Rapid Response Analysis of GRB Optical Afterglows

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April 16, 2004

Collaborators:

Copenhagen GRB group:

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The ESO GRACE collaboration.

Contents

1. GRB Phenomenon

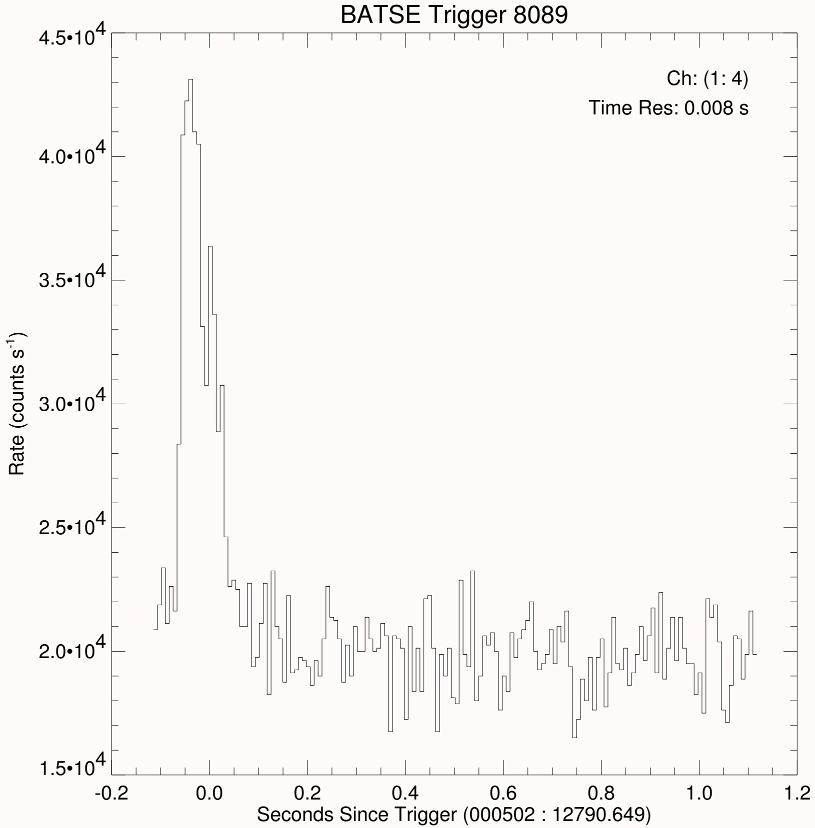
- First GRB observed in 1969.
- First GRB long-wavelength counterpart observed in 1997.
- GRB high-energy characteristics:
  - Wide range of GRB lightcurves observed, differing in both complexity and duration.
  - GRBs can be classified according to duration and spectral hardness.
  - GRBs observed to be uniformly distributed on the sky, indicating a cosmological origin.
  - Cosmological origin imply a very high energy output of GRBs.

GRB Model

GRB Lightcurves

High-energy lightcurve profiles of GRBs

... From single peak, short duration bursts, to...

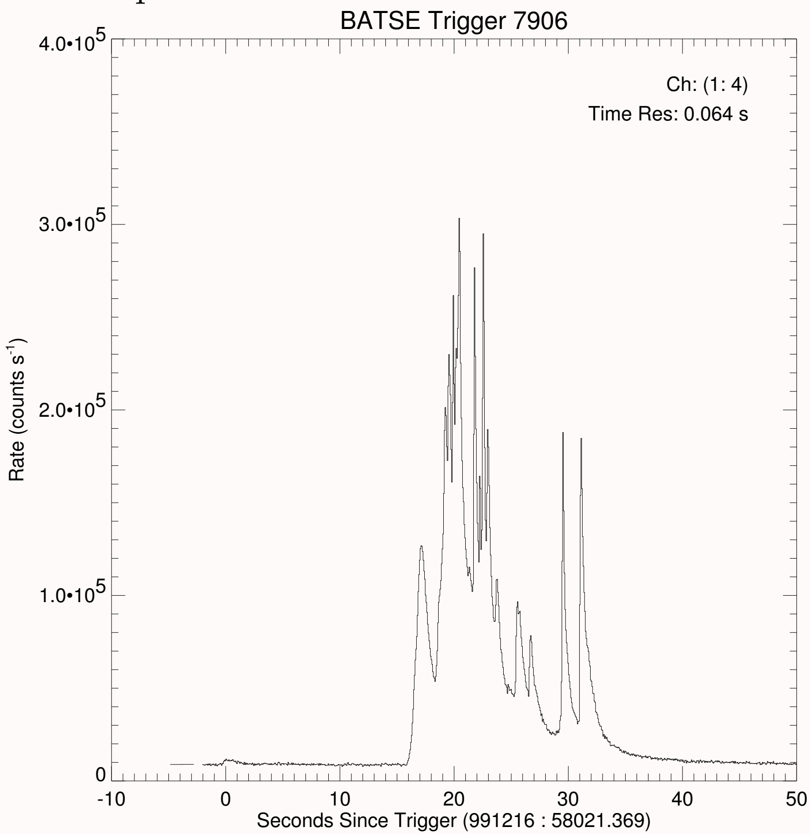


(here, duration $\approx 0.05\,\mathrm{s}$)

GRB Lightcurves

High-energy lightcurve profiles of GRBs

. . . complex, long duration bursts.



(here, duration $\approx 40\,\mathrm{s}$)

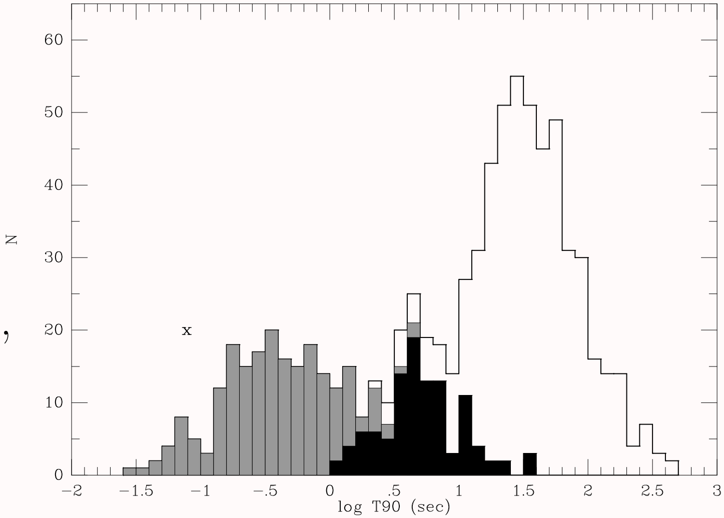
GRB Classification

GRB classification based on duration:

Grey:
Short duration,
Hard spectrum.

