Recent Topics on Gamma-Ray Bursts:

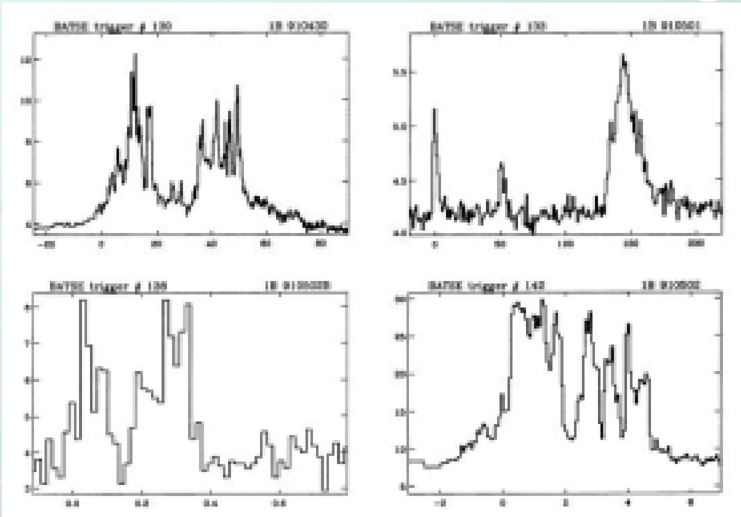
戸谷　友則
TOTANI, Tomonori
(Dept. Astronomy, Kyoto Univeristy)

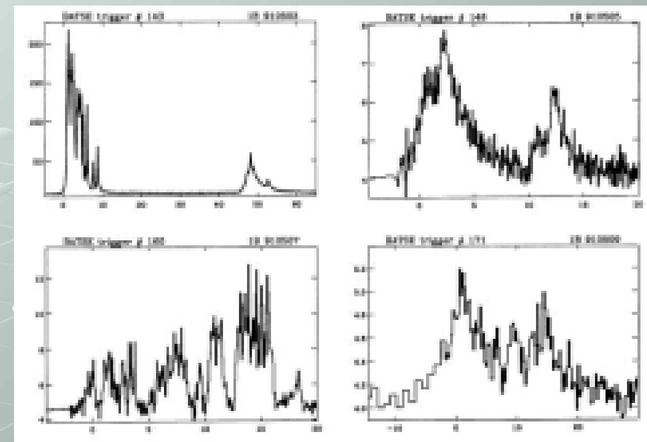
Outline

- Brief Introduction for GRBs
- Theory vs. Observations of long GRBs
  - Afterglows
  - GRB-SN Connection
  - Central Engines
- Short GRBs
- Neutrinos and high energy emission from (long) GRBs
  - Gamma-rays, neutrinos, and UHE cosmic rays
- GRB Cosmology
  - cosmic star formation history
  - reionization
  - standard candle and dark energy probe

GRB Light Curves

Fishman+ ‘94





Duration
two populations

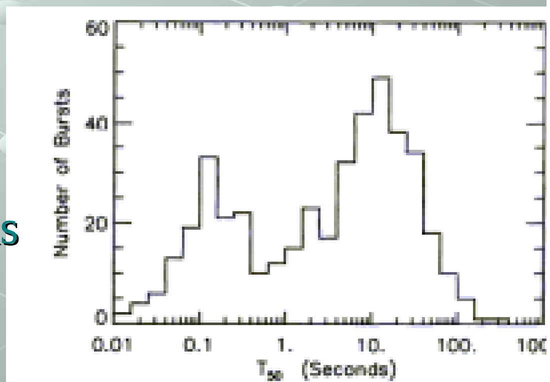


FIG. 11a

FIG. 11.—Duration distributions for 427 bursts in the 3B catal
T_{50}, and (b) T_{90}.

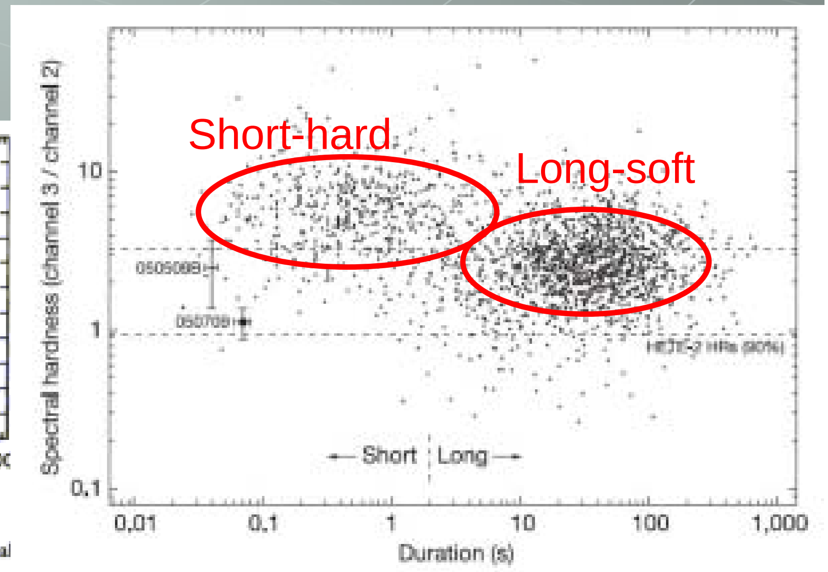


Figure 1 | The classic BATSE duration–spectral hardness diagram[1].

GRB Spectrum

nonthermal spectra

E_{peak} in νF_ν ~MeV

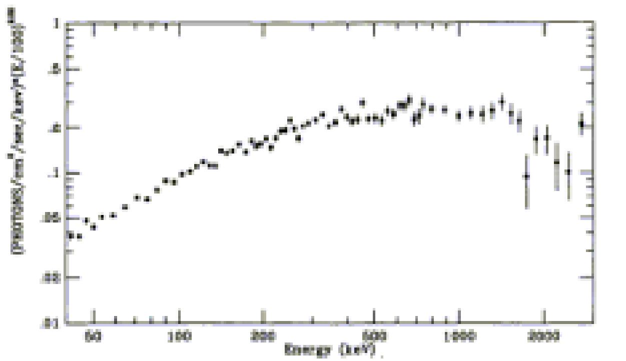


FIG. 11.—Photon spectrum for burst 1B 910503. For additional details, see the caption to Fig. 9.

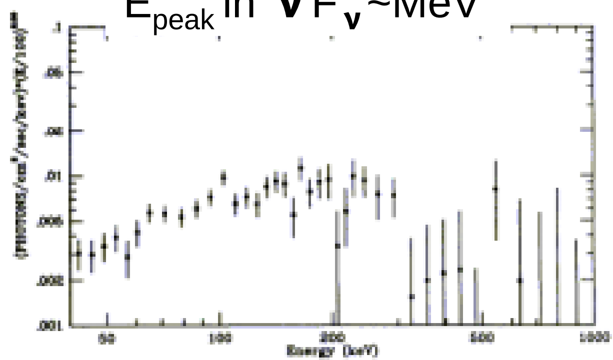


FIG. 12.—Photon spectrum for burst 1B 910507. For additional details, see the caption to Fig. 9.

Schaefer+ '94

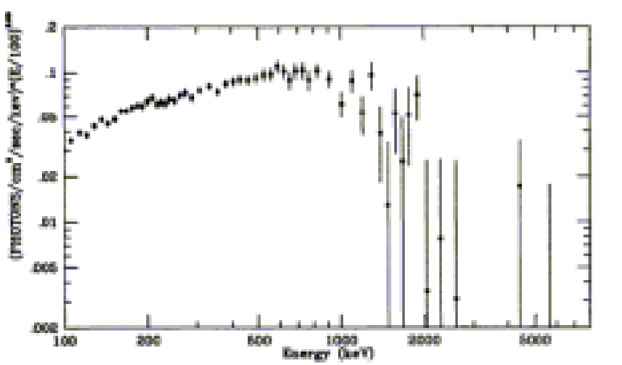


FIG. 13.—Photon spectrum for burst 1B 910601. For additional details, see the caption to Fig. 9.

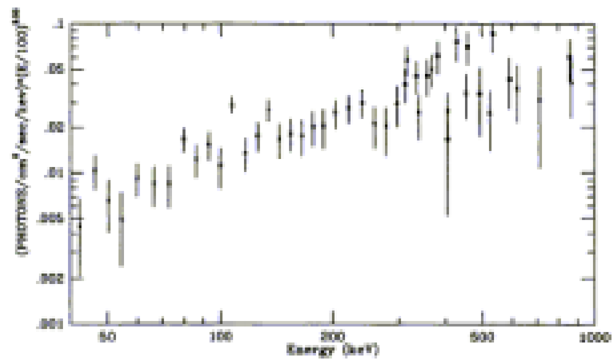
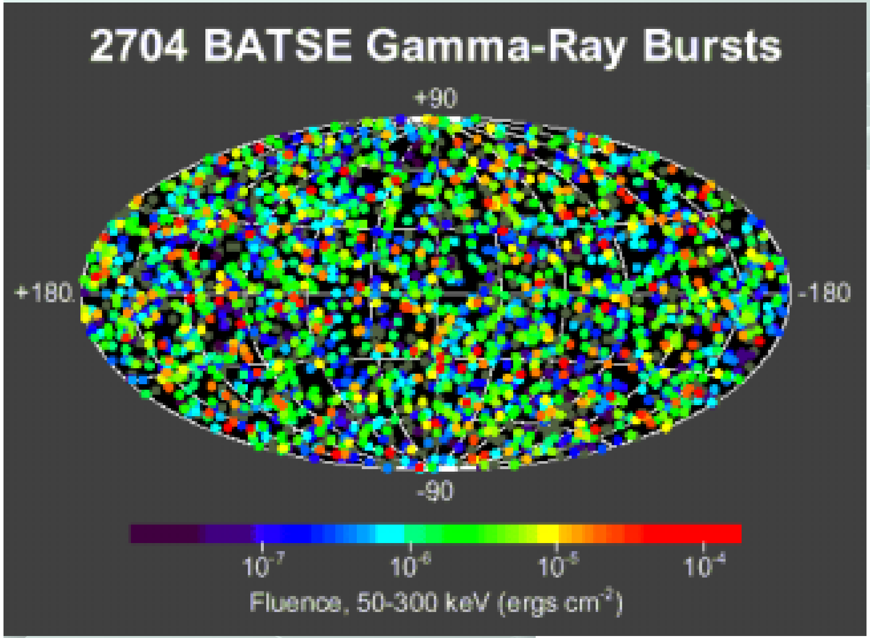


FIG. 14.—Photon spectrum for burst 1B 910609. For additional details, see the caption to Fig. 9.

Spatial Distribution



Isotropic, but not homogeneous indicating a cosmological distribution

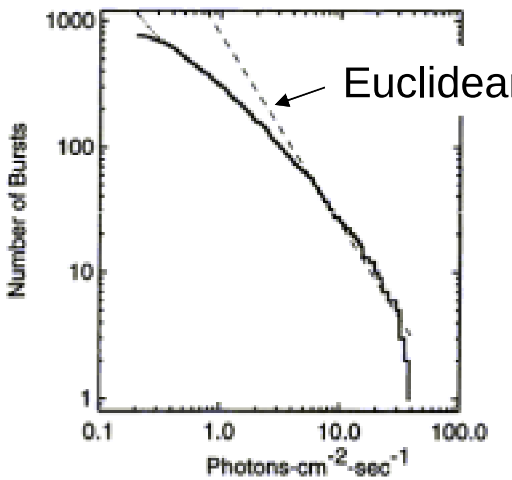


FIG. 9c

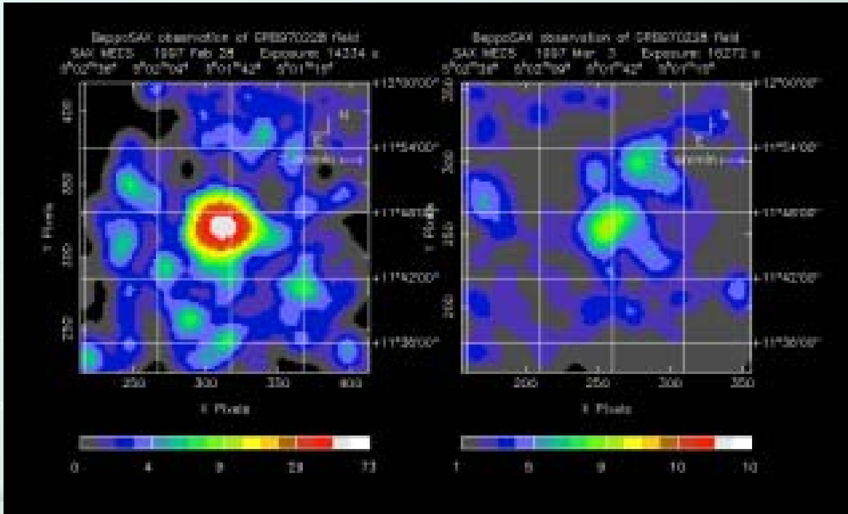
FIG. 9.—Integral log N–log P distributions. The energy range is 50–300 keV. The solid curve represents the uncorrected data. The dot-dashed curve represents the data corrected for efficiency; this is known to be an overcorrection at low fluxes because it does not incorporate the additional flux from atmospheric scattering. Each figure shows only events above threshold on the designated timescale. The dashed line indicates the −3/2 slope expected for homogeneous sources. (a) 64 ms trigger timescale, showing, from top to bottom, 700 total events, 634 nonoverwrite events, and 66 overwrite bursts; (b) 256 ms trigger timescale, containing 765 bursts; and (c) 1024 ms trigger timescale, containing 772 bursts.

Meegan+ '96

Event rate: a few / day / all sky for the BATSE sensitivity

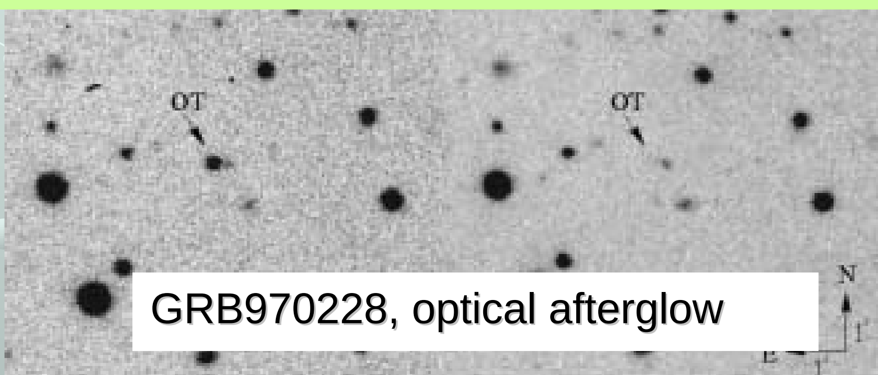
Long GRBs (L-GRBs):
Theory versus Obsrevations

Afterglows



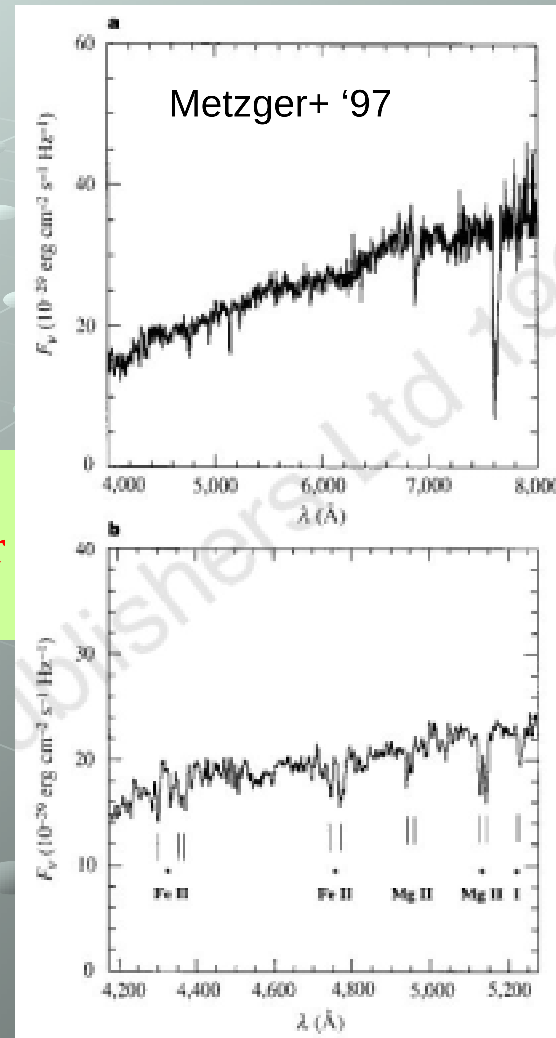
GRB970228, first X-ray afterglow by BeppoSAX

Almost 10 years ago from now, and almost 10 years after the discovery of SN 1987A (Feb 23, 1987)



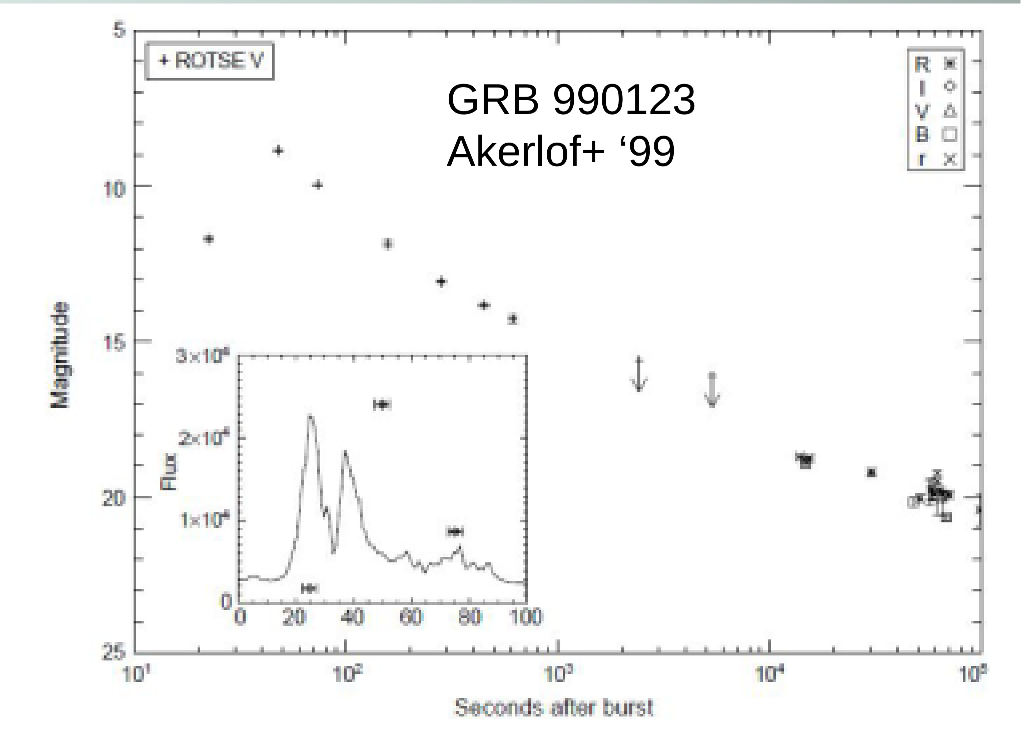
GRB970228, optical afterglow

GRB970508, first redshit (z=0.835)



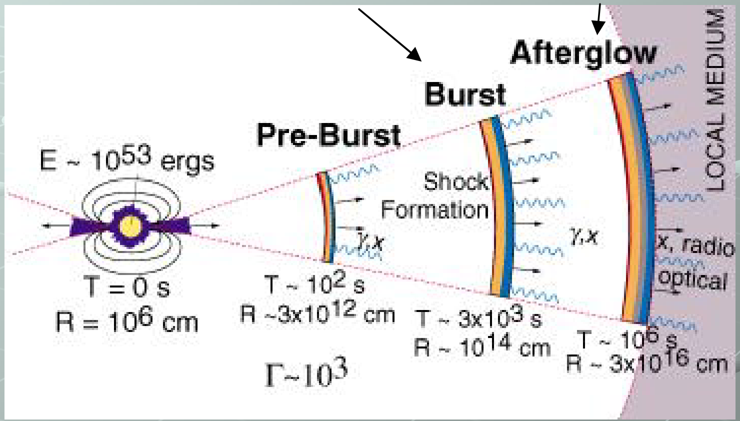
Bright and Extremely Energetic

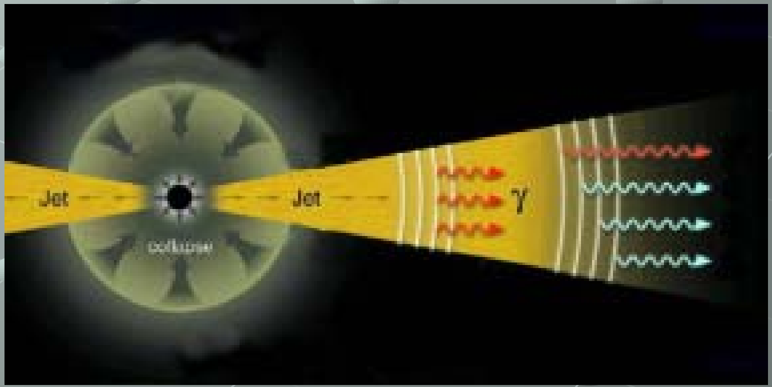
- GRB 990123 (z=1.6)
  - $E_{iso,\gamma} \sim 3x10^{54}$ erg $\sim 2M_{sun}c^2$
  - same GRB detectable out to z~20
  - Peak optical mag~9 from z=1.6
- $E_{\gamma,iso} \sim 10^{51-54}$ erg
- Note: afterglows and distance for short GRBs only since 2005



