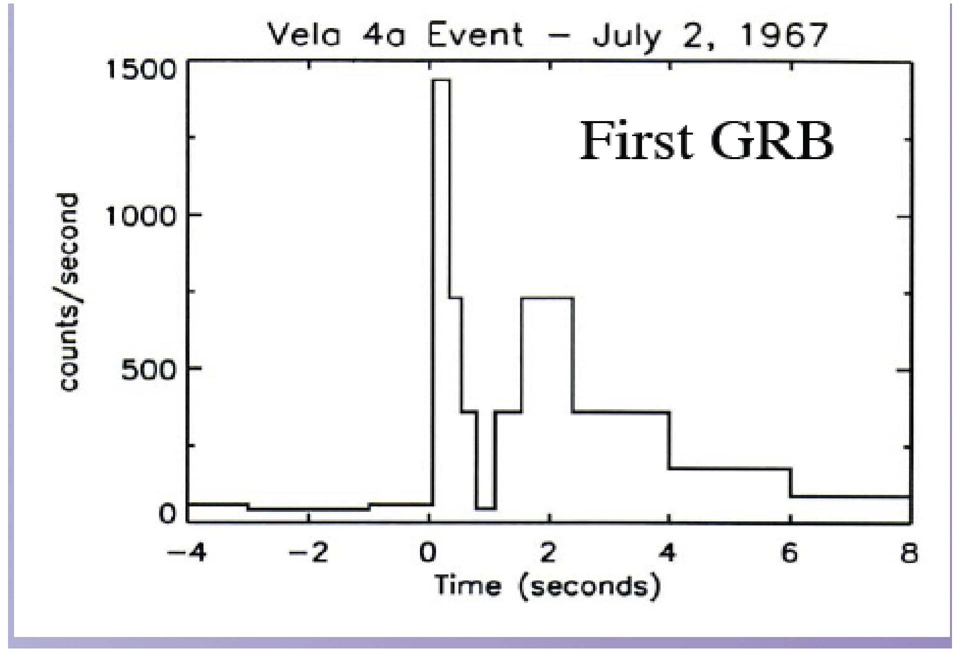
Gamma-Ray Bursts

- 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.
  - 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
- What are they??- short timescales imply compact object ; what could the energy reservoir be- 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 ?
  - Location of long γRBs is in and near star forming regions in smallish galaxies- associated with star formation
  - A few γRBs have been associated with a type Iic supernova

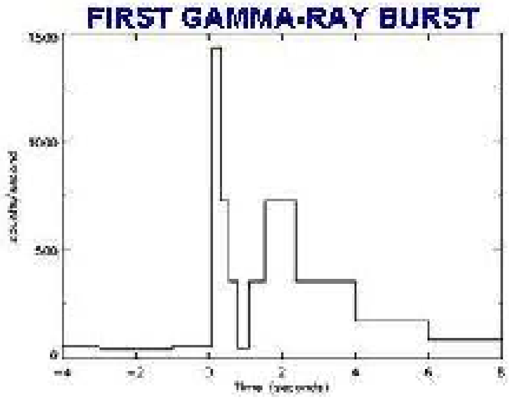
Gamma-Ray Bursts

- Cosmic γ-ray bursts (GRBs) were first reported in 1973 by Klebesadel et al (1973) 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 $\to$ 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) $\to$ 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: $\sim 10^{-7}\,\mathrm{yr}^{-1}\,(3 \times 10^{45}\,\mathrm{J}/\epsilon\,\mathrm{E})$

GRBs are powerful explosions

- visible across the universe
- 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

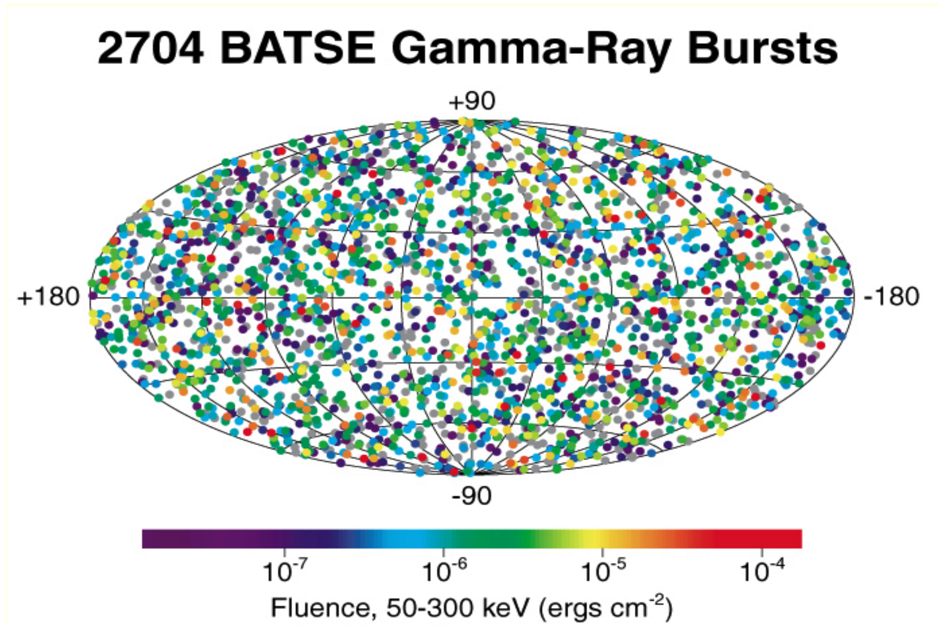
- associated with old stellar populations
- likely caused by NS-NS mergers
- less energetic than long bursts
- exciting sources for gravitational wave joint observations

Isotropic on Sky

For 25 years their nature was unknown but they were the brightest γ-ray sources in the sky - but occurred randomly in time and lasted 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



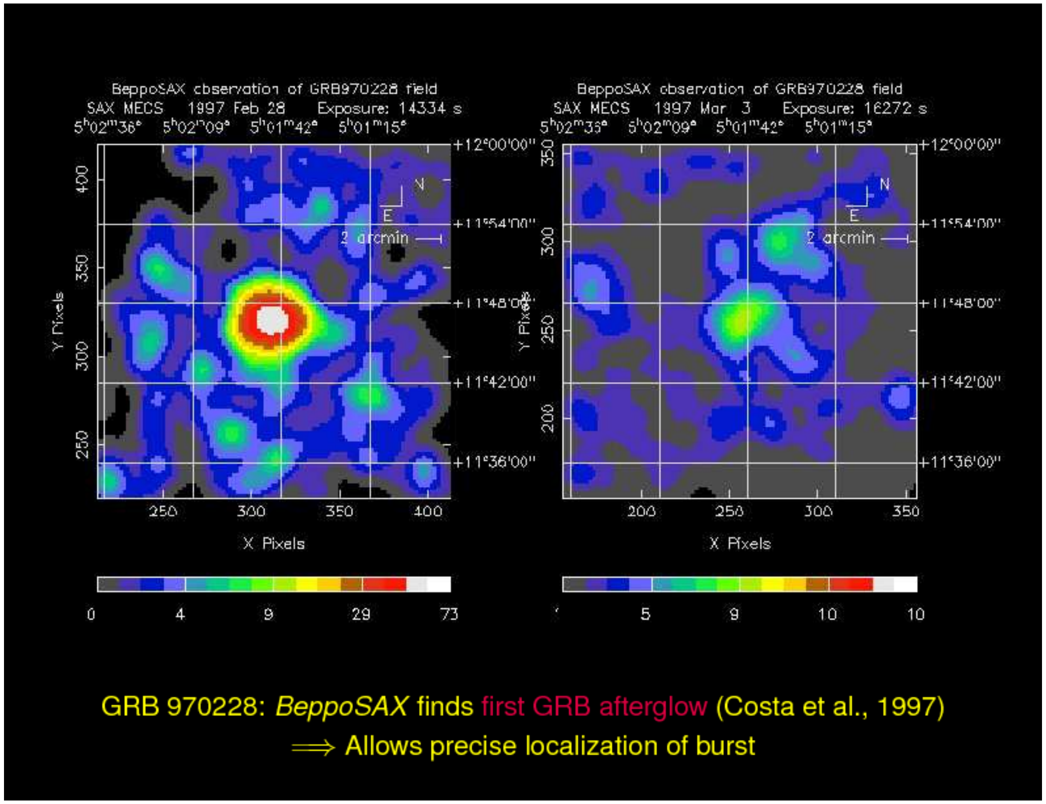
Breakthrough

- 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 chap 7 of R+B for lots more material on GRBs + Melia sec 11.2

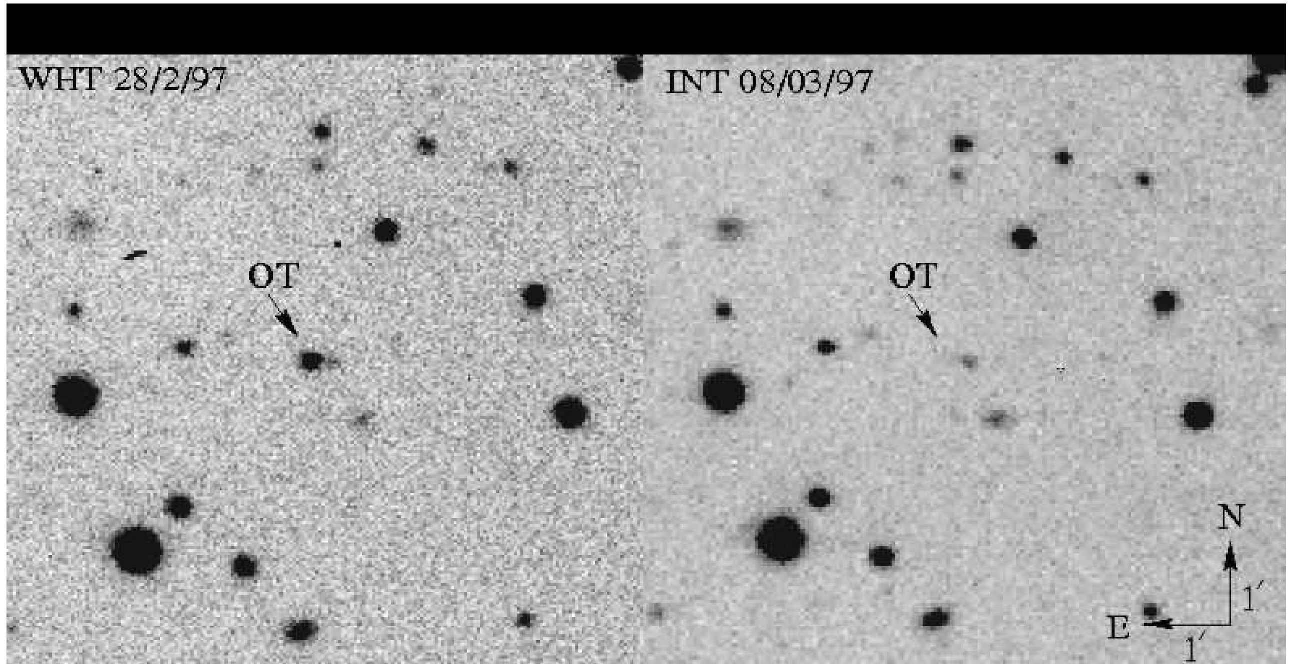
•Breakthru was the discovery of 'afterglows' in the x-ray by the BeppoSax satellite (1998GRB 970228 Piro et al - ARAA 2000. 38:379 van Paradijs et al)