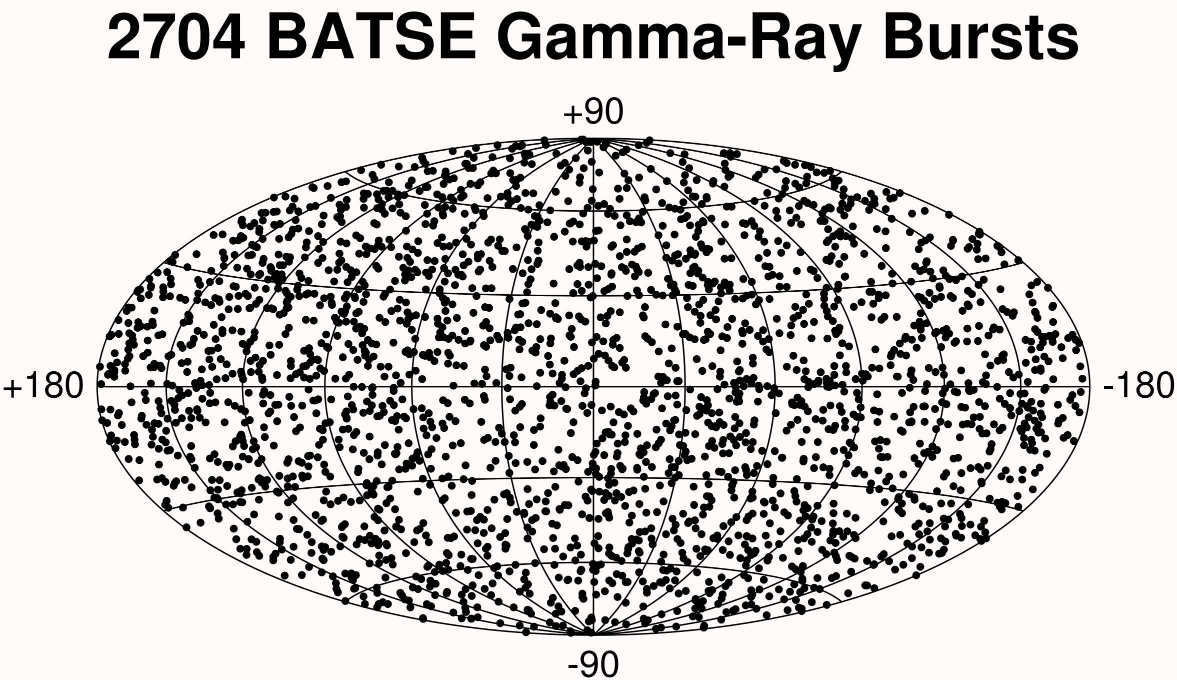
Black:
Intermediate duration,
Soft spectrum.

White:
Long duration,
Intermediate spectrum.



GRB Distribution

GRB angular distribution on the sky, as observed by the BATSE instrument in the period 1991 – 2000:



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GRB Energetics

The equivalent emitted isotropic energy release at Cosmological distances for GRBs corresponds to $10^{51} - 10^{54}$ erg.

An energy output of 10^{54} erg amounts to the energies of $\sim 10^3$ Super Novae (or $10^{11} L_\odot \sim$ the approximate luminosity of the Milky Way).

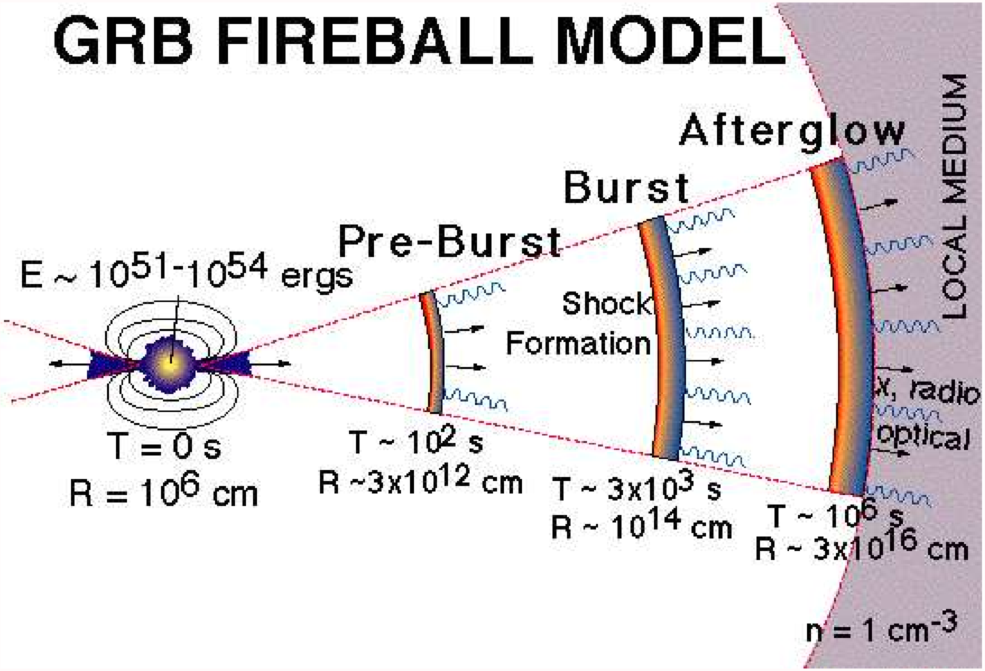
2. GRB Model

- GRB modelling.
- Progenitor mechanism. Current, most favoured, models:
  - Long/soft bursts: **Collapsar model**.
  - Short/hard bursts: **Compact merger model**.
- Afterglow modelling.
  - Afterglow Spectral Energy Distribution (SED).
  - Afterglow Lightcurve.
  - Afterglow Geometry – isotropic or collimated emission.
- GRB Redshift Distribution.

ToO

GRB Modelling

Sketch of the Simple GRB Fireball scheme.



Blastwave/jet expanding into surrounding interstellar medium.

