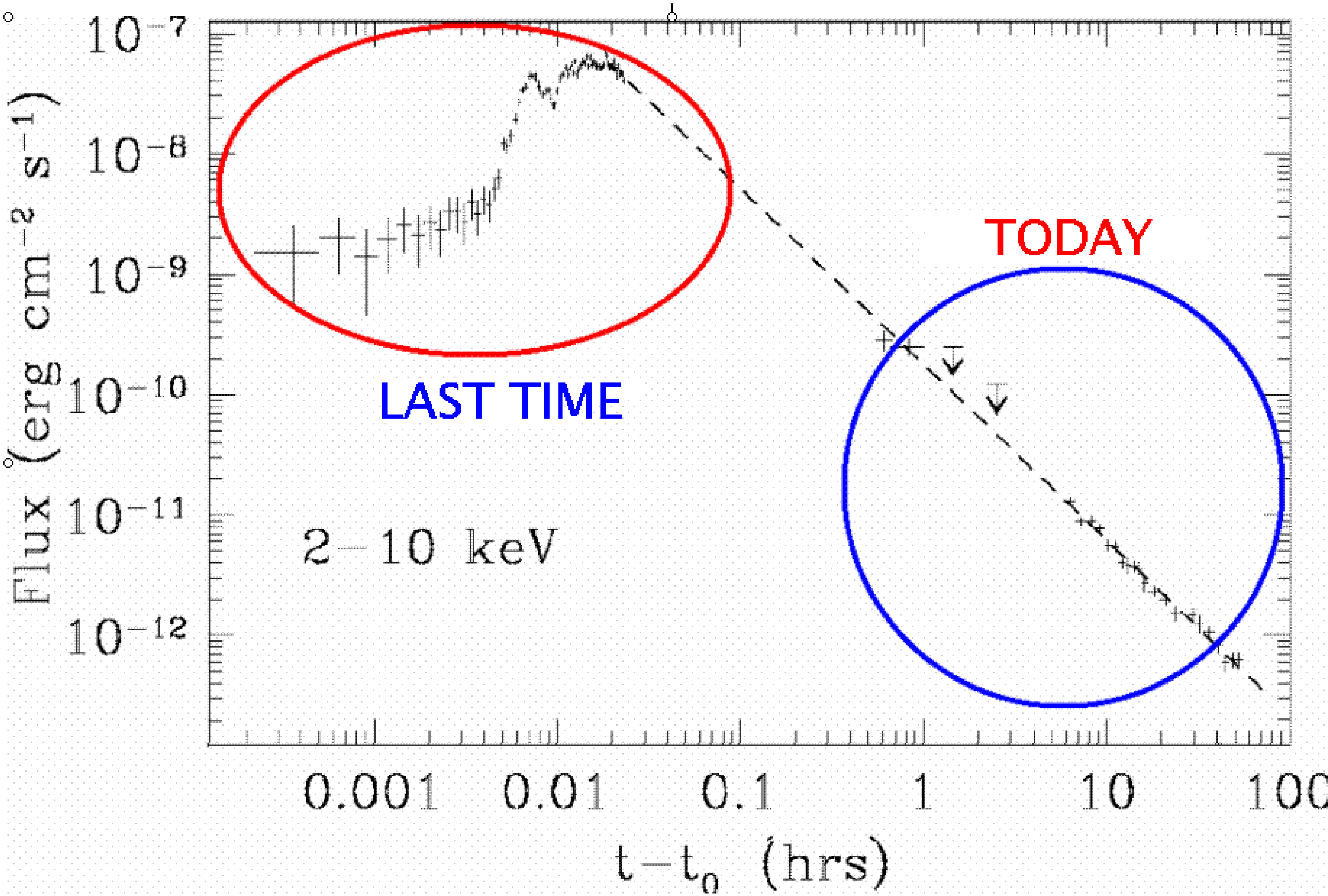
Gamma Ray Bursts II



Content

- Description of afterglow phenomenon The SN-GRB association
- Explanation of prompt and afterglow phenomenon
- Host galaxies
- Future of GRB research

- Norbert Langer will discuss the central engine on June 10th

The situation of 1996

- Although cosmological models were already favored, Galactic models could not be ruled out 100%
- Gamma-rays alone are not sufficient for a complete explanation of the phenomenon. In particular: they don't reveal the distance -> unknown energy budget
- Desperate need for optical counterparts. If cosmological, redshifted spectral lines or edges should be obvious
- Optical counterparts can only be found through arcminute GRB localizations -> IPN attempts fruitless due to delay
- Alternative method: localize quasi-promptly through X-rays instead of gamma-rays. Ginga X-ray measurements of GRBs at the end of the 1980s proved potential -> High-Energy Transient Explorer. Conceived in 1981/6, built in 1992/6, November 1996 launch failed (no stage 3 separation), rebuilt and launched in Oct 2000
- Coincidence passed the coin to a Dutch instrument on an Italian satellite which was launched in April 1996

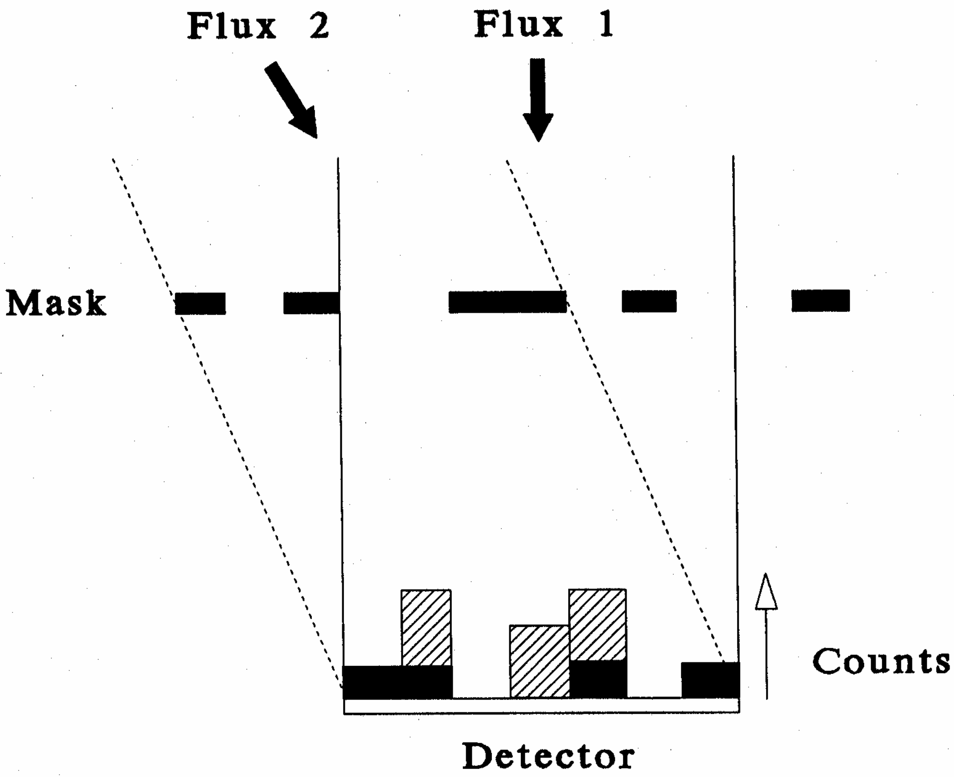
Locating GRBs quickly in practice

- Problem 1: focusing techniques don't work in gamma-rays (will change in next decade with multilayer mirrors for < 100 keV)
- Problem 2: focusing techniques do not allow large field of views in gamma-rays
- Problem 3: position-sensitive gamma-ray devices only recently possible (solid state devices instead of crystals)

- -> solution in ~1990: go to X-rays and use coded aperture imaging technique

Principle of coded aperture imaging

- principle: 'camera obscura' or pinhole camera. No optics, but still imaging
- for astronomical purposes need more collecting area -> use multiple holes in a random pattern → coded aperture camera
- angular resolution set by hole size / detector distance
- multiple images require algorithm to reconstruct sky image out of detector image
- image quality set by pattern and reconstruction
- nature of imaging makes it less sensitive than direct (focusing) techniques, but offers arbitrarily large field of views for any wavelength
- For illustration, see introduction



GRB experiments based on coded aperture imaging

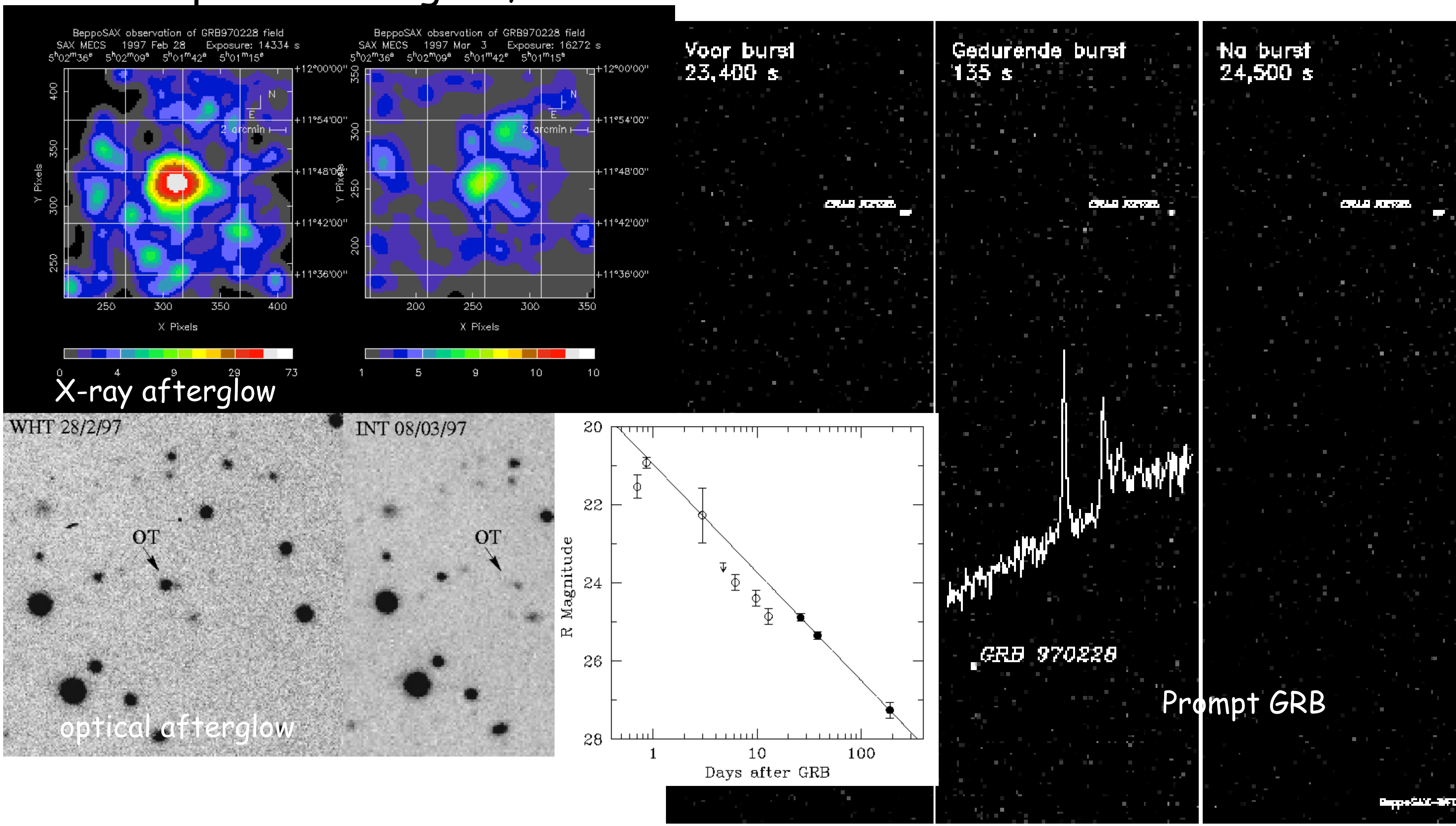
BeppoSAX	Italy+NL	1996-2002	92 localized
HETE	USA+France+Japan	2000-2007	80
INTEGRAL	ESA+Russia	2002-	48..
SWIFT	USA+UK+Italy	2004-	344..

Swift-BAT mask: big!

INTEGRAL-IBIS mask

Start of ‘afterglow era’

- February 28, 1997 (30 yrs after first detected GRB) → X-ray and optical afterglow, but no immediate distance



Progress in afterglow detections

(approximate numbers)

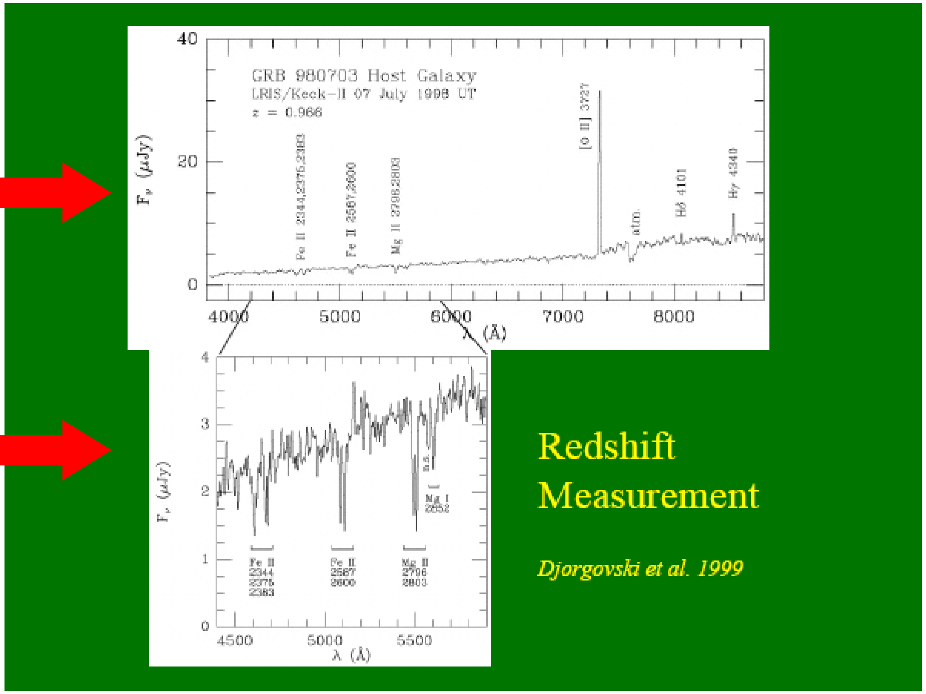
1997	10 (SAX)
1998	11 (SAX)
1999	18 (SAX)
2000	12 (SAX)
2001	16 (SAX)
2002	46 (SAX+HETE)
2003	37 (HETE+INTEGRAL)
2004	37 (HETE+INTEGRAL)
2005	109 (HETE+INTEGRAL+Swift)
2006	122 (HETE+INTEGRAL+Swift)
2007	109 (INTEGRAL+Swift)

General (for followed up cases; as of May 14, 2008):
6/7 X-ray afterglows (325), 2/3 optical (220), 1/4 radio (55)

