What we know, what we believe we know and what we don't know about the physics of gamma-ray bursts (GRBs)

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Outline

- What we know
- What we believe we know
- What we don't know (but we have some ideas…)

  … and what we really don't know
- Conclusion and perspectives

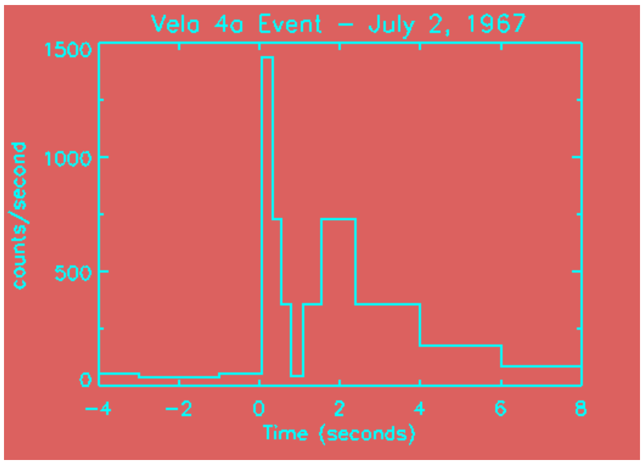
International Workshop on LHC, Astrophysics, Medical and Environmental Physics, Shkodra, 6-8 october 2014

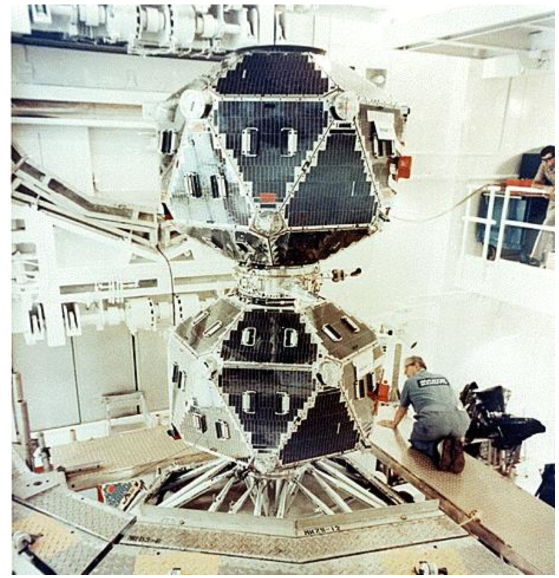
What we know

1) The distance scale

But it took 30 years !

1967: first GRB is observed by the Vela satellites





1973: discovery is first announced

OBSERVATIONS OF GAMMA-RAY BURSTS OF COSMIC ORIGIN

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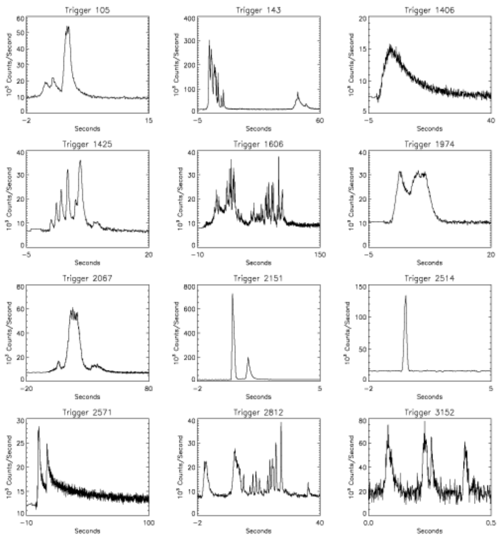
ABSTRACT

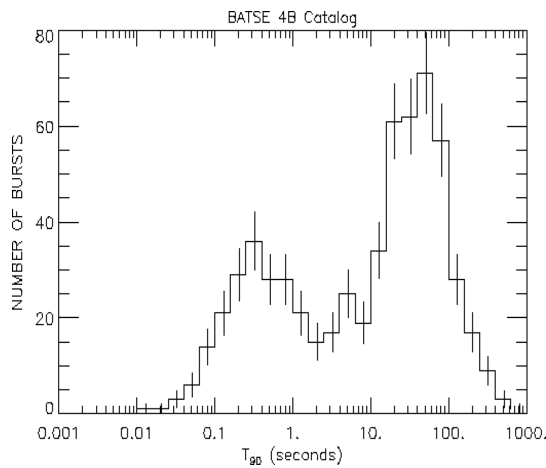
Sixteen short bursts of photons in the energy range 0.2–1.5 MeV have been observed between 1969 July and 1972 July using widely separated spacecraft. Burst durations ranged from less than 0.1 s to ~30 s, and time-integrated flux densities from $\sim10^{-5}$ ergs cm^{-2} to $\sim2 \times 10^{-4}$ ergs cm^{-2} in the energy range given. Significant time structure within bursts was observed. Directional information eliminates the Earth and Sun as sources.

