# Optical observations of GRB afterglows

*Shashi B. Pandey*

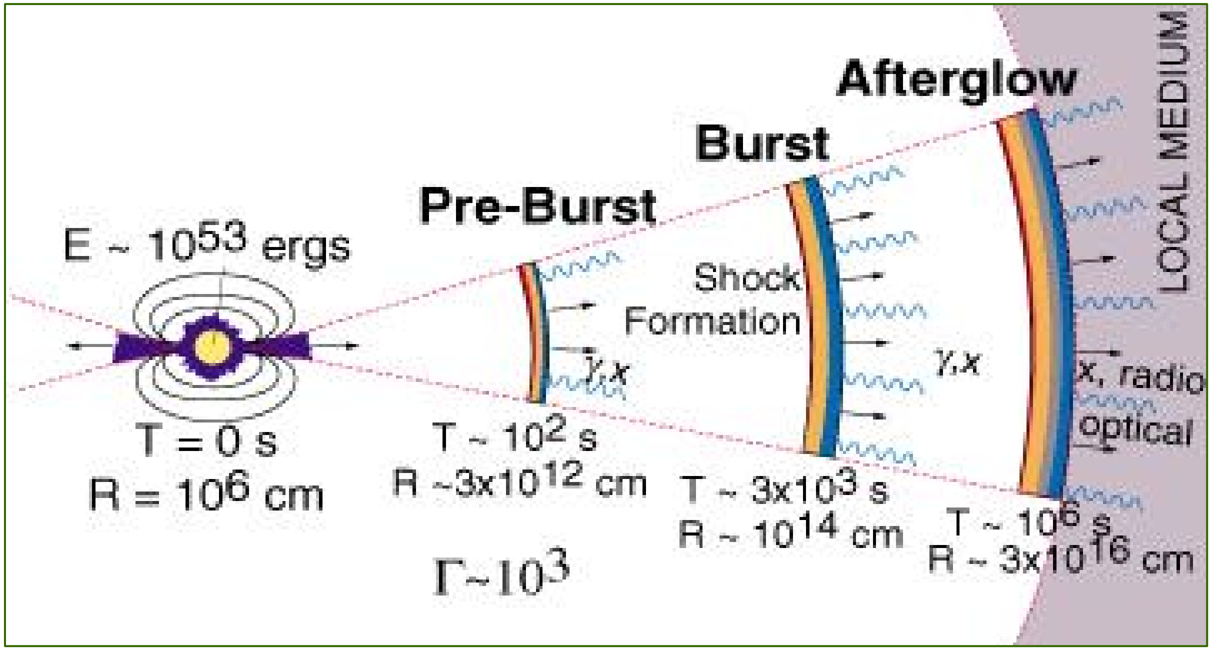
*IAA, Granada, Spain*

# Plan of the talk

- Introduction to afterglows of GRBs
- Observations of optical afterglows
- LCs and SEDs of  afterglows
- Modeling of afterglows
- Results

# Afterglows of GRBs

- Relativistic shells ejected from the central engine, form shocks, convert their kinetic energy into radiation.
- Shocks interact with ISM, emits non-thermal synchrotron radiation ranging from X-ray, optical to radio known as *afterglows.*

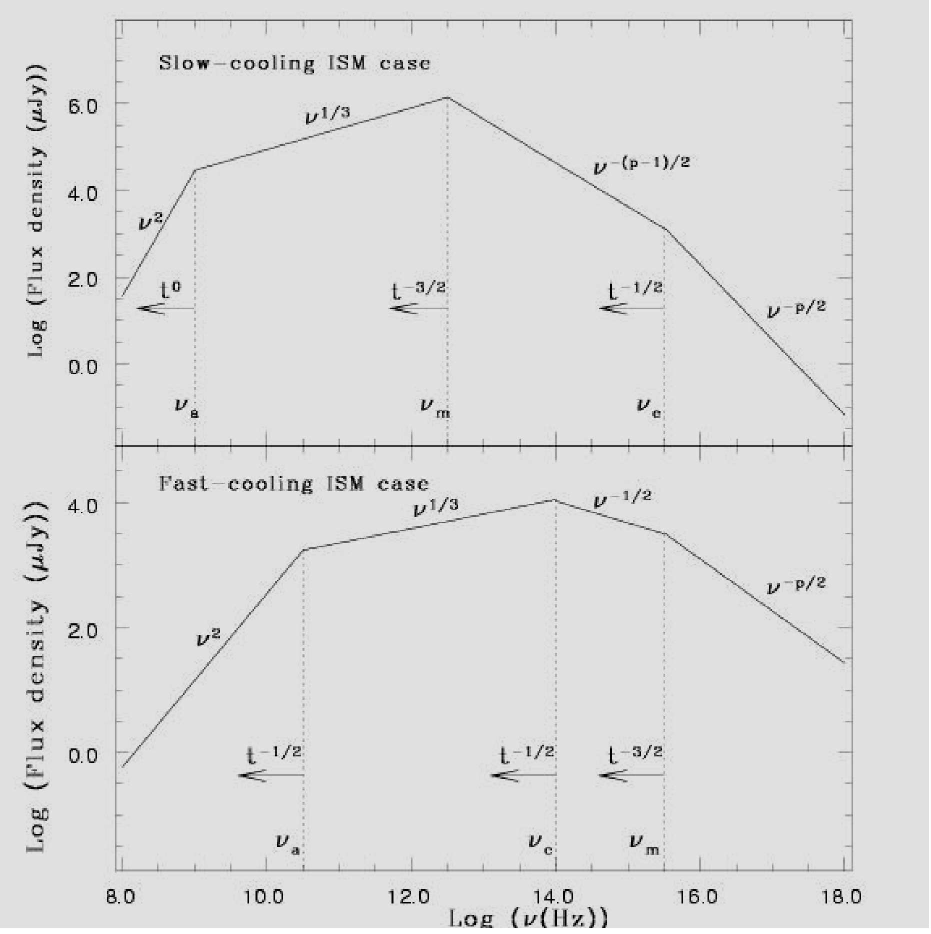



Cartoon of fireball model

# Importance of afterglow observations

- **Long baseline in temporal and spectral domains**
- **Indirect probe to know about the progenitor**
- **Surroundings, distance and energetics**
- **Host galaxies**
- **Multi-band afterglow modeling** ***(ISM Vs. WIND)***