GRB Afterglow

The evolution of the GRB afterglow flux, as a function of frequency, ν, can be characterised by:

$$F_\nu \propto t^\alpha \, \nu^\beta,$$

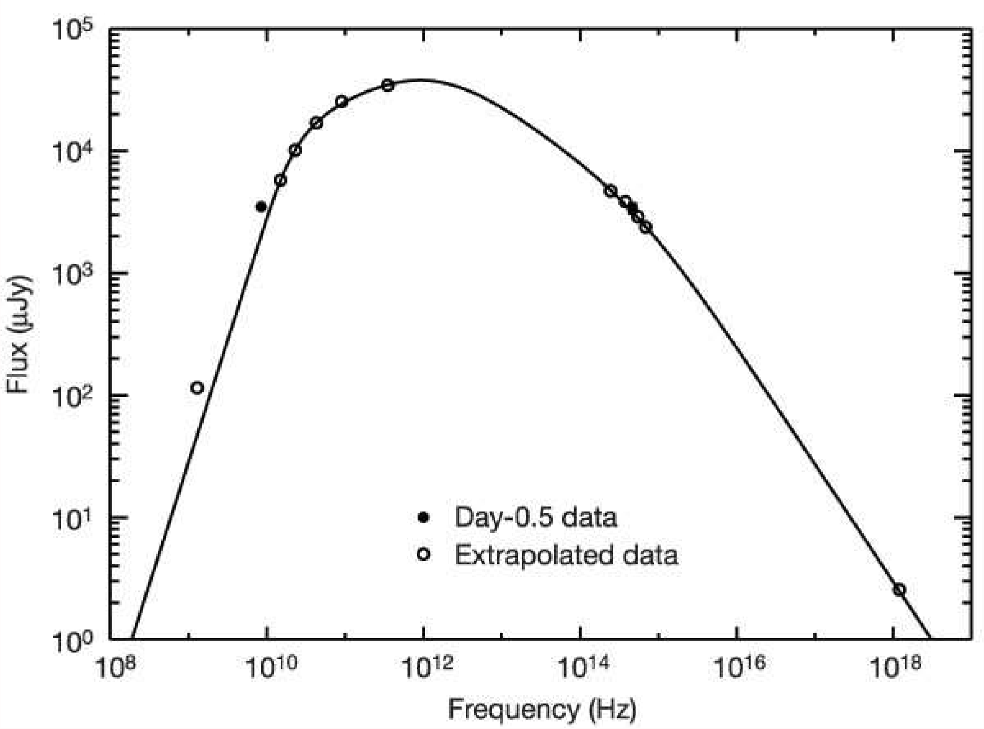
α : lightcurve power law decay index.
Typically in the range of $\alpha \approx [-0.5, -2.0]$

β : Spectral decay index.
Typically in the range of $\beta \approx [-0.5, -0.9]$

Although individual exceptions abounds, especially in the case of lightcurve evolution, where the lightcurve has been observed to consist of, typically, two power-law segments, with decay indices α_1 and α_2.

GRB Afterglow SED

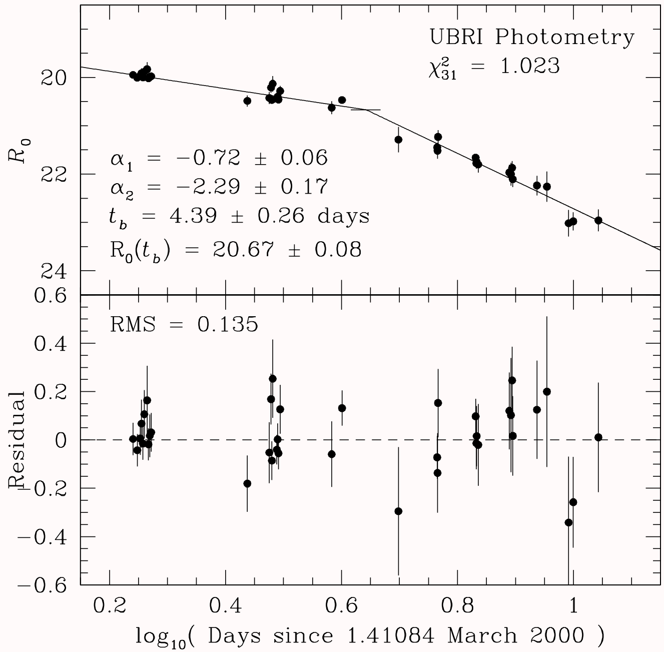
Determination of the afterglow Spectral Energy Distribution (SED) can yield the spectral index β.



GRB Afterglow lightcurve

GRB Model

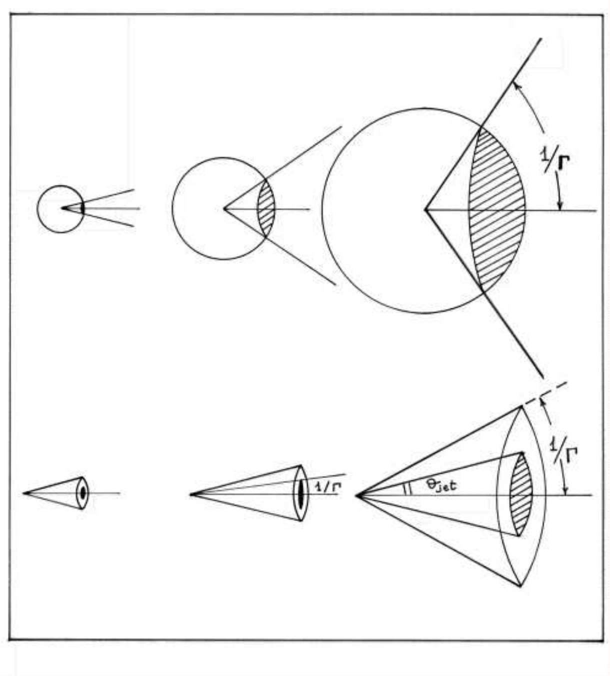
Modelling of the optical afterglow lightcurve can yield the lightcurve decay rate, α, and, potentially, the time of the lightcurve break, t_{break}.



GRB Afterglow Geometry

The geometry of the afterglow emission can be determined from the evolution of the afterglow lightcurve.

- In the isotropic case, the afterglow undergoes a steady decay with approximately constant α.
- In the collimated case, the afterglow undergoes a break in the lightcurve.
- The opening angle of the geometrical jet is sensitive to the time of the break in the afterglow lightcurve, t_{break}.



GRB Afterglow Opening Angle

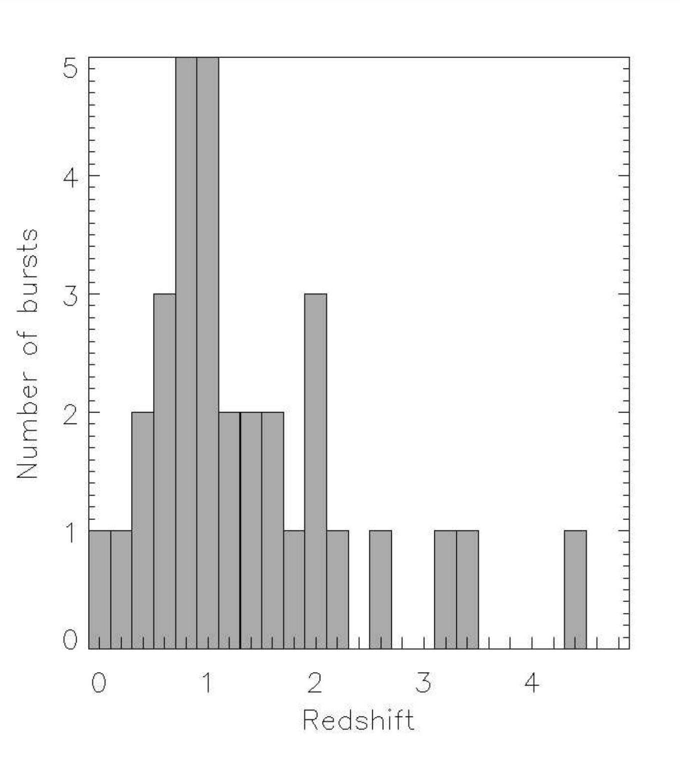
The Opening Angle of a collimated jet can be determined from:

$$\theta = 0.057 \left(\frac{t_{break}}{1\,\mathrm{day}}\right)^{3/8} \left(\frac{1+z}{2}\right)^{-3/8} \left[\frac{E_{\mathrm{iso}}(\gamma)}{10^{53}\,\mathrm{erg}}\right]^{-1/8} \left(\frac{\nu_\gamma}{0.2}\right)^{1/8} \left(\frac{n_0}{0.1\,\mathrm{cm}^{-3}}\right)^{1/8}$$

t_{break} : Measured lightcurve break time.
z : Redshift.
$\mathrm{E}_{iso}(\gamma)$: Equivalent isotropic γ-ray energy.
ν_γ : Efficiency of fireball.
n_0 : Mean ambient circumburst density.

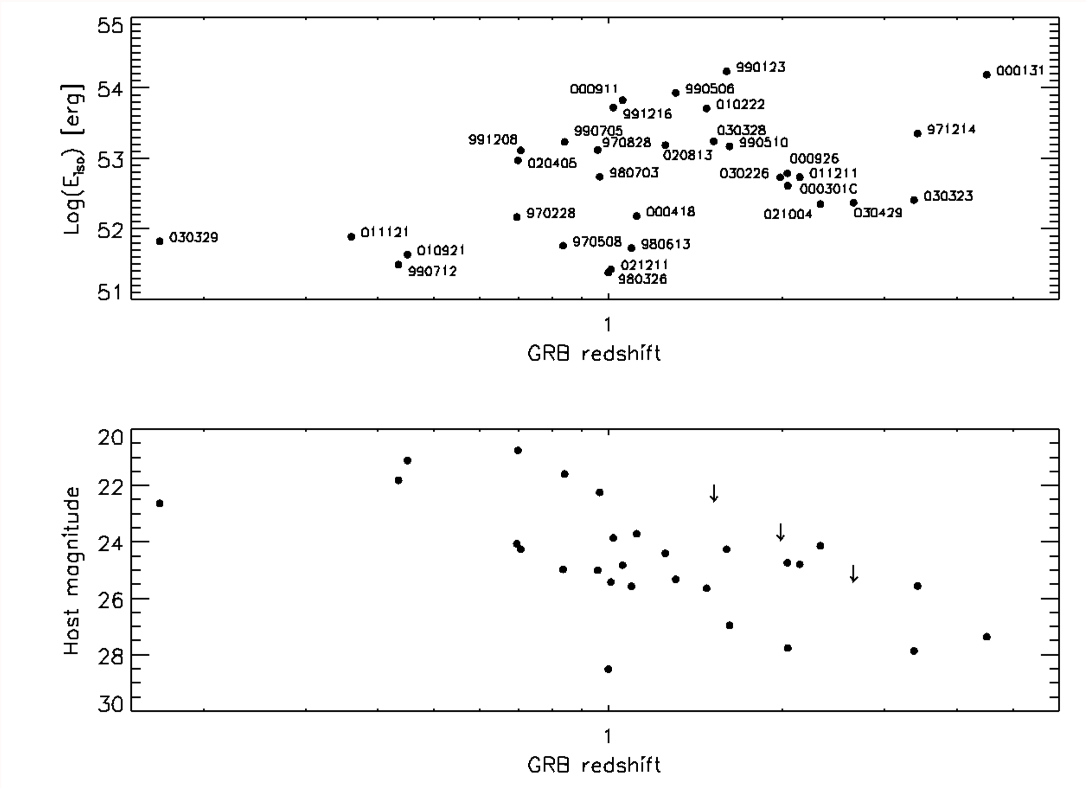
Afterglow opening angles of $0.02 < \theta < 0.2$ have been measured, corresponding to beaming relaxations of the energy requirements by factors of 10 – 100.

GRB Redshift Distribution



Redshift distribution of 32 GRBs with known redshift. All redshifts are within 0.1 – 4.5 with a median redshift of $<z>= 1.1$.

GRB Redshift Distribution



GRB Prompt Energy and GRB Host-galaxy distribution as function of redshift.

3. ToO Operations

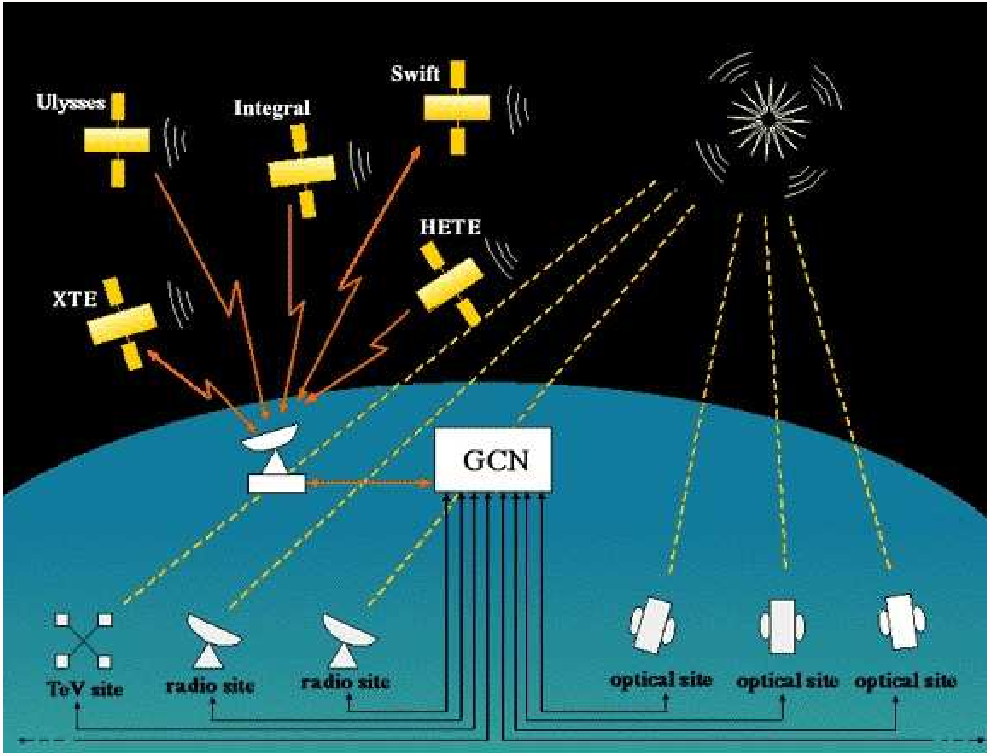
Typical GRB Target of Opportunity (ToO) Activation:

- Issuance of a GRB localisation alert by the GRB Coordinates Network (GCN).
- Rapid analysis and evaluation of the GRB localisation and the external conditions for a ToO activation.
- ToO requests for observations are submitted to relevant telescope(s).
- Images obtained are rapidly inspected and analysed.
- Further follow-up observations are planned and executed.
- Any significant results are issued to the community through the GCNCs and publications.

