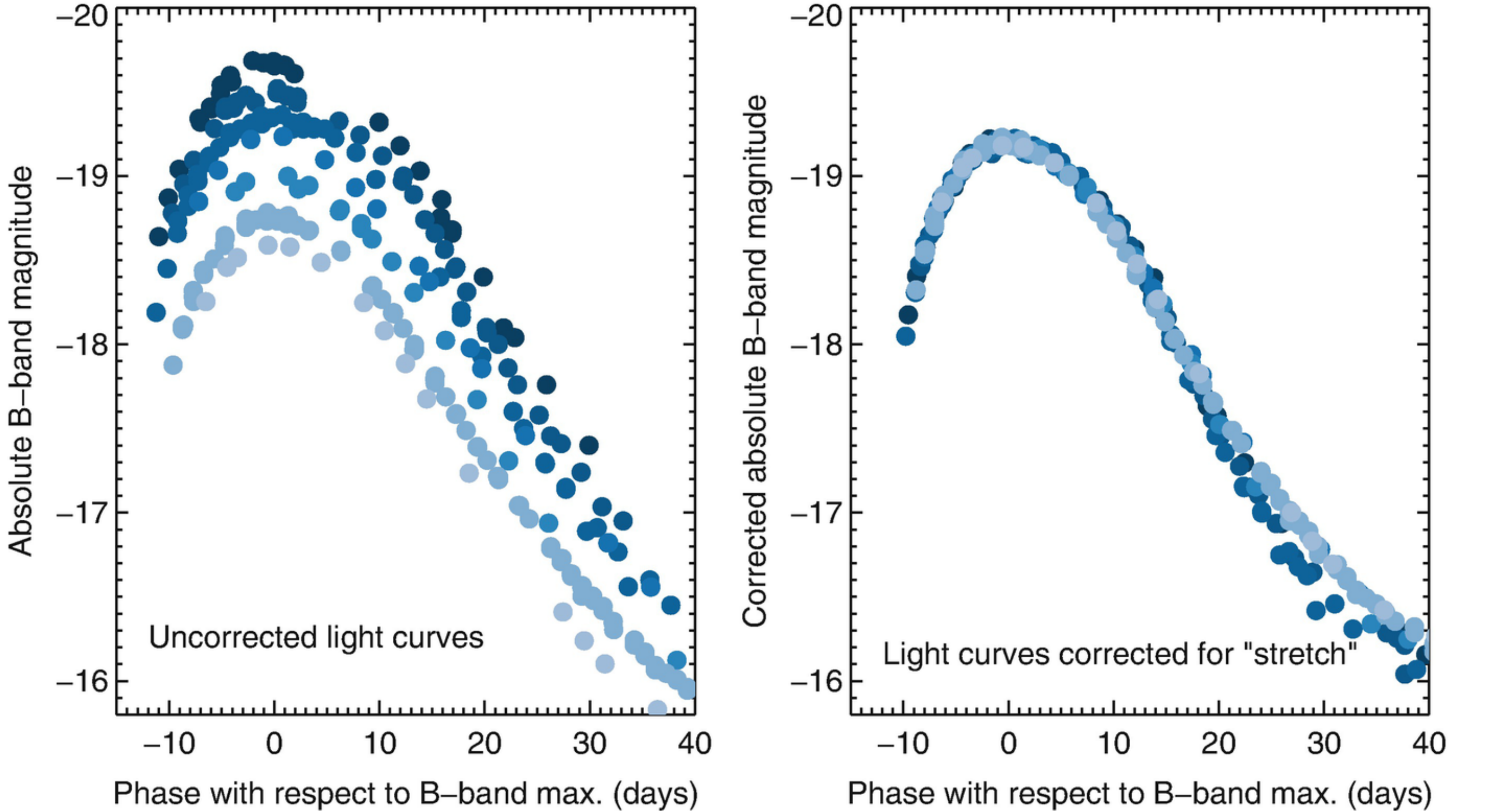
Type Ia Supernovae

Type Ia Supernovae are Standard Candles



Stellar explosions of White Dwarfs

- Endpoints of stellar evolution ($M < 10M_{\odot}$): no E_{nuc} available; compression until electrons become degenerate
- Chemical composition: He, CO, ONe; masses: typical 0.6 $M_{\odot}$, maximum: $M_{Chandrasekhar}$ ($\sim 1.4M_{\odot}$)
- When isolated, they cool down to very low L ($\sim 10^{-4.5}L_{\odot}$):

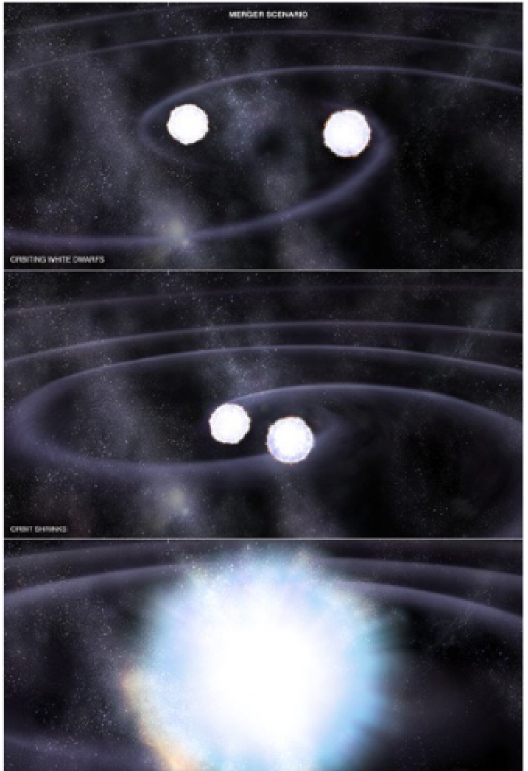
→ "fossils" allowing to do "stellar archeology" (age of the Galaxy, star formation rate)

- When in interacting binary systems, they can be "rejuvenated" and eventually explode

Stellar explosions: WDs in close binary systems
Scenarios/Progenitors of SNIa

Single degenerate: WD+MS or WD+RG

Double degenerate: mergin of two white dwarfs



Favors Single Degenerate Scenario

PTF 11kx: A Type Ia Supernova with a Symbiotic Nova Progenitor

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Science **337**, 942 (2012)

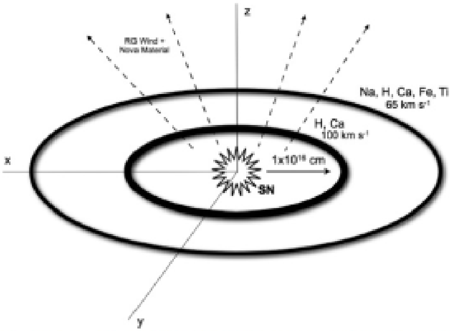

Fig. 4. Schematic showing the interpretation of the observations of PTF 11kx. In the symbiotic nova progenitor system, a red giant wind deposits CSM into the system, which is concentrated in the orbital plane. Episodic nova events further shape the CSM, resulting in expansion velocities of ~50 to 100 km s^{-1}. There is an inner region of material containing at least H and Ca, moving at ~100 km s^{-1}, surrounded by more distant material containing H, Ca, Na, Fe, Ti, and He, moving at ~65 km s^{-1}. The presence of hydrogen in the inner region is inferred from the onset of emission, concurrent with the onset of Ca II emission. This geometry, and the delay in the onset of CSM emission, is consistent with a relatively recent nova whose ejecta are sweeping up the CSM and decelerating. The inner boundary of CSM is at a distance of ~10^{16} cm, as determined from the onset of interaction.

There is a consensus that type Ia supernovae (SNe Ia) arise from the thermonuclear explosion of white dwarf stars that accrete matter from a binary companion. However, direct observation of SN Ia progenitors is lacking, and the precise nature of the binary companion remains uncertain. A temporal series of high-resolution optical spectra of the SN Ia PTF 11kx reveals a complex circumstellar environment that provides an unprecedentedly detailed view of the progenitor system. Multiple shells of circumstellar material are detected, and the SN ejecta are seen to interact with circumstellar material starting 59 days after the explosion. These features are best described by a symbiotic nova progenitor, similar to RS Ophiuchi.

