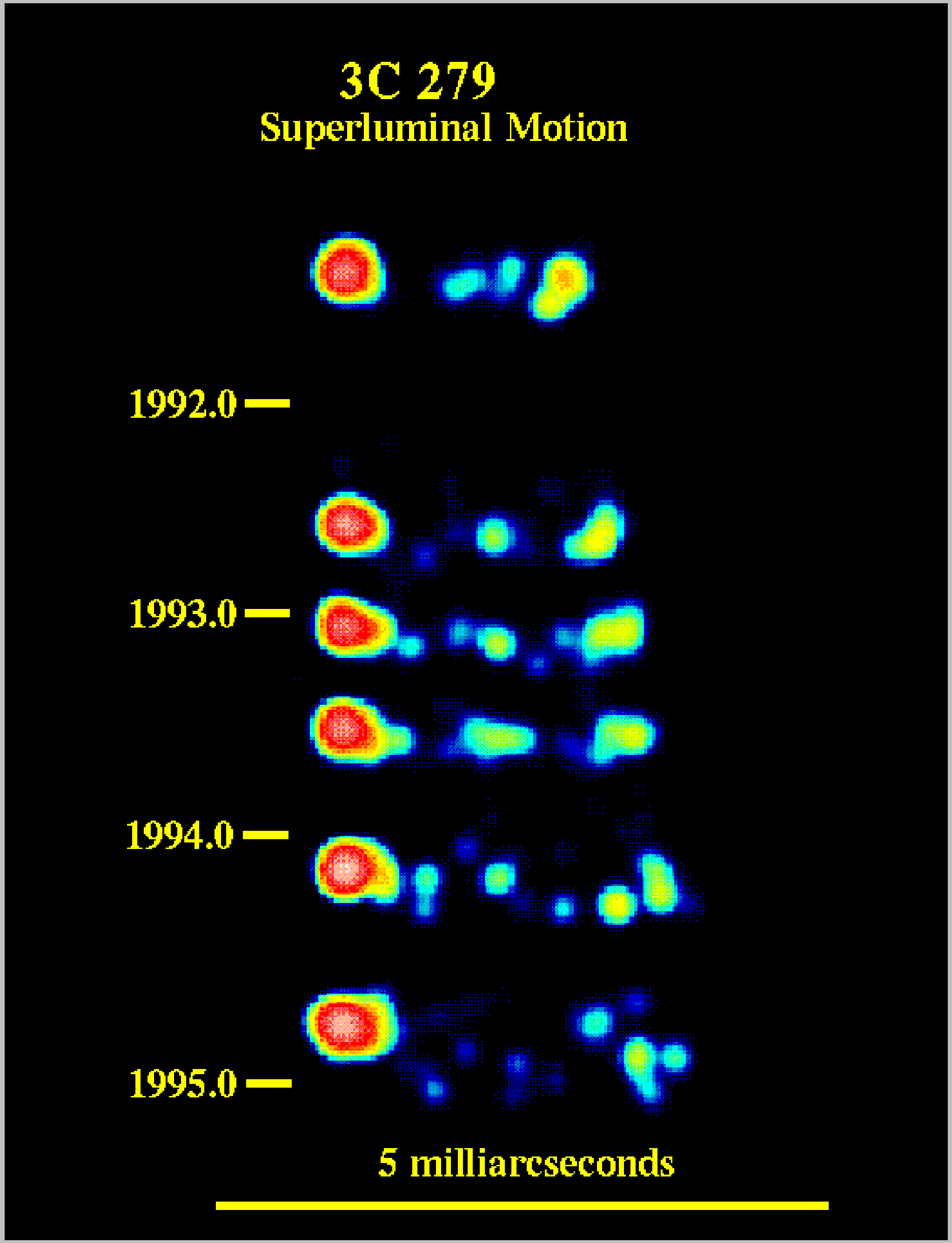
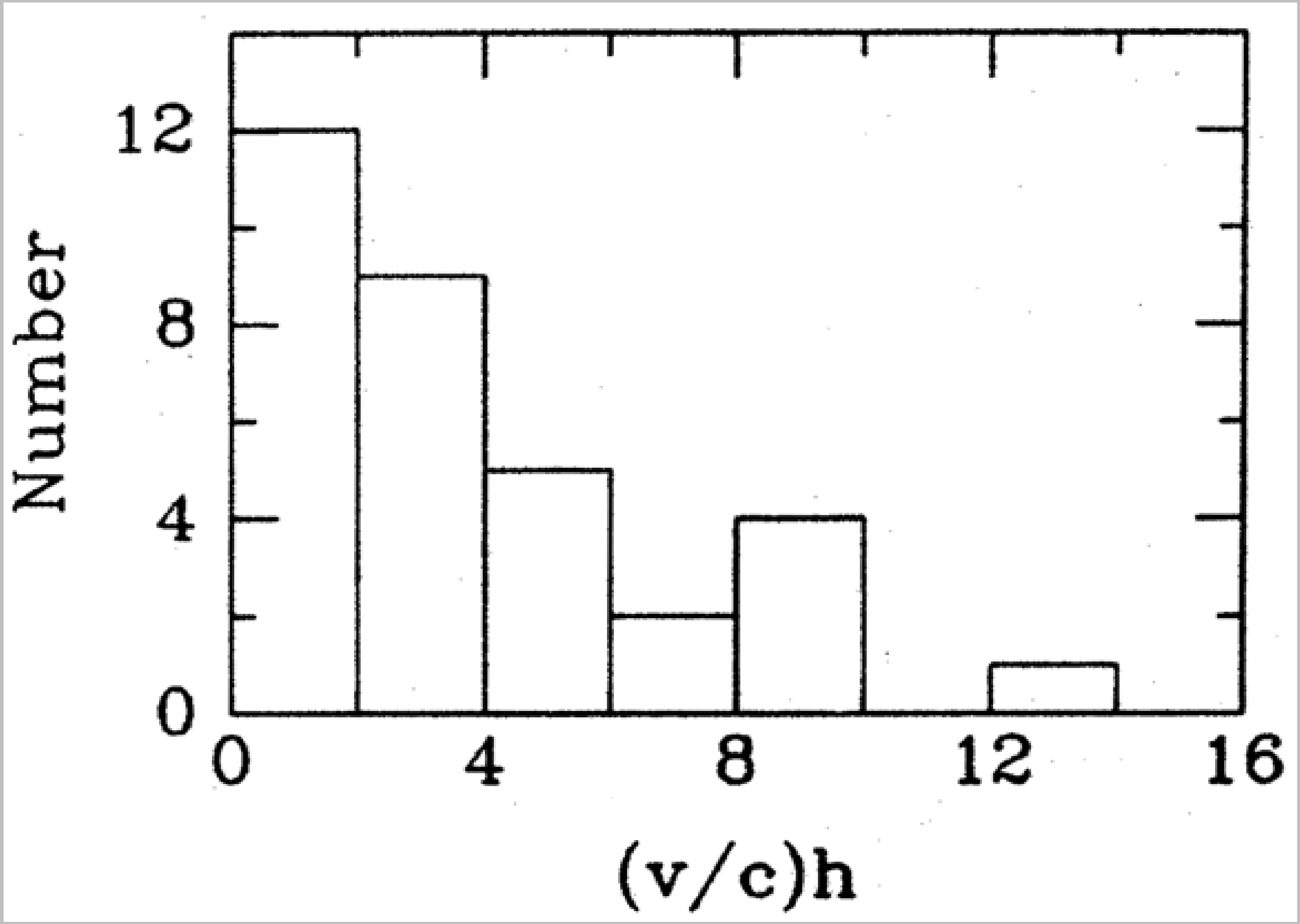
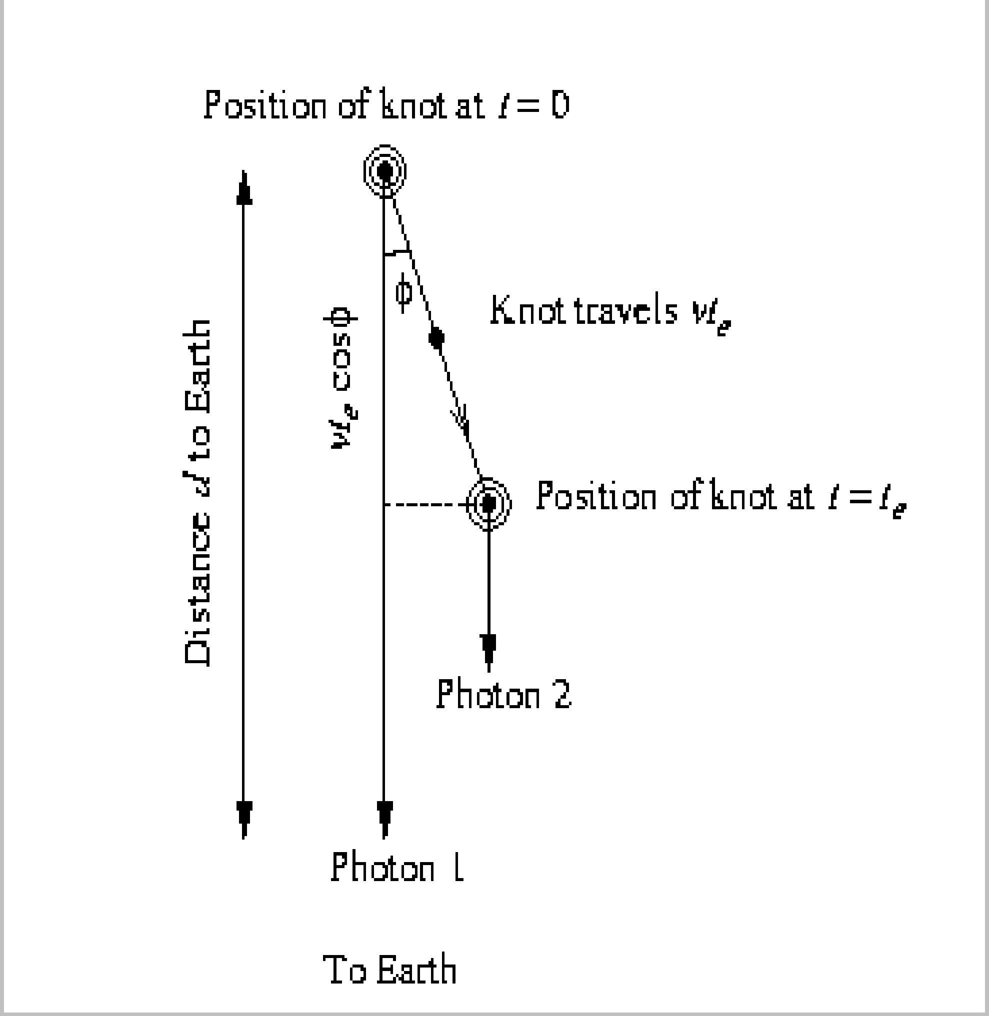


Measuring the apparent motion of the “blobs” gives you v ~ 4c
New Physics??



V/C for a sample of 33 jets

Superluminal Motion



The knots are moving towards us at an angle ϕ measured from the line of sight.

A photon emitted along the line of sight at time t=0, travels a distance d to us, taking a time t_1 to arrive:
$t_1 = d/c$

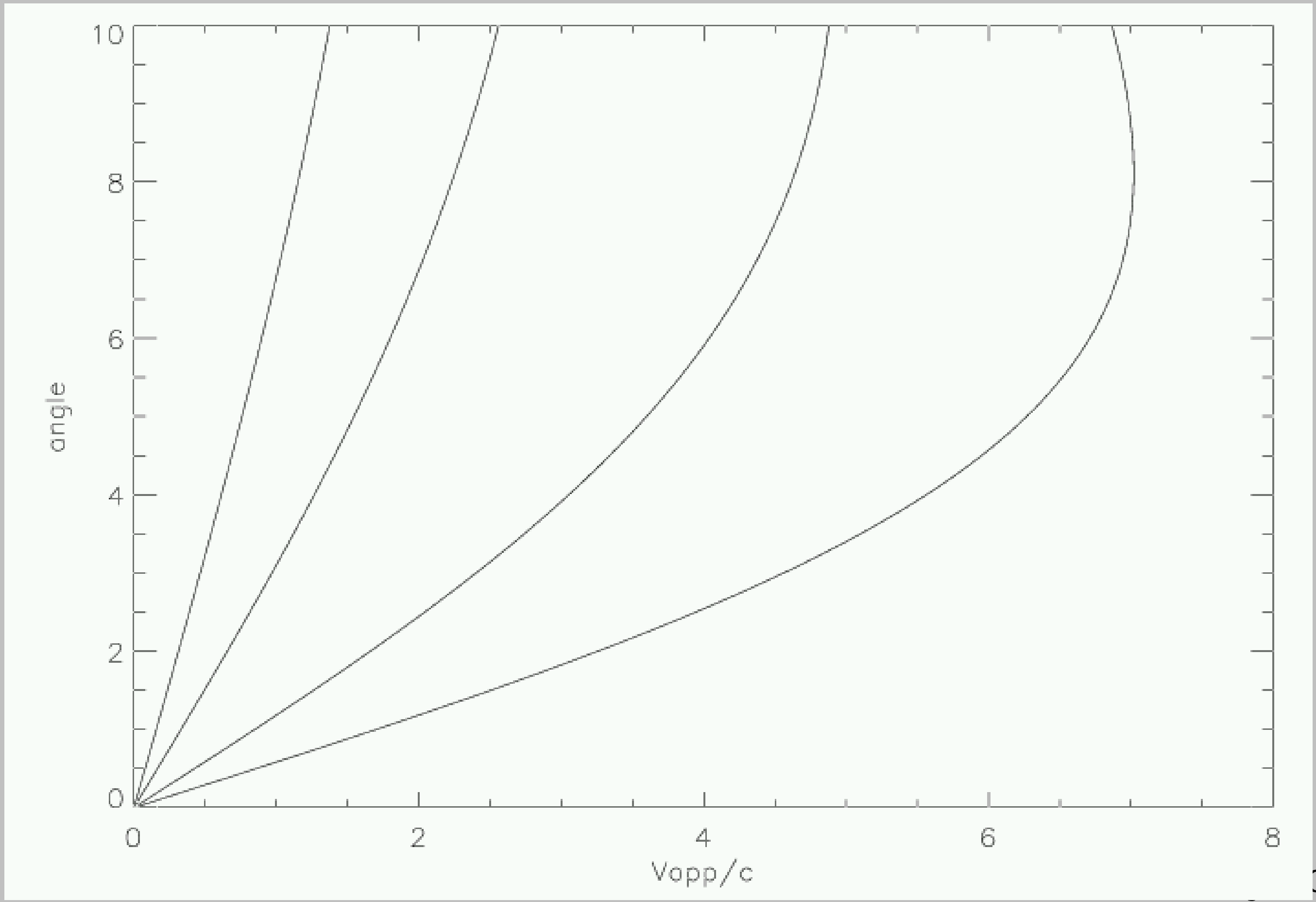
A second photon is emitted at a time t later, when the blob is a distance $d - vt\cos\phi$ away from us. The second photon arrives at $t_2 = t + (d - vt\cos\phi)/c$

The observed difference in the time of arrival from photon 1 & 2 is:
$\Delta t_{obs} = t_2 - t_1 = \Delta t\,(1 - v\cos\phi/c) < \Delta t$

Superluminal Motion

The apparent transverse velocity is

$$V_{app} = vT_e \sin(\phi)/ \Delta t$$
$$= v \sin(\phi)/(1-v\cos(\phi)/c) \text{ let } \beta=v/c$$
$$= \beta c \sin(\phi)/\{1-\beta\cos(\phi)\}$$



Superluminal Motion cont.

Let $\gamma = 1/(1- v^2/c^2)^{1/2}$, this is the Lorentz factor. Then: $v_{app} \leq \gamma v$ (the maximum observed velocity) which occurs when $\cos\phi = v/c$. We will only observe superluminal motion when the jets are pointed within an angle of $1/\gamma$ towards the line of sight.

This light will be beamed and brightened.

Superluminal Motion cont.

