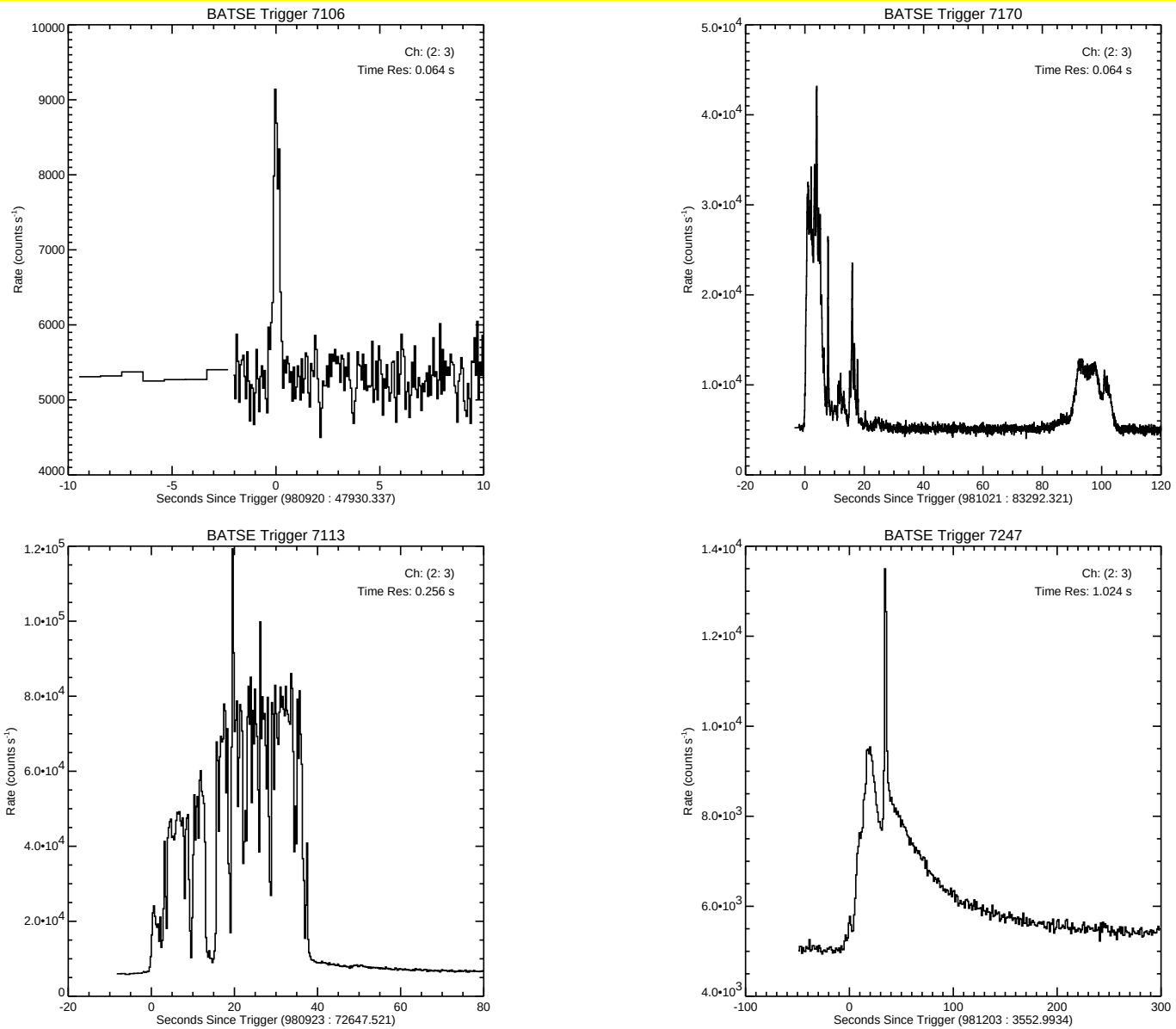
A Bit Of Gamma-Ray Bursts

Carlo Graziani

What Are Gamma-Ray Bursts?

- Bursts of gamma rays arrive at the Earth at a rate of about 1-2 per day.
- The arrival directions are uniform on the sky.
- The durations range from a few milliseconds to hundreds of seconds.
- The light curve morphologies are quite varied — some are smooth, some spiky and chaotic, some are composed of a single pulse, some have several episodes of emission.

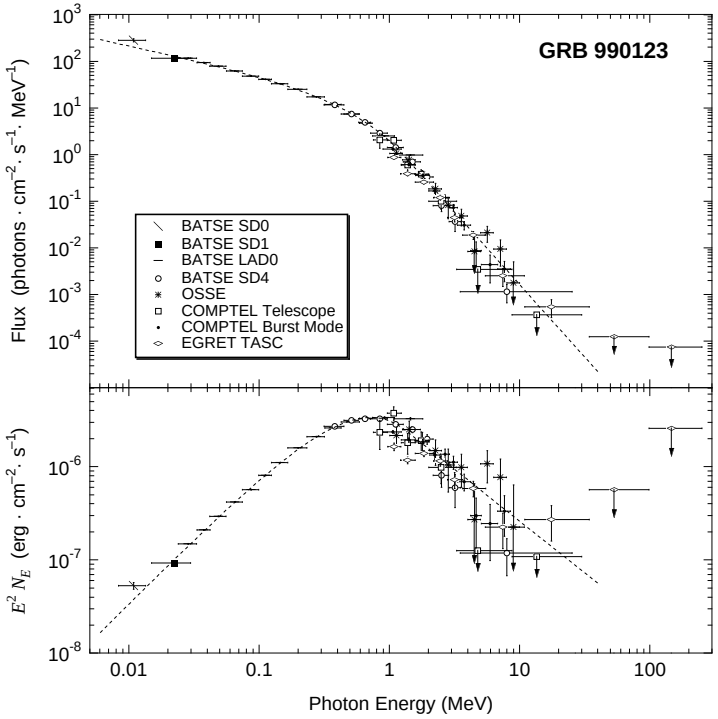
GRB Light Curves



Source: NASA/MSFC

http://www.batse.msfc.nasa.gov/

GRB Spectra



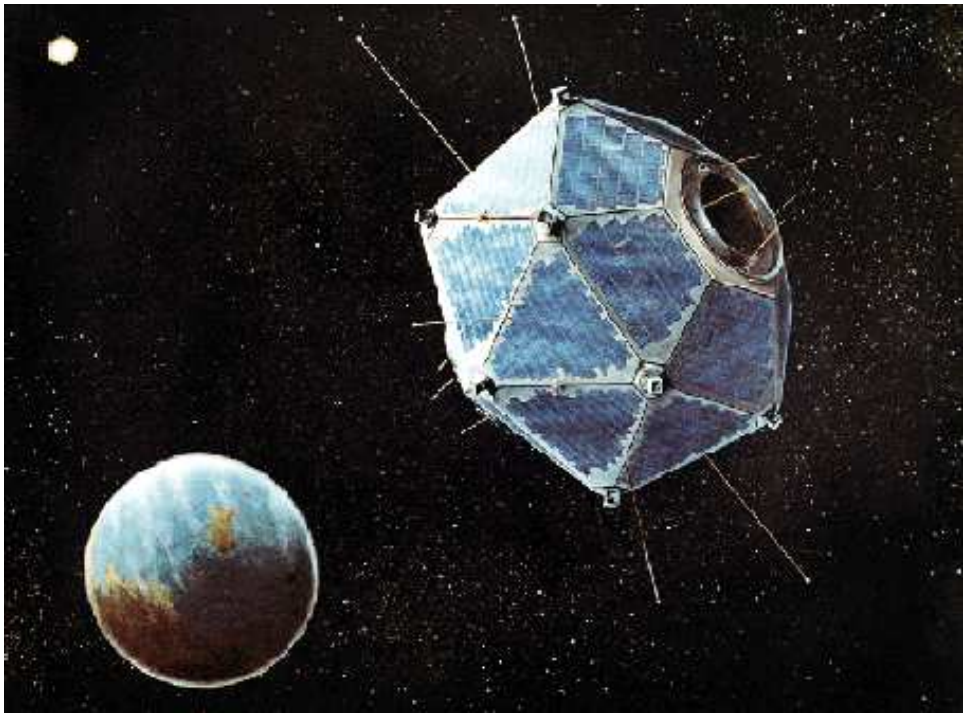
Source: Briggs et al. 1999

`http://xxx.lanl.gov/abs/astro-ph/9903247`

- The spectra are broad and non-thermal, peaking anywhere between 10 keV and 1 MeV, and extending well past 1 Mev.

A Brief History Of Gamma-Ray Bursts

- Between 1967 and 1973, the VELA treaty-monitoring satellites made a startling and unexpected observation: flashes of gamma-rays from deep space — Gamma-Ray Burst.



Source: HEASARC

(`http://antwrp.gsfc.nasa.gov/apod/ap951105.html`)

A Brief History Of Gamma-Ray Bursts

- The arrival directions of these bursts were determined by time-of-flight triangulation between widely-separated spacecraft, a technique now known as “Interplanetary Network” (IPN) location.
- In this manner, the VELA team found that the bursts were coming from random directions on the sky (and not, in fact, from the Earth, the Moon, or anywhere in the plane of the Ecliptic).

