Supernovae

Pols 13
Glatzmaier and Krumholz 17, 18
Prialnik 10

SUPERNOVAE

- A supernova is the explosive death of a star.

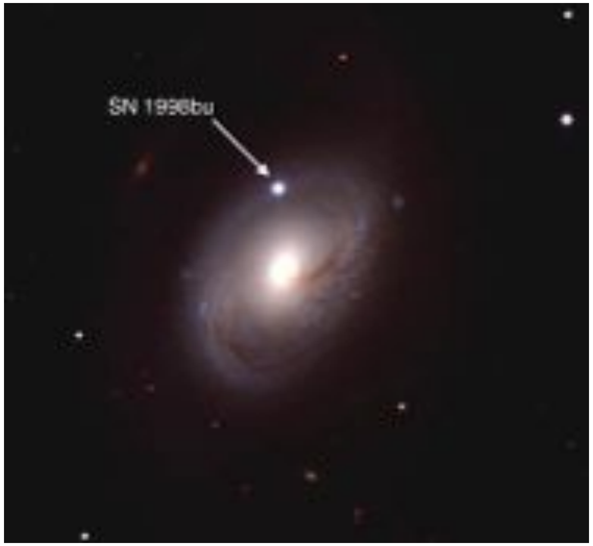
- Two types are easily distinguishable by their spectrum. Type II has hydrogen (H_α). Type I does not.

- Very luminous. Luminosities range from a few times 10^{42} erg s^{-1} (relatively faint Type II; about 300 million L_{sun}) to 2 x 10^{43} erg s^{-1} (Type Ia; 6 billion L_{sun}) - roughly as bright as a large galaxy.

(Recently some rare supernovae have been discovered to be even brighter)