Monthly Notices
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ROYAL ASTRONOMICAL SOCIETY

MNRAS 431, 1541–1546 (2013)
Advance Access publication 2013 March 7
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Explaining the Type Ia supernova PTF 11kx with a violent prompt merger scenario

Noam Soker,[1★] Amit Kashi,[2] Enrique García–Berro,[3,4] Santiago Torres[3,4]
and Judit Camacho[3,4]

We argue that the multiple shells of circumstellar material (CSM) and the supernovae (SNe) ejecta interaction with the CSM starting 59 d after the explosion of the Type Ia SN PTF 11kx are best described by a violent prompt merger. In this prompt merger scenario, the common envelope (CE) phase is terminated by a merger of a white dwarf (WD) companion with the hot core of a massive asymptotic giant branch star. In most cases, the WD is disrupted and accreted on to the more massive core. However, in the rare cases, where the merger takes place when the WD is denser than the core, the core will be disrupted and accreted on to the cooler WD. In such cases, the explosion might occur with no appreciable delay, i.e. months to years after the termination of the CE phase. This, we propose, might be the evolutionary route that could lead to the explosion of PTF 11kx. This scenario can account for the very massive CSM within ∼1000 au of the exploding PTF 11kx star, for the presence of hydrogen, and for the presence of shells in the CSM.

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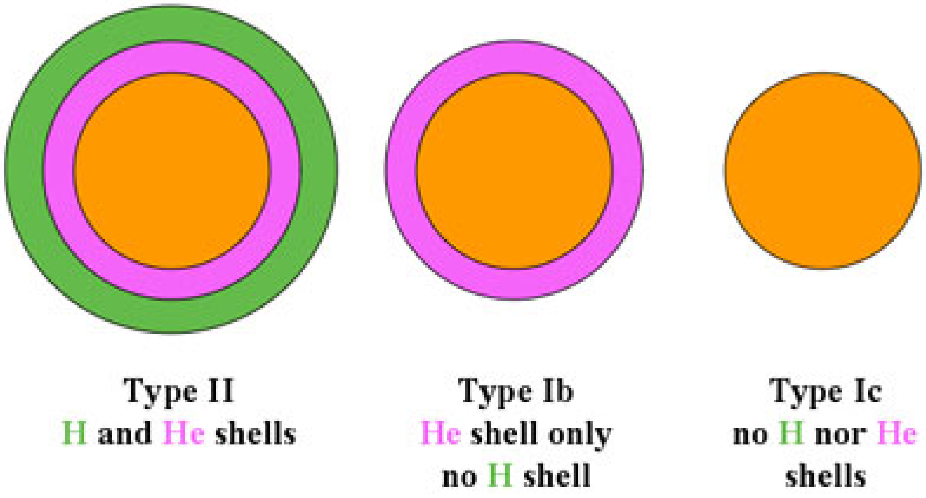
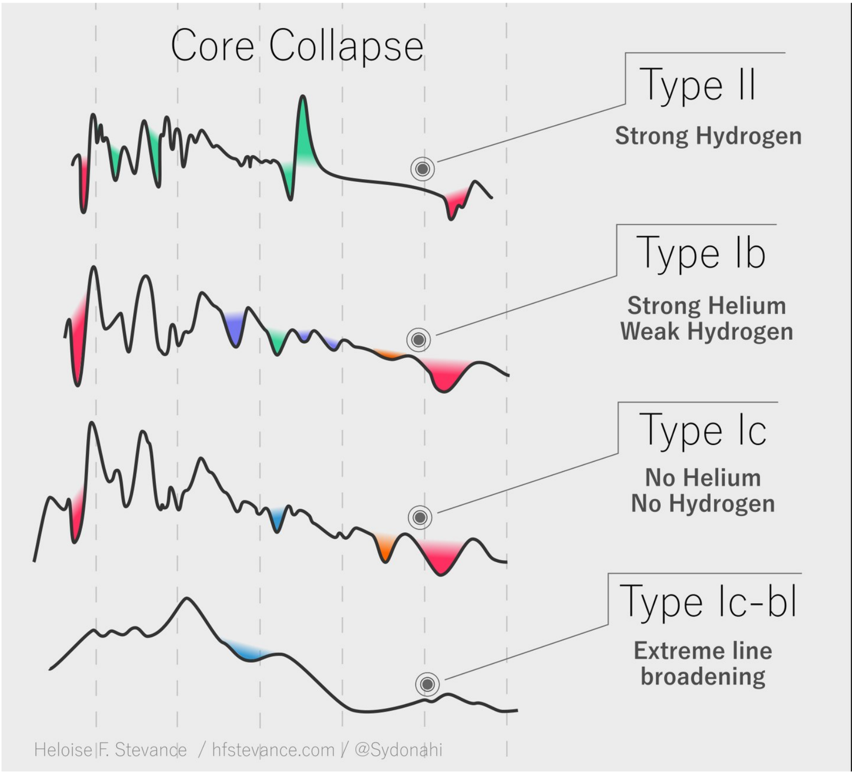
Discards the single degenerate scenario

We argue that the multiple shells of circumstellar material (C[illegible]pernovae (SNe) ejecta interaction with the CSM starting 59 d after th[illegible] Type Ia SN PTF 11kx are best described by a violent prompt mer[illegible]pt merger scenario, the common envelope (CE) phase is terminated [illegible] white dwarf (WD) companion with the hot core of a massive asym[illegible]ch star. In most cases, the WD is disrupted and accreted on to the [illegible]. However, in the rare cases, where the merger takes place when the [illegible] the core, the core will be disrupted and accreted on to the cooler WD. In suc[illegible], the explosion might occur with no appreciable delay, i.e. months to years after the termination of the CE phase. This, we propose, might be the evolutionary route that could lead to the explosion of PTF 11kx. This scenario can account for the very massive CSM within ~1000 au of the exploding PTF 11kx star, for the presence of hydrogen, and for the presence of shells in the CSM.

