GRB progenitors: collapsars, kilonovae, supernovae

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Astronomical transients

Selected chapters from astrophysics, fall semester, 2022

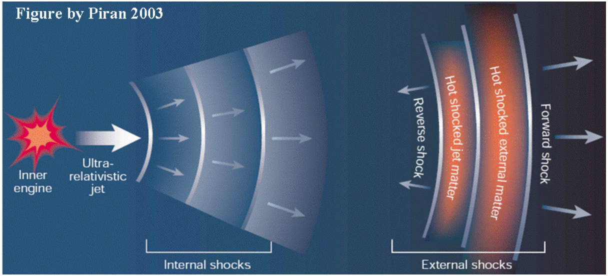
GRBs: the brightest EM transients

- **Solar luminosity**: $L_{\odot} \approx 4 \times 10^{33}\,\mathrm{erg\,s^{-1}} \Rightarrow$ the whole expected radiated energy within 10^{10} yrs: $\approx 10^{51}$ ergs
- Canonical **SN energy**: $\sim 10^{51}$ ergs (without neutrinos)
- **GRB energy**: $\sim 10^{51}$ - 10^{54} ergs
- Among the **most distant objects** (events) in Universe: $z_{\mathrm{max}} \sim 9$ (GRB 090429B $\rightarrow z = 9.4$ by photometric estimate, GRB 090423 $\rightarrow z = 8.2$ by spectroscopic estimate) / the nearest GRB: 170817A $\rightarrow z = 0.009727$ (1.3×10^{8} ly; higher redshift than GRB 980425, but in closer galaxy)
- Most Luminous: GRB 110918A (z = 0.984) $\rightarrow L_{\mathrm{max}} = 4.7 \times 10^{40}$ erg (Frederiks+ 2013)
- Most energetic photons: GRB 190829A (z=0.0785) $\rightarrow$ 3.3 TeV; this has also the longest duration for afterglow emission $\sim$ 56 hours (H.E.S.S. Collaboration 2021)
- Longest duration: GRB 111209A $\rightarrow \sim$ 7 hrs
- Shortest duration: GRB 820405 $\rightarrow \sim$ 12 ms

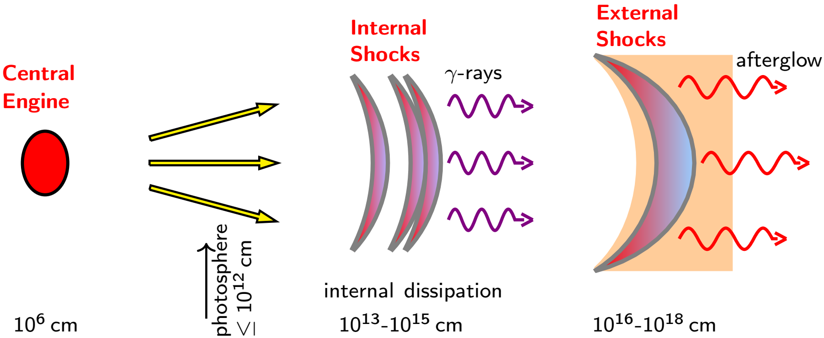
GRBs: the brightest EM transients

- **Isotropic distribution** on the sky
- Most typical values: flashes of 0.1 MeV γ rays that last 1 - 100 s
- Temporal variability: most show $\Delta t \sim 64$ ms, Some $\Delta t \sim 1$ ms (Guetta 2013)
- **Rate**: $R \approx 300$/yr BATSE and 100/yr Swift
- **Bimodal** GRB duration distribution: 0.1 - 1 s (mainly) $\rightarrow$ short bursts; 10 - 100 s $\rightarrow$ long bursts (e.g., Briggs+ 2002)
- Short GRBs are **harder** than long GRBs (e.g., Fishman & Meegan 1995; Tavani 1996)

The internal/external shock scenario

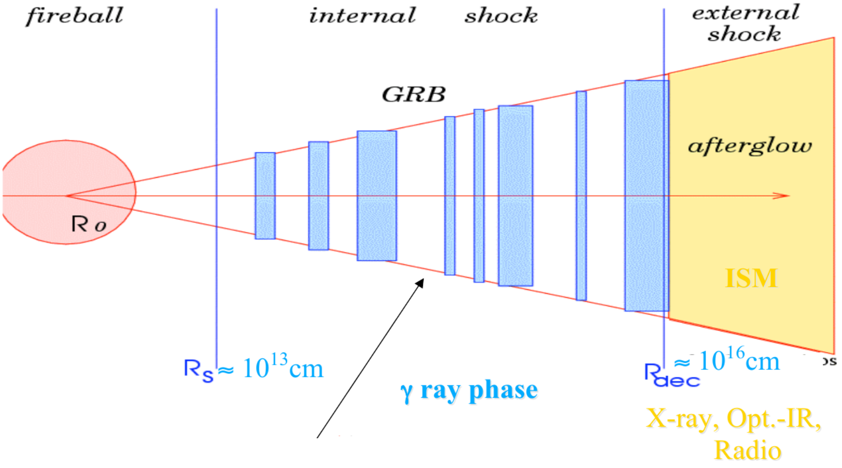


GRB engines



The internal/external shock scenario

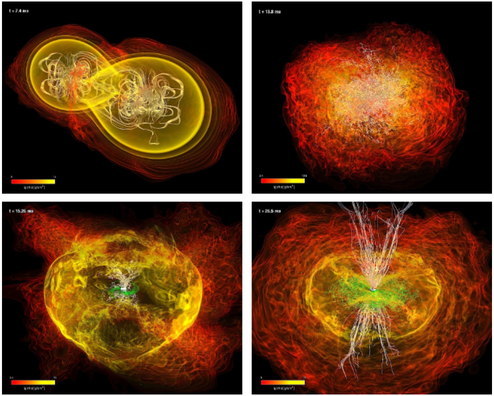
[Rees & Meszaros 1992, '94]



efficient!

