High-redshift Gamma-Ray Bursts

Frédéric Daigne
(Institut d'Astrophysique de Paris)

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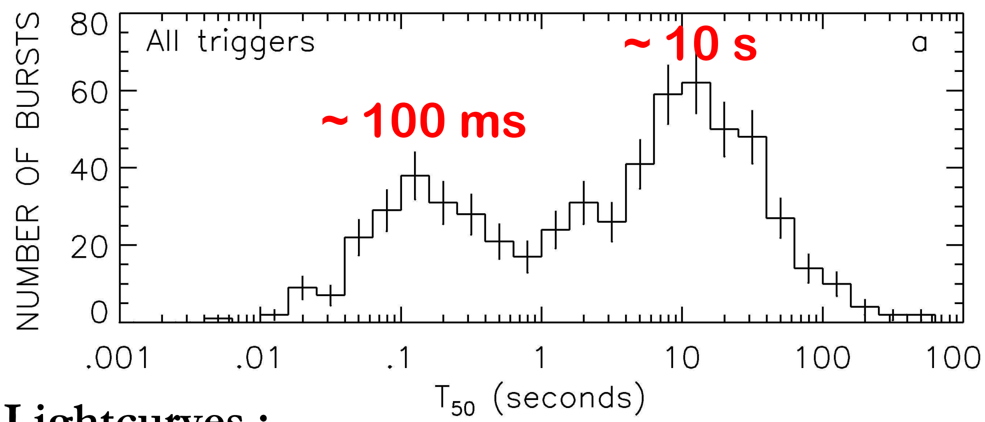
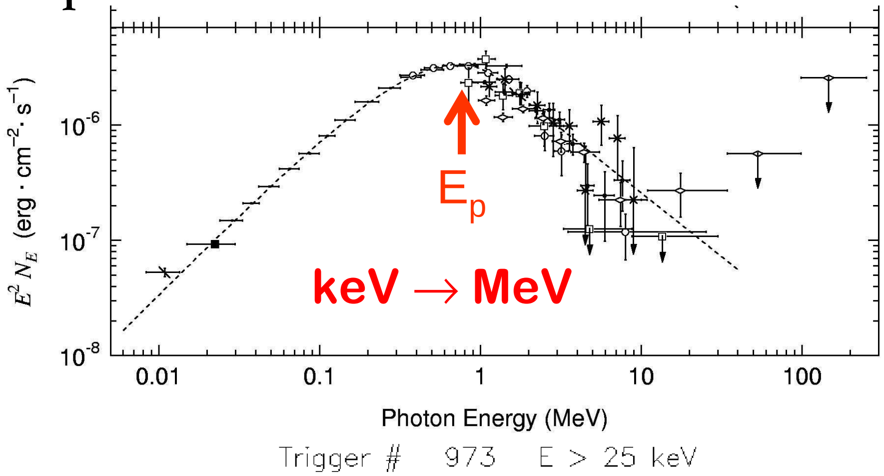
GRB prompt emission :

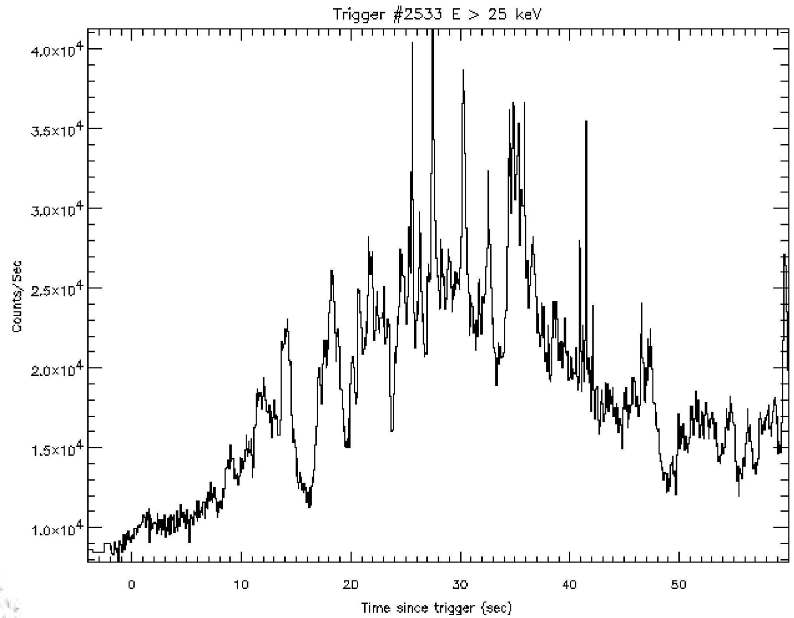
Duration :

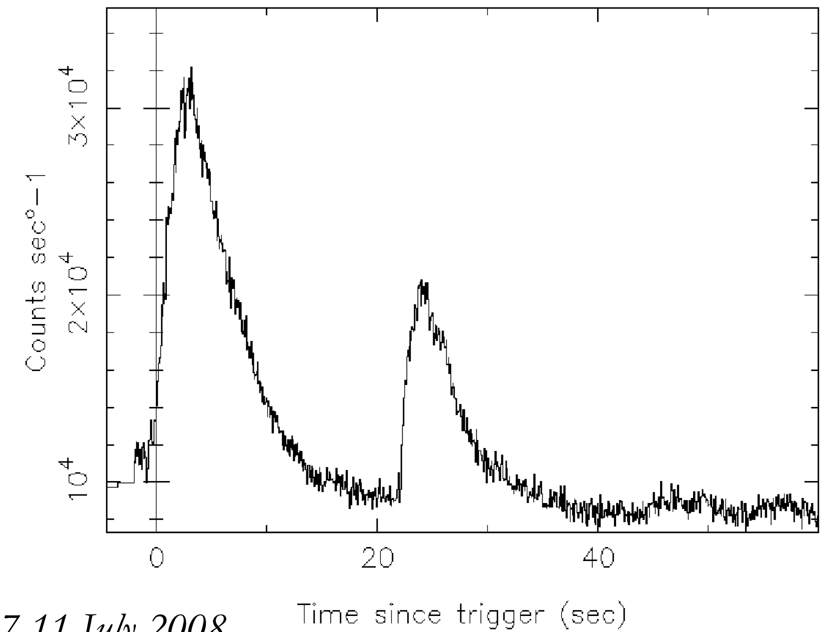


Spectrum :



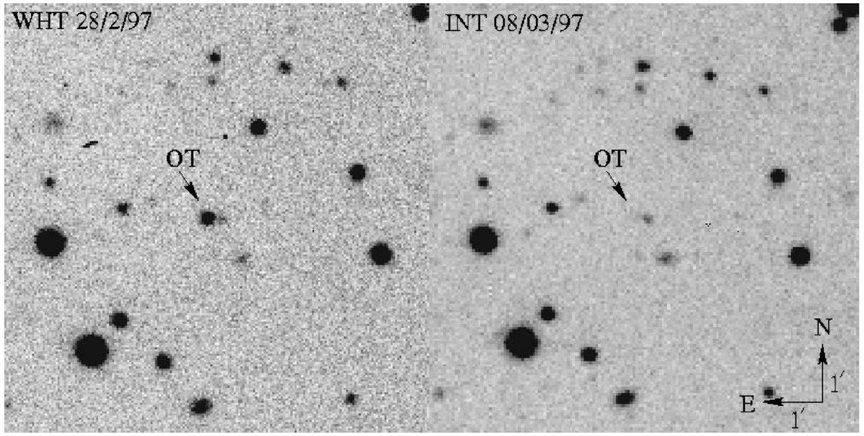
Lightcurves :

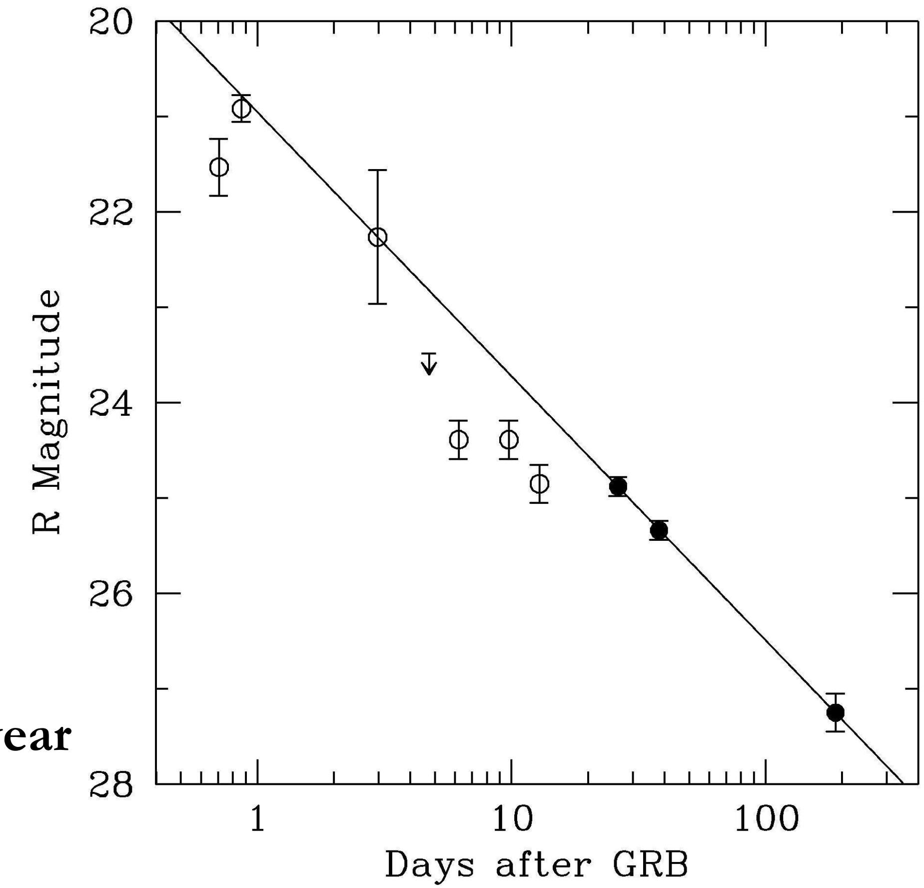




GRB afterglows :

GRB 970228 : **1st afterglow**
localization by BeppoSAX, optical afterglow by van Paradijs et al.

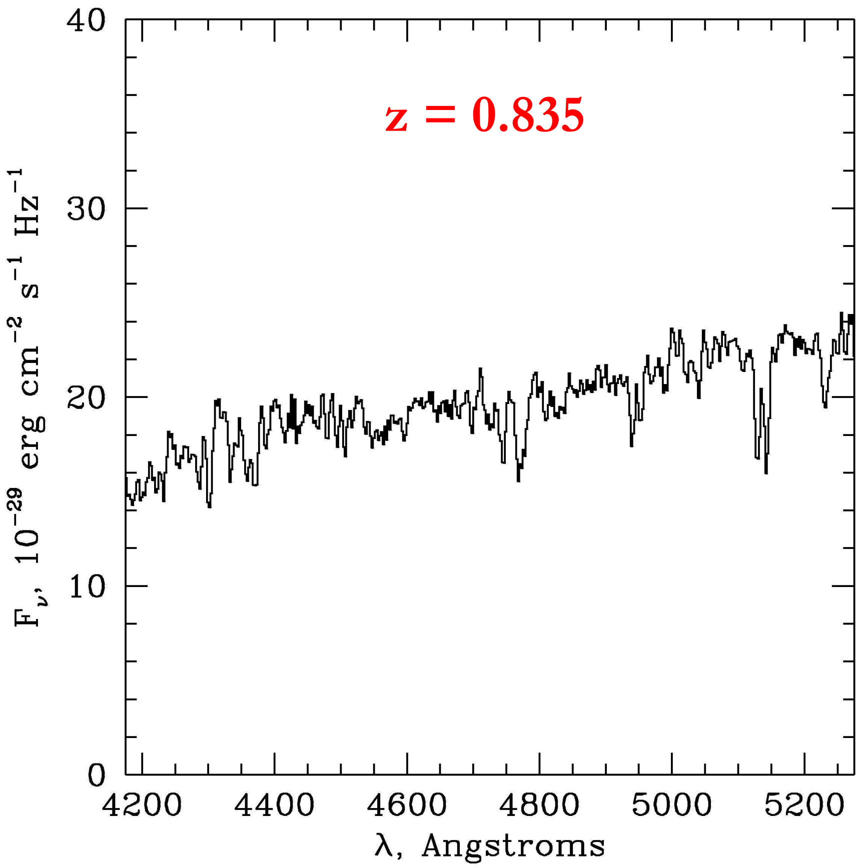


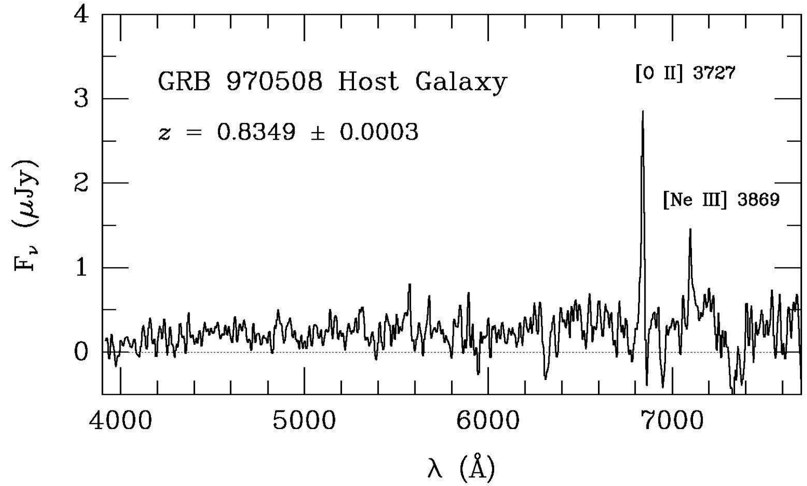


GRB afterglows
→ **rapid decay : hours, days, months, year**
→ **spectral evolution : X,V,radio**

GRB afterglows :

GRB 970508 : 1st redshift (Metzger et al. 1997)

