SUPERNOVAE
PhD Course 2013, SISSA

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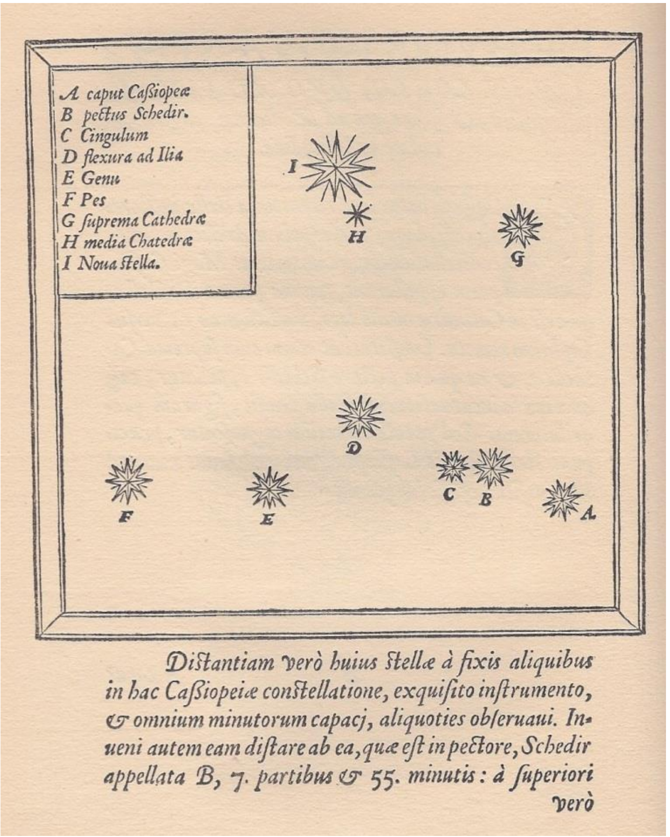
I. Introduction

New Stars

Historical 'New Stars'

Appearance of a *new star* recorded in the most ancient documents (comets, novae and supernovae)

- Earliest recorded by Chinese astronomers in 185 AD: SN 185 (SNR RCW 86)
- Brightest historical supernova: SN 1006 (SNR 1006)
- Supernova SN 1054 produced the Crab Nebula
- Supernovae SN 1572 (Tycho SNR) and SN 1604 (Kepler SNR), the latest to be observed with the naked eye in the Milky Way galaxy



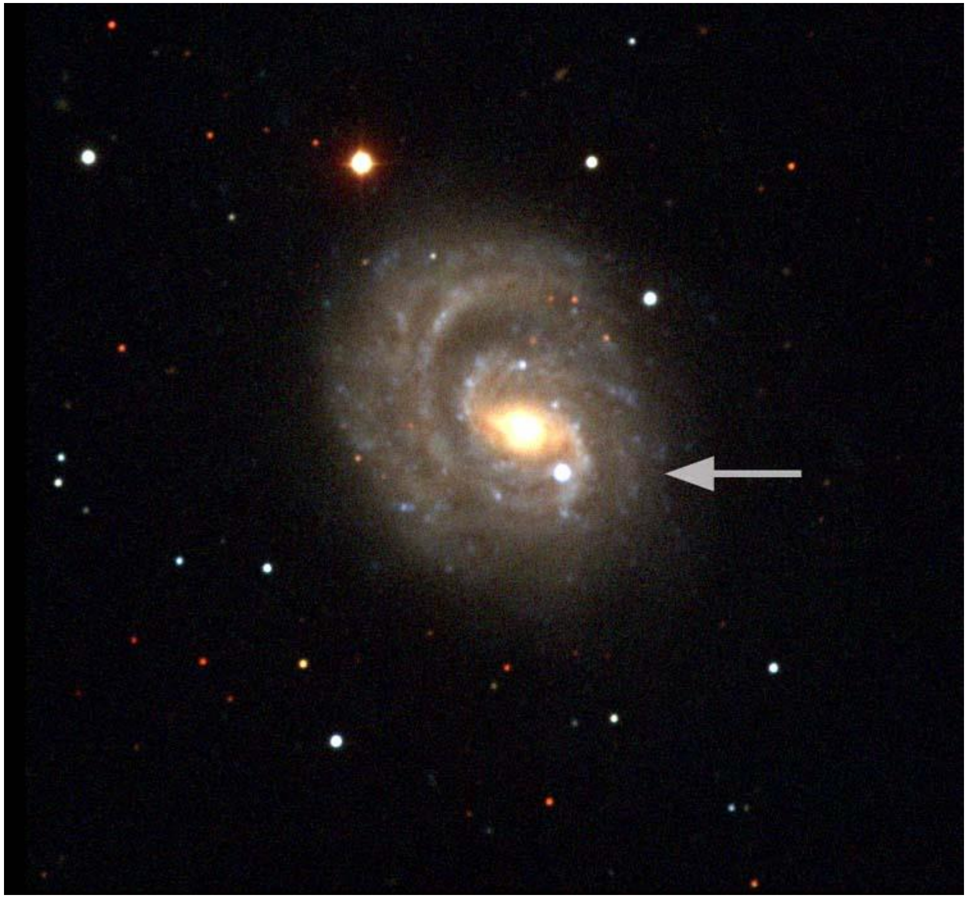
Picture of SN 1572 from Tycho Brahe's *De nova et nullius aevi memoria prius visa stella* ("Concerning the New Star, never seen before in the life or memory of anyone")

A bit more history

Modern history of supernovae began in 1885 with the discovery of a bright event in the Andromeda galaxy. A few other events were found serendipitously during the early telescopic observations of spiral nebulae

“*It is quite possible that we have to deal with two distinct classes of Novae: one 'upper class' having comparatively few members and reaching an absolute magnitude more or less equal to the absolute magnitude of the system in which they appear: one 'lower class' in the mean 10 magnitudes fainter* …” (Lundmark 1925)

Enormous luminosity of these events definitely established after the extragalactic nebulae were placed at their actual distances, leading Baade & Zwicky (1934) to define them as **super-novae**

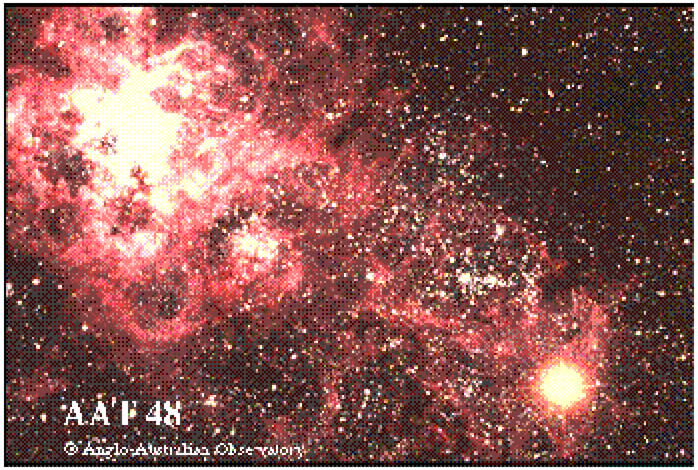


BVI image of Supernova 1999em in
NGC 1637. Credit: Nick Suntzeff

This color image of Supernova 1998bu
in M96 was made with BVI data.
(Credit: Nicholas B. Suntzeff)

HST image of Supernova 1994D in NGC 4526 from CfA taken on 5/9/94

SN 1987A



• February 23, 1987: Shelton and Jones (1987) announce the discovery of a supernova in the Large Magellanic Cloud, **SN 1987A**