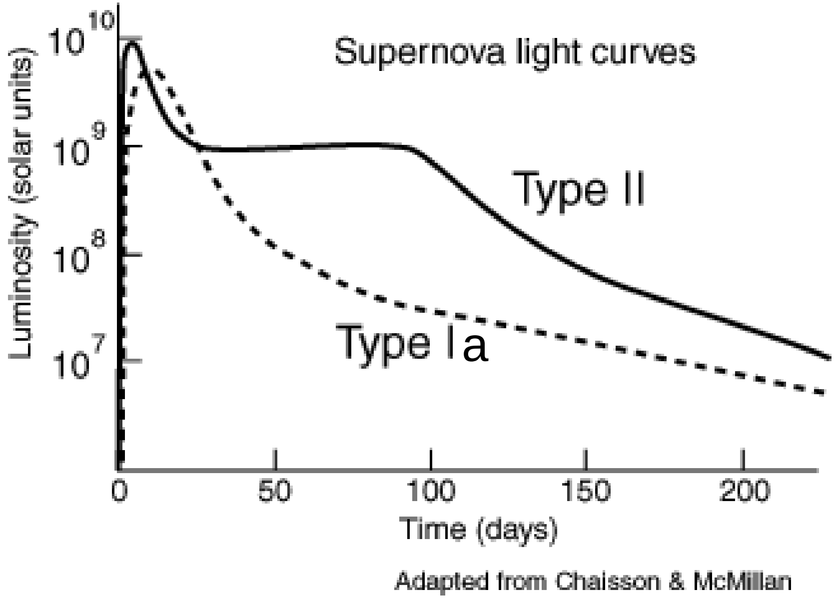
Core-Collapse Supernovae

Core Collapse Supernovae

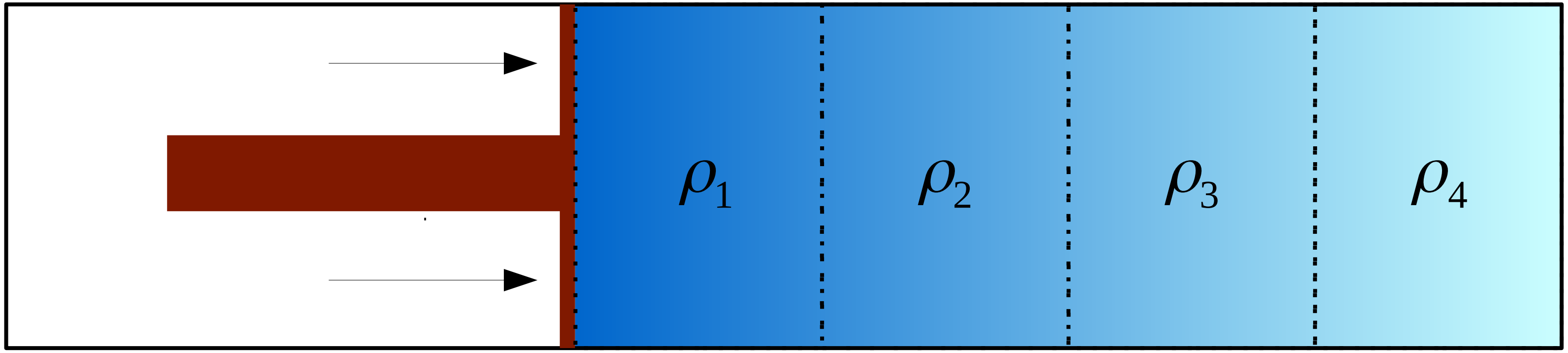


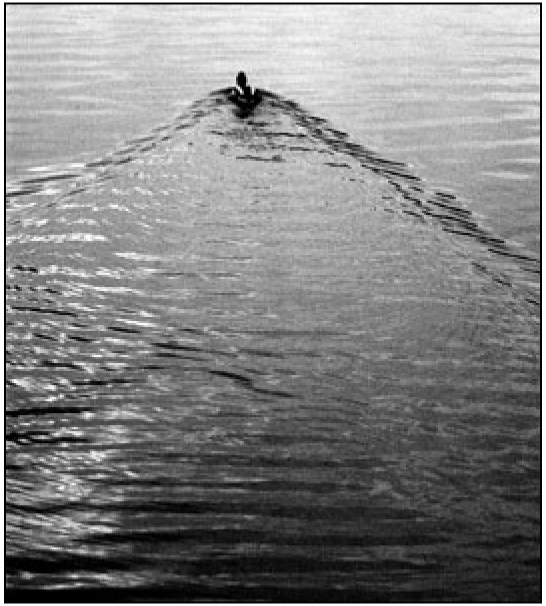


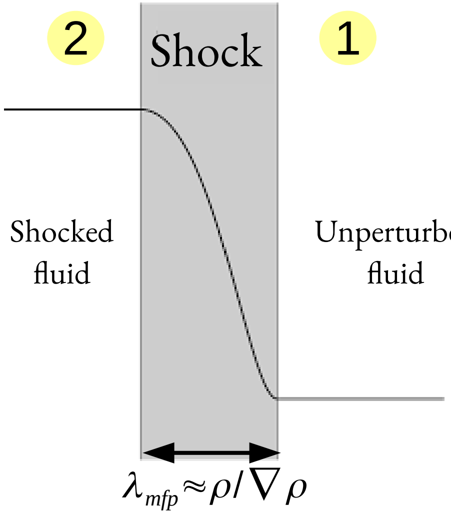
Lightcurves



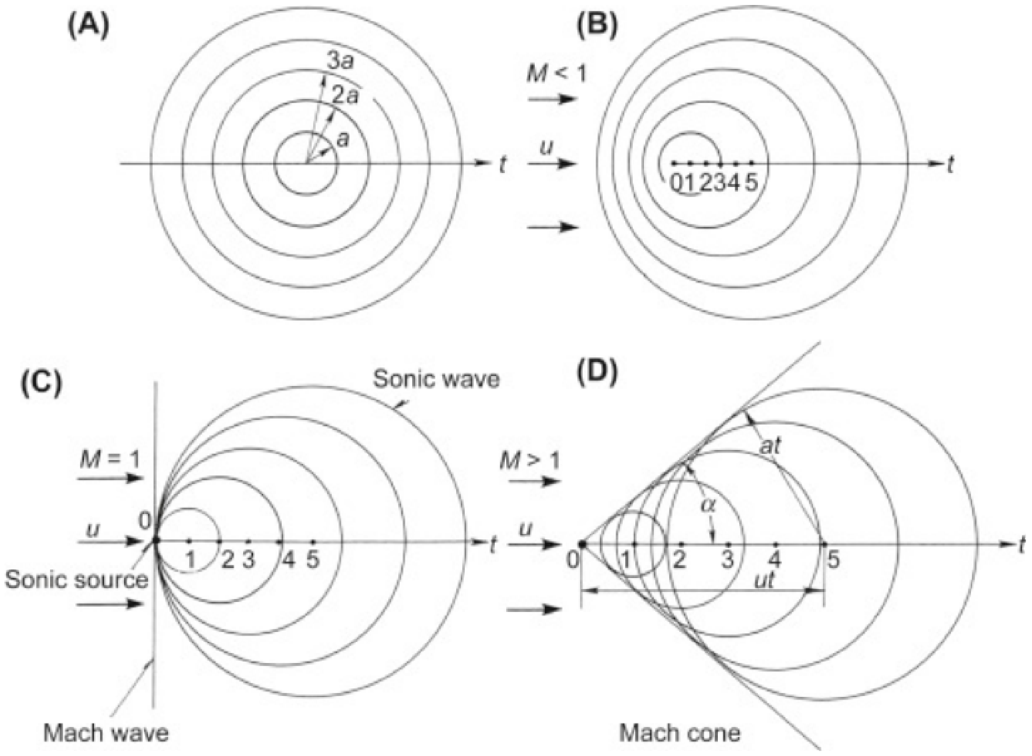
Core-collapse SNe show a characteristic plateau in their light curves a few months after initiation. This plateau is reproduced by computer models which assume that the energy comes from the expansion and cooling of the star's outer envelope as it is blown away into space. This model is corroborated by the observation of strong hydrogen and helium spectra for the Type II supernovae, in contrast to the Type Ia. There should be a lot of these gases in the extreme outer regions of the massive star involved.


ρ_1
ρ_2
ρ_3
ρ_4




2
Shock
1
Shocked fluid
Unperturbed fluid
$\lambda_{mfp} \approx \rho / \nabla \rho$

Mach Number and Mach Cone



(A) & (B)
subsonic flow

(C) & (D)
supersonic flow

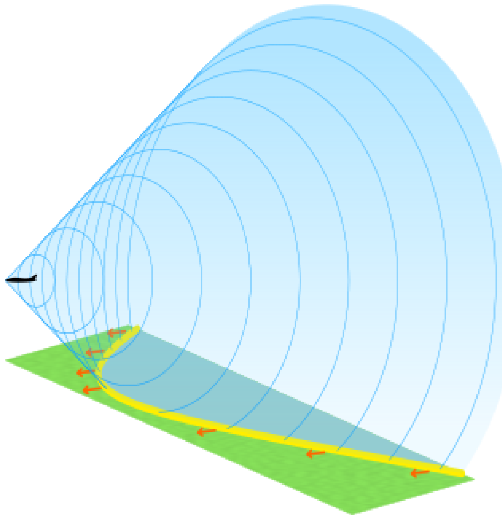
From Science Direct

$$\sin\alpha = \frac{c_s}{v}$$

MACH CONE

$$M \equiv \frac{v}{c_s}$$

$$\therefore \quad \sin\alpha = \frac{1}{M}$$



Adapted from
lecture of
Vasily Belokurov

https://people.ast.cam.ac.uk/~vasily/Lectures/AFD_2021_Reynolds/AFDLecture09_10Feb2021.pdf

