25 years of GRB Afterglows
Lesson Learned

By

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Hands-on the Extreme Universe with High Energy Gamma-ray data

Sexten 18 Jul 2022, 10:00 → 22 Jul 2022,

On 2010 the Italian Physics Society (S.I.F.) awarded Filippo Frontera ad myself with the Enrico Fermi Prize

During the year Conference of the S.I.F. we gave a talk with our reconstruction of the Story of the Discovery of Afterglows.

In my opinion the reconstruction of the History of the discovery for the GRB Afterglows is correct.
I apologize it is a bit Italy-centric

Therefore I present the same slides.

At the end I add a few slides by myself only

A story of an Italian excellence:

Discovery of the Gamma Ray Burst afterglow with BeppoSAX

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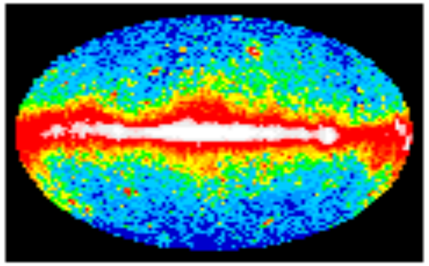
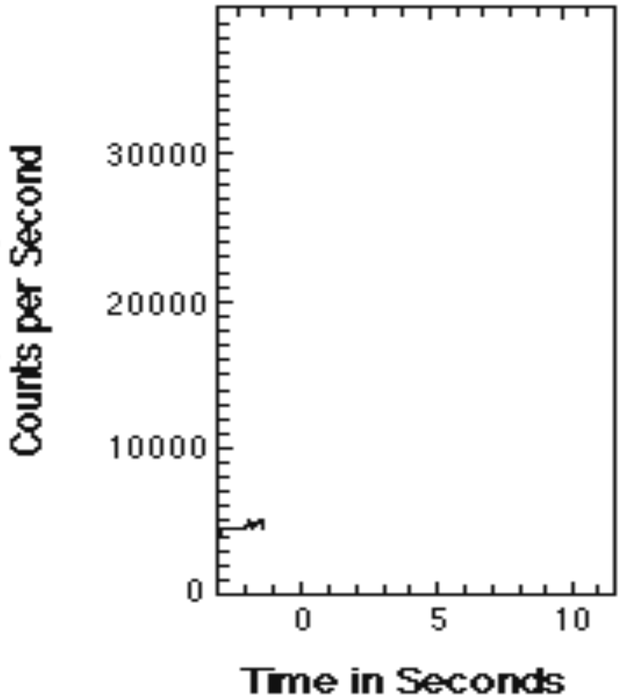
XCVI Congresso SIF – Premio Fermi 2010
Bologna, 20 Sept 2010

The GRB phenomenon

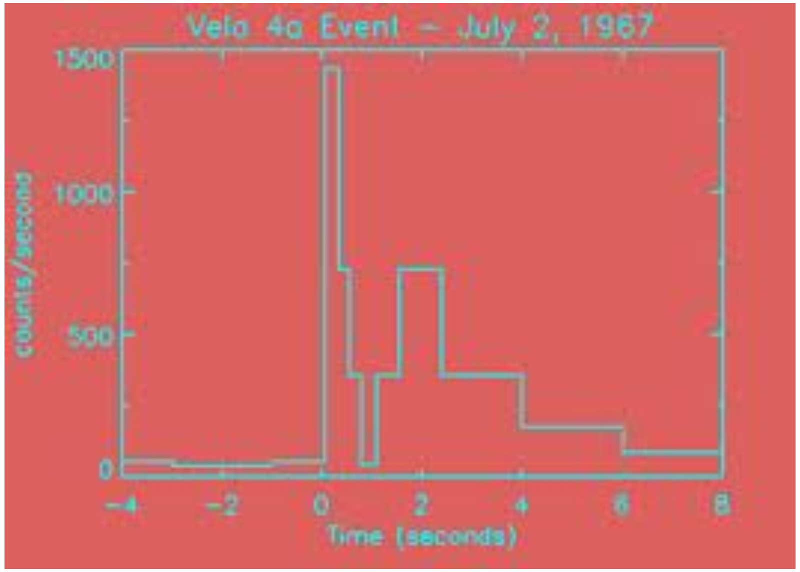




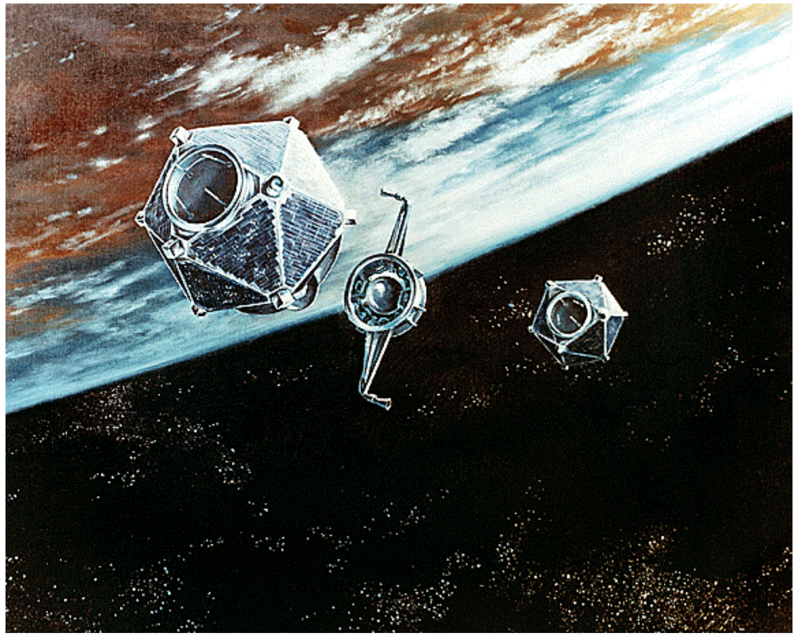
- Sudden flashes of bright hard X--/soft gamma-ray radiation
- Variable duration of tens of milliseconds to tens of seconds
- 4-5 events/day
- Unpredictable sky directions
- Unpredictable arrival times

GRB discovery

- Discovered at the end the 60's with the American Vela spy satellites, devoted to monitor compliance with the 1963 "Partial Test Ban Treaty" by the Soviet Union, and other nuclear-capable states.
- Published by R. Klebesadel, I. Strong & R. Olson (1973)



