Short Gamma Ray Bursts: observations, physics, GW

(I)

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NewCompStar School 2017 - “Neutron stars: theory, observations and gravitational waves emission”

Outline of the lectures

I. The Gamma-Ray Bursts phenomenon

- *Basic Observations*
- *Standard scenarions for progenitors and physics*
- *Main open issues*
- *GRB cosmology*

II. Short Gamma-Ray Bursts

- *Short vs. long: classification issues*
- *Short vs. long: physics*
- *Short vs. long: progenitors*
- *Associated X-ray and GW emission*

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- *Short vs. long: progenitors*
- ***Associated X-ray and GW emission*** ***HOT!!!***

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- *Short vs. long: progenitors*
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GRBs basic observations

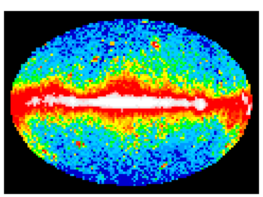
➢ *70s – 80s: GRBs = sudden and unpredictable bursts of hard X / soft gamma rays with huge flux*

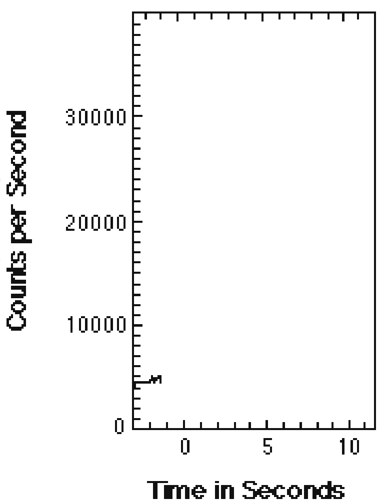
❑ most of the flux detected from 10-20 keV up to 1-2 MeV

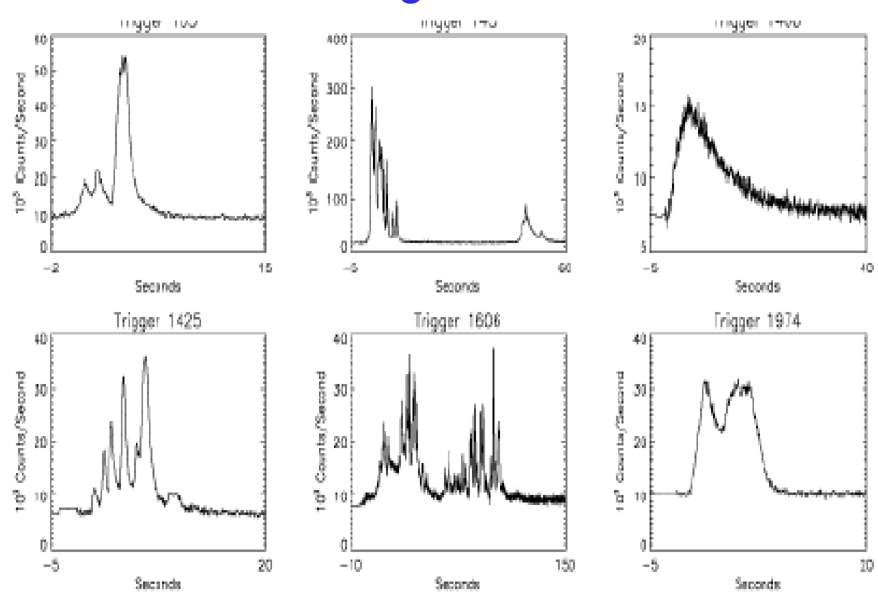
❑ measured rate (by an all-sky experiment on a LEO satellite): ~0.8 / day; estimated true rate ~2 / day

❑ 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

- 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

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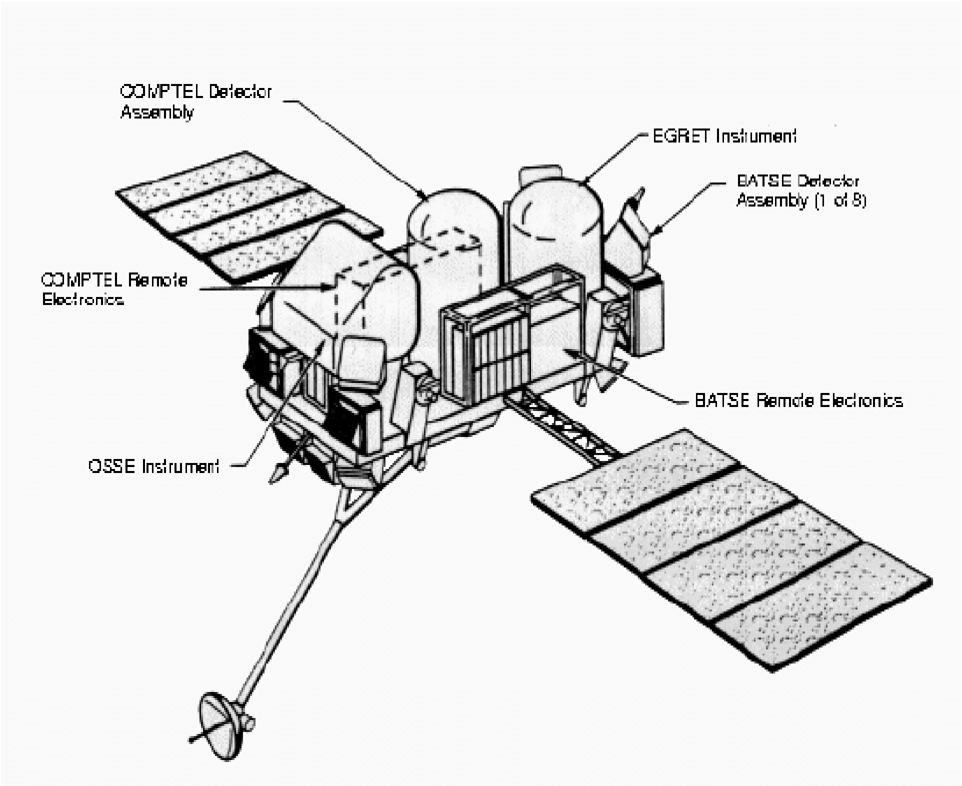
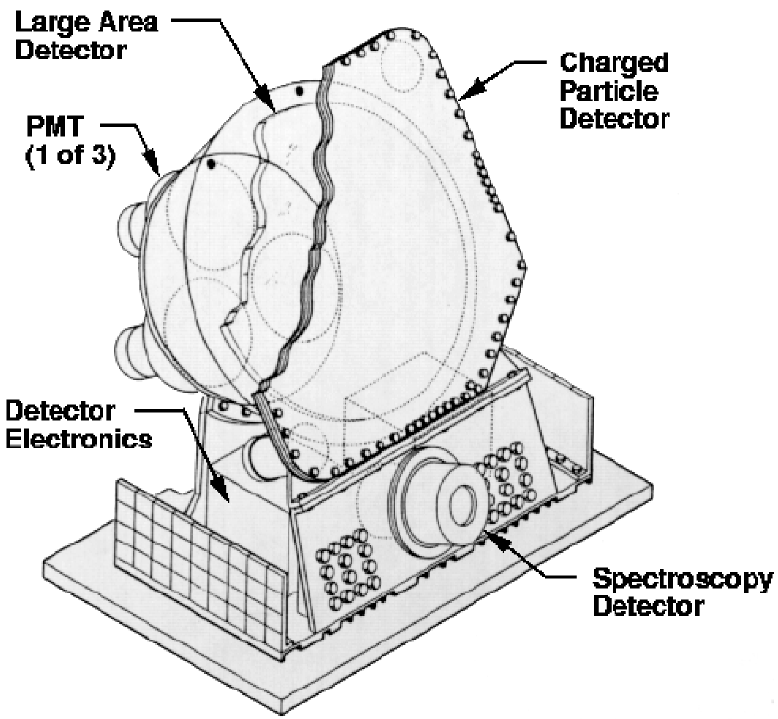
➢ *'90s: the contribution of CGRO/BATSE*

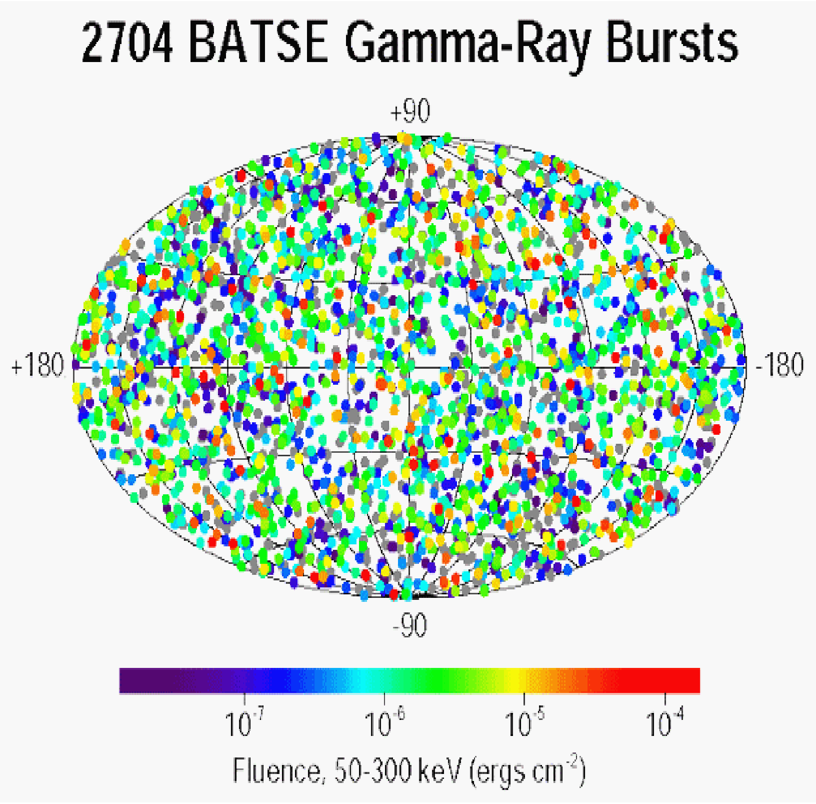
- ❑ major contribution came in the '90s from the NASA BATSE experiment (25-2000 keV) onboard CGRO (1991-2000)
- ❑ based on NaI scintillator detectors; 8 units covering a ~2π FOV

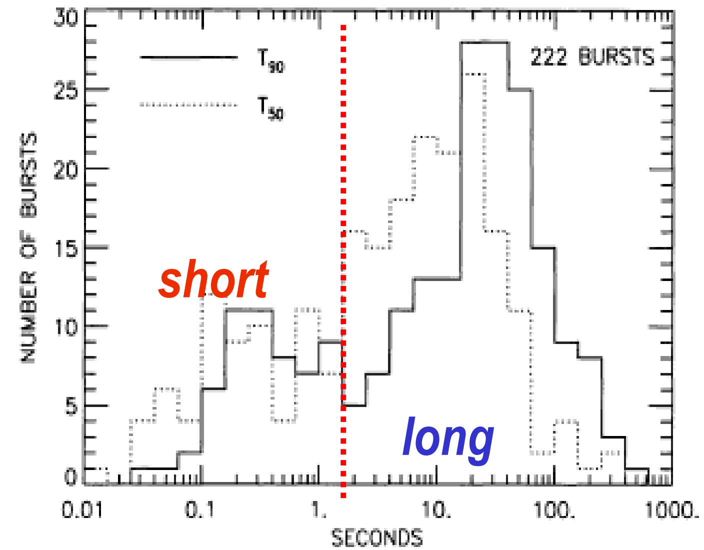


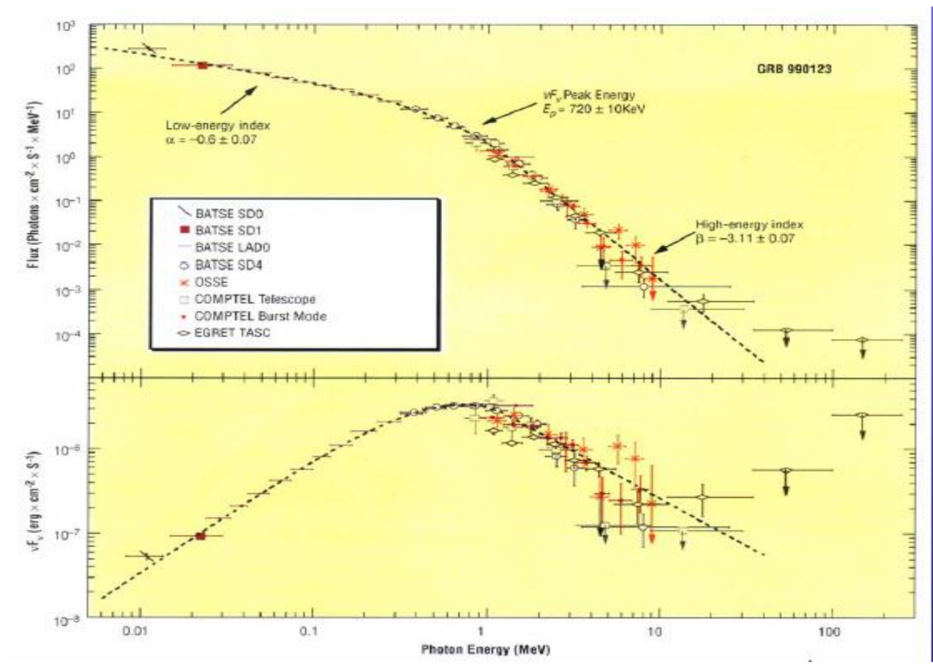


➢ *’90s: the contribution of CGRO/BATSE*

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



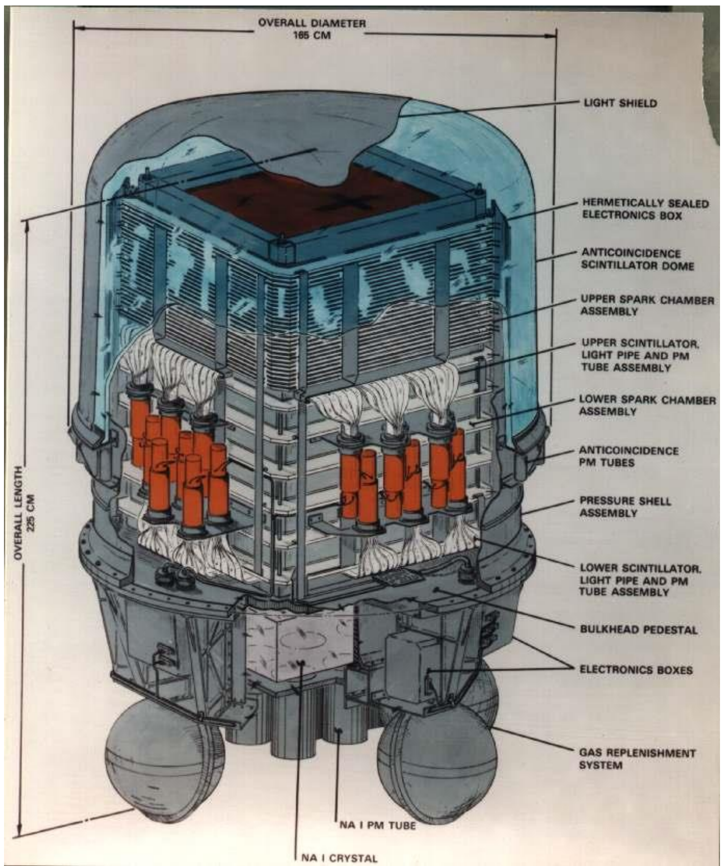


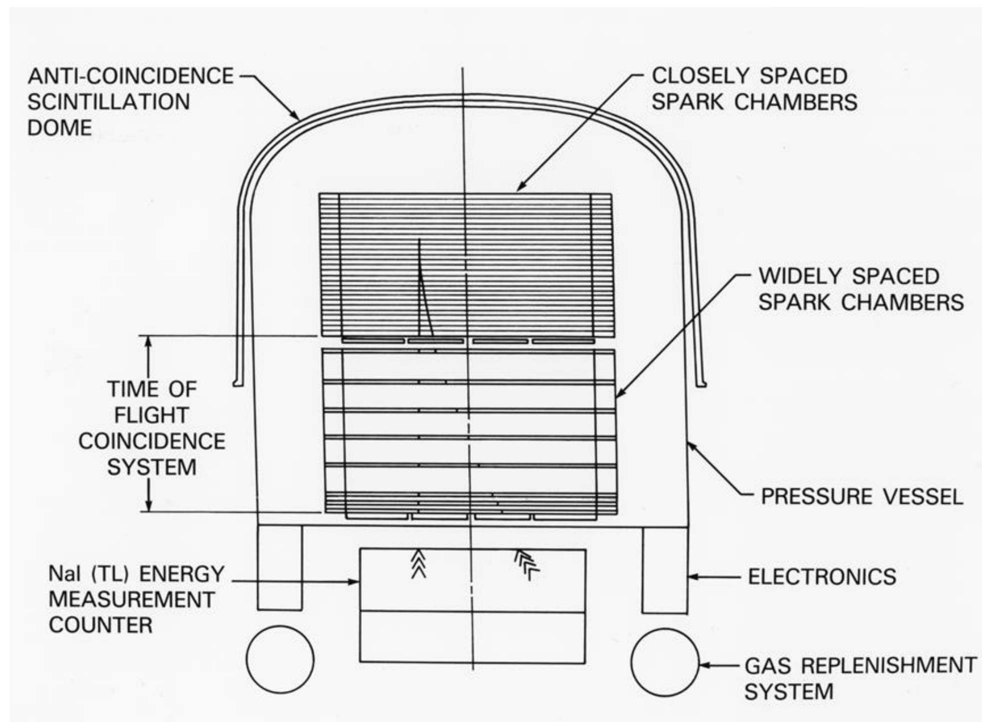


BATSE team

➢ *'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

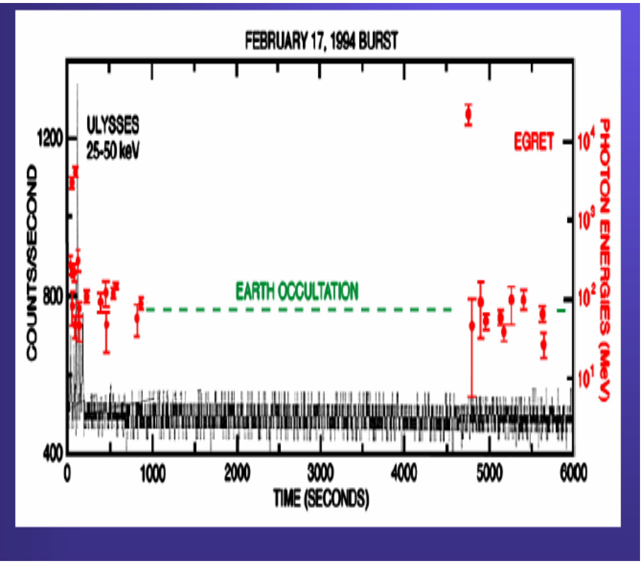


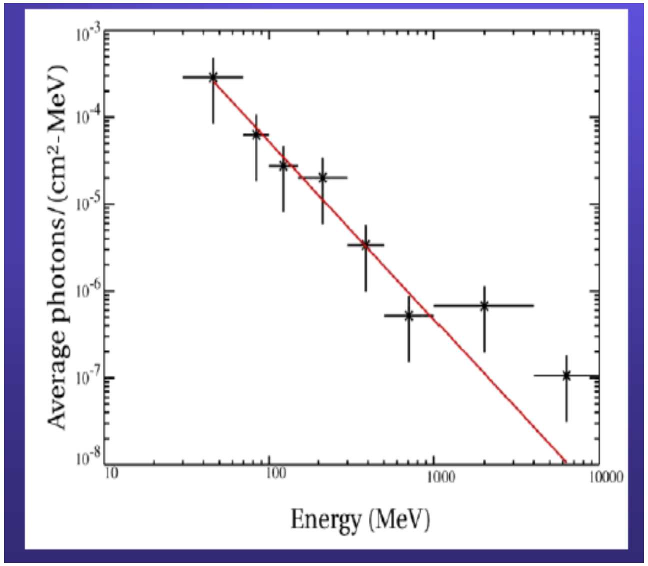


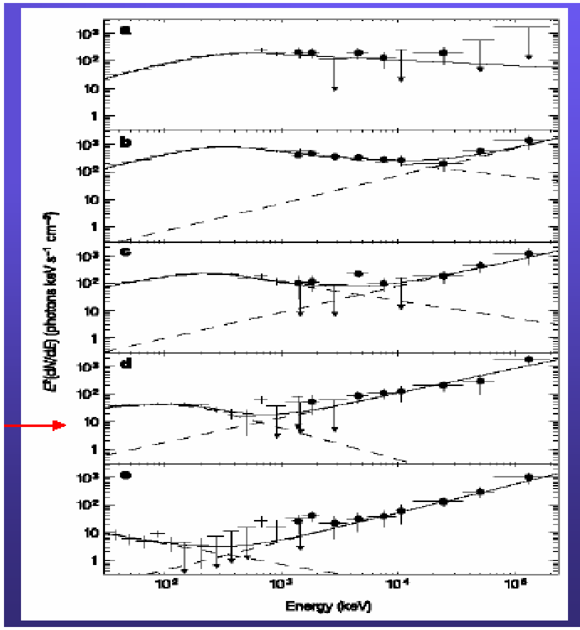
BATSE/EGRET team

➢ ’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



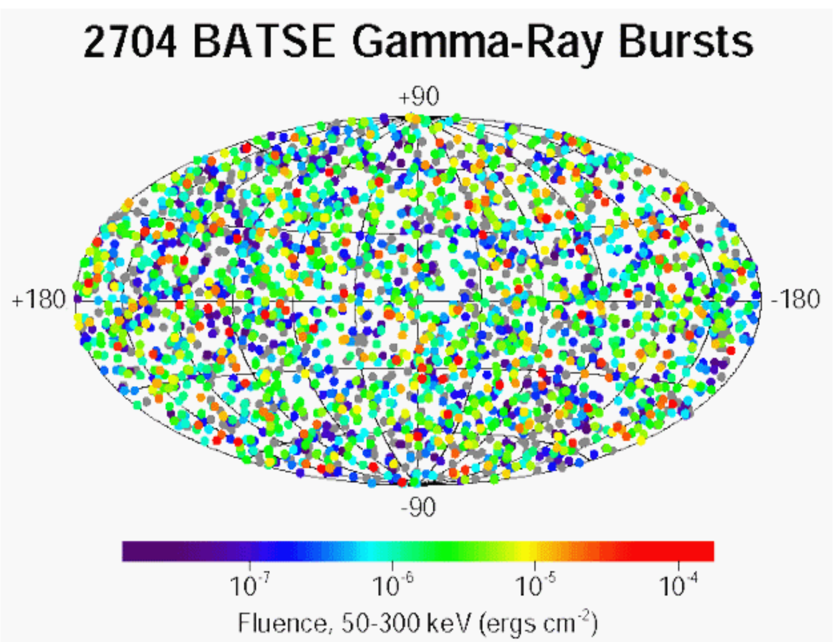


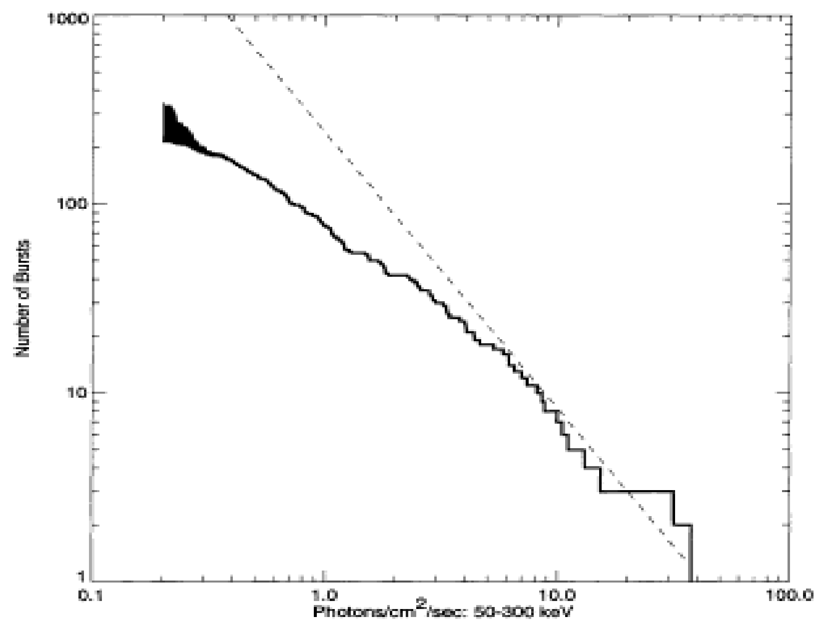


BATSE/EGRET team

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

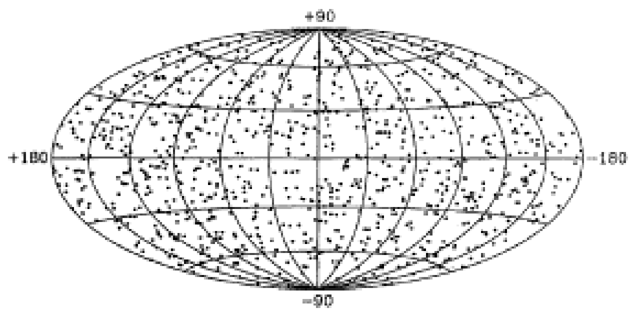


FIG. 1—Sky map of the first 1005 gamma-ray bursts observed by BATSE. Of these, 485 are from the second BATSE catalog and have positional uncertainties of about 7°. The remainder have preliminary positions or are affected by gaps in the telemetry stream, and have more uncertain positions. (From Briggs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

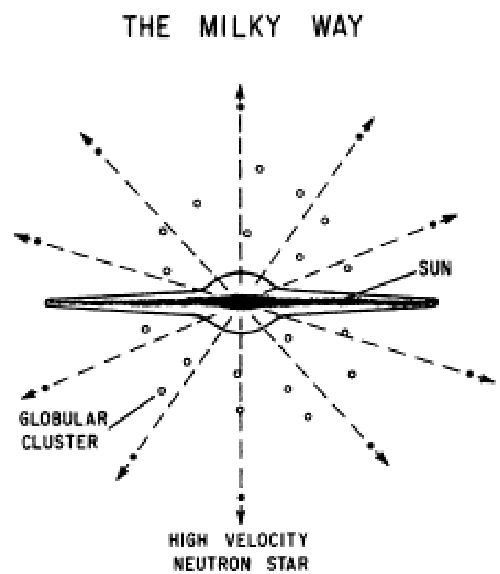
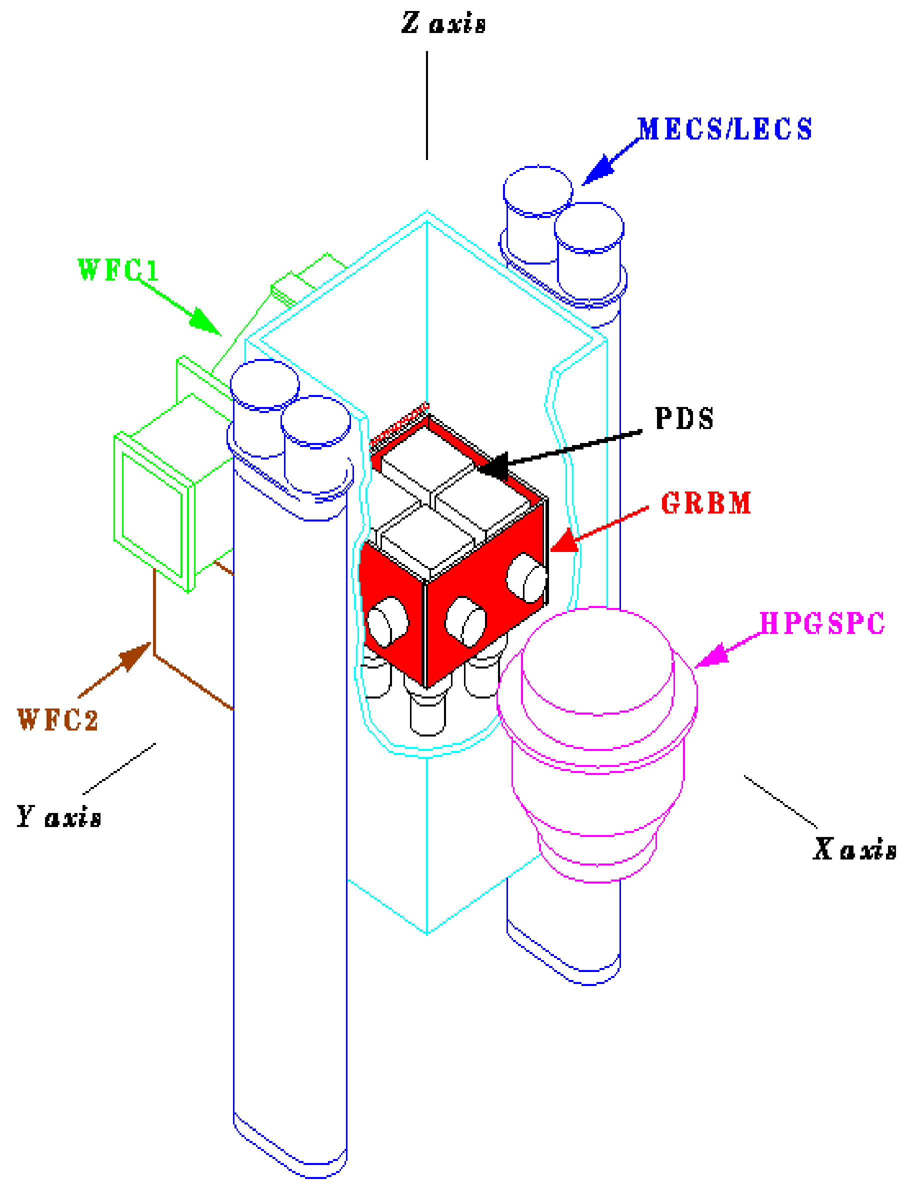


FIG. 3—Side view of the Milky Way. The Galactic bulge and disk are clearly visible; the dark lane along the plane of the Galaxy is due to dust. Also shown are the Sun, the globular clusters which surround the Galactic disk, and the trajectories of high-velocity neutron stars which are escaping from the 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.

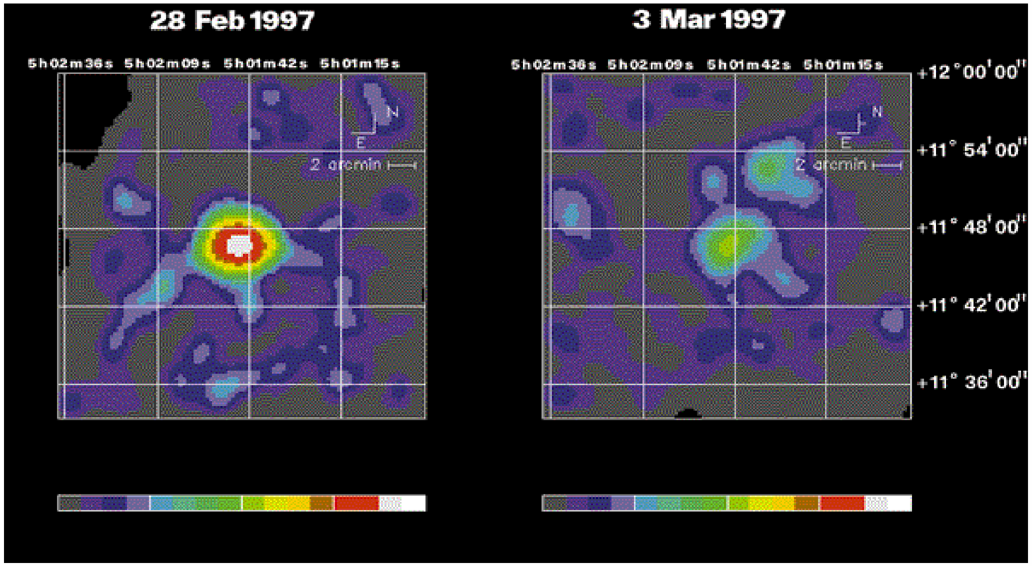
- *Need of a substantial improvement in the ocation accuracy several degrees (BATSE, scintillators) to arcmin*

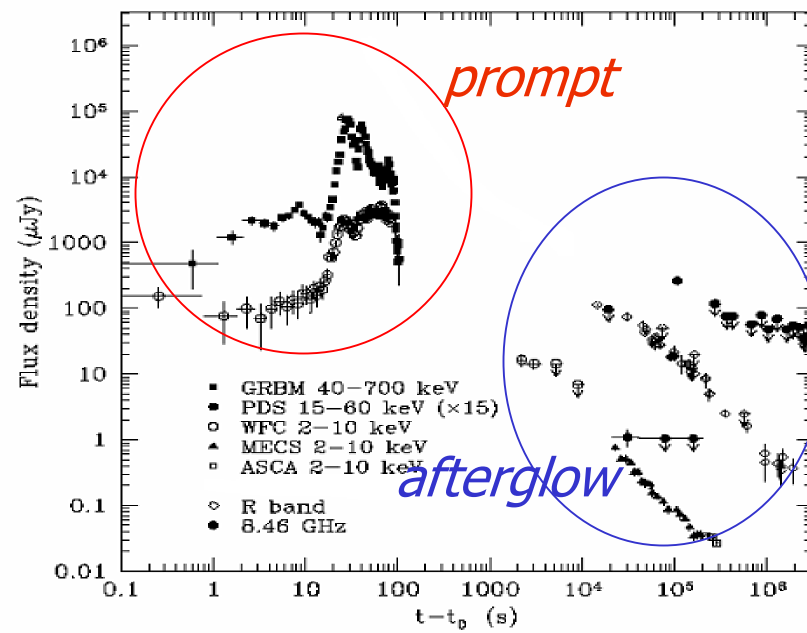
➢ *The BeppoSAX revolution (1996 – 2002):*

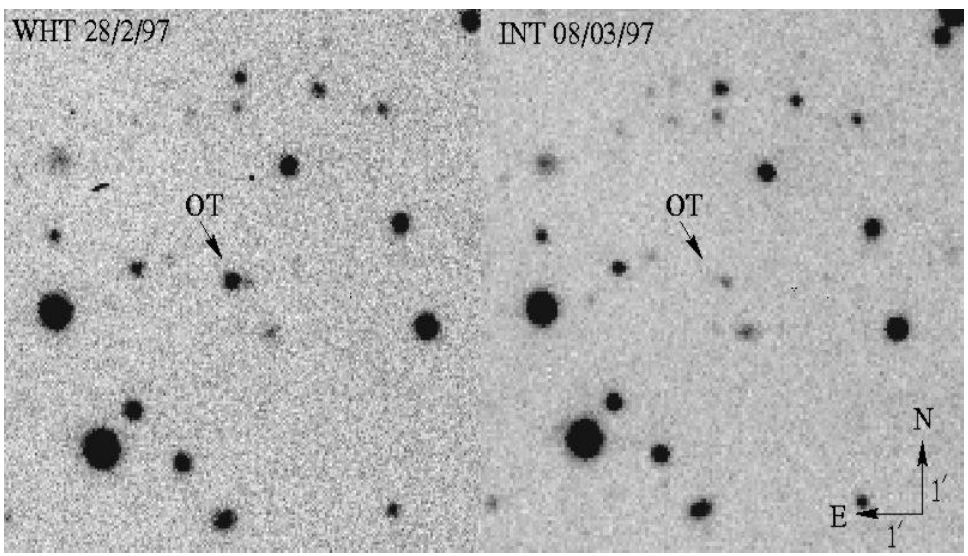
- ❑ NFI (X-ray focusing telescopes, 0.1-10 keV + PDS, 15-200 keV)
- ❑ WFC (2 units, proportional counters + coded mask, FOV 20°x20° each unit, 2-28 keV)
- ❑ GRBM (4 units, CsI scintillators, large FOV, GRB triggering, 40-700 keV)
- ❑ <u>WFC and GRBM co-aligned</u>

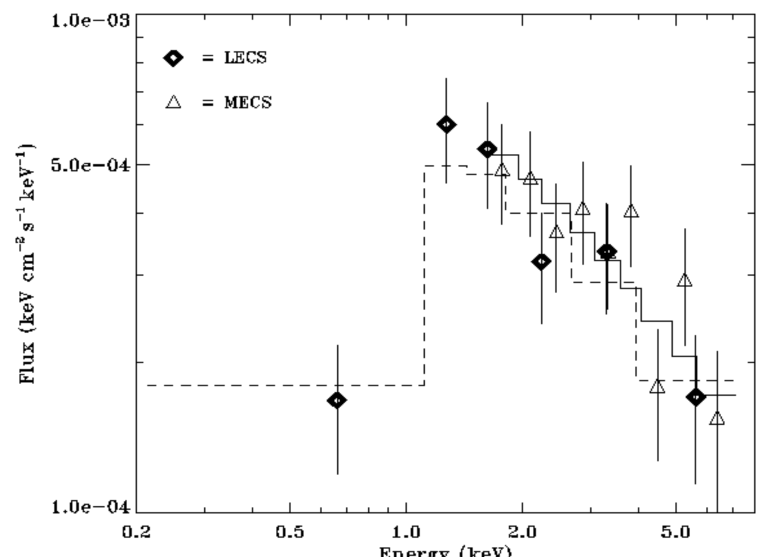


➢ *BeppoSAX: afterglow emission (late '90s):* power-law decay and spectrum (with exceptions)









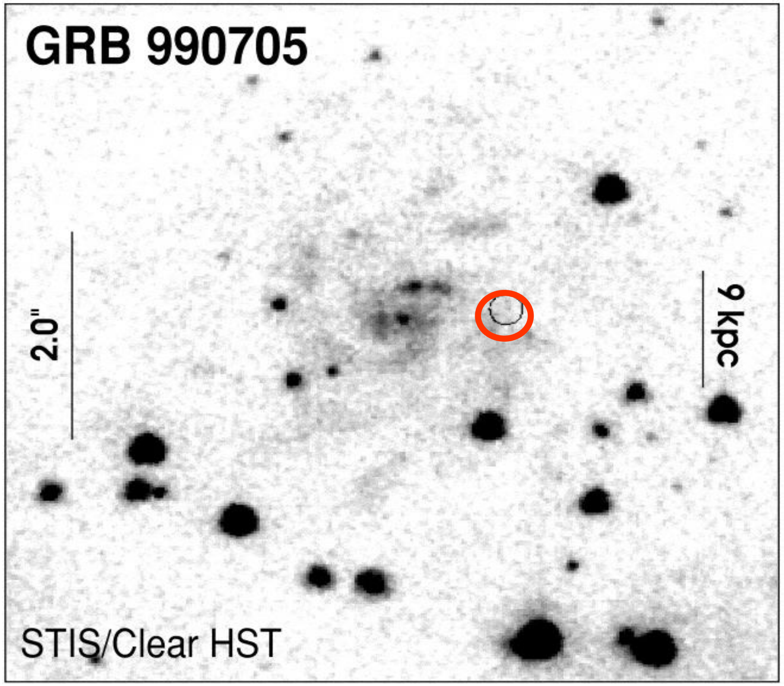
Costa et al. 1997, Van Paradijs et al. 1997, SAX team

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

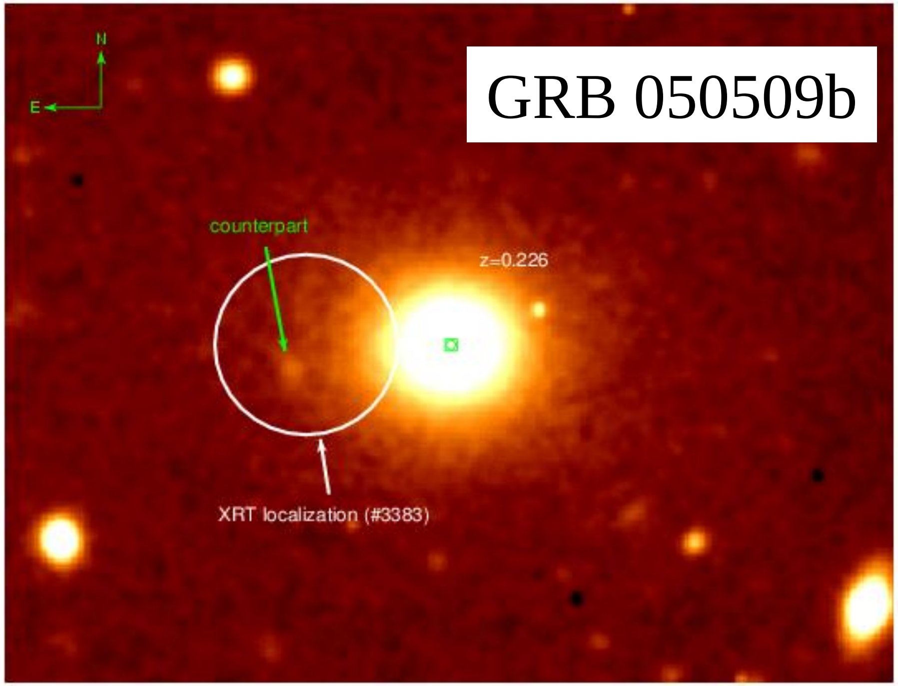
❑ host galaxies long GRBs: blue, usually regular and high star forming, GRB located in star forming regions

