GRB Lecture I

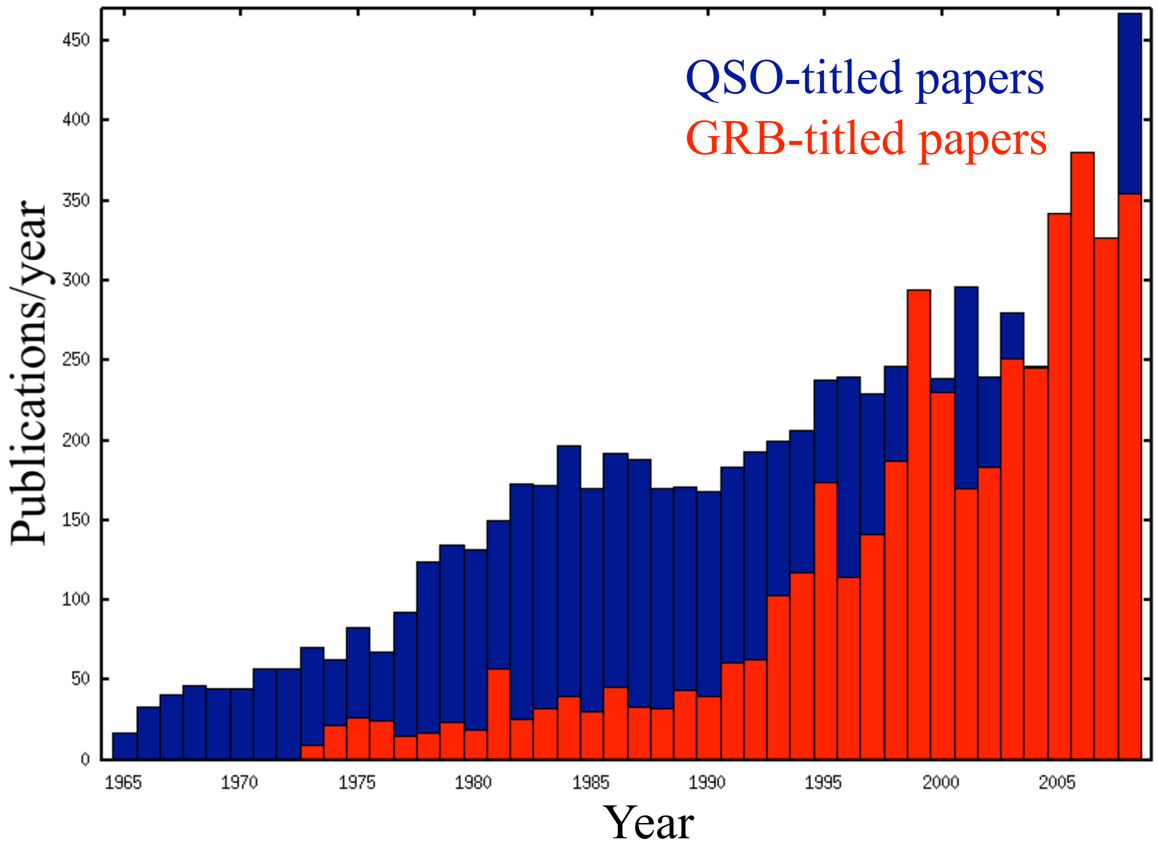
Darach Watson
Dark Cosmology Centre

- Historical Context
- What do we know about Gamma-Ray Bursts?
- How do we know it? — Major Milestones

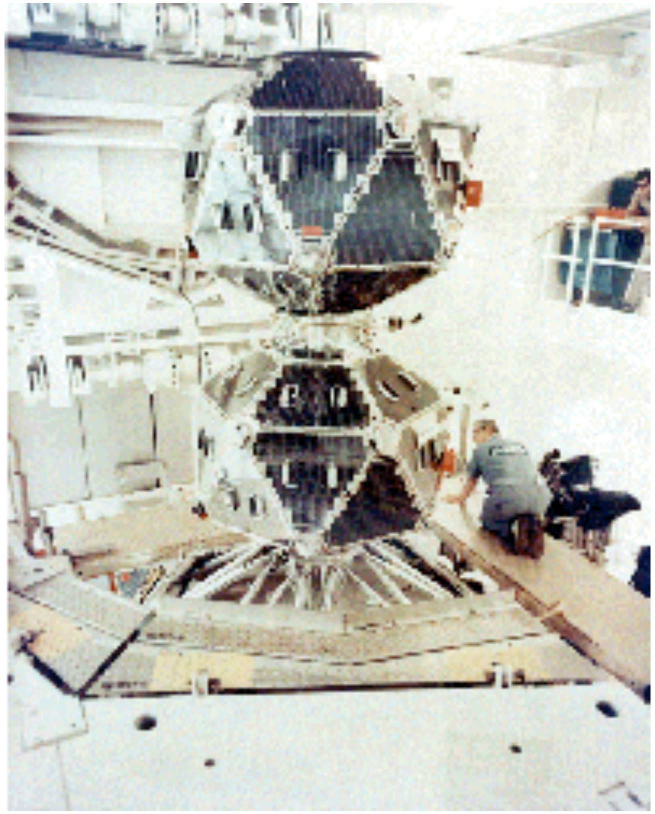
- Next Lecture: GRBs as tools

GRB science is young

- First detection reported in 1973
- Rapid rise of publication rate of GRB papers

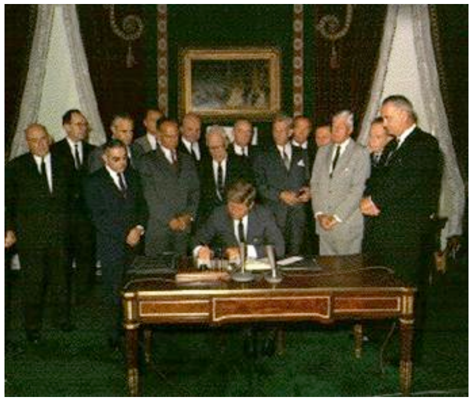


Vela-satellites (1964-1972)



- The Vela-satellittes were launched to monitor complience with the Limited Nuclear Test Ban Treaty (designed to detect atmospheric nuclear explosions)
- First satellite pair launched in October 1963.
- The project continued till 1972 (Vela 6a and 6b).

Historical Context



- Famous commencement address By JFK at American University 1963 paved the way for the Treaty:

  "Our problems are manmade--therefore, they can be solved by man. And man can be as big as he wants."

- → Limited Nuclear Test Ban Treaty 1963
- → Vela Satellites
- →Discovery of GRBs

Early Theory

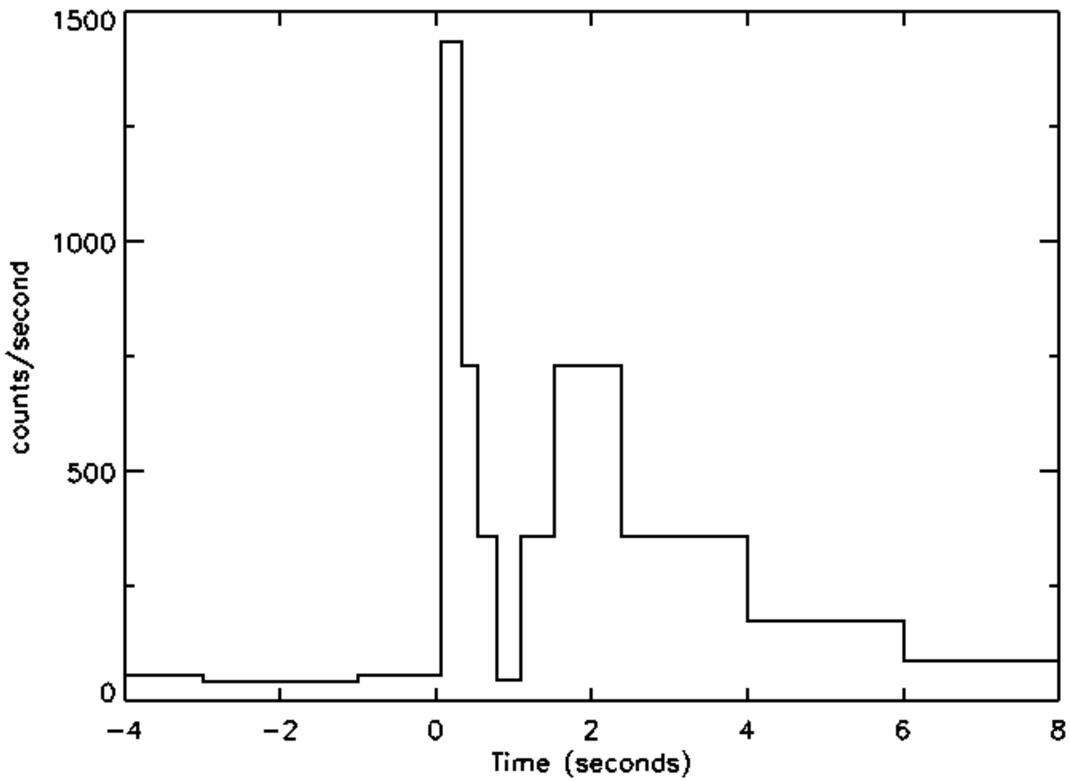
- Stirling Colgate suggested searching the Vela data for signs of gamma rays emitted during the initial stages of a supernova
- Colgate was more correct than we knew, suggesting as early as 1959 that SNe could produce bursts of gamma-rays

Major Observations in GRBs

- 1973 — Discovery
- 1984, 1993 — Two Classes (long & short)
- 1992 — Isotropic & non-Euclidean distributions
- 1997 — Afterglows of long GRBs
- 1997 — Redshift of long GRBs
- 1998, 2003 — SN-GRB connection
- 2005 — Afterglows of short GRBs
- 2006 — SN-less GRBs
- 2009 — $z > 7$ GRB

GRB670702: The first known burst

gamma-ray burst = burst of γ-rays



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OBSERVATIONS OF GAMMA-RAY BURSTS OF COSMIC ORIGIN

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ABSTRACT

Sixteen short bursts of photons in the energy range 0.2–1.5 MeV have been observed between 1969 July and 1972 July using widely separated spacecraft. Burst durations ranged from less than 0.1 s to $\sim$30 s, and time-integrated flux densities from $\sim 10^{-5}$ ergs cm^{-2} to $\sim 2 \times 10^{-4}$ ergs cm^{-2} in the energy range given. Significant time structure within bursts was observed. Directional information eliminates the Earth and Sun as sources.

Subject headings: gamma rays — X-rays — variable stars

II. INSTRUMENTATION

Conclusions

- Gamma-ray bursts are short intense bursts of γ-rays. They do not originate from the earth or the sun.

The Compactness Problem

Many photons with energy above 500keV. Hence, pair creation is possible:

$$\gamma + \gamma \rightarrow e^{+} + e^{-}$$

Variability on 10 ms timescale. Hence, very compact source:

$$R \leqslant c\,\delta t \approx 3 \times 10^{6}\,\mathrm{m}$$

Cosmological distance scale implies extremely high photon densities: → Optically thick.

$$\tau_{\gamma\gamma} \approx 10^{13} f_p \left(\frac{F}{10^{-7}\,\mathrm{erg/cm^2}}\right)\left(\frac{D}{3000\,\mathrm{Mpc}}\right)^{2}\left(\frac{\delta T}{10\,\mathrm{ms}}\right)^{-2}$$

Spectrum non-thermal: Optically thin	⇔	Size & Energy: Optically thick

Solution: highly relativistic motion

t_1 $\longrightarrow$ t_2

$v\Delta t$

$$\Delta t = t_2 - t_1$$

$$\Delta t_{obs} = \Delta t - \frac{v\Delta t}{c} = \Delta t(1-\beta)$$

$$\gamma^2 = \frac{1}{1-\beta^2} = \frac{1}{(1+\beta)(1-\beta)} \rightarrow 1-\beta = \frac{1}{\gamma^2(1+\beta)} \approx \frac{1}{2\gamma^2}$$

$$\rightarrow \Delta t_{obs} = \frac{\Delta t}{2\gamma^2}$$

Rees (1966)

Solution: highly relativistic motion

Photons in the source frame have much smaller energi:

$$E_{source} = E_{obs}/\gamma$$

The true timescale is much larger so the size limit is much less severe.

$$\Delta t_{obs} = \frac{\Delta t}{2\gamma^2}$$

Optical depth strongly reduced:

$$\tau_{\gamma\gamma} \approx \frac{10^{13}}{\gamma^{4+2\alpha}} f_p \left(\frac{F}{10^{-7}\,\mathrm{erg/cm^2}}\right) \left(\frac{D}{3000\,\mathrm{Mpc}}\right)^2 \left(\frac{\delta T}{10\,\mathrm{ms}}\right)^{-2}$$

$$\tau_{\gamma\gamma} < 1 \rightarrow \gamma \geqslant 100$$

Conclusions

- Gamma-ray bursts are short intense bursts of γ-rays. They do not originate from the earth or the sun.
- GRBs are highly-relativistic phenomena.

Major Observations in GRBs

- 1973 — Discovery [Vela]
- 1984, 1993 — Long & short [Vela, CGRO-BATSE]
- 1992 — Isotropic & non-Euclidean distribs [BATSE]
- 1997 — Afterglows of long GRBs
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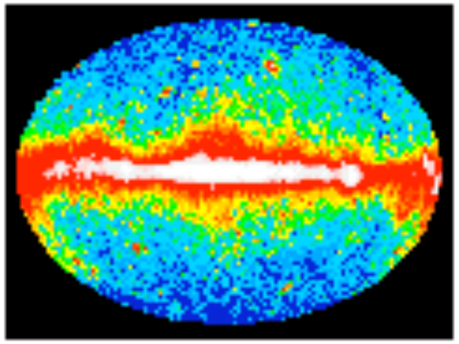
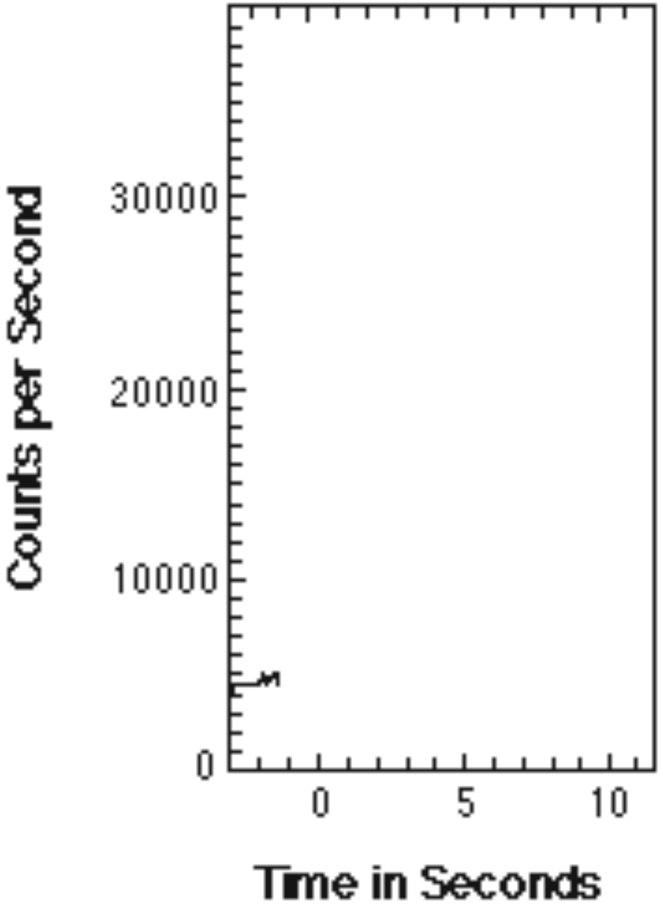




Counts per Second
30000
20000
10000
0
0
5
10
Time in Seconds

#	Author	Year Pub	Reference	Main Body	2nd Body	Place	Description
1.	Colgate	1968	CJPhys, 46, S476	ST		COS	SN shocks stellar surface in distant galaxy
2.	Colgate	1974	ApJ, 187, 333	ST		COS	Type II SN shock brem, inv Comp scat at stellar surface
3.	Stecker et al.	1973	Nature, 245, PS70	ST		DISK	Stellar superflare from nearby star
4.	Stecker et al.	1973	Nature, 245, PS70	WD		DISK	Superflare from nearby WD
5.	Harwit et al.	1973	ApJ, 186, L37	NS	COM	DISK	Relic comet perturbed to collide with old galactic NS
6.	Lamb et al.	1973	Nature, 246, PS52	WD	ST	DISK	Accretion onto WD from flare in companion
7.	Lamb et al.	1973	Nature, 246, PS52	NS	ST	DISK	Accretion onto NS from flare in companion
8.	Lamb et al.	1973	Nature, 246, PS52	BH	ST	DISK	Accretion onto BH from flare in companion
9.	Zwicky	1974	Ap & SS, 28, 111	NS		HALO	NS chunk contained by external pressure escapes, explodes
10.	Grindlay et al.	1974	ApJ, 187, L93	DG		SOL	Relativistic iron dust grain up-scatters solar radiation
11.	Brecher et al.	1974	ApJ, 187, L97	ST		DISK	Directed stellar flare on nearby star
12.	Schlovskii	1974	SovAstron, 18, 390	WD	COM	DISK	Comet from system's cloud strikes WD
13.	Schlovskii	1974	SovAstron, 18, 390	NS	COM	DISK	Comet from system's cloud strikes NS
14.	Bisnovatyi- et al.	1975	Ap & SS, 35, 23	ST		COS	Absorption of neutrino emission from SN in stellar envelope
15.	Bisnovatyi- et al.	1975	Ap & SS, 35, 23	ST	SN	COS	Thermal emission when small star heated by SN shock wave
16.	Bisnovatyi- et al.	1975	Ap & SS, 35, 23	NS		COS	Ejected matter from NS explodes
17.	Pacini et al.	1974	Nature, 251, 399	NS		DISK	NS crustal starquake glitch; should time coincide with GRB
18.	Narlikar et al.	1974	Nature, 251, 590	WH		COS	White hole emits spectrum that softens with time
19.	Tsygan	1975	A&A, 44, 21	NS		HALO	NS corequake excites vibrations, changing E & B fields
20.	Chanmugam	1974	ApJ, 193, L75	WD		DISK	Convection inside WD with high B field produces flare
21.	Prilutski et al.	1975	Ap & SS, 34, 395	AGN	ST	COS	Collapse of supermassive body in nucleus of active galaxy
22.	Narlikar et al.	1975	Ap & SS, 35, 321	WH		COS	WH excites synchrotron emission, inverse Compton scattering
23.	Piran et al.	1975	Nature, 256, 112	BH		DISK	Inv Comp scat deep in ergosphere of fast rotating, accreting BH
24.	Fabian et al.	1976	Ap & SS, 42, 77	NS		DISK	NS crustquake shocks NS surface
25.	Chanmugam	1976	Ap & SS, 42, 83	WD		DISK	Magnetic WD suffers MHD instabilities, flares
26.	Mullan	1976	ApJ, 208, 199	WD		DISK	Thermal radiation from flare near magnetic WD
27.	Woosley et al.	1976	Nature, 263, 101	NS		DISK	Carbon detonation from accreted matter onto NS
28.	Lamb et al.	1977	ApJ, 217, 197	NS		DISK	Mag grating of accret disk around NS causes sudden accretion
29.	Piran et al.	1977	ApJ, 214, 268	BH		DISK	Instability in accretion onto rapidly rotating BH
30.	Dasgupta	1979	Ap & SS, 63, 517	DG		SOL	Charged intergal rel dust grain enters sol sys, breaks up
31.	Tsygan	1980	A&A, 87, 224	WD		DISK	WD surface nuclear burst causes chromospheric flares
32.	Tsygan	1980	A&A, 87, 224	NS		DISK	NS surface nuclear burst causes chromospheric flares
……							
99.	Pineault	1990	Nature, 345, 233	NS	COM	DISK	Young NS drifts through its own Oort cloud
100.	Trofimenko et al.	1991	Ap & SS, 178, 217	WH		HALO	White hole supernova gave simultaneous burst of g-waves from 1987A
101.	Melia et al.	1991	ApJ, 373, 198	NS		DISK	NS B-field undergoes resistive tearing, accelerates plasma
102.	Holcomb et al.	1991	ApJ, 378, 682	NS		DISK	Alfen waves in non-uniform NS atmosphere accelerate particles
103.	Haensel et al.	1991	ApJ, 375, 209	SS	SS	COS	Strange stars emit binding energy in grav rad and collide
104.	Blaes et al.	1991	ApJ, 381, 210	NS	ISM	DISK	Slow interstellar accretion onto NS, e- capture starquakes result
105.	Frank et al.	1992	ApJ, 385, L45	NS		DISK	Low mass X-ray binary evolve into GRB sites
106.	Woosley et al.	1992	ApJ, 391, 228	NS		HALO	Accreting WD collapsed to NS
107.	Dar et al.	1992	ApJ, 388, 164	WD		COS	WD accretes to form naked NS, GRB, cosmic rays
108.	Hanami	1992	ApJ, 389, L71	NS	PLAN	COS	NS - planet magnetospheric interaction unstable
109.	Meszaros et al.	1992	ApJ, 397, 570	NS	NS	COS	NS - NS collision produces anisotropic fireball
110.	Carter	1992	ApJ, 391, L67	BH	ST	COS	Normal stars tidally disrupted by galactic nucleus BH
111.	Usov	1992	Nature, 357, 472	NS		COS	WD collapses to form NS, B-field brakes NS rotation instantly
112.	Narayan et al.	1992	ApJ, 395, L83	NS	NS	COS	NS - NS merger gives optically thick fireball
113.	Narayan et al.	1992	ApJ, 395, L83	BH	NS	COS	BH - NS merger gives optically thick fireball
114.	Brainerd	1992	ApJ, 394, L33	AGN	JET	COS	Synchrotron emission from AGN jets
115.	Meszaros et al.	1992	MNRAS, 257, 29P	BH	NS	COS	BH-NS have neutrinos collide to gammas in clean fireball
116.	Meszaros et al.	1992	MNRAS, 257, 29P	NS	NS	COS	NS-NS have neutrinos collide to gammas in clean fireball
117.	Cline et al.	1992	ApJ, 401, L57	BH		DISK	Primordial BHs evaporating could account for short hard GRBs
118.	Rees et al.	1992	MNRAS, 258, 41P	NS	ISM	COS	Relativistic fireball reconverted to radiation when hits ISM

