Gamma-Ray Bursts

A Puzzle Being Resolved

Tsvi Piran

HU, Jerusalem

(also Columbia and NYU)

During the last years one of the longest open mysteries in Astrophysics is being resolved.

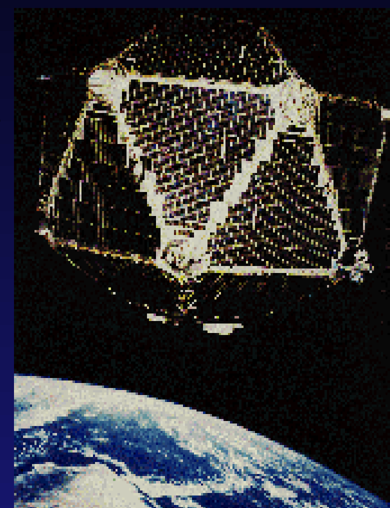
- W. Benz
- M. Davies
- David Eichelr
- Jonathan Katz
- Shiho Kobayashi
- C. Kochaneck
- P. Kumar
- Mario Livio
- R. Narayan
- B. Paczynski
- David Schramm
- Jacob Shaham

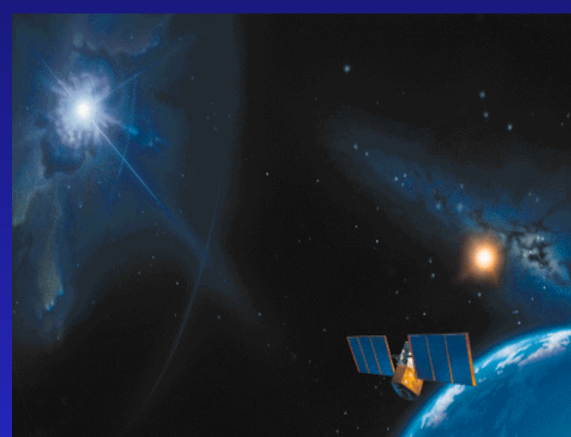
- Re’em Sari
- F. Thielmann

- Shai Ayal
- Ehud Cohen
- Jonathan Granot
- Amotz Shemi

THE DISCOVERY

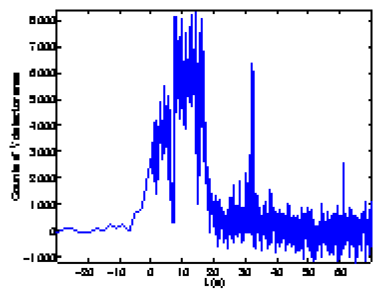
- GRBs were discovered accidentally by Klebesadal Strong and Olson in 1967 using the Vela satellites (defense satellites sent to monitor the outer space treaty). The discovery was reported first only in 1973.



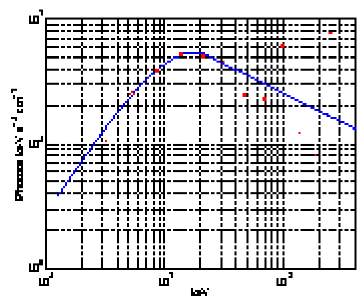


- Short bursts
  - 0.1-100 sec
  - 100keV- few MeV
  - Nonthermal spectrum.
- No counterparts in any other part of the spectrum (Until 28 Feb 1997).

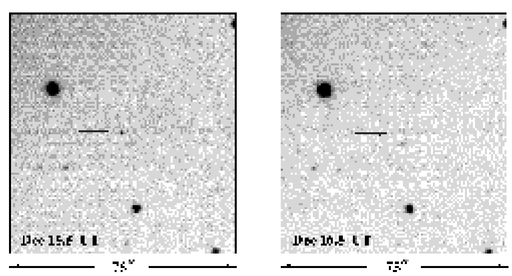
GRB971214



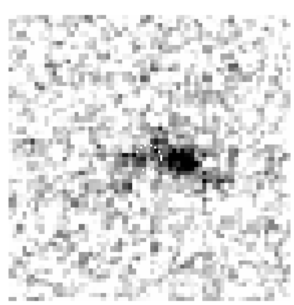
(a) BATSE's counts as a function of time.



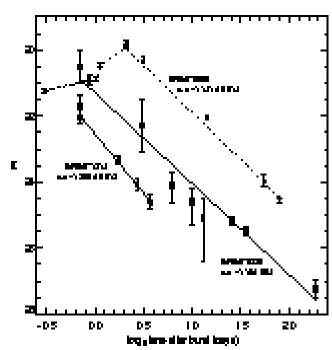
(b) The spectrum, integrated over the entire duration of the burst. The solid line depicts the best-fit Band spectra with $\beta = -2.5, \alpha = -0.45$, and $H = 180$ keV. The crosses are non-parametric SVD spectra.



(c) The afterglow (Halpern et al., 1997)



(d) The host galaxy at a red-shift of 3.42 (Odewahn et al., 1998).



(e) Light curve of the decaying afterglow for several bursts (Diercks et al., 1998).

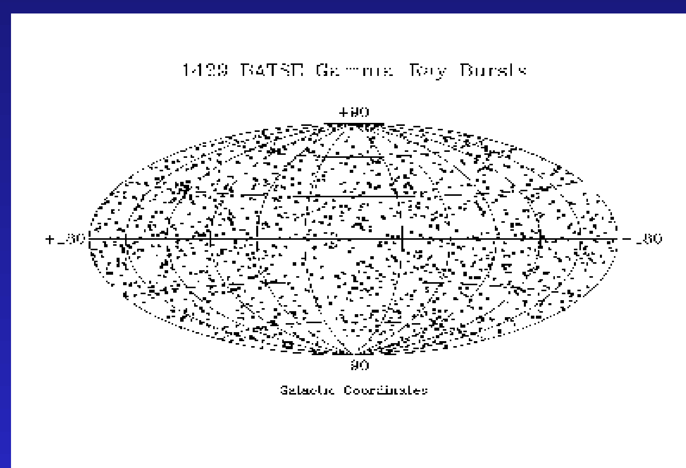
Figure 1.1: GRB971214: From the burst itself to the afterglow and the host galaxy.

Outline

- GRBs
- The Fireball Model and Predictions
- Observations
- The "standard model"
- Comparison with Observations
- More Observations
- More Predictions
- Even More Observations
- Then I will run out of time…..
- Conclusions

BATSE -
The First Revolution
Cosmological GRBs

- **BATSE on Compton - GRO (Fishman et. al.) GRBs are distributed isotropically:**

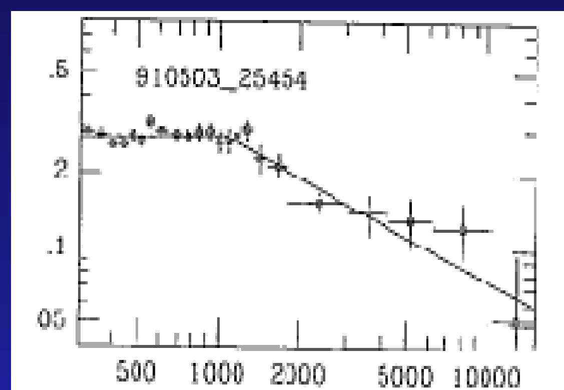


- **With emission of 10^{52} ergs (or more) in a few seconds GRBs are the (electromagnetically) most luminous objects in the Universe.**

THE COMPACTNESS PROBLEM

$\gamma\gamma \rightarrow e^+e^-$

- Variability Scale: $\delta T \leq .1$ sec
  $\Rightarrow R \leq c\delta T = 3\ 10^9$ cm
- Spectrum:
  - $E \cong 10^{51}$ergs,
  - many photons above 500 keV.



➨ $\tau_{\gamma\gamma} = n_\gamma \sigma_T R \geq 10^{15}$
(Probability for a photon to escape is $\exp[-\tau_{\gamma\gamma}]$)

✷ No Photons above 500keV!

The Solution

Relativistic Motion

$\Rightarrow R \le c\,\gamma^2 \delta T$

$\Rightarrow E_{ph}$ (obs) $= \gamma\, E_{ph}$ (emitted)