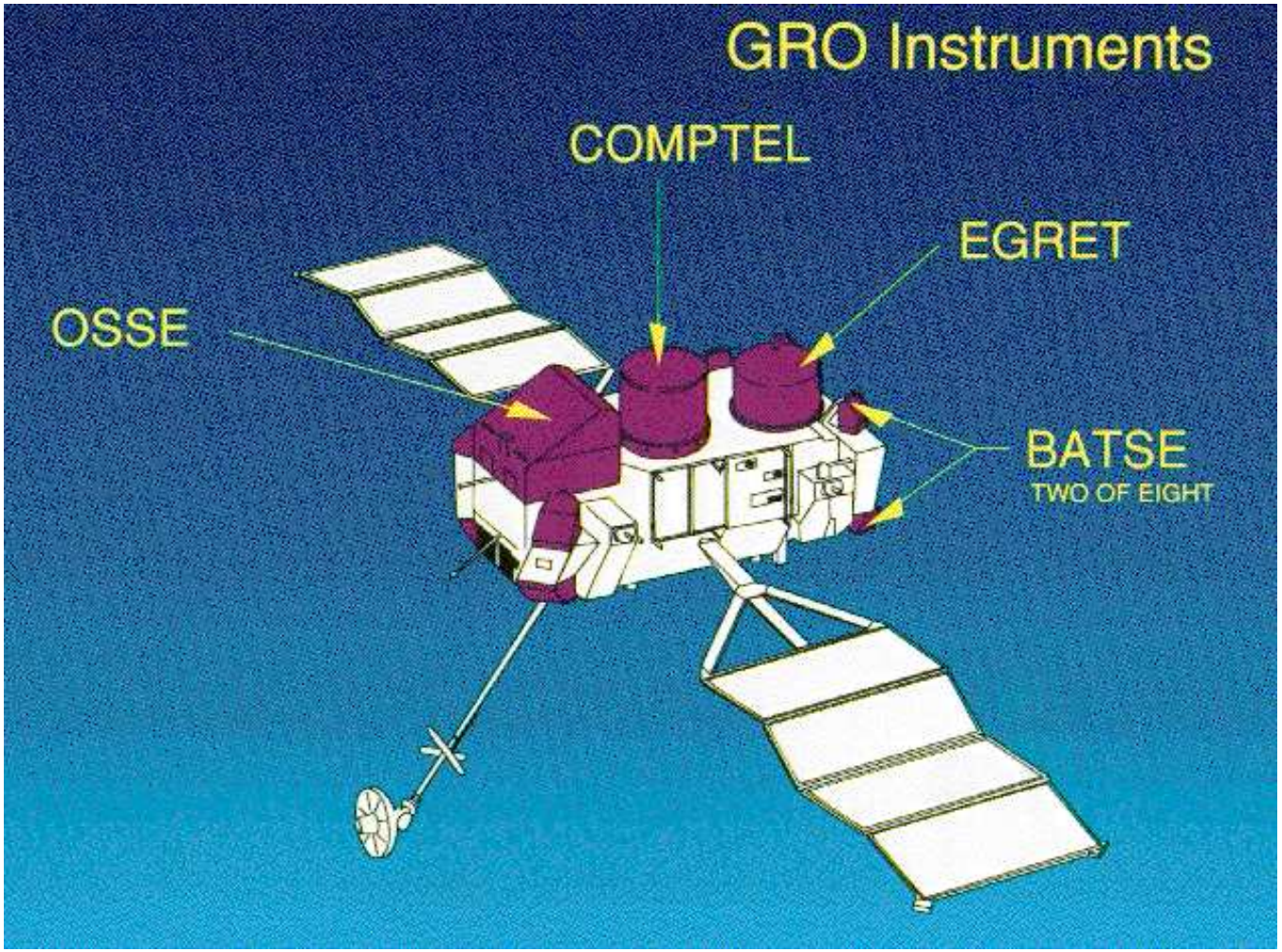
Slow Progress

- After the initial discovery, progress in understanding Gamma-Ray Bursts was very slow for about twenty years. During that time, the field was largely crippled by the technological difficulty of obtaining precise — and prompt — direction-of-arrival information for GRBs.
- No accurate — and timely — GRB locations meant no possibility of follow-up at other wavelengths, to attempt to observe the embers of the explosion. This in turn foreclosed the possibility of connecting the GRB phenomenon to other known astrophysical phenomena.
- As a consequence, researchers could not even agree on the distance scale to the sources (Galactic or Cosmological?), let alone the nature of the sources and physical mechanisms involved.

No Hosts

- Among the “facts” that everyone “knew” about GRBs up to the mid-1990’s was that when accurate locations were available (from IPN), no obvious source could be discerned in the error-box. This became known as the “No-Host” problem.
- We now understand this to be due to limitations in the available GRB location techniques:
  - IPN: Accurate ($< 1^\circ$), but long delays (many days).
  - BATSE: Prompt (minutes), but too inaccurate (many degrees).

BATSE



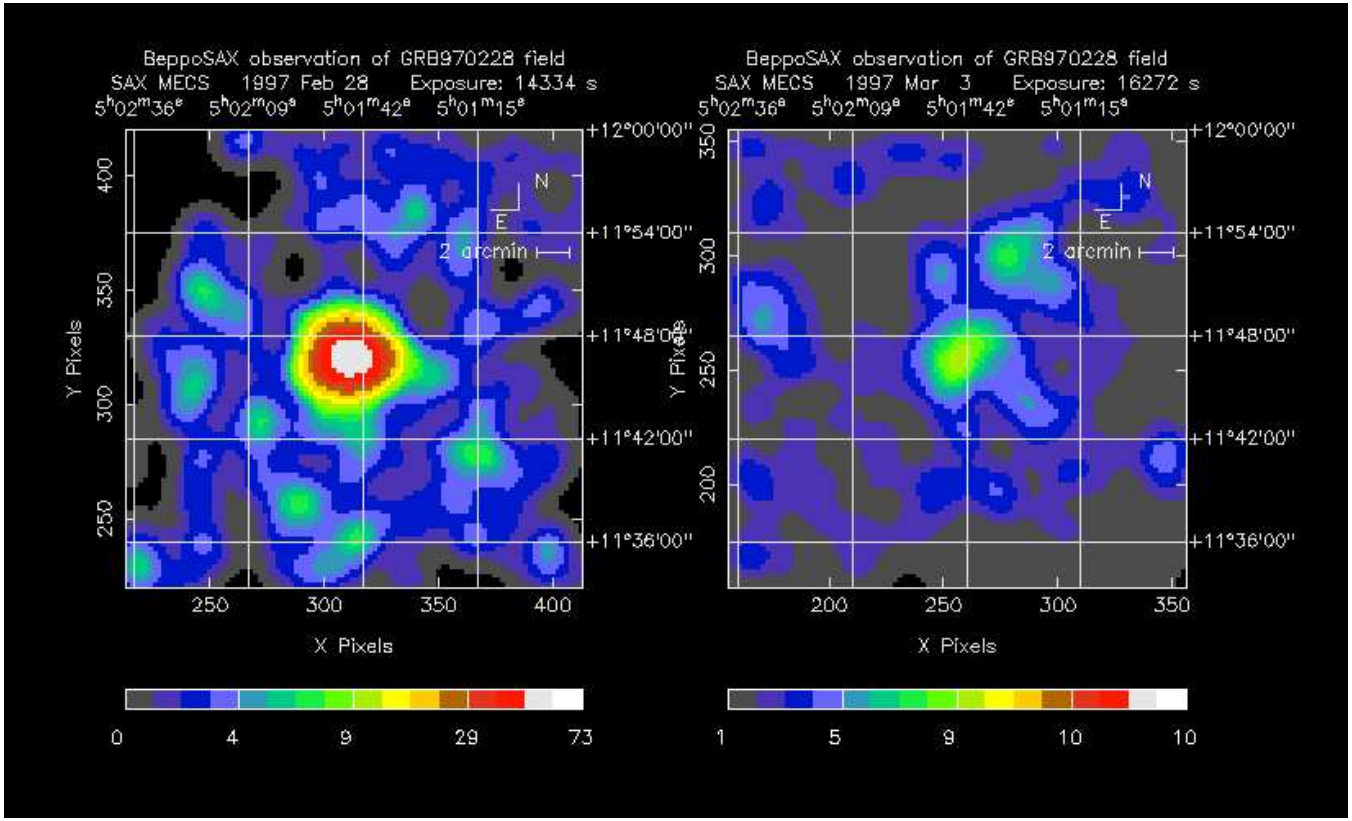
Source: COMPTON Science Support Center

(`http://cossc.gsfc.nasa.gov/images/cgro`)

The Breakthrough

- The field finally began to break open in 1997, after the launch of the BeppoSAX satellite.