The Big Picture of GRBs

- Ultra-relativistic fireball/outflow (Γ ~100-1000)
  - Required for the emission region optically thin to $e^{\pm}$ pair-production (size limited from time variability)
- Afterglow: relativistic supernova remnants
  - (most likely) jet-like explosions
    - Theoretically reasonable energy
      - Isotropic-equivalent energy > 10^{54} erg!
    - Afterglow light curve break
  - E~10^{51} erg (jet corrected)
  - $E_{jecta} \sim E/\Gamma \sim 10^{-5} M_{sun}$





Obsrevational Evidence for Relativistic Outflow

- GRB 970508 at z=0.835
- cease of variability by interstellar scintillation in our Galaxy set lower limit on radio image size at ~2 weeks
- Superluminal motion
  - 3 **μ** as at 2 weeks
  - apparent velocity ~ 4 c
  - mildly relativistic speed required (**Γ** ~1)

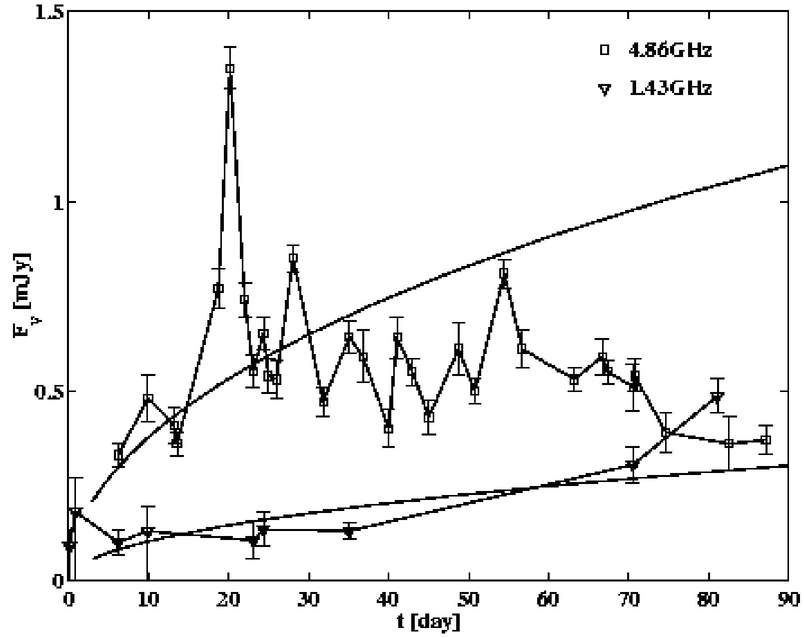


Fig. 1a.— Light curves of the radio afterglow of GRB970508 at 4.86GHz and 1.43GHz, compared with the predictions of the adiabatic fireball model (Waxman 1997b).

Frail et al. 1997

More Direct Proof:
Superluminal Expansion of Radio Afterglow Image

- GRB 030329 at $z = 0.1685$
- resolved image showing superluminal motion
  - 0.07 mas at 25 days, 0.17 mas at 83 days
  - ~ 3-5 c
- upper limit on proper motion < 0.3 mas at 83 days

Taylor et al. 2004, 2005

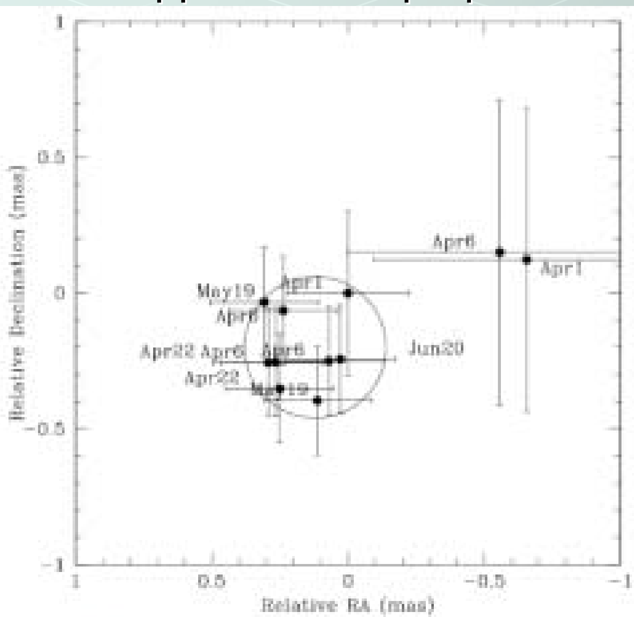


Fig. 1.— The positions derived from the observations in the first five epochs relative to the first determination on April 1st at 8.4 GHz. Observations at multiple frequencies at a given epoch have been plotted separately since they are independent measurements. A circle with a radius of 0.28 mas (2σ) is shown to encompass all measurements except those taken at 5 GHz, which suffer from systematic errors (see text for details). These observations provide a constraint on the proper motion of 0.10 ± 0.14 mas over 80 days.

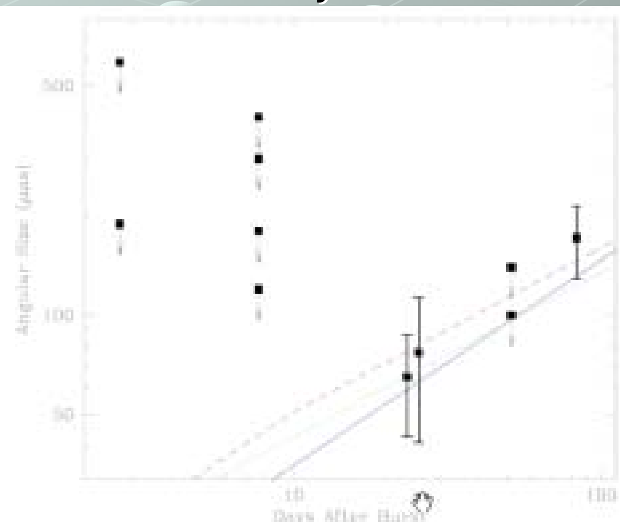


Fig. 2.— Measured angular diameters (or limits) for the radio afterglow from GRB030329, along with the expected evolution of the angular size for different representations of the fireball model. The solid line is the apparent angular size for a spherical fireball expanding in a constant density medium with $E_{52}/n_1=1.0$. The dotted line is an early jet model ($t_j=0.5$ d) with $E_{52}/n_1=100$, while the dashed line is a late jet model ($t_j=10$ d) with $E_{52}/n_1=20$. The general tendency is that the more narrowly collimated the outflow, the larger the energy that is required to produce agreement with the angular diameter measurements. Note that the plotted models assume that the circumburst density is constant (ISM). Wind models over this time range give similar estimates of the angular diameter.

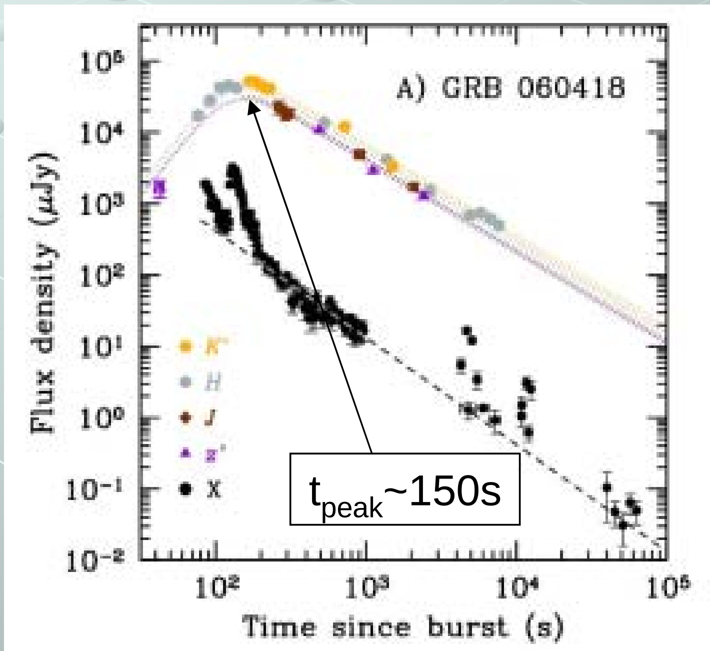
Estimate of Initial Lorentz factor Γ_0

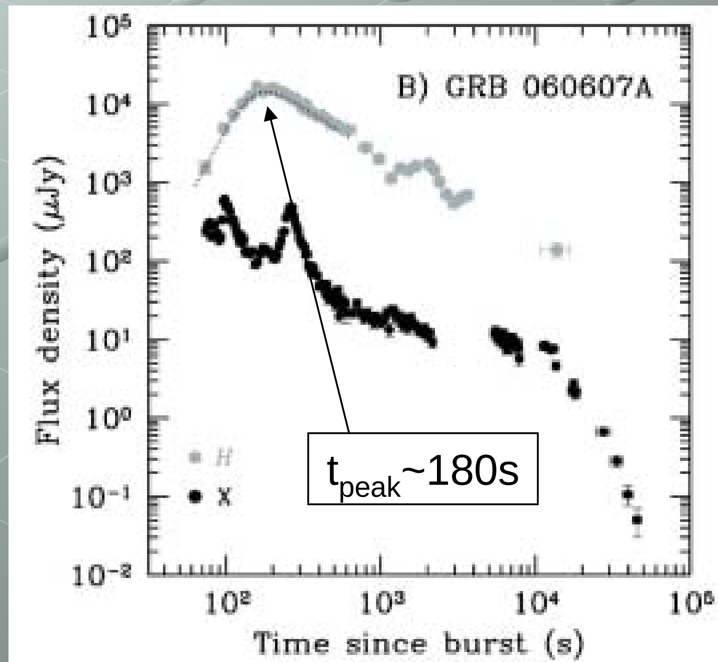
- The onset time of afterglow is a good estimator for Γ_0

$$\Gamma(t_{\rm peak}) = \left[\frac{3E_\gamma(1+z)^3}{32\pi n m_{\rm p} c^5 \eta t_{\rm peak}^3}\right]^{1/8} \sim 160 \left[\frac{E_{\gamma,53}(1+z)^3}{\eta_{0.2} n_0 t_{\rm peak,2}^3}\right]^{1/8},$$

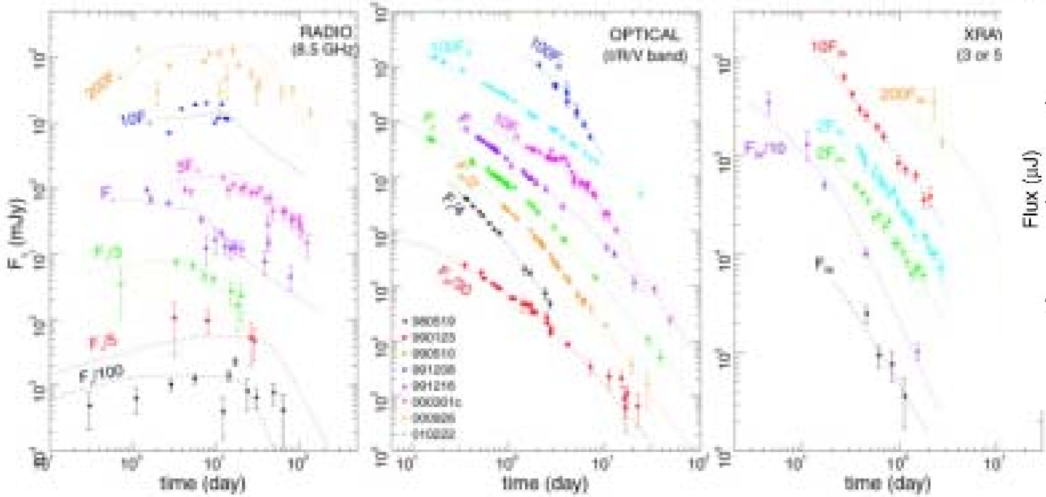
- First estimates for two GRBs: $\Gamma_0 \sim 400$ (Molinari+ '06)
  - GRB 060418 (z=1.489, $E_{iso,\gamma} \sim 9\times10^{52}$ erg)
  - GRB 060607A (z=3.082, $E_{iso,\gamma} \sim 10^{53}$ erg)

Molinari+ '06

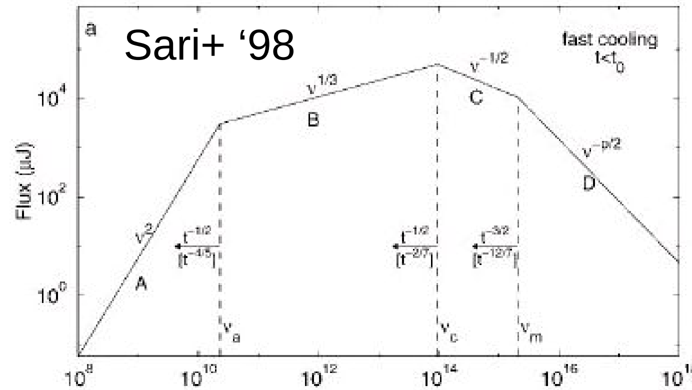


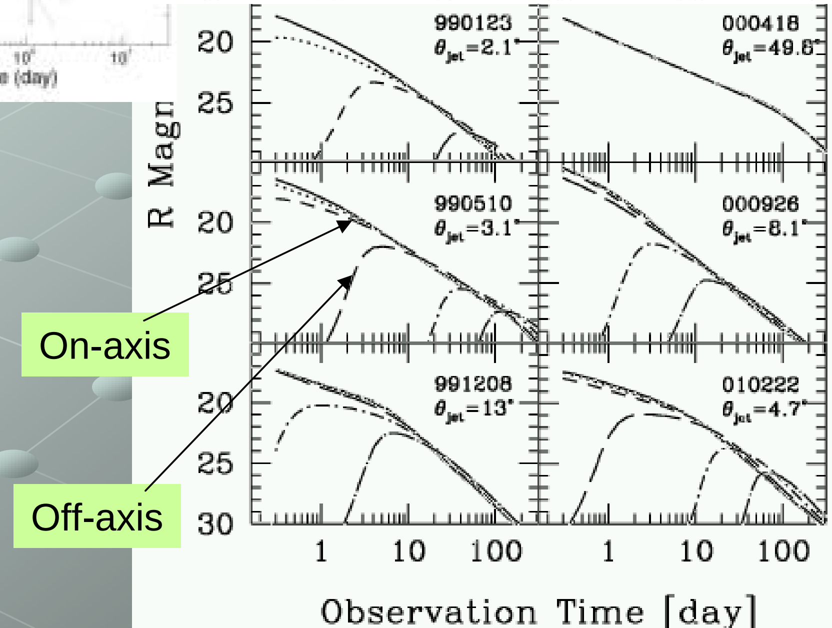


Afterglow Theory Well Tested



Panaitescu & Kumar ‘01



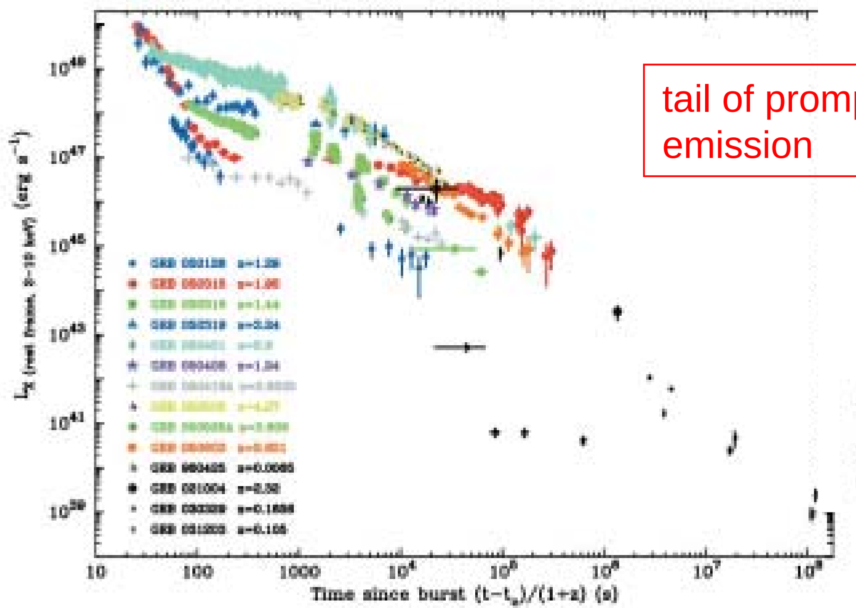


Totani & Panaitescu ‘02

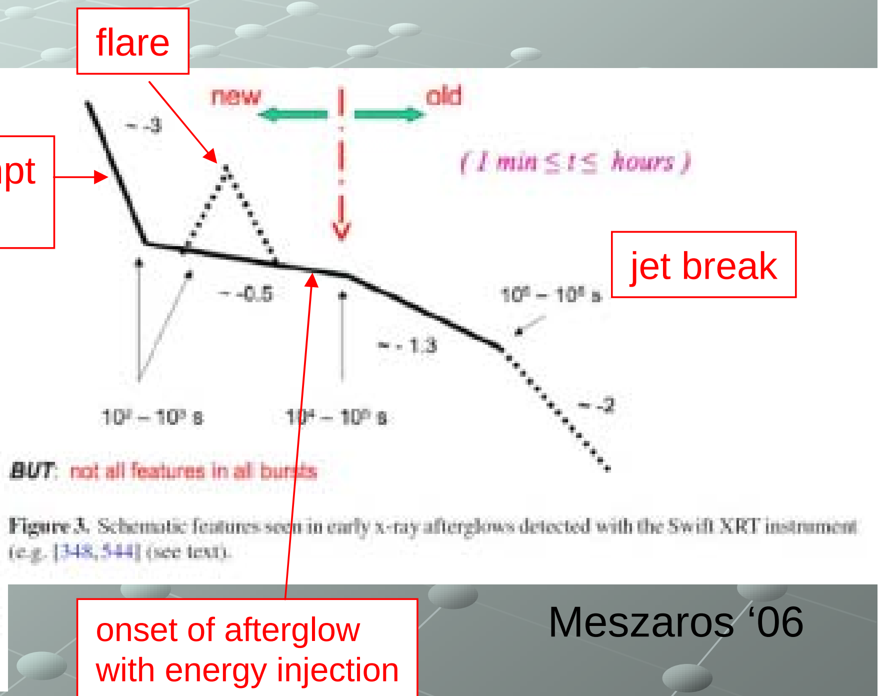
- Radiation by synchrotron of accelerated electons
  - Power-law flux decay ($\propto t^{-1}$ to t^{-2})
  - Power-law spectral energy distribution
- Evidence of jet: light curve break
  - $\theta_{jet}\ \Gamma(t_{break}) \sim 1$

