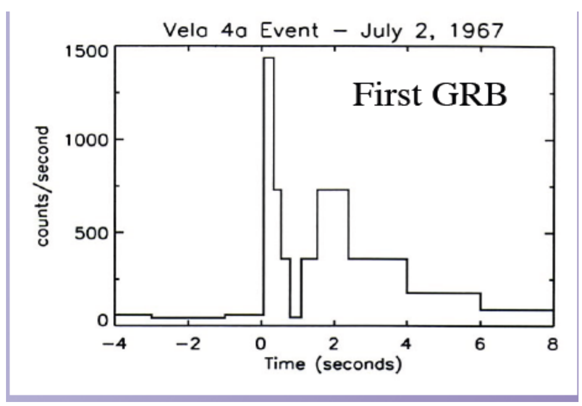
Gamma-Ray Bursts Longair 22.7

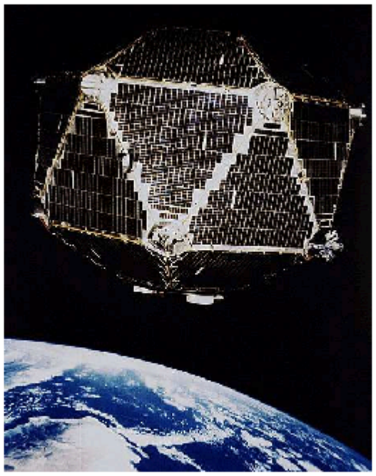
- Are bright flashed of γ-rays- for short period of time (<100 sec)
- fluxes of ~0.1-100 photon/cm^2/sec/keV emitted primarily in the 20-500 keV band. Some are detected up to 30 GeV!
  - Distribution is isotropic on the sky
- Because of these properties it took ~30 years from their discovery (1967) to their identification
  - **They are at very large distances (z up to 8 (!)) with apparent luminosities of 3x10^{54} erg/sec**
  - Rate is ~10^{-7}/yr/galaxy
- Gamma-ray emission, has a rich phenomenology in terms of duration, variability, spectral parameters, fluence, peak flux, temporal and spectral evolution, and various correlations between these parameter- detailed studies of these patterns did not lead to an understanding of their origin.
- See N. Gehrels, E. Ramirez-Ruiz, D.B. Fox Ann.Rev.Astron.Astrophys.47:567-617,2009

Gamma-Ray Bursts

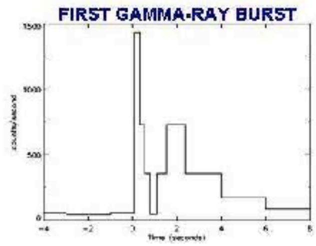
- Cosmic γ-ray bursts (GRBs) were first reported in 1973 by Klebesadel et al (l973) but were first seen on July 2, 1967, based on data from US satellites designed to monitor Russian nuclear weapons tests in space
- They are the sign of the birth of a stellar mass black hole (not all BHs start as a γ-ray burst)
- Gehrels, Ramirez-Ruiz & Fox, ARAA 2009
- GRBs/GRB afterglows: brightest radiation from most distant sources in the universe



Discovery



Sketch of one of the Vela satellites to search for violations of the nuclear test ban treaty.



1967: Vela satellites find extremely bright flares from the sky, with durations of a few seconds: Gamma-Ray Bursts (GRBs; total of 73 GRBs found between).

Reported in 1973 only (Klebesadel et al., 1973).

> During the burst, GRBs are the *brightest* gamma-ray objects in the sky, brighter than the Sun!

Gamma-Ray Bursts (GRBs)

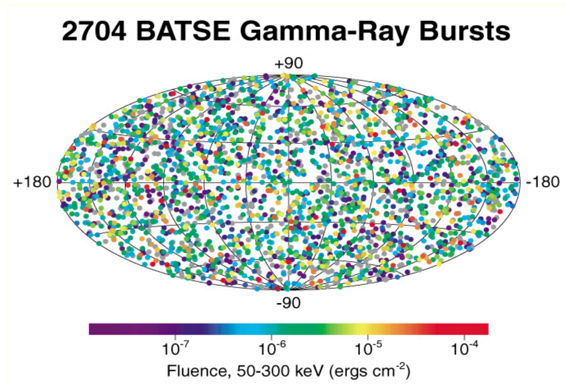
- **discovered by U.S. spy satellites (1967; secret till 1973)**
- **have remained one of the biggest mysteries in astronomy until 1998 (isotropic sky distribution; location: solar system, Galactic halo, distant Universe?)**
- **discovery of afterglows in 1998 (X-ray, optical, etc.) with redshifted absorption lines has resolved the puzzle of the location of GRBs → GRBs are the some of the most energetic events in the Universe**
- **duration: 10^{-3} to 10^{3} s (large variety of burst shapes)**
- **bimodal distribution of durations: 0.3 s (short-hard), 20 s (long-soft) (different classes/viewing angles?)**
- **GRBs are no standard candles! (isotropic) energies range from 5×10^{44} to 2×10^{47} J**
- **highly relativistic outflows (fireballs): ($\gamma \gtrsim 100$), possibly highly collimated/beamed**
- **GRBs are produced far from the source ($10^{11} - 10^{12}$ m): interaction of outflow with surrounding medium (external or internal shocks) → fireball model**
- **relativistic energy $\sim 10^{46} - 10^{47}\,\mathrm{J}\,\epsilon^{-1} f_\Omega$ (ϵ: efficiency, f_Ω: beaming factor; typical energy 10^{45} J?)**
- **event rate/Galaxy: $\sim 10^{-7}\,\mathrm{yr}^{-1}\,(3 \times 10^{45}\,\mathrm{J}/\epsilon\,\mathrm{E})$**

Isotropic on Sky

occur randomly in time and space and last 10's of secs

In the 1990's the BATSE experiment on GRO detected ~3000 bursts; 2-3 per day and showed that they occur isotropically over the entire sky suggesting a distribution with no dipole or quadrupole components-e.g. a spherical dist (cosmological??)

Because they occur randomly and are isotropically distributed identification of counterparts in other wavelengths was very difficult



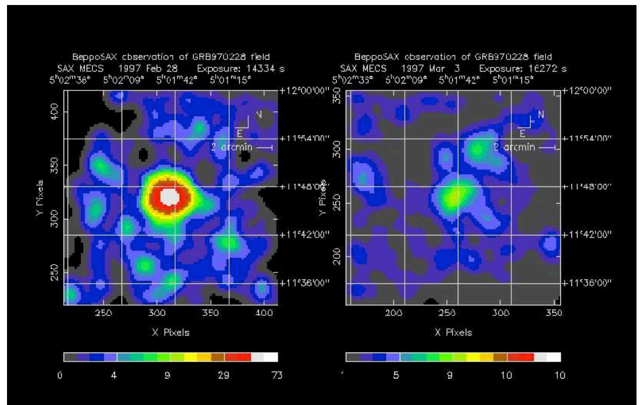
Breakthrough

- Breakthrough in 1997 with BeppoSax- an x-ray mission was slewed rapidly to a localized region containing the burst
- Found x-ray afterglows- source flux decayed rapidly but if got to it soon enough an 'new' x-ray source was always found.
- The x-ray position was accurate enough to identify an optical counterpart.

- See **THE PHYSICS OF GAMMA-RAY BURSTS Tsvi Piran** Reviews of Modern Physics 2014
-

•Breakthru was the discovery of 'afterglows' in the x-ray by the BeppoSax satellite (1998GRB 970228 Piro et al - ARAA 2000. 38:379 van Paradijs et al)

- •A 'new' x-ray source appeared and faded with time
- –this allowed accurate positions and the identification of the γ-ray afterglow with 'normal' galaxies at high redshifts

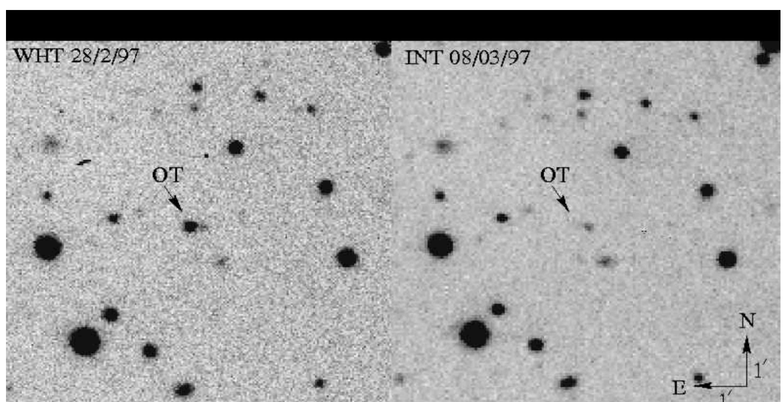


GRB 970228: *BeppoSAX* finds first GRB afterglow (Costa et al., 1997)

$\Longrightarrow$ Allows precise localization of burst

Optical Counterpart Identified

- Fades rapidly... but redshift of 0.695 measured.
- GRBs are distant

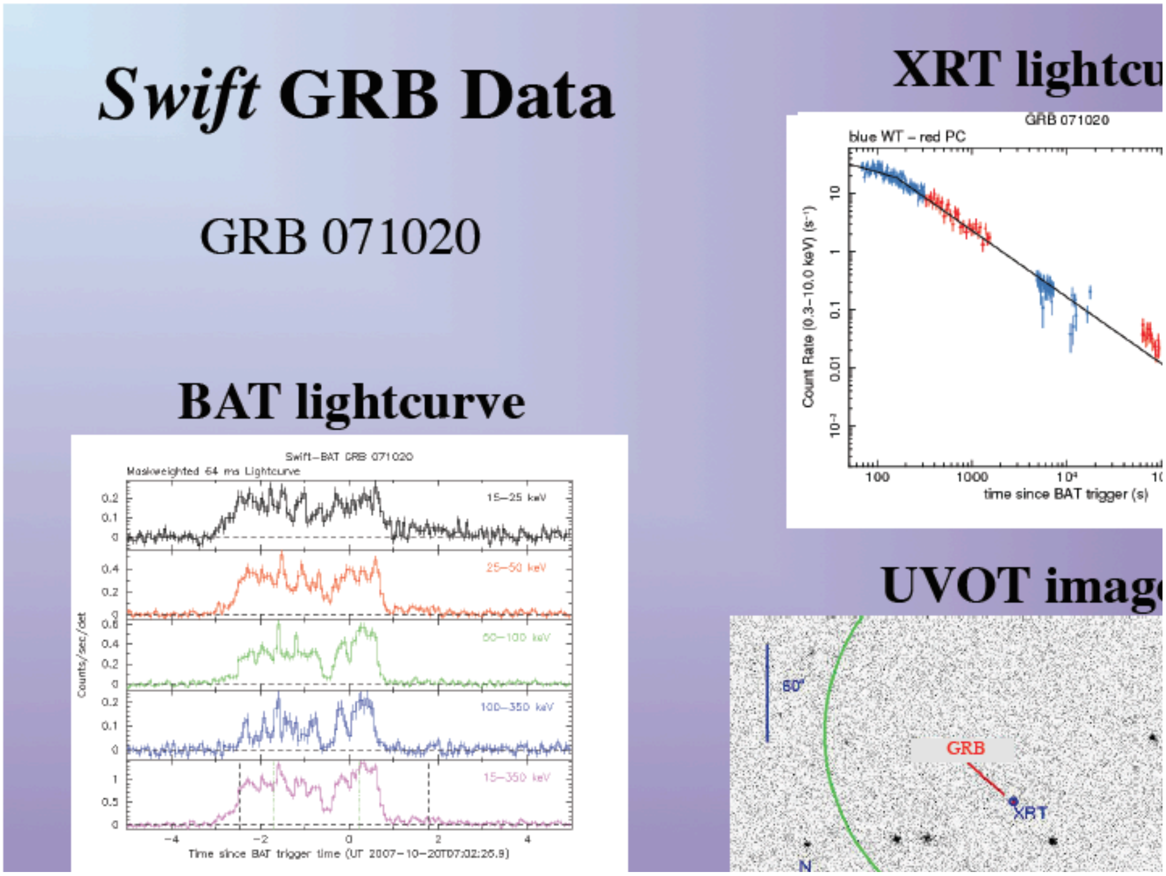


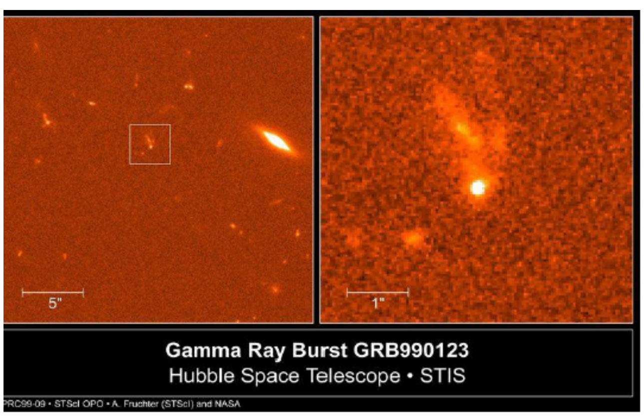
Groot et al. (IAUC 6584): Optical transient of GRB 970228, fades quickly

Seen by many others as well. . .

