Supernovae:
from Stellar Evolution to Cosmology

Lesson b

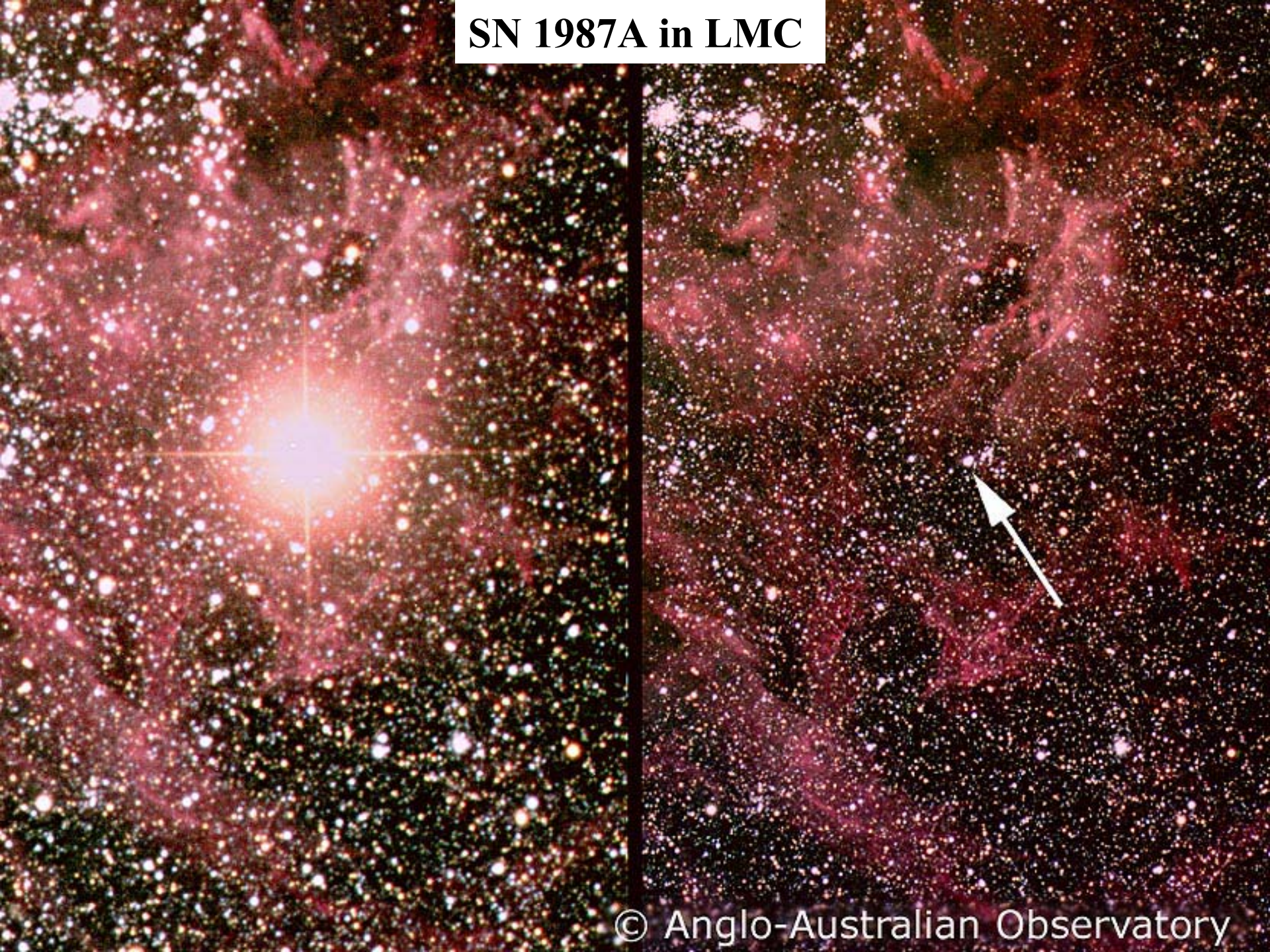
SN 1987A in LMC

Massimo Turatto – Padova - Italia

LMC
(50 kpc)

SN 1987A

SN 1987A in LMC



The early history of SN 1987A

Feb 22.4 Sk-69 202 still at 12 mag

Feb 23.08 SN not seen in an LMC picture

Feb 23.12 Five pulses detected with the Mont Blanc ν-telescope

Feb 23.32 Neutrinos detected in Kamiokande II and IMB

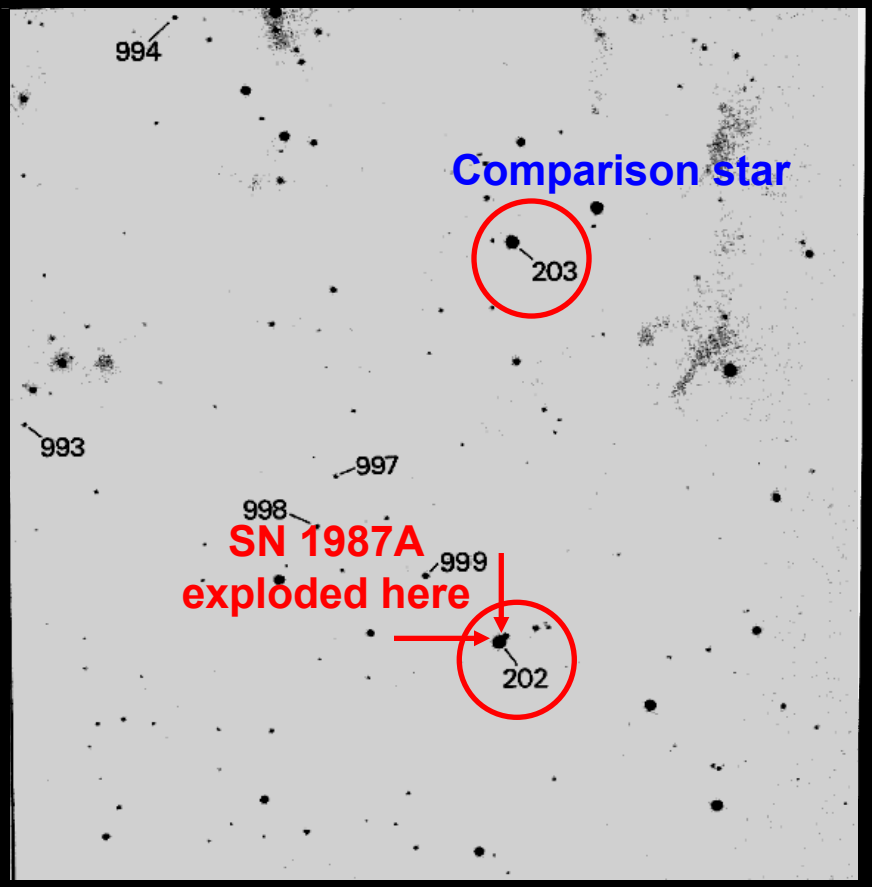
Feb 23.44 Pre-discovery detection of SN at 6.1 mag

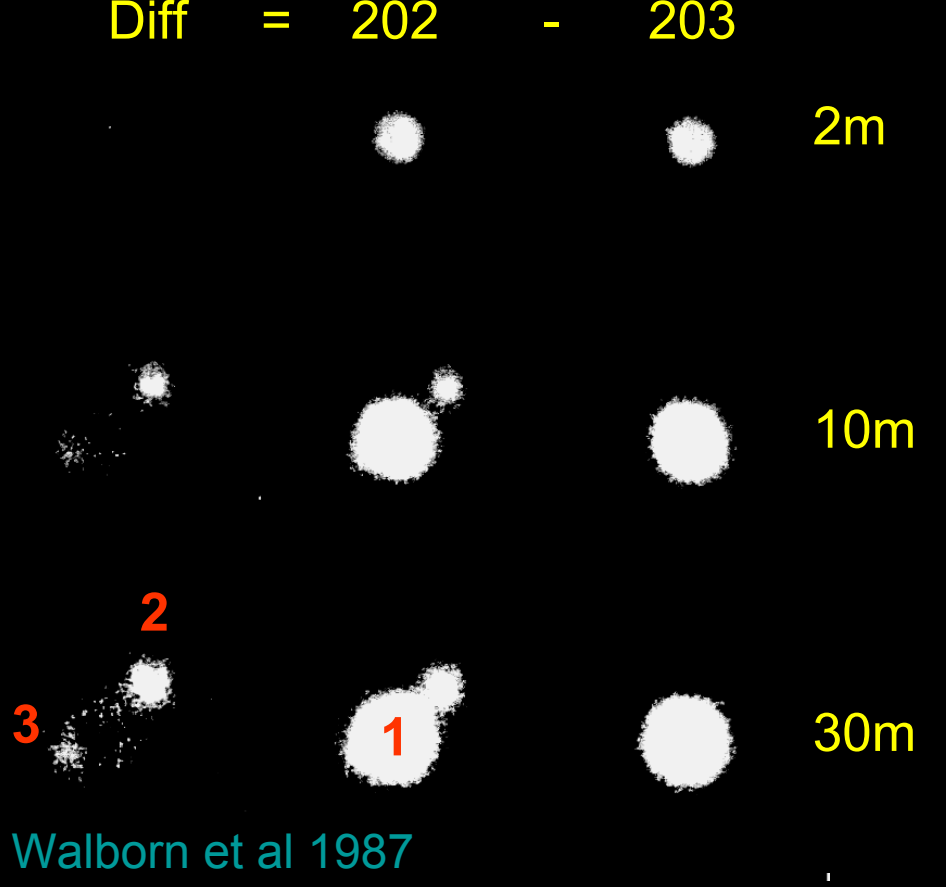
Feb 24.23 Ian Shelton discovers the SN at about 5 mag

Feb 24.4 IAU telegram announces the discovery

Feb 24.82 The SN is first observed with the IUE

The progenitor *Sk-69º202*

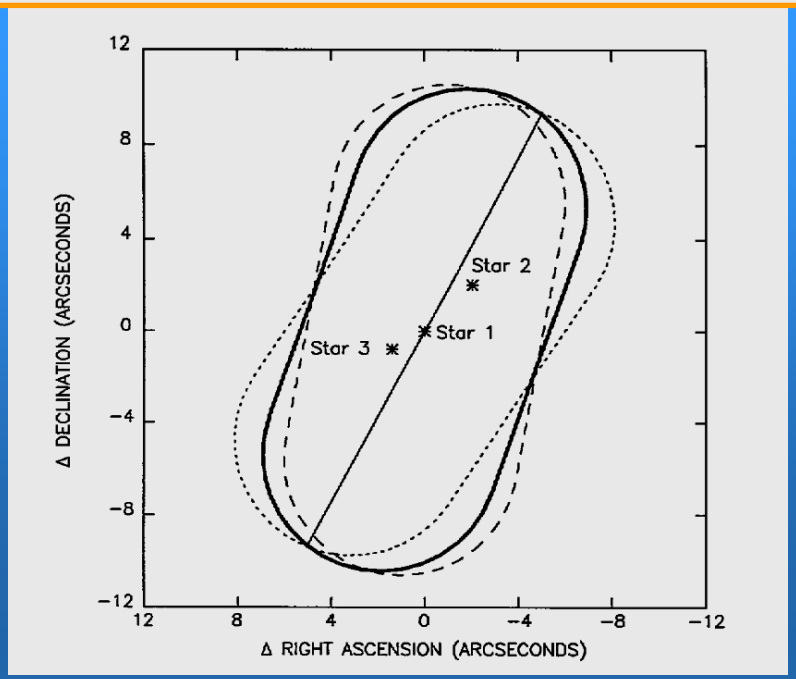


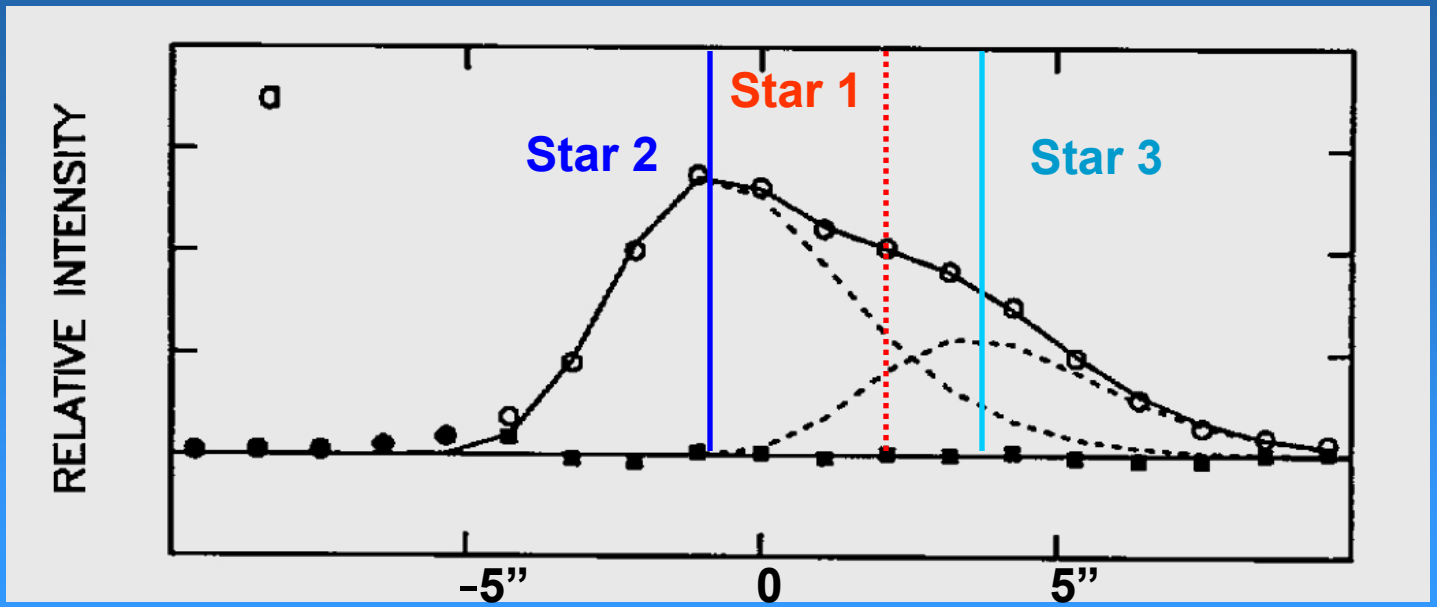


Walborn et al 1987

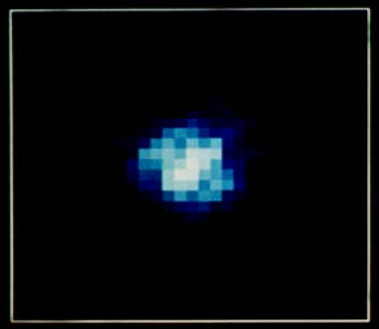
Star 1 was missing !!
The star ***Sk-69º202***,
a ***B3 supergiant***, had
exploded as a SNII!