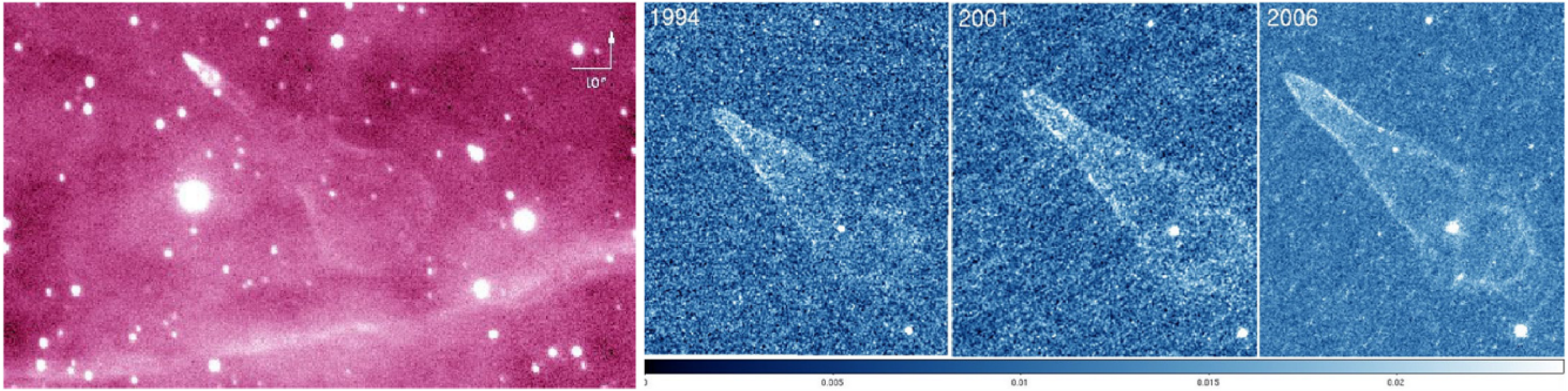
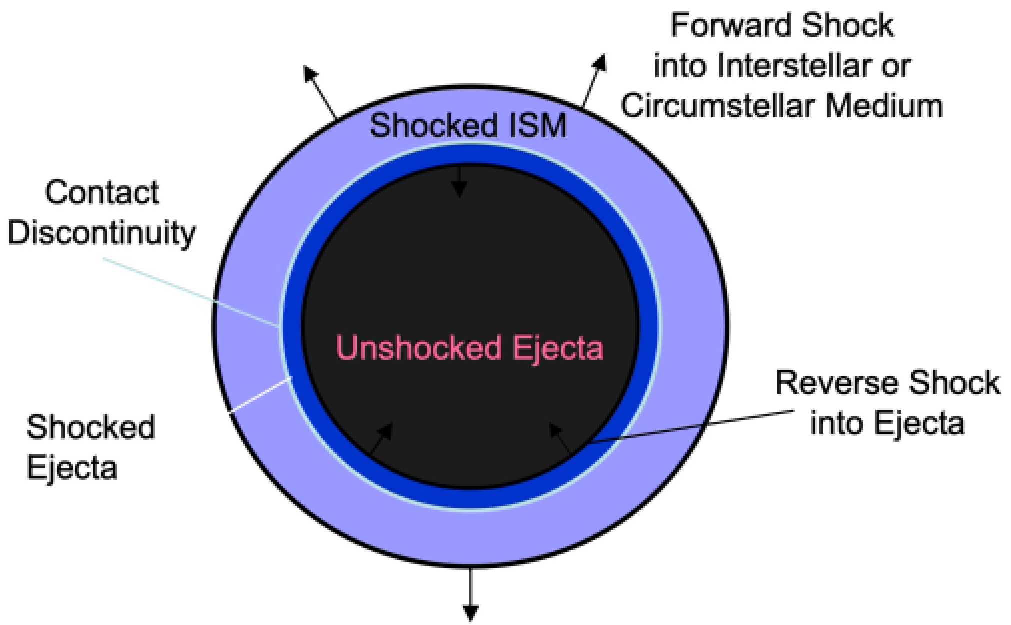


Figure 1. Left-hand panel: The Guitar Nebula in H α, imaged with the 5-meter Hale Telescope at the Palomar Observatory, 1995 (Cordes et al. 1993). Right-hand panel: The head of the Guitar Nebula in H α, imaged with the Hubble Space Telescope in 1994, 2001, and 2006 (Gautam et al. 2013). The change in shape traces out the changing density of the ISM.

Toropina, Romanova & Lovelace 2019, MNRAS 484, 1475



Forward shock: propagates in the circumstellar and then interstellar medium

Reverse shock: propagates into ejecta from the ISM inward (note: the reverse shock propagates outward in the lab frame and inward in the contact discontinuity lab frame).

The expanding shocked material outputs copious amounts synchrotron radiation due to the acceleration of electrons in the presence of a magnetic field. This expanding shell surrounds an area of relatively low density, into which the supernova ejecta expands freely, typically with velocities of around 10,000 km/s. This free expansion phase lasts for around 100/200 years until the mass of the material swept up by the shock wave exceeds the mass of the ejected material.

Supernova remnants (SNRs) - X-rays from shocks & search for 44Ti (γ-rays and hard X-rays)

➢ Supernova explosion: dense ejecta expanding at supersonic speed

- KE (kinetic energy): 10^{51} erg (*1 foe*= 10^{51} erg)
- Ejected mass: ~ 1.4 $M_\odot$ (SNe Ia) ; > 10 $M_\odot$ (core collapse SNe)
- $v_{ejecta} >> 10^4$ km/s

➢ Phases of SNRs

➢**Free expansion** phase: ambient medium at rest, ejecta expanding supersonically → outward-propagating shock wave - ***forward shock***

- When it has swept a significant amount of ambient medium mass, the forward shock begins to slow down (decelerate). Expanding matter (still in free expansion) collides with swept-up ambient medium → ***reverse shock*** formed, travelling inwards: heating of the ejecta (previously cooled by free expansion) → thermal X-ray emission

➢Adiabatic expansion phase (non significant radiative losses): reverse shock disappears, once all ejecta have been heated. Mass swept-up by forward shock becomes larger than ejecta mass

➢Radiative phase : once speed of forward shock decreases, T decreases (no X-ray emission anymore). Radiation becomes efficient. Shock wave decelerated; expansion driven by gas pressure instead of KE.

➢Dispersion into the ISM

Remnant of the Tycho Brahe supernova (1572) seen in X-rays (Chandra satellite)

