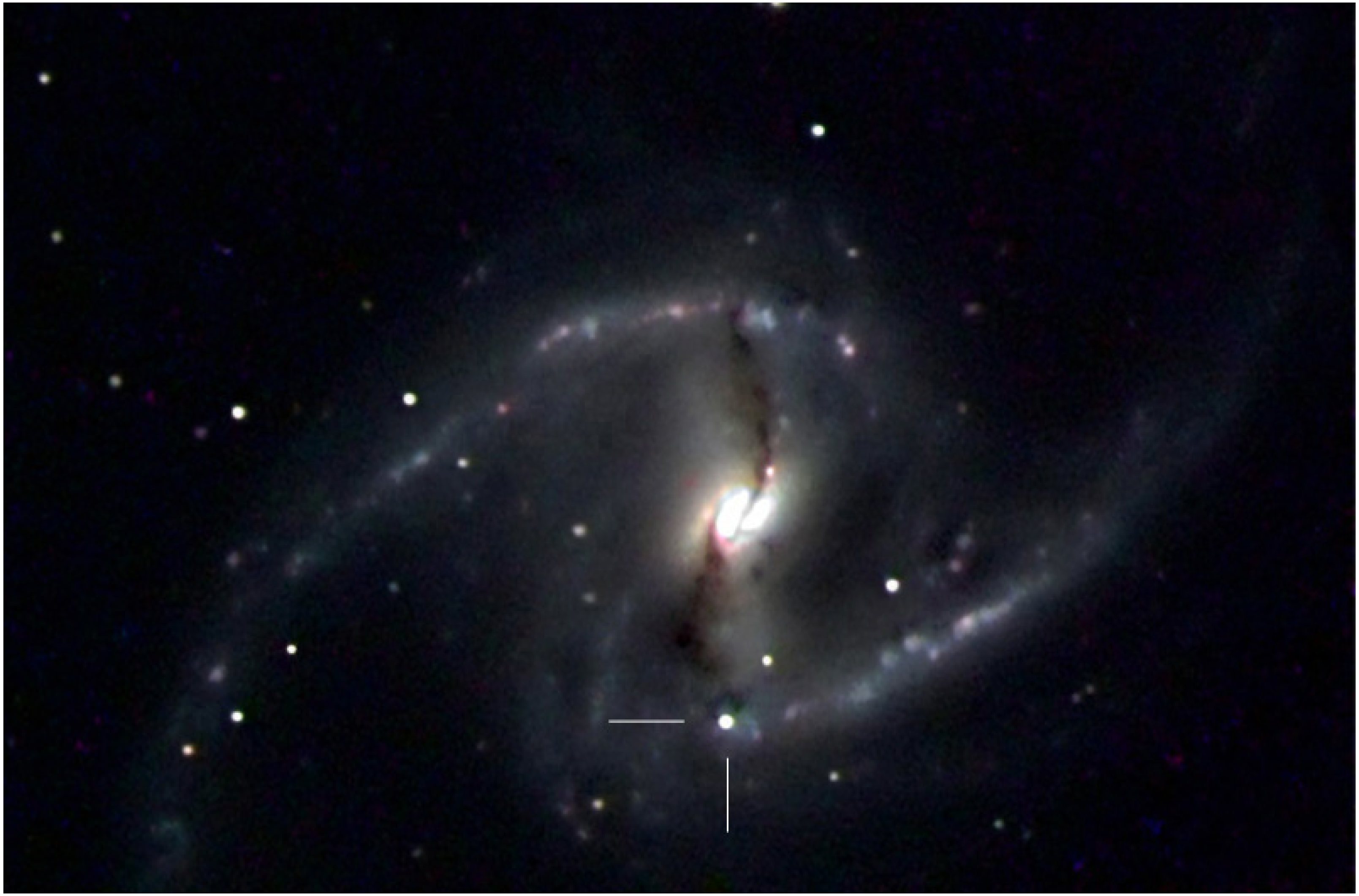
SUPERNOVAE: A COSMIC CATASTROPHE



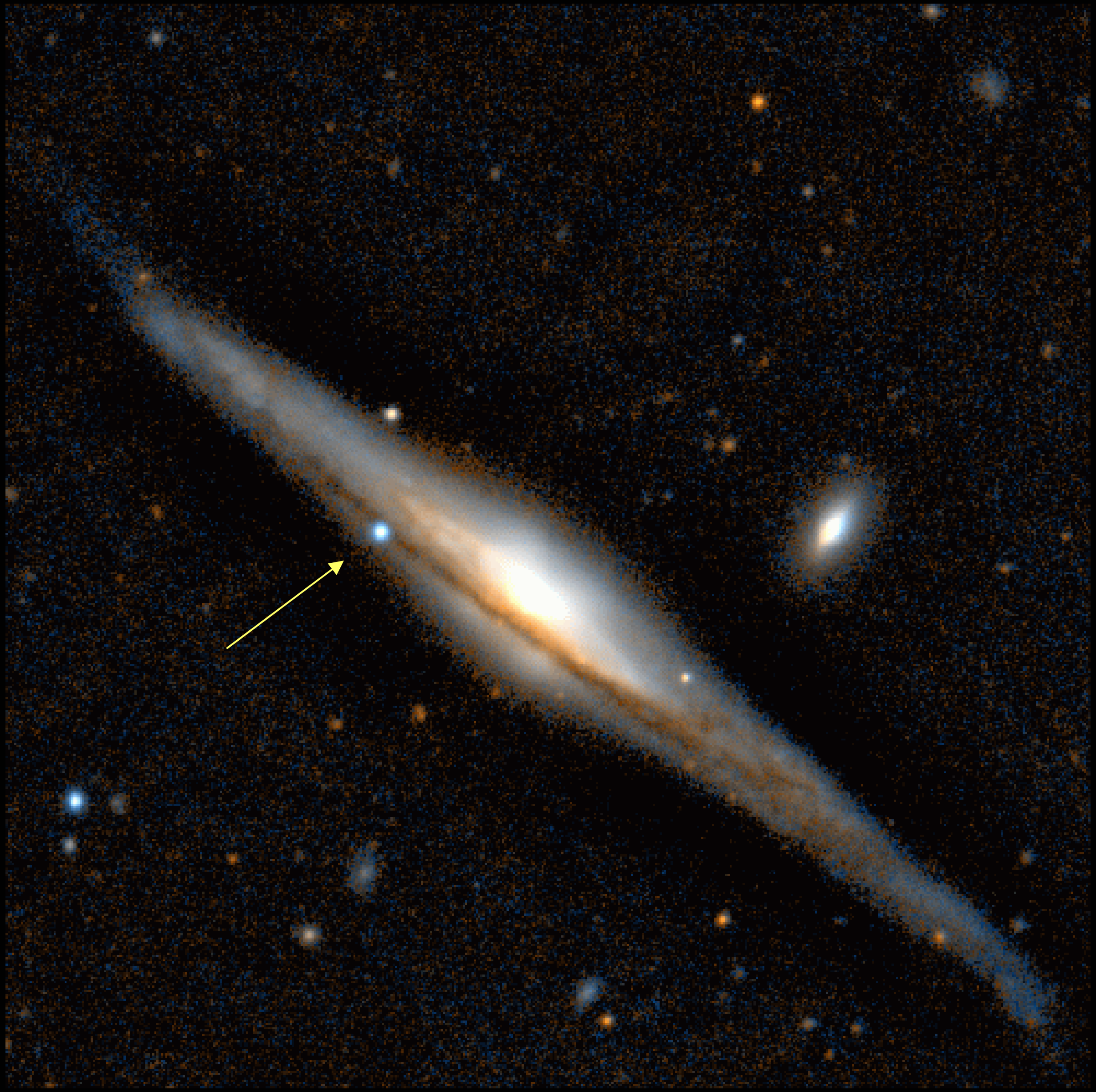
Gloria Dubner
IAFE- ARGENTINA

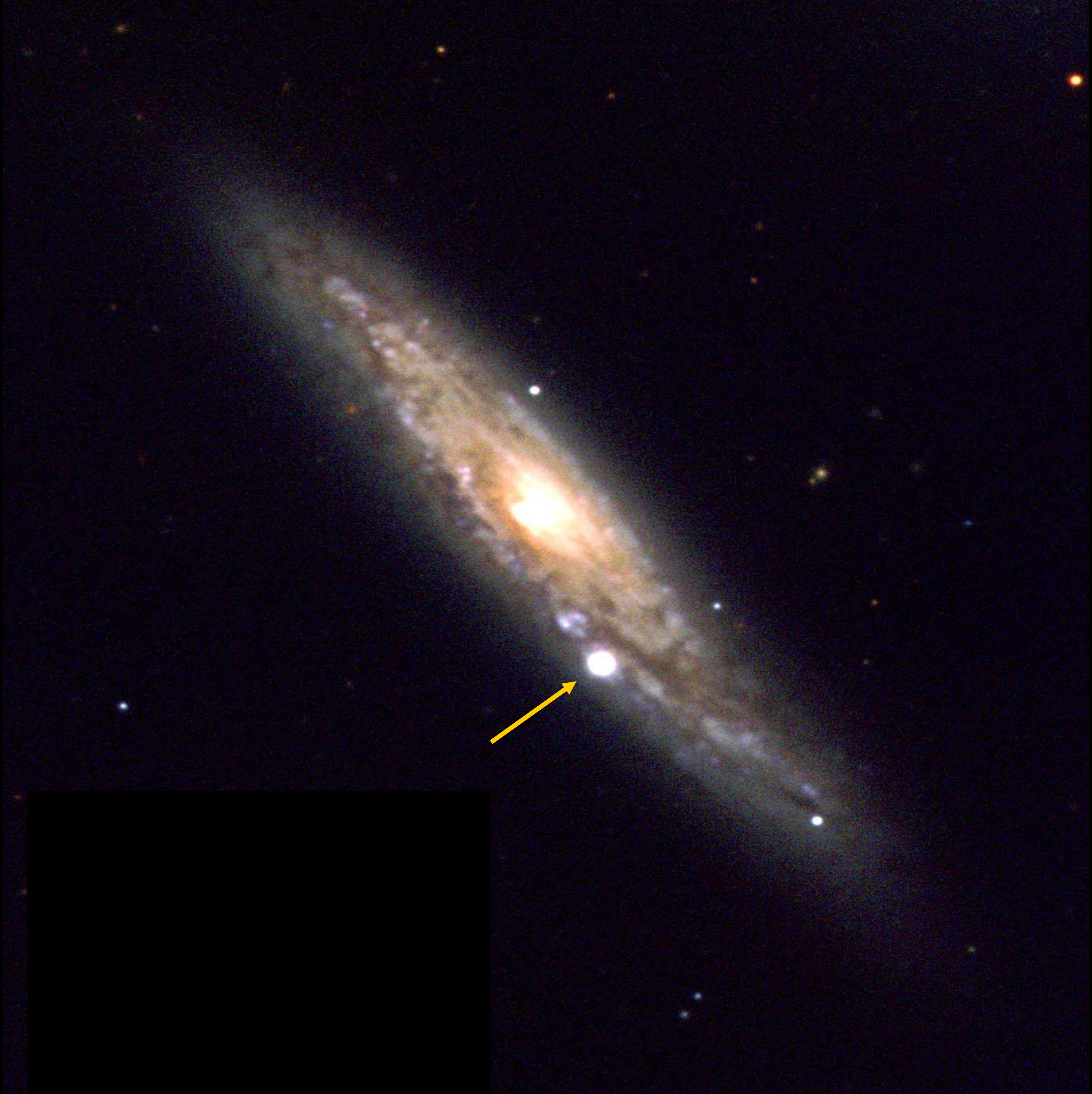
A Supernova is not an object, but an event

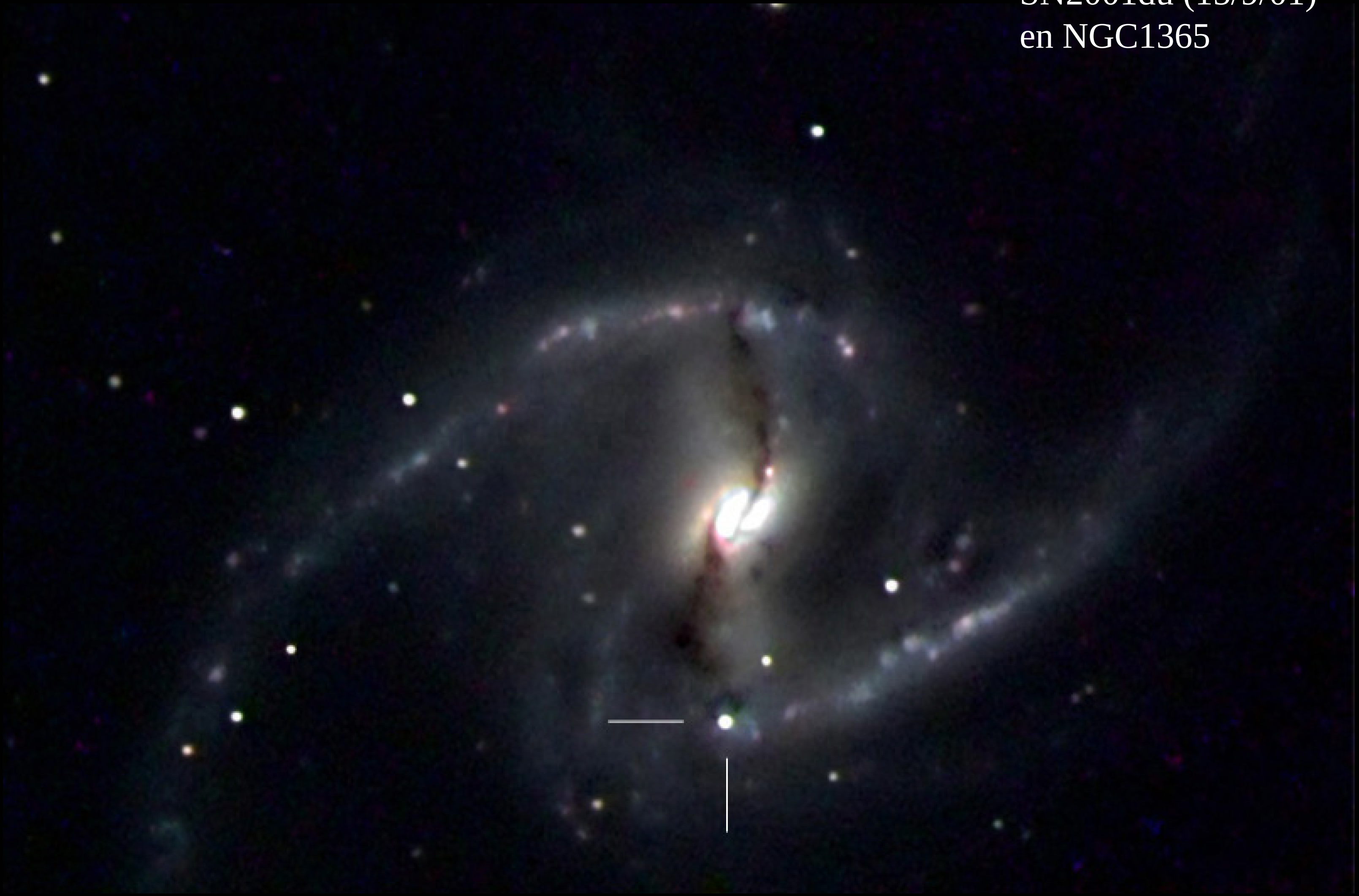
It is the catastrophic end of a long stellar life.
It represents the sudden injection of:

