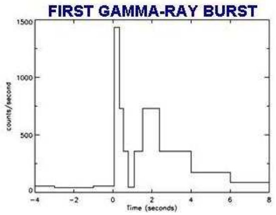
Gamma-Ray Bursts

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!

1990s: CGRO era

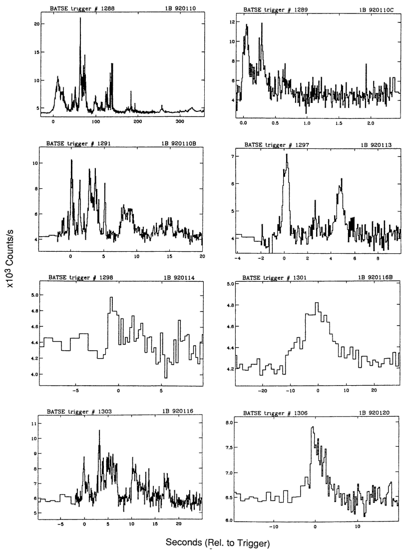
Due to short duration of bursts, no detailed studies were available for a long time.

This changed with the Burst and Transient Science Experiment (BATSE) on the Compton Gamma-Ray Observatory (*CGRO*; launch 1991): All Sky Monitor, first systematic study of Gamma-Ray Bursts.

Gamma-Ray Bursts are very common: BATSE saw 1 GRB day^{-1}, taking into account BATSE covering factor: 600 GRB day^{-1}

Movie time: `movies/grb_animation.gif`

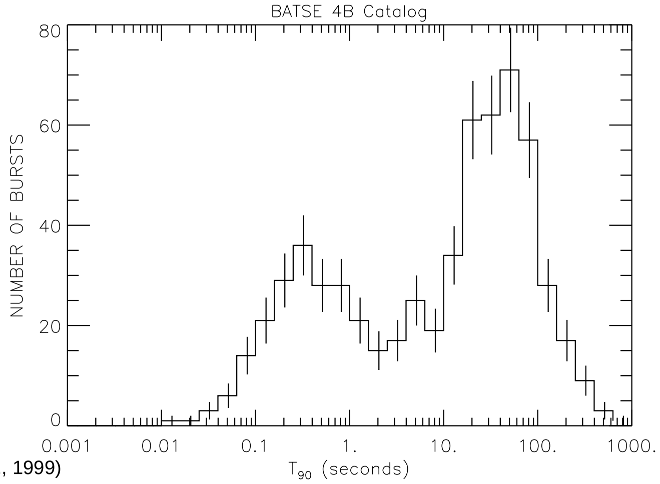
1990s: CGRO era



There is a wide variety of burst lightcurves, both in duration and morphology.

(Fishman & Meegan, 1995, Fig. 1)

1990s: CGRO era

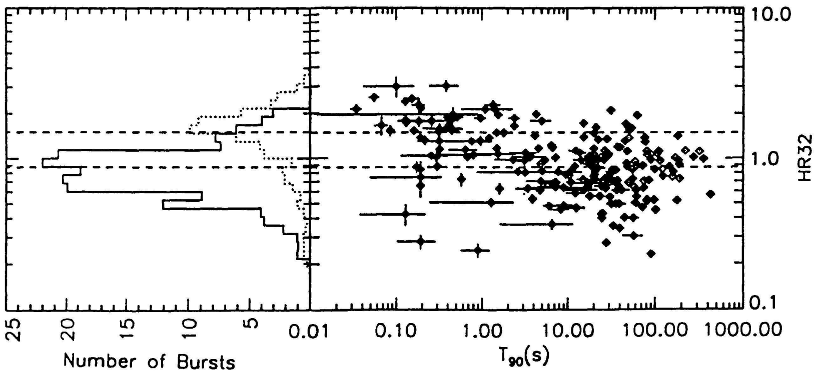


(Paciesas et al., 1999)

Kouveliotou et al. (1993): There are two classes of Gamma-Ray Bursts:

long bursts ($t_\gamma > 2$ s) and short bursts ($t_\gamma < 2$ s).

1990s: CGRO era

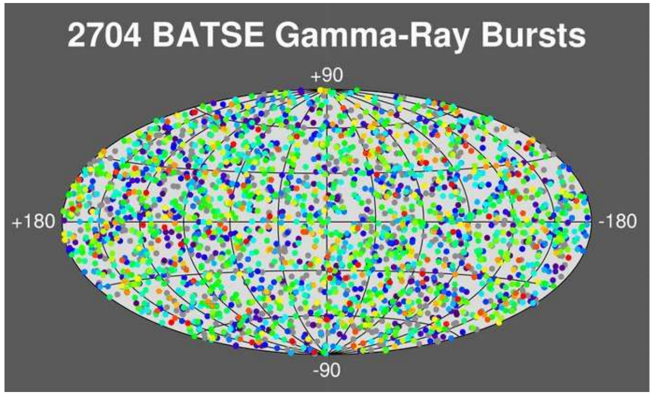


(Kouveliotou et al., 1993, Fig. 4)

There is a correlation between spectral shape and duration of the burst:

Shorter bursts tend to have harder X-ray/gamma-ray spectra.