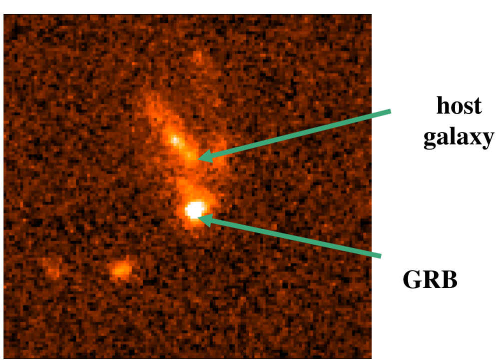
Bloom et al. (2001): Host galaxy is subluminous, but fairly normal; has $z = 0.695$

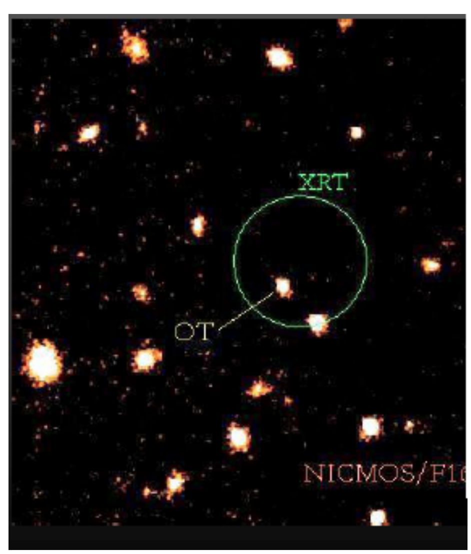
$\Longrightarrow$ GRB had $L_{20-2000\,\mathrm{keV}} \sim 1.4 \pm 0.3 \times 10^{52}$ erg fluence (assuming isotropy).





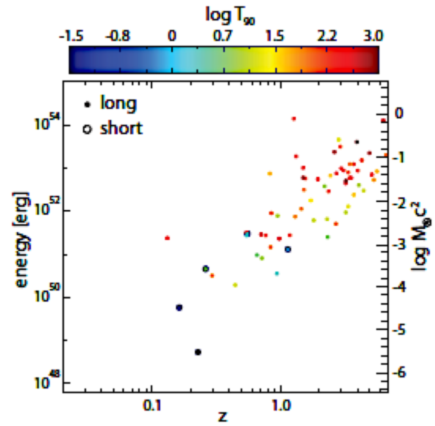
- Identification based on positional agreement with x-ray afterglow and fading of optical point source

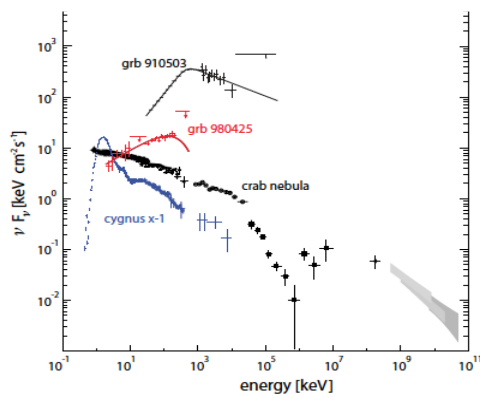


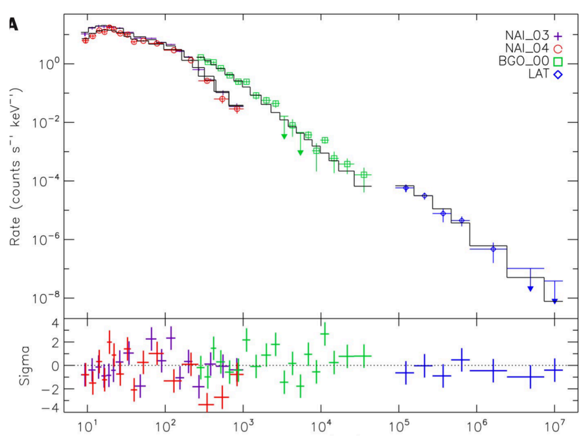


Gamma-Ray Bursts Spectra

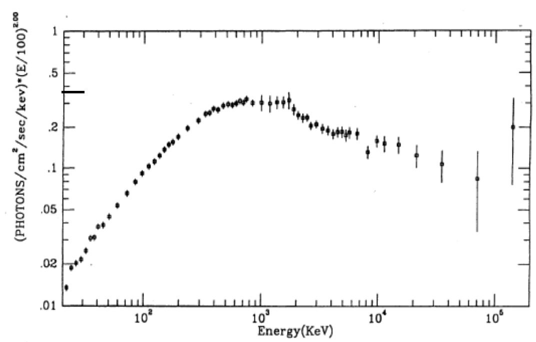
- fluxes of ~0.1-100 ph/cm^2/sec/keV energy emitted primarily in the 20-500 keV band. (100x brighter than the brightest non-burst γ-ray sources) with apparent luminosities up to 10^{54} ergs/sec (brightest objects in universe for a few seconds)~$M_\odot c^2$
  - spectrum peaks in hard x-rays
  - some spectra extend out to Gev
  - low energy photon index ~-1 with a cutoff (break) E~300 keV







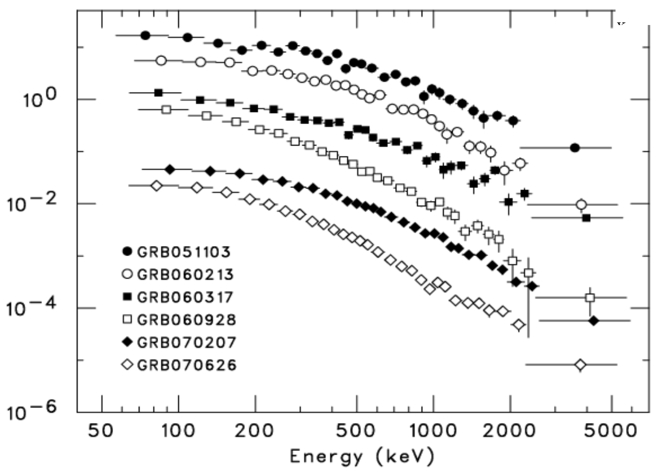
Broad band (x-ray to γ-ray) high energy spectrum of GRB 10-10^7keV

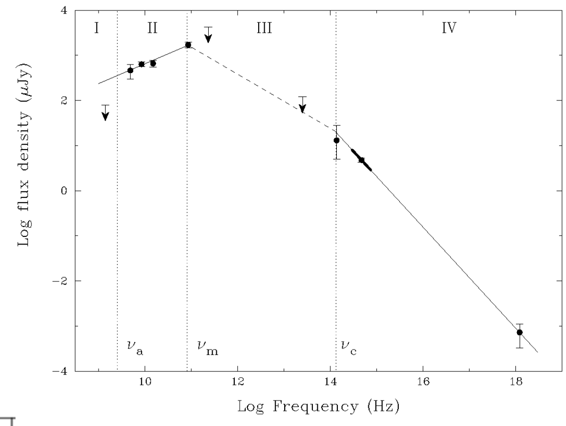


Broad band (x-ray to γ-ray) high energy spectrum of GRB 10-10^5keV

recent reviews
SN connection (Woosley and Bloom 2006), short GRBs (Lee and Ramirez-Ruiz 2007, Nakar 2007a), afterglows (van Paradijs et al. 2000, Zhang 2007) and theory (Meszaros 2002)

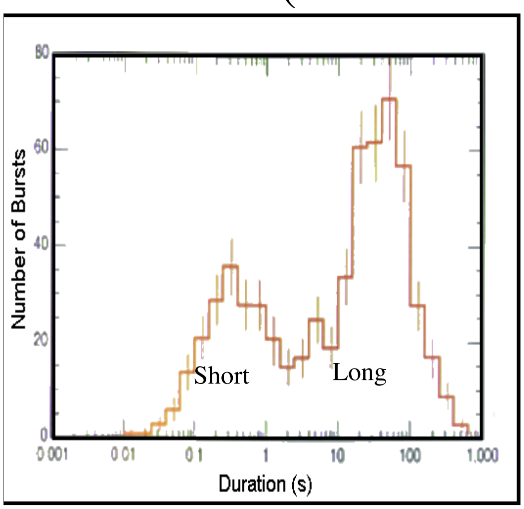
γ-ray **spectra** of a set of bursts, well fit by a 'Band' model (e.g. a broken power law flat at low E steep at high E)



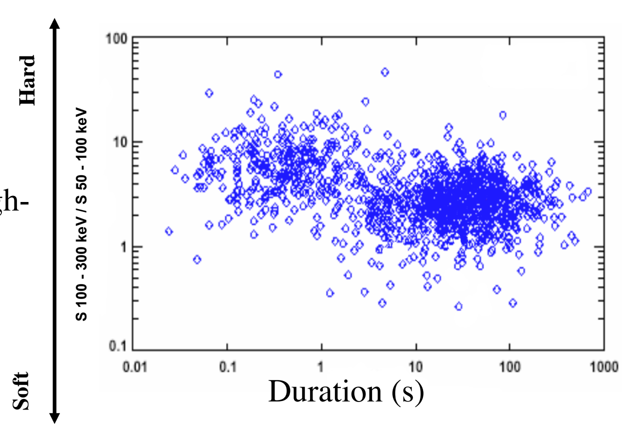


Radio thru x-ray spectrum

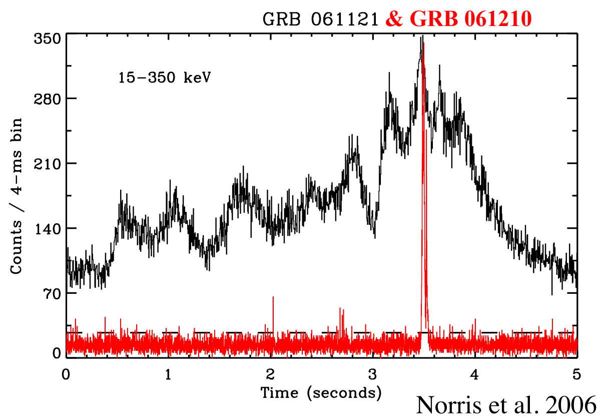
Two classes (Kouveliotou et al. 1993) short and long



