Gamma Ray Bursts: Physics and Cosmology (I)

Lorenzo Amati

INAF – IASF Bologna (Italy)

Outline of the lectures

I. The Gamma-Ray Bursts phenomenon

- *Basic Observations*
- *Standard scenarions for progenitors and physics*
- *Main open issues*
- *Next generation experiments and perspectives*

II. Cosmology with Gamma-Ray Bursts

- *Backgorund and motivations*
- *Measuring cosmological parameters with GRBs*
- *Shedding light on the early Universe with GRBs*

Outline of the lectures

I. The Gamma-Ray Bursts phenomenon

- Basic Observations
- Standard scenarions for progenitors and physics
- Main open issues
- Next generation experiments and perspectives

II. Cosmology with Gamma-Ray Bursts

- Backgorund and motivations
- Measuring cosmological parameters with GRBs
- Shedding light on the early Universe with GRBs

GRBs basic observations

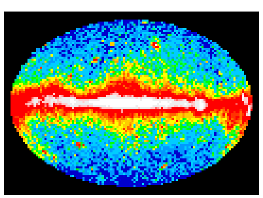
➢ *70s – 80s: GRBs = sudden and unpredictable bursts of hard X / soft gamma rays with huge flux*

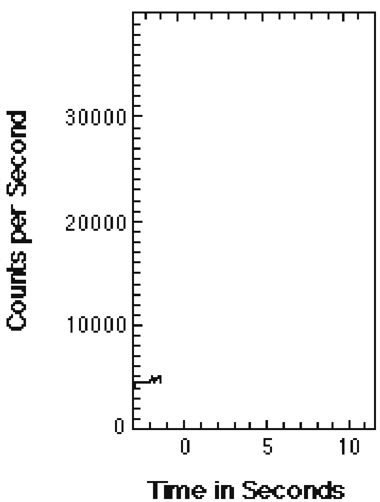
❑ most of the flux detected from 10-20 keV up to 1-2 MeV

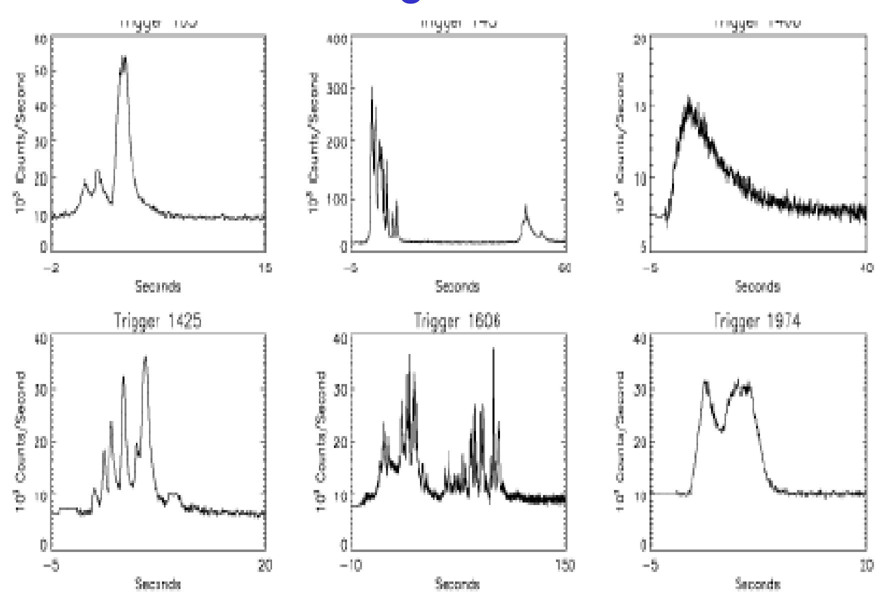
❑ measured rate (by an all-sky experiment on a LEO satellite): ~0.8 / day; estimated true rate ~2 / day

❑ complex and unclassifiable light curves

❑ fluences (= av.flux * duration) typically of ~10^{-7} – 10^{-4} erg/cm^2







❑ Detectors in the energy range from a few keVs to a few MeVs

- <u>proportional counters (classical):</u> ~1.5 – 30 keV, gas (e.g., 90% argon, 10% methane), photoelectric, imaging with a few arcmin accuracy (position sensitive + coded mask), energy resolution of ~1 keV, timing a few hundreds of μs

- <u>silicon-based detectors (more recent):</u> ~0.1 – 15 keV (CCD) or ~1.5 – 50 keV (SDD), photoelectric, imaging with a few arcmin accuracy (+ coded mask), energy resolution of ~100-200 eV, timing a few hundreds of μs (CCD) or a few μs (SDC)

- <u>crystal scintillators (classical):</u> ~15 keV – 50 MeV, crystals (NaI, CsI, BGO,Br3La4), photoelectric + Compton, non imaging, energy resolution from 30% (60 keV) to 10% (600 keV), timing of 1-2 ~μs

- <u>solid-state detectors (more recent</u>): ~6 keV – ~300 keV, CdTe or CZT, photoelectric + Compton, imaging with a few arcmin accuracy (+ coded mask), energy resolution of ~1 keV, timing of 10-100 μs

❑ X-ray telescopes

- <u>X-ray optics + CCD (since middle '80s:</u> ROSAT, SAX, XMM, Chandra): 0.1 – 10-15 keV, imaging with high sensitivity and accuracy down to 1 arcsec, narrow FOV

❑ Detectors in the energy range from a few keVs to a few MeVs

➢ proportional counters (classical): ~1.5 – 30 keV, gas (e.g., 90% argon, 10% methane), photoelectric, imaging with a few arcmin accuracy (position sensitive + coded mask), energy resolution of ~1 keV, timing a few hundreds of μs

➢ silicon-based detectors (more recent): ~0.1 – 15 keV (CCD) or ~1.5 – 50 keV (SDD), photoelectric, imaging with a few arcmin accuracy (+ coded mask), energy resolution of ~100-200 eV, timing a few hundreds of μs (CCD) or a few μs (SDC)

➢ crystal scintillators (classical): ~15 keV – 50 MeV, crystals (NaI, CsI, BGO,Br3La4), photoelectric + Compton, non imaging, energy resolution from 30% (60 keV) to 10% (600 keV), timing of 1-2 ~μs

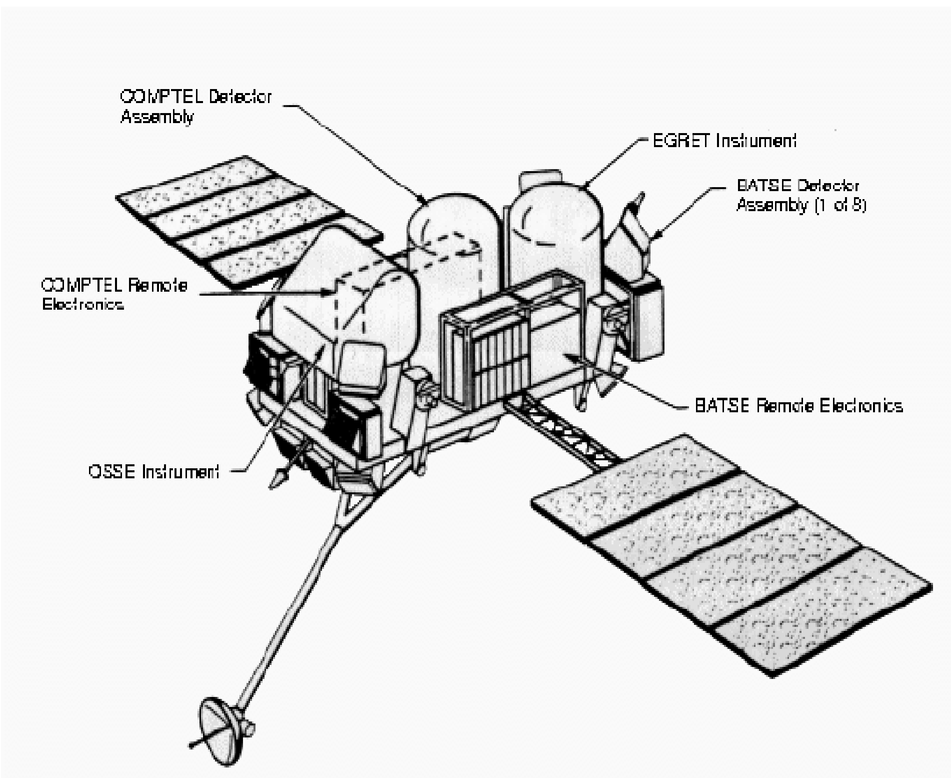
➢ solid-state detectors (more recent): ~6 keV – ~300 keV, CdTe or CZT, photoelectric + Compton, imaging with a few arcmin accuracy (+ coded mask), energy resolution of ~1 keV, timing of 10-100 μs

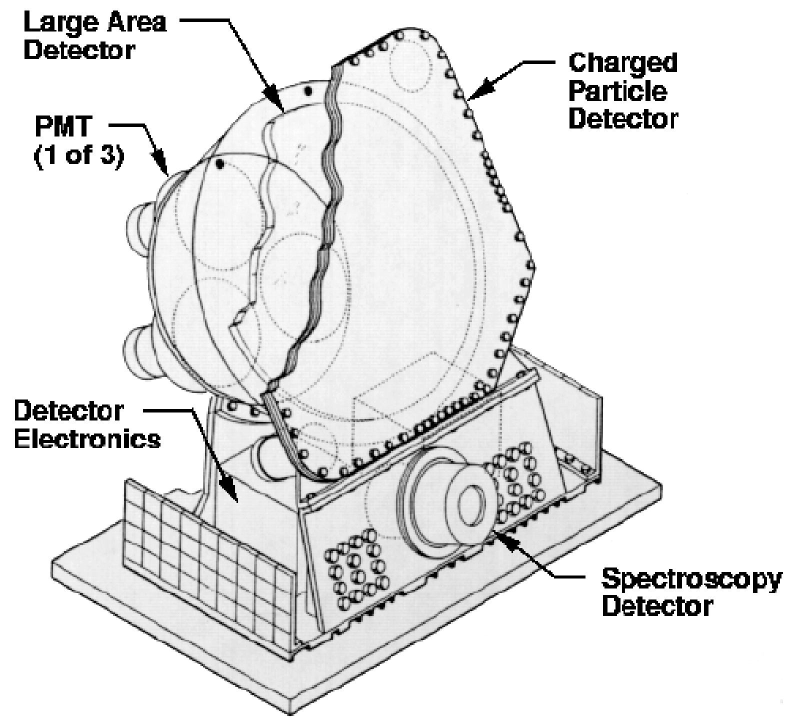
❑ X-ray telescopes

➢ X-ray optics + CCD (since middle '80s: ROSAT, SAX, XMM, Chandra): 0.1 – 10-15 keV, imaging with high sensitivity and accuracy down to 1 arcsec, narrow FOV

➢ *'90s: the contribution of CGRO/BATSE*

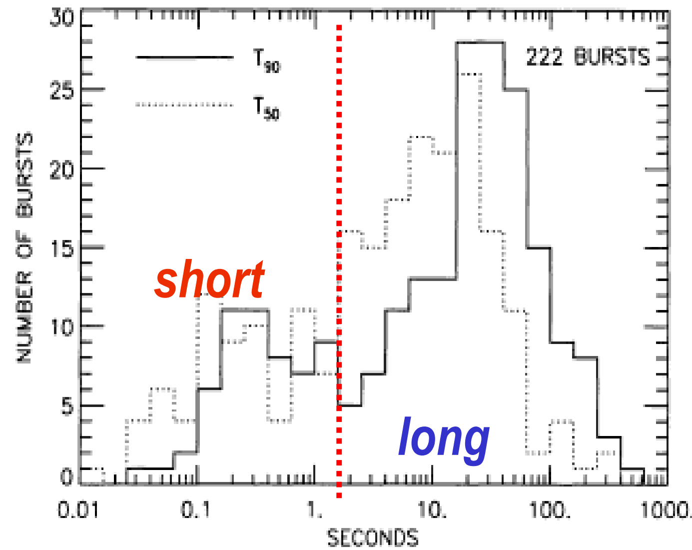
- ❑ major contribution came in the '90s from the NASA BATSE experiment (25-2000 keV) onboard CGRO (1991-2000)
- ❑ based on NaI scintillator detectors; 8 units covering a ~2π FOV

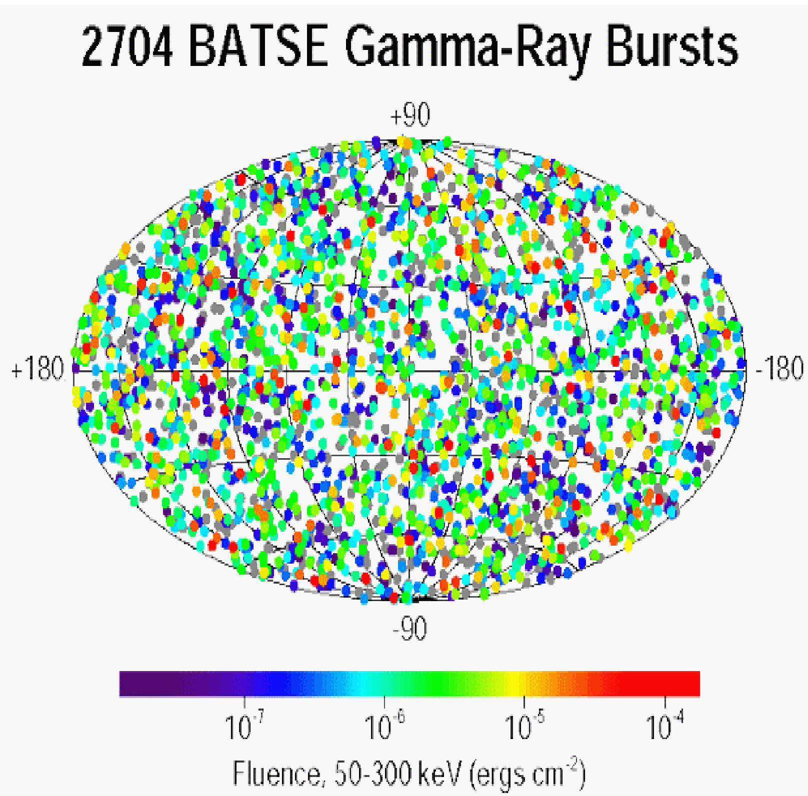


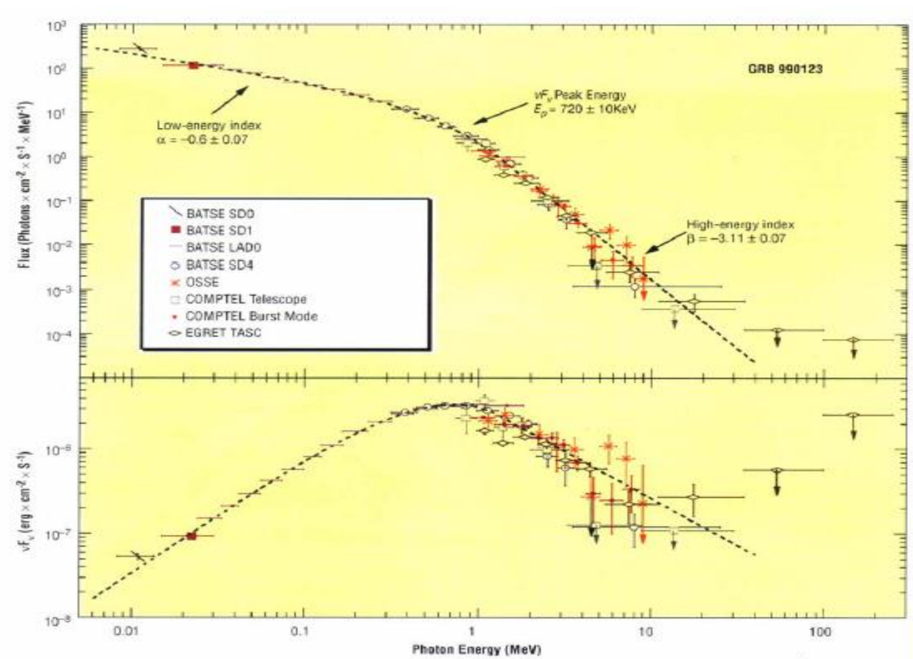


➢ ’90s: the contribution of CGRO/BATSE

- ❑ bimodal distribution of durations
- ❑ characterization of GRB non thermal spectra
- ❑ isotropic distribution of directions



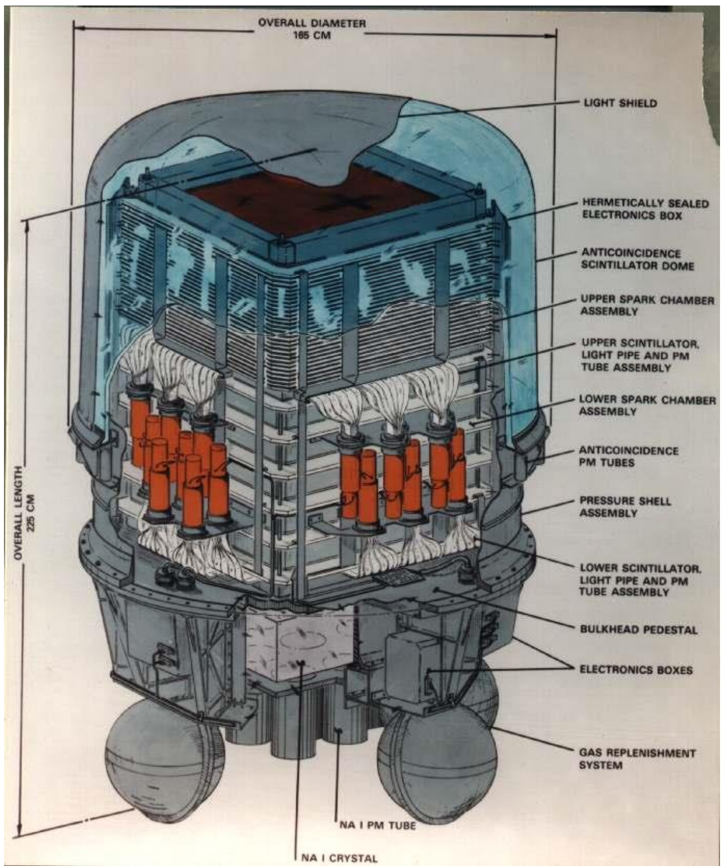


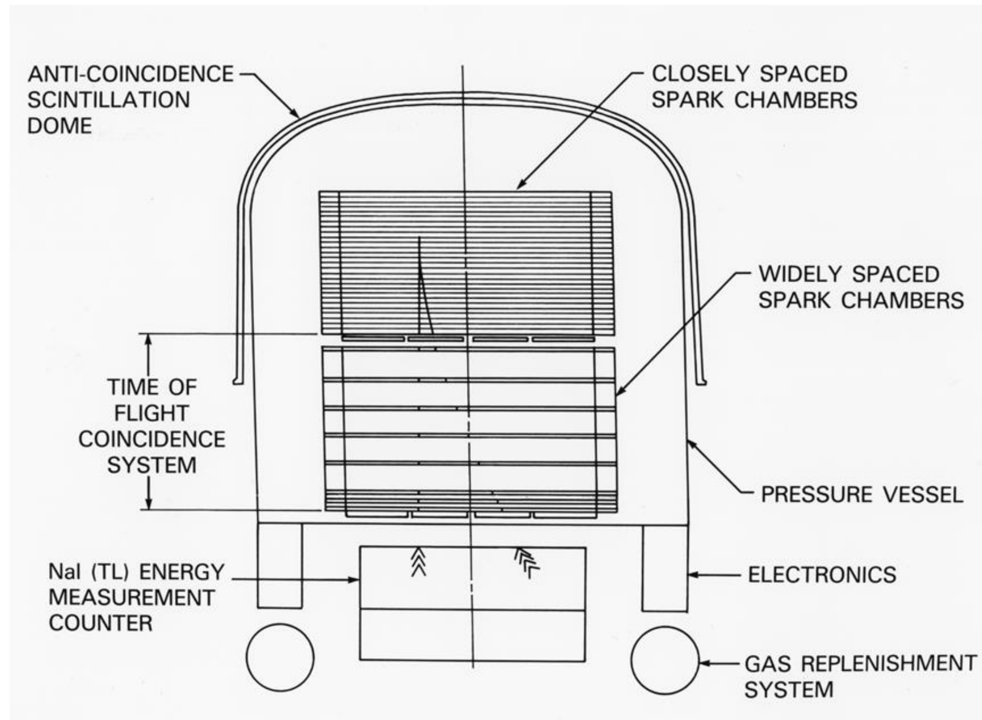


BATSE team

➢ ’90s: dection of GRB VHE emission by CGRO/EGRET

❑ pair conversion gamma-ray telescope based on spark chambers sensitive in the 20 MeV – 30 GeV energy band

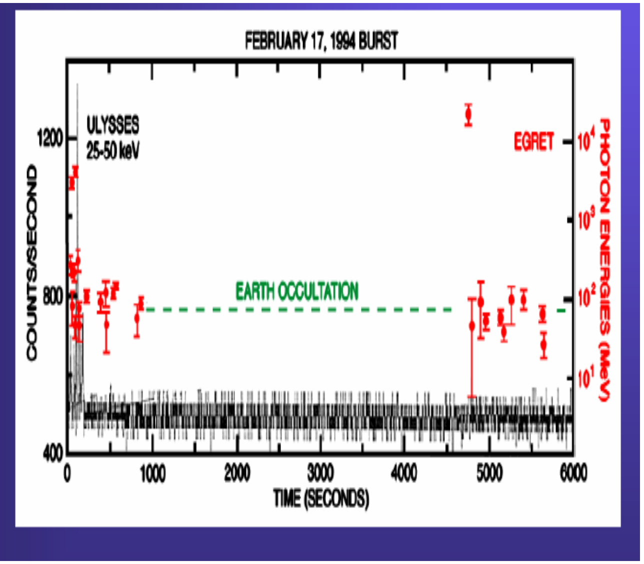


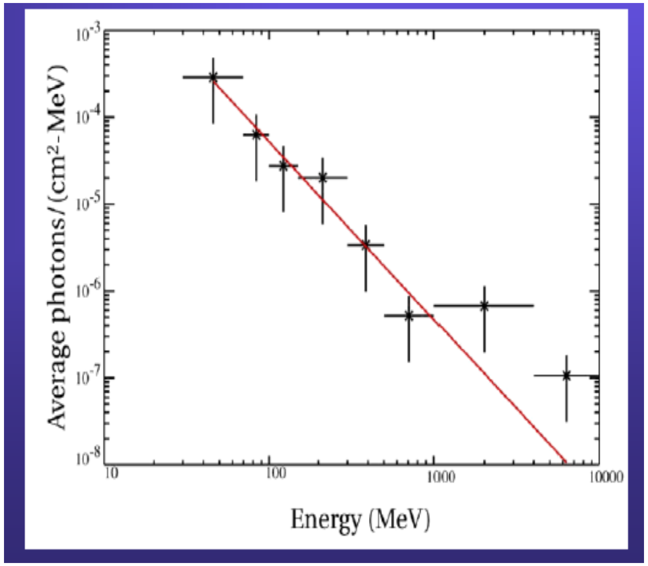


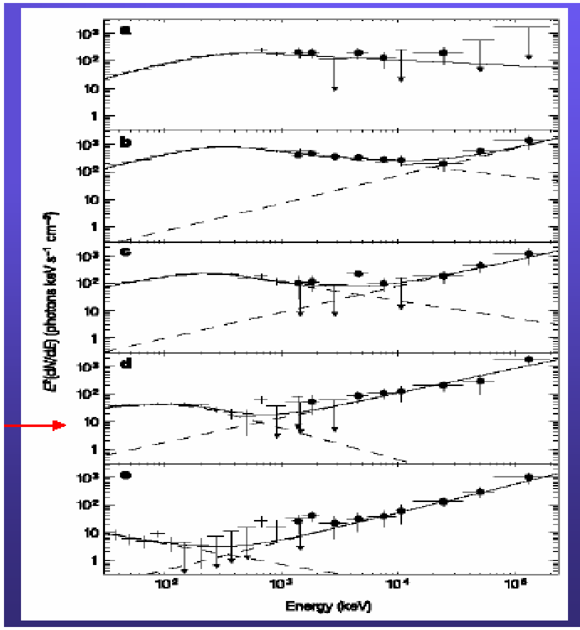
BATSE/EGRET team

➢ '90s: dection of GRB VHE emission by CGRO/EGRET

- ❑ CGRO/EGRET detected VHE (from 30 MeV up to 18 GeV) photons for a few GRBs
- ❑ VHE emission can last up to thousends of s after GRB onset
- ❑ average spectrum of 4 events well described by a simple power-law with index ~2 , consistent with extension of low energy spectra
- ❑ GRB 941017,measured by EGRET-TASC shows a high energy component inconsistent with synchrotron shock model
- ❑ Strong improvement expected form AGILE and, in particular, Fermi/GLAST



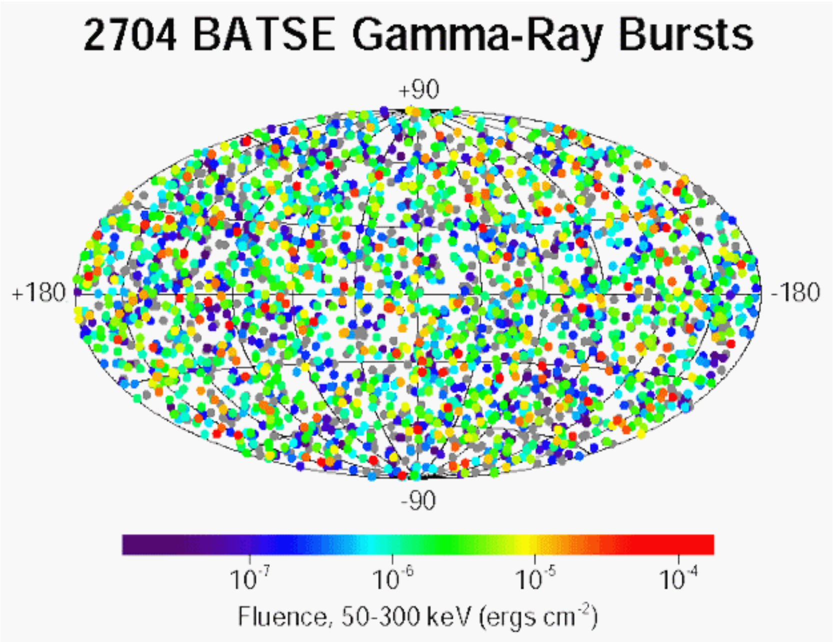


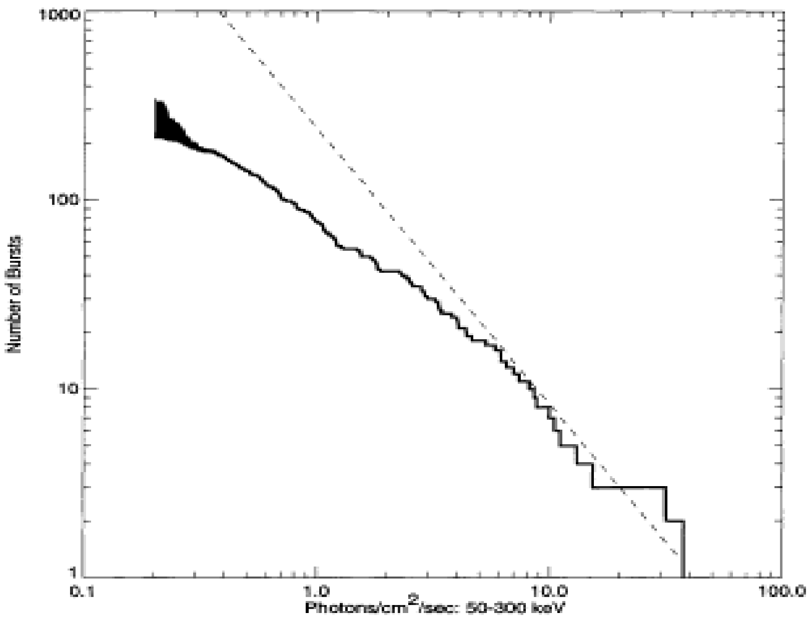


BATSE/EGRET team

Early evidences for a cosmological origin of GRBs

- ❑ *isotropic distribution of GRBs directions*
- ❑ *paucity of weak events with respect to homogeneous distribution in euclidean space*
- ❑ ***given the high fluences (up to more than 10^{-4} erg/cm2 in 20-1000 keV) a cosmological origin would imply huge luminosity***
- ❑ *thus, a "local" origin was not excluded until 1997 !*





The Distance Scale to Gamma-Ray Bursts Great Debate in 1995

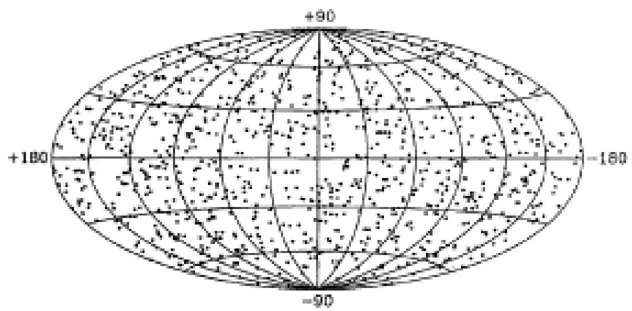


FIG. 1—Sky map of the first 1005 gamma-ray bursts observed by BATSE. Of these, 485 are from the second BATSE catalog and have positional uncertainties of about 7°. The remainder have preliminary positions or are affected by gaps in the telemetry stream, and have more uncertain positions. (From Briggs et al. 1995.)

piece of evidence. But eventually, through the process of weighing-up the evidence, scientists reach a conclusion.

Paczyński (1995) focuses on the isotropic sky distribution of gamma-ray bursts. He describes the impact that the announcement that the sky distribution of faint bursts is consistent with isotropy had on him and on some others when it was made by the BATSE team in September 1991 (Meegan et al. 1992). The isotropy of the bursts on the sky is an important piece of evidence. The cosmological hypothesis is consistent with it. But the Galactic hypothesis is also consis-

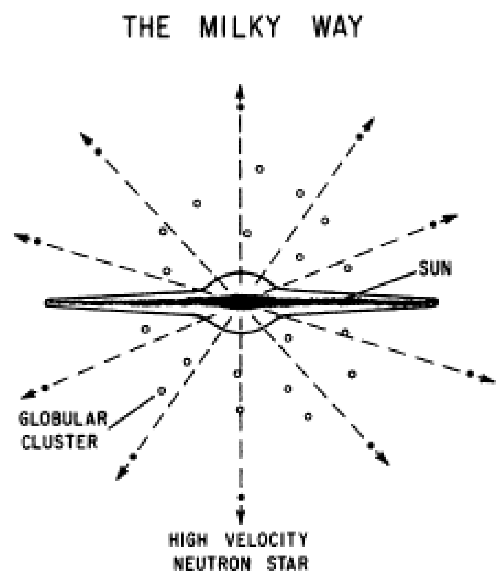
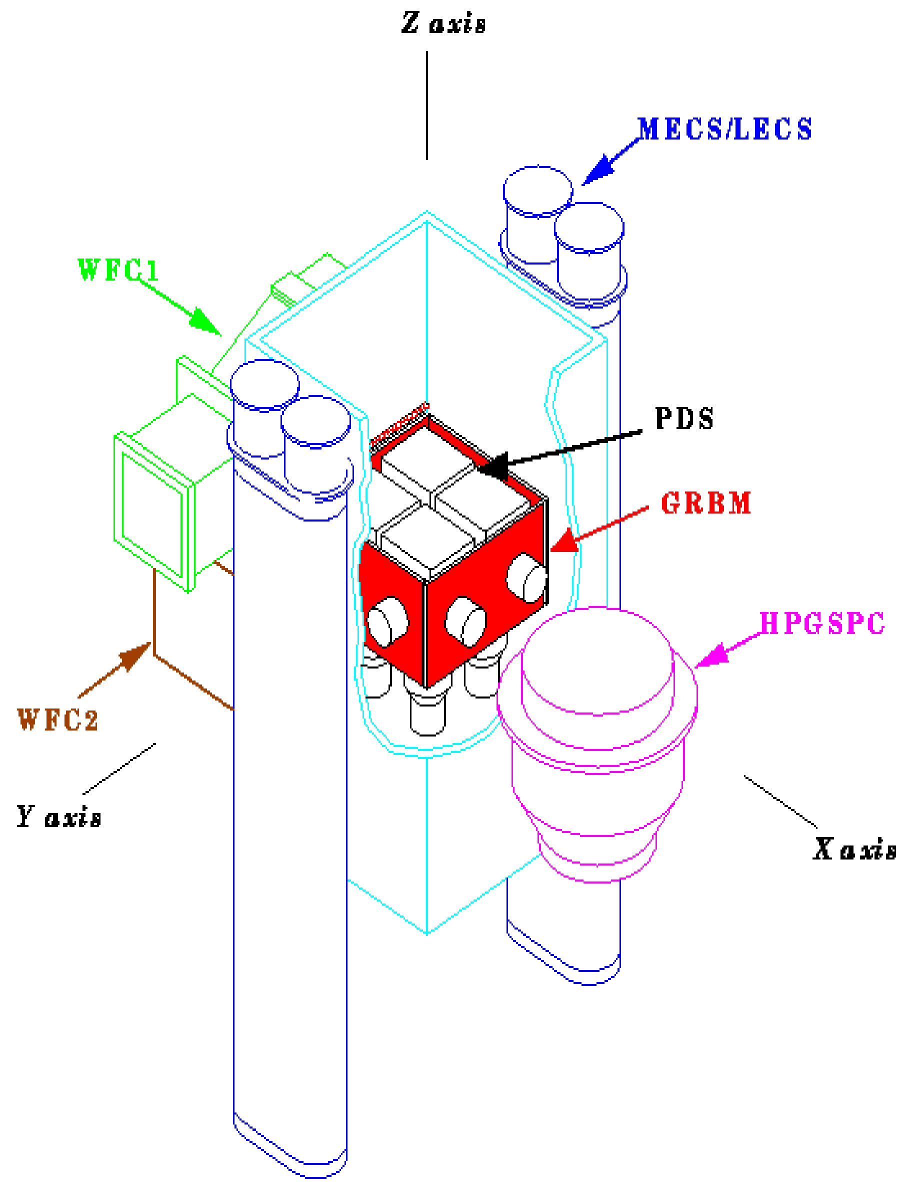


FIG. 3—Side view of the Milky Way. The Galactic bulge and disk are clearly visible; the dark lane along the plane of the Galaxy is due to dust. Also shown are the Sun, the globular clusters which surround the Galactic disk, and the trajectories of high-velocity neutron stars which are escaping from the Milky Way. These high-velocity neutron stars form a previously unknown Galactic "corona." The corona contains an ample population of neutron stars which appears isotropic when viewed from Earth. Many scientists believe that this population of distant neutron stars is the source of gamma-ray bursts.

