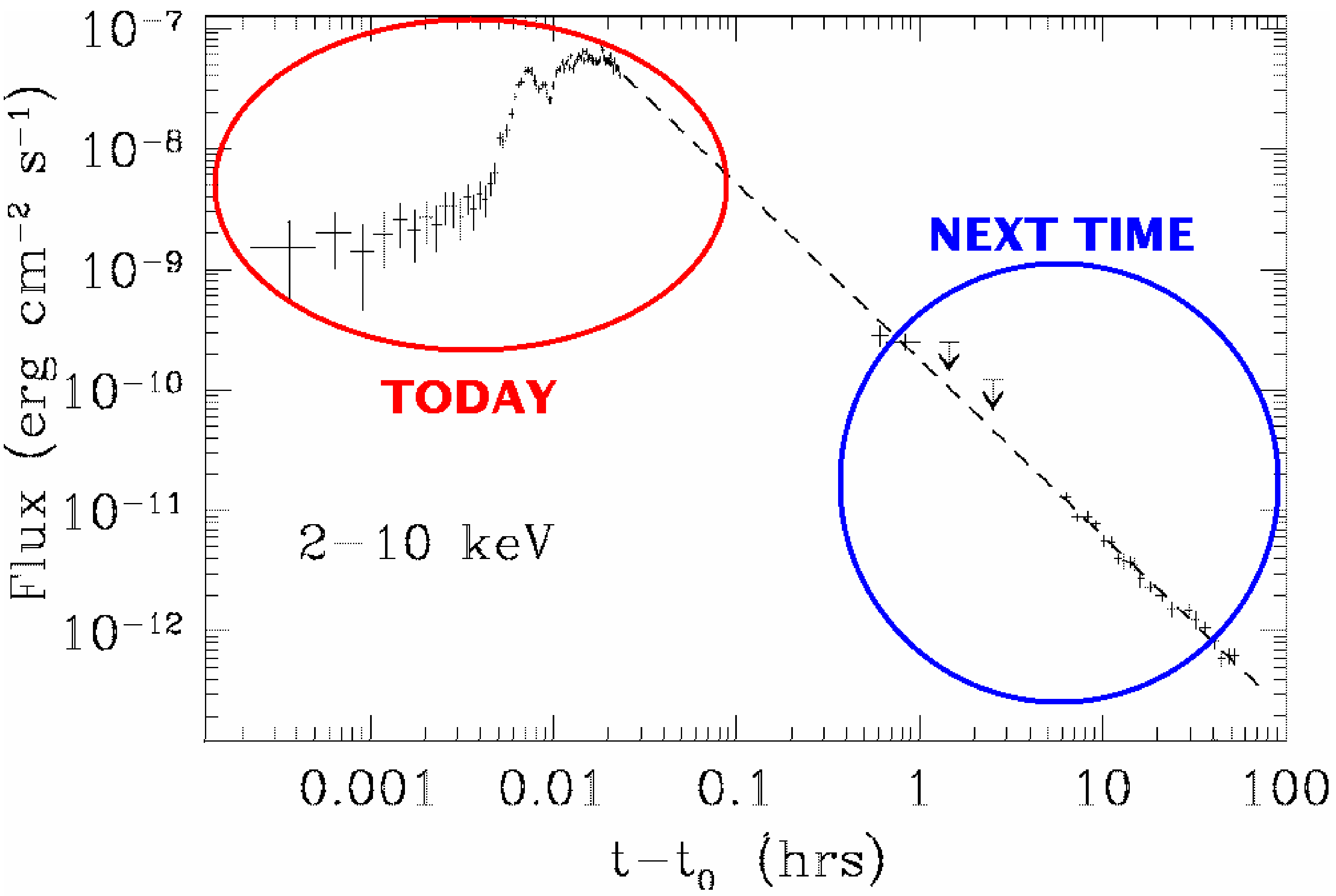
Gamma-Ray Bursts - I



Gamma-ray bursts (GRBs) ..

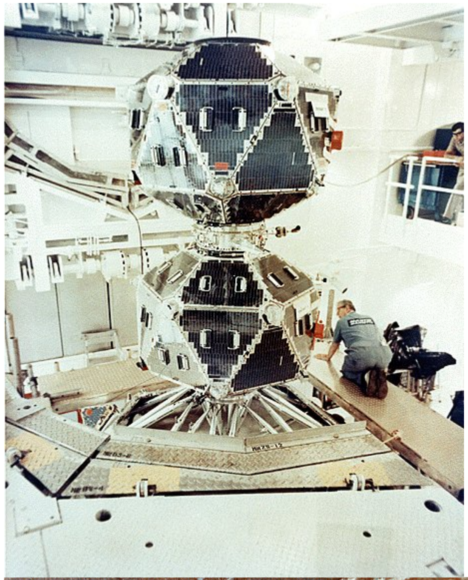
- are brief (10^{-2} – 10^{+3} s) and bright transients of ~1-10^3 keV radiation happening a few times per day at arbitrary positions in the sky
- have peak energy flux up to an equivalent of m_V=5 mag star at z=3 or 10-100 x Sun @ few kpc
- are followed by an afterglow phenomenon that can be observed to decay sometimes over years
- have 3 phases: 1) 'central engine'; 2) prompt emission; 3) afterglow
- are not only detected at γ-rays but throughout the spectrum, from IR to TeV wavelengths (prompt), and from radio to 60 keV X-rays (afterglow)

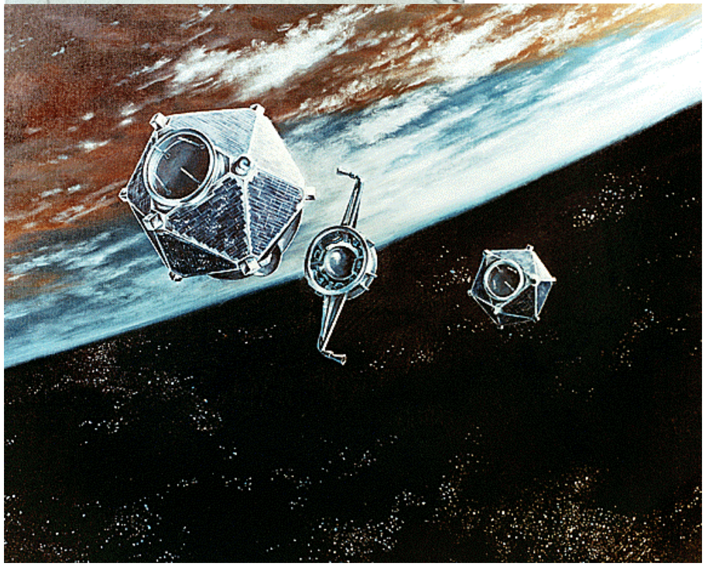
- ***Today***: prompt emission - getting the max out of the least
- ***Next time***: the afterglow phenomenon – distances and details
- ***Later***: central engine – collapsars (Norbert)

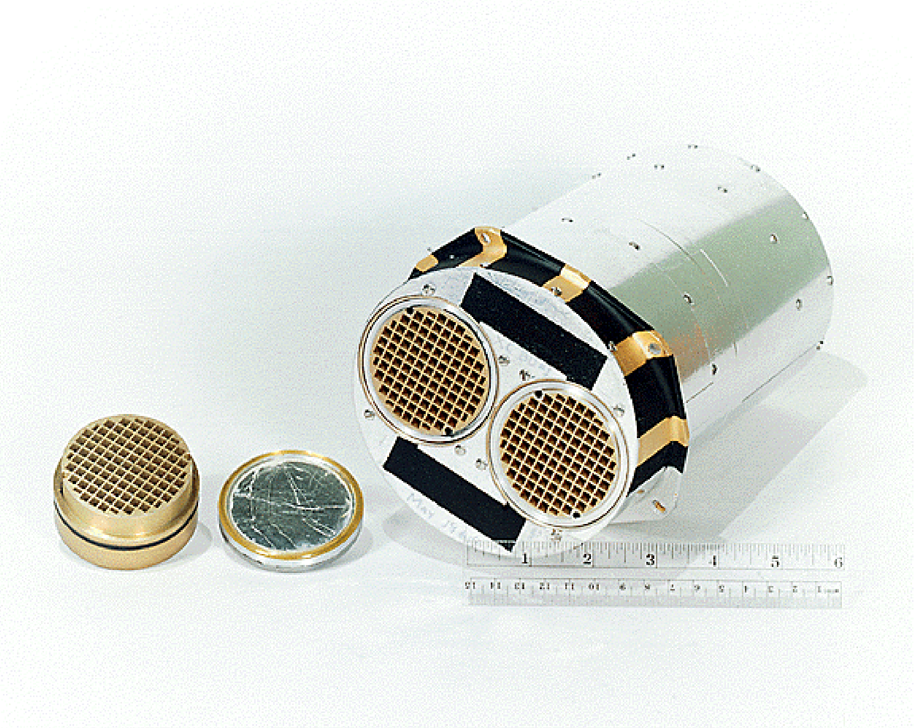
What rays?

- radio: λ mm-m / synchroton radiation (jets, pulsar nebulae)
- submm: 100 micron – mm / molecule vibration lines (like from water)
- IR: 10 – 100 micron / thermal emission of cool gas (circumstellar dust, planets)
- NIR: 0.8-10 micron / heavily extincted stars
- optical: 0.4-0.8 micron / traditional band
- UV: 0.1-0.4 micron / hot stars, accretion disks
- EUV: 10 – 100 nm / thermal emission (white dwarfs)
- X-rays: 0.1 – 10 nm / thermal emission from MK plasma (accreting compact objects)
- gamma-rays: < 0.1 nm / comptonization, nuclear spectroscopy (pulsars, SNR, GRBs)

GRBs - the beginning..

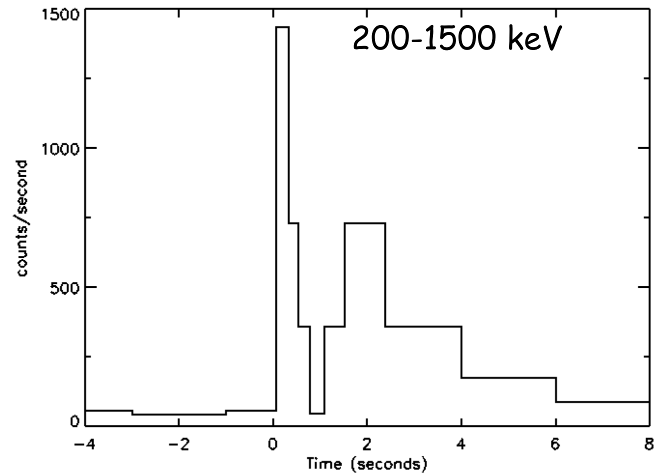


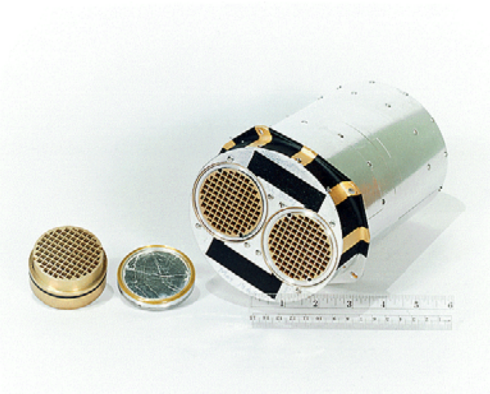


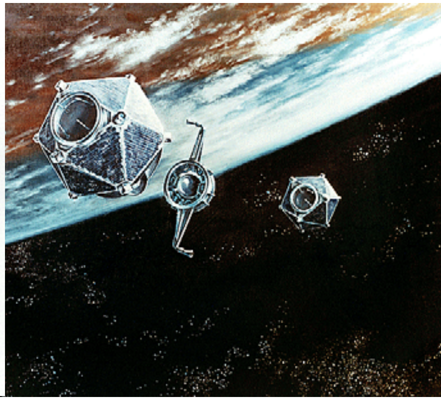


GRB 670212 – the first

- USA launched 6 pairs of Vela satellites from 1963 to 1970 to verify nuclear test ban in atmosphere and space. These carried gamma-ray detectors. Stirling Colgate and Edward Teller urged investigators to search for signals from SNe, after suggestions from Russians
- Velas 5 and 6 had enough time resolution to resolve light travel distance between satellites and thus determine directions (a la IPN, see later)
- first GRB was discovered in 1967 in Velas 3 and 4 data
- First publication in 1973, with 16 GRBs detected with Velas 5a, 5b, 6a and 6b in 0.2-1.5 MeV (Klebesadel et al. 1973)