Various and Canonical Afterglow Light Curves

- early X-ray light curve samples by Swift



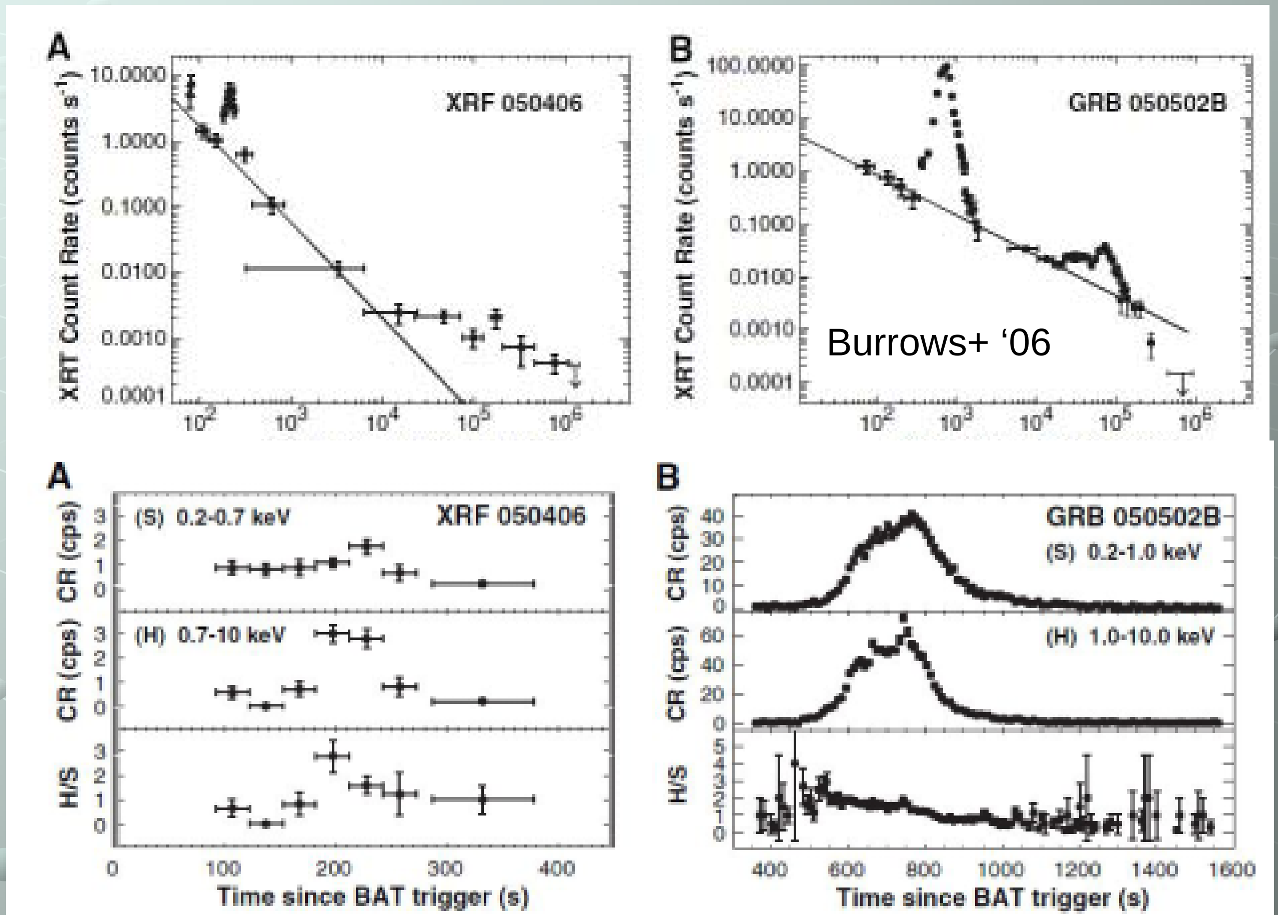
Nousek et al. '06



Meszaros '06

Flares/late time activity in afterglow

- flare energy: from a few % to a value comparable (GRB050502B) with the prompt emission



Interpretation by external shock is difficult, indicating internal shock and late/long-term activity of central engine or slower ejecta

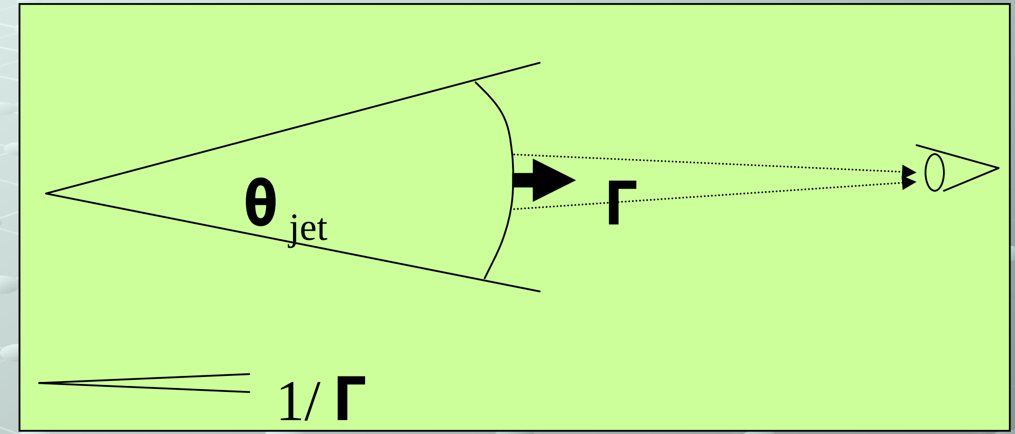
Search for Orphan Afterglows

- Possible mechanism of orphan afterglows without observable prompt gamma-rays
  - Jet-like explosions
  - Dirty fireball (low bulk Lorentz factor)

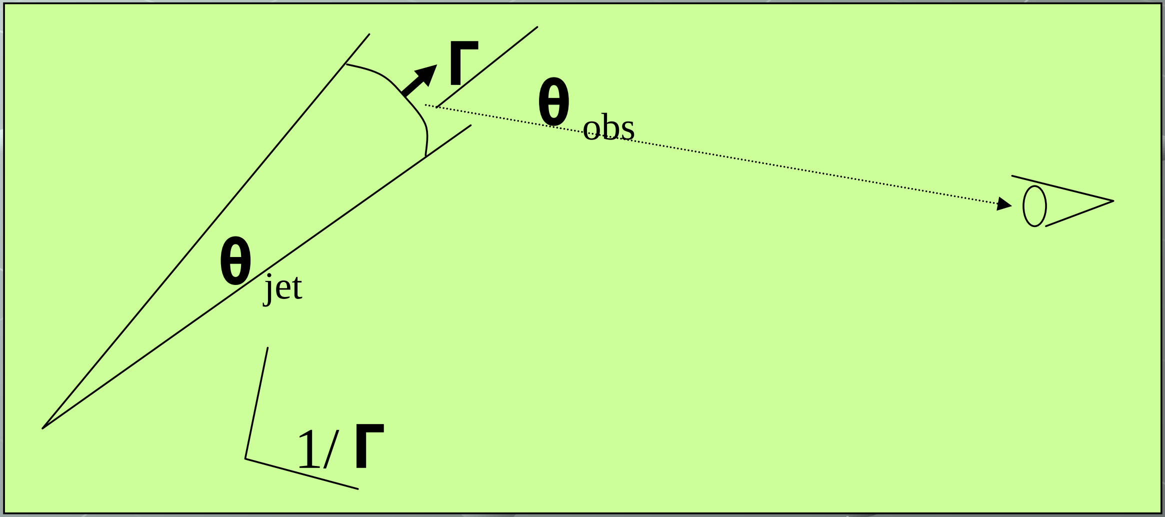
- Predictable orphan afterglow rate from off-axis GRBs
  - Test for the jet hypothesis

Off-axis orphan afterglows

- $\Gamma > \theta_{jet}$



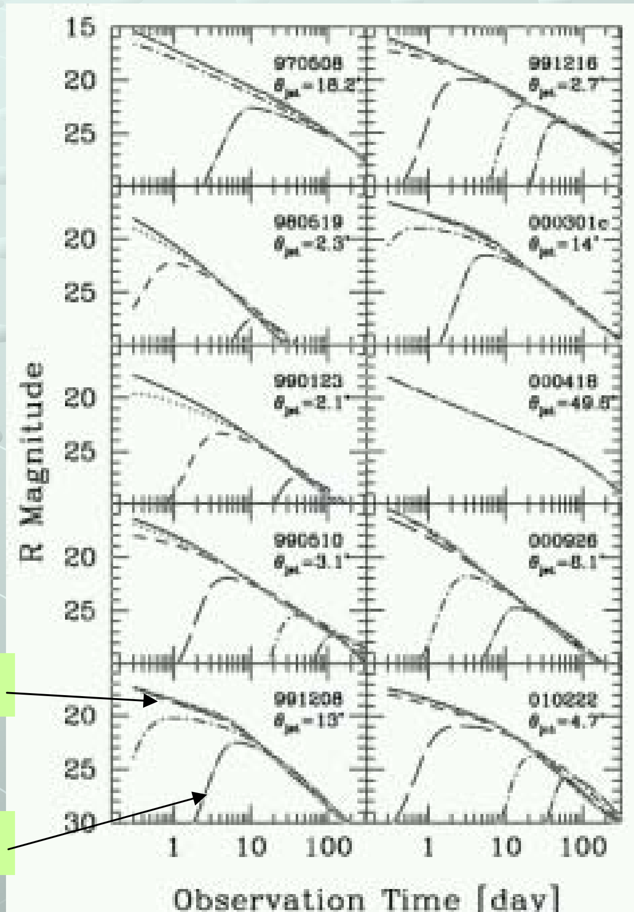
- $\Gamma < \theta_{jet}$



Orphan Rate Prediciton

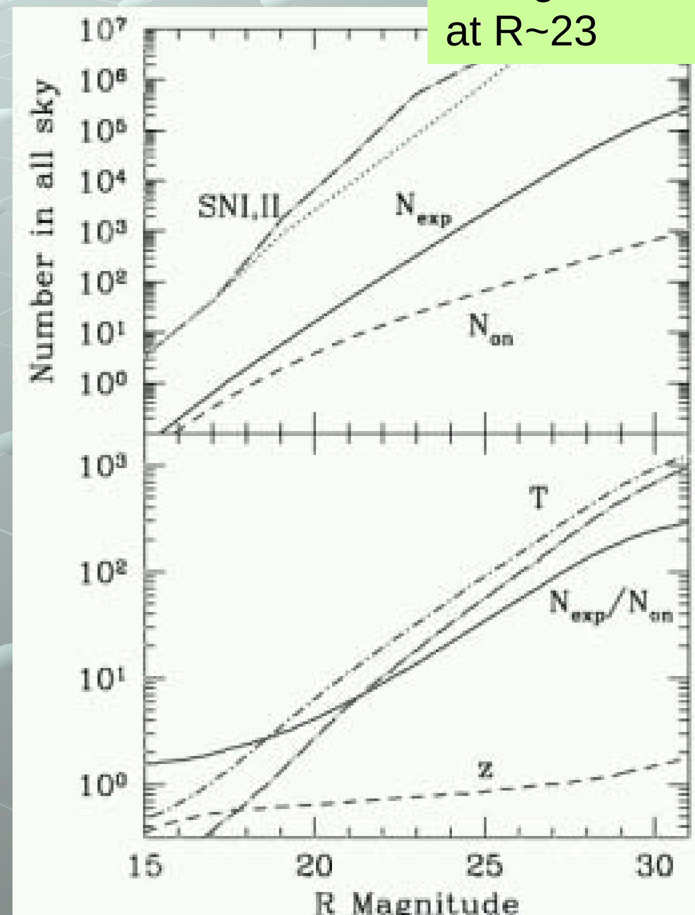
- Orphan afterglow prediction by TT & Panaitescu ‘02

X~10 more orphans than on-axis afterglows at R~23



On-axis

Off-axis



Search for Orphan Afterglows

- CFHTLS search down to r'=22.5 for 490 deg^2, 1 day interval
- three candidates
  - two likely variable stars
  - one probably afterglow
- If the one is real, the rate consistent with the prediction of TP02
- Theoretical prediction strongly dependent on the distribution of afterglow parameters
- More observations needed!

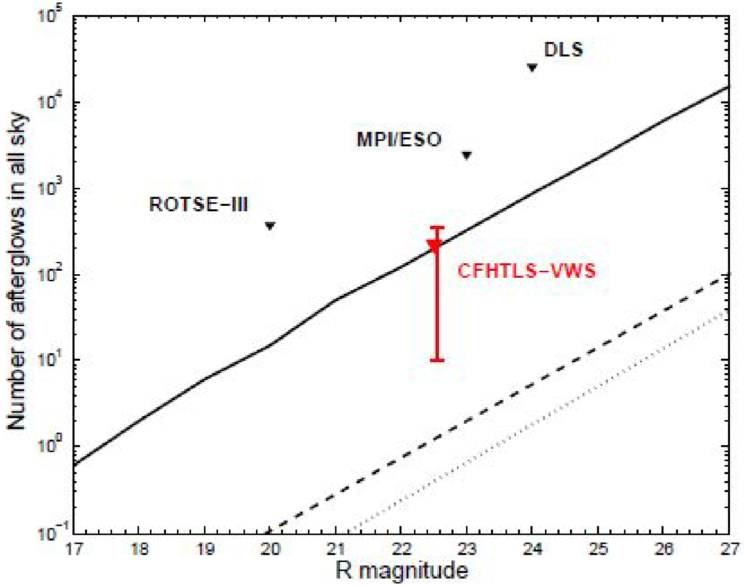
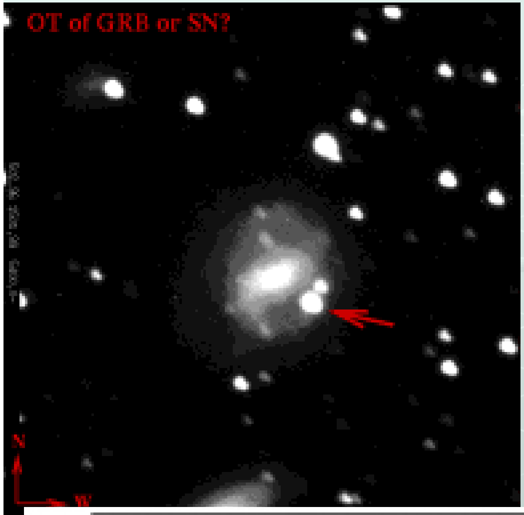


Fig. 3. Constraints provided by our observations (VWS), compared to the results of ROTSE-III (Rykoff et al. 2005), of the MPI/ESO survey (Rau et al. 2006), and of the DLS (Becker et al. 2004). The upper limit assumes the detection of zero afterglow and the error bar the detection of one afterglow in our survey (see section 2 for additional explanations). Also shown are the theoretical predictions of Totani & Panaitescu (2002, solid line), of Nakar, Piran & Granot (2002, dashed line), and of Zou et al. (2006, dotted line).

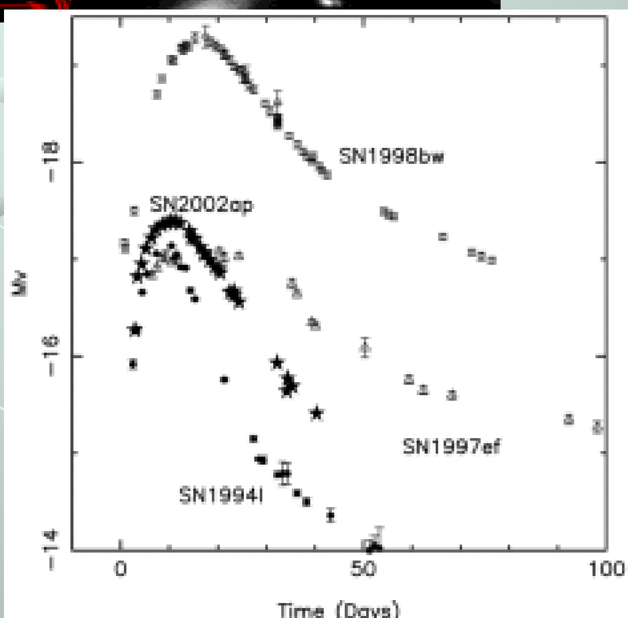
Malacrino+ '07

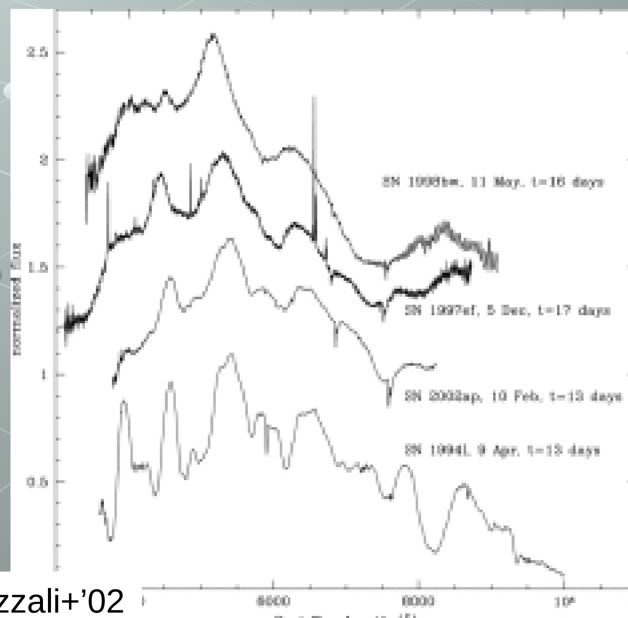
L-GRBs and SN Connection

The First Shock: GRB 980425/SN 1998bw



- A very peculiar type Ic supernova (hypernova)
  - Large explosion energy ~ 3 x 10^{52} erg >> 10^{51} erg
  - one of the brightest supernovae with ~0.7 M_{sun} ^{56}Ni production (c.f. 0.075 M_{sun} for SN 1987A)
  - strong radio emission powered by ~10^{49} erg relativistic electrons
  - z=0.0085(!) << ~1 for typical long GRBs
- An even more peculiar GRB: E_{GRB}~8x10^{47} erg
  - c.f. typical long GRBs at z~1: $E_{GRB,iso}$~10^{51-54} erg

