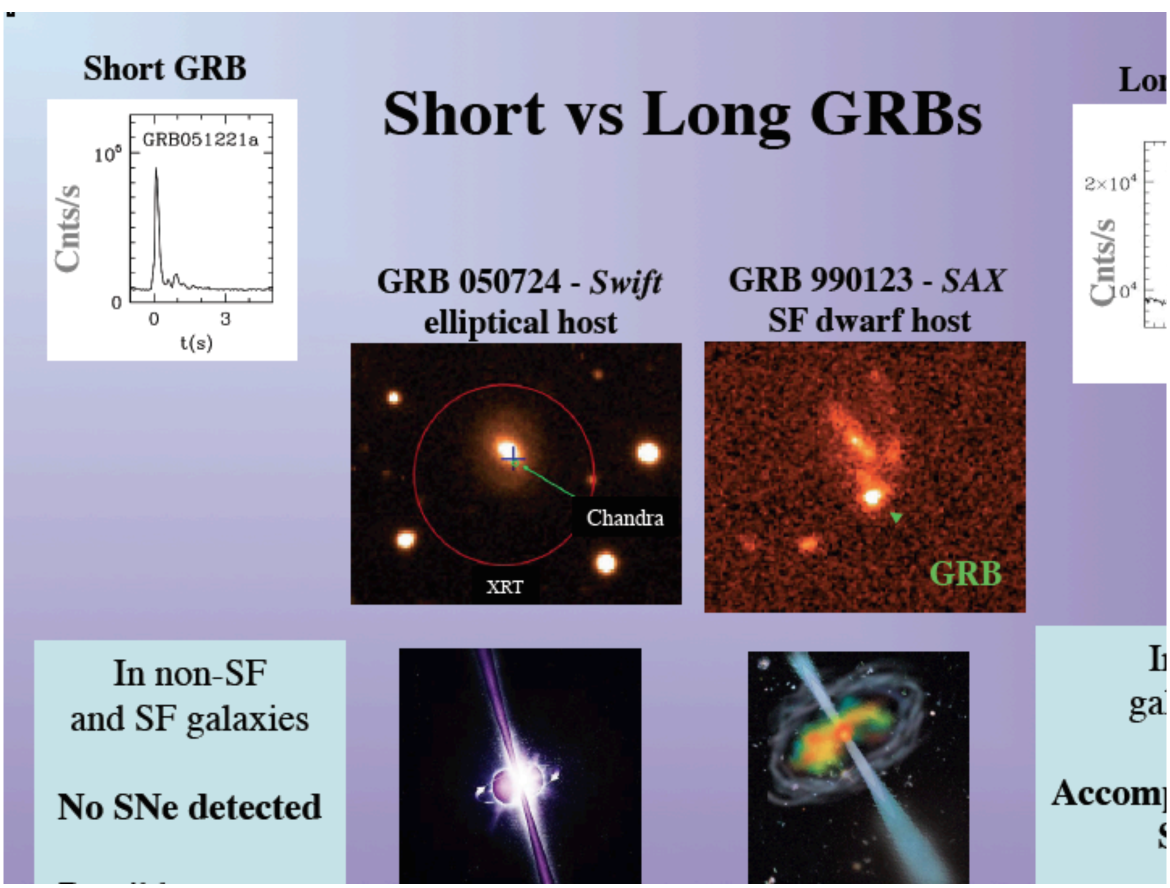
- the CourseEvalUM website (www.CourseEvalUM.umd.edu) is open till May 11. The evaluations are confidential
- Have you been challenged and learned new things? Have I been effective, responsive, respectful, engaging, etc?-or dull, boring, stodgy, unprepared?
- Please do this - What did we do that you liked-disliked? How can I improve? **Only 2 students have filled it in so far !!!**



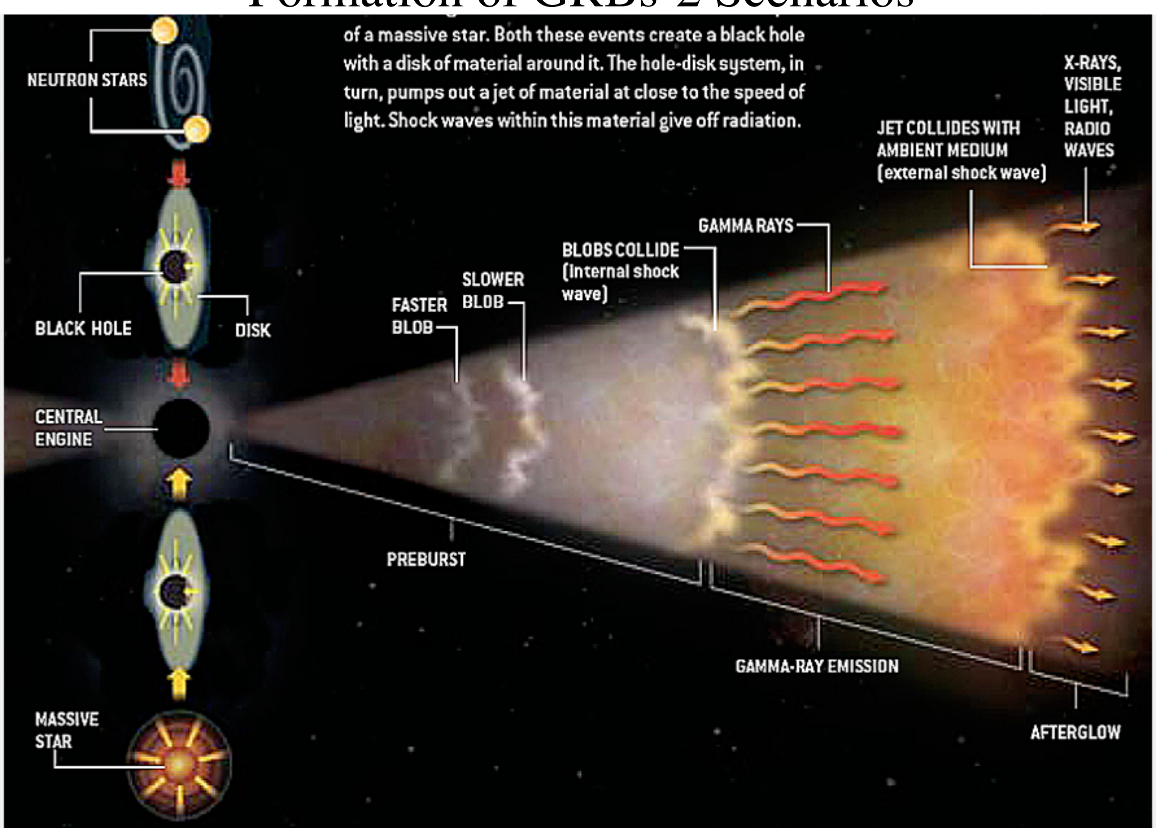
Short Bursts- Progenitor

- One of the ideas is that short bursts are the result of the merger of 2 neutron stars (B. Paczynski 1991)
- Observational support based on their observed properties
  - lack associated supernovae
  - occur in a mix of star-forming and elliptical galaxies
  - have a broad spatial distribution around their hosts, with some events offset by tens of kpc and are located in low-density parsec-scale environments

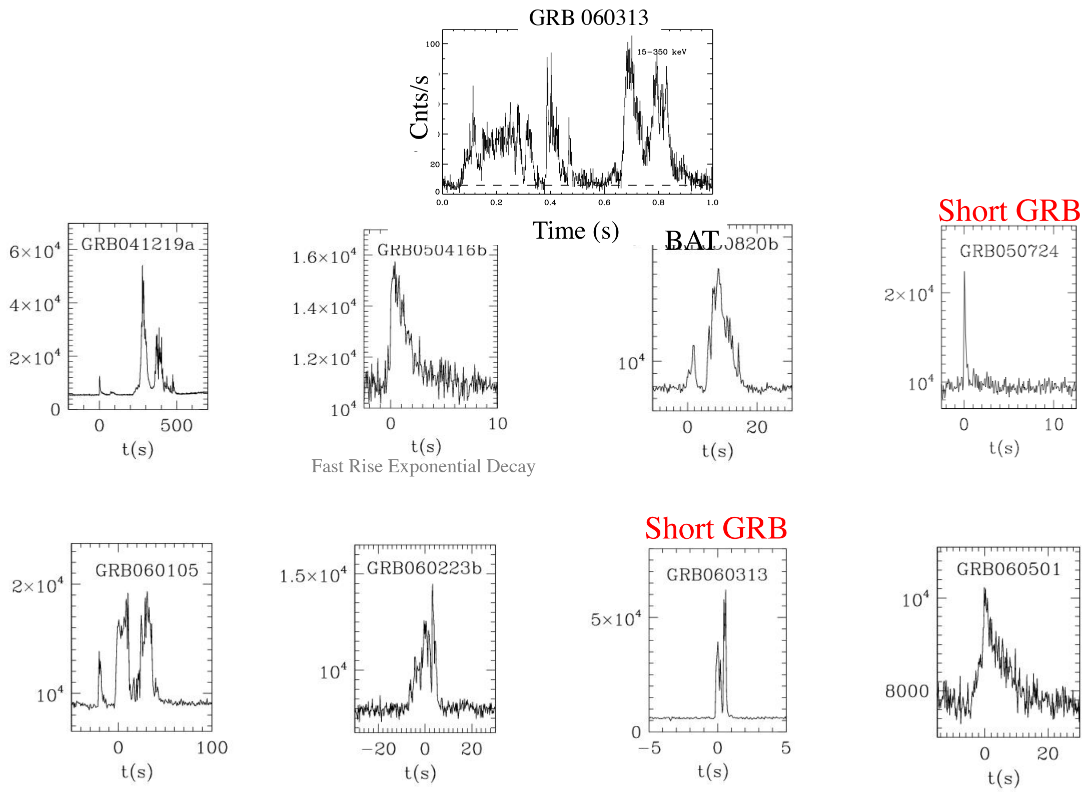
The confluence of these characteristics provides support to the popular model of compact object (CO) mergers (Stone et al 2013) –e.g runaway NS stars which merge.

strong impact on gravitational wave searches.

