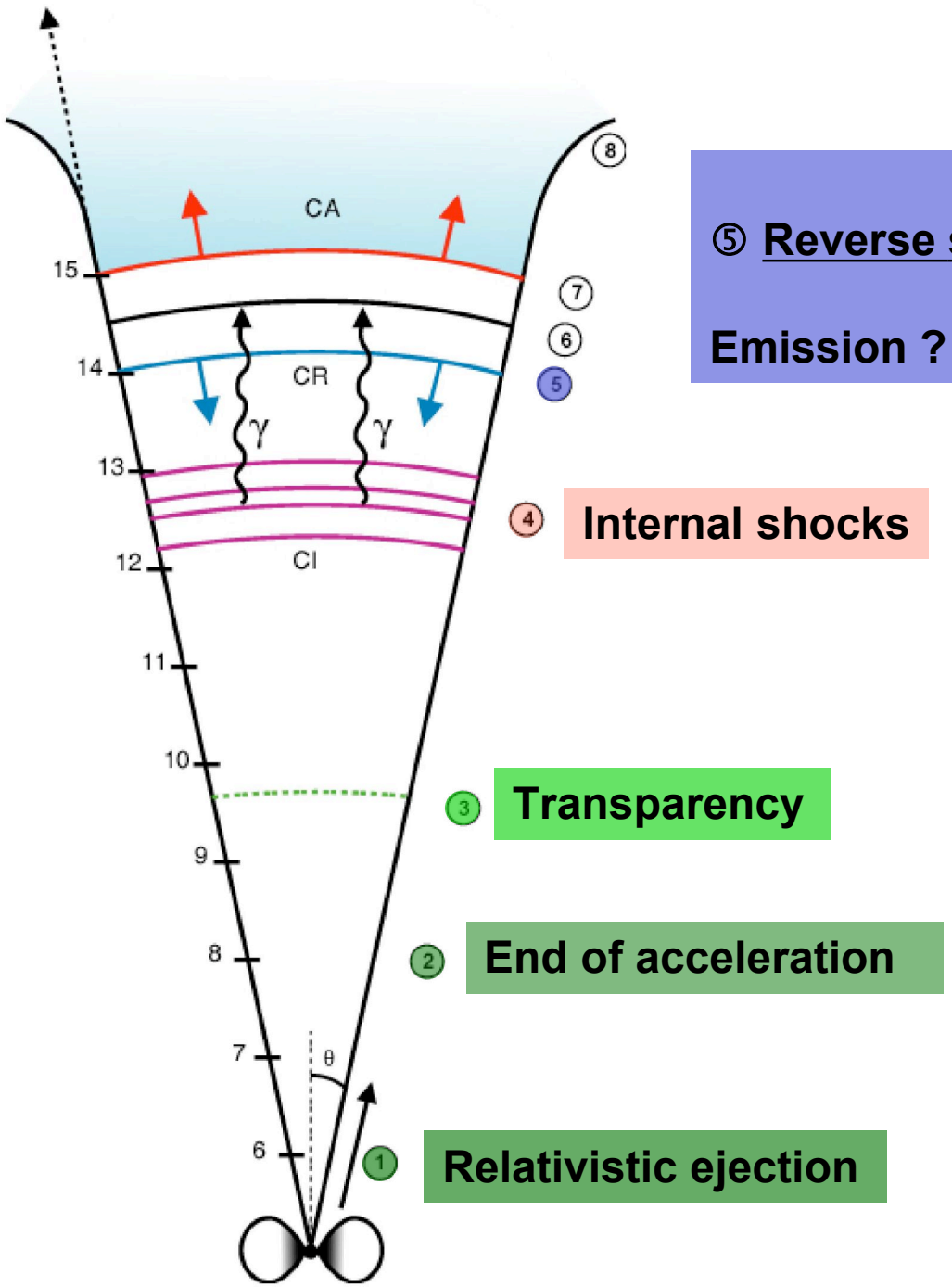
- Width ~ $3.10^{10}\ t_{w,s}$ cm
- Variable Lorentz factor (mean value $\Gamma \geq 100$)

R_{is} : internal shocks

$R_{is} \sim 6.10^{14}\ \Gamma_2^{\,2}\ t_{var,s}$ cm

- Kinetic energy $L_{kin} \sim 10^{51}$- 10^{55} erg/s (isotropic eq.)

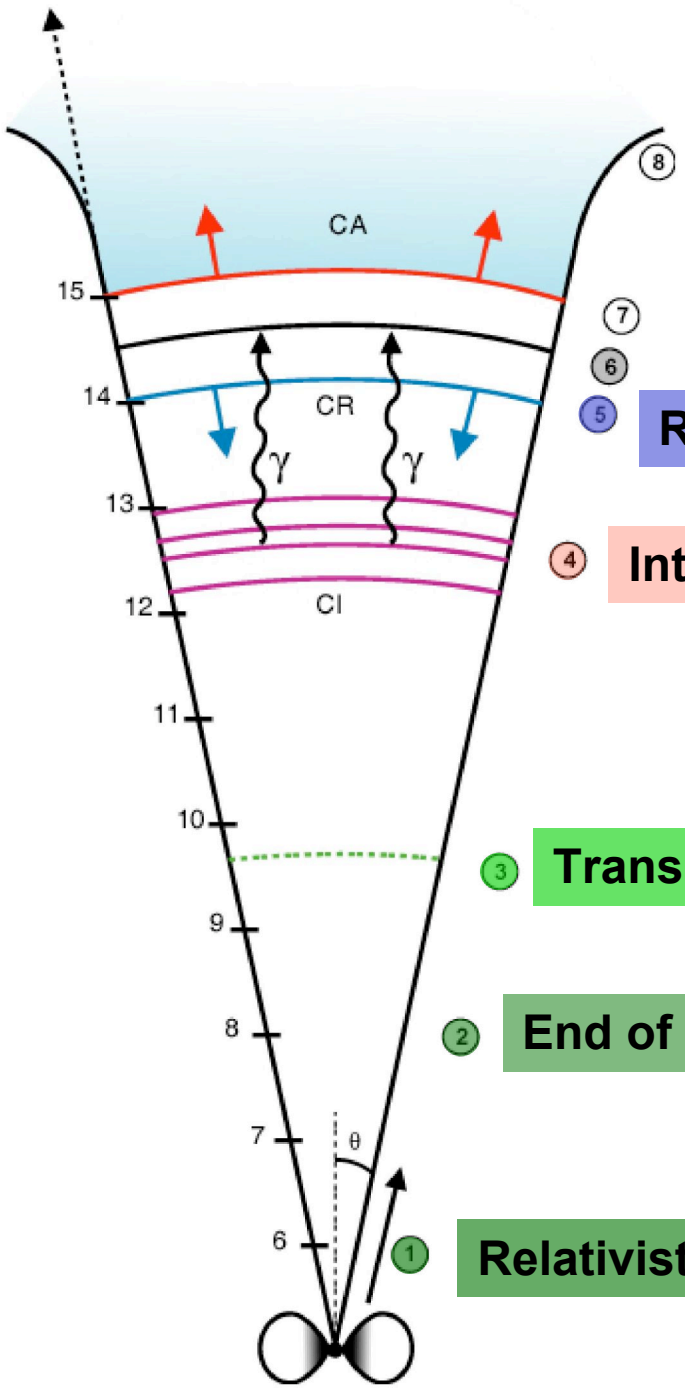
Scenario



⑤ **Reverse shock :**

Emission ? (visible ; X-rays)

Scenario



⑥ **Contact discontinuity :**

External medium : density profile ?

Reverse shock

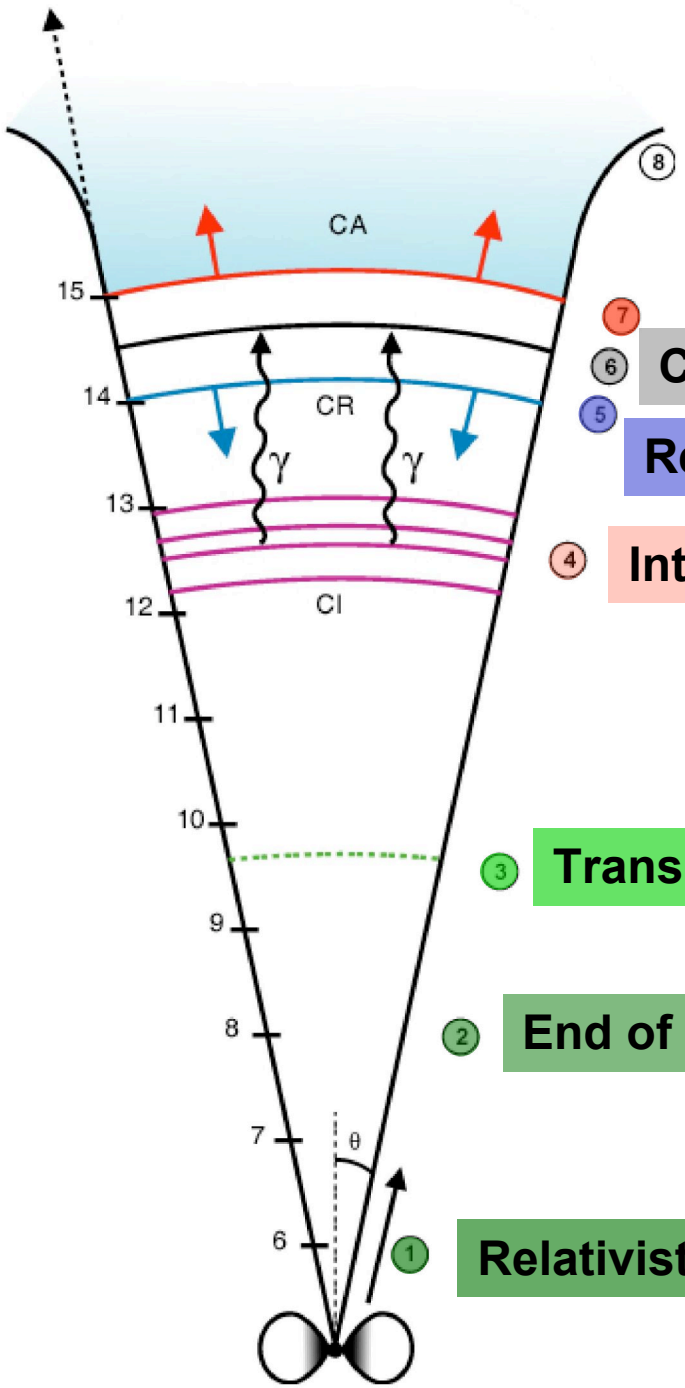
Internal shocks

Transparency

End of acceleration

Relativistic ejection

Scenario



⑦ **Forward shock :**

Deceleration of the relativistic ejecta.
Emission = afterglow.

⑦ ⑥ **Contact discontinuity**

⑤ **Reverse shock**

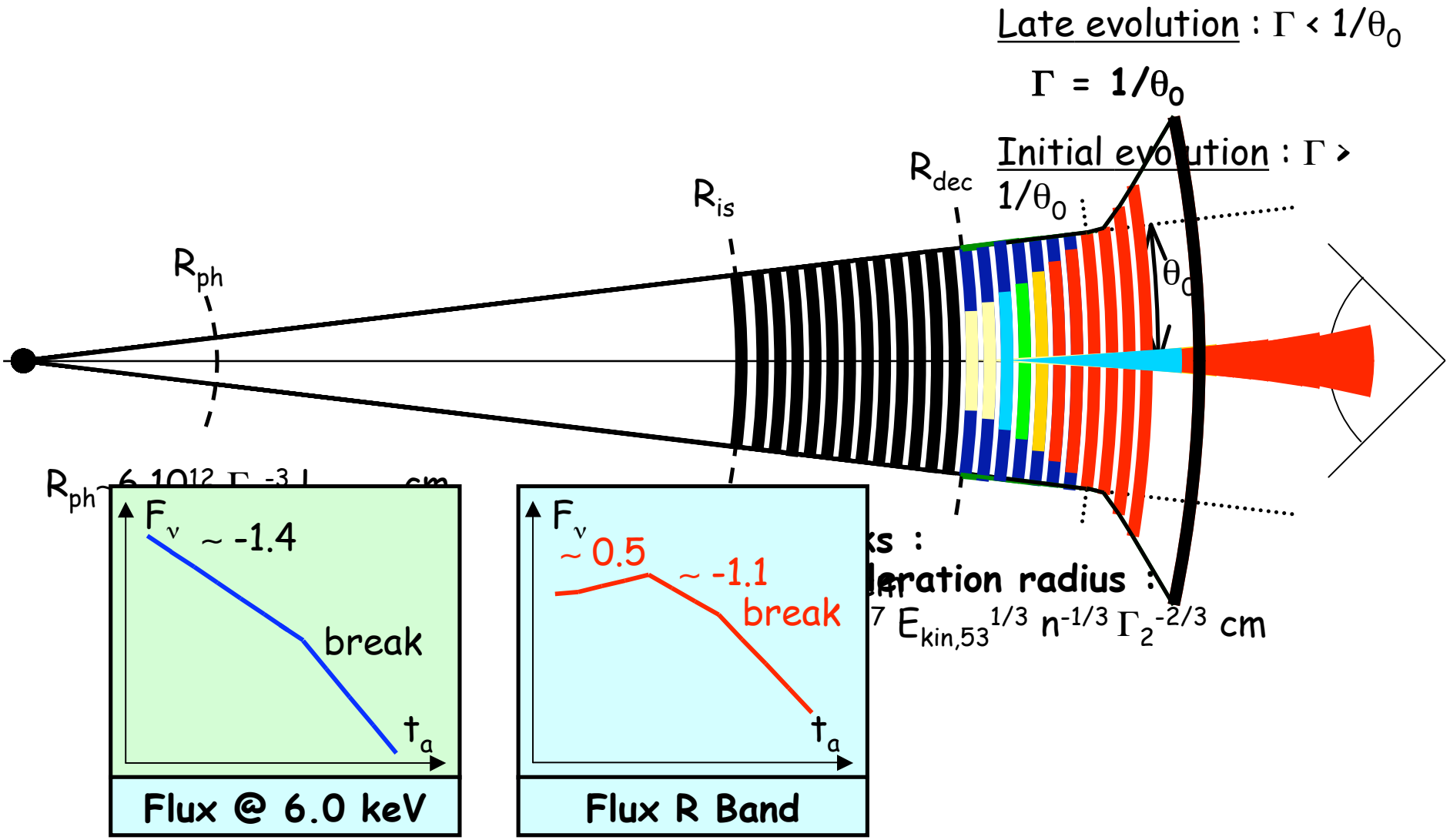
④ **Internal shocks**

③ **Transparency**

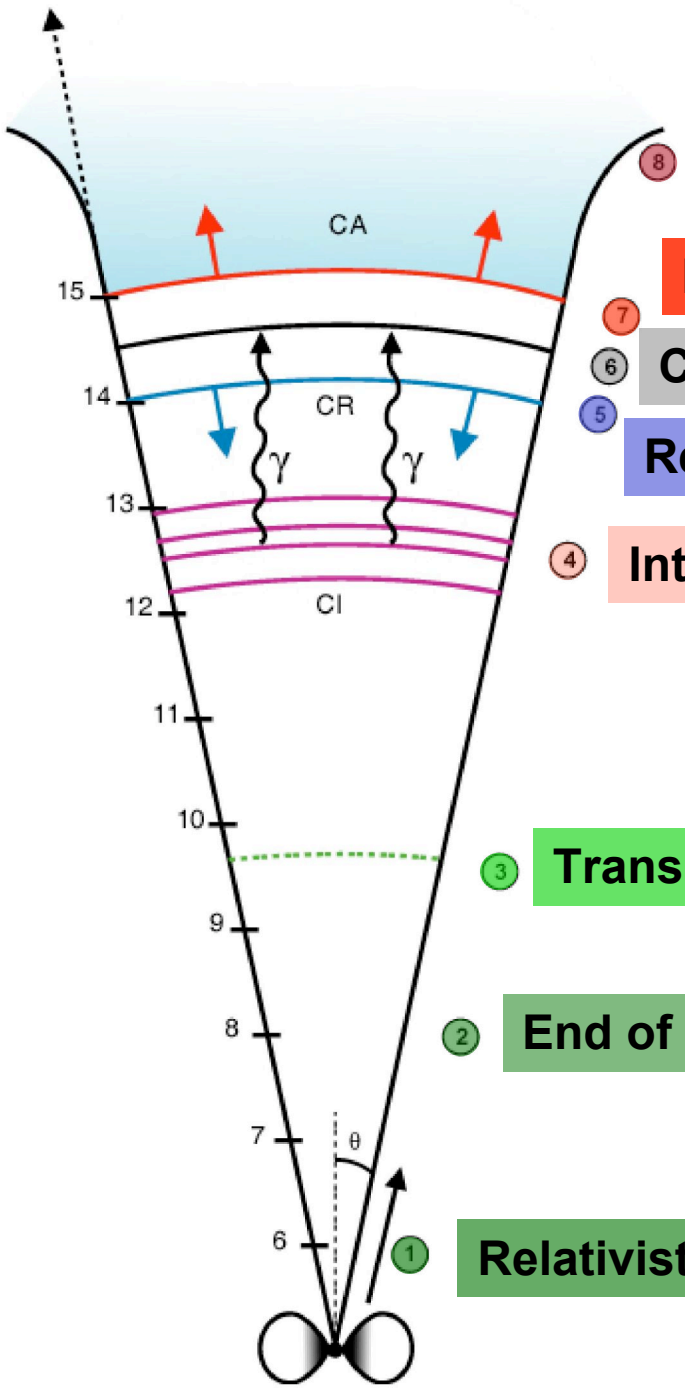
② **End of acceleration**

① **Relativistic ejection**

External shock



Scenario



⑧ **Lateral expansion :**
Starts when the Lorentz factor has decreased.