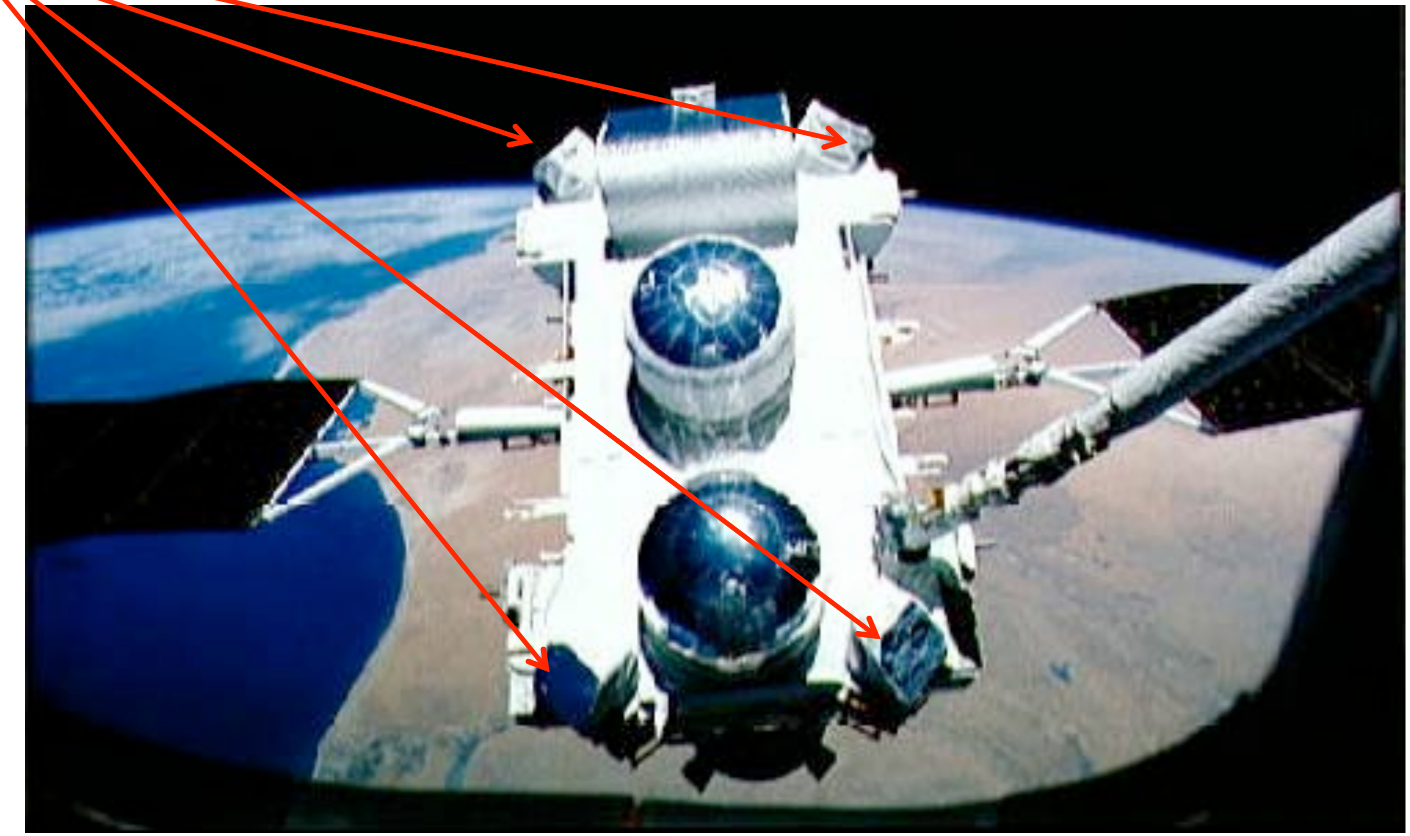
What causes GRBs

?

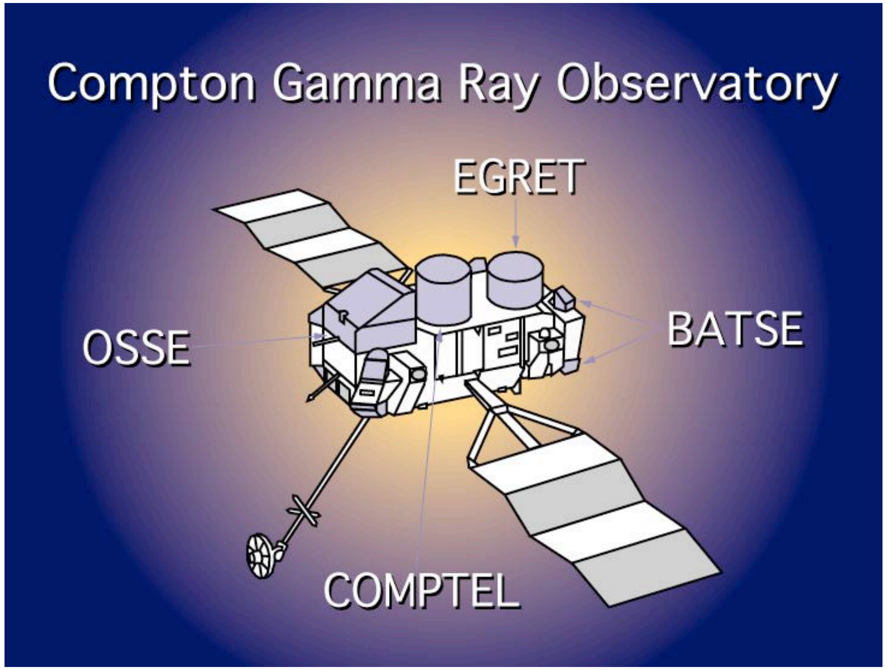
How find the answer?

CGRO

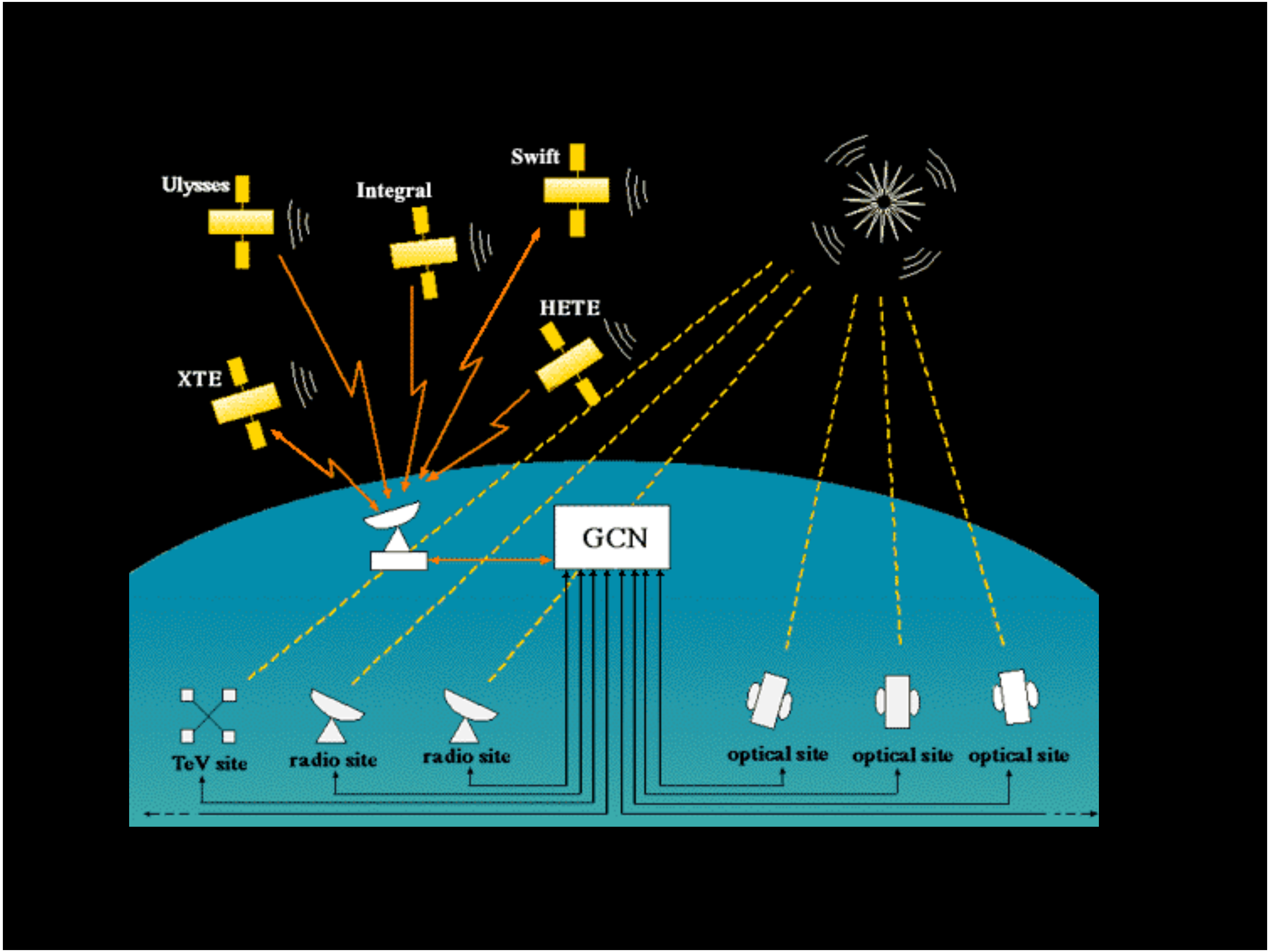
BATSE



BATSE – A minor part of CGRO



- CGRO (Compton Gamma Ray Observatory)
- The satellite was launched in 1991 and deorbited into the Atlantic in June 2000.
- The main purpose of BATSE (Burst and Transient Source Experiment was to study GRBs.
- BATSE triggered on 2704 GRBs during its nine years of operation (ca. 1 per day).


Ulysses
Integral
Swift
HETE
XTE
GCN
TeV site
radio site
radio site
optical site
optical site
optical site

Evidence of polarisation in the prompt gamma-ray emission from GRB 930131 and GRB 960924

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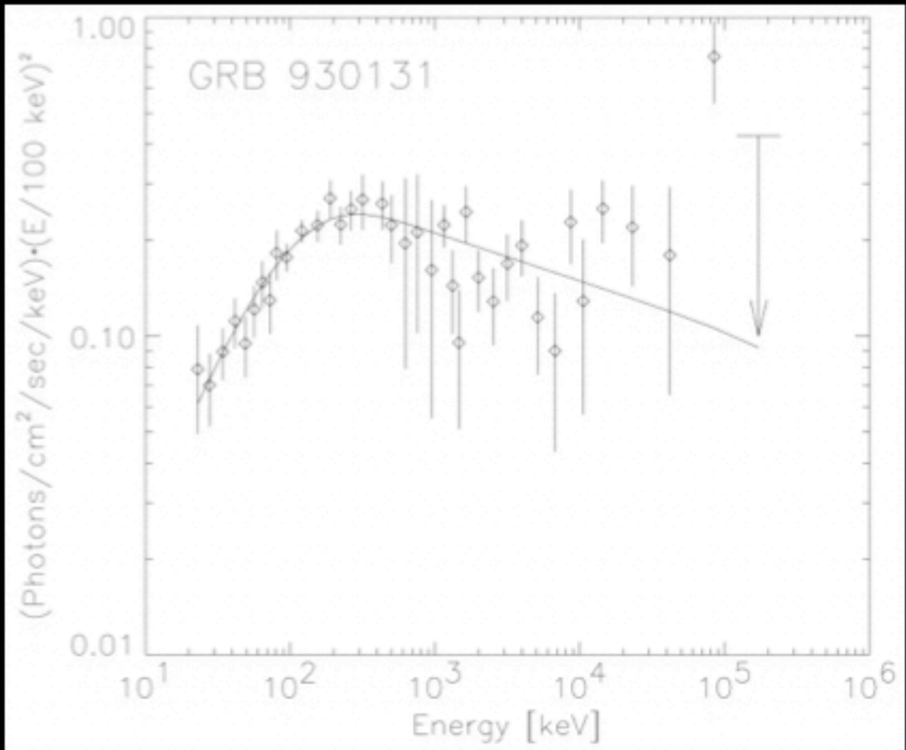
Abstract. The true nature of the progenitor to GRBs remains elusive; one characteristic that would constrain our understanding of the GRB mechanism considerably is gamma-ray polarimetry measurements of the initial burst flux. We present a method that interprets the prompt GRB flux as it Compton scatters off the Earth's atmosphere, based on detailed modelling of both the Earth's atmosphere and the orbiting detectors. The BATSE mission aboard the *CGRO* monitored the whole sky in the 20 keV–1 MeV energy band continuously from April 1991 until June 2000. We present the BATSE Albedo Polarimetry System (BAPS), and show that GRB 930131 and GRB 960924 provide evidence of polarisation in their prompt flux that is consistent with degrees of polarisation of $\Pi > 35\%$ and $\Pi > 50\%$ respectively. While the evidence of polarisation is strong, the method is unable to strongly constrain the degree of polarisation beyond a systematics based estimation. Hence the implications on GRB theory are unclear, and further measurements essential.

Key words. gamma-rays: bursts – techniques: polarimetric – methods: data analysis – polarization

Spectral properties: Non-thermal

High energy spectra:
(Band function)

$$N(E) = \begin{cases} A E^{\alpha} \exp\left(-\frac{E}{E_0}\right) & E < (\alpha-\beta) E_0 \\ B E^{\beta} & E > (\alpha-\beta) E_0 \end{cases}$$

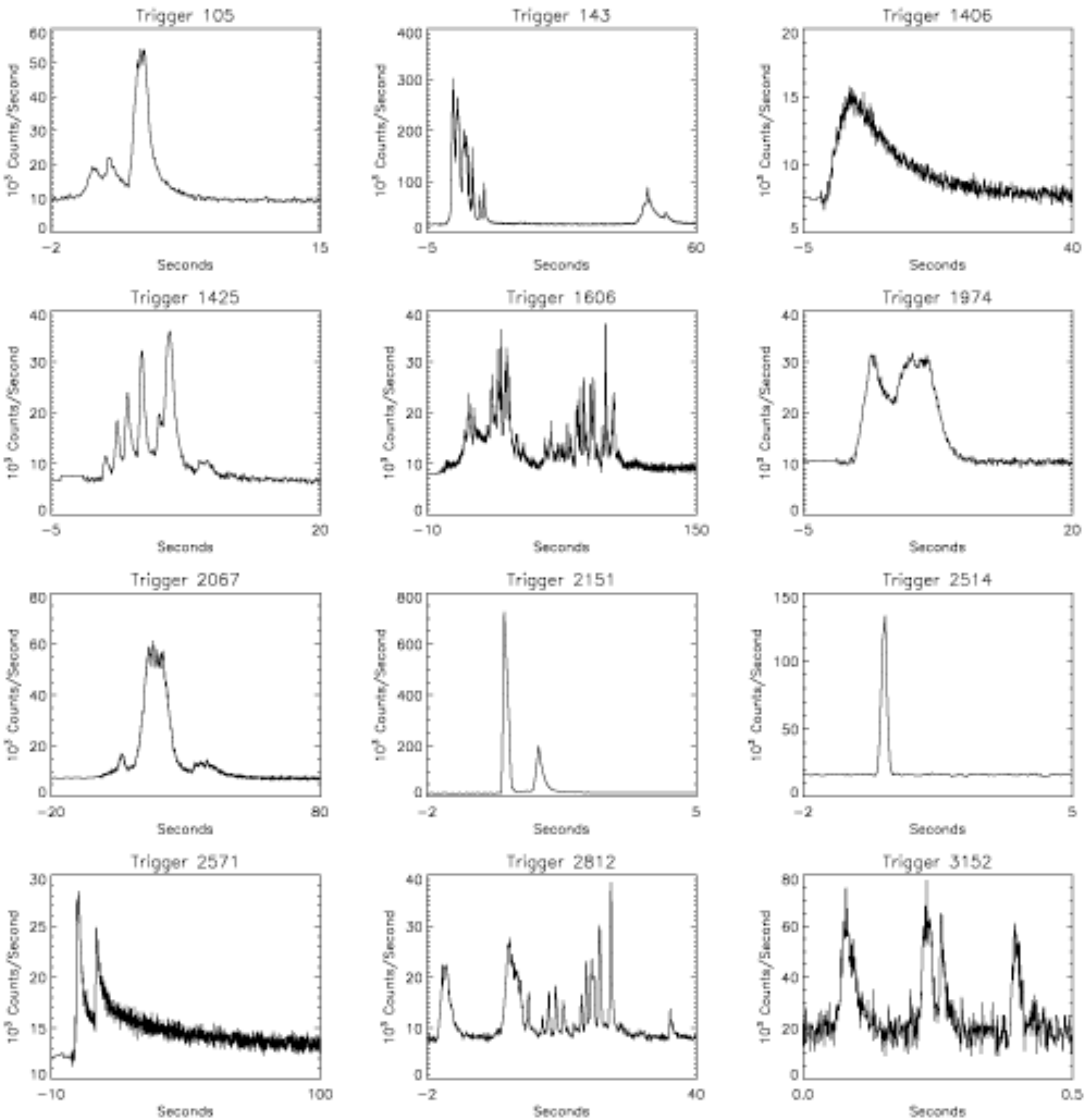


$$E_{peak} = E_0 \times (2+\alpha)$$

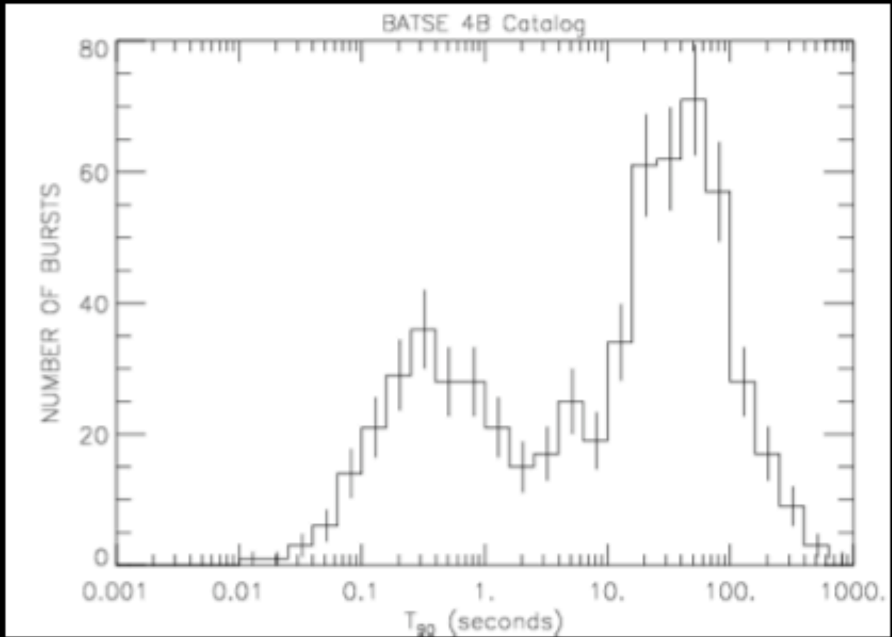
E_{peak} ~250 keV (within factor 2-3)

