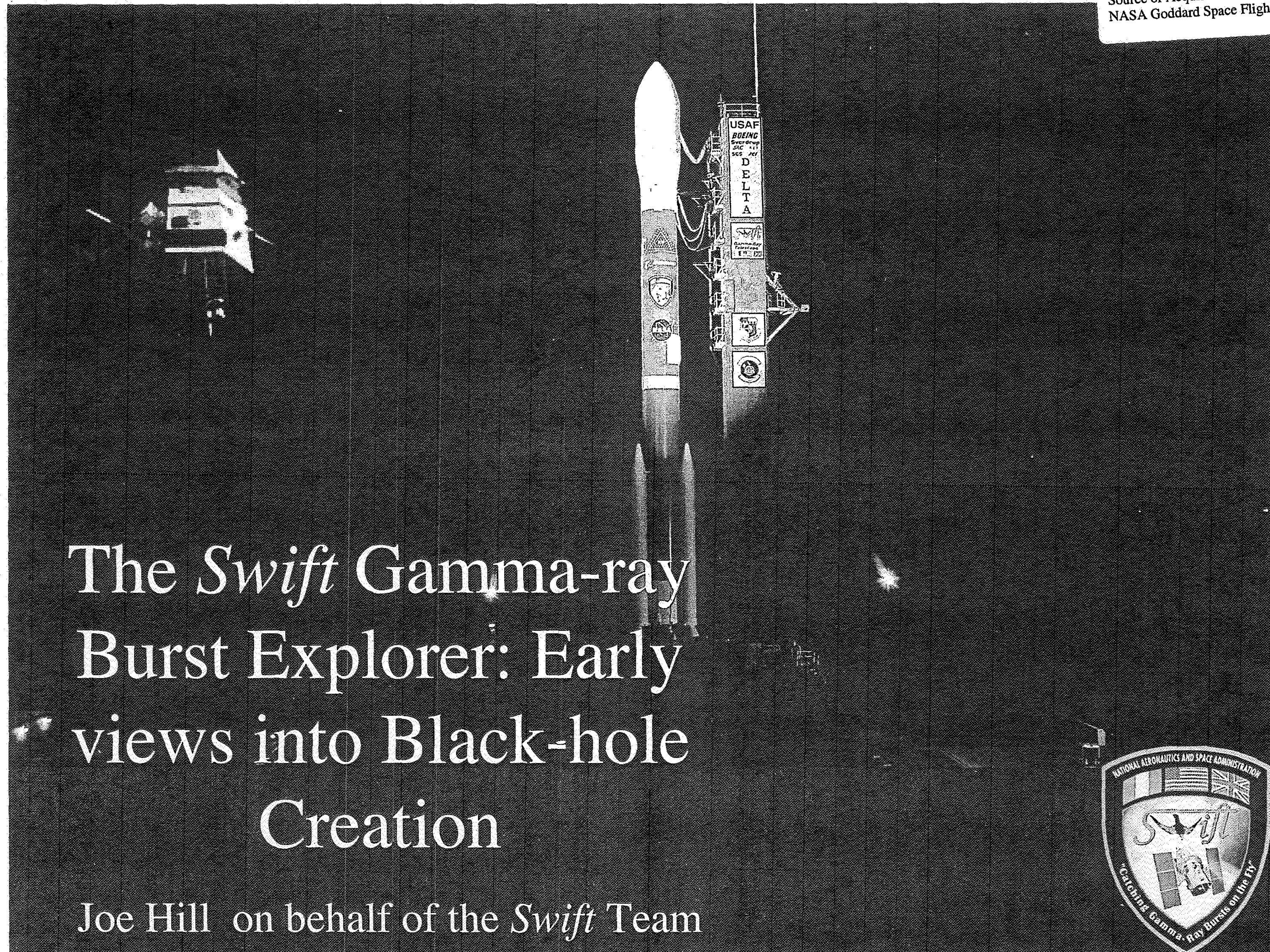


The *Swift* Gamma-ray Burst Explorer: Early views into Black-hole Creation

Joe Hill on behalf of the *Swift* Team

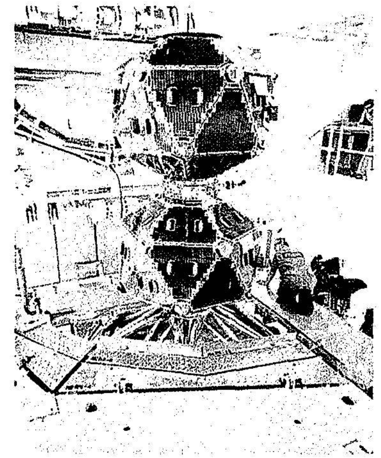
Overview

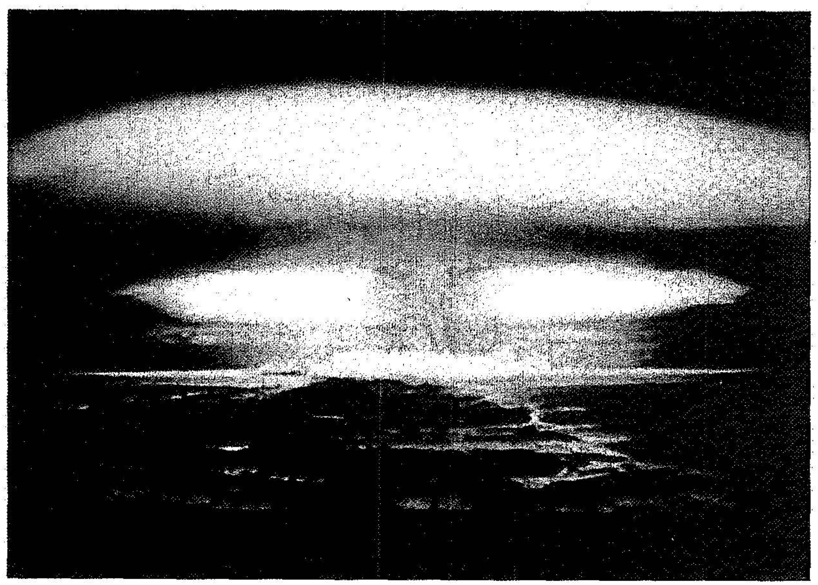
- The discovery of Gamma-ray Bursts
- The *Swift* Mission
- *Swift* afterglows - an early insight
- The detection of the elusive Short Burst
  - Catching the afterglow for the first time
- The detection of a huge explosion in the early universe
  - The most distant GRB ever detected

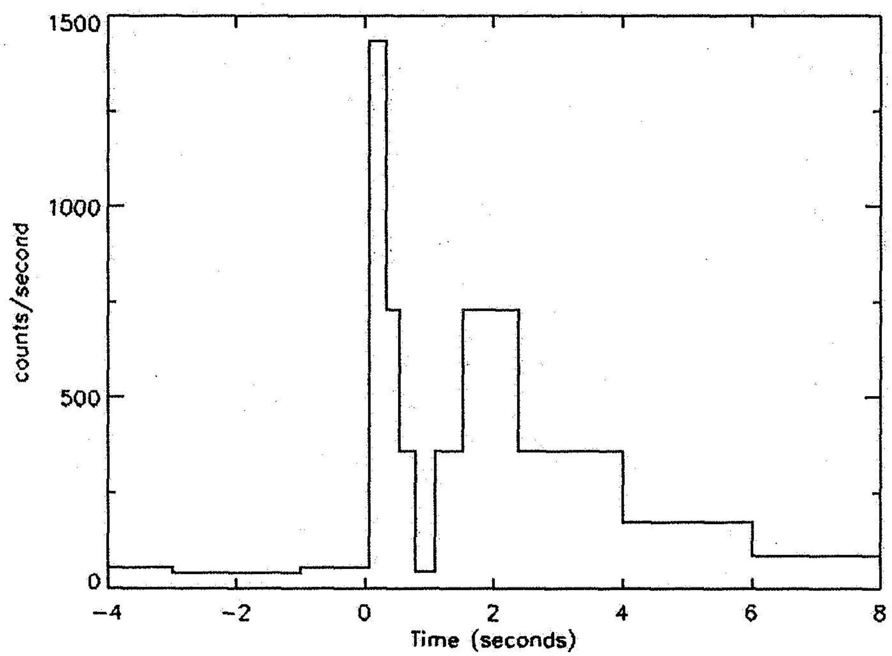
The Discovery of Gamma-ray Bursts: 1967

- Vela satellites launched in mid-1960s to monitor the Atmospheric Test Ban Treaty
  - Strange pulses discovered in 1969 by Ray Klebesadel of LANL

    Data classified until 1973







1977-1991

Interplanetary Network

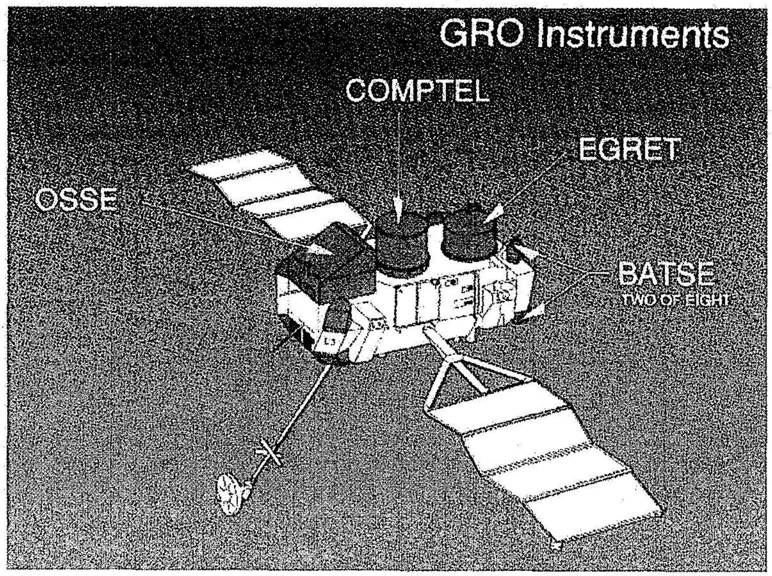
- A group of spacecrafts equipped with gamma-ray detectors used to localize gamma-ray bursts (GRB) and soft gamma repeaters (SGRs, or magnetars).
- Locations of GRBs are determined by the comparison of the arrival times of the event at the locations of the detectors used on different space missions.
- The primary disadvantage is the 1-1.5-day delay in the acquisition of data from all the spacecraft in the network.

BIG Questions of the time:

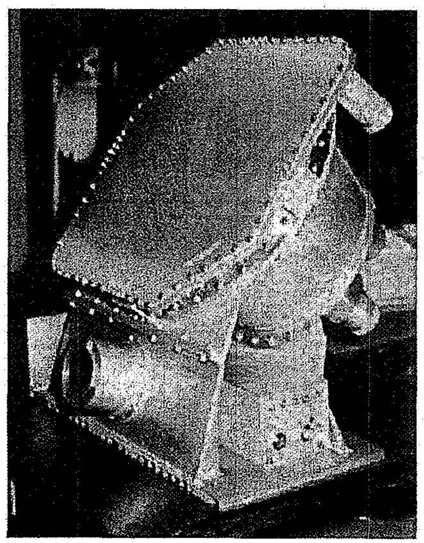
Where do GRBs come from?

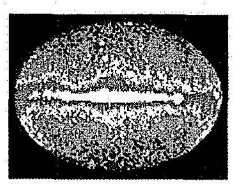
Are they local or from out-side our galaxy?

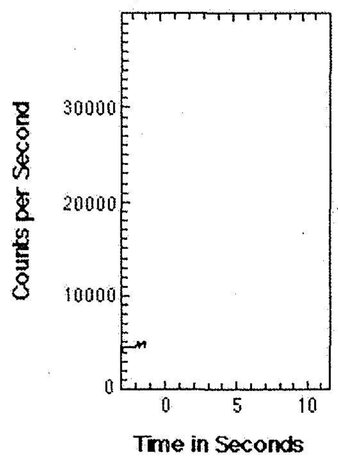
~30 Years after discovery: 1991



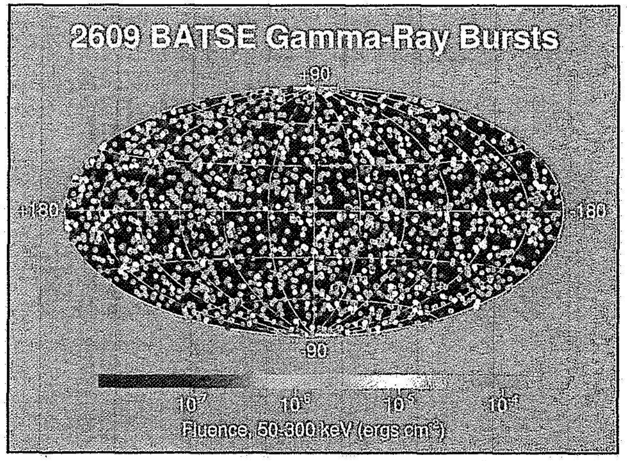
- Compton Gamma-Ray Observatory launched in April 1991
- BATSE: 2609 bursts in 8.5 years
  - Bursts are isotropic
  - Frequency ~ 1 burst per day
  - Not clear whether they are nearby or distant

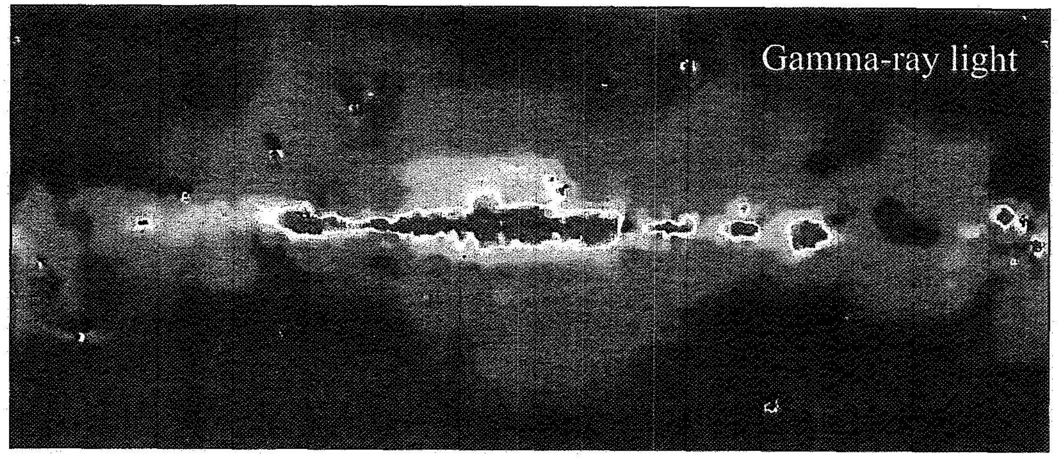


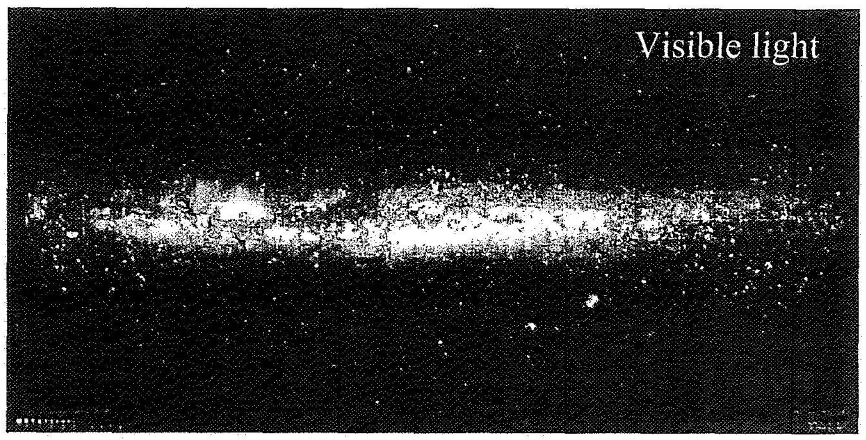


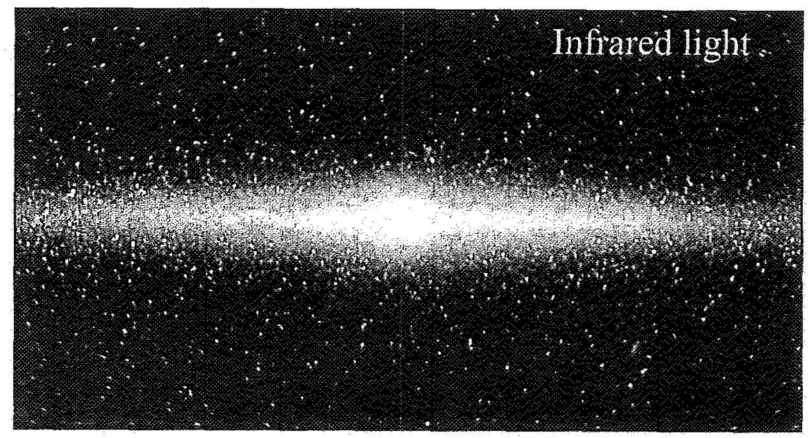


The celestial sky





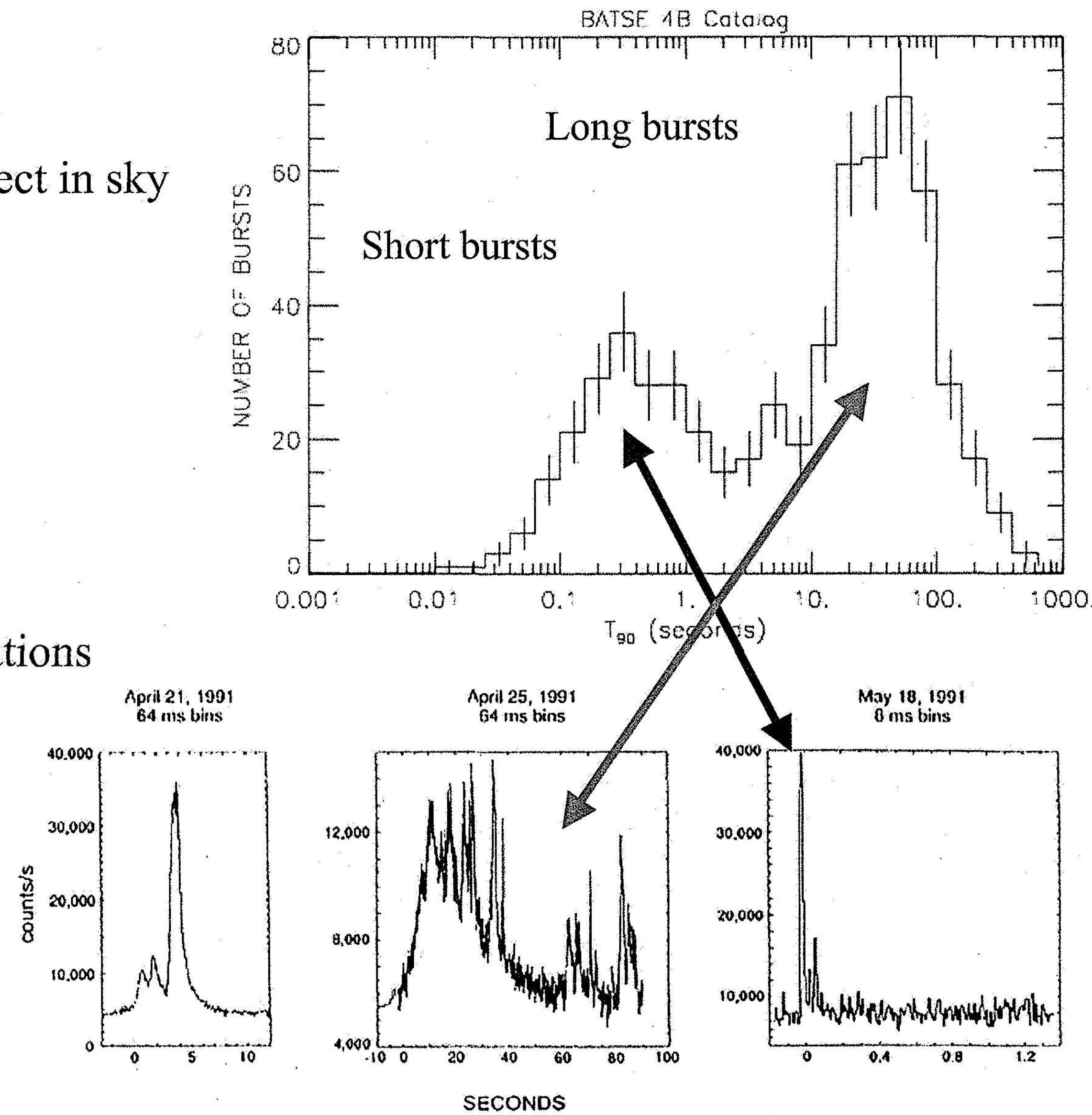




GRBs are distributed isotropically on the sky.

GRB Characteristics (BATSE)

- Characteristics:
  - About 1 per day
  - Powerful: brightest γ-ray object in sky
    - Typically 10^{51} ergs
  - Isotropic distribution
  - Finite Extent
  - Unique lightcurves
  - Bi-model distribution of durations



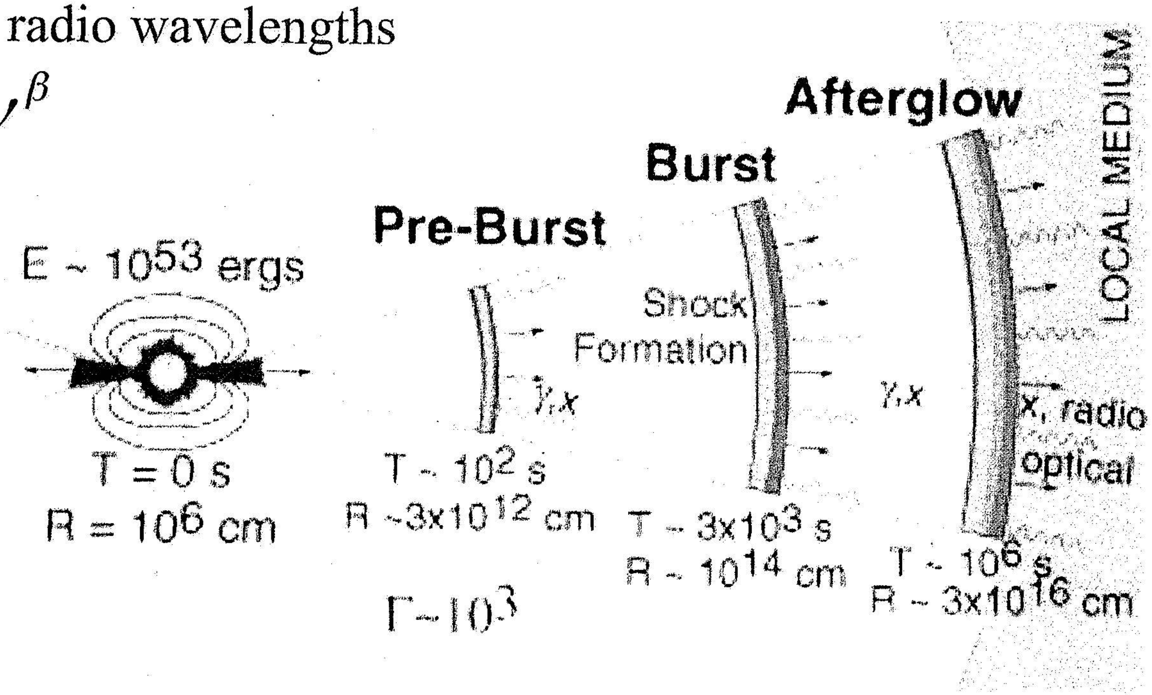
Theoretical Predictions

1992/1993: Emission mechanism: synchrotron emission from power-law distribution of electrons in highly relativistic outflows.
Prediction of external shocks from ISM deceleration.