# Basic GRB afterglow theory



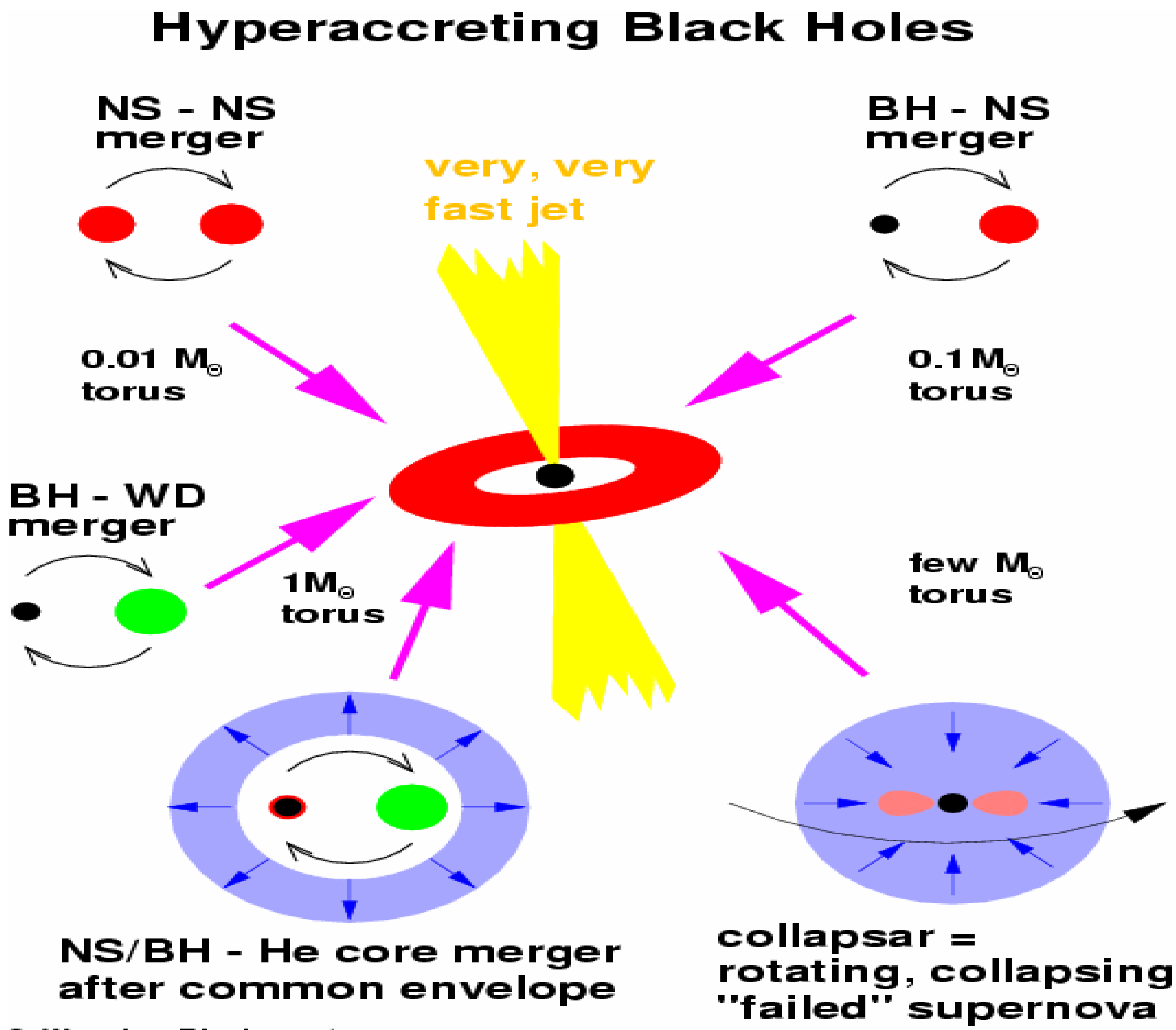

**The energy distribution of the injected electrons is a power-law:**

$$N(\gamma_e) \propto \gamma_e^{-p}, \quad \gamma_m < \gamma_e < \gamma_u$$

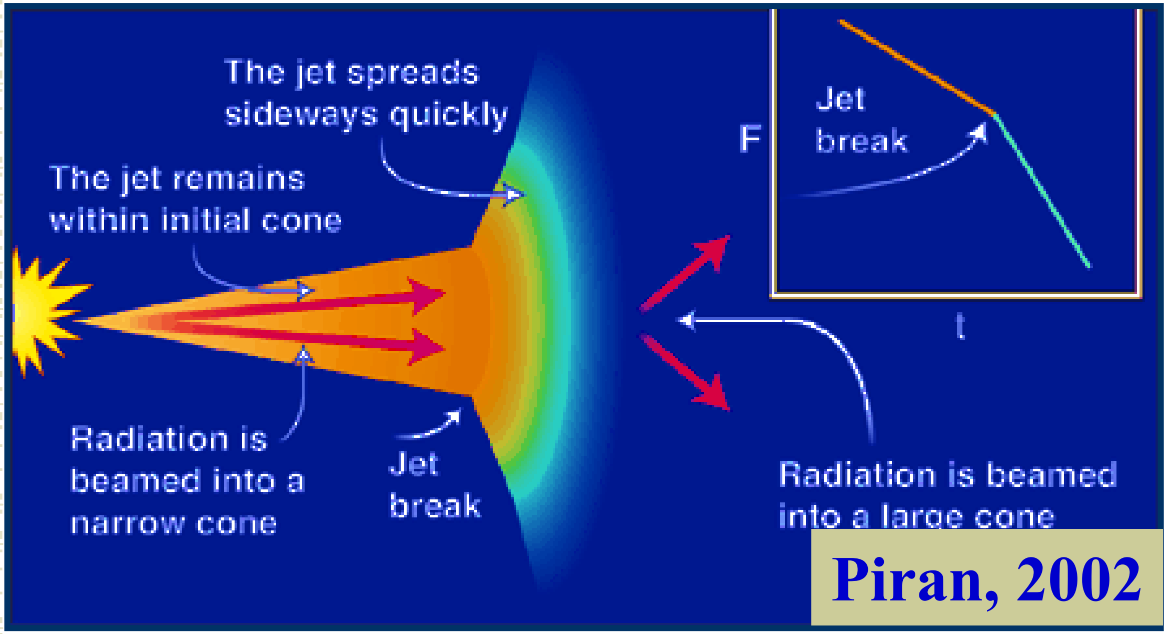
***p, the electron energy index***

**Theoretical spectral energy distribution of GRB afterglows (Synchrotron radiation)**
**(Sari Piran & Narayan 1998)**

# Possible progenitors



# Jet Signatures - I



Piran, 2002

**Output γ-ray energy & No. of bursts**

↑

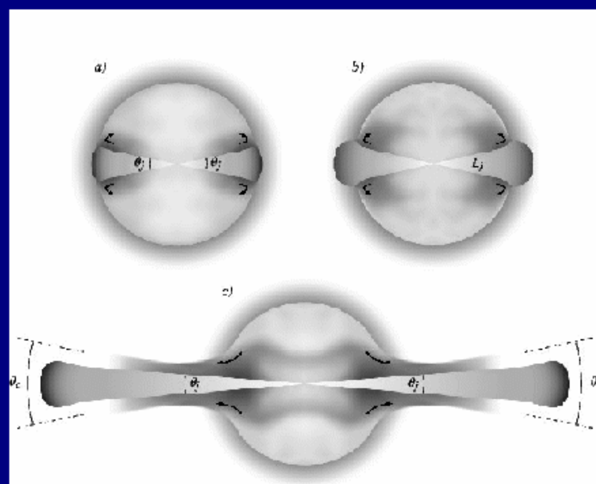
$$E_\gamma = (1 - \cos\theta_j)\ E_{iso,\gamma}$$

↑

***Achromatic break in observed LCs***

$$f_\nu(t) = 2^{1/s} f_0 / [(t/t_j)^{\alpha 1 s} + (t/t_j)^{\alpha 2 s}]^{1/s} + f_g \quad \rightarrow \quad \theta_j$$

# Jet Signatures - II



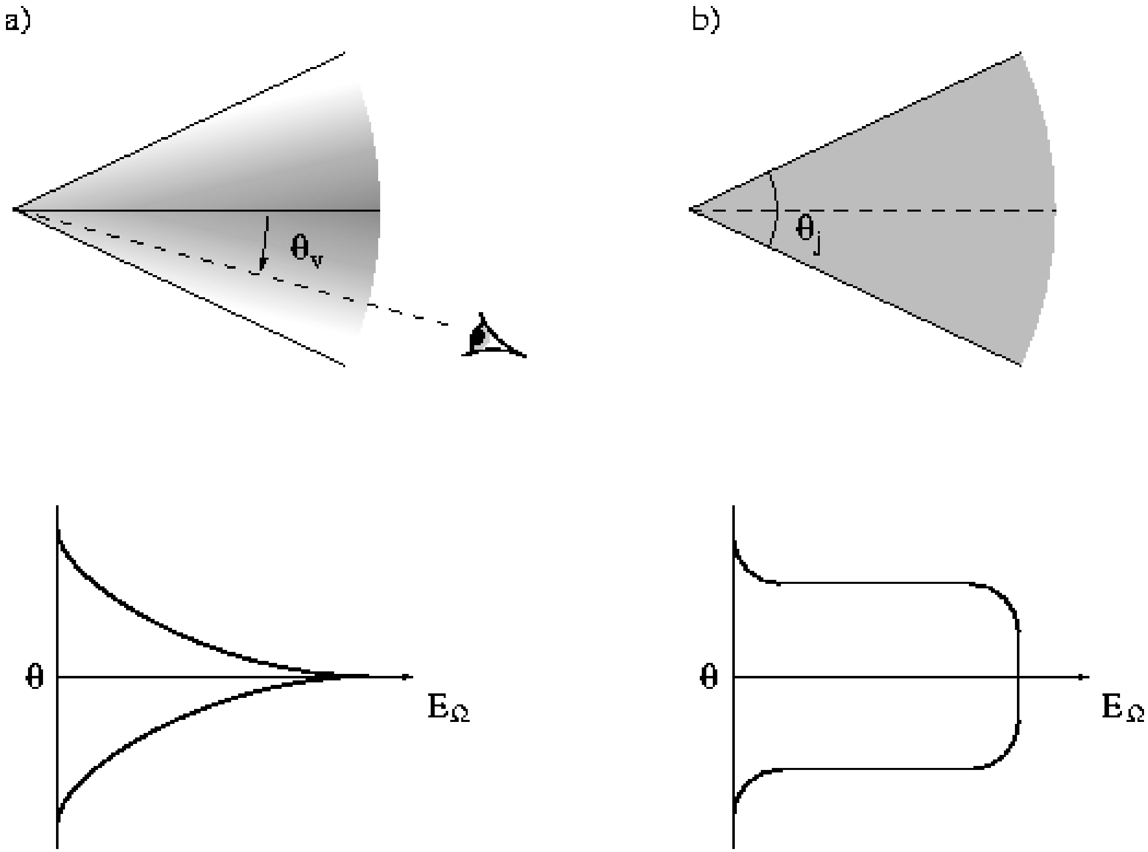
Jet powered by newly formed central Black Hole emerging from the stellar envelope.
The envelope is eventually expelled in a supernova (hypernova?)

*Ramirez-Ruiz et al 2002, Woosley et al 2002, 2003*

**Massive (M > $25_{sun}$), Stellar Collapse simulations**

**Signatures of "Two-Jet model"**

# Jet structure, UJ & USJ Models



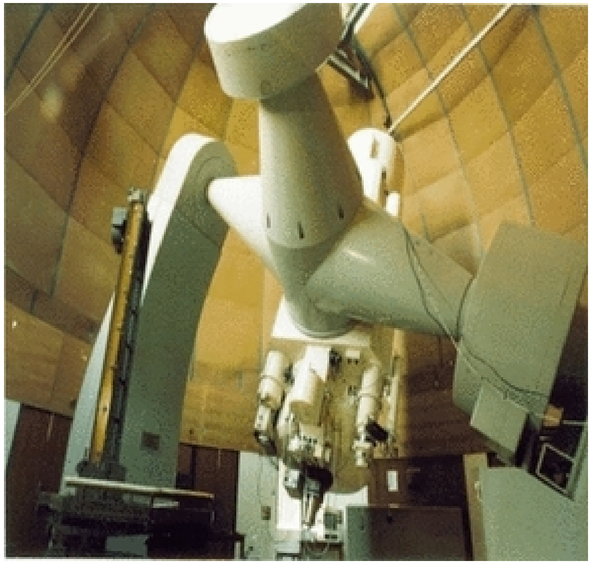

***Universal Structured Jet***

***Uniform Jet***

# GRB Optical afterglow observations

- Since Jan 99, We probed > 30 fields from IPN, BeppoSAX, HETE, INTEGRAL
- Observed 13 afterglows, from Jan 1999 to May 2003, presented in the Thesis
- Using CCD (1K∗1K, 2K∗2K & 2K∗4K), in UBVRI filters
- Photometry/Spectroscopic data reductions using standard packages IRAF, MIDAS and DAOPHOT-II
- Calibrations using our own secondary standards in most of the GRB fields
- Calibrations and data are published in (Sagar R. et al. 2001a,b, 2002 and Pandey S. B. et al. 2003a,b & 2004)