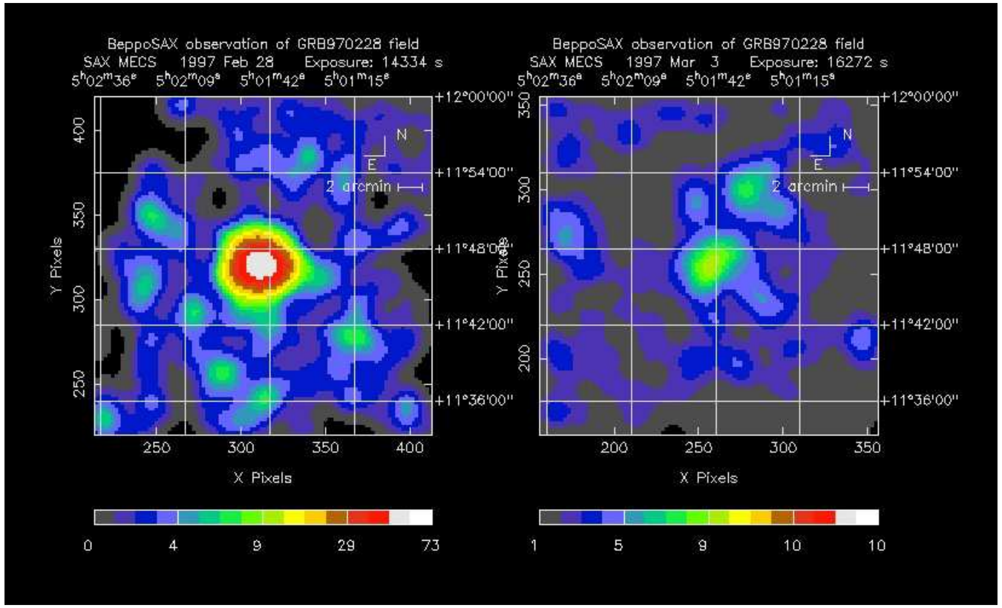
1990s: CGRO era



9 years of *CGRO*-BATSE GRBs

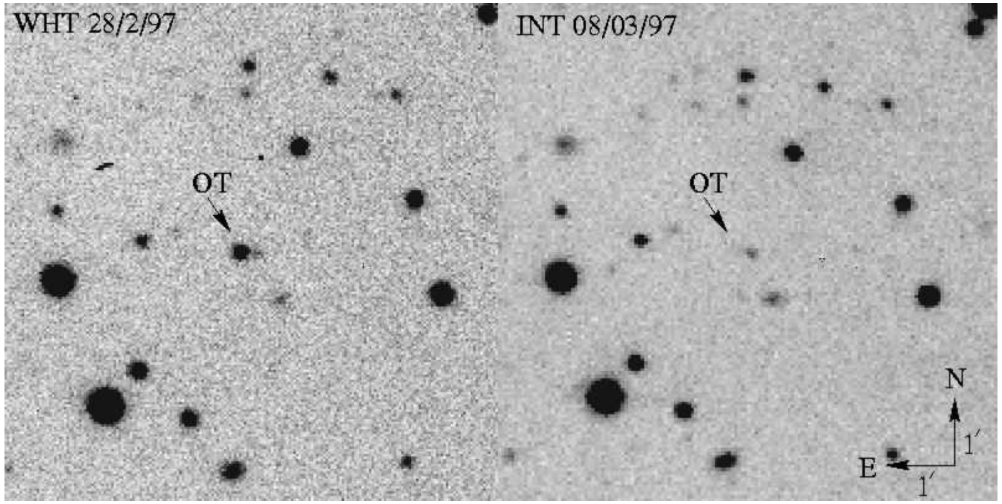
Bursts are distributed isotropically on sky:

they are either very close (solar system) or at cosmological distances).



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

$\Longrightarrow$ Allows precise localization of burst

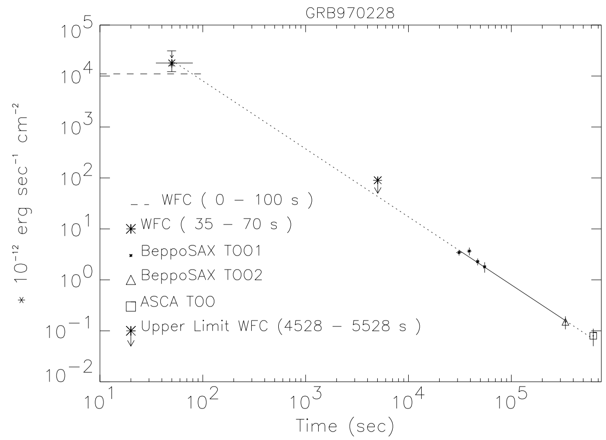


Groot et al. (IAUC 6584): Optical transient of GRB 970228, fades quickly

Seen by many others as well...

Bloom et al. (2001): Host galaxy is subluminous, but fairly normal; has $z = 0.695$
$\Longrightarrow$ GRB had $L_{20-2000\,\text{keV}} \sim 1.4 \pm 0.3 \times 10^{52}$ erg fluence (assuming isotropy).

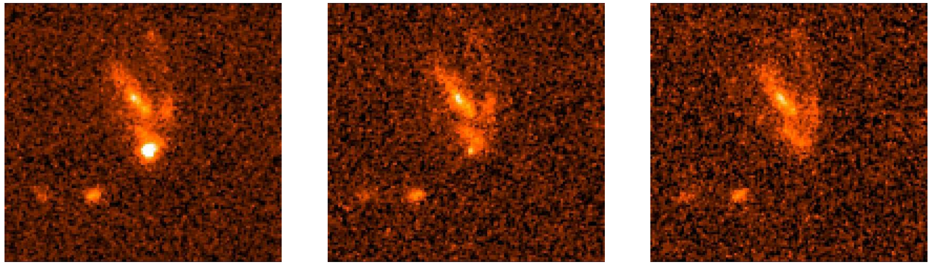
BeppoSAX: GRB Afterglows



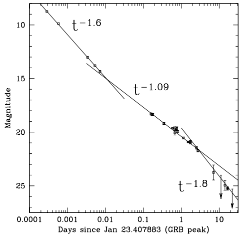
(Costa et al., 1997, Fig. 3)

Flux evolution of afterglow is a power-law: $F \propto t^{-\alpha}$, where $\alpha = 1.33^{+0.13}_{-0.11}$

GRB 990123

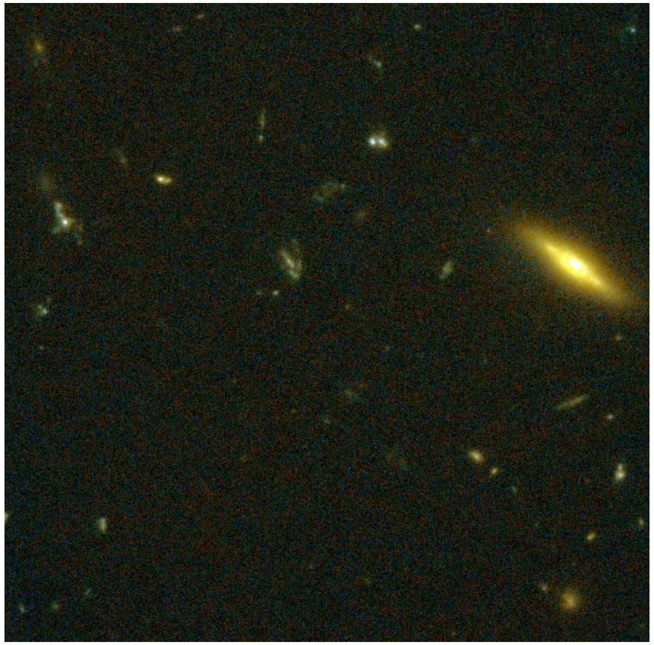


Feb 1999 Mar 1999 Feb 2000



Fading of the optical transient of GRB 990123.
Lightcurve is also a power law.