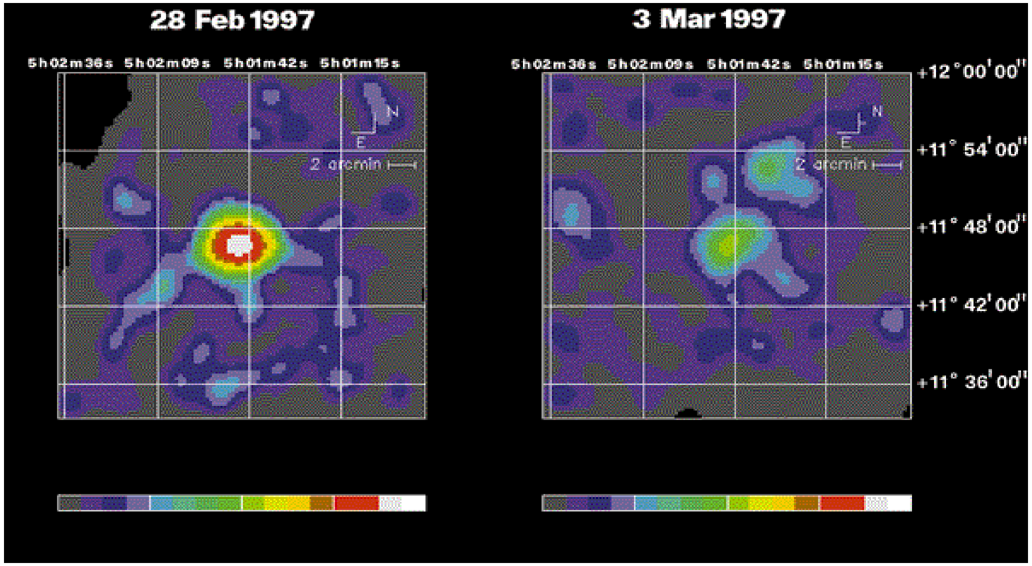
- *Need of a substantial improvement in the ocation accuracy several degrees (BATSE, scintillators) to arcmin*

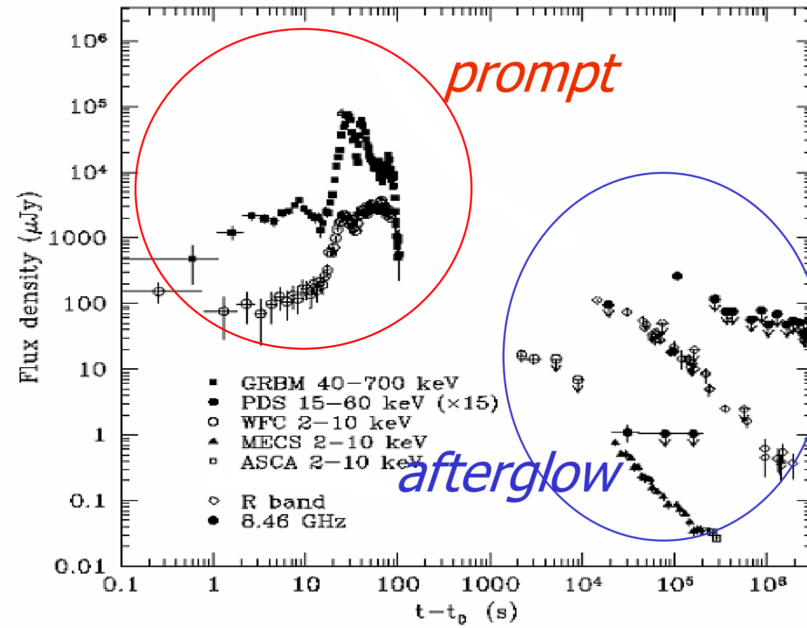
➢ *The BeppoSAX revolution (1996 – 2002):*

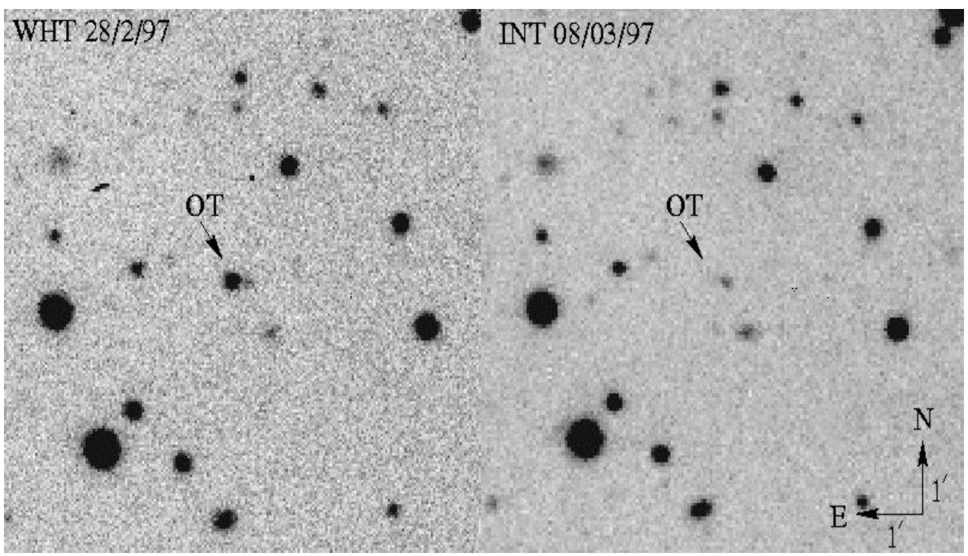
- ❑ NFI (X-ray focusing telescopes, 0.1-10 keV + PDS, 15-200 keV)
- ❑ WFC (2 units, proportional counters + coded mask, FOV 20°x20° each unit, 2-28 keV)
- ❑ GRBM (4 units, CsI scintillators, large FOV, GRB triggering, 40-700 keV)
- ❑ <u>WFC and GRBM co-aligned</u>

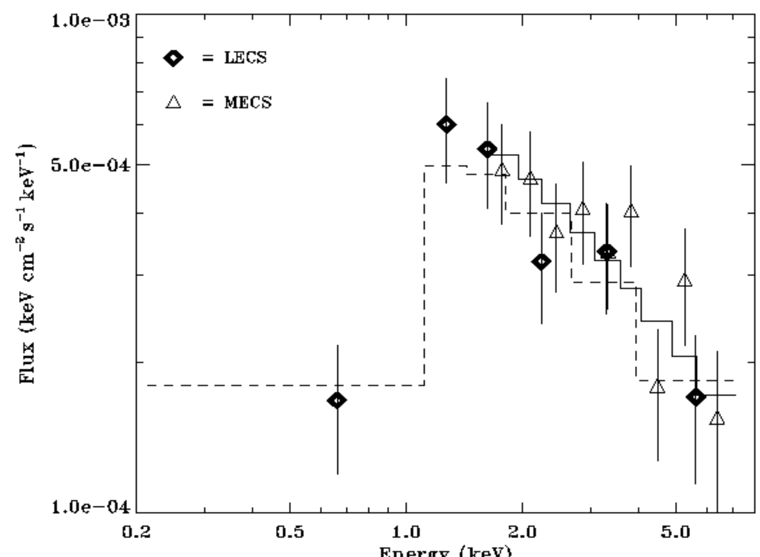


➢ *BeppoSAX: afterglow emission (late ’90s):* power-law decay and spectrum (with exceptions)









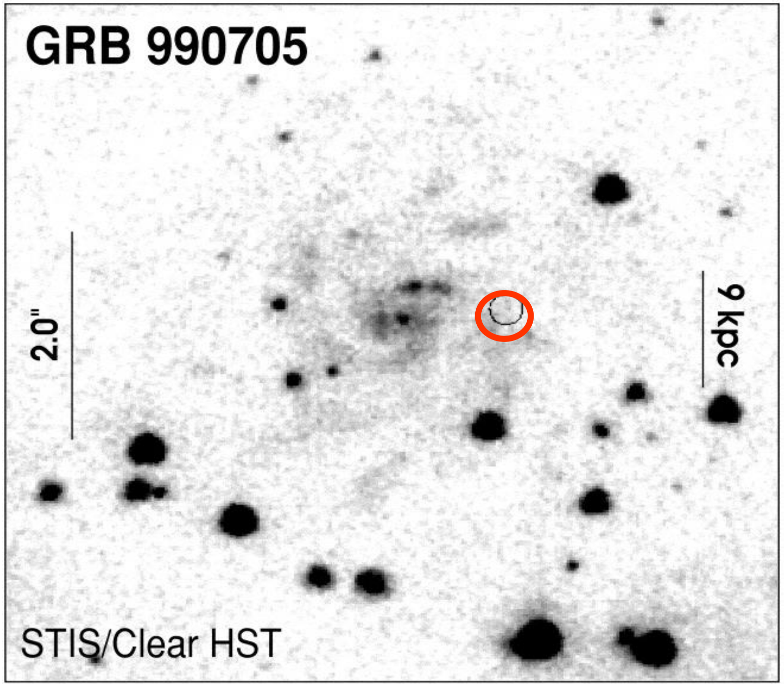
Costa et al. 1997, Van Paradijs et al. 1997, SAX team

➢ *Host galaxies (>1997, X-ray loc. + optical follow-up)*

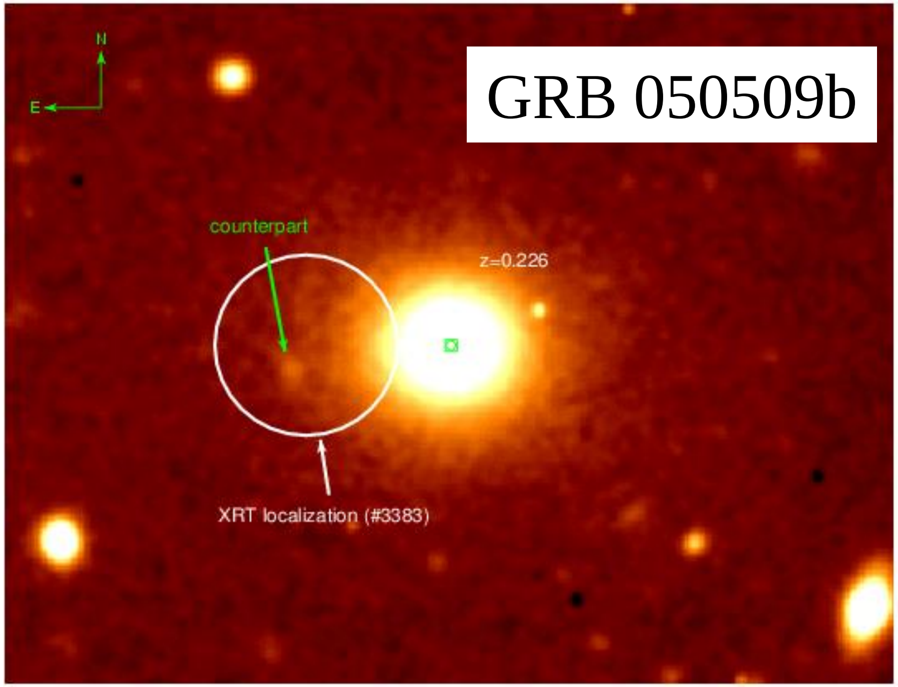
❑ host galaxies long GRBs: blue, usually regular and high star forming, GRB located in star forming regions

❑ host galaxies of short GRBs (more recent): no preferred type

Long



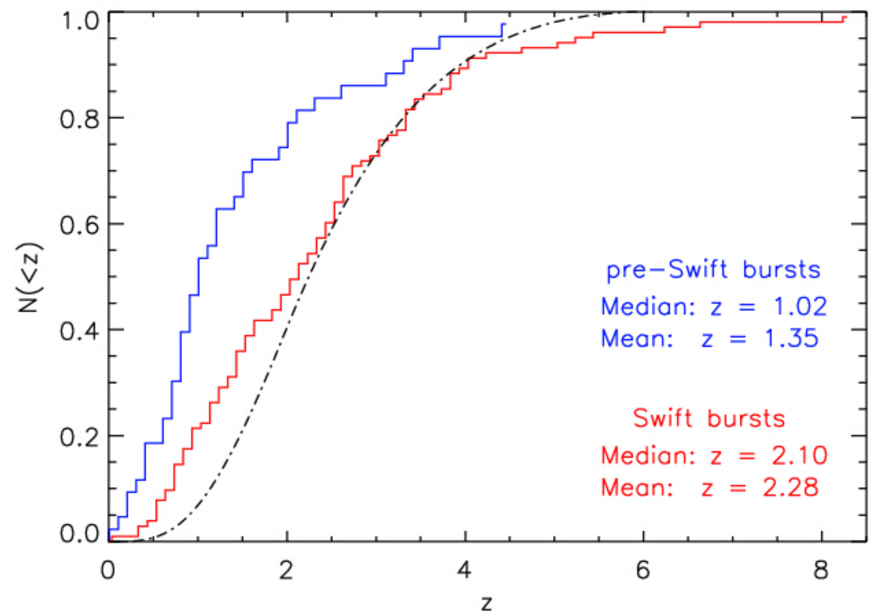
Short

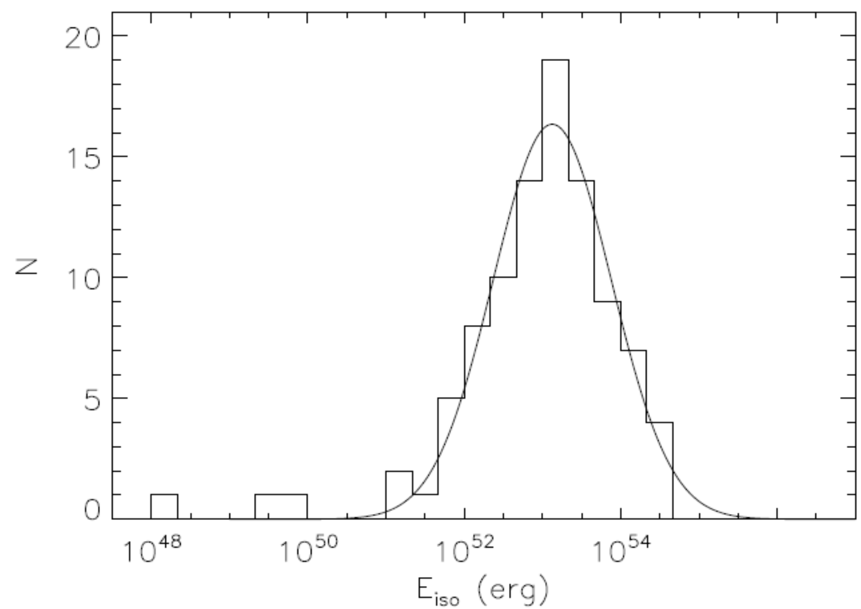


Bloom et al. 2002 , 2006

➢ *Distance and luminosity (>1997)*

- ❑ from optical spectroscopy (OT or HG) -> redshift estimates
- ❑ **all GRBs with measured redshift (~320) lie at cosmological distances (except for the peculiar GRB980425, z=0.0085)**
- ❑ **isotropic equivalent radiated energies can be as high as > 10^{54} erg**
- ❑ short GRB lie at lower redshifts (<~1) and are less luminous (Eiso < ~10^{52} erg)

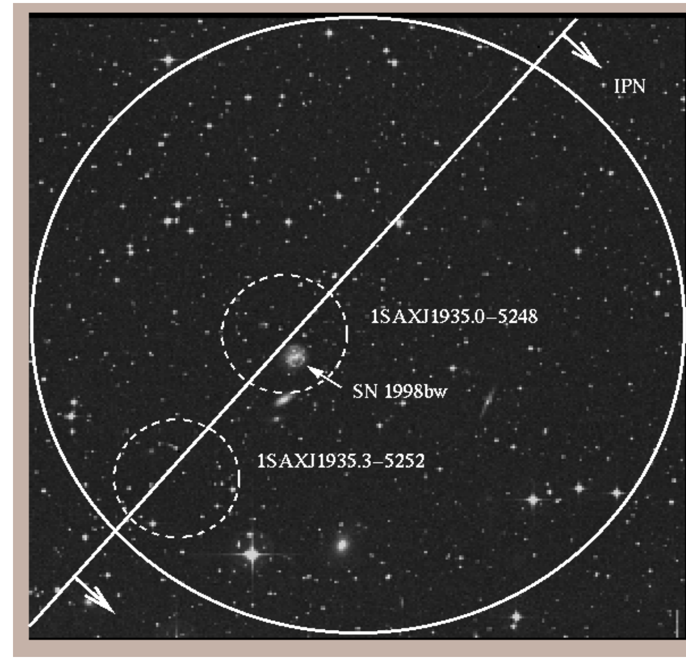




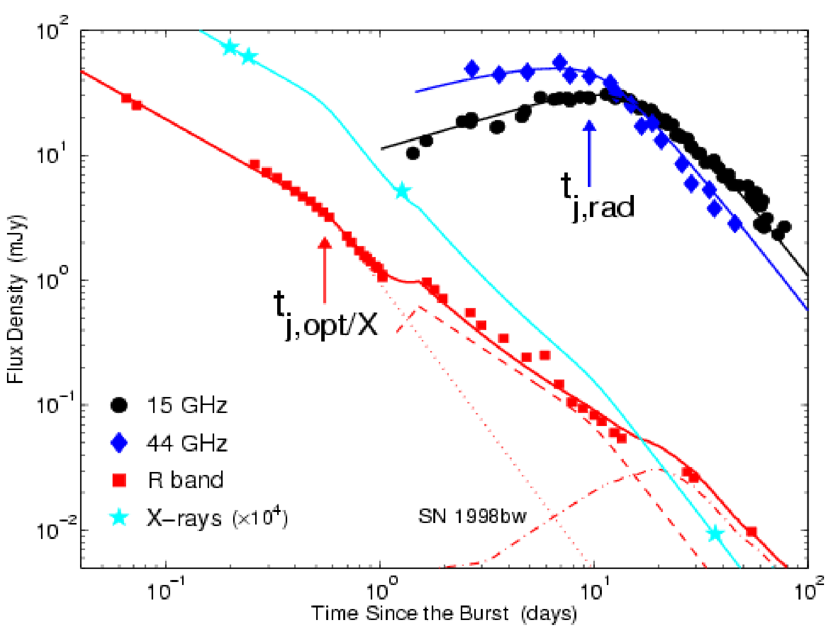
Amati 2009

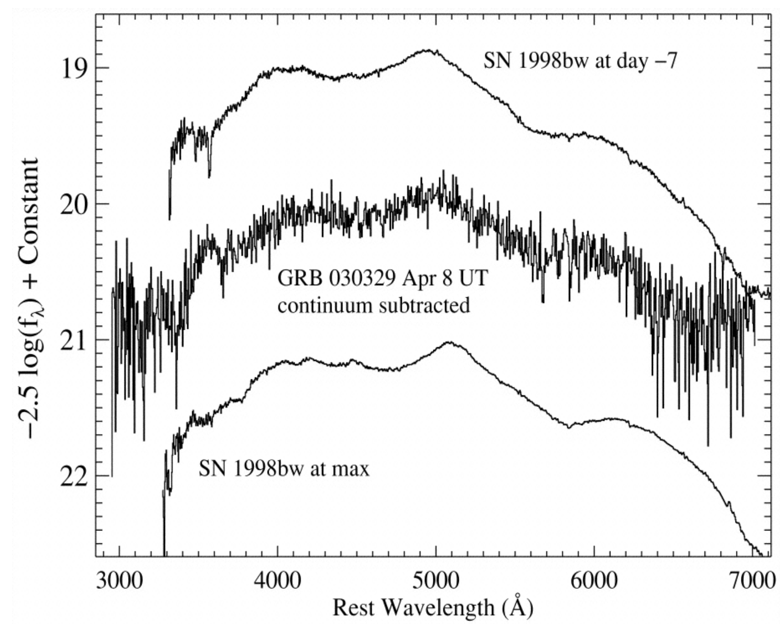
➢ GRB/SN connection (> 1998)

➢ GRB 980425, a normal GRB detected and localized by WFC and NFI, but in temporal/spatial coincidence with a type Ib/c SN at z = 0.008 (chance prob. 0.0001)



➢ further evidences of a GRB/SN connection: bumps in optical afterglow light curves and optical spectra resembling that of GRB980425 (e.g., GRB 030329)

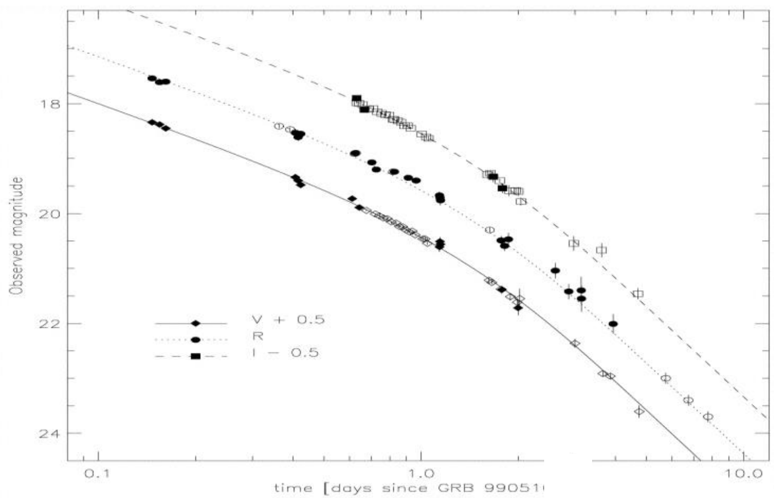




Galama et al. 1998, Hjorth et al. 2003

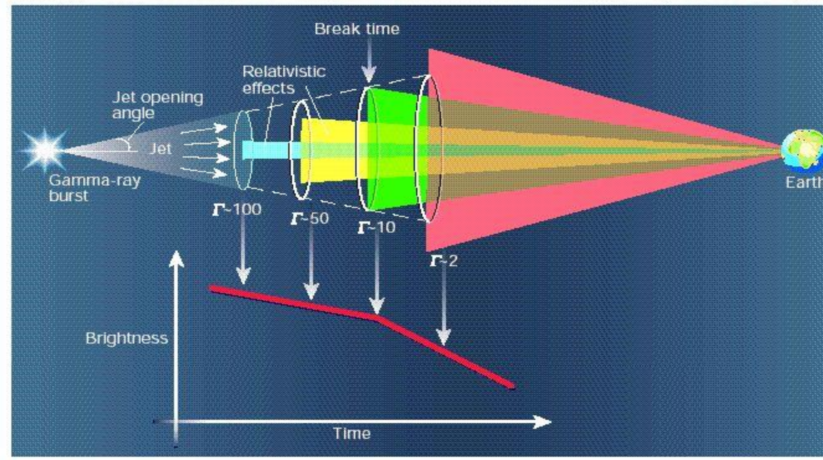
➢ *Evicence for collimation (late ’90s, ’00)*

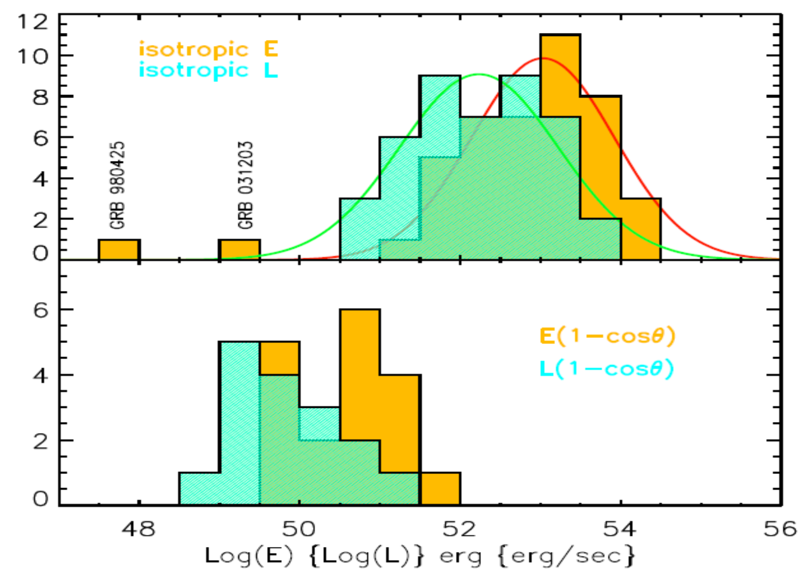
- ❑ jet angles derived from achromatic break time are of the order of few deg
- ❑ the collimation-corrected radiated energy spans the range ~10^{50} – 10^{52} erg



$$\theta = 0.09 \left(\frac{t_{jet,d}}{1+z}\right)^{3/8} \left(\frac{n\,\eta_\gamma}{E_{\gamma,iso,52}}\right)^{1/8}$$

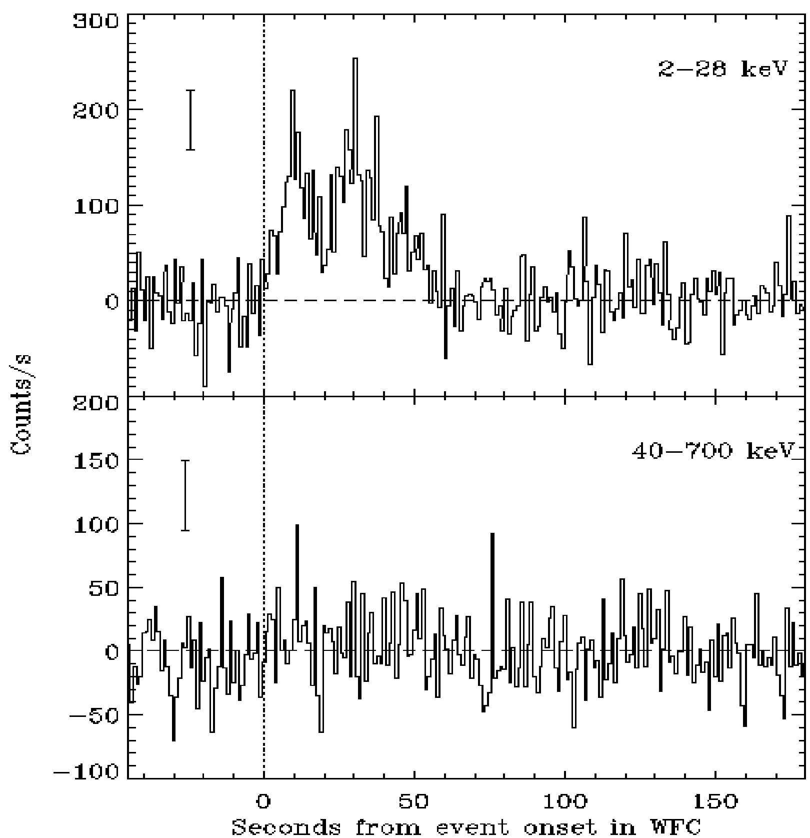
$$E_\gamma = (1 - \cos\theta)\, E_{\gamma,iso}.$$

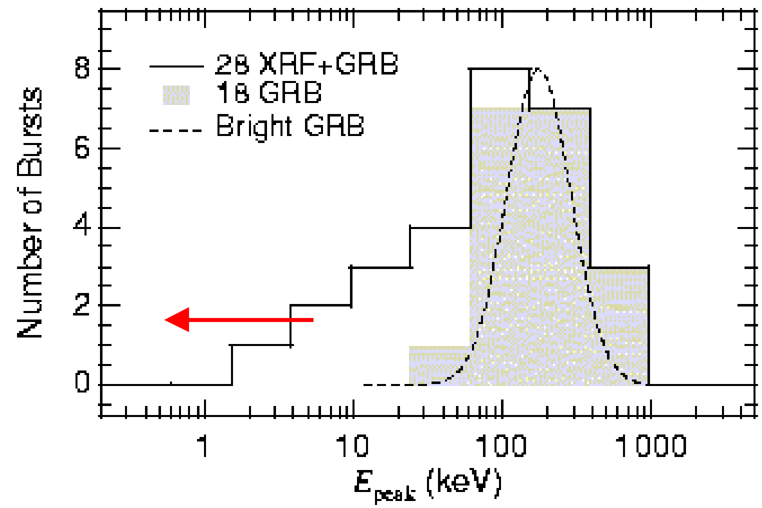


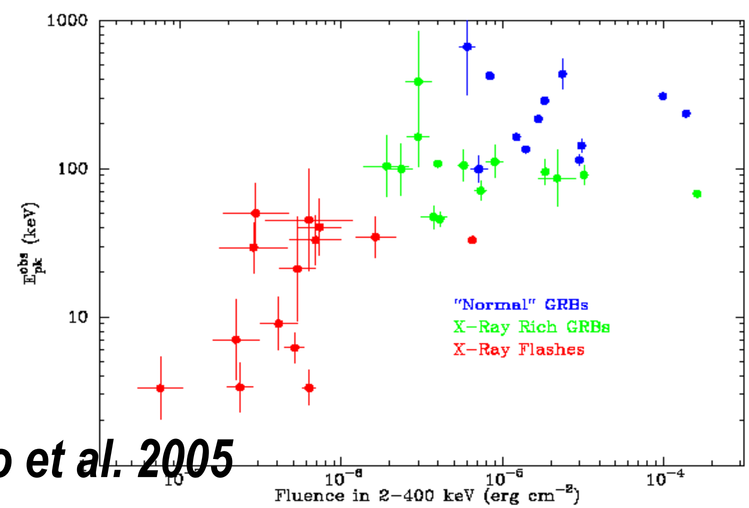


➢ *X-Ray Flashes (late '90s – early '00s , main contribution by BeppoSAX and HETE-2)*

❑ GRBs with only X-ray emission (BeppoSAX, HETE-2) -> distribution of spectral peak energies has a low energy tails



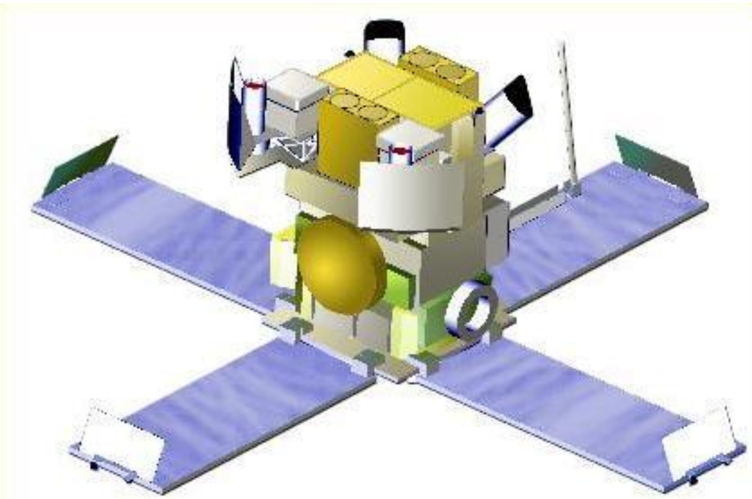


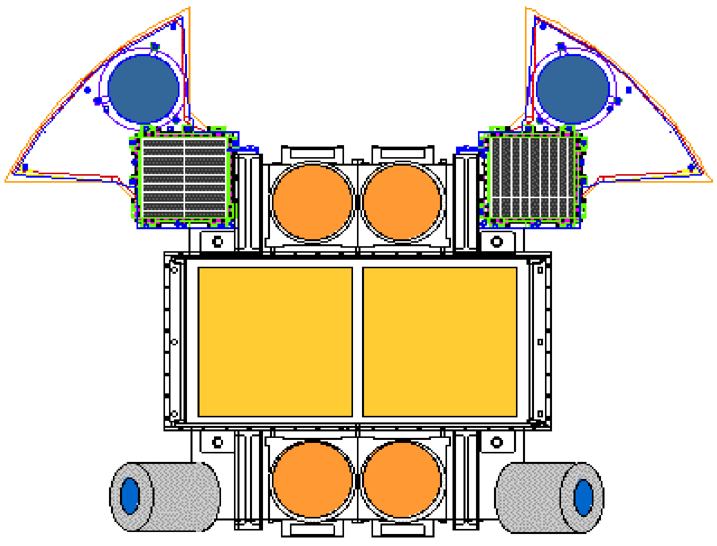


Amati et al. 2004, Kippen et al. 2001, Sakamoto et al. 2005

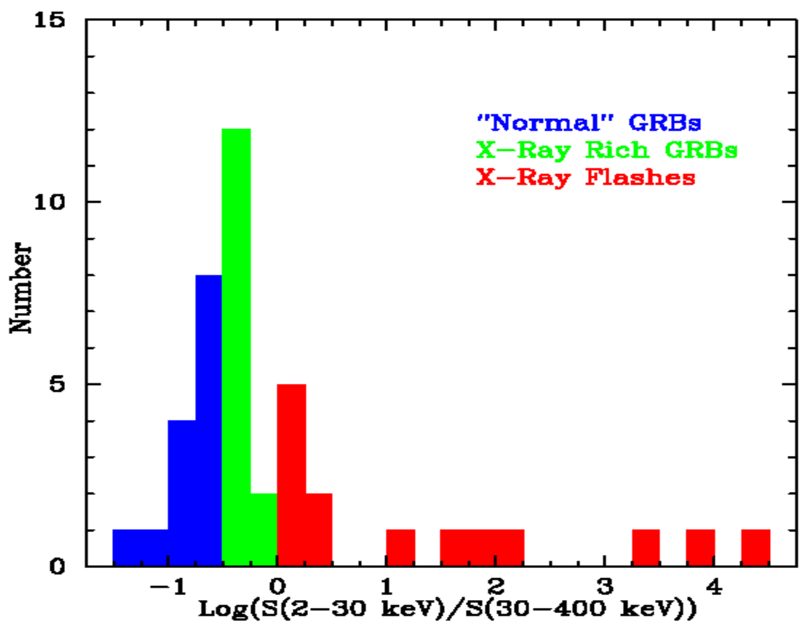
➢ *HETE-2 (2000 – 2007): extending the sample of X-ray rich GRBs and XRFs*

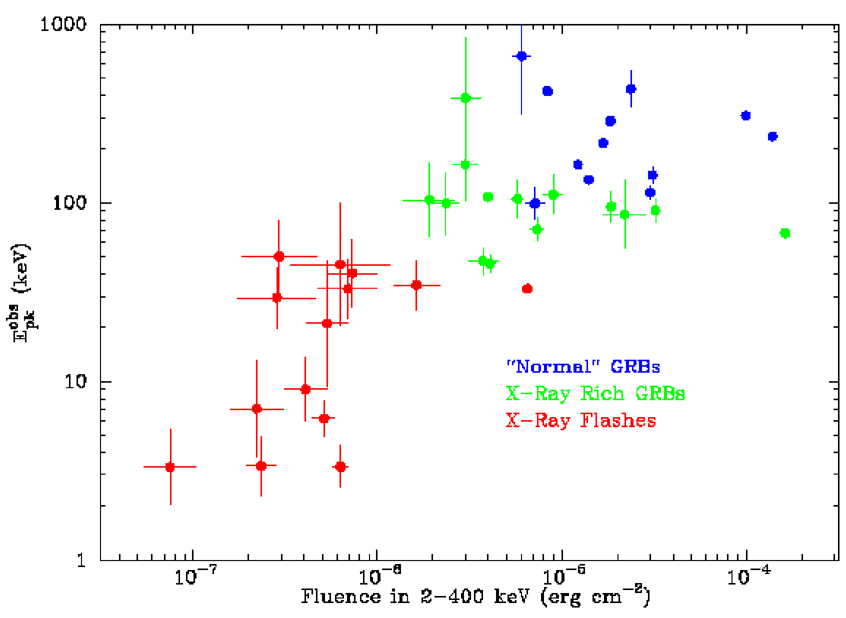
- ❑ FREGATE: NaI crystal scintillators, 6-400 keV, FOV = 3 sterad
- ❑ WXM: 2 units, gas proportional counters + 1-D codedmask, 2-25 keV , localization of few arcmin
- ❑ SXC: 2 units, CCD + 1-D coded mask. 0.5 – 10 keV, ~30 arcsec
- ❑ accurate localization (few arcmin) and fast position dissemination
- ❑ study of prompt emission down to X-rays





- normal GRBs, XRRs and XRFs are found to be in the ratio 1:1:1
- recent XRF redshift estimates: z in the 0.1 – 1 range
- GRBs, XRRs and XRFs form a continuum in the Ep – fluence plane: evidence of a common origin
- most likely explanation: inefficient internal shocks due to low contrast of $\Delta\Gamma$ between colliding shells with respect to fireball bulk Γ

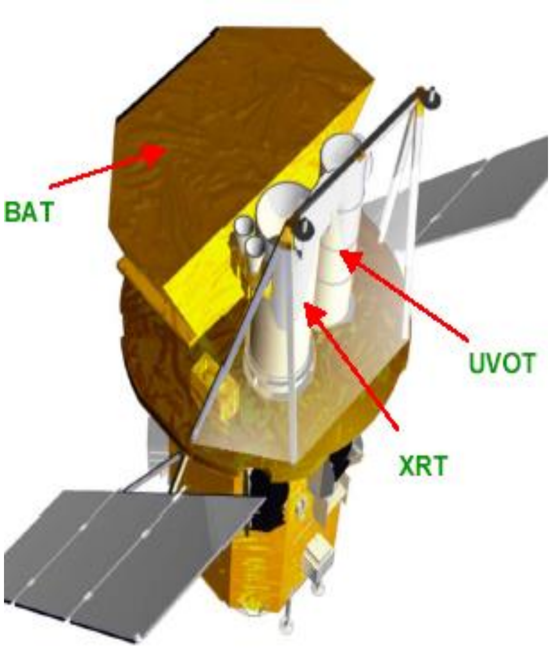




➢ *Swift (> 2004): transition from prompt to afterglow*

- **Swift**: NASA mission dedicated to GRB studies launched 20 Nov. 2004 USA / Italy / UK consortium

- main goals: afterglow onset, connection prompt-afterglow, substantially increase of conunterparts detection at all wavelengths (and thus of redshift estimates)

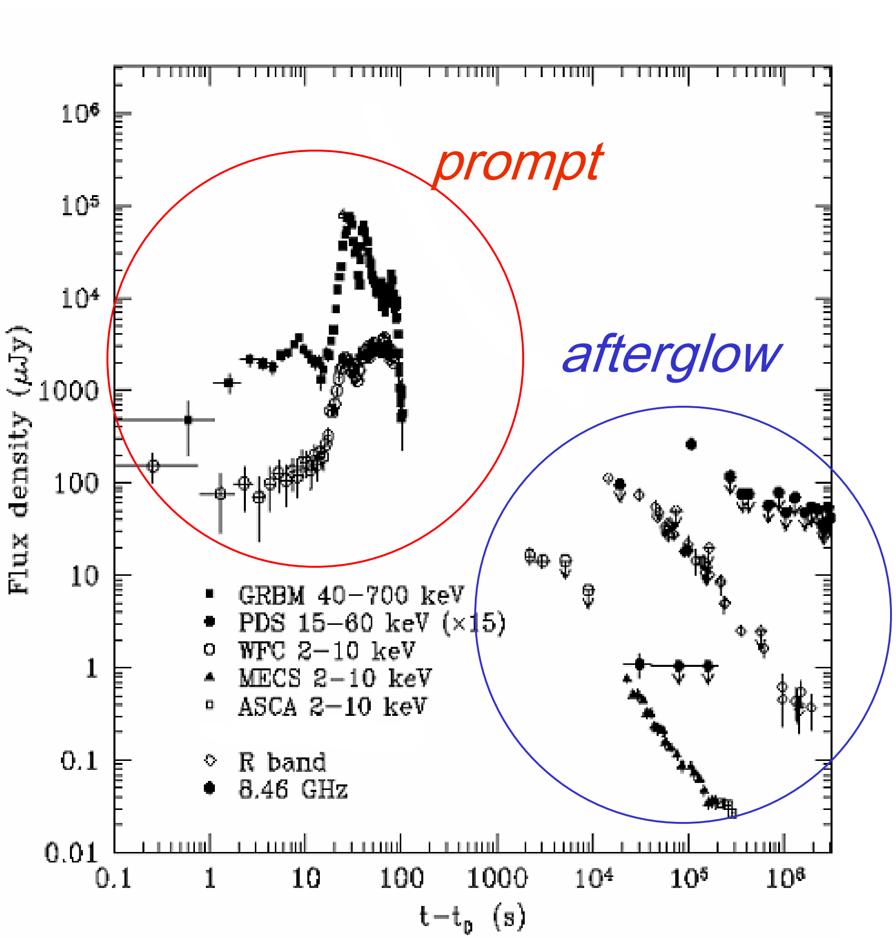


- payload: BAT (CZT+coded mask, 15-150 keV, wide FOV, arcmin ang. res.), XRT (X-ray optics, 0.3-10 keV, arcsec ang.res.), UVOT (sub-arcsec ang.res. mag 24 in 1000 s)

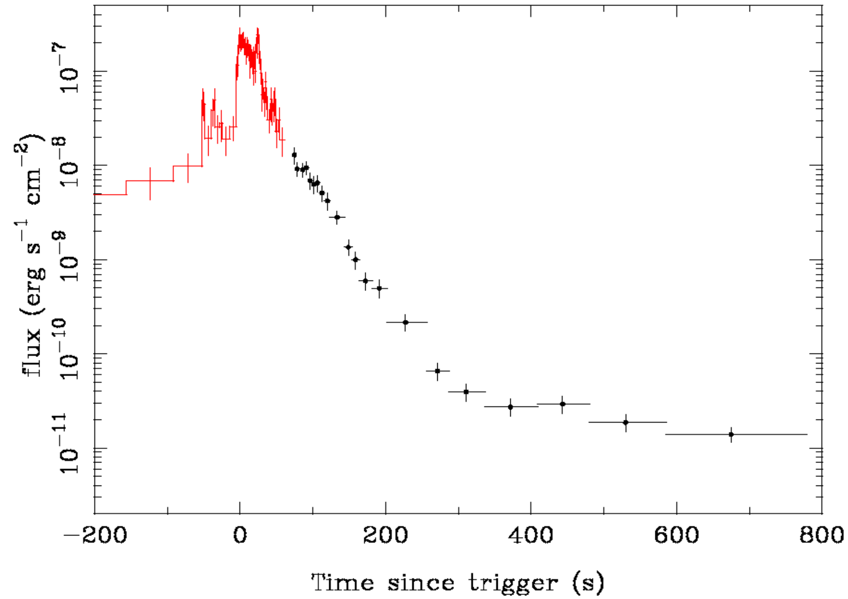
- spacecraft: automatic slew to target source in ~1 - 2 min.