- •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



Optical Counterpart Identified

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

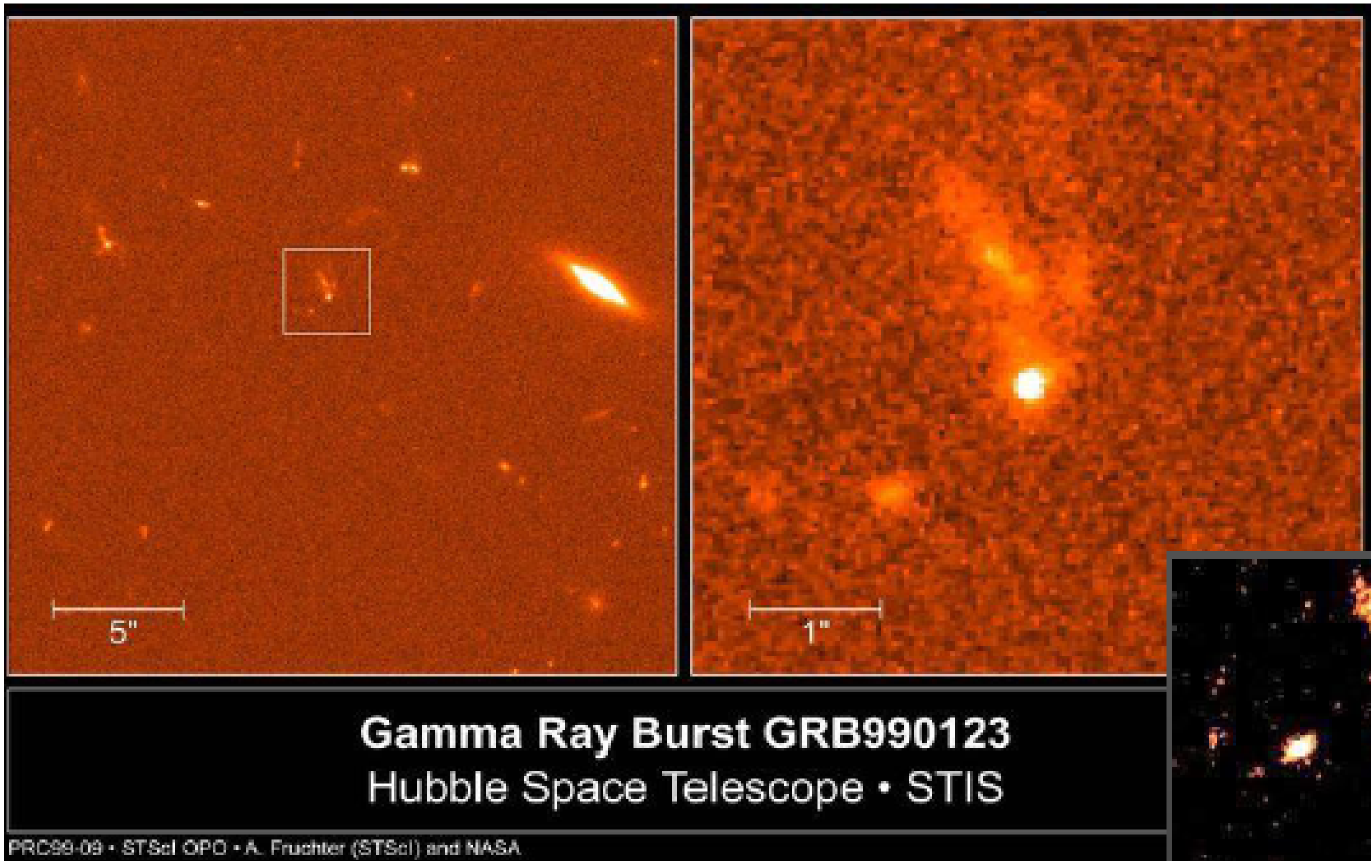


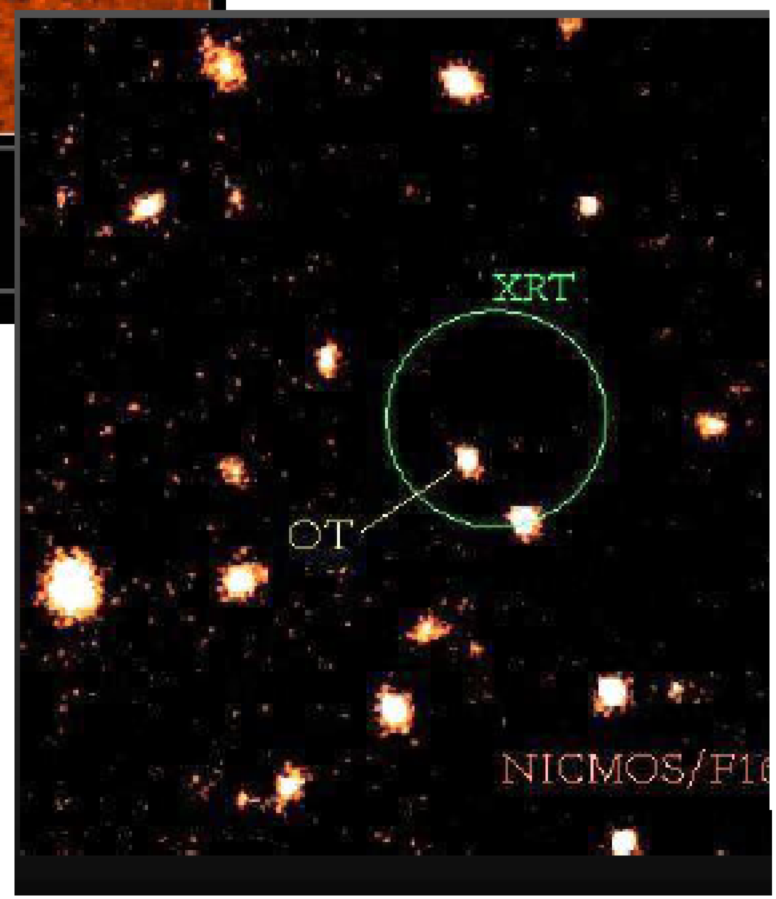
Groot et al. (IAUC 6584): Optical transient of GRB 970228, fades quickly

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

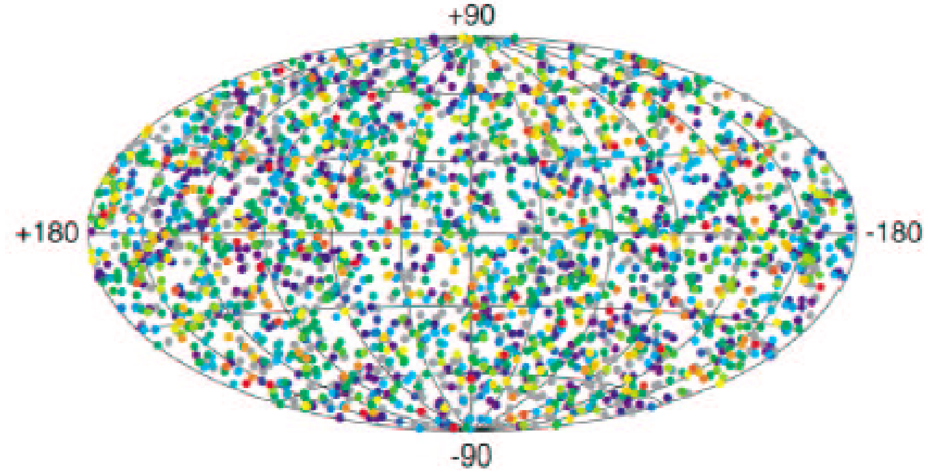
Gamma-Ray Bursts

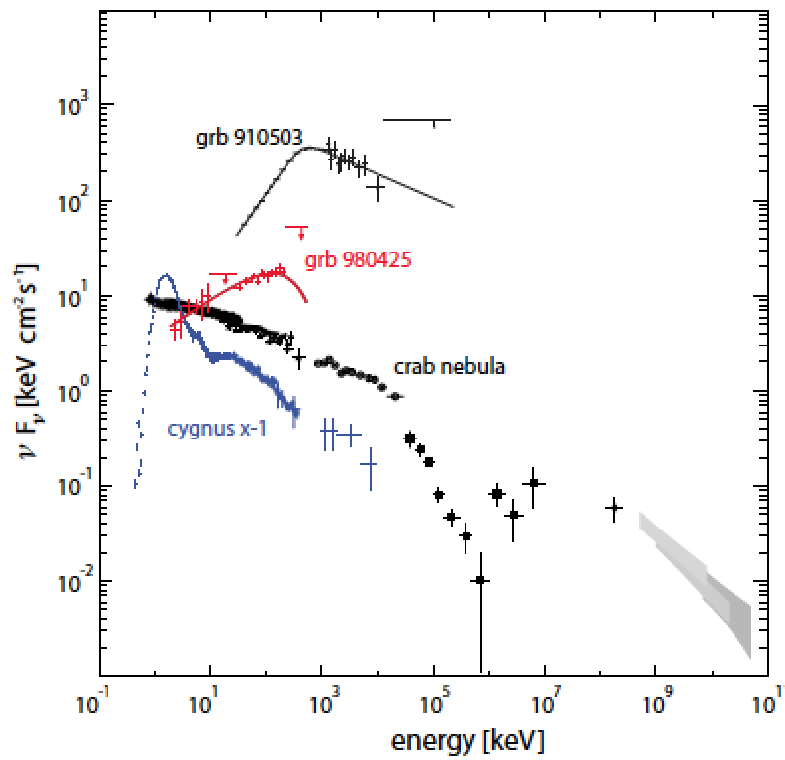
- Bright flashes of γ-rays- for a short period of time (<100 sec) fluxes of ~0.1-100 ph/cm^2/sec/keV

  energy emitted primarily in the 20-500 keV band. (100x brighter than the brightest non-burst γ-ray sources)
  - Distribution is isotropic on the sky
  - They are at very large distances (z up to 8 (!)) with apparent luminosities of