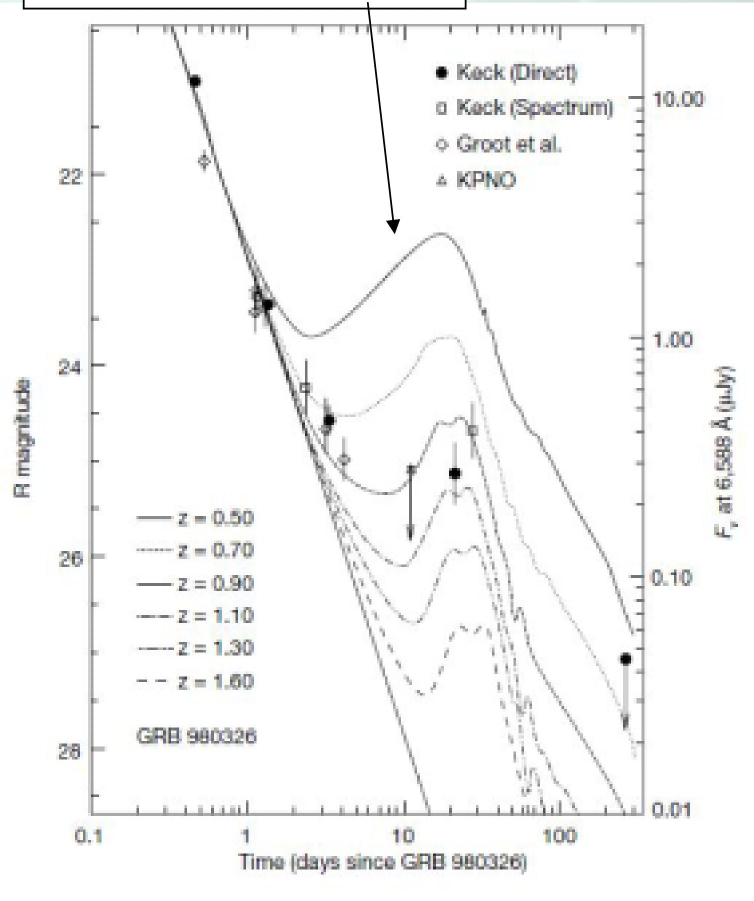




Mazzali+’02

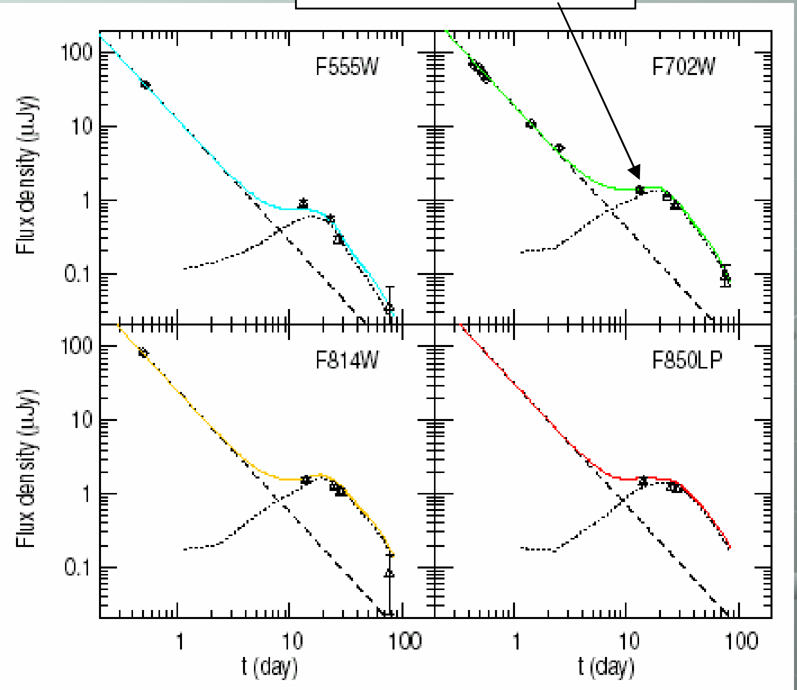
SN evidence in GRBs at z~1

SN 1998bw at various z



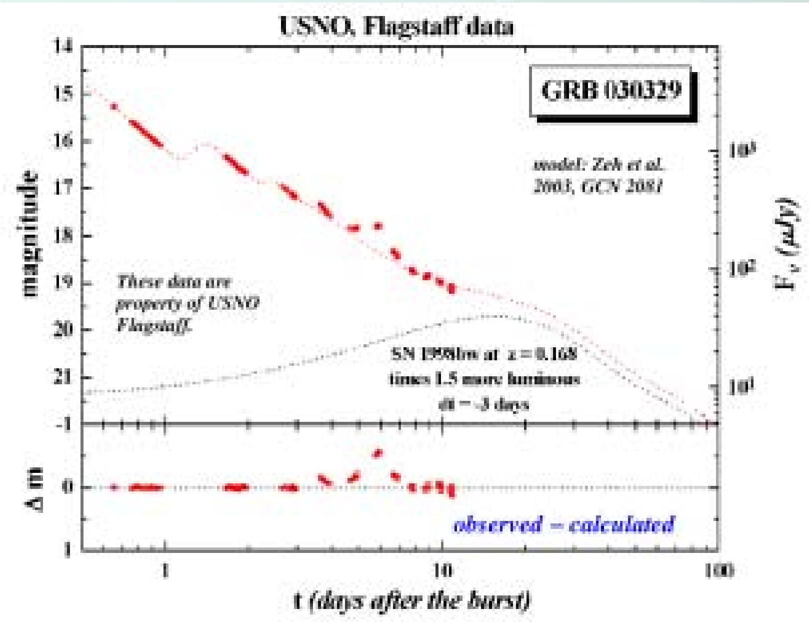
Bloom+ '99, GRB 980326

SN1998bw x 0.55

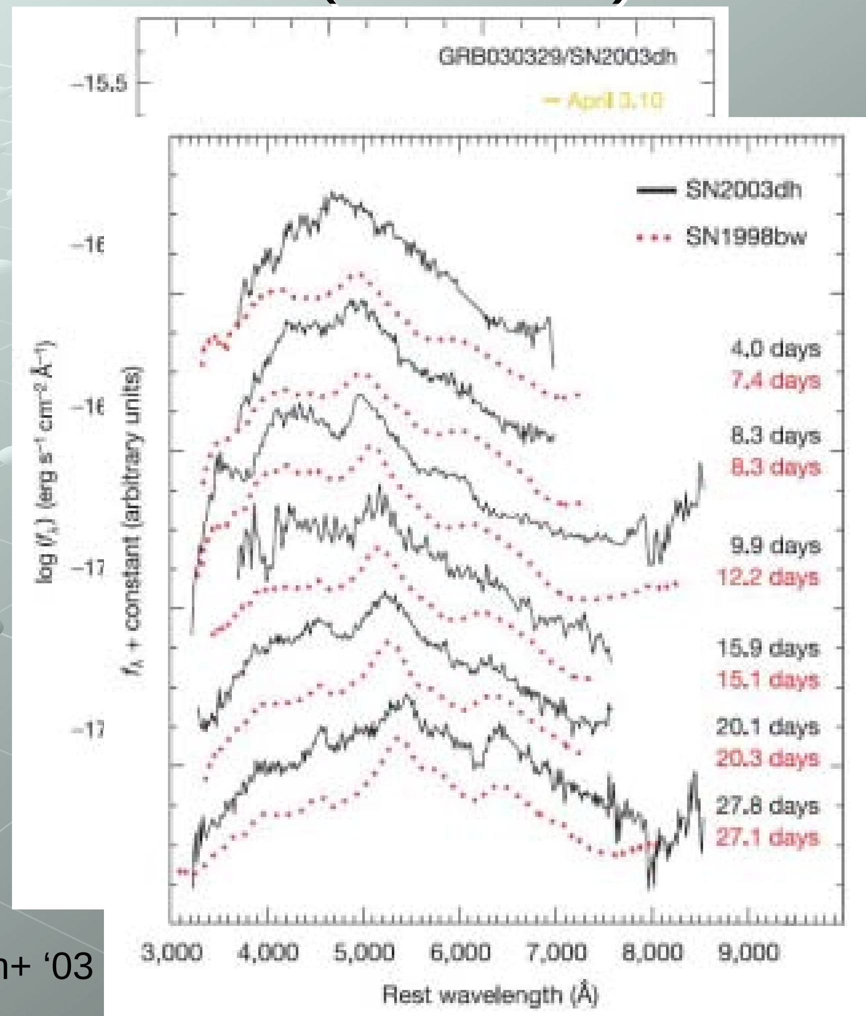


Bloom+ '02, GRB 011121@z=0.36

Ultimate proof of association: GRB 030329/SN 2003dh (z=0.168)



Henden+ '03



Hjorth+ '03

a "normal" GRB with $E_{\gamma,iso}$~$9x10^{51}$ erg!

GRB/hypernova: clear association cases

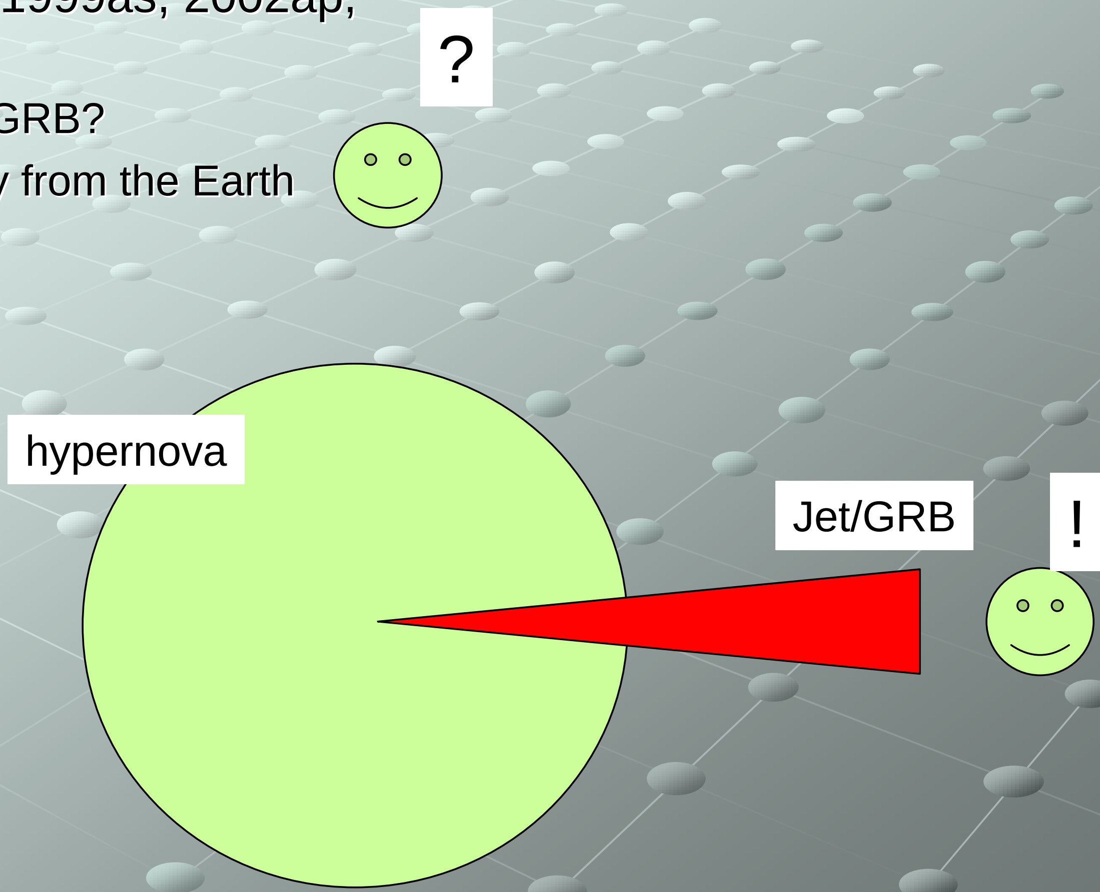
↓ from Nomoto

GRB	SN	$M_{CO}/M_{\odot}$	$M_{ms}/M_{\odot}$	$E/10^{51}$erg	$M(^{56}Ni)/M_{\odot}$	z	$E_{GRB,iso}$(erg)
980425	1998bw	14	40	30	0.4	0.0085	$8x10^{47}$
030329	2003dh	11	35	40	0.35	0.168	$9x10^{51}$
031203	2003lw	16	45	60	0.55	0.1055	$\sim10^{50}$
XRF 060218	2006aj	3.3	20	2	0.21	0.033	$6.2x10^{49}$

- All SNe are type Ic:
  - H, He shell removed, leaving C+O core
- GRB031203/SN2003lw:
  - Intermediate between typical z~1 GRBs and 980425/1998bw event
- XRF060218/SN2006aj:
  - First X-ray flash case, indicating small progenitor mass?

Non-GRB hypernovae

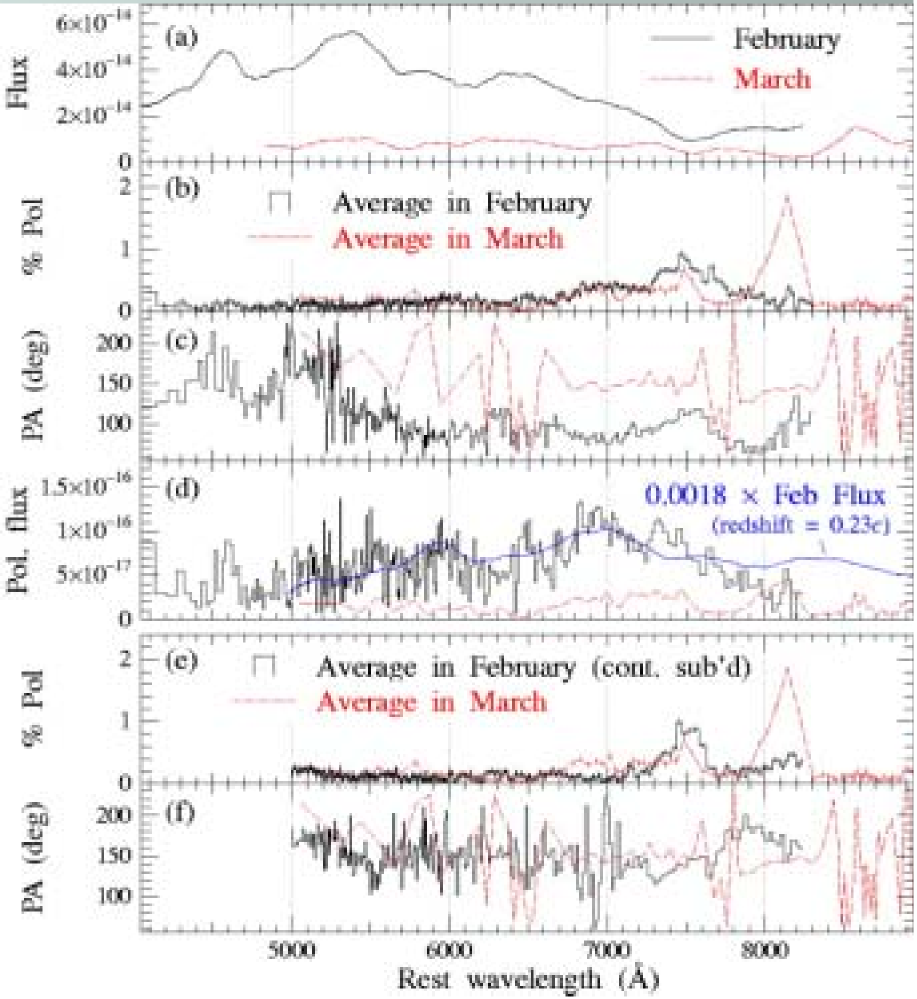
- SNe 1997ef, 1999as, 2002ap, 2003jd
  - Really no GRB?
  - Jet is away from the Earth direction?



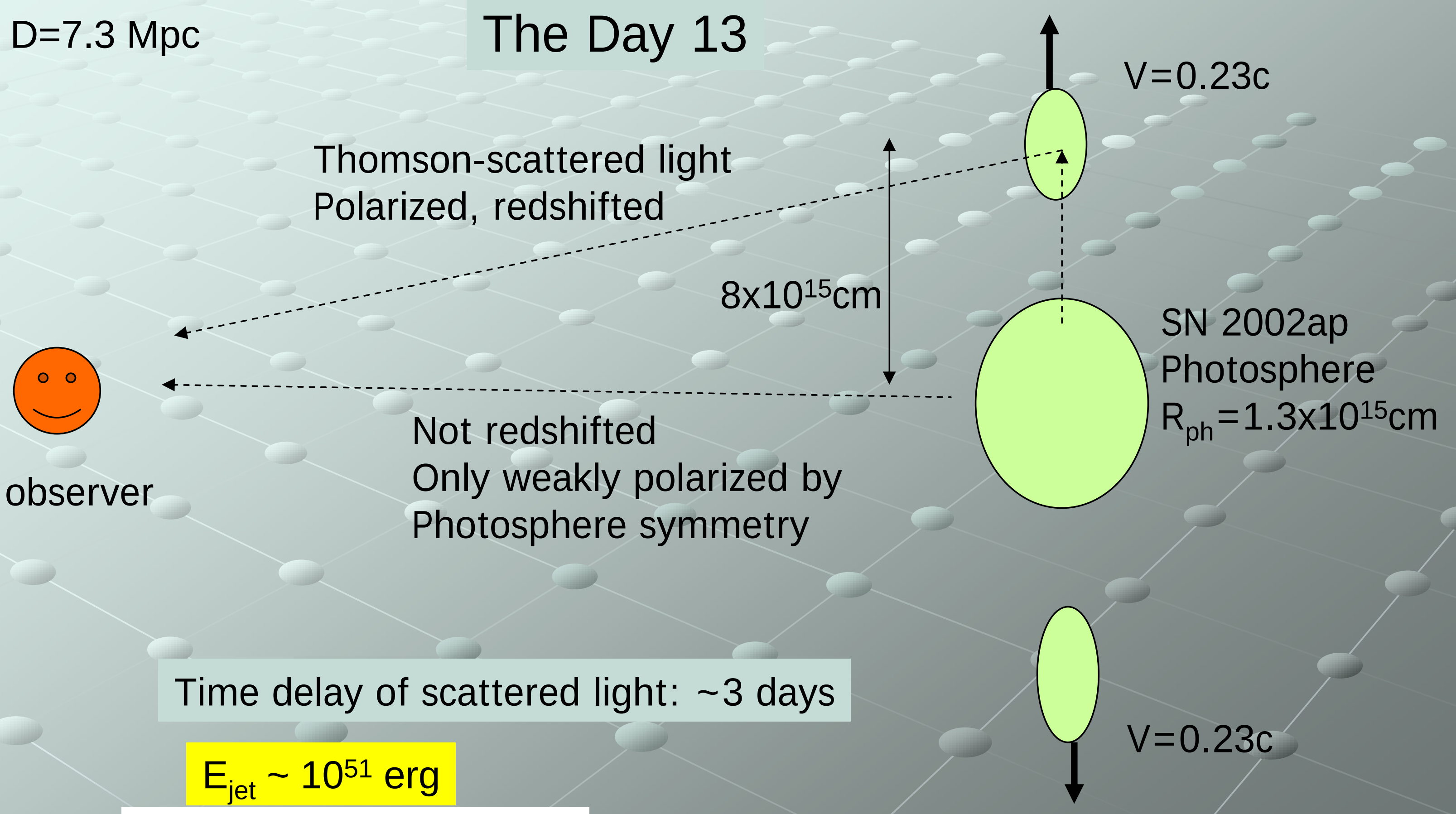
Slow massive jet from SN 2002ap?

Kawabata+ '03

- E_{kin}~10^{51} erg, v~0.2c inferred from spectropolarimetric observation (Kawabata+ 03; Totani '03)



Jet from SN 2002ap?