⑦ **Forward shock**

⑥ **Contact discontinuity**

⑤ **Reverse shock**

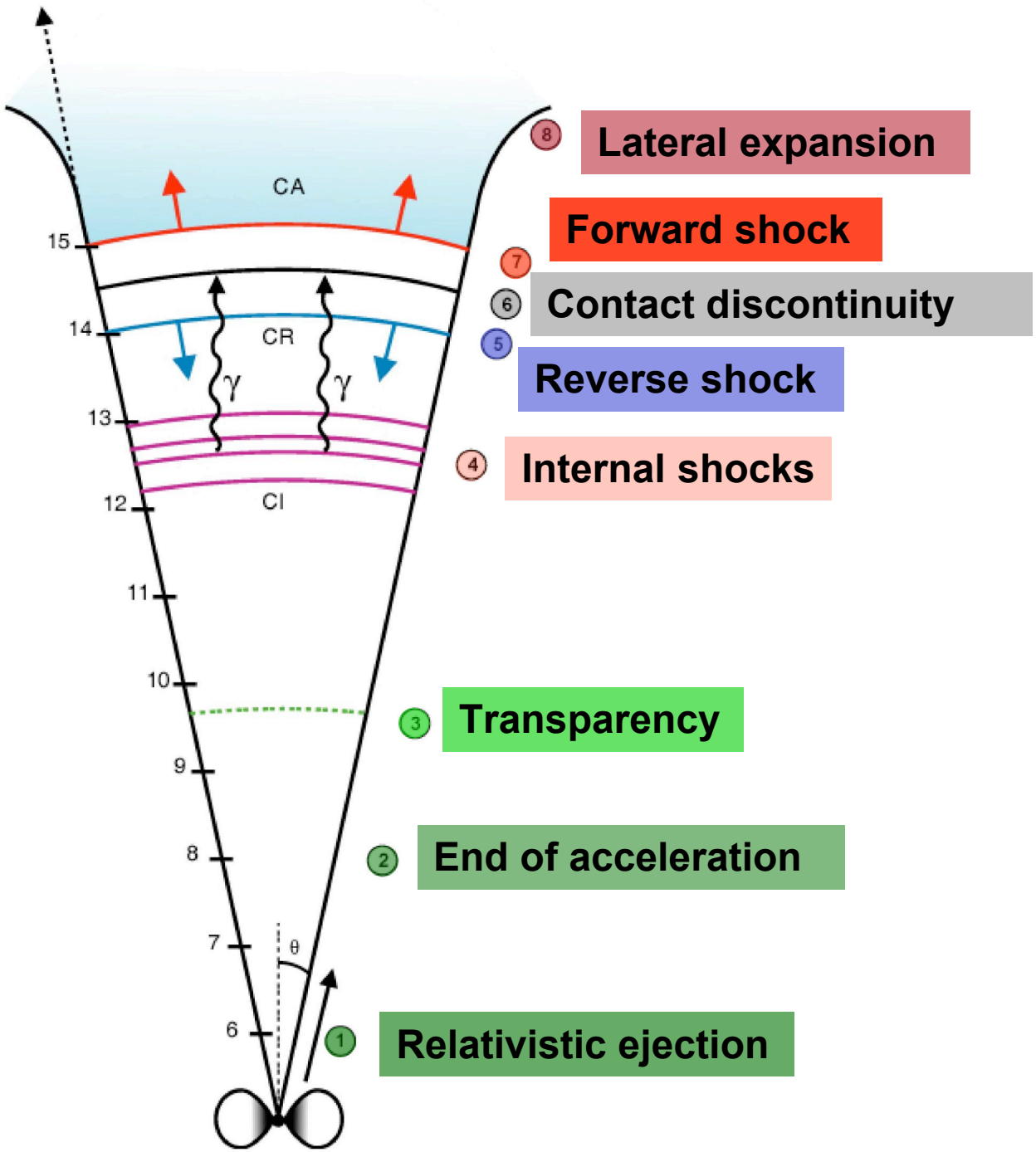
④ **Internal shocks**

③ **Transparency**

② **End of acceleration**

① **Relativistic ejection**

Scenario


CA
CR
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9
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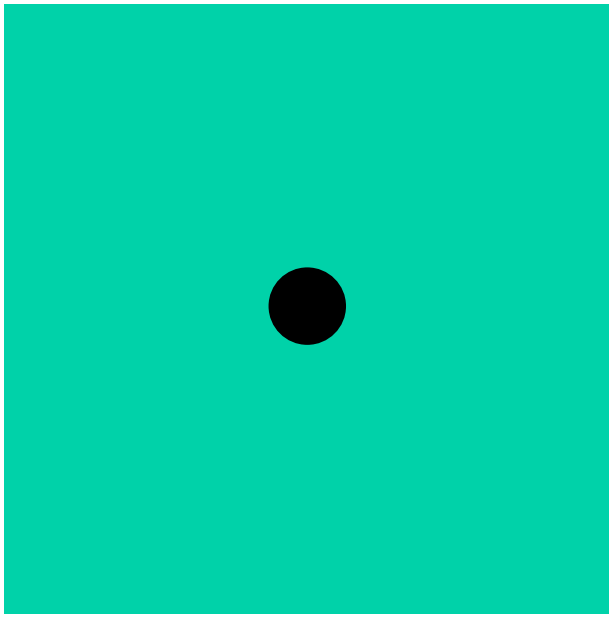
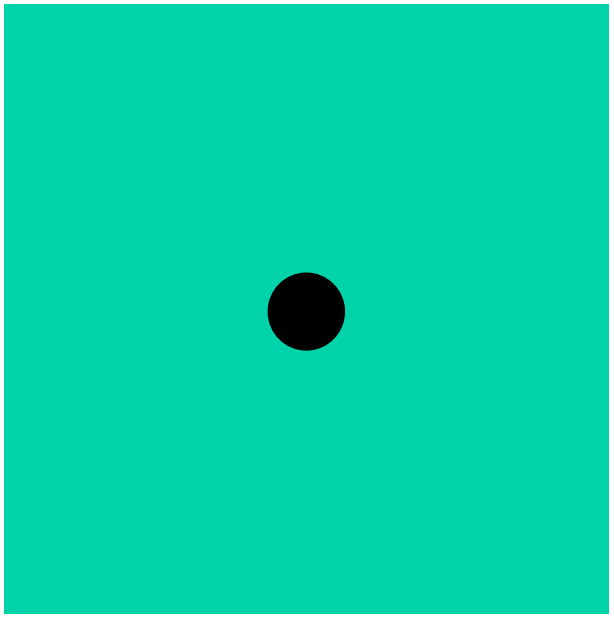
7
6
8 Lateral expansion
Forward shock
7
6 Contact discontinuity
5
Reverse shock
4 Internal shocks
3 Transparency
2 End of acceleration
1 Relativistic ejection

Initial event and central engine

Stellar mass black hole formation



Collapsar…



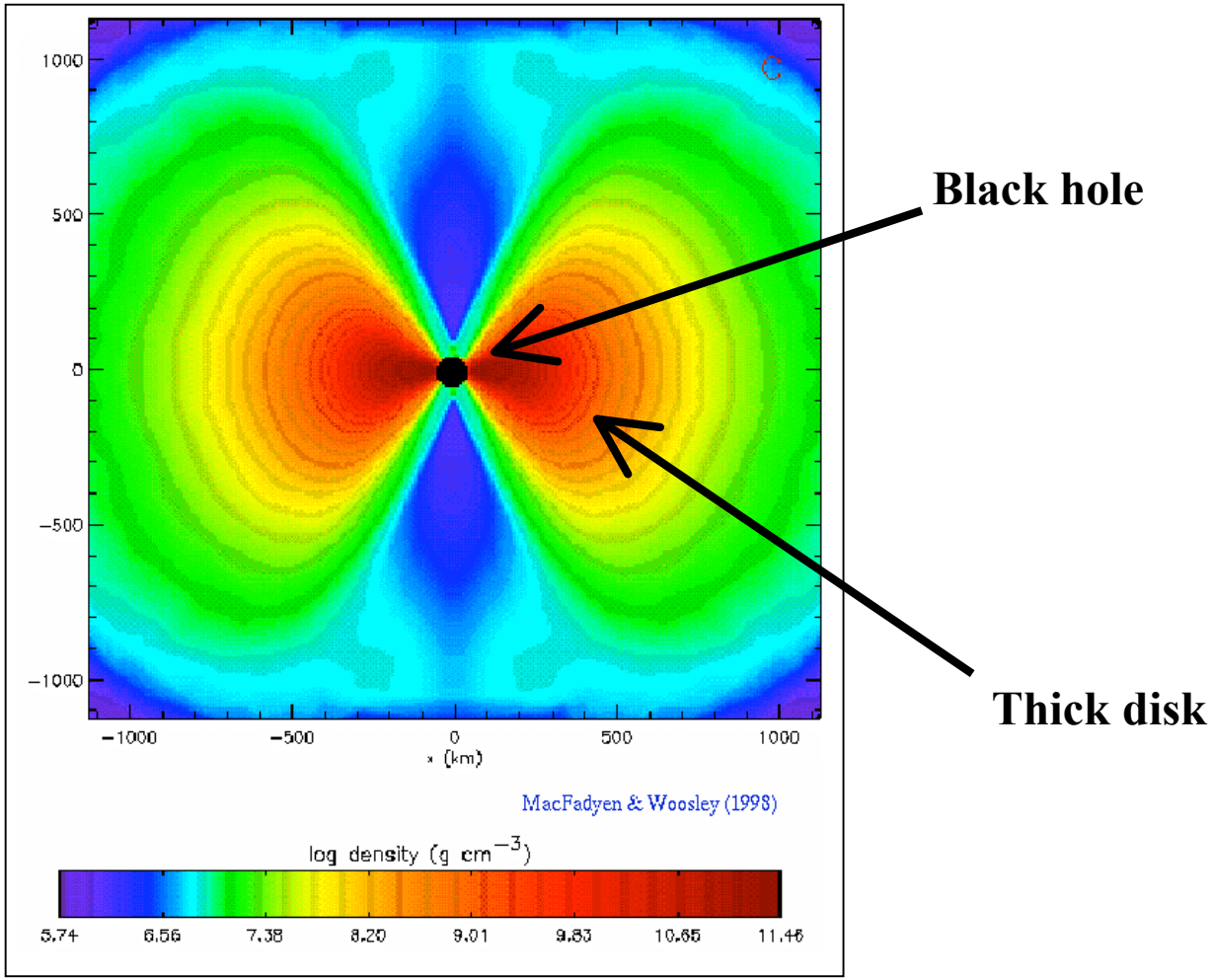
… or NS/BH+NS merger ?

Collapsars

Progenitor : 35 $M_\odot$

(helium core : 14 $M_\odot$)

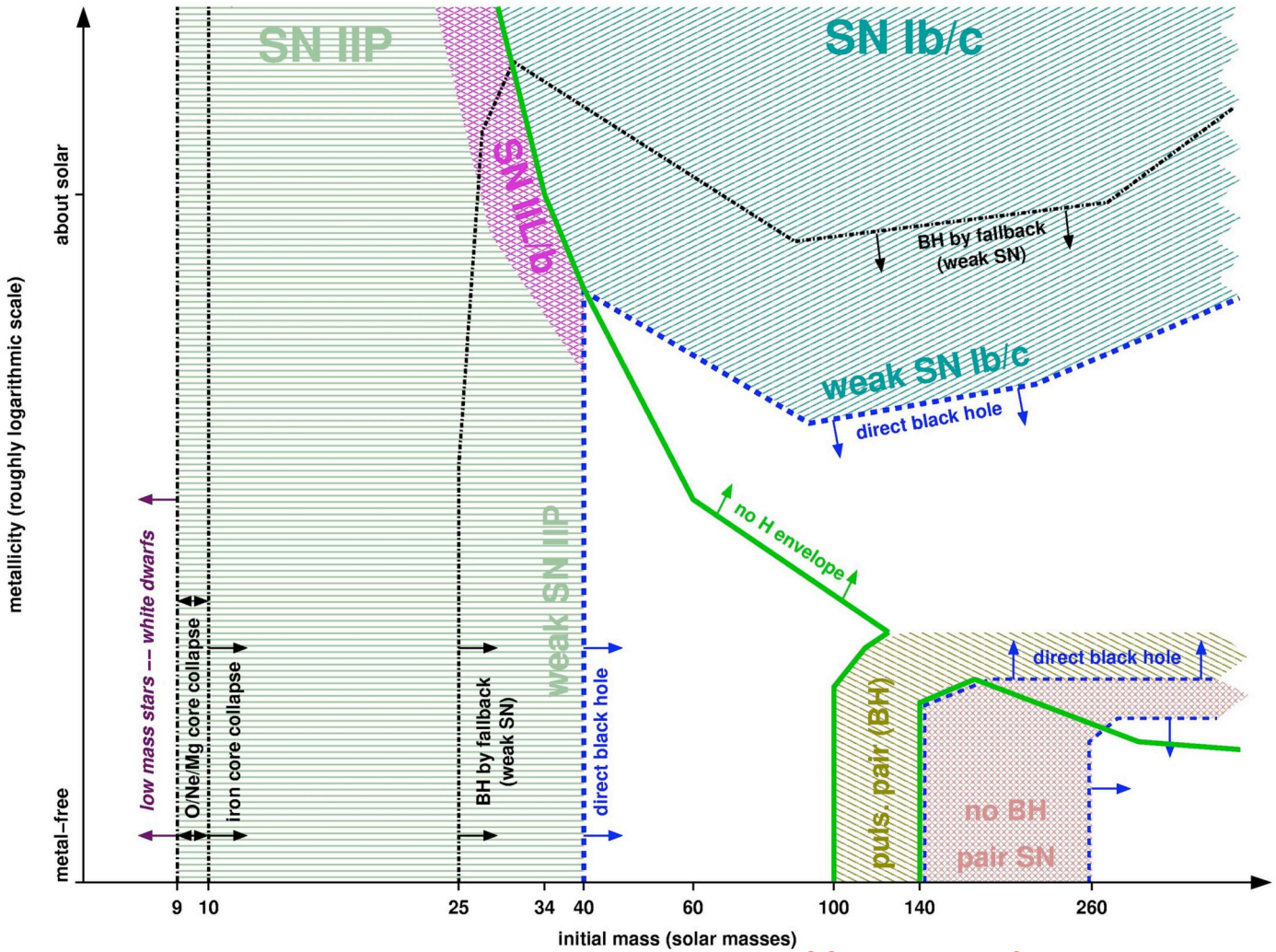
(MacFadyen & Woosley 1999)



Massive stars

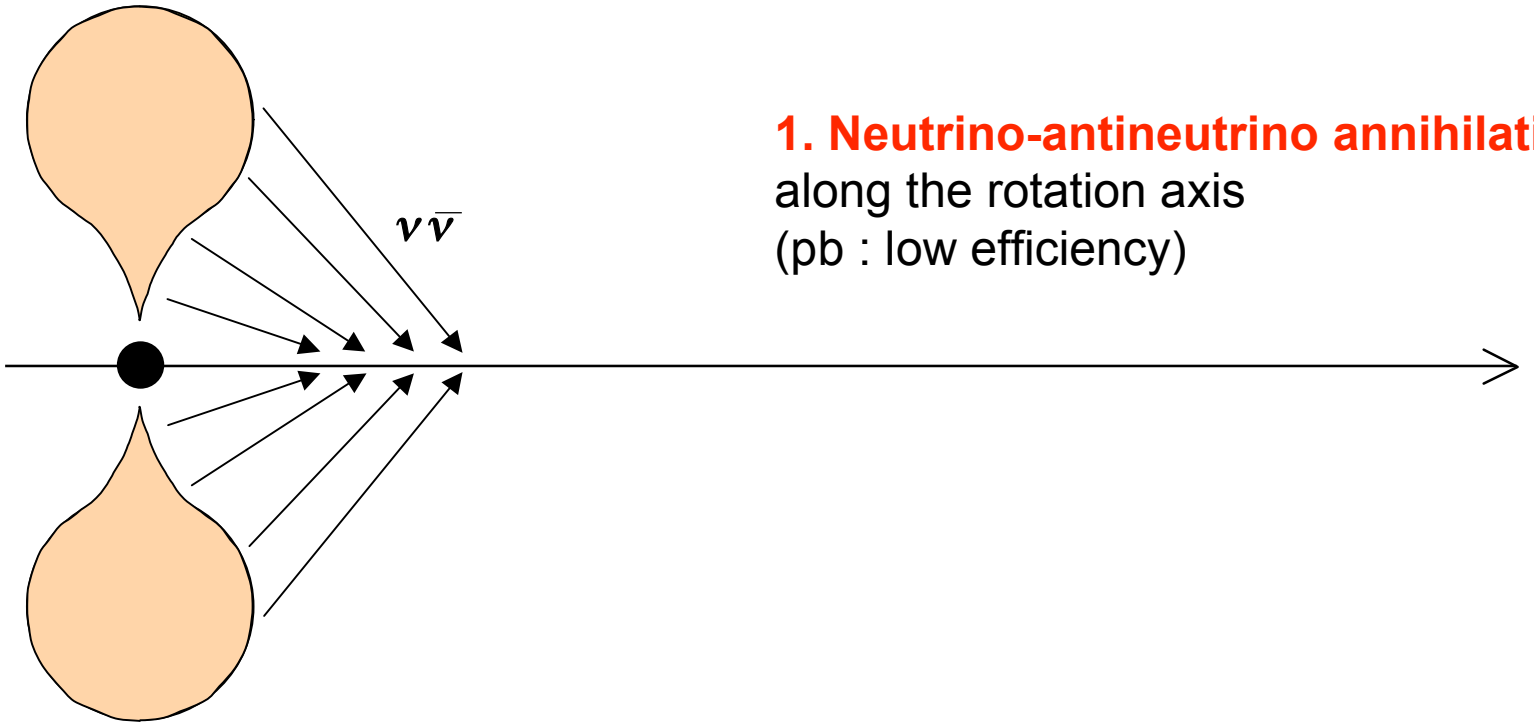
Many possibilities :

*** Two steps collapse : SN + a possible GRB**
*** Direct collapse : GRB without SN ?**
(NB: a dense wind could mimic a SN lightcurve)



Heger et al.