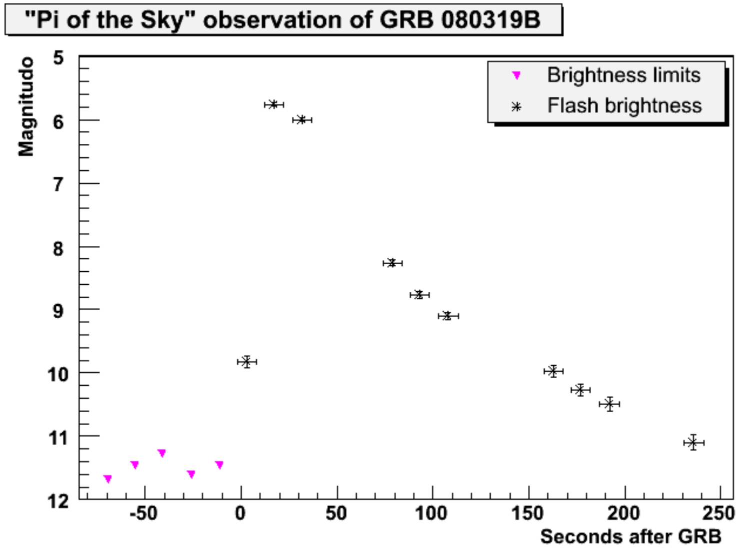




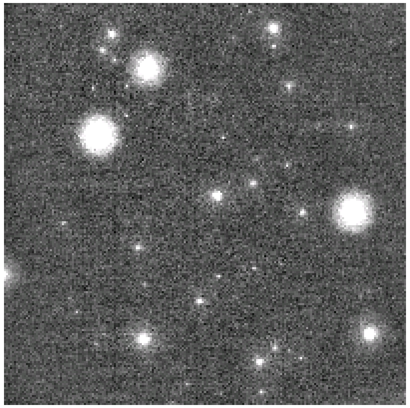


From then to now: a recent (interesting one) - GRB 080319B

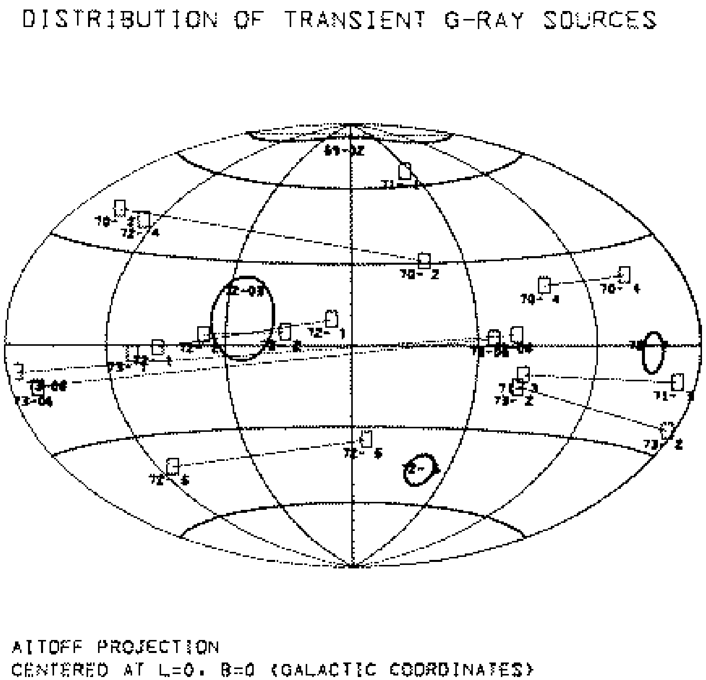
- The brightest optical GRB sofar at 5.8 mag. Previous record (GRB 990123), 8.95 mag, held 9 years
- This is the farthest object that could have been seen with the naked eye at $z = 0.94$
- 2.5 million times more luminous than SNe



Reported using 40 cm telescopes (Polish, in Chili, 'Pi of the sky')



First Galactic map of GRBs



Does not look like the origin is galactic

Appendix

Chronological list of all known gamma-ray bursts. Event numbers were assigned by year and in the order in which events were identified. The satellites providing the initial identification are listed first. Italicising of a satellite denotes spectral data.

Event Number	Date	UT Seconds	Estimated flux (ergs cm^{-2})	Observations
67-1	2 July, 1967	51 568	$\sim 1\times10^{-4}$	2 Velas
69-1	3 July, 1969	26 233	2×10^{-5}	2 Velas
69-5	19 July, 1969	13 606	1×10^{-4}	OSO-5; 1 Vela
69-2	7 October, 1969	26 790	2×10^{-4}	2 Velas; *OSO-6*; OGO-5
69-3	17 October, 1969	11 927	2×10^{-5}	2 Velas
69-4	17 October, 1969	78 113	4×10^{-5}	2 Velas; OGO-3
70-7	25 January, 1970	18 090	?	*OSO-6; OGO-5
70-5	10 July, 1970	19 066	4×10^{-5}	2 Velas
70-2	22 August, 1970	60 571	1×10^{-4}	3 Velas; OGO-5
70-6	1 October, 1970	56 532	1×10^{-4}	OSO-6; OGO-5, 1 Vela
70-3	1 December, 1970	72 059	4×10^{-6}	2 Velas; OSO-6; OGO-5
70-4	30 December, 1970	25 337	3×10^{-4}	3 Velas
71-1	2 January, 1971	69 056	1×10^{-4}	3 Velas; SAS-1
71-6	27 February, 1971	62 857	7×10^{-5}	2 Velas; OSO-6
71-2	15 March, 1971	40 827	5×10^{-5}	3 Velas; *IMP-6*, OGO-5
71-3	18 March, 1971	55 685	1×10^{-4}	3 Velas; *IMP-6*; SAS-1; *OGO-5*; OSO-6
71-4	21 April, 1971	11 919	$3-10^{-6}$	2 Velas; SAS-1
71-5	30 June, 1971	63 059	5×10^{-4}	2 Velas; *IMP-6*; SAS-1; *OGO-5*
72-1	17 January, 1972	63 556	7×10^{-5}	3 Velas; *IMP-6*; SAS-1; COSMOS-461
72-2	12 March, 1972	57 194	5×10^{-5}	4 Velas
72-3	28 March, 1972	49 587	1×10^{-4}	2 Velas; *IMP-6*
72-6	27 April, 1972	39 512	3×10^{-5}†	*Apollo 16*; 1 Vela
72-4	14 May, 1972	13 591	2×10^{-4}	3 Velas; *IMP-6*; *OSO-7*; TD-1
72-5	1 November, 1972	68 206	7×10^{-6}	3 Velas
72-8	13 November, 1972	55 758	$1\times\sim10^{-5}$	*IMP-7*, 1 Vela
72-7	18 December, 1972	73 659	1×10^{-4}	2 Velas; *IMP-7*; 1972-076B
73-10	25 January, 1973	54 900	$<3\times10^{-6}$	*IMP-7*; 2 Velas
73-3	2 March, 1973	85 475	3×10^{-4}	3 Velas; *IMP-7*; SAS-2
73-12	16 April, 1973	45 550	$\sim3\times10^{-5}$	*IMP-7*; SAS-2; 1 Vela
73-1	7 May, 1973	29 071	6×10^{-5}	3 Velas; (Not SAS-2)
73-14	17 May, 1973	05 678	?	*IMP-7 only
73-9	6 June, 1973	25 648	1×10^{-4}	*IMP-7*; SAS-2; 1 Vela
73-4	6 June, 1973	67 630	?	SAS-2; *IMP-7*; 2 Velas
73-2	10 June, 1973	75 582	1×10^{-4}	3 Velas; *IMP-7*
73-5	21 July, 1973	32 113	2×10^{-4}	3 Velas; *IMP-7*; 1972-076B
73-6	25 July, 1973	61 674	2×10^{-4}	3 Velas; *IMP-7*
73-15	20 August, 1973	59 956	?	*IMP-7 only

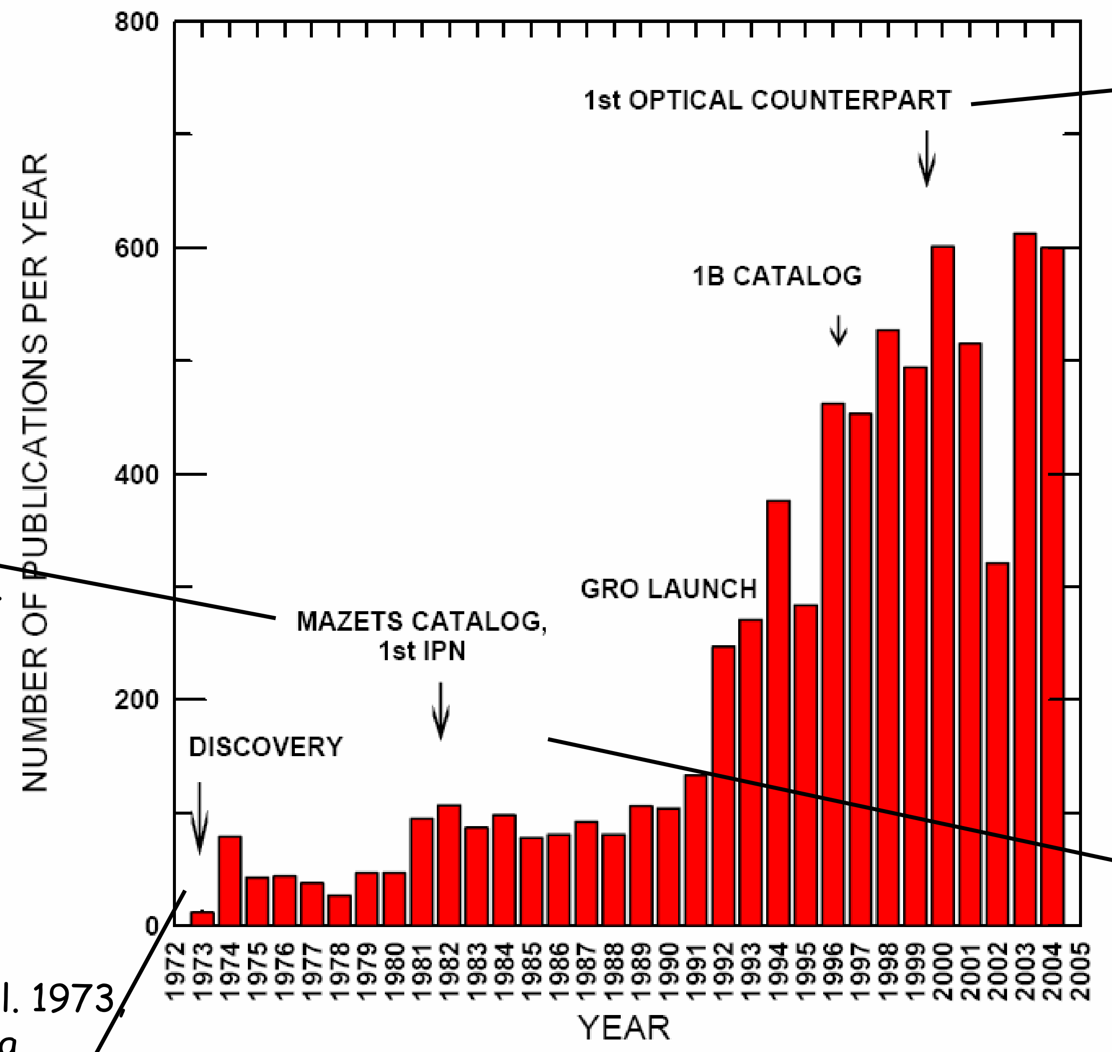
GRB experiments and approximate counts (as of early May 2008)