- short bursts have relatively more high-energy γ-rays than long bursts



Comparing Short and Long GRBs

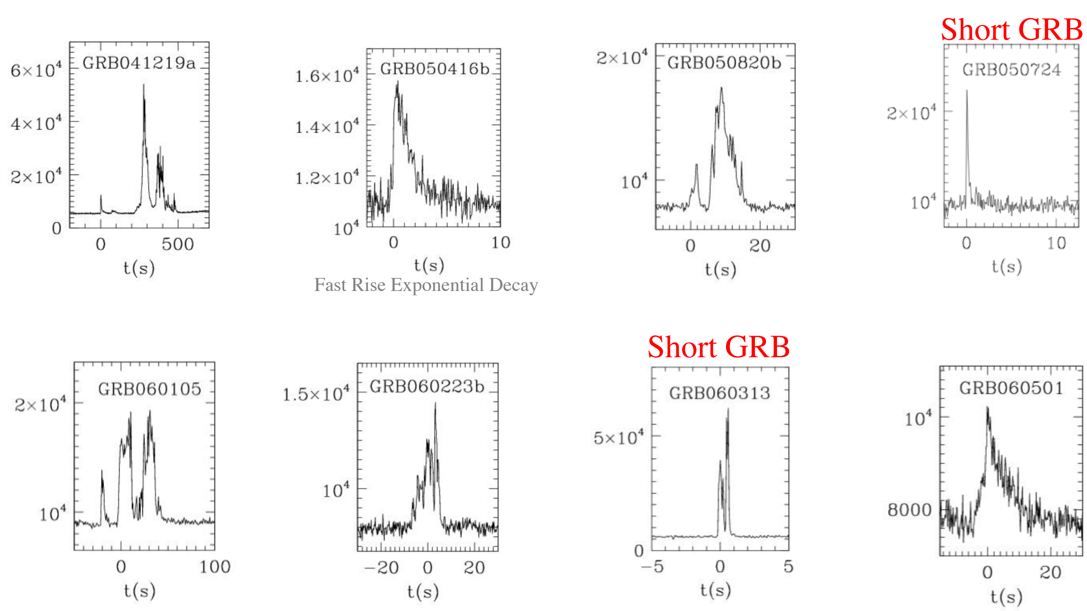


Norris et al. 2006

GRB 061121 = brightest long GRB
GRB 061210 = brightest short GRB

SWIFT Gallery of Bursts

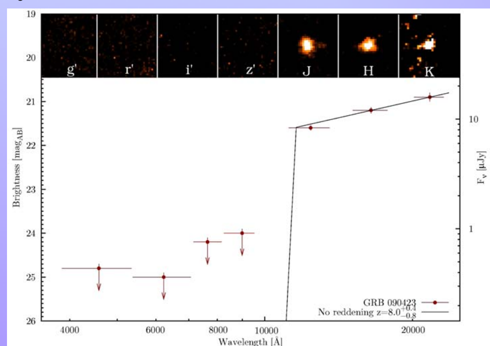
~100 GRBs per year
82% with x-ray detections
50% with optical detection



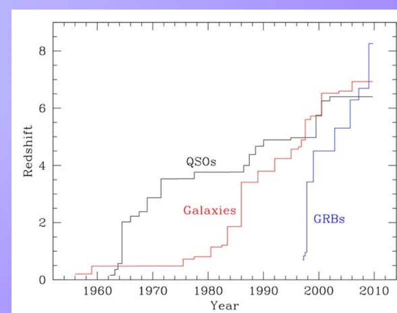
Blast from the past!
GRB 090423

z = 8.2 look back time = 13.0 billion light years

Lyman break redshifted from UV to IR



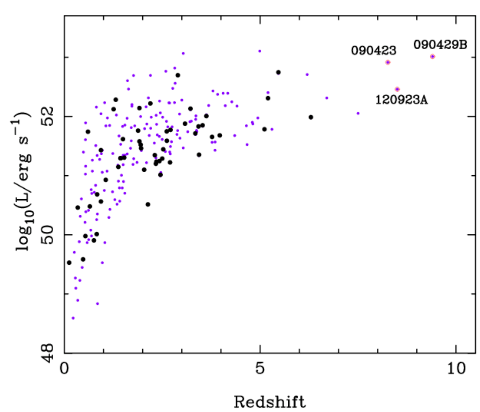
Redshift records



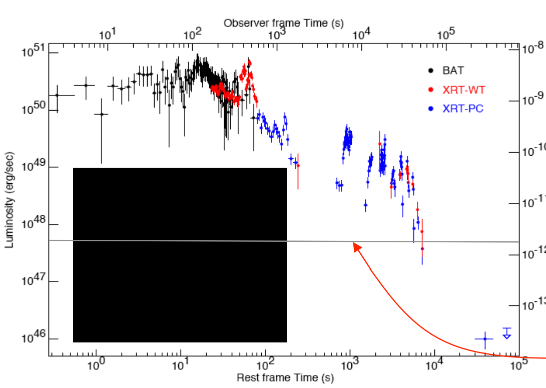
GROND Grenier et al

Tanvir et al. 2009; Salvaterra et al.

High Redshift Bursts



GRB 050904
Redshift **z= 6.29 (12.8 Gyr)**
T_{90} = 225 sec
S (15-150 keV) = 5.4×10^{-6} erg cm^{-2}
$E_{iso} = 3.8\times10^{53}$ erg



GRB 090423, z=8.2
still highest with good redshift
GRB 090429B z=9.4 photometric z

Very bright in IR
J= 17.5 @ **3 hours**
(SOAR)

Flux x100 of high-z
luminous X-ray AGN

γ-ray bursts are heterogeneous in temporal properties see Longair 22.7.2 The properties of γ -ray bursts

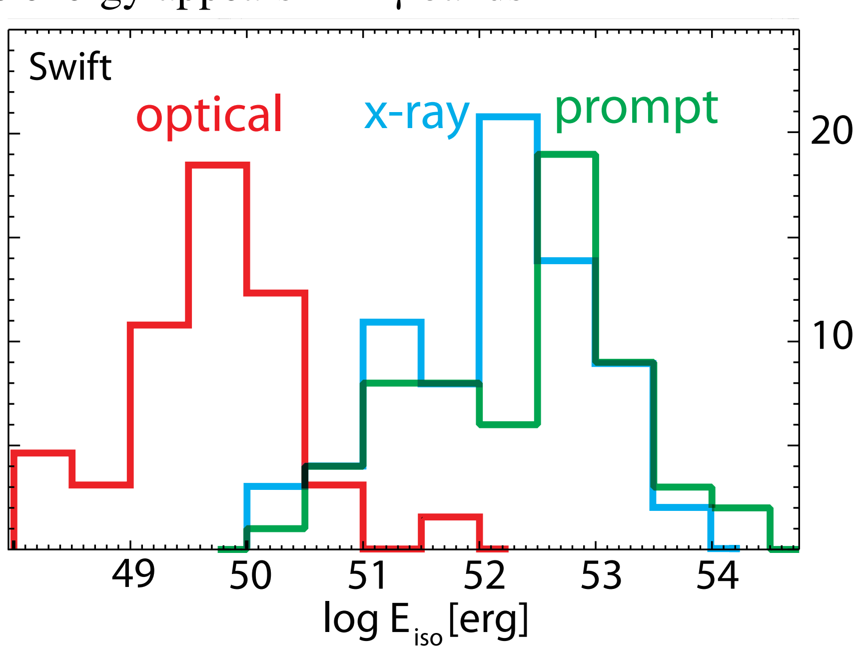
- the emission is primarily in gamma rays (νF(ν) peaks in the hundreds of keV
- the events have a limited duration milliseconds to about a thousand seconds,
- a broad bimodal distribution of durations, one peak being less than a second and the other being at 10-20 seconds.
- profile of the flux with time is not universal.
- distribution of locations of bursts is isotropic
- extremely broad range of flux 10^{-3} erg cm^2/s to the flux limits of detectors, down to 10^{-8} erg cm^2/s
- 'All' bursts that have been localized sufficiently for pointed follow-up have X-ray afterglows lasting days -weeks and about half have detectable optical afterglows
- Broad band (x-ray to γ-ray) spectra are simple (broken power law) − but parameters are hetergenous (slopes, break energy)

at z = 1, a 10^{-5} erg cm^2/s burst has isotropic luminosity of 10^{51} erg/s

Gamma-Ray Bursts Longair 22.7

–

– Most of the energy appears in x-γ bands



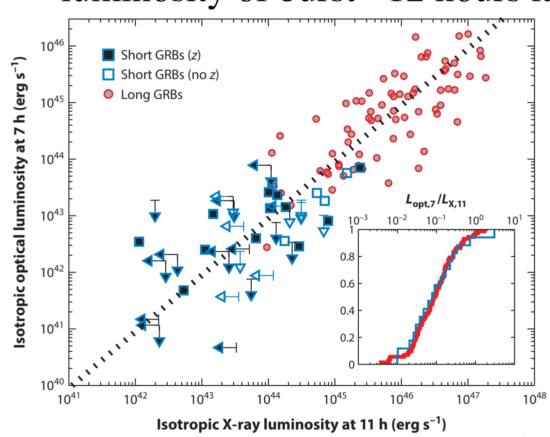
A Major Problem

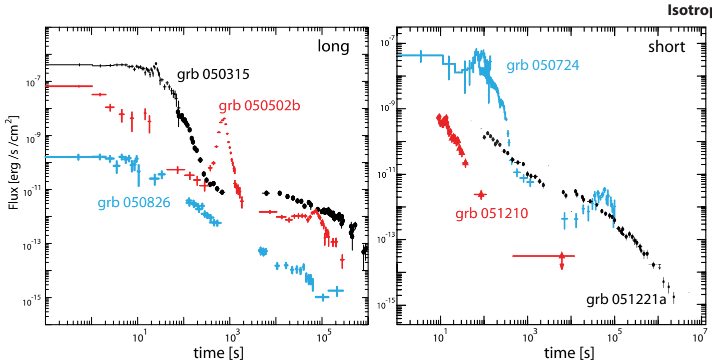
- Short variability timescale (down to milliseconds), and nonthermal gamma-ray spectra
  - "compactness problem"; these properties imply an enormous optical depth to the pair-production process
  - This problem can be resolved by invoking relativistic expansion with a large bulk Lorentz factor of $\Gamma \gtrsim 10^2$

Afterglows (Berger 2014, Gehrels et sl 2009

After the burst for many GRBS there is longer lasting emission

Comparison of optical and x-ray luminosity of burst ~12 hours later





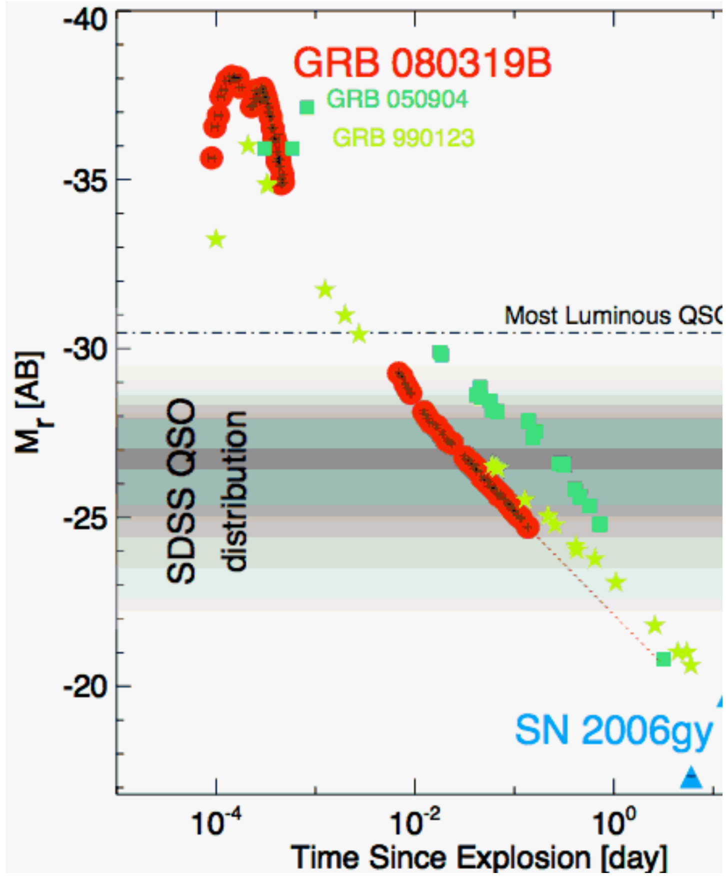
Representative examples of X-ray afterglows of long and short Swift events

GRBS compared to Quasars

GRBs are so bright that they can be used to study galaxies at the earliest epochs to probe galaxies at the epoch of re-ionization.

