Observations of Gamma-Ray Bursts and X-Ray Flashes with High Energy Transient Explorer 2

(HETE-2)

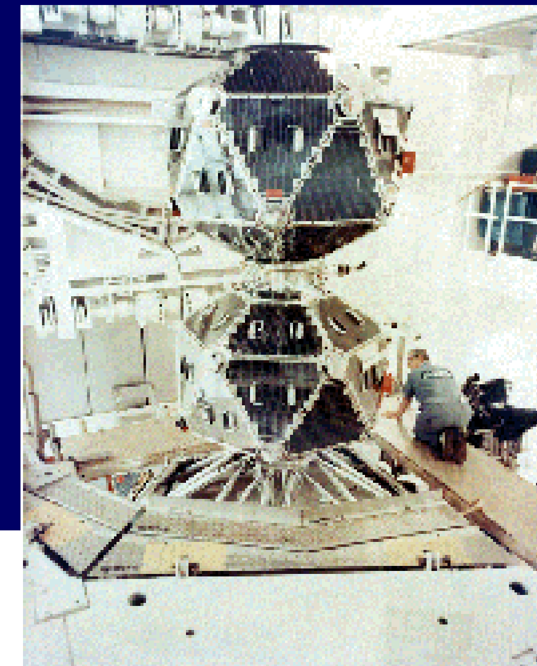
Nobuyuki Kawai
Tokyo Institute of Technology/RIKEN

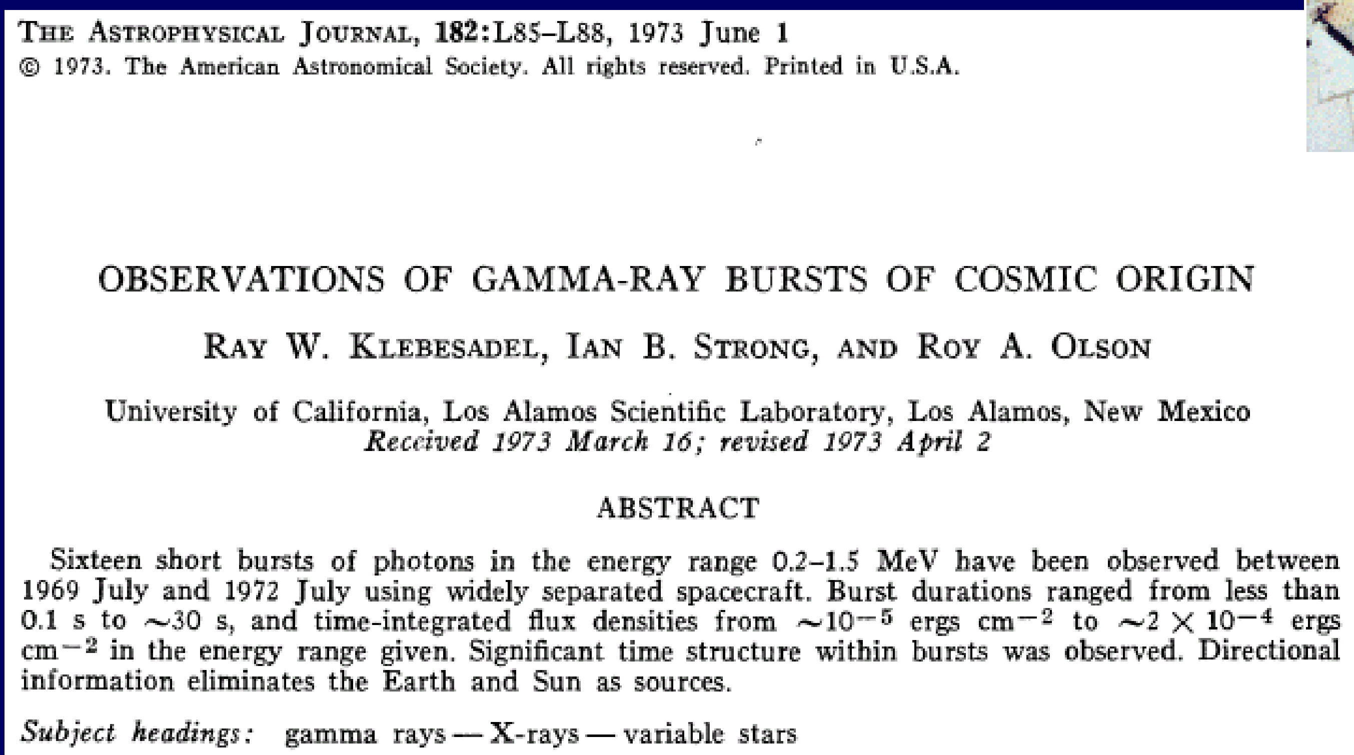
On behalf of
HETE-2 Science Team
MIT, RIKEN, CESR,
AGU, NASDA, NAO, Miyazaki Univ
LANL, Univ Chicago, UCB, UCSC, GSFC, CNR

Outline

- Issues on gamma-ray bursts
- Description of HETE-2
- Results
  - Rapid notification and early afterglow light curves
  - Optically dark GRBs
  - Supernova-GRB connection
  - X-ray rich GRBs and X-ray flashes

Discovered serendipitously in 60s





THE ASTROPHYSICAL JOURNAL, 182:L85–L88, 1973 June 1

OBSERVATIONS OF GAMMA-RAY BURSTS OF COSMIC ORIGIN

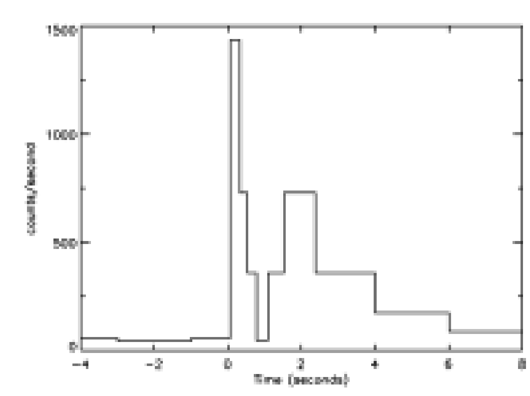
RAY W. KLEBESADEL, IAN B. STRONG, AND ROY A. OLSON

University of California, Los Alamos Scientific Laboratory, Los Alamos, New Mexico
Received 1973 March 16; revised 1973 April 2

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 ~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

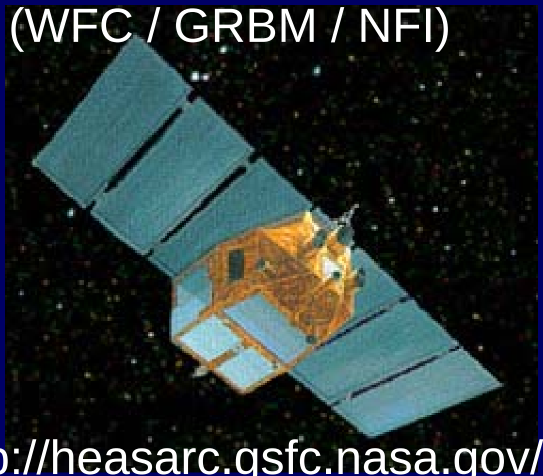


Gamma-Ray Bursts (GRBs)

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

(http://cossc.gsfc.nasa.gov/images
/epo/gallery/cgro/index.html)

BeppoSAX
(WFC / GRBM / NFI)



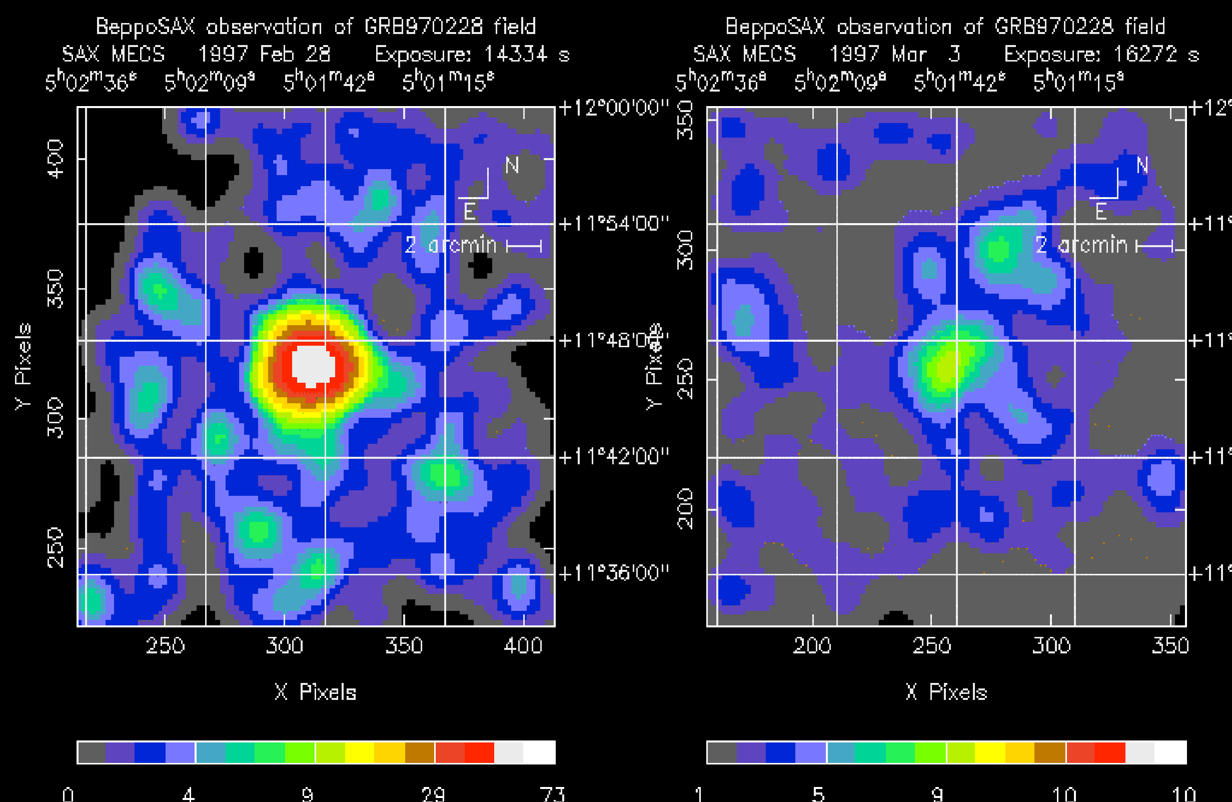
(http://heasarc.gsfc.nasa.gov/docs/
sax/gallery/inst.html)

- Bright in the hard X ray to the γ ray energy band (50-300 keV)
- “Spiky” light curves
- Long / short duration GRBs   click
- Uniform sky distribution and lack of very faint GRBs

- Discovery of afterglow
- Redshift of GRB, $z \sim 1$

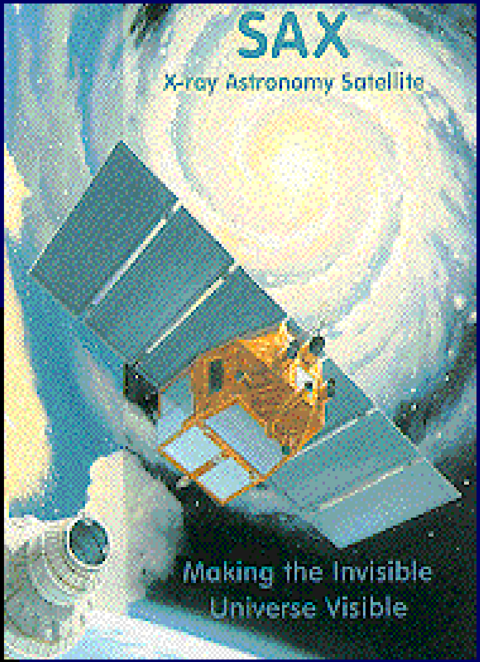
Breakthrough 30 years after the discovery:

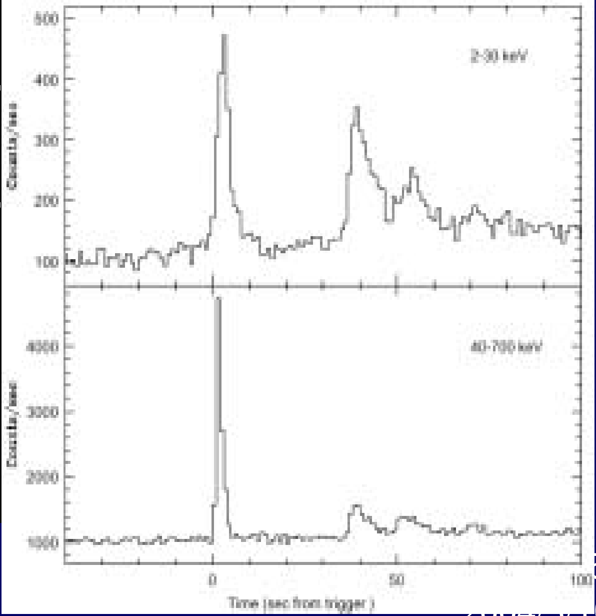
Discovery of X-ray afterglow by BeppoSAX (GRB970228)



1997 Feb 28

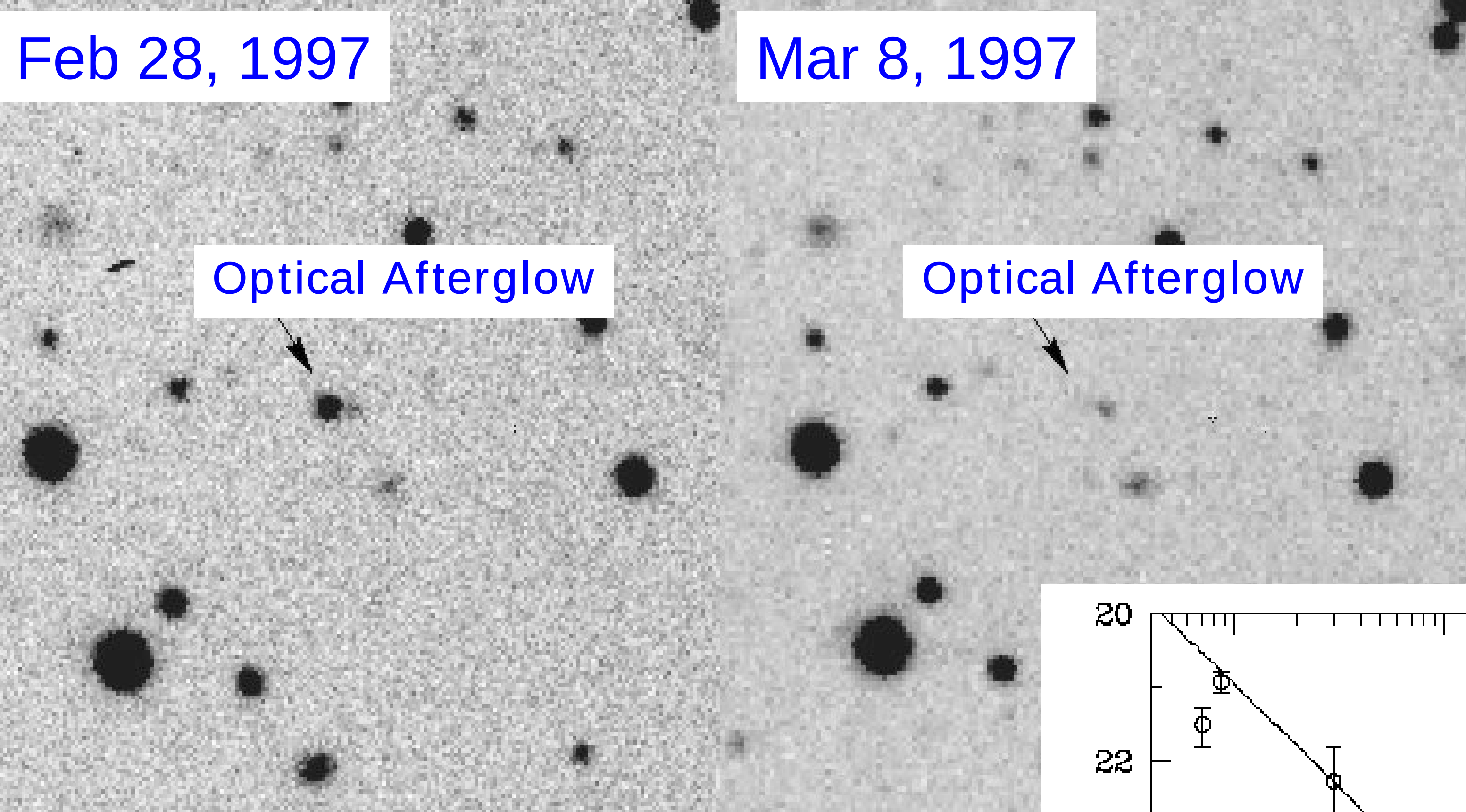
1997 Mar 3





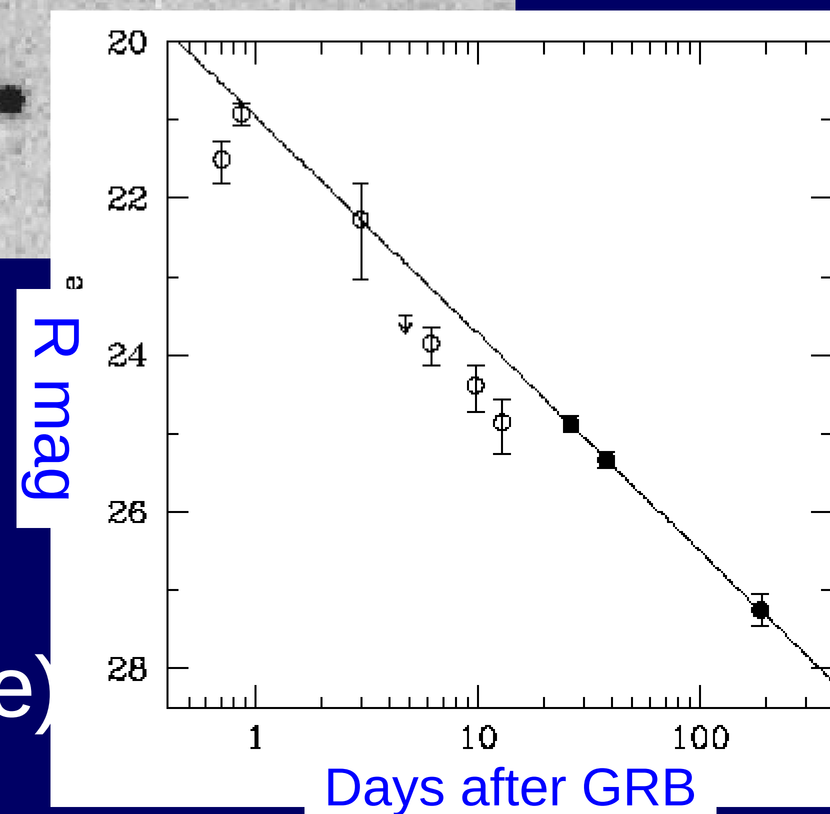
8 hours

3 days



Optical Afterglow of GRBs

→Redshifts (distance, age)



Questions answered

- X-ray and/or optical afterglows found for long soft GRBs
- Consistent with Cosmological Fireball model
  - Power-law decay: days—months duration of afterglows
  - Broadband spectra (radio — X-ray)
- Redshifts determined by spectral features
  - z~0.4—4.5 (1 typical)
- Host galaxies identified
  - GRB in galaxies, but off-center (not an AGN)
  - Star forming galaxies
- Beaming (Jet-like geometry) ~1/100
  - True energy ~ 10^{51} ergs

Origin?

- Collapse of massive star
  - Extreme case of core-collapse SN
  - Rate OK: only 1 in 10^{4-5} of SN
  - Consistent with locations in SFR
- Neutron star merger
  - Rate roughly OK
  - Predicts locations out of galaxy disk

Remaining Questions

- Nature of GRBs with no optical afterglows
  - Short hard GRB
  - X-ray rich GRB (X-ray Flash)
  - Dark Burst
- First one hour
- Light curve variation on short time scales
- Emission lines in X-ray afterglow

HETE-2: Goals and Program

~ FIRST DEDICATED γ-RAY BURST SATELLITE ~

GOALS:

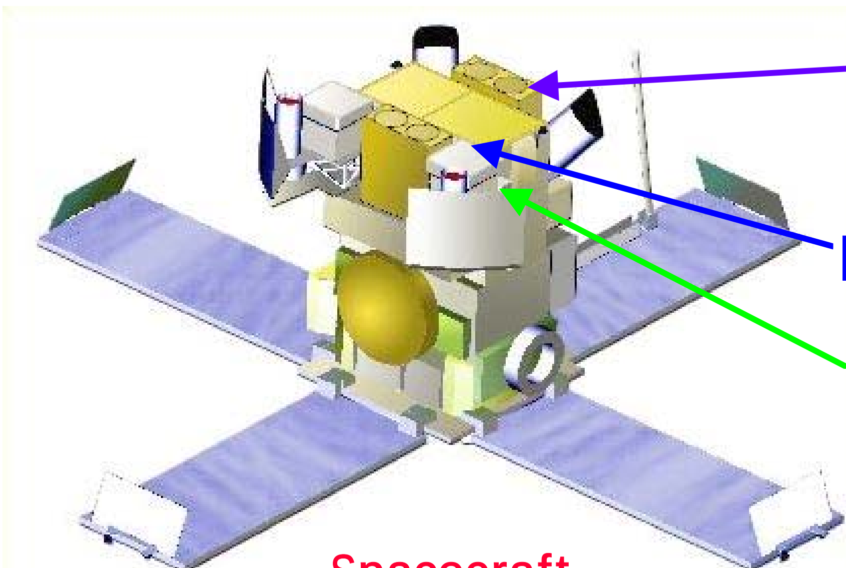
- Locate GRBs Accurately (~10′ — 10″)
- Distribute Locations Rapidly (≤ 10 s delay)
- Measure multi-wavelength spectra

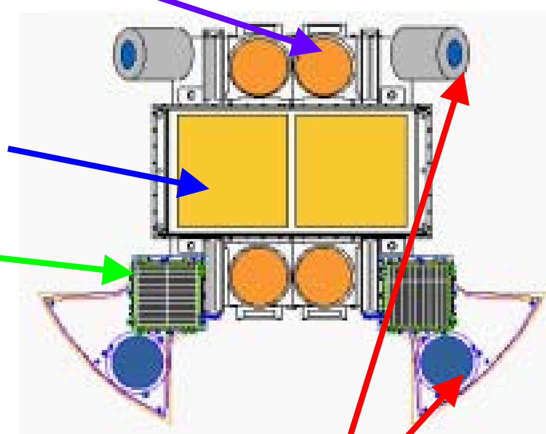
  [Soft X-ray ~ γ-ray; 0.5 keV ~ 500 keV]

PROGRAM:

- University-managed; NASA +Japan+France +Italy+India+Brazil
- University-constructed spacecraft
- 1/3 cost of NASA Small Explorer (SMEX)