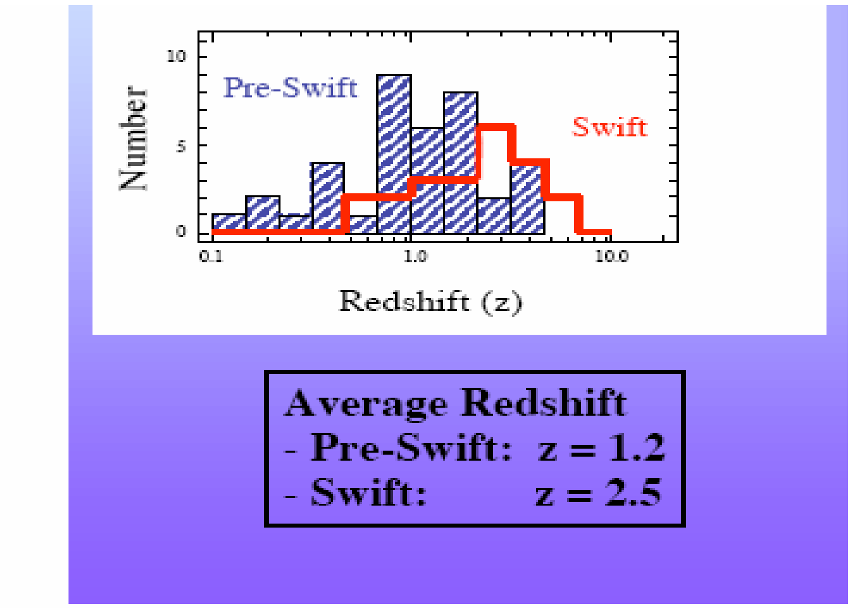
Redshift determinations

Either through

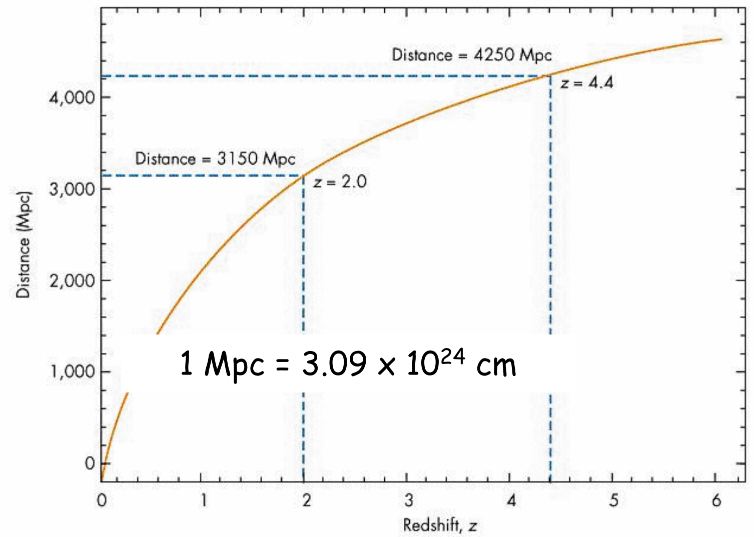
- emission features in the spectrum of the host galaxy long after the GRB occurred
- absorption features in the GRB optical spectrum



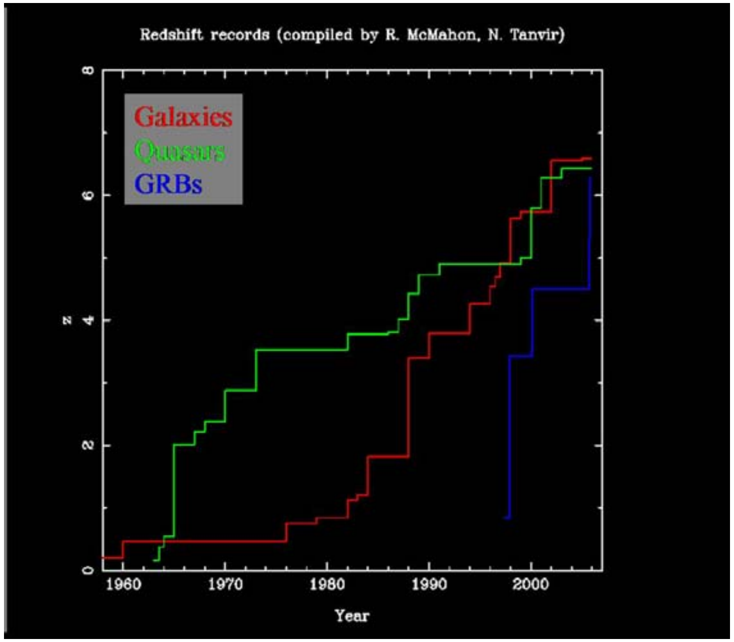
Distribution of 74 redshifts (based on 2006 data)



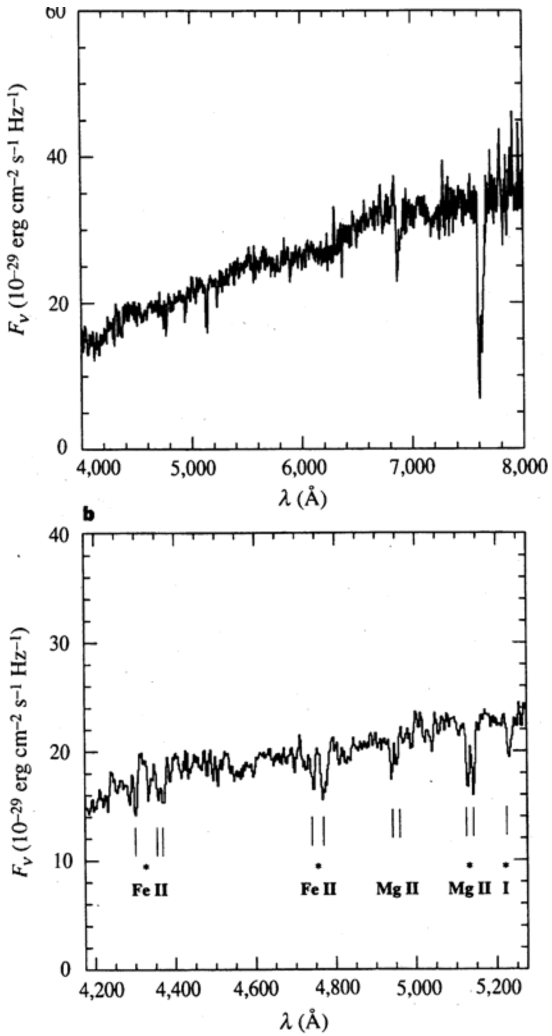
This histogram is a few years old. As of May 14, 2008, there are 140 certain redshifts



The speed of GRBs probing the early universe is faster than of galaxies or quasars



GRB 970508: first quick redshift, first radio afterglow, first direct evidence for relativistic expansion



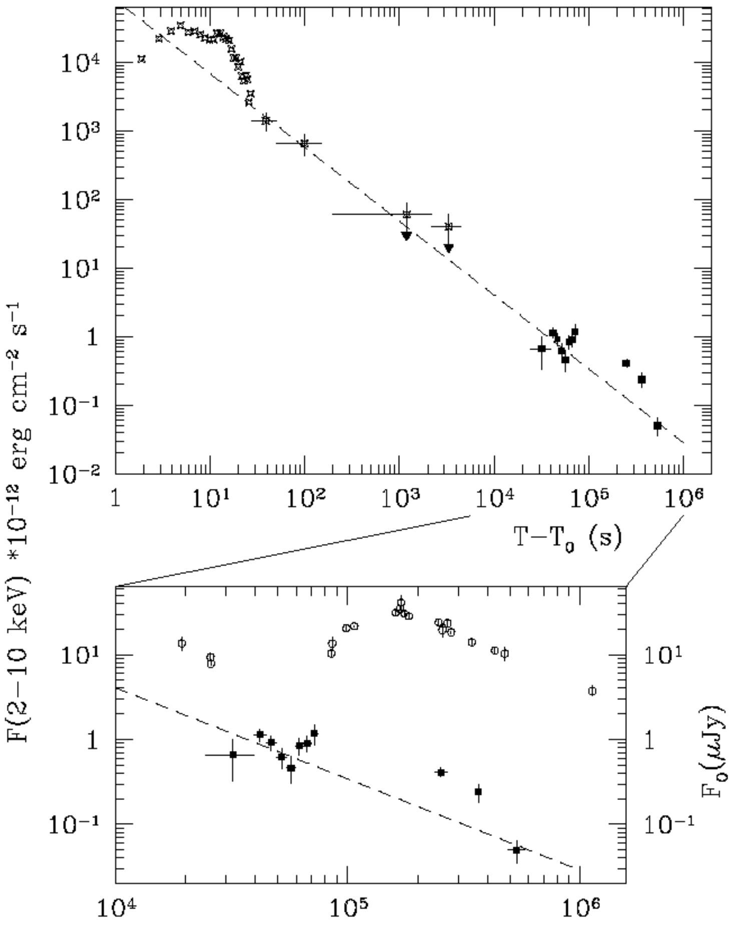
z = 0.837 ->

DL = 1.4 x 1028 cm →

E_{iso} = 7 x 10^{51} erg

GRB 970508 afterglow light curves

X-rays



Optical (red)

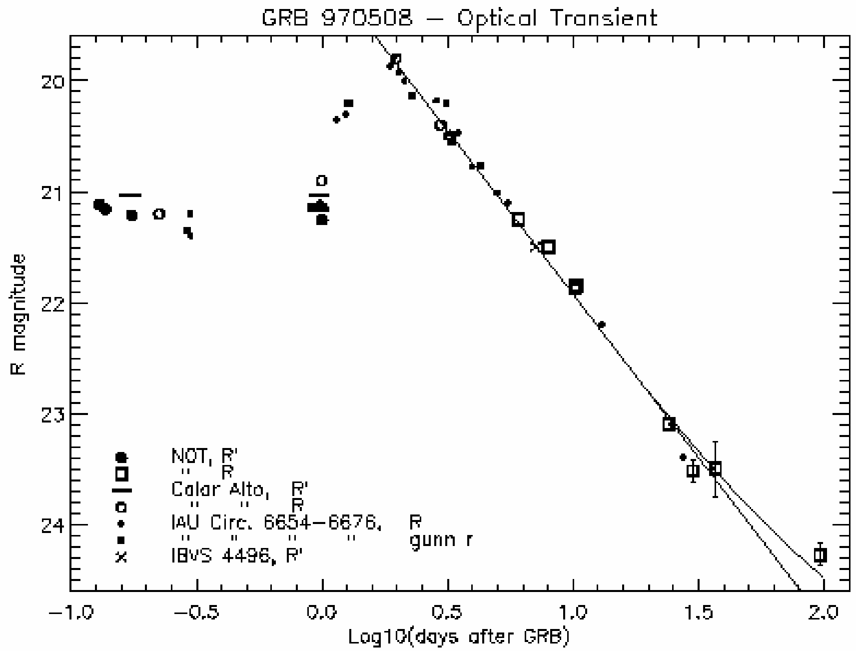
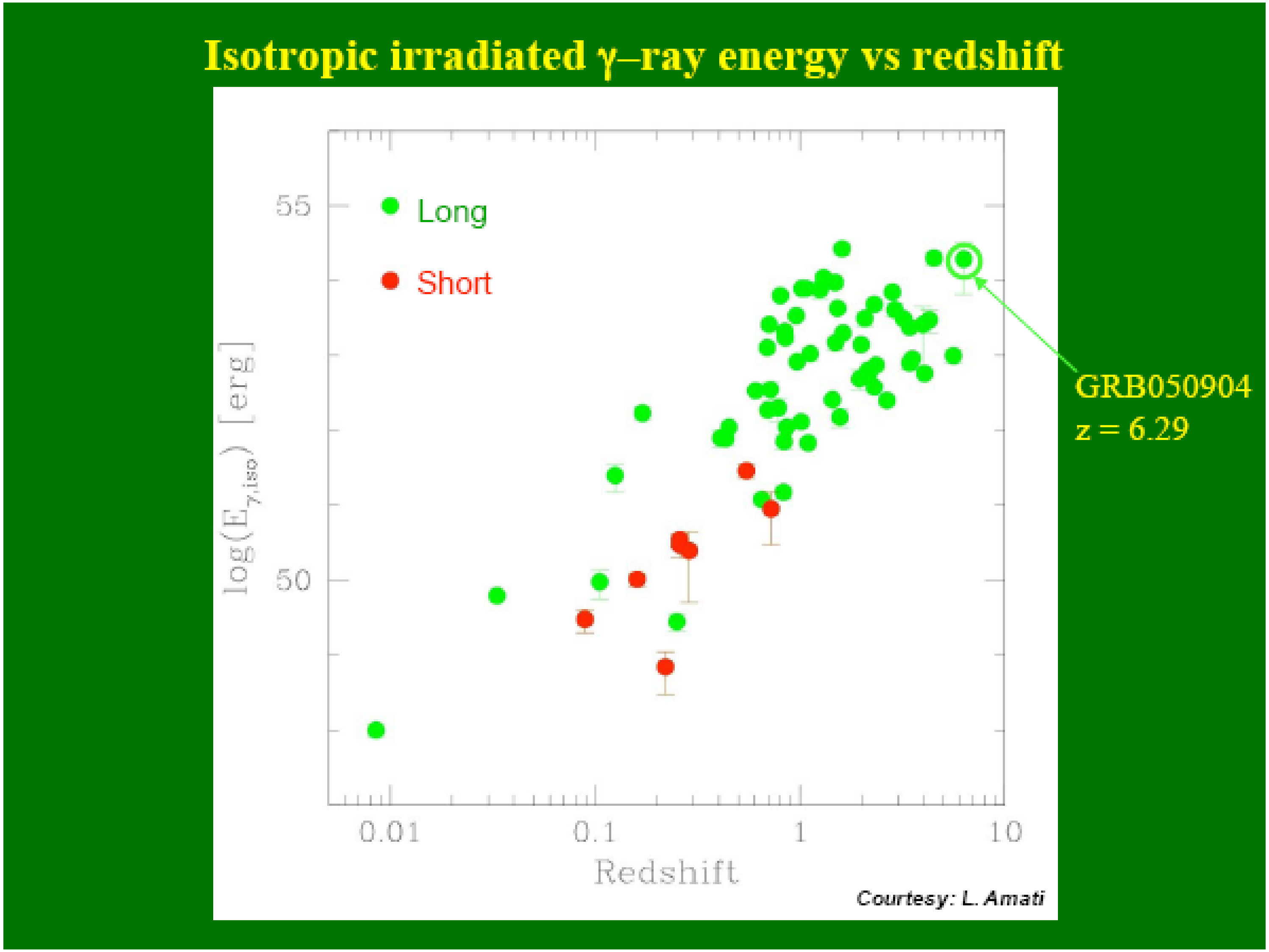


Diagram of isotropic energy vs redshift

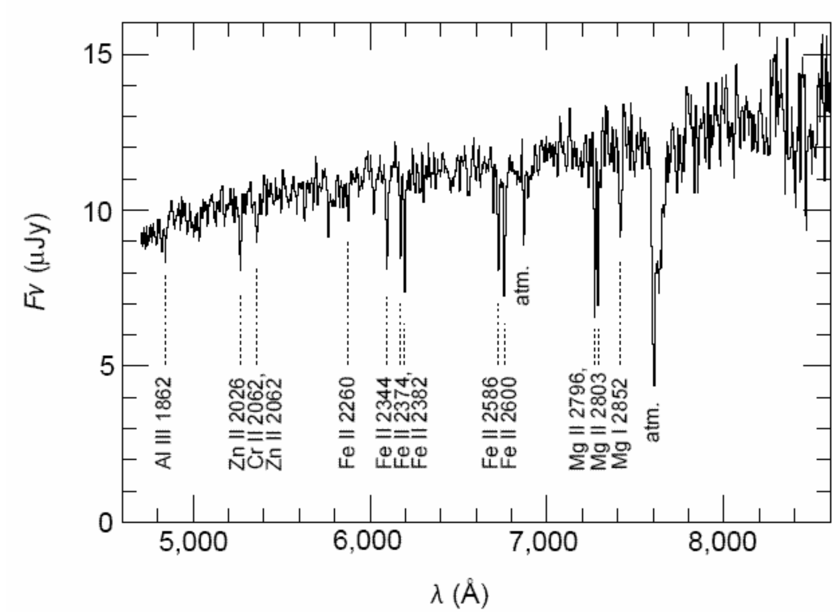


One would not expect a relation, but two selection effects give such an appearance: 1) there are more low-fluence bursts than high-fluence (which is why we haven't seen high-fluence ones yet in the nearby universe due to small volume covered); 2) the low-fluence bursts at high redshifts are below detection threshold