Vela satellites

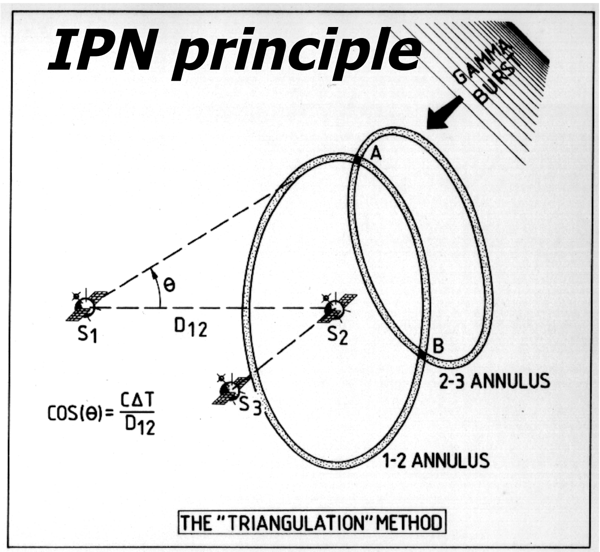


Major issues

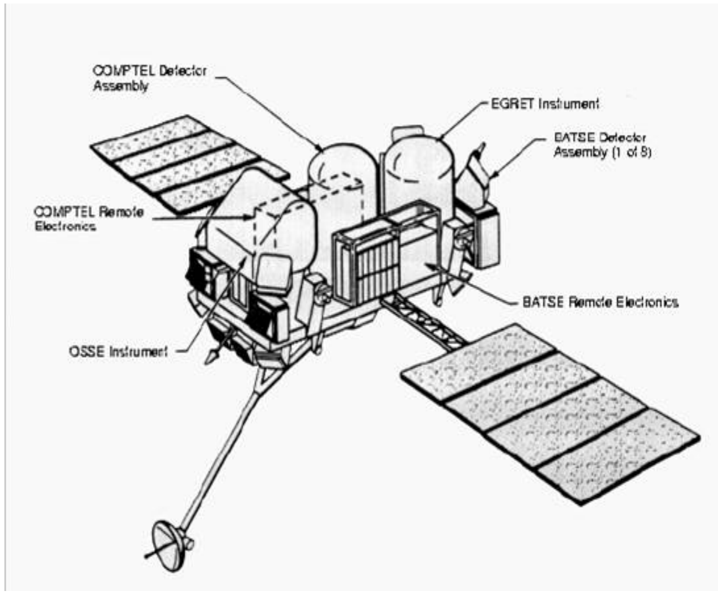
- **Major astrophysical problems:**
  - **Which are their progenitors? Normal stars? Compact stars (WD, NS, BH)? Comets? Insterstellar medium?**
  - **Which are their sites (Local, our Galaxy, Extragalactic) and the power involved?**

- **Major observational problems:**
  - **Accurate localization of the event: a tough task in this energy band, where detectors, mainly based on Compton scattering, give coarse source directions;**
  - **Search for the GRB counterparts at longer wavelengths (a new born source or one already existing?)**

From GRB discovery to BeppoSAX launch



- **Many satellite missions (most French-Russian), but small progress:**
  - **Very rough localizations. The most accurate with IPN after a long time from events.**
  - **No evidence of counterparts.**
  - **No idea of the power output.**
- **The largest effort with BATSE experiment (20-2000 keV, 8 NaI(Tl), full sky) aboard Nasa CGRO satellite (1991-2000).**

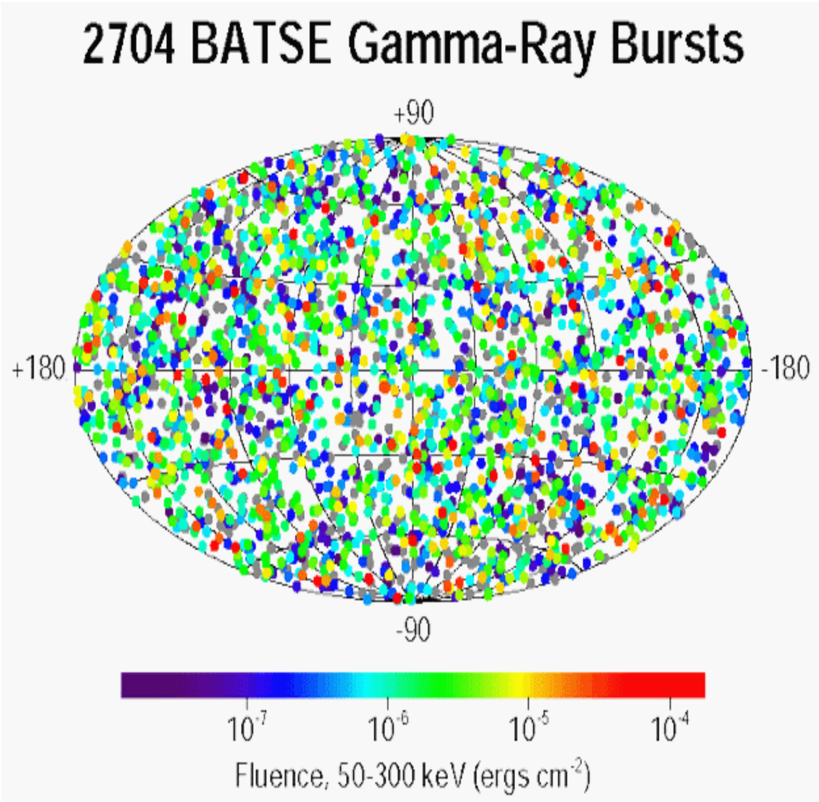


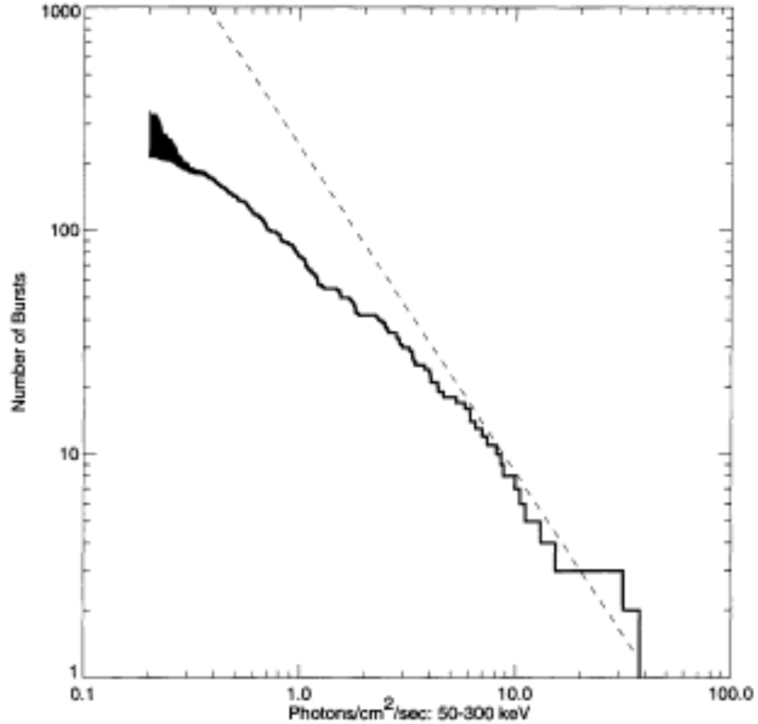
Major BATSE Results

• Isotropic distribution of GRBs directions (localization uncertainty ranging from 2° to 30°)

• Paucity of weak events with respect to what expected in an euclidean space

• Hints for a cosmological origin of GRBs, but also consistent with a local origin or Galactic halo.