GRB 000301C

GCN

- GCN system schematics – Progress of a GRB alert.



GRB ToO

In order to reduce the critical time delay from the localisation of a GRB to the onset of ToO observations, a set of ToO follow-up tools have been developed.

- Field Information Generator.
- Finding Chart Generator.

These tools are automatically activated for each new GRB localisation.

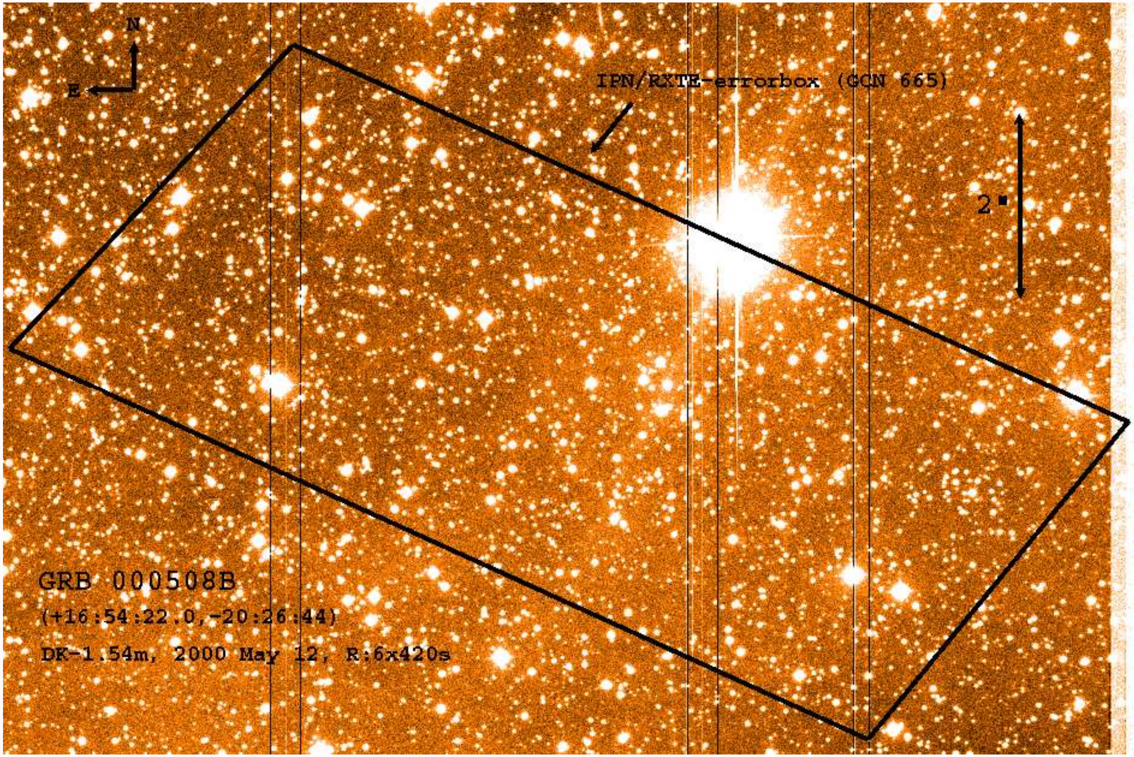
Telescopes

Typical groundbased facilities used in the GRB ToO-activation:

- The Nordic Optical Telescope (NOT) on La Palma.
- The Danish 1.5m Telescope (DK-1.5m) at La Silla, Chile.
- The ESO Paranal Telescopes (VLT), Chile.
- The ESO La Silla Telescopes (ESO-2.2m, NTT, ESO-3.6m), Chile.

ToO Image Analysis

Rapid image inspection and analysis. . .



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ToO Results

Summary of GRB ToO-activities:

- More than 200 GRB alerts evaluated.
- ToO activation and follow-up for more than 70 GRBs.
- Discovery of 7 GRB optical afterglows.
- Successful observation and monitoring of 32 GRBs and host galaxies.
- Acquisition of about 40 scientifically useful upper limits for optically Dark Bursts.

Details of the results of GRB ToO-activation that this work has contributed to, are published in:

- 20 refereed papers.
- 72 GCN Circulars.

4. Case: GRB 000301C

Case example of well-observed burst, **GRB 000301C** (Jensen, Fynbo, Gorosabel et al., 2001):

- Localised by the InterPlanetary Network.
- Discovered with the Nordic Optical Telescope.
- Duration and spectral hardness place it in the *intermediate* class of bursts.
- VLT spectroscopy yields a redshift of $z = 2.04$.

ToO Results

GRB 000301C

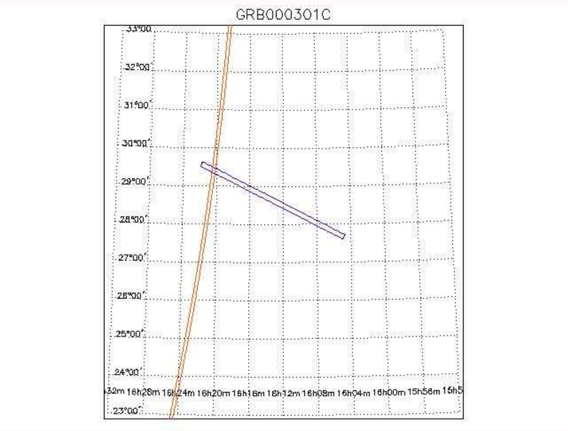
Case example of well-observed burst, **GRB 000301C** (Jensen et al., 2001):

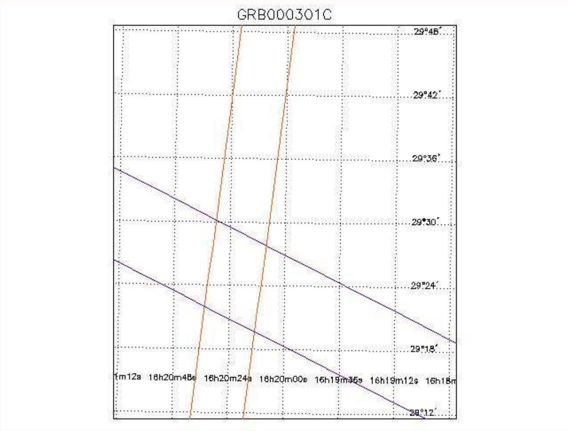
- Fitting an SMC-like extinction curve to the OA SED, provides a modest extinction of $A_V = 0.09 \pm 0.04$, and a spectral index $\beta = -0.70 \pm 0.09$.
- Interpretation of the lightcurve yields a most likely model for the afterglow to be one of a sideways expanding jet in an ambient medium of constant density.
- Fitting the lightcurve yields an opening angle for the burst of $\theta \approx 15° n_0^{1/8}$.
- A very high `HI` column density ($\log(N\texttt{HI}) = 21.2 \pm 0.5$) argue for a connection of the GRB 000301C host galaxy to the class of Damped Ly-α Absorbers.