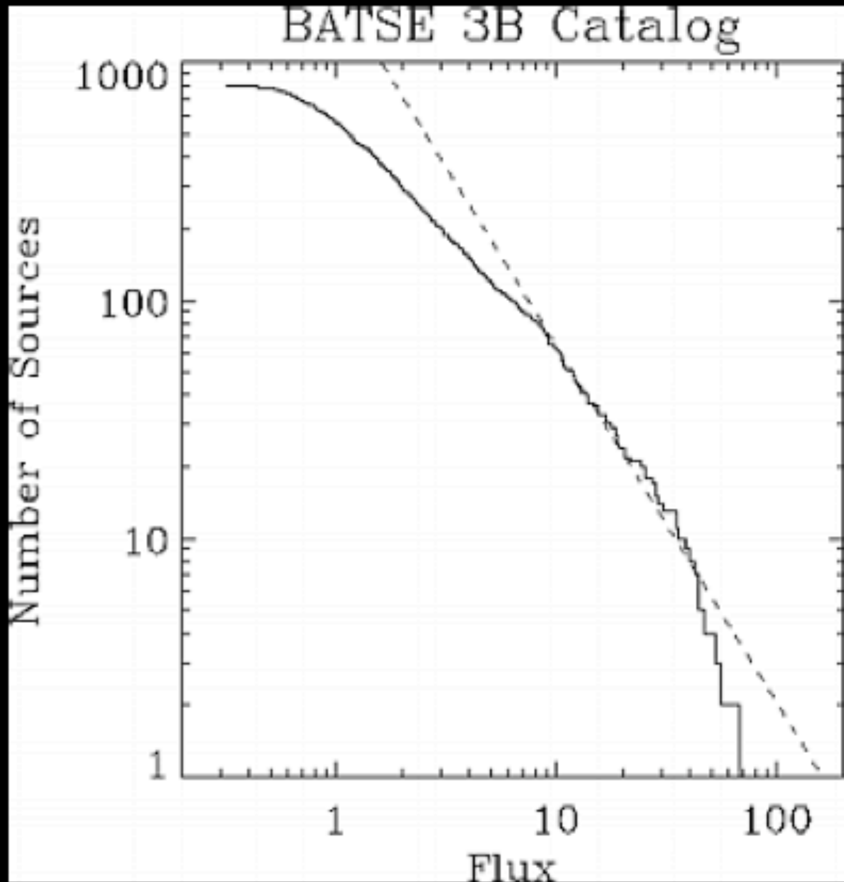
$\alpha \in [-2,0]$ $\beta \in [-4,-2]$

BATSE: Examples of GRB lightcurves



Other key BATSE results

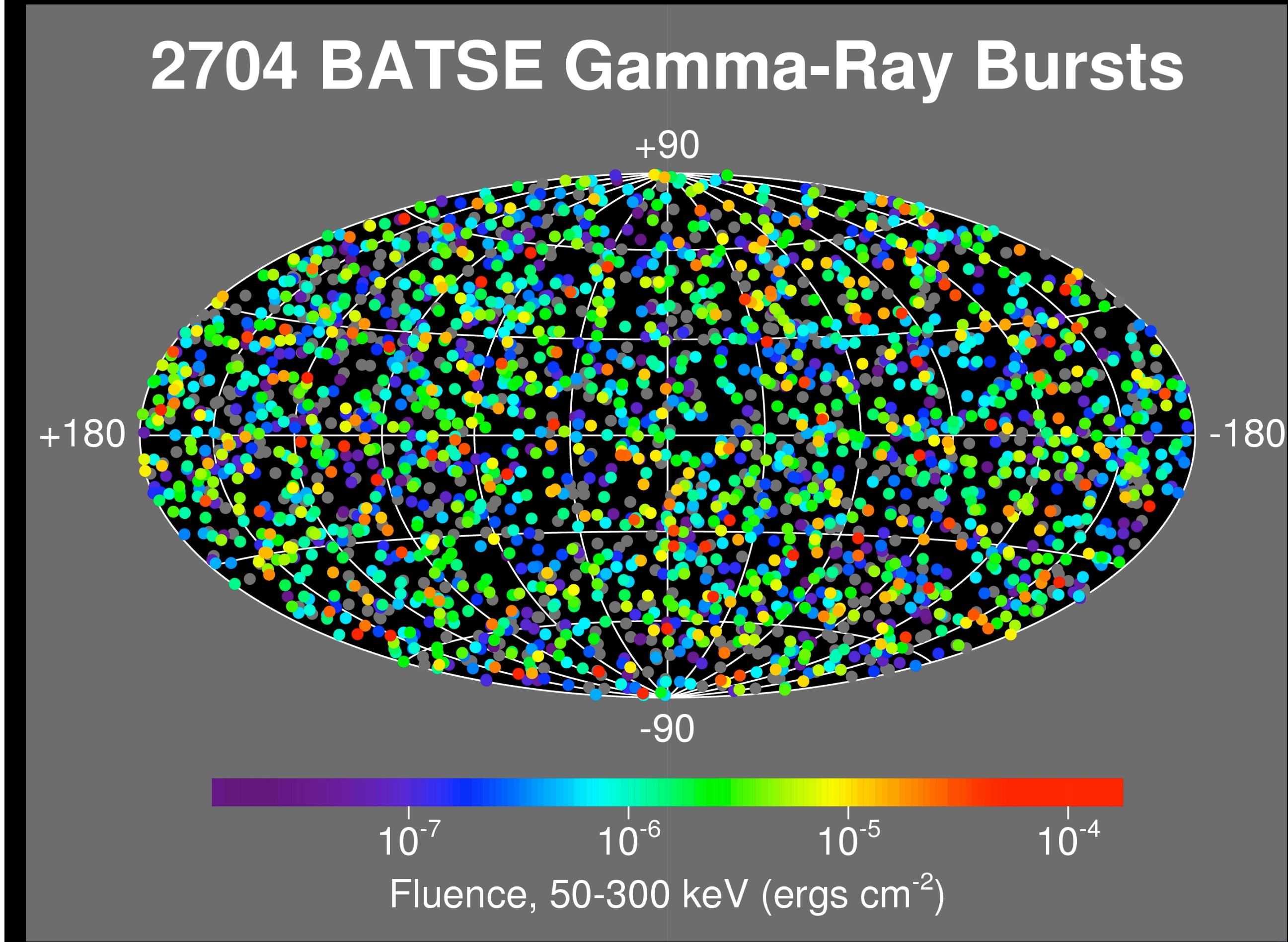




Two classes of GRBs: short and long duration GRBs. Short GRBs have harder spectra than long GRBs.

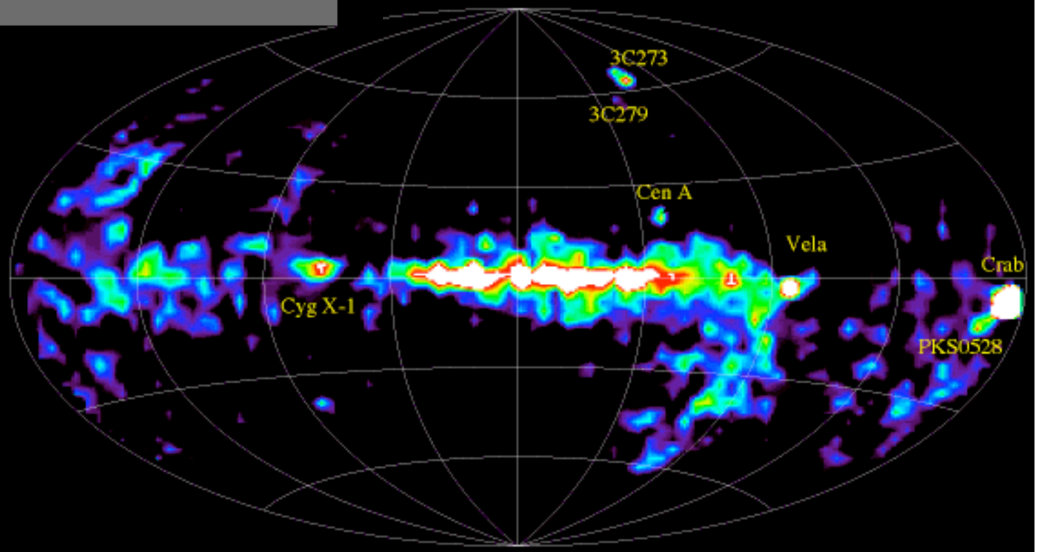
A deficit of faint sources is a strong hint that the soucers have a cosmological distribution (or that we see the end of the distribution).

$$F \propto \text{distance}^{-2}, N \propto \text{distance}^{3}$$
$$\rightarrow N \propto F^{-3/2}$$



← distribution of GRBs on the sky: Isotropic

Distribution on the sky of persistent γ-ray sources →
Mainly in the Milky Way disk (or AGN)



Conclusions

- Gamma-ray bursts are short intense bursts of γ-rays. They do not originate from the earth or the sun.
- GRBs are highly-relativistic phenomena
- GRBs are isotropically distributed on the sky and are non-Euclidean.
- They come in at least two flavours (long and short)

What can be inferred from the celestial distribution of GRBs?

The Great Debate 1995

http://antwrp.gsfc.nasa.gov/diamond_jubilee/debate95.html

- Bohdan Paczyński
- Extragalactic

Explosions in remote galaxies.

- Donald Q. Lamb
- Galactic (Milky Way)

Neutron stars ejected from the disk with large velocities and hence distributed in an extended halo.

Tests: precise positions

Andromeda galaxy

Major Observations in GRBs

- 1973 — Discovery [Vela]
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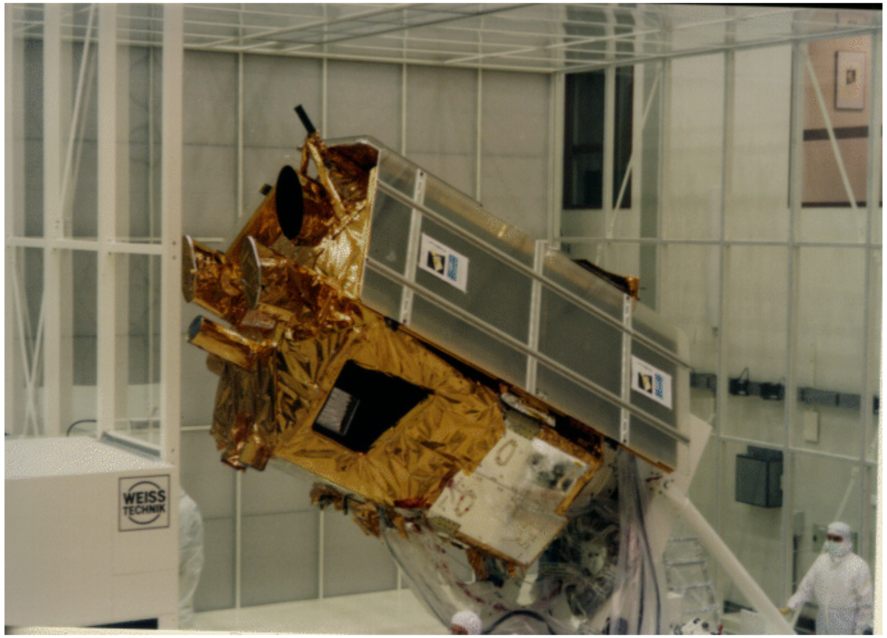
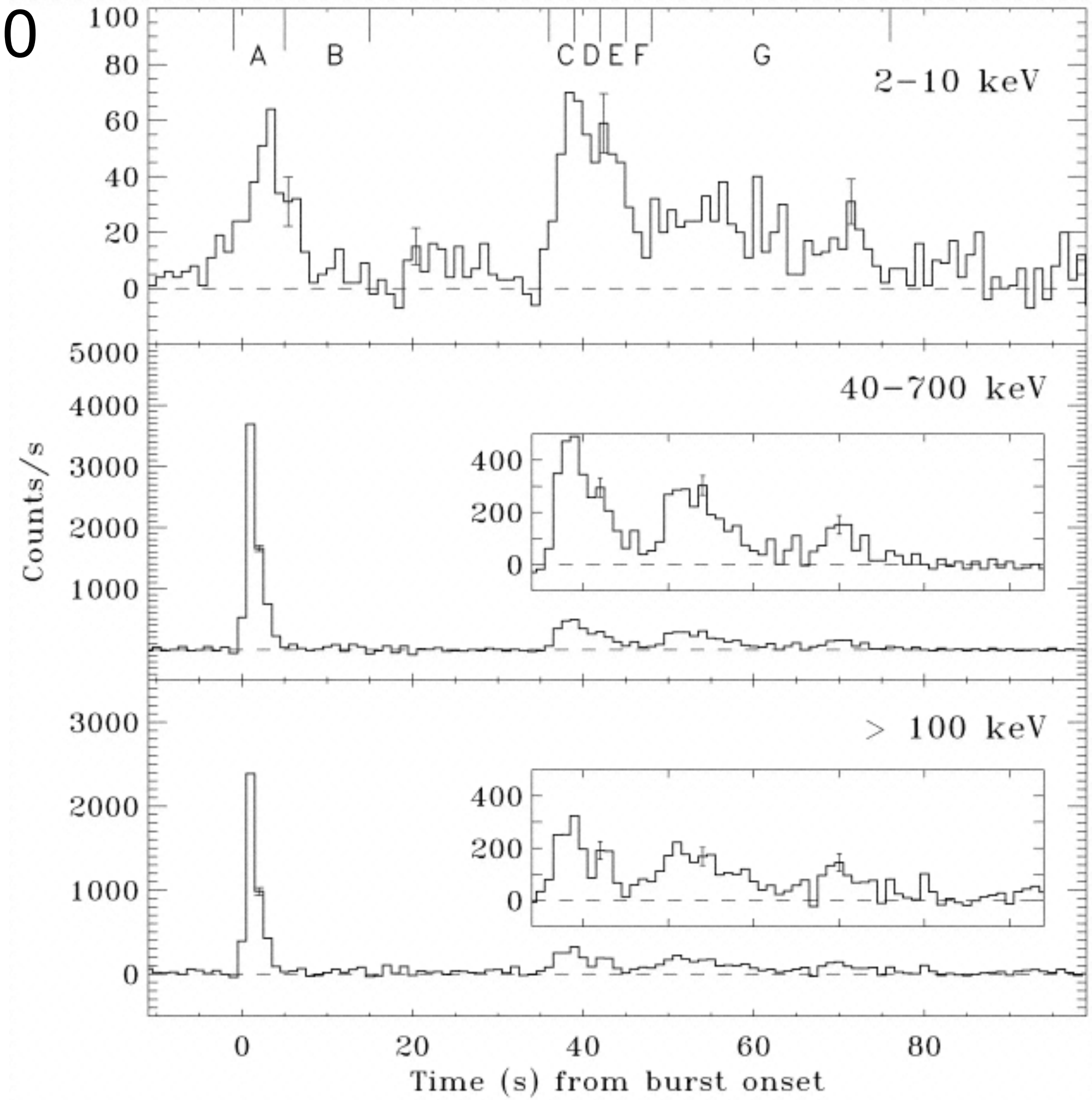
- 2009 — $z > 7$ GRB