Formation of GRBs-2 Scenarios



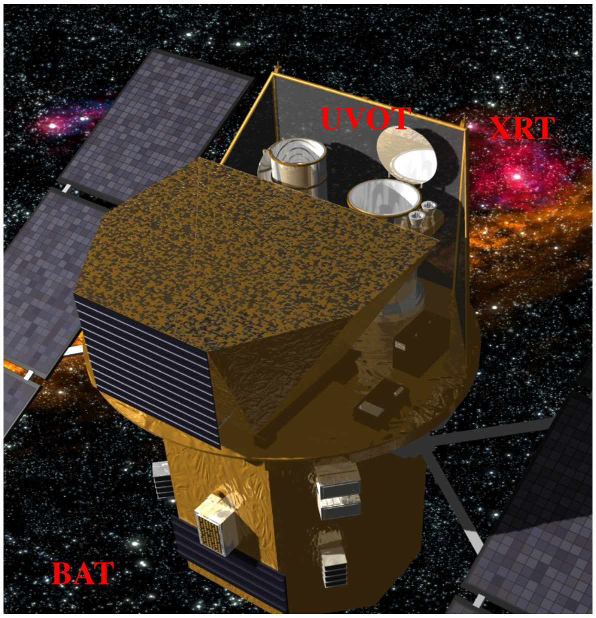
Gallery of GRB Lightcurves



Gamma-Ray Bursts

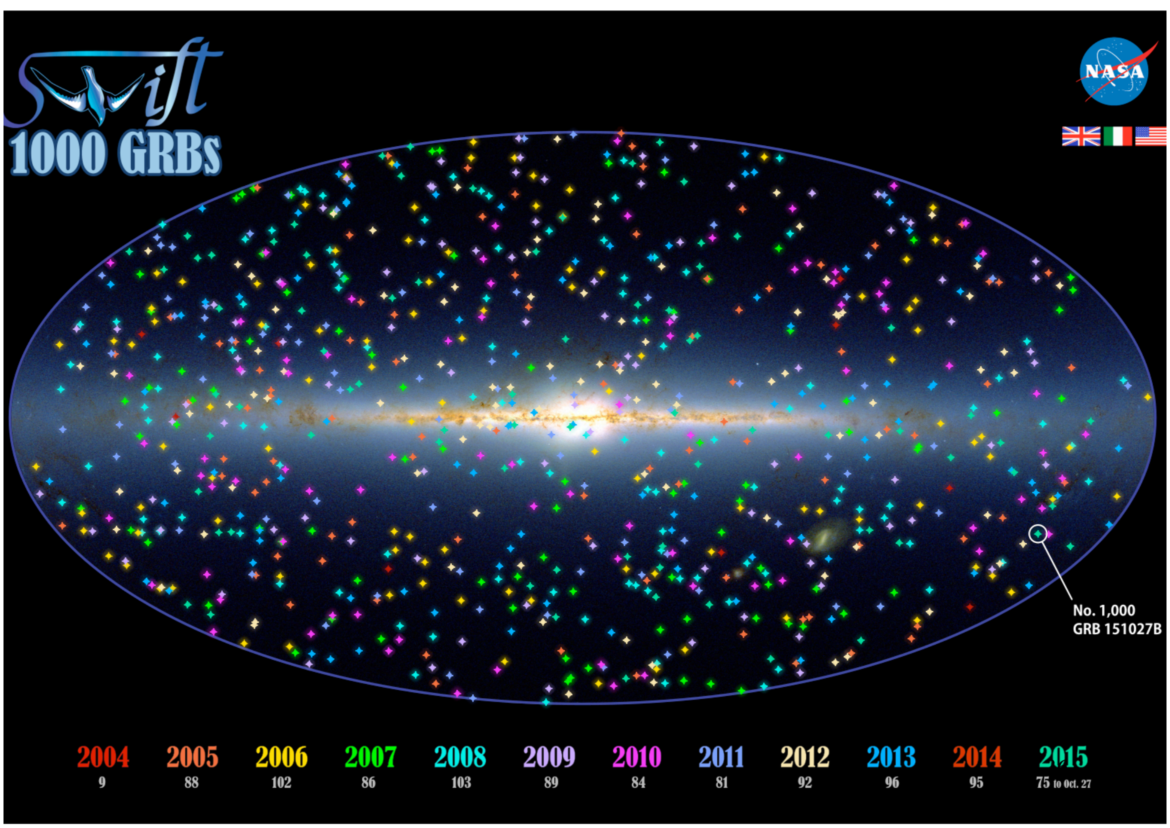
- thought that they are ʻbeamedʼ - the energy is emitted in a ʻnarrowʼ cone, via particles moving close to the speed of light.

- The material behind the shock has relativistic temperatures; because energy transfer between particles in two-body collisions becomes less efficient with increasing temperature, many common emission mechanisms are very inefficient in the shock-heated gas.
- The one mechanism that does well with relativistic particles is synchrotron radiation—provided a significant magnetic field is present. These efficiency considerations made synchrotron emission a favored model



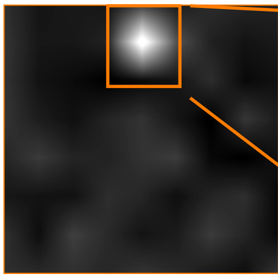
Swift was designed to find and study GRBs
BAT- GRB finder and localizer
UVOT, XRT: UV/optical and x-ray telescopes to study afterglow and identify source