To a stationary observer, the “clocks” on the knot appear to run slow by a factor of γ, from before,

$\Delta t_{obs} = \Delta t\,(1 - v\cos\phi/c)$

$\Delta t_{obs} = \Delta t_e\,\gamma\,(1 - v\cos\phi/c)$

So the observed frequency of the light is

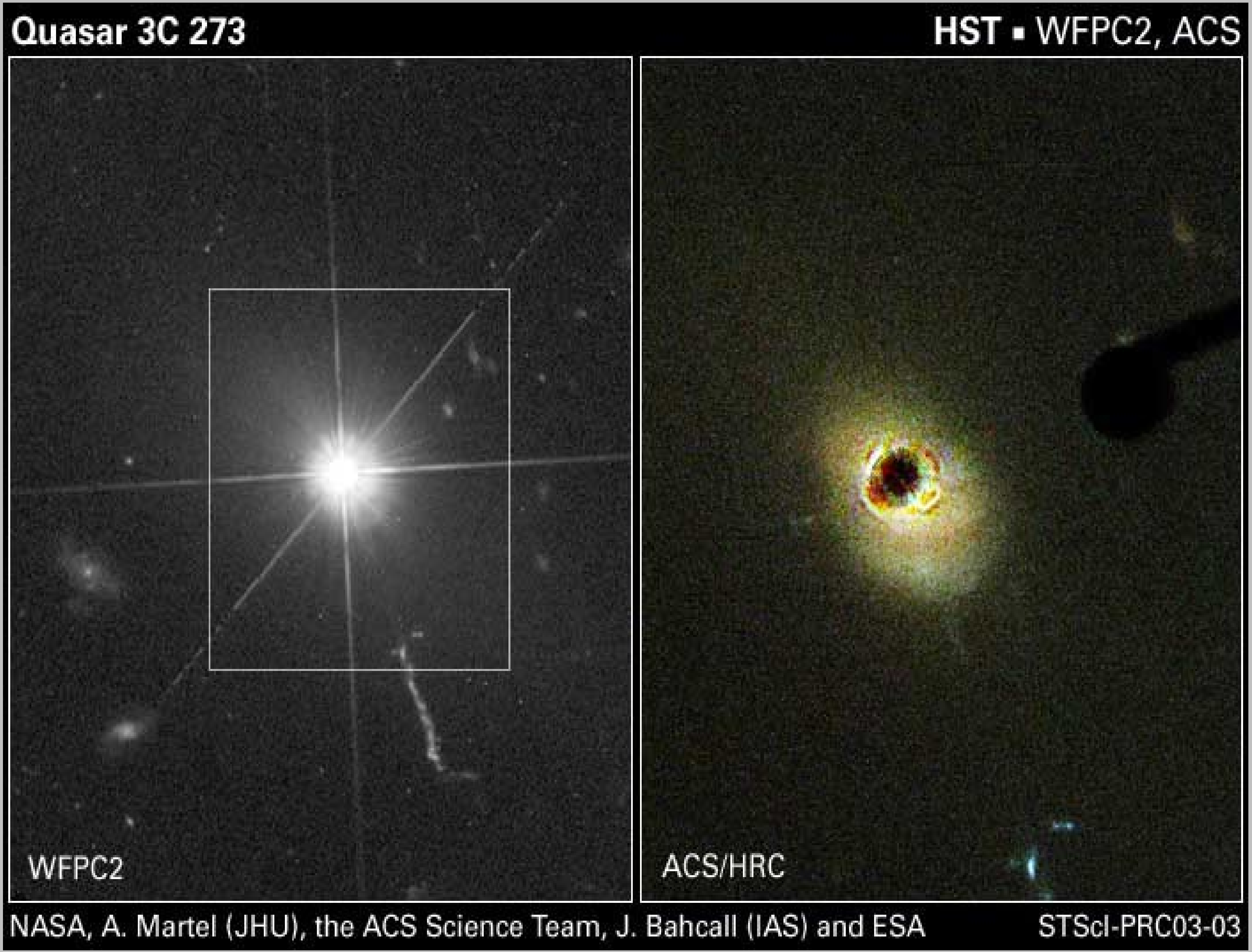
$\nu_{obs} = \nu_e[\gamma\,(1 - v\cos\phi/c)]^{-1}$

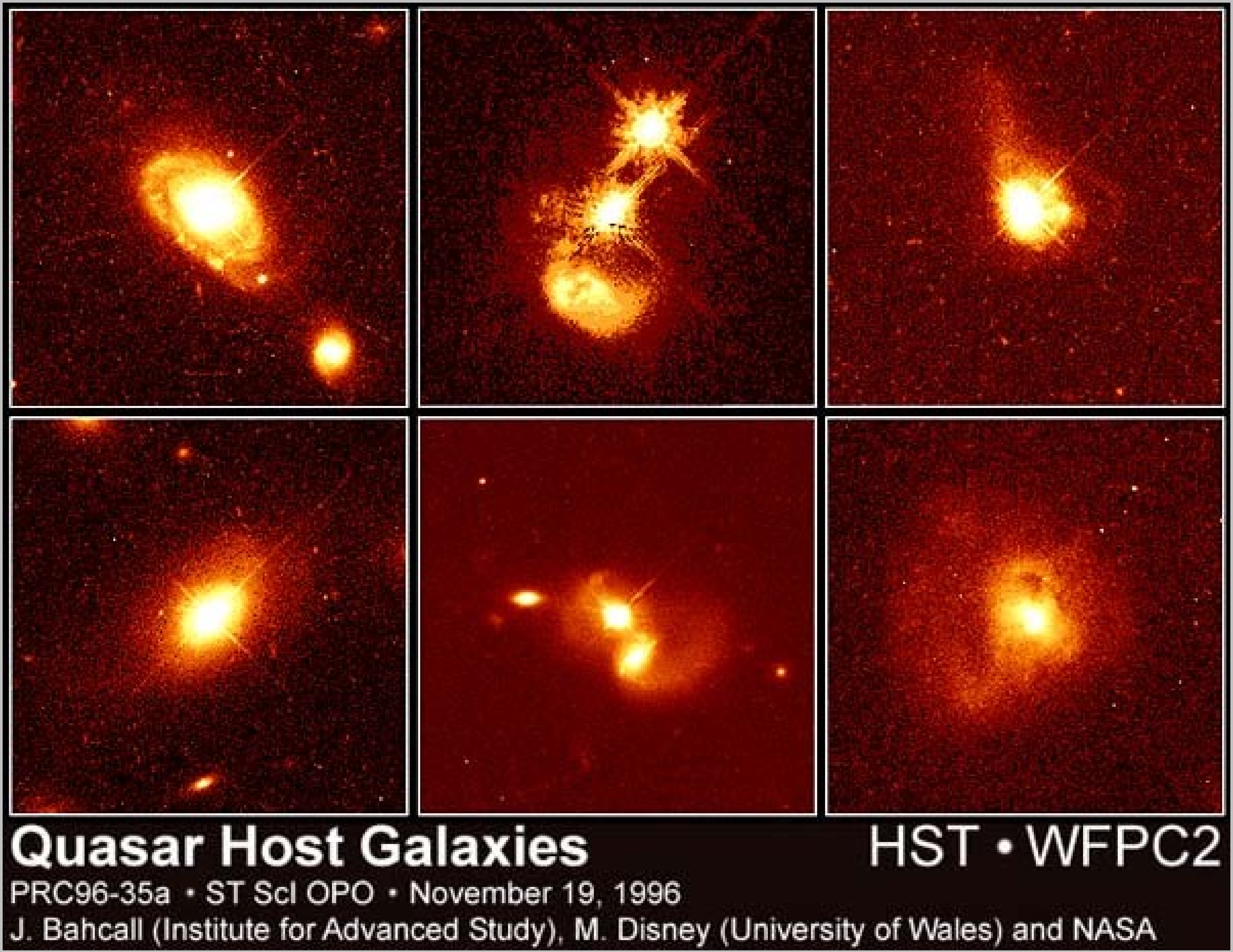
When $\gamma >> 1$, all the light is focused into a narrow cone of $\sin\phi = 1/\gamma \sim \phi$, and compressed in time by $\Delta t_{obs} = \Delta t_e / 2\gamma$. Thus the light will be brightened by a factor of $1/(2\gamma)^2$

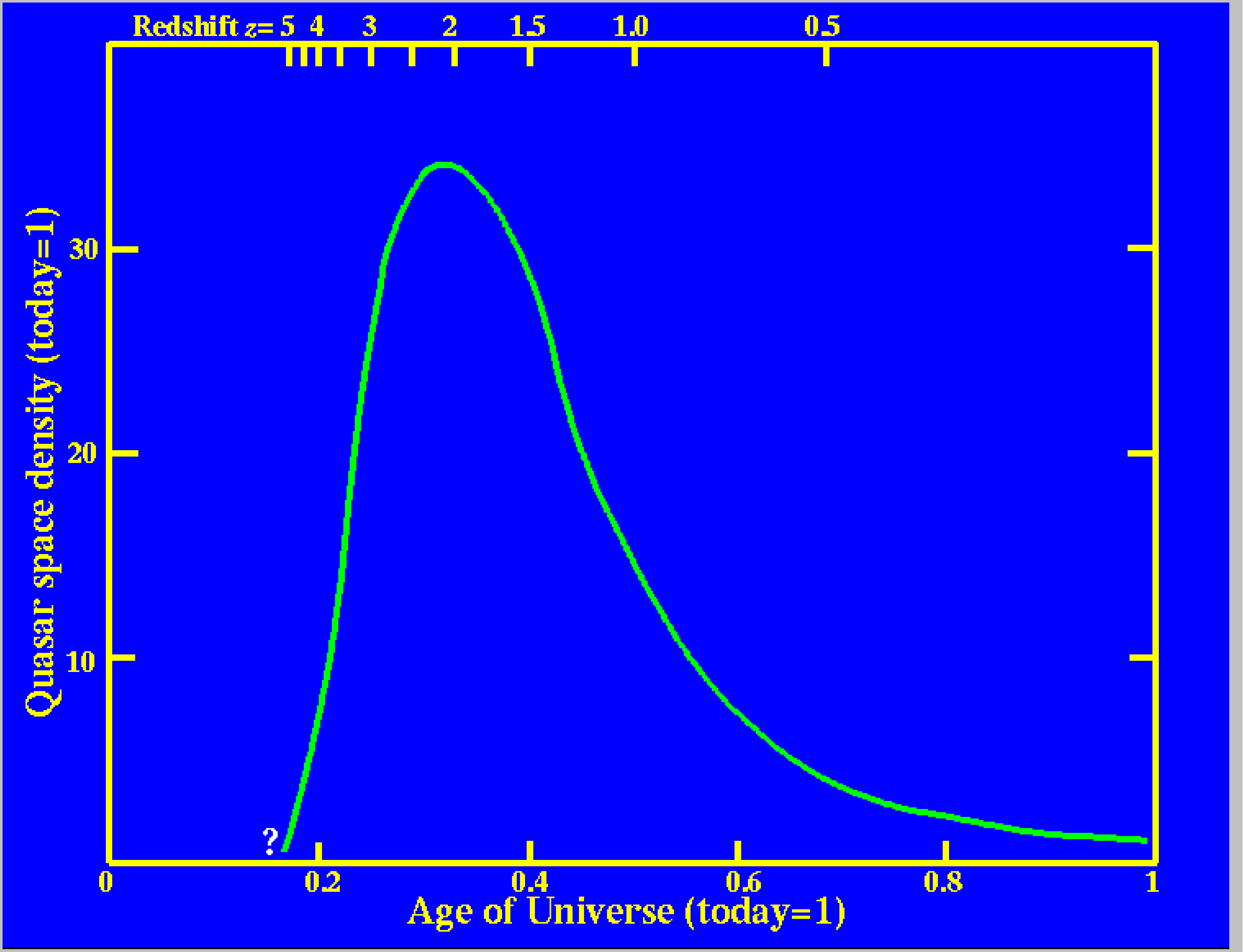
This explains why we usually only see one relativistic jet, the one being beamed towards us.

Quasar Host Galaxies

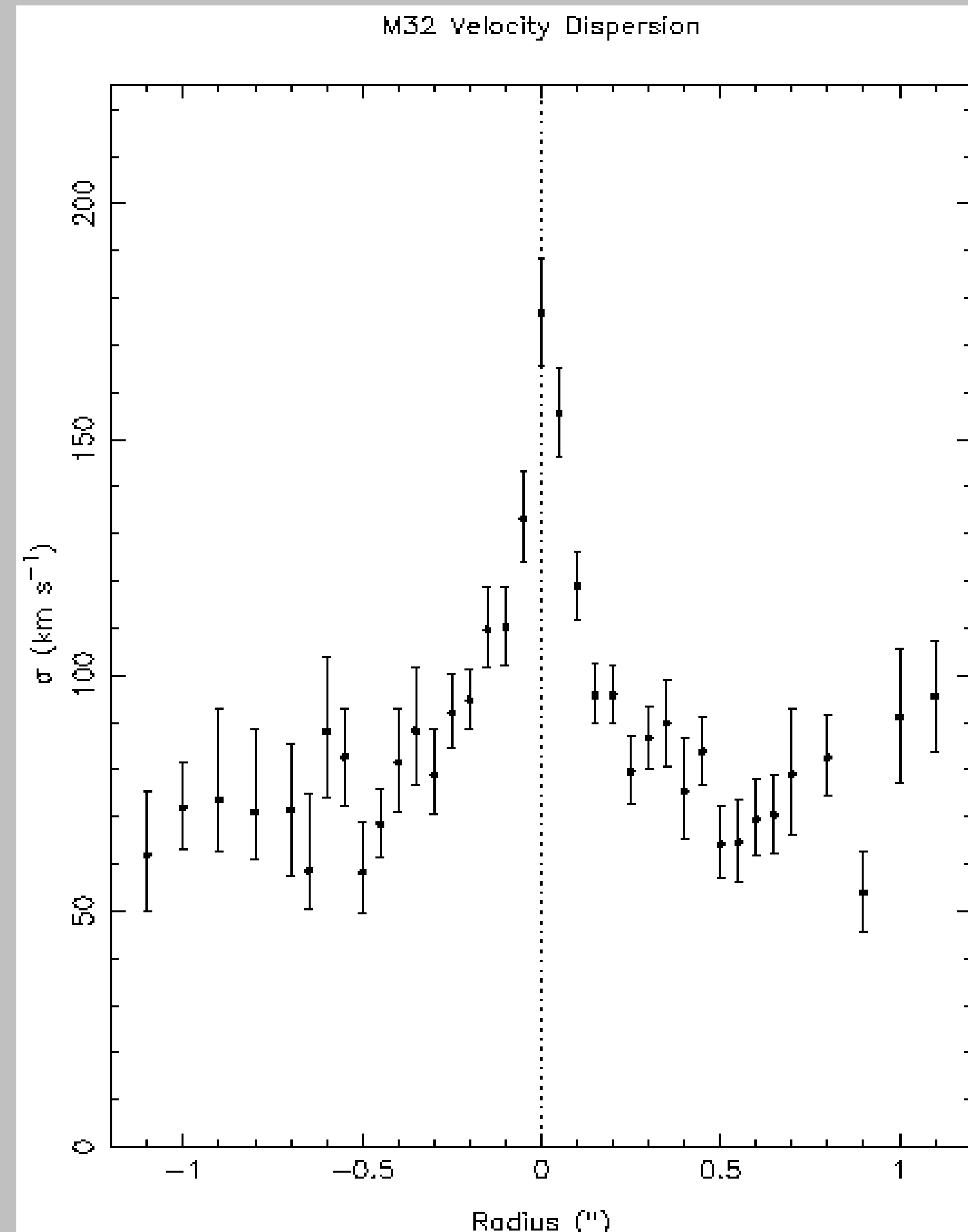
- With good telescopes (and some image processing) the quasar light can be subtracted and the host galaxy revealed
  - One can image quasar hosts with HST
  - Many are interacting – does interactions trigger AGN activity? Promote fueling gas into centers?
- Not all galaxies with SMBH are AGN (even the Milky Way)
- Quasars were much (~1000x) more numerous at z~3 than today
  - Is an AGN a requirement for galaxy formation? Does every galaxy have a SMBH?
  - More interactions in the past?
- Quasars were also much more luminous in the past
- There is probably some combination of luminosity and density evolution!


