La Thuile 28/2/2012

SN 1987A: the supernova that changed our views
(Arnon Dar, Technion)

Dar, right after SN 1987A :

From virtually all supernovae, only electromagnetic radiation is observed. The sole exception is the first supernova that was observed this year (SN 1987A) in the Large Magellanic Cloud (LMC). This event confirmed the basic theory for core-collapse supernova and the origin of neutron stars, yielded new limits on neutrino properties and signaled the birth of neutrino astronomy.

25y later:

The newly born neutron star or black hole is still missing

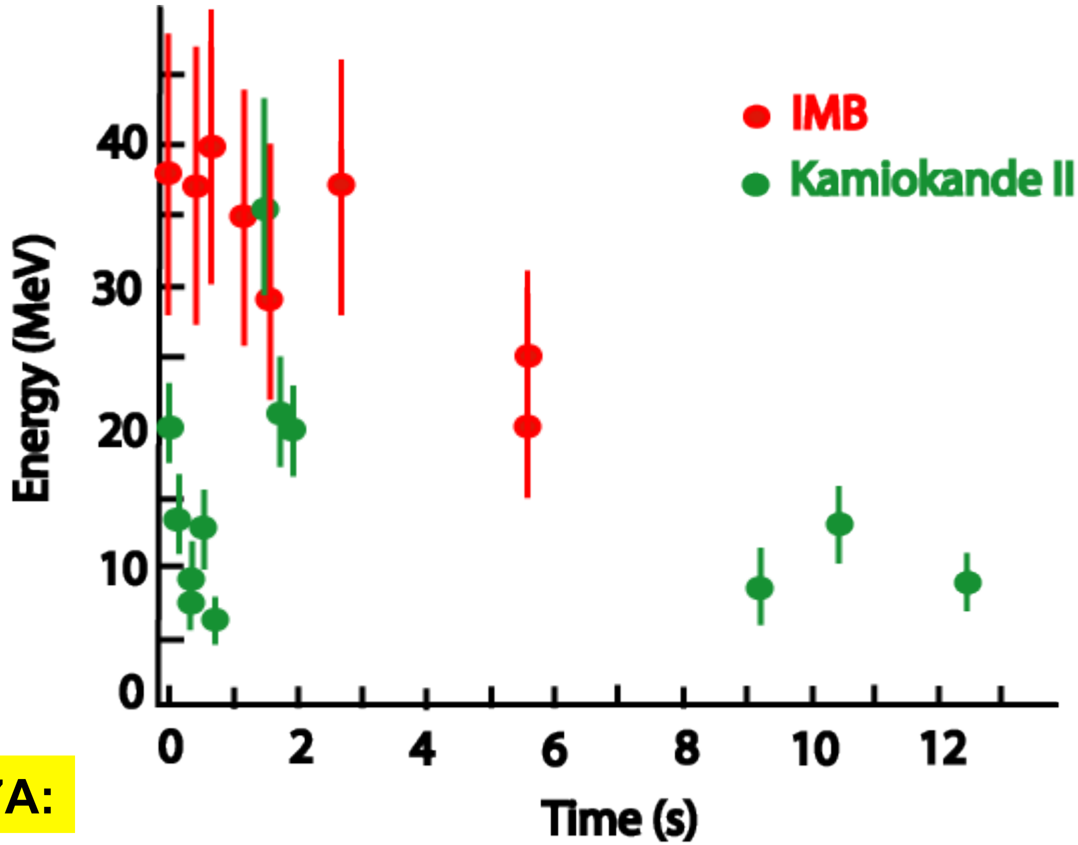
The exploding star was a blue supergiant, while standard stellar evolution theory expects that only red super-giants explode as core-collapse supernovae.

The complex hour-glass shaped nebula with the progenitor star at its center was unexpected and still not well understood

So far, neutrinos from other cosmic sources were not detected

The nutrino signal in the Mont Blanc tunnel and the claimed gravitational wave detection are still debated

The most precise measurements of neutrino masses , mixings and flavors used accelerator, reactor , atmospheric and solar neutrinos



The Neutrinos from SN1987A:

The 8 neutrinos detected by the IMB experiment have greater average energy than the 12 neutrinos detected by Kamiokande II and the 5 neutrinos detected by the Baksan detector because the IMB detector had a higher energy threshold for neutrino detection than the Kamiokande II and the Baksan detectors.

The LVD detector underneath Mont Blanc, saw 5 neutrino events 5 hours before those detected by the other three detectors.The sensitivity of LVD is such that it should only see 1 neutrino from the supernova. The spurious time, the unexpectedly high count rate, and the inability of theory to easily account for such neutrinos cause most astronomers to doubt that this detector observed the supernova. The ambiguity generated by this measurement will persist until other supernovae are seen by neutrino detectors

Despite SN 1987A breakthrogh,

After 40 years and enormous efforts, the most advanced calculations do not reproduce the observed SN explosions :

SNe II: Progenitors produced by numerical codes of stellar evolution do not produce in numerical simulation (with 1D, 2D or 3D codes) core collapse SNe , but end up in a complete collapse to a black hole .

SNe Ia : The leading mechanism for thermo-nuclear supernova explosions - the single-degenerate model in which a progenitor white dwarf accretes material from a non-degenerate companion star and cross The Chandrasekhar mass limit and collapses, (Whelan & Iben 1973) or the double-degenerate model in which two white dwarf in a compact binary merge due to gravitational wave emission Webbink 1984; Iben & Tutukov 1984)- have not been shown in numerical calculations to produce SNe Ia. Deep searches of a left over companion have not found any and archival searches for a double degenerate progenitors of observed SN Ie have not found any one.

MISSING CENTRAL COMPACT OBJECT ?