SN 1998aq

SN 1998dh



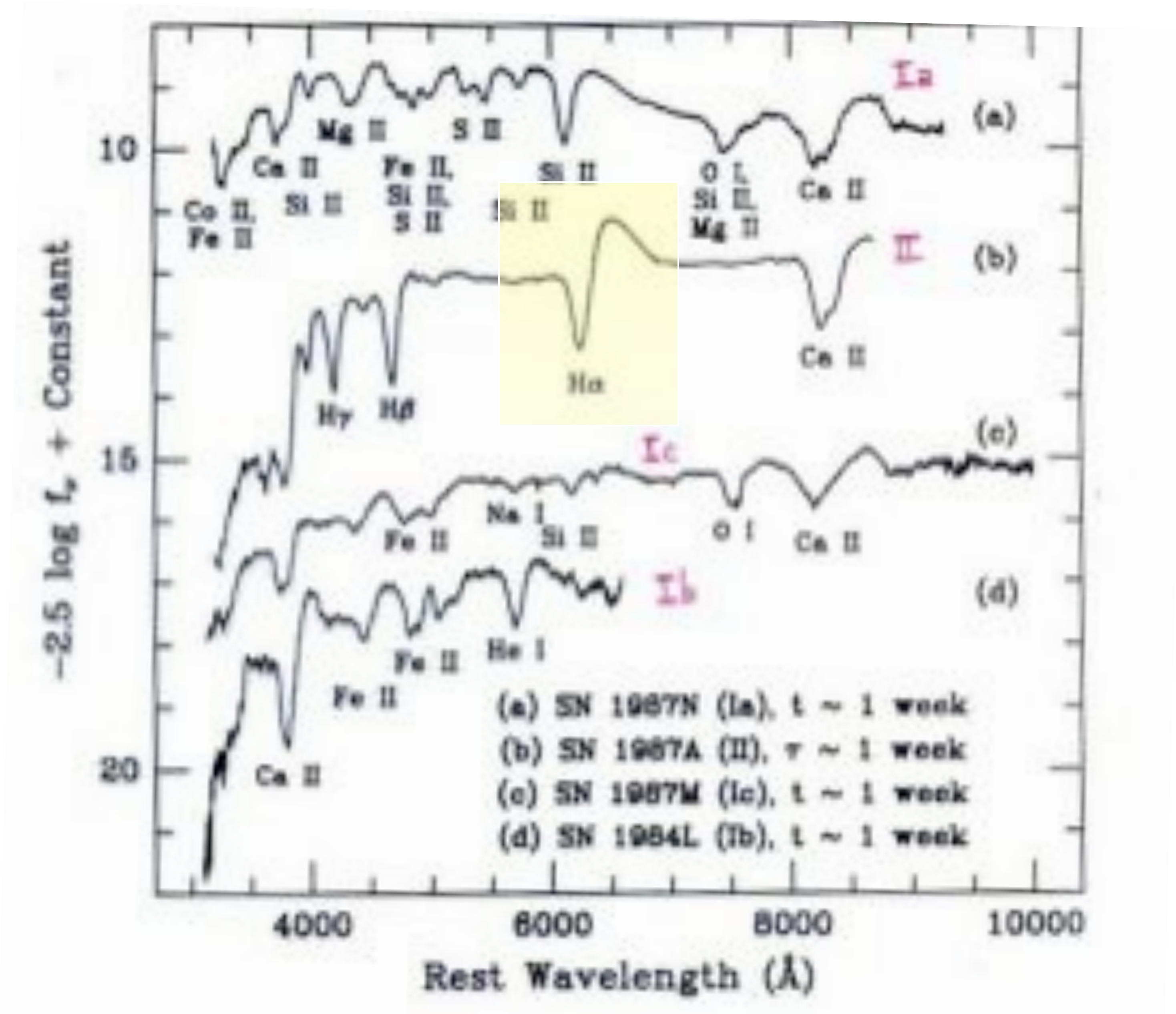
SN 1998bu

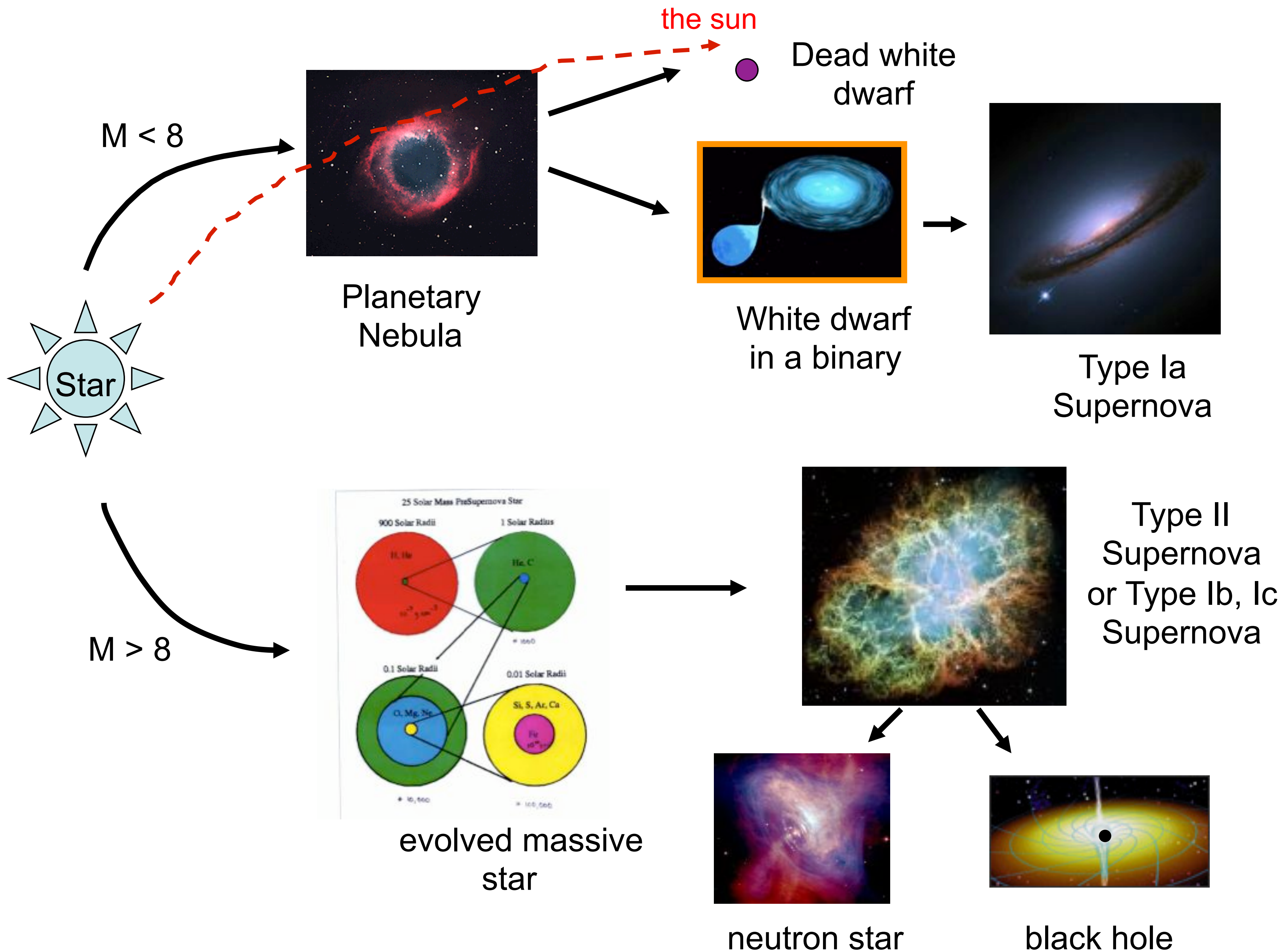
SN 1994D

For several weeks a supernova's luminosity rivals that of a large galaxy.

Supernovae are named for the year in which they occur + A .. Z, aa – az, ba – bz, ca – cz, etc
Currently at SN 2012gx

SPECTROSCOPICALLY





the sun
Dead white dwarf
M < 8
Planetary Nebula
White dwarf in a binary
Type Ia Supernova
Star
M > 8
25 Solar Mass PreSupernova Star
900 Solar Radii
1 Solar Radius
H, He
He, C
0.1 Solar Radii
0.01 Solar Radii
O, Mg, Ne
Si, S, Ar, Ca
Fe
evolved massive star
Type II Supernova or Type Ib, Ic Supernova
neutron star
black hole

Core-collapse Supernovae

- The majority of supernovae come from the deaths of massive stars whose iron cores collapse. If the star that explodes has not lost its hydrogen envelope, the supernova is Type II. Otherwise it is Ib or Ic.

- Because massive stars are short lived these supernovae happen in star forming regions – in spiral and irregular galaxies, in spiral arms, near H II regions, never in elliptical galaxies

- The vast majority of the energy, 99% (3 x 10^{53} erg) is released as a neutrino burst (only detected once). 1% of the energy (10^{51} erg) is the kinetic energy of the ejecta, 0.01% of the energy (10^{49} erg) is light.

Type IIp Supernovae

- The most common kind of supernova is a Type II-plateau, so called because the luminosity stays nearly the same for months. The spectrum is dominated by the Balmer lines of hydrogen.

- Radii inferred on the plateau are about 10^{15}cm (100 AU). The emission resembles a blackbody with T_{eff} approximatey 5500 K

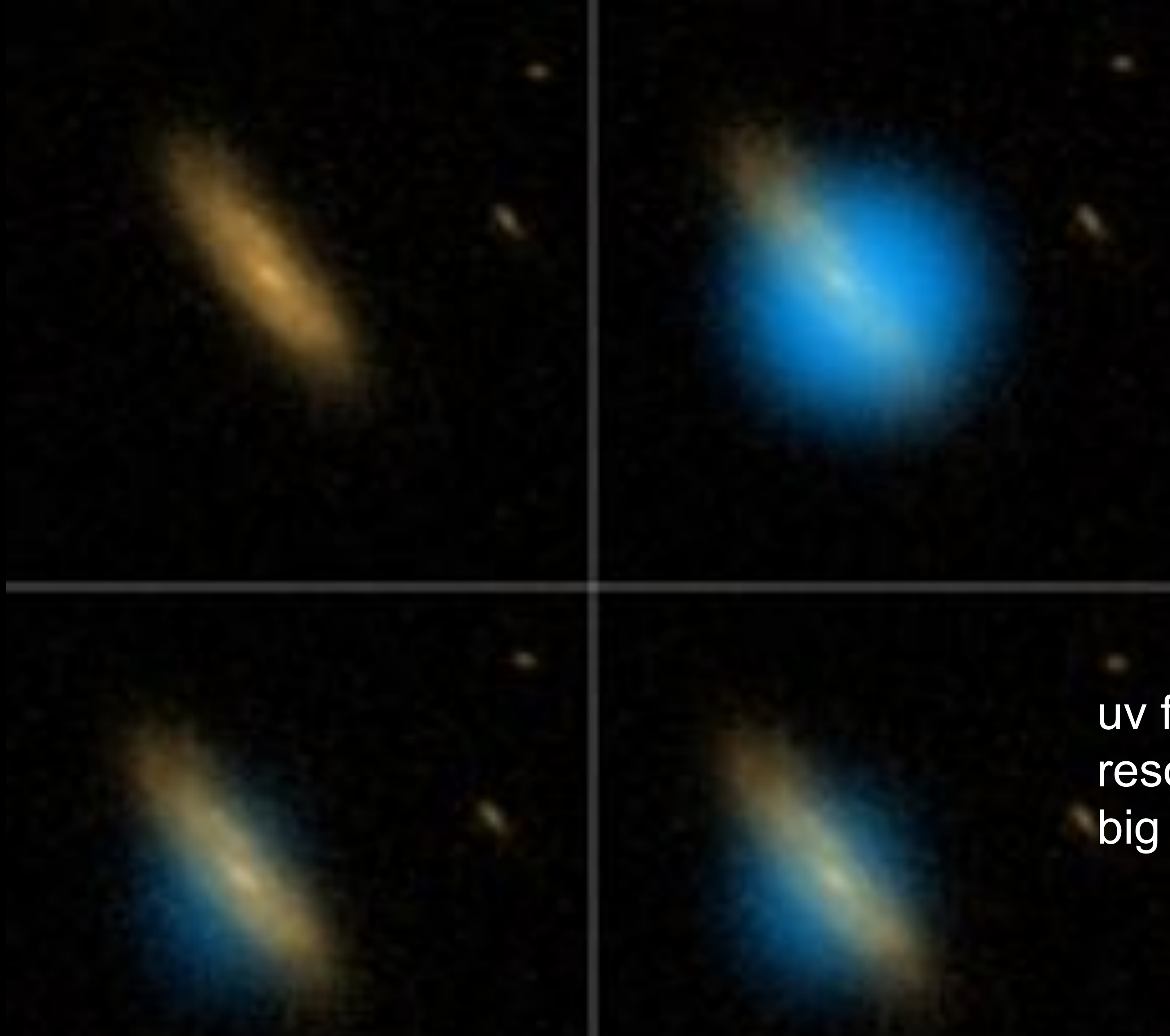
- Type II supernovae always leave behind either a neutron star or a black hole. In many instances the neutron star is a “pulsar”