IUE slot cross-cut, few weeks past explosion

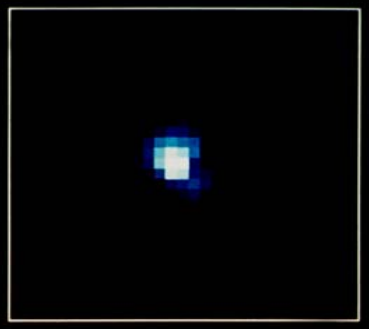




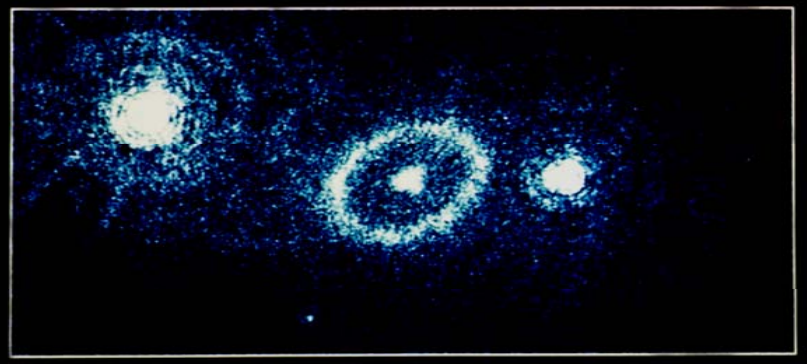
late confirmation



SN1987A



Comparison Star



SN1987A Circumstellar Ring

Neutrinos

SN1987A optical discovery triggered the neutrino search in recorded data by all active detectors

23 Feb 1987 – Within ~10s:

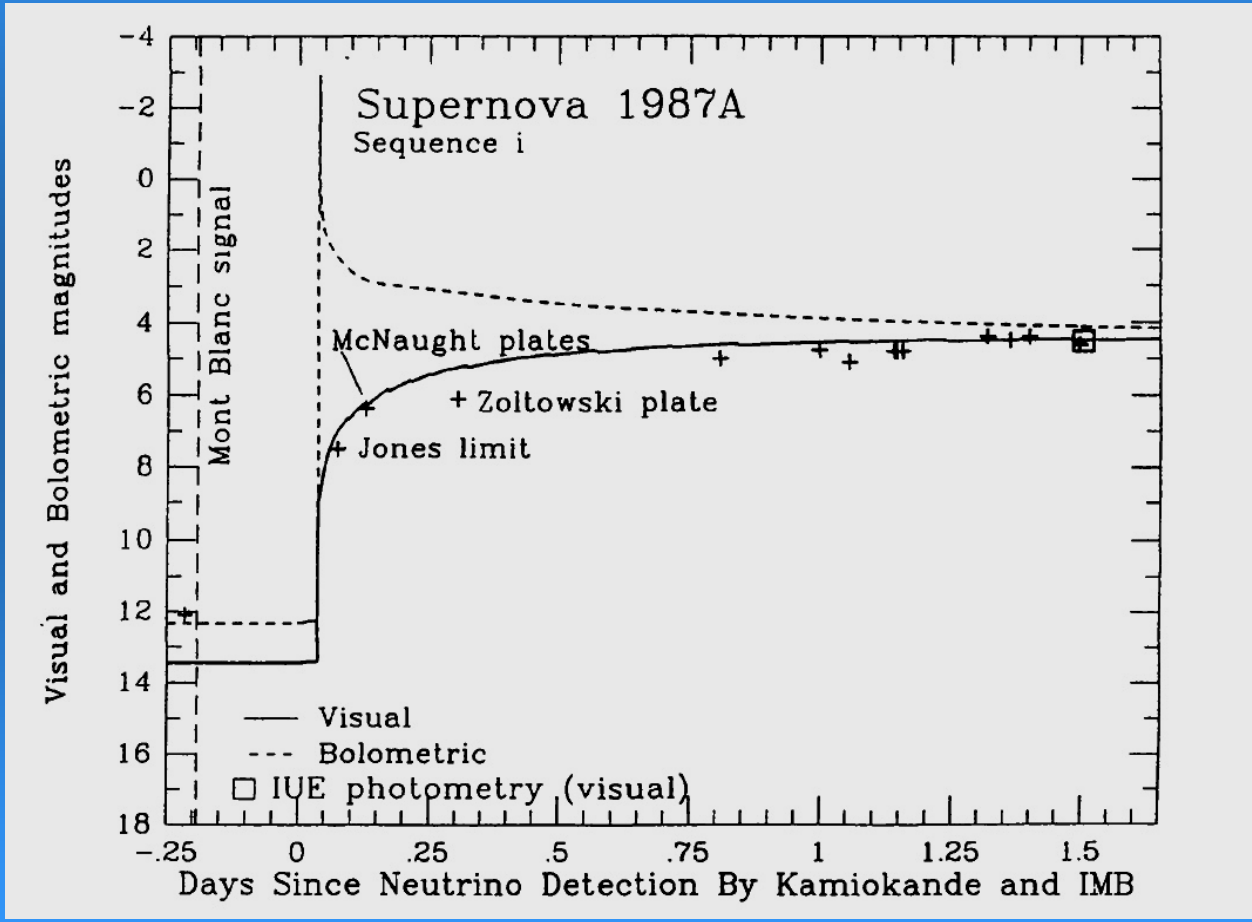
12 events in Kamiokande (2kT H_2O, 7 MeV threshold)
8 events in IMB (10kT H_2O, but 20 MeV threshold)
5 events in Baksan (scintillator) Not used in analysis

Mistery: 5 events in Mt. Blanc ~5h earlier

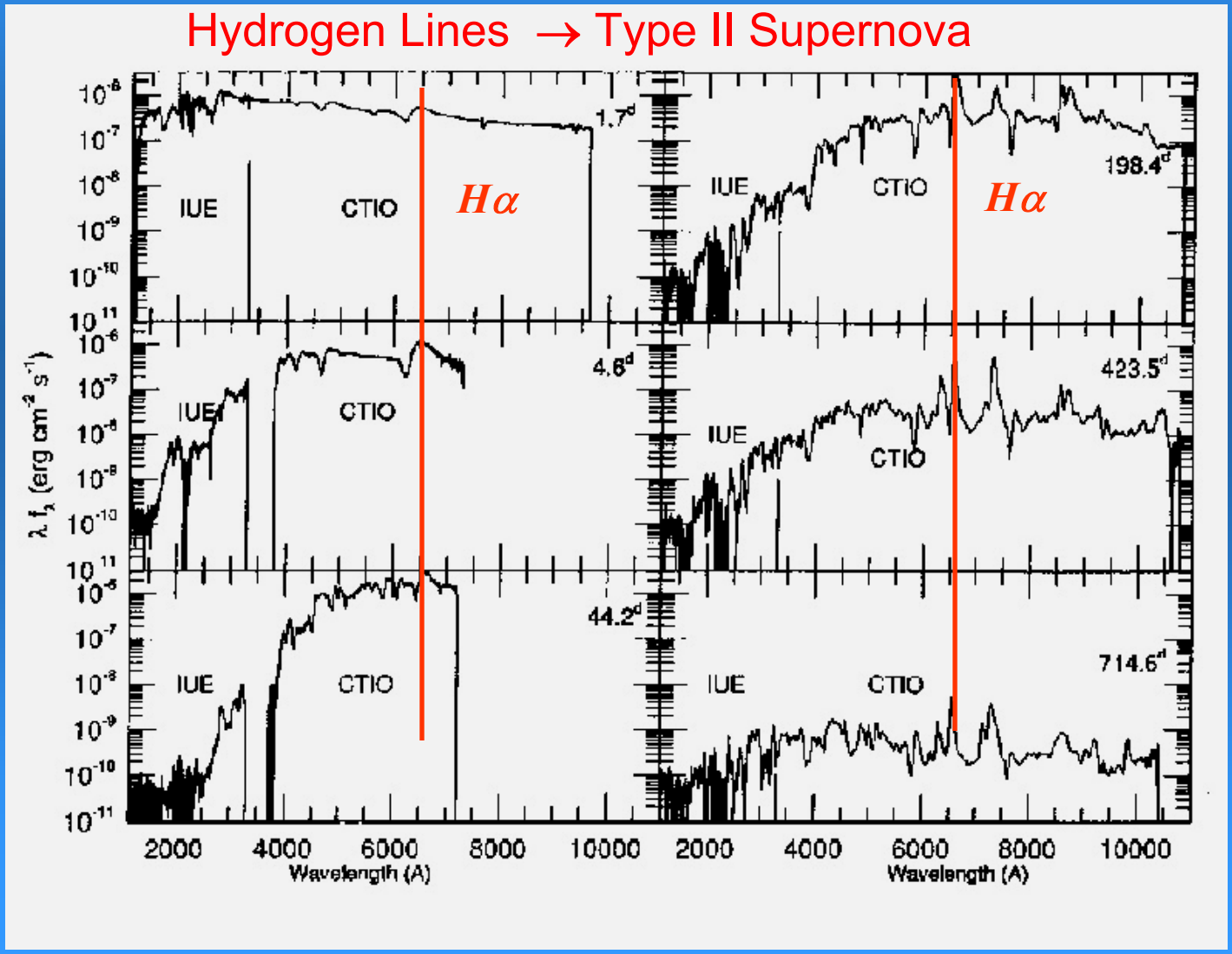
11 Kamiokande + 8 IMB events were confirmed to come from SN
Perfect agreement with theory if $e_T = 3\ 10^{53}$ erg

