Gamma-Ray Bursts
and
High Energy Astrophysics

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(Royal Society Wolfson Research Merit Award Holder)

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Outline of the Talk:

- High energy Astrophysics:
  - What is it ? (some possible definitions)
  - Relevant astrophysical objects and physics
- Gamma-Ray Bursts (GRBs):
  - Chronological Overview
    (demonstrates how a field evolves)
  - Mention the most important space missions
  - Overview of main observations & theory
  - Last few years: some highlights from *Swift*
  - Prospects for the future
    (potential areas for a PhD thesis)

What is high-energy astrophysics?

Some possible definitions:

- Study of astronomical objects known to produce high-energy photons
- Interpretation of phenomena seen in X-ray and gamma-ray observations
- Study of astronomical objects **that produce** high-energy **particles**
- Observations at wavelengths in the X-ray regime or above (high energy **astronomy**)

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Relevant Objects or Phenomena

- Compact objects: white dwarfs, neutron stars, **black holes** (talk by Prof. Chris Done)
- Active Galactic Nuclei (Dr. Dave Alexander)
- Cosmic rays, neutrinos, gravitational waves (astro-particle physics; talk by Dr. Jim Hinton)
- Galaxy clusters (talk by Dr. Judith Croston)
- Supernova explosions and remnants
- Pulsars, Pulsar Wind Nebulae, Magnetars
- X-ray binaries, micro-quasars (Chris's talk ~)
- Gamma-ray Bursts (GRBs; most of this talk)

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Relevant Physics

- Extreme densities and/or magnetic field
- Strong field gravity (Neutron Stars, Black Holes)
- Particle acceleration
- (Relativistic) Collisionless shock physics
  (particle acceleration, magnetic field amplification,…)
- Relativistic flows MHD/RMHD/GRMHD
- Radiative processes, radiative transfer
- Magnetic fields, plasma physics
- Nuclear physics (Neutron Stars, Supernovae)

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General Types of Work:

- **Instrumentation**: help design and/or build instruments to observe relevant objects
- **Observation**: plan, perform and analyze relevant observations of these objects
- **Phenomenology**: Interpret & provide a general picture of particular phenomena
- **Theory**: study of the underlying physical processes at work behind the observations (often common to different objects)
- A typical PhD involves 1 or 2 of the above (the borderlines are not always very clear)

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Gamma-Ray Busts (GRBs): Discovery

THE ASTROPHYSICAL JOURNAL, 182:L85–L88, 1973 June 1

OBSERVATIONS OF GAMMA-RAY BURSTS OF COSMIC ORIGIN

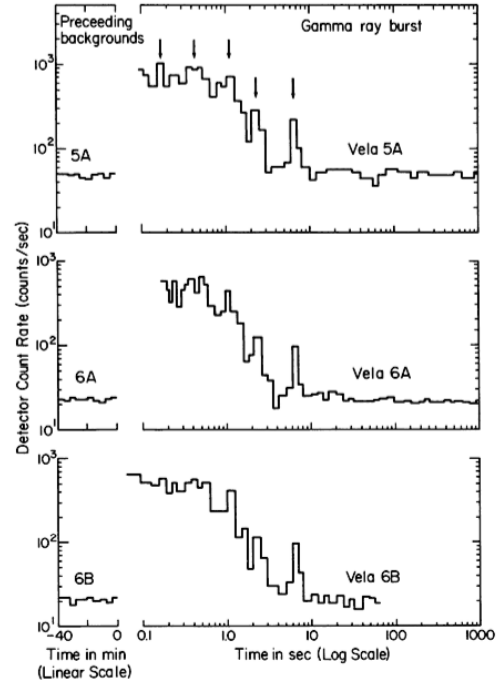
RAY W. KLEBESADEL, IAN B. STRONG, AND ROY A. OLSON

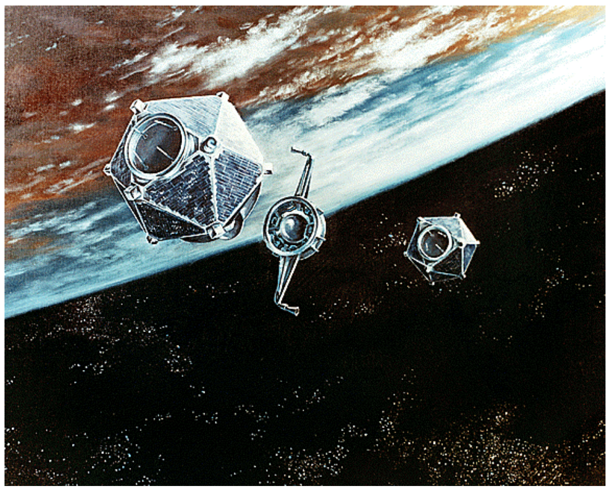
University of California, Los Alamos Scientific Laboratory, Los Alamos, New Mexico
Received 1973 March 16; revised 1973 April 2

ABSTRACT

Sixteen short bursts of photons in the energy range 0.2–1.5 MeV have been observed between 1969 July and 1972 July using widely separated spacecraft. Burst durations ranged from less than 0.1 s to ~30 s, and time-integrated flux densities from ~10^{-5} ergs cm^{-2} to ~2×10^{-4} ergs cm^{-2} in the energy range given. Significant time structure within bursts was observed. Directional information eliminates the Earth and Sun as sources.

Subject headings: gamma rays — X-rays — variable stars

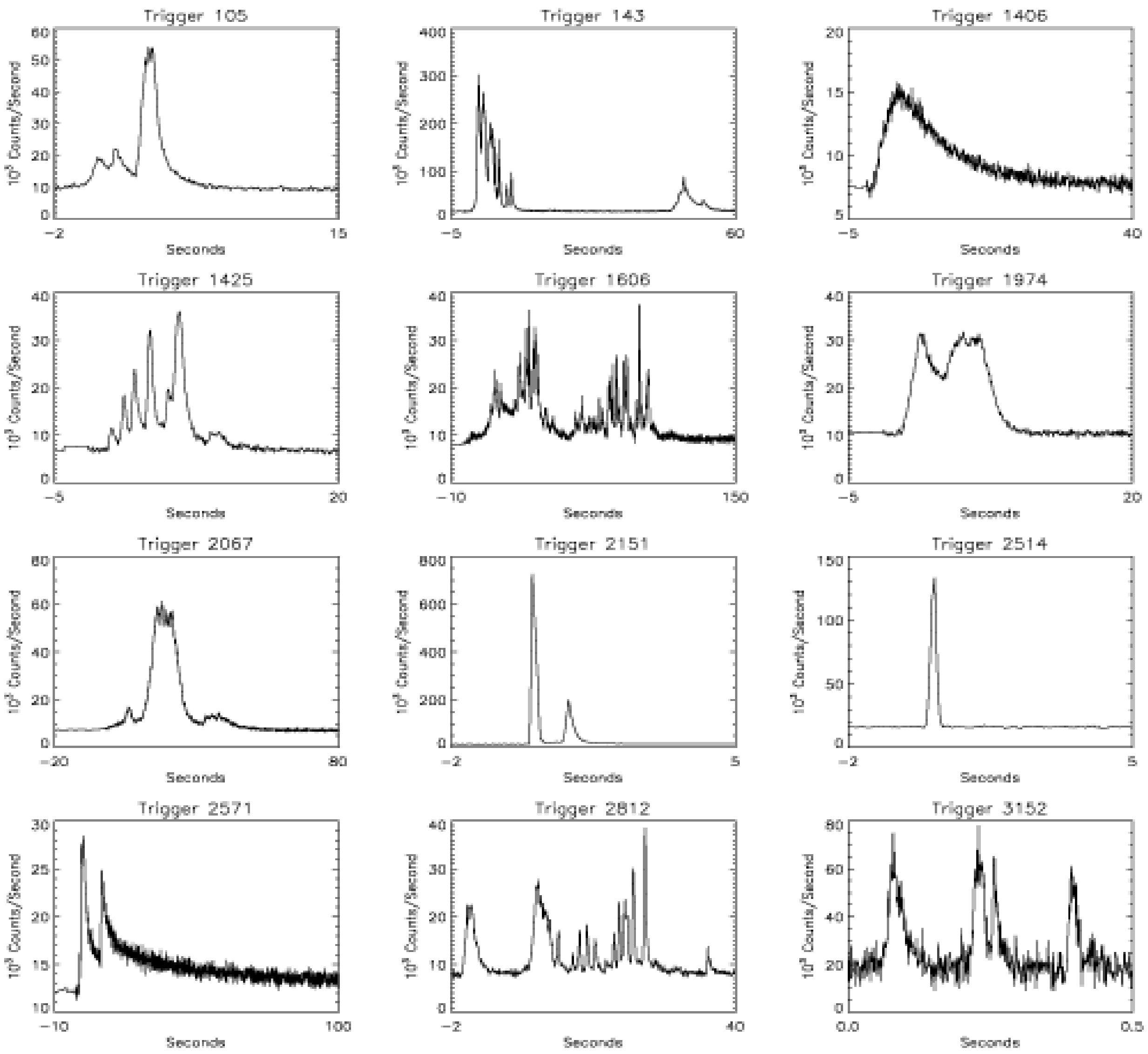




- "Vela" series of 1960s US satellites intended to monitor treaty banning nuclear tests in space
- **First GRB detected in July 2, 1967**
- This was determined only in 1969
- **Declassified and published only in 1973**
- Triangulation showed these events

Examples of gamma-ray light curves

(diverse & typically highly variable)



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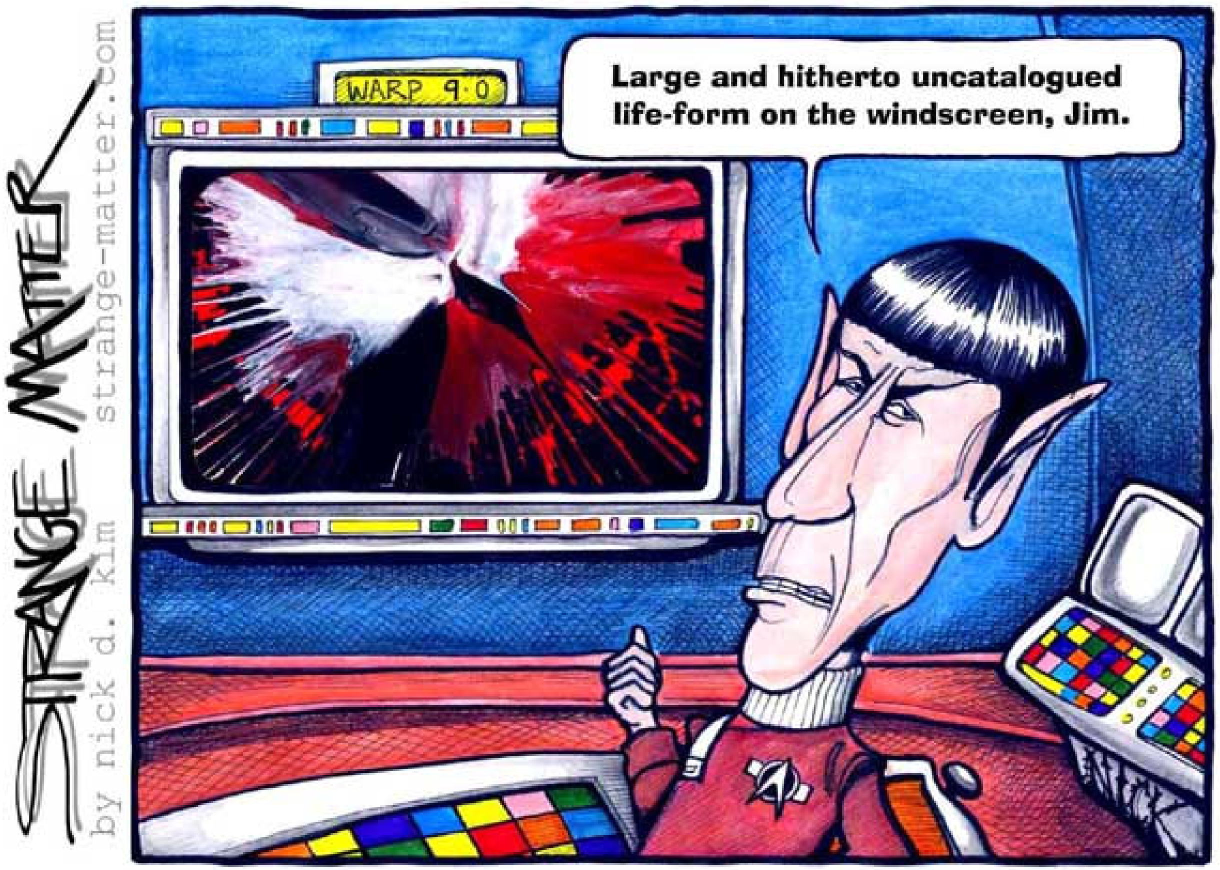
Some bizarre explanations were considered…



- **In the early years**: many theories, most of which invoked a Galactic (typically NS) origin; at some point $N_{theories} > N_{GRBs}$!!!
- Hard to make progress without knowing the distance scale

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A few people liked the idea that GRBs may be extragalactic, possibly high redshift (notably Bohdan Pazcynski 1986).

(1940 - 2007)

But then the energies would be huge!