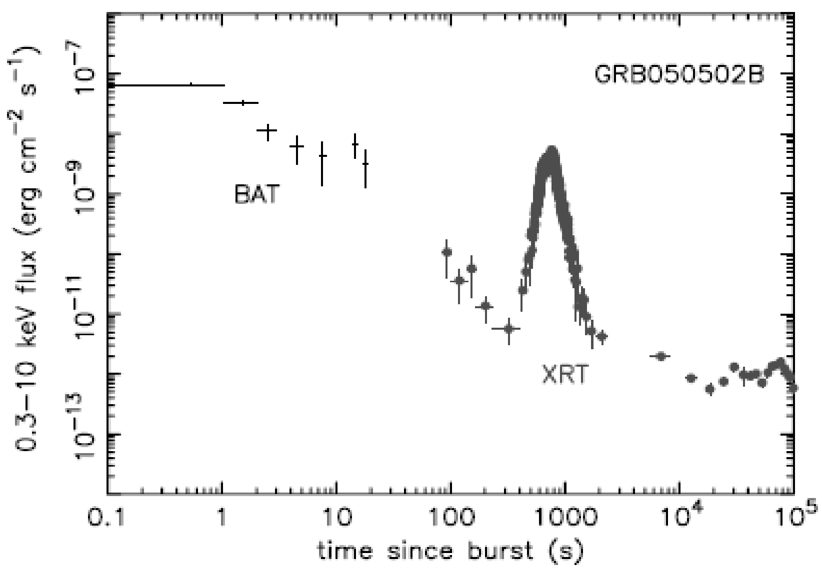
➢ *Swift: transition from prompt to afterglow (>2005)*

❑ BeppoSAX era



❑ Swift era

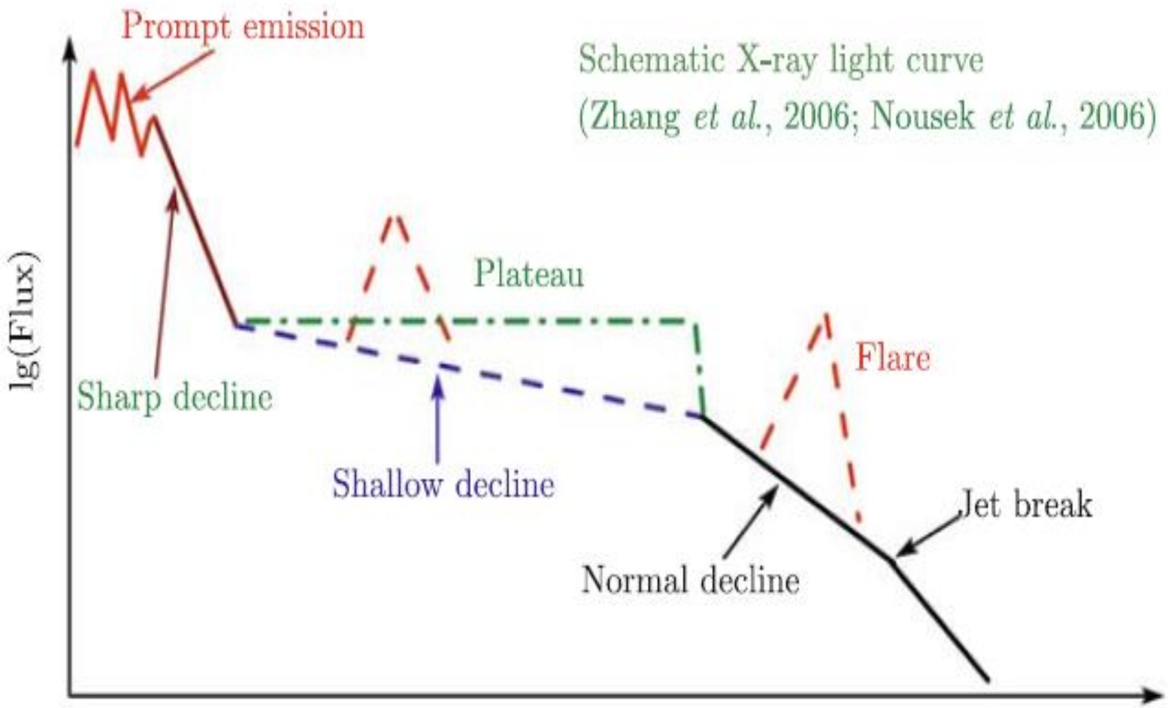




Maiorano et al., 2005 ; Swift team

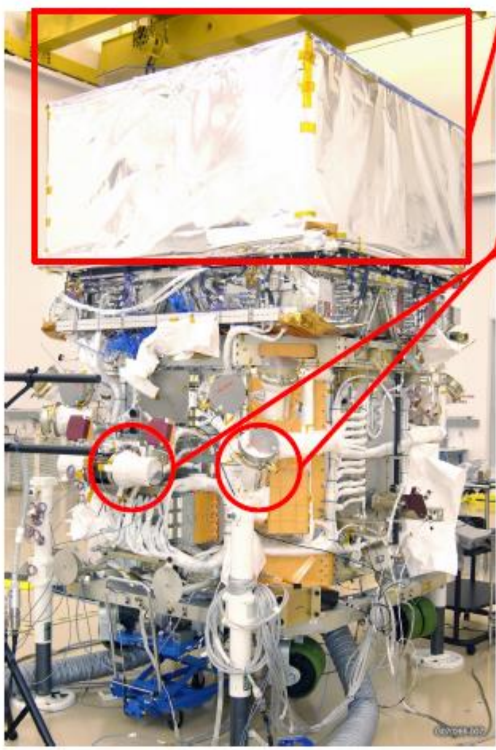
➢ *Early X-ray afterglow*

- ❑ new features seen by Swift in X-ray early afterglow light curves (initial very steep decay, early breaks, flares) mostly unpredicted and unexplained
- ❑ initial steep decay: continuation of prompt emission, mini break due to patchy shell, IC up-scatter of the reverse shock sinchrotron emission ?
- ❑ flat decay: probably “refreshed shocks” (due either to long duration ejection or short ejection but with wide range of Γ) ?
- ❑ flares: could be due to: refreshed shocks, IC from reverse shock, external density bumps, continued central engine activity, late internal shocks…



➢ *Fermi (> 2008): broad band prompt emission and VHE*

- ❑ Detection, arcmin localization and **study of GRBs in the GeV energy range** through the ***Fermi*/LAT instrument**, with dramatic improvement w/r CGRO/EGRET
- ❑ Detection, rough localization (a few degrees) and **accurate determination of the shape of the spectral continuum of the prompt emission of GRBs from 8 keV up to 30 MeV through the** Fermi/GBM instrument

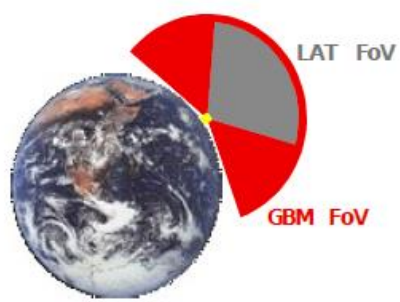


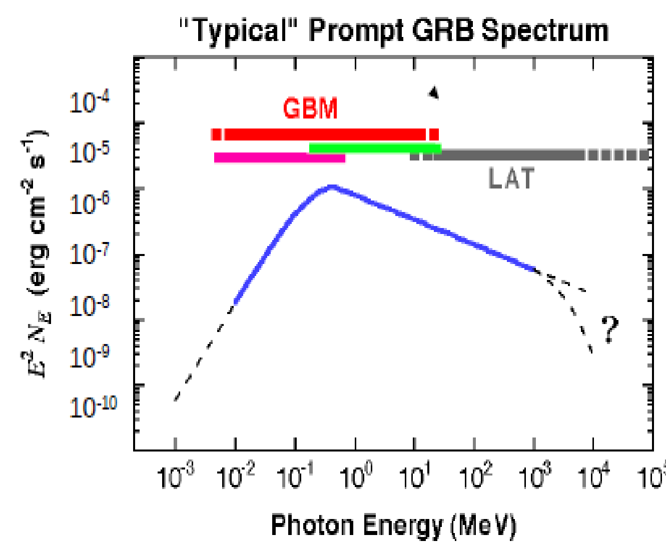
Large Area Telescope (LAT)

- Pair conversion telescope.
- Independent on-board and ground burst trigger, spectrum from 20 MeV to 300 GeV

Gamma-ray Burst Monitor (GBM)

- 12 NaI detectors, 2 BGO detectors.
- Onboard localization over the entire unocculted sky, spectrum from 8 keV to 40 MeV.

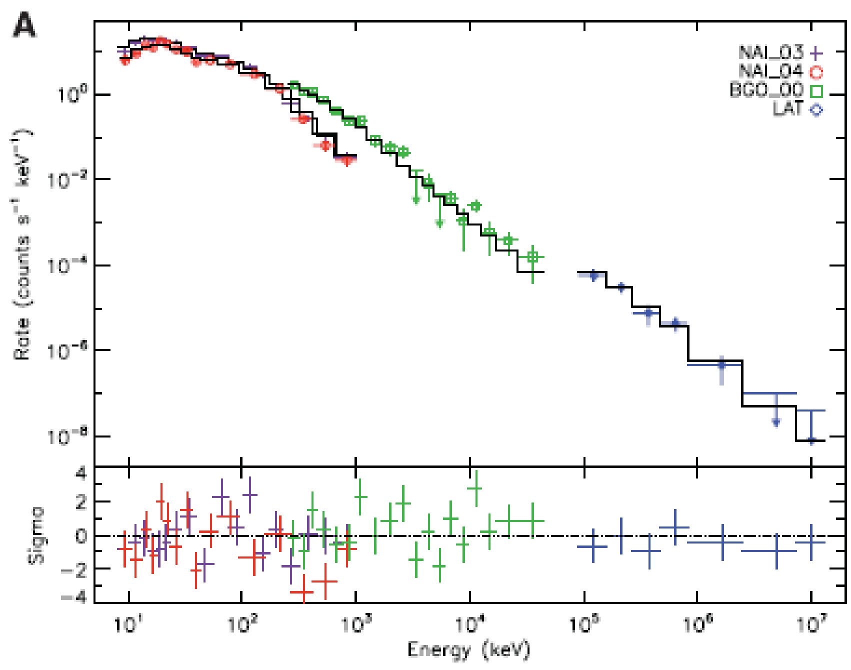


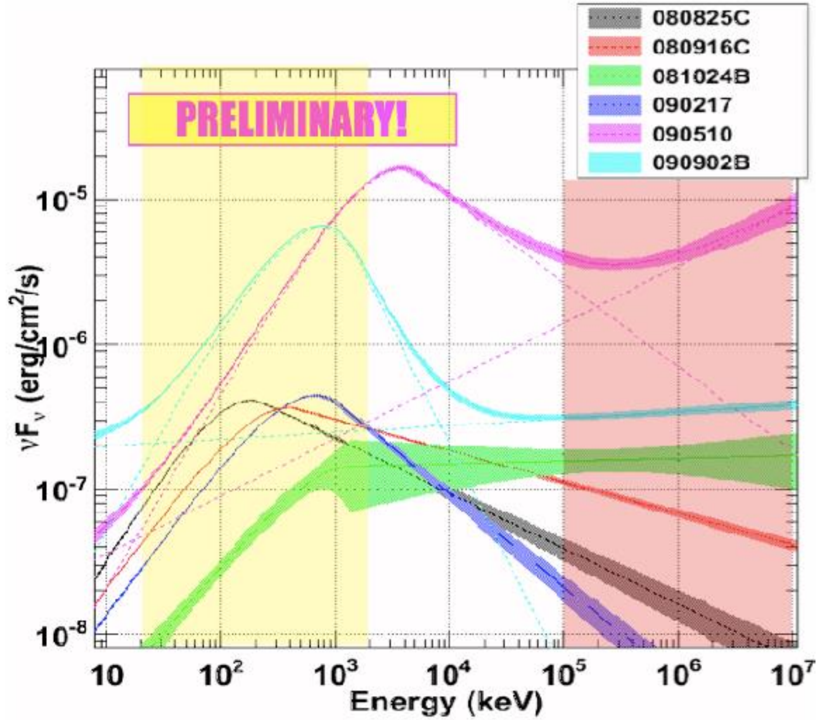


➢ *VHE (> 100 MeV) properties of GRBs by Fermi and AGILE*

- ❑ the huge radiated energy, the spectrum extending up to VHE without any excess or cut-off and time-delayed GeV photons of GRB 080916C measured by Fermi are challenging evidences for GRB prompt emission models

- ❑ nevertheless, an excess at E > 100 MeV, modeled with an additional power-law component, is detected in some GRBs (e.g., GRB 090902B, GRB090510): SSC of lower energy sinchrotron emission, IC of photospheric emission, hadronic processes



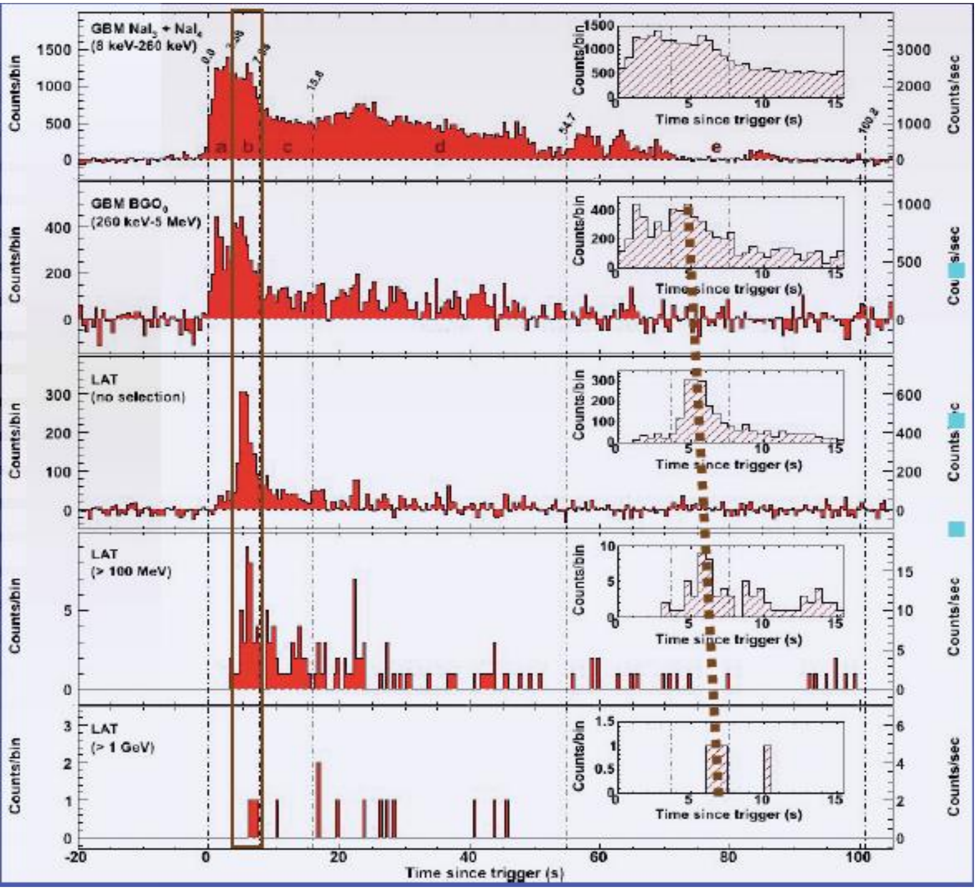


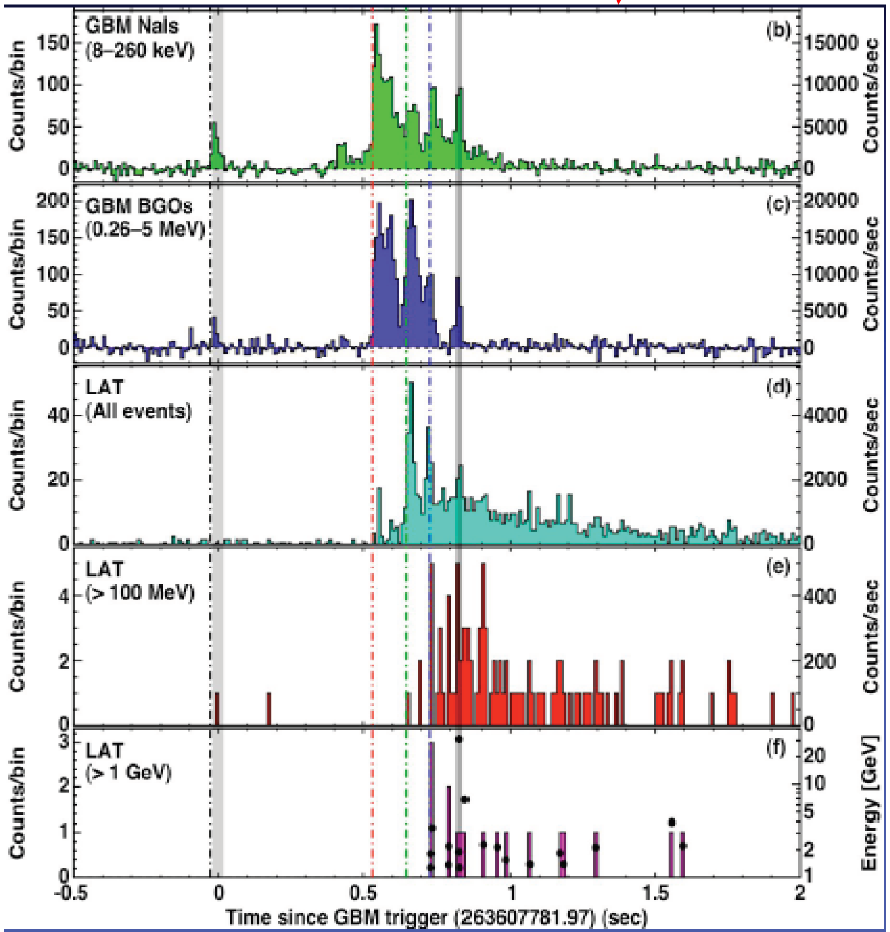
Abdo et al. 2009

- significant evidence (at least for the brightest GRBs) of a delayed onset of VHE emission with respect to soft gamma rays;

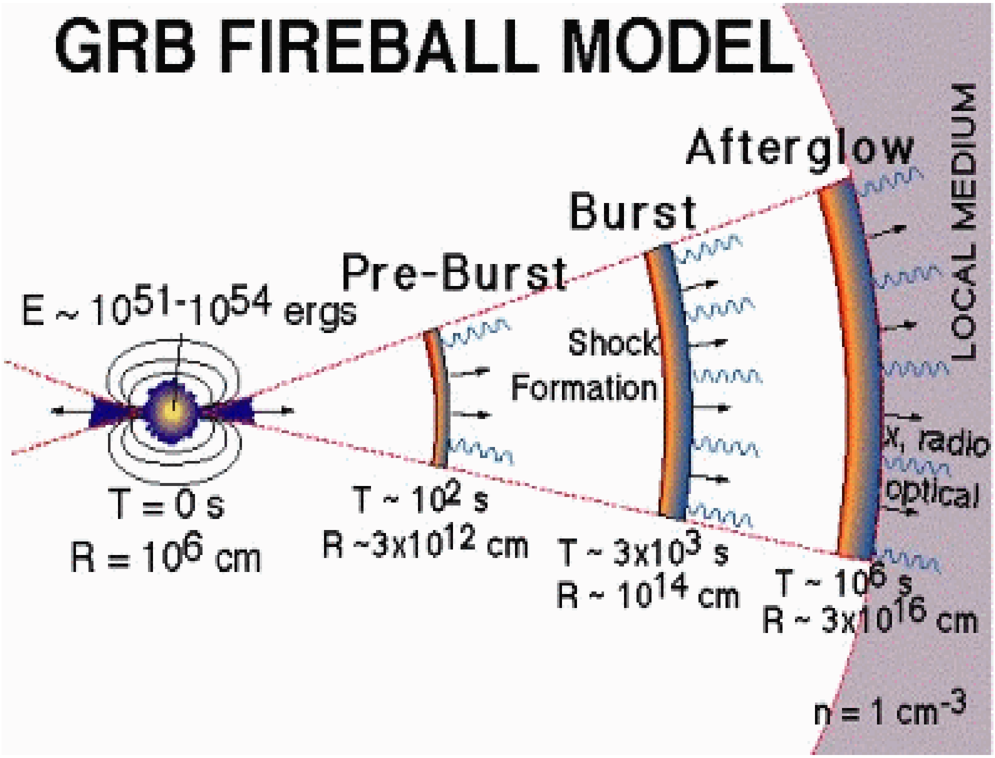
- the time delay appears to scale with the duration of the GRB (several seconds in the long GRBs 080916C and 090902B, while 0.1 − 0.2 s in the short GRBs 090510 and 081024B)

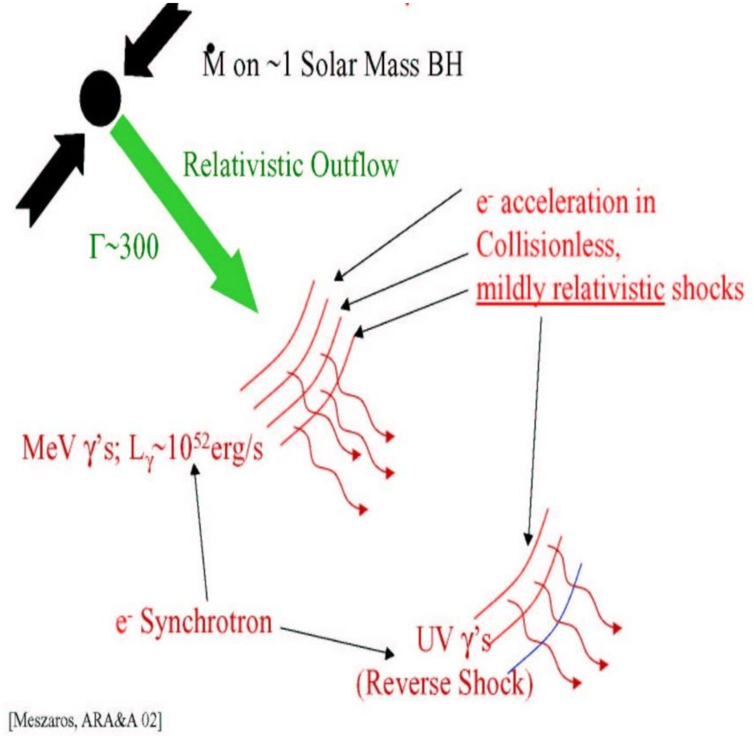
- again, challenging for models (hadronic: e.g., proton acceleration time ?)





Standard scenarios for GRB phisics

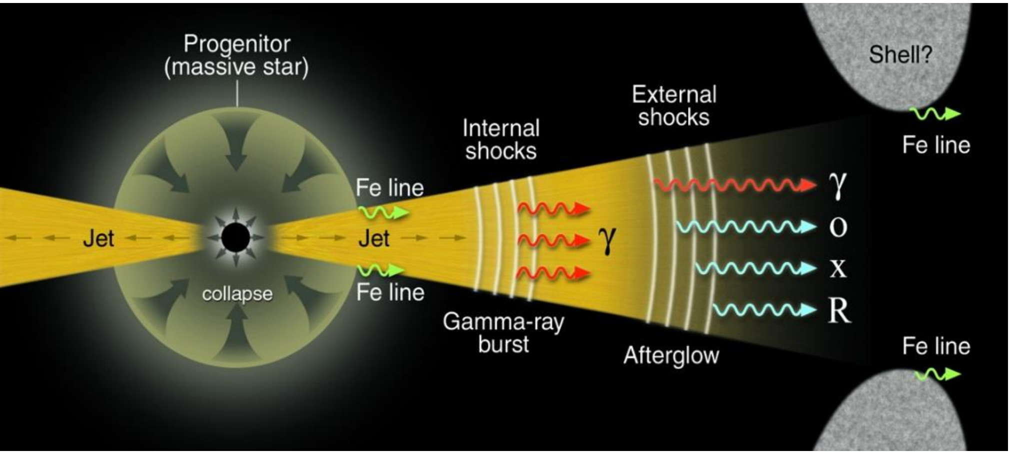




- ms time variability + huge energy + detection of GeV photons -> plasma occurring ultra-relativistic (Γ > 100) expansion (fireball or firejet)
- non thermal spectra -> shocks synchrotron emission (SSM)
- fireball internal shocks -> prompt emission
- fireball external shock with ISM -> afterglow emission

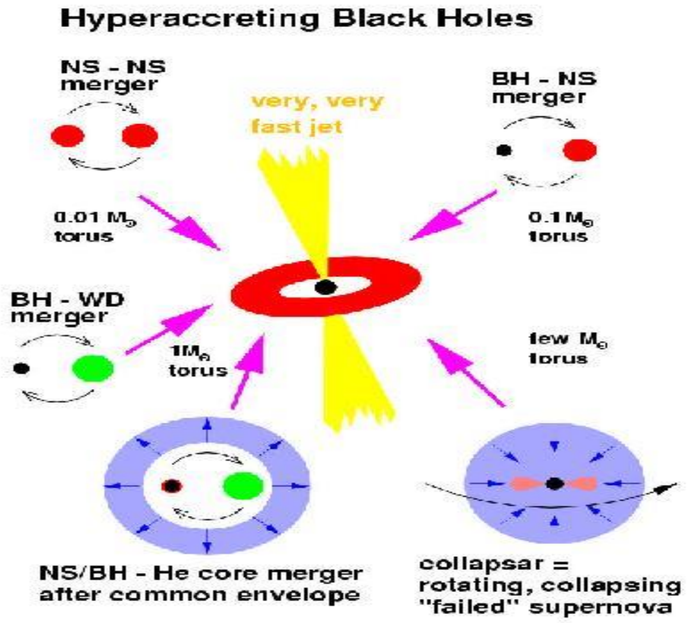
Standard scenarios for GRB progenitors

LONG



- energy budget up to $>10^{54}$ erg
- long duration GRBs
- metal rich (Fe, Ni, Co) circum-burst environment
- GRBs occur in star forming regions
- GRBs are associated with SNe
- likely collimated emission

SHORT

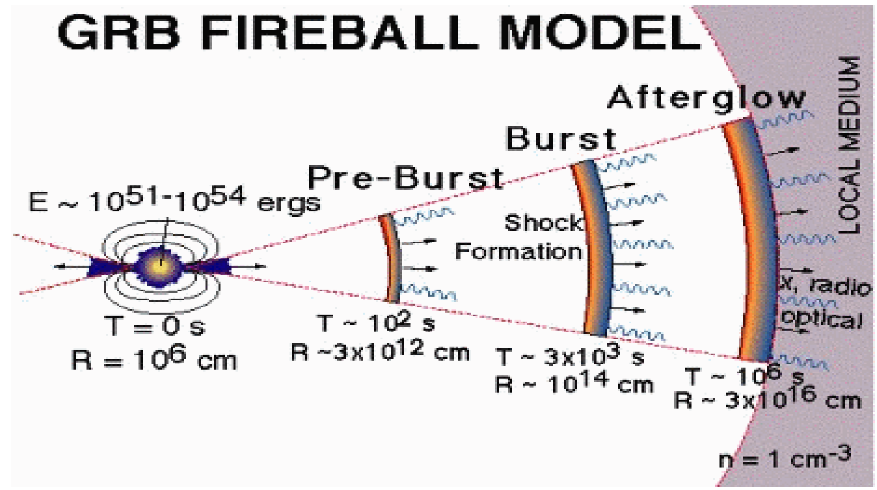


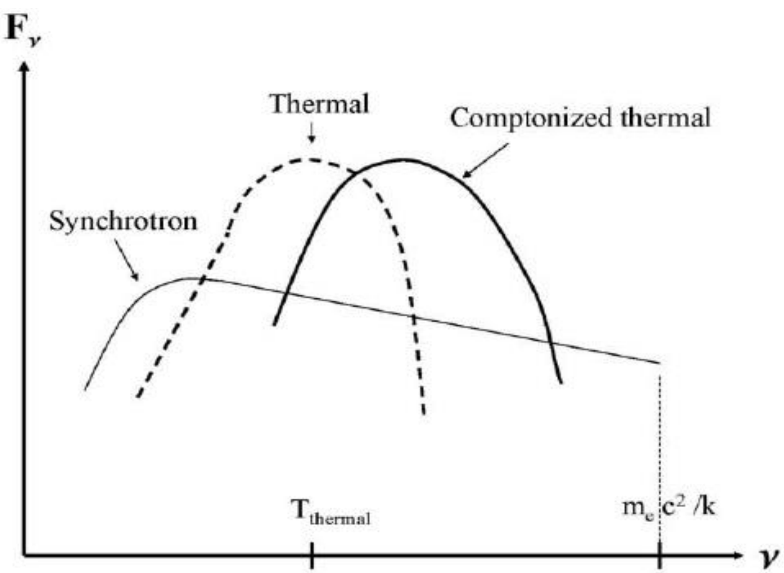
- energy budget up to 10^{51} - 10^{52} erg
- short duration (< 5 s)
- clean circum-burst environment
- old stellar population

Open issues (several, despite obs. progress)

➢ *GRB prompt emission physics*

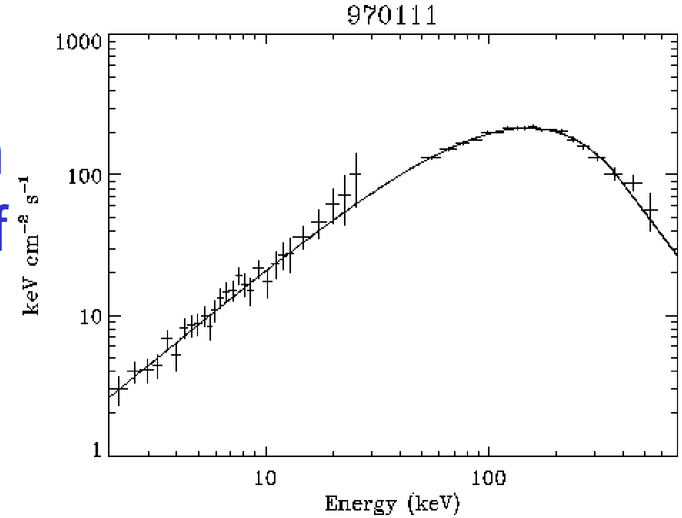
❑ physics of prompt emission still not settled, various scenarios: SSM internal shocks, IC-dominated internal shocks, external shocks, photospheric emission dominated models, kinetic energy dominated fireball , Poynting flux dominated fireball

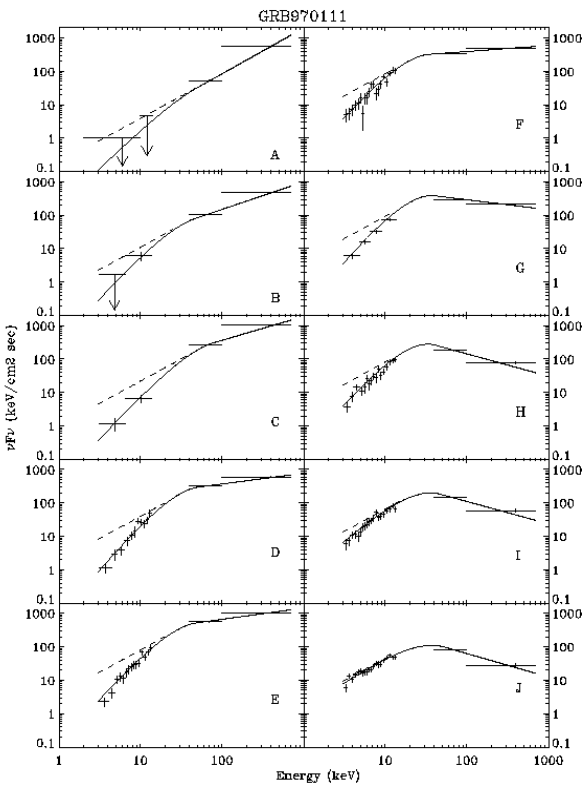


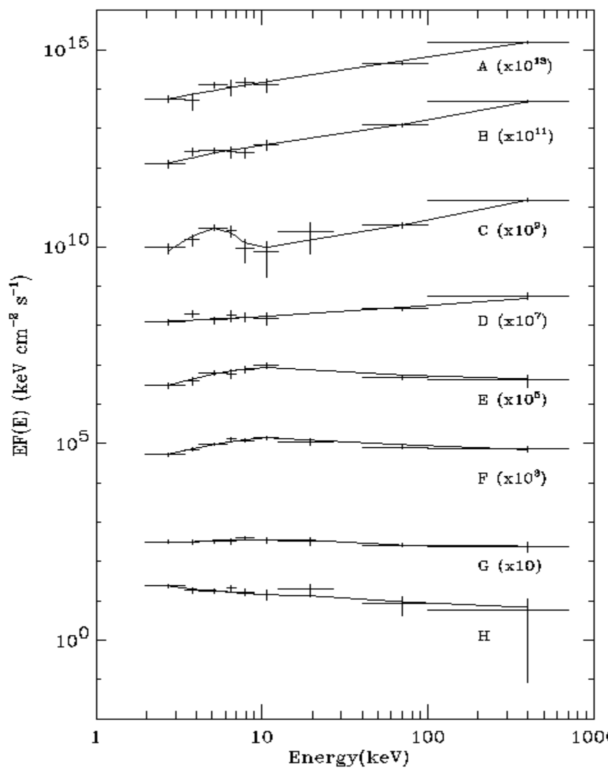


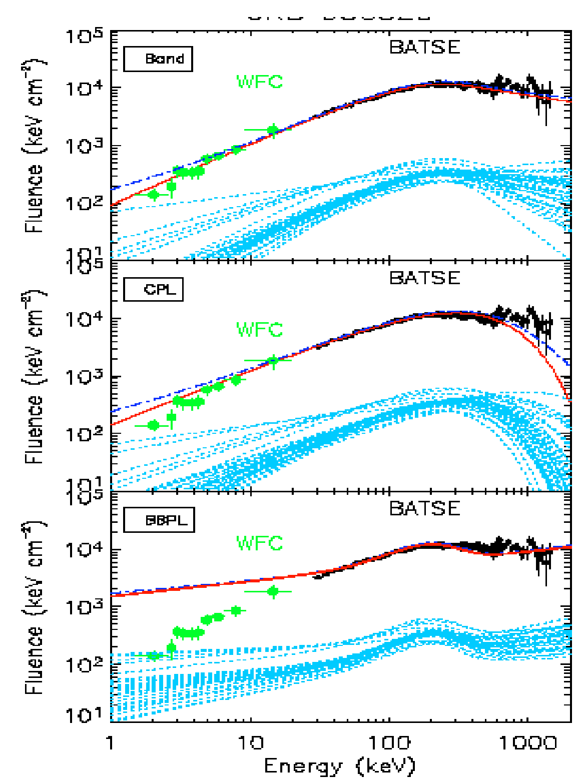
α $N(E)$	$\alpha+1$ $F(E)$	$\alpha+2$ EF_E	model/spectrum
-3/2	-1/2	1/2	Synchrotron emission with cooling
-1	0	1	Quasi–saturated Comptonization
-2/3	1/3	4/3	Instantaneous synchrotron
0	1	2	Small pitch angle/jitter
			inverse Compton by single e^-
1	2	3	Black Body
2	3	4	Wien