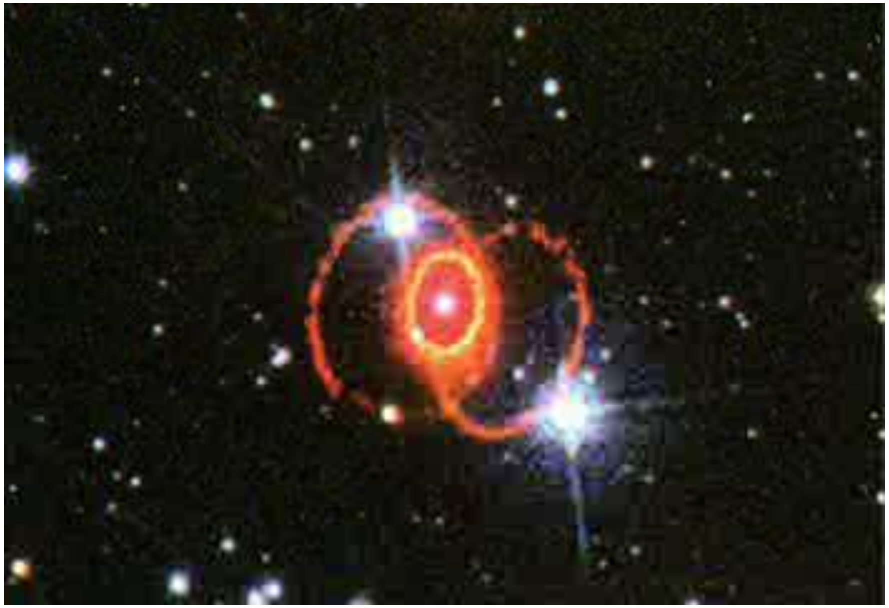
• *Brightest supernova observed after that recorded by Kepler in 1604 (SN 1604)*

• First supernova to be observed in every band of the electromagnetic spectrum (from radio to gamma-rays)

• First detected through its initial burst of neutrinos, revealed by the Mont Blanc, Kamiokande, IMB and Baksan underground detector

• For a review on SN1987A see Arnett et al. (1989), McCray (1993), Panagia (2005)

SN 1987A: rings



SN 1987A, its companion stars, and the circumstellar rings (Credit: Dick McCray)

Initial flash of light from the supernova explosion causes the ring to glow. Debris hurls into space, the fastest moving at 1/10 the speed of light. The supernova's shockwave and the impact with the ejecta cause the ring to glow again. The closer the pieces of the ring are to the shockwave, the sooner they light up
(Credit: T. Goertel, The Space Telescope Science Institute)

- Ejected ~20000 years before explosion
- Only the inner surfaces of a much greater mass

Light curves and spectra of supernovae

Supernovae: The most luminous and energetic stellar events

Typical peak luminosity and duration:

L = 3.0e42 erg/s (a billion time the Sun luminosity)

t = 100 days = 8.0e6 s

Radiated energy: ***Er = L t = 1.0e49 erg*** (emitted by the Sun in 100 million years)

Typical ejecta mass and velocity:

(A) *M = 1 Msun = 2.0e33 gr*

V = 5.0e8 cm/s

(B) *M = 5 Msun = 1.0e34 gr*

V = 3.0e8 cm/s

Kinetic energy of the ejecta: ***Ek = M V2 = 1.0e51 erg*** *(1 foe) = 100 Er*

SN Types: classification

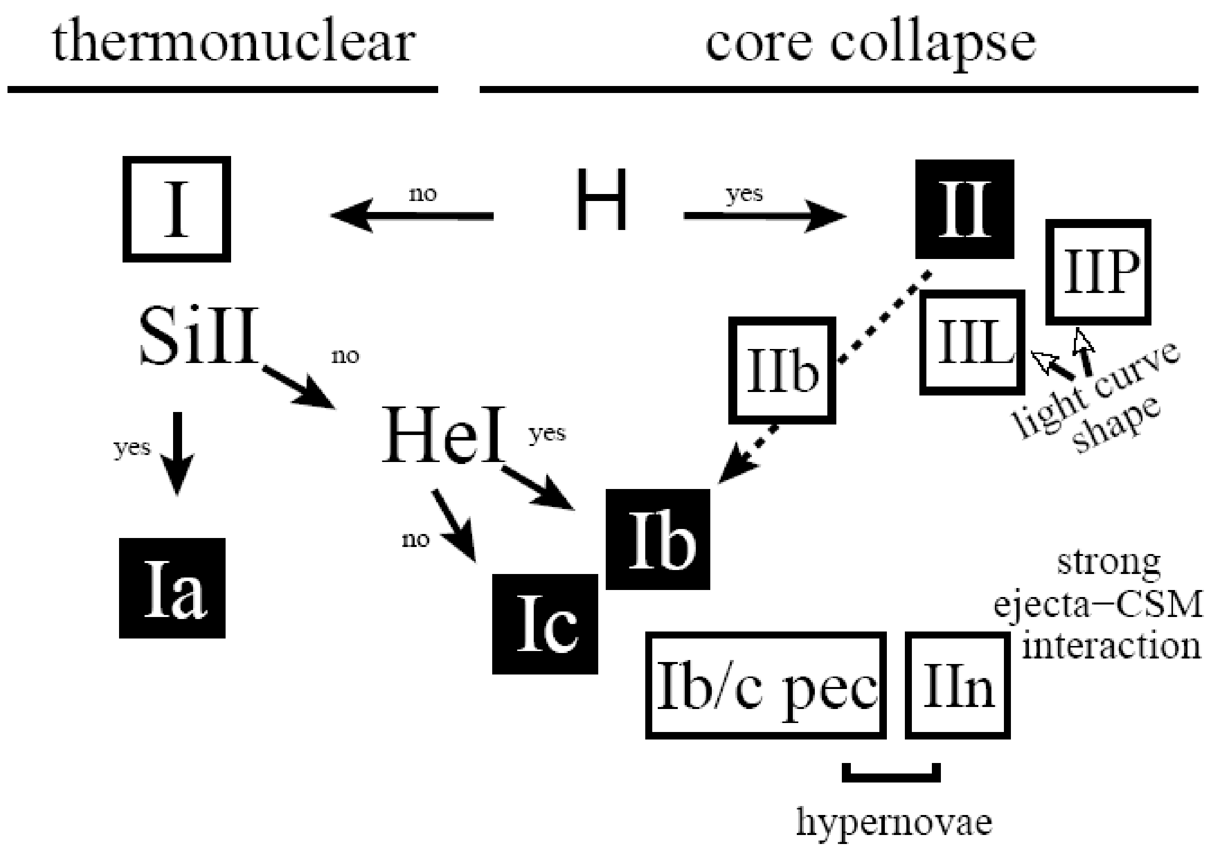
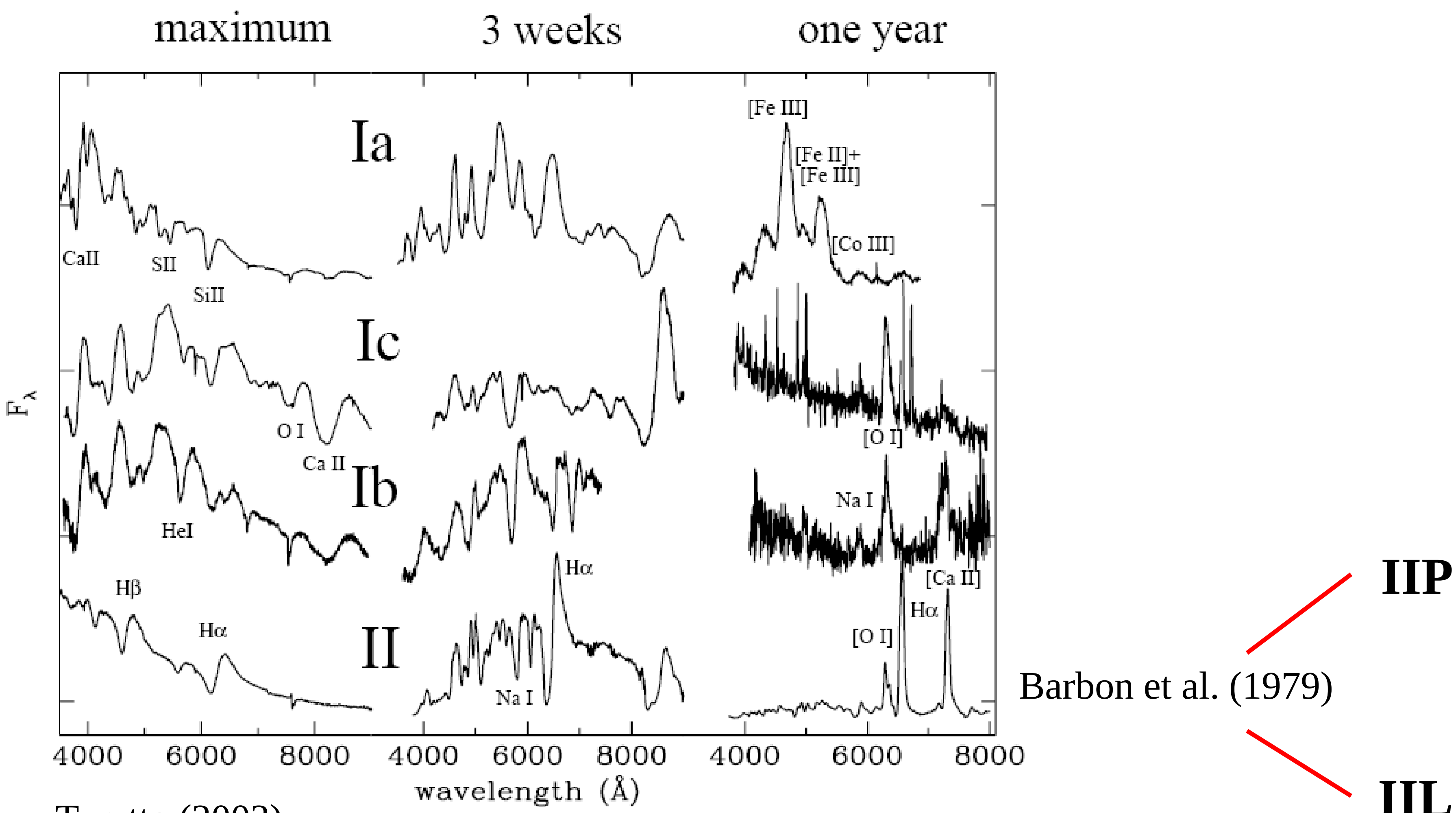