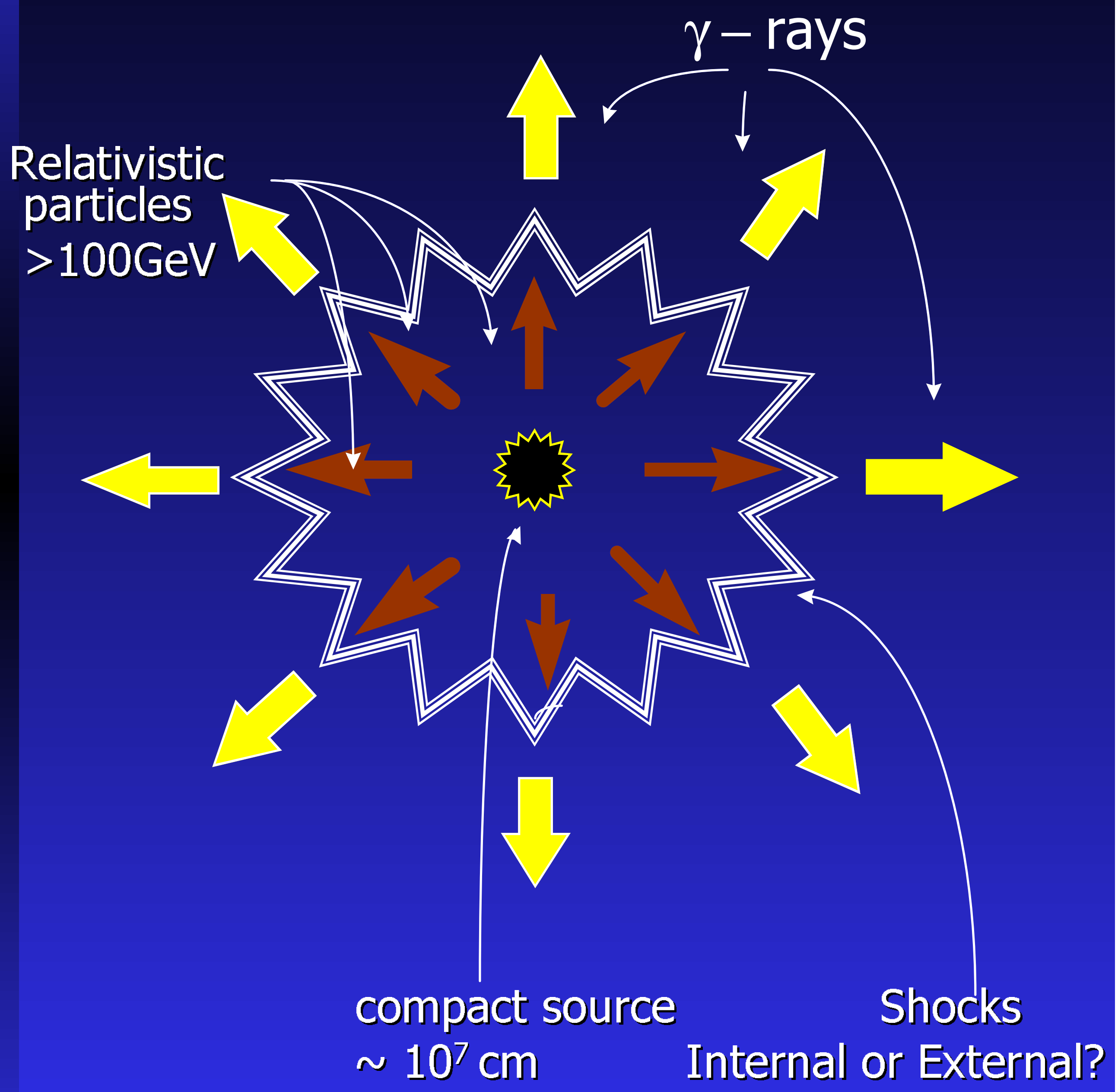
$$\tau_{\gamma\gamma} = \gamma^{-(4+\alpha)} n_\gamma \sigma_T R \ge 10^{15}/\gamma^{(4+\alpha)}$$

$$\gamma \ge 100 \quad (\alpha \cong 2)$$

(Goodman, Paczynski, Krolik & Pier, Piran & Shemi)

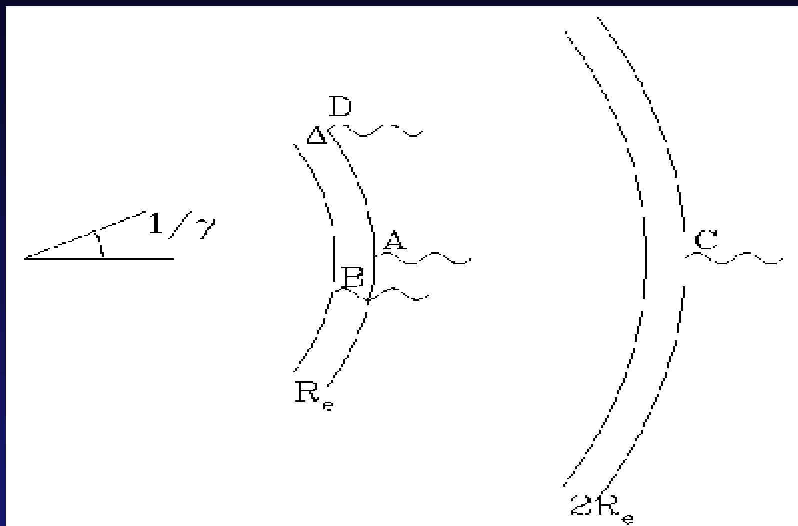
$\Rightarrow$ The Fireball Model

The Fireball Model



Goodman; Paczynski; Shemi &Piran, Narayan, Paczynski & Piran; Meszaros & Rees,

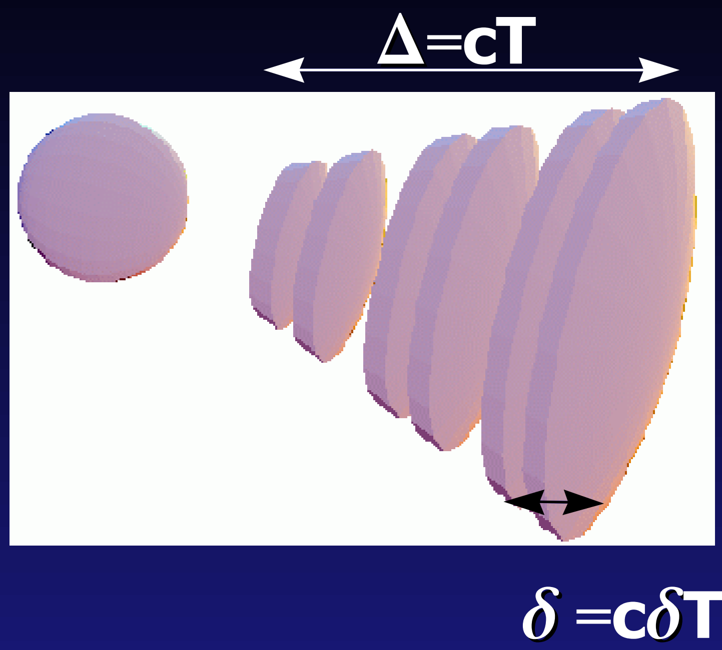
Time scales in Relativistic Fireballs



- $T_{angular}=T_D - T_A = R/c\,\gamma^2$: The angular time Scale.
- $T_{radial} = T_C - T_A = R/c\,\gamma^2$: The radial time scale.
- ❷ $\Delta T = T_C - T_A = \Delta/c$: The width of the shell.
- T_{cool}: The cooling time scale.
- ☞ Generally (but not during afterglow)

$$T_{cool} << T_{radial}, T_{angular}, \Delta T$$

Internal Shocks

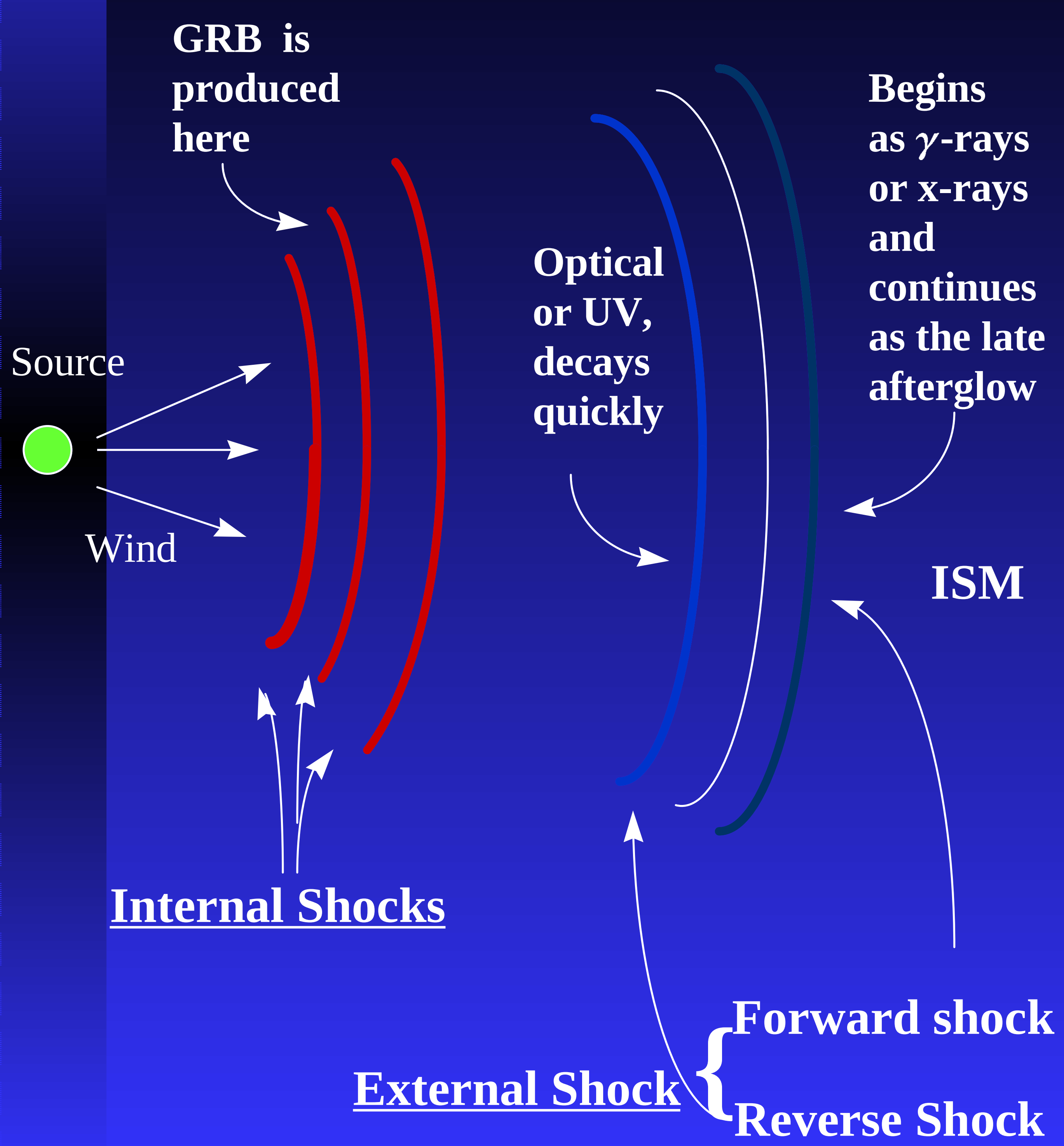


- $\delta T = R/c\gamma^2 = \delta/c \leq \Delta/c = T$

☞ Internal shocks can convert only a fraction of the kinetic energy to radiation (Mochkovich et. al., Kobayashi, Piran & Sari).