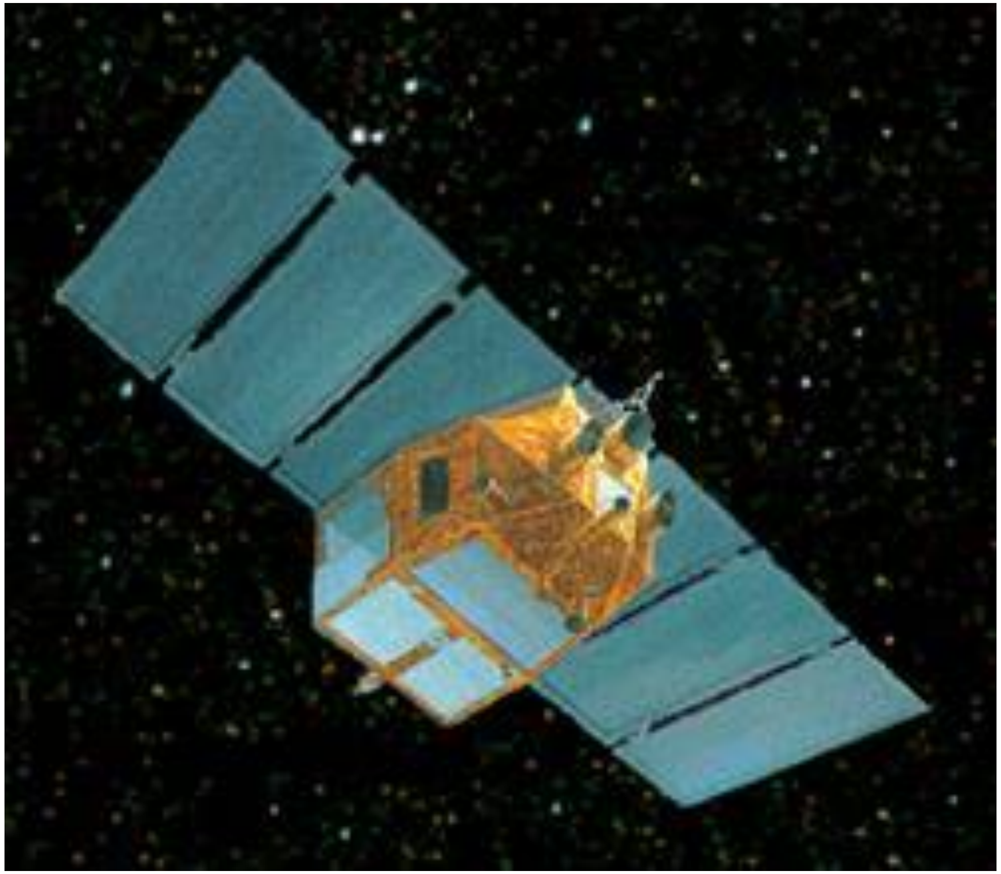




The BeppoSAX revolution

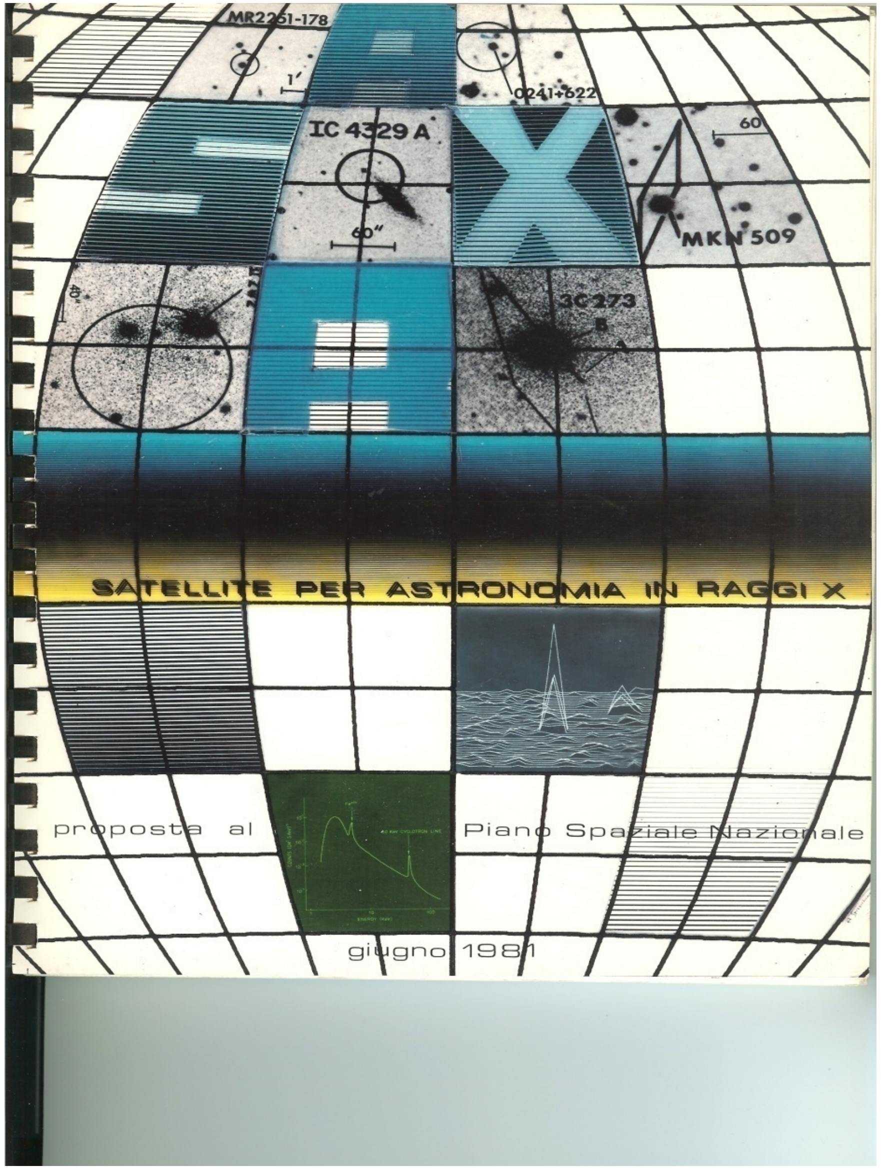
- In only 6 months in 1997, BeppoSAX results have allowed to establish that
- **GRBs are huge explosive events in galaxies at cosmological distances.**

- **Why BeppoSAX?**



BeppoSAX initial goals

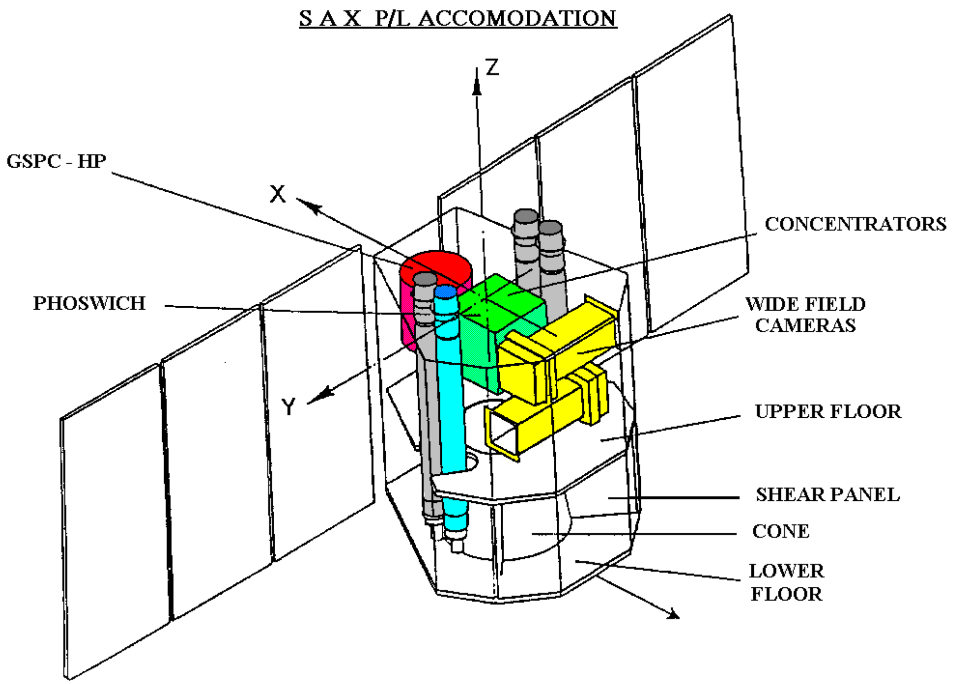
- **SAX initial proposal (1981) to PSN (later ASI) did not include GRBs as science goals:**
  - **Study celestial X-ray sources in a broad band 0.1-300 keV with narrow field instruments;**
  - **X-ray sky monitoring, in particular of the Galactic plane.**