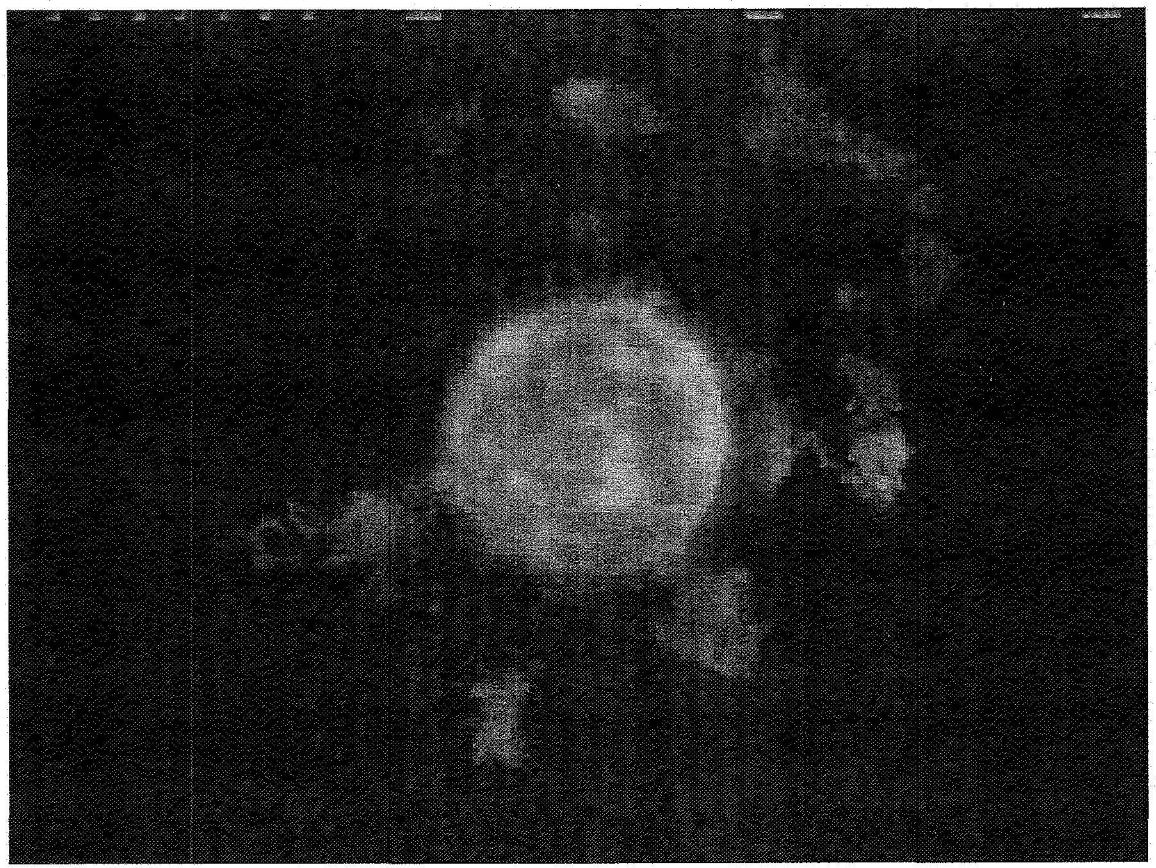
1994: Fireball-shock scenario involving colliding shells in the fireball out flow causing short timescale variability.

10th Feb 1997: Meszaros and Rees GRB relativistic fireball model published in ApJ; predicted broadband afterglows at optical, X-ray and radio wavelengths

$$F(\nu,t) \propto t^{\alpha}\nu^{\beta}$$

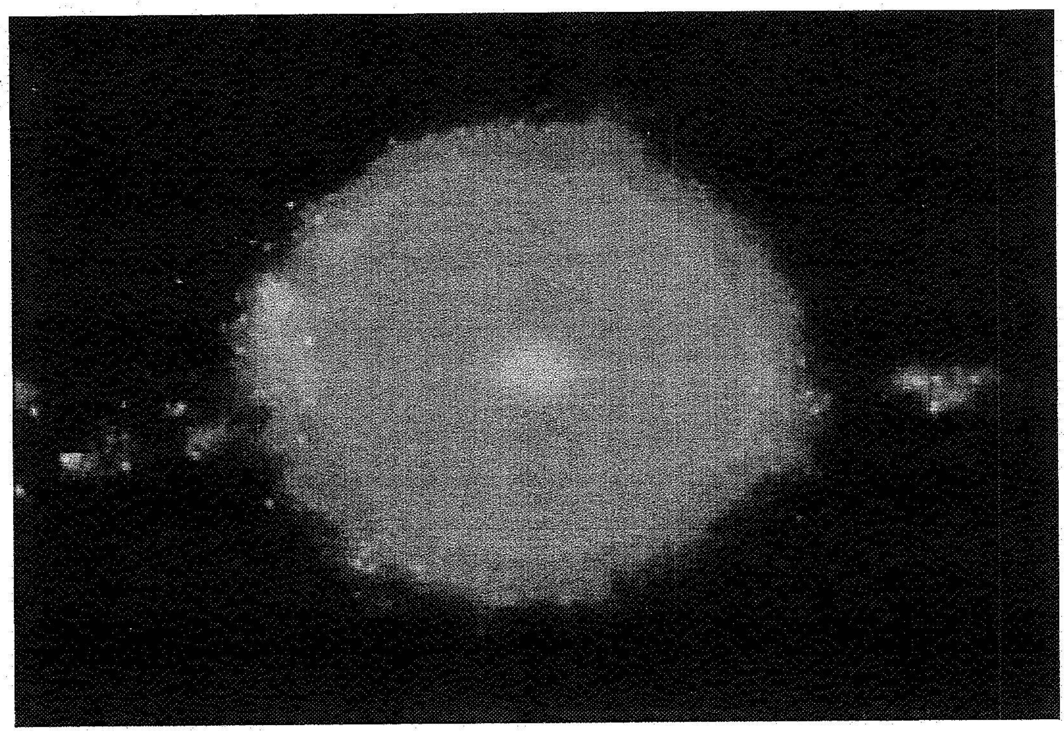


Hypernova



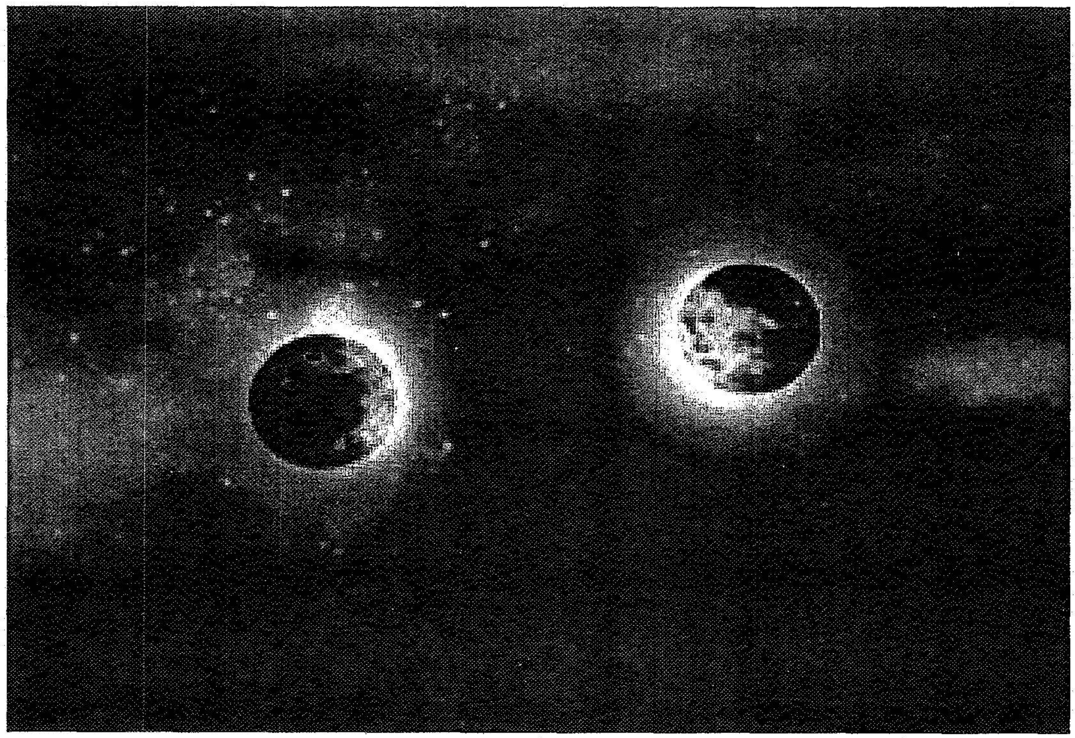
- The collapse of the core of a massive star to form a Black-Hole…..
- ~millions years before the explosion the fuel start to dwindle
- The envelope is lost
- Remaining fuel is depleted loosing radiation pressure
- Core collapses and forms a Black-Hole
- After ~few seconds streaming particle jets blast through the outer shells of the star

Supernova Theory



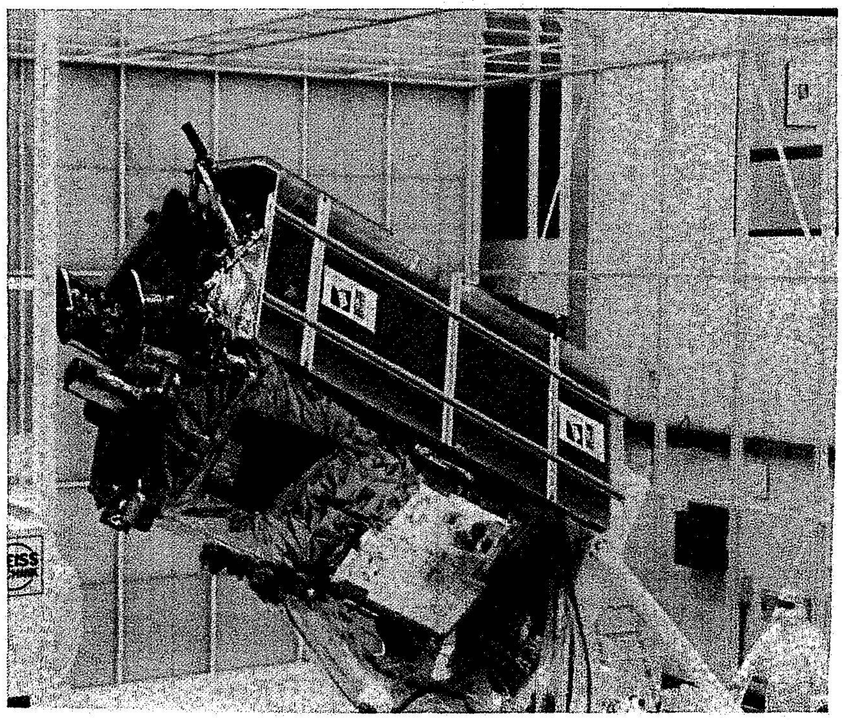
- A common SN explosion occurs when there is no longer enough fuel to maintain the fusion process………
- It begins to burn fuel faster quickly depleting the H_2 - swelling into a red Super-giant
- The Core continues to shrink until there is only Fe left and no more energy
- In <1 sec, the core implodes crushing the Fe atoms together
- The temperature rises to > 100 billion degrees
- The internal pressure overcomes Gravity causing gas to shoot out from the heart of the star in an explosive shock-wave

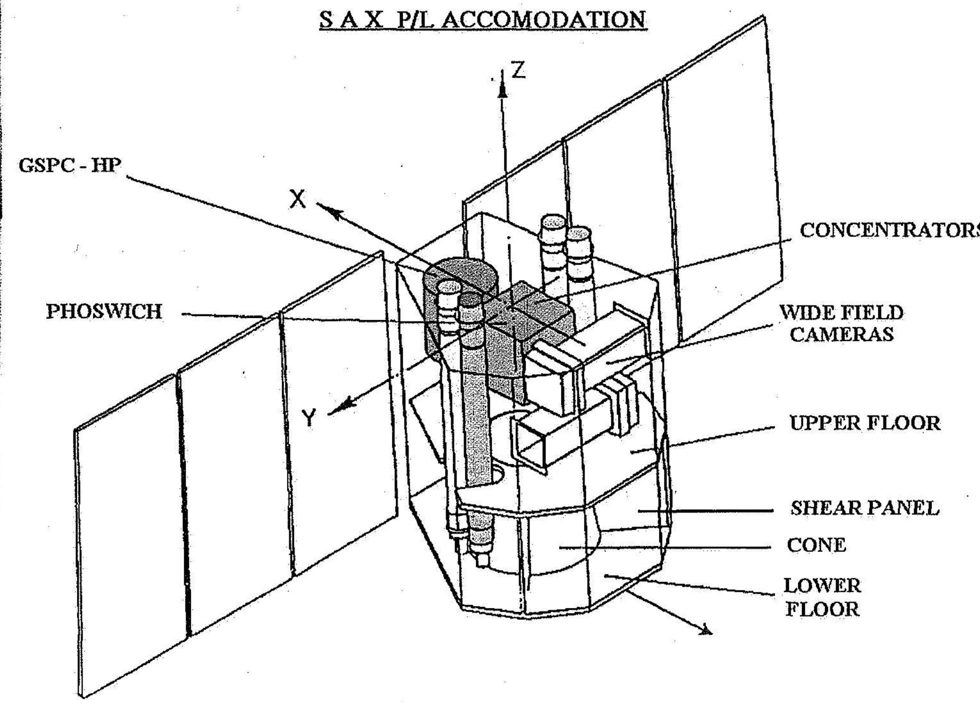
Binary Merger Theory



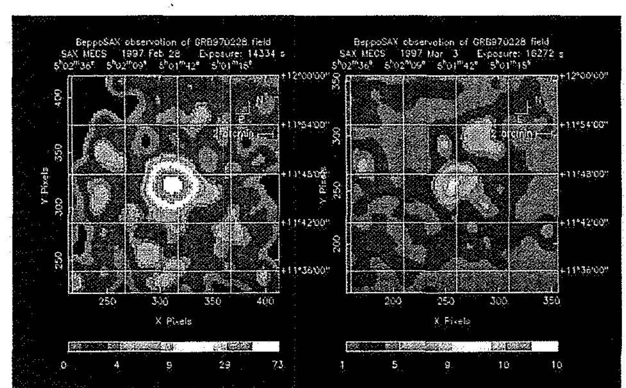
- Start with a NS-NS or an NS-BH pair orbiting each other…….
- The huge Gravitational force causes them to orbit each other with increasing velocities
- As they get closer together, they begin to become misshapen as they rip each other apart
- They finally merge in an instant, forming a Black-Hole shooting out jets of gamma-rays

Observational Breakthrough: 1997





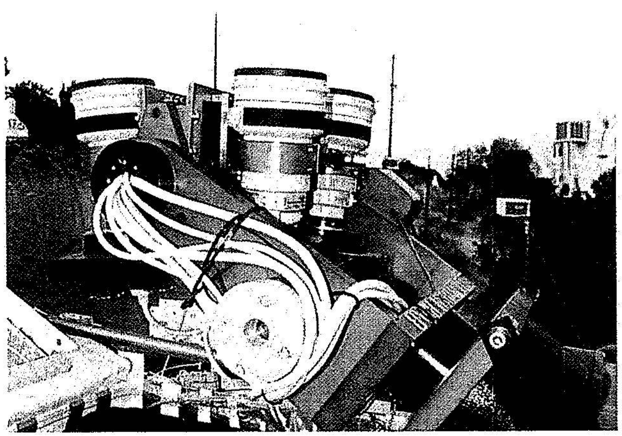
- Beppo-SAX makes the first X-ray image of a GRB afterglow.

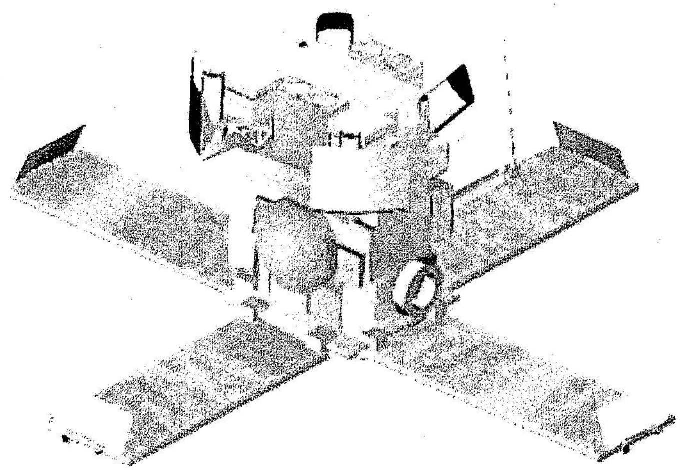


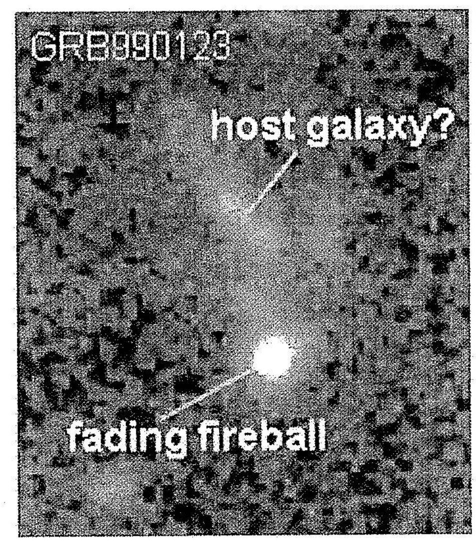
28 Feb 1997 3 March 1997

The Beppo-SAX / HETE-II era

- GRB 970228: first detection of X-ray and optical afterglows
- GRB 970508:
  - First redshift of GRB afterglow (Keck)
  - Also first radio detection of afterglow (VLA – scintillation)
    - Scintillation demonstrated that central source was compact => BH
    - Scintillation also proved superluminal expansion => fireball shock model
- GRB 990123: first optical observation of GRB (ROTSE)
  - "Biggest explosion since Big Bang"
- 55 afterglows discovered by Beppo-SAX and HETE-2
  - Typical delay of 6-8 hours in position determination

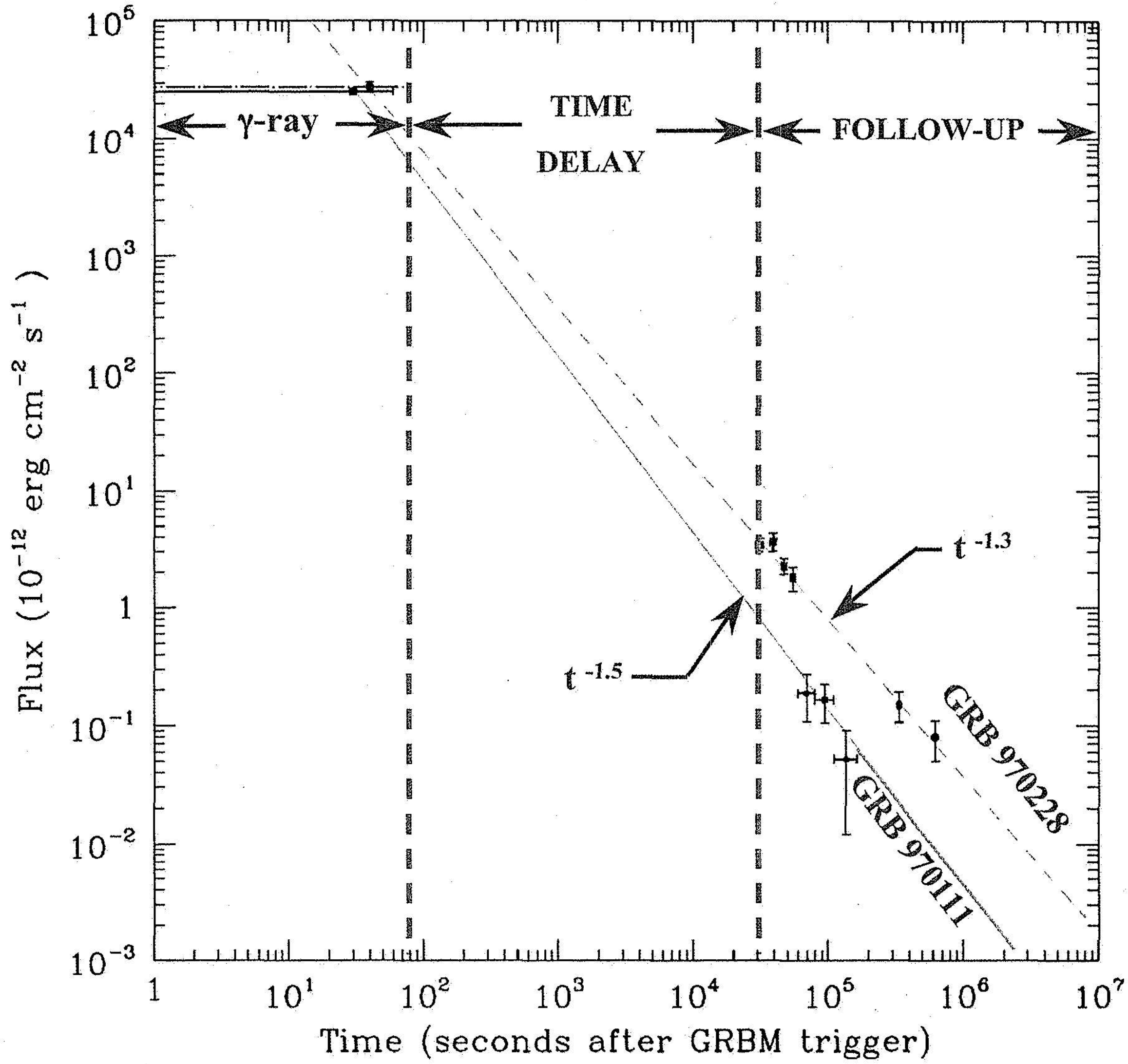




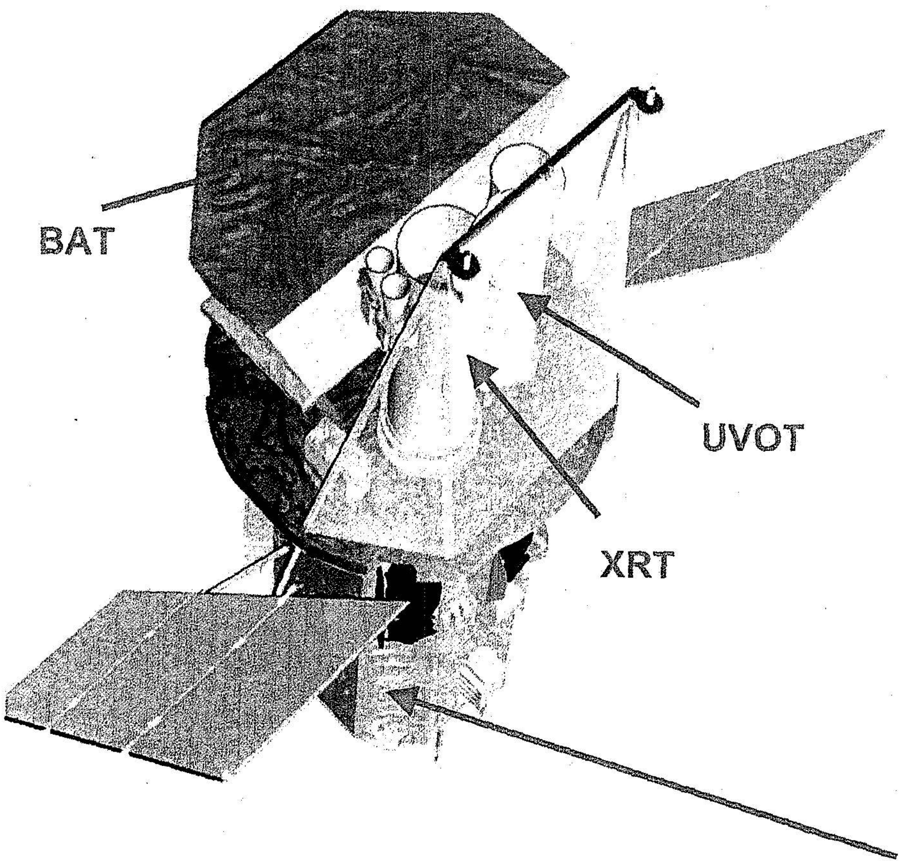


What Next?