GRB 990123: first evidence for a jet

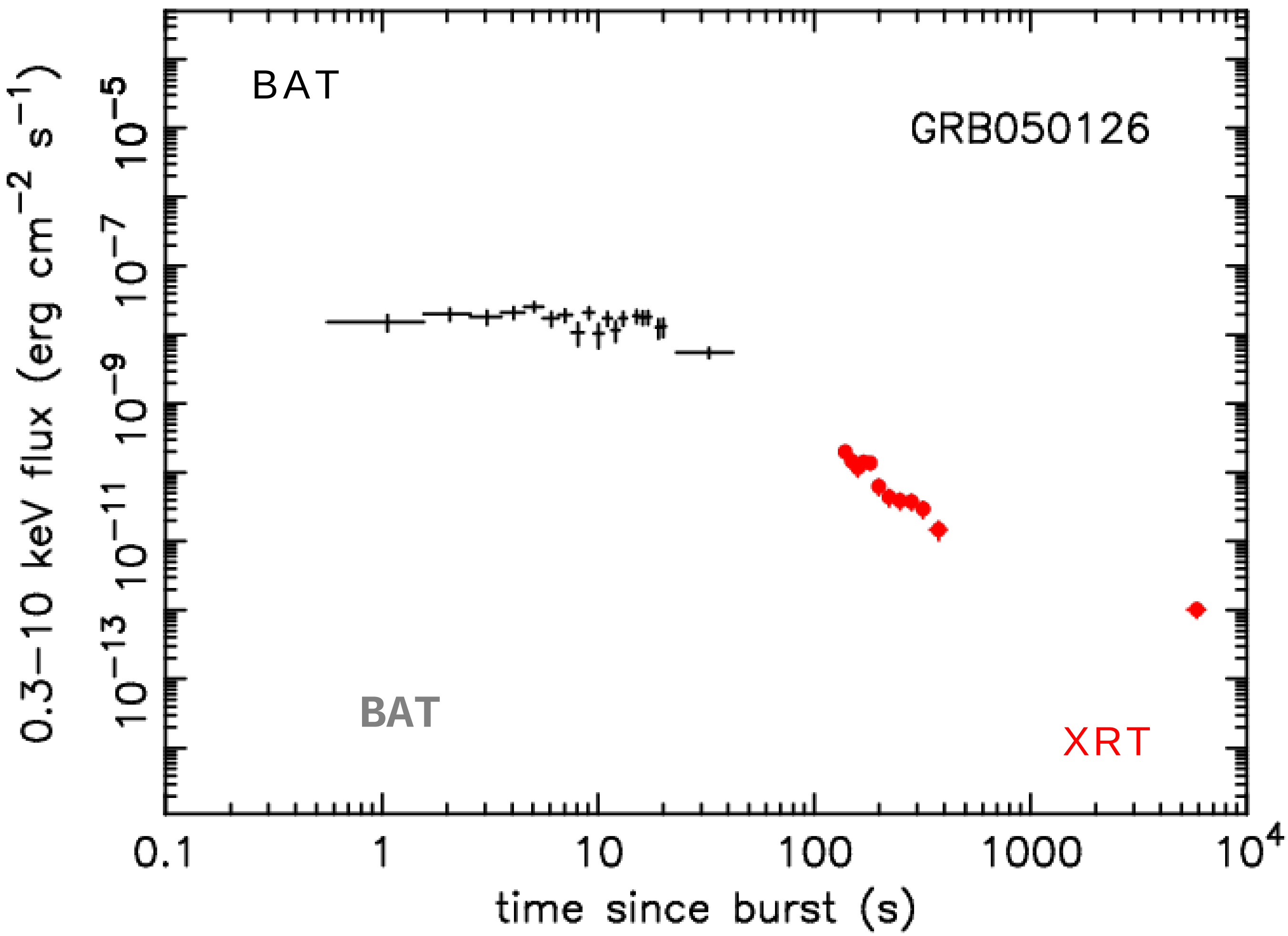
- z = 1.6
- implies prompt radiative energy of 3.4×10^{54} ergs $= 3\ M_{sun}\ c^2$ = ~ 100 SNe. Impossible.

-> there must be a jet that we're looking straight into!



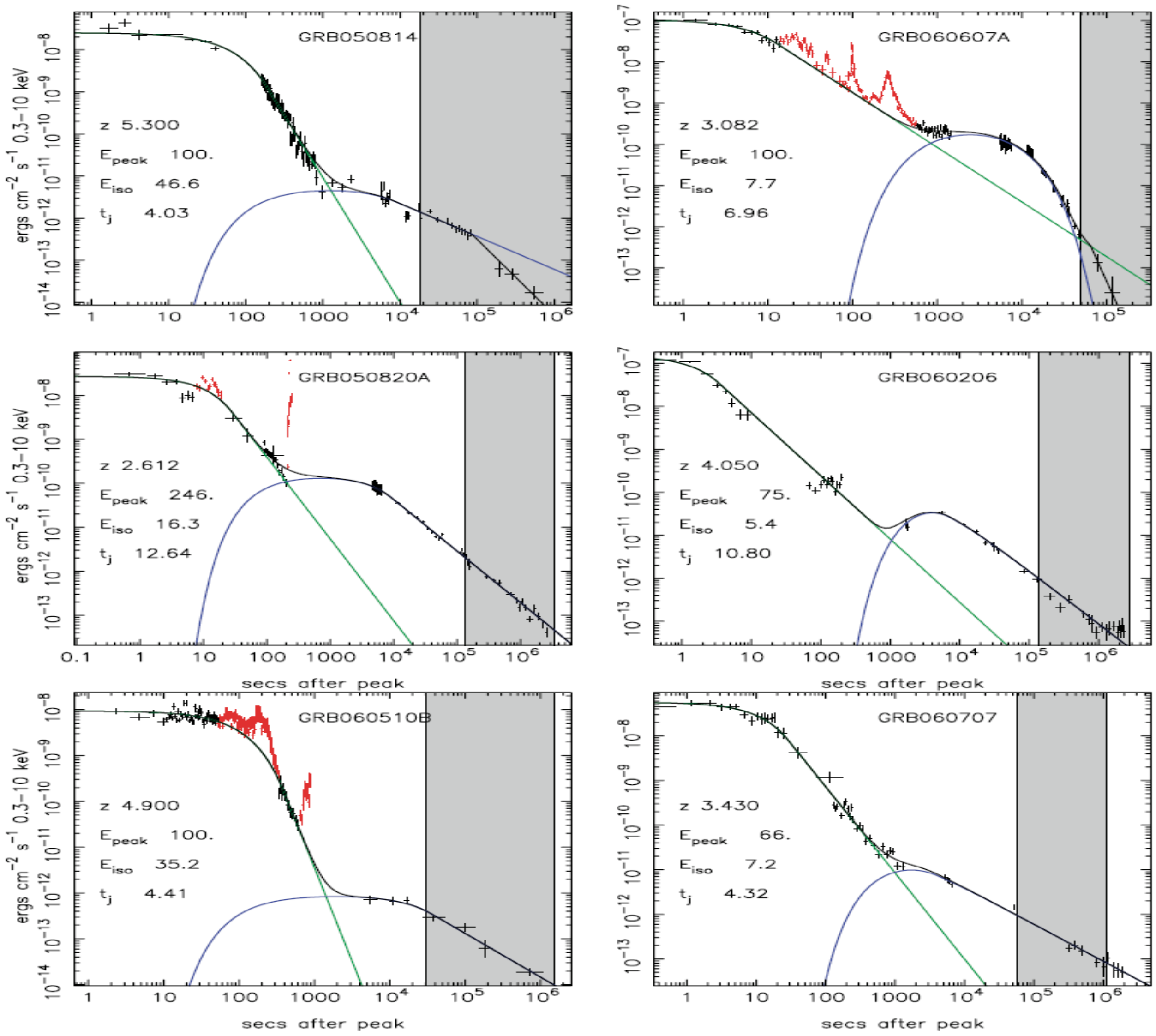
Kulkarni et al. 1999

Early X-ray lightcurves - The Swift Movie



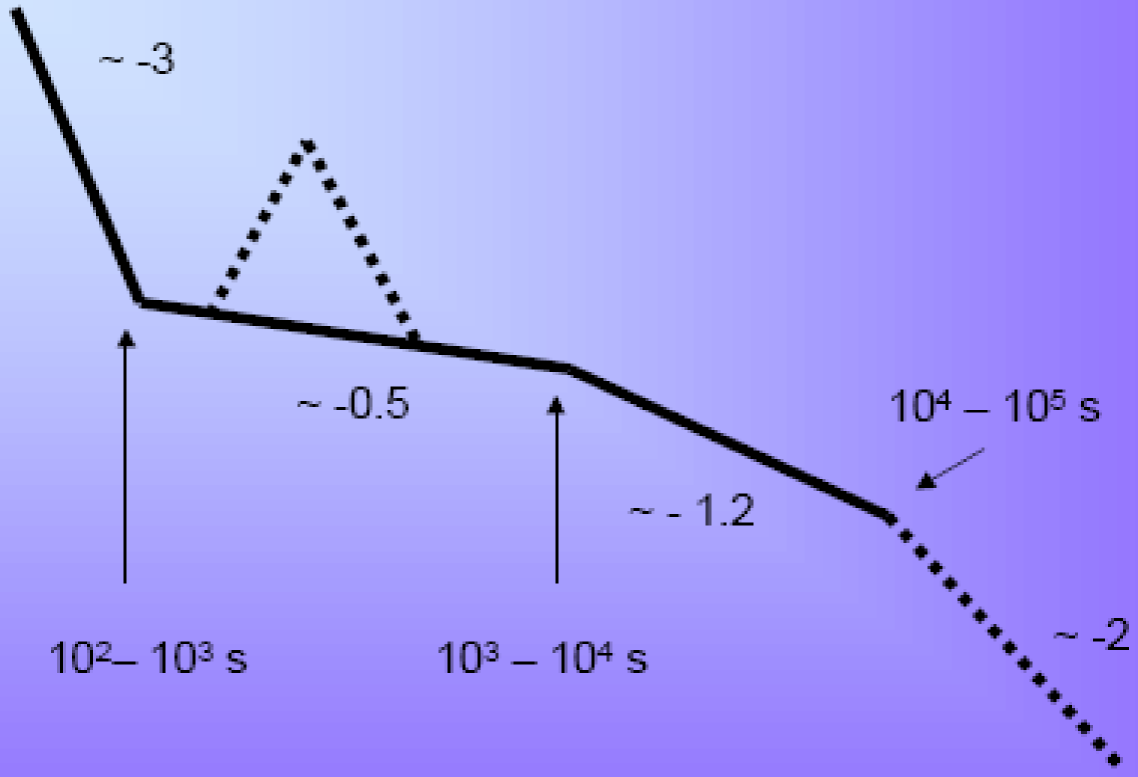
Paul O'Brien / UL

Late afterglow light curves in X-rays



O'Brien ApSS 311, 167 (2007)

Generic X-ray Lightcurve



Zhang et al., Nousek et al. 2005

Afterglow light curves in the optical

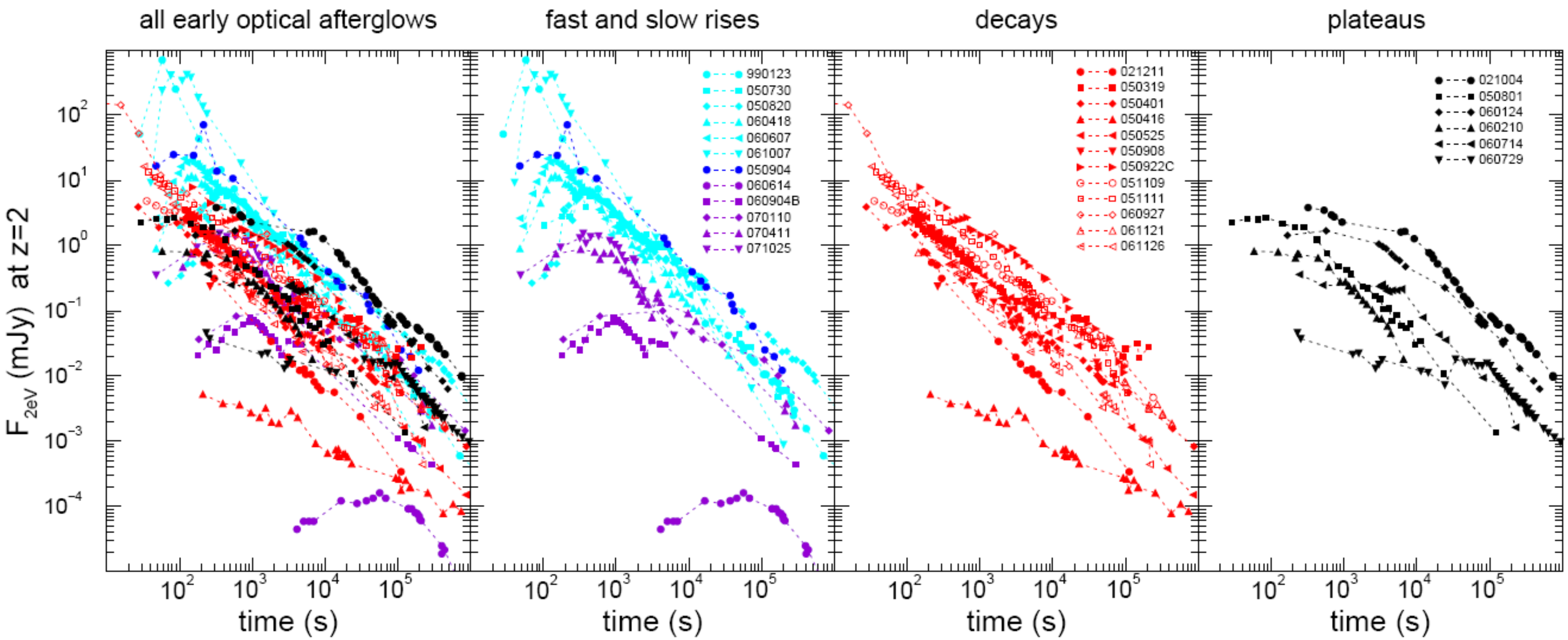
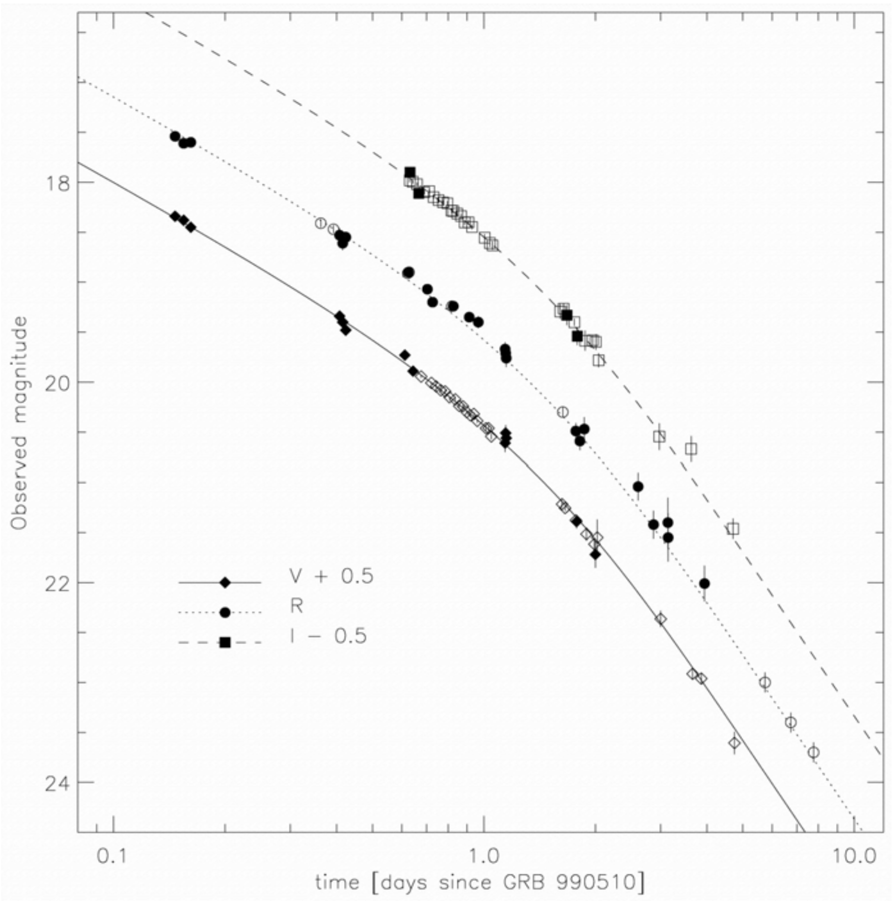