BeppoSAX
an ASI mission led by L. Scarsi

Payload

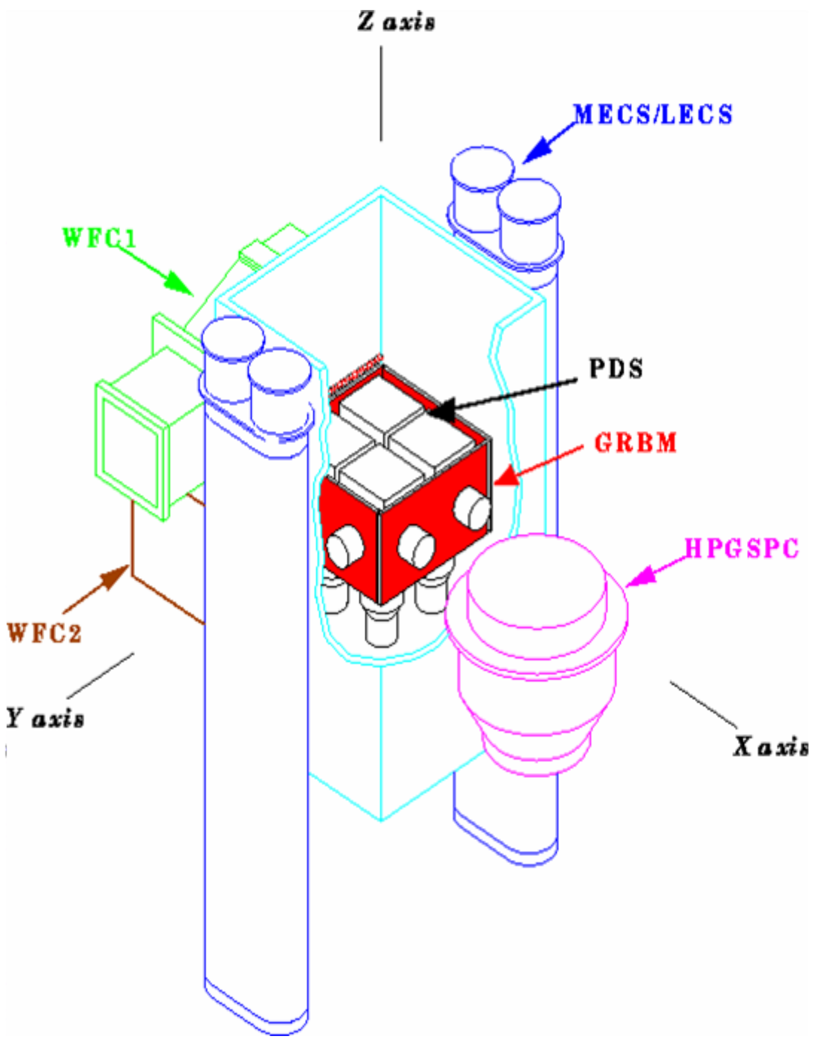
- **Narrow Field Instruments:**
  - 4 focusing telescopes LECS+MECS (0.2-10 keV), PI G. Boella
  - HPGSPC (4-60 keV), PI G. Manzo
  - PDS (15-200 keV), PI FF (Deputies: EC, D. Dal Fiume)



- **WFCs (2-28 keV, PI R. Jager):**
  - 2 units in opposite directions,
  - proportional counters + coded mask, ang. res. 3'-4'
  - FOV 20°x20° (fwhm)

The Gamma Ray Burst Monitor

- Proposed by FF during the phase A study (1983-84), exploited the PDS Anti-Coincidence shield;
- 4 units, CsI(Na) scintillators, almost all sky view, 40-700 keV, 4200 cm^2.
- 2 units coaligned with WFCs
- Expectations: 2-3 GRBs/yr detected with GRBM could be localized with WFCs (arcmin accuracy).

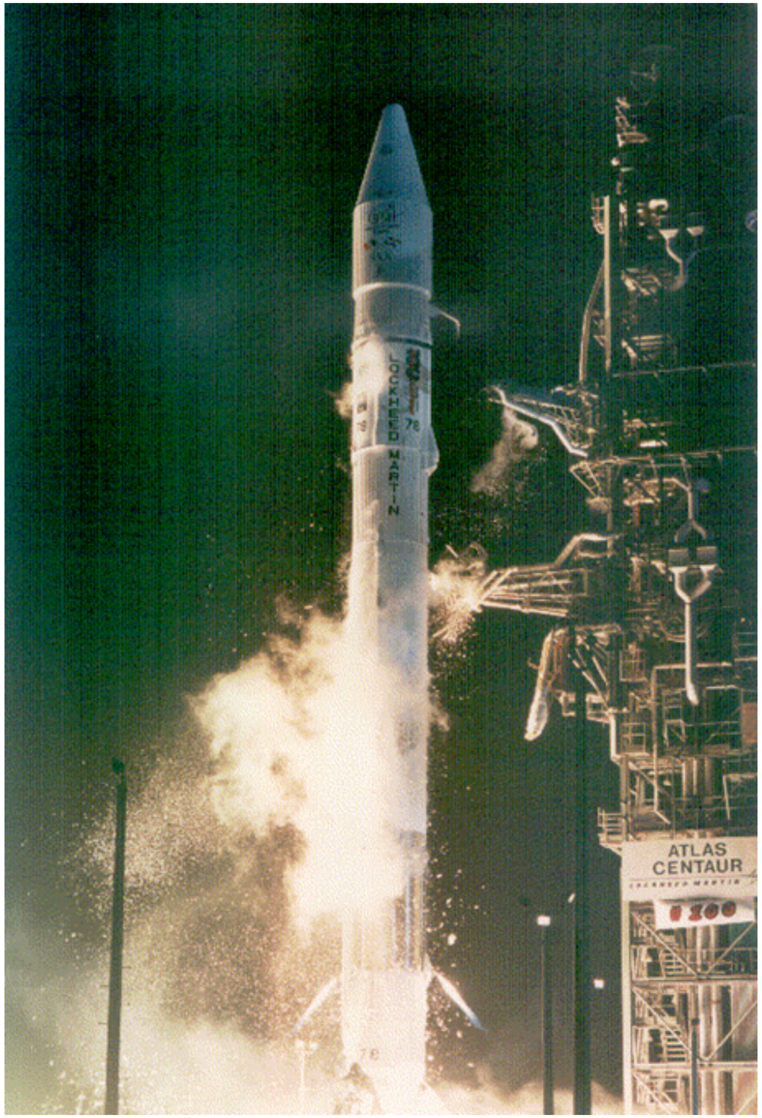


GRBM development steps

- GRBM proposal, approved by SAX Consortium in 1990.
- GRBM design, later developed:
  - A trigger system to identify GRB events
  - 4 electronic chains for getting continuously spectra and ratemeters from each GRBM unit;
  - Gain monitoring;
  - In case of a trigger: high time resolution ratemeters (down to 0.5 ms).
- GRBM prototype developed in the Institutes, also with repeated testing with the SATURNE proton accelerator (Saclay).
- Flight model (developed by Laben) under the FF supervision.
- Calibration campaign after integration in the satellite at ESTEC (Noordwijk, NL) led by EC.

BeppoSAX launch and phases

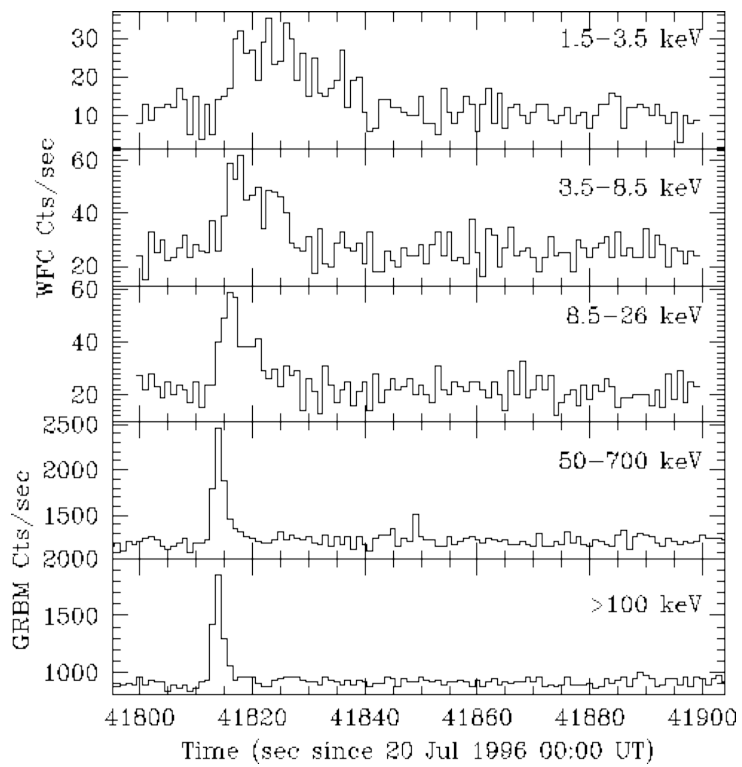
- Launch, on 30 April 1996 from Cape Canaveral with an Atlas-Centaure rocket ;
- Commissioning phase: 2 months;
- Science Verification Phase (SVP): July - September 1996;
- Operational phase: from October 1996.