Vela 4-6		USA	1967-1979	~100 GRBs
Prognoz 6, 7, 9		USSR	~ 1980	~100
Helios-B		USA+Germany	1976-1981	~30
ISEE-3	IP	USA	1978-1991?	?
Venera 11-14/SIGNE	IP	USSR	1978-1983	235
Pioneer Venus Orbiter	IP	USA	1978-1988	225
SMM		USA+ESA	1980-1989	177
Ginga		Japan+UK+USA	1987-1991	120
Granat/Watch		USSR+France+Denmark	1989-1994	95 (47 localized)
Granat/Phebus+KONUS		USSR	1989-1999	?
Ulysses	IP	ESA+USA	1989-2001	461
CGRO/BATSE		USA+ESA	1991-2000	2704 (all localized)
NEAR	IP	USA	1999-2001	372
WIND	IP	USA+Russia	1994-	1200..
BeppoSAX		Italy+NL	1996-2002	944 (92 localized)
HETE		USA+France+Japan	2000-2007	80 (all localized)
MARS Odyssey/Hend	IP	USA+Russia	2001-	few
INTEGRAL		ESA+Russia	2002-	600.. (48 localized)
SWIFT		USA+UK+Italy	2004-	344.. (all localized)
GLAST/GBM		USA	June 2008	

shaded: experiments with independent localization capability better than 10 degrees

Interplanetary Probe

Burst bibliography gathered by Kevin Hurley (up to 2005)



Start of'afterglow era', distances measured, energy budgets knonw

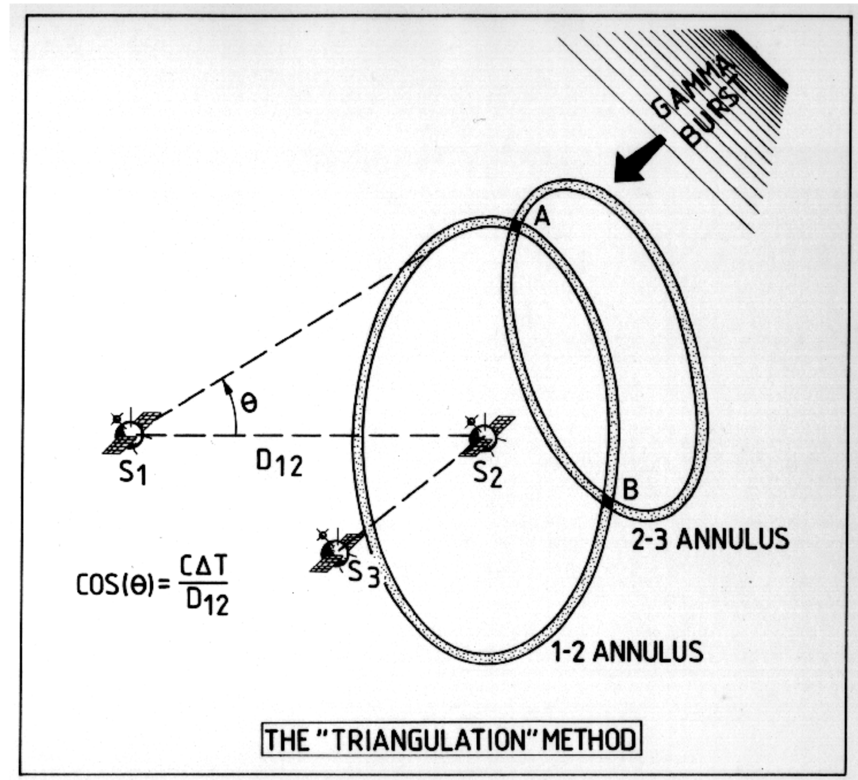
First results of dedicated Russian GRB detectors, first arcminute locations

Eighties: detection of cyclotron lines in GRB spectra → NS hypothesis popular

Klebesadel et al. 1973, Vela catalog

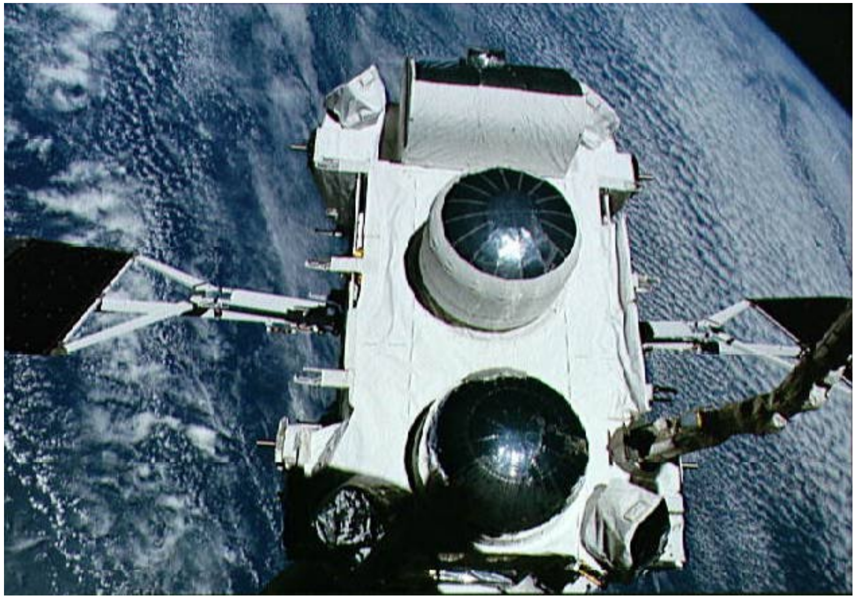
Locating GRBs – InterPlanetary Network (IPN)

- Already applied in 1970s
- Advantage: arcminute accuracies without the need for an imaging device. Matches field of view of most optical telescopes
- Disadvantage: long delays due to travel time from far away satellites (~1 hr), data reduction (for 1970s and 1980s) and instrument clock intercalibrations
- Principle, see figure →

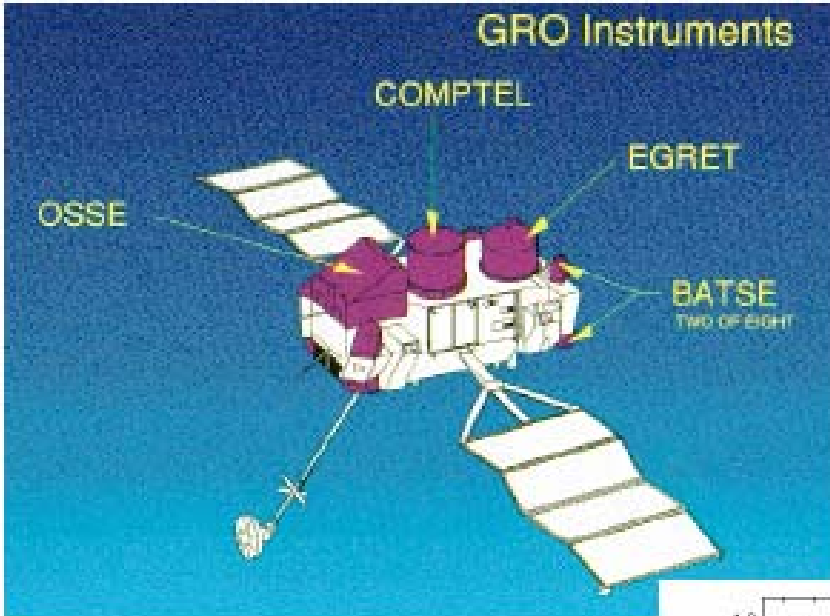


BATSE (Burst And Transient Source Experiment) on CGRO (Compton Gamma-Ray Observatory)

- enabled important step forward due to 4π field of view (although earth blocked ~30% of sky) and excellent sensitivity
- consisted of 8 non-imaging NaI detectors at corner points of CGRO
- detected 1 GRB per day, between 1991 and 2000. Produced a catalog of 2704 GRBs
- could locate to a few degrees accuracy by employing measurement of cosine factor over the 3-4 detectors that could 'see' GRB
- in combination with EGRET, had broad spectral coverage from 15 keV to tens of GeVs. This coverage will only now be restored by the launch of GLAST in June 2008
- had a large support team
- data were immediately public -> large involvement of community -> many publications