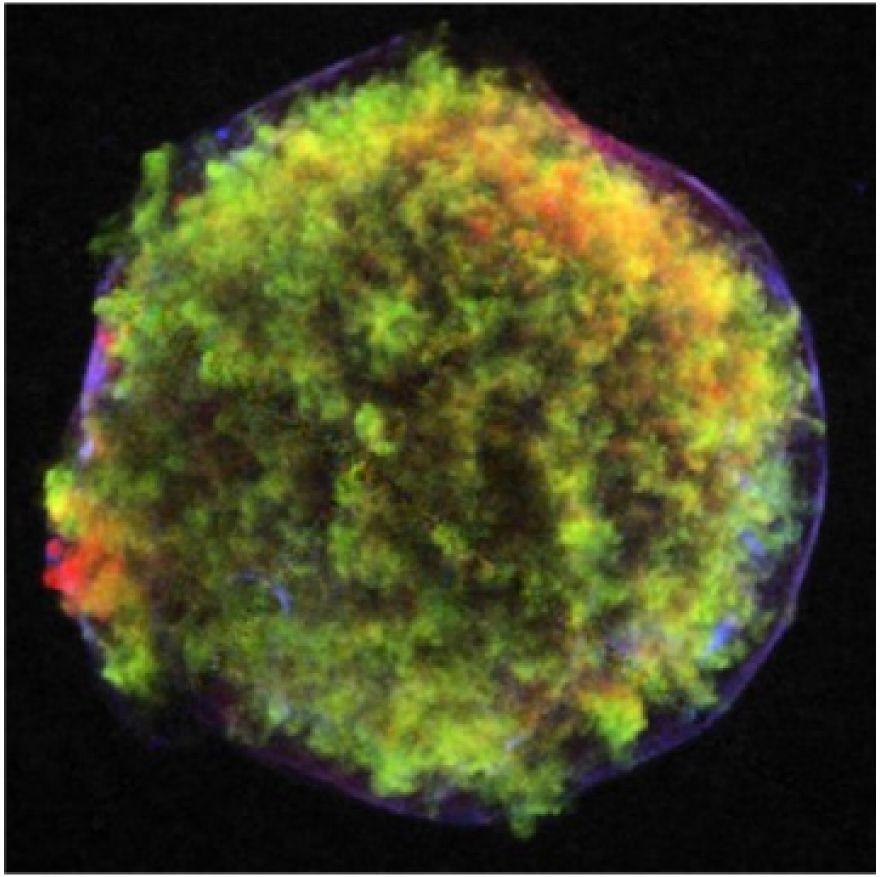
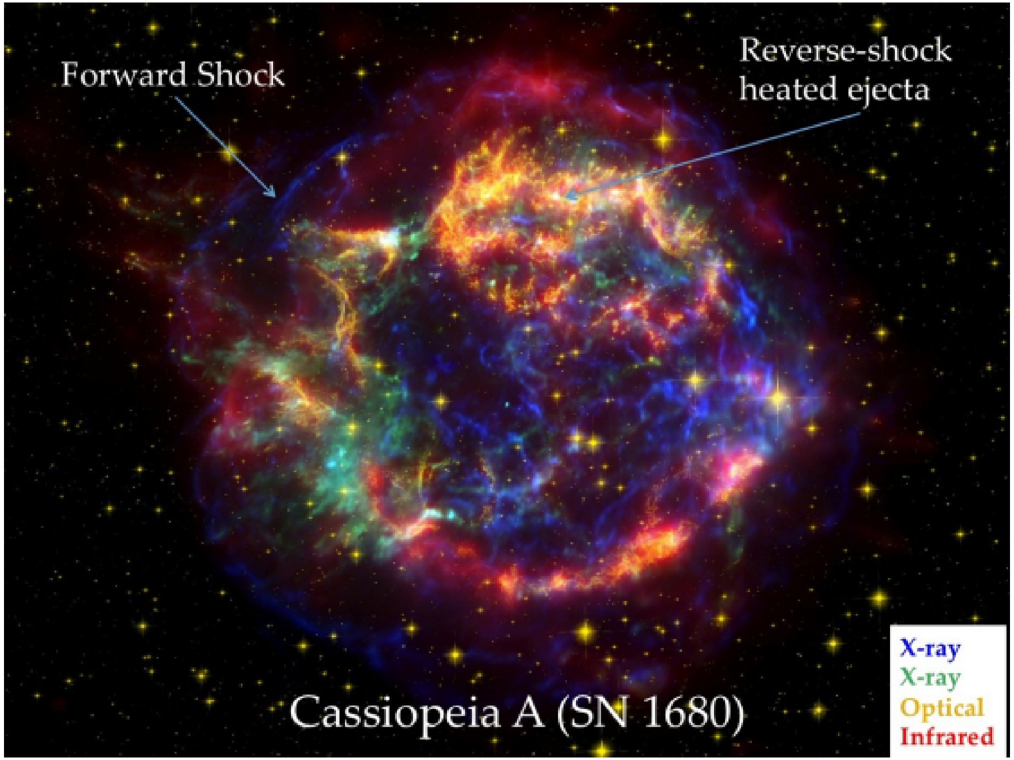
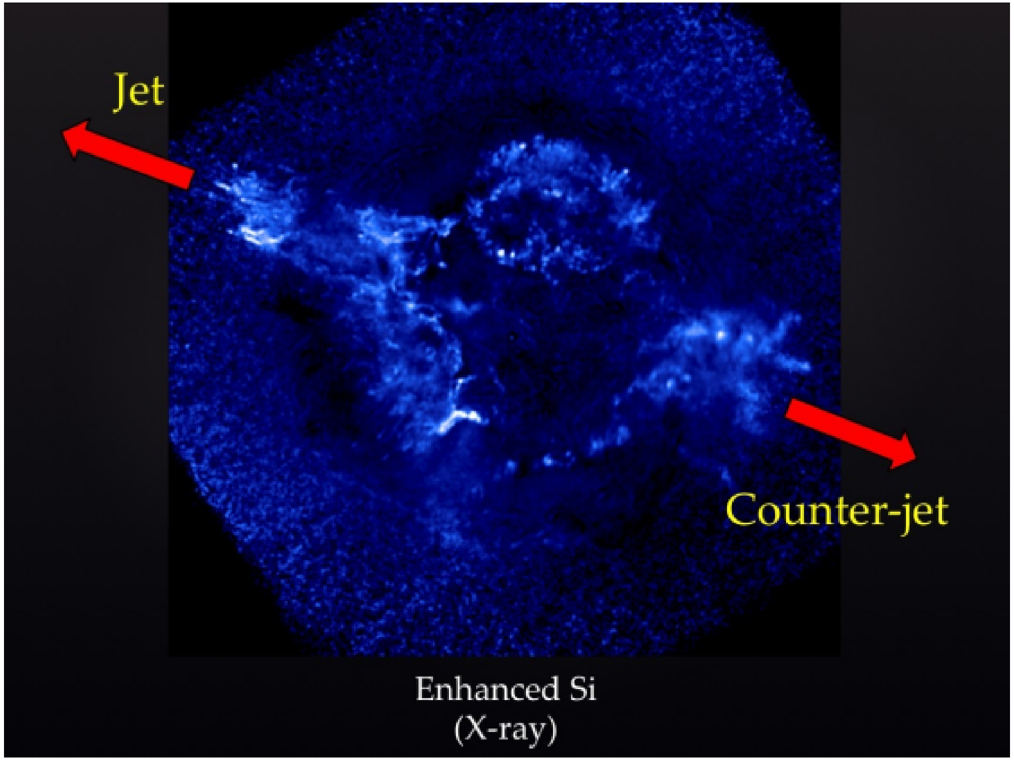


Fig. 1 Three-color *Chandra* image of Tycho's SNR (SN 1572/G120.1+1.4). The color *red* shows Fe-L-shell emission, *green* Si XIII, and *blue* continuum (4–6 keV). Note the very narrow continuum rims near the shock front (*blueish/purple* in this image), caused by X-ray synchrotron radiation from electrons with energies up to 100 TeV (image made by the author from *Chandra* data, see also Hwang et al. 2002; Warren et al. 2005)