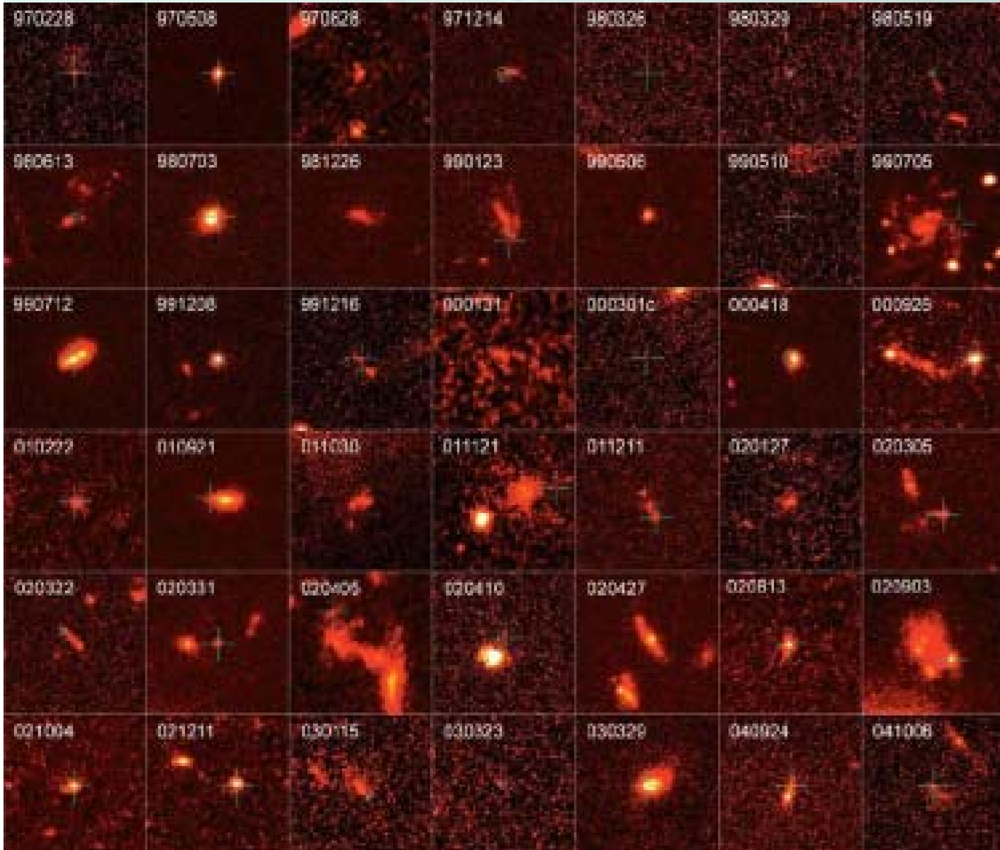


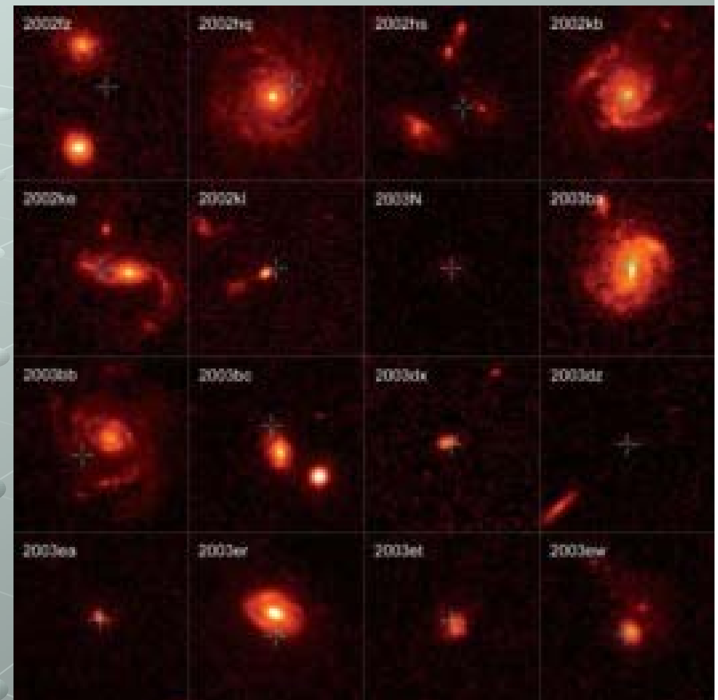
Time delay of scattered light: ~3 days

E_{jet} ~ 10^{51} erg

Kawabata+ 03; Totani 03

Different environment from SNe





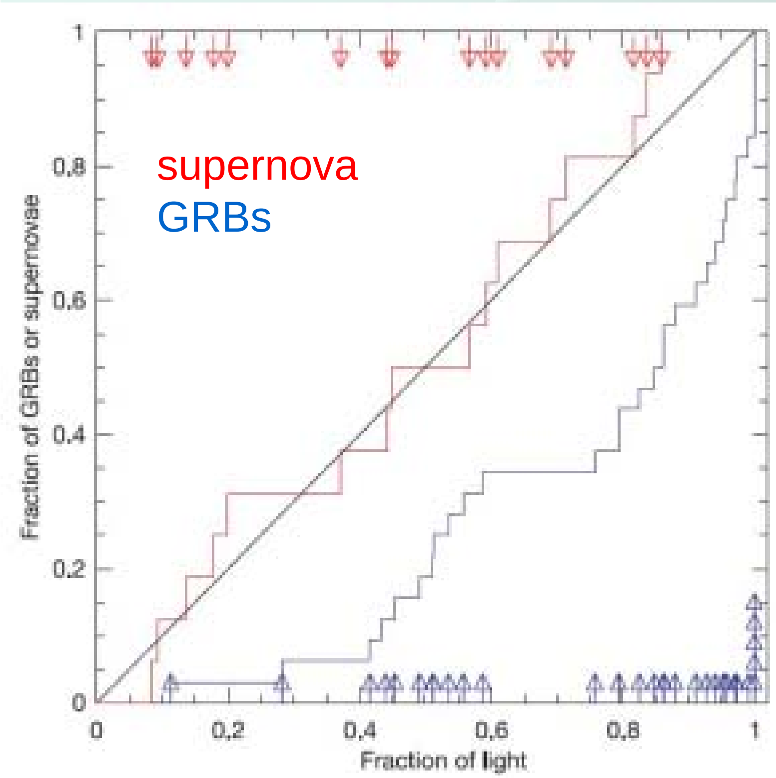
core-collapse
supernova hosts

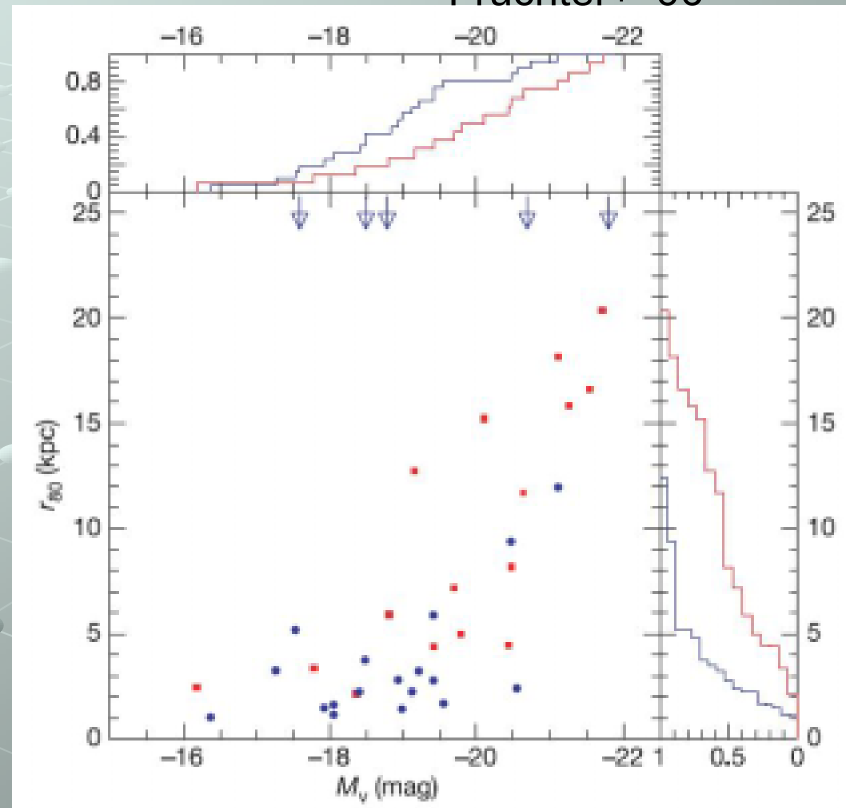
Long GRB hosts

Fruchter+ ‘06

Different environment from SNe

Fruchter+ '06





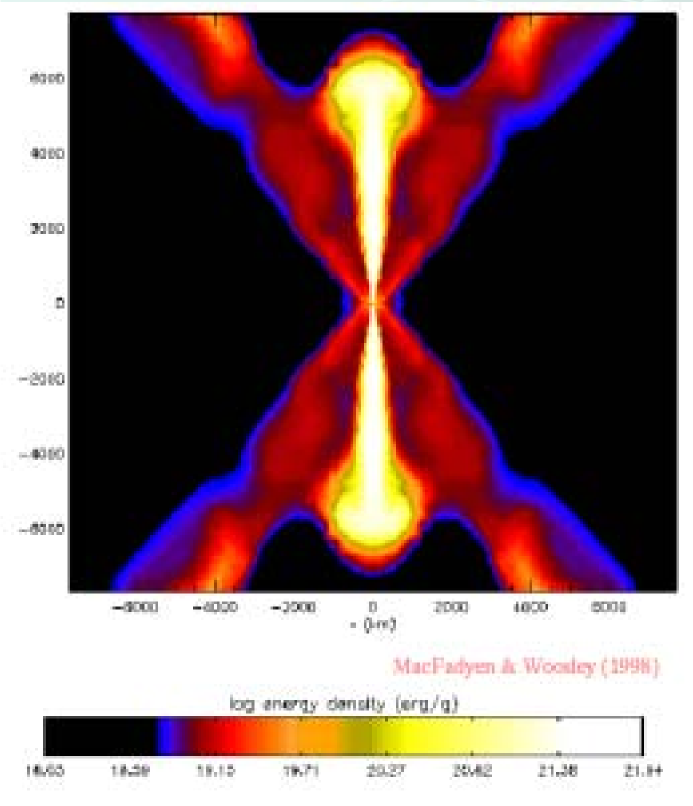
(in pixels brighter than GRB/SNe location)

GRB occurs at regions with higher surface brightness

GRB occurs in fainter and more compact host galaxies

Metallicity effect!?

Perspectives of Theoretical Understanding of the Central Engine of Long GRBs



- Long GRBs = Jet from stellar collapse = “collapser”
- Formation of jet?
  - The “classical” astrophysical jet problem from accretion disks
- Initial condition of stellar collapse
  - Is stellar mass the only one parameter?
    - Metallicity?
    - Angular momentum?
    - IMF?
- penetration of jet in the stellar CO core
  - Initial jet vs. final jet to GRBs
- acceleration up to **Γ** >100
  - Small mass, most outer part/skin?
  - Much more lower **Γ** ejecta likely

Short GRBs

Short-hard GRBs (SHBs): compact binary mergers?

- some SHBs occurs in nearby old, elliptical galaxies
- No supernova association

Gehrels+ '05

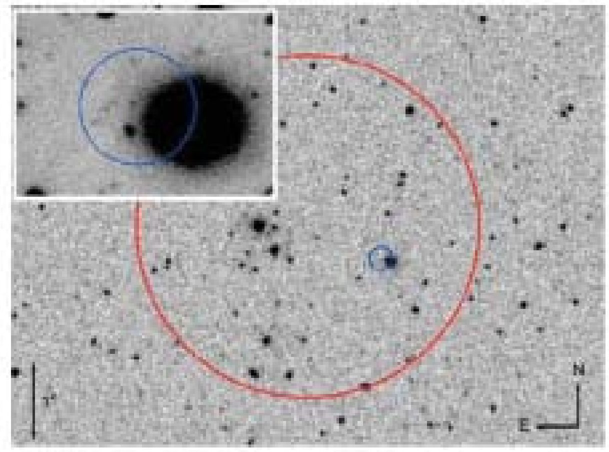


Figure 1 | Optical images of the region of GRB 050509B showing the association with a large elliptical galaxy. The Digitized Sky Survey image. The large red circle is the BAT position error circle, and the smaller blue circle is the XRT position error circle. The BAT position is 12 h 36 m 18 s,

GRB050509B (z=0.225)

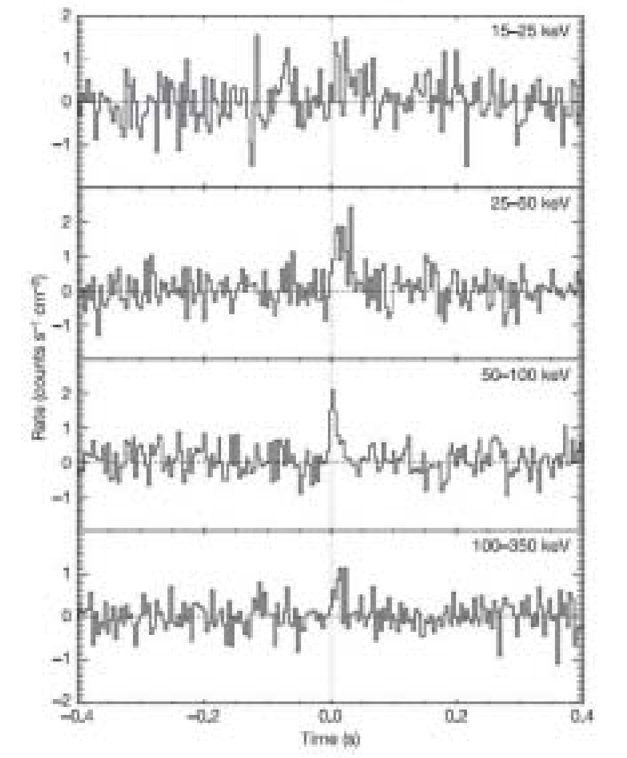


Figure 2 | BAT light curves for the short GRB 050509B, showing the short duration of this GRB. The light curves are given in four photon energy

Hjorth+ '05

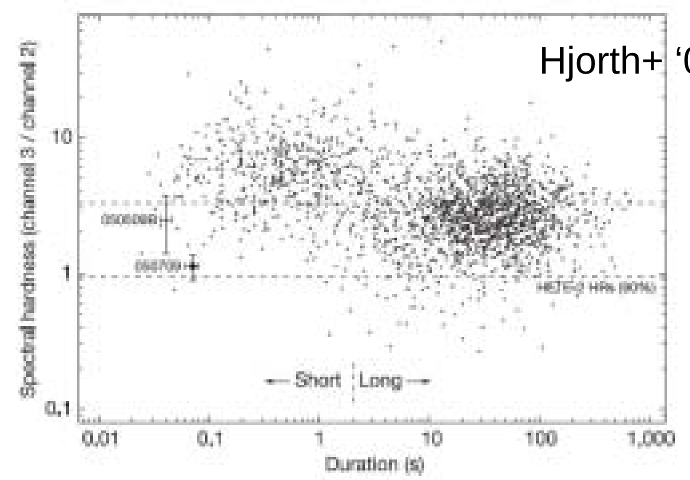


Figure 1 | The classic BATSE duration–spectral hardness diagram[1].

Properties of SHBs

- inconsistent with collapsars or young stellar populations
  - Occur both in young and old galaxies
  - Large distance from the center of host galaxies
- consistent with binary mergers (NS-NS or NS-BH)

Table 2 | Physical properties of short-hard bursts and their host galaxies

Property	GRB 050509B	GRB 050709	GRB 050724	GRB 050813
Redshift	0.225	0.160	0.258	0.722
T_{90}	40 ± 4 ms	70 ± 10 ms	3 ± 1 s	0.6 ± 0.1 s
Fluence (erg cm^{-2})	9.5×10^{-9}	2.9×10^{-7}	6.3×10^{-7}	1.2×10^{-7}
Fluence band	15–350 keV	30–400 keV	15–350 keV	15–350 keV
$E_{\gamma,iso}$ (erg)	4.5×10^{48}	6.9×10^{49}	4.0×10^{50}	6.5×10^{50}
$L_{\gamma,peak}$ (erg s^{-1})	1.4×10^{50}	1.1×10^{51}	1.7×10^{50}	1.9×10^{51}
L_X (erg s^{-1})	$<7 \times 10^{41}$	3×10^{42}	8×10^{43}	9×10^{43}
f_b	-	0.03	0.01	-
E_γ (erg)	$<4.5 \times 10^{48}$	2.1×10^{48}	4.0×10^{48}	$<6.5 \times 10^{50}$
Host L/L_*	1.5	0.10	1.6	-
Host star-formation rate ($M_\odot$ yr^{-1})	<0.1	0.2	<0.03	-
Offset (kpc)	44^{+12}_{-23}	3.8	2.6	-
Offset (r/r_e)	13^{+3}_{-7}	1.8	0.4	-
Supernova limit, M_R (mag)	>−13.0	>−12.0	-	-
References	4, 5, 6	10; this work	21, 42	*

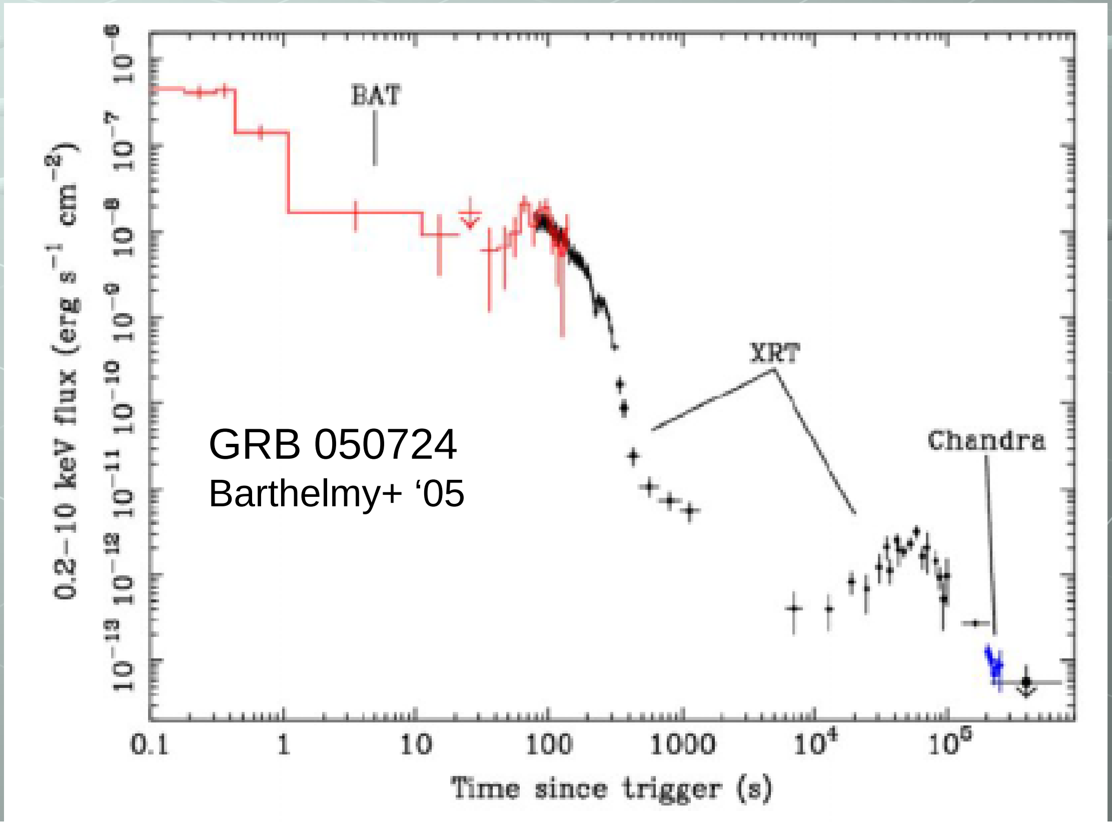
In order, the table shows: the burst redshift; the duration of the 90%-inclusive interval of high-energy emission (T_{90}); the measured burst fluence and corresponding energy bandpass; the peak burst luminosity; the isotropic-equivalent γ-ray burst energy; the isotropic-equivalent luminosity in X-ray at 10 h post-burst; the beaming fraction, calculated from the jet collimation angle θ_j as $f_b = 1 - \cos(\theta_j)$; the γ-ray energy release corrected for beaming fraction, $f_b E_{\gamma,iso}$; the host galaxy luminosity; the host star-formation rate; the burst offset from its host, in physical units and referred to the scale length of the host galaxy's light profile; and the absolute magnitude limit on any associated supernova. Empty cells are unconstrained by the data at present; values without uncertainties are known to roughly 20% precision. The values of $E_{\gamma,iso}$ and $L_{\gamma,peak}$ have been increased by a factor of four, representing a mean correction from the BATSE sample for converting these observed fluences to the 25–2,000 keV band.

* D.B.F. *et al.* (manuscript in preparation); M. Gladders *et al.* (manuscript in preparation).

Fox et al. ‘05

Flares in SBH afterglows

- late phase activity also in SBHs
- ~10% energy of prompt emission (GRB 050724)
- long duration activity of the central engine? slow ejecta?



short GRBs by SGR giant flares in nearby galaxies?

- Not all, but <~15% (Nakar+ '06) of short GRBs could be giant flares of **soft gamma-ray repeaters (SGRs)** in nearby galaxies, as inferred from SGR flares in our Galaxy
- a good candidate: GRB 051103
  - associated with M81/M82 (3.6 Mpc)

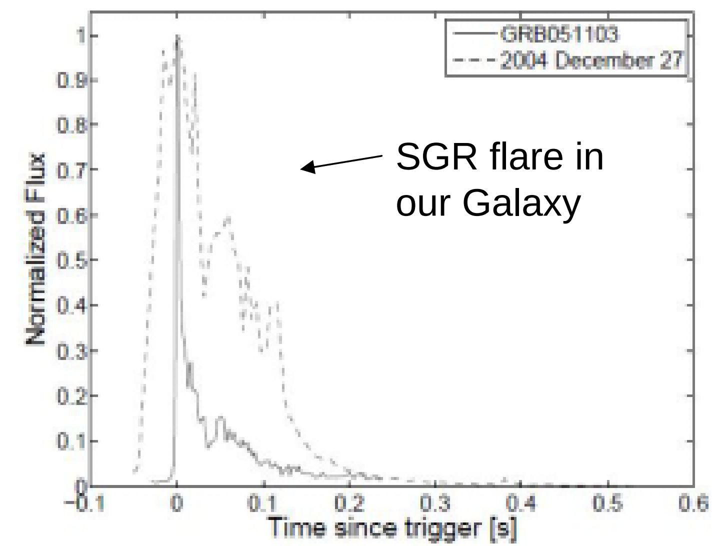
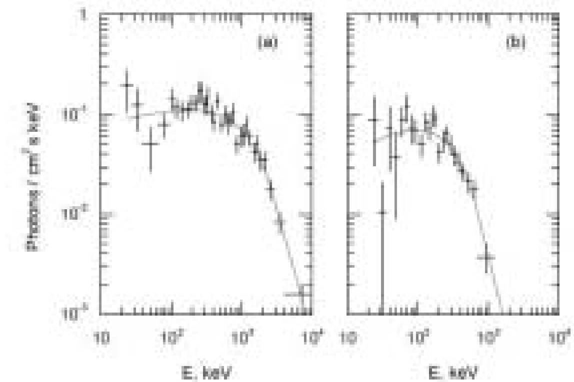


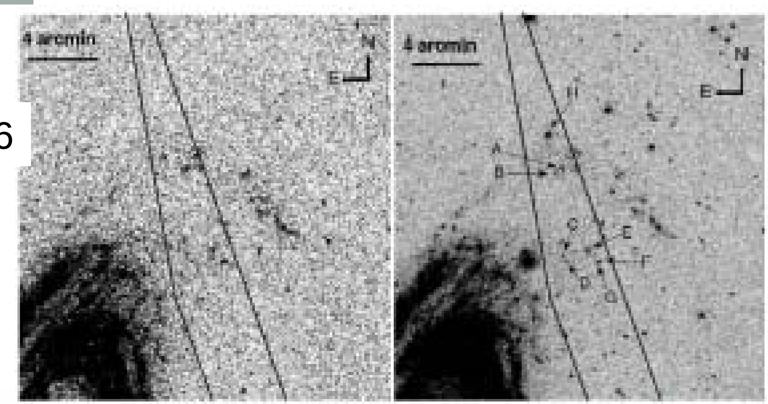
FIG. 1.— The Konus/Wind gamma-ray light curve of GRB 051103 (solid line), compared with the light curve of the 2004 December 27 SGR giant flare (dashed line). The light curve of the 2004 December 27 SGR giant flare is based on a digitization of Figure 1 in Terasawa et al. (2005), while the light curve of GRB 051103 is based on a digitization of the 18-1160 keV-band light curve from the Konus/Wind website.



measured in the time intervals 0-64 ms (a) and 65-192 ms

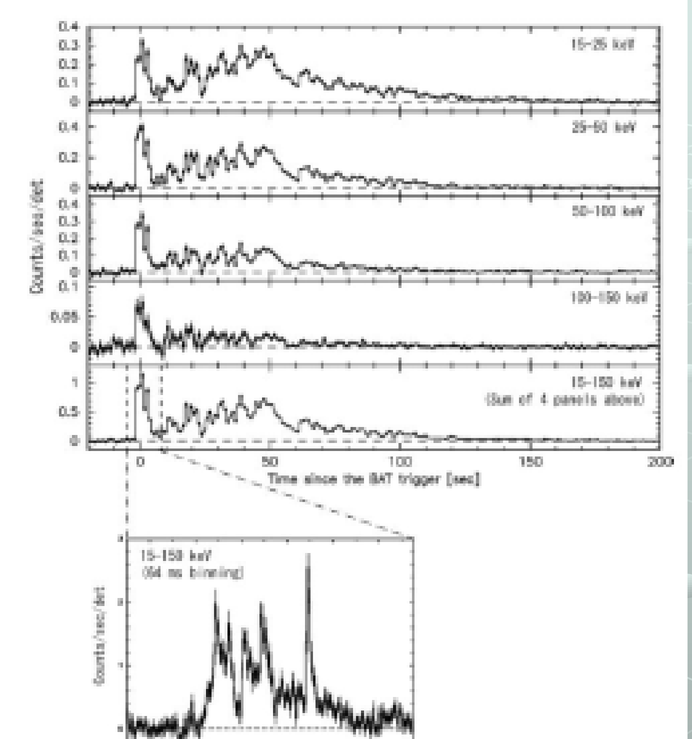
Frederiks+ '06

Ofek+ '06

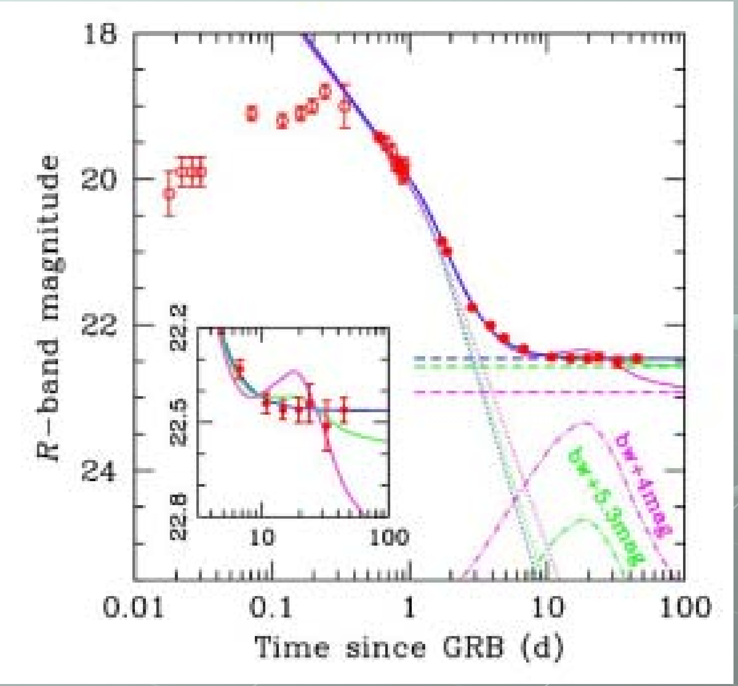


A New Class!?