- most time averaged spectra of GRBs are well fit by synchrotron shock models
- at early times, some spectra inconsistent with optically thin synchrotron: possible contribution of IC component and/or thermal emission from the fireball photosphere
- thermal models challenged by X-ray spectra



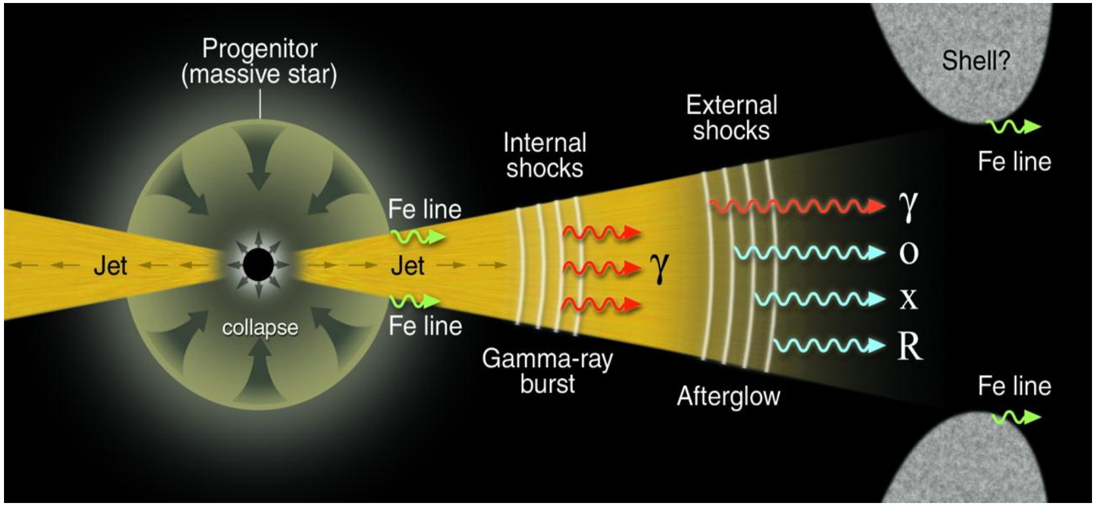


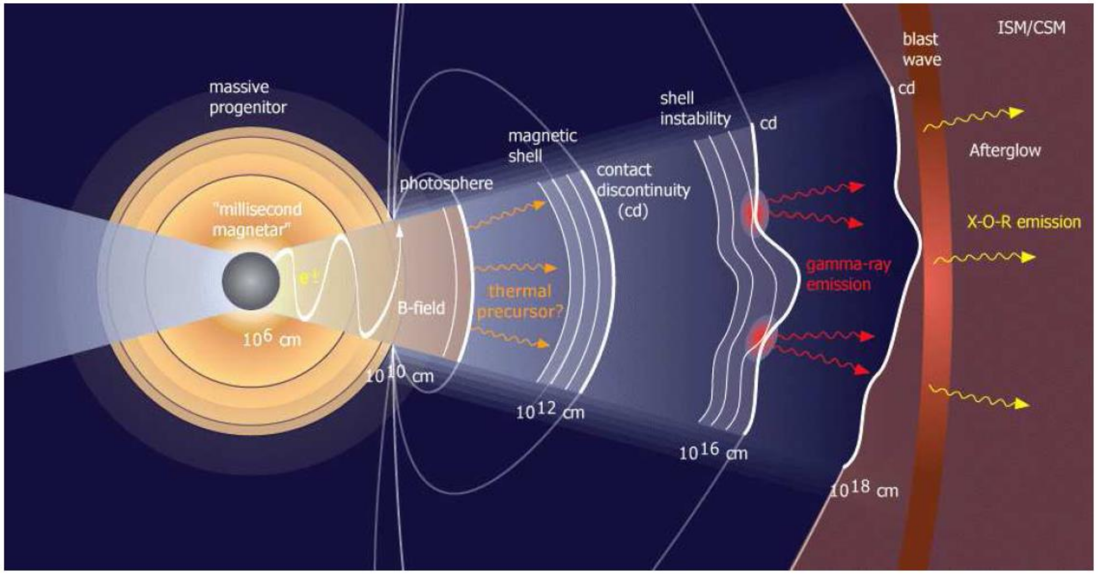




Amati et al. 2001, Frontera et al. 2000, Frontera et al. 2001, Ghirlanda et al. 2007

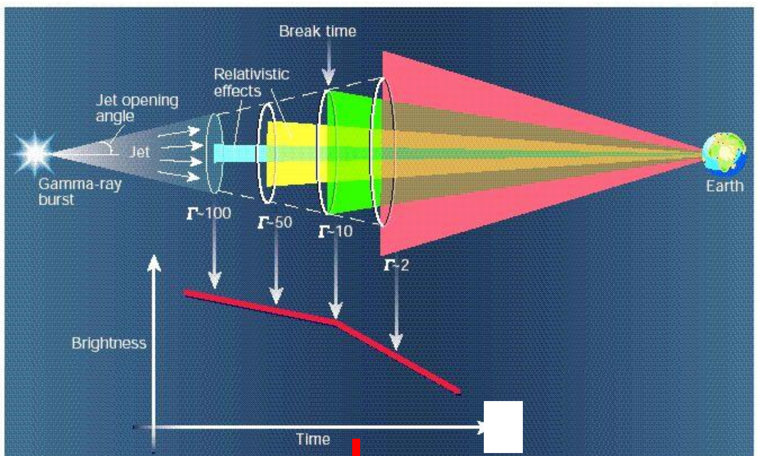
❑ Fireball nature : (baryon kinetic energy or Poynting flux dominated) and bulk Lorentz factor Γ are still to be firmly established





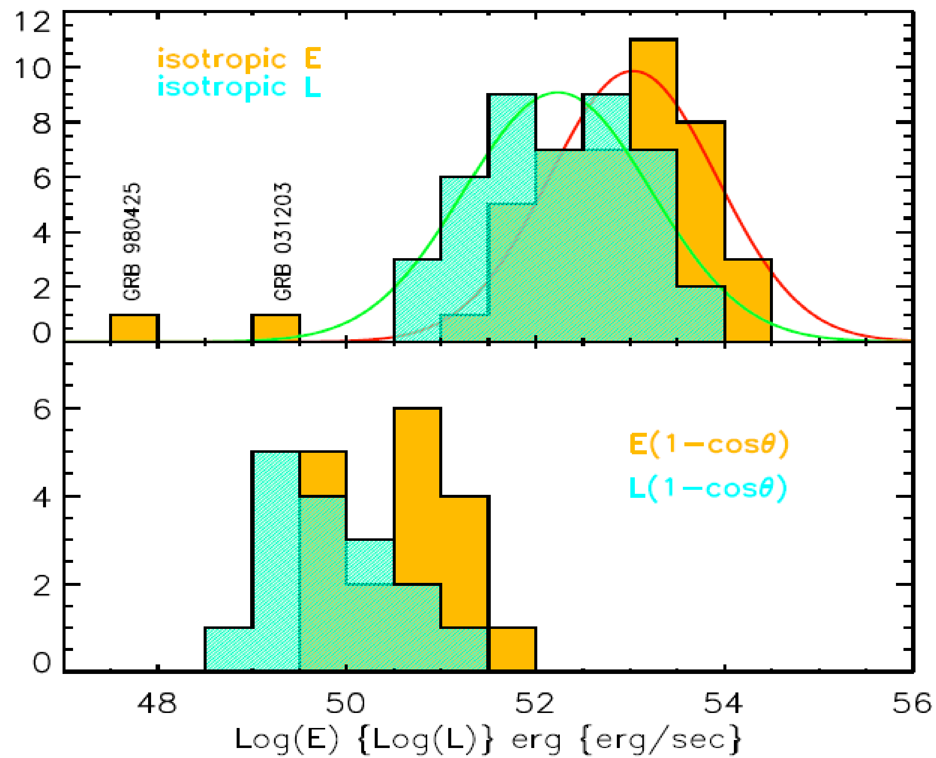
➢ *Collimated or isotropic ? The problem of missing breaks*

- ❑ jet angles, derived from break time of optical afterglow light curve by assuming standard scenario, are of the order of few degrees
- ❑ the collimation-corrected radiated energy spans the range ~$5x10^{49}$ – $5x10^{52}$



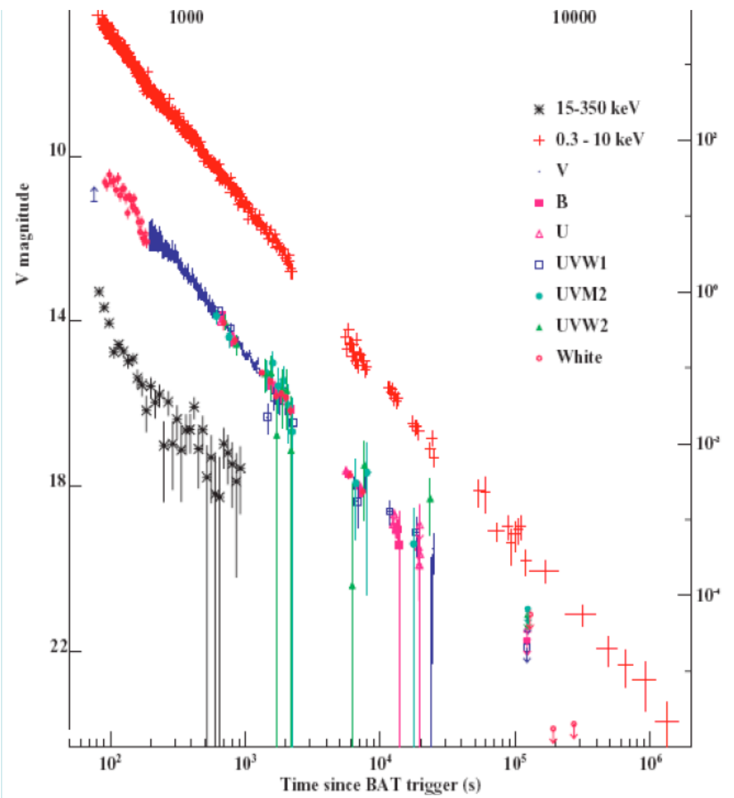
$$\theta = 0.09 \left(\frac{t_{jet,d}}{1+z}\right)^{3/8} \left(\frac{n\,\eta_\gamma}{E_{\gamma,iso,52}}\right)^{1/8}$$

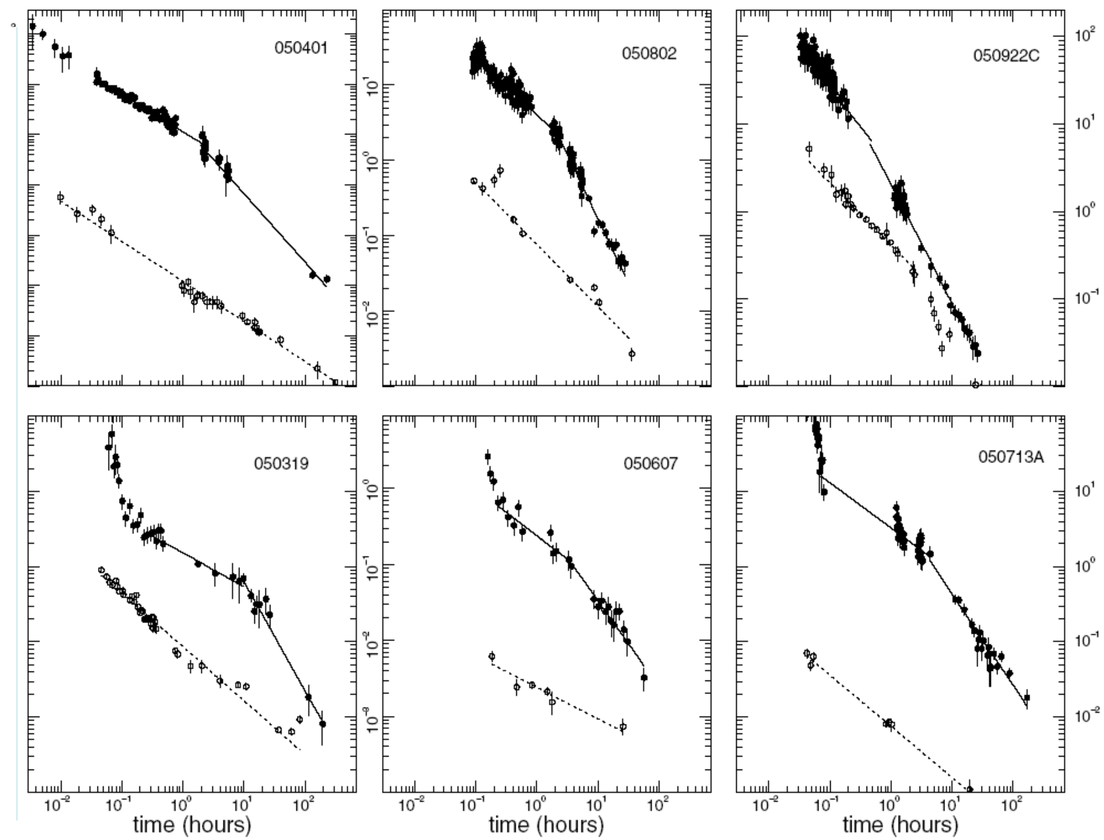
$$E_\gamma = (1 - \cos\theta) E_{\gamma,iso}.$$



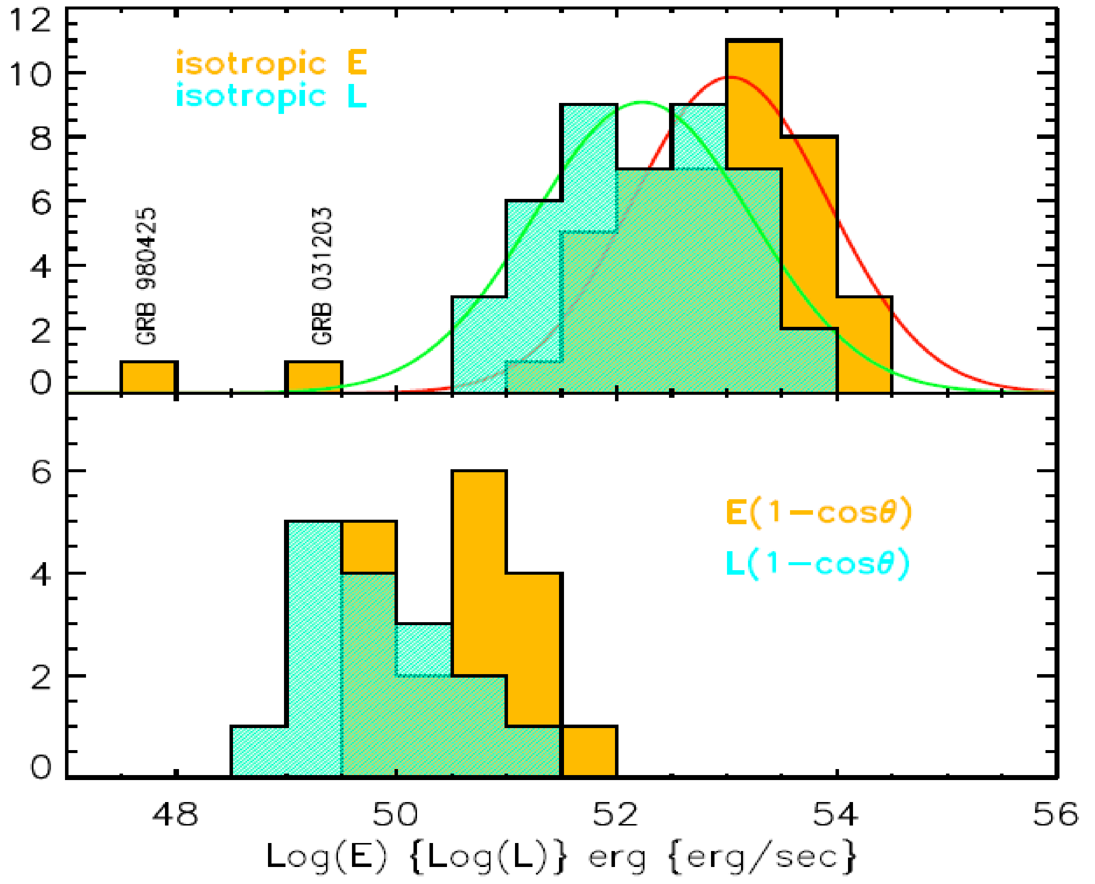
Ghirlanda et al., 2006

- lack of jet breaks in several Swift X-ray afterglow light curves, in some cases, evidence of achromatic break
- challenging evidences for Jet interpretation of break in afterglow light curves or due to present inadequate sampling of optical light curves w/r to X-ray ones and to lack of satisfactory modeling of jets ?



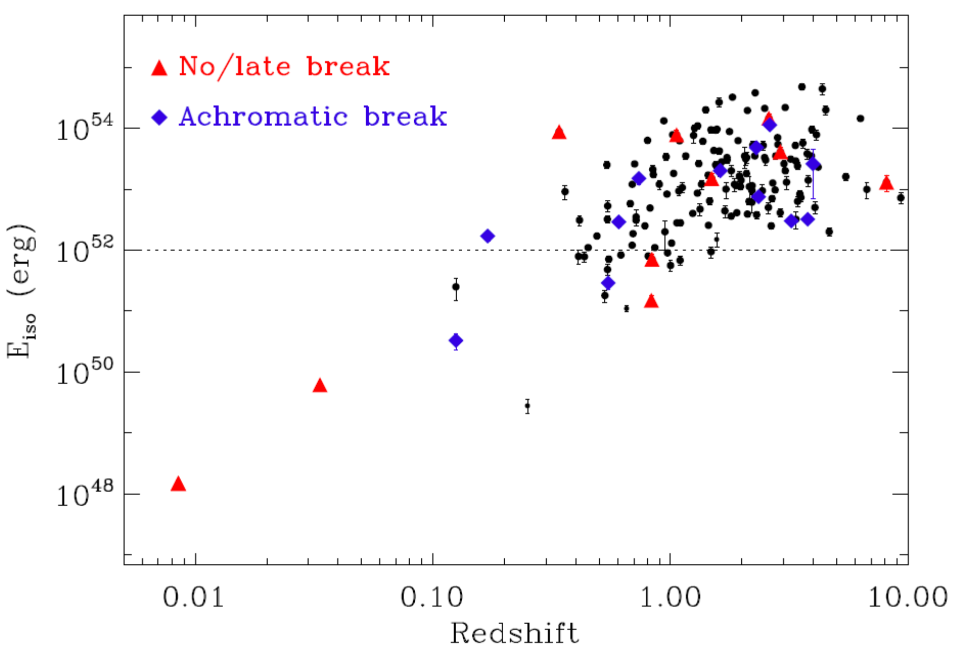


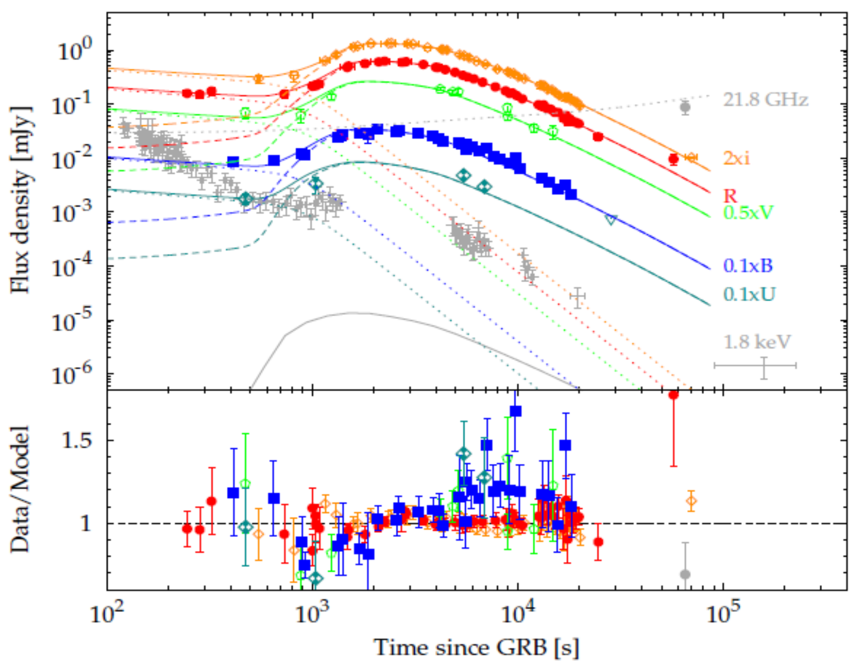
- jet angles, derived from break time of optical afterglow light curve by assuming standard scenario, are of the order of few degrees
- the collimation-corrected radiated energy spans the range ~$5 \times 10^{49} - 5 \times 10^{52}$



Ghirlanda et al., 2006

- achromatic break predicted by semplified afterglow + uniform jet scenario observed only in 10-15 cases (collination angles of ~5-10°)
- in several cases, no break is observed after long standing follow-up -> poorly collimated GRBs (very high energy budget)?
- Recent more sophisticated models: good description of multi-wavelength emission and larger opening angles (e.g., GRB121204A, 23°, ~10^{53} erg)

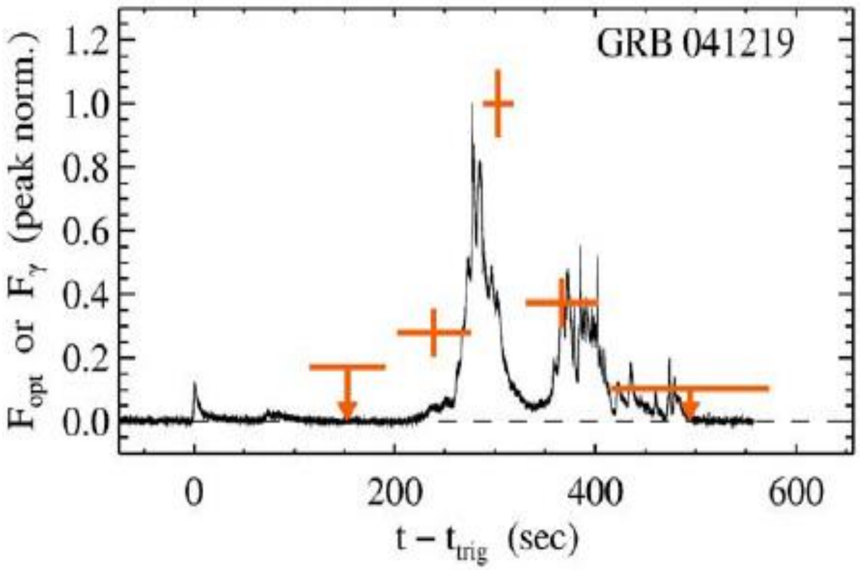


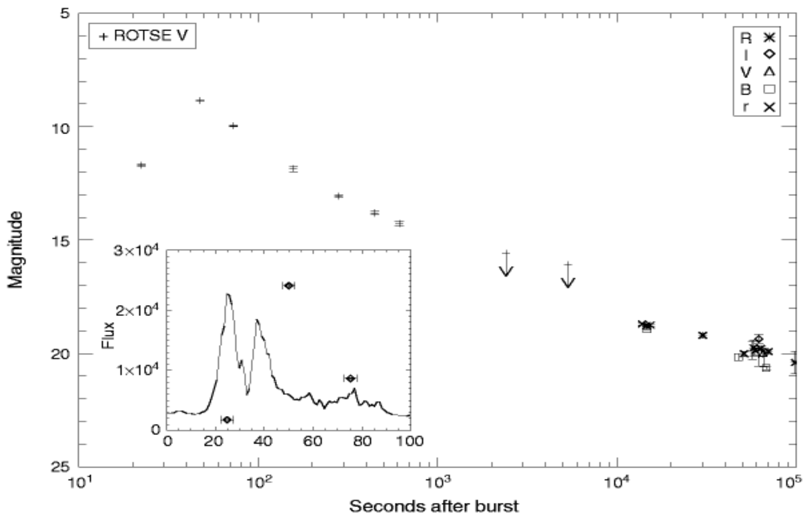


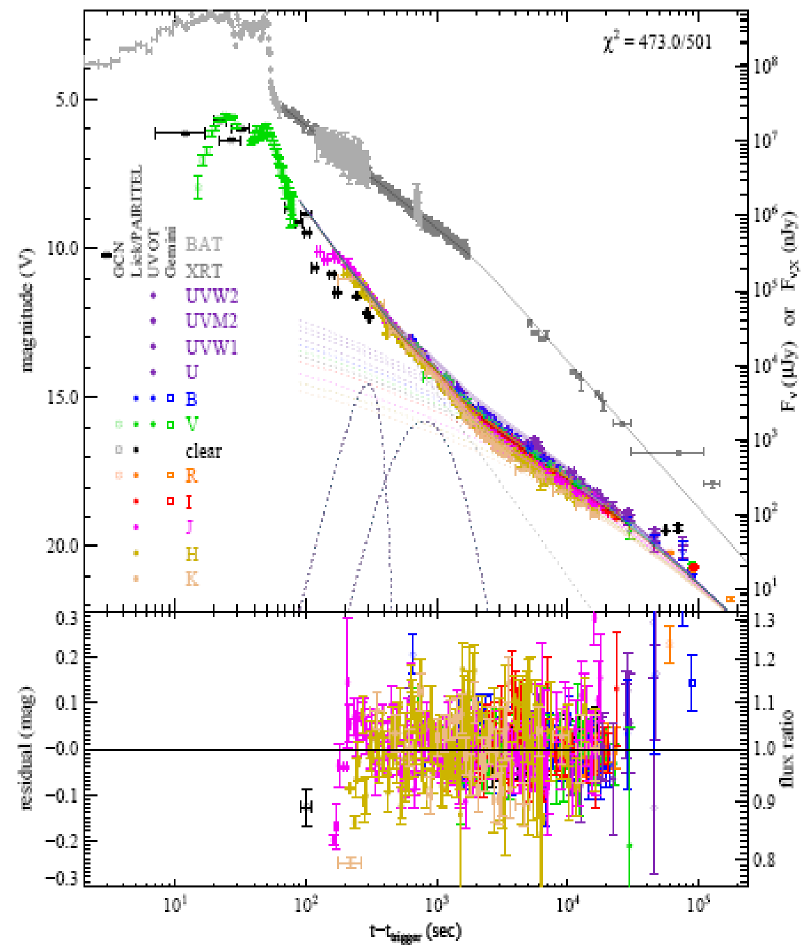
Amati 2013, Guidorzi et al. 2013

➢ *Prompt optical emission*

❑ prompt x and optical emission: usually significantly different behaviours (optical from reverse shock ? optical from synchrotron and gamma from SSC ?)

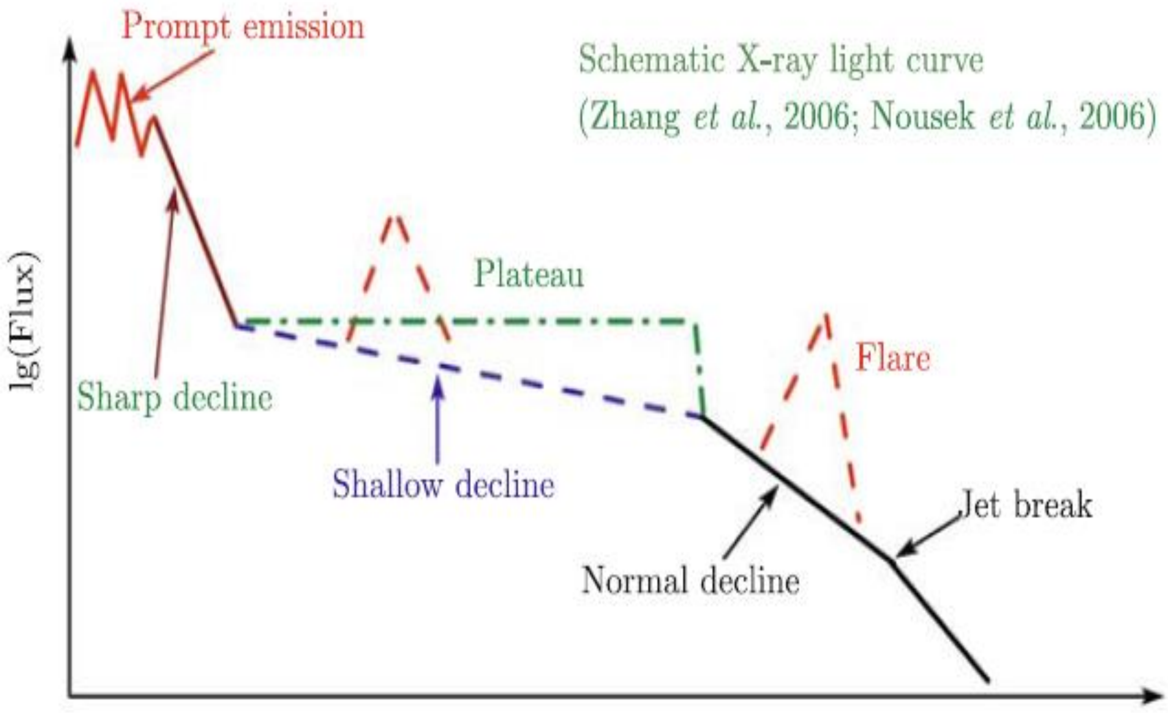






➢ *Early X-ray afterglow*

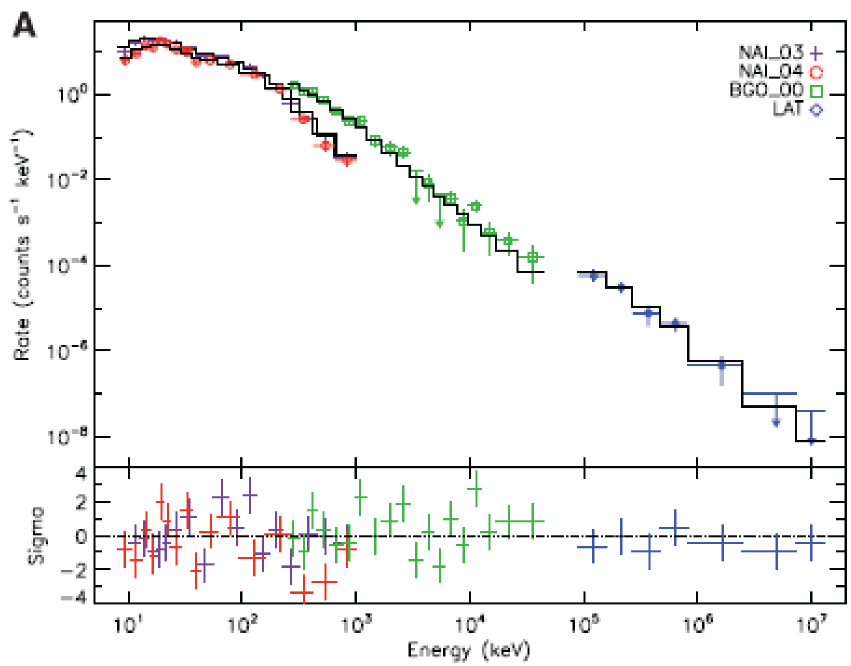
- new features seen by Swift in X-ray early afterglow light curves (initial very steep decay, early breaks, flares) mostly unpredicted and unexplained
- initial steep decay: continuation of prompt emission, mini break due to patchy shell, IC up-scatter of the reverse shock sinchrotron emission ?
- flat decay: probably “refreshed shocks” (due either to long duration ejection or short ejection but with wide range of Γ) ?
- flares: could be due to: refreshed shocks, IC from reverse shock, external density bumps, continued central engine activity, late internal shocks…

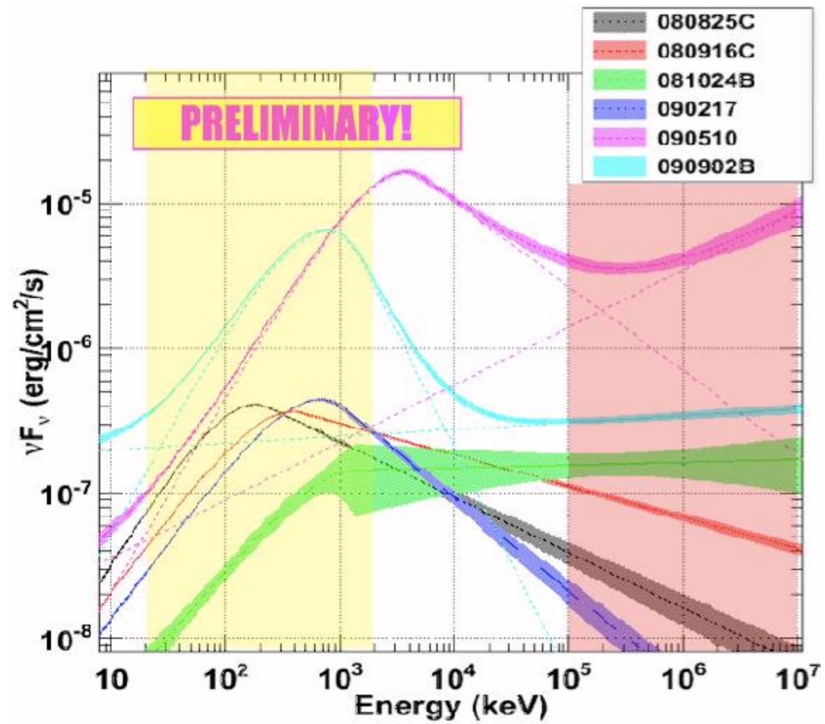


➢ *VHE (> 100 MeV) properties of GRBs by Fermi and AGILE*

❑ the huge radiated energy, the spectrum extending up to VHE without any excess or cut-off and time-delayed GeV photons of GRB 080916C measured by Fermi are challenging evidences for GRB prompt emission models

❑ nevertheless, an excess at E > 100 MeV, modeled with an additional power-law component, is detected in some GRBs (e.g., GRB 090902B, GRB090510): SSC of lower energy sinchrotron emission, IC of photospheric emission, hadronic processes