# The Optical facilities used



**1.04m, ST, Naini Tal**

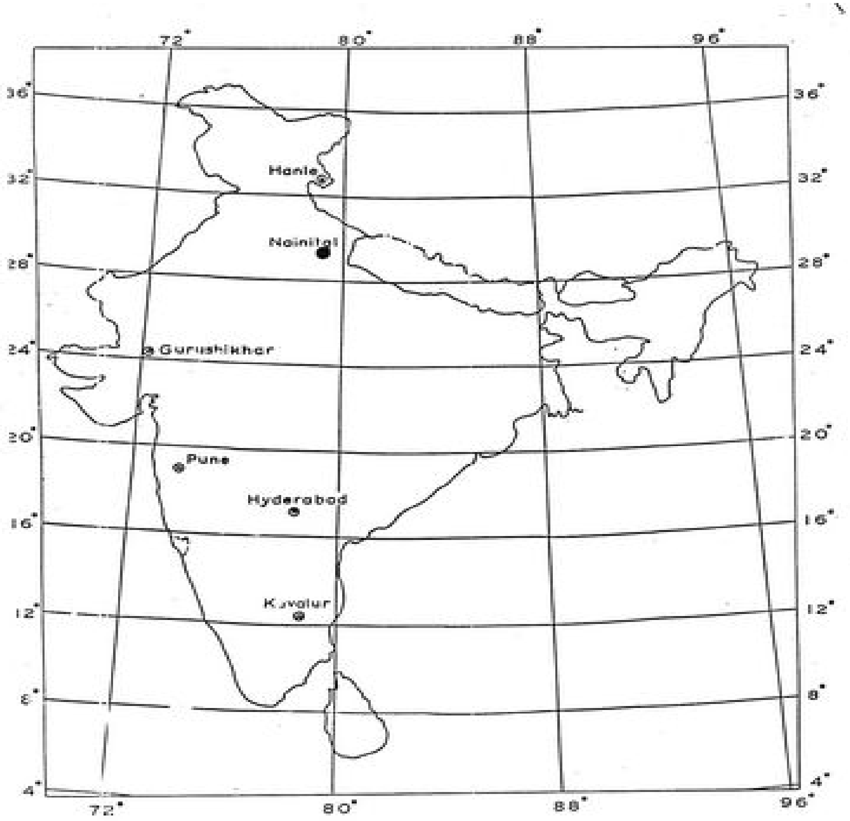
**f/13 Cassegrain**

**2.01m, HCT, IAO**

**f/9 Cassegrain**

**2.34m, VBT, Kavalur**

**f/13 Cassegrain**




**Importance of geographical location of India for GRB afterglow observations**

# List of observed optical afterglows of GRBs

| (GRB Name) | (Filters Observed) | (Localizations by) |
|---|---|---|
| GRB 990123 | BVR | BeppoSAX/WFC |
| GRB 991208 | I | Uly/Konus/NEAR |
| GRB 991216 | R | BAT/PCA |
| | | |
| GRB 000301C | VRI | ASM/Uly |
| GRB 000926 | R | Uly/Konus/NEAR |
| | | |
| GRB 010222 | VRI | BeppoSAX/WFC |
| GRB 011211 | R | BeppoSAX/WFC |
| | | |
| GRB 020405 | I | Uly/MO/BeppoSAX |
| GRB 021004 | BVRI | HETE-II |
| GRB 021211 | BVRI | HETE-II |
| | | |
| GRB 030226 | UBVRI | HETE-II |
| GRB 030227 | R | INTEGRAL |
| GRB 030328 | BVRI | HETE-II |
| GRB 030329/SN 2003dh | UBVRI | HETE-II |

# Observational facts from optical afterglows

- **Afterglow Light-curves**

  # Break in the afterglow light-curves
  # Superimposed variability
  # Late time flattening due to underlying host galaxy
  # Late time SN-bumps

- **Spectral energy distributions**

  # Tells about the location of break frequencies $\nu_c$ and $\nu_m$

  # Spectral slope $\beta$, in combination with temporal slopes $\alpha$ can tell about the electron energy index p

  # Deviation from expected power law due to reddening in different regime tells about intrinsic host extinction

# Optical afterglows of GRBs

- **In the synchrotron afterglow model, temporal slope $\alpha$ & spectral slop $\beta$ are observed as a power-law decay**

**related as $F_\nu (t, \nu) \propto t^{-\alpha} \nu^{-\beta}$, with no spectral breaks.**

**$\alpha$ and $\beta$ are function of p, the power law exponent of the electron Lorentz factor.**

**Models ➡**

**Isotropic emission** **Sari, Piran & Narayan (1998)**

**Non-isotropic emission** **Rhoads (1999), Sari Piran & Halpern (1999)**
**Rossi, Lazzati & Rees (2002)**

# Breaks in the afterglow LCs

- **Passage of break frequencies through observed frequency, chromatic**

  $\Delta\alpha$ **=** 1/4, passage of cooling break through observed frequency

- **Jet break, achromatic**

**A.** **Beaming angle $1/\Gamma$ exceeds collimation angle $\theta$ (Geometric effect)**

**light curve steepening $\Delta\alpha = \alpha_1 - \alpha_2 = (3 - s)/(4 - s)$**

**( s = 0 *for ISM* & s = 2 *for WIND*) (Panaitescu Meszaros & Rees 1998)**

**B.** **Sideways expansion of the jet (Due to Dynamical evolution)**

**late time temporal slope $\alpha_2 = p$ (Rhoads, 1999)**

# $\alpha$, $\beta$ and p relations

1. **Before jet break**

if $\nu_m < \nu < \nu_c$ , $\alpha_1 = 3(p-1)/4$ , $\beta = (p-1)/2$ , $\alpha_1 = 3\beta/2$

if $\nu > \nu_c$ , $\alpha_1 = (3p-2)/4$ , $\beta = p/2$ , $\alpha_1 = 3\beta/2 - 1/2$

2. **After jet break**

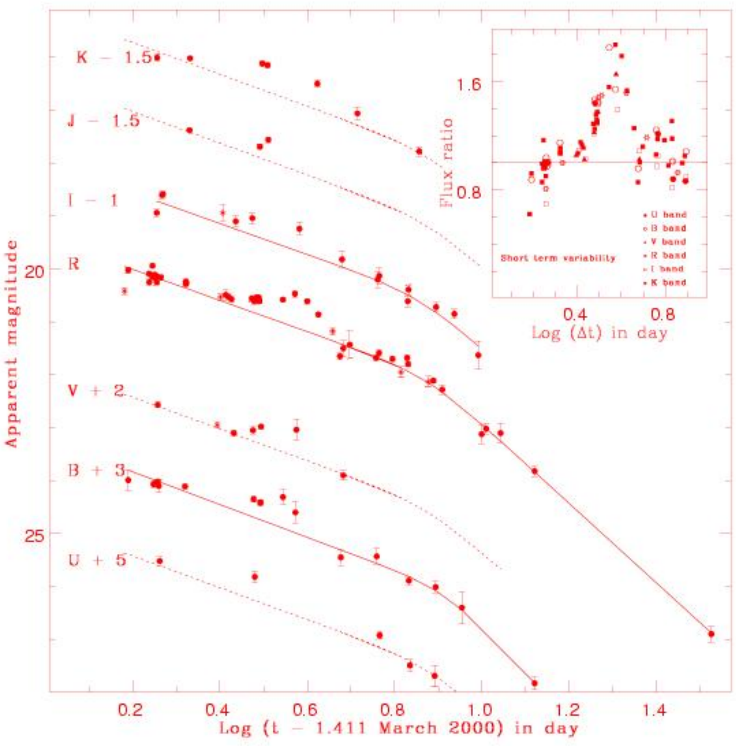
if $\nu_m < \nu < \nu_c$ , $\alpha_2 = p$ , $\beta = (p-1)/2$ , $\alpha_2 = 2\beta + 1$

if $\nu > \nu_c$ , $\alpha_2 = p$ , $\beta = p/2$ , $\alpha_2 = 2\beta$

Sari Piran & Halpern (1999)

# GRB 000301C, afterglow LCs

- **Achromatic break is clear in all passbands**
- **Averaged temporal slopes $\alpha_1$ = 1.2±0.1, $\alpha_2$ = 3.0±0.5 and $t_j$ = 7.6±0.06 day**
- **Explained in terms of ISM Jet model Predictions in combination with spectral Index, except the overlapped variability**

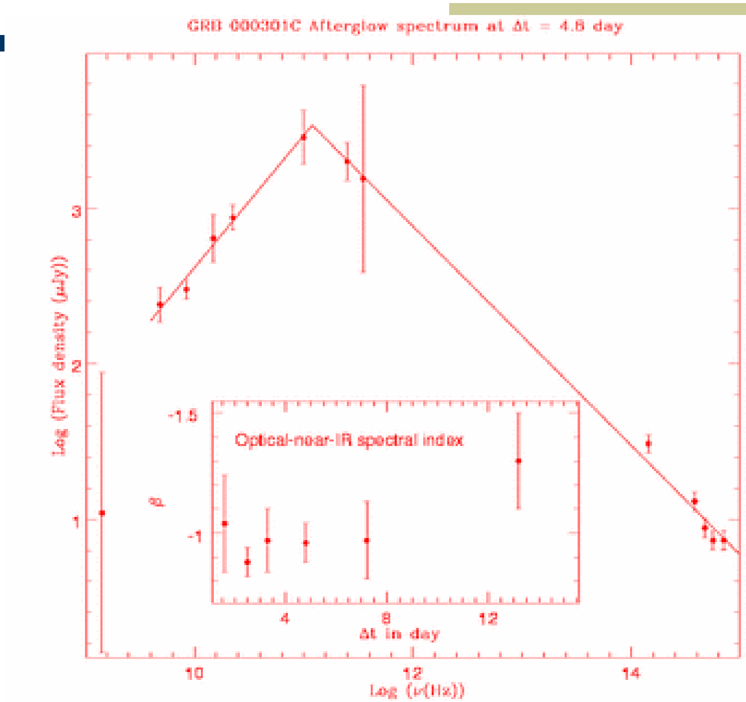



**GRB 000301C, Sagar et al., (2000)**

# GRB 000301C, afterglow SEDs

- **Spectral slope $\beta$ from optical data with other frequencies can be used to constrain the break frequencies $\nu_m$ and $\nu_c$ and electron energy index p.**

**In this case, at $\Delta t$ = 4.8 day, $\beta$ = 0.73±0.06**
**E(B –V) = 0.05 mag, Galactic extinction**




**GRB 000301C SED, Sagar et al. (2000)**

- **Cooling frequency $\nu_c$ is above optical at the epoch.**
  **It is clear from the single spectral slop from IR – optical bands.**