GRB 970228

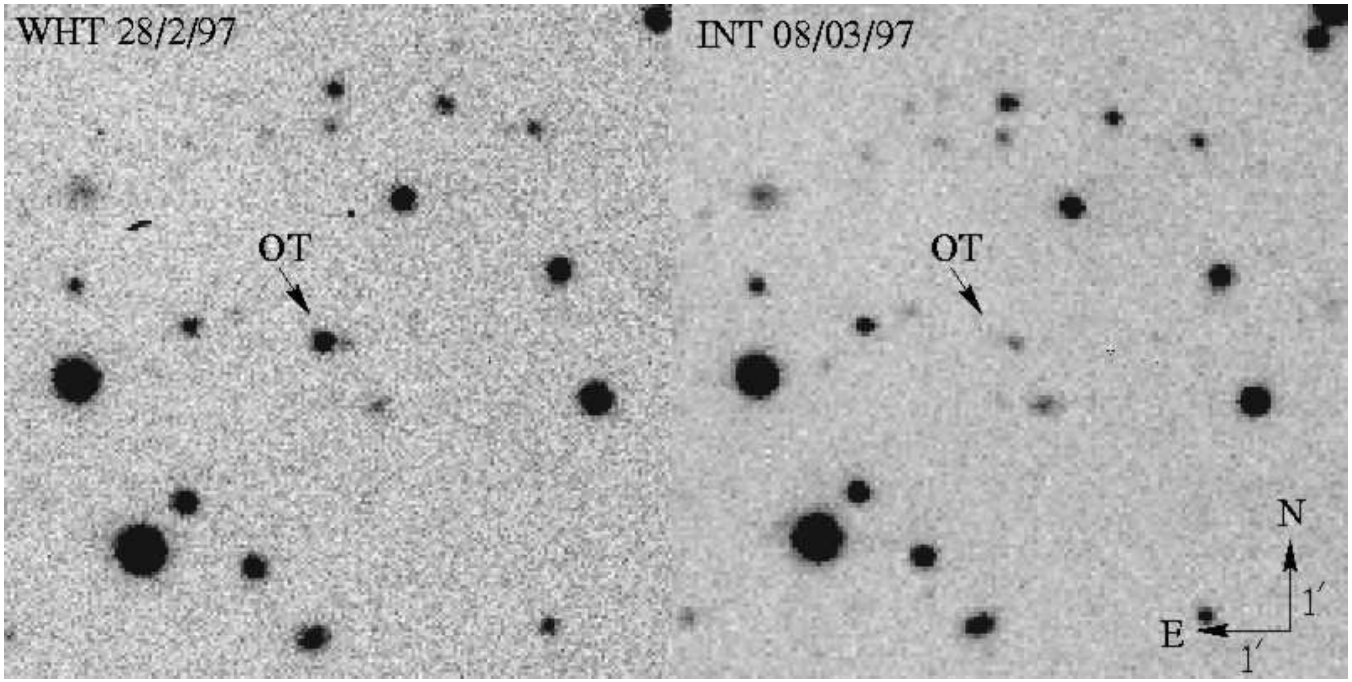


Source: BeppoSAX Science Data Center

(`http://www.asdc.asi.it/bepposax/first/grb970228.html`)

The Breakthrough — Cont'd

GRB 970228

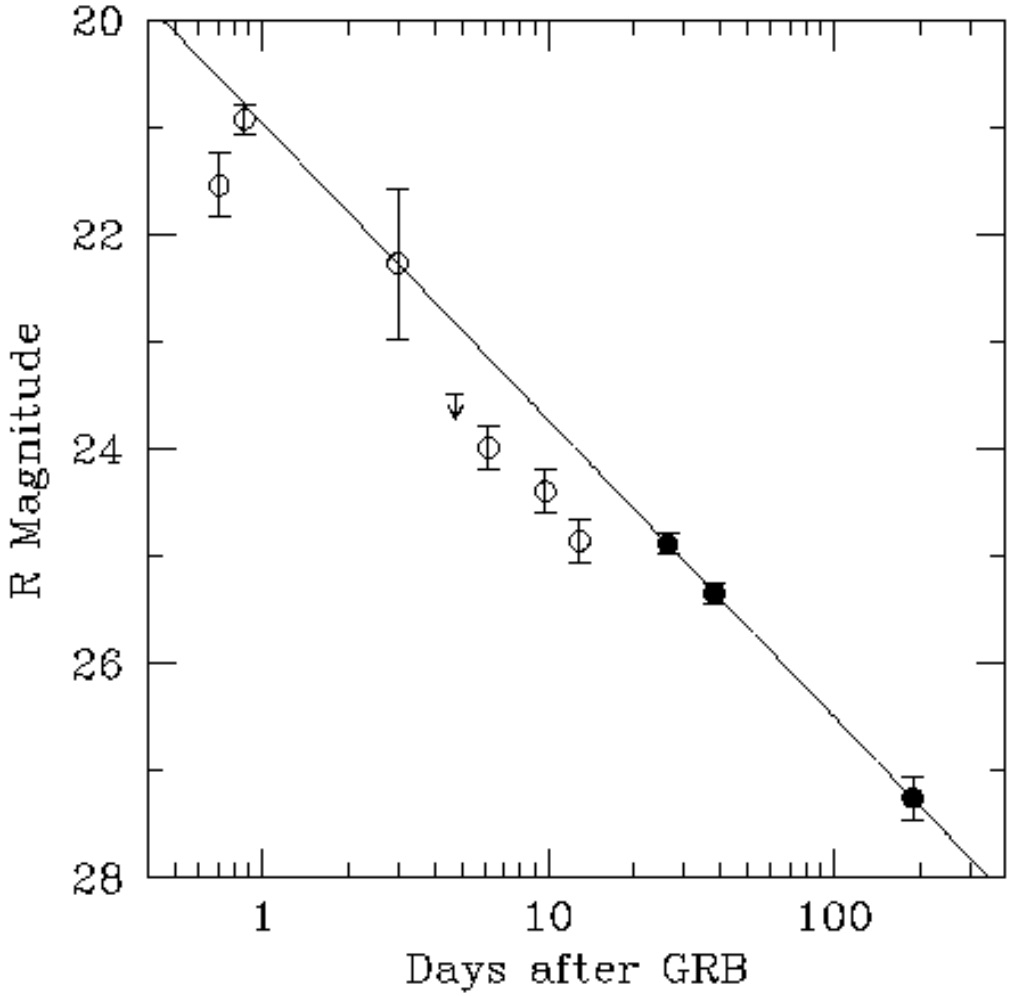


Source: Groot et al. 1997, IAUC 6584

(`http://www.mpe.mpg.de/ jcg/grb970228.html`)

The Breakthrough — Cont'd

GRB 970228

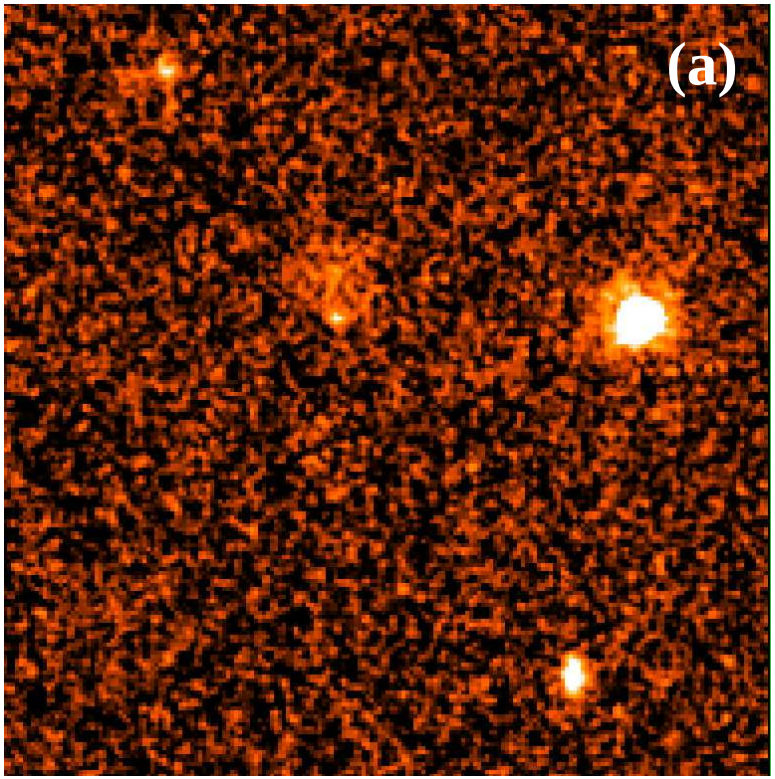


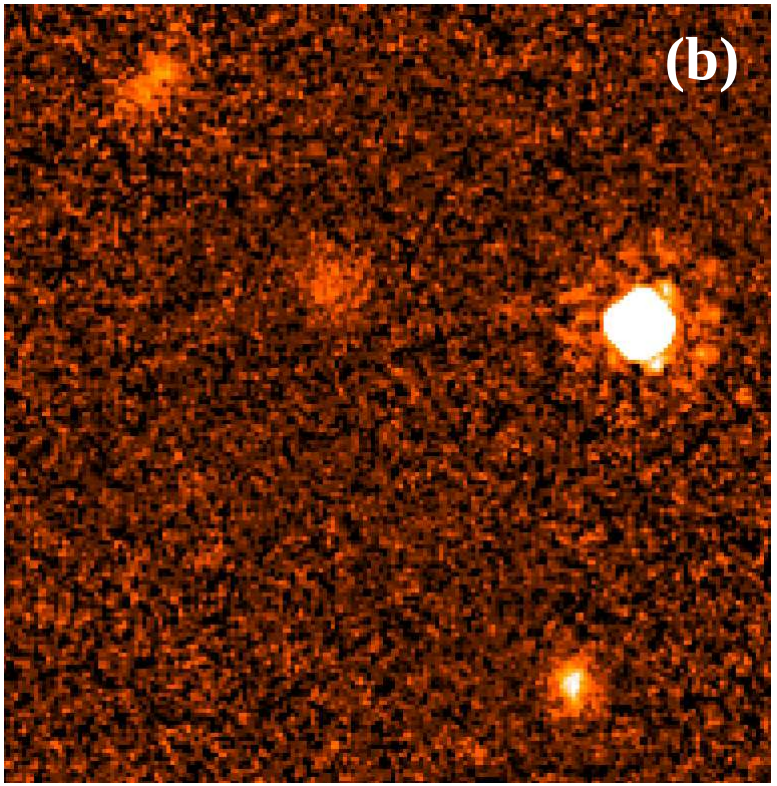
Source: Fruchter et al. 1998

(`http://xxx.lanl.gov/abs/astro-ph/9807295`)

The Breakthrough — Cont'd

GRB 970228





Source: Fruchter et al. 1998

(`http://xxx.lanl.gov/abs/astro-ph/9807295`)