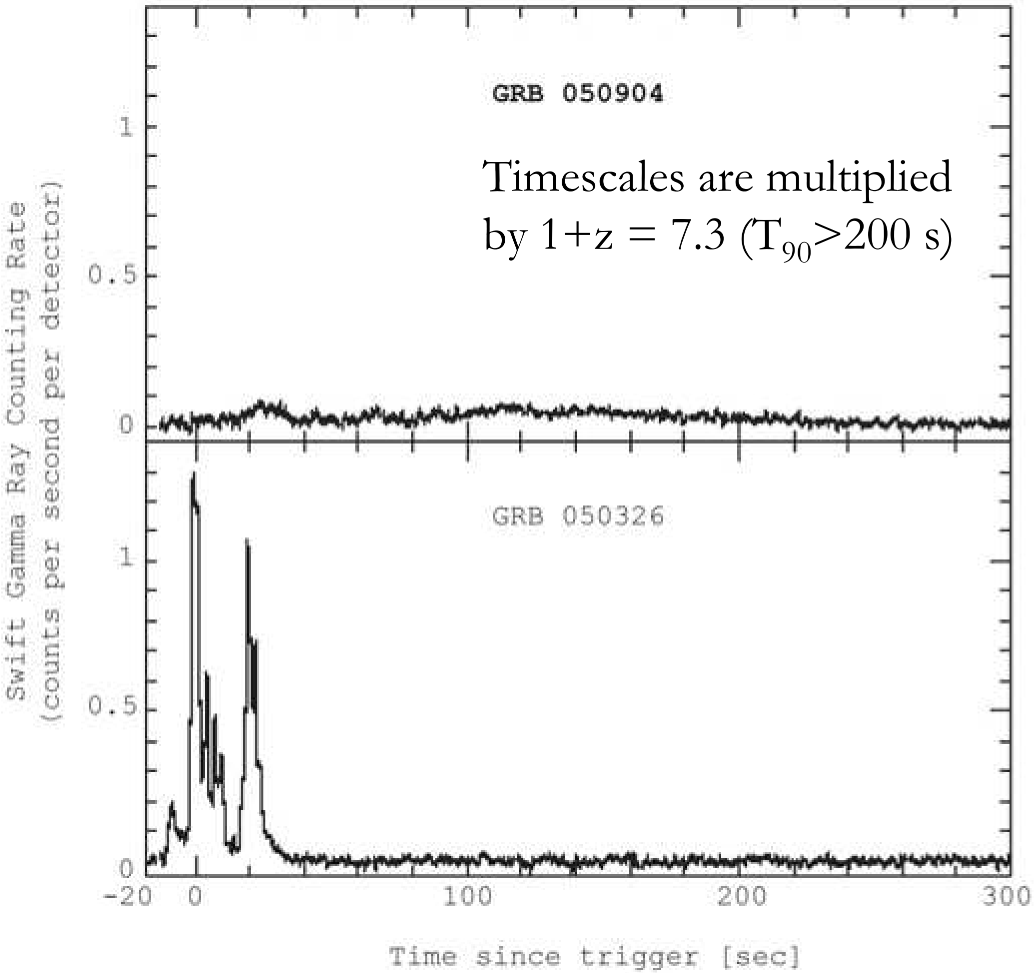


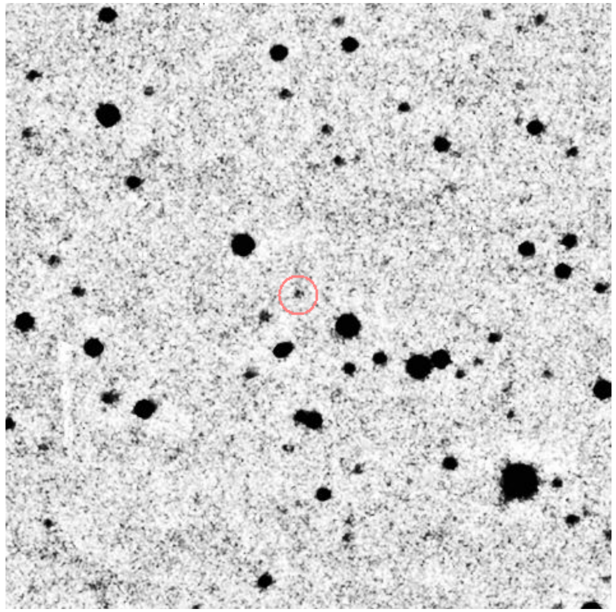


Host galaxy : z = 0.835

GRB afterglows :

GRB 050904 : z = 6.29 ! **Localization by Swift ; Redshift at Subaru (Kawai et al. 2005)**





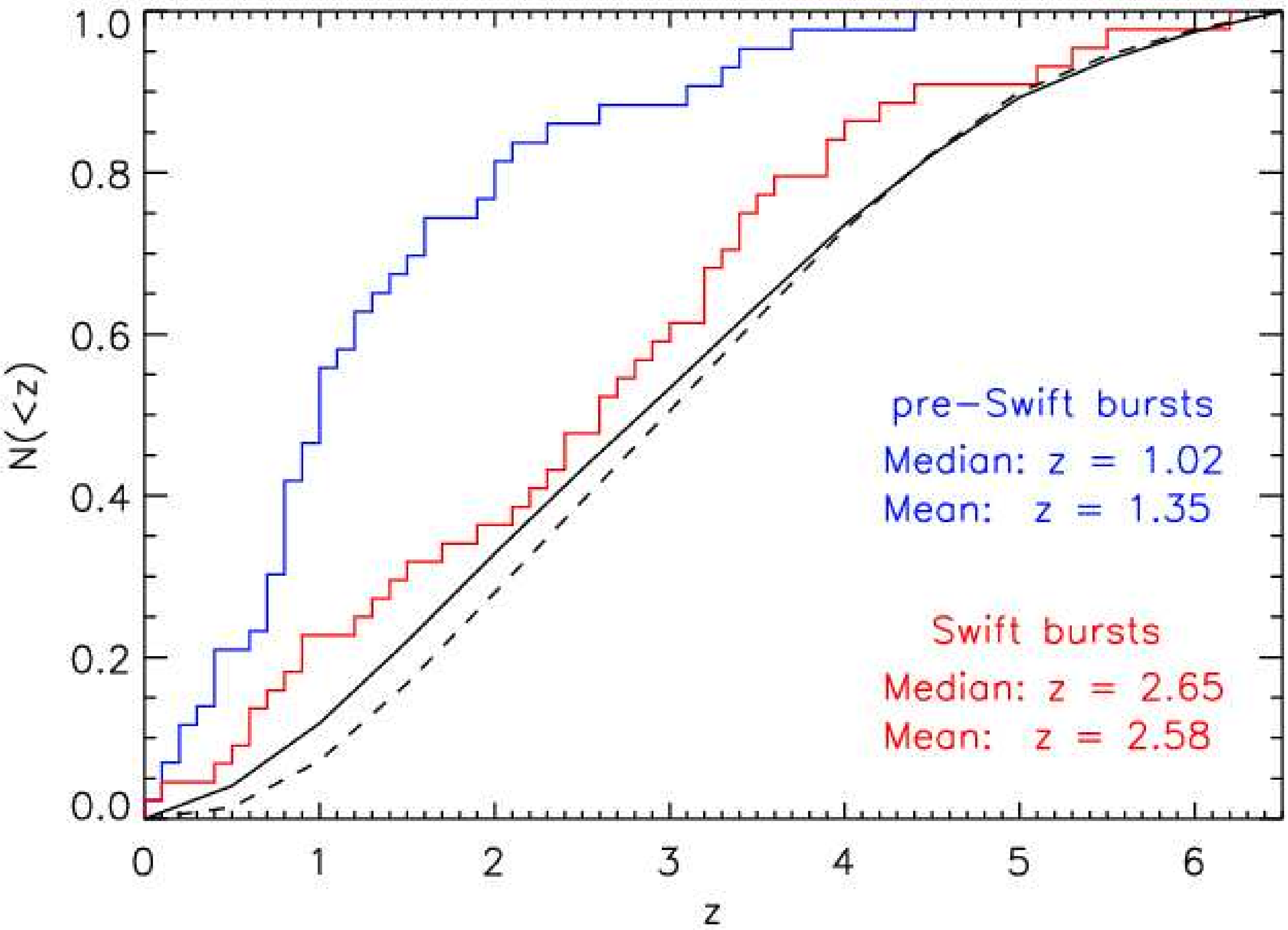
TAROT detection @ 86 s after trigger

I ~ 16 (Boër et al. 2006)

(Quasar : z = 6.37, I=23.3)

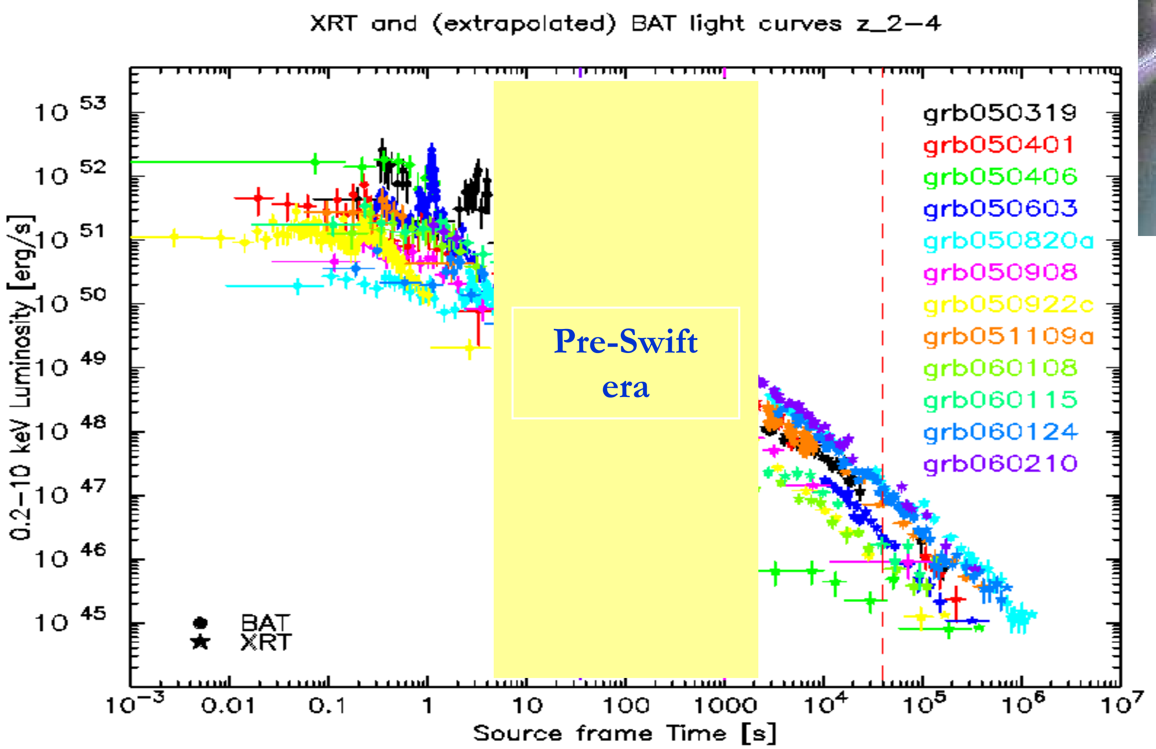
GRB afterglows :

SWIFT : redshift distribution of long GRBs (Jakobsson et al. 2006; see also poster P32)



GRB afterglows :

Swift :
- X-ray afterglow in almost 100 % of cases
- Rapid localisation (~min)
- Increased efficiency in measuring z
- The early afterglow shows a very surprising evolution



(Mangano et al, 2006)

Swift : 2004-

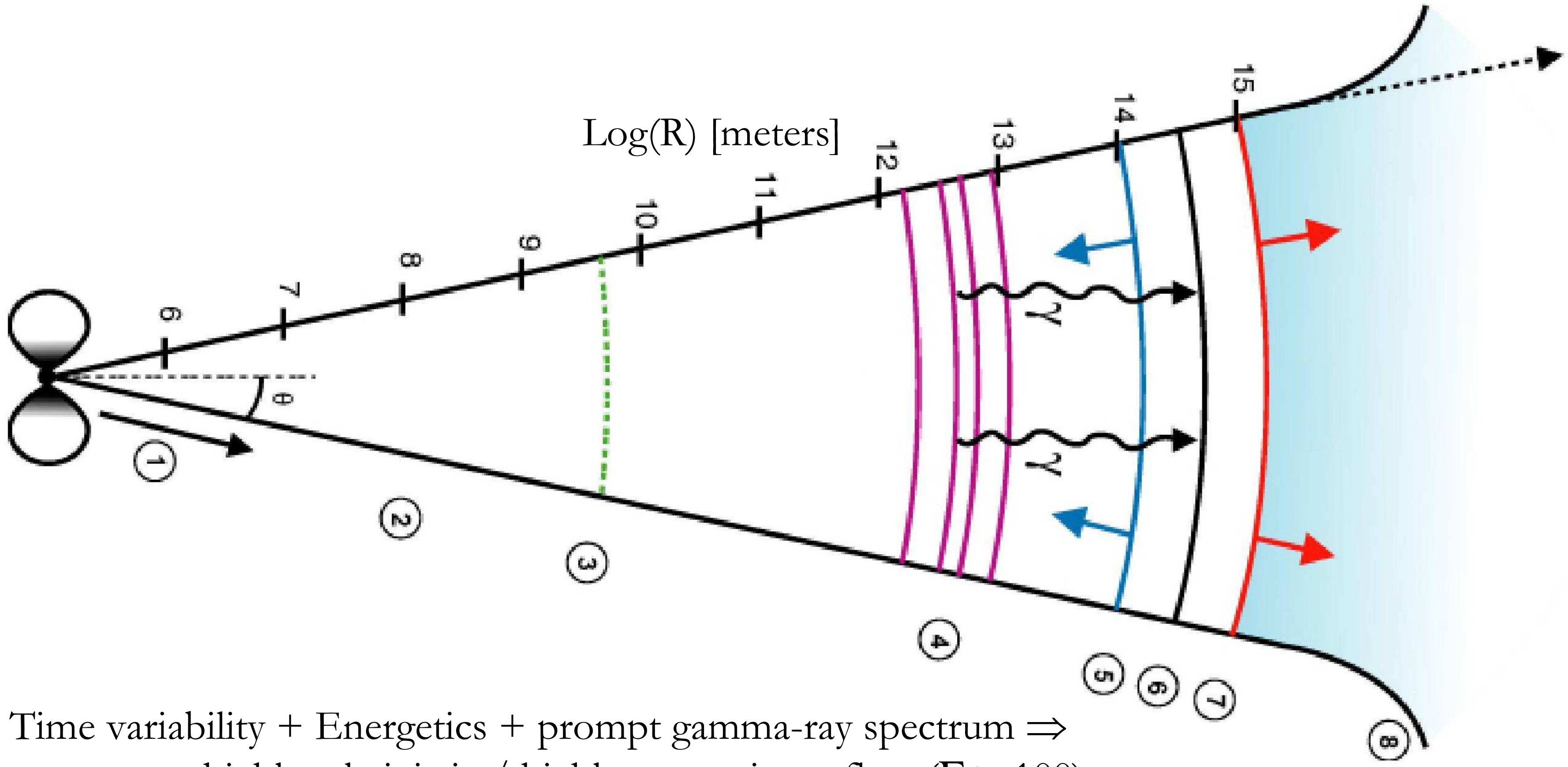
Gamma-ray bursts : models

Energetics : $10^{51} - 10^{54}$ **erg (isotropic)**
10^{51} **erg (after correction for beaming) ?**
(Frail et al. 2001)