    3x 10^{54} erg/sec
  - Rate is ~10^{-7}/yr/galaxy/yr

2704 BATSE Gamma-Ray Bursts



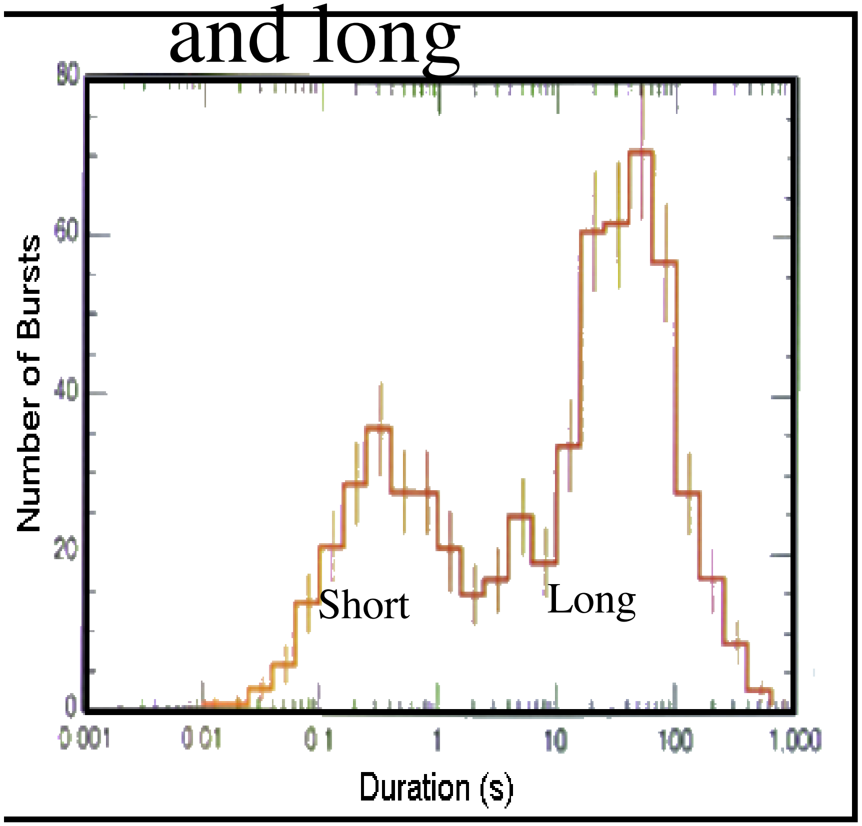


γ-ray bursts are heterogeneous in temporal properties

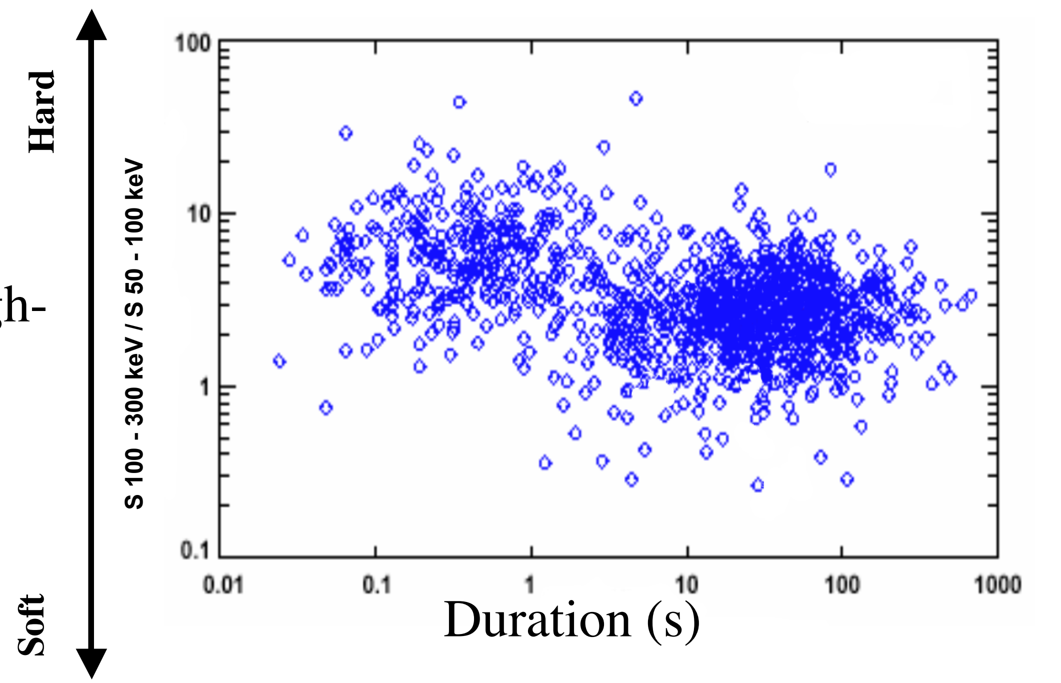
- the emission is primarily in gamma rays ($\nu F(\nu)$ peaks in the hundreds of keV
- the events have a limited duration milliseconds to about a thousand seconds,
- a broad bimodal distribution of durations, one peak being less than a second and the other being at 10-20 seconds.
- profile of the flux 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)

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

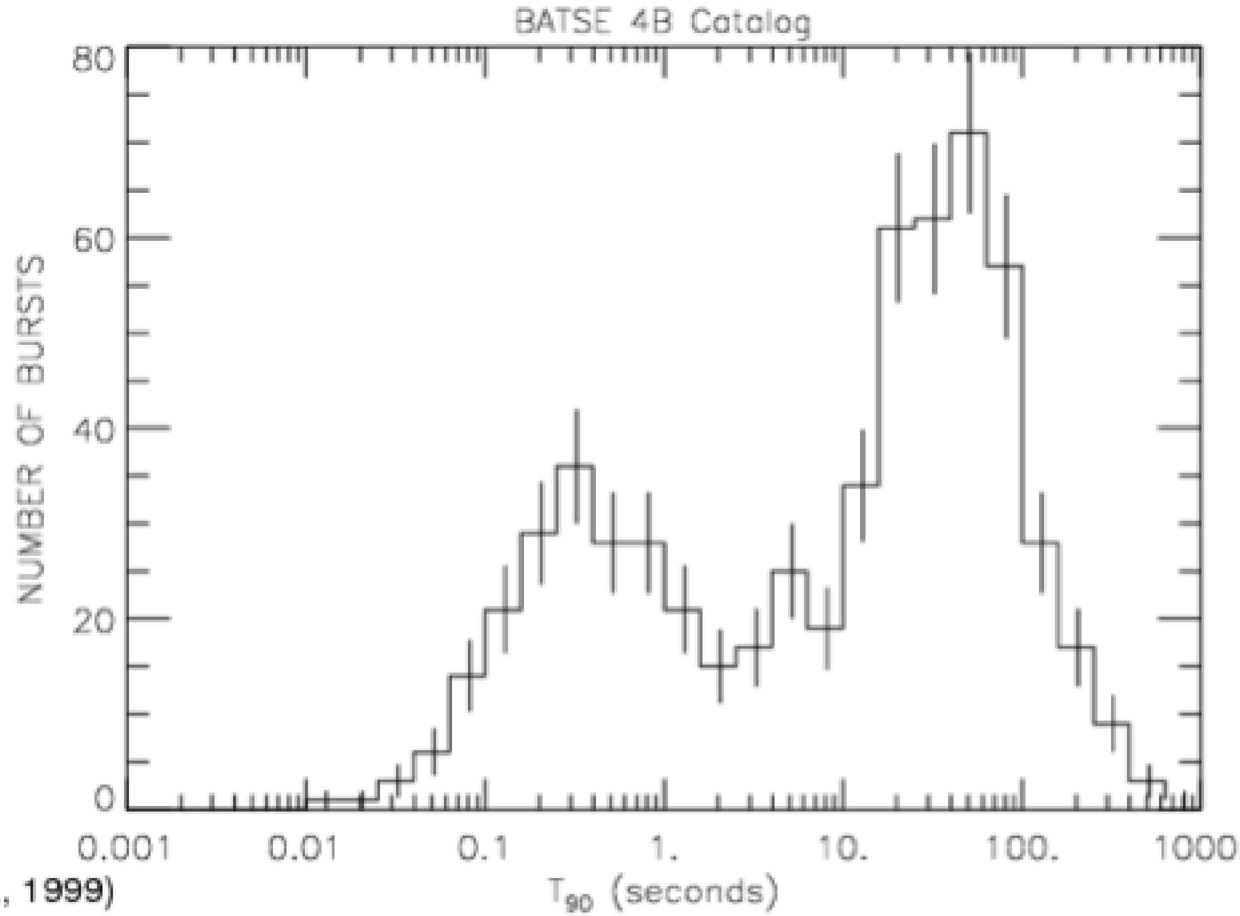
Two classes (Kouveliotou et al. 1993) short and long



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



~1 Burst/day seen by GRO
Very wide variety of burst profile
Spectra are 'hard' fit by a power law with an exponential cutoff, cutoff energy ~20-1000keV
2 classes- short/long



l., 1999)