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

Long



Short



Bloom et al. 2002 , 2006

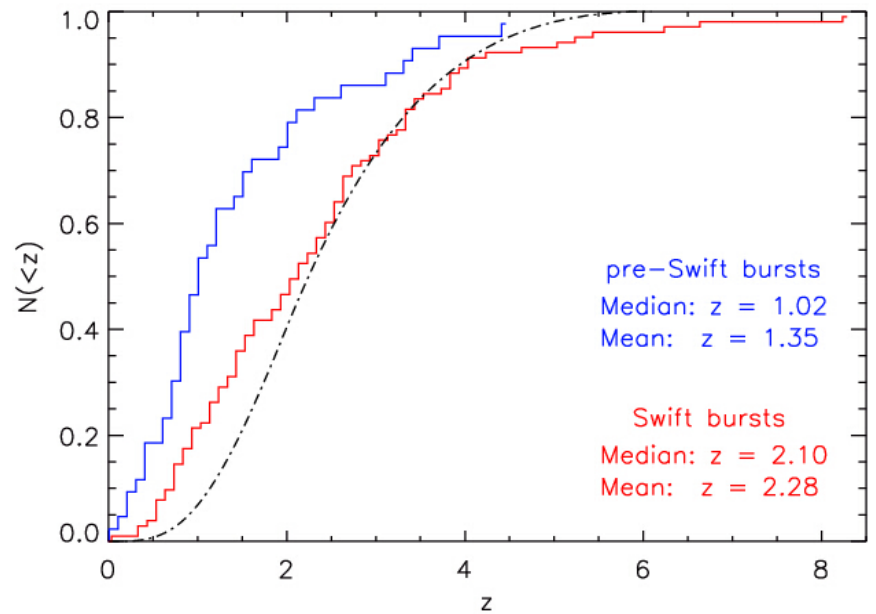
➢ *Distance and luminosity (>1997)*

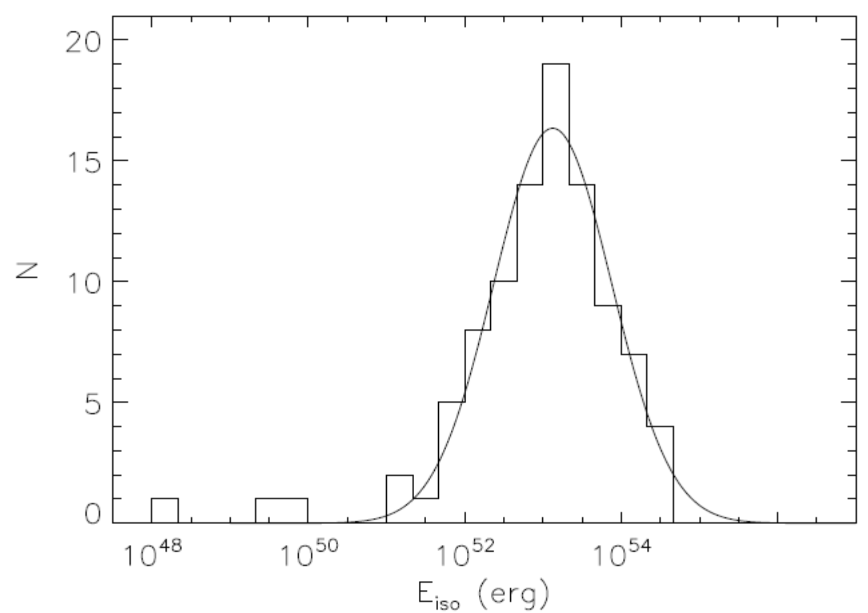
- ❑ from optical spectroscopy (OT or HG) -> redshift estimates

- ❑ **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)



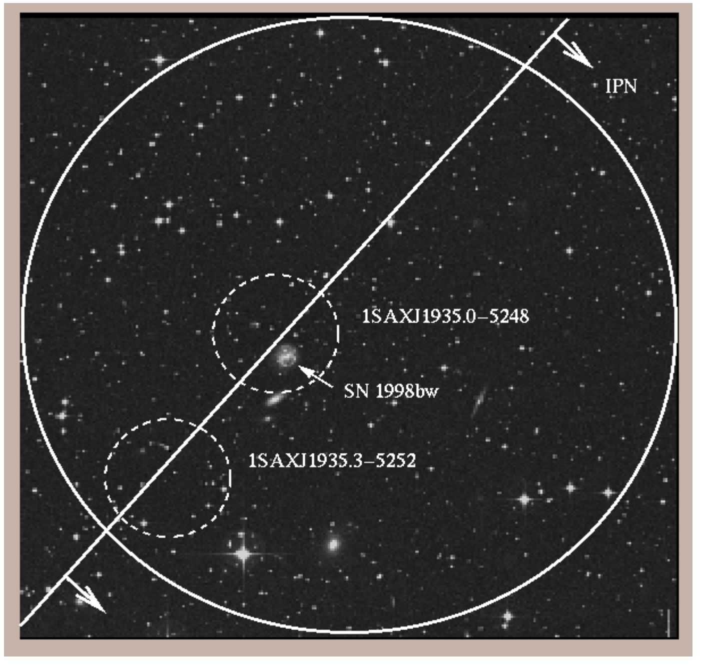


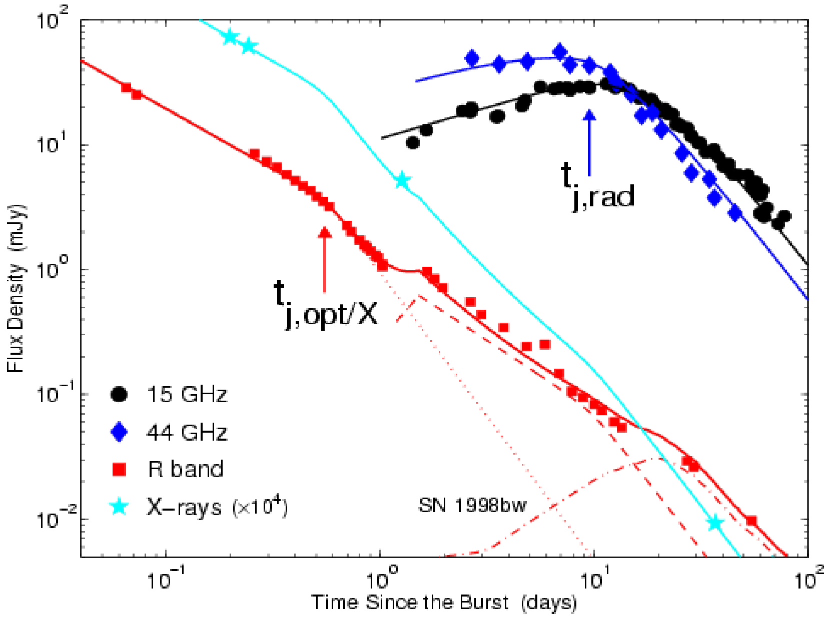
Amati 2009

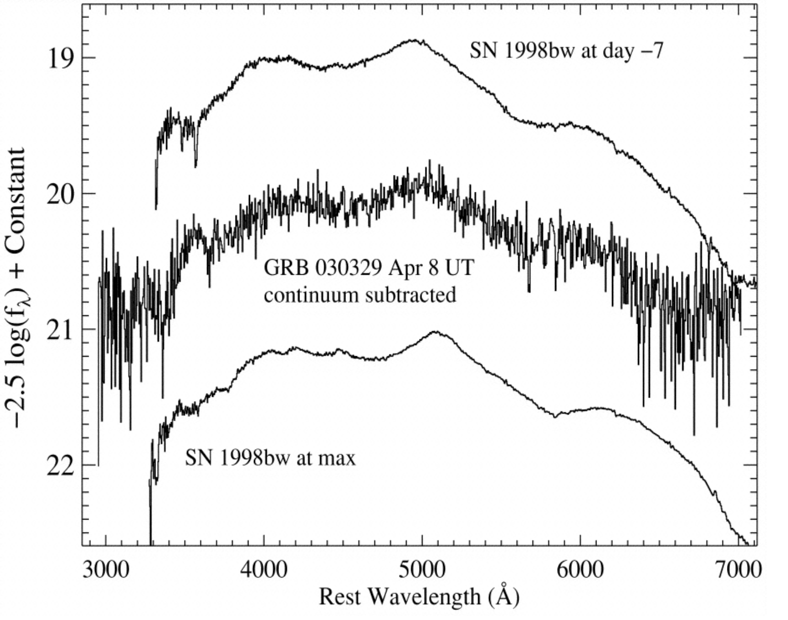
➢ GRB/SN connection (> 1998)

➢ 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)



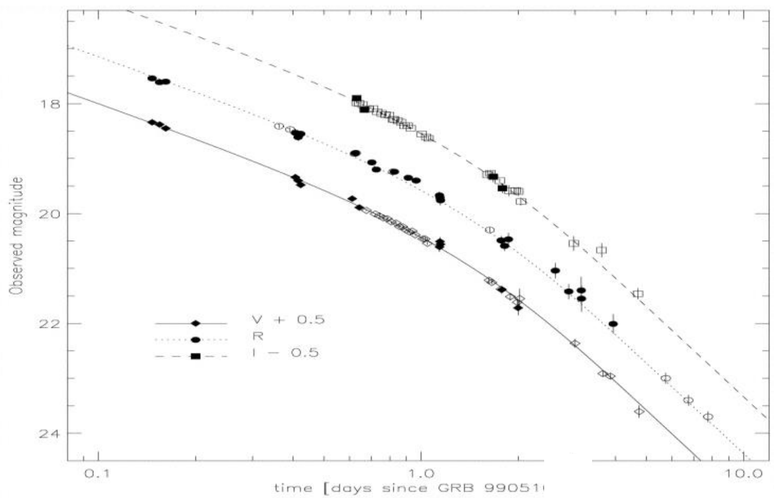




Galama et al. 1998, Hjorth et al. 2003

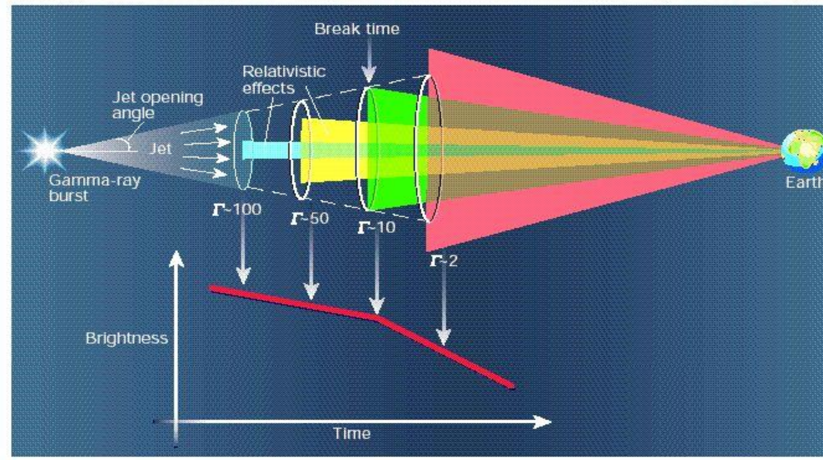
➢ *Evicence for collimation (late ’90s, ’00)*

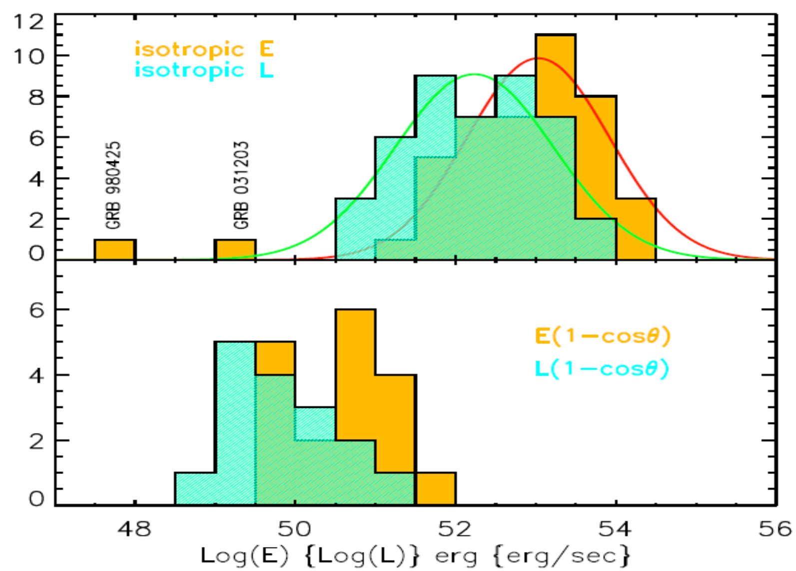
- ❑ jet angles derived from achromatic break time are of the order of few deg
- ❑ the collimation-corrected radiated energy spans the range ~10^{50} – 10^{52} erg



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

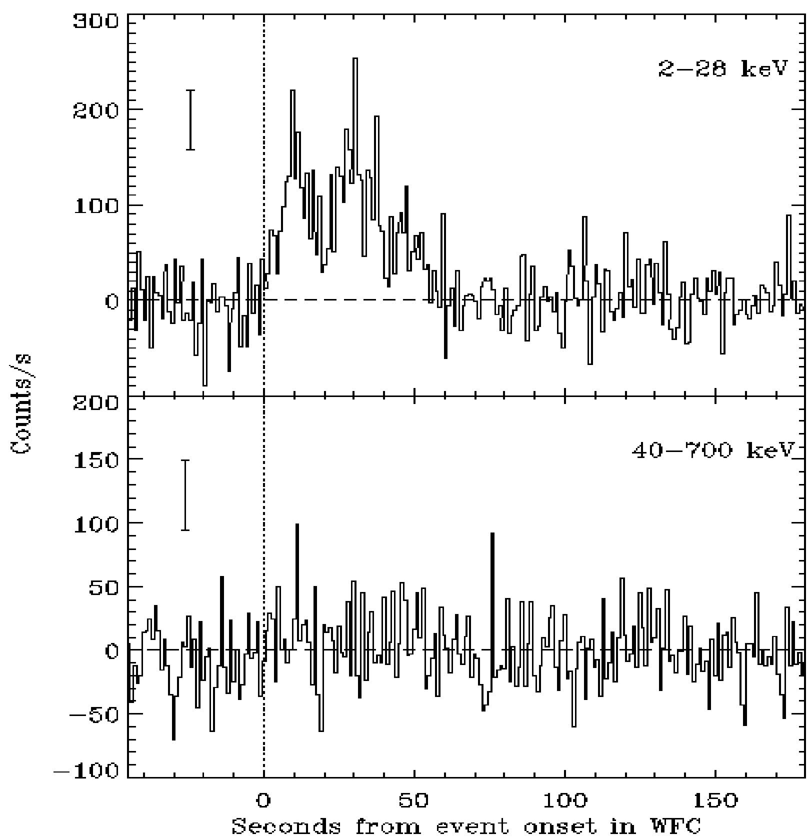
$$E_\gamma = (1-\cos\theta)\,E_{\gamma,iso}.$$

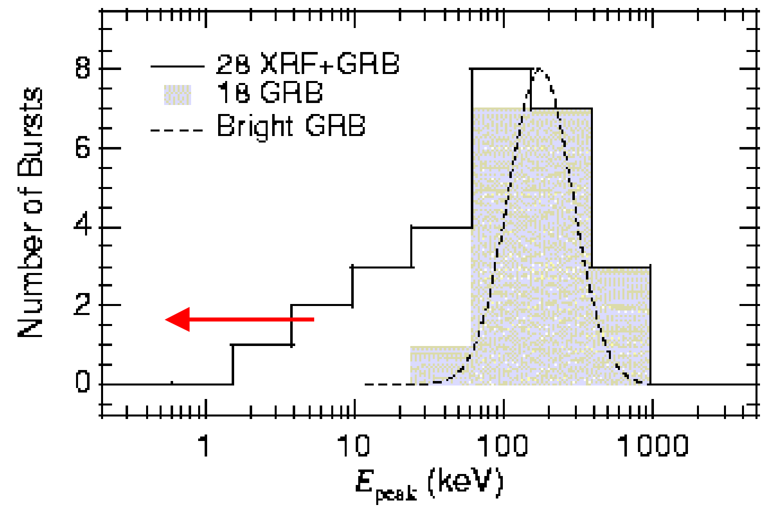


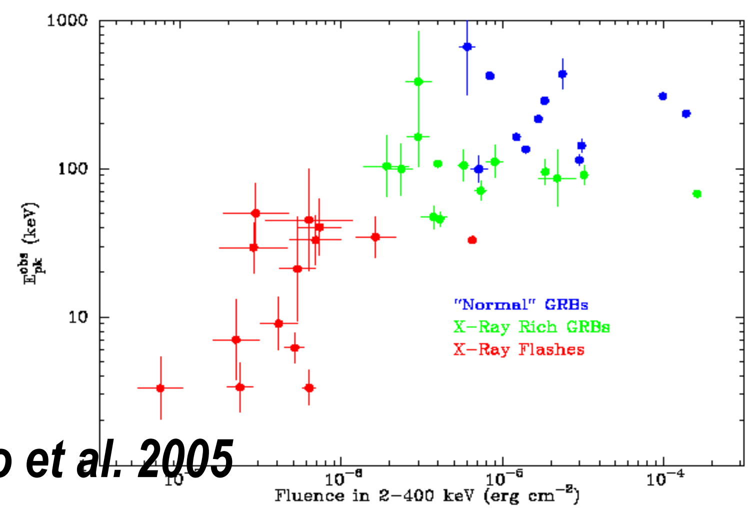


➢ *X-Ray Flashes (late '90s – early '00s , main contribution by BeppoSAX and HETE-2)*

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



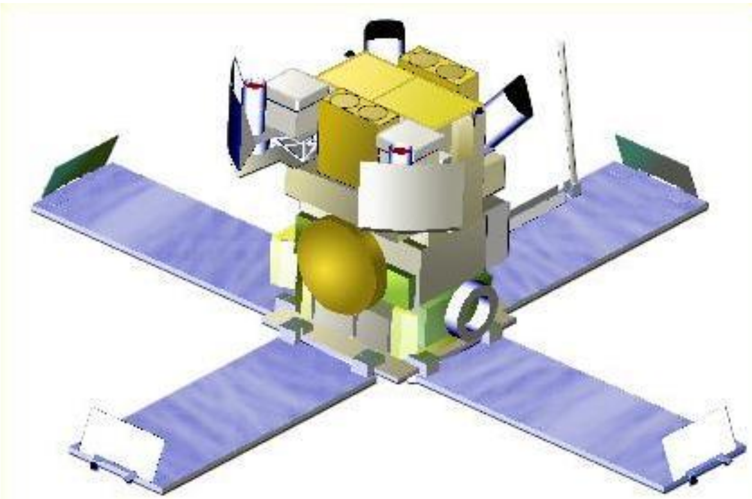


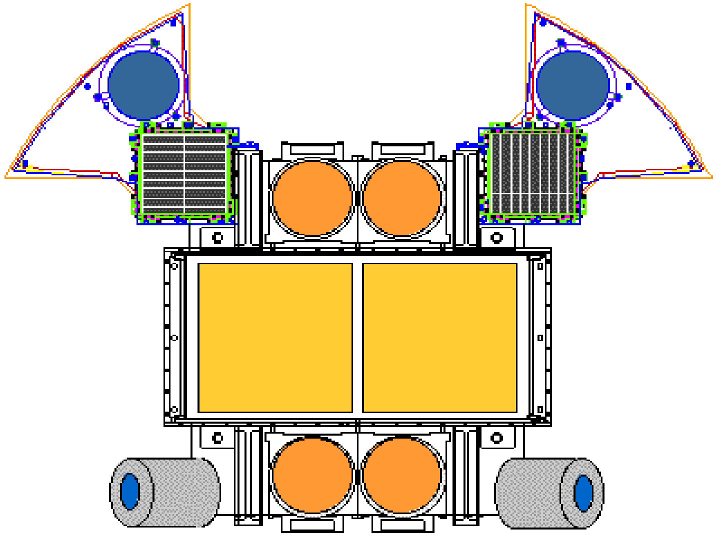


Amati et al. 2004, Kippen et al. 2001, Sakamoto et al. 2005

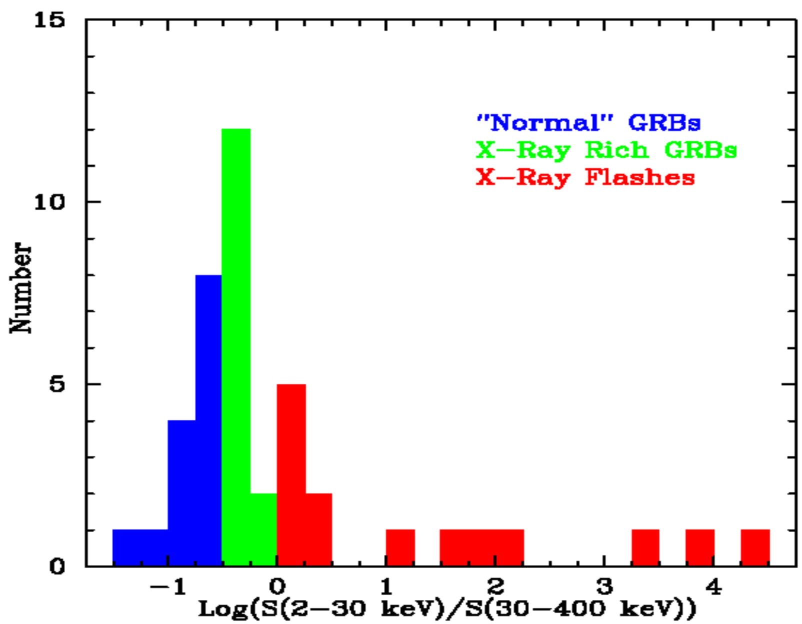
➢ *HETE-2 (2000 – 2007): extending the sample of X-ray rich GRBs and XRFs*

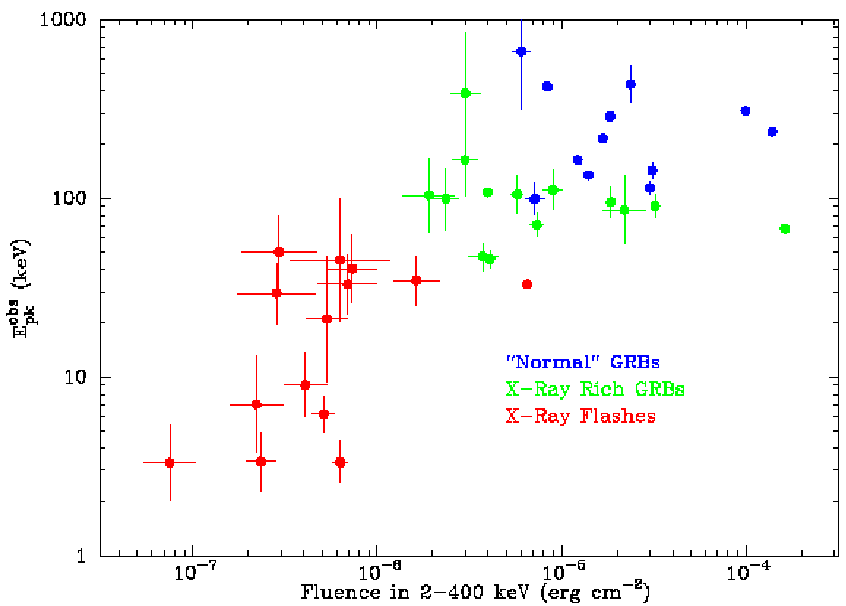
- ❑ FREGATE: NaI crystal scintillators, 6-400 keV, FOV = 3 sterad
- ❑ WXM: 2 units, gas proportional counters + 1-D codedmask, 2-25 keV , localization of few arcmin
- ❑ SXC: 2 units, CCD + 1-D coded mask. 0.5 – 10 keV, ~30 arcsec
- ❑ accurate localization (few arcmin) and fast position dissemination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

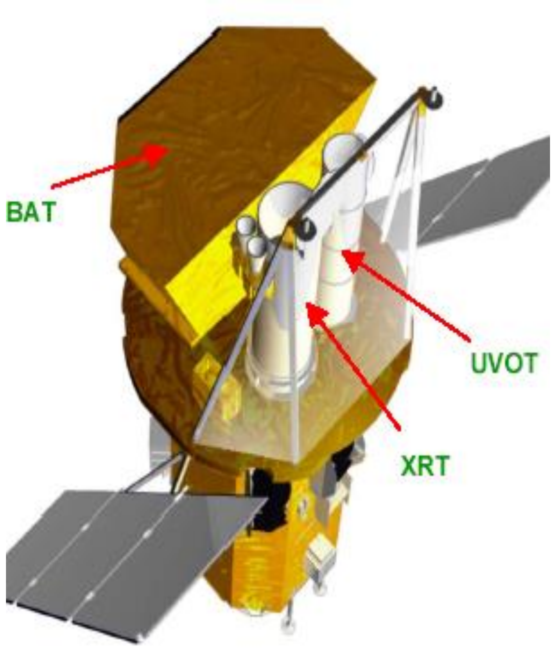




➢ *Swift (> 2004): transition from prompt to afterglow*

❑ **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)

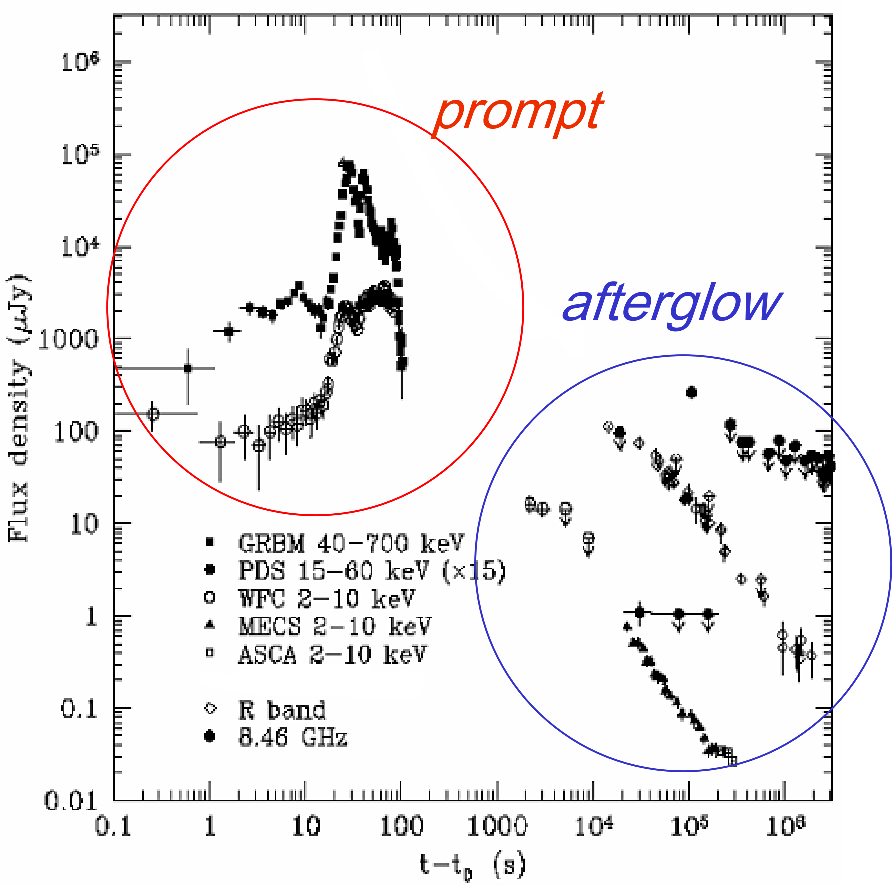


❑ payload: BAT (CZT+coded mask, 15-150 keV, wide FOV, arcmin ang. res.), XRT (X-ray optics, 0.3-10 keV, arcsec ang.res.), UVOT (sub-arcsec ang.res. mag 24 in 1000 s)

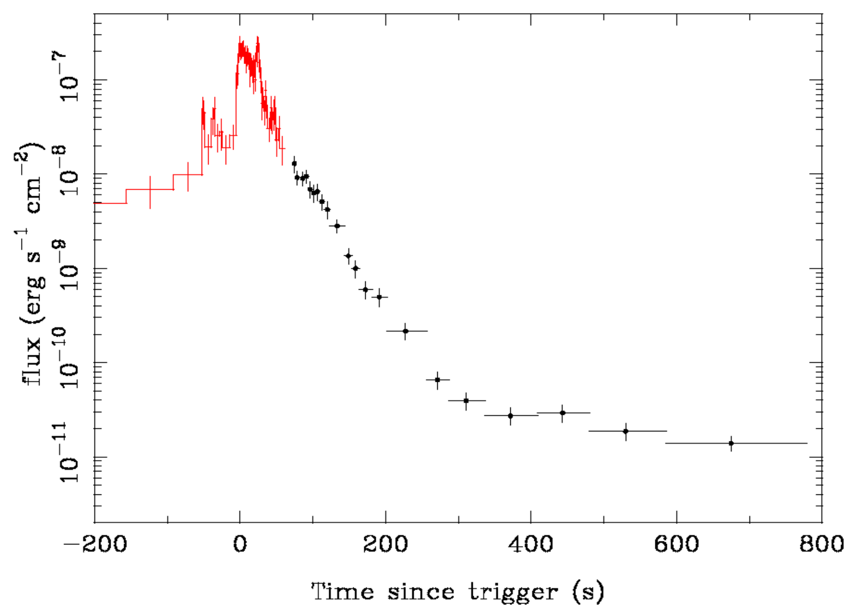
❑ spacecraft: automatic slew to target source in ~1 - 2 min.

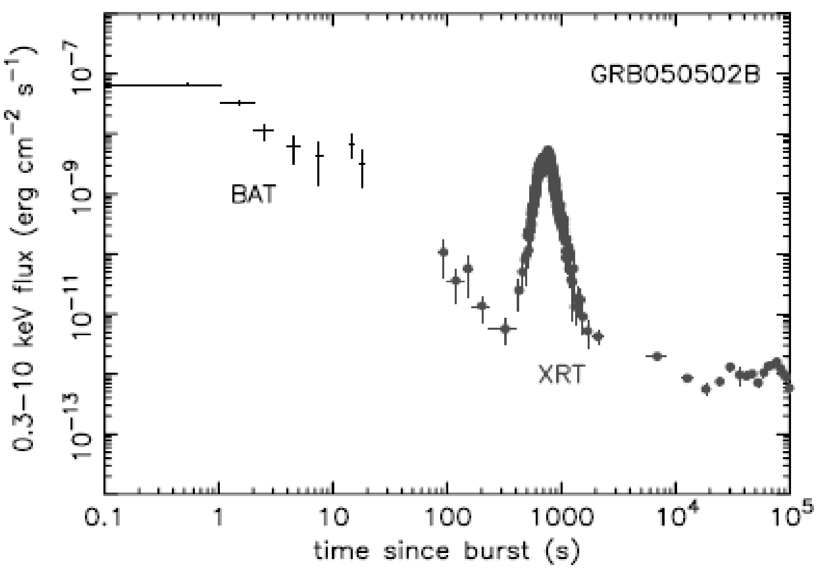
➢ *Swift: transition from prompt to afterglow (>2005)*

❑ BeppoSAX era



❑ Swift era

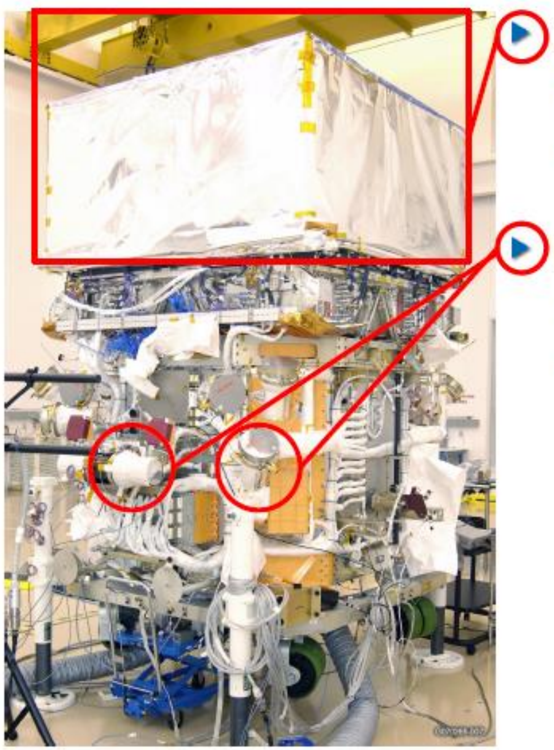




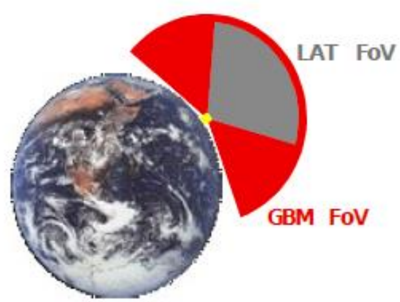
Maiorano et al., 2005 ; Swift team

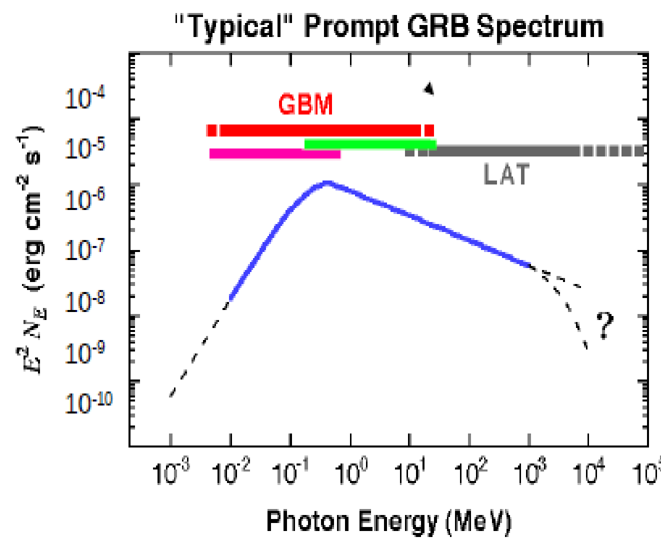
➢ *Fermi (> 2008): broad band prompt emission and VHE*

- ❑ 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.