HETE-2 Instruments





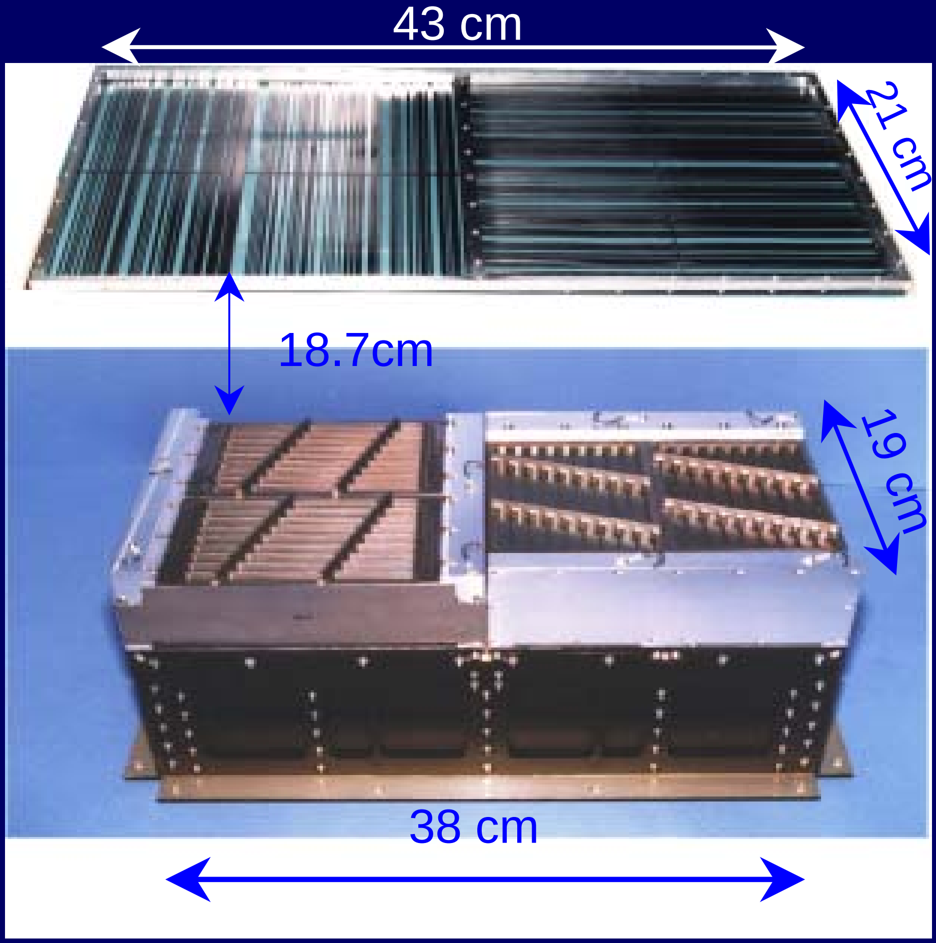
Weight 124 kg
Height 89 cm
WIdth 66 cm
Orbit Alt. 625 km 、
Equatorial
life > 2 years (3 years now)
Attitude anti-solar

Uplink S-band (2.272 GHz) 250 kbps
VHF (137.96 MHz) 300 bps
Downlink S-band (2.092 GHz) 31 kbps

Characteristics of HETE-2

(1) Real time localization of GRB for the ground follow-up observers
(2) Broad band spectroscopy (2-400 keV) of the prompt emission of GRB

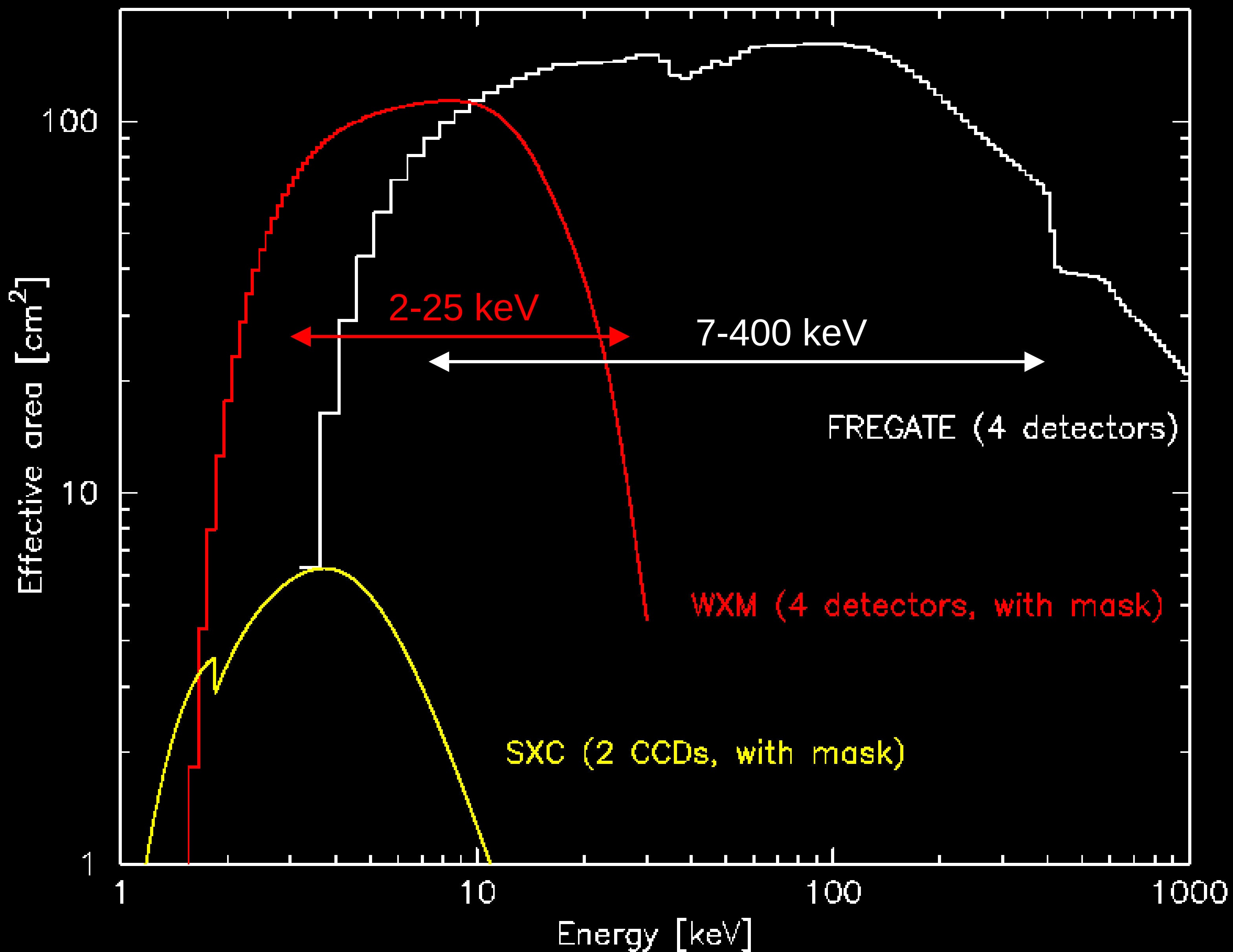
Wide-field X-ray Monitor (WXM)



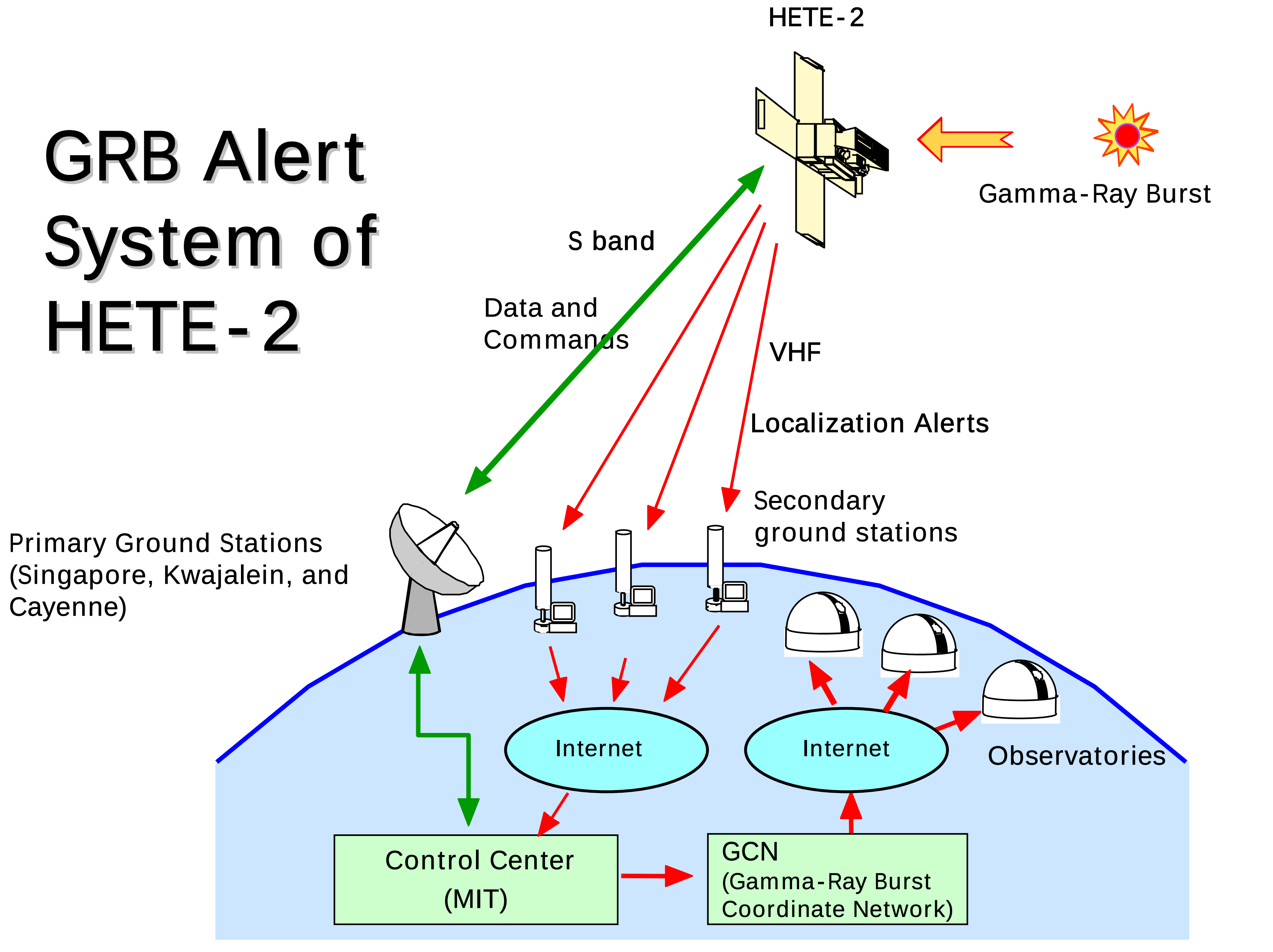
French Gamma-ray Telescope (FREGATE)

WXM (2-25 keV) + FREGATE (7-400 keV)

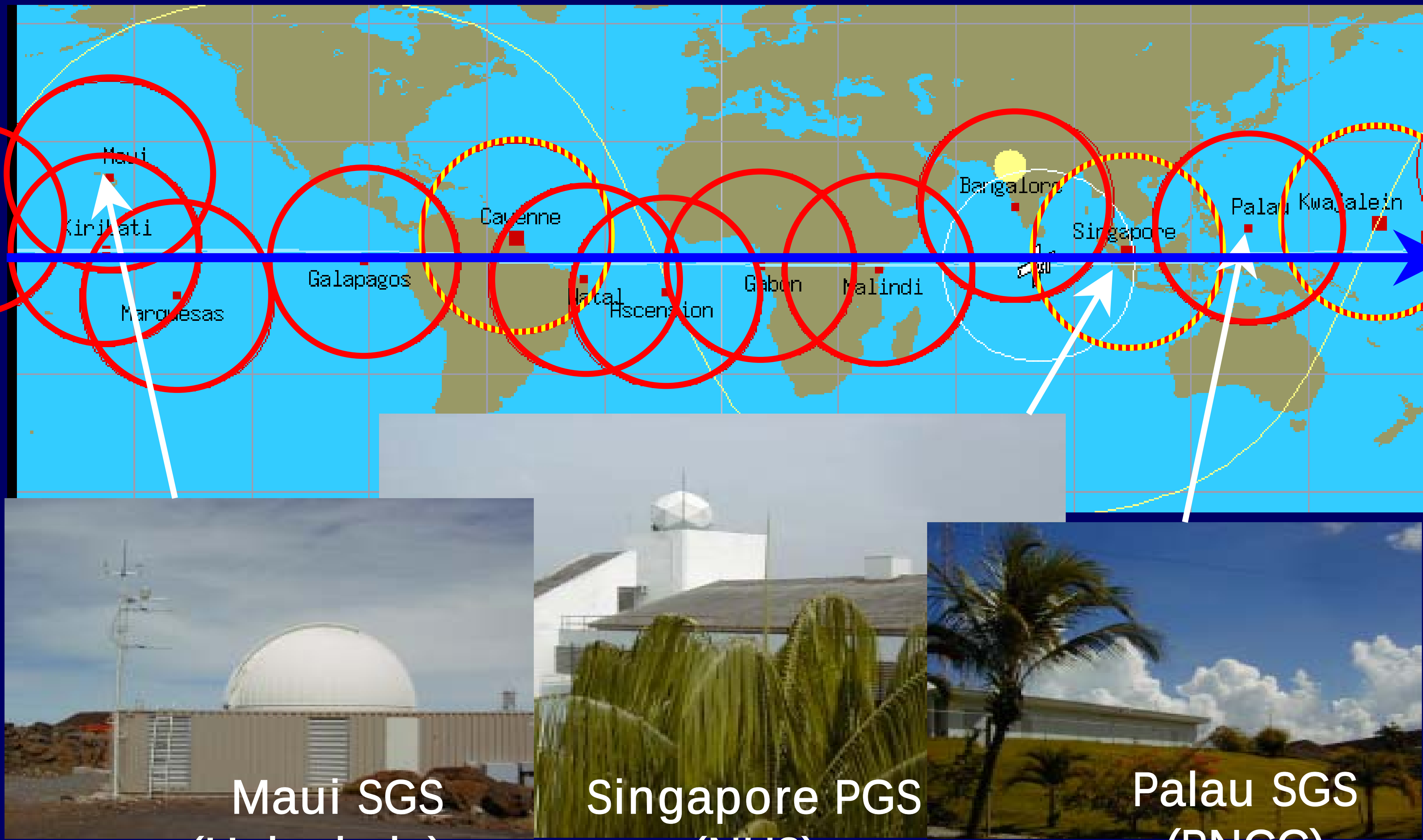
Effective area curve



GRB Alert System of HETE-2



HETE-2 Burst Alert Network

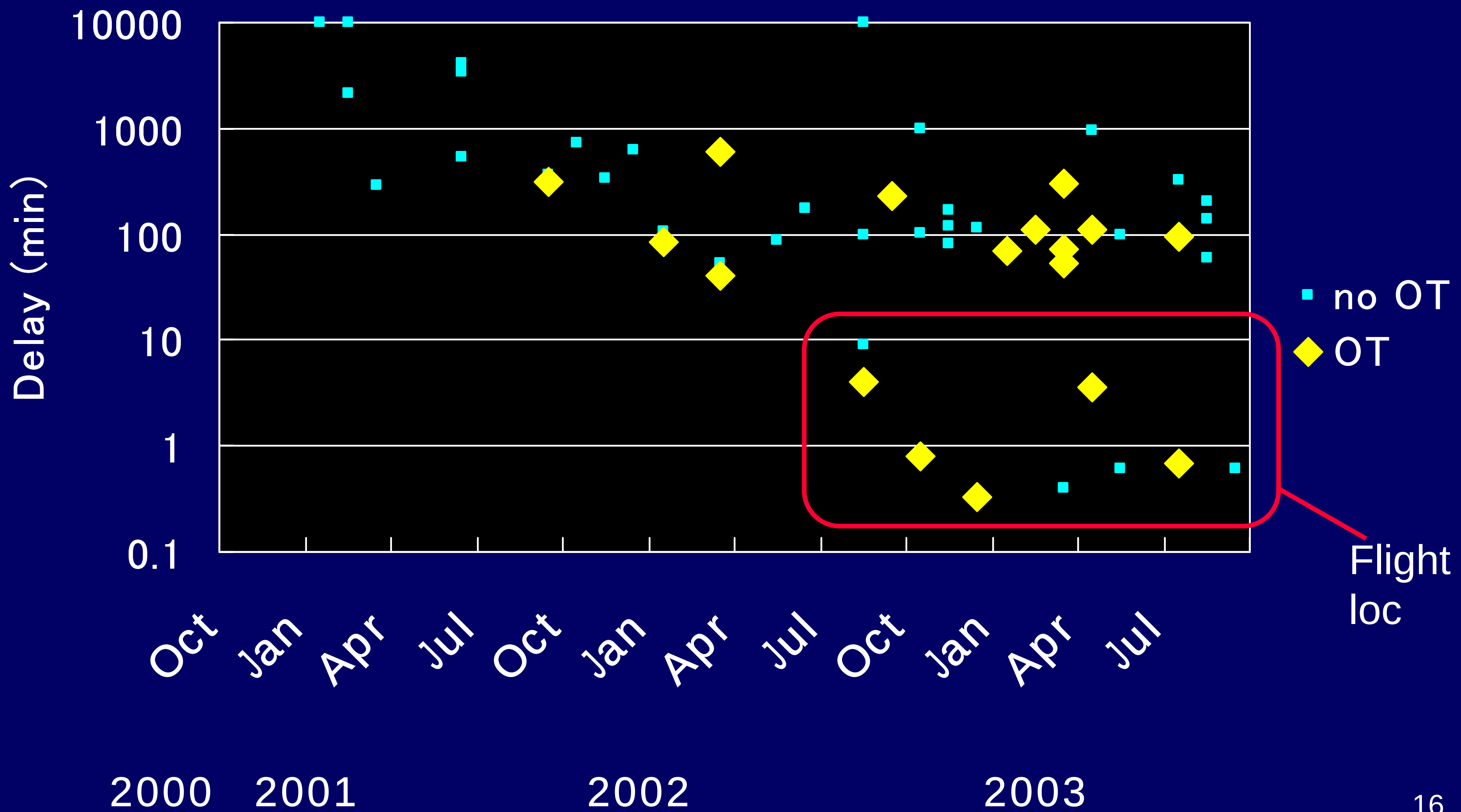


Maui SGS (Haleakala)

Singapore PGS (NUS)

Palau SGS (PNCC)