The BeppoSax Years: 1996-2002

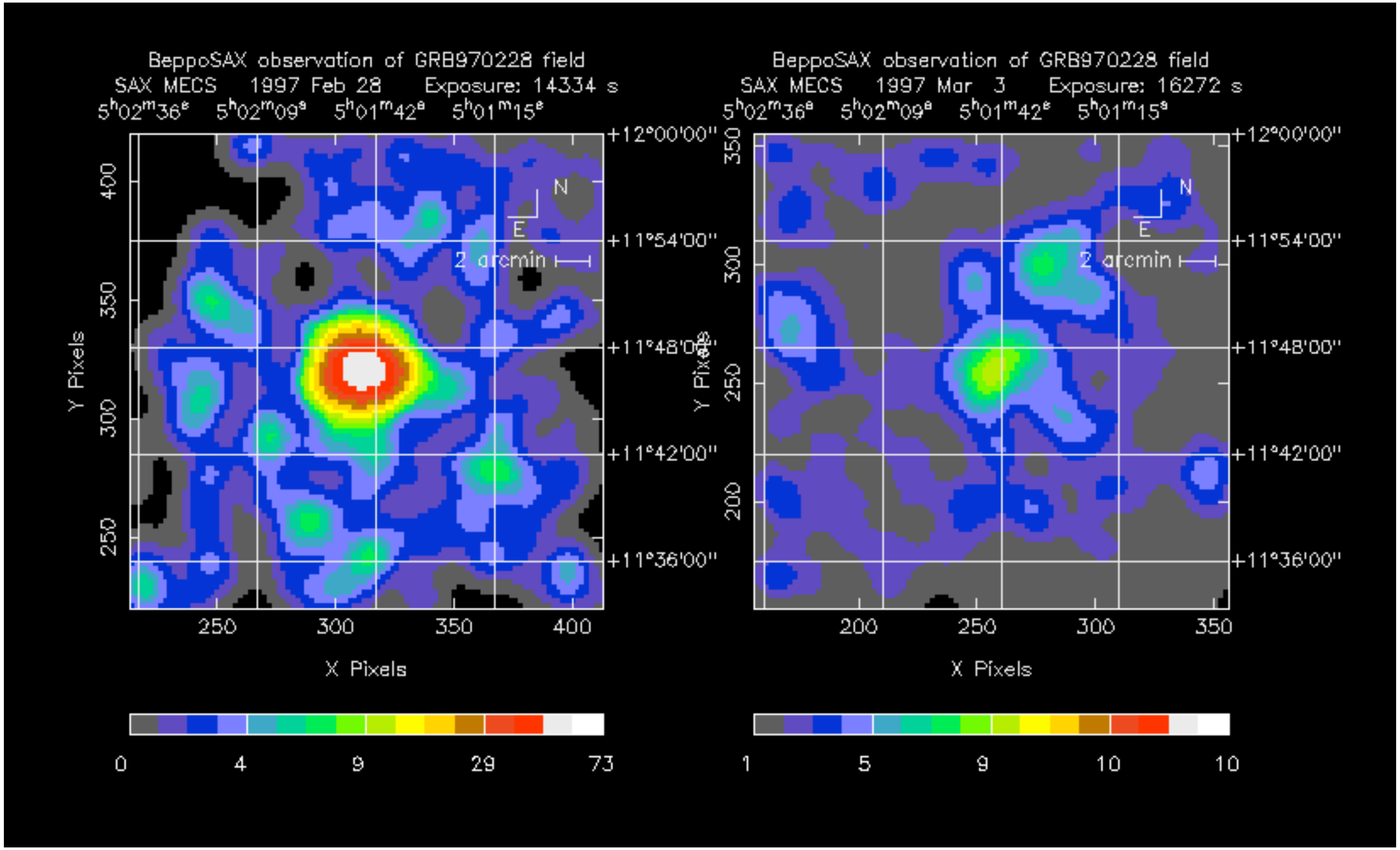


GRB970228: breakthrough

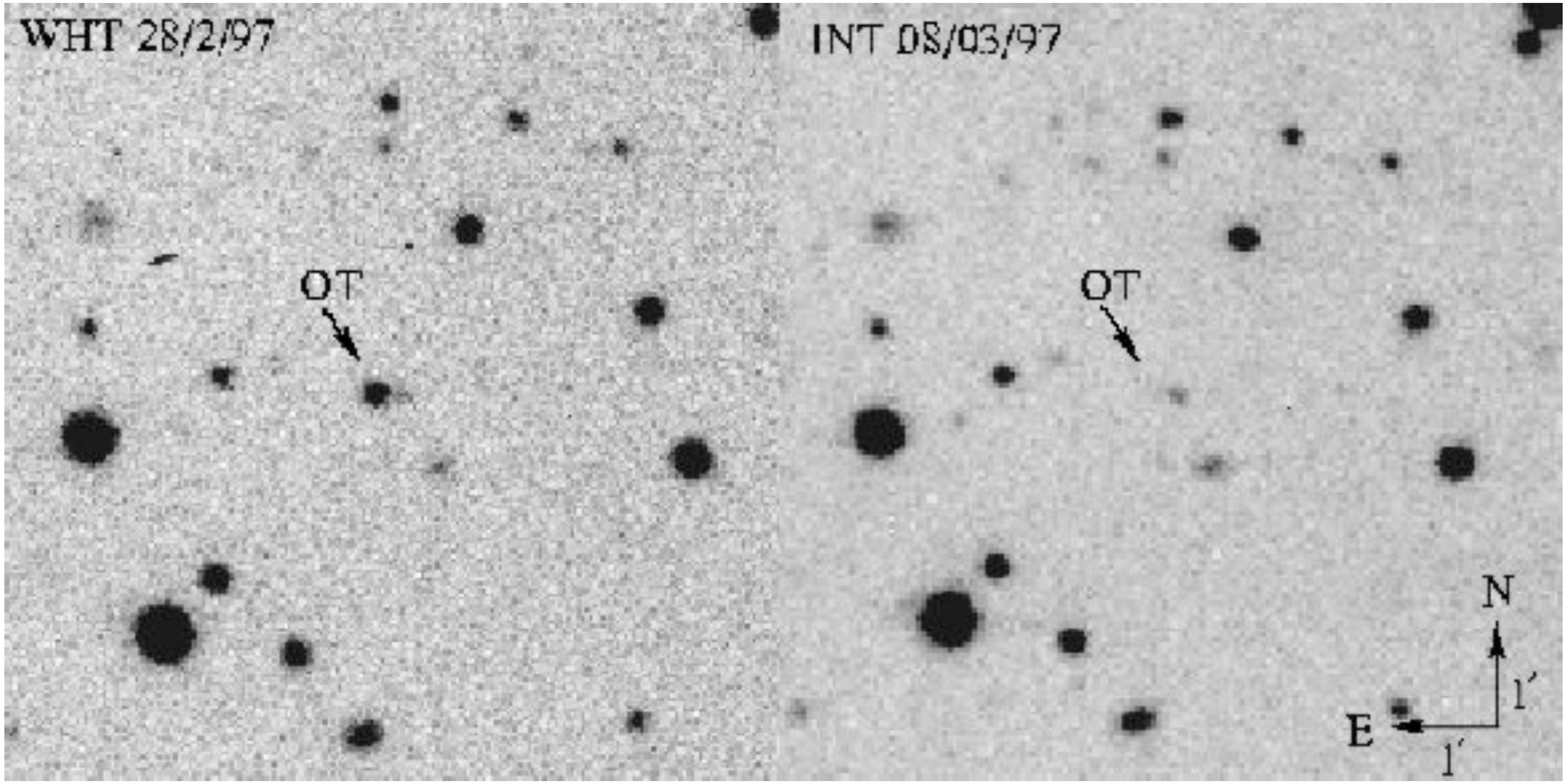
February 28.123620



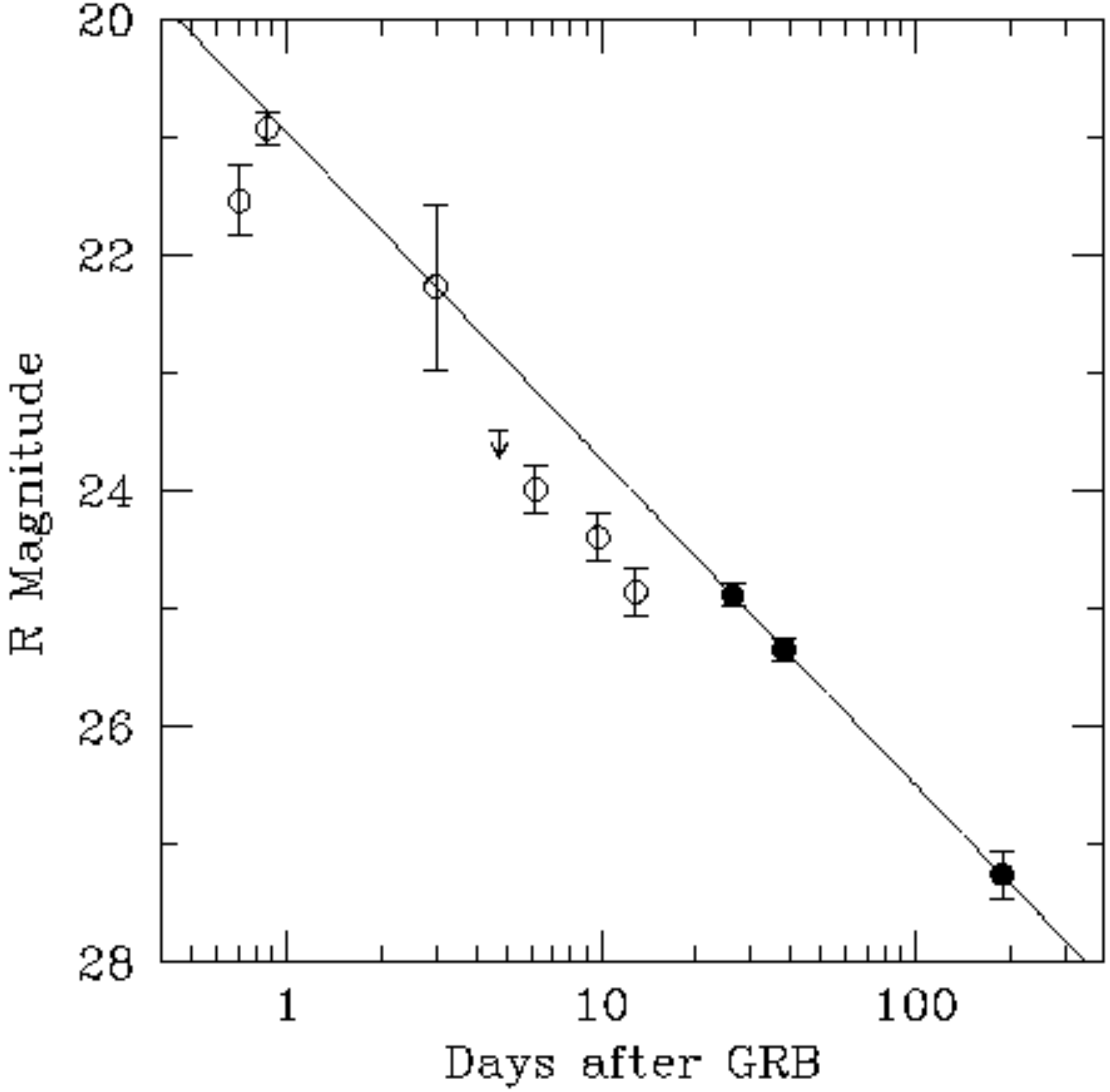
GRB970228: X-ray afterglow



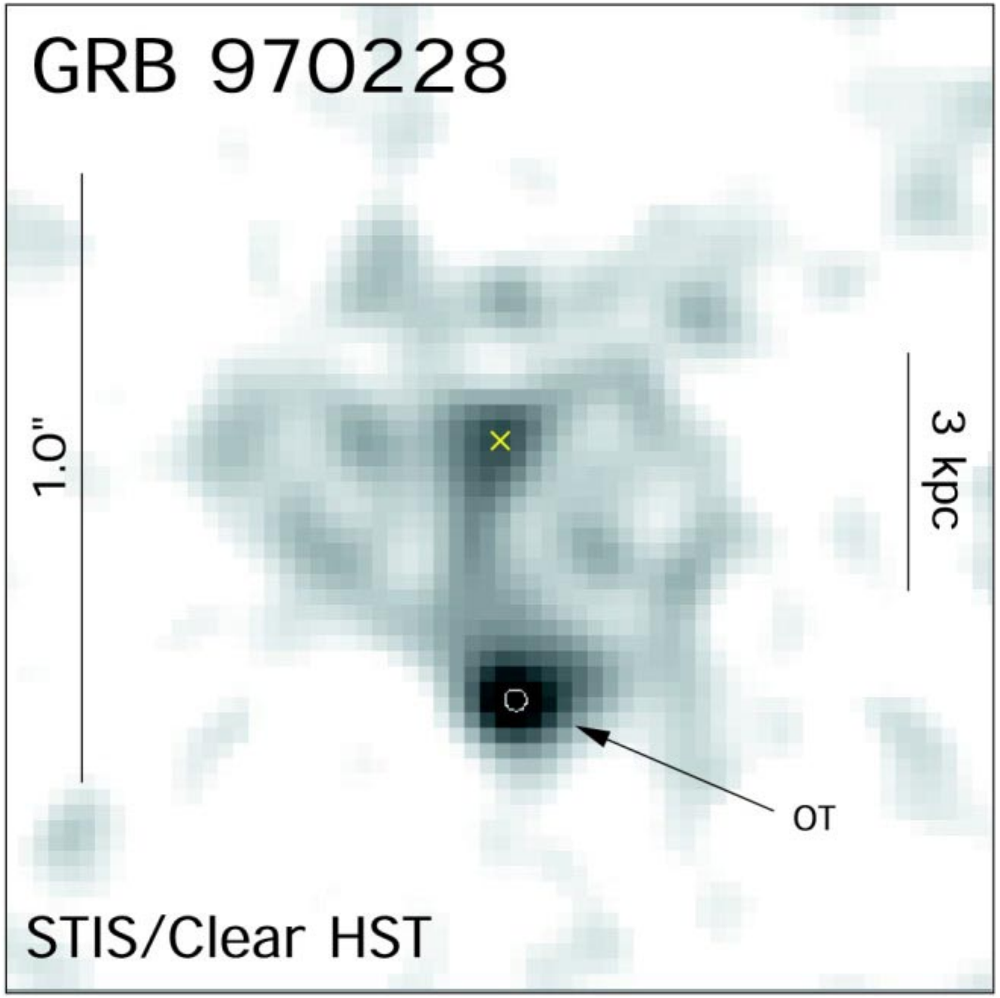
GRB970228: optical afterglow



Lightcurve for the optical afterglow of GRB970228: powerlaw



Host galaxy (z=0.695, d=4.2 Gpc)



↓

COSMOLOGICAL!

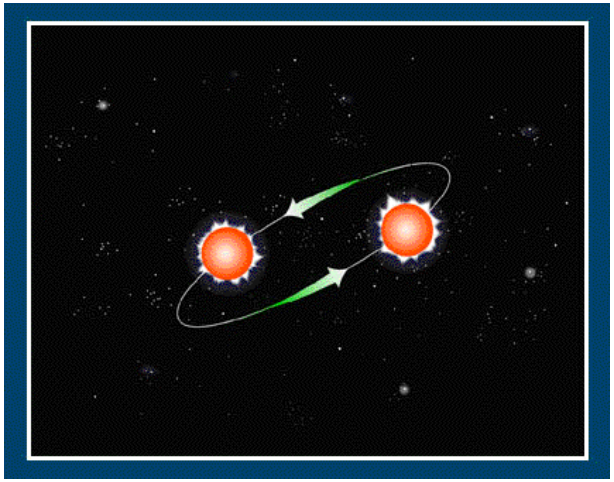
Conclusions

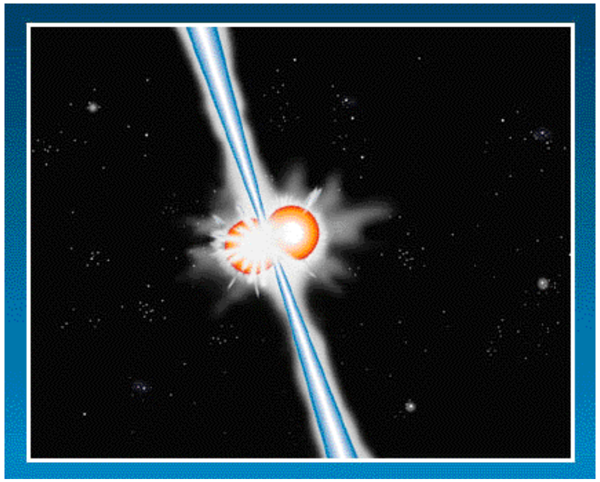
- Gamma-ray bursts are short intense bursts of γ-rays. They do not originate from the earth or the sun.
- GRBs are highly-relativistic phenomena
- GRBs are isotropically distributed on the sky and are non-Euclidean.
- They come in at least two flavours (long and short)
- Long GRBs originate from galaxies at "cosmological" distances. Extremely energetic explosions. Synchrotron radiation from highly relativistic electrons?

Jets in GRBs

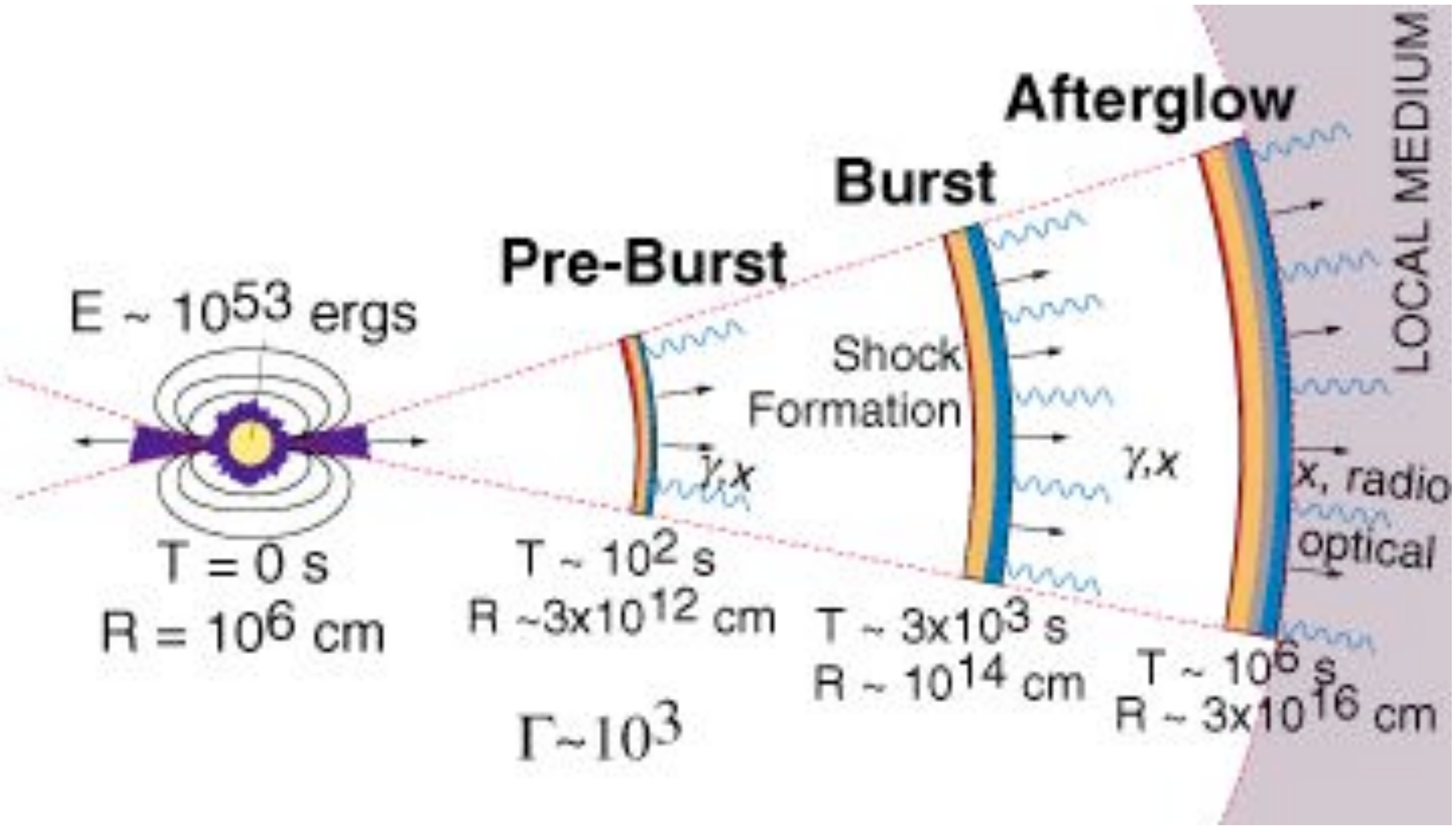
- GRBs are ultra-relativistic
- Bursts must be relativistically beamed
- Equivalent isotropic energy release in Gamma-rays can be as high as 10^{54} ergs, so total energy release likely much lower
- Collapsar model suggests collimation → jets
- Many astrophysical sources have jets

Likely “inner engines”