SN 1987A appears to be a core-collapse supernova, which should result in a compact star such as a pulsar (a neutron star or a quark star ?) or a stellar mass black hole. The size/mass of the original star and the neutrino burst (total energy, spectrum, light-curve) indicate that a compact object did form at the star's core. However, since the supernova first became visible no evidence of a central compact object like that in Cas A was found so far in radio, mm, FIR, Optical, UV, X-ray and gamma-ray observations.

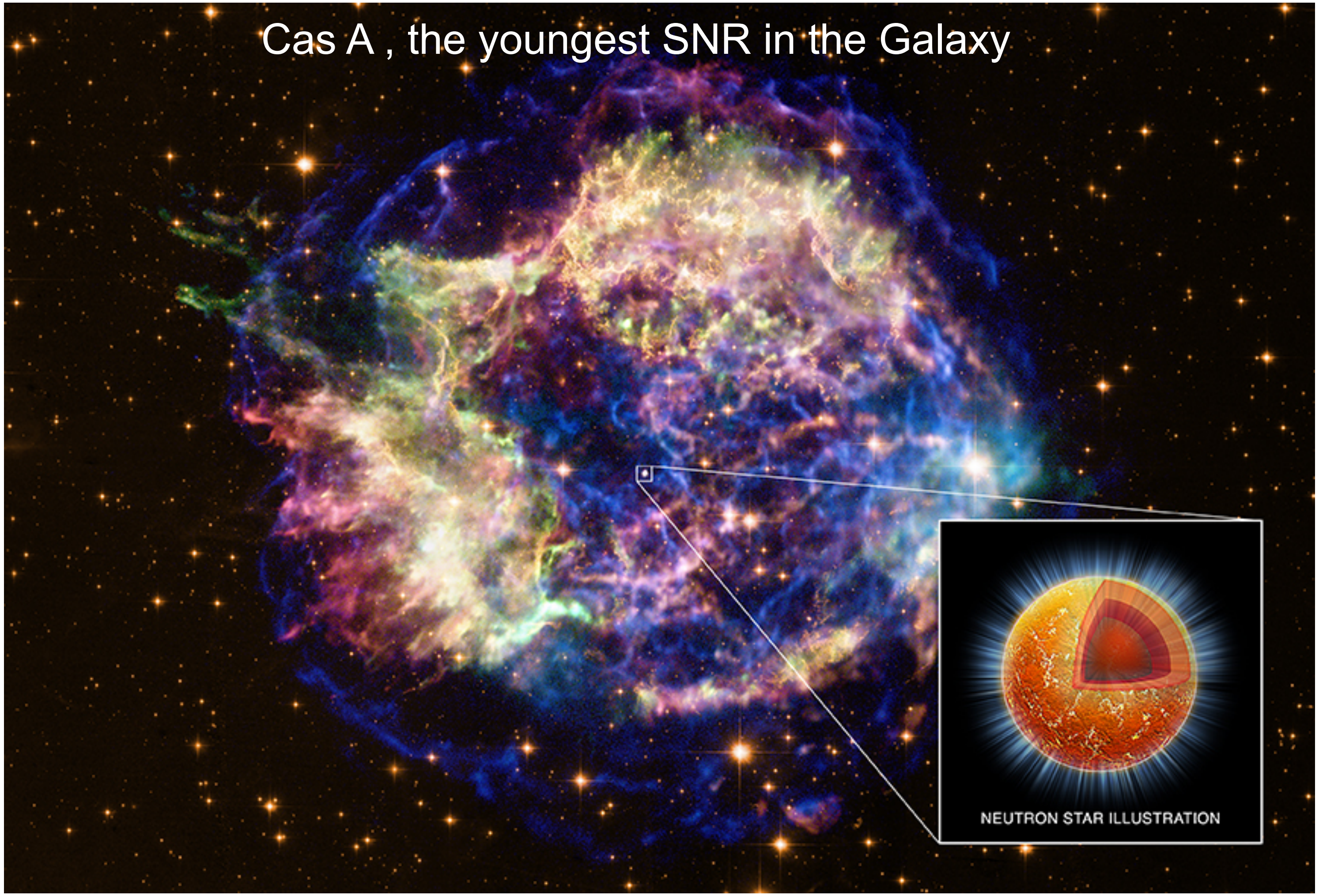
A number of possibilities for the 'missing' compact star have been considered, although none is clearly favored:

The compact star has cooled more rapidly than expected

The compact star is enshrouded in dense dust clouds and cannot be seen.

A pulsar was formed, but with an unusually small magnetic field
to be detected as a normal pulsar.

The compact star collapsed into a black hole by large amounts of material which fell back on it but it is very dim and avoids detection because of too small mass accretion rate - only little material was left near it.



The expanding debris cloud spans about 15 light-years in this composite X-ray /optica image, while the bright source near the center is a neutron star (insert illustration) . 10 years of observations with the orbiting Chandra X-ray observatory find that the neutron star is cooling so rapidly that probably a large part of its core consists of a frictionless superfluid.