Swift γ-ray Burst Chaser over 1000 GRBs



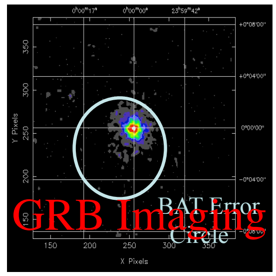
Swift Data- Multi-Wavelength

BAT Burst Image



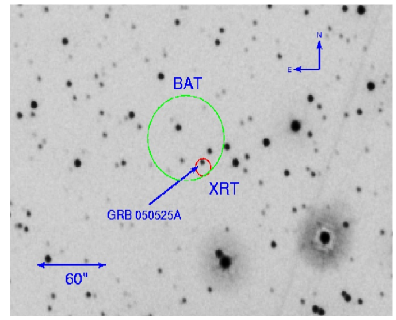
T<10 sec

XRT Image

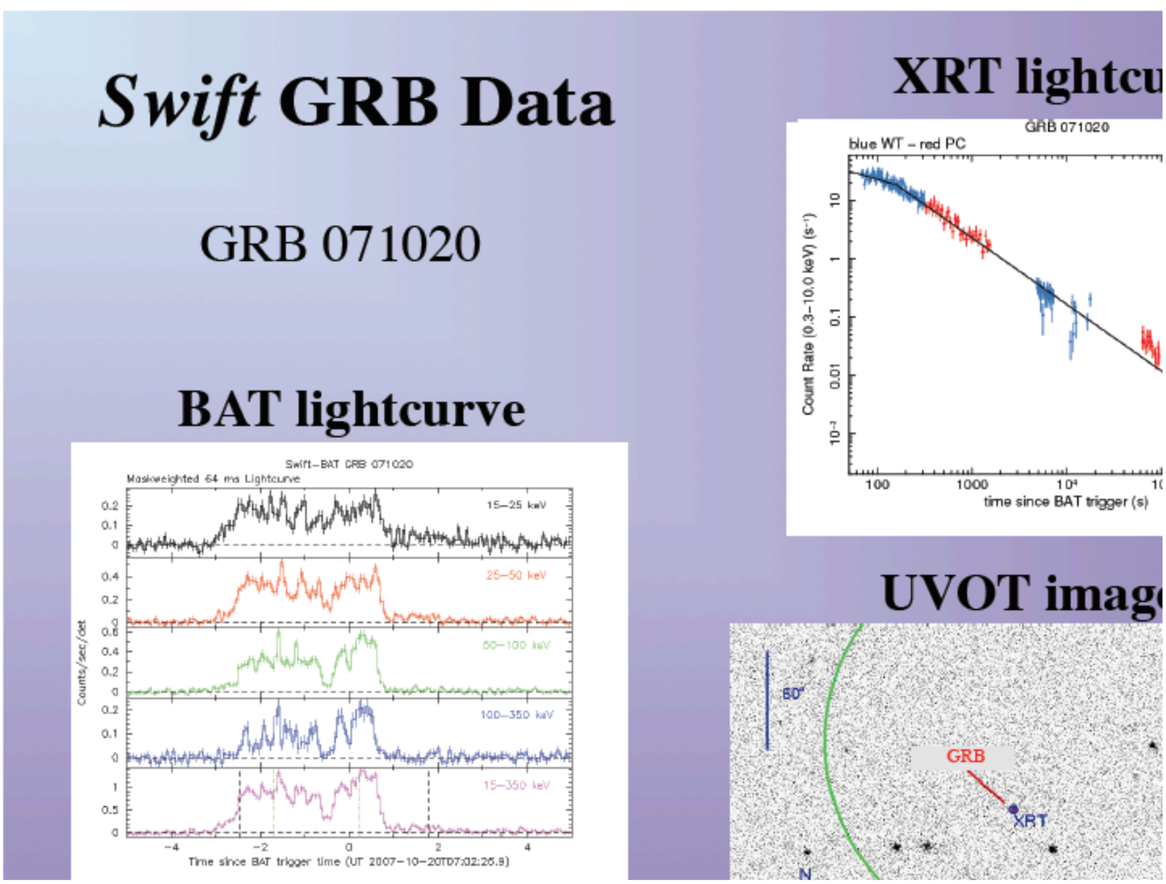


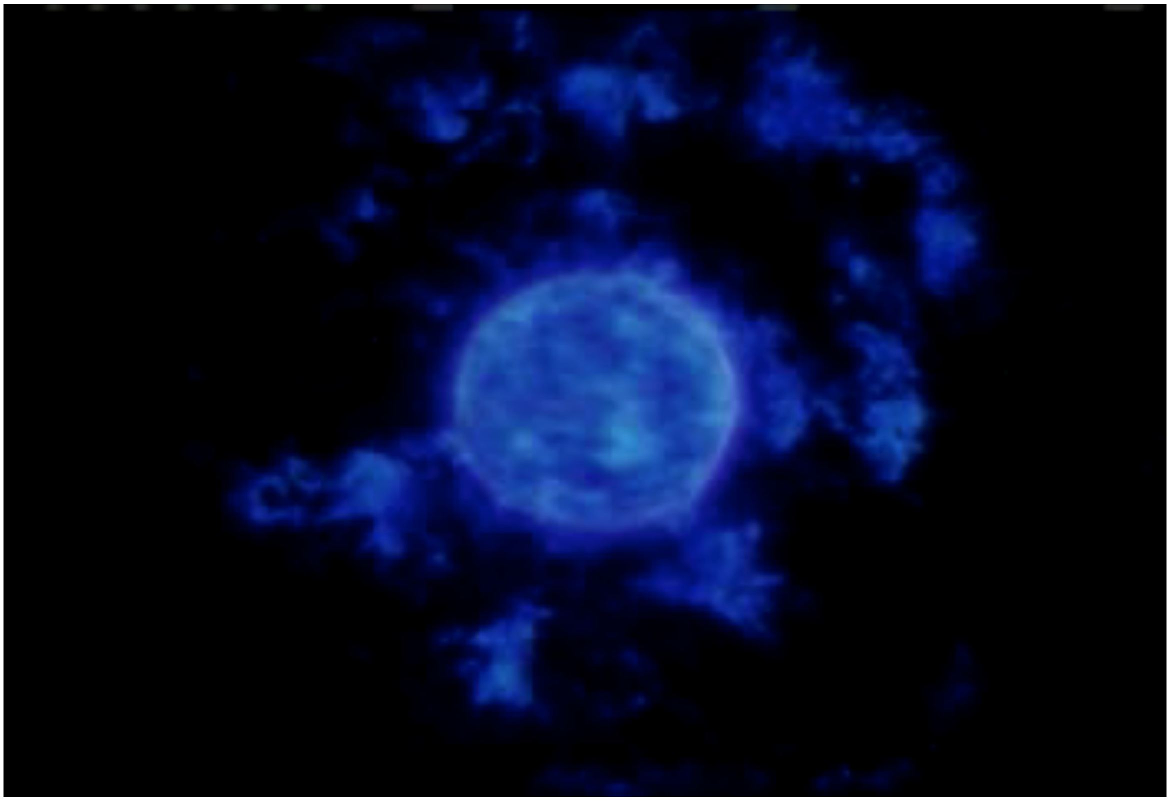
T<90 sec

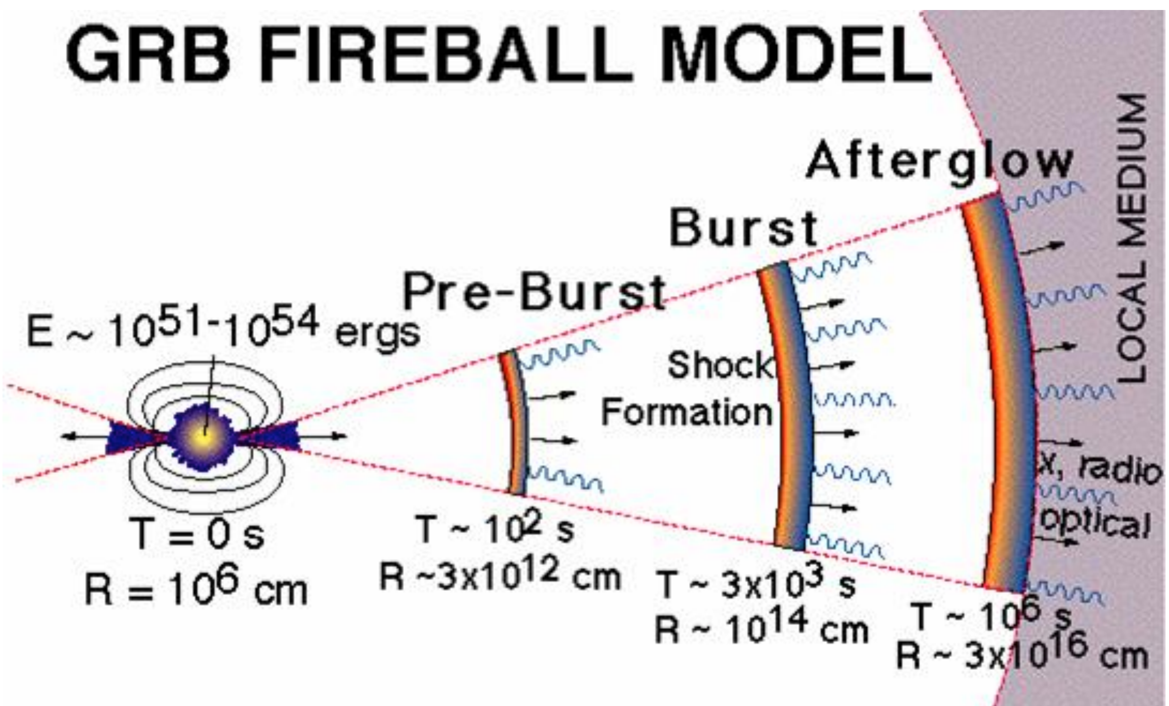
UVOT Image



T<2 min



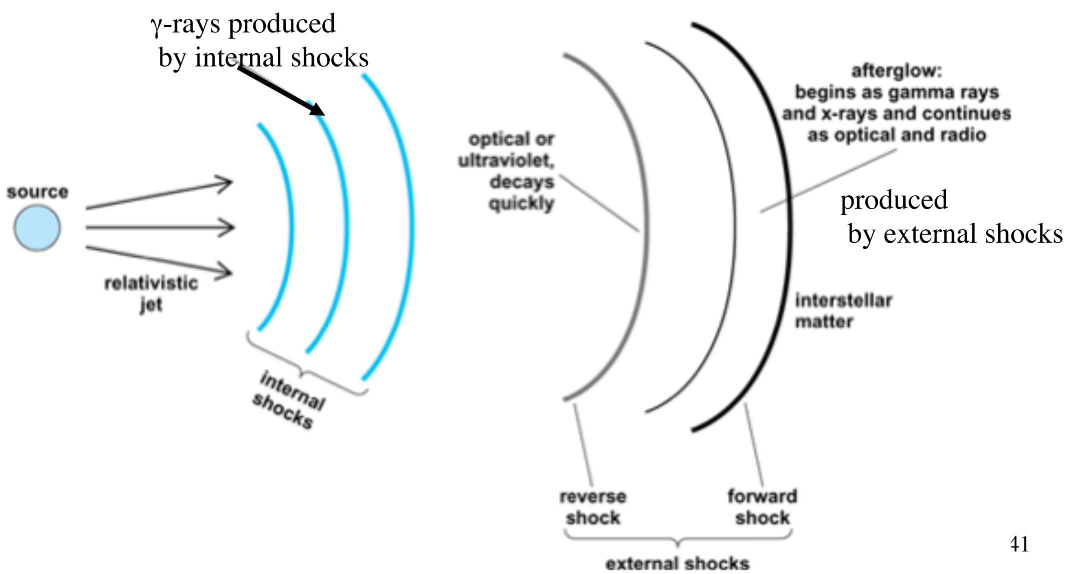




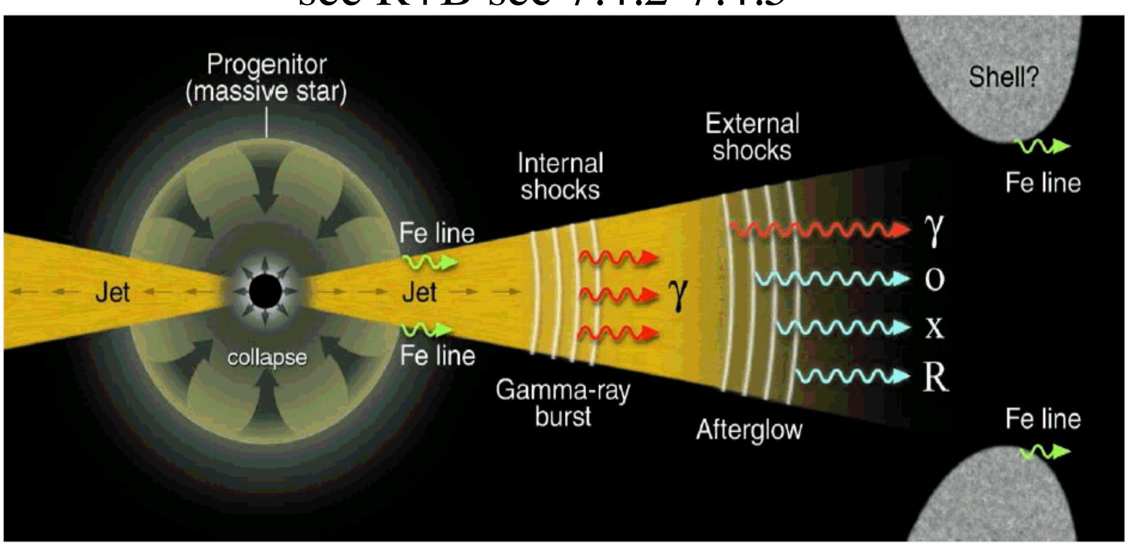
γ-ray bursts can be produced if part of a relativistic bulk flow is converted back into high-energy photons through particle acceleration in a relativistic shock between the outflow and the surrounding medium