Figure 1. Optical light-curves of 28 GRB afterglows with known redshift, most of which were followed starting 1–few minutes after trigger. Optical fluxes have been corrected for Galactic and host dust extinction (the latter being estimated from the observed optical spectral slope and assuming an intrinsic slope of 0.75) and calculated for a common redshift $z = 2$. Color coding: light-blue for 6 afterglows with a fast rise, purple for 5 slow risers, dark-blue for GRB 050904 of uncertain type (fast or slow-rise), red for 12 afterglows with a decay since first observation (i.e. their peaks occurred earlier than first measurement and have been missed), black for 6 afterglows with optical plateaus. Note that the luminosity of the afterglows with fast rises has a very narrow distribution at 0.5–5 ks, although they peak at different times. The other types of optical afterglows (plateaus and decays) have much wider luminosity distributions.

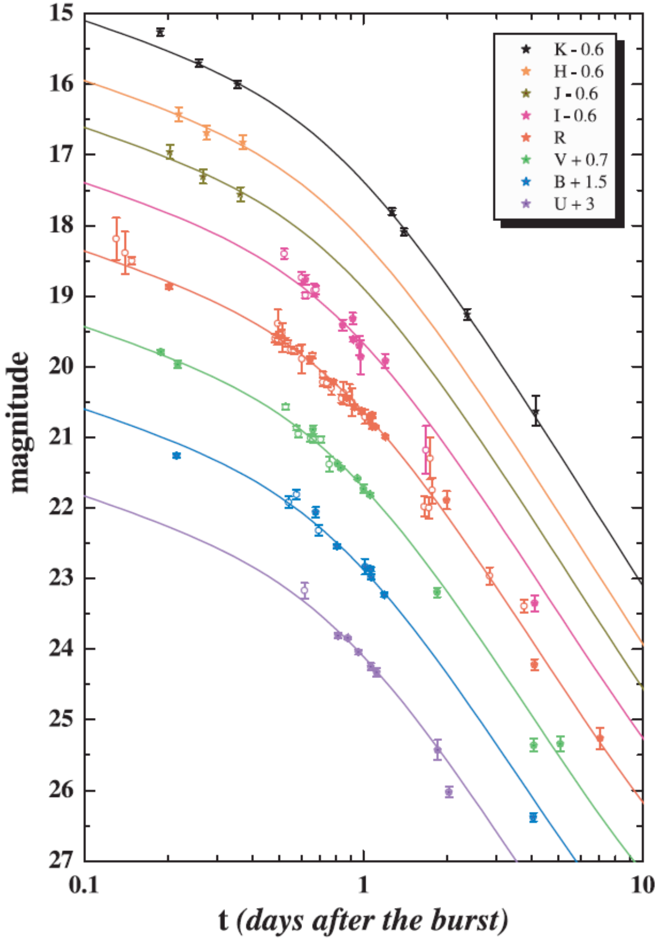
Panaitescu & Vestrand
arXiv:0803.1872

Achromatic decay breaks..

GRB 990510



GRB 030326

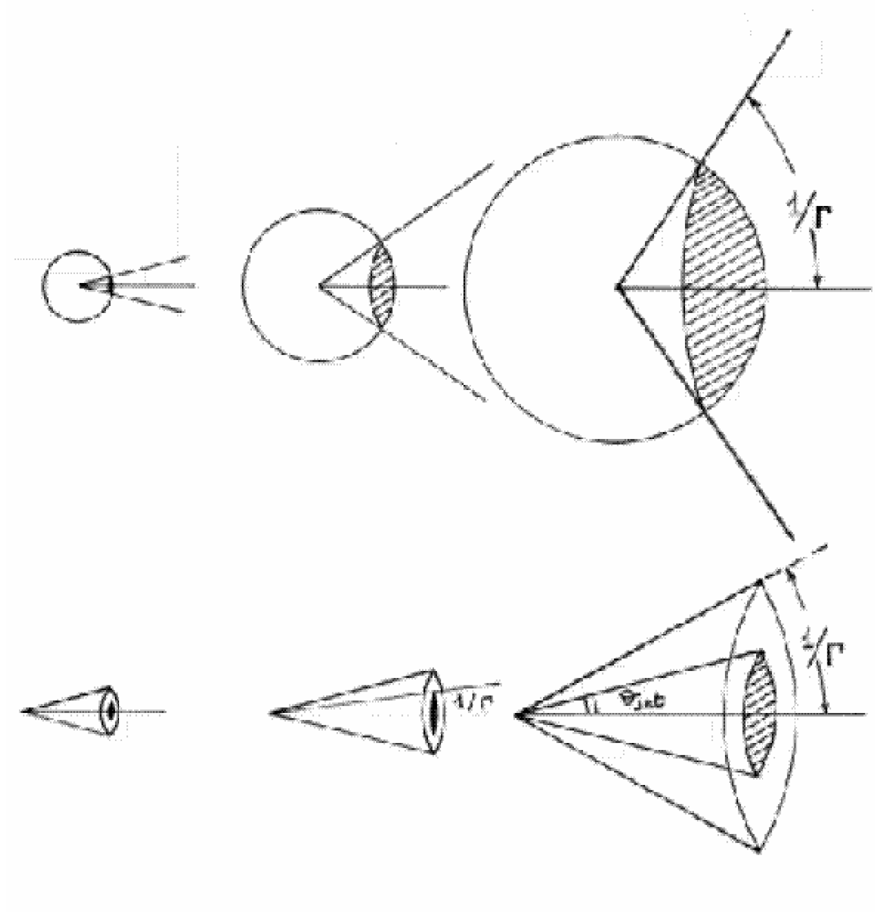


Achromatic break due to jet

- Achromatic break happens if the relativistic beaming angle $\theta_r = \Gamma^{-1}$ passes over the jet angle
- Time of break constrains the jet angle θ_j :

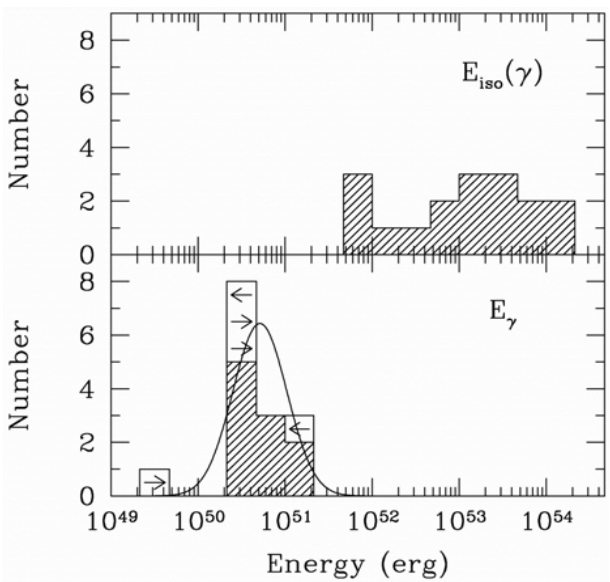
$$t_{\rm jet} \approx 6.2 (E_{52}/n_1)^{1/3} (\theta_0/0.1)^{8/3}\ \rm hr.$$

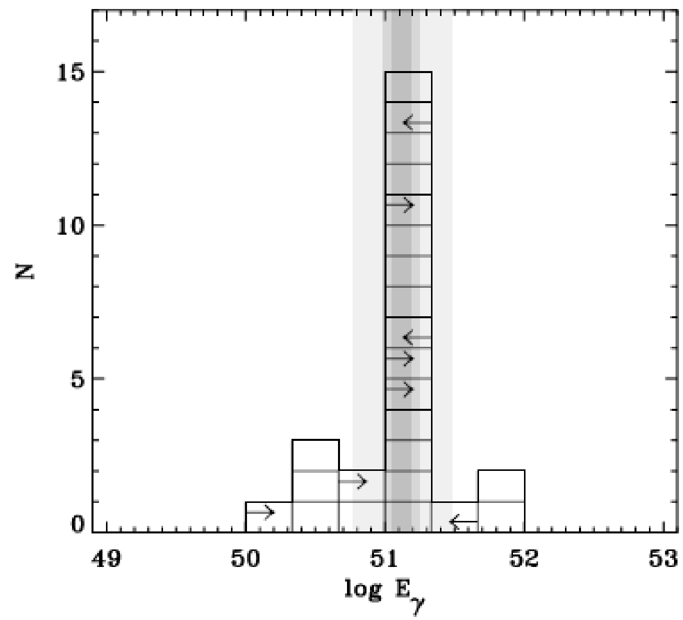
  with E_{52} isotropic energy in units of 10^{52} ergs , n particle density in cm^{-3} of environment and θj full width of jet in rad (Sari et al. 1999)
- Problem: only minority of multi-wavelength GRB afterglows shows clear break..



Burst energetics

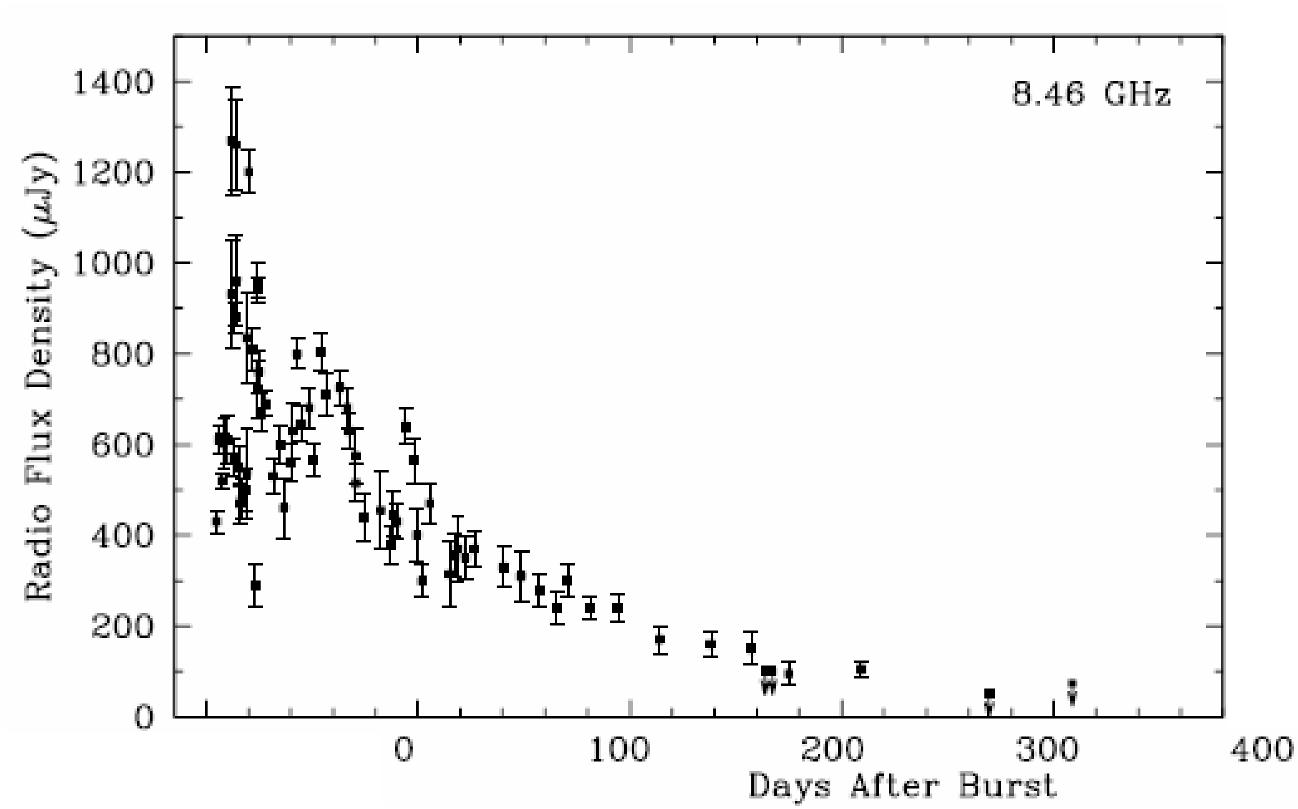
- isotropic prompt energies for GRBs with redshifts show a range of 10^3
- many show marginal evidence for achromatic breaks in their afterglow decays, yielding jet angles
- correct for beaming and the GRB energies narrow down to 1.3 foe





Frail et al. 2001; Bloom et al. 2003

Just a quick note on radio afterglows

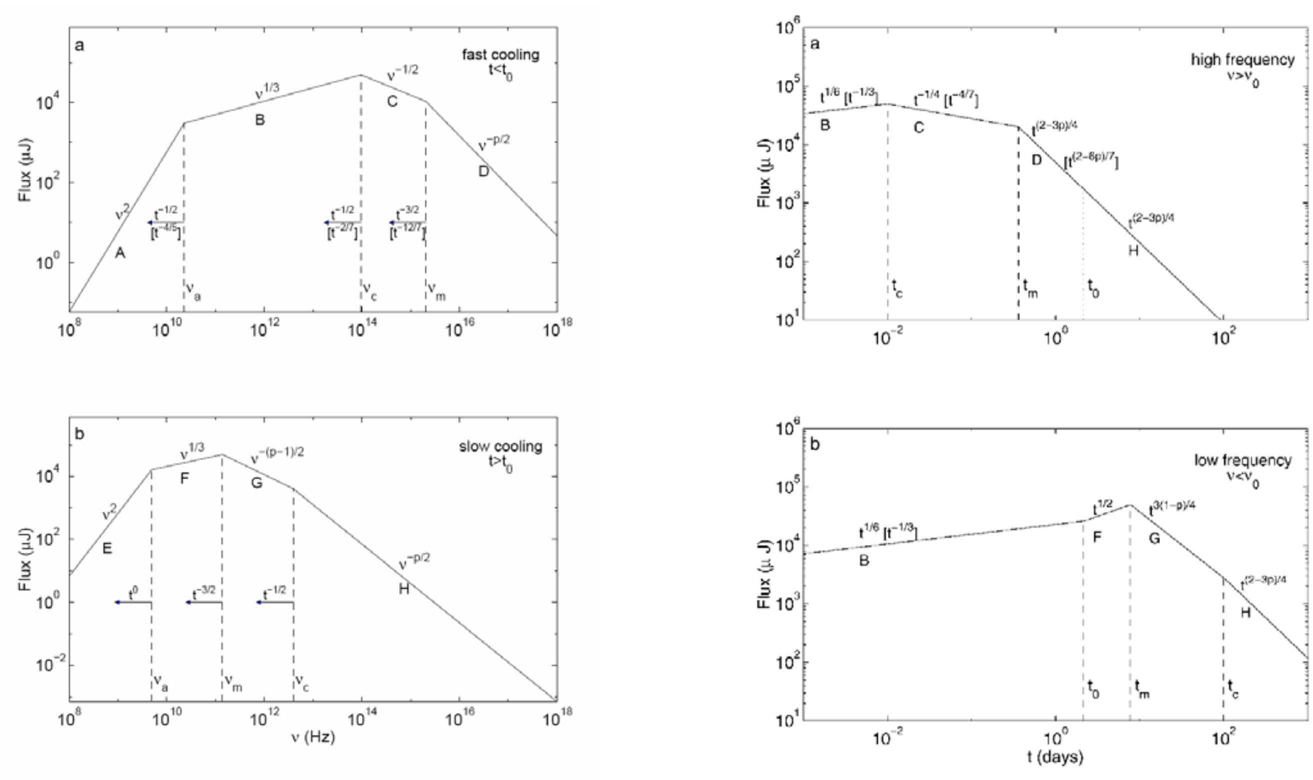


GRB 970508 (Frail et al. 2000)

Early variability due to changing refractive scintillation as a result of expanding source. No other radio afterglow showed this.