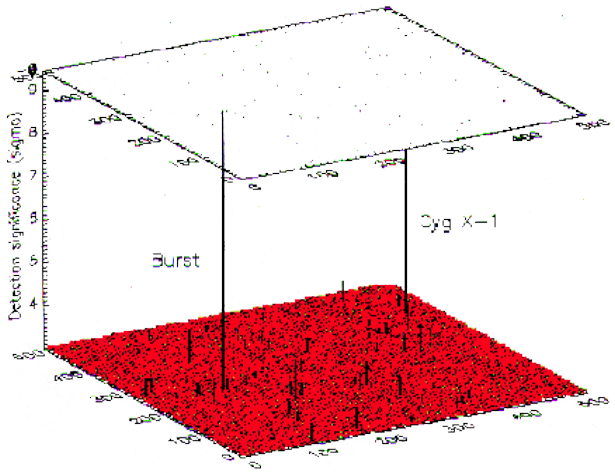


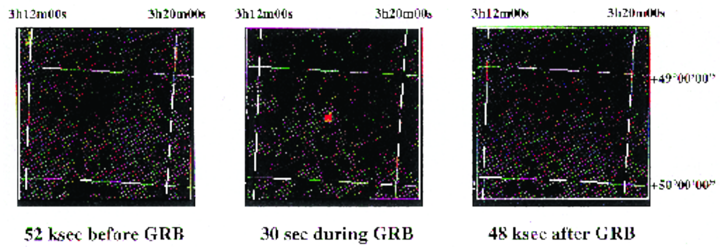
• During SVP, several GRBs detected in off-line analysis with GRBM.

• In coincidence with one of these, GRB960720 (1996 July 20) was found in WFC data and accurately localized one month after the event.

• A pointing of the NFIs toward the GRB direction was performed, but no X-ray counterpart found.







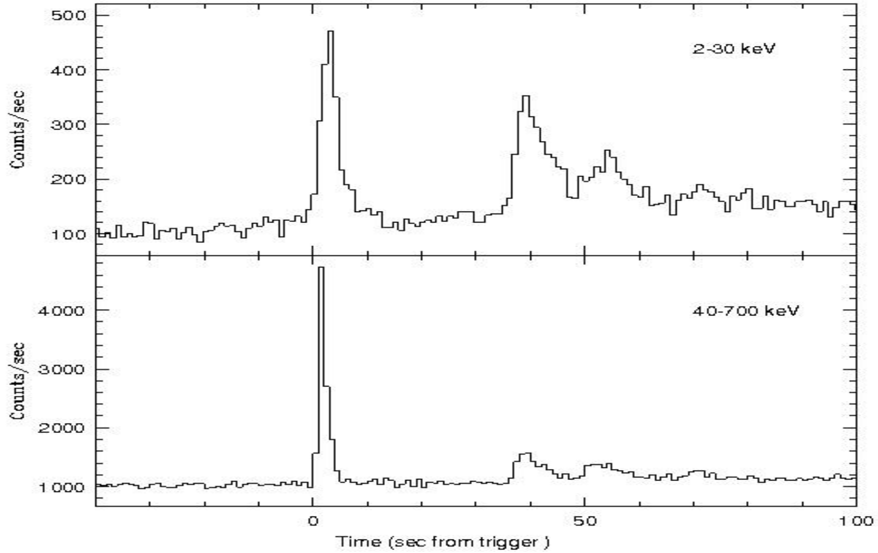
Observation strategy set up

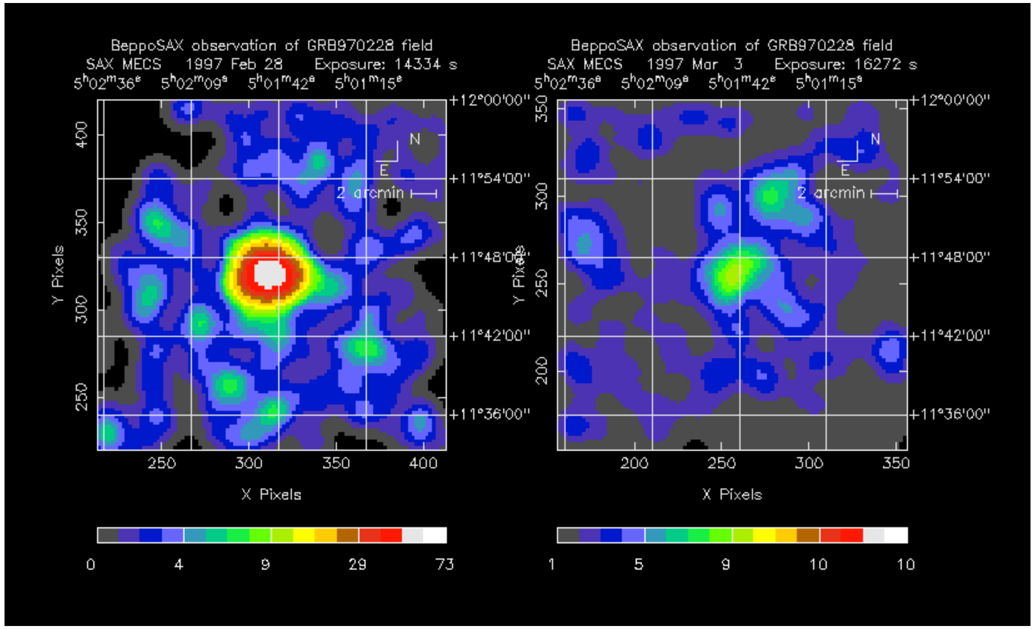
- From GRB960720 experience , two alternatives:
  - No X-ray residual radiation at all;
  - A rapidly fading X-ray source.
- A prompt follow up would be the next attack.
- Observation strategy devised:
  - Prompt analysis of the GRBM data and validation of real bursts.
  - WFC data analysis in coincidence with detected GRBs;
  - In the case of a positive detection/localization with WFC, follow-up with NFIs.
- This observation strategy became operative in Jan 1997.

GRB afterglow discovery

- Unsuccessful search with the first localized GRB GRB970111.

- Second GRB promptly identified and well localized: GRB970228
- Follow up after 8 hrs: afterglow emission discovered.