- Prolific element factories

Light Curve of Type IIp Supernovae

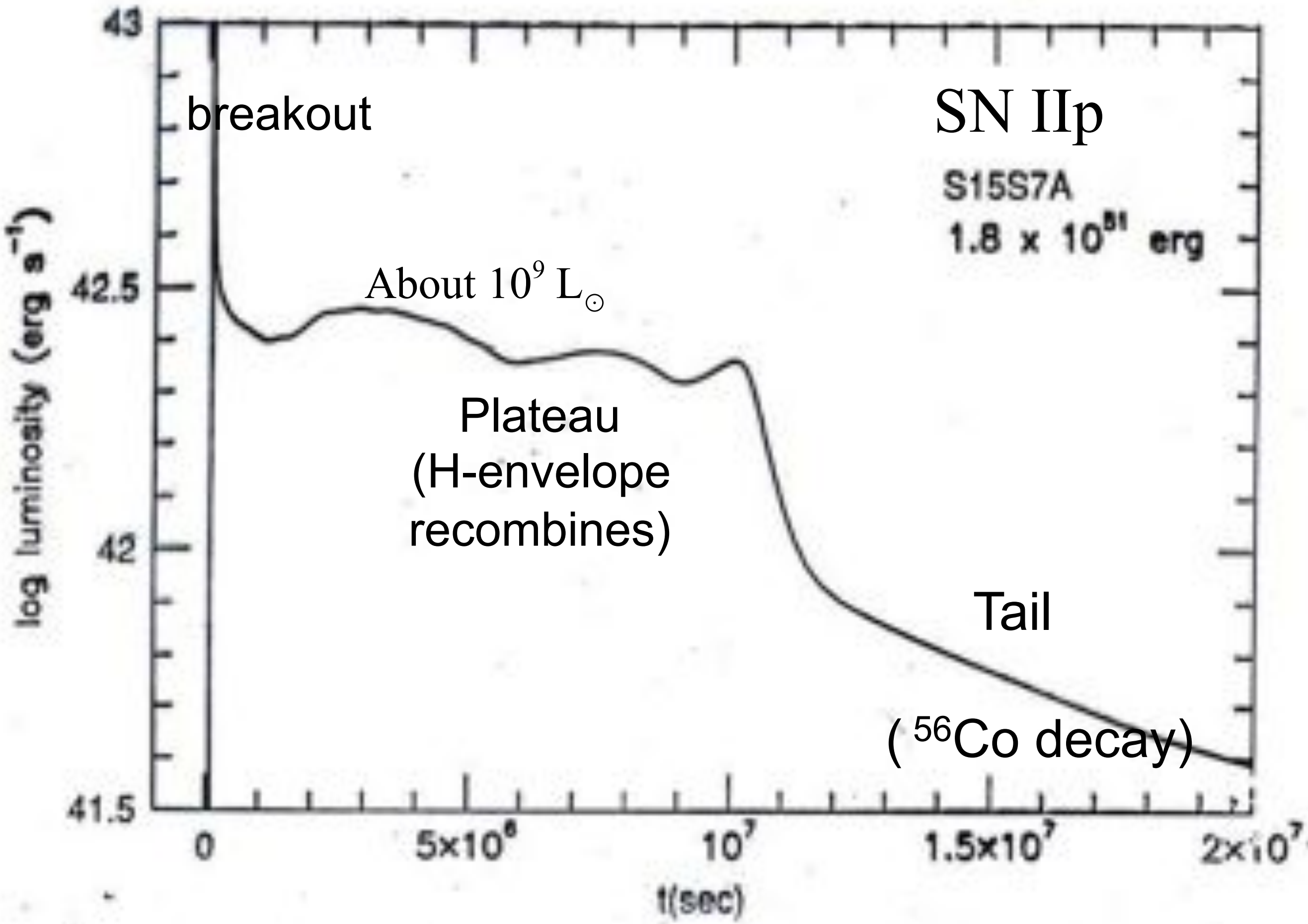
- There are three stages in the light curve of a Type II – plateau supernova – shock breakout, the "plateau", and the decline.

- Breakout is the first time the supernova brightens. The shock wave erupts from the star's surface heating it to about 200,000 K for about 2000 s. It declines to 30,000 K after one day. Meanwhile the luminosity declines from about 10^{11} solar luminosities to about 10^{9} solar luminosities.
  This emission, in UV has been seen in at least two supernovae less than one day after their explosion



uv flash poorly resolved - not as big as galaxy!

A sequence of ultraviolet images released in June 2008 shows shock break out.
Just before the explosion, the host galaxy (top left) appears relatively quiet.
Then a bright ultraviolet flash signals the onset of the supernova



breakout
SN IIp
S15S7A
1.8 x 10^51 erg
About 10^9 L_⊙
Plateau
(H-envelope
recombines)
Tail
(^56Co decay)
log luminosity (erg s^-1)
43
42.5
42
41.5
0
5x10^6
10^7
1.5x10^7
2x10^7
t(sec)

Light Curve of Type IIp Supernovae (cont'd)

- As the hydrogen envelope expands and cools it eventually reaches 5500 K where the hydrogen starts to recombine. This recombination moves into the expanding envelope as a wave over a period of about 3 months. The recombination reduces the opacity and lets out the energy deposited by the shock as it passed through the envelope. This is the plateau. The temperature stays pegged to 5500 K.

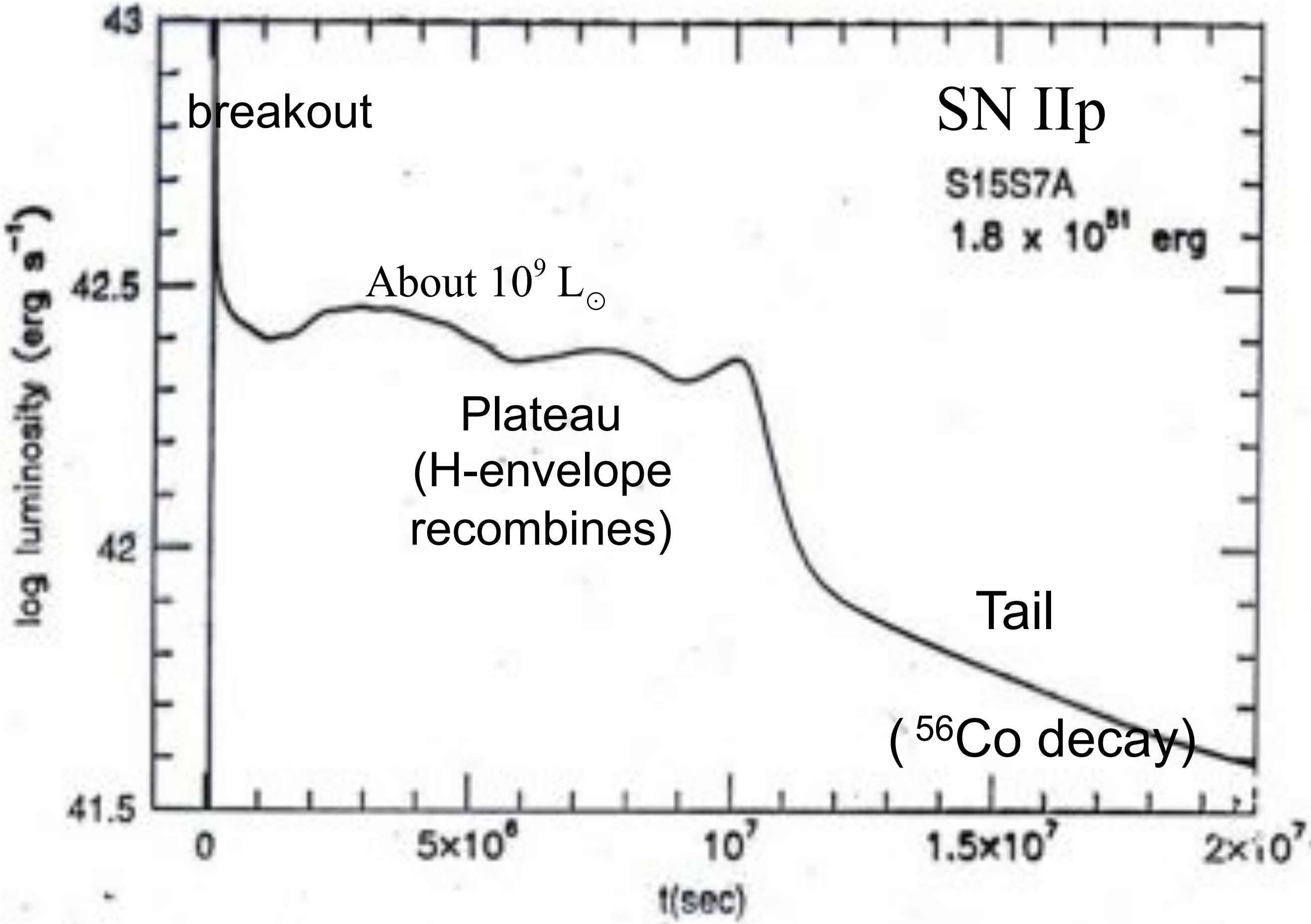
- Still later the decay of radioactivity produced in the supernova keeps it bright for years.

$$^{56}\mathrm{Ni} + e^- \rightarrow {}^{56}\mathrm{Co} + \nu_e + \gamma \quad (6.1\ \mathrm{days})$$

$$^{56}\mathrm{Co} + e^- \rightarrow {}^{56}\mathrm{Fe} + \nu_e + \gamma \quad (77\ \mathrm{days})$$

Together these release 9.4×10^{16} erg g^{-1}. Thus 0.1 solar masses of ^{56}Ni releases 2×10^{49} erg