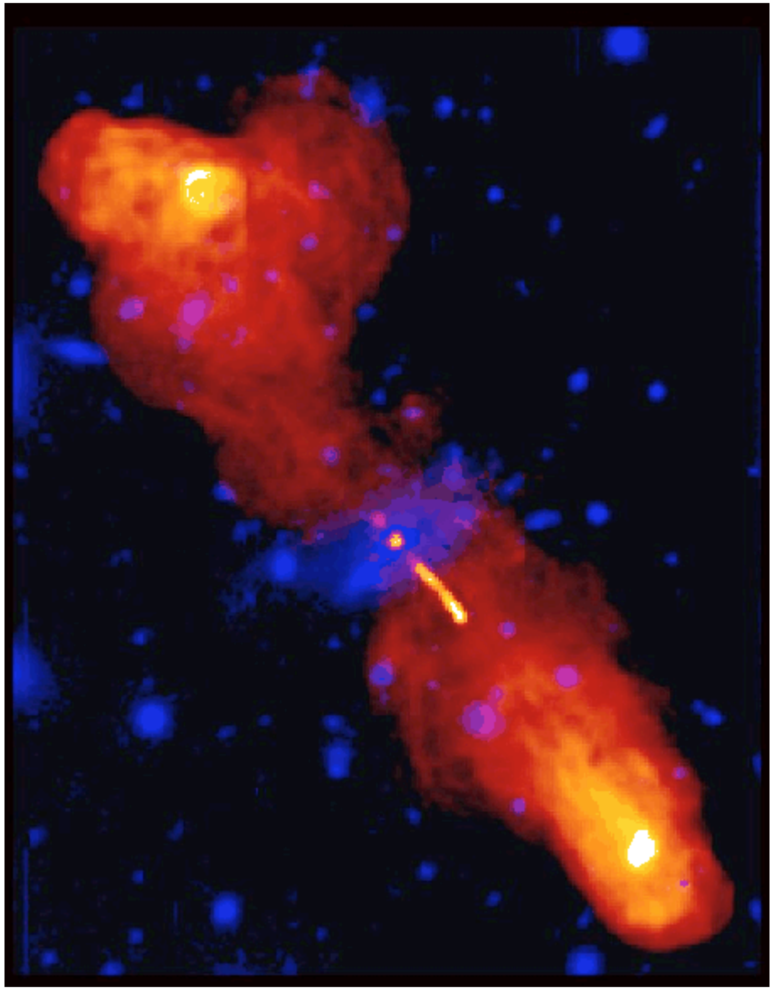


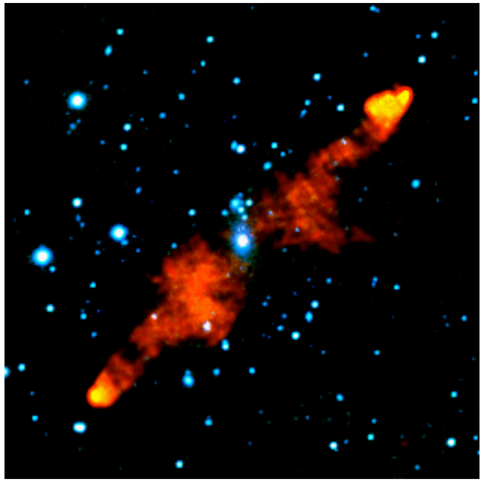


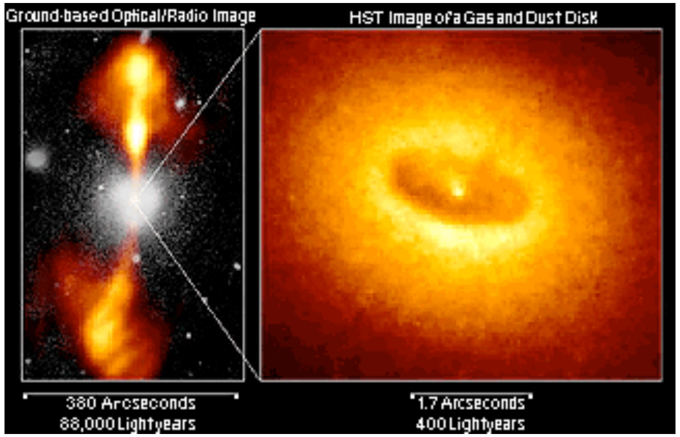
Sketch model for GRBs

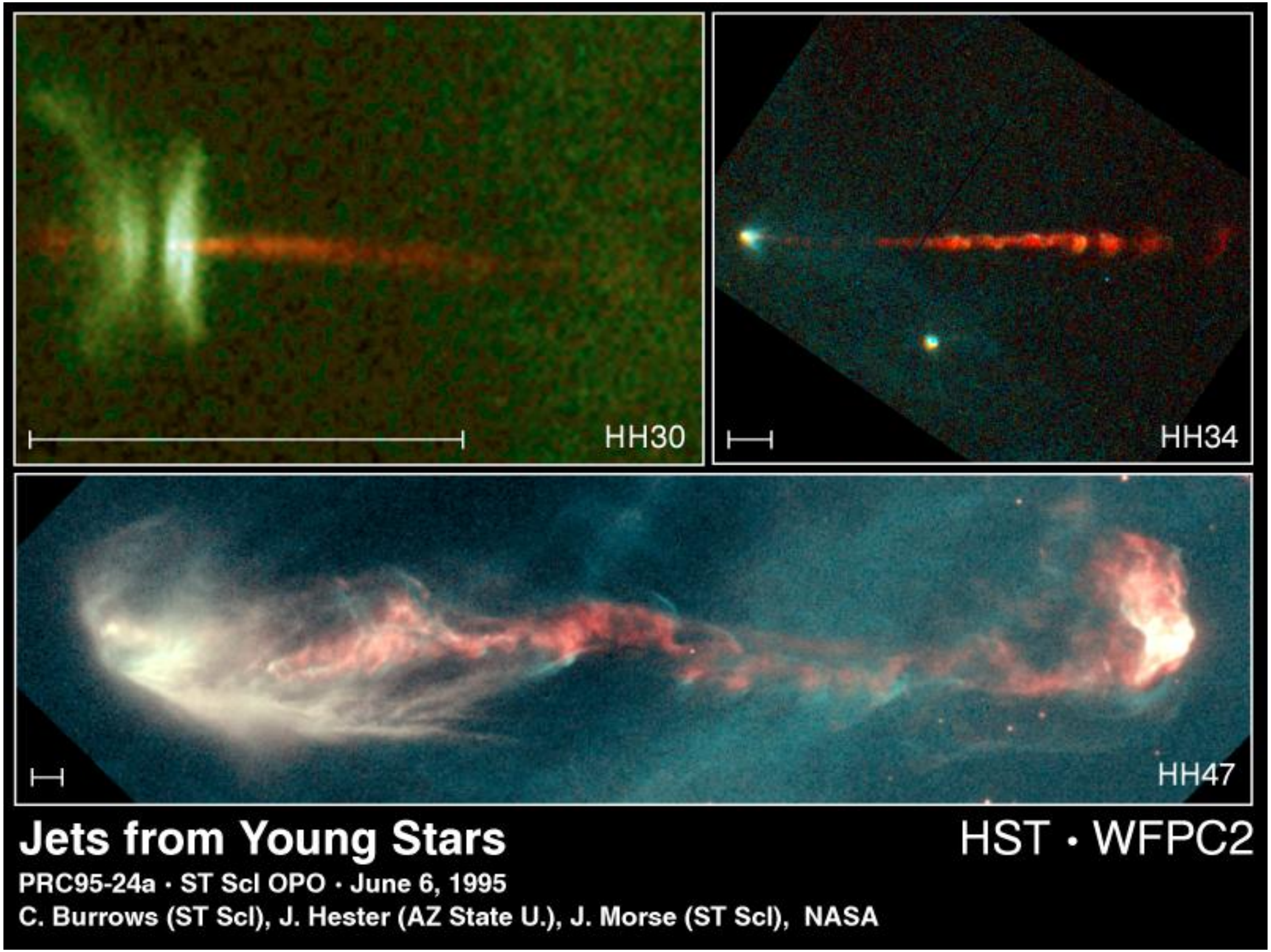


Other objects that produce jets








HH30
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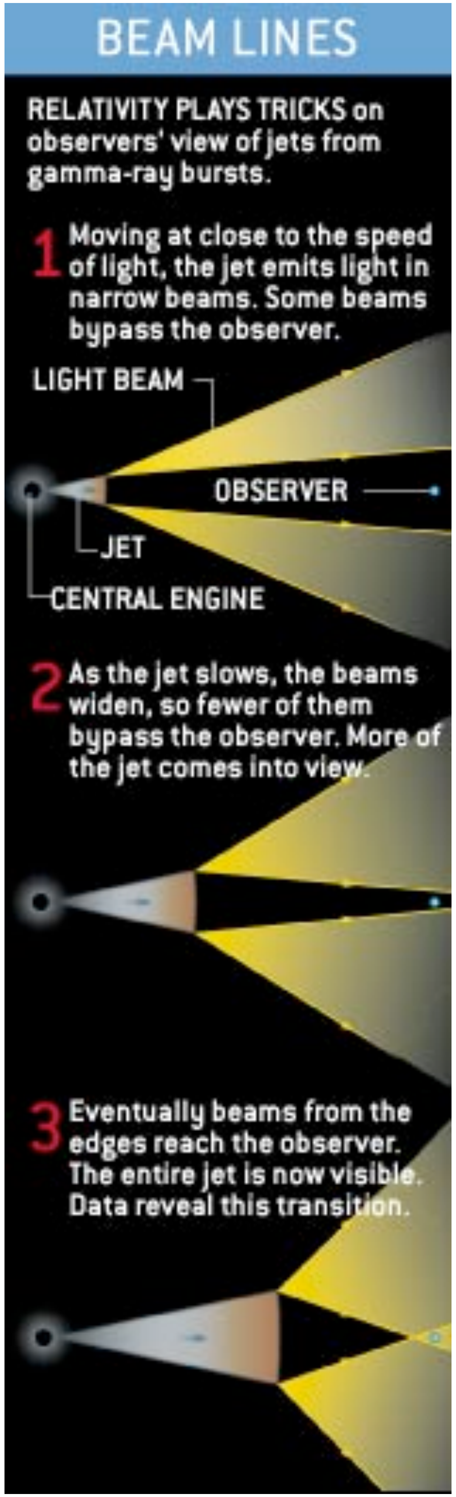
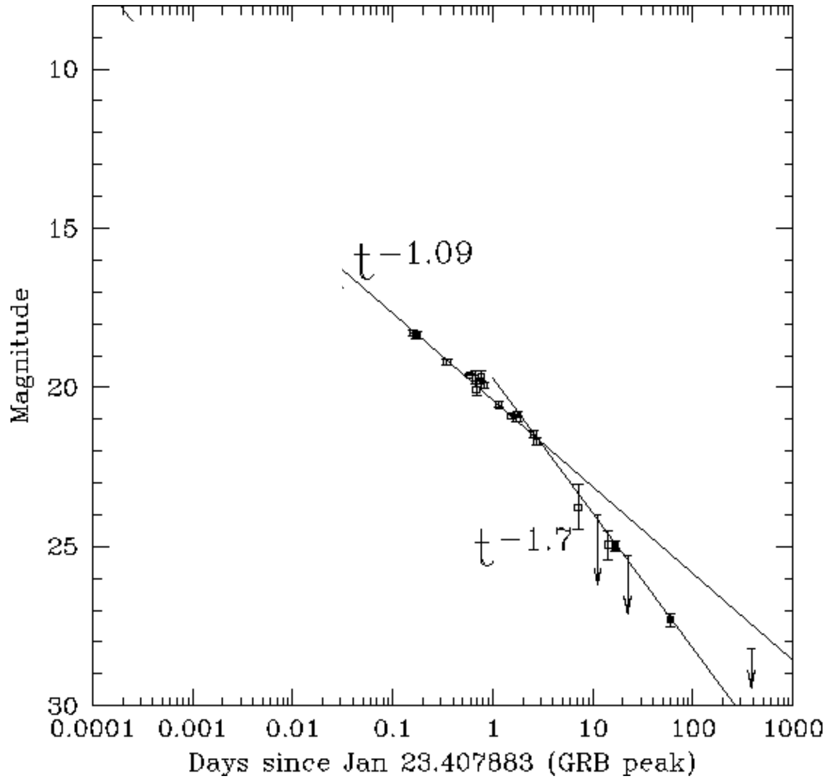
HH47
Jets from Young Stars
HST · WFPC2
PRC95-24a · ST ScI OPO · June 6, 1995
C. Burrows (ST ScI), J. Hester (AZ State U.), J. Morse (ST ScI), NASA



$E_{iso} = 4.5\times10^{54}$ erg

More than rest-energy of the sun!

Collimation solves the energy problem, but at the expense of increasing the rate by factor ~100-500!



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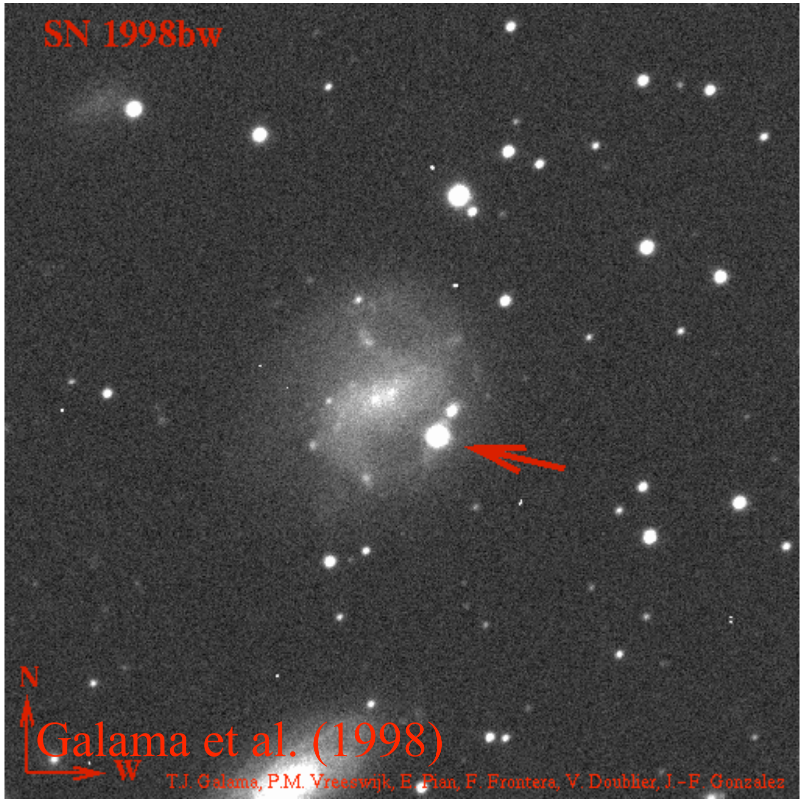
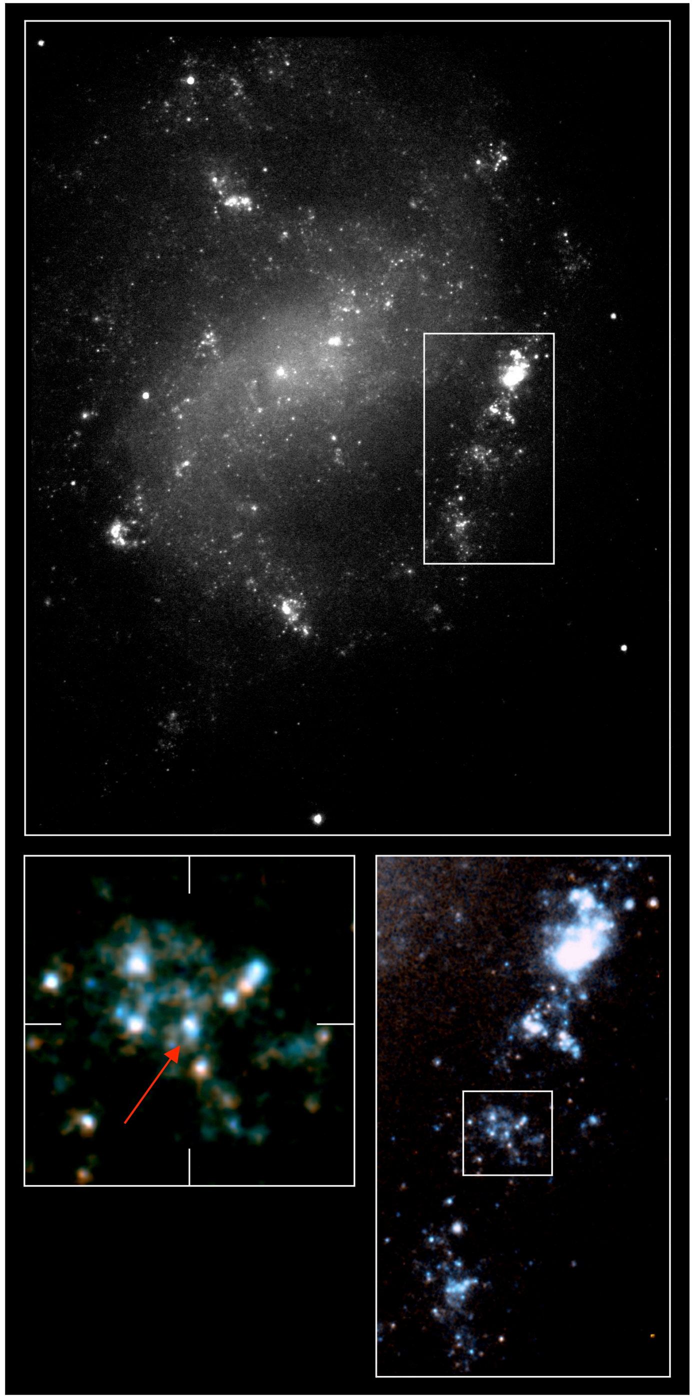
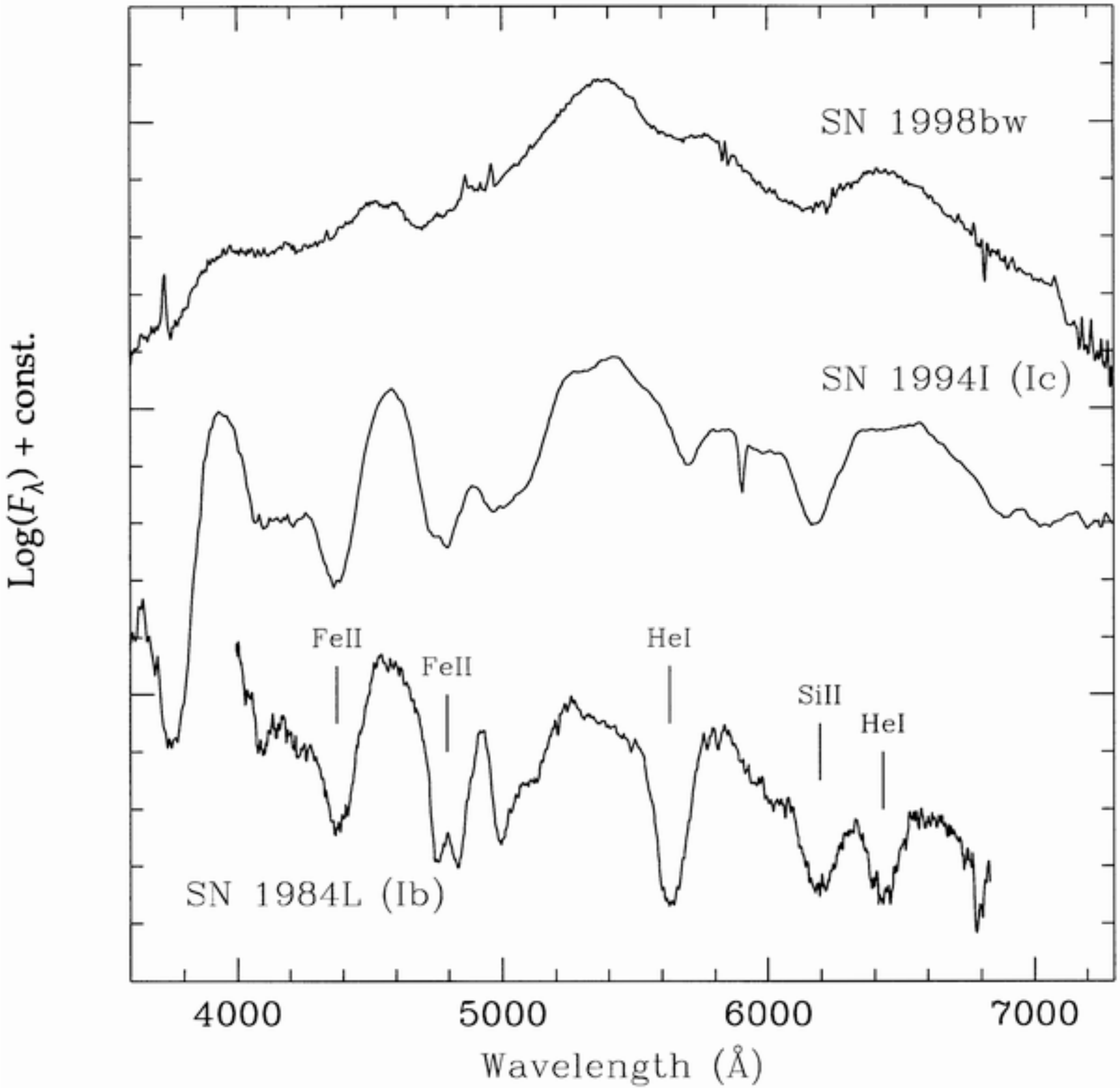
GRB980425: supernova

z=0.0085 (nearby!). No optical afterglow!, but a bright SN Ib/c SN1998bw – SN of the century!







SN 1998bw
SN 1994I (Ic)
FeII
FeII
HeI
SiII
HeI
SN 1984L (Ib)
Log(F_λ) + const.
4000
5000
6000
7000
Wavelength (Å)

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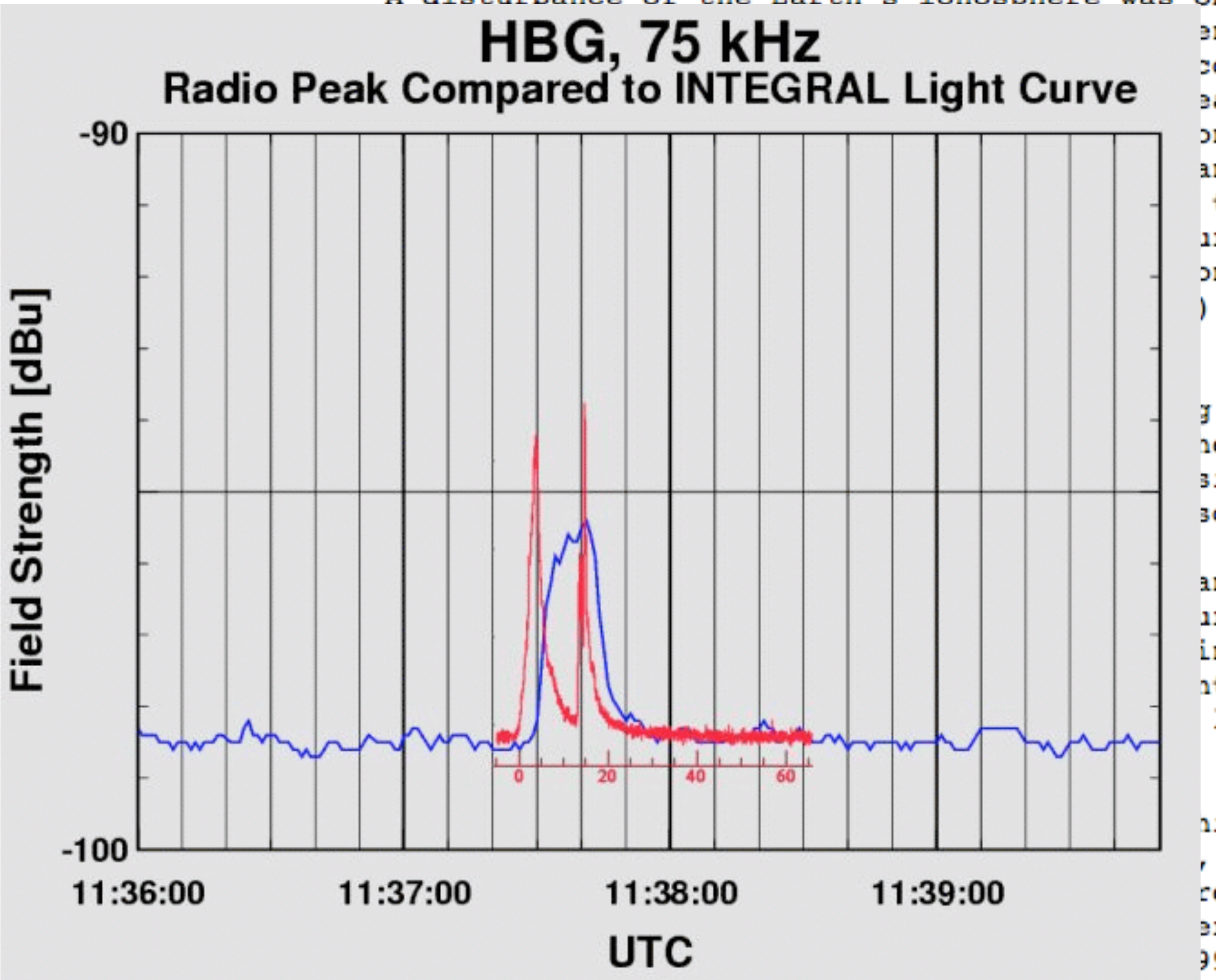
FROM: Doug Welch at McMaster U,PhysAstro. <welch@physics.mcmaster.ca>

P.W. Schnoor, D.L. Welch, G.J. Fishman and A. Price report, on behalf of the AAVSO GRB-SID Network, on the detection of GRB030329 as a sudden ionospheric disturbance (SID), observed by Peter Schnoor of Kiel, Germany.