- about 10^{53} ergs
- almost instantaneously
- in a point-like region of the space

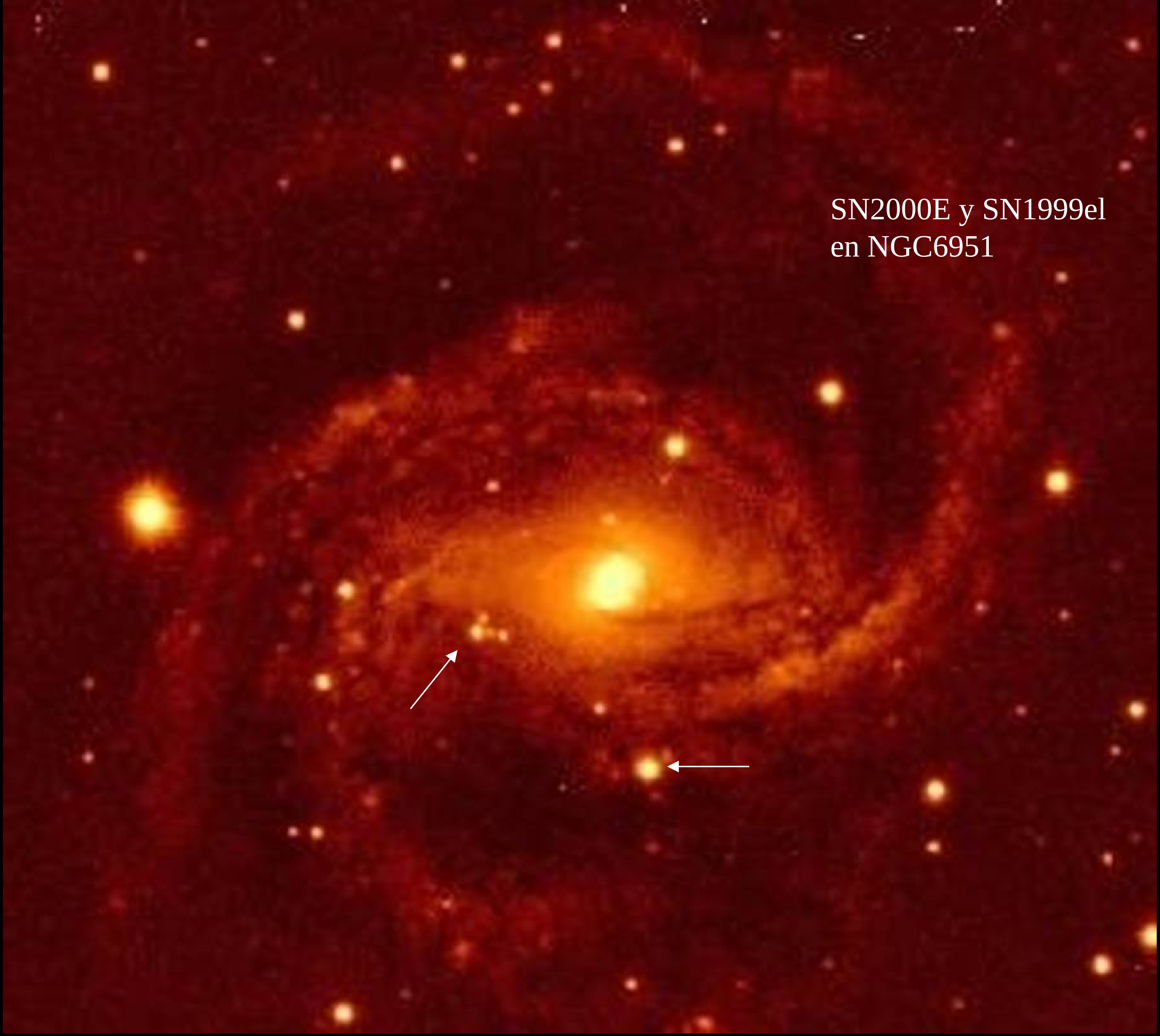
As a consequence, at their maximum, a supernova is brighter than the whole parent host galaxy







