Gamma-Ray Burst Explorer:

Latest Results

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1 8 5 5

Astro-PF, CAMK, Warsaw, Poland, 4 October 2006

Talk Outline

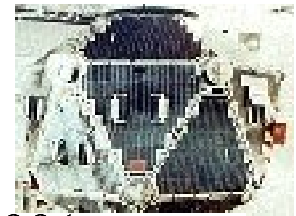
- GRBs – Pre-*Swift*
  - GRB Phenomenon
  - Pre-*Swift* GRB Paradigm
- *Swift* Era
  - *Swift* satellite
  - *Swift* discoveries
- Challenges to the GRB Paradigm
  - Short GRBs
  - 'Canonical' X-ray light curves
  - Lack of jet breaks/chromatic jet breaks
  - X-ray 'flares'
- GRB anomalies/ prototypes?
- *Swift & GRB science in the future*
  - What to do with *Swift* for the next four years?

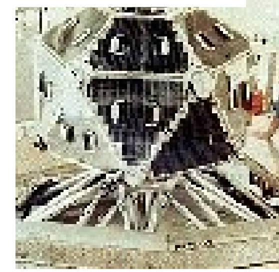
GRBs – Pre-*Swift*

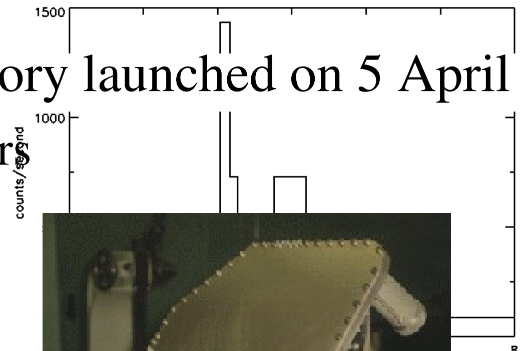
What did we know about GRBs before *Swift?*

History of GRBs

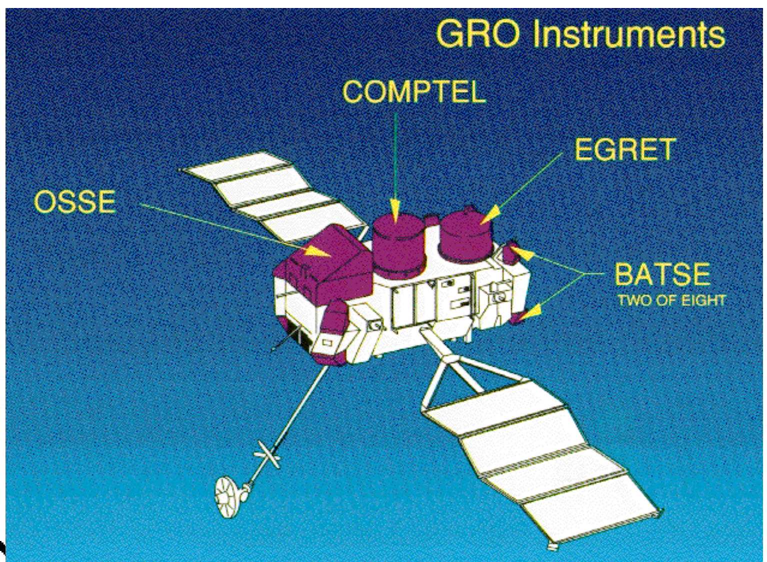
- GRBs discovered in 1969 by Ray Klebesadel of LANL
  - Vela satellites: monitored Nuclear Test Ban treaty
  - Data published in 1973

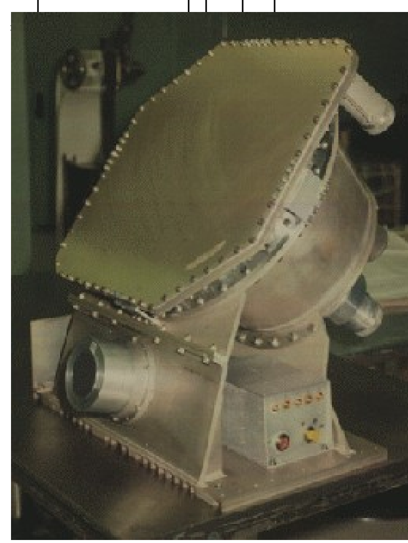




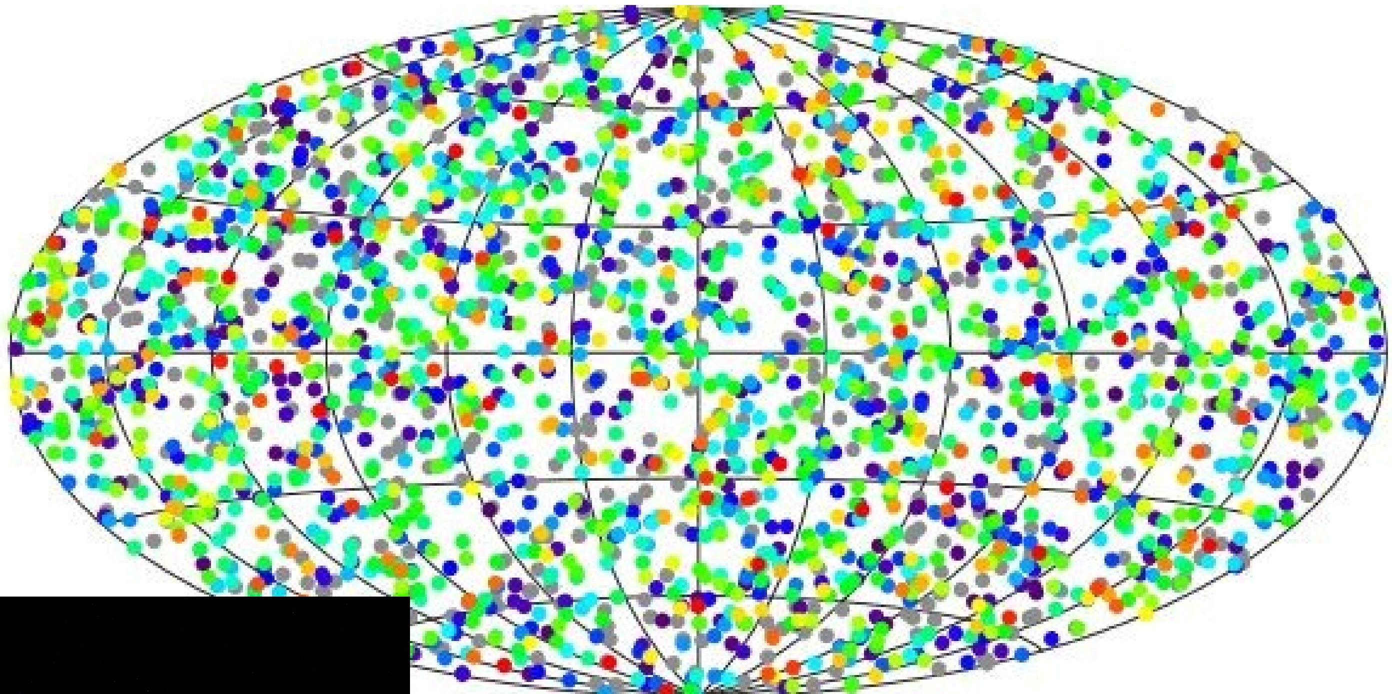


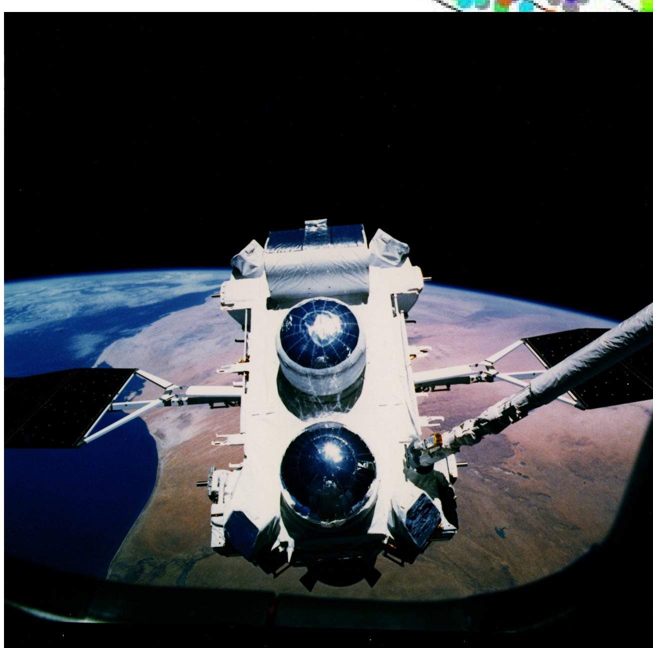
- Compton Gamma-Ray Observatory launched on 5 April 1991
  - BATSE: 2609 bursts in 8.5 years