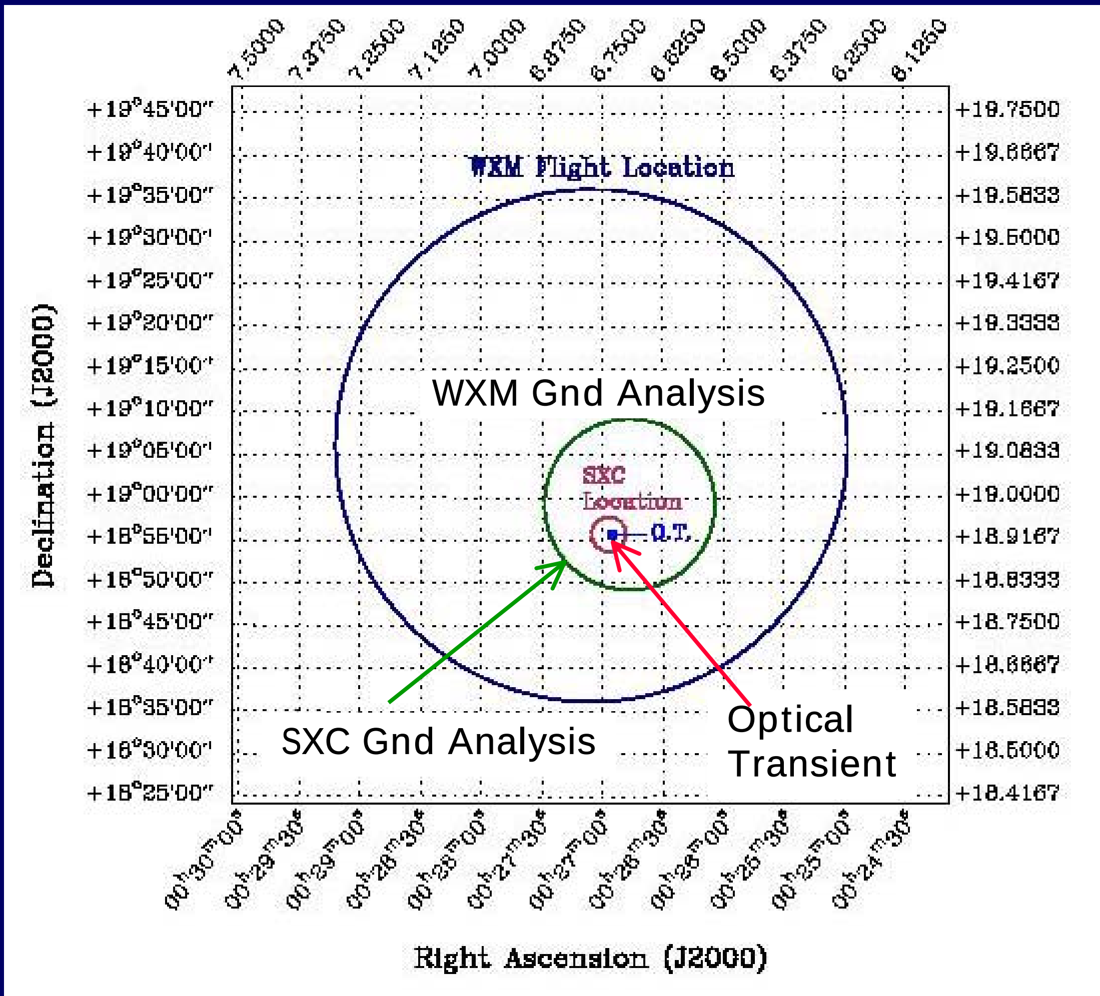
Delay of Location Alerts

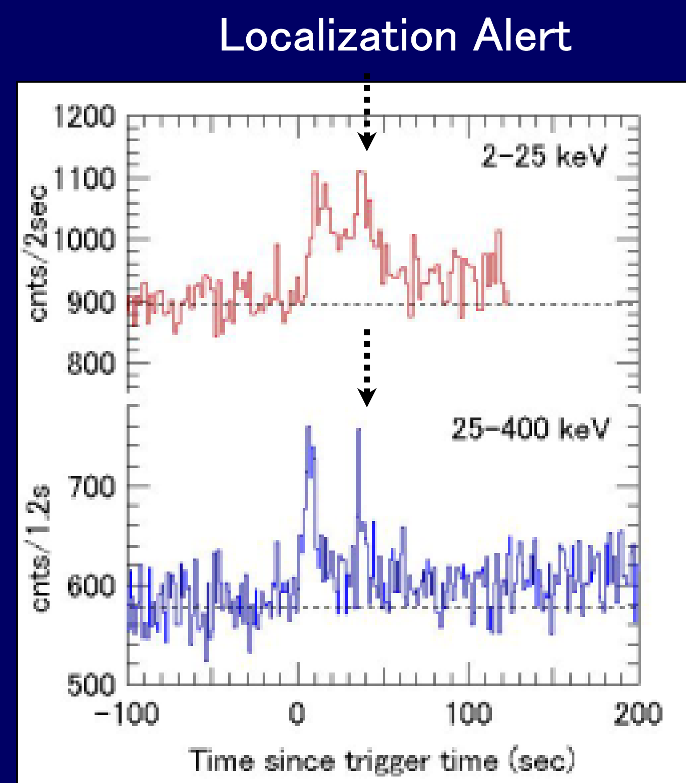


Major results by HETE-2 :
Very early afterglow light curves

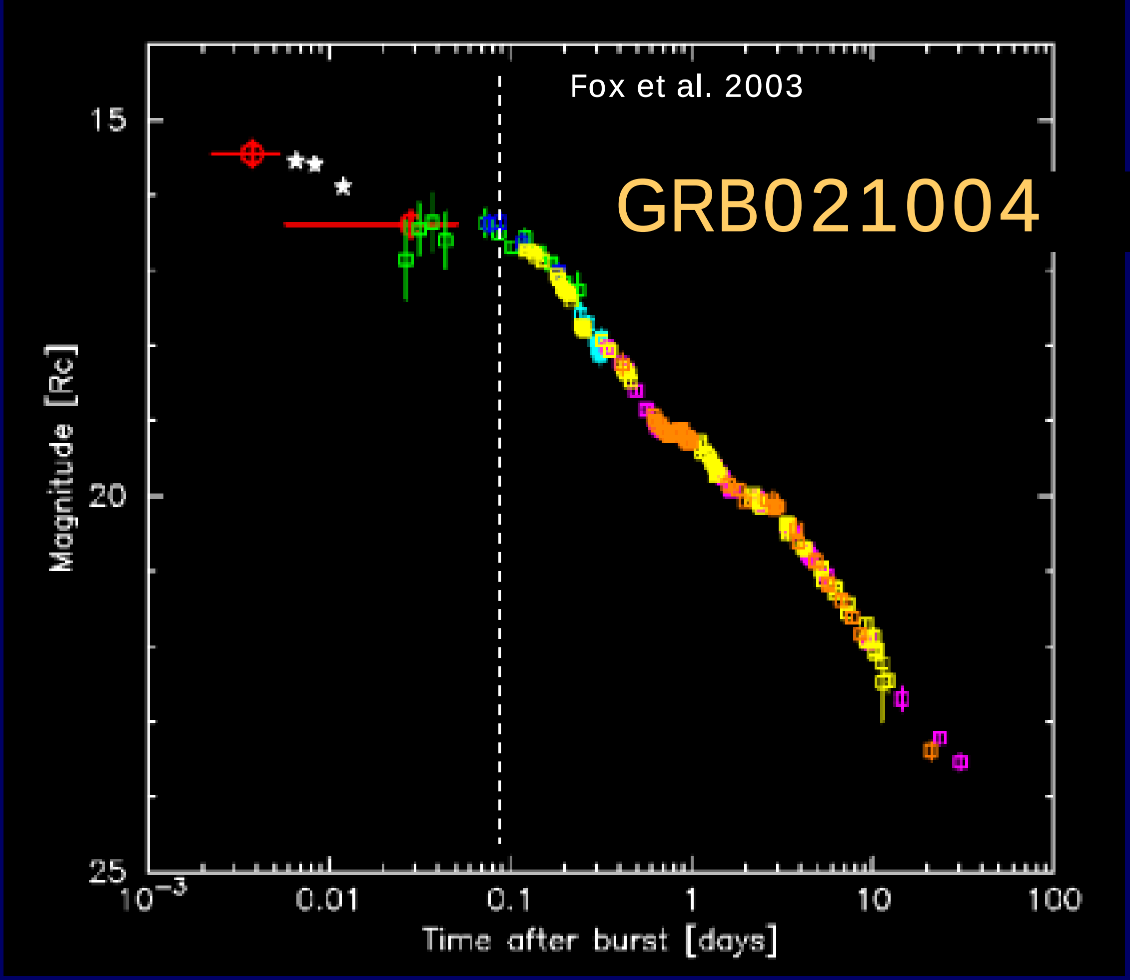
- Made possible by HETE-2
- Variety in intensity, slope, and color
- Dense observation
  - wiggles and bumps

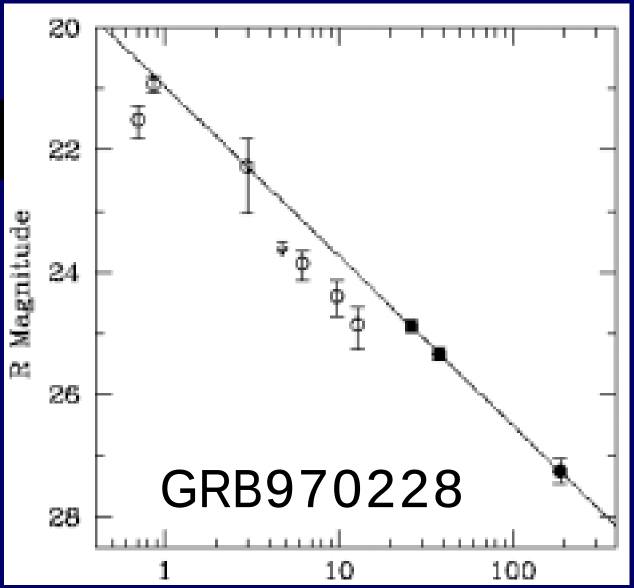
GRB021004 localization alert





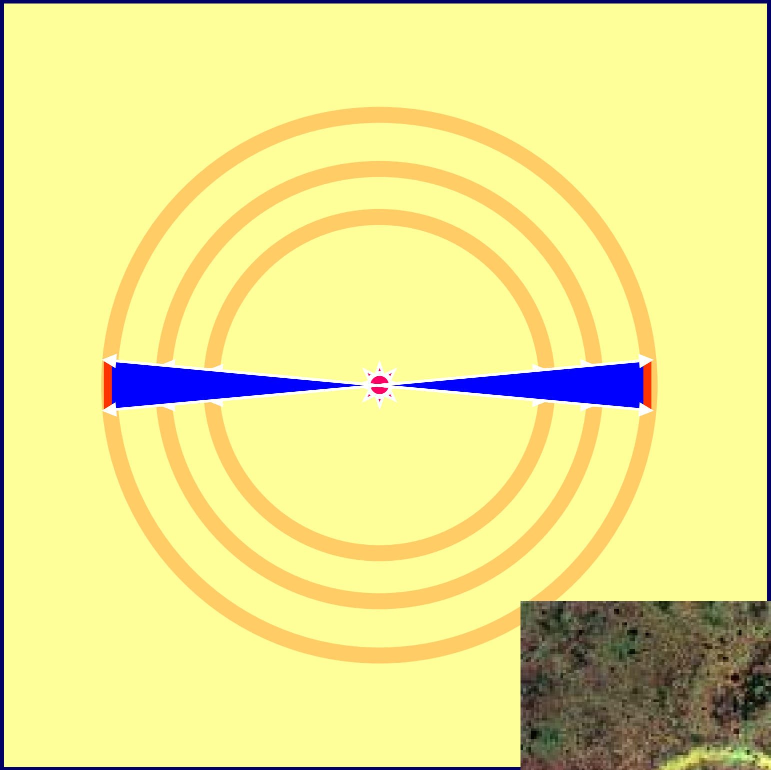
Elaplsed Time		Uncertainty
48 s	Flight Location	60 arcmin
74 min	Ground Analysis	20 arcmin
154 min	SXC Gnd Analysis	4 arcmin



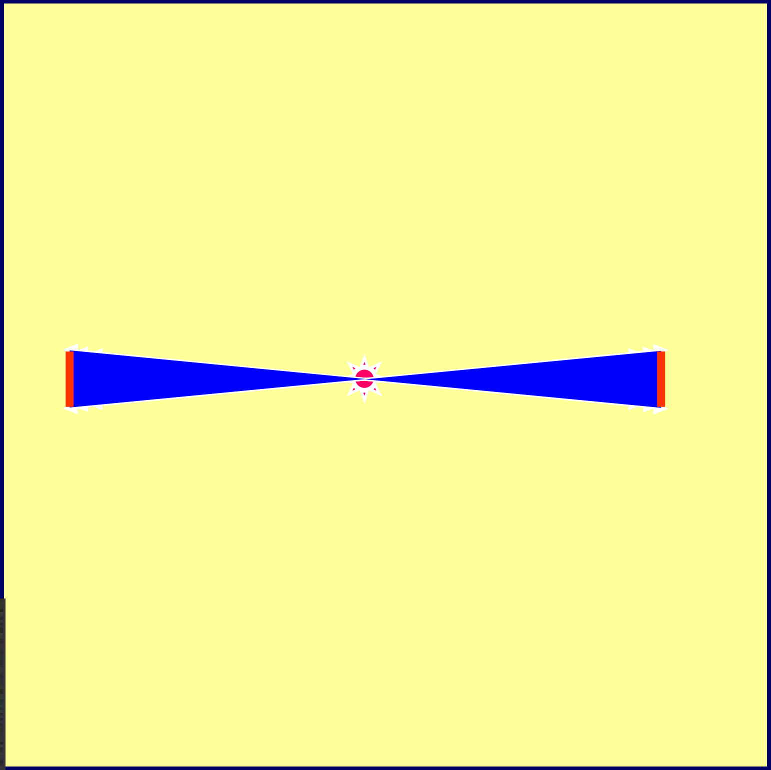


- earlier by two orders of mag
  - -capture bright phase
- “movie” vs. “snapshots”
  - -structure in light curve

“Wiggles and bumps”



circumstellar shells

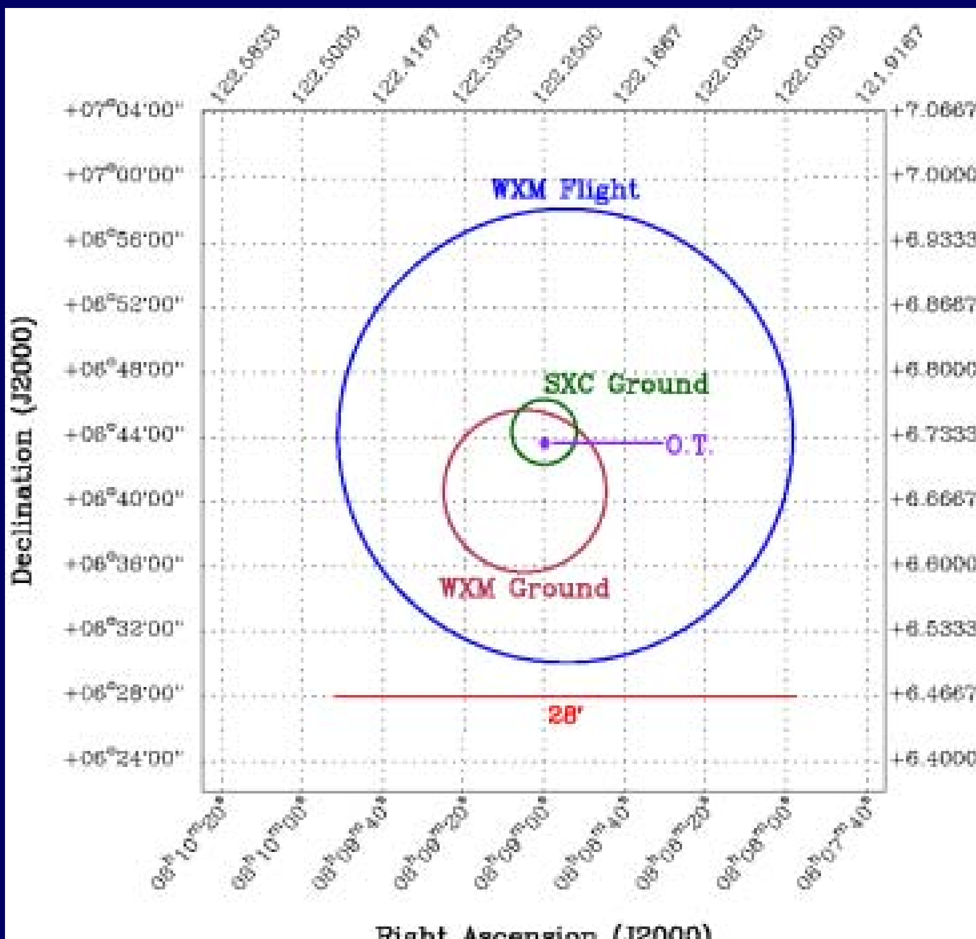


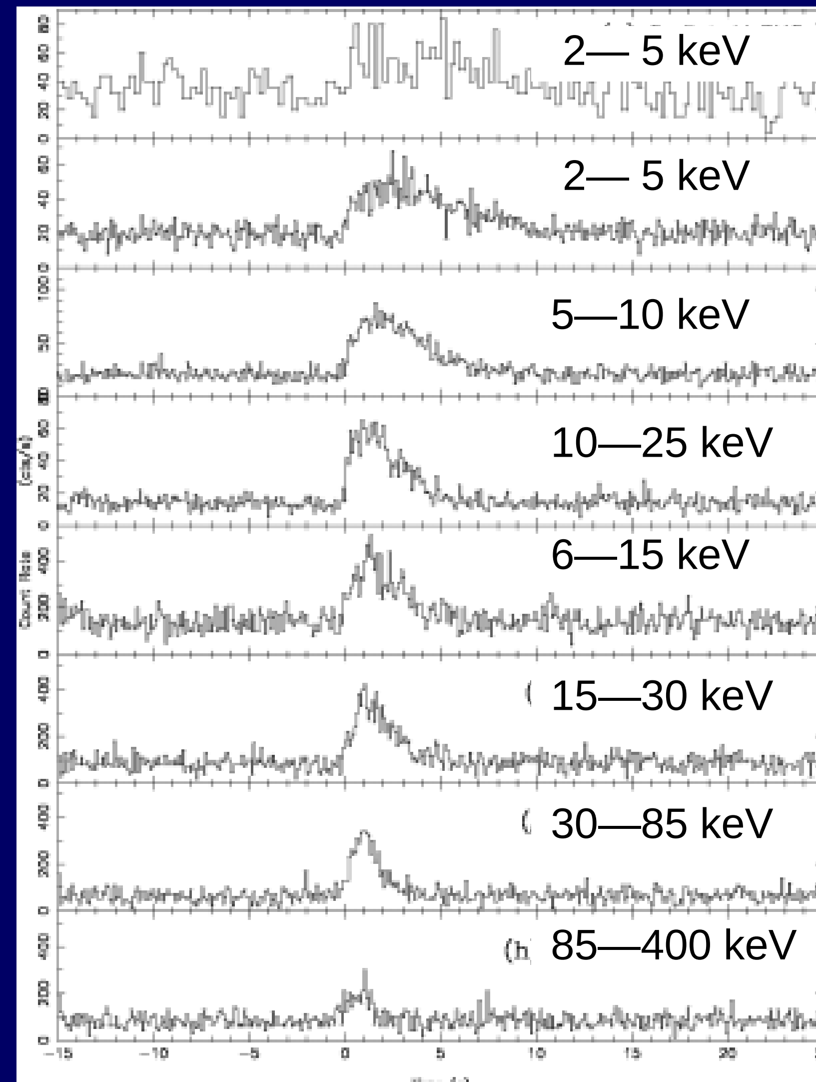
repeated energy injection

Optically dark GRBs

- No optical transients found for about half of the well-localized bursts
- Three explanations of “optically dark” GRBs have been discussed:
  - Optical afterglows are extinguished by dust (star forming region) in the host galaxy (see, e.g., Reichart and Price 2001)
  - Some optical afterglows are intrinsically very faint (see, e.g., Fynbo et al. 2001; Berger et al. 2002)
  - GRBs lie at very high redshifts (Lamb and Reichart 2000)

GRB021211
location disseminated in 22 s

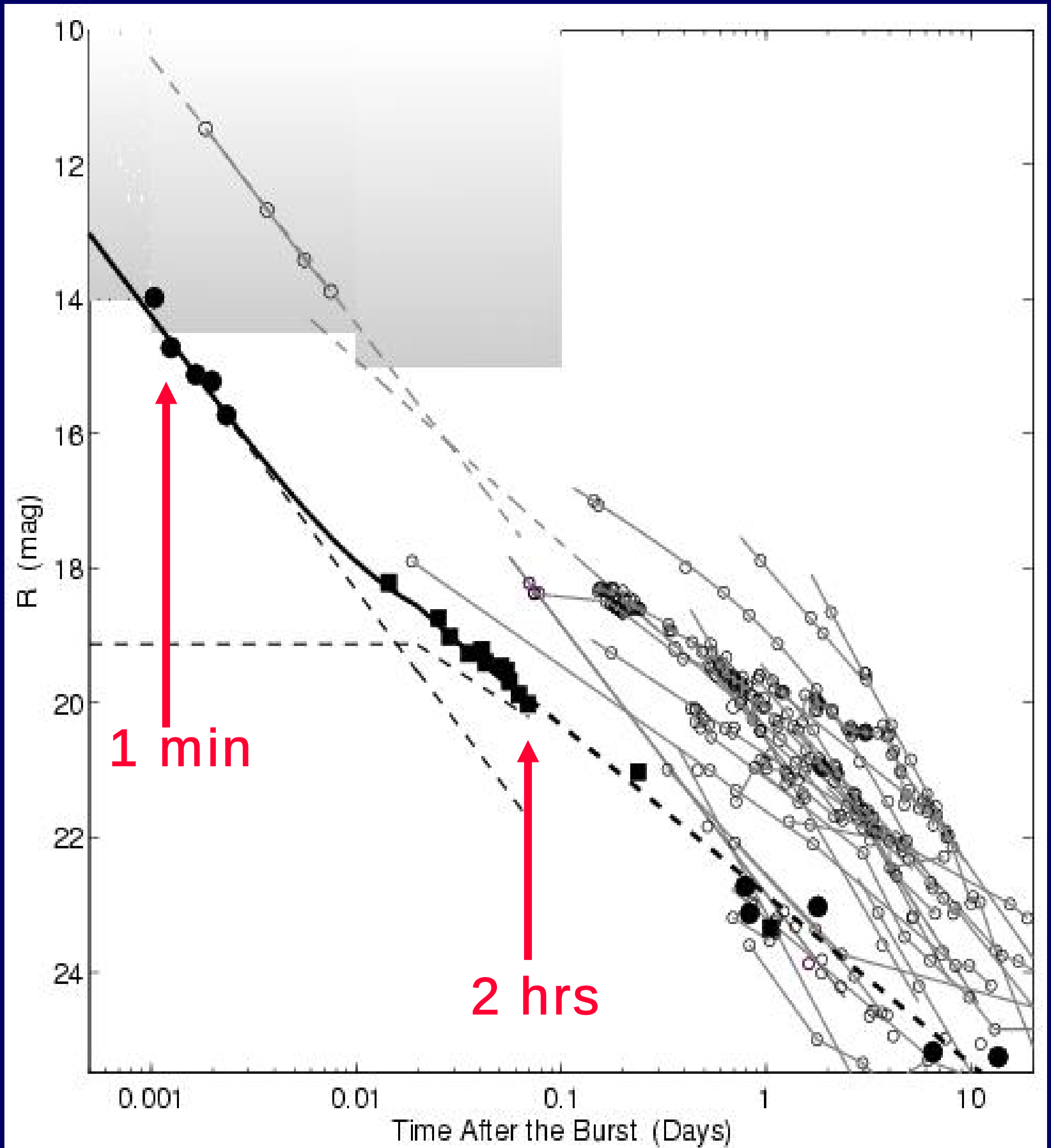




Rapid Response

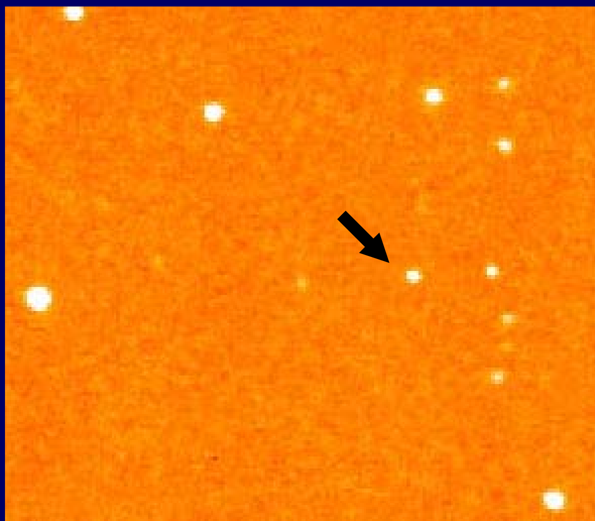
- R=14.1 at t=60 s
  - GCN#1738 Wood-Vasey et al. (RAPTOR)
- R=15.2 at t=143s
  - GCN#1736 H.S.Park et al. (Super-LOTIS)
- R=15.3 at t=171s
  - GCN#1737 Li et al. (KAIT)

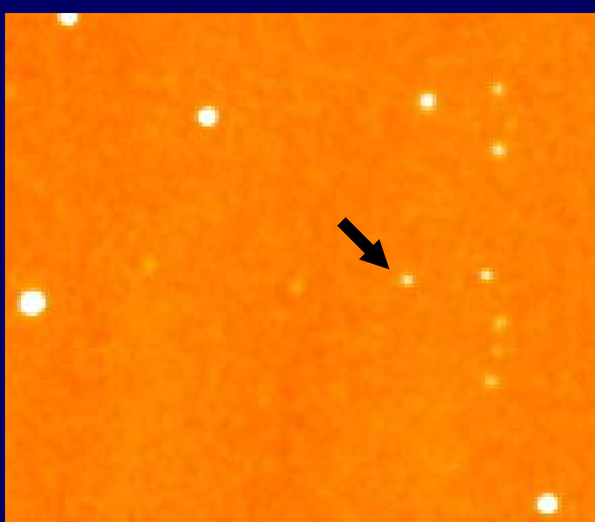
GRB021211: Afterglow Light Curve Relative to Those of Other GRBs



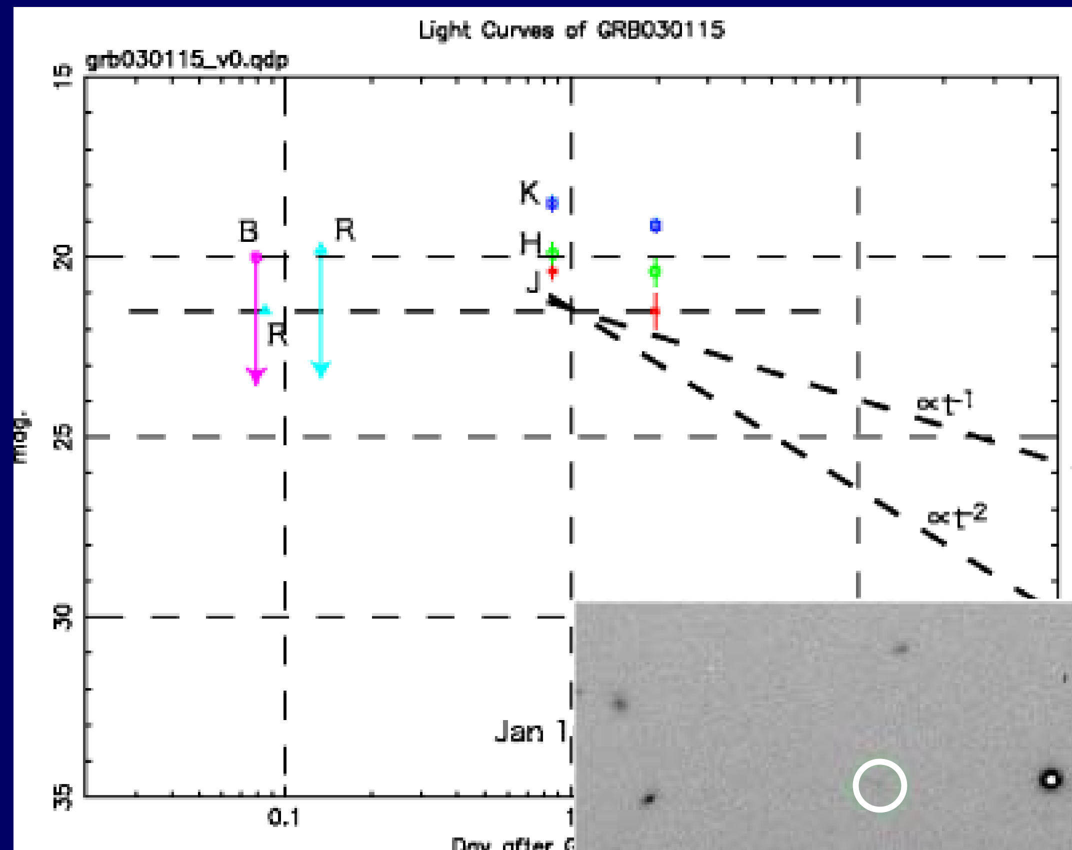
Fox et al. (2003)

GRB030115 Infrared afterglow





Levan et al. 2003



IRSF/SIRIUS Kato, et al.