General Schema of Fireball

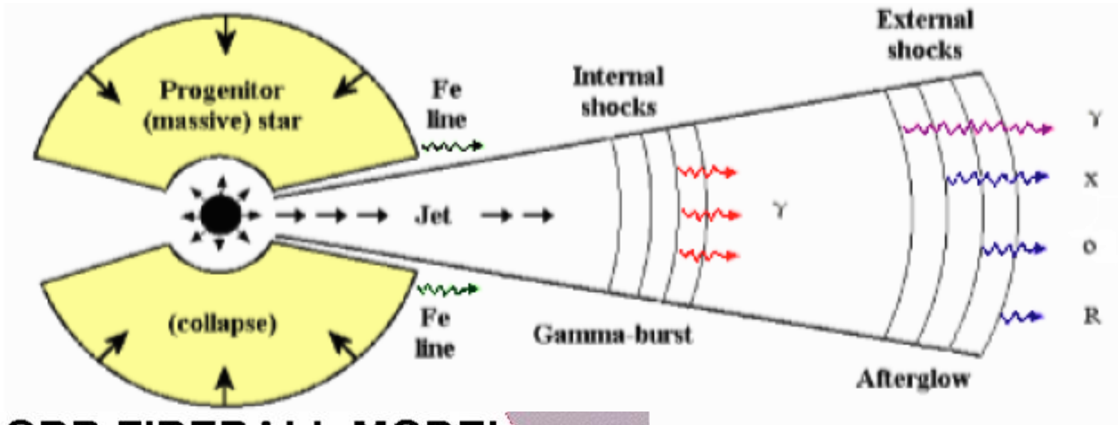
- Compact central engine drives a collimated ($\theta<10^0$) ultra-relativistic, $\Gamma>10$, outflow with a high ratio of energy to rest mass. Expands at ultra-relativistic velocities

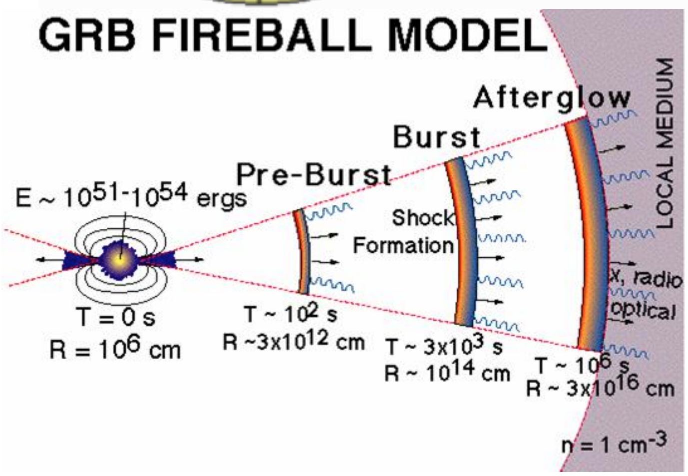


see R+B sec 7.4.2-7.4.5



- Energy density in a GRB event is so large that an optically thick pair/photon fireball is expected to form, not clear how to turn the energy of a fraction of a stellar rest mass into predominantly gamma rays with the right non-thermal broken power law spectrum with the right temporal behavior
- Meszaros, P. and Rees M ARA& a40 (2002) 137-169 Theories of Gamma-Ray Bursts





Fireball Model, emission is separated into 2 components:
•the prompt outburst phase (strong gamma-ray and X-ray emission) due to **internal shocks in the relativistic blast-wave,**
•the afterglow (strong X-ray, optical and radio emission) - arises from the cooling fireball and its **interaction with the surrounding medium.**

43

Particle Acceleration

- The continuum radiation from GRBs is due to highly relativistic particles
- just like in SNR collisionless shocks are thought to be the main agents for accelerating ions as well as electrons to high energies (e.g., Blandford and Eichler 1987, Achterberg et al. 2001).
- Particles are reflected from the shock and from scattering centers behind it in the turbulent compressed region and experience multiple scattering and acceleration by First-order Fermi acceleration when coming back across the shock into the turbulent upstream region.
- With each reflection at the shock the particles gyrate parallel to the moving electric field, picking up energy and surfing along the shock surface.

Direct Evidence of Relativistic Expansion

Just as the Earth's atmosphere causes visible starlight to twinkle, interstellar plasma causes radio waves to scintillate (diffractive scattering)
Early observations showed erratic, short term (~ hrs) fluctuations in the radio emission. The origin of these variations is the scattering of the radio emission, owing to the small angular size of the fireball, as it propagates through the turbulent ionized gas of our Galaxy.
After a few weeks the fluctuations stopped- indicating that the source has grown in size such that it now longer 'twinkled'

The observed "quenching" of this scintillation pattern at t~2 weeks lead to a determination of a size of 3μas, implying a mean apparent motion of 4c (!)

Direct Evidence of Relativistic Expansion

Radio VLBI can also measure very small sizes (Taylor et al 2004) showed a observed expansion velocity of 3-5c

Applying ' standard' superluminal jet theory (Rees 1969) requires a small angle to the line of sight and $\Gamma>7$

$\beta_\perp$, is given by $\beta_\perp = \sin\theta / (1 - \cos\theta)$, then to get an apparent superluminal expansion of 5c requires Lorentz factors of ~7, and values of $\beta_\perp$ close to unity

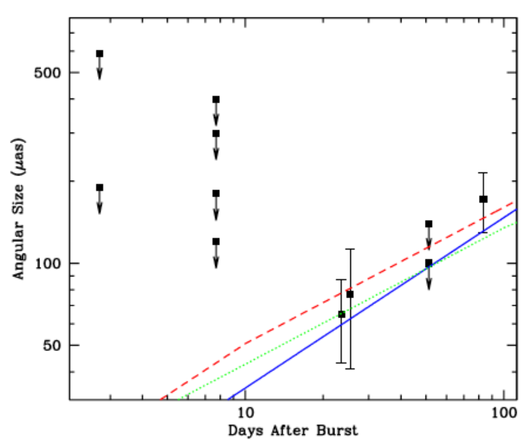


Fig. 2.— Measured angular diameters (or limits) for the radio afterglow from GRB 030329, along with the expected evolution of the angular size for different representations of the fireball model. The solid line is the apparent angular size for a spherical fireball expanding

Evidence for relativistic beaming- aka jets

- Brightness temperature is> 10^{12}K (Compton catastrophe)

γ-rays seen up to 7GeV; to avoid e+/e– pair production (and the accompanying thermal spectrum), the GRB jet must be moving toward the observer with ultra-relativistic speeds (the "compactness" problem; Cavallo & Rees 1978)

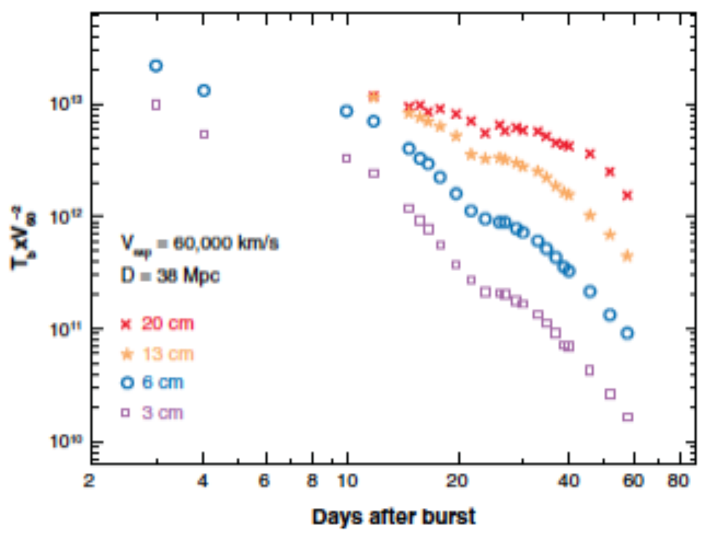


Figure 1 The evolution of the brightness temperature of radio SN 1998bw, the most luminous radio SN ever recorded. The brightness temperature is computed under the assumption that the radio photosphere expanded with the same velocity inferred from optical spectroscopy (~0.2c). In order for the true brightness temperature to be less than the "Compton Catastrophe" value ($T_{CC} \approx 10^{12}$ K), relativistic motion in the first week after GRB 980425 is required. From Kulkarni et al. (1998b).