- Need gamma-ray burst detector with large FoV
- Rapid follow-up ~minutes
  - X-ray Afterglow
  - Optical Afterglows
- Need to get localised positions rapidly to the ground

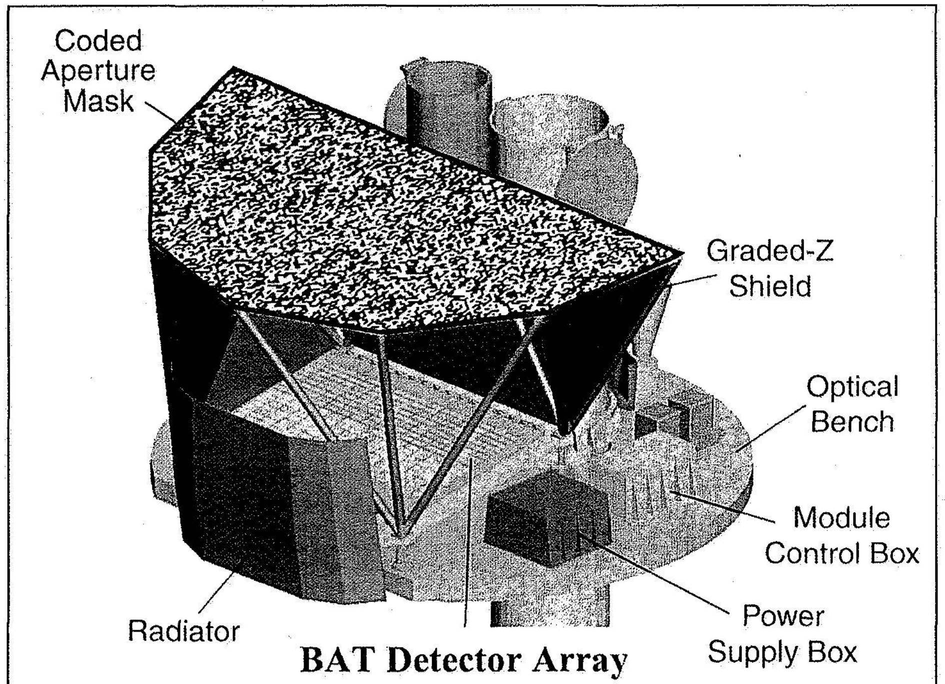


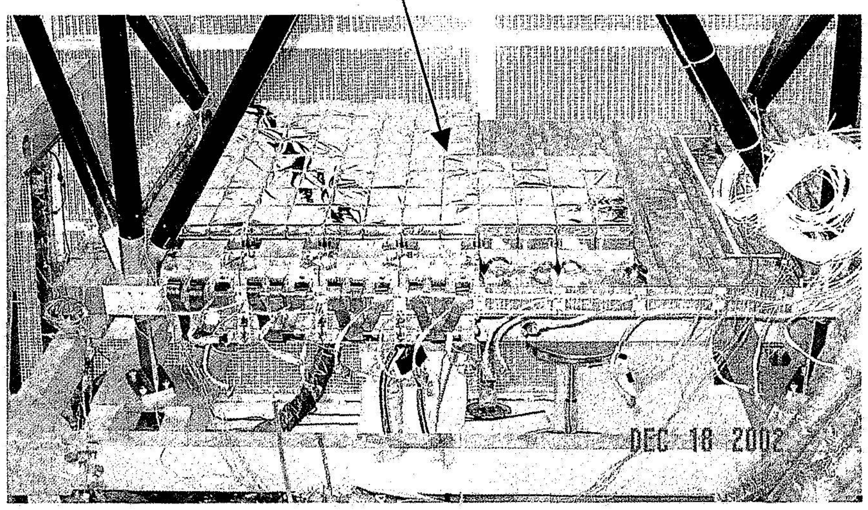
Swift Instruments



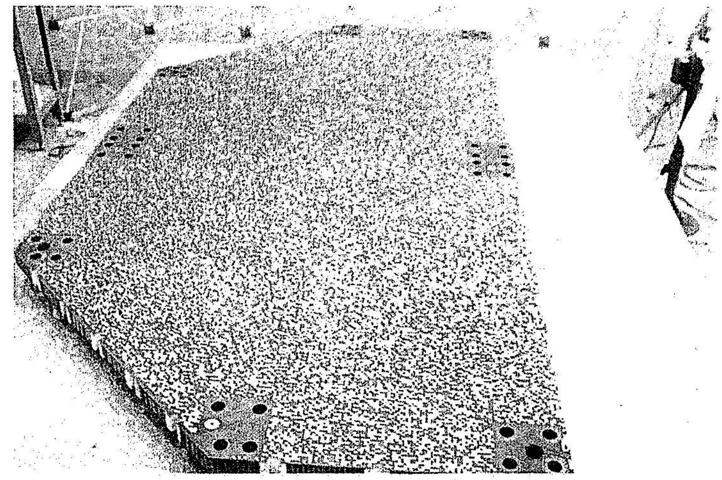
- Burst Alert Telescope (BAT)
  - New CdZnTe detectors
  - Detect ~100 GRBs per year depending on logN-logS
  - Most sensitive gamma-ray imager ever
- X-Ray Telescope (XRT)
  - Arcsecond GRB positions
  - CCD spectroscopy
- UV/Optical Telescope (UVOT)
  - Sub-arcsec imaging
  - Grism spectroscopy
  - 24^{th} mag sensitivity (1000 sec)
  - Finding chart for other observers
- Spacecraft
  - Autonomous re-pointing, 20 - 75 sec
  - Onboard and ground triggers

Burst Alert Telescope (BAT)





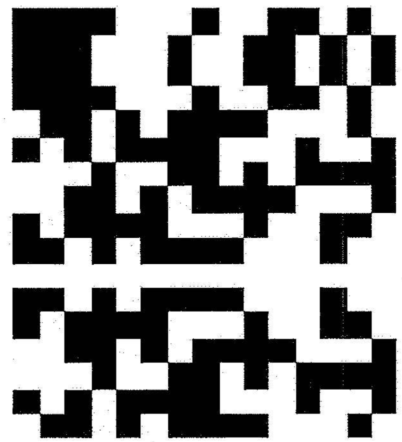
Coded Aperture Mask



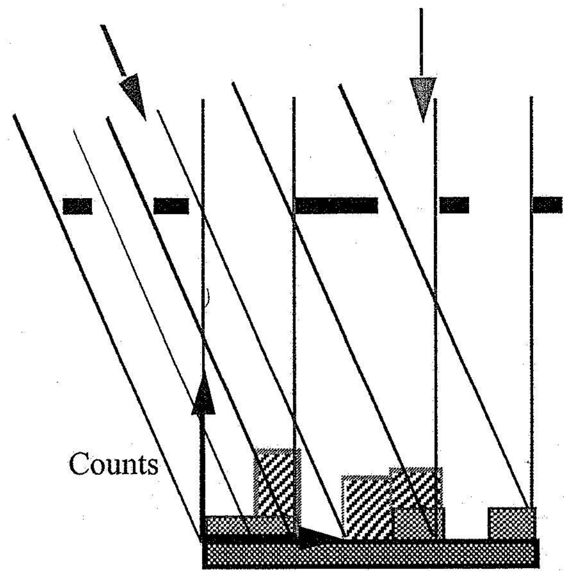
Telescope	Coded Aperture
Aperture	2.7 m^2
Energy Range	15 - 150 keV (12-300 keV)
Energy Resolution	7 keV (5 keV)
Location Resolution	1-4 arcmin (1' - 4')
Sensitivity	$1x10^{-8}$ erg sec^{-1} cm^{-2}
Field of View	1.4 steradian
PSF	17 arcmin
Detector	32 000 CZT
Mode	Photon-Counting (Autonomous)

Coded-Aperture Imaging

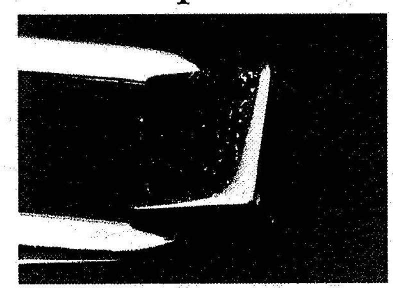
Coded Aperture
Mask Pattern



5 mm square Pb tiles



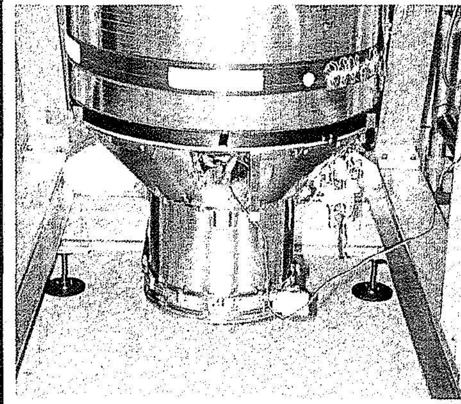
4 mm square CZT

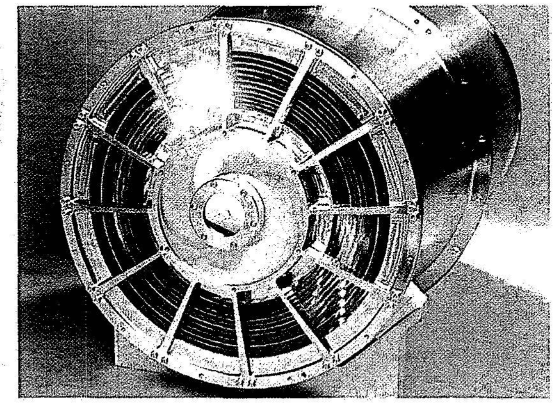


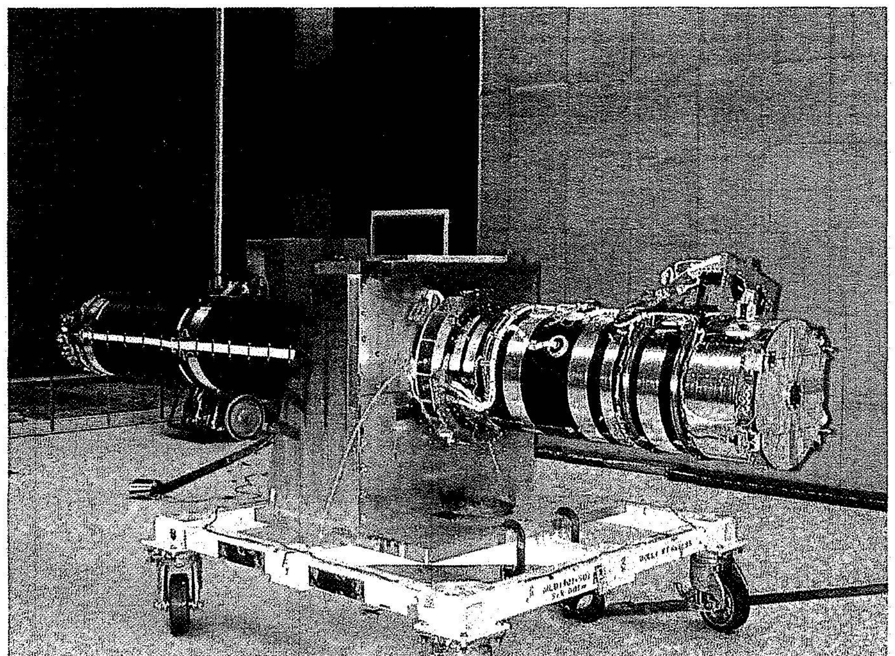
- Source Photons "Encoded" by Partially Blocked Aperture
- Can be Decoded in Data Analysis to Determine Source Position
- Missing Pixels = Graceful Degradation in Sensitivity

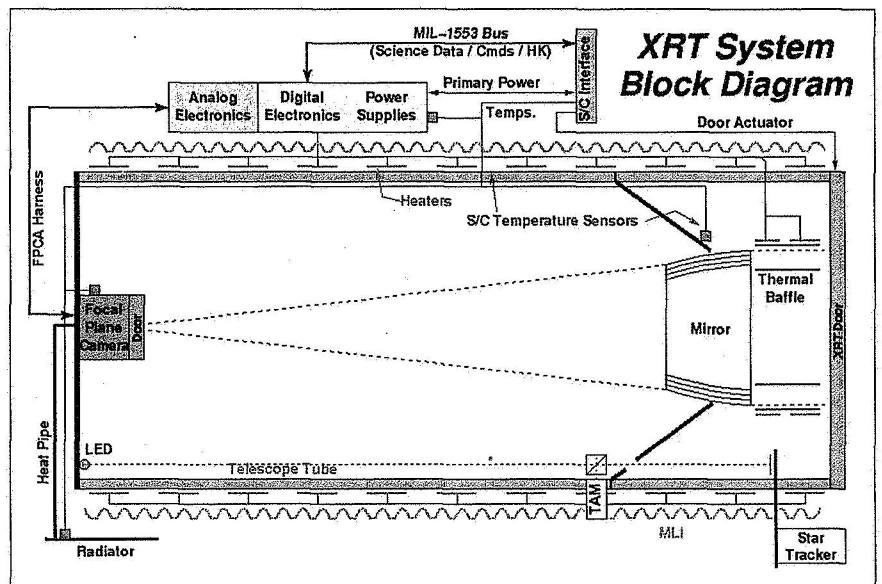
The X-Ray Telescope

Telescope	Wolter I
Energy Range	0.2-10 keV
Aperture	0.51 m
Sensitivity	1x10^{-14} erg sec^{-1} cm^{-2} in 10 000 s
Field of View	23.6 x23.6 arcmin^2
PSF	18 arcsec FWHM @ 1.5 keV
Detector	e2v CCD-22
Mode	Autonomous

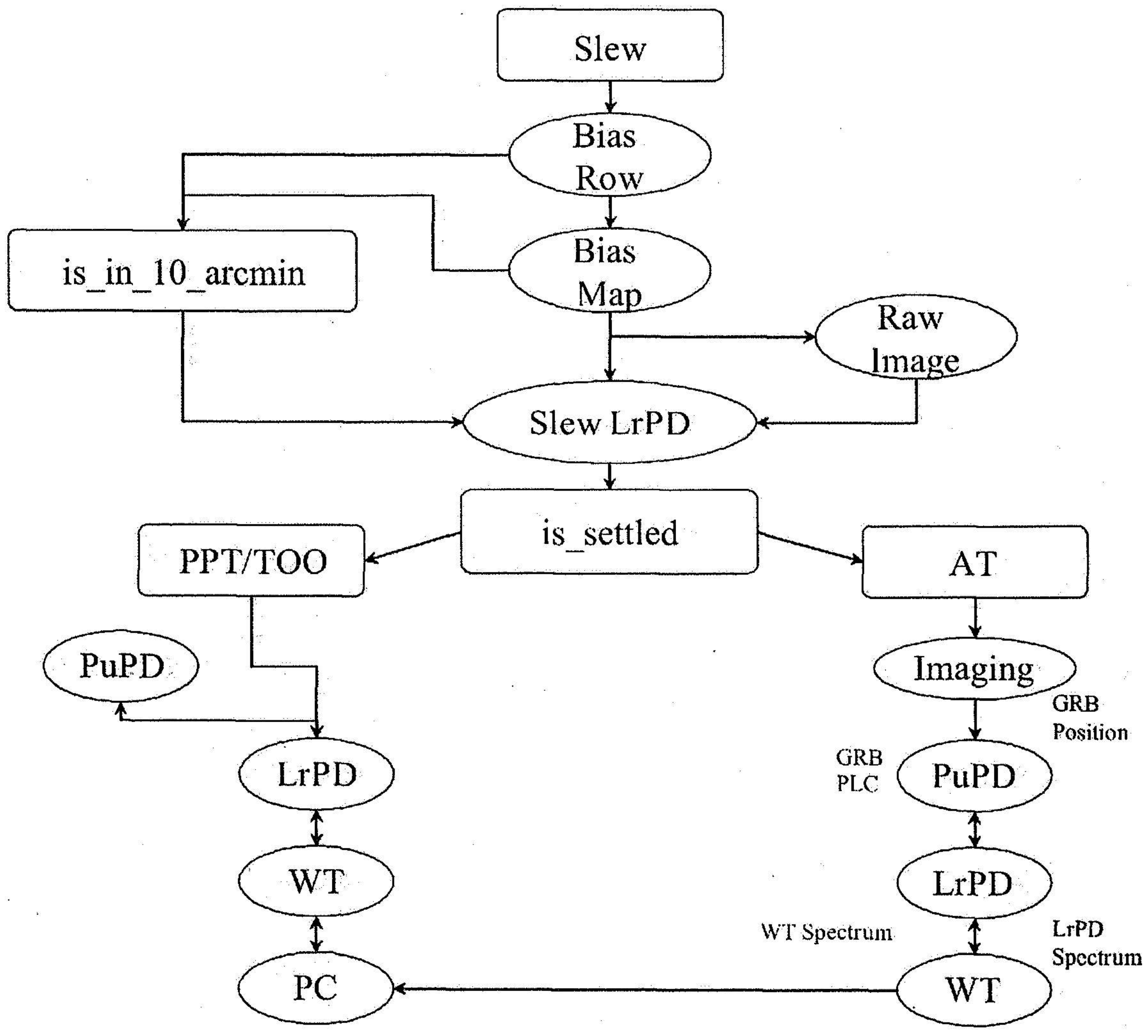






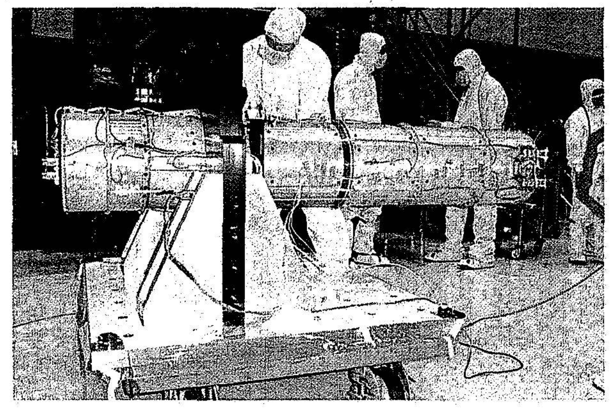


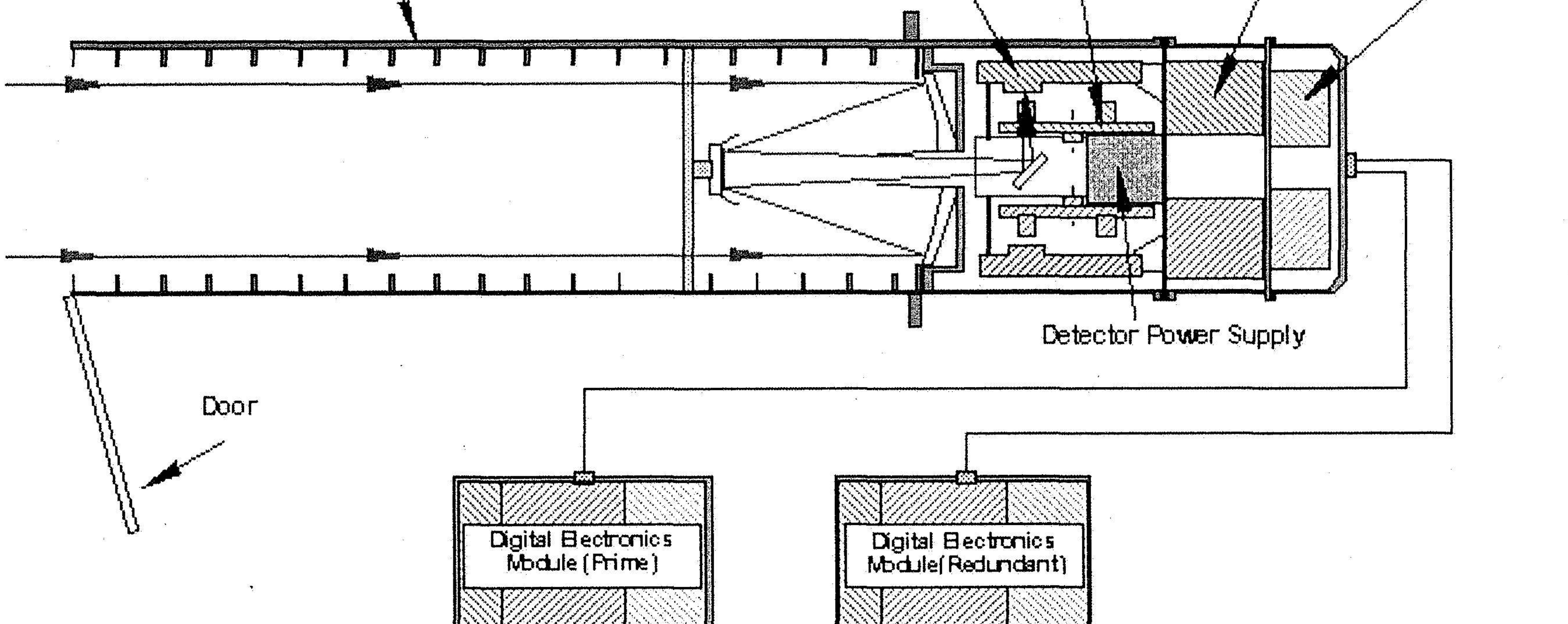
Autonomous Operation of the XRT



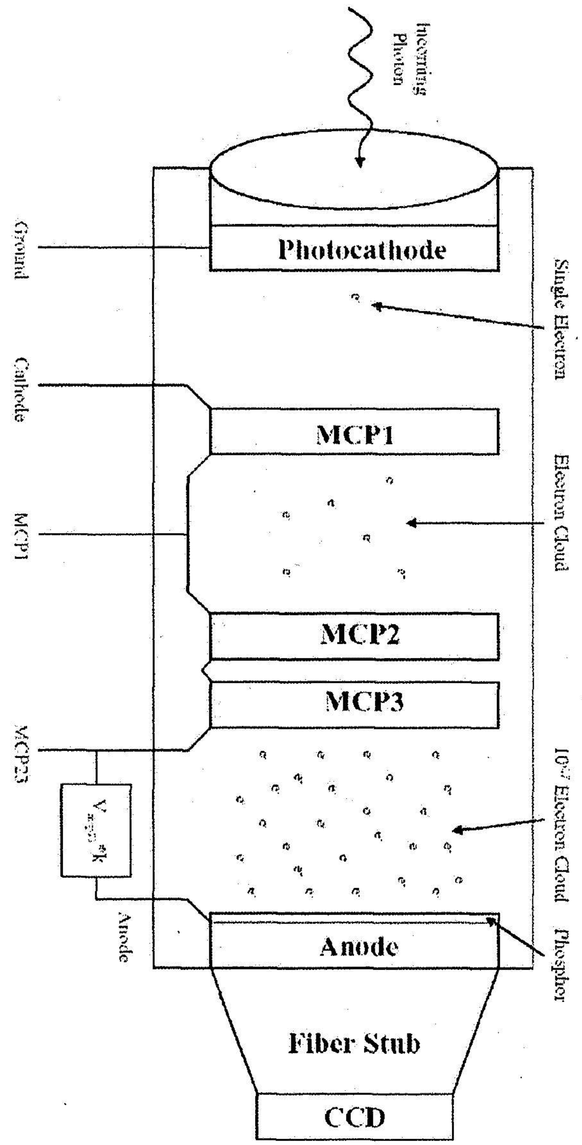
The UV/Optical Telescope

Telescope	Modified Ritchey-Chrètien
Aperture	30 cm diameter
Wavelength	170-600 nm
Sensitivity	m_B=24.0 in white light in 1000 s
Field of View	17 x17 arcmin^2
PSF	0.9 arcsec FWHM @ 350 nm
Detector	MCP Intensified CCD
Mode	Photon Counting