Redshift : $0.008 \rightarrow 6.3$

Gamma-ray bursts : emission mechanisms

Paczynski, Rees, Meszaros, Piran, …



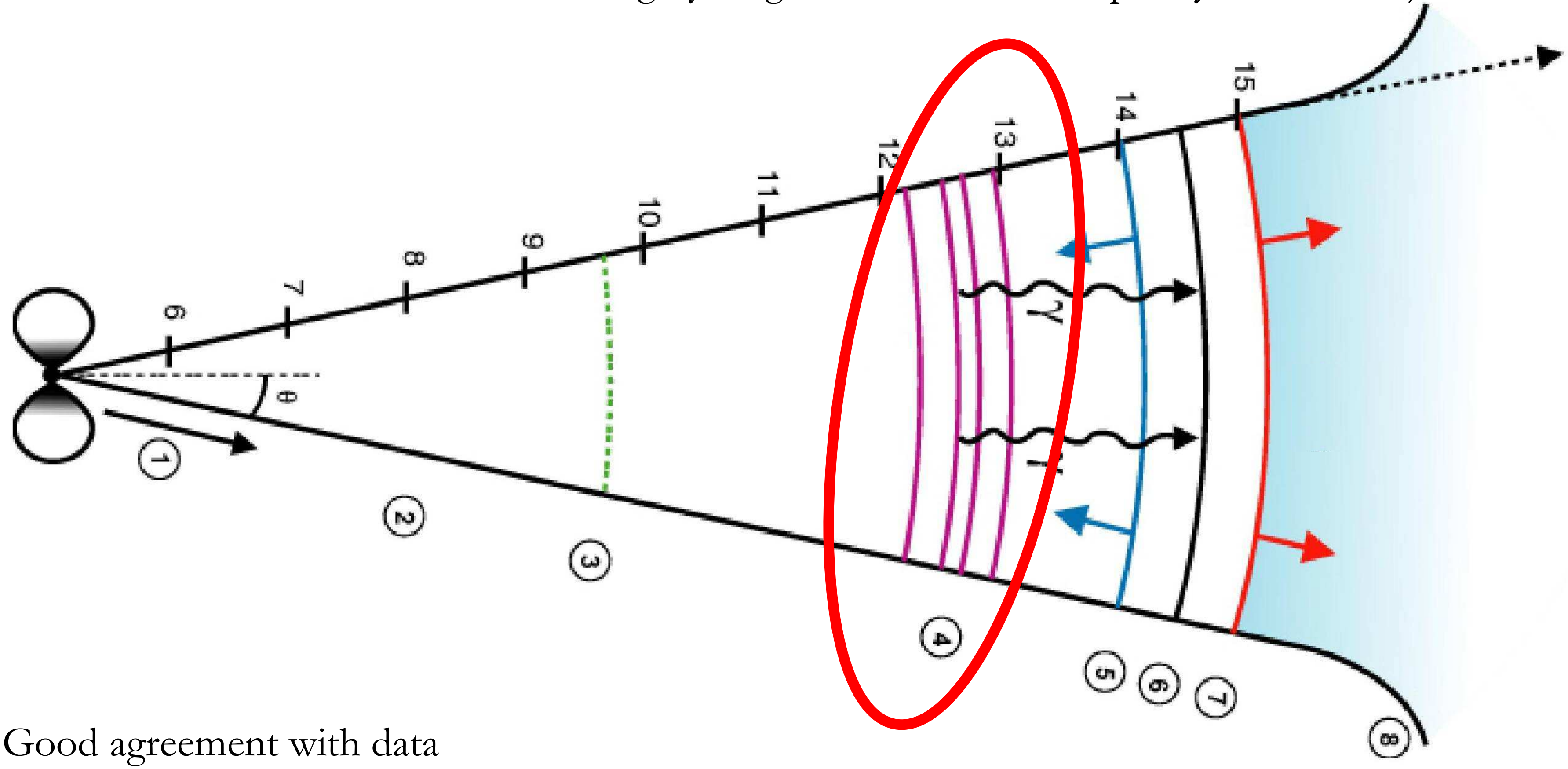
Time variability + Energetics + prompt gamma-ray spectrum ⇒

- highly relativistic / highly energetic outflow ($\Gamma > 100$)
- ejected by a compact source (BH, NS)
- formed in a cataclysmic event (collapsars, coalescence, …)

Gamma-ray bursts : emission mechanisms

Internal shocks : gamma-ray prompt emission

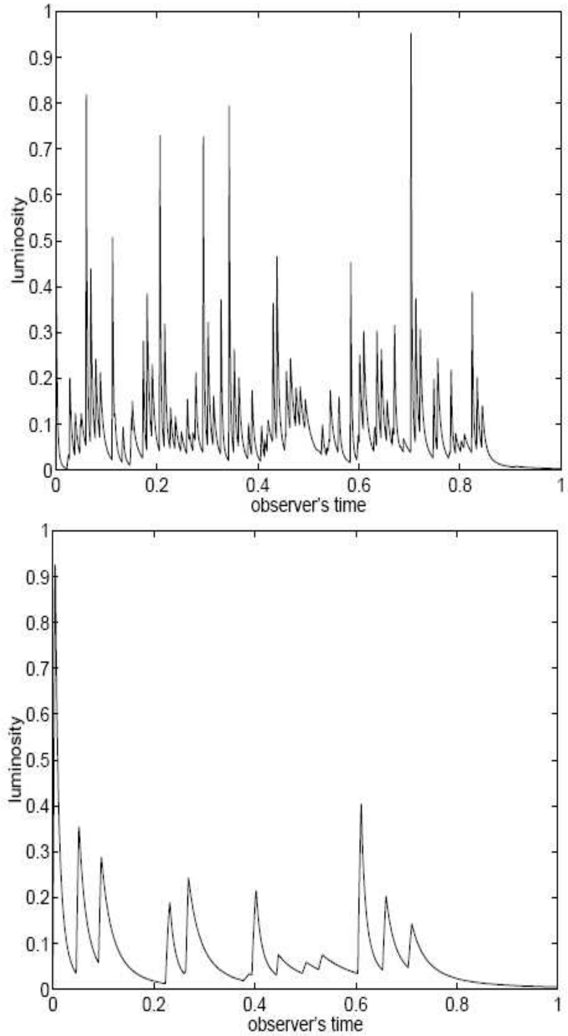
(alternative models : reconnection in a highly magnetized outflow / a purely em outflow)

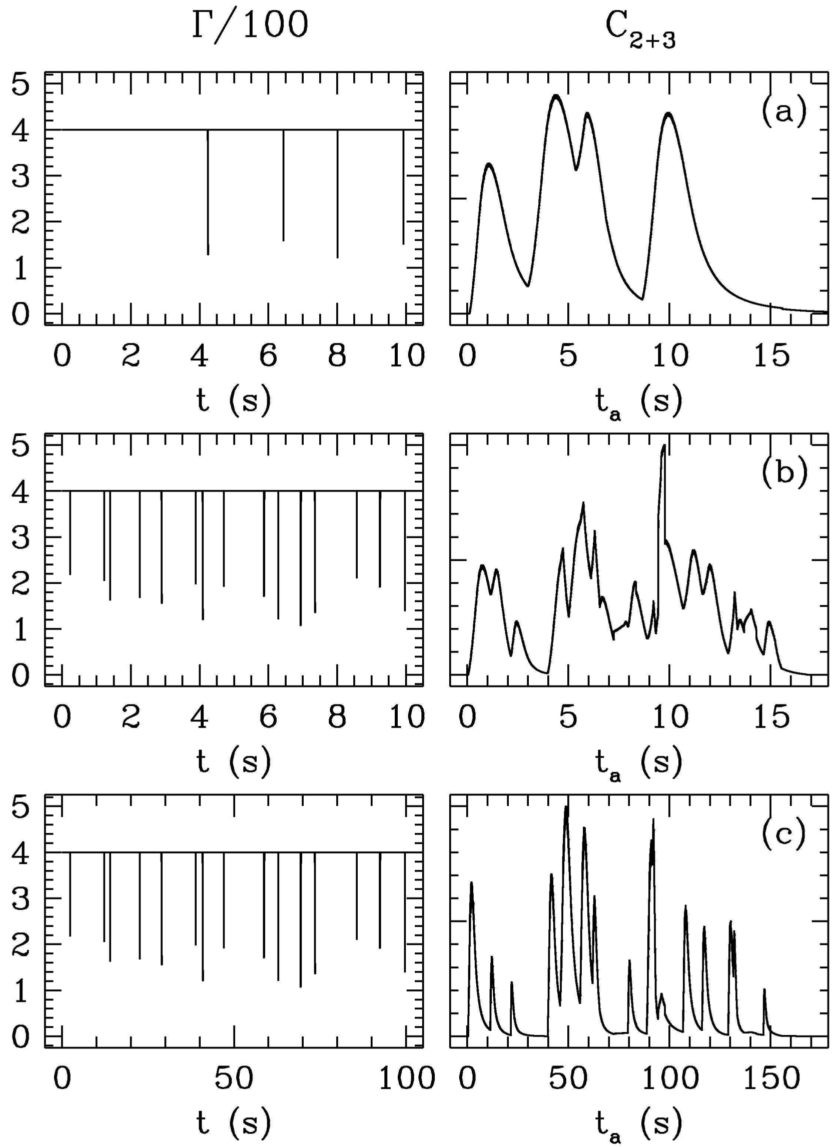


- Good agreement with data
- Main issues : efficiency, origin of the prompt optical emission (e.g. « naked eye burst »)

Gamma-ray bursts : emission mechanisms

Kobayashi, Piran & Sari 1997



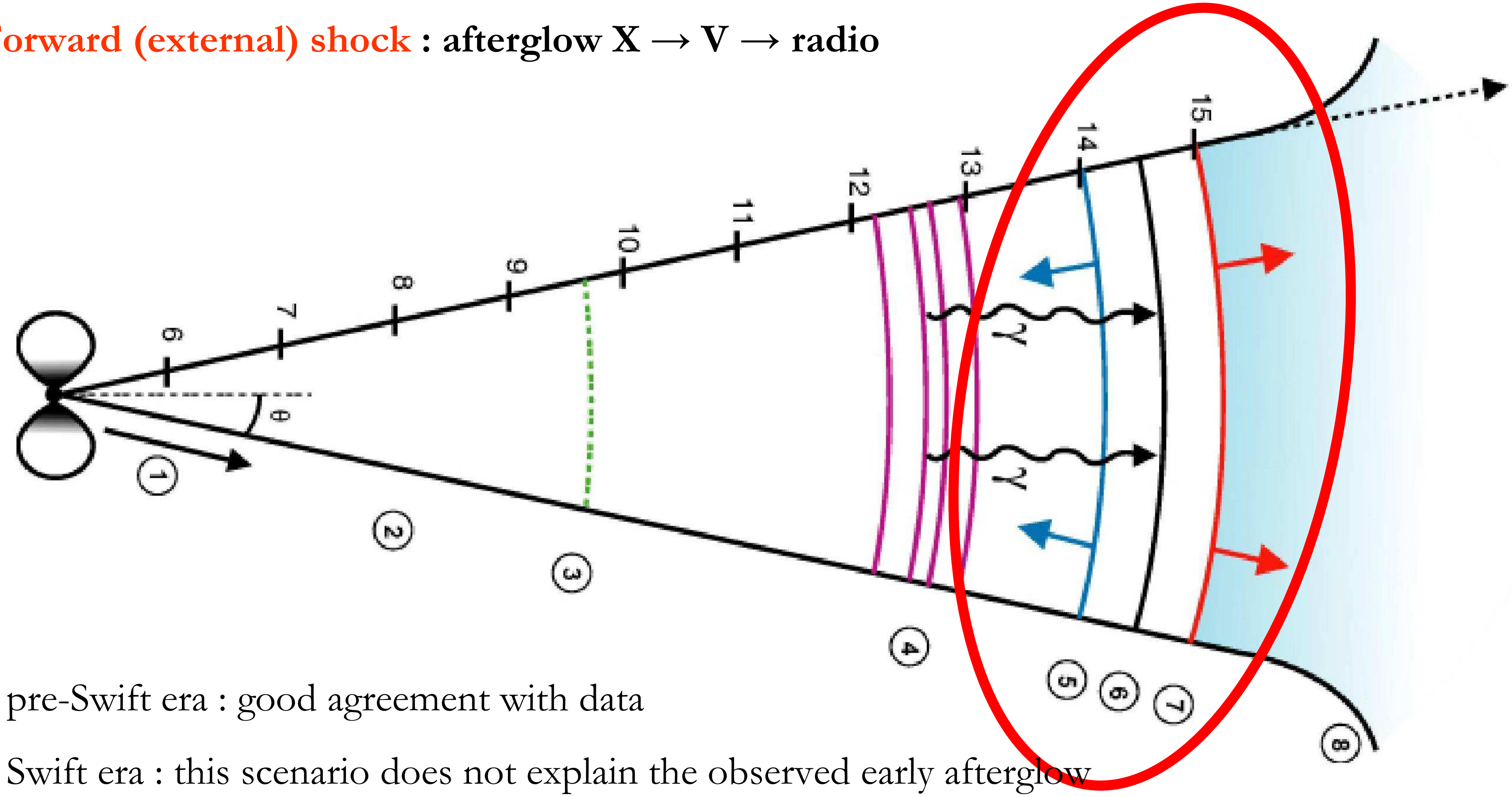


Daigne & Mochkovitch 1998

Gamma-ray bursts : emission mechanisms

Reverse shock : optical flash ?

Forward (external) shock : afterglow X → V → radio



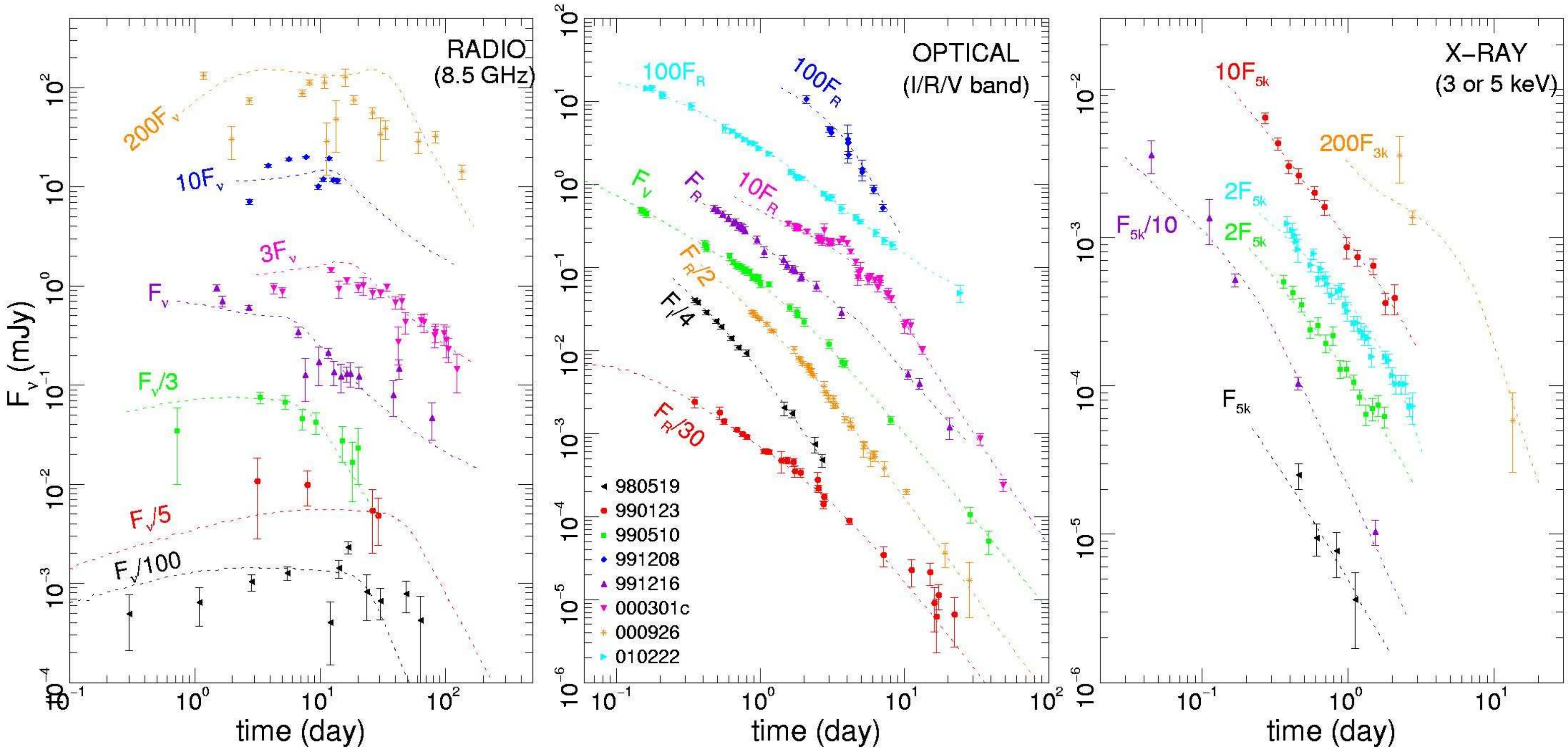
- pre-Swift era : good agreement with data
- Swift era : this scenario does not explain the observed early afterglow