Gamma-Ray Bursts

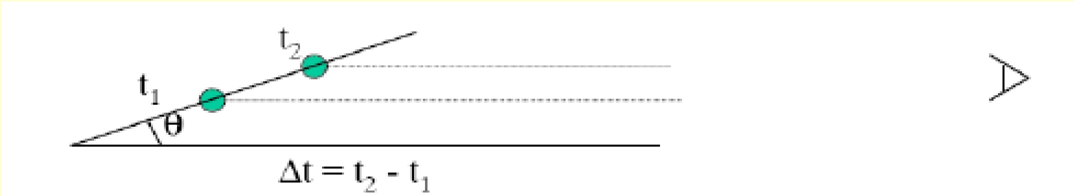
What are they??- short timescales imply compact object ; -apparent luminosities of $\sim 10^{53}$ -3x 10^{54} erg/sec

- energy reservoir - Mc^2 implies $M \sim 10^{33}$ 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 $C = L\sigma_T/m_p c^3 R \sim 10^{12} F_{-4}\, d^2_{Gpc}/\Delta t_{ms}$

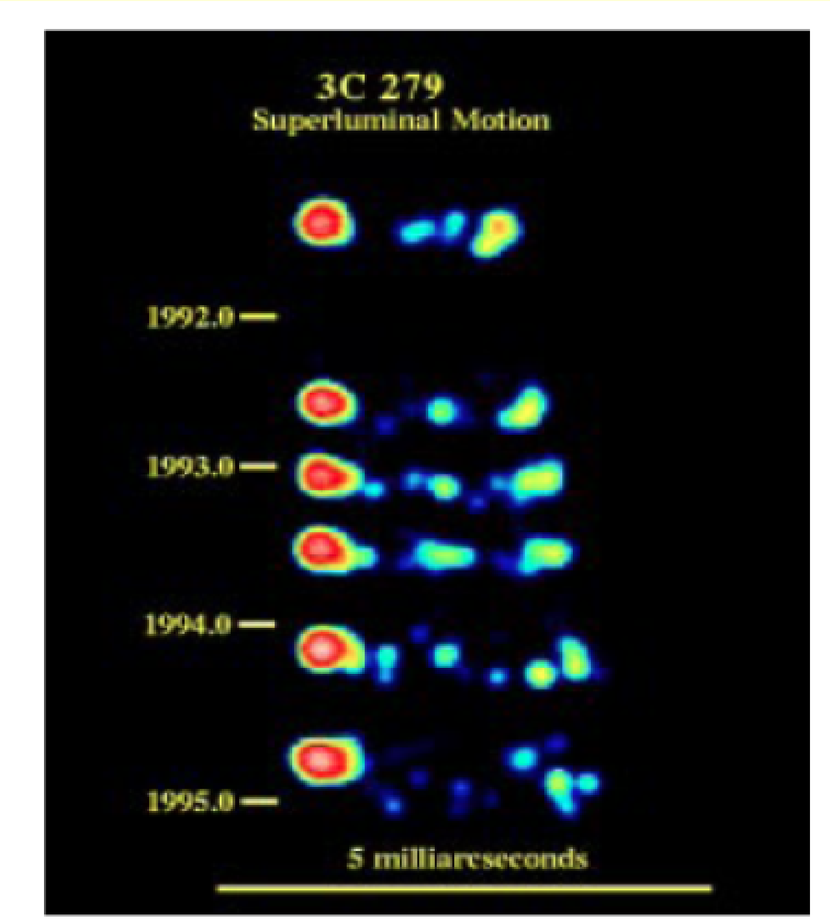
F_{-4} the γ-ray flux in units of 10^{-4} erg/cm^2/sec

- For C>1 the source is optically thick to pair creation via $\gamma - \gamma$ interaction;
- to create pairs from 2 photons of energy E_a, E_b colliding at an angle θ one needs $E_a E_b = 2(m_e c^2)^2/(1-\cos\theta)$; 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 $\gamma_{bulk}^2 > E_a E_b/4(m_e c^2)^2$ or $\gamma_{bulk} > 100(E_a/10\text{Gev})^{1/2}(E_b/\text{Mev})^{1/2}$
- 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 $\gamma > 100$

SUPERLUMINAL MOTION



Assume a spherical source moving with velocity υ 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 $\Gamma^{-1} < \theta \ll 1 \Rightarrow \beta_{\perp,app} \approx 2\theta^{-1} \gg 1$

$\beta_{\perp,app}^{max} = \dfrac{\beta}{\sqrt{1-\beta^2}}$ for $\cos\theta \simeq \beta$

β	$\beta_{\perp,app}$
.99	7
.999	22

–Location of long γRBs is in and near star forming regions in smallish galaxies- associated with star formation

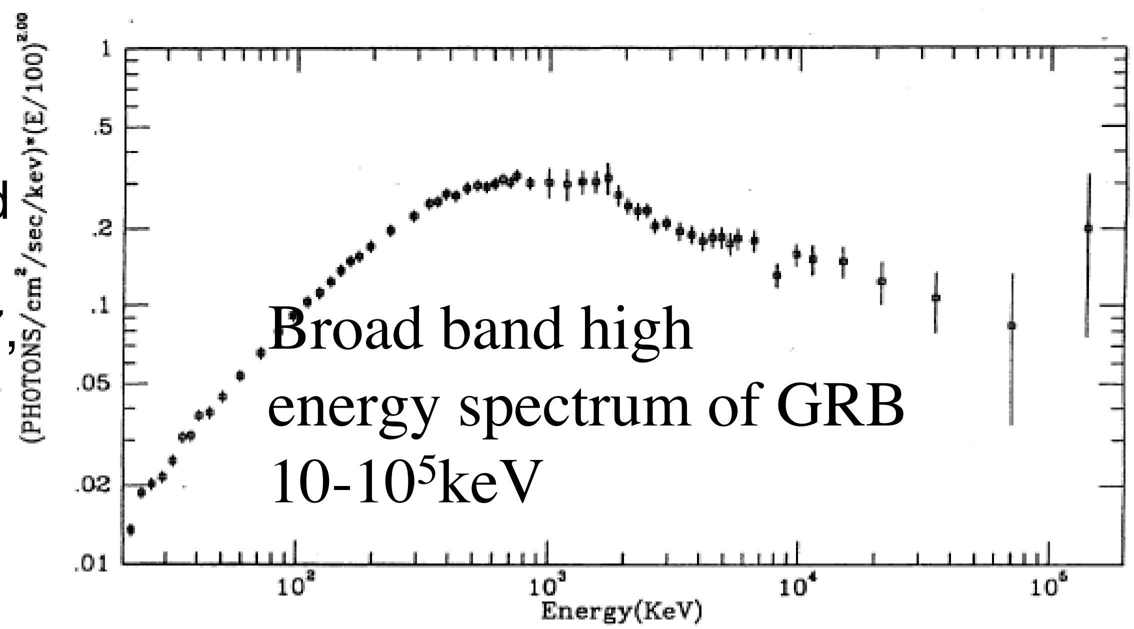
–A few γRBs have been associated with a type IIc supernova

→ Long GRBs
- Probes of distant universe
- New window on supernovae
- Black hole birth

→ Enigmatic short GRBs
- Host galaxy discoveries
- Stellar mergers & collisions
- Black hole birth

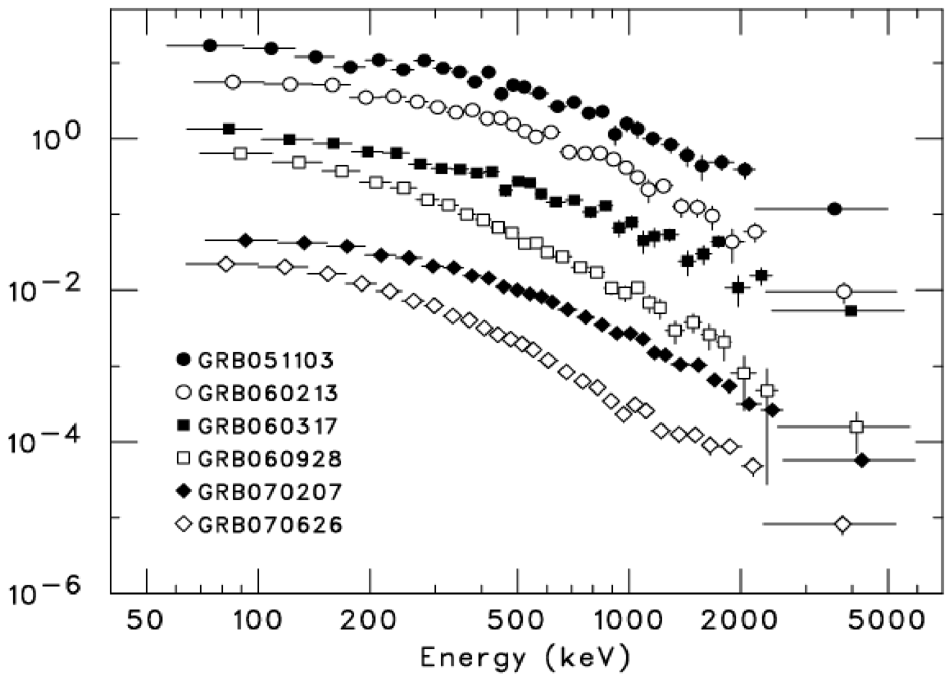
recent reviews

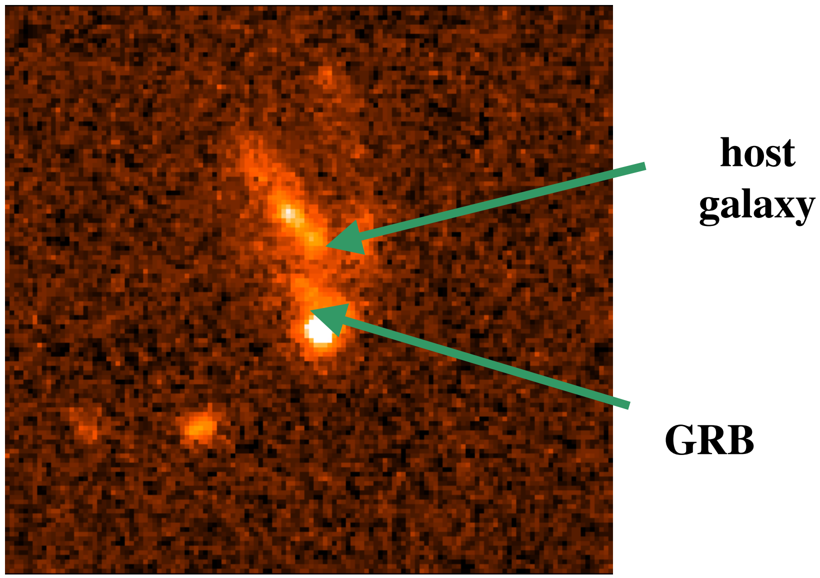
SN connection (Woosley and Bloom 2006), short GRBs (Lee and Ramirez-Ruiz 2007, Nakar 2007a), afterglows (van Paradijs et al. 2000, Zhang 2007) and theory (Meszaros 2002)