1973 – 1997: GRBs observed in gamma-rays only

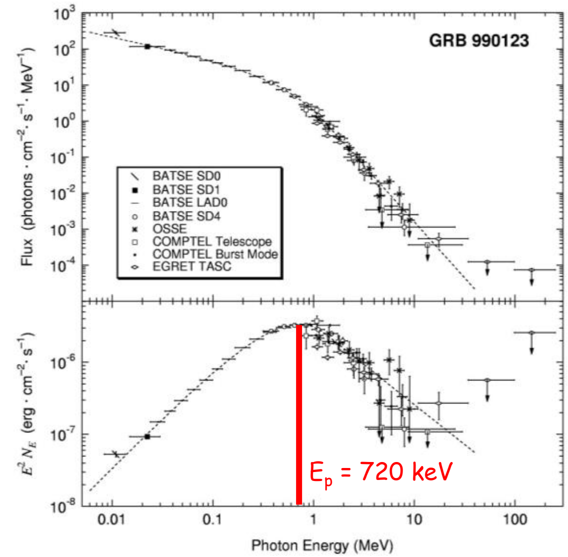
many results on the temporal and spectral properties



diversity of light curves



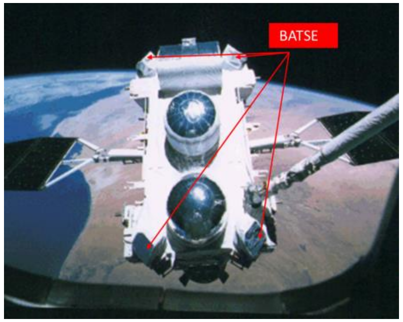
bimodal distribution of durations

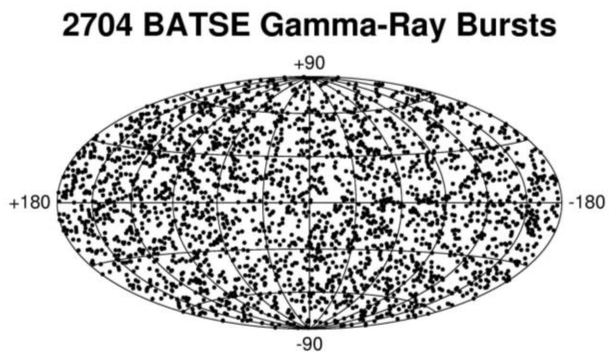


simple broken power-law spectra

No image → large error boxes in gamma-rays → no optical counterpart → no distance

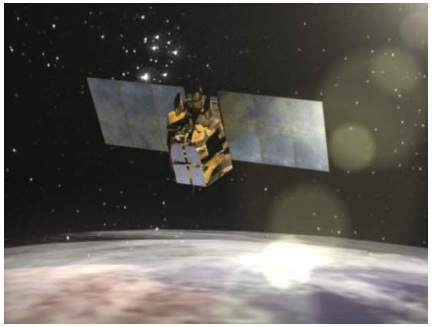
1991: BATSE experiment on board Compton GRO



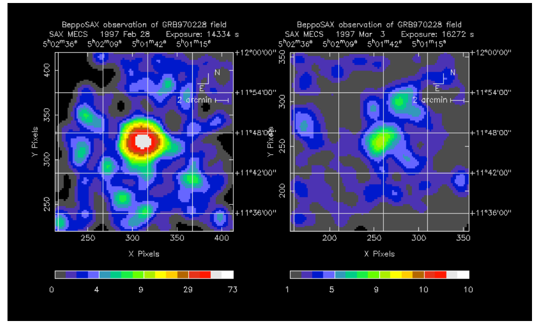


First hint of a cosmological distance scale

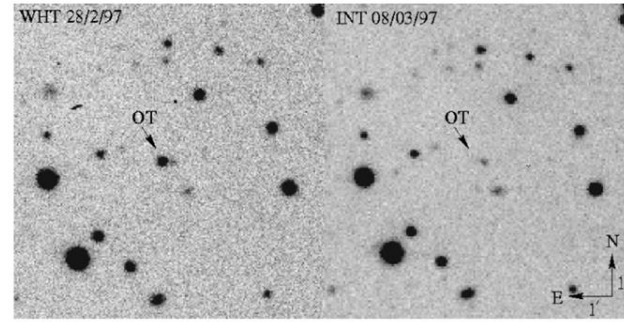
1997: Beppo-SAX and the afterglows



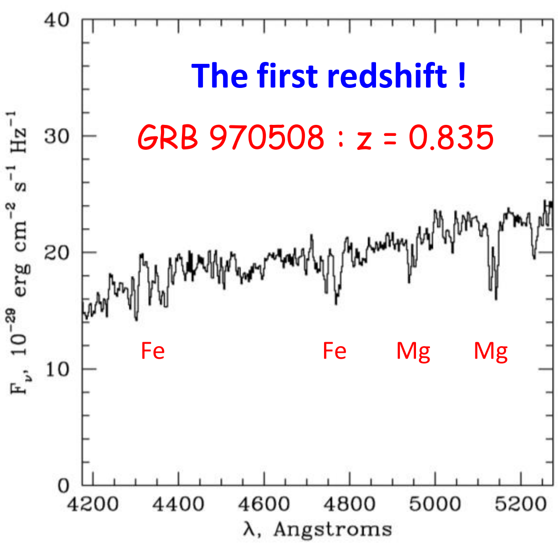
gamma-ray “telescope”
+ X-ray cameras

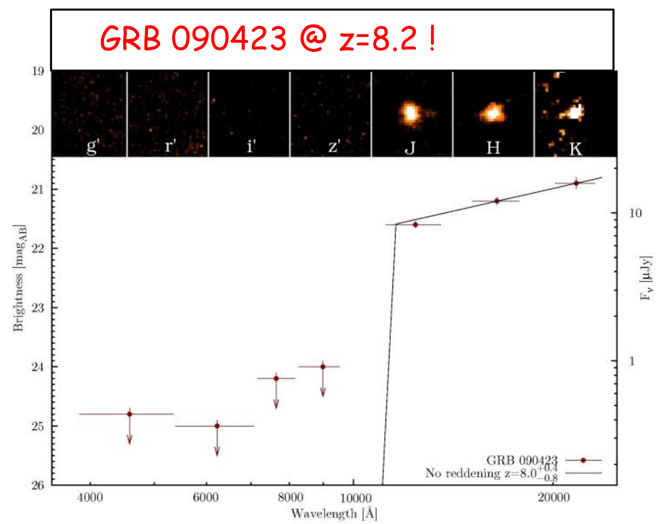


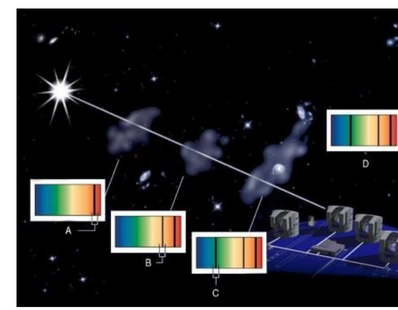
X-ray images (2/28 and 3/3)



the first optical counterpart !
(2/28 and 3/8)







absorption along the line of sight

Gamma-ray bursts are the most distant objects in the Universe !