Fig. 1. The current classification scheme of supernovae. Type Ia SNe are associated with the thermonuclear explosion of accreting white dwarfs. Other SN types are associated with the core collapse of massive stars. Some type Ib/c and IIn SNe with explosion energies $E > 10^{52}$ erg are often called hypernovae.

(Turatto 2003)

SN Types: classification

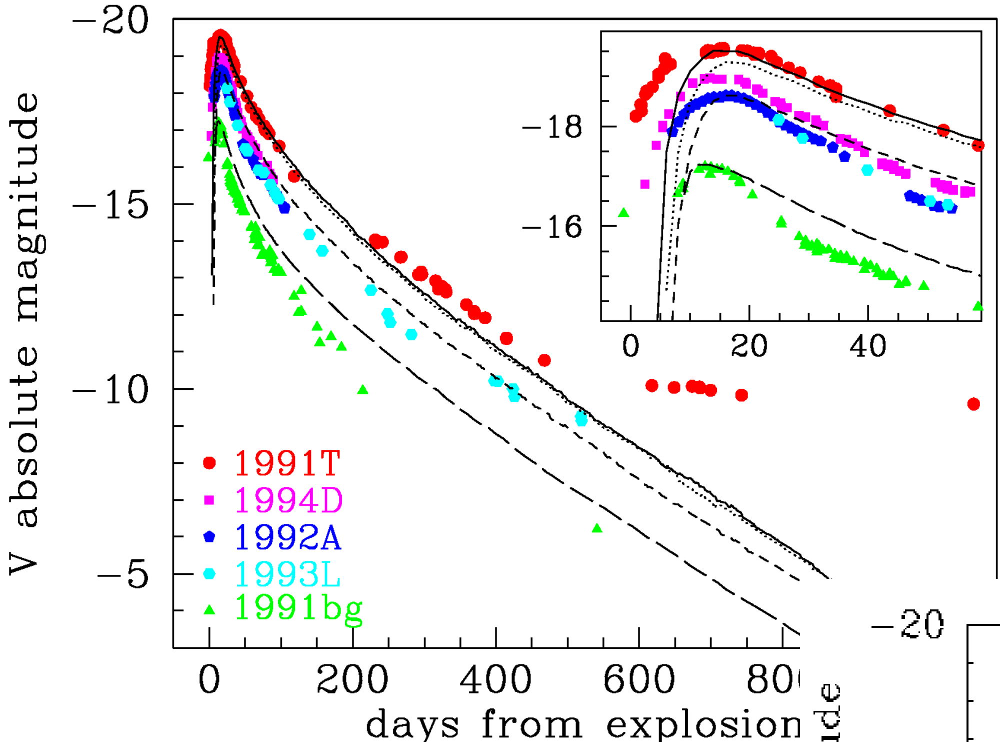


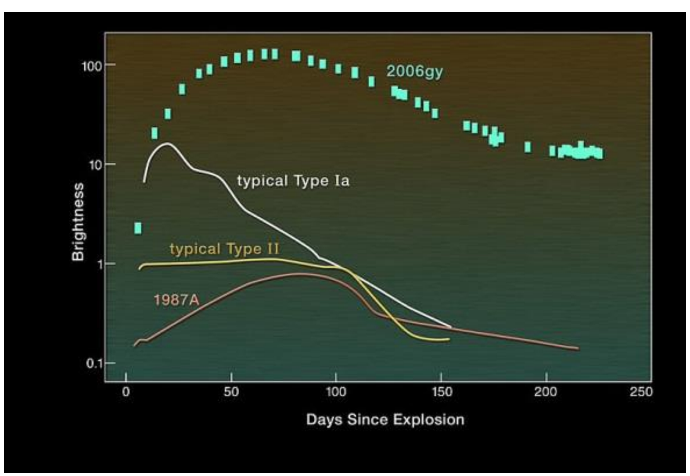
Turatto (2003)

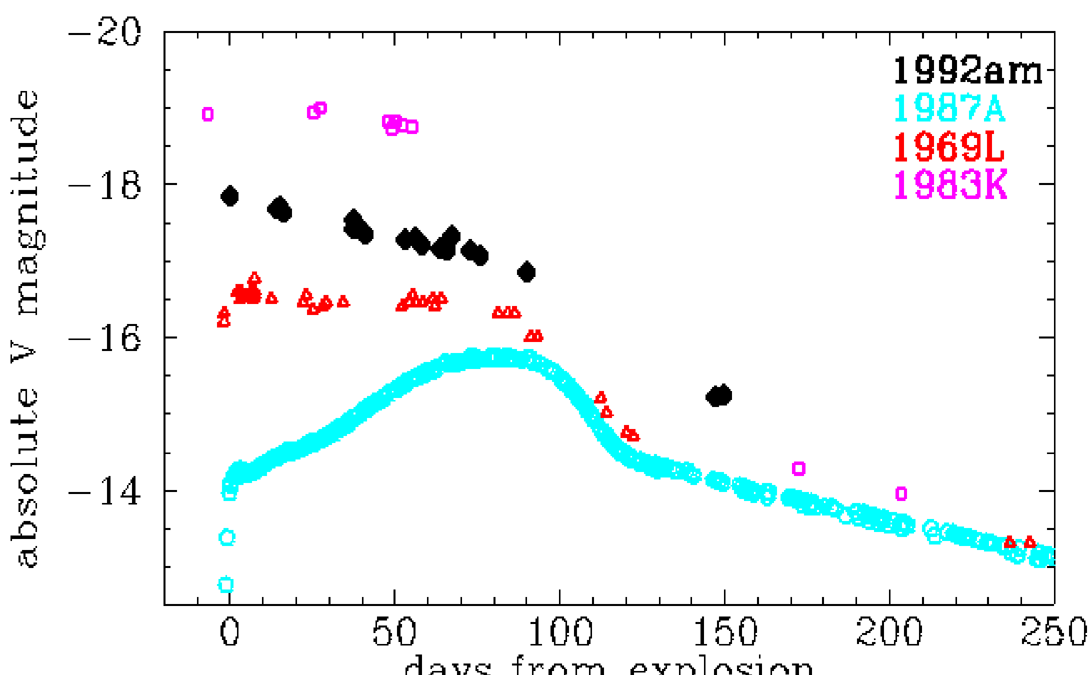
Barbon et al. (1979)