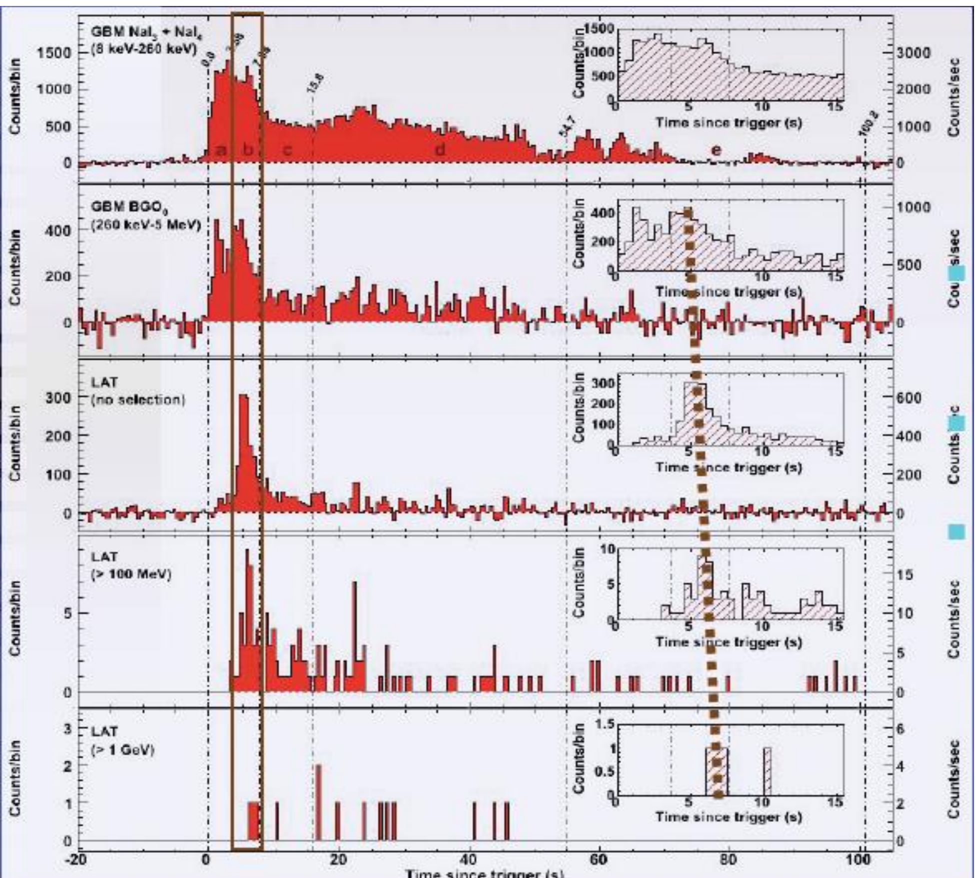


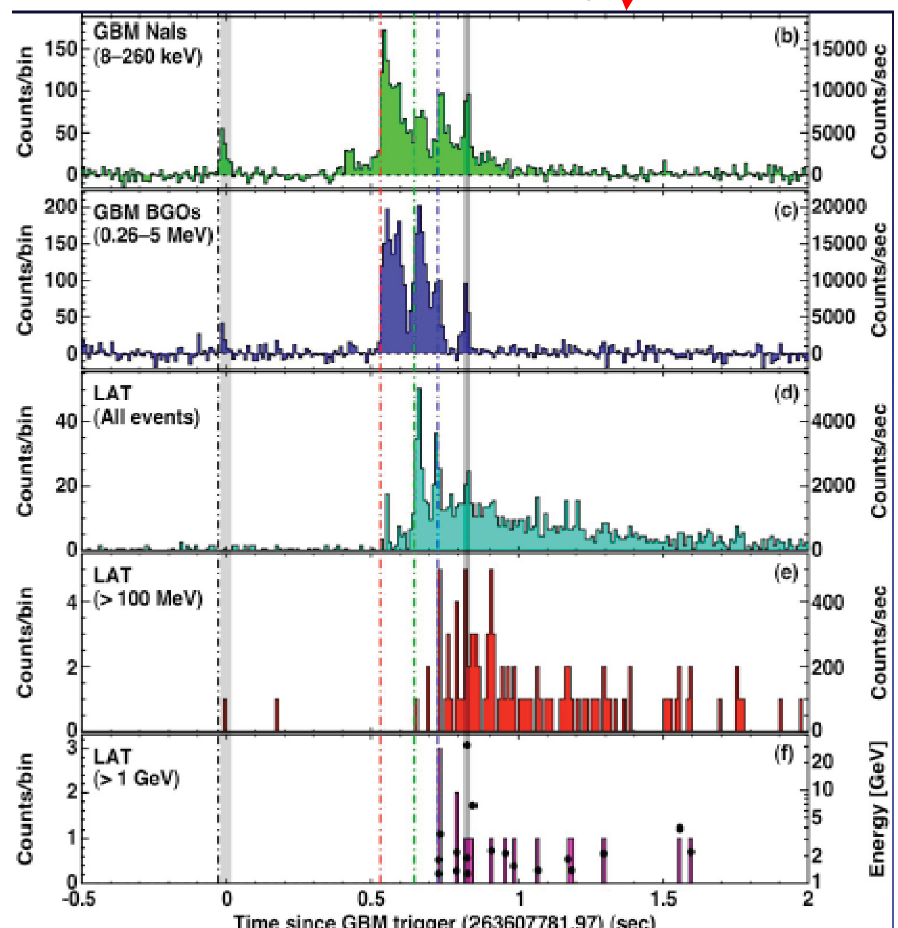
Abdo et al. 2009

❑ significant evidence (at least for the brightest GRBs) of a delayed onset of HE emission with respect to soft gamma rays;

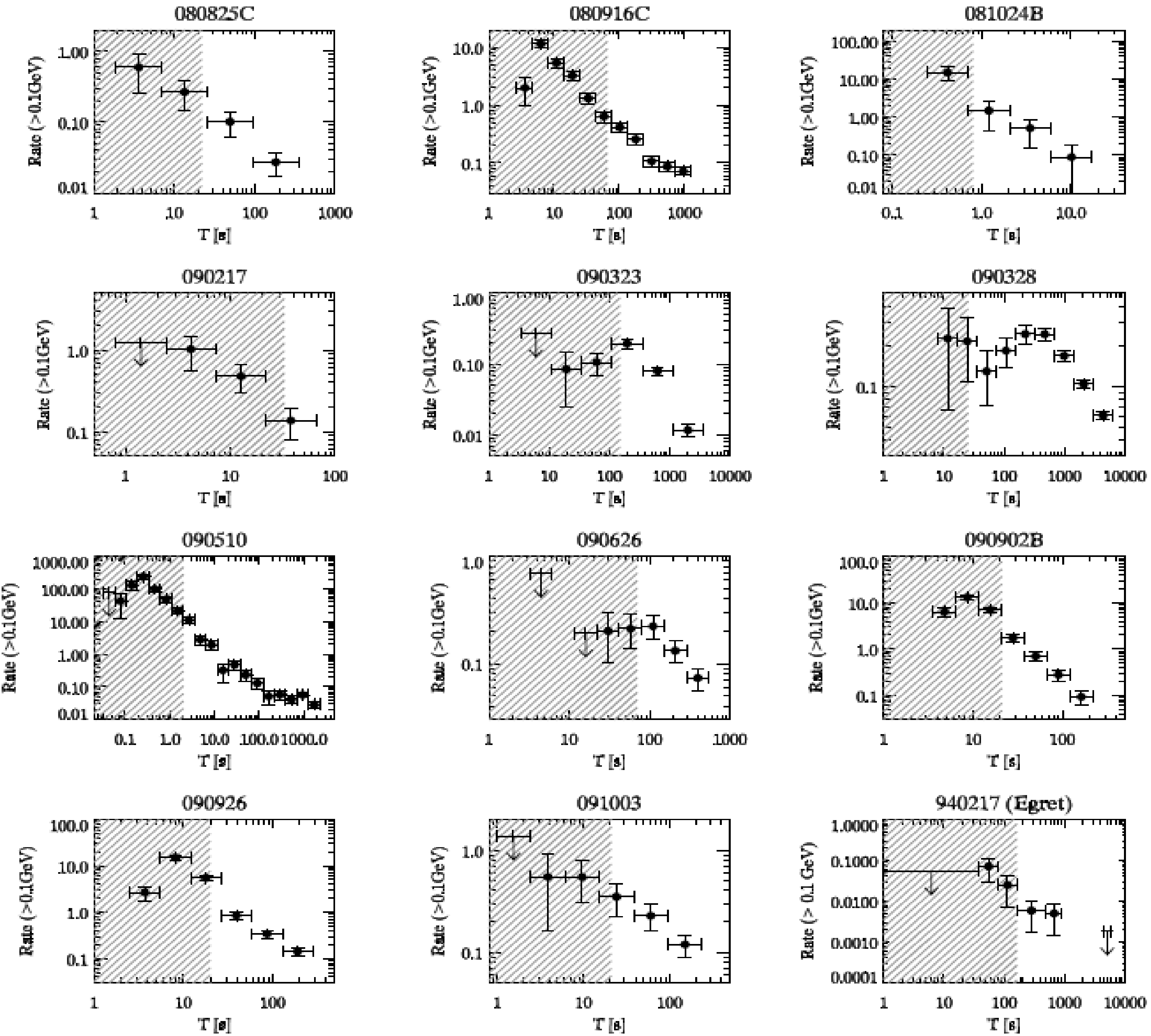
❑ the time delay appears to scale with the duration of the GRB (several seconds in the long GRBs 080916C and 090902B, while 0.1 − 0.2 s in the short GRBs 090510 and 081024B)

❑ again, challenging for models (hadronic: e.g., proton acceleration time ?)

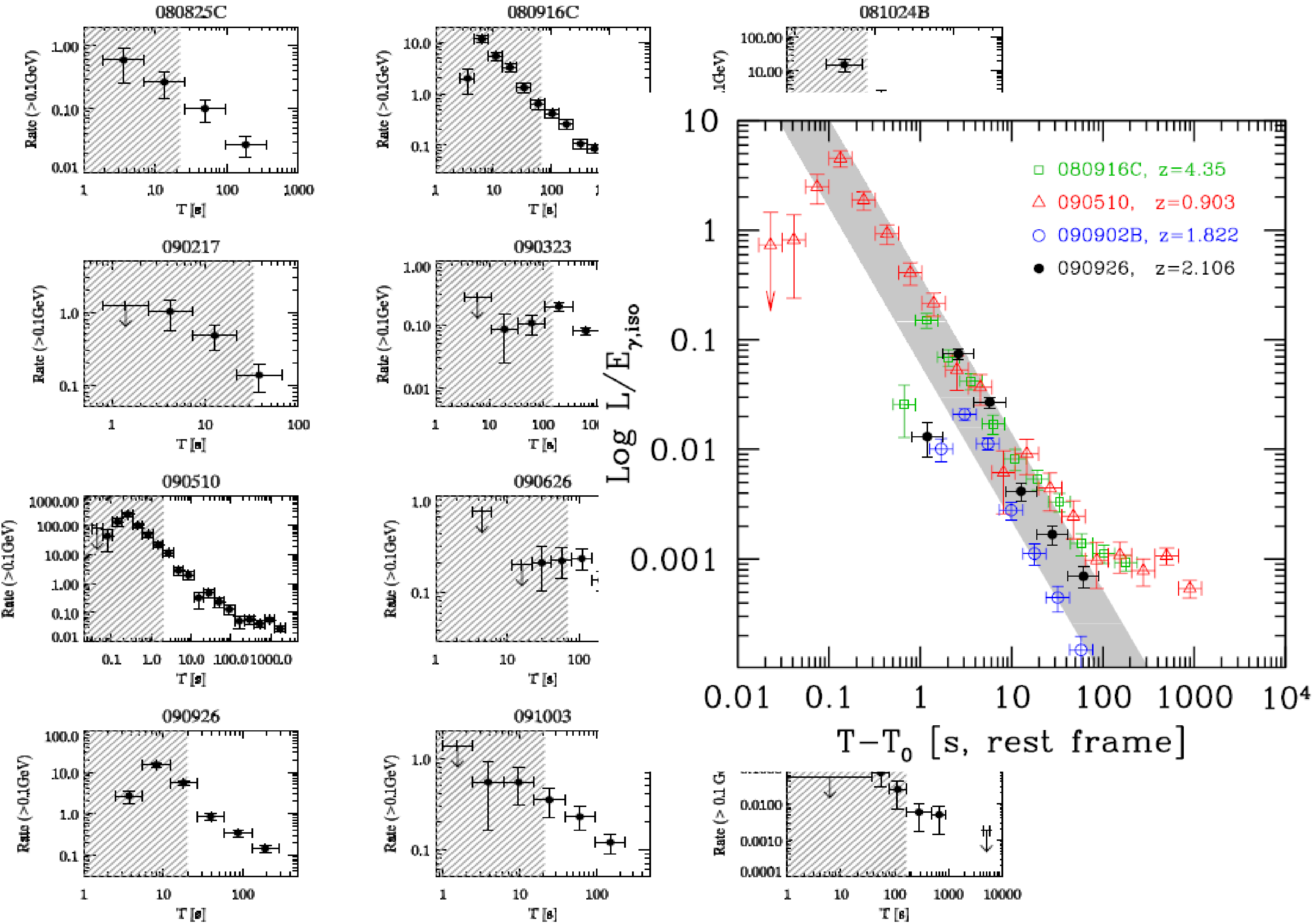




❑ prolonged HE emission: afterglow ? (e.g., Ghisellini et al. 2010)



❑ prolonged HE emission: afterglow ? (Ghisellini et al. 2010)



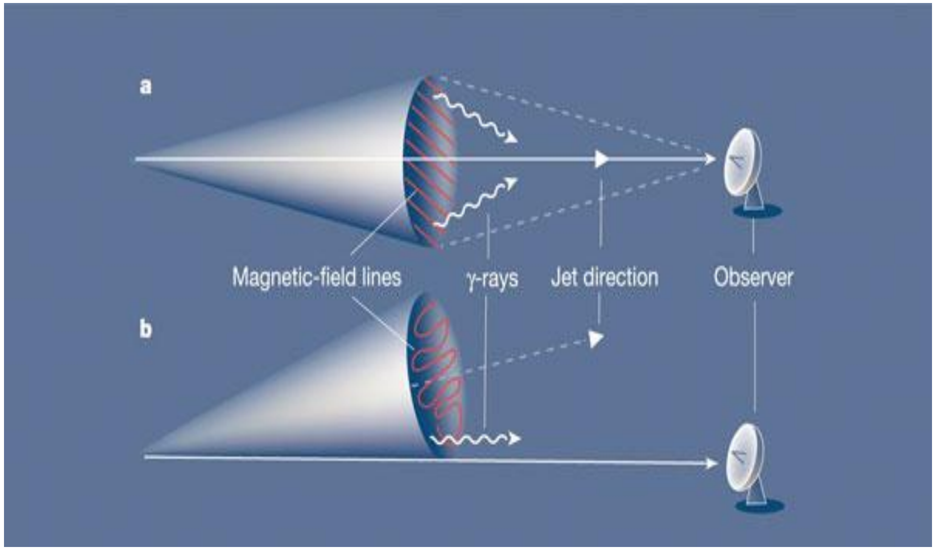
➢ *Polarization*

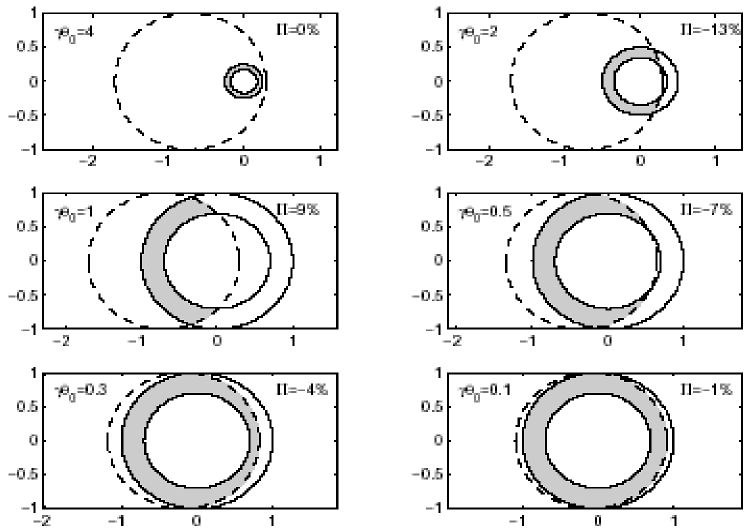
❑ until 2010, no secure detection of polarization of prompt emission (some information from INTEGRAL?), very recently measurements of 10-30% by GAP for few GRBs;

❑ polarization of a few % measured for some optical / radio afterglows

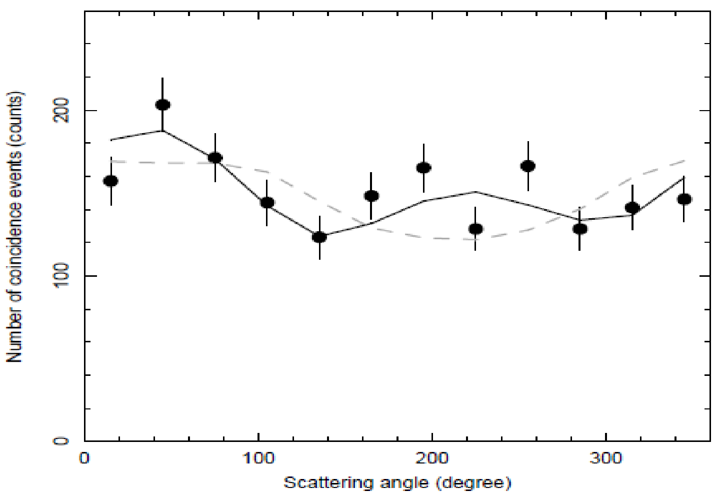
❑ radiation from synchrotron and IC is polarized, but a high degree of polarization can be detected only if magnetic field is uniform and perpendicular to line of sight

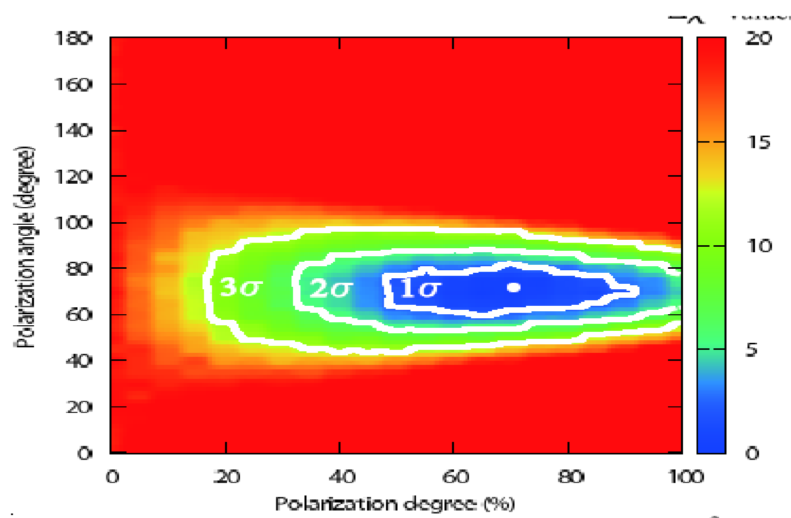
❑ small degree of polarization detectable if magnetic field is random, emission is collimated (jet) and we are observing only a (particular) portion of the jet or its edge

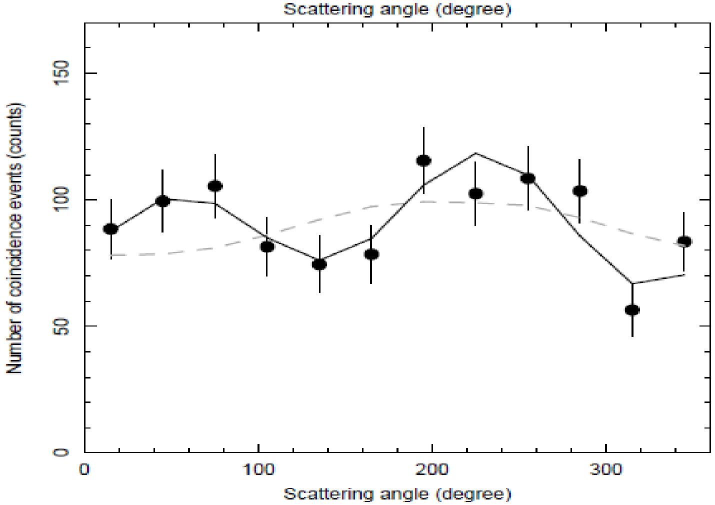


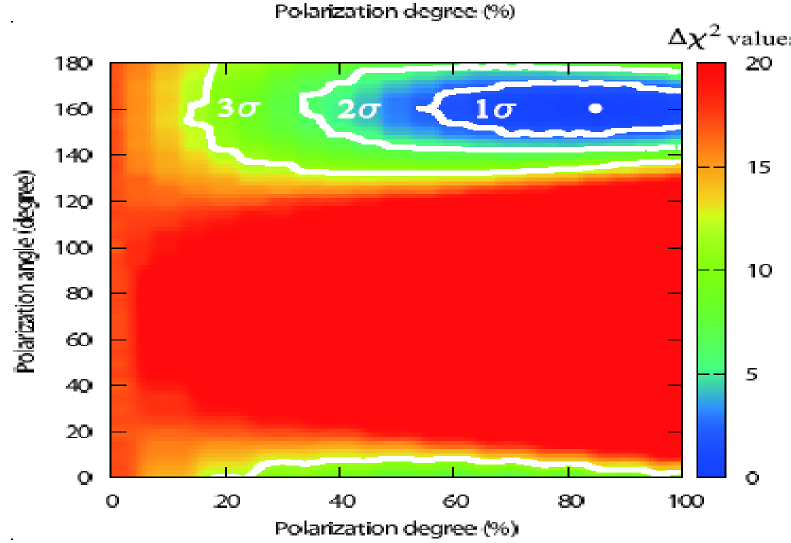


❑ high degree of linear polarization of prompt emission of GRB100826A, GRB110301A and GRB110721A recently measured by GAP (Yonetoku et al. 2011, 2012): confirmation of synchrotron against thermal ? Globally ordered magnetic fields advected by central engine ?





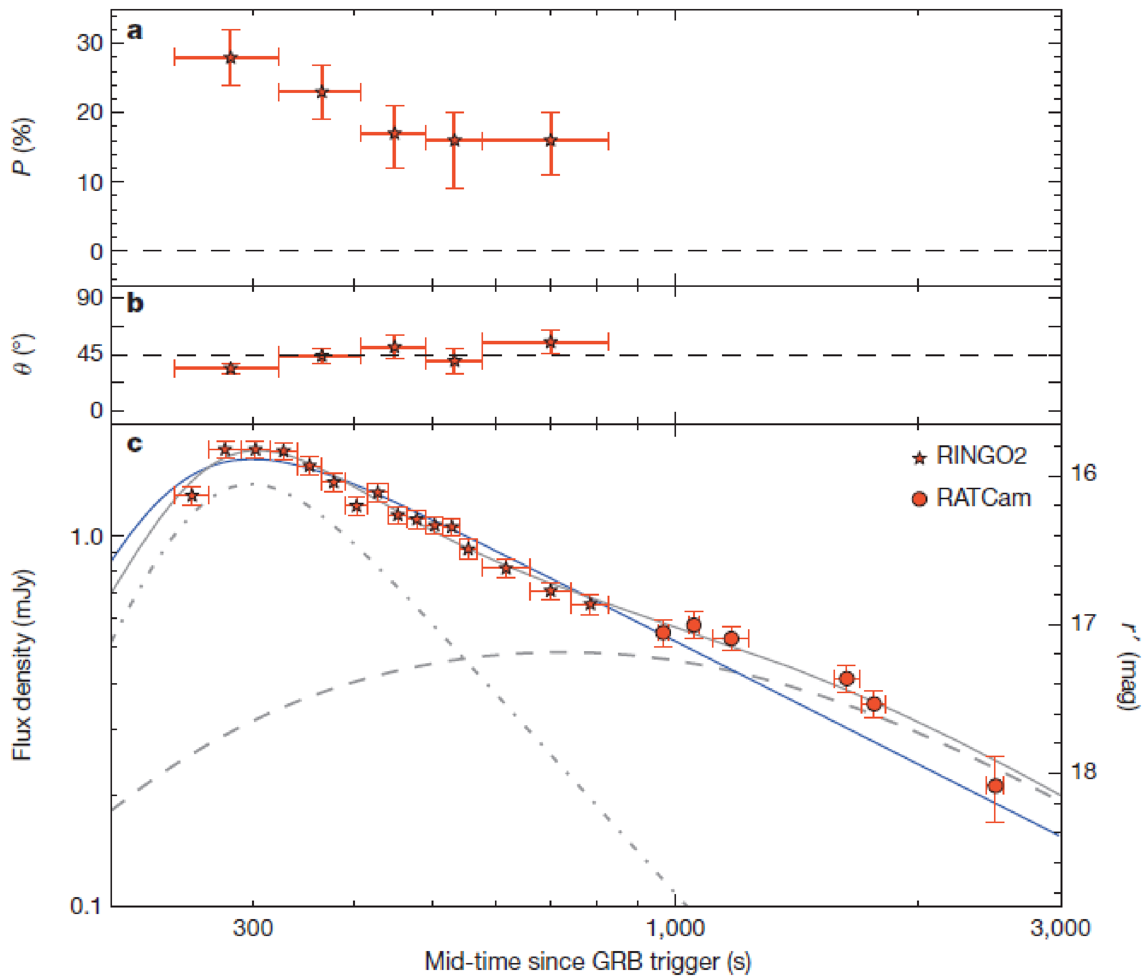




Highly polarized light from stable ordered magnetic fields in GRB 120308A

C. G. Mundell[1], D. Kopač[2], D. M. Arnold[1], I. A. Steele[1], A. Gomboc[2,3], S. Kobayashi[1], R. M. Harrison[1], R. J. Smith[1], C. Guidorzi[4], F. J. Virgili[1], A. Melandri[5] & J. Japelj[2]

- very recent report of high degree (~30%) of polarization with stable angle of early optica afterglow of GRB120308A -> evidence of magnetized baryonic jets with large-scale uniform fields that can survive long after the initial explosion

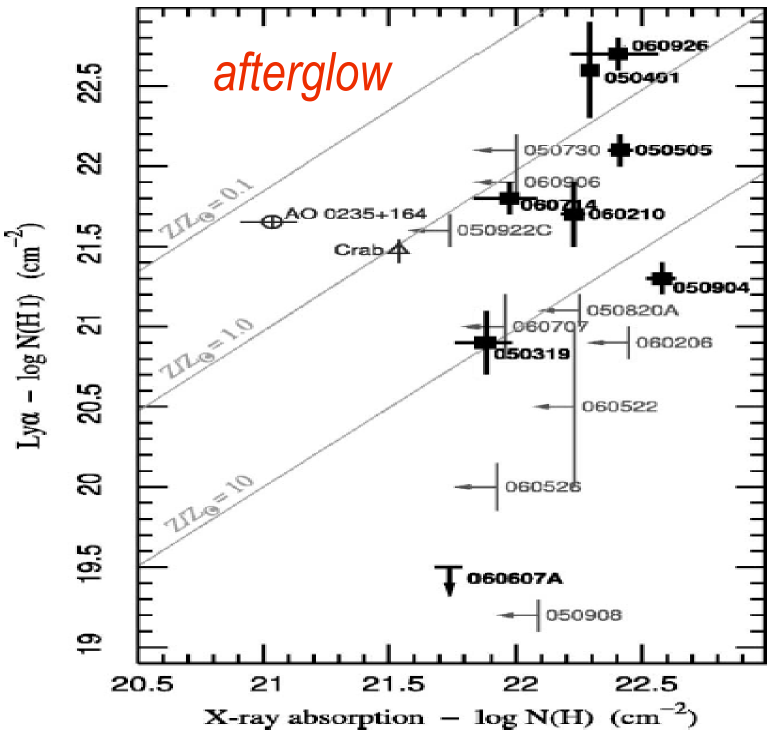


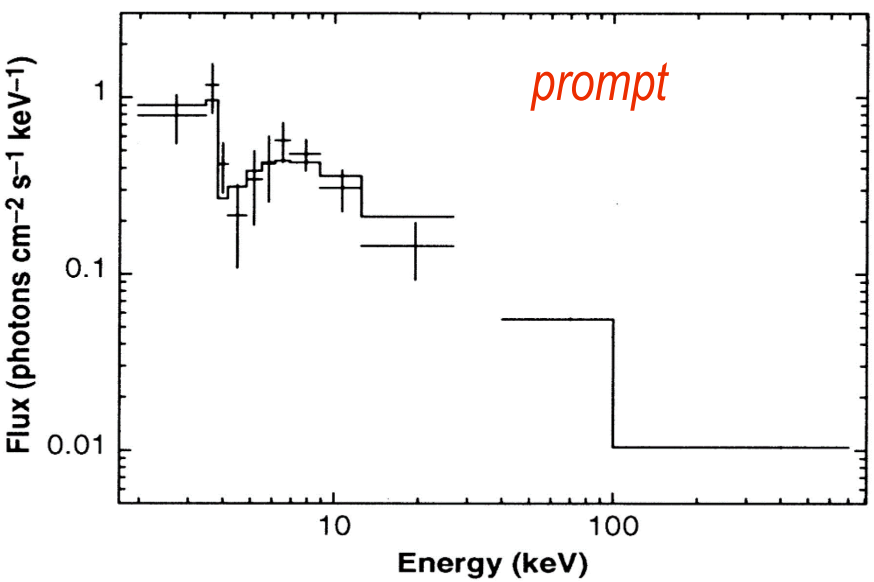
➢ *Circum-burst environment*

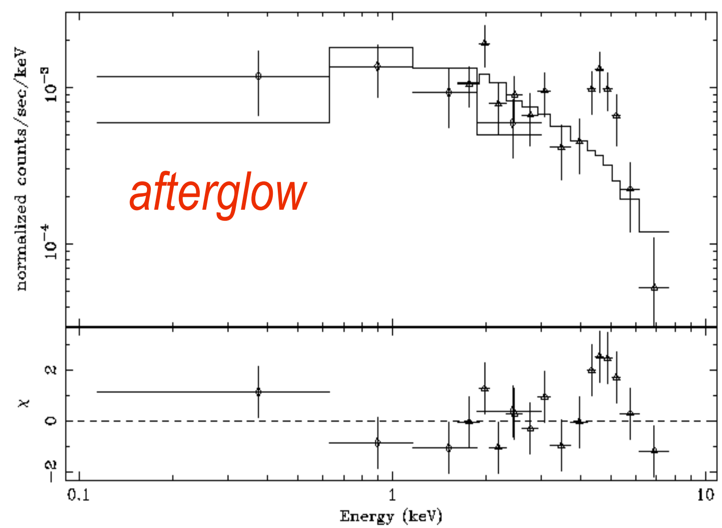
- ❑ evidence of overdense and metal enriched circum-burst environment from absorption and emission features

- ❑ emission lines in afterglow spectrum detected by BeppoSAX but not by Swift

- ❑ Swift detects intrinsic NH for many GRB afterglows, often inconsistent with NH from optical (Lyα)

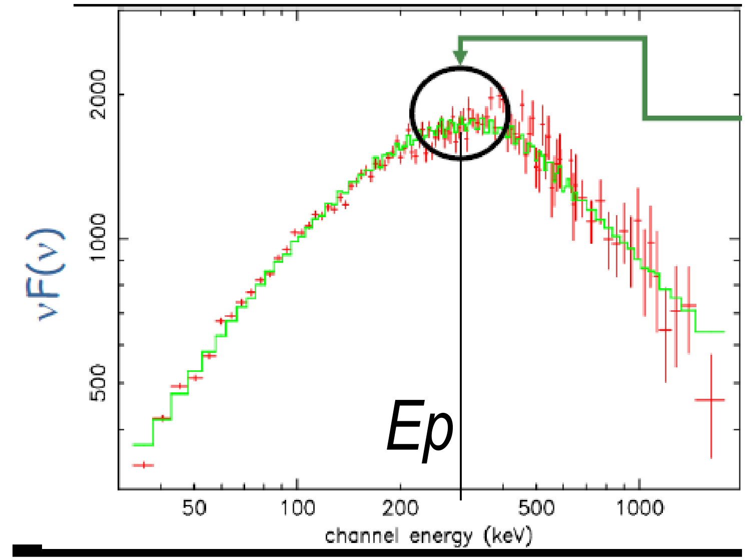




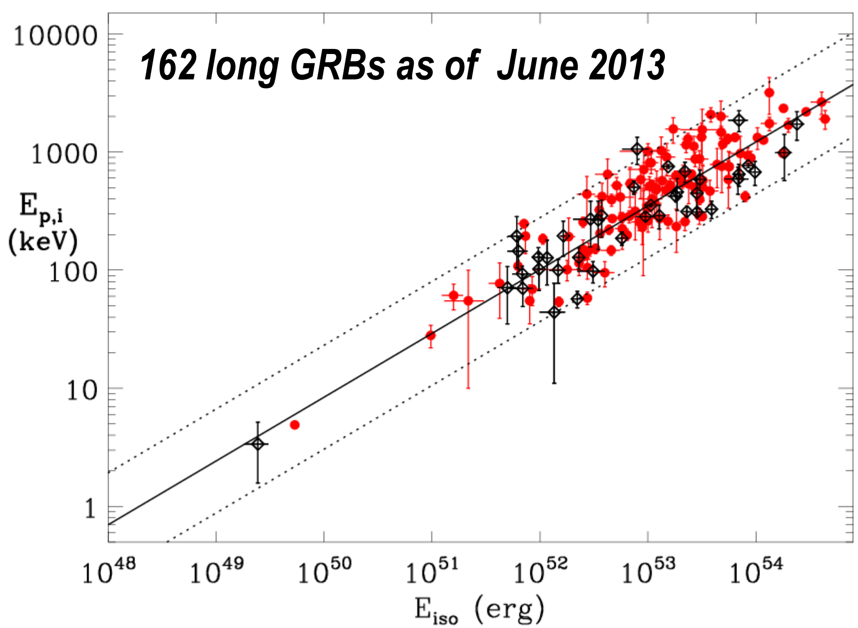


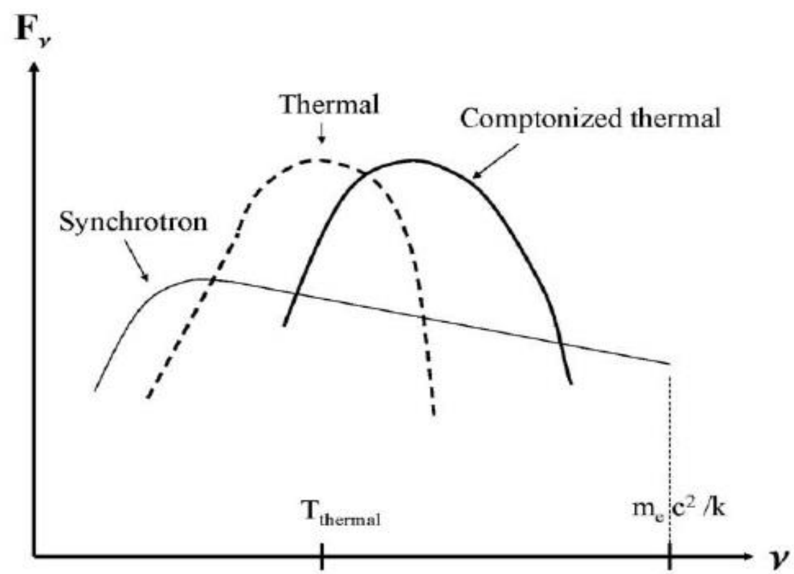
Amati et al. 2000, Watson et al. 2007, Antonelli et al. 2000

➢ *Spectrum-energy correlations: GRB physics, short/long, debates*



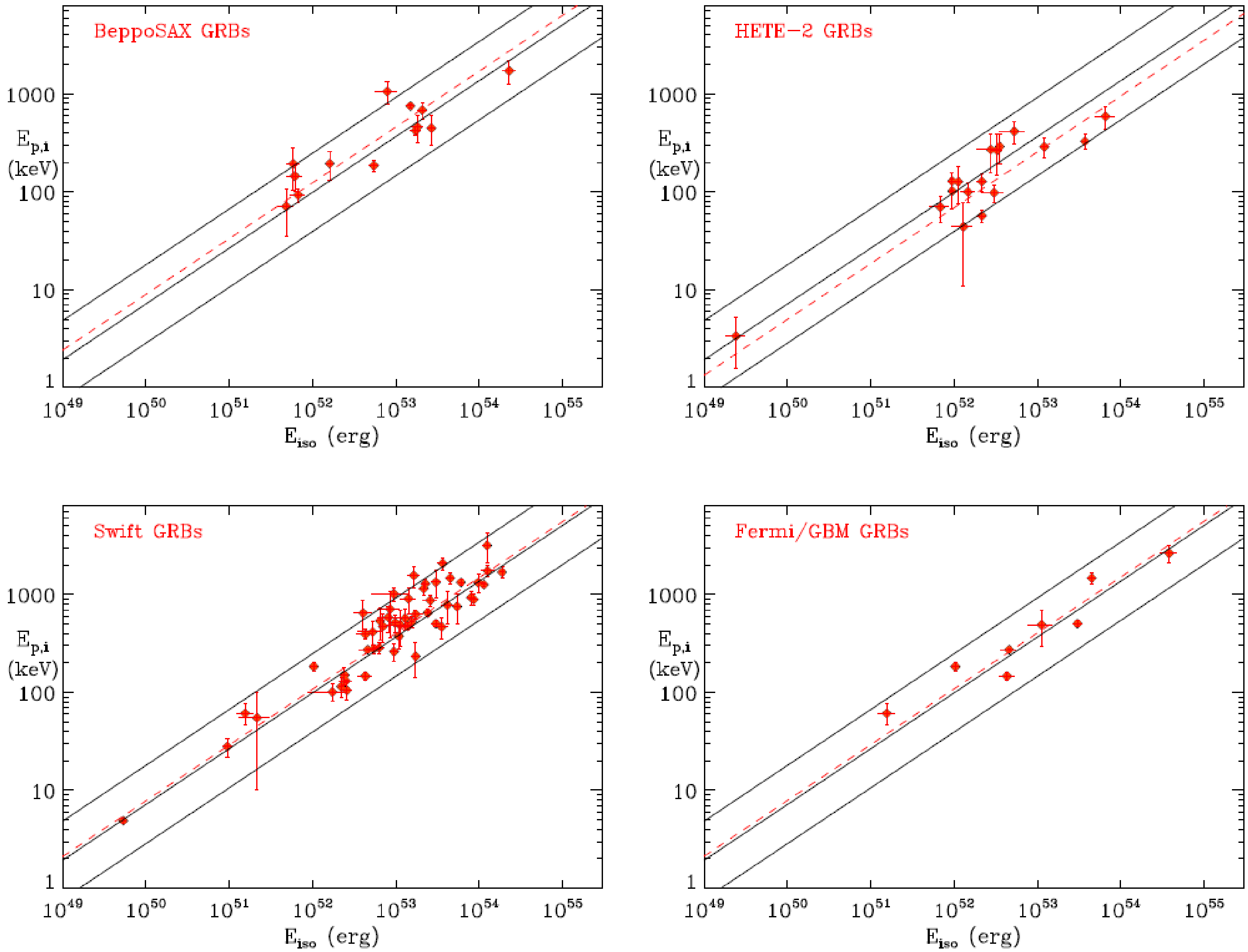
- ❑ Strong correlation between Ep,i and Eiso for long GRBs: test for prompt emission models (physics, geometry, GRB/XRF unification models), identification and understanding of sub-classes of events, GRB cosmology
- ❑ debate on the impact of detectors thresholds