SN1987A Limit On The Neutrino Speed

$$\Delta t_{\nu\gamma} = \Delta t_{\nu\gamma}(\mathrm{SN1987}) + \frac{D}{c}\left[\frac{c - v}{v}\right] < 3\mathrm{h}$$

$$\left[\frac{c - v}{v}\right] < 3\mathrm{h}\,\frac{c}{D} \approx 2\cdot 10^{-9}$$

IF OPERA's MEASUREMENTS OF THE NEUTRINO SPEED WERE CORRECT THEY WOULD IMPLY THAT NEUTRINOS ARE NOT TACHYONS

$$\Delta t_{\nu\gamma} \equiv t_{\nu}(d) - t_{\gamma}(d) = t_{\nu}(S) + \frac{D}{V} - \left[t_{\gamma}(S) + \frac{D}{c}\right]$$

$$V_g = \frac{\partial E}{\partial p} = \frac{pc}{E} \quad \text{for } E^2 = p^2c^2 + m_{\nu}{}^2c^4$$

$$0 \le V \le c \qquad \text{for } m^2 \ge 0 \qquad (\text{ordinary particles})$$

$$c \le V \le \infty \qquad \text{for } m^2 < 0 \qquad (\text{tachyons})$$

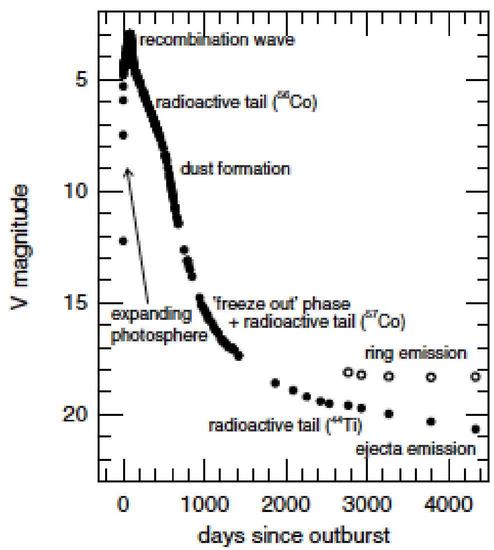
$$\Delta t_{\nu\gamma} = \Delta t_{\nu\gamma}(S) + \frac{D}{c}\left[\frac{E}{pc} - 1\right],$$

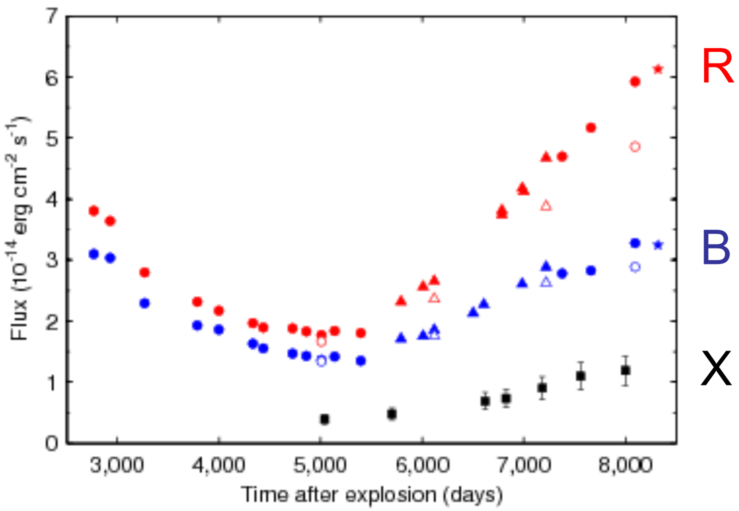
$$\Delta t_{\nu\gamma} = \Delta t_{\nu\gamma}(S) + \frac{D}{c}\,\frac{m_{\nu}{}^2c^4}{2E^2} \qquad \text{for } \left|m_{\nu}{}^2c^4\right| << E^2$$

What powers the lightcurve of supernovae ?

When a massive star explodes as a supernova, substantial amounts of radioactive elements—primarily 56**Ni,** 57**Ni and** 44**Ti are produced. After the initial flash of light from shock heating, the fading light emitted by the supernova is due to the decay of these elements (Stirling Colgate). However, after decades, the energy for a supernova remnant comes from the interaction between the ejecta and the surrounding medium. The transition to this phase has now been seen for the first time in SN 1987A**