Theoretical light curve of a Type IIp supernova

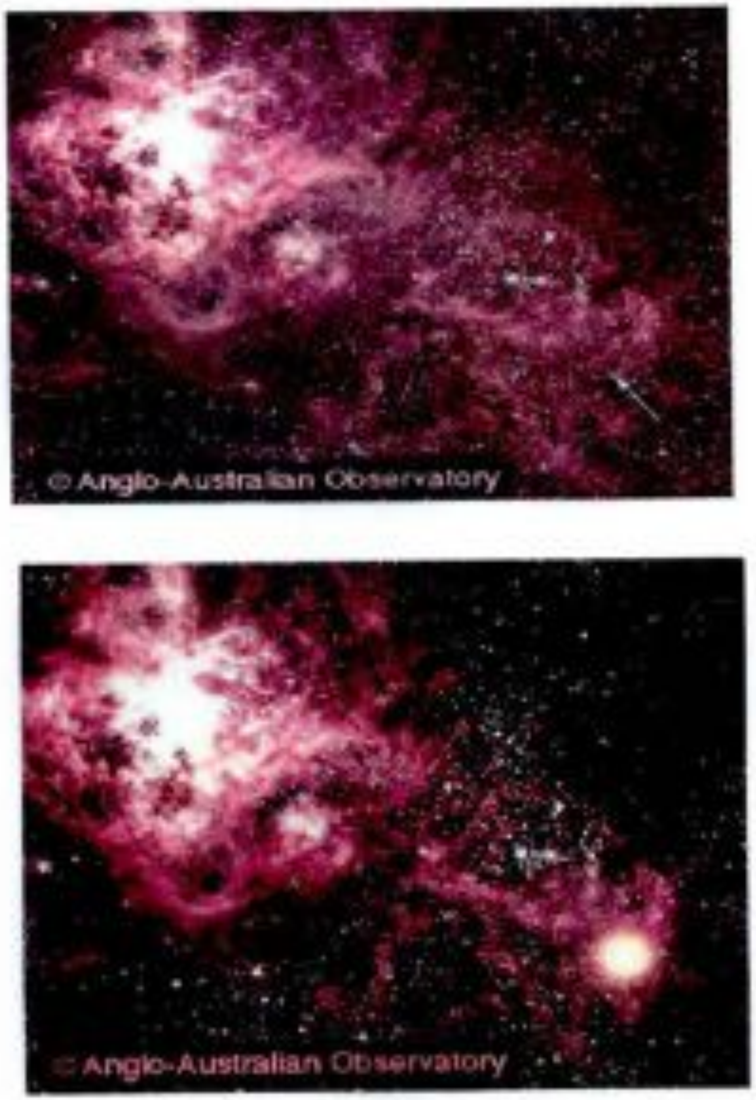


Progenitor stars of Type IIp

Supernova 1987A

before

after



February 23, 1987
(+160,000 years)

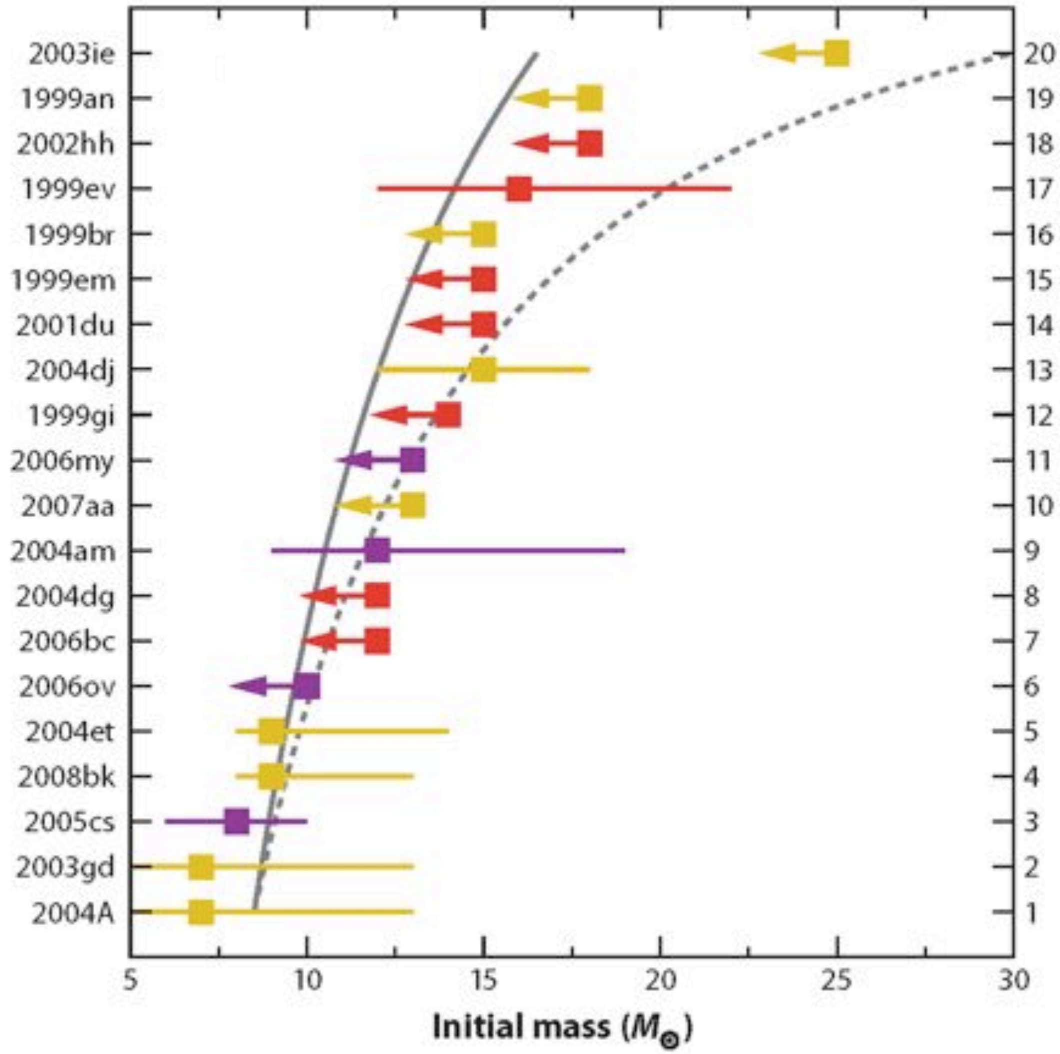
Brightest supernova in over 400 years.

In the 30 Doradus H II region in the Large Magellanic Cloud.

Progenitor star was a previously catalogued blue supergiant Sk 202-69. Mass = 18 solar masses.