A disturbance of the Earth's ionosphere was observed coincident with the



en as an increase in the signal
con received in Kiel, transmitted
ear Geneva, 920 km from the
on of GRB030329; this
and/or gamma-rays from GRB030329
the radio propagation properties
urst longitude and latitude and
ons and monitoring stations, this
) where GRB030329 illuminated the 4

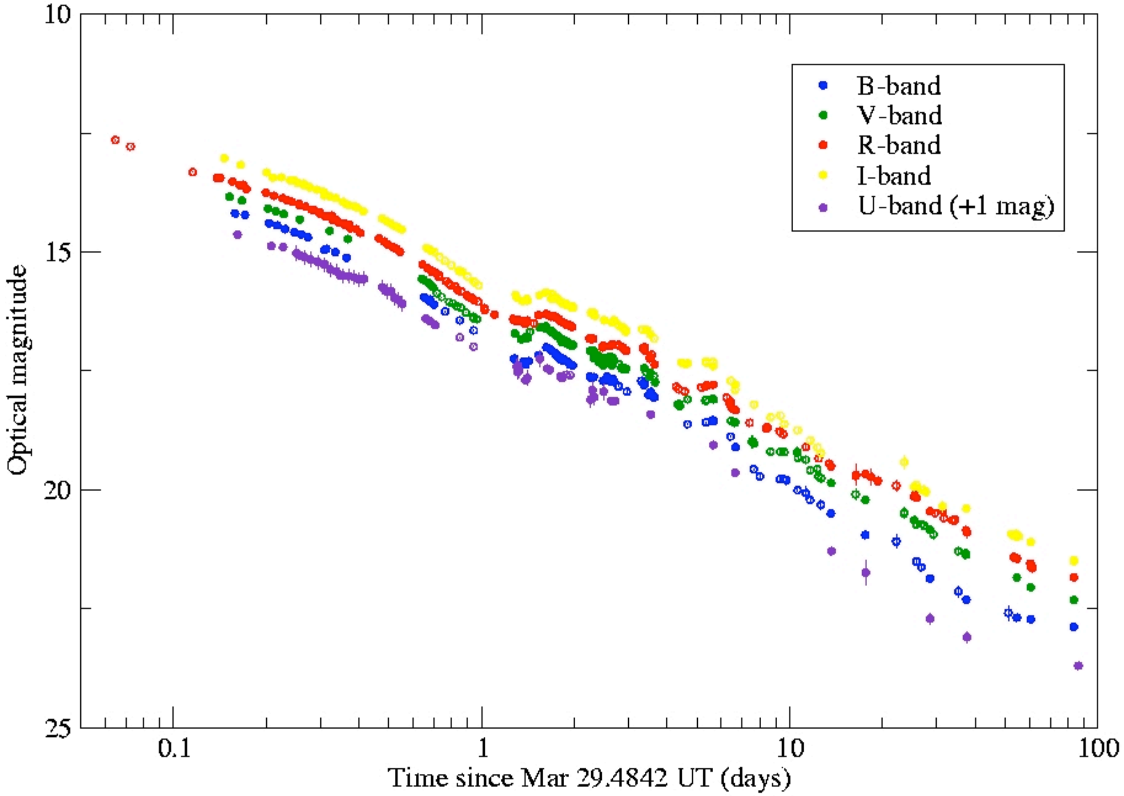
g one with an overlay of
he URL
sid/index.html
so available at this site.

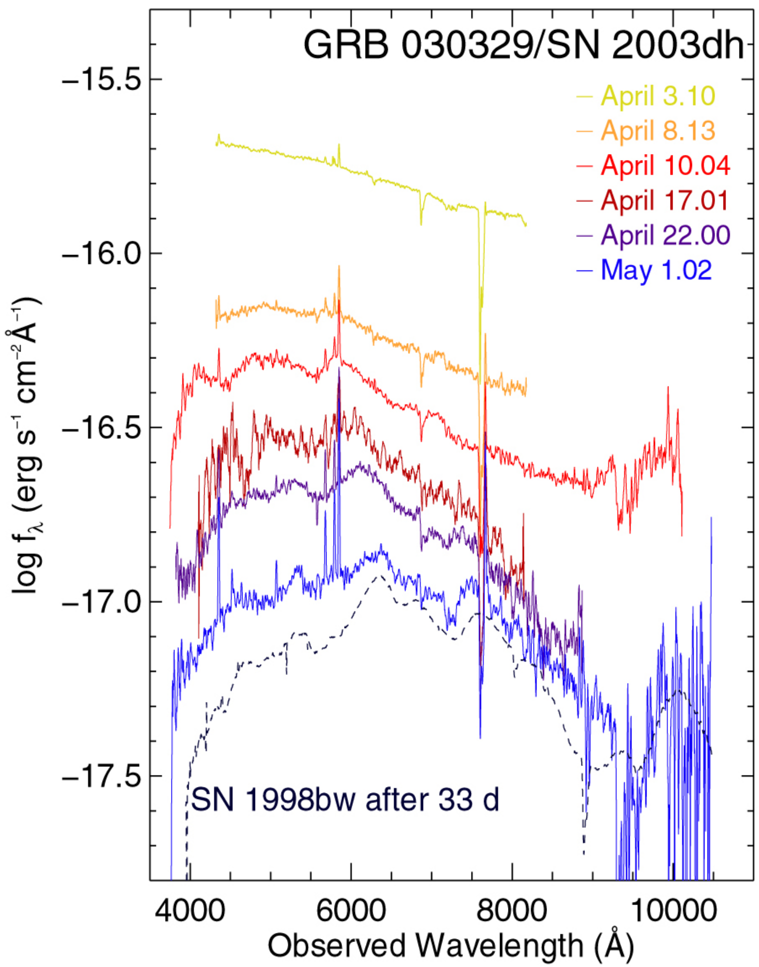
antitative, future observations
urement to be made of the prompt,
incident at the Earth over an
nt is not now attainable with any
launch of the NASA GLAST mission

high-energy sources have
, as measured with VLF
re v.331, p.418, 1988); XRF
er-flare from SGR 1900+14 (Inan,
999).

The AAVSO SID-GRB network is a worldwide network of observers monitoring VLF and LF beacons for SIDs of non-solar origin. The AAVSO Solar Committee has been monitoring and reporting solar-induced SIDs since the 1950's. This group intends to continue and expand this monitoring network.

GRB 030329 optical afterglow and SN

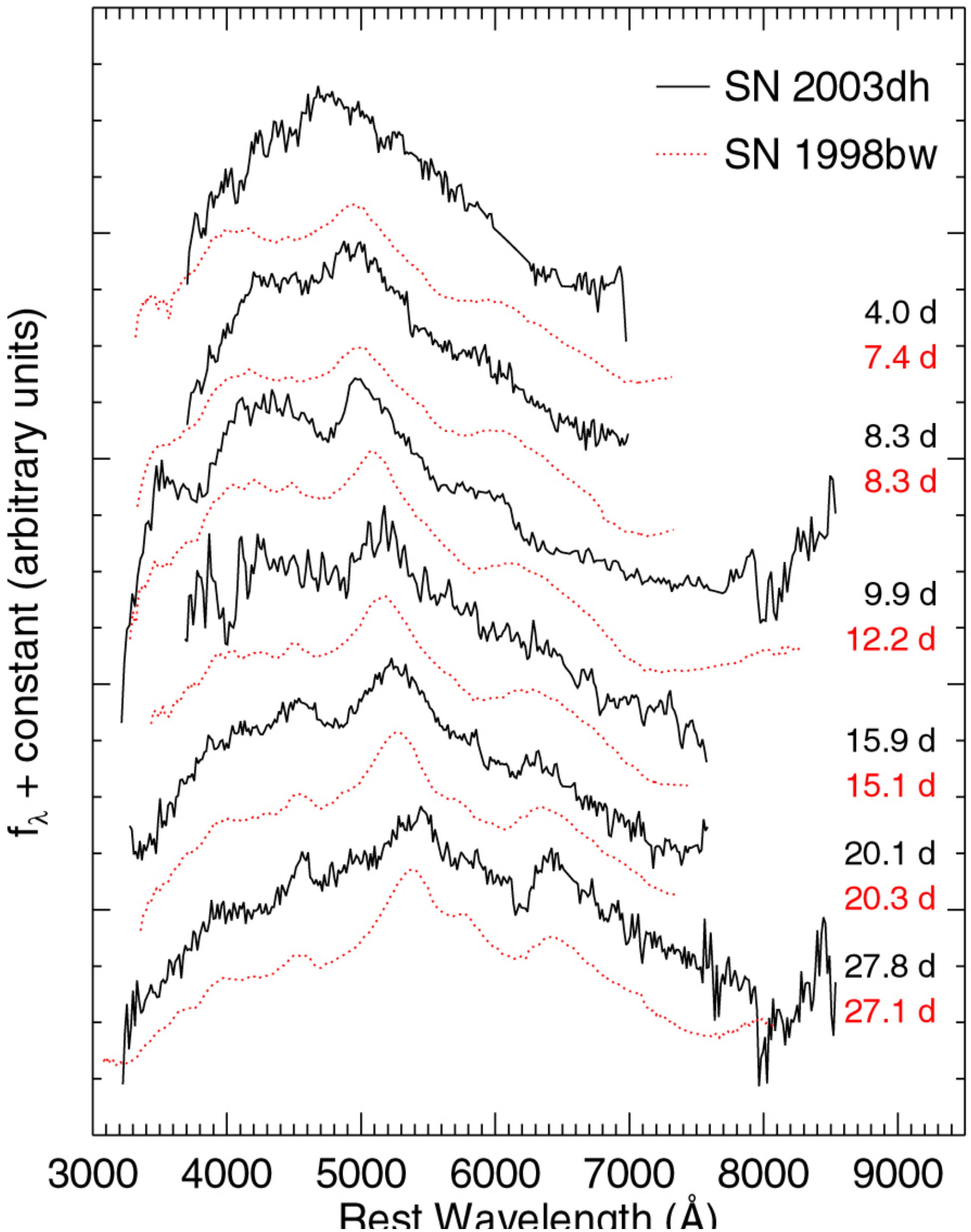




Redshift: z=0.1685 (0.810 Gpc).

Afterglow: very bright X-ray/optical/radio

SN 2003dh/GRB030329



Very similar to SN1998bw:

-broad lines → large Expansion velocity

- type Ic (no H or He abs.)
- very bright
- "Hypernova"

→ Progenitor Wolf Rayet star ("envelope stripped").

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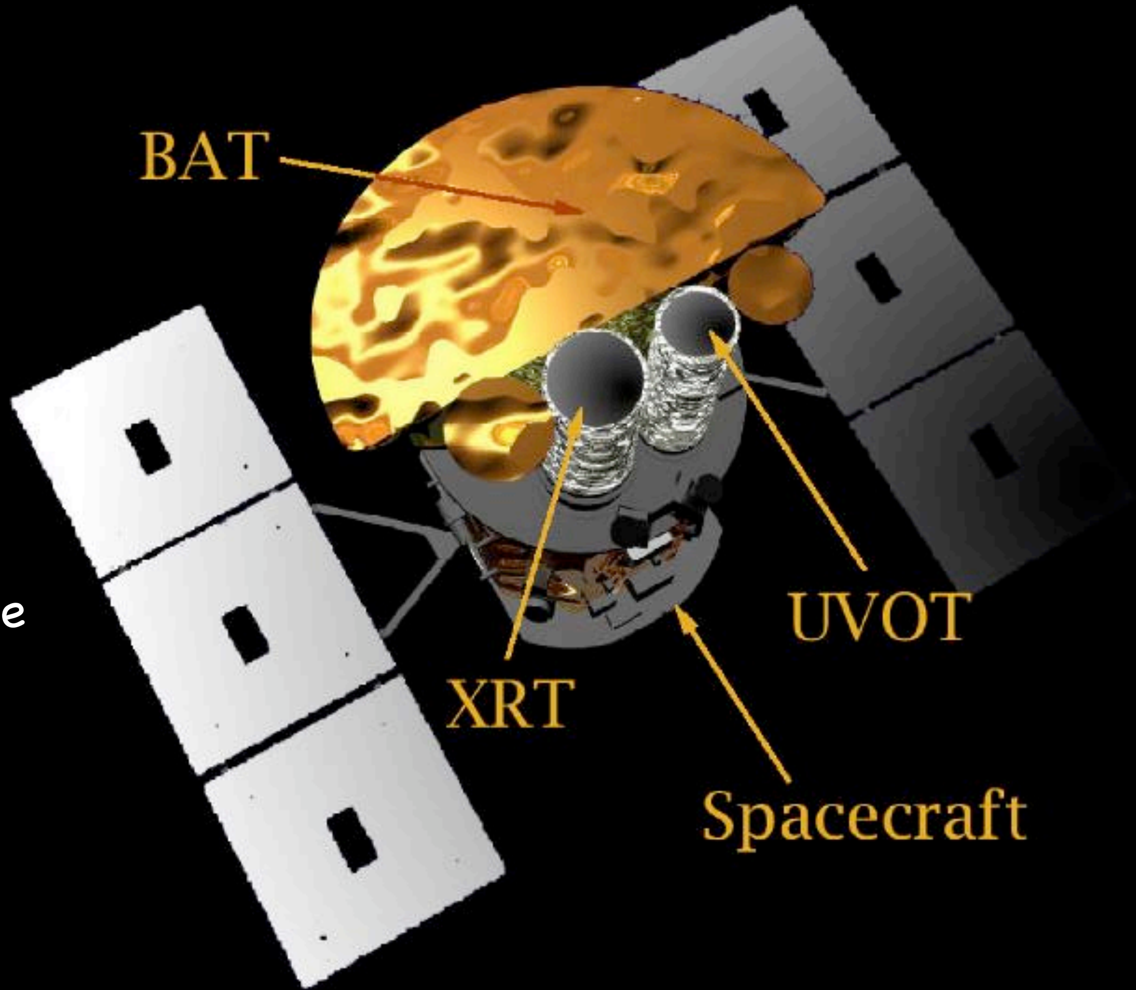
The *Swift* Era (November 2004 –)

- Detections (1 per week)
- More precise positions
 BAT: 1–3 arcmin / 100%
 XRT: 2–6 arcsec / >90%
 UVOT: <1 arcsec / 30%
- More rapid (few sec after the bursts)



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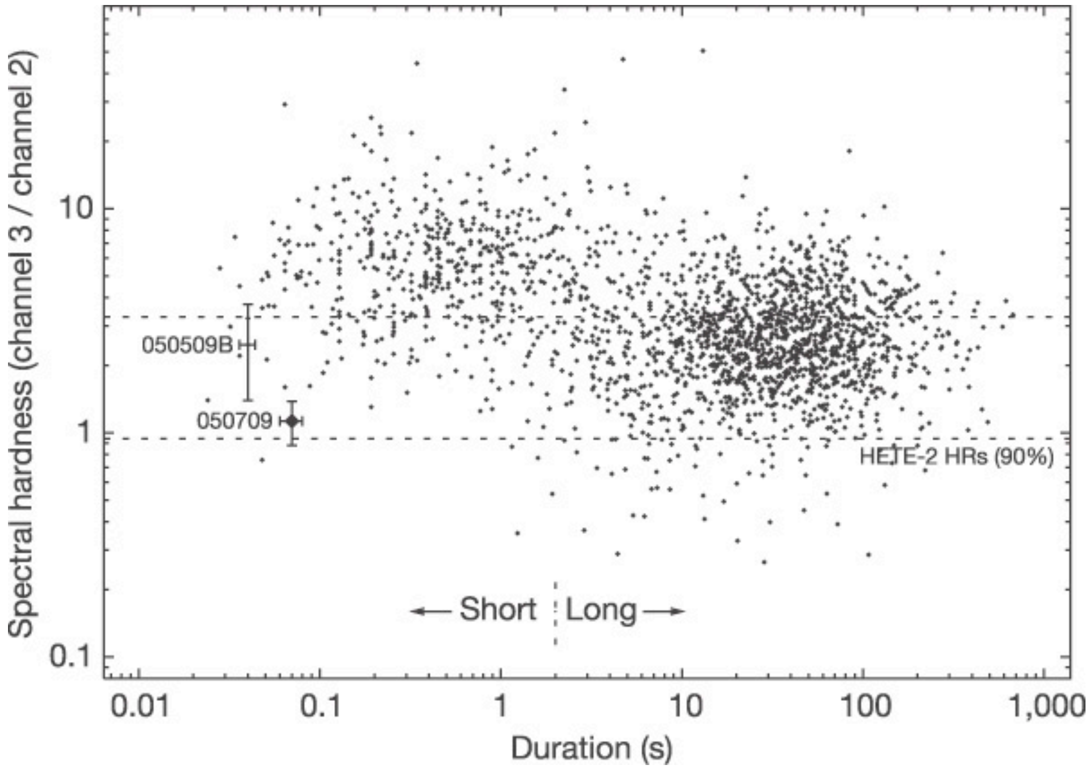
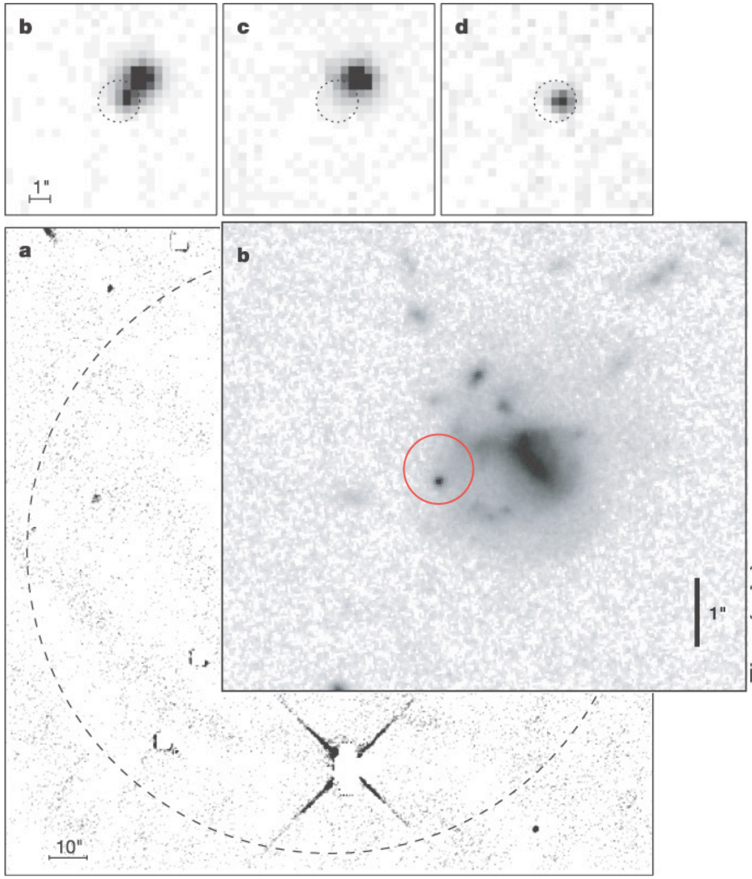
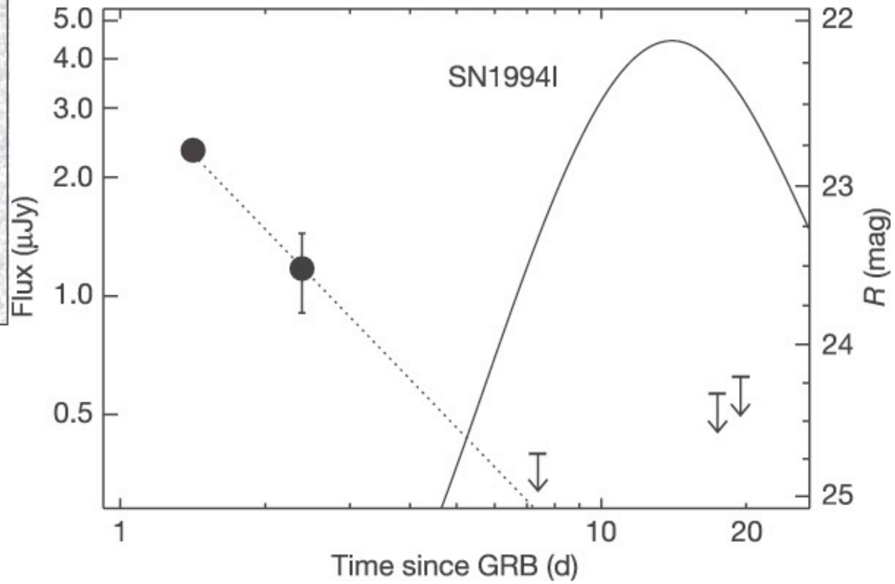
Short vs. Long GRBs