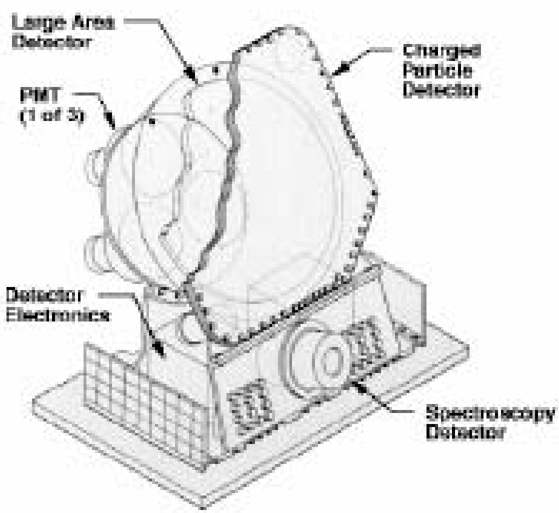


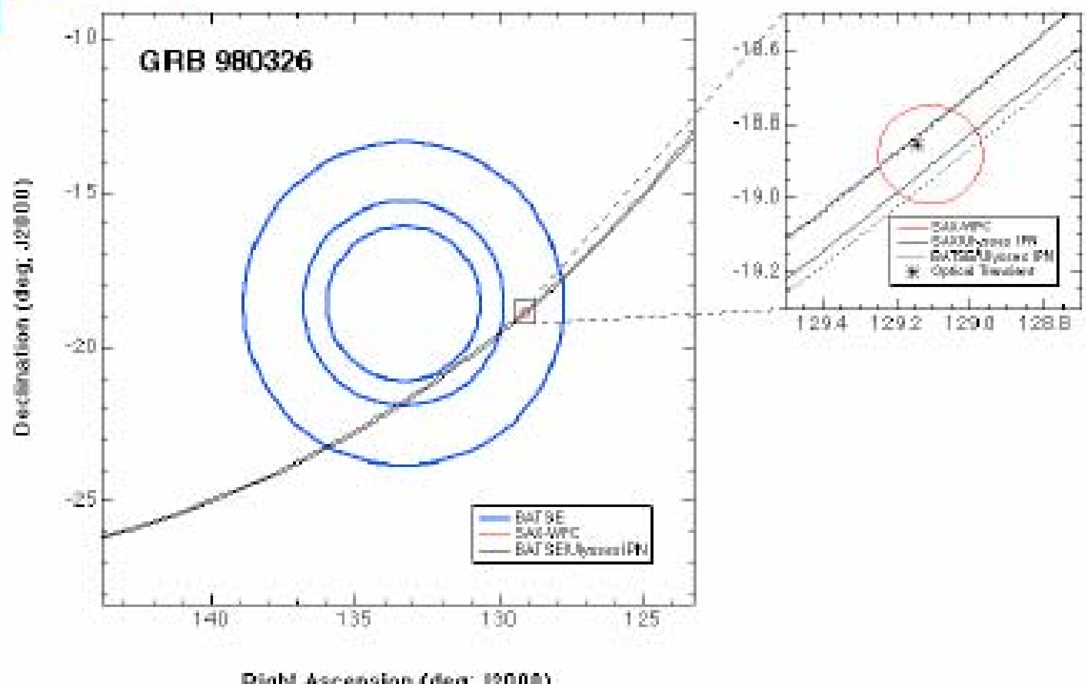
CGRO released from Space Shuttle



2. Cross detector fluxes

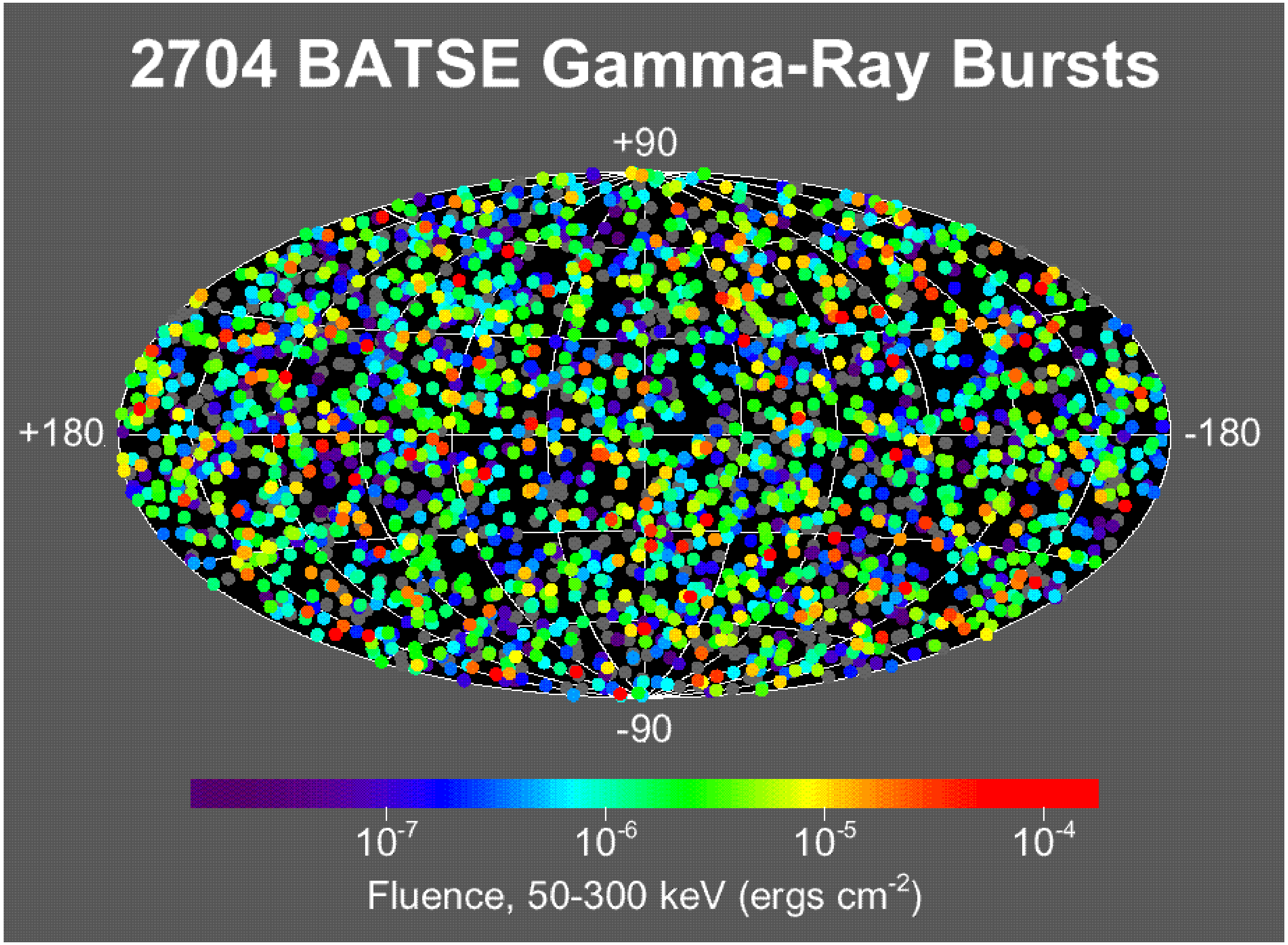
- BATSE had 8 LAD
- each gives relative cos θ to burst





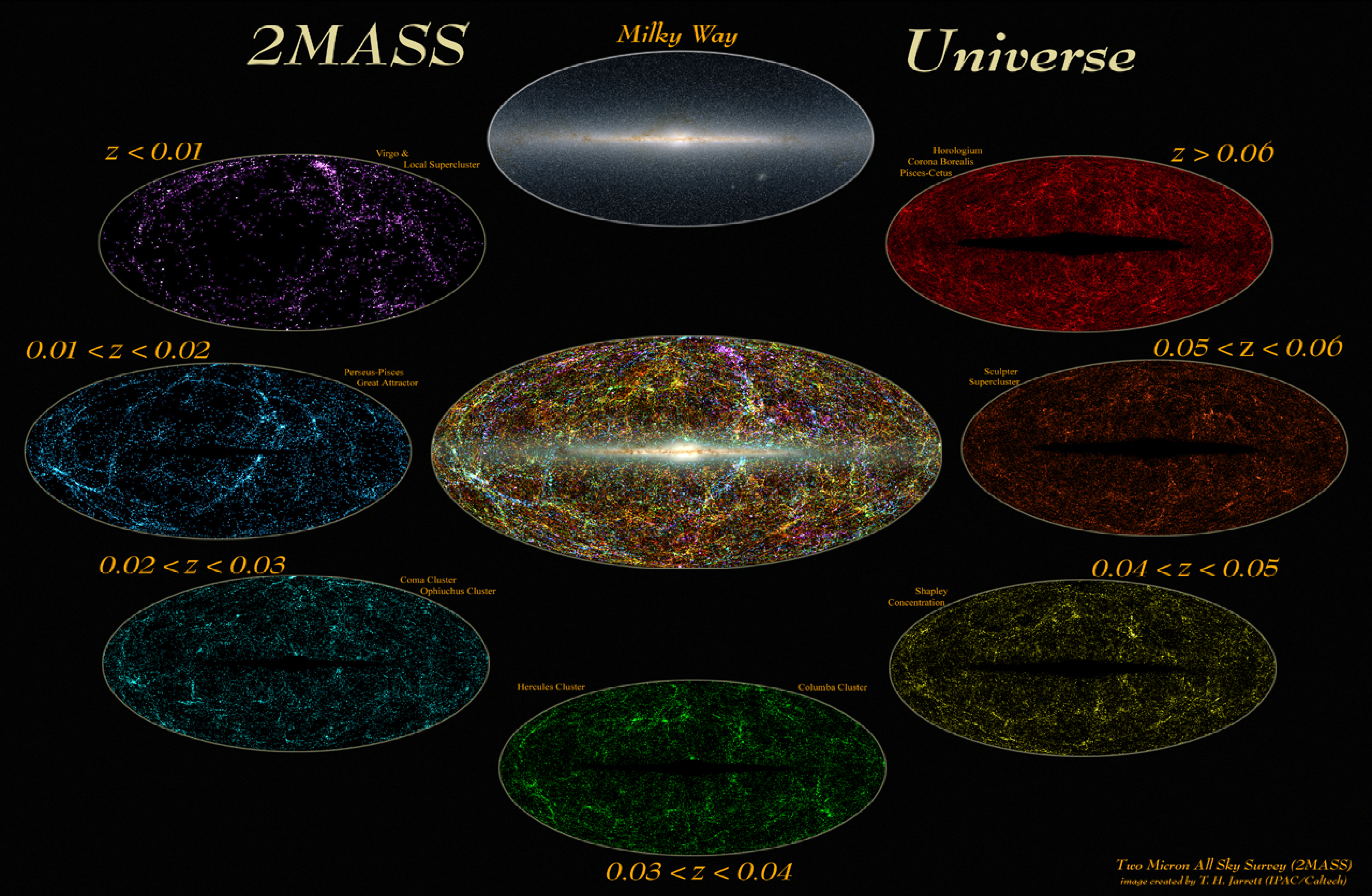
Locations of ~few degrees
(covariances of DRM and position)

Sky distribution



Final BATSE catalog

Compare with distributions of sources at various distances → cosmological hypothesis supported (but not proven)



Isotropy quantified → high degree of isotropy

Moment	Type	Coordinates	Value	Deviation with respect to isotropy
$\langle \cos\Theta \rangle$	Dipole	Galactic	-0.025+/-0.014	-1.1σ
$\langle \sin^2 b - 1/3 \rangle$	Quadrupole	Galactic	-0.001+/-0.007	+0.4
$\langle \sin\delta \rangle$	Dipole	Ecliptic	0.024+/-0.014	+0.4
$\langle \sin^2 \delta - 1/3 \rangle$	Quadrupole	Ecliptic	0.025+/-0.007	+0.1

Probing GRB distribution in 3rd dimension: $\log N(>P)$ – $\log P$ studies

If all GRBs have same peak luminosity L_{peak} and fill space uniformly with density n, then all GRBs nearer than d_{max} have a flux brighter than