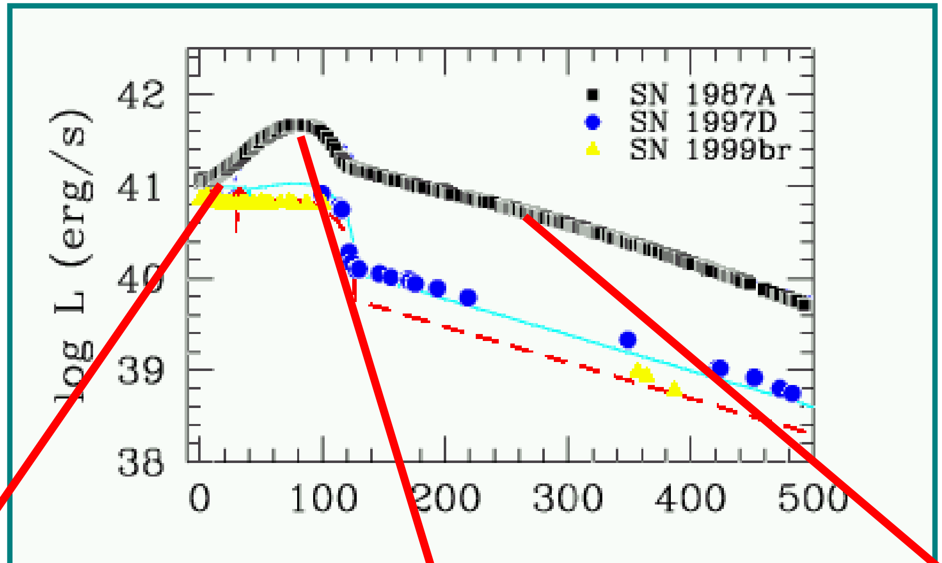
Light curves

Type Ia: more homogeneous
Type II: much more heterogeneous

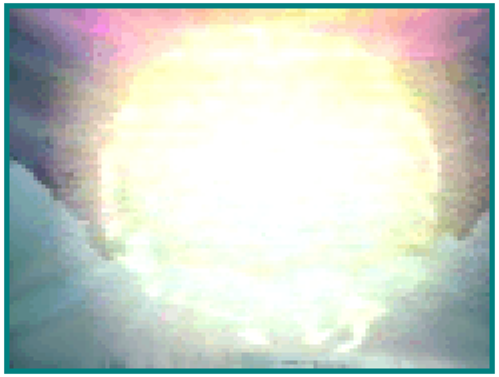




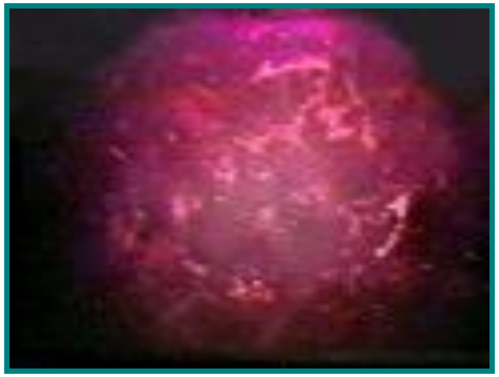




Photospheric diffusion phase



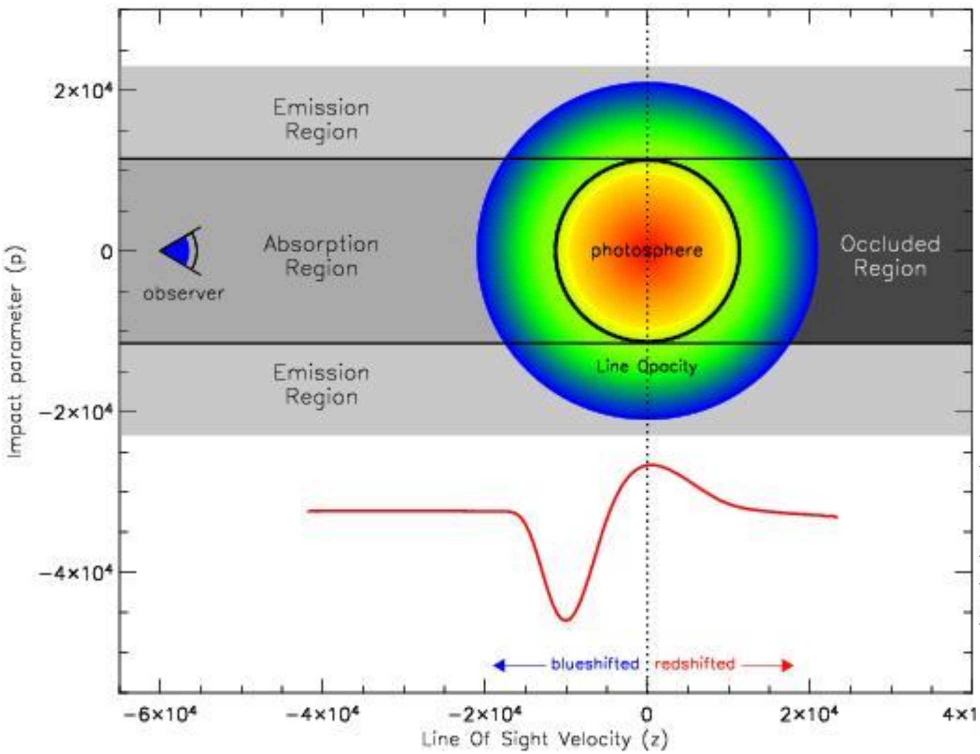
Photospheric recombination phase



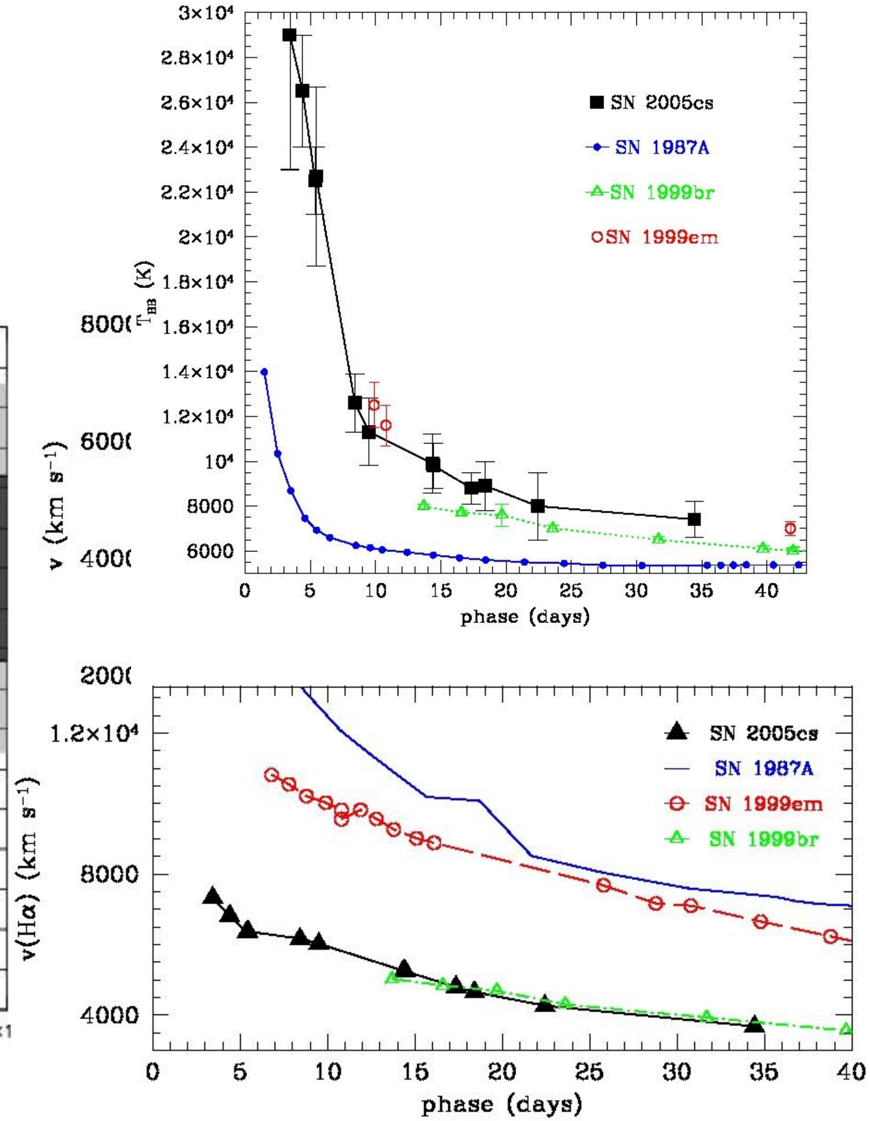
Nebular phase

Photospheric velocity and temperature

V determined from the minimum of the absorption through of P Cygni line profiles



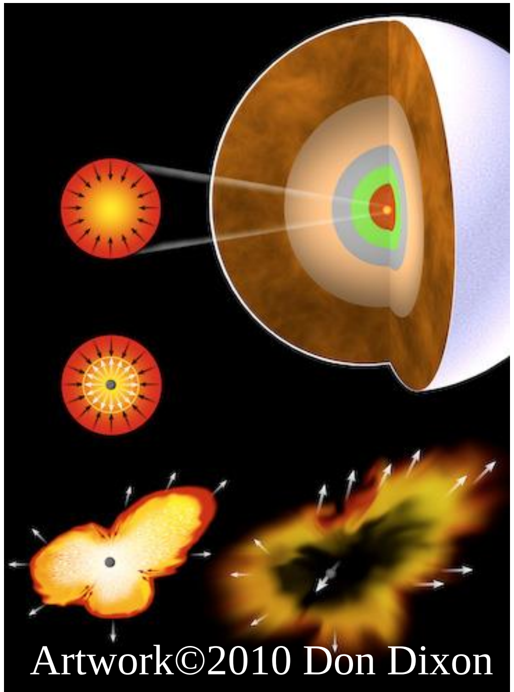
P cygni line profile
(from http://supernova.lbl.gov/~dnkasen)



Pastorello et al. (2006)

Basic explosion mechanisms

Core-collapse of massive stars



cosmographica.com