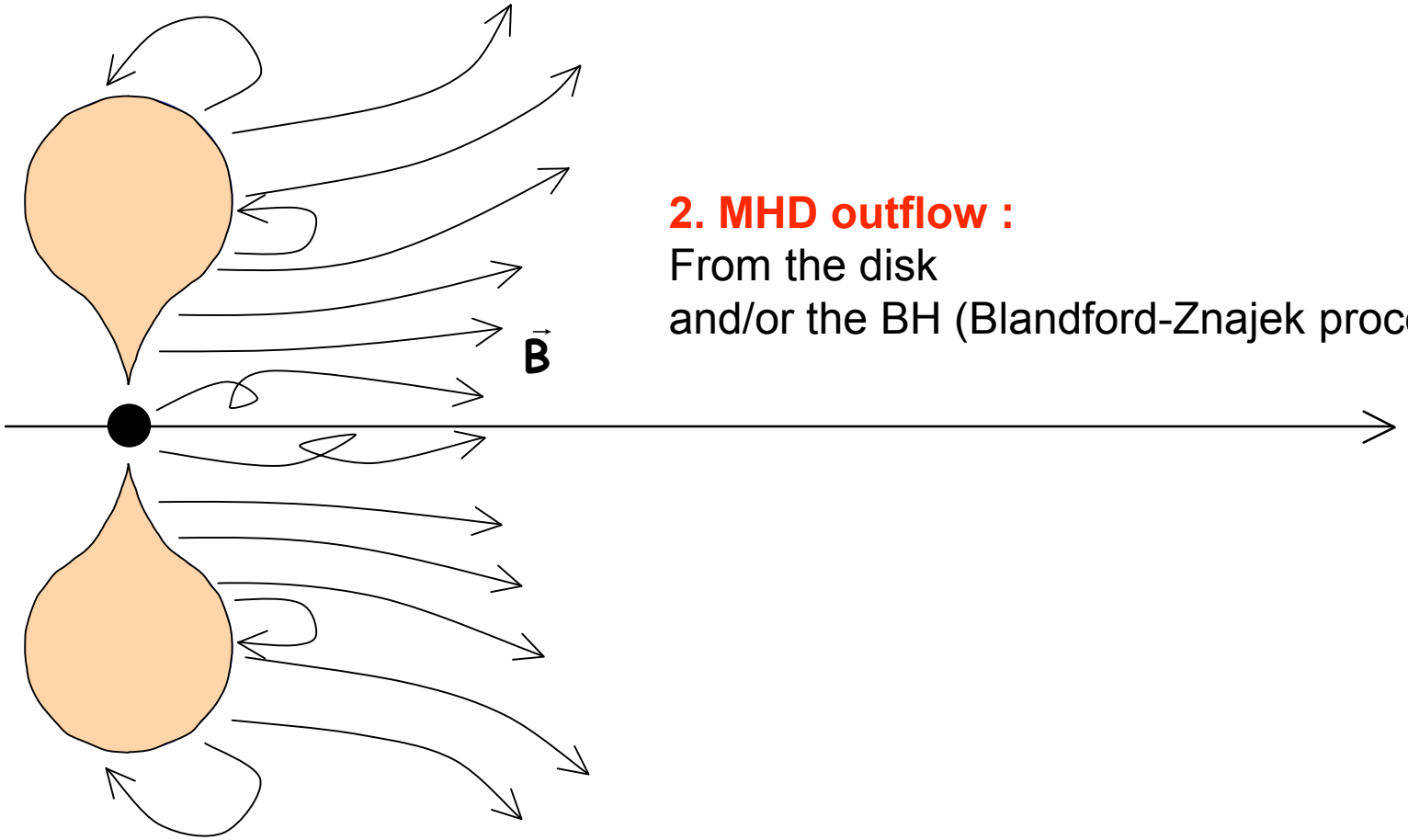
Relativistic ejection



1. Neutrino-antineutrino annihilation
along the rotation axis
(pb : low efficiency)

Baryonic pollution : must be small.

Relativistic ejection

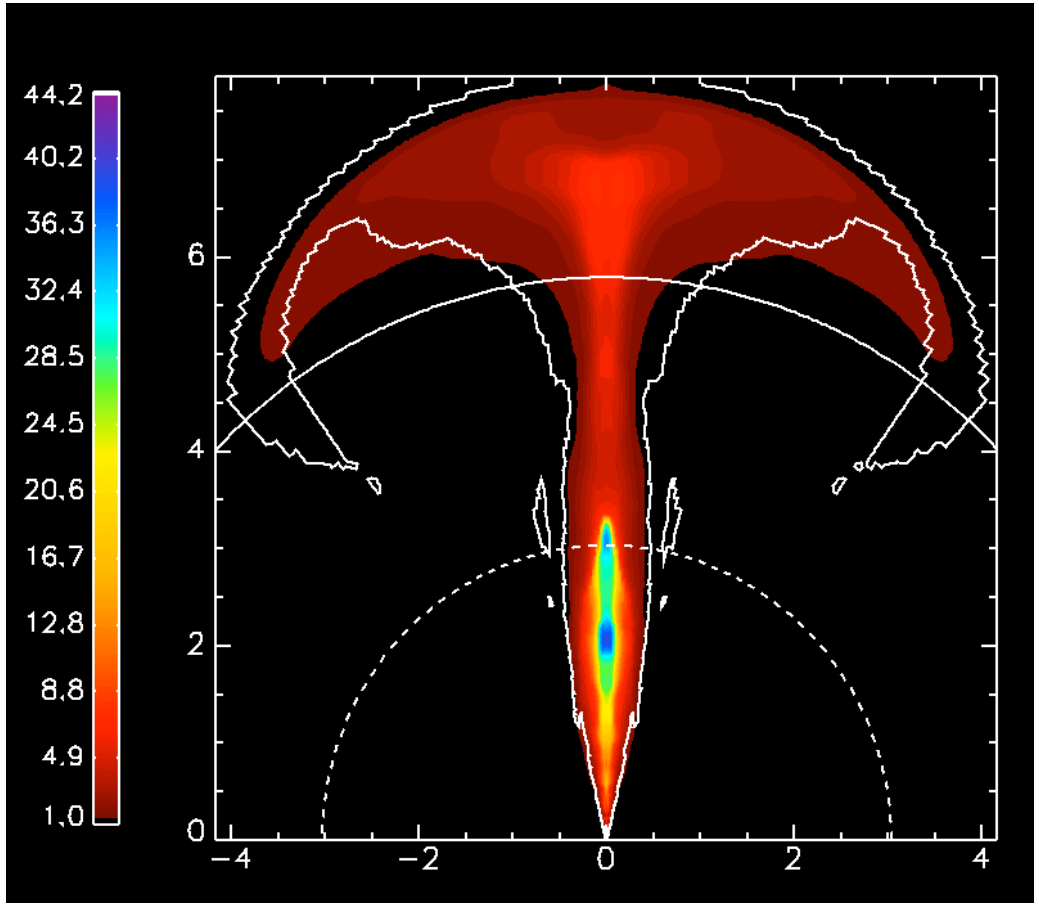


2. MHD outflow :
From the disk
and/or the BH (Blandford-Znajek process)

Baryonic pollution : must be small.

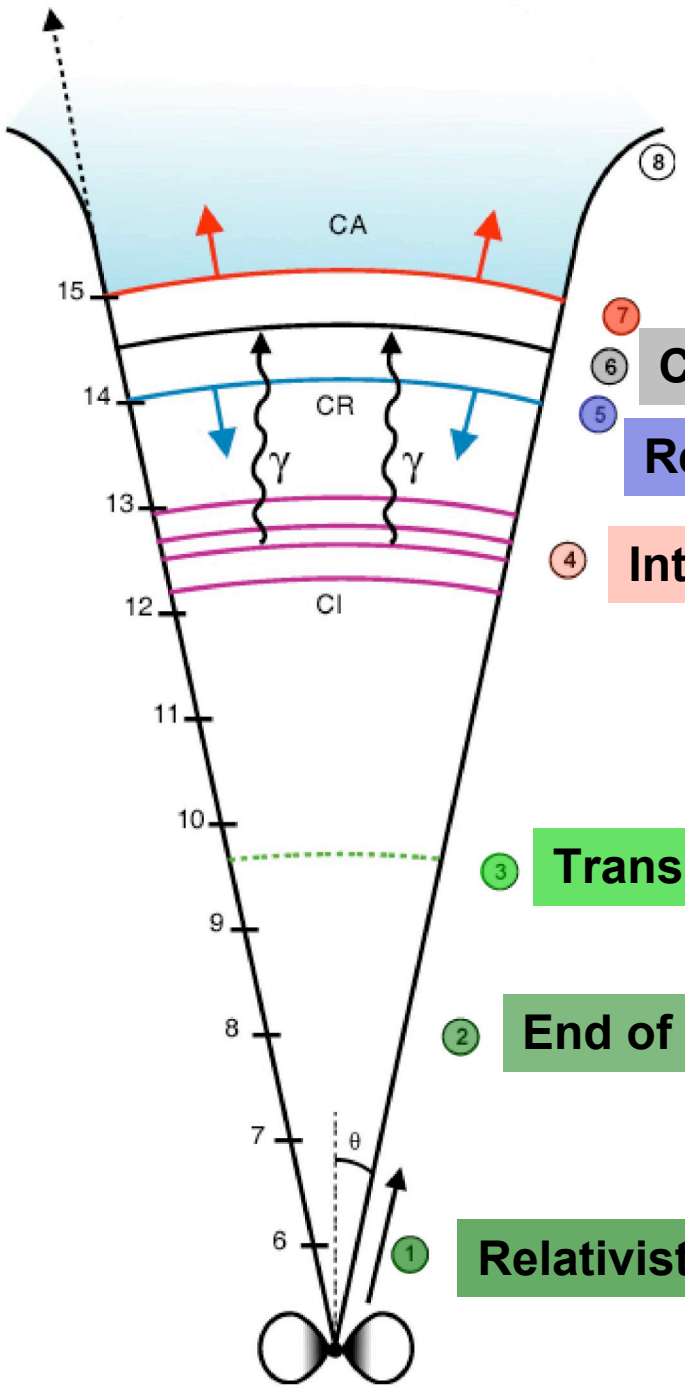
Relativistic ejection

- Poorly understood process
- Two energy reservoirs : binding energy of the disk (accretion)
  + rotation energy of the black hole (BZ)
- Magnetic field ?
- How to escape the collapsing star ?
- Baryonic pollution ?



Physical conditions to reach an ultra-relativistic (Γ>100) and ultra-energetic (>10^{50} erg) outflow ?

Scenario



⑦ **Forward shock :**

Deceleration of the relativistic ejecta.
Emission = afterglow.

⑦ ⑥ **Contact discontinuity**

⑤ **Reverse shock**

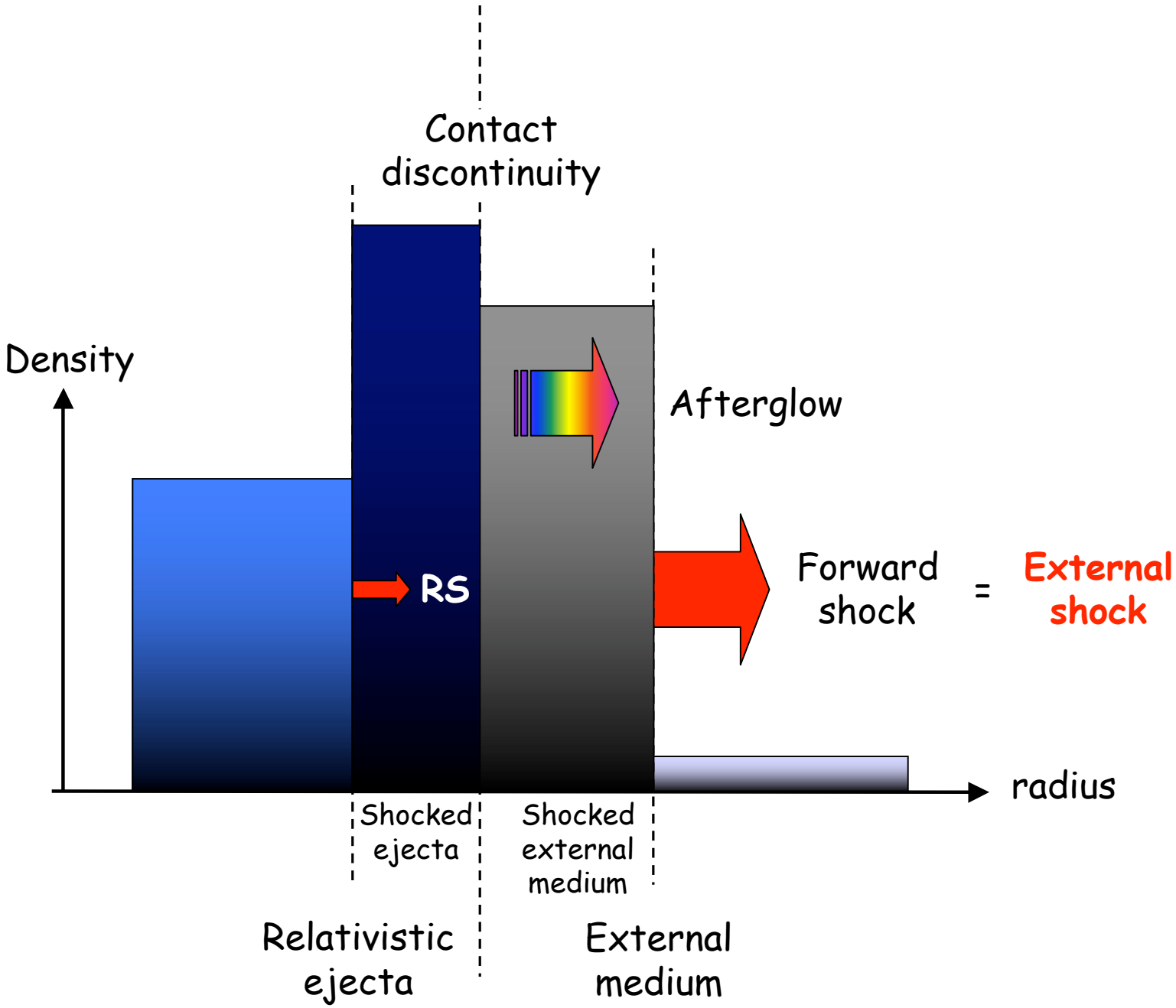
④ **Internal shocks**

③ **Transparency**

② **End of acceleration**

① **Relativistic ejection**

External shock



External shock

Dynamics

The swept-up mass M_{ext} depends
on the density profile in the external medium :

$$\rho = A / r^s$$

$$M_{ext} = 4\pi/(3-s)\ A\ r^{3-s}$$

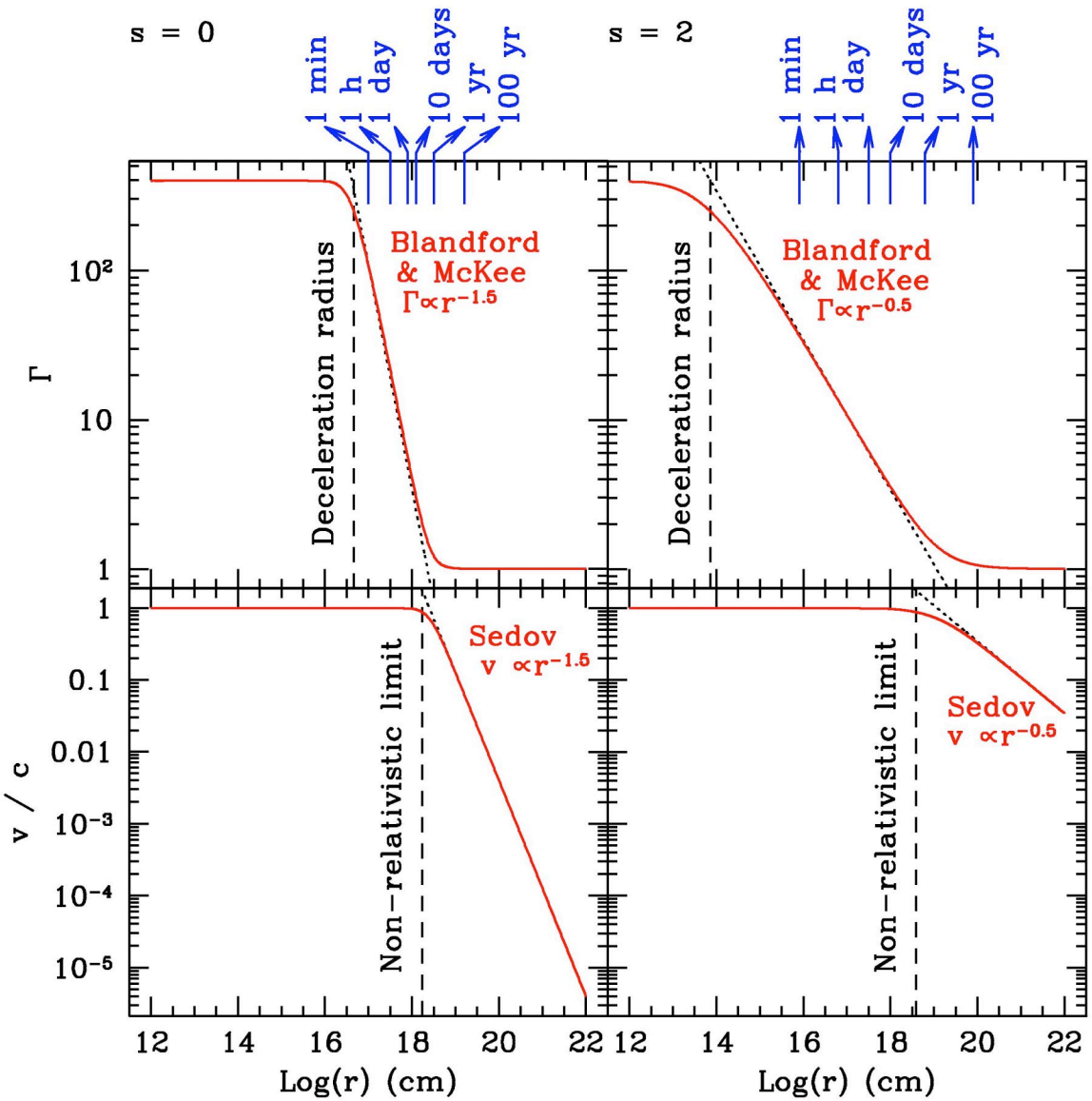
Deceleration radius : $M_{ext} = M_0/\Gamma_0 = E_0 / \Gamma_0^2\ c^2$

$$R_{dec} = [\ (3-s)/4\pi\ \ E_0 / A\ \Gamma_0^2\ c^2\ ]^{1/(3-s)}$$

$R_{dec} = 1.2\ 10^{17}\ E_{53}^{1/3}\ n_0^{-1/3}\ \Gamma_2^{-2/3}$ cm for $s = 0$ and $A = n\ m_p$