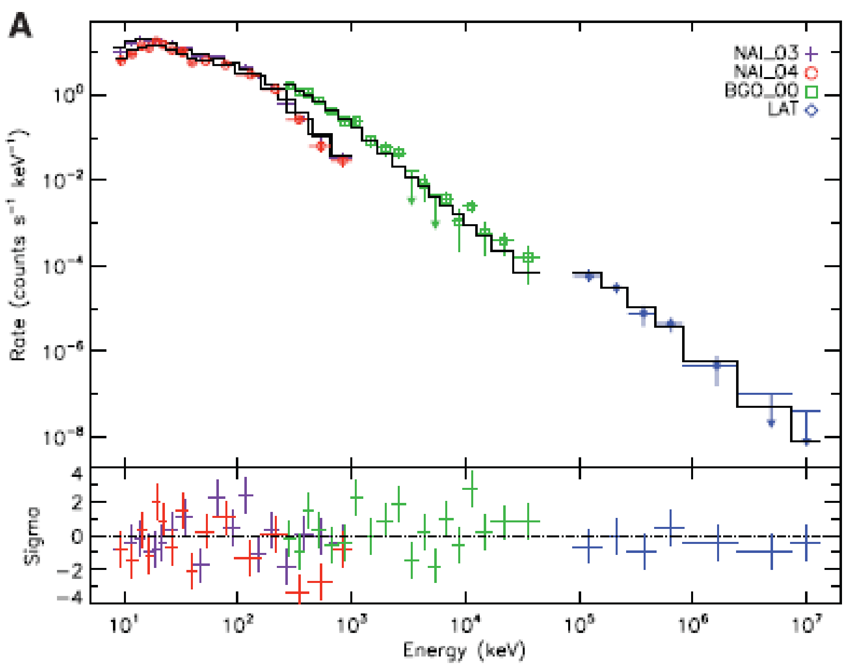


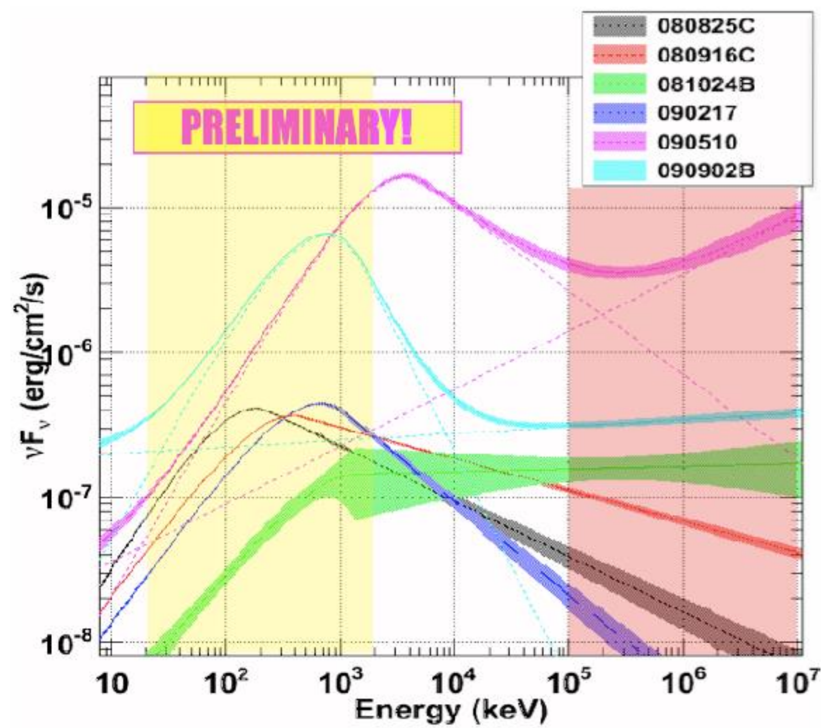


➢ VHE (> 100 MeV) properties of GRBs by Fermi and AGILE

- ❑ 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)

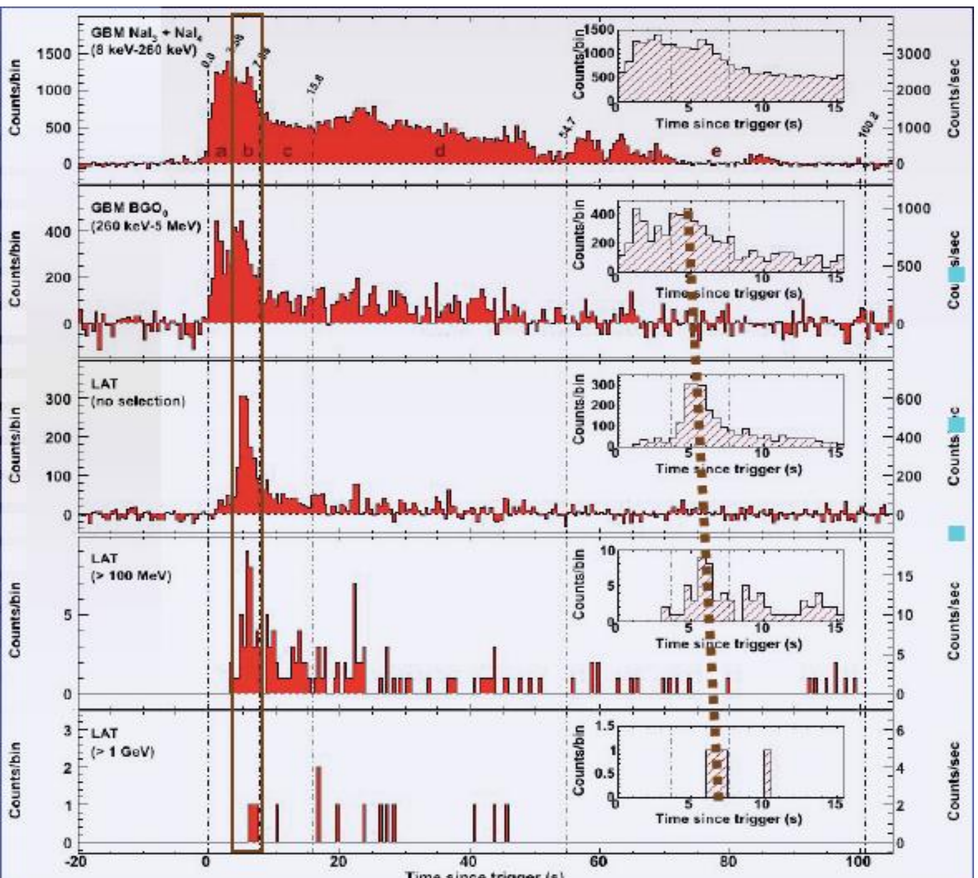


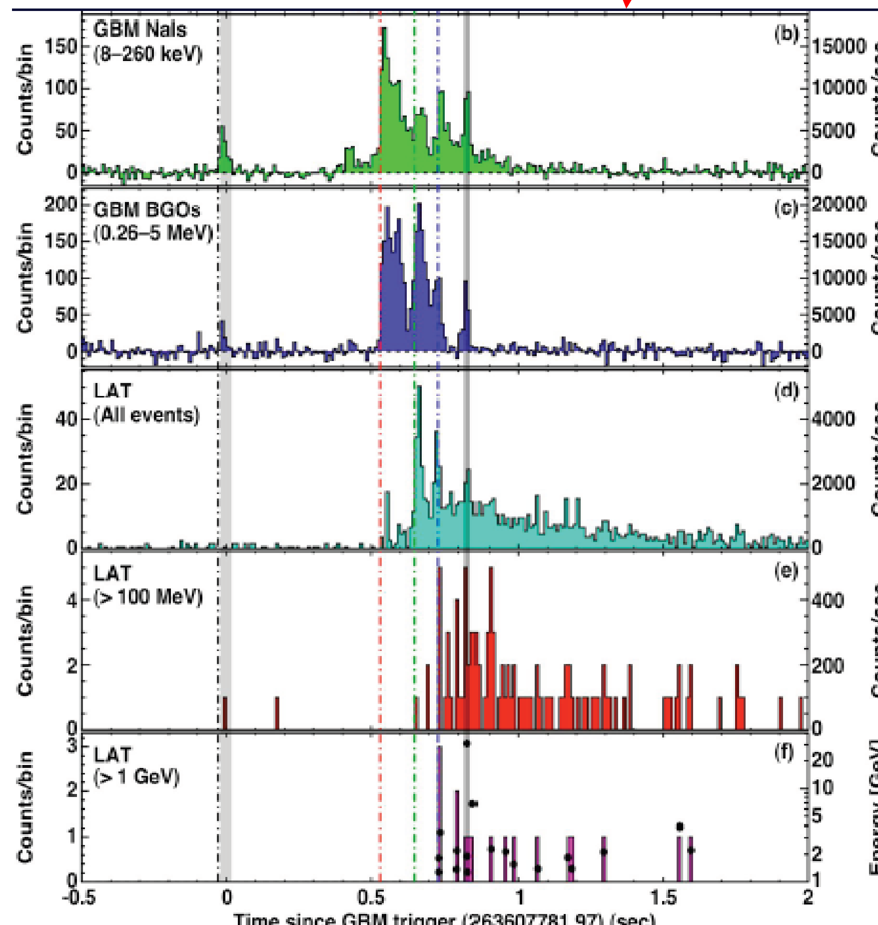


Abdo et al. 2009

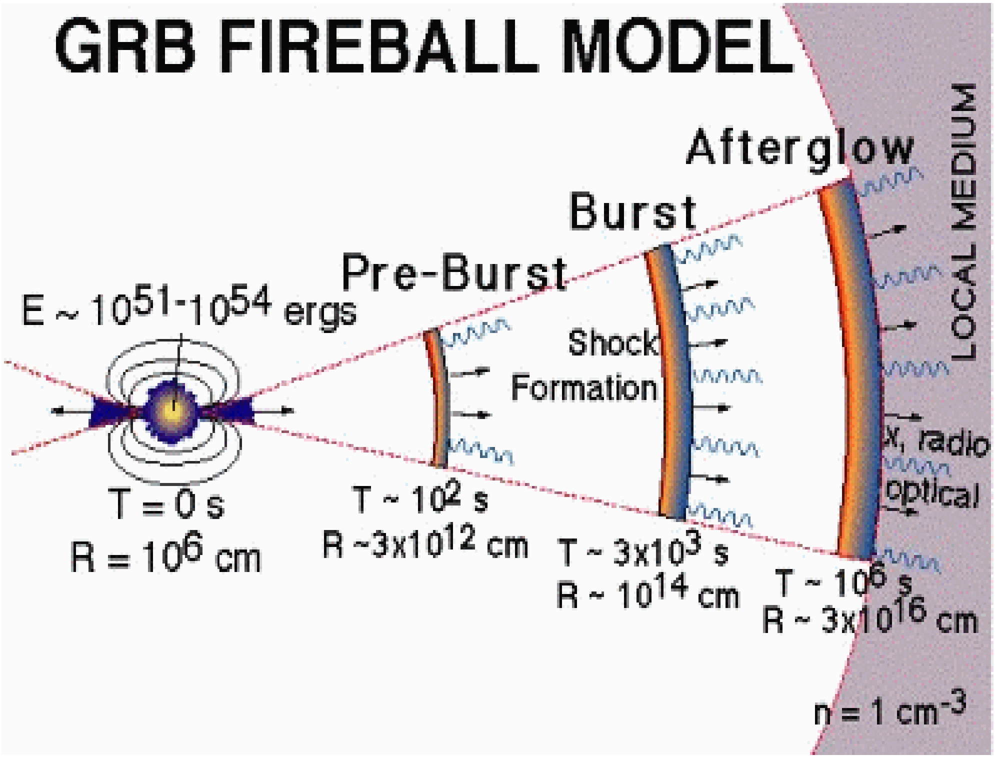
❑ significant evidence (at least for the brightest GRBs) of a delayed onset of VHE emission with respect to soft gamma rays;

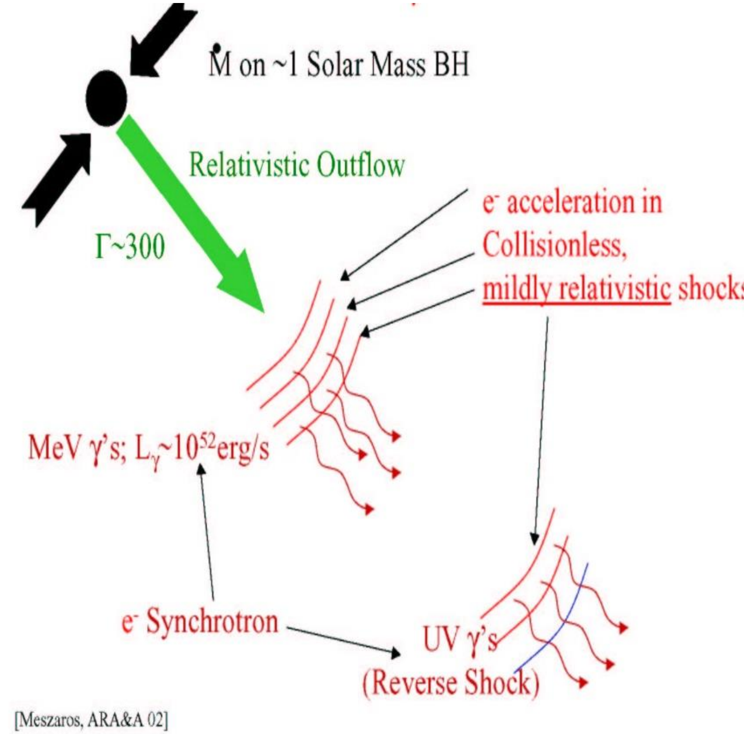
❑ the time delay appears to scale with the duration of the GRB (several seconds in the long GRBs 080916C and 090902B, while 0.1 − 0.2 s in the short GRBs 090510 and 081024B)





Standard scenarios for GRB phisics

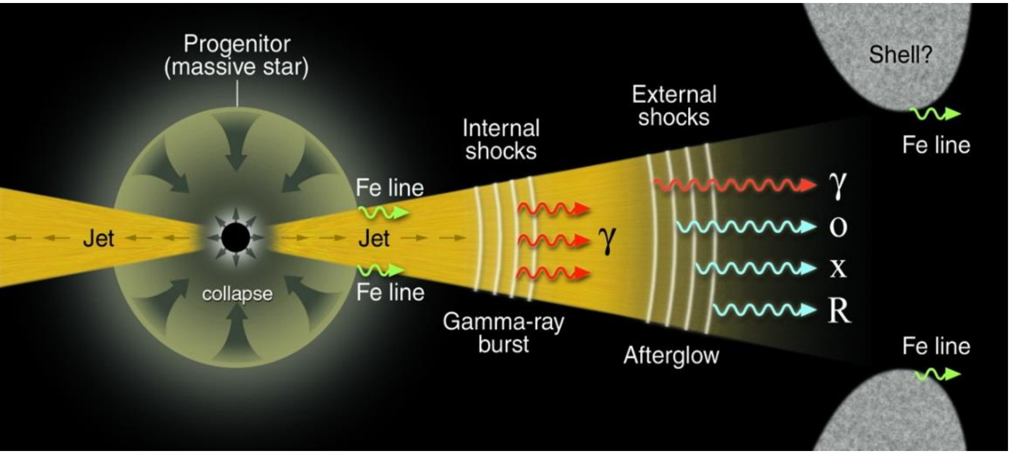




- ms time variability + huge energy + detection of GeV photons -> plasma occurring ultra-relativistic ($\Gamma > 100$) expansion (fireball or firejet)
- non thermal spectra -> shocks synchrotron emission (SSM)
- fireball internal shocks -> prompt emission
- fireball external shock with ISM -> afterglow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

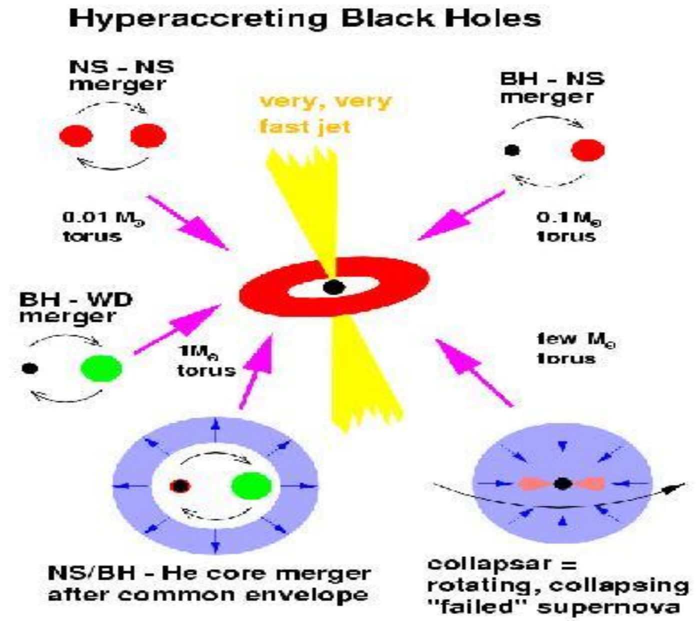
Standard scenarios for GRB progenitors

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

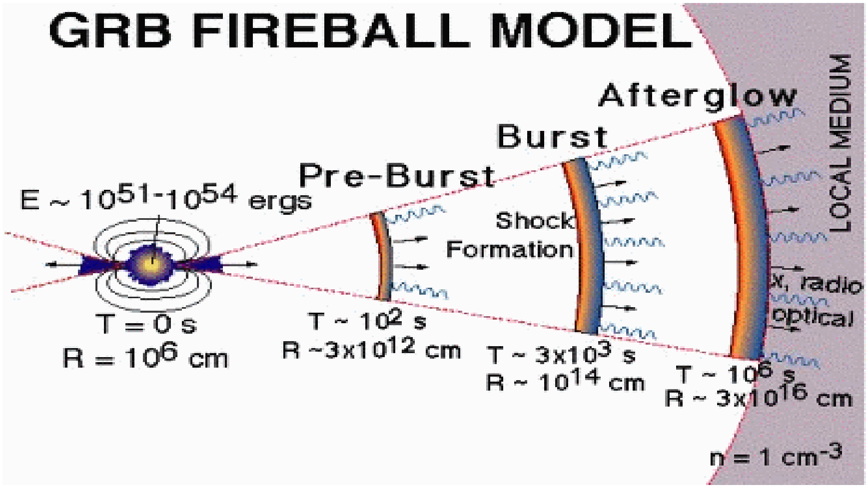


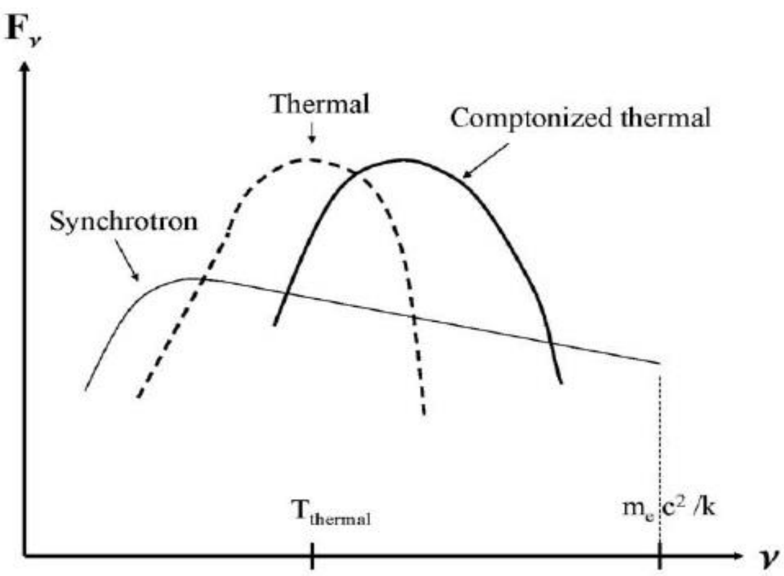
- energy budget up to 10^{51} - 10^{52} erg
- short duration (< 5 s)
- clean circum-burst environment
- old stellar population

Open issues (several, despite obs. progress)

➢ *GRB prompt emission physics*

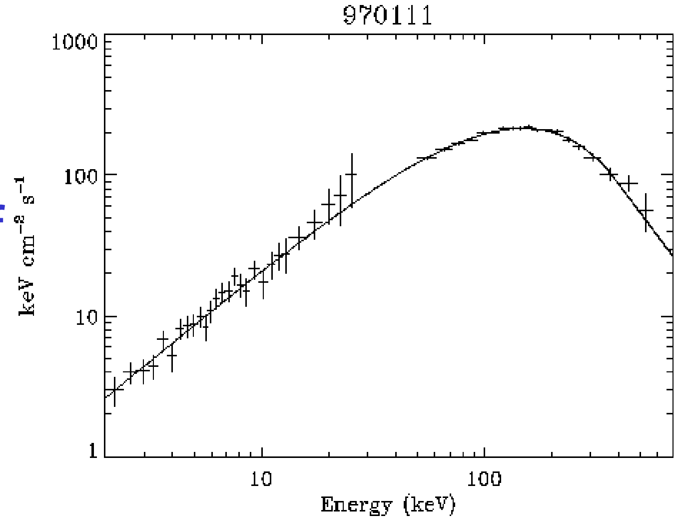
❑ physics of prompt emission still not settled, various scenarios: SSM internal shocks, IC-dominated internal shocks, external shocks, photospheric emission dominated models, kinetic energy dominated fireball , Poynting flux dominated fireball

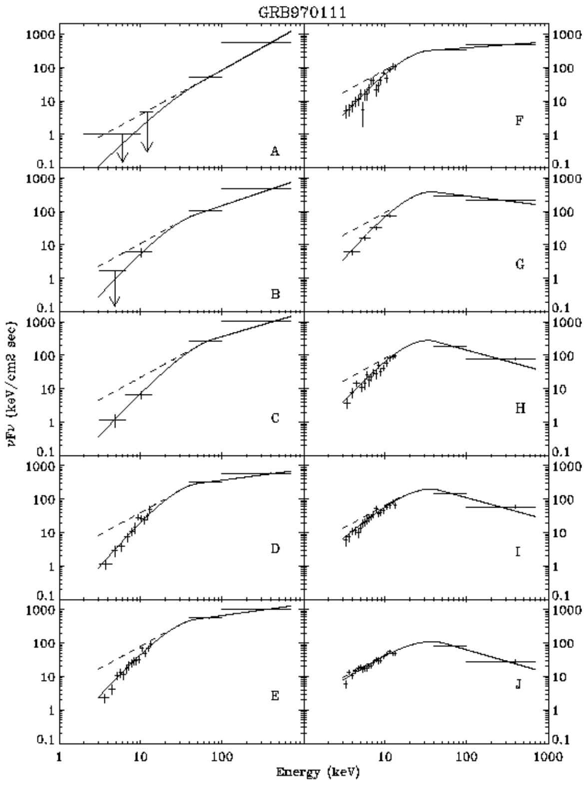


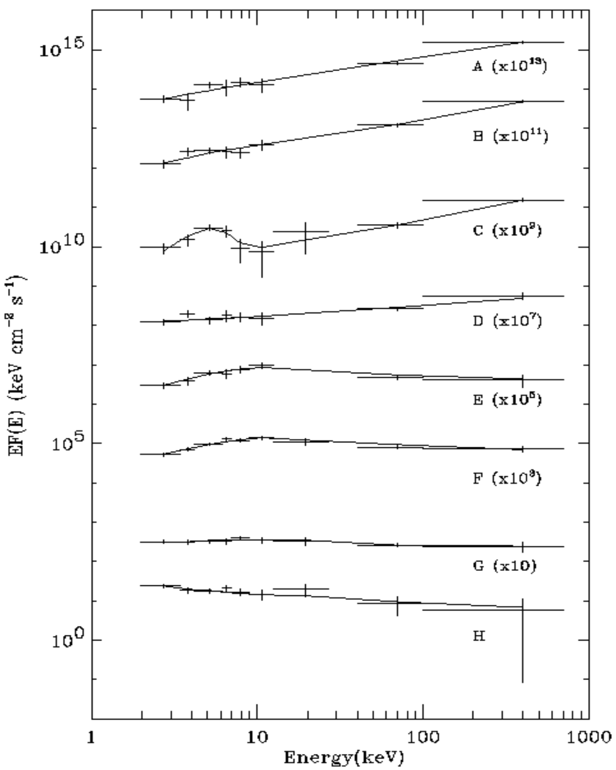


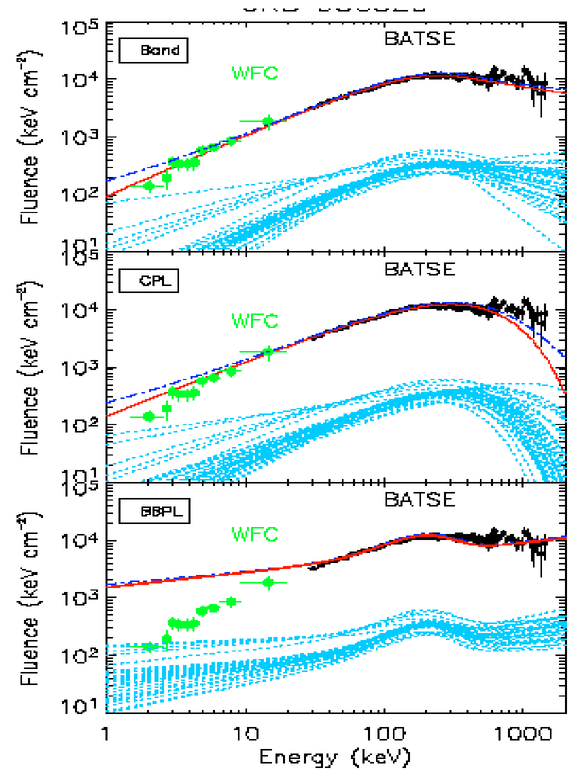
α $N(E)$	$\alpha+1$ $F(E)$	$\alpha+2$ EF_E	model/spectrum
-3/2	-1/2	1/2	Synchrotron emission with cooling
-1	0	1	Quasi–saturated Comptonization
-2/3	1/3	4/3	Instantaneous synchrotron
0	1	2	Small pitch angle/jitter
			inverse Compton by single e^-
1	2	3	Black Body
2	3	4	Wien

- 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



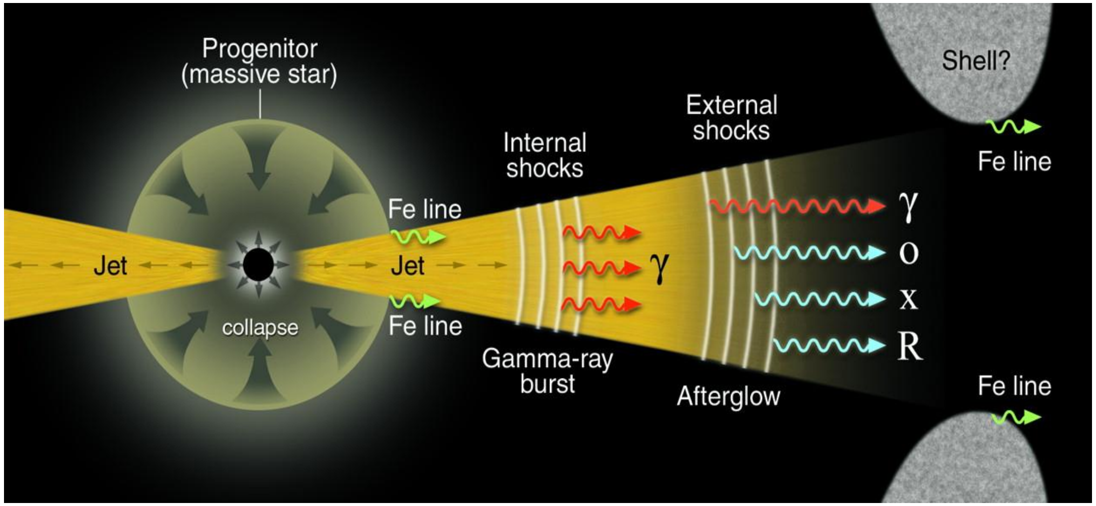


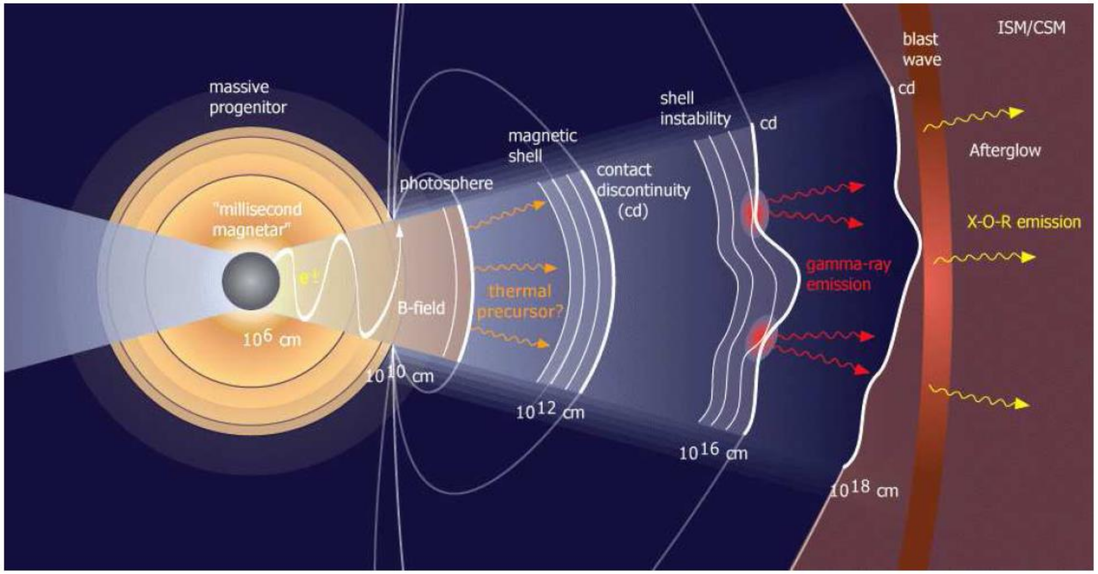




Amati et al. 2001, Frontera et al. 2000, Frontera et al. 2001, Ghirlanda et al. 2007

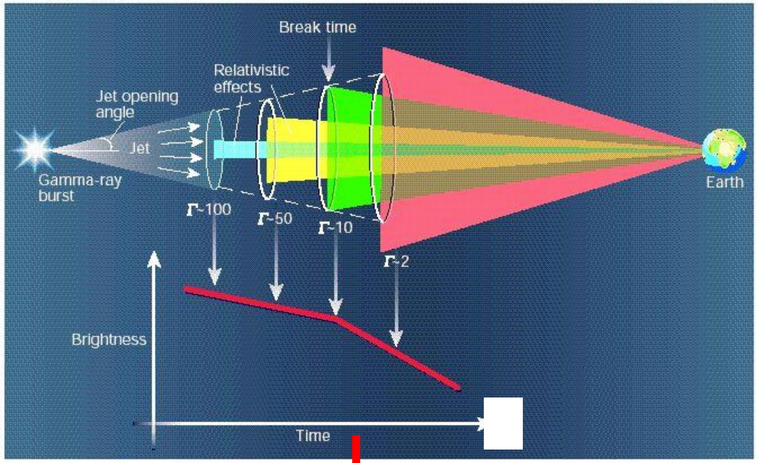
❑ Fireball nature : (baryon kinetic energy or Poynting flux dominated) and bulk Lorentz factor Γ are still to be firmly established





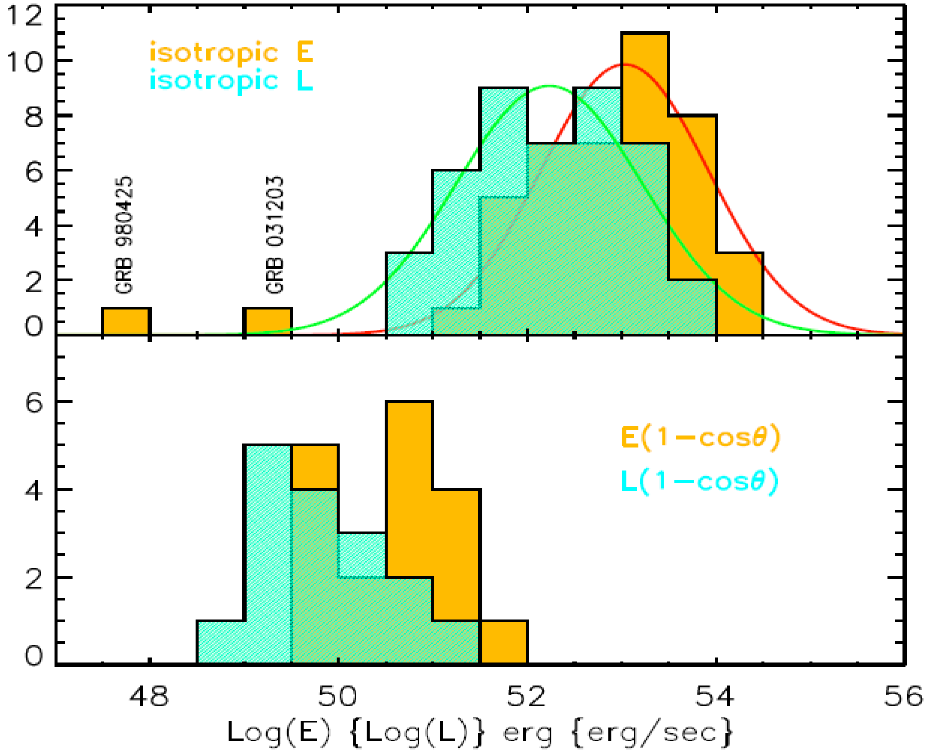
➢ *Collimated or isotropic ? The problem of missing breaks*

- ❑ 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}



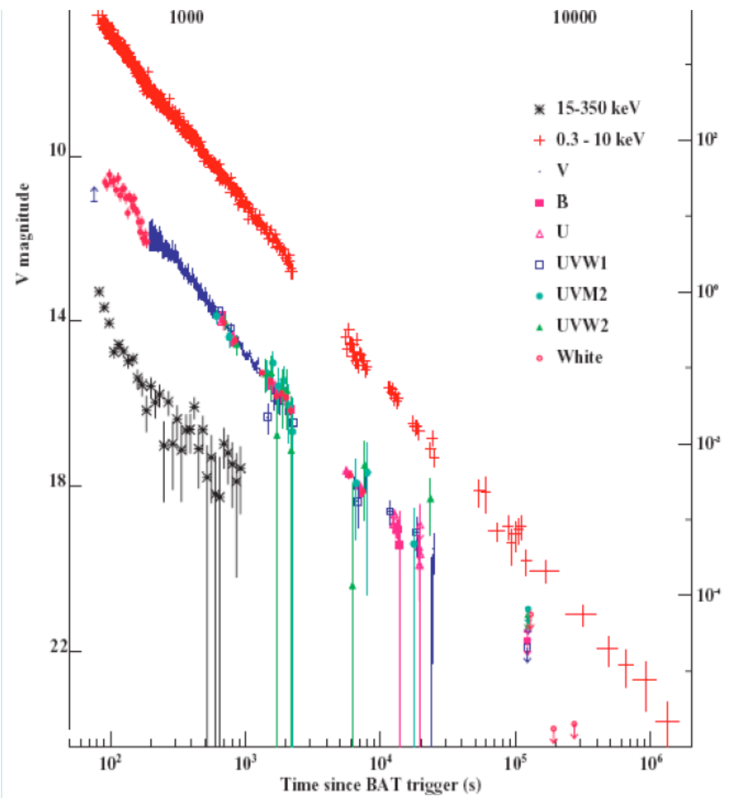
$$\theta = 0.09 \left(\frac{t_{jet,d}}{1+z}\right)^{3/8} \left(\frac{n\,\eta_\gamma}{E_{\gamma,iso,52}}\right)^{1/8}$$

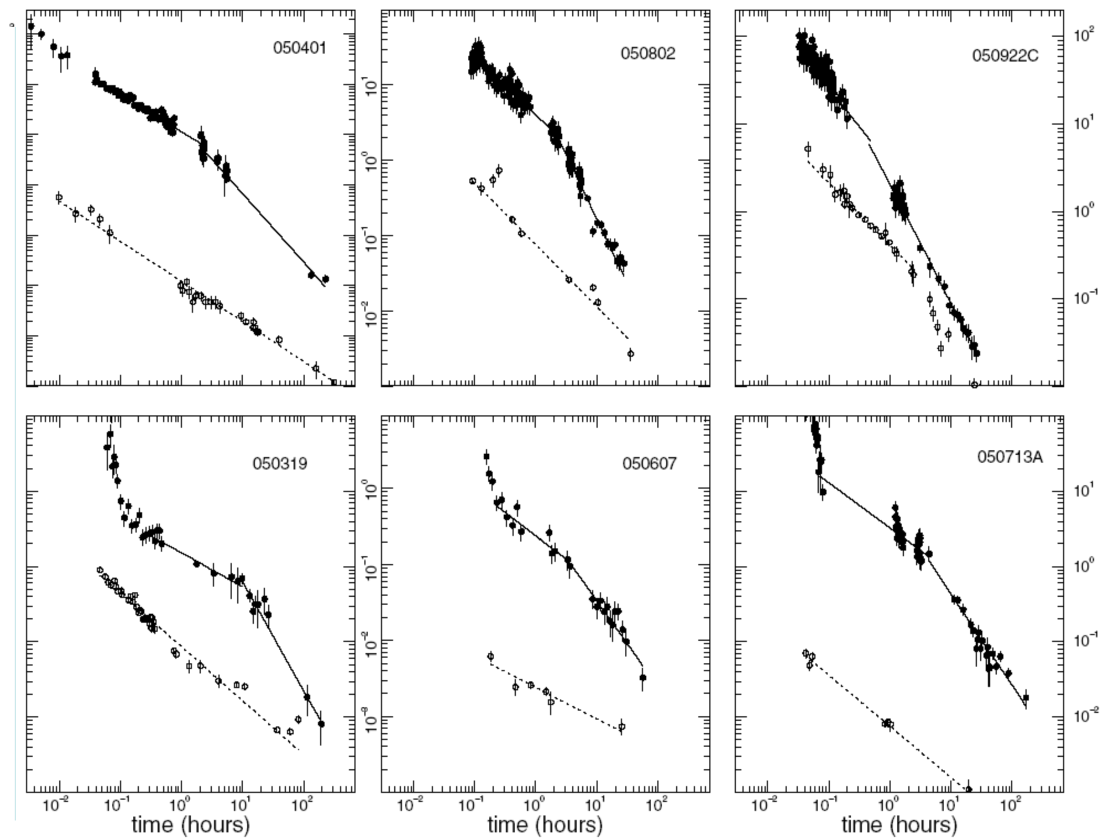
$$E_\gamma = (1-\cos\theta)E_{\gamma,iso}.$$



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
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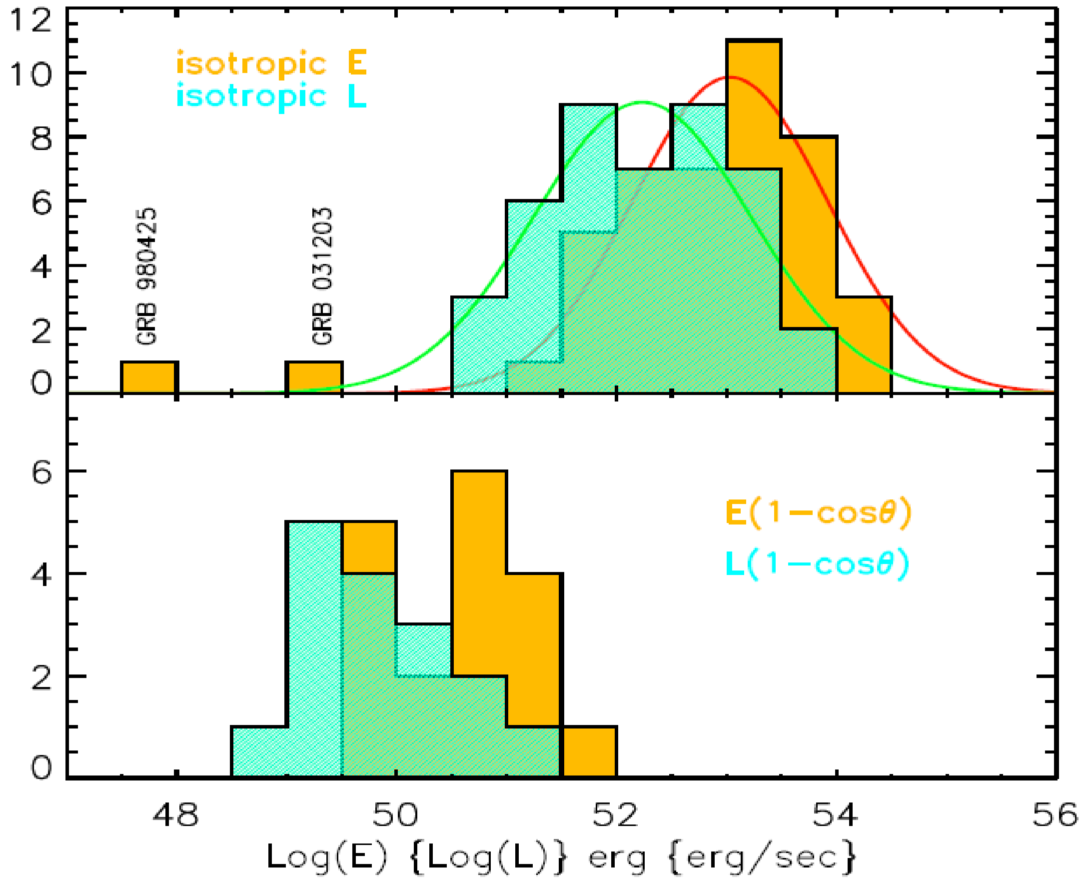
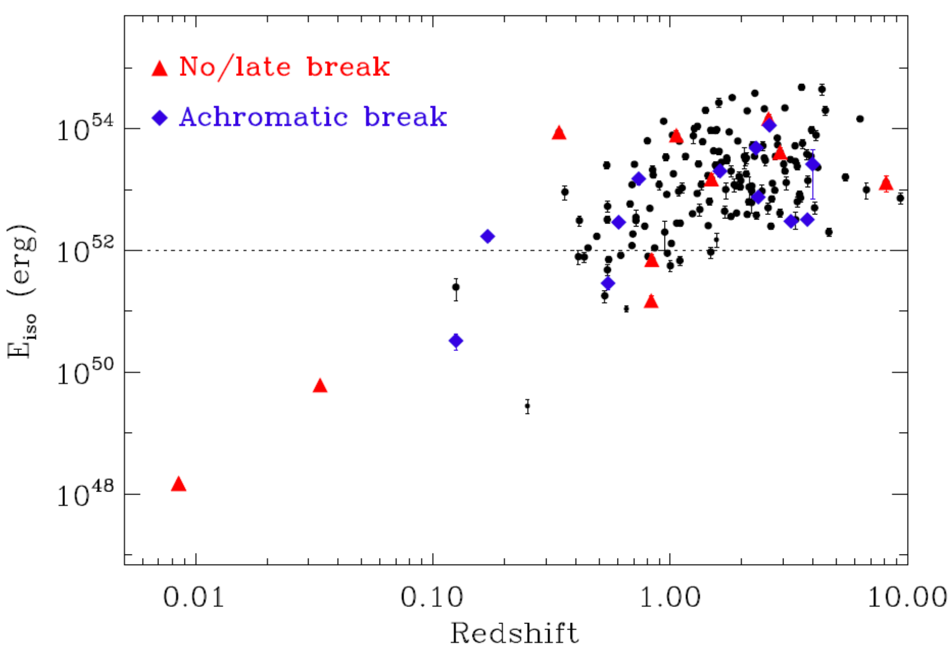
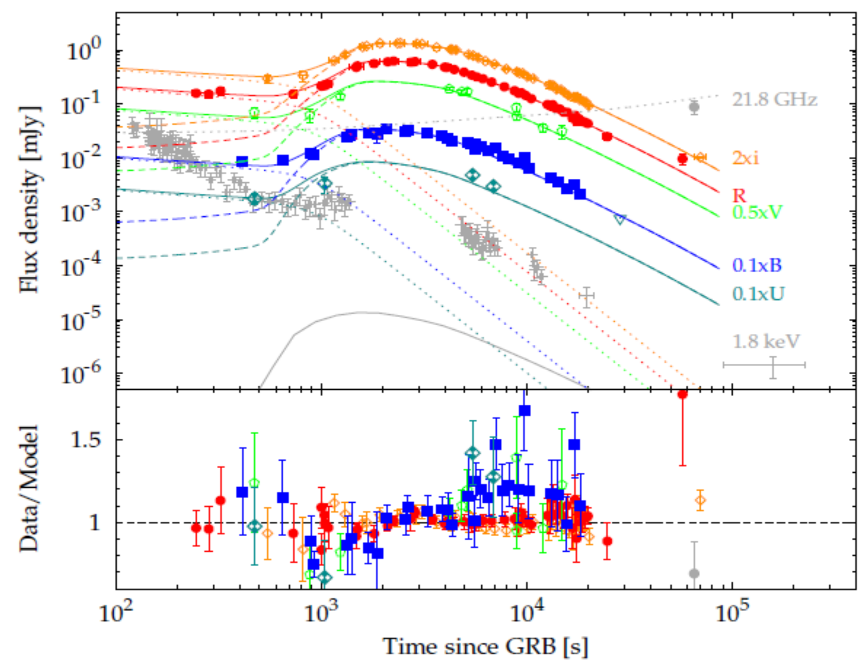


Ghirlanda et al., 2006

- 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)