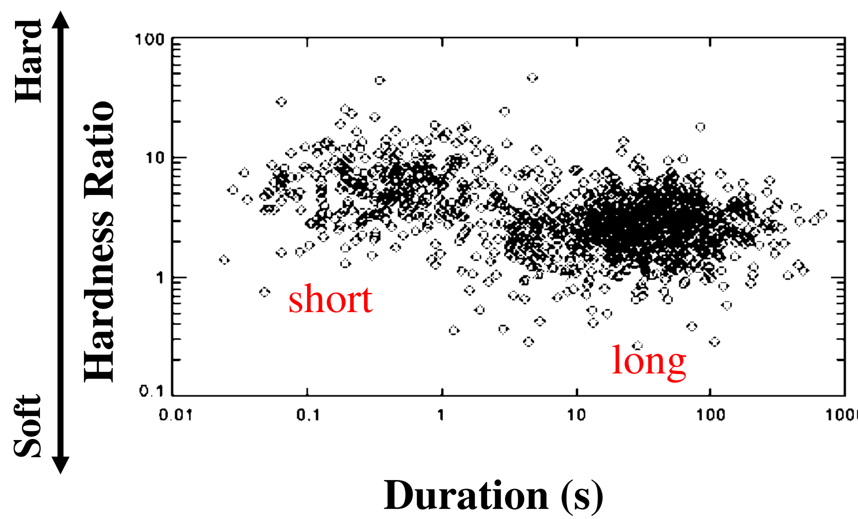




Compton Observatory Era

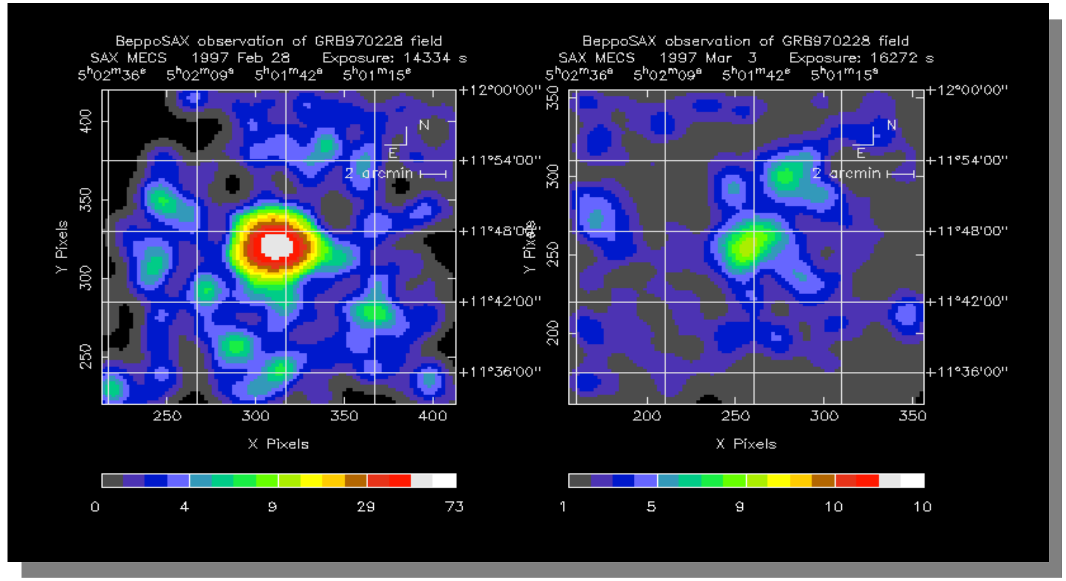




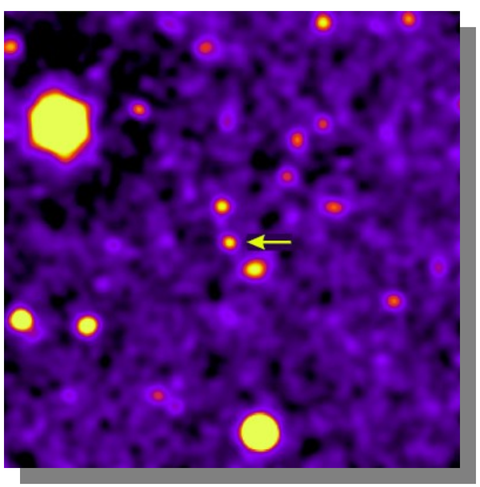


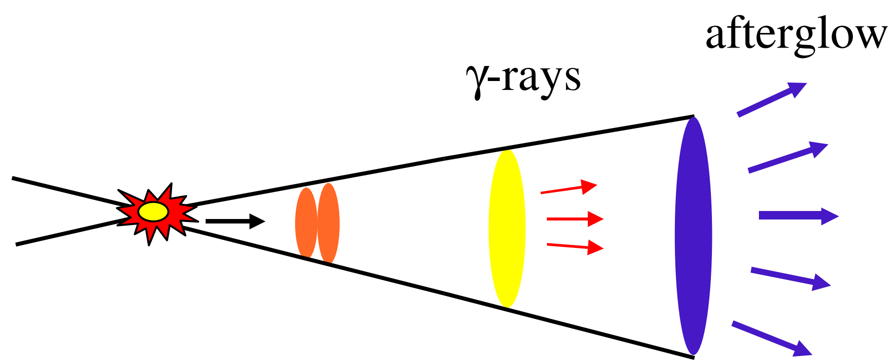
Beppo-SAX & HETE-2 Era

GRB 970228 - BeppoSAX



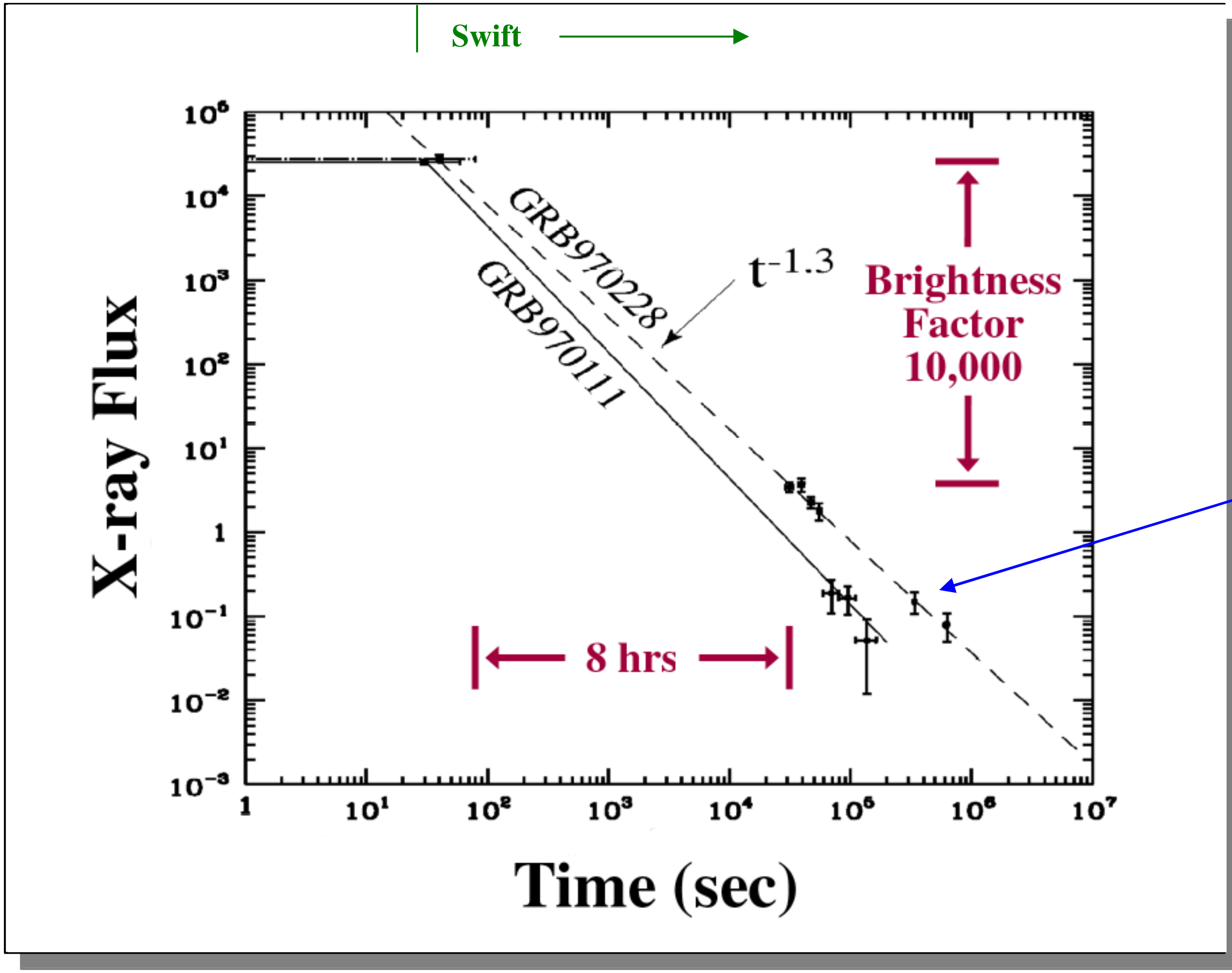
GRB 971214 - Keck





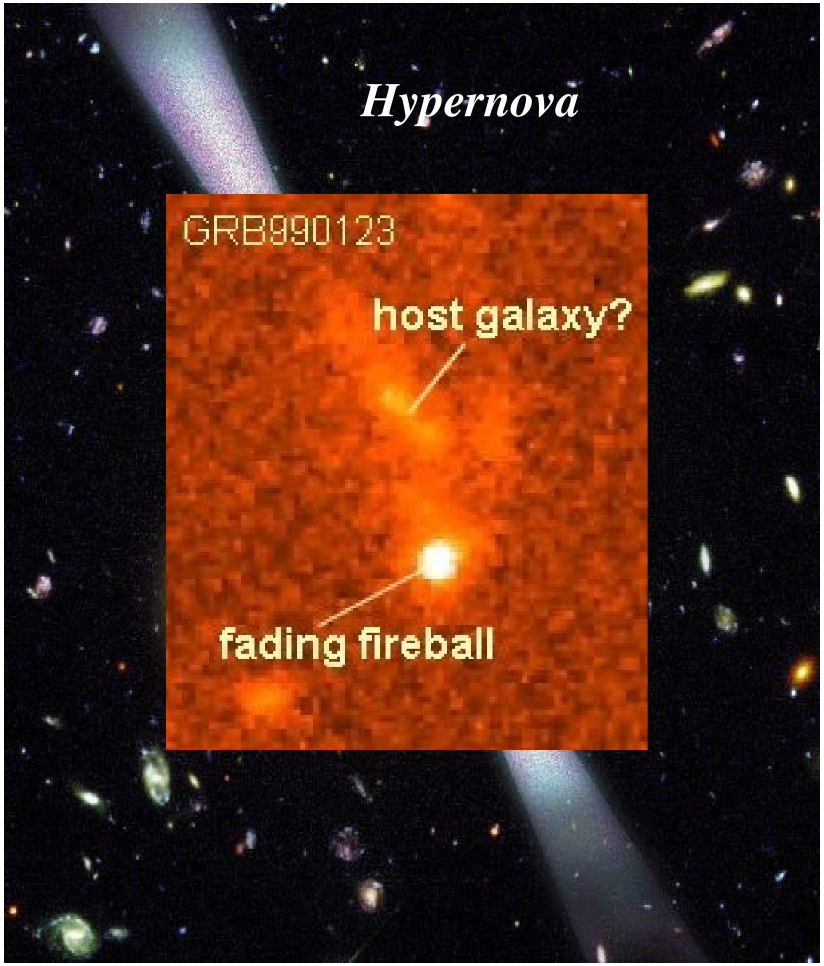
Fireball Model
(Meszaros & Rees 1997)

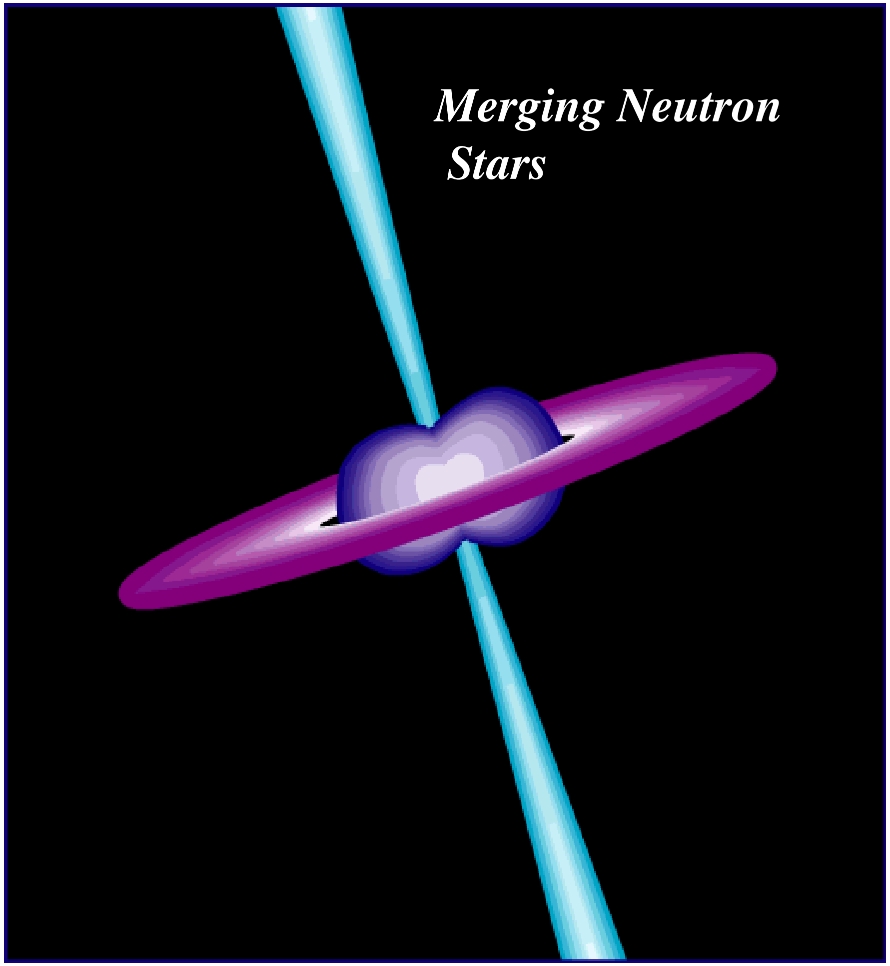
The Time Gap



Swift
X-ray Flux
Time (sec)
GRB970228
GRB970111
t$^{-1.3}$
Brightness Factor 10,000
8 hrs
Beppo SAX data

GRB Progenitors





The *Swift* Era

What have we learned so far from *Swift*?

Swift launch:

20 Nov 2004 !!

MOC Facility

Located in State College, PA

~ 4 km. from Penn State campus

Flight Operations Team (FOT)

– responsible for observatory Health & Safety

Science Operations Team (SOT)

- responsible for scientific operation of Swift

Has continuously operated *Swift* successfully from L+80 minutes to now!

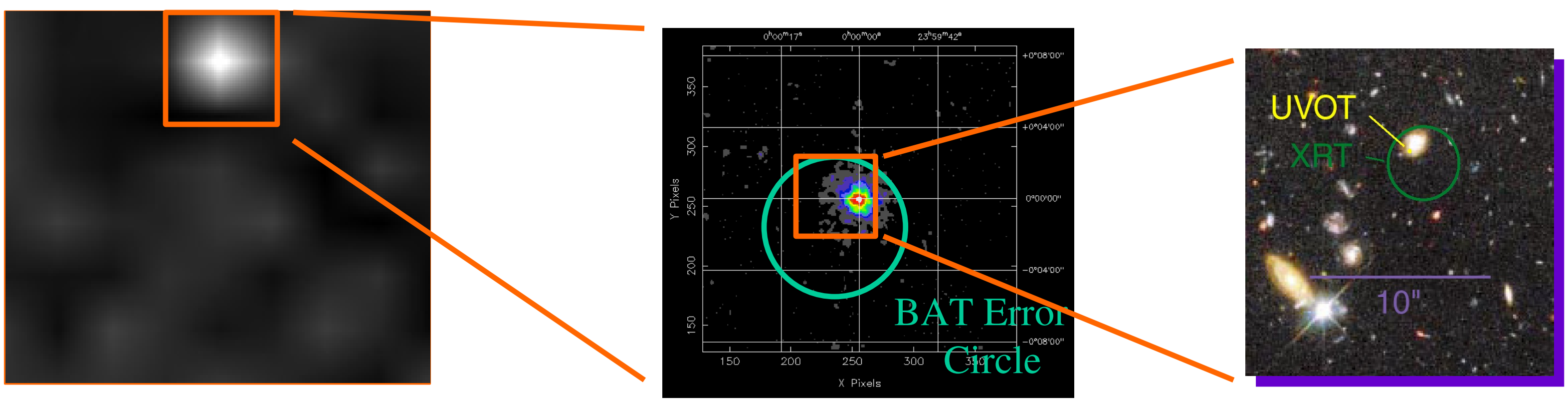
PENNSTATE

1855

Observing Scenario

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

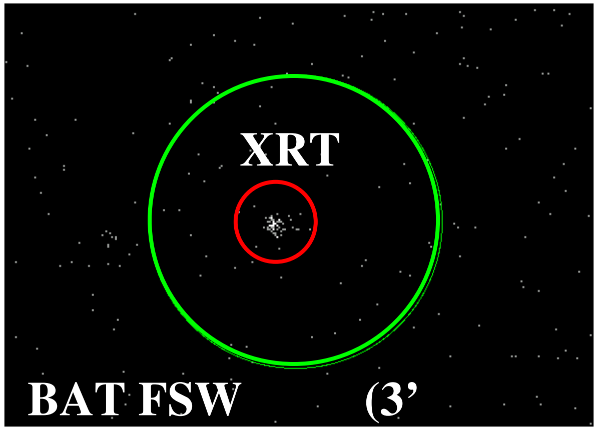
BAT Burst Image | XRT Image | UVOT Image



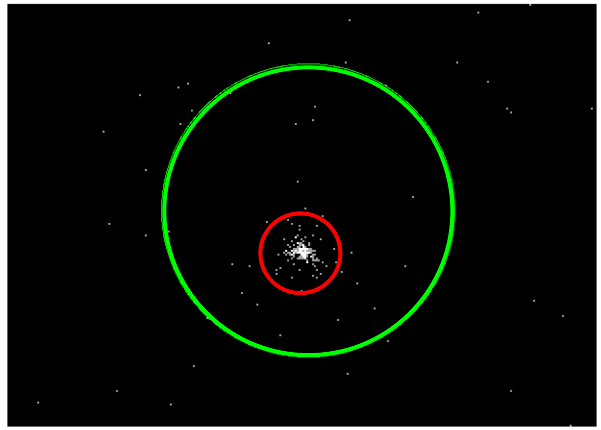
T<10 sec | *T<90 sec* | *T<120 sec*

BAT GRB Position Accuracy

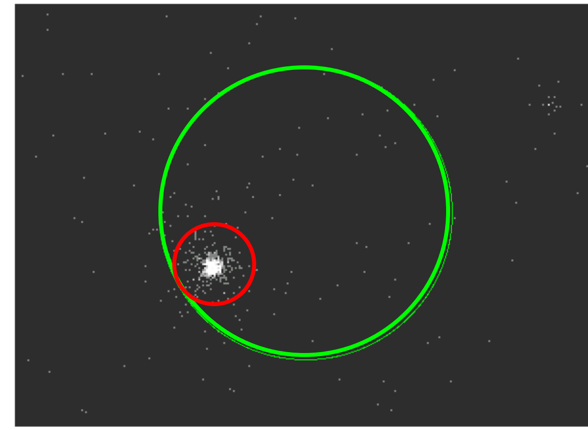
GRB 050215b



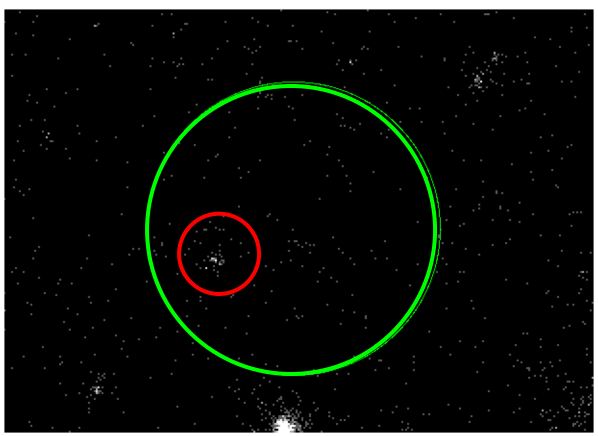
GRB 050315



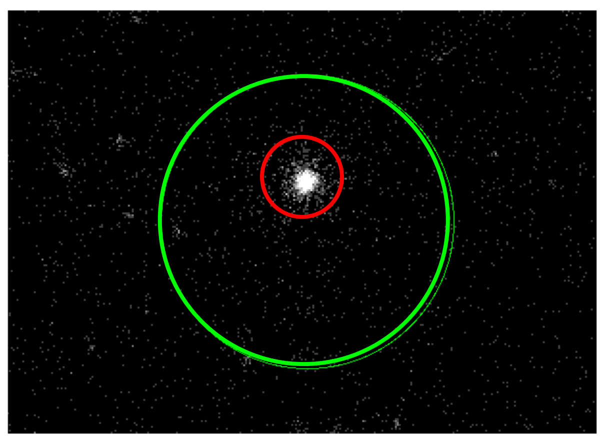
GRB 050319



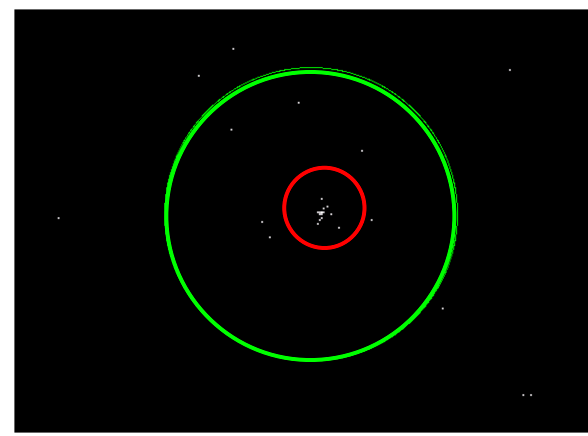
GRB 050406



GRB 050416a



GRB 050509a



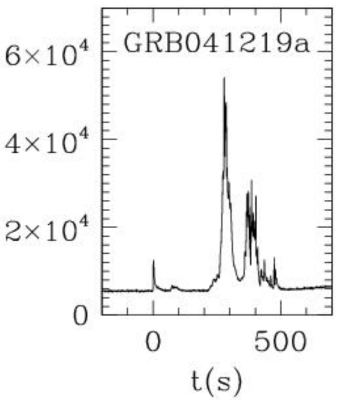
Mean BAT position error: 52 arcseconds

T. Sakamoto

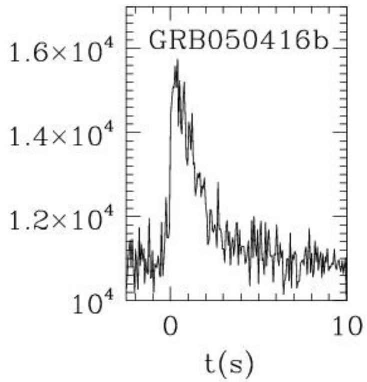
Swift Statistics:

180 GRB as 3 Oct 2006
~105 GRBs per year
85% with x-ray detections
95% with XRT @ T<200 ks
~58% with optical detection

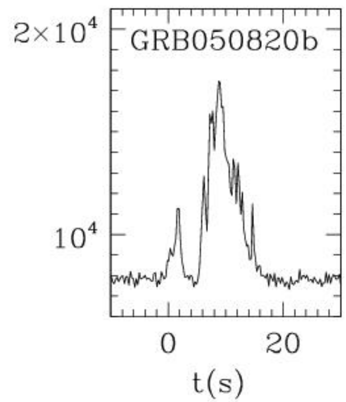
~175 non-GRB TOO's
>50,000 slews



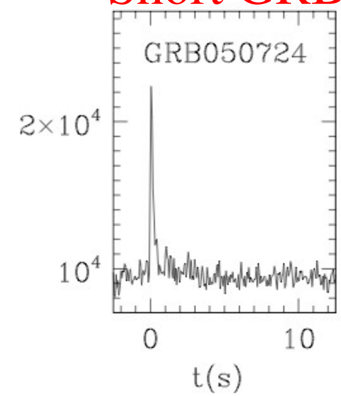
FRED

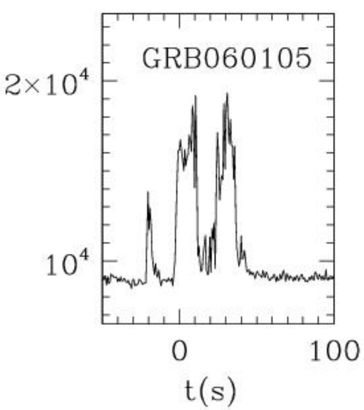


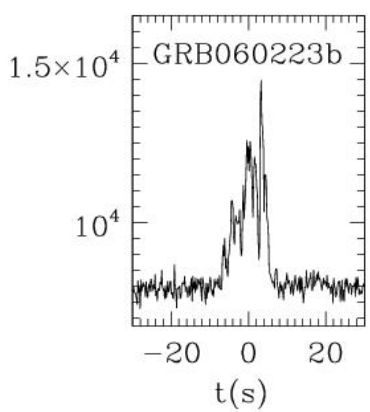
Fast Rise Exponential Decay



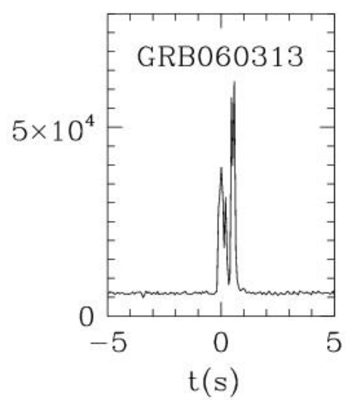
Short GRB

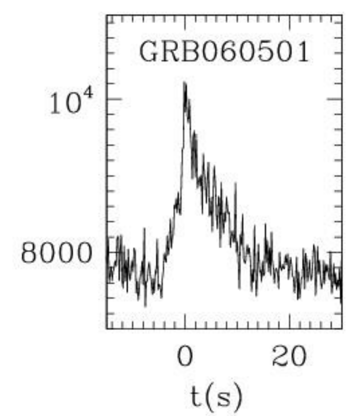




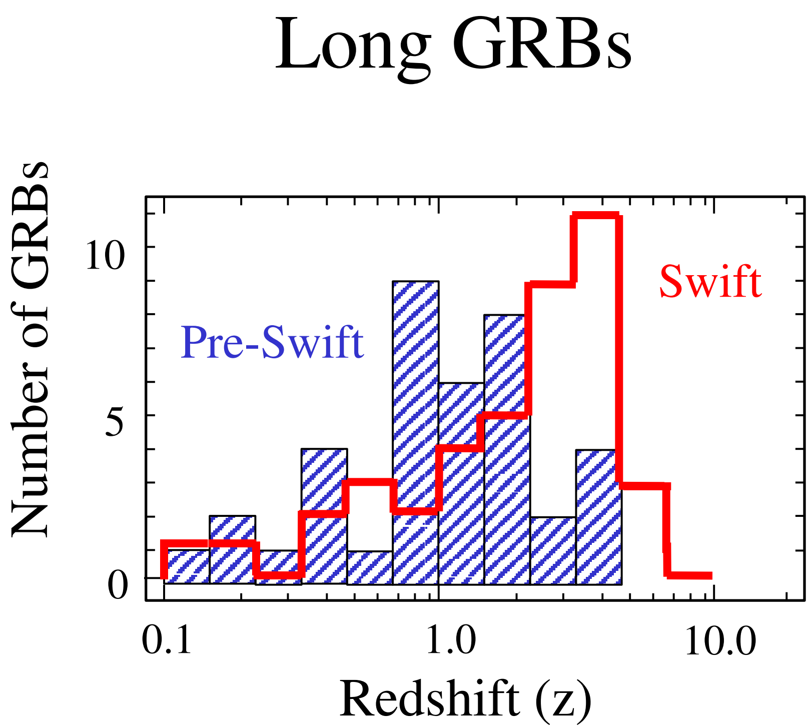


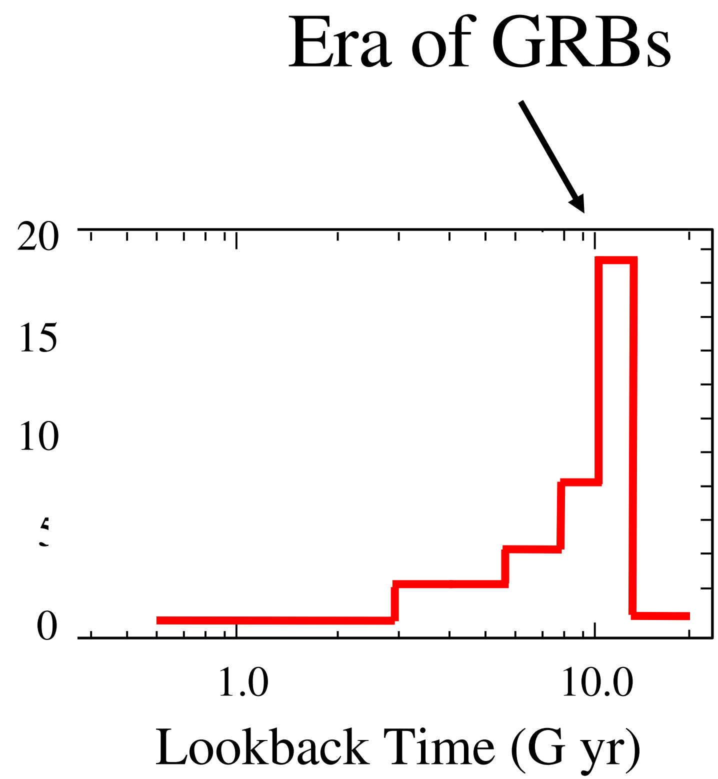
Short GRB





Redshift and Time Distributions





Average Redshift
- Pre-Swift: z = 1.2
- Swift: z = 2.3

Analysis by Neil Gehrels

6.29	050904
5.3	050814
5.11	060522
4.9	060510B
4.41	060223A
4.27	050505
4.05	060206
3.97	050730
3.91	060210
3.71	060605
3.69	060906
3.53	060115
3.43	060707
3.34	050908
3.24	050319
3.21	060526
3.08	060607A
2.90	050401
2.82	050603
2.71	060714
2.68	060604
2.61	050820A

2.43	060908
2.35	051109A
2.30	060124
2.20	050922C
1.95	050315
1.71	050802
1.55	051111
1.51	060502A
1.49	060418
1.44	050318
1.29	050126
0.94	051016B
0.83	050824
0.70	060904B
0.65	050416A
0.61	050525A
0.54	060729
0.44	060512
0.125	060614
0.089	060505
0.033	060218

Swift Redshifts

43 total with accurate z

World total more than doubled

7 GRBs at z > 4

3 at z > 5

Bromm & Loeb predicted 10%

Jakobbson et al. predicted 7%

measured value is 7%

2 at z < 0.1

Royal Society talk by Neil Gehrels

Since 18 Sept 2006: 7 more GRBs

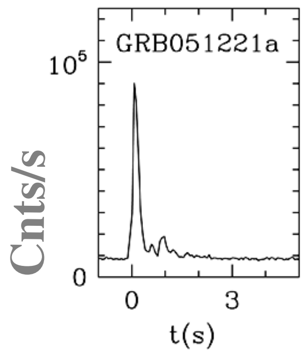
2 more z's – GRB060926 z=5.6!

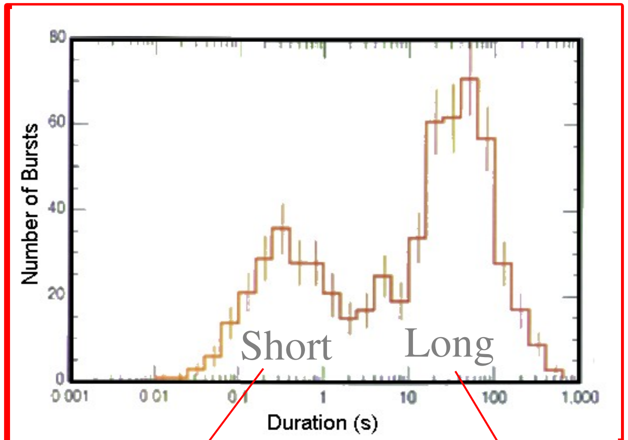
GRBs – now in the *Swift* era

How has the paradigm changed with the Swift discoveries?

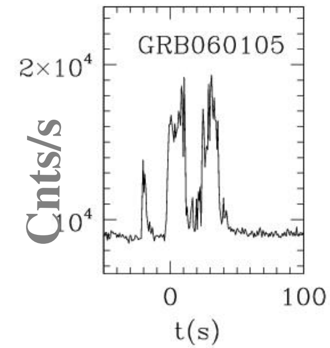
Short vs Long GRBs

Short GRB





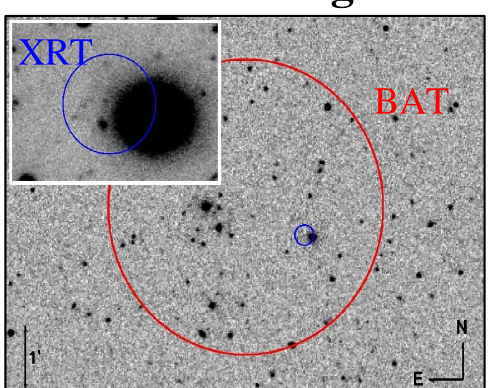
Long GRB



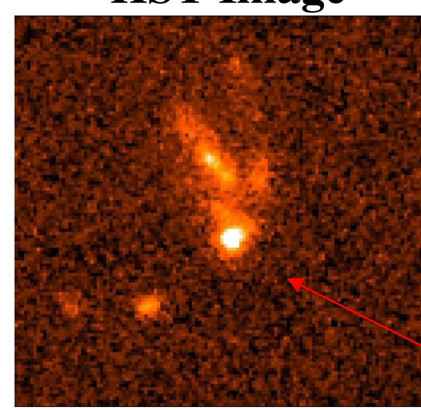
Swift first to discover counterpart to short GRB!

Short GRBs
in non-SF
galaxies/regions

GRB 050509B - Swift
VLT Image



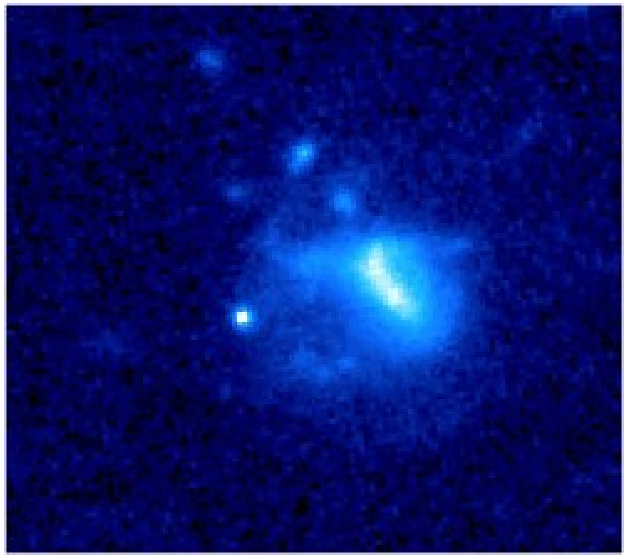
GRB 990123 - BeppoSAX
HST Image



Long GRBs
in SF
galaxies

GRB

GRB 050709



Fox et al.

z = 0.161

SF galaxy, but in dark region

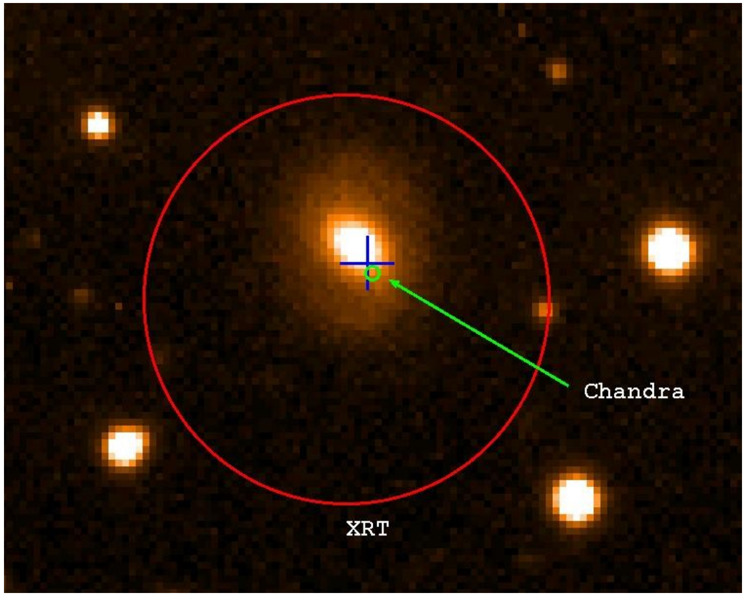
XT - XRT, Chandra

OT - ground-based, HST

No supernova seen

HETE-2 Villasenor et al. 2005

GRB 050724



z = 0.258

Elliptical host galaxy

XT - XRT, Chandra

OT - ground-based

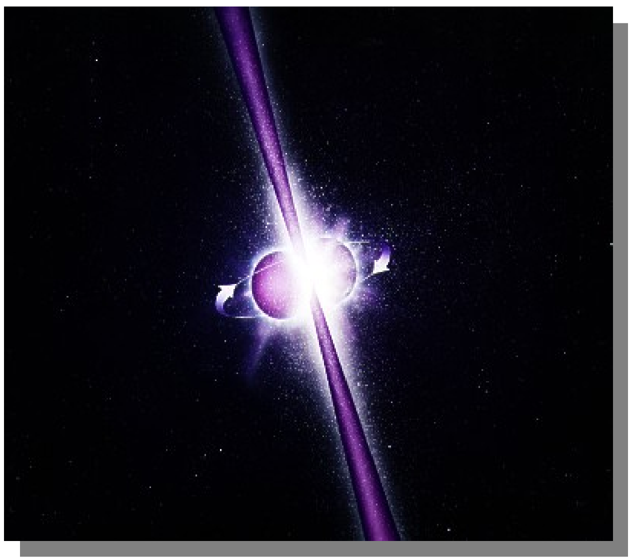
RT - VLA

Barthelmy et al. 2005

Interpretation

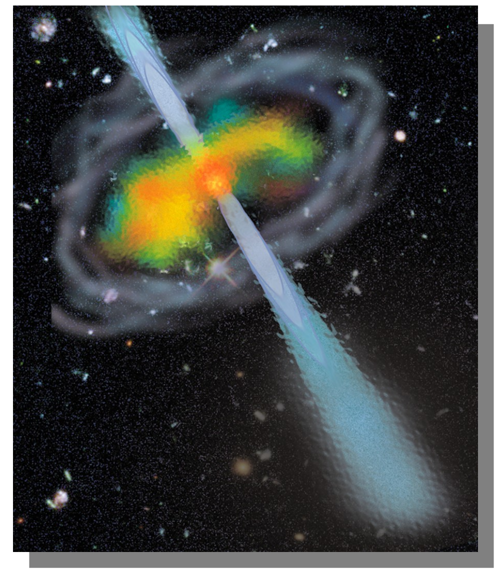
Short GRB

Neutron Star Merger



Long GRB

Collapsar - Massive Star Explosion



Black Hole Birth

however, ...

Short GRB Summary Table

Name	Redshift	Afteglow	Host	E_{iso} (10^{50} erg)	Duration (s)	Temporal Lag (ms)	Extended ?	Origin /Comment
050509B	**0.225**	**X**	**elliptical@**	**~0.06**	**0.03**	**4.3±3.2**	**N**	**low SF region**
050709*	**0.161**	**X, O**	**SF galaxy**	**0.6**	**0.07**	**0.0±2.0**	**Y**	**low SF region**
050724	**0.258**	**X, O, R**	**elliptical**	**~4.7**	**3.0**	**-2±6**	**Y**	**low SF region**
050813	**? 0.7, 1.8**	**X**	**galaxy**	**2 - 17**	**0.60**	**-9.7±14?**	**N**	**-**
050906	**0.03?**	**-**	**? galaxy**	**0.001?**	**0.13**	**-**	**N**	**BAT only**
050911	0.165?	late slew	cluster@	0.9?	16	-20±20?	Y	is it short?
050925#	**-**	**-**	**in gal. plane**	**-**	**0.07**	**-**	**N**	**non-GRB?**
051105A	**-**	**-**	**-**	**-**	**0.03**	**6.3±5.3?**	**N**	
051210	**0.11?**	**X**	**? cluster@**	**0.1?**	**1.4**	**-1.0±16.0?**	**N**	**-**
051221A	**0.547**	**X, O, R**	**SF galaxy**	**31.**	**1.4**	**0.0±0.4**	**N**	**-**
051227	**-**	**X**	**-**	**-**	**0.9**	**2±10?**	**Y**	**-**
060121*	**>1.5**	**X, O**	**galaxy**	**-**	**2**	**2±29?**	**N**	**-**
060313	**-**	**X, O**	**? cluster@**	**-**	**0.7**	**0.8±0.6**	**N**	**-**
060502B	**0.287?**	**X**	**? elliptical**	**0.1?**	**0.09**	**-4.0±3.0**	**N**	**-**
060505	0.089	X, O	galaxy	~0.5	4.0	n.a.	?	is it short?
060614	0.125	X, O	dwarf gal.	3.7	103 (5)	3±6	Y	is it short?
060801	**1.131**	**X**	**galaxy?**	**~13.**	**0.5**	**8±8?**	**N**	**-**

* HETE GRB
\# soft spectrum
@ galaxy in cluster

Data assembled by Neil Gehrels

Comparison to Long GRBs

Smaller Redshift

$< z > = 0.5$ short

$< z > = 2.3$ long

Weaker x-ray afterglow (at t_o+90s)

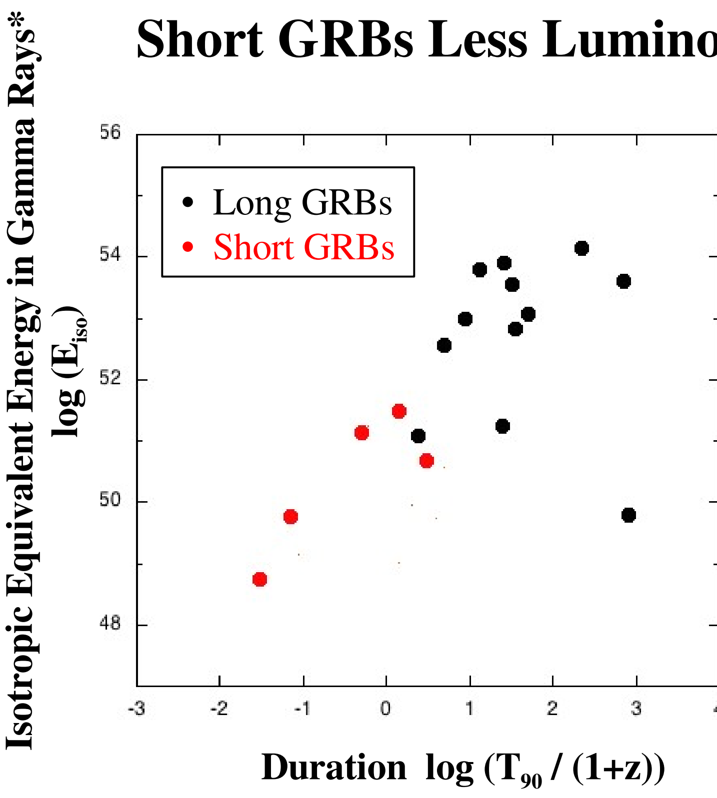
$< F_X > = 7 \times 10^{-10}$ erg cm^{-2} s^{-1} short