Fruchter et al. (1999) and
`http://www.stsci.edu/~fruchter/GRB/990123/index.html`



26.3″ × 26.3″ HST image of field of GRB 990123 (A. Fruchter; priv. comm.)

Host galaxy is peculiar, bluish

GRB 990123

Bright and prompt optical flashes and radio flares are associated with some GRBs

First seen for GRB 990123

X-ray afterglows (seen in long bursts) allow localization of GRB

BeppoSaX/ground based: Galaxies hosting GRB 970508 and GRB 971214 have large redshifts

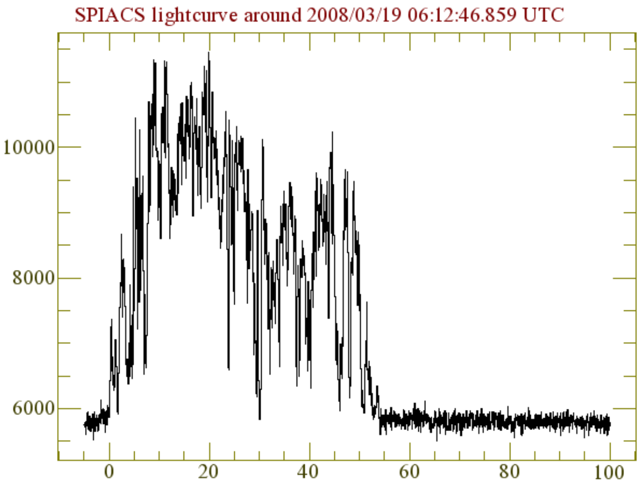
Gamma-Ray Bursts are at cosmological distances.

Redshifts known for >50 GRBs to date, typical $z \sim 1$, but there are extremes, e.g., GRB 050904 with $z = 6.29$ (end of cosmological dark ages!).

$\Longrightarrow$ Gives fluences $\sim 10^{53\ldots 54}(\Omega_\gamma/4\pi)$ erg, varying by about 1 order of magnitude.

Ω_γ is correction factor for beaming.

GRB 080319



INTEGRAL/V. Beckmann

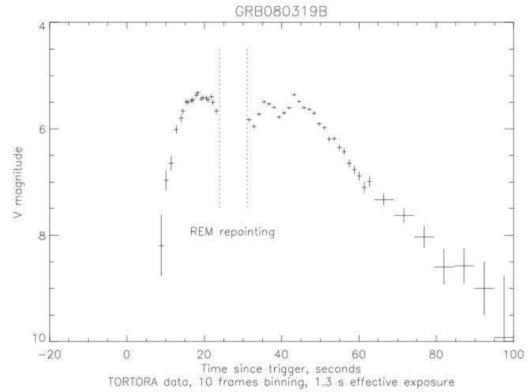
GRB 080319B (one of four GRBs seen on that date!)

GRB 080319

REM and TORTORA

ESO Press Photo 08a/08 (2 April 2008)

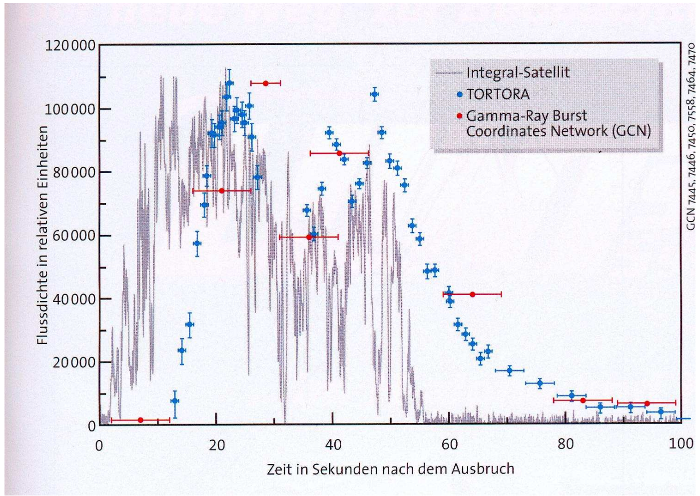
Tortora Video camera on REM: one image every 0.13 s



Karpov et al. (2008; GCN 7558)

GRB080319B: 1st GRB confirmed to be visible to the naked eye!

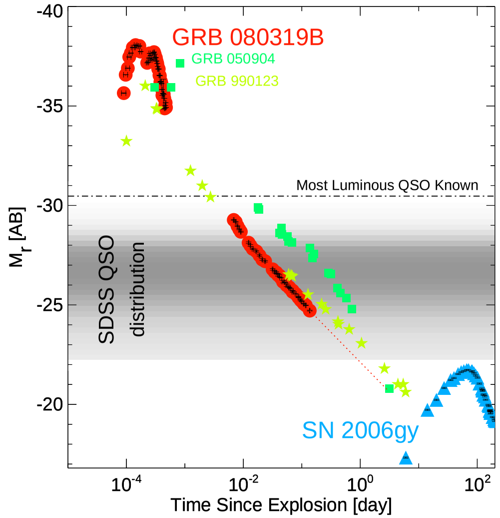
GRB 080319



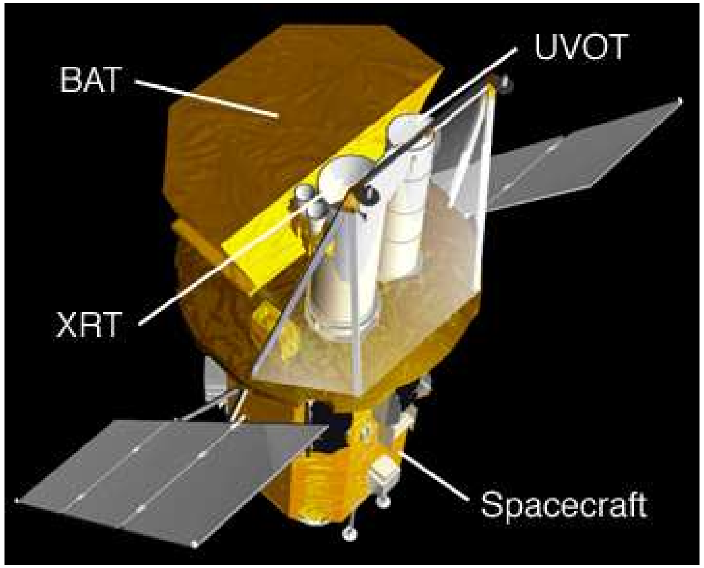
Long duration GRB, optical afterglow 6 s after the GRB (SuW 5/2008)

Movie time: grb080319b.avi (`http://vo.astronet.ru/~karpov/`)