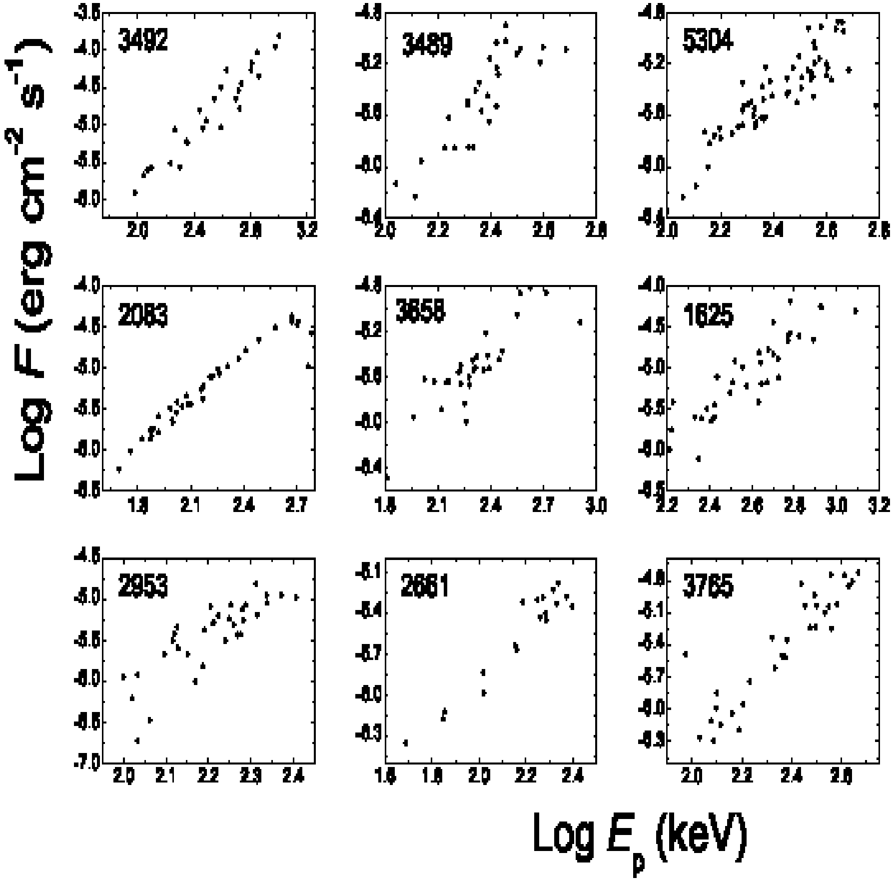
Amati et al. 2002 - 2009

❑ the normalization of the correlation varies only marginally using GRBs measured by individual instruments with different sensitivities and energy bands

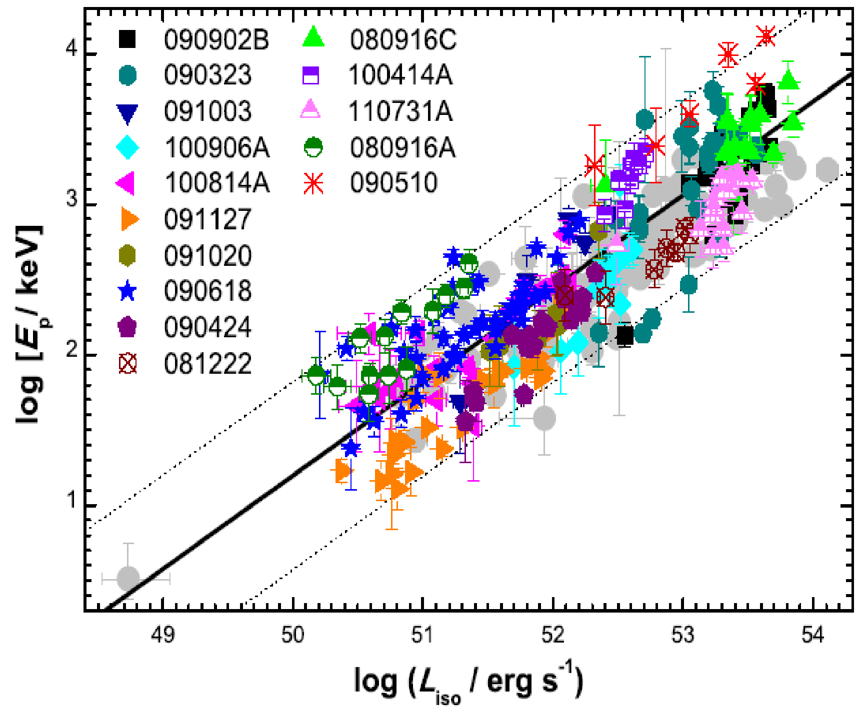


Amati , Frontera & Guidorzi 2009

➢ the Ep,i– Liso correlation holds also within a good fraction of GRBs (Liang et al.2004, Firmani et al. 2008, Frontera et al. 2012, Ghirlanda et al. 2009): **robust evidence for a physical origin and clues to explanation**



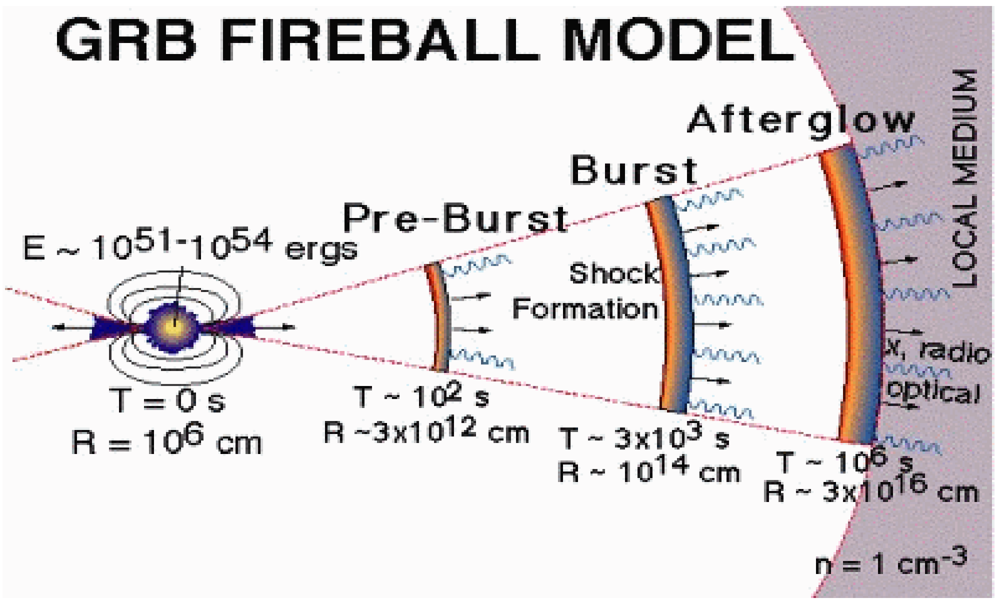
BATSE (Liang et al., ApJ, 2004)

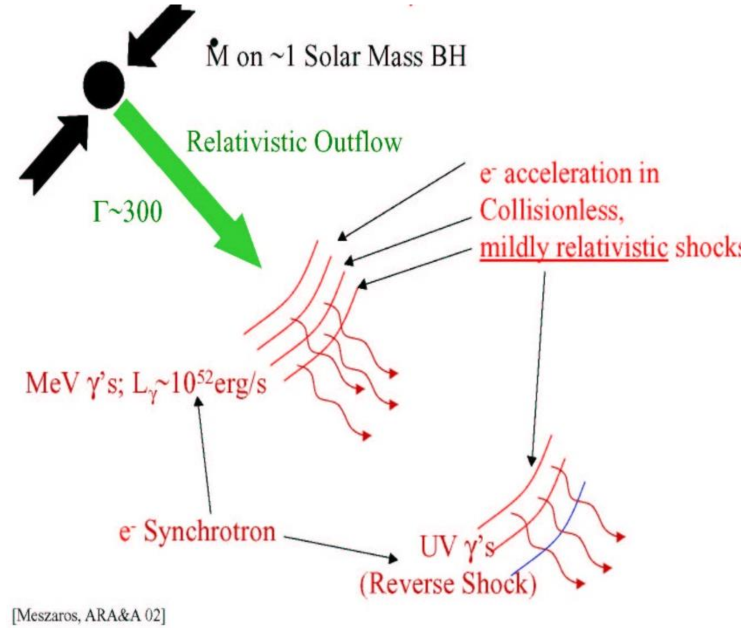


Fermi (e.g., Li et al. , ApJ, 2012)

❑ Understanding the physical grounds of the Ep,i – Intensity correlation

➢ Ep is a fundamental parameter in GRB prompt emission models





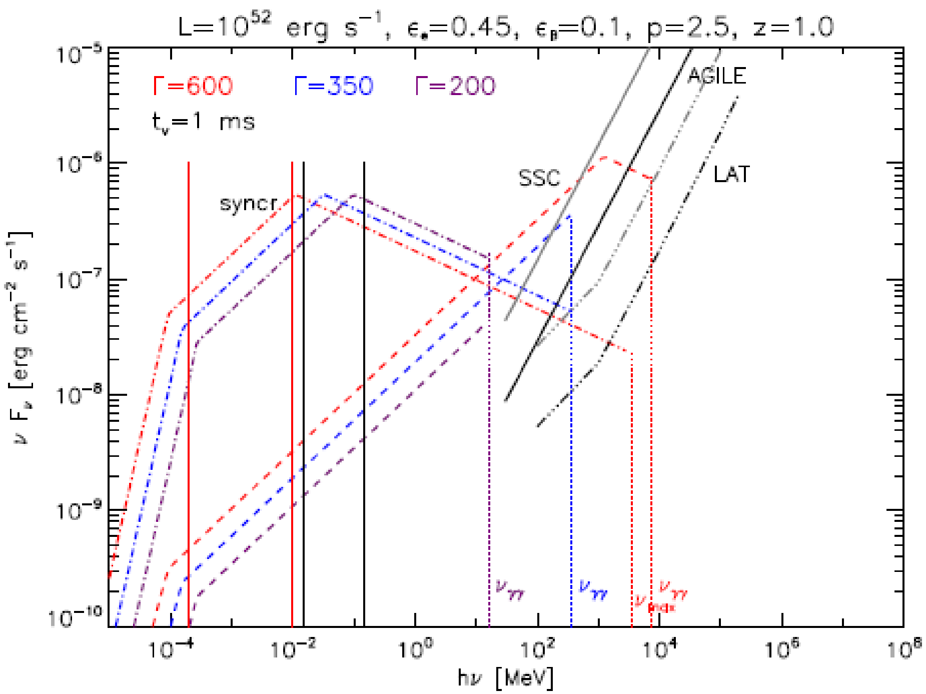
➢ ms time variability + huge energy + detection of GeV photons -> plasma occurring ultra-relativistic (Γ > 100) expansion (fireball or firejet)

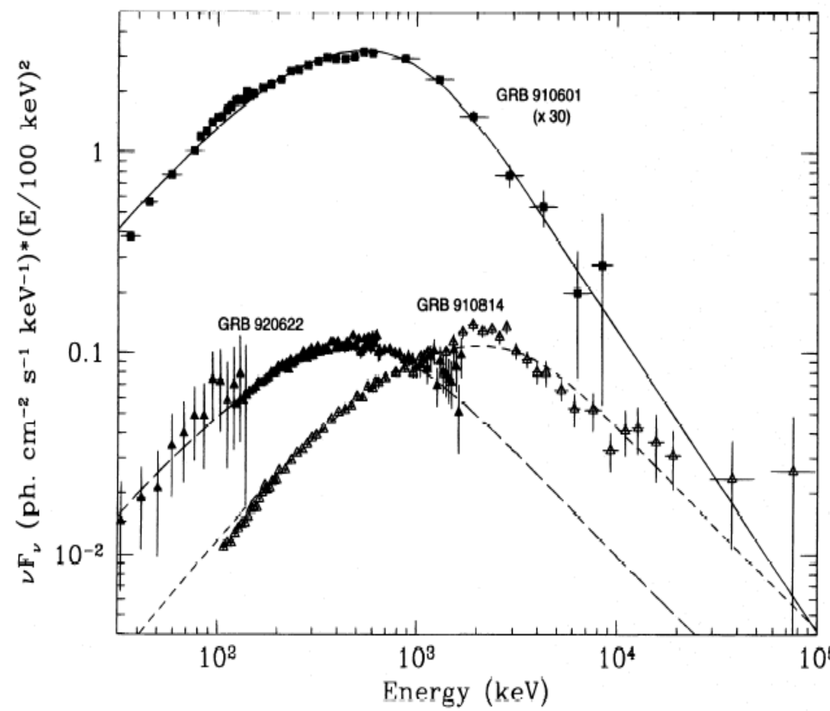
➢ non thermal spectra -> shocks synchrotron emission (SSM)

➢ fireball internal shocks -> prompt emission

➢ fireball external shock with ISM -> afterglow emission

➢ e.g., in synchrotron shock models (SSM) it may correspond to a characteristic frequency (possibly ν_m in fast cooling regime) or to the temperature of the Maxwellian distribution of the emitting electrons

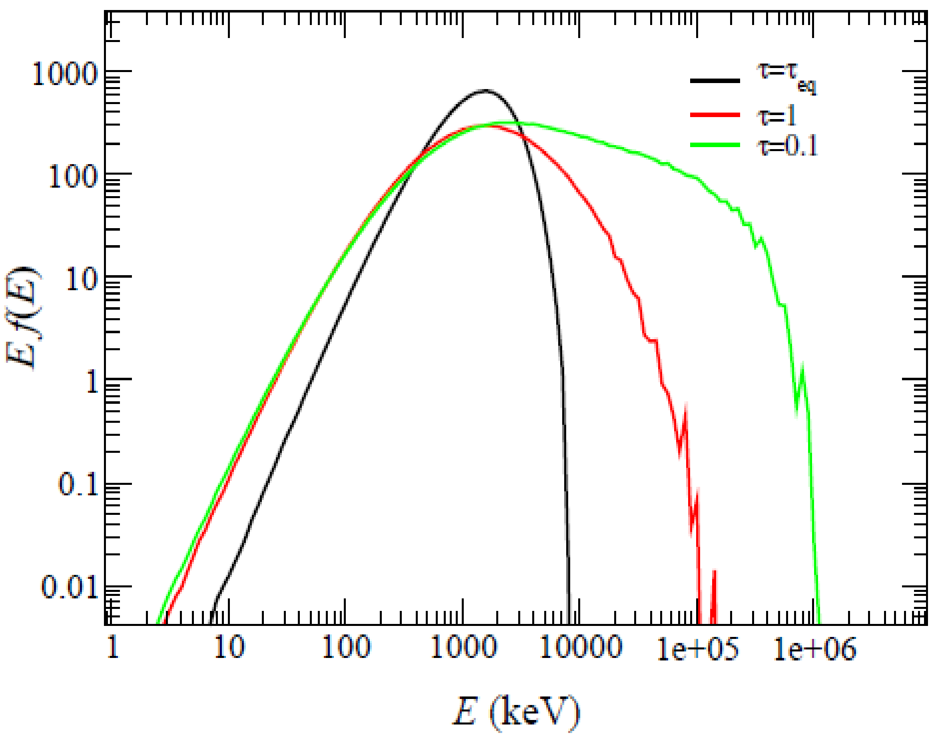




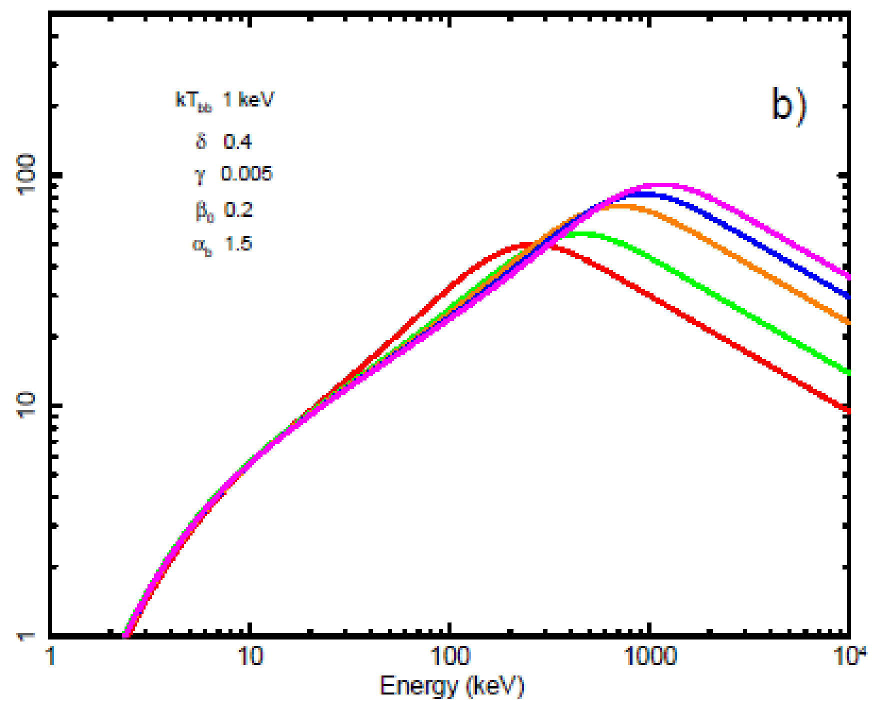
Galli & Guetta 2007

Tavani, ApJ, 1995

➢ e.g. in photospheric-dominated emission models it is linked to the temperature of BB photons (direct) or of scattering electrons (Comptonized)



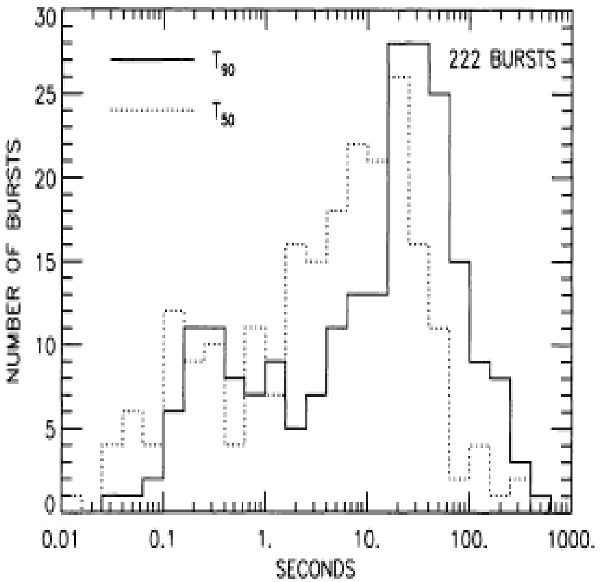
Giannios 2012

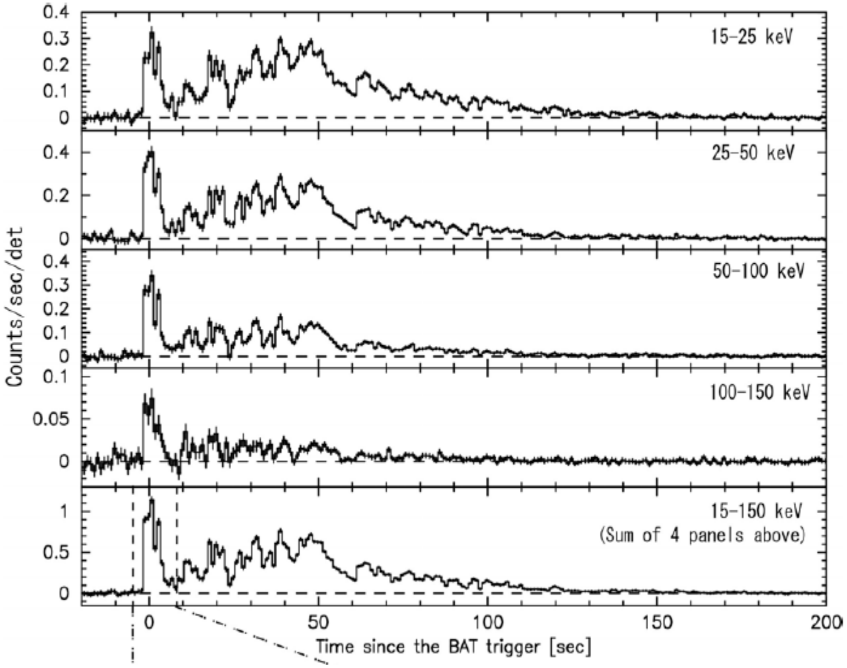


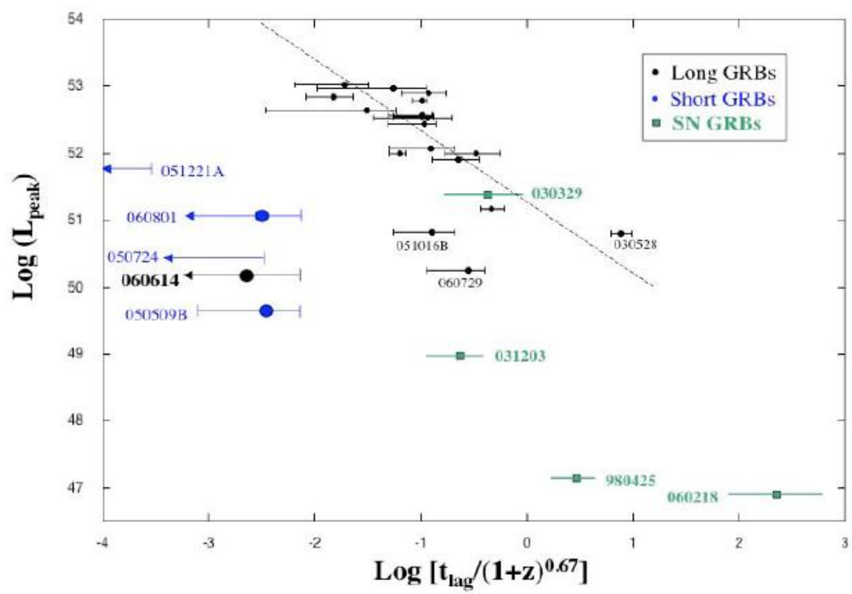
Titarchuk et al., ApJ, 2012

➢ Short / long classification and physics

- ❑ Swift GRB 060614: a long GRB with a very high lower limit to the magnitude of an associated SN -> association with a bright GRB/SN is excluded
- ❑ high lower limit to SN also for GRB 060505 (and, less stringently, XRF 040701)
- ❑ In the spectral lag – peak luminosity plane, GRB06061 lies in the short GRBs region -> need for a new GRB classification scheme ?







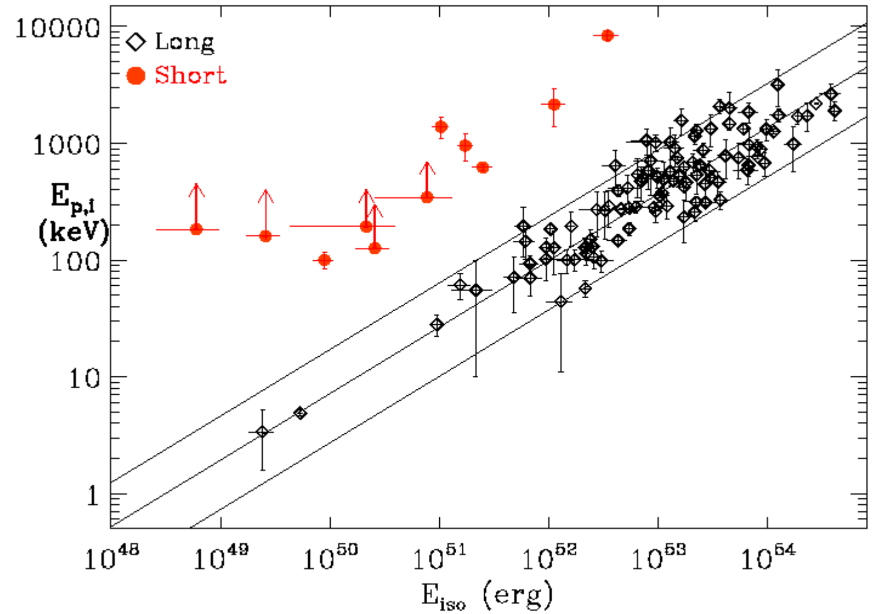
Gehrels et al., 2006

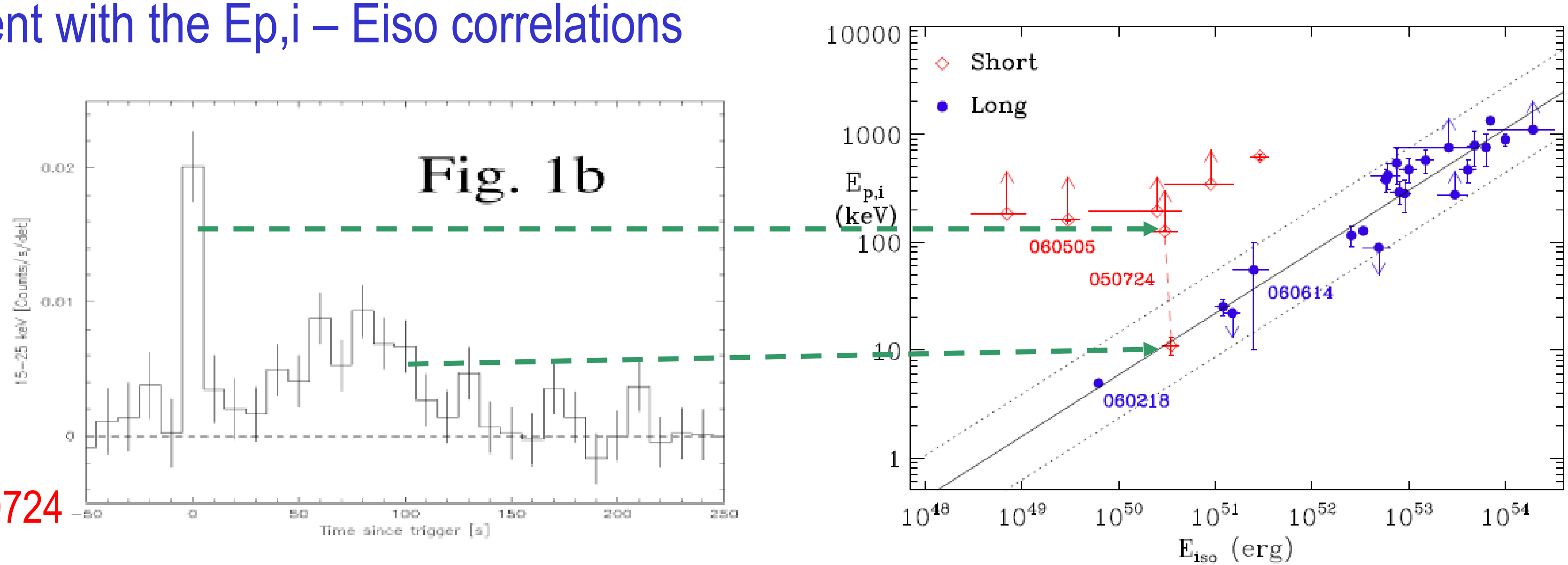
❑ only very recently, redshift estimates for short GRBs

❑ estimates and limits on Ep,i and Eiso are inconsistent with Ep,i-Eiso correlation holding for long GRBs

❑ low Eiso values and high lower limits to Ep,i indicate inconsistency also for the other short GRBs

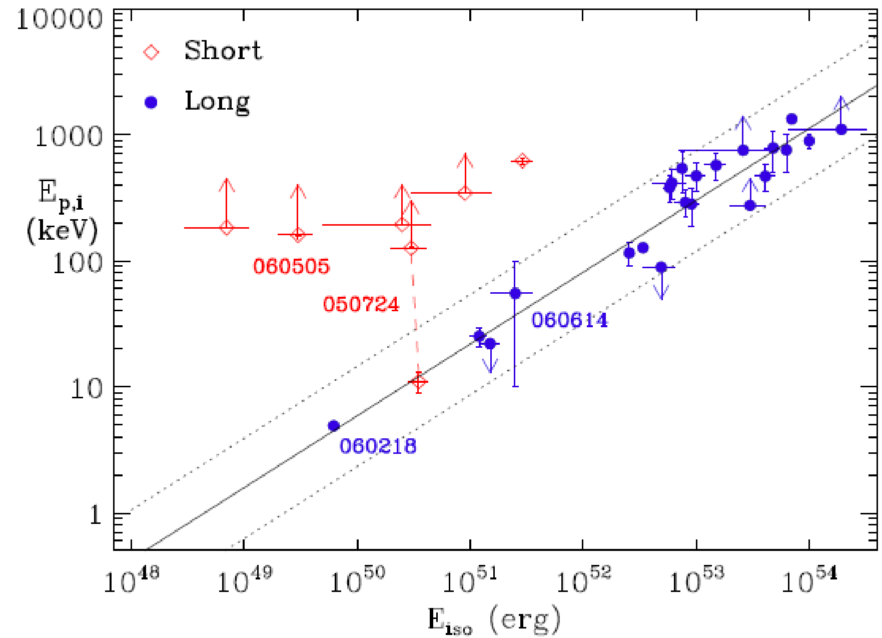
❑ long weak soft emission in some cases, consistent with the Ep,i – Eiso correlations

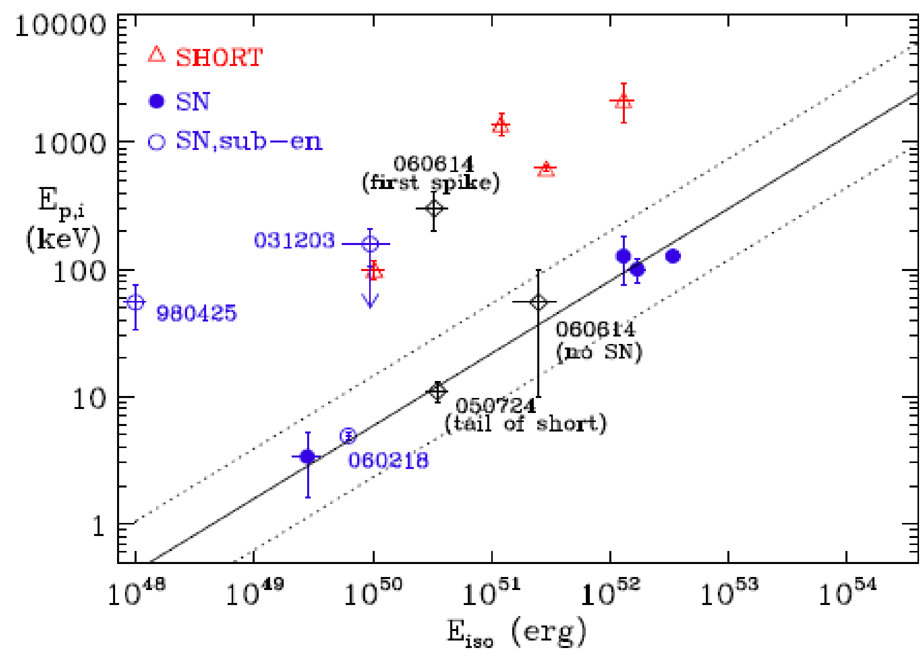




GRB0050724

- only very recently, redshift estimates for short GRBs
- all SHORT Swift GRBs with known redshift and lower limits to Ep.i are inconsistent with the Ep,i-Eiso correlation
- intriguingly, the soft tail of GRB050724 is consistent with the correlation
- GRB 060614: no SN, first pulse inconsistent with correlation, soft/long tail consistent: evidence that two different emission mechanisms are at work in both short and long GRB, with different relative efficiency in the two classes (-> "intermediate" GRB)

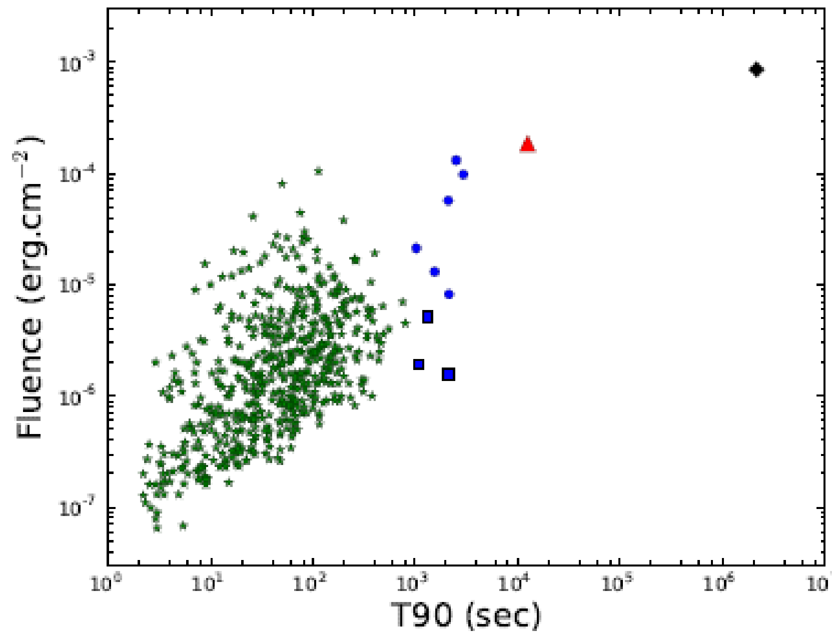


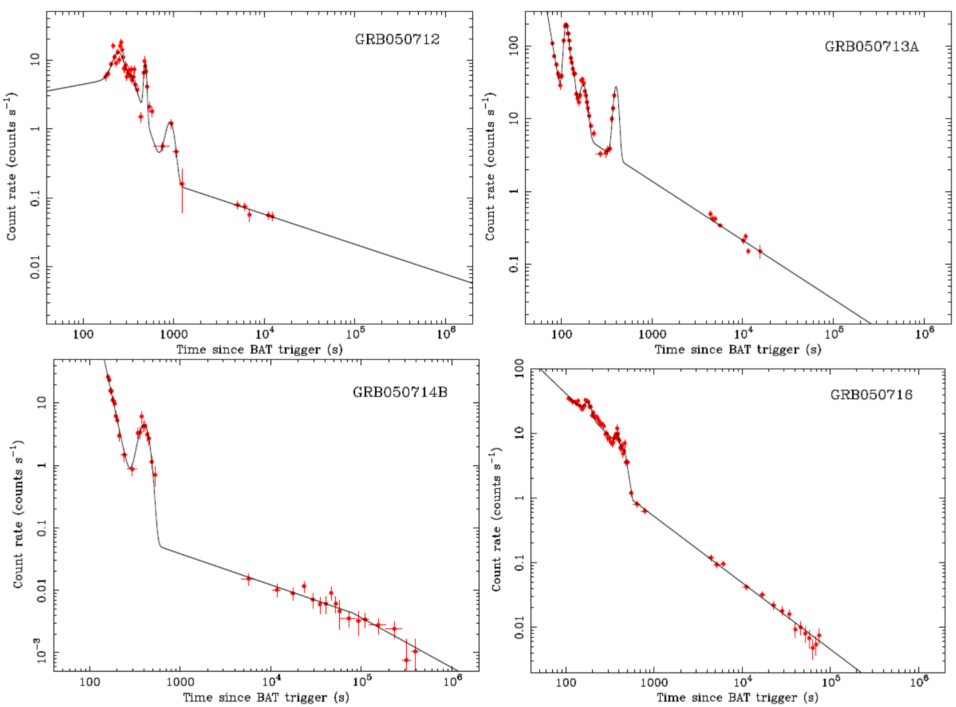


Amati 2006, Amati+ 2007

➢ *Duration of the central engine: X-ray flares and ultra-long GRBs*

❑ The X-ray flares, discovered by Swift, super-imposing to the early afterglow and the recently investigated class of ultra-long GRBs (i..e. lasting hours instead of minutes) are challenging evidences for models of long GRB central engine and progenitors

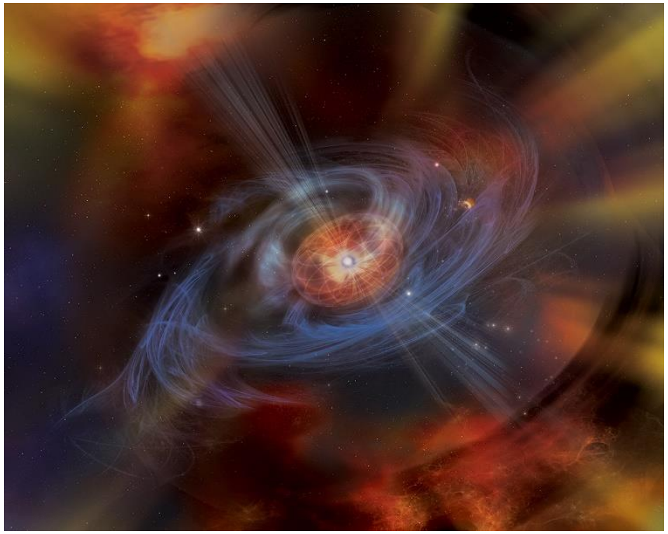


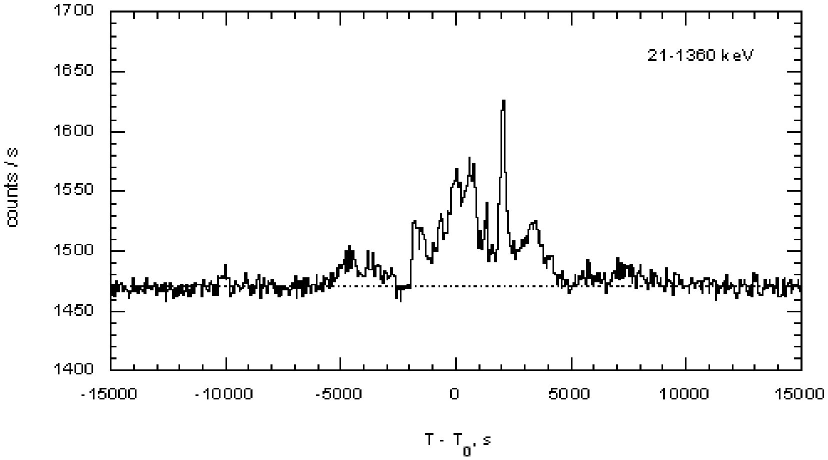


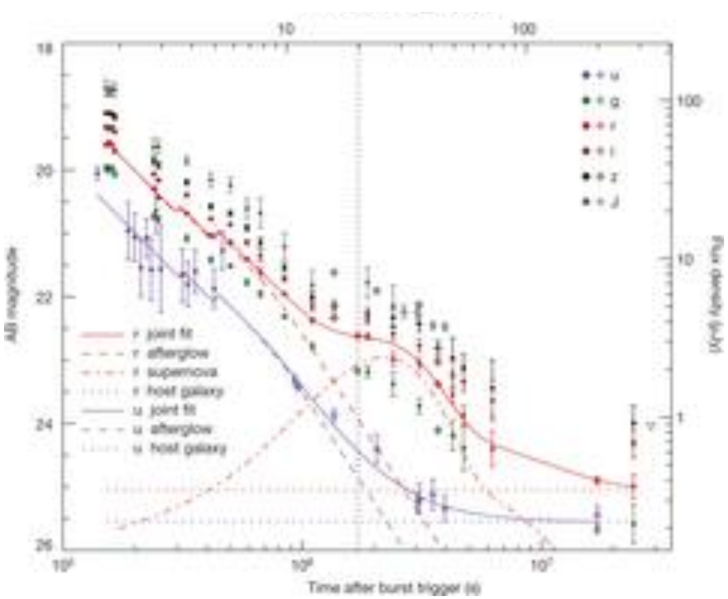
FROM GENDRE ET AL. (2013) UPDATED FROM LEVAN ET AL. (2013) WHEN APPLICABLE.