Brightness Temperature Catastrophe

- If you keep scattering the same electrons, if the system is dense enough, the system runs away: e.g. the amplification of scattered radiation energy density, or a "Compton Cooling Catastrophe".
- This occurs if $L_{IC} >> L_{synch}$
  - Remember that $L_{IC}/L_{synch} = U_{photon}/U_{magnetic\ field}$
  - (U is energy density)
- in order to avoid having infinite energy in the Compton scattered electrons, there has to be a limit on the brightness temperature – a measure of the photon energy density.*
- This is a self-regulating process–if the brightness temperature goes too high, an infinite energy demand is set up, knocking it back down

*__Brightness temperature__ is the __temperature__ a black body in thermal equilibrium with its surroundings would have to be to duplicate the observed intensity.

Pair Production and a limit on the Relativistic Factor

Lithwick And Sari 2001

a photon with energy E' can annihilate a second photon with energy greater than $(m_e c^2)^2/E'$ yielding an electron-positron pair,(m_e is the electron mass).

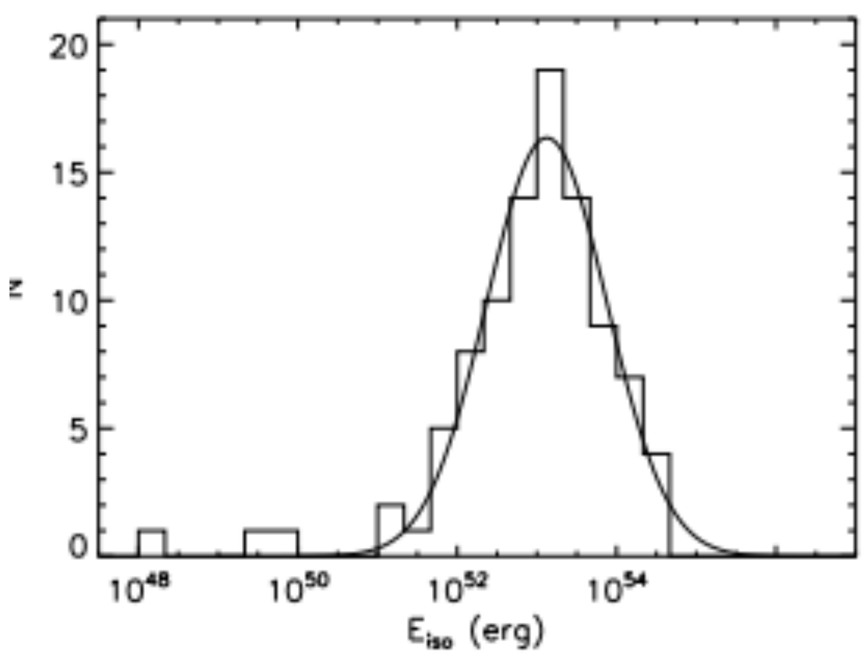
When the energy of the second photon is ~ $(m_e c^2)^2/E'$ then the cross section for this process is approximately the Thomson cross section,σ_T The cross section falls as a power law of the annihilating photon energy (Klein-Nishina)

Averaging over the observed photon distribution the average cross section is $\sim 0.06\sigma_T$

If the emitting material is moving toward the observer with a Lorentz factor γ, the photons are blueshifted by γ. Thus, a photon with detected energy $E=\gamma E'$ can only annihilate photons whose detected energies are greater than $(\gamma m_e c^2)^2/E$. Since most of the photons are at low energies, the photon with the highest energy will be most susceptible to annihilation by other photons.

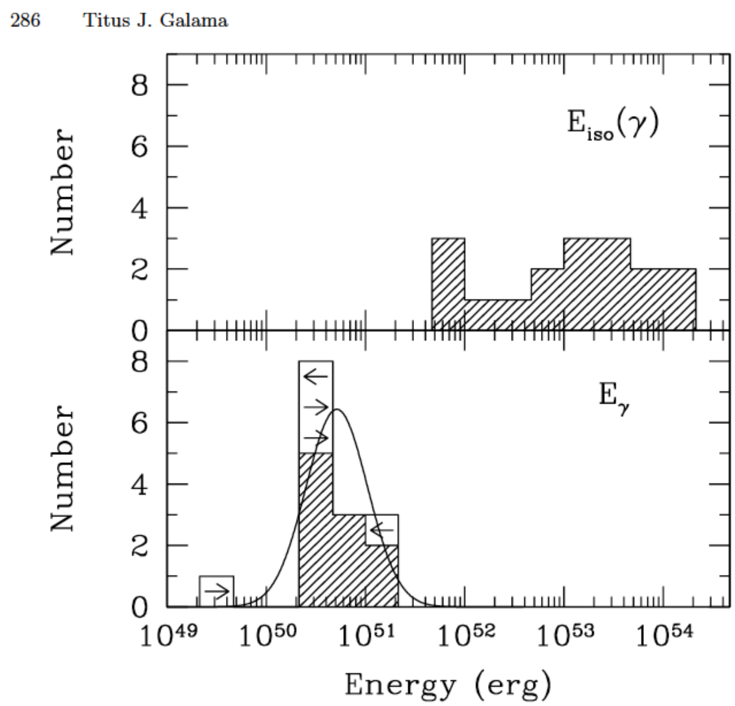
a lower limit on the Lorentz factor can be obtained by requiring that the photon with energy E_{max} will have optical depth smaller than unity.

Observed distribution of burst luminosities (Amati 2009)



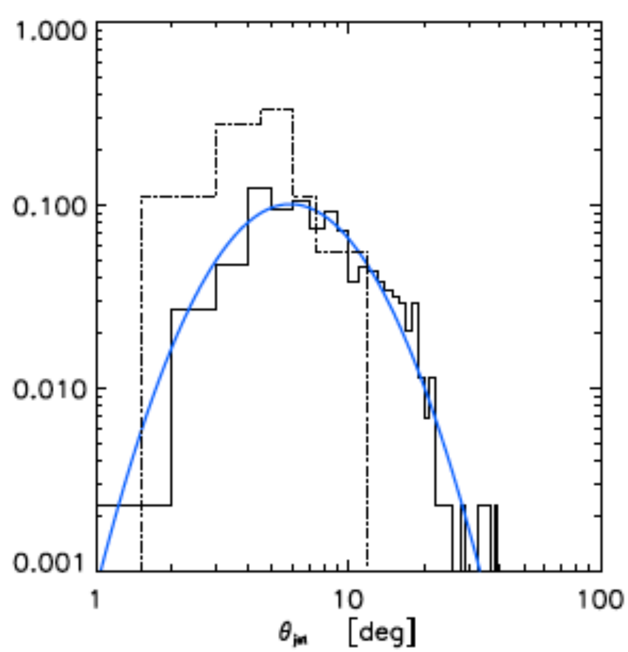
Luminosity 'Corrected' for Beaming

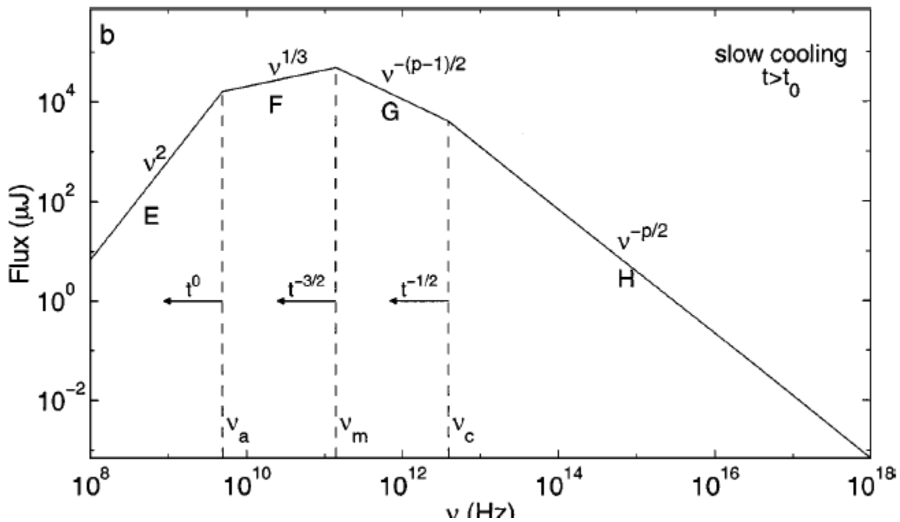
- Absolute luminosity and variance reduced
- Number of bursts in universe increased by 1/ beaming factor
- E_{iso} is the observed luminosity, E_γ is the luminosity corrected for beaming.



Implied Jet Opening Angle Distribution

- Rather narrow implied beaming angle distribution- but this is a selection effect
- small number of objects at small angles, at large angles flux is severly reduced





- The predicted time dependence and shape of the emitted synchrotron spectrum from a fireball model- synchrotron emission from a slowing down relativistic shell that collides with an external medium. (Sari et al 1998)
- Notice the different time dependences and spectral slopes

- Radio to x-ray spectrum of GRB afterglow 12 days after the burst
- Fireball looks like a good description of data.