(alternatives : late energy injection / late activity : problems for the central engine; long-lived reverse shock model, …)

Gamma-ray bursts : emission mechanisms

Multi-wavelength fits (external shock model)

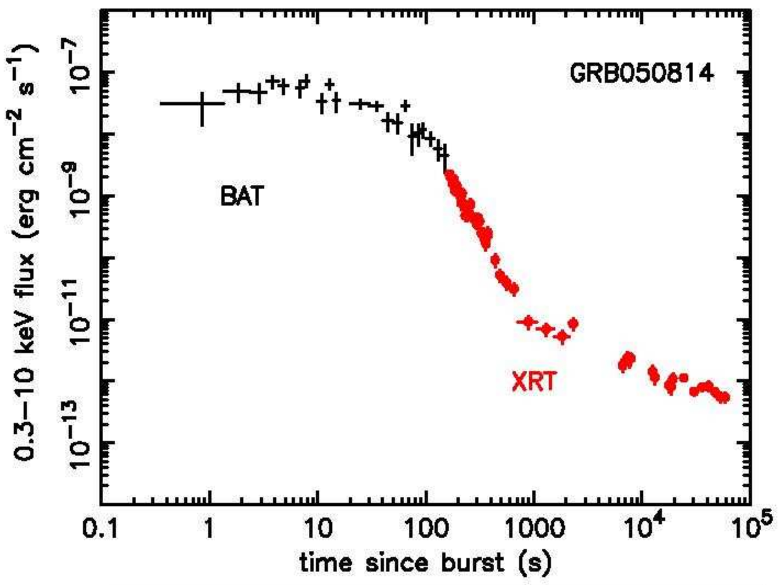
Panaitescu & Kumar 2001



Gamma-ray bursts : emission mechanisms

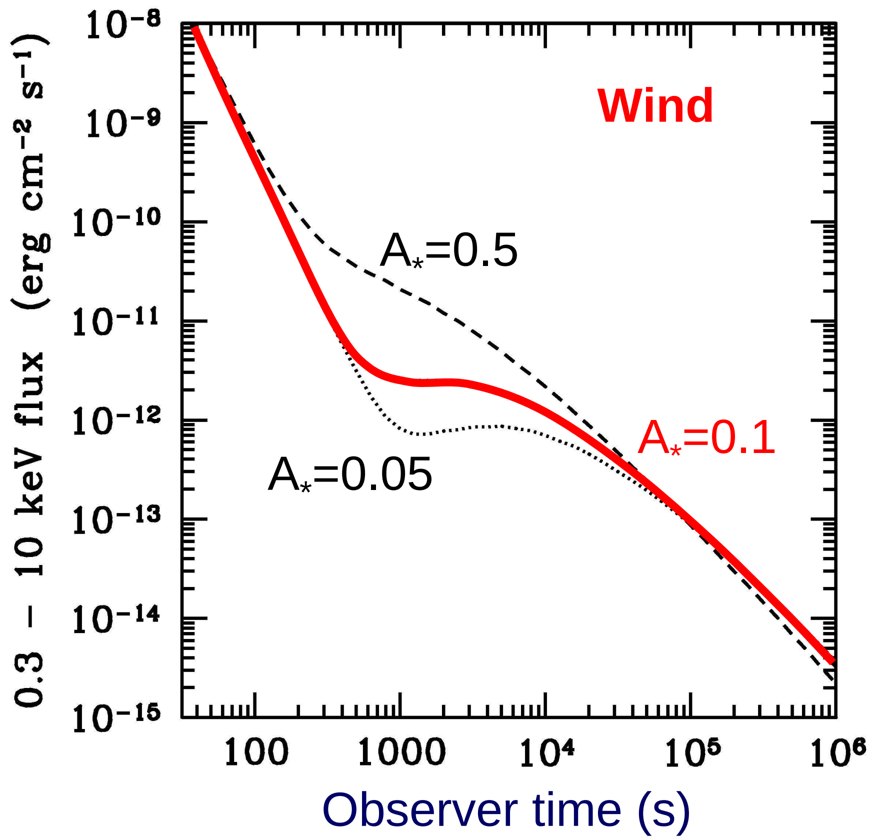
XRT observations :

O'Brien et al. 2006



Long-lived RS model :

Genet, Daigne & Mochkovitch 2007 :



Gamma-ray bursts : the central engine

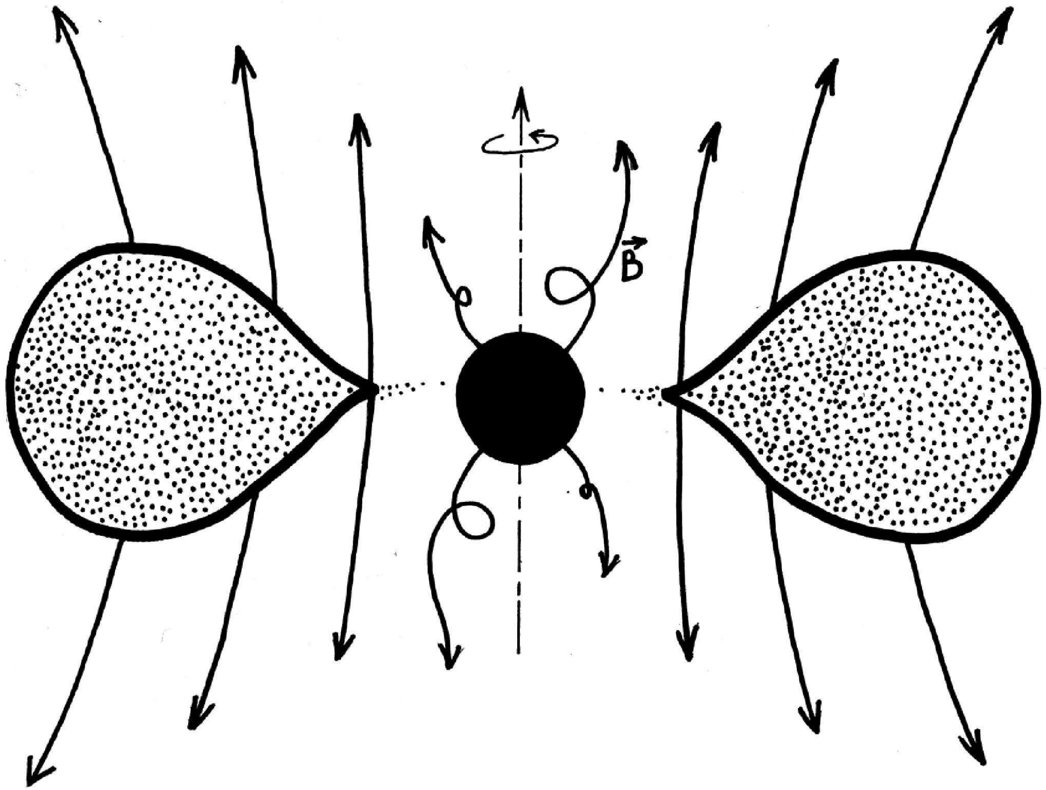
A thick disc surrounding a stellar mass black hole :

- Shortest variability timescale ~ ms (orbital period in the inner region of the disc)

- Energy reservoirs : (i) accretion

  (ii) BH rotation (extracted by Blandford-Znajek process)

Alternative : magnetars…



Gamma-ray bursts : initial event

Initial event responsible for the formation of the BH + thick disc system :

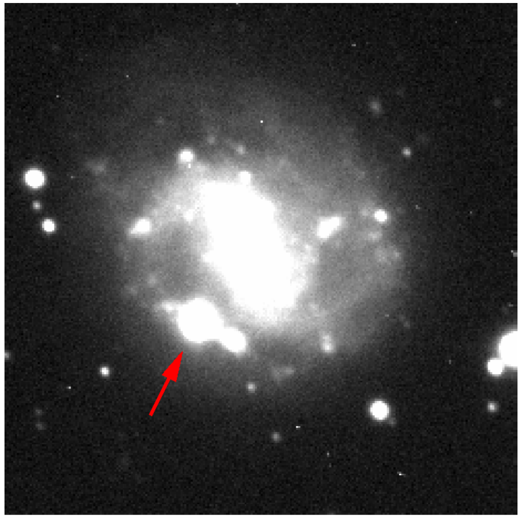
- Gravitational collapse of a massive star into a black hole (« collapsar » model) ;

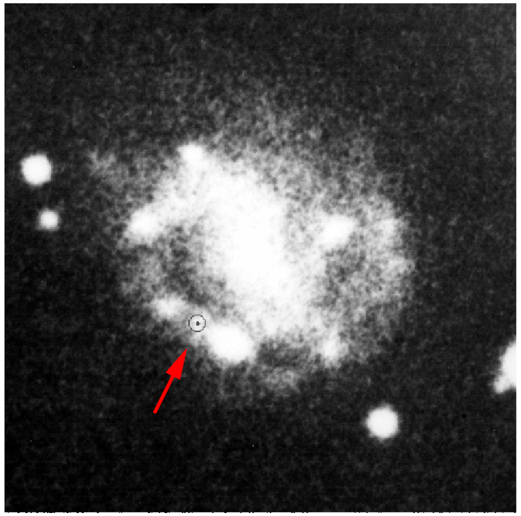
This model is favored for long GRBs (SN association, association with star formation, …)

- Some GRBs are associated with supernovae (e.g. GRB 980425, GRB 030329)

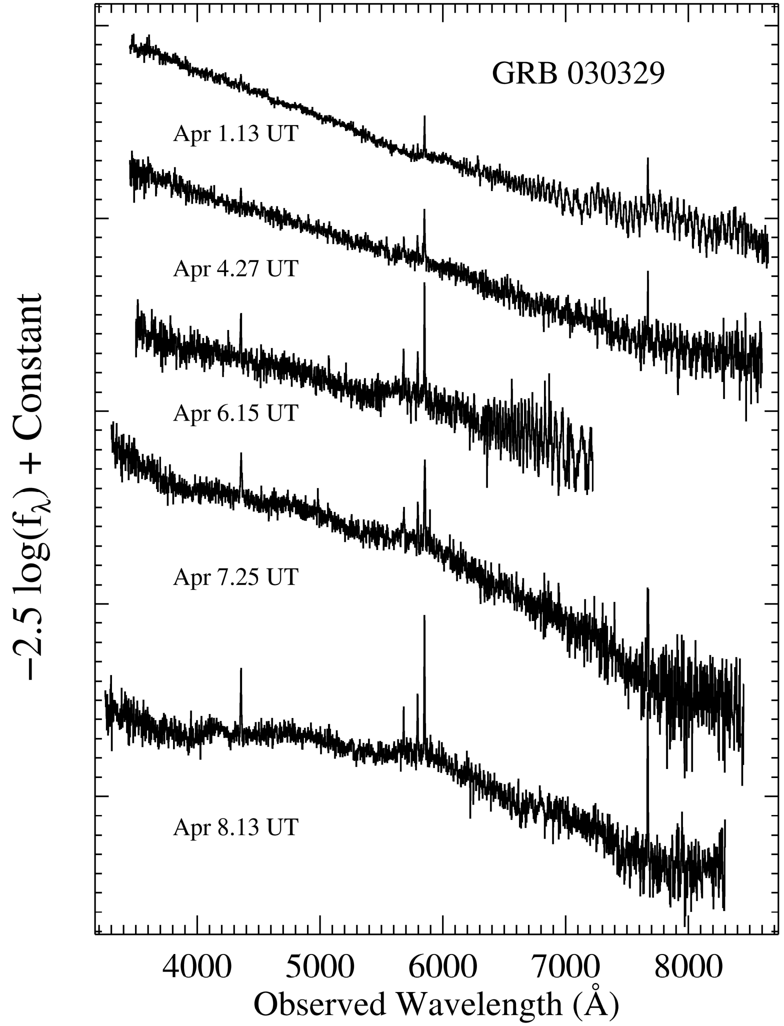
Long GRBs are associated with massive stars

GRB 980425 / SN 1998bw
z=0.008 (Galama et al. 1998)





GRB 030329 / SN 2003dhr
z=0.168 (Stanek et al. 2003)



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- Some GRBs are associated with supernovae (e.g. GRB 980425, GRB 030329)
- Some are not (e.g. GRB 060505 :
  nearby burst, $z = 0.09$, intense photometric/spectroscopic searches :
  no visible SN, Fynbo et al. 06; Gal-Yam et al. 06, Della Valle et al. 06)

In the framework of the « collapsar » model, we should always expect a supernova in association with a gamma-ray burst ?