There is strong evidence that **Type II and Ibc** SNe are produced by the collapse of the core of a massive (> 8 Msun) star at the end of its evolution

No further nuclear burning can support the Fe core, as Fe is the most tightly bound nucleus (9 MeV per nucleon)

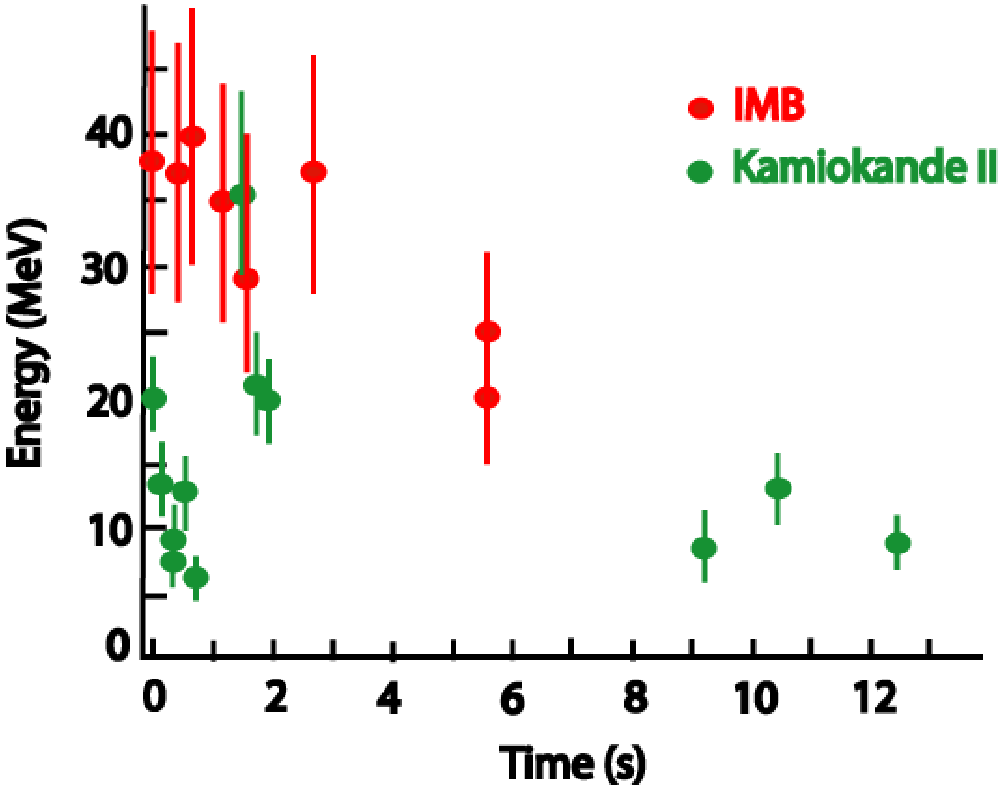
The Fe core collapses until nuclear forces halt it, releasing a huge amount of gravitational binding energy

Core mass and radius: **Mc~1 Msun, rc~10 km**

Explosion energy $\mathbf{E \sim GM_c^2/r_c \sim 10^{53}}$ **erg**: 99% neutrinos (confirmed by SN 1987A)

A shock wave forms and propagates through the envelope, determining how energy is deposited in it and what is the outcome of the explosion:

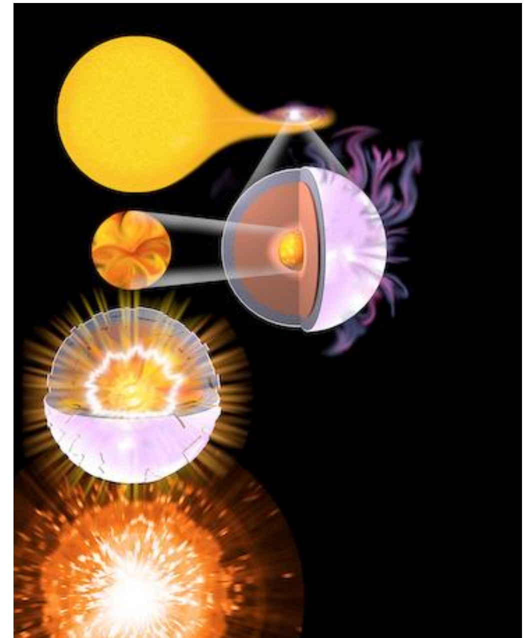
- 1% kinetic energy of the expanding ejecta
- 0.01% radiation