~~Very high z~~

Local extinction (SFR?)

HETE-2 is Solving Mystery of “Optically Dark” GRBs

- Rapid follow-up observations of HETE-2—localized burst GRB030115 show that this burst is best case to date of extinction by dust

- Rapid follow-up observations of HETE-2—localized burst GRB021211 show that this burst is “optically dim” – without rapid follow-up would have been classified as “optically dark”

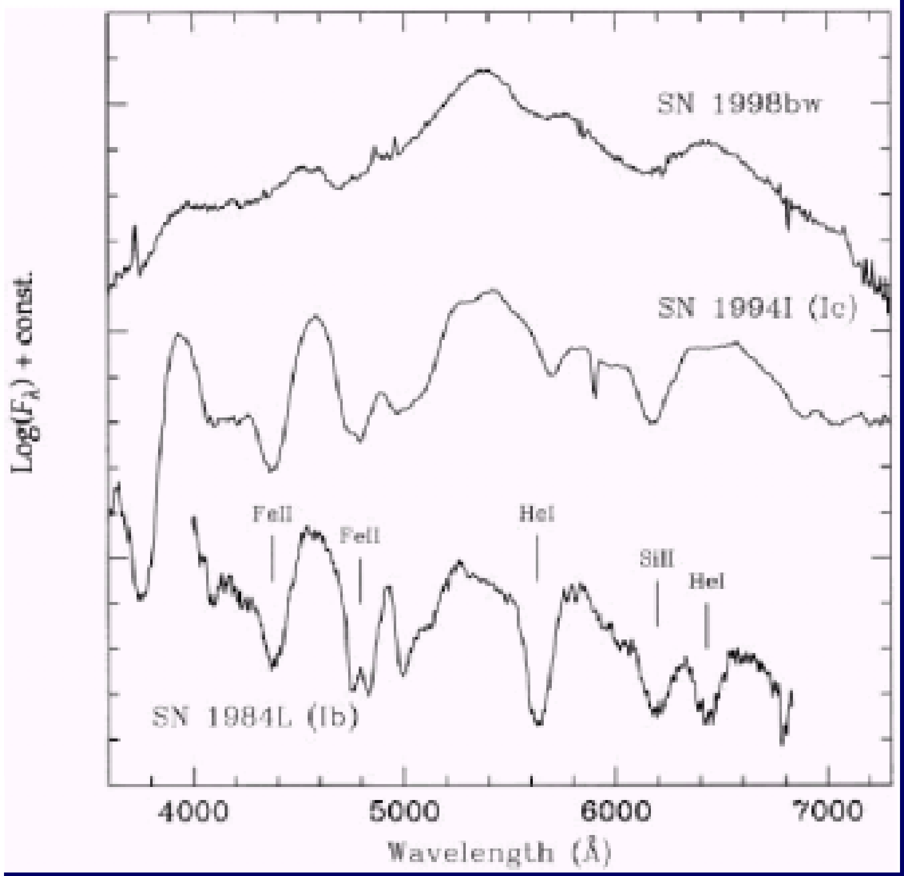
- Very high-z events yet to be detected

Supernova connection

SN1998bw: Type 1c SN at z=0.008

found at the position of GRB 980425

But unusually powerful



Galama et al.

SN1998bw = GRB980425?

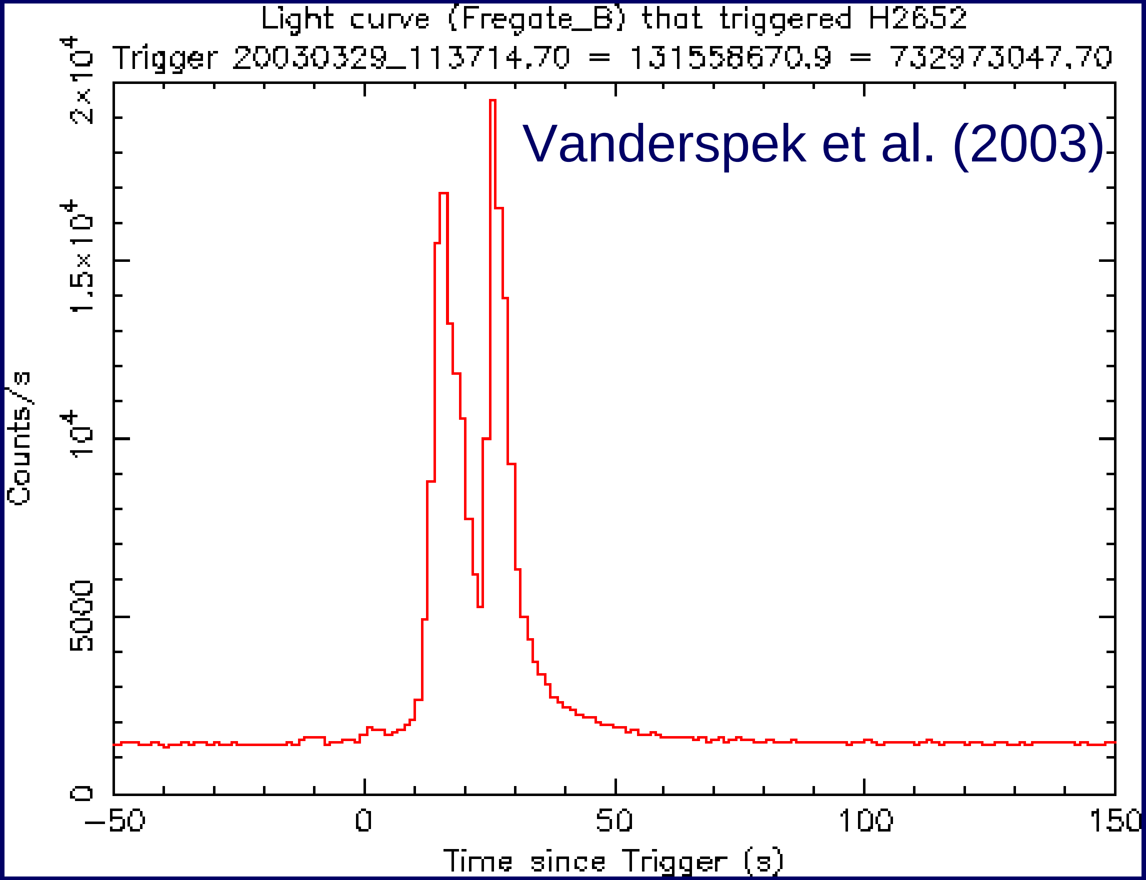
- GRB/SN: time and location consistent
- Most radio-luminous SN
- Radio obs suggests relativistic expansion
- Unusual optical spectrum
- Unusual optical light curve

- Luminosity: 10^{-6} of typical GRB
- SN energy >> GRB energy
  - (no "GRB afterglow" seen)

→ Maybe associated, but different from ordinary GRB

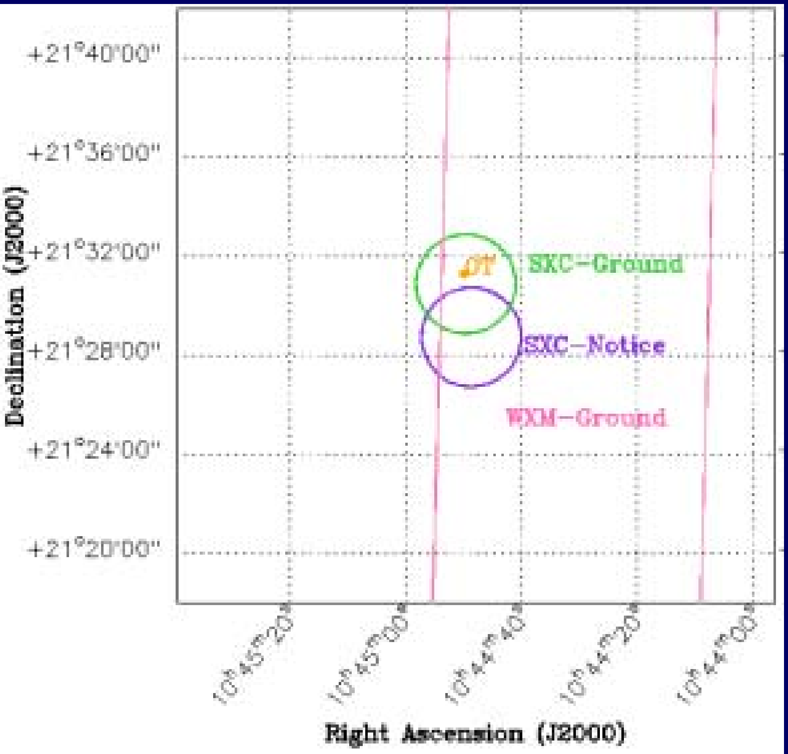
“Monster GRB”

GRB030329



The brightest GRB localized by HETE-2

Localization by HETE-2



Trigger	11:37:14	
Alert	11:38:41	
SXC	12:50:24	(+73 min)
OT	12:52:09	(+75 min)

Torii #1986
Peterson #1985

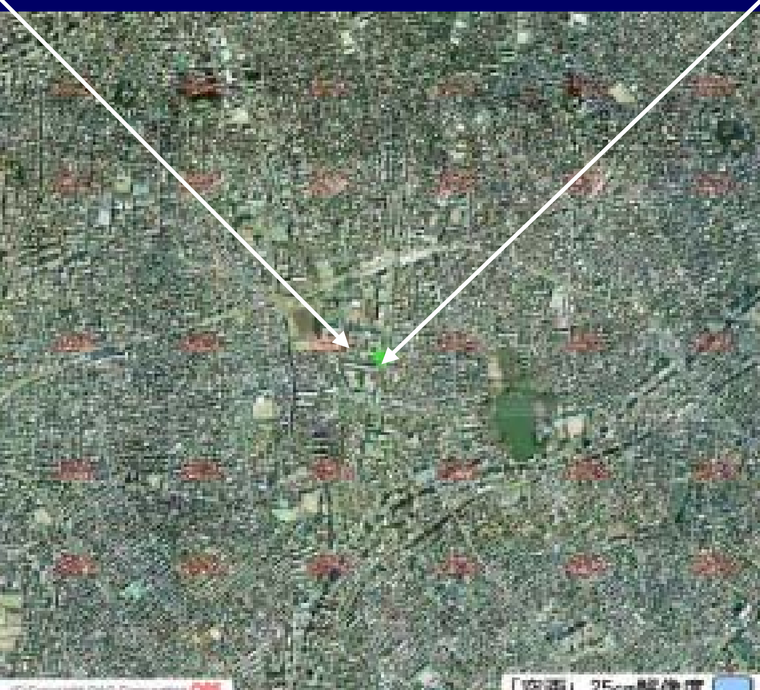
- The fluence of the burst ~1 x 10^{-4} ergs cm^{-2}
- peak flux over 1.2 s was > 7 x 10^{-6} ergs cm^{-2} s^{-1}

(i.e., > 100 x Crab flux in the same energy band)

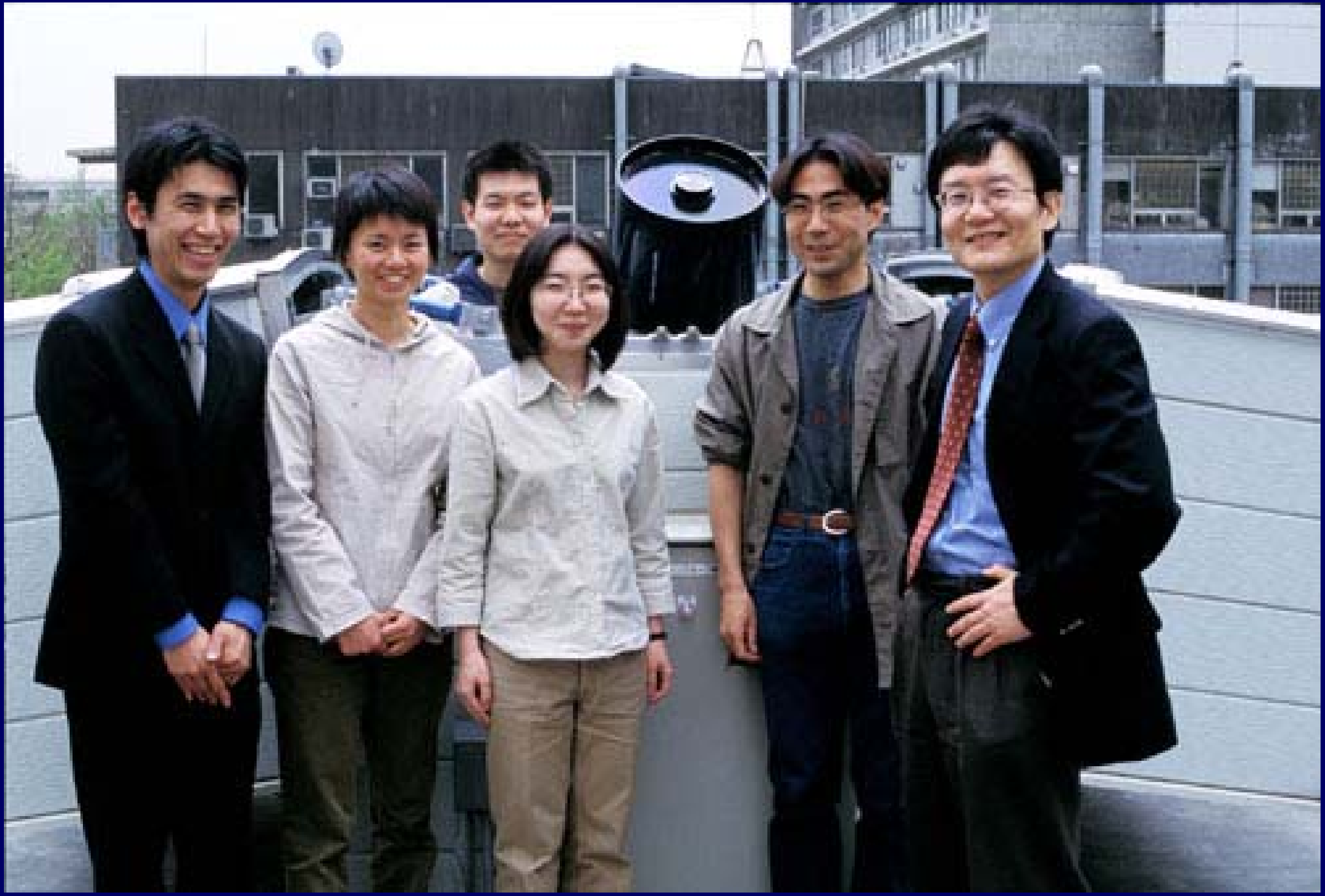
- X-ray afterglow: 7 mCrab (RXTE, +5 hr)

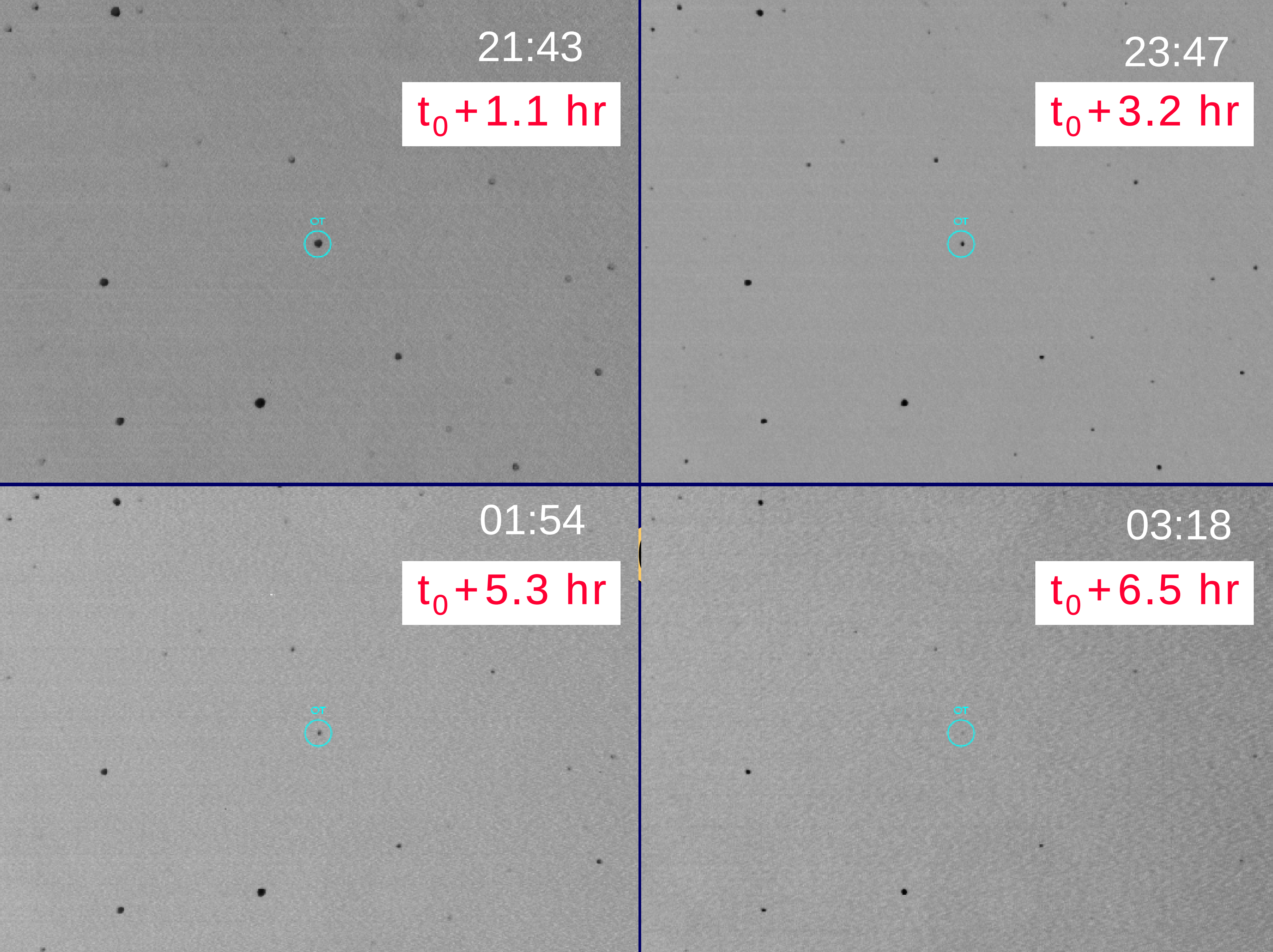
z = 0.1675 ⇔ probability of detecting a GRB this close by is ~1/3000
=> unlikely that HETE-2 or *Swift* will see another such event

in the city light ...