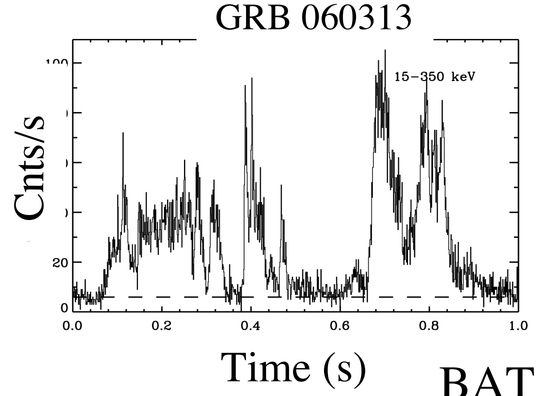
Broad band high energy spectrum of GRB $10\text{-}10^5$keV γ-ray **spectra** of a set of bursts, well fit by a 'Band' model (e.g. a broken power law flat at low E steep at high E)

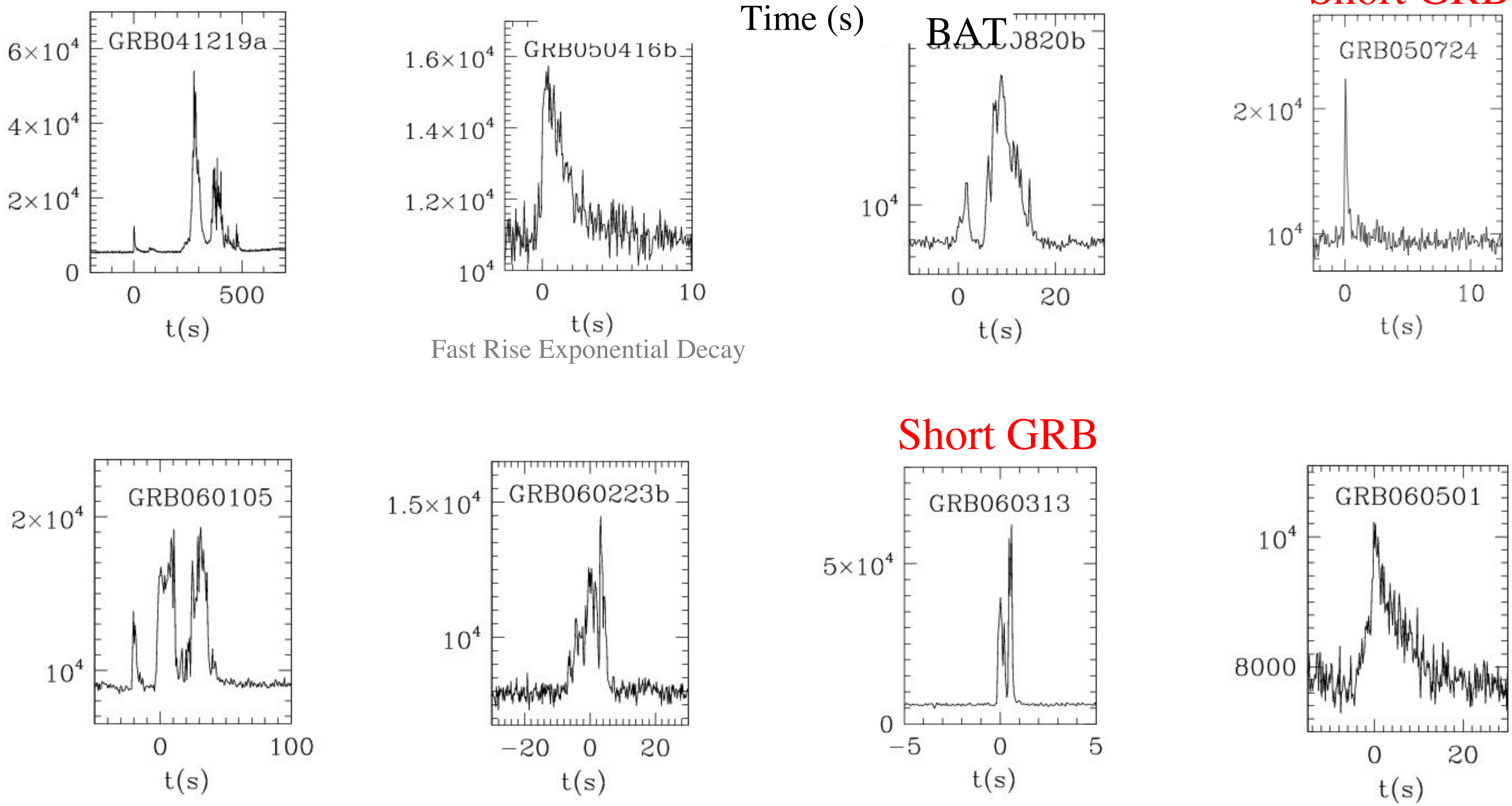
HST image of host galaxy and the GRB itself





Gallery of GRB Lightcurves





Short GRB

Short GRB

Gamma-Ray Bursts

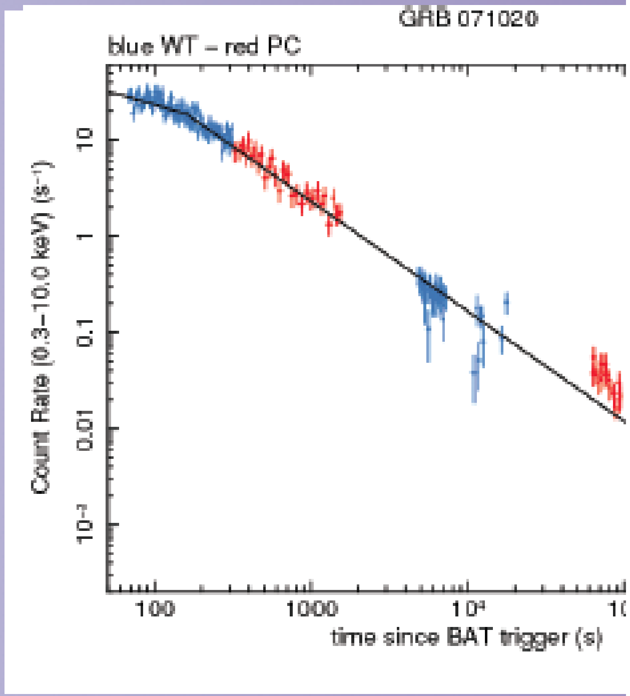
- thought that they are ‘beamed’- the energy is emitted in a ‘narrow’ cone, via particles moving close to the speed of light.