GRBs allow observations of objects further back in time than what is currently possible with QSOs- 'can be 'easily' detected at z>10

•In what type of galaxies did most of the star formation happened at z > 8, and what was the nature of the sources responsible for the re-ionization of the universe .



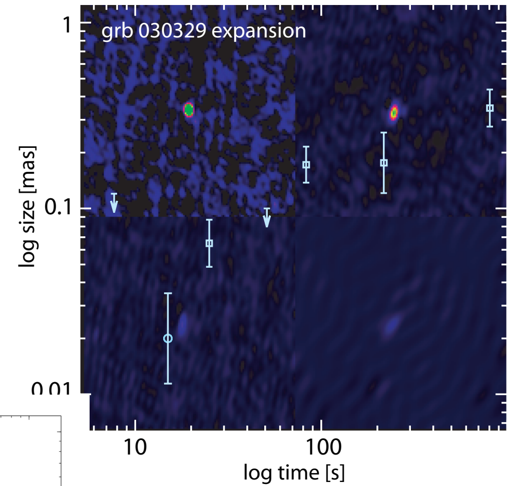
Afterglows

- The afterglow emission:
  - observational evidence for relativistic expansion (Waxman, Kulkarni & Frail 1998; Taylor et al. 2004),
  - jet collimation with typical opening angles of~3–10°(Harrison et al. 1999,)
  - a beaming-corrected energy scale of~10^{51}erg (Bloom, Frail & Sari 2001; Frail et al. 2001; Berger, Kulkarni & Frail 2003),
  - typical circumburst density of~1–10 cm^{-3}

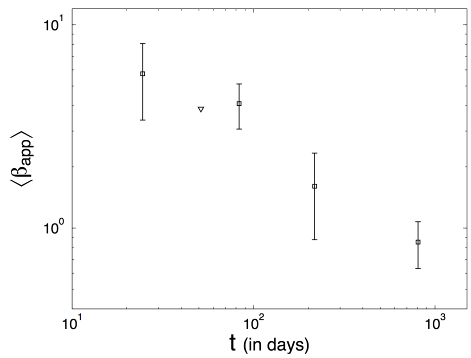
Direct Evidence for Relativistic Expansion

Radio VLBI observations of one burst shows superluminal motion apparent expansion rates (β=v/c>1)

The angular diameter of the radio afterglow is measured to be 0.347+/-0.09 mas, at t= 806 days corresponding to 0.99+/-0.26 pc at the redshift of GRB 030329 (z=0.1685) one of the closest GRBs



wth of GRB 030329 with time as measured using VLBI (by Pihlström
erences therein). In the background are the images from (a) April 2003



Gamma-Ray Bursts

Short timescales imply compact object ; -apparent luminosities of $\sim 10^{53}$ -3x 10^{54} erg/sec

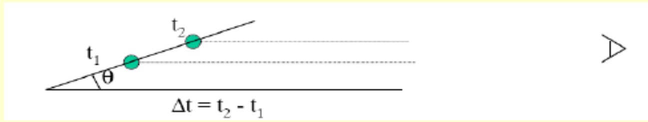
- energy reservoir ~ Mc^2 implies M~10^{33} gms~ M_{sun} if total conversion of mass into energy How does all this energy end up as γ-rays ?
- the very small sizes (implied by a short variability time, Δt) and high luminosities imply a high photon density at the source.

- Compactness parameter $C=L\sigma_T/m_pc^3R\sim 10^{12} F_{-4}\, d^2_{Gpc}/\Delta t_{ms}$

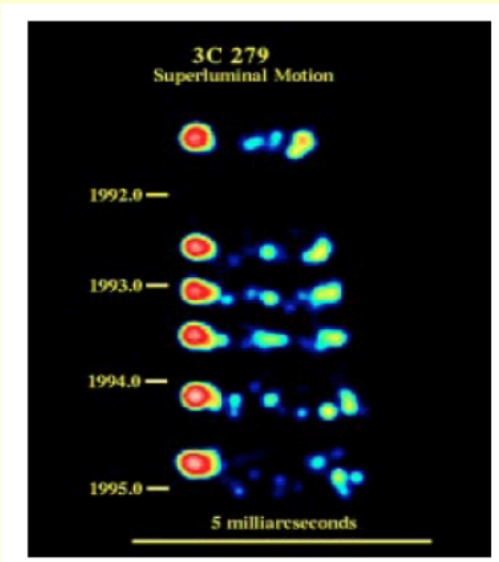
F_{-4} the γ-ray flux in units of 10^{-4} erg/cm^2/sec

- For C>1 the source is optically thick to pair creation via γ–γ interaction;
- to create pairs from 2 photons of energy $\mathbf{E_a, E_b}$ colliding at an angle θ one needs $E_aE_b = 2(m_ec^2)^2/(1-\cos\theta)$; since one sees both MeV and 10Gev photons one needs $\theta\sim 180$; for beamed radiation opening angle of beam $\theta\sim 1/\gamma$
- Suggests that $\gamma_{bulk}^2 > E_aE_b/4(m_ec^2)^2$ or $\gamma_{bulk} > 100(E_a/10Gev)^{1/2}(E_b/Mev)^{1/2}$
- Relativistic motion is the solution to the quandry (see R+B pg 261-263) the optical depth to pair production is proportional to the relativistic beaming factor γ^{-6}. **Need γ>100**

SUPERLUMINAL MOTION



Assume a spherical source moving with velocity u making an angle θ with our line of sight



Apparent velocity $\beta_{\perp,app} = \dfrac{\beta\cos\theta}{1-\beta\sin\theta}$

For $\beta_{\perp,app} > 1 \Rightarrow$ both $\beta \simeq 1$ and $\cos\theta \simeq 1$ required

$$\beta_{\perp,app} \approx \frac{2\theta}{\Gamma^{-2}+\theta^2}$$

e.g. if $\Gamma^{-1} < \theta \ll 1 \Rightarrow \beta_{\perp,app} \approx 2\theta^{-1} \gg 1$

$$\beta^{max}_{\perp,app} = \frac{\beta}{\sqrt{1-\beta^2}} \text{ for } \cos\theta \simeq \beta$$

β	$\beta_{\perp,app}$
.99	7
.999	22

Two Classes

- Long γRBs are associated with the collapse of massive stars
- The progenitors of long GRBs have been identified as massive stars based on
  - association with Type Ic core-collapse supernovae (SNe),
  - strong correlation with bright UV regions within their host galaxies
  - Location of long γRBs is in and near star forming regions in smallish galaxies- associated with star formation

Hosts
of Long GRBS

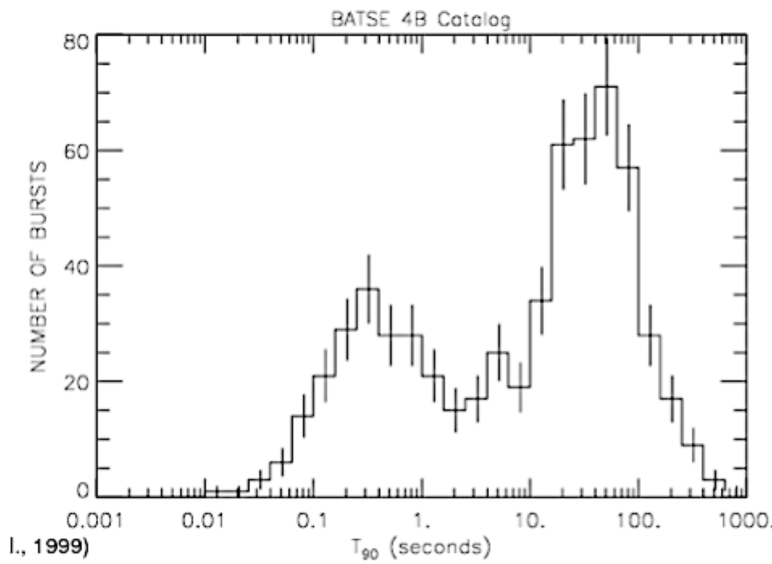
- Always in in star-forming galaxies (Bloom et al. 1998; Djorgovski et al. 1998; Christensen, Hjorth & Gorosabel 2004; Wainwright, Berger & Penprase 2007)
- their positions follow the radial distribution expected for star formation in disk galaxies (Bloom, Kulkarni & Djorgovski2002) and are spatially correlated with bright star-forming regions in their hosts (Fruchter et al.2006).
- Associated with Type Ic SNe on the basis of both photometric and spectroscopic observations (Galama et al. 1998, Hjorth & Bloom 2012)
- The environment and SN associations indicated that **long GRBs arise from the death of massive stars**
  - However these massive stars are a bit unusual- collapsars (rapidly rotating and low metallicity (https://ned.ipac.caltech.edu/level5/March04/Piran/Piran9_4.html)

Two Classes

- Short γRBs (Berger, ARA&A 2014)
  - mix of host-galaxy types
  - absence of associated SNe
  - Short γRB have harder spectra than long GRBs owing to a combination of a shallower low-energy spectral slope and a higher spectral peak (e.g., Paciesas et al. 2003; Ghirlanda et al. 2009;
  - Short γRBs are less luminous than long GRBs

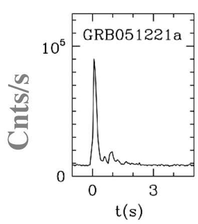
  Origin in compact object binary progenitors (NS mergers – LIGO result)

~1 Burst/day seen by GRO
2 classes- short/long

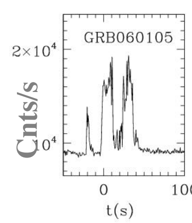


Short vs Long GRBs

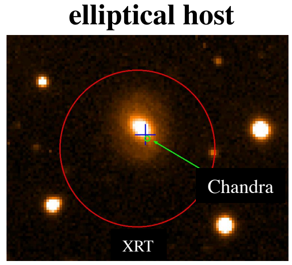
Short GRB



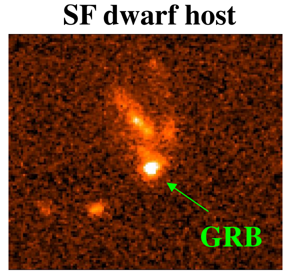
Long GRB



GRB 050724 - *Swift*
elliptical host



GRB 990123 - *SAX*
SF dwarf host

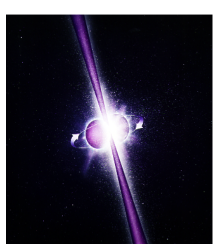


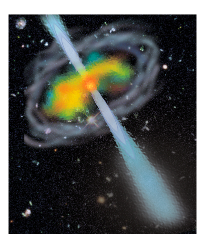
In non-SF
and SF galaxies

No SNe detected

less likely to have
afterglow

Possible **merger**
model



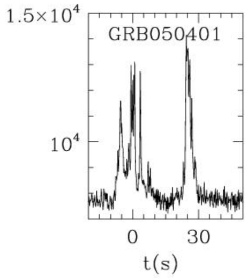


BH

In SF
galaxies

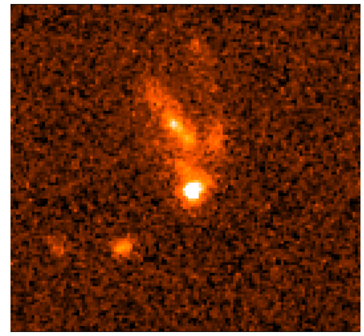
Accompanied by
SNe

Collapsar model
well supported



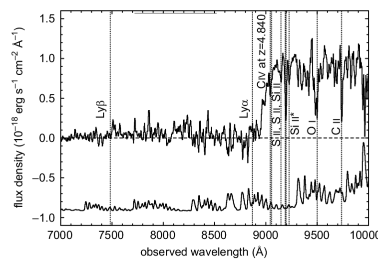
Long GRBs

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
Jet Outflow:	highly relativistic (Γ > 100)
Variability:	msec time structure in prompt burst
Power source:	gravitational infall on new-born BHs

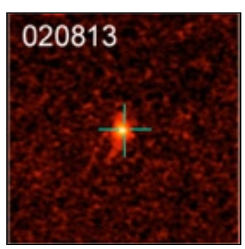
GRB 050904 z = 6.29 - Subaru

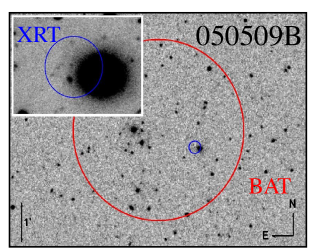


Long GRBs

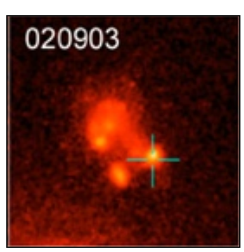
Short GRBs

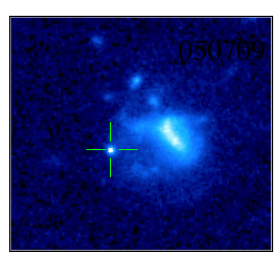
SF irregulars
(Fruchter et al.)