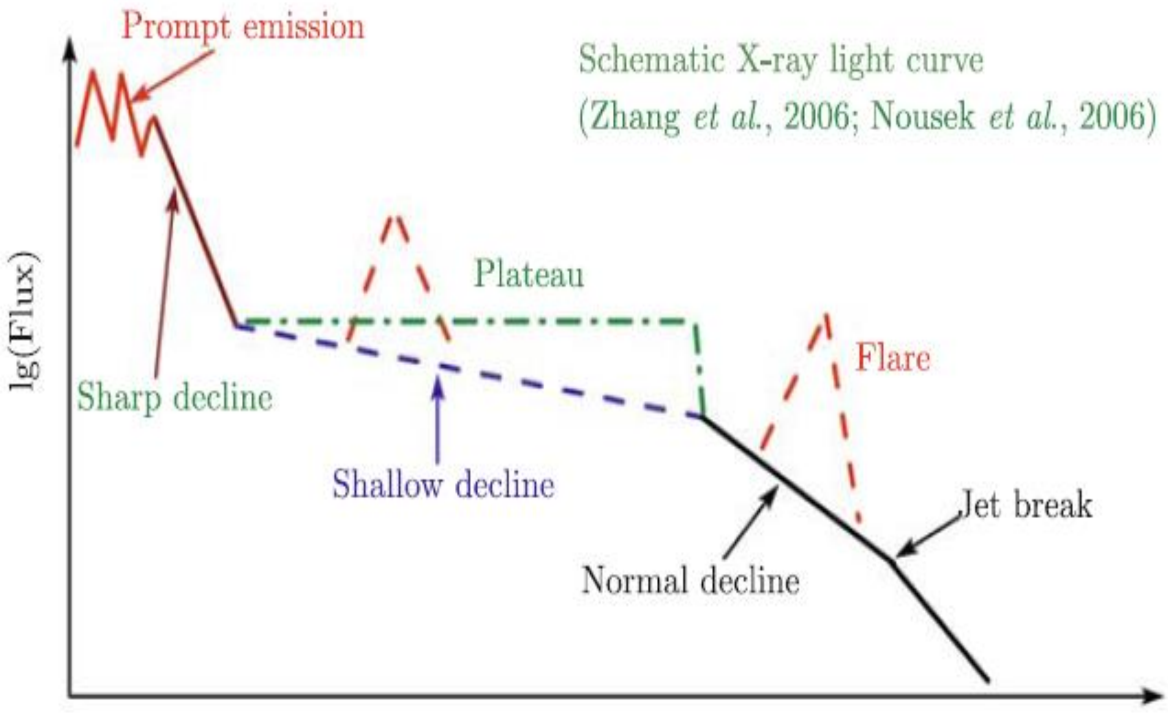




Amati 2013, Guidorzi et al. 2013

➢ *Early X-ray afterglow*

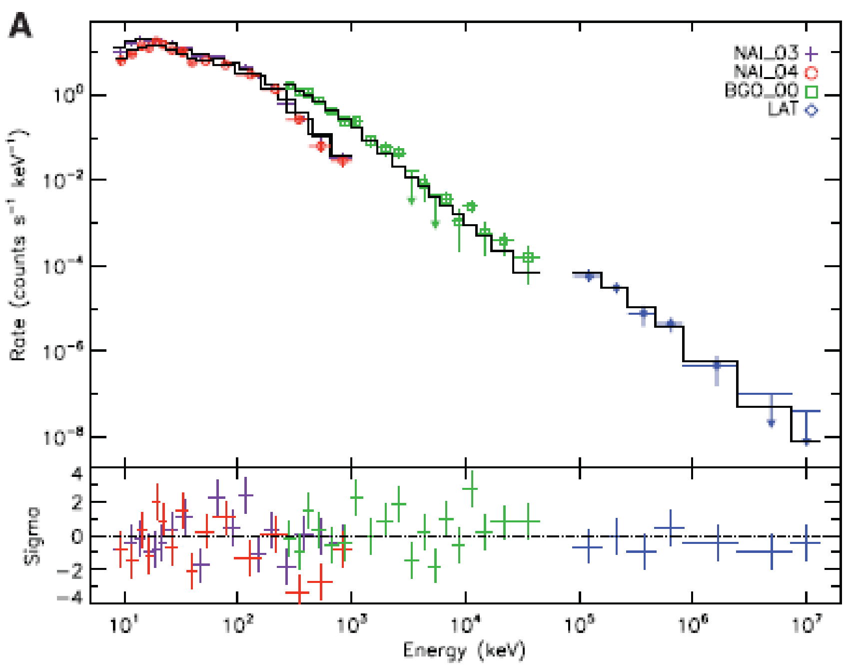
- ❑ new features seen by Swift in X-ray early afterglow light curves (initial very steep decay, early breaks, flares) mostly unpredicted and unexplained
- ❑ initial steep decay: continuation of prompt emission, mini break due to patchy shell, IC up-scatter of the reverse shock sinchrotron emission ?
- ❑ 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…

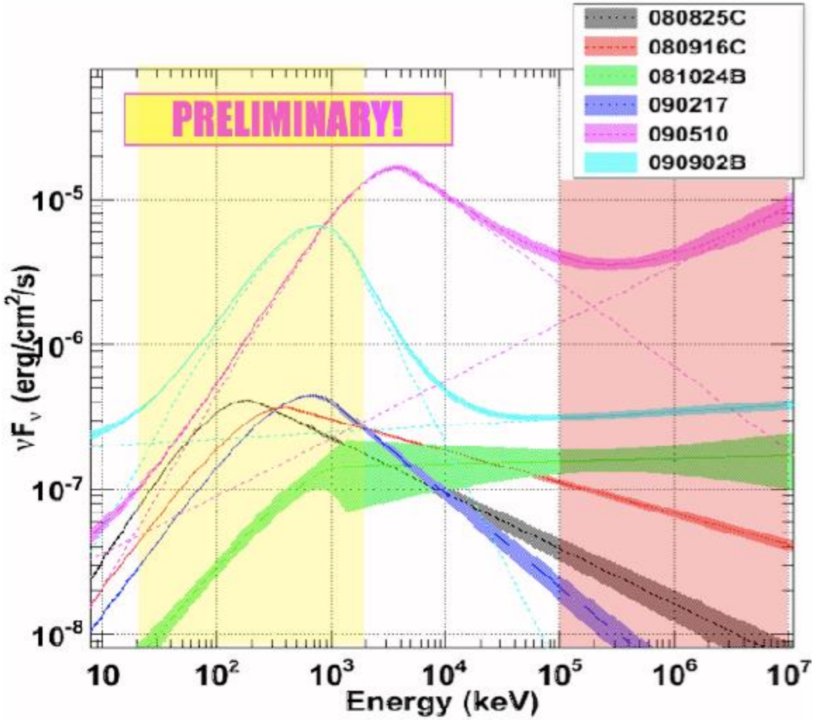


➢ VHE (> 100 MeV) properties of GRBs by Fermi and AGILE

❑ 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



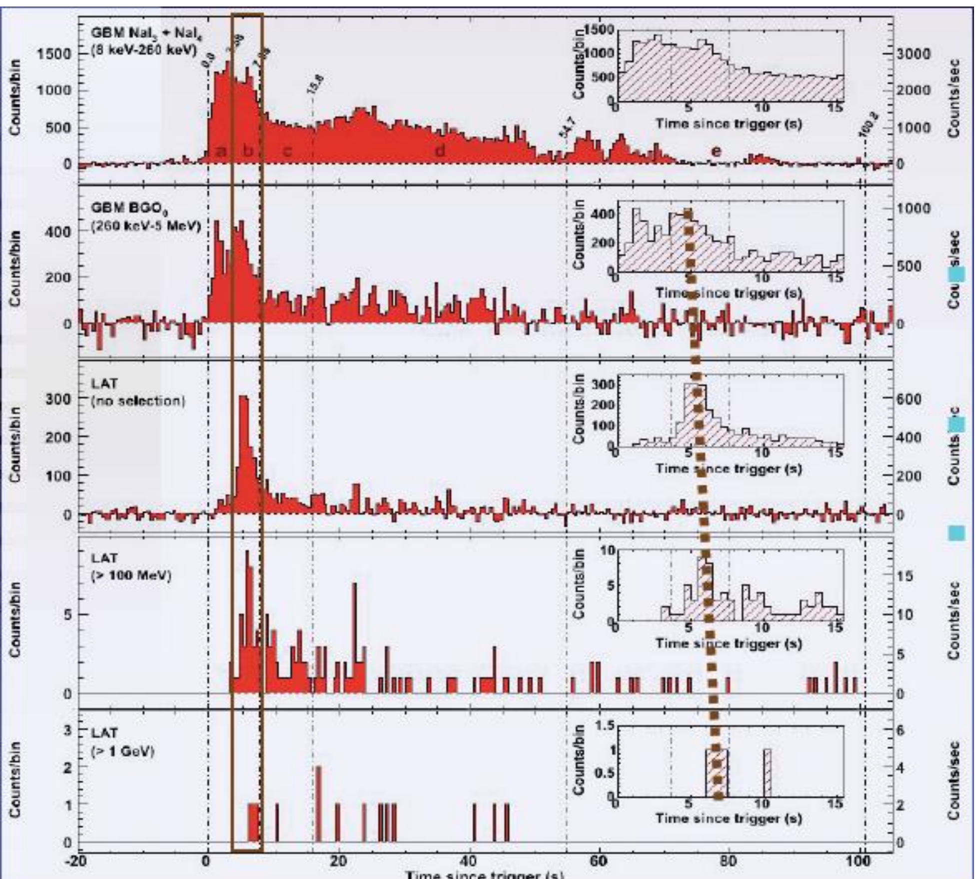


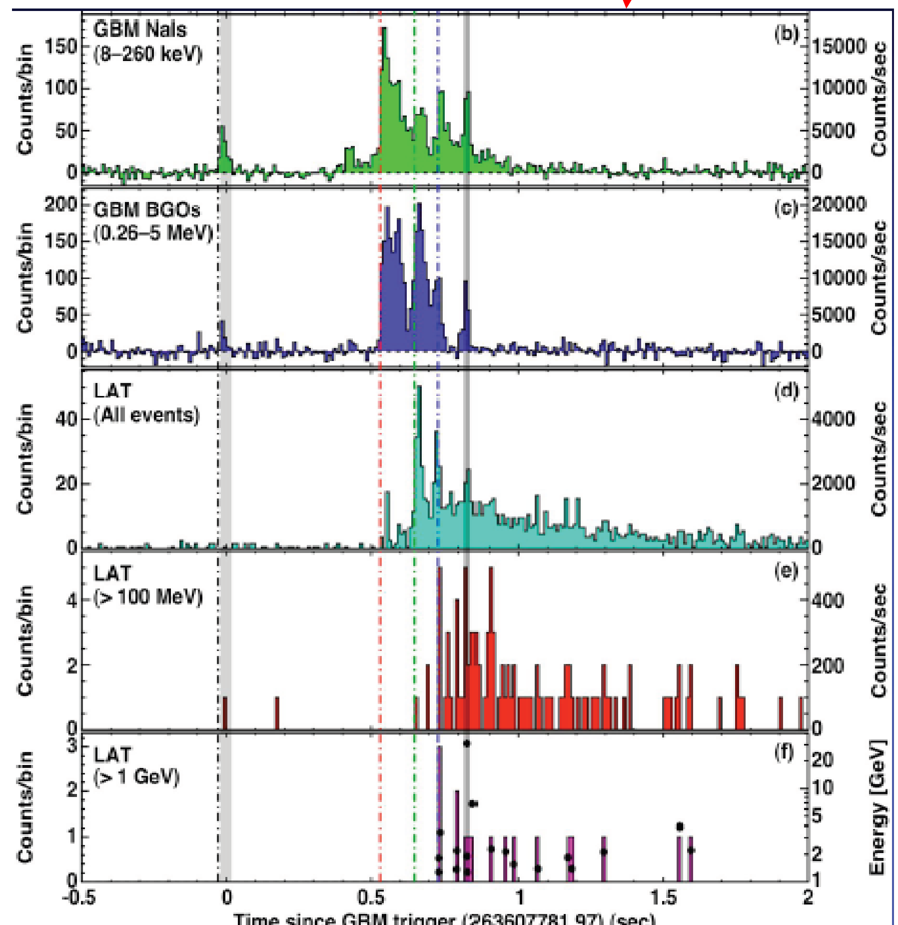
Abdo et al. 2009

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

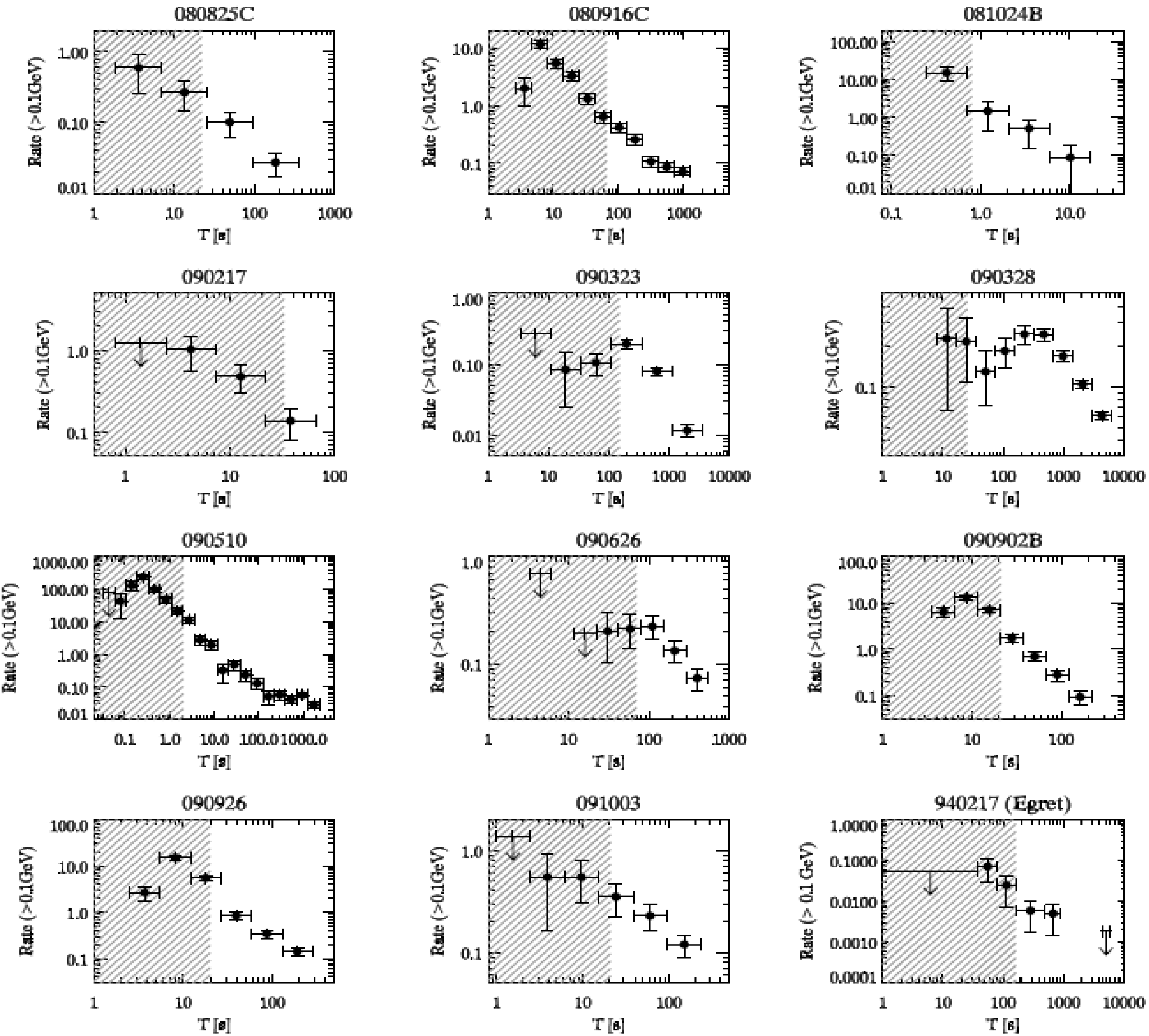
- ❑ the time delay appears to scale with the duration of the GRB (several seconds in the long GRBs 080916C and 090902B, while 0.1 − 0.2 s in the short GRBs 090510 and 081024B)

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





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



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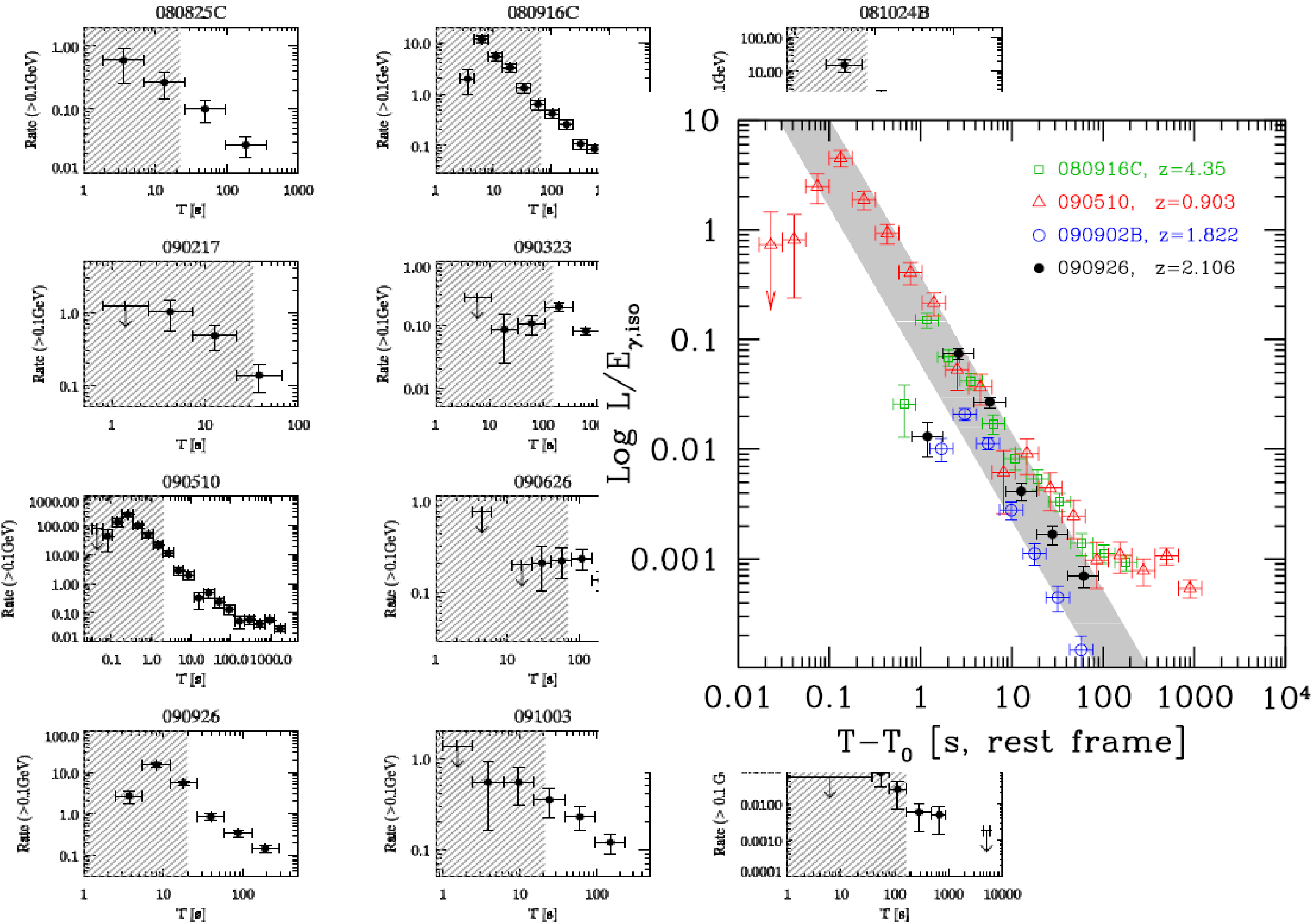
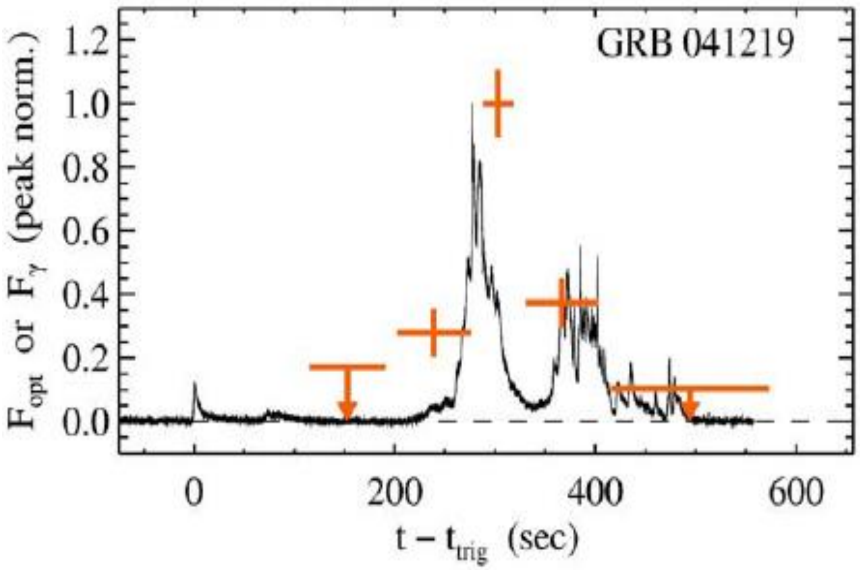
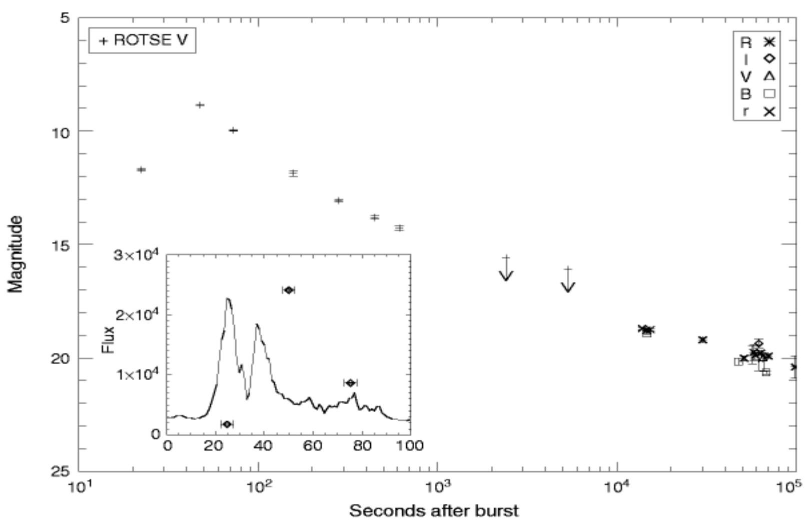
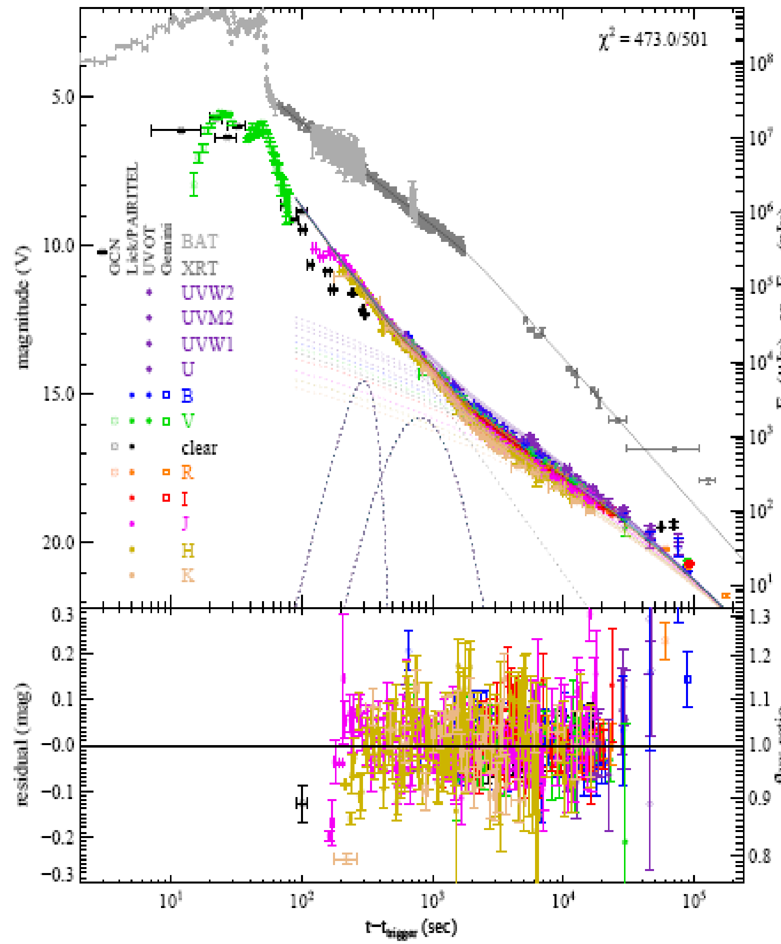


➢ *Prompt optical emission*

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







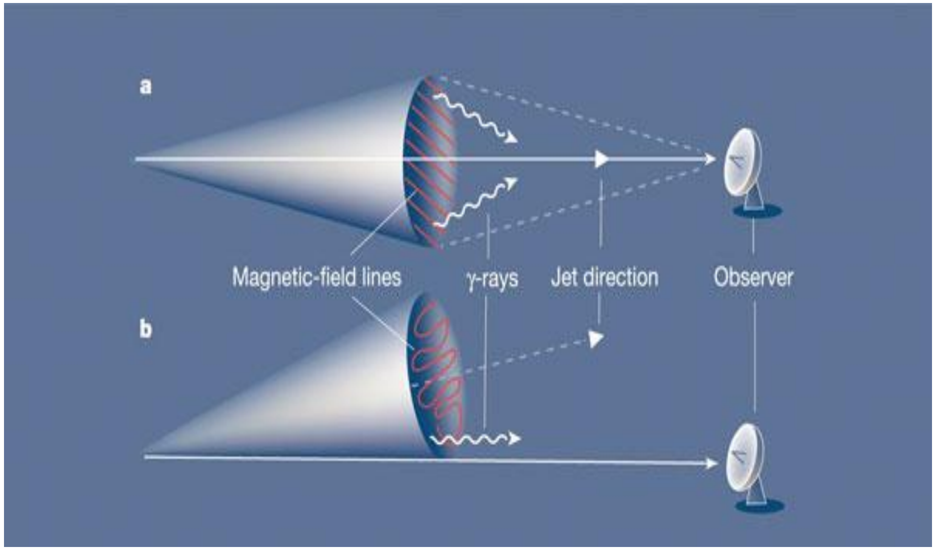
➢ *Polarization*

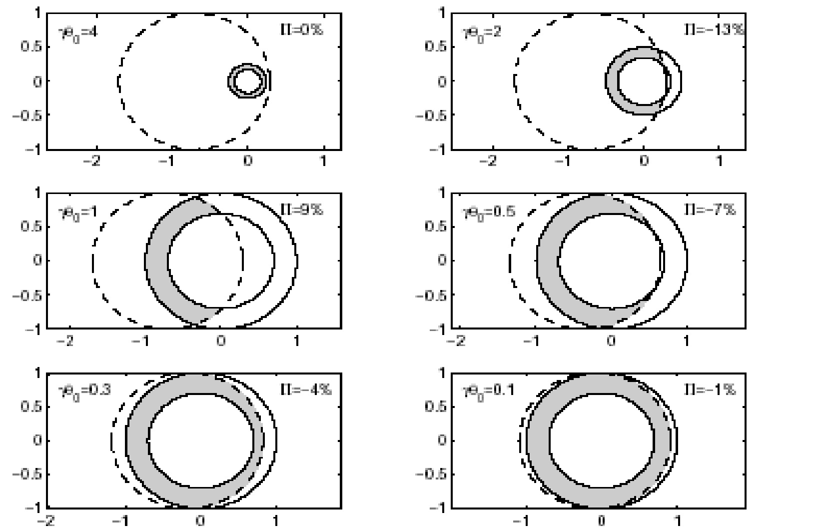
❑ until 2010, no secure detection of polarization of prompt emission (some information from INTEGRAL?), very recently measurements of 10-30% by GAP for few GRBs;

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

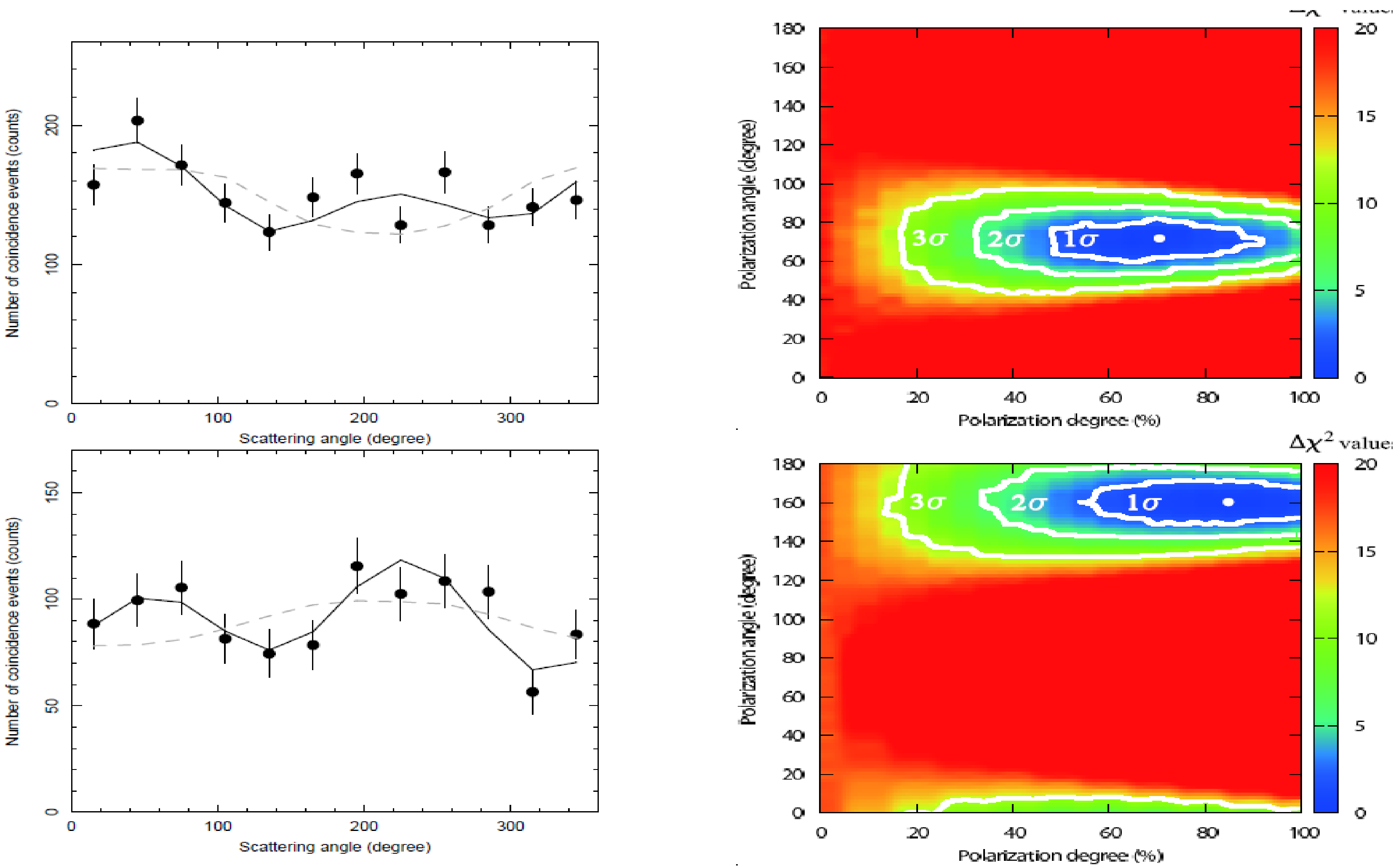
❑ radiation from synchrotron and IC is polarized, but a high degree of polarization can be detected only if magnetic field is uniform and perpendicular to line of sight

❑ 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





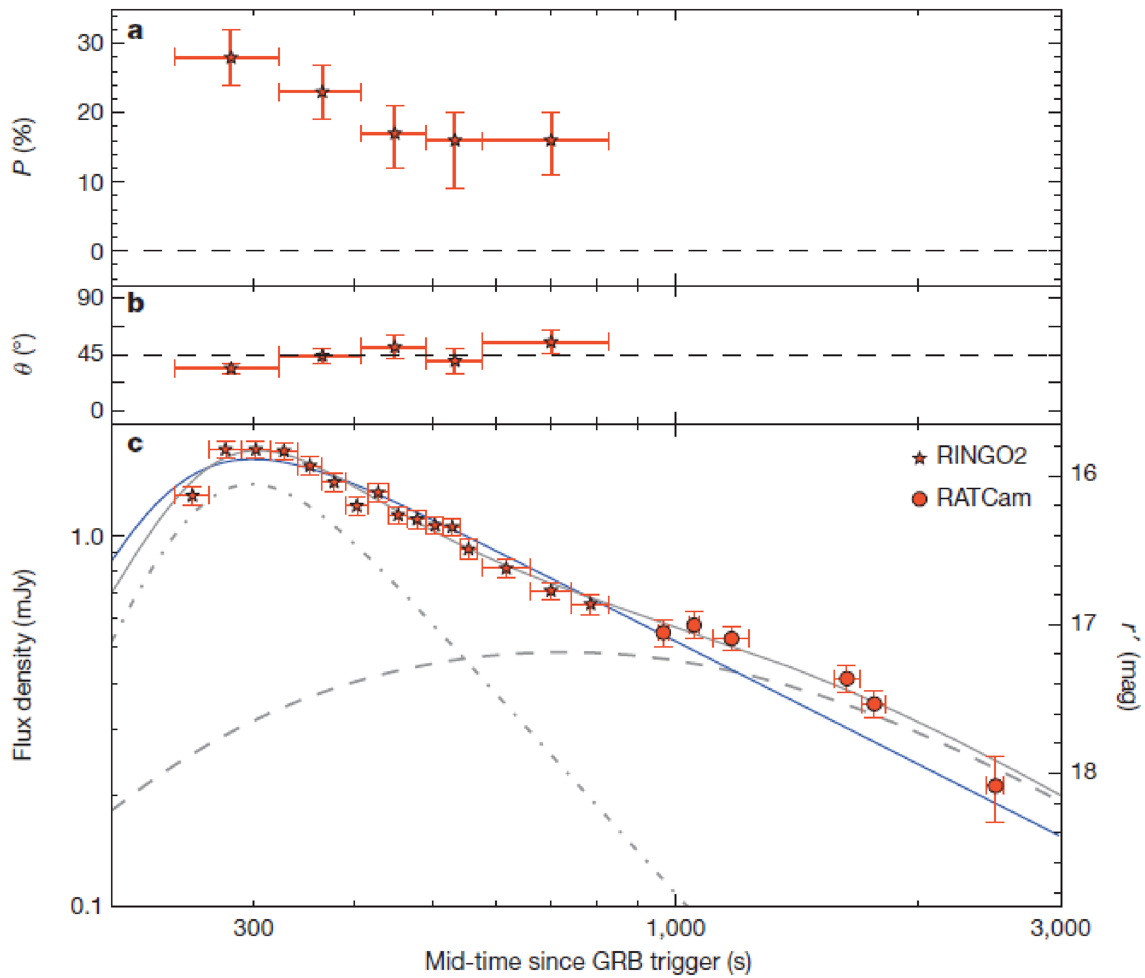
❑ high degree of linear polarization of prompt emission of GRB100826A, GRB110301A and GRB110721A recently measured by GAP (Yonetoku et al. 2011, 2012): confirmation of synchrotron against thermal ? Globally ordered magnetic fields advected by central engine ?