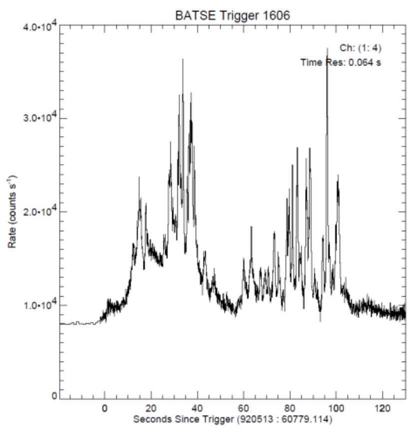
2) Gamma-ray bursts are produced within relativistic outflows

GRBs are the brightest sources in the Universe:

Cosmological distance scale $\rightarrow L_\gamma \sim 10^{17\text{-}18}\ L_\odot$!!! ($10^{8\text{-}9}$ galaxies)

(one single object can be as bright as the whole observable Universe!)

But the short time scale variability indicates that the sources are compact (δt = 1 ms $\leftrightarrow l$ = c δt = 300 km)



$\rightarrow$ huge photon density + spectrum extending beyond 511 keV

risk of extensive pair creation via $\gamma\gamma \rightarrow e^+e^-$: the "opacity problem"

Solution: the source is moving at relativistic velocity toward the observer $\rightarrow$
the energy of the observed photons is boosted by the relativistic factor $\Gamma = 1/\sqrt{(1-v^2/c^2)}$ and they are confined by relativistic beaming within an angle $1/\Gamma$

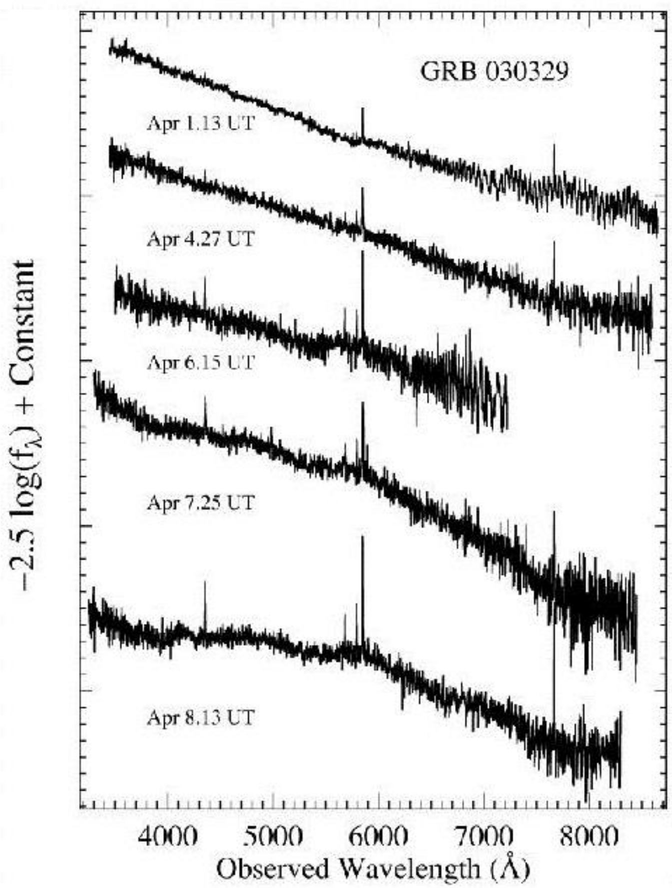
In the source rest frame the photon energy is much smaller
In the observer frame photons move along nearly parallel paths
$\rightarrow$ pair creation much reduced

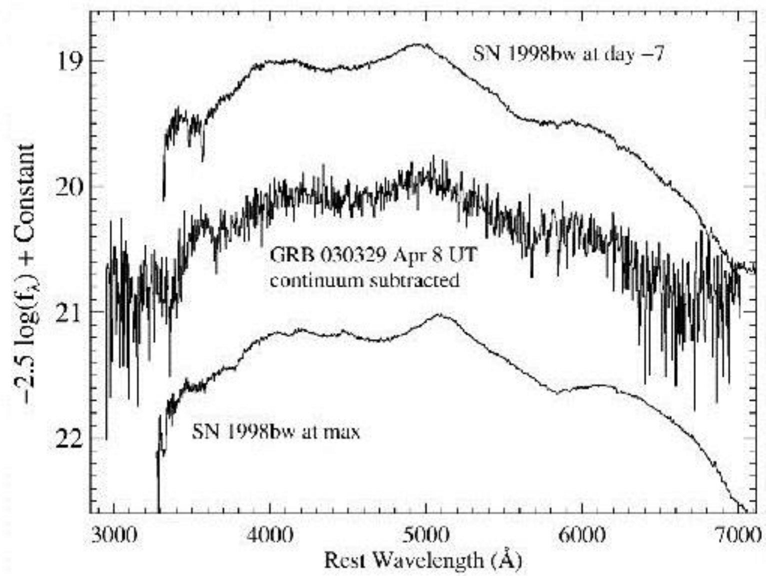
This imposes a lower limit on Γ of 100 – 1000 or v/c = 1 – ε with $\varepsilon \sim 10^{-5}$