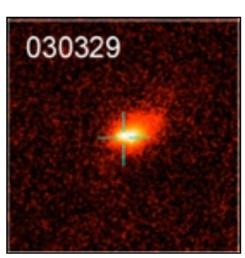


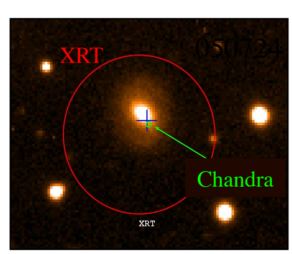
cD elliptical
SFR < 0.2 M_O yr^{-1}





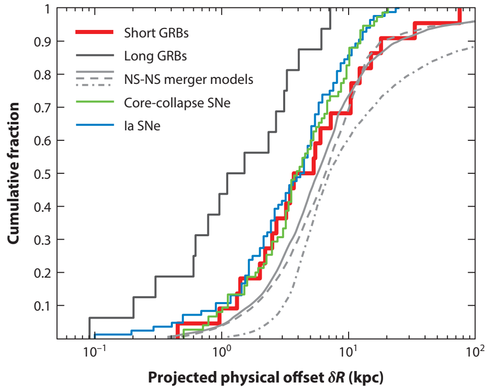
SF galaxy
with offset



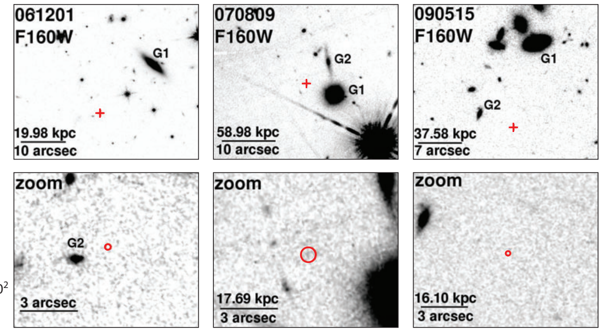


elliptical
SFR < 0.02 M_O yr^{-1}

Lots of Short GRBs are Far from their Hosts



Images go down to 26th mag

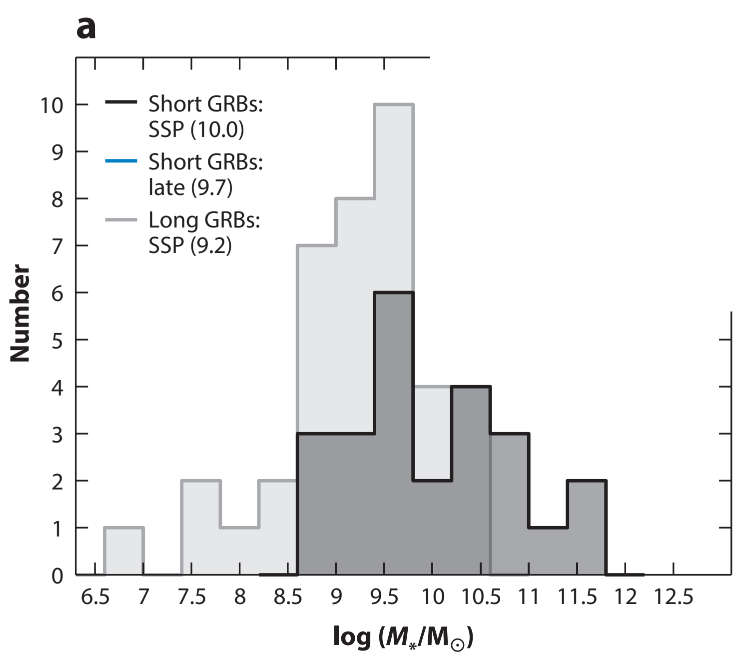


Consistent with kick velocities v_{kick} ~ 20–140 km s^{-1} with a median value of about 60 km s^{-1} (Fong & Berger 2013)- similar to the kick velocities derived for Galactic NS-NS binaries

Nature of Hosts of Short GRBs- Berger 2014

The luminosity and metallicity of host galaxies of short GRBs are similar to the general galaxy population at the same redshift

Long GRB hosts are lower in metallicity and have high star formation rate than field.



Short GRBs Compared to Long GRB

Lower Redshifts

< z > = 0.4 short

< z > = 2.3 long

Weaker Afterglows

$< F_X > = 7\mathrm{x}10^{-10}$ erg cm^{-2} s^{-1} short

$< F_X > = 3\mathrm{x}10^{-9}$ erg cm^{-2} s^{-1} long

Less Jet Collimation ?

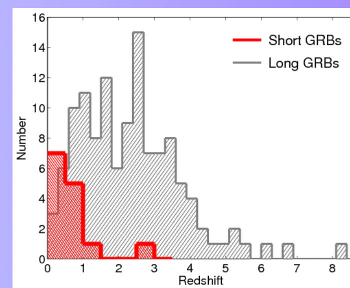
~ 15˚ (wide spread) short

~ 5˚ (wide spread) long

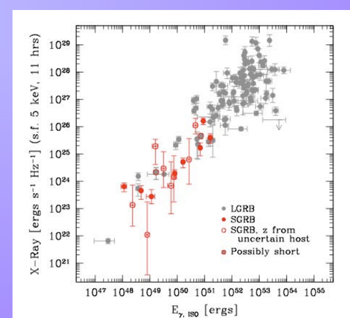
Less Total Energy

~ 10^{49} ergs short

~ 10^{51} ergs long

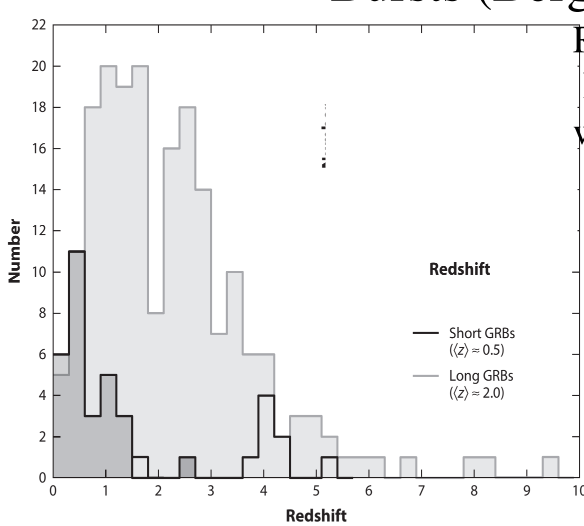


Berger 2009

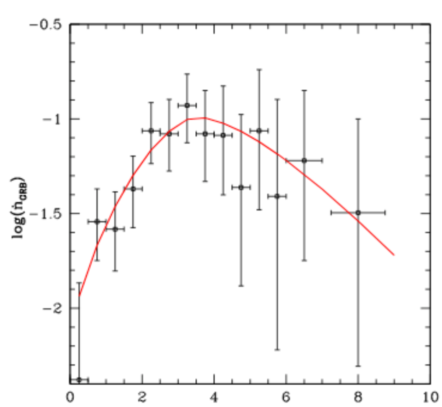


Nysewander, Fruchter & Pe'er 2009

Redshift Distribution of Short and Long Bursts (Berger 2014)



Redshift distribution of long bursts is roughly consistent with tracking of star formation rate



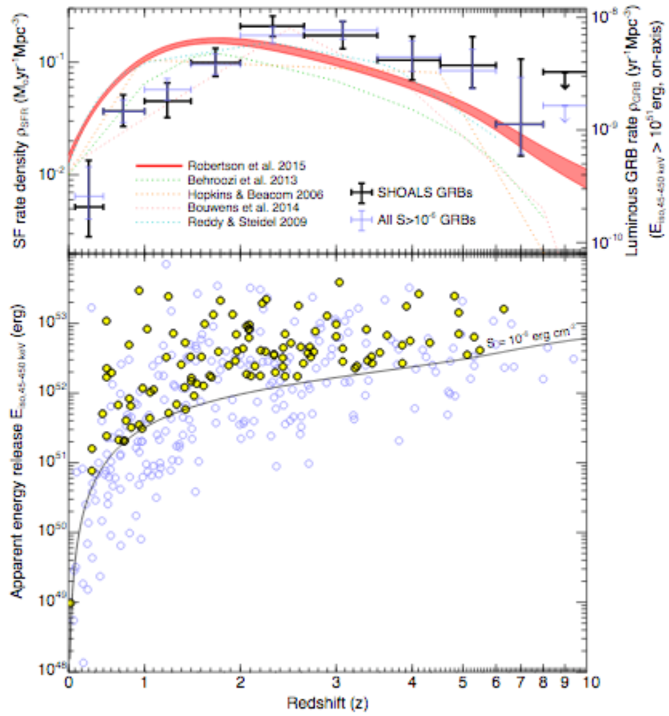
About 20% of GRBs are heavily dust obscured- rapidly star forming galaxies

Data points are gamma-ray burst rate per unit volume, red line is prediction if burst rate is related to SFR (Trenti et al 2014)

Tracing Star Formation

The match is not perfect (Perley et al 2016)- gRBs are "relatively" more common in high z universe

probably due to drop in metallicity with z



Predictions of NS-NS Merger Hypothesis for short bursts

the delay time between the binary formation and eventual merger should span a wide range that depends on the initial separation and constituent masses, $\tau_{GW} \propto a^4/(\mu M)^2$, where a is the initial binary separation, $M \equiv M_1+M_2$ is the total binary mass and $\mu \equiv M_1M_2/M$ is the reduced mass.