Gamma-ray bursts : initial event

Initial event responsible for the formation of the BH + thick disc system :

THE ASTROPHYSICAL JOURNAL, 524:262–289, 1999 October 10

COLLAPSARS: GAMMA-RAY BURSTS AND EXPLOSIONS IN "FAILED SUPERNOVAE"

A. I. MACFADYEN AND S. E. WOOSLEY
Department of Astronomy, University of California, Santa Cruz, Santa Cruz, CA 95064; andrew@ucolick.org; woosley@ucolick.org
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ABSTRACT

Using a two-dimensional hydrodynamics code (PROMETHEUS), we explore the continued evolution of rotating helium stars, $M_\alpha \gtrsim 10\ M_\odot$, in which iron-core collapse does not produce a successful outgoing shock but instead forms a black hole of 2–3 $M_\odot$. The model explored in greatest detail is the 14 $M_\odot$ helium core of a 35 $M_\odot$ main-sequence star. The outcome is sensitive to the angular momentum. For $j_{16} \equiv j/(10^{16}\ \mathrm{cm^2\ s^{-1}}) \lesssim 3$, material falls into the black hole almost uninhibited. No outflows are expected. For $j_{16} \gtrsim 20$, the infalling matter is halted by centrifugal force outside 1000 km where neutrino losses are negligible. The equatorial accretion rate is very low, and explosive oxygen burning may power a weak equatorial explosion. For $3 \lesssim j_{16} \lesssim 20$, however, a reasonable value for such stars, a compact disk forms at a radius at which the gravitational binding energy can be efficiently radiated as neutrinos or converted to beamed outflow by magnetohydrodynamical (MHD) processes. These are the best candidates for producing gamma-ray bursts (GRBs). Here we study the formation of such a disk, the associated flow patterns, and the accretion rate for disk viscosity parameter $\alpha \approx 0.001$ and 0.1. Infall along the rotational axis is initially uninhibited, and an evacuated channel opens during the first few seconds. Meanwhile the black hole is spun up by the accretion (to $a \approx 0.9$), and energy is dissipated in the disk by MHD processes and radiated by neutrinos. For the $\alpha = 0.1$ model, appreciable energetic outflows develop between polar angles of 30° and 45°. These outflows, powered by viscous dissipation in the disk, have an energy of up to a few times 10^{51} ergs and a mass $\sim 1\ M_\odot$ and are rich in ^{56}Ni. They constitute a supernova-like explosion by themselves. Meanwhile accretion through the disk is maintained for approximately 10–20 s but is time variable ($\pm 30\%$) because of hydrodynamical instabilities at the outer edge in a region where nuclei are experiencing photodisintegration. Because the efficiency of neutrino energy deposition is sensitive to the accretion rate, this instability leads to highly variable energy deposition in the polar regions. Some of this variability, which has significant power at 50 ms and overtones, may persist in the time structure of the burst. During the time followed, the average accretion rate for

Gamma-ray bursts : initial event

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This model is favored for long GRBs (SN association, association with star formation, …)

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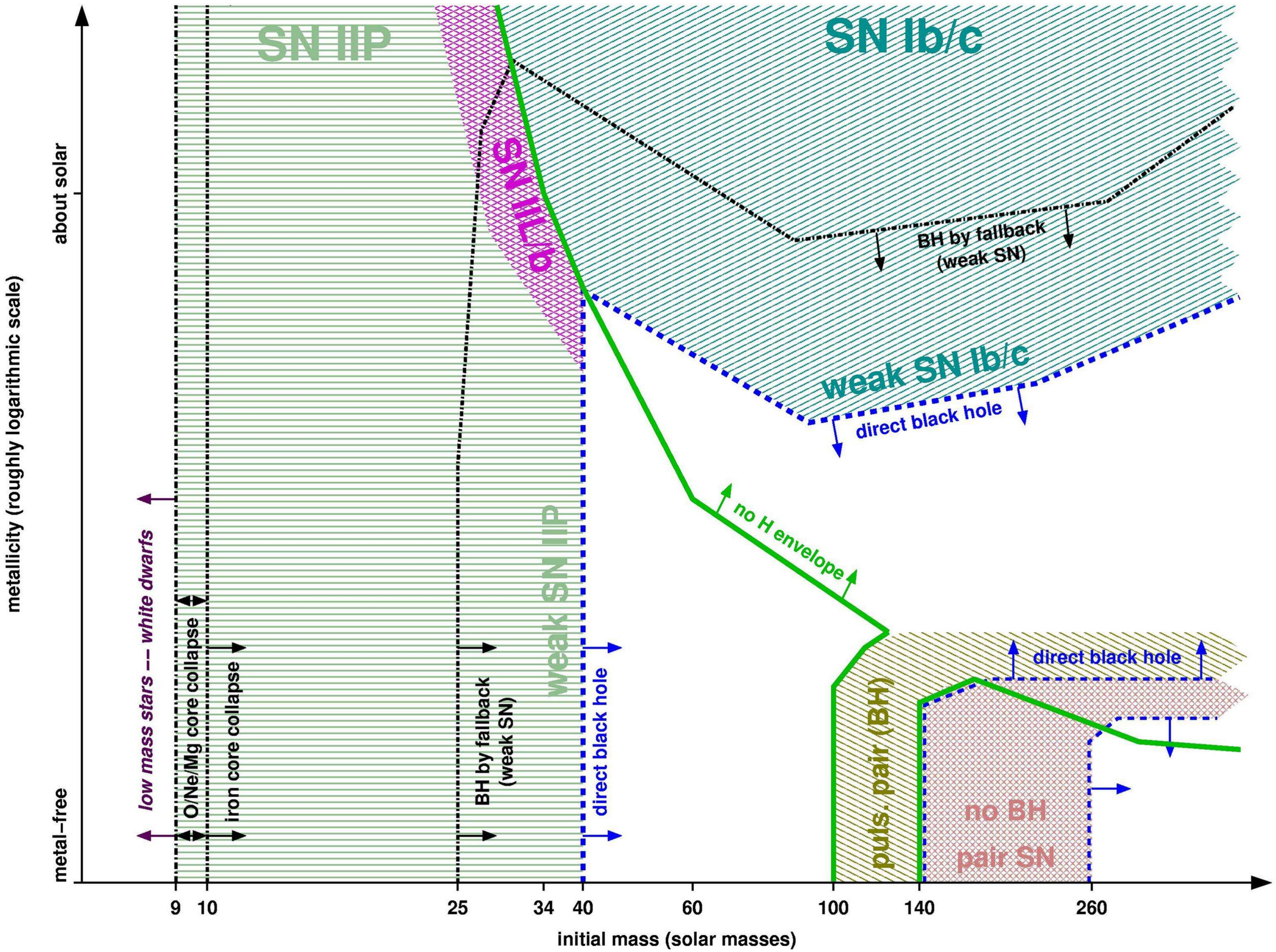
In the framework of the « collapsar » model, we should always expect a supernova in association with a gamma-ray burst ? **no !**

Stellar collapse :
- direct collapse into a NS : normal SN (type : II, Ib, Ic depending on the mass of the progenitor)
- direct collapse into a BH : original collapsar model, a GRB is possible, a supernova is a priori excluded (but…)
- two-steps collapse : (i) NS ; (ii) BH. A GRB is possible, a supernova is expected.

Gamma-ray bursts : initial event



Heger & Woosley

Gamma-ray bursts : initial event

Initial event responsible for the formation of the BH + thick disc system :

- Gravitational collapse of a massive star into a black hole (« collapsar » model) ;

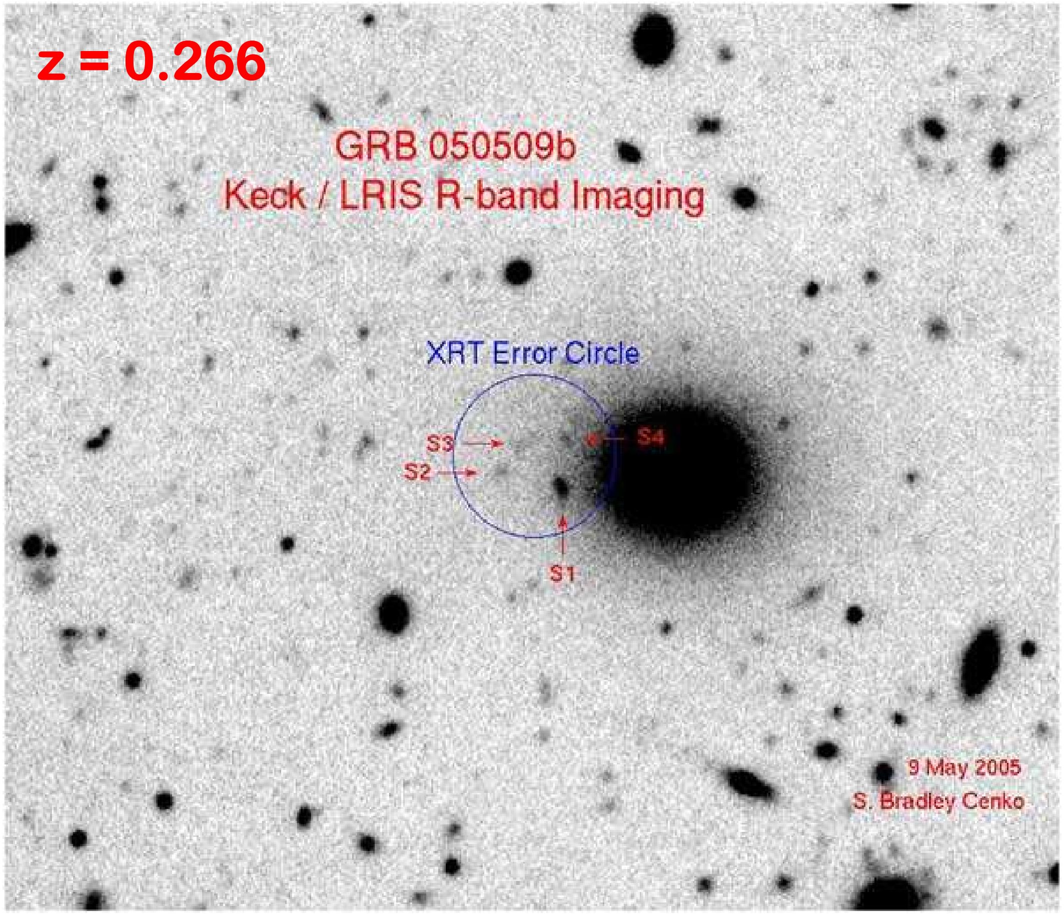
- Coalescence of two neutron stars (or BH/NS merger).

Often suggested for short GRBs, still uncertain.

Short GRBs : NS-NS mergers ?

Weak optical afterglows

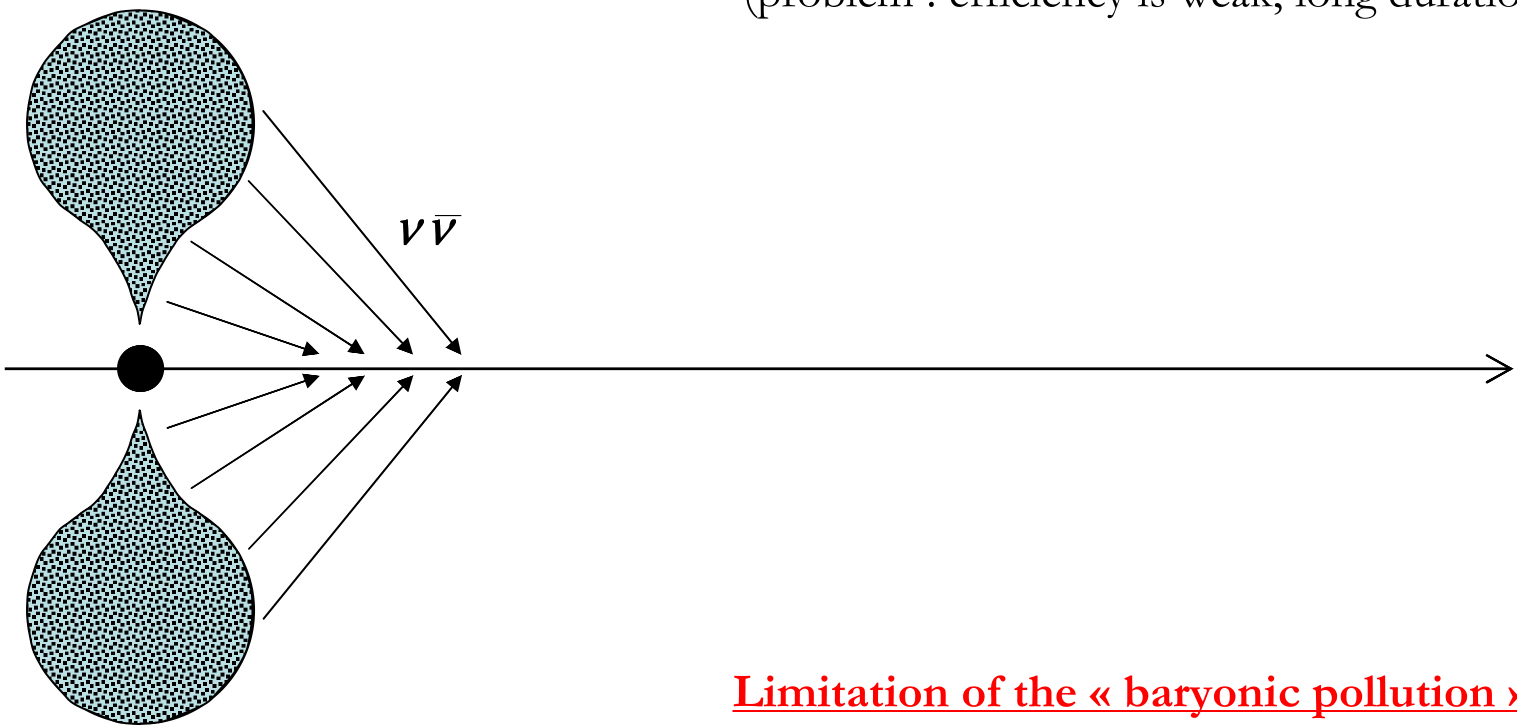
Host : **elliptical : 4**
irregular : 1
starforming : 1…



Gehrels et al. 2005

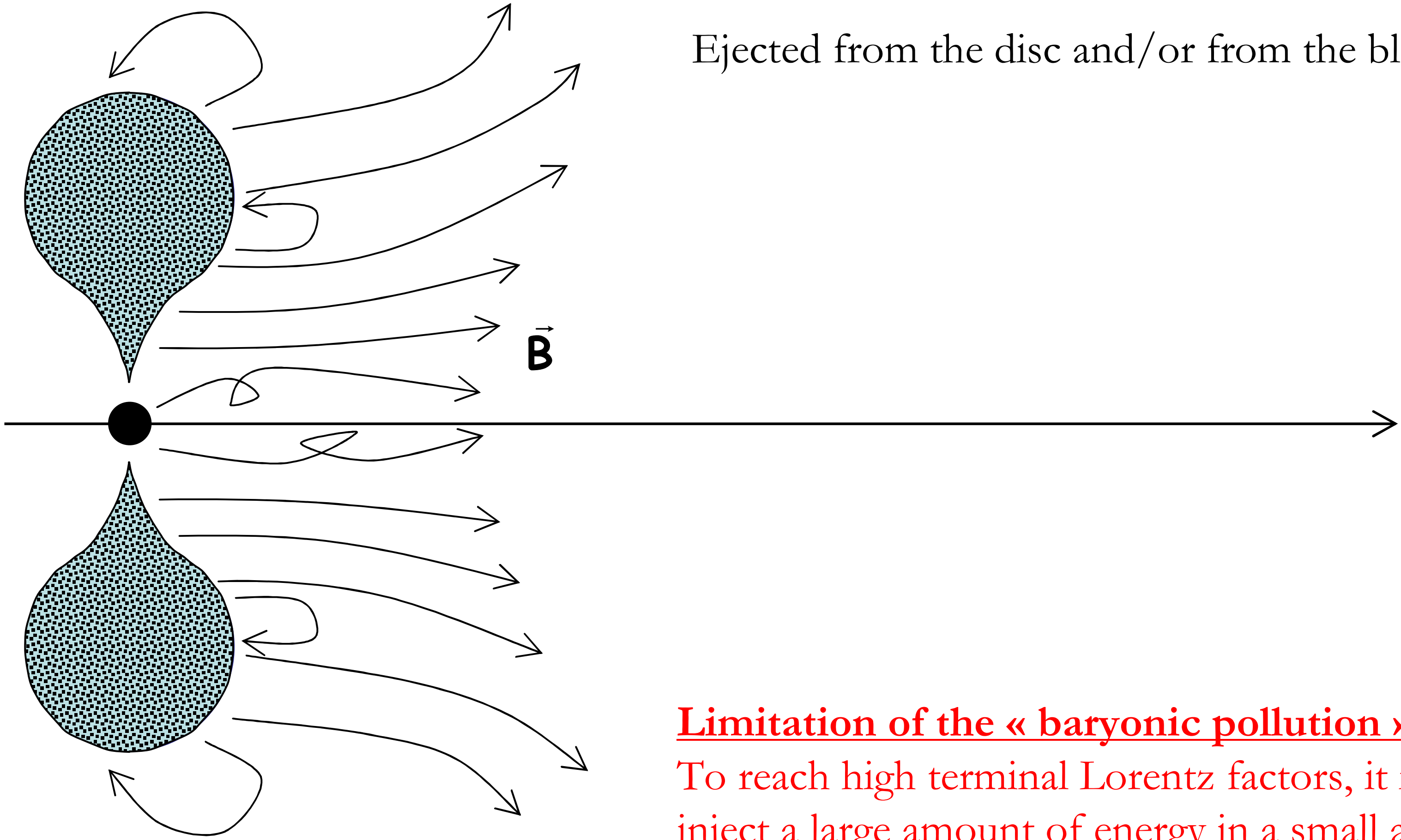
Gamma-ray bursts : relativistic ejection

Neutrino-antineutrino annihilation
along the rotation axis of the system
(problem : efficiency is weak, long duration is difficult)



Limitation of the « baryonic pollution » :
To reach high terminal Lorentz factors, it is necessary to inject a large amount of energy in a small amount of matter, i.e. to have $E / Mc^2 >> 1$.