$R_{dec} = 1.8\ 10^{15}\ E_{53}\ A_*^{-1}\ \Gamma_2^{-2}$ cm for $s = 2$ and $A = 7.6\ 10^{11}\ A_*$ g/cm (WR)

External shock



Relativistic ejecta :

$\Gamma_0 = 400$

$E_0 = 10^{53}$ 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): $A_* = 1$

External shock

Radiation

(1) Physical conditions in the shocked medium:
given by BM solution.

$$\varepsilon_* = \Gamma c^2$$
$$\rho_* = 4 \Gamma \rho_{ext}$$

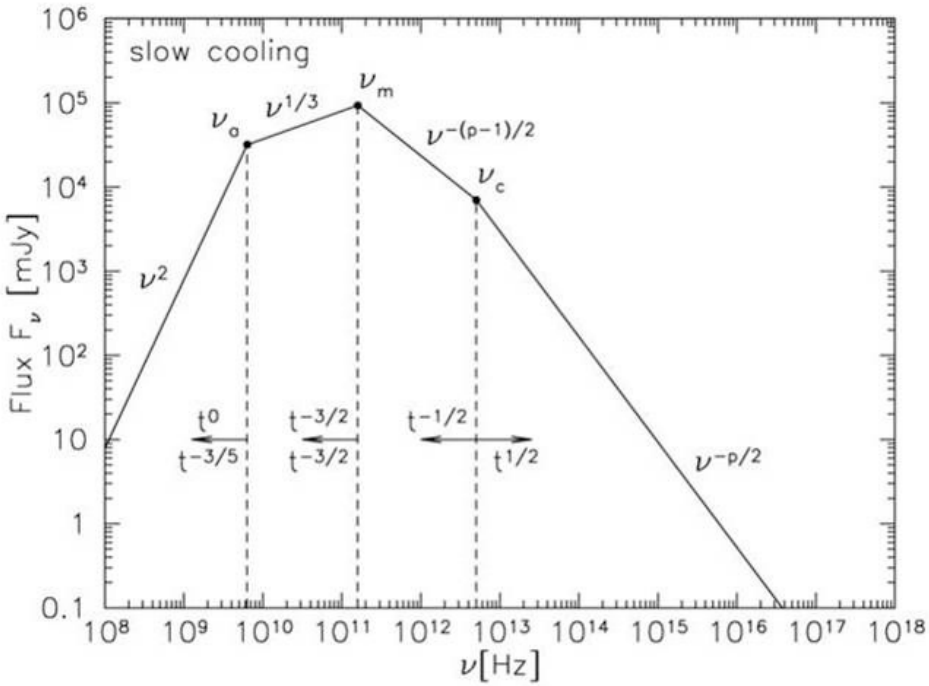
(2) Magnetic field–Relativistic electrons: "equipartition"

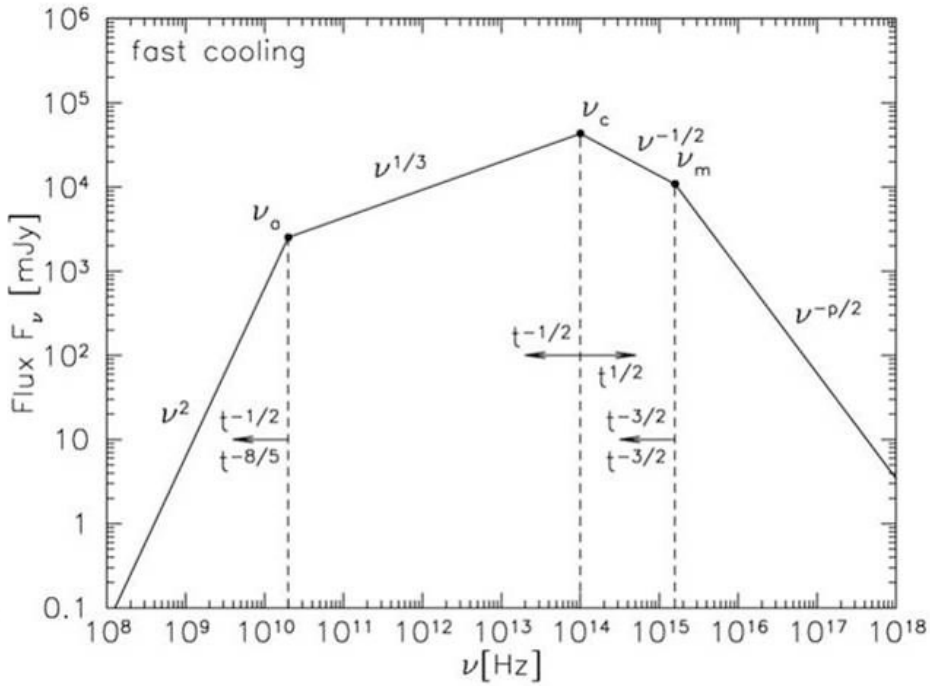
$$B^2 / 8\pi = \alpha_B \rho_* \varepsilon_* \quad \Rightarrow \quad B = (32 \pi \alpha_B \rho_{ext})^{0.5} \Gamma c$$

$$(\rho_*/m_p)\Gamma_e m_e c^2 = \alpha_e \rho_* \varepsilon_* \quad \Rightarrow \quad \Gamma_e = (m_p / m_e) \varepsilon_*/c^2$$

(3) Synchrotron spectrum : fast or slow cooling (Sari et al. 1998)

External shock





$t'_{ex} = R / \Gamma c$

$t'_{syn} = 6\pi\, m_e\, c / \sigma_T / B^2 / \Gamma_e$

$= t'_{ex} (\Gamma_e / \Gamma_c)^{-1}$

$\Gamma_e > \Gamma_c$: efficient radiative cooling

For $\Gamma_{min} > \Gamma_c$: « fast cooling »
all electrons lose radiatively their energy in t'_{ex}.

For $\Gamma_{min} < \Gamma_c$: « slow cooling »
most electrons do not radiate efficiently.

External shock

Other effects

(1) Opening angle of the "jet" :

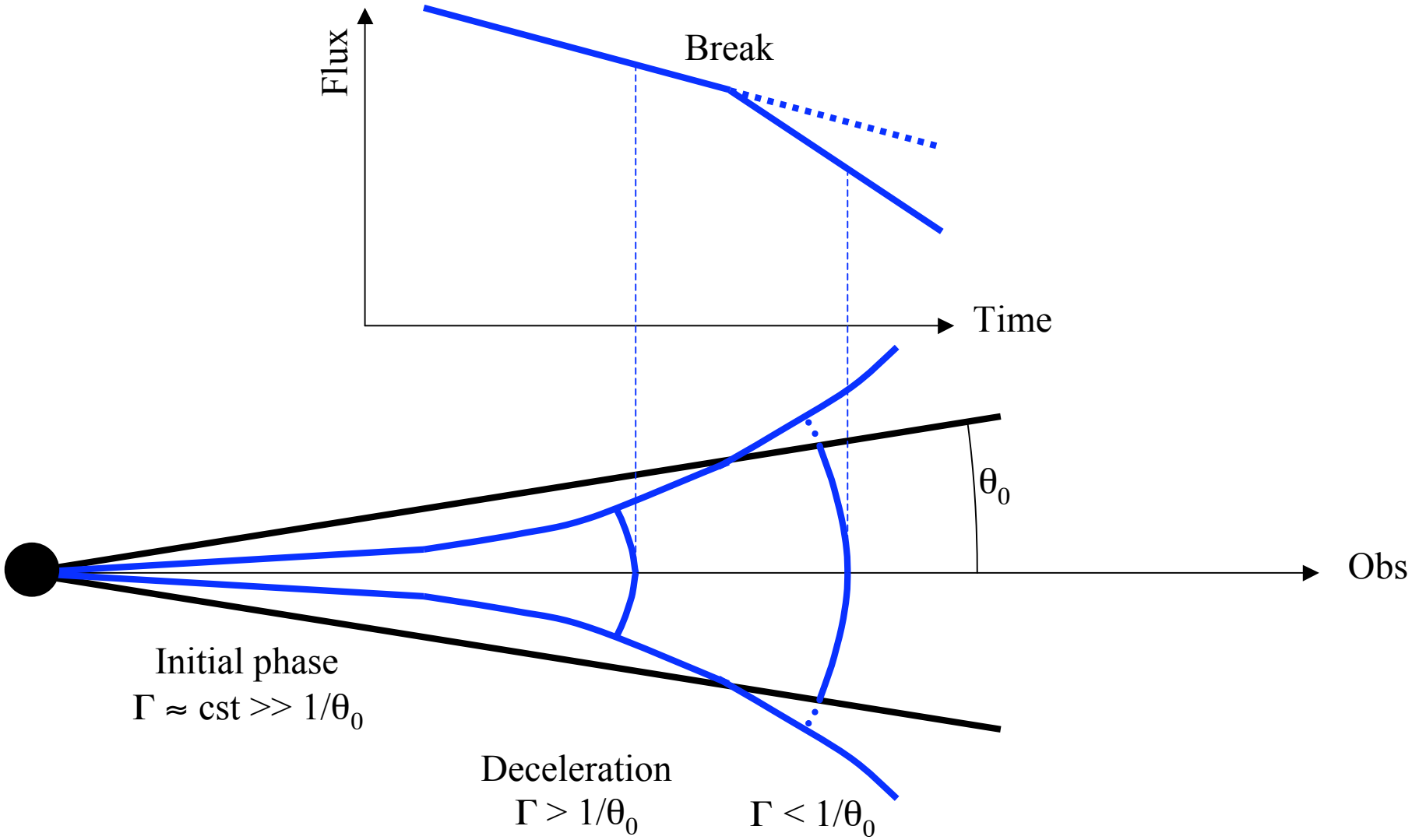
Break in the afterglow lightcurve :

$$< (\Omega/4\pi)^{-1} > \approx 500 \text{ (Frail et al. 2002)}$$

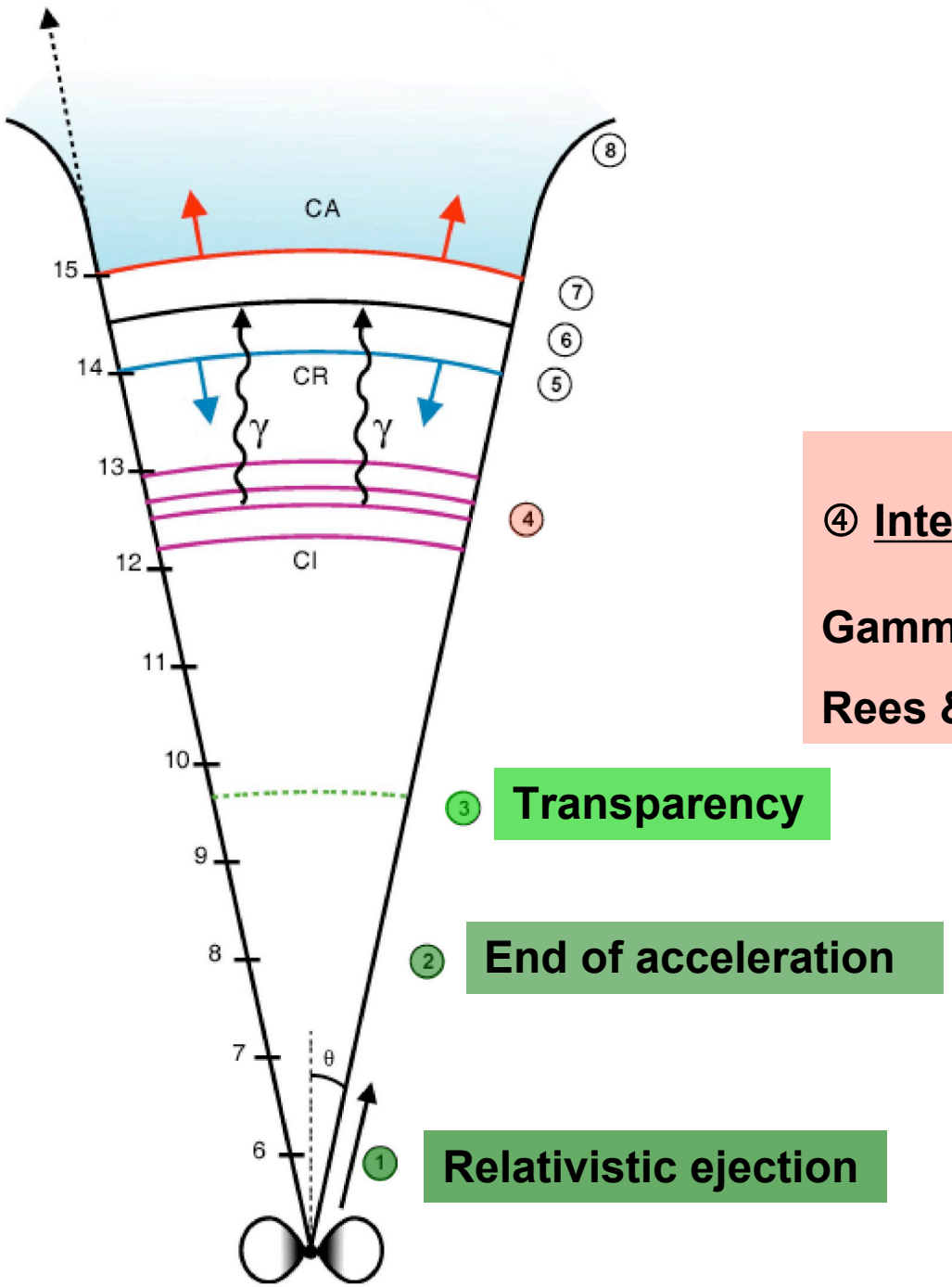
(2) Modification of the dynamics due to radiative losses

(3) More realistic radiative processes : Compton inverse, etc…

Opening angle ?



Scenario

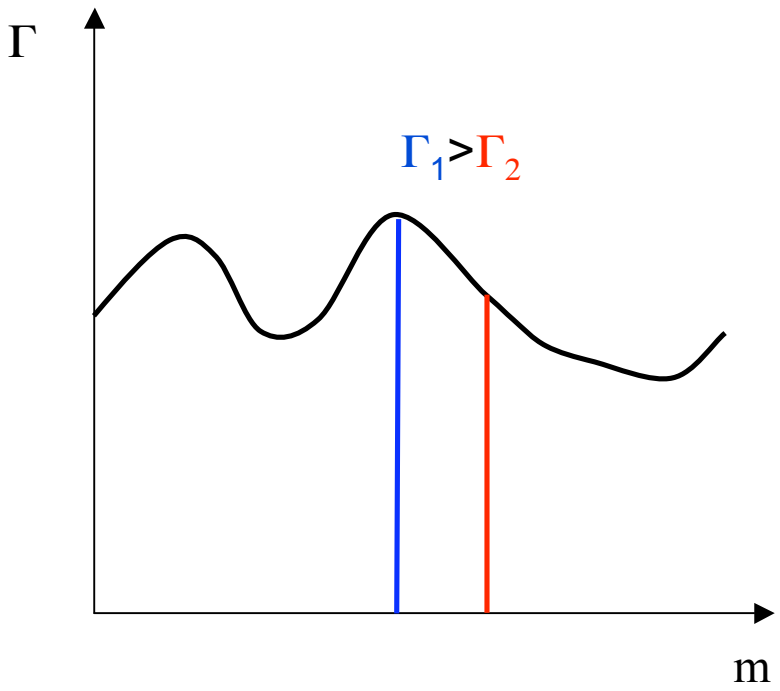


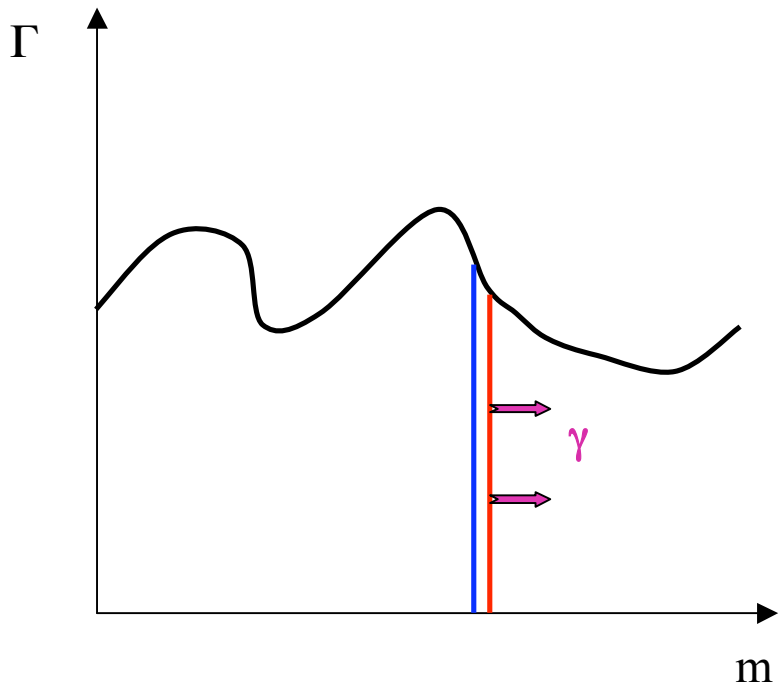
④ **Internal shocks :**

Gamma-ray emission = GRB.