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

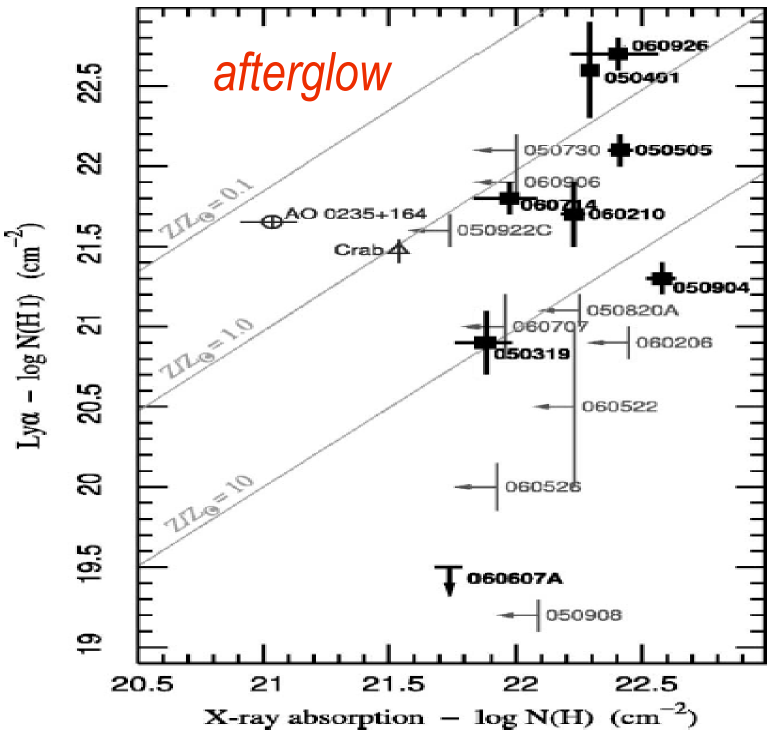


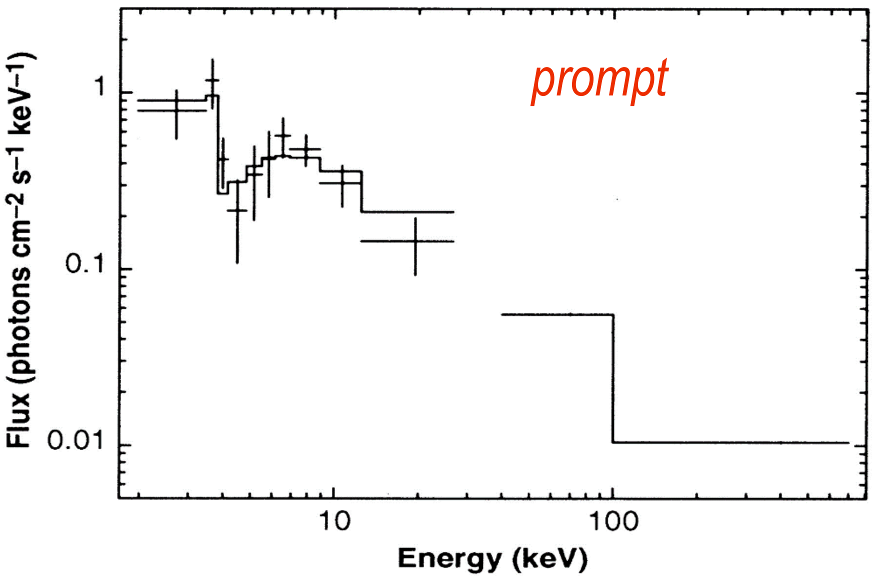
➢ *Circum-burst environment*

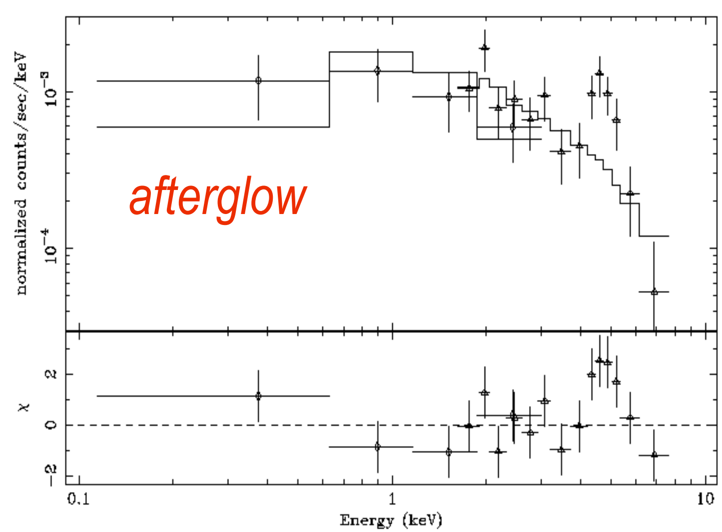
- ❑ evidence of overdense and metal enriched circum-burst environment from absorption and emission features

- ❑ 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)

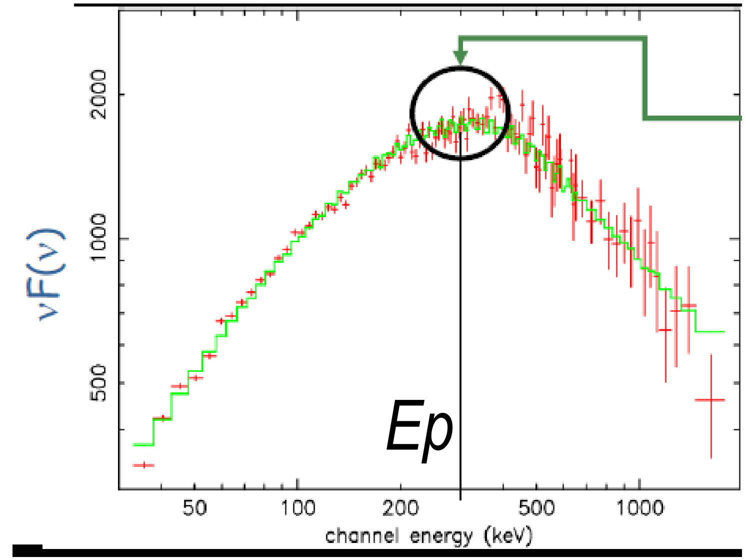




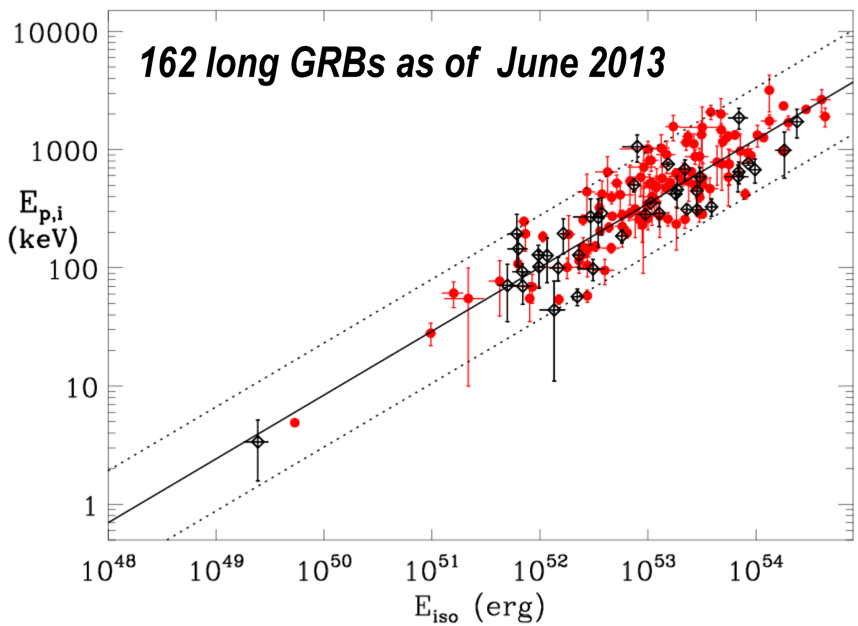


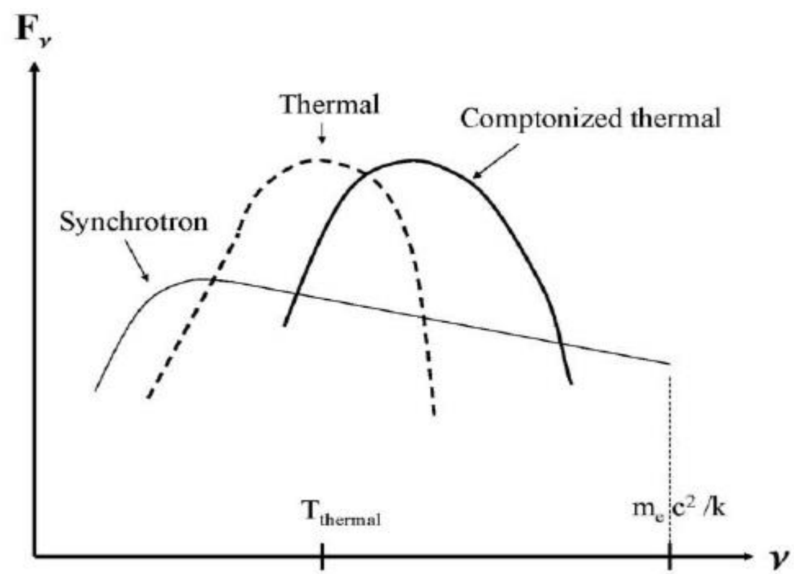
Amati et al. 2000, Watson et al. 2007, Antonelli et al. 2000

➢ *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

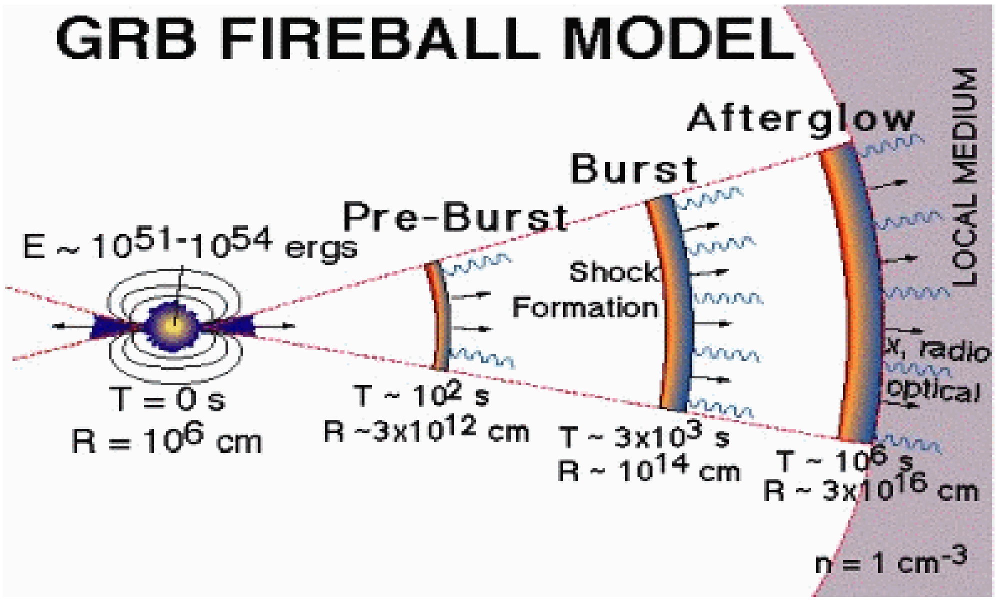


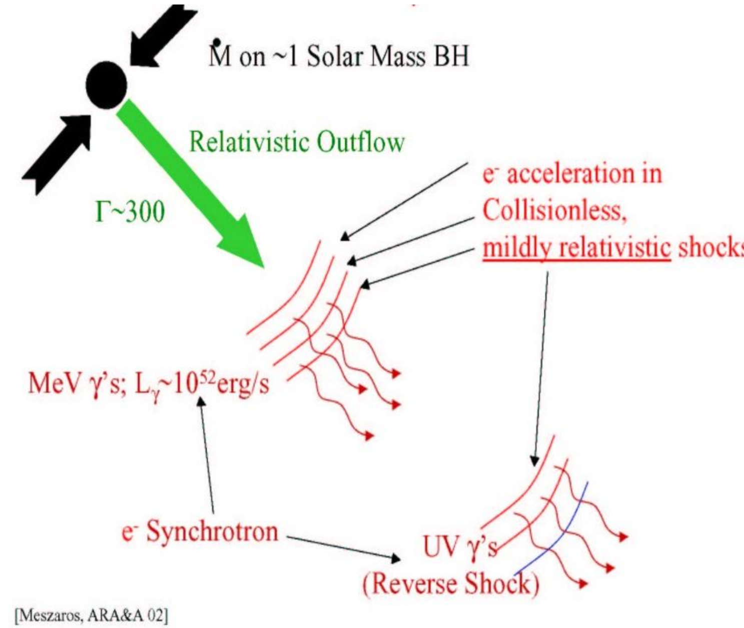


Amati et al. 2002 - 2009

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

➢ **Ep is a fundamental parameter in GRB prompt emission models**





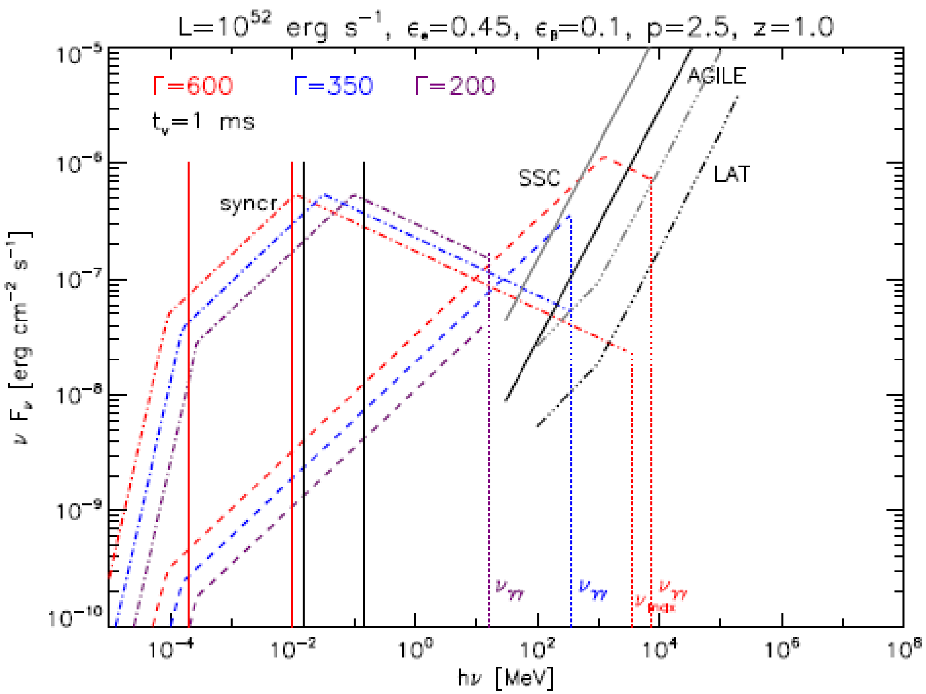
➢ ms time variability + huge energy + detection of GeV photons -> plasma occurring ultra-relativistic (Γ > 100) expansion (fireball or firejet)

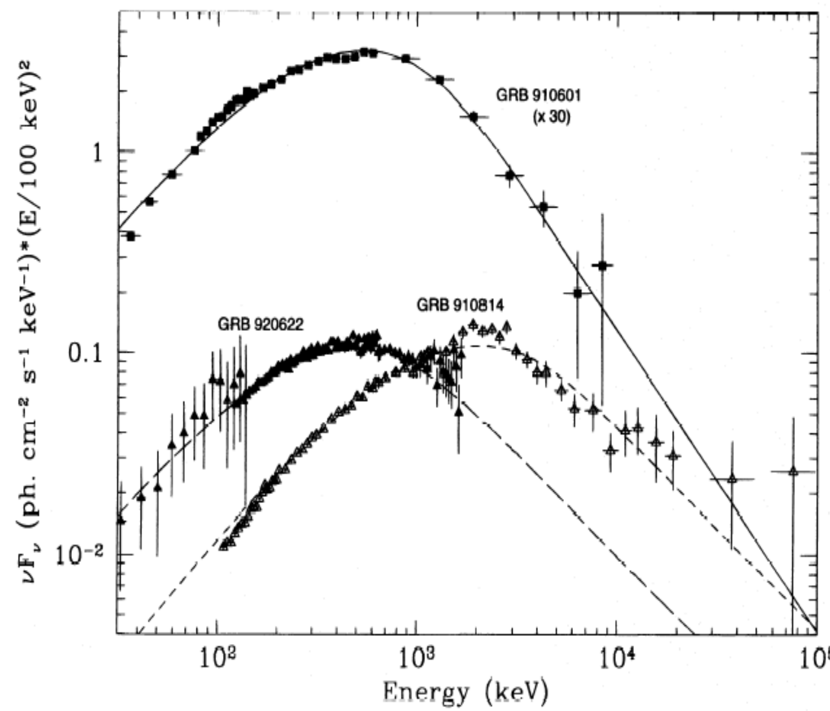
➢ non thermal spectra -> shocks synchrotron emission (SSM)

➢ 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

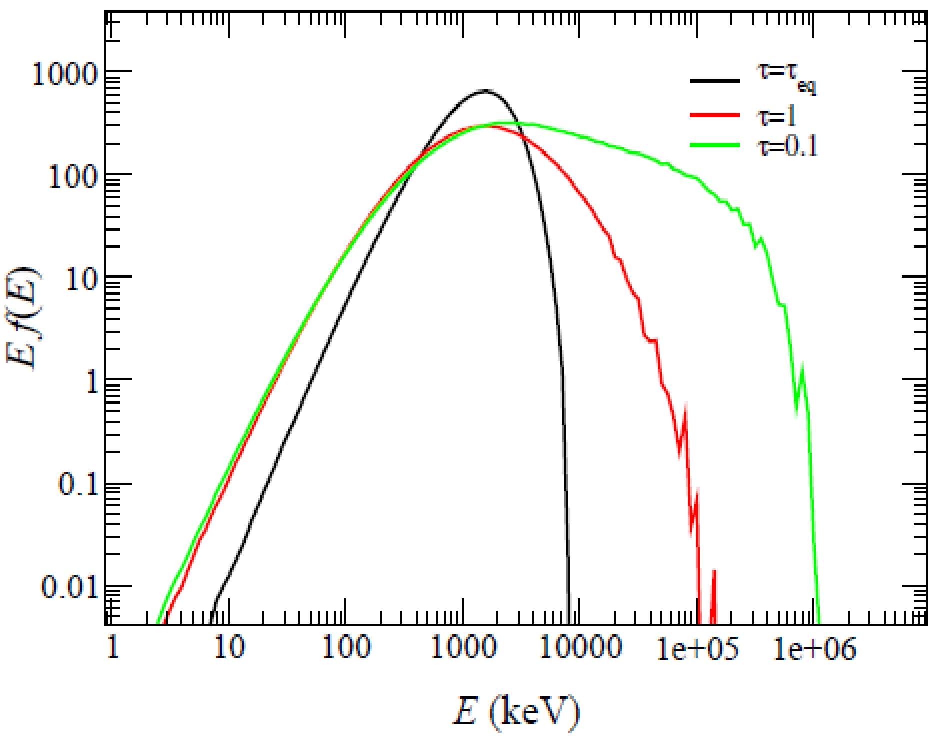




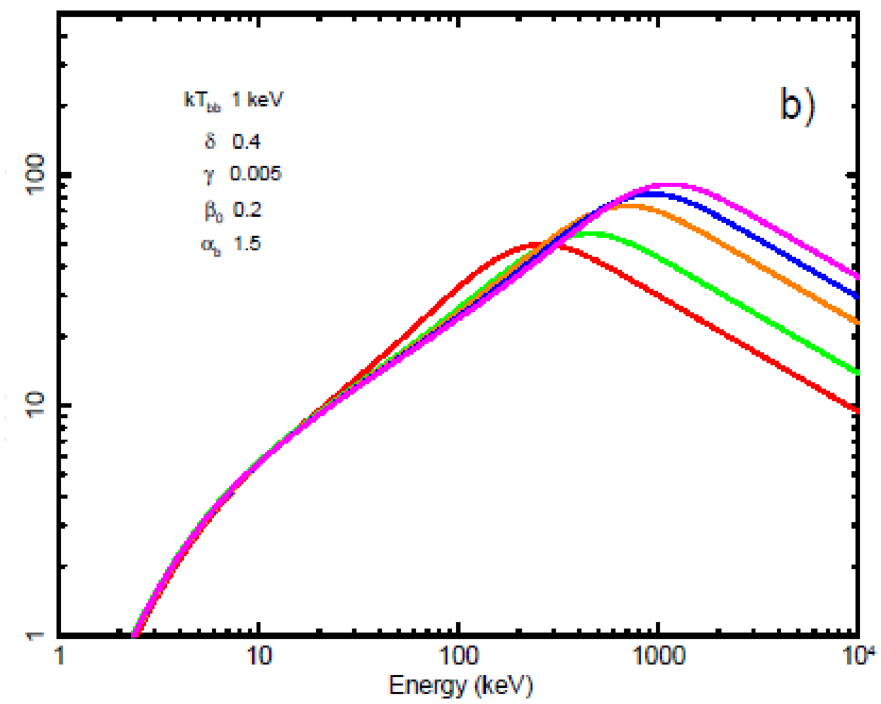
Galli & Guetta 2007

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)



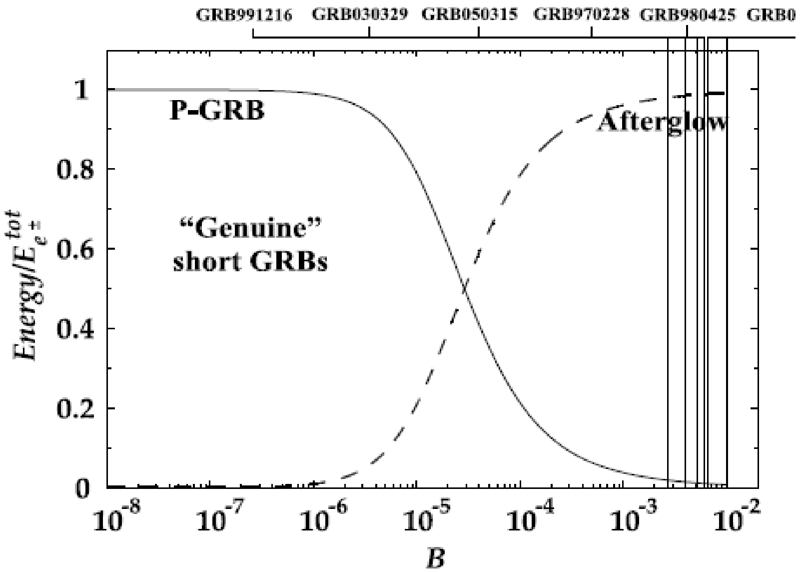
Giannios 2012

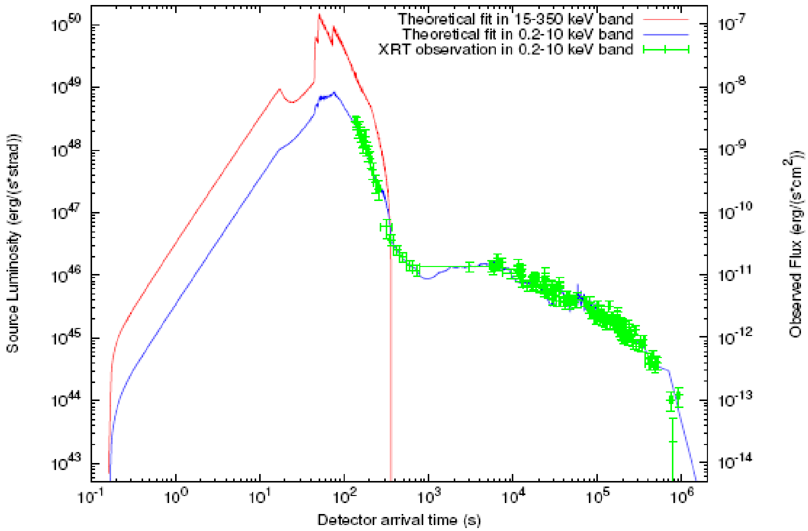


Titarchuk et al., ApJ, 2012

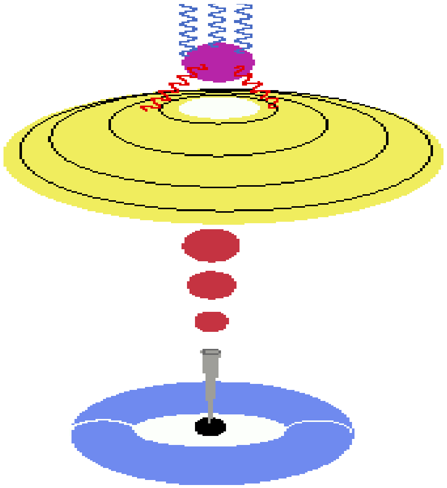
➢ *Alternative scenarios*

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





❑ CannonBall (CB) (Dar et al.)

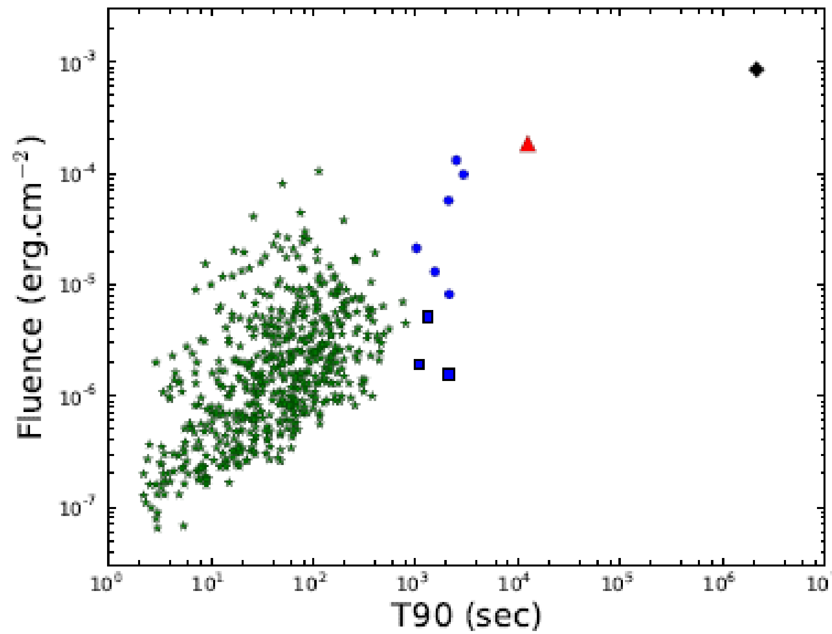


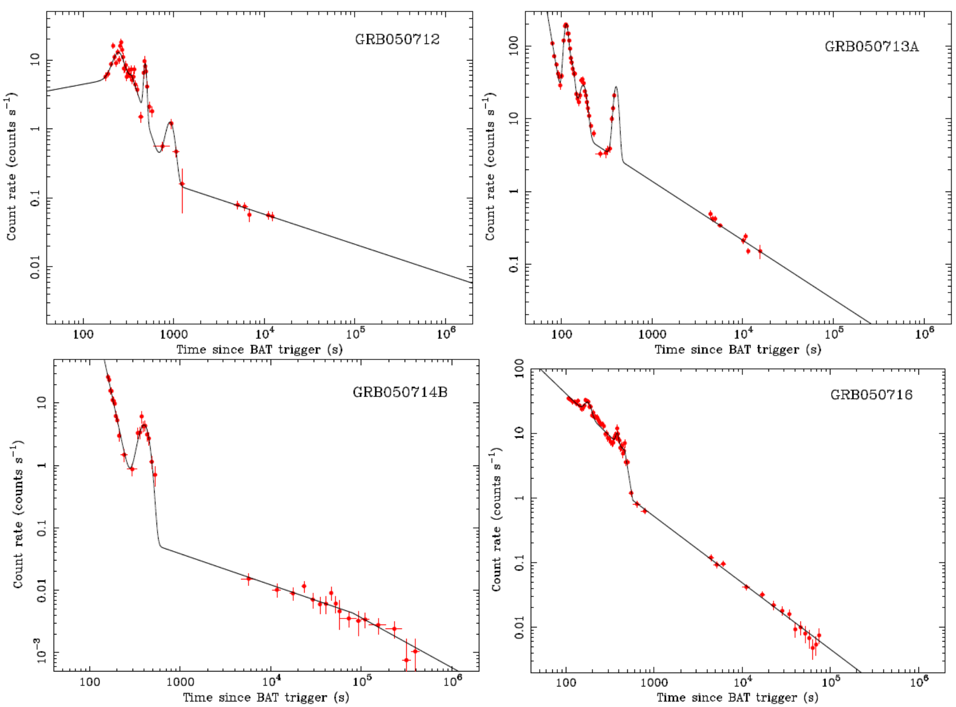
❑ Precessing jet (Fargion et al.), stochastic wakefield plasma acceleration (Barbiellini et al.), ns-quark star transition, …

❑ Short GRB as SGR giant outbursts

➢ *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

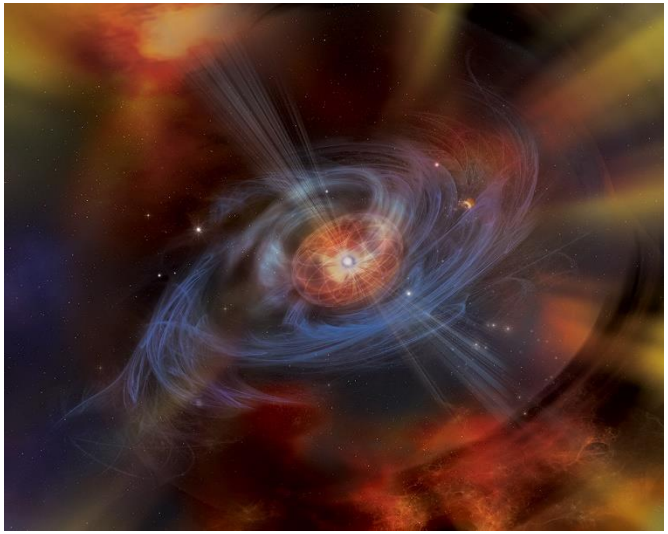


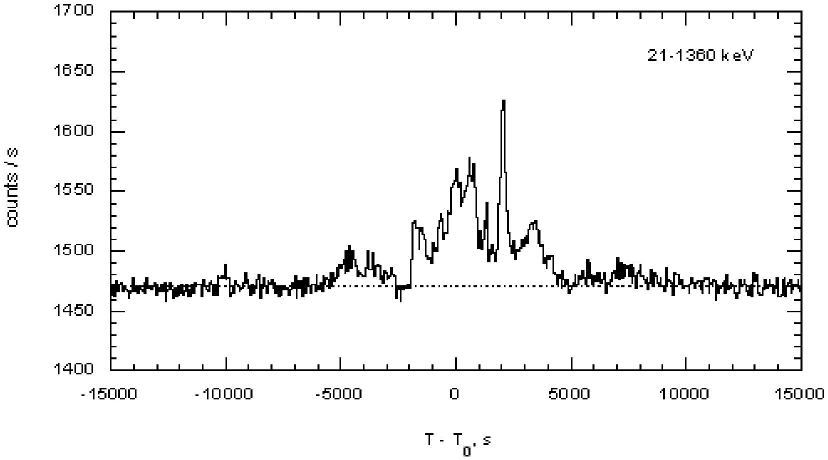


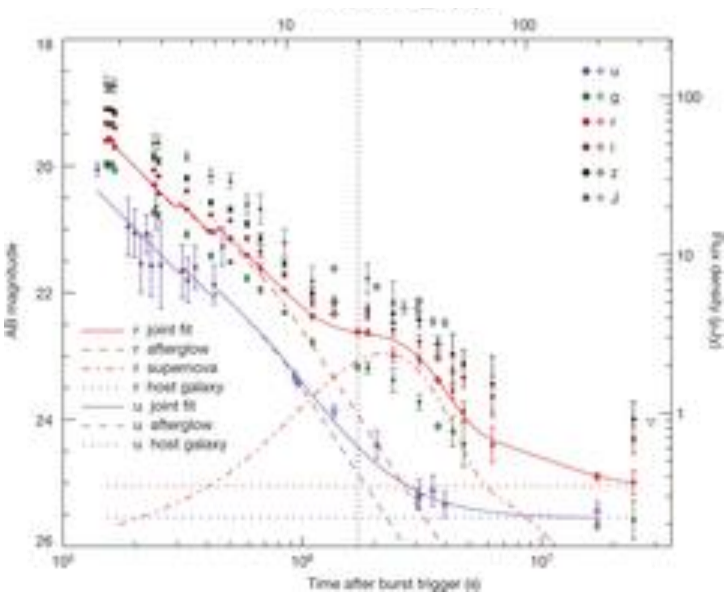
FROM GENDRE ET AL. (2013) UPDATED FROM LEVAN ET AL. (2013) WHEN APPLICABLE.

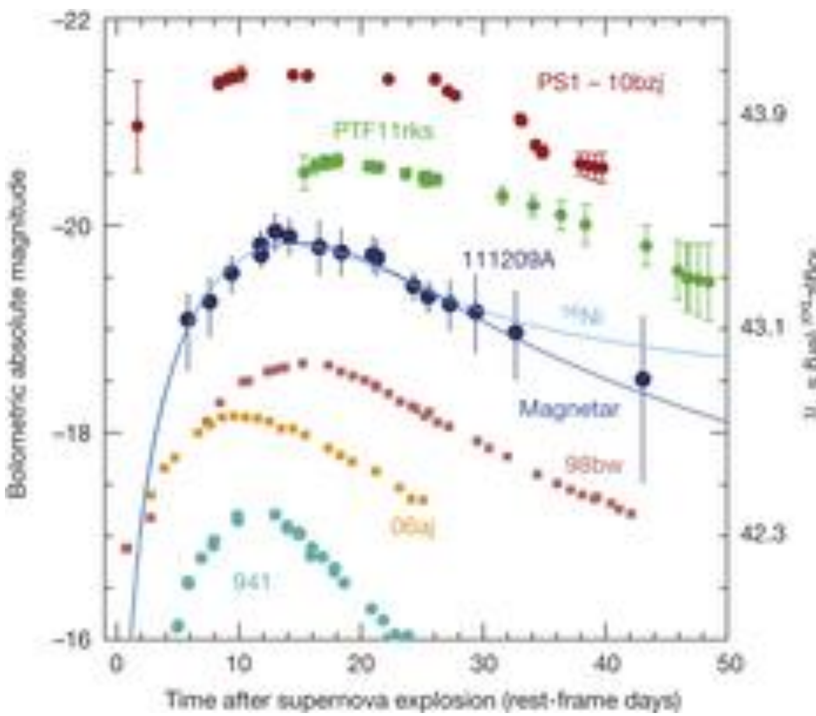
Quantity	E_p (keV)	E_{iso} (10^{51} erg)	Fluence (erg cm^{-2})	Duration (T90, s)	Distance (redshift)	Reference
GRB 971208	144	n.a.	2.6×10^{-4}	2500	n.a.	Pal'Shin et al. (2008)
GRB 020410	n.a.	n.a.	2.8×10^{-5}	1550	n.a.	Nicastro et al. (2004)
GRB 060218	4.9	0.062	1.7×10^{-5}	2100	0.0331	Campana et al. (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 ?





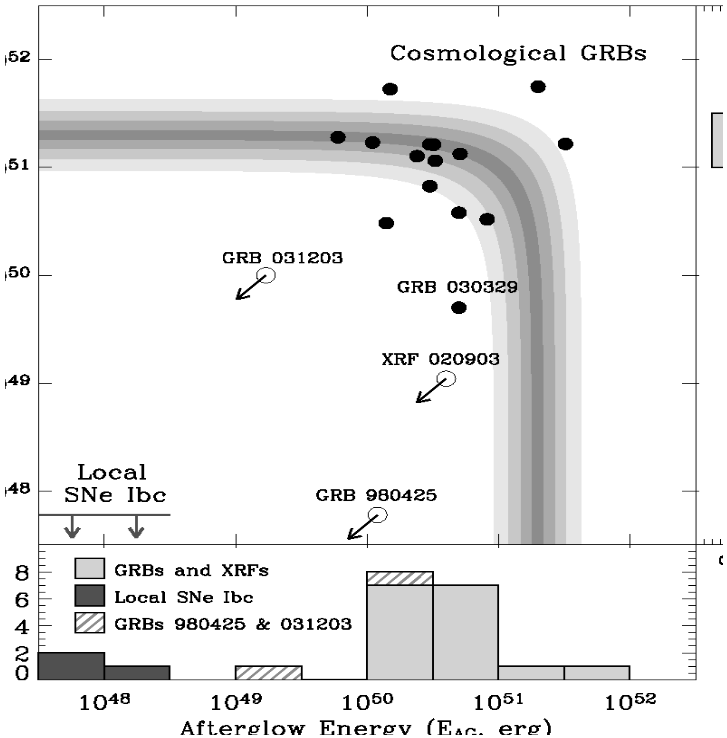


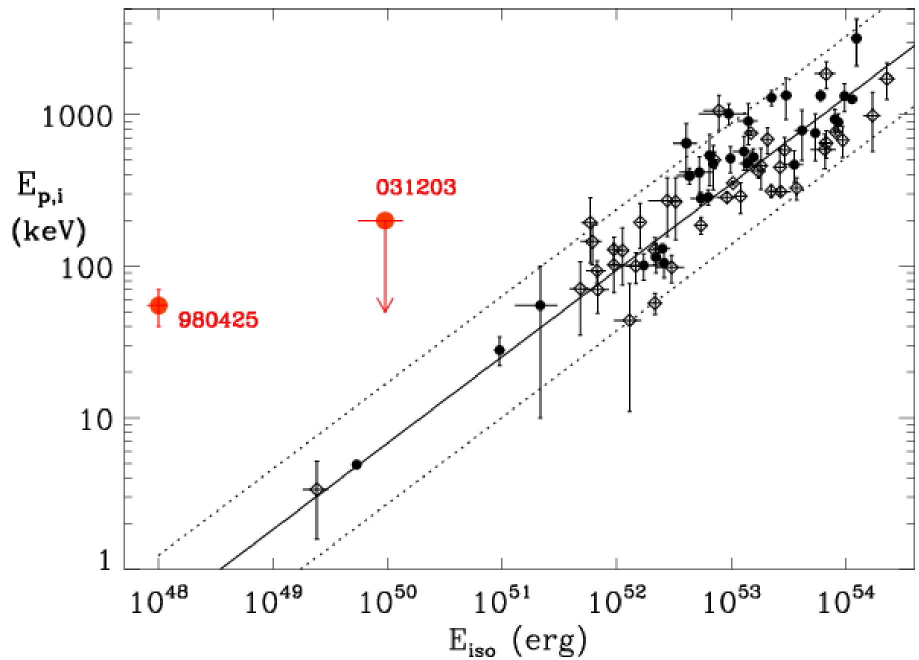


➢ *Sub-energetic GRBs*

❑ 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

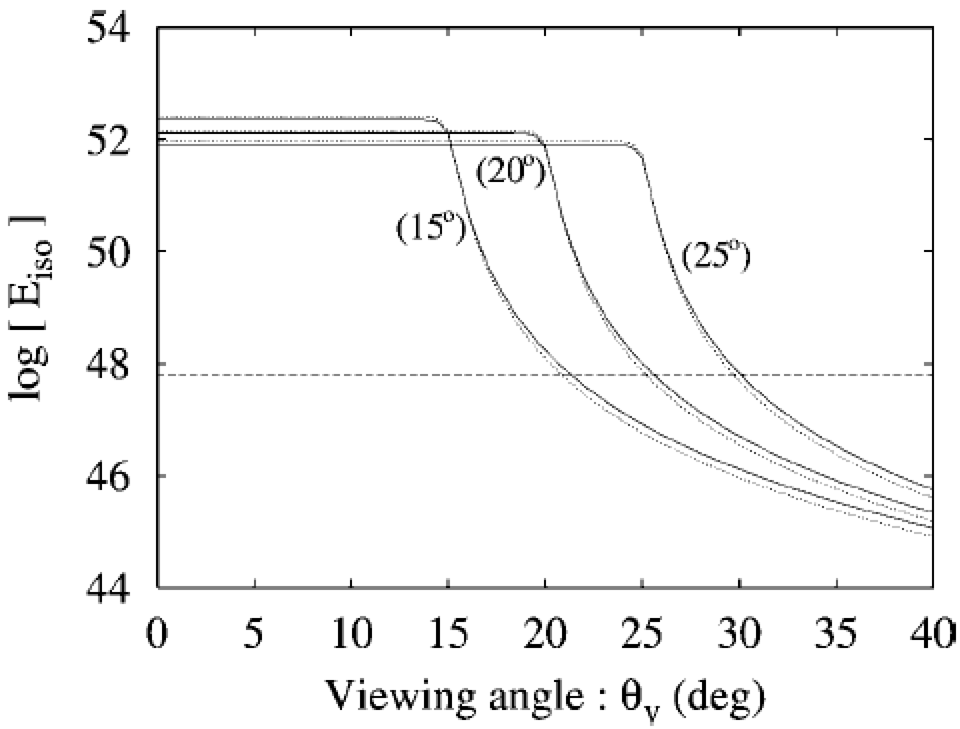


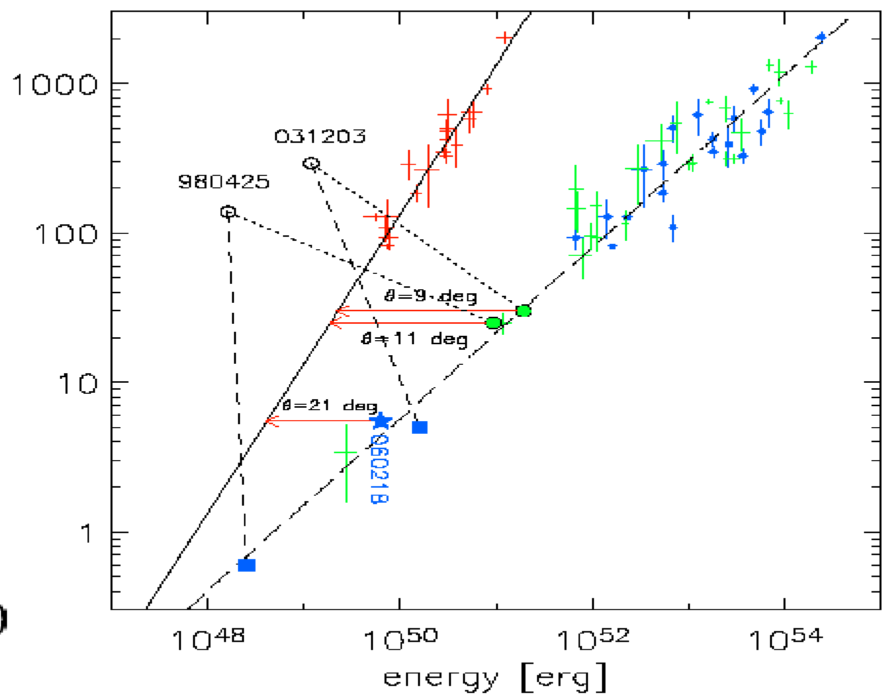


Soderberg et al. 2006

- 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)
- $\delta=[\gamma(1 - \beta\cos(\theta v - \Delta\theta))]^{-1}$, $\Delta Ep \propto \delta$, $\Delta Eiso \propto \delta^{(1+\alpha)}$