$< F_X > = 3 \times 10^{-9}$ erg cm^{-2} s^{-1} long

Fewer detected by XRT in rapid-slew observations

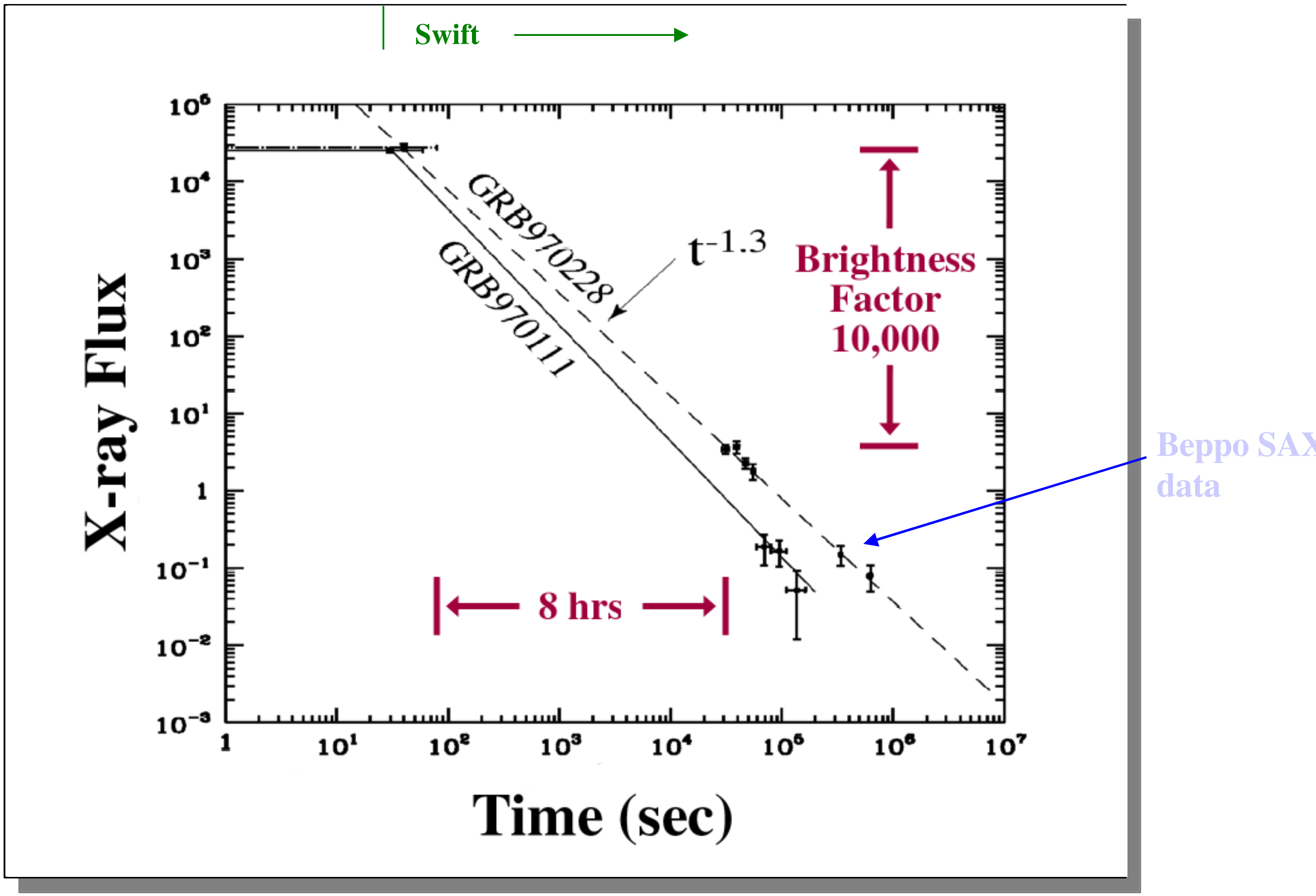
80%	short
100%	long

Short GRBs Less Luminous

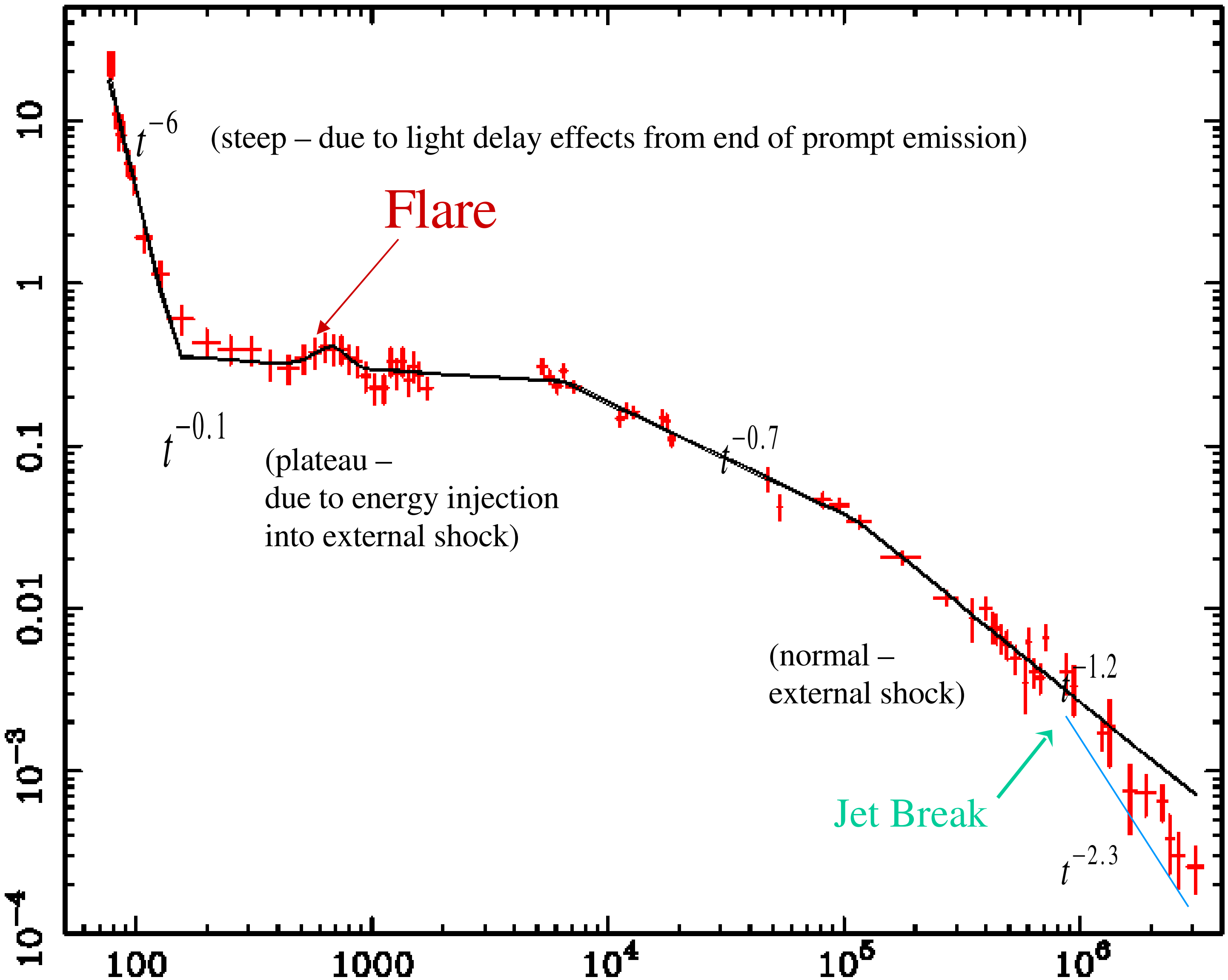


* E_{iso} : 1 - 10,000 keV band in source frame

Pre-*Swift* X-ray light curve

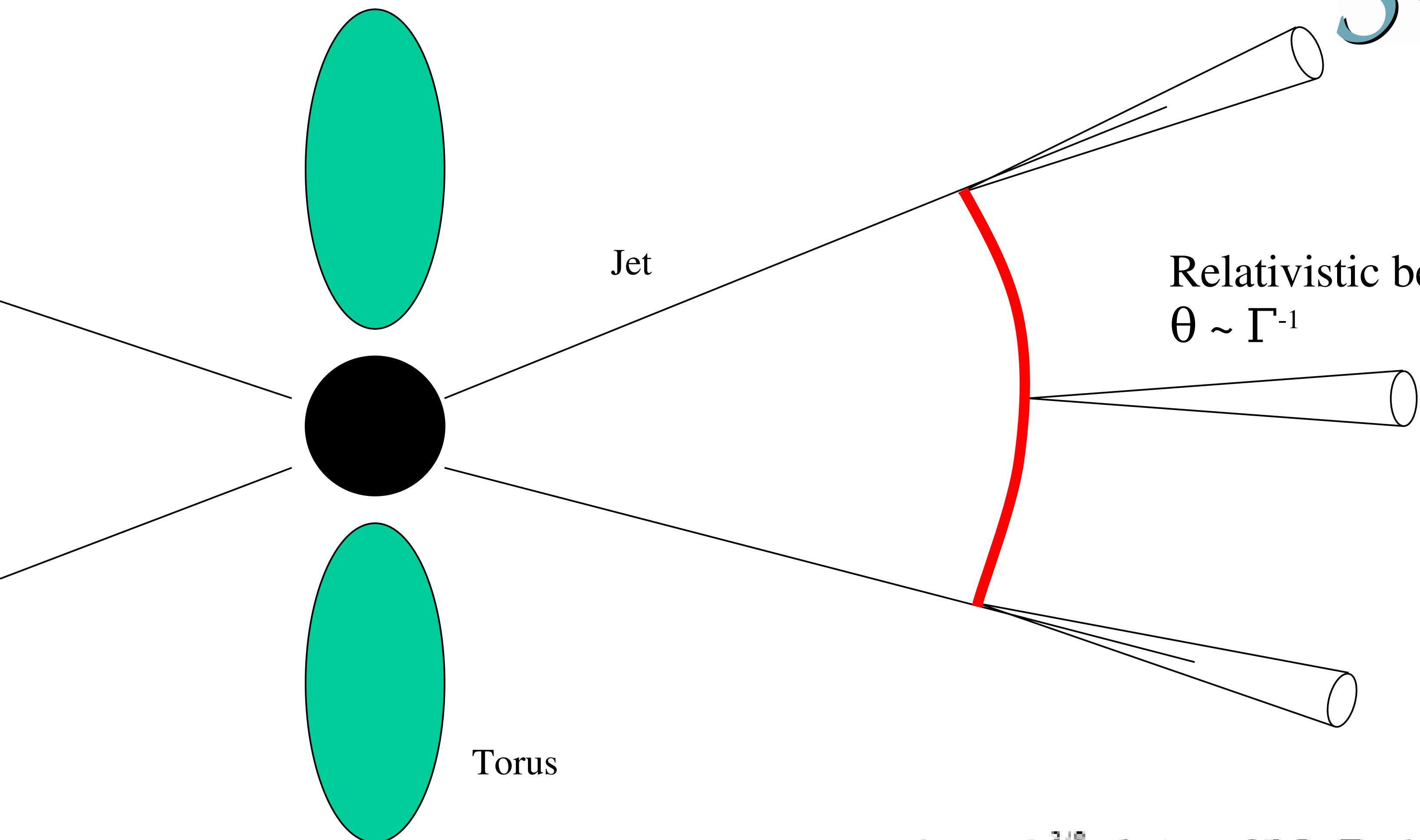


Canonical *Swift* XRT Light Curve



GRB060428A – Courtesy of D. Burrows

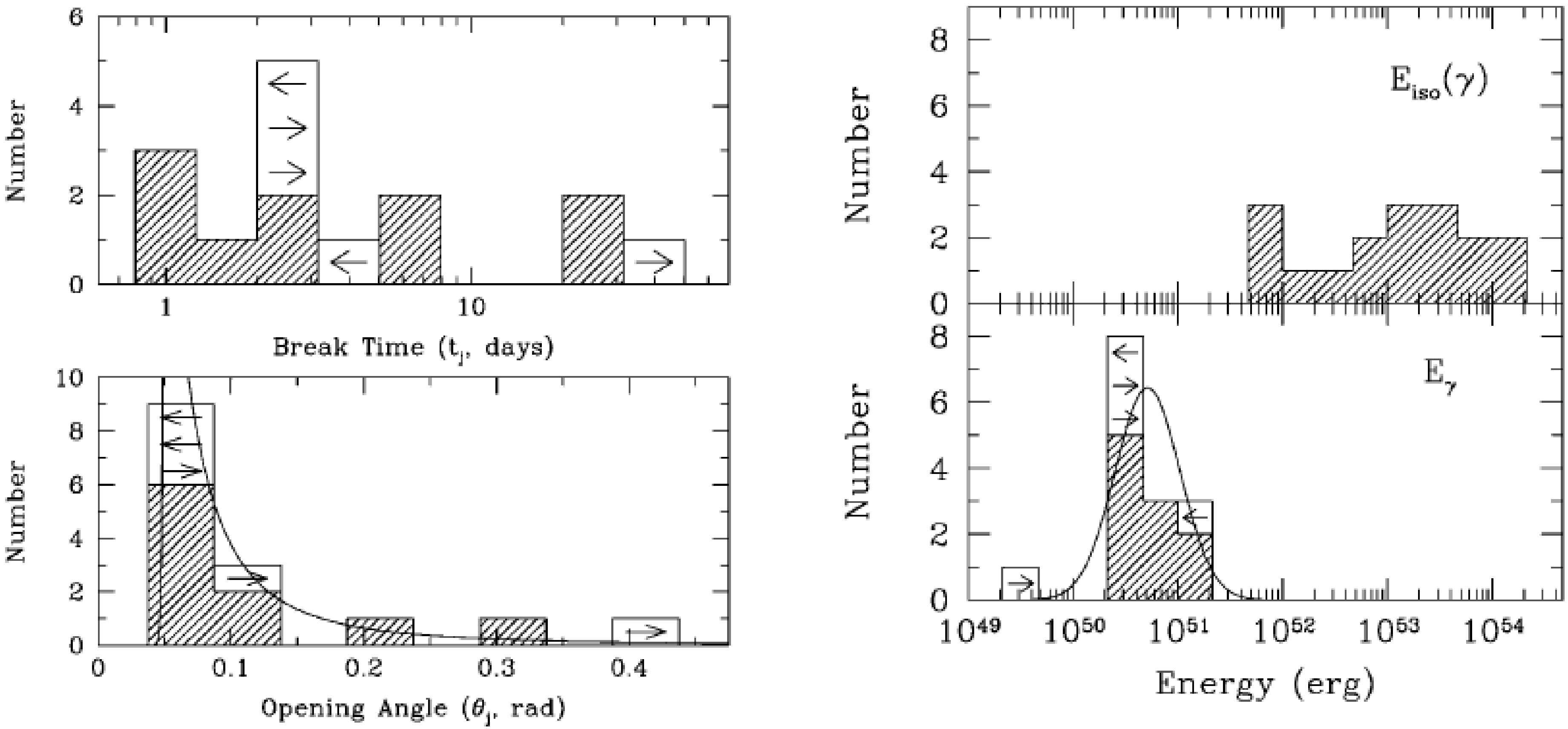
Jet Break



$$\theta_j = 0.057 \left(\frac{t_j}{1\ \mathrm{day}}\right)^{3/8} \left(\frac{1+z}{2}\right)^{-3/8} \left[\frac{E_{\mathrm{iso}}(\gamma)}{10^{53}\ \mathrm{ergs}}\right]^{-1/8} \times \left(\frac{\eta_\gamma}{0.2}\right)^{1/8} \left(\frac{n}{0.1\ \mathrm{cm}^{-3}}\right)^{1/8},$$