3) Long GRBs (at least some of them) are produced in type Ic supernova explosions

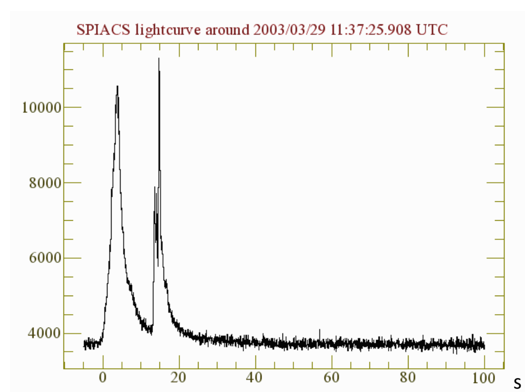
(Type Ic supernovae: exploding Wolf-Rayet stars)

Spectroscopic evidence: optical afterglow of GRB 030329 from 3 to 10 days after the burst





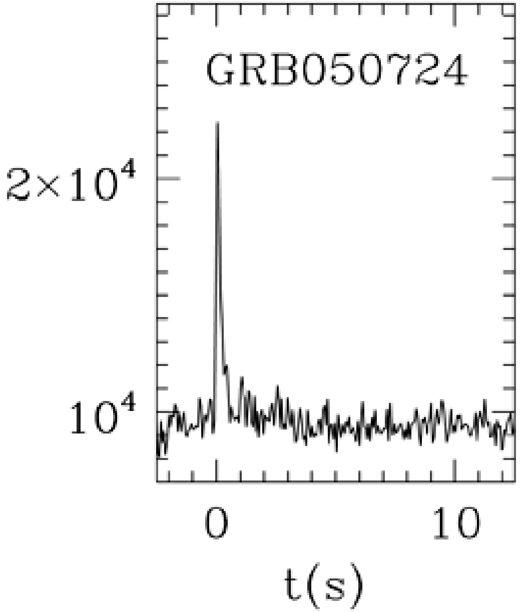
underlying type Ic supernova spectrum

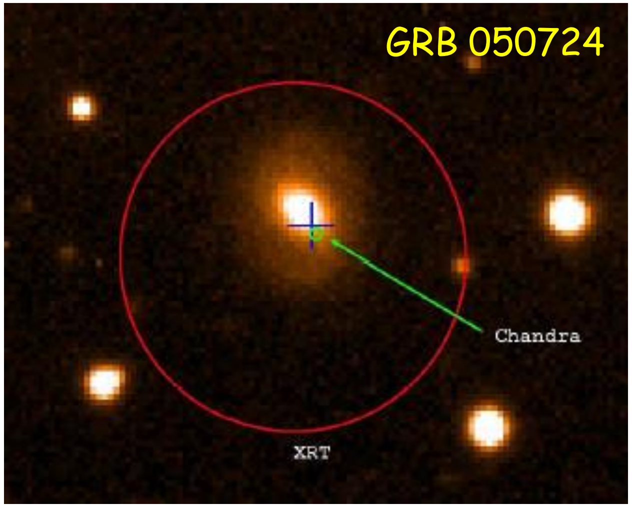


What we believe we know

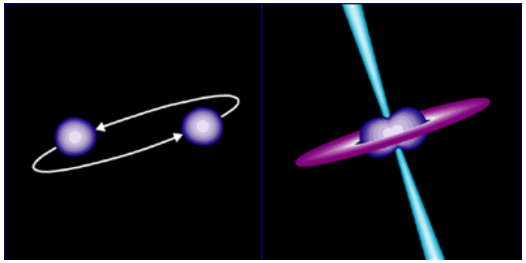
1) **Short GRBs are produced in the coalescence of two compact objects (2NS or 1NS + 1 BH)**