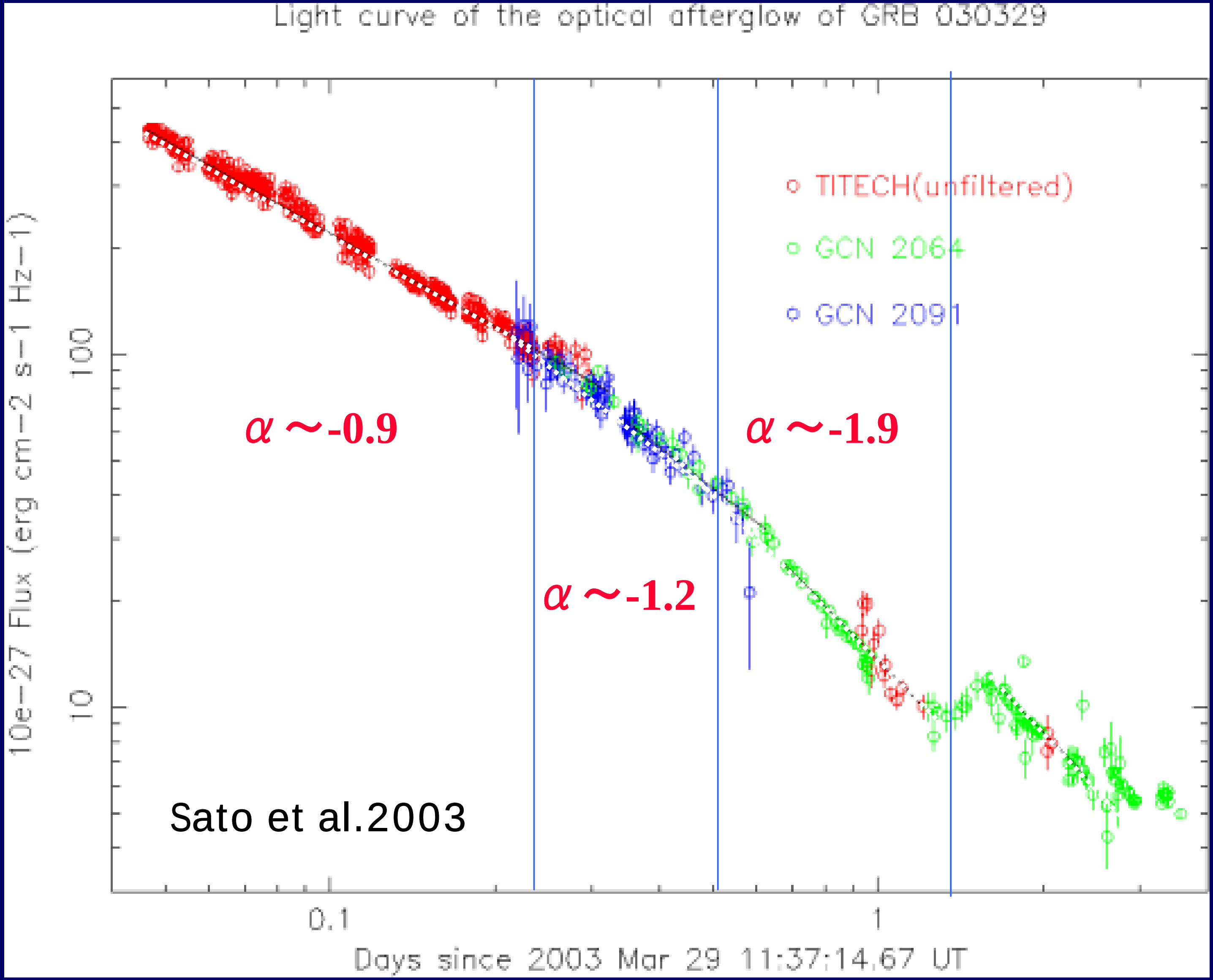


30 cm Telescope on the Tokyo Tech roof

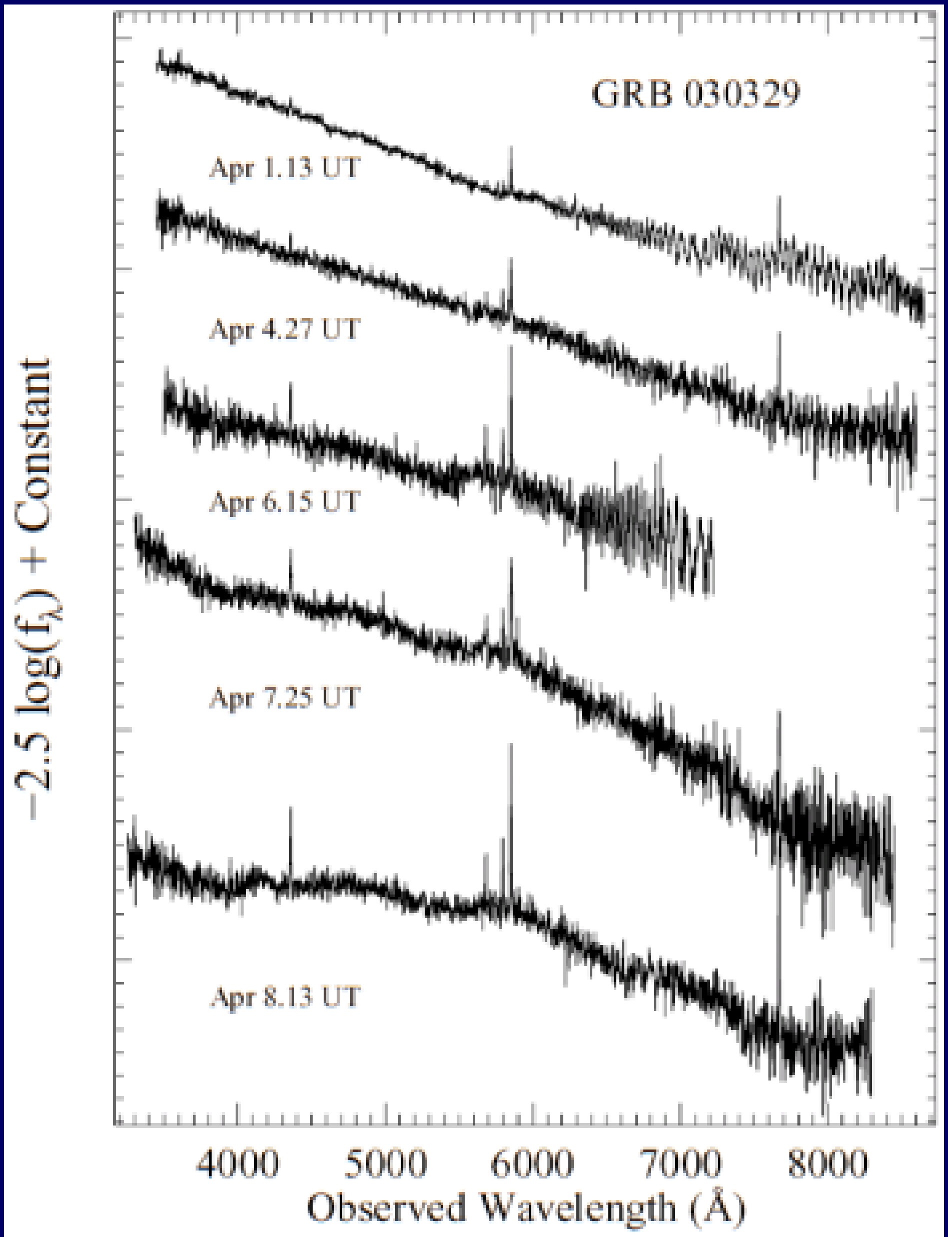


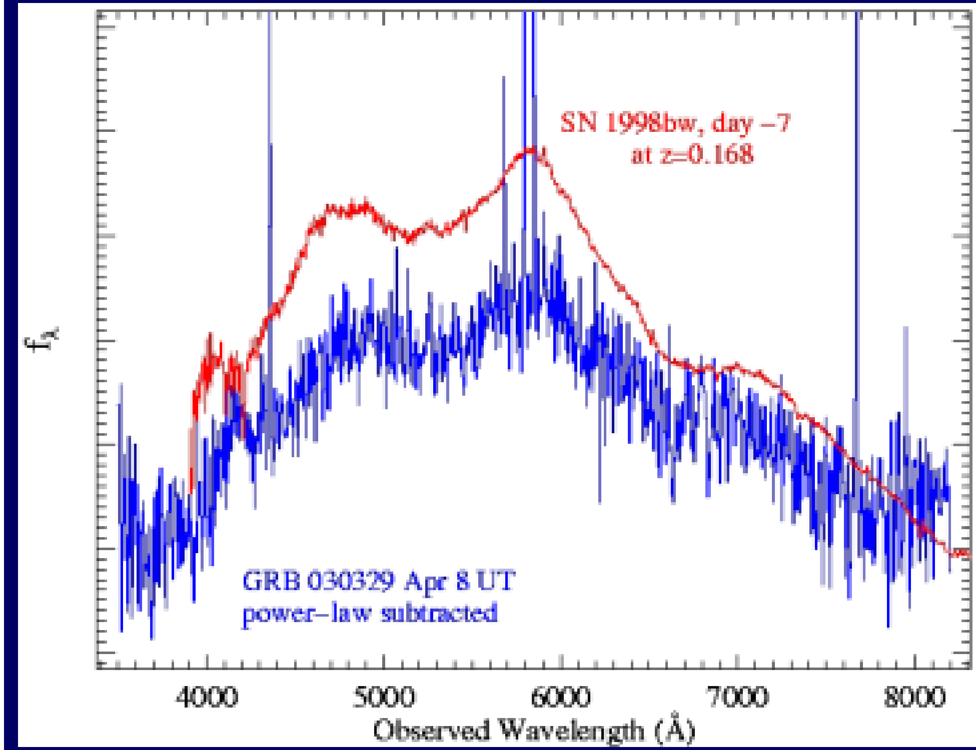

21:43
t_0+1.1 hr
OT
23:47
t_0+3.2 hr
OT
01:54
t_0+5.3 hr
OT
03:18
t_0+6.5 hr
OT

Tokyo Tech data + GCN

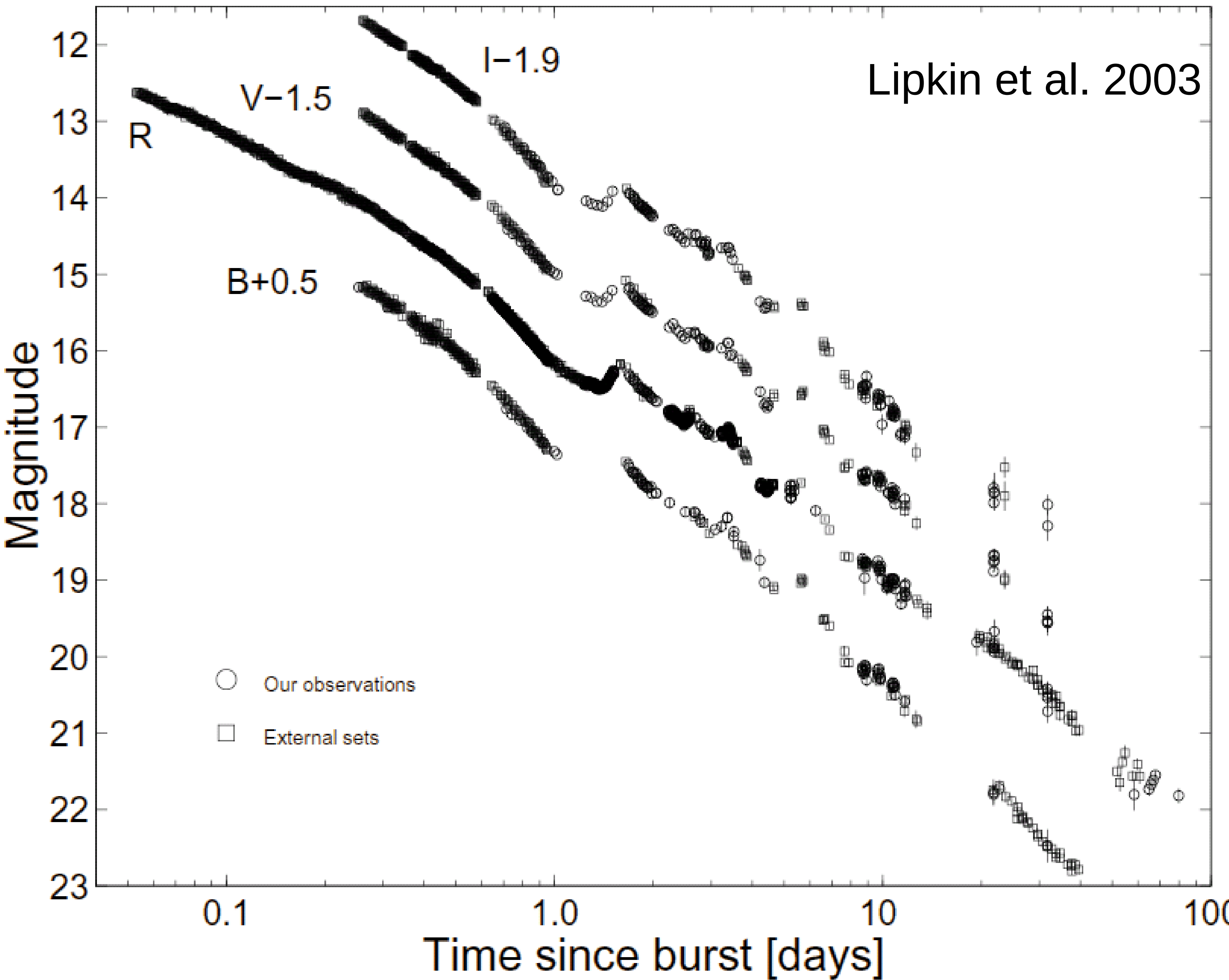


Supernova connection established





Stanek et al. 2003
also Hjorth et al. 2003
Kawabata et al. 2003

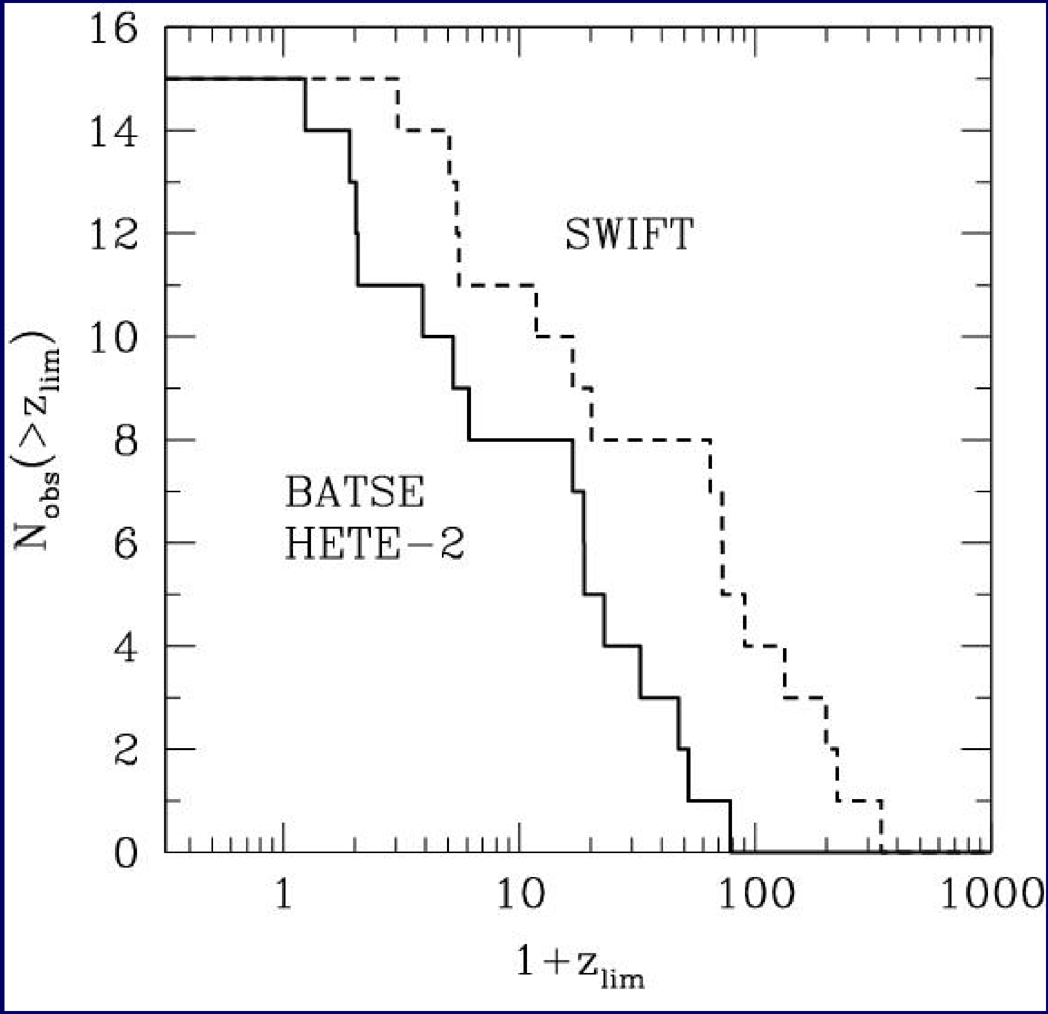

Lipkin et al. 2003
I−1.9
V−1.5
R
B+0.5
Magnitude
12
13
14
15
16
17
18
19
20
21
22
23
Our observations
External sets
0.1
1.0
10
100
Time since burst [days]

GRB030329: Implications

- HETE-2—localized burst GRB030329/SN 2003dh confirms the GRB – SN connection

- Implications:
  - We must understand Type Ib/Ic core collapse SNe in order to understand GRBs
  - Conversely, we must understand GRBs in order to fully understand Type Ib/Ic core collapse SNe
  - Result strengthens the expectation that GRBs occur out to $z \sim 20$, and are therefore *a powerful probe of the early universe*

GRBs Are Easily Detectable at z ~ 20



Sample of 15 GRBs with known redshifts

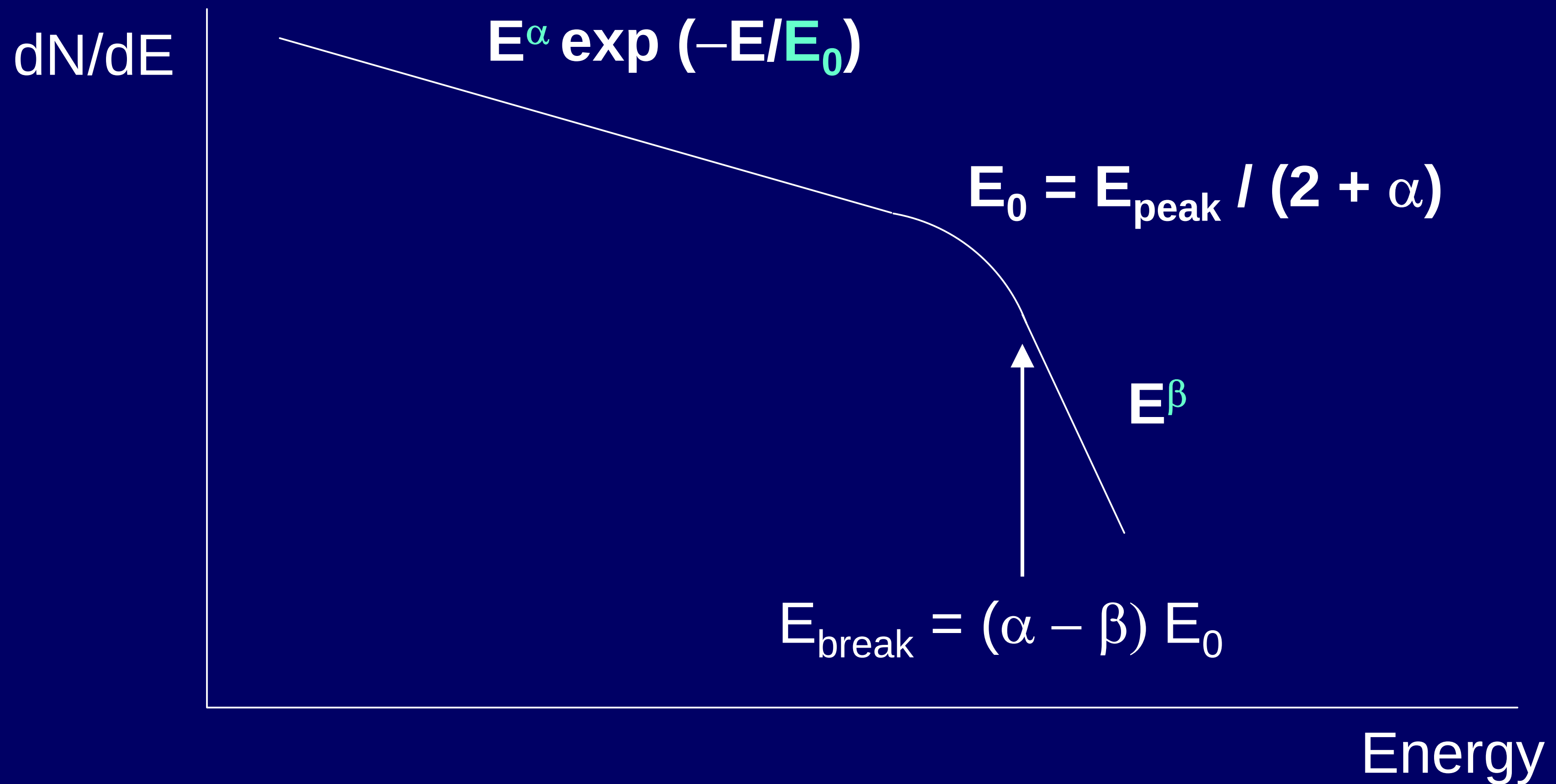
flux scaled to larger redshift

Lamb & Reichart (2000; see also Ciardi and Loeb 2000)

X-ray rich GRBs and XRFs (X-ray flash)

Empirical spectral models of GRBs

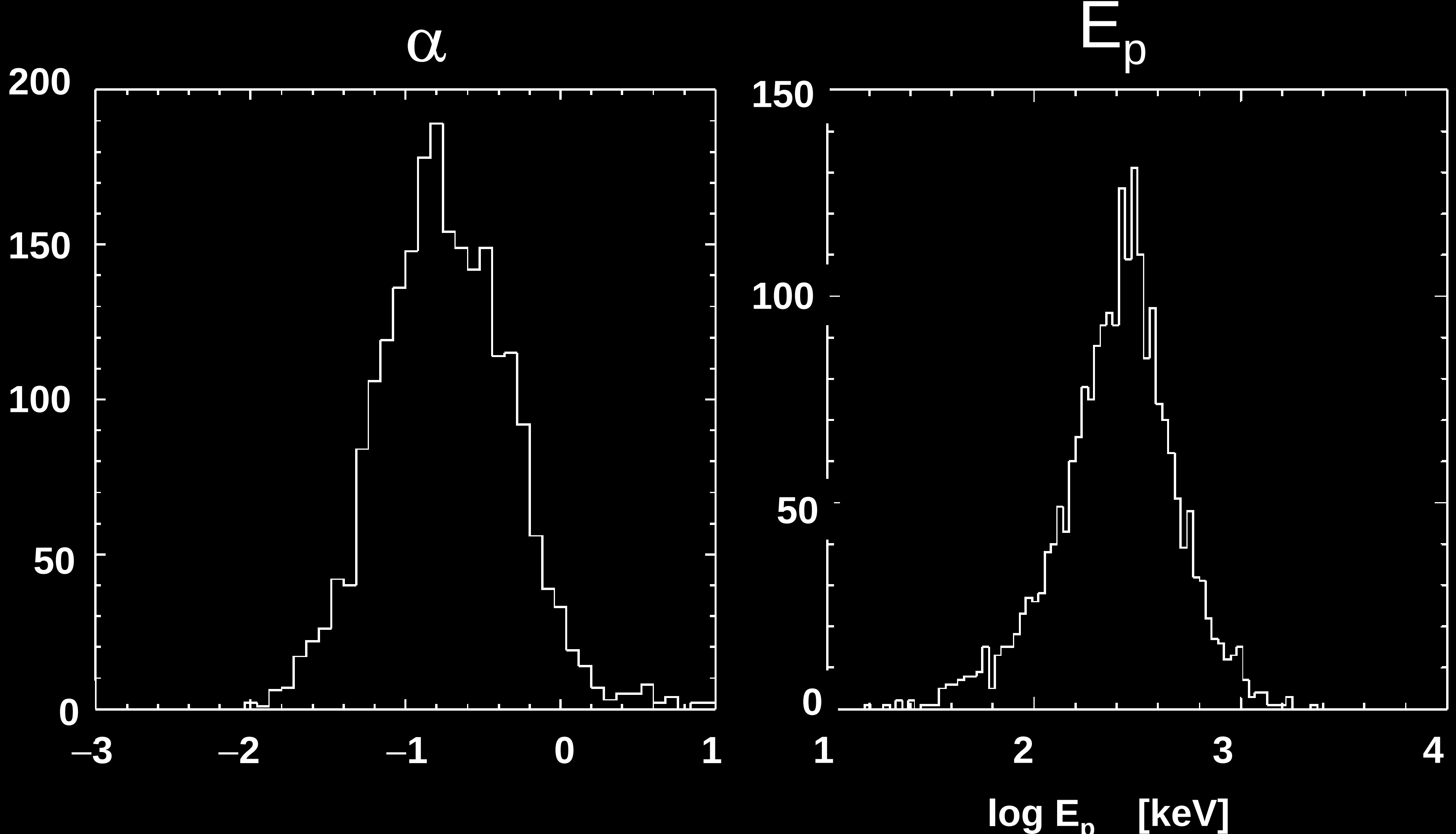
Band function



Spectral parameters of GRBs (BATSE)