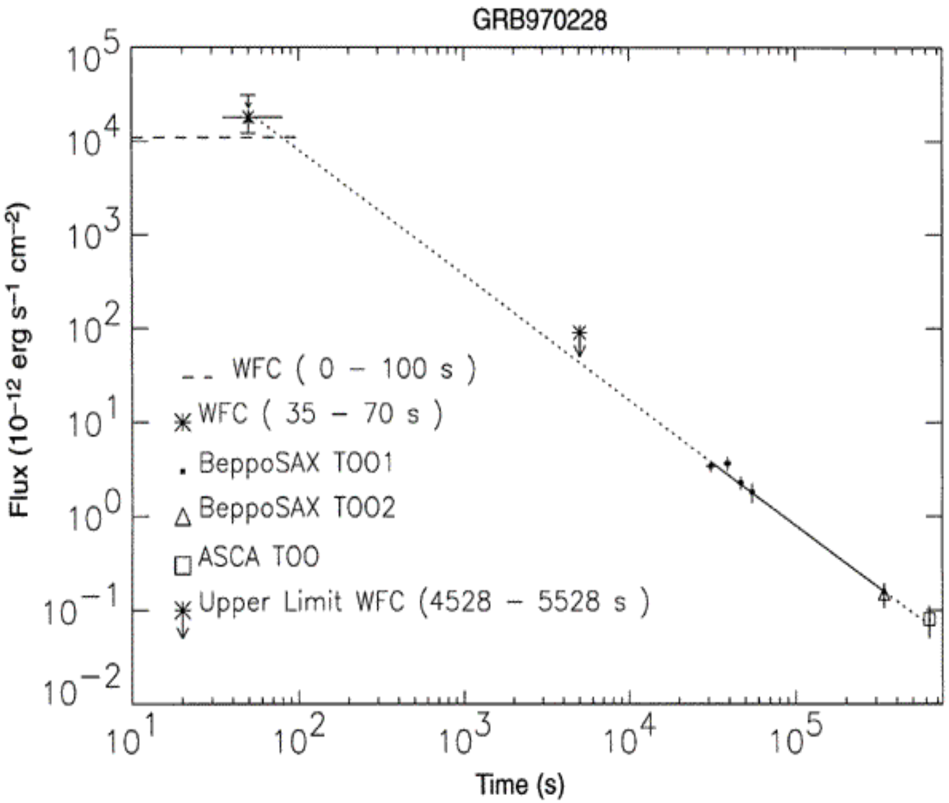


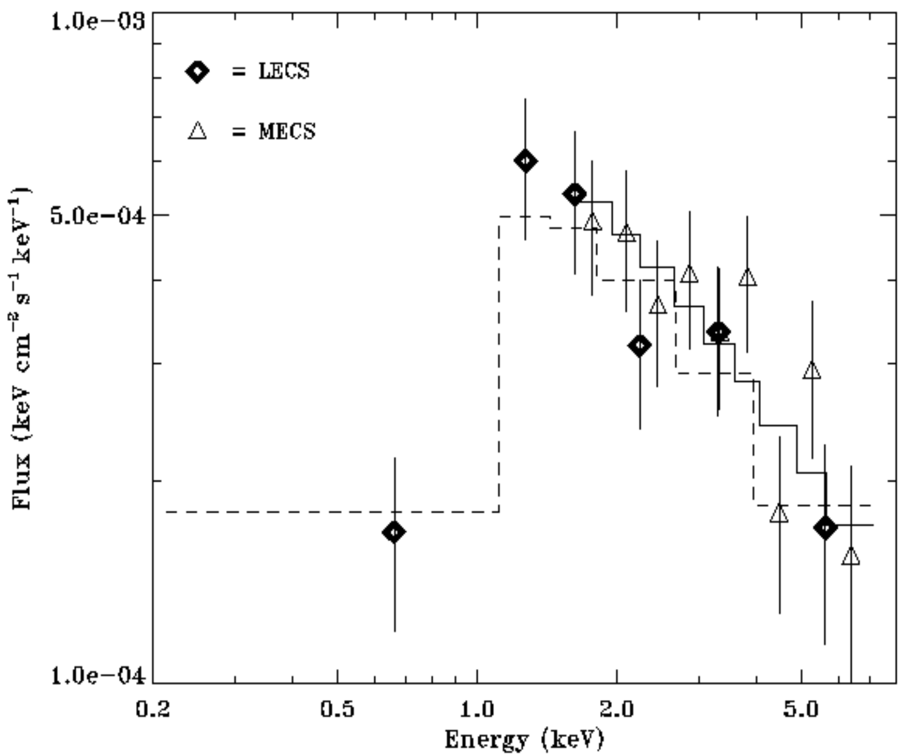


Costa, Frontera et al. 1997

X-ray Afterglow emission properties of GRB970228

Power- law decay and power-law spectrum





$\boldsymbol{F} \sim t^{1.3}$

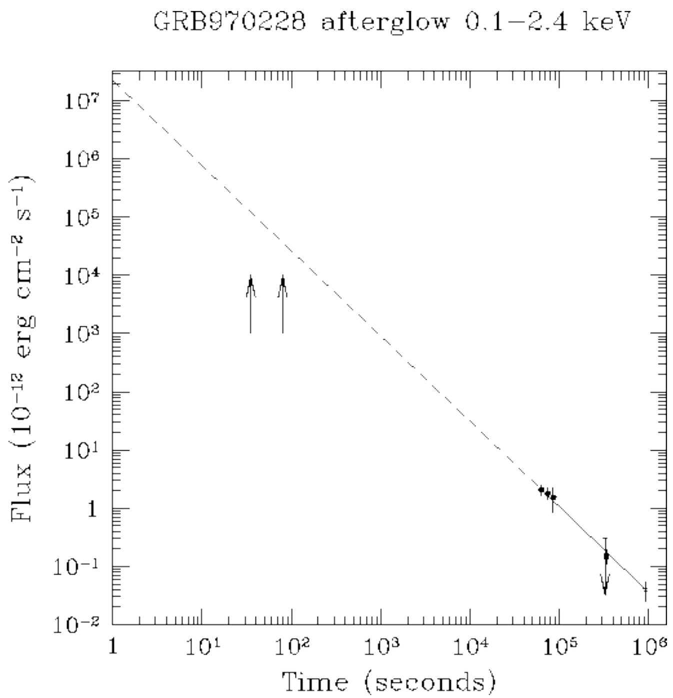
Costa, Frontera et al. 1997

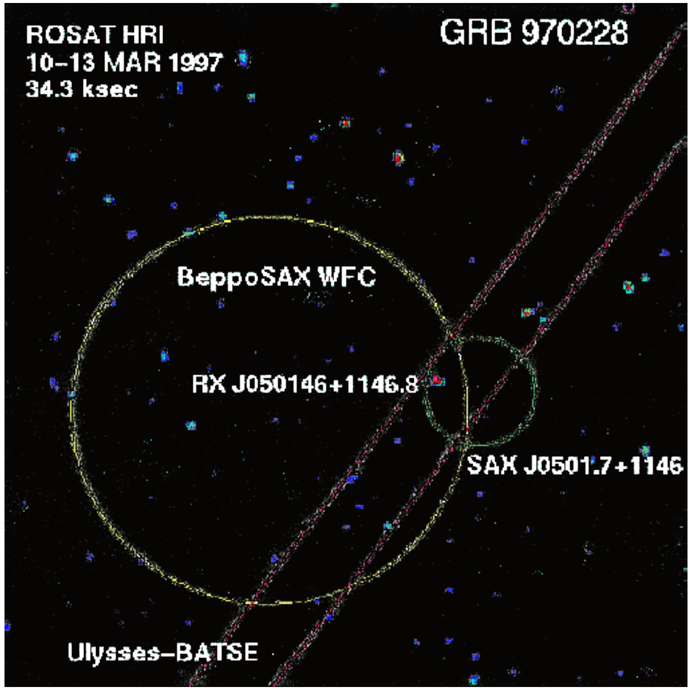
$\boldsymbol{F} \sim E^{-2.1}$

Frontera, Costa et al. 1998

GRB970228 afterglow observation with ROSAT

- ROSAT was the most sensitive Soft X-ray telescope at the epoch. We asked for a pointing in the direction of the burst. After 10 days the afterglow was still there.