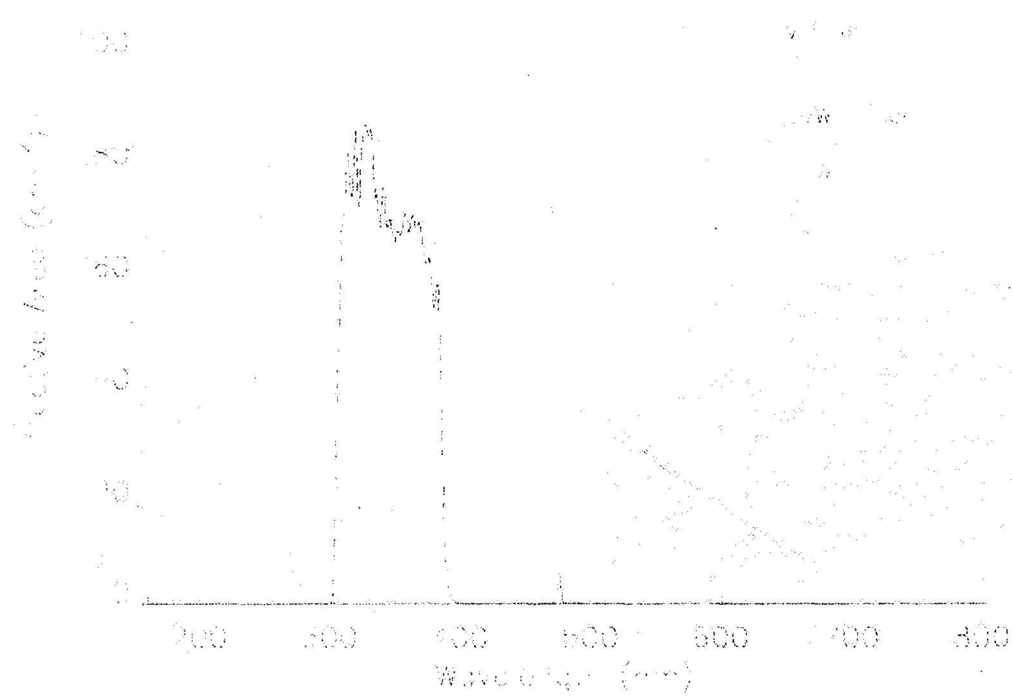




The UV/Optical Telescope



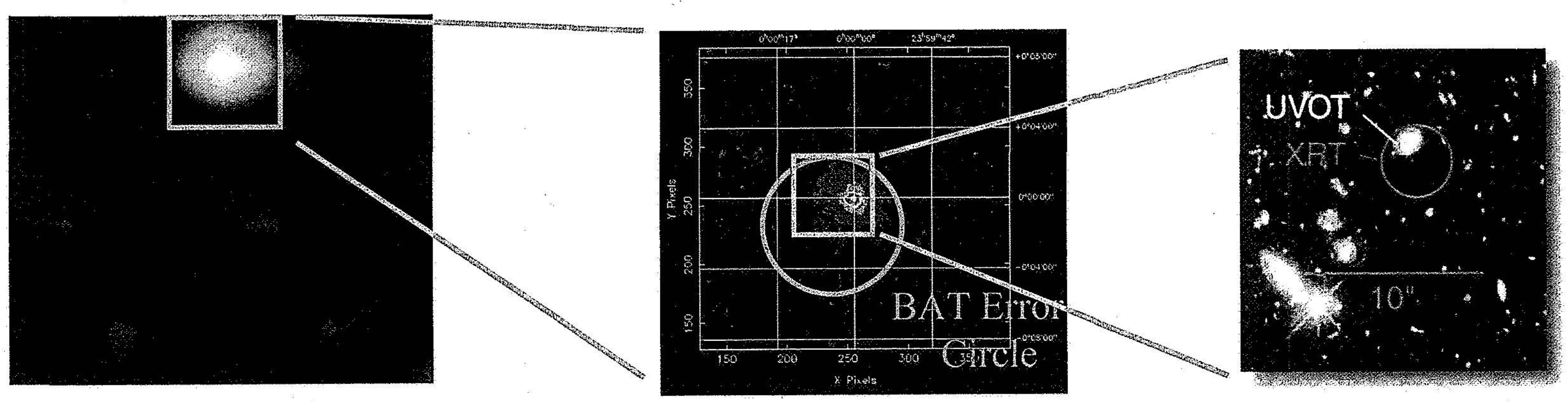
10.8 ms readout of 17 x17 arcmin FoV
Onboard centroiding provides photon positions



Observing Scenario

1. Burst Alert Telescope triggers on GRB, calculates position to ~ 1 arcmin
2. Spacecraft autonomously slews to GRB position in 20-70 seconds
3. X-ray Telescope determines position to ~ 3 arcseconds
4. UV/Optical Telescope images field, transmits finding chart to ground

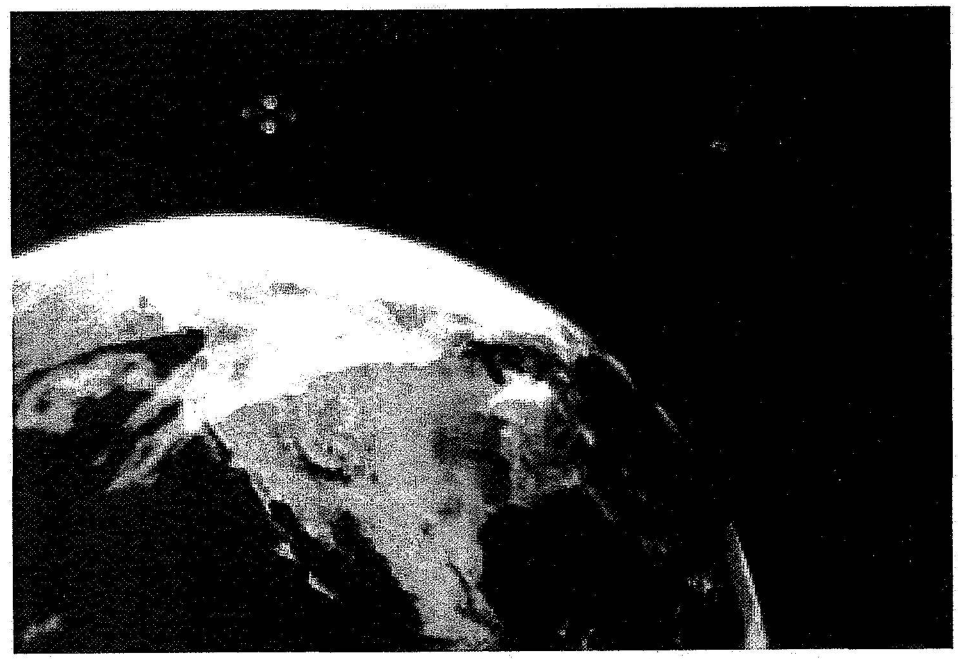
BAT Burst Image | XRT Image | UVOT Image



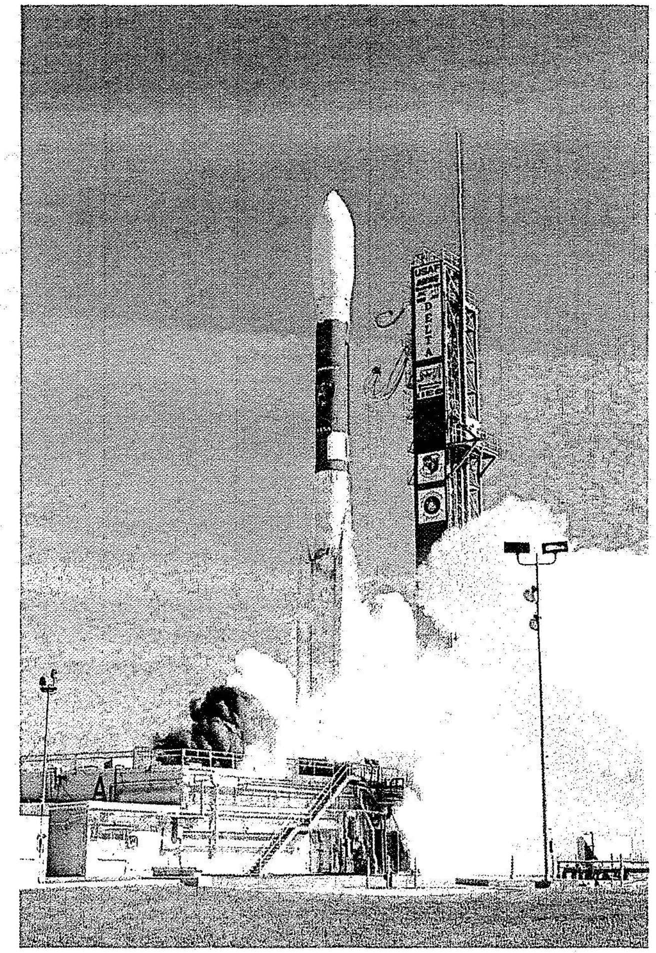
T~10 sec | T~100 sec | T~300 sec

Data transmission

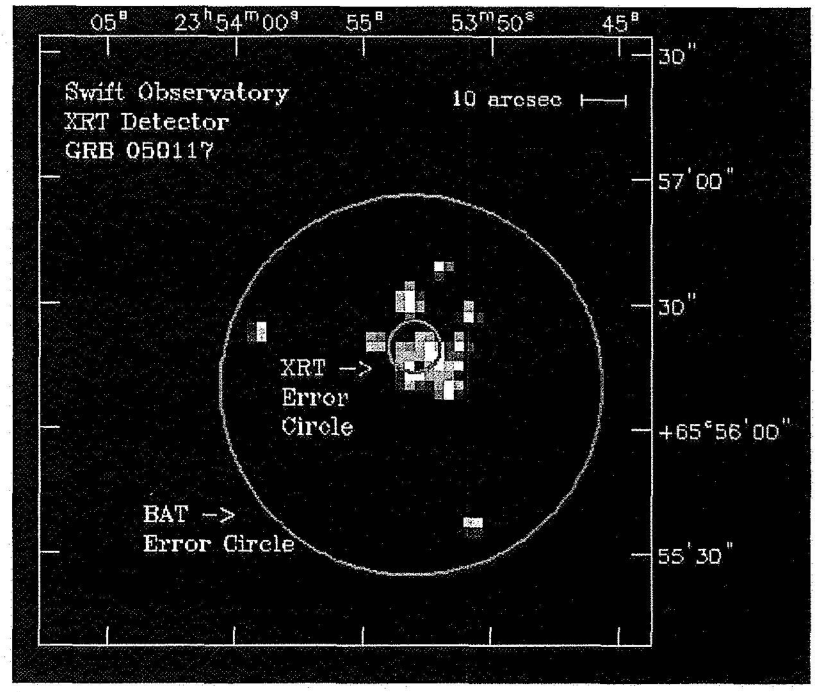
- Rapid dissemination of data to the world via TDRSS
  - Positions
  - Quicklook Lightcurves
  - Raw Images
  - Quicklook spectra
- Ground pass over Malindi to telemeter data from the solid state recorder on the spacecraft for ground processing
  - Event files
  - Processed lightcurves
  - Refined positions
  - Spectral characteristics



The Swift Observatory



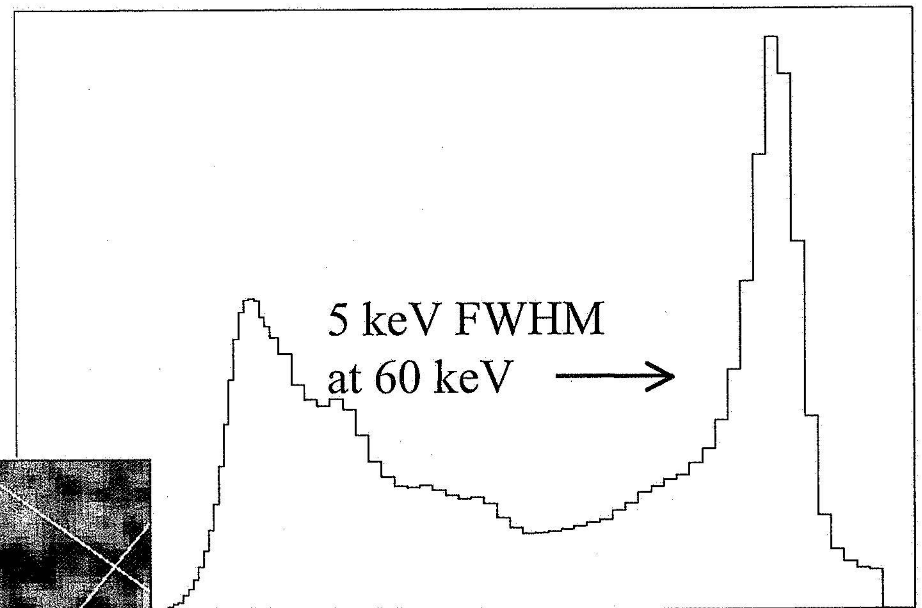
- Launched: 20 November 2004
- BAT First Light: 3 December 2004
- XRT First Light: 11 December 2004

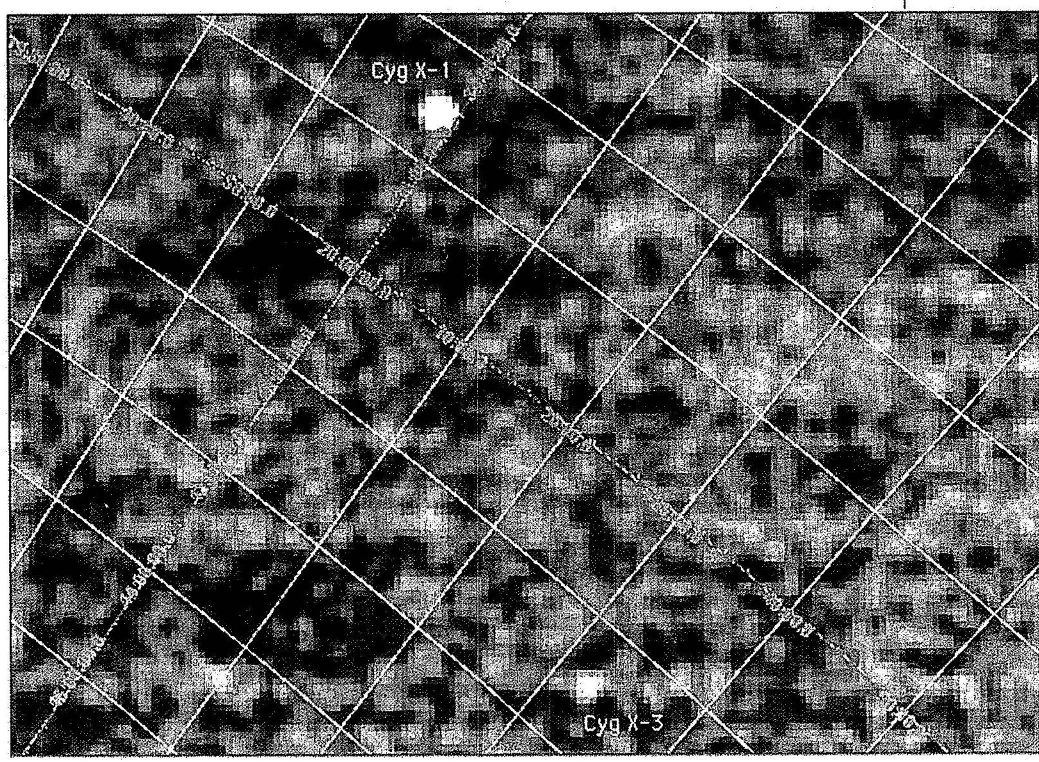


- First BAT Burst: 17 December 2004
- First XRT Afterglow: 23 December 2004
- UVOT First Light: 12 January 2005
- Data public since 5 April 2005

BAT First Light

On-Orbit Am241 Cal Spectrum
32K detectors summed together



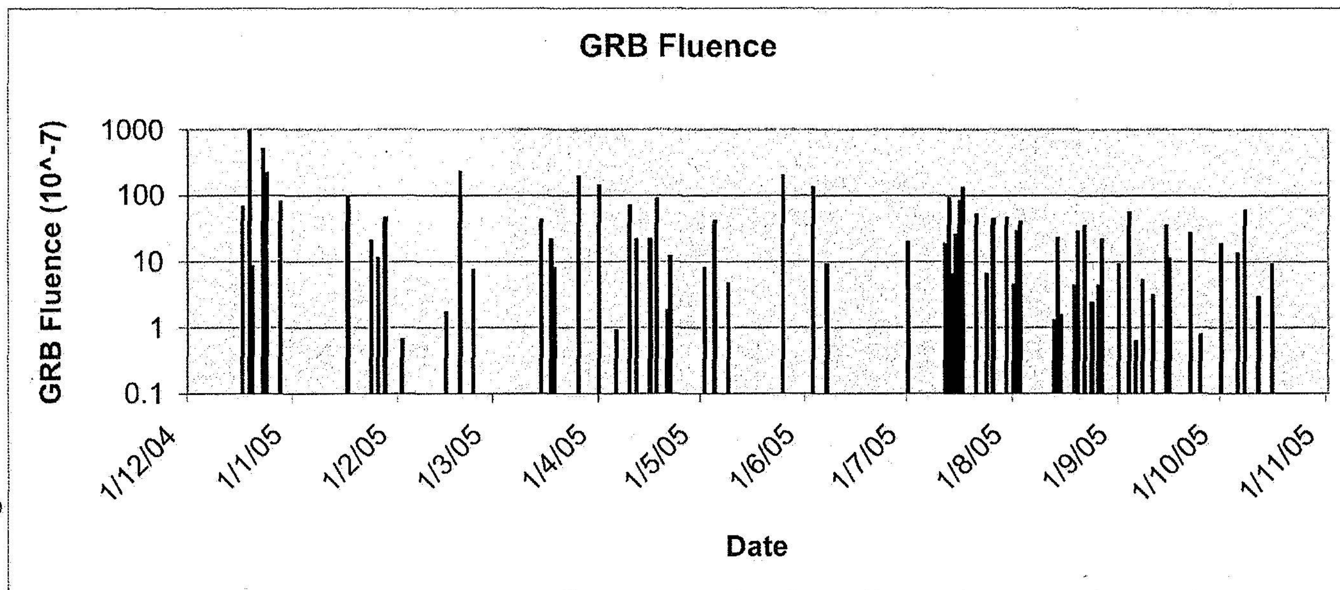


Pixel = 17'
FWHM = 22'
Position < 4'