(BATSE spectral catalog, Preece et at. 2000)

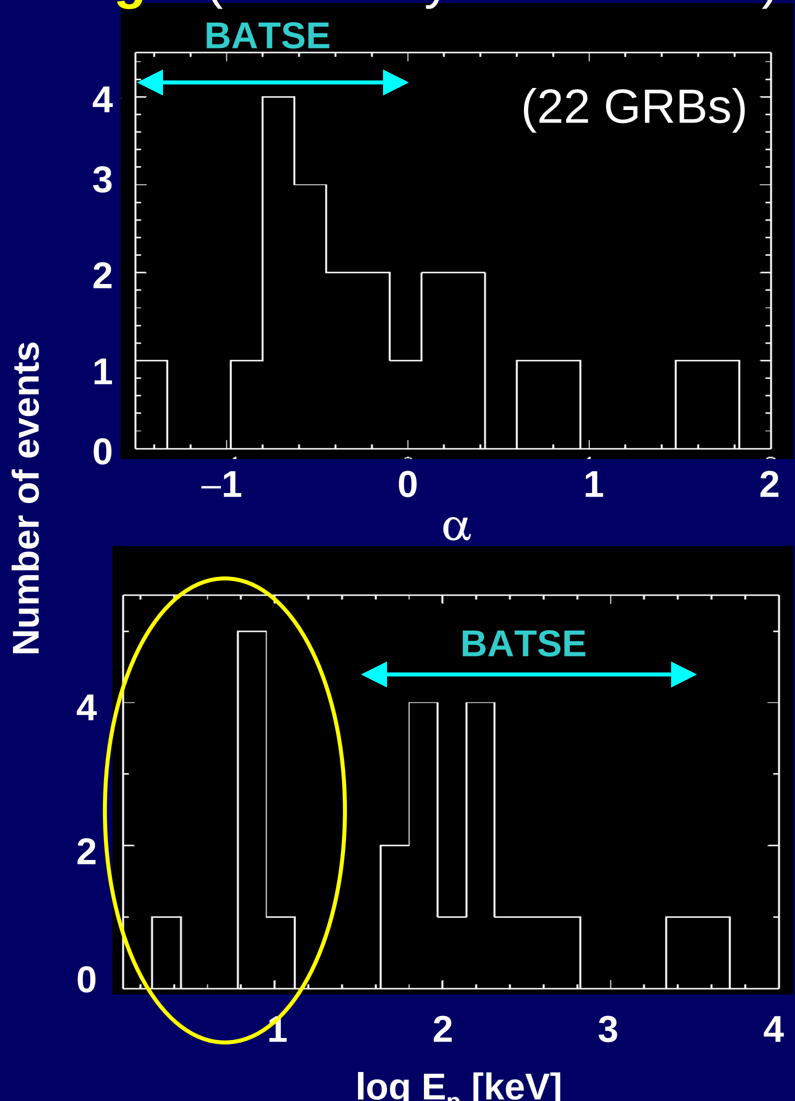
Band function



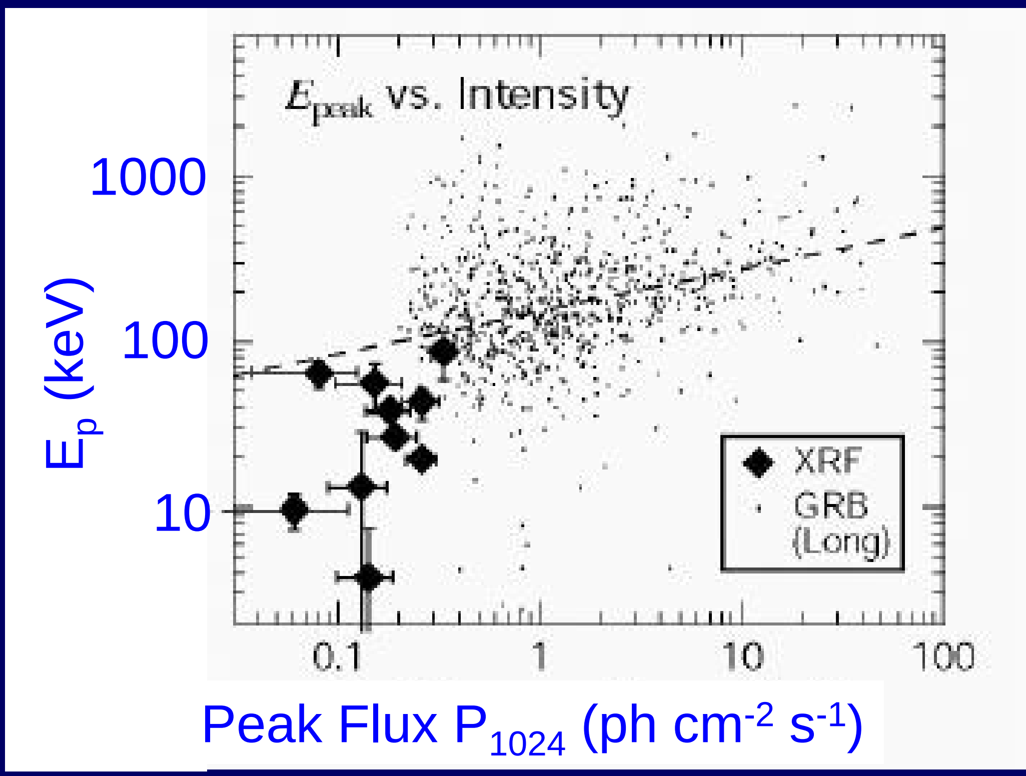
(β ~ –2.5)

X-Ray Flashes (XRFs) and X-ray rich GRBs
(Ginga and BeppoSAX WFC)

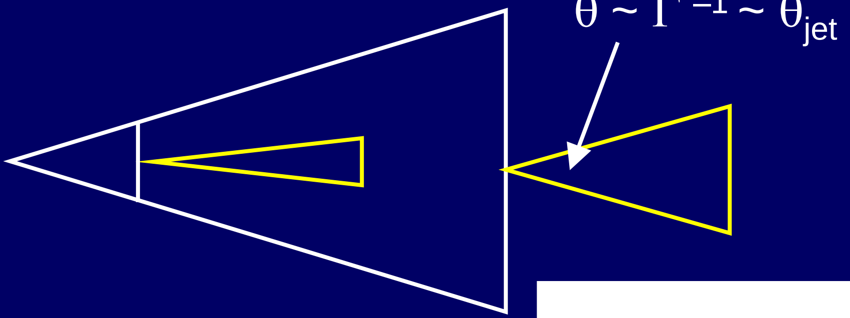
Ginga (Strohmayer et al. 1998)

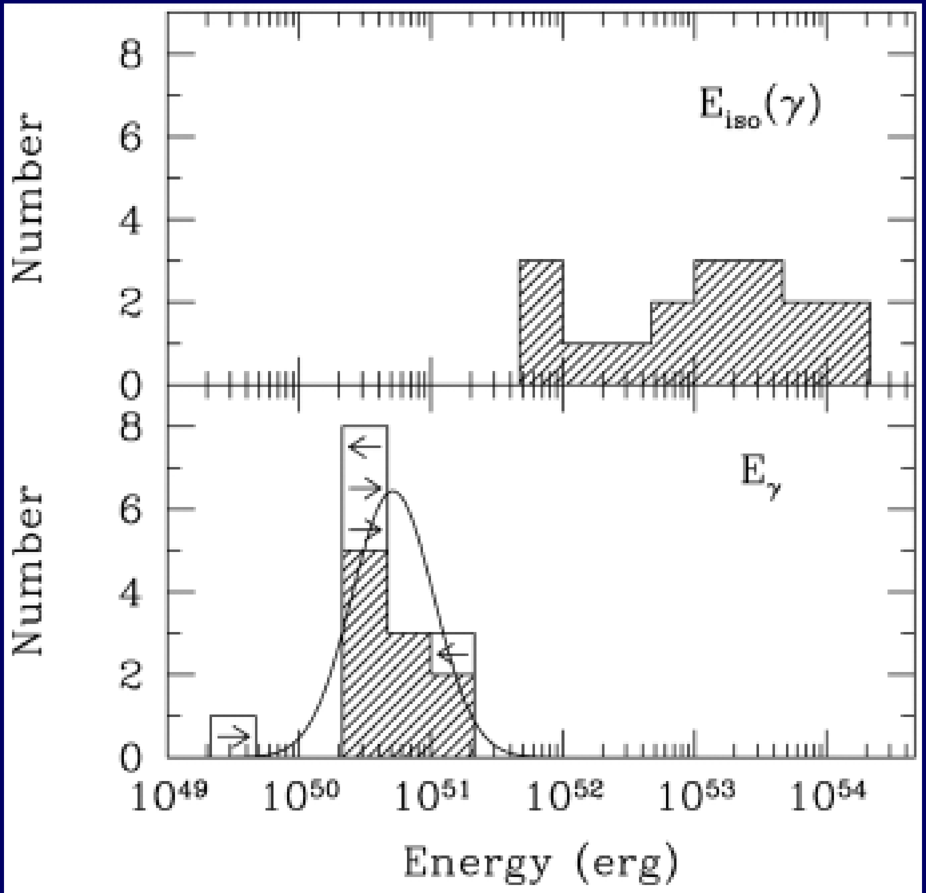


WFC / BATSE (Kippen et al. 2002)

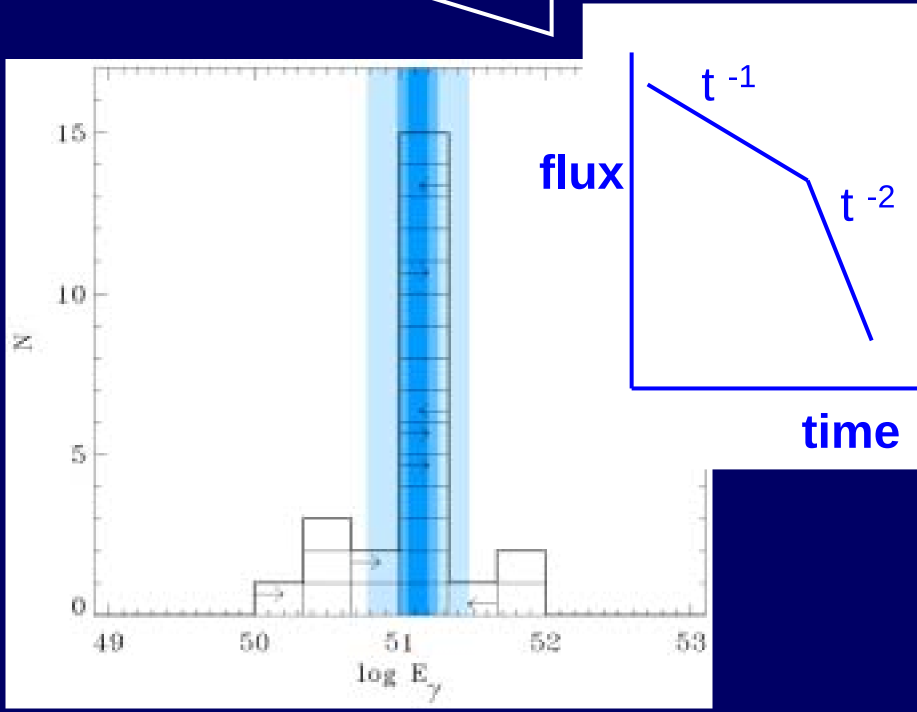


"Standard energy" Frail's relation





(Frail et al. 2001)



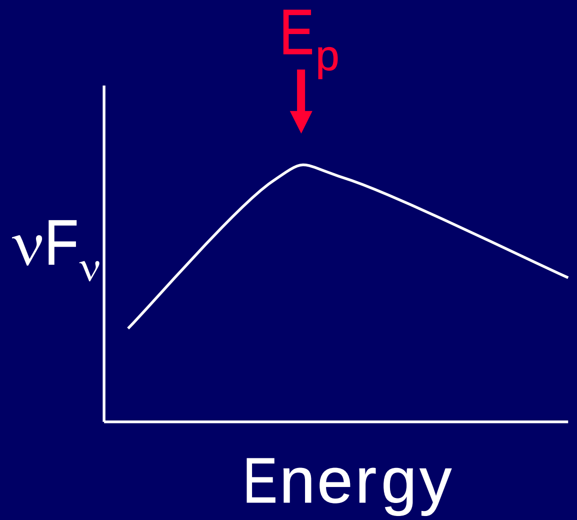
(Bloom et al. 2003)

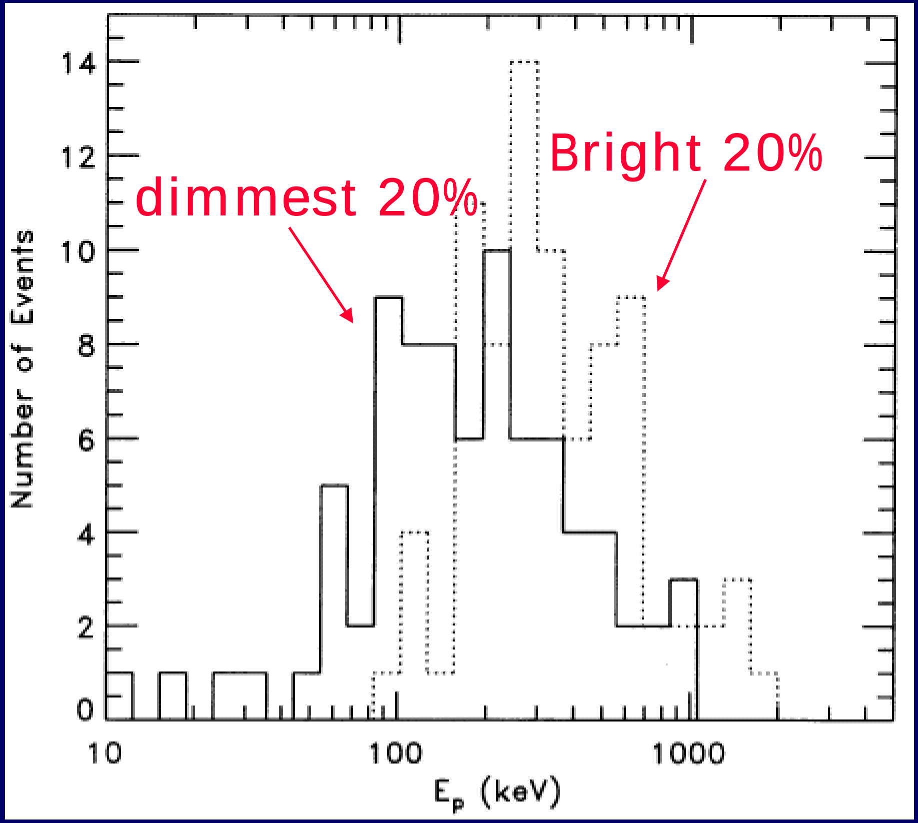
$E\gamma = (1.33 \pm 0.07) \times 10^{51}$ erg

click

Spectra of GRB prompt emission -- broken power-law

- E_p = a few 100 keV in BATSE sample





Mallozzi et al. 1995

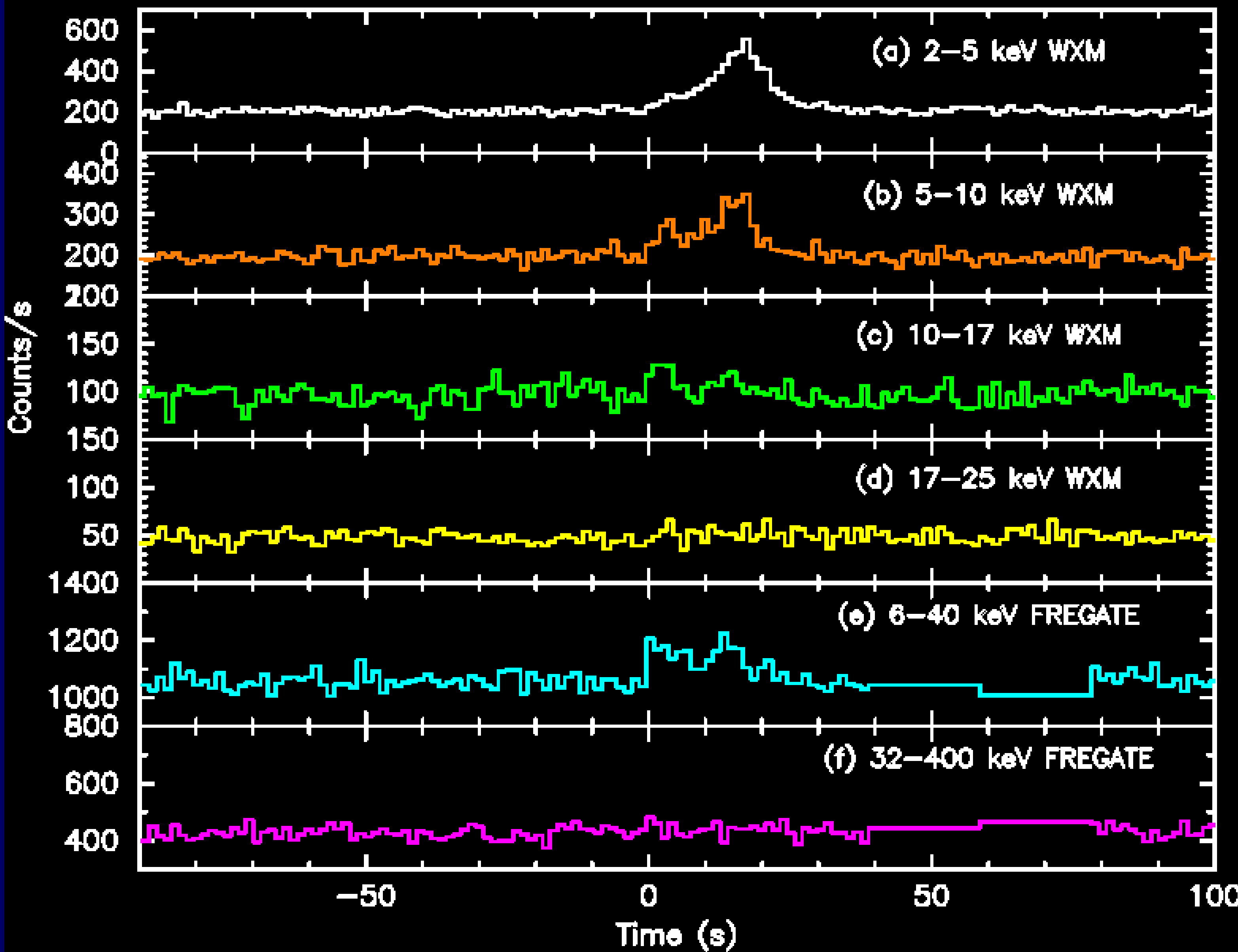
XRF010213

- Burst time : 13 February 2001 12:35:35 UT
  (4 months after the launch)
- Burst location: (R.A., Dec.) = ($10^h31^m26^s$, $5^o30'30''$) (J2000)
  with a 95% error radius of 30'

Burst Properties

- Duration: 20.9 s (T90 WXM 2-25 keV band)
- X-ray / γ -ray fluence ratio:
  S (2-30 keV) / S (30-400 keV) = 13.5
- Total fluence (2 - 30 keV) : (6.3 ± 0.6) x 10^{-7} erg cm^{-2}
- Peak flux
- No afterglow was found.
  (Boer et al., Hudec et al., Henden et al.,
  Berger et al. and Zhu et al.)

XRF010213



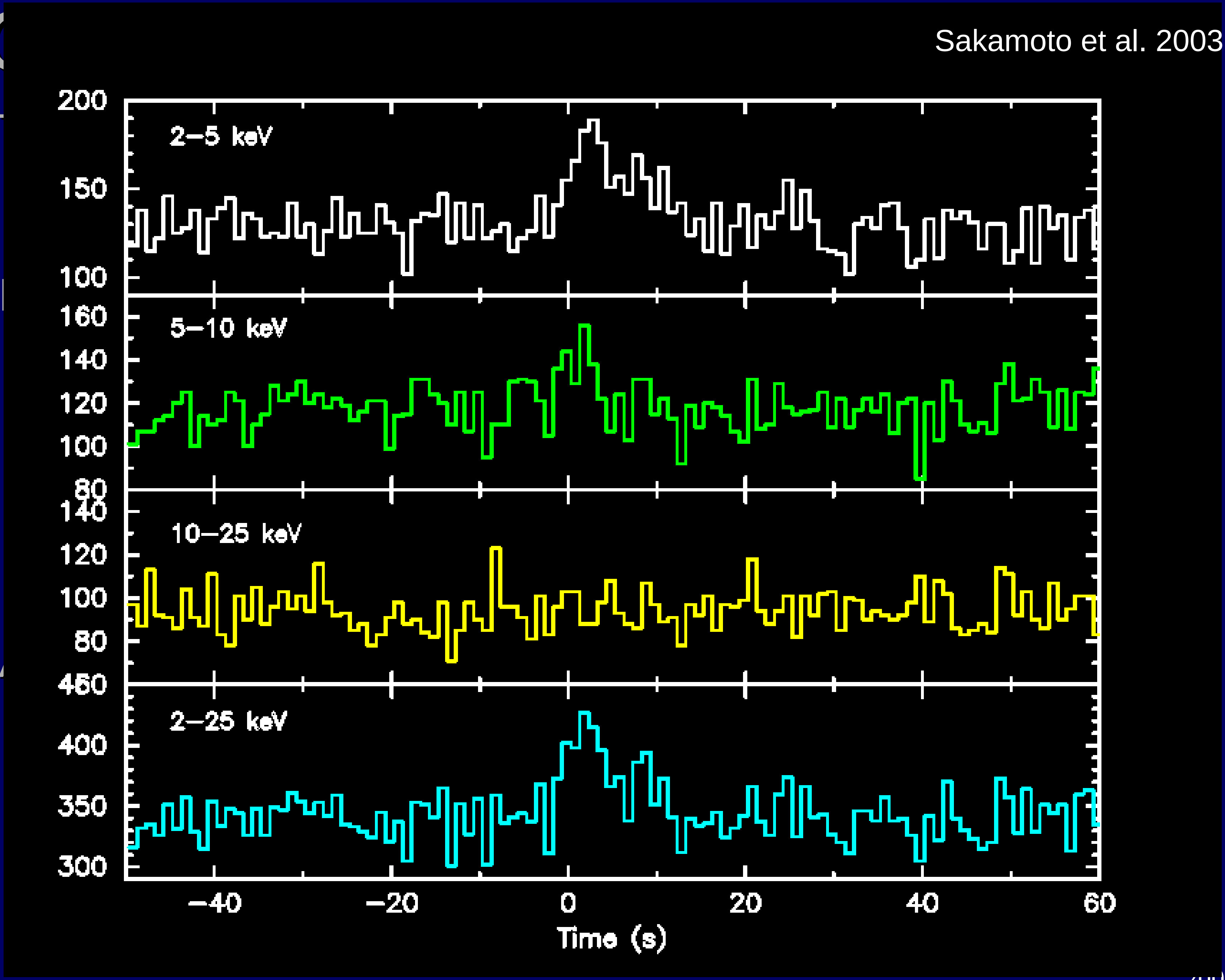
Sakamoto et al. 2004

Definition of XRF/XRR/GRB

Fluence in 2-30 keV : S_X, Fluence in 30-400 keV : S_γ
(in the best fit spectral model)