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



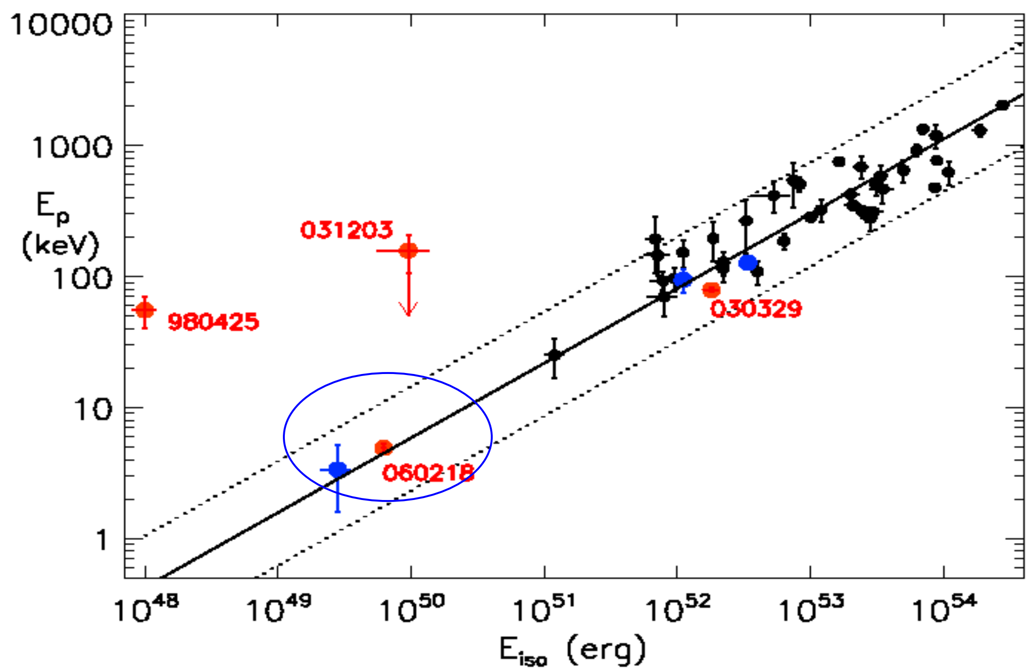


Yamazaki et al., ApJ, 2003

- 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

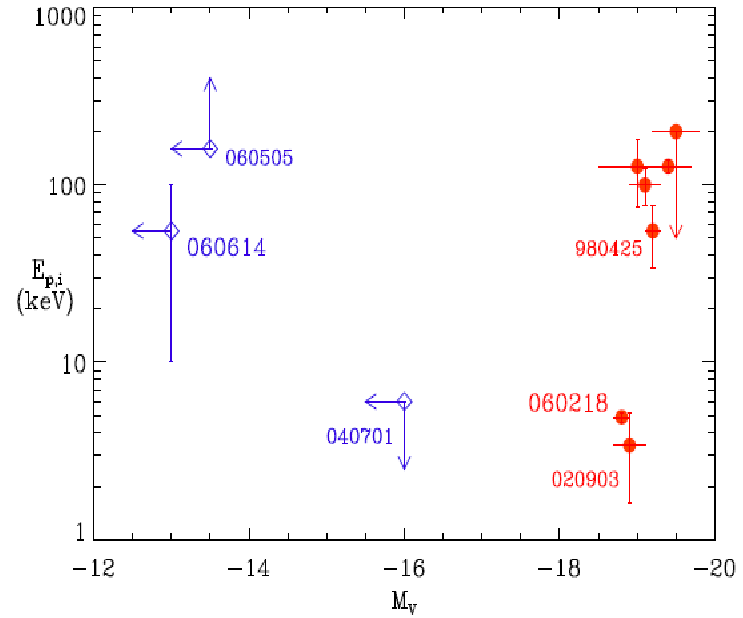
- also XRF 020903 is very weak and soft (sub-energetic GRB prompt emission) and is consistent with the Ep-Eiso correlation



Amati et al., 2007

➢ GRB/SN connection

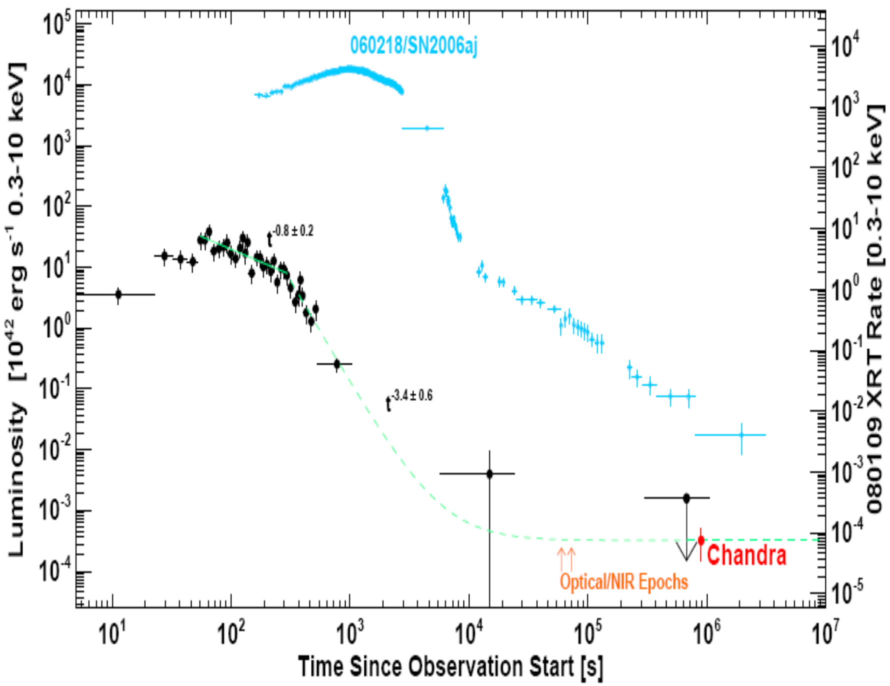
- are all long GRB produced by a type Ibc SN progenitor ?
- which fraction of type Ibc SN produces a GRB, and what are their peculiarities ?
- are the properties (e.g., energetics) of the GRB linked to those of the SN ?
- long GRBs with no (or very faint) associated SNe



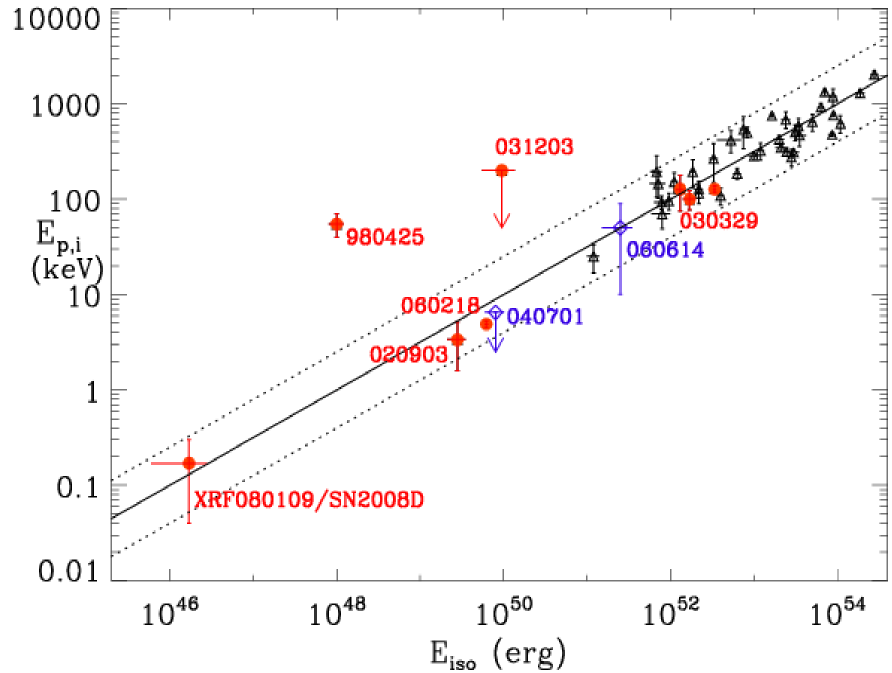
GRB/SN	z	$E_{p,i}$ (keV)	E^{iso}_{prompt} (10^{50} erg)	θ_{jet} (deg)	E^{jet}_{prompt} (10^{50} erg)	SN $E^{iso(a)}_{K}$ (10^{50} erg)	SN peak mag
980425/SN 1998bw	0.0085	55±21	0.01±0.002	-	<0.012	200-500	M_V=−19.2±0.1
060218/SN 2006aj	0.033	4.9±0.3	0.62±0.03	>57	0.05–0.65	20–40	M_V=−18.8±0.1
031203/SN 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 ~ −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 ~ −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 >~ −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 ?



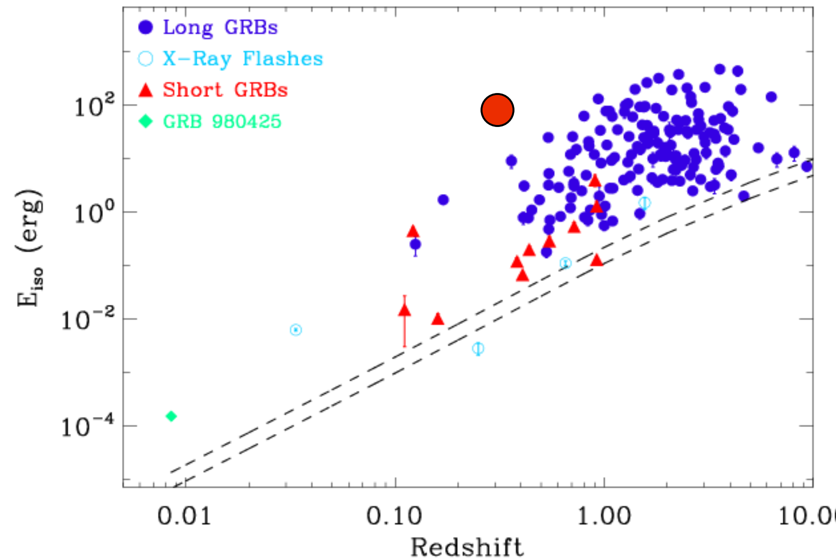
Modjaz et al., ApJ, 2008

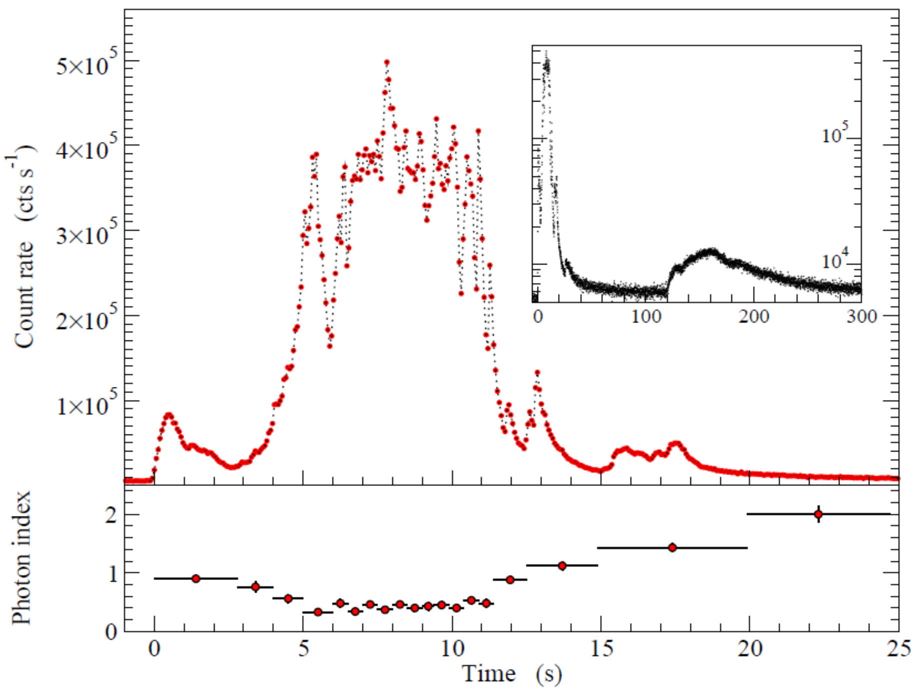


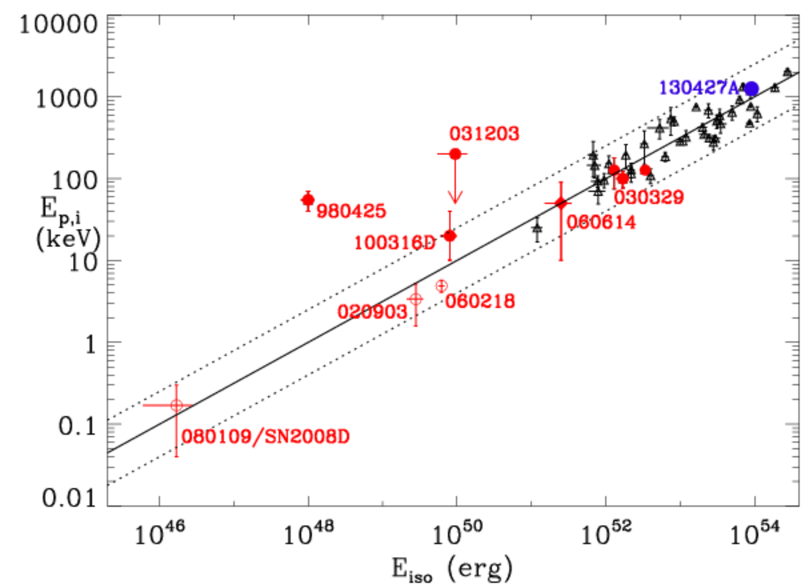
Amati, 2008, this workshop

GRB 130427A: a Nearby Ordinary Monster

- An unusually "nearby" very energetic GRB ($z=0.34$, Eiso ~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







➤ *Fundamental physics with GRBs*

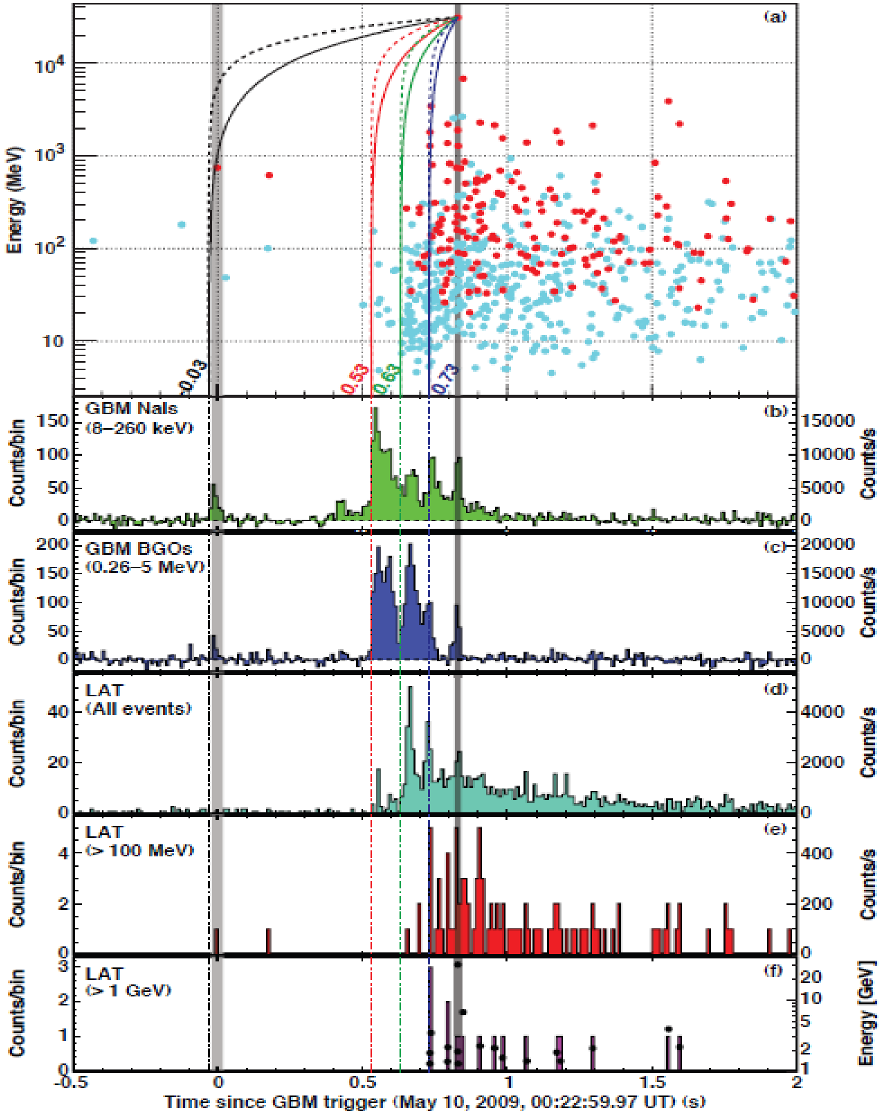
❑ Using time delay between low and high energy photons to put Limits on Lorentz Invariance Violation (allowed by unprecedent Fermi GBM + LAT broad energy band)

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

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

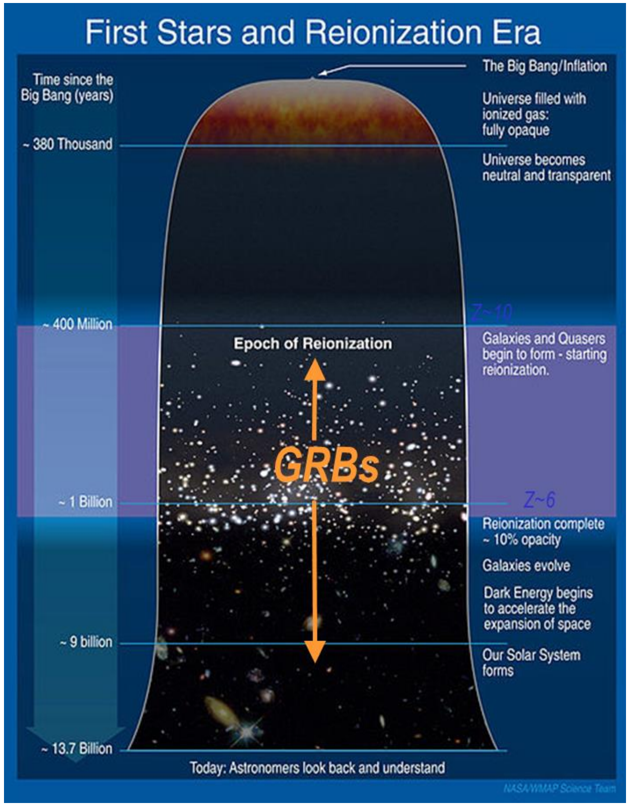
GRB 990510 $E_h = 30.53^{+5.79}_{-2.56}$ GeV

$t_{\rm start}$ (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
$\lvert\frac{\Delta t}{\Delta E}\rvert < 30\ \frac{\rm ms}{\rm GeV}$		lag analysis of all LAT events	—	±1	> 1.22



➢ GRB as cosmological tools

Gamma-Ray Bursts are the most luminous and remote phenomena in the Universe, with isotropic-equivalent radiated energies in X-gamma rays up to more than ***10^{54} erg released in a few tens of seconds,*** *association with star-forming regions and a redshift distribution extending to at least* ***z = 9-10****. Thus, they are in principle very powerful tools for cosmology*

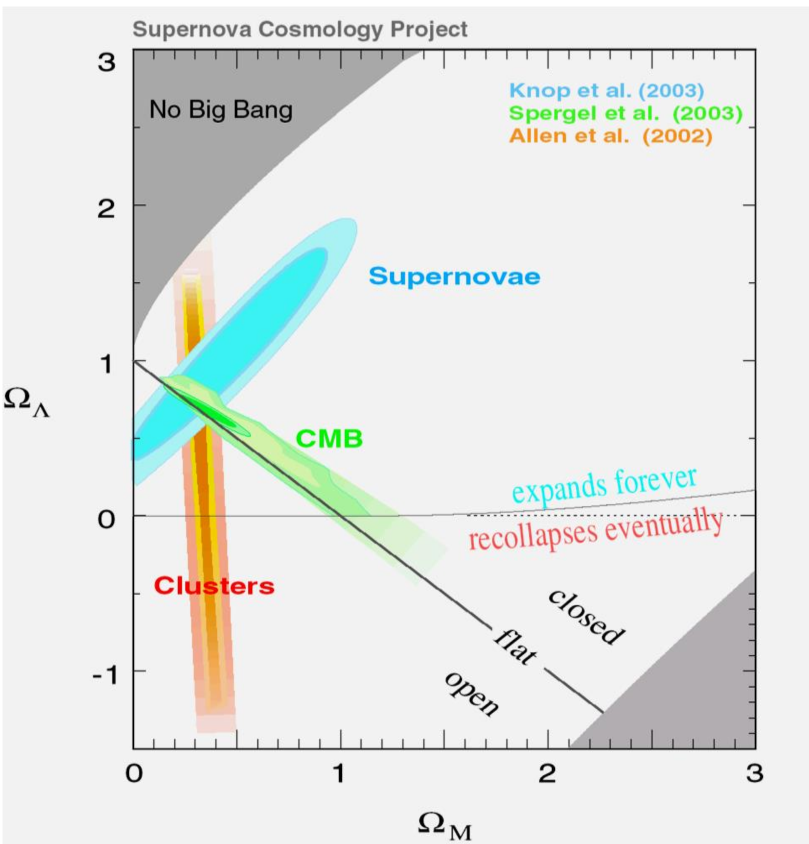


a) *Investigating the expansion rate and geometry of the Universe, thus getting clues to "dark energy" properties and evolution*

b) *Exploring the early Universe (re-ionization, first stars, star formation rate and metallicity evolution in the first billion of years*

Why looking for more cosmological probes ?

❑ *different distribution in redshift -> different sensitivity to different cosmological parameters*



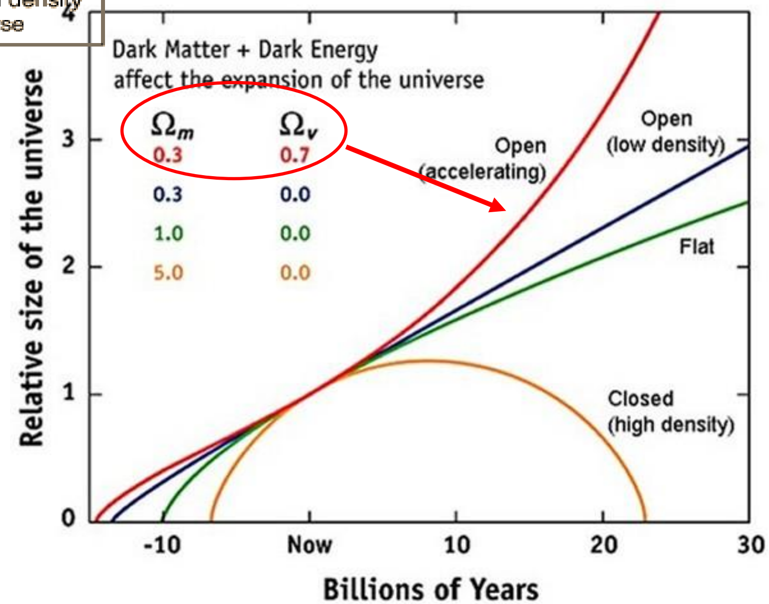
$$\Omega = \Omega_{m} + \Omega_{rel} + \Omega_{\Lambda}$$

Total density parameter
$\Omega = \frac{\rho}{\rho_c}$
$\Omega = 1$ for critical density universe

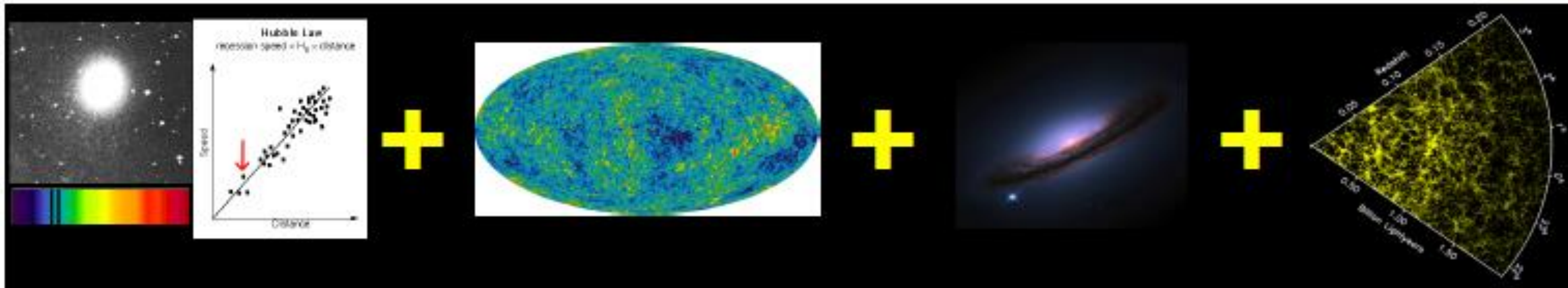
Mass density including ordinary mass (baryonic mass) plus dark matter.

Effective mass density of relativistic particles (light plus neutrinos).

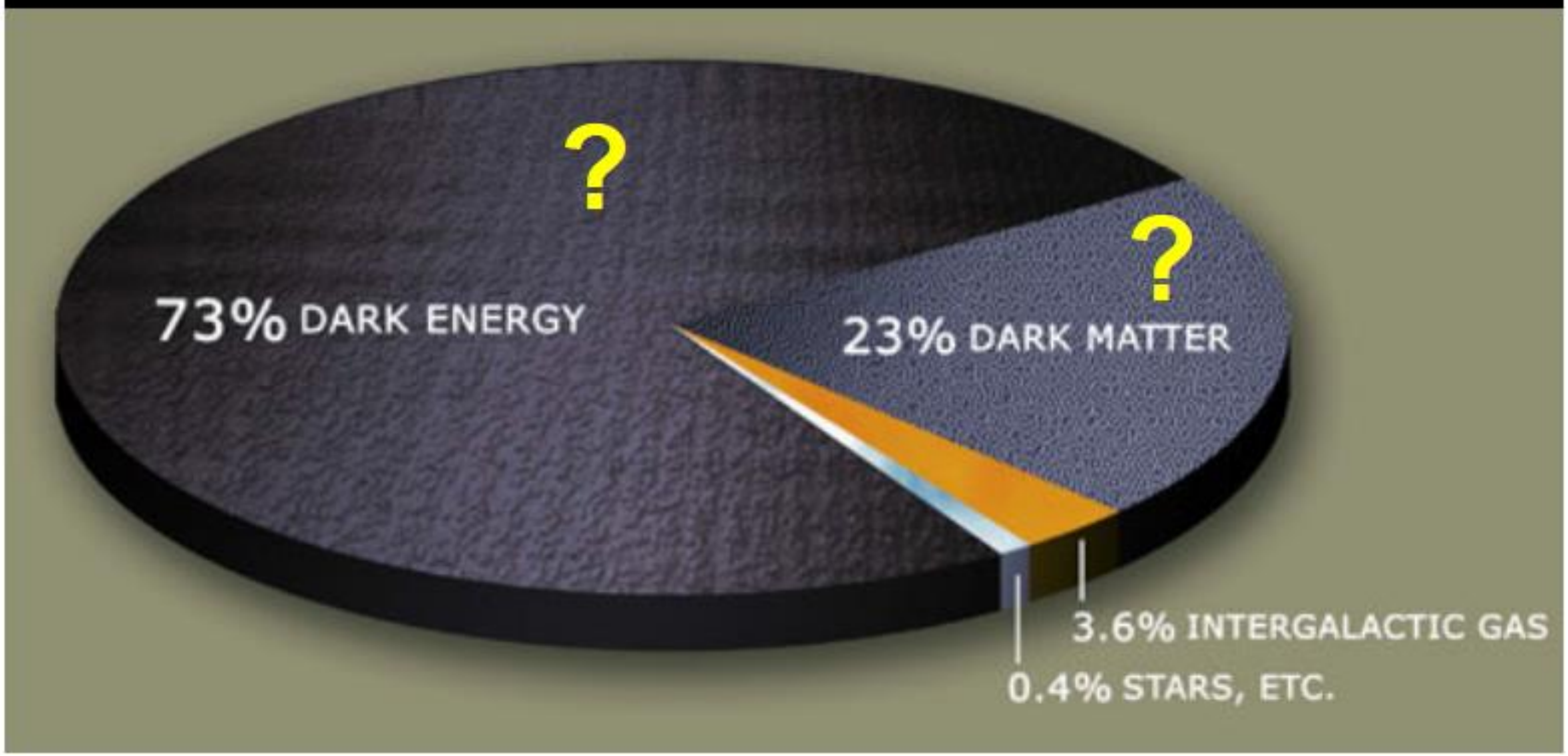
Effective mass density of the dark energy, taking the role described as the cosmological constant.

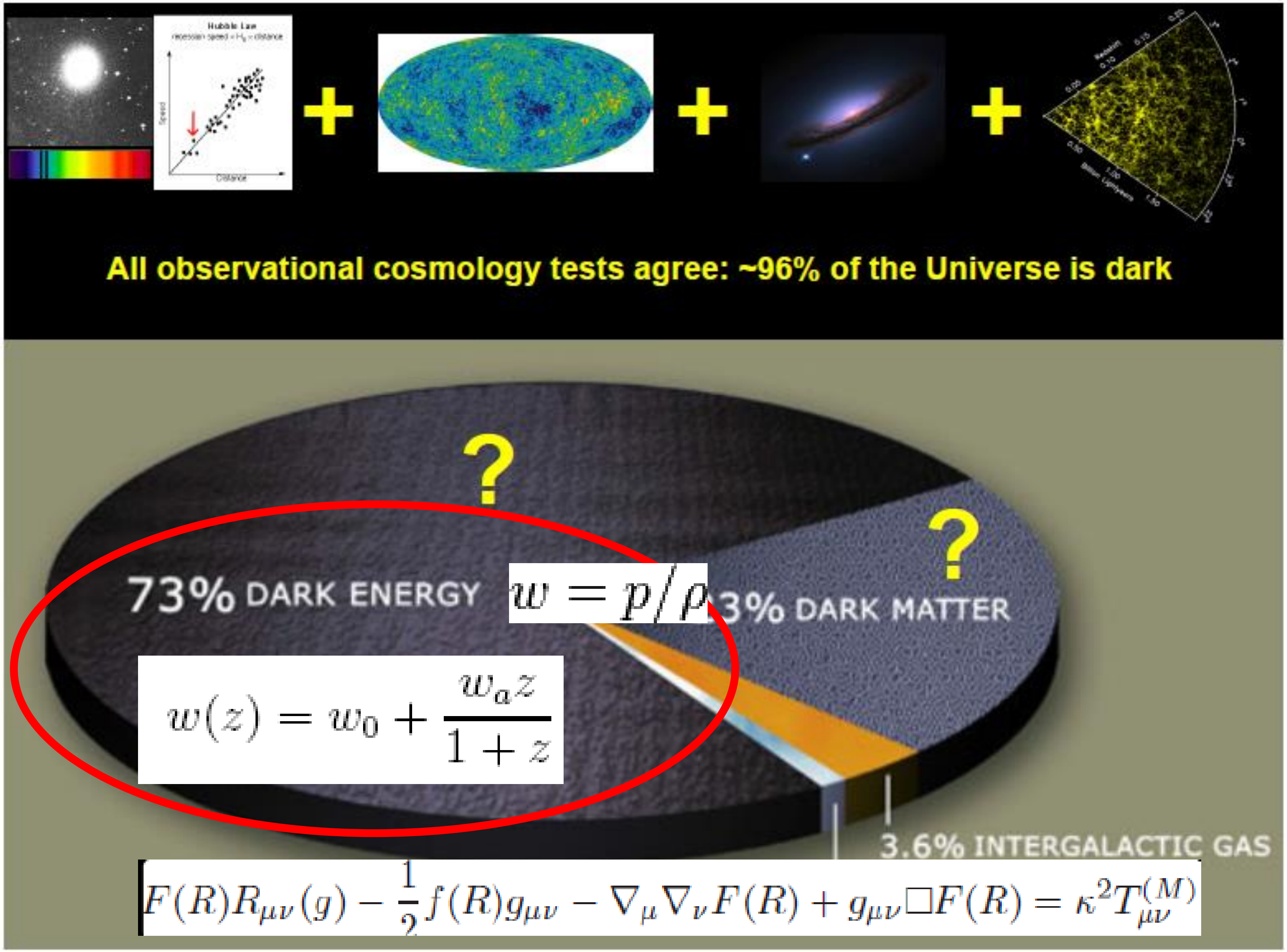


$$D_L = (1+z)c \div H_o \,|k|^{0.5} \times S\left\{ |k|^{0.5} \int_0^z \left[k(1+z)^2 + \Omega_M (1+z')^3 + \Omega_\Lambda \right]^{-0.5} dz' \right\}$$



All observational cosmology tests agree: ~96% of the Universe is dark




Hubble Law
All observational cosmology tests agree: ~96% of the Universe is dark
?
?
73% DARK ENERGY
$w = p/\rho$
23% DARK MATTER
$w(z) = w_0 + \frac{w_a z}{1+z}$
3.6% INTERGALACTIC GAS
$F(R)R_{\mu\nu}(g) - \frac{1}{2}f(R)g_{\mu\nu} - \nabla_\mu\nabla_\nu F(R) + g_{\mu\nu}\Box F(R) = \kappa^2 T^{(M)}_{\mu\nu}$

"Standardizing" GRB with the Ep,i - Intensity correlation

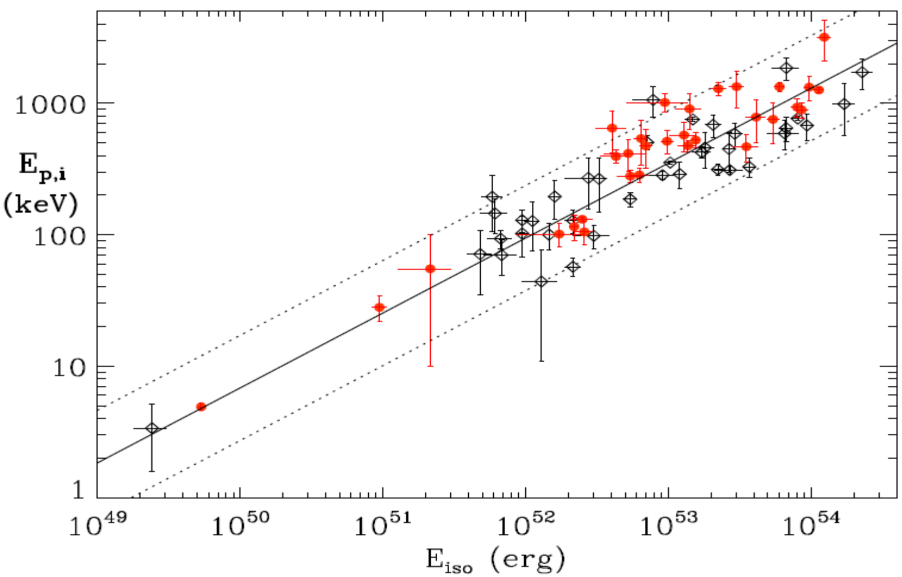
$$E_{p,i} = E_{p,obs} \times (1 + z)$$

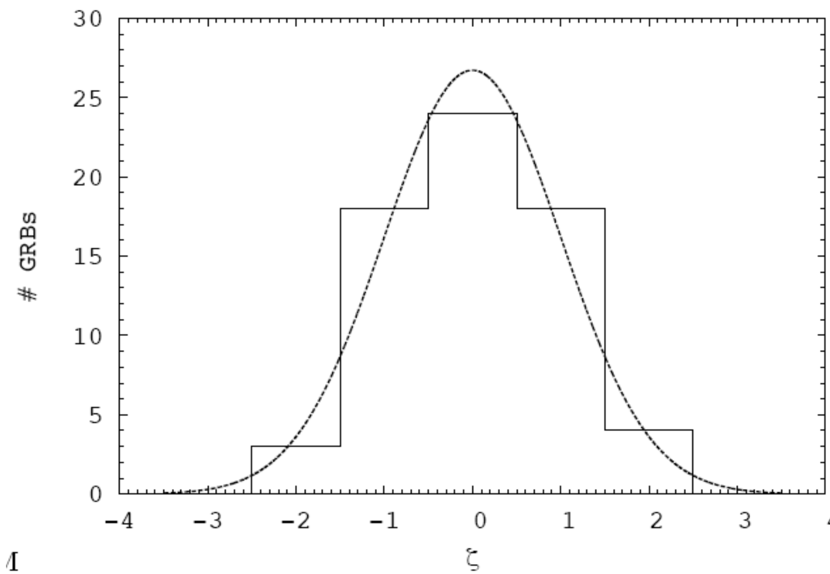
$$E_{\gamma,iso} = \frac{4\pi D_l^2}{(1+z)} \int_{1/1+z}^{10^4/1+z} E\,N(E)\,dE \quad \text{erg}$$

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

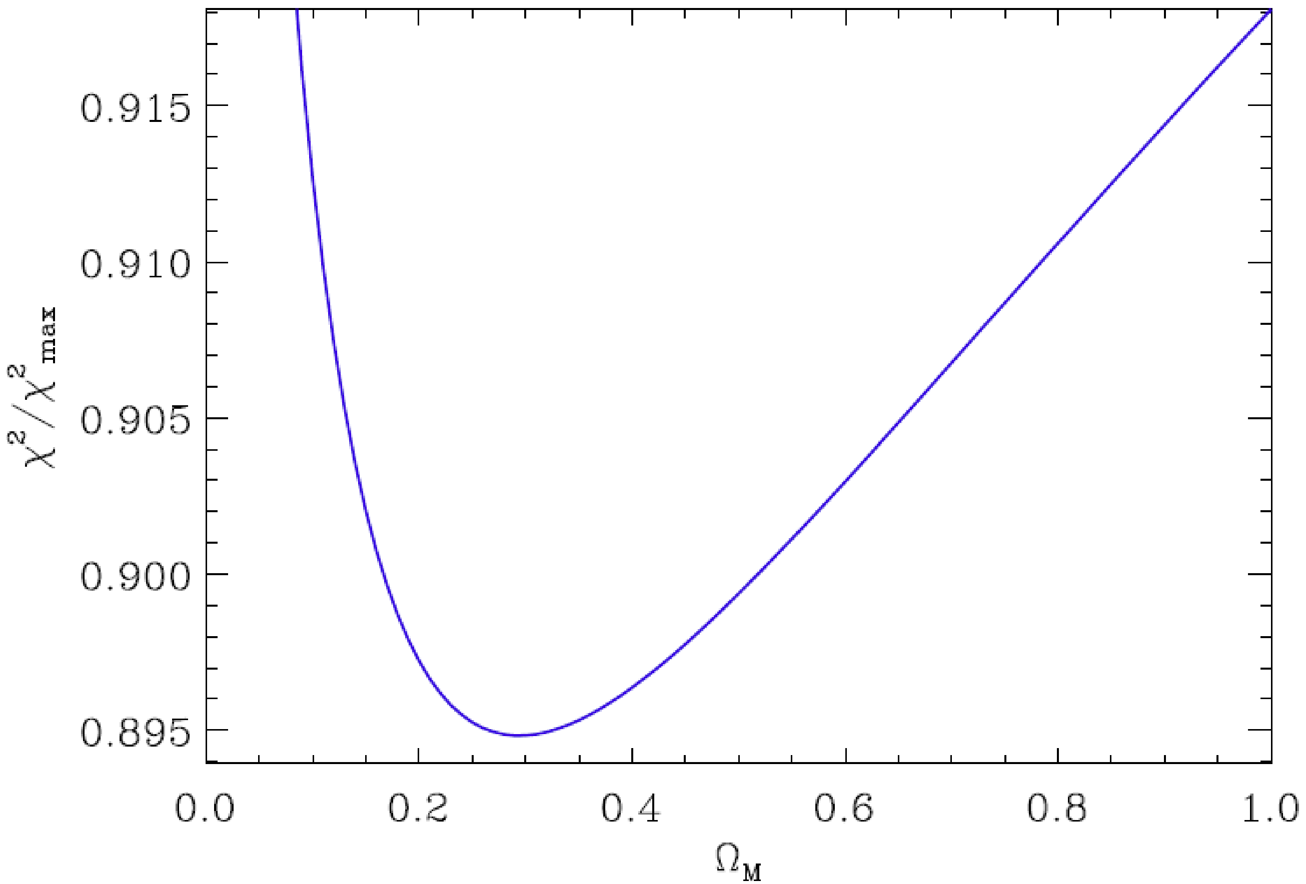
- ***not enough low-z GRBs for cosmology-independent calibration -> circularity is avoided by fitting simultaneously the parameters of the correlation and cosmological parameters***

- ***does the extrinsic scatter and goodness of fit of the Ep,i-Eiso correlation vary with the cosmological parameters used to compute Eiso ?***