Gamma-ray bursts : relativistic ejection



MHD outflow

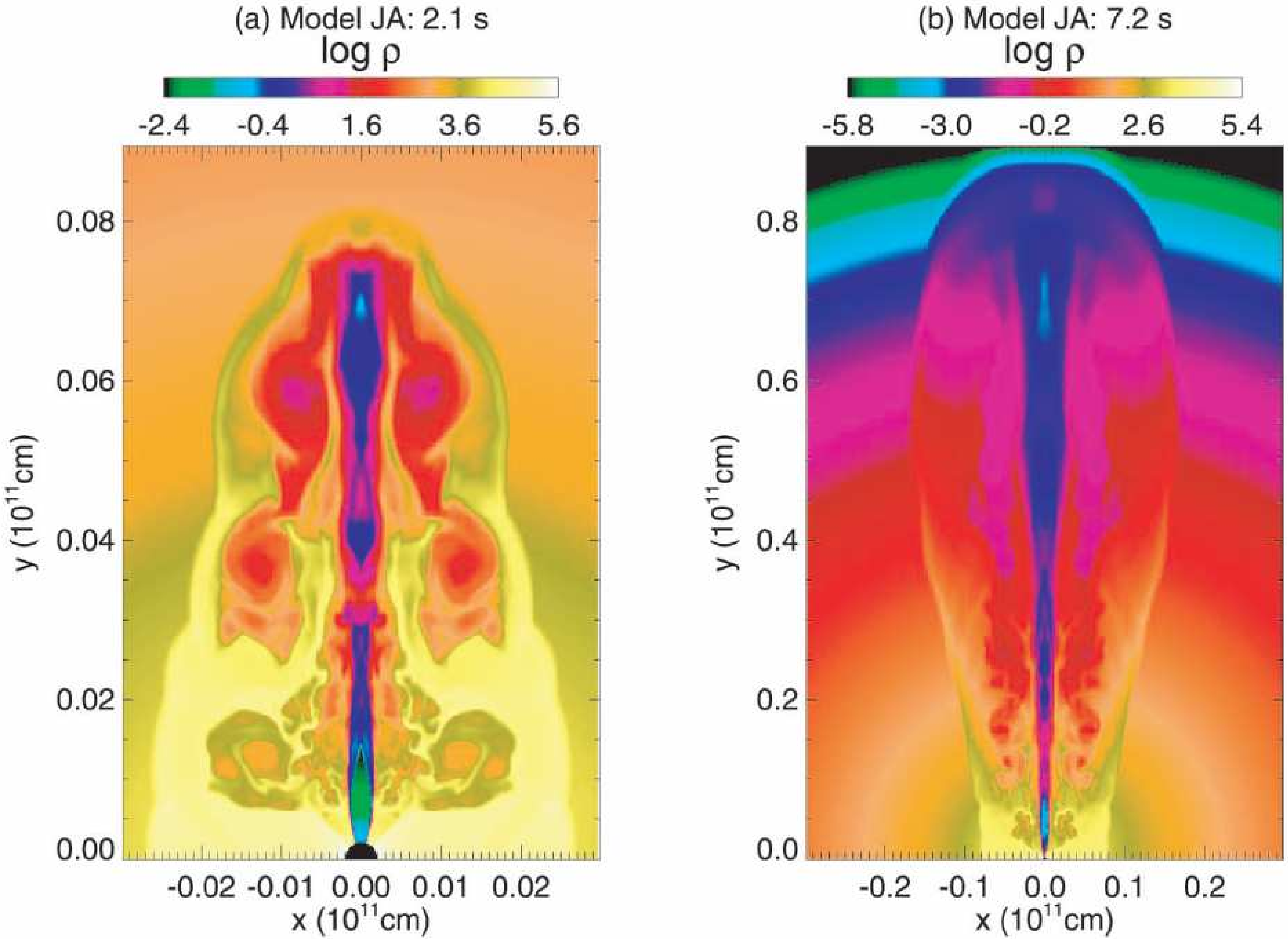
Ejected from the disc and/or from the black hole

Limitation of the « baryonic pollution » :

To reach high terminal Lorentz factors, it is necessary to inject a large amount of energy in a small amount of matter, i.e. to have $E / Mc^2 >> 1$.

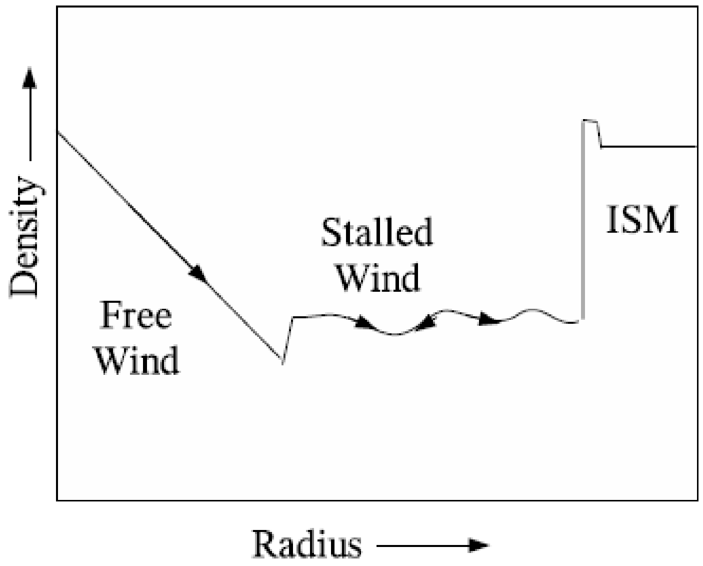
Gamma-ray bursts : escaping a collapsing star

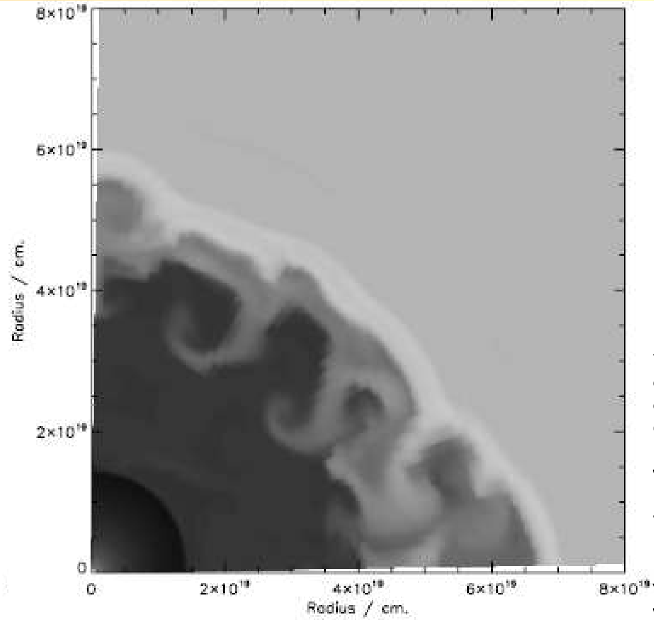
Zhang, Woosley & MacFadyen 2003

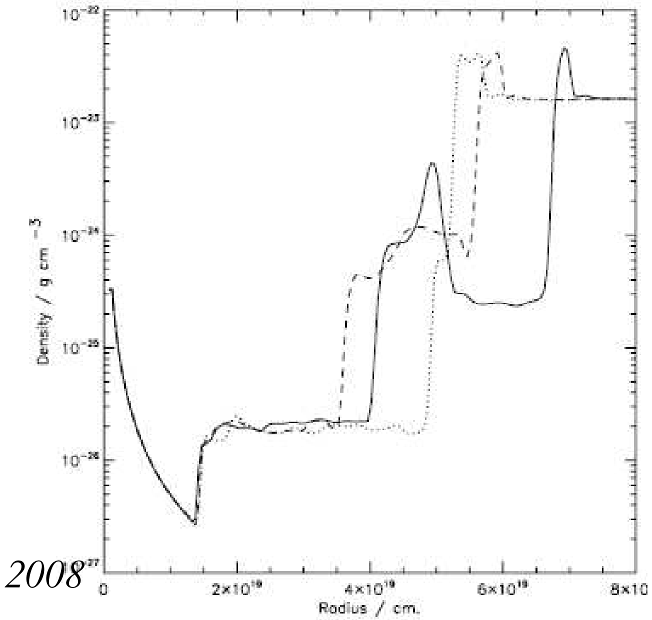


Gamma-ray bursts : propagating in a dense medium ?

A complex circumburst environment is expected :







Eldridge, Genet, Daigne & Mochkovitch 2006

Afterglow fits using the external shock model : usually a low-density uniform medium is prefered !

e.g. GRB 030329 n ~ 2 cm^{-3} (Berger et al. 2003)

Weak stellar wind ? (van Marle 2007, Chen et al. 2007, …)

Gamma-ray bursts : rates

Gamma-ray bursts pointing towards the Earth :

~ 1 GRB for 10^6 supernovae (this ratio could vary with z)

True rate :

× beaming correction ~ 1000 ? (Frail et al.)

(see also Soderberg et al.)

How to produce a Gamma-Ray Burst ?

Summary :

- A highly relativistic / highly energetic outflow ejected by a compact source (BH) seems necessary to explain the observed properties of GRBs;

- For **long GRBs**, the event responsible for the formation of the central engine is most probably the collapse of a massive star.

  The detailed conditions (mass, metallicity, rotation, …) that are necessary for a star to produce a gamma-ray burst are very poorly understood.

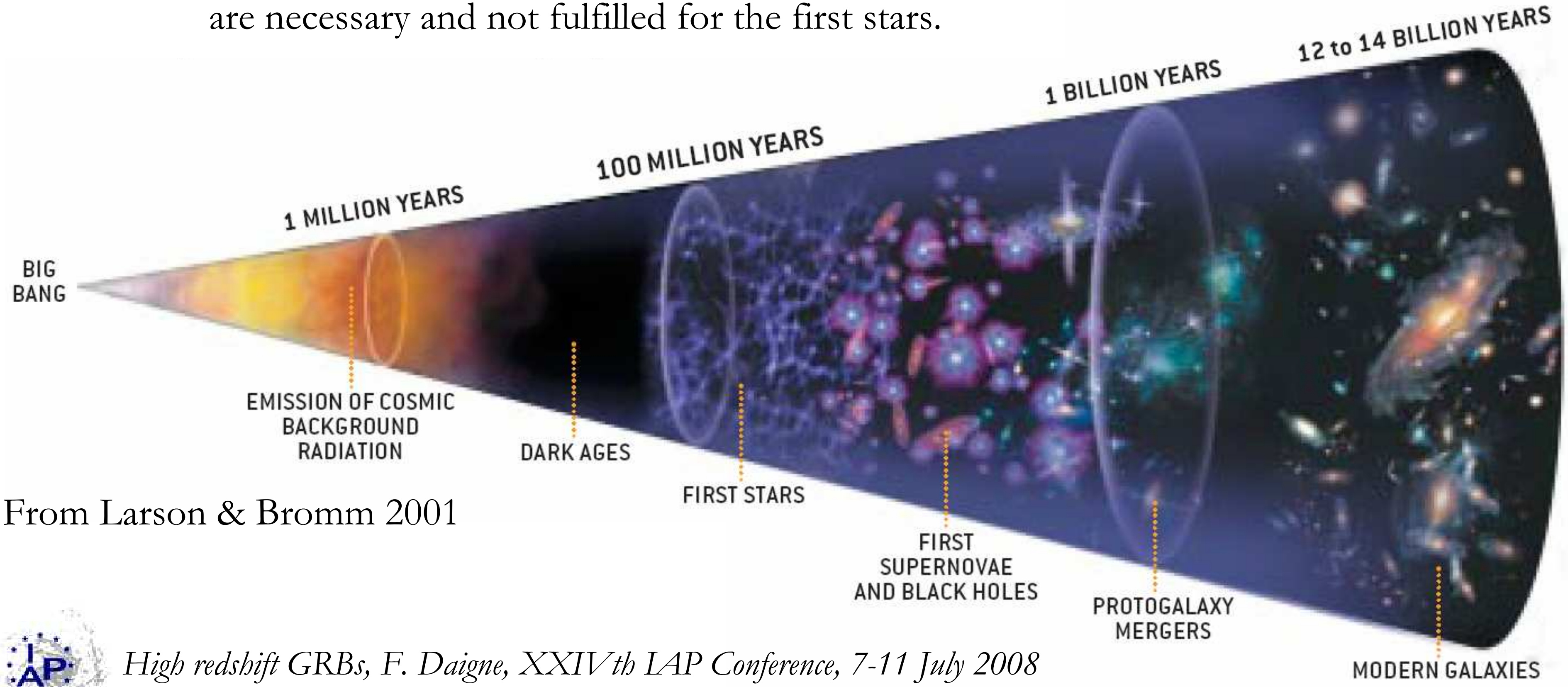
  Long GRBs should occur in star-forming regions. The circumburst medium should be dominated by the matter ejected by the progenitor.

- The status of short GRBs is less clear. If the NS+NS merger scenario is correct, they should occur far from the center of their host galaxy, in a low density medium, and have weak afterglows. They should not occur at very high redshift.

Should we expect high redshift (long) GRBs ?

Yes - because first massive stars are expected at very high redshift ($z \sim 30$);
- a low metallicity seems to favor the production of gamma-ray bursts.

No - if the first massive stars do not end as a black hole (PISNae) or collapse entirely into a black hole;
- if other conditions that are not identified (rotation, binarity, …) are necessary and not fulfilled for the first stars.