GRB 080319



GRB080319B = the biggest bang since the Big Bang

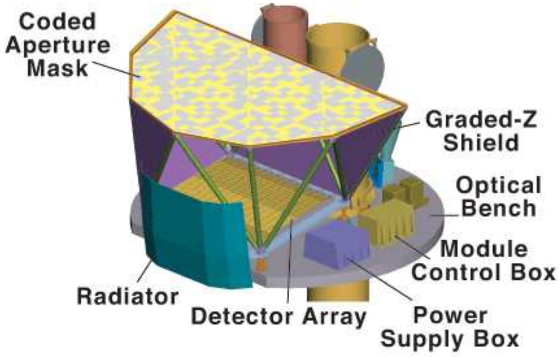


(Gehrels et al., 2004, Fig. 2)

Swift: Launch November 2004, allows broad band monitoring of GRBs

Since *CGRO* and *Beppo-SAX* only some progress through observations with *HETE*-2 and Gamma-ray detectors on interplanetary probes.

Swift-BAT



(Gehrels et al., 2004, Fig. 4)

Swift-Burst Alert Telescope (BAT):

Coded-mask:

- ~54000 pixels (Pb, 5 × 5 × 1 mm),
- 1 m away from detector,
- 1.4 sr field of view

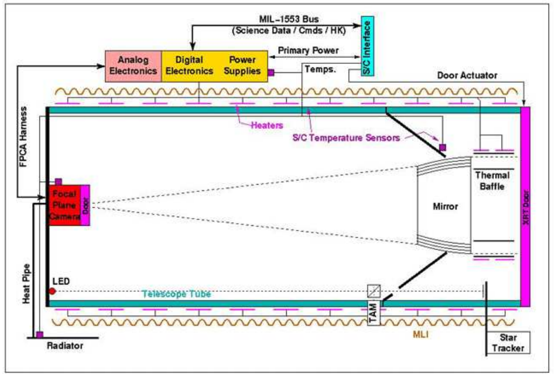
Detector:

- 1.2 × 0.6 m detector area,
- 32768 pixel of 4 × 4 × 2 mm CdZnTe (CZT);
- imaging in 15–150 keV, sensitivity up to 500 keV.

After burst: Autonomous calculation of rough position within ~10 s

$\Longrightarrow$ slew to burst and alert community of burst via TDRSS

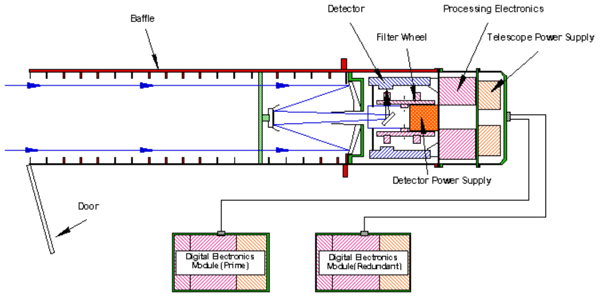
Swift-XRT



(Gehrels et al., 2004, Fig. 6)

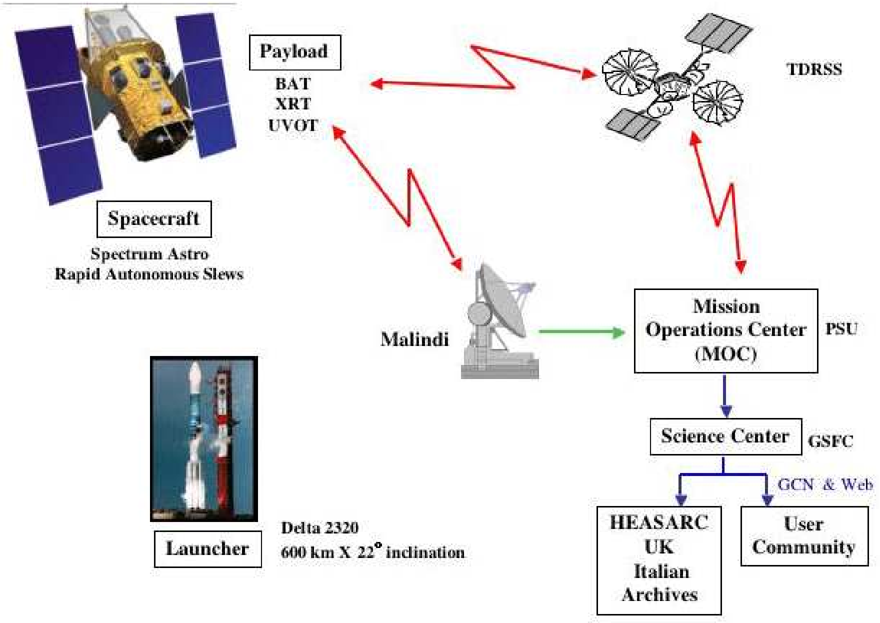
Swift X-Ray Telescope (XRT): focusing X-ray telescope (Wolter I), 110 cm^2 effective area, 23′ field of view, 18″ resolution (half-power diameter), 600 × 600 pixel Si-CCD detector (similar to *XMM-Newton* EPIC-MOS, sensitive in 0.2–10 keV.

Swift-UVOT



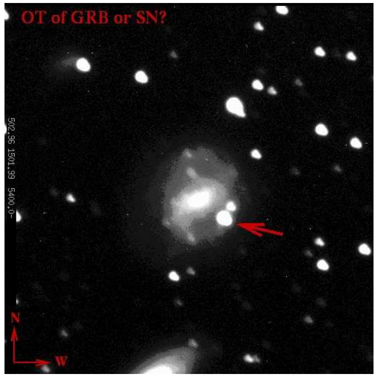
(Gehrels et al., 2004, Fig. 8)

Swift UV- and Optical Telescope (UVOT): based on *XMM-Newton* optical monitor; coaligned with XRT. Optical layout: 30 cm clear aperture Ritchey-Chrétien telescope, f-ratio of $f/2.0$, increased to $f/12.72$ after secondary, coaligned with XRT, 11 position filter wheel (grisms, broadband UV/visible photometry), detector: microchannel plate intensified CCD (MIC).