ToO Results

GRB 000301C – Localisation

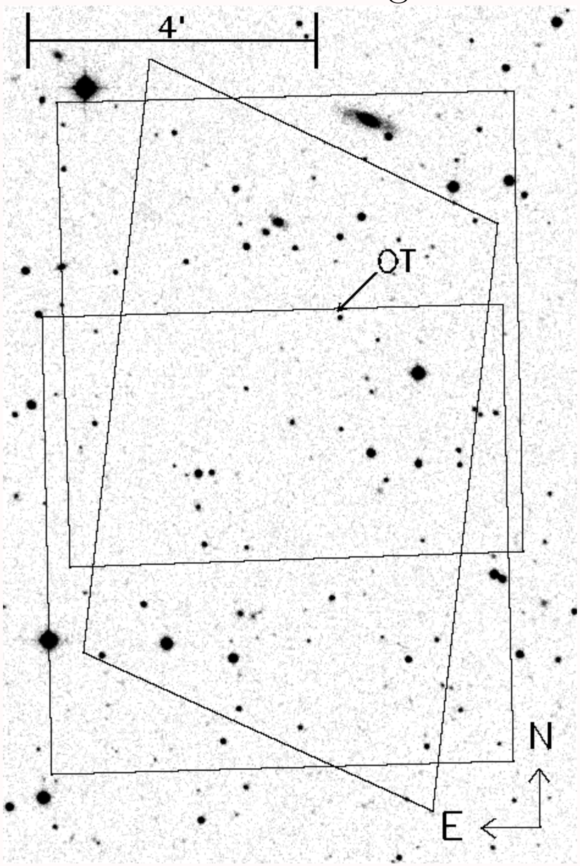
GRB 000301C localisation

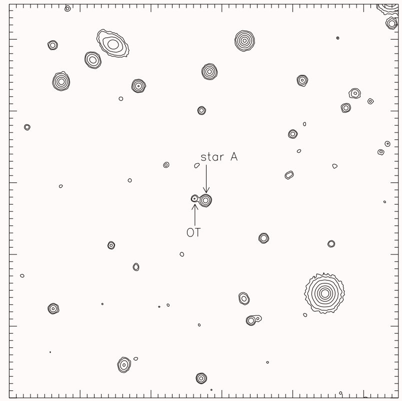


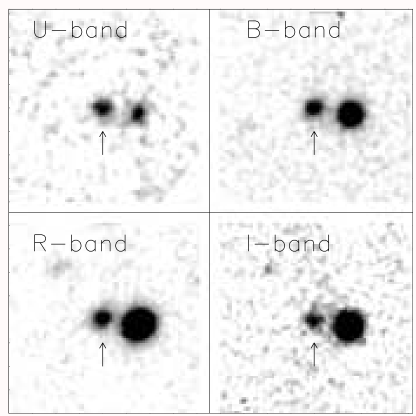


GRB 000301C – Finding Chart

GRB 000301C finding chart







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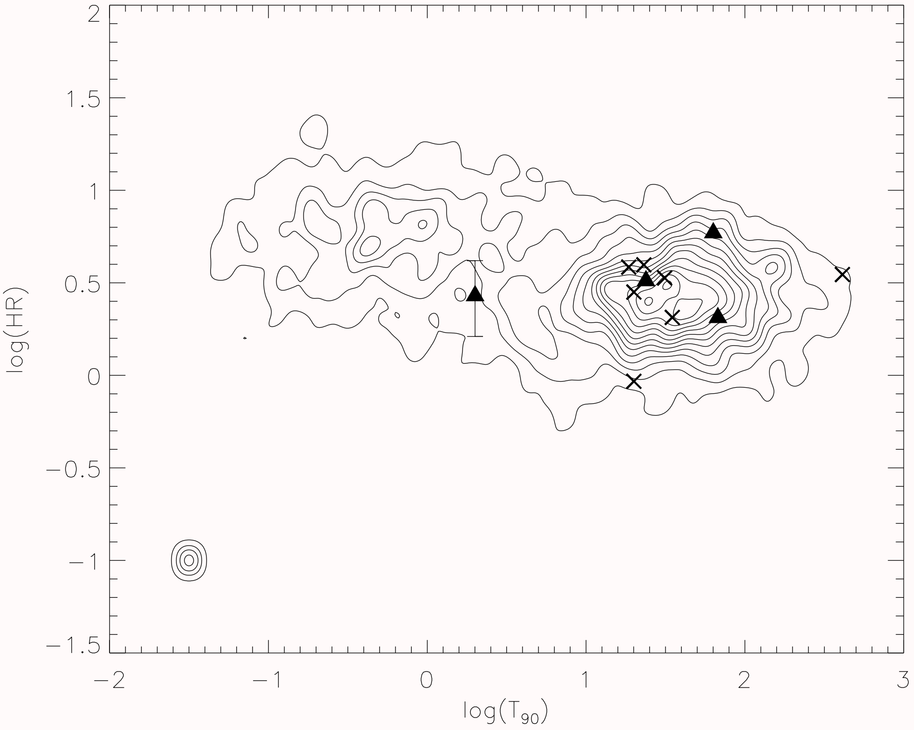
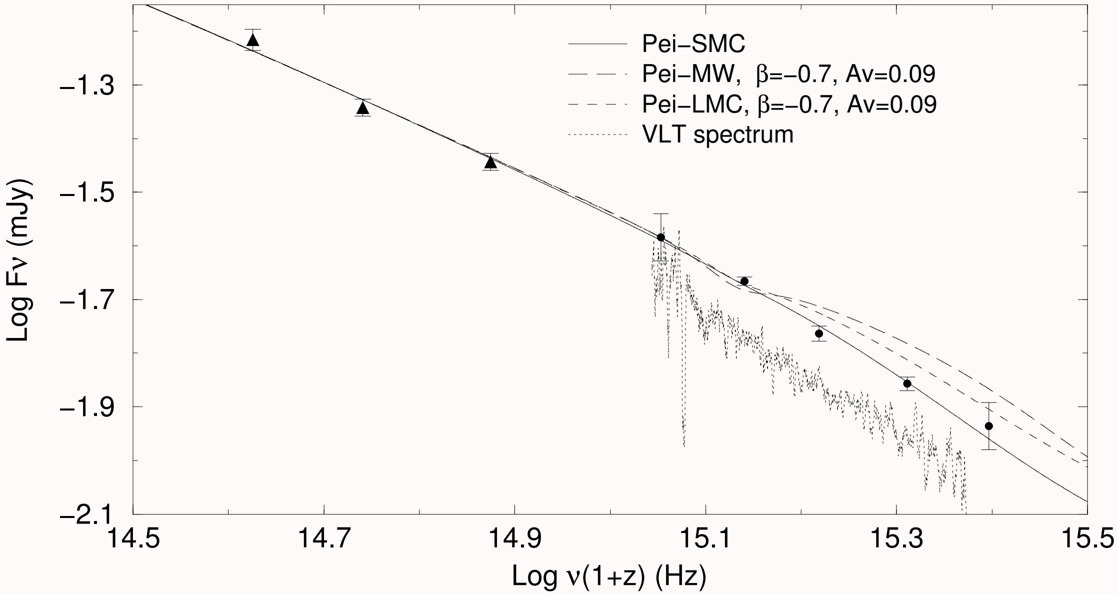
GRB 000301C – Intermediate burst