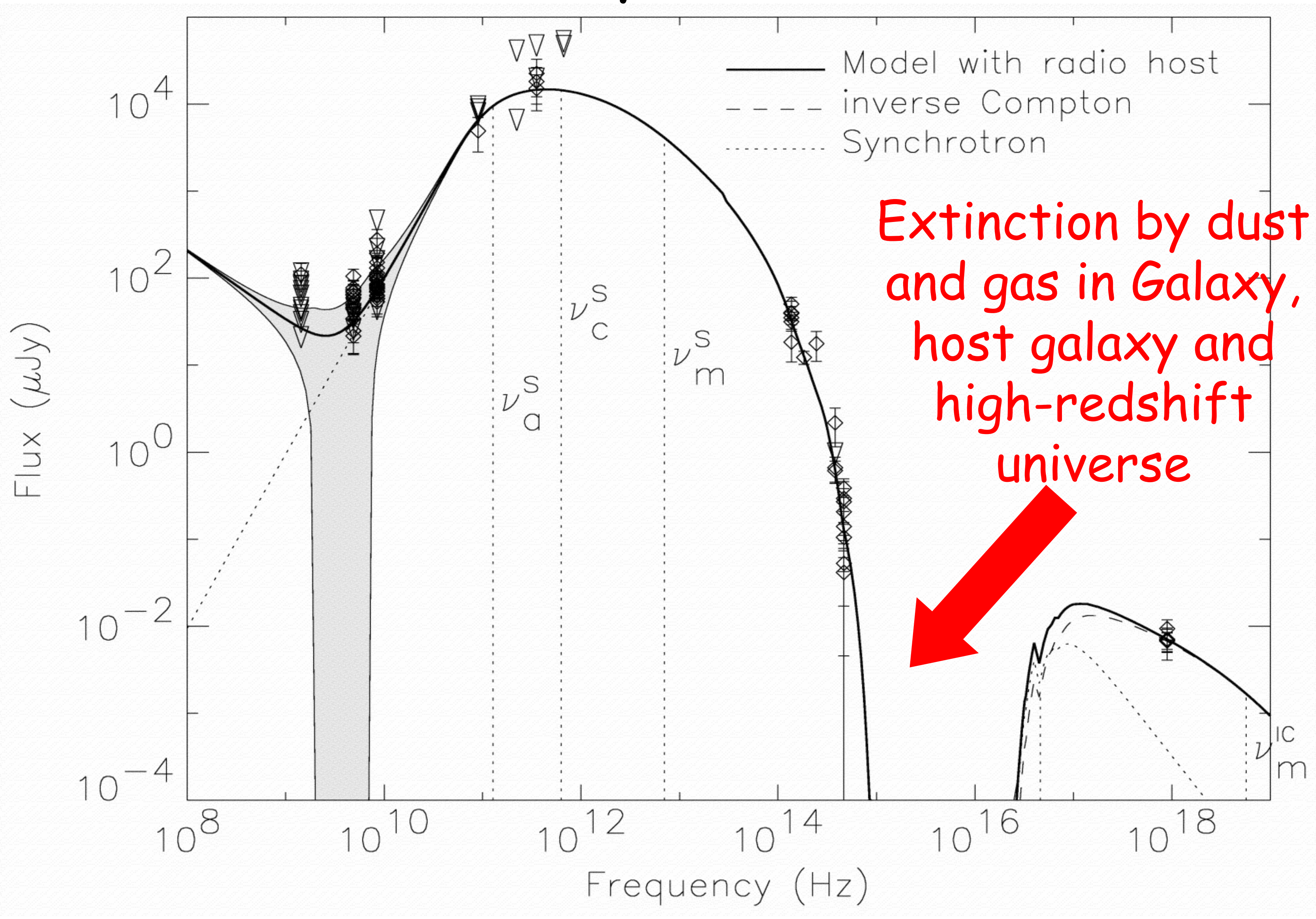
Afterglow spectra

- Synchrotron spectra with evolving breaks
- Parameter: electron power-law index p = 2.2-2.5 (N_e (:) Γ^{-p}), consistent with shock acceleration
- As time goes by, remnant expands and slows, and the spectra go to lower energies, dictating the multi-wavelength behavior



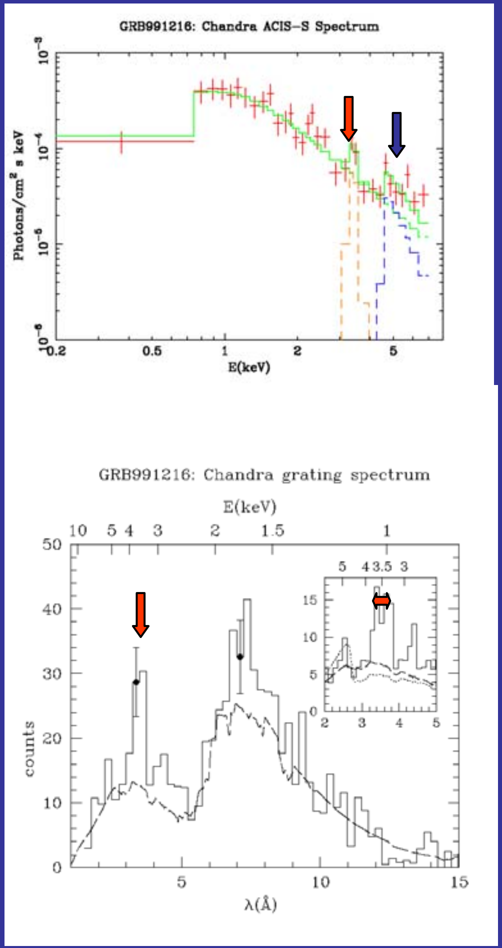
Sari et al
1998

GRB 980329 on day 2 (Yost et al. 2002)

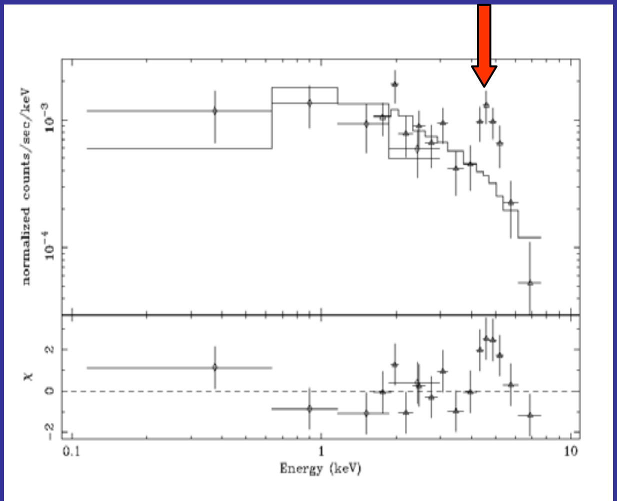


Iron features in X-ray afterglows, not seen since 2002 → false & due to incomplete instrument calibrations?

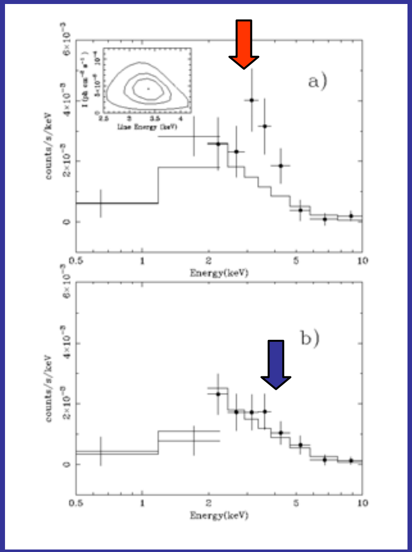
•GB991216 (Piro et al 2000)



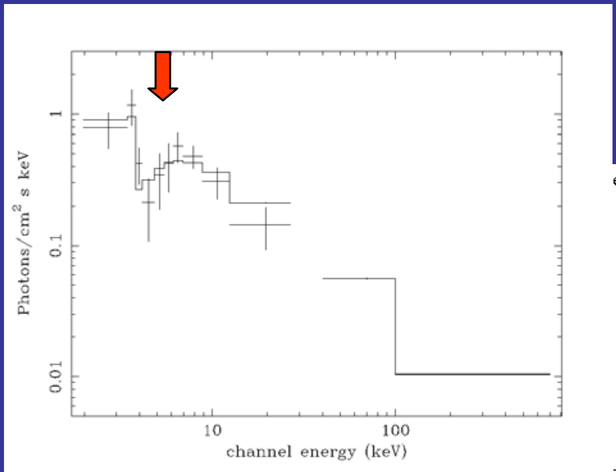
•GB000214 (Antonelli et al 2000)



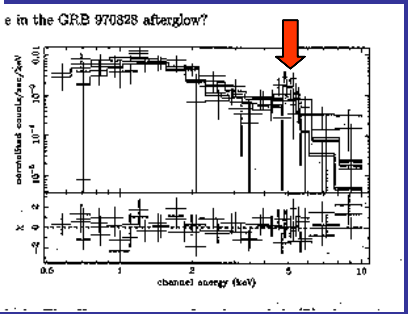
•GB970508 (Piro et al 1999)



•GB990705 (Amati et al 2000)



•GB980828 (Yoshida et al 1999)



General afterglow characteristics

- First order behavior:

  F (:) E $^{-\alpha}$ t $^{-\delta}$ erg s^{-1} keV^{-1} cm^{-2} with

  $\alpha_X \approx 1$ and $\delta_X \approx 1.4$ and $\delta_{opt} \approx 0.7$
- Emitted energies between 1 and 100% of prompt energy
- Lightcurves often show considerable structure, for instance flaring early on. This must be related to diversity and structure in the jet and environment
- X-ray lightcurves can be followed for at most 10 days, optical/radio sometimes for years
- Spectra are predicted to be combinations of various power laws with indices that are correlated with decay indices and breaks
- Peak fluxes are not standard candles, like in Type Ia Sne
- Incidental suggestions for narrow spectral features not seen in Swift era

The GRB-SN connection → central engine!

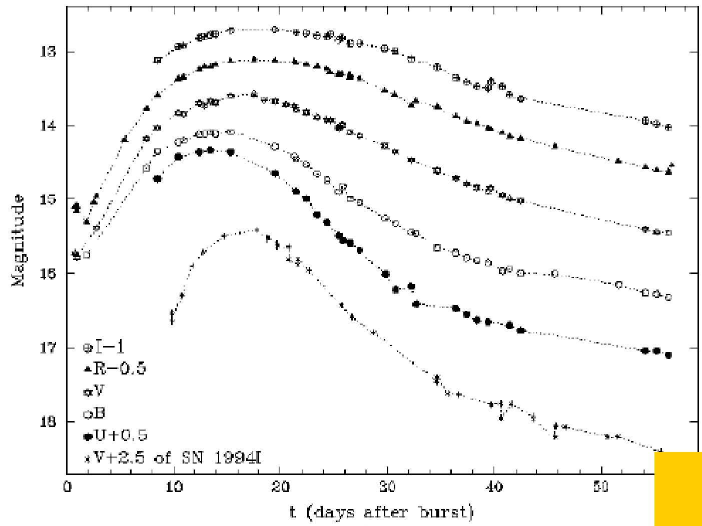
GRB980425
Supernova 1998bw (Type Ic)

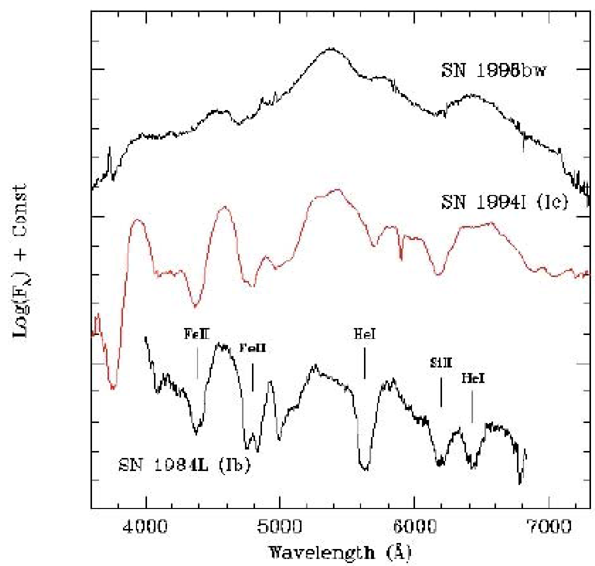
SN 1998bw in Spiral Galaxy ESO184-G82

z = 0.0085

ESO PR Photo 39a/98 (15 October 1998)

© European Southern Observatory



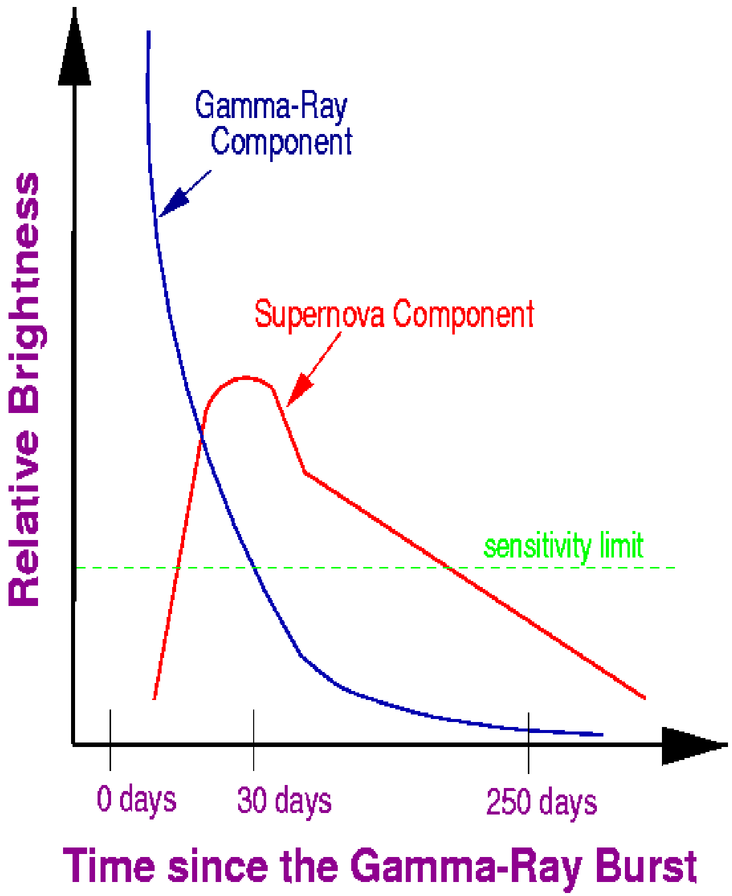


The distinguishing factor between afterglow and SN light: a much later peak

Finding GRB/SNe

- SN light much fainter than average GRB afterglow
  - → Need nearby GRBs to see it
  - → Need faint afterglow to see it
- Thus far, 4 GRB-associated SNe found among 220 optical afterglow cases:

GRB 980425	SN 1998bw	z=0.0085
GRB 030329	SN 2003dh	z=0.168
GRB 031203	SN 2003lh	z=0.105
GRB 060218	SN 2006aj	z=0.033



Type Ic SNe lightcurces

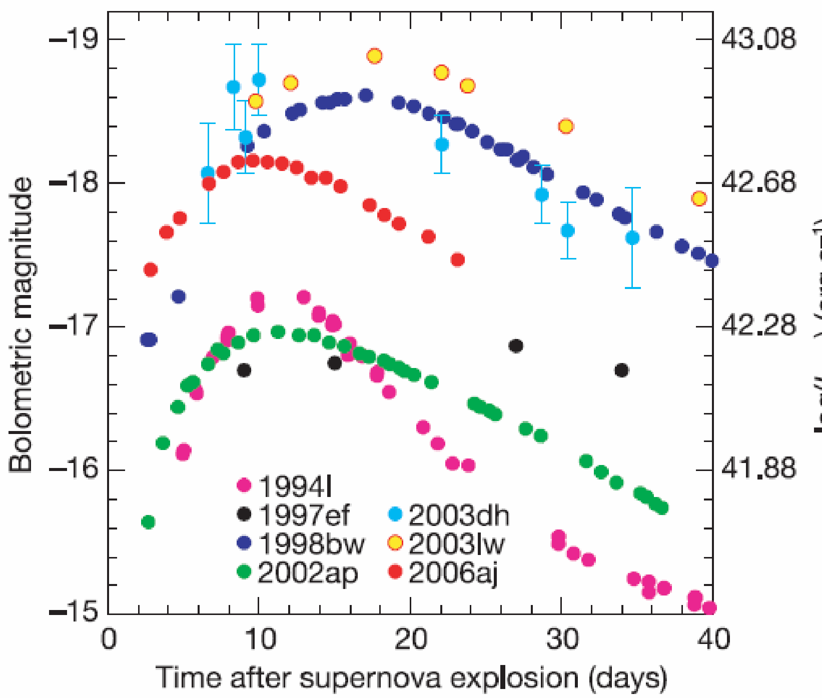


Figure 1 | Bolometric light curves of type Ic supernovae. We report, as a function of time, the luminosity and corresponding absolute magnitude of (1) the four spectroscopically identified supernovae associated with GRBs and XRFs, namely SN 1998bw (GRB 980425, $z = 0.0085$), SN 2003dh (GRB 030329, $z = 0.168$), SN 2003lw (GRB 031203, $z = 0.1055$), and SN 2006aj (XRF 060218, $z = 0.03342$); (2) of two broad-lined supernovae (not accompanied by a GRB), SN 1997ef and SN 2002ap; and (3) of the normal, intensively monitored SN 1994I. All represented supernovae are type Ic. The light curves, reported in their rest frame, have been constructed in the 3,000–24,000 Å range, taking into account the Galactic and, where appropriate, the host galaxy extinction[16,25–28]. For SN 2006aj, we used the optical light curves obtained during our monitoring and the near-infrared data reported by ref. 29, and a total extinction value of $E(B - V) = 0.13$ mag (see text). We adopted the extinction curve of ref. 30 with $R_V = 3.1$. The galaxy contribution has also been subtracted where significant. The initial time has been assumed to coincide with the XRF detection time, 18 February 2006 at 03:34:30 UT. The systematic errors (about 0.2 mag) have been omitted, for clarity. Error bars are 1σ. The shape of the light curve of SN 2006aj is similar to that of SN 2002ap, as are the spectra[18].

→ GRB Type Ic SNe are more luminous than non-GRB cases → 'hypernova'

What may make GRB Type Ic's different?

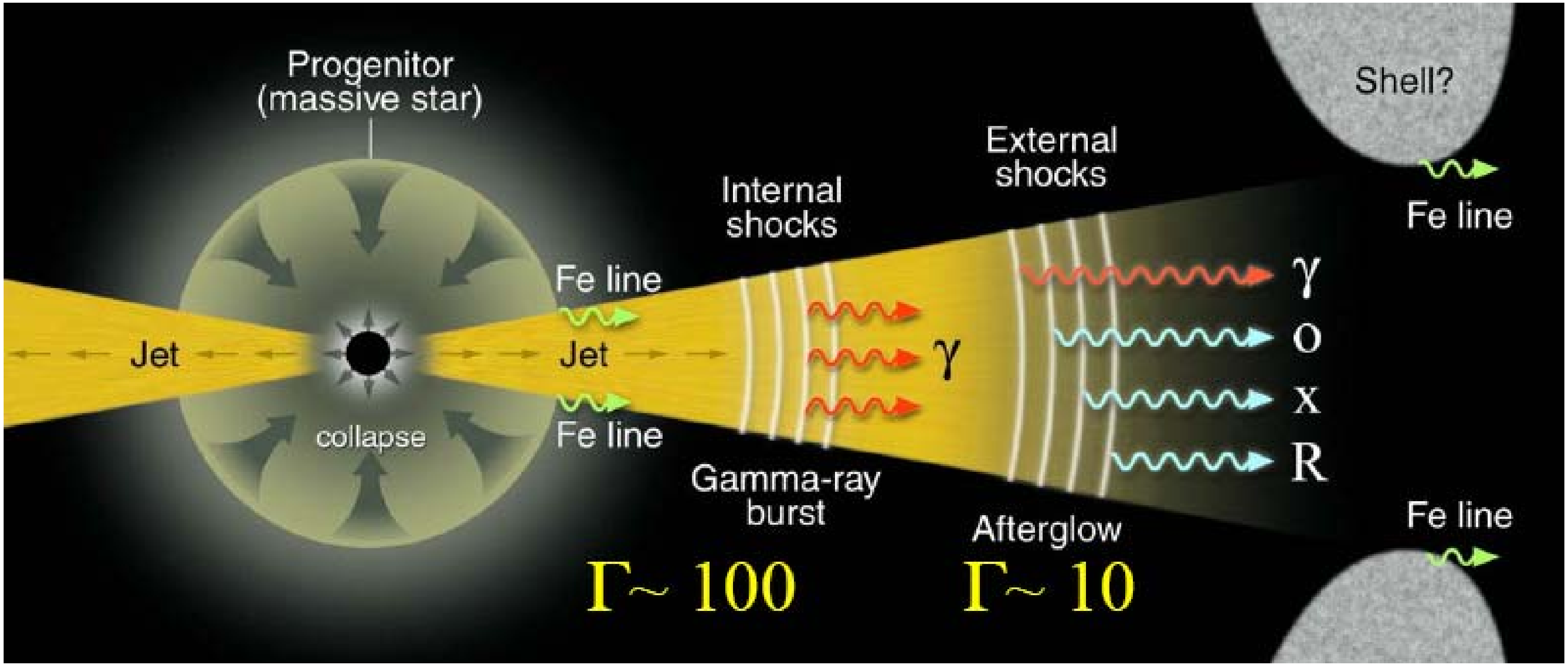
- Faster rotation of progenitor → highly collimated jet?

→ See Norbert Langer's lecture on the subject

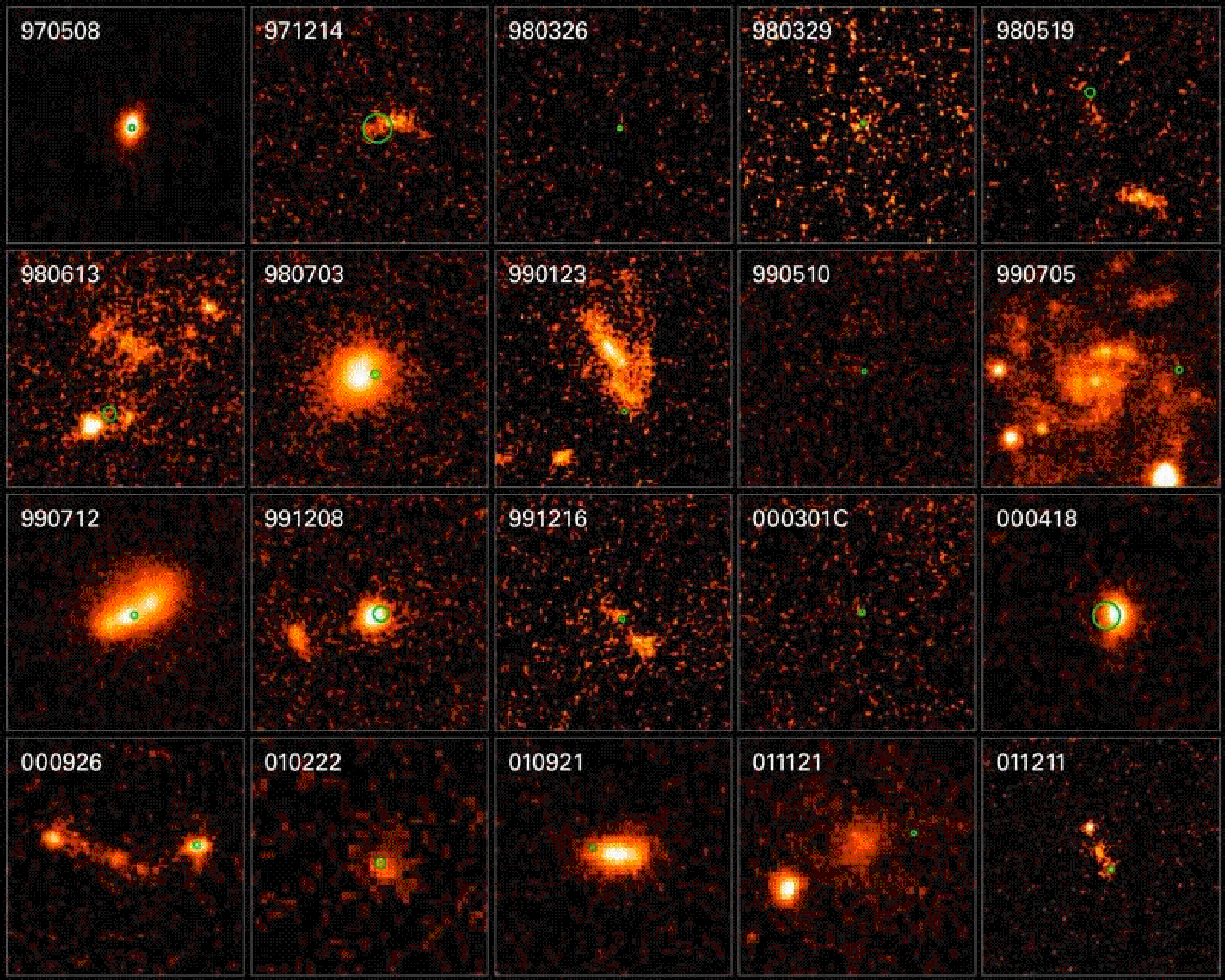
General physical picture of long GRBs:

Internal shocks are responsible for prompt emission

External shocks are reponsible for afterglow emission

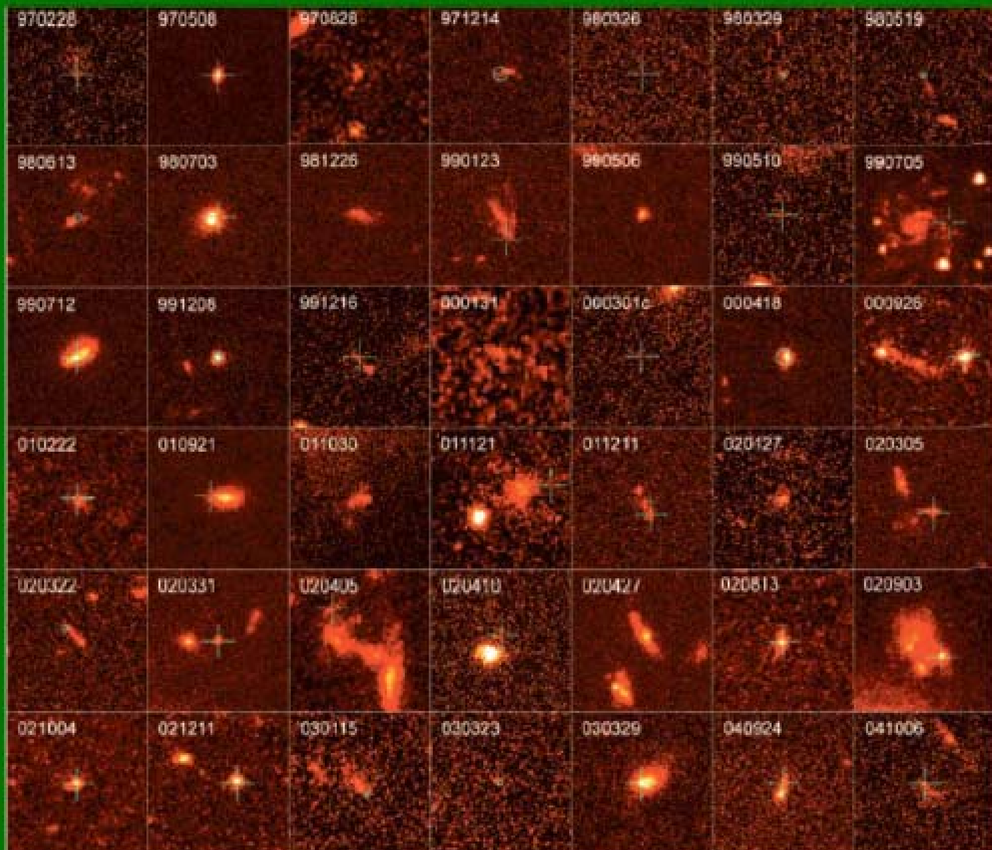


Host galaxies with HST



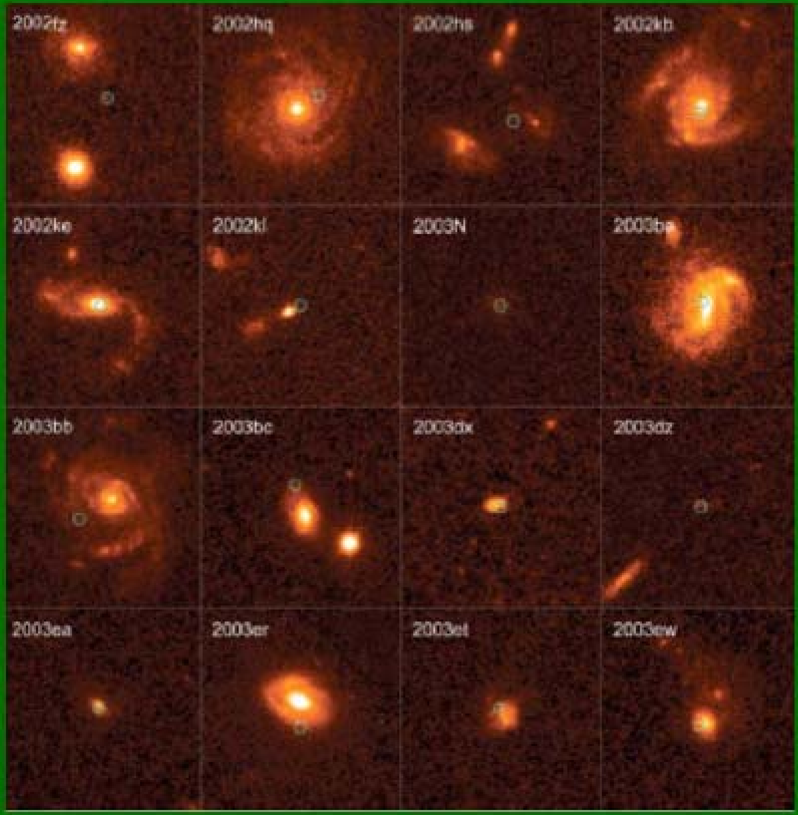
Fruchter et al., Kulkarni et al.