➔ Extraordinary confirmation of core collapse model

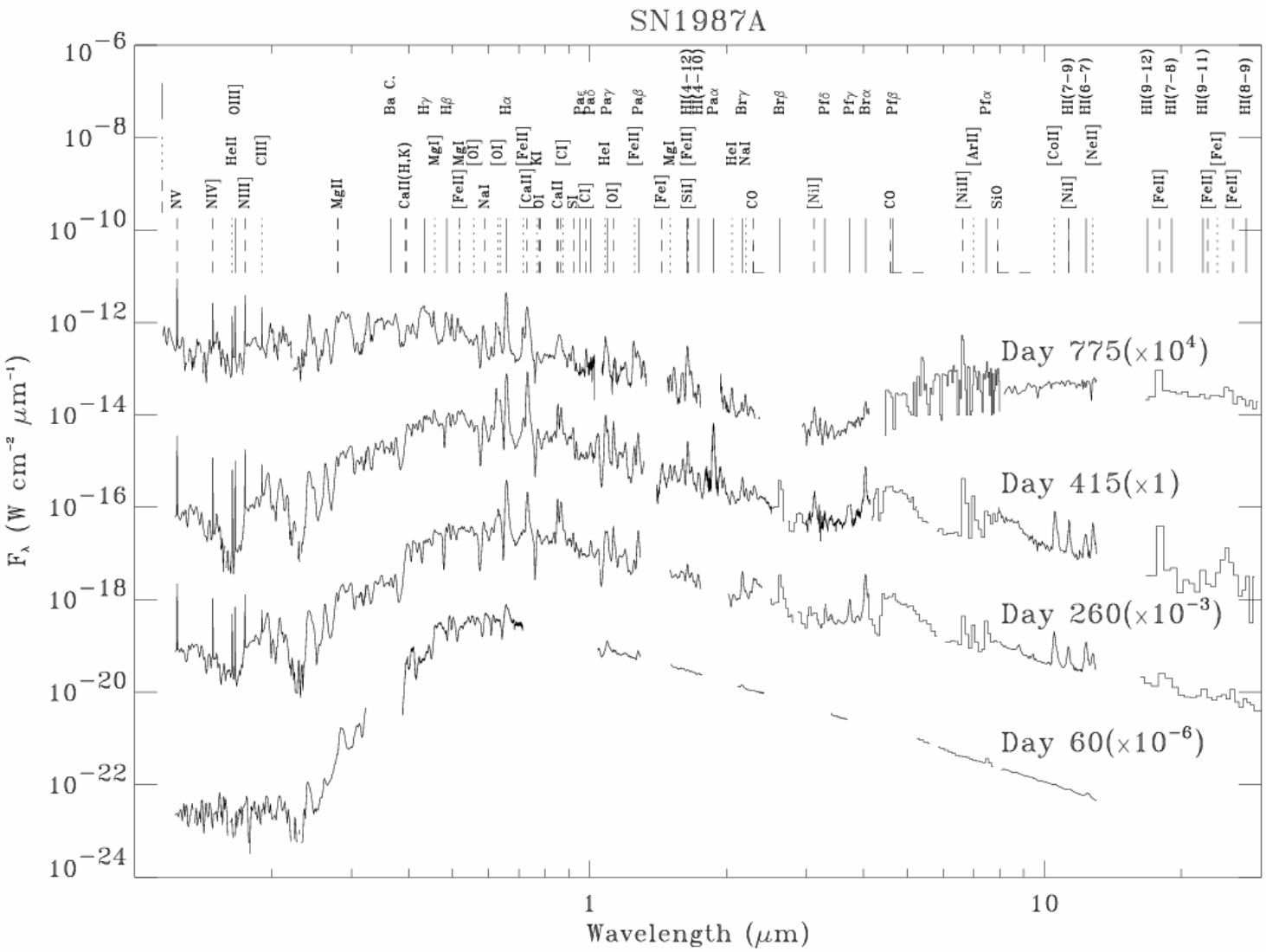
Early Optical Evolution

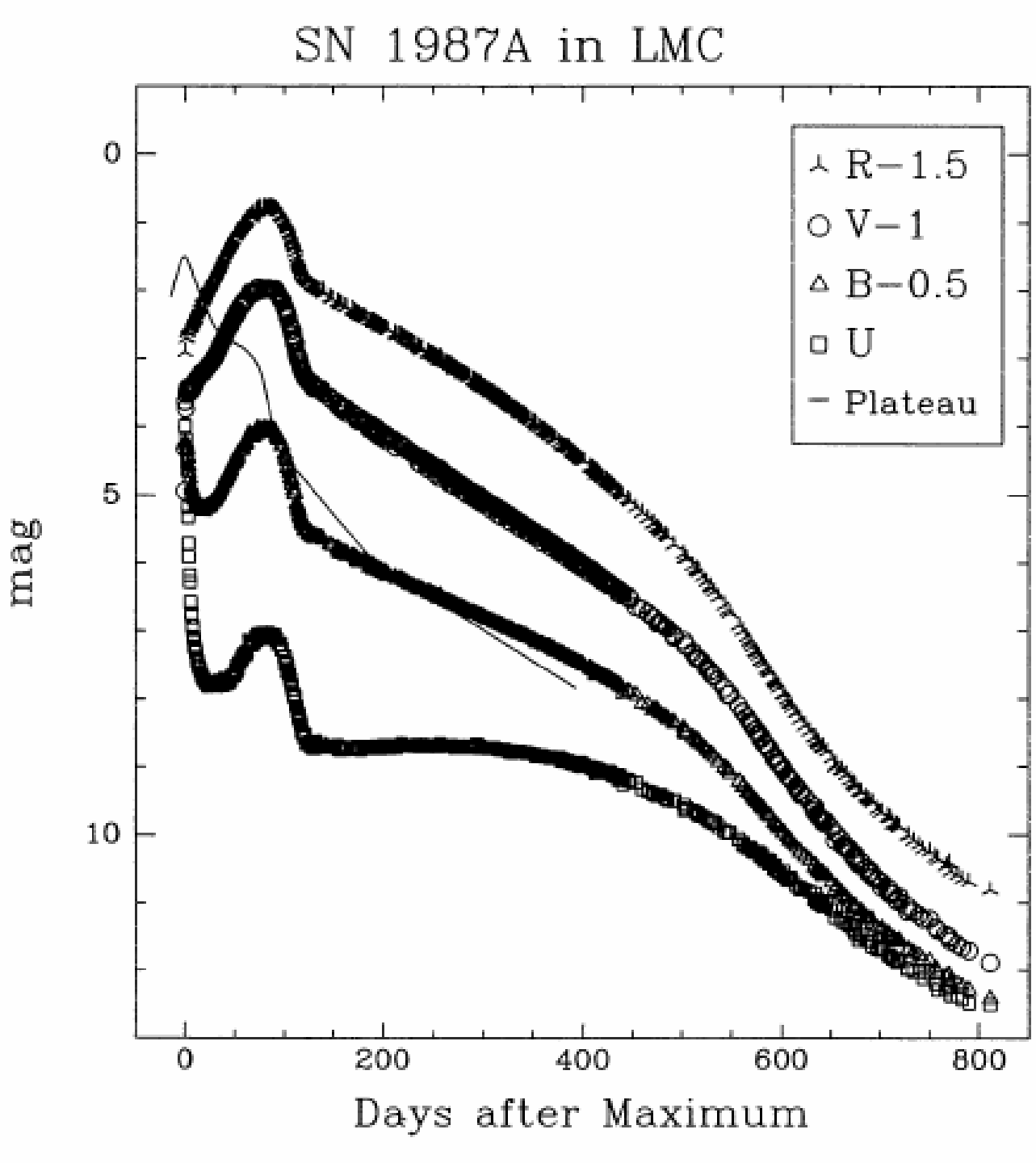


SN 1987A: 2 years of Spectral Evolution



Panagia 2005


SN1987A
NV
NIV]
HeII
OIII]
NIII]
CIII]
MgII
Ba C.
CaII(H,K)
Hγ
Hβ
MgI]
[FeII]
MgI]
[OI]
NaI
[OI]
Hα
[CaII]
OI
[FeII]
KI
CaII
SI
[CI]
[CI]
HeI
[OI]
[FeII]
Paε
Paδ
Paγ
Paβ
[FeI]
MgI
[SiI]
[FeII]
HI(4-12)
HI(4-10)
Paα
HeI
NaI
CO
Brγ
Brβ
[NiI]
Pfδ
Pfγ
Brα
Pfβ
CO
[NiII]
[ArII]
SiO
Pfα
[CoII]
[NiI]
HI(7-9)
HI(6-7)
[NeII]
HI(9-12)
[FeII]
HI(7-8)
HI(9-11)
[FeI]
[FeII]
HI(8-9)
Day 775(×10^4)
Day 415(×1)
Day 260(×10^-3)
Day 60(×10^-6)
F_λ (W cm^-2 μm^-1)
10^-6
10^-8
10^-10
10^-12
10^-14
10^-16
10^-18
10^-20
10^-22
10^-24
1
10
Wavelength (μm)


SN 1987A in LMC
R−1.5
V−1
B−0.5
U
Plateau
mag
0
5
10
0
200
400
600
800
Days after Maximum

Compact progenitor

RSG ??

1994

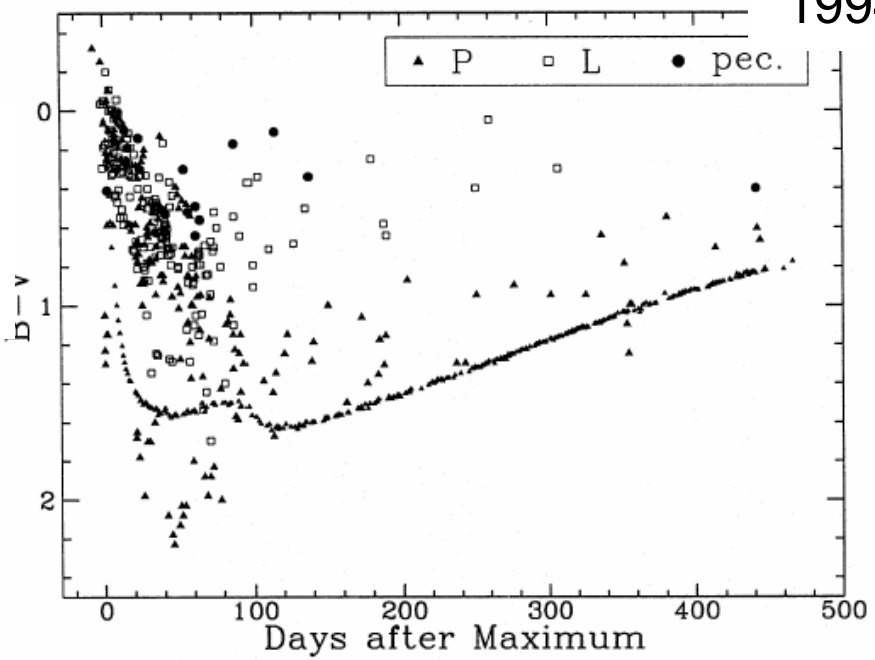


Fig. 3. $(B-V)$ color curves, dereddened for galactic extinction, for 21 selected objects (SNe 1959D, 1962M, 1968L, 1969L, 1970G, 1972Q, 1973R, 1979C, 1980K, 1983K, 1984E, 1985G, 1985L, 1985P, 1986E, 1987A, 1987B, 1987F, 1988A, 1988Z, 1989C)

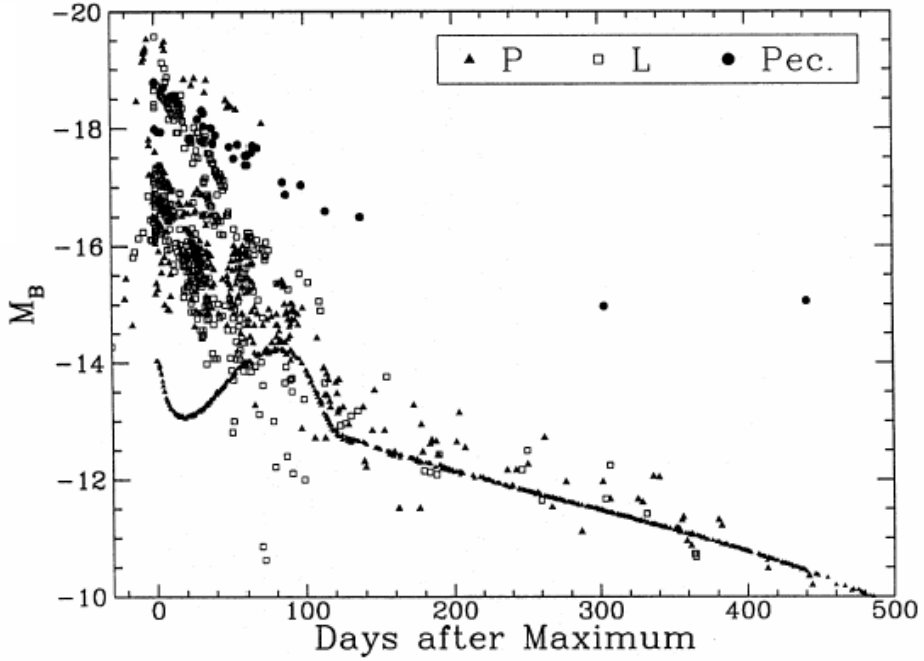
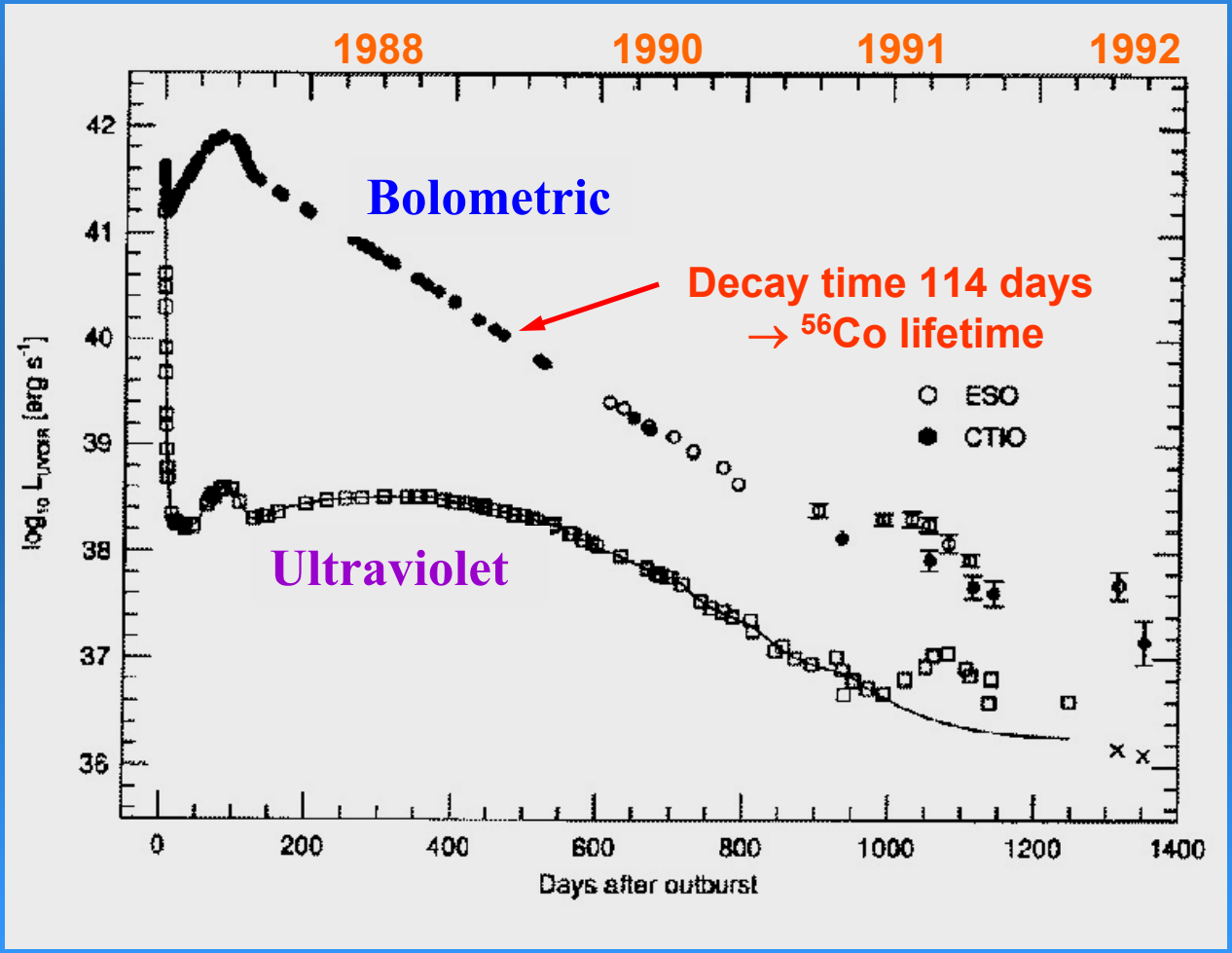