☞ **It should be followed by additional emission.**

The Internal-External Scenario



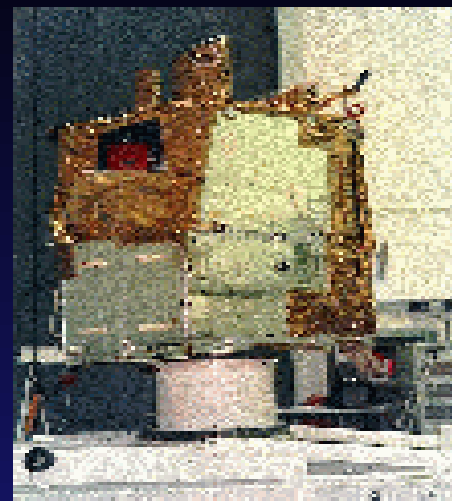
AFTERGLOW PREDICTIONS

- Extrapolation of the GRB
  - Paczynski and Rhoads 1994
  - Katz 1994
  - Meszaros and Rees 1997
  - Vietri 1997
- The Internal - External Scenario

The GRB and the afterglow are produced by different phenomenon

  - Sari and Piran 1997

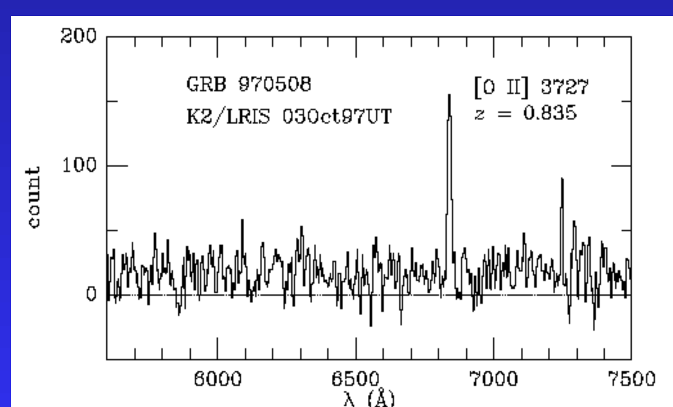
The Second Revolution: GRB Afterglow



- The Italian/Dutch satellite **Beppo/SAX** discovered GRB x-ray afterglow on 28 February 1997 (Costa et. al.).

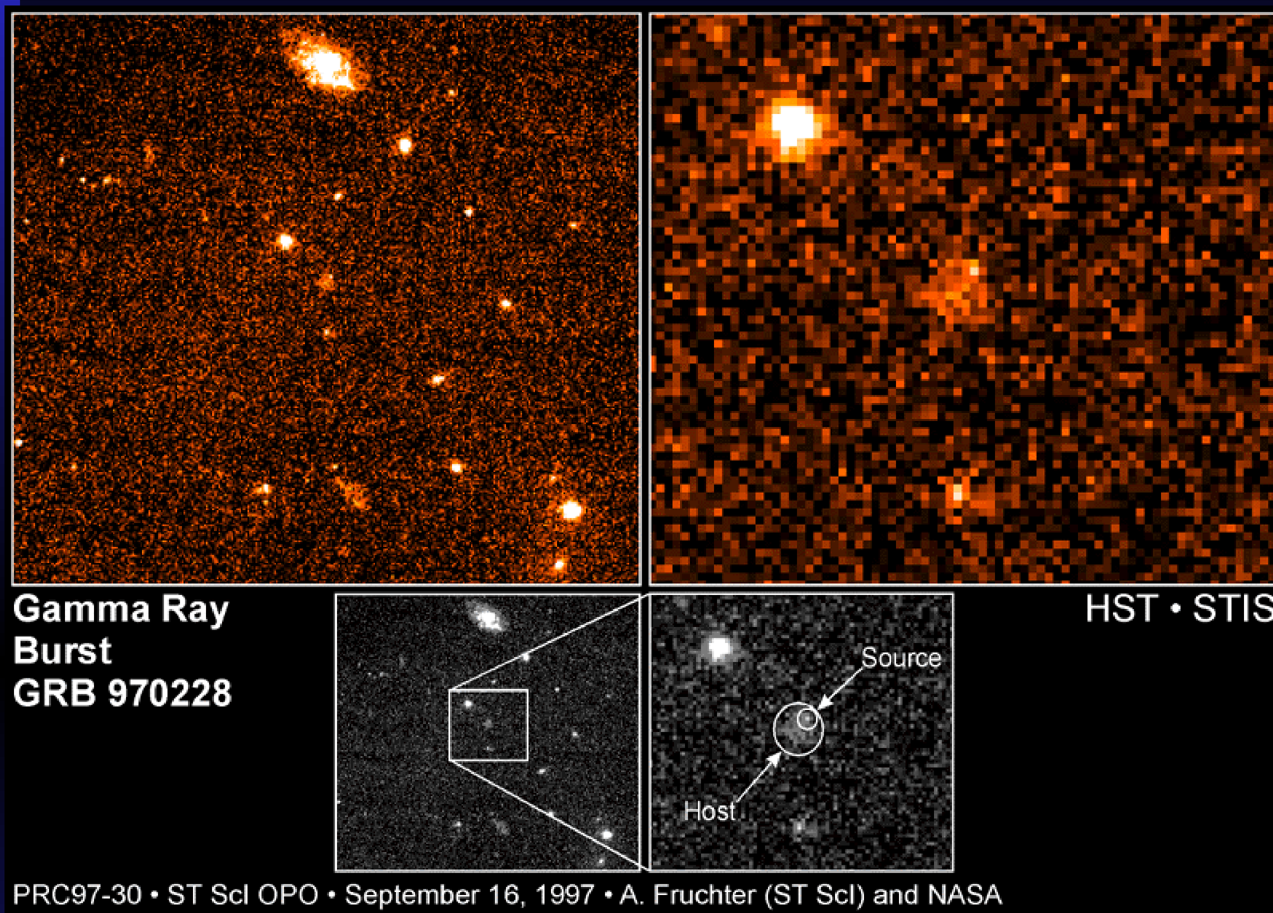
The exact position of the GRB led to the discovery of an optical afterglow (van Paradijs et. al) .

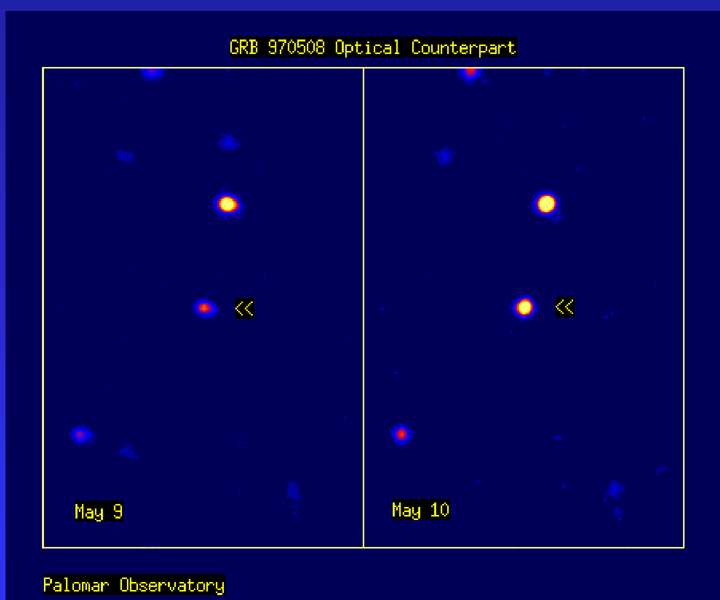
- Matzger et. al. measured a red-shift z=0.835 in the afterglow of GRB970508.



GRBs are Cosmological!!!