Neutrino events from SN 1987A (courtesy of Dick McCray)

Thermonuclear explosion of a CO White Dwarf

There is strong evidence that **Type Ia** SNe are produced by the thermonuclear detonation/deflagration of a Carbon-Oxygen White Dwarf (WD)



Artwork©2010 Don Dixon cosmographica.com

The explosion is triggered when the WD reaches 1.4 Msun by accretion from a companion star and becomes unstable (*Chandrasekhar limit*)

Thermonuclear burning of CO-rich material into Fe-peak elements releases a huge amount of nuclear binding energy

CO nuclear binding energy: **epsilon~10^{18} erg/g**

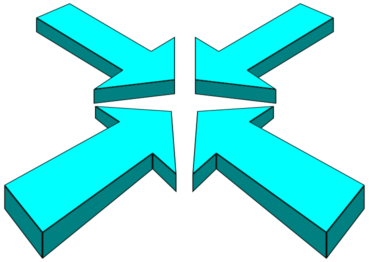
The incineration of a CO mass Mco=1 Msun releases **E~epsilon Mco~10^{51} erg**

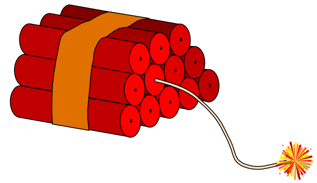
A thermonuclear burning front forms and propagates through the envelope.
C ignition in the degenerate interior of a WD can result in a centered/off-centered ignition and in the propagation of a supersonic/subsonic wave, depending on the internal WD structure.

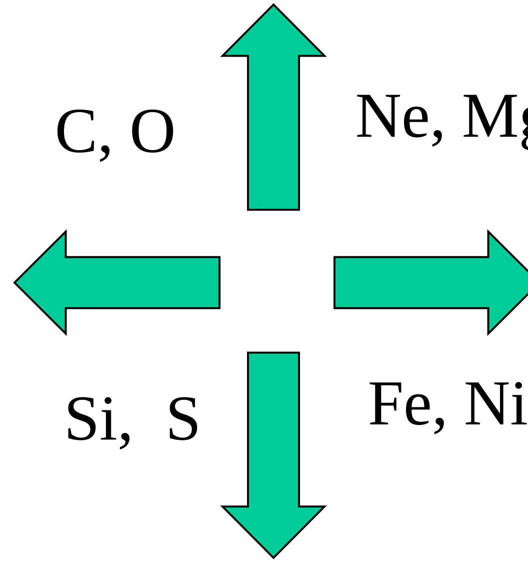
The most prolific sources of elements in the Galaxy

Chemical yields

H, He





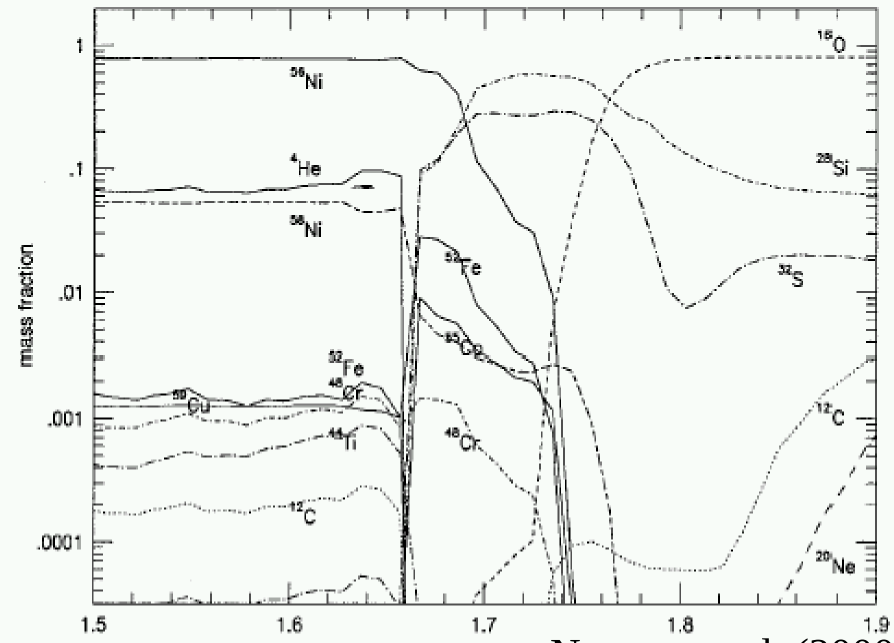


Hoyle (1946) was the first to propose that heavy elements in the Universe are synthetized in stars. Later Burbridge et al. (1957) and Cameron (1957) identified the theoretical framework for the synthesis of atomic nuclei in stars via nuclear reactions.

After synthetizing them in their interiors, stars return this processed material to the interstellar medium through various hydrostatic or explosive processes, thereby enriching it in metals.

A crucial problem for studying the chemical enrichment of galaxies is determining the chemical yields of SNe as a function of progenitor mass:

- Core-collapse SNe → intermediate mass elements (C, O, Ne, Mg, Al)
- Thermonuclear SNe → iron group elements (Fe, Ni)



Nomoto et al. (2000)

Figure 1. The isotopic composition of the ejecta from the 20 $M_\odot$ star (6 $M_\odot$ He core).

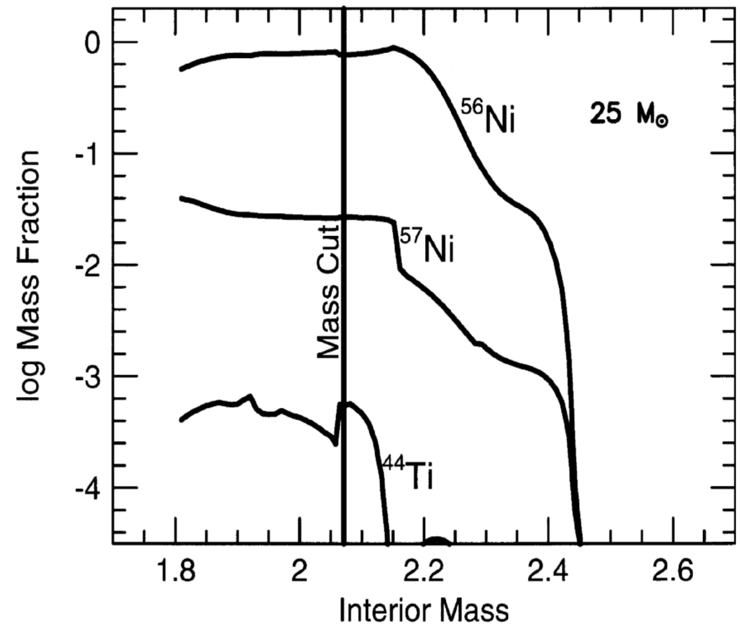


FIG. 8.—Mass profiles of ^{44}Ti and ^{56}Ni for a 25 $M_\odot$ core-collapse supernova model (adapted from Hoffman et al. 1995).