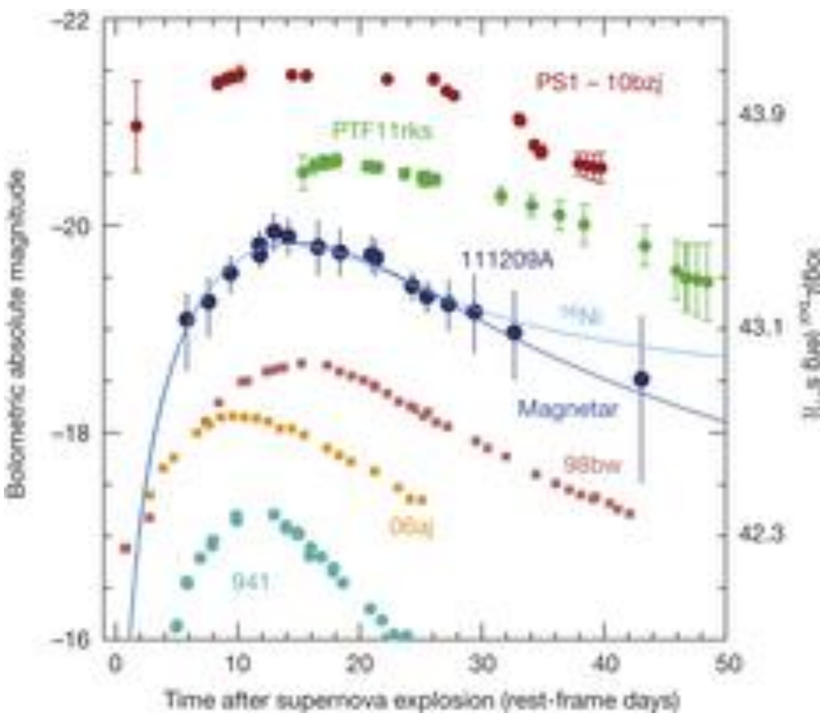
Quantity	E_p (keV)	E_{iso} (10^{51} erg)	Fluence (erg cm^{-2})	Duration (T90, s)	Distance (redshift)	Reference
GRB 971208	144	n.a.	2.6×10^{-4}	2500	n.a.	Pal'Shin et al. (2008)
GRB 020410	n.a.	n.a.	2.8×10^{-5}	1550	n.a.	Nicastro et al. (2004)
GRB 060218	4.9	0.062	1.7×10^{-5}	2100	0.0331	Campana et al. (2006)
GRB 060814B	341	n.a.	2.4×10^{-4}	2944	n.a.	Pal'Shin et al. (2008)
GRB 080407	287	n.a.	4.5×10^{-4}	2100	n.a.	Pal'Shin et al. (2012)
GRB 090417B	> 150	> 7.3	8.2×10^{-6}	> 2130	0.345	Holland et al. (2010)
GRB 091024	280	350	1.1×10^{-4}	1200	1.09	Golenetskii et al. (2009)
GRB 100316D	10-42	0.049	5.1×10^{-6}	1300	0.0591	Starling et al. (2011)
GRB 101225A	38	12	2.6×10^{-6}	10^4	0.847	Levan et al. (2013)
Swift J1644+57	n.a.	n.a.	8.6×10^{-4}	2160000	0.354	Burrows et al. (2011)
GRB 111209A	520	580	4.9×10^{-4}	> 25000	0.677	Gendre et al. (2013)

❑ ultra-long GRB 111209A associated with a very luminous SN (Greiner et al. 2015): newly born magnetar as engine of (at least) ultra-long GRBs ?





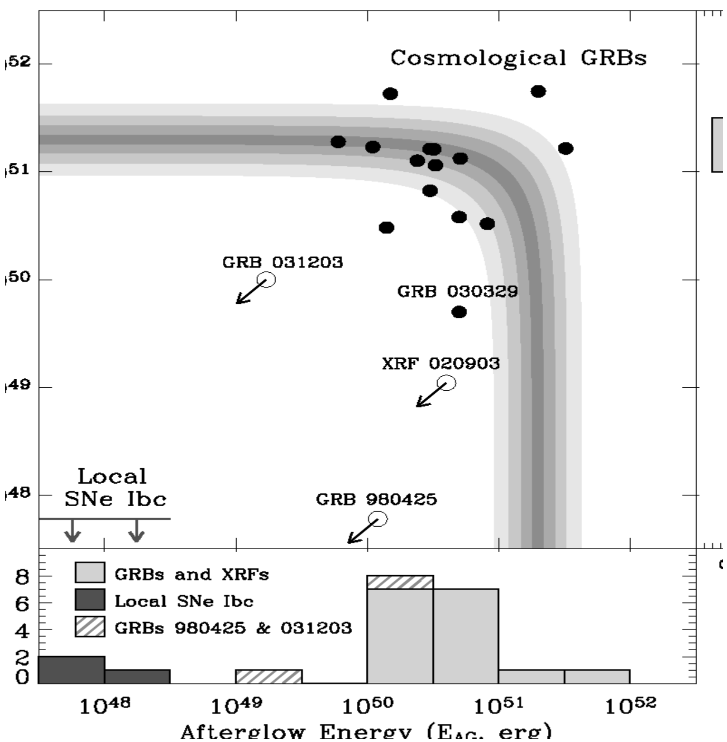


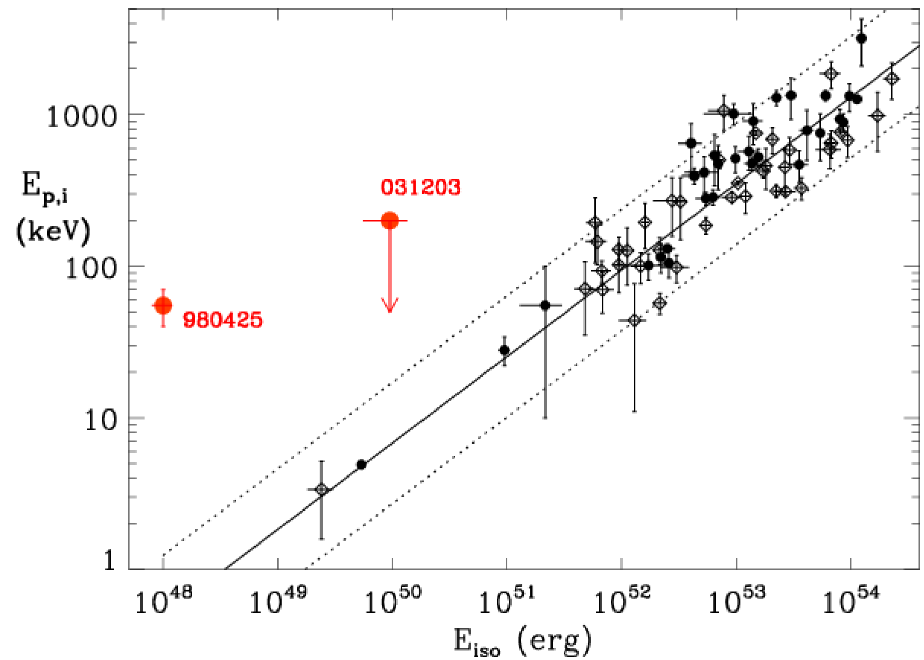


➢ *Sub-energetic GRBs*

❑ GRB980425 not only prototype event of GRB/SN connection but closest GRB (z = 0.0085) and sub-energetic event (Eiso ~ 10^{48} erg, Ek,aft ~ 10^{50} erg)

❑ GRB031203: the most similar case to GRB980425/SN1998bw: very close (z = 0.105), SN2003lw, sub-energetic

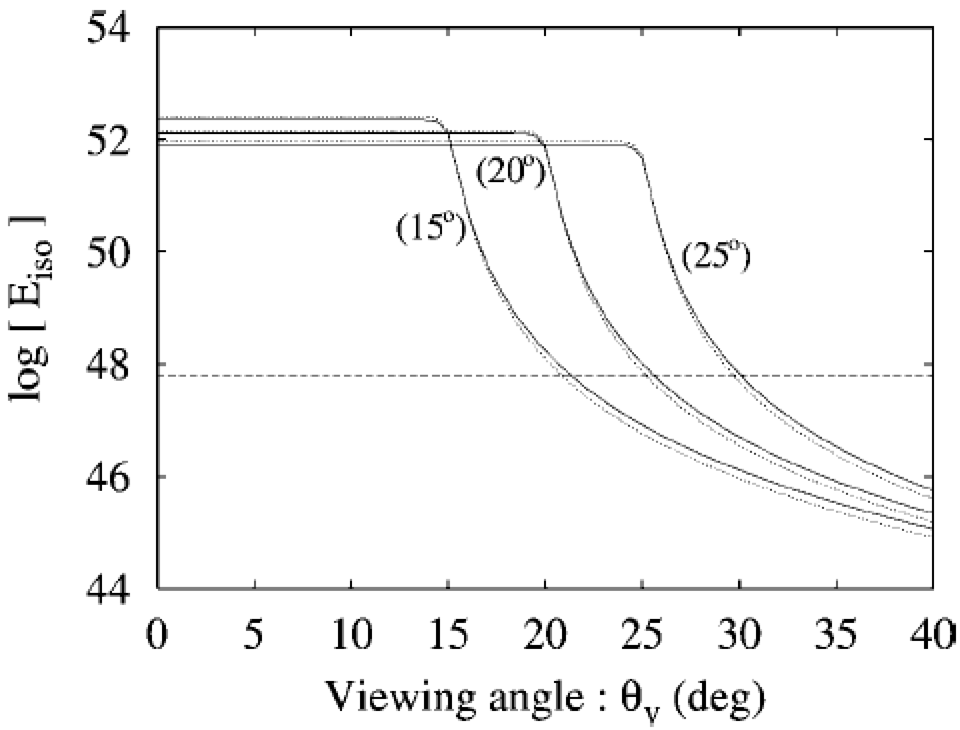


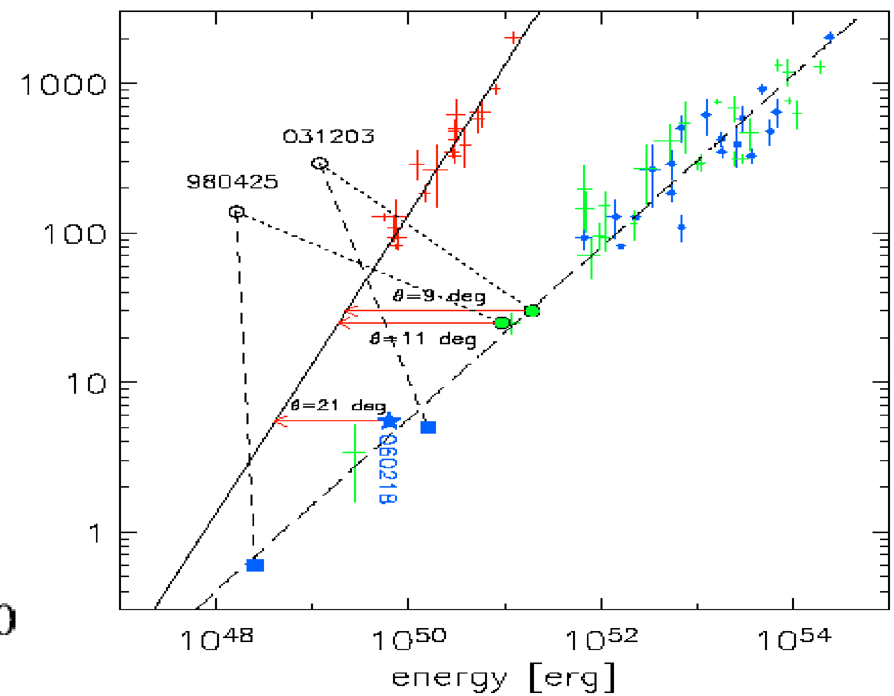


Soderberg et al. 2006

- the most common explanations for the (apparent ?) sub-energetic nature of GRB980425 and GRB031203 and their violation of the Ep,i – Eiso correlation assume that they are NORMAL events seen very off-axis (e.g. Yamazaki et al. 2003, Ramirez-Ruiz et al. 2005)
- $\delta=[\gamma(1 - \beta\cos(\theta v - \Delta\theta))]^{-1}$, $\Delta Ep \propto \delta$, $\Delta Eiso \propto \delta^{(1+\alpha)}$

  $\alpha=1\div2.3$ -> $\Delta Eiso \propto \delta^{(2 \div 3.3)}$



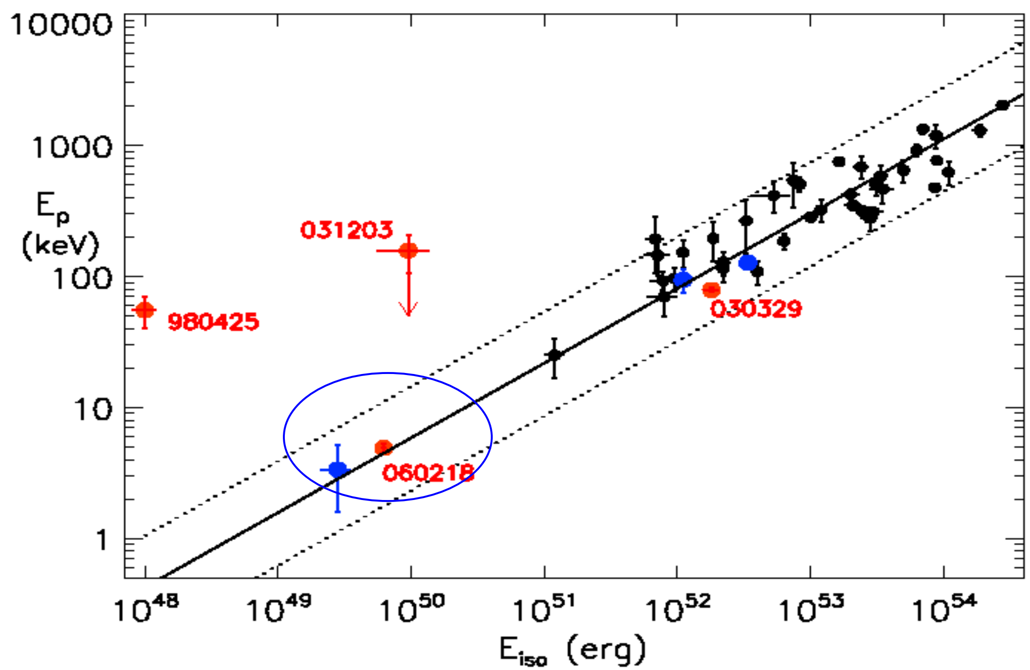


Yamazaki et al., ApJ, 2003

- GRB 060218, a very close (z = 0.033, second only to GRB9809425), with a prominent association with SN2006aj, and very low Eiso (6 x 10^{49} erg) and Ek,aft -> very similar to GRB980425 and GRB031203

- but, contrary to GRB980425 and (possibly) GRB031203, GRB060218 is consistent with the Ep,i-Eiso correlation -> evidence that it is a truly sub-energetic GRB -> likely existence of a population of under-luminous GRB detectable in the local universe

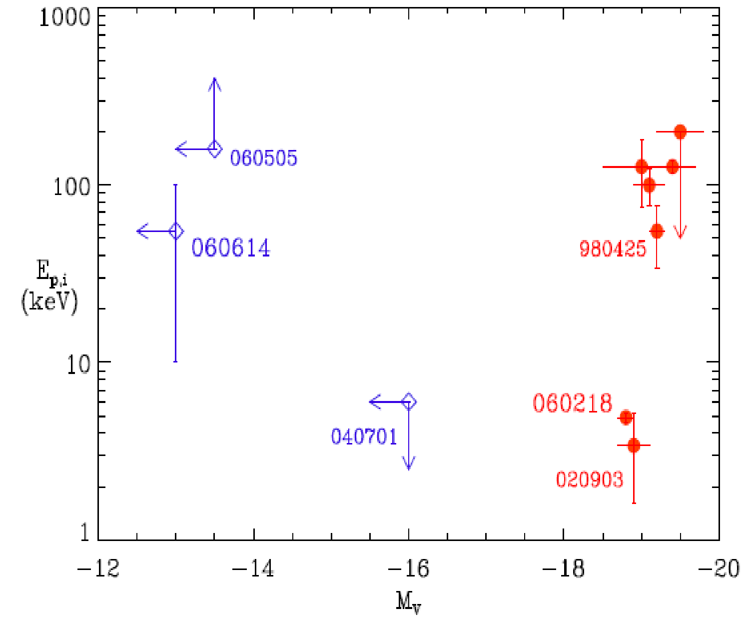
- also XRF 020903 is very weak and soft (sub-energetic GRB prompt emission) and is consistent with the Ep-Eiso correlation



Amati et al., 2007

➢ *GRB/SN connection*

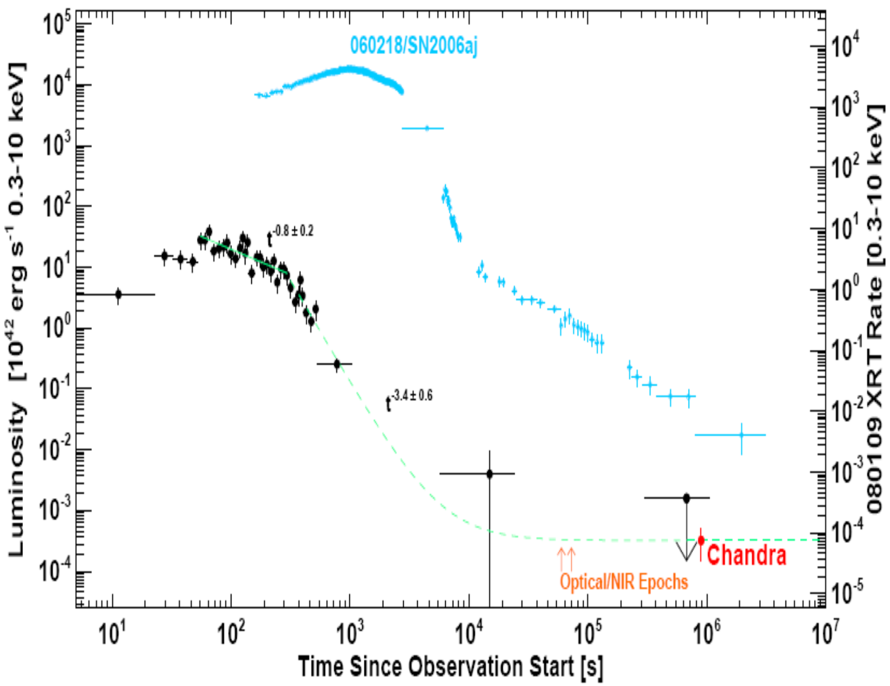
- ❑ are all long GRB produced by a type Ibc SN progenitor ?
- ❑ which fraction of type Ibc SN produces a GRB, and what are their peculiarities ?
- ❑ are the properties (e.g., energetics) of the GRB linked to those of the SN ?
- ❑ long GRBs with no (or very faint) associated SNe



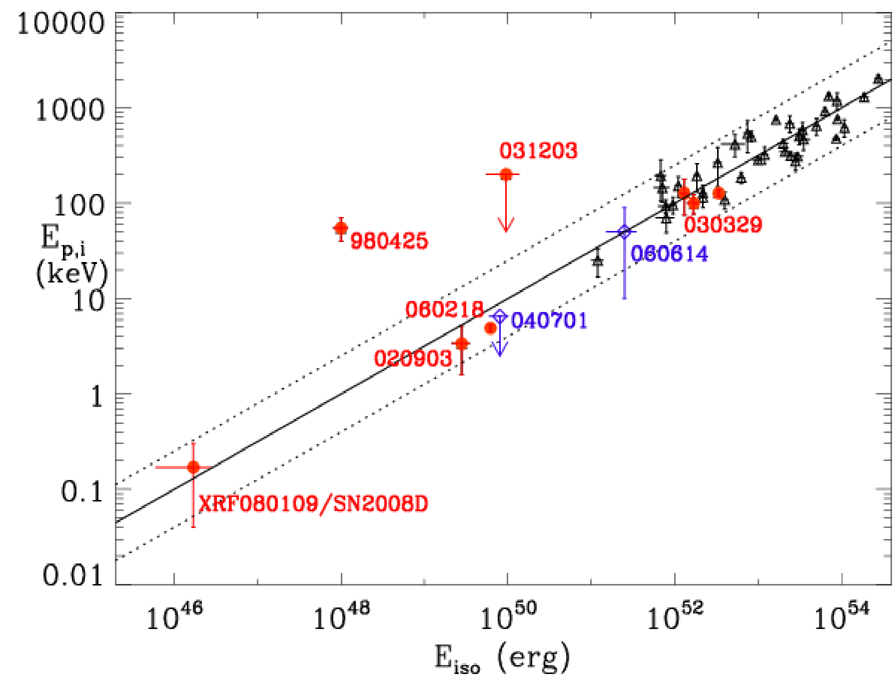
GRB/SN	z	$E_{p,i}$ (keV)	E^{iso}_{prompt} (10^{50} erg)	θ_{jet} (deg)	E^{jet}_{prompt} (10^{50} erg)	SN $E^{iso\,(a)}_{K}$ (10^{50} erg)	SN peak mag
980425/SN 1998bw	0.0085	55±21	0.01±0.002	-	<0.012	200-500	M_V=−19.2±0.1
060218/SN 2006aj	0.033	4.9±0.3	0.62±0.03	>57	0.05–0.65	20–40	M_V=−18.8±0.1
031203/SN 2003lw	0.105	<200	1.0±0.4	–	<1.4	500-700	M_V=−19.5±0.3
030329/SN 2003dh	0.17	100±23	170±30	5.7±0.5	0.80±0.16	~400	M_V=−19.1 ± 0.2
020903/BL-SNIb/c	0.25	3.4±1.8	0.28±0.07	–	<0.35	–	$M_V \sim -18.9$
050525A/SN 2005nc	0.606	127±10	339±17	4.0±0.8	0.57±0.23	–.	$M_B = -18.9^{+0.1}_{-0.5}$
021211/SN 2002lt	1.01	127±52	130±15	8.8±1.3	1.07±0.13	–	$M_U \sim -18.9$
060505	0.089	>160	0.3±0.1	–	–	–	$M_R > -13.5$
060614	0.125	10–100	25±10	~12	0.45±0.20	–	$M_V >\sim -13$
040701	0.215	<6.	0.8±0.2	–	–	–	$M_V > -16$

Amati et al. 2007

- Swift detection of an X-ray transient associated with SN 2008D at z = 0.0064, showing a light curve and duration similar to GRB 060218
- Debate: very soft/weak XRF or SN shock break-out ?
- Peak energy limits and energetics consistent with a very-low energy extension of the Ep,i-Eiso correlation (Li 2008, based on XRT and UVOT data)
- Evidence that this transient may be a very soft and weak GRB (XRF 080109), thus confirming the existence of a population of sub-energetic GRB ?



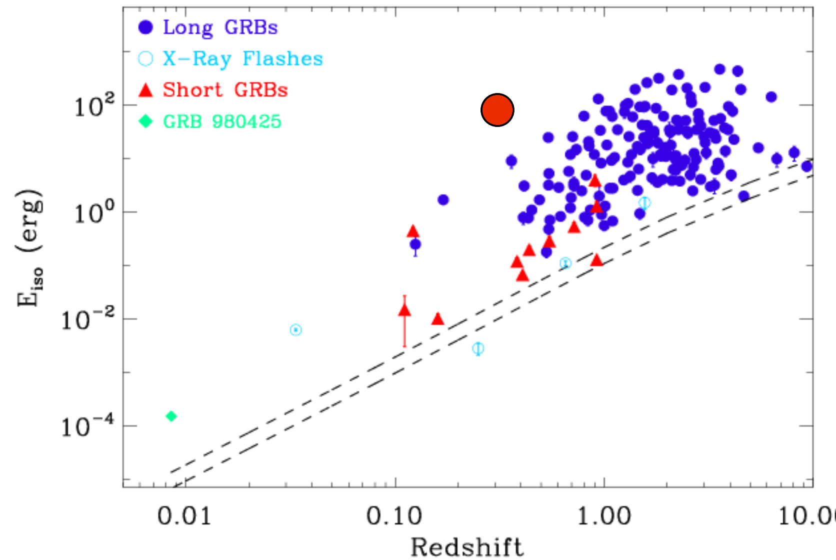
Modjaz et al., ApJ, 2008

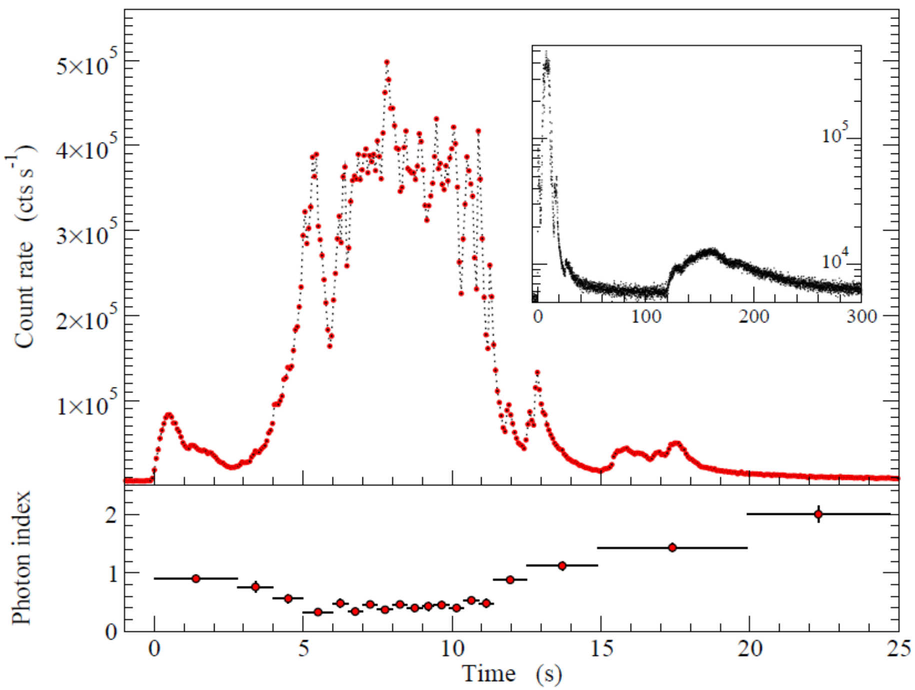


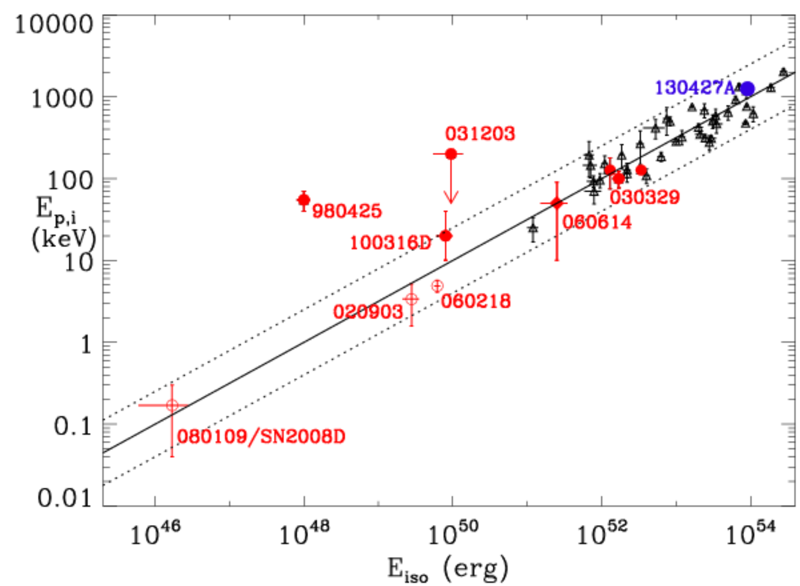
Amati, 2008, this workshop

GRB 130427A: a Nearby Ordinary Monster

- An unusually "nearby" very energetic GRB ($z=0.34$, $E_{iso} \sim 10^{54}$ erg)
- Evidence of an associated SN (SN 2013cq) with properties similar to those of classical weak GRBs in the local Universe
- Extension of the long GRB/SN paradigm to classical bright/cosmological GRBs

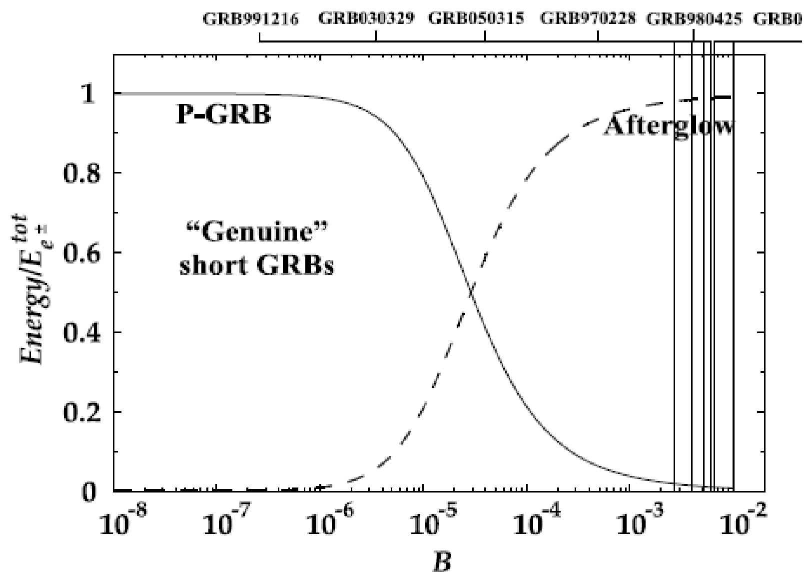


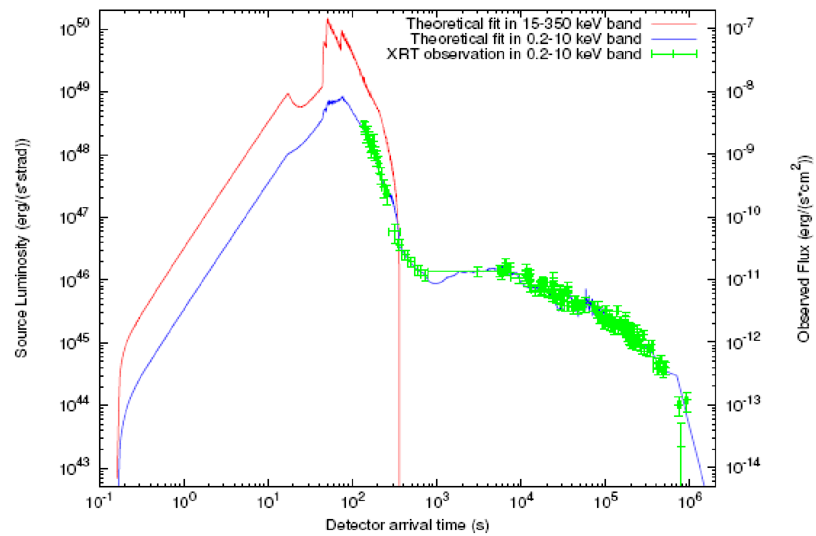




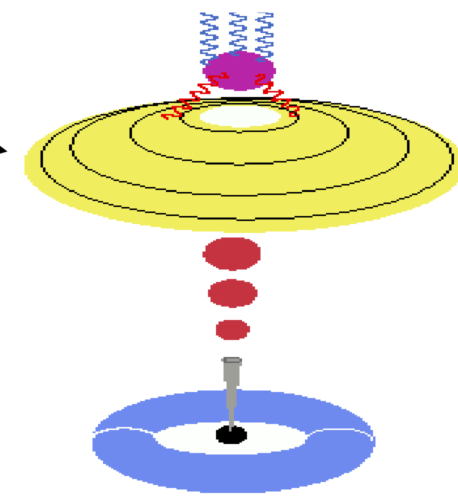
➢ *Alternative scenarios*

❑ EMBH / fireshell model (Ruffini et al.) – IGC scenario





❑ CannonBall (CB) (Dar et al.)