Fig. 4. Absolute B light curves of SNII. Observations have been dereddened only for galactic extinction. The following 34 SNe are included: 1909A, 1936A, 1940A, 1940B, 1941A, 1948B, 1959D, 1961F, 1961U, 1962M, 1965H, 1965L, 1965N, 1966B, 1968L, 1969B, 1969L, 1970G, 1971S, 1975T, 1979C, 1980K, 1983E, 1983K, 1984E, 1985L, 1985P, 1986E, 1987B, 1987A, 1987F, 1988A, 1988Z, 1989C

SN 1987A: 4 years of Light Curves



Most of gamma rays are trapped inside the exploding star ➔ massive progenitor

SN 1987A

Leibundgut and Suntzeff

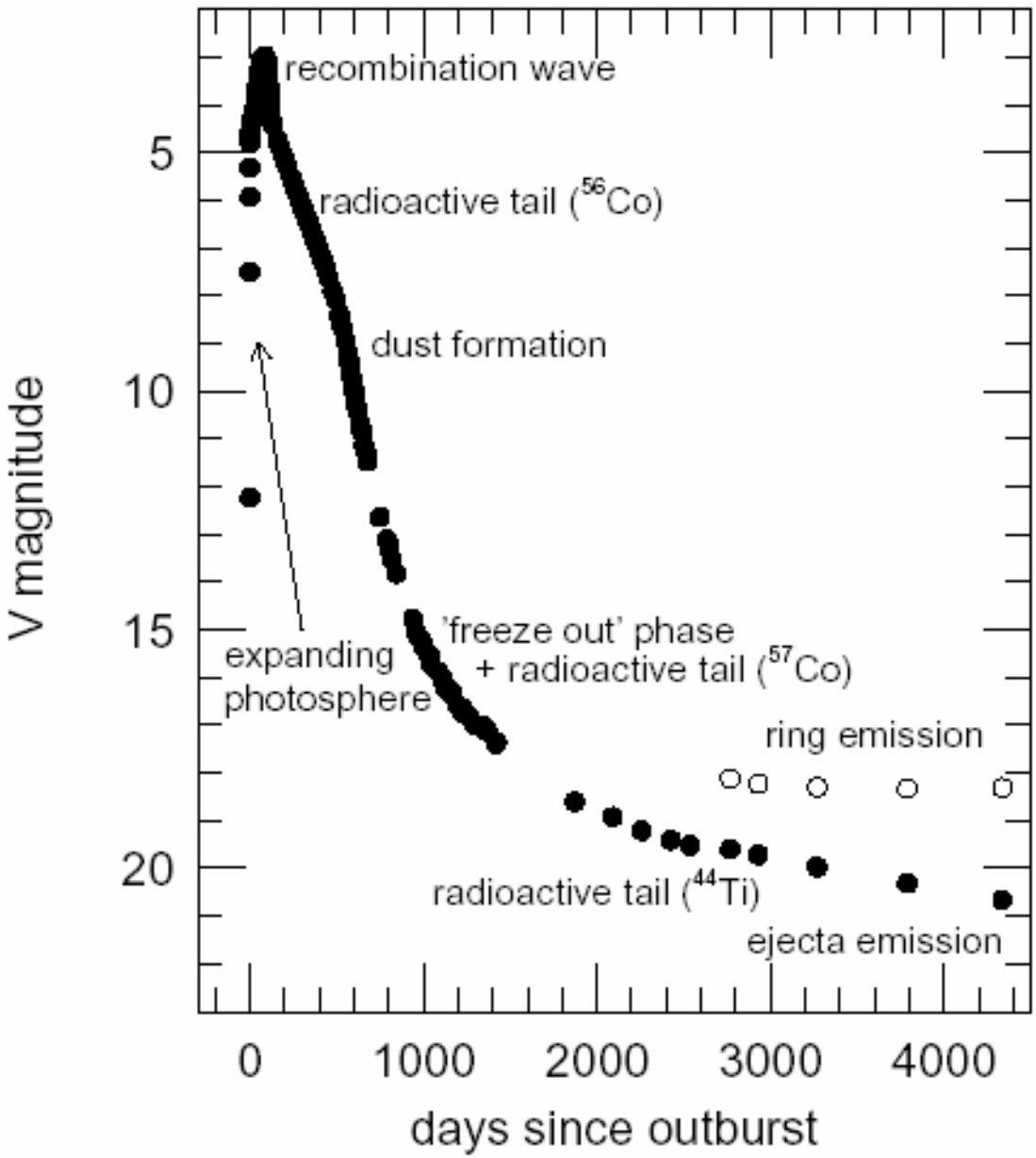
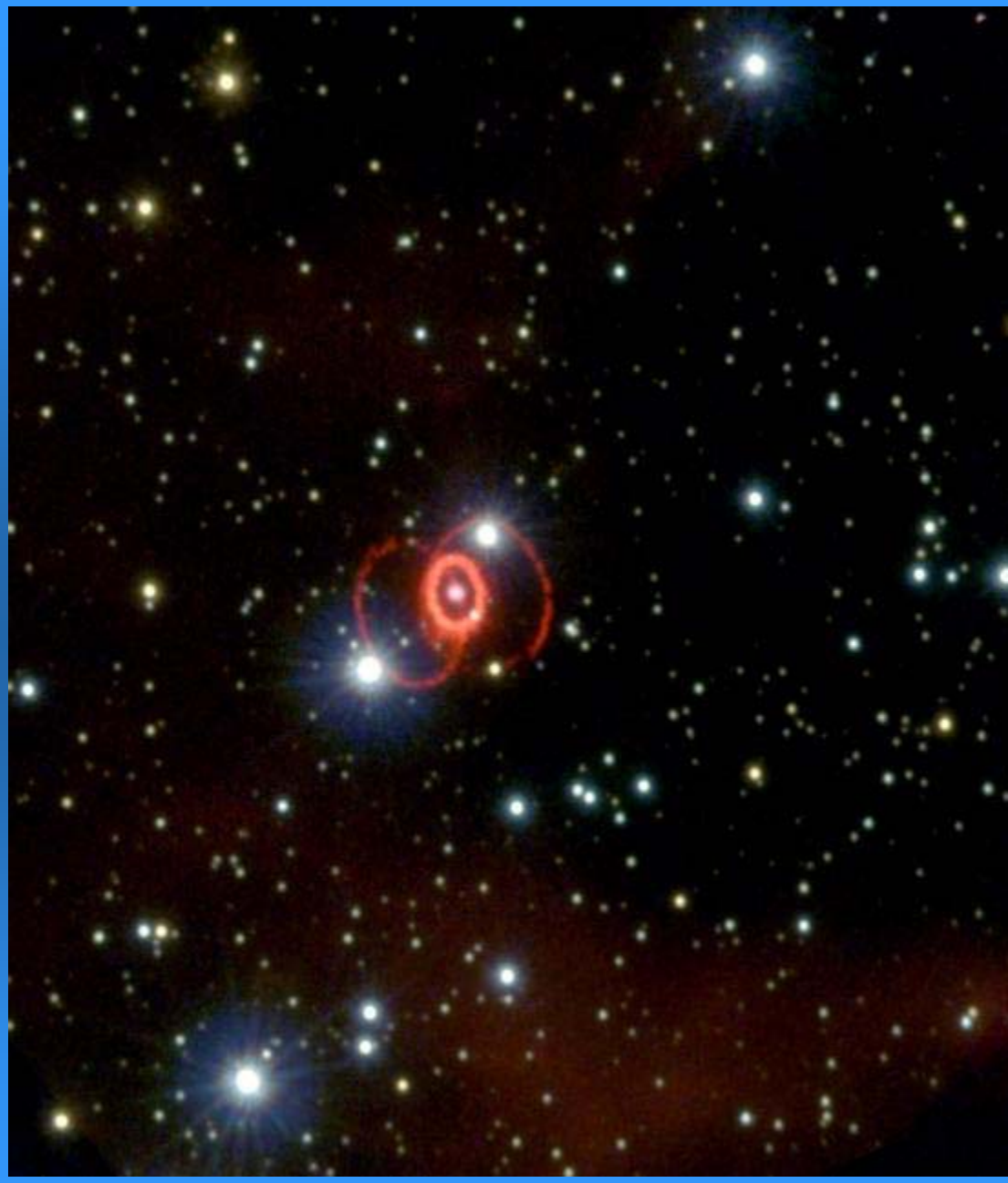


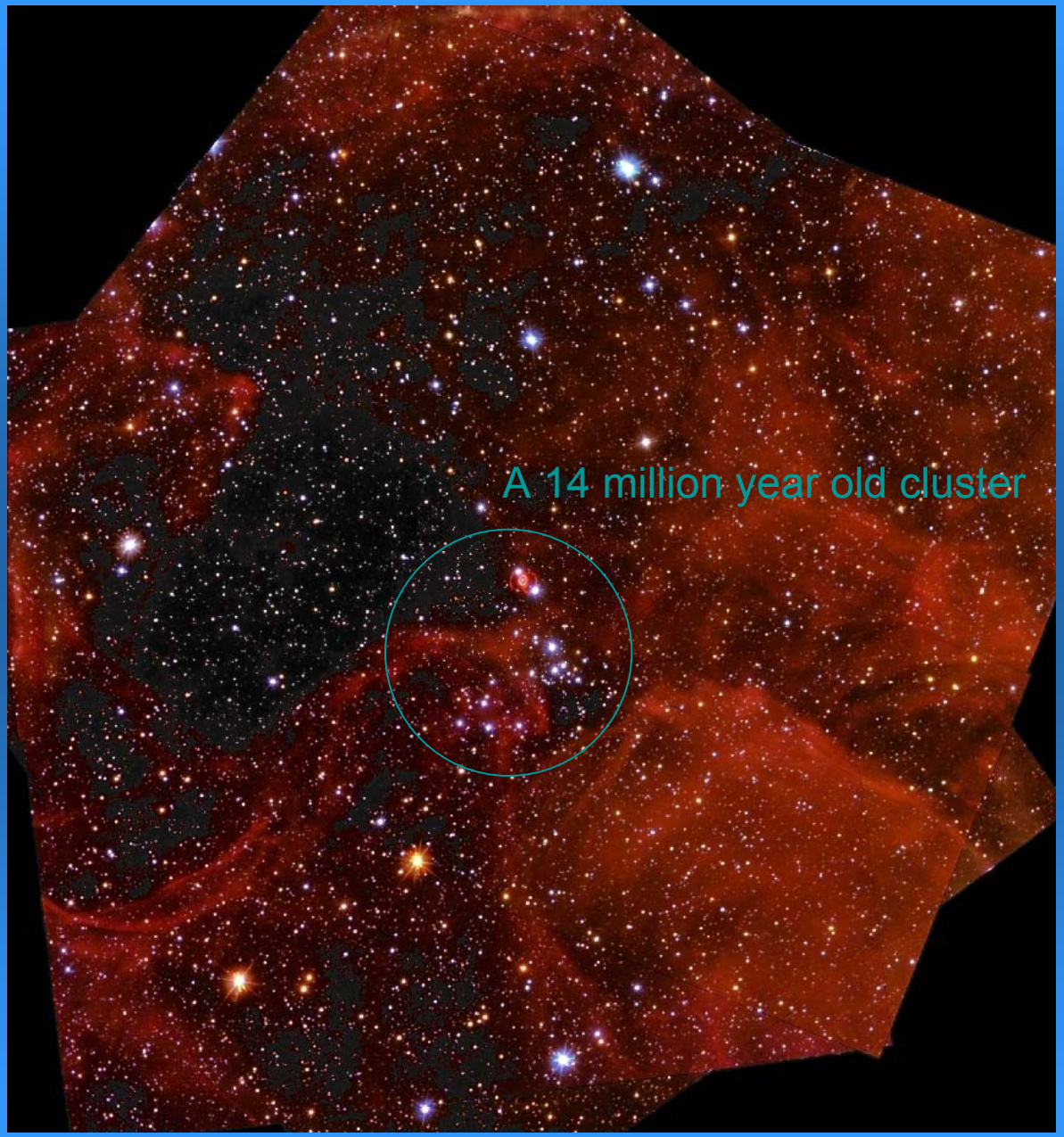
Fig. 1. V light curve of SN1987A. The various phases are labeled.