Frail et al. 2001, ApJ, 562, L55

Jet Break

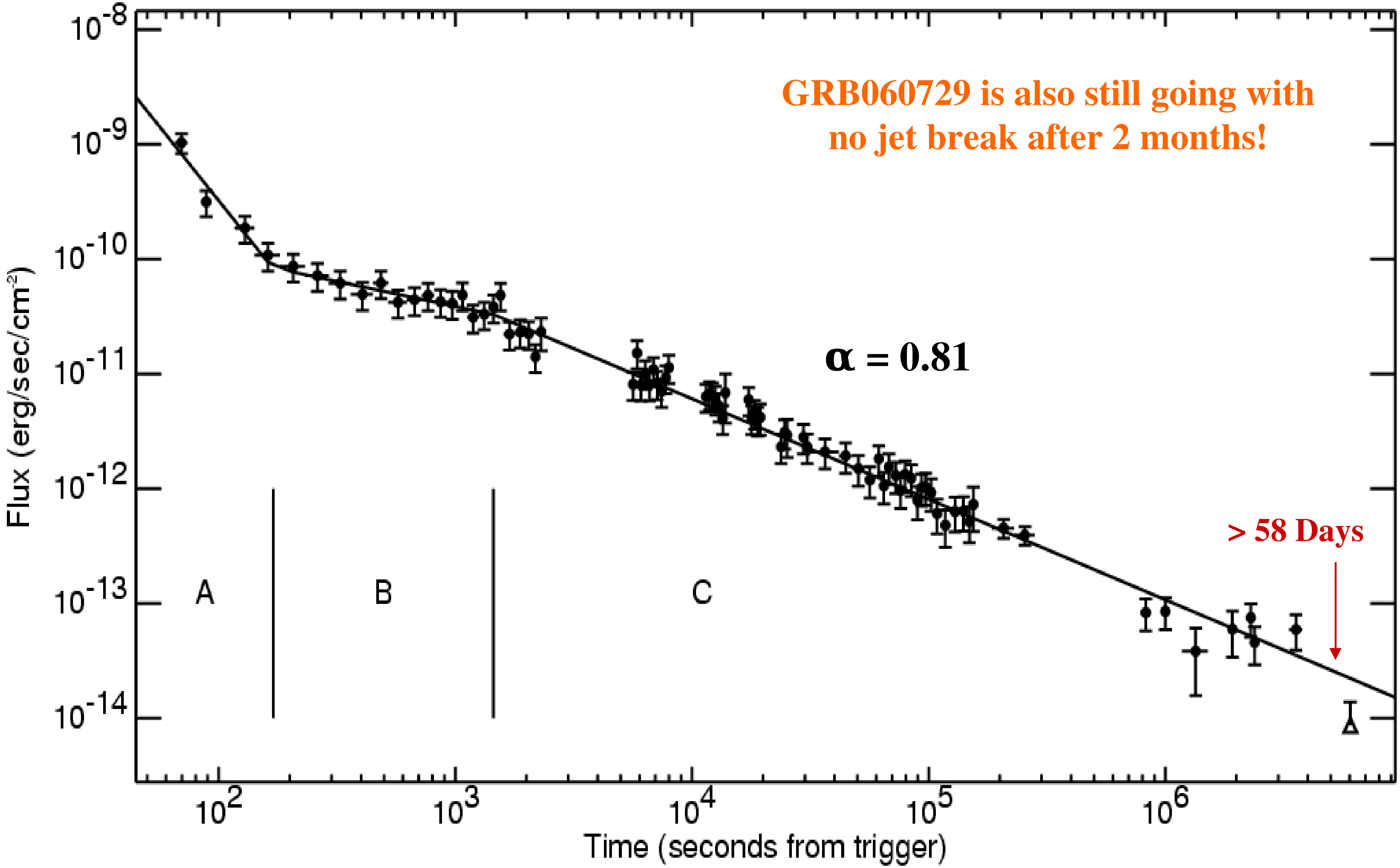


Jet break knowledge is critical for GRB energetics:

$$E_\gamma = E_{iso}(1-\cos\theta_j)$$

Frail et al. 2001, ApJ, 562, L55

GRB050416A



GRB060729 is also still going with
no jet break after 2 months!
α = 0.81
> 58 Days
A
B
C
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
Flux (erg/sec/cm^{2})
10^{2}
10^{3}
10^{4}
10^{5}
10^{6}
Time (seconds from trigger)

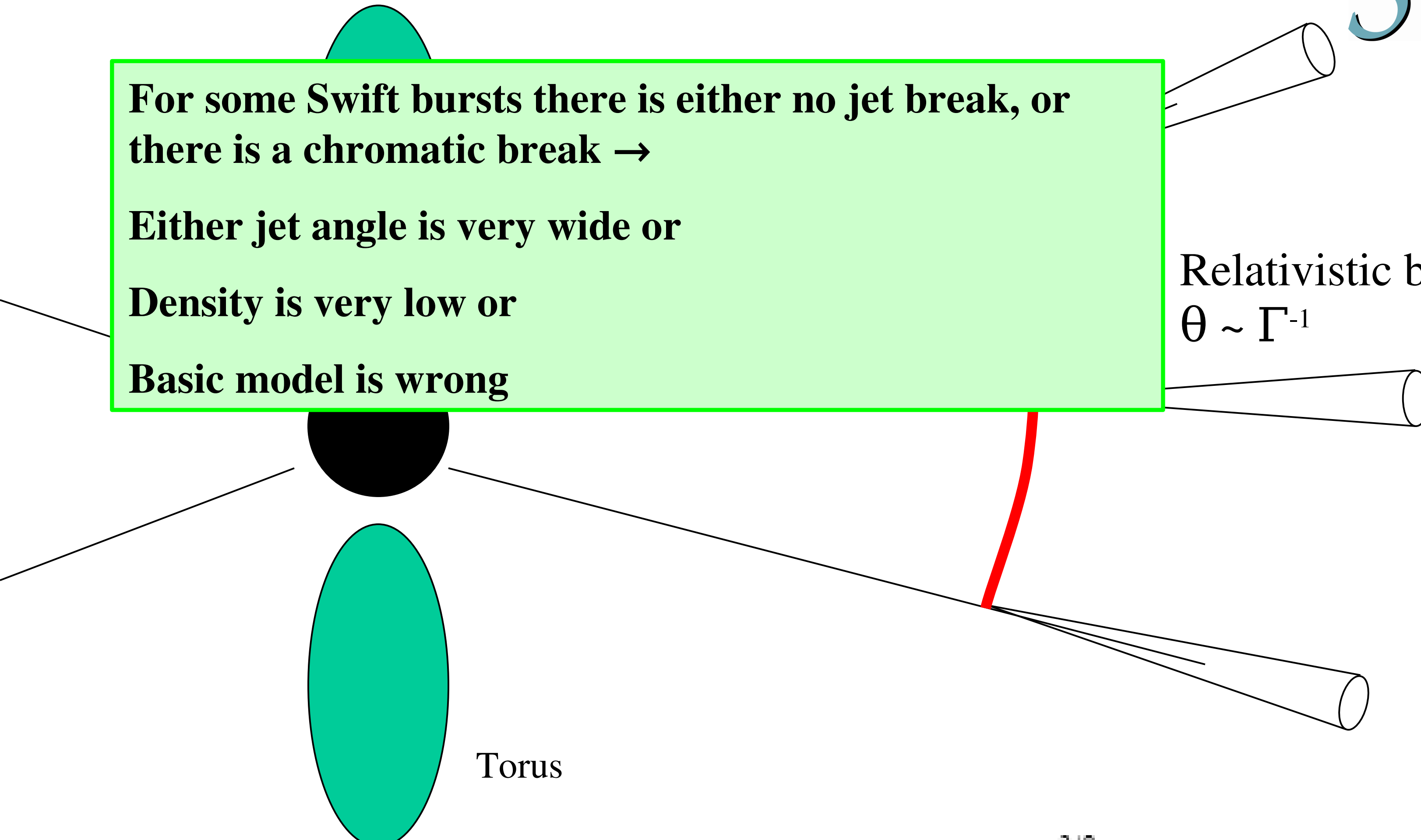
Jet Break

For some Swift bursts there is either no jet break, or there is a chromatic break →

Either jet angle is very wide or

Density is very low or

Basic model is wrong

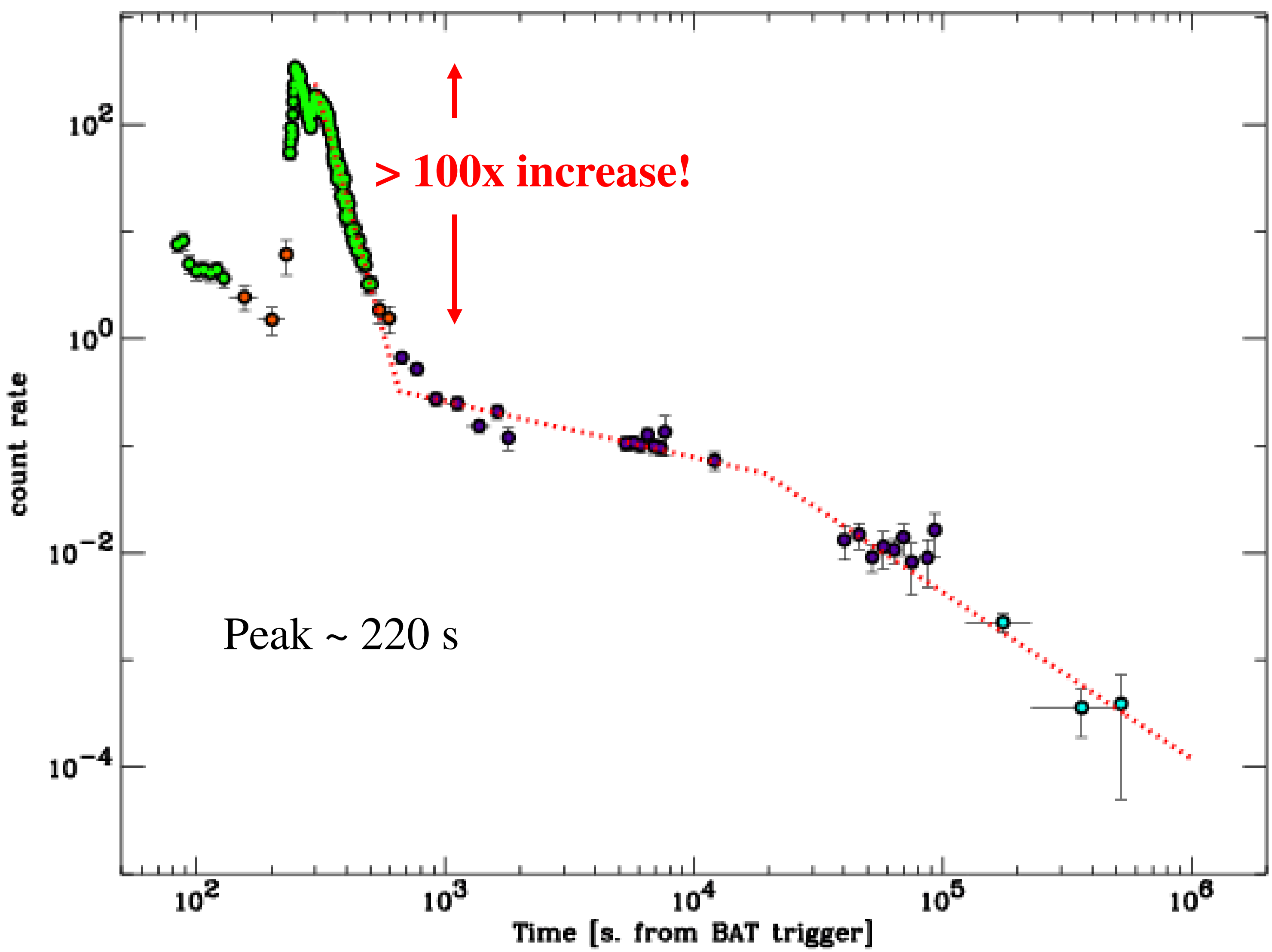


Relativistic beaming:
$\theta \sim \Gamma^{-1}$

$$\theta_j = 0.057 \left(\frac{t_j}{1\ \mathrm{day}}\right)^{3/8} \left(\frac{1+z}{2}\right)^{-3/8} \left[\frac{E_{\mathrm{iso}}(\gamma)}{10^{53}\ \mathrm{ergs}}\right]^{-1/8} \times \left(\frac{\eta_\gamma}{0.2}\right)^{1/8} \left(\frac{n}{0.1\ \mathrm{cm}^{-3}}\right)^{1/8},$$

Frail et al. 2001, ApJ, 562, L55

Giant X-ray Flare: GRB 060526



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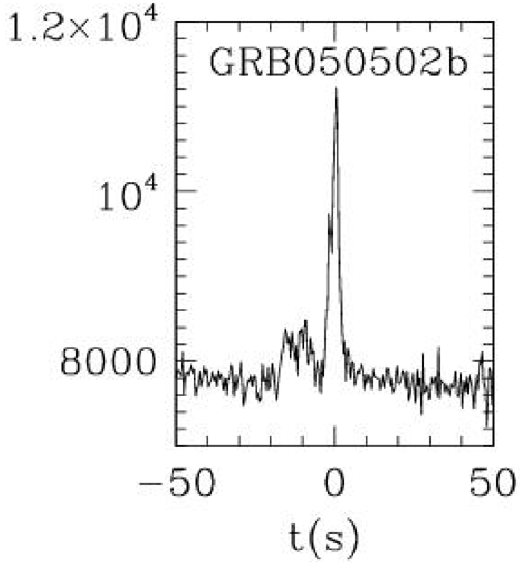
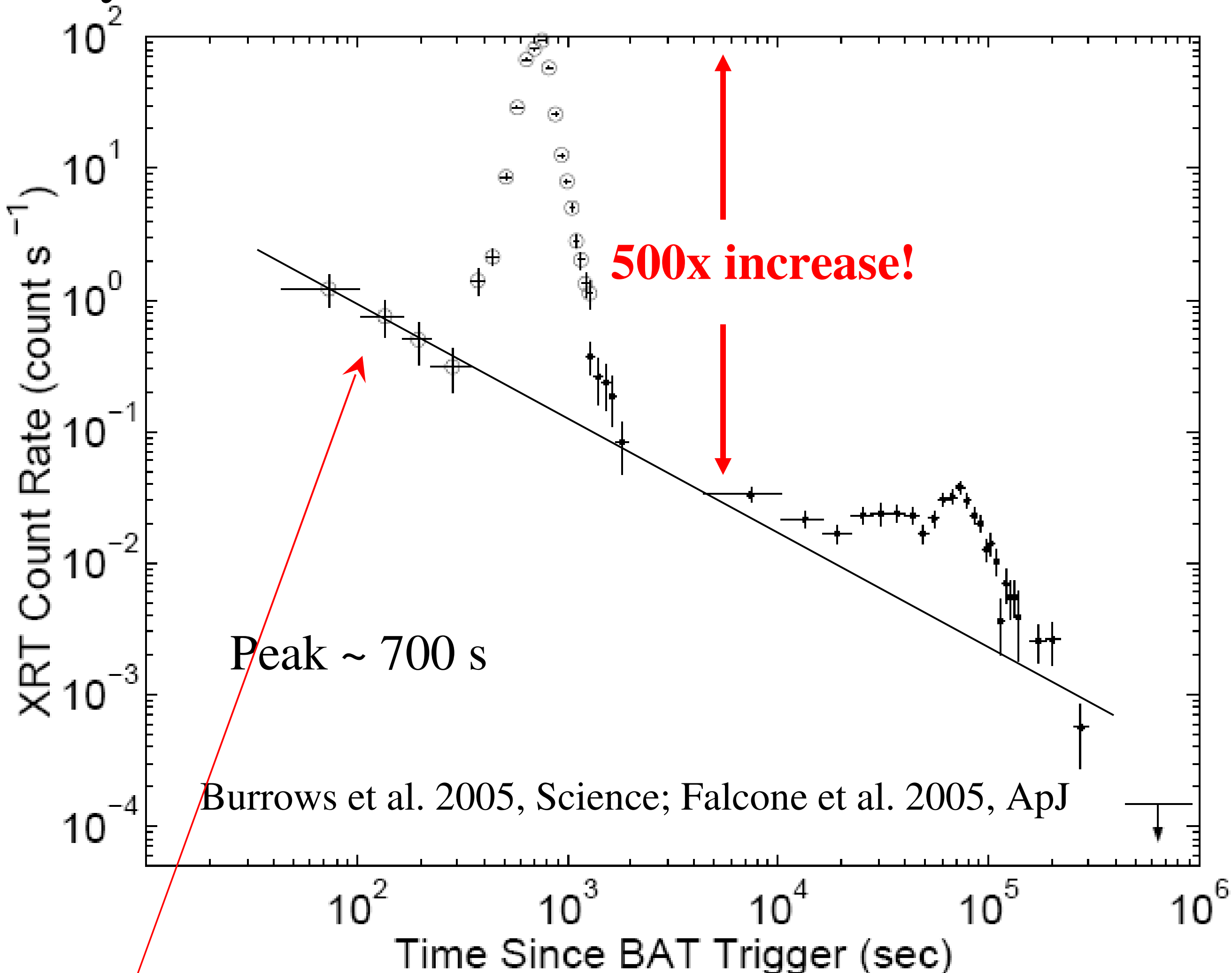
Giant X-ray Flare: GRB 050502B