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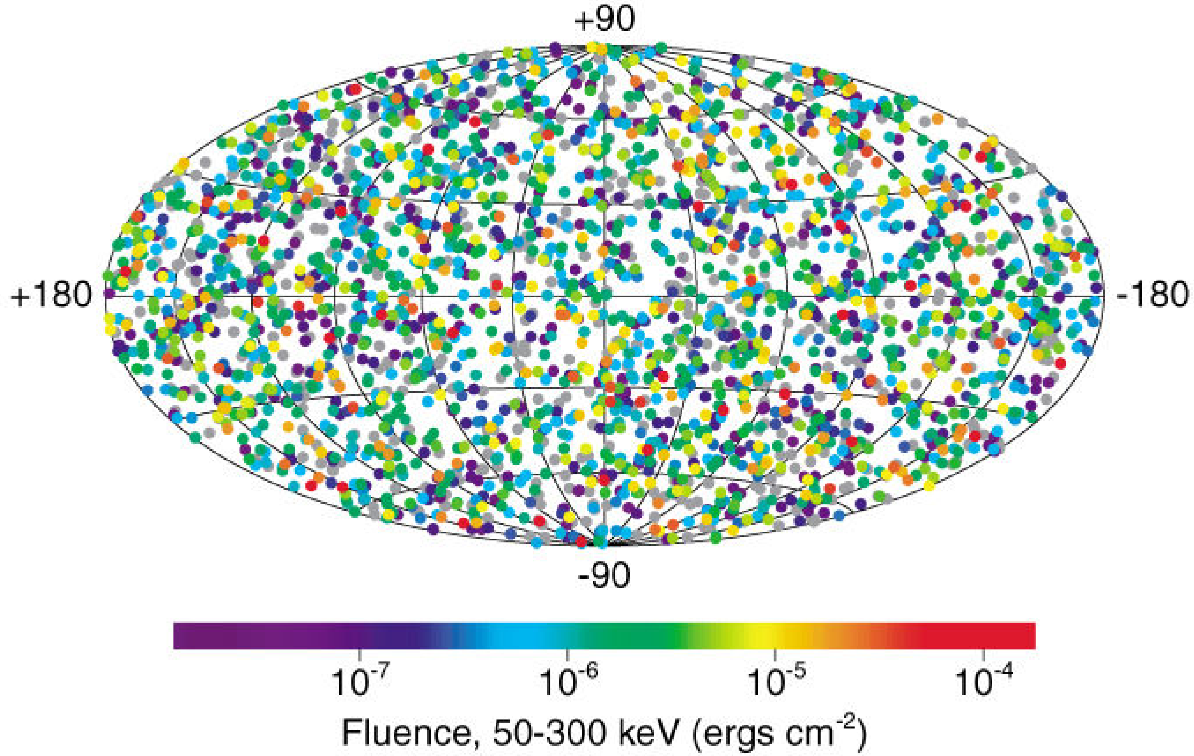
Compton Gamma-Ray Observatory

(1991-1999)

2704 BATSE Gamma-Ray Bursts



- **BATSE**: sensitive all sky GRB detector **(30 keV – 2 MeV)**
- Found an isotropic distribution of GRBs on the sky
- This favours a cosmological origin (though some still invoked an extended Galactic halo)

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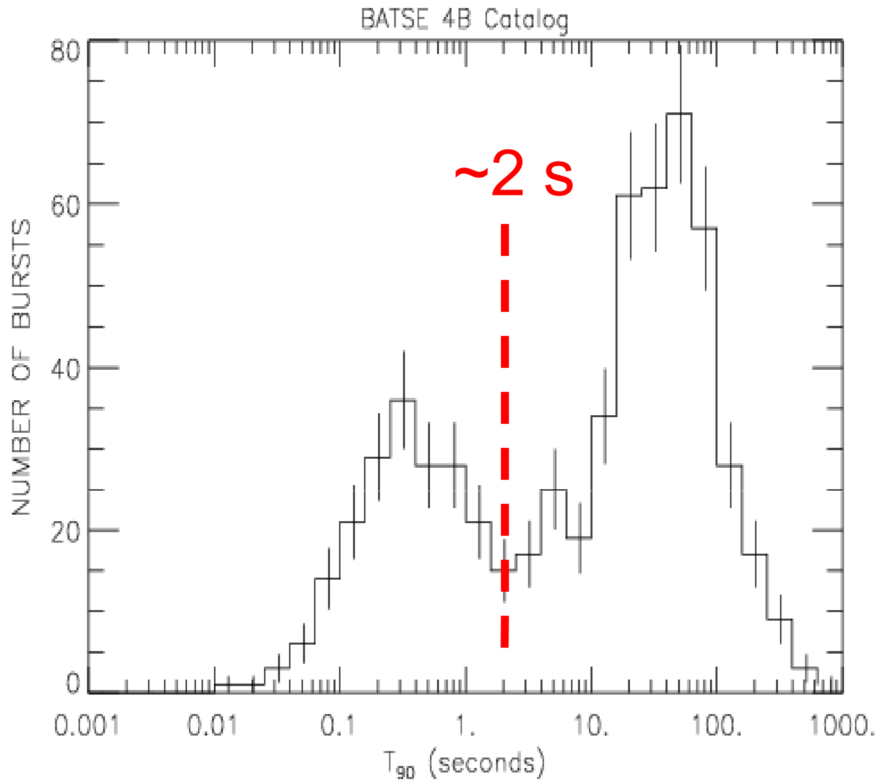
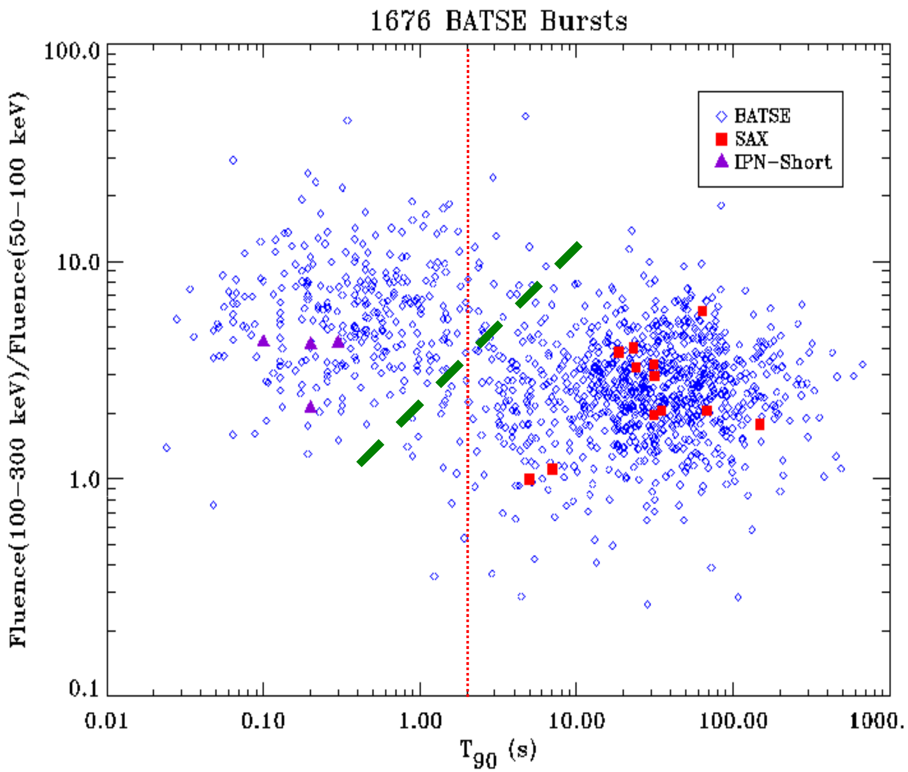
Bimodal Distribution: Long vs. Short

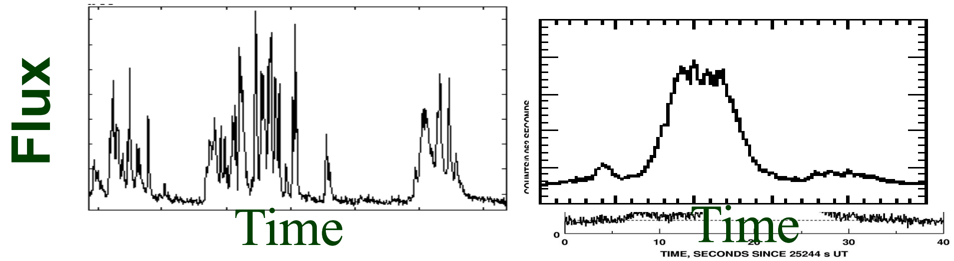




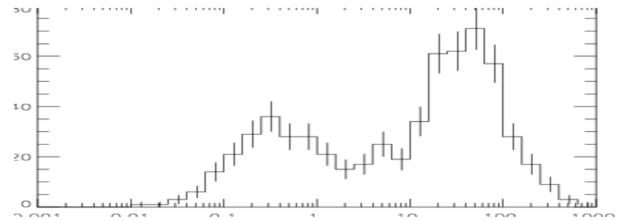
- This suggested two distinct classes of bursts

GRBs: Observations - Prompt GRB

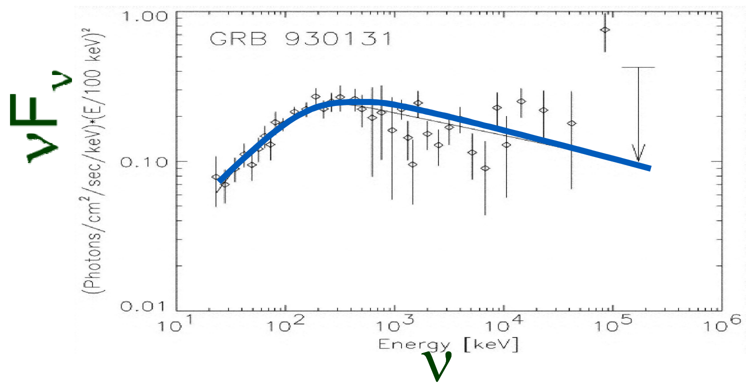
- Variable light curve



- Duration: $\sim 10^{-2} - 10^{3}$ sec



- Spectrum: non-thermal
  νF_ν peaks at ~ 0.1-1 MeV



- Rapid variability, non thermal spectrum & z ~ 1
  $\Rightarrow$ relativistic source ($\Gamma \gtrsim 100$) (compactness problem: Schmidt 1978; Fenimore et al. 1993; Woods & Loeb 1995;…)

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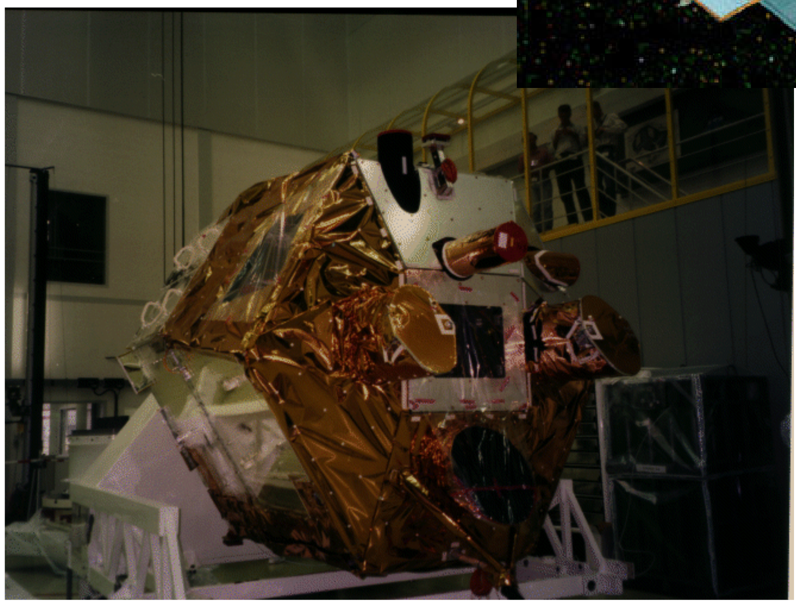
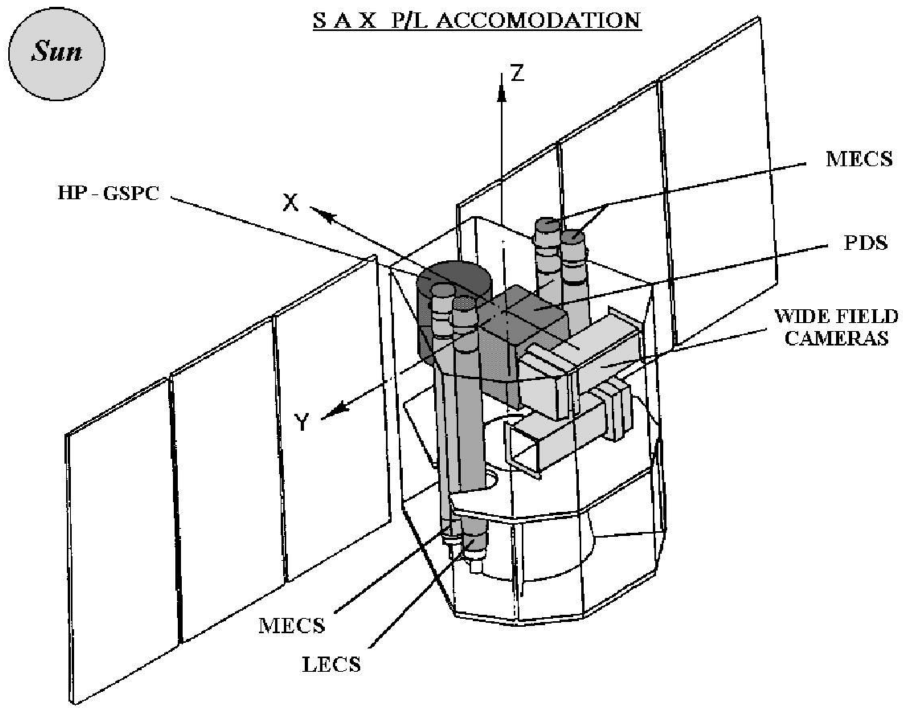
BeppoSAX & the discovery of GRB Afterglow (1997)

- Wide Field Camera: 40°×40°, 2-30 keV
  (+ PDS shielding – nearly all sky @ 100 - 600 keV)
- Narrow Field Instruments: (~1'-0.5°) 0.1-300 keV





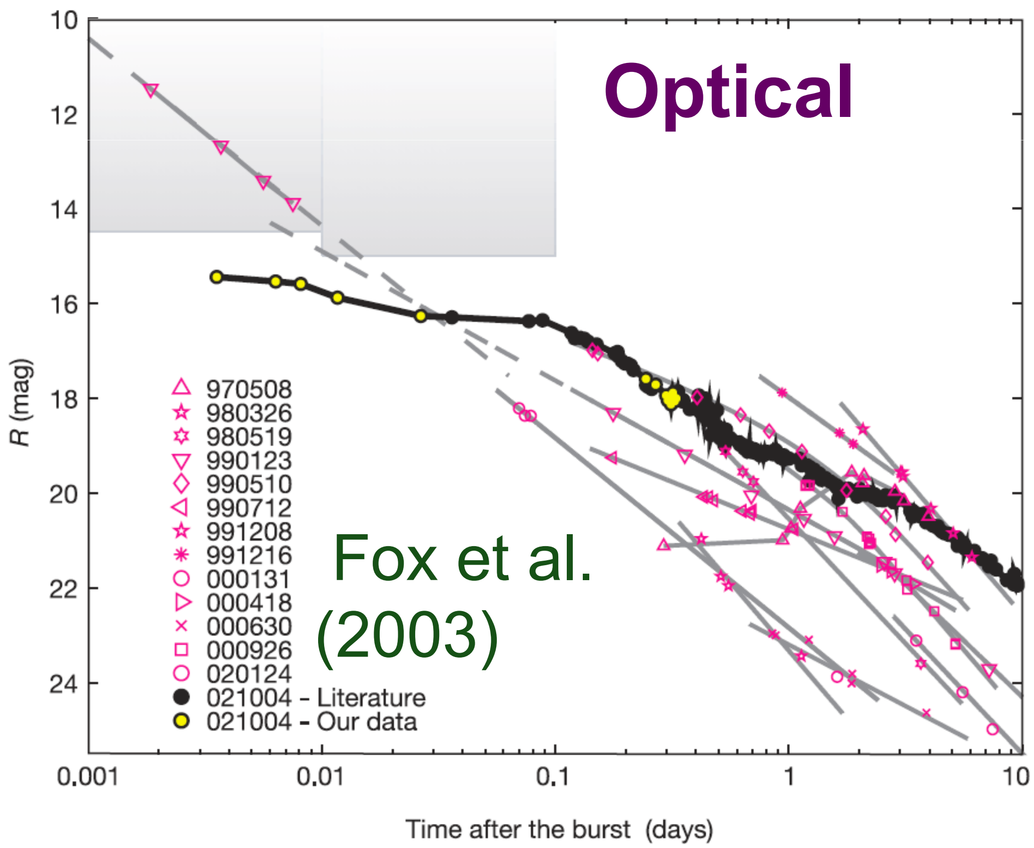
BeppoSAX & the discovery of GRB Afterglow