- **Maximum synchrotron frequency $\nu_m$ seems to lie in millimeter region.**

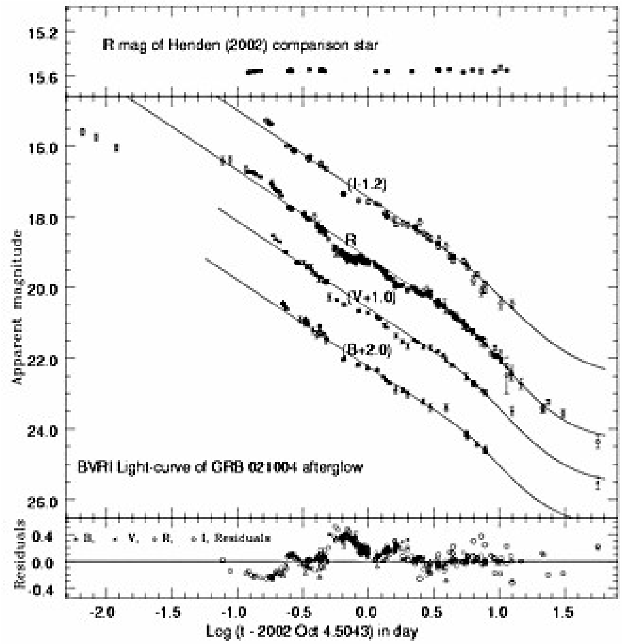
# GRB 021004, afterglow LCs

**Used t > 2 data only to determine parameters**

**$\alpha_1$ =0.99±0.05, $\alpha_2$=2.0±0.2, $t_j$ = 6.5±0.2 day**

**Early 3 data points in R band are explained
Due to reverse shock emission**

**Late time host galaxy contribution is clear**



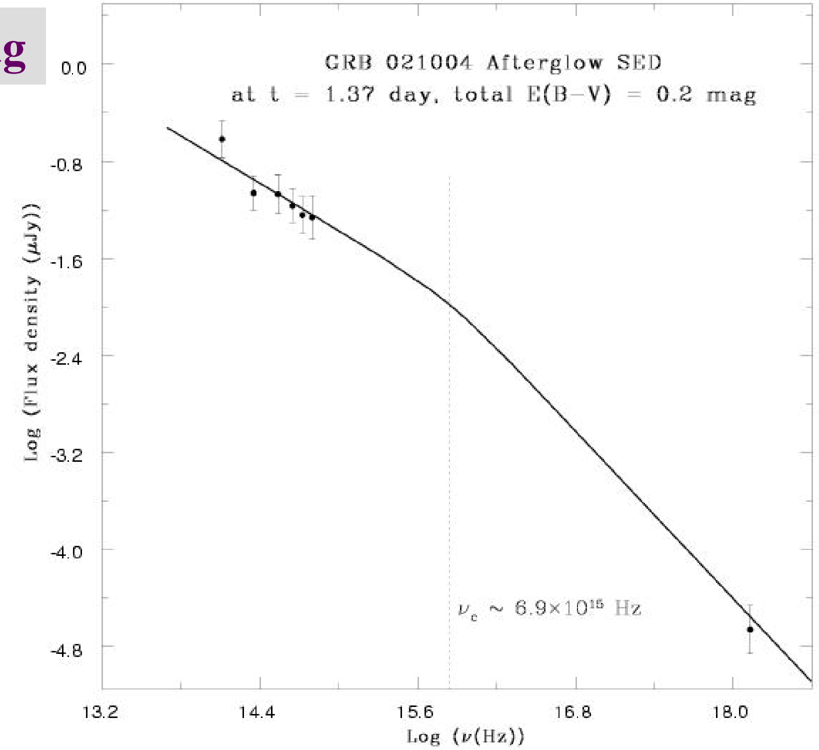

**Pandey et al., 2003**

# GRB 021004, afterglow SED

**SED at 1.37 day, Galactic E(B-V) = 0.02 mag**

**$\nu_c$ ~ 6.9*$10^{15}$ Hz, p = 2.27, E(B-V) = 0.2 mag**

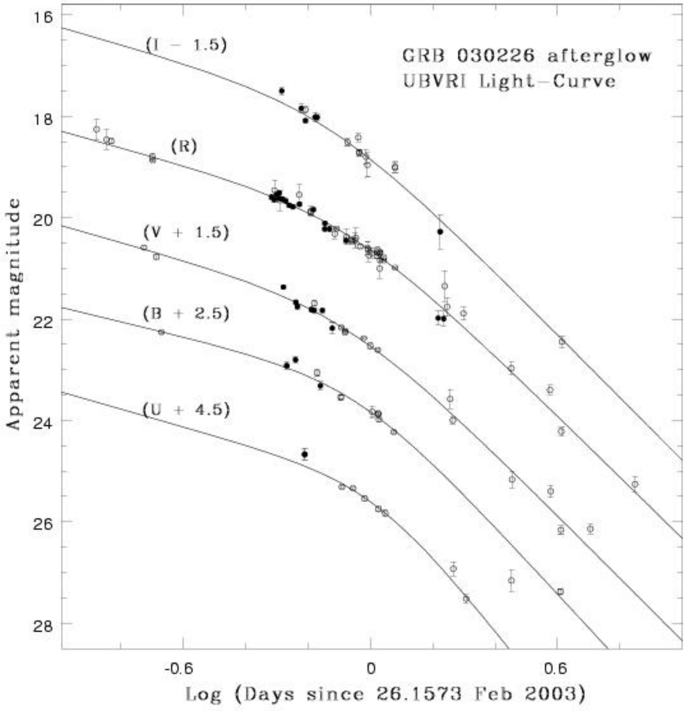
**This SED determines Host extinction In the burst direction and determined parameters are explained in terms of ISM Jet model (UJ)**



# GRB 030226, afterglow LCs

- $\alpha_1 = 0.67 \pm 0.02$, $\alpha_2 = 2.5 \pm 0.03$, $t_j = 0.86 \pm 0.03$ day
- Determined spectral index $\beta$ and so the electron energy index $p \sim \alpha_2$
- Explained in terms of sideways expansion of jet
- Our photometric calibrations don't indicate for density-jump in the ambient medium.

(Dia & Wu 2003)



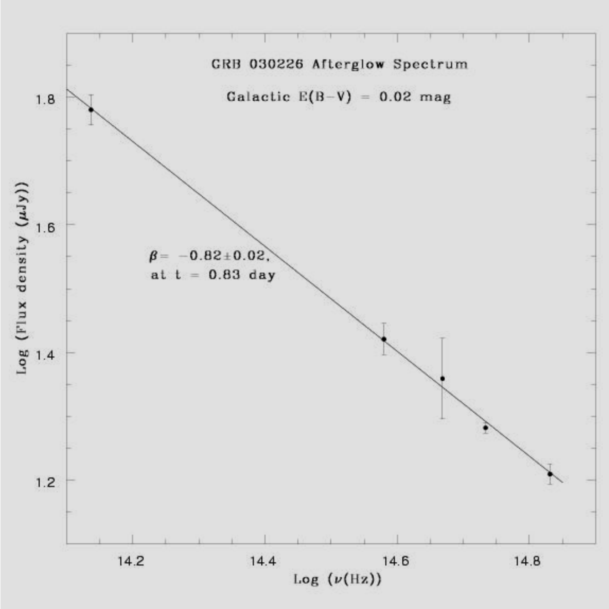

GRB 030226, Pandey et al., (2004)

# GRB 030226, afterglow SED

- Present case, around jet break, using BVRIK data, spectral slope $\beta$ = -0.82±0.0, small Galactic E(B – V) = 0.02

- Temporal slopes $\alpha_1$ = 0.67±0.02 $\alpha_2$ =2.5±0.03 and $t_j$ = 0.86±0.03

- If $\nu > \nu_c$ , $\alpha_2$ ~ p but predicted $\alpha_1$ is steeper, not in agreement with observed one




GRB 030226 SED, Pandey et al. (2004)

# Optically Dark GRBs

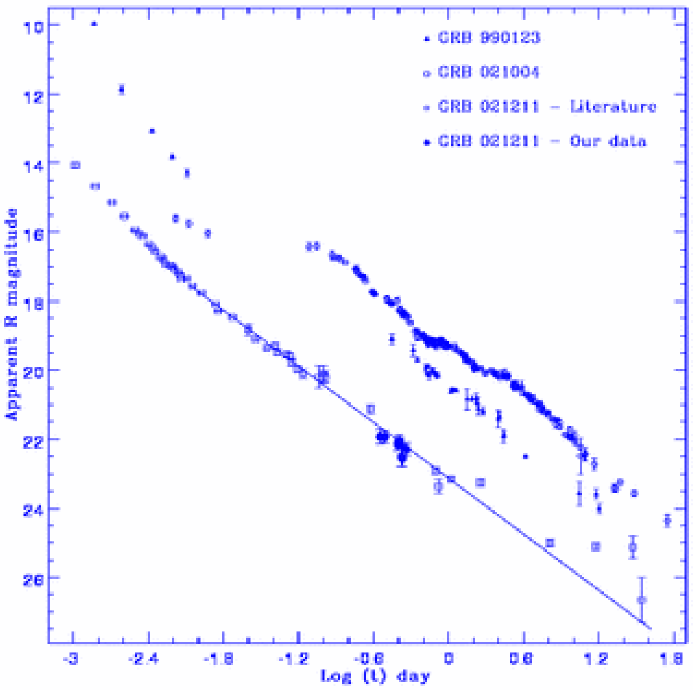
- GRBs with no optical afterglows but having X-ray, radio afterglows
- ~ 40 % of the afterglows are optically dark

**Explanations** ➡

- Failure to image quickly and/or deeply enough
- Intrinsically dim bursts
- Absorption due to circumburst extinction
- High red shift bursts (optical absorption in Ly$\alpha$ forest)

# GRB 021211 afterglow, Optically dim burst

- Optically dim, ~3 mag fainter than GRB 990123
- Detected ~90 sec after the burst
- R band, single power law ~ 11 min to 35 days with decay index $\alpha$ ~ 1.1
- Compared with GRB 000630 (Fynbo et al, 2001) GRB 020224 (Berger et al, 2002)
- Detected R ~ 23 mag, one day after the burst and similar temporal decay
- It would have been classified as optically dark burst in absence of rapid follow-up



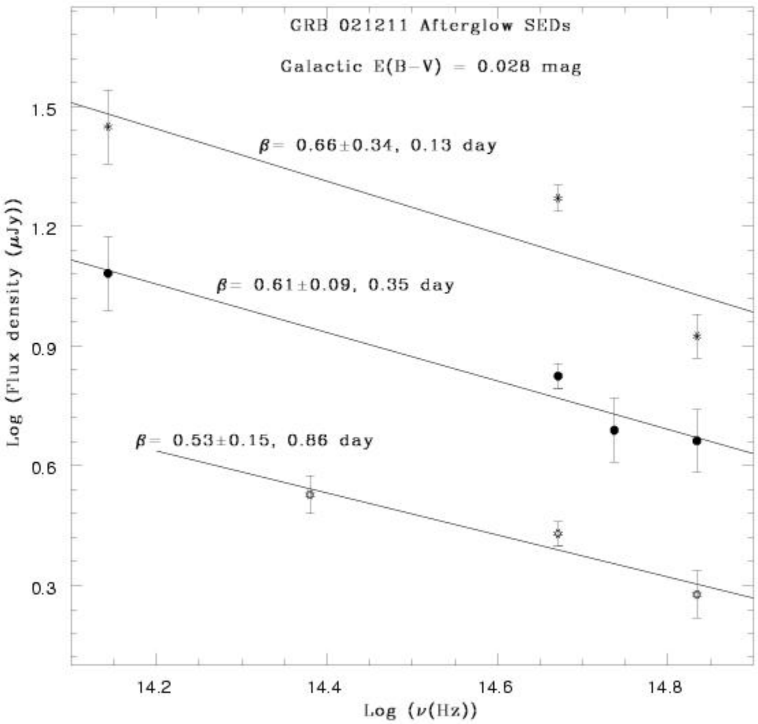

GRB 021211, Pandey et al., 2003b

# SED of GRB 021211 afterglow

**In this case, at $\Delta t$ = 0.13, 0.77 and 0.86 day and $\beta$ = 0.66±0.34, 0.61±0.09 and 0.53±0.15, E(B–V) = 0.028**

**No jet-break signature was observed**

**$\nu_c$ lying below optical frequencies**



# Variability in afterglow LC

**Variability (?)**

**Density fluctuations**

- Clumpy ISM
- Variable Stellar wind

**Energy fluctuations**

- Velocity effect (Refreshed shock model)
- Angular effect (Patchy shell model)