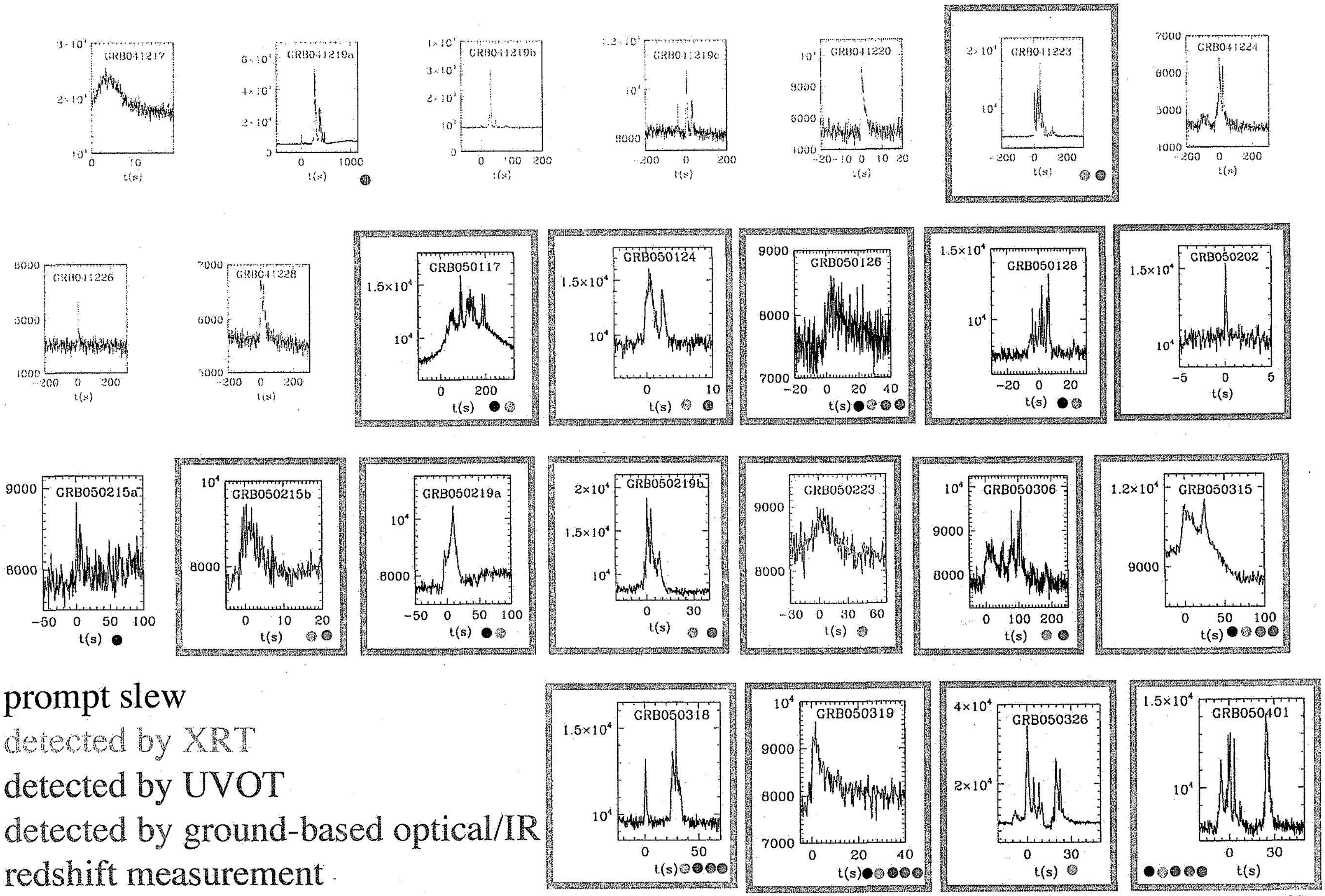
BAT Bursts

- **84 GRBs detected/imaged since 17 Dec. 04 (45 weeks as of 20 Oct. 05)**

041217	050315	050410a,b	050502b	050603	050715	050730	050815	050827
041219a,b,c	050318	050412	050505	050607	050716	050801	050819	050904
041220	050319	050416a,b	050507	050701	050717	050802	050820a,b	050906
041223	050326	050418	050509a,b	050712	050721	050803	050822	050908
041224	050401	050421	050525	050713a,b	050724	050813	050824	050911
041226	050406	050422	050528 (?)	050714b	050726	050814	050826	050915a,b
041228								050916
050117								050922b,c
050124								050925 (?)
050126								051001
050128								051006
050202								051008
050215a								051012
050215b								051016a,b
050219a,b								
050223								
050306								



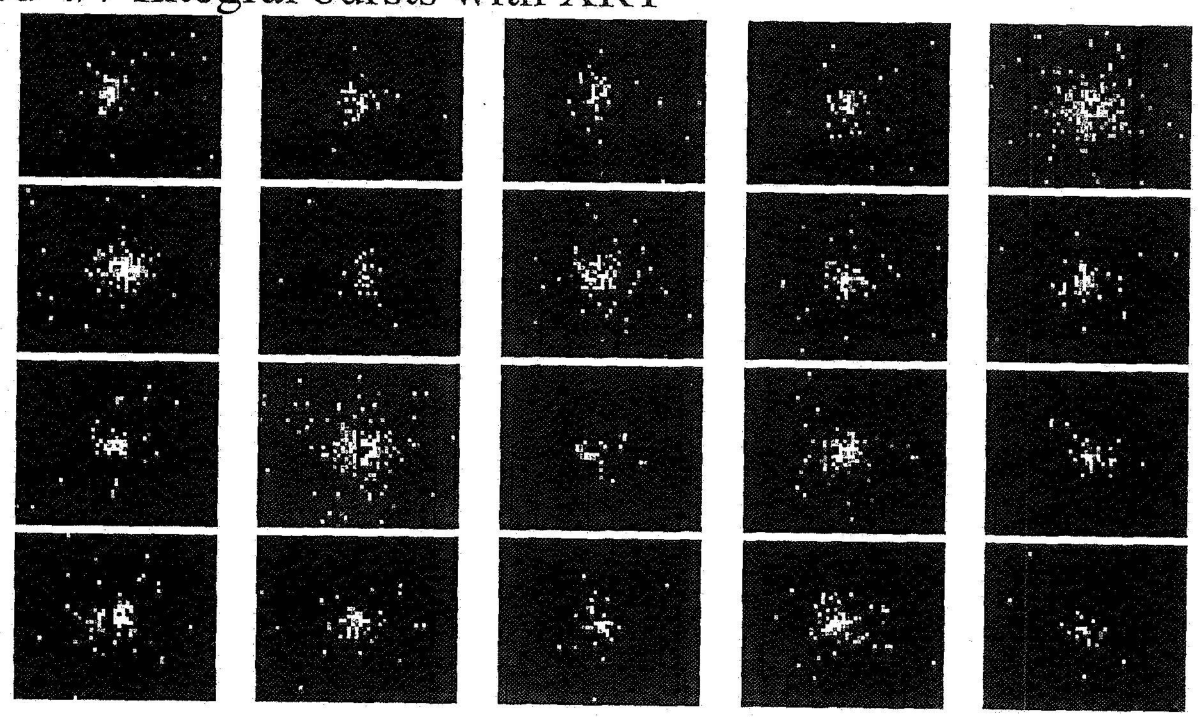
Light Curves of First 25 BAT GRBs



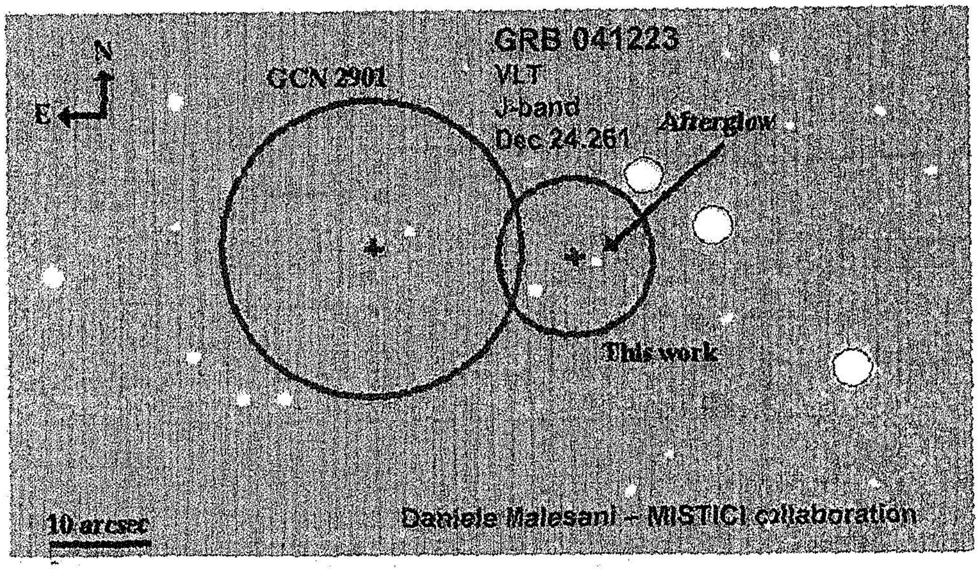
- ● = prompt slew
- ● = detected by XRT
- ● = detected by UVOT
- ● = detected by ground-based optical/IR
- ● = redshift measurement

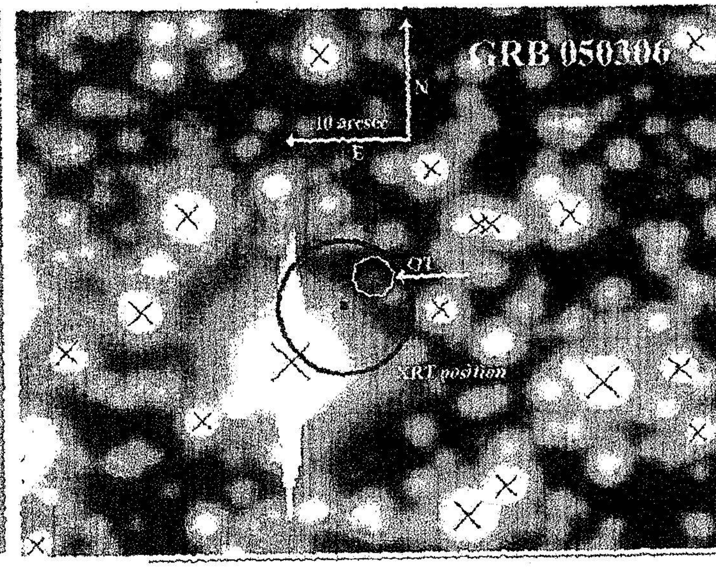
XRT Detections of BAT GRBs

- Detected 68/70 with XRT (observed @ T < 200 ks)
  - Observed four during burst: 050117, 050717, 050820a, 050904
  - 70% Swift detections were prompt observations (< 350 s)
    - 82% have fast decline or flare within first ~5 minutes
  - 22 have redshift measurements:
    - Average redshift: 1.8 (compared with about 1 for Beppo-SAX bursts)
    - Highest redshift: 6.29 (Highest on record)
- Detected 2/3 HETE burst with XRT
- Detected 4/7 Integral bursts with XRT

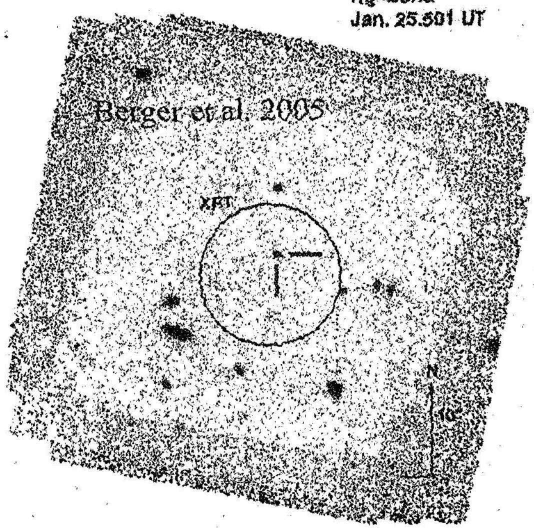


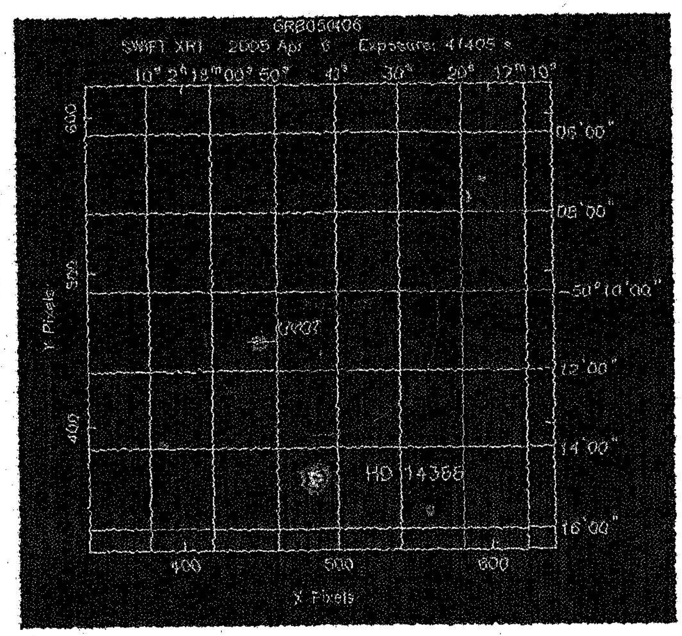
XRT Positional Accuracy



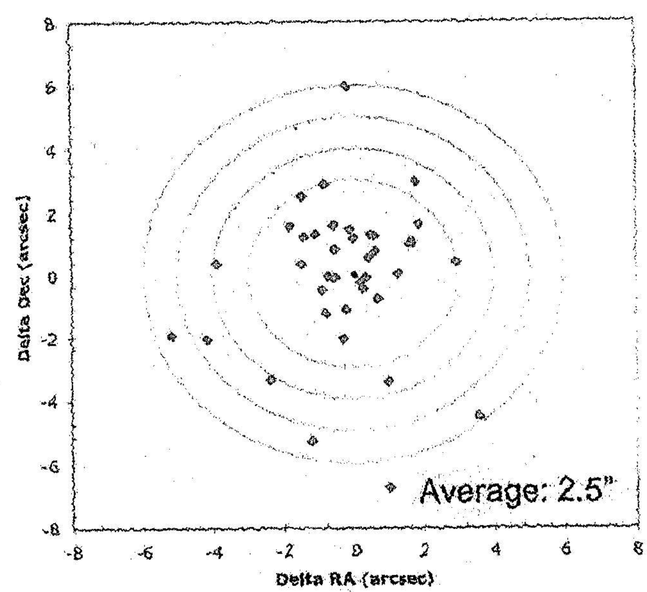


GRB 050124
Keck/NIRC
K_s-band
Jan. 25.501 UT



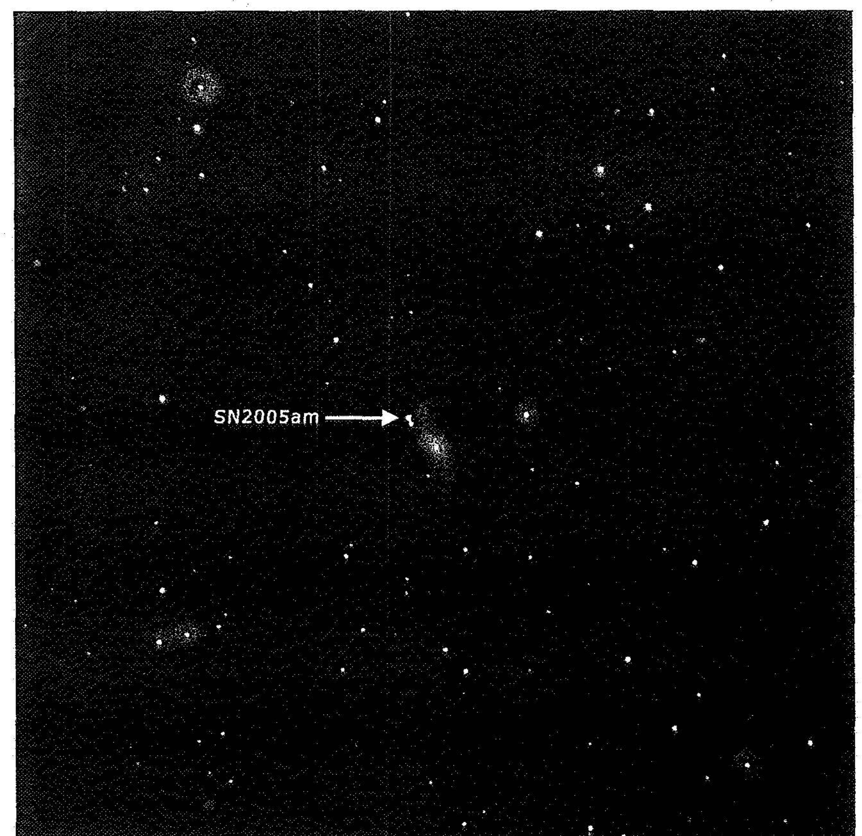


XRT GRB Position Errors



UVOT Detections of BAT GRBs

- Detected 16/70 with UVOT
  - Why so few? Big mystery! (Roming et al. astro-ph 0509273)
  - UVOT upper limits are quite faint and very early for many bursts
  - More ground-based detections (typically R, I, J, or K)
    - High z
      - Evidence in some cases
    - Dust extinction
      - Evidence supporting this for some bursts
    - Intrinsically Dark
      - Magnetic suppression?



GRB 050318: the first UVOT afterglow

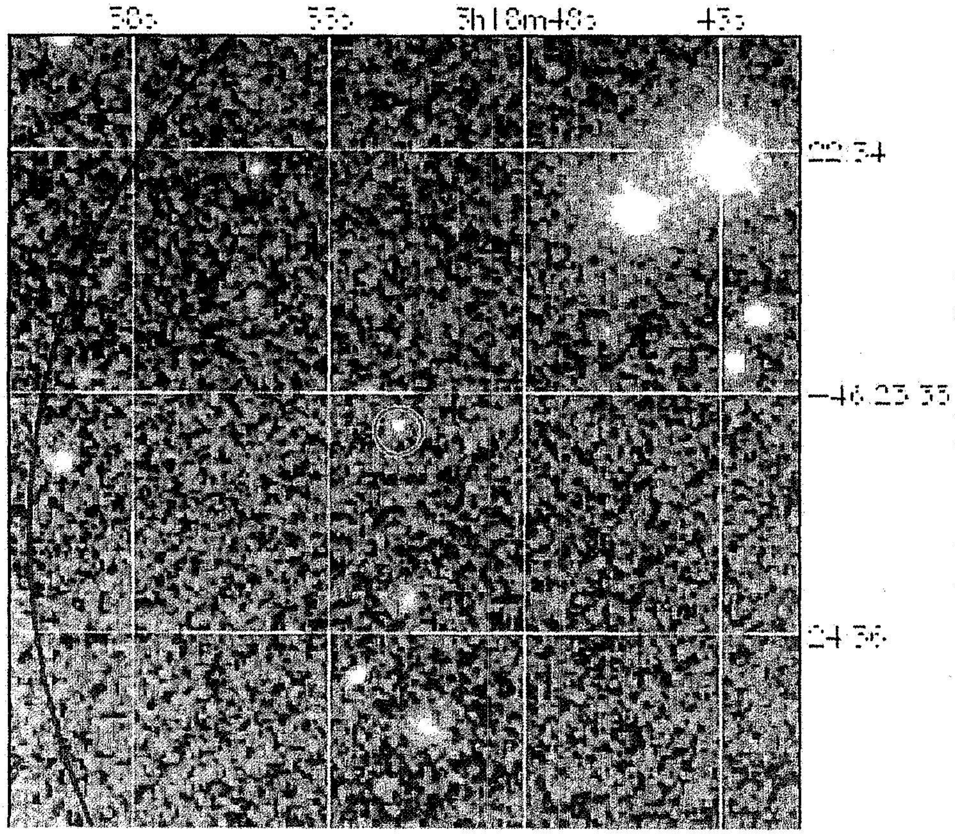
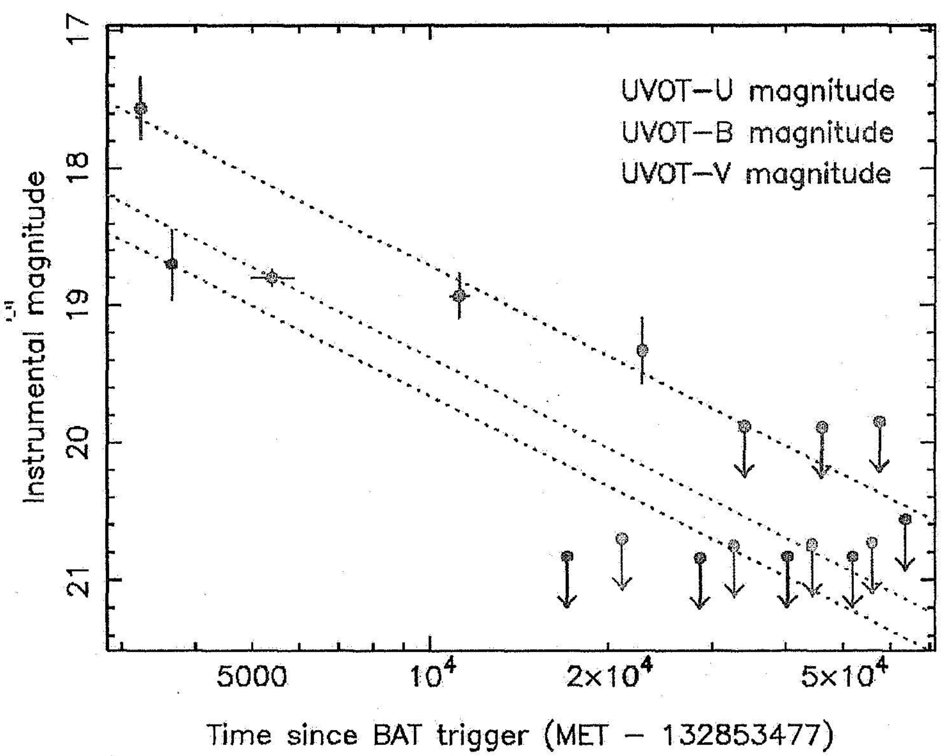
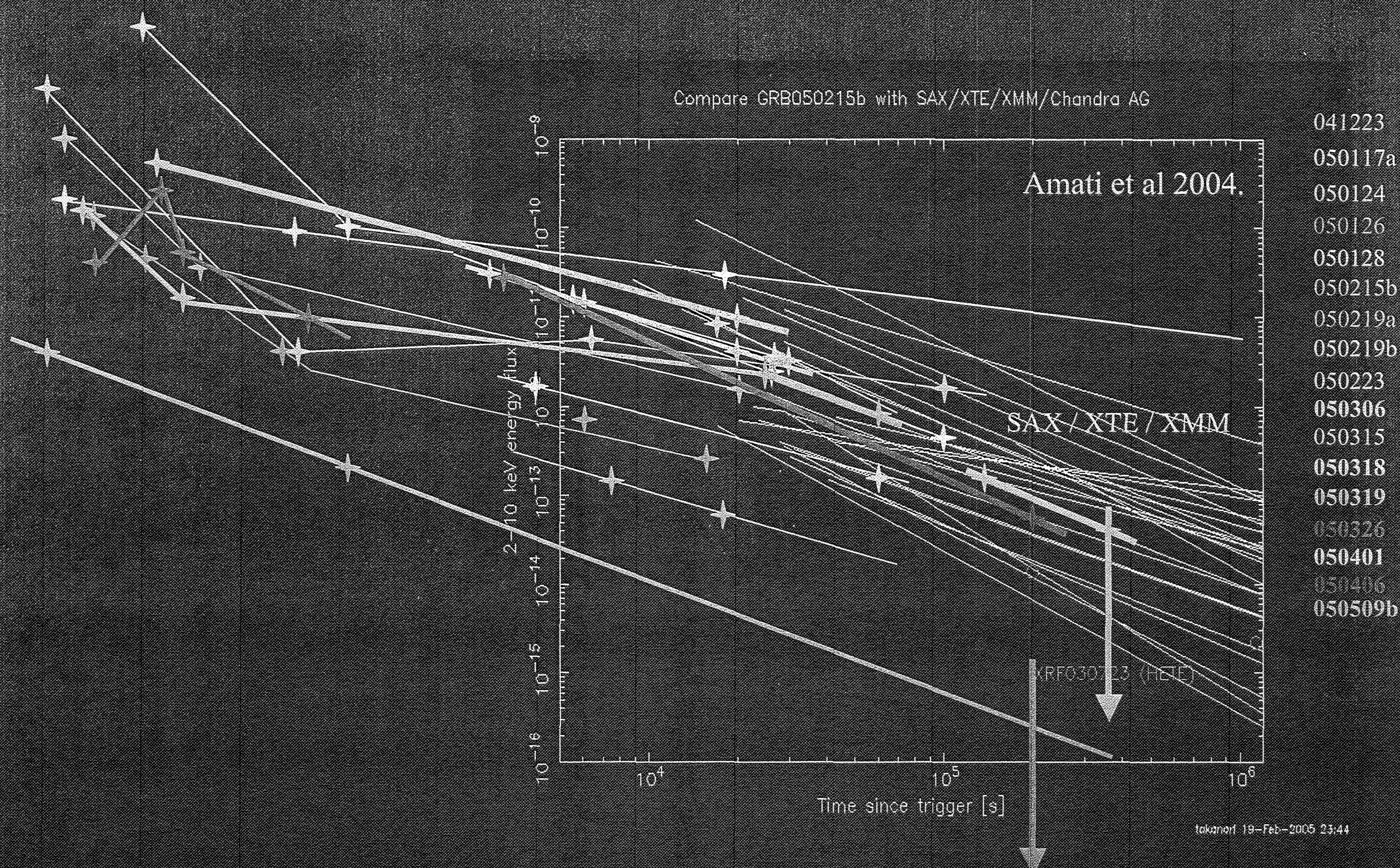


FIG. 1.— Stacked UVOT-V filter image of the field with the transient source at RA = $03^h\ 18^m\ 51^s.15$, Dec = $-46^\circ\ 23'\ 43''.7$ (J2000) and a $3'$ BAT error circle and $6''$ XRT error circle overlaid. Total exposure time for the stacked image is 3,732s.