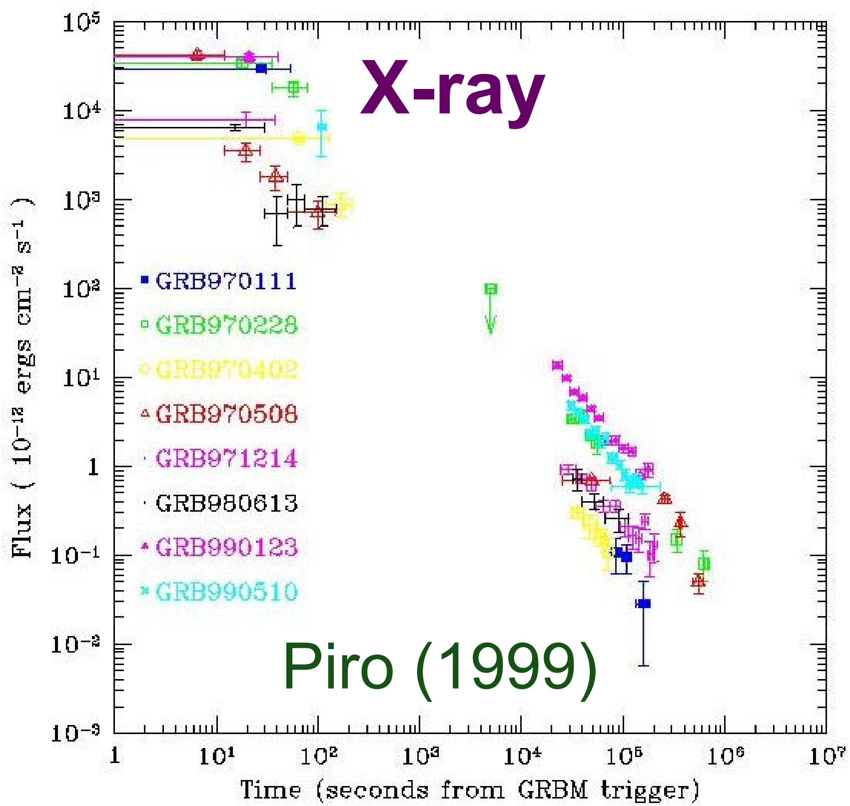
- WFC → ground → point NFI → ground (hours)
- Its abilities led to **afterglow** detection (1997) in X-rays, optical, radio (for long GRBs - LGRBs)
- This led to redshift measurements: clear cut determination of the distance/energy (LGRBs) $E_{\gamma,iso} \sim 10^{52}$-$10^{54}$ erg, narrow jets: $E_\gamma \sim 10^{51}$ erg
- Afterglow observations provided many new constraints on beaming (narrow jets $\theta_j \sim 3° - 30°$), event rate ($\sim 10^{-5.5}$ yr^{-1} Galaxy^{-1}), host galaxies (star forming), external density ($\sim 10^{-3} - 10^{2}$ cm^{-3}), Supernova connection, etc.

Afterglow Observations: pre-Swift

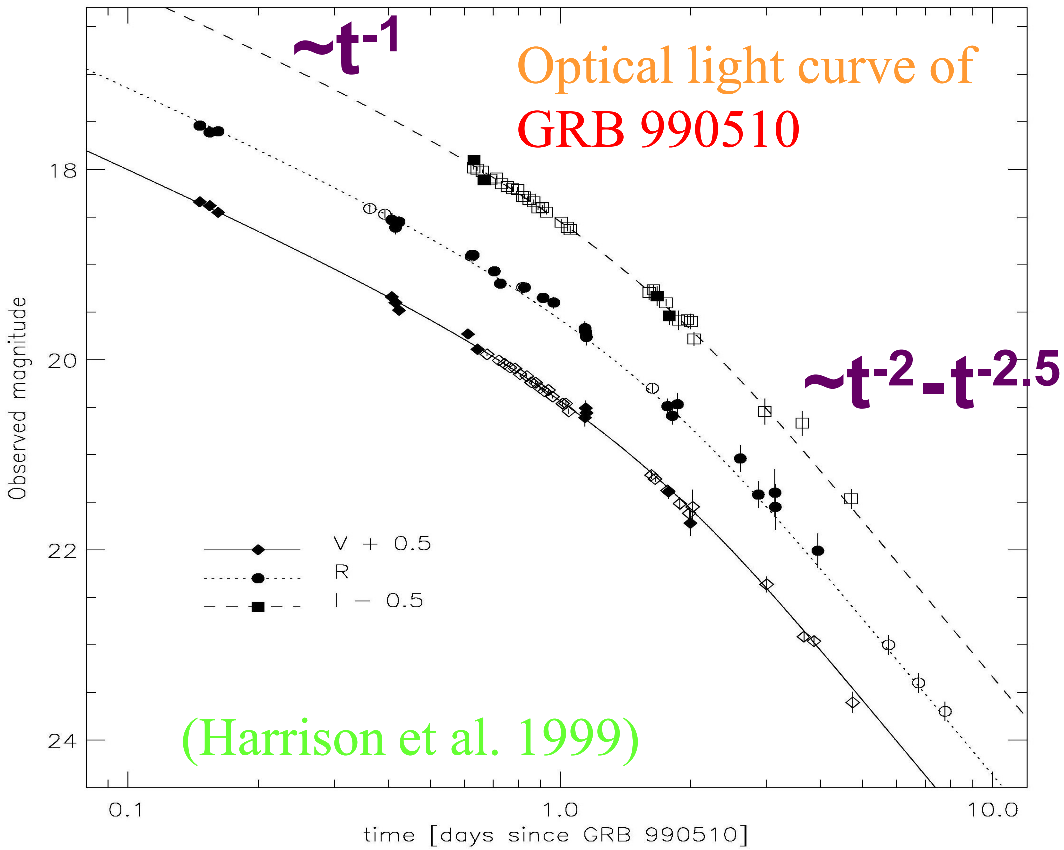
(basic features the model needs to produce)

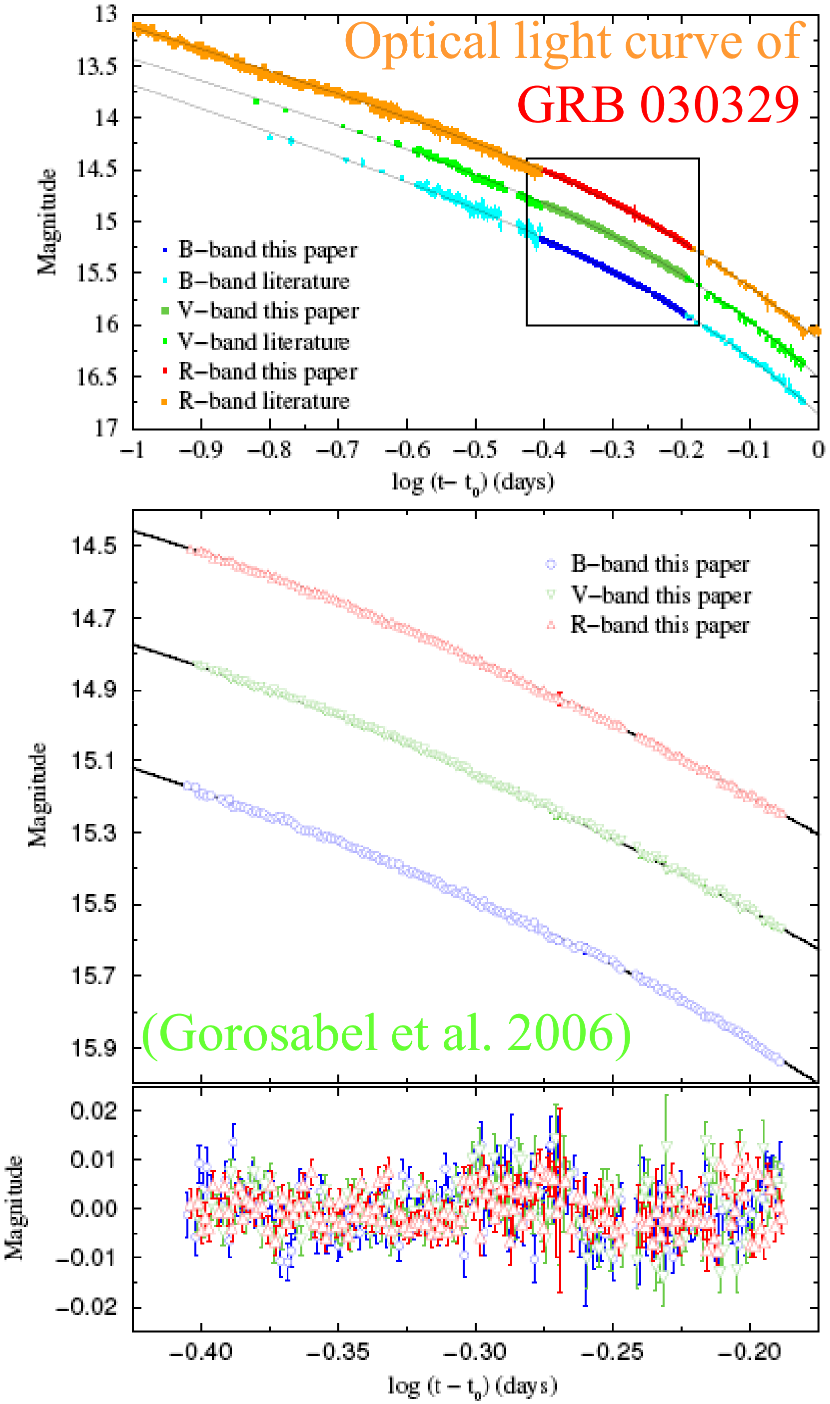
- X-ray, optical & radio emission over (pre-*Swift*) days, weeks & months, respectively, after GRB
- **Light curves**: power-law decay





Some afterglows show an Achromatic Steepening of the Light Curve ("Jet Break")

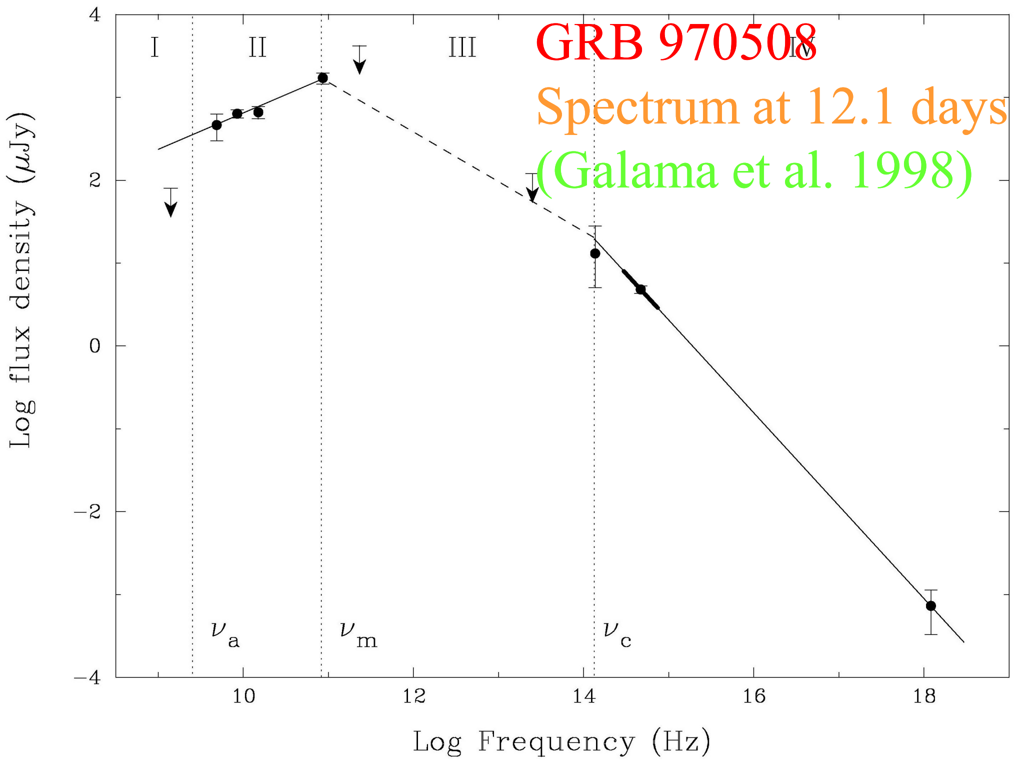




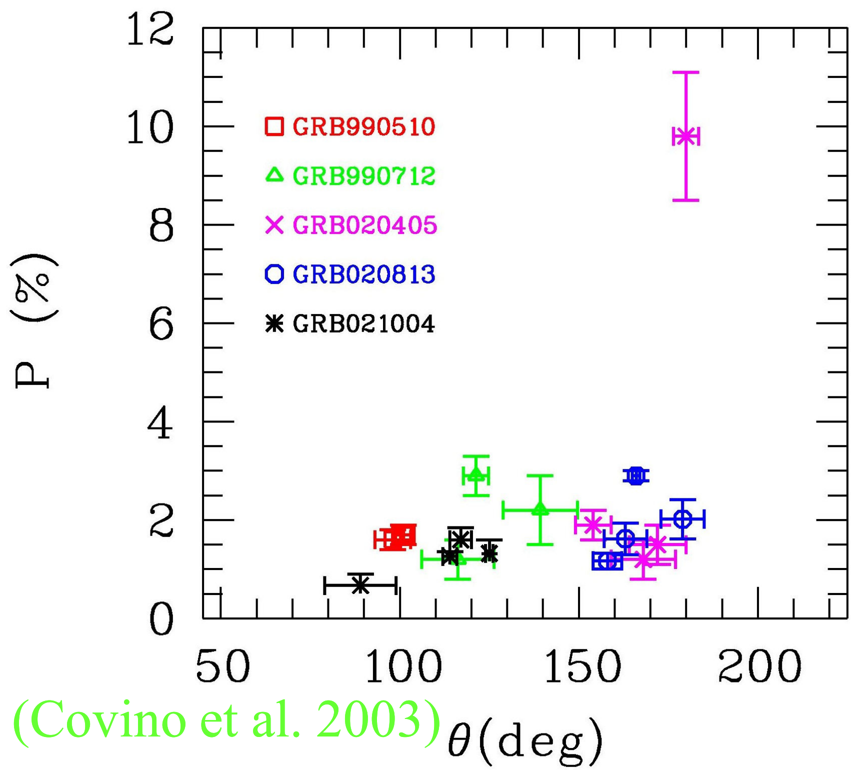
Spectrum & Linear Polarization

- **Spectrum:** consists of **several power law segments** & is well fit by synchrotron emission
- **Linear polarization of ~ 1%-3% was detected in several optical/NIR afterglows ⇒ likely synchrotron emission**