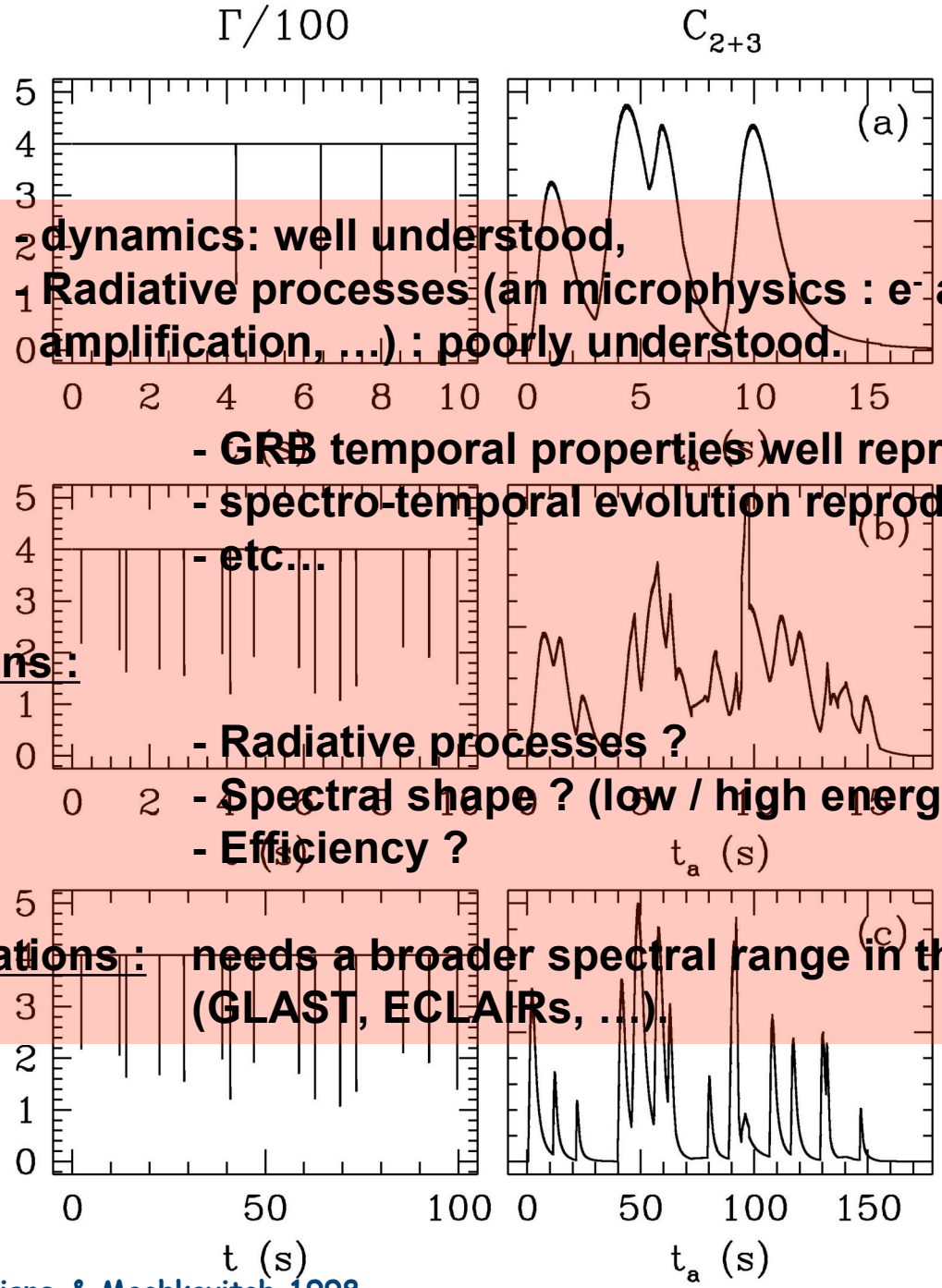
Rees & Meszaros 1993

Internal shocks





Internal shocks



Status : - dynamics: well understood,
- Radiative processes (an microphysics : e^- acceleration, B amplification, …) : poorly understood.

Model :
- GRB temporal properties well reproduced,
- spectro-temporal evolution reproduced,
- etc…

Questions :
- Radiative processes ?
- Spectral shape ? (low / high energy ?)
- Efficiency ?

Observations : needs a broader spectral range in the prompt phase (GLAST, ECLAIRs, …).

Daigne & Mochkovitch 1998

Internal shocks

Internal shocks :

the prompt emission is dominated by the radiation of shock-accelerated electrons.

Initial kinetic energy flux

Luminosity : $$L_{rad,4\pi} \approx \alpha_e \times f_d \times L_{kin}$$

Internal shock efficiency

Fraction of the dissipated energy which is injected in the non-thermal population of electrons

Internal shocks

Internal shocks :
the prompt emission is dominated by the radiation of shock-accelerated electrons.

Luminosity : $$L_{rad,4\pi} \approx \alpha_e \times f_d \times L_{kin}$$

Peak energy (source frame) : $$E_p \approx 2\Gamma \times E_p^{com} \approx K \frac{L_{kin}^{x}\ \Phi_{xy}(\kappa)}{\Gamma^{6x-1}\ \tau^{2x}}$$

Standard synchrotron process : x=0.5, y=2.5

Initial kinetic energy flux

Typical ratio $\Gamma_{max} / \Gamma_{min}$ in internal shocks

Mean Lorentz factor in the flow

Typical timescale ~ observed GRB duration

Internal shocks

$$E_p \approx K \frac{L_{kin}^{x} \, \Phi_{xy}(\kappa)}{\Gamma^{6x-1} \, \tau^{2x}}$$

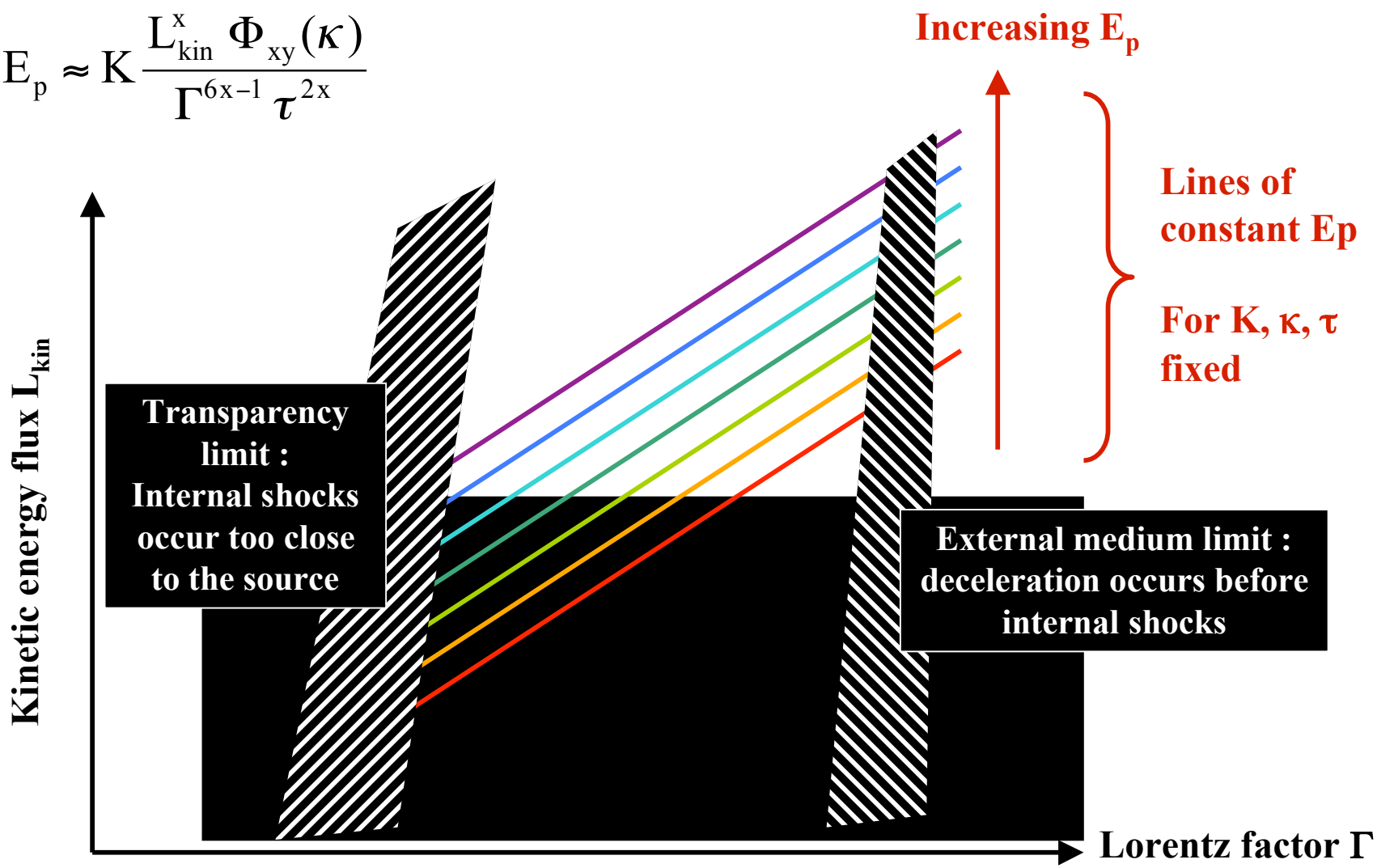
Amati relation is possible if there is a low dispersion of K, κ, Γ, τ…

If there is no intrinsic correlation between some of the parameters, the internal shock model predicts a lot of scatter.

However, « unusual » events (980425, 021203, …) seem to indicate that there is indeed some diversity in the GRB population…

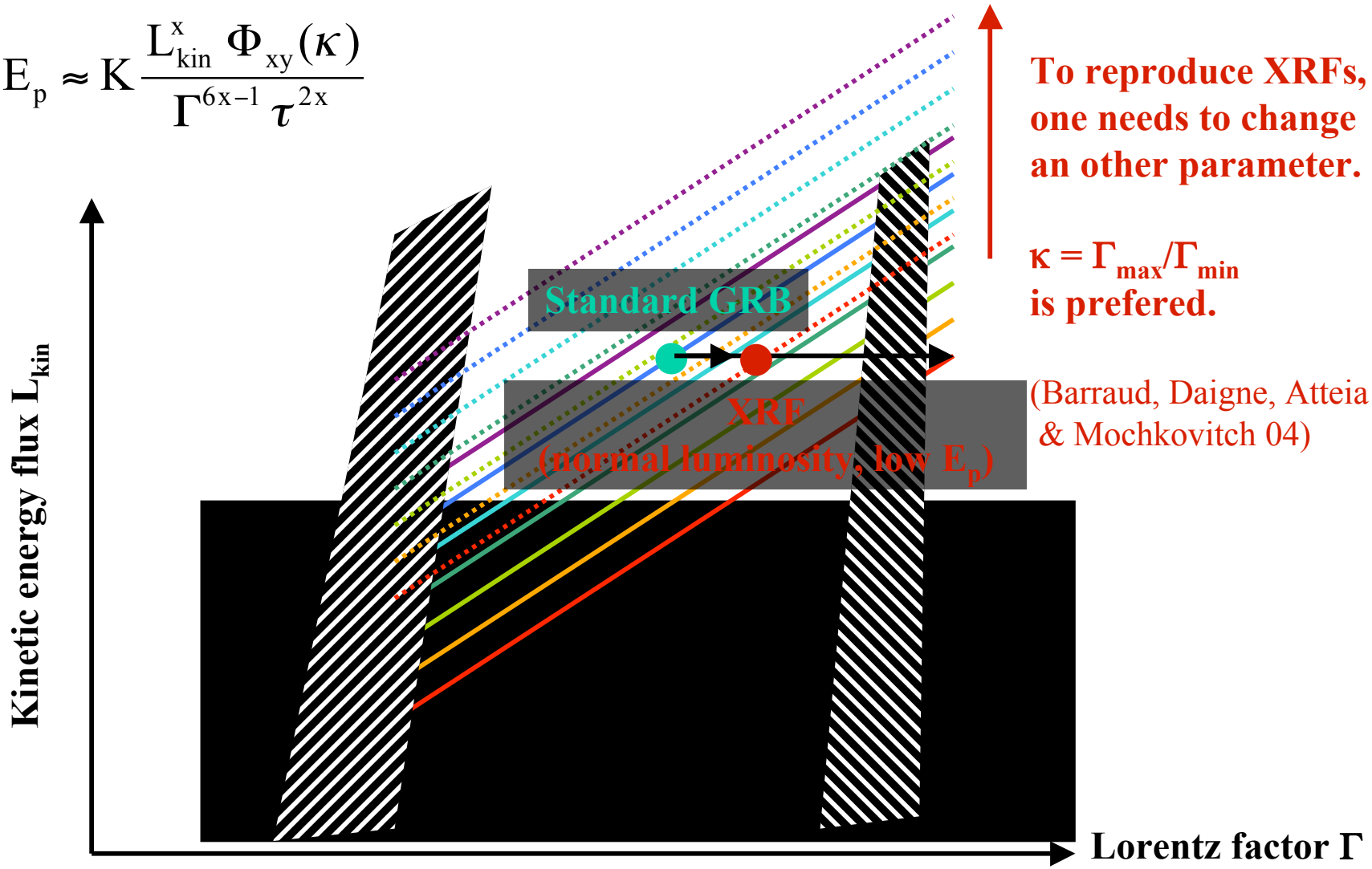
Internal shocks

$$E_p \approx K \frac{L_{kin}^{x}\, \Phi_{xy}(\kappa)}{\Gamma^{6x-1}\, \tau^{2x}}$$



Internal shocks

$$E_p \approx K \frac{L_{kin}^{x}\, \Phi_{xy}(\kappa)}{\Gamma^{6x-1}\, \tau^{2x}}$$



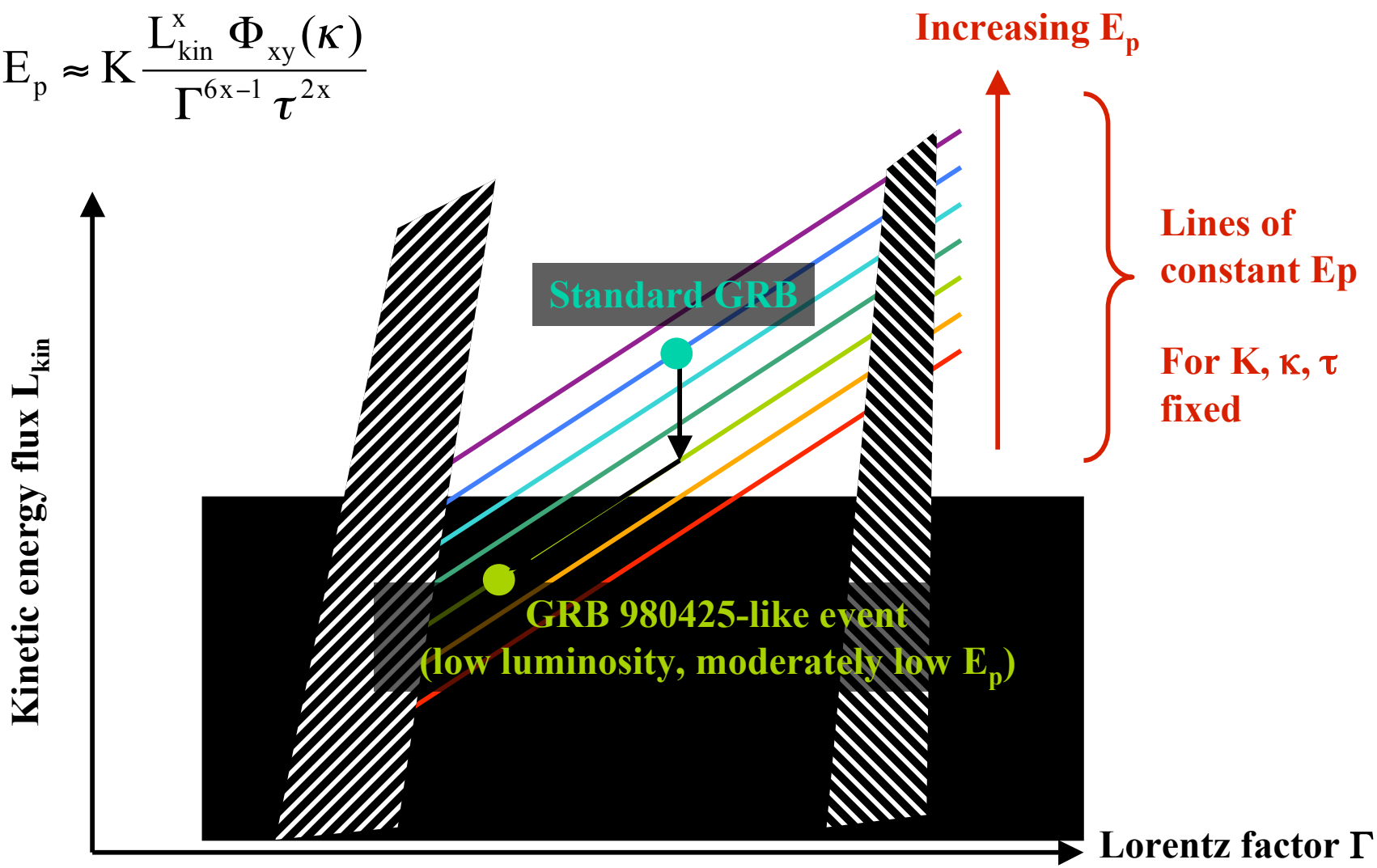
To reproduce XRFs, one needs to change an other parameter.

$\kappa = \Gamma_{max}/\Gamma_{min}$ is prefered.