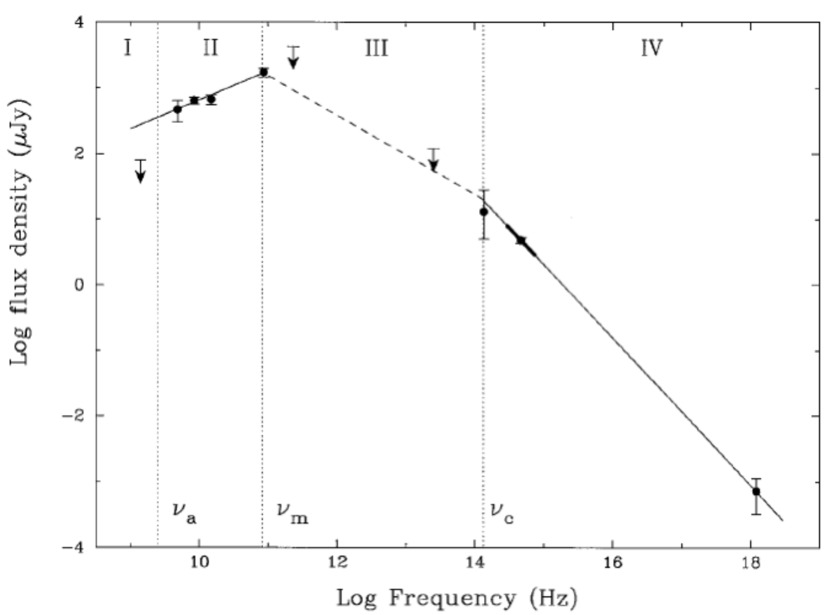
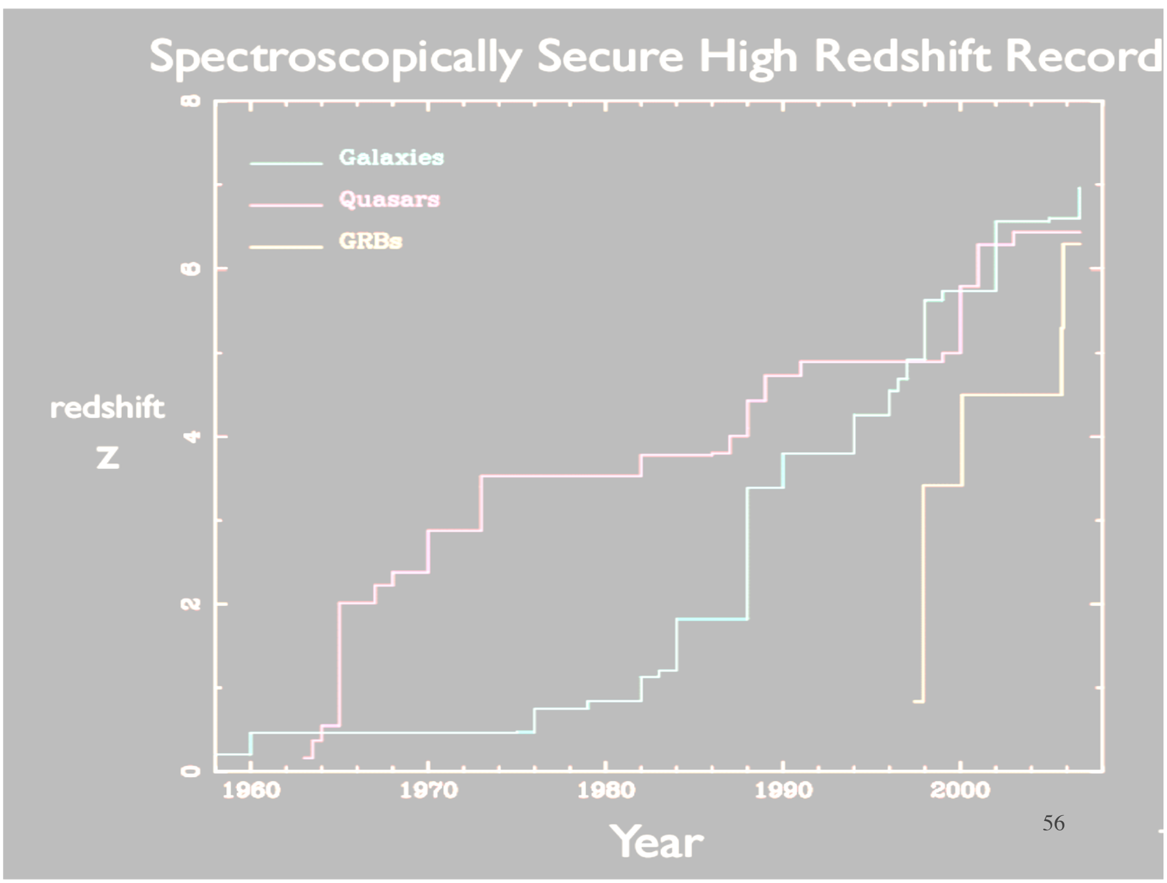


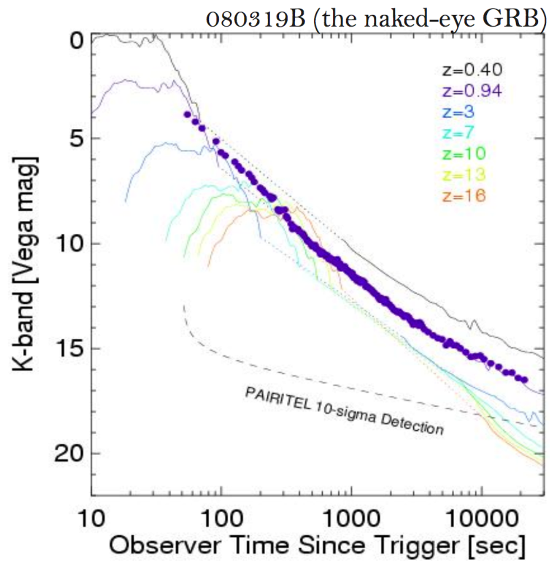
Figure 12 The radio to X-ray spectrum of the afterglow of GRB 970508, 12.1 days after trigger, showing all the characteristics of synchrotron emission (Galama et al 1998d).

Full Solution (Zheng et al 2011)

- Generally, the prompt emission can be modeled as originating from internal shocks or the photosphere of the fireball eject aor magnetic dissipation from a magnetically dominated jet,
- the afterglow emission originates from external shocks that may include both forward shock and reverse shock components (Meszaros & Rees 1997, 1999; Sari & Piran 1999).
- For some GRBs many of the physical parameters can be determined if the full optical and X-ray afterglow lightcurves can be interpreted within the standard reverse shock (RS) + forward shock (FS) model.
  - appling the standard fireball model
    - the radiation mechanism is synchrotron,
    - the radius of prompt emission, R_{GRB}~3 x 10^{13} cm
    - initial Lorentz factor of the outflow (Γ_0~ 250)
    - the eject a are mildly magnetized
    - collimation angle ~3-4°
    - the total energy budget ~7x10^{50} ergs.



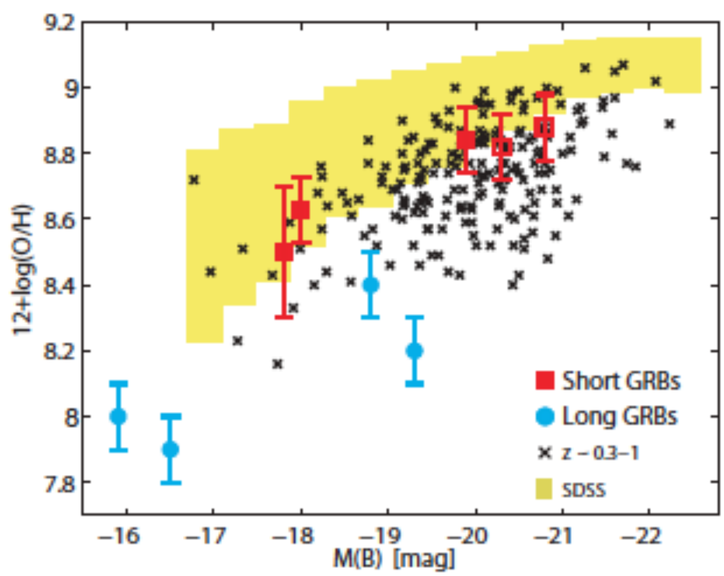
- Only180/540 of the SwiftBAT GRBs have a redshift due to
  - observing conditions from ground (wrong instruments at the telescope)
  - bad weather
  - high galactic extinction
- Strong evolution of luminosity or density distribution is needed to account for observations



ghtest events are observable with 1m-class telescopes up to z>16

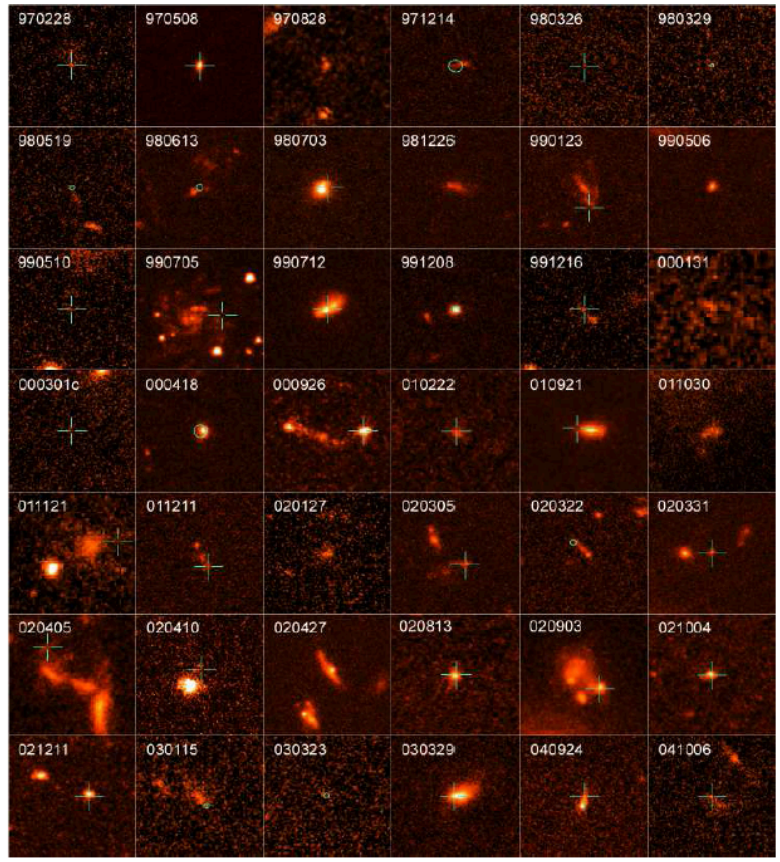
Where GRBS occur- clues to their origin

- Long GRBs occur preferentially in low mass and low metallicity galaxies at z<1
- Tend to occur in regions of high star formation rate (see next page)- consistent with origin in high mass stars



yellow band is distribution of luminosity and metallicity of 'random' galaxies at low z from SDSS