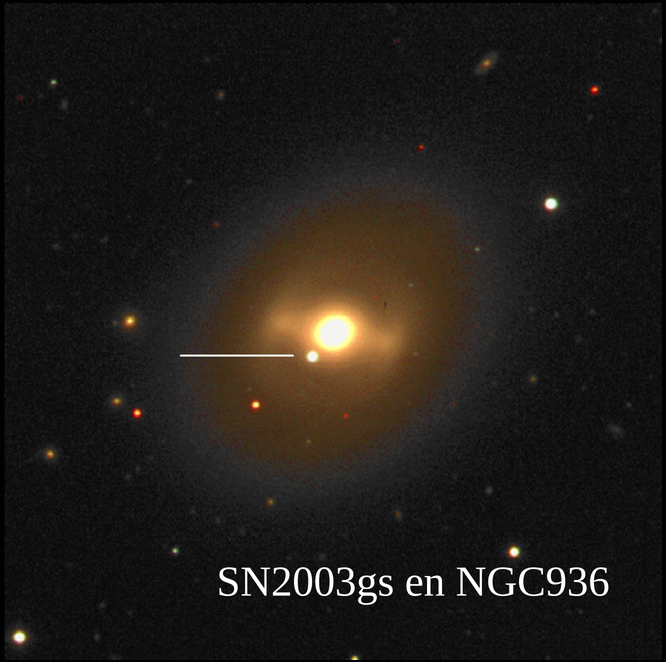
SN2001du (15/9/01)
en NGC1365



SN2000E y SN1999el
en NGC6951

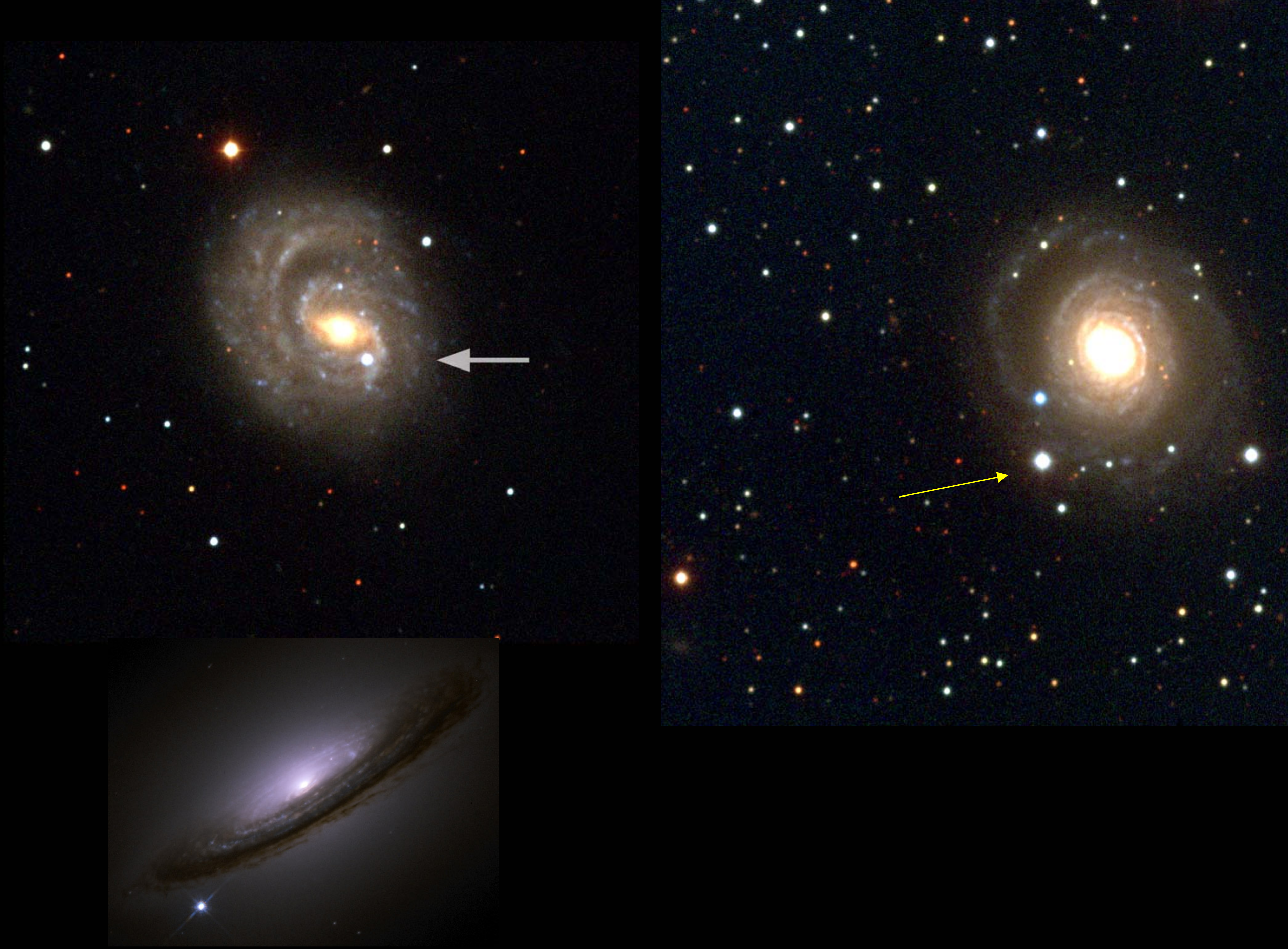
SN2001cm en NGC5965

SN2002bo en NGC3190
en Virgo



SN2003gs en NGC936

SN2004bv en NGC6907
(24/5/04).La más brillante de 2004

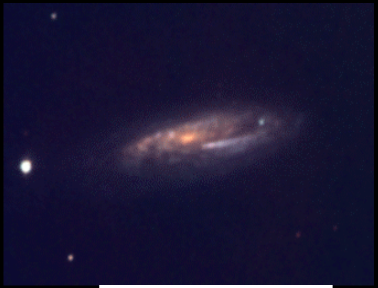


29/7/98

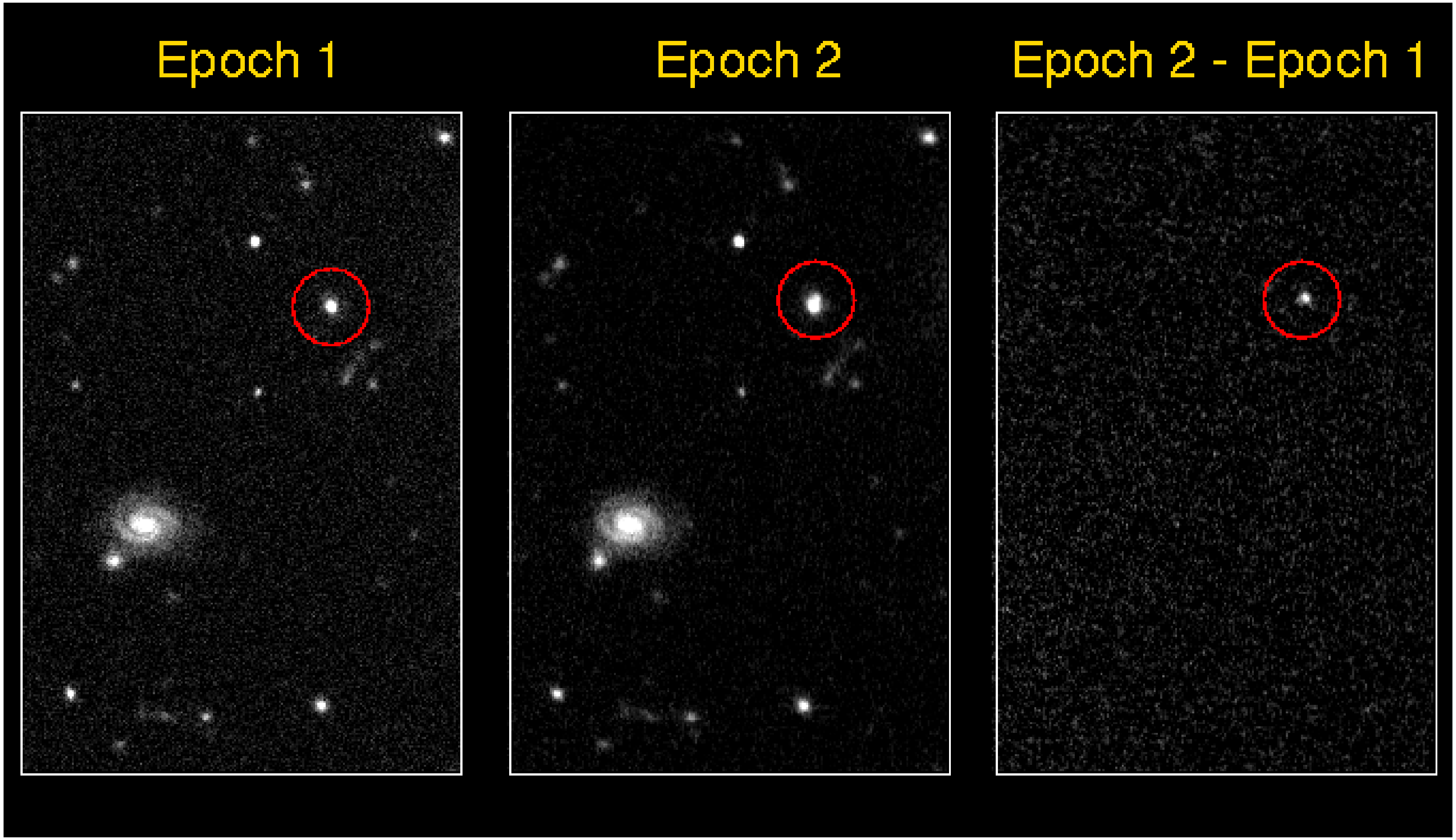
4/8/98

30/8/98

20/9/98



14/11/98

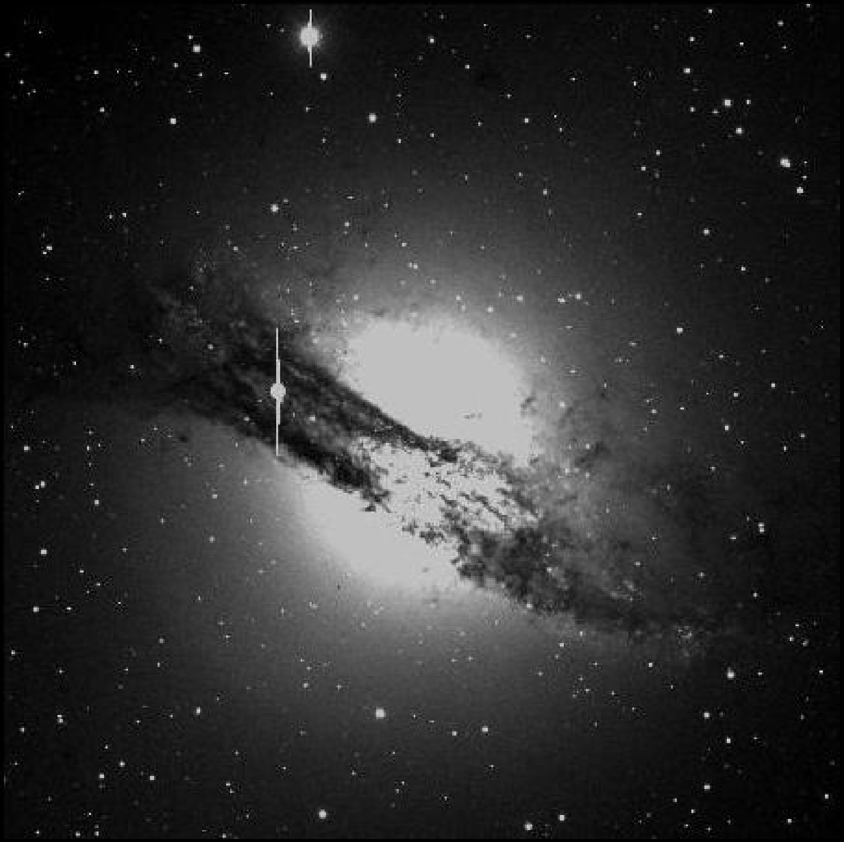


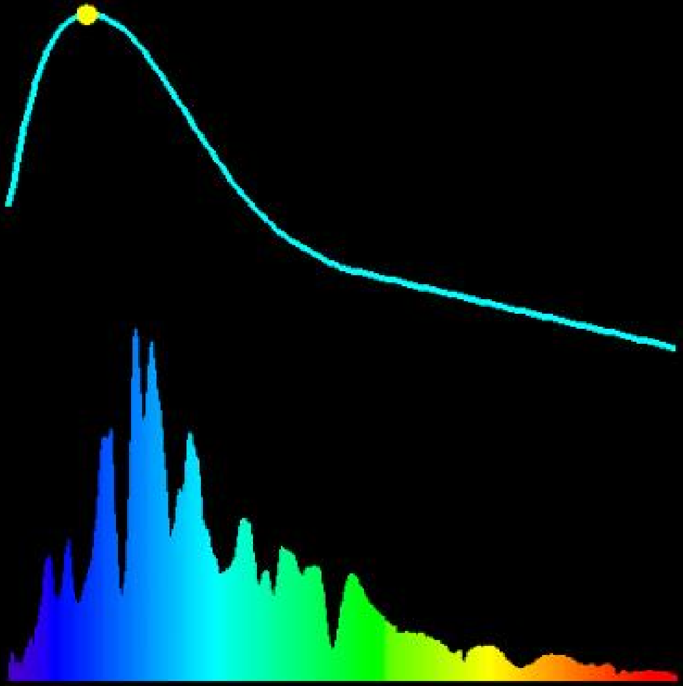
Epoch 1

Epoch 2

Epoch 2 - Epoch 1

Light declines with the days and change the color





➢ Such cosmic catastrophe irreversibly modifies all the interstellar gas up to ~ 100 pc or more around the site of the explosion.

➢ They constitute one of the main sources of energy in the interstellar gas.

➢ They are probably the main source of cosmic rays in the Galaxy

➢ They are the only way that the stars have to release the heavy elements processed in their interiors

➢ Their implications in the galactic ecology are so strong, that they are even responsible for the existence of life in this planet

The study of supernovae involves the physical processes of:

- the pre-supernova star
- the different explosion mechanisms
- the consequences of the explosion
- the short and long term evolution of the debris of stars

The study of supernovae lead us to the frontiers of physics.
During and after the explosion extreme conditions of density and pressure are attained.

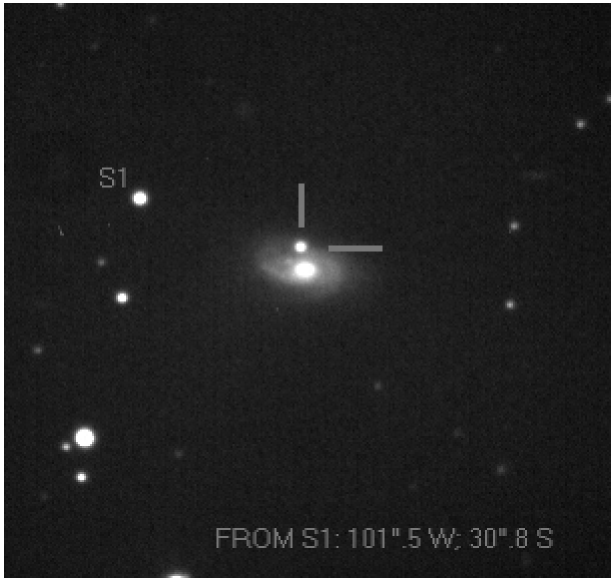
Such extremes are used:

- to explore the Universe and calculate its size and age.
- to investigate the physics that can never be reproduced in a terrestrial laboratory
- to understand the origin of life, etc.

GENERAL OUTLINE

- to understand the different physical processes involved in the death of a star:
  - What kind of information can we have ?
  - What is this information telling us?
  - How can be interpreted?

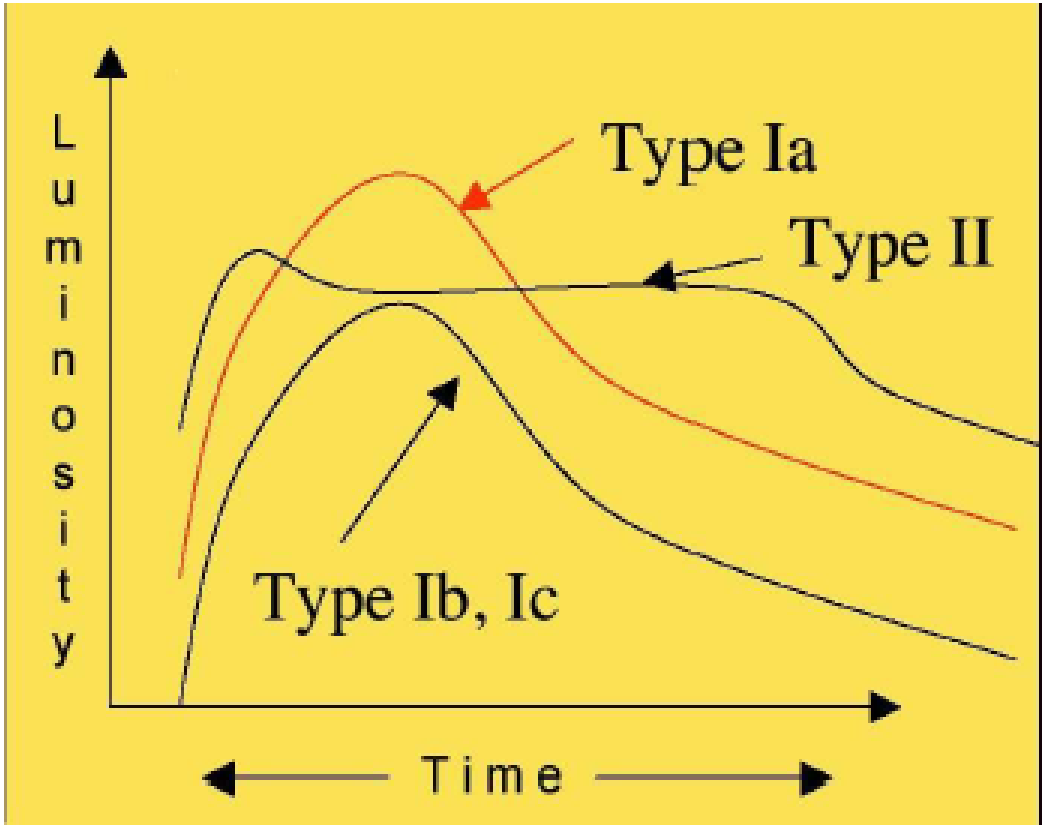
- what is left after a stellar explosion
  - neutron stars
  - heavy elements in the interstellar medium
  - supernova remnants

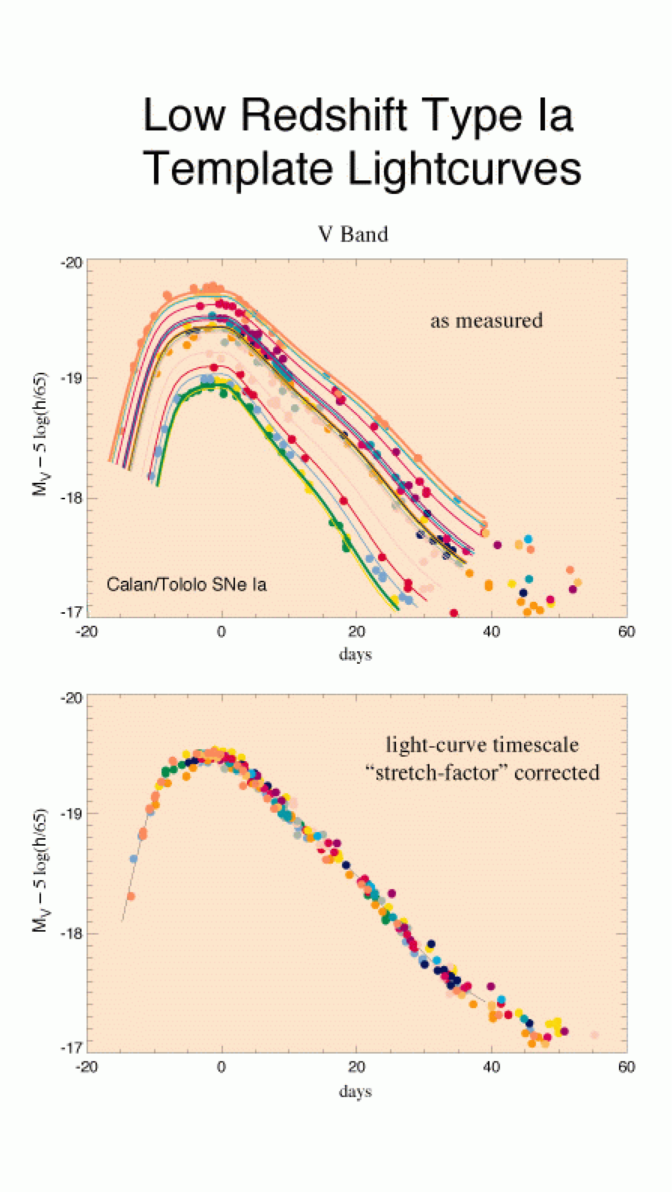


Once a new SN is discovered,

what information can we have?

- light curves
- early spectra
- late spectra
- morphological class of the host galaxy




Low Redshift Type Ia Template Lightcurves

SNe Type Ia attain M_V= -19.5

SNe Type II M_V = -18

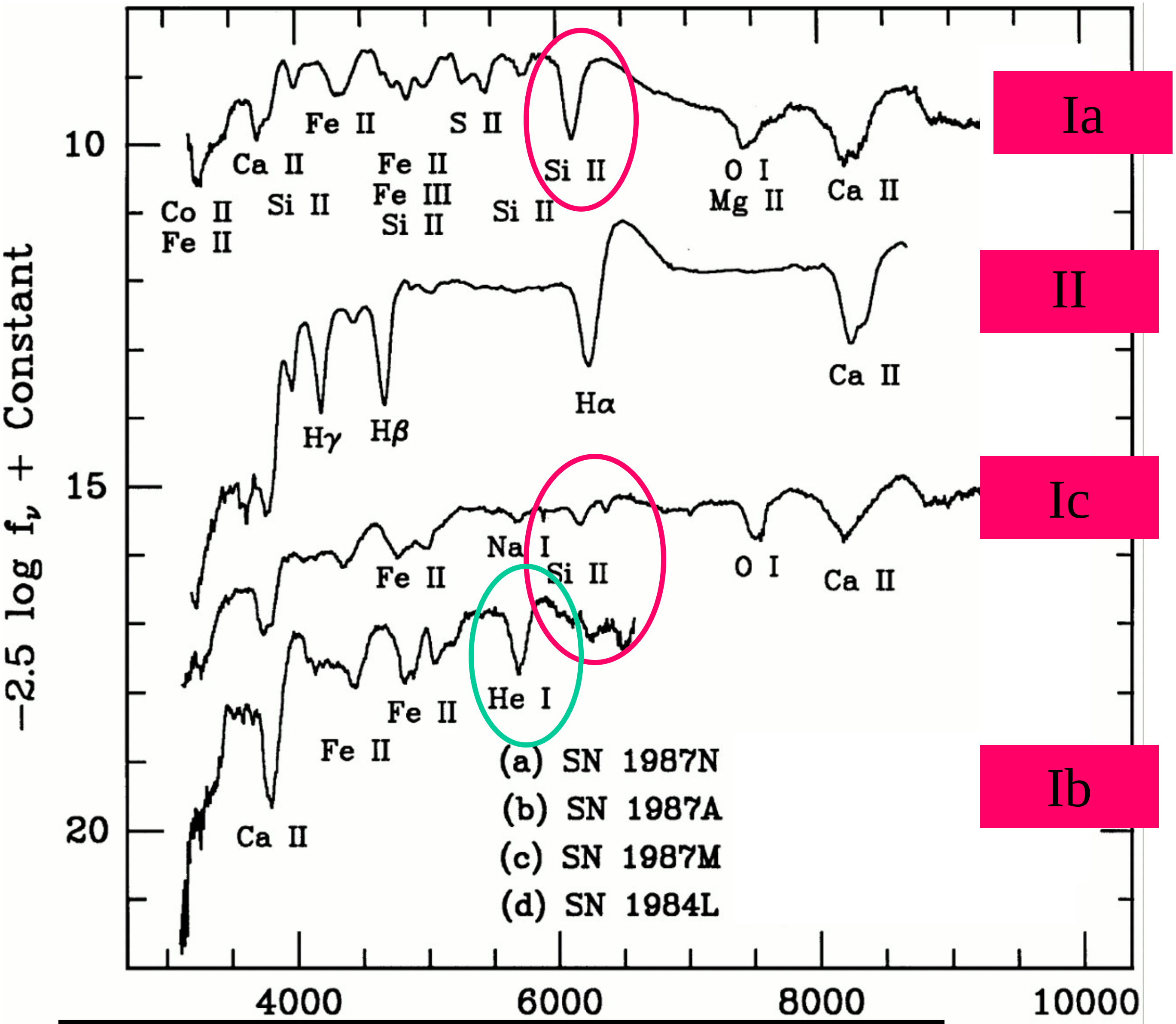
Early spectra of different SNe at τ ~ 1 week after maximum light