DEPENDENCE ON MASS CUT: YIELD ($M_\odot$)

	MASS CUT (25 $M_\odot$ MODEL)[a]			MASS CUT (20 $M_\odot$ MODEL)[b]			
ELEMENT	1.42	1.54	1.62	1.42	1.55	1.62	MAIN ELEMENT
Fe	2.44E−01	1.62E−01	1.14E−01	1.72E−01	9.53E−02	5.50E−02	^{56}Ni
Cr	1.30E−03	1.27E−03	1.24E−03	1.31E−03	1.20E−03	1.14E−03	^{52}Fe
Mn	3.38E−04	3.37E−04	3.37E−04	3.35E−04	3.34E−04	3.33E−04	^{55}Co
Co	6.87E−04	4.84E−04	3.01E−04	5.33E−04	2.33E−04	7.00E−05	^{59}Cu
Ni	8.71E−02	5.48E−02	3.64E−02	6.42E−02	2.70E−02	7.16E−03	^{58}Ni

[a] $M_{\rm core} = 8\ M_\odot$, $E_{\rm exp} = 1.0 \times 10^{51}$ ergs, $Y_e^{\rm deep} = 0.4950$.
[b] $M_{\rm core} = 6\ M_\odot$, $E_{\rm exp} = 1.0 \times 10^{51}$ ergs, $Y_e^{\rm deep} = 0.4940$.

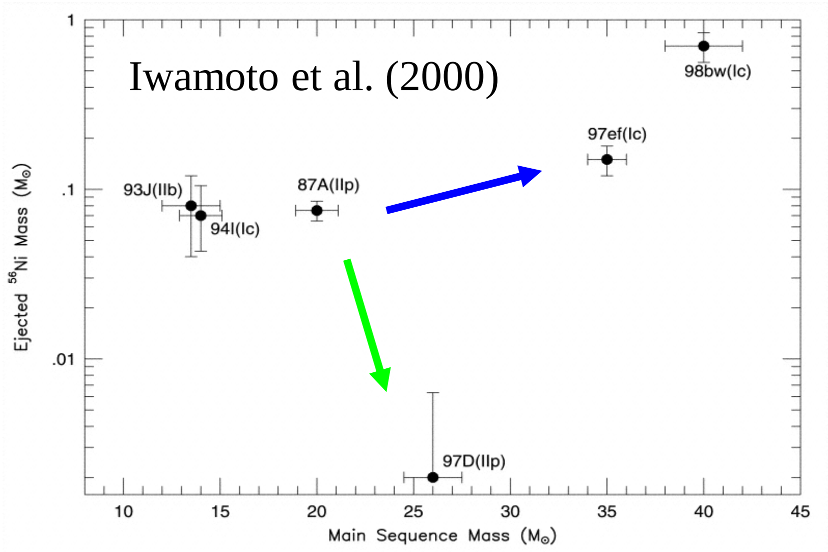
Nakamura et al. (1999)

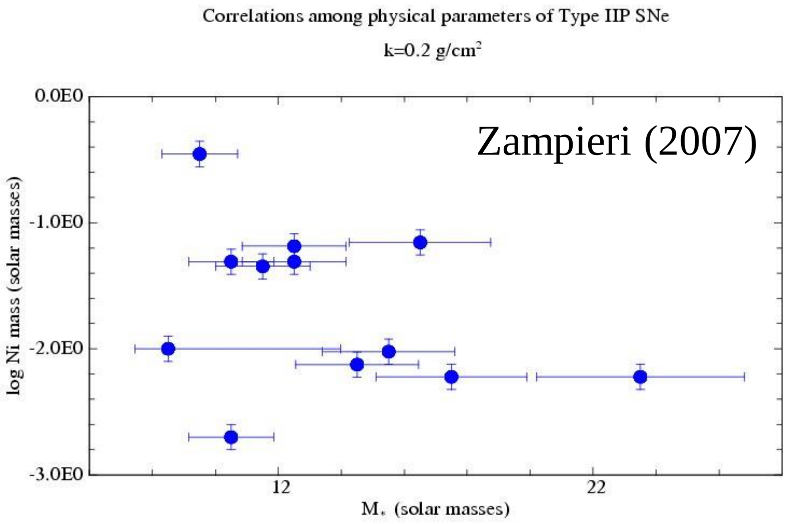
The problem of the Ni yield in CC SNe

Crucial dependence of **Mni** on mass cut, mixing, fall-back

a) Mni can be computed “almost directly” from observations

b) M can be obtained from modelling the observations or direct detection of the progenitors (e.g. Smartt et al. 2004, 2008)





CC SNe: compact remnant?

CC SNe: Birth places of neutron stars

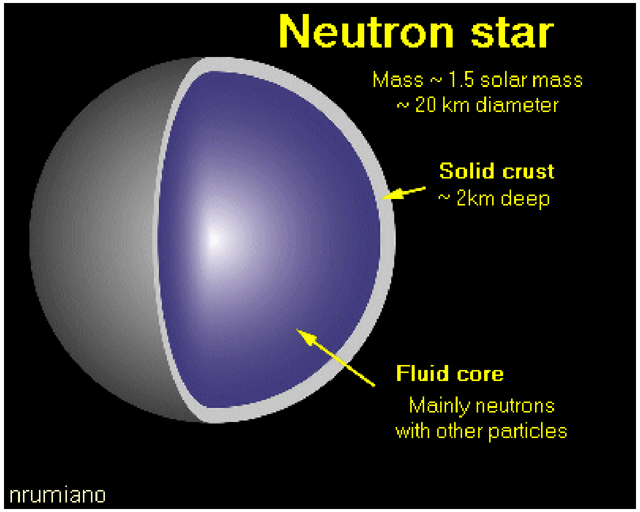
CC SNe are believed to be the birth place of neutron stars (NSs)

When the core reaches nuclear densities (*rho=1.0e14 g/cm*^{3}), nuclei and free nucleons are so tightly bound that start to feel the short-range nuclear force (which is repulsive at very small distances)

The collapsing inner core rebounds. It is very hot (*1.0e10 K*) and dense (*1.0e14 g/cm*^{3}) → *proton-neutron star* (PNS)

Cooling of the PNS is driven by neutrino diffusion and convection. In a few tens of seconds the proto-NS becomes a NS

Mass=1.5 Msun
Radius=20 km
Rotational period=1.0e-3 s
Magnetic field=1.0e13 G

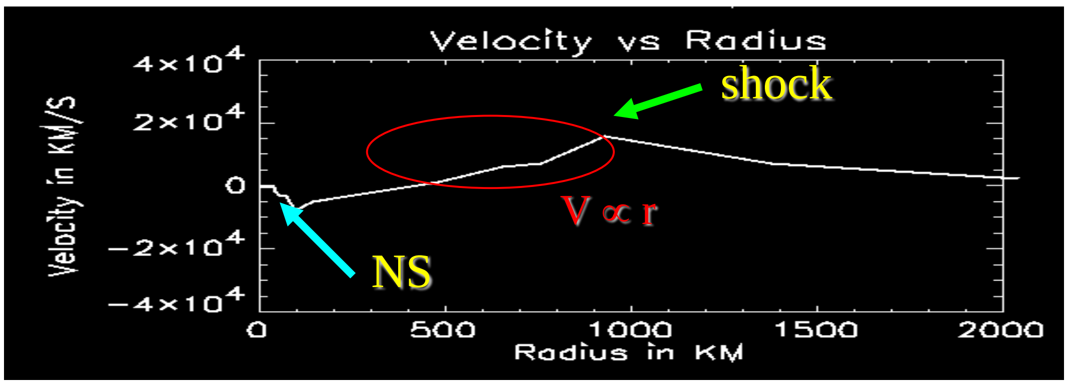


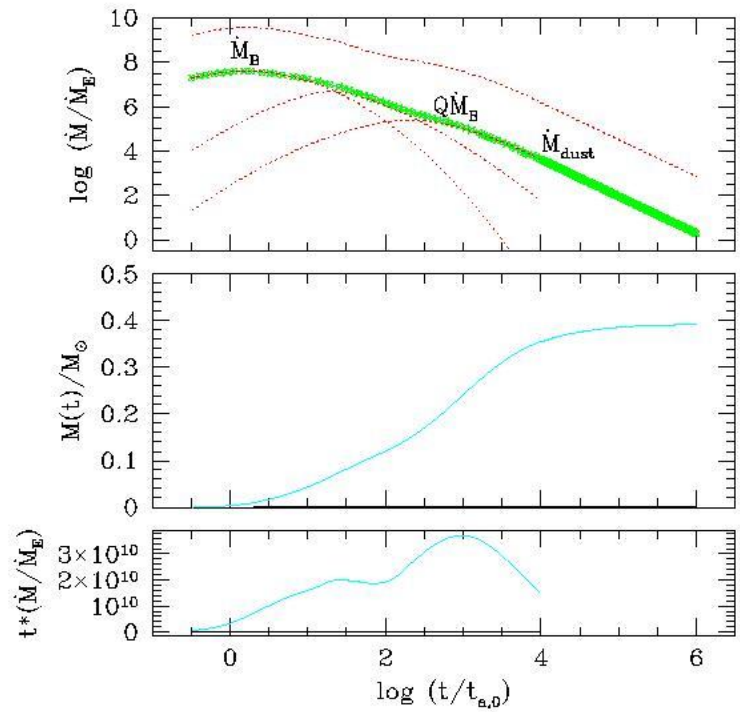
http://nrumiano.free.fr/Images/Neutron_star_E.gif