- 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

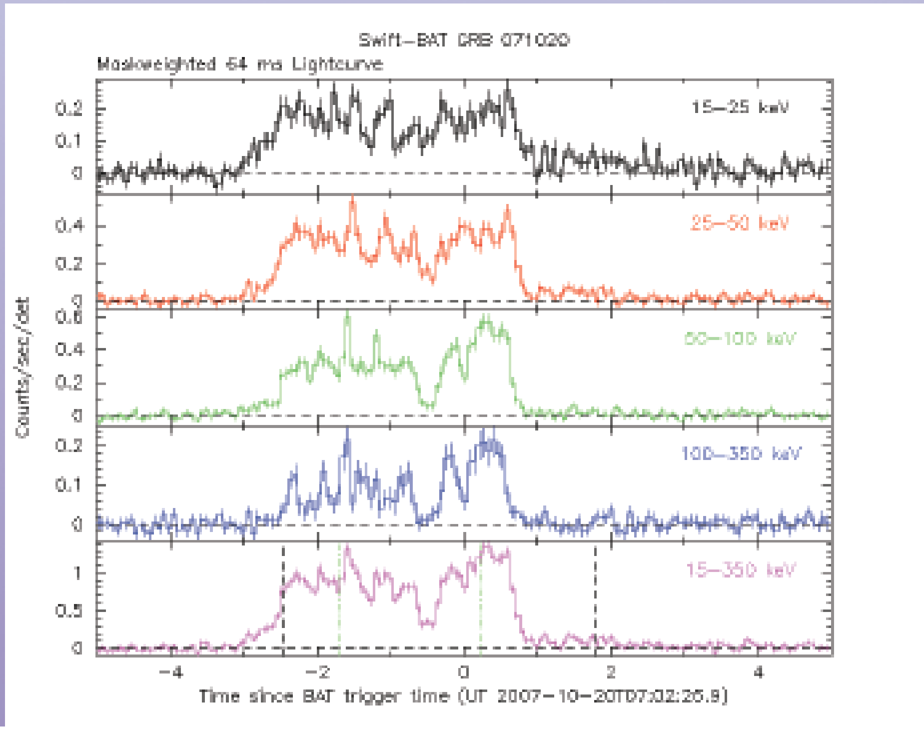
Swift GRB Data

GRB 071020

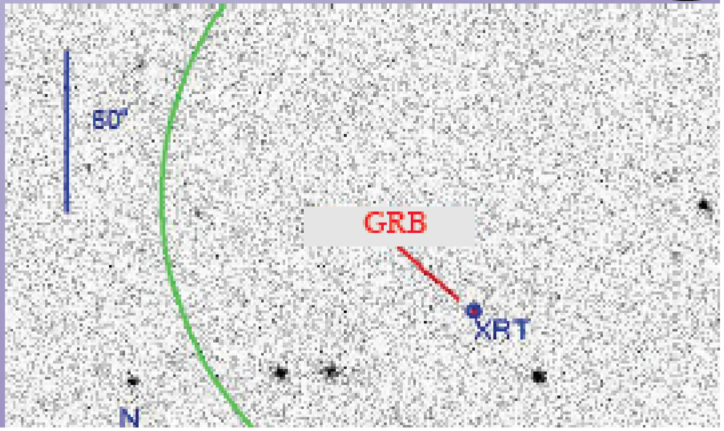
XRT lightcu



BAT lightcurve



UVOT imag

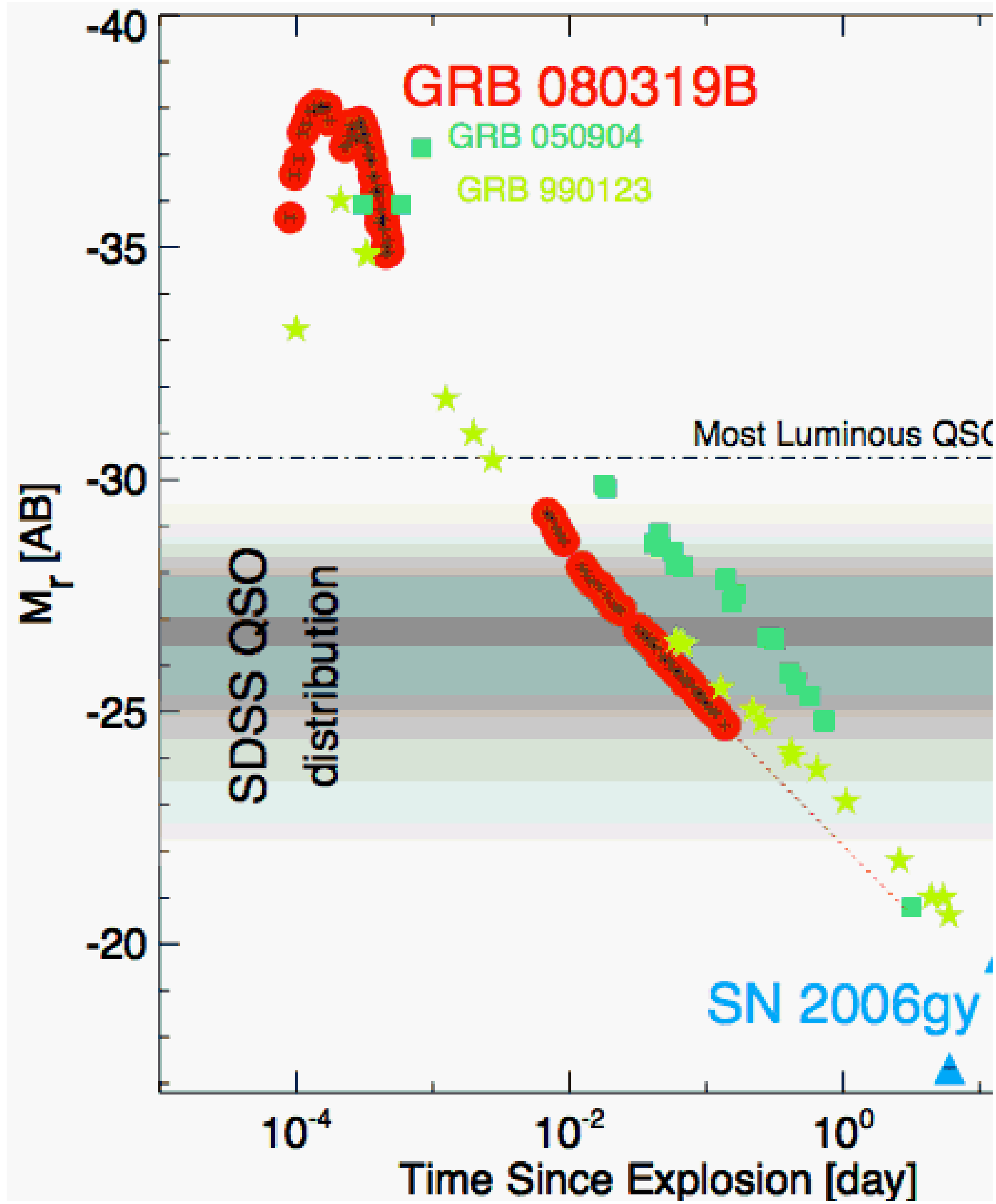


GRBS compared to Quasars

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.

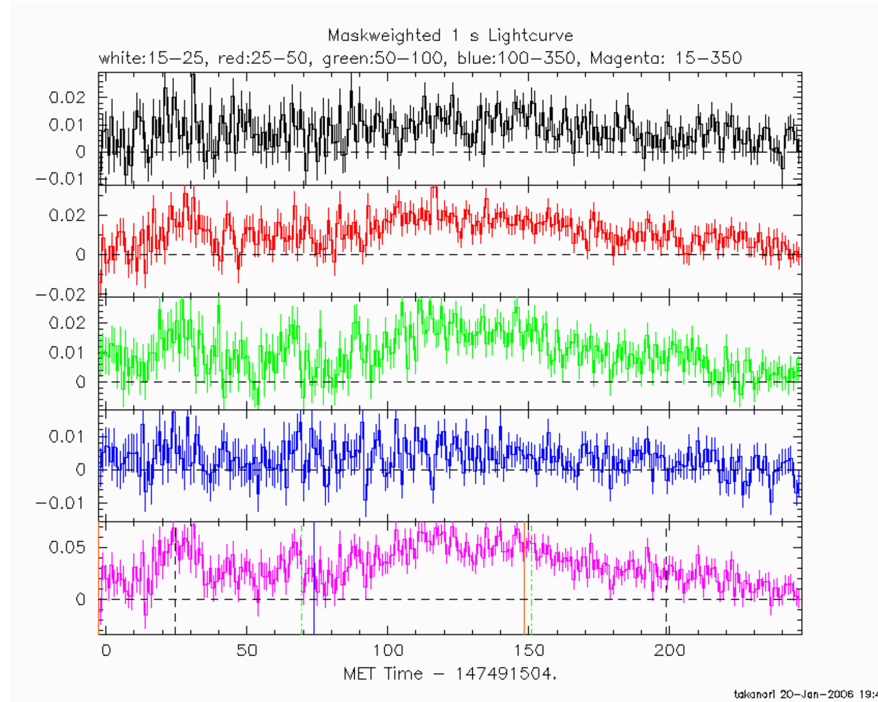
GRBs allow observations of objects further back in time than what is currently possible with QSOs- 'can be 'easily' detected at z>10

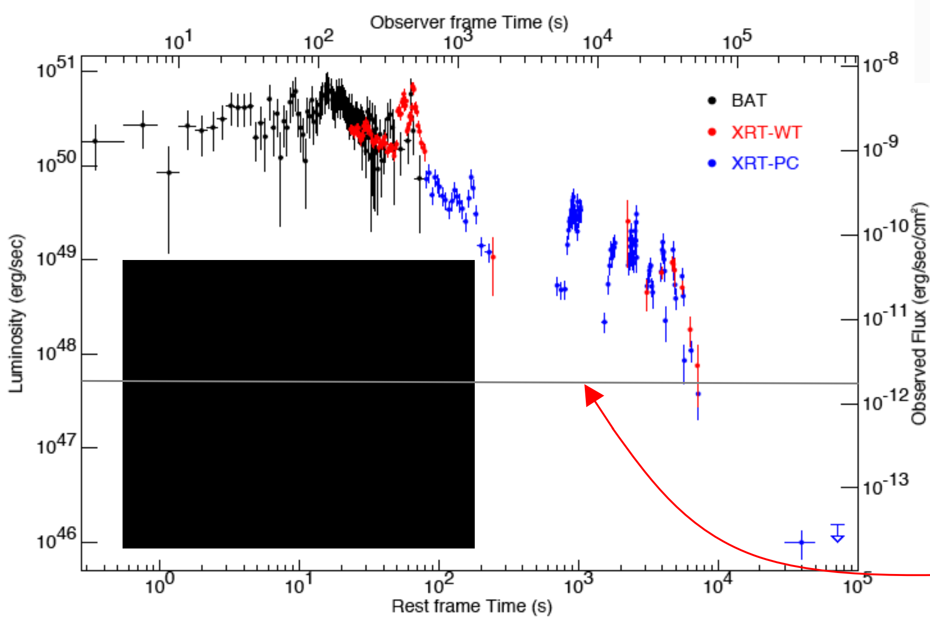
•In what type of galaxies did most of the star formation happened at z > 8, and what was the nature of the sources responsible for the re-ionization of the universe .