Afterglow Observations

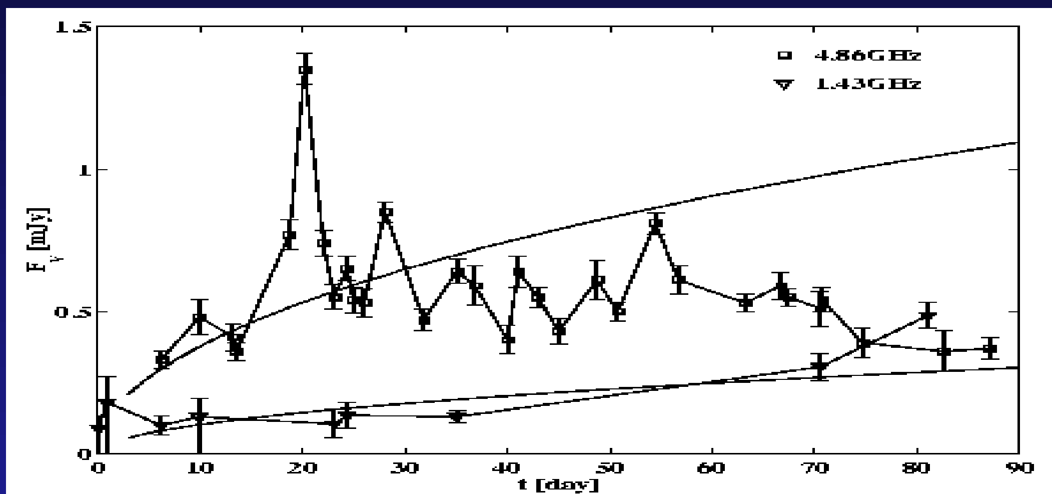




Radio Observations -

A confirmation of the fireball model

- Afterglow of GRB970508 (Frail et. al):



- Variability:
  - → Scintilations (Goodman)
  - → Size after one month ≅10^{17}cm.
- Rising Spectrum at low frequencies:
  - →Self absorption (Katz & Piran)
  - → Size after one month ≅10^{17}cm.

➨ **Relatvistic Motion!!!**

Testing the Model

- Light Curve: $t^{-\beta}$
  - $\beta=(3p-2)/4$
- Observations of $\beta=1.2$ suggest

$\Rightarrow$ p=2.5

- Upper Spectral Index: $F_\nu \propto \nu^{-\alpha}$
  - $\alpha=p/2$

$\Rightarrow$ $\boldsymbol{\beta=(3\alpha-1)/2}$.

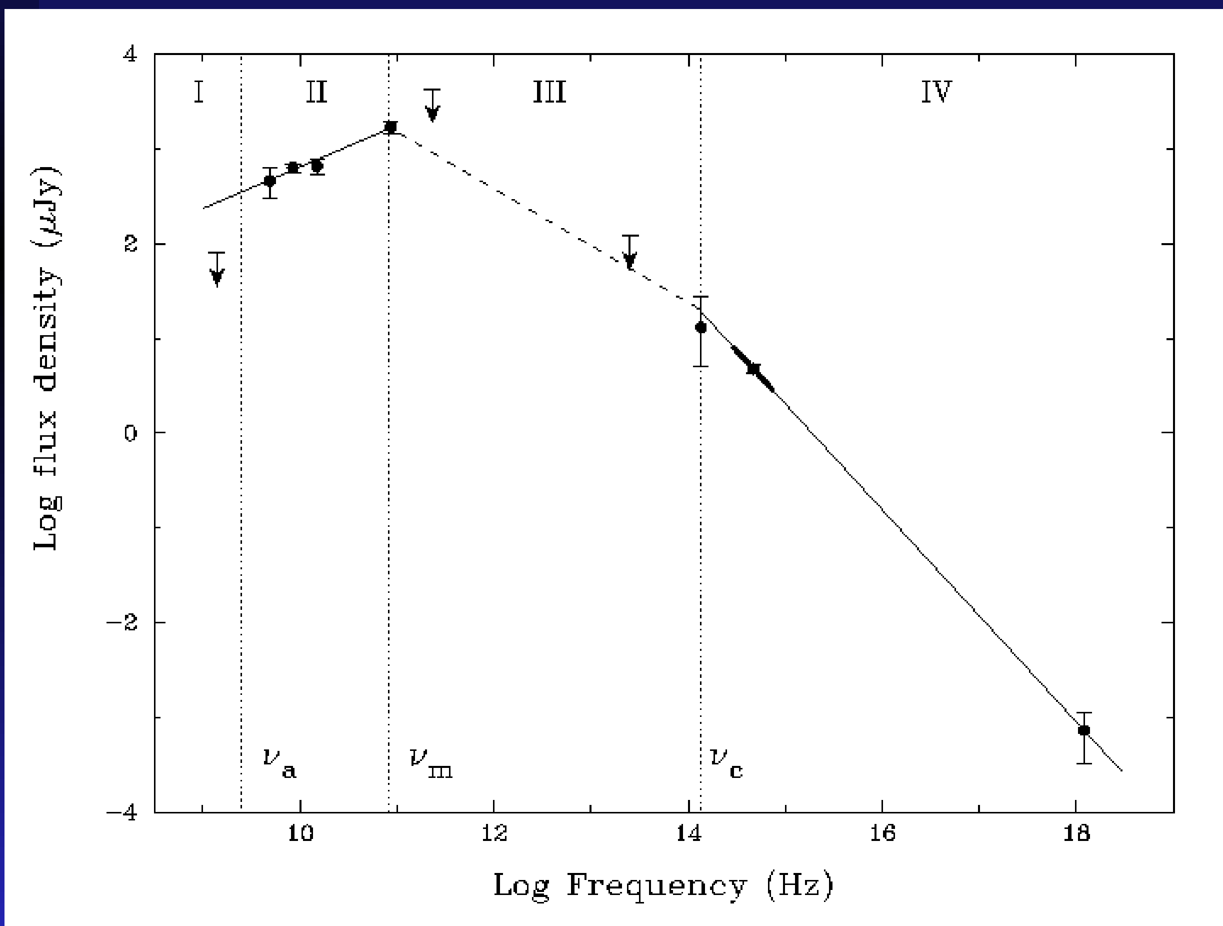
- For GRB970508:

  $\boldsymbol{\alpha=1.12,\ \beta=1.14}$ **and p=2.24**.

Comparison with Observations

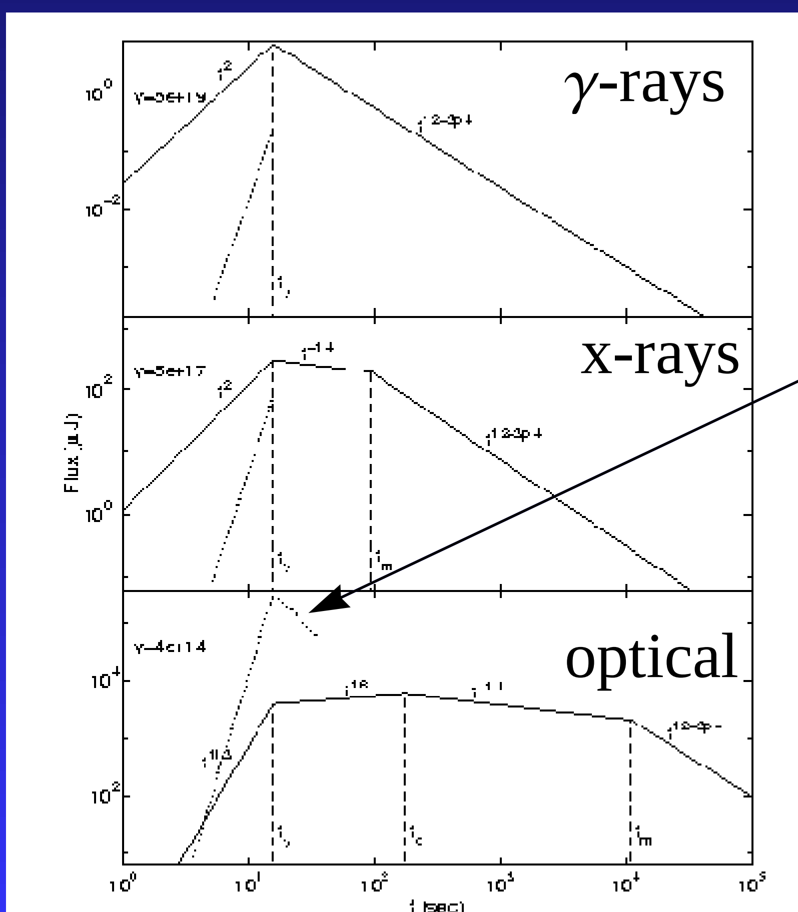
Spectrum of GRB970508

(Sari, Piran & Narayan, Wijers & Galama)



The Early Afterglow and the Optical Flash

- The late afterglow observations confirmed relativistic motion.
- But how to proof that γ>100 during the GRB phase?
- This could be tested by early afterglow observations (Sari \& Piran (Rome, Oct 1998 and Astro-ph/11/1/1999):



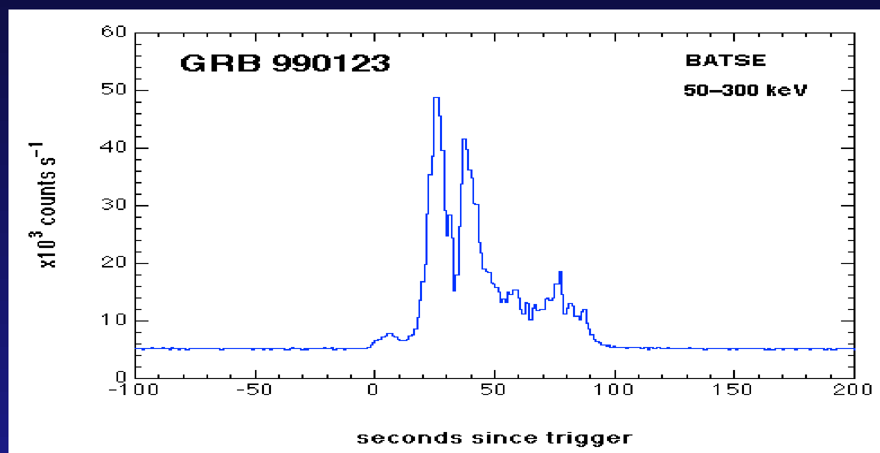
A very strong optical flash conciding with the GRB