Quasar 3C 273
HST ▪ WFPC2, ACS
WFPC2
ACS/HRC
NASA, A. Martel (JHU), the ACS Science Team, J. Bahcall (IAS) and ESA
STScI-PRC03-03


Quasar Host Galaxies
HST • WFPC2
PRC96-35a • ST ScI OPO • November 19, 1996
J. Bahcall (Institute for Advanced Study), M. Disney (University of Wales) and NASA


Redshift z= 5 4 3 2 1.5 1.0 0.5
Quasar space density (today=1)
30
20
10
?
0
0.2
0.4
0.6
0.8
1
Age of Universe (today=1)

M32



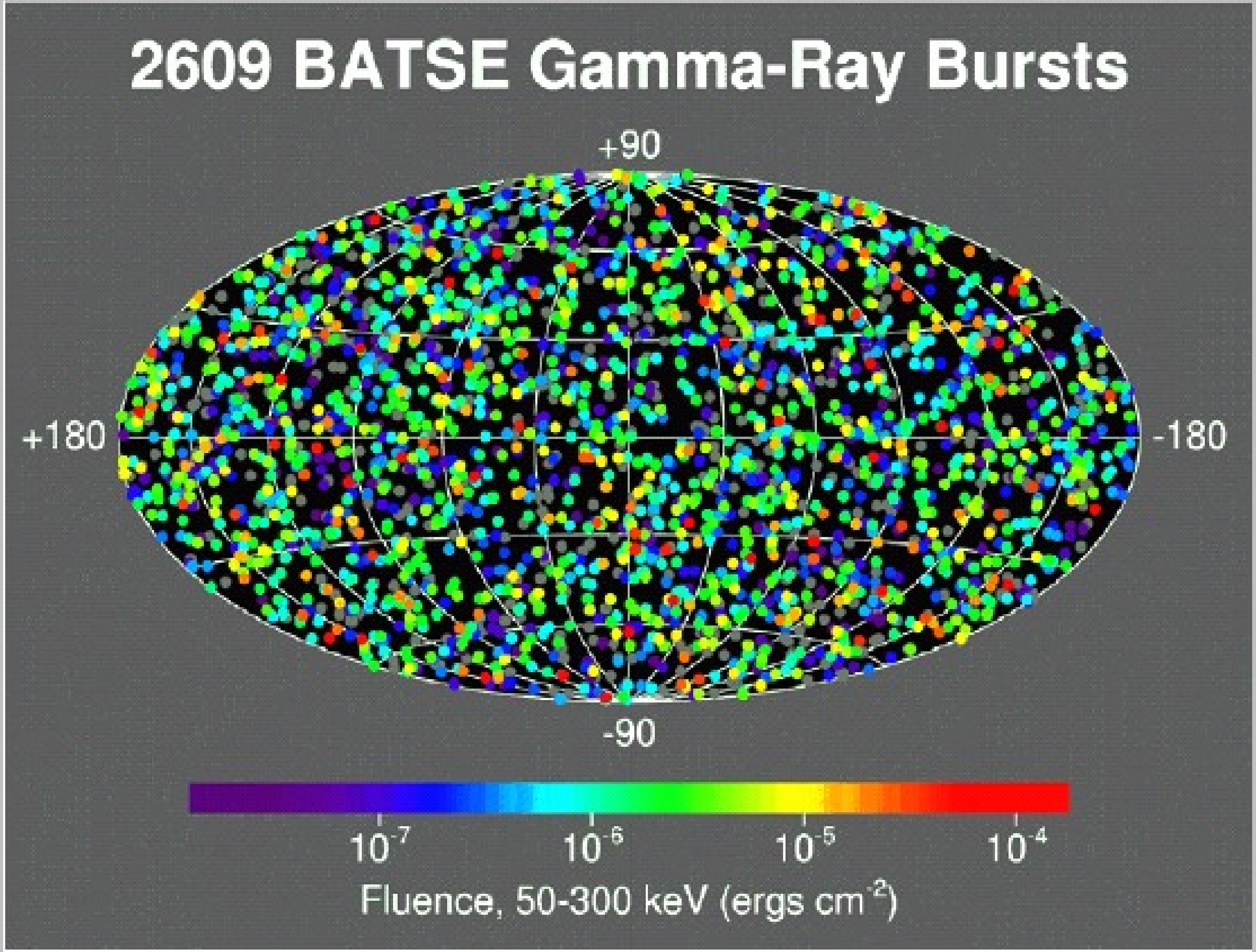
There is evidence that most if not all galaxies have a BH in their center but many of these are quiet! Not being fed(?) so they are hard to detect

Gamma-ray Bursts

- Very bright γ-ray flashes
- Isotropic on the sky
- 10^{-3} sec to minutes duration
- Occur ~once per day

Gamma-ray Bursts cont.

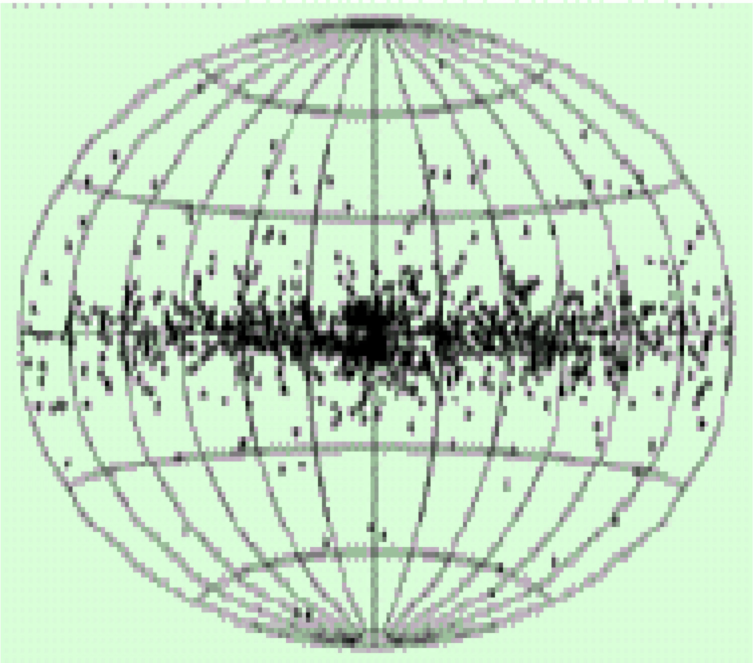
- First detected in the late 60's
  - Vela military satellites (US)
  - Konus military satellites (USSR)
- Their identity was completely unknown
  - Short timescales (~minutes)
  - Poor spatial localizations


2609 BATSE Gamma-Ray Bursts
+90
+180
-180
-90
10-7
10-6
10-5
10-4
Fluence, 50-300 keV (ergs cm-2)

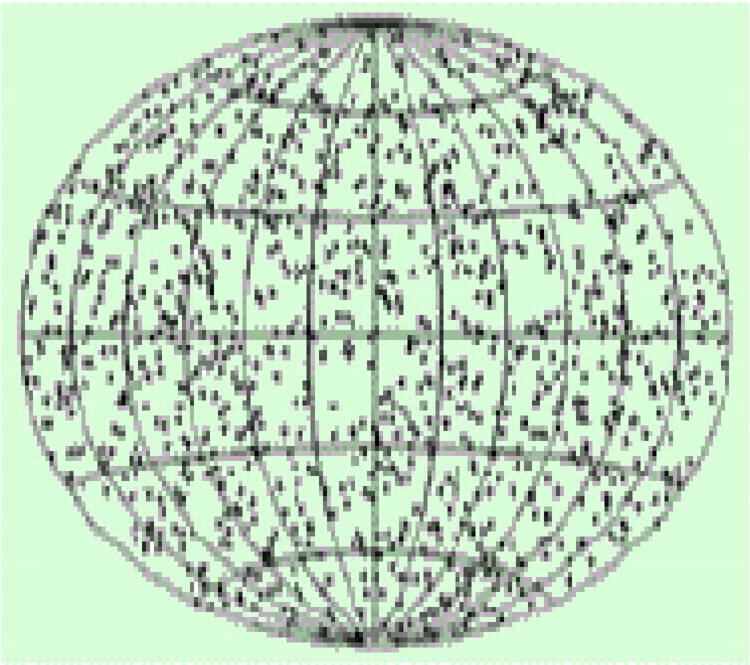
GRB Advances

- CGRO (Compton Gamma Ray Observatory) showed that GRB's were isotropically distributed
  - Therefor they were much more likely to be at cosmological distances rather than in our Galaxy.
  - Showed that the spectrum was non-thermal
  - Two classes of bursts long t>2s and short t< 2s

Distribution of Gamma-Ray Bursts on the Sky



Expected



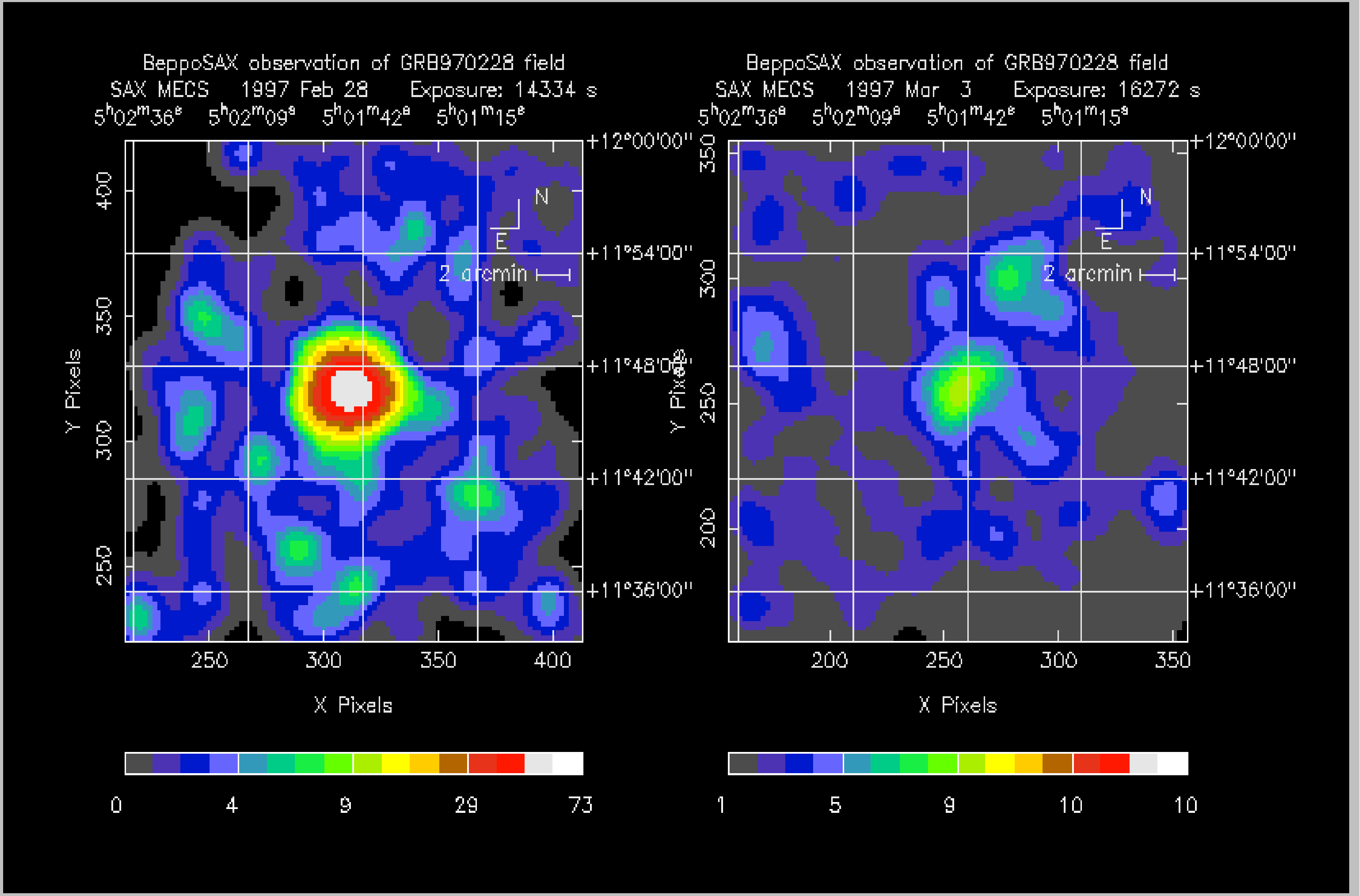
Observed

GRB Advances (1997)

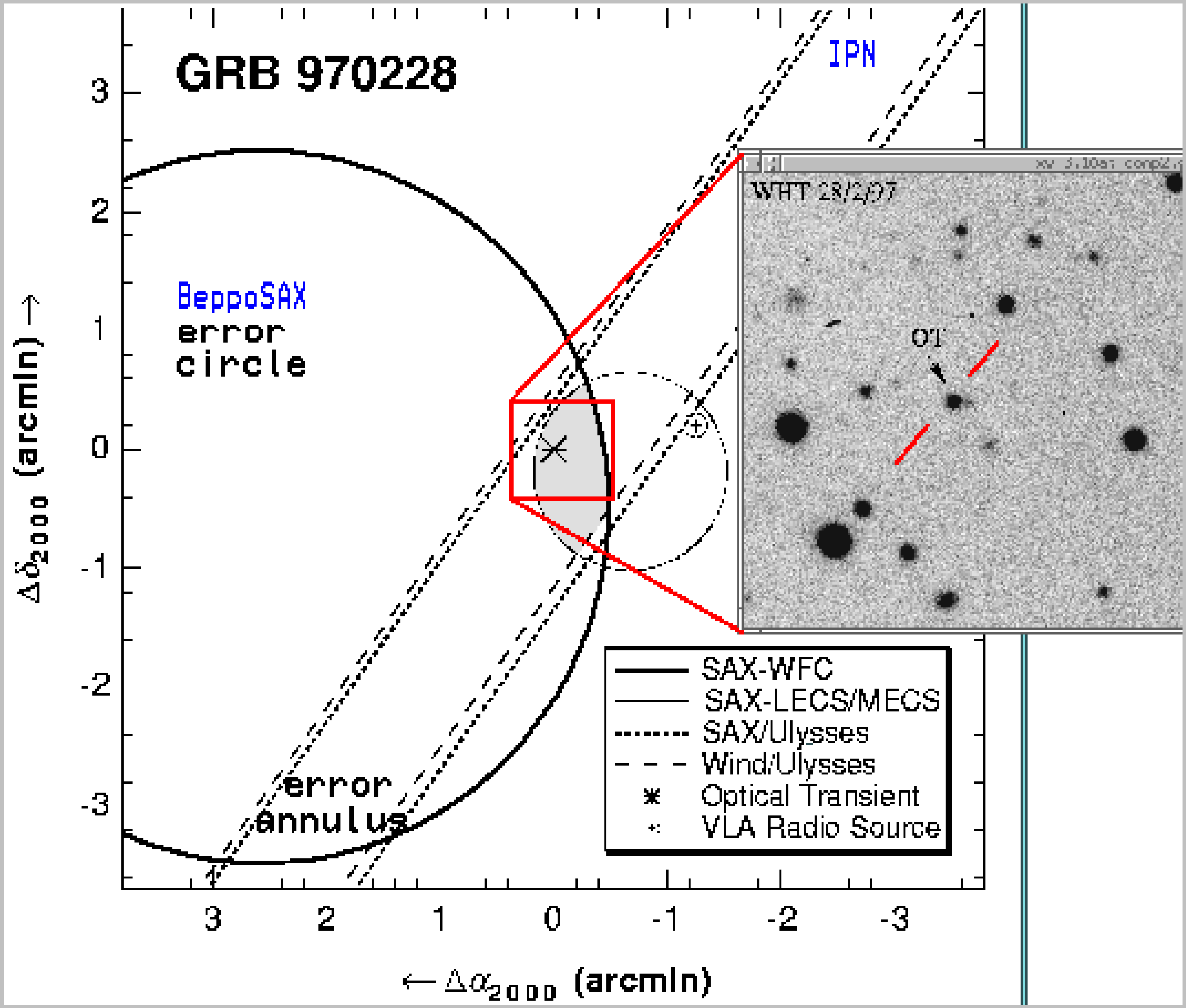
- Initially GRB positions were not known accurately enough (error circle of degrees) so that observations at other wavelengths could be done.
  - No optical or radio counterparts
  - No redshift & thus distance was unknown!

GRB Advances cont.

- 2/10/97: Meszaros and Rees GRB relativistic fireball model predicted broadband afterglows (Ap J 1997)
- 2/28/97: First X-ray/optical afterglows discovered
  - Beppo-SAX: combination of wide field hard X-ray imager and narrow-field soft X-ray imager



GRB970228: first detection of X-ray and optical afterglows

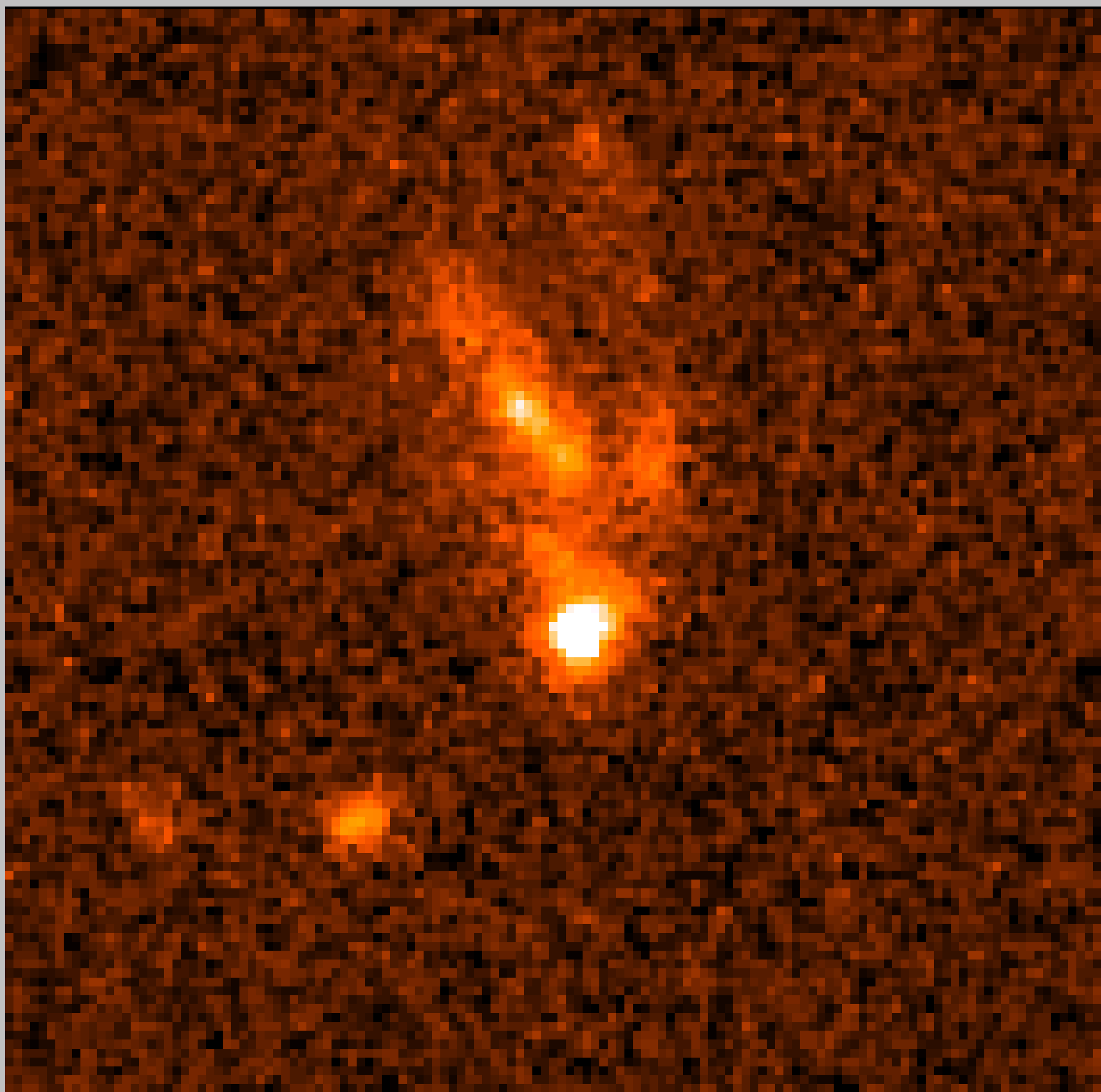


GRB 970228
IPN
BeppoSAX
error
circle
WHT 28/2/07
OT
error
annulus
SAX-WFC
SAX-LECS/MECS
SAX/Ulysses
Wind/Ulysses
Optical Transient
VLA Radio Source
$\Delta\delta_{2000}$ (arcmin) →
← $\Delta\alpha_{2000}$ (arcmin)

GRB Advances cont.