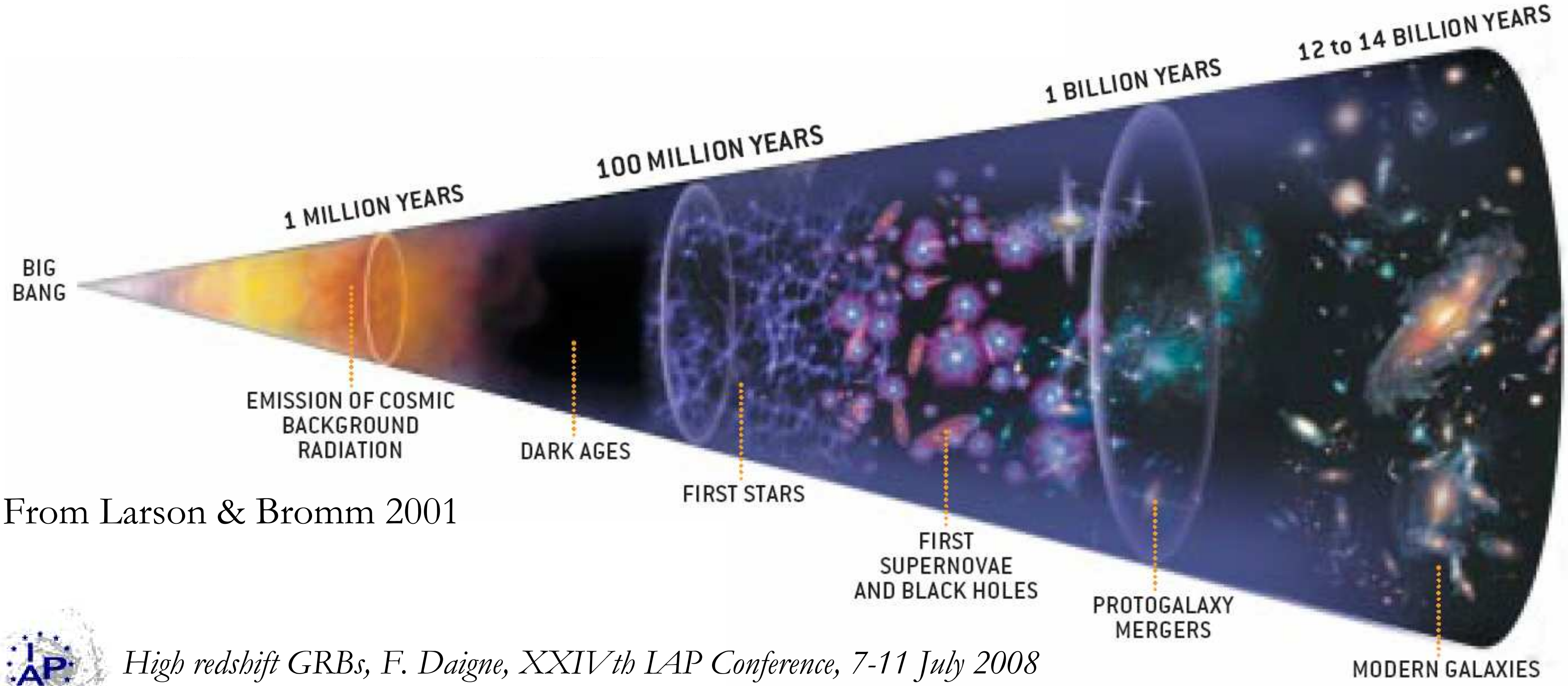


From Larson & Bromm 2001

Should we expect high redshift (long) GRBs ?

In the redshift range z ~ 6 - 10 : yes, very probably

as massive stars in the same mass range as in the low-redshift Universe are already formed and a large range of metallicities can be expected in star-forming structures at this epoch.



From Larson & Bromm 2001

Can we detect high-redshift GRBs ?

Prompt emission : - GRBs are intrinsically very bright
- the Universe is transparent for low energy gamma-rays.

Yes ! - it has already be done (GRB 050904 at $z = 6.3$)
- for a GRB with a known redshift, one can estimate the maximum redshift allowing detection with a given instrument : in many cases, $z \sim 10$ or higher.

Afterglow : - one needs to search for the afterglow as soon as possible after the trigger :

Yes but it is difficult.

for an observation at t_{obs} = 10 minutes :

t = 5 minutes at z=1
t = 2 minutes at z = 4
t = 1 minute at z = 9
in the source frame

the increase of D_L can be partially compensated by the increase of the instrinsic luminosity (afterglows are decaying sources).

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Yes but it is difficult… - one needs to observe in infrared (visible is absorbed).

See e.g. discussion in Lamb & Reichart 2000

Can we detect high-redshift GRBs ?

(1) GRB detection :

t_0 satellite with real-time localization (1')

t_0 +10s transmission to the ground

SWIFT
SVOM (2012), ...

(2) Afterglow detection : **SWIFT/XRT**

t_0 +30s robotic telescope : localization (1")

t_0 +1-2 min real-time transmission

+ infrared is needed (high-redshift / dust)

RAPTOR, REM, ROTSE, TAROT, ...

(3) Afterglow follow-up :

t_0 +1-2min→weeks photometry (early times « small telescopes »)

e.g. GROND, see Greiner's talk

t_0 +1-2min→hours minimal spectroscopy : redshift

high-resolution spectroscopy (large telescopes)

KECK
VLT/UVES
VLT/XSHOOTER ('08)

+ infrared is needed (high-redshift / dust)

An exemple :

GRB 060418 : Vreeswijk et al. 2007

Trigger by SWIFT/BAT :	t_0	3'
X-ray afterglow SWIFT/XRT :	t_0+1min	5"
VLT/UVES using the « rapid response mode » : (+ a human astronomer at t_0+7 min to align the UVES slit (1") on the afterglow)	t_0+10 min	1"

Spectra at **t_0+11, 16, 25, 41, 71 min**
resolving power 7 km/s
S/N = 10-15

Soon :

XSHOOTER @ VLT
is a spectrometer (UV, V, IR) especially designed for such studies (first light : end of 2008)

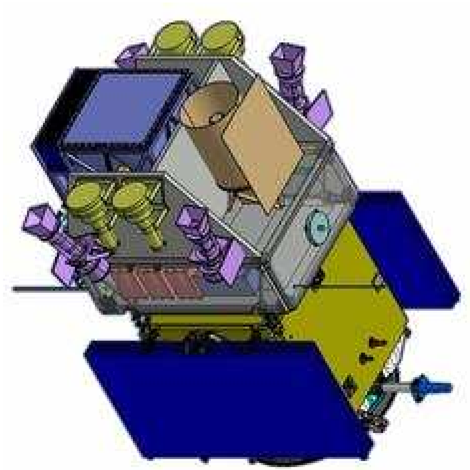
Real time alerts with accurate positions

- **Swift** still funded for at least 3 more years;

- **GLAST** : -low energy (GBM) : large error boxes (~ BATSE)
  - high-energy (LAT) : accurate positions (expected rate ?)

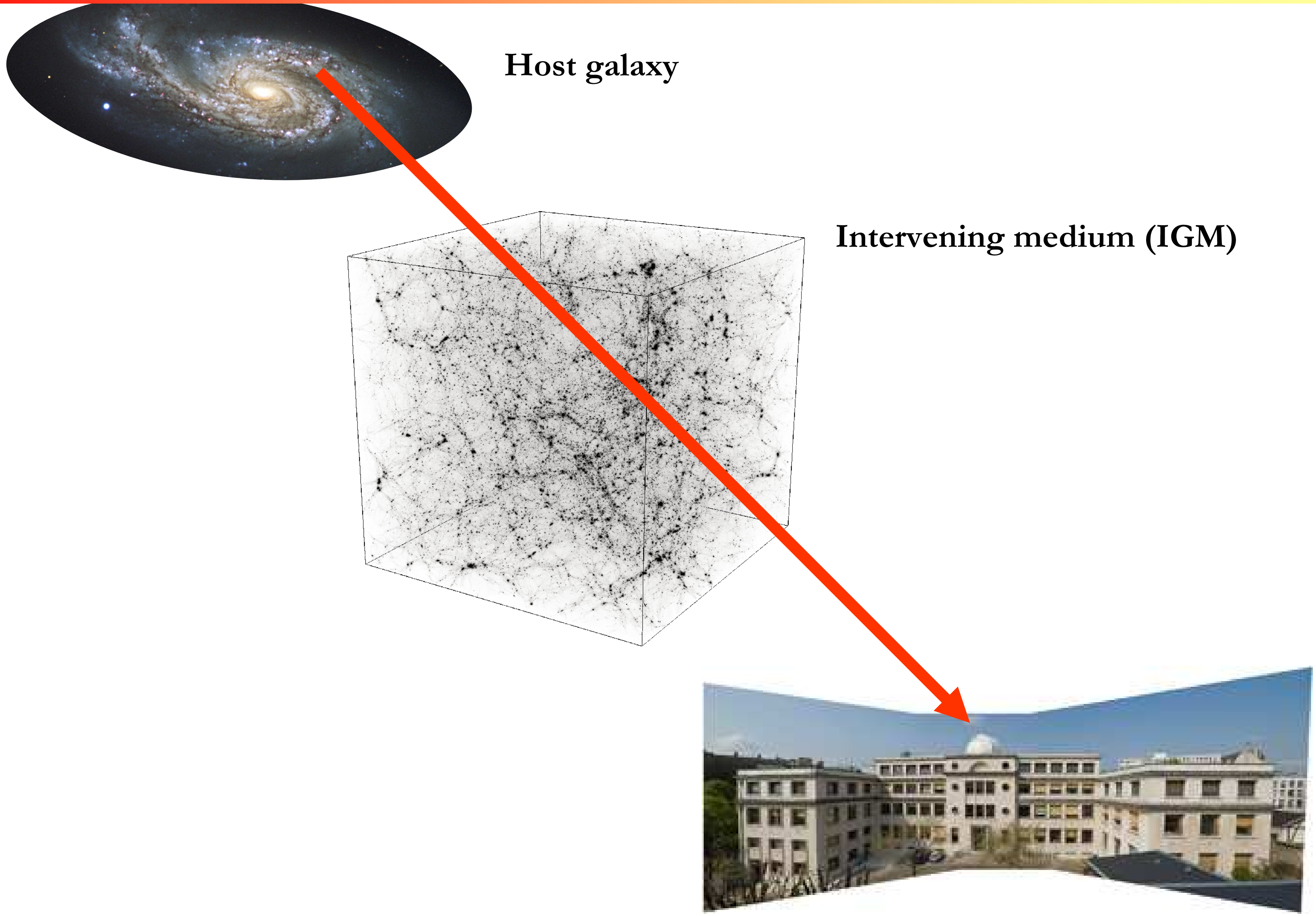
- Future missions : several projects have been proposed

SVOM : a Sino-French satellite to be launched in 2012.

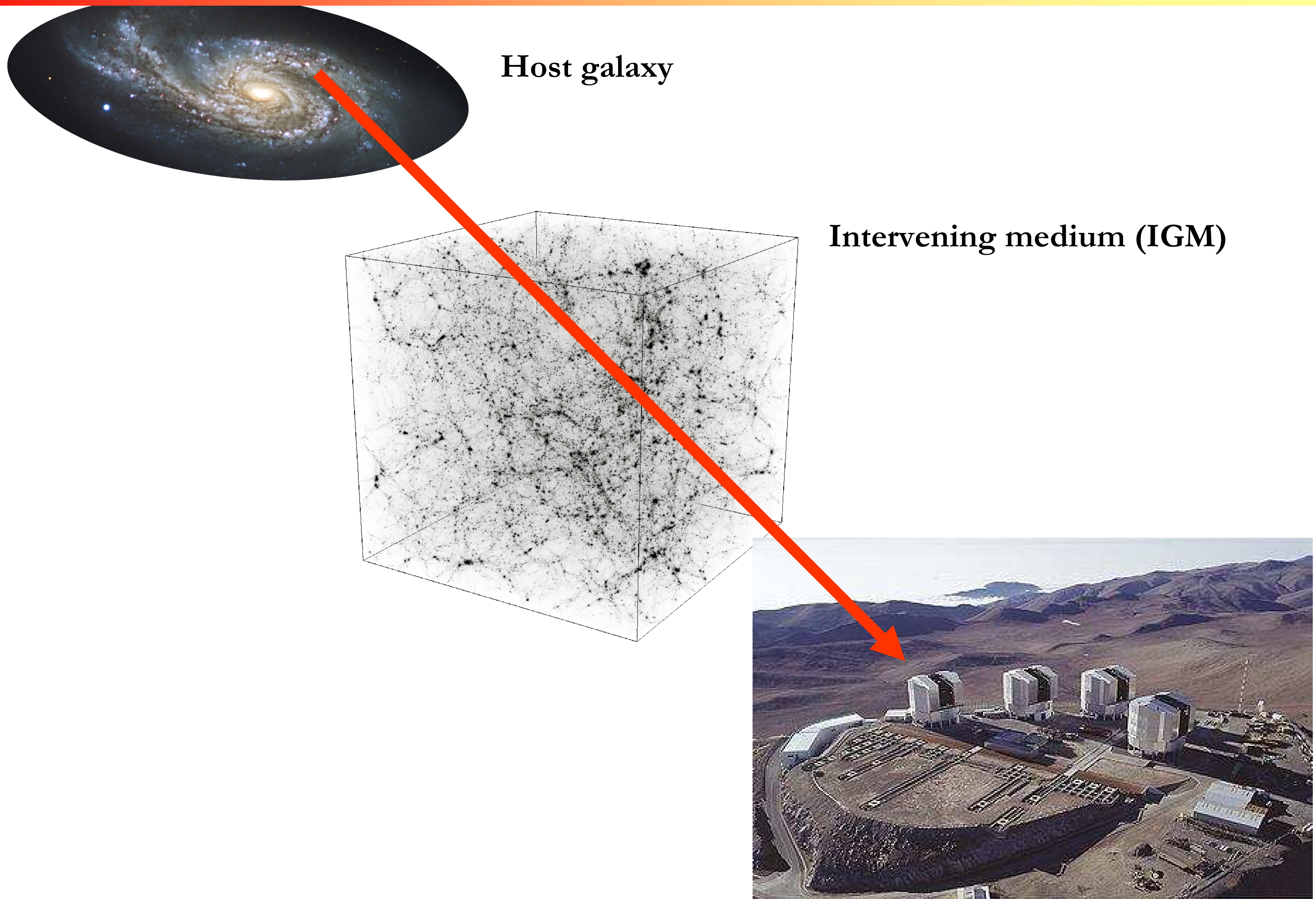


- gamma-ray telescope (coded mask) trigger + real time position (4-300 keV)
- gamma-ray detector (50 keV-5 MeV)
- X-ray telescope
- Optical telescope
+ 2 robotic ground-based telescopes (GFC)
+ GWAC (prompt optical)

GRBs and cosmology : afterglow spectroscopy



GRBs and cosmology : afterglow spectroscopy



GRBs and cosmology : afterglow spectroscopy

Host galaxy :

- **a sample of high-redshift galaxies** (e.g. the study of the host of GRB 050904 at z=6.3 by Berger et al. 2007)
- **circumburst medium**
- **ISM**