Spectrum



Linear Polarization



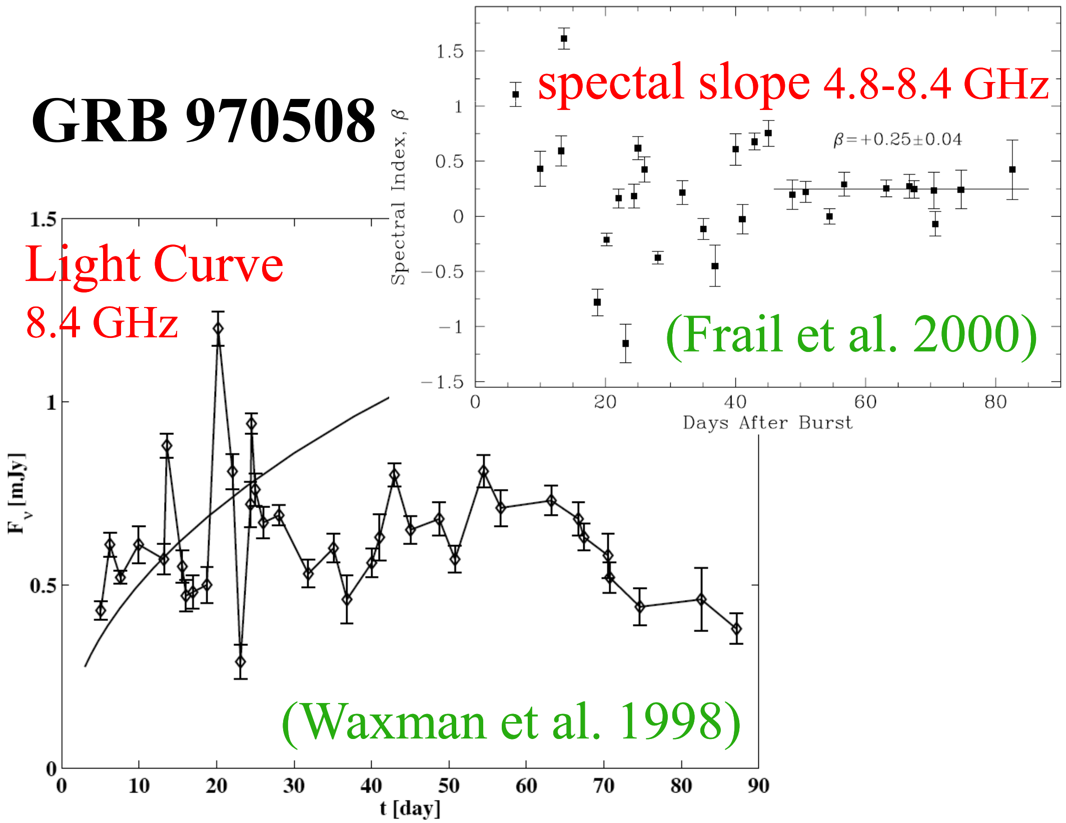
(Covino et al. 2003)

The Size of the Afterglow Image

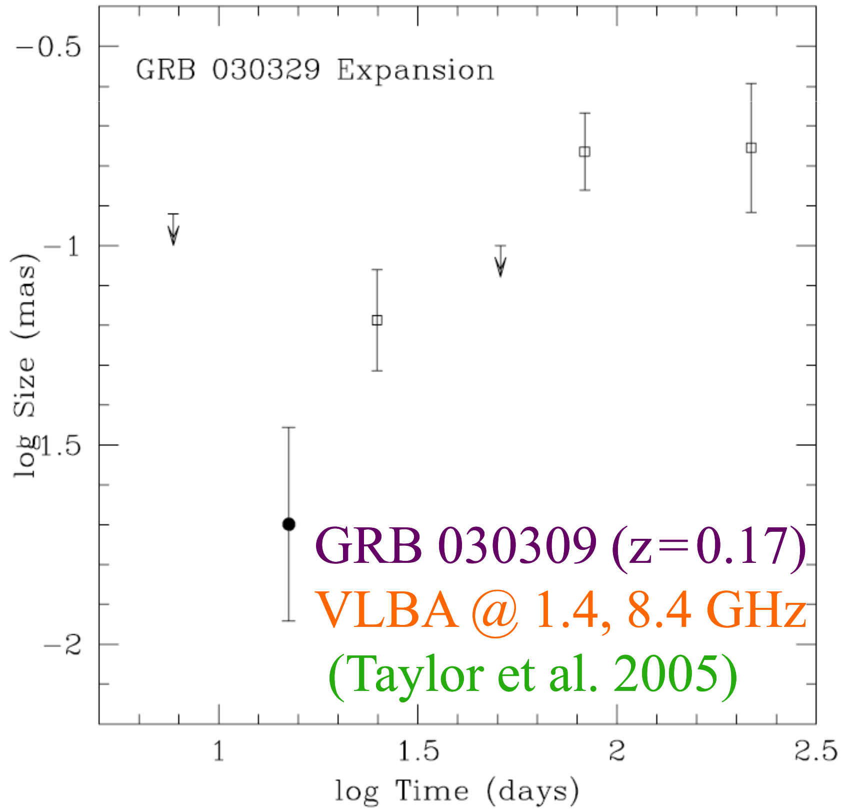
- Quenching of diffractive scintillations after ~ 30 days in the radio afterglow of GRB 970508 $\Rightarrow$ $R_{\perp} \sim 10^{17}$ cm
- The radio afterglow of GRB 030329 was (marginally) resolved **directly** using the VLBA (Taylor et al. 04,05)

Indirect: Scintillation

GRB 970508



Direct: VLBA



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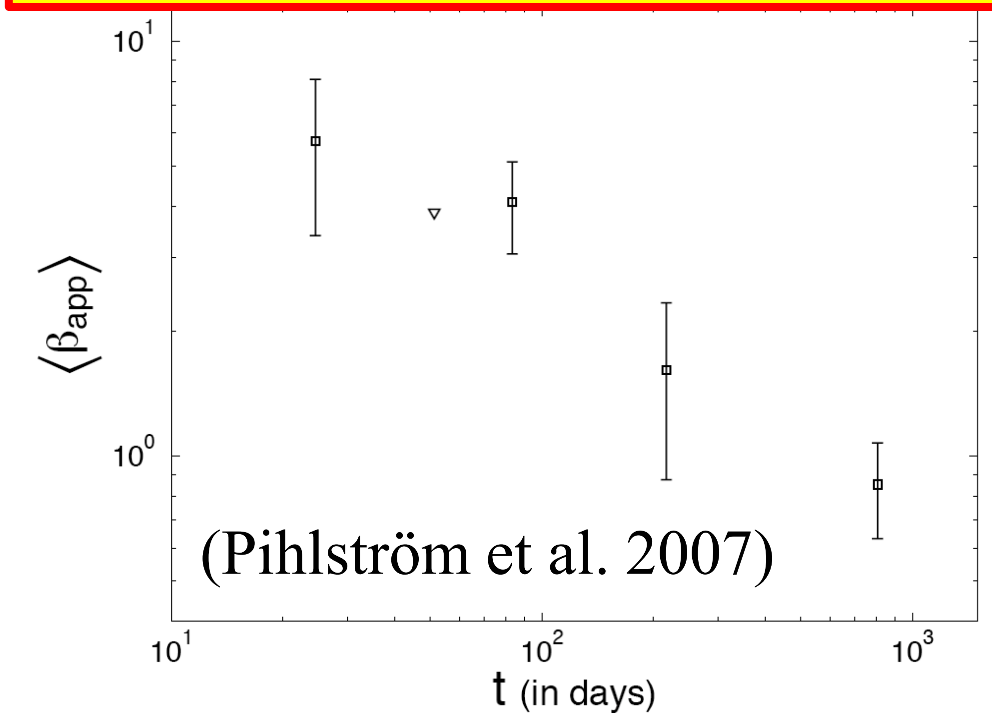
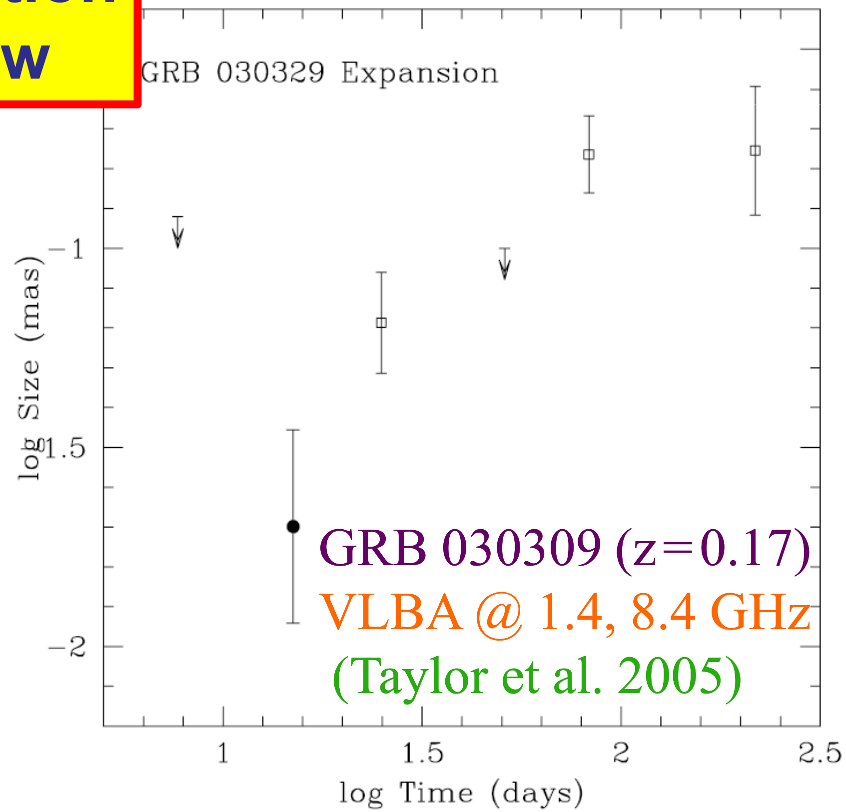
Direct evidence for relativistic motion & deceleration during the afterglow

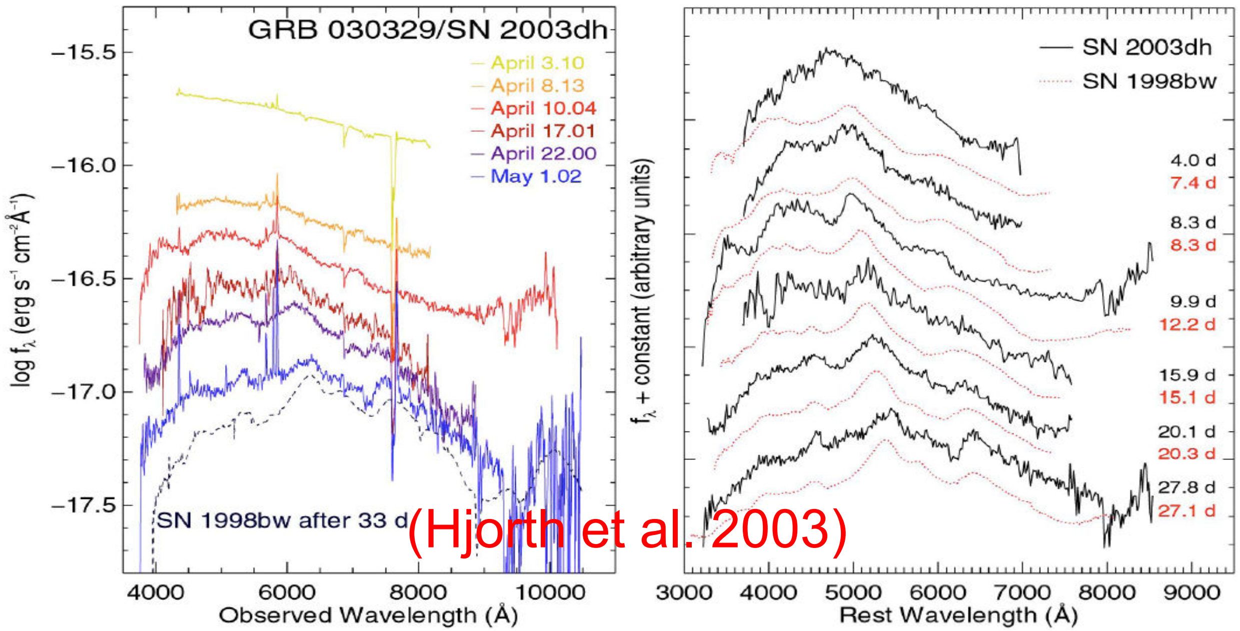


Direct: VLBA

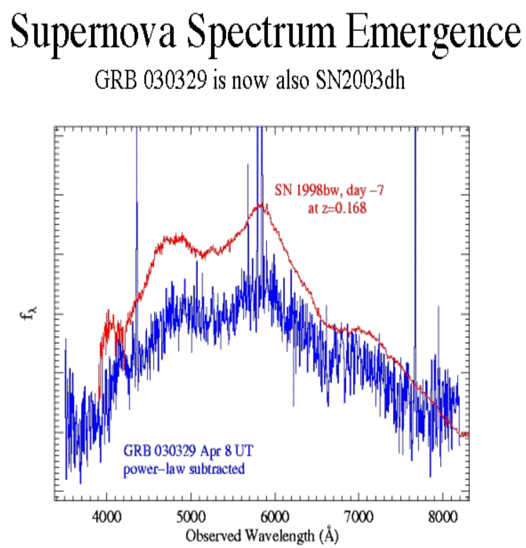


(Long) GRB – SN (Type Ic) Connection

- Firmly established the connection between long GRBs and core collapse Supernovae (in 2003; circumstantial or less conclusive evidence exited earlier)
- Progenitor: massive star sripped of its H & He
- Supports the “Collapsar” model, in which a BH is formed during the collapse of a massive star

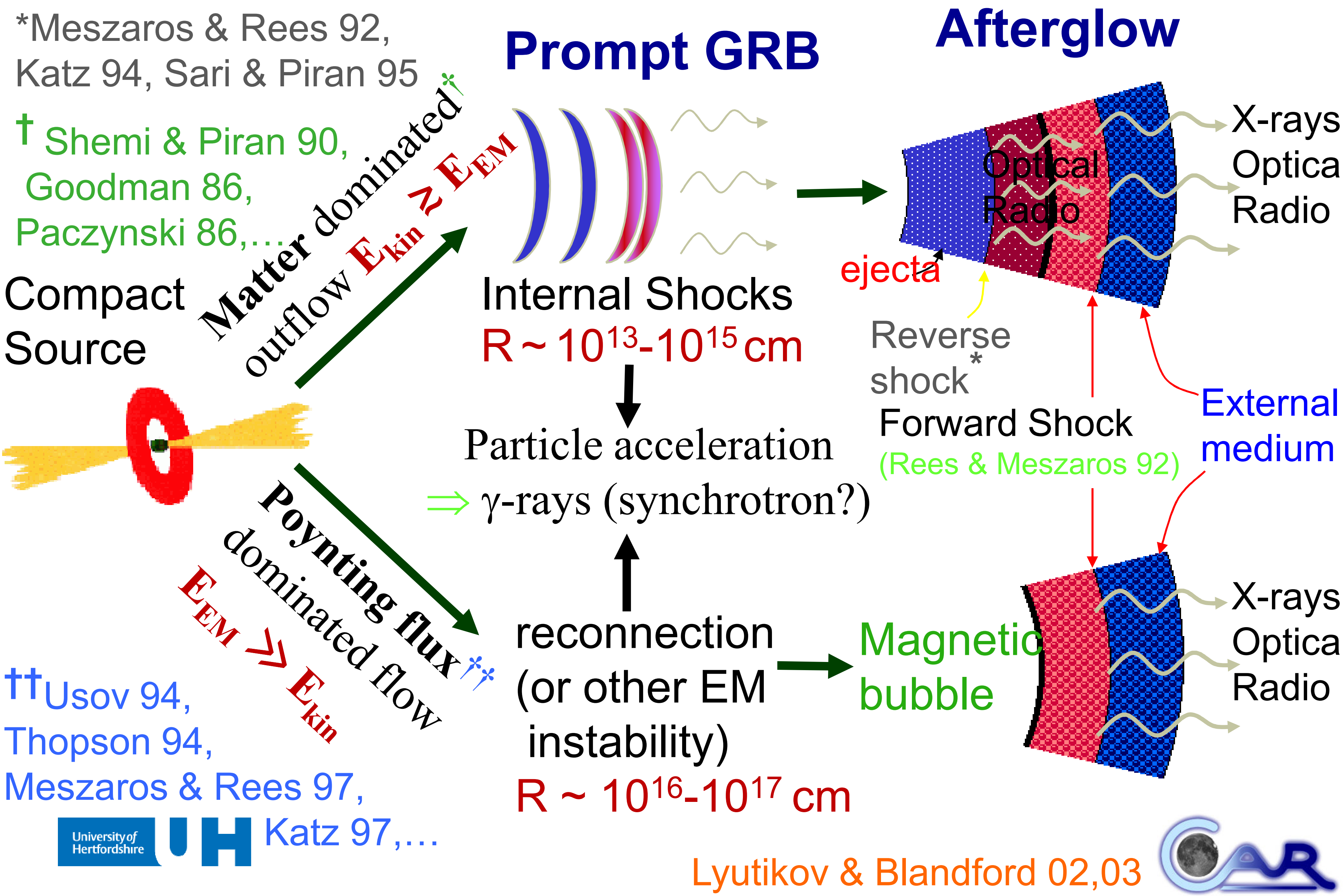


(Hjorth et al. 2003)