Paper by J. Vink

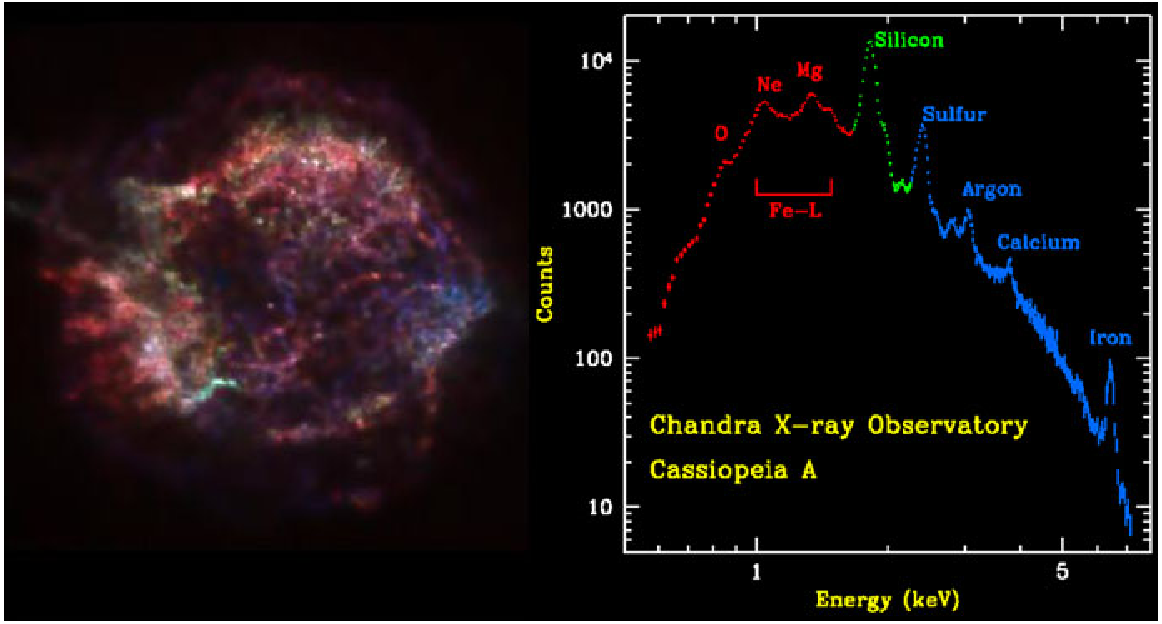
SNR Cas A: Shocks

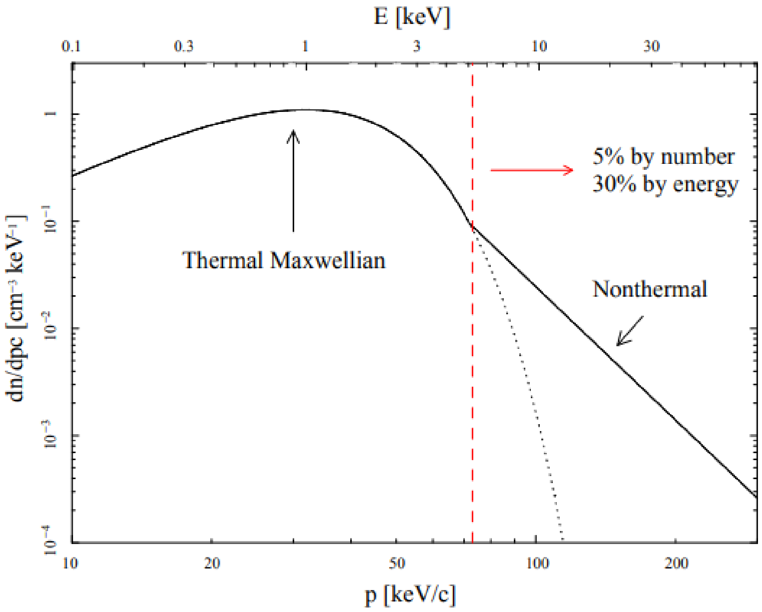




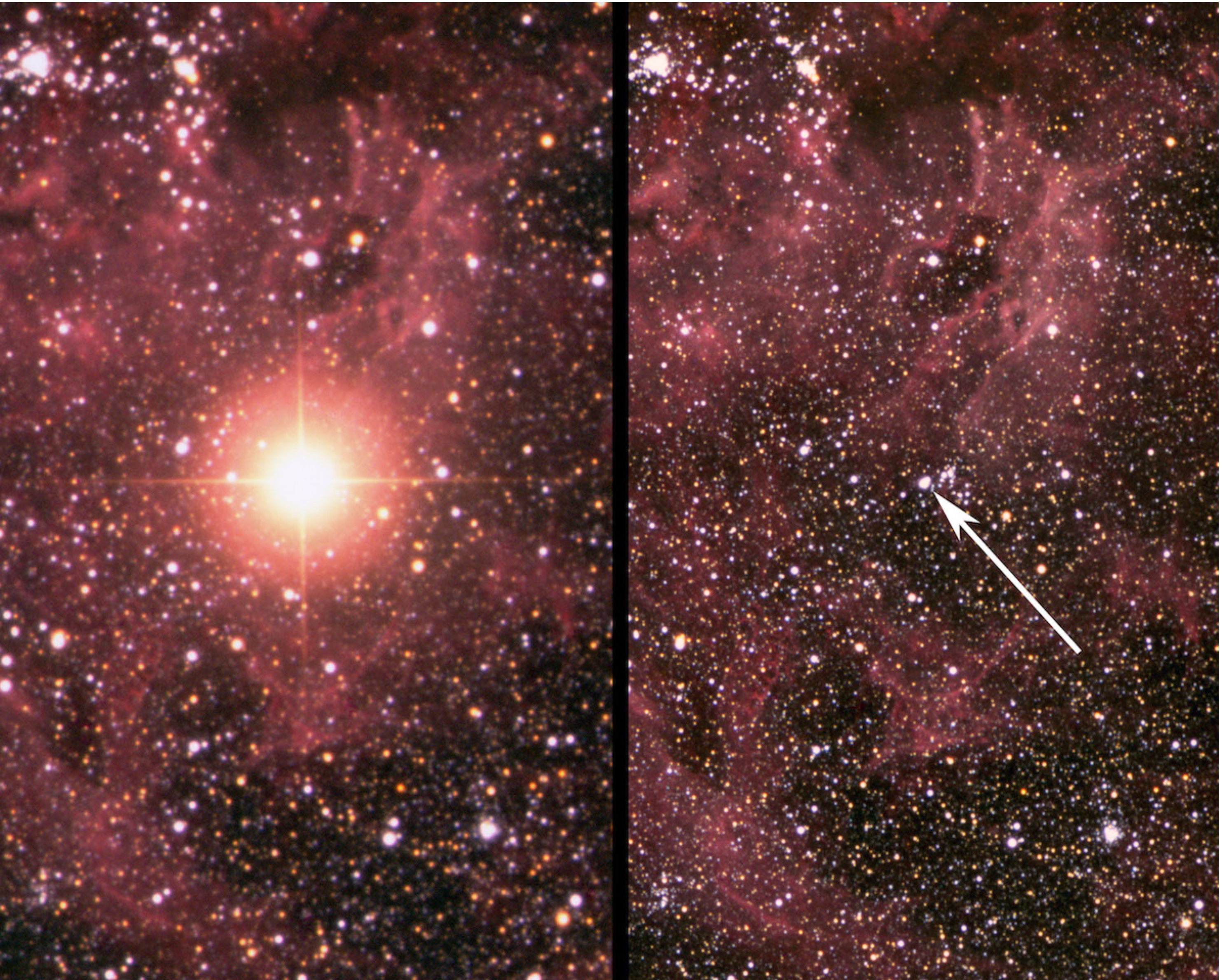
Type II supernova

SNR Cas A: Bremsstrahlung continuum + lines

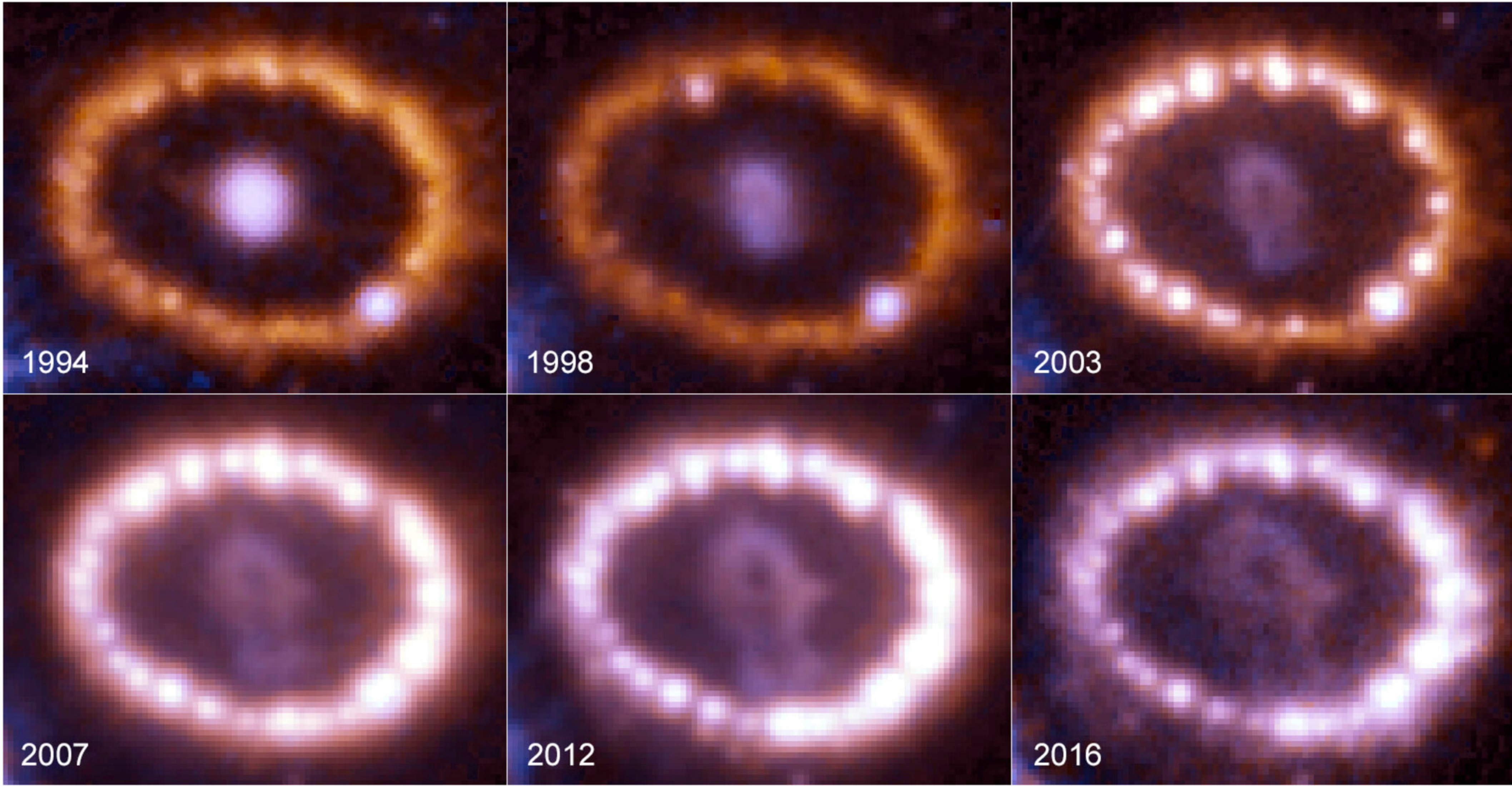




SNR formed after Type II supernova. High energy spectrum shows thermal continuum (bremsstrahlung) + a non-thermal tail. It could be due to either non-thermal bremsstrahlung or synchrotron (with B~0.1 mG). Electron energies of ~57-40 TeV. Inverse Compton/pion decay produces TeV radiation! (*Vink & Laming 2003*)