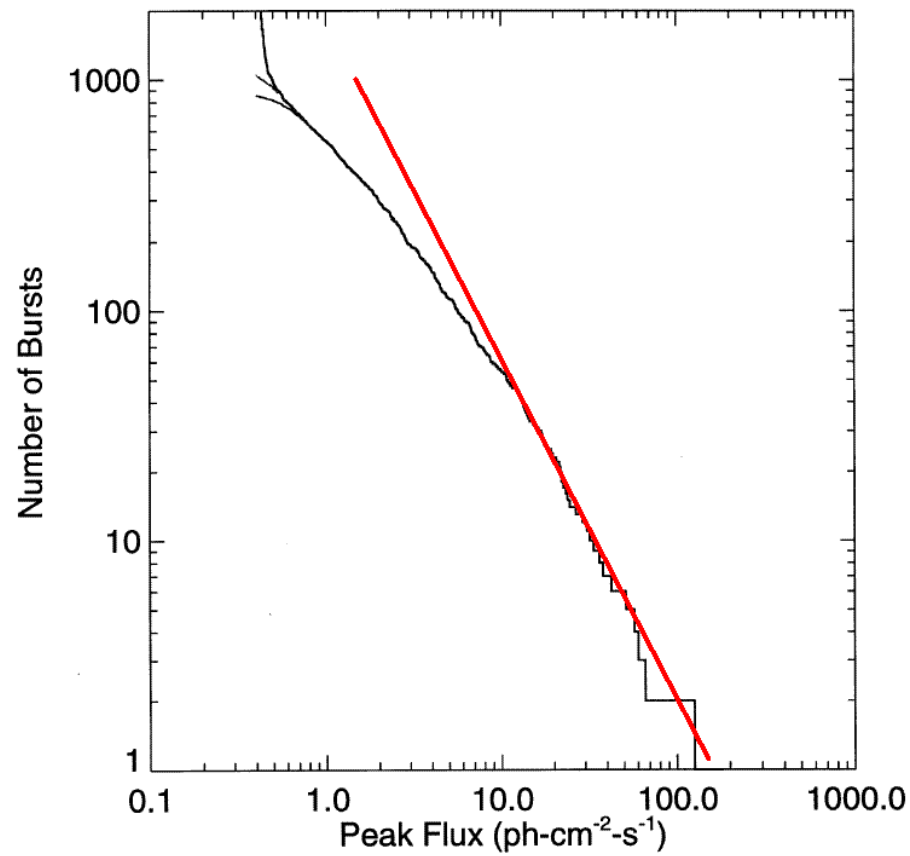
$$P = L_{peak} / 4\pi d_{max}^{2}$$

Since

$$N = n\,(4\pi/3)\,d_{max}^{3},$$

then

$N(>P)$ (:) $P^{-3/2}$



$\log N(>P) - \log P$ *modeling*

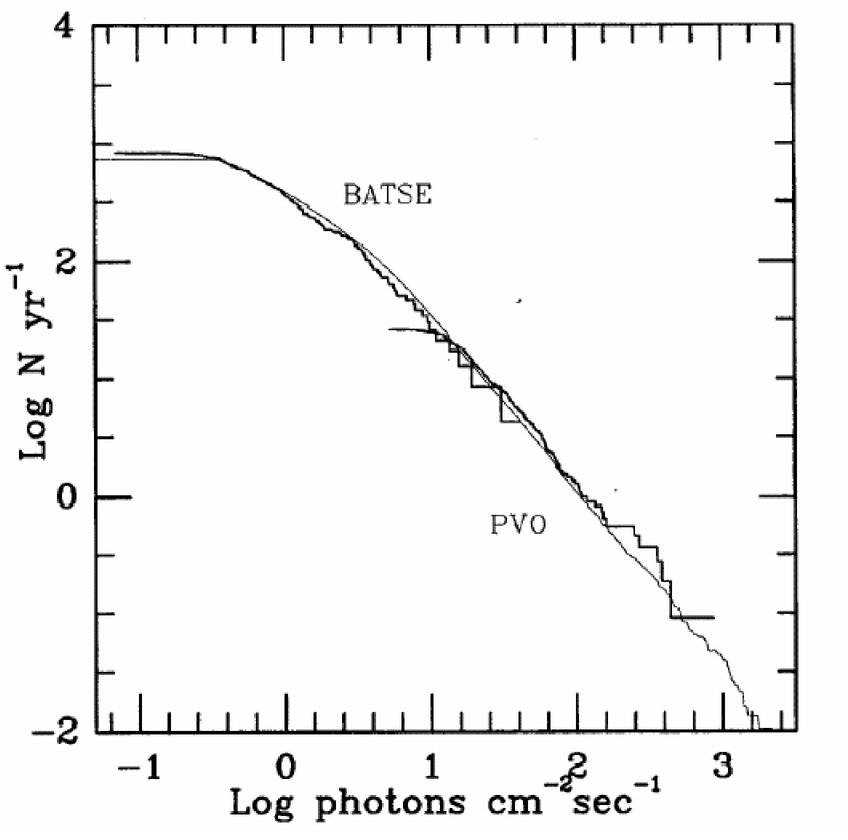
If modeled by a standard candle GRB which is redshifted out of bandpass ->

$L = 6.9 \times 10^{50}\ h^{-2}_{65}$ erg/s

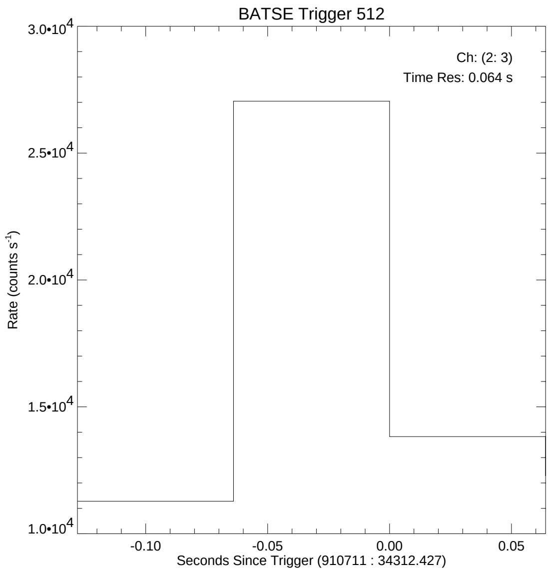
and

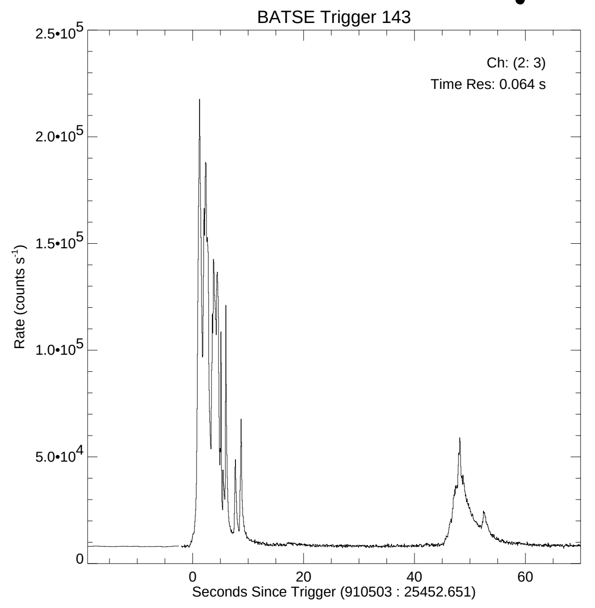
$z_{thres} = 0.79$

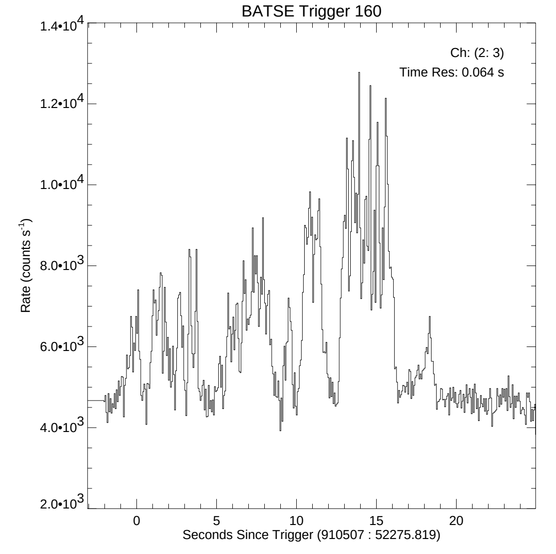
(Fenimore et al. 1993)