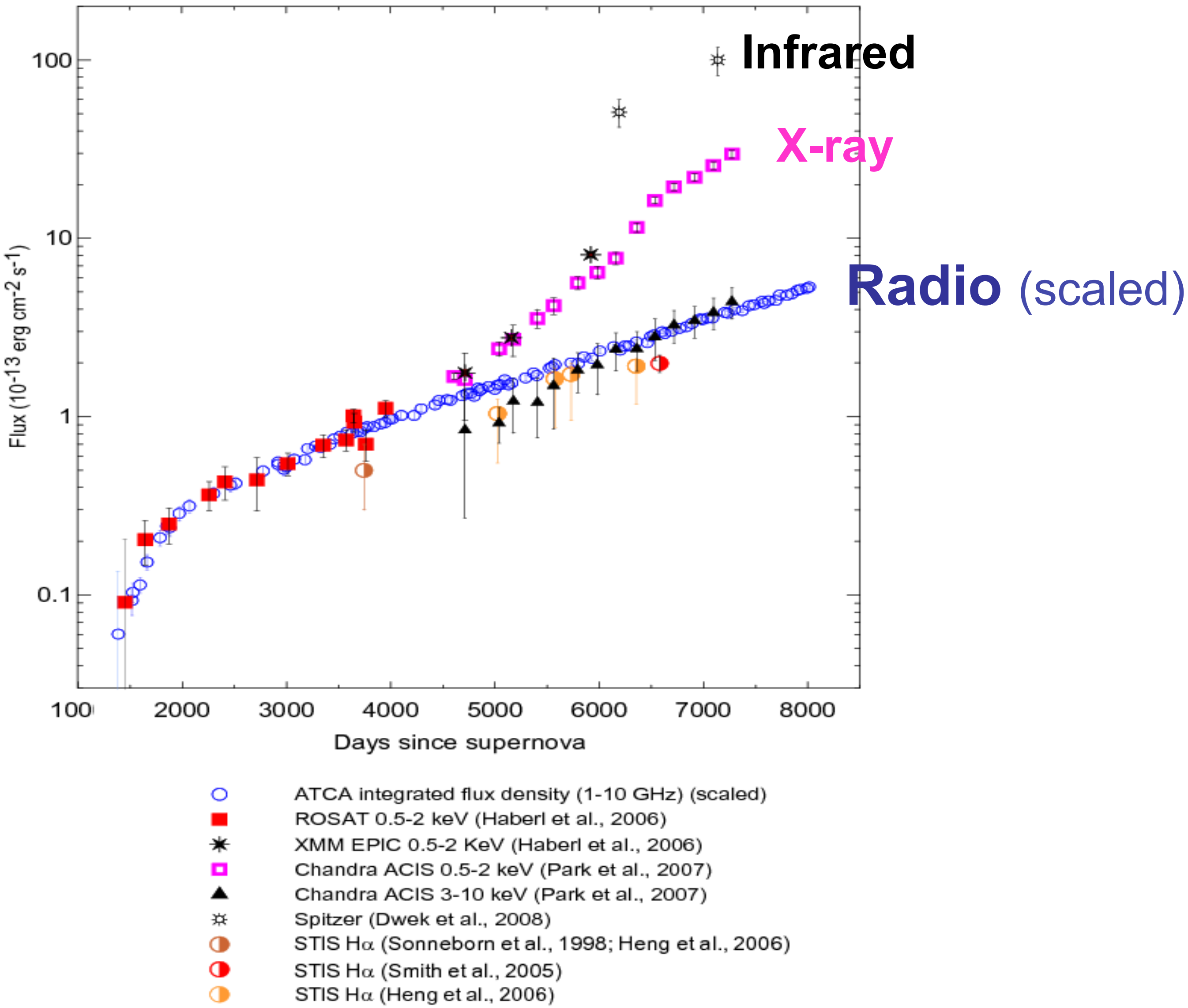
Bruno Leibundgut

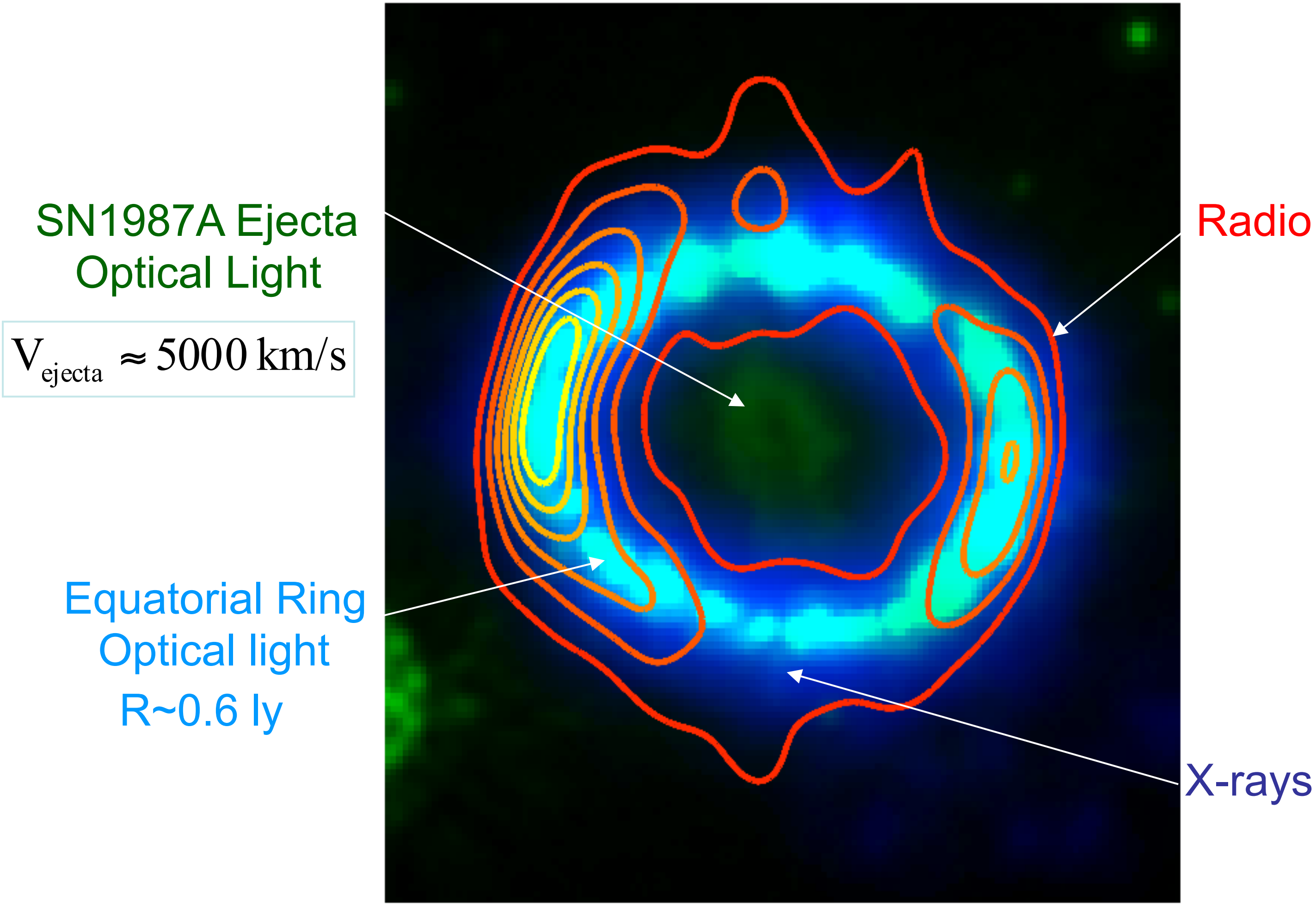




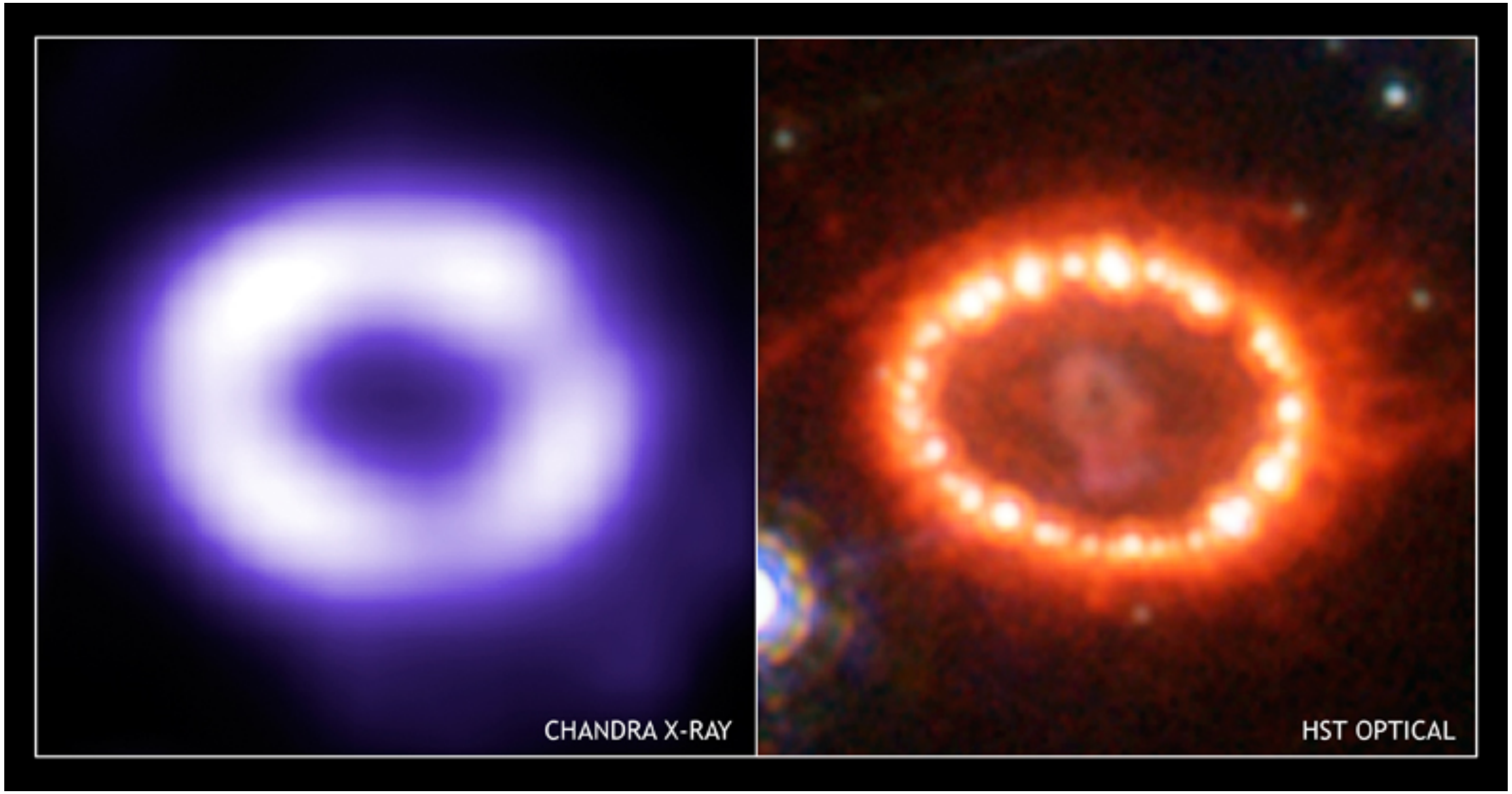
What powers the rising optical light curve of SN 1987A ?

X-ray illumination of the ejecta of Supernova 1987A (Larson et al. Nature 2011) ?
The impinging ISM particles in the ejecta rest frame (like in a Roentgen machine) ?