© Anglo-Australian Observatory

Presupernova stars – Type II



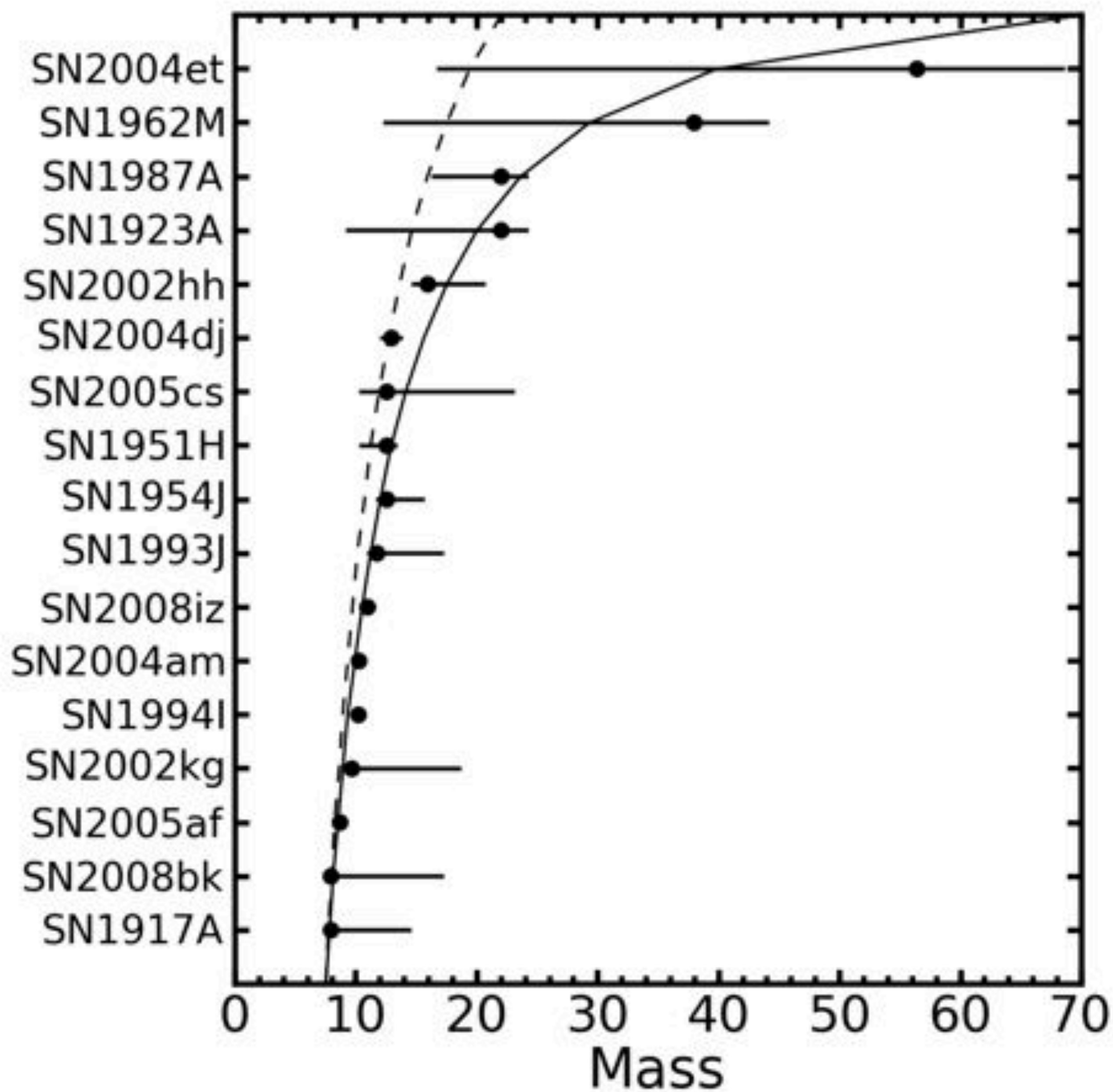
Smartt, 2009
ARAA

Progenitors heavier than 20 solar masses excluded at the 95% confidence level.

More recent work by Jennings et al (2014) suggests a somewhat weaker limit

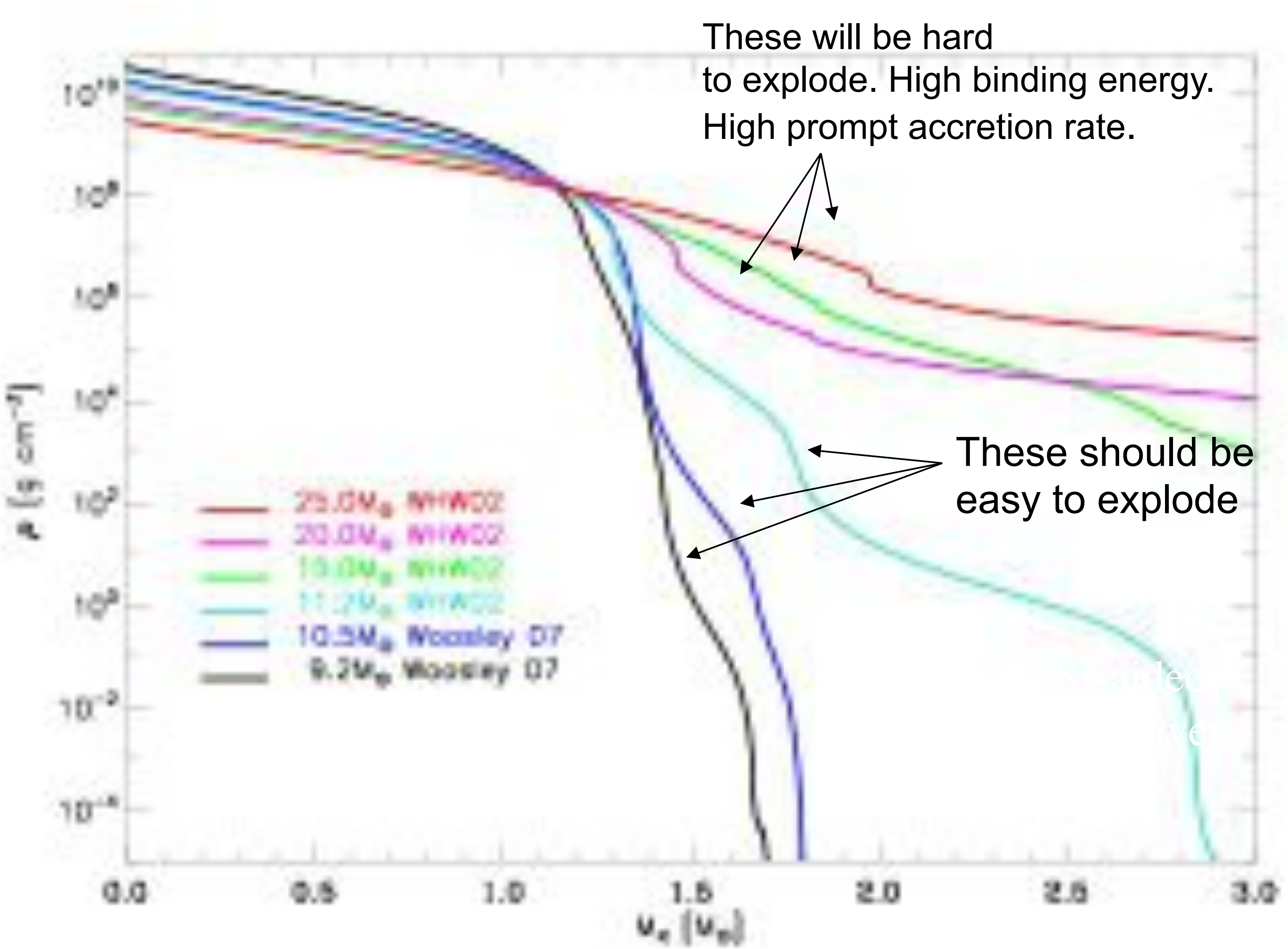
The solid line is for an IMF with a maximum mass of 16.5 solar masses. The dashed line is an IMF with a maximum of 35 solar masses

Jennings et al (2014) – more progenitors; still no heavies with good mass determinations