GRB990123

- A very strong GRB (among 0.3% of the strongest bursts)

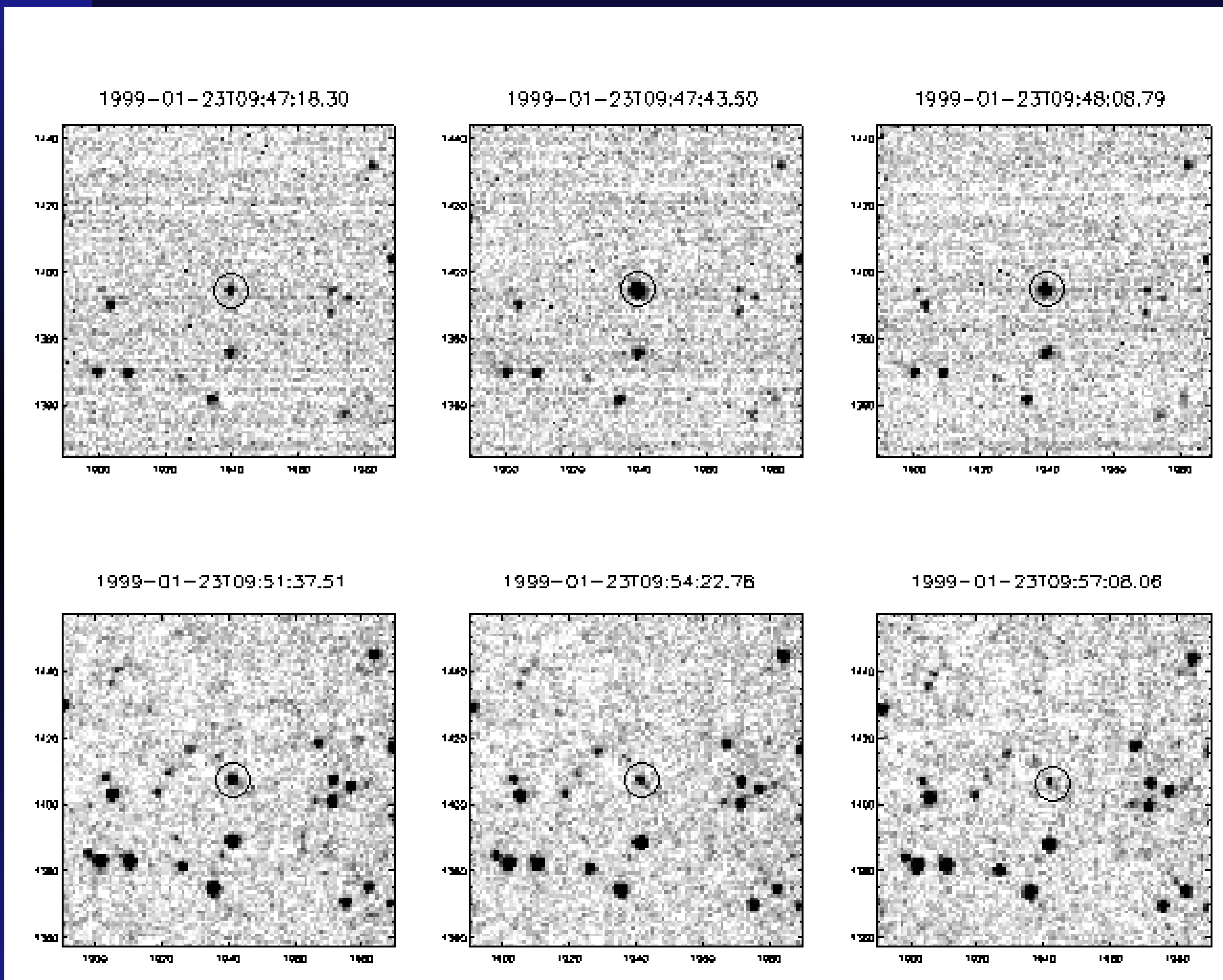
γ-ray flux:

10^{-4}ergs/cm^2/sec



- X-ray Afterglow - 10^{-11}ergs/cm^2/sec six hours after the burst,
- Optical Emission coinciding with the GRB at 9th magnitude.
- z=1.6 → 2 10^{54} ergs
- ~~Another Galaxy at z=0.2 → Lensed?~~
- Break in the decay - Jet!

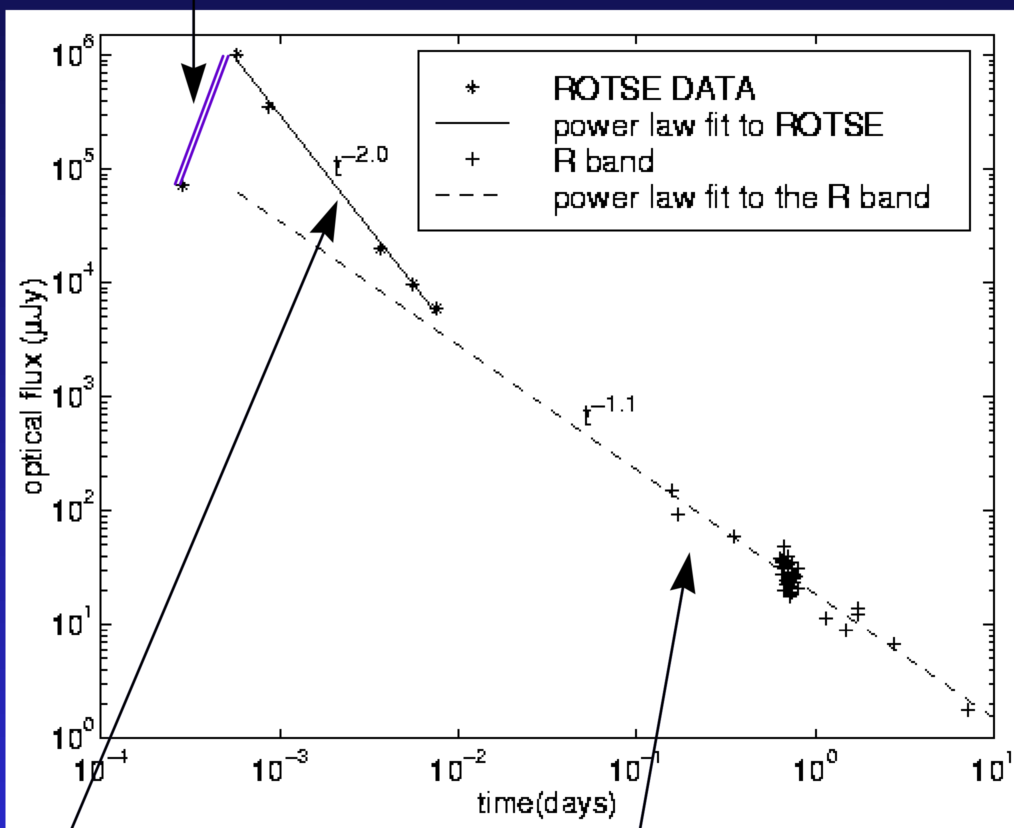
GRB990123 - The Prompt Optical Flash



- ROTSE detection of prompt 9th magnitude optical flash.