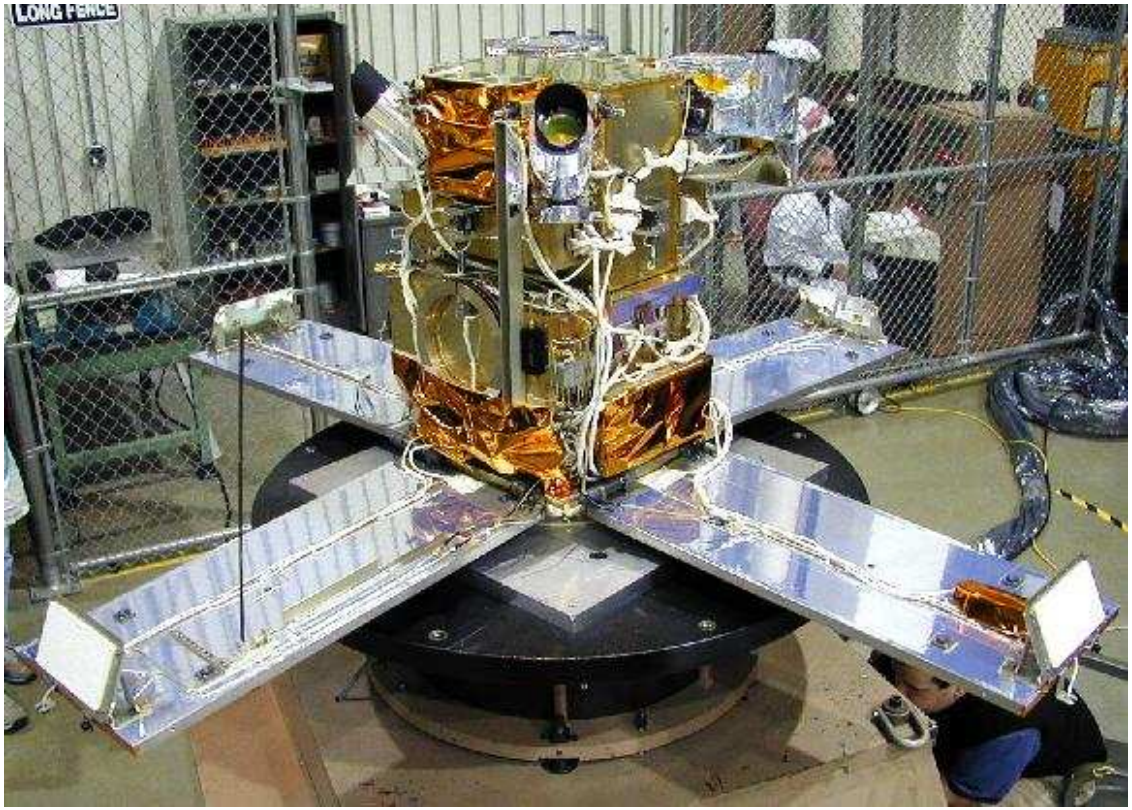
What Did We Learn From BeppoSAX?

- GRB sources are in distant ($z \sim 1$) galaxies.
- The sources are almost invariably in star-forming regions.

  $\Rightarrow$ Massive star collapse a likely culprit.
- Energetics and evolution of light curves (breaks) suggest collimated outflow.
- Further progress to be achieved by probing the accurate location – short delay regime. Specifically, the follow-up time required advancement, from T+hours to T+seconds.
  - Enter HETE.

HETE-2: The High-Energy Transient Explorer

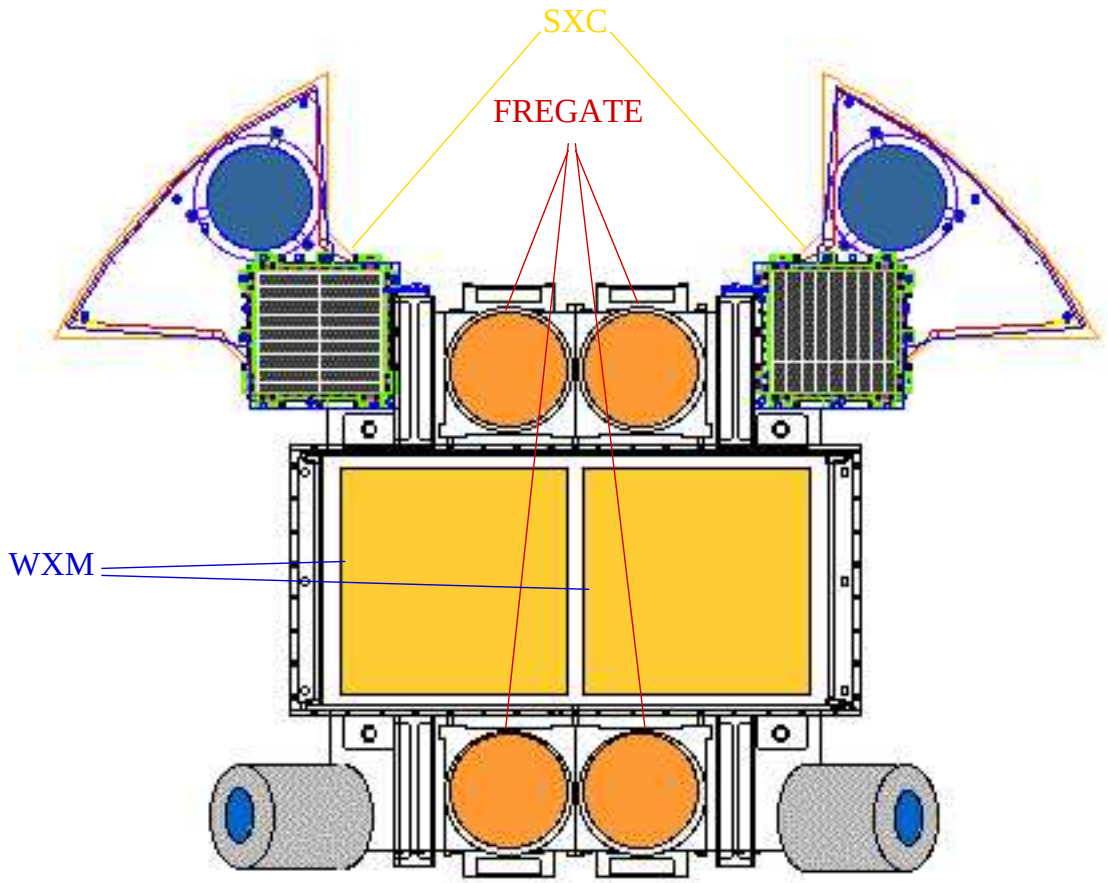
- Launched in October 2000, HETE-2 was designed to obtain GRB locations in real-time, and propagate them over the Internet to observatories around the world for prompt follow-up.



Source: HETE Home Page

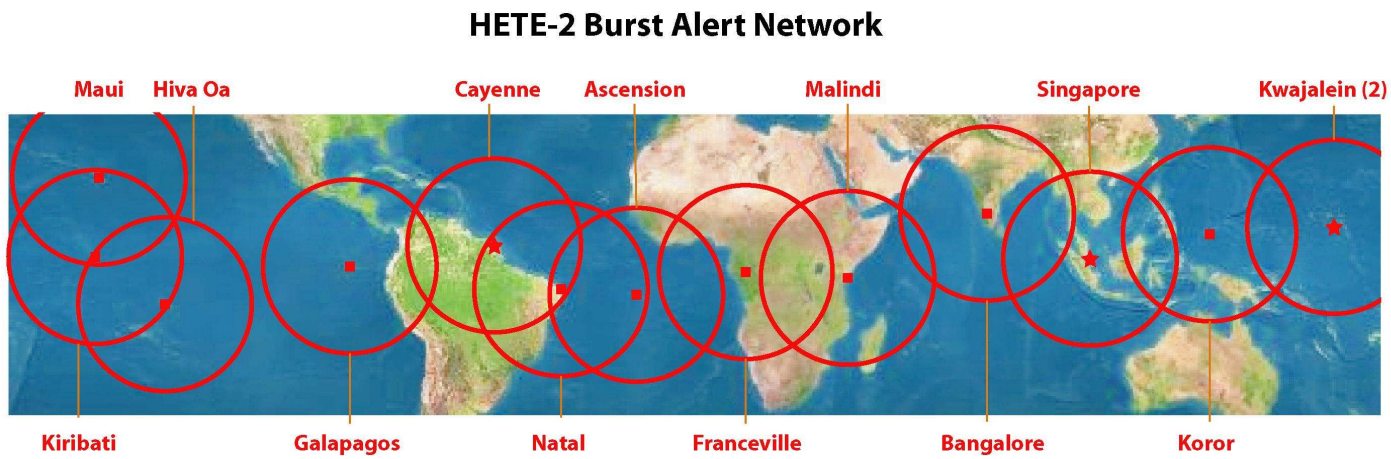
(`http://space.mit.edu/HETE/gallery.html`)

The HETE-2 Instruments



- FREGATE energy response: 6-400 keV
- WXM location accuracy: 5-20 Arcminutes
- SXC location accuracy: 1-2 Arcminutes

The Ground Station Network



- Three Primary Ground Stations (PGSs) for high-bandwidth data download and spacecraft commanding.
- Net of 15 low-bandwidth Secondary Ground Stations (SGSs) ring the globe.
- SGSs relay Burst Alerts to Ops Center at MIT, where they are sent on to the GRB Coordinates Network (GCN) system at Goddard. Observers who subscribe to the GCN can get Notices within tens of seconds of a GRB trigger.