Frontera et al. 1998

But the error box had shrinked down to 5 arcseconds

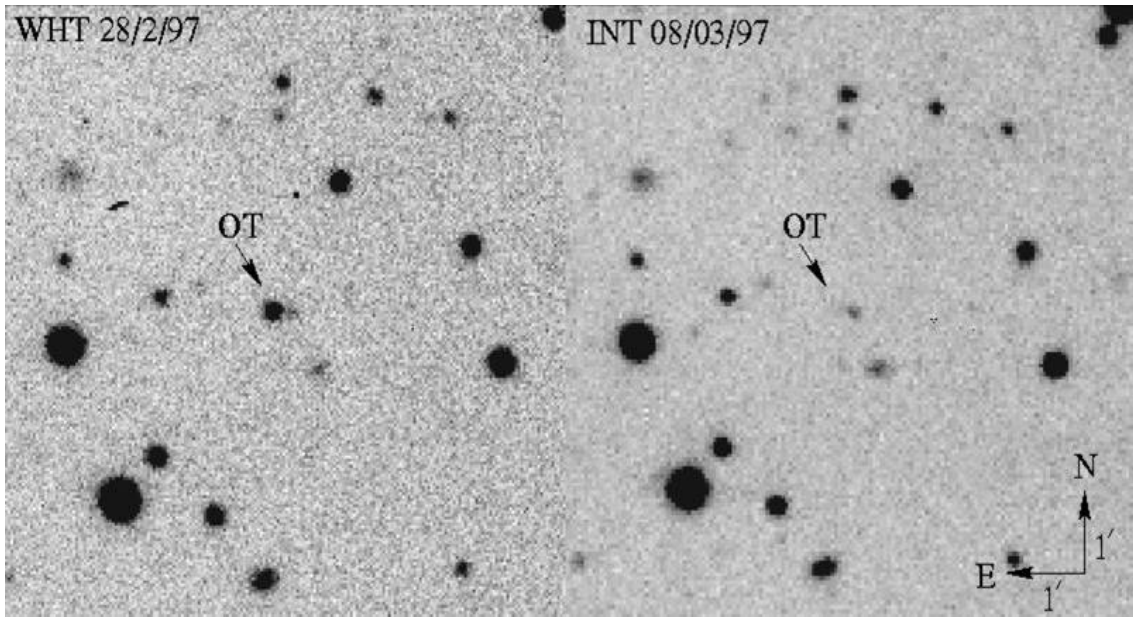
First discovery of the optical afterglow from GRB970228

The error box given by BeppoSAX was at last compatible with a search in optical images within a reasonable small field.

Various teams observed the field at the BeppoSAX coordinates distributed by a telegram to the International Astronomical Union (Costa et.al 1997)

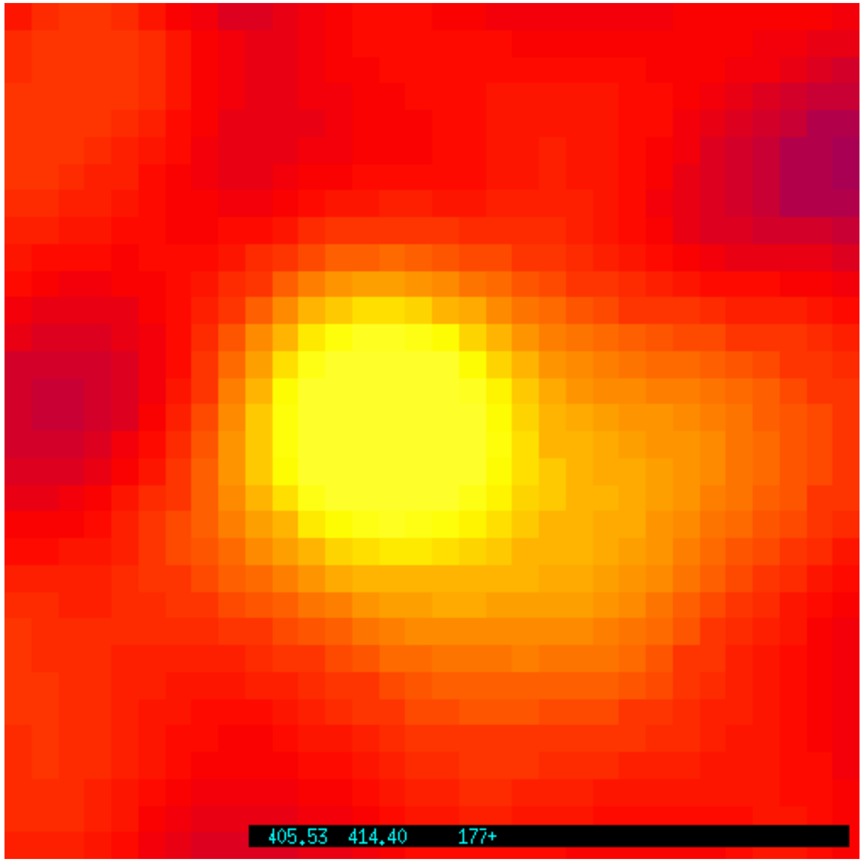
Van Paradjis, Groot, Galama et al. 1997

Paul Groot of the team of Ian Van Paradijs was the first to observe twice the field with William Herschel Telescope and to detect the optical afterglow decaying with the same power-law index of X-ray afterglow.



GRB970228 afterglow observation with HST

- The AG was observed with HST. A decaying point source was included within a faint nebulosity, possibly a far galaxy.



The ladder

SAX – GRBM	**~ 45°**	**100 m**
↓		
SAX – WFC	**5-3 arcmin**	**3h**
↓		
SAX – NFI	**1 arcmin**	**8h**
↓		
Optical Telescopes	**1 arcsec**	**2-10d**
↓		
Hubble	**0.2 arcsec**	**1 month**

- ***Every improved error box is included in the previous and has a transient object.***
- ***All detected transients decay with the same power-law.***

It is the same object

Why was the ladder needed?

A posteriori we know that:

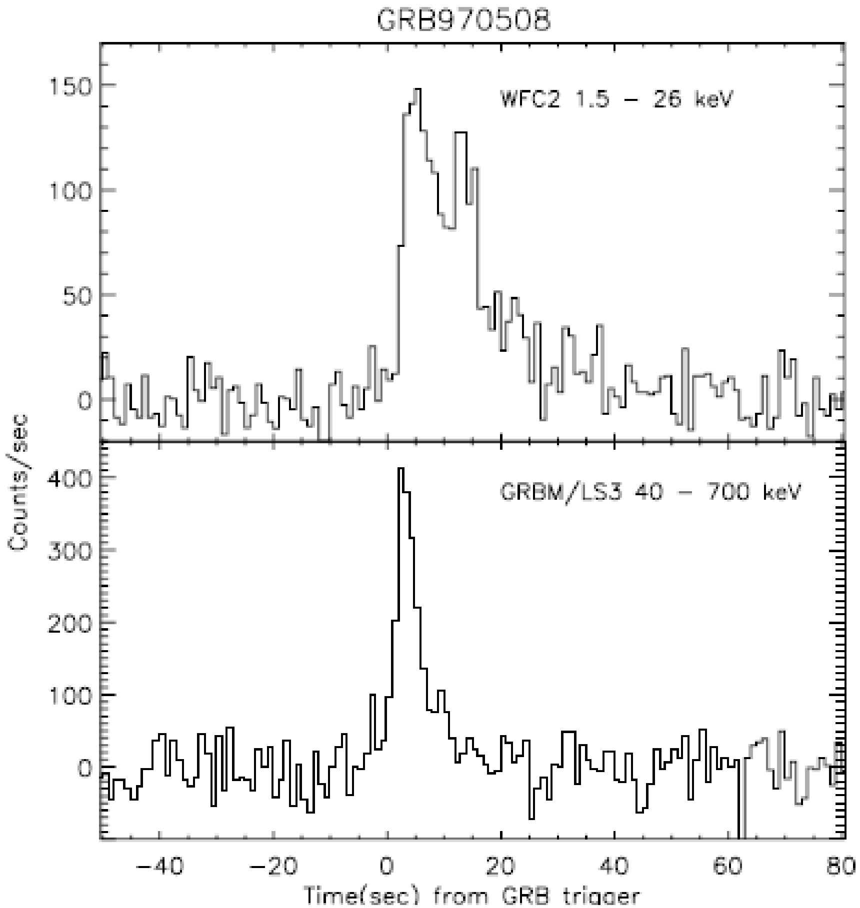
- **Even if GRBs are outstanding, namely stronger than any source (but Solar flares) at 100 keV-1MeV, the instrument s have a coarse angular resolution (≥2°): almost any astrophysical object can be associated!**