GRB Fluence:
8E-7 ergs/cm²

Flare Fluence:
9E-7 ergs/cm²

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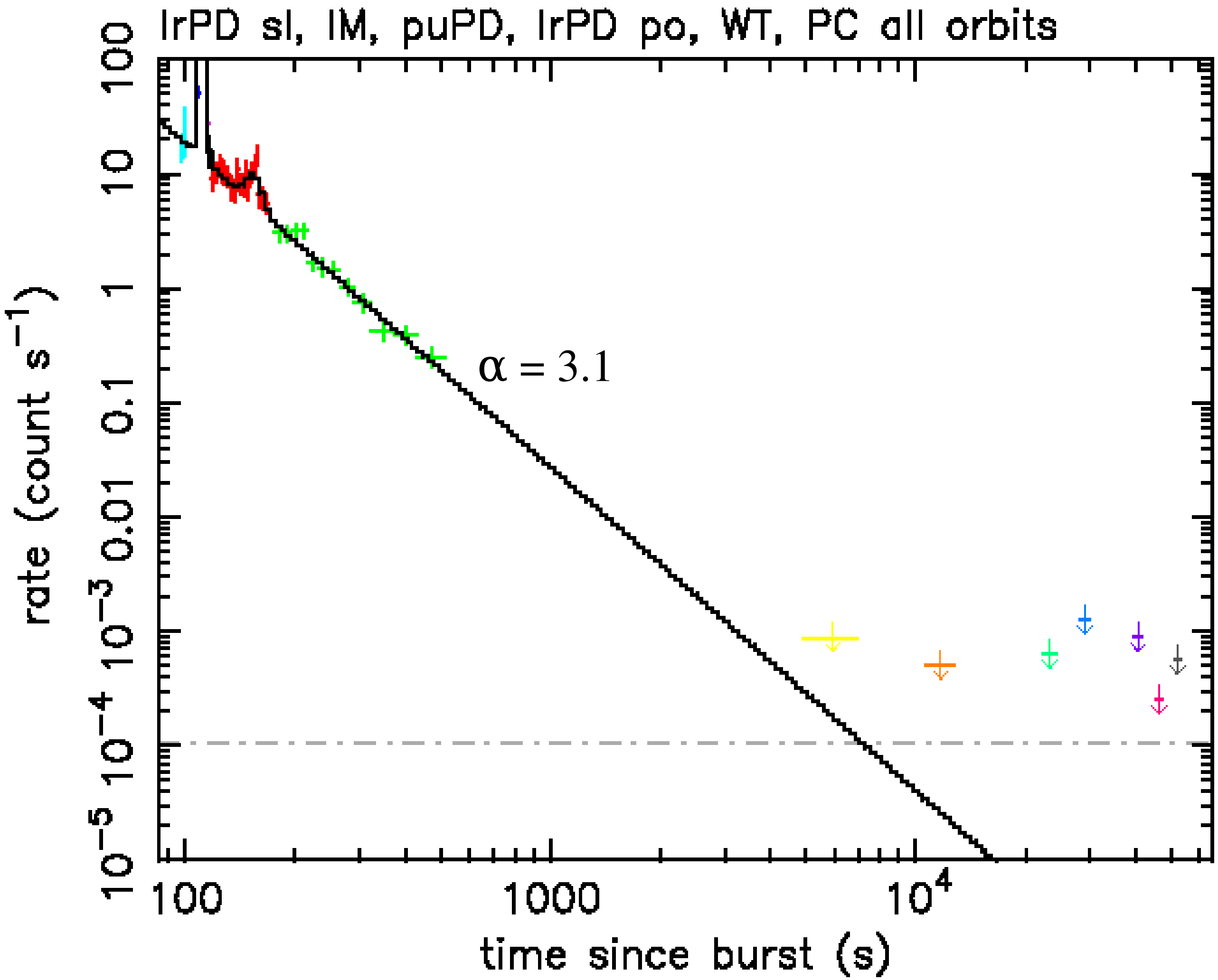
Note establishment of AG before flare begins.

Flare in Naked GRB: GRB 050421



No afterglow seen, two flares in first 200 s

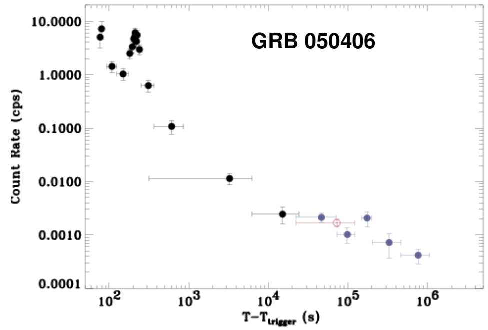
Swift XRT X-ray Flares

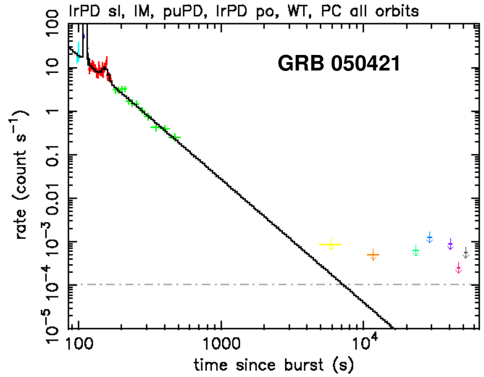
116 prompt afterglow detections

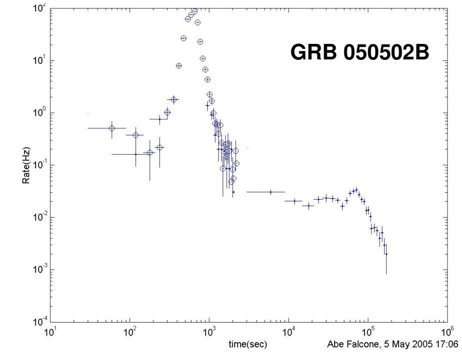
~ 50% have X-ray flares

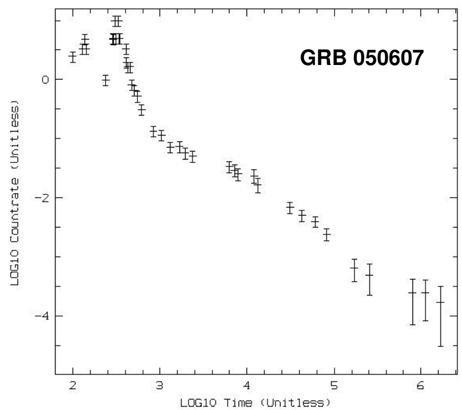
Typically in first 20 min.

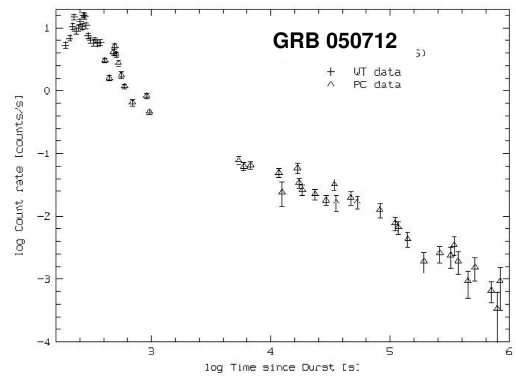
Dynamic range: 1.3x – 500x

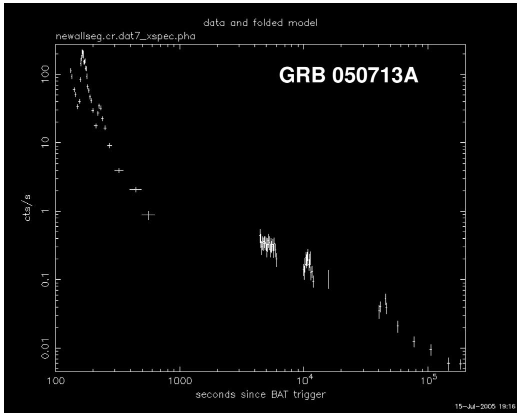


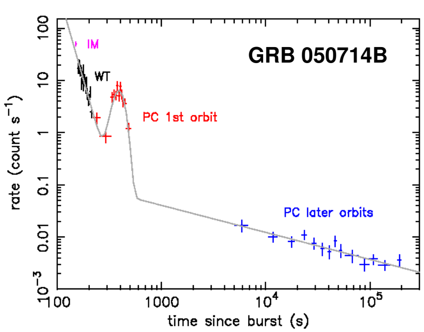


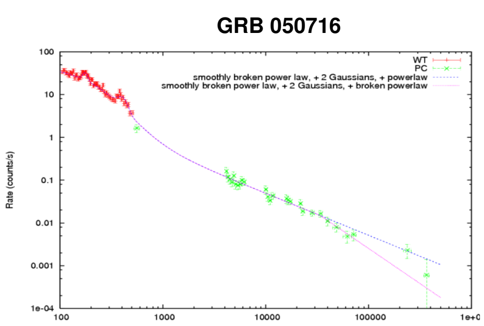


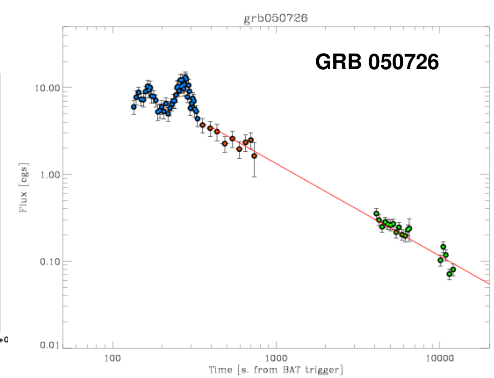


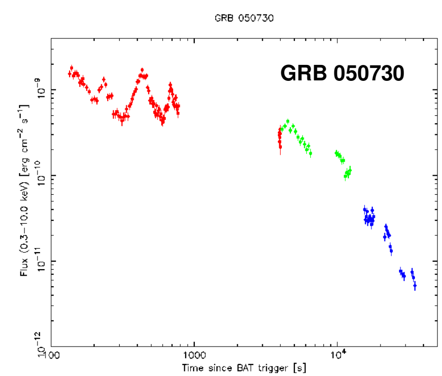










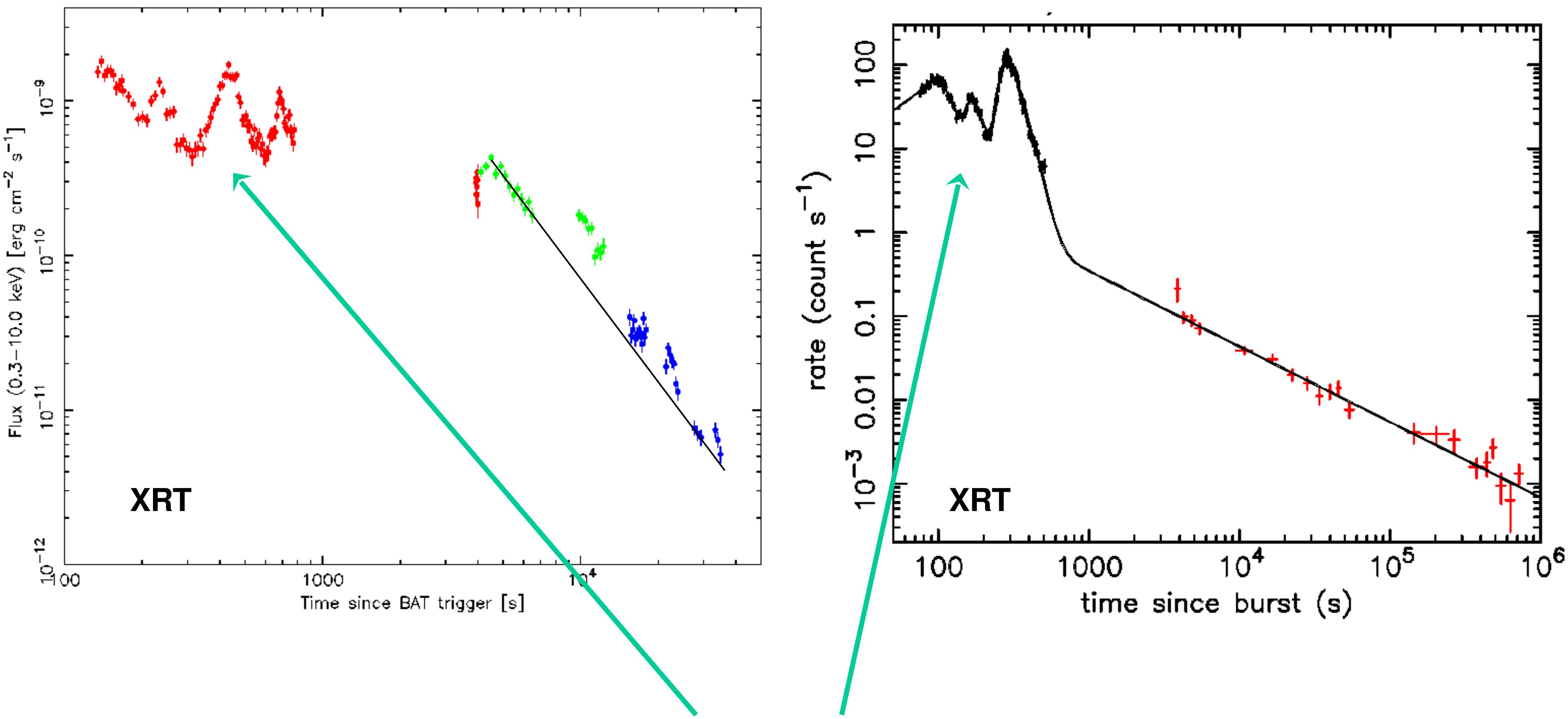


Flare analysis courtesy of Dave Burrows

Multiple flares are common

GRB 050730

GRB 060111



Multiple flares

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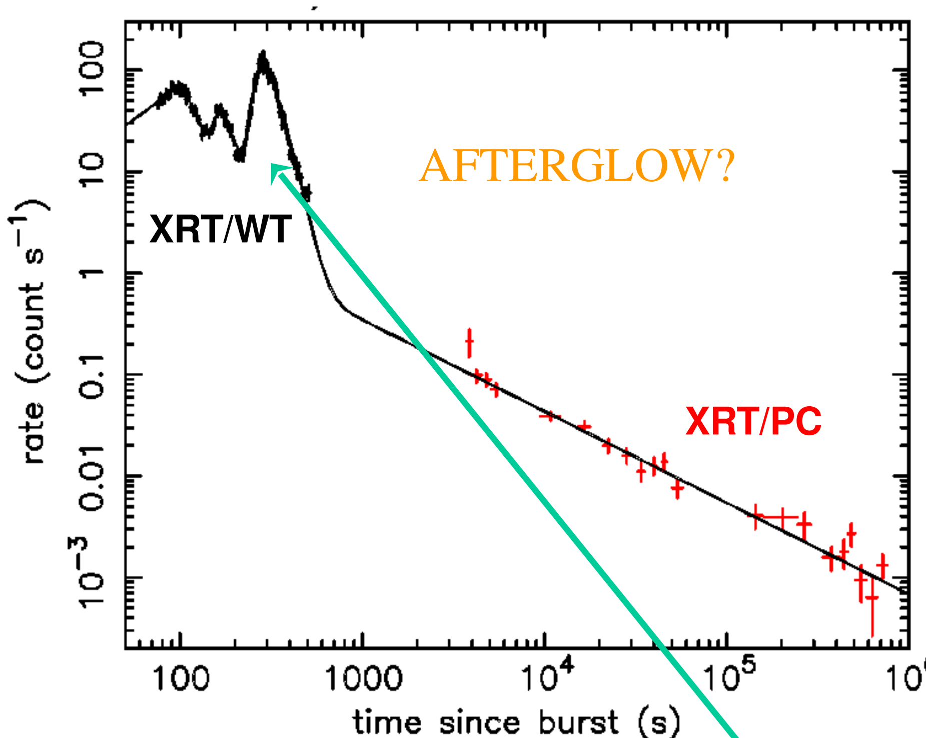
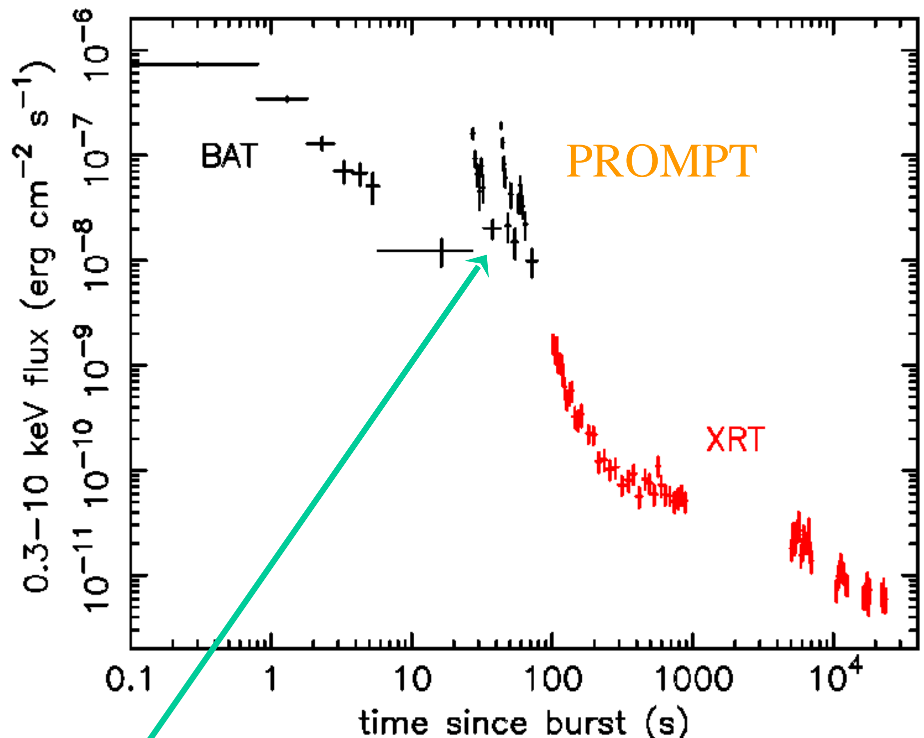
Comparing BAT and XRT