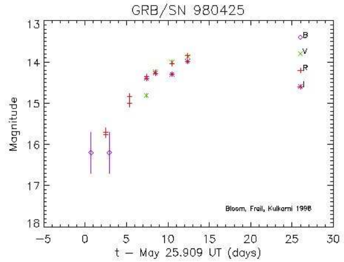


(Gehrels et al., 2004, Fig. 9)

GRB–SN association



UvA



Bloom et al. (IAUC 6899)

- 26 April 1998: IAUC 6884: GRB 980425 detected with *BeppoSAX*-WFC
- 29 April 1998: Galama et al. (GCN Report 60): GRB 980425 located off center on arms of in barred spiral ESO 184-82

- Several GCNs: nothing seen in optical
- 7 May 1998: Galama et al. (IAUC 6895): Point source at GRB position, brightens

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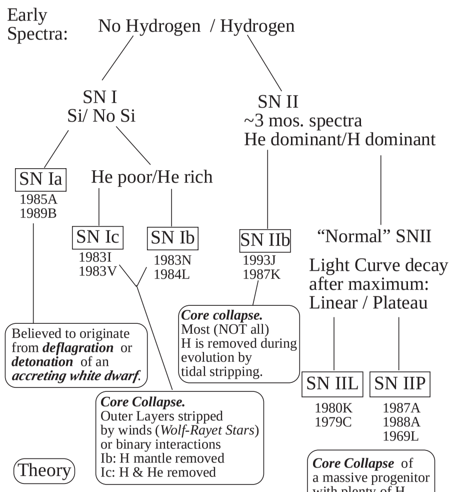
GRB–SN association



Early Spectra: No Hydrogen / Hydrogen

SN I
Si/ No Si

SN II
~3 mos. spectra
He dominant/H dominant

SN Ia
1985A
1989B

He poor/He rich

SN Ic
1983I
1983V

SN Ib
1983N
1984L

SN IIb
1993J
1987K

“Normal” SNII
Light Curve decay after maximum:
Linear / Plateau

SN IIL
1980K
1979C

SN IIP
1987A
1988A
1969L

Believed to originate from ***deflagration*** or ***detonation*** of an ***accreting white dwarf.***

Core collapse.
Most (NOT all) H is removed during evolution by tidal stripping.

Core Collapse.
Outer Layers stripped by winds (*Wolf-Rayet Stars*) or binary interactions
Ib: H mantle removed
Ic: H & He removed

Core Collapse of a massive progenitor with plenty of H .

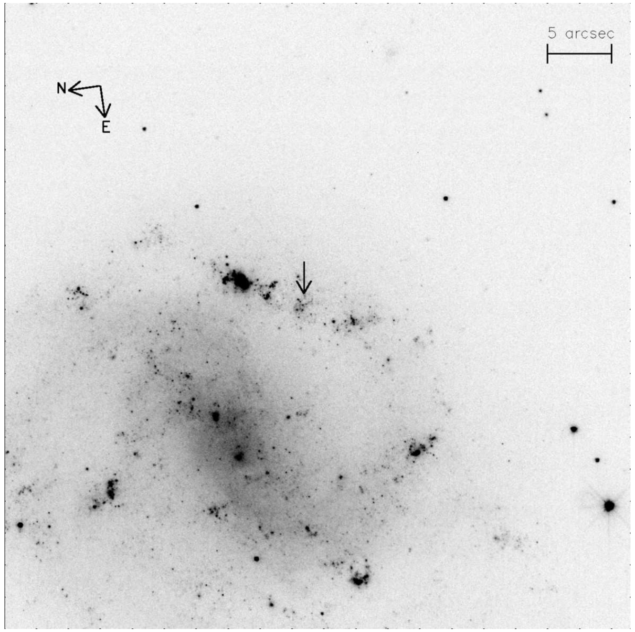
Theory

courtesy M.J. Montes

- 7 May 1998: Lidman et al. (IAUC 6895): Spectroscopy: point source at location of GRB 980425 is possibly a supernova, designated *SN 1998bw*:
  - no H-lines
    $\Longrightarrow$ not a type-II supernova
  - no Si lines
    $\Longrightarrow$ not regular Ia Supernova.

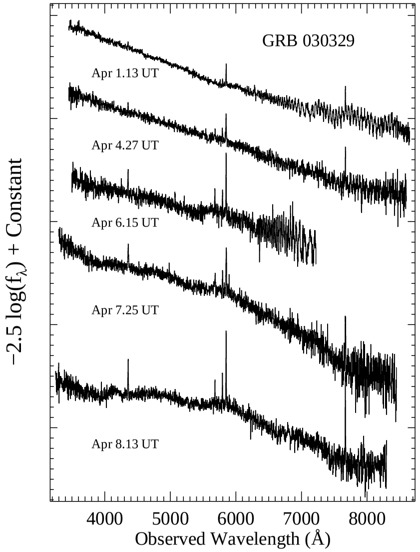
  $\Longrightarrow$ peculiar SN Ic

  “The nature of this puzzling object still evades identification, as does its relation to GRB 980425 or to the galaxy.”.



Fynbo et al. (2000): ESO 184-G82 is a star-forming SBc galaxy
GRB was located in star forming region

GRB–SN association



After 980425: brightening (“humps”) in GRB afterglows as if due to SN seen in eight more GRBs

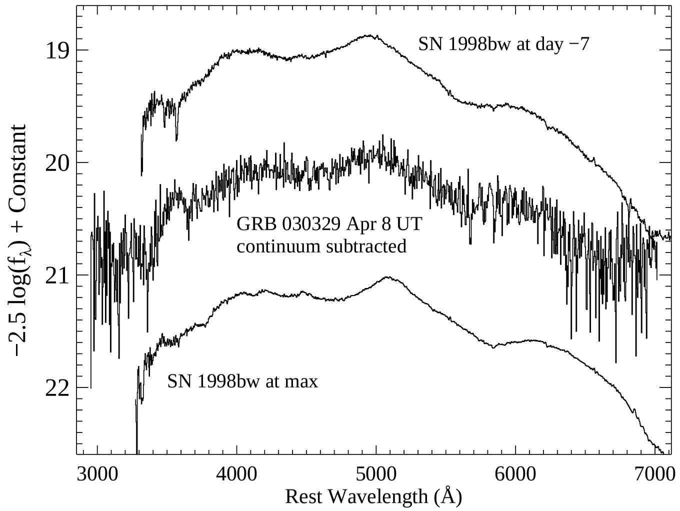
First unambiguous supernova signature in nearby ($z = 0.168$) GRB 030329: SN 2003dh

Since then several more, such as GRB060218/SN2006aj

Generally found: long bursts occur in regions of large star formation rate.