The VHF Console

```
GPS time 779993285.810 [20040923_164752], ORBIT DAY, TT=9.4, Kwaj-PGS [31]
Location: Long=173.0 deg W, Lat=1.7 deg N, Alt=564.5 km, Orbit phase=0.72
SC:       M0 Tx 2-off CM-2 Free-55 Pri-00
          NC = 0019 A26B 7049 5058
          MS = 5189 TIN71 RZP0 SEQ0 NODES = 7775 LINKS = FFFF
          MM  3145.0   215.5  3161.0  3639.0 kB
          Bus = 31.252V ppt0 =  2.524A ppt1 =  3.073A
          Cur =  3.476A pscF = 0000  Charge = 86.69%
          SP.. RFon SAXon MWDon TCDon GPSon IPSon
          HTR... FGTon WXMonHV  SXC.. OPTon RBMon
          ACS mode8 s_hat(0.0049 0.0044 1.0000)
          whl(94.04) omega(-0.58 0.53 0.55) '/s
gamma:    MODESURVEY, burst #36
          U 2, msg 2854; 1598, 633 cts/5s; seuil4 = 78
          U 3, msg 2855; 1516, 650 cts/5s; seuil5 = 20
WXM:      standard vhf diagnostics        mode is 0x0007  ON_PORTC_HV
          SSI IRQs: 9165
          voltage -- State: 0x8c   HVA: 216    HVB: 214
          LAST_CMD: 0x50d7
          COUNTS -- XA:   128   XB:   155   YA:   125   YB:     0
sxc:      idle
opt:      running n51, next idle
          state:  OV=4,0 OB=3,9 AS=4,15 DR=3,3
          HK error flag = 0x0000
          CTEMPS = -41C, -46C
          Star word = 0xf070
          RA, dec, roll = 182.962 -0.906 46.358
          Latest sync ends (lower 8 bits):  241 241
gps-status: 406084.375 s gdop: 0.00 Val: (ok) 80 00 85 00
gps-SatId:      1     3    11    16    19    20    25     0
gps-State:      4     4     4     4     4     4     4     0
gps-C/N:    32.75 37.75 38.75 35.25 33.75 37.00 32.75  0.00
gps-hk: vco 6.835 agc 3.320 ref 1.230 temp 35.0 C (!ETX)
TM:       active, next burst ID 3564
          gamma UP, wxm UP, sxc down, opt UP

GPS time 779993299.966 [20040923_164806], ORBIT DAY, TT=12.6, Kwaj-PGS [31]
Location: Long=172.2 deg W, Lat=1.7 deg N, Alt=564.6 km, Orbit phase=0.73
SC:       M2 Tx 2-off CM-2 Free-55 Pri-00
          NC = 0019 A26B 7049 5058
          MS = 5189 TIN71 RZP0 SEQ0 NODES = 7775 LINKS = FFFF
          MM  3153.0   215.5  3170.5  3653.5 kB
          Bus = 31.311V ppt0 =  2.530A ppt1 =  3.056A
          Cur =  3.446A pscF = 0000  Charge = 86.81%
          SP.. RFon SAXon MWDon TCDon GPSon IPSon
          HTR... FGTon WXMonHV  SXC.. OPTon RBMon
          ACS mode8 s_hat(0.0054 0.0039 1.0000)
          whl(94.04) omega(-1.04 0.38 2.95) '/s
gamma:    MODESURVEY, burst #36
          U 0, msg 2856; 1467, 632 cts/5s; seuil6 = 504
          U 1, msg 2857; 1511, 664 cts/5s; +15V = 424
WXM:      standard vhf diagnostics        mode is 0x0007  ON_PORTC_HV
          SSI IRQs: 9198
          voltage -- State: 0x8c   HVA: 216    HVB: 214
          LAST_CMD: 0x50d7
          COUNTS -- XA:   124   XB:   112   YA:   137   YB:     0
sxc:      idle
opt:      running n51, next idle
          state:  OV=4,0 OB=3,9 AS=4,15 DR=3,2
          HK error flag = 0x0000
          CTEMPS = -41C, -46C
          Star word = 0xf090
          RA, dec, roll = 182.956 -0.895 46.304
```

Normal State

```
GPS time 700424146.035 [20020317_181533], ORBIT NIGHT, TT=N/A, Palau [31]
Location: Long=127.1 deg E, Lat=1.9 deg S, Alt=594.0 km, Orbit phase=0.61

************ BEEP **************

burst!    in progress, ID = 1959, GAMMA triggered
          Trigger time = 700424144.429152 [20020317_181531.429]
          Long=127.0 deg E, Lat=1.9 deg S, alt=593 km, orbit NIGHT, phase=0.61
          Running:        gamma YES, wxm YES, sxc YES, opt  NO
          Responded:      gamma YES, wxm  NO, sxc  NO, opt  NO
          TI=1.3s, BE=5-120 keV, DC=2+3, pS=0, pG=0, pX=5, cts=557

GPS time 700424147.018 [20020317_181534], ORBIT NIGHT, TT=N/A, Palau [31]
Location: Long=127.2 deg E, Lat=1.9 deg S, Alt=594.0 km, Orbit phase=0.61

************ BEEP **************

burst!    in progress, ID = 1959, GAMMA triggered
          Trigger time = 700424144.429152 [20020317_181531.429]
          Long=127.0 deg E, Lat=1.9 deg S, alt=593 km, orbit NIGHT, phase=0.61
          Running:        gamma YES, wxm YES, sxc YES, opt  NO
          Responded:      gamma YES, wxm  NO, sxc  NO, opt  NO
          TI=1.3s, BE=5-120 keV, DC=2+3, pS=0, pG=0, pX=5, cts=557
          SXC full localization is 132 658, S/N 1.6 0.9
          SXC region localization is 1679 1668, S/N 0.3 0.2

GPS time 700424147.739 [20020317_181534], ORBIT NIGHT, TT=N/A, Palau [31]
Location: Long=127.2 deg E, Lat=1.9 deg S, Alt=594.0 km, Orbit phase=0.61

************ BEEP **************

burst!    in progress, ID = 1959, GAMMA triggered
          Trigger time = 700424144.429152 [20020317_181531.429]
          Long=127.0 deg E, Lat=1.9 deg S, alt=593 km, orbit NIGHT, phase=0.61
          Running:        gamma YES, wxm YES, sxc YES, opt YES
          Responded:      gamma YES, wxm  NO, sxc  NO, opt  NO
          TI=1.3s, BE=5-120 keV, DC=2+3, pS=0, pG=0, pX=5, cts=557
          SXC full localization is 132 658, S/N 1.6 0.9
          SXC region localization is 1679 1668, S/N 0.3 0.2
          OPT bitmap is 0x800a, RA, dec, roll are 355.909 -1.560 170.190

GPS time 700424150.622 [20020317_181537], ORBIT NIGHT, TT=N/A, Palau [31]
Location: Long=127.4 deg E, Lat=1.9 deg S, Alt=594.1 km, Orbit phase=0.61

************ BEEP **************

burst!    in progress, ID = 1959, GAMMA triggered
          Trigger time = 700424144.429152 [20020317_181531.429]
          Long=127.0 deg E, Lat=1.9 deg S, alt=593 km, orbit NIGHT, phase=0.61
          Running:        gamma YES, wxm YES, sxc YES, opt YES
          Responded:      gamma YES, wxm YES, sxc  NO, opt  NO
          TI=1.3s, BE=5-120 keV, DC=2+3, pS=0, pG=0, pX=5, cts=557
          WXM flag 0, no trigger with S/N>3 found [0]
          WXM position (-0.3022 0.2574) goodness (2.0,3.2) virtue (6.8,3.0)
          SXC full localization is 132 658, S/N 1.6 0.9
          SXC region localization is 1638 430, S/N 0.1 0.6
          OPT bitmap is 0x800a, RA, dec, roll are 355.909 -1.560 170.190

GPS time 700424151.999 [20020317_181538], ORBIT NIGHT, TT=N/A, Palau [31]
Location: Long=127.4 deg E, Lat=1.9 deg S, Alt=594.1 km, Orbit phase=0.61
```

Burst Alert!

3.75 Years Of HETE: Summary

- HETE has localized 70 GRBs in 3.75 yrs of operation.
- 26 of these localizations have led to the detection of X-ray, optical, or radio afterglows.
- As of today, redshifts have been reported for 14 of these afterglows.

A Typical HETE GRB Trigger

- *T=0:* One of the on-board instruments detects a sudden change in the count rate, and declares a trigger.
- *T=1-10 sec:* VHF messages are relayed through the Secondary Ground Station (SGS) network to the operations center at MIT. HETE Science team members receive automatic beeper alerts. An automatic alert also goes to the Gamma-Ray Burst Coordinate Network (GCN), at NASA/Goddard Space Flight Center in Maryland. This alert is propagated over the Internet to interested parties at observatories around the World.