❑ Precessing jet (Fargion et al.), stochastic wakefield plasma acceleration (Barbiellini et al.), ns-quark star transition, …

❑ Short GRB as SGR giant outbursts

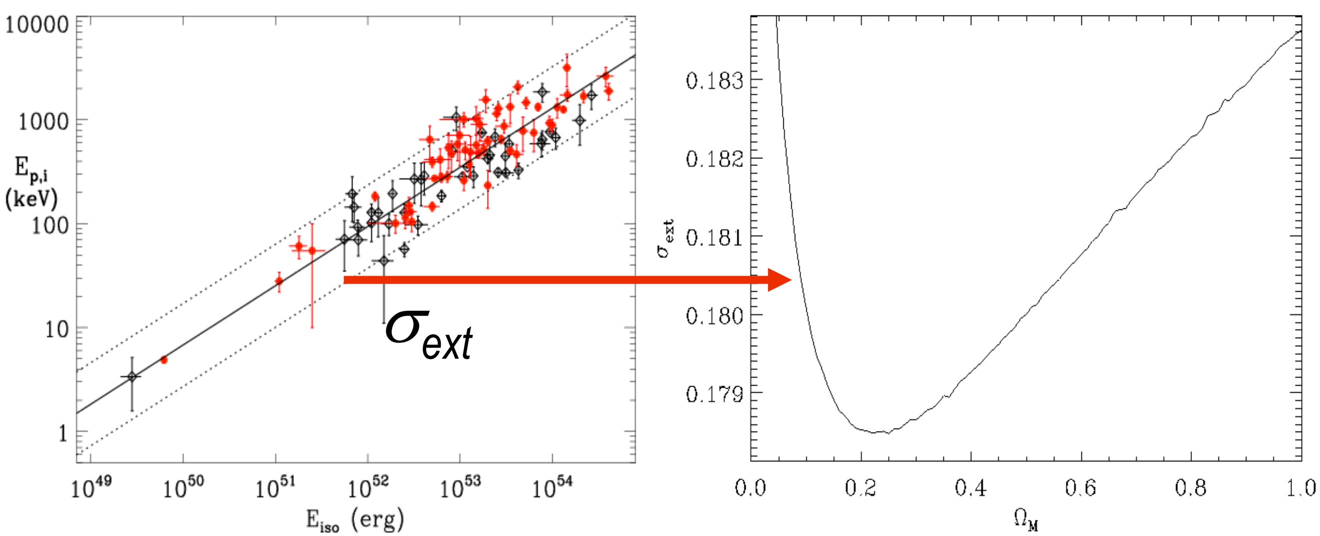
➢ *Cosmology and fundamental physics with GRBs*

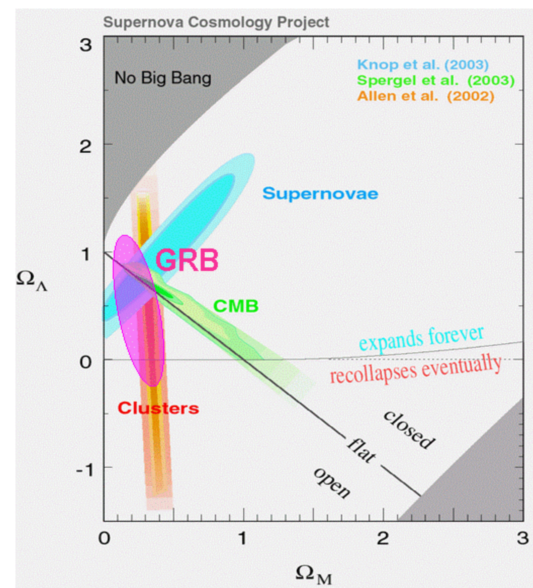
- ❑ GRB have huge luminosities and a redshift distribution extending far beyond SN Ia and even beyond that of AGNs
- ❑ high energy emission -> no extinction problems
- ❑ **potentially powerful cosmological sources**
- ❑ estimate of cosmological parameters through spectrum-energy correlations ?

$$E_{p,i} = E_{p,obs} \times (1 + z)$$

$$E_{\gamma,iso} = \frac{4\pi D_l^2}{(1+z)} \int_{1/1+z}^{10^4/1+z} E\,N(E)\,dE \quad \text{erg}$$

$$D_l = D_l(z, H_0, \Omega_M, \Omega_\Lambda, \ldots)$$





Amati et al. 2008, 2012

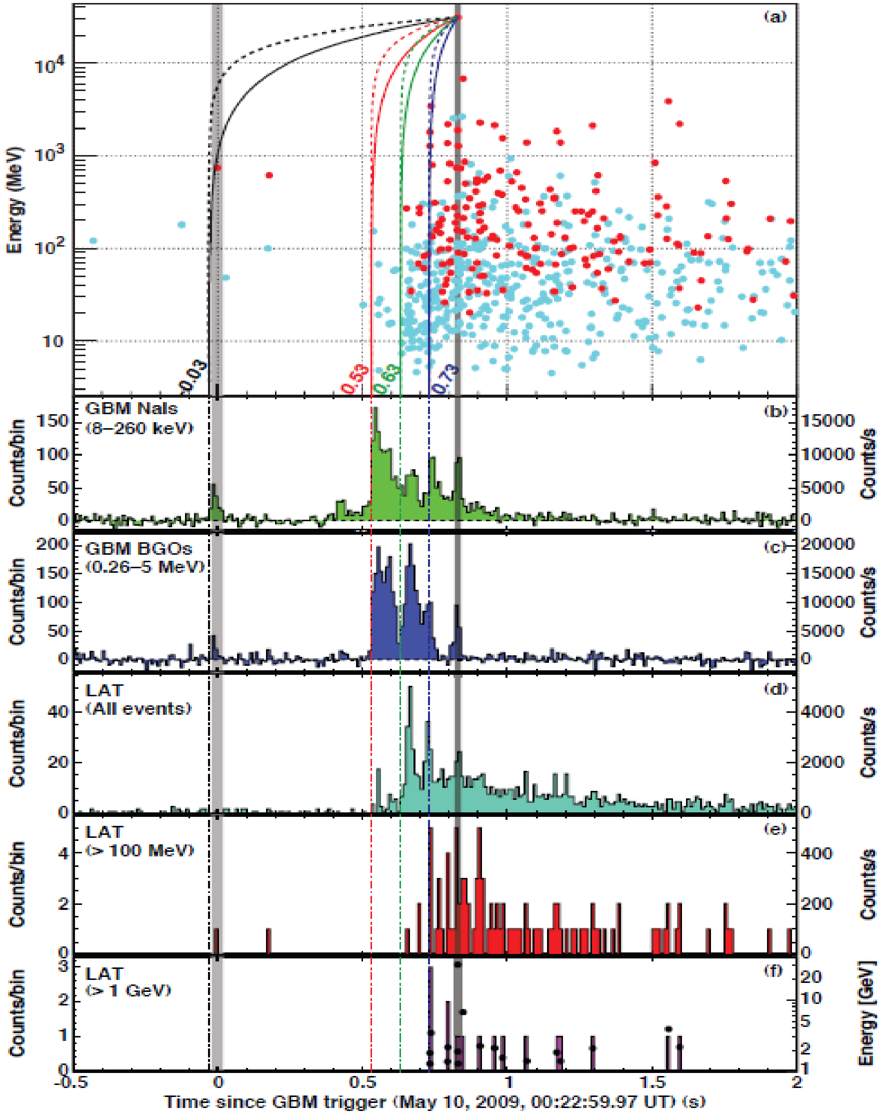
❑ Using time delay between low and high energy photons to put Limits on Lorentz Invariance Violation (allowed by unprecedent Fermi GBM + LAT broad energy band)

$$v_{\rm ph} = \frac{\partial E_{\rm ph}}{\partial p_{\rm ph}} \approx c \left[1 - s_n \frac{n+1}{2} \left(\frac{E_{\rm ph}}{M_{{\rm QG},n}c^2}\right)^n\right]$$

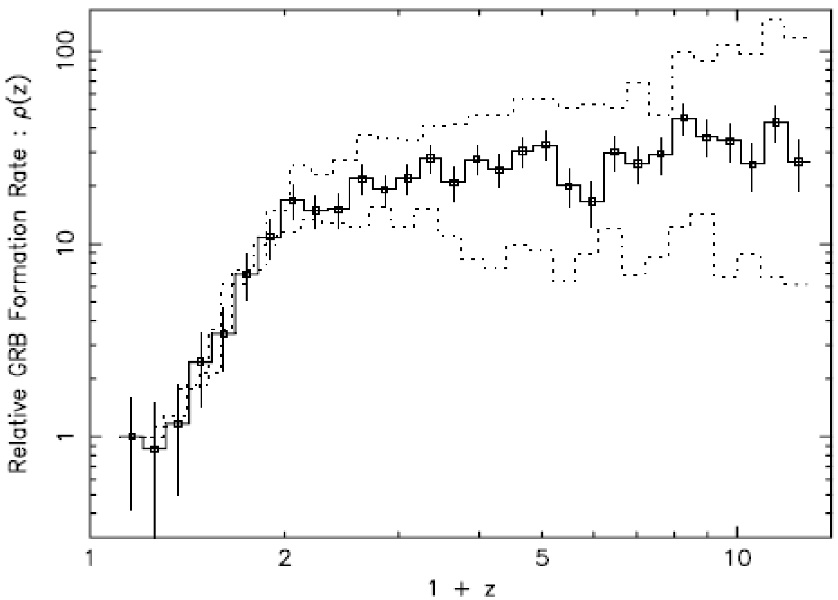
$$\Delta t = s_n \frac{(1+n)}{2H_0} \frac{(E_h^n - E_l^n)}{(M_{{\rm QG},n}c^2)^n} \int_0^z \frac{(1+z')^n}{\sqrt{\Omega_m (1+z')^3 + \Omega_\Lambda}} dz'$$

GRB 990510 $E_h = 30.53^{+5.79}_{-2.56}$ GeV

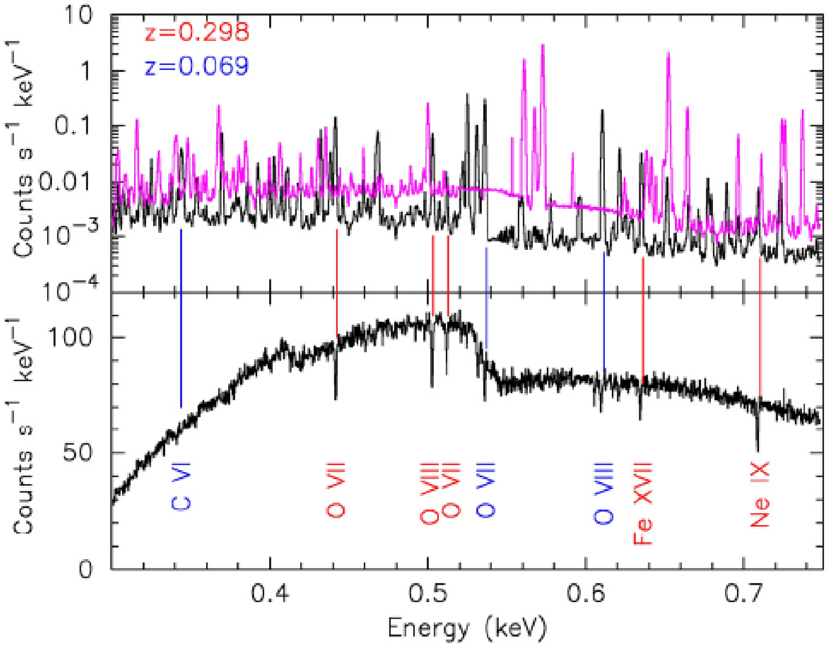
$t_{\rm start}$ (ms)	limit on $\lvert\Delta t\rvert$ (ms)	Reason for choice of $t_{\rm start}$ or limit on Δt	E_l (MeV)	valid for s_n	lower limit on $M_{\rm QG,1}/M_{\rm Planck}$
-30	< 859	start of any observed emission	0.1	1	> 1.19
530	< 299	start of main < 1 MeV emission	0.1	1	> 3.42
630	< 199	start of > 100 MeV emission	100	1	> 5.12
730	< 99	start of > 1 GeV emission	1000	1	> 10.0
—	< 10	association with < 1 MeV spike	0.1	± 1	> 102
—	< 19	if 0.75 GeV γ is from 1st spike	0.1	± 1	> 1.33
$\left\lvert\frac{\Delta t}{\Delta E}\right\rvert < 30\ \frac{\rm ms}{\rm GeV}$		lag analysis of all LAT events	—	± 1	> 1.22



- use of GRBs as tracers of star formation up to the dark ages of the universe
- evidence that GRBs are biased SFR tracers if not accounting for metallicity evolution
- use of GRBs as cosmological beacons for the study of the ISM and the IGM (e.g., WHIM) evolution up to very high z

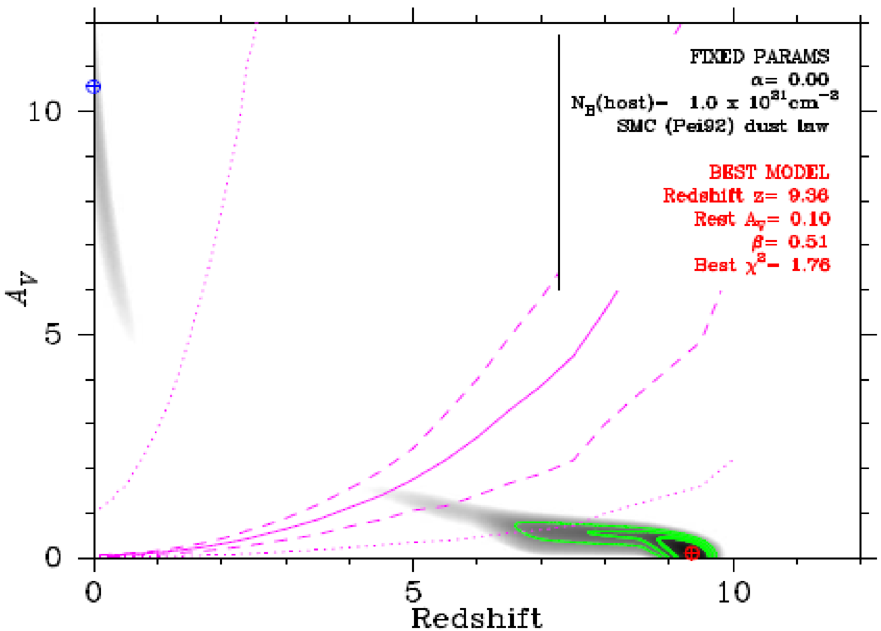


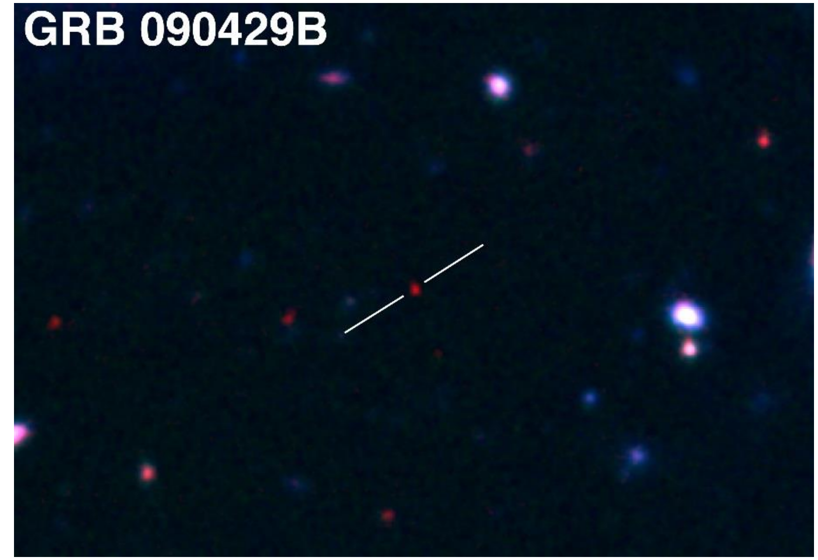
Yonetoku et al. 2004

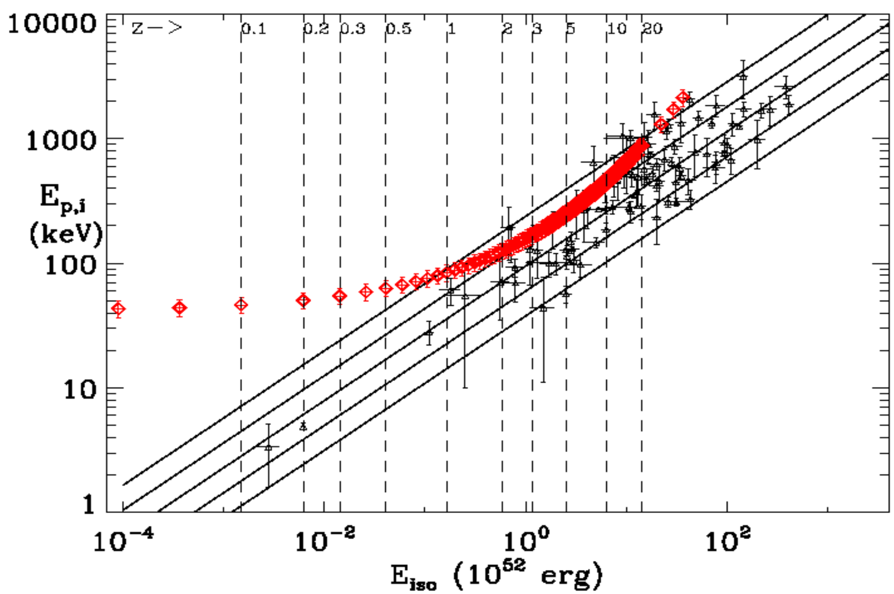


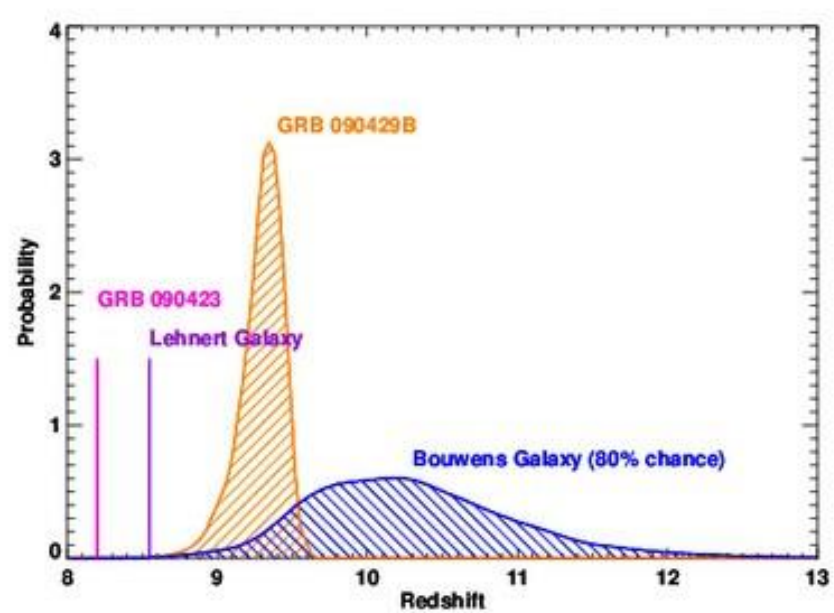
Branchini et al. 2009, ORIGIN team

❑ The case of GRB 090429B at a photometric redshift of ~9.4 ! (Cucchiara et al. 2011): a (pop III ?) star exploded at only 500 millions years since big-bang



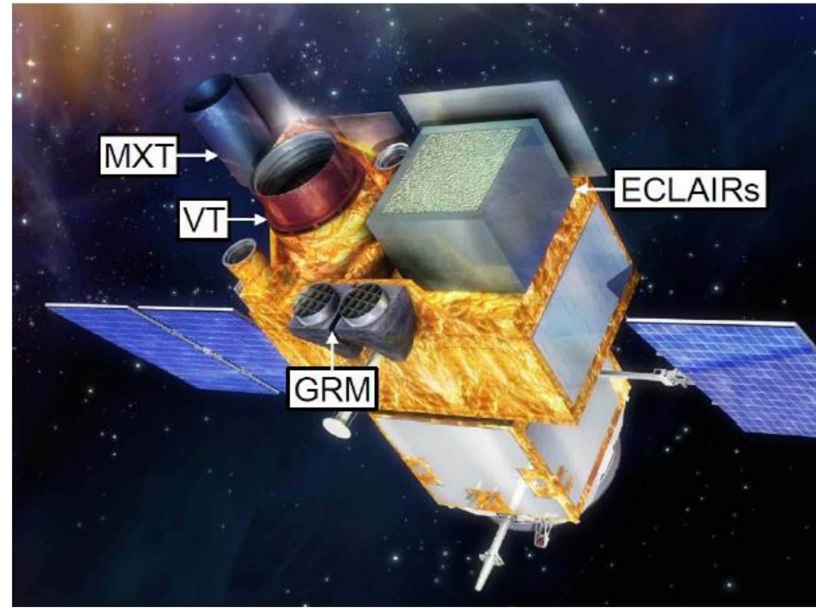






Next generation GRB missions under implementation or study

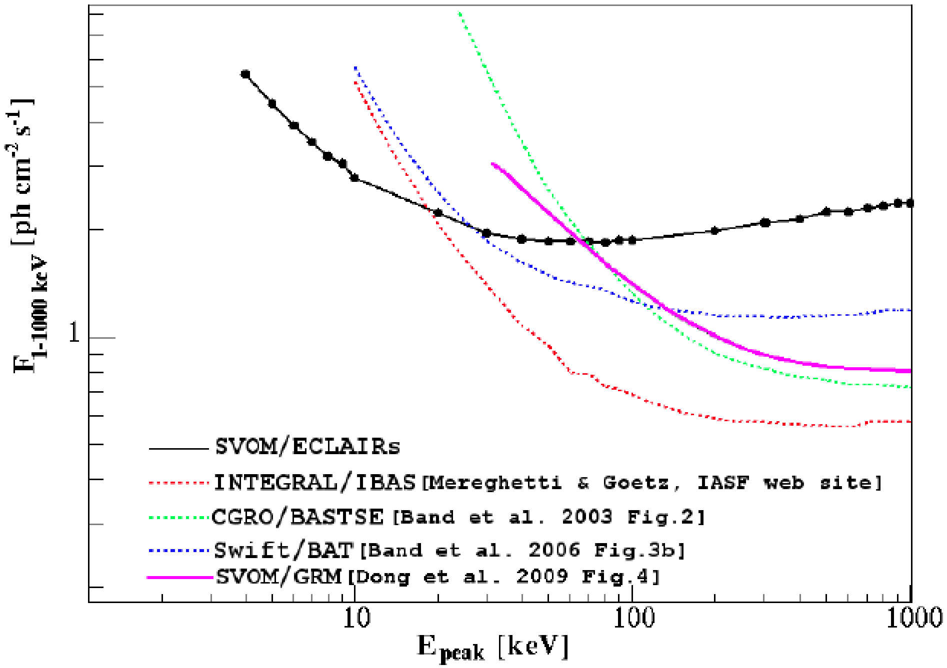
❑ SVOM



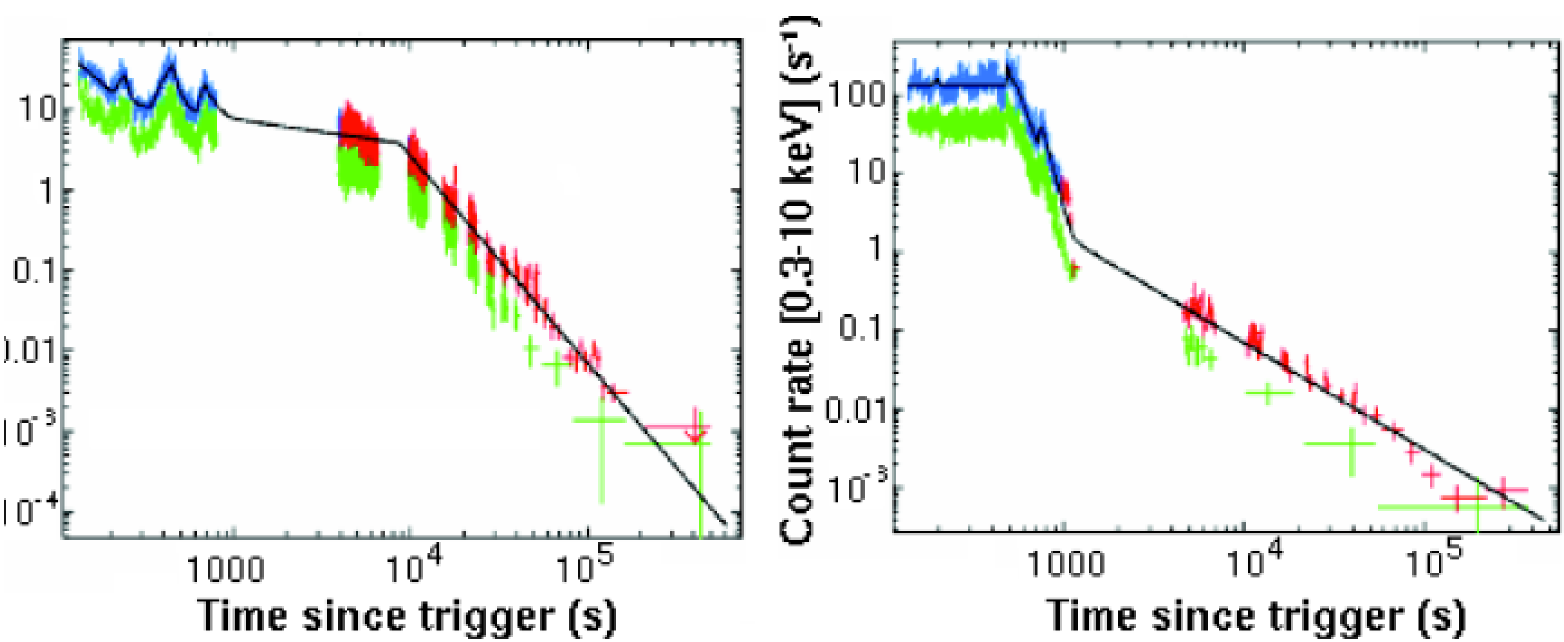
- ***Time frame**: 2021 – 2025 ?*
- ***Collaboration**: bil-lateral China – France; contributions by UK and D*
- ***Status**: scheduled in the Chinese space programme; final decision on France contribution (ECLAIRs, MXP) taken by CNES in February 2014*
- ***Goals**: GRB detection, broad band (few keV – few MeV) spectroscopy and arcmin localization (<60s to ground)+ X-ray and optical follow-up (within 5min) for early afterglow study, arcsec localization (-> redshift determination through follow-up)*
- ***Payload**: ECLAIRs (coded mask camera, 5 – 150 keV), GRM (phoswich, 50 keV – 5 MeV), MXT (MCP X-ray telescope, 0.2 – 10 keV), VT (optical telescope, 0.45m, V and R), GWAC (ground, set of wide field optical V cameras covring a total 8000° FOV), GFT (ground, BVRIJK)*
- ***Italian contribution**: science, hardware contribution (MXP, ground follow-up); coordinated by Mereghetti (ASI support ?)*

ECLAIRs		Gamma-Ray Monitor	
Type	coded mask camera mask aperture fraction: 40% mask-to-detector distance: 46 cm	Type	non-imaging spectrometer
Consortium	IRAP, CEA-Saclay (France) APC (France)	Consortium	IHEP Beijing (China)
Field of view	$\sim$ 2 sr (89×89 deg^2) Fully coded: 0.15 sr (22.1×22.1 deg^2)	Field of view	$\sim$ 2 sr
Energy band	4 – 150 keV	Energy band	50 keV – 5 MeV
Effective area	$\sim$ 1000 cm^2 @ 20-50 keV $\sim$ 150 cm^2 @ 4 keV	Effective area	280 cm^2 @ 200 keV $\sim$ 160 cm^2 @ 5 MeV
Detector	6400 Schottky CdTe detectors Pixel: 4×4 mm^2 – 1 mm in thickness	Detector	2$\times$ Phoswich NaI/CsI
FWHM	< 2 keV @ 60 keV		
Readout time	10 μs	Readout time	-

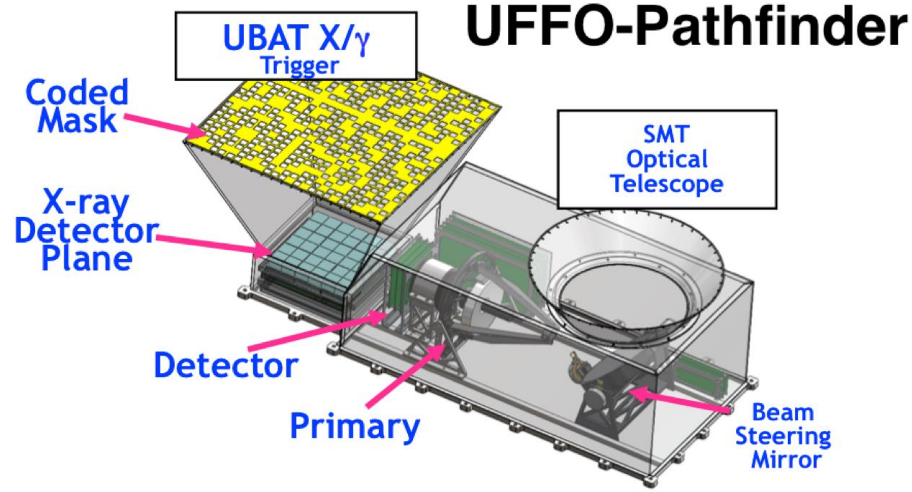
Micro channel X-ray Telescope		**Visible Telescope**	
Type	Wolter-I telescope	Type	Ritchey-Chrétien telescope
Consortium	IRAP, CEA-Saclay, LAM (France) University of Leicester (UK) MPE, IAAT (Germany)	Consortium	NAOC Beijing (China)
Field of view	64×64 arcmin^2	Field of view	21×21 arcmin^2
Energy band	$0.2 - 10$ keV	Energy band	V & R band
Effective area	~ 50 cm^2 @ 1.5 keV		
PSF FWHM	3.7 arcmin @ 1.5 keV	Resolution	0.6 arcsec
Focal length	1 m	Focal length	450 cm
Diameter	~ 21 cm	Diameter	45 cm
Detector	256×256 pn-CCD pixel: 75×75 μm^2	Detector	Two 2048×2048 CCDs
FWHM	75 eV @ 1 keV		
Readout time	100 ms	Exposure time	15 s



Instrument	Sensitivity
ECLAIRs (4-150 keV)	50 mCrab @ 1 orbit
MXT (0.2-10 keV)	10^{-10} erg cm^{-2} s^{-1} in 10 s (5 σ) $\sim 2 \times 10^{-12}$ erg cm^{-2} s^{-1} in 10 ks (5 σ)
VT	$m_V \sim 23$ mag in 300 s (10 σ) $m_R \sim 23.4$ mag in 1 ks (10 σ)
GWAC†	$m_V \sim 15$ mag in 10 s (5 σ)
GFT	$m_R \sim 21.5$ mag in < 1 min (10 σ)



❑ Lomonosov / UFFO-p



➢ ***Time frame***: *2015 – 2020 ?*

➢ ***Collaboration***: *Russia + Korea + contributions by Denmark, Spain, USA*

➢ ***Status***: *scheduled in the Russian space programme for launch by end of 2014*

➢ ***Goals***: *GRB detection and arcmin localization + very fast optical follow-up for prompt optical emission detection, arcsec localization (-> reshift determination through follow-up)*

➢ ***Payload***: *BDRG (scintillator, 10 keV – 3 MeV, 130 cm2), UFFO-p/UBAT (pixellated YSO scintillator + coded mask, 5-200 keV), UFFO-p/SMT (100 cm, optical, orientation of the mirror to GRB position in ~1s), SHOCK (wide-field optical cameras, 2000° FOV in total)*

➢ ***Italian contribution***: *none (?)*

Table 2. The BDRG device parameters

Parameter, unit	Value
Energy range, MeV	0.01–3.0
Effective area (for one detector), cm^2	~120
Temporal resolution, ms	1 (for burst mode)
Mass (for one detector unit), kg	5.5
Information capability, MB/day	~300
Field of view, sr	2π
Area of effective burst localization, sr	$\pi/2$
Sensitivity to burst detection, erg/cm^2	$\sim 10^{-7}$
Accuracy of burst localization	~1°–4° (for bright events)
Expected number of detected bursts per year	~100
Power consumption (one unit), W	3.0

Table 3. Parameters of the UBAT and SMT telescopes in the UFFO device

UBAT	X-ray camera with coded aperture	SMT	The Ritchey-Chrétien optical system with rotating mirror
Field of view, sr	~1.85 (90.2° × 90.2°)	Aperture, cm	10 (diameter)
Width of response function at half maximum	≤10' (7σ)	Number of F	11.4
Energy range, keV	5–200	Field of view when directing	17′ × 17′
Number of pixels	48 × 48	Field of view when rotating mirror	90° × 90°
Pixel size, mm^3	2.88 × 2.88 × 2	Receiver	Advanced *CCD*
Effective area, cm^2	191.1	Number of photodetector pixels	256 × 256
Energy resolution, keV	2, FWHM at 60 keV	Pixel angular resolution	4″
Quantum efficiency	99% at 100 keV	Localization accuracy	0.5″
Sensitivity, mCrab (10-s exposition at 40–50 keV)	310	Sensitivity in white light at 100-s exposition	$B = 19.5$ (5σ)
Mass, kg	10	Wavelength range, nm	200–650
Power consumption, W	10	Brightness limit	$mv = 6$ *mag*
		Mass, kg	10.5
		Power consumption, W	10

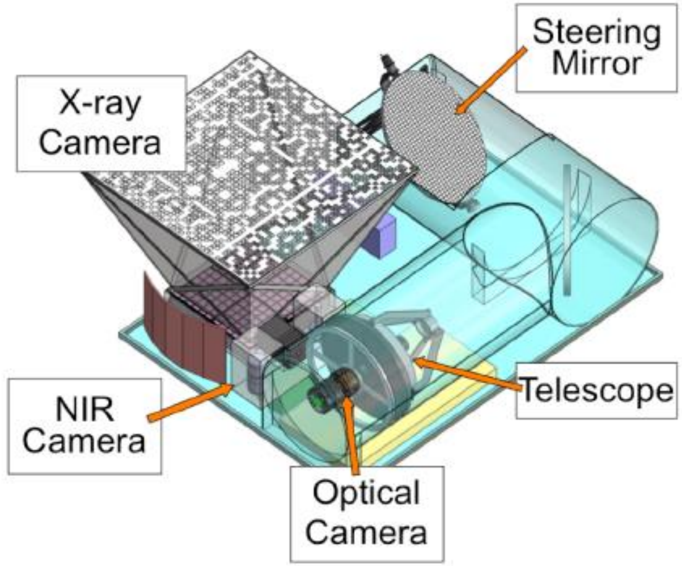


Fig. 11 Rendering of the UFFO-100 (compact configuration) design. In this configuration, the overall envelope is minimized by use of a folding mirror.

X-ray Camera Characteristics	
Detector	**CdZnTe crystal**
Active Area	**1024 cm^2**
Band	**15-200 keV**
Optics	**coded mask aperture**
Source Location	**r < 8.5',(90% prob., 8 σ)**
FOV	**HCFOV=1.4 Sr**
Mask-Detector Sep	**400 mm**
Mask Width	**575 mm**
Mask Element Size	**5.5mm**
Npix	**16,384**
Data/GRB	**<5 MB**
Mass	**46.0 kg**
Power	**50.7 W**

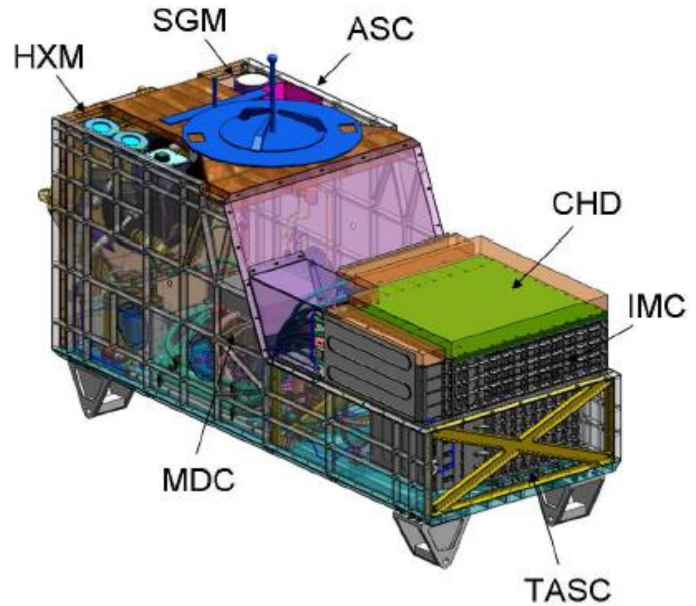
NIR Camera Characteristics	
Band	**0.9 – 1.7 μm**
Thermal Design	**Lyot Stop, Narcissus baffles, 1 cooled lens, Linear Pulse Tube Cooler**
Detector	**H2RG HgCdTe array**
Cooling	**Linear Pulse Tube Cooler**
FOV	**17.1'**
Npix	**2048 X 2048**
Operations modes (noise for 2 reads)	**500kHz read (23e-), 100 kHz read (15 e-).**
Data/GRB	**640 MB**
Mass	**5.1 kg**
Power	**55.4 W**

❑ CALET/GBM

➢ ***Time frame**: 2014 – 2018 ?*

➢ ***Collaboration**: Japan + contribution by USA and Italy*

➢ ***Status**: scheduled for a launch to the ISS (japanese payload facility) by end of 2014*



➢ ***Goals**: GRB detection and prompt emission broad band spectroscopy from ~10 keV to TeV range (plus few optical detetions)*

➢ ***Payload**: CGBM (LaBr3 + BGO, 7 keV – 20 MeV, > 3sr, ~80 cm2), CAL (single particle telescopes for electrons and photons in the ~GeV – 10 TeV range), ASC (small optical camera)*

➢ ***Italian contribution**: significant Italian contribution to the CALET mission (Siena, Firenze IFAC, Padova, Pisa, Tor Vergata)*

Table 1: GRB Observations with CALET.

	CAL	CGBM	ASC
Energy (Wavelength)	a few GeV–10 TeV	7 keV–20 MeV	300∼800 nm
Effective area	~ 600 cm^2	68 cm^2(HXM) 82 cm^2(SGM)	—
Field of view	~ 2 str.	~ 3 str.(HXM) 4π str.(SGM)	$18.4^\circ \times 13.4^\circ$
Angular resolution	2.5° @1 GeV 0.35° @10 GeV	No capabilities	—
Time resolution	62.5 μs	62.5 μs	1/16∼4 sec
Deadtime per event	1.8 ms	40 μs	—