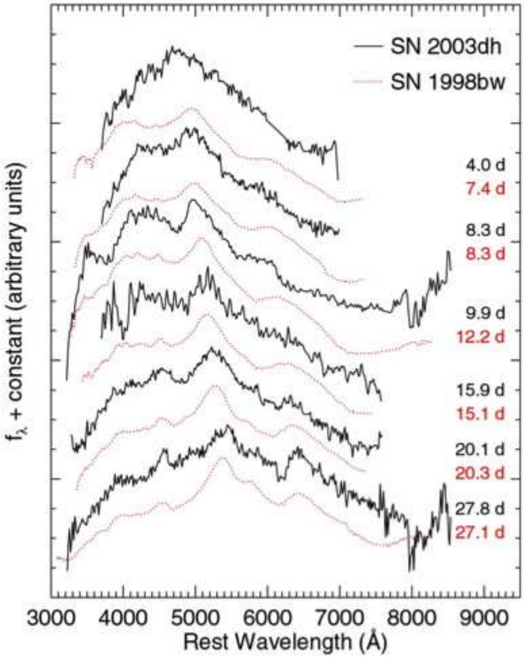
(Stanek et al., 2003, Fig. 1)

GRB–SN association



SN 2003dh and SN 1998bw have similar spectra
$\Longrightarrow$ similar type of supernova!

Stanek et al. (2003, Fig. 2)



Spectral evolution of SN1998bw and SN2003dh is also very similar!

(Woosley & Bloom, 2006, Fig. 5)

Hypernovae: Models

Colgate (1968): First prediction of prompt gamma-rays and X-rays from supernovae.

Due to breakout of relativistic shock from SNe surface.

Before discovery of GRBs was announced!

Observations: (Most?) Long GRBs coincide with core-collapse supernovae

(and are located in star forming regions)

Because these explosions are very luminous: hypernova explosions. Energetics:

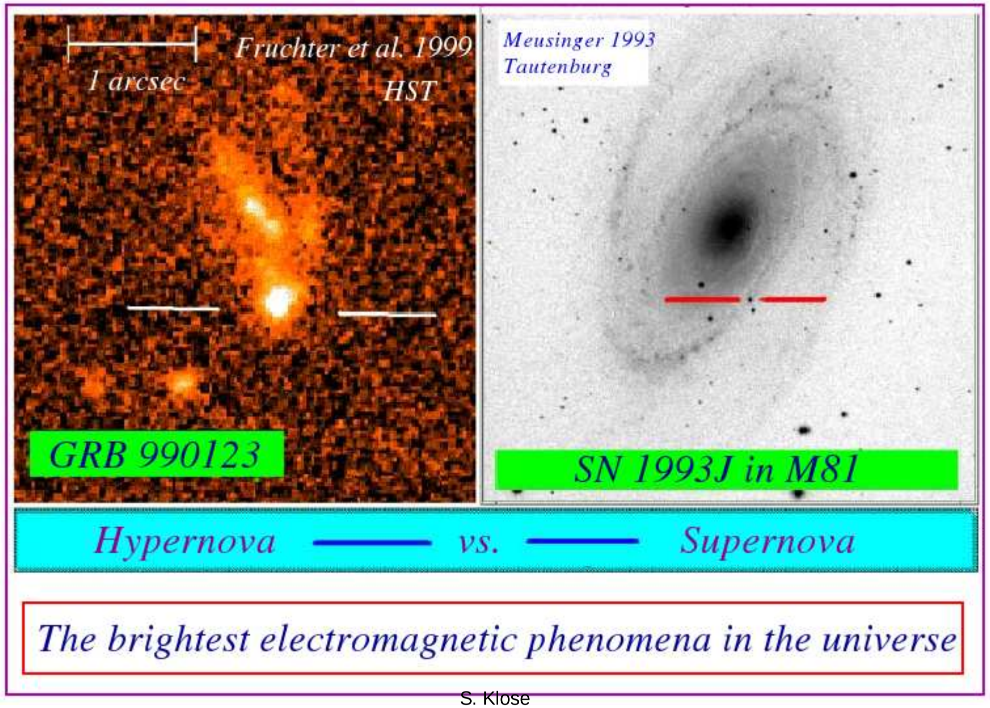
- GRBs: after correction for beaming 10^{51} erg; *brightest* exlosions in the universe
- Core collapse SNe also produce kinetic energy of 10^{51} erg

  Light per solid angle for SNe is 10^{10} fainter than for GRB

Note: Sun: $M_\odot c^2 = 2 \times 10^{54}$ erg

Very good review: Woosley & Bloom (2006)

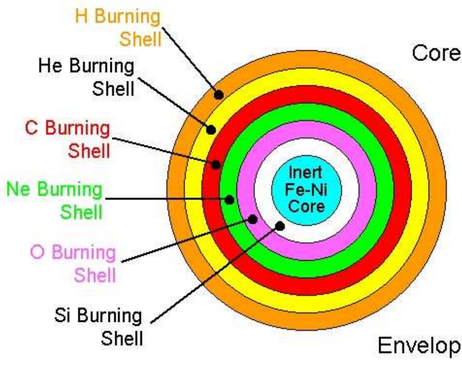
Note that for short GRBs this model does not work. See later. . .



The brightest electromagnetic phenomena in the universe

S. Klose

Hypernovae: Models



Core Radius: ~1 $R_{\rm earth}$

Envelope Radius: ~ 5 AU

Successive stages of nuclear burning in a massive star:

1. H burning, ash: He
2. He burning, ashes: C, O, Ne, Mg
3. C burning, ashes: Ne, Na, Mg
4. Ne burning, ashes: O, Mg . . .
5. O burning, ashes: Si, P, S, . . .
6. Si burning, ashes: Fe, Ni

Final state: “onion-shell”

Hypernovae: Models

Standard core-collapse supernova model:

$t = 0$ **s:** Collapse of Fe core of star with main sequence mass $>10\,M_\odot$, triggered by electron capture and photodisintegration of Fe ($T \sim 10^{10}$ K, $\rho \sim 10^{10}$ g cm^{-3}).