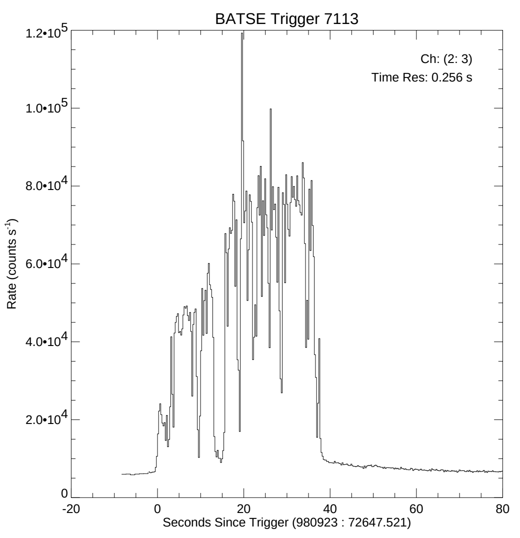


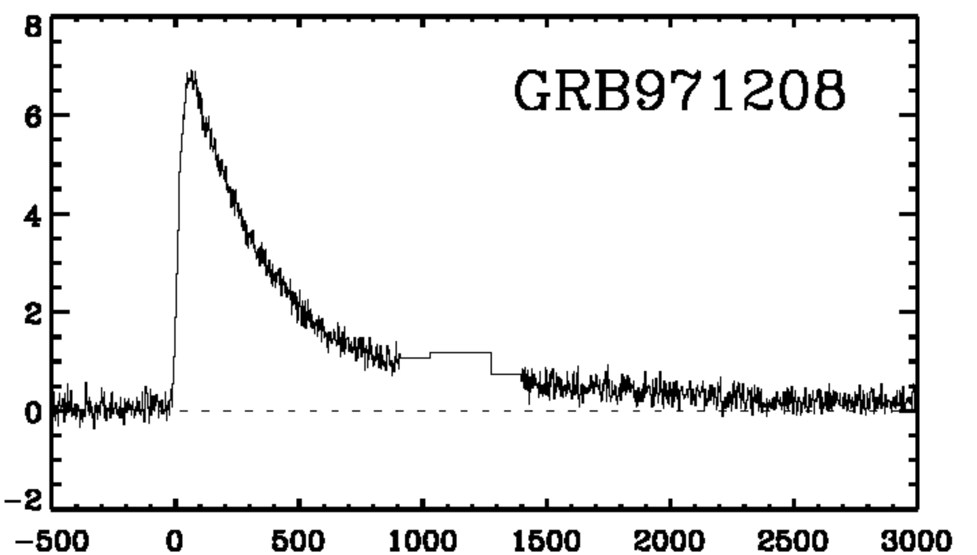
Time profiles: diversity & ms spikes





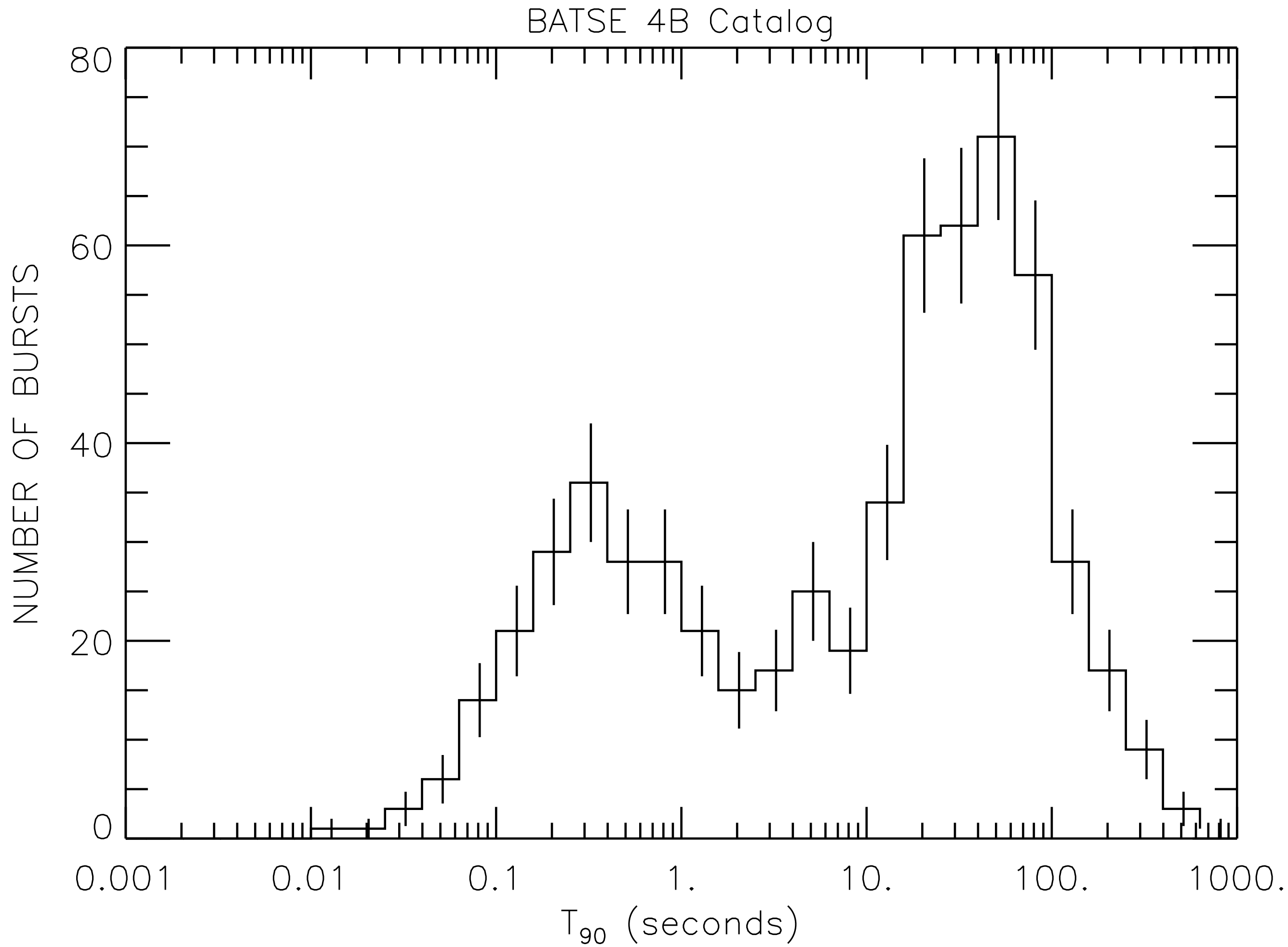




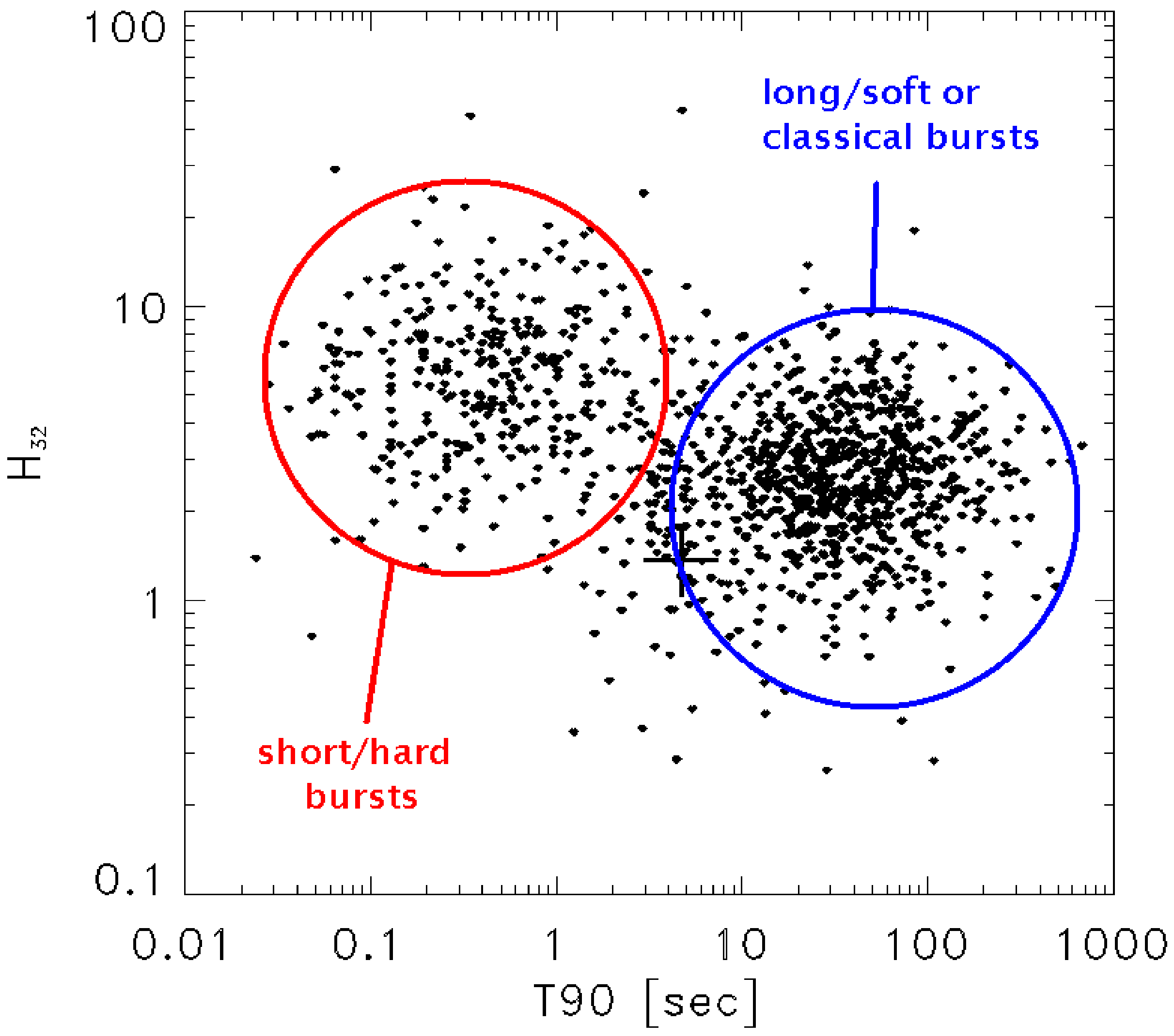


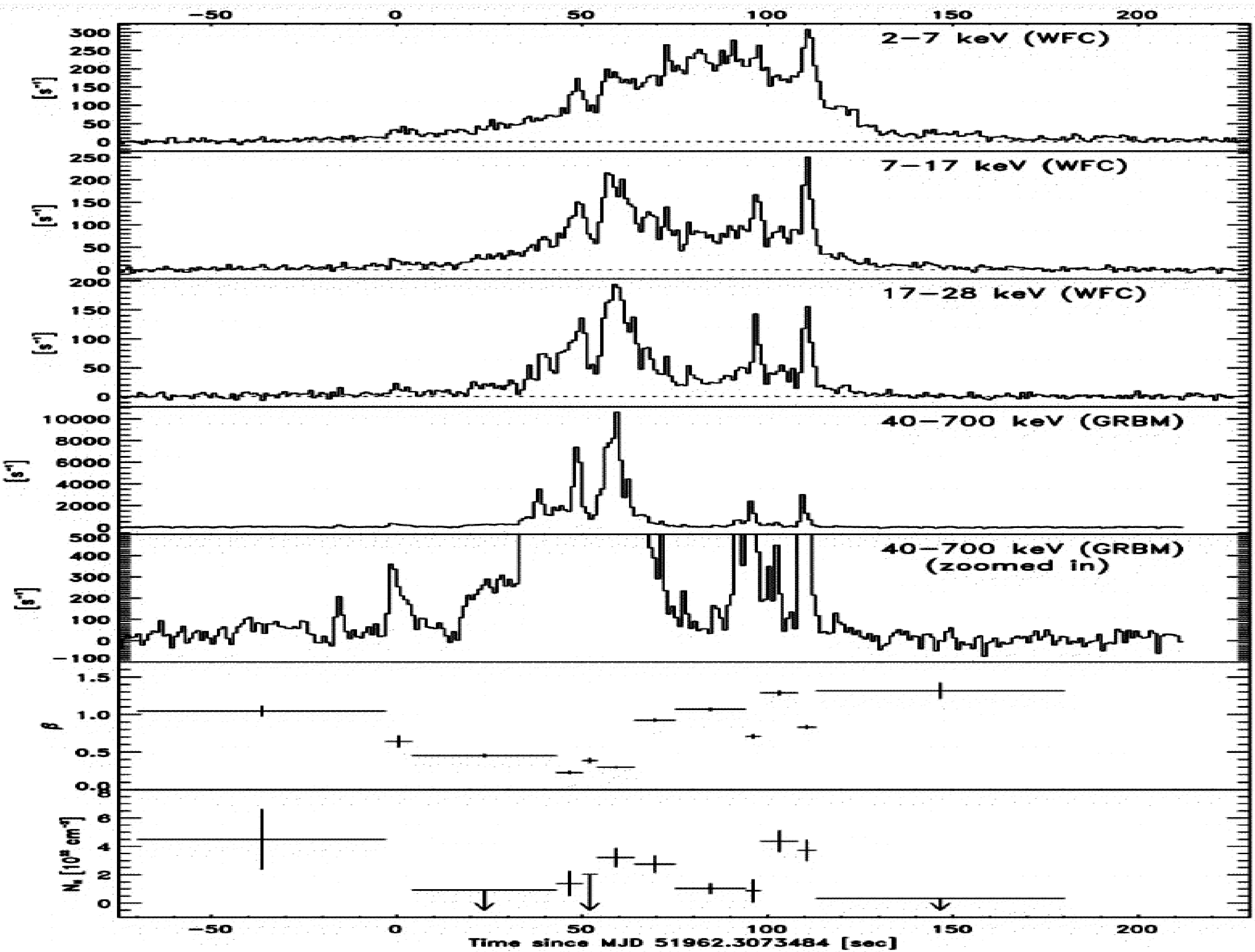
Durations

<u>standard GRB duration measure</u>: T90 = time it takes to collect from 5 to 95% of all photons



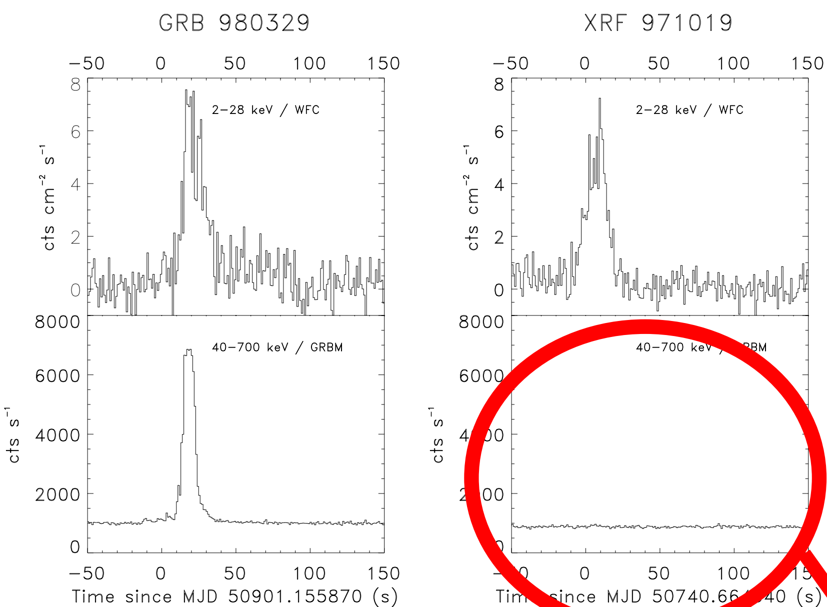
Spectral hardness vs durations: evidence for 2 classes of GRBs

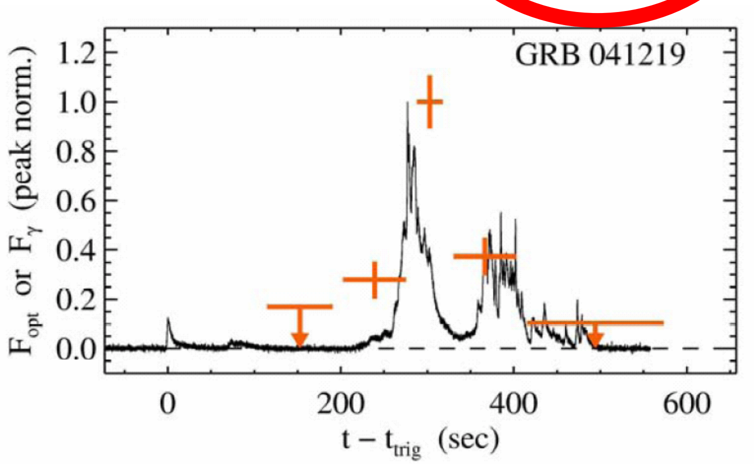


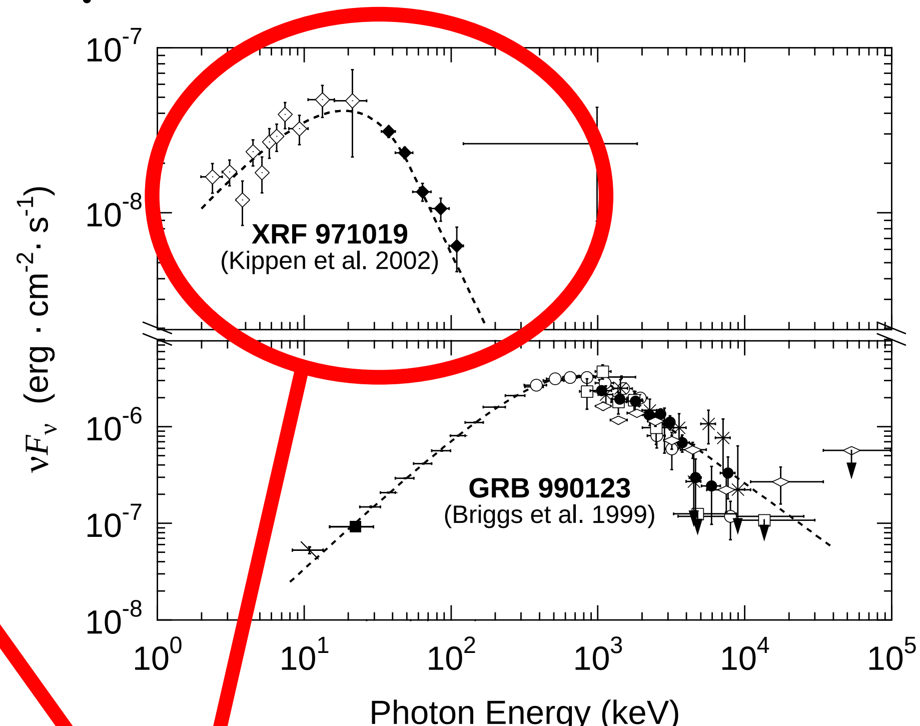


2–7 keV (WFC)
7–17 keV (WFC)
17–28 keV (WFC)
40–700 keV (GRBM)
40–700 keV (GRBM)
(zoomed in)
β
Time since MJD 51962.3073484 [sec]