Several short bursts are associated to elliptical (non star forming) galaxies

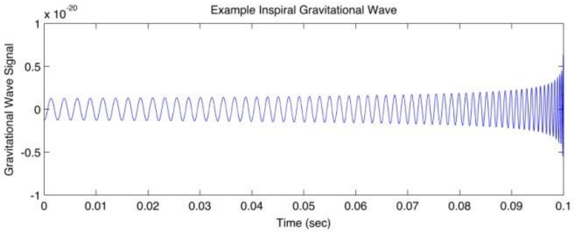




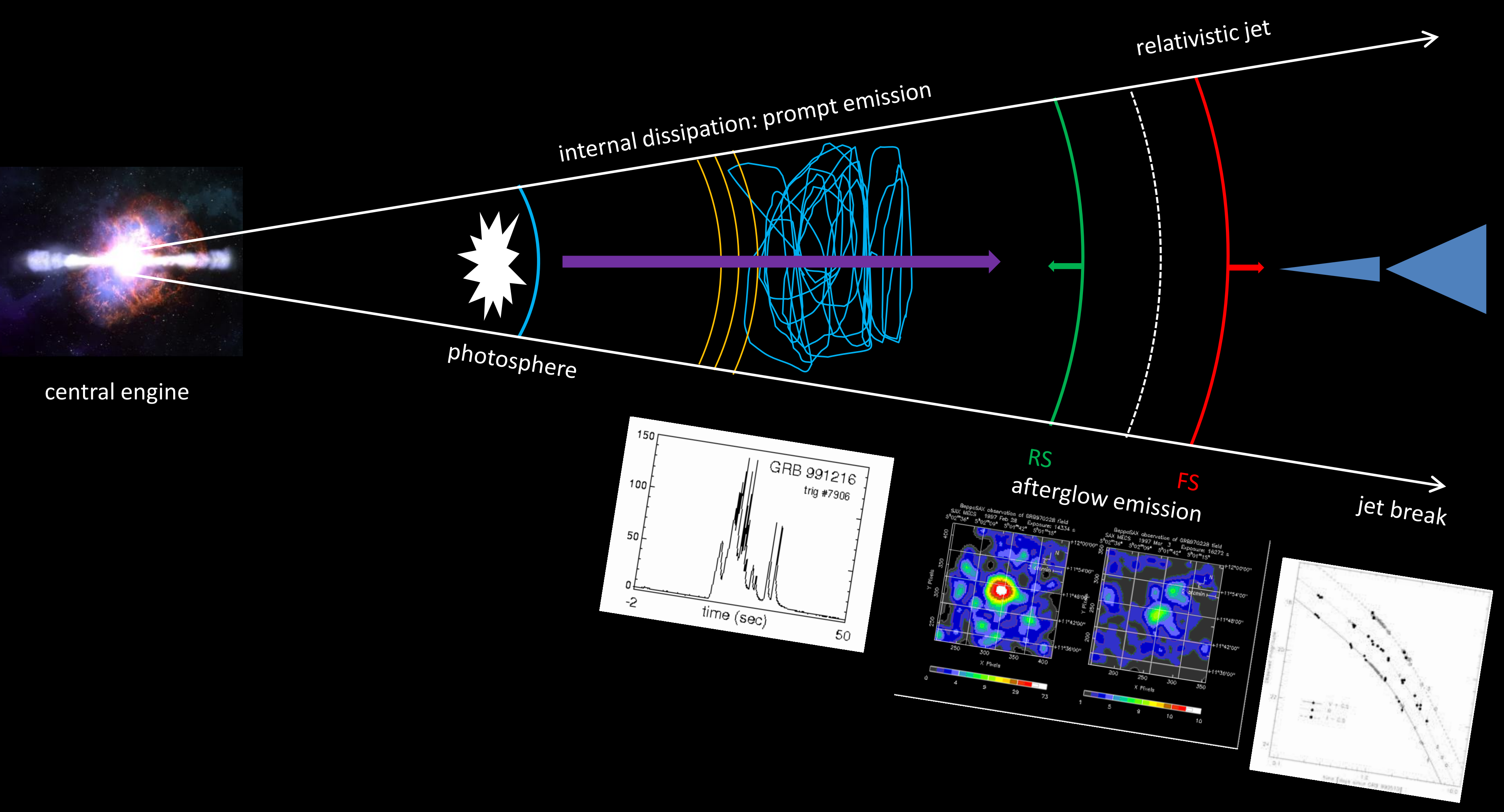
Wolf-Rayet star + type Ic supernova excluded
Best candidate: neutron star + neutron star merger



Confirmation expected in the coming years (2018+) from a gravitational wave signal in coincidence with a short GRB



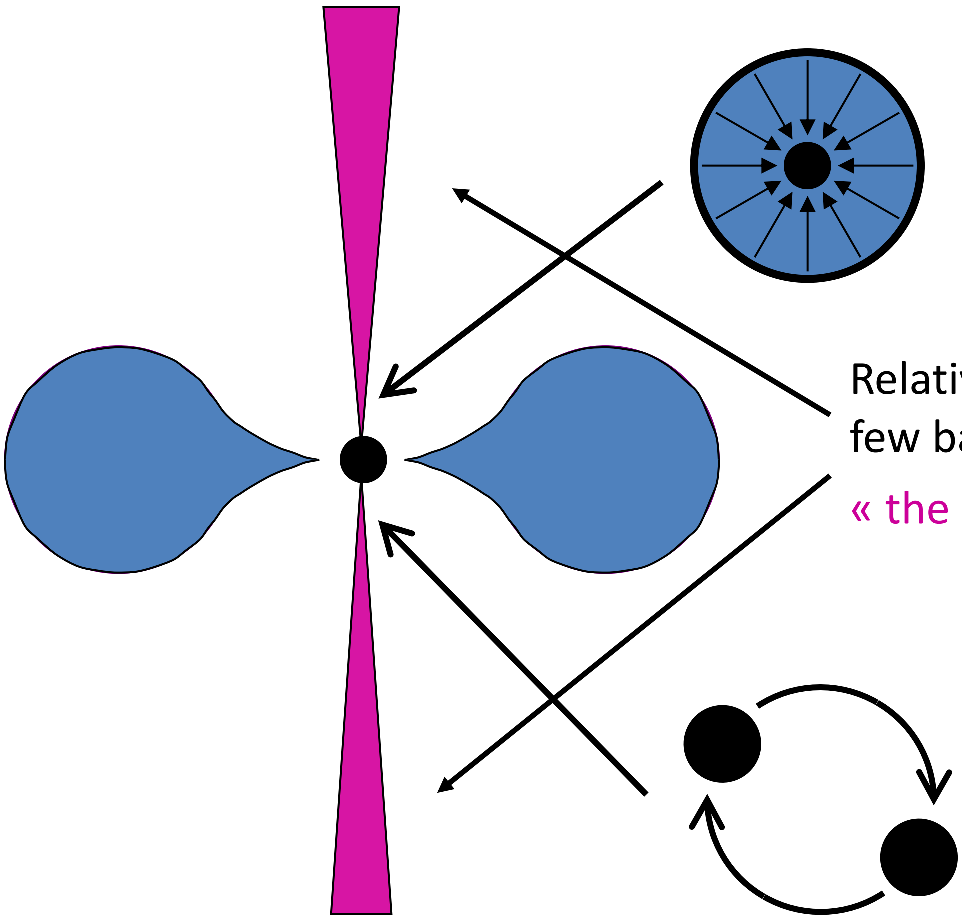
2) The basic features of a possible standard scenario