# Variability in afterglow LC

- **Density dominated fluctuations are effective for $\nu < \nu_c$**
  - * Produce only weak fluctuations
  - * Can't produce sharp changes in LC

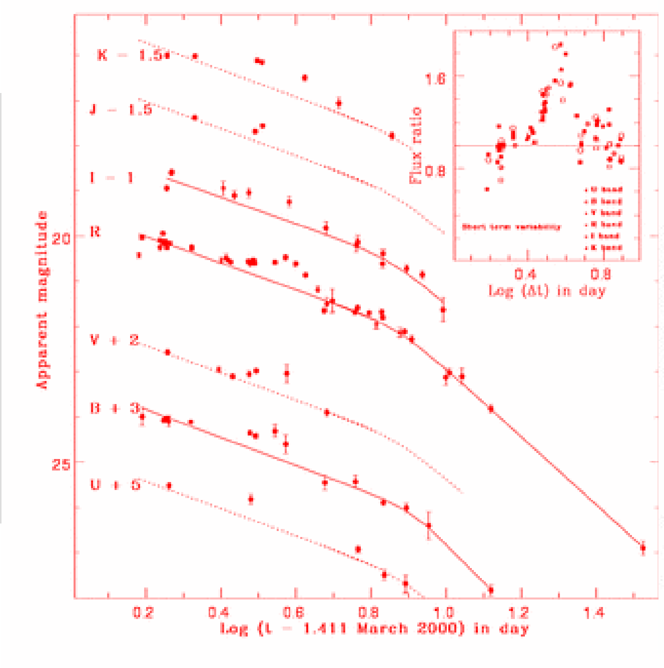
- **Energy variations will produce fluctuations below & above $\nu_c$**

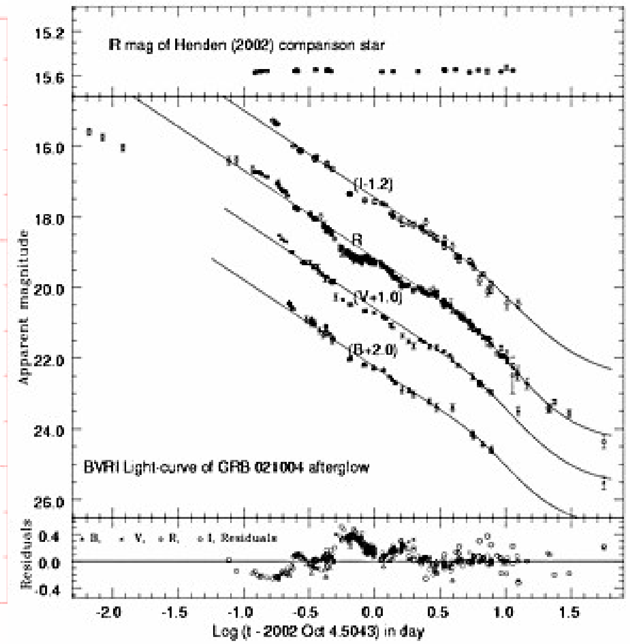
- **Refreshed shock model** (Produce random fluctuations)

- **Patchy shell model** (Hot or Cold spots in the jet)
  Intrinsic angular structure
  As the blast-wave decelerates, the angular size increases more than $1/\Gamma$, we see more and more jet structure.

# Superimposed variability in the afterglow LCs

- **Deviation from simple power-law i.e.. Bumps & Wiggles In the light curve or achromatic flux variations**

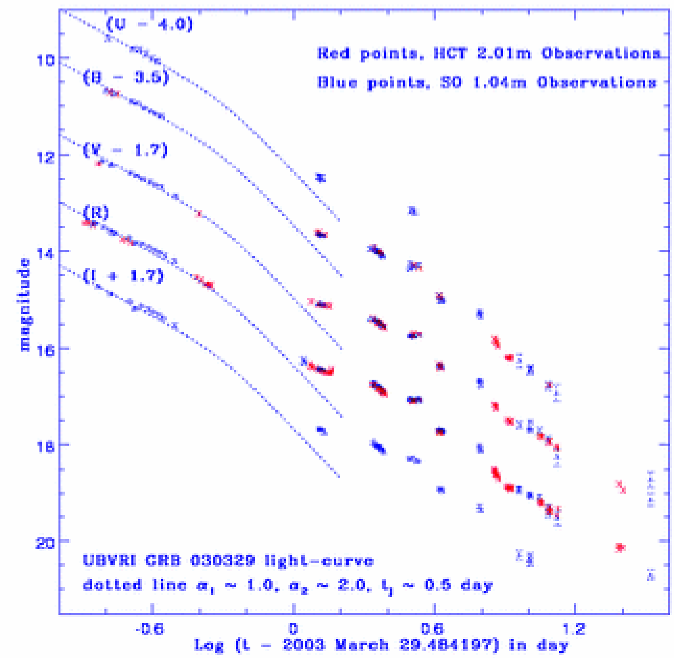



**GRB 000301C (Sagar et al. 2000), GRB 021004 (Pandey et al. 2003)**

# GRB 030329, Variability with SN-bump

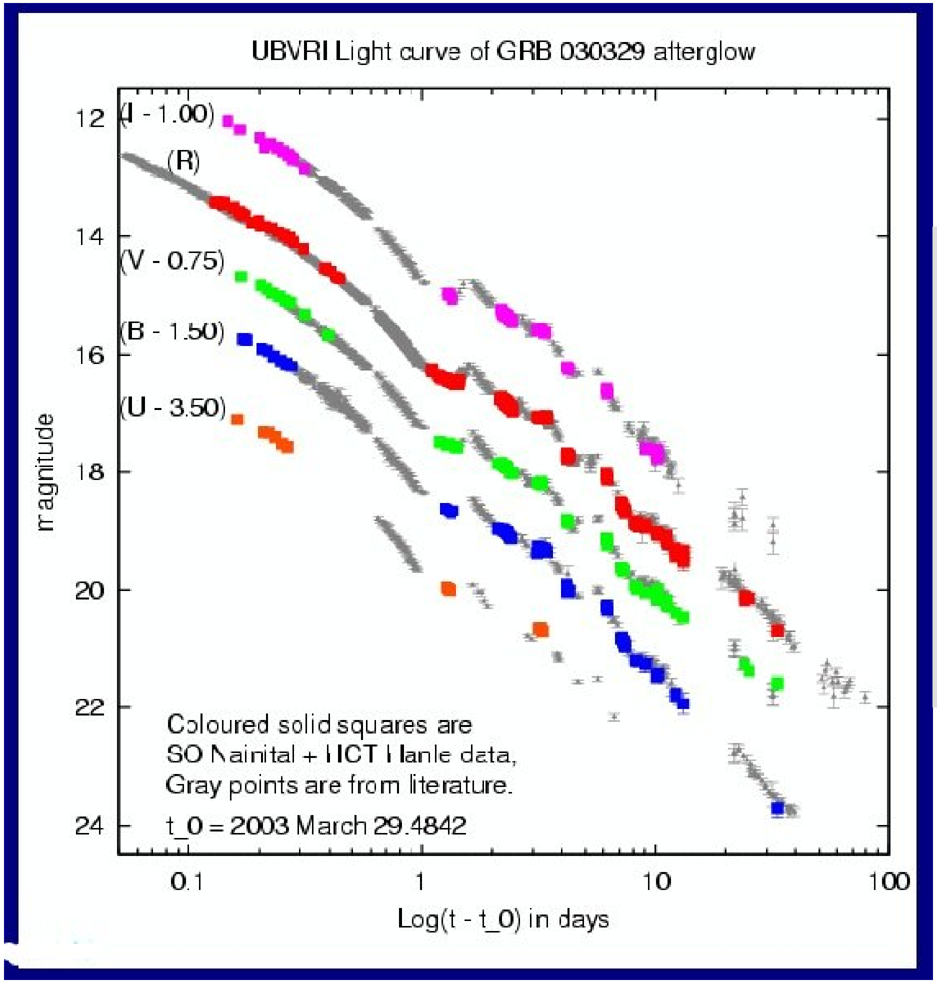
- First evidence GRB 980425/SN 1998bw (Galama et al., 1998)
- Unambiguous supernova signature was detected for GRB 030329 by (Stanek et al., 2003)
- Late time red-bumps, weeks after the GRB show change in colour from the afterglow in GRB 970828 (Reichart et al., 1999), GRB 980326 (Bloom et al., 1999), GRB 011121 (Garnavich et al., 2002), GRB 020405 (Price et al., 2003) and GRB 021211 (Della Valle et al. 2003) too.




GRB 030329 UBVRI light-curve

- Recently, Resmi et al. (2005) modeled the BVRI data of GRB 030329 in terms of two-component jet model by Berger et al. (2003) fitted early ≤ 1.5 day optical, X-ray data as ultra-relativistic *N A J* component and > 1.5 day optical and radio data using mildly relativistic *W A J* component.