First Optical Afterglow



- Optical afterglow
- Near a z = 0.16 galaxy
- No associated SN



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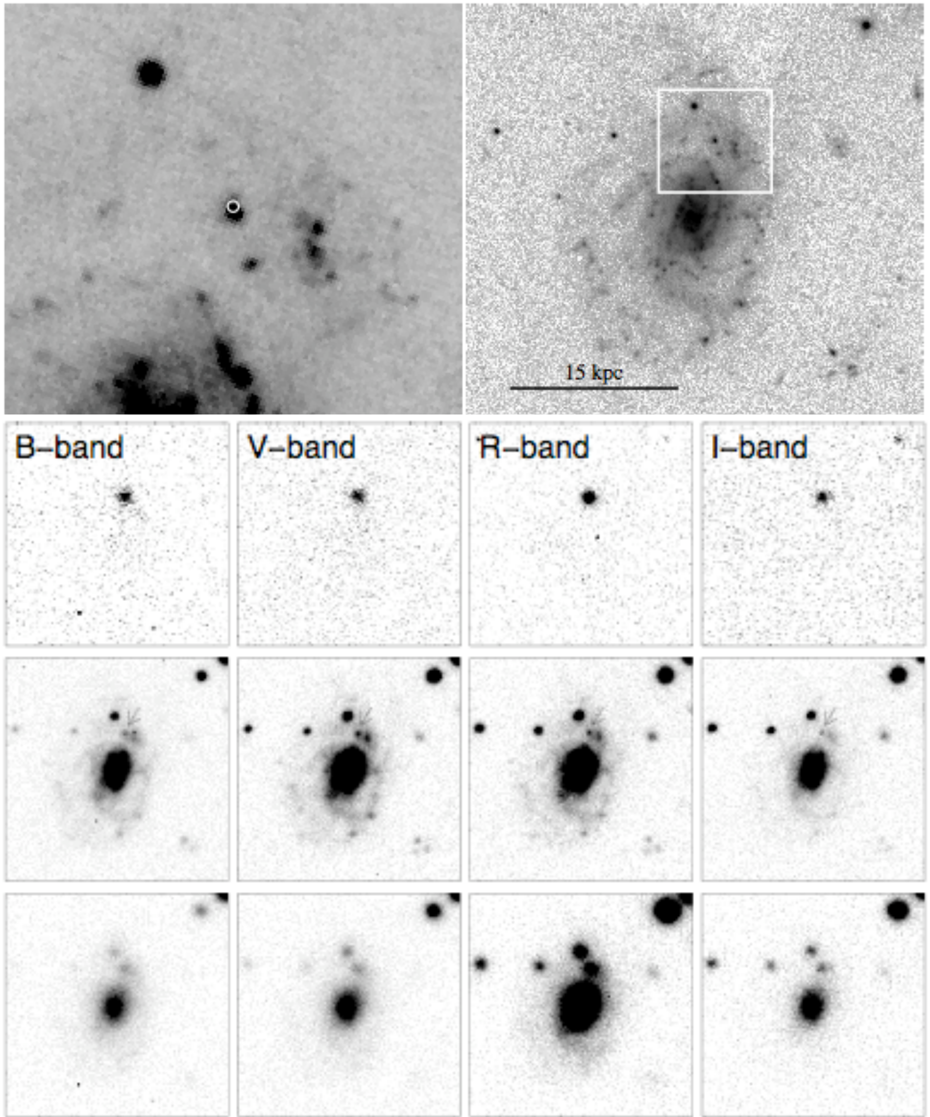
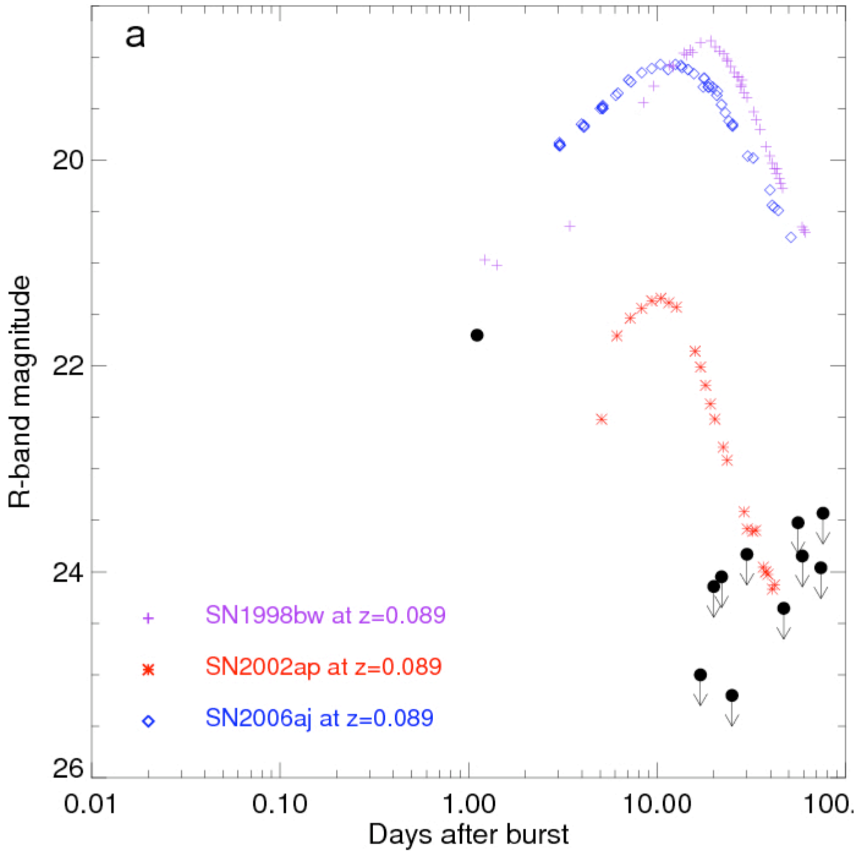
GRB060505: Can massive stars die without supernova-explosions?





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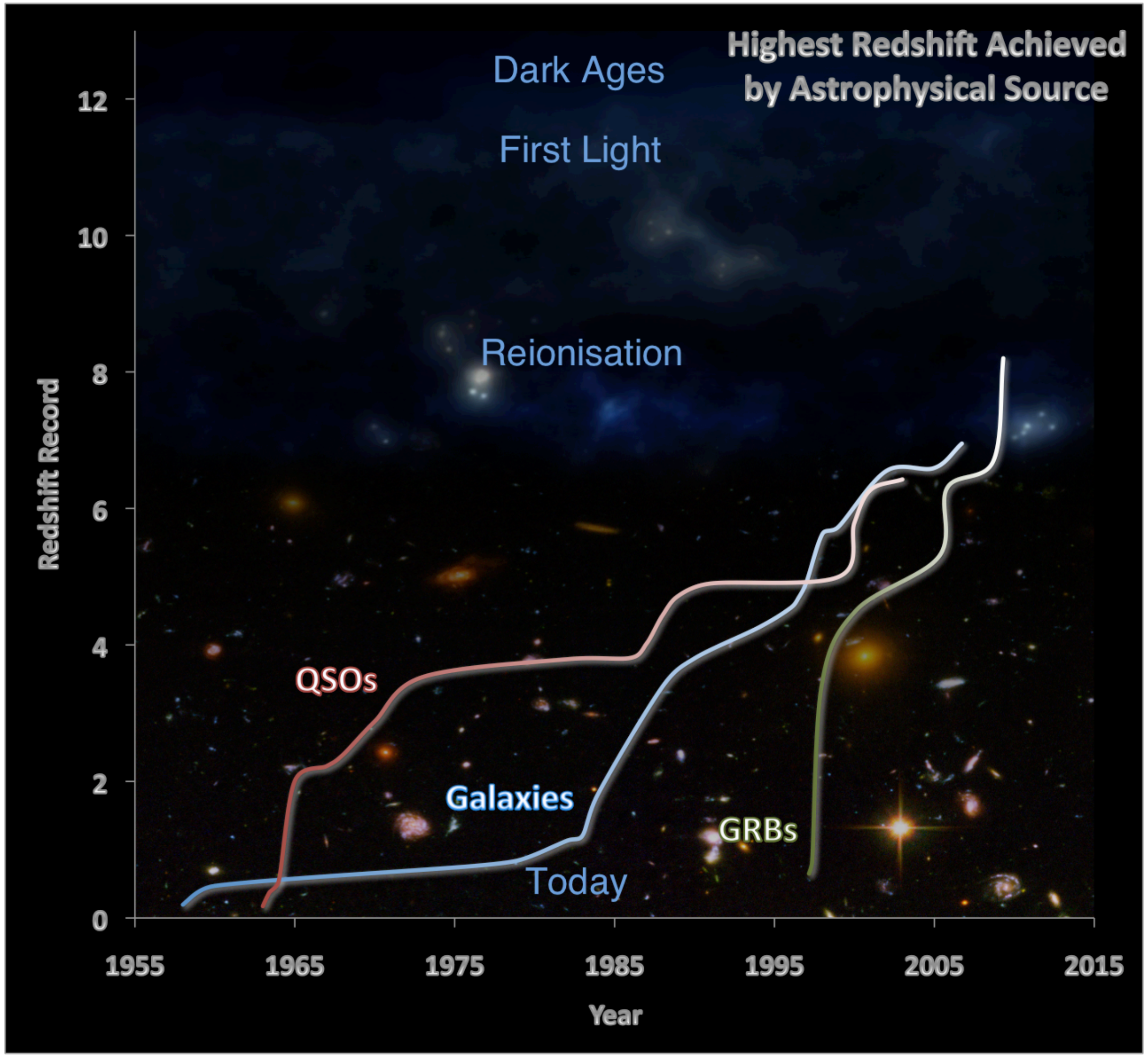
GRBs reach into Reionisation



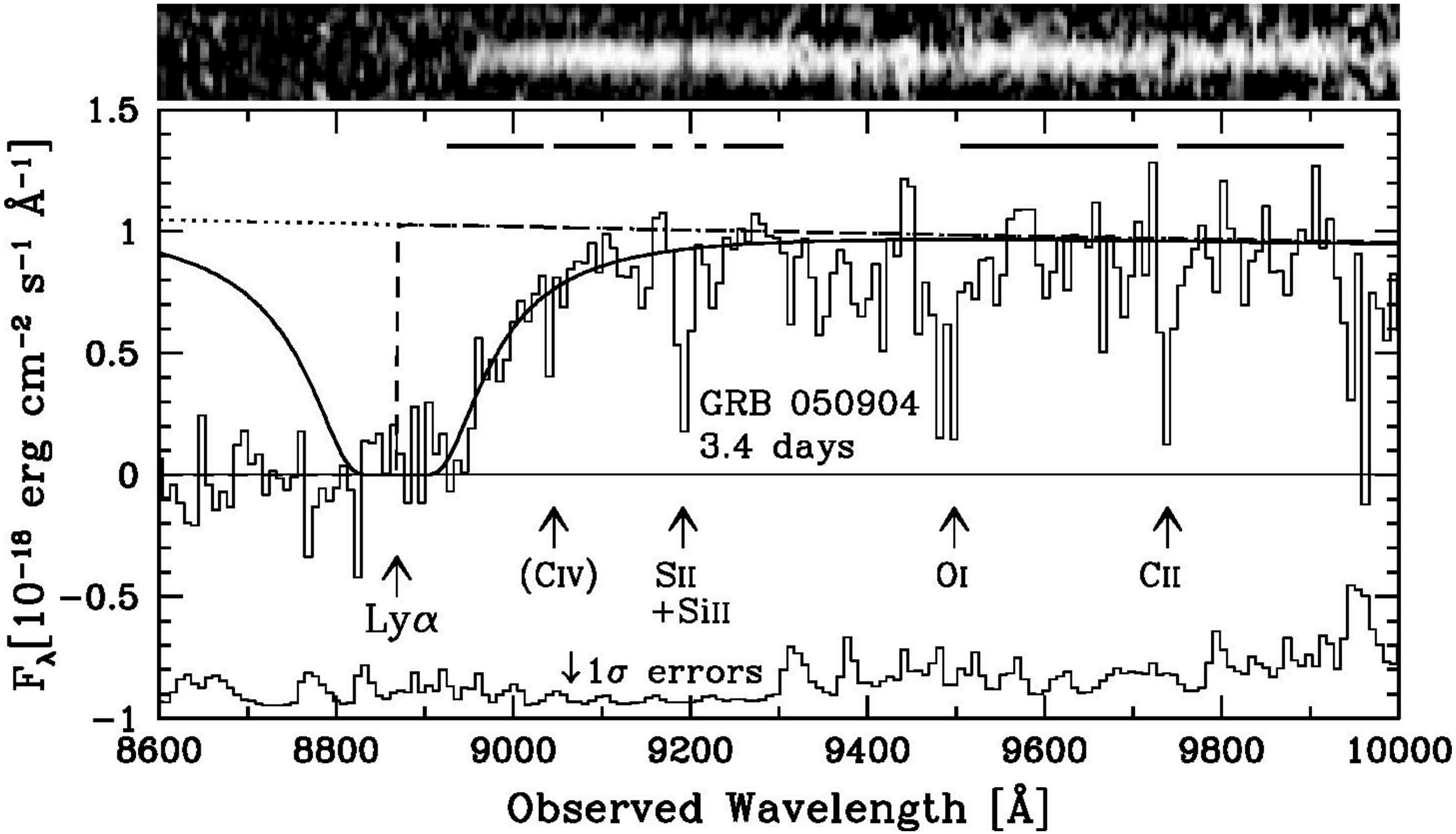
GRB Redshift Record Holders

- $z = 6.3$ (GRB 050904)
- $z = 6.7$ (GRB 080913)
- $z = 8.3$ (GRB 090423)

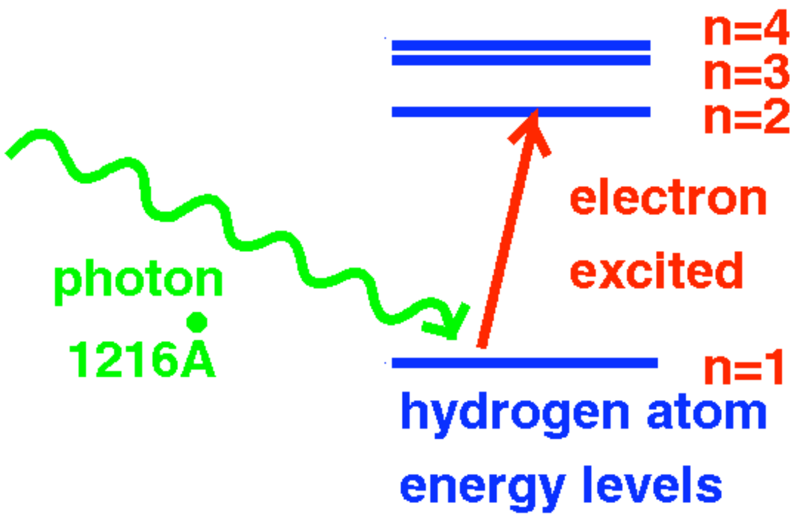
Most distant galaxy, $z = 6.96$

GRB050904

z=6.30, 860 Mio yr after BB

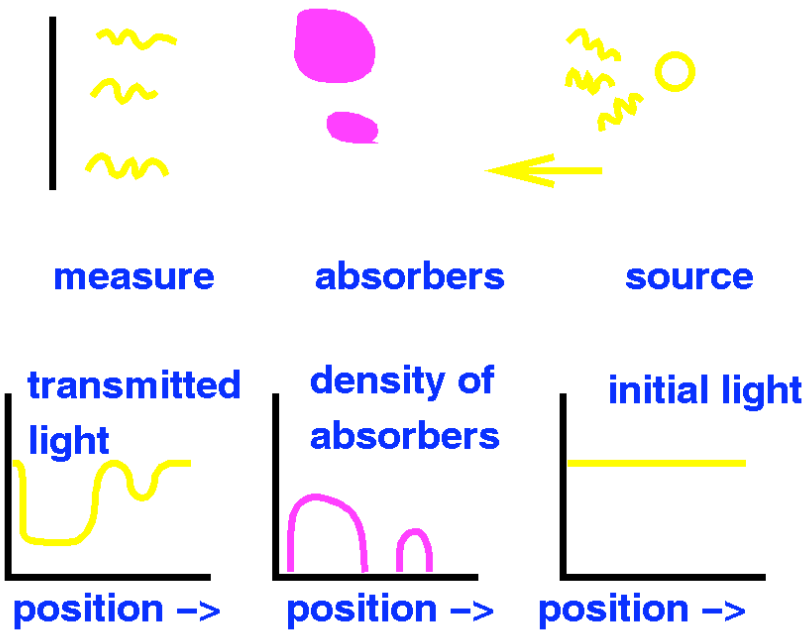


Lyman-alfa skoven

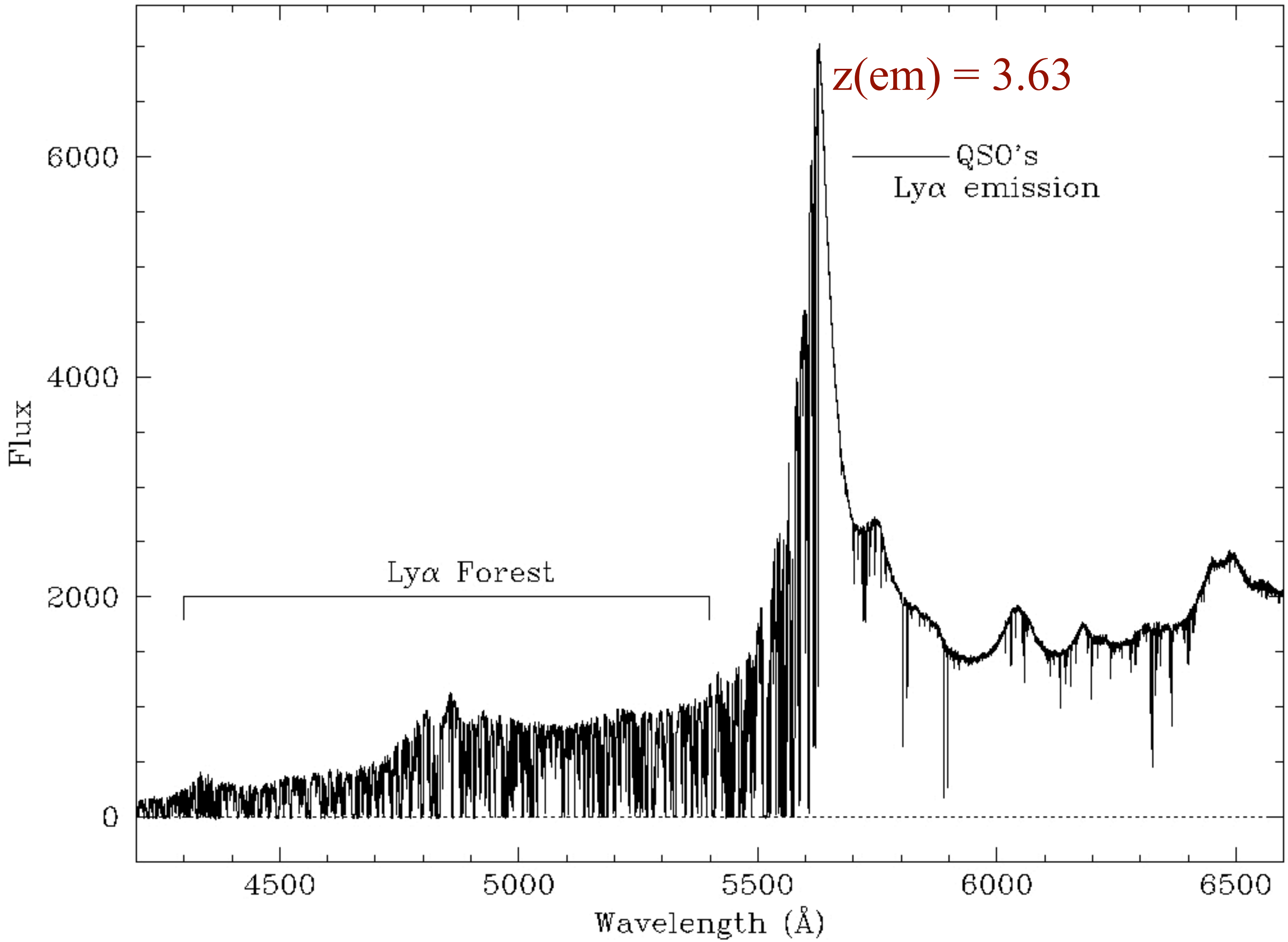


- Lyman-alfa absorption: en foton med bølgelængde 1216Å exiterer en elektron fra grundtilstanden til første exiterede niveau i brint.
- Dette er den stærkeste overgang i brint, og brint er langt det hyppigste grundstof i universet.