- GRB970508: first redshift of GRB afterglow (Keck)
  - Also first radio detection of afterglow (VLA)
- GRB990123: first optical observation of GRB (ROTSE)
  - Biggest explosion since Big Bang : 2×10^{54} erg

GRB 990123



Host galaxy
Irr?

GRB990123

Animation from Andy Fruchter's GRB page 16, 59 and 380 days past burst

GRB Advances cont.

- Observations of GRB 021206 with RHESSI indicate that GRB's are highly polarized 80±20%
  - GRB's are located in regions of very high magnetic fields that are extremely well ordered.
  - We observed GRB 021206 along the edge of a very narrow jet

Swift Mission

Burst Alert Telescope (BAT)

New CdZnTe detectors

Most sensitive gamma-ray imager ever flown

X-Ray Telescope (XRT)

Arcsecond GRB positions

CCD spectroscopy

UV/Optical Telescope (UVOT)

Sub-arcsec imaging

Grism spectroscopy

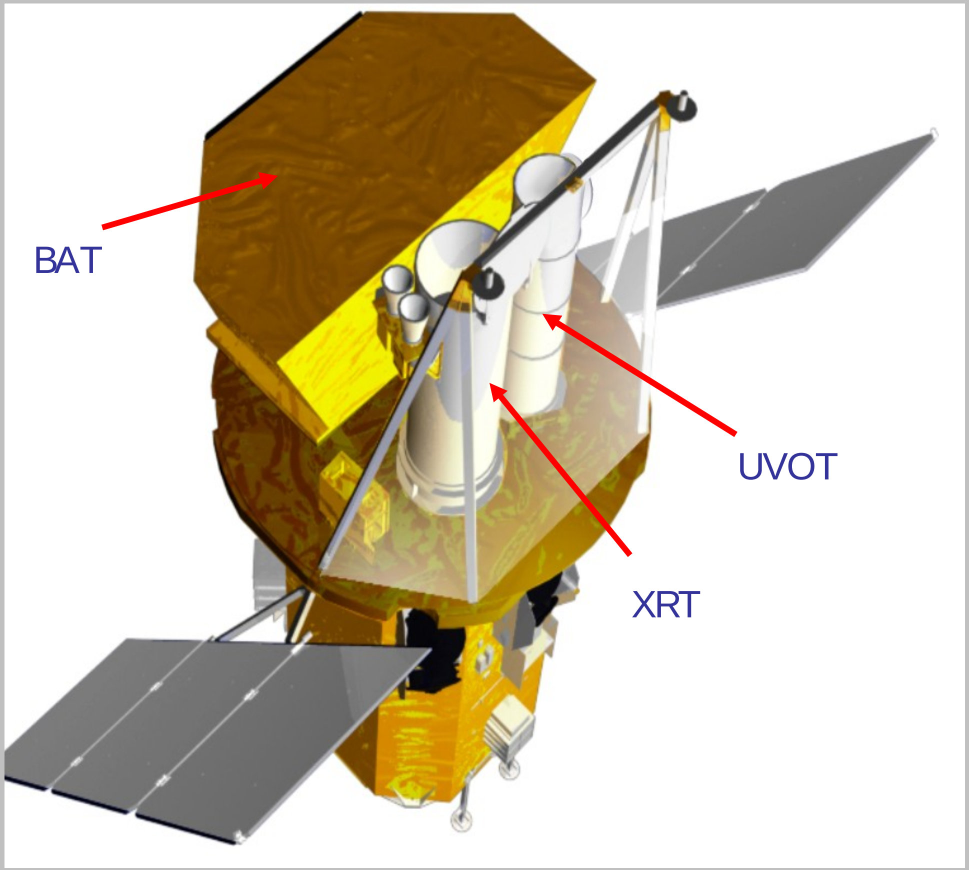
24^{th} mag sensitivity (1000 sec)

Finding chart for other observers

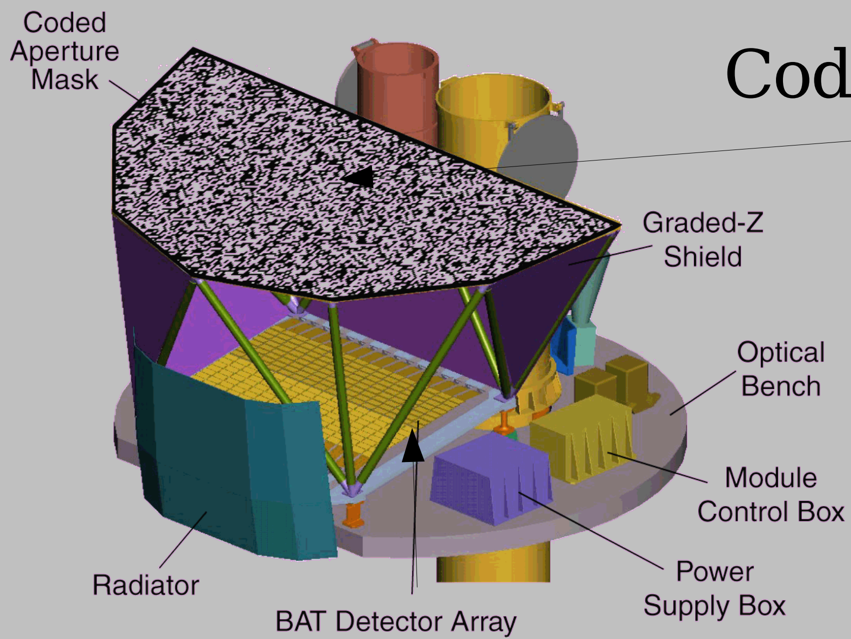
Spacecraft

Autonomous re-pointing, 20 - 75 s

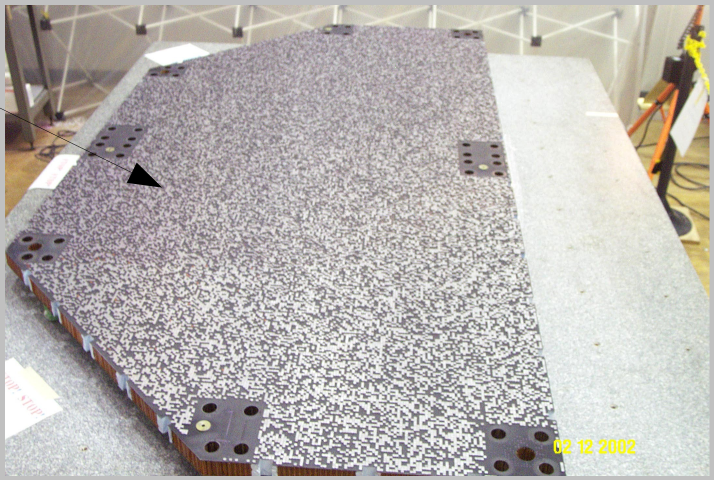
Onboard and ground triggers



Burst Alert Telescope (BAT)

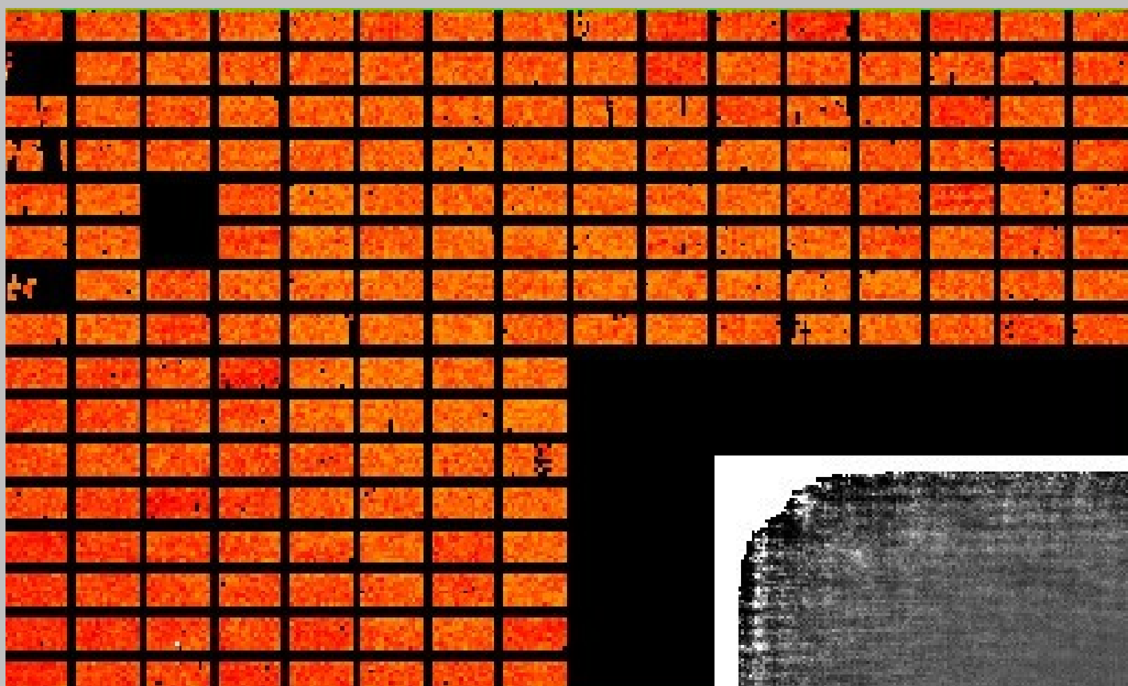


Coded aperture mask

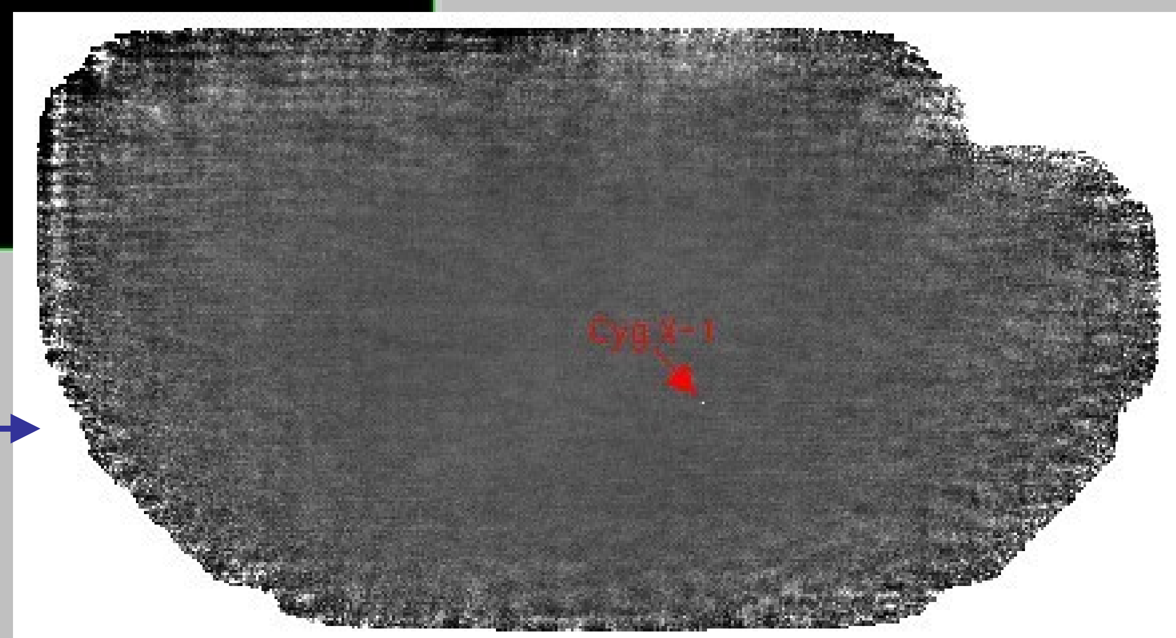


BAT Characteristic	Required Value	Value on-Orbit
Energy Range (keV)	15 - 150	12 - 300
Energy Resolution (keV)	7	5
GRB Location Accuracy (arcmin)	1 - 4	1 - 4
PSF (arcmin)	22	21.8
GRB Position Computation Time (s)	12	~6

BAT First Light (with only 3/4 of the array activated)



Detector Plane Image

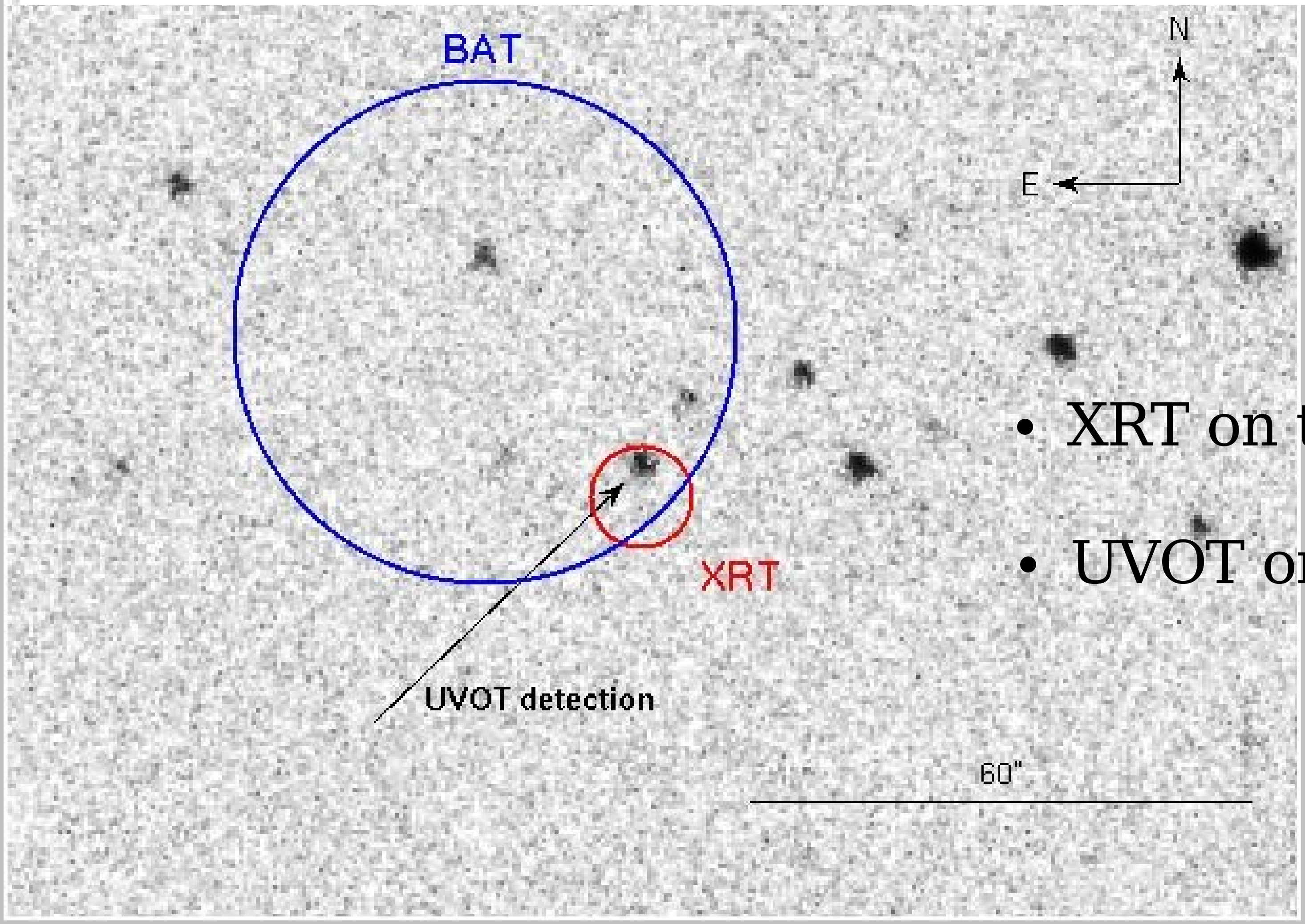


Sky Image

Analysis by Hans Krimm

GRB 050525

Second most fluent GRB observed by Swift to date, and first bright low redshift burst observed by all three instruments onboard