$\log (S_X / S_\gamma) > 0$	XRF
$-0.5 < \log (S_X / S_\gamma) \leq 0$	XRR
$\log (S_X / S_\gamma) \leq -0.5$	GRB

XRF : X-ray flash
XRR : X-ray rich GRB
GRB : Hard GRB


Sakamoto et al. 2003
2–5 keV
5–10 keV
10–25 keV
2–25 keV
200
150
100
160
140
120
100
80
140
120
100
80
450
400
350
300
−40
−20
0
20
40
60
Time (s)

GRB020903

Trigger time:

10:05:37.96 on 2002 September 3

Burst properties:

- Duration (2-10 keV): 4.9 s (T50), 9.8 s (T90)
- X-ray / γ –ray fluence ratio:

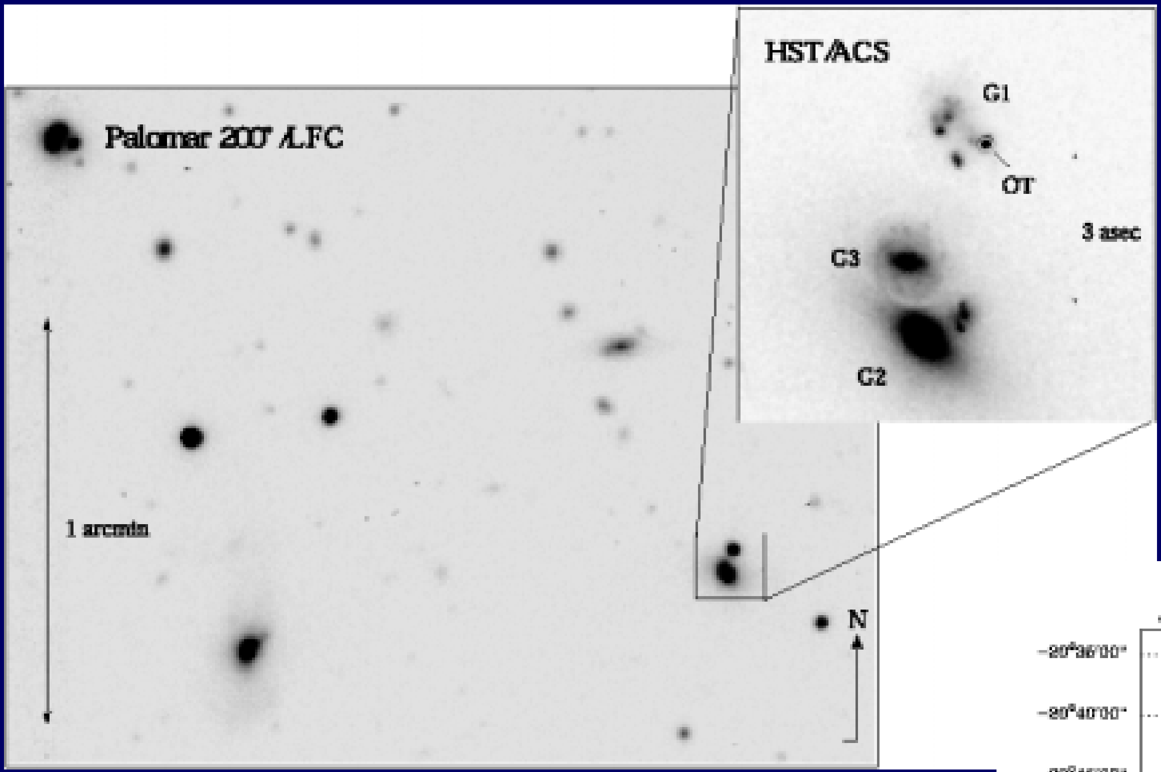
  S(2-30 keV) / S(30-400 keV) = 5.6
- Peak flux (1s, 2-10 keV): (2.2 ± 0.8) ph cm^{-2} s^{-1}
- Total fluence (2-10 keV): $(5.9 \pm 1.4) \times 10^{-8}$ erg cm^{-2}

Afterglow candidate:

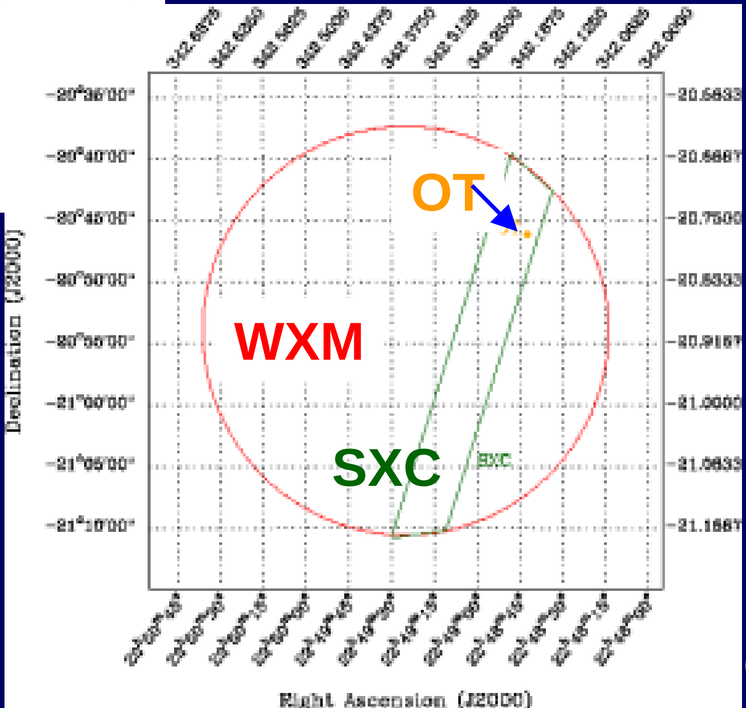
- Optical transient (Palomar 200-inch, Soderberg et al.)
- Redshift of underlying galaxy $z = 0.25 \pm 0.01$

  (Soderberg et al., Chornock & Filippenko)
- Radio source at OT position (VLA, Berger et al.)
- Host galaxy is an irregular galaxy (HST, Levan et al.)

GRB020903



Soderberg et al 2003



Constrain Ep of GRB020903

WXM spectrum

- power-law model with photon index $\alpha = -2.8$
  ($\alpha < -2$ at 99.3% confidence level)

→ Ep lies near or below 2 keV (WXM lower energy boundary)

Constrained Band function

- parameterized Ep and β (high-energy index)
- Only the high-energy part of the Band function is allowed to produce a pure power-law spectrum.

Ep of GRB020903 using the *constrained* Band function

1.1 keV < Ep < 3.6 keV, 68%
Ep < 4.1 keV, 95%
Ep < 5.0 keV, 99.7%

Sakamoto et al. 2003

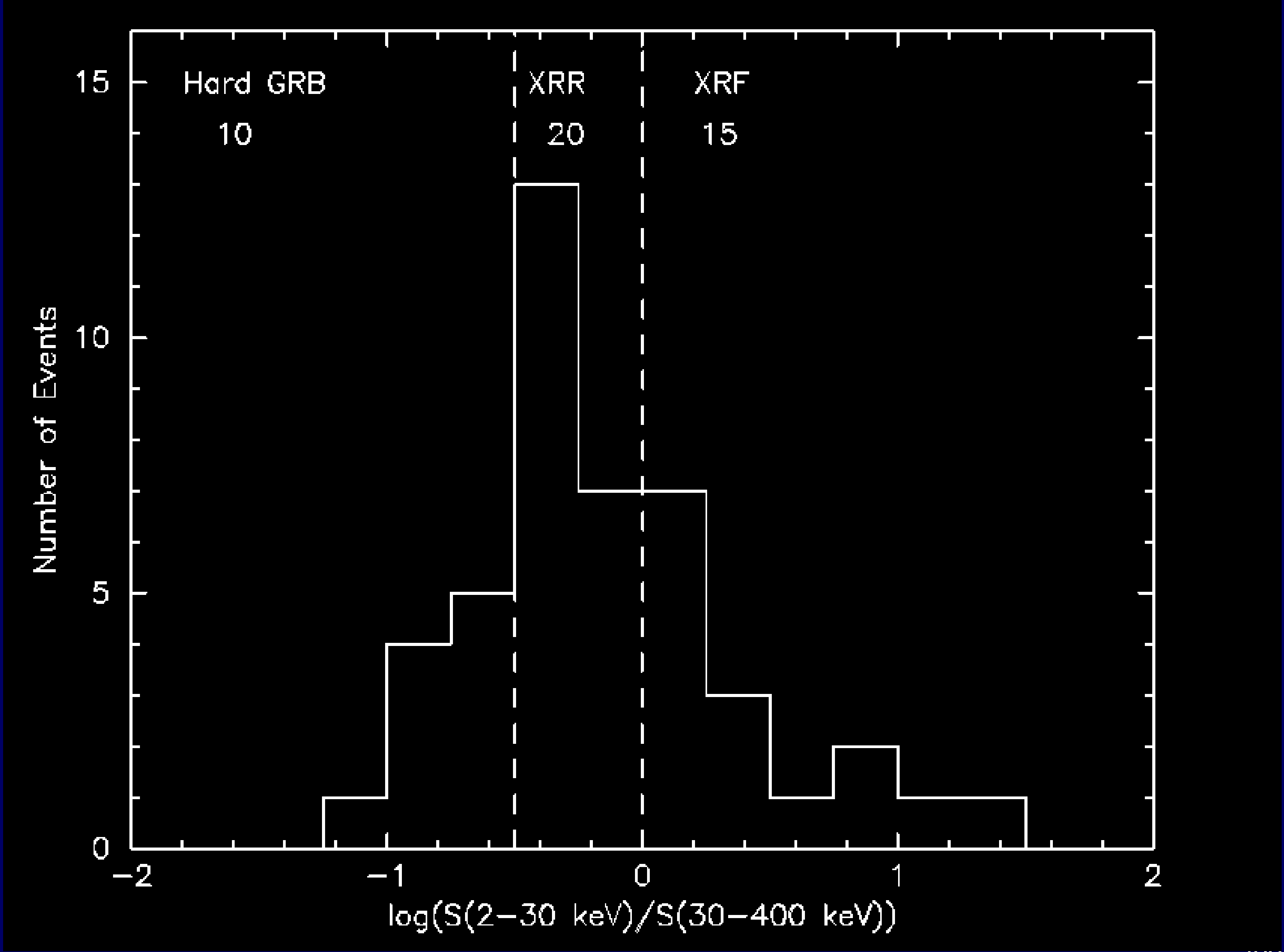
Summary (1)

- XRFs/XRRs are similar to hard GRBs
  - duration
  - temporal profile
  - spectral softening

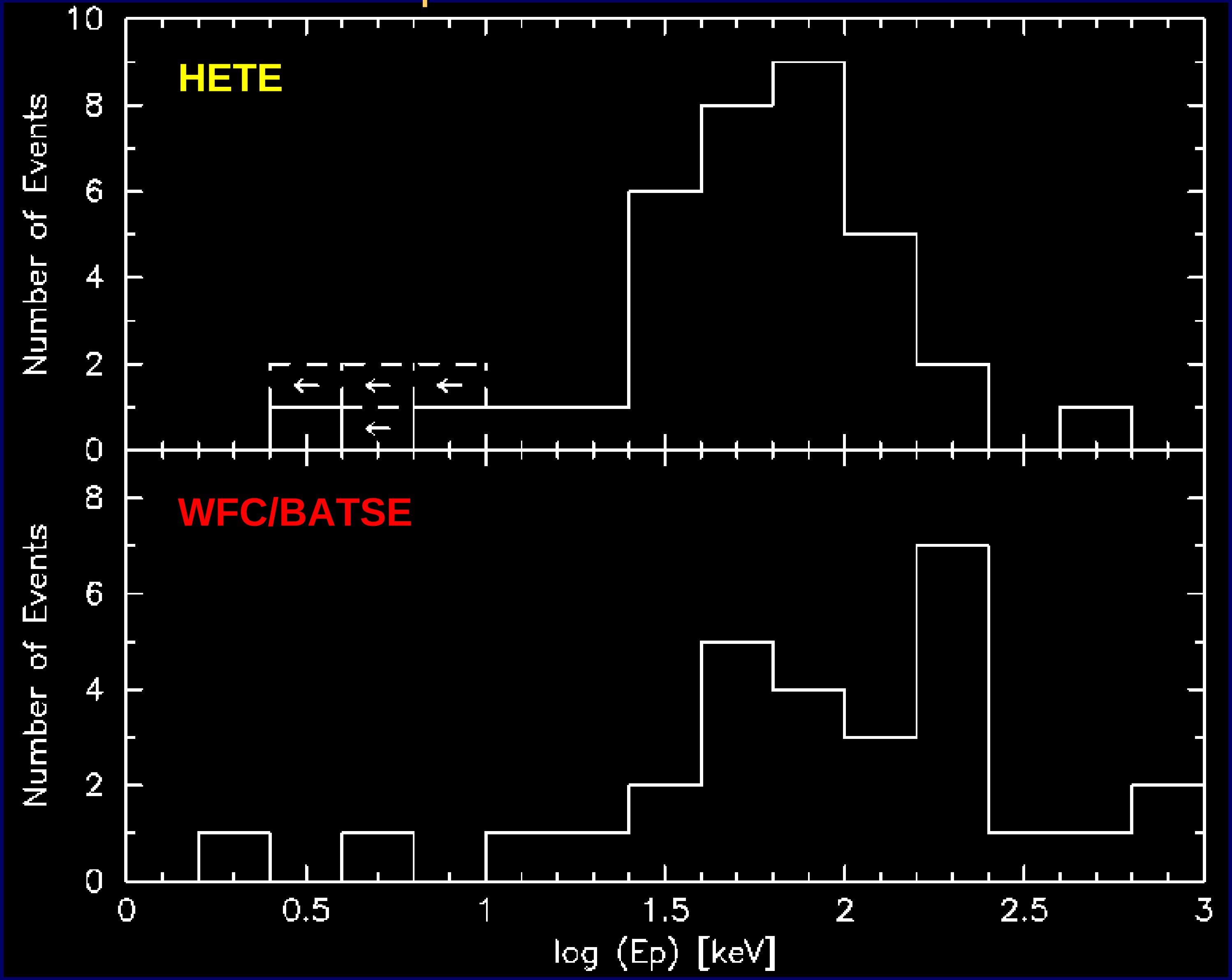
- The lower E_{peak} energies for XRFs/XRRs (No difference in α and β)
  - Six XRFs with E_{peak} of a few keV

- The afterglow of XRFs are generally very faint.

Fluence ratio distribution



Comparison with WFC/BATSE XRF E_{peak} distribution



Analysis

HETE localized GRBs

1) the burst signal is seen in both WXM and FREGATE

2) both WXM and FREGATE data have a enough statistics to carry out the spectral analysis

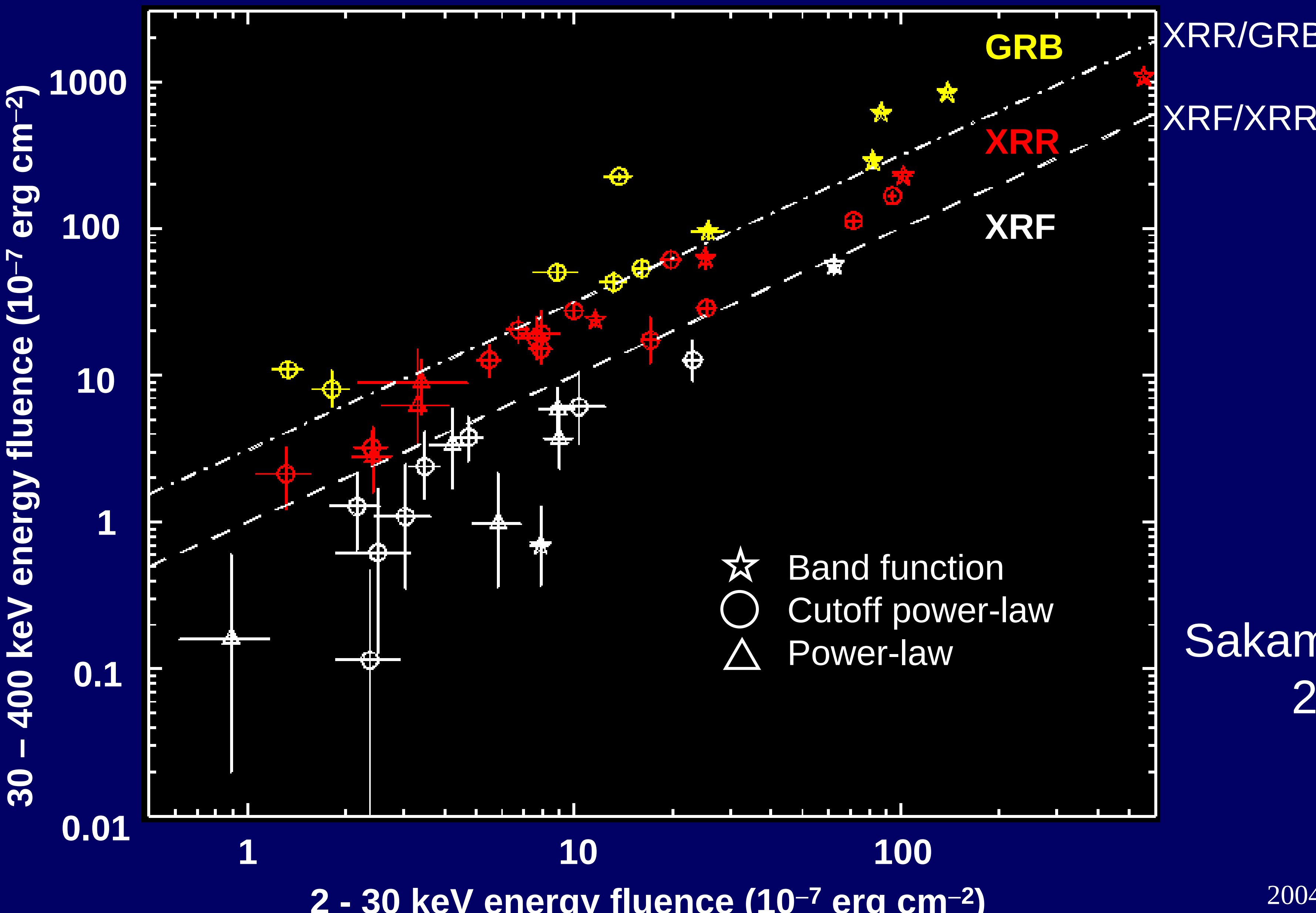
- HETE GRBs from February 2001 to September 2003
- Time-average spectral analysis

↓

45 GRBs

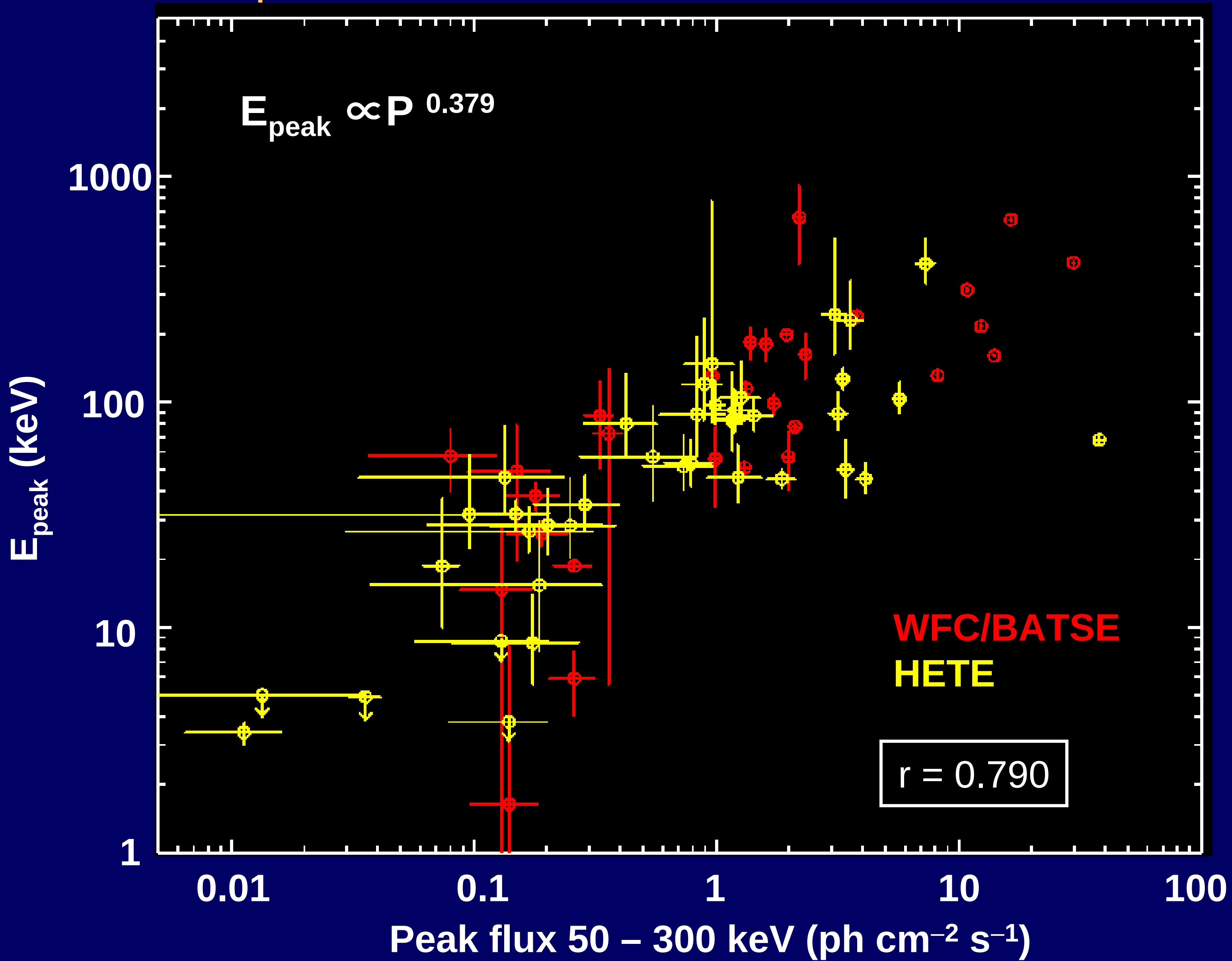
15 X-ray flashes | 20 X-ray rich GRBs | 10 hard GRBs