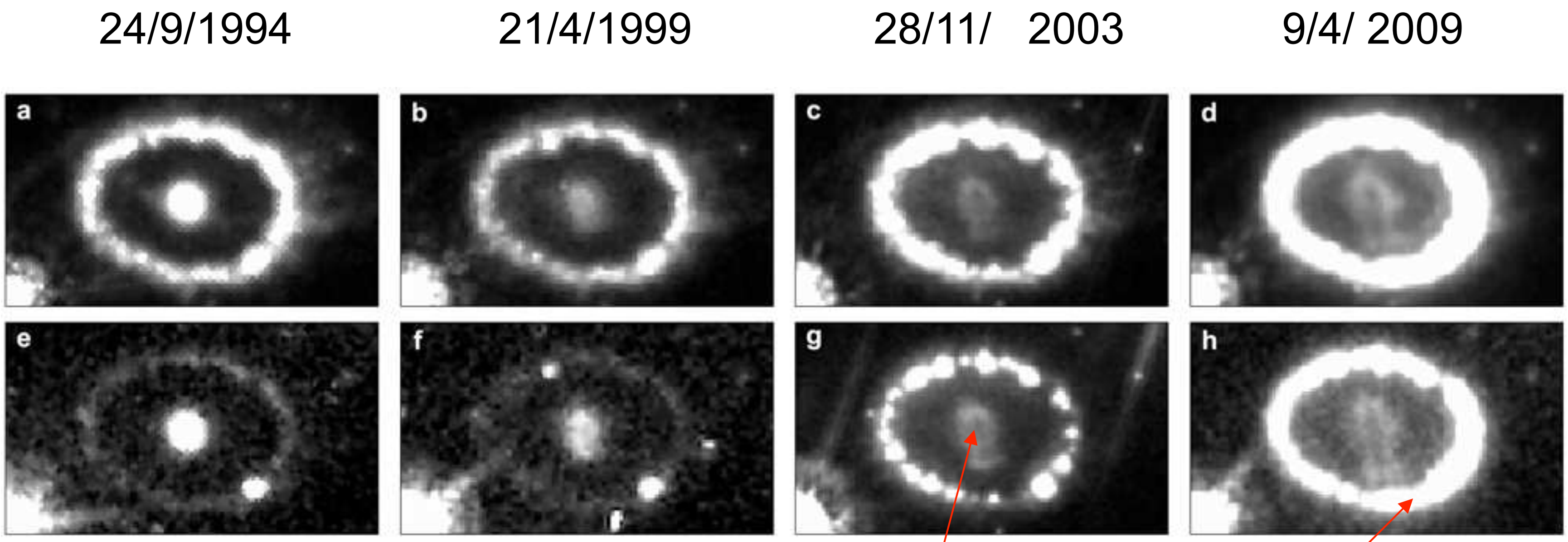




SN1987A: Overlay of the combined HST 2006 Dec 6 optical (green), Chandra 2008 Jan 9-11 X-ray (blue), and ATCA 2008 Oct 36.2 GHz radio images (orange-yellow contours) formed by shifting the optical and X-ray coordinate systems to center on the radio ring from the 2008 Oct 36.2 GHz radio image at robust=0.5 weighting. Radio contours are at 14 (orange), 30, 40, 60, 70 and 85% (yellow) of the maximum at 2.4 mJy beam^{-1}. The outermost contour and the contour within the optical ring are at the same 14% level.


CHANDRA X-RAY
HST OPTICAL

HST images of SN 1987A. (J. Larsson et al. 2011)

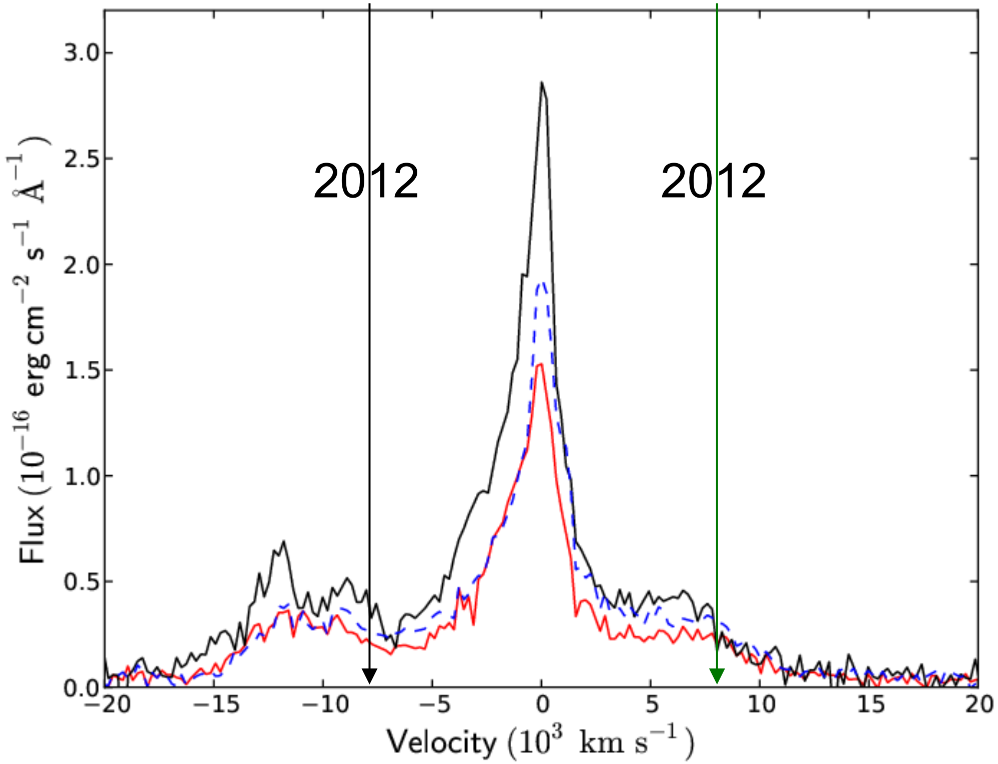


The images show the evolution of the ejecta and the equatorial ring as a function of time. The top row shows the R-band and the bottom row shows the B-band. Note the expansion of the ejecta and the brightening of spots in the equatorial ring.

Superposition of velocities seen in a slit centered on the ejecta

flight time (years) of the velocity components to the equatorial ring

10 13 20 40 ∞ 40 20 13 10



Hubble Space Telescope Hα profiles of the ejecta. The red and black lines are for a 0.2″ slit placed in the north-south direction and centred on the ejecta in 2004 and 2010, respectively. The

Fig. 1.— An image of the Helix nebula obtained with the Subaru Telescope. At an approximate distance of 700 light years, the Helix Nebula is the closest example of a planetary nebula created at the end of the life of a Sun-like star. The most striking feature of the Helix, first revealed by ground-based images, is its collection of more than 40,000 distinct gas blobs that resemble comets due to their compact heads and long, streaming tails. Each 'cometary blob' is about twice the size of our solar system and has about an Earth's-mass of hydrogen and other gases that were expelled from the nebula's central star thousands of years ago. Image Credit: Matsuura, M. et al. (National Astronomical Observatory of Japan).