GRB 050904

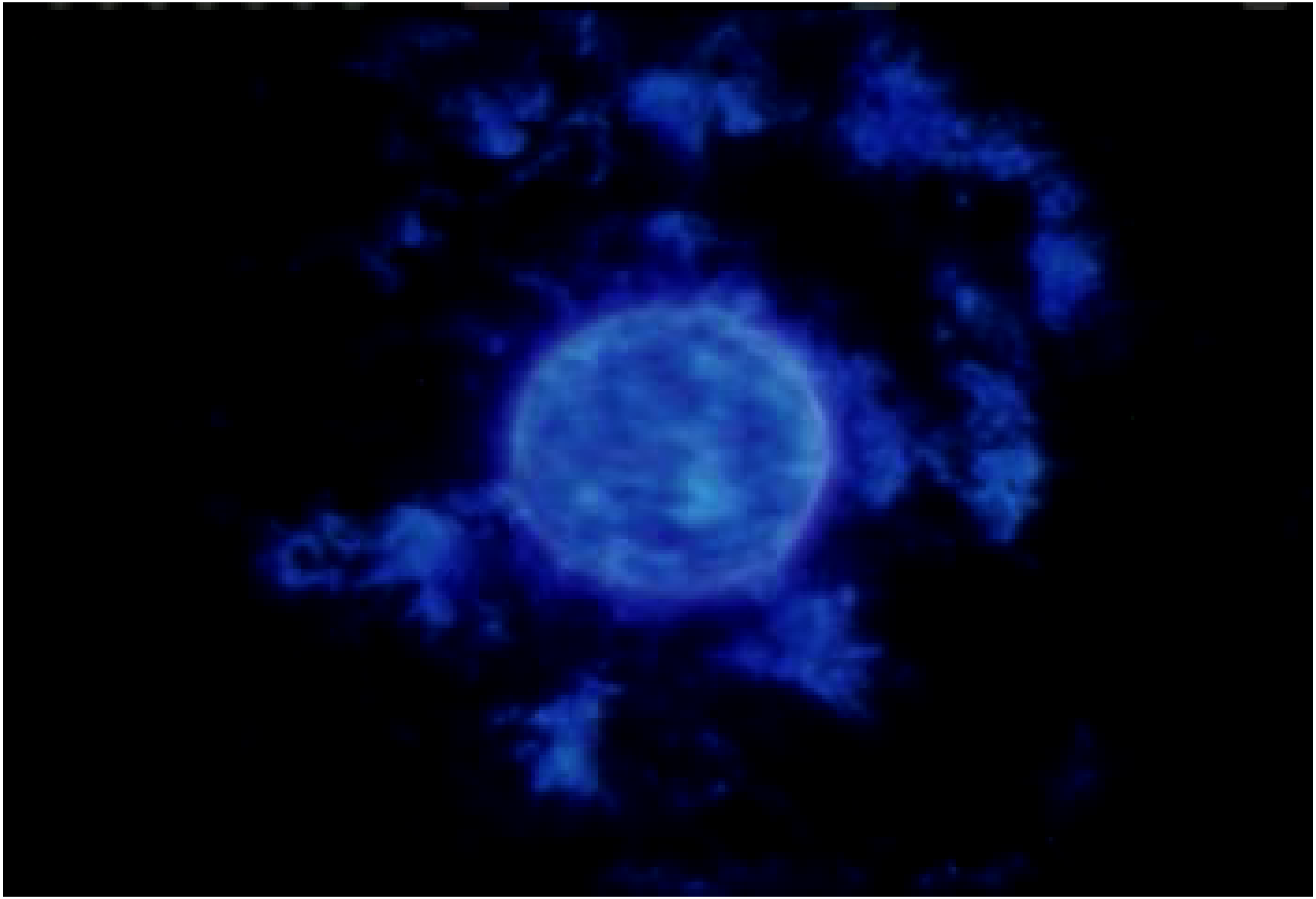
Redshift **z= 6.29 (12.8 Gyr)**
T_{90} = 225 sec
S (15-150 keV) = 5.4×10^{-6} erg cm^{-2}
$E_{iso} = 3.8 \times 10^{53}$ erg

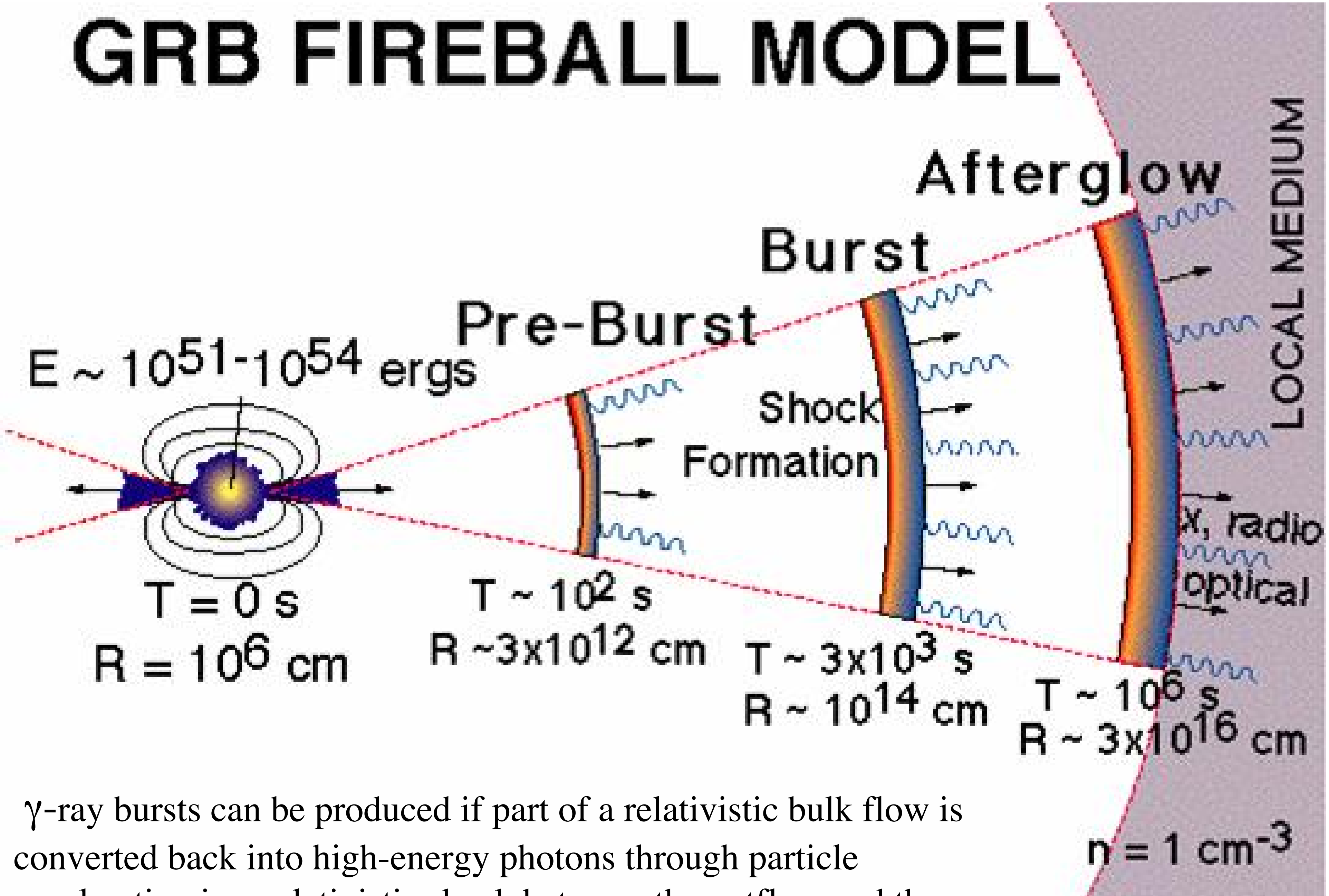




Very bright in IR
J= 17.5 @ **3 hours**
(SOAR)