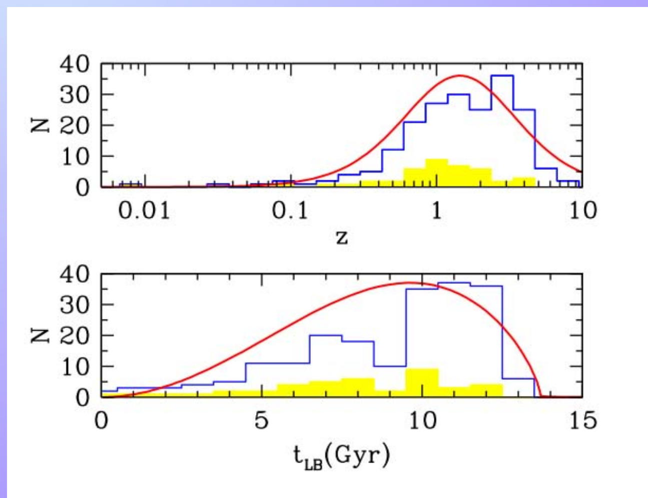
natal kicks imparted to the binary system during the SN explosions that gave rise to the neutron stars and/or black hole, coupled with the broad range of merger timescales, should lead to some mergers at large offsets from their birth location

the mergers will be accompanied by strong GW emission, detectable with the Advanced LIGO/Virgo detectors to about 200 Mpc

mergers will produce neutron-rich ejecta, which will in turn lead to r-process nucleosynthesis; very unusual optical spectra and long lasting but very weak 'kilo-nova'

No supernova accompanying burst

Swift GRB Distance Distribution



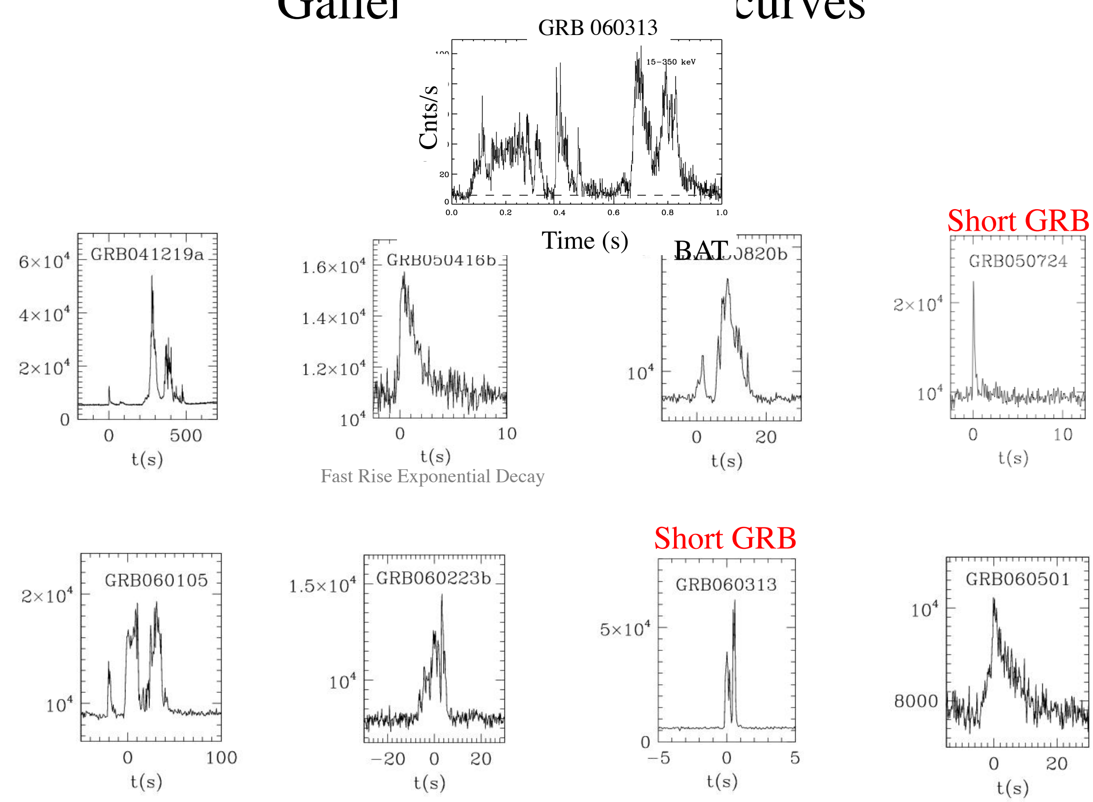
redshift

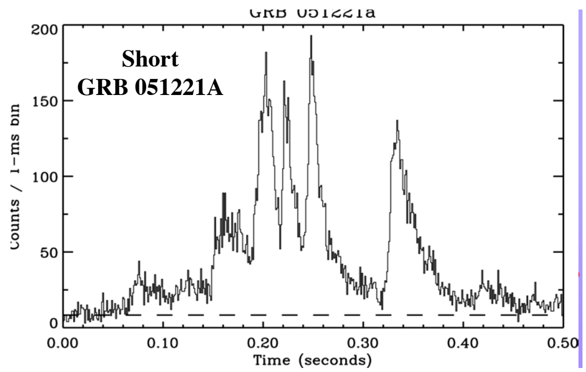
look-back time

Gehrels, Ramirez-Ruiz & Fox 2009

Swift
Pre-Swift
comoving volume

Gallery of GRB Lightcurves





Use of GRBs as Cosmological White Light Sources

As the brightest sources at high z and with no intrinsic spectral features the GRB probes the host galaxy and the IGM along the line of sight

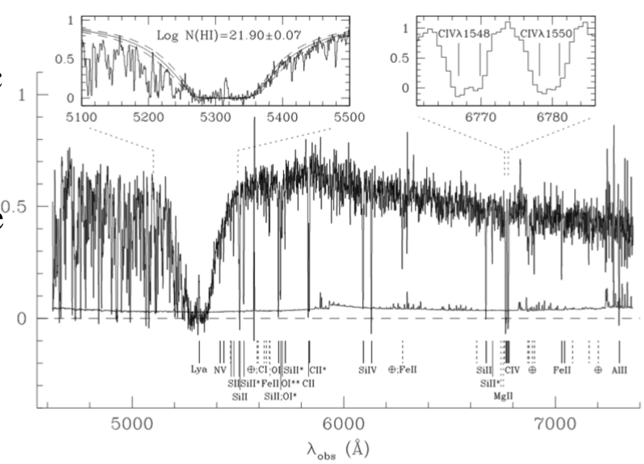
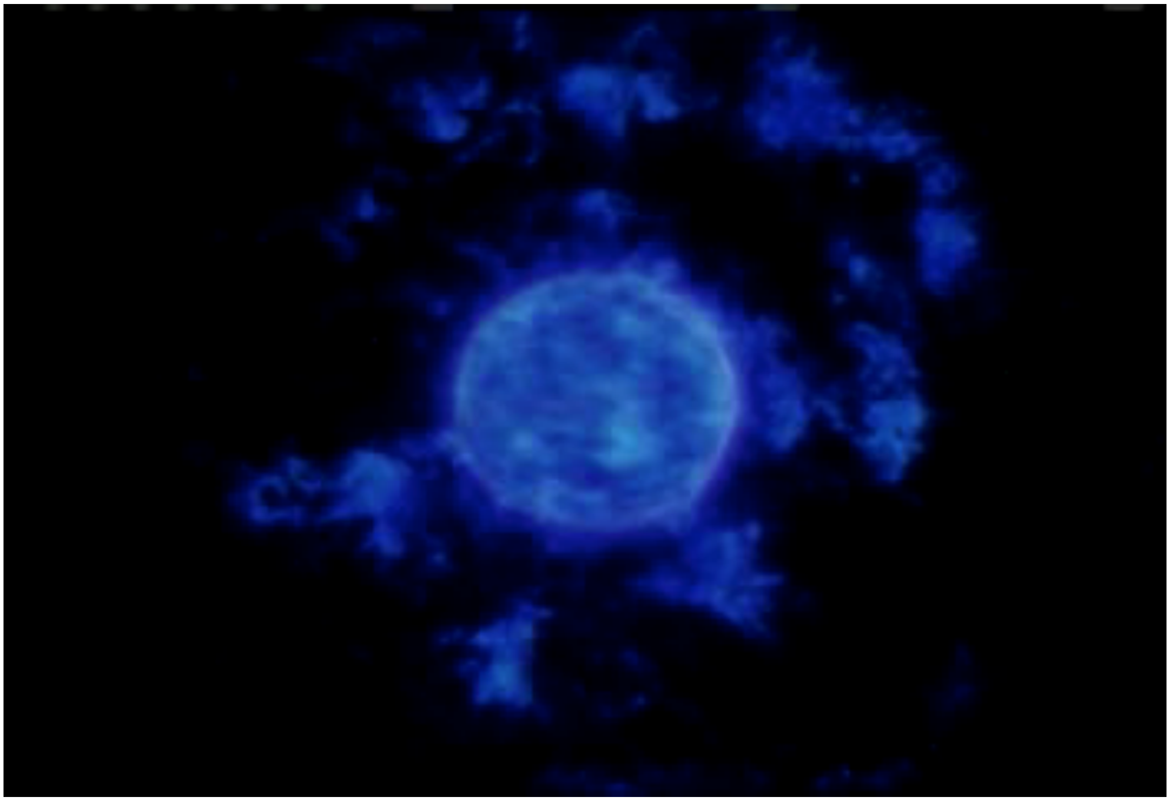


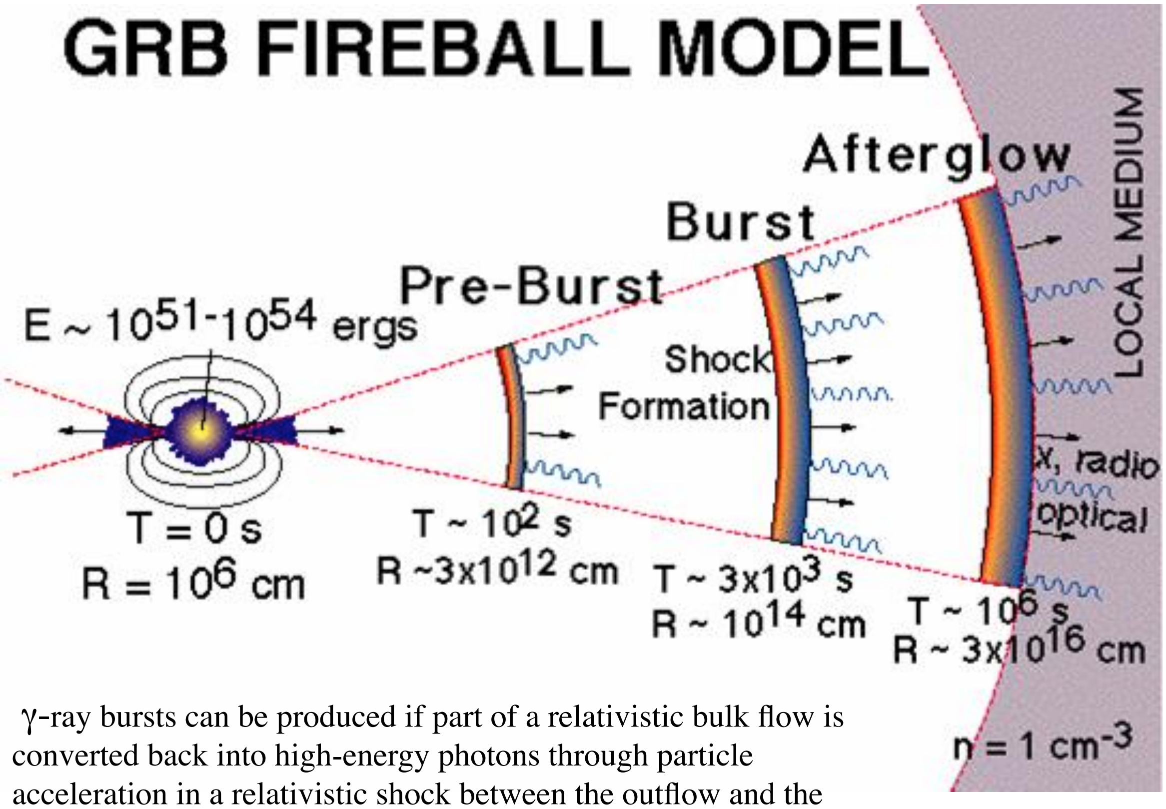
Figure 1. VLT/FORS2 spectrum of GRB 030323 at z=3.372. Damped Lyman-α and several