Numerous open questions:

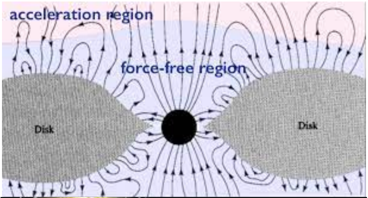
Crashing NSs can make GRBs

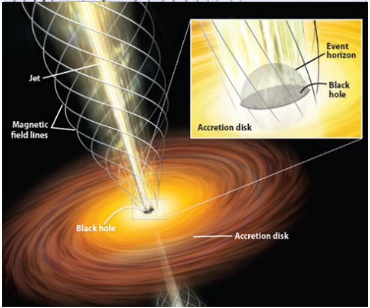


Credit: Rezzolla+ 2011

Blandford & Znajek?

Extraction of spin energy by threading the horizon of a spinning BH surrounded by an accretion disc with B-field

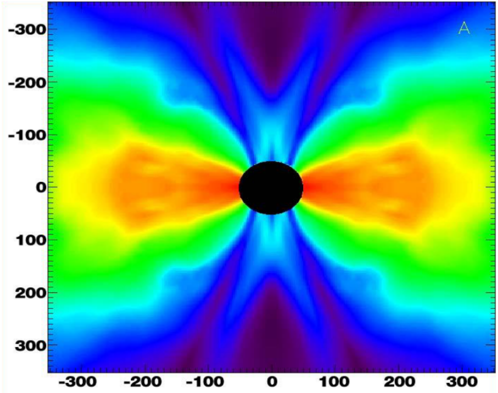




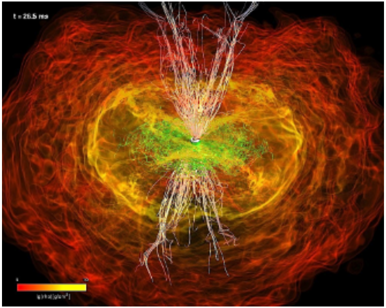
Numerous open questions:

What is the jet composition?

Baryonic or Poynting flux?



Sim: Woosley



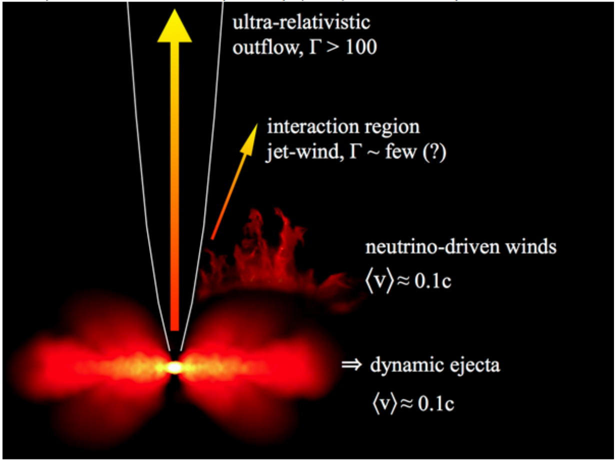
Sim: Koppitz & Rezzolla

Main properties of short GRBs:

- **Prompt emission**
  - Typical duration 0.1 - 2 s
  - Brightness variability < 0.1 s (in some cases < 0.01 s)
  - Isotropic equivalent $L \sim 10^{50}$ - 10^{52} erg s^{-1}
  - Nonthermal spectrum with $E \sim 300$ - 500 keV
  - Very efficient: $\gtrsim 10\%$ of the energy in γ-rays
- **Extended emission**
  - Some GRBs show emission over 100 s with E comparable to the prompt
  - Late flares suggest prolonged engine activity for hours and possibly days
- **Additional properties**
  - Host galaxies of all types and all SFRs (spiral, elliptical, irregular)
  - Most are bound to their host, but large offset from SF regions
  - Typical redshift $z \sim 0.5$, no association with SNe
  - Rate *without* beaming correction: $\sim 10\,\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$ ($\sim 10^5$ SNe rate)

Short GRBs:

Compact binary mergers eject material via different channels: a)"dynamic ejecta" (unbound by hydrodynamic interaction and gravitational torques) and b) various types of "winds". What we subsume loosely as winds can have different physical origines, for example driven off by neutrino absorption, magnetically launched winds or by accretion disk matter that becomes unbound by viscous and nuclear heating. These channels are sketched in the following figure (Rosswog, Philosophical Transactions of the Royal Society A, 2013; arXiv:1210.6549).



Dynamic and wind ejecta differ in their "electron fractions Ye" (number of electrons per nucleon= number of protons per nucleon): dynamic ejecta have very low Ye (~0.1) while wind ejecta have a distribution of Ye around 0.3. But any standard, both channels eject **extremely neutron-rich matter**.

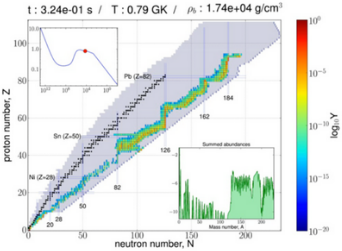
Credit: Stefan Rosswog's webpage

Short GRBs:

The ejecta of compact binary mergers are primary sites where the heaviest elements in the cosmos are forged. These ejecta are very different from any other cosmic explosion we know: while supernovae produce elements up to the iron group near Z = 26, the dynamic ejecta of neutron star mergers consist entirely of rapid-neutron capture ("r-process") elements up to the third ("platinum") peak near Z = 90, and should thus leave a distinctive imprint on the observable electromagnetic display. While both channels produce heavy elements via r-process, there are substantial differences which are displayed in the following figures.