Flux x100 of high-z
luminous X-ray AGN

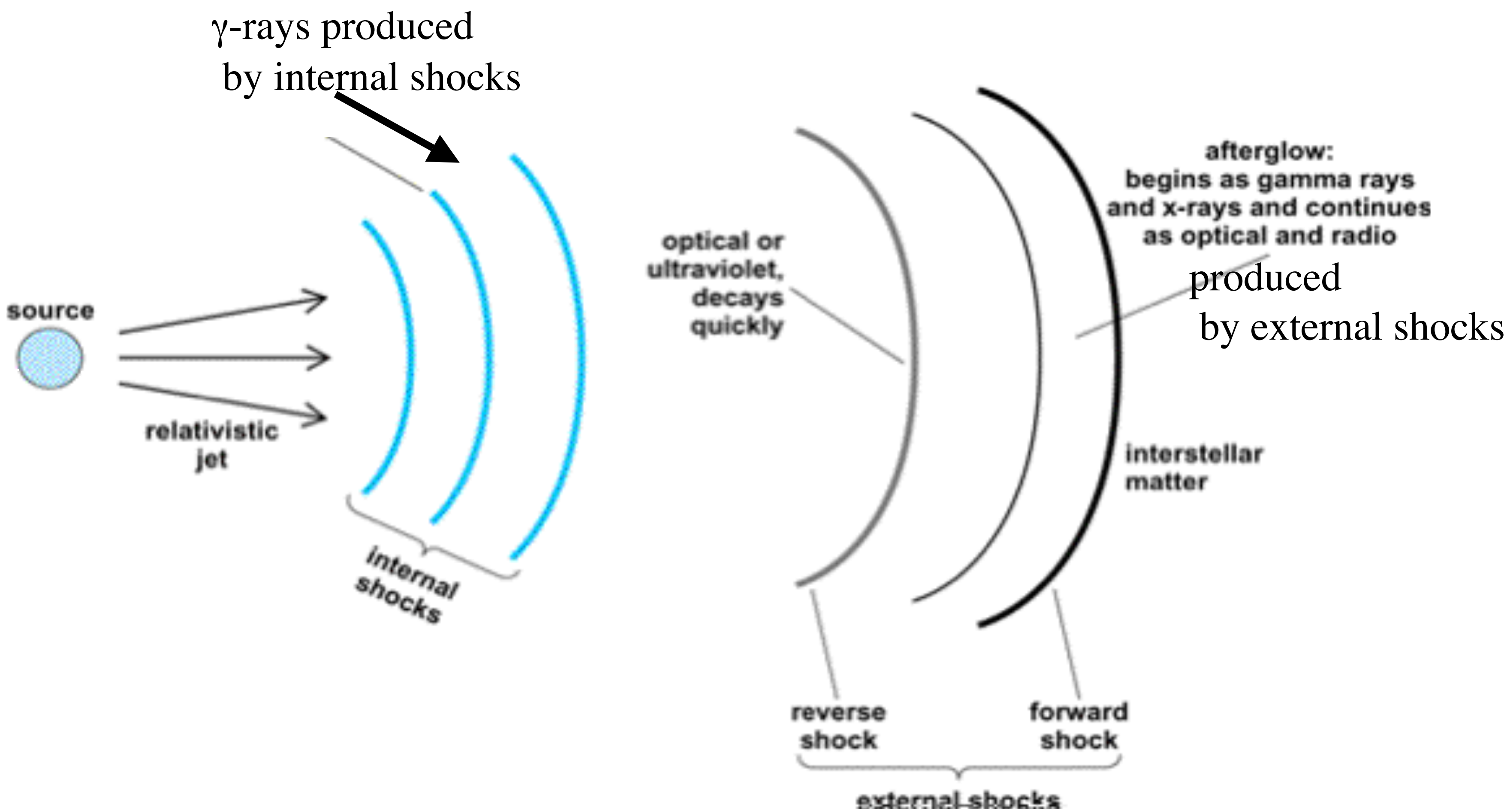




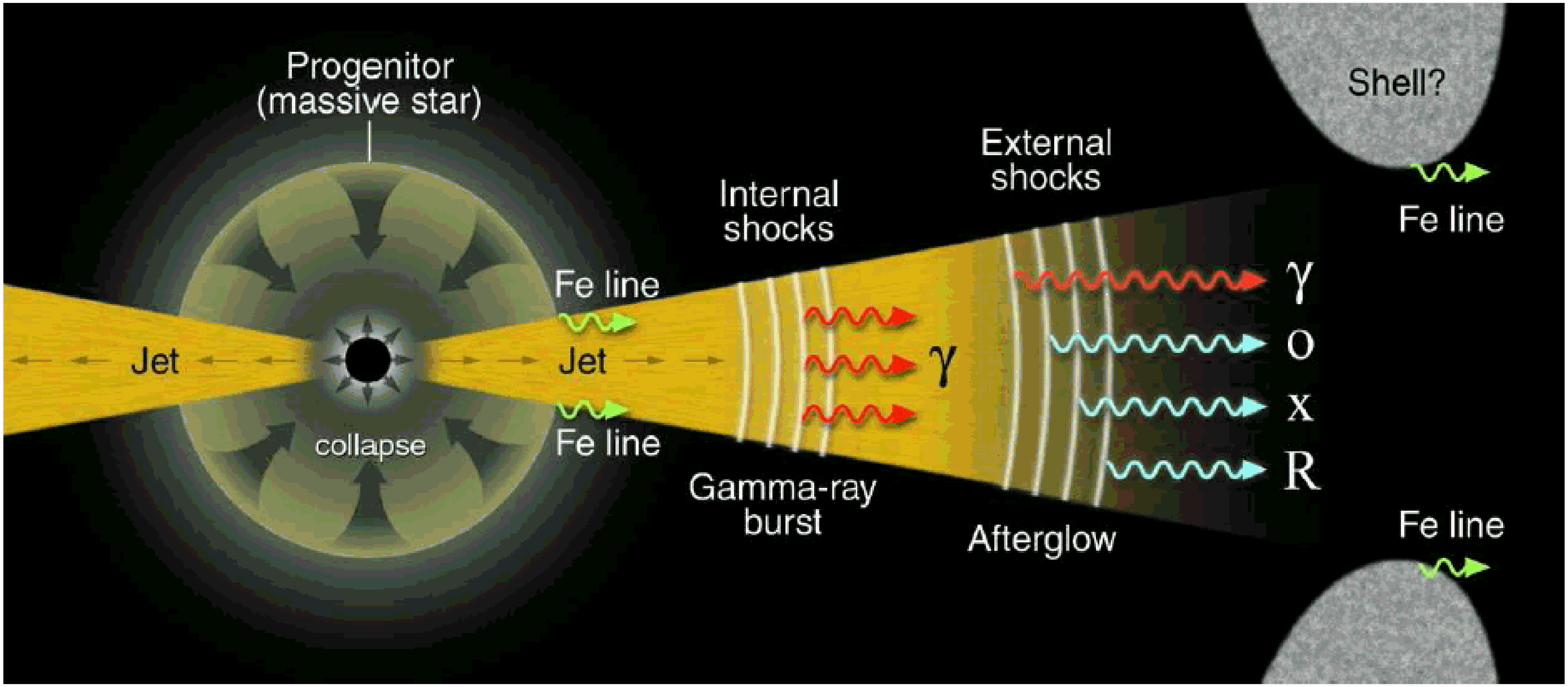
γ-ray bursts can be produced if part of a relativistic bulk flow is converted back into high-energy photons through particle acceleration in a relativistic shock between the outflow and the surrounding medium

General Schema of Fireball

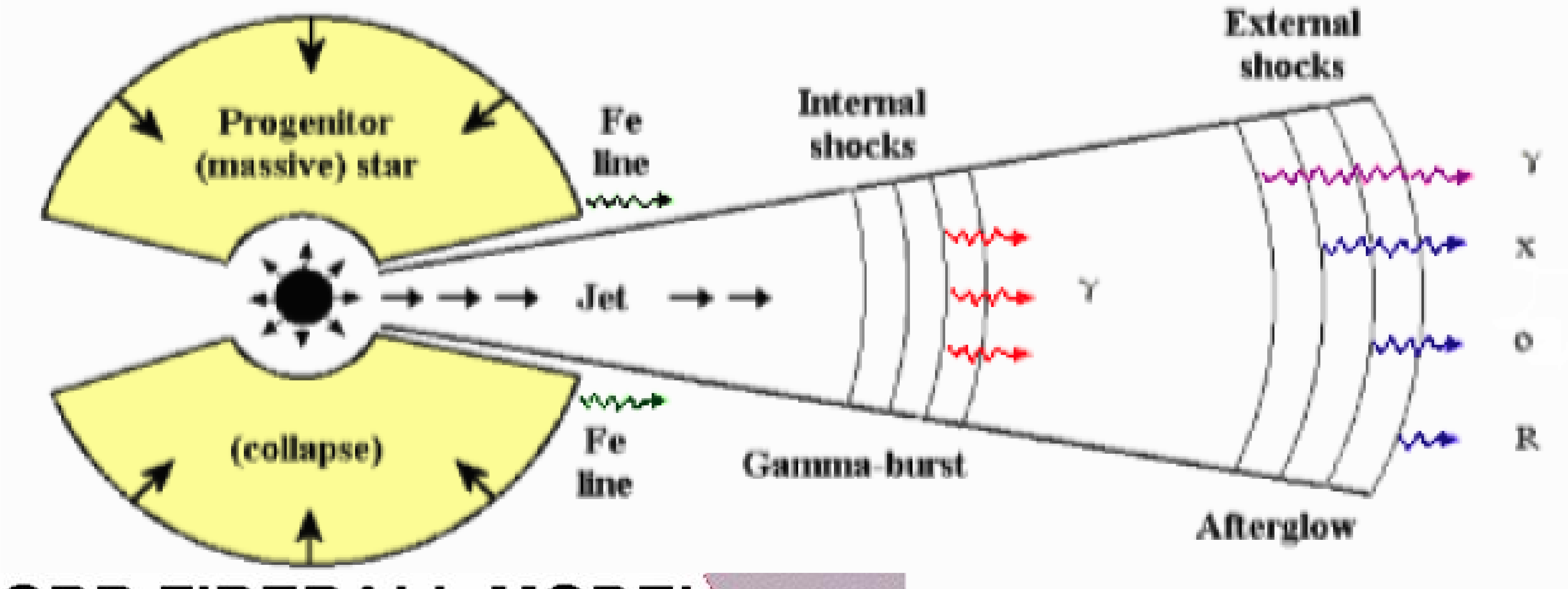
- Compact central engine drives a collimated ($\theta < 10^0$) ultra-relativistic, $\Gamma > 10$, outflow with a high ratio of energy to rest mass. Expands at ultra-relativistic velocities

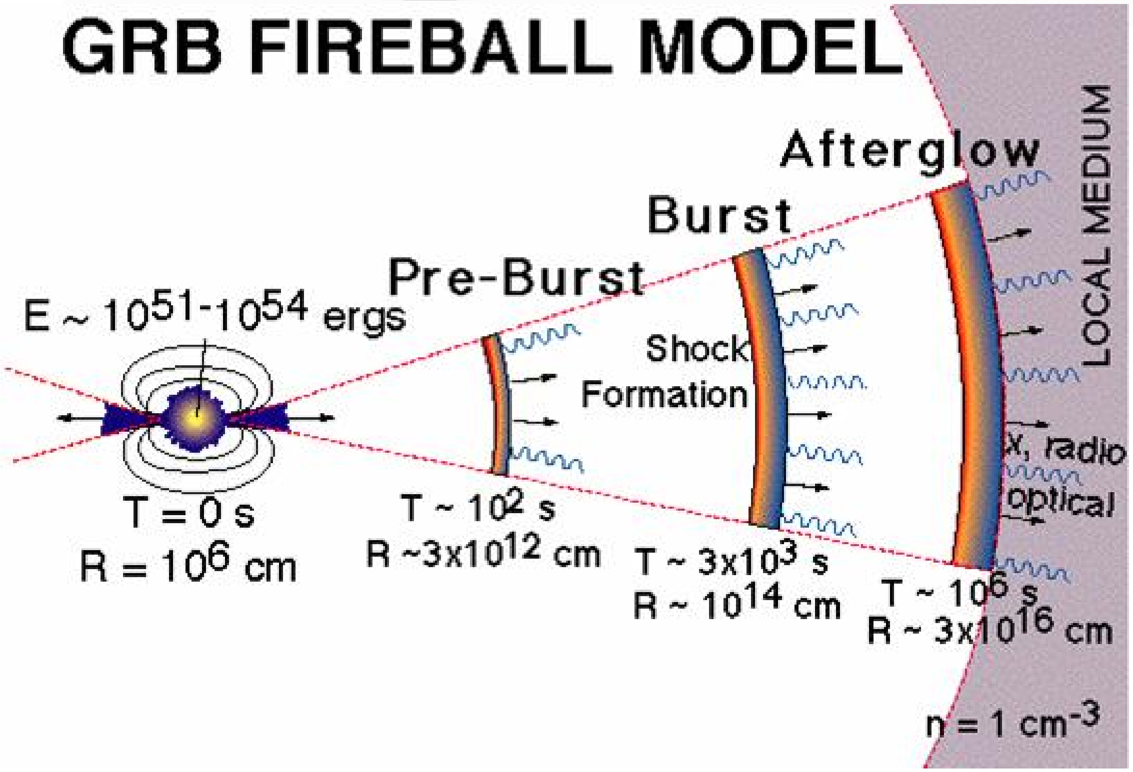


see R+B sec 7.4.2-7.4.5



- 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&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.

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.