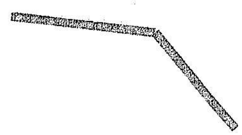
XRT Afterglow Summary



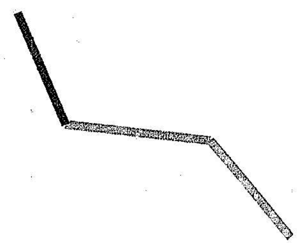
XRT Afterglow Types

From the first 49 prompt observations, there are at least 3 shapes of afterglow lightcurves:

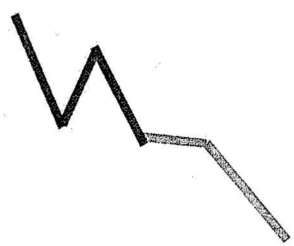
- Type A



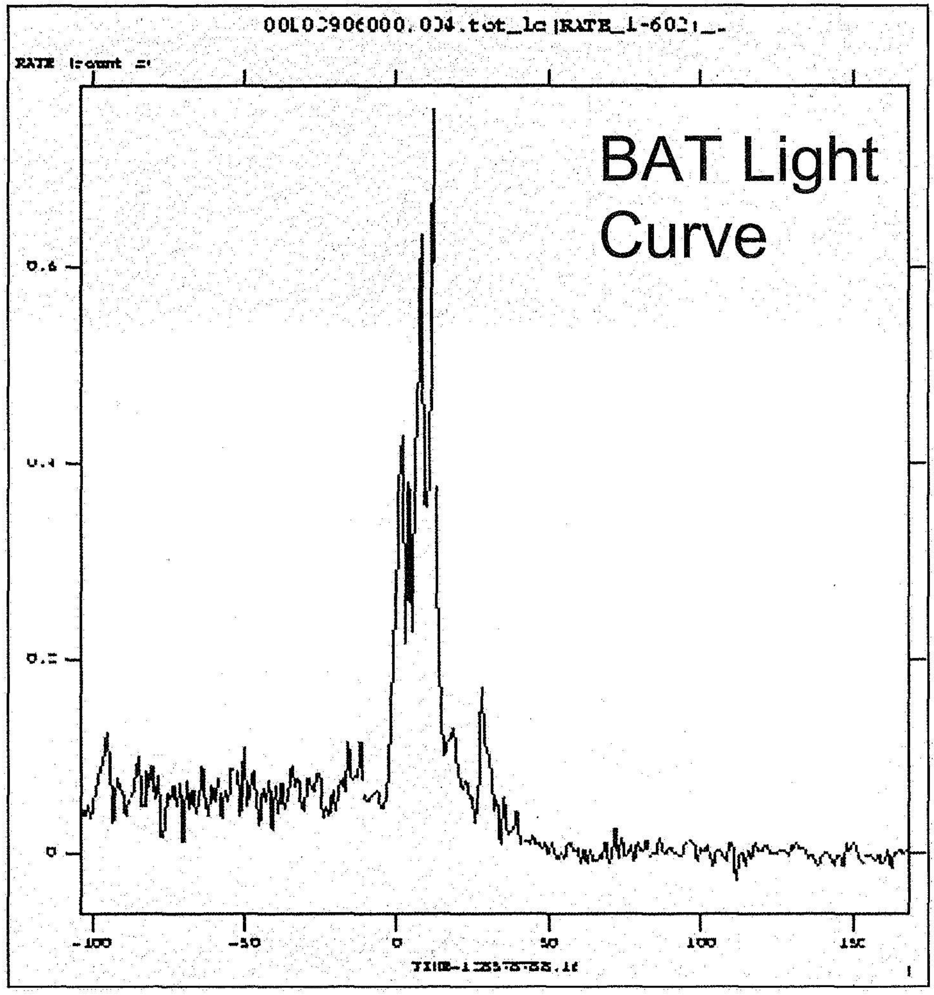
- Type B



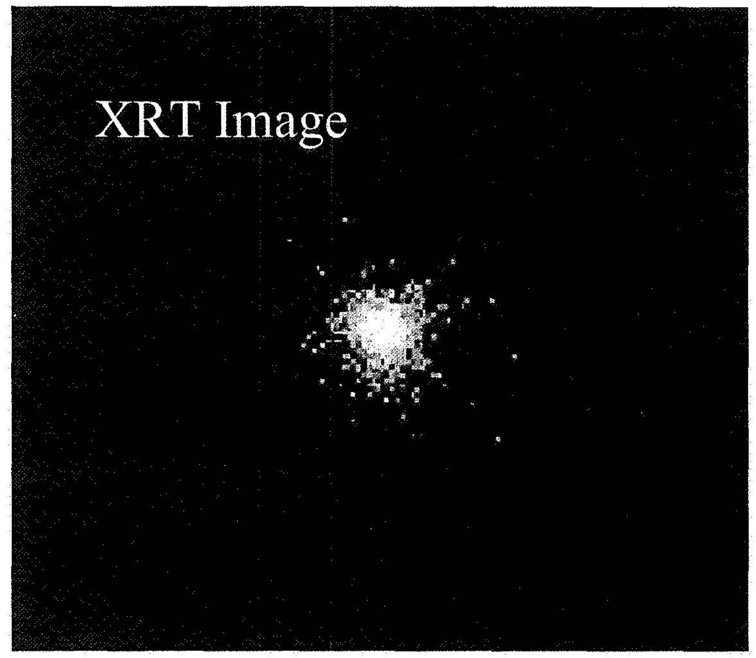
- Type C



Type A afterglow: GRB 050128

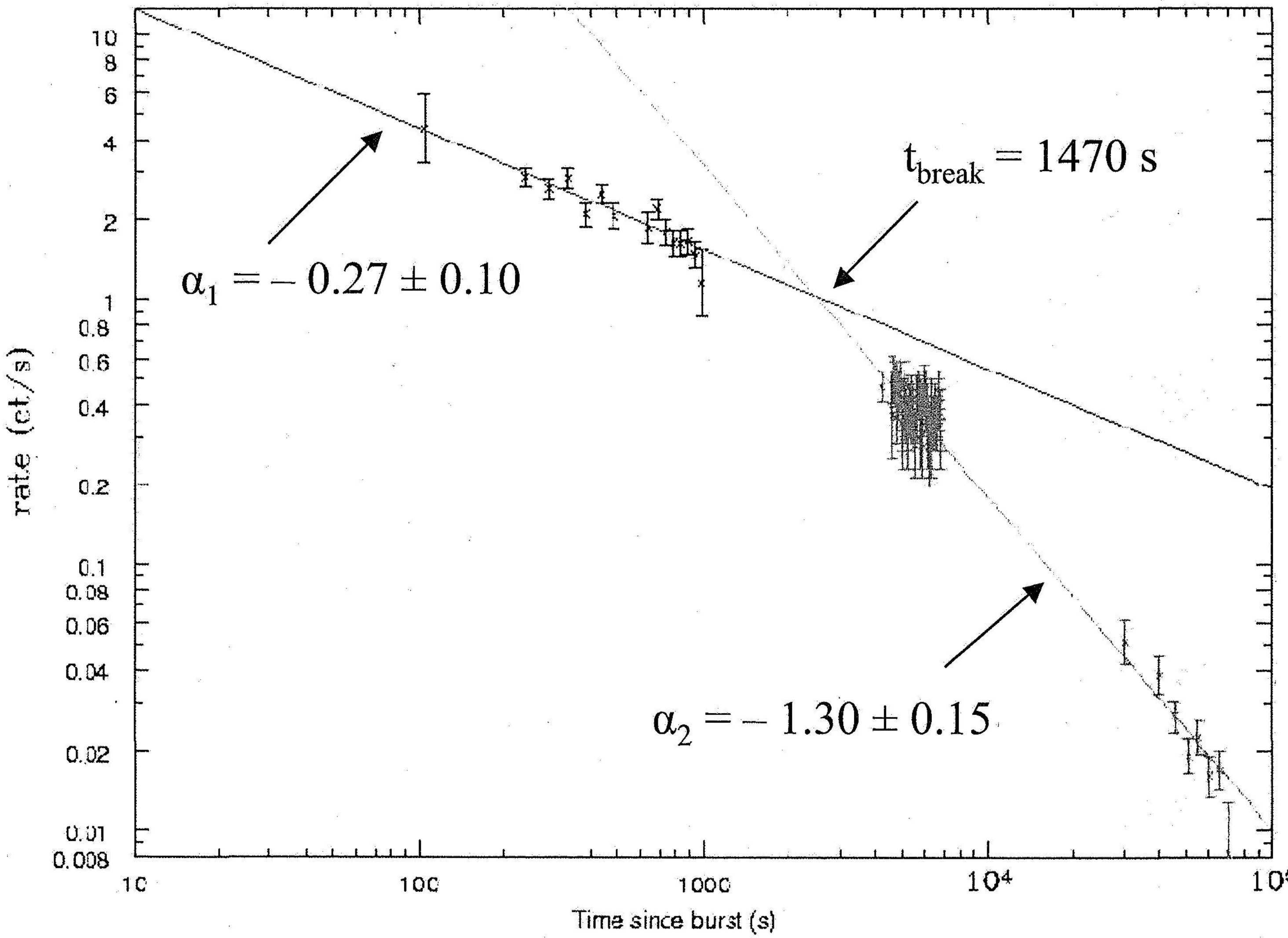


XRT in Manual State, PC Mode
- **108 s after burst trigger**
- Bright, piled-up X-ray source
- Very shallow decay index in first orbit



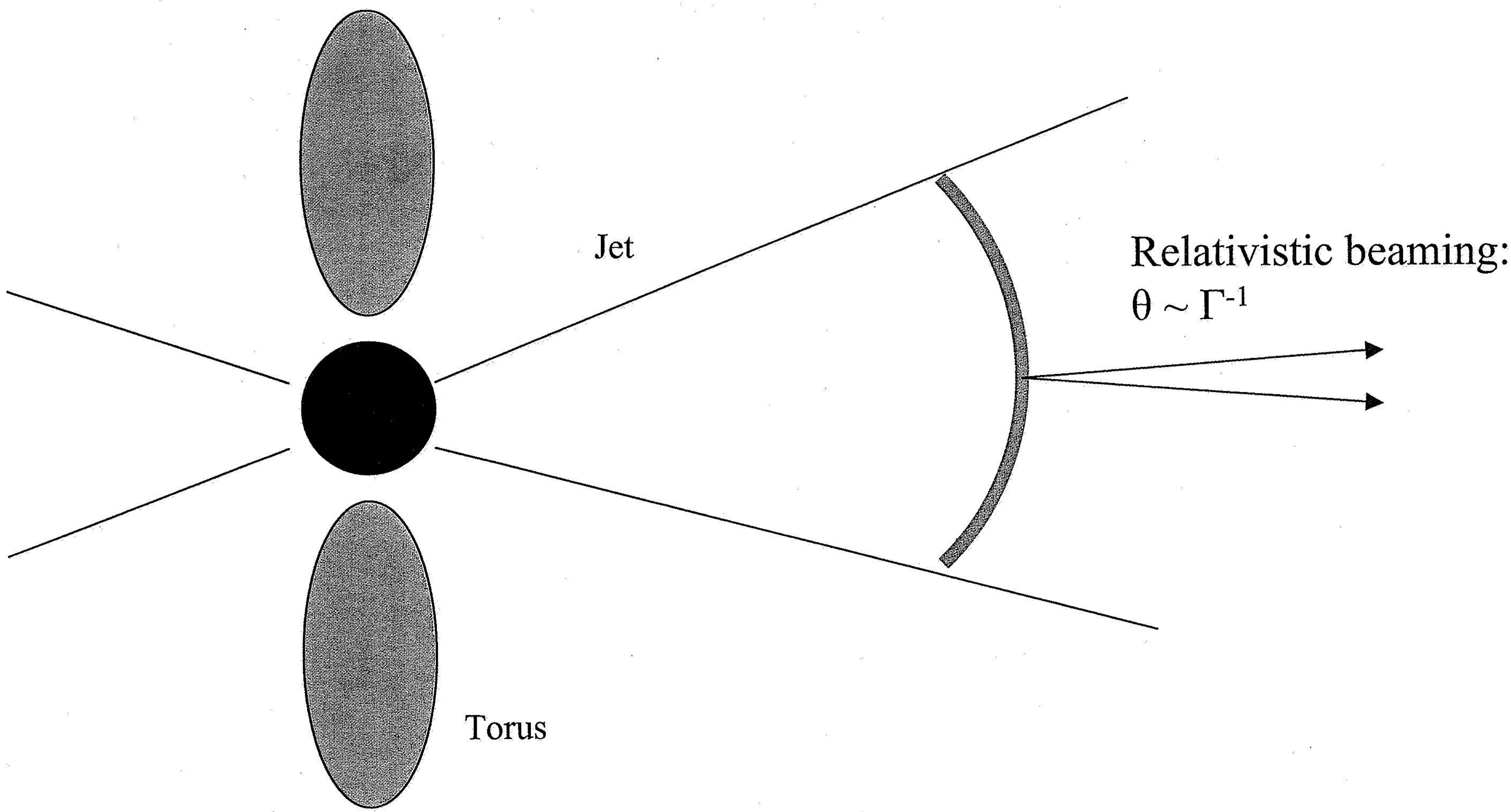
GRB 050128 XRT Lightcurve

$F_x \propto t^{\alpha}$



Campana et al. 2005, ApJL

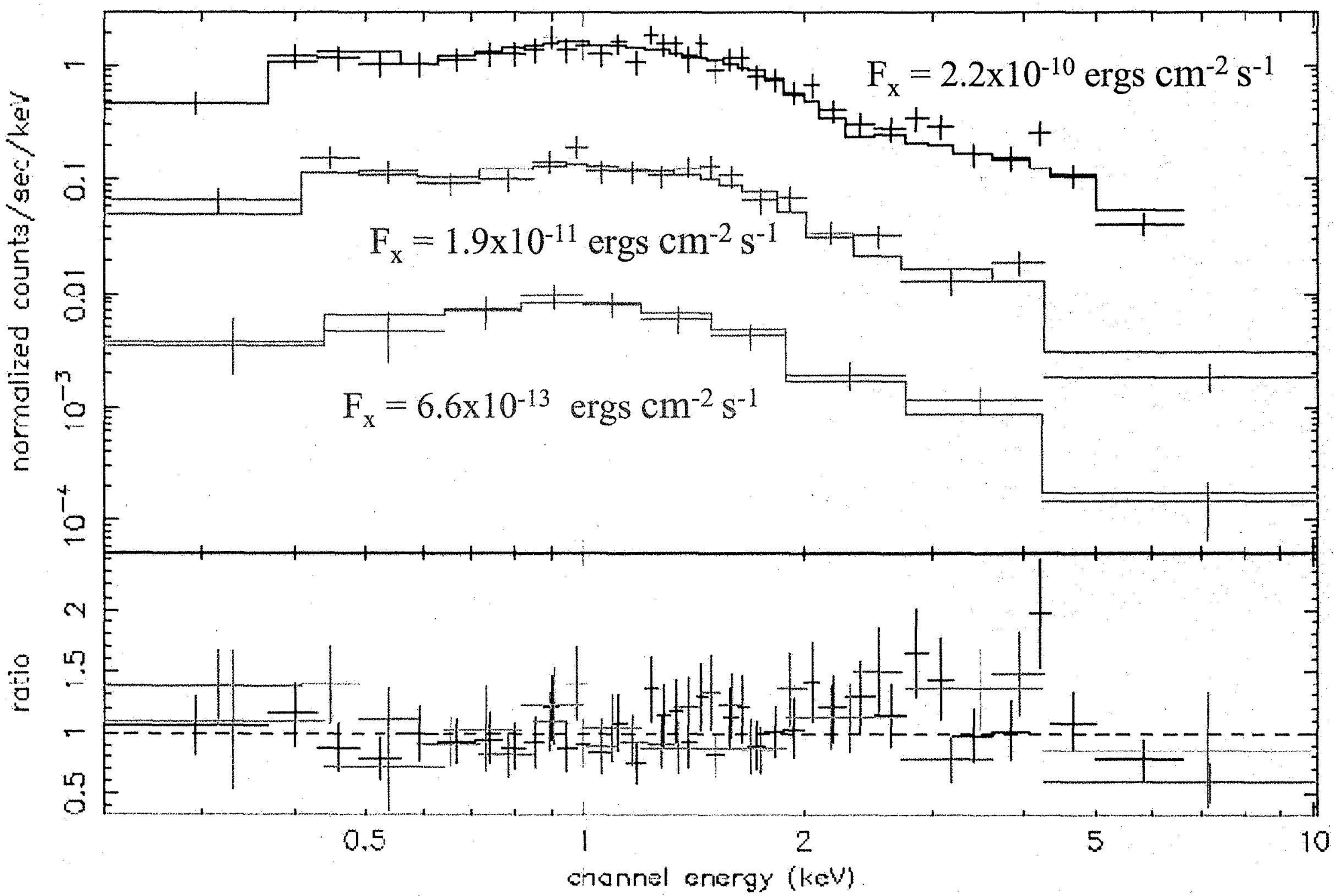
Jet Break



GRB 050128 spectrum

Photon Index=1-β = 1.66 ± 0.07

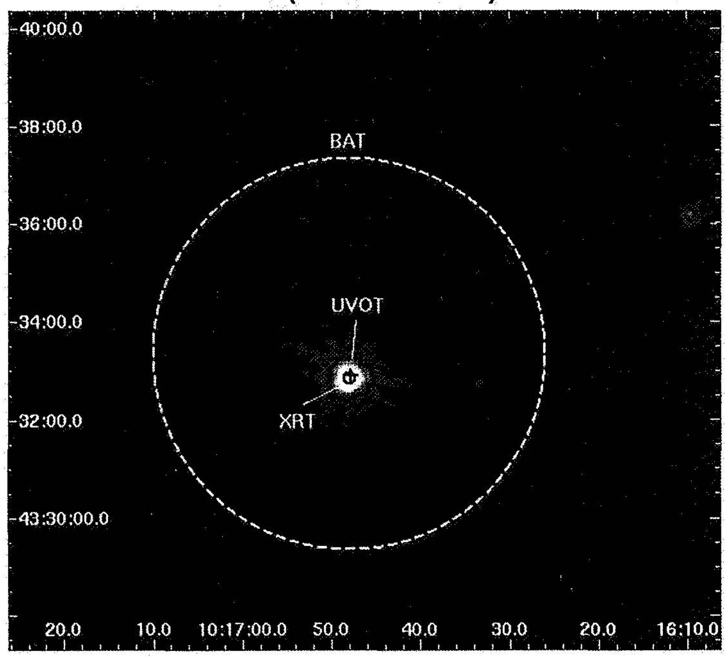
Galactic Absorbing Column = N_H = 4.8x10^{20} cm^{-2} (for all three orbits)

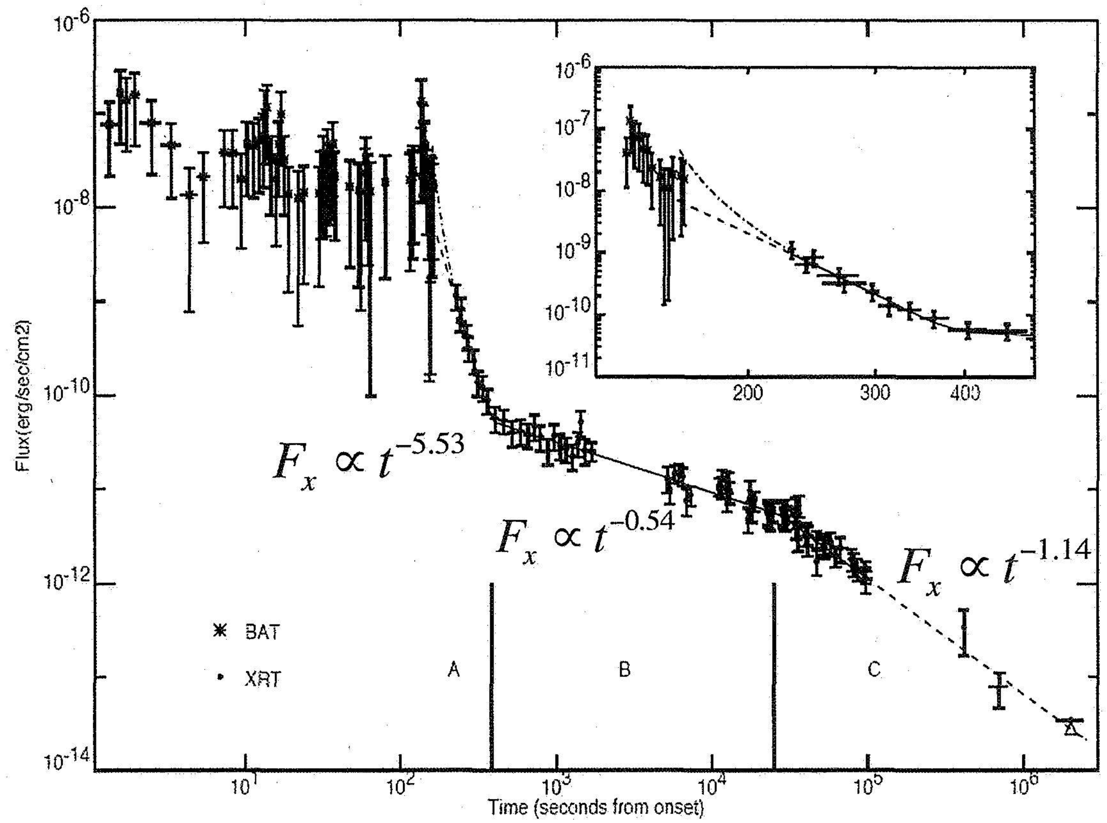


Campana et al. 2005, ApJL

Type B afterglow: GRB 050319

Detected at 09:31:18 UT
(T+ 225 s)





Source is at:
RA(J2000) = 10h 16m 48.1s,
Dec(J2000) = +43d 32' 52.3"