GRB990123 Early Light Curve

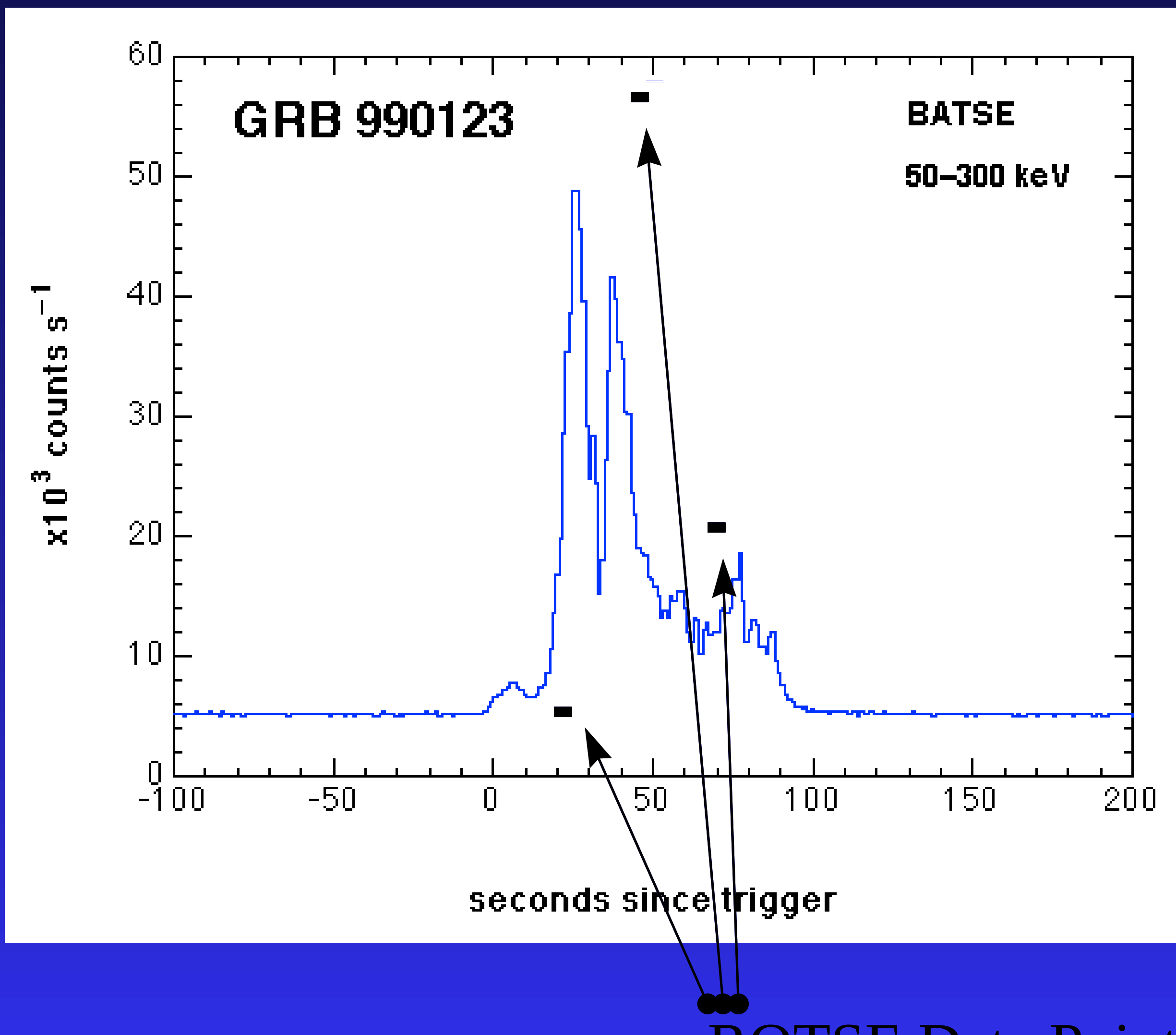
Sharp initial rise



Fast initial decay

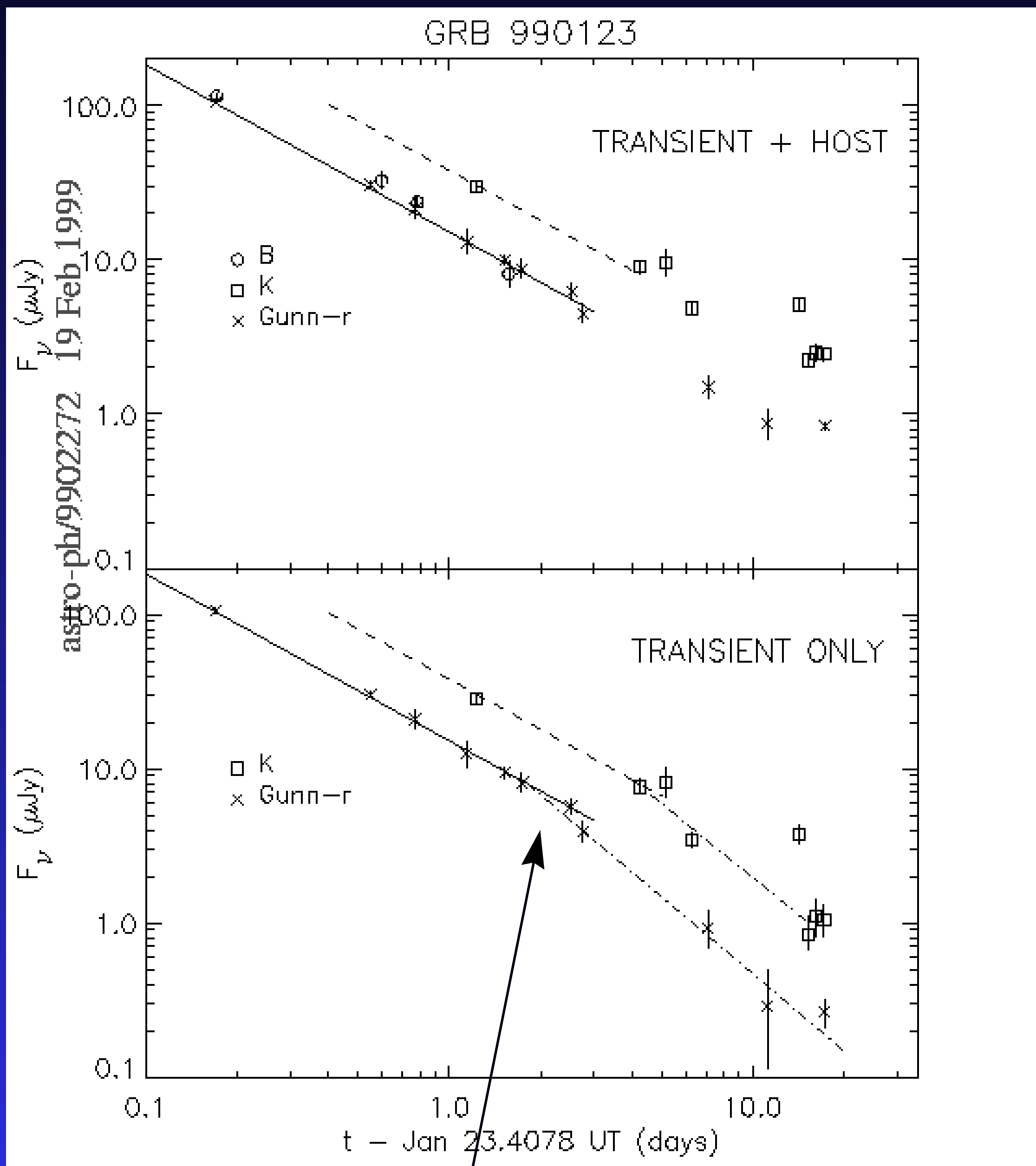
Slow decay of the "standard" afterglow

Gamma vs. Optical in GRB990123



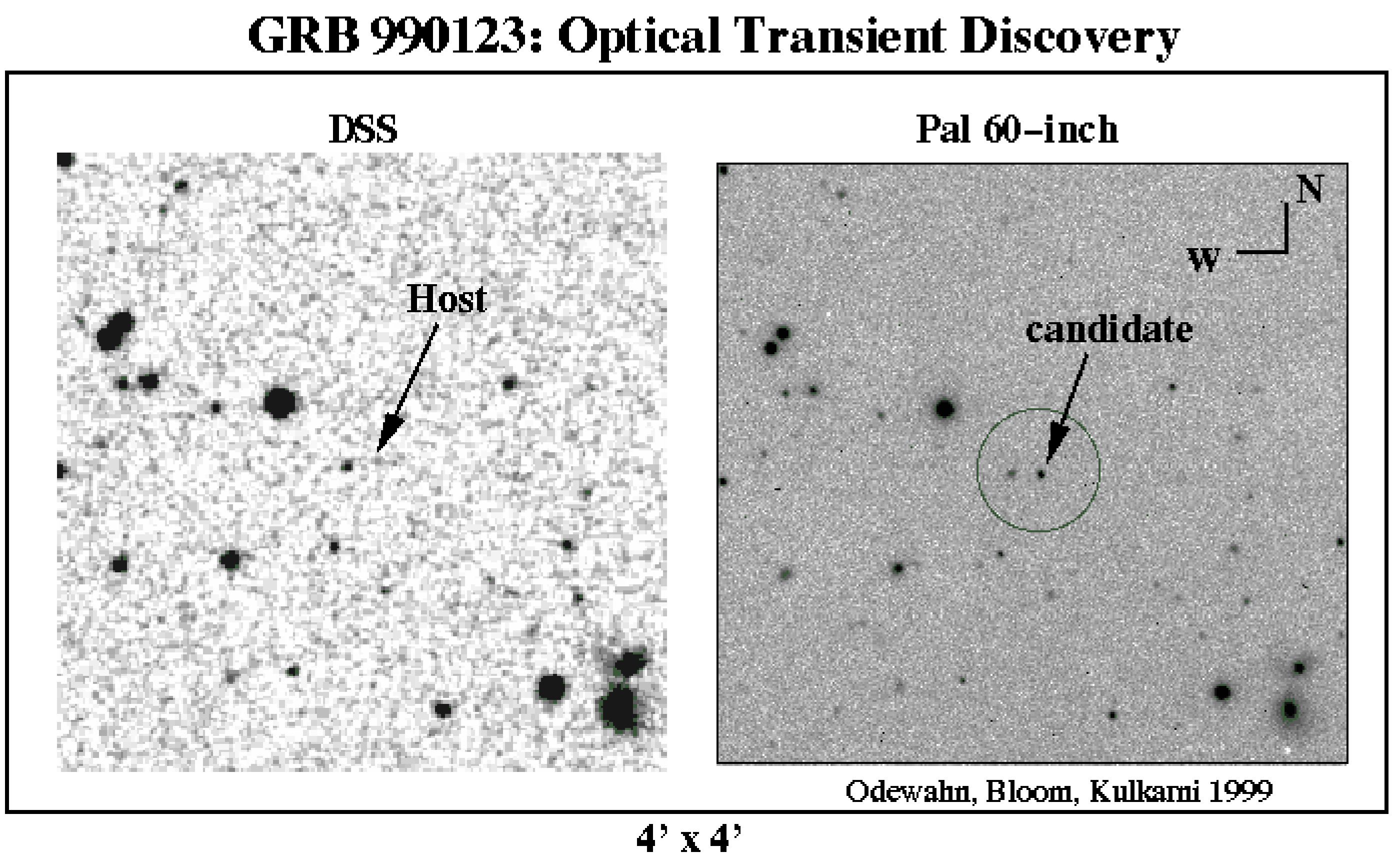
ROTSE Data Points

990123 Late Light Curve



Break when $\gamma = \theta^{-1}$

GRB990123 Discovery Plate

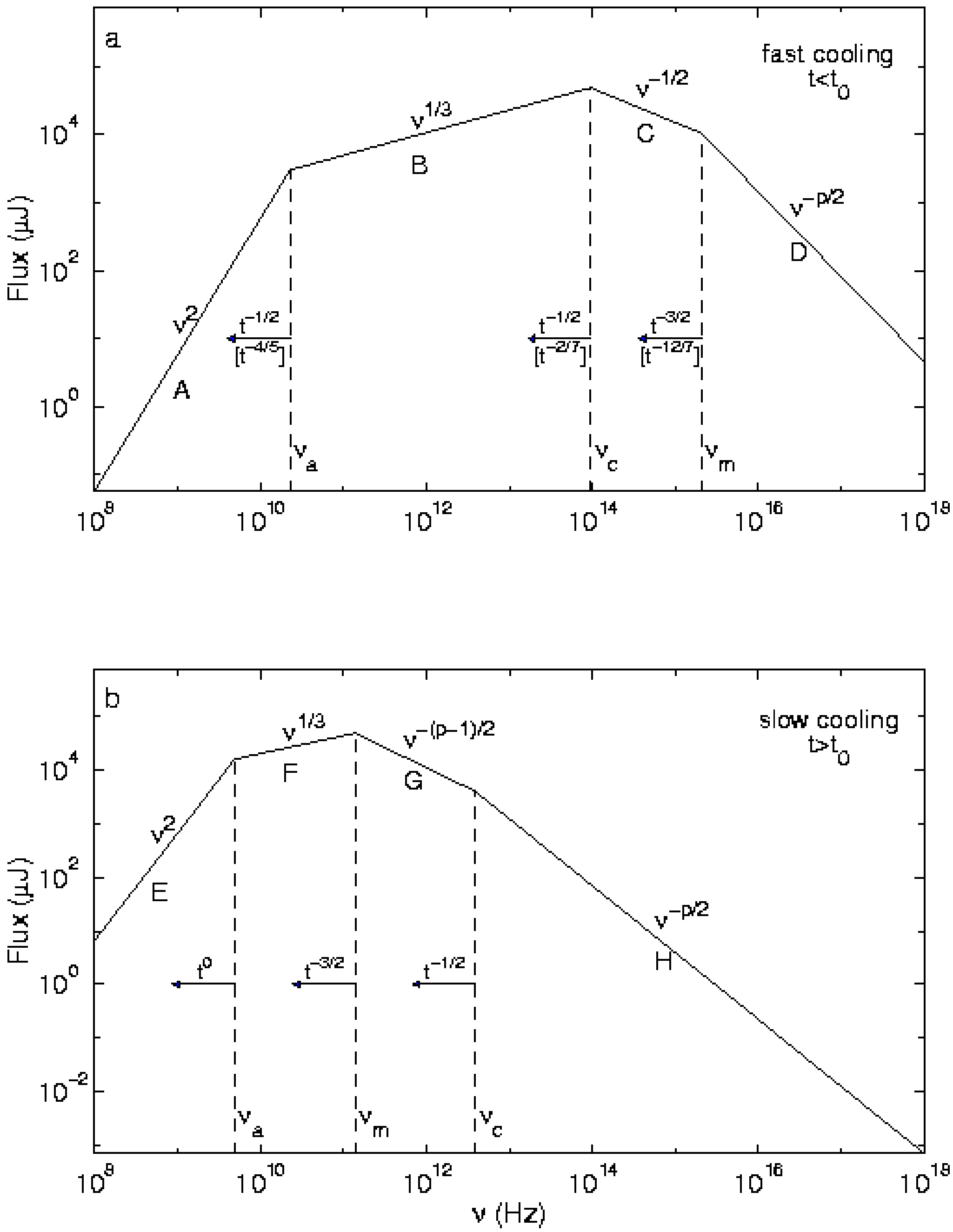


Observed Afterglows

Gamma-Ray Bursts with Optical Counterparts							
GRB	Peak Fluxes					Host Galaxy[5]	z
	g[1]	X[2]	g/X Ratio	Opt[3]	Radio[4]		
970228	3.5	2.3	80	20.5	-	24.6	-
970508	1.2	3.0	25	19.8	1.2	25.8	0.835[6]
971214	2.3	2.5	56	21.7	-	25.5	3.412[7]
980326	1.3	4.7	17	21.0	-	25.3	-
980329	13.3	70.0	12	23.6	0.25	~ 29 ?	~ 5 ??
980425	1.1	2.6	26	13.7	49	14.3	0.0085[7]
980519	4.7	2.9	100	20.4	0.1	24.7	-
980613	0.63	0.7	57	22.9	-	24.4	1.096[7]