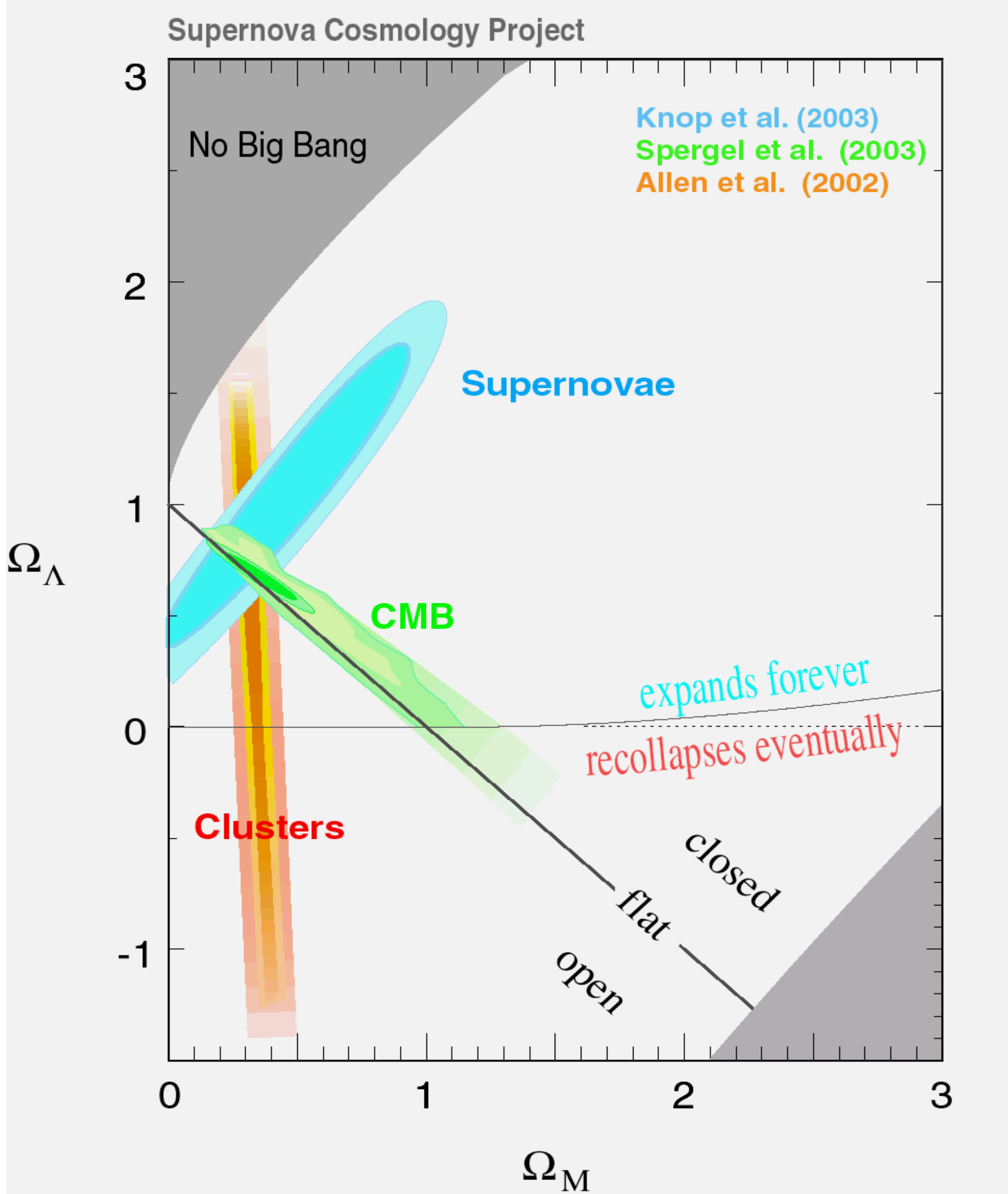




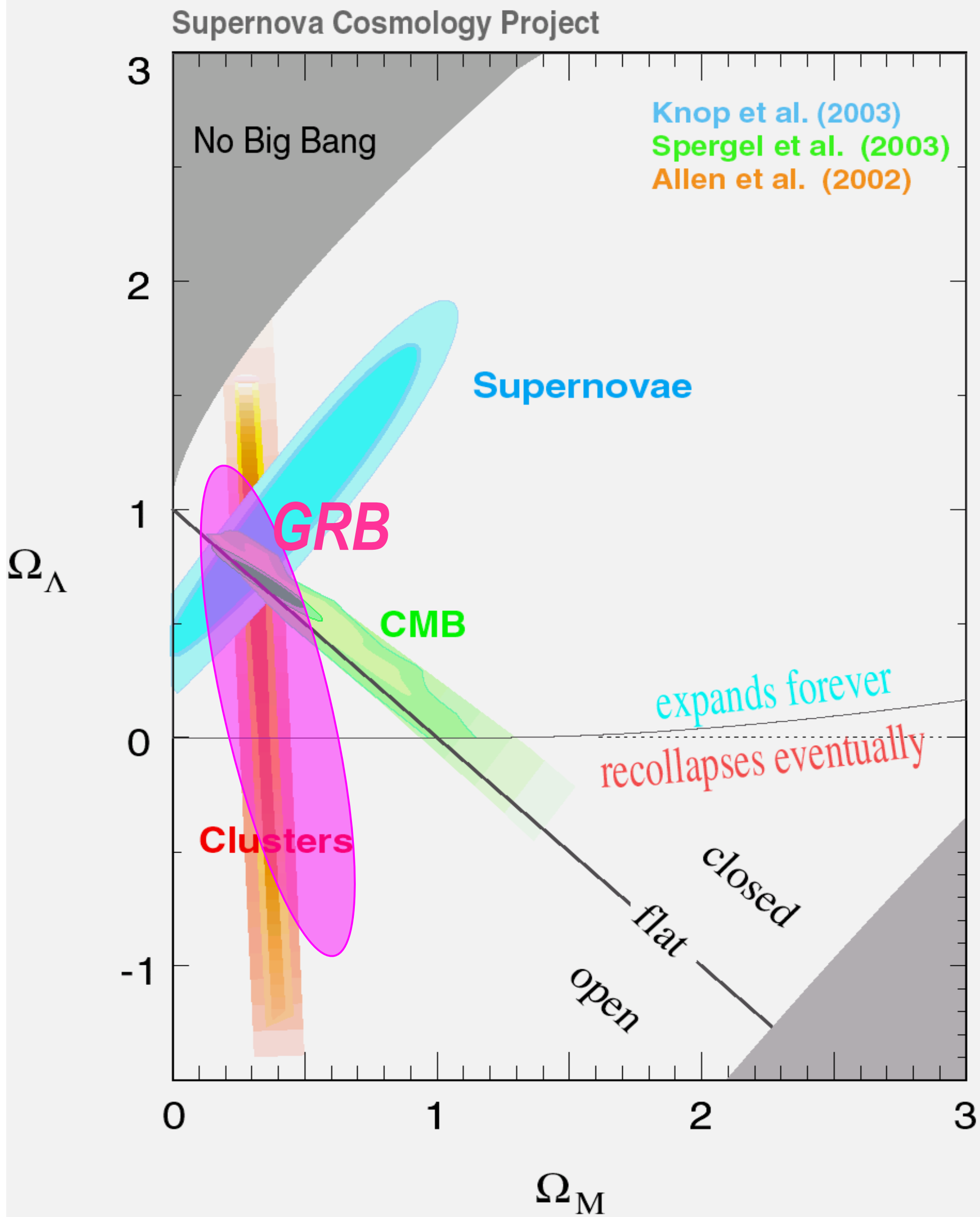
- *a fraction of the extrinsic scatter of the $E_{p,i}$-E_{iso} correlation is indeed due to the cosmological parameters used to compute E_{iso}*
- *Evidence, independent on SN Ia or other cosmological probes, that, if we are in a flat ΛCDM universe , Ω_M is lower than 1 and around 0.3*



Amati et al. 2008, Amati & Della Valle 2013



Supernova Cosmology Project
No Big Bang
Knop et al. (2003)
Spergel et al. (2003)
Allen et al. (2002)
Supernovae
CMB
Clusters
expands forever
recollapses eventually
closed
flat
open
Ω_Λ
Ω_M
3
2
1
0
-1
0
1
2
3



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0
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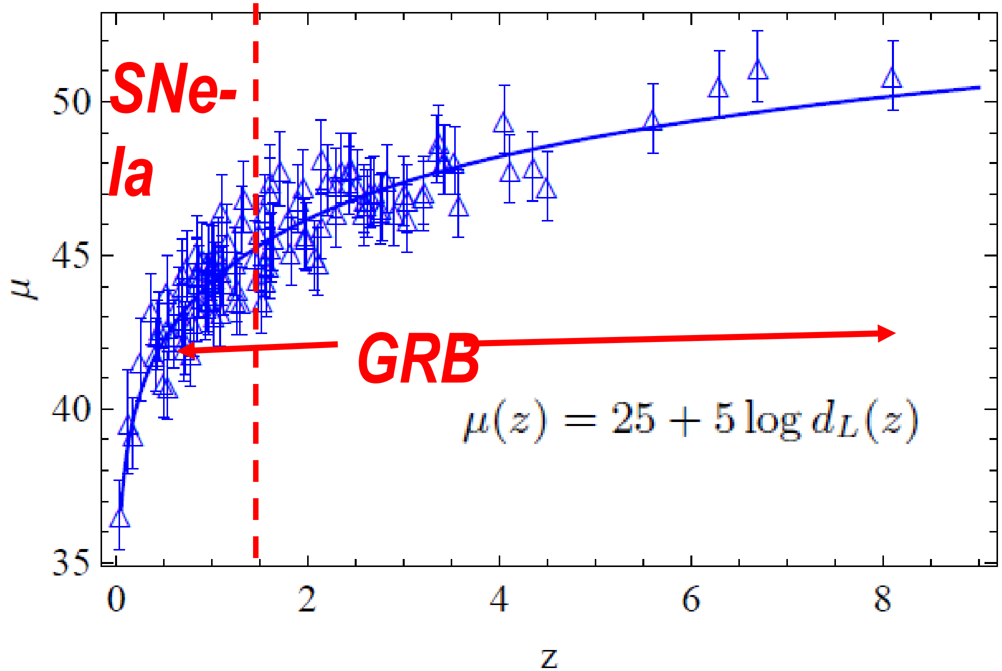
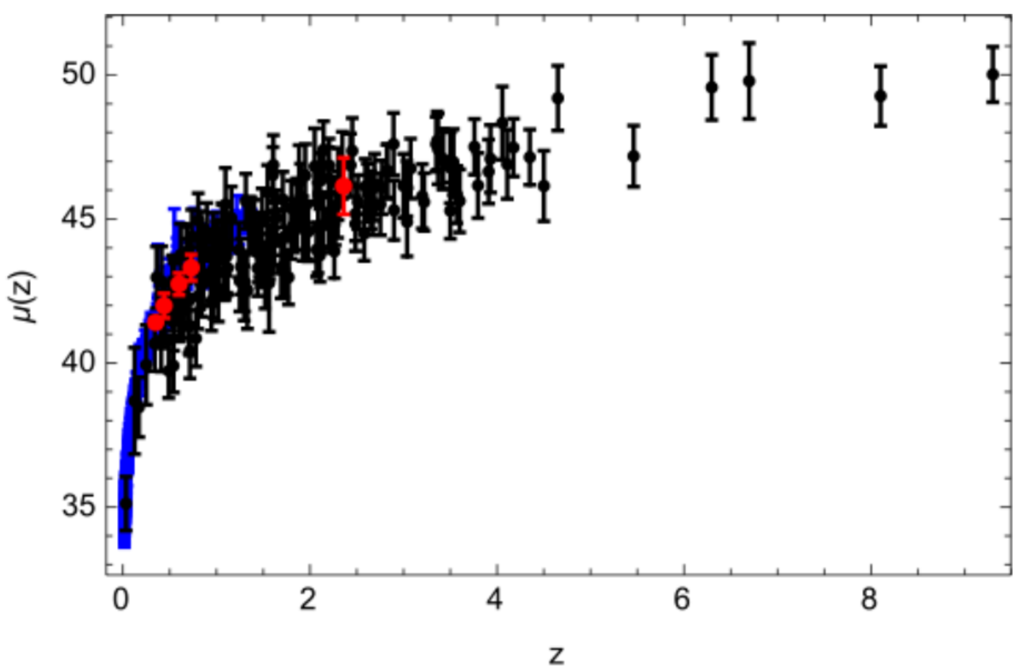
0
1
2
3
Ω_Λ
Ω_M

- The GRB Hubble diagram extends to much higher z w/r to SNe Ia

- **The GRB Hubble diagram is consistent with SNe Ia Hubble diagram and BAO points at low redshifts: reliability**





e.g., Demianski et al. 2017

Enlargement of the sample (+ self-calibration)

- the simulatenous operation of Swift, Fermi/GBM, Konus-WIND is allowing an increase of the useful sample (z + Ep) at a rate of 20 GRB/year, providing an increasing accuracy in the estimate of cosmological parameters
- future GRB experiments (e.g., SVOM) and more investigations (in particular: reliable estimates of jet angles and self-calibration) will improve the significance and reliability of the results and allow to the nvestigation of dark energy

GRB #	Ω_M (flat)	w_0 (flat, Ω_M=0.3, w_a=0.5)
70 (real) GRBs (Amati+ 08)	$0.27^{+0.38}_{-0.18}$	<-0.3 (90%)
156 (real) GRBs (Amati+ 13)	$0.29^{+0.28}_{-0.15}$	$-0.9^{+0.4}_{-1.5}$
250 (156 real + 94 simulated) GRBs	$0.29^{+0.16}_{-0.12}$	$-0.9^{+0.3}_{-1.1}$
500 (156 real + 344 simulated) GRBs	$0.29^{+0.10}_{-0.09}$	$-0.9^{+0.2}_{-0.8}$
156 (real) GRBs, calibration	$0.30^{+0.06}_{-0.06}$	$-1.1^{+0.25}_{-0.30}$
250 (156 real + 94 simulated) GRBs, calibration	$0.30^{+0.04}_{-0.05}$	$-1.1^{+0.20}_{-0.20}$
500 (156 real + 344 simulated) GRBs, calibration	$0.30^{+0.03}_{-0.03}$	$-1.1^{+0.12}_{-0.15}$

Amati & Della Valle 2013

$$w(z) = w_0 + \frac{w_a z}{1+z}$$

❑ *Enlargement of the sample (+ self-calibration)*

- *the simulatenous operation of Swift, Fermi/GBM, Konus-WIND is allowing an increase of the useful sample (z + Ep) at a rate of 20 GRB/year, providing an increasing accuracy in the estimate of cosmological parameters*
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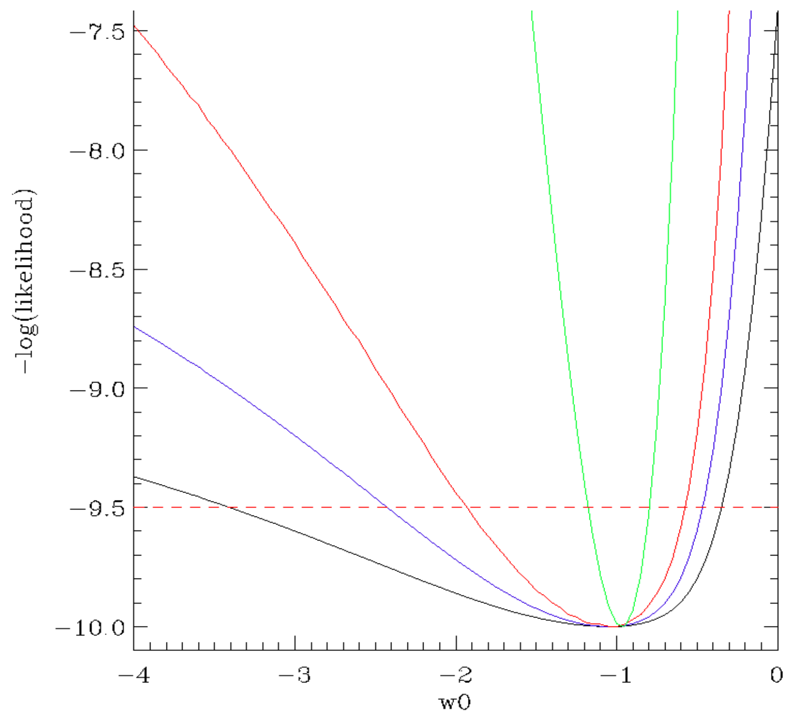
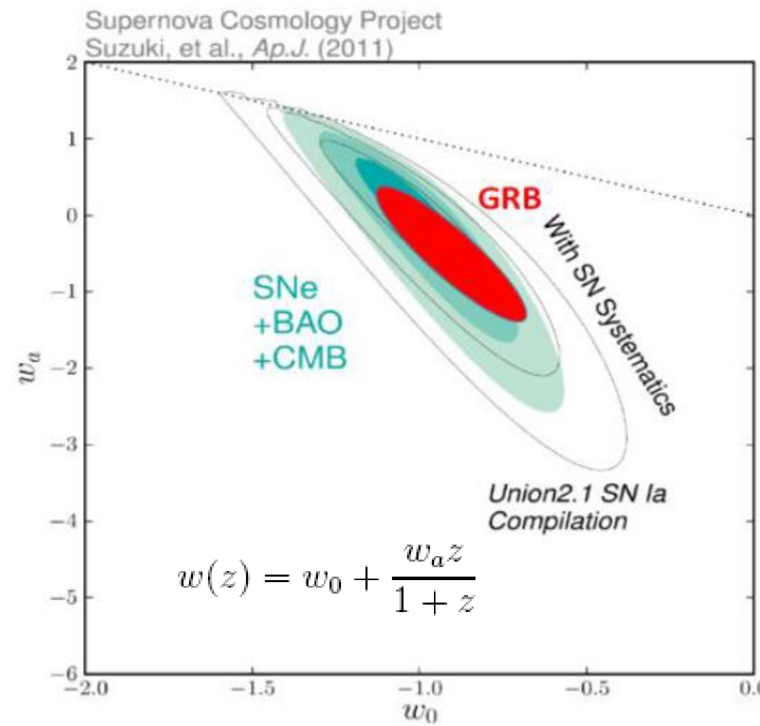
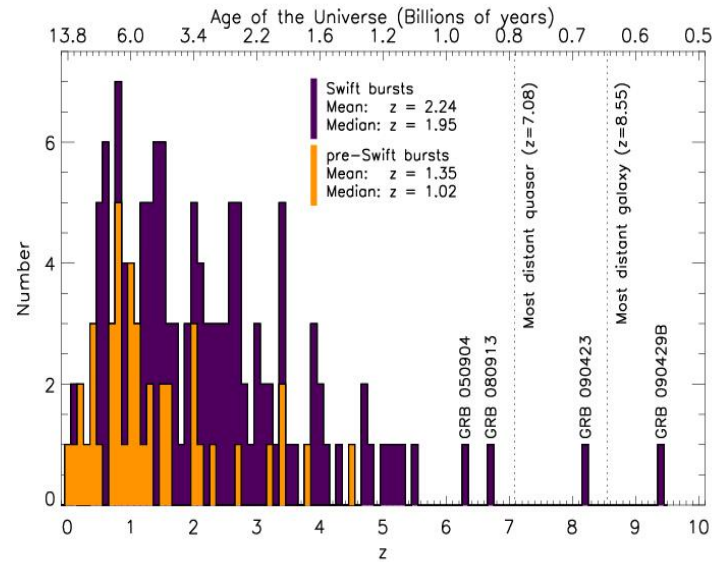




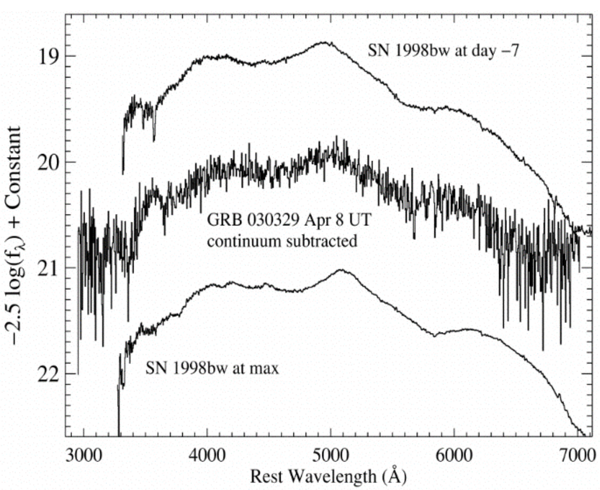
Amati & Della Valle 2013

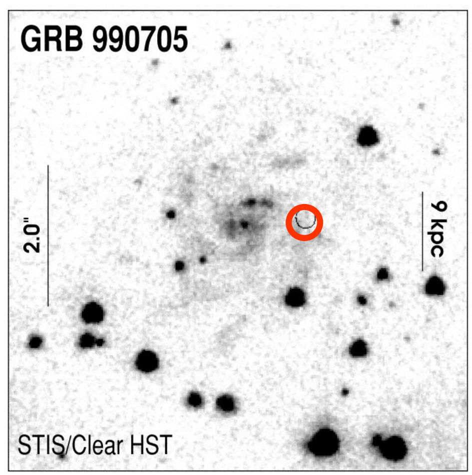
Shedding light on the early Universe with GRBs

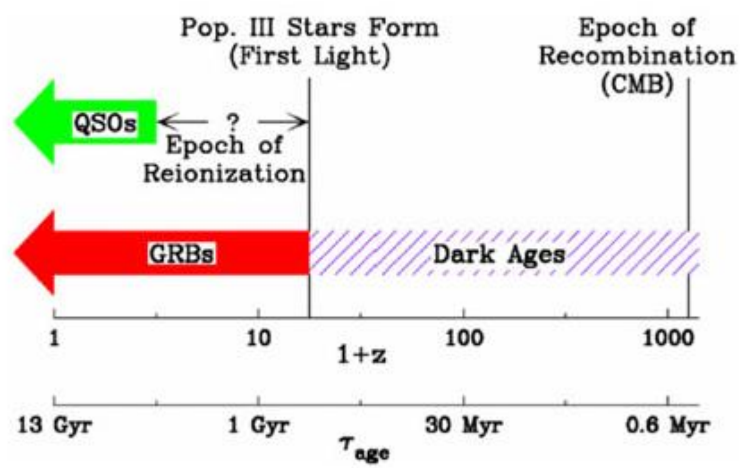
Because of their huge luminosities, mostly emitted in the X and gamma-rays, their redshift distribution extending at least to z ~9 and their association with explosive death of massive stars and star forming regions, GRBs are unique and powerful tools for investigating the early Universe: **SFR evolution, physics of re-ionization, galaxies metallicity evolution and luminosity function, first generation (pop III) stars**



GRBs in Cosmological Context



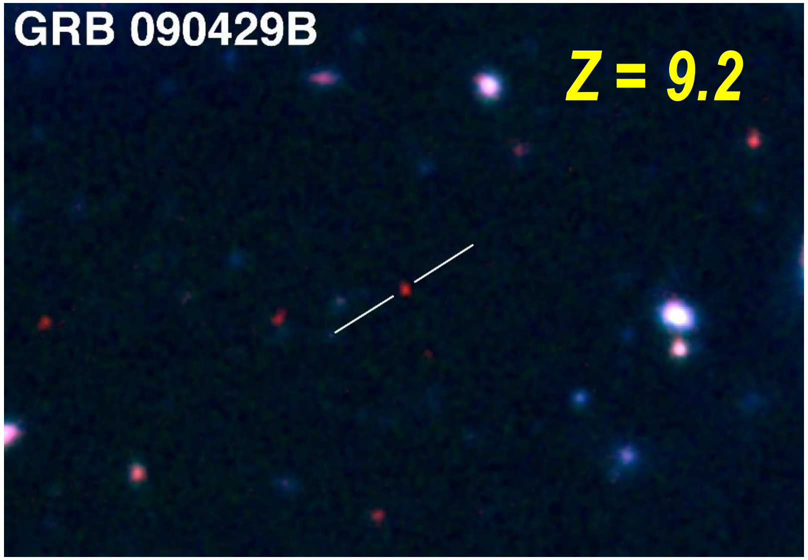


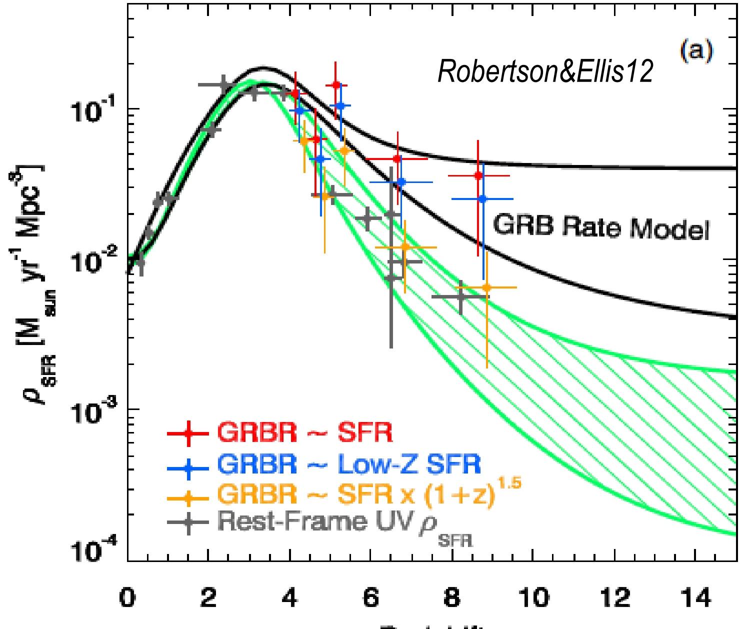


Lamb and Reichart (2000)

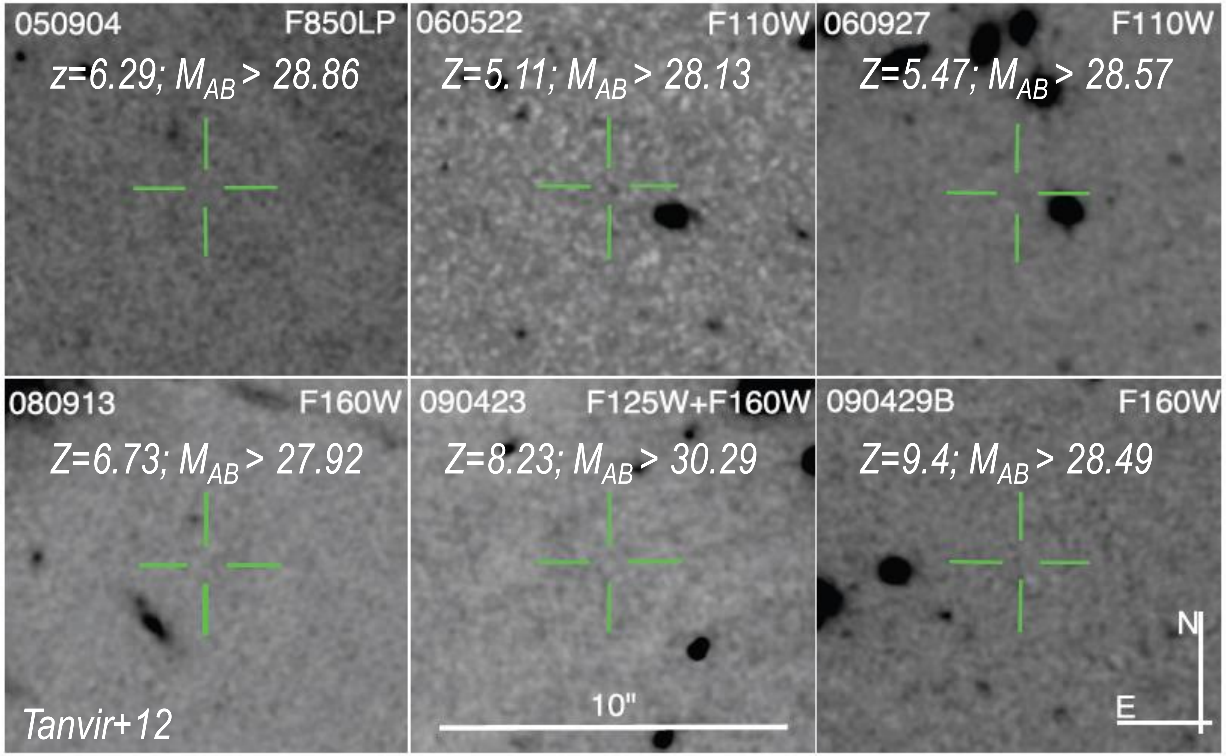
A statistical sample of high–z GRBs can provide fundamental information:

- *measure independently the **cosmic star–formation rate**, even beyond the limits of current and future galaxy surveys*
- *directly (or indirectly) detect the first population of stars (pop III)*





- *the number density and properties of low-mass galaxies*

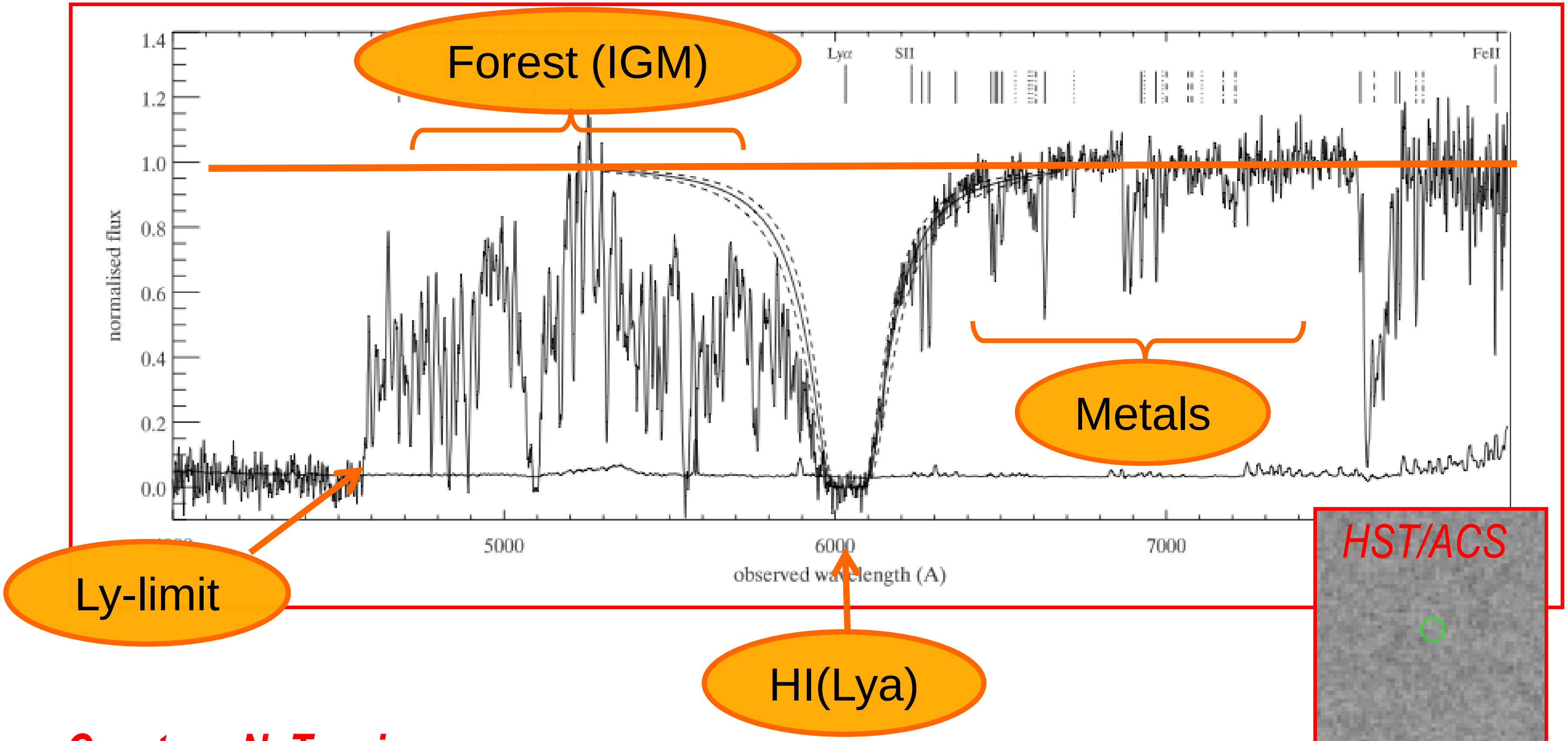


Robertson&Ellis12

Even JWST and ELTs surveys will be not able to probe the faint end of the galaxy Luminosity Function at high redshifts (z>6-8)

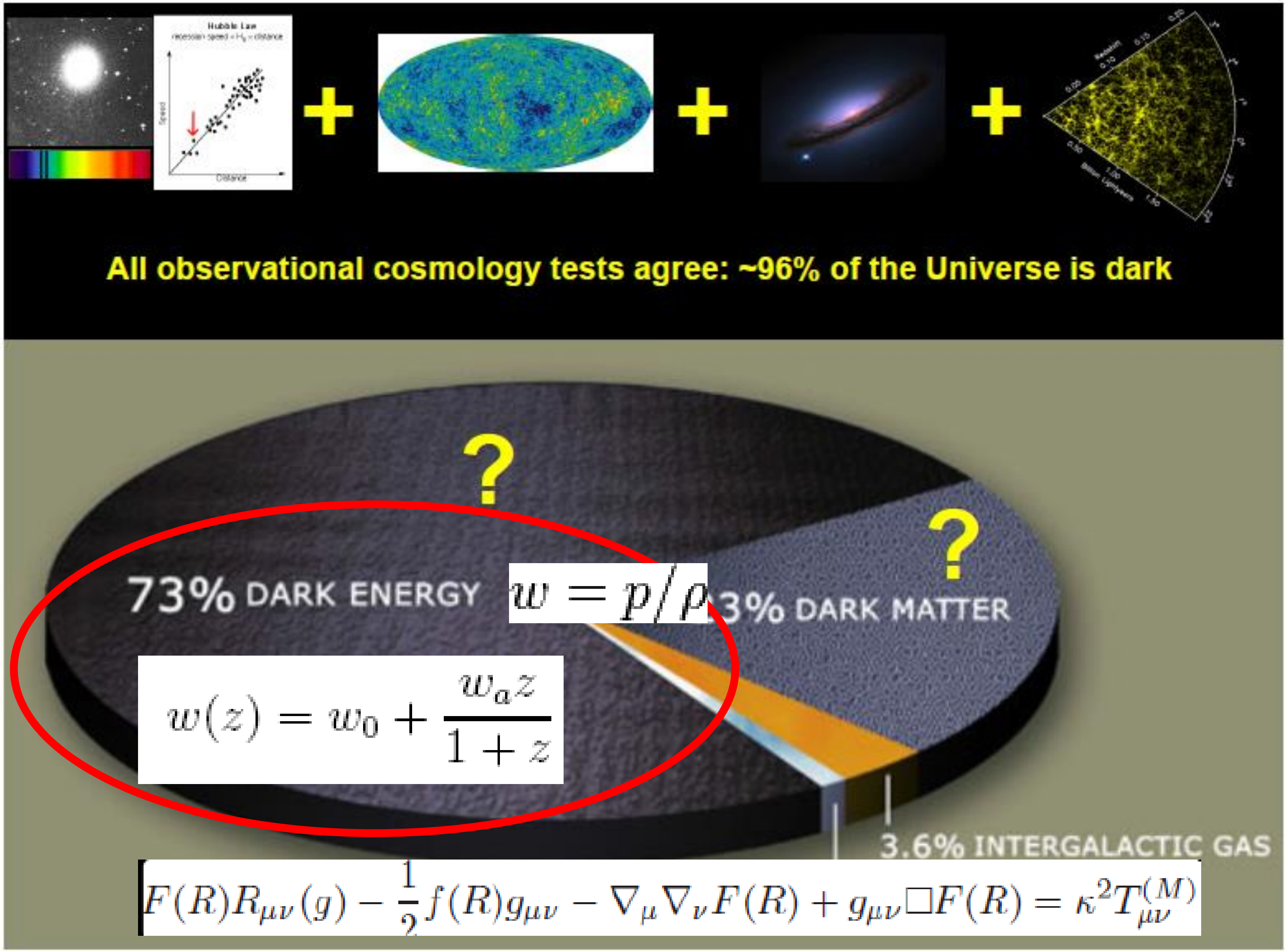
- *the neutral hydrogen fraction*
- *the escape fraction of UV photons from high-z galaxies*
- *the early metallicity of the ISM and IGM and its evolution*

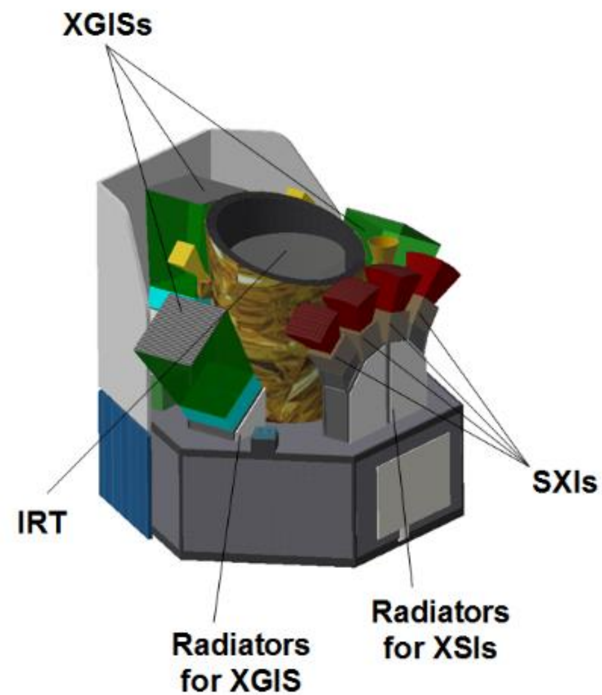
Abundances, HI, dust, dynamics etc. even for very faint hosts. E.g. GRB 050730: faint host (R>28.5), but z=3.97, [Fe/H]=-2 and low dust, from afterglow spectrum (Chen et al. 2005; Starling et al. 2005).