SN 1987A field

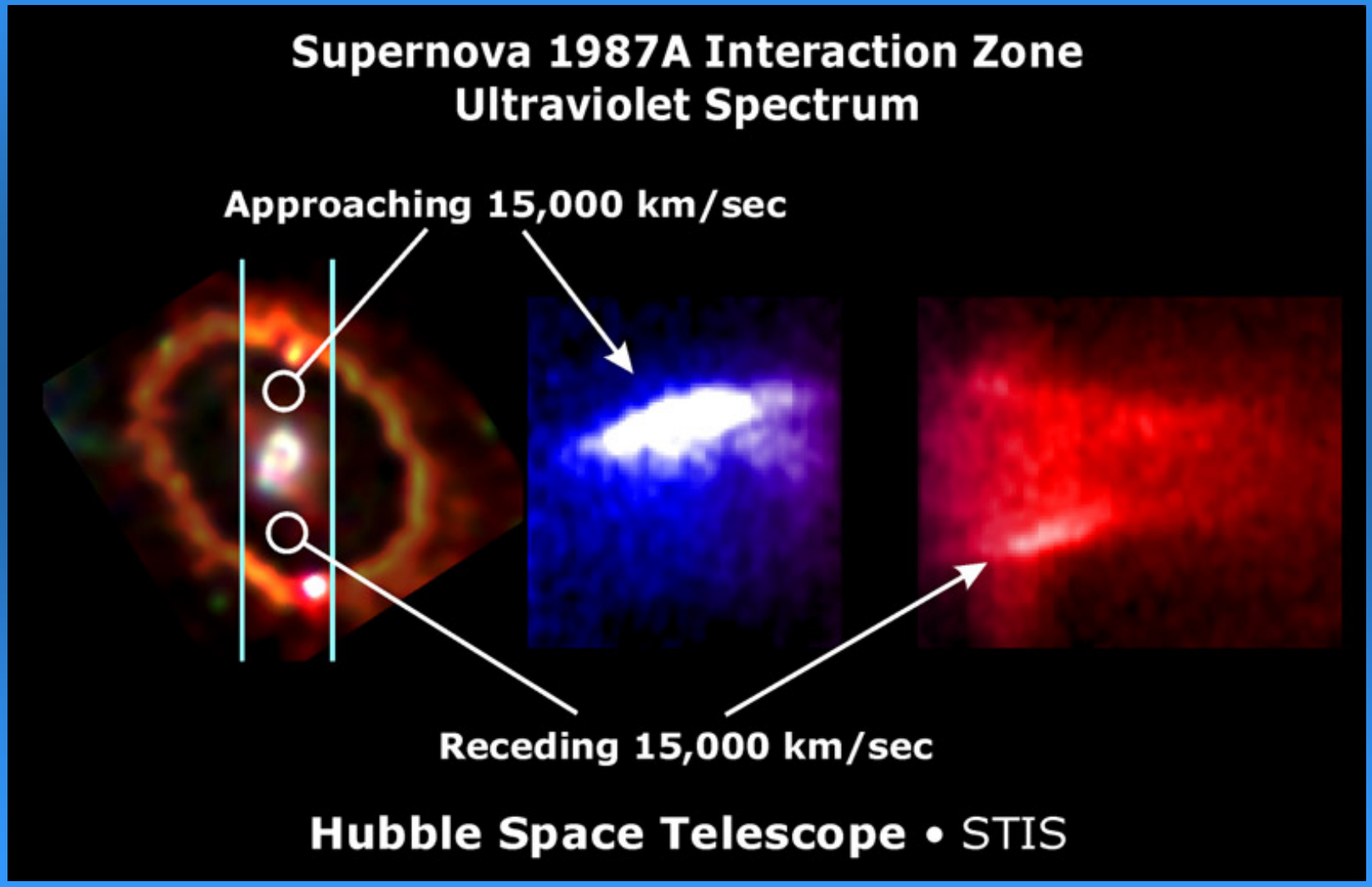
HST-WFPC2,
P.Challis & SINS Collaboration



HST-WFPC2,
Panagia et al 2002

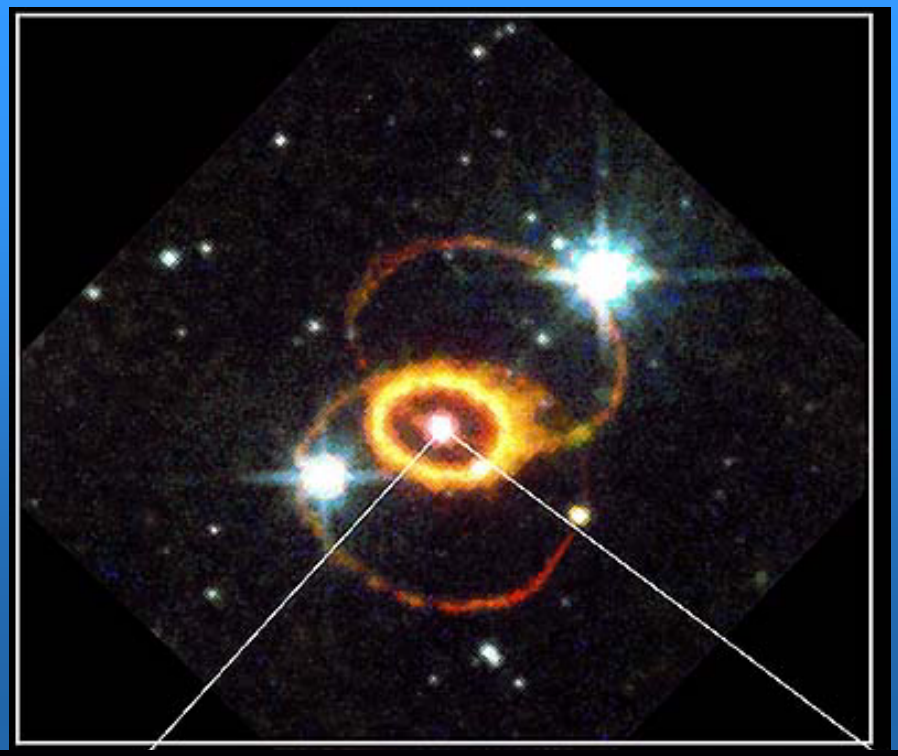


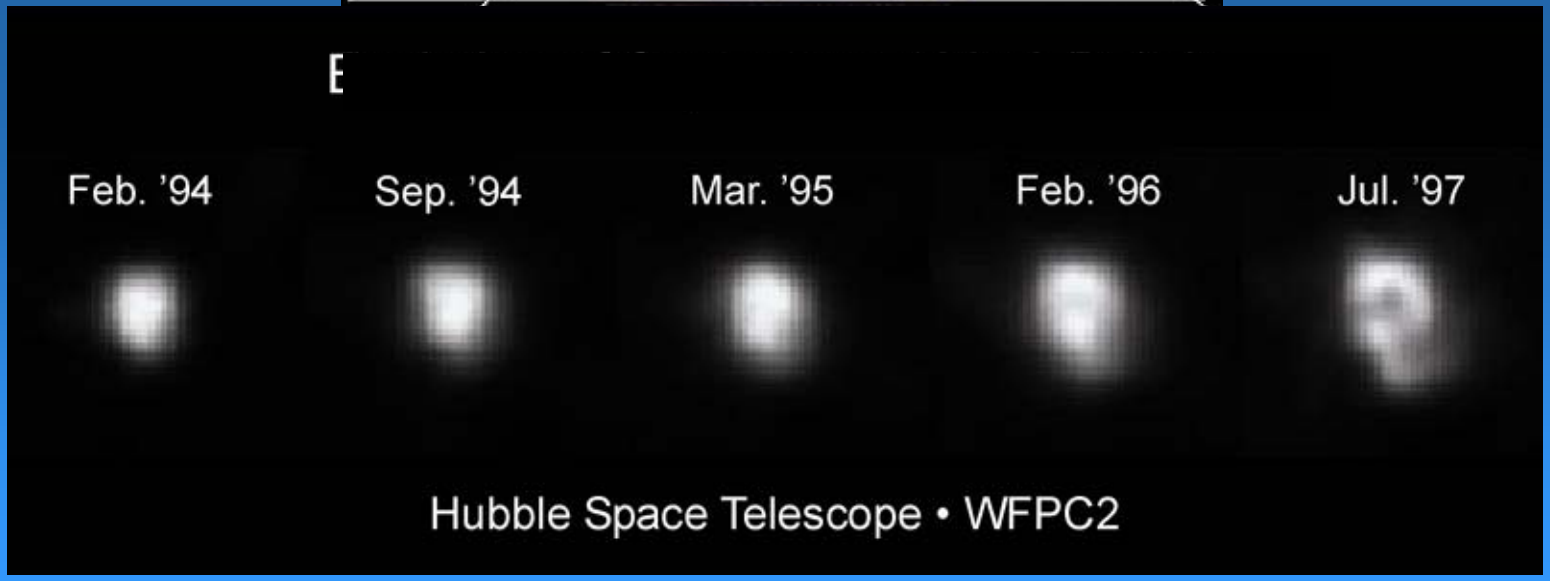
STIS Ly-α Spectroscopy



3D shape of the rings

Expansion of the ejecta





Early X-ray Evolution

(Dotani et al 1987, Sunyaev et al 1987)

X-rays are detected as early as ~100 days after explosion.

This is evidence for:

-either "leaky ejecta"
- or ^{56}Ni distributed within the ejecta

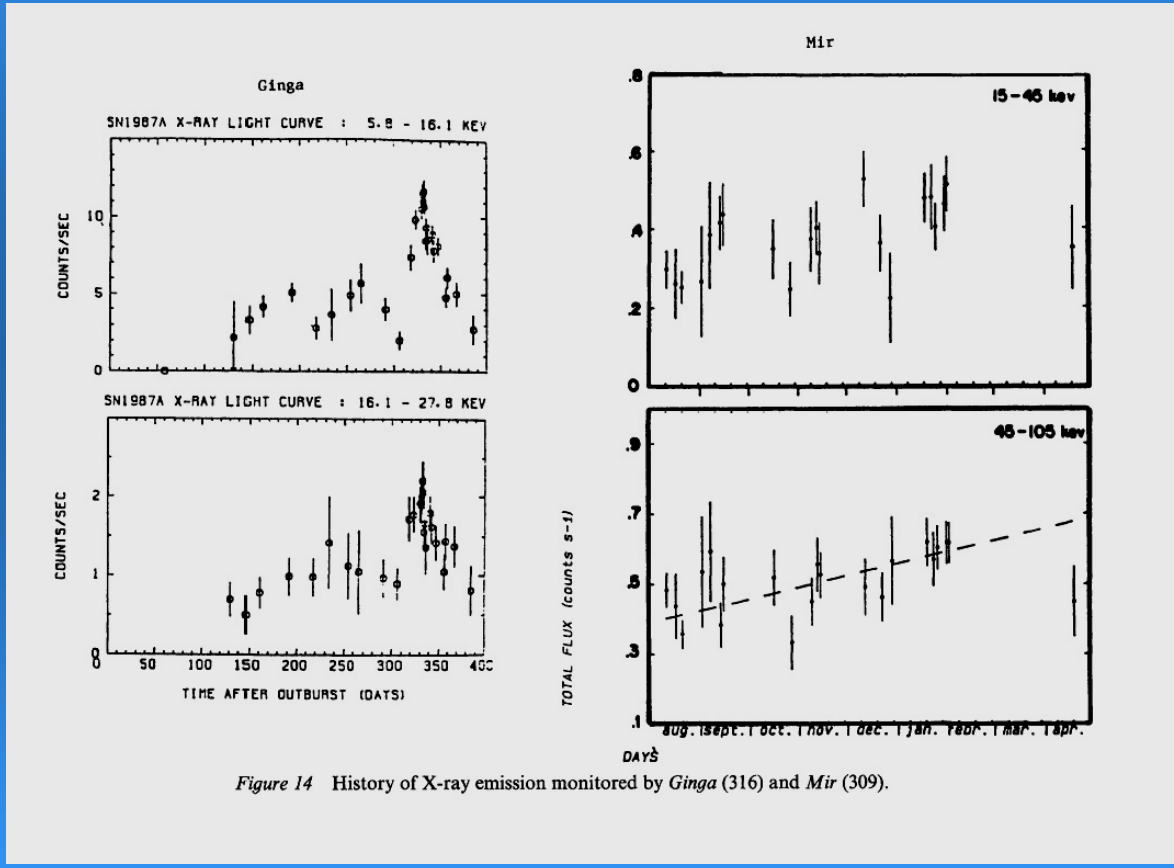


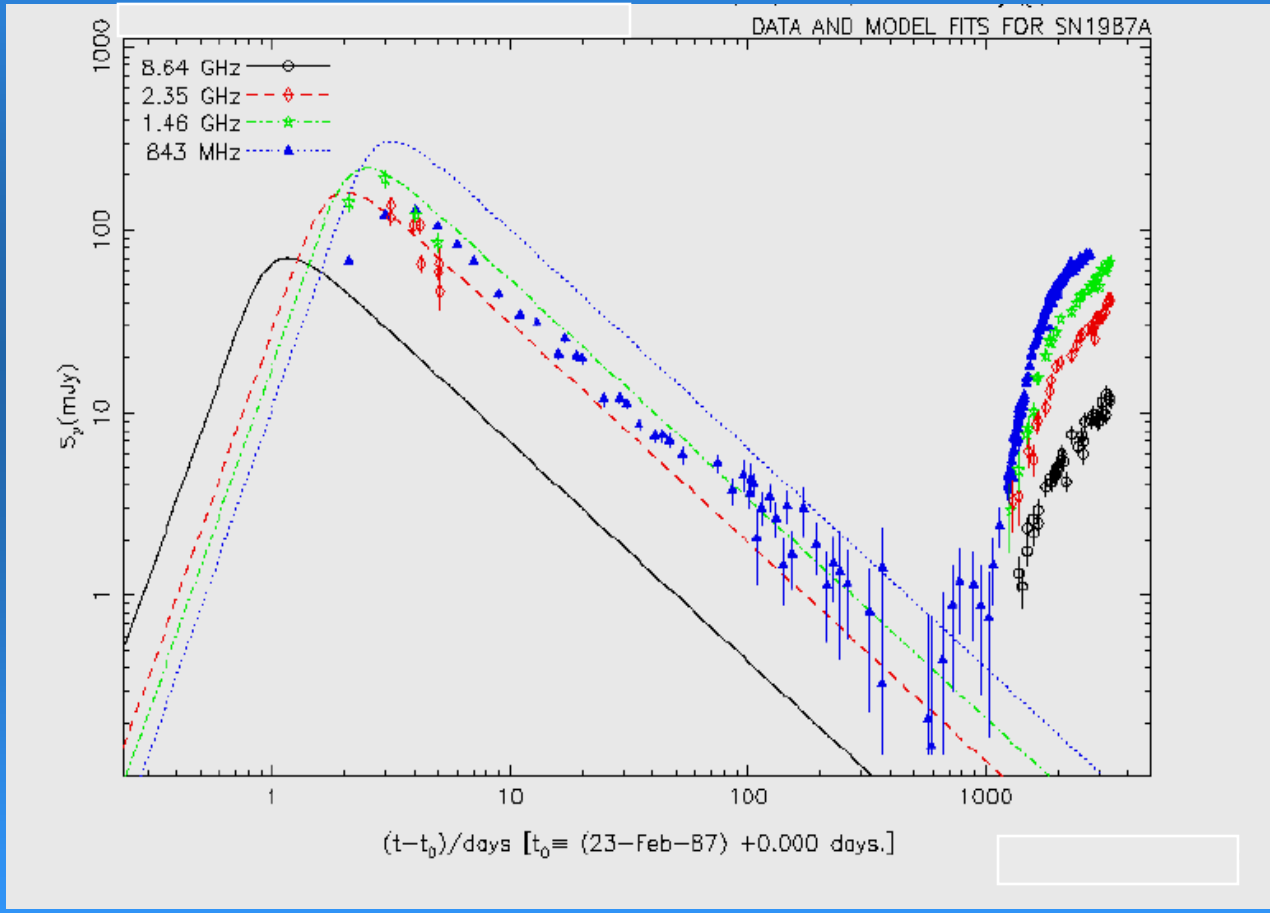
Figure 14 History of X-ray emission monitored by *Ginga* (316) and *Mir* (309).

Early Radio Evolution

Prompt, low flux radio emission and quick decay

➔ substantial mass loss but high wind velocity

⇒ B supergiant progenitor

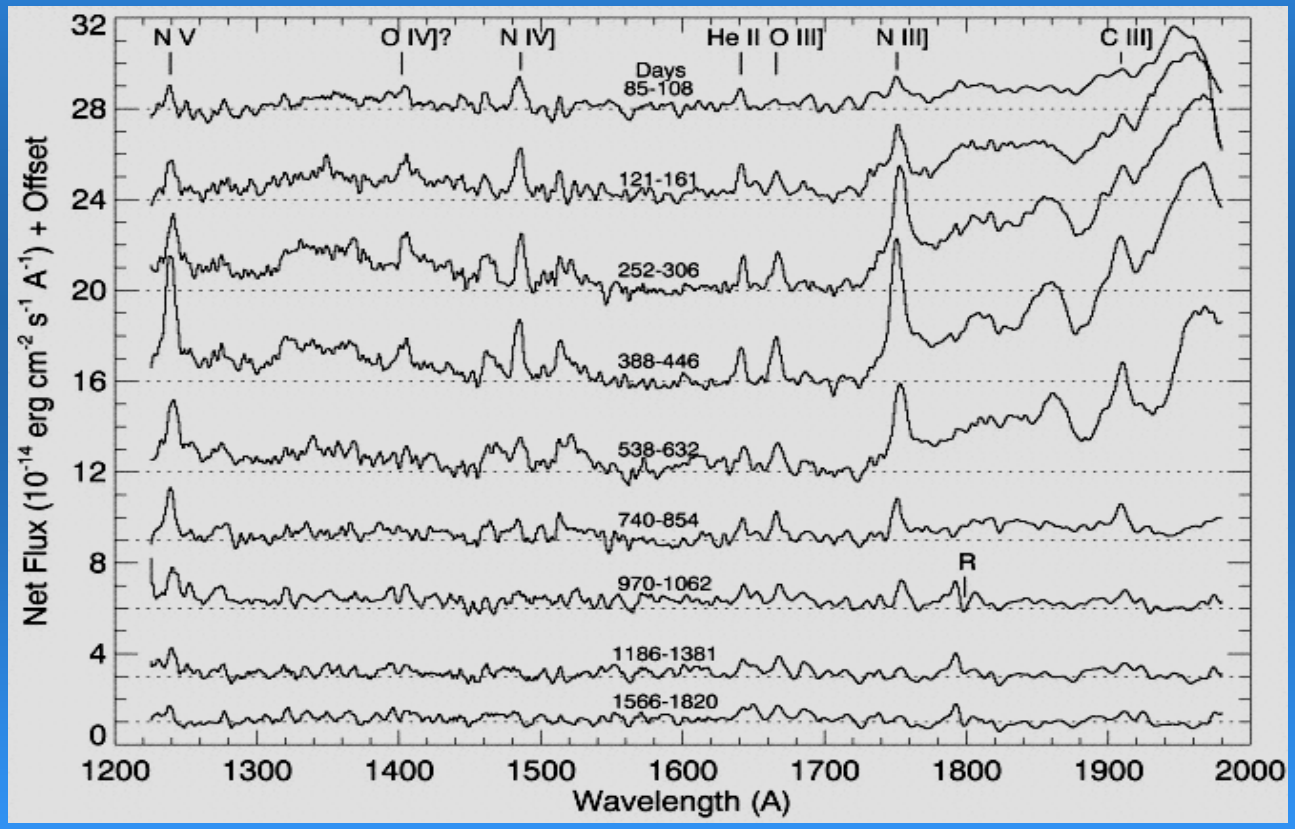


IUE spectra
(Sonneborn et al. 1997)

Emission lines of highly ionized species

Unusually strong Nitrogen lines

Narrow lines (v<30km/s)



Chemical Abundances in the equatorial ring

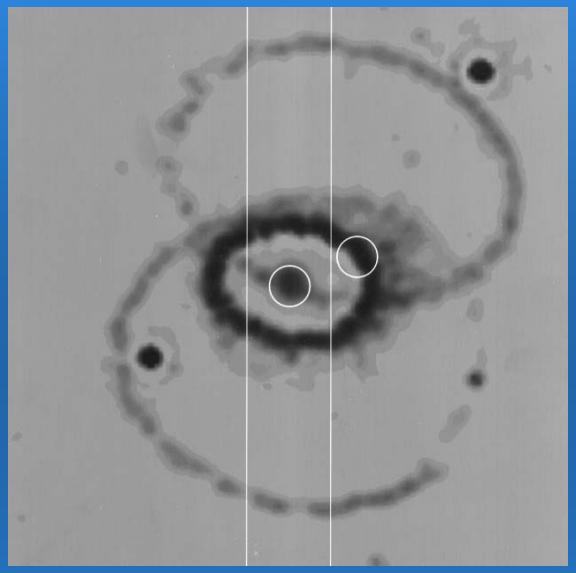
The inner ring abundances

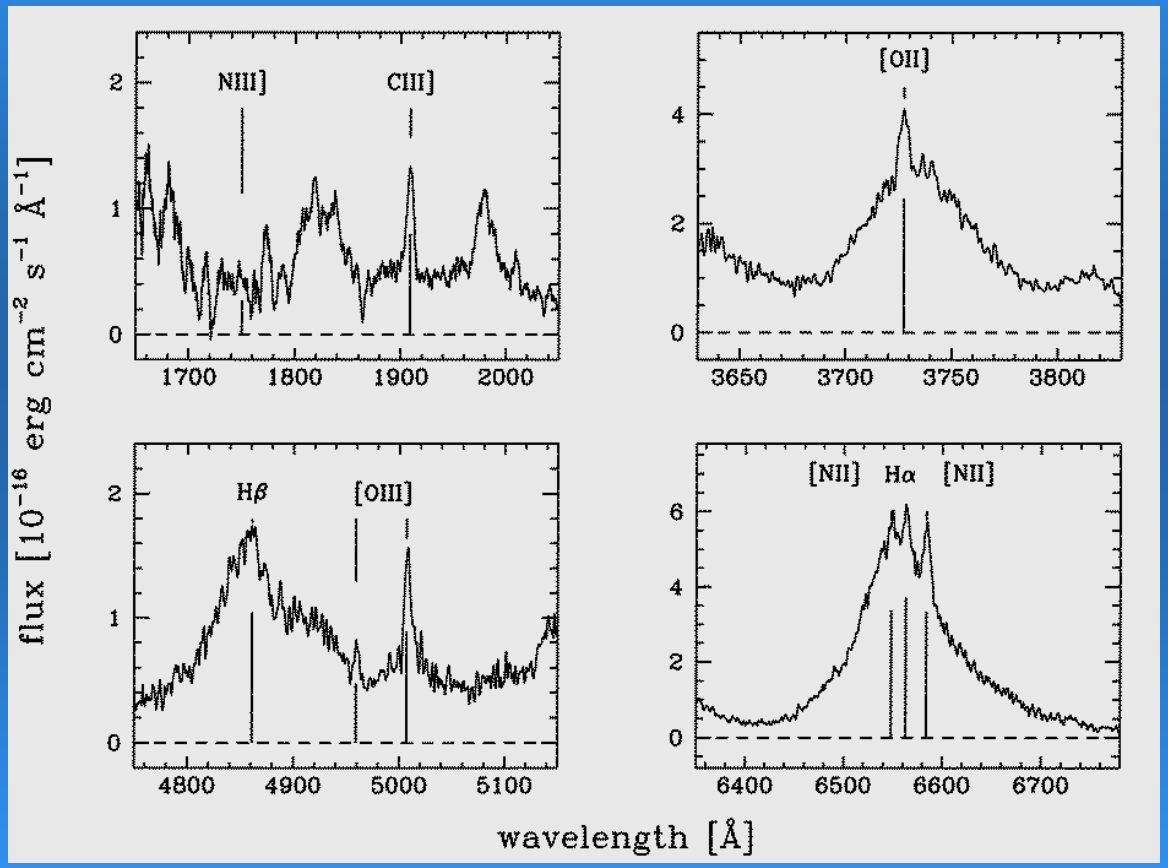
- A factor of 30 enhancement of the N/C ratio
- A *total* CNO abundance ~1/3 solar (=LMC)
- A 20-30% enrichment in Helium

CNO processed material, ejected at ~11 km/s some 10,000 years before the explosion