No H

H dominant

No H

No H



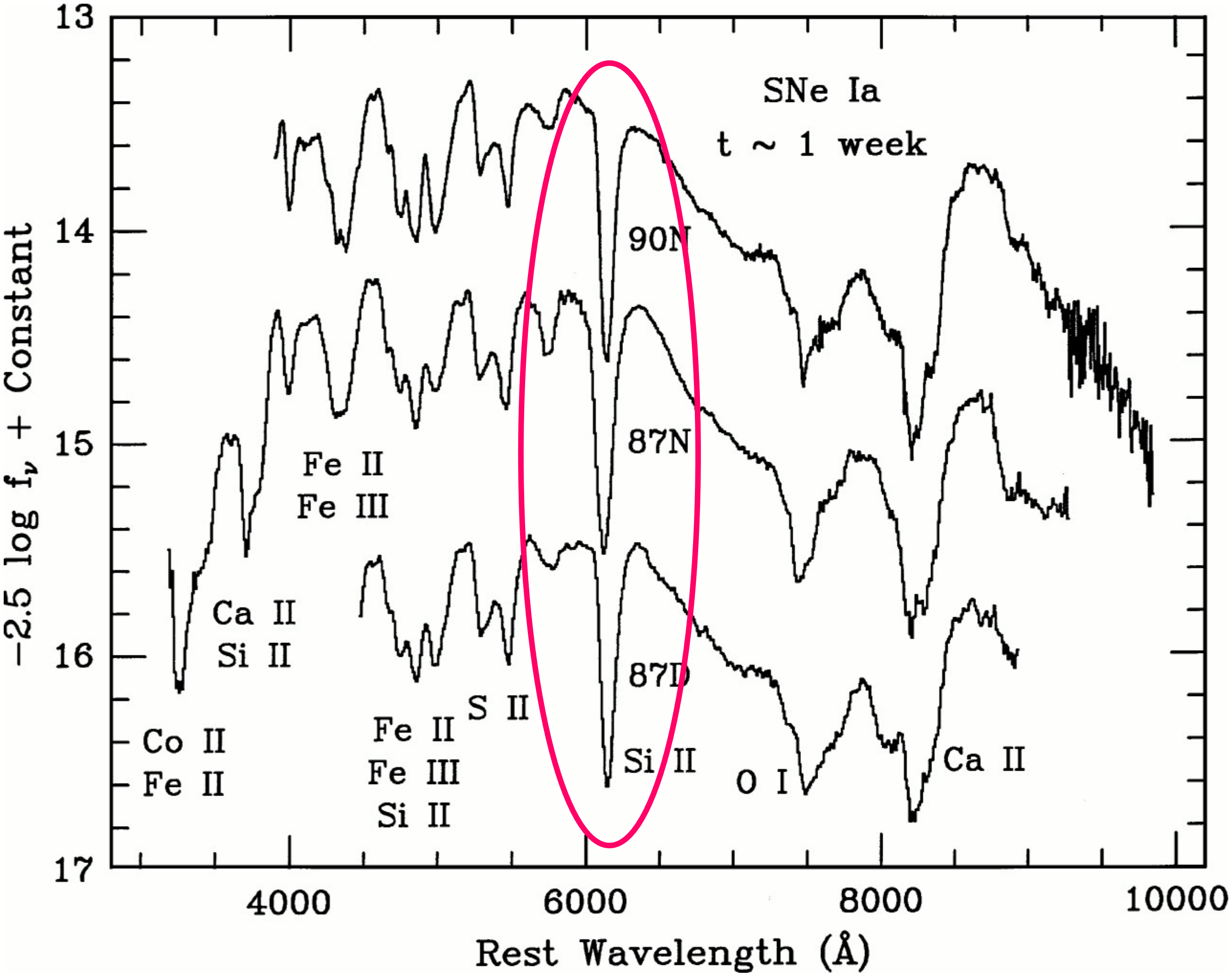
Ia

II

Ic

Ib

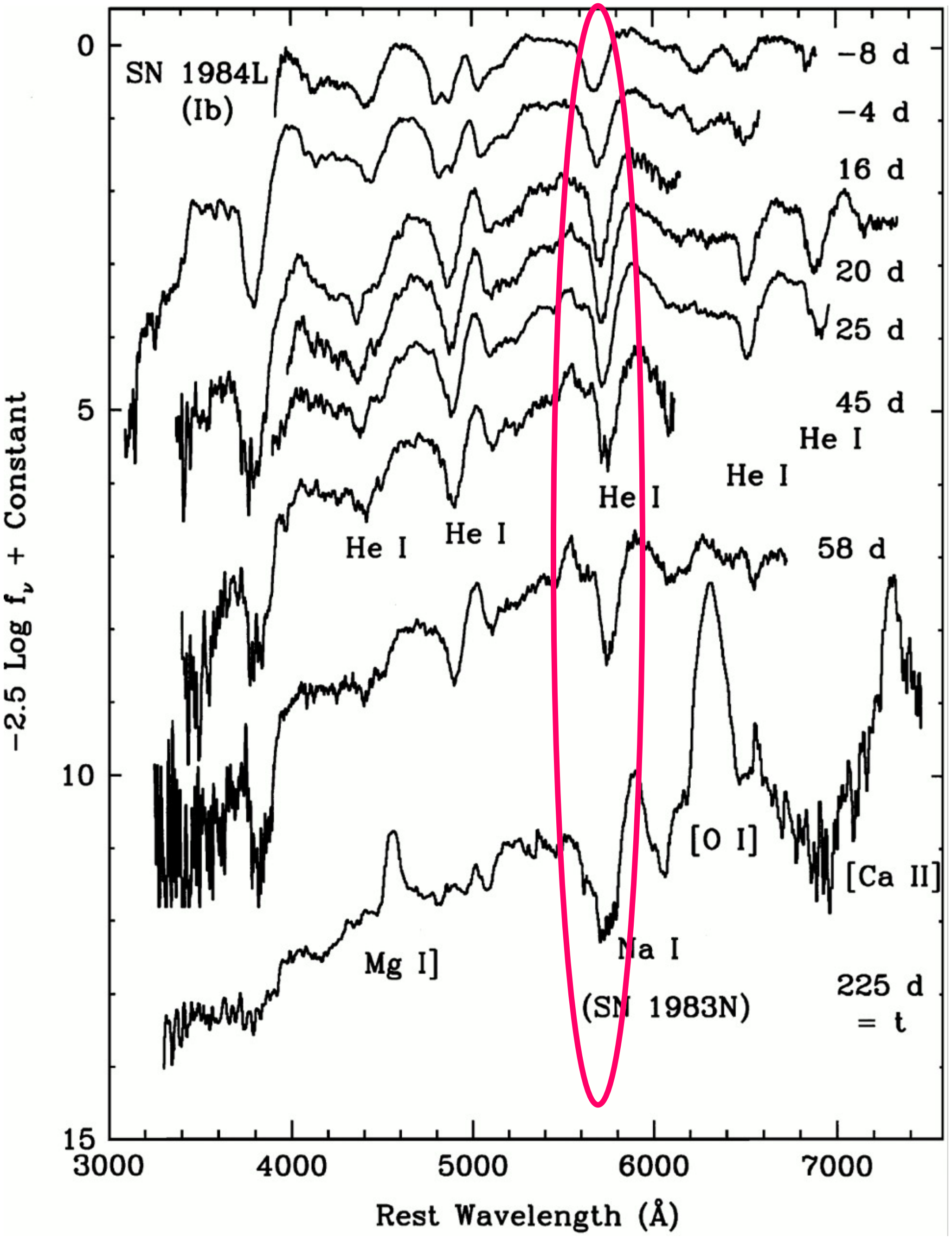
Lines are broad → high velocity ejecta



Early spectra of SN Type Ia

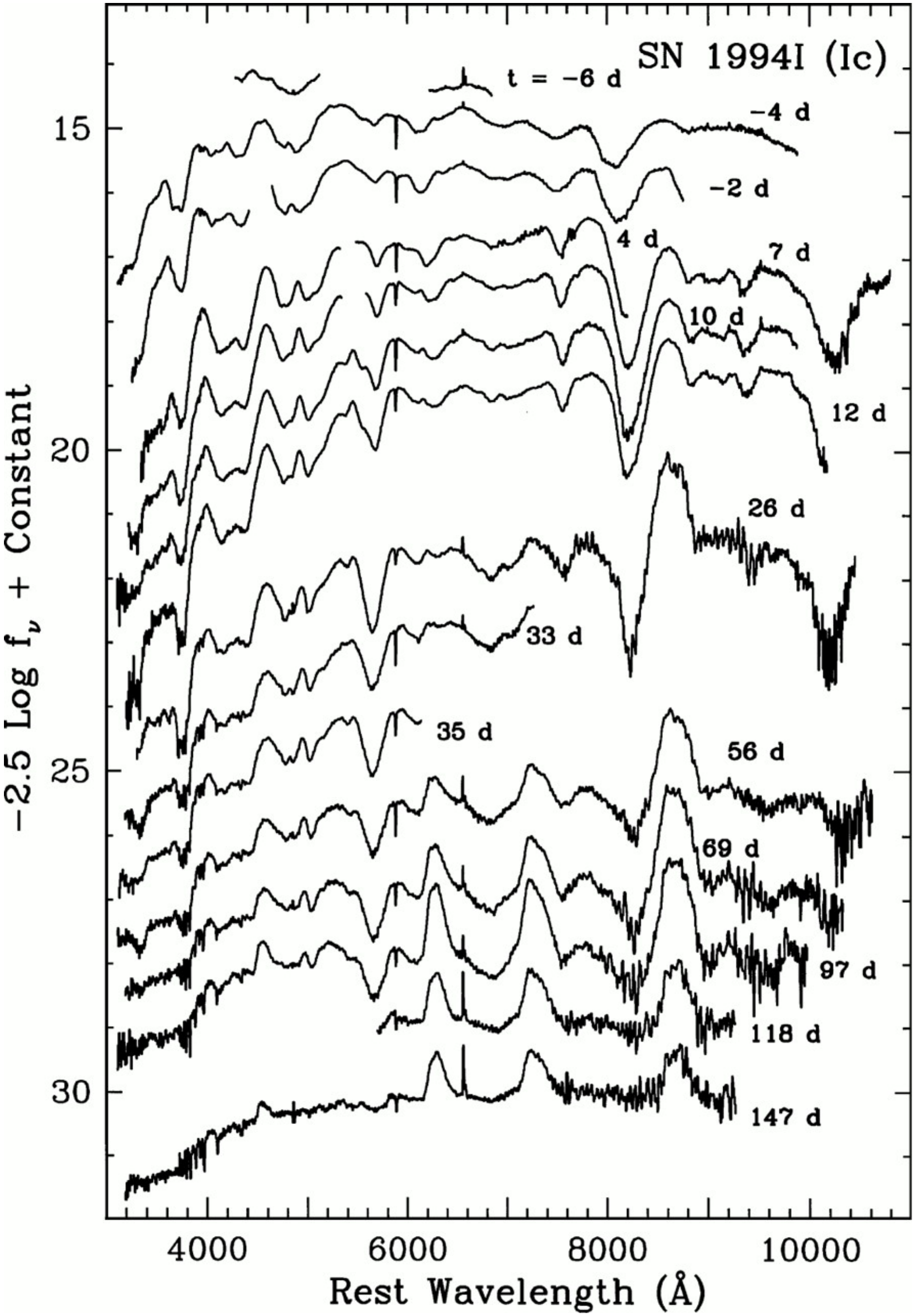
✓ No H

✓ Strong Si



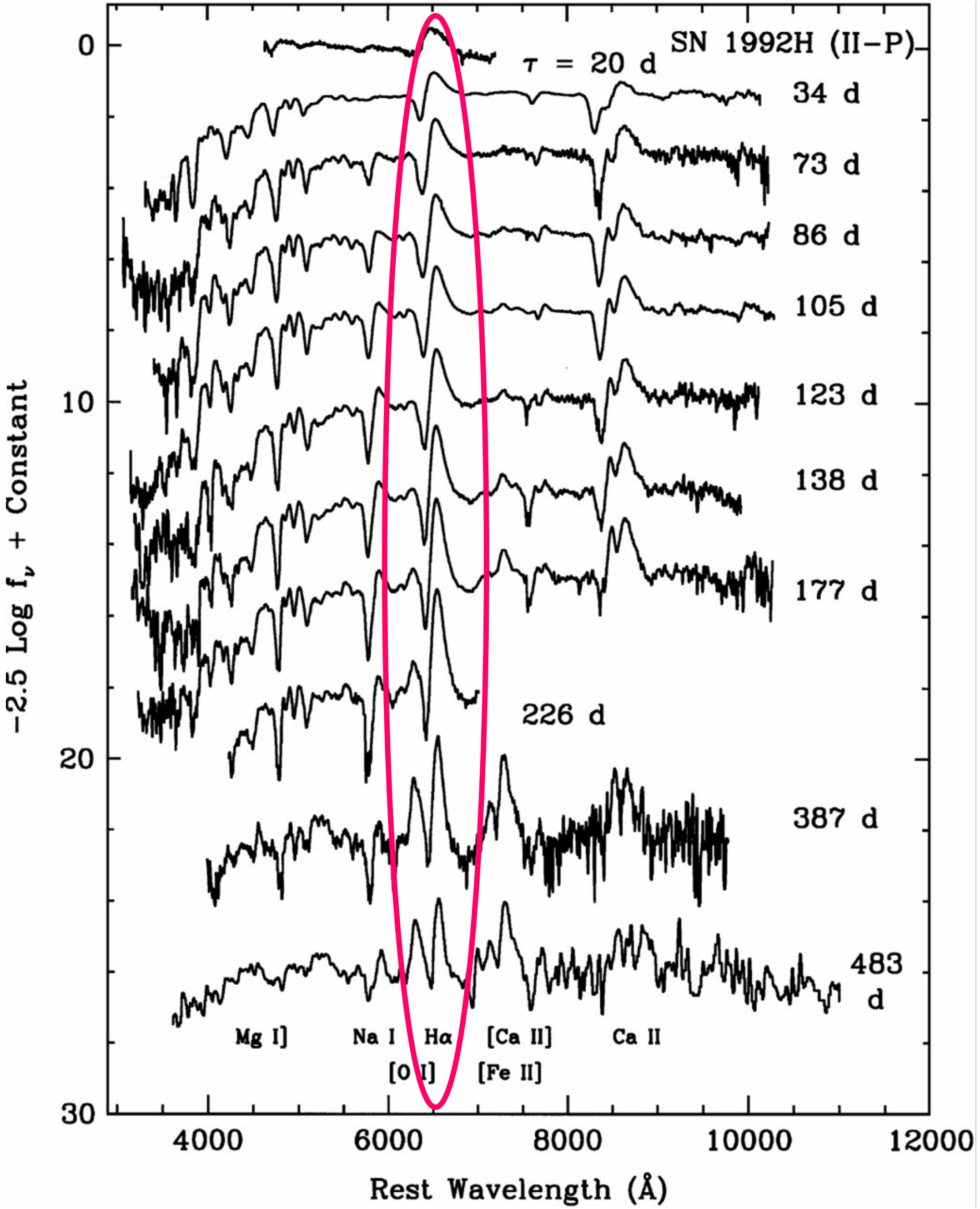
SN Type Ib

- ✓ No H
- ✓ No Si
- ✓ He rich



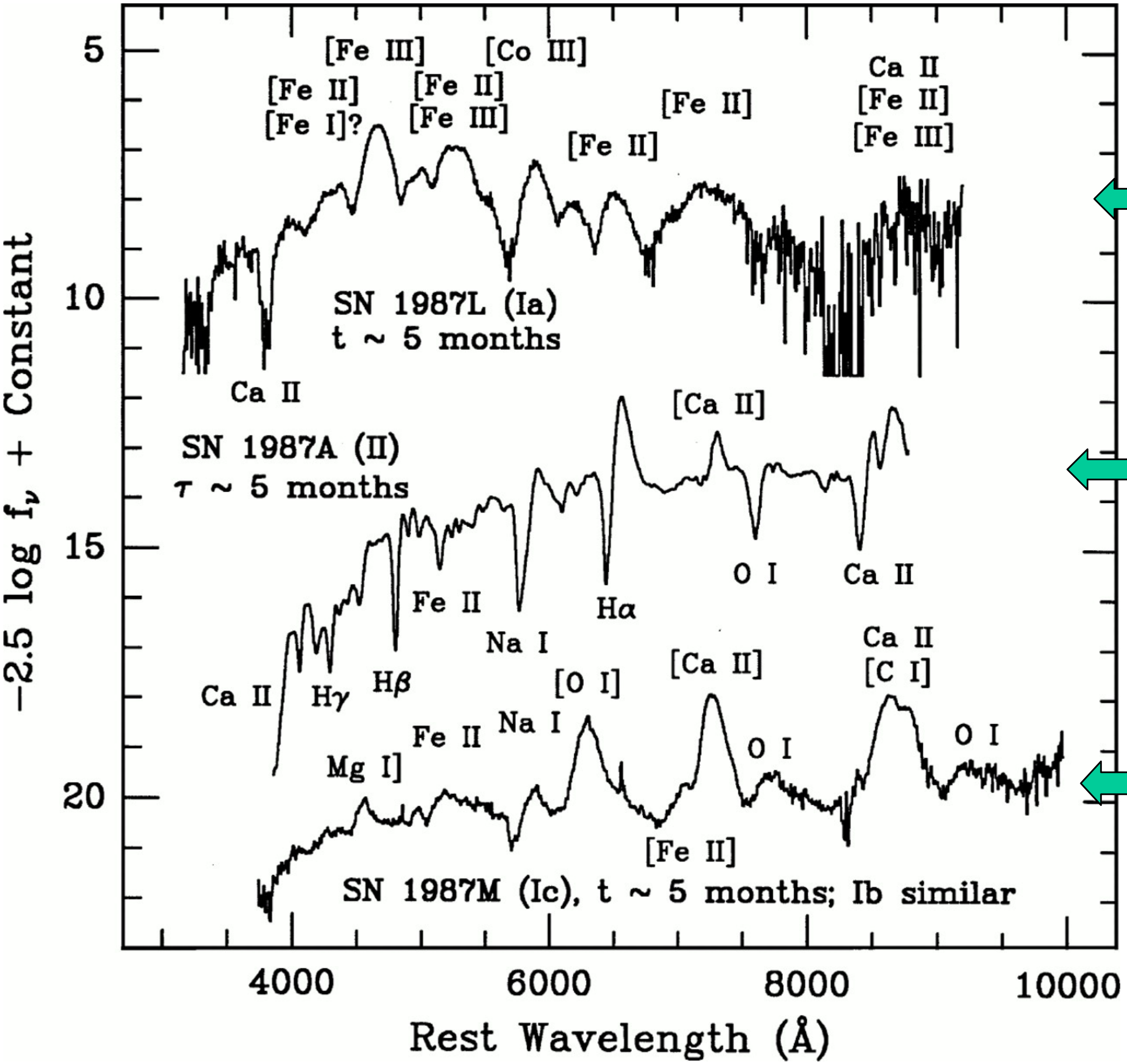
SN Type Ic

- ✓ No H
- ✓ No Si
- ✓ He poor



SN Type II
strong H

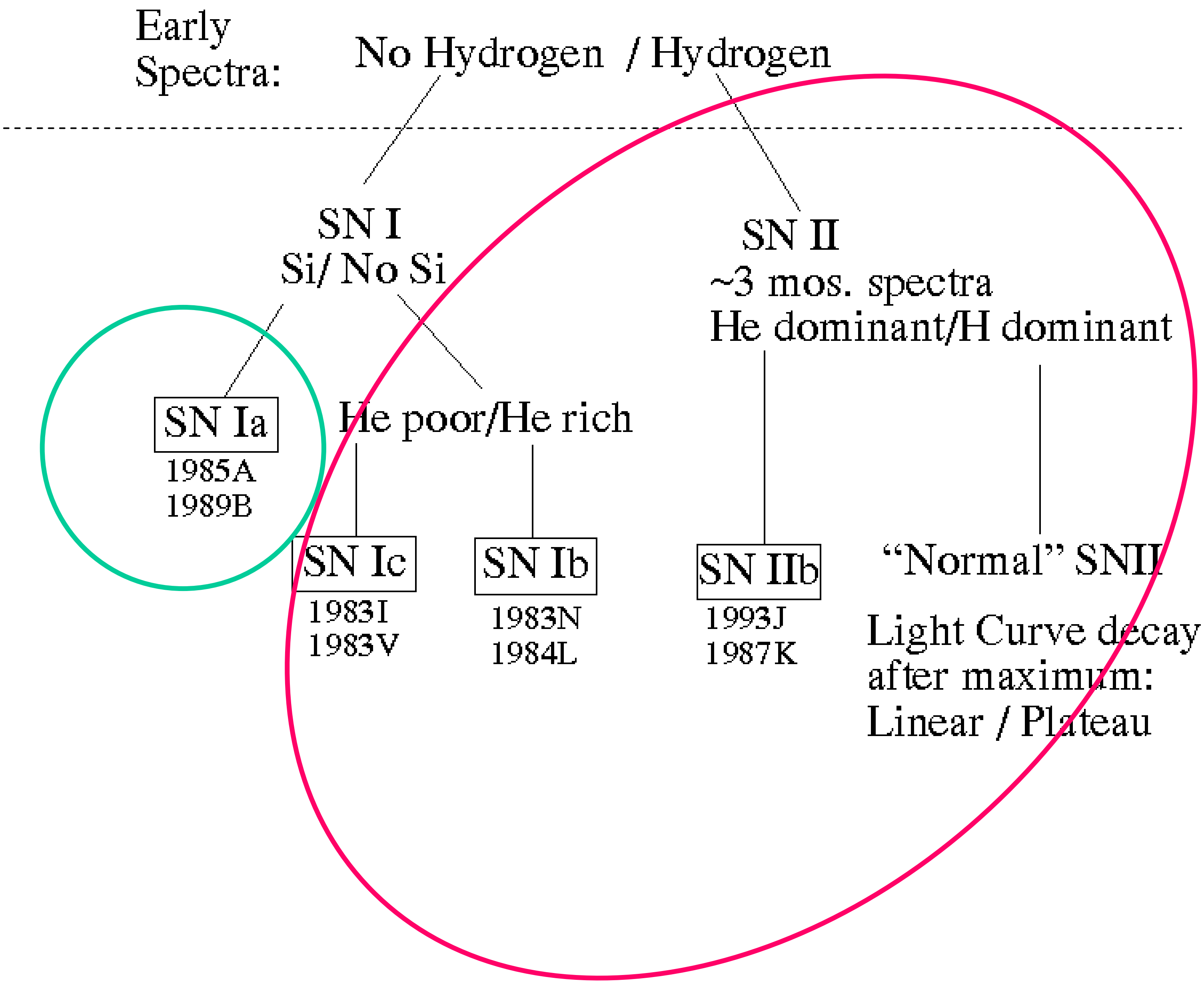
Late spectra of different supernovae



Type Ia

Type II

Type Ic



Early Spectra:

No Hydrogen / Hydrogen

SN I
Si/ No Si

SN II
~3 mos. spectra
He dominant/H dominant

SN Ia
1985A
1989B

He poor/He rich

SN Ic
1983I
1983V

SN Ib
1983N
1984L

SN IIb
1993J
1987K

"Normal" SNII

Light Curve decay
after maximum:
Linear / Plateau

Classification of hosts galaxies of Supernovae

- Based on studies of over 400 galaxies it was demonstrated that: the probability that SNe Ia and SN II have a different distribution of host galaxy Hubble types is 99.7 %.

- A significant difference is found between the distribution of host galaxies of SNIa and SN Ib/c

- No significant difference is detected between SN II and SN Ib/c

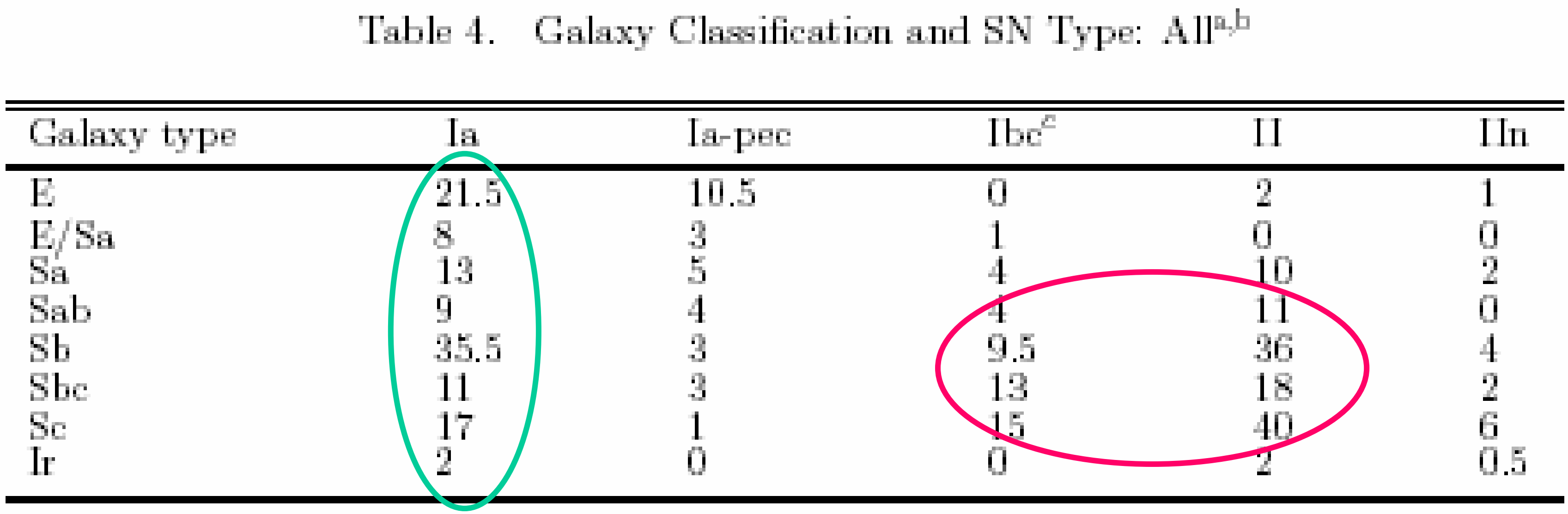


Table 4. Galaxy Classification and SN Type: All[a,b]

Galaxy type	Ia	Ia-pec	Ibc[c]	II	IIn
E	21.5	10.5	0	2	1
E/Sa	8	3	1	0	0
Sa	13	5	4	10	2
Sab	9	4	4	11	0
Sb	35.5	3	9.5	36	4
Sbc	11	3	13	18	2
Sc	17	1	15	40	6
Ir	2	0	0	2	0.5