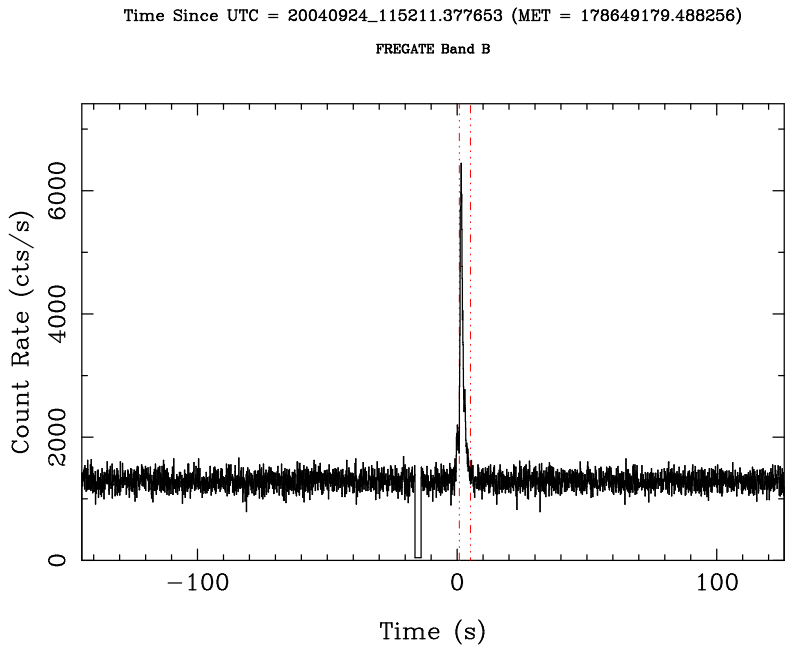
A Typical HETE GRB Trigger — Cont'd

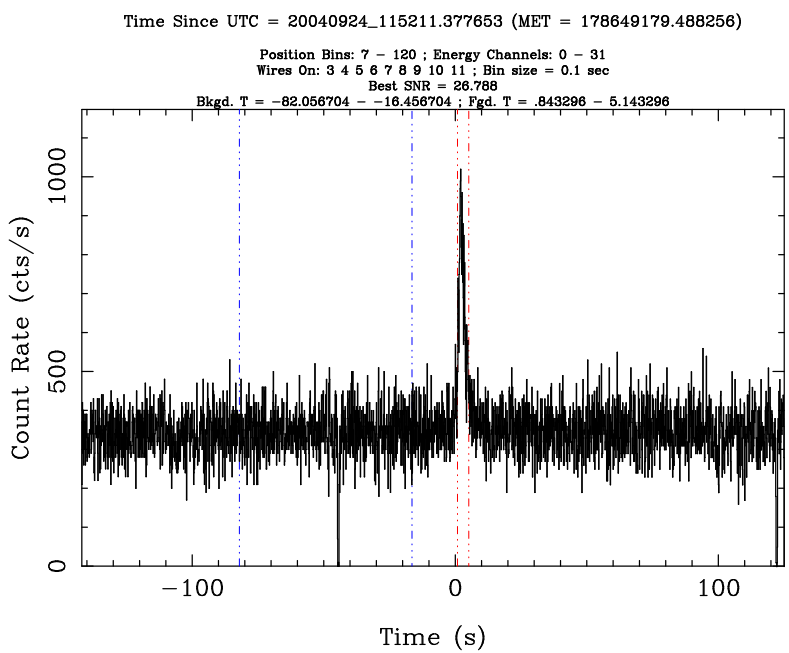
- *T=5-60 sec:* Meantime, back on the spacecraft, WXM is attempting to obtain a location for the GRB. It will do this repeatedly, attempting to improve the location accuracy by selecting better and better stretches of data. Each location is relayed to the ground through the SGS net, then to MIT. If it meets certain quality criteria, it will be forwarded on to the GCN, and to astronomical observatories.
- *T=1-5 minutes:* The Science Team gathers on the Internet, using `hchat`, a special purpose HETE chat room, to communicate. We make preliminary assessments about the event on the basis of information transmitted over VHF.

A Typical HETE GRB Trigger — Cont'd

- *T∼10-40 minutes:* HETE passes over one of it's three Primary Ground Stations (PGS) and sends high-resolution Burst data products to the ground. These are relayed to MIT for further analysis.
- *T∼15-50 minutes:* The data is processed by the automatic Burst Data Processing Pipeline at MIT. If the event is a GRB its location is refined, if possible. Lots of files are examined by lots of people, and `hchat` gets very busy as various analysts share the results.
- *T∼40 minutes - 8 hours:* The data may be subjected to various special-purpose, non-automatic analyses, in order to understand better the nature of the event and to refine the location coordinates. If refined locations based on ground analysis are obtained, they are disseminated over the Internet.

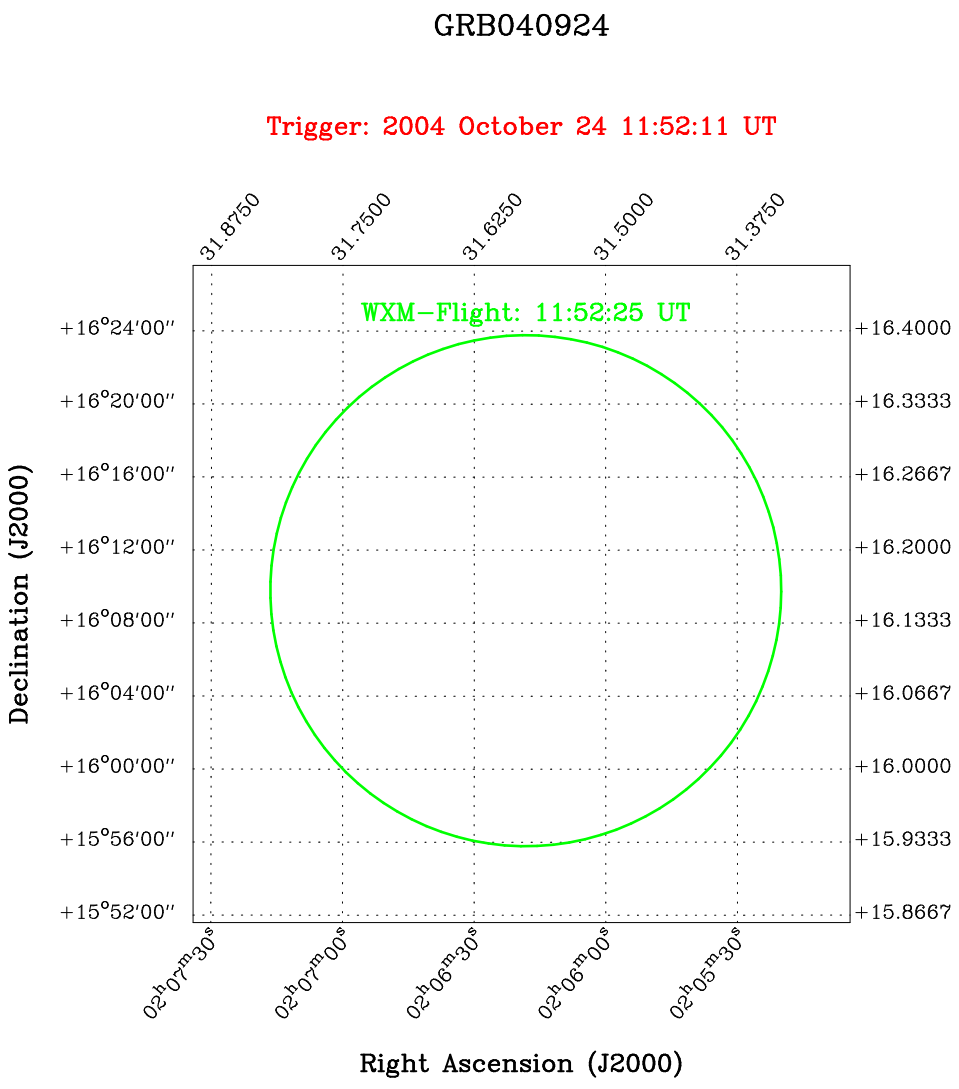
This Morning(!)



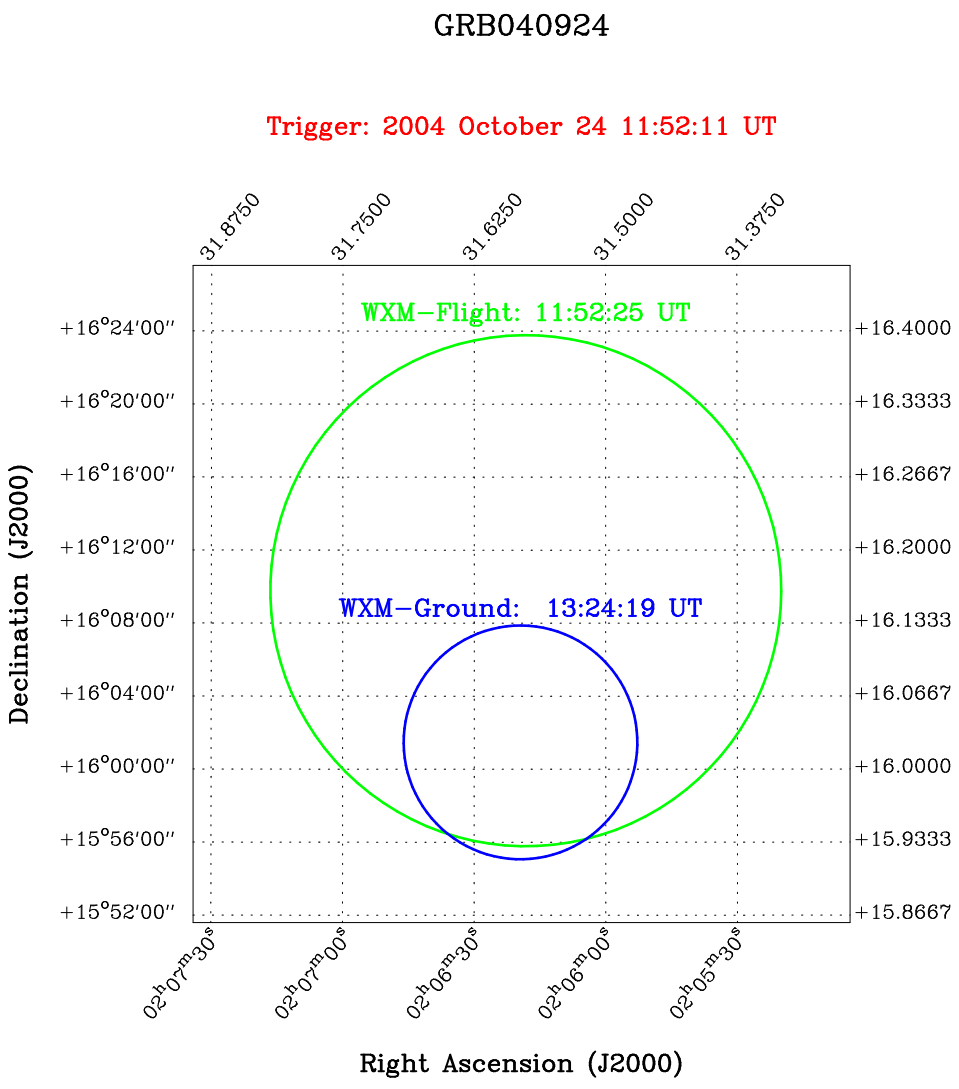


- Trigger in FREGATE Band B (6-80 keV).
- Trigger time: 11:52:11 UT (6:52 CDT)
- Location distributed at 11:52:25 UT (T + 14s).