# GRB 030329/SN 2003dh

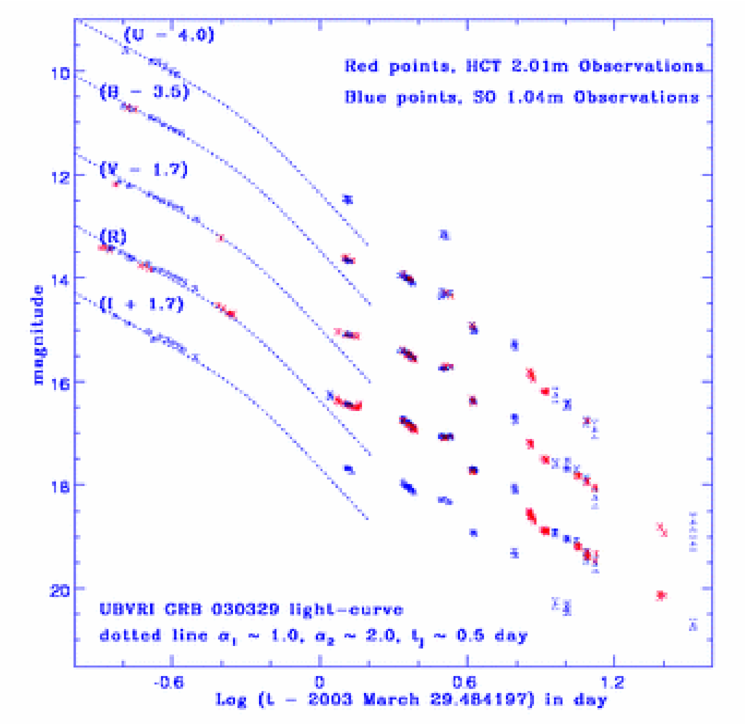


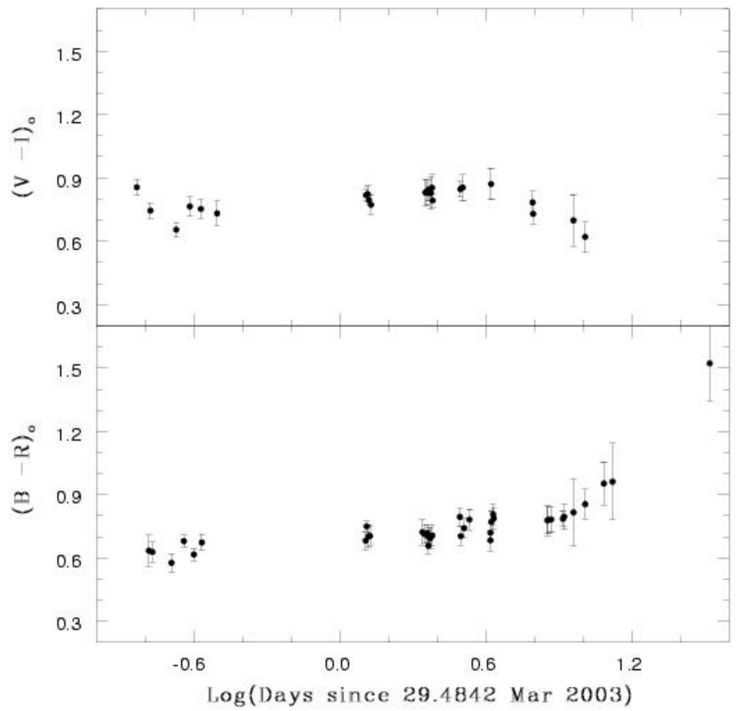

**Monitored from 3 hours to 33 days After the burst**

**UBVI, earliest observations**

**Peculiar afterglow light curves with Overlapped variability and SN 2003dh contribution**

# GRB 030329/SN 2003dh

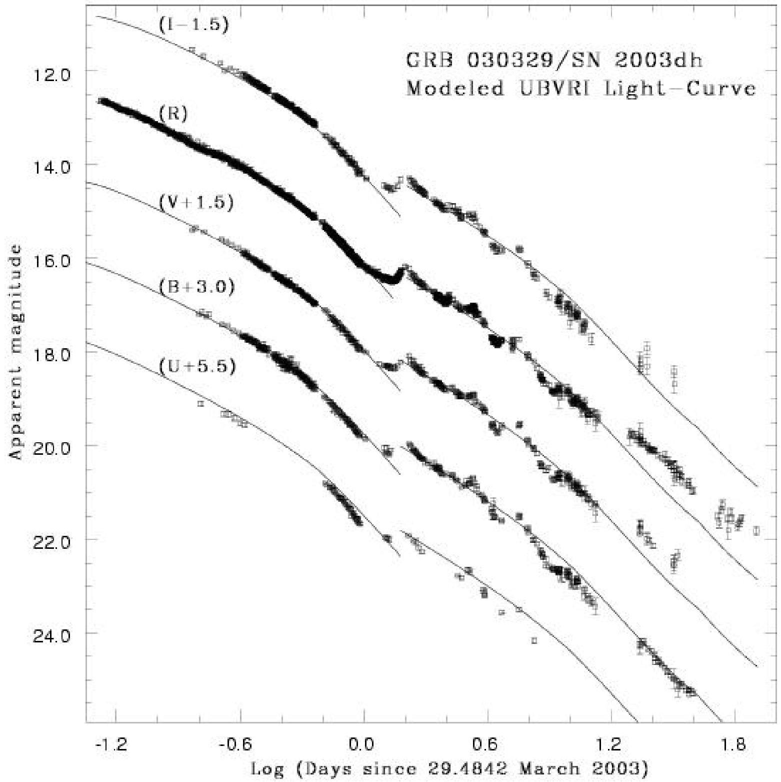


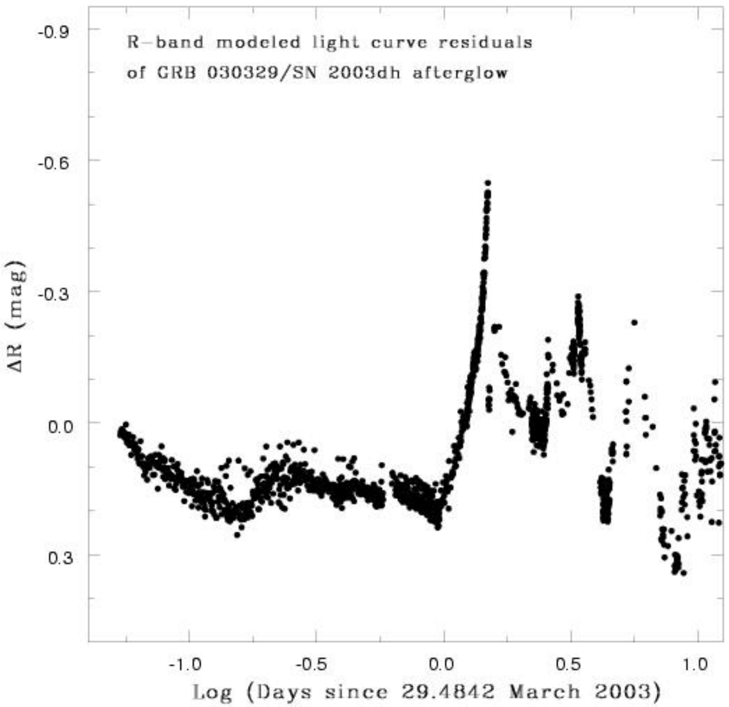




**Deviation from a broken power-law**
**Phases of re-brightening**
**Later part dominated by SN 2003dh contribution**

**(B-R) grows redder, (V-I) grows Bluer, after 6 days, typical for a SN evolution**

# GRB 030329/SN 2003dh




**Two-jet model, NAJ for < 1.5 day WAJ for > 1.5 data**

**R-band residuals, show step-like profile, expected from Patchy shell Model, re-freshed shocks**

# Broad-band afterglow modeling

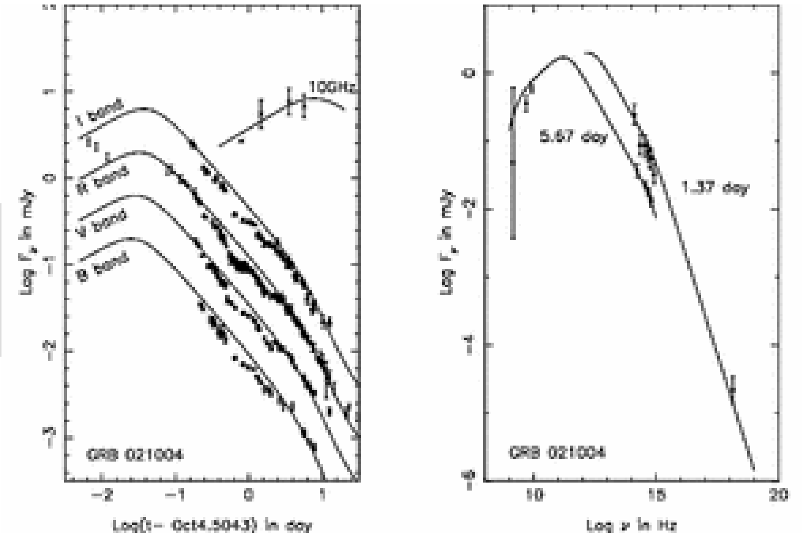
- Test for the synchrotron fireball model predictions
- Infer spectral break frequencies ($\nu_a$ , $\nu_m$ , $\nu_c$)
- Important to know the physical parameters
  n, $\varepsilon_e$, $\varepsilon_b$, p, $\theta$, $E_{52}$ (afterglow kinetic energy) of the burst
- Intrinsic extinction to host reveals conditions in the surrounding media
- Non-relativistic evolution of the fireball
- Test for other underlying mechanisms like Inverse-Compton scattering

# Broad-band afterglow modeling

- Use simple fireball synchrotron ISM model (UJ) predictions
- Use break-frequencies and peak flux evolutions in fast,slow cooling cases
- Also include non-relativistic evolution of the fireball
- Use Granot Sari (2002) approach to get the modeled flux
- Used $\chi^2$ minimization method to get a fitted model parameters
- Model parameters are E_52, Peak flux, n, p, E(B-V), 3 break frequencies,t_j,t_nr
- Calculation of physical parameters after inverting the model equations given in standard papers like (Wijers & Galama 1999, Rhoads 1999)

# Broad-band afterglow modeling

- we modeled the 10 GHz, BVRI light-curve and SED at $\Delta t$ = 1.37 and 5.67 day with following parameters including intrinsic extinction