(Barraud, Daigne, Atteia & Mochkovitch 04)

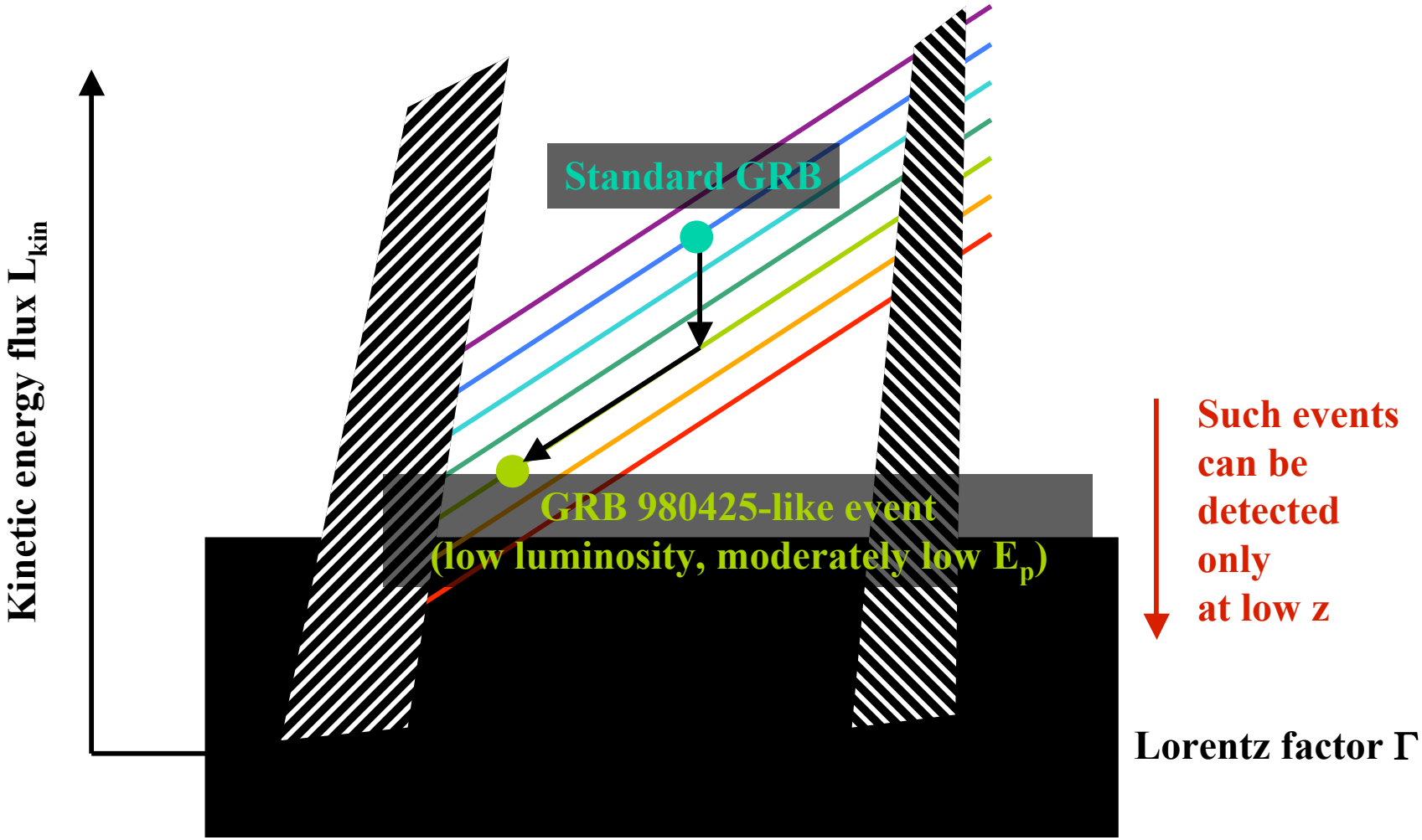
Internal shocks

$$E_p \approx K \frac{L_{kin}^{x}\, \Phi_{xy}(\kappa)}{\Gamma^{6x-1}\, \tau^{2x}}$$

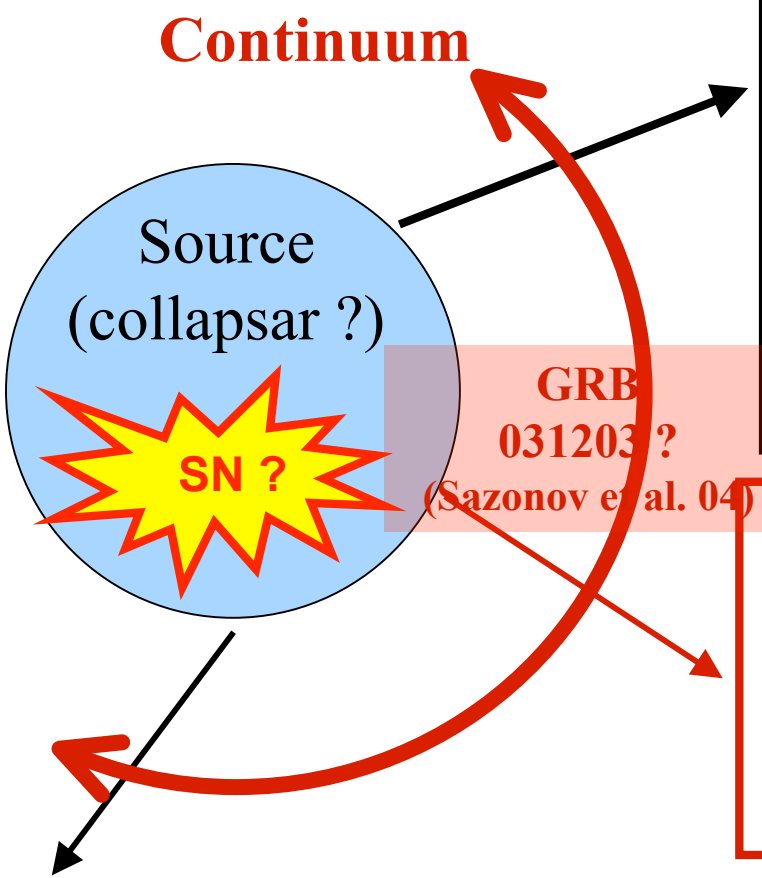


Internal shocks

$$E_p \approx K \frac{L_{kin}^{x}\, \Phi_{xy}(\kappa)}{\Gamma^{6x-1}\, \tau^{2x}}$$



Internal shocks



Small fraction of events can produce a highly energetic / highly relativistic outflow :

*** standard GRBs**

*** X-ray rich GRBs / XRFs (lower baryonic pollution / smoother ejection)**

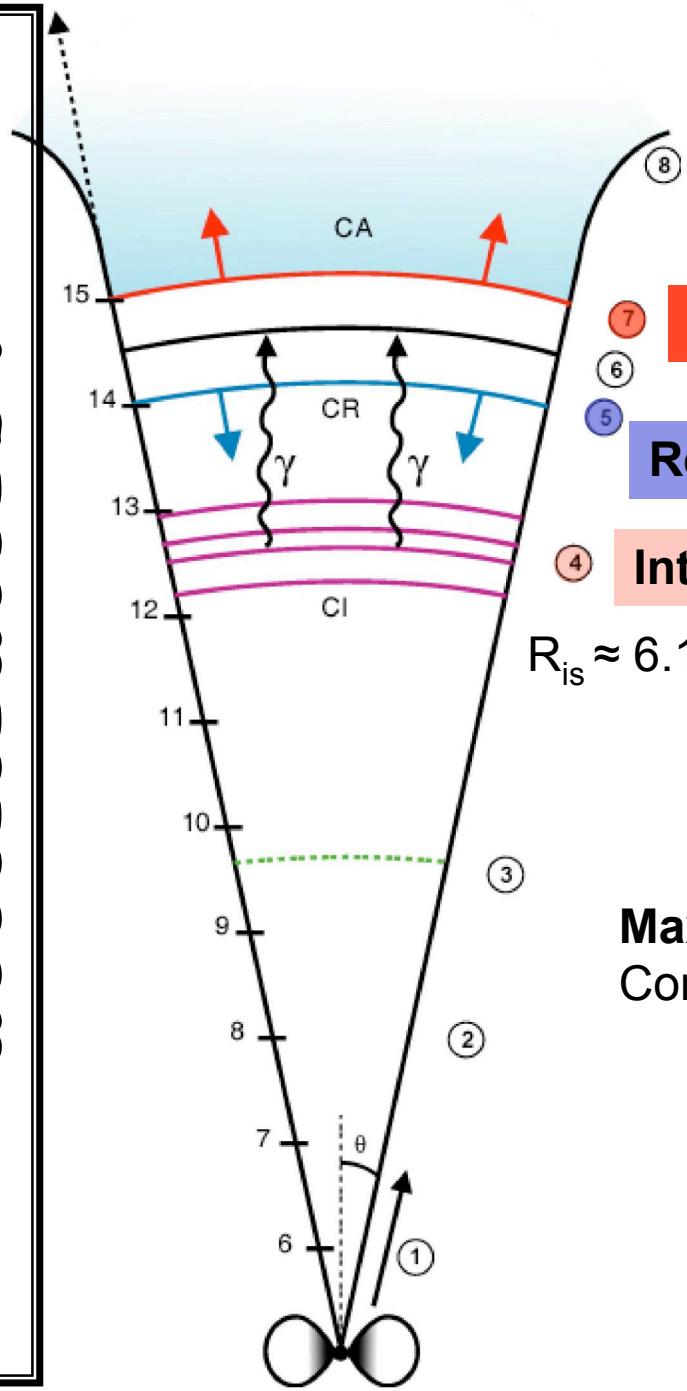
These events can be detected at large z. They have normal afterglows.

A larger but still small fraction of events lead to a midly energetic / less relativistic outflow :

*** GRB 980425-like events**
These events can be detected only locally.
They have weak afterglows. (see Soderberg et al. 04)

Most events do not produce a relativistic outflow.

GRBs as particle accelerators ?



$R_{dec} \approx 1.10^{17}\ \Gamma_2^{-2/3}\ E_{53}^{1/3}\ n^{-1/3}$ cm

Forward shock

Reverse shock

Internal shocks

$R_{is} \approx 6.10^{14}\ \Gamma_2^{2}\ t_{var}$ cm

3 possible sites :

Maximum Lorentz factor ?

Comparison :
- acceleration timescale
- escape probability
- radiative timescale

Cf. Waxman, Lemoine & Sigl, Pelletier, etc.

GRBs as particle accelerators ?

+ External shock : difficult ofr UHECRs,

uniform : $E_{max} \approx 6 \times 10^{15}\, E_{53}^{1/3}\, n_0^{-1/3}\, \Gamma_2^{1/3}\, B_{-6}\ eV$

stellar wind : $E_{max} \approx 9 \times 10^{13}\, E_{53}\, A_*^{-1}\, \Gamma_2^{-1}\, B_{-6}\ eV$

+ Internal shocks :

$$[illegible] \approx [illegible] \times [illegible]\, \kappa_1^{-1}\, \Gamma_1^{[illegible]}\, [illegible]$$

* favored by large B

* late shocks : **reverse shock ?**

+ Protons VHE + gamma-rays : neutrino production
(10^{15} eV neutrinos do not imply 10^{19} eV protons)

GRB local rate …

~1 GRB for 2000 supernovae
i.e. 1 GRB every 100 000 years per galaxy.

This gives 1 GRB poiting towards us every 1000 years within 100 Mpc…

Accélération : choc externe

Accélération : $t'_{acc} \approx \frac{E'}{\Gamma e B} \approx 6\times10^{7}\, E_{19}\, B_{-6}^{-1}\, \Gamma_2^{-2}\ s$

Echappement : $t'_{esc} \approx \frac{R}{\Gamma c} \approx 3\times10^{4}\, R_{17}\, \Gamma_2^{-1}\ s$

Pertes synchrotron : $t'_{syn} \approx \left(\frac{m_p}{m_e}\right)^4 \frac{6\pi\left(m_e c^2\right)^2}{\sigma_T c} \frac{1}{E' B^2} \approx 1\times10^{11}\, E_{19}^{-1}\, B_0^{-2}\, \Gamma_2\ s$

Dynamique : $\Gamma \approx \Gamma_0 \left(\frac{R}{R_{dec}}\right)^{-\frac{3-s}{2}}$ $\qquad B \approx \left(32\pi\alpha_B \frac{A}{R^s}\right)^{1/2} \Gamma c \propto R^{-3/2}$

Maximum d'efficacité à R_{dec} :

+ cas s=0 (esc) : $E_{max} \approx 6\times10^{15}\, E_{53}^{1/3}\, n_0^{-1/3}\, \Gamma_2^{1/3}\, B_{-6}\ eV$

+ cas s=2 (esc): $E_{max} \approx 9\times10^{13}\, E_{53}\, A_*^{-1}\, \Gamma_2^{-1}\, B_{-6}\ eV$

Accélération : chocs internes

Accélération : $t'_{acc} \approx \kappa \frac{E'}{eB} \approx 6\kappa_1 E_{19} B_4^{-1} \Gamma_2^{-2}$ s

Echappement : $t'_{esc} \approx \frac{R}{\Gamma c} \approx 30 R_{14} \Gamma_2^{-1}$ s

Pertes synchrotron : $t'_{syn} \approx \left(\frac{m_p}{m_e}\right)^4 \frac{6\pi (m_e c^2)^2}{\sigma_T c} \frac{1}{E' B^2} \approx 1\times 10^3 E_{19}^{-1} B_4^{-2} \Gamma_2$ s

Dynamique : $R \approx 2c\Gamma^2 t_{var} \approx 6\times 10^{14} \Gamma_2^2 t_{var}$ cm

Energie maximum : Lim 1 : esc $E_{max} \approx 3\times 10^{20} \kappa_1^{-1} \Gamma_2^3 B_4 t_{var}$ eV

Lim 2 : syn $E_{max} \approx 1\times 10^{20} \kappa_1^{-1/2} \Gamma_2^{3/2} B_4^{-1/2}$ eV

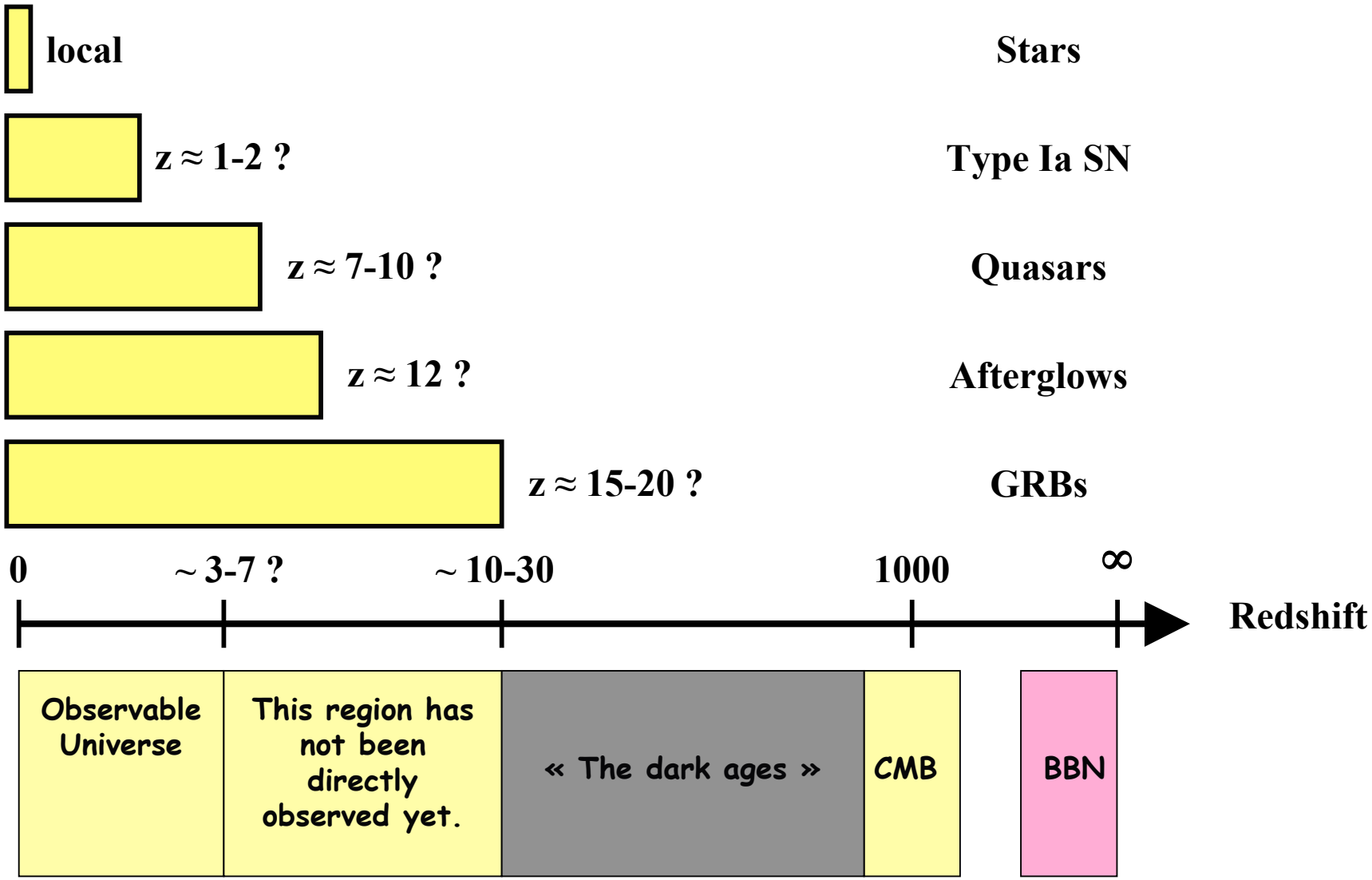
Contrainte sur B : Syn : $E_{syn} \propto \Gamma B \Gamma_e^2$ soit $B \approx 4\times 10^4 \Gamma_2^{-1} (E_p/400\,\text{keV})$ G

IC : $E_{ic} \propto \Gamma B \Gamma_e^4$ soit $B \approx 1\times 10^{-2} \Gamma_2^{-1} (E_p/400\,\text{keV})$ G

Cosmology :

Probing the distant Universe using GRBs

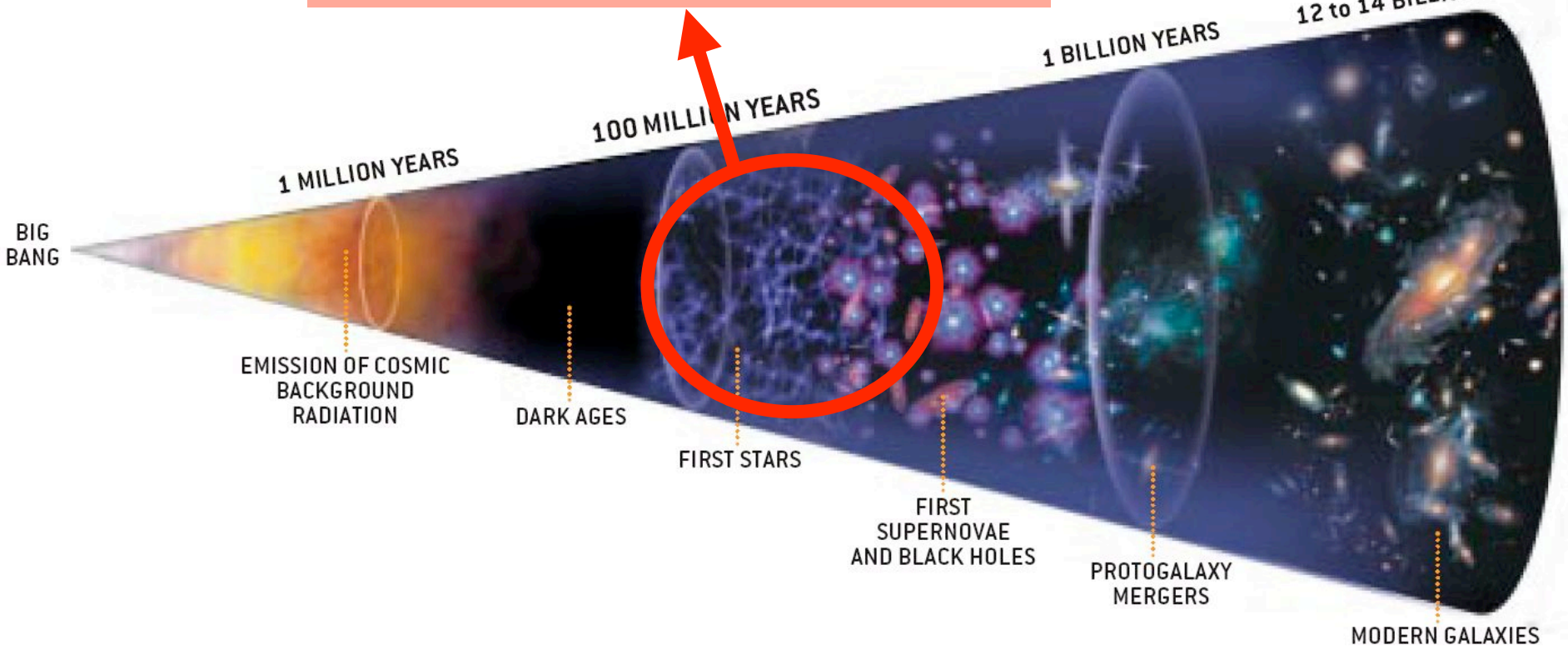
GRBs can be detected at very large distance



There are probably GRBs at very high z.