GRB and Core Collapse SNe hosts observed with Hubble Space Telescope



GRBs

CC-SNe from Hubble High-z SN Search + HST GOODS



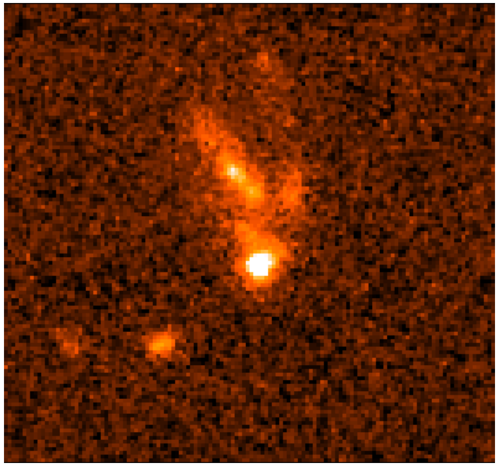
z < 1.2

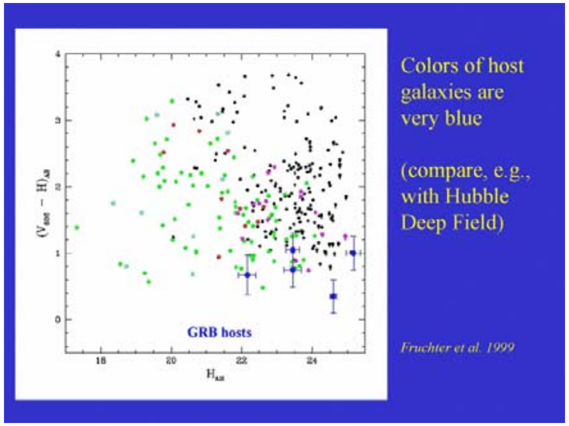
Morphologies are significantly different

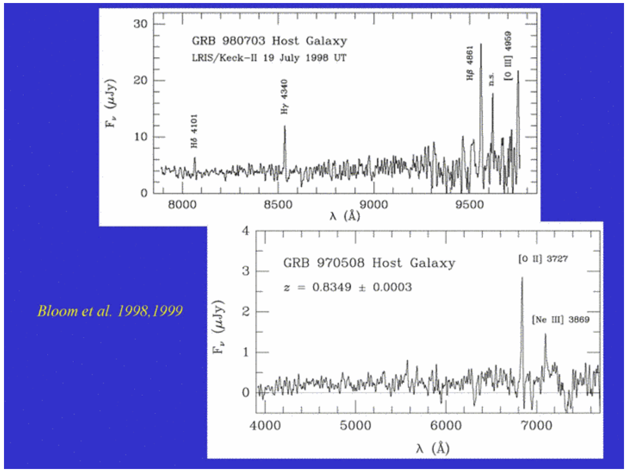
Fruchter et al.2006

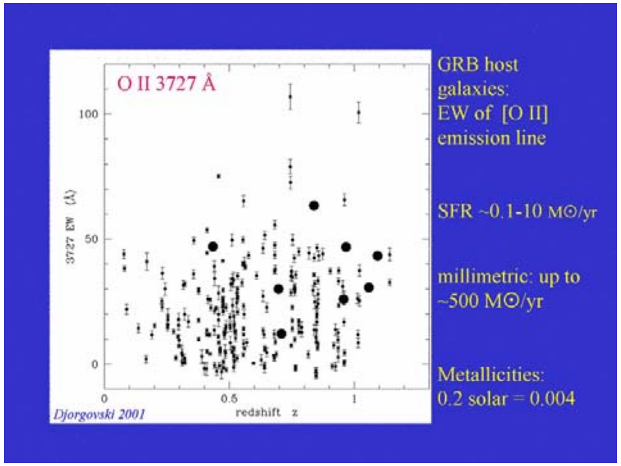
Host galaxies

- Are blue, faint (~0.1 $L_{milky\ way}$), irregularly shaped and low metallicity (similar to Magellanic Clouds).
- Consistent with abundant presence of massive stars
- Increased star formation rates (indicated by OII line), but not large (faint in Spitzer which measures cloud masses) unless expressed per galaxy mass
- Morphology different from non-GRB CC SNe
- GRBs sit on brightest parts of host galaxies, contrary to non-GRB CC SNe



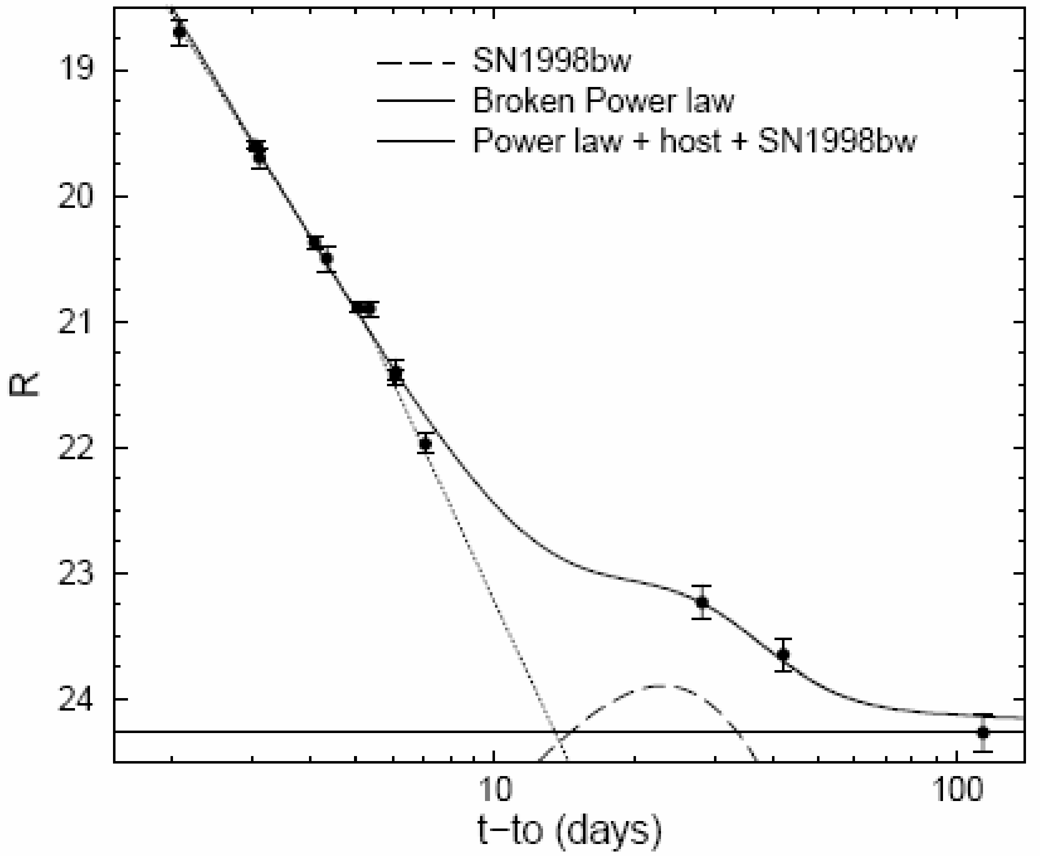






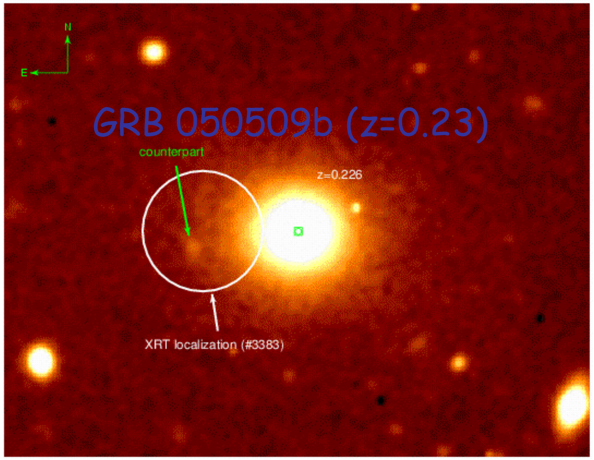
Lightcurve contributions

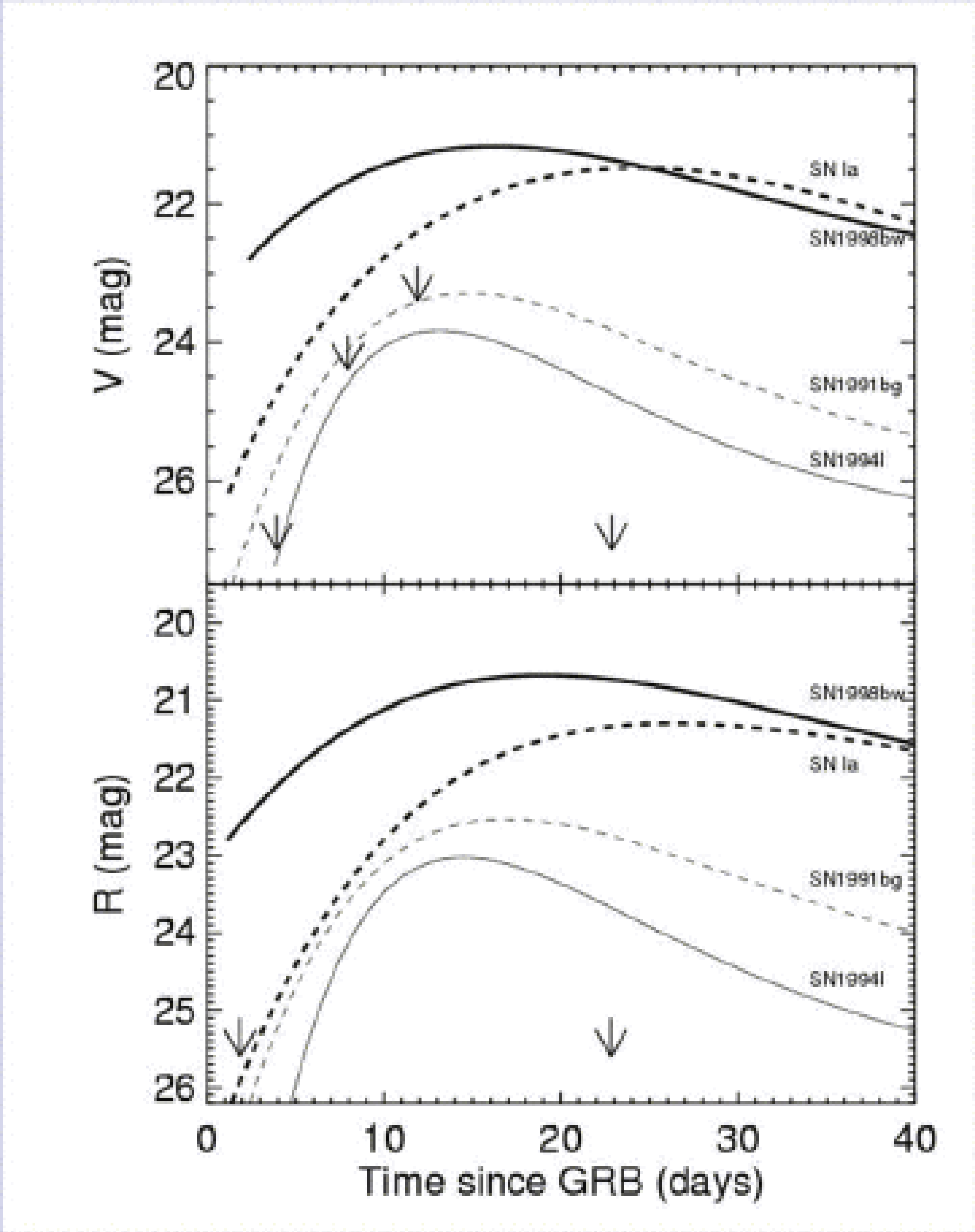
- Prompt emission; may extend for 10^4 s
- Afterglow emission
- Supernova, peaking days to weeks after collapse
- Host galaxy; constant level



Afterglows of the short GRB class

- Untill May 2005, all afterglows were for long/soft GRBs
- Now, there are 6 afterglow detections with host galaxies
- Afterglows are a factor of ~100 less luminous (i.e., after correction for distance), but otherwise look like those of long bursts
- The host galaxies are different from those of long bursts: 4 are ellipticals, 1 is an irregular and 1 a star-forming galaxy → consistent with binary merger model
- There are 4 short GRBs with very low redshifts → sensitive upper limits on SN contribution → there is no concurrent SN → progenitor different from that for long GRBs





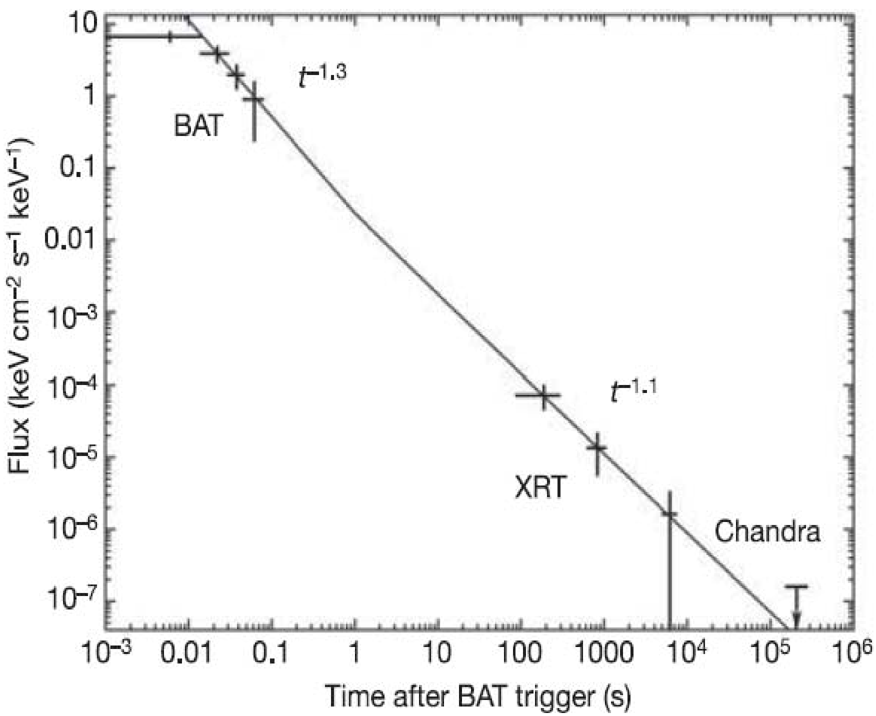
GRB050509b (z = 0.22)