Nucleosynthesis for dynamic ejecta

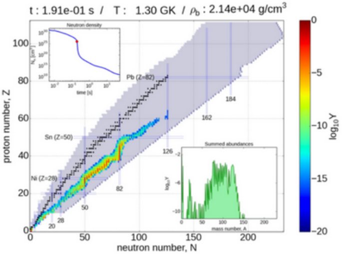
(snapshot; Korobkin et al. 2012)



- extremely neutron-rich (Ye ≈ 0.04)
- close to neutron drip-line
- extending to very large neutron (N≈ 200) and proton numbers (Z≈ 90)
- forging the heaviest elements (A>130) in the Universe (e.g. gold and platinum)

Nucleosynthesis for neutrino-driven winds

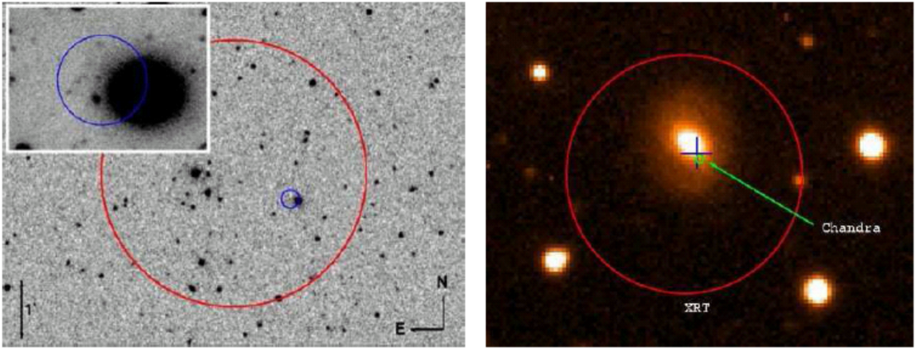
(snapshot; Martin et al. 2015)



- neutron-rich, broad distribution (0.2< Ye < 0.4)
- further away from neutron drip-line
- extending to moderately large neutron and proton number
- forging heavy elements, but usually with nucleon numbers A < 130

Credit: Stefan Rosswog's webpage

Short GRBs:

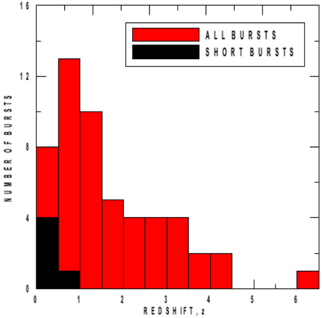


Short GRBs associated with elliptical galaxies. *left:* GRB 050509B; z=0.226 (Gehrels et al. 2005; Bloom et al. 2006a), the red and blue circles are BAT and XRT error boxes, respectively; *Right:* GRB 050724; z=0.257 (Barthelmy et al. 2005b; Berger et al. 2005a)

Short GRBs:

GRB	X-RAY?	OPTICAL?	RADIO?	REDSHIFT	GALAXY	ENERGY erg
050509	YES	NO	NO	0.225?	ELLIPTICAL?	1.1×10^{48}?
050709	YES	YES	NO	0.1606	EARLY	2.8×10^{49}
050724	YES	YES	YES	0.257	ELLIPTICAL	9.9×10^{49}
050813	YES	NO	NO	0.722?	?	1.7×10^{50}?
050906	NO	NO	NO	0.03?	BLUE, SPIRAL	1.2×10^{47}?

- Found in both elliptical and SF galaxies
- No evidence for SN emissions
- Centered or offset from host galaxies



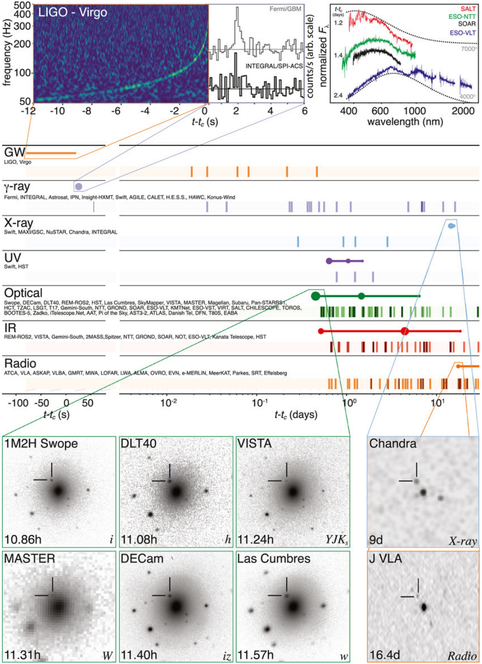
Short GRBs:

GRB	Mission	T_{90}(s)	z	Host galaxy	Location	Refs
050509B	Swift	0.04 ± 0.004	0.226	elliptical	outskirts?	[1, 2]
050709	HETE	0.07 ± 0.01	0.1606	irregular	outskirts	[3–5]
050724	Swift	3.0 ± 1.0	0.257	elliptical	outskirts	[6–9]
050813	Swift	0.6 ± 0.1	–	–	–	[10]
050911*	Swift	~ 16	0.1646?	galaxy cluster?	–	[11, 12]
051210	Swift	1.4 ± 0.2	–	–	–	[13]
051221A	Swift	1.4 ± 0.2	0.5465	star forming galaxy	slightly off-center	[14, 15]
051227*	Swift	8.0 ± 0.2	–	–	–	[16, 17]
060121	HETE	4.25 ± 0.56	1.7? or 4.6?	early-type?	outskirts?	[18–20]
060313	Swift	0.7 ± 0.1	–	–	–	[21]
060502B	Swift	0.09 ± 0.02	0.287?	early-type?	outskirts?	[22, 23]
060505	Swift	4.0 ± 1.0	0.089?	star-forming galaxy	–	[24–26]
060614*	Swift	102 ± 5	0.125	star-forming galaxy	off-center	[27, 28]
060801	Swift	~ 0.50	1.1304??	–	–	[29, 30]
061006	Swift	~ 0.42	–	–	–	[31, 30]

- Short hard GRBs differ from long-duration ones on the basis of:
  - Type of a host galaxy
  - Energies
  - Distribution of a typical redshift
  - Lag-luminosity relation

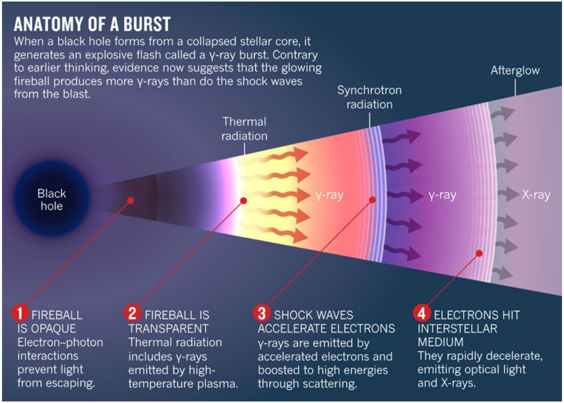
Low-luminosity short GRBs:

- GRB 170817A that accompanied the NS merger GW 170817 was a low-luminosity GRB
- The total L was $3\text{-}4 \times 10^{46}$ ergs $\rightarrow$ about three orders of magnitude lower than the weakest short GRB with a known redshift and about five orders of magnitude lower than a typical short GRB



Long GRBs: **schematic collapsar model with 30 $M_\odot$ progenitor**

- The core of a rotating massive star collapses to a BH
- Material far from the rotational axis does not fall straight in $\rightarrow$ first forms an accretion disk
- Dissipative effects in the disk convert E_k into heat
- Energy deposition over the poles powers jets (by the BZ effect)

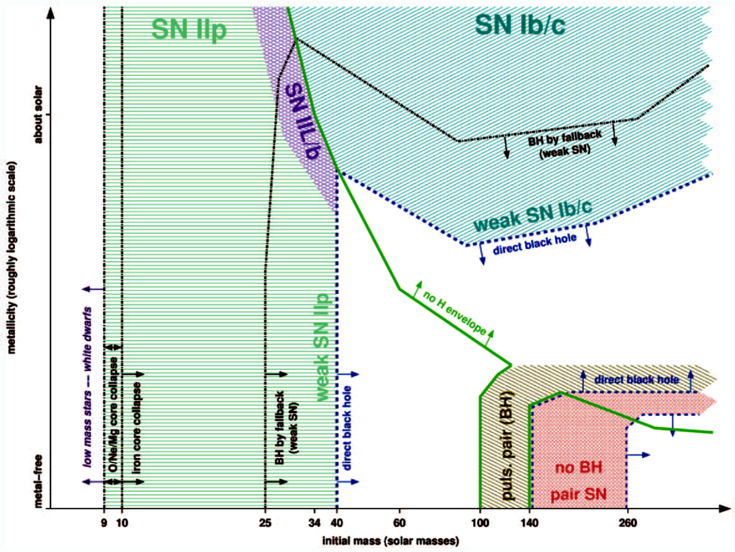


- Mass $> 30\,M_\odot$, "lifetime" 4 - 7 Myr
- Loses its hydrogen envelope through strong stellar winds $\rightarrow$ forms a WR star with He core $> 12\,M_\odot$ and (finally) with Fe core $> 2\,M_\odot$
- Prior to collapse $\rightarrow$ rapidly rotates with $v_\mathrm{rot,\,eq} \approx 200\,\mathrm{km\,s^{-1}}$

Long GRBs mechanism:

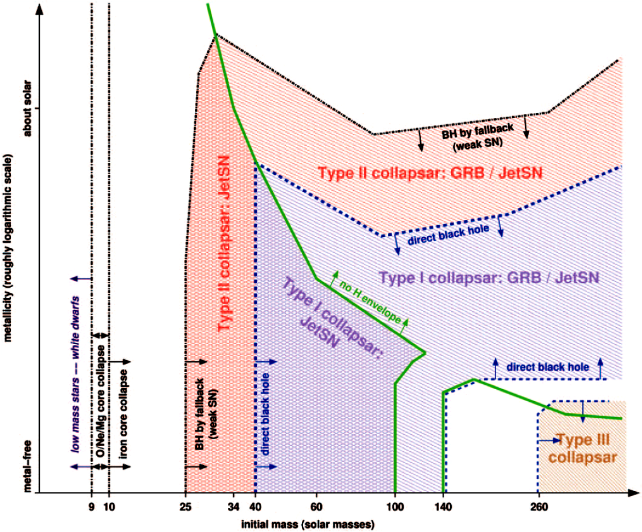
- **Phases**
  - the central engine ($t \sim 10^{-3}$ s)
  - the burst phase ($t \sim 10^{-1}$ - 10^{2} s)
  - the afterglow ($t \sim 10\,\mathrm{s} \rightarrow \infty$)
- **The central engine**
  - extracts energy from collapse
  - rest-mass energy from disk: (42% rotating BH; 6% non-rotating BH)
  - BH spin energy: up to 29% by BZ mechanism
  - all models tend to have a disc (accretion torus): $M_{\mathrm{disk}} \sim 10^{-2}$ - $1\,M_{\odot}$
- **Maximum extractable energy**
  - from torus: 1 - $10 \times 10^{53}\,\mathrm{erg}\,(M_{\mathrm{disk}}/M_{\odot})$
  - from BZ: $5 \times 10^{53}\,\mathrm{erg}\,(M_{\mathrm{BH}}/M_{\odot})\,f(a) \rightarrow f(a) = J$ parameter
- **Production of relativistic jet**
  - $\nu\nu \rightarrow \mathrm{e}^{+}\mathrm{e}^{-}$ along rotation axis; probably not enough efficient
  - more likely: MHD jet (Poynting jet)