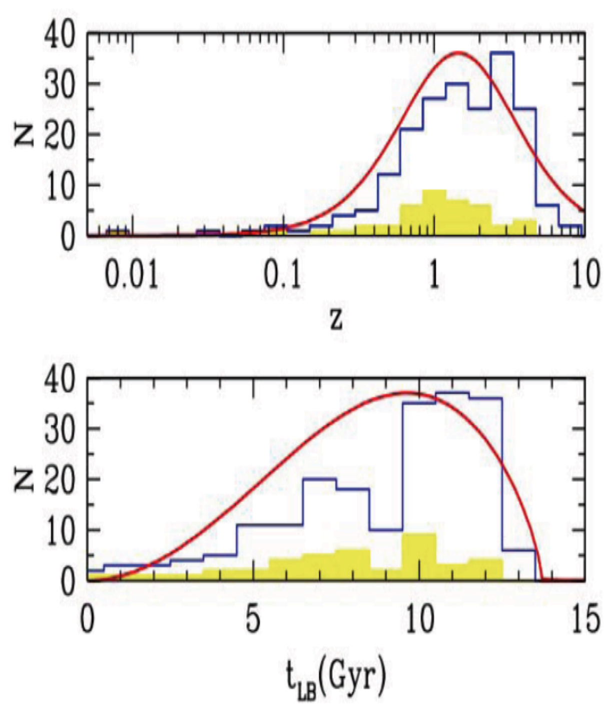
- HST images of GRB host galaxies (Fruchter et al 2006)- cross is position of GRB- tends to occur in bright spot in host galaxy.

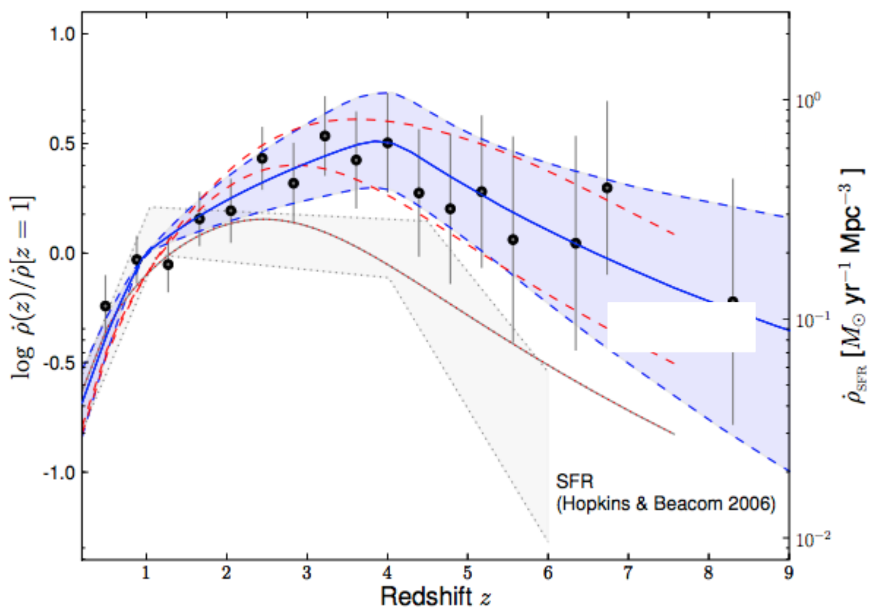


γ-ray Burst Rate Per Unit Time/Redshift

- Red line is a constant rate per co-moving volume- more bursts per unit volume at higher redshifts.
- Maybe related to the increase in star formation rate at higher redshifts-GRBs as a tracer of cosmic star formation rate.

yellow- short bursts
blue - long bursts

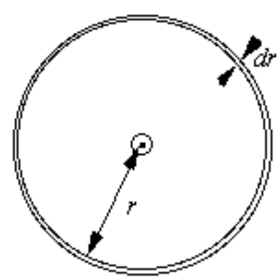




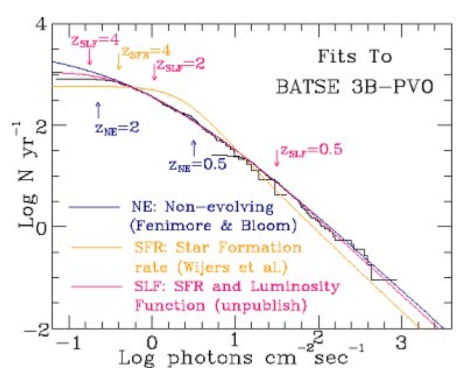
- Co-moving rate density of GRBs normalized to z=1
- compared to the star formation rate (Butler 2010)

LOG N-LOG S

- Consider a homogeneous distribution of sources of luminosity L and space density n and flux f



- derivation: $f=L/4\pi r^2$; $df/dr=r^{-3}$
- $n(f)df=n\,4\pi r^2 dr= n\,4\pi r^2 dr$
- $n(f)= n\,4\pi r^2 dr/df \sim f^{-5/2}$
- Number of sources brighter than f = $\int n(f)df = f^{-3/2}$

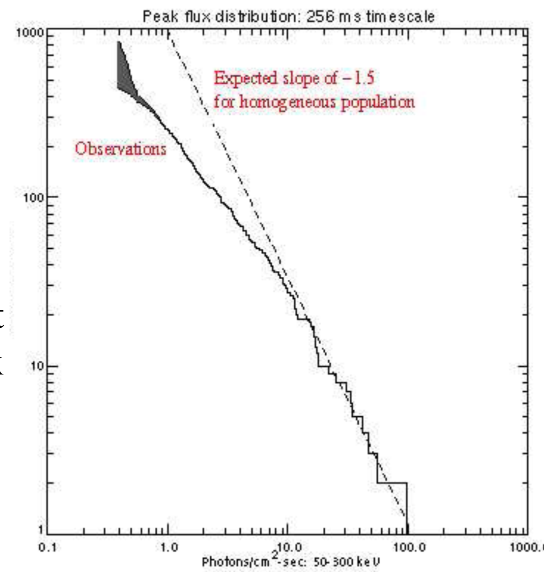


- GR Volume element is different; assumes n is not a function of r

LOG N-LOG S- Numbers of sources with a flux >S

- At high fluences slope is consistent with Eucledian
- At lower fluences deviation is seen (flatter)
  - generic reason is have reached the end of the distribution or the volume element is no longer Eucledian
  - For a narrow distribution in intrinsic luminosity sources distributed randomly in Eucledian space have a slope of 1.5 in log N-log S

\# per unit flux

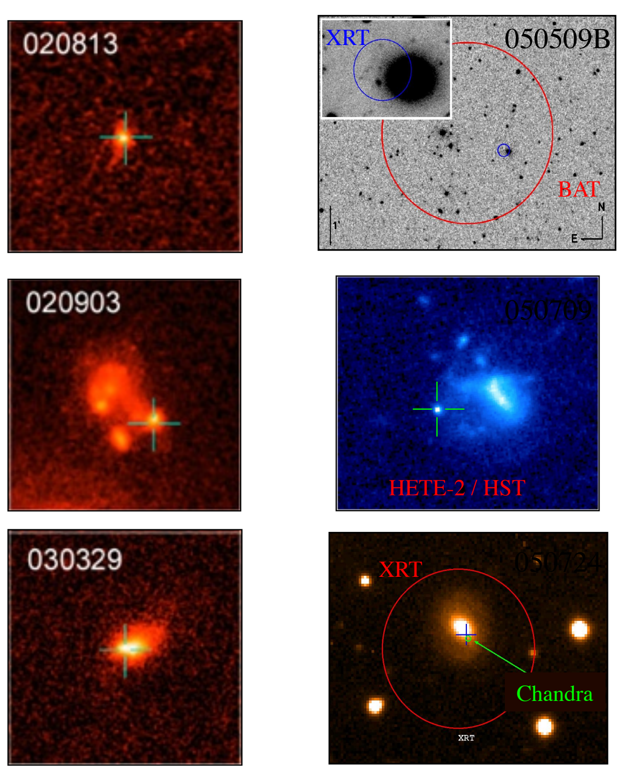


flux

Long GRBs Short GRBs

SF irregulars

Fruchter et al.