Lyman-alfa skoven

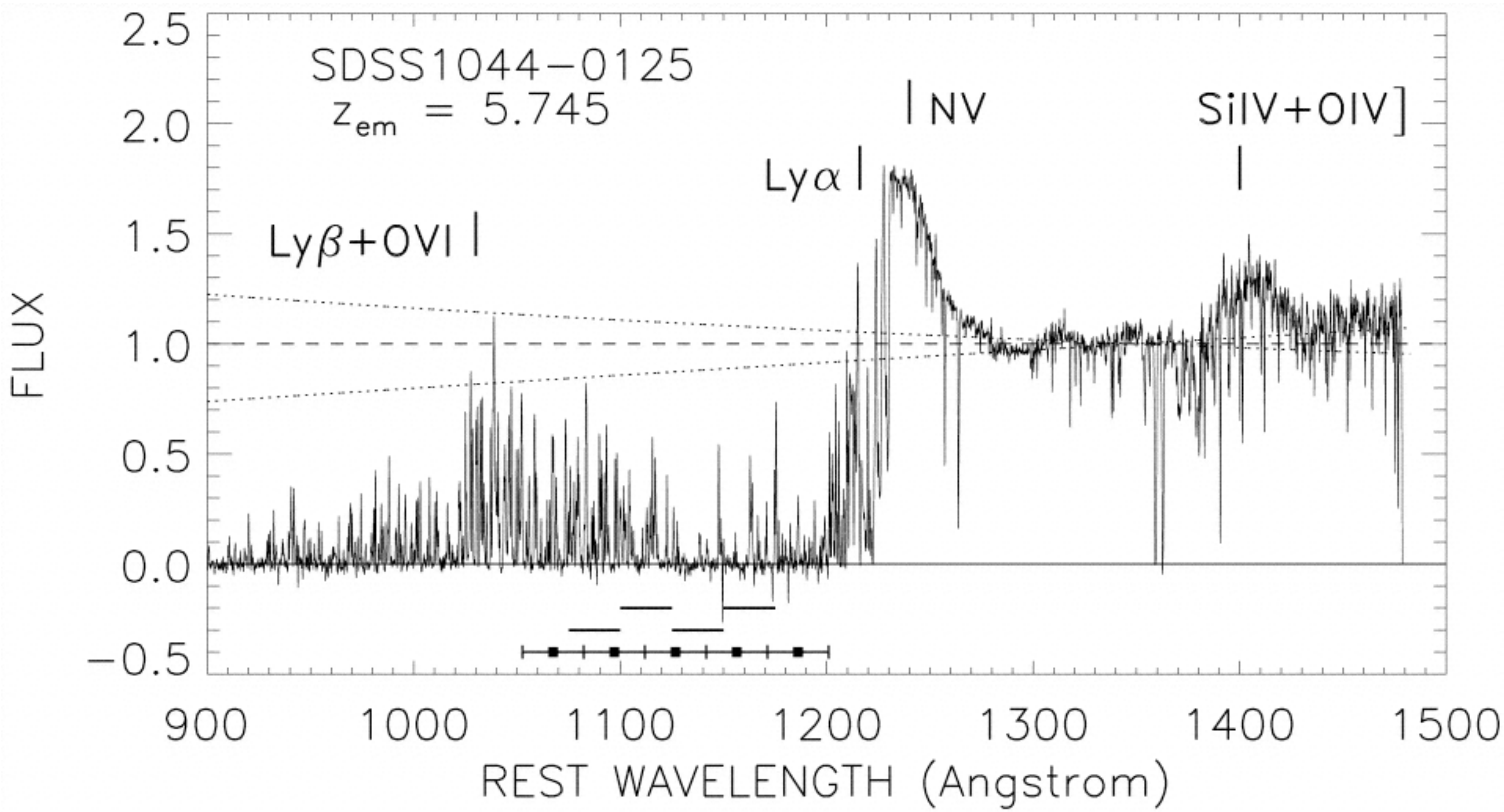


- Alle brintskyer mellem en fjern kvasar og jorden giver anledning til en absorptionslinie.
- En sky ved rødforskydning z absorbere ved (1+z)*1216Å.
- Da z<z(kvasar) ligger alle disse absorptionslinier på den blå side af kvasarens Lyman-alfa emissionslinie.

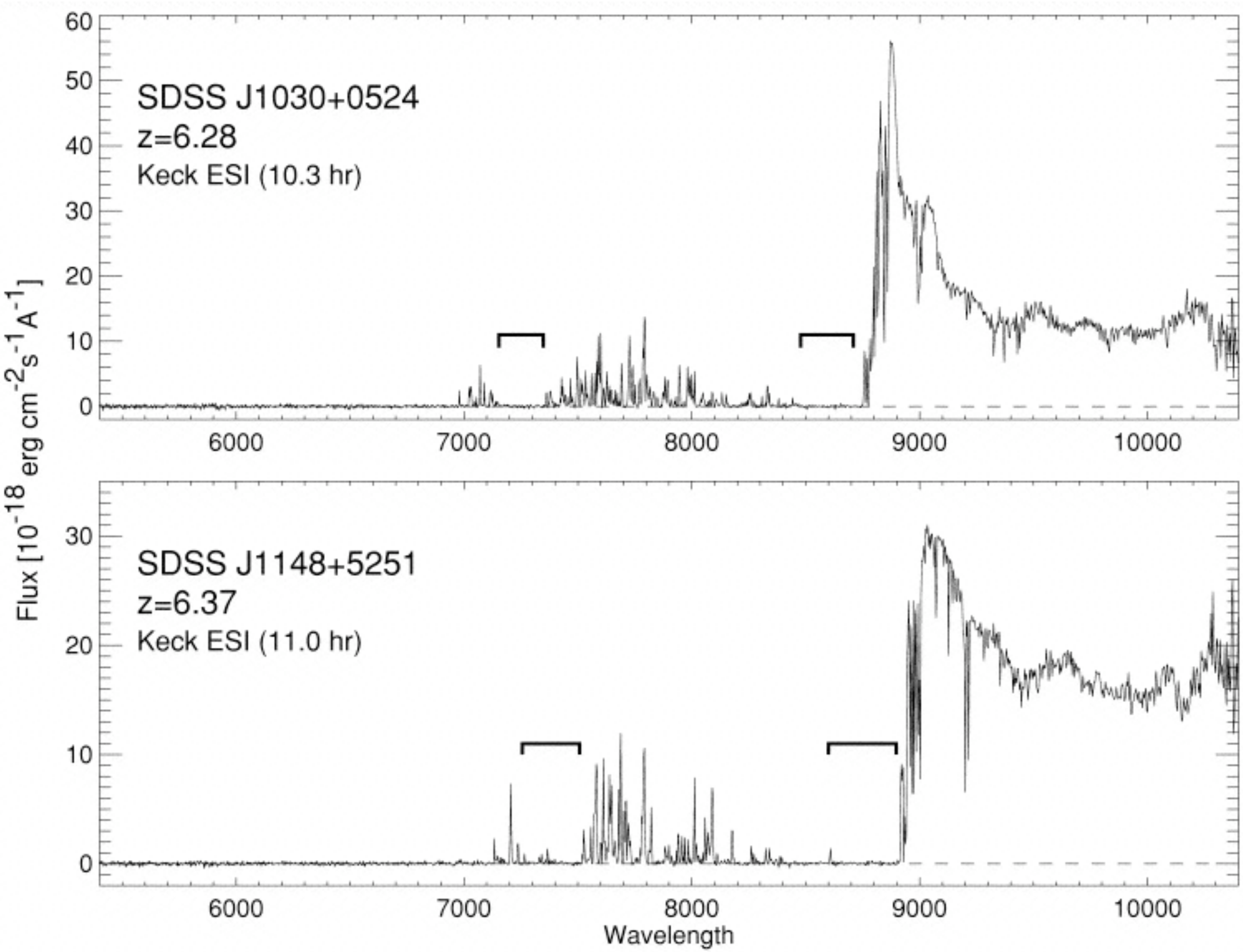


z(em) = 3.63
QSO's
Lyα emission
Lyα Forest
6000
4000
2000
0
Flux
4500
5000
5500
6000
6500
Wavelength (Å)

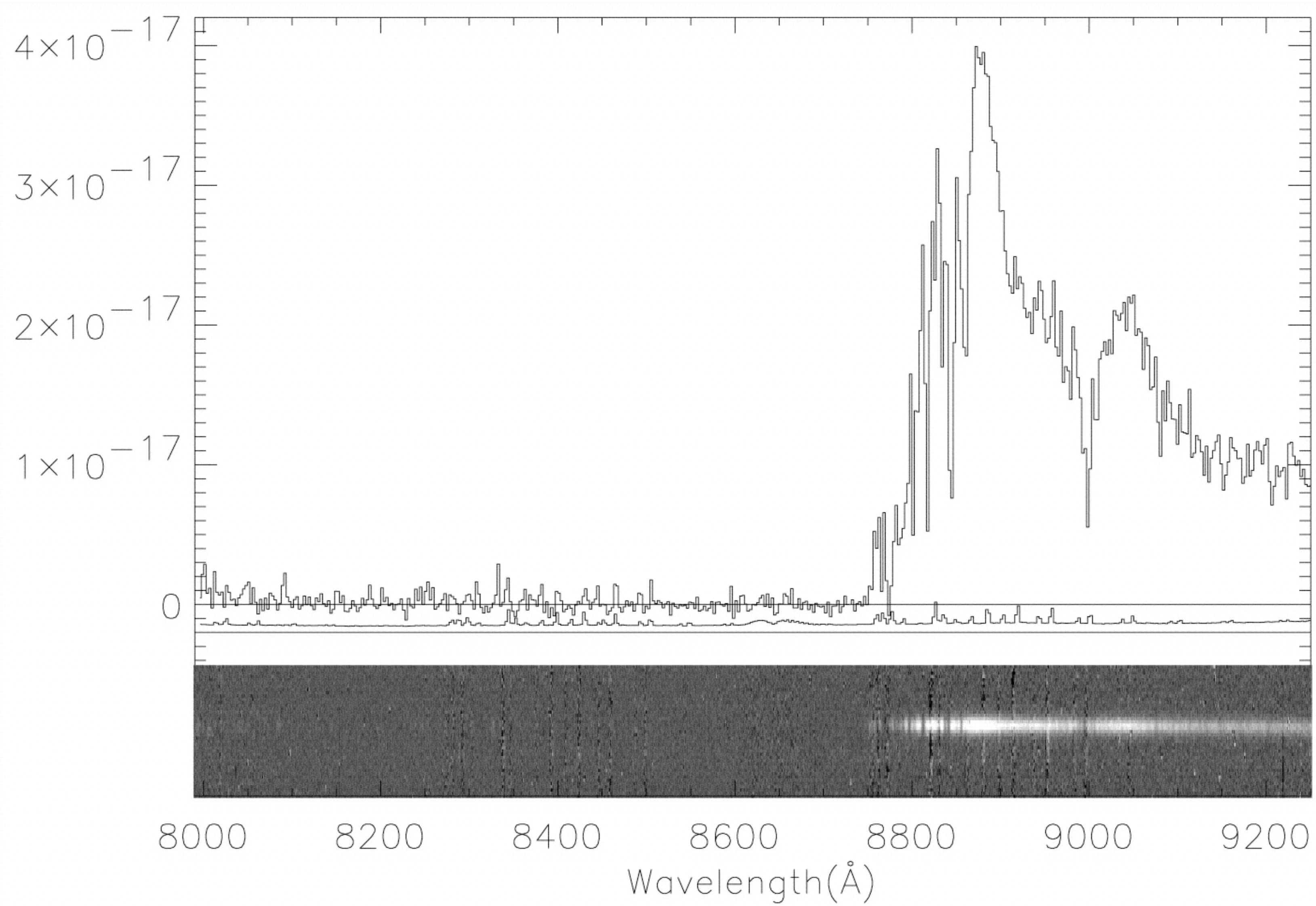
z(em) = 5.745



SDSS1044−0125
z_{em} = 5.745
Lyβ+OVI
Lyα
NV
SiIV+OIV]
FLUX
REST WAVELENGTH (Angstrom)
2.5
2.0
1.5
1.0
0.5
0.0
−0.5
900
1000
1100
1200
1300
1400
1500


SDSS J1030+0524
z=6.28
Keck ESI (10.3 hr)
SDSS J1148+5251
z=6.37
Keck ESI (11.0 hr)
Flux [10^-18 erg cm^-2 s^-1 A^-1]
Wavelength
6000
7000
8000
9000
10000
0
10
20
30
40
50
60

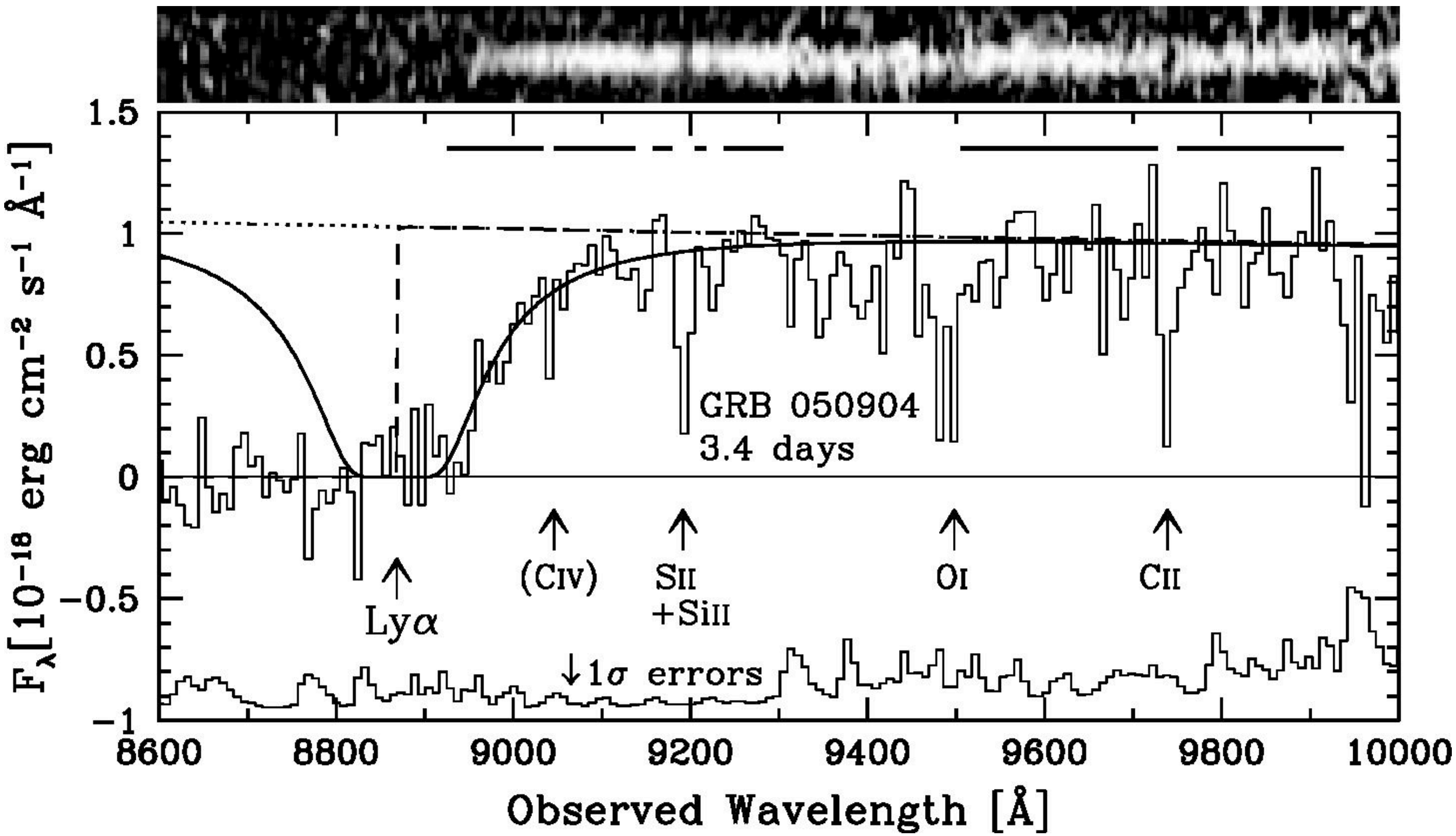
z(em) = 6.28

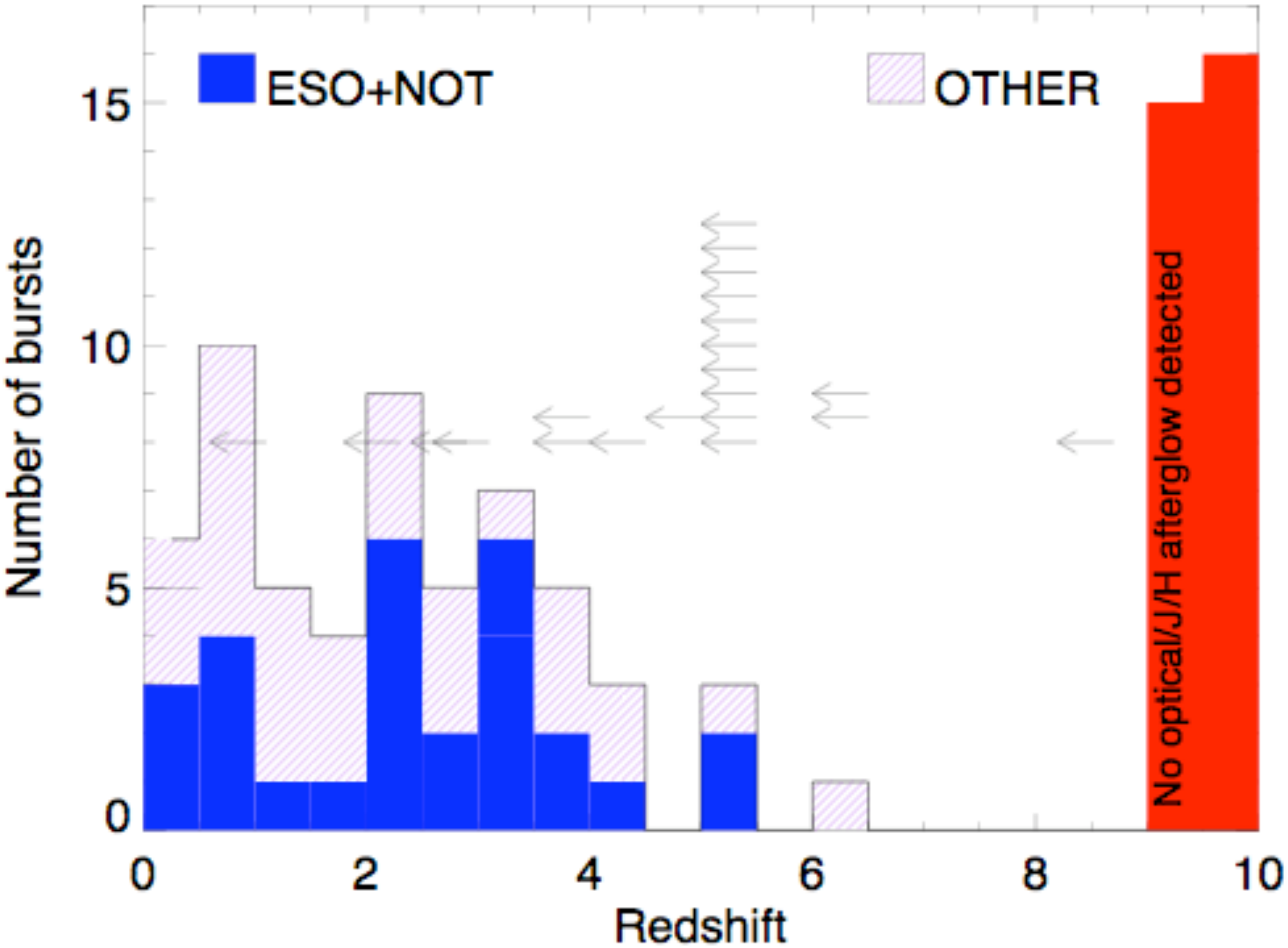


4×10⁻¹⁷
3×10⁻¹⁷
2×10⁻¹⁷
1×10⁻¹⁷
0
8000
8200
8400
8600
8800
9000
9200
Wavelength(Å)

GRB050904: det fjernest glimt

z=6.30, 860 Mio år efter BB, >12 Mia år “tilbageblik”





ESO+NOT
OTHER
No optical/J/H afterglow detected
Number of bursts
Redshift
0
5
10
15
0
2
4
6
8
10

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