980703	2.6	4.0	40	20.1	1.0	23.0	0.967[6]
990123	16.4	4.0	252	8.95	2.6	24.3	1.61[6]

[1] photons cm^{-2} s^{-1} (50-300 keV); conversion factor, photons to ergs, = 6.15×10^{-7}
[2] $\times 10^{-8}$ ergs cm^{-2} s^{-1} (2-10 keV)
[3] R band magnitude
[4] milli Jansky, at 8.4 GHz (10 GHz for GRB 980425)
[5] R band magnitude, corrected for galactic extinction
[6] redshift from OT
[7] redshift from host galaxy

Afterglows are not scaled to the GRBs



a
fast cooling
t<t0
ν^1/3
ν^−1/2
ν^−p/2
ν^2
A
B
C
D
t^−1/2 [t^−4/5]
t^−1/2 [t^−2/7]
t^−3/2 [t^−12/7]
νa
νc
νm
Flux (μJ)
b
slow cooling
t>t0
ν^1/3
ν^−(p−1)/2
ν^2
ν^−p/2
E
F
G
H
t^0
t^−3/2
t^−1/2
νa
νm
νc
Flux (μJ)
ν (Hz)

The Energy Crisis and Beaming

- z=3.42 for GRB971214
  $E_{isotropic} > 10^{53}$ ergs
- z=1.6 for GRB990123
  $E_{isotropic} > 10^{54}$ ergs

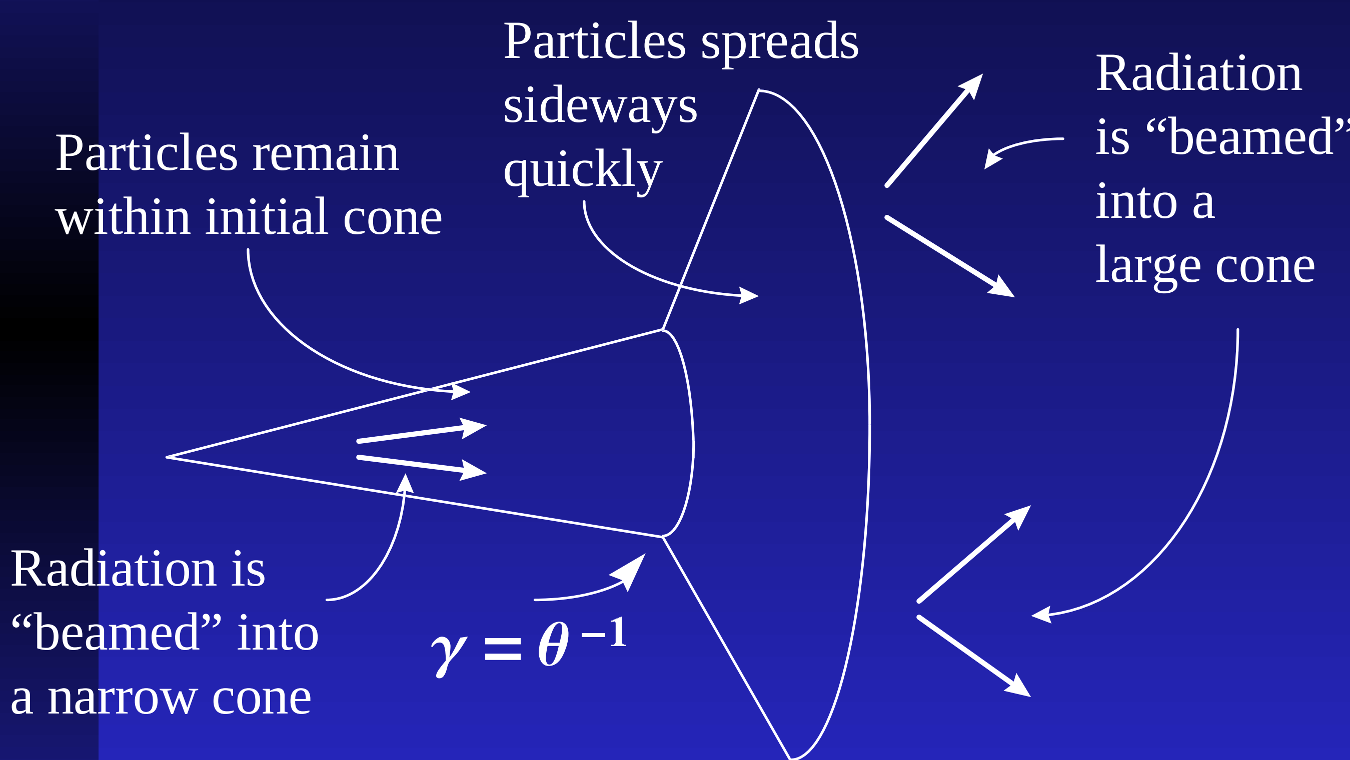
⇒ Beaming?