T. Matheson (CfA), GCN 2120

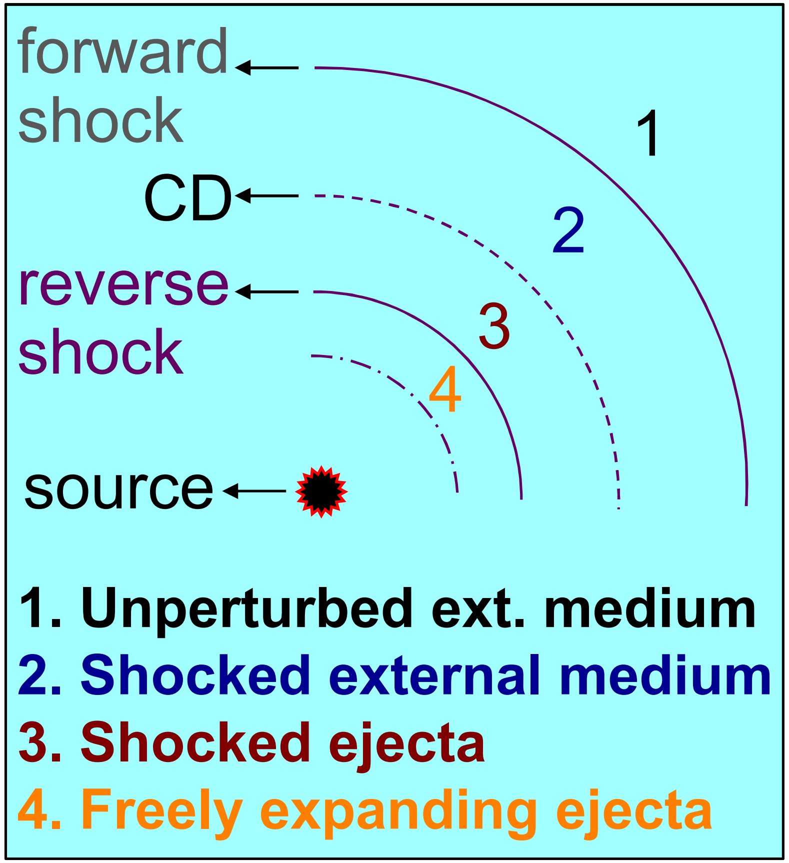
GRB Theory: Fireball vs. Poynting Flux



Afterglow Theory: Dynamics

1. A spherical outflow (relativistic analog of SNR)

- A compact source ejects a relativistic outflow
- Dissipation within the outflow causes the prompt GRB
- a relativistic **forward shock** sweeps up external medium
- **The outflow is decelerated by a reverse shock**
- **When most of the energy is transferred to the shocked external medium the flow approaches self-similarity (Blandford & McKee 1976)**
- **Finally the flow becomes Newtonian (Sedov-Taylor)**



Emission: Synchrotron Radiation

- Relativistic electrons gyrating in a magnetic field
- The electrons are presumably shock-accelerated to a power-law distribution $dN/d\gamma_e \propto \gamma_e^{-p}$ $(\gamma_e > \gamma_m)$
- Convenient parameterization of our ignorance: the electrons & the magnetic field are assumed to hold fractions ε_e & ε_B of the internal energy
- Individual electron: $P_\nu \propto \nu^{1/3}$ @ $\nu < \nu_{syn} \propto \gamma B' \gamma_e^2$
- Break frequencies: $\nu_m = \nu_{syn}(\gamma_m)$, $\nu_c = \nu_{syn}(\gamma_c)$, ν_a
- Synchrotron-self Compton may also be relevant

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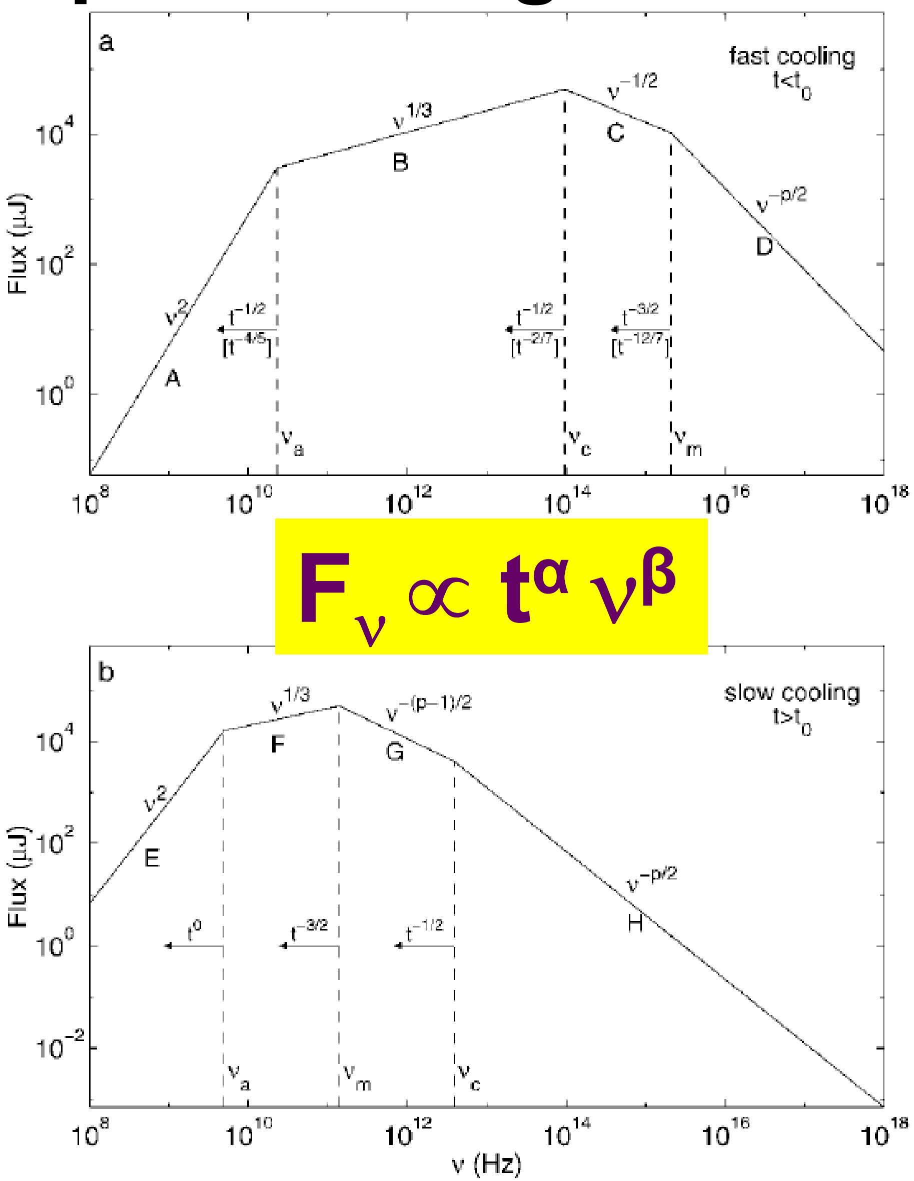
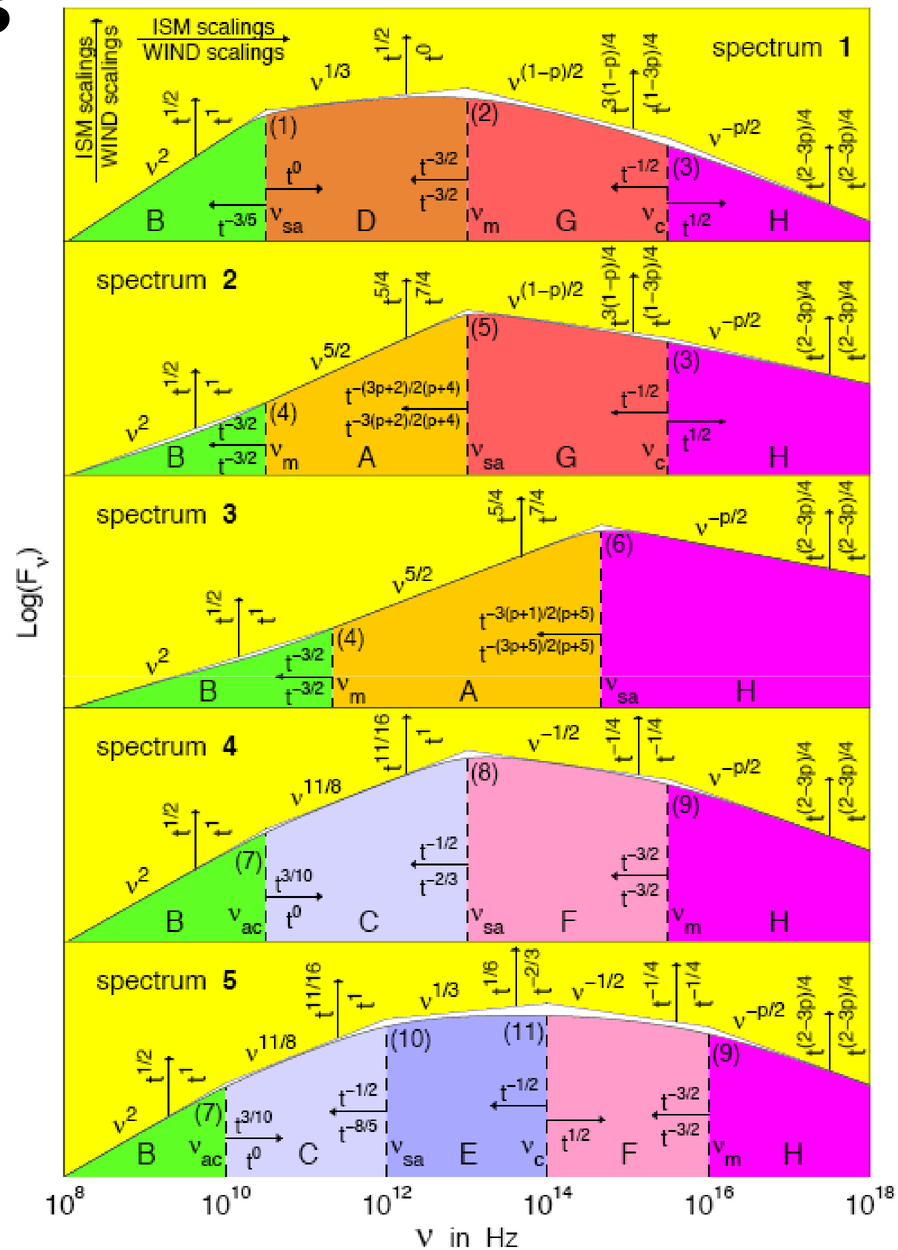
Spectra & Light Curves



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

(Sari, Piran & Narayan 1998)

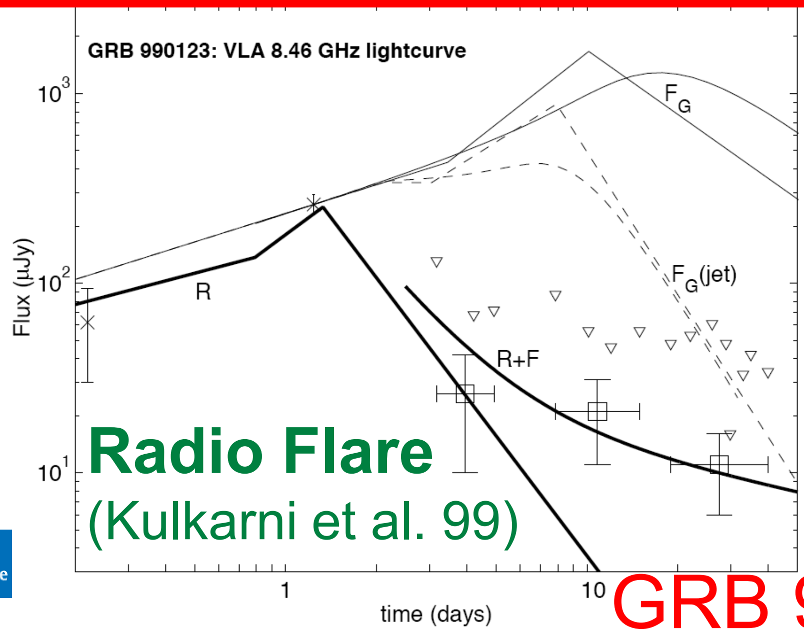


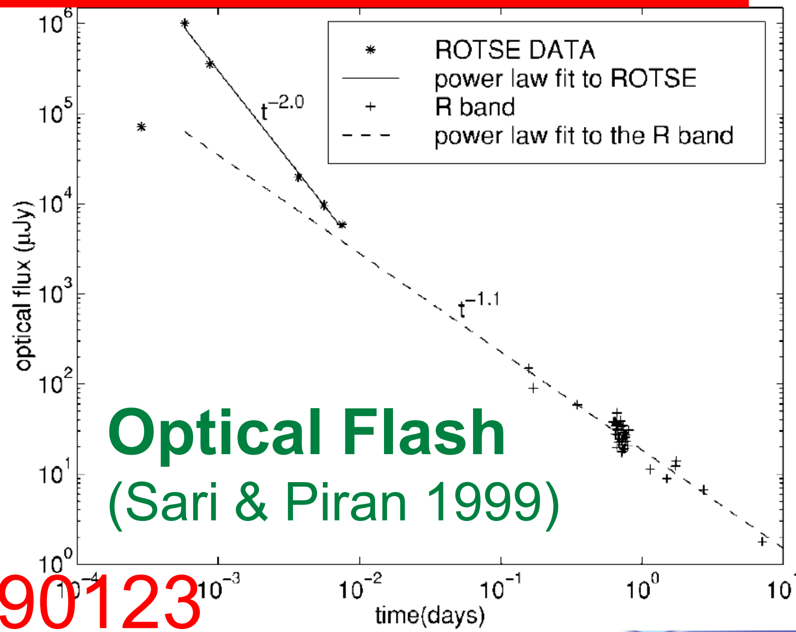
(JG & Sari 2002)

Origin of Different Emission Components:

- The **long lived** afterglow **emission** lasting days, weeks, & months in the X-ray, optical & radio is