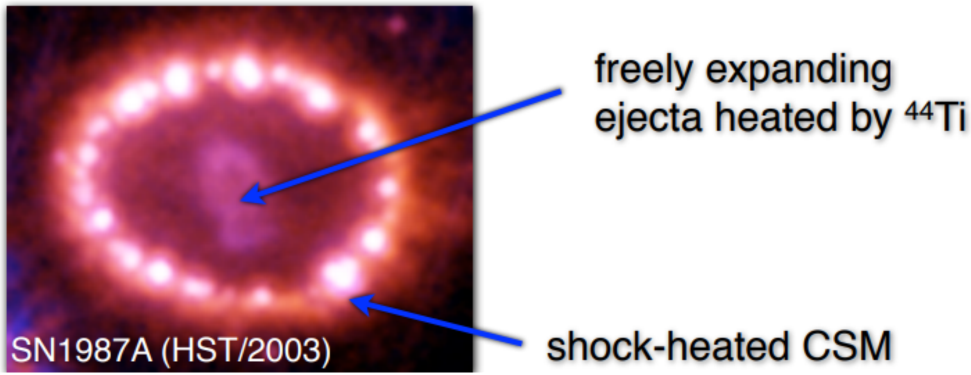


SN 1987a (core collapse)



1994
1998
2003
2007
2012
2016

SN 1987a (Type II)



SN expands → ejecta cools → formation of dust
- Ejecta may still be warmed by late time radio-active heating (e.g., Ti-44)
- Depending on the circumstellar density
    1. outer shock wave heats up a shell that may be detected in X-rays
    2. shock wave may accelerate particles → relativistic electrons → radio emission

This happens if the CSM is dense enough which is a rare event → rarely seen in radio.

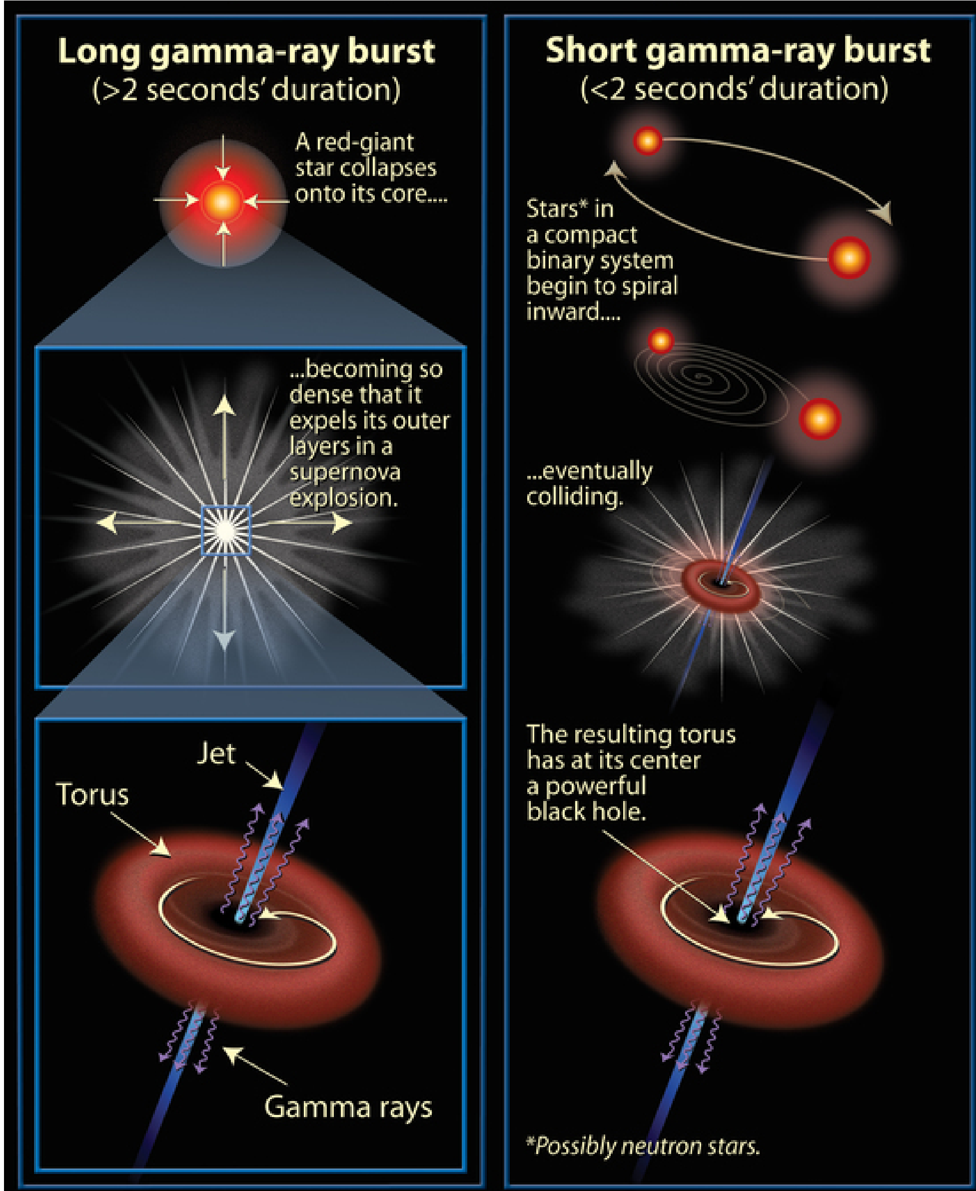
Gamma Ray Bursts

Two types: **long & short**

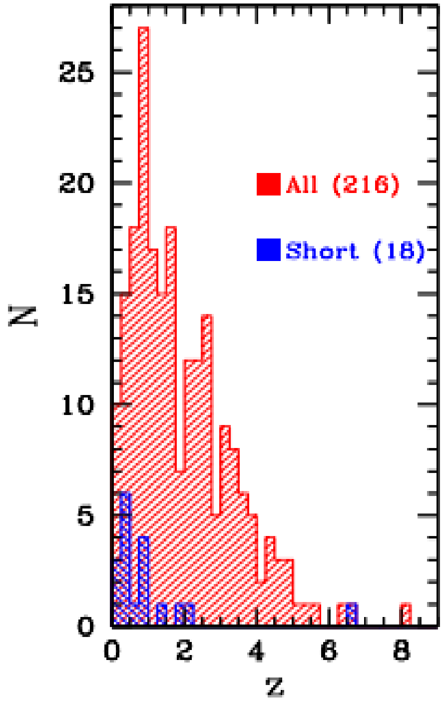
Long → core collapse of a massive star

Short → merger of two neutron stars

Following slides from: *Ghisellini 2010*



Gamma Ray Bursts are Cosmological

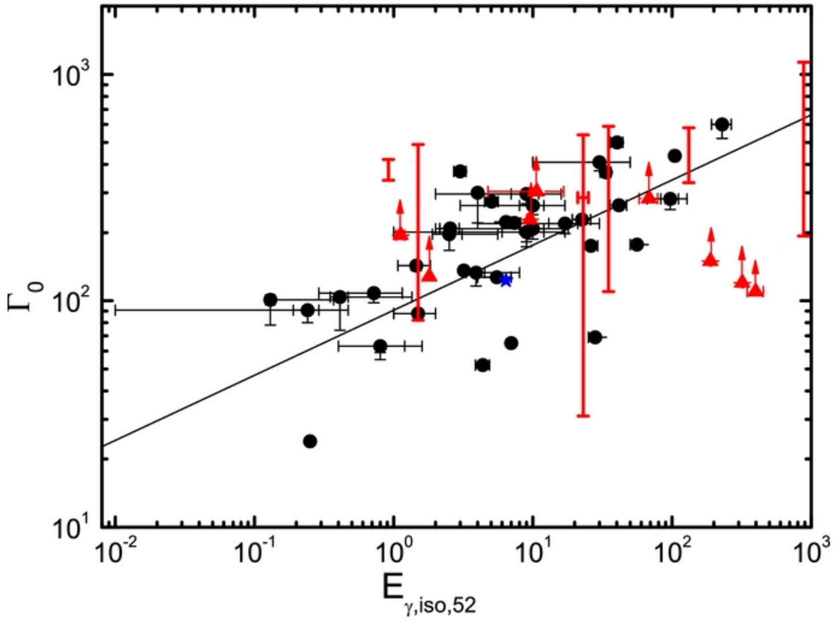


Highest z~8.1 → age of the universe just 600 Myr!