A New Class? GRB 060614



Gehrels+ '06

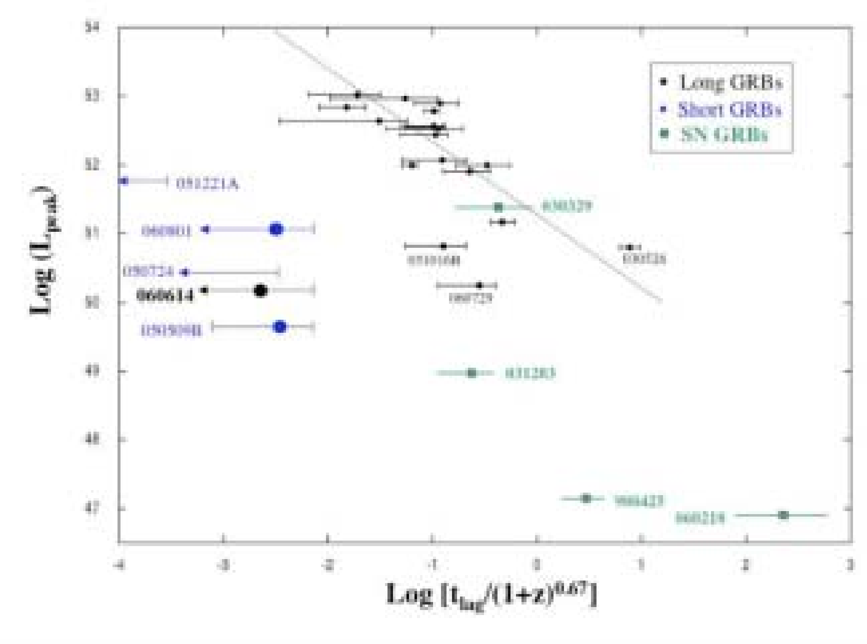


Della Valle+ '06

- a long GRB according to the classical definition
- dwarf galaxy at z=0.125
  - SFR=0.0035 M_{sun}/yr, specific SFR = 0.23 M_{sun}/yr/L* (<< typical LGRBs)
- No supernova, M_{Ni} <~ 10^{-3} M_{sun}

A New Class? GRB 060614

- Interpretations:
  - collapsar without SN / Ni production?
  - peculiarly long “short GRB” or mergers?
    - time variability properties consistent as a short GRB
    - some short GRBs have later long component as GRB 060614 (Gehrels+’06)
  - chance alignment of a more distant long GRB?
    - Cobb+ ’06; Schaefer+ ’06, but see also Gehrels+’06



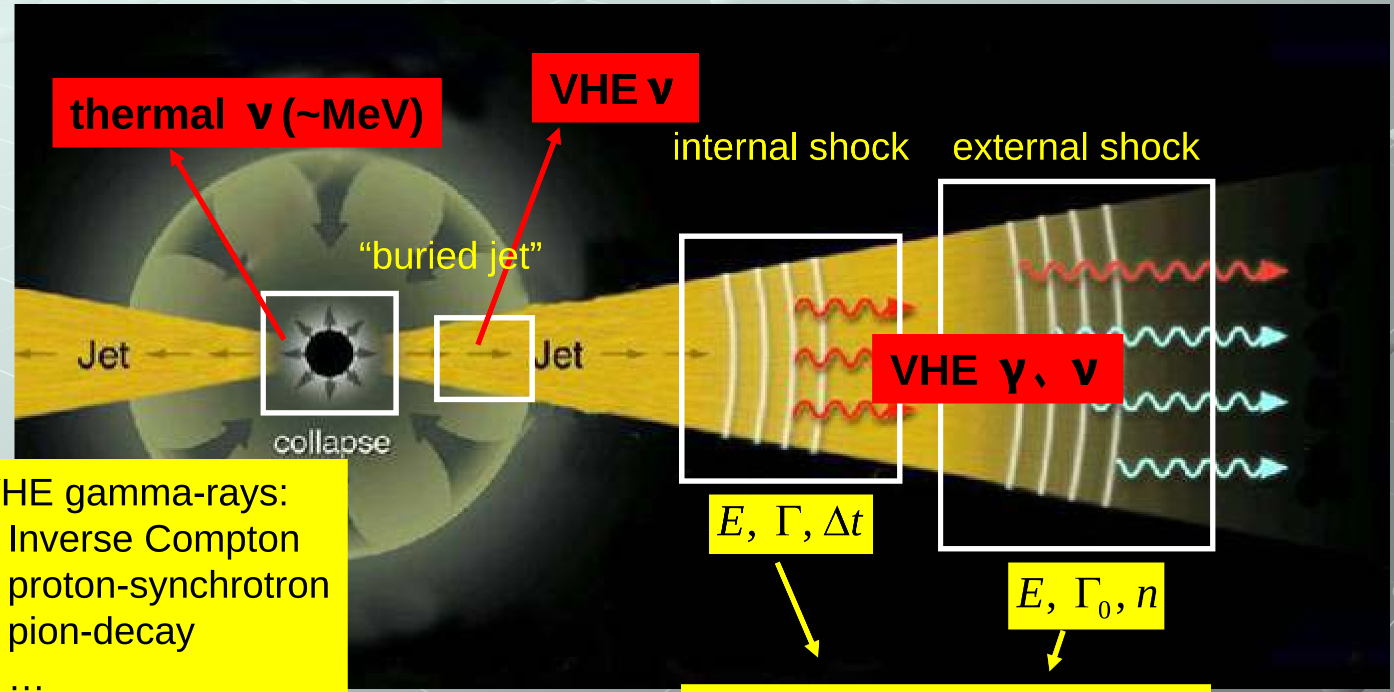
Gehrels+ ‘06

- GRB 060505 (Fynbo+ ’06)
  - a faint GRB with a duration of 4 s, z=0.089, no supernova
  - long tail of genuine short GRBs?
  - See also Ofek+ ‘07

Neutrino and High Energy Emission from GRBs

Particle Acceleration and Very High Energy Emission from GRBs

- GRB shocks can accelerate protons to 10^{20} eV and electrons to 10^{14} eV



density, B, optical depth, etc.

VHE gamma-rays:
- Inverse Compton
- proton-synchrotron
- pion-decay
- …

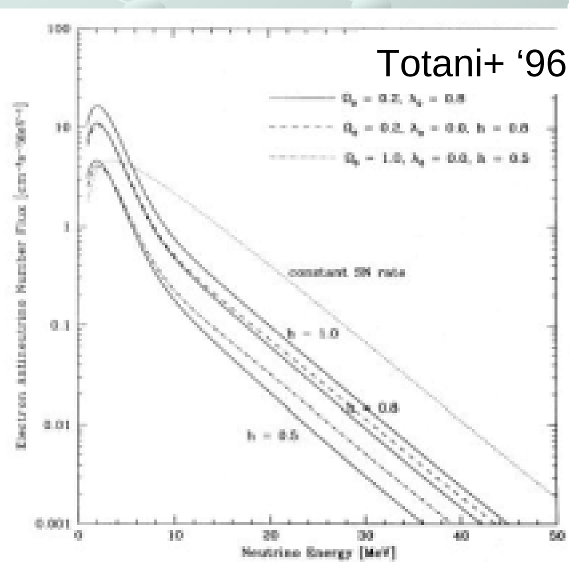
VHE neutrinos
- p-p → pions
- p-gamma → pions
- n-p (bulk) → pions
- …

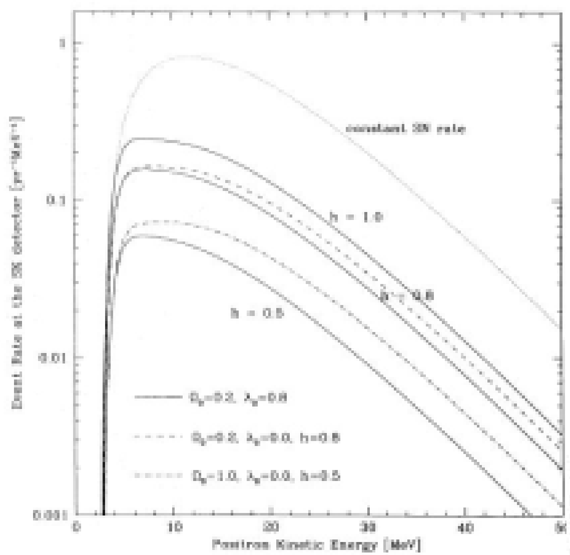
thermal ν from GRBs

- Theoretically uncertain compared with normal core-collapse SNe
  - Massive → ~10 times more gravitational energy
  - Effect of disk? Spectrum?
- Neutrinos from one GRB: too distant
  - Closest GRB is ~35 Mpc (GRB 980425/SN1998bw)
- Contribution to background supernova neutrinos: too low event rate
  - Super-K upper limit is quite close to theoretical prediction for all SNe
  - GRB rate <~10^{-4} x supernovae

Malek+ ‘03

Totani+ ‘96





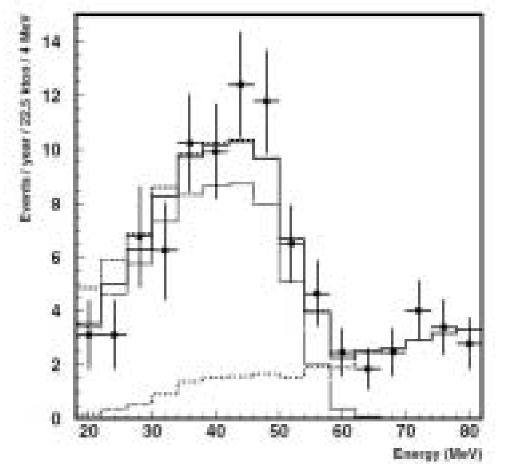
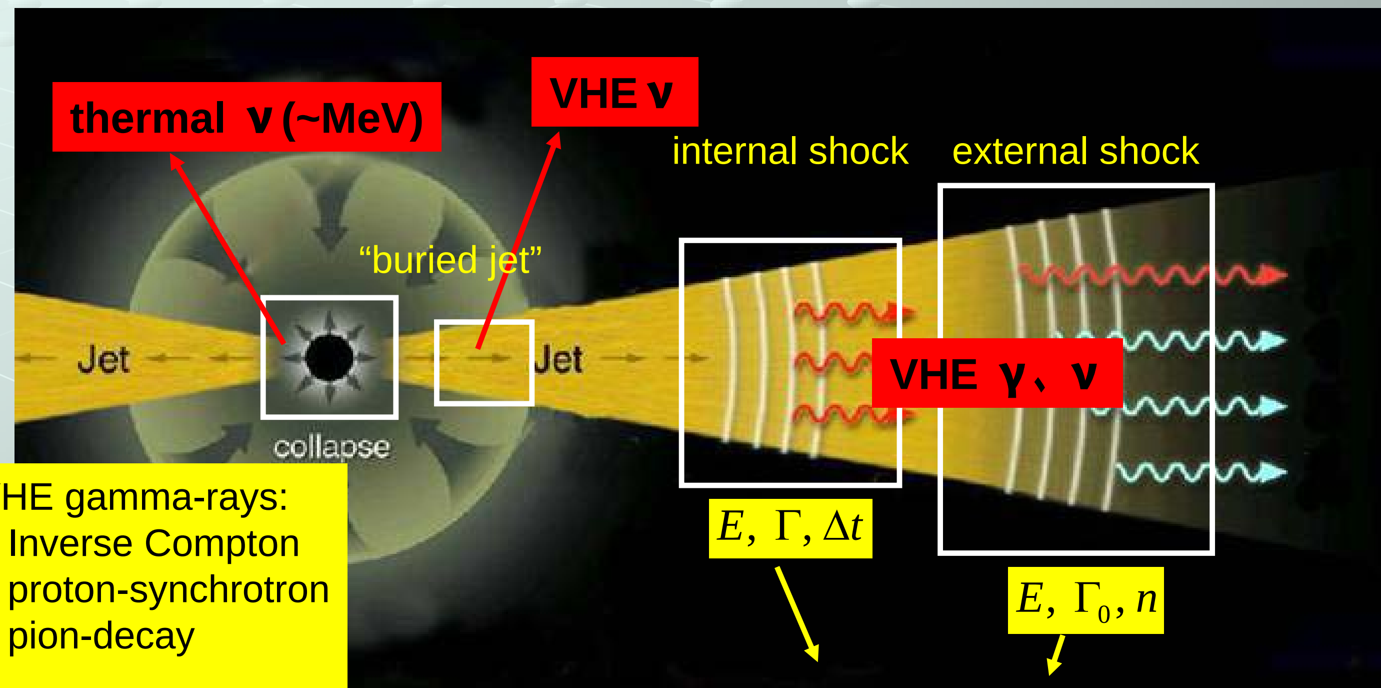


FIG. 2. Energy spectrum of SRN candidates. The dotted and dash-dotted histograms are the fitted backgrounds from invisible muons and atmospheric ν_e. The solid histogram is the sum of these two backgrounds. The dashed line shows the sum of the total background and the 90% upper limit of the SRN signal.

Particle Acceleration and Very High Energy Emission from GRBs

- GRB shocks can accelerate protons to 10^{20} eV and electrons to 10^{14} eV



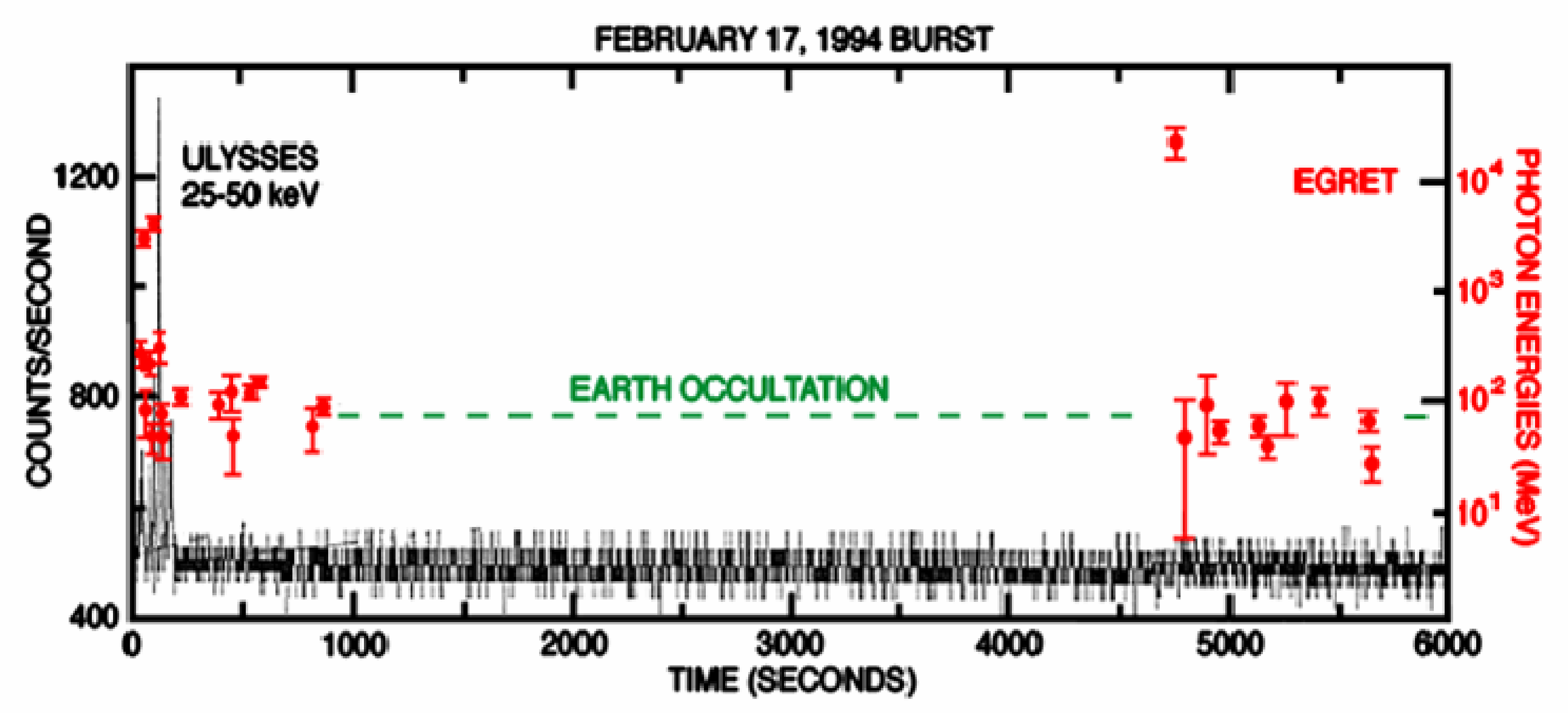
VHE gamma-rays:
- Inverse Compton
- proton-synchrotron
- pion-decay
- …

VHE neutrinos
- p-p → pions
- p-gamma → pions
- n-p (bulk) → pions
- …

density, B, optical depth, etc.