GRBs associated with first stars ?

(pop. III stars)



Larson & Bromm, Scientific American, 2001

How to detect a high z GRB ?

- Infrared is needed (absorption in visible)
- Rapid observations are needed :

Observing …	10 min after the burst
means in the source frame …	5 min after the burst at z = 1 55 s after the burst at z = 10

The source is intrinsically brighter, which partially compensates for the larger luminosity distance.

How to detect a high z GRB ?

HETE-2 / INTEGRAL :	good location (a few arc minutes)
SWIFT / ECLAIRs	in quasi real-time (1 min)
TAROT / REM / … :	automatic pointings
	afterglow detected ? : better location (arc second)
VLT / XSHOOTER :	pointings in ~ 10-15 minutes !
	Good spectroscopy of the afterglow.

Cosmology with GRBs

1. Spectroscopy : ISM (host galaxy), IGM.

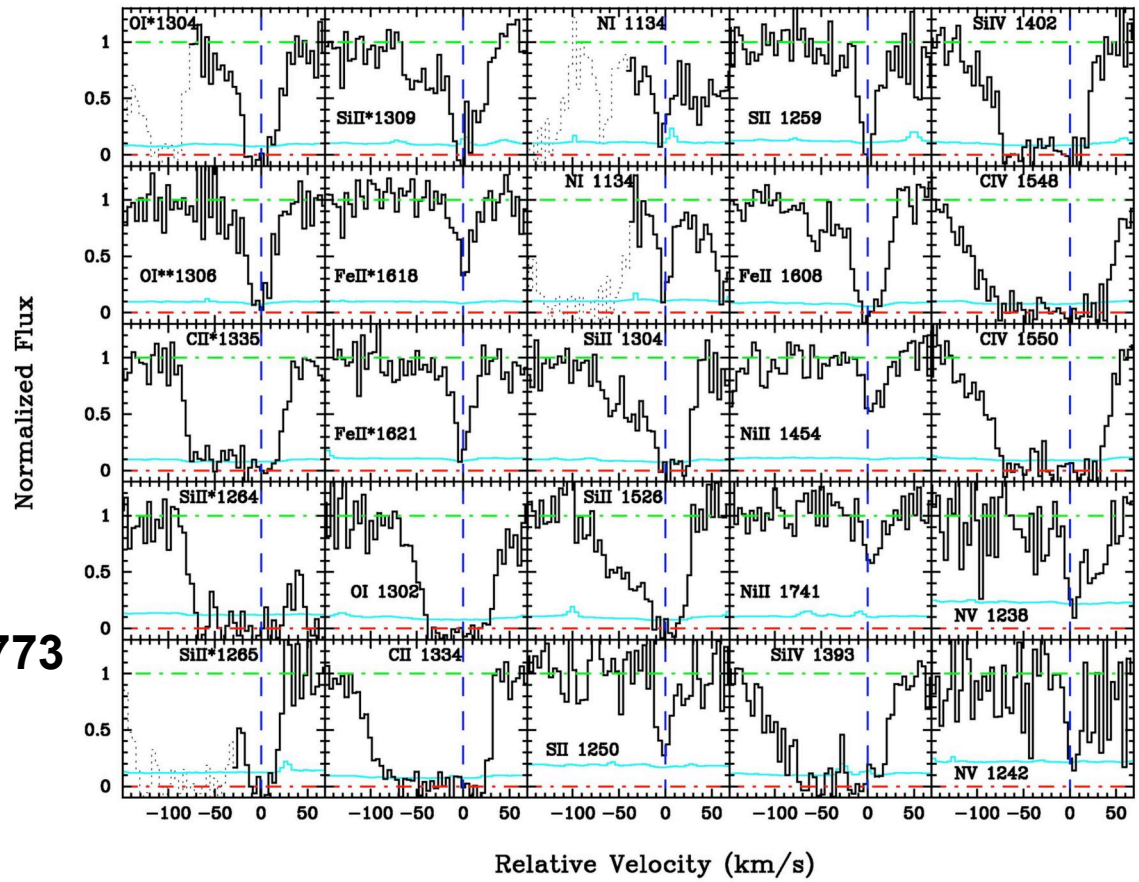
Example : GRB 050730 z=3.969

(Chen et al. 2005)

R=17.7, 4 hours after the burst.

ISM : N(HI)=22.15
$Z/Z_{\odot}$~1/100

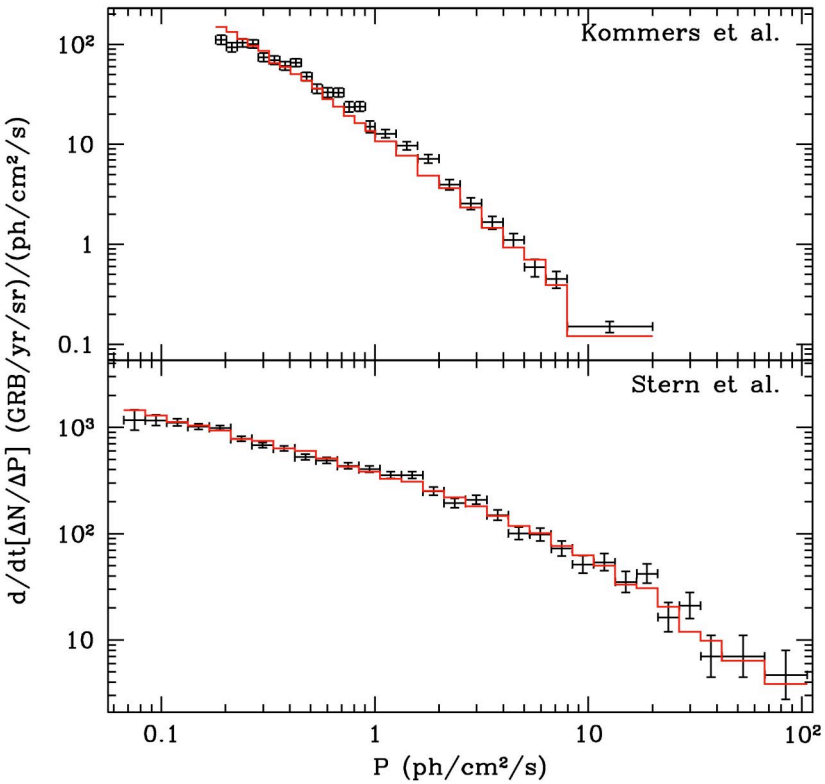
IGM : DLA @ z=3.564
LLS @ 3.022
MgII abs. @ z=2.253,1.773



Cosmology with GRBs

2. Detecting the first stars ? (do pop. III stars produce GRBs ?)

3. Tracing the high-z SFR ? (GRB progenitors ? evolution ?)



Daigne, Rossi, Mochkovitch 2006.

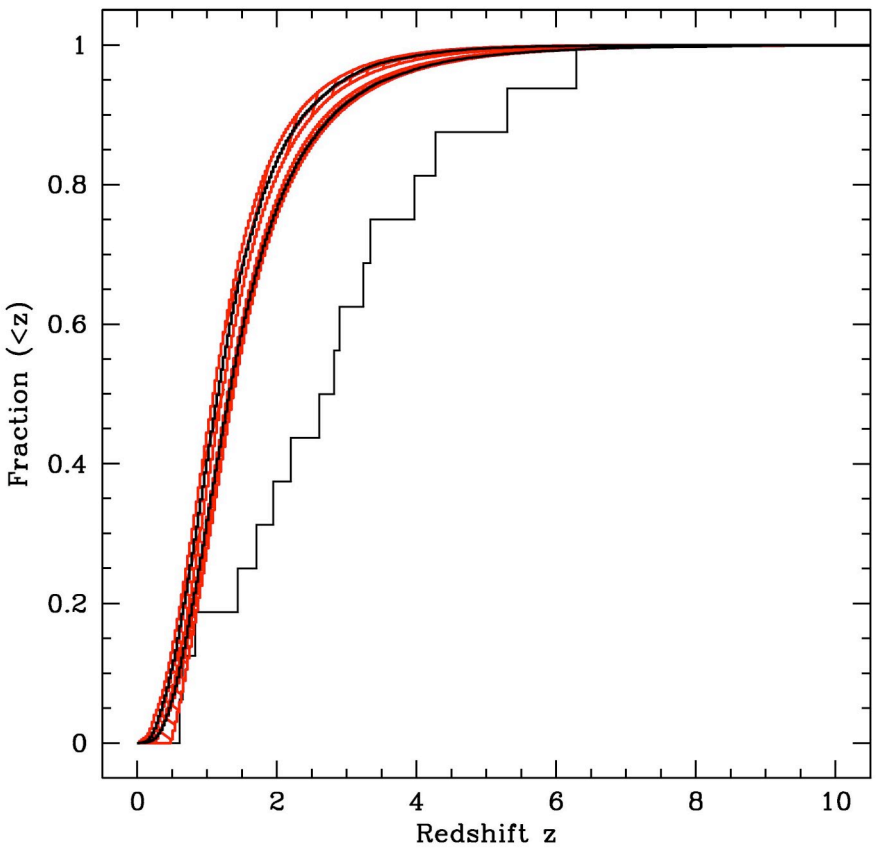
-Montecarlo simulations;
-Fit : log N–log P, E_p distribution and and XRR/XRFs fraction.

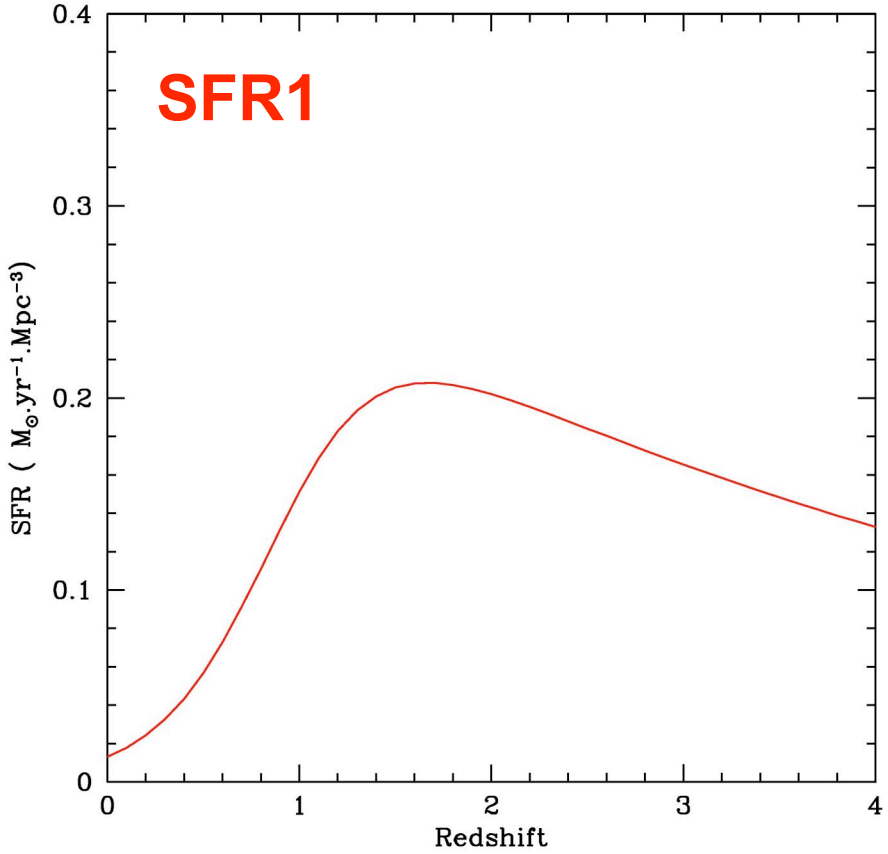
Impact of :

- Unknown intrinsic GRB physics;

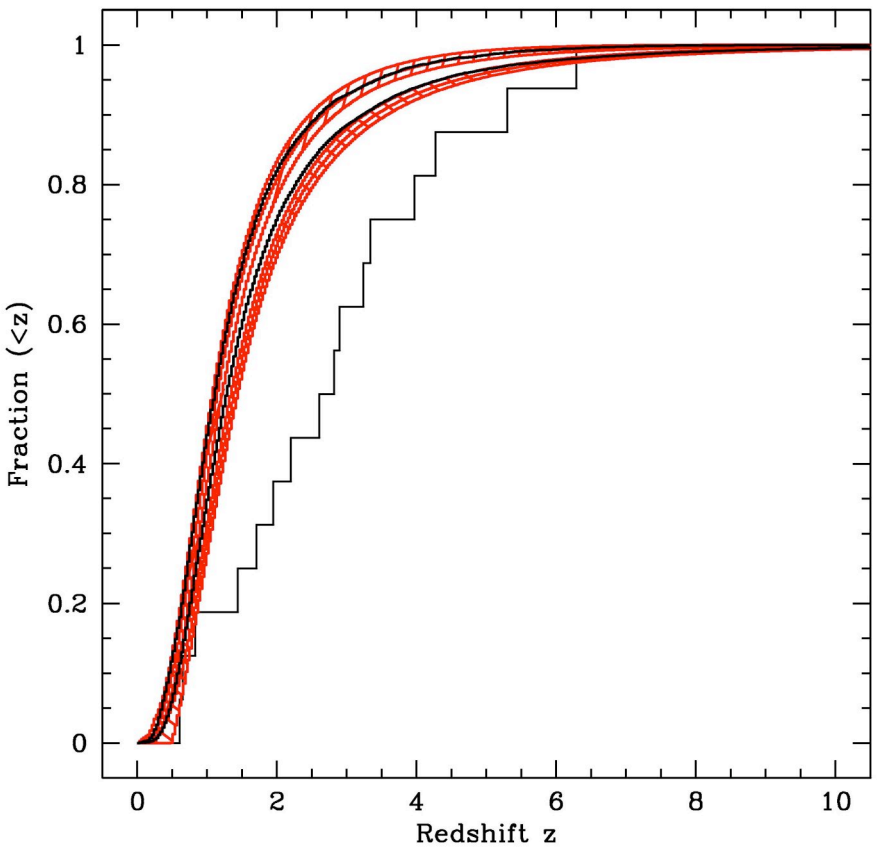
- Intrinsic rate.