The simplest spherical model was very successful in explaining afterglow observations during the first ~ 2 years after the detection of afterglow in 1997





GRB 990123

Complications: variants of basic model

motivation: both theoretical & observational

- **Radiative losses** (Blandford & McKee 67; Cohen, Piran & Sari 98; Panaitescu & Meszaros 98; Meszaros, Rees & Wijers 98)
  - Were expected theoretically in the early afterglow
  - invoked to reduce the high prompt γ-ray efficiency
- Wind-like external density $\propto R^{-2}$ (Chevalier & Li 2000)
  - Motivation: expected for massive star progenitor
- **Jets**: narrowly collimated outflow (Rhoads 97, 99;…)
  - Motivation: in analogy to other relativistic sources & reduces total energy output in γ-rays
  - Predicted a “jet break” which was soon observed

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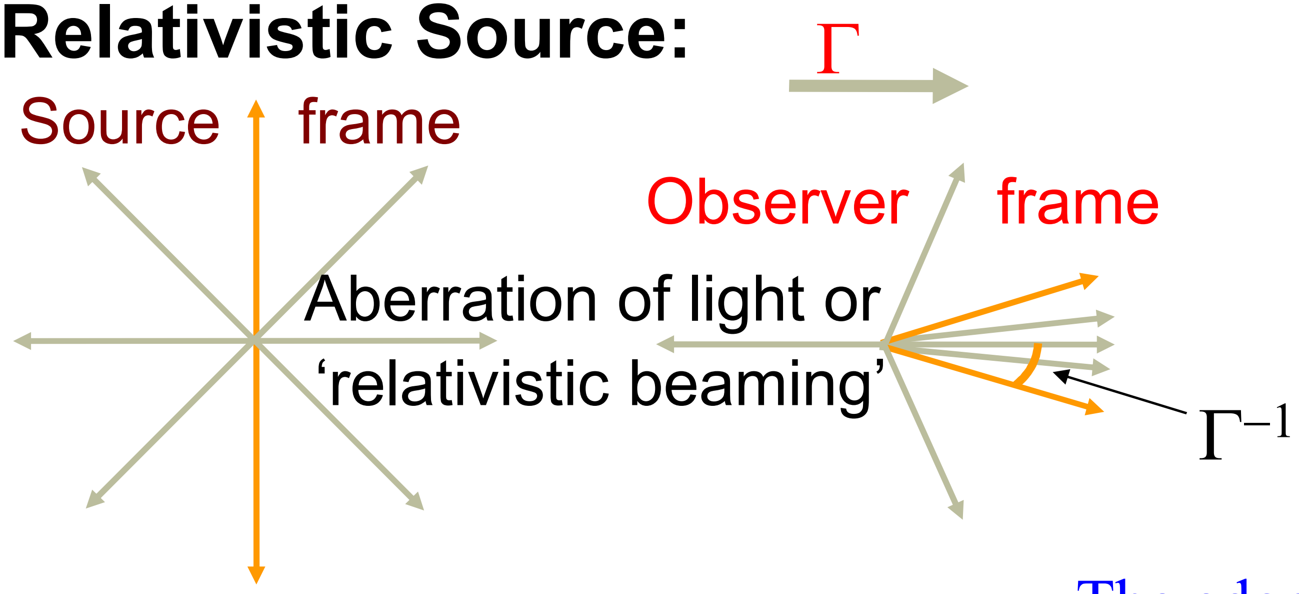
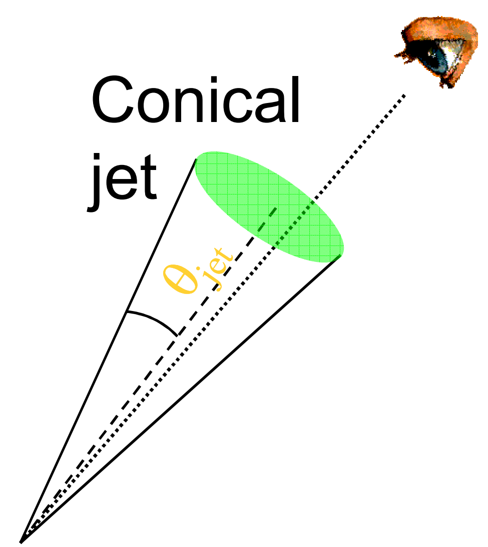
What causes a Jet Break in GRB Afterglows

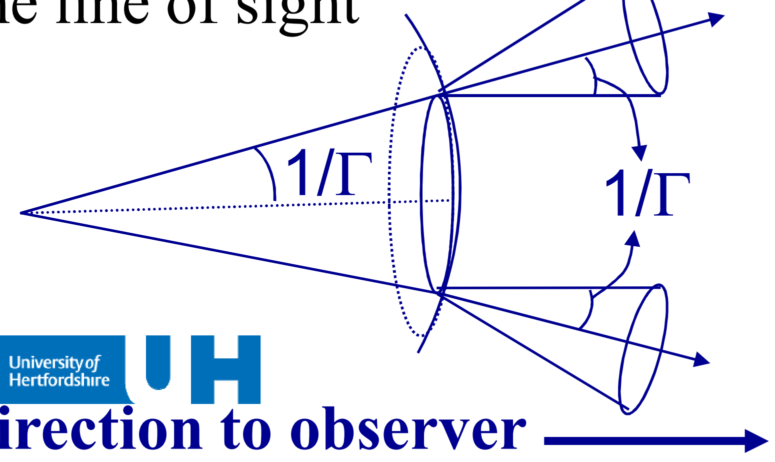
Relativistic Source:





The edges of the jet become visible when Γ drops below $1/\theta_{jet}$, causing a jet break

The observer sees mostly emission from within an angle of $1/\Gamma$ around the line of sight



For $v_{\perp} \sim c$, $\theta_{jet} \sim 1/\Gamma$ so there is not much "missing" emission from $\theta > \theta_{jet}$ & the jet break is due to the decreasing $dE/d\Omega$ + faster fall in $\Gamma(t)$

The *Swift* Era: (launched November 20, 2004)

- Observes a GRB in γ-rays, then slews to its position autonomeously, whithin tens of senonds, & observes in X-rays, Ultra-Violet (UV) and optical
- Detects ~100 GRB/yr + X-ray afterglow for most
- Its early afterglow observations filled the gap between the prompt γ-ray emission and pre-Swift "late" afterglow observations, hours after the GRB
- Discovered unexpected behavior of early afterglow
- Led to the discovery of **afterglow** from **short** GRBs
  → host galaxies, redshifts, energy, rate, progenitors?

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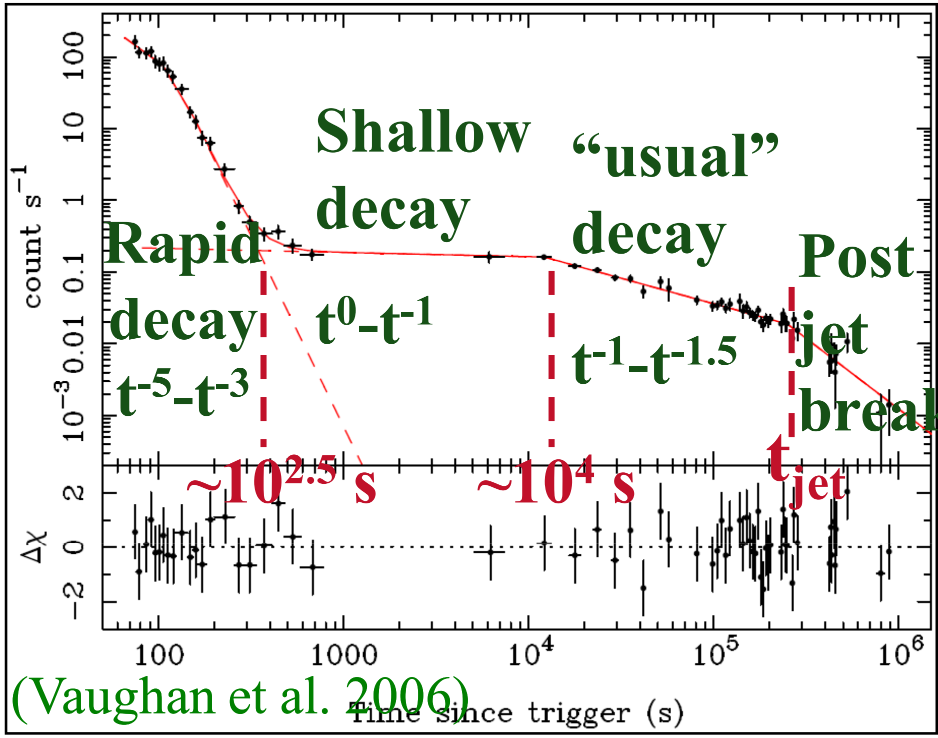
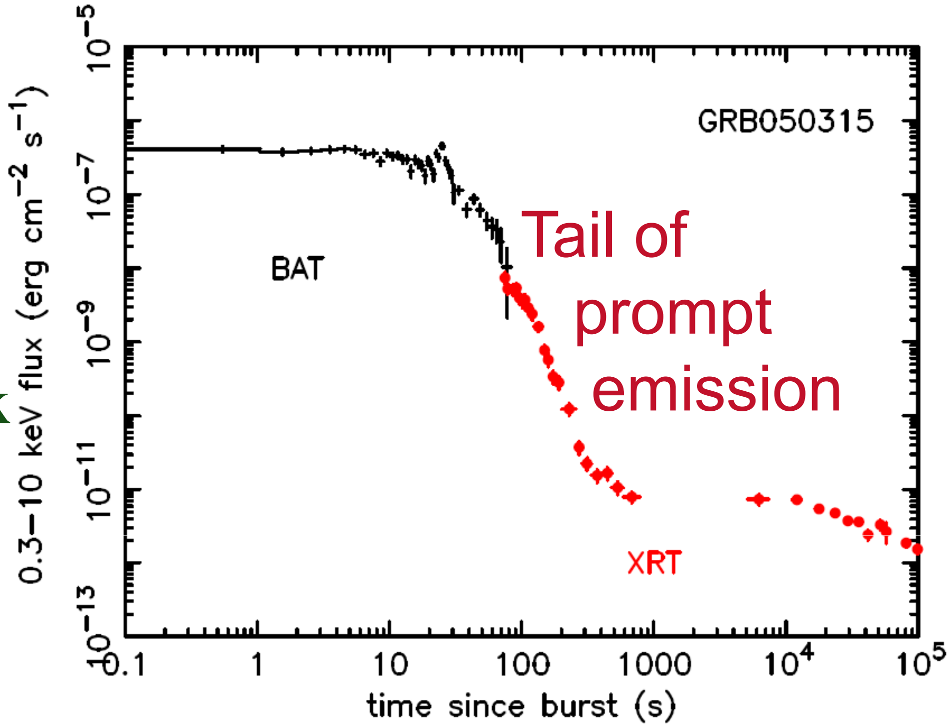
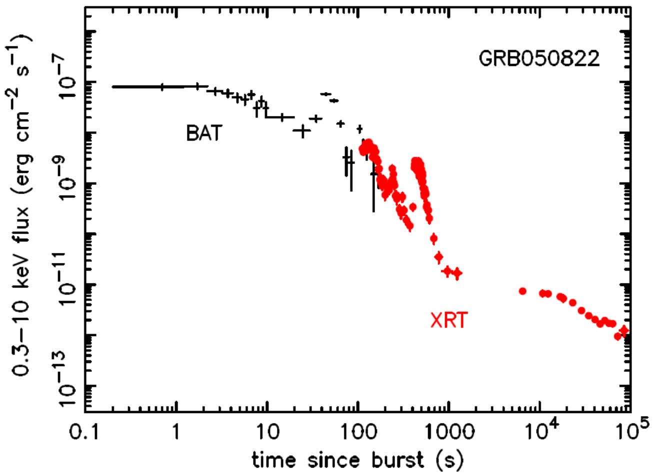
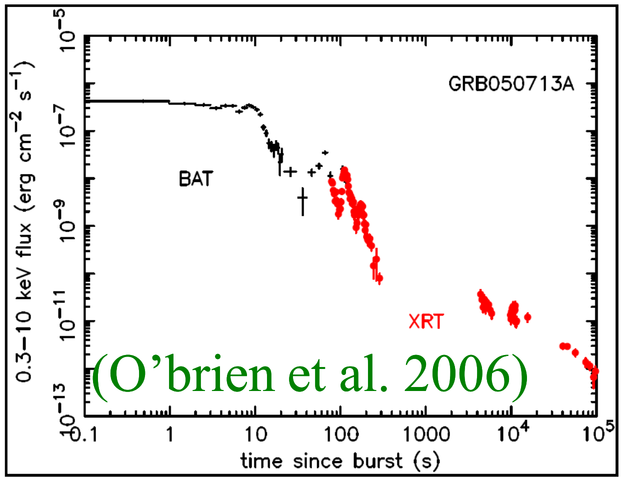
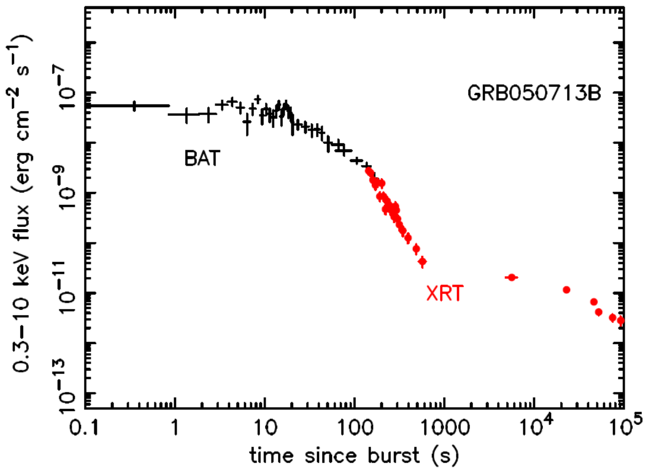
Early X-ray Afterglows from Swift:











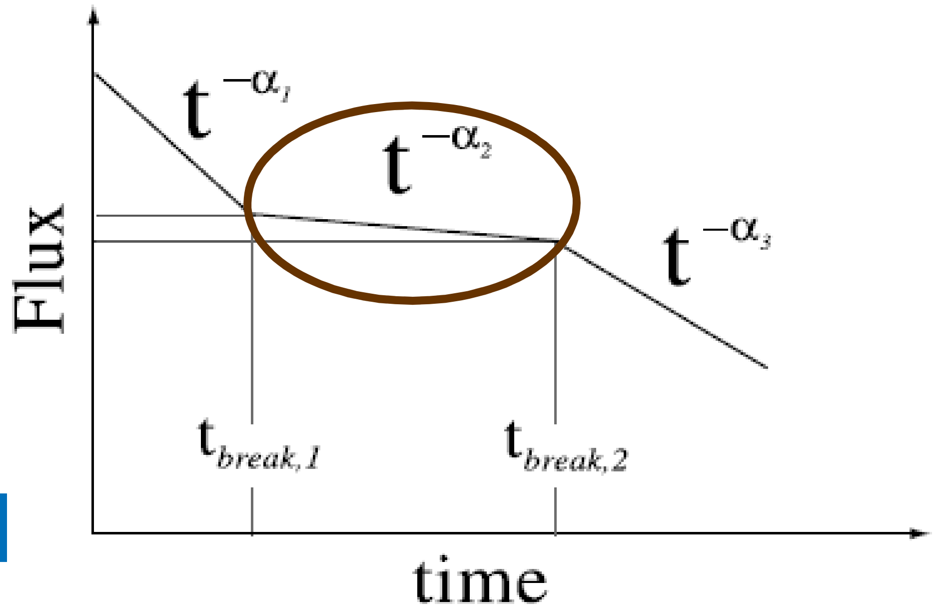
Possible Explanations for the Shallow Decay

$$\frac{\varepsilon_x(t)E_{k,iso}(t)}{tF_x(t)} \approx 4\pi d_L^2(1+z)^{\beta-\alpha-1}$$ where $\varepsilon_x(t) \equiv \dfrac{t\,L_x(t)}{E_{k,iso}(t)}$ is the afterglow efficiency (fraction of kinetic energy radiated in the dynamical time).