2-30 keV – 30-400 keV fluence



Sakamoto 2004

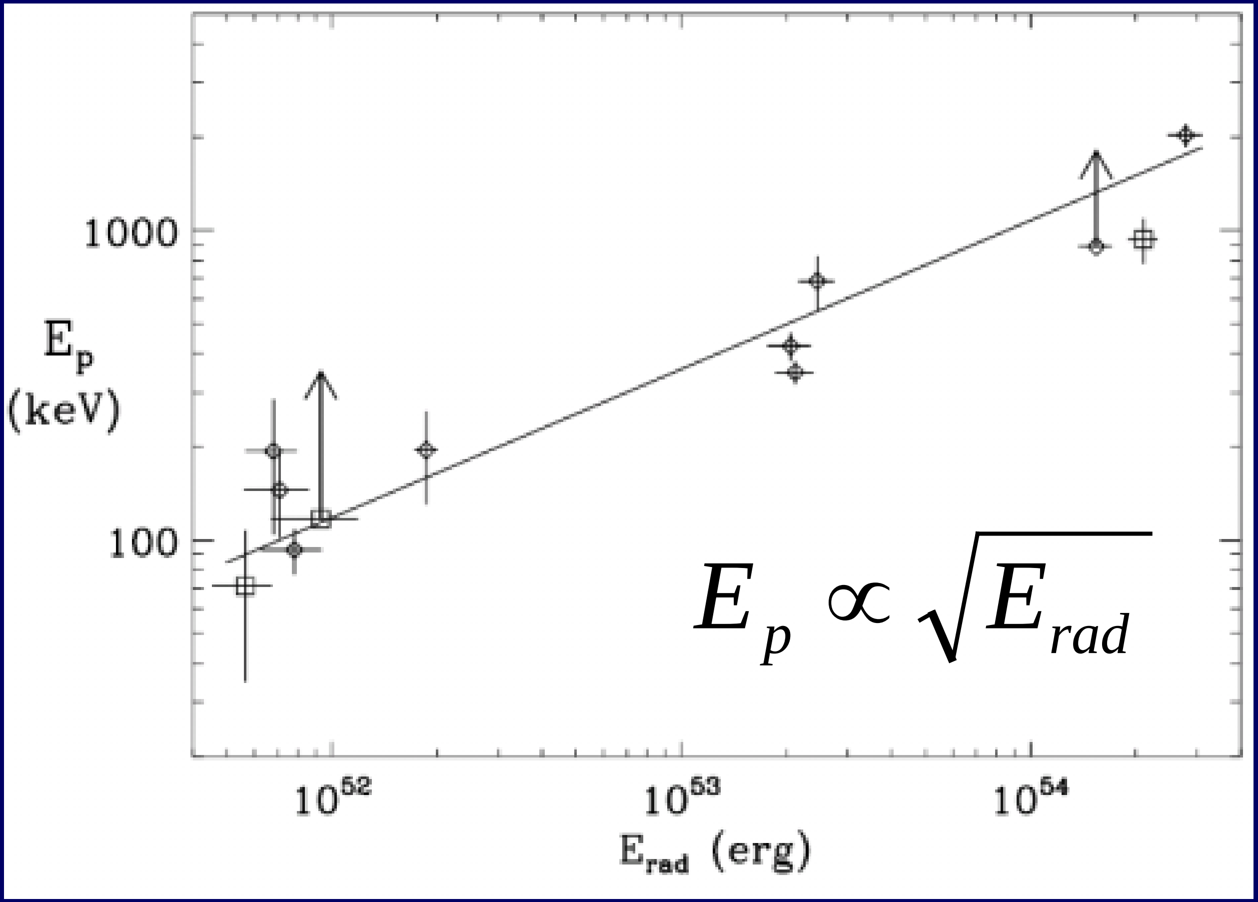
Comparison with WFC/BATSE XRF E_{peak} vs. 50-300 keV peak flux



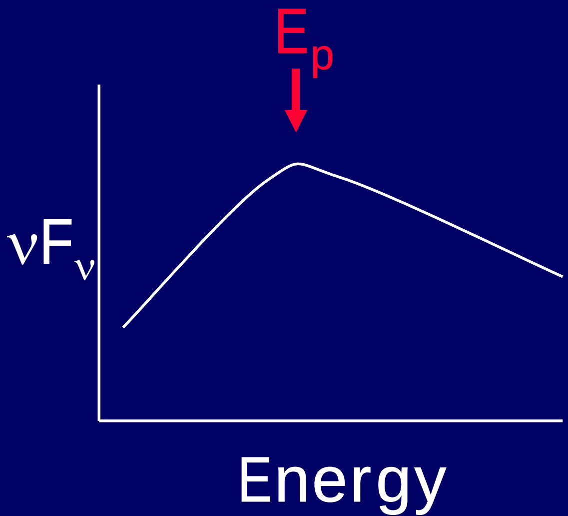
Sakamoto 2004

SED peak energy (at source) vs. isotropic radiated energy

BeppoSAX events by Amati et al. 2002

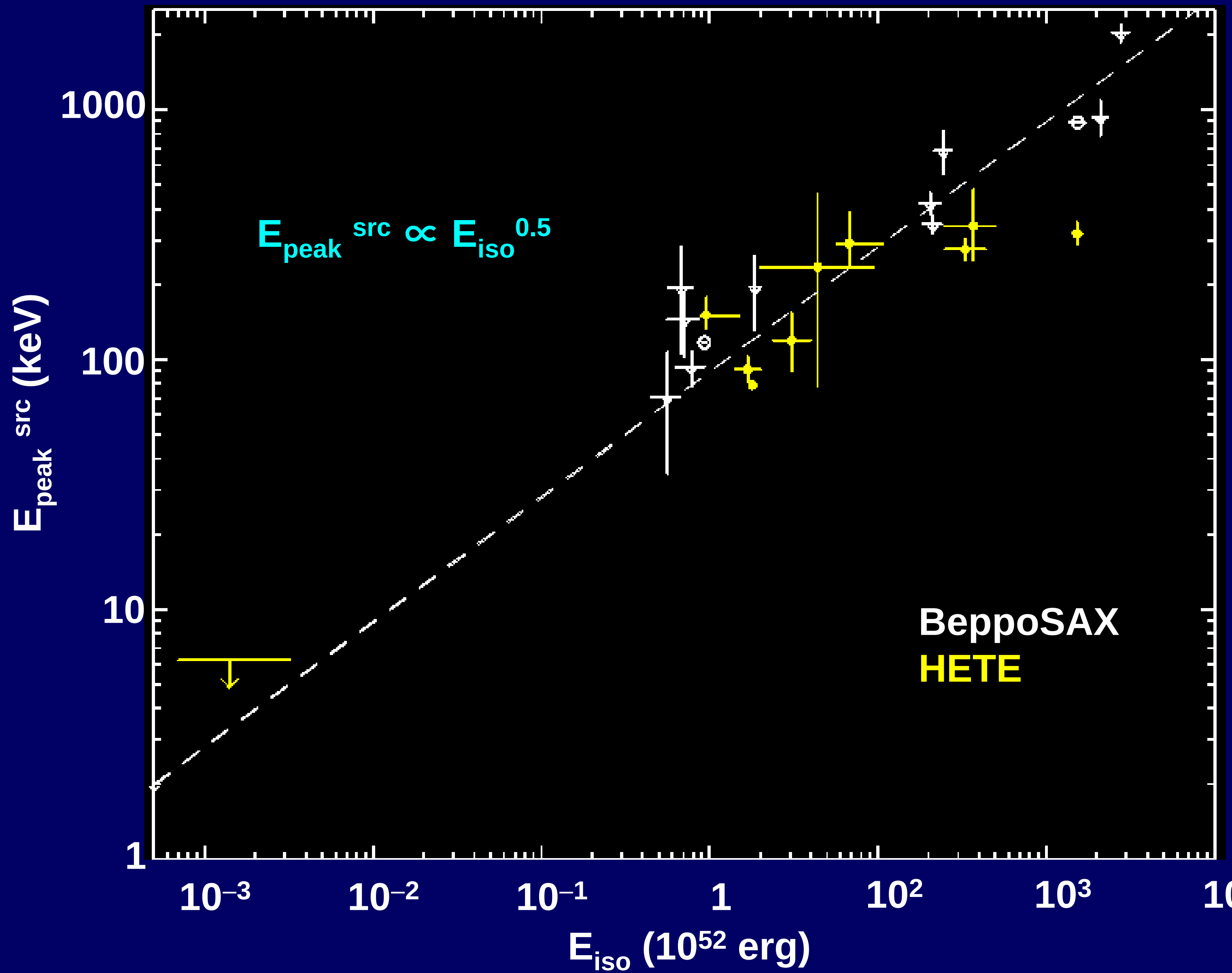


$$E_p \propto \sqrt{E_{rad}}$$



“Extended” Amati’s relation

(Amati et al. 2002; sakamoto et al. 2004; Lamb et al. 2004)

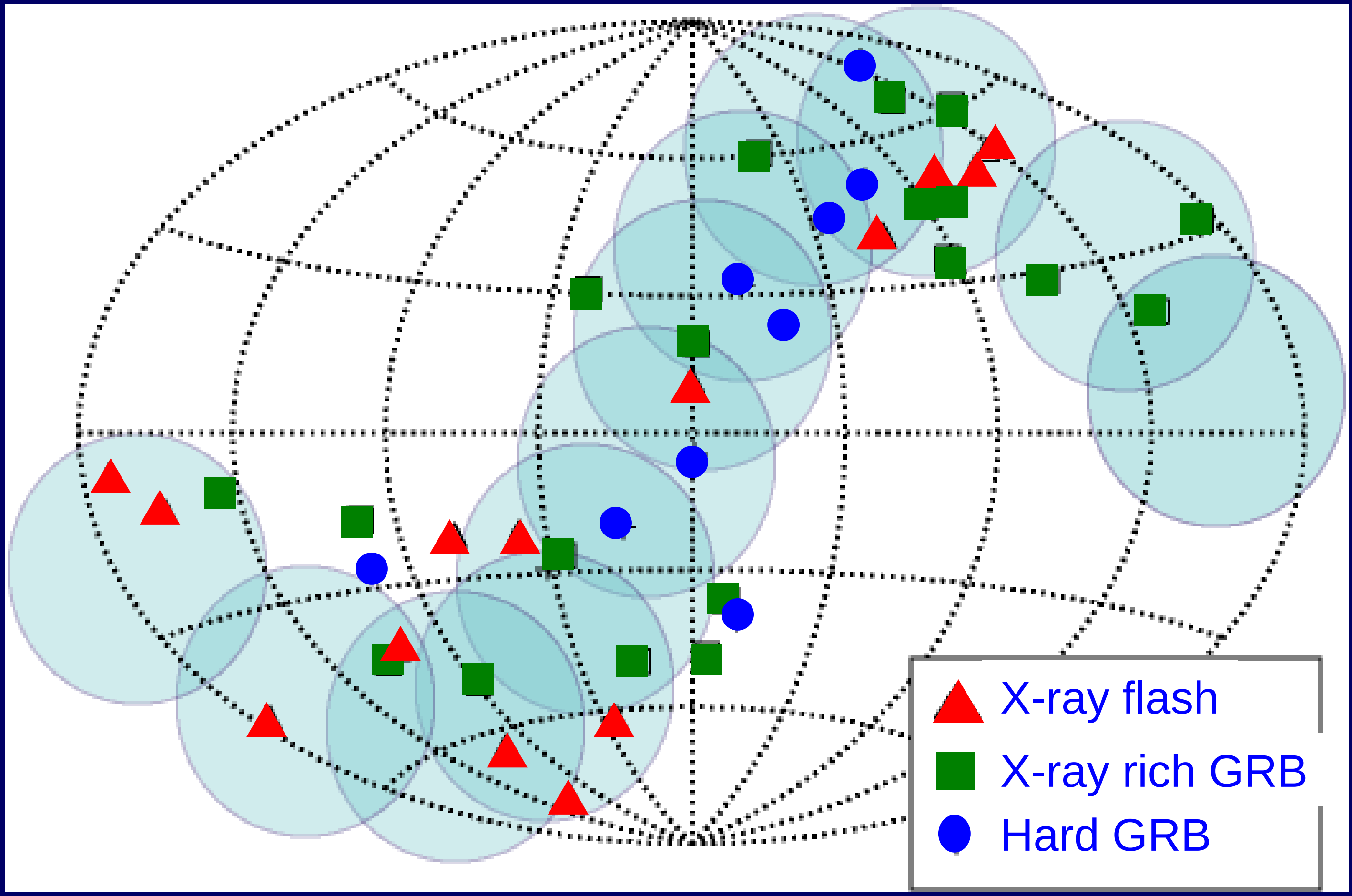


click

Summary (2)

- No boundaries between XRFs, XRRs, and hard GRBs.
- The E_{peak} energy seems to be distributed in much lower energy, unlike the BATSE E_{peak} distribution.
- $E_{peak} \propto$ time-average γ –ray flux
  $\propto \gamma$ –ray peak flux
- “Extended” Amati’s relation
  $E_{peak}^{src} \propto E_{iso}^{0.5}$ (from XRF to GRB)

Sky distribution of XRF/XRR/GRB



Sakamoto 2004

All GRBs are populated uniformly in the sky

Event rates of XRF/XRR/GRB

- February 2001 - September 2003
  - XRF: 15, XRR: 20, GRB: 10
- WXM HV on time
  - 1.1 years
- Field of view of WXM
  - $60^{O} \times 60^{O}$

XRF: 160 yr^{-1}
XRR: 220 yr^{-1}
GRB: 110 yr^{-1}

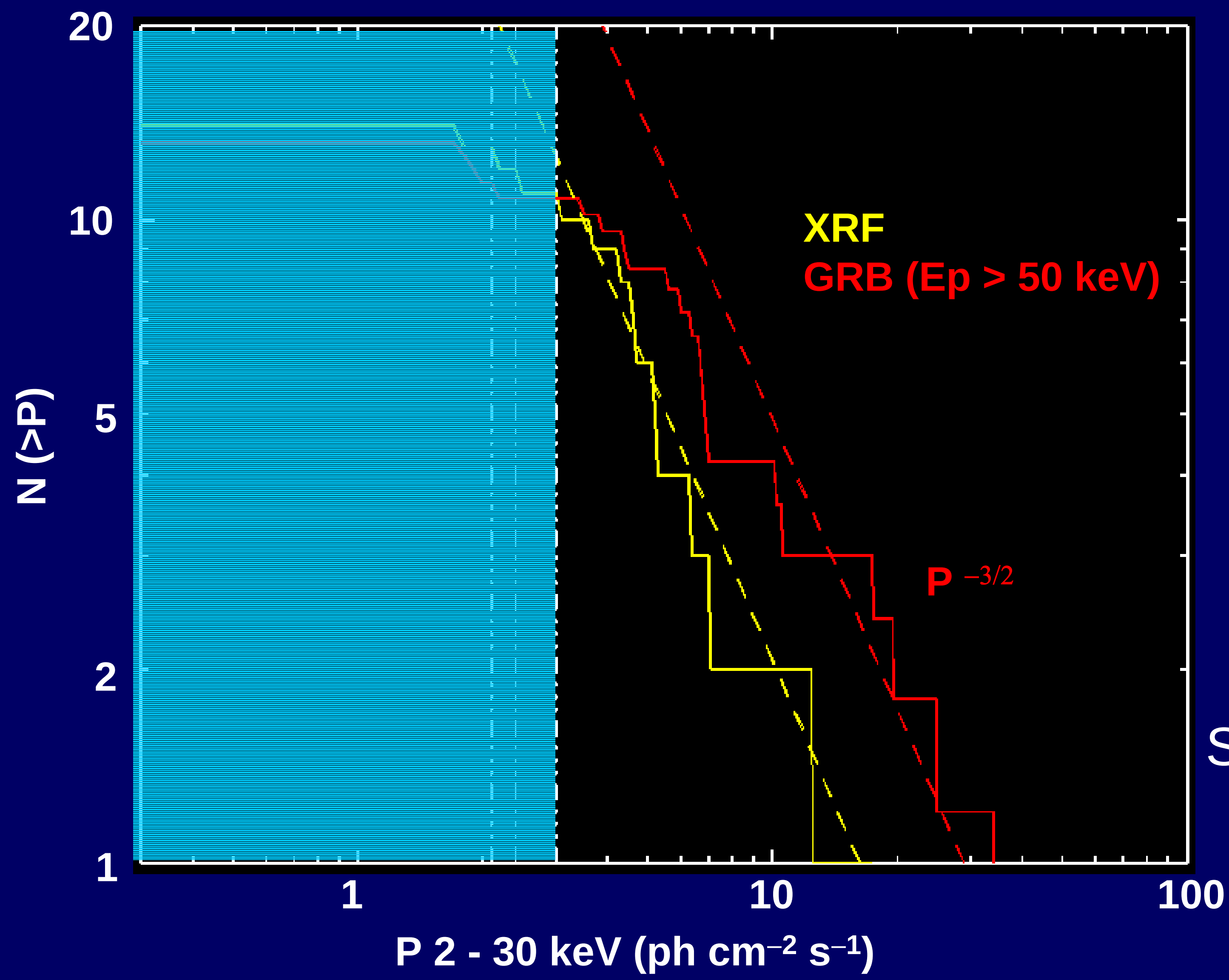
BeppoSAX XRFs: ~ 100 yr^{-1} (Heise et al. 2002)

Underestimation? …. HETE has better sensitivity for detecting XRFs

Event rates of each GRBs XRF ~ XRR ~ GRB

$$\text{XRF} \sim \text{GRB} \sim \frac{1}{3}\text{All GRBs}$$

Distance scale of XRFs

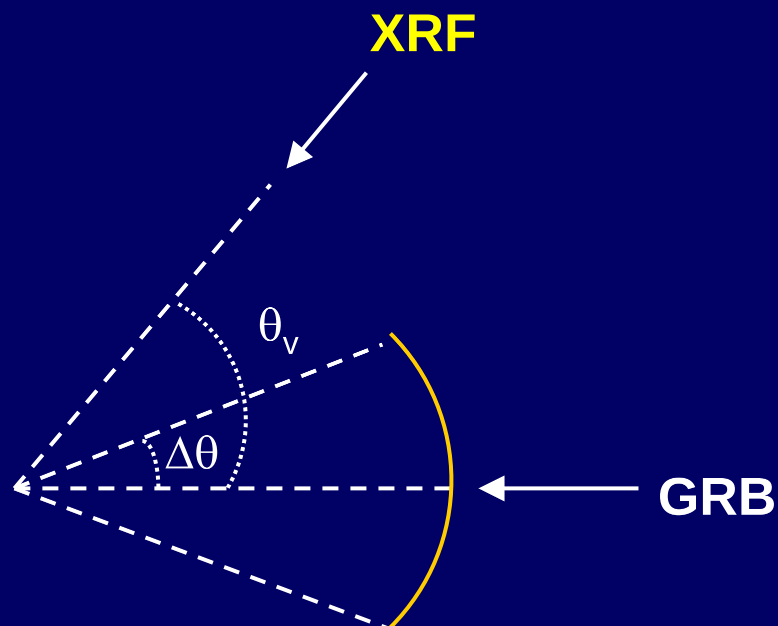


Sakamoto 2004

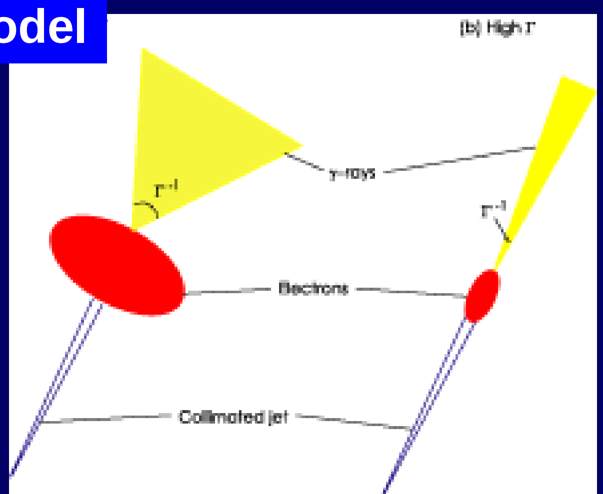
The **distance of XRFs** are close to the **Euclidean space.**

Theoretical models of XRFs

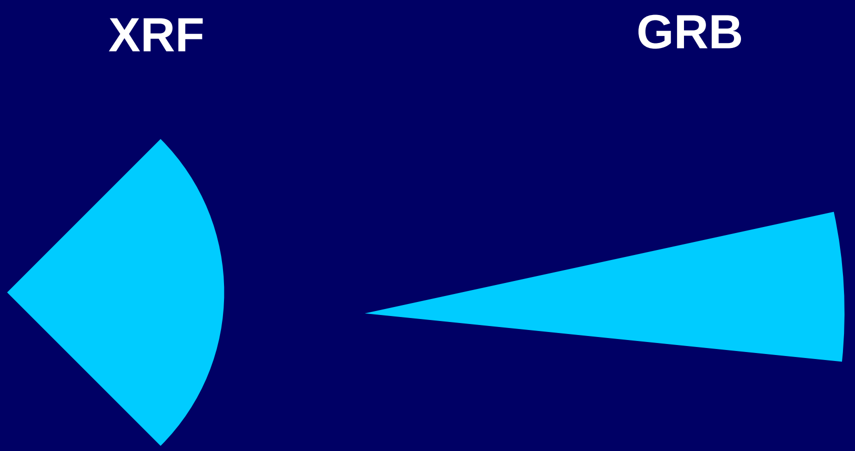
Off-axis jet model (Yamazaki et al.)



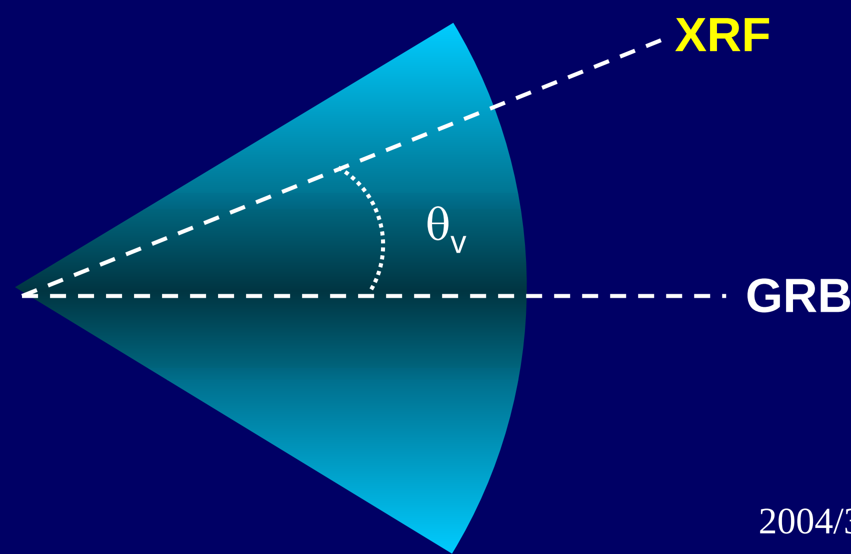
Beamed jet model



Unified jet model (Lamb et al.)



Structure jet model (Rossi et al.)



Conclusion

- XRFs/XRRs/GRBs form a continuum and are a single phenomenon (broad E_{peak} distribution).
- "Extended" Amati's relation will be a key for discussing the prompt emission of GRBs.

Future

We need larger sample of XRFs with the measurement of E_{peak} and redshifts.

E_{peak} of XRF	: X-ray detector
Redshift	: Rapid follow-up observation

The best solution will be…

HETE XRFs → Follow-up by Swift