What we don’t know (but we have some ideas…)

1) The details of the scenario

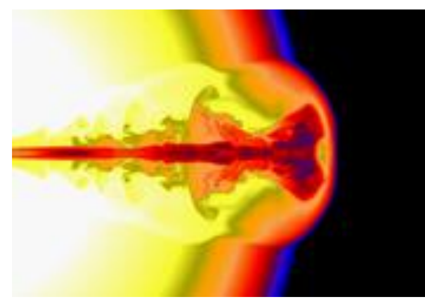
- The central engine



Collapse of a massive rapidly rotating star (long GRBs)

Relativistic jets : a lot of energy injected into very few baryons ($\Gamma = E/Mc^2 >> 1$)

« the baryonic pollution problem »

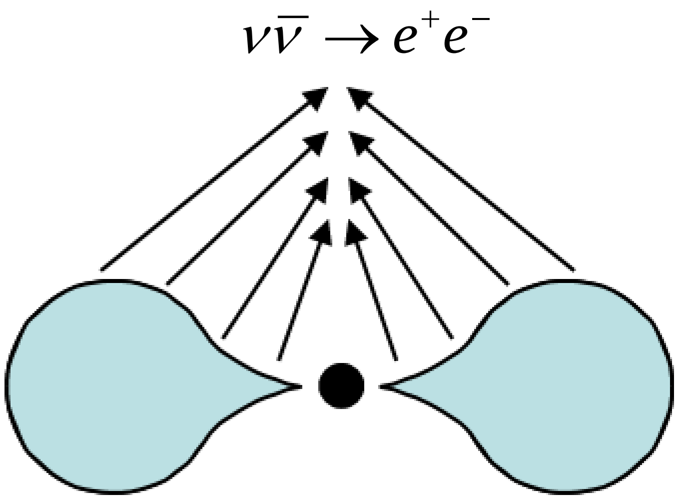


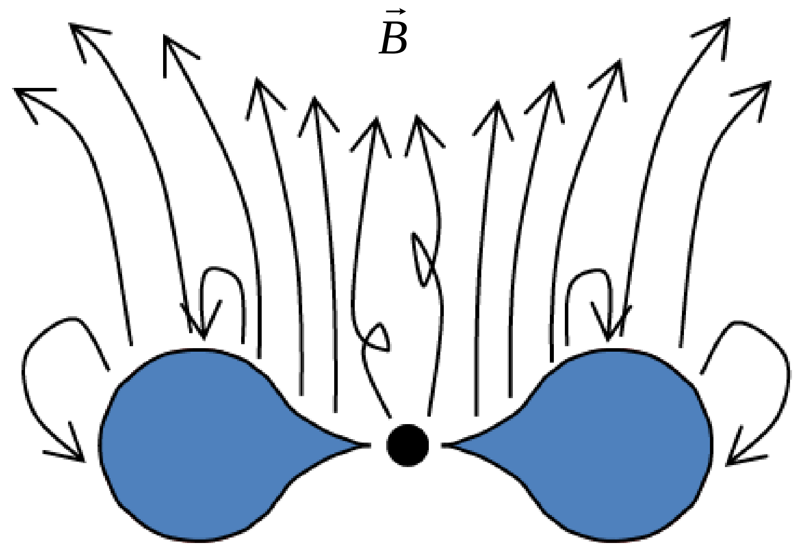
ompact objects

Zhang, Woosley & Heger, 2004

Very difficult physics: GR, 3D MHD !

- <u>The extraction of energy</u>





gravitational energy of the torus
accretion $\rightarrow$ heating $\rightarrow \nu\bar{\nu} \rightarrow e^{+}e^{-}$

rotational energy of the black hole
(Blandford-Znajek effect)

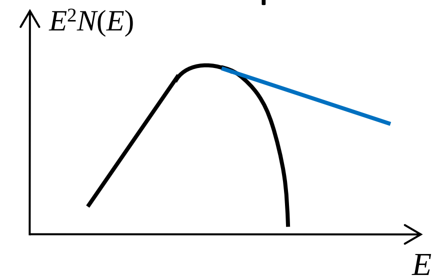
- <u>The acceleration of the flow</u>

Thermal acceleration (fireball model): adiabatic expansion of a hot plasma

Magnetic acceleration: frozen-in plasma follows magnetic field lines
(centrifugal acceleration; “bead on a wire model”)

- <u>Restitution of energy: the prompt emission</u>

(*i*) <u>Thermal energy</u>: photospheric emission released when the jet becomes transparent



→ Planck spectrum a priori expected but does not fit the data

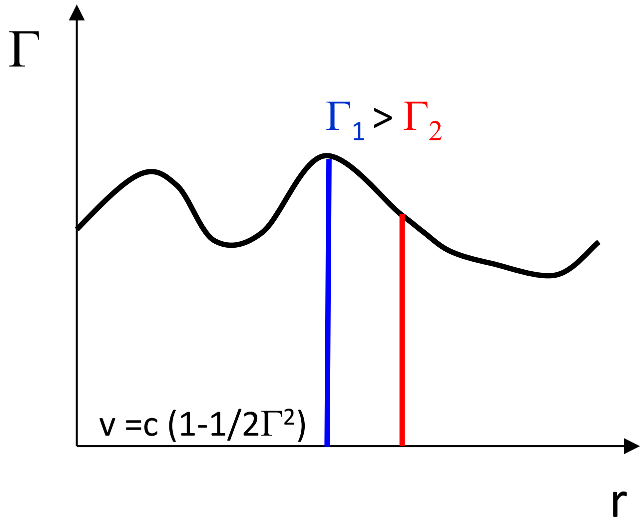
→ Planck spectrum modified by sub-photospheric dissipation ?