CC SNe types by initial mass vs. metallicity



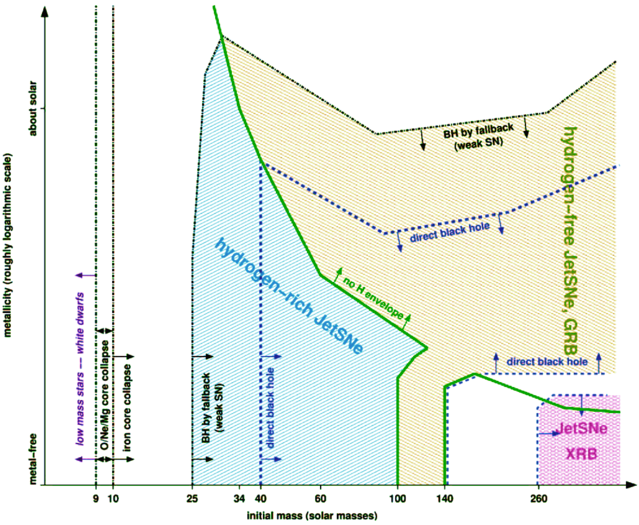
Credit: Heger+ 2003

CC SNe types by initial mass vs. metallicity



- **collapsar types** Credit: Heger+ 2003

CC SNe types by initial mass vs. metallicity



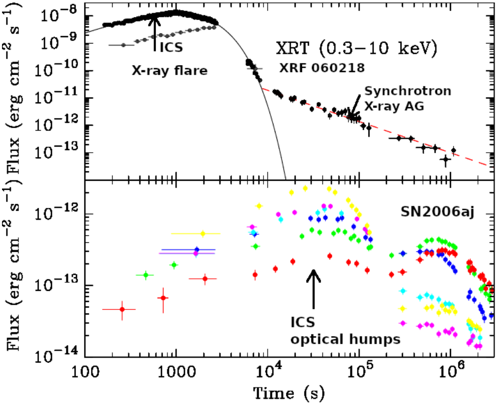
- **jet-driven types of SNe**

Credit: Heger+ 2003

Hypernovae, collapsars → GRBs:

- More energetic SN with an E range: $5 - 10 \times 10^{51}$ erg (Mazzali, Nomoto, Maeda)
- Classification criterion: broad lines → high E_k → high explosion energy
- Some are directly associated with long-duration GRBs (SN 98bw, SN 03dh)
- Likely associated with the formation of a BH from a rapidly rotating compact core (Woosley)
- Two-step BH formation: NS, accretion from massive disc → BH → relativistic jet → drills hole through remaining stellar envelope → escaping jet → GRB
- Requires rapidly rotating He (or CO) star
- Currently, all hypernovae have been classified as SNe Ic, but only 1 in 100 Ib/Ic SNe are hypernovae (Podsiadlowski+ 2004)
- HNe/GRBs are rare! ($10^{-5}\,\text{yr}^{-1}$)
- Note: HNe are efficient producers of Fe (just like SNe Ia)

GRB/SN connections: GRB060218 - a "mysterious transient"

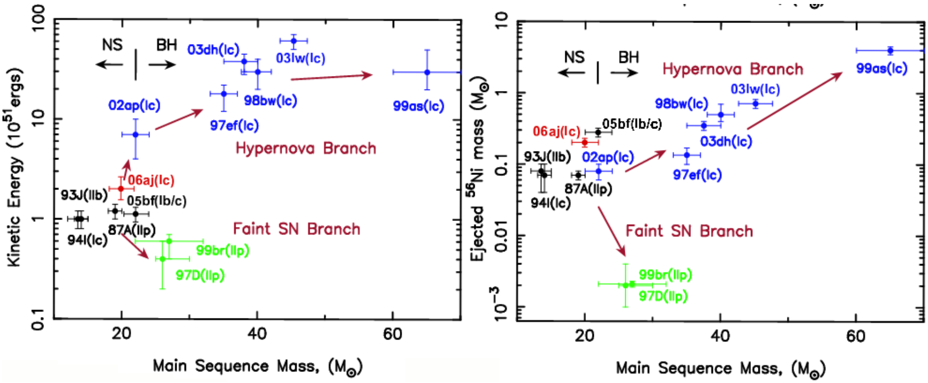


Credit: Campana+ 2006

- Long-term Swift light curve of GRB060218
- Upper panel: the XRT light curve (0.3-10 keV)
- Lower panel: the UVOT light curve
- Clearly identified type SN Ic
- Comparing to "usual" GRB-SNe $\sim$ 100times more powerful
- Shows high speed ($v \sim 0.1\, c$) of the outflow