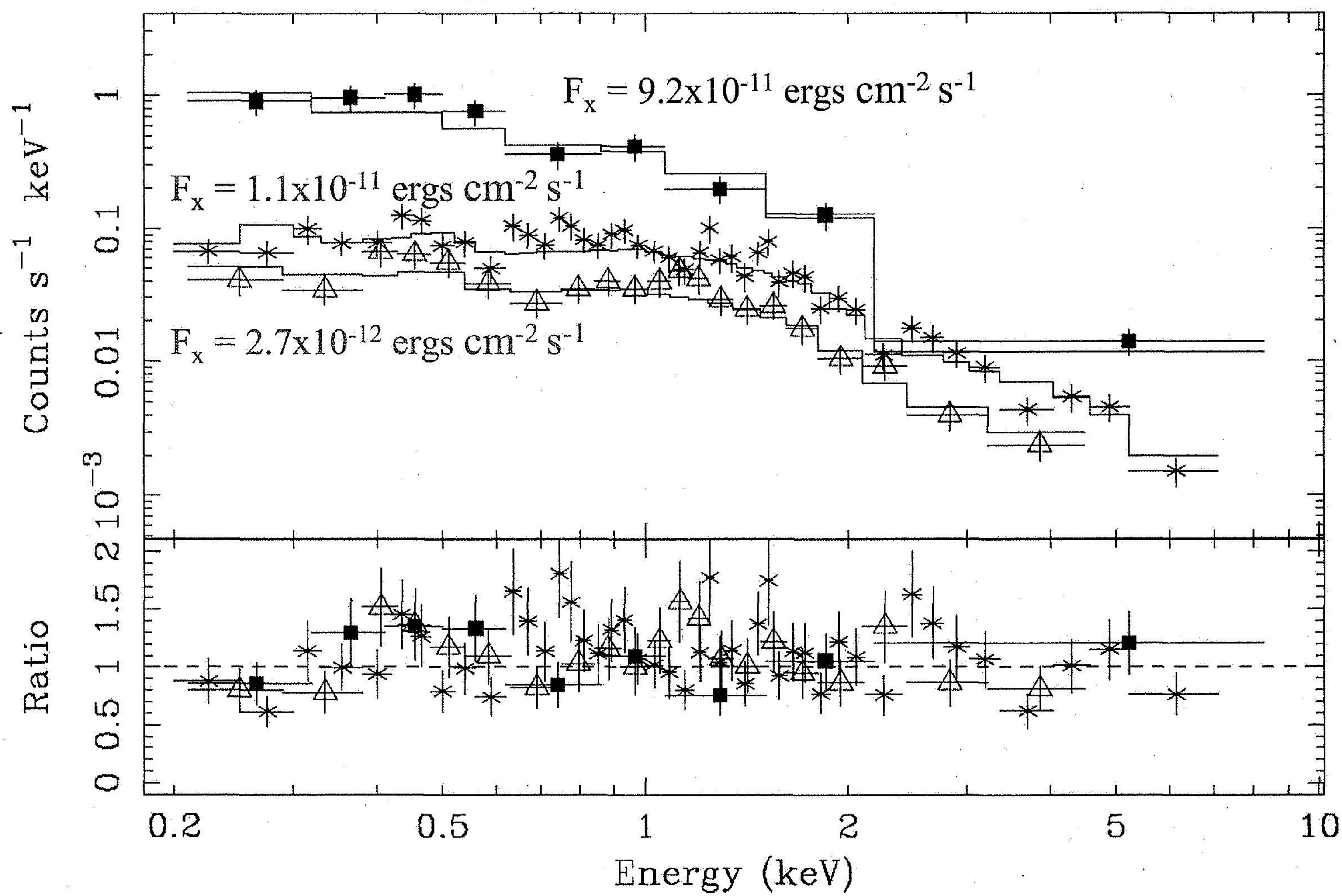
- Auto State - Determined GRB position onboard
- 3.1 arcseconds from ROTSE counterpart

Cusumano et al. 2005, ApJ

GRB 050319 Spectrum

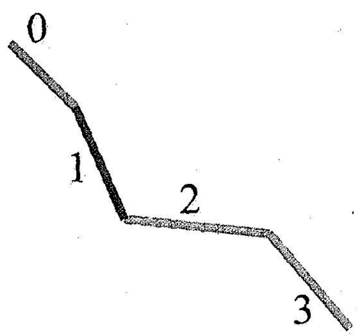
Photon index=1 - β = 2.6, 1.7 and 1.8 i.e. Starts softer and becomes harder

Galactic Absorbing Column = N_H = 1.13x10^{20} cm^{-2} (for all three phases)



Cusumano et al. 2005, ApJ

Possible models for initial decay



1. t0 offset: expect single power-law, $\beta_1 = \beta_2$
2. Prompt shock stops: expect $\beta_0 = \beta_1$
3. More exotic mechanisms

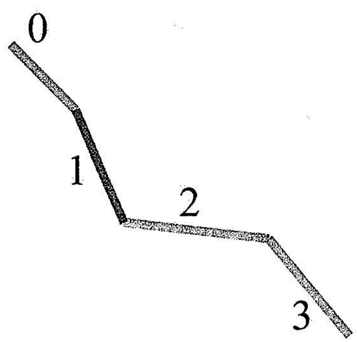
Observationally:

$\beta_0 > \beta_1 = \beta_2$ for GRB 050219a

$\beta_1 < \beta_2$ for GRB 050315

$\beta_1 < \beta_2$ for GRB 050319

Possible models for initial decay



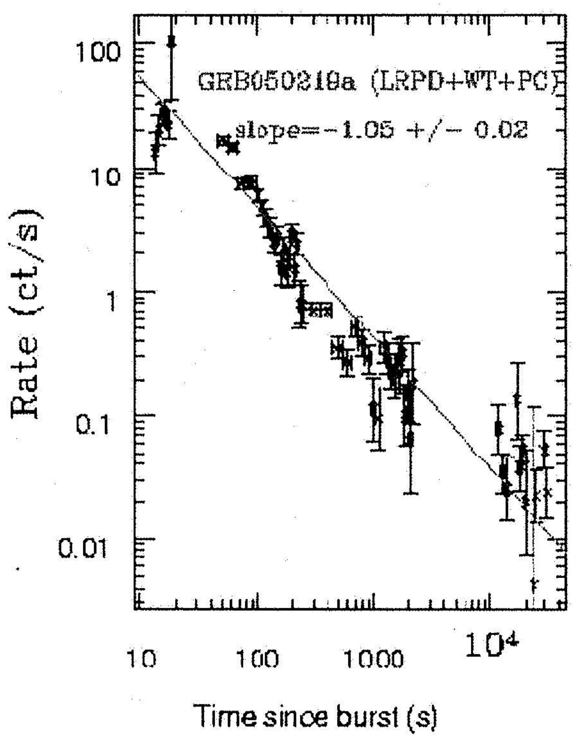
1. t0 offset:

   Q: when does the afterglow begin fading as a power-law?

   a) when burst occurs? Or

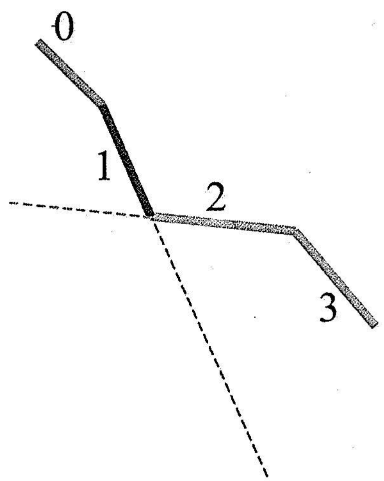
   b) when shocks hit external medium?

Perhaps we are using the wrong t0 and these bursts are really a single power-law decline, beginning when the afterglow (external shock) begins



M. Goad et al. 2005, ApJ

Possible models for initial decay



2. Unified mechanism:

Q: Are we seeing a single mechanism that is responsible for segments 0 and 1?

The behavior in segment 1 could be a continuation of the end of the prompt emission under several scenarios:

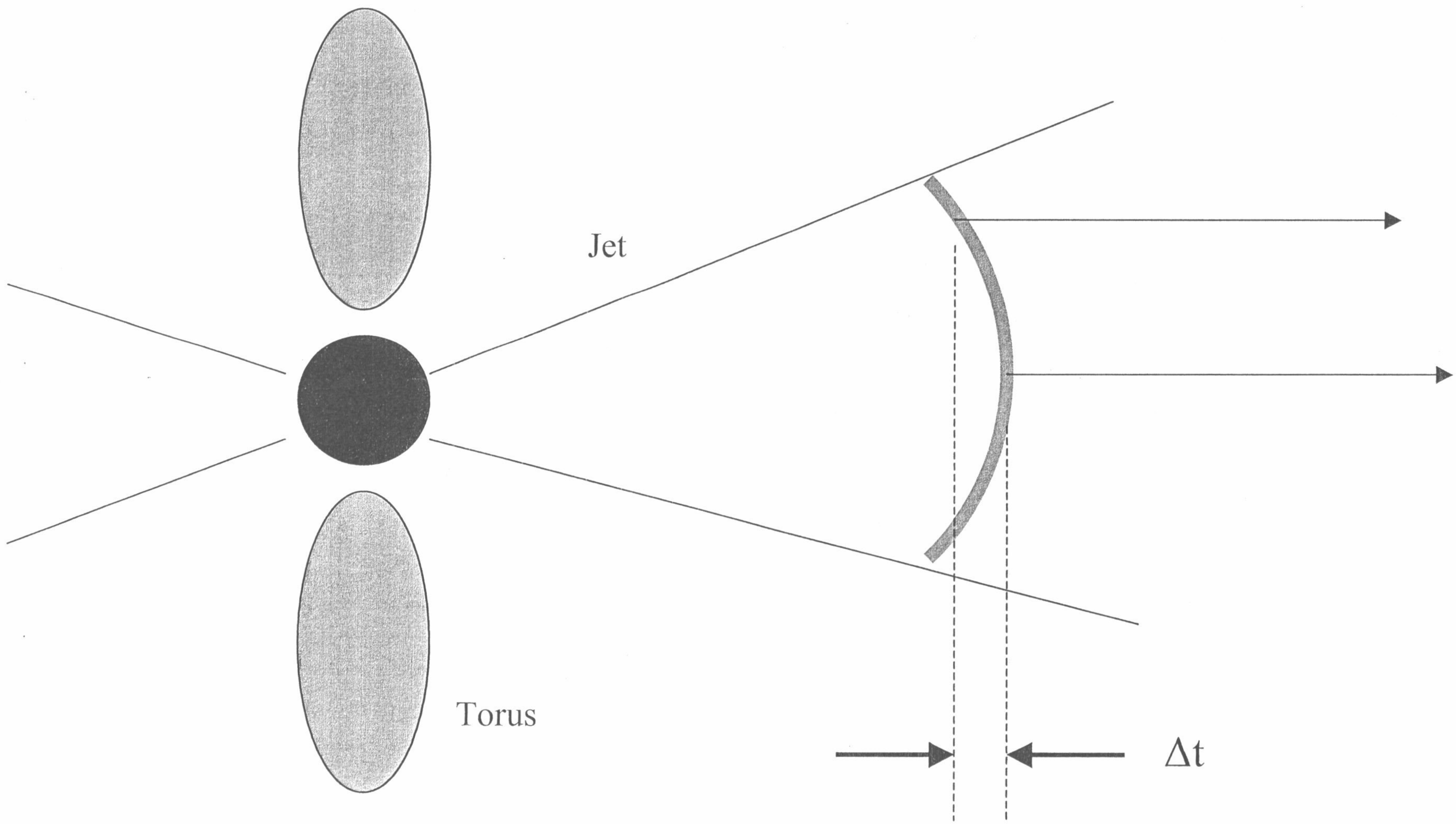
a) Internal shock ends

b) Off-axis emission and light delay effects

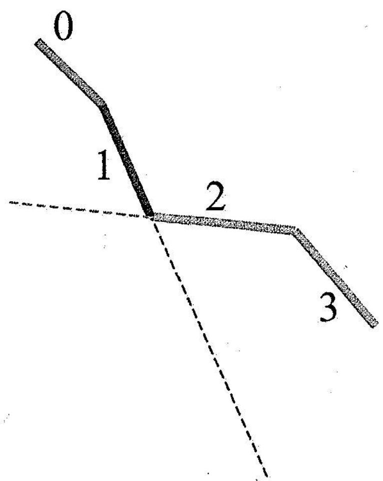
In these cases, expect smooth transition from segment 0 to segment 1.

No relationship between segment 1 and segment 2 (as shown).

High Latitude Emission



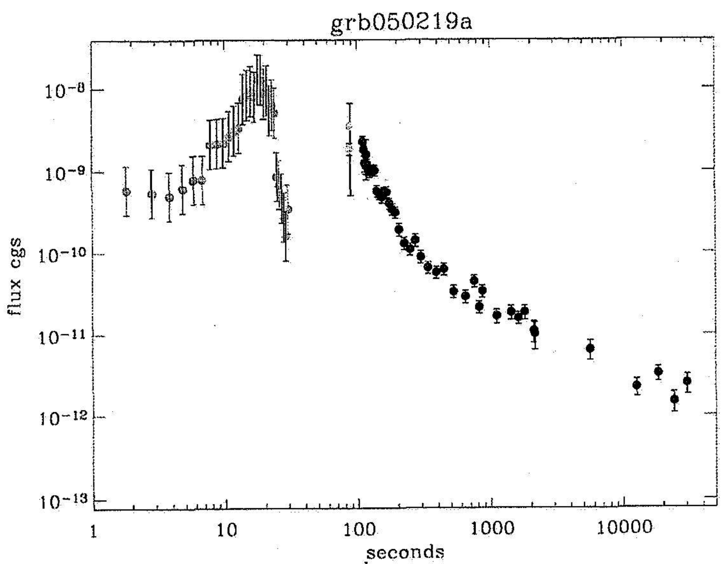
Possible models for initial decay



3. Unrelated to prompt emission. Possible "exotic" models for segment 1:
   a) Photospheric emission
   b) Jet cocoon: thermal emission
   c) Multiple collimated mini-jets

In these cases, expect no relationship between segment 0 to segment 1.

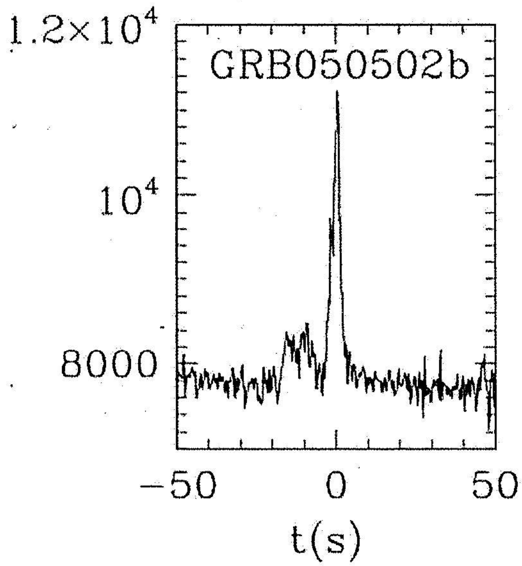
No relationship between segment 1 and segment 2 (as shown).



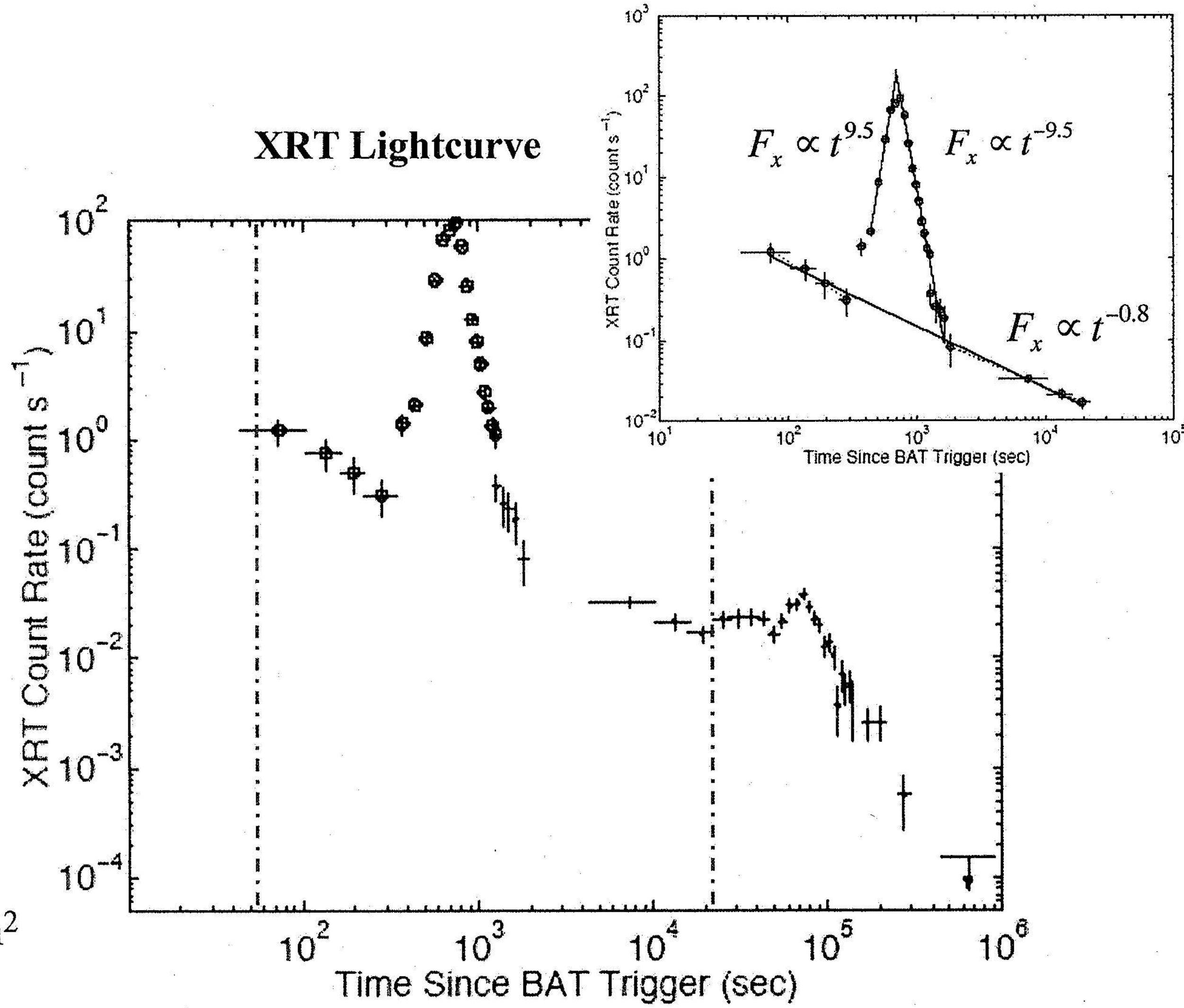
M. Goad et al. 2005, ApJ

Type C: Giant X-ray Flare, GRB 050502b

BAT Lightcurve



XRT Lightcurve



GRB Fluence: 8x10^{-7} ergs/cm^2

Flare Fluence: 9x10^{-7} ergs/cm^2

Burrows et al. 2005, Science; Falcone et al. 2005, ApJ

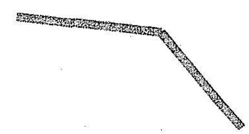
Flare Mechanism

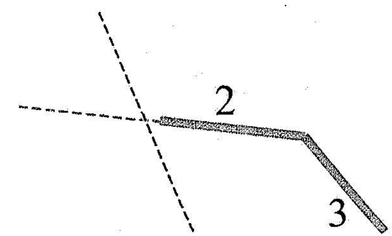
- Rapid increase and decrease
  - Inconsistent with external shock
- Enormous increase in GRB 050502b
  - Inconsistent with Inverse Compton mechanism
- Same underlying afterglow before and after
  - Inconsistent with additional energy added to external shock
- Most likely explanation is that internal shocks continue at much later times than the prompt γ-ray emission.
  - Late-time emission occurs at larger radius, resulting in slower rise/fall and softer energies.
  - Late emission also has higher Lorentz factor because shocks expand in channel evacuated by earlier shocks.