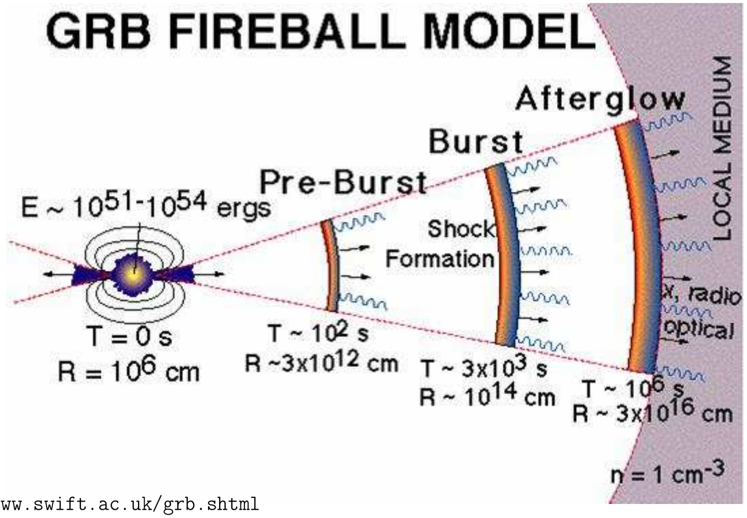
rebound: outer material rebounds off core, looses velocity because of photodisintegration and neutrino loss

$t = 0.1$ **s:** proto-neutron star formed with $R \sim 30$ km, $M = 1.4\,M_\odot$, standing shock ~150 km above neutron star

$t = 0.1$ **s until** $t = 0.2$ **s:** start to radiate ~10^{53} erg s^{-1} as neutrinos, triggers convection, heats material by depositing 10^{51} erg ($\longrightarrow$ convection)

$t = 0.2$ **s:** SN explosion is triggered

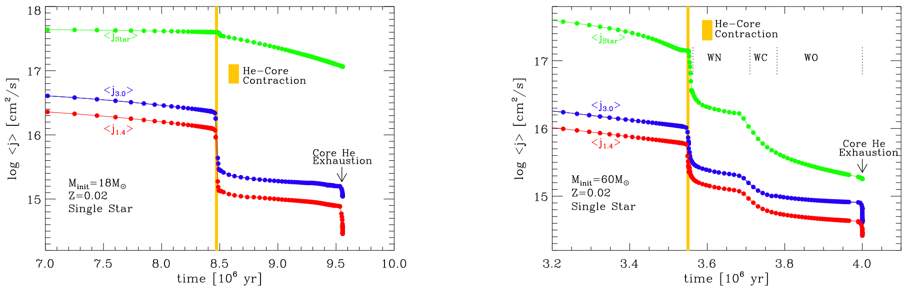
Hypernovae: Models



`http://www.swift.ac.uk/grb.shtml`

GRB model: Relativistic fireball model (Rees & Mészáros, 1992)

Hypernovae: Models



(Yoon et al., 2008)

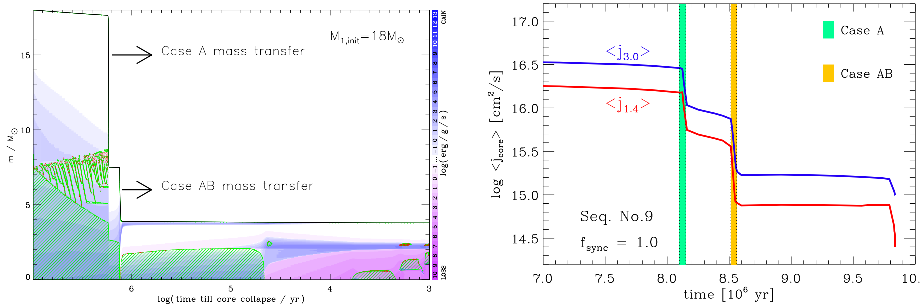
Large isotropic luminosity of GRBs is easier to explain if there is a jet ⟹ need stellar rotation

Angular momenta: need $j \gtrsim 10^{16}\,\mathrm{cm}^2\,\mathrm{s}^{-1}$ for core.

Because of friction between core and envelope, as well as angular momentum loss in winds during Wolf-Rayet phase, single stars do usually not rotate when they undergo core-collapse.

See Yoon et al. (2008) for discussion; there are exceptions, e.g., for very low initial metallicity.

Hypernovae: Models



Yoon et al. (2008): Evolution of 18 $M_\odot$ primary star in a 4 d orbit with a 17 $M_\odot$ star. Two mass loss phases. At the end, a 4 $M_\odot$ WR star survives.

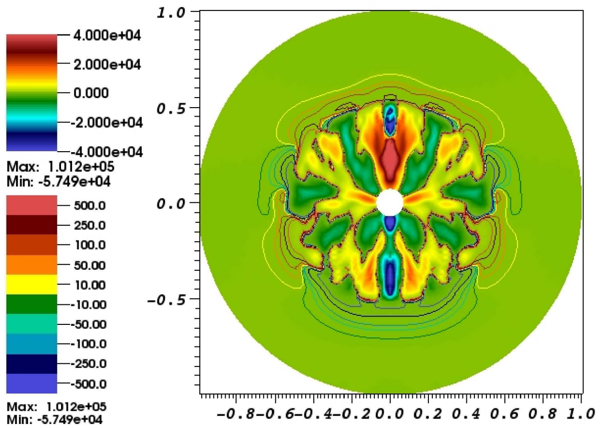
In most binary evolution models, angular momentum of the WR star is too small.

Possible scenario: first star evolves ⟹ SN ⟹ accretion on secondary star

⟹ Spin up ⟹ disrupt system (supernova kick!) ⟹ GRB of 2nd star.

⟹ SN Ic / GRB progenitor is/was probably in a binary system

Hypernovae: Models

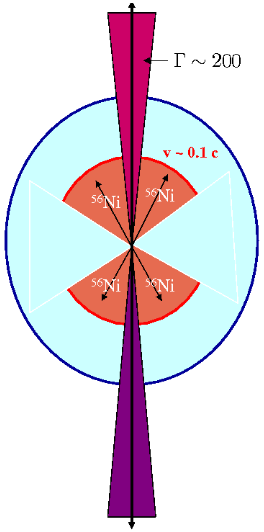


Radial B-fields in a 12 $M_\odot$ main sequence star (Yoon et al., 2008)

If star rotates: rotationally induced hydrodynamic instabilities

⟹ dynamo ⟹ B-fields

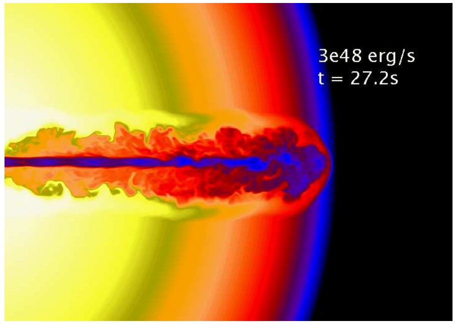
Hypernovae: Models



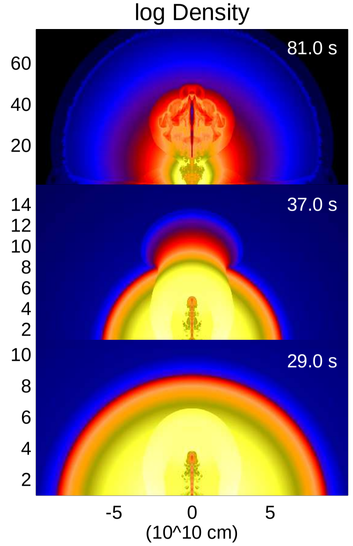
To make GRB with SN, we need

1. Highly relativistic jet to make burst
2. Broad (∼1 rad) subrelativistic outflow which triggers explosion of star and which produces enough ^{56}Ni to make bright supernova.