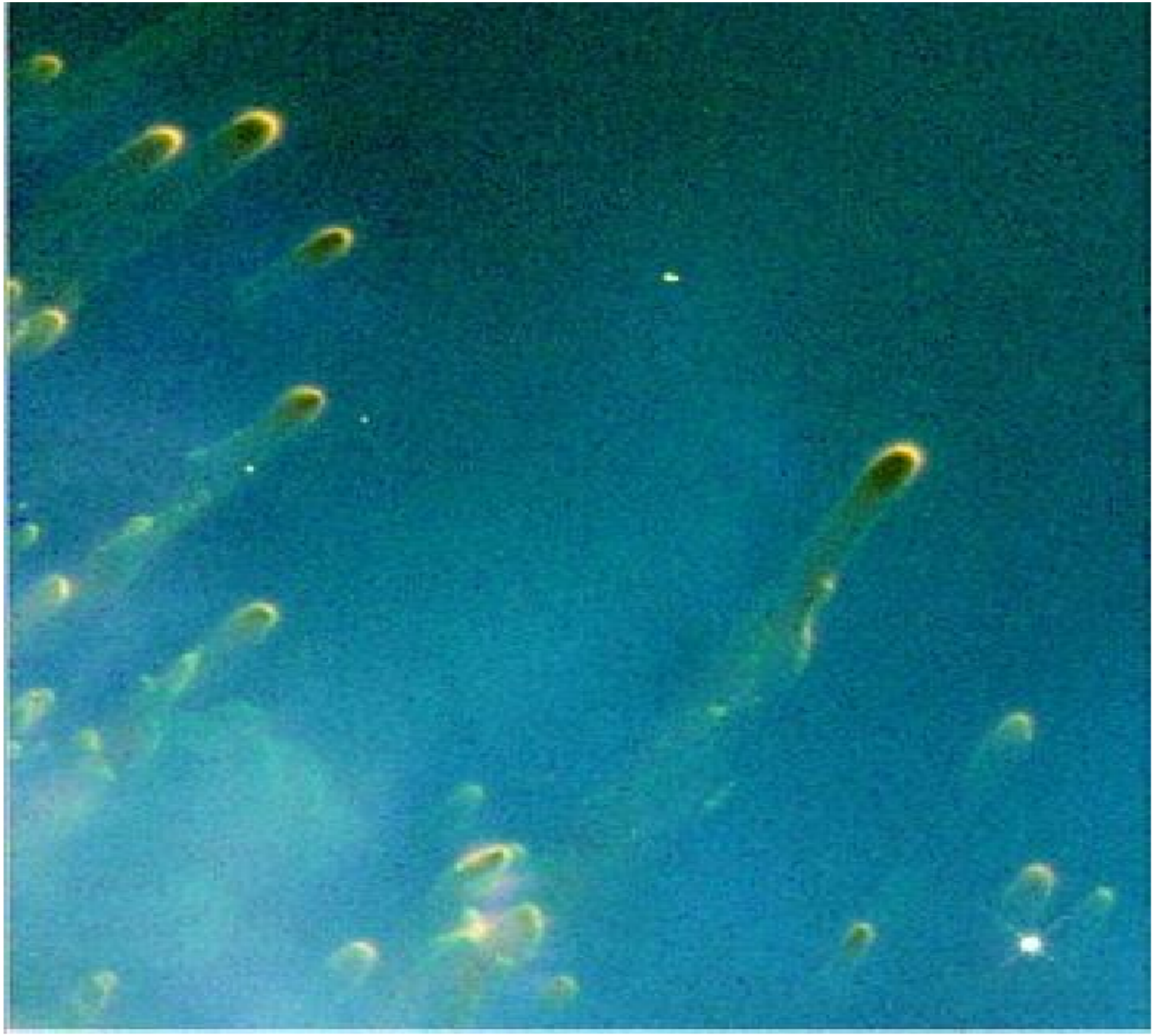
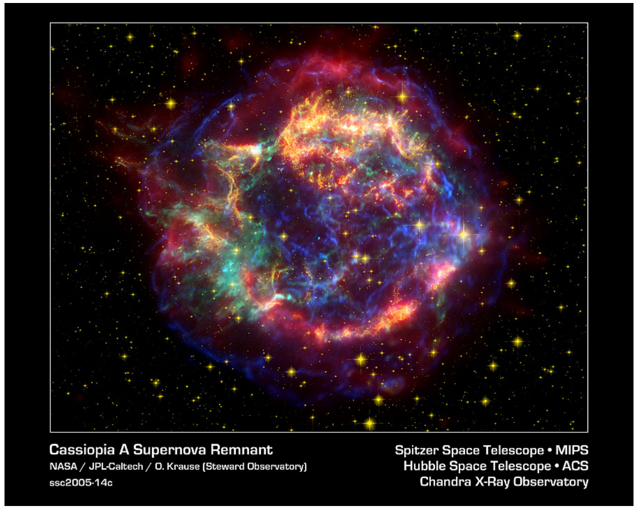


Fig. 2.— Hubble Space Telescope zoom on a section of the Helix Nebula showing in great detail some of its cometary blobs. The tails of these gas blobs, which resemble the much

Are the ejecta of SNe Clumpy?



The outer 1825 CBs observed with HST in the SNR Cass A (Fesen et al. 2006) have typical velocities V≈ 10, 000 km/s, a radius R ≈ 0.1″ corresponding to 0.002 pc (at 3.4 kpc, the estimated distance to Cas A), and n(b) ≥ n(e) = 0.7 × 10^4 cm−3, i.e., a mean column density N~6 × 10^19 cm−2, and a mass ≥1.2 × 10^28 g (~twice that of Earth).

The measured radial velocities of over 450 CBs in SNR 3C 58, reveal (Fesen et al. 2007) two distinct populations, one with average projected velocities of 770 km/s, and the other showing velocities less than 250 km/s. It was suggested that the low velocity populations were formed in the ejecta of the progenitor star long before its supernova explosion while the higher velocity CBs were formed during or after the SN explosion.