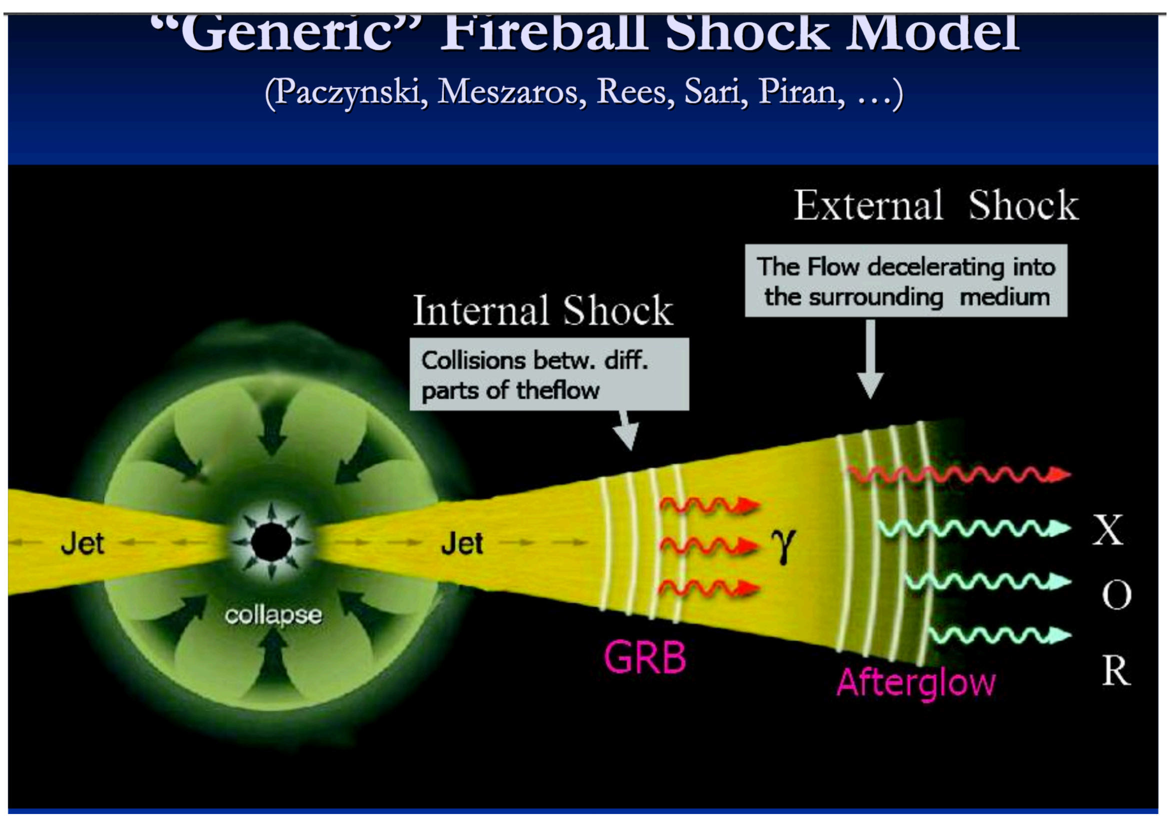
Gamma-Ray Bursts

- thought that they are ‘beamed’ - the energy is emitted in a ‘narrow’ 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
  - Relativistically beamed synchrotron emission due to the interaction of the relativistic outflow with the circumburst medium.



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

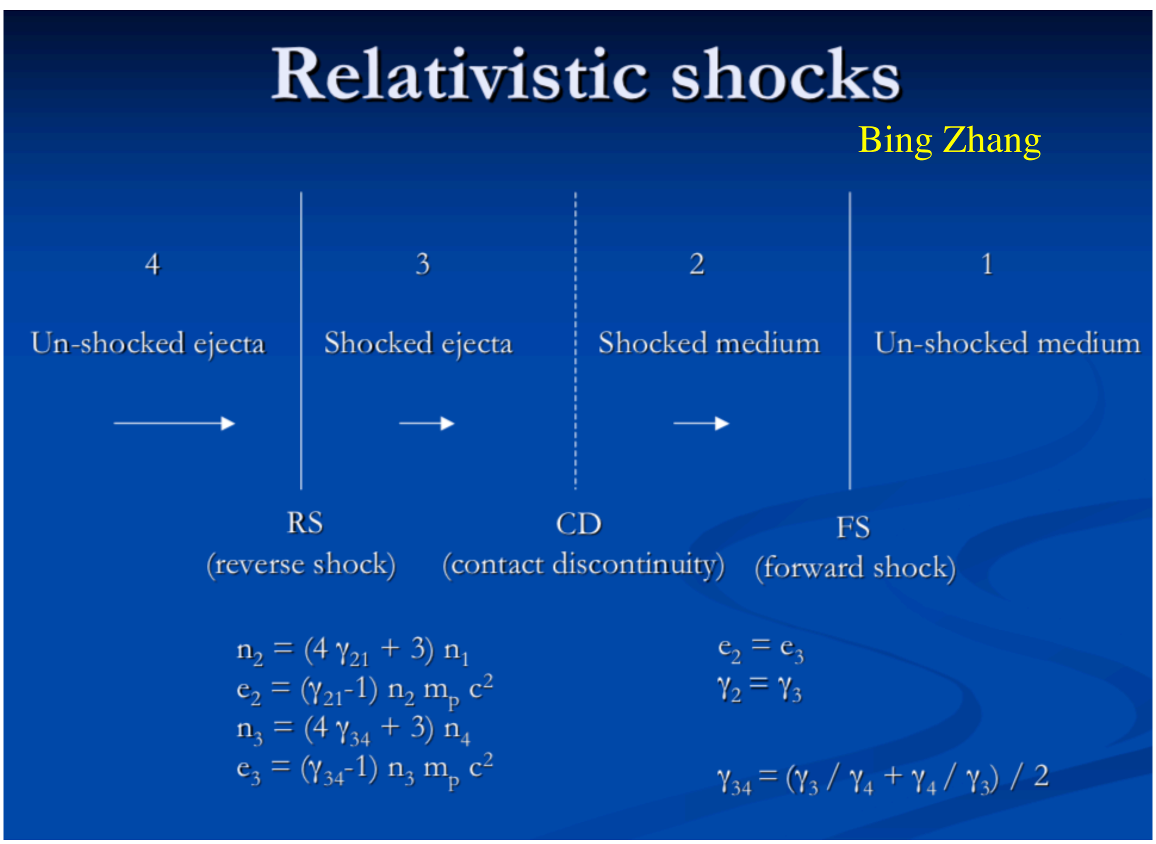


Emission Models

The situation is rather complex being dominated by relativistic collisionless shocks and particle acceleration
the source is taken to be a relativistic fireball , meaning a highly relativistically expanding sphere which heats the surrounding gas and drives a relativistic shock wave into it (M´esz´aros and Rees, 1993) emitting via synchrotron emission (fig 22.2 in Longair)

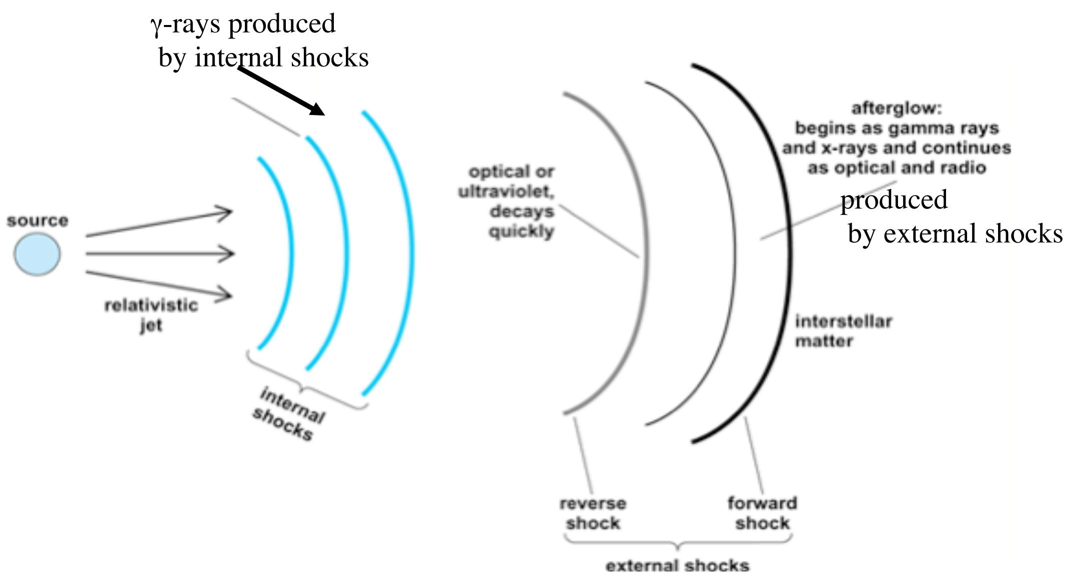
This requires a relativistic blastwave theory that describes interaction between the "fireball" — which moves with Lorentz factor Γ_0 before deceleration & has total "isotropic equivalent" energy E— and the circumburst medium (CBM) described by the density profile, $n(R) = (A/m_p)R^{-k}$.

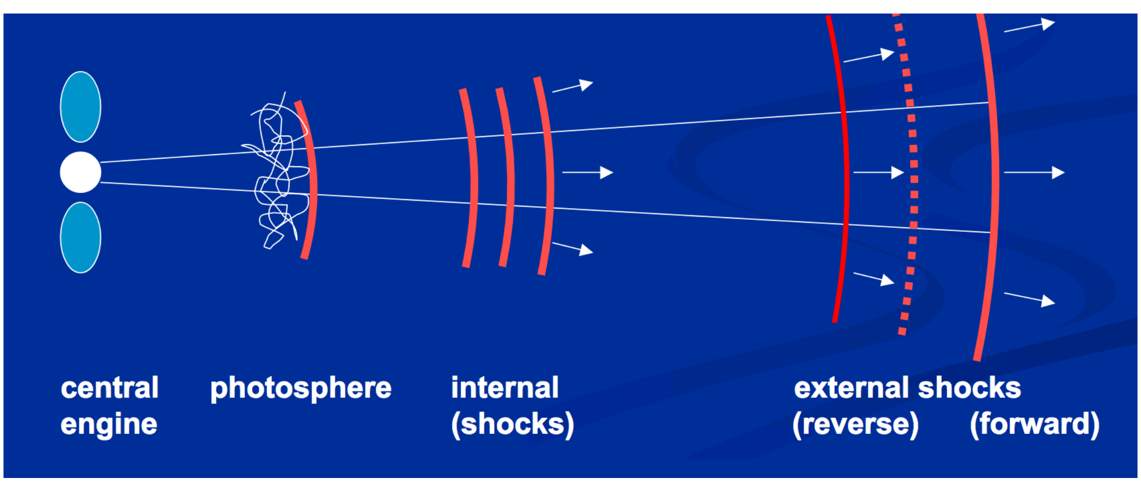
See The Physics of Gamma-Ray Bursts &Relativistic Jets
Pawan Kumar & Bing Zhang Physics Reports1410.0679.pdf



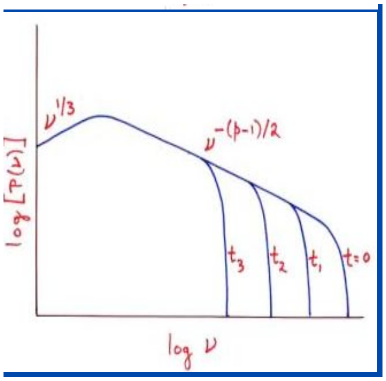
General Schema of Fireball

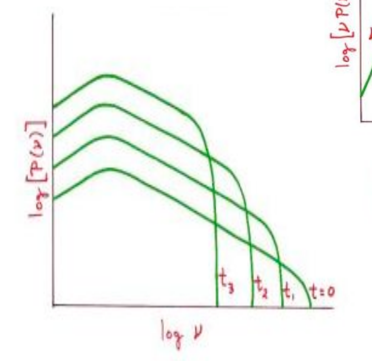
- Compact central engine drives a collimated ($\theta<10^0$) ultra-relativistic, $\Gamma>10$, outflow with a high ratio of energy to rest mass. Expands at ultra-relativistic velocities