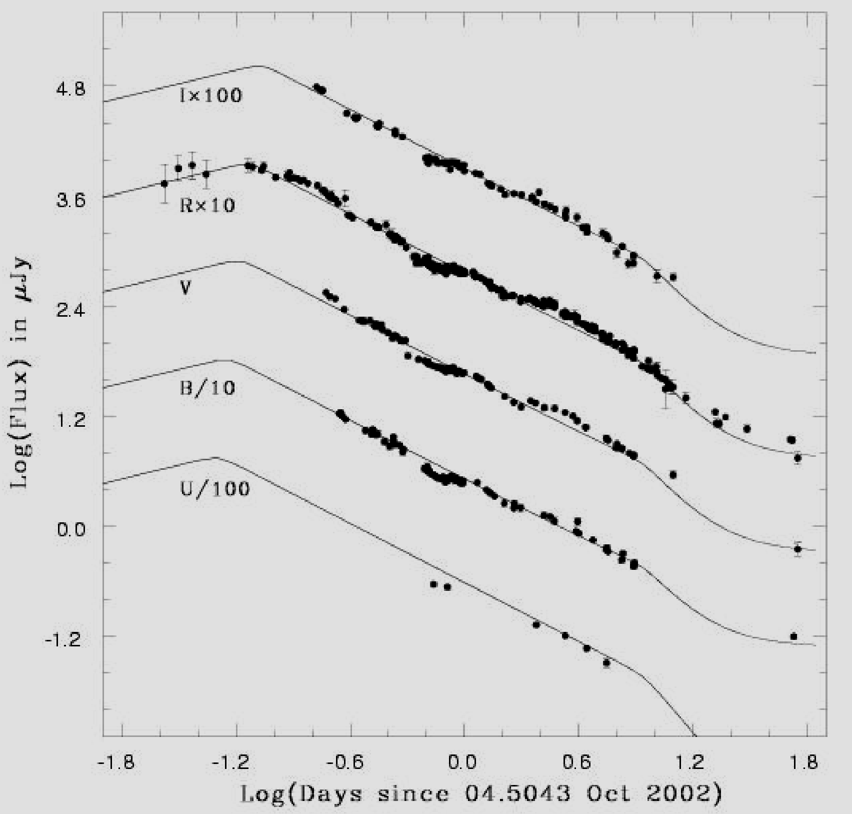

**Results, GRB 021004 ➡**

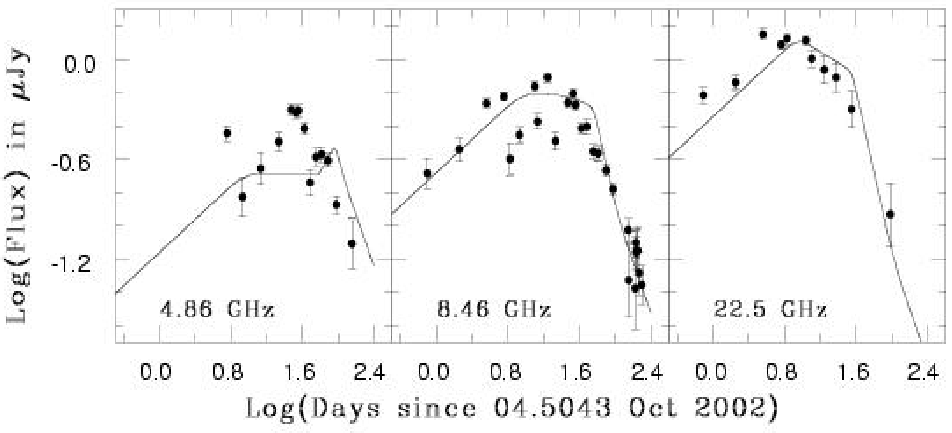
**GRB 021004, Pandey et al. (2003)**

- Using derived break frequencies $\nu_a$ ~ 2.1 GHz, $\nu_m$ ~ $2.5*10^{14}$ Hz & $\nu_c$ ~ $3.3*10^{16}$ Hz
  Jet break time $t_j$ = 8.8 day and p = 2.27,
  k-corrected energy $E_{52}$ = 4.6, $\varepsilon_e$ = 0.1, $\varepsilon_b$ = 0.01
  and total extinction E(B –V) = 0.20 in the burst direction.

**Data points used 596, t_nr ~ 108 day, n ~ 45 atoms/cc**

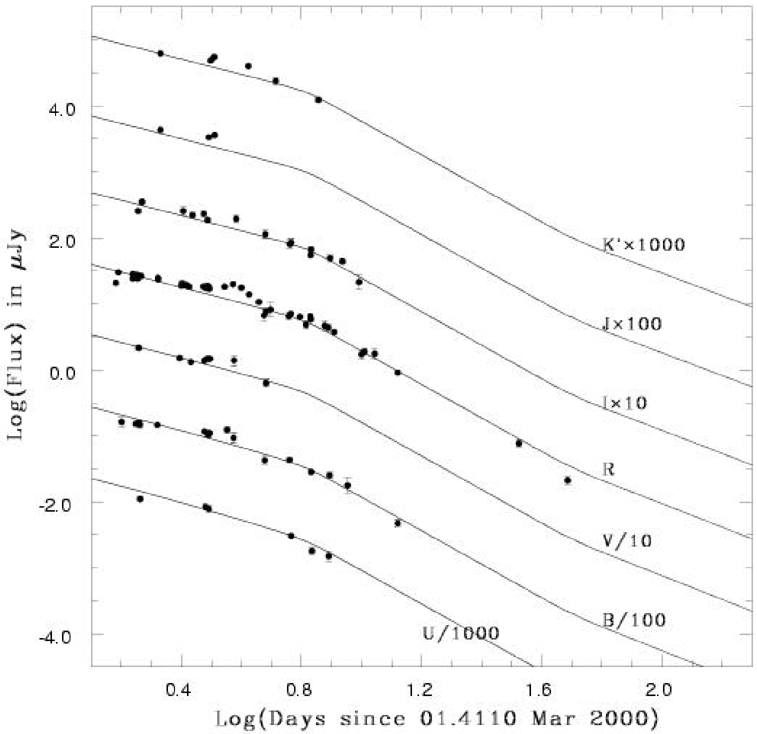
# Broad band afterglow modeling

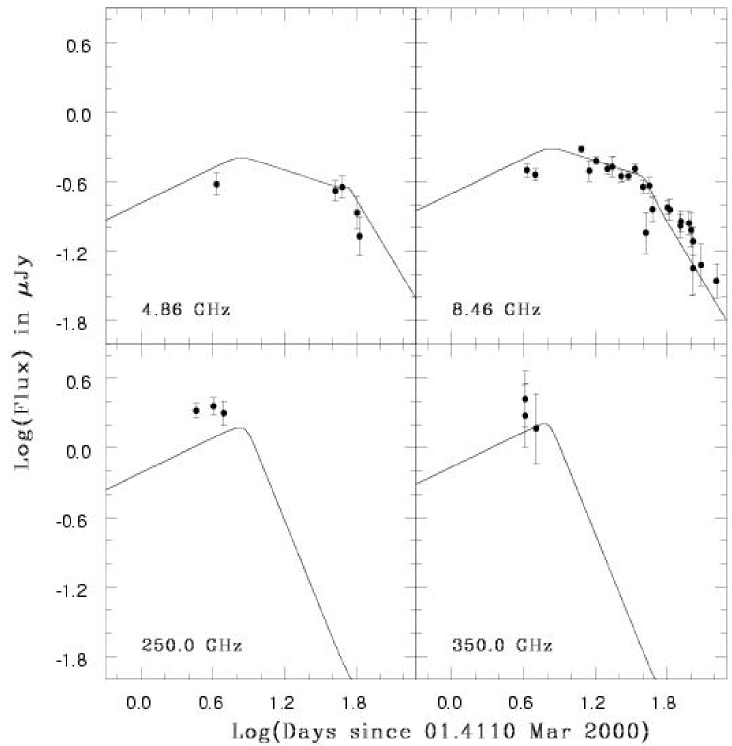



GRB 021004

# Broad band afterglow modeling



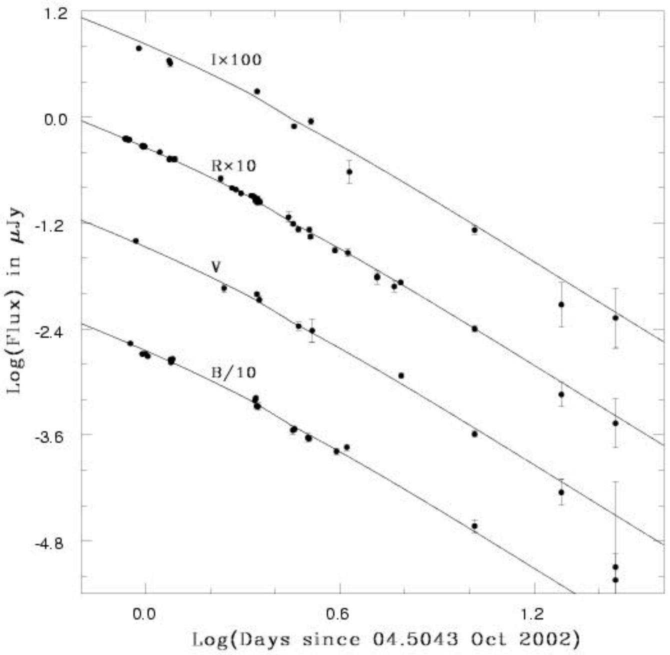

- Using derived break frequencies $\nu_a$ ~ 1.1 GHz, $\nu_m$ ~ $5.1*10^{11}$ Hz & $\nu_c$ ~ $5.7*10^{14}$ Hz, $t_j$ = 6.6 day p = 2.27, excluded 3 - 4.3 day data from the fit, k-corrected energy $E_{52}$ = 0.11, $\varepsilon_e$ = 0.01, $\varepsilon_b$ = 0.09, n ~ 0.001, at 8.46 GHz, 23 mJy Host contribution added

# Broad band afterglow modeling

- BVRI, optical data,
  Galactic E(B-V)=0.022 mag
  Intrinsic extinction = 0.26 mag

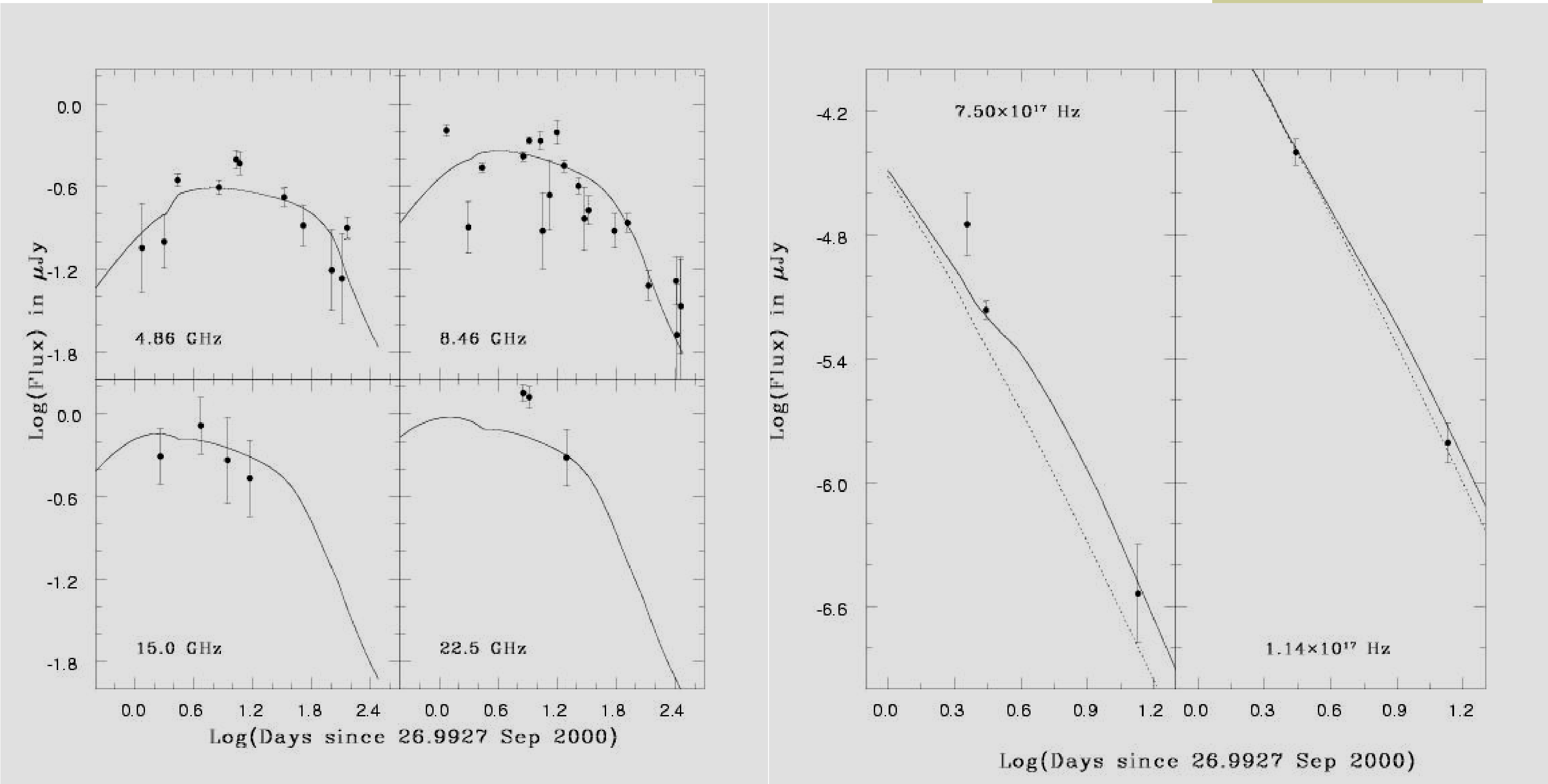
- Needs Inverse-Compton effect with Synchrotron to explain the high frequency