Intergalactic medium

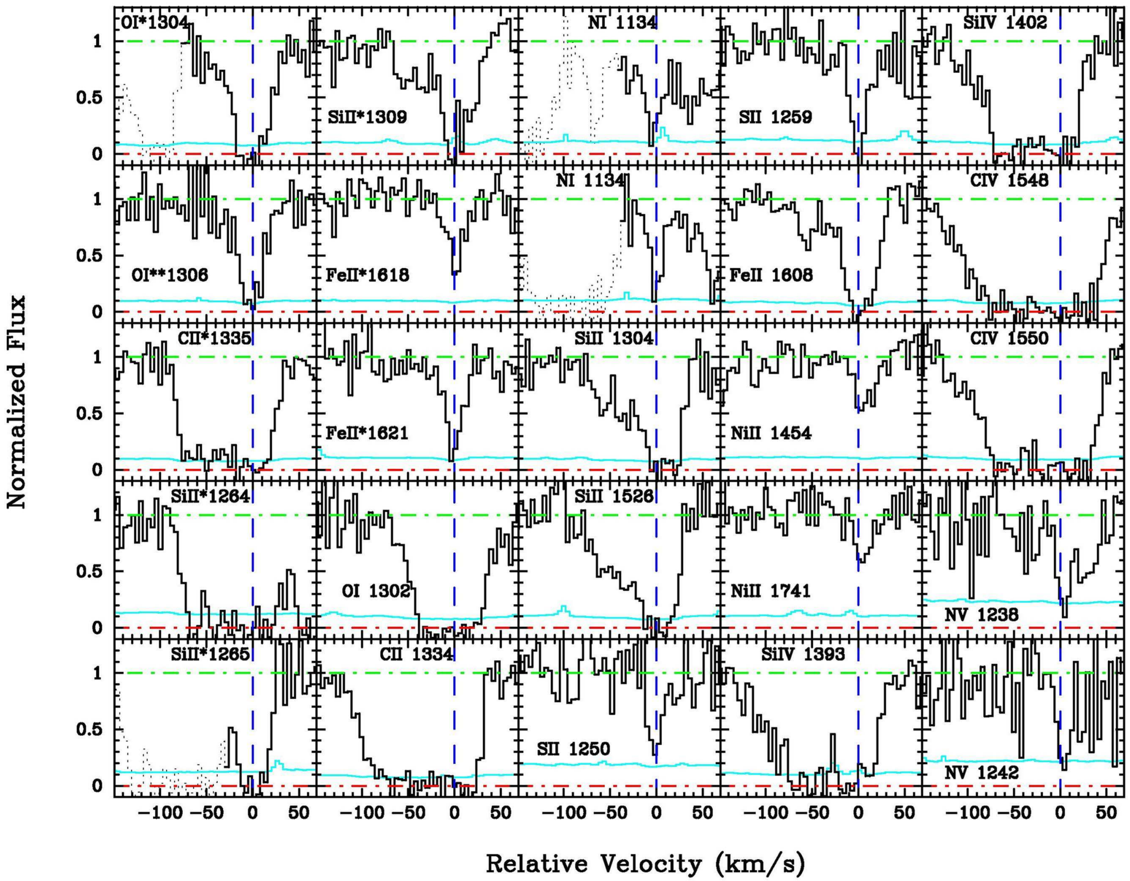
e.g. GRB 050730 z=3.969

(Chen et al. 05)

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



GRBs and cosmology : afterglow spectroscopy

Host galaxy : - a sample of high-redshift galaxies
- circumburst medium
- ISM

Intergalactic medium

► **Chemical evolution (structures, IGM) (see Sandra Savaglio's talk)**

► **Reionization ? The question of host-DLAs : GRBs occur in the central regions of galaxies : frequent association with HI absorption.**
(see Prochaska et al. 2007, McQuinn et al. 2007 and simulations by Nagamine et al. 2008)

► **QSOs vs GRBs : some differences e.g. frequency of MgII absorbers (see Poster P35 by Vergani et al. and discussion therein)**

GRBs and cosmology : tracing the SFR ?

GRB host galaxies can be studied, and this include the measurement of the SFR.

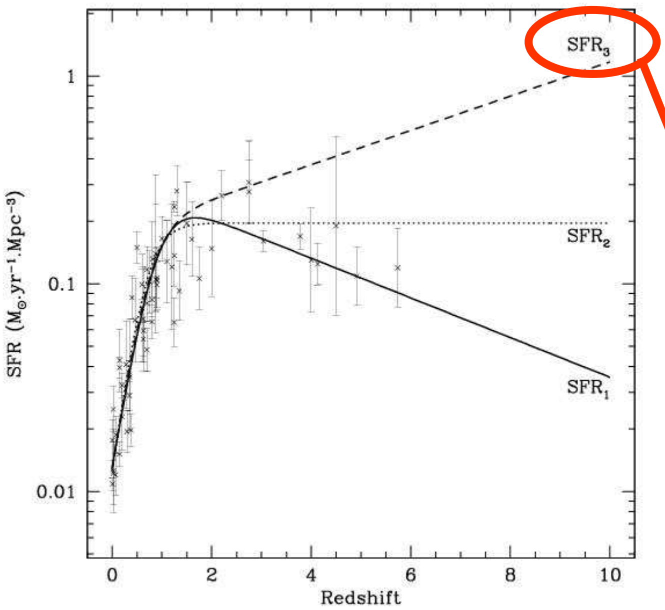
On the other hand, deducing the cosmic SFR directly from the GRB rate is probably not possible, as observations give some evidence that the GRB rate is not proportionnal to the SFR.

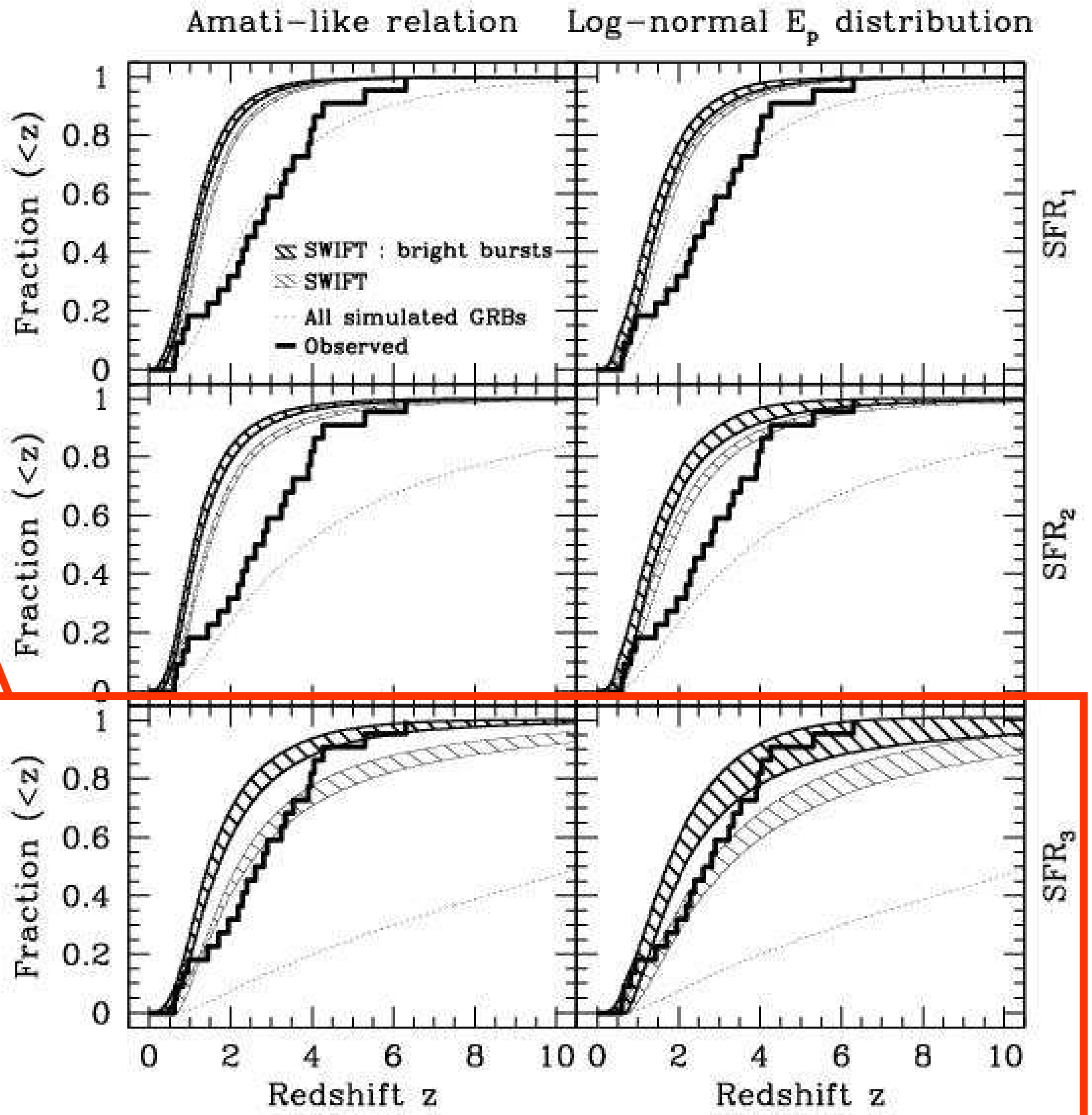
- GRBs occur usually in low-metallicity small blue galaxies, which are not representative of the star formation rate at a given redshift

Le Floch et al. 2003 ; Le Floch et al. 2006

- the observed GRB redshift distribution does not support the assumption that GRB trace the SFR (Daigne et al. 2006; Dermer et al. 2006; Piran & Guetta 2007).

GRBs and cosmology : tracing the SFR ?





Daigne, Rossi & Mochkovitch 2006

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The efficiency of GRB production by stars increase with z ?

see Poster 33 Lapi et al. and Poster 31 Campisi et al.

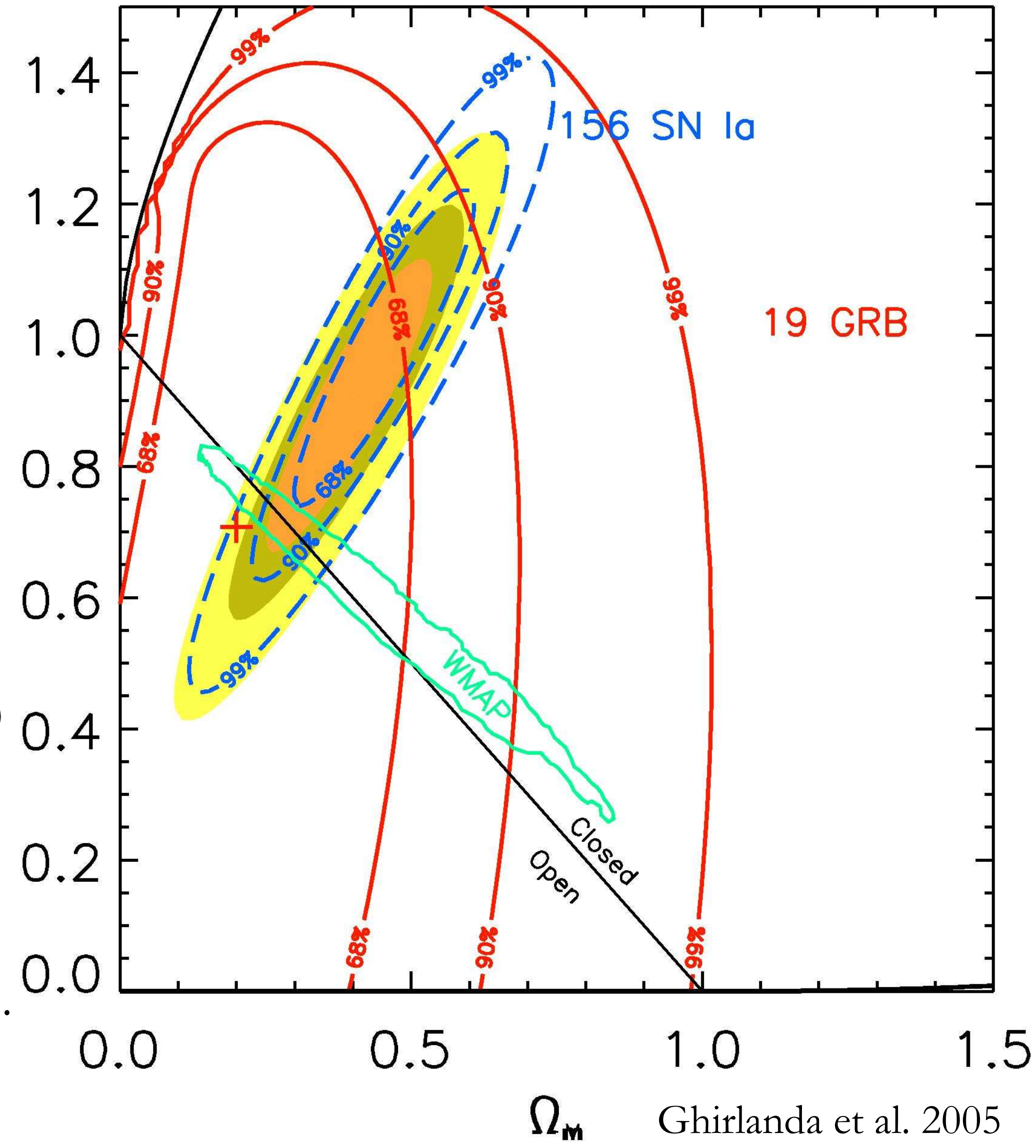
GRBs and cosmology : measuring (Ω_m,Ω_Λ) and even more ?

- GRBs are not standard candles ($E_{\gamma,iso} \sim 10^{50} - 10^{54}$ erg)

- Observed correlation could in principle be used to « standardize » GRBs (e.g. « Ghirlanda relation » between E_p and $E\gamma$)

However :
- The reality of these relations is debated (instrumental effects ? Physical origin ?)
- Dispersion is large.
- Calibration is difficult (low-z GRBs are rare)

On the other hand :
- high-z GRBs could help in separating cosmological models that differ only at high z.



Ghirlanda et al. 2005

Conclusion

12 years after the discovery of the first GRB afterglow :

- the strategy to discover afterglows when they are still very bright has been well identified. It involves a complex chain of instruments (γ-ray satellites, real time transmission of the position; automatic response by robotic telescope and large telescopes in rapid mode).

- this strategy is well illustrated by the efficiency of Swift.

First year of Swift :	INTEGRAL :	14 GRBs (2-3')	1 redshift
	HETE2 :	11 GRBs (2-15')	3 redshifts
	Swift	110 GRBs (2-4')	29 redshifts

- however the maximum redshift is « only » $z_{max} = 6.3$ and there are « only » 4 GRBs at $z > 5$. The full potential of using GRBs to probe the distant Universe is still not achieved.

(chemical evolution, reionization, host galaxy properties, …)

- Many new instruments are starting now or soon (e.g. GROND, XSHOOTER, …). Rapid follow-up in (near)-infrared band should help to identify higher redshift GRBs. Optimization of triggers could be necessary (Swift ? ; SVOM).