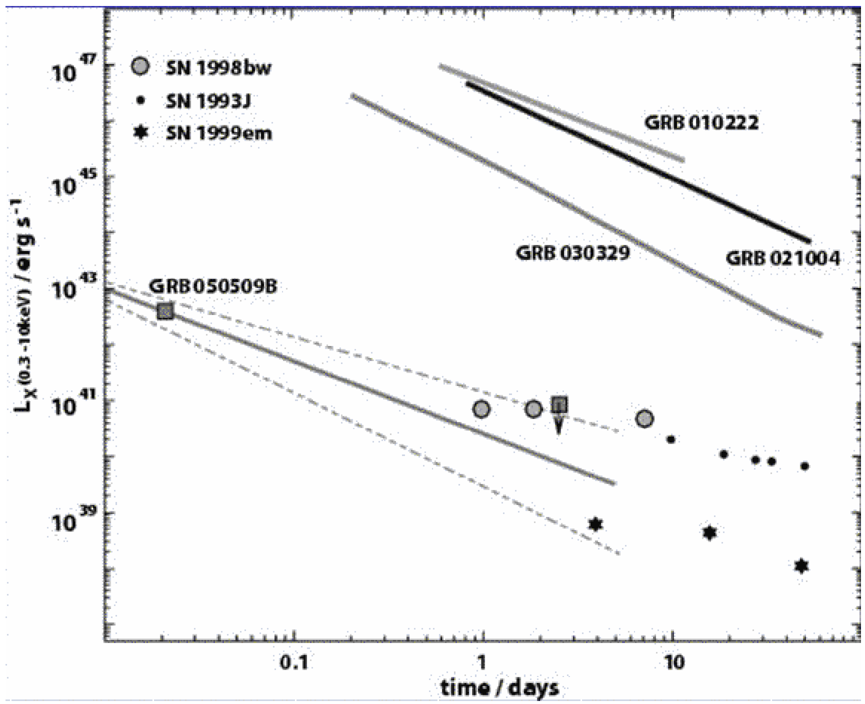
Upper limits on optical
Flux are inconsistent
With supernova

→ Different from
long GRBs

Hjorth et al. 2005

Short GRB afterglows





→ Similar as long afterglows, but less luminous

Models for short GRBs

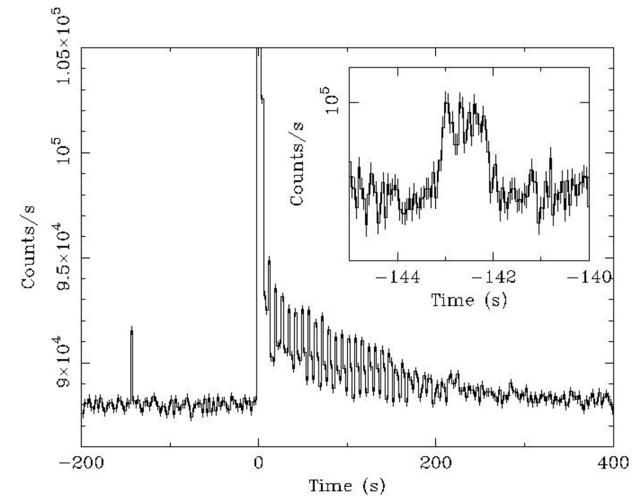
	giant flare (see next 2 slides)	merger
Energy (erg)	10^{46}	$\sim 10^{50}$
Distance scale	Mpc	Gpc
Timescale	OK	OK
Progenitor	young NS	old NS binary
Environment	star-forming galaxies	in/near all types of galaxies
Signatures	possibility of repeat	possible mini-SN

SGR giant burst

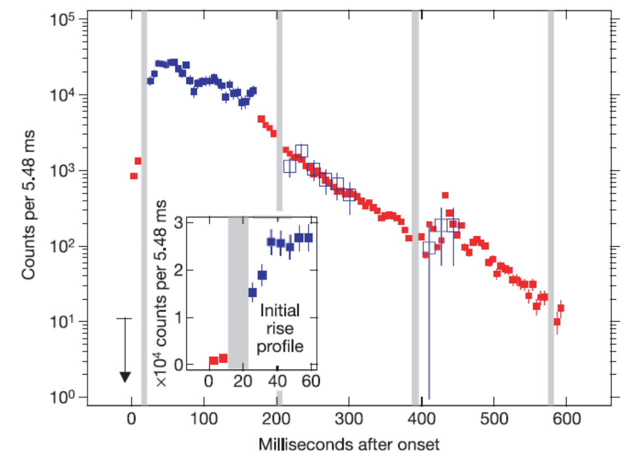
The brightest transient ever (dd 27-12-2004)

- Peak flux 20 erg s^{-1} cm^{-2} (>50 keV) !
- Peak luminosity 10^{47} erg/s/cm^2 @ 15 kpc, but lasting very short (~0.1 s)
- Total energy output 10^{46} erg (solar output over 100 Myr)
- Like other 3 giant flares (that were 10^2 times less energetic
- Source is magnetar = galactic NS with B ~ 10^{15} G, as evidenced by pulsar signal with P ~ 8 s and measured P-dot
- Similar bursts would be detectable out to 40 Mpc (≈distance to closest localized GRB)
- Recurrence time long (~50 yr)

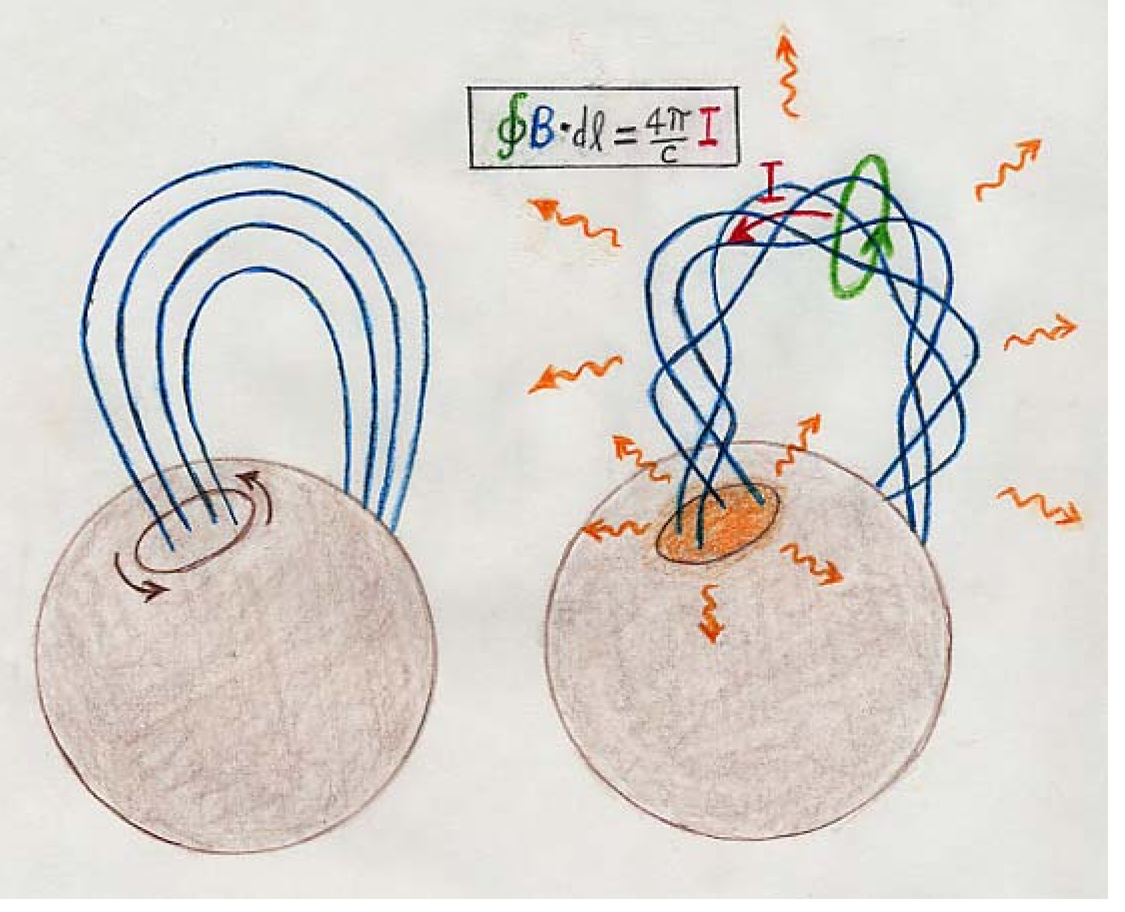
Long time scale light curve with saturated peak (Hurley et al. 2005)



light curve unsaturated peak (Terasawa et al. 2005) → note 4 orders of magnitude decay within 1 sec



Energy release due to B-twisting & reconnection



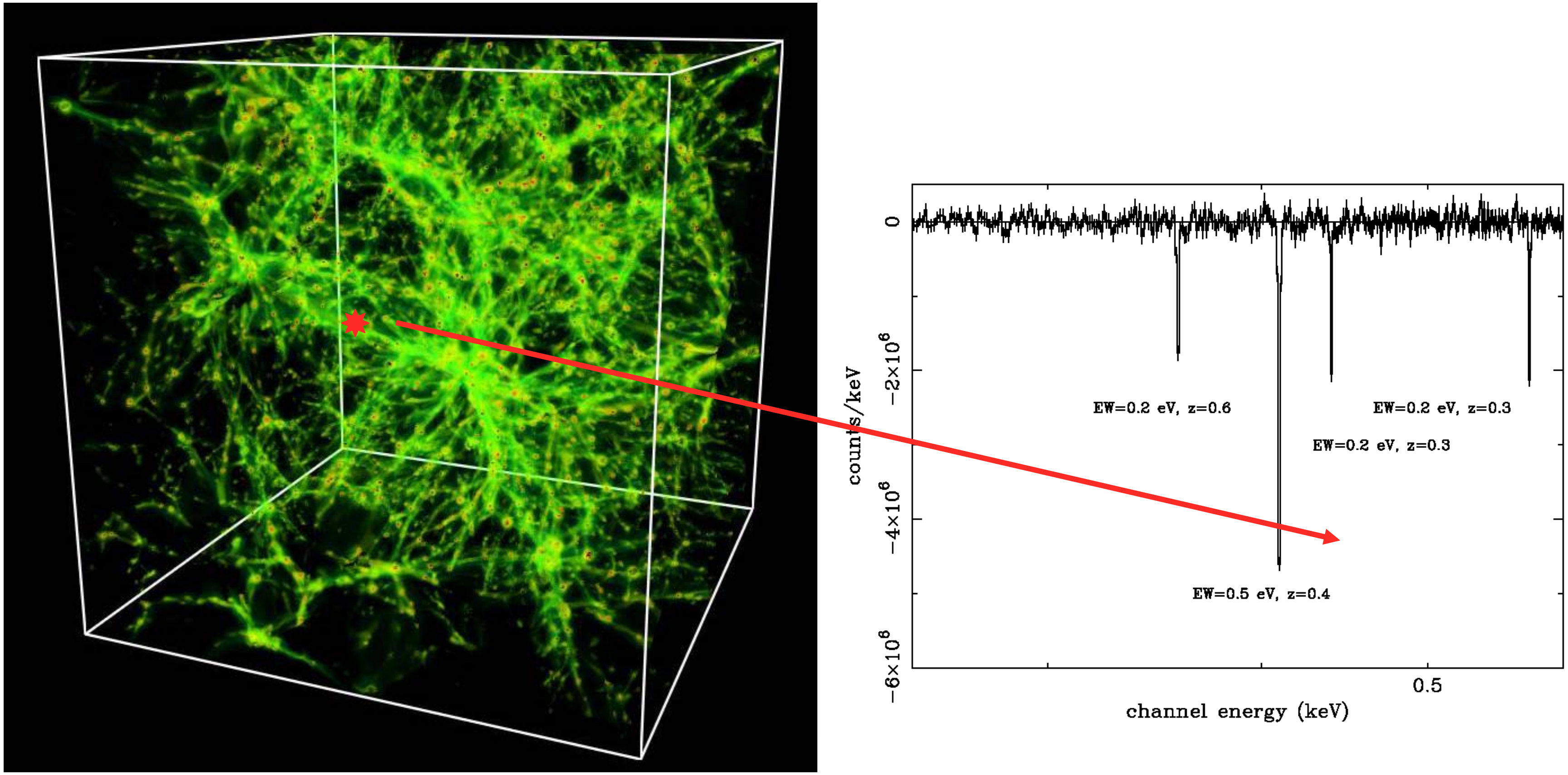
From: Robert Duncan web site on magnetars

The future of GRB research

- Restore broad-band coverage (in particular MeVs+GeVs)
  → GLAST launch in June 2008
- Go to higher redshifts, to search for evolution with metalicity and probe early universe
  Optically very faint
  → use X-rays (=cosmologically redshifted gamma-ray emission!) to measure redshift
  → new instrumentation needed (sensitive X-ray telescope on a swiftly re-orienting satellite), proposed @ ESA and NASA but not yet approved
- Search neutrino signals, to test viability of GRBs as source of ultra-high energy cosmic rays
  → Employ IceCube which is halfway built now
- Search GW signal, to test merger scenario for short GRBs (and collapsar as well?) with LIGO-e and LISA

Probe the cosmic web

Structure simulation from Cen & Ostriker (1999)



Simulations of WHIM absorption features from OVII as expected from filaments (at different z, with EW=0.2-0.5 eV) in the l.o.s. toward a GRB with fluence=$4 \cdot 10^{-6}$ as observed with ESTREMO (in 100 ksec). About 10% of GRB (10 events per year per 3 sr) with ~ $4 \cdot 10^{6}$ counts in the TES focal plane detector

Summary

- The existence of the afterglow phenomenon enabled distance measurements
- Afterglow measurements show various facets of collimated ultra-relativistic expansion (decay breaks)
- Afterglow measurements make possible inferences about the progenitors (ie, like for SNe: stellar winds)
- SN associations are clear for 4 nearby cases (SN Ibc according to the spectrum) and indicative (light curve bumps) for others
- Compared to ordinary SNe, GRB are characterized by the presence of an ultra-relativistic jet and the combination with a hypernova
- Current GRB research excitement focuses on finding afterglows of short GRBs, finding higher-redshift cases, and searching more constraints on the central engine
- GRBs may have use for cosmology, ie. use as beacons from the early universe, e.g. quick high-resolution spectroscopy of prompt emission to investigate intracluster matter which has a temperature that invokes absorption lines at soft (<1 keV) X-rays

GRB basic numbers

- Distance: $z = 0.0085 .. 6.2$, or $d = 10^{26} .. 10^{28}$ cm
- Fluence $10^{-7} .. 10^{-4}$ erg cm^{-2}
- Radiated energy: $10^{48} .. 10^{51}$ erg (prompt+afterglow; corrected for beaming) $= L_\odot \times 10^{10}$ yr $= L_{gal} \times 1$ yr
- Peak energy 2 .. 2000 keV
- Early jet angles: 1 .. 30 degrees
- Early Lorentz factor: ~100
- If SN id, the type is Ibc
- Rate: ~10^{-6} yr^{-1} galaxy^{-1} times beaming correction (compare with SNe : 10^{-2} yr^{-1} galaxy^{-1}) or ~few per day per universe (compare SNe : 1 per second per universe)

Literature

- Many reviews, recent one: Meszaros / astro-ph/0605208
- Summer reading: 'Flash' by Govert Schilling
- Many websites, for instance Jochen Greiner's GRB web site at http://www.mpe.mpg.de/~jcg/grbgen.html

Acknowledgements

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