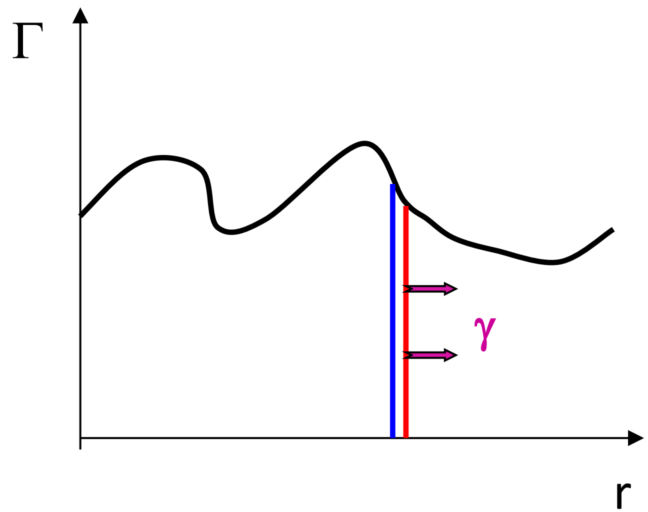
(*ii*) <u>Kinetic energy</u>: “internal shocks”

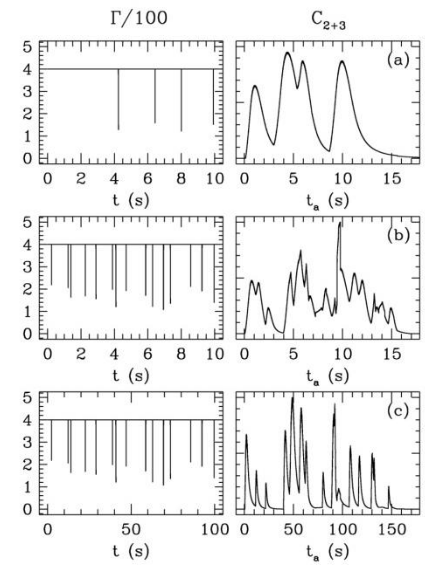
non uniform distribution of the Lorentz factor in the flow

→ shocks between fast and “slow” shells at large distance from the sourc

shock accelerated electrons emit synchrotron radiation







Dissipate the fluctuations, not the bulk of the kinetic energy → low efficiency

(*iii*) <u>Magnetic energy</u>: reconnection of the field lines in a magnetized ejecta

(from a high to a low energy magnetic configuration)

All three possibilities have pros and cons: none is fully convincing

- <u>Restitution of energy: the afterglow</u>

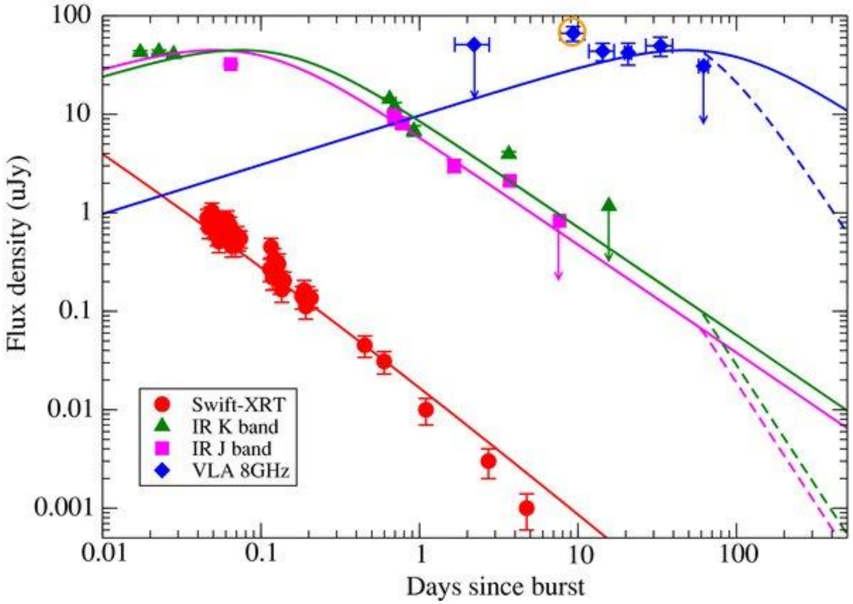
The afterglow results from the deceleration of the flow by the external medium

But what are the respective contributions of the forward and reverse shocks ?

Simple self-similar solutions for the evolution of the forward shock

$\Gamma \propto r^{-3/2}$ (uniform medium) $r^{-1/2}$ (stellar wind)

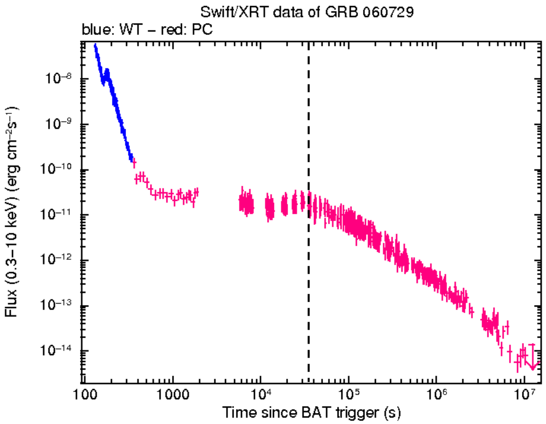
Light curves in various spectral domains represented by power-law segments