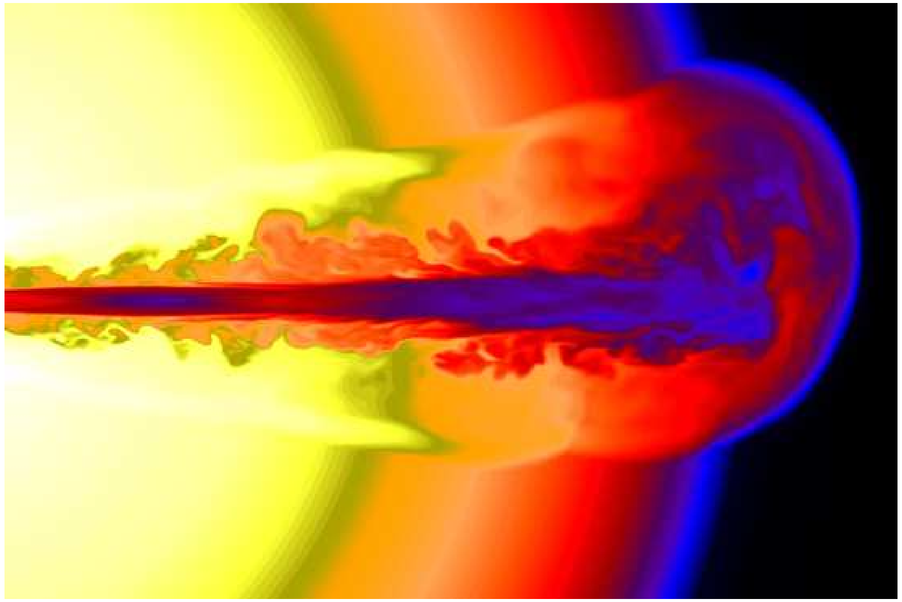
(Woosley & Zhang, 2007)



Density profile for jet with $3 \times 10^{48}\,\mathrm{erg\,s^{-1}}$ in a WR-star

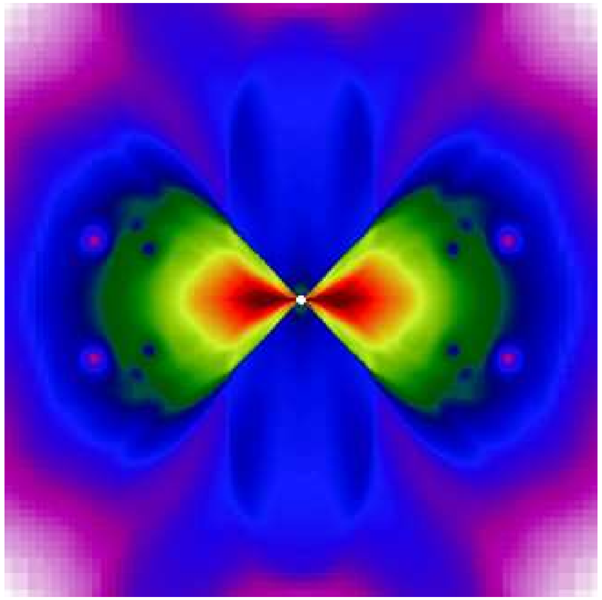


Jet with $1 \times 10^{47}\,\mathrm{erg\,s^{-1}}$ in an exploding SN. At $t = 81\,\mathrm{s}$, jet has overtaken SN shock



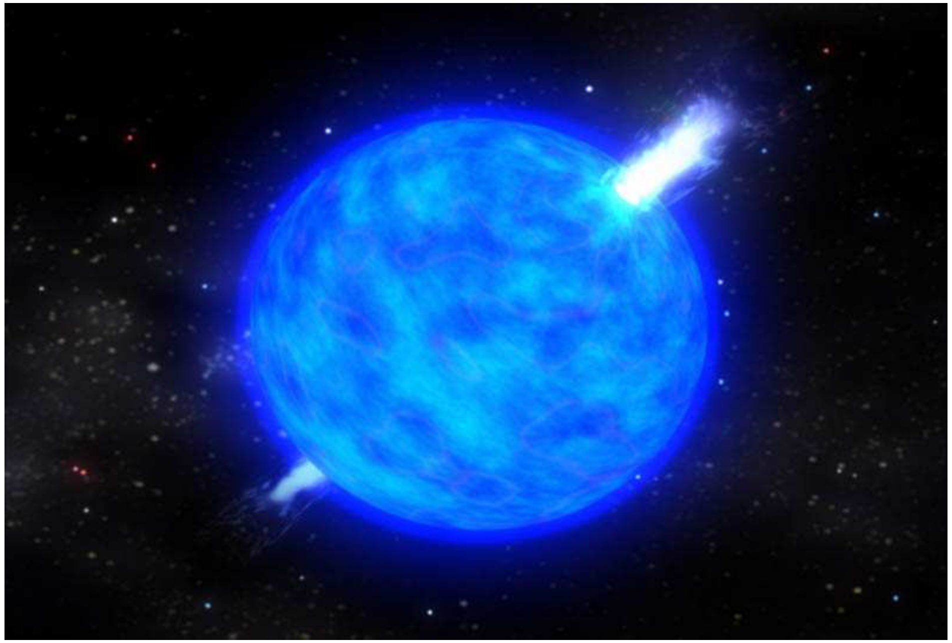
(Woosley & Bloom, 2006, Fig. 9)

Break out of relativistic GRB jet from a 15 $M_\odot$ WR star (radius 8.9×10^{10} cm), 8 s after collapse. Jet power: $3 \times 10^{50}\,\mathrm{erg\,s^{-1}}$, Lorentz-factor $\Gamma \sim 200$.



(size: 1800 km, inner boundary: 13 km Woosley & Bloom, 2006, Fig. 10)

Core collapse of a 14 $M_\odot$ WR star, at $t = 20\,s$: Black Hole with 4.4 $M_\odot$ has formed. Largest density: $10^8\,\mathrm{g\,cm^{-3}}$.



NASA/SkyWorksDigital

MOVIE Time: GRBstar2.mov