GRB 060111



GRB 060306

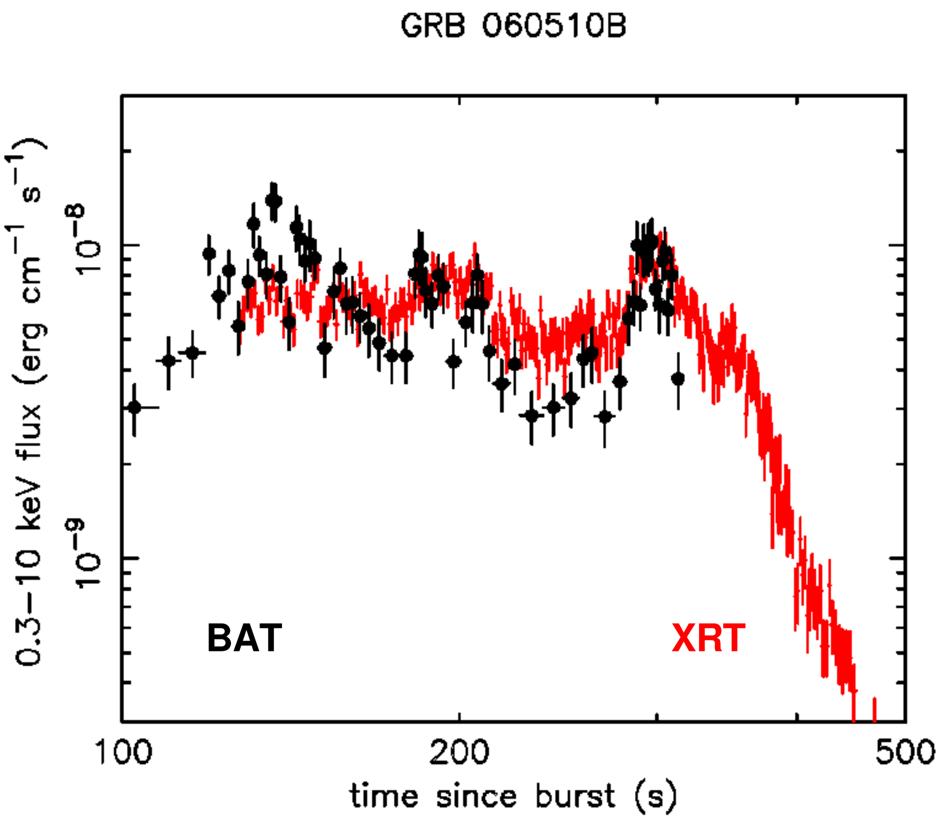


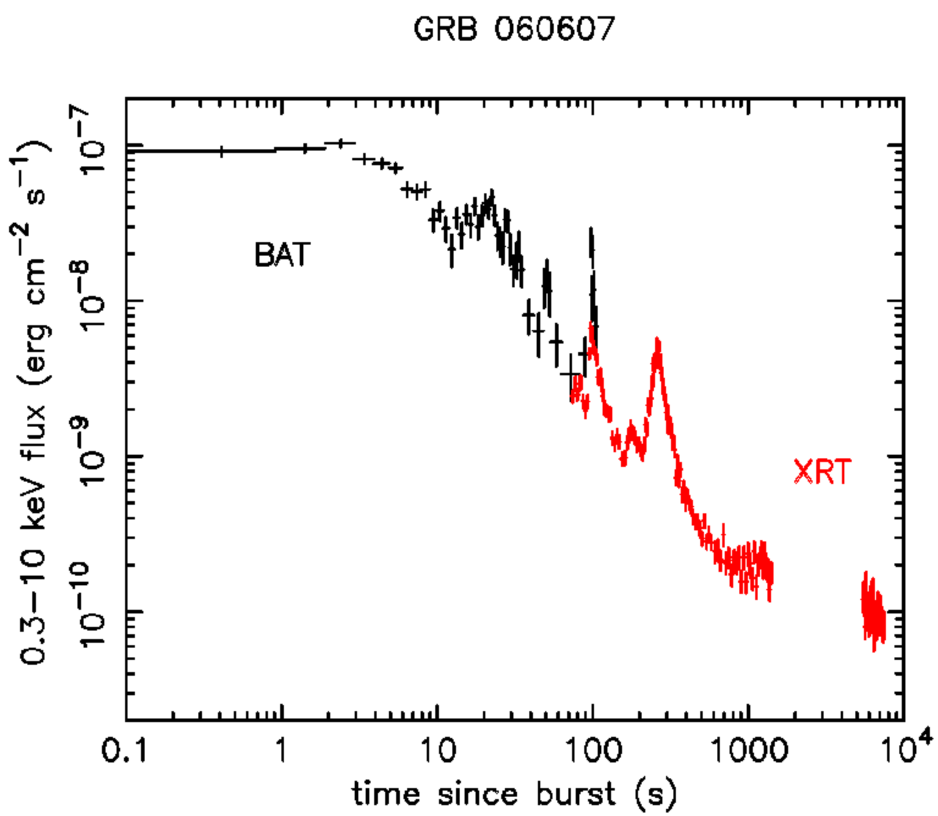
Multiple flares

Only obvious differences are:

- energy band
- pulse widths

XRT Observations During Prompt Emission

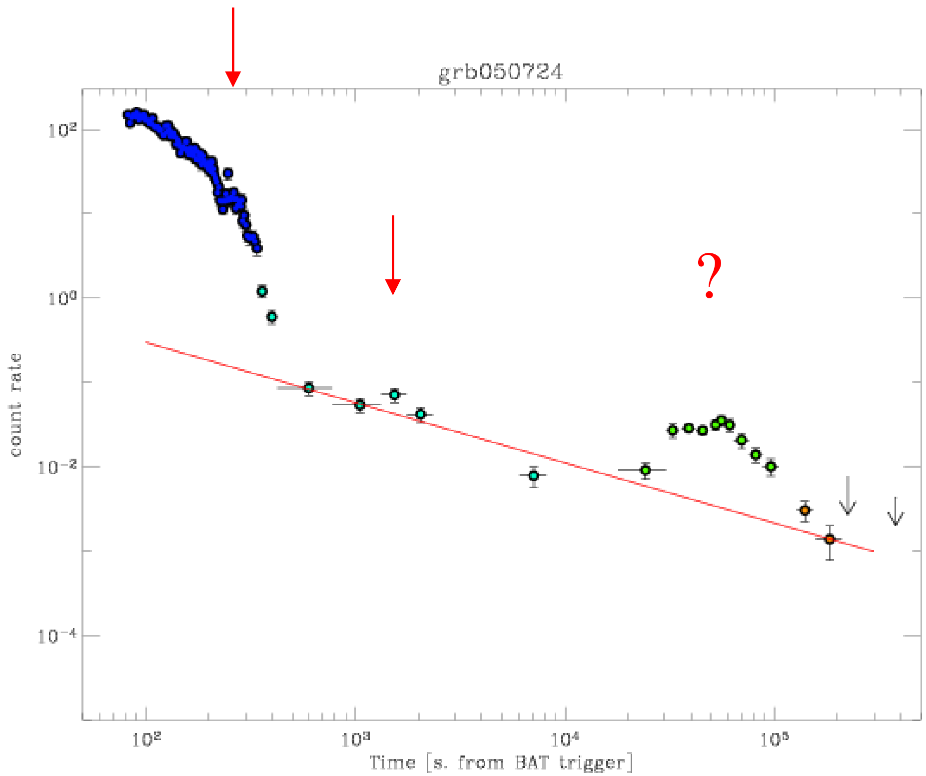


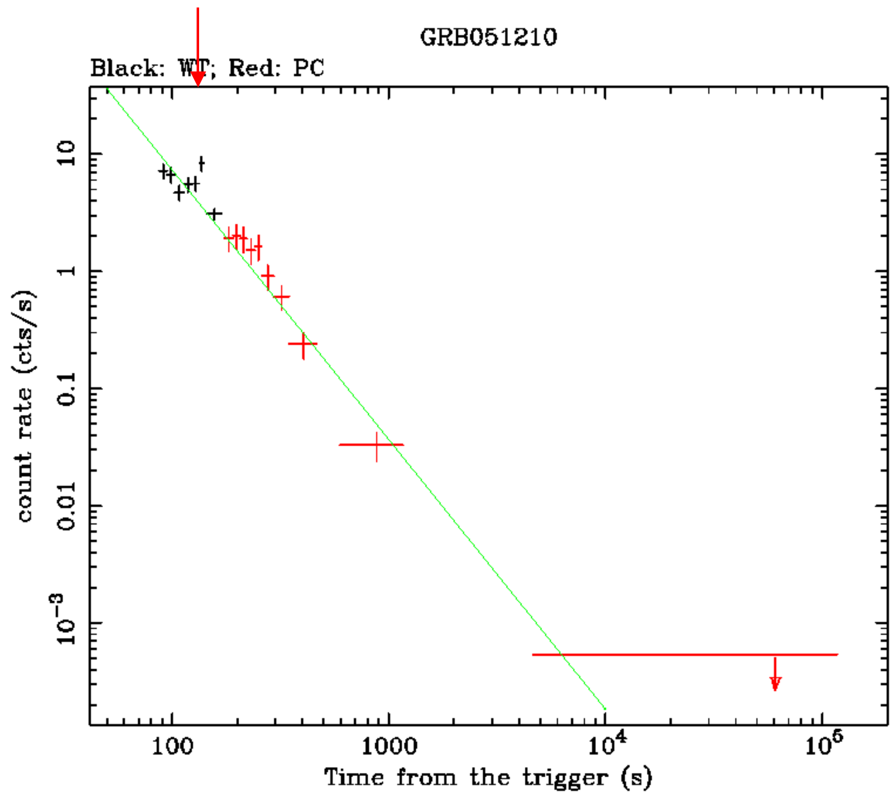


Soft (XRT) peaks are significantly broader than hard (BAT) peaks for the same pulse

Soft X-ray manifestation of GRB pulses look very similar to later X-ray flares

Flares in Short GRBs





Mechanism for flares must also operate in the context of short GRBs.

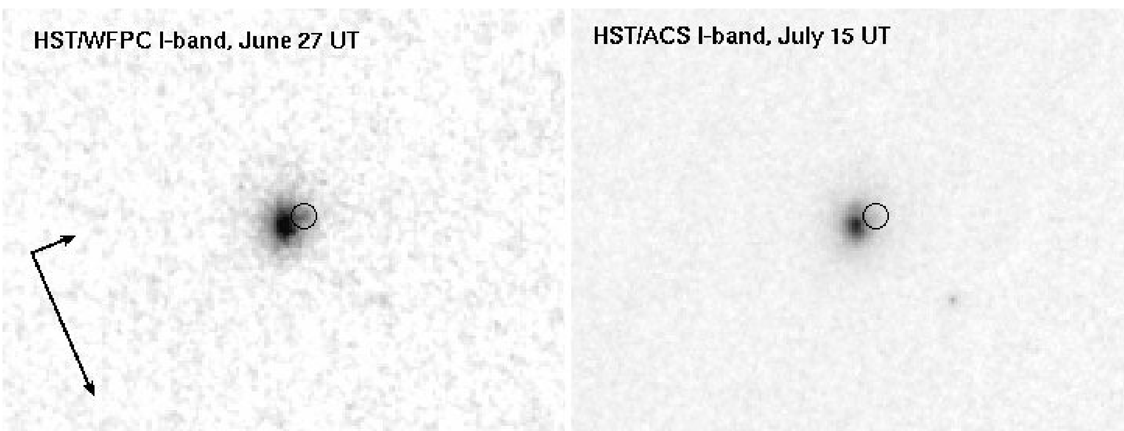
GRB anomalies (or prototypes?)

A collection of GRBs which don't seem to fit.

GRB 060505 & 060614

Two nearby "long" GRBs with no supernova

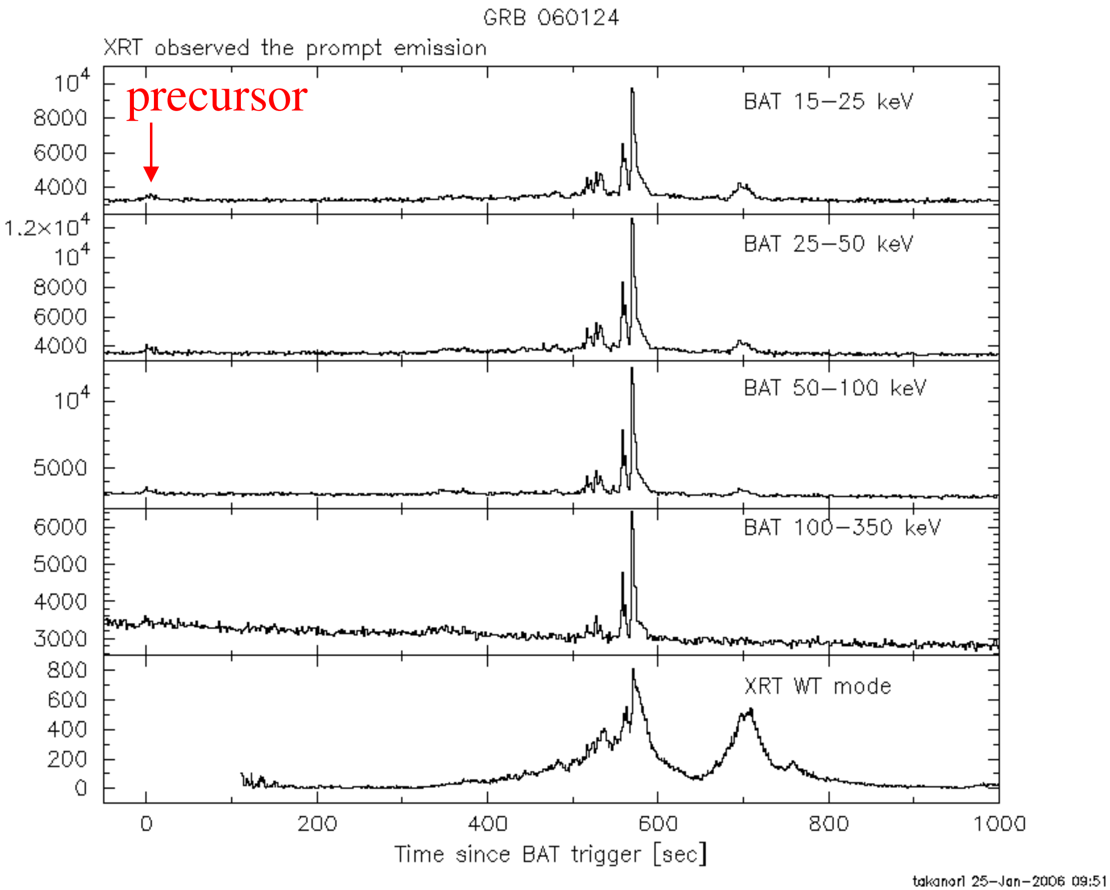
GRB 060505 z = 0.089 (Fynbo et al.)
GRB 060614 z = 0.125 (Gal-Yam et al., Fynbo et al., Della Valle et al.)



GRB 060614
HST images

(Gal-Yam et al. 2006)

GRB Precursors



GRB 060124

Precursor 500 s before burst!

z = 2.3

S_γ(precursor) = 5x10^{-7} erg cm^{-2}

S_γ(main pusle) = 7x10^{-6} erg cm^{-2}

E_{peak} = 285 keV (Konus)

GRB 060614

BAT Lightcurves

T_{90} = 103 s

Could it be in "short" category?