VHE gammas already detected

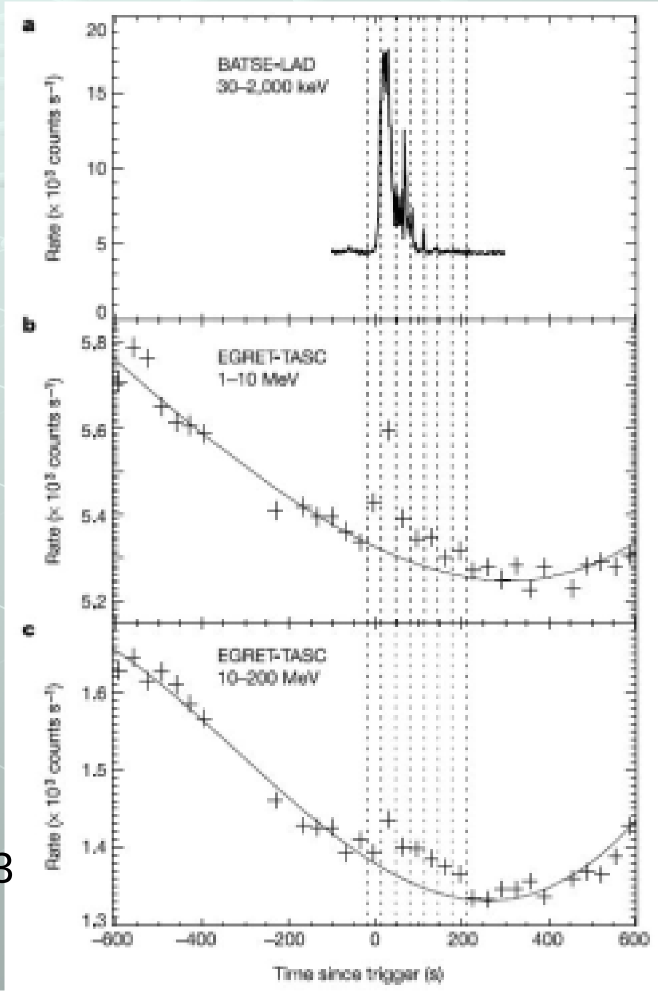
- <~18 GeV photons from GRB 940217 for ~2 hours

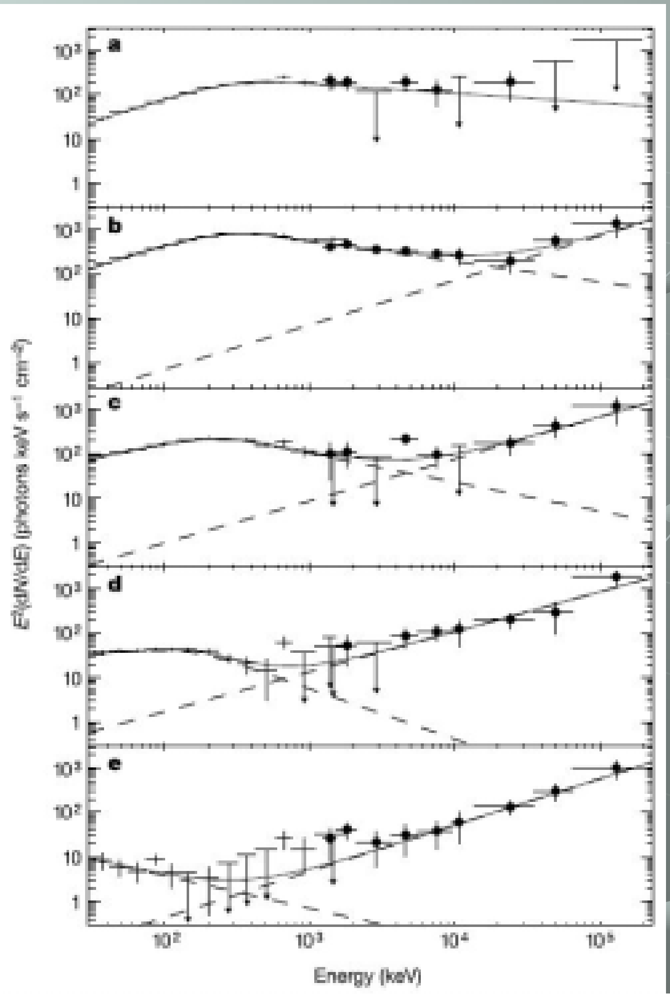


Hurley+ '94

VHE gammas already detected

- ~100 MeV emission showing different temporal behavior to <~MeV photons from GRB 941017

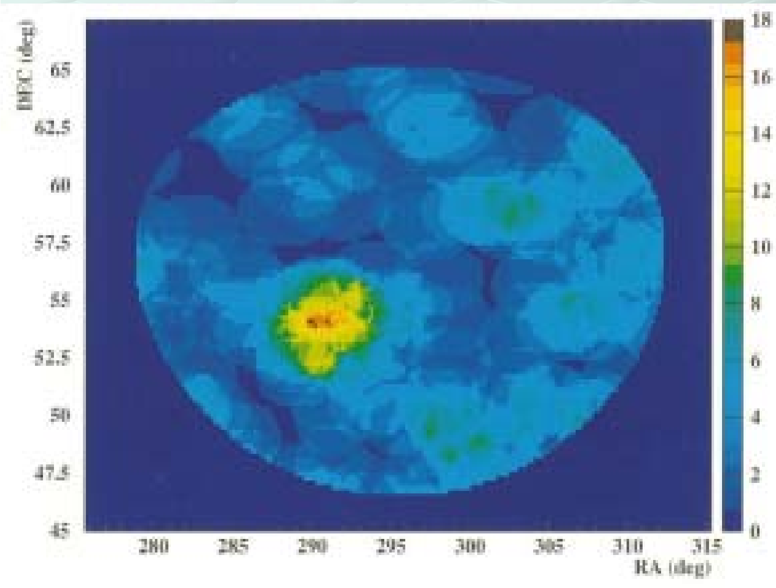


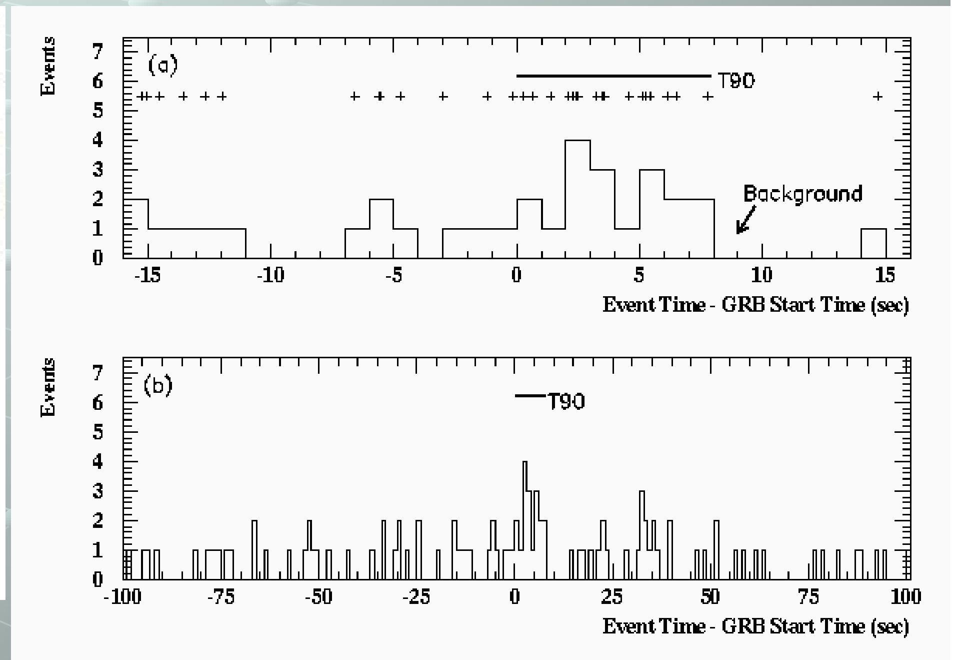


Gonzalez+ ‘03

Evidence for >TeV gamma, but needs confirmation

- Milagrito observation for GRB 970417a (Atkins+ '00)

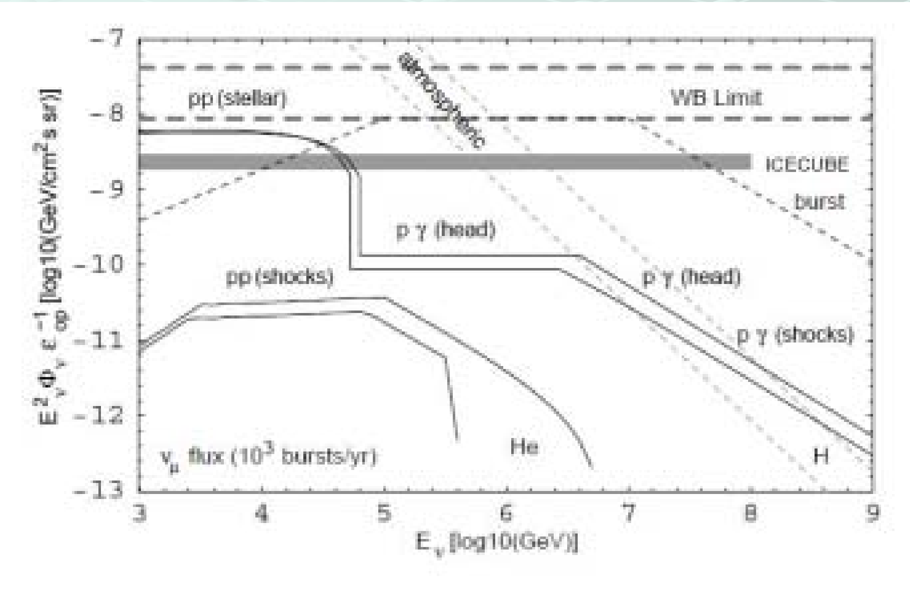




- see also
  - Tibet air shower (Amenomori+ '96)
  - HEGRA (Padilla+ '98)
  - GRAND (Poirier+ '03)

Prediction for VHE Neutrinos

Diffuse background flux, Razzaque+ '03



- The prediction is close to the WB limit if:
  - GRBs are responsible for UHECRs
  - Interaction efficiency of pp or p **γ** reactions is ~1

prediction for
GRB 030329/SN2003dh-like
events at z~0.168
(Razzaque+ '04)

TABLE I. Neutrino events in a km scale under-ice detector at the South Pole from the GRB 030329 and the associated SN 2003dh. We have also calculated events assuming similar GRB-SN cases with declinations 90° (upward events denoted by ↑) and 0° (horizontal events denoted by →). We have not considered detector response for our calculation.

Flux component	TeV-PeV		PeV-EeV	
	μ track	e cascade	μ track	e cascade
Precursor I	9×10^{-3}	2×10^{-3}		
	6×10^{-3} ↑	2×10^{-3} ↑		
	0.01 →	2×10^{-3} →		
Precursor II	4.1	1.1	3×10^{-3}	2×10^{-4}
	2.9 ↑	0.9 ↑		
	4.4 →	1.2 →	0.01 →	8×10^{-4} →
Burst	1.8	0.2	1.4	0.1
	0.3 ↑	0.04 ↑		
	2.9 →	0.3 →	7.6 →	0.4 →
Afterglow (ISM)	2×10^{-4}	2×10^{-5}	2×10^{-4}	1×10^{-5}
	3×10^{-5} ↑	4×10^{-6} ↑		
	2×10^{-4} →	2×10^{-5} →	0.01 →	5×10^{-4} →
Afterglow (wind)	0.03	3×10^{-3}	0.05	3×10^{-3}
	5×10^{-3} ↑	7×10^{-4} ↑		
	0.05 →	5×10^{-3} →	1.4 →	0.06 →

GRB Cosmology

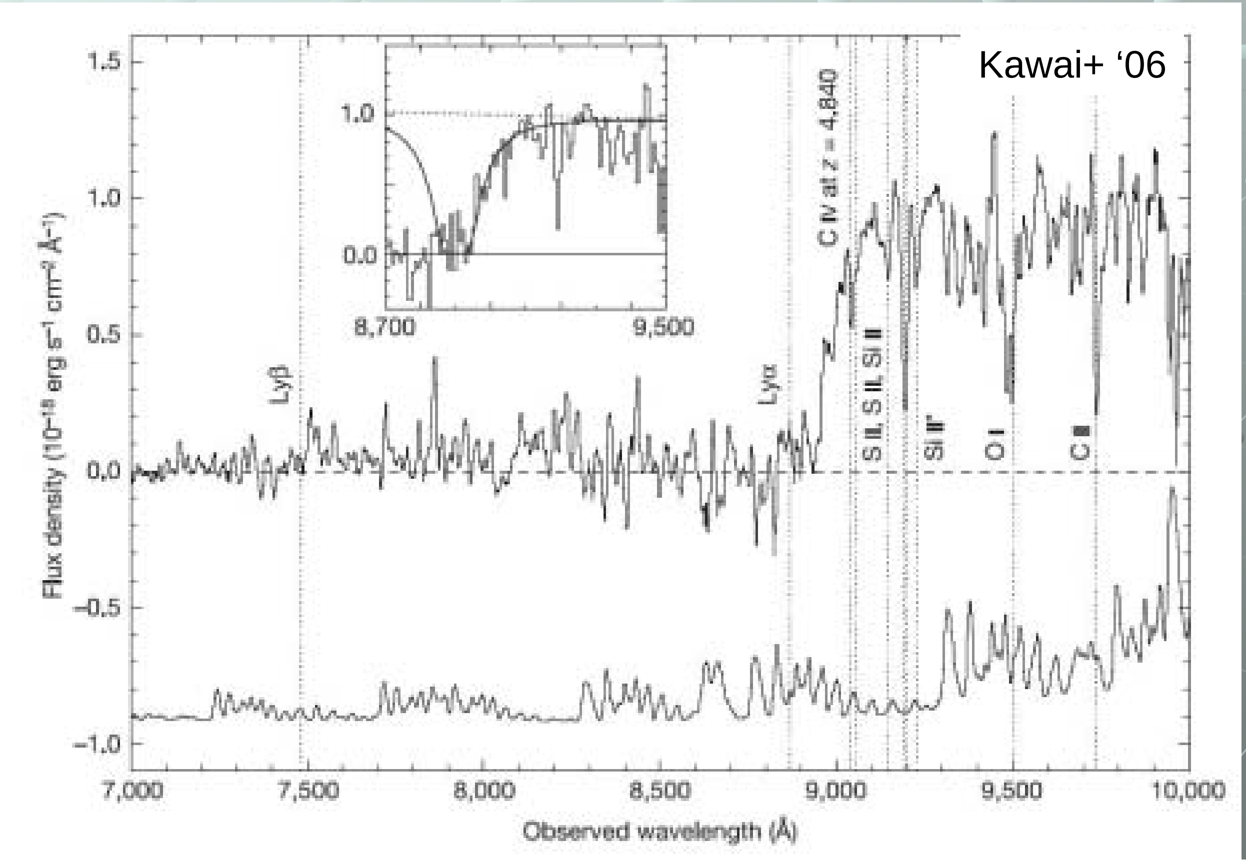
GRBs as a Cosmological Probe

- GRBs are extremely bright, detectable even out to z~20!

- Possible Uses of GRBs for cosmology
  - Star formation indicator at high-z
    - long GRBs associated with massive star formation
    - short GRBs associated with compact binary merger (?)
    - gamma-ray flux insensitive to dust
    - detectable in small galaxies
  - Probe of physical status of high-z universe
    - reionization / intergalactic medium
    - insterstellar/circumstellar matter in high-z host galaxies
  - Measure of the geometry of the universe / Dark energy probe
    - if they are standard candle (?)

The Breakthrough: GRB 050904 at z=6.3

- Swift detection and spectral confirmation by Subaru
- z=6.3 (previous record was z=4.5)
  - almost comparable with the highest galaxies and quasars



Implications for star formation history

- Swift GRB z distribution is consistent with star formation history inferred from galaxy observations

- Some caveats: selection effects
  - detectability of afterglows
  - efficiency of measuring redshift
  - poorly known…

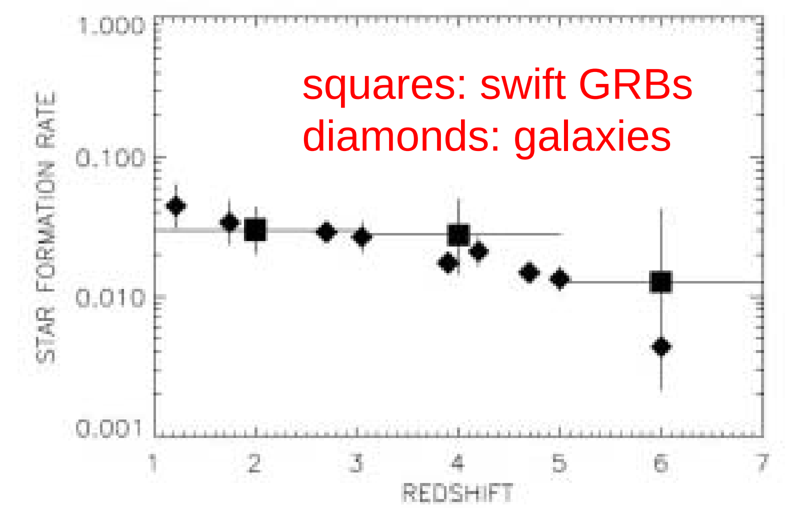
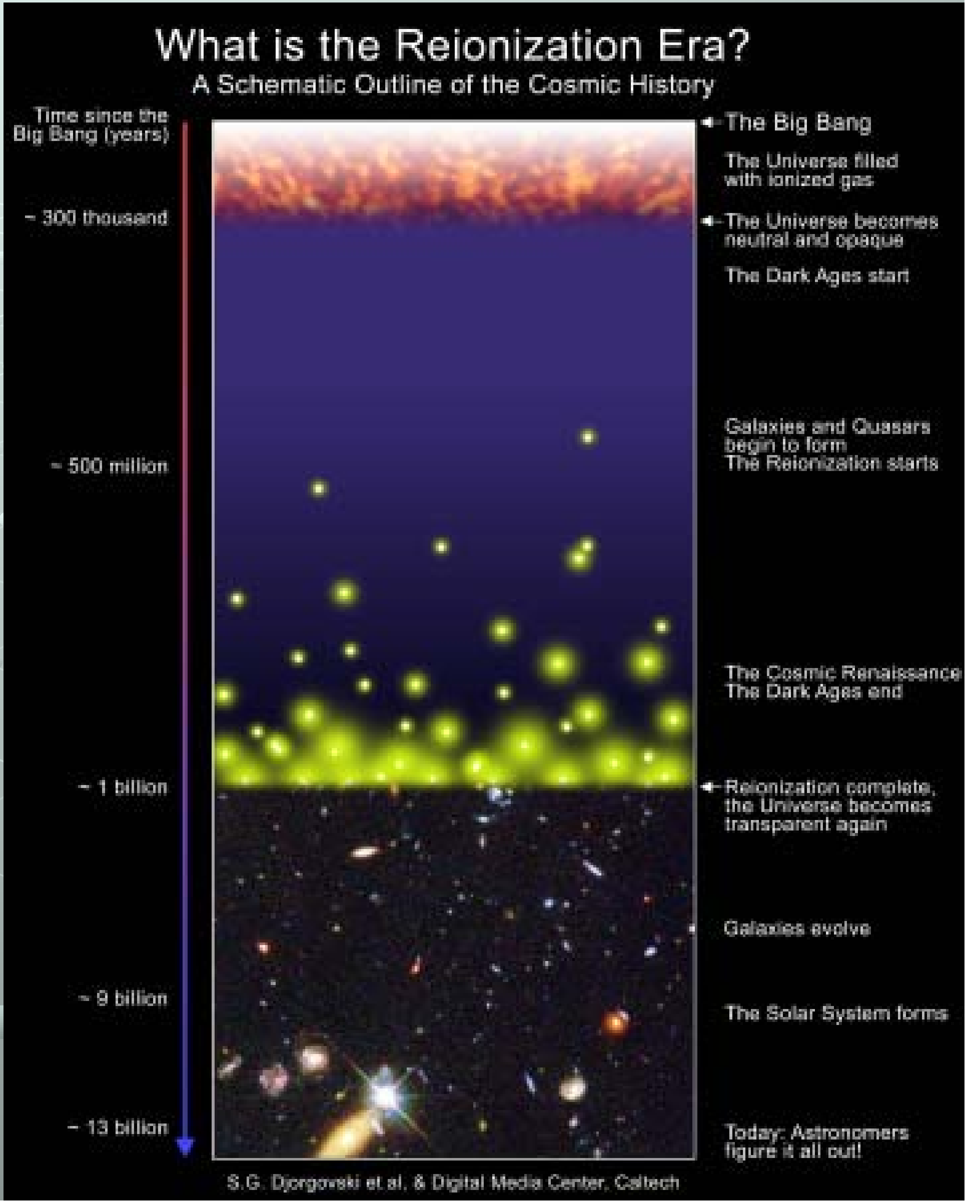


FIG. 4.—Star formation rate as a function of redshift in units of solar masses per Mpc^3, taken from the compilation of Bunker et al. (2004), is shown by diamonds. The squares with 1 σ error bars show the corresponding determinations from the *Swift* GRBs for a normalizing constant of 0.0033 in the same units.