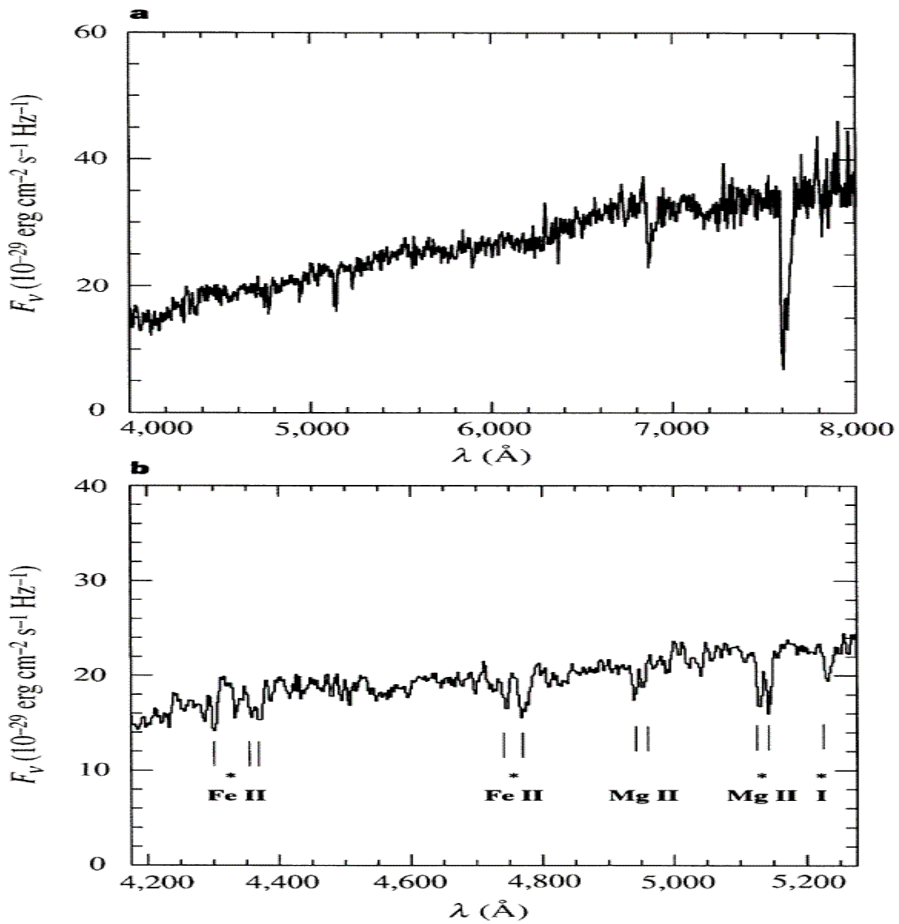
- **In the optical band, both the GRB afterglow and its host galaxy are in general quite weak:**
  - **afterglow magnitude of about >20 (most GRB)**
  - **Host galaxy magnitude of 23-25**

- **Thus the association is only possible with very large instruments and arcsecond angular resolution.**

➢First measurement of GRB redshift: GRB970508 **(*z* = 0.835)**

Metzger et al 1997





Consequences of the redshift measurement

- From the distance we derived the energetics of GRB970508. Assuming isotropy:

$$E_{iso} = (0.61 \pm 0.13) \times 10^{52} \text{ ergs}$$

- On December 14, 1997 the redshift of another BeppoSAX GRB (971214) was determined: z = 3.42.
- The corresponding energetics was $E_{iso} = (2.45 \pm .28) \times 10^{53}$ ergs → 0.14 $m_{\odot} \times c^2$

International resonance 1/2

- In the first two years the number of papers citing BeppoSAX (mainly for GRBs) is equivalent to those citing HST.
- ESA modified the data of the INTEGRAL satellite in order to allow a prompt localization of GRBs with the on ground analysis of the gamma-ray Imager (IBIS) data.
- NASA issued an Announcement of Opportunity for a new medium-size scientific satellite: many missions dedicated to GRBs were submitted and one (SWIFT) selected.
- SWIFT is based on the same “ladder” of BeppoSAX, but the localization and re-pointing are automatically performed in a much shorter time.

International resonance 2/2

- The major optical and radio telescopes dedicated observing time to follow up GRBs.
- Some of them modified their procedures or their equipment to make these observations faster.
- Several optical or NIR telescopes were built with robotic pointing on coordinates distributed by BeppoSAX through the GCN network set up by NASA.

- Bruno Rossi prize 1998 of the American Astronomical Society.
- Descartes prize 2002 of the European Commission.

Some major BeppoSAX results after the afterglow discovery

Radio Afterglow – Scintillation – Direct evidence of relativistic expansion

Association of GRB with SuperNovae

E_{peak} – E_{iso} relation (very promising for Cosmology)

Main results from following missions (HETE-2, SWIFT, AGILE, Fermi)

Short Bursts

Plateau and flares in the early afterglow light curve

High Energy (>50 MeV) emission

Z up to 8.1

$E_{iso} \approx m_{\odot} \times c^2$

Tighter connection GRB/SN

A tool to test fundamental physics

The collapse

Search for evidence of a double collapse to proof an intermediate state of Quark Gluon Plasma.

The propagation

Search for delays as a function of the energy and of the distance as evidence of string Quantum Gravity Theories.

Search for rotation of the polarization angle as a function of the square of the energy and of the distance as evidence of Loop Quantum Gravity Theories.

Impact on the Italian Community

Participation (with hadware contribution) to

SWIFT (X-ray telescope)

AGILE (all italian)

GLAST/Fermi (Gamma-ray Tracker)

+ numerous X/γ-ray experiments proposed to ASI, ESA, NASA and other agencies with GRBs in the core science

Correlated observations (O/IR)

One of the communities most active in the world for Data Analysis/Interpretation and for Theory

End of Talk to SIF by Costa and Frontera

A few more slides by myself

More Discoveries (after 2010)

AG up to Z ≈ 10
GRB at VHE
Short GRB associated to GW and kilonova
GRB associated to FRB (and SGR)
[no neutrinos]

Things still to understand (a lot)

- e.g.
- Which is the energy of the AG? No data on the AG above 10 keV (maybe 40keV)

- Is the HE GRB a part of the prompt or the AG?

More Prizes

Shaw Prize 2011 to Enrico Costa annd Gerald Fishman

Marcel Grossmann Award 2012 to Filippo Frontera

The Lesson I

Approach to a mission

- Solid experimental groups to test and verify every choice and to control the activity of industry
- Be maniacal with possible problems with the radiation environment
- Do not save on telemetry
- Be ready with software. Use as possible public software. Do not start debugging with real mission data.
- Do not save on the ground segment: 24 hours is ≥ 3 shifts. Quick science is done by people who unfortunately pretends to be payed.

The lesson II

Sociology of science

- Difficult things can be done: think big
- Each Community has a wealth of experience: Recombine Communities. Do not be afraid to cooperate with old enemies. New enemies will immediately arrive.
- Complications give opportunities: resist to pressure for simplifications. But do not do things that you will not have time to test.
- Involve theoreticians from the beginning bu do not rely completely to them. Missions are slower than fashions.
- Every experiment, even producing breakthrough data, is only giving a piece of the puzzle. Think in advance to a network. Point to the best and not necessarily to friends or policy or nation. Agencies will advocate for that.
- A science revolution is accompanied by a certain level of change of personality and newcomers arrive. Do not be too Confucian!

The lesson III

Approach to Science

- A complex phenomenology can hide very different things: the difference from one burst to the other was also hiding a crowd of other transient families
- The Occam razor is not for every bird: sometime the most exotic hypothesis is the true one
- Even if you will be always asked to focus on the core science fight to preserve discovery space

Last but not Least Lesson

Listen to everybody

Don't believe to anybody

Included myself