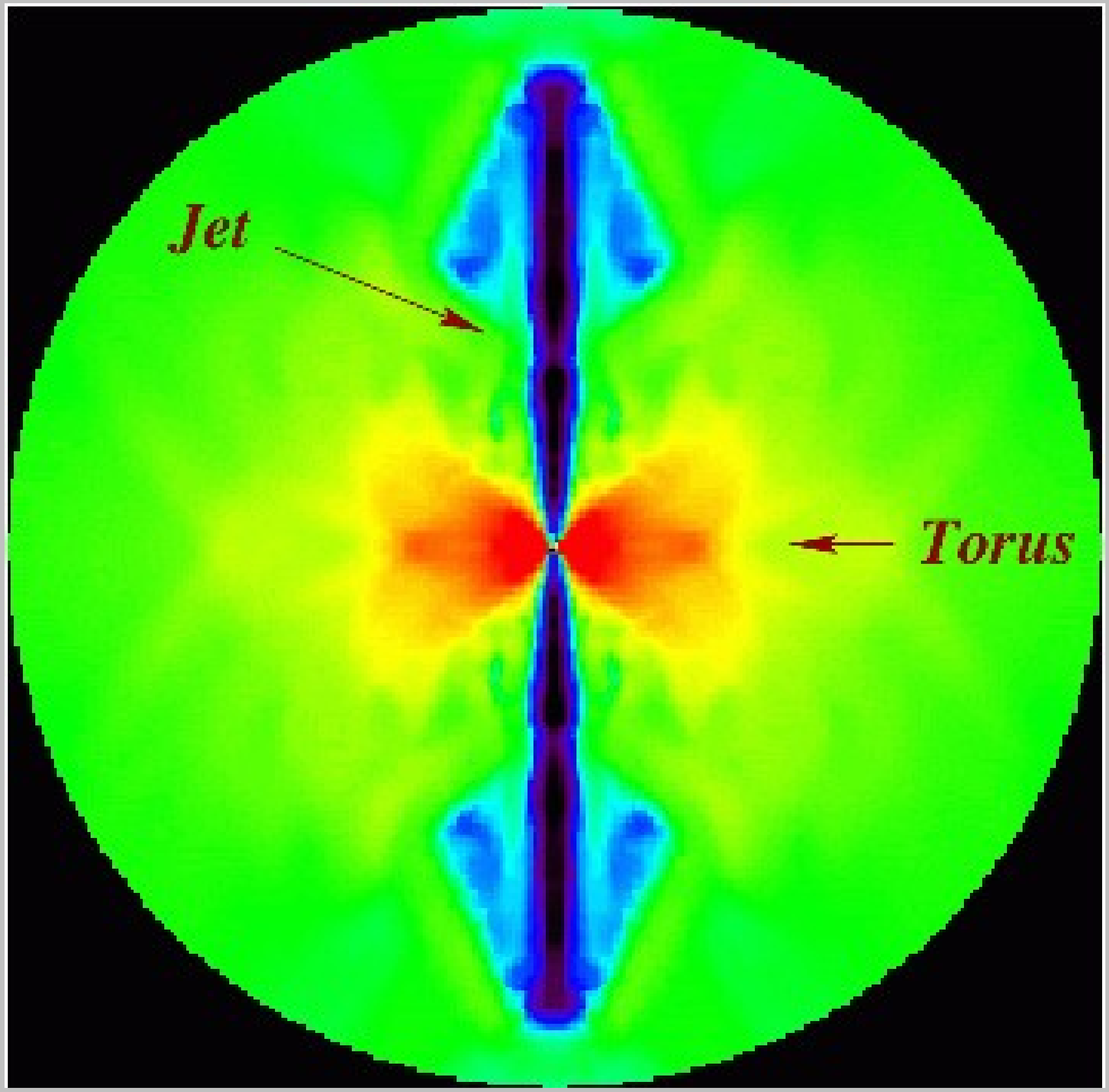
- XRT on target at T+125s
- UVOT on target at T+65s

GRB progenitors

- Compact object merger
  - NS binary merger
  - NS-BH merger
  - BH-WD merger
- Timescales for these mergers is long
  - Therefor should not occur near regions of active star formation
  - Any debris will be accreted onto the BH
- No significant X-ray line emission or absorption!

GRB progenitors cont.

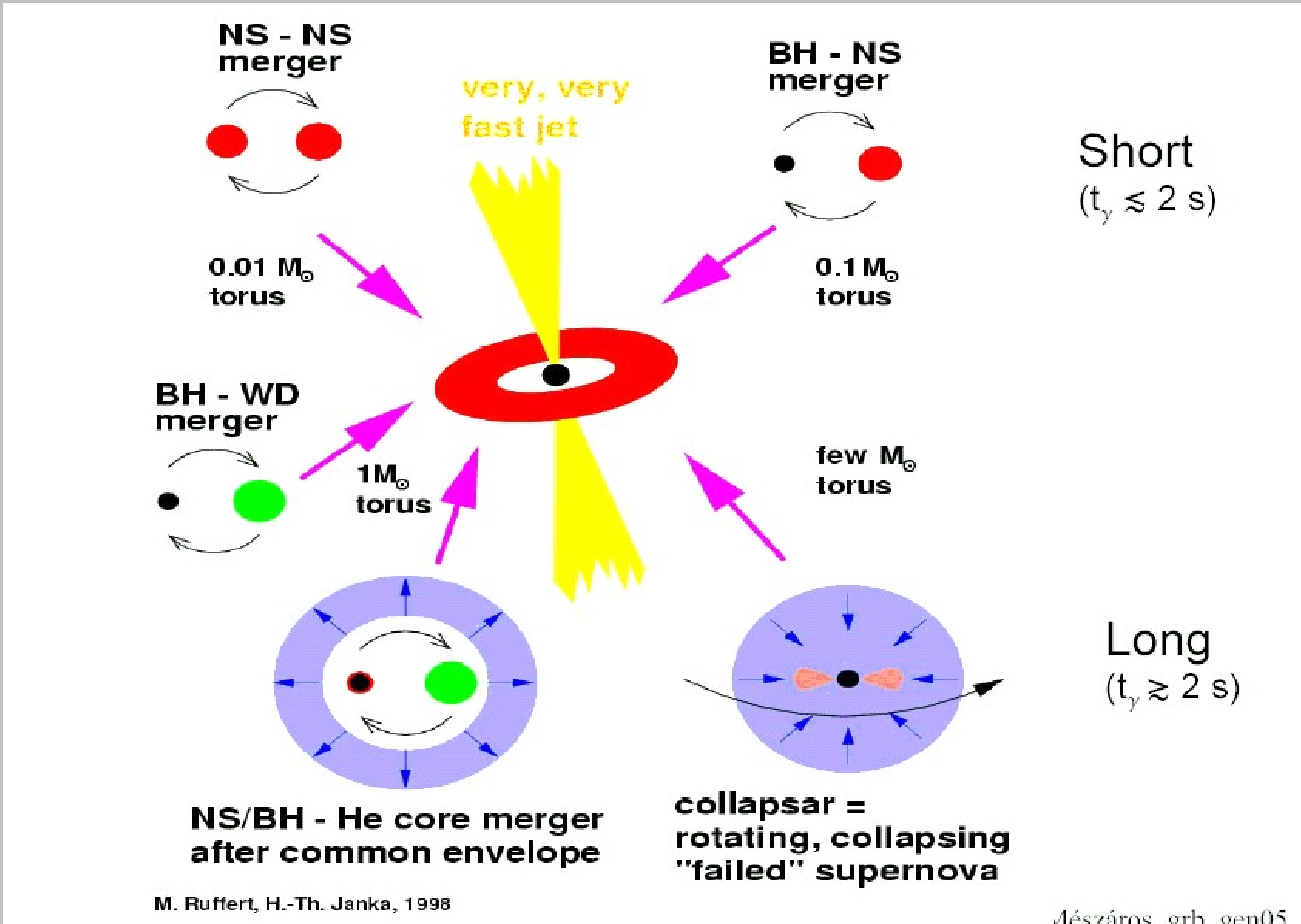
- Collapsar/Hypernova
  - A SNe where the blast wave does not eject most of the material and some is left to fall back and feed the black hole.
  - Most commonly formed from binary star merger
    - Naturally forms jets along the common rotation axis



Collapsar jet model (A. MacFadyen)

GRB progenitors cont.

- BH-He core merger
  - BH and a He core WD merge and collapse
  - Like the collapsar model the GRB is expected to be beamed along the rotation axis
  - Works best for long duration GRB's

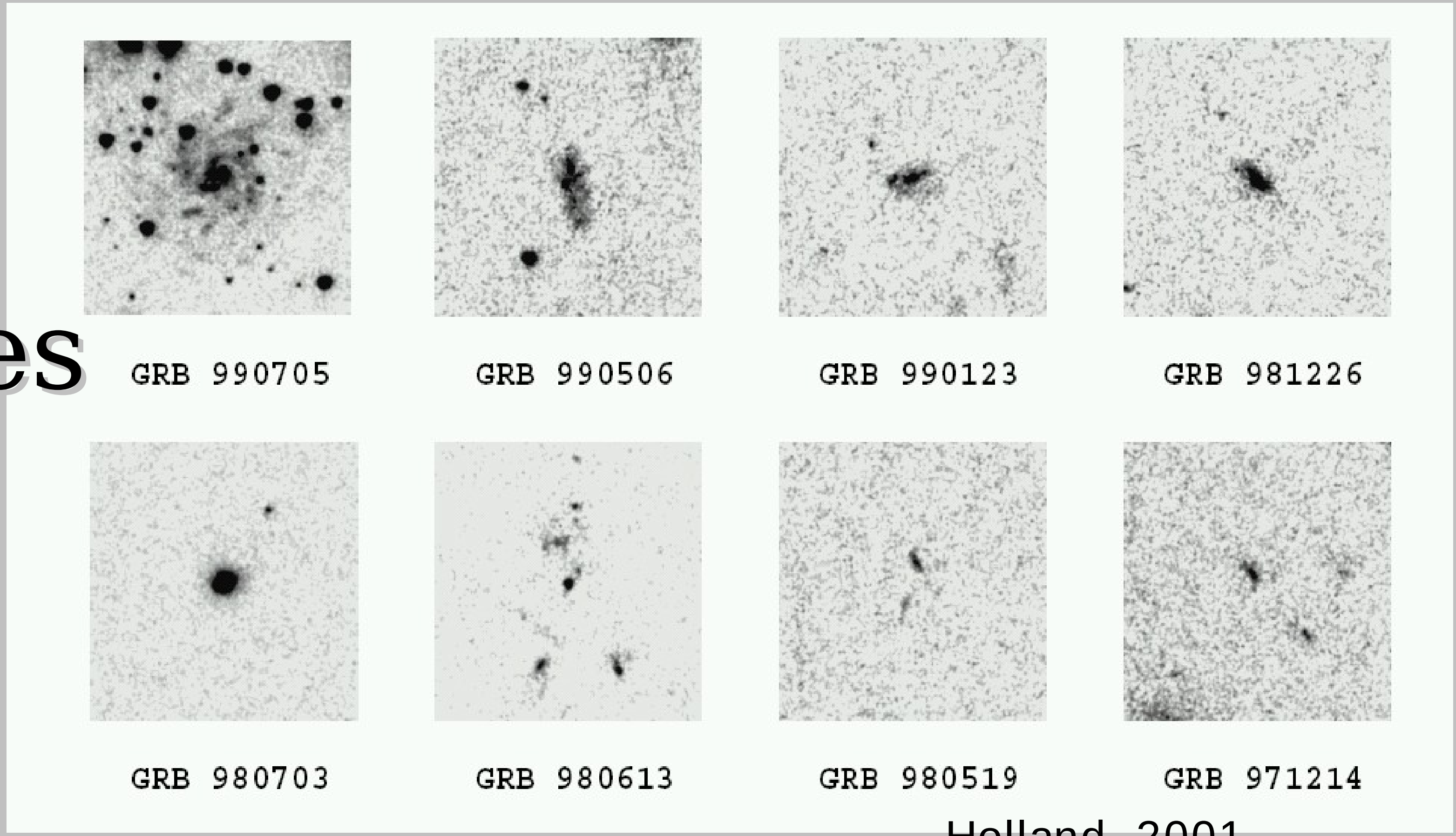


From Mezsaros

GRB progenitors cont.

- Supernova
  - Mass ejection provides a ready source for X-ray, radio or optical emission
    - Simulations show that for short bursts
    - Long bursts (~25s) are not consistent with the SNe collapse time.

Host Galaxies



Holland 2001

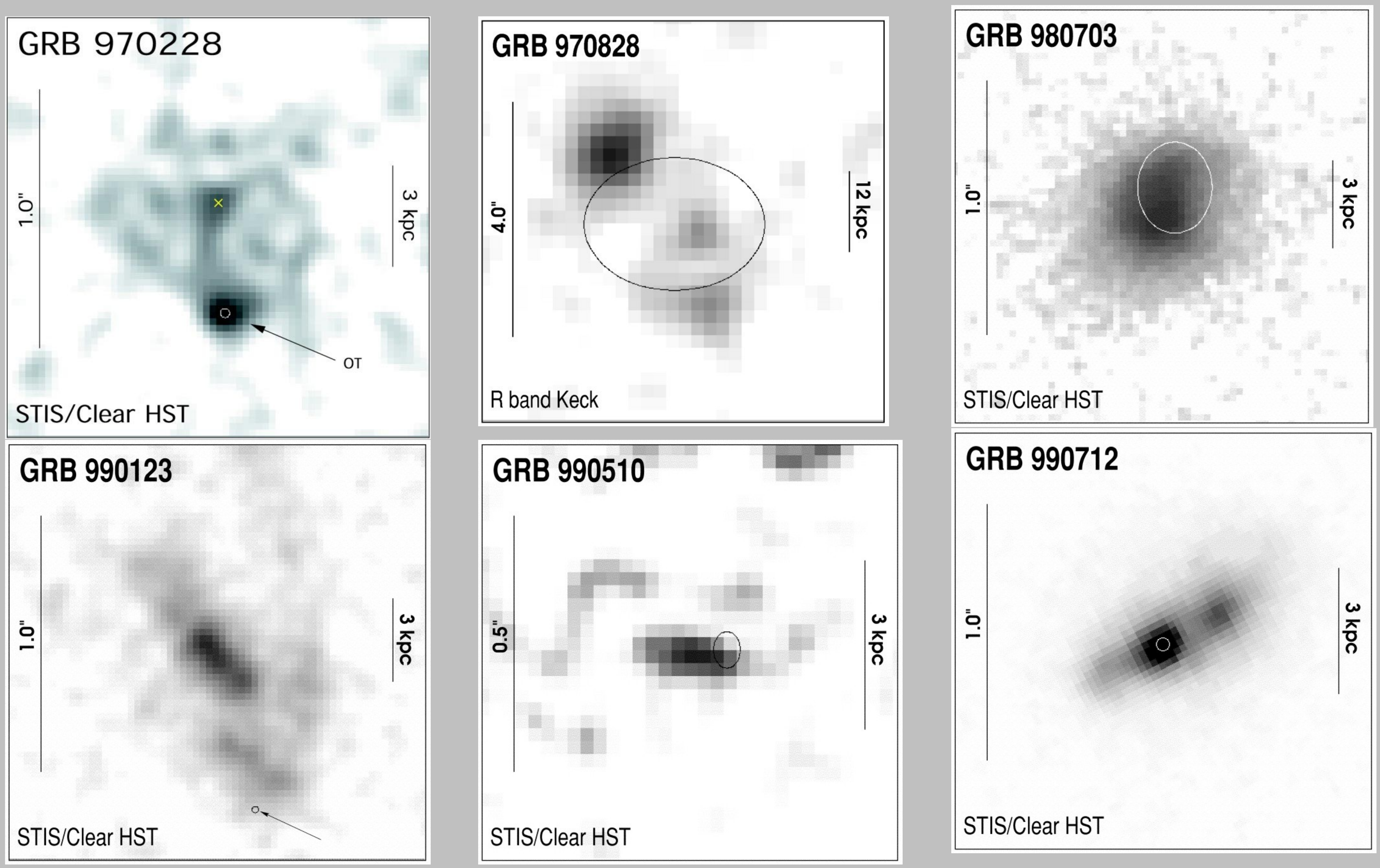
TABLE 1. Specific star-formation rates for several GRB host galaxies.