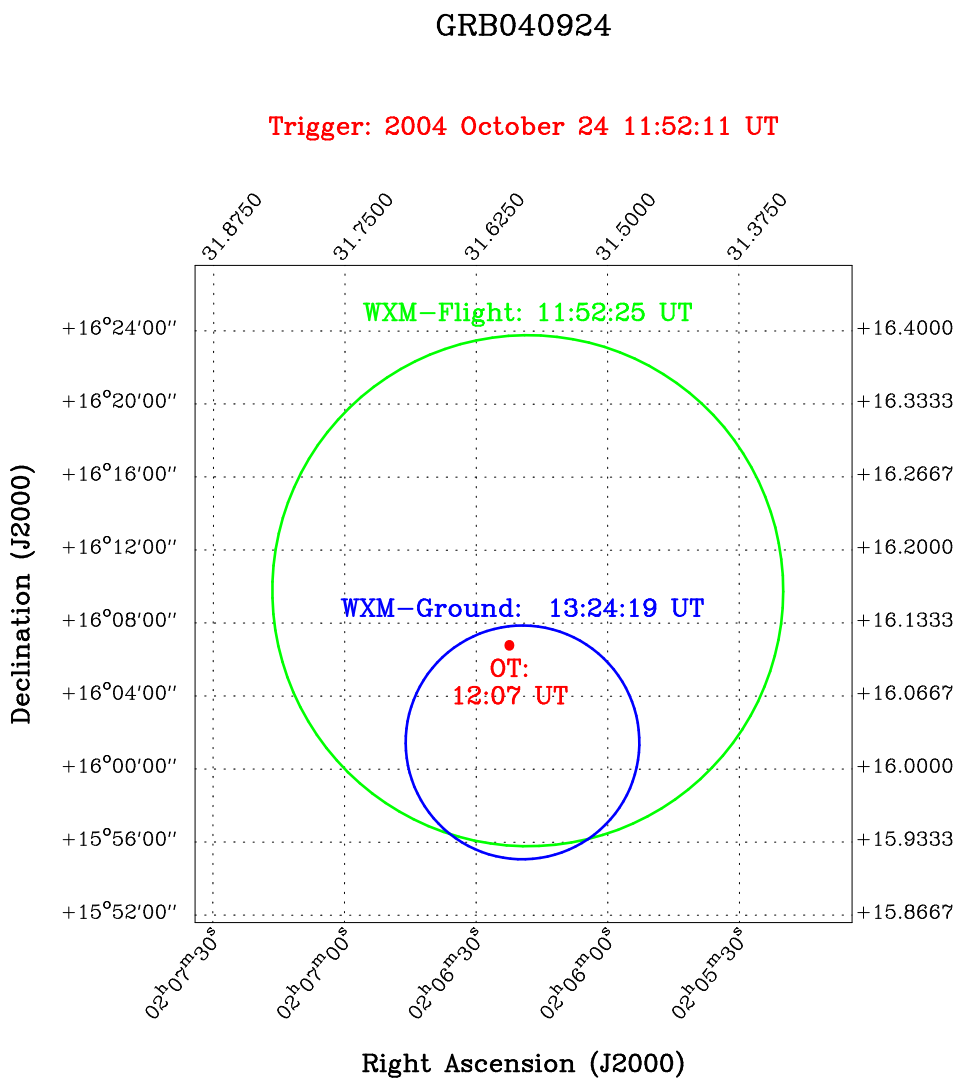
This Morning — Cont'd



This Morning — Cont'd

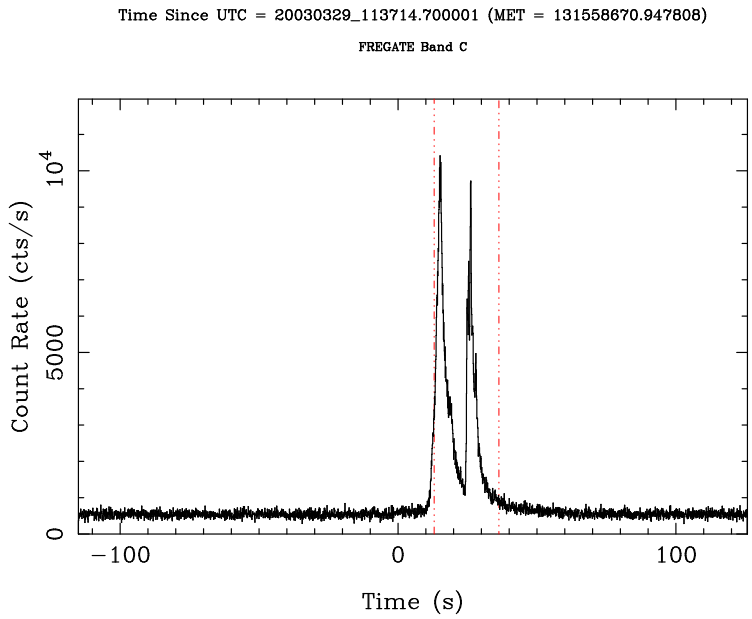


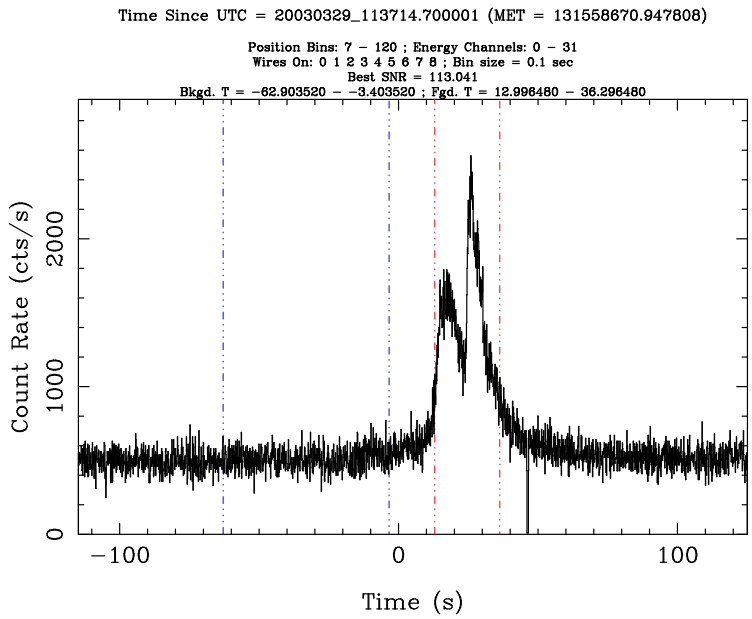
This Morning — Cont'd



- D.Fox & D. Moon: R-magnitude ~ 17 at T + 15min (GCN 2734).

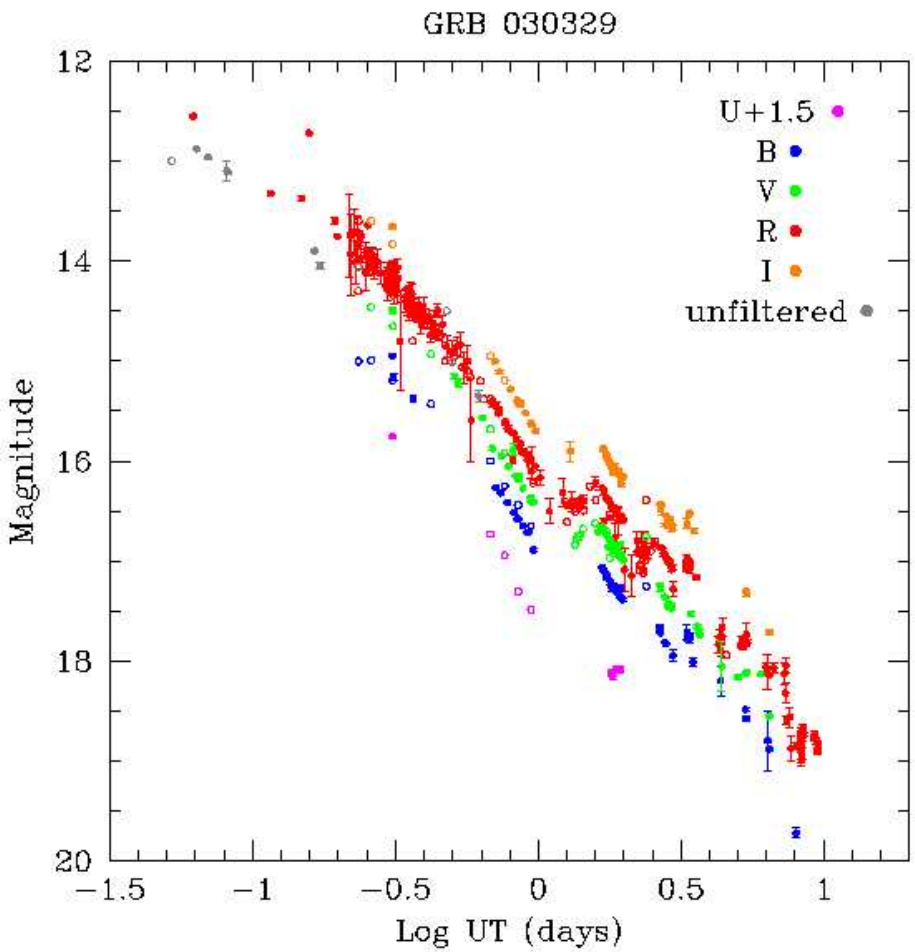
The GRB Rosetta Stone: GRB 030329





- Brightest GRB seen by HETE (by a long shot!), in BATSEs top 4.
- Optical afterglow detected at an R=13(!), 75minutes after the GRB.
- Redshift measured from H emission lines in spectrum: z=0.1685, second-closest GRB afterglow yet observed, after GRB980425.