from Van den Bergh & Filippenko,2003

The stellar population of the progenitors:

Ia ≠ II

Ia ≠ Ib/c

II ≈ Ib/c

The principal peculiarity of SN Type I is:
there is NO Hydrogen in such events

The H envelope that surrounds most stars has been either:

consumed → Type Ia

Occur in all type of galaxies

ejected → Type Ib and Ic

Occur only in spirals and irregulars

Progenitors

Ia: White dwarfs in a close binary system

Ib/c, II: supergiant star

Life and death of a star

- the whole stellar life is a battle between the outward radiation pressure and the inward pull of gravity.

- this leads to successive thermonuclear processes where the building block is a Helium nucleus.

each of the successive elements consists of

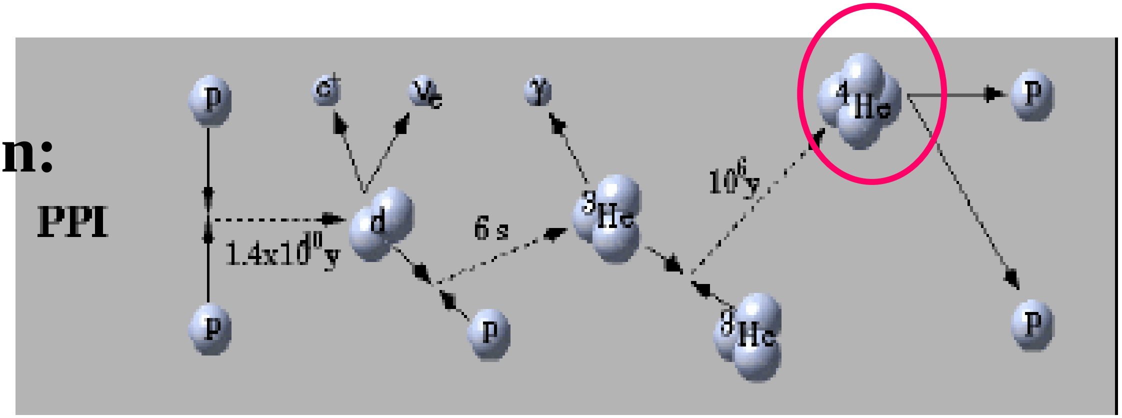
2 more p^+ and 2 more n

than the previous one

Nuclear Fusion

Nuclear fusion of light elements into heavier elements releases binding energy

1) proton- proton chain:



$^1H + {^1H} \rightarrow {^2H} + e^+ + \nu$

$^2H + {^1H} \rightarrow {^3He} + \gamma$

$^3He + {^3He} \rightarrow {^4He} + {^1H} + {^1H}$

2) **The CNO-Cycle**: Fusion of four H nuclei into a single ^{4}He nucleus

3) Triple-alpha process: At $T > 10^8$ K, ^{4}He is transformed into ^{12}C

H→He→C→O

here is the end of evolution of stars with $M \sim M_o$

For sufficiently massive stars, the process continues:

Ne→ Mg→ Si→ S→ Ar→ Ca→ Ti

Massive stars evolve forming cores within core of ever heavier elements until the innermost regions are turned into Fe.