Spectra - broad characteristics & non-thermal spectra

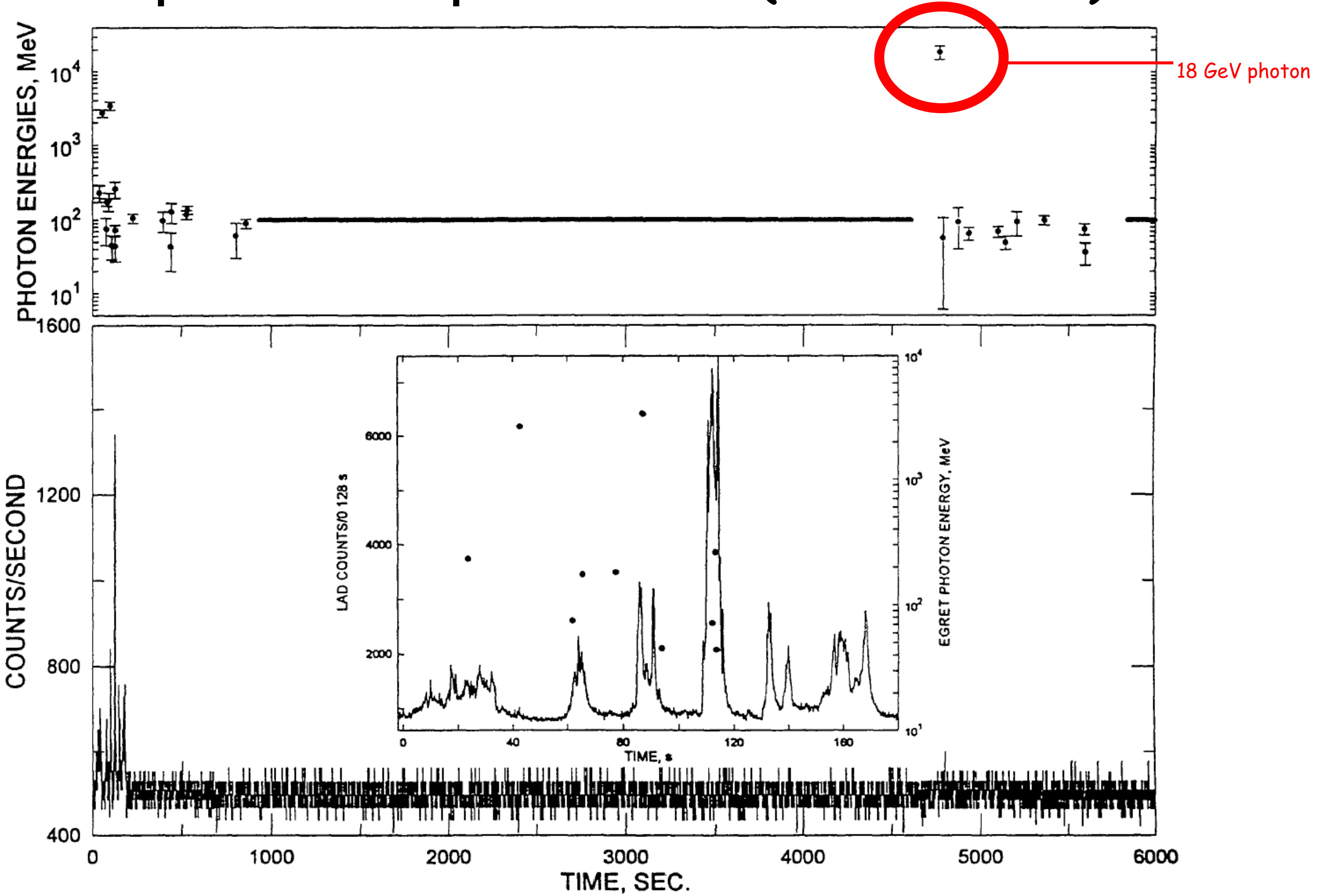




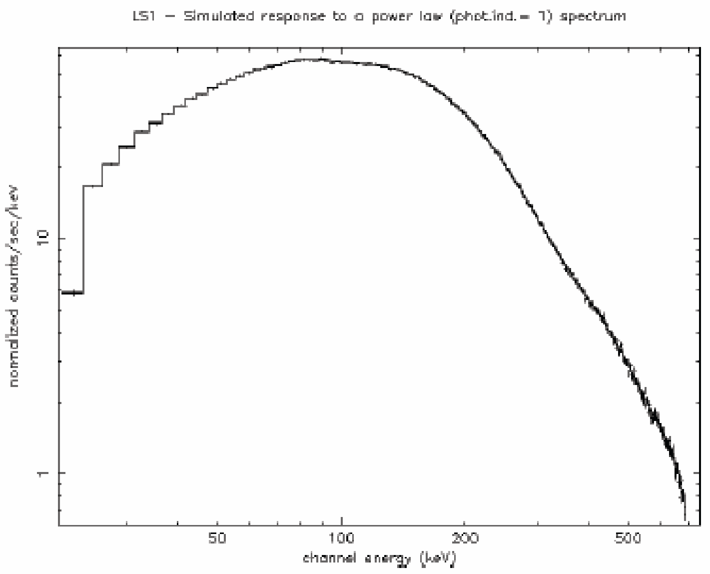


Gamma-ray less GRBs are called **X-ray flashes**. Could be different population but probably not

Spectra - up to GeVs (and TeVs?)



Note that measured spectra are heavily distorted by instrument response!

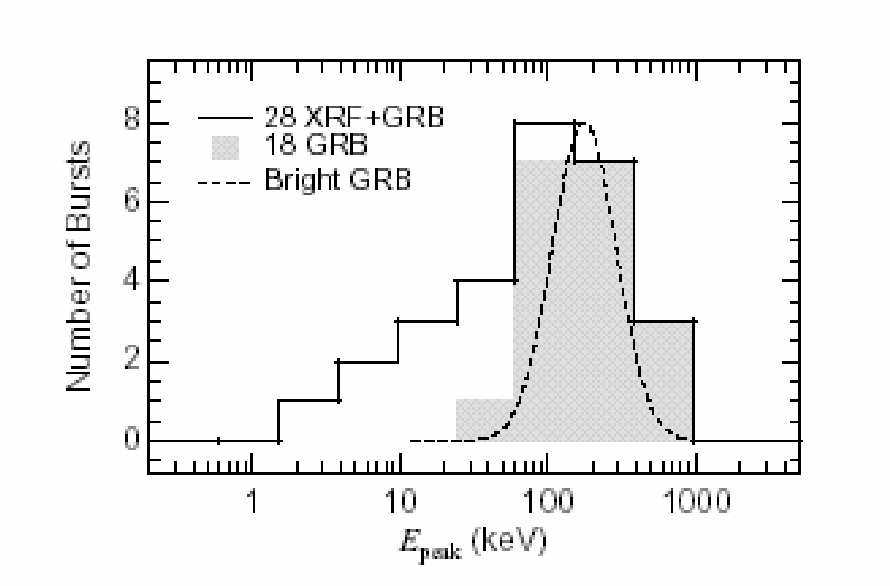


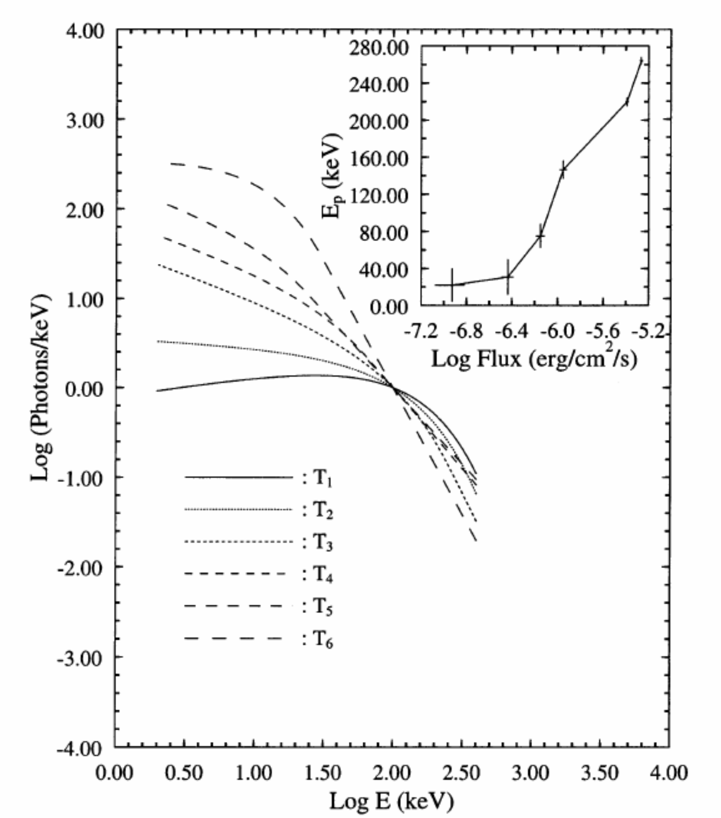
Response to a power law with $N_{phot} \propto E^{-1}$

http://www.bo.iasf.cnr.it/~amati/tesi

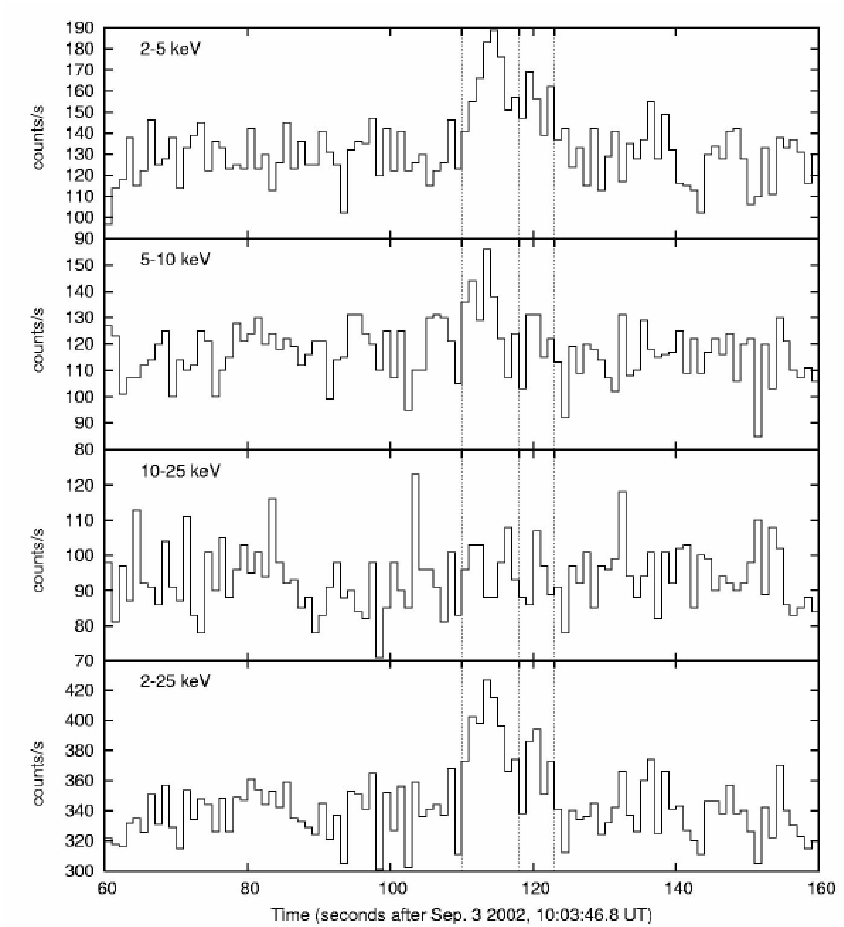
The empirical 'Band' spectrum

- The spectrum of all GRBs can be described by an empirical 4-parameter function, the 'Band' function:
  - if $E < E_0$: $N(E) = K_1 E^{\alpha} \exp(-E/(\alpha-\beta)E_0)$
  - if $E > E_0$: $N(E) = K_2 E^{\beta}$
- this is a smoothly broken power law with a continuous derivative (K_1 and K_2 are dependent)
- There is no physical interpretation for this function