Above a certain main the collapse may make black holes

Density Profiles of Supernova Progenitor Cores



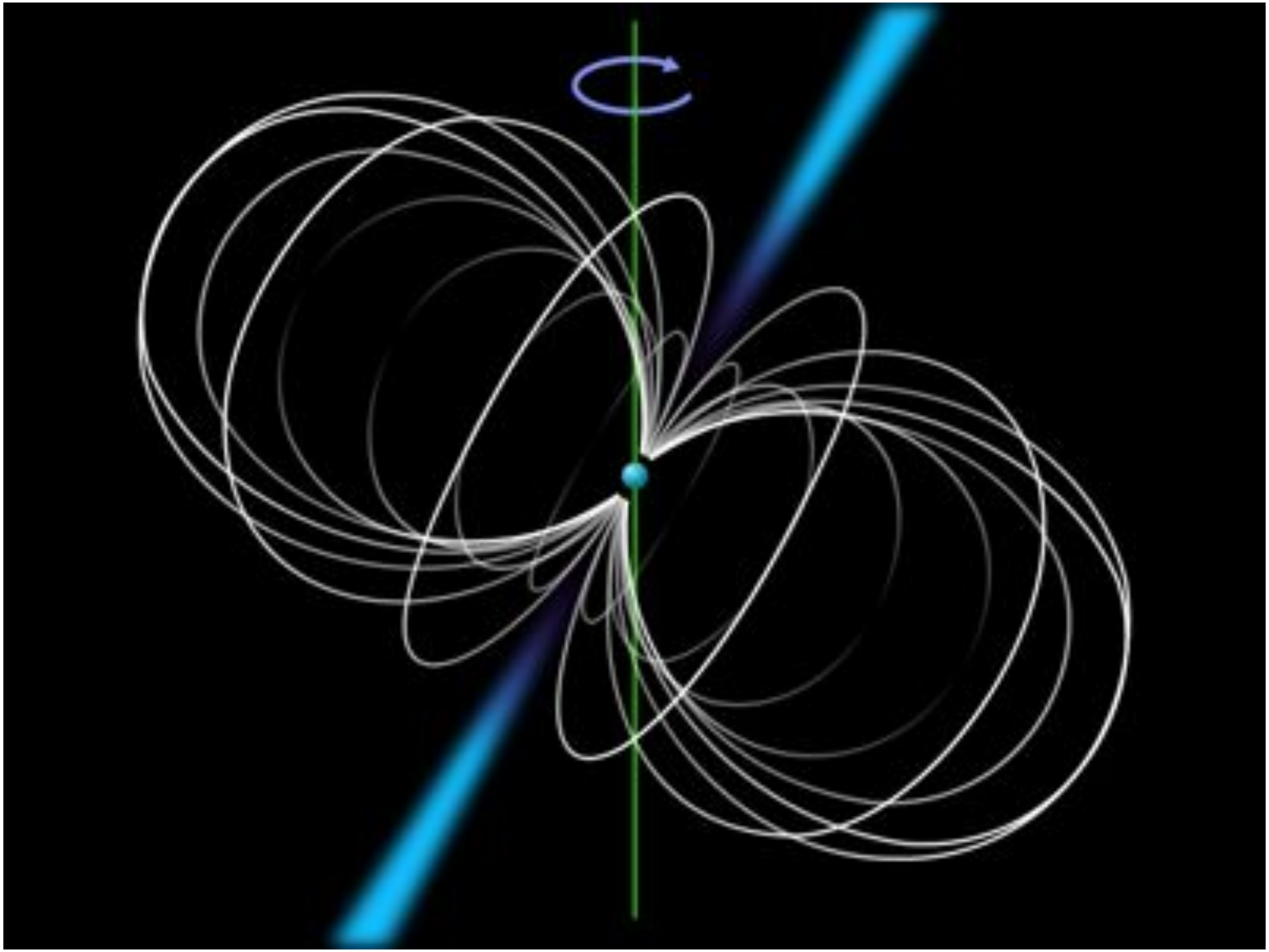
PULSARS

- Iron-core-collapse supernovae leave behind bound remnants that are either black holes or neutron stars

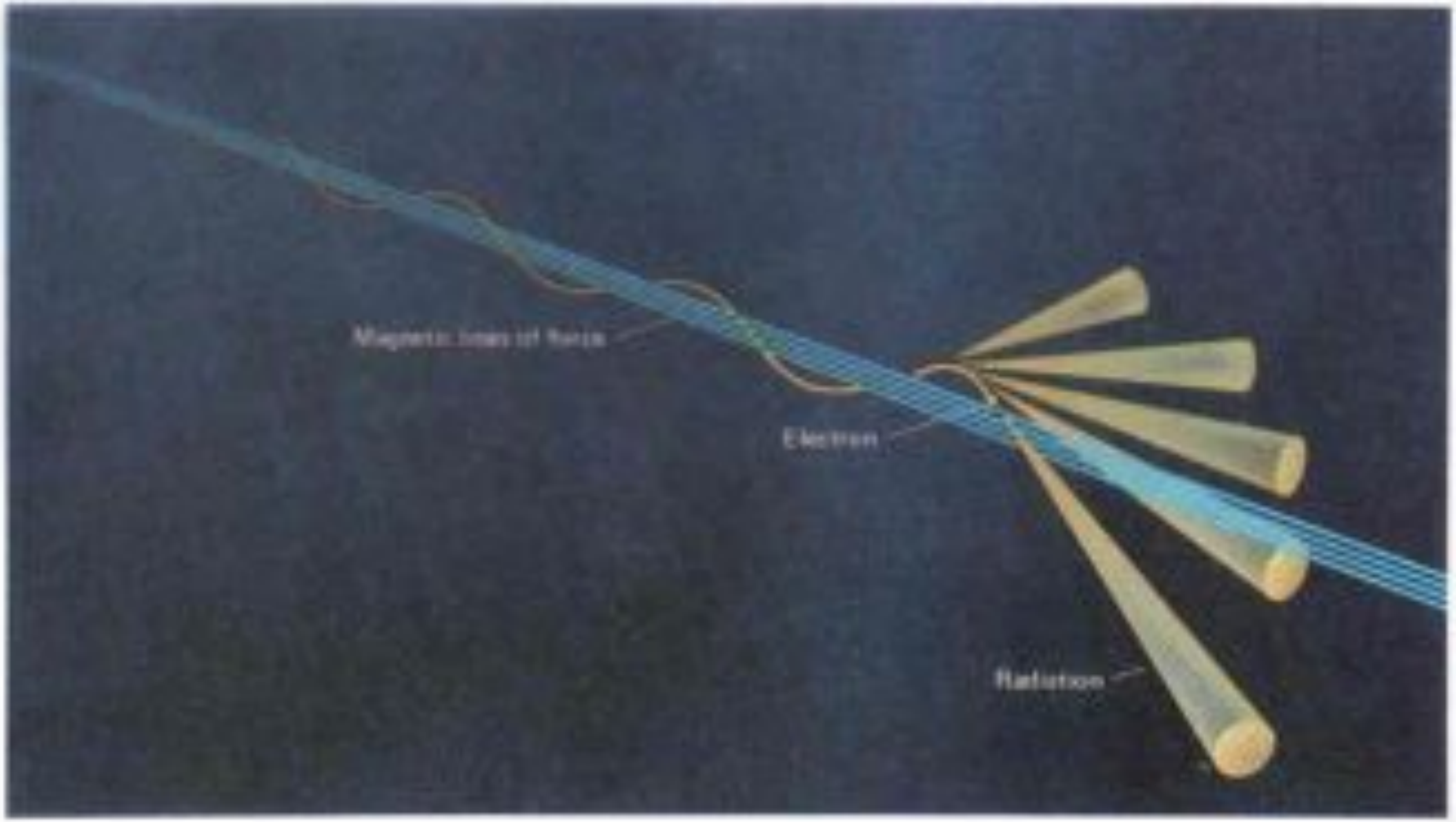
- If the neutron star is rapidly rotating (ms to 100's of ms) and has a strong magnetic field (10^{12} – 10^{13} gauss), it may be a pulsar (if the magnetic axis and rotation axis are not alligned)

- The most rapidly a neutron star can rotate without substantially deforming and either coming apart or emitting copious gravitational radiation is 1 ms. Pulsars with rotation rates that rapid are seen but have weaker magnetic fields (10^{8} – 10^{9} gauss) and may have been spun up in binaries.