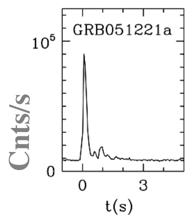
cD elliptical
SFR < 0.2 M_O yr^{-1}
z = 0.225

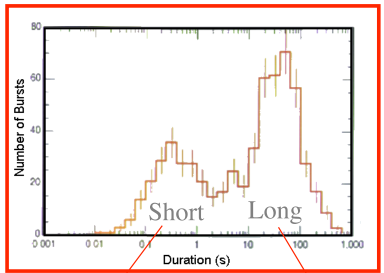
SF galaxy
with offset
z = 0.161

elliptical
SFR < 0.02 M_O yr^{-1}
z = 0.258

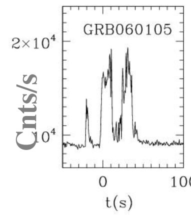
Short vs Long GRBs

Short GRB

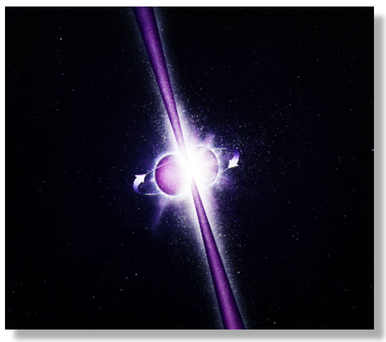


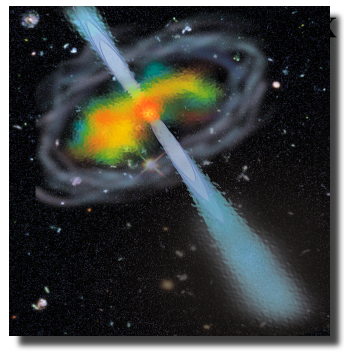


Long GRB



Short GRBs in non-SF elliptical galaxies

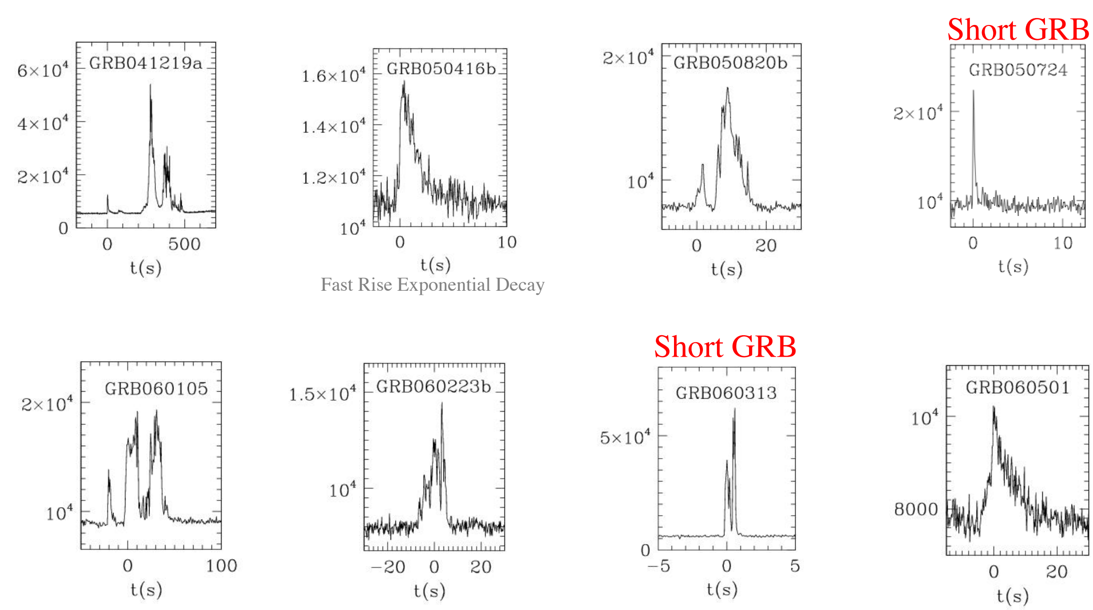


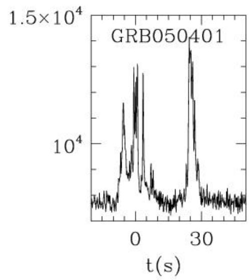


Long GRBs in SF galaxies

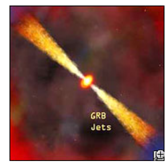
Montage of Burst Light Curves

~100 GRBs per year
82% with x-ray detections
50% with optical detection

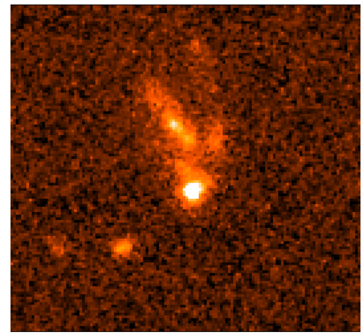




Long GRBs

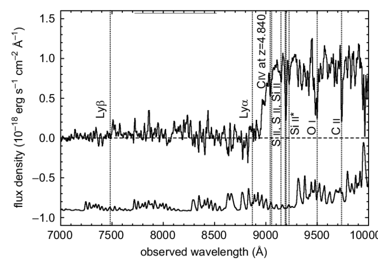


GRB 990123 - HST

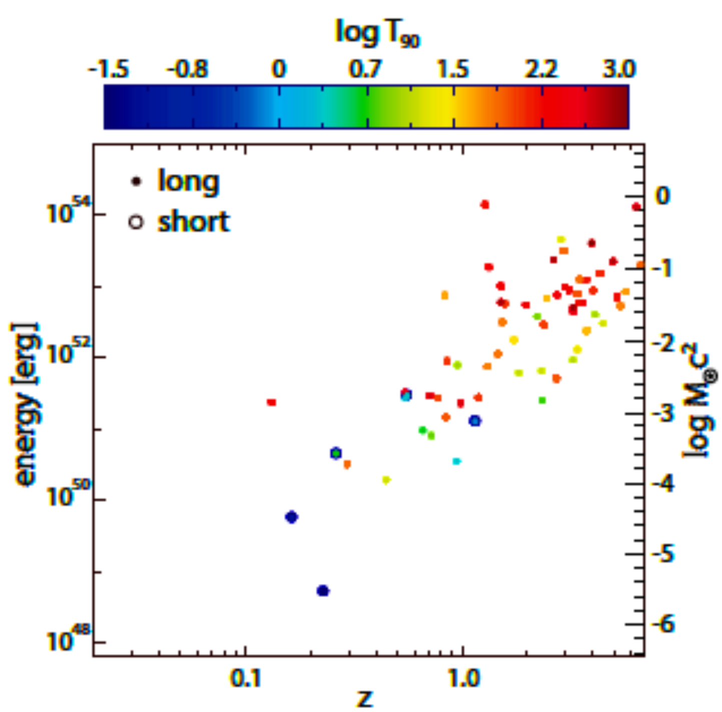


Energy:	~10^{51} ergs in γ-rays (~5° beams) ≤ 10^{51} ergs in afterglow ~10^{52} ergs in outflow
Distance:	<z>=2.3 (*Swift* average - long GRBs) 11 Gyr light travel time
Jet Outflow:	highly relativistic (Γ > 100)
Variability:	msec time structure in prompt burst
Power source:	gravitational infall on new-born BHs

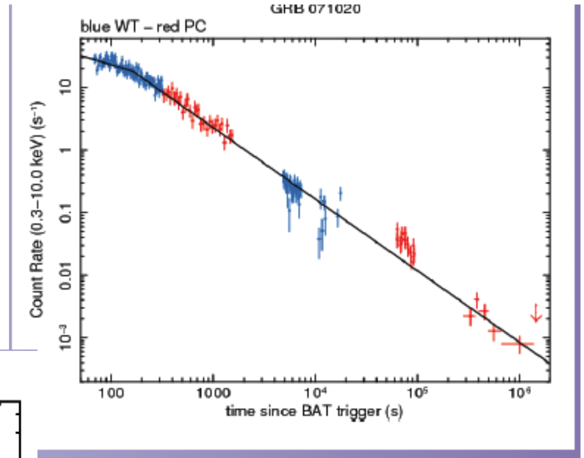
GRB 050904 z = 6.29 - Subaru

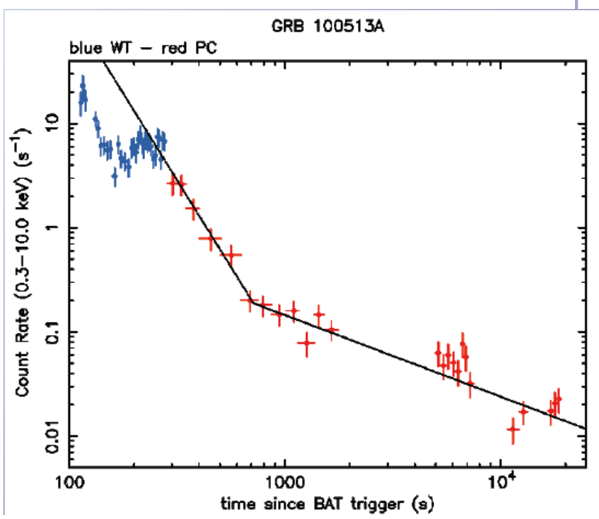


- Averaged over the burst, long bursts (red/yellow) are more luminous that short bursts (blue)



- Flux often declines as a power law in time- but not always





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