$\Rightarrow$ The progenitor was a RED Supergiant

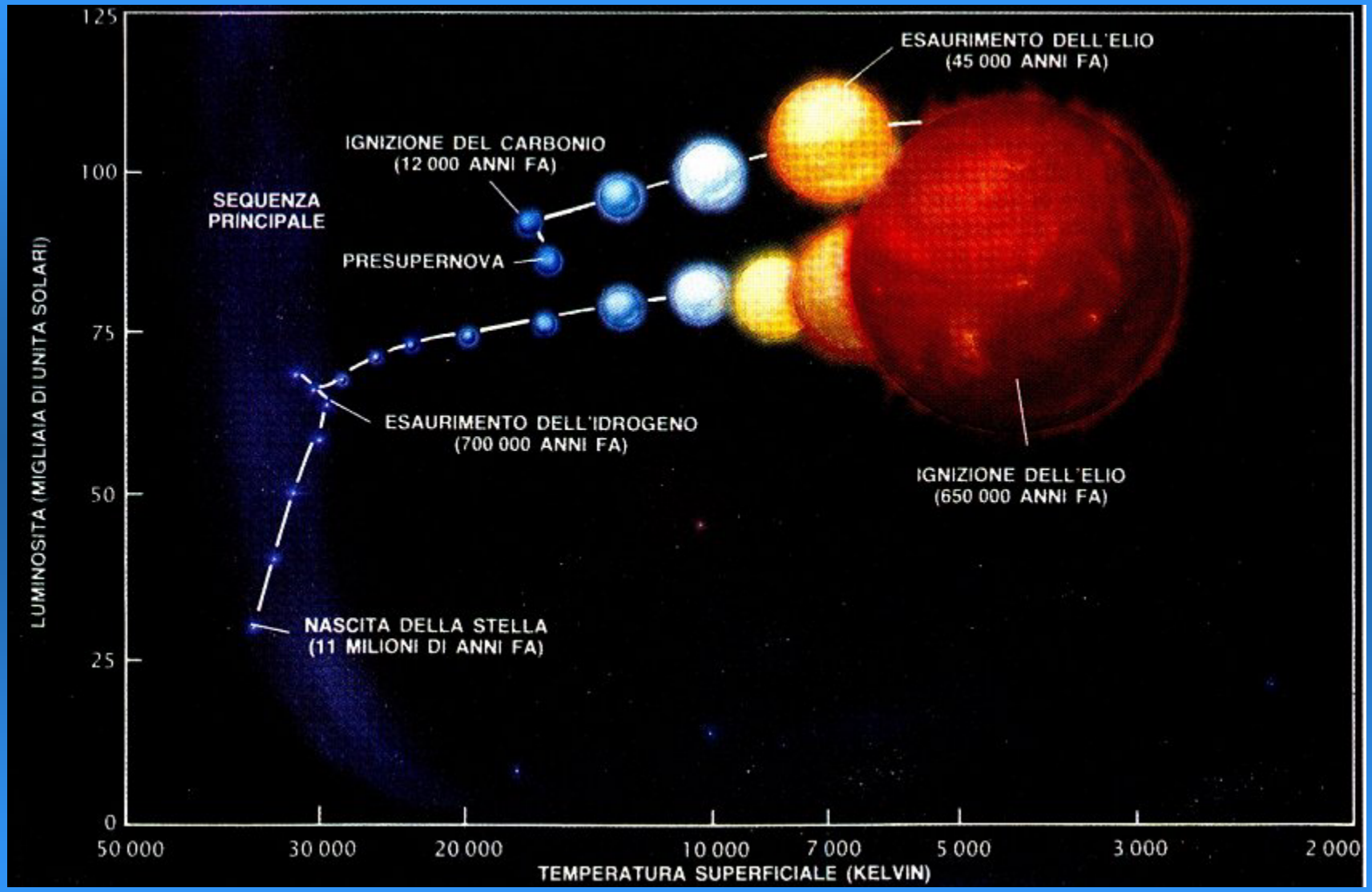
HST-FOS Spectroscopy of the Northern Ring





The N/C ratio in the outer rings is about ½ lower than in the equatorial ring

→ **An earlier ejection about 20,000 years before explosion**

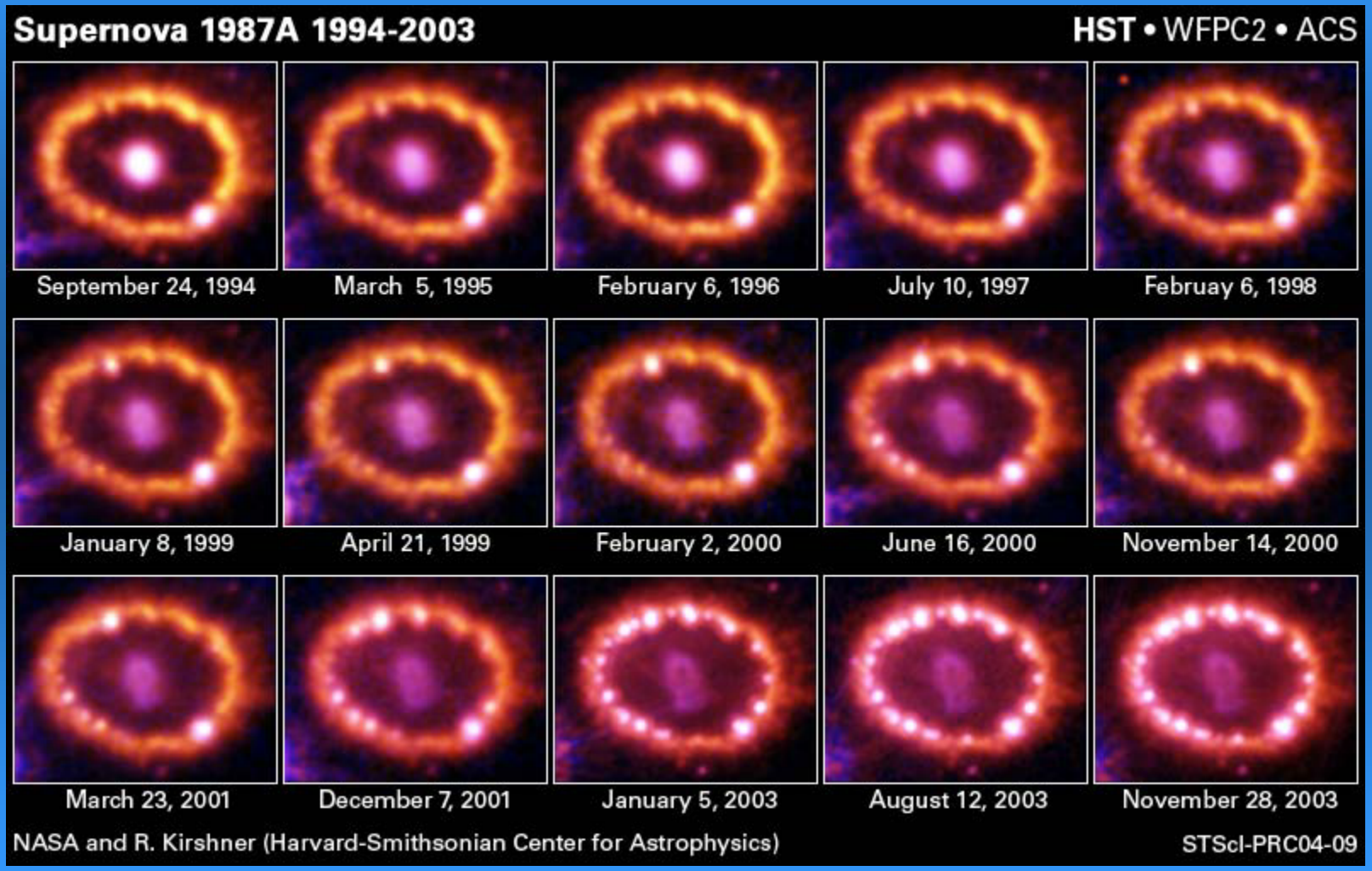

ESAURIMENTO DELL'ELIO
(45 000 ANNI FA)
IGNIZIONE DEL CARBONIO
(12 000 ANNI FA)
SEQUENZA
PRINCIPALE
PRESUPERNOVA
ESAURIMENTO DELL'IDROGENO
(700 000 ANNI FA)
IGNIZIONE DELL'ELIO
(650 000 ANNI FA)
NASCITA DELLA STELLA
(11 MILIONI DI ANNI FA)
LUMINOSITA (MIGLIAIA DI UNITA SOLARI)
125
100
75
50
25
0
50 000
30 000
20 000
10 000
7 000
5 000
3 000
2 000
TEMPERATURA SUPERFICIALE (KELVIN)

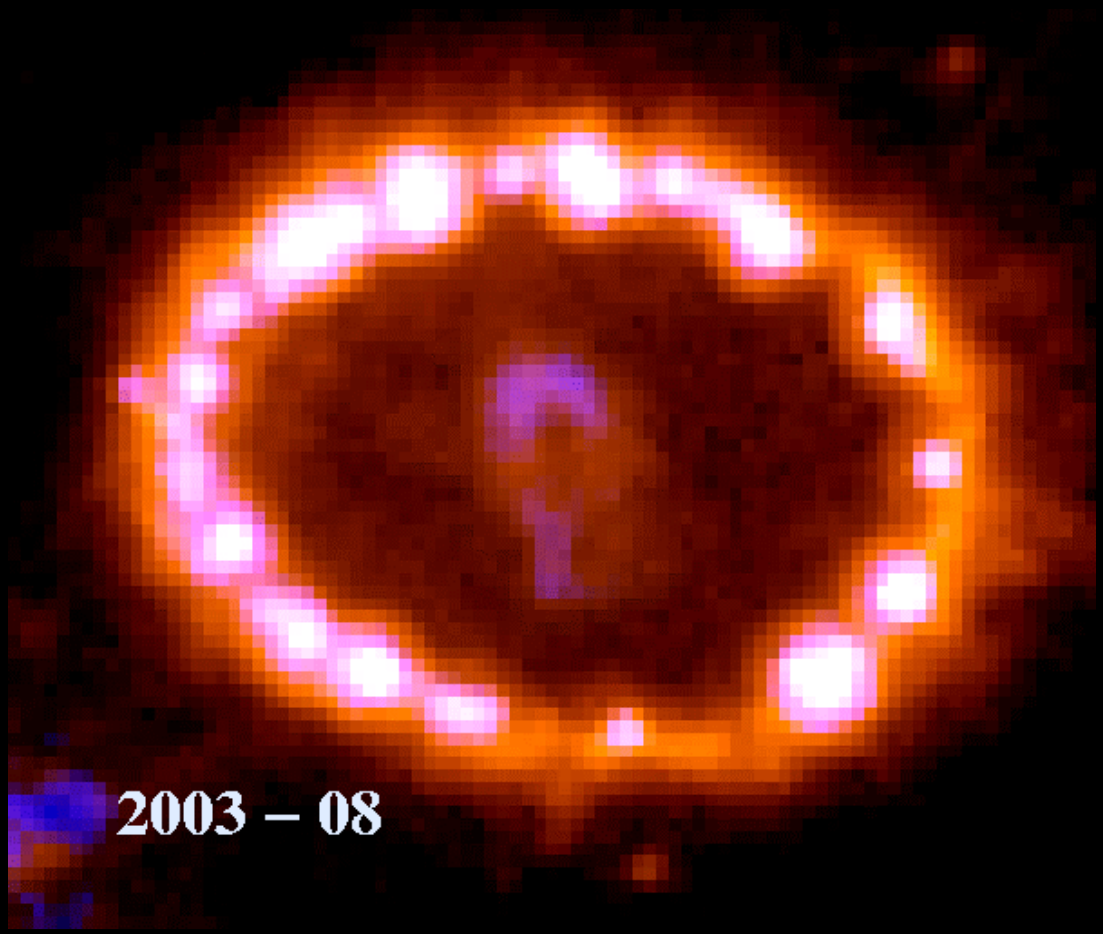
ER

ESTRELLA ROJA

Seguimos evolucionando...