During the shallow decay phase $\varepsilon_x(t)E_{k,iso}(t) \propto tF_x(t)$ increases with time.

For $\nu_x > \max(\nu_m, \nu_c)$ and $p > 2$, under standard afterglow theory $\varepsilon_x(t)$ decreses with time,and therefore $E_{k,iso}(t)$ must increase with time.

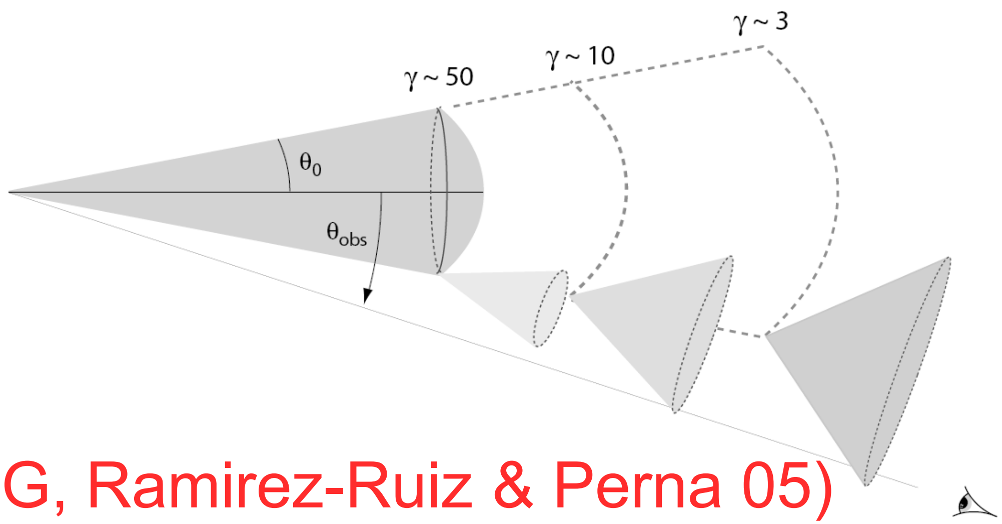
Alternatively, $\varepsilon_x(t)$ can increase in time under less standard assumptions



(JG, Königl & Piran 2006)

Possible Explanations for the Shallow Decay

- **Energy injection** into afterglow: (Nousek et al. 06)
  - **I.** Continuous relativistic wind $L \propto t^{-0.5}$ (magnetar?)
  - **II.** Slower material ejected during the prompt GRB gradually catches up the decelerating afterglow shock
- Afterglow efficiency increases with time (varying shock micro-physics parameters; JG, Königl & Piran 06)
- Observer outside emitting region (Eichler & JG 06)



(JG, Ramirez-Ruiz & Perna 05)

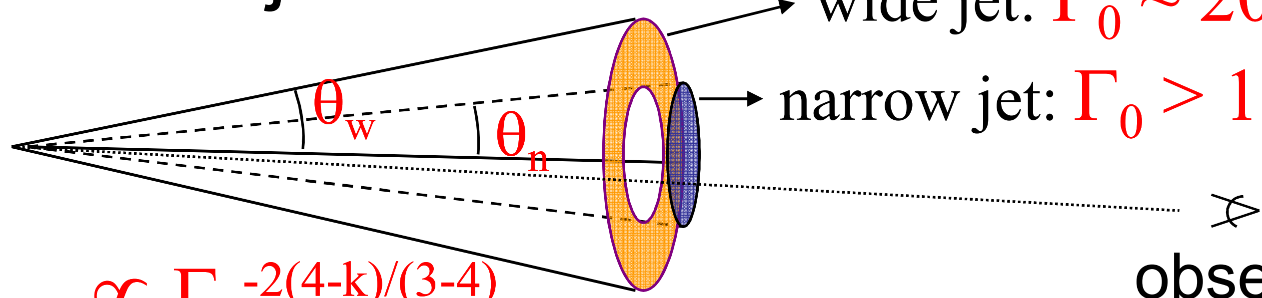
Possible Explanations for the Shallow Decay

- **Energy injection** into afterglow: (Nousek et al. 06)
  - I. Continuous relativistic wind $L \propto t^{-0.5}$ (magnetar?)

It isn't clear which of these explanations, if any, is indeed the dominant cause for the shallow decay phase

- ... ck
- shock micro-physics parameters; JG, Königl & Piran 06)
- Observer outside emitting region (Eichler & JG 06)
- Two component jet:

(JG, Königl & Piran 06)



wide jet: $\Gamma_0 \sim 20\text{-}50$

narrow jet: $\Gamma_0 > 100$

$t_{dec} \propto \Gamma_0^{-2(4-k)/(3-4)}$

for $\rho_{ext} \propto r^{-k} \Rightarrow t_{dec,n} \ll t_{dec,w}$

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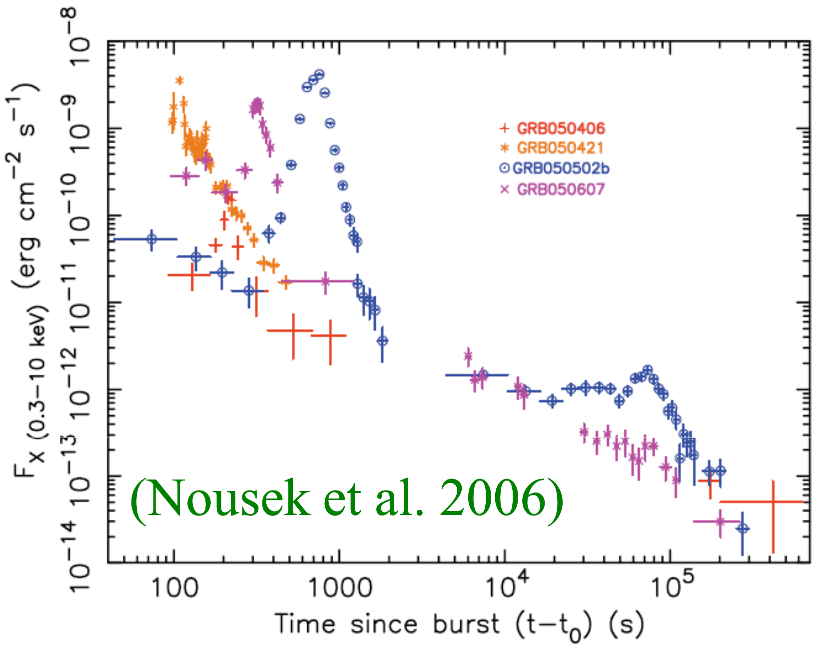
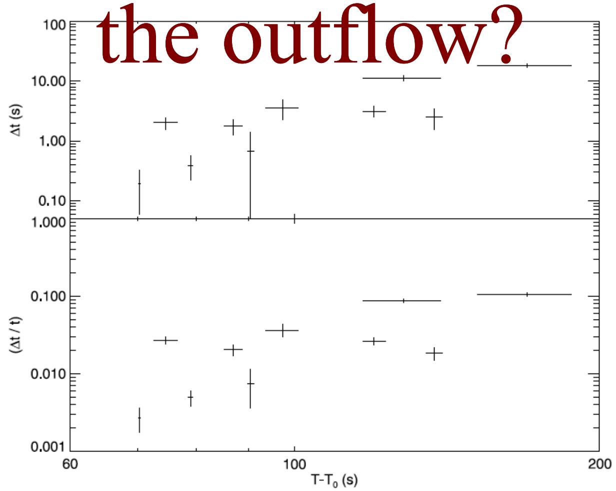
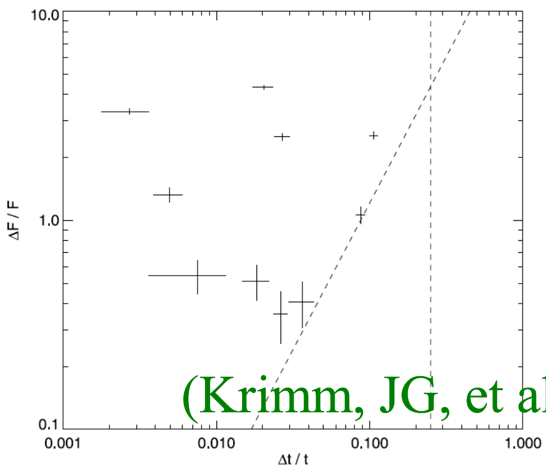
X-ray Flares: prolonged source activity?

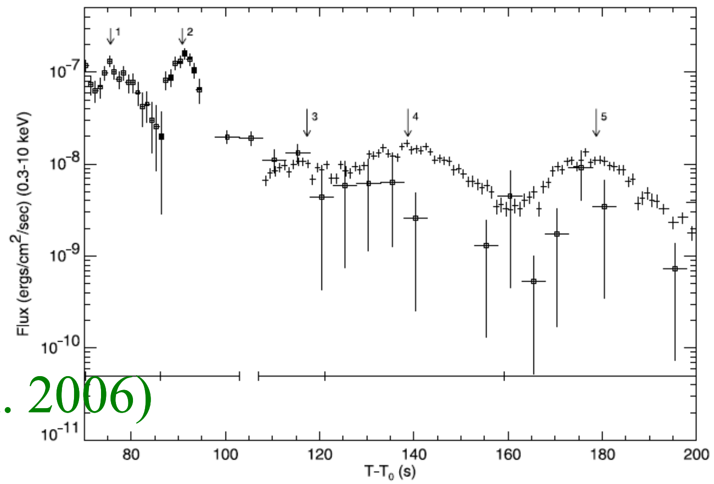
- Short time scale ($\Delta t \ll t$) Large amplitude ($\Delta F \gtrsim F$) rule out an afterglow origin
- They are most likely due to **long lived central source** activity (late time fallback?)
- Late & localized dissipation events within the outflow?



(Nousek et al. 2006)

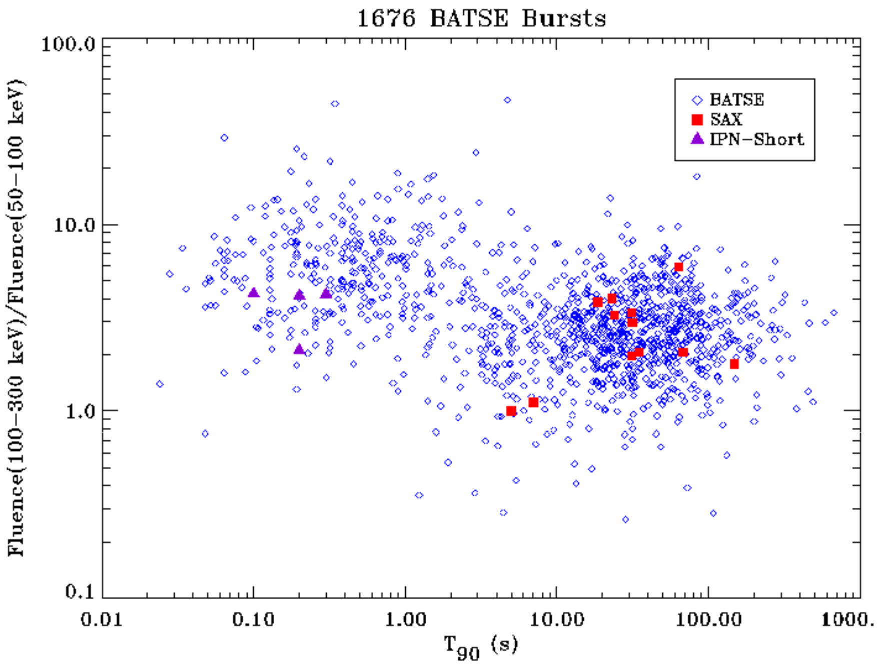






(Krimm, JG, et al. 2006)

Short GRBs

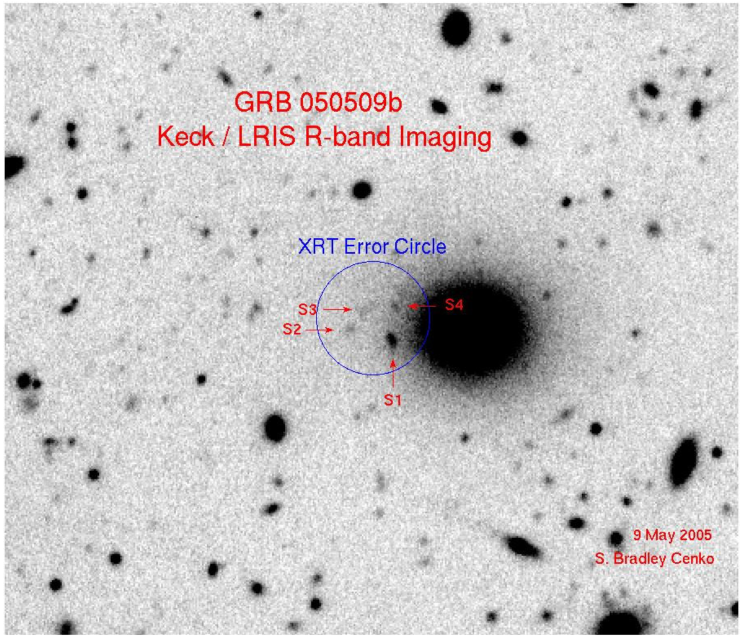


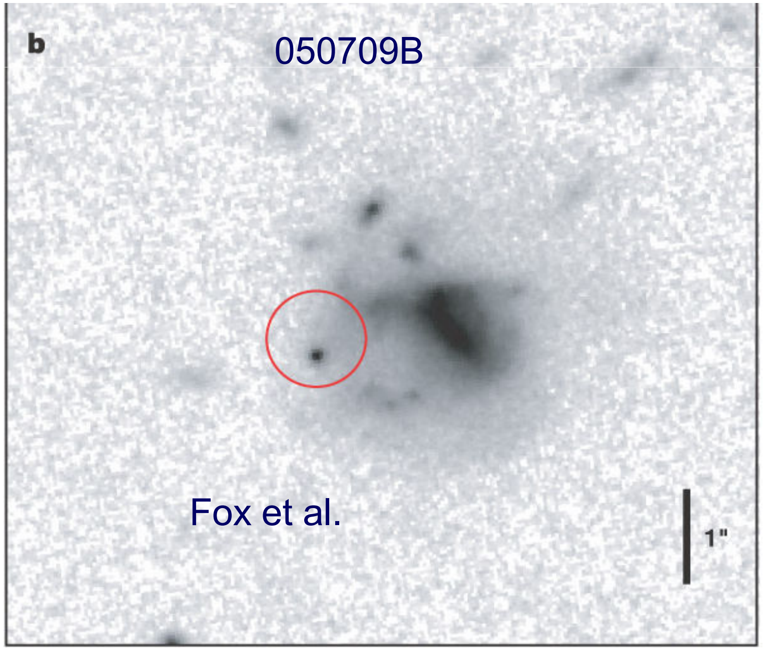
~ 1/4 of BATSE bursts

Short GRBs with good localisations

Since 2005 several short bursts have been localised by Swift and HETE-II and seem, by GRB standards, moderate energy (~10^{48} - 10^{50} ergs), moderate redshift (z~0.1-0.5) events, associated with a variety of host galaxies (and no associated supernovae).