GRB 030329 — Cont'd

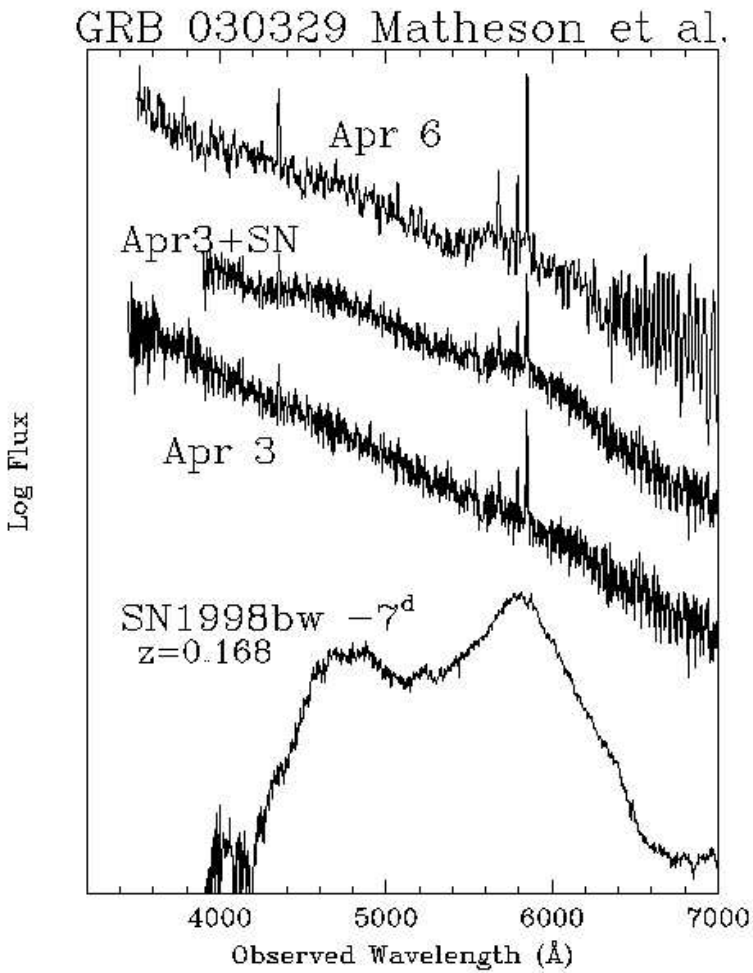


- Collected light curve (Zeh et al., GCN 2047) shows persistently bright afterglow. R=19 ten days after the burst!
- "Jet Break" after a few hours followed by two mysterious periods of re-brightening.

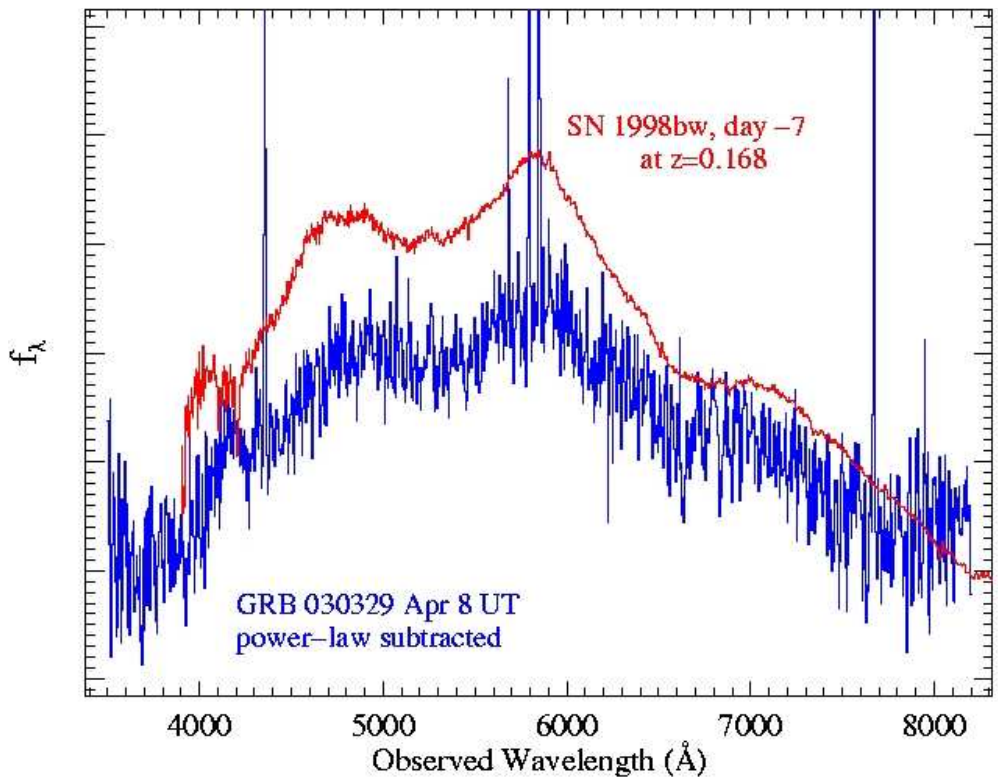
Source: Zeh et al. GCN 2047

(`http://www.mpe.mpg.de/~jcg/grb030329.html`)

GRB 030329 — Cont'd



- A Type Ib-Ic Supernove spectrum emerges from the featureless afterglow spectrum at T+8 days!



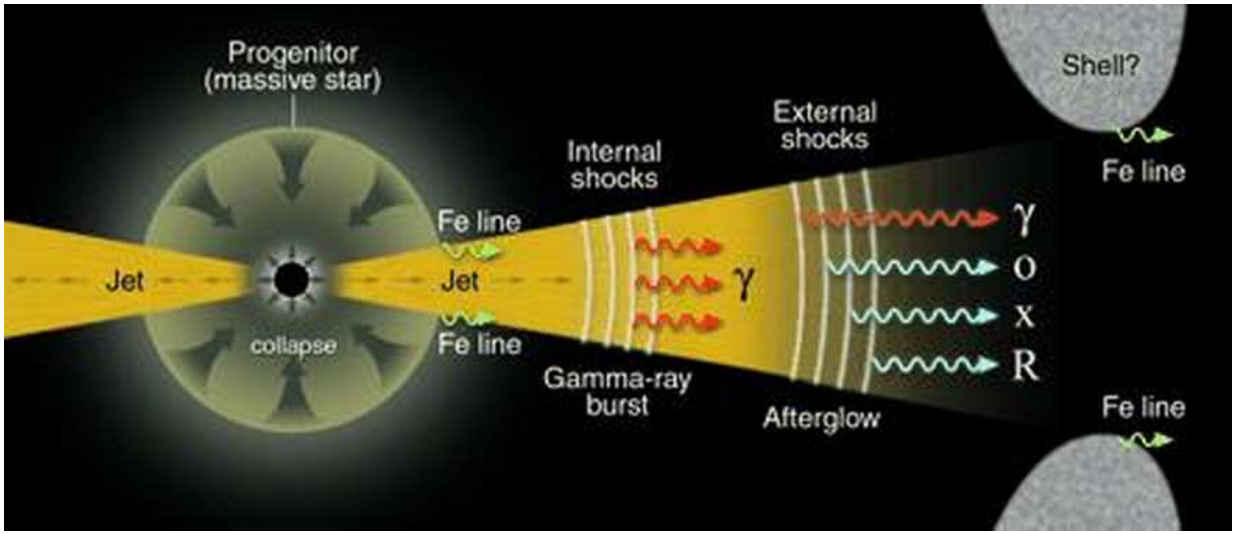
Source: Matheson et al. GCN 2107 & 2120

(`http://www.mpe.mpg.de/~jcg/grb030329.html`)

What We Learned From GRB 030329

- The GRB – SN connection is observationally confirmed!
- Implications:
  - We need to understand Type Ib/Ic core collapse SNe in order to understand GRBs.
  - Conversely, we need to 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 cosmology and the early universe.

What Are GRBs?



Source: P. Meszaros

- A massive, probably rotating, possibly magnetized star undergoes gravitational collapse.
- A highly collimated relativistic jet blasts away.
- Prompt emission arises from collisions between internal shocks.
- Afterglow arises from external shock.