The destiny of the stars

low mass stars

C/O white dwarfs

slowly cooling off supported
by the quantum pressu
its electron

vae
ype Ia

THERMONUCLEAR
COLLAPSE

massive stars

pernovae
Type II, Ib, Ic

neutron star

black hole

GRAVITATIONAL
COLLAPSE

H→He→C→O

here is the end of ev s
with $M \sim M_{\odot}$

THERMONUCLEAR
COLLAPSE

For sufficiently massive stars, the process continues:

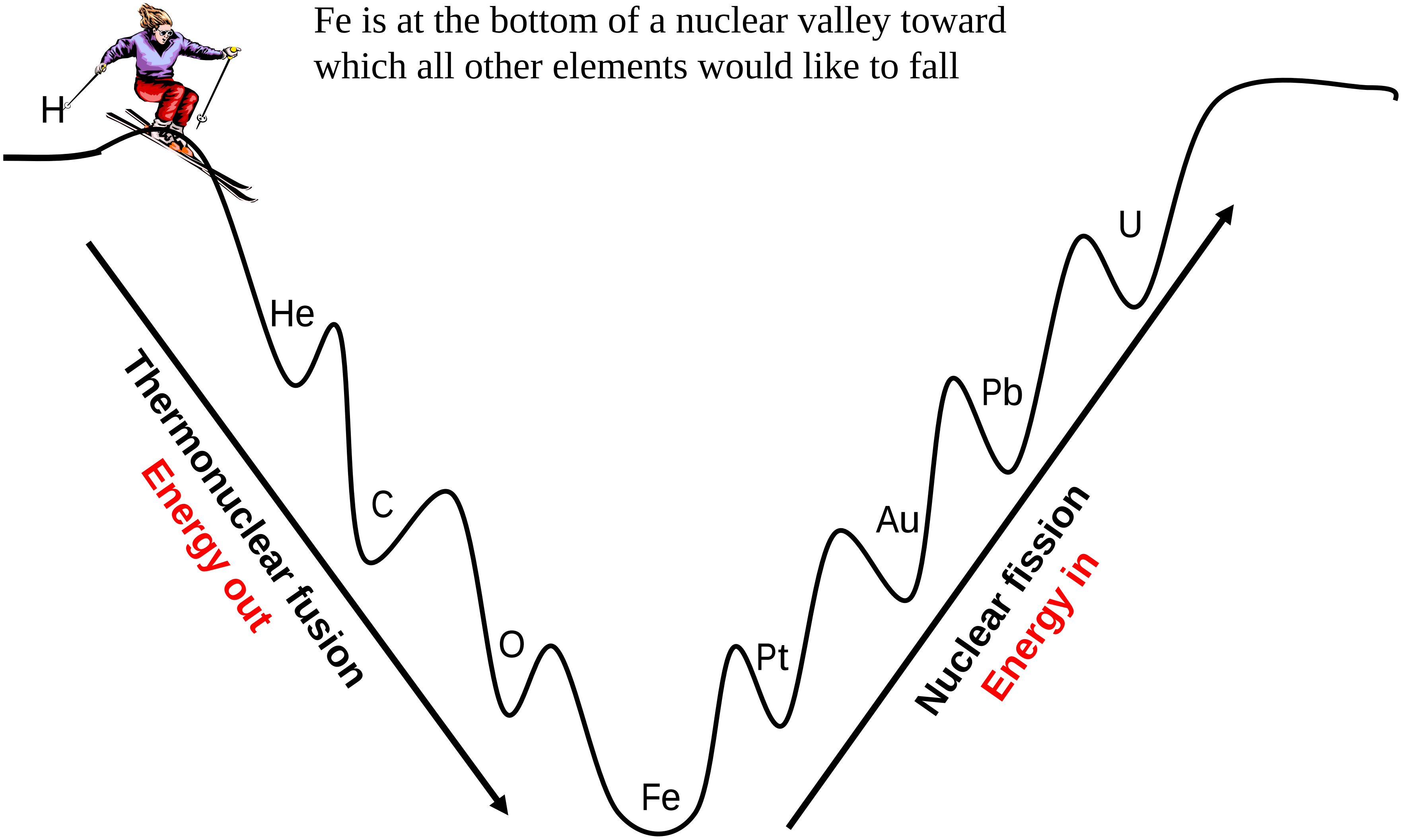
Ne→ Mg→ Si→ S→ Ar→ Ca→ Ti

GRAVITATIONAL
COLLAPSE

Massive stars evolve forming cores with ever heavier
elements until the innermost regions are tu ned into Fe.

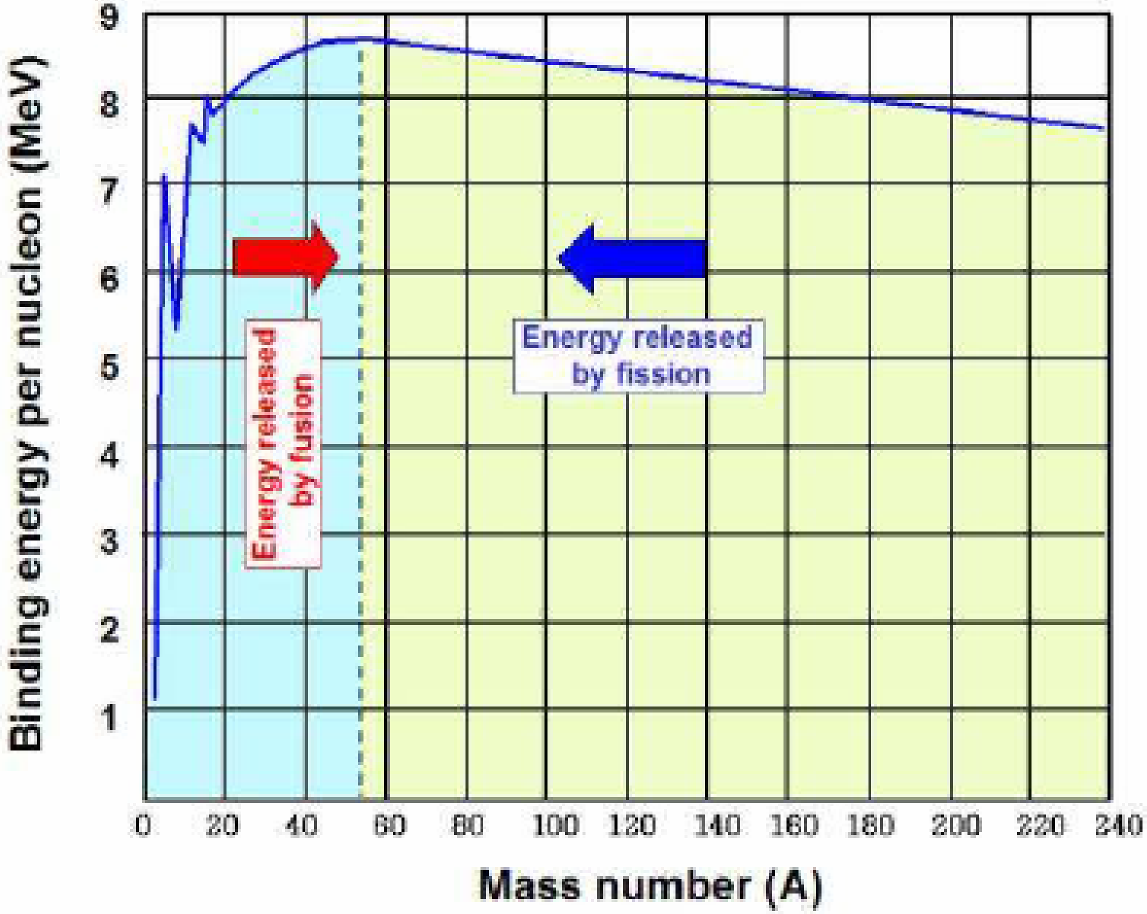
GRAVITATIONAL COLLAPSE

Fe is at the bottom of a nuclear valley toward which all other elements would like to fall



A ^{56}Fe nucleus = 14 ^{4}He but where 2 of the p^{+} have converted into neutrons. Therefore the particles in a ^{56}Fe nucleus are more tightly bound together than in any other element.

Fusion of light elements into heavier elements up to ^{56}Fe

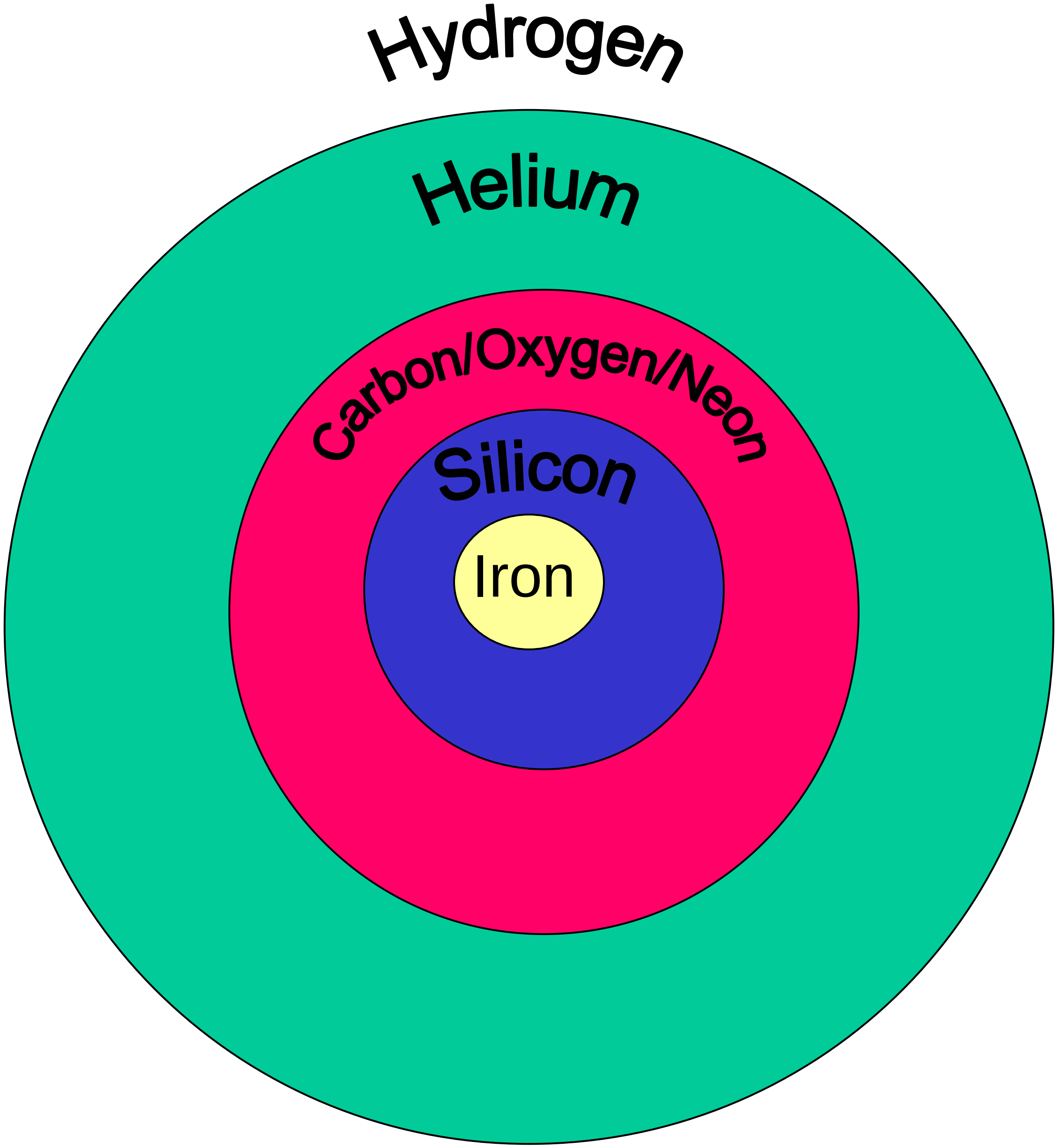


The result is that Fe can only absorb energy from a star

never produce it

For heavier elements, their p+ are less tightly bound that those of Fe → they tend to split apart into lighter elements through nuclear fission

After the core of a star reached the iron stage,
no more energy can be derived from that core


Hydrogen
Helium
Carbon/Oxygen/Neon
Silicon
Iron

- The star continues radiating energy into space, but there is no more energy input.