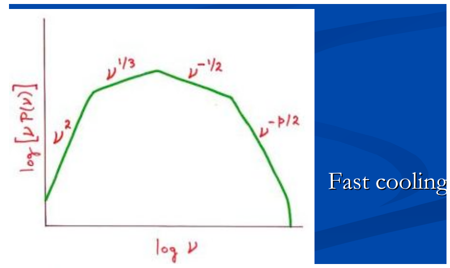




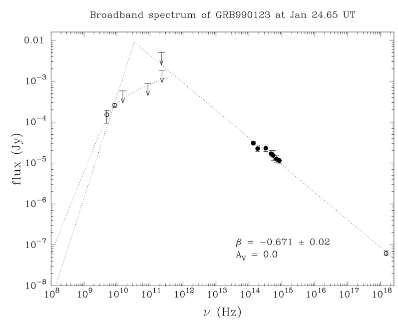
Synchrotron Spectra



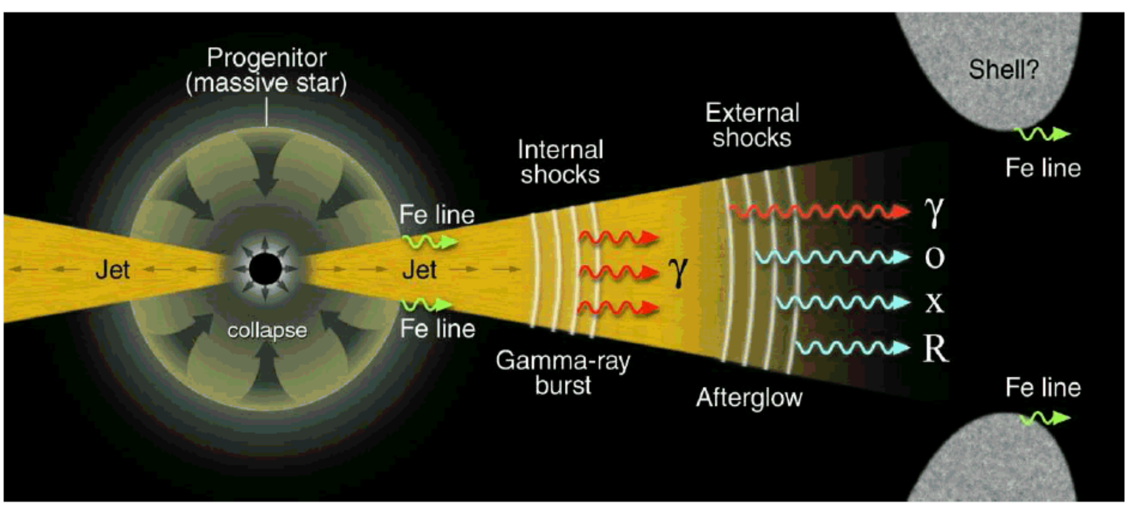




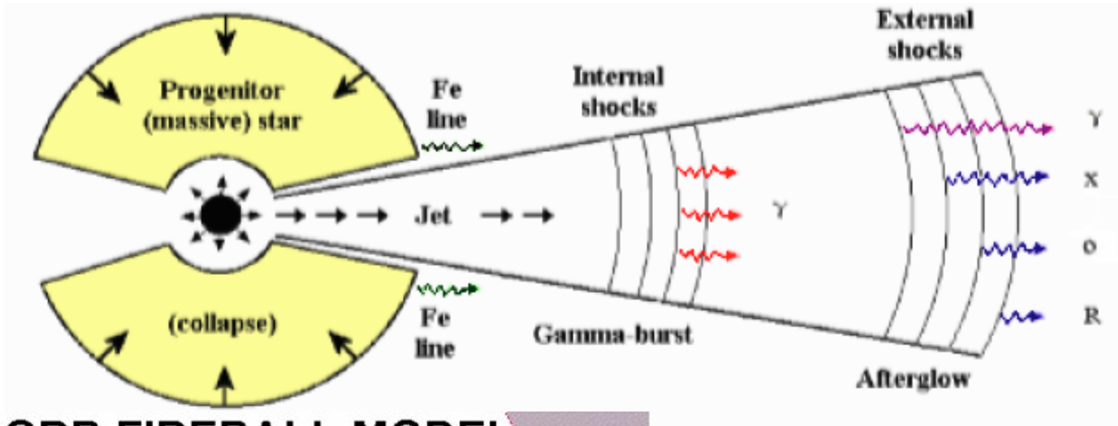
Power law injection and cooling   Continuous injection

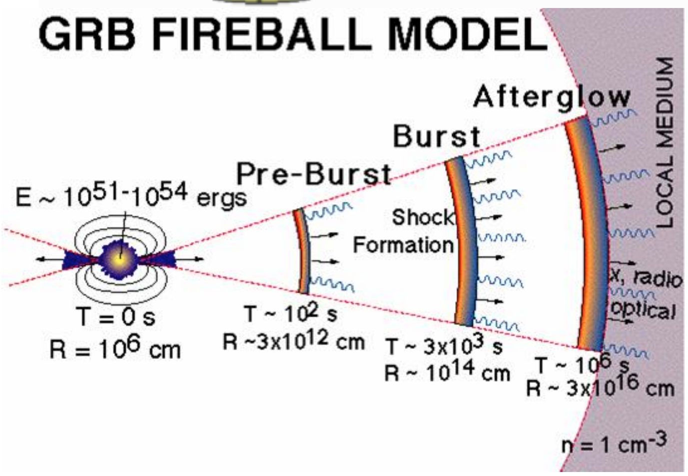


Data (Galama et al 1998)



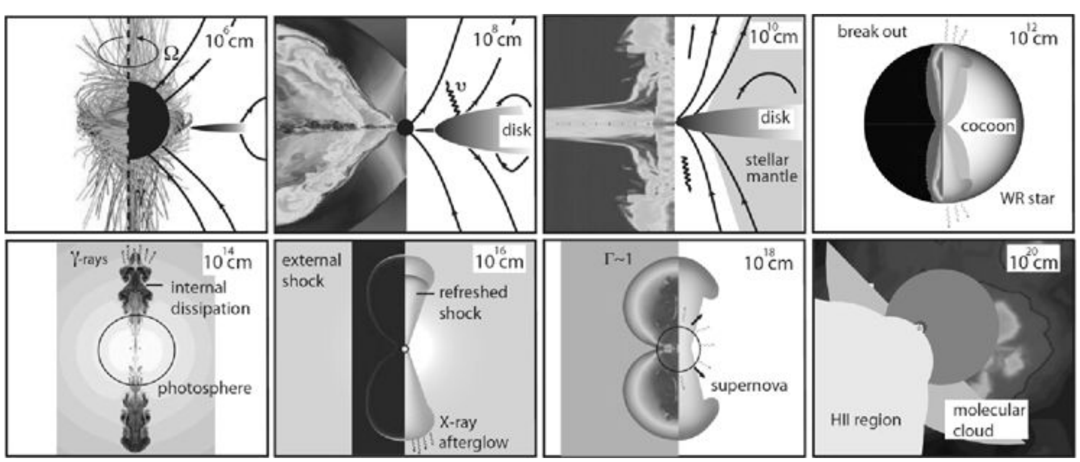
- Energy density in a GRB event is so large that an optically thick pair/photon fireball is expected to form, not clear how to turn the energy of a fraction of a stellar rest mass into predominantly gamma rays with the right non-thermal broken power law spectrum with the right temporal behavior
- Meszaros, P. and rees M ARA&A 40 (2002) 137-169   Theories of Gamma-Ray Bursts





Fireball Model, emission is separated into 2 components:

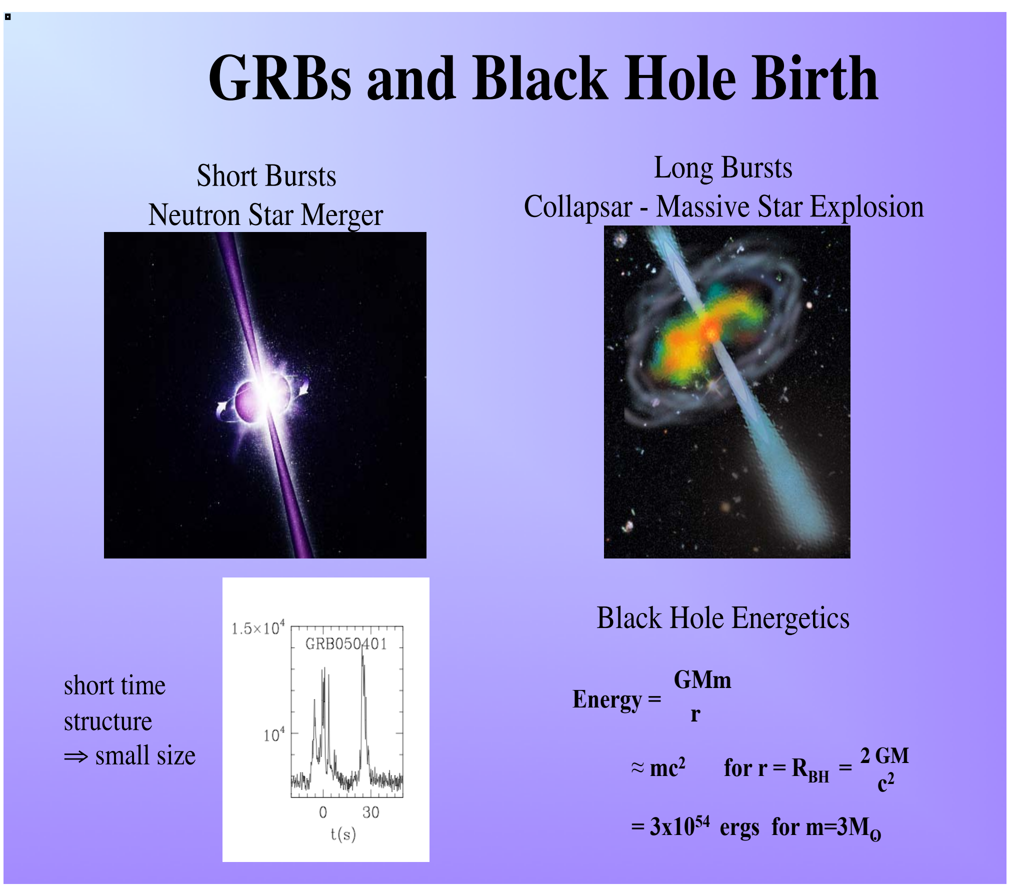
- the prompt outburst phase (strong gamma-ray and X-ray emission) due to internal shocks in the relativistic blast-wave,
- the afterglow (strong X-ray, optical and radio emission) - arises from the cooling fireball and its interaction with the surrounding medium.



Illustrating the evolution of a γ-ray burst on increasing physical scales (Gehrels *et al.*, 2009).

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 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.
- Second-order or stochastic Fermi acceleration in the broadband turbulence downstream of collisionless shocks will also contribute to acceleration.
- With each reflection at the shock the particles gyrate parallel to the moving electric field, picking up energy and surfing along the shock surface.



- visible across the universe $z_{max} \sim 9$
- most luminous sources across the electromagnetic spectrum
- afterglow lasts for days

Long GRBs

- due to core collapse to black hole of massive star
- new probe of reionization era
- produce energetic, high-velocity hypernovae (Ib/c)

possibility to use GRBS to trace star formation at high redshifts

Short GRBs

- associated with old stellar populations
- likely caused by NS-NS mergers
- less energetic than long bursts
- exciting sources for gravitational wave joint observations

Conclusions

Short GRBs

- occur in external galaxies
- are less distant than long bursts
  $<z> = 0.4$ short, $<z> = 2.3$ long
- do not occur preferentially in star forming regions
- are less energetic than long bursts
  $E_\gamma \sim 10^{48}$ short; $E_\gamma \sim 10^{51}$ long

Short GRB seem to

- be associated with old stellar populations
- be less beamed than long GRBs
- have a wide redshift distribution

Short GRB may

- caused by NS-NS mergers
- have 2 types associated with offset distance from host galaxy
-