Pluses:

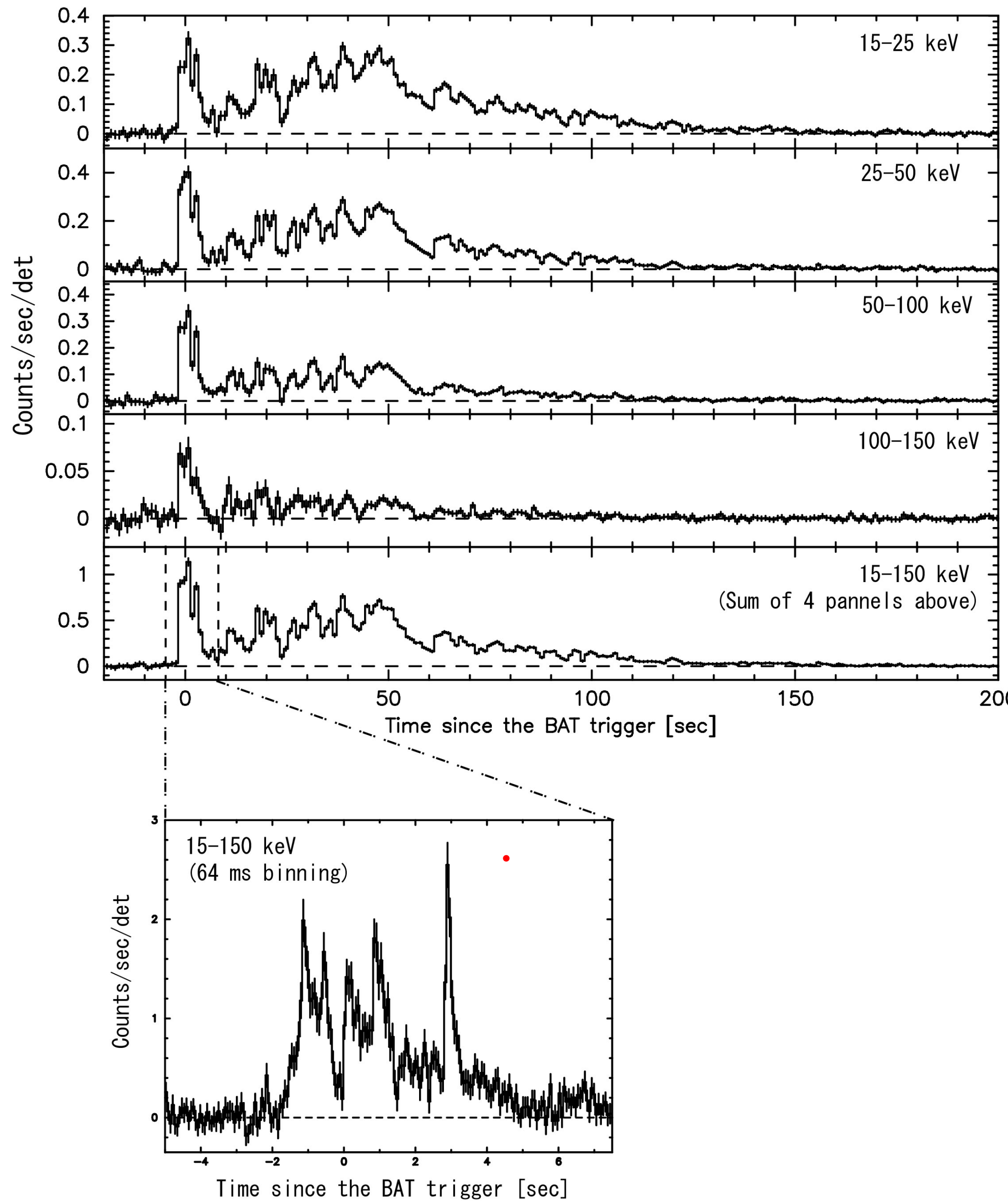
- **Hard short episode followed by long softer hump**

- **Short "lag" (Norris & Bonnell)**

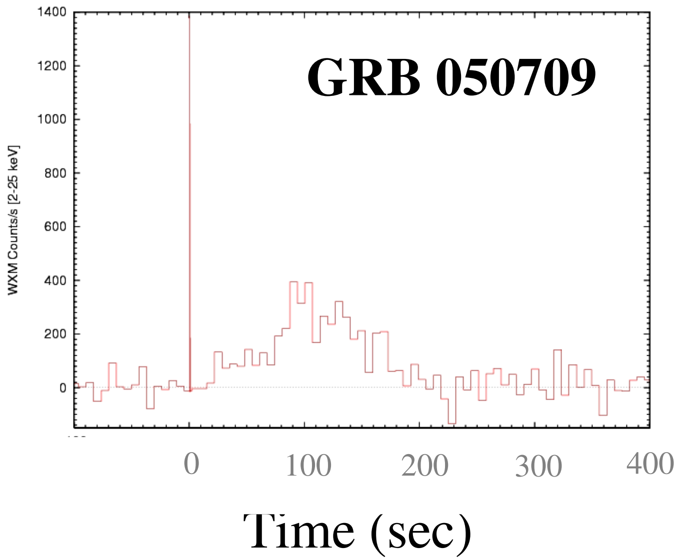
Minuses:

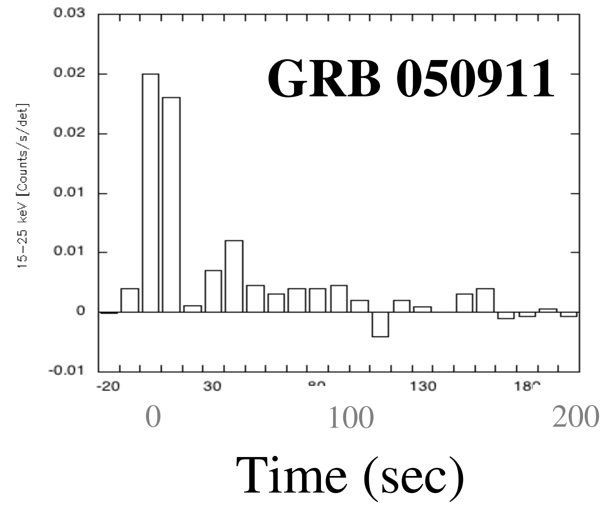
- **5 s duration of hard episode**

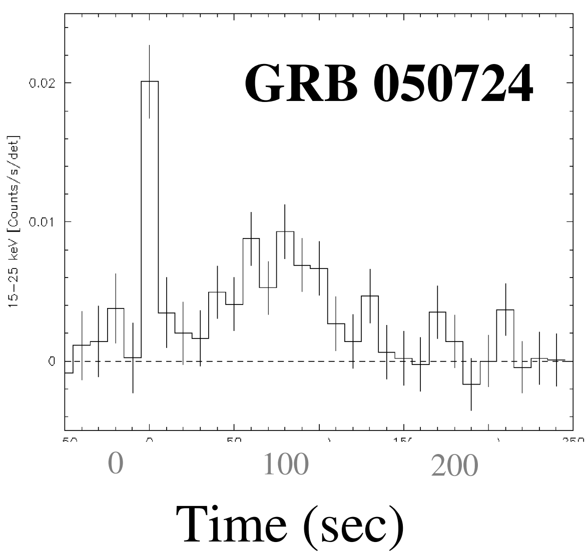
- **Brighter & more variable hump emission than others**

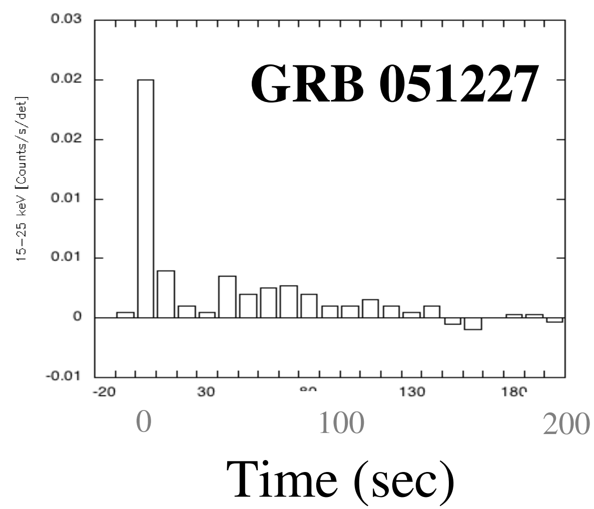


Soft Gamma Ray Component

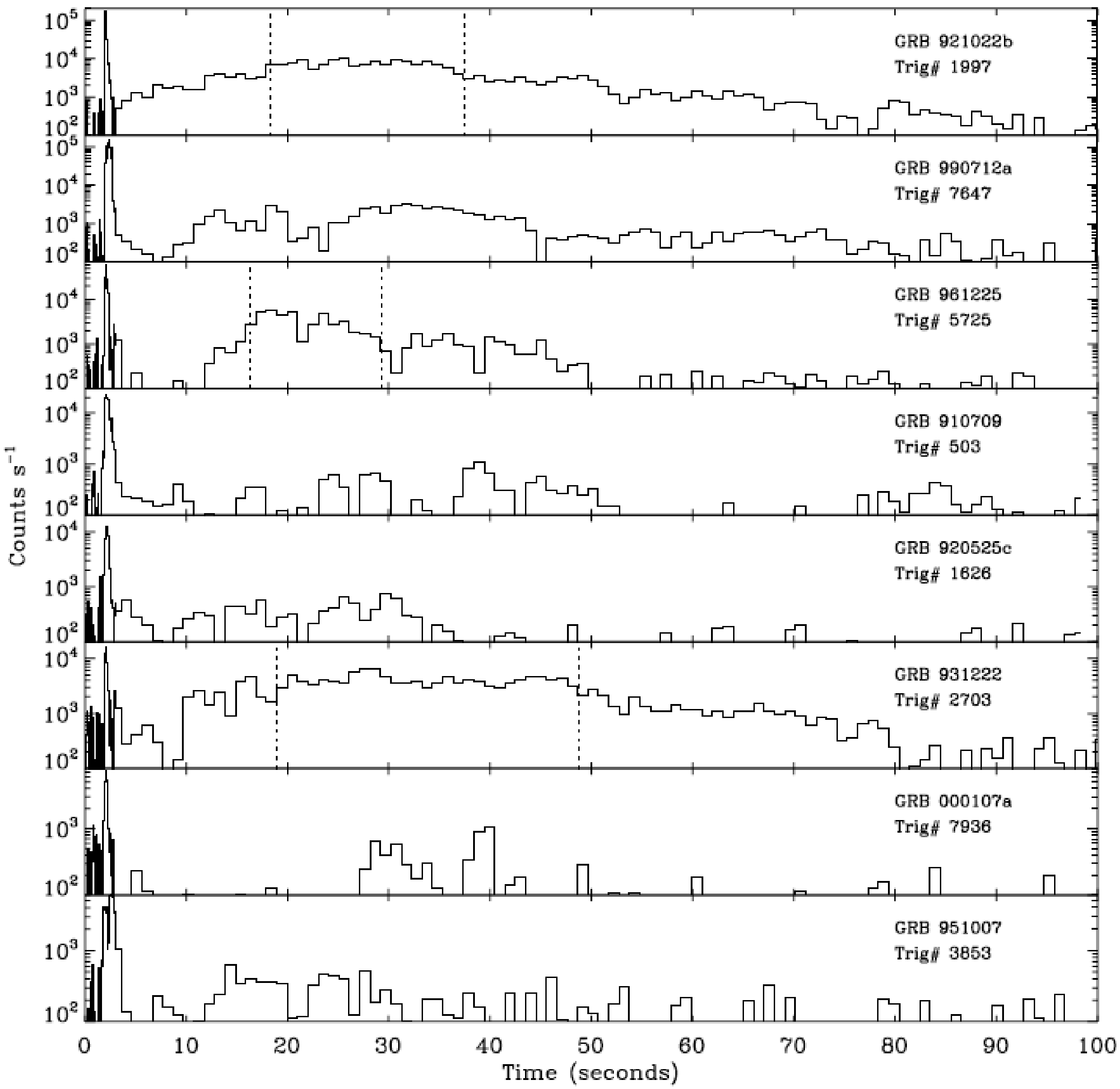








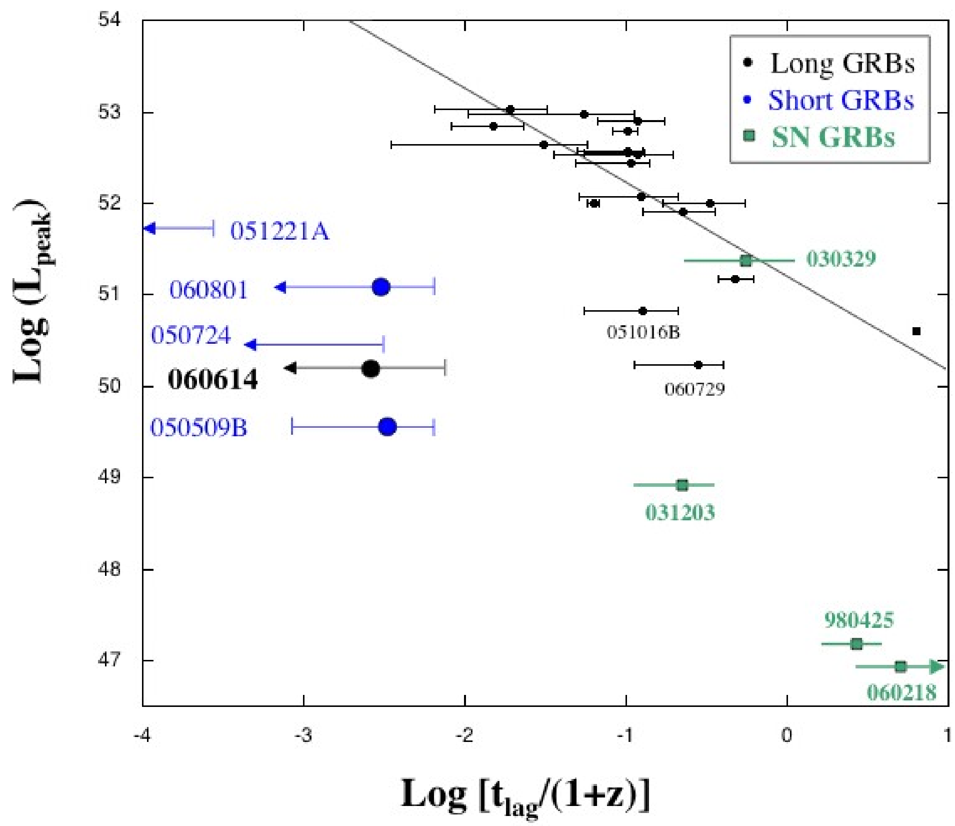
BATSE



Norris & Bonnell
(2006)

BATSE long GRBs with short-hard episode and long softer hump

Peak Luminosity vs Spectral Lag



030528
HETE-2

Neil Gehrels

Royal Society talk

1) **"Long" and "short" GRBs are all Swift except 030528**
2) **Lag in energy ranges 50-100 keV / 15-25 keV**
3) **GRB 030329 reanalysis for different lag energy ranges by T. Sakamoto**

Conclusions for GRB 0606014 from BAT

060614 mixes characteristics of "short" and "long" GRBs

If a merger:

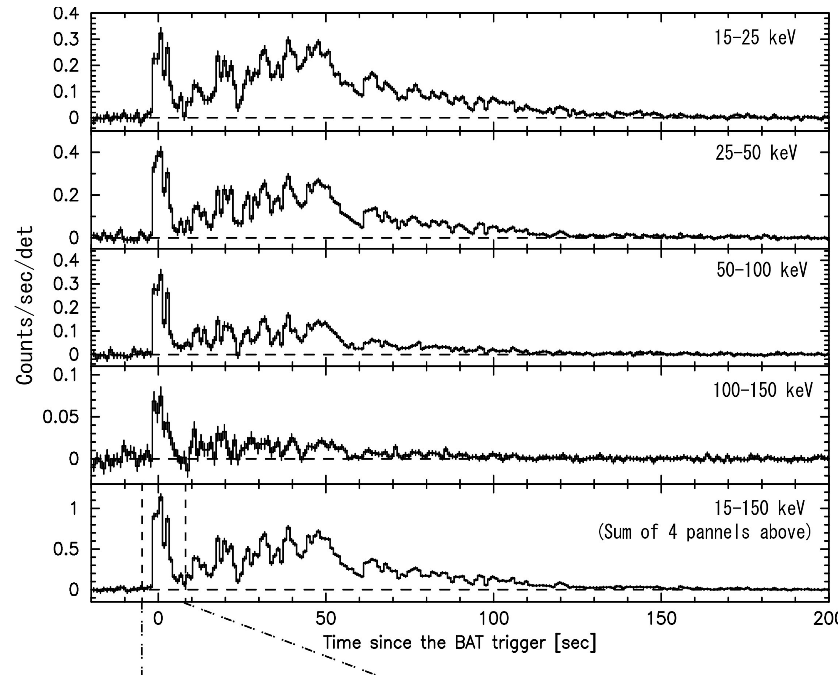
- Long lasting variable emission difficult for NS-NS merger models

- Possible signature of BH-NS merger (Faber et al. 2006)

If a collapsar:

- Lack of SN hard to understand

- Short lag may be clue to different jet parameters related to no SN



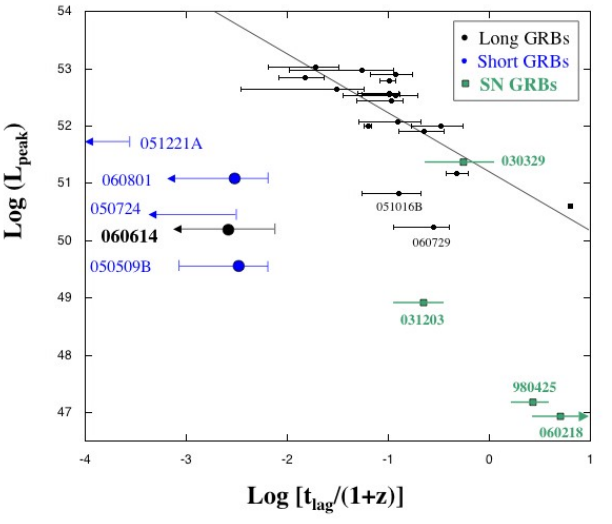
Neil Gehrels

Royal Society talk

Conclusions for GRB 030329 from Lags

Of GRBs with confirmed SNe, 030329 is most like a classical GRB

- $E_{iso} \sim 10^{52}$ erg (others 10^{48} - 6×10^{49})
- lag-luminosity is consistent with classical long GRBs



$\Rightarrow$ Lag results provided added evidence that classical GRBs can be accompanied by SNe

The Future

What to do with *Swift* for the next four years?

Swift Observing Statistics

- *Swift* observing time divided its time as follows:

All GRB obs:		56.3%
New triggers		8.4%
Planned follow-up		42.6%
GRB ToOs		5.5%
Non-GRB ToO*s:		8.8%
Calibration:		5.1%
Planned non-GRB targets:		17.6% (5 Msec/yr)
SAA & non-science:		12%

Cycle 3 will open ToO's to GI proposal

Cycle 4 will open planned non-GRB targets to GI proposal

* 153 ToO's requested/ 103 approved. Examples: Comet Tempel, RS Oph, supernovae

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Statistics through May 16 – courtesy of Kim Page

Whither Swift? – the future of rapid-response astronomy

Charting the Future for the World's Most
Responsive Space Astrophysics Observatory

In April, 2007, the Swift GRB MIDEX Mission is expected to complete its first two year segment of normal operations. Swift was proposed, built and operated following a set of strategic priorities based on discovering GRBs and identifying their X-ray and optical counterparts.

A workshop to discuss observing strategies for Swift in its extended operations phase: 2007 and beyond

To be held at Penn State, May 1-3, 2007

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Swift Institutions

<u>Executive Committee</u>

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