consistent with binary coalescence (NS-NS, NS-BH) origin, but still inconclusive





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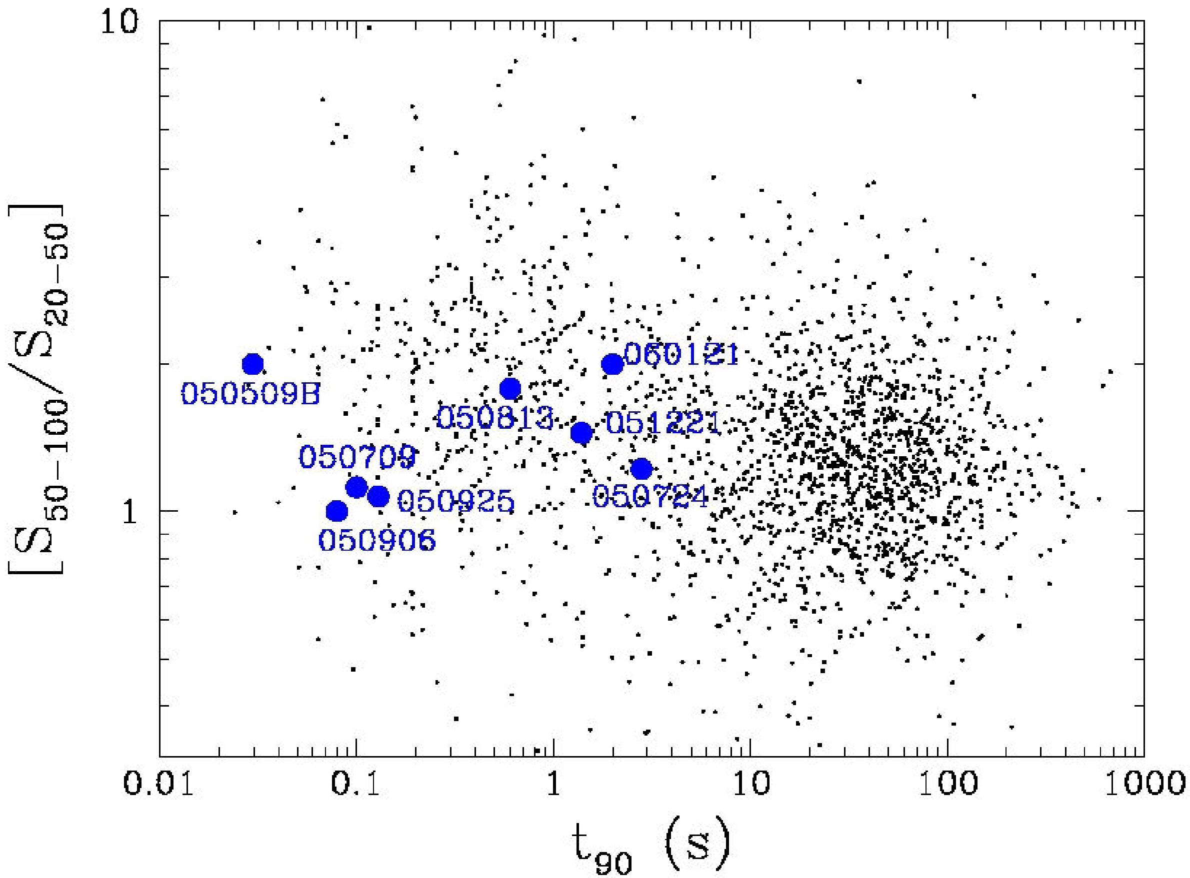
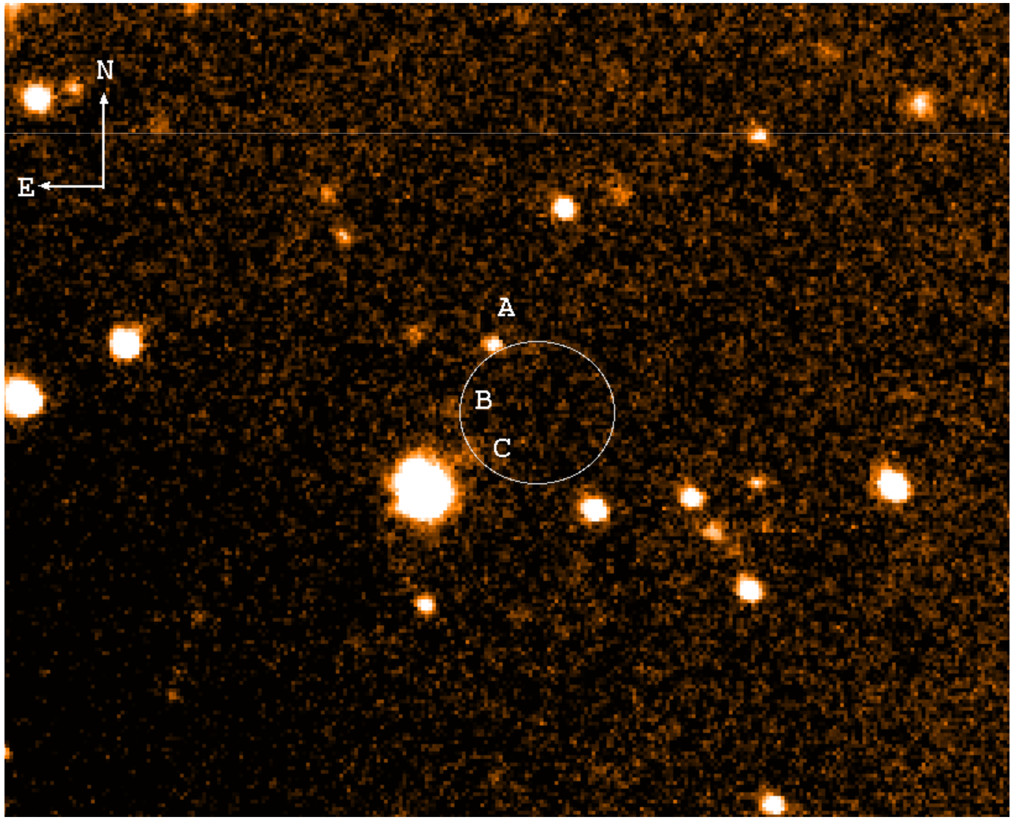
Short GRBs with good localisations

but these tend not to have been very typical short bursts in the hardness-duration sense, and there is evidence that some of the other short bursts are higher energy, higher redshift events.



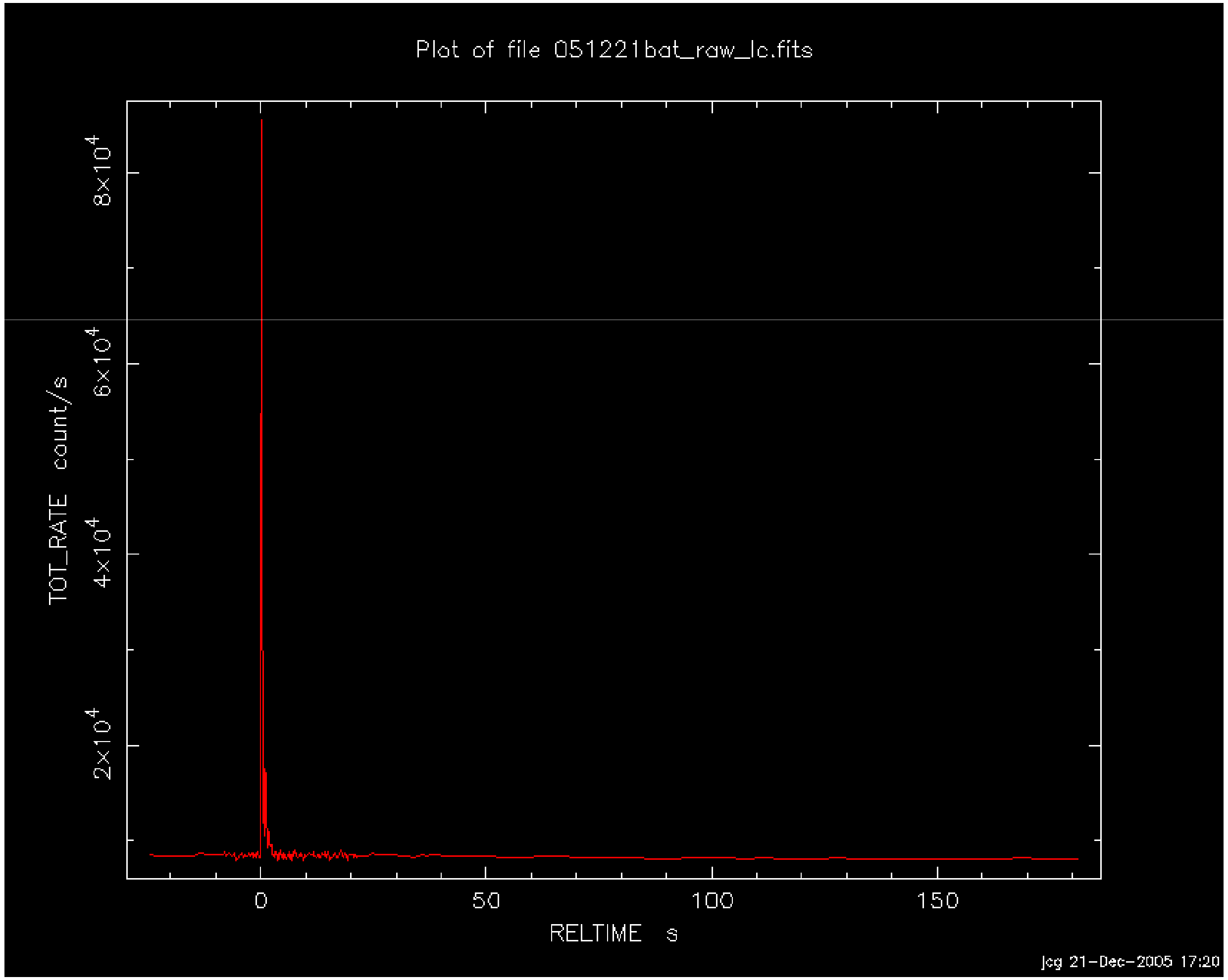
GRB 050813

- No optical afterglow.
- XRT position suggests possible association with galaxies at z~0.7, although even nearer (on sky) galaxies at z~1.8 (Berger).



GRB 051221

- **A bright short burst, at z~0.55. E_{iso}~2x10^{51} erg** (Soderberg et al. 2006)



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Some Open Questions:

- What are the progenitors of short GRBs?
- How are GRB jets launched and collimated?
- What is the outflow composition (e^+e^- p-e, B-fields)?
- What is the γ-ray emission mechanism?
- The (angular) structure & dynamics of GRB jets
- Physics of collisionles relativistic shocks (particle accelration, magnetic field amplification,…)
- Do GRBs produce the highest energy cosmic rays?
- Do long GRBs form BH or millisecond magnetars?

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Prospects for the Future (I)

- Short GRB progenitors: more observations, mini-SN, gravitational waves (Advanced LIGO, LISA; ‘smoking gun’ for binary merger)
- Launching & collimation of GRB jets: GRMHD simulations, self-similar analytic solutions
- Outflow composition: constraints from observations, high-energy neutrinos (IceCube,…) or cosmic rays (Auger,…) - ‘smoking gun’ for protons or heavy ions
- γ-ray emission mechanism: Fermi Gamma-Ray Space Telescope, launched June 20, 2008, will help

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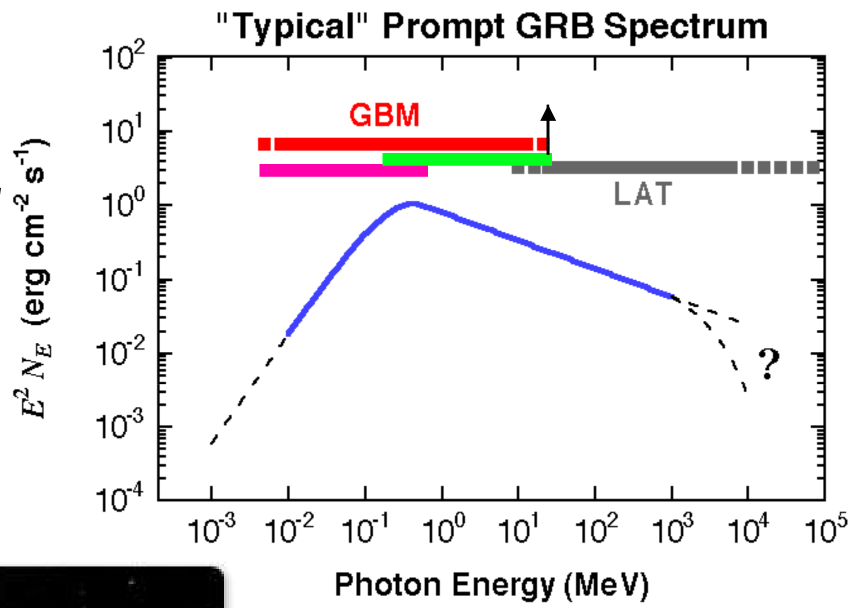
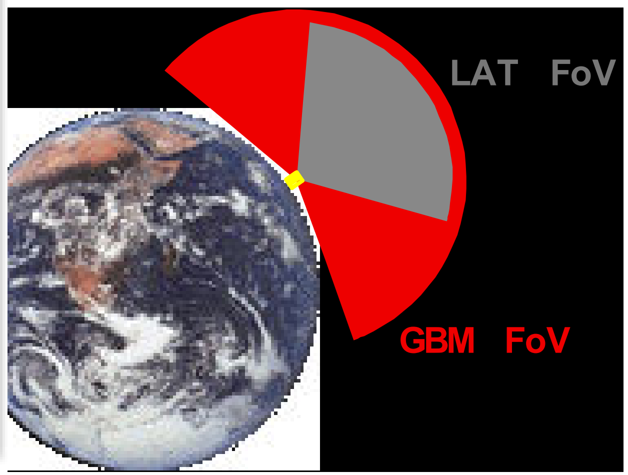
Fermi Gamma-Ray Space Telescope

(Formerly GLAST; launched on June 11, 2008):

- Fermi Gamma-ray Burst Monitor (GBM): 10 keV – 25 MeV, full sky
- Slightly less sensitive than BATSE expected to detect ~ 200 GRB/yr ($\gtrsim$ 60 in the LAT FoV)
- Large Area Telescope (LAT): 20 MeV – 300 GeV, FoV ~ 2.4 sr





Prospects for the Future (II)

- Structure & dynamics of GRB jets: modeling of observations, special relativistic hydro-simulations, self-similar solutions
- Physics of collisionles relativistic shocks: analytic or semi-analytic studies + particle in cell simulations
- Highest energy cosmic rays: modeling the observations of the Auger cosmic ray observatory
- BH or magnetars from long GRBs: theoretical work (analytic & numrical modeling of massive star evolution & collapse) + modeling observations

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