GRB 000301C – duration-hardness:



Consistent with GRB 000301C being an intermediate burst.

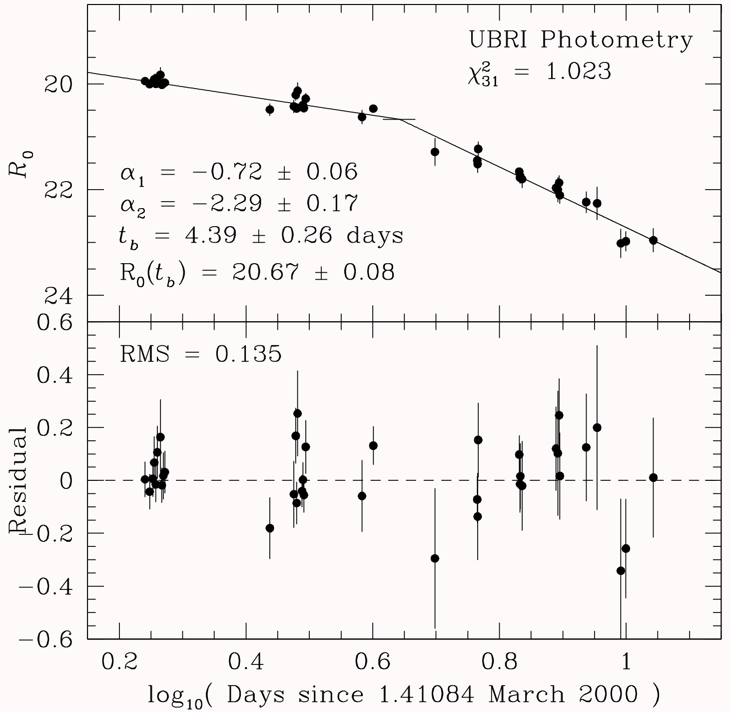
GRB 000301C – Spectral Energy Evolution:



Fitting the afterglow SED with three canonical extinction laws (provided by Pei, 1992) for the *Milky Way* (MW) and the *Large* and *Small Magellanic Clouds* (LMC and SMC). The best fit is provided by the SMC-like extinction curve.

GRB 000301C lightcurve

GRB 000301C, lightcurve:



5. Dark Bursts

Dark Bursts:

- No detectable optical afterglow.
- Dark burst fraction is $\approx 50\%$ (and falling).

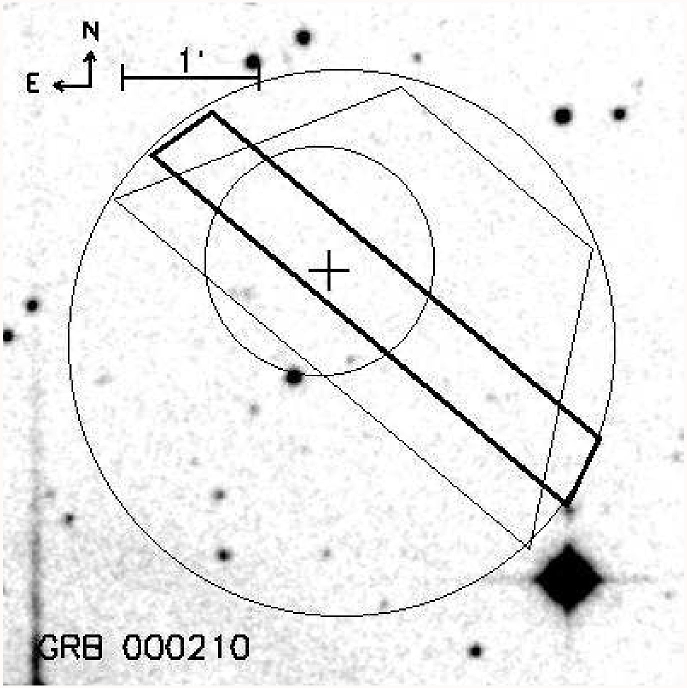
Possible origins for Dark Bursts:

- Selection effects caused by bad localisations (*tested*).
- An intrinsically low afterglow flux, caused by e.g.:
  - Off-axis viewing of a collimated outflow.
  - A less dense circumburst medium.
- An unusually rapid decay rate.
- Very high redshift.
- Obscuration.