The discovery of pulsars in 1967 by Jocelyn Bell e Antony Hewish (Nobel in 1974) confirmed the existence of neutron stars. Their association to supernova remnants confirm that they are produced in supernova explosions

Fallback and BH formation

- After shock passage, ejecta are in homologous expansion: $V \propto r$
- Low velocity, inner part of the expanding envelope (inside the He layer) may remain gravitationally bound → **fallback** (Woosley & Weaver 1995; Colpi et al. 1996; Zampieri et al. 1998)





$M_{rem} = M_{core} + M_{fb}$ → **BH** or **NS** ?

$M_{rem} < M_{cr}$ → **NS**

$M_{rem} > M_{cr}$ → **BH**

Fallback (and direct collapse) determines the mass distribution of stellar BHs

Themonuclear SNe: the most powerful cosmological lampposts

Thermonuclear SNe: standard candles

It has long been recognized that Type Ia SNe could be very useful distance indicators (e.g. Branch & Tammann 1992; Branch 1998) because they have:

- *exceedingly high luminosity: L=1.0e43 erg/s (B band magnitude=-19)*
- *small dispersion among their peak absolute L (<0.3 mag)*
- *homogeneous spectral properties, if compared at similar phases (Riess et al. 1997)*

Research on Type Ia SNe in the 1990s has demonstrated their enormous potential as cosmological distance indicators (80% of them are homogeneous; Branch et al. 1993).

Until the mid-1990s it was assumed that they are perfect ‘standard candles’ (Vaughan et al. 1995) with:

$$\langle M_B(\mathrm{max})\rangle = (-19.74 \pm 0.06) + 5\log(H_0/50)\ \mathrm{mag}$$

Sandage et al. (1996) and Saha et al. (1997) combined similar relations with HST Cepheid distances to derive H_0.

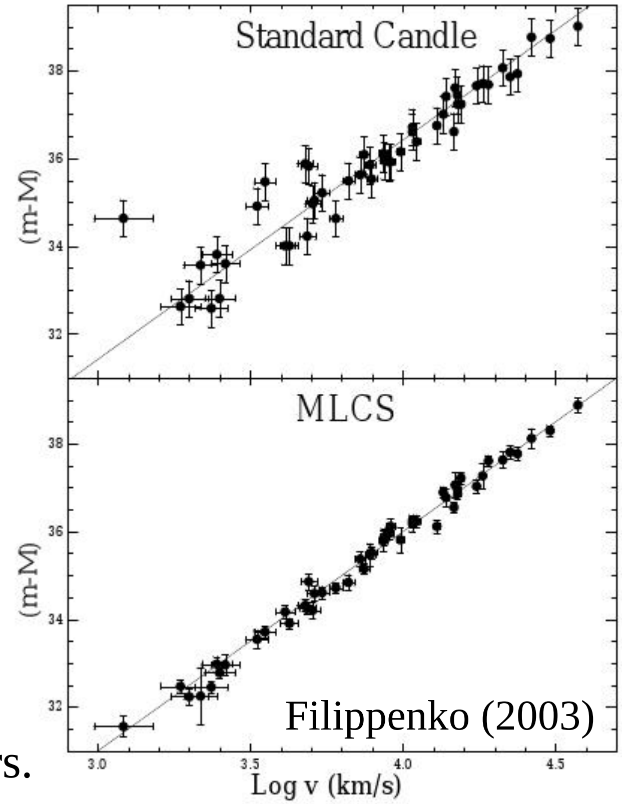
Thermonuclear SNe: the Universe is accelerating

For nearby SNe, knowing M_B and m_B, and the expansion velocity of the host galaxy V, it is possible to construct the **Hubble diagram**:

$$m\text{-}M = 5\log D - 5$$
$$D = V/H_0$$
$$m\text{-}M = -5 - 5\log H_0 + 5\log V$$

The scatter is caused by the fact that Type Ia SNe are not perfect 'standard candles'. After correcting *M* with suitable calibration relations, the correlation is significantly improved.

Extending the Hubble diagram to higher redshifts, it is possible to probe additional cosmological parameters.



Filippenko (2003)

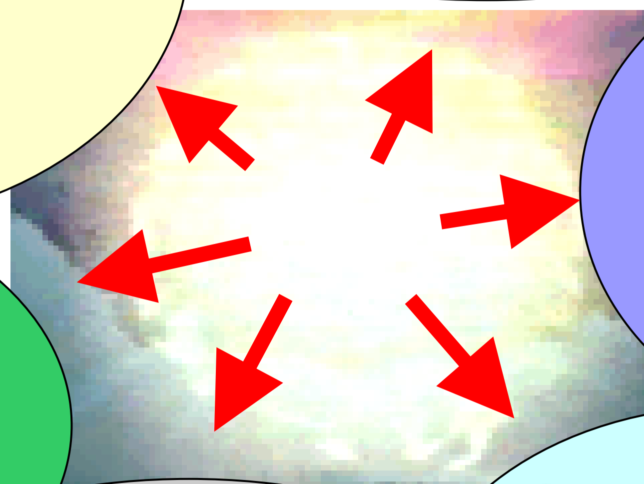
Two major teams were involved in this research in the 1990s: the 'Supernova Cosmology Project' (SCP) led by Saul Perlmutter and the 'High-Z Supernova Search Time' (HZT) led by Brian Schmidt and Adam Riess. *They were awarded the 2011 Nobel Prize in Physics "for the discovery of the accelerating expansion of the Universe through observations of distant supernovae".*

SNe at the crossroads of many challenging problems

Thermonuclear SNe: used as standard candles to probe the structure of space-time and determine cosmological parameters

Iron core-collapse SNe: Explosion mechanism, shock/jet propagation and energy deposition

Acceleration of Galactic Cosmic Rays



Supernova yields: affected by mass cut, explosion energy, mixing, fallback; crucial to determine chemical yields as a function of M

Hypernovae: connection with Gamma Ray Bursts, jet-induced SNe, Supranovae?

Failed SNe: direct collapse to a BH, formation of massive stellar BHs?

Compact remnants: formation and mass distribution of NSs and BHs, direct detection of BHs in SNe?

Some useful review papers or books

- Arnett, *Supernovae and Nucleosynthesis*, 1996

- Filippenko, 2003, in “Measuring and Modeling the Universe”, Carnegie Observatories Astrophysics Series, Vol. 2, ed. W. L. Freedman (Cambridge: Cambridge Univ. Press): *Evidence from Type Ia Supernovae for an Accelerating Universe and Dark Energy*

- Jose' and Iliadis, 2011, Reports on Progress in Physics, **74,** 096901: *Nuclear astrophysics: the unfinished quest for the origin of the elements*