GRB	z	R_{host}	$\mathcal{M}_{\odot}\,\mathrm{yr}^{-1} {L_B^{*}}^{-1}$
970508	0.835	25.20	11.0
980613	1.096	24.56	20.0
980703	0.966	22.57	6.5
990123	1.600	24.07	11.0
990712	0.434	21.91	4.4

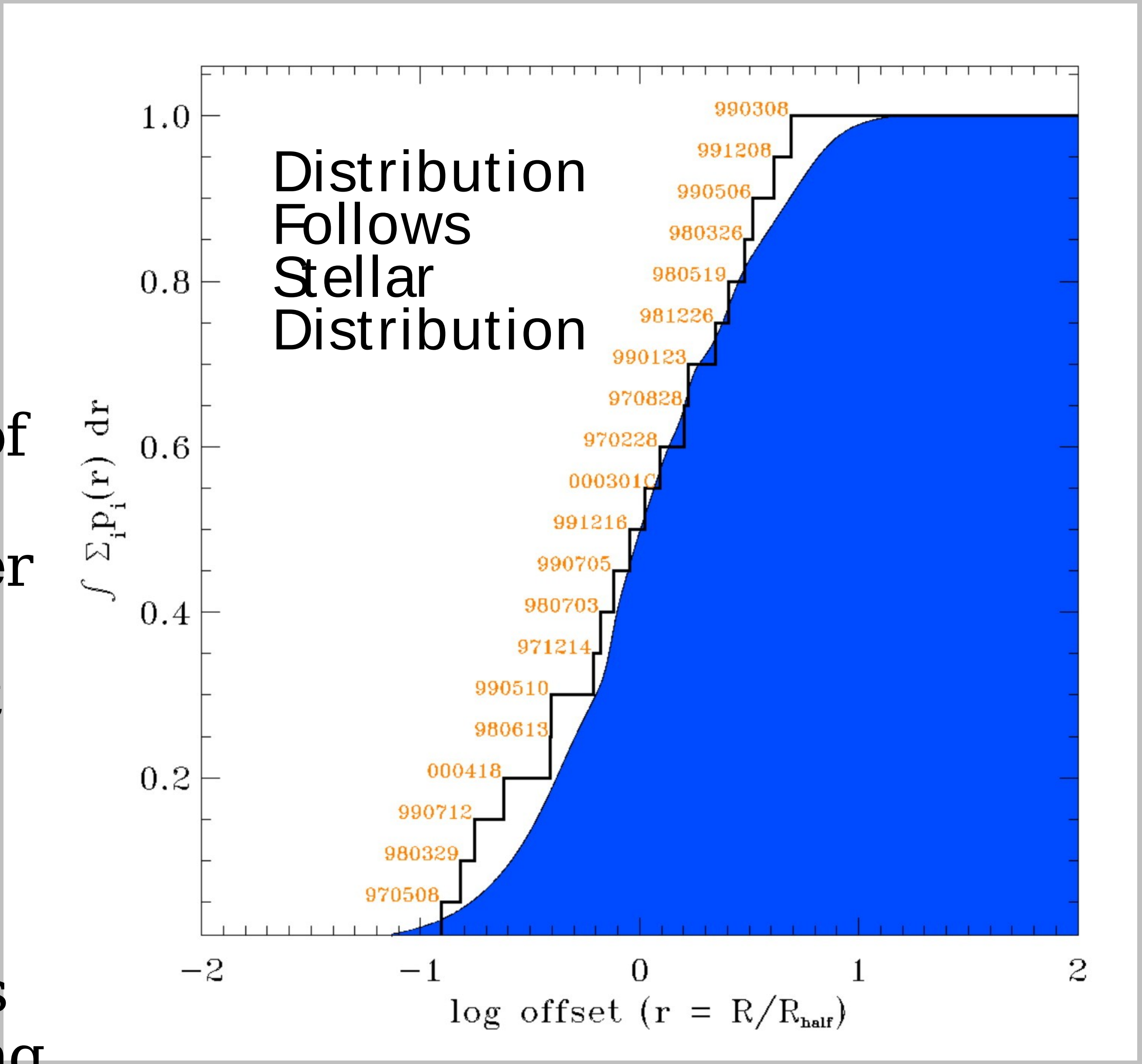
Hosts are similar to star-forming galaxies at similar redshifts.

High star formation rates.

Location of GRB within Host



Location of GRB within Host



The environments of GRBs show higher gas densities, higher metallicities, and higher dust content than random locations in host galaxies.

Suggests that GRBs occur in star forming regions.

GRB Locations

- GRB hosts are star-forming galaxies
- GRBs trace the stellar distribution (in distance from galaxy center)
- GRBs occur in dense environments (probably star forming regions)

- Suggests collapsar model over merger model

Supernova connection

SN 1998bw was found in the 8’ error circle of GRB 980425 in observations made 2.5 days after the burst.

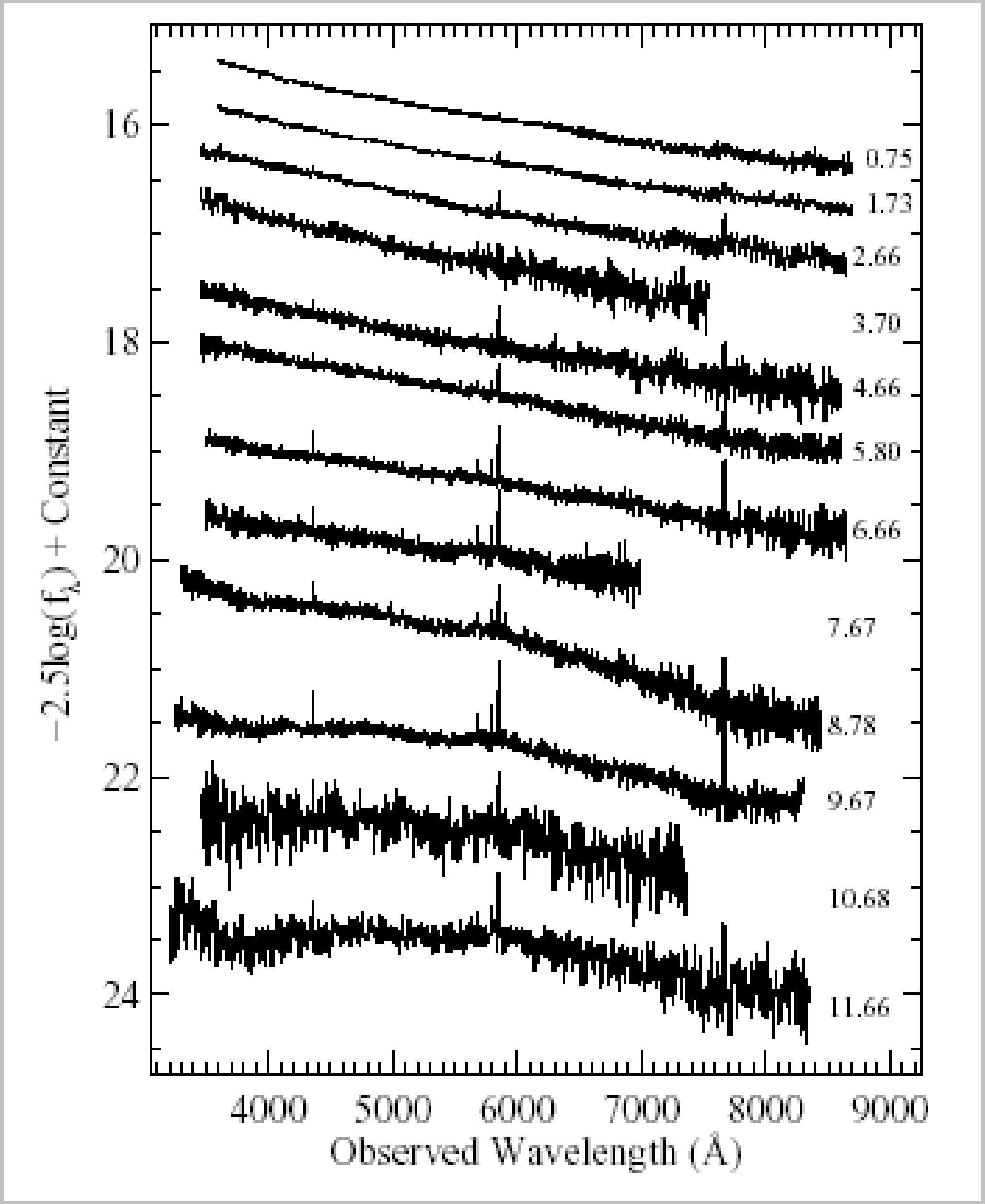
A slowly decaying X-ray source was subsequently found in the same galaxy (z = 0.0085) and identified with the GRB.

However, the GRB was very underluminous and the SN was very usual with peculiar line emission (no H, no He, no Si at 615 nm.

Radio emission a few days after GRB indicated relativistic outflow with energy ~ 3×10^{50} erg.

Thought to be oddball GRB and SN.

GRB030329 and SN 2003dh

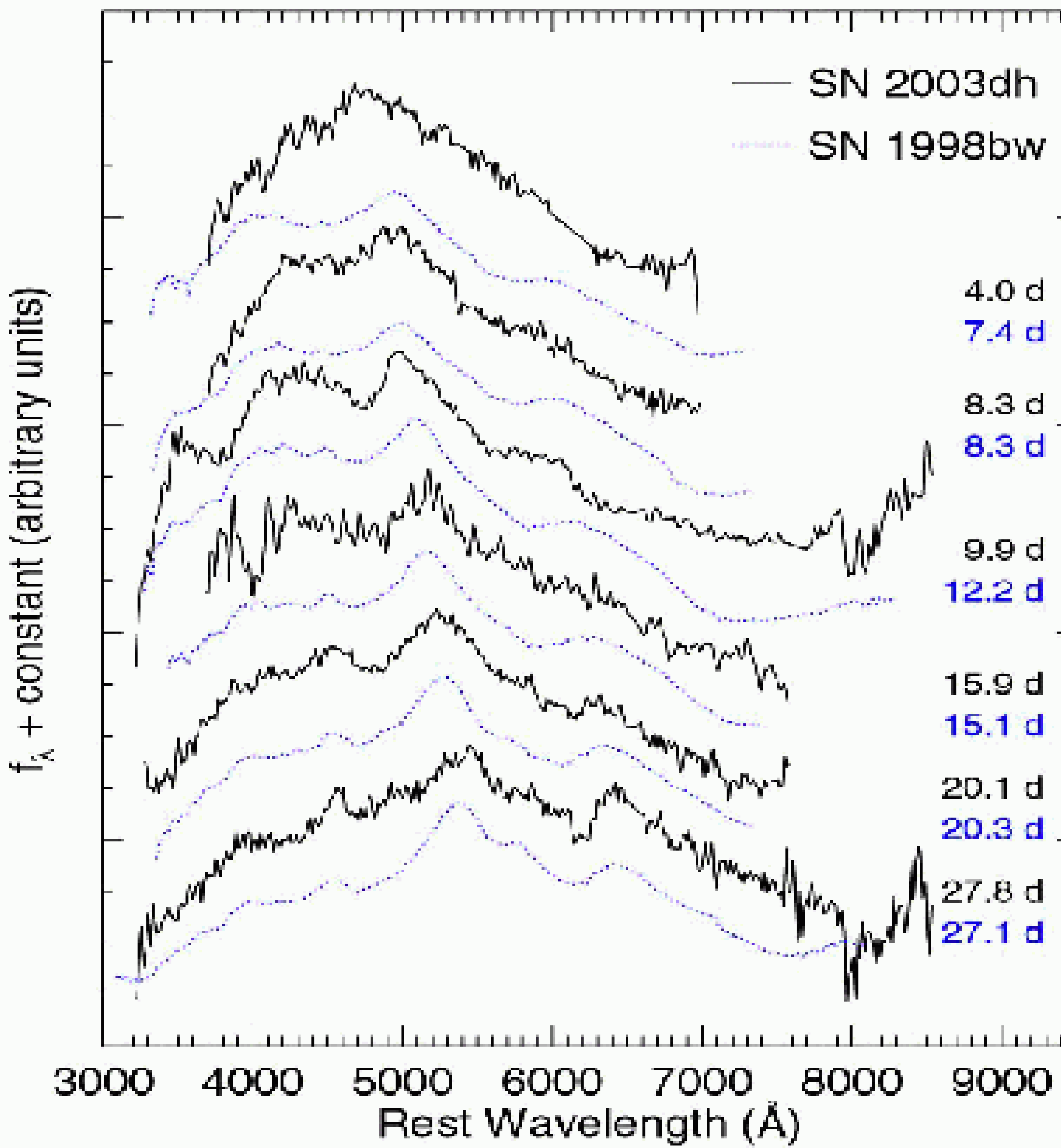


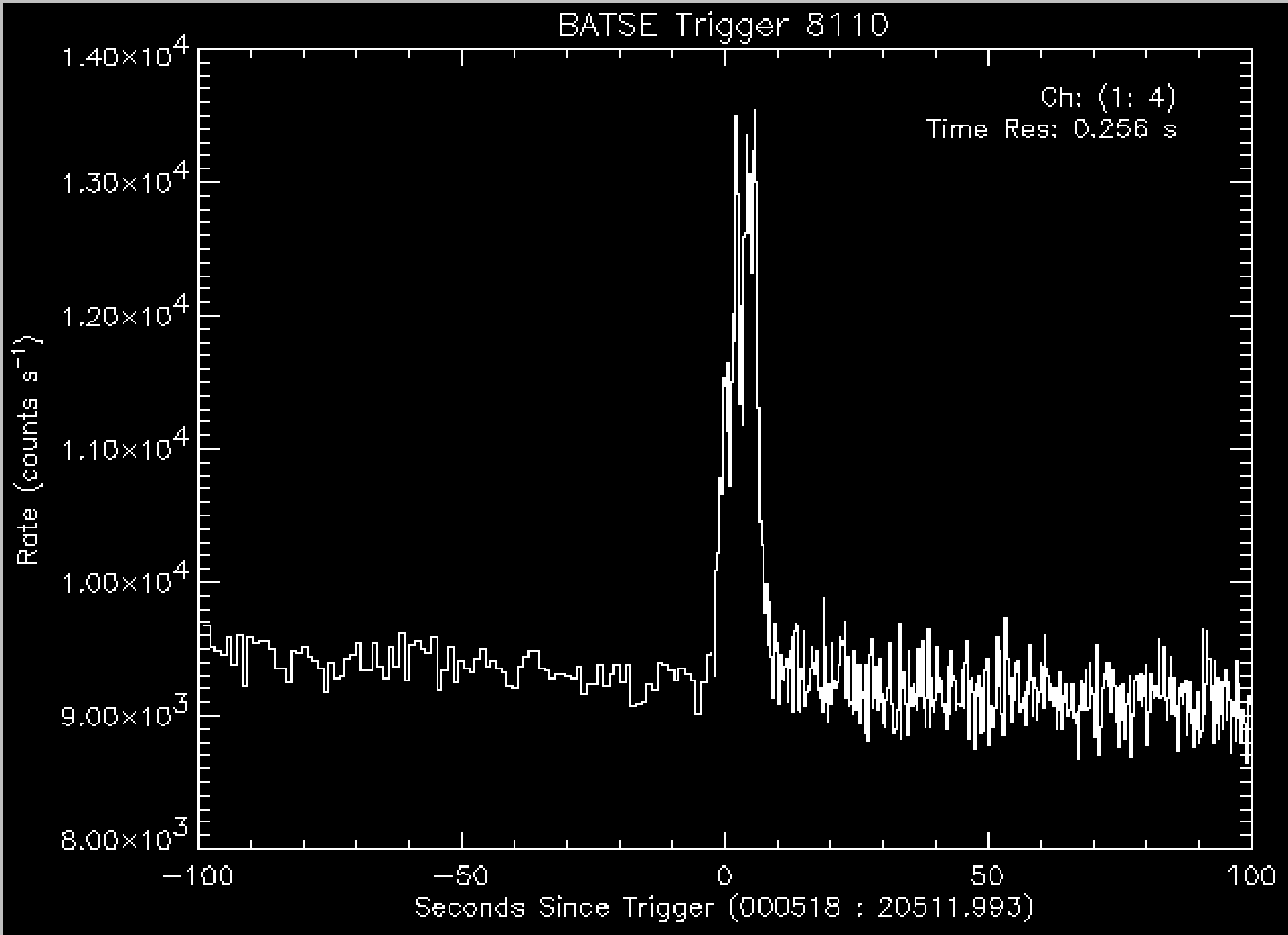
Clear spectroscopic signature of a SN, broad emission lines, found after decay of afterglow of GRB030329.