Summary

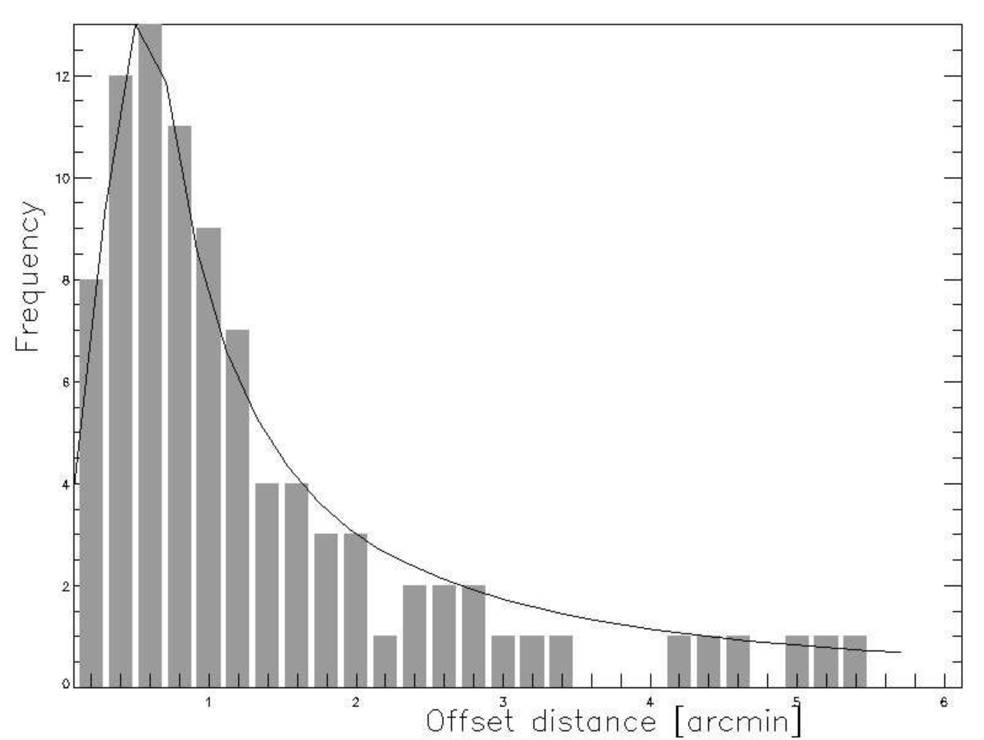
GRB Localisations

GRB localisation of GRB 000210, localised with the BeppoSAX satellite (circles) and the InterPlanetary Network (polygonals).



GRB Localisations

Distribution of (GRB – localisation centre) offset distances, fitted with a corresponding normalised gaussian distribution.

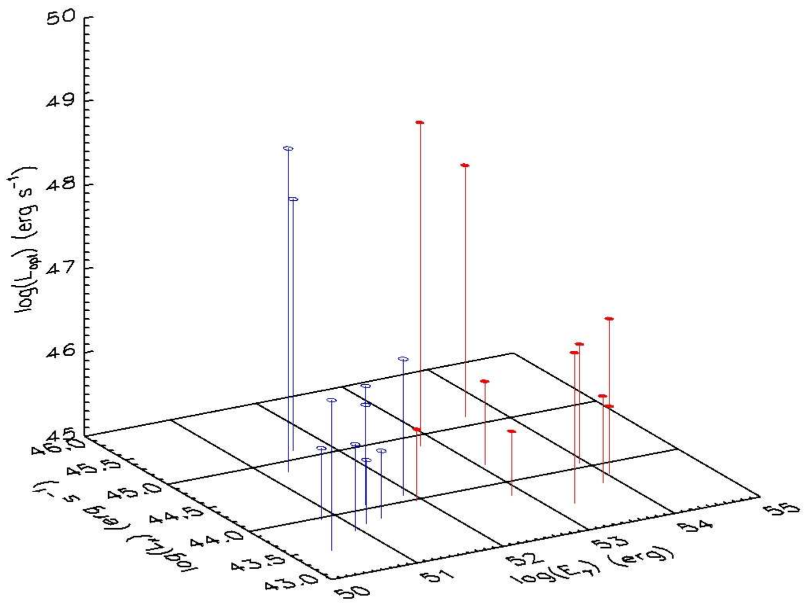


The relatively good fit ($\chi^2_{red} = 0.20$) indicates that the localisations are, in general, not affected by significant systematics.

Hence, Dark Bursts are, in general, not caused by bad localisations.

Energetics and Beaming

GRB – Afterglow energetics.



GRB – Afterglow energetics.

Energies of GRB prompt emission (X-axis), optical (Y-axis) and X-ray (Z-axis) afterglows for 10 GRBs. Afterglow energies are beaming and k-corrected.
Red corresponds to beaming **un-corrected** prompt emission.
Blue corresponds to beaming **corrected** prompt emission.

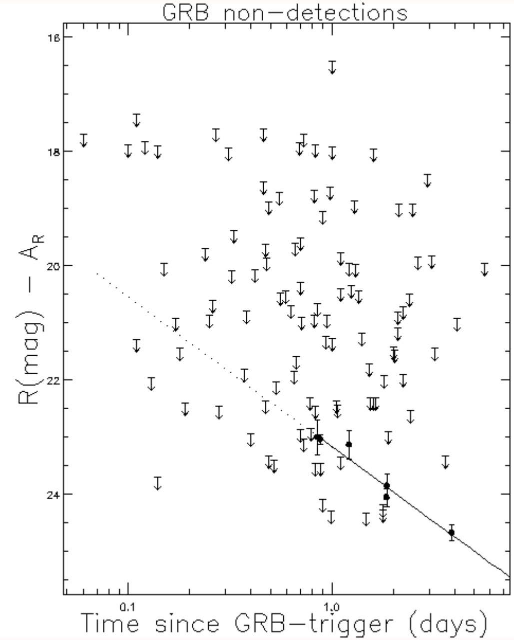
Dark Bursts

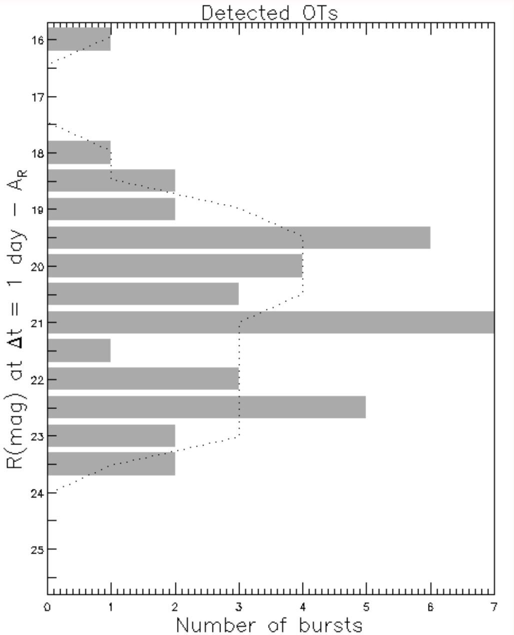
In summary, these preliminary conclusions can be drawn:

- Dark Bursts are, in general, not caused by bad localisations.
- The clustering in the energetics indicate a coupling in the afterglow energetics of the optical and X-ray afterglows. Combined with the typically lower X-ray flux of dark bursts, this indicate that extinction/absorption cannot completely account for all Dark Bursts.

GRB Upper limits

GRB upper limits (extinction corrected):





Left: Most constraining upper limits for 84 Dark Bursts.

Right: Distribution of detected optical afterglow (OA) magnitudes at $\Delta t = 1$ day.

6. Summary and Conclusion

Main results:

- Development of successful ToO-system.
- Very successful GRB Rapid Response ToO-activation and follow-up.
- Testing validity of specific Dark Burst assumptions.
- Findings support that a significant sub-set of the Dark Bursts may represent a distinct class.

Do we still need more GRBs?

- Not just better statistics (but also important!)
- GRBs can prove to be an indispensible cosmological tool, tracing the star-formation history of the Universe and probing the high-redshift Universe.
- . . . but we need to properly determine the associated biases first. . .