BUT

⇒ Light curves in GRB970228 and GRB980508 are not broken

⇒ No evidence for orphan radio afterglow

JETS and BEAMING

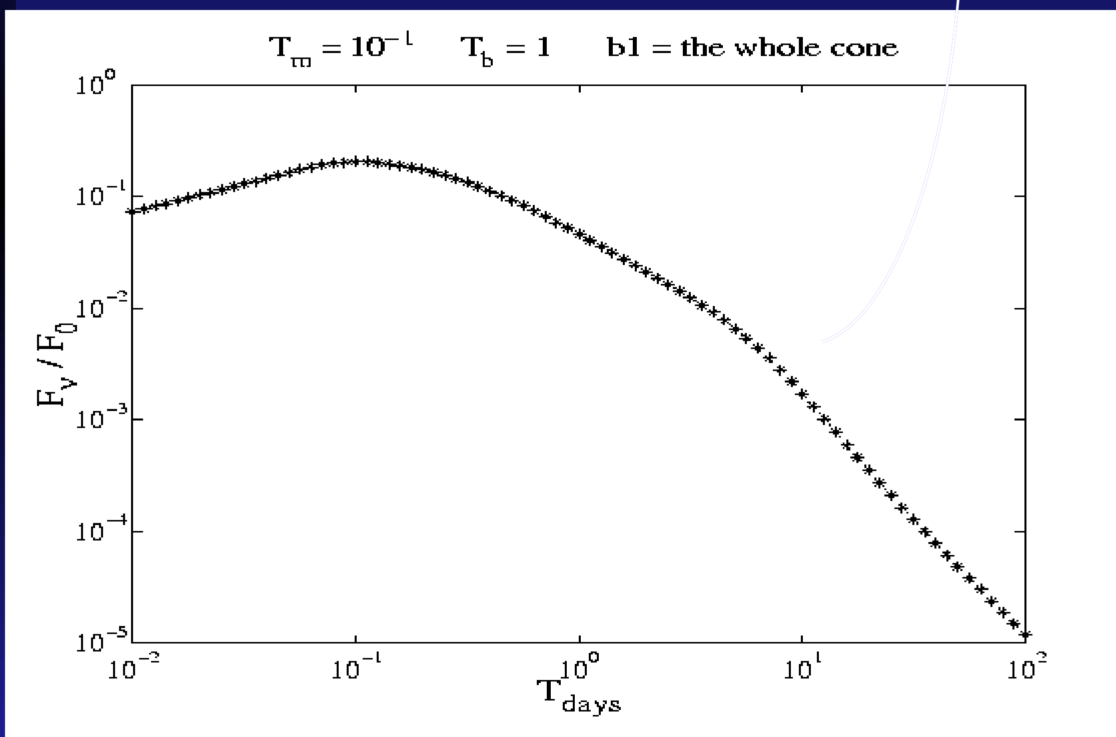


Jets with an opening angle θ expand forwards until $\gamma = \theta^{-1}$ and then expand sideways rapidly lowering quickly the observed flux.

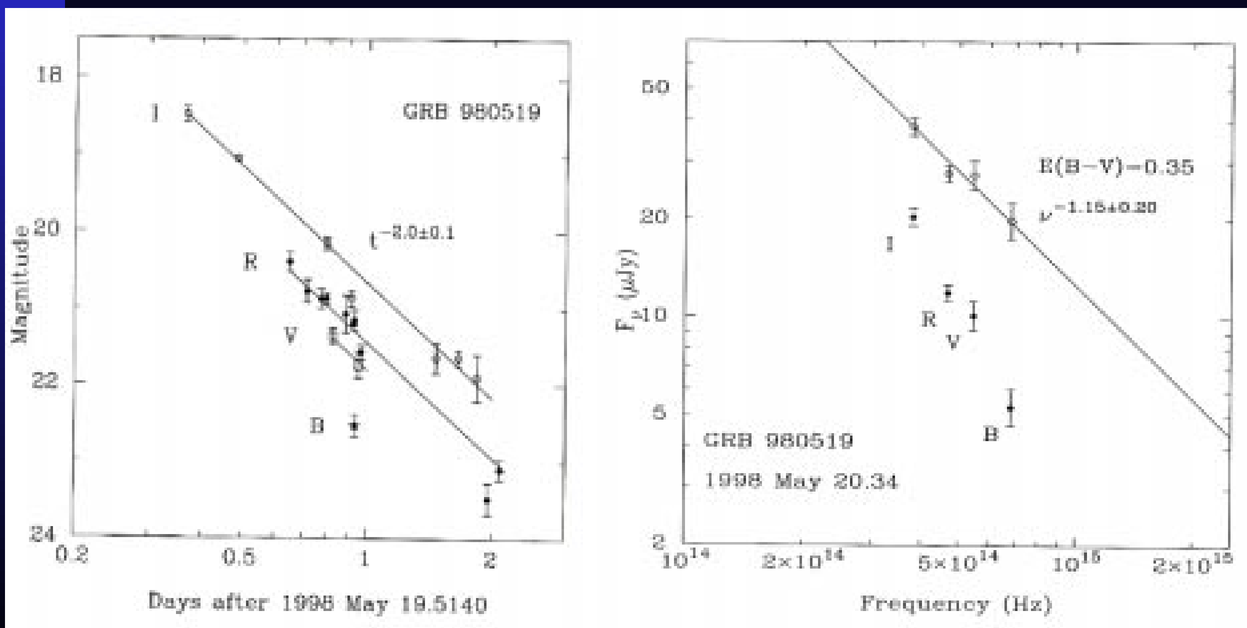
Expected Light Curve from a Jet

(Granot, Piran, Sari 1999)

Break at $\gamma = \theta$



GRB980519 - The Jet?



Data from J. Halpern

- $\alpha = 1.15 +\!- 0.2$
- $\beta = -2.0 +\!- 0.1$

- Consistent with a jet:
  - $\alpha = p/2$
  - $\beta = p$
  - p=2.1 ➡ $\alpha = 1.05$; $\beta = 2.1$

CONCLUSIONS

- Additional Verification of the Fireball and External-Internal Model
- **BUT** GRB/afterglow variability is still a puzzle.
- A Speculation: 970228 and 970508 are the exceptions and 980519 and GRB990123 are the rule
  - ➨ Jets in most GRBs.

☚ GRBs are less energetic than what was earlier believed.

⇒ Search for "Orphan" afterglows

❁ GRBs have a wide luminosity function.

❁ There is no "no host" problem

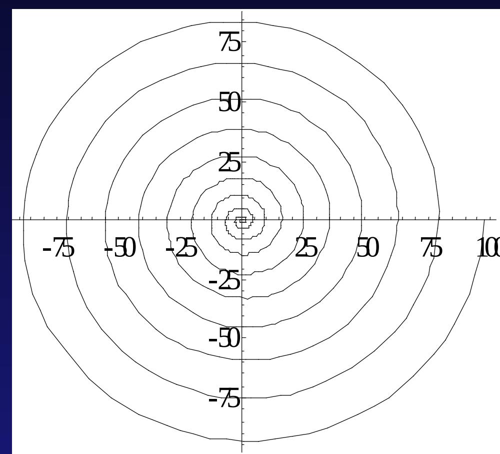
❁ GRBs may or may not follow SFR.

Sources of GRBs?

- **The fireball model does not tell us what is the inner source .**
- **The observed temporal structure shows:**
  - The source must be compact (<10^7cm).
  - Should operates for ≈ 1 - 1000 seconds.
  - Should be highly variable.
  - ⇒ **Most likely powered by accretion onto a newly formed black hole**
- **Association with star forming galaxies.**
- **The Rate of GRBs (one burst observed per day by BATSE) corresponds to:**
  - one burst per galaxy per million years
  - following the star formation rate?

Binary Neutron Star Mergers

* 1916+13: The Binary pulsar (Hulse & Taylor) displays a decay of its orbit due to gravitational radiation emission. Its two stars will collide and merge after 3×10^9 years.



- GRBs are produced by colliding neutron stars at cosmological distances (Eichler, Livio, Piran & Schramm).

- The rate of binary neutron star merges (Narayan, Piran & Shemi; Phinney) agrees with the observed GRB rate.

Implications of GRBs

- The Fireball model:
  - Additional source of cosmic rays (Shemi and Piran).
  - Origin of EEV cosmic rays (Waxman, Vietri, Milgrom & Usov).
  - High energy neutrino burst (Bahcall & Waxman).
- The neutron star merger model:
  - Associated low energy neutrinos burst.
  - Associated gravitational radiation signal (the prime target of the gravitational radiation detectors LIGO and VIRGO).
- Red-shift measurements:
  - GRBs could be used explore the early Universe.
- After 30 years the mystery of GRBs has been (at least partially) resolved.