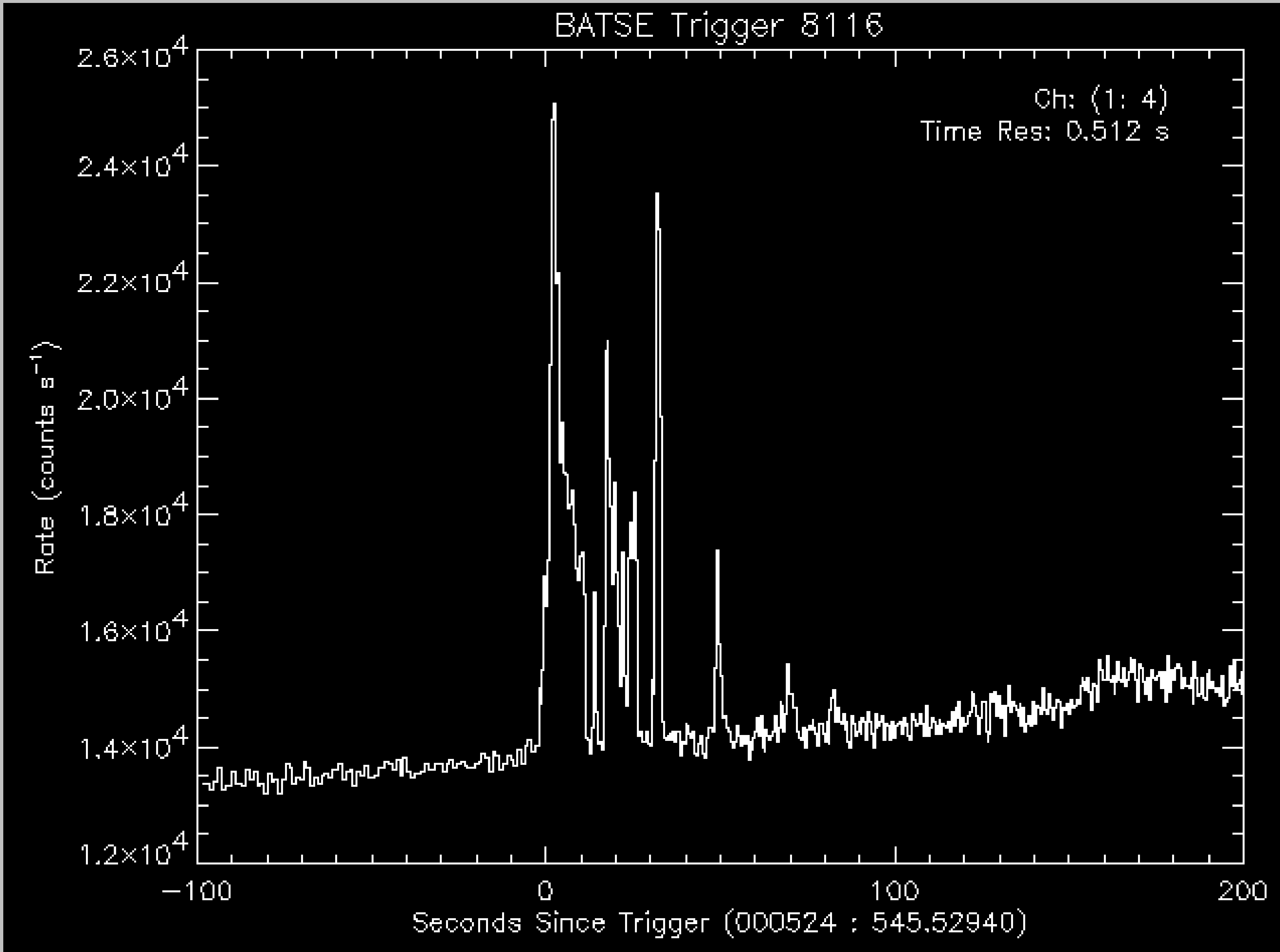
"Smoking gun" linking GRBs and SNe.

GRB SNe connection

- Since 1997 > 2 dozen GRB afterglows have been observed
  - Often the excess light could be attributed to an SNe but spectroscopic evidence was needed to be sure
  - The Gamma-Ray Burst Afterglow Collaboration at ESO (GRACE) showed that the afterglow from GRB030329 was a supernova


SN 2003dh
SN 1998bw
4.0 d
7.4 d
8.3 d
8.3 d
9.9 d
12.2 d
15.9 d
15.1 d
20.1 d
20.3 d
27.8 d
27.1 d
f_λ + constant (arbitrary units)
3000
4000
5000
6000
7000
8000
9000
Rest Wavelength (Å)


BATSE Trigger 8110
Ch: (1: 4)
Time Res: 0.256 s
Rate (counts s^-1)
1.40×10^4
1.30×10^4
1.20×10^4
1.10×10^4
1.00×10^4
9.00×10^3
8.00×10^3
−100
−50
0
50
100
Seconds Since Trigger (000518 : 20511.993)



BATSE Trigger 8116
Ch: (1: 4)
Time Res: 0.512 s
Rate (counts s^{-1})
2.6×10^4
2.4×10^4
2.2×10^4
2.0×10^4
1.8×10^4
1.6×10^4
1.4×10^4
1.2×10^4
−100
0
100
200
Seconds Since Trigger (000524 : 545.52940)

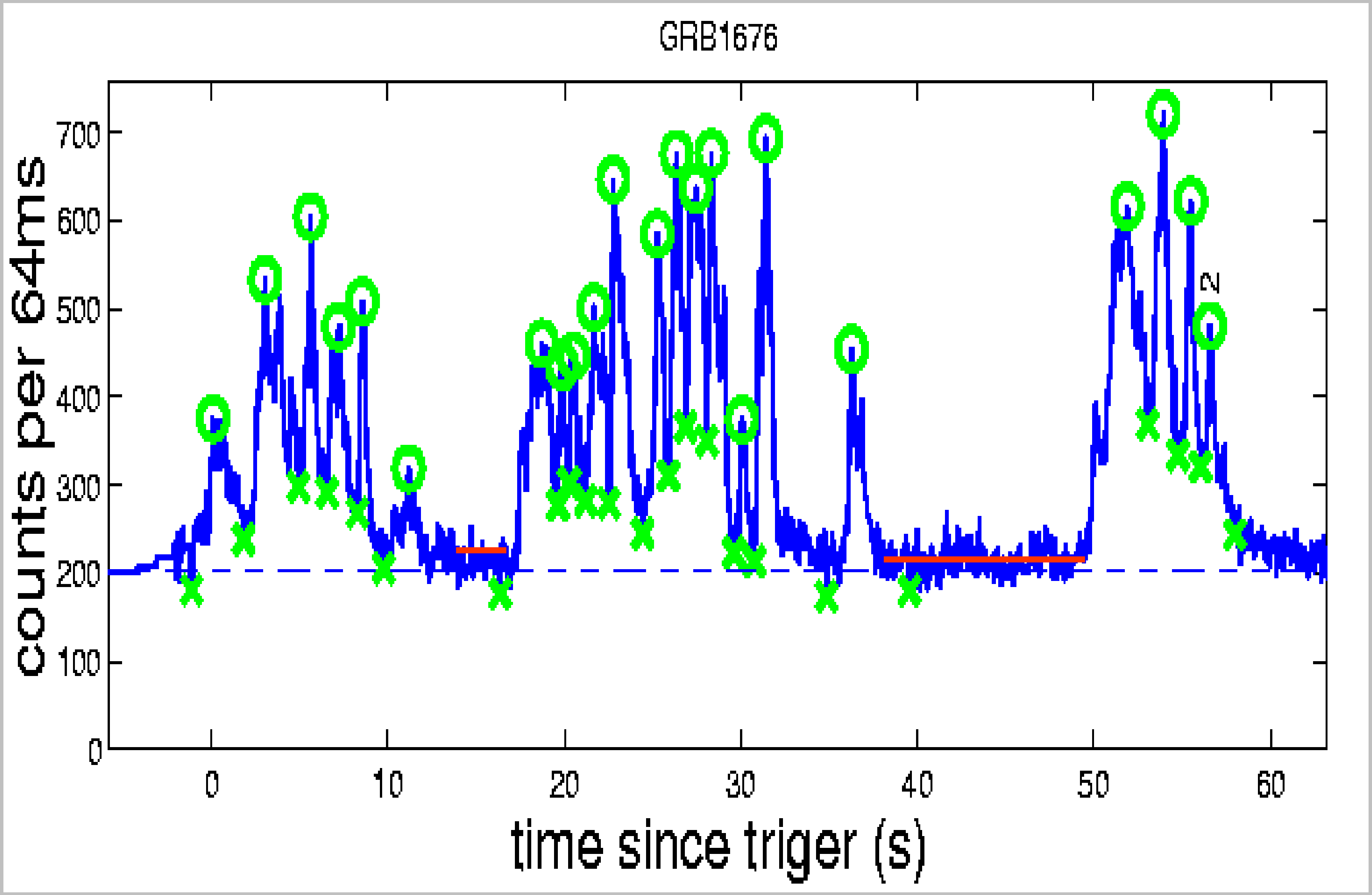
GRB's

- If the emission is isotropic then the energy required for GRB's is~10^{54} erg
- This is liberated in a region < 100 km across
  - From the timing
- The energy, timing, spectrum and lightcurve can be explained by the fireball-shock model but there can be two types of shocks
  - External
  - Internal

External Shocks

External Shocks are between the relativistic ejecta and the ISM. This predicts the optical emission should be <1s after the burst.

Optical emission is also produced much later. Also predicts a smooth light curve

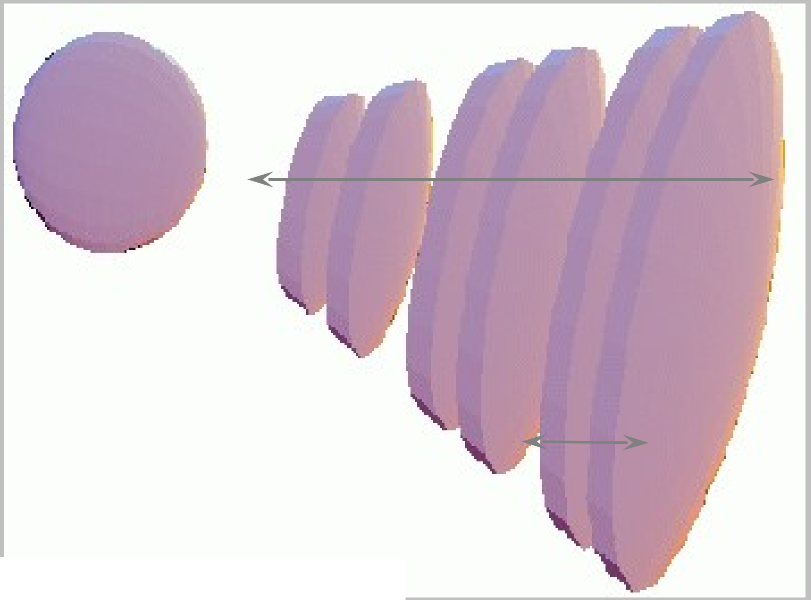


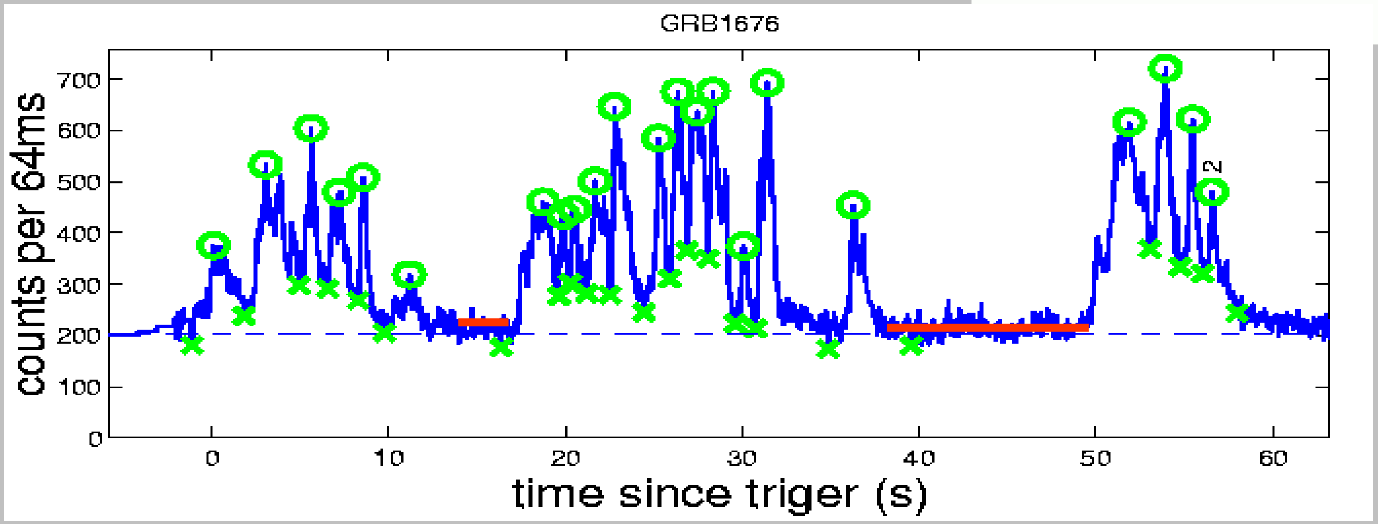
This doomed the external shock model

Internal Shocks

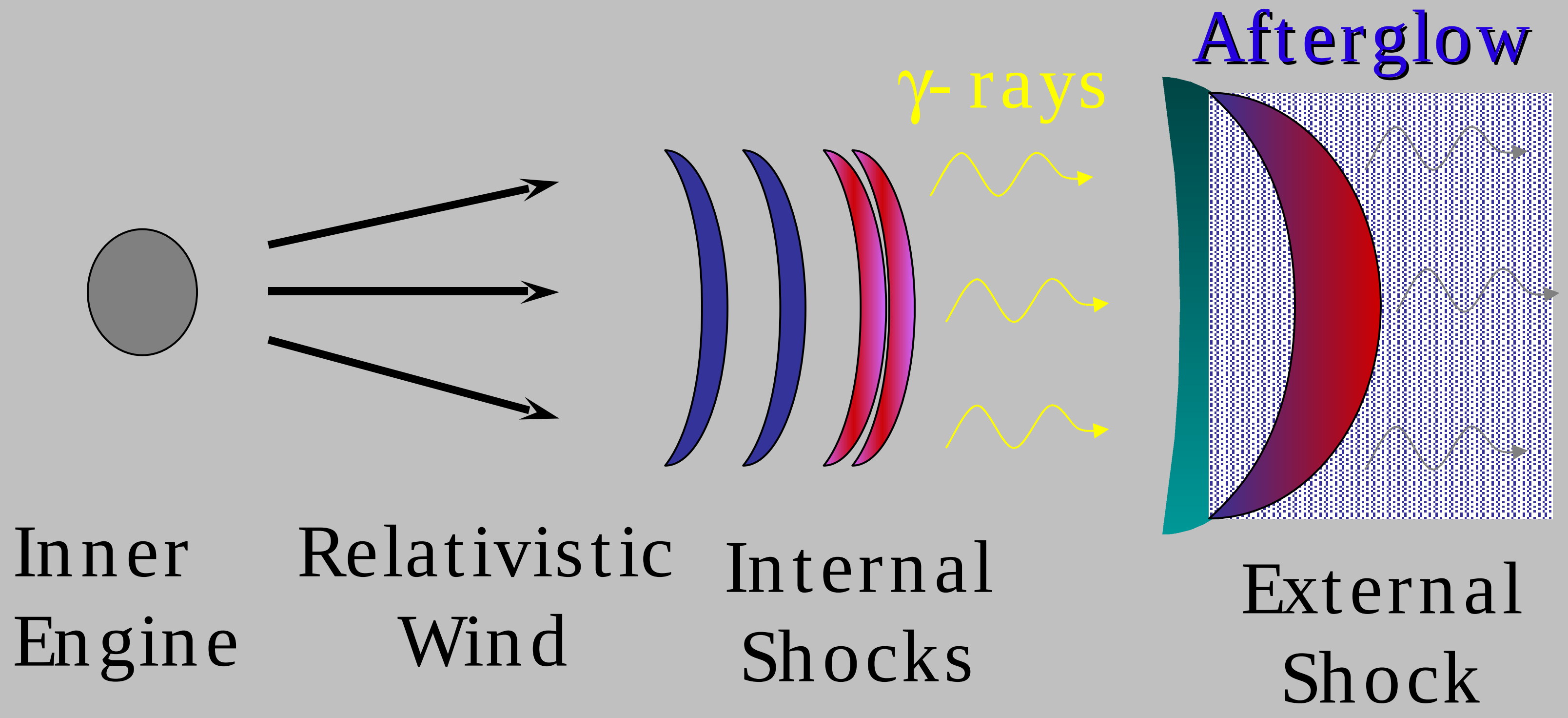
Here the shocks are between different shells of the ejected relativistic matter