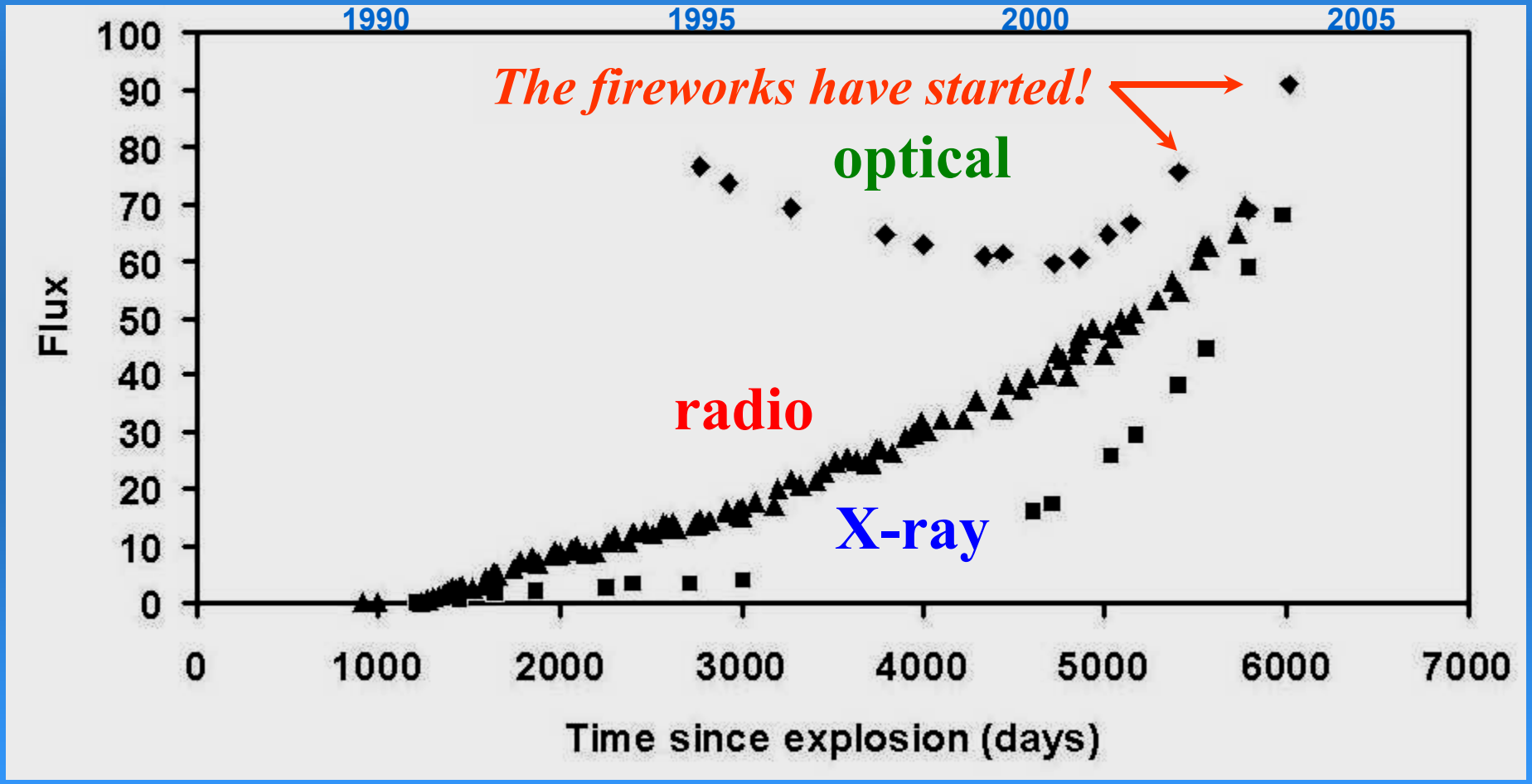
Evolution of SN 1987A Equatorial Ring





- Over the next decade, as the entire ring will light up
- Brightest object in LMC
- mass loss history will be revealed

Optical, X-ray, & Radio light curves of SN1987A ring



SN 1987A Energetics

Source	Collapse	Radioactivity	Expansion
Definition	$\sim GM_{\odot}^2/R_{N^*}$	$^{56}Ni \rightarrow {}^{56}Co \rightarrow {}^{56}Fe$ ($0.07\ M_{\odot}$)	$\int \frac{1}{2} v^2\, dM$
Outcome	Neutrinos (*kT ~ 4MeV*)	Opt, IR (+X, γ)	X-rays (+R, IR, O, UV)
Energy (erg)	10^{53}	10^{49}	10^{51}
Timescale	~ 10 seconds	~1 year	10-1000 years

Summary

- observed at
- neutrinos (c
- exp.vel. 400
- mixing of H
- dust formati
- evidence of
  - –decay rate
  - –IR lines of [
  - –γ-ray lines
- time depend
- controversia
- complex env
- fireworks ju

Progenitor: SK -69° 202 spectral type B3 I
$M_V = 12.29 \pm 0.04 \quad M_B = 12.32 \pm 0.06$
$R = (3 \pm 1) \times 10^{12}$ cm $\quad T_{\rm eff} = 16\,500 \pm 1500$ K
$L = (4.5 \pm 1.5) \times 10^{38}$ erg s^{-1}
Main sequence mass=(15–20)$\mathcal{M}_\odot$
Helium core mass= $(6 \pm 1)\ \mathcal{M}_\odot$
Hydrogen envelope mass at explosion=$\sim$10$\mathcal{M}_\odot$

Explosion:
Kinetic energy= $(1.3 \pm 0.2) \times 10^{51}$ erg
Total neutrino energy= $(2 \pm 1) \times 10^{53}$ erg
Neutrino temperature= (4 ± 1) MeV
Mean neutrino energy= 12.5 ± 3.0 MeV
Mass of ^{56}Ni= $(0.069 \pm 0.003)\mathcal{M}_\odot$
Detected γ-ray lines: ^{56}Co 0.847, 1.238 2.599, 3.250 MeV; ^{57}Co 122, 136 keV

Polarization:
Position angle=$\sim 120^\circ$
Percent polarization=0.6 (V band, day 40)

Circumstellar Ring:
Semimajor axis= 0.858 ± 0.011 arcsec= 6.4×10^{17} cm at 50 pc
Width= 0.122 ± 0.022 arcsec= $(9.0 \pm 1.6) \times 10^{16}$ cm at 50 kpc
Tilt angle= $44 \pm 1^\circ$
Position angle major axis= $89^\circ \pm 3^\circ$
Expansion velocity$\simeq$ 10.3 km s^{-1}

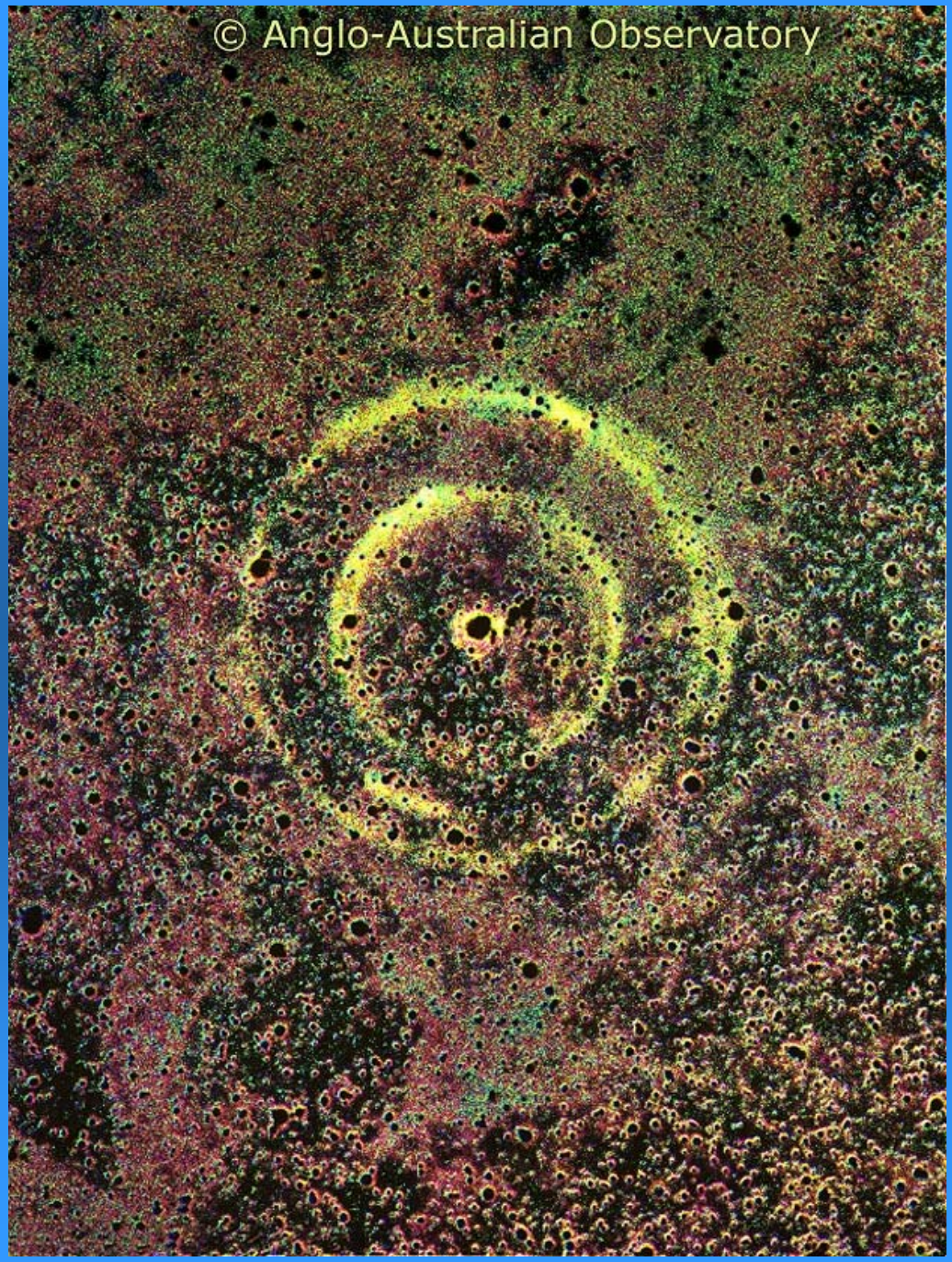
Supernova 1987A

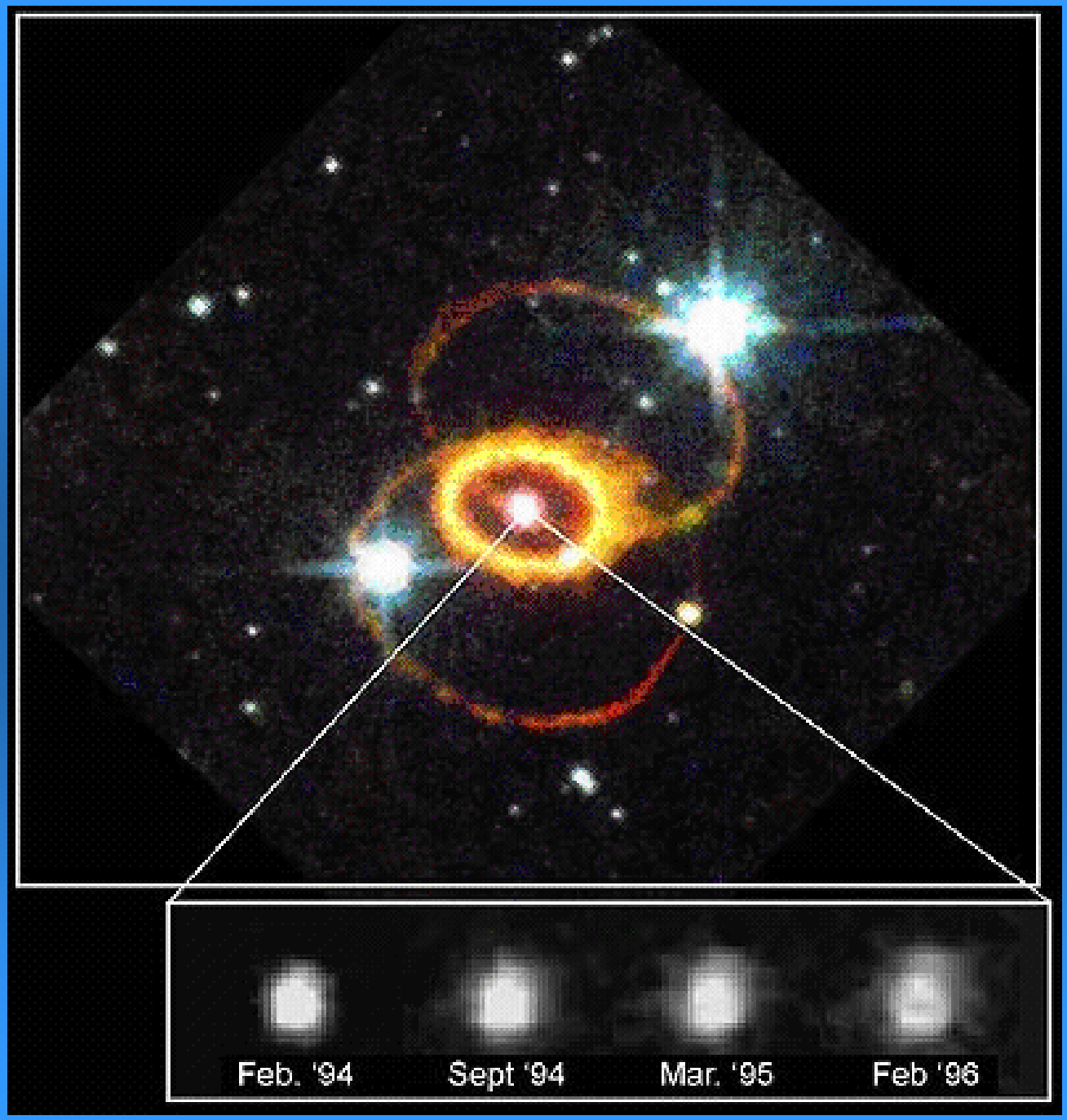
(HST-WFPC2, P.Challis & SINS Collaboration)

Late 1994

SN 1987A

light echo




Feb. '94
Sept '94
Mar. '95
Feb '96