- Gravity squeezes them and temperature goes up

The response of the Fe is:
a) to go up, and most of it breaks apart into lighter nuclei
b) some of the Fe will undergo fusion reactions that lead to heavier particles

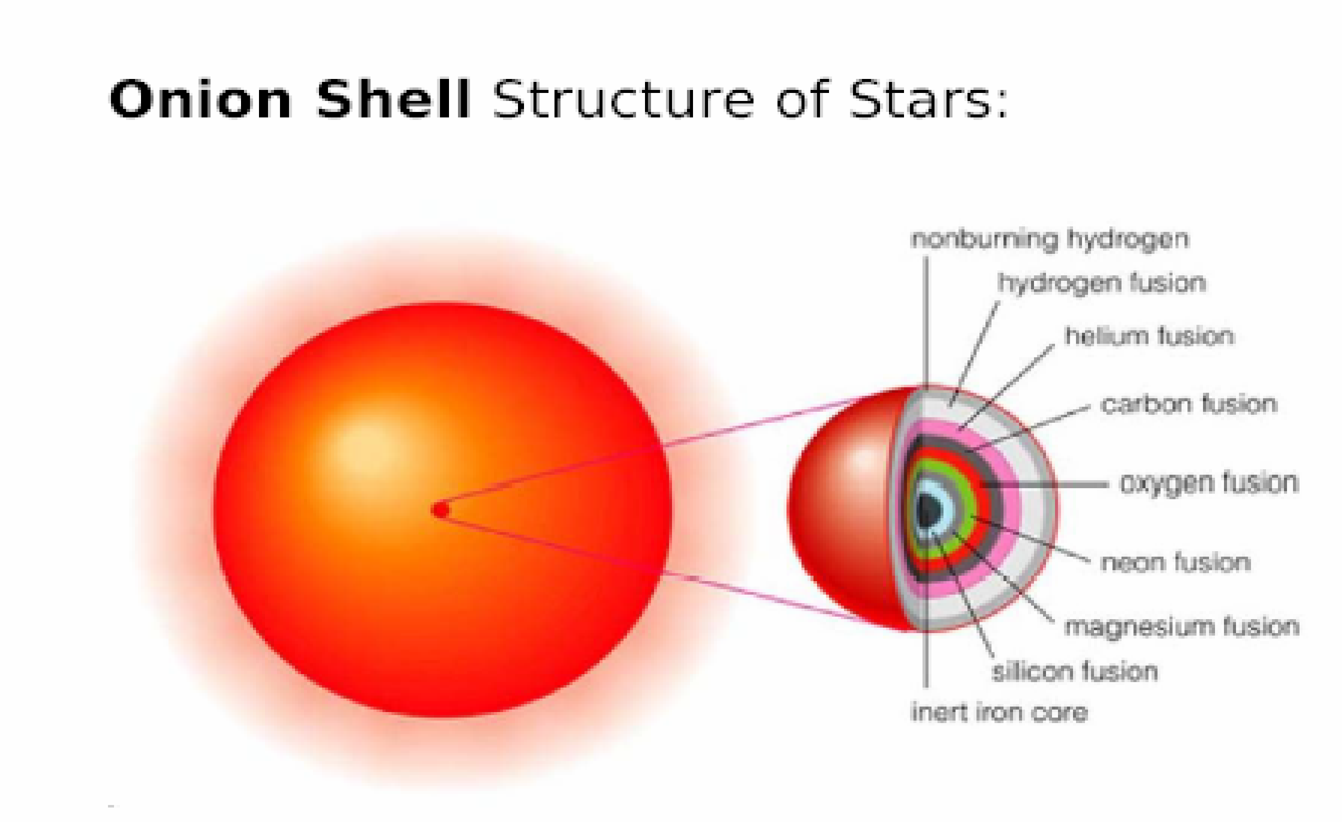
Rather than releasing energy to repel gravity attraction,
in both cases energy is consumed

The iron core absorbs heat energy from the star

Gravity compress it even more, and then more energy is absorbed

this is the end of thermonuclear life of the star

Evolutionary Time Scales for a 15 $M_\odot$ Star



The core contracts and the density increases enormously

The quantum pressure of e^- is too feeble

e^- and p^+ combine ➔ n
to conserve the lepton number, the reaction produces= $n + \nu$

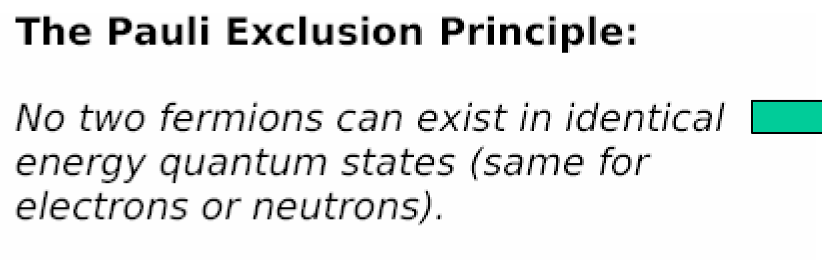
An entirely new type of astronomical object is formed:
a neutron star

Mass > Chandrasekhar limit= 1.44 M_o
Radius ~ 10 km
Density ~ 10^{14} g/cm^3

What can stop the compression?

At large enough density the quantum pressure of n can be sufficiently great to overcome the force of gravity and restore the condition of dynamic equilibrium.

Quantum pressure is aided by the nuclear force which become repulsive.



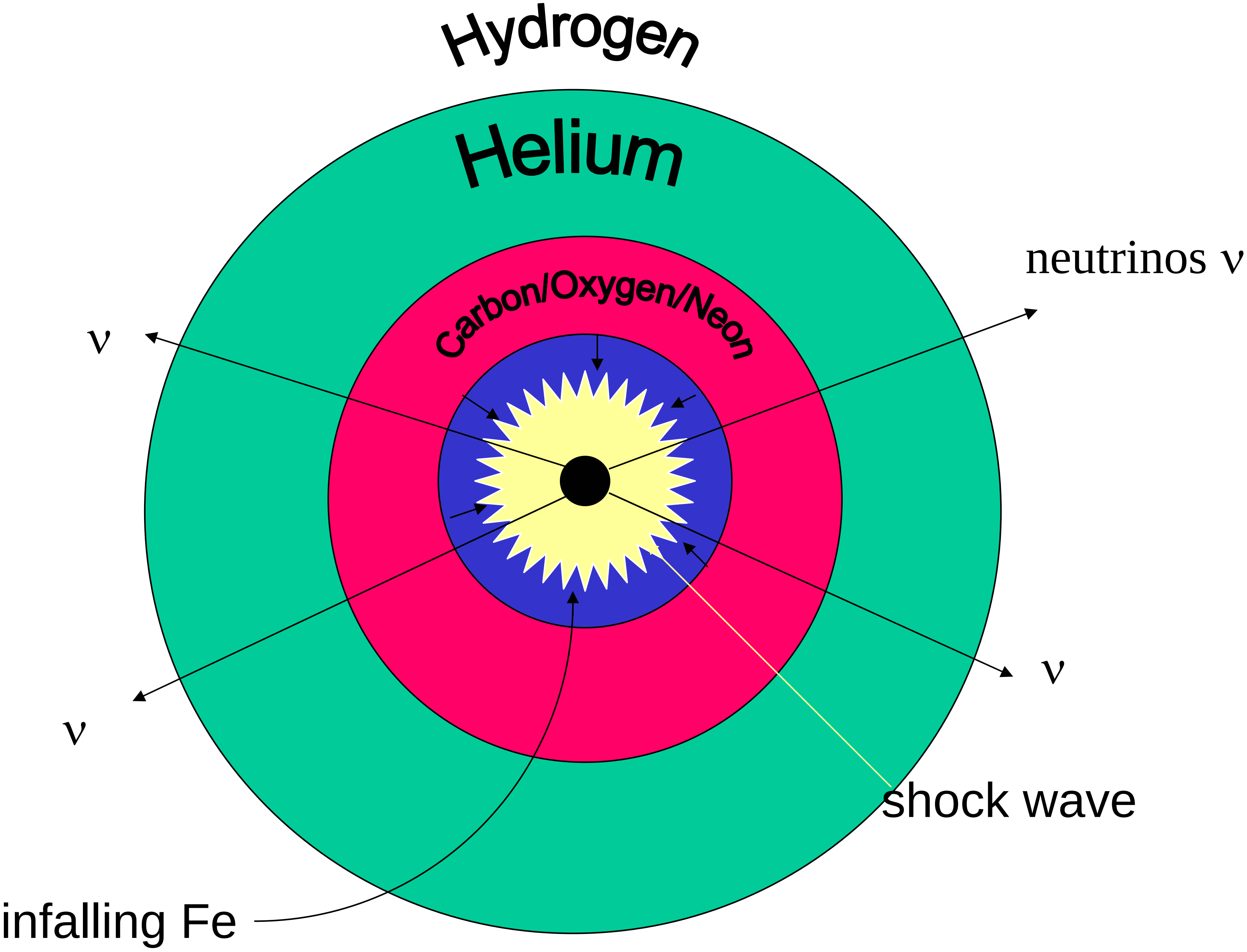
The Pauli Exclusion Principle:

No two fermions can exist in identical energy quantum states (same for electrons or neutrons).

→

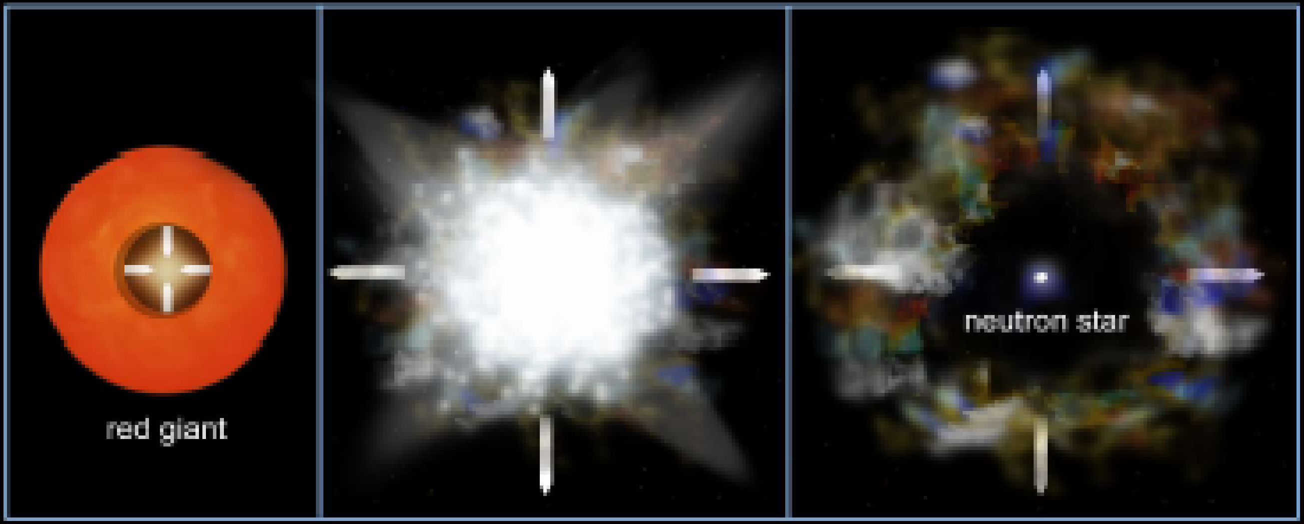
Electron degeneracy stops the collapse of a star to a White Dwarf

Neutron degeneracy stops the further collapse of stars to Neutron Stars.


Hydrogen
Helium
Carbon/Oxygen/Neon
neutrinos ν
ν
ν
ν
shock wave
infalling Fe

Birth of a Neutron Star and Supernova Remnant

(not to scale)



Core Implosion → **Supernova Explosion** → **Supernova Remnant**

- All outer layers of the star are expelled away

- 99% of the gravitational energy produced in the creation of a neutron star is given to the neutrinos. They escape carrying most of the energy off into space

- The whole process requires less than 1 sec in the life of a star that has lived for millions of years

What happens if the energy is not enough to eject the outer portions of a star?

All the mass fall over the collapsed iron core and the neutron star is crushed out

A black hole is formed

THERMONUCLEAR COLLAPSE

The principal peculiarity of SN Type I is:
there is NO Hydrogen in such events

The H envelope that surrounds most stars has been either:

consumed → Type Ia

Occur in all type of galaxies

ejected → Type Ib and Ic

Occur only in spirals and irregulars

Facts:

Elliptical galaxies have converted essentially all their gas into stars long ago. They have probably ceased the making of stars and are thought to consist of only : old, low-mass, long-lived stars.

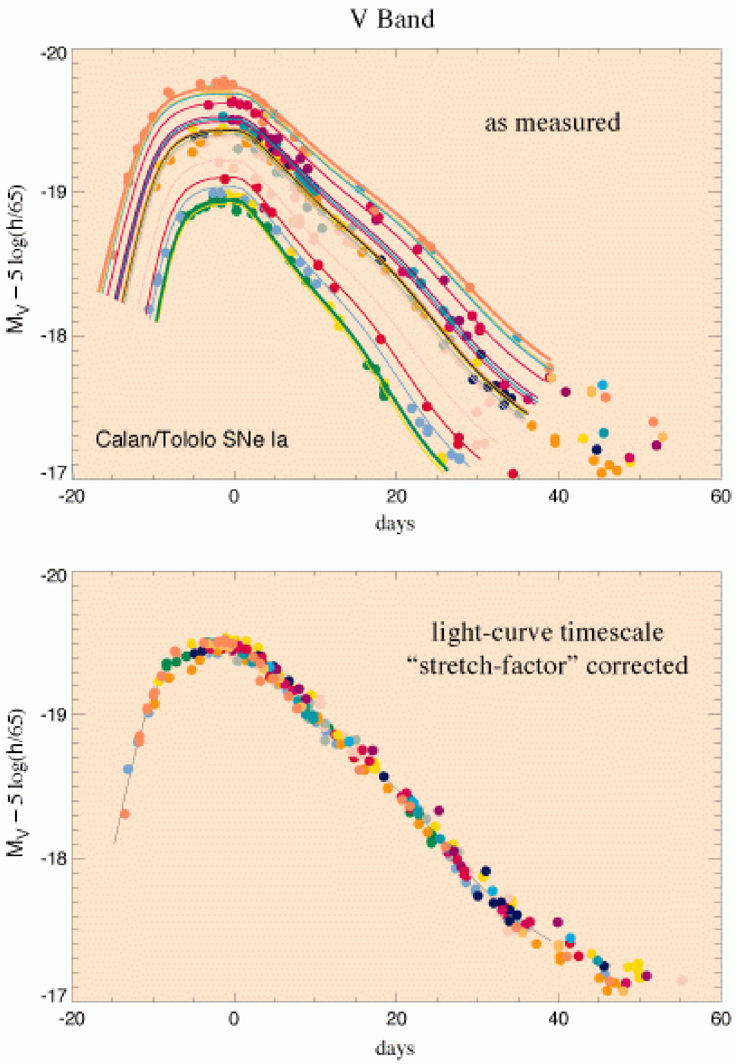
- In ellipticals there are mostly SNe Type I

Spiral galaxies contain a mix of high- and low-mass stars.