Each time these collide we get a peak in the light curve



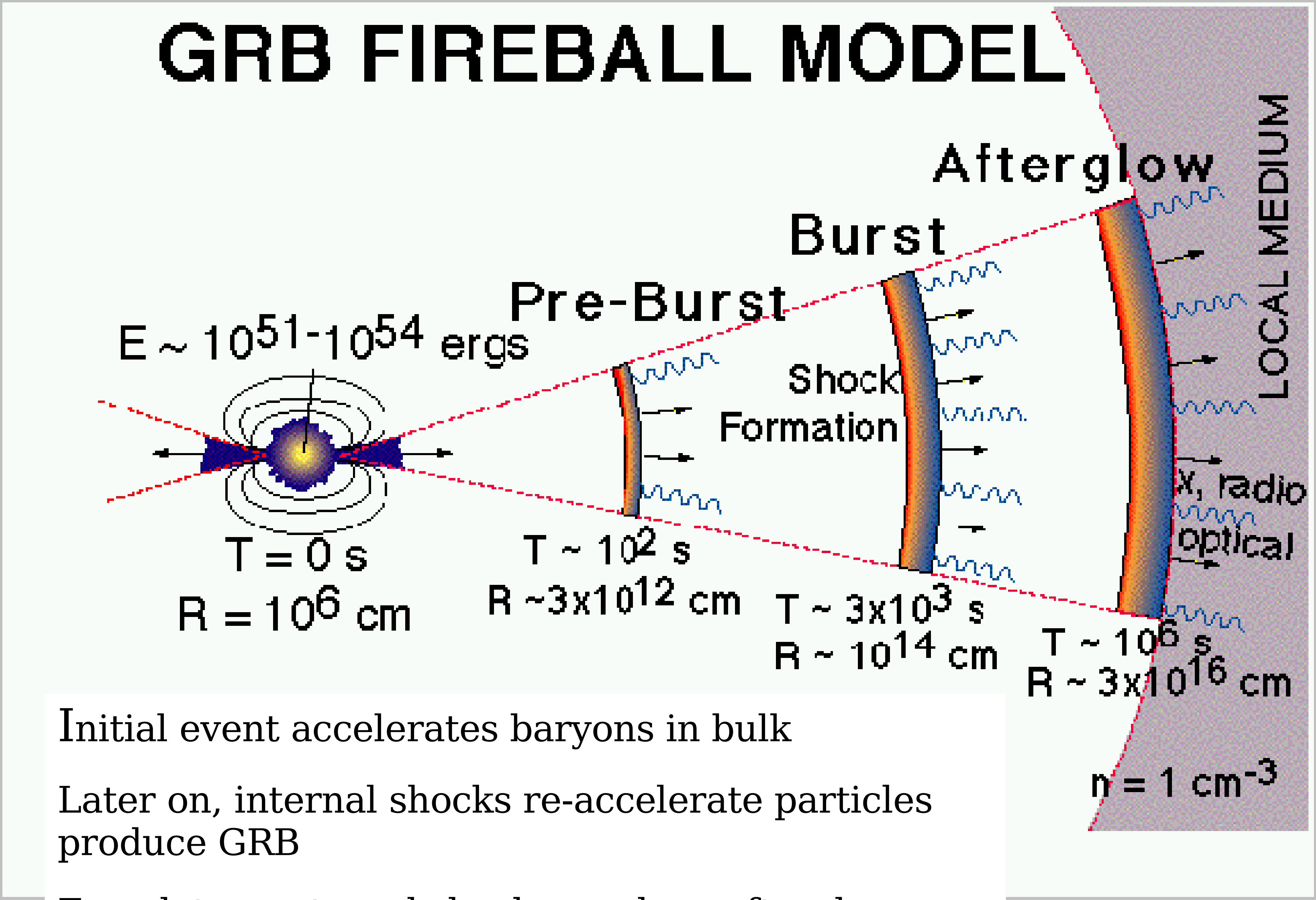


But no afterglow



The basic fireball model is consistent with the observations of GRB's
Internal shock give you the prompt optical emission and gamma rays.

External shocks give you the afterglow



Initial event accelerates baryons in bulk

Later on, internal shocks re-accelerate particles produce GRB

Even later, external shocks produce afterglow

Swift Results

- Launched in 2004.
- Detects about 100 bursts/year
- More afterglow detections than all previous satellites combined
- GRB with redshift of $z = 6.29$
- Average redshift = 2.7 compared to pre-Swift $\langle z \rangle = 1.2$
- Expect 40 GRB with $z > 5$ and 4 with $z > 8$.

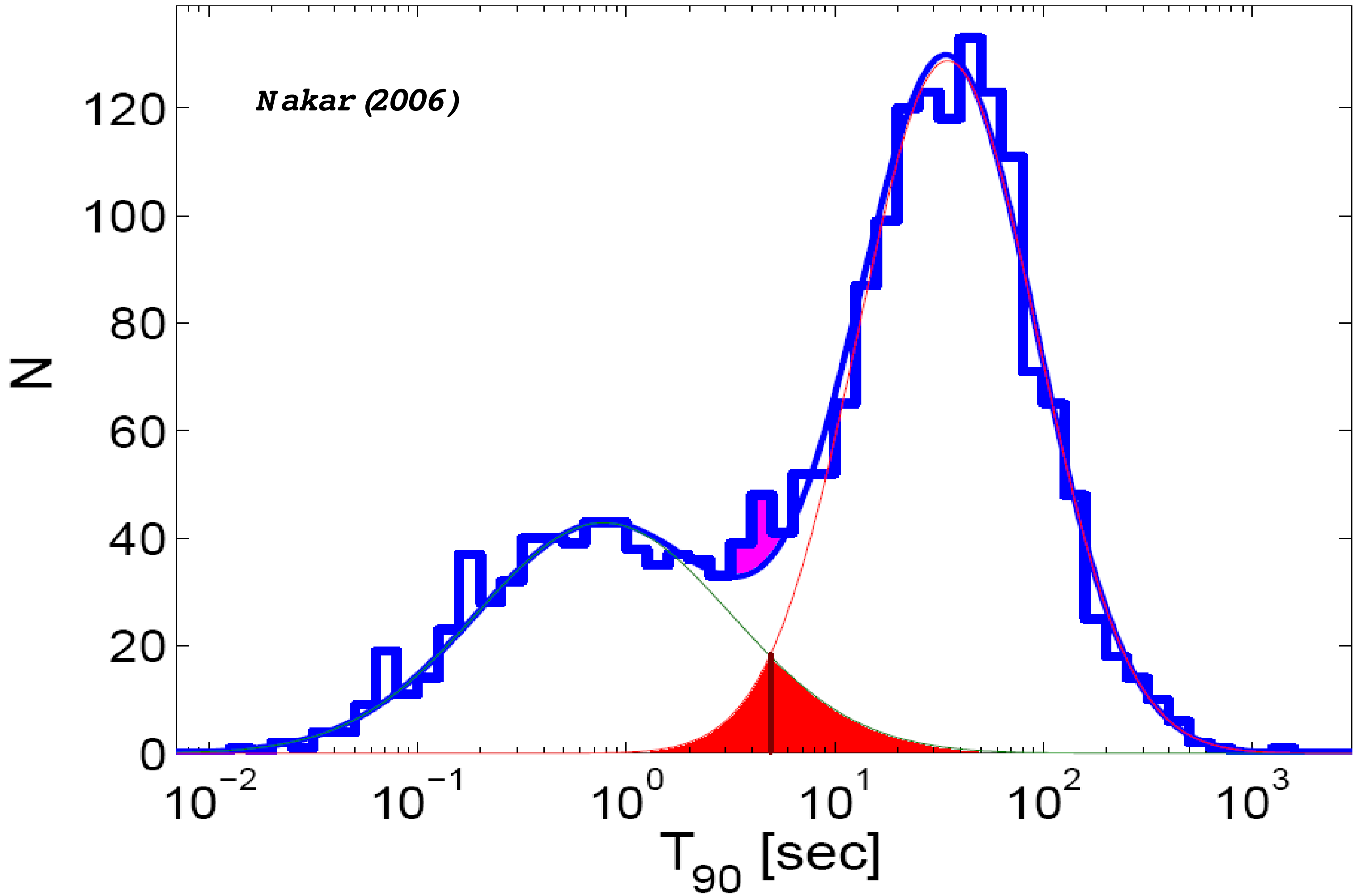
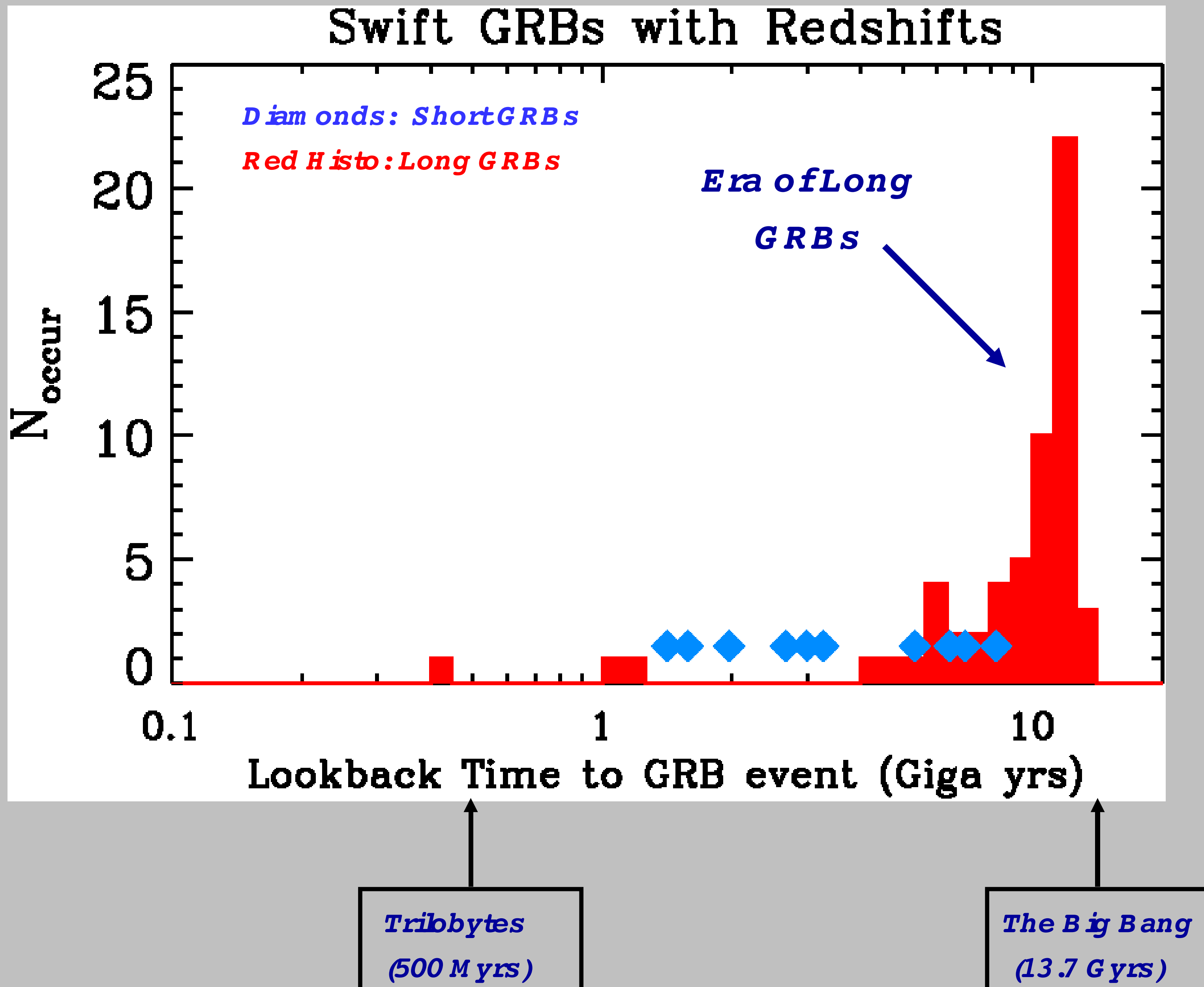
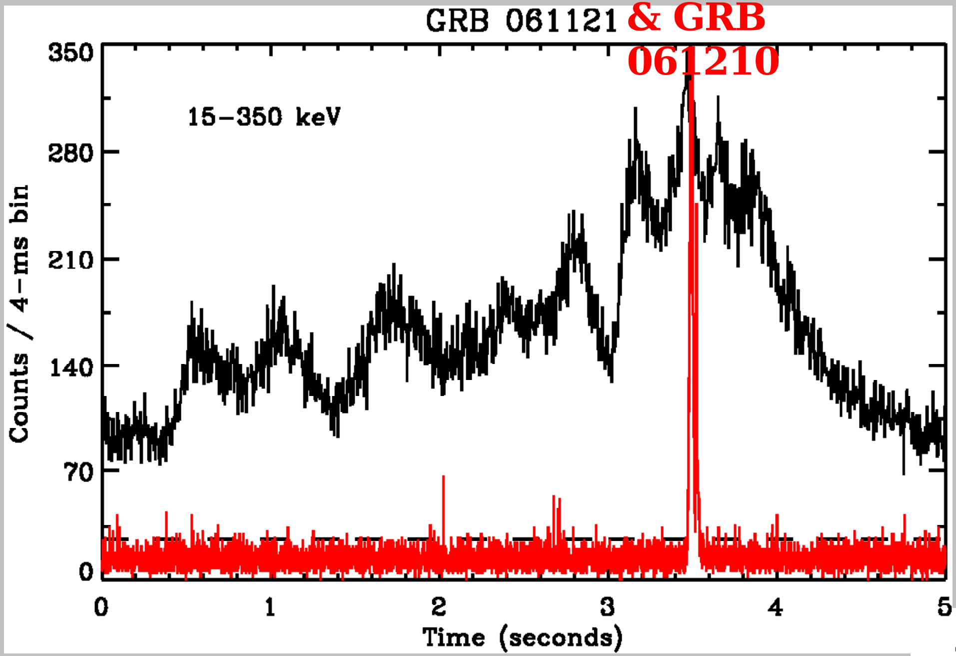


Fig. 1. The bimodal duration distribution of GRBs. The observations (2041 bursts in the current *BATSE* catalog) are marked by the thick stairs. The decomposition of the distribution into two lognormal distributions, as determined by Horváth (2002), (*thin solid lines*) and the sum of these components (*thick solid line*) are superposed.



Swift GRBs with Redshifts
Diamonds: Short GRBs
Red Histo: Long GRBs
Era of Long GRBs
25
20
15
10
5
0
N_{occur}
0.1
1
10
Lookback Time to GRB event (Giga yrs)
Tribbytes (500 M yrs)
The Big Bang (13.7 G yrs)

Pulse Widths: Brightest Short & Long GRBs

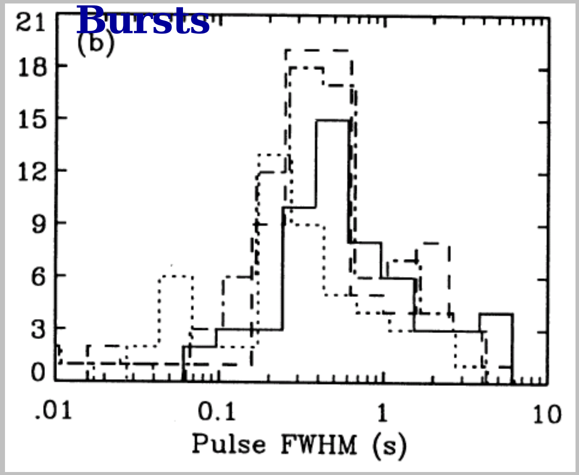


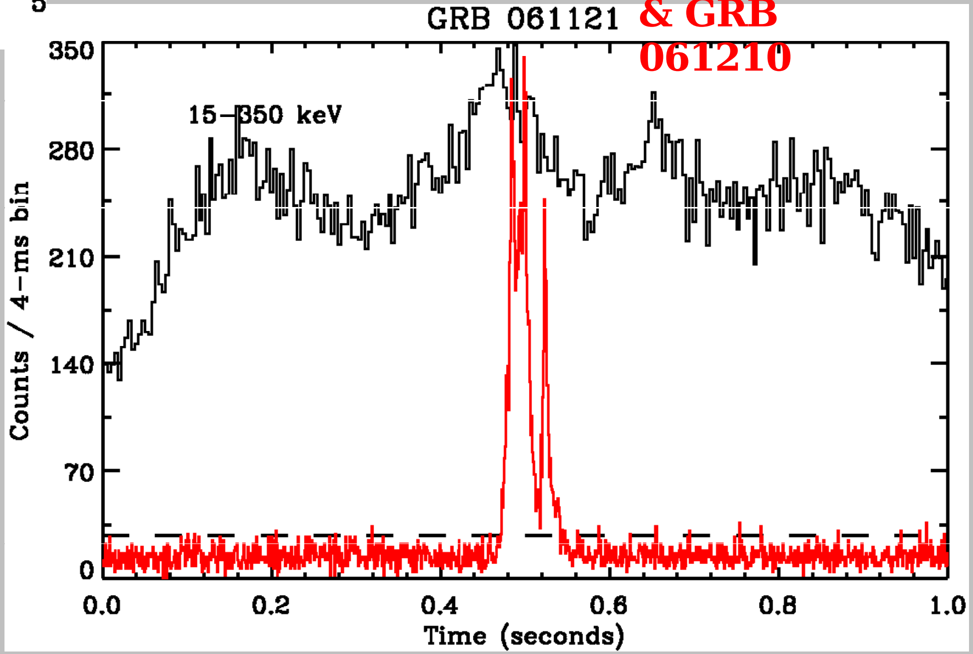
__Generalities__ *(when good S/N)*

(1) Long bursts nearly always have pulse FWHM > 100 ms, even when lag is very short.

(2) Short bursts usually have pulse FWHM ~ 5–30 ms.

Bright BATSE Long Bursts





Long & Short GRB's

- Long GRB's
  - Associated with core-collapse Sne
  - Star forming host galaxies
- Short GRB's
  - Not associated with recent star formation
  - A variety of host galaxies
  - No SNe
  - Binary mergers?
  - Collapsar