- Do all SN Ic "make" GRBs? Radio surveys of SNe Ic afterglows show that not most of SN Ic produce GRBs, nor have relativistic ouflows
- Some have mildly relativistic outflows (SN 2009bb), but no γ emission
- Some have highly relativistic outflows (connection to Sne Ic-BL)

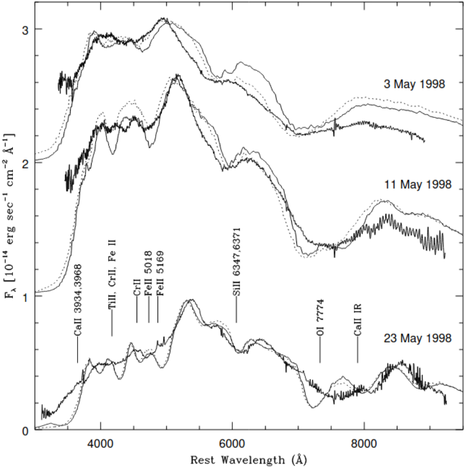
GRB/SN connections:

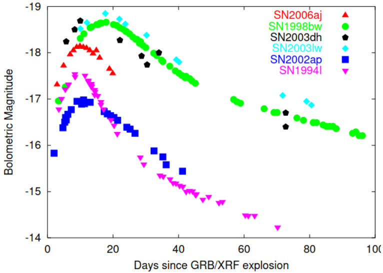


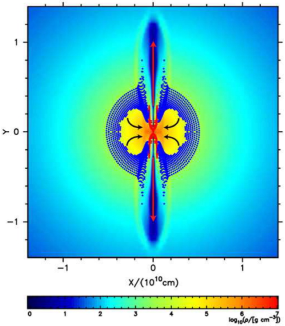
Credit: Nomoto+ 2007

- *Left panel*: The kinetic explosion energy E_k as a function of the main sequence mass M of the progenitors for several SNe/HNe
- *Right panel*: The ejected ^{56}Ni mass as a function of the same.

GRB/SN connections:



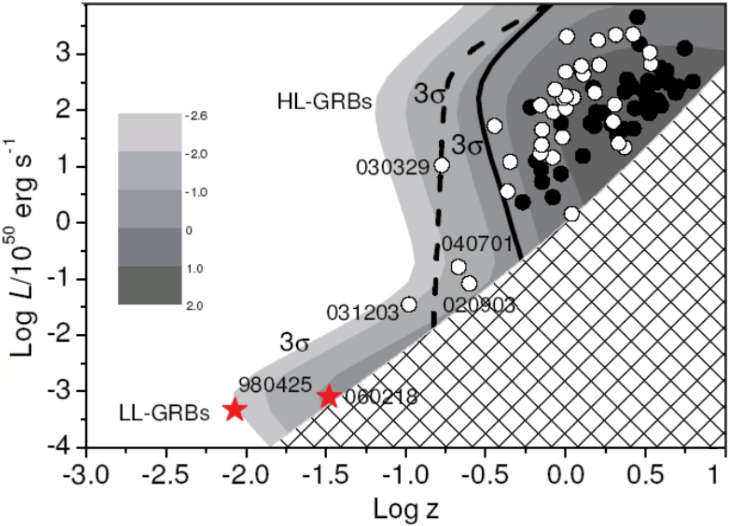




Credit: Nomoto+ 2005, 2007

- *Left panel*: Time evolution of various spectra of long GRBs
- *Upper right panel*: LCs of long GRBs

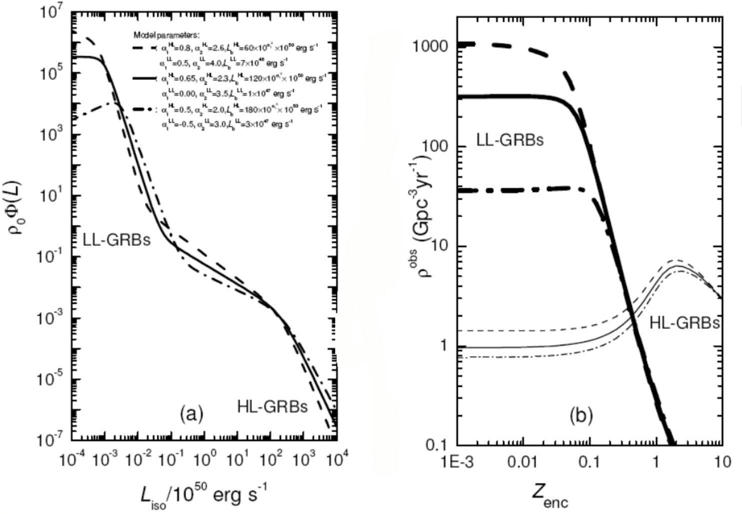
Low-luminosity GRBs:



GRB 980425: z = 0.0085
GRB 060218: z = 0.0331

Zhang (2007)

Low-luminosity GRBs as a separate population:

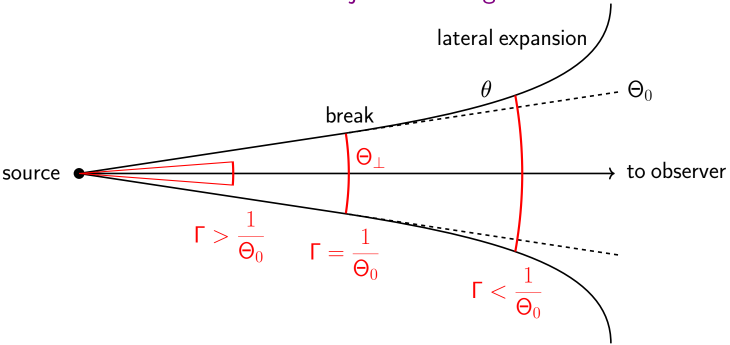


- Event rate density: long GRBs $\sim 1\,\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$ vs LLGRBs $\sim 800\,\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$; z and L distribution indicate a separate population