XRT Afterglow Types

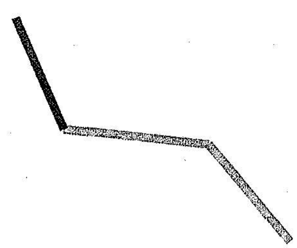
It is possible that all three types are related and we are viewing different parts of the lightcurve

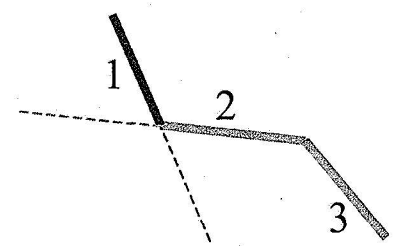
– Type A



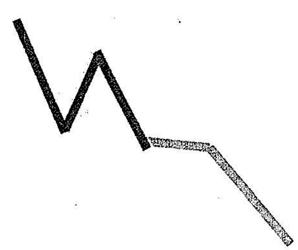


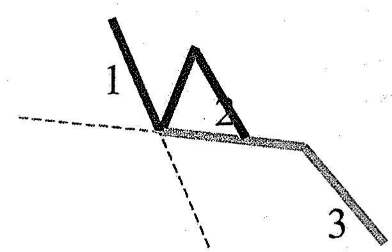
– Type B





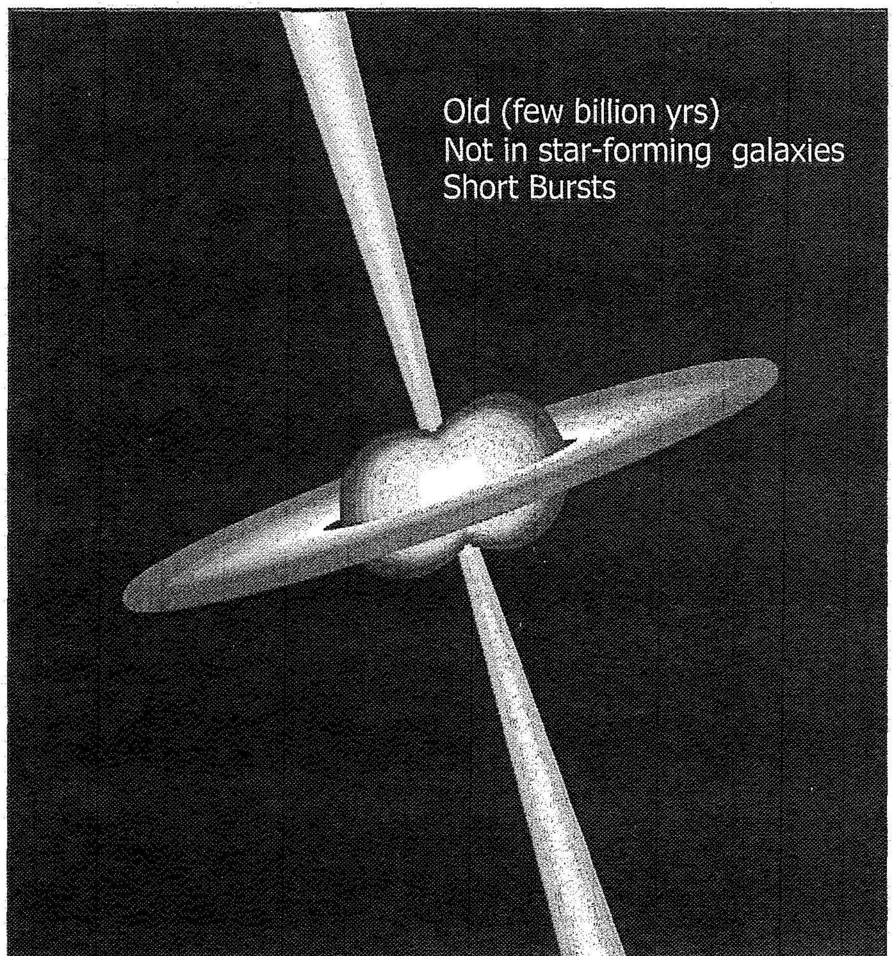
– Type C



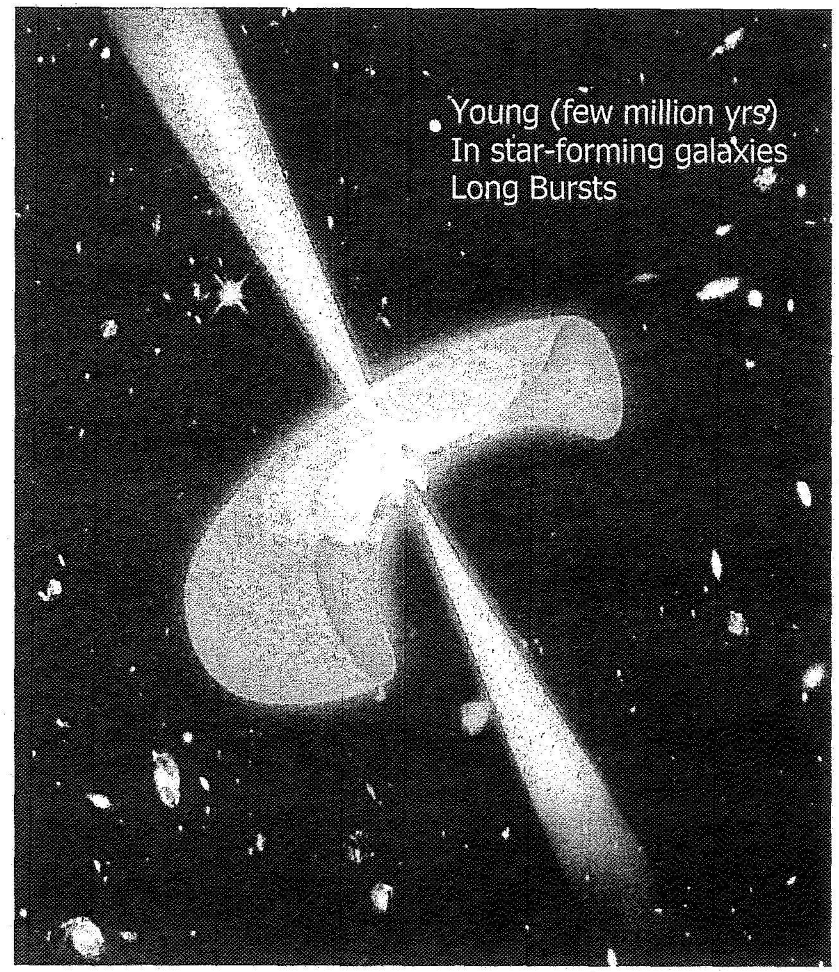


GRB Models

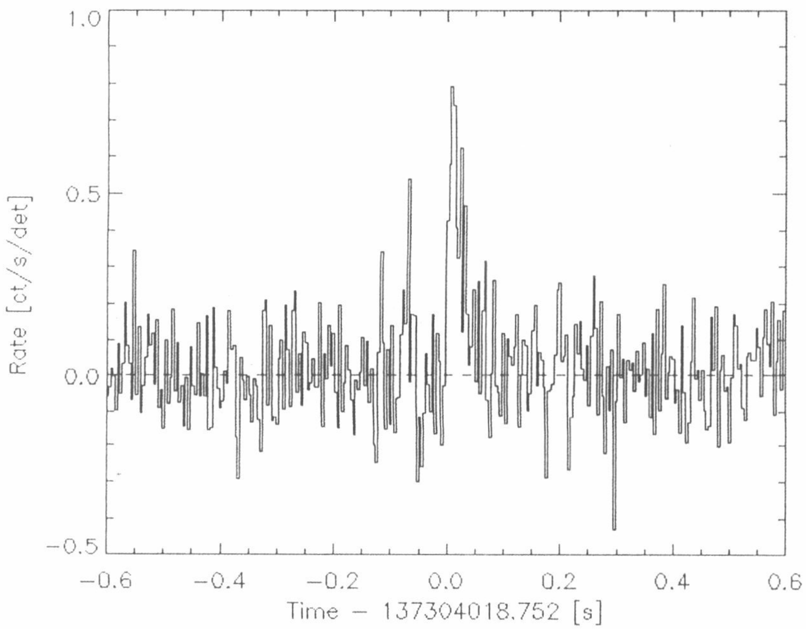
Merging Neutron Stars

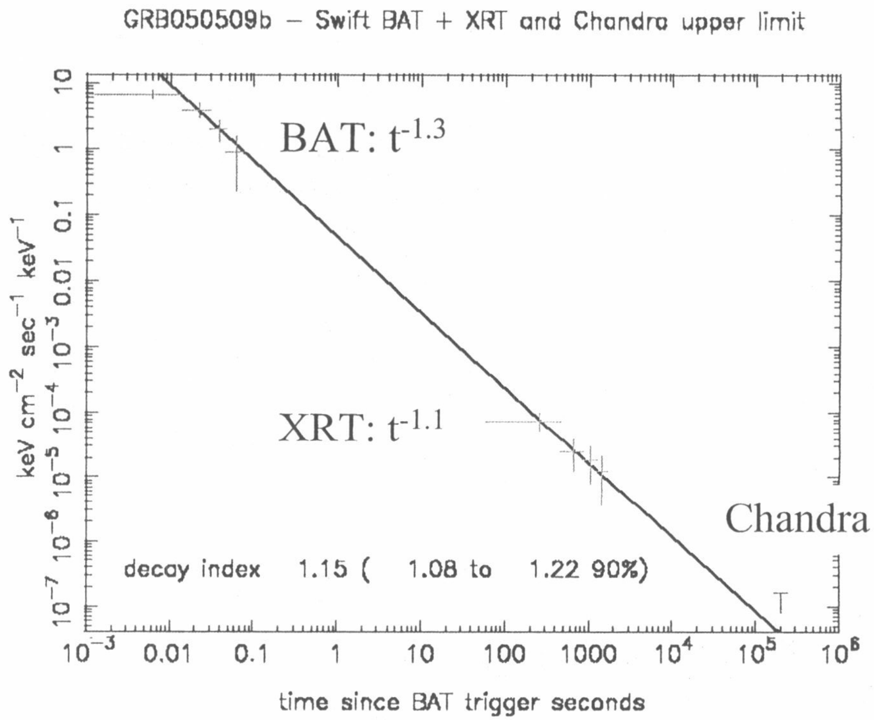


Hypernova



GRB 050509b: First Short GRB Afterglow



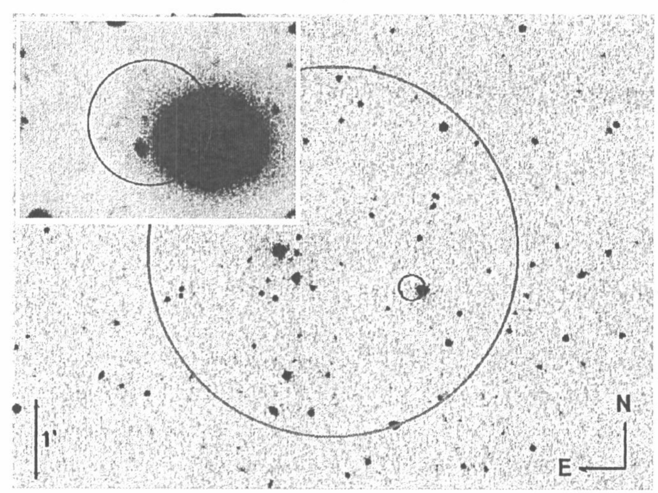


$t_{90} = 0.04$ s, Fluence = 2×10^{-8} ergs/cm^2

XRT counterpart in first 400 s, fades rapidly. 11 photons total.

Location in cluster at z=0.226, near early-type galaxy.

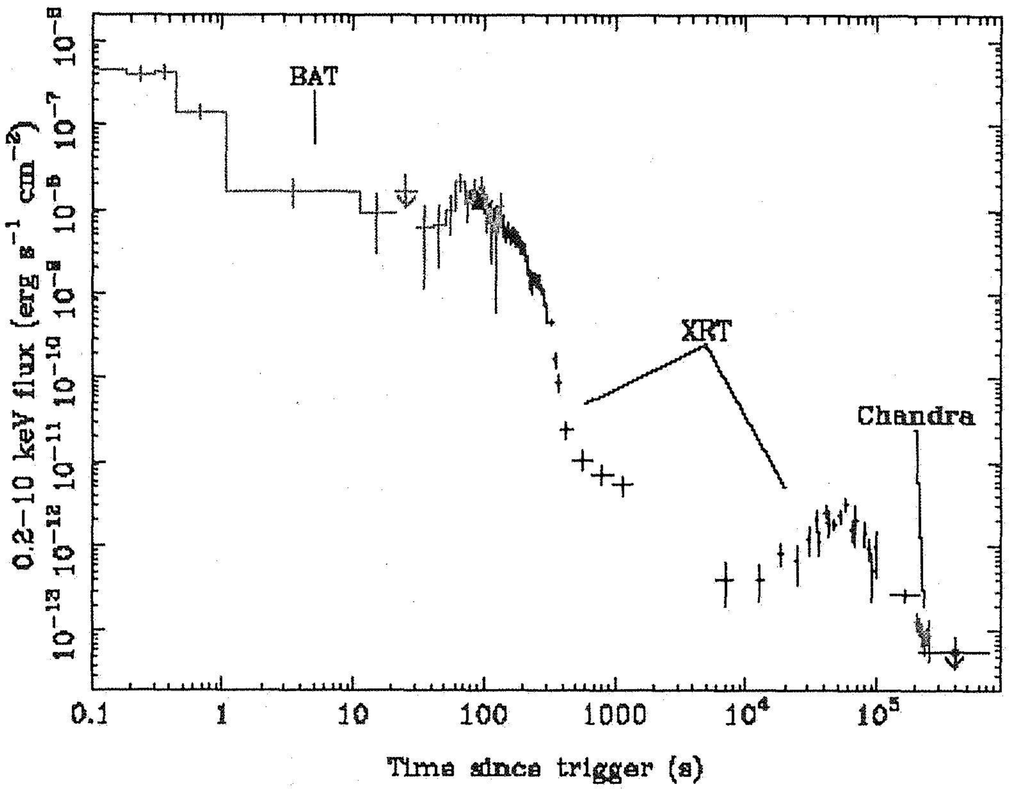
Possible NS-NS merger



XRT error circle on VLT image. XRT position is 9.8" from a bright elliptical galaxy at z=0.226

Gehrels et al. 2005, Nature

GRB 050724: Flares in a Short GRB Afterglow



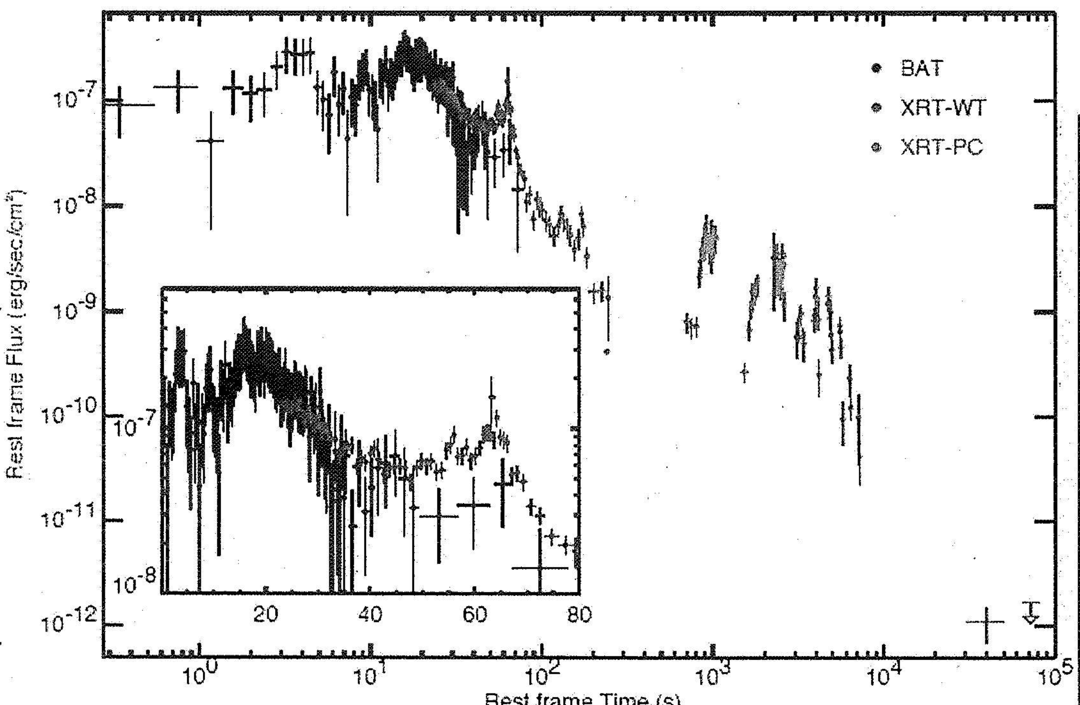
- Bright Complex lightcurve
- Associated with an elliptical galaxy
- Extended central engine activity
- Death call of a Neutron Star?

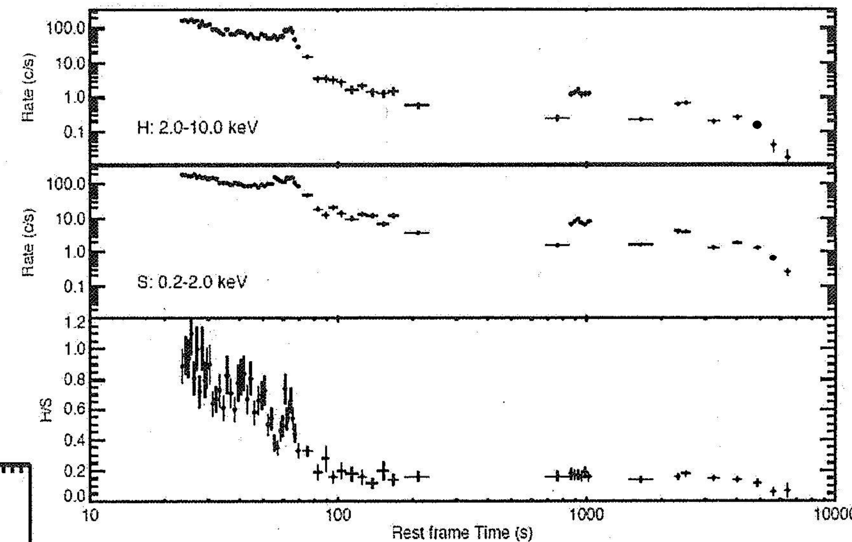
Burrows et al. 2005, Barthelmy et al. 2005, Nature

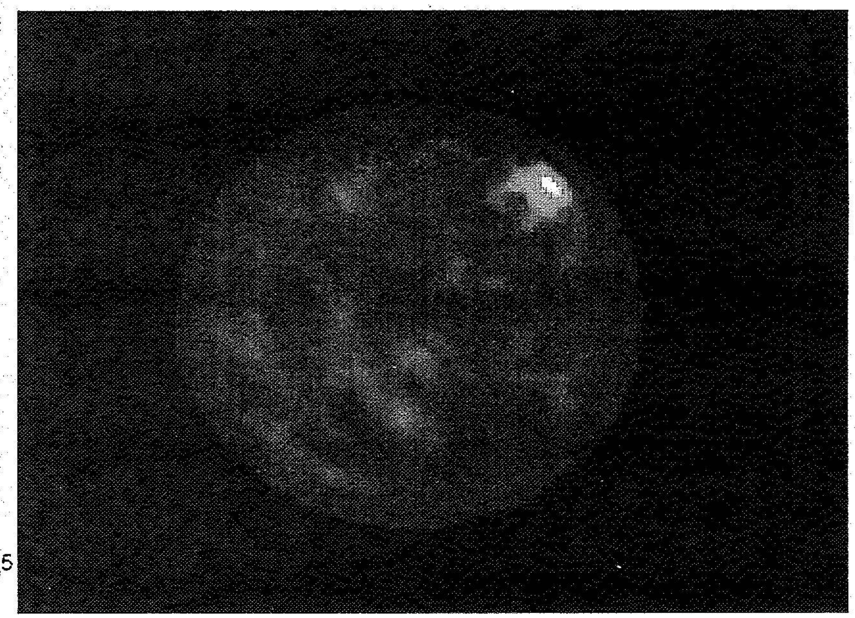
A Huge Explosion in the Early Universe Swift

GRB 050904: Redshift of z = 6.29

- The most distant cosmic explosion ever observed
- Corresponds to 13 billion light years from Earth
- The Universe was just 700 - 750 million years old.
- Indicates the presence of massive stars only 700 million years after the big bang







Cusumano et al. 2005, Nature

Summary

- *Swift* has exceeded every pre-launch predicted advance in GRB science
- Discovered the farthest GRB ever seen
- Identified counterparts to Short GRBs
- Discovered new GRBs at a rate of 100/year
- Explored a brand new time interval in GRB lightcurves
  - Revealing unpredicted phenomena of GRB flares
  - Revealing unpredicted rapid X-ray afterglow declines
- As the *Swift* catalogue increases, we expect new insights into GRB formation and environments
- *Swift* has conducted 20 000 successful slews to sources and is predicted to stay in orbit until 2022
- Public data release began April 5, 2005
  - http://swift.gsfc.nasa.gov/docs/swift/sdc/

Summary

- XRT has now observed 70 afterglows
  - 68 detected
  - 49 prompt slews (< 6 minutes after burst)
  - Three prompt emission
  - Four short burst afterglows
  - Average positional accuracy for the
    for 39 with ground positions: **2.5 arcseconds**
  - > 50% of spectral fits have excess (intrinsic) $N_H > 10^{21}$

- XRT is observing afterglows $10^2 - 10^3$ times fainter than similar observations with Beppo-SAX. New behaviors are appearing at early times.

Summary

- Public data release began April 5, 2005
  - http://swift.gsfc.nasa.gov/docs/swift/sdc/
- As the *Swift* catalogue increases, we expect new insights into GRB formation and environments
  - Solution to Short GRB mystery (merging NS?)
  - Systematic investigation of GRB environments (ISM vs wind)
  - Redshifts
  - X-ray spectral lines - Maybe still to come

XRT Collaborators

Penn State:
- David Burrows
- Joanne Hill*
- Judith Racusin
- Shiho Kobayashi
- Peter Meszaros
- John Nousek
- Jamie Kennea
- David Morris
- Claudio Pagani

OAB:
- Guido Chincarini
- Gianpiero Tagliaferri
- Sergio Campana
- Alberto Moretti
- Patrizia Romano
- Daniele Malesani
- Stefano Covino
- Paolo D'Avanzo

UL:
- Paul O'Brien
- Alan Wells
- Julian Osborne
- Tony Abbey
- Andy Beardmore
- Mike Goad
- Kim Page
- Dick Willingale
- Olivier Godet

INAF:
- Giancarlo Cusumano
- Valentina Laparola

GSFC:
- Neil Gehrels
- Lorella Angelini

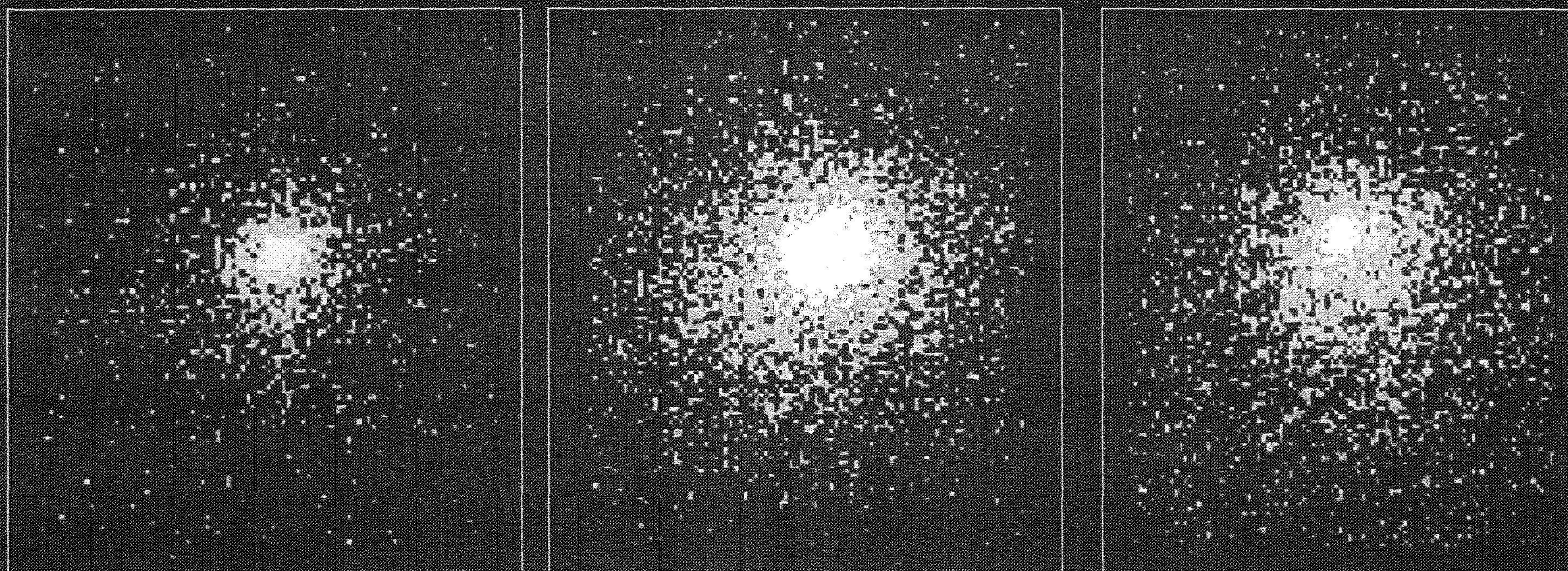
UNLV:
- Bing Zhang

ASDC:
- Paolo Giommi
- Francesca Tamburelli
- Barbara Saija
- Milvia Capalbi
- Matteo Perri

* GSFC/USRA http://mysite.verizon.net/jeh22/

Swift and Deep Impact Event

UVOT images in UVW1 filter



30 min before the impact | 6 hours after the impact | 34 hours after the impact

Swift Deep Impact Team