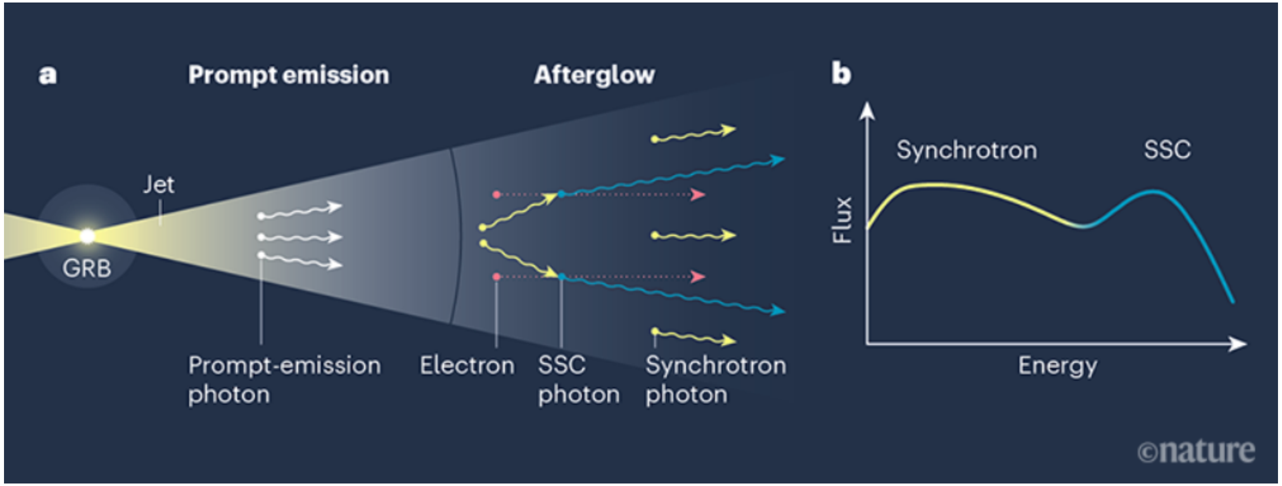
Assuming isotropic emission, the case of GRB990123 is really impressive: only in the gamma-ray domain, it released 3x10^54 ergs, i.e. about twice the rest mass of the Sun. If one supposes a jet-like emission, the energy requirements are reduced by a factor of Omega/4pi with respect to the spherical emission (Omega is the solid angle subtended by the emission cone). On this subject, searches for the so-called ``orphan afterglows'', corresponding to GRBs beamed away from our line of sight, have been performed, only providing limits on the beaming factor.

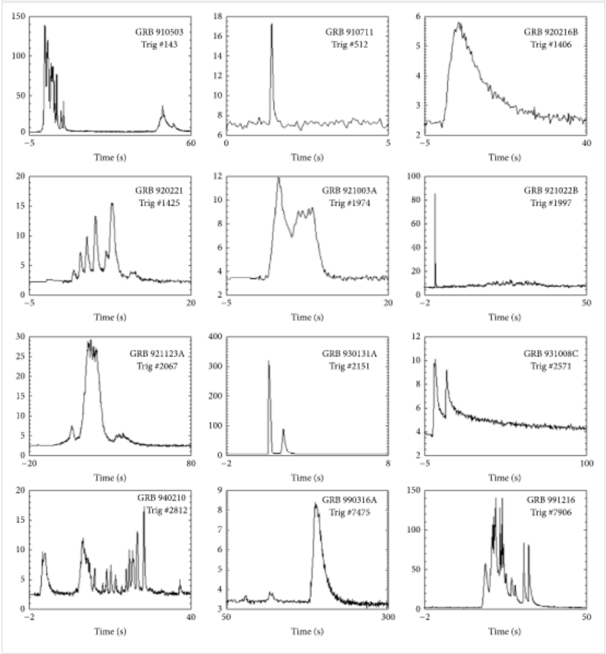
Gamma Ray Bursts are the fastest extended objects in the Universe

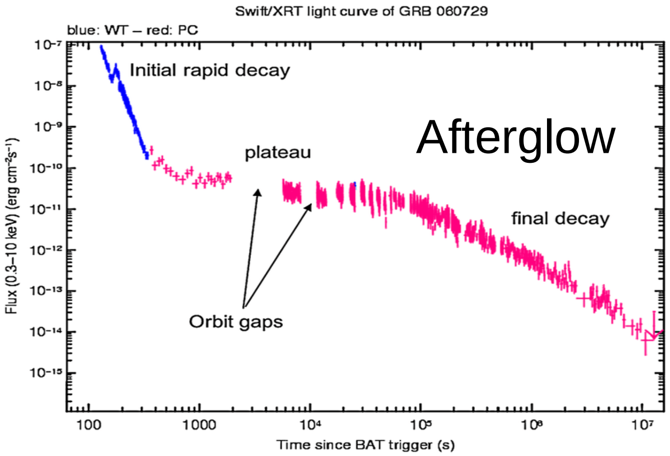
GRBs are the fastest extended objects of Nature, with bulk Lorentz factors Γ that can exceed 1000. The first evidence came from theory: injecting a colossal amount of energy in a small volume (of the order of a few Schwarzschild radii of size) leads inevitably to the formation of electron–positron pairs that makes the so–called “fireball” opaque to the huge internal pressure. The fireball is then obliged to expand, becoming relativistic with $\Gamma \propto R$ until the internal energy is converted into bulk motion (if the fireball remains opaque).



Prompt vs. Afterglow Emission



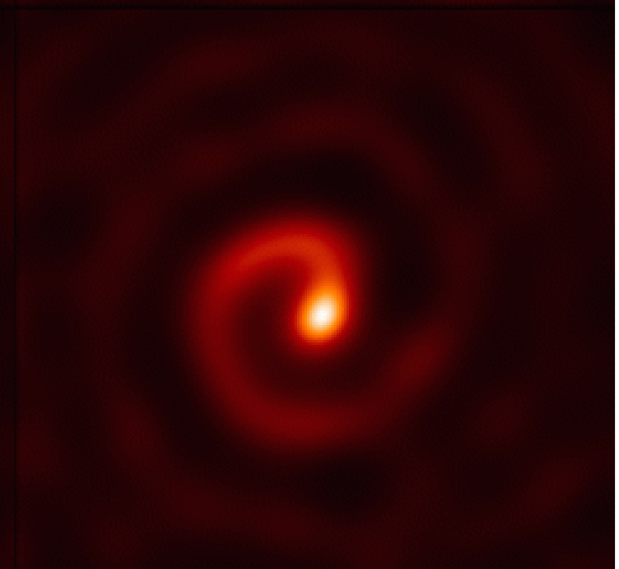




The GRB emission has two phases, the erratic, γ–ray (or hard X–ray) prompt phase, and a smoother afterglow phase. This means that not all the energy of the fireball is radiated away during the prompt, but some remains.

Progenitors

We believed that long GRBs are associated to Supernovae Ib,c, but not all SN Ib,c are associated to GRBs (Soderberg et al. 2006 estimated a fraction less than 1%). The evidence comes from spectroscopy (for nearby events) and re–brightening of the optical light curve (up to z $\sim$1). The association strongly indicates that the progenitor of long GRBs is a massive stars, that has lost its hydrogen and helium envelopes. But there are at least two nearby bursts (GRB 060614, Gal–Yam et al. 2006, and GRB 060505, Ofek et al. 2007) where the SN was not found. If present, it would be at least two orders of magnitude less luminous than SN1998bw (associated to GRB 980425).



Candidate Progenitors in the Milky Way

WR 104 is a massive (25 Msun) Wolf-Rayet star in our galaxy. Its rotation axis was believed to be 16 degrees from Earth. This star might generate a GRB, in which case it would destroy 25% of Earth's atmosphere (despite d = 2.6 kpc).
More recent measurements indicate i~30-40 deg
so the beam of the jet would not be directed towards the solar system...