Did SN1987A Bang Twice ? -- Evidence From Gamma Ray Bursts (GRBs)?

Flares 200-800 s after GRBs by fall-back (accreted) matter ?

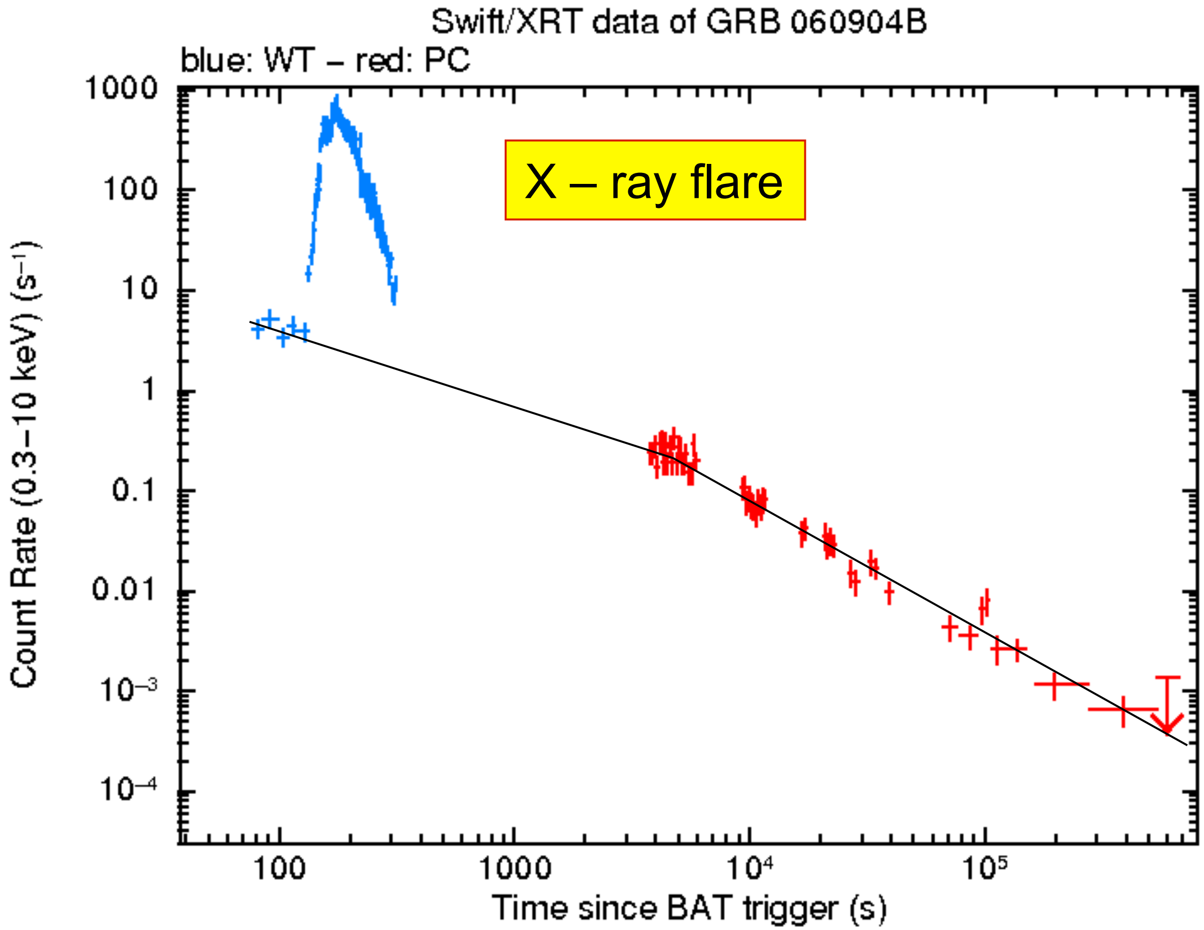
GRBs produced in SNIb/c
Progenitors lost H+He envelope
➔Large Blue Star Progenitors

$$R \sim 10^{11}\,\mathrm{cm}$$

SN1987A
Progenitor: Blue Supergiant

$$R \sim 10^{12}\,\mathrm{cm}$$

Ratio of free fall-back times



$$t_{ff}(\mathrm{SN1987A}) \sim \left(\frac{R_{BSG}}{R_{LBS}}\right)^{3/2} T'_{flares}(\mathrm{GRBs}) \sim 30\, T'_{flares}(\mathrm{GRBs}) \sim 2\mathrm{h}$$

Neutrino astronomy – a dream which has not been realized ?

When the first large underground water Cerenkov detectors, IMB and Kamiokande, were constructed to look for proton decay, it was suggested that they can also perform as neutrino telescopes (e.g., Dar PRL 1983) which may detect neutrino bursts from galactic supernova explosions and the diffuse cosmological neutrino background from stellar evolution and past supernovae. It was dramatically demonstrated when the Kamiokande IMB telescopes detected the neutrino burst from SN 1987A.

This monumental success has probably convinced physicists and funding agencies that galactic and extragalactic neutrino astronomy are not just a dream but are important achievable scientific goals: The Universe is opaque to very high energy gamma rays because of e+e- pair production on intergalactic background photons. It is, however, transparent to neutrinos and it was anticipated that large enough neutrino telescopes ($\sim 1\ km^3$), may detect very high energy neutrinos from Active Galactic Nuclei at cosmological distances, from Gamma Ray Bursters, from galaxy clusters and the intergalactic space, and from other unexpected sources, and may identify the cosmic ray accelerators and solve the 100 years old mystery of the origin of the high energy cosmic rays.

AMANDA/IceCube detector under the south pole, and Baikal , NESTOR and ANTARES deep sea projects: So far, no detection of cosmic neutrinos