GRBs: the achromatic jet break

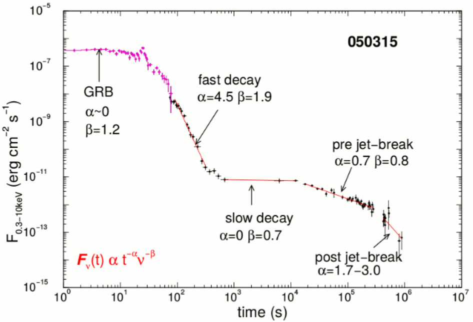
The following slides (except the last one) are adapted from and shown with courtesy of Jakub Řípa

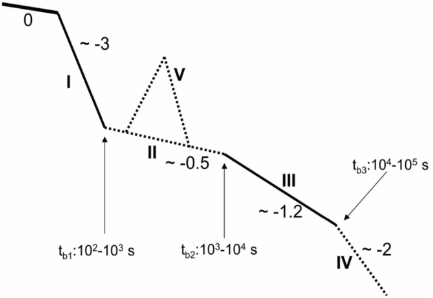
- Achromatic (λ-independent) break happens if the relativistic beaming angle (relativistic aberration) of the emitted photons $\Theta_\perp \sim \Gamma^{-1}$ increases over the jet angle Θ_0
- Time of the break constraints the jet break angle θ



- Problem: Only a minority of multi-wavelength GRB afterglows show clear break

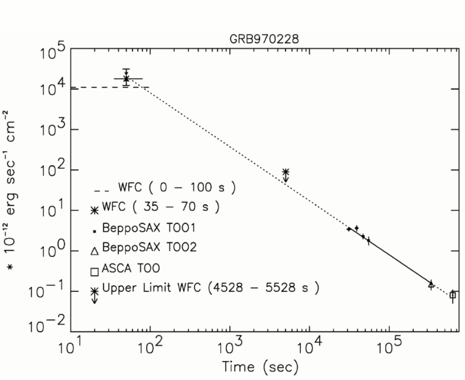
GRBs: the typical X-ray afterglow LCs profile

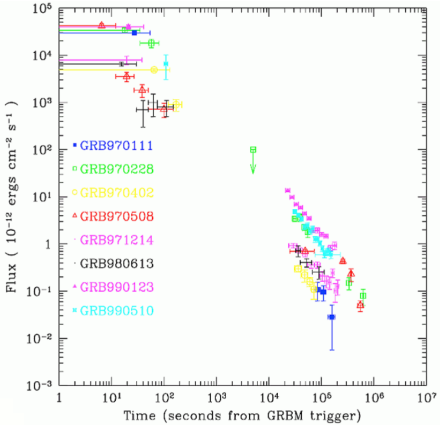




- *Left panel*: Phases of afterglow of GRB 050315; red lines indicates a fit to each phase, and the values of alpha (temporal decay index) and beta (spectral index) are shown (Panaitescu 2006)
- *Right panel*: Synthetic X-ray LC based on the Swift XRT observational data. The phase "0" denotes the prompt emission, "I" the prompt decay phase, "II" is the shallow phase with "V" being a possible X-ray flare (Zhang+ 2006)

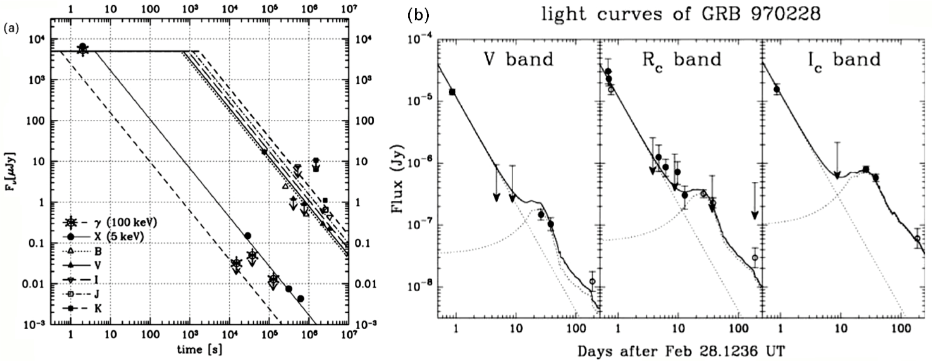
GRBs: typical X-ray afterglow LCs profile





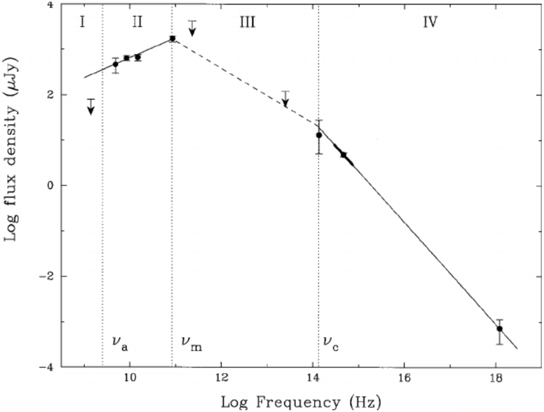
- *Left panel*: Time variation of the X-ray flux from GRB 970228; in the 2 - 10 keV energy range (Costa+ 1997)
- *Right panel*: X-ray fading source: Power-law decay $F \propto t^{-1/3}$