Price+ '06

Reionization

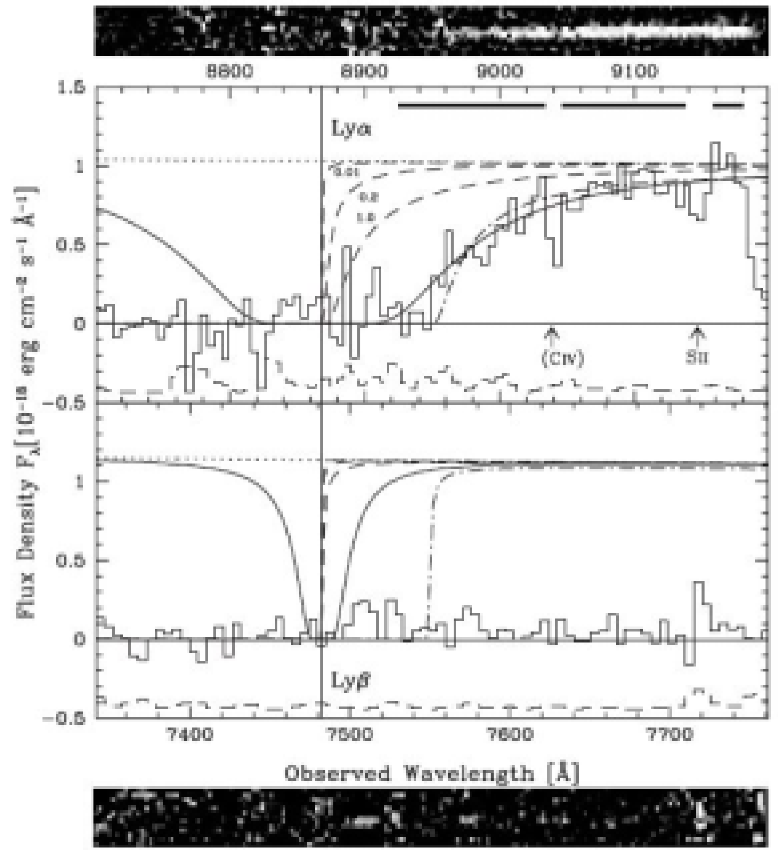
- the Cosmic Dark Age:
  - from recombination ($z \sim 1100$) to reionization ($z \sim 6$? 20?)
  - reionization: marks the beginning of galaxy formation and end of the dark age
- Previous constraints:
  - hydrogen absorption in quasar specta
    - $z_{reion} > \sim 6$
  - CMB polarization
    - $z_{reion} \sim 15$



GRB is (potentially) a better probe than quasars

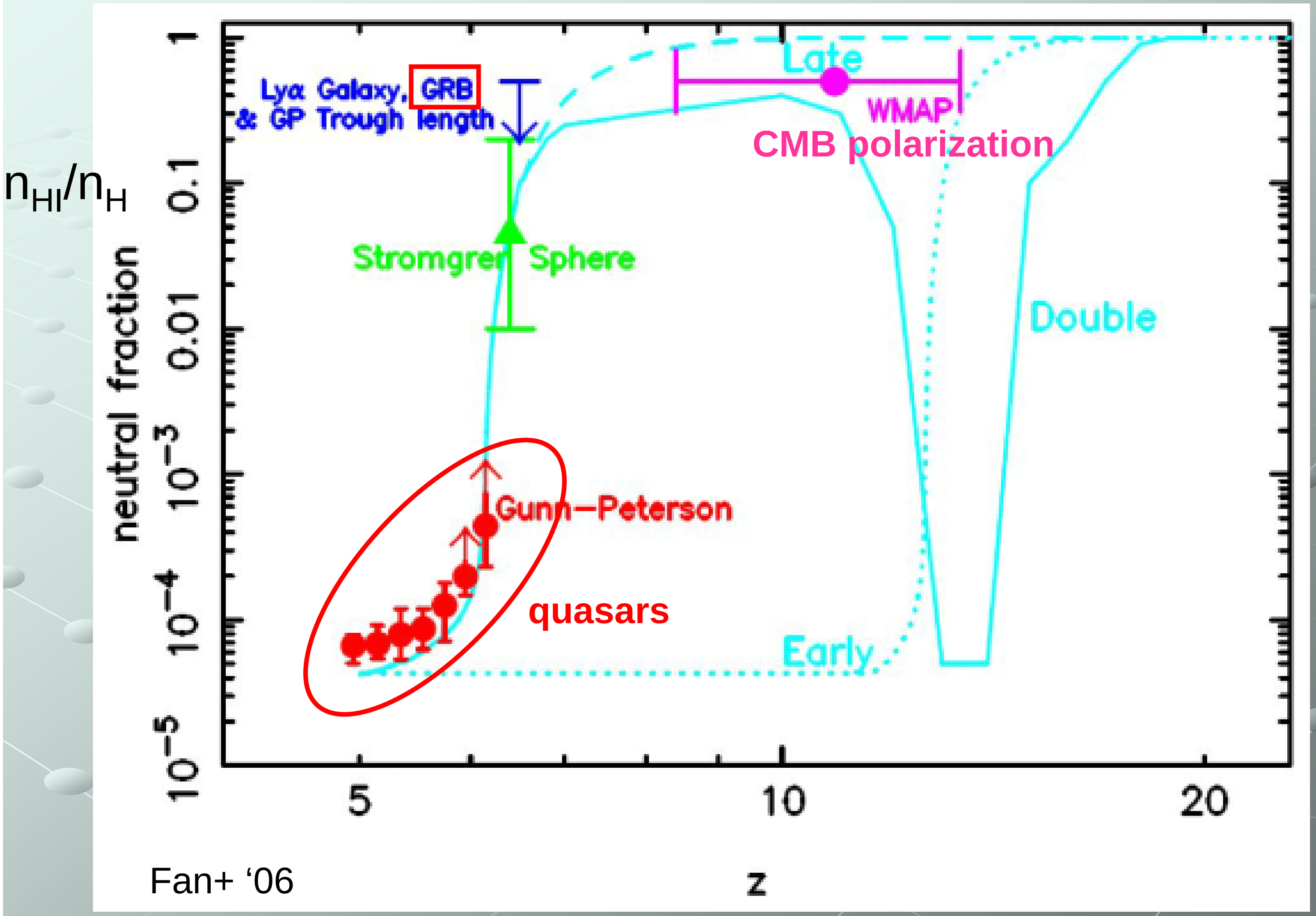
- Merits:
  - GRBs detectable at z>>6
  - Probe for more normal region in the universe
    - GRBs detectable even in small dwarf galaxies
    - No proximity effect
  - simple power-law spectrum of optical afterglows

- First constraint from GRB 050904
  - damping wing analysis (not possible for quasars)
  - first quantitative upper bound on neutral fraction at z>6
    - n_{HI}/n_H < 0.17 (68%CL) or 0.60 (95%CL) at z=6.3



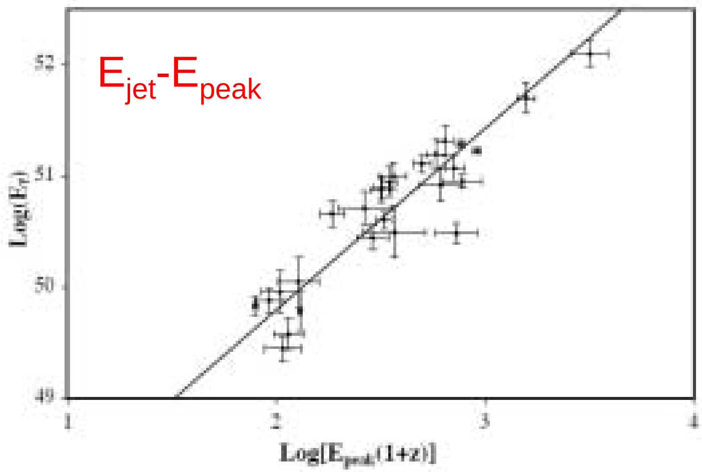
Totani+ '06

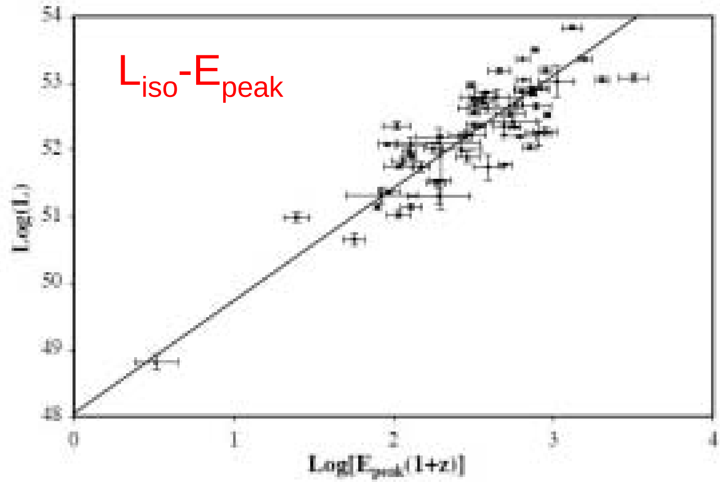
Constraints on Reionization



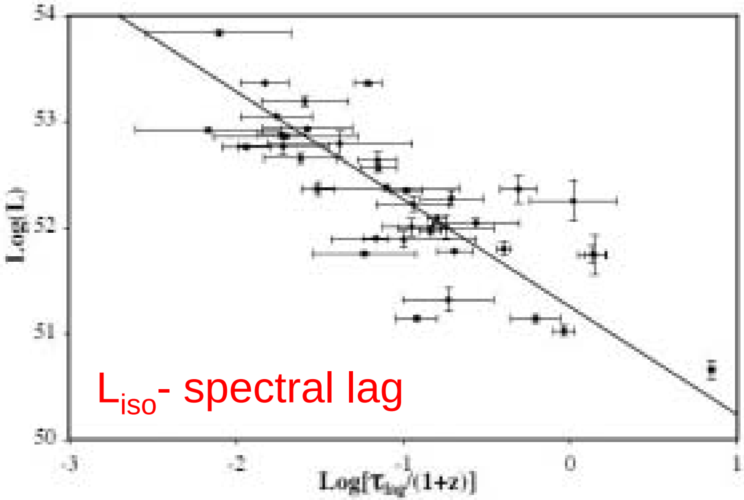
Fan+ '06

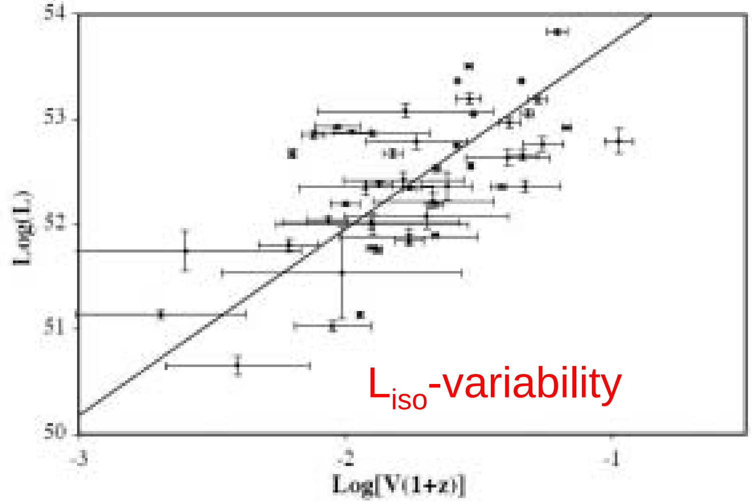
Luminosity/distance indicators of GRBs





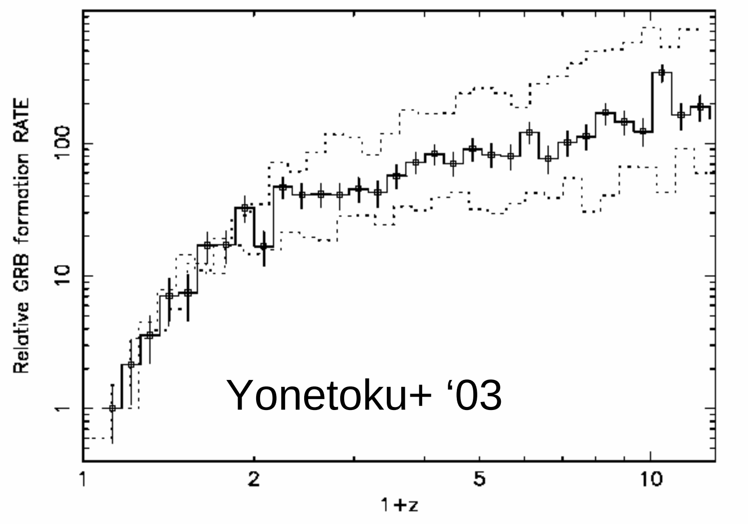
Schaefer '06



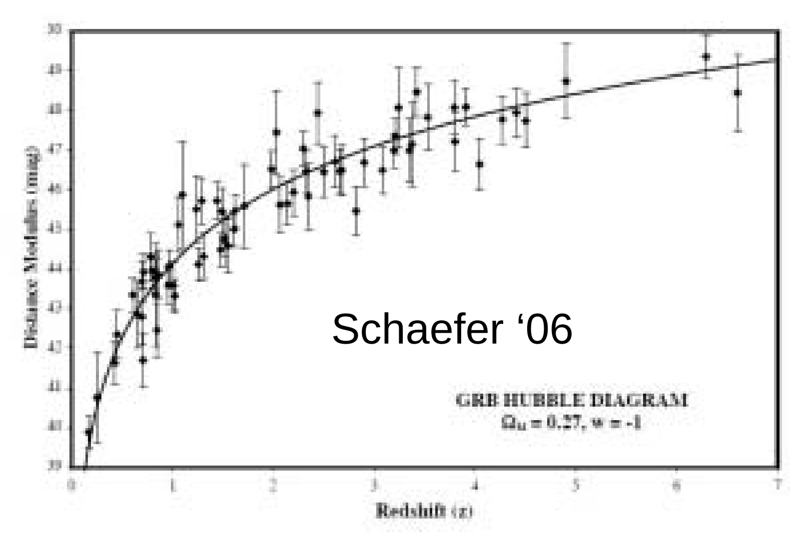


Applications

- star formation history
  - By using GRBs without z



- Hubble diagram



Constraint on Dark Energy?

- Pros: Highest-z probe for dark energy
- Cons: systematics

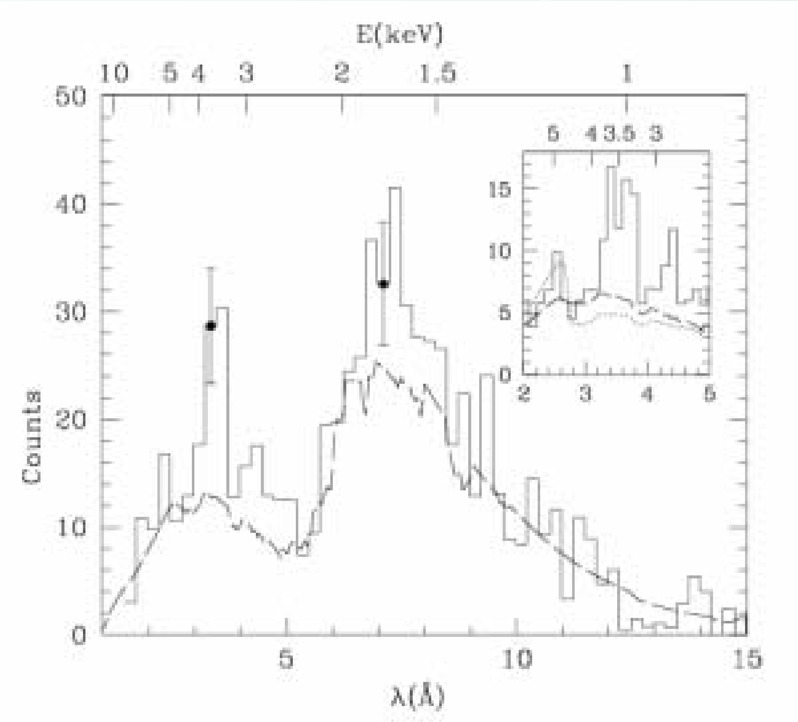
- Current problem of GRB Hubble diagram:
  - same data set for L-indicator calibration and hubble diagram
    - circular argument / tautology

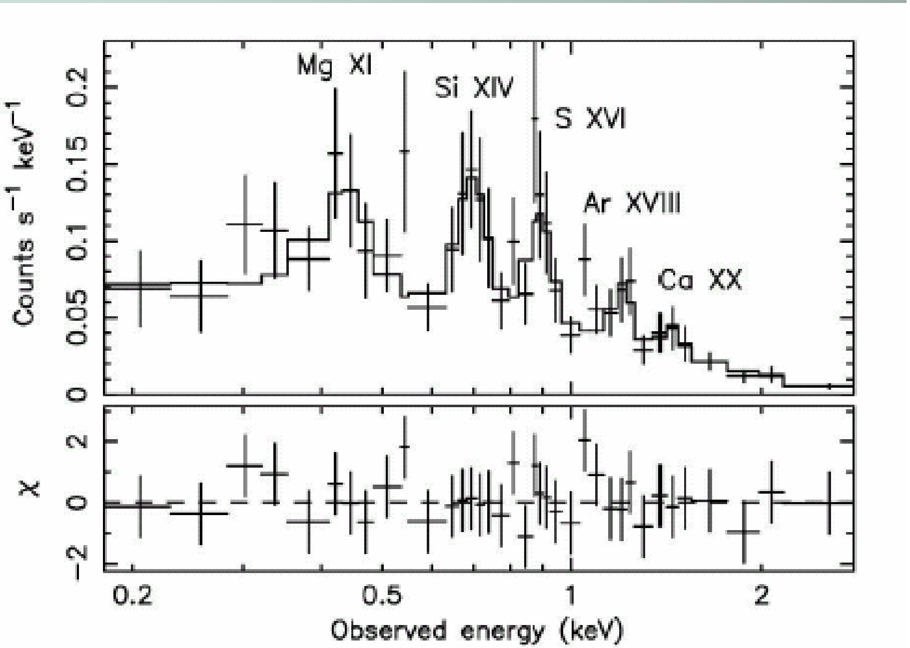
- For the real Hubble diagram, we need:
  - L-indicator calibration by independent data set!
    - e.g., another distance measure (Cepheid etc.)
    - e.g., low-z GRB sample

- Still, systematics even in the real Hubble diagram…
  - evolution?
    - GRBs seem to depend strongly on environment and metallicity
    - …

backup slides

X-ray Emission Lines





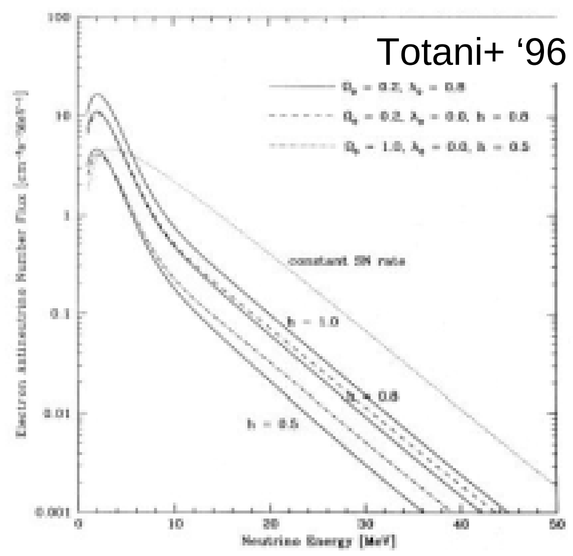
GRB991216, Chandra, Fe lines GRB011121, XMM-Newton

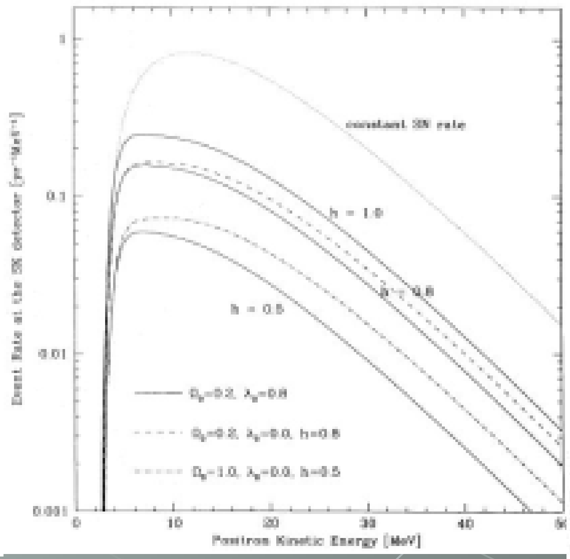
Reeves et al. (2002), but see also
Rutledge et al. and Borozdin et al.

thermal ν background from SNe/GRBs

- typical theoretical prediction:
  - $F_\nu \sim n_\nu/c \sim 50\ cm^2 s^{-1}(4\pi\ sr)^{-1}$ (whole)
  - $F_\nu \sim n_\nu/c \sim 0.5\ cm^2 s^{-1}(4\pi\ sr)^{-1}$ (E_ν >~ 20 MeV) = ~ a few events / yr in Super-K
- Super-K upper limit:
  - $1.2\ cm^2 s^{-1}$ for E_ν>19.3 MeV (Malek+ '03)
- GRBs?
  - total energy of ν's may be ~10 times higher
  - event rate <~10^{-4} x supernovae
  - neutrino spectrum ??

Totani+ '96





Malek+ '03

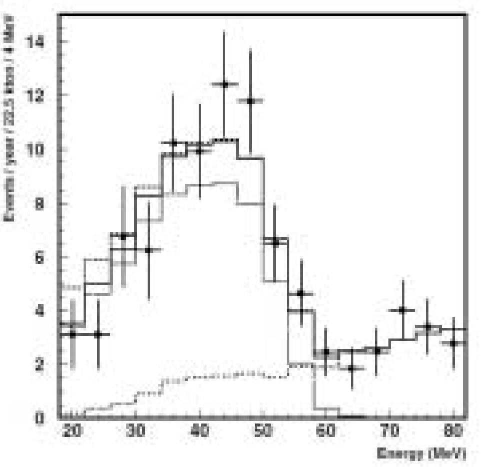


FIG. 2. Energy spectrum of SRN candidates. The dotted and dash-dotted histograms are the fitted backgrounds from invisible muons and atmospheric ν_e. The solid histogram is the sum of these two backgrounds. The dashed line shows the sum of the total background and the 90% upper limit of the SRN signal.