- In spirals there are SNe Type I and Type II

SNe Type I must come from low-mass stars

Low Redshift Type Ia Template Lightcurves

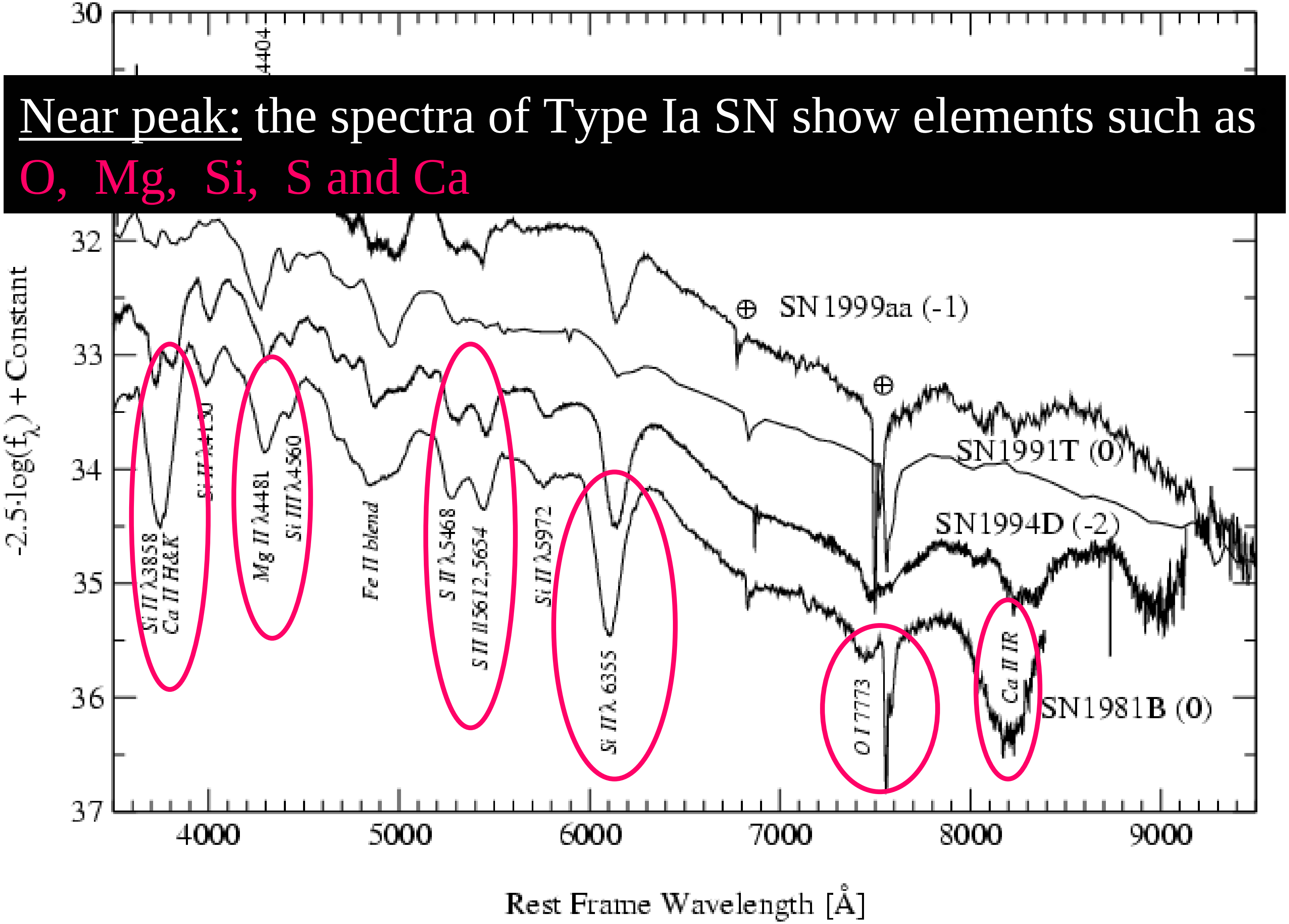


The observed properties among hundreds of SN Ia are remarkably similar.

This points to a common origin

Core-collapse SNe, on the contrary, present a wide range of spectral and photometric properties (probably due to the state of the H and He envelopes in the progenitor at the time of explosion)

Spectra of several SN Type Ia



<u>Near peak:</u> the spectra of Type Ia SN show elements such as O, Mg, Si, S and Ca

Near peak: the spectra of Type Ia SN show elements such as: O, Mg, Si, S and Ca

These are the elements expected if a mixture of C and O burns to produce heavier elements consisting of different numbers of He nuclei “bricks”

Later spectra: dominated by Fe and other similar heavy elements

These elements can be produced by burning C and O all the way to Fe

The exact nature of the combustion is still being explored.

Successful models adopt a progenitor that is a C/O white dwarf with a mass that is very near, but less than, the Chandrasekhar mass (1.44 M_o)

sub-Chandrasekhar WD

Controversial issues:

✓ the nature of the burning front : subsonic? supersonic? mixture? Detonation? Deflagration? A mixture?

✓ the mass of the progenitor : can be sub-Chandrasekhar? 1% less than Chandrasekhar mass

✓ the nature of the companion: red giant?,
another white dwarf?

Attention!

It is usually said that to make a Type Ia SN: matter is added to a WD until the Chandrasekhar mass is exceeded and the WD collapse

WRONG

- ✓ Mass is added increasing the density in the center of a WD until C can ignite
- ✓ Carbon ignition produces unregulated thermonuclear runaway when the WD has a mass about 1% less than 1.4 M_o, and it blow the WD up completely. There is NO COLLAPSE

Steps in a Type Ia SN explosion

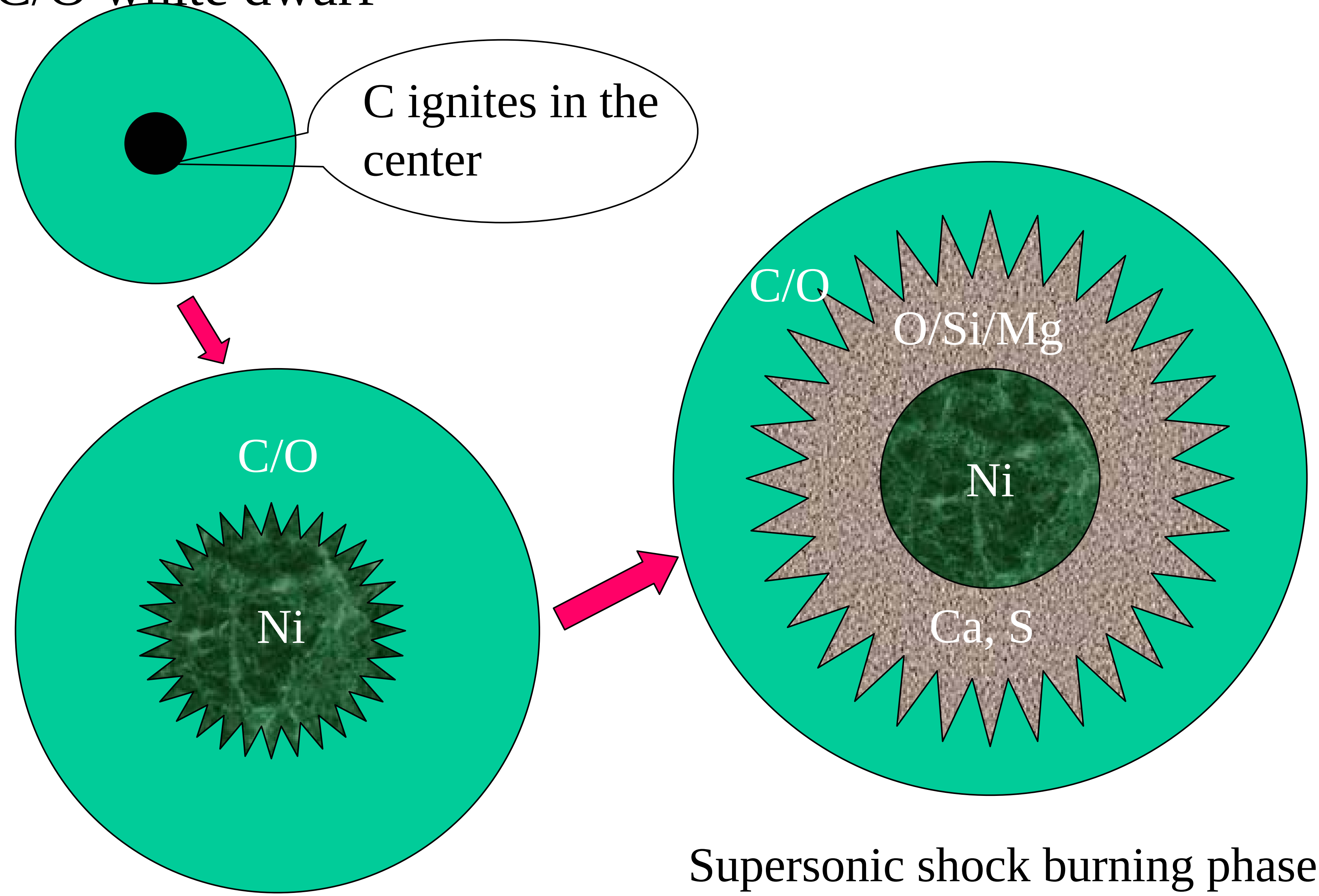
1) begins with the ignition of C near the center of a WD
2) a turbulent, rolling burning front moves at $v < v_{sound}$

This convert all the burning matter to radioactive nickel

The pressure waves from this burning cause matter in external regions to expand ahead of the burning

3) at some point, the burning front begins to propagate supersonically, producing a shock wave → a detonation wave
4) this wave moves so rapidly that the outer portions of the star cannot escape of the burning
5) the detonation wave leaves behind O, Mg, Si, S and Ca
6) A thin layer of unburned C and O can survive on the outside

C/O white dwarf



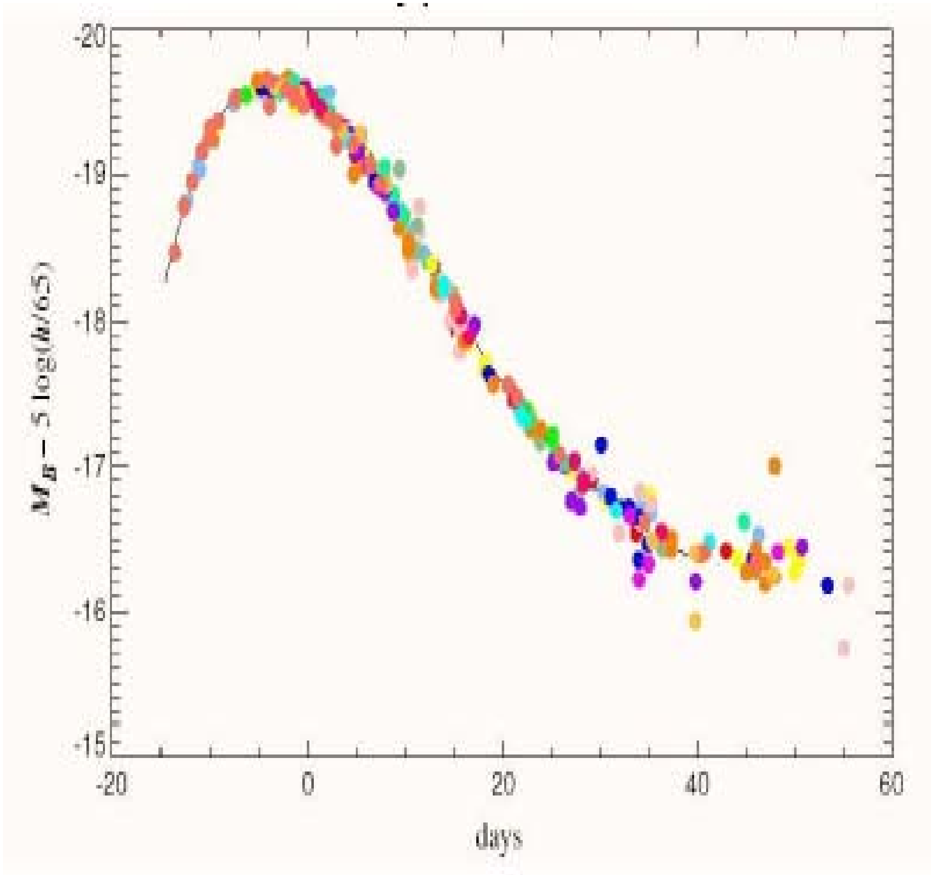
C ignites in the center

Subsonic turbulent burning phase:
deflagration

Supersonic shock burning phase:
detonation

Type Ia lightcurve:

$$^{56}\mathrm{Ni} \rightarrow {}^{56}\mathrm{Co} + e^{+} + \nu_e + \gamma$$
$$^{56}\mathrm{Co} \rightarrow {}^{56}\mathrm{Fe} + e^{+} + \nu_e + \gamma$$



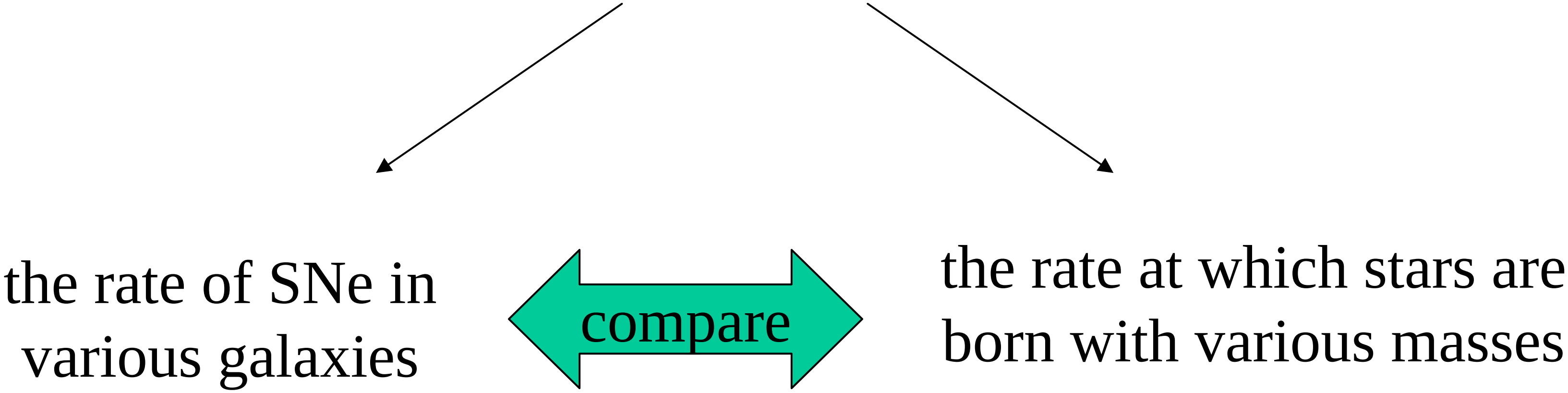
- At early times, radiation from ^{56}Ni decay is trapped by the high opacity.

- As the expanding shell gets thinner, the SN gets brighter, reaches the peak and then fades.

- Later the curve flattens and is characterized by the decay time of ^{56}Co

What are the mass limits that define the fate of stars?

One way to deduce masses of stars that make supernovae is to examine



the rate of SNe in various galaxies

compare

the rate at which stars are born with various masses

Other way: to ask which stars do not explode forming white dwarfs that die quietly, and count them in stellar clusters of various ages

Stars with $M < 30\ M_o$: can lose a good amount of mass. This can alter details of the evolution, but does not affect the qualitative behavior of the star

Stars with $50\ M_o < M < 30\ M_o$: do become red giants. Undergo appreciable mass loss → the complete red giant envelope is ejected exposing the core

Stars with $M > 50\ M_o$: there is no observed red giant phase. So much mass is lost on the MS that no outer H envelope is left to expand and become a red giant.
The bare core composed of He and heavier elements are exposed to view →Wolf Rayet star