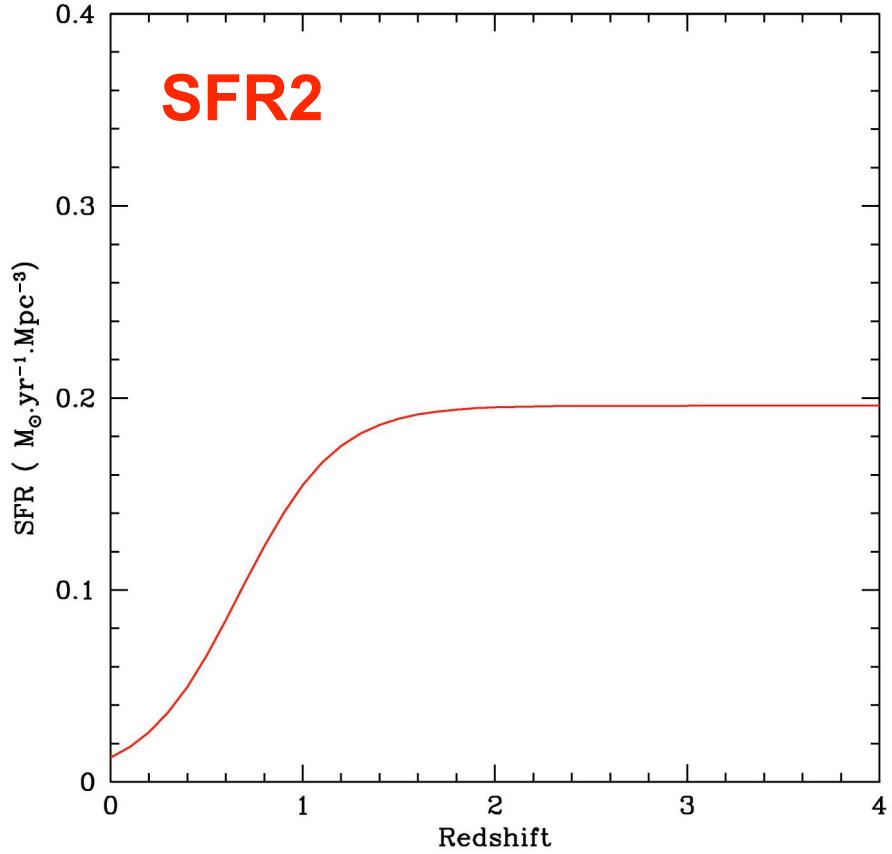
The rate of high z GRBs



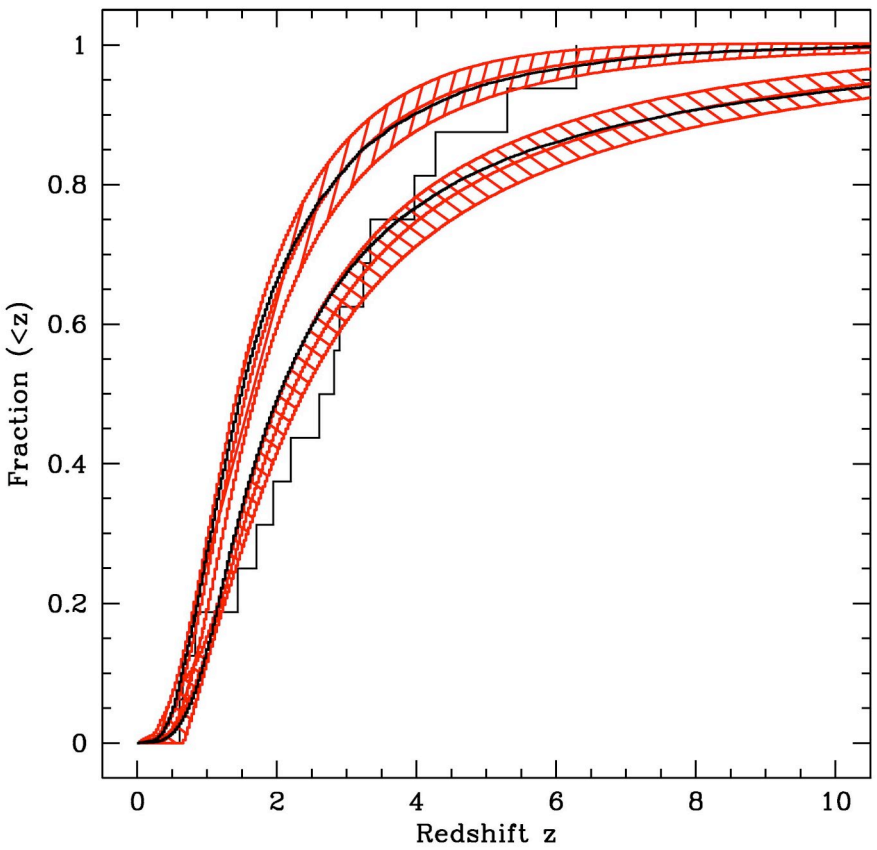


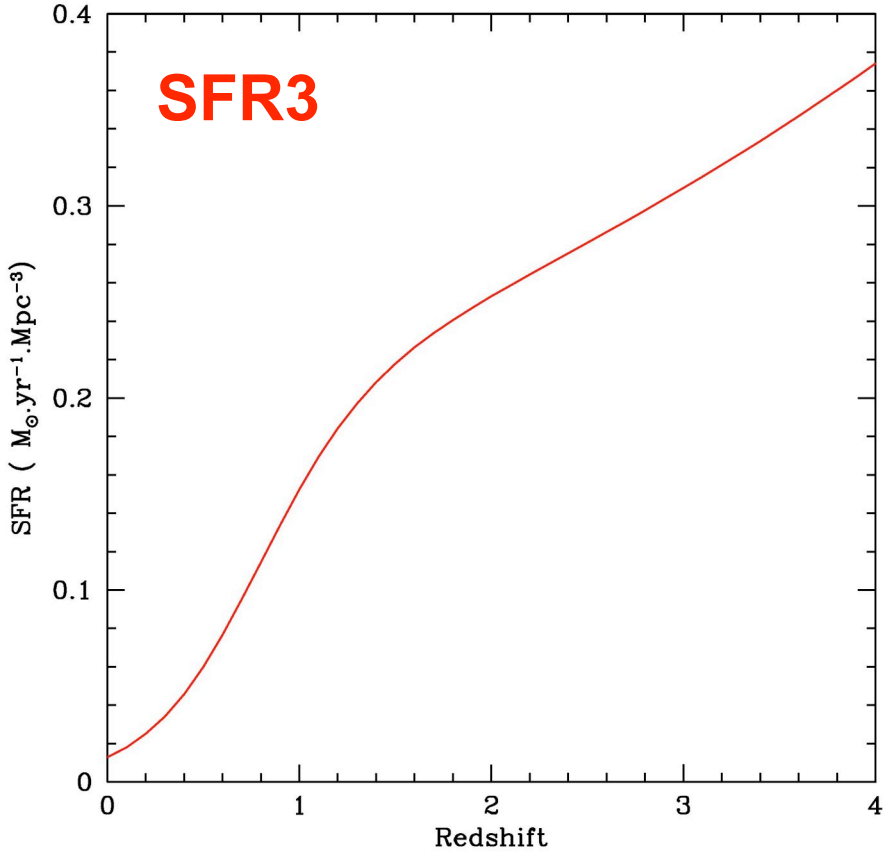
The rate of high z GRBs





The rate of high z GRBs





The rate of high z GRBs

- SFR3 seems prefered by SWIFT data.

- This SFR is irrealistic (still increases beyond z=6) : evolution effect ?

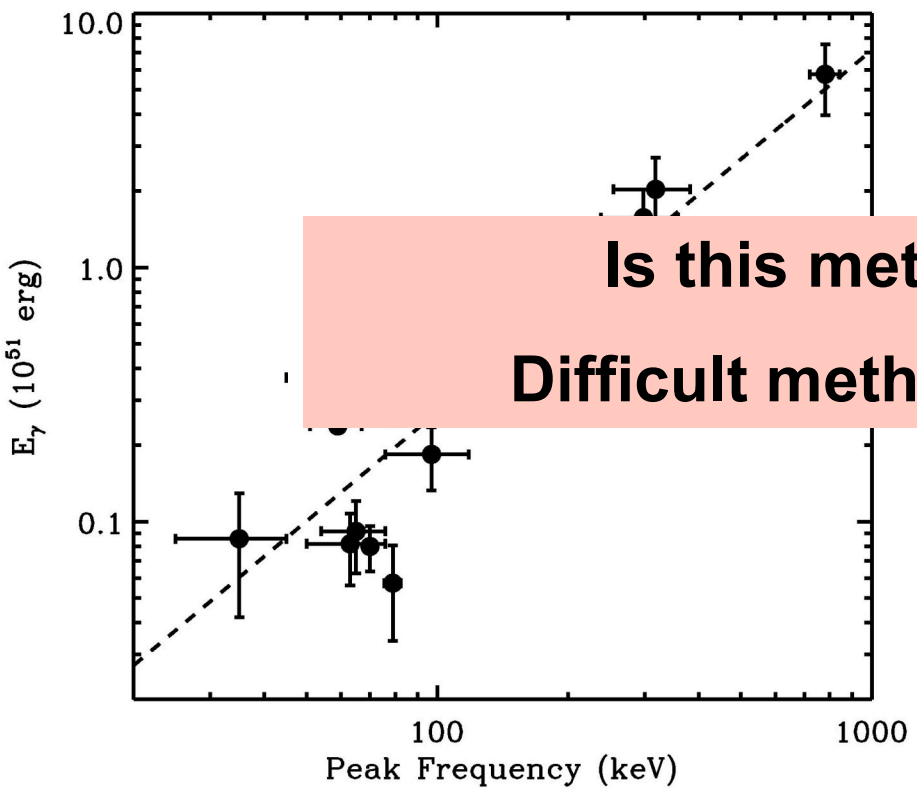
- SWIFT : Fraction(z>5) = 2% → 20 %
  Fraction(z>7) = 0,5% → 10 %

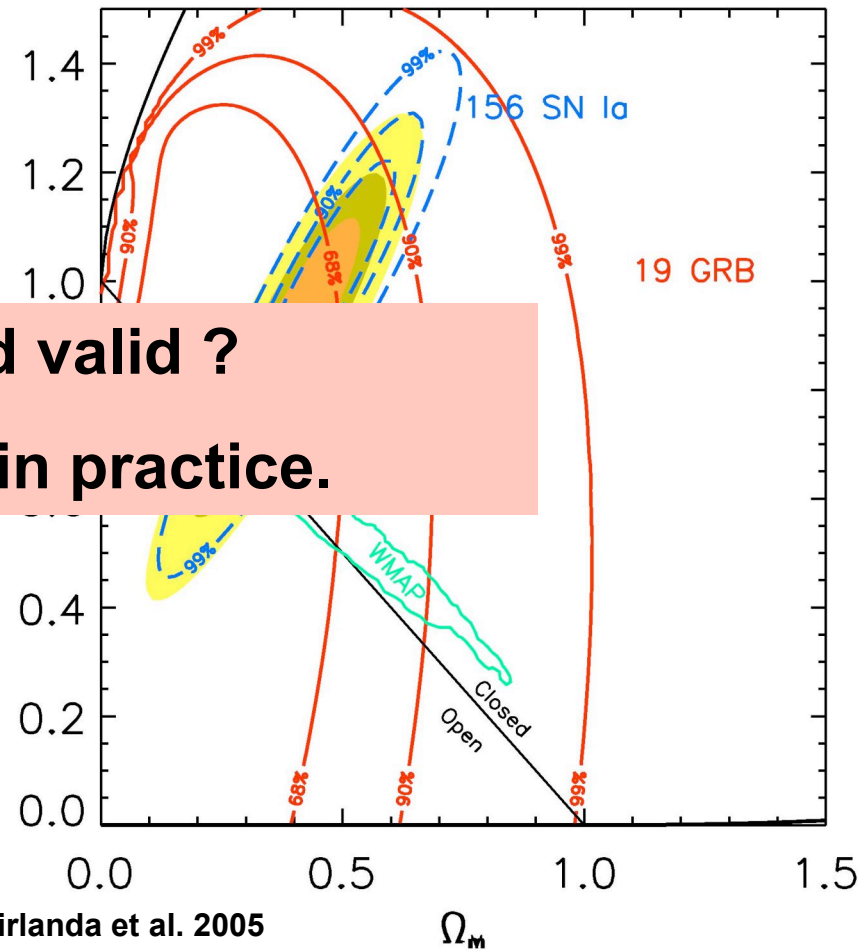
- Bright GRBs : Rate(z>5) = 0,2 per year → 2,5 per year
  Rate(z>7) = 0 → 0,7 per year

Measuring cosmological parameters ?

→ **GRBs are not standard candels.**

→ Studies are based on Amati-like relations : correlation between
E_γ : γ-ray luminosity (corrected for beaming)
E_p : spectral peak energy





Is this method valid ?

Difficult method in practice.

Ghirlanda et al. 2005

1. The discovery of GRBs

2. Main properties

3. The GRB distance scale

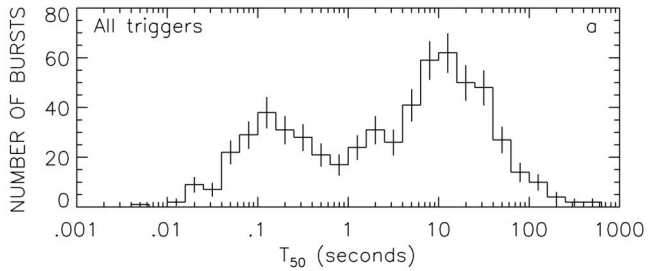
4. The afterglow era

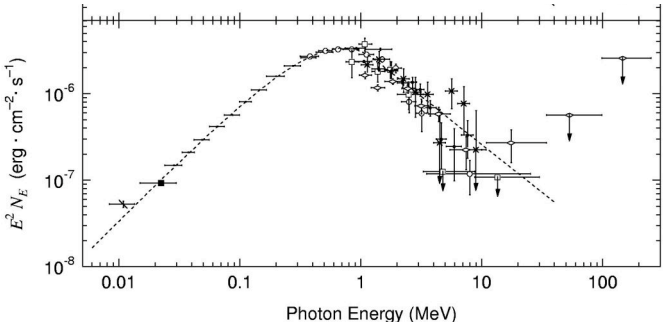
5. Recent results : SWIFT

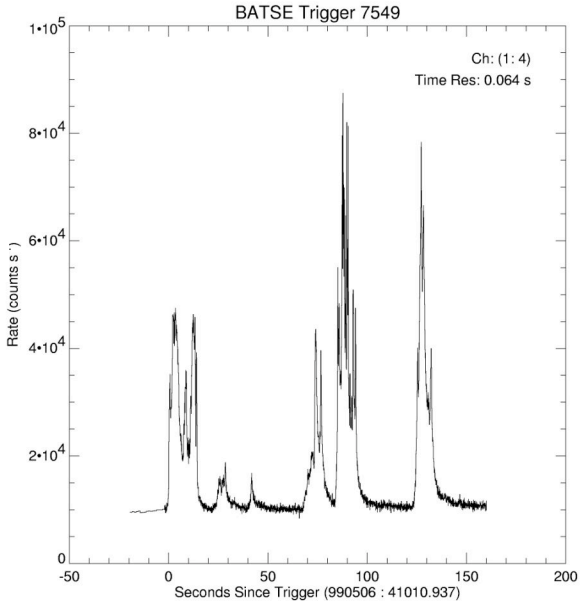
6. How to produce a GRB

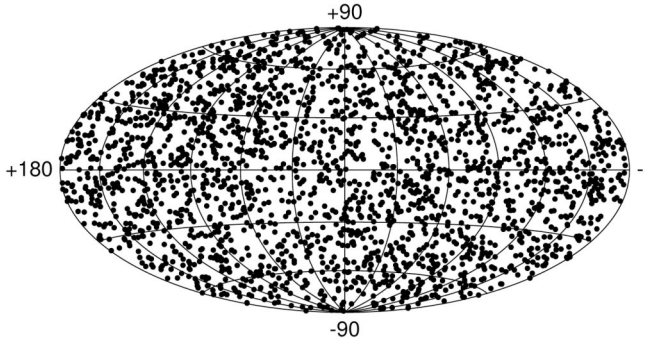
7. GRBs and cosmology

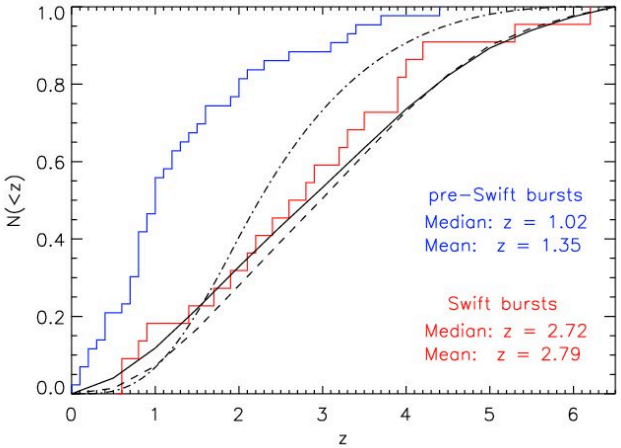
Summary

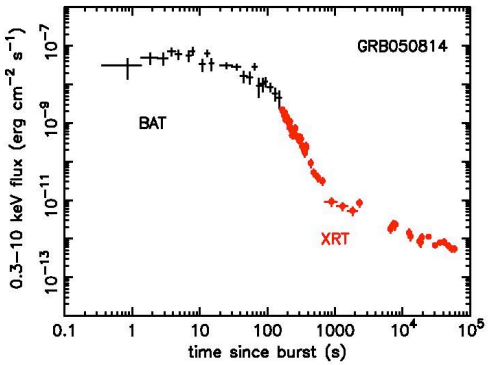

All triggers
a
NUMBER OF BURSTS
T_{50} (seconds)

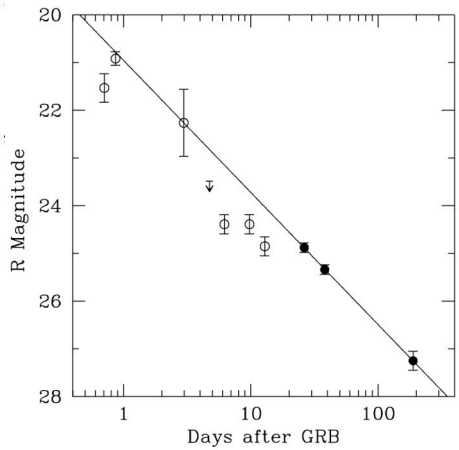

$E^2 N_E$ (erg · cm^{-2} · s^{-1})
Photon Energy (MeV)

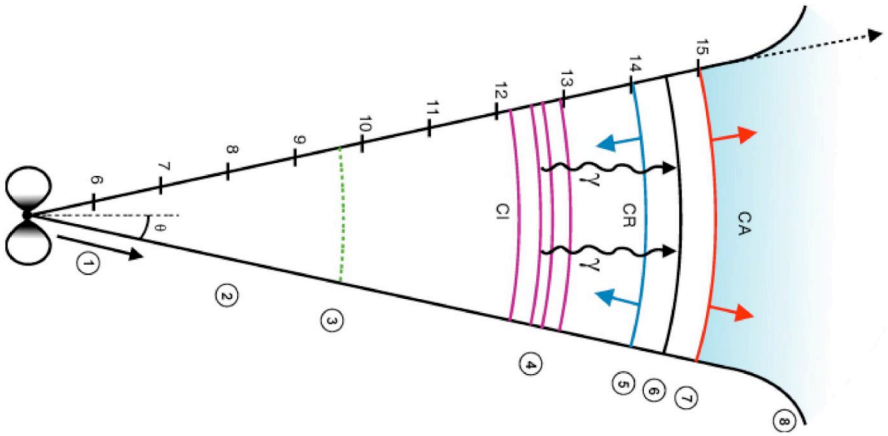

BATSE Trigger 7549
Ch: (1: 4)
Time Res: 0.064 s
Rate (counts s^{-1})
Seconds Since Trigger (990506 : 41010.937)


+90
+180
-90


N(<z)
z
pre−Swift bursts
Median: z = 1.02
Mean: z = 1.35
Swift bursts
Median: z = 2.72
Mean: z = 2.79


GRB050814
BAT
XRT
0.3–10 keV flux (erg cm^{-2} s^{-1})
time since burst (s)


R Magnitude
Days after GRB


CI
CR
CA
θ
γ