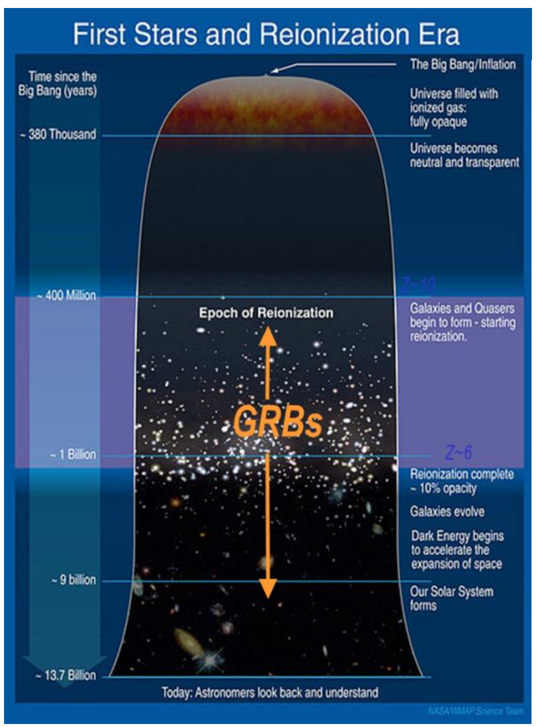


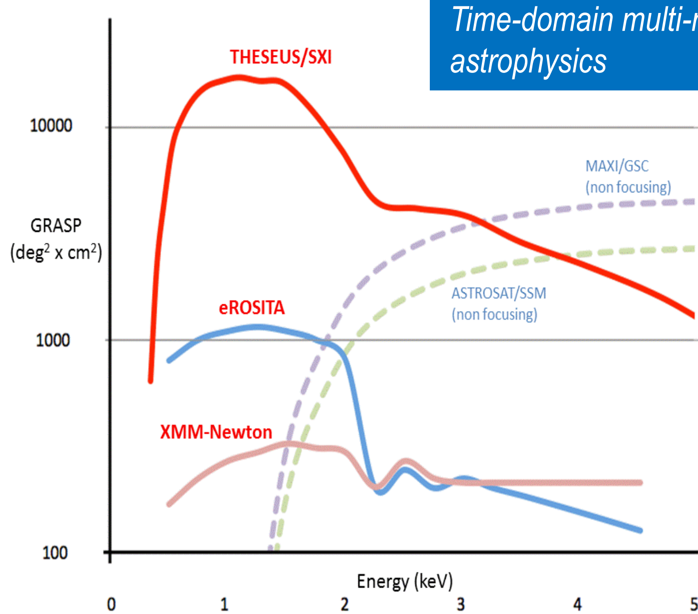
Courtesy N. Tanvir

Perspectives

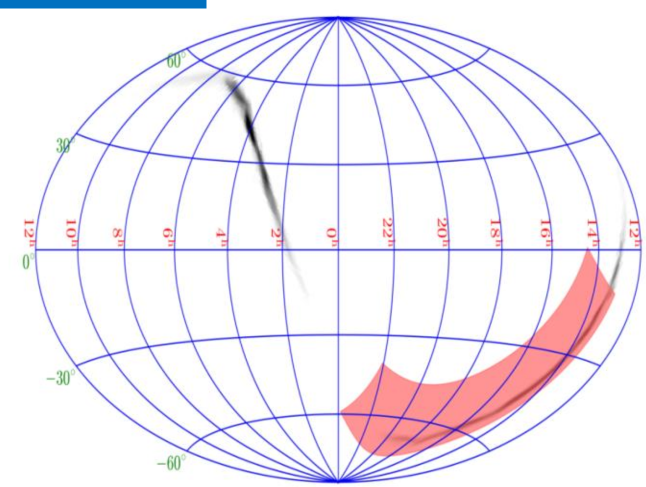








Time-domain multi-messenger astrophysics



Back-up slides

Most common X-ray emission processes in astrophysical sources

I. Thermal

- *Black body emission*
- *Thermal Bremssthrahlung*

II. Non thermal

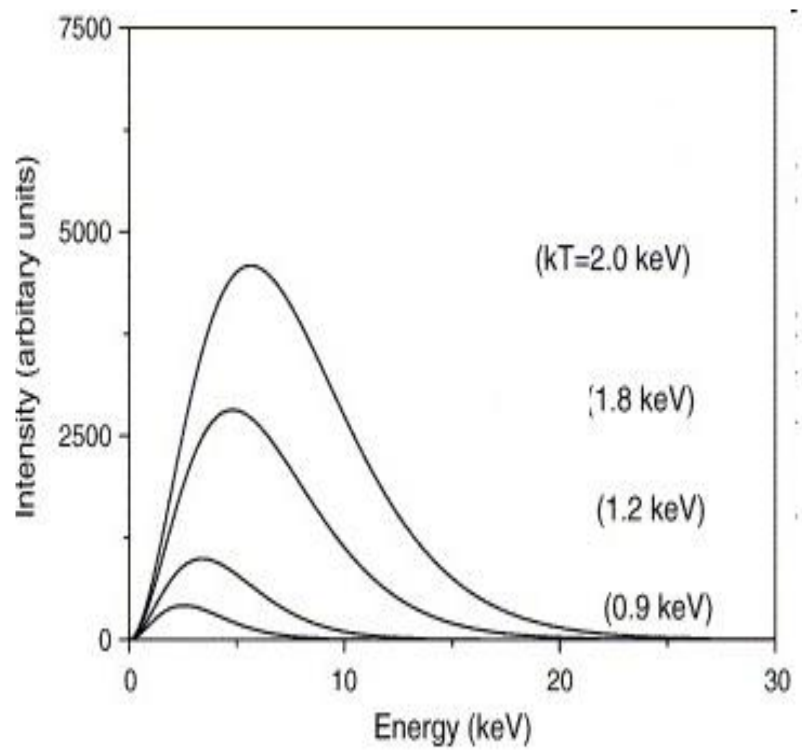
- *Synchrotron emission*
- *Inverse Compton / Comptonization*

In many classes of astrophysical sources, more than one of these processes is at work.

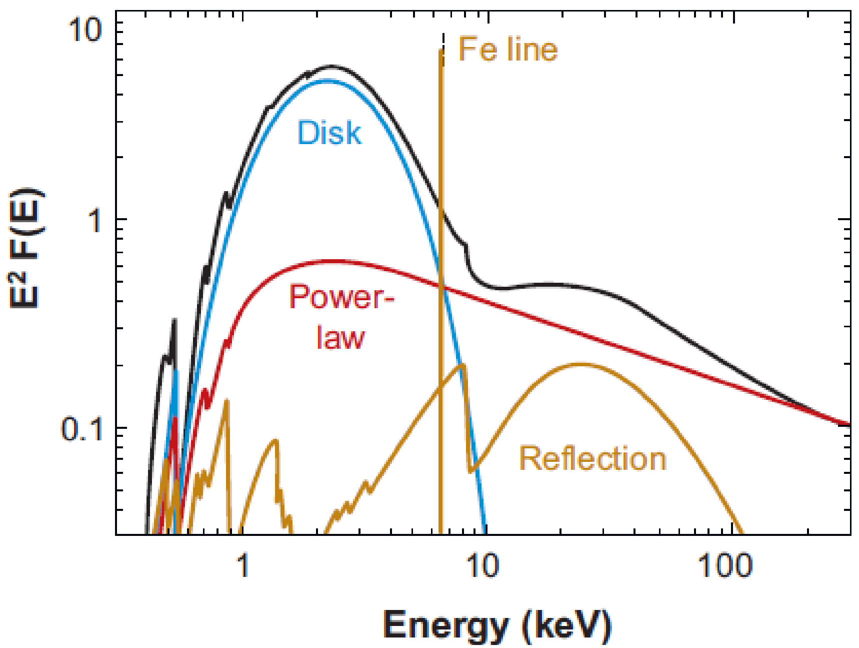
❑ ***Thermal processes: black-body emission***

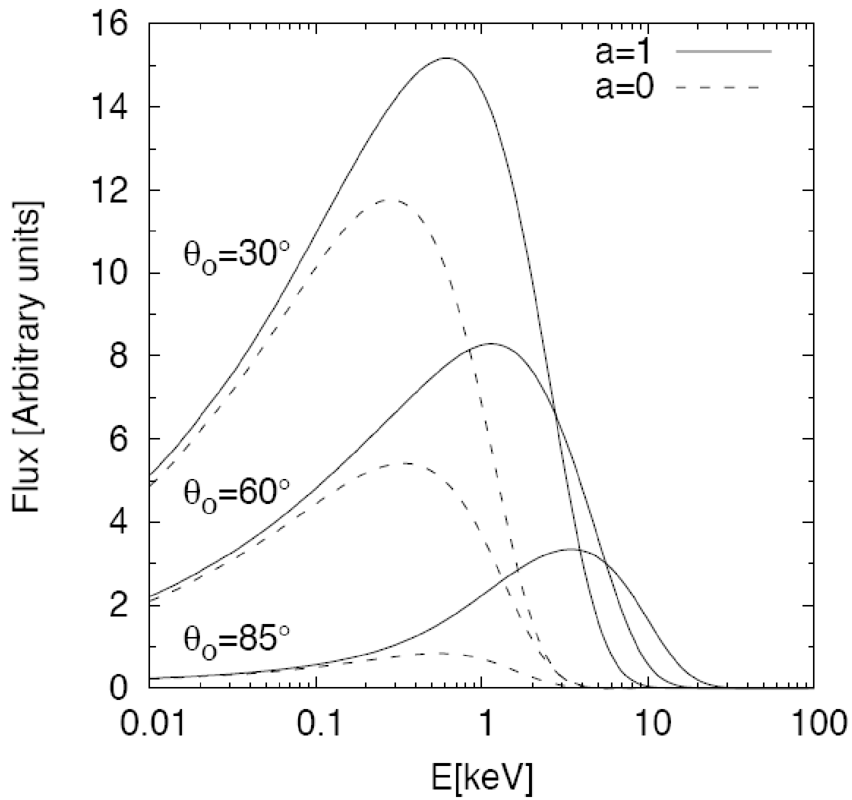
- *occurrs in optically thick medium*
- *matter heated at **temperatures from ~10^6 to ~10^9 K** emit black-body radiation in the **X-ray energy band from ~0.1 to ~100 keV***
- *the continuum has the well-known Planckian shape*

$$I(\nu)\mathrm{d}\nu = \frac{8\pi h\nu^3}{c^3}\cdot\frac{1}{\exp\left(\frac{h\nu}{kT}\right)-1}d\nu$$



- *physical information: temperature of the emitting medium (kT)*
- *examples: accretion disks in X-ray binaries and AGNs*
- *the actual shape of the continuum may depend on the radial profile of the disk temperature, on the metrics (e.g, Schwarzchild or Kerr black hole), on the viewing angle*



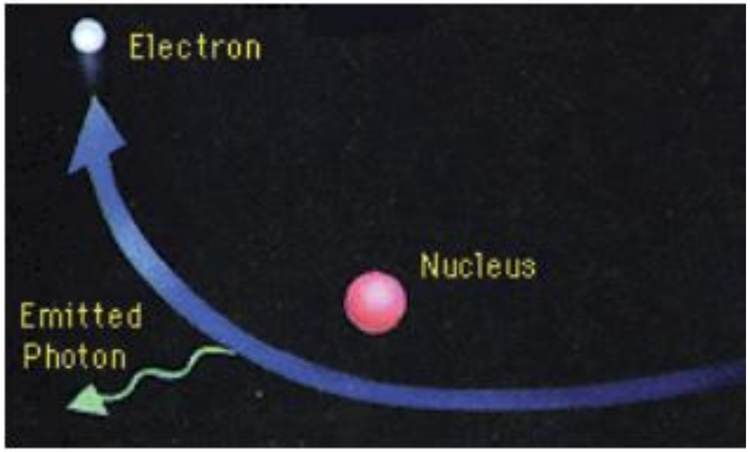


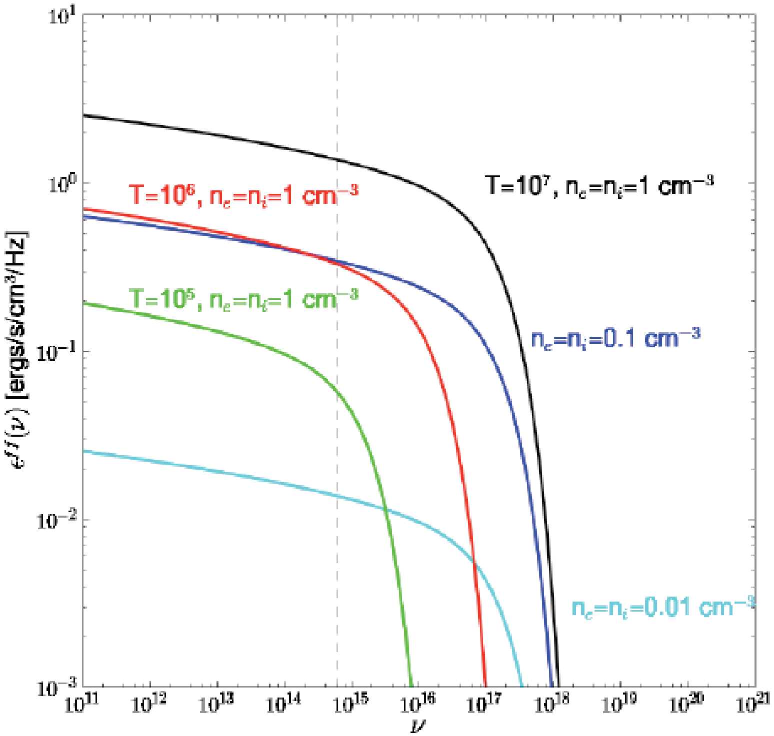
❑ *Thermal processes: thermalized bremsstrahlung*

➢ *occurs in optically thin plasma in thermal equilibrium*

➢ *Bremsstrahlung emission is due to the change in acceleration of a charged particle due to another particle. It is is also sometimes referred to as 'free-free' emission*

$$\epsilon_\nu^{ff} = 6.8 \times 10^{-38} Z^2 n_e n_i T^{-1/2} e^{-h\nu/kT} \overline{g_{ff}}$$

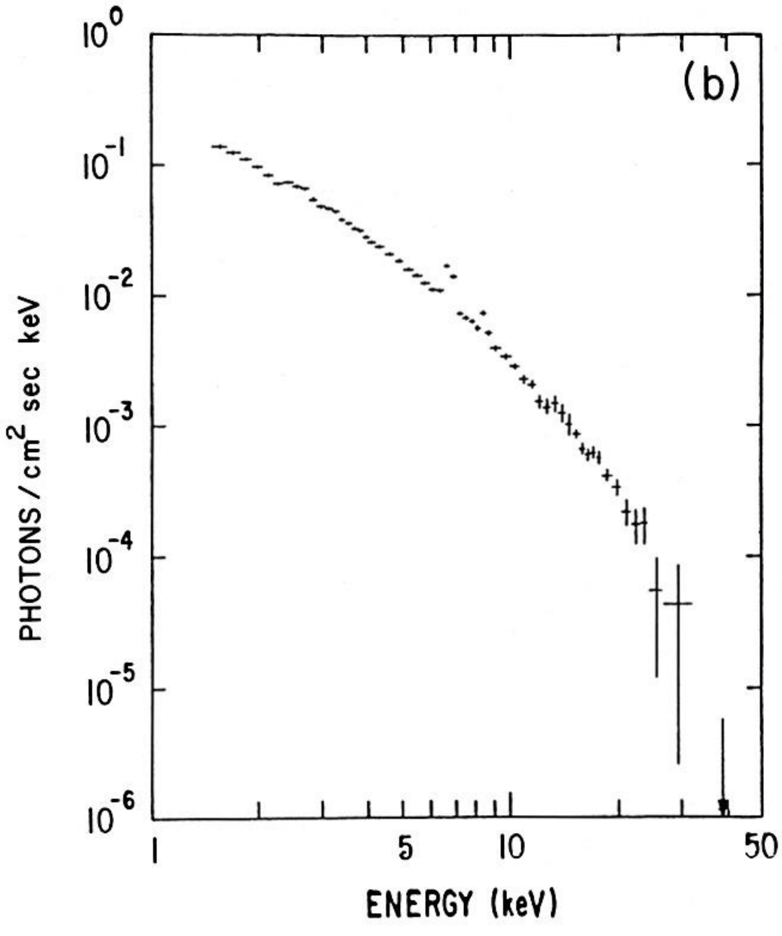




➢ *physical information: temperature (kT) and properties of the emitting plasma*

➢ *examples: stellar coronae, galaxy clusters, young SNR*

➢ *e.g., by combining surface brightness mapping and spatial resolved X-ray spectroscopy, it is possible to map the density and temperature distribution and the "total" mass (galaxies + gas + DM) in clusters*



Perseus cluster

❑ *Non thermal processes: synchrotron*

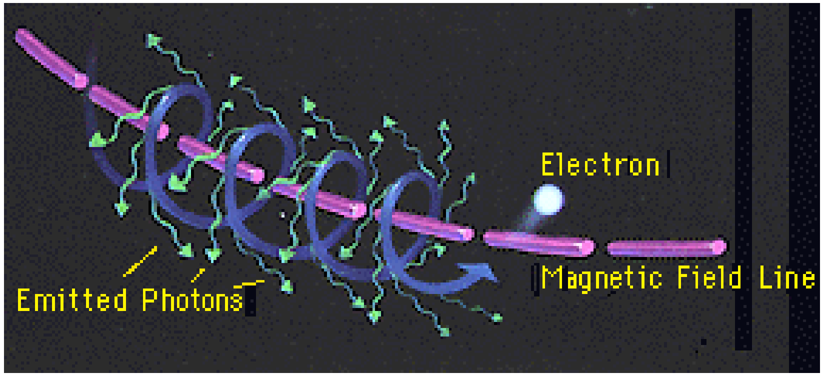
➢ *Synchrotron radiation is due to the movement of an electron charge in a magnetic field.*

The frequency of synchrotron radiation is:

$$\omega_B = \frac{qB}{\gamma mc}$$

The total power emitted of each electron is:

$$\frac{dE}{dt} = \frac{4}{3}\sigma_T c \beta^2 \gamma^2 U_B$$



➢ *of particular astrophysical interest is the synchrotron emission by a population of electrons with with kinetic energies distributed as a power-law*

$$I(\nu) = a(\rho)\frac{e^3}{m_e c^2}\left(\frac{3e}{4\pi m_e^3 c^5}\right)^{(\rho-1)/2} B^{(\rho+1)/2} K L \nu^{-(\rho-1)/2} \ \mathrm{erg\ cm^{-2} s^{-1} sr^{-1}\ Hz^{-1}}$$

For an input electron distribution given by:

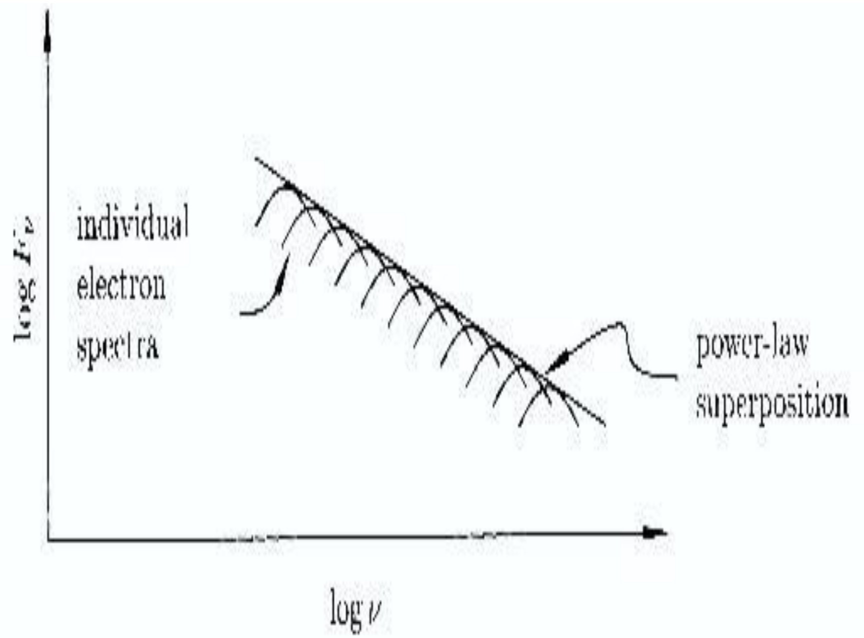
$$N(E)dE = CE^{-p}dE$$

It can be shown that the power will be related to the frequency by:

$$P \propto \nu^{-(p-1)/2}$$

And so the spectral index s is related to the power law of the input electron index p, by:

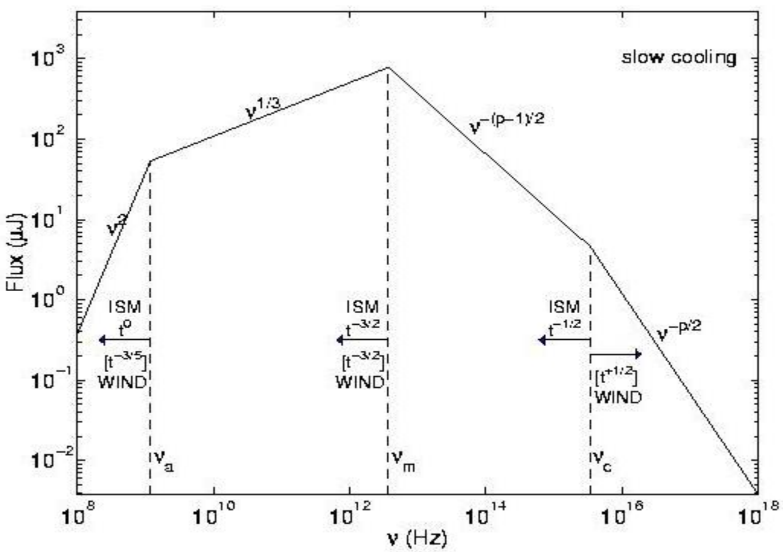
$$s = \frac{p-1}{2}$$



Synchrotron self-absorption:

➢*A photon interacts with a charged particle in a magnetic field and is absorbed (energy transferred to the charge particle).*

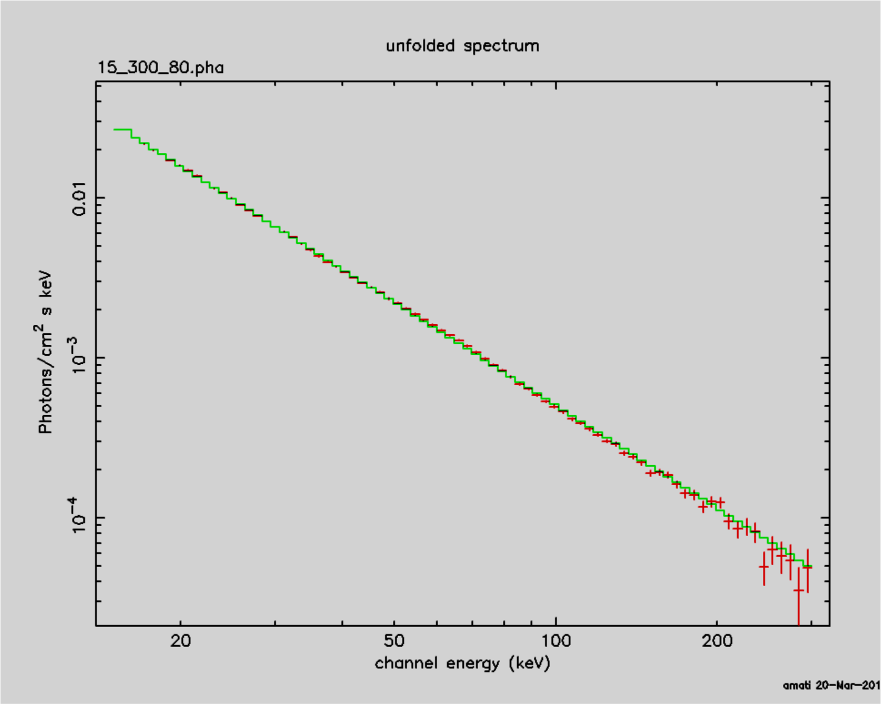
➢*This occurs below a cut-off*

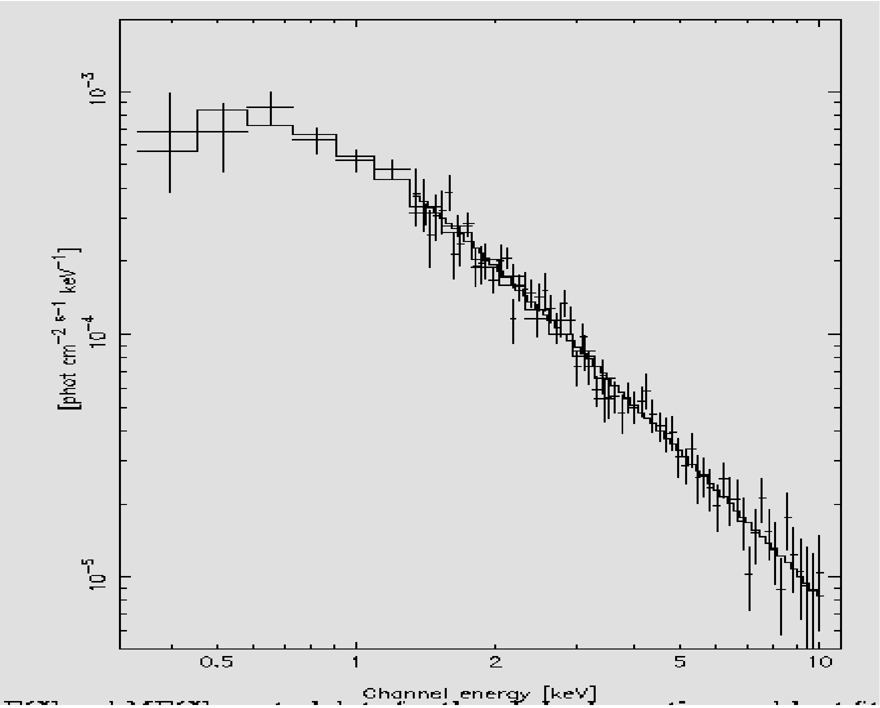


Synchrotron shock emission model for GRB afterglows

➢ *physical information: distribution of the emitting electrons (p), properties of the magnetic field (B)*

➢ *examples: SNR, pulsars, GRB afterglows (and prompt ?)*



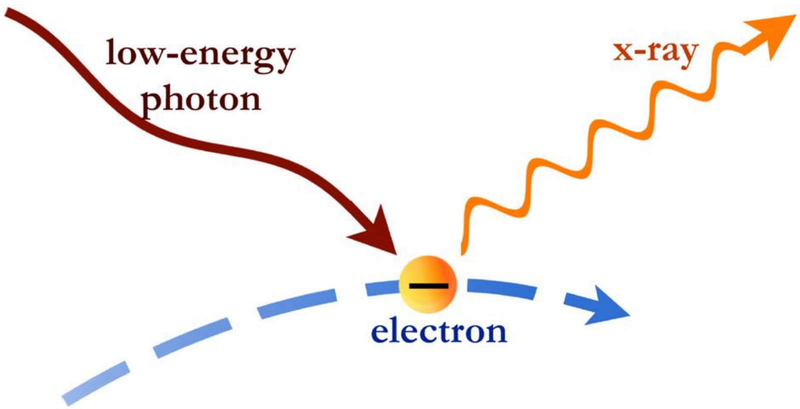


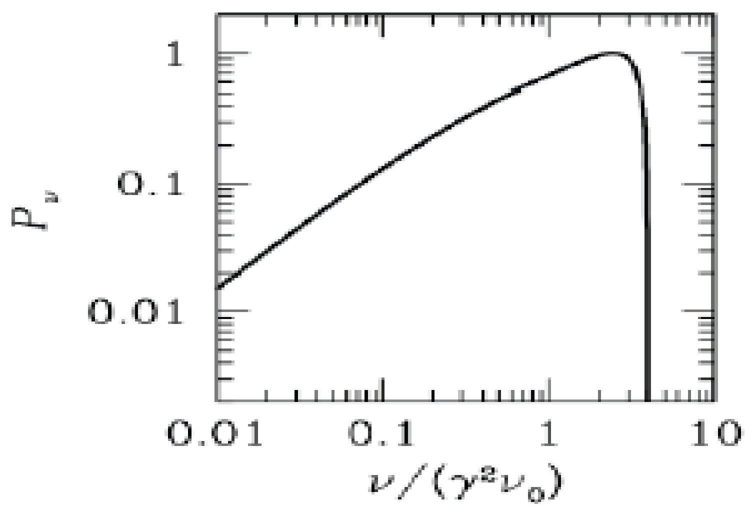
Crab nebula spectrum by BeppoSAX/PDS

Typical X-ray spectrum of a GRB (PL absorbed by Galactic

❑ *Non thermal processes: inverse Compton and Comptonization*

➢ *Inverse Compton Scattering (IC) is due to interaction between a low-energy photon and a relativistic electron.*





From Blumenthal and Gould (1970), for a single frequency photon field, the change in the spectral will be given by:

$$I(\nu)d(\nu) = \frac{3\sigma_T c}{16\gamma^4}\frac{N(\nu_o)}{\nu_o^2}[2\nu ln(\frac{\nu}{4\gamma^2\nu_o}) + \nu + 4\gamma^2\nu_o - \frac{\nu^2}{2\gamma^2\nu_o}]d\nu$$

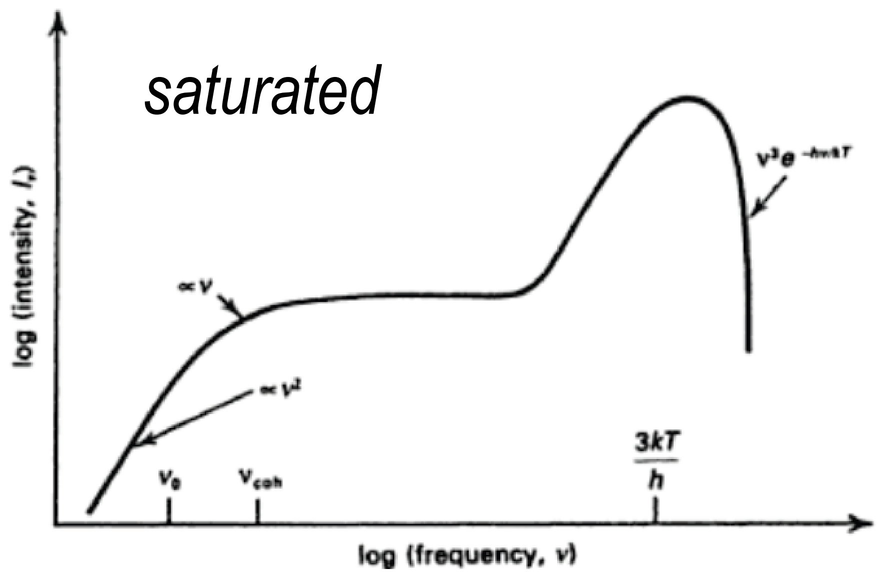
The maximum and average frequency of the scattered photons are:

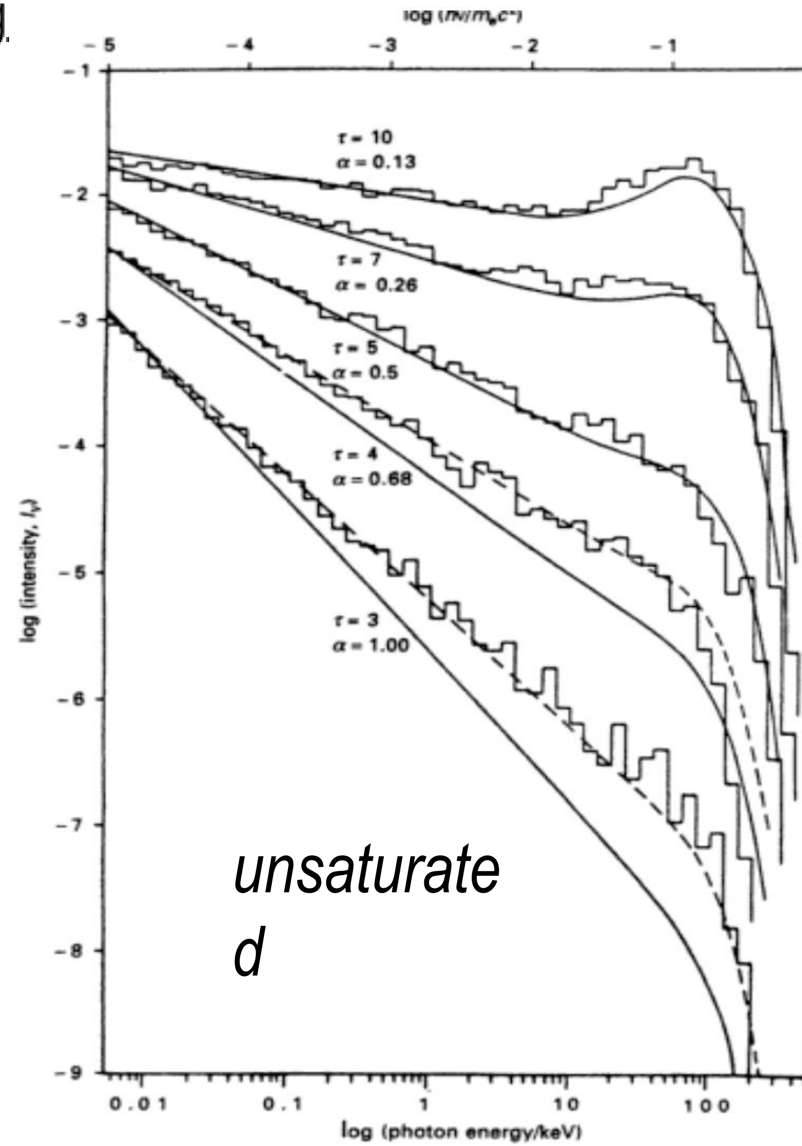
$$\nu_{max} \approx 4\gamma^2\nu_o \qquad <\nu>= \frac{4}{3}\gamma^2\nu$$

➢ *Comptonization in electron – photon plasma*

y=[average fractional energy changed per scattering]
[mean number of scatters]

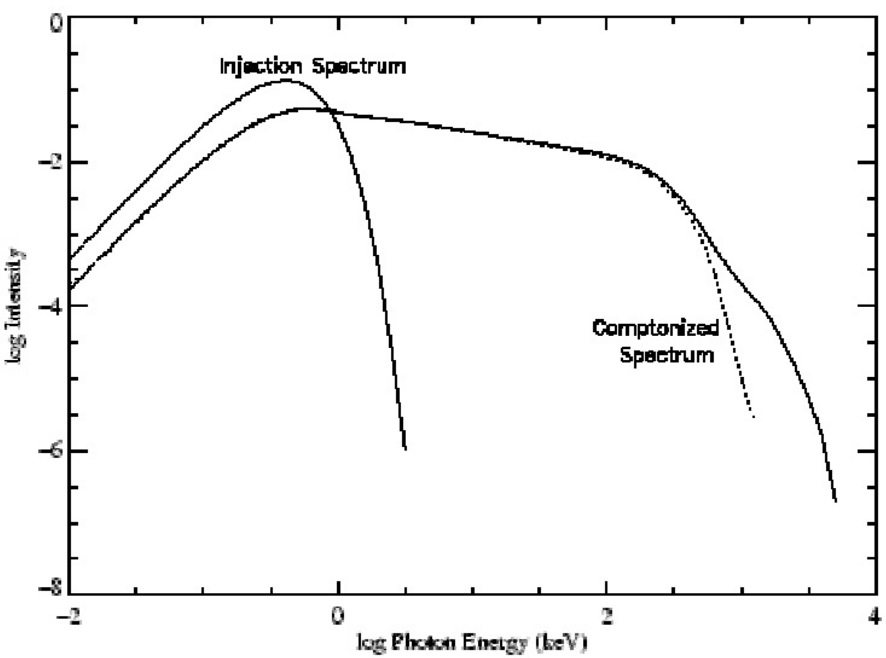
$$y \approx \int \frac{4kT_e}{mc^2}\sigma_T n_e dx$$



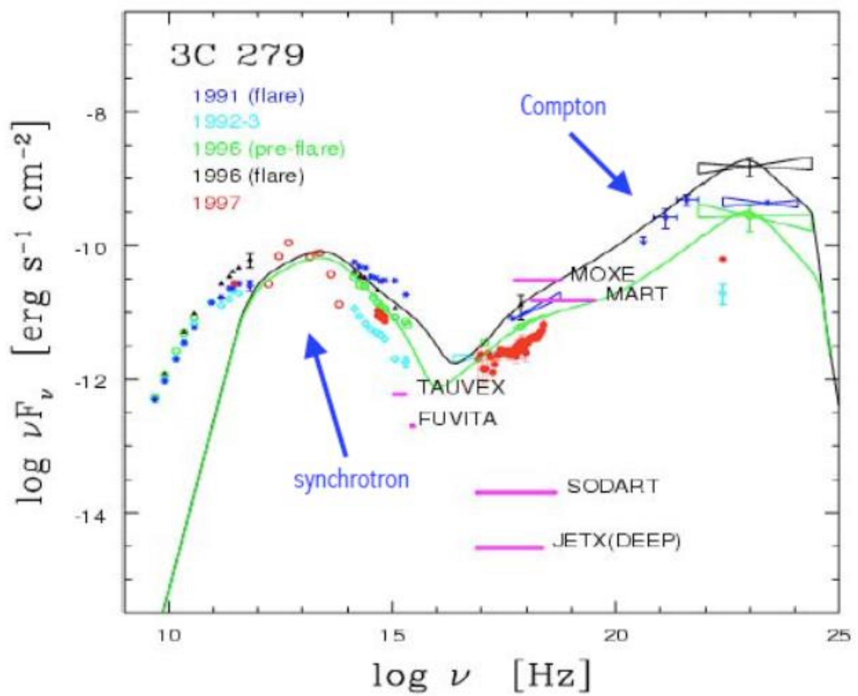


➢ *physical information: temperature (kTe) / distribution of the electrons, spectrum of the seed photons, optical depth and geometry of the source*

➢ *examples: X-ray binaries, AGNs, blazars…*



Comptonization of bb seed photons (BHC, AGNs)



Comptonization of Synchrotron radiation (Blazars)

❑ ***Thus, the determination of the spectral continuum over a broad energy band (as often, in X-rays) is fundamental for discriminating the emission process***

Blackbody

Optically Thick

$$B_\nu(T) = \frac{2h}{c^2}\frac{\nu^3}{e^{h\nu/kT}-1}$$

Bremsstrahlung

Optically Thin

$$\epsilon_\nu^{ff} = 6.8\times10^{-38}\frac{ergs}{s\ cm^3\ Hz}\ Z^2 n_e n_i T^{-1/2} e^{-h\nu/kT}\bar{g}_{ff}$$

Synchrotron

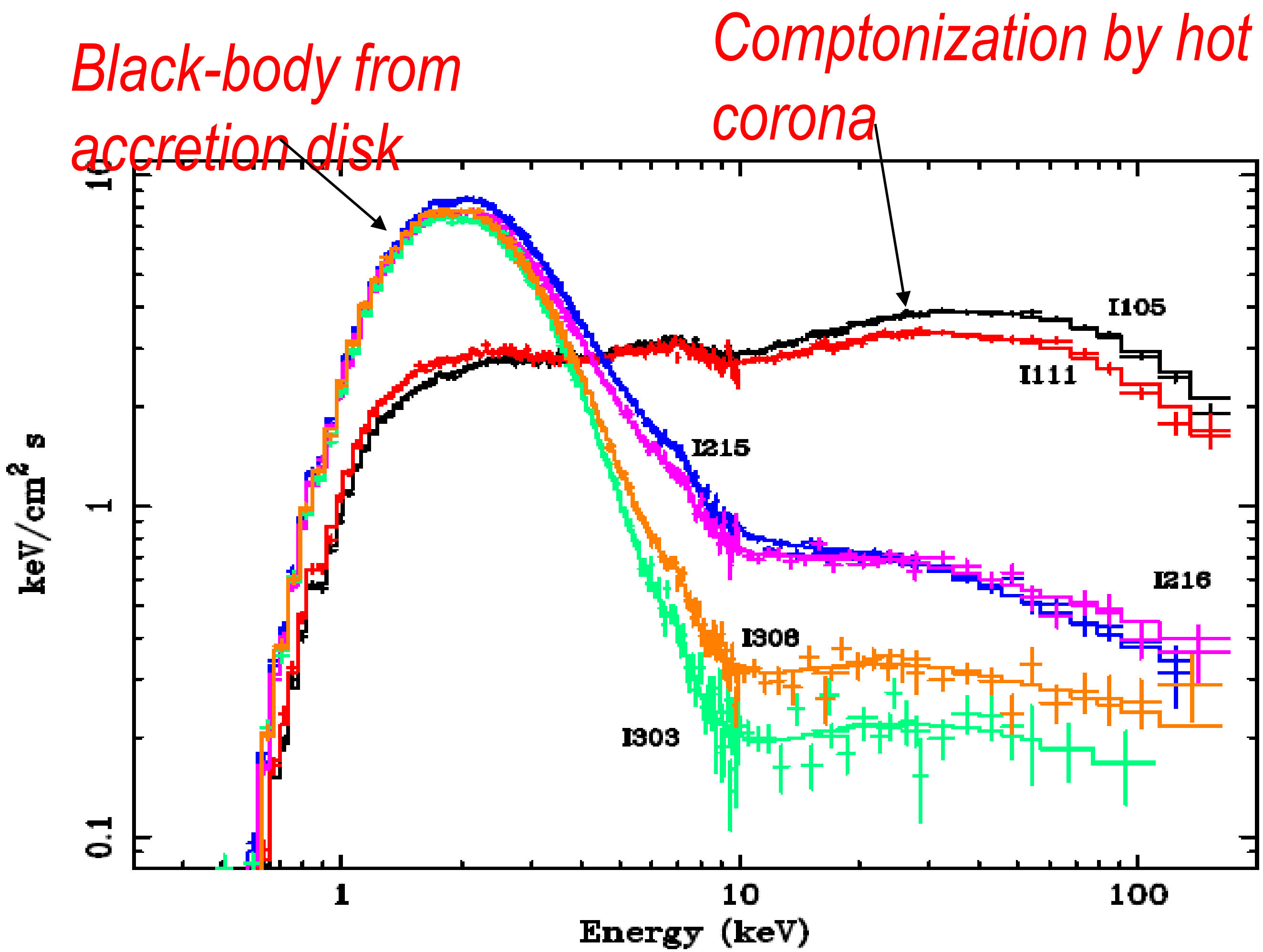
Optically Thin

$$\frac{dE}{dt\,dV\,d\nu} = \frac{\sqrt{3}q^3}{mc^2(p+1)}\left(\frac{3q}{2\pi mc}\right)^{\frac{p-1}{2}} C_\gamma B_\perp^{\frac{p+1}{2}} \nu^{-\frac{p-1}{2}} \Gamma_1\Gamma_2$$

Optically Thick

$$S_\nu \sim \nu^{5/2}$$

❑ ***in many classes of sources, more than one process is at work***



Spectral states in BHC XTE1650-500