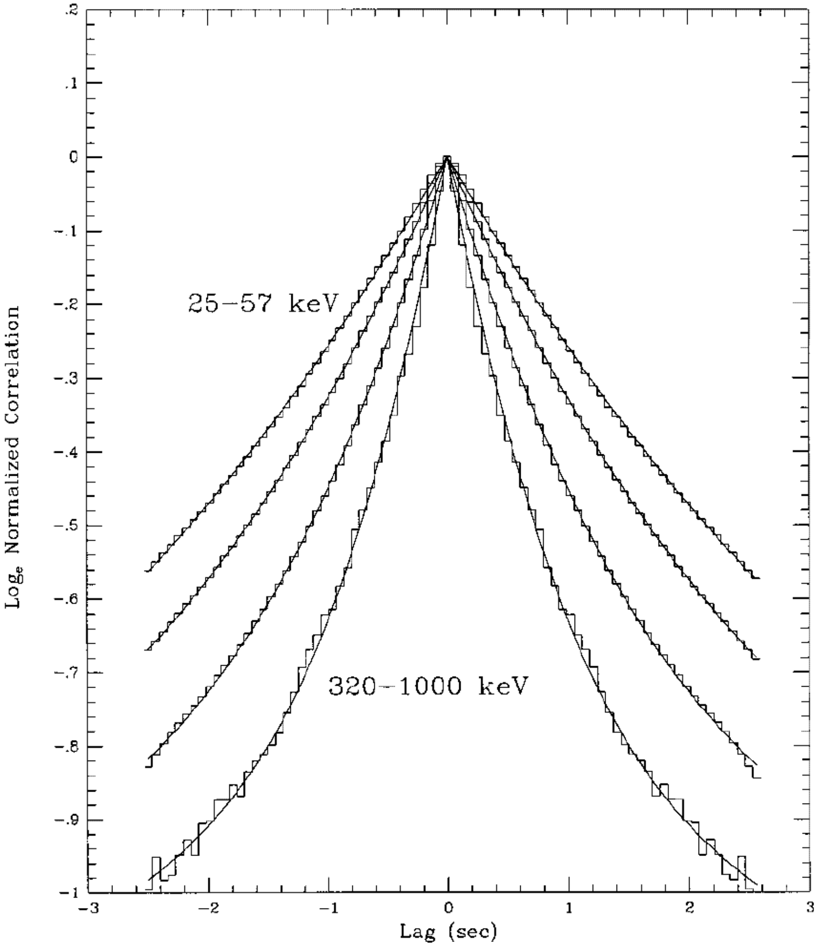


The 'softest' GRB (020903) E_{peak} = 3 keV



E_{peak} is defined as the peak in the 'nu-f-nu' spectrum. Such a spectrum is the histogram of energy flux spectrum in units of keV $s^{-1}cm^{-2}keV^{-1}$ (usually we employ phot s-1cm-2keV-1)

Energy dependence of spikes



- Plot shows normalized and average autocorrelation function over many bright GRBs for 4 bandpasses
- Width (:) $E^{-0.46}$
- Width decreases with photon energy

Fenimore et al. 1995

Quick-look physics from prompt emission

- Smallest time scale of variability (~10 ms) suggests size smaller than few thousand km
- Isotropic sky distribution suggests either cosmological origin, or very nearby (few hundred parsecs to stay within height of Galaxy) or in halo (~100 kpc)
- Peak flux distribution points to seeing the far end of the population -> could be cosmological redshift
- 18 GeV photons: next slide

'Compactness problem' (the need for speed)

- Non-thermal spectra point to an optically thin plasma
- But: photon density is so high it must be optically thick:
  - $\rho = 4\pi d^2 F \Delta T / (4\pi/3)(c\Delta T)^3$
    - Most bursts have F = 1-1000 phot s^{-1} cm^{-2} (see slide on log*N*-log*P*)
    - $\Delta T \approx 0.001$ s → volume 10^{23} cm^3
    - d = 100 kpc → $\rho > 10^{20-23}$ phot cm^{-3}
    - d = 1 Gpc → $\rho = 10^{30-33}$ phot cm^{-3}
  - $\tau = \rho\, \sigma_T\, (c\,\Delta T) > 30$, with σ_T of order 10^{-26} cm^{-2} . This is a conservative lower limit. For half the bursts F > 30 phot s^{-1} cm^{-2} so that $\tau > 1000$
- Also: MeV/GeV/TeV photons have no chance of escaping due to pair production $\gamma_1\,\gamma_2$ → e^+e^- for $E_1E_2 > (m_ec^2)^2$. Cross section approximately equal to $(0.1\text{-}1)\times(3/16)\sigma_T \approx 10^{-25}$ cm^2
- Solution: relativistic bulk motion towards observer
  - Doppler boosting and shifting → intrinsic size factor Γ larger and $E_{obs} = \Gamma\, E_{emitted.}$ Optically thin if Γ > 5 (Galactic *d*) or > 100 (cosmic)
  - → $E_{th} = 2(mc^2)^2/E_t(1-\cos\theta) \gg 511$ keV thanks to relativistics beaming (photons are more or less moving in the same direction → less 'collisions')

Relativistic beaming

- Relativistic beaming is introduced by relativistic bulk motion
- It has the effect of
  - Apparent changes of the luminosity
  - Apparent changes of the geometry
- The effect increases with 'Doppler factor' $$D = \frac{1}{\Gamma(1 - \beta\cos\theta)}$$
  with $\beta = v/c$, Γ = Lorentz factor $(1- \beta^2)^{-1/2}$
  and θ = angle between v and line of sight
- Examples are jets in BH-LMXBs & active galactic nuclei (visible as Seyfert I galaxies and blazars) with $\Gamma \sim 2$ and GRB fireballs with $\Gamma \sim 100$

Relativistic beaming – luminosity effects

- These are due to
  - Aberration: L (:) D^2 (from Doppler boosting and cosine-effect)
  - Time dilation: L (:) D^1
  - Blueshift: L (:) $D^{-\alpha}$ if α is power law index
- Combined: L (:) $D^{3-\alpha}$

Relativistic beaming – geometrical effects

- One can only see up to $\Theta = \Gamma^{-1}$ from line of sight of a relativistically expanding shell or jet
  - We only see a fraction $\theta^2/4\pi$ of the GRBs
- Γ decreases with time → ever larger part seen of shell or jet
  - there may be 'orphan afterglows' = afterglows without prompt emission

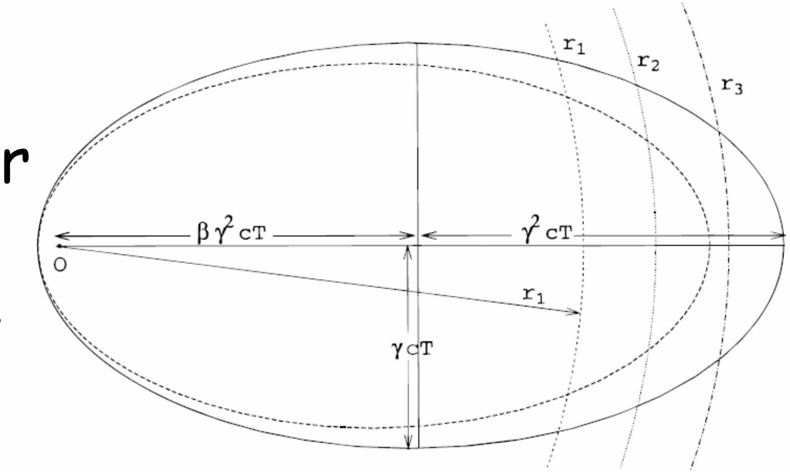


Figure shows the shape of a relativistically expanding spherical shell, exploding from location 'O'. It is distorted due to relativistic Doppler effect

The end of the enigmatic pre-afterglow era: Galactic versus cosmological debate (Don Lamb versus Bohdan Paczynski 1995)

At the end of the 1980s it became clear that NSs can get high kicks during a SN (1st figure shows a kick) so that they can travel far distances in relatively short times, into the Galactic halo which has a radius of up to 100 kpc. Combined with the detection of cyclotron lines in X-ray spectra the support for the NS hypothesis for GRBs was relatively strong. This ended after a few years of BATSE observations which confirmed isotropy to a high degree of confidence. In 1995 a public debate was organized, see http://antwrp.gsfc.nasa.gov/diamond_jubilee/debate95.html

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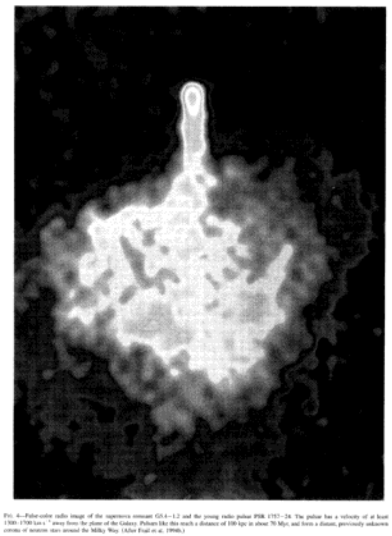

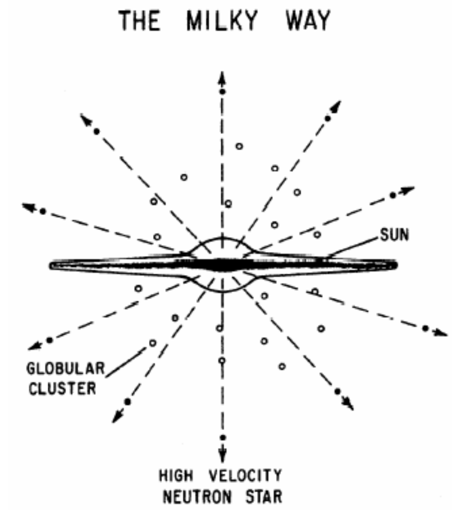

Debate – points for Galactic camp

1) Some NSs burst (soft gamma-ray repeaters), sometimes with similar spectra as GRBs
2) Some GRBs seemed to repeat – no destructive process
3) Some GRBs exhibited cyclotron lines – NSs
4) GRB error boxes lacked galaxies
5) NSs were shown to exhibit such high kick velocities that they can go to 100 kpc from the plane -> isotropy

End: 2), 3) and 4) turned out to be false measurements

Summary

- GRBs are isotropic and homogeneous till the far end of the observable GRB universe
- Early attempts for optical identifications were fruitless, due to long delays of accurate enough IPN localizations
- Prior to 1997, GRBs were almost always localized with non-imaging devices (GRANAT/Watch being the exception)
- There are two kinds of GRBs (long/soft, short/hard)
- Prompt spectra cover almost all wavelengths from IR to hard gamma rays, and between X-rays and gamma-rays (1 keV – 1 GeV) are well described by a 4-parameter empirical model
- Non-thermal spectra and > 2 x 511 keV radiation point to relativistic bulk motion
- Although many models were proposed, cosmological ones were already favored at the start of the afterglow era