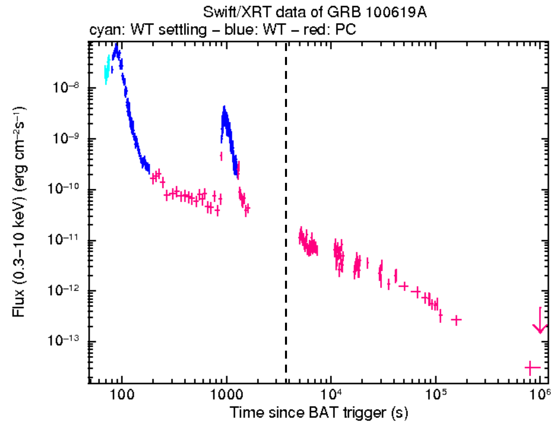


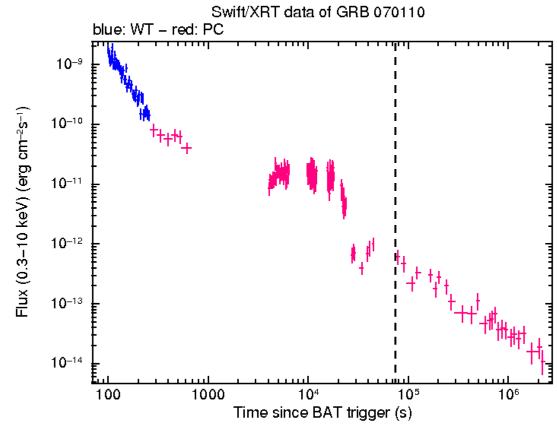
GRB 090423

→ satisfactory fit of the afterglow after a few hours

But problems with the early afterglow







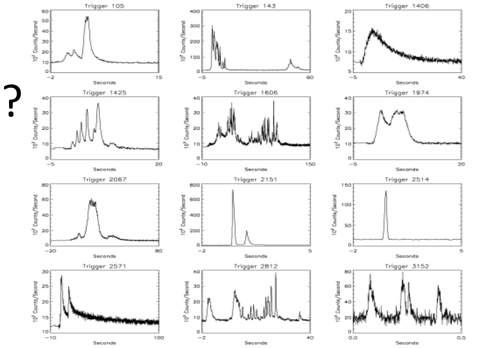
The plateaus flares steep breaks, bumps

are not easily reproduced (or even expected) within the forward shock scenario

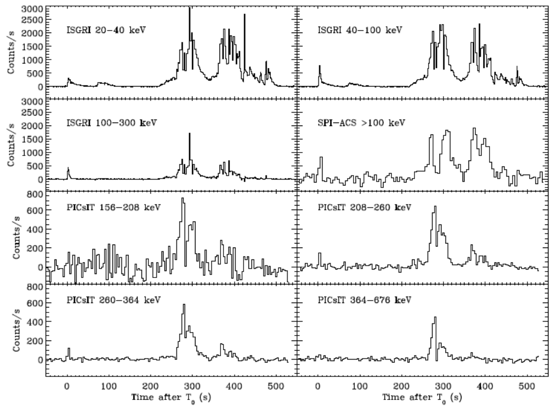
A contribution from the reverse shock ?

During its propagation the reverse shock performs a “tomography” of the ejecta
→ more flexibility to reproduce the various accidents of the early afterglow

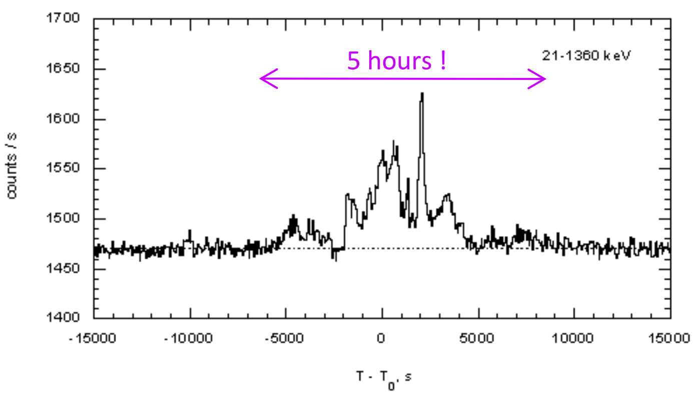
What we really don’t know (just a few questions)



- Why are some light curves so simple and others so complicated ?
- How to explain “precursors”?



- Under which conditions a type Ic supernova can produce a GRB ?
- What is the origin of ultra-long GRBs ?



Conclusions ("GRBs as an enigma and a tool")

We learned a lot about GRBs in the past twenty years

- cosmological distance scale
- energetics
- necessity of an ultra-relativistic outflow
- progenitors

$\longrightarrow$ all this provides the basis for a general scenario (but still many unsolved issues)

Where do we stand now ?

Large set of data from BATSE, Beppo-SAX, HETE2 and now Swift and Fermi
$\longrightarrow$ We know more but do we understand better ?

Perspectives:

SVOM: a future chinese-french GRB mission (2021)
optimized for the detection and identification of high-z GRBs

GRBs remain a unique laboratory for extreme physics

(ultra-relativistic outflows, GRB – GW association, ultra-high energy cosmic rays)

GRBs as a tool for cosmology (z_{max} = 8.2 $\longrightarrow$ 9 ?)

(GRBs as distance indicators (Lag – Luminosity relation), line of sight analysis, large scale structure)

GRBs for testing of fundamental physics (Lorentz invariance)