GRB 970228: from NIR to X-rays LCs - connection to SNe



- *Left panel*: LCs of the afterglow of GRB 970228 from X-rays to NIR; the lines indicate a quite convincing comparison with prediction of the simplest external shock scenario (Wijers+ 1997)
- *Right panel*: Afterglow of GRB 970228 measured in different bands beyond 1 day; the LCs present a bump that is interpreted as a contribution from an underlying SN (Reichart 1999, Galama+ 2000)

GRB 970508: from Radio to X-rays LCs



The radio to X-ray energy spectrum of GRB 970508 as measured 12.1 days after the burst (Galama+ 1998)

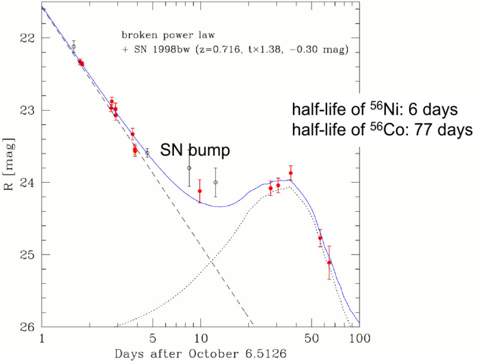
- The afterglow of GRB 970508; the first to be observed simultaneously over almost the whole EM spectrum; this strongly supports the idea that GRB afterglows are powered by **synchrotron emission accelerated in relativistic shock**

LGRBs: connection to SNe Ic

- *Left:* First GRB/SN association was GRB 980425/1998bw at $z \sim 0.0085$ ($\sim$ 37 Mpc), type Ic SN, about 10 times brighter than an ordinary SN; some (not all) long GRBs are associated with CC Ic SNe

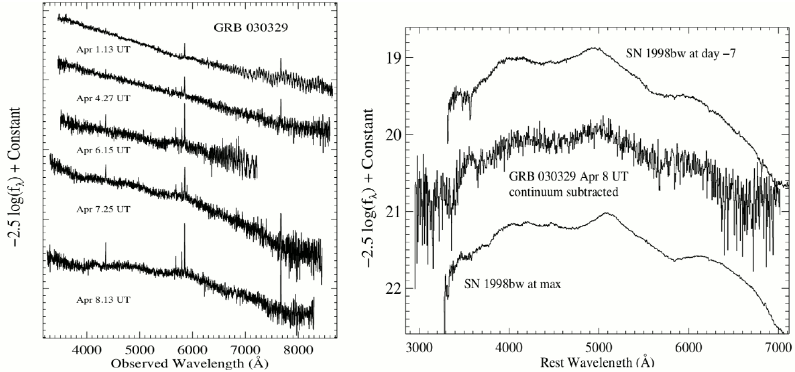
GRB 980425 / SN 1998bw

Another example: GRB 041006



- *Right:* Late R-band light curve for GRB 041006; open circles are GCN data, filled circles are the own data; early-time broken power-law decay is shown as the dashed line, a k-corrected SN 1998bw LC is shown as the dotted curve, the combined power law and stretched SN 1998bw LC is given by the solid curve (Stanek+ 2005)

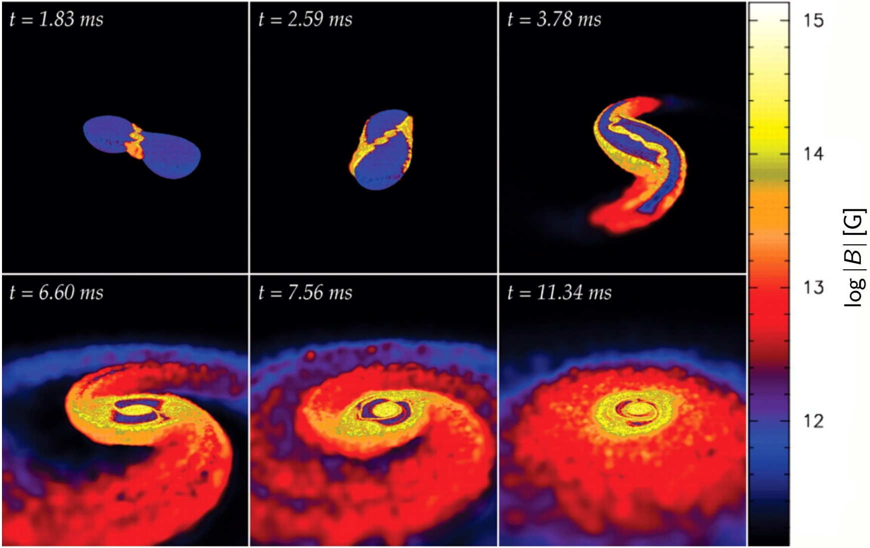
LGRBs: connection to SNe Ic - spectra



- *Left panel*: Evolution of the GRB 03029/SN 2003 spectrum; the early spectra consist of a power-law continuum ($F_\nu \propto \nu^{-0.9}$) with narrow emission lines originating from H II regions in the host galaxy at a redshift of $z \sim 0.168$ Spectra taken after April 5 show the SN-like development
- *Right panel*: Residual spectrum with broad bumps at approximately 5000 and 4200 Å (rest frame), which is similar to the spectrum of the peculiar type Ic SN 1998bw a week before maximum light (both: Stanek+ 2003)

NS merger - MHD sim

- MHD simulation of a magnetized NS merger; left-to-right dimension of panels is $\sim 140\,\mathrm{km}$ (Price & Rosswog 2006)



The evolving composition of the Universe