- Used Additional parameter C = $\varepsilon_e / \varepsilon_b$




- Using derived break frequencies $\nu_a$ ~ 20.0 GHz, $\nu_m$ ~ $6.6*10^{13}$ Hz & $\nu_c$ ~ $8.8*10^{12}$ Hz
  Jet break time $t_j$ = 2.1 day and p = 2.3, n ~ 8.77
  k-corrected energy $E_{52}$ = 4.6, $\varepsilon_e$ = 0.1, $\varepsilon_b$ = 0.01
  Inverse-Compton dominated Synchrotron gives better fit to the high frequency data

# Broad band afterglow modeling




**Modeled Radio and X-ray afterglow light curves of GRB 000926**

# Results

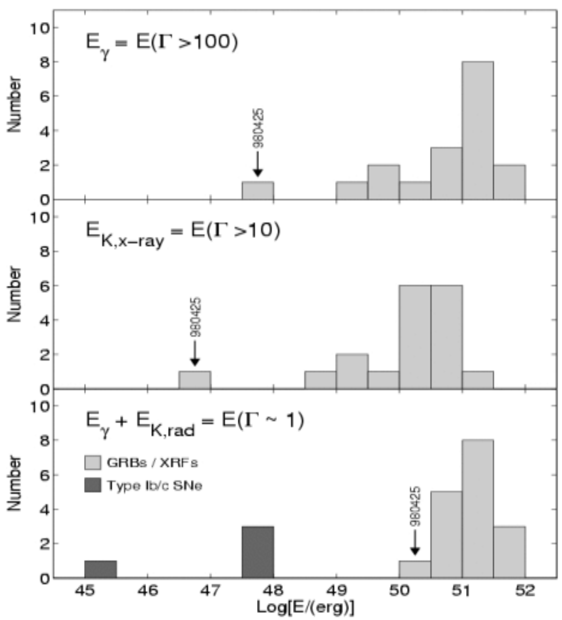
- Optical afterglow observations of GRBs (LCs and SEDs) are explained in terms of ISM jet model predictions, based on the afterglow LCs and SEDs.

- Most of the afterglow light curves can be well explained in terms of jetted outflow, constraining total output energy.

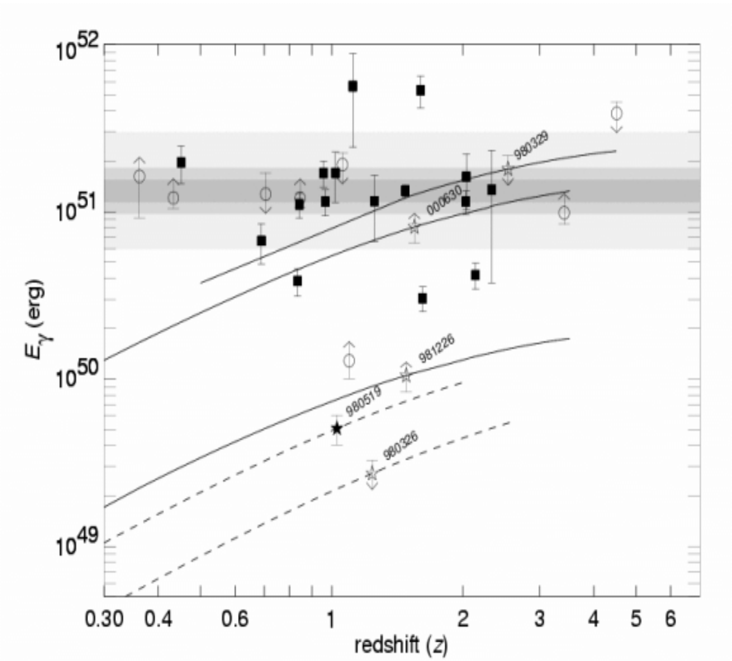
- K-corrected, jetted output energy of the GRBs falls in the range of standard energies. clustered around 1.3 X $10^{51}$ ergs.

# Explanation/Energetics

**GRB Energetics -I**




**GRB Energetics-II**




**Modeled energy is in the range of the narrow clustering of ~ $10^{51}$ erg**

(Frail et al., 2001, Bloom et al., 2003)

# Results

- GRB 021211 afterglow observations show, Dark bursts might be just the optically dim bursts, rapid and deep follow up is needed to explore the fact
- Overlapped variability in the afterglow light curve, indicate towards complex structure surrounding bursts.
- Observed intrinsic extinction in the burst direction shows GRBs to occur in gas rich region of the host galaxies.
- Optical data in combination with other frequencies, constrain the break frequencies, physical parameters using the afterglow models (ISM).
- Observed complex afterglow light curve of GRB 030329/SN 2003dh strengthening the GRB progenitors as collapse of massive stars.

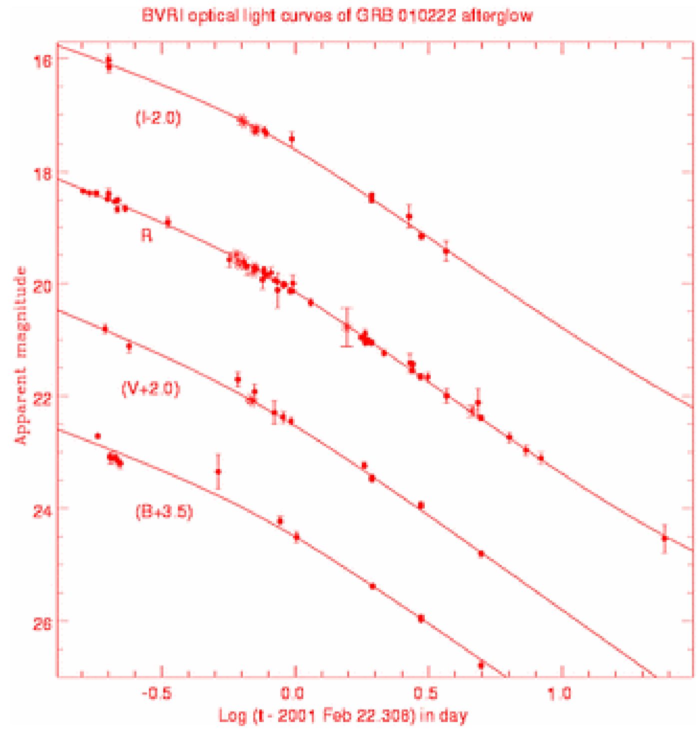
# Need to know…

- **Jet structure** ***UJ or USJ, Polarization in afterglows***
- **Progenitors** ***Collapsars or Compact-binary mergers***
- **Underlying total output energy, non-electromaganetic ?**
- **GRB-SN connection** ***Supernova model***
- **Types of GRBs** ***short-duration afterglows?***

***THANKS…***

# GRB 010222, afterglow LCs

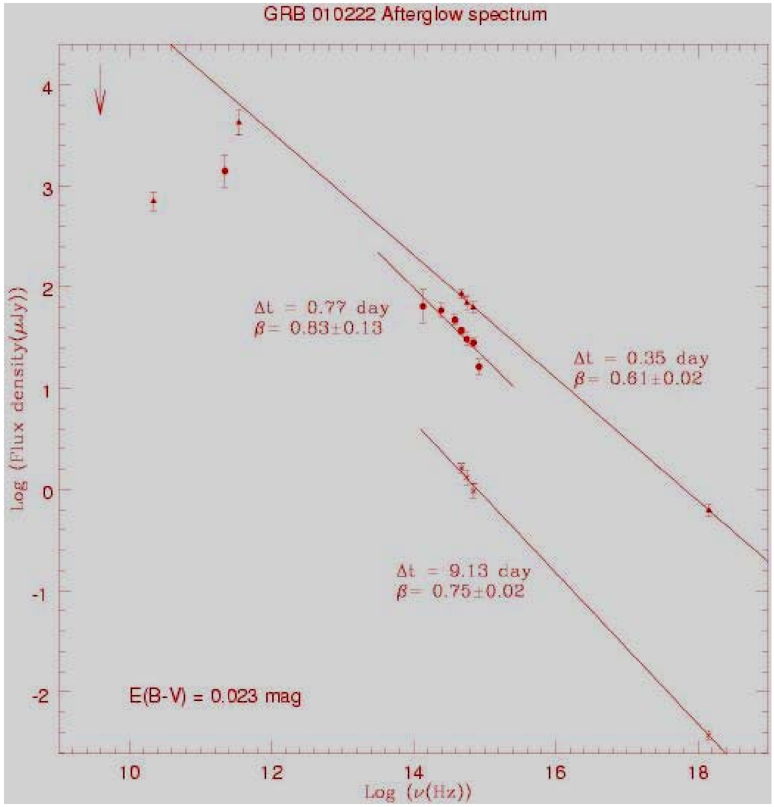
- $\alpha_1 = 0.74 \pm 0.05$, $\alpha_2 = 1.35 \pm 0.04$, $t_j = 0.7 \pm 0.07$ day
- Spectral index $\beta$ and temporal indices can be explained as sideways expansion of the jet
- Harder electron energy index $p < 2$ is needed to explain it, as modeled by
  Bhattacharya D. (2001)
- GRB 000301c is another example modeled with non-standard value $p < 2$
  Panaitescu & Kumar (2001)




GRB 010222, Sagar et al. (2001)

# GRB 010222, afterglow SEDs

In this case, at $\Delta t$ = 0.35, 0.77 and 9.13 day and $\beta$ = 0.61±0.02, 0.83±0.13 and 0.75±0.02, E(B –V) = 0.023




$\nu_m$ lie in millimeter region and $\nu_c$ between optical and millimeter.

GRB 010222, Sagar et al. (2001)