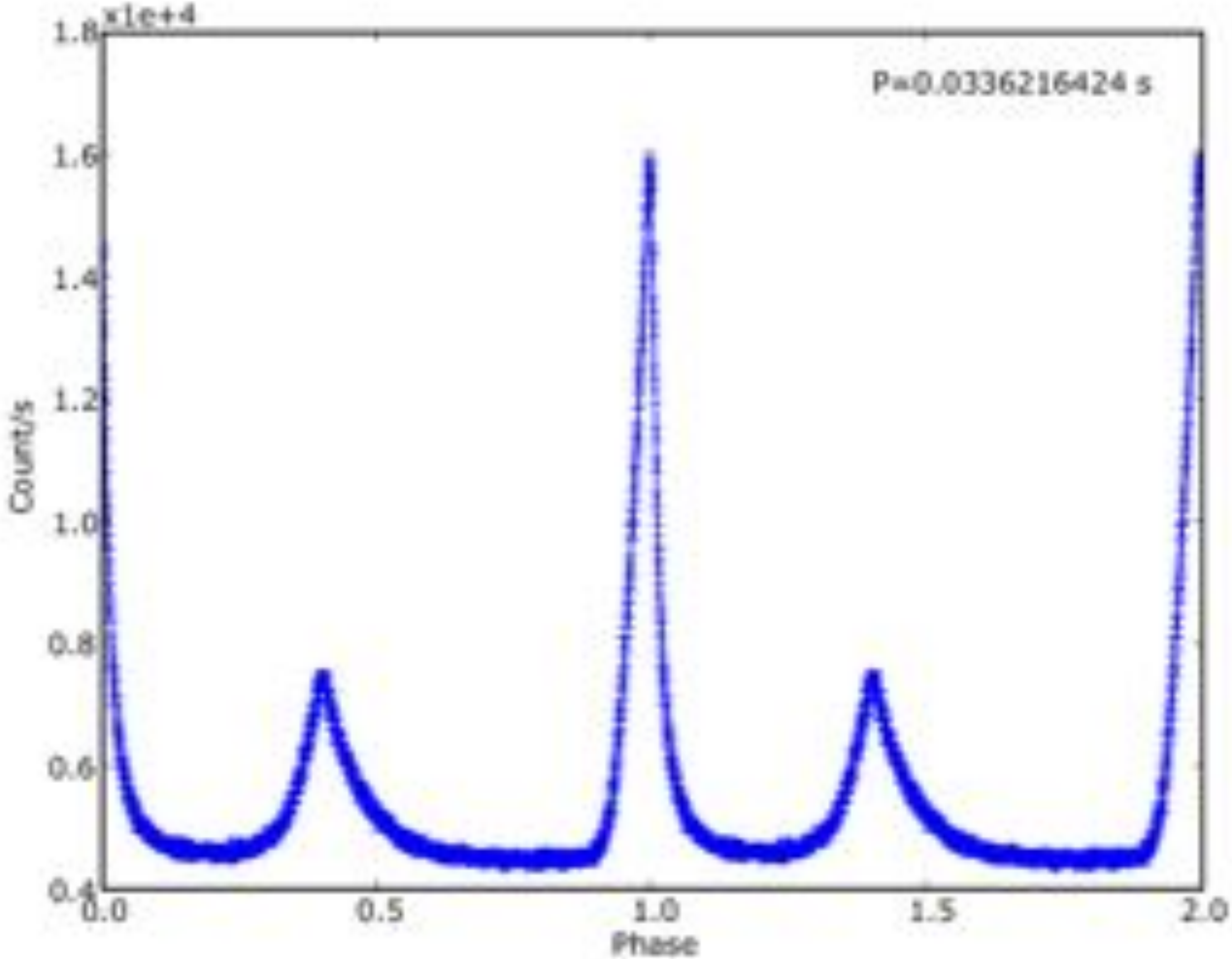
PULSAR

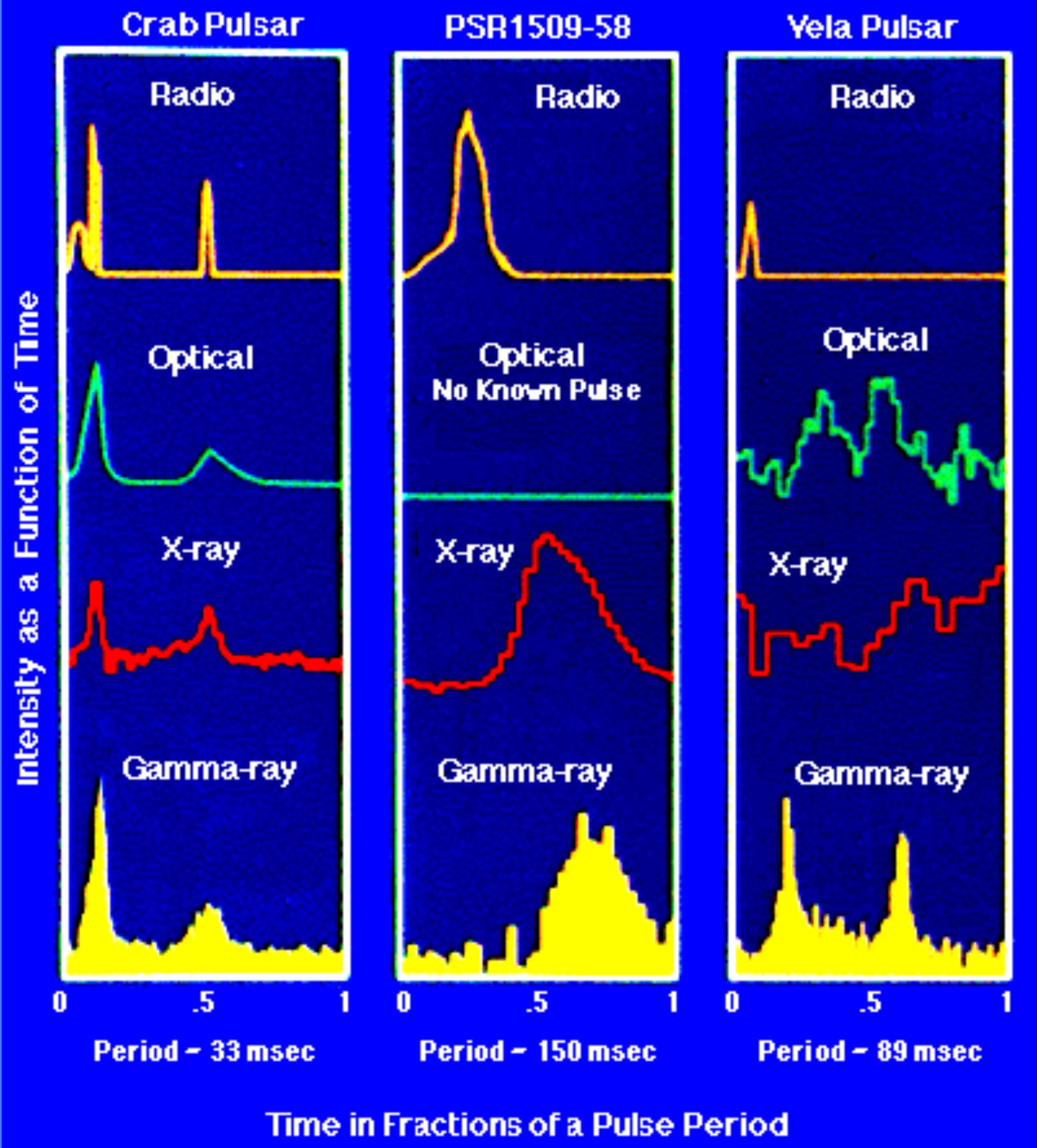


SYNCHROTRON RADIATION



Crab pulsar – optical light curve



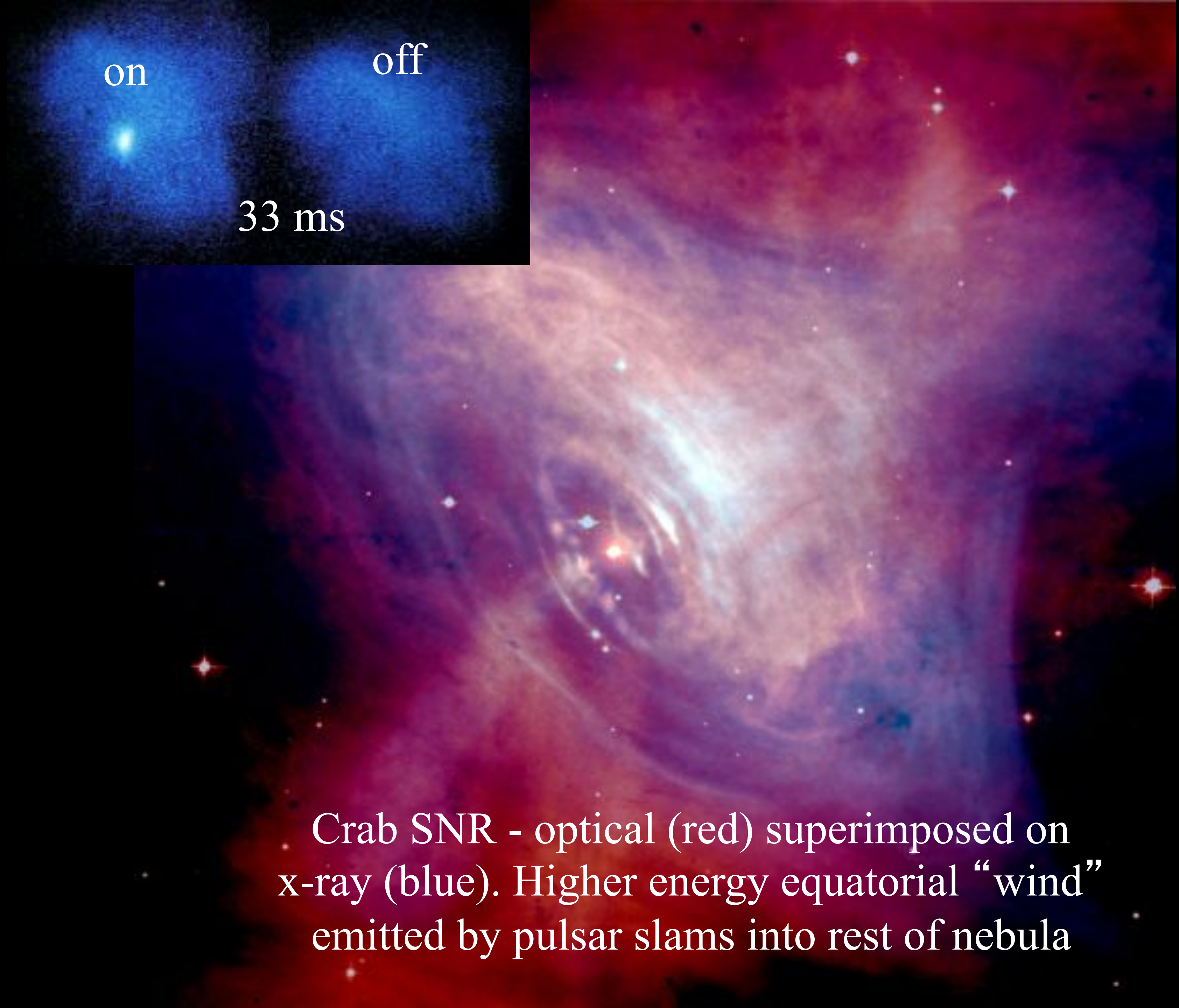

Crab Pulsar
PSR1509-58
Vela Pulsar
Radio
Optical
No Known Pulse
X-ray
Gamma-ray
Intensity as a Function of Time
0
.5
1
Period ~ 33 msec
Period ~ 150 msec
Period ~ 89 msec
Time in Fractions of a Pulse Period

PULSARS

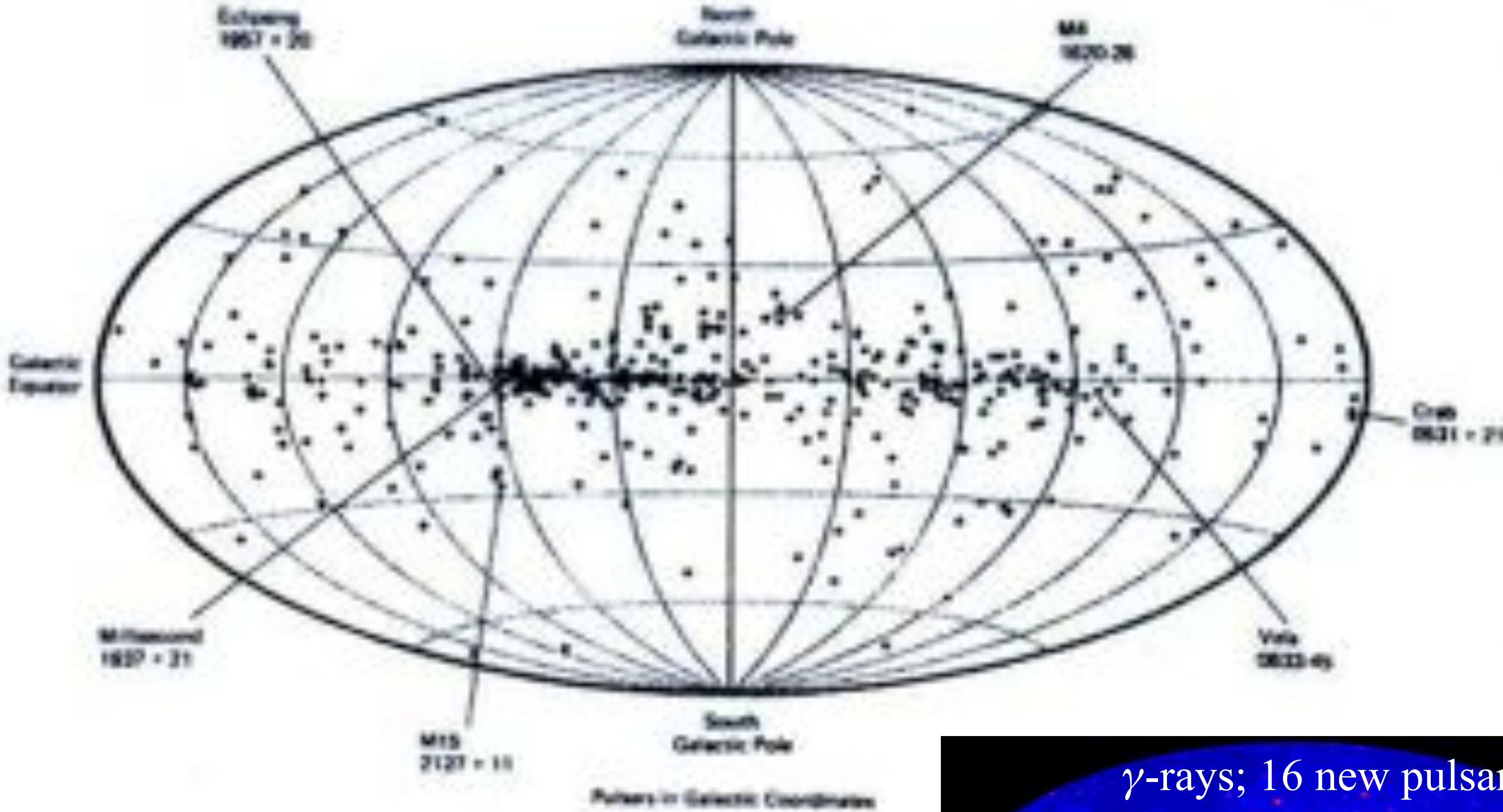
- Over 1000 now known. Periods range from about 1 ms to over 5 seconds. Accurate clocks (16 decimal places). Concentrated towards Galactic disk. Gradually slowing.

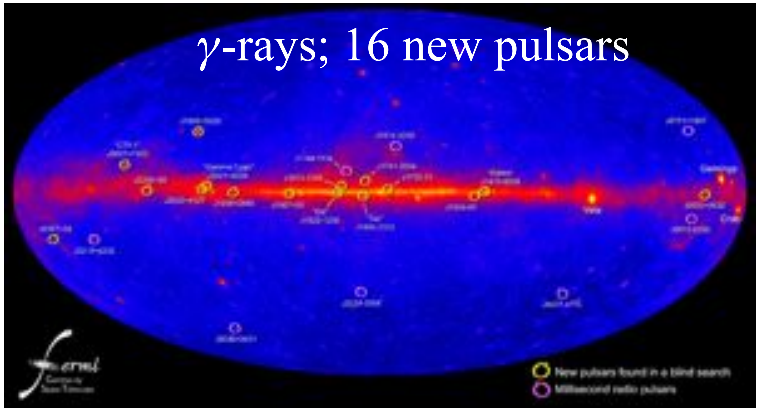
- Evidence for high "peculiar" velocities of typically several hundred km s^{-1}. May get "kicked" in the explosion. Many leave the galaxy.

- Some evidence they turn off after ~ 10^7 years due to magnetic field decay and spin down.



Crab SNR - optical (red) superimposed on x-ray (blue). Higher energy equatorial “wind” emitted by pulsar slams into rest of nebula





Listen to pulsars:

http://csep10.phys.utk.edu/astr162/lect/pulsars/pulsars.html

PULSARS (continued)

- Occasionally experience abrupt changes in period due to "starquakes"

- Emit pulsed radiation at all wavelengths. Not blackbody emitters.

- Spin down times for solitary neutron stars in supernova remnants are thousands of years consistent with the ages of the remnants in which they are found

- Most rapid rotators in mass exchanging binaries – probably spun up.

- Sometimes in binaries with other pulsars, white dwarfs or black holes - and even a planet

http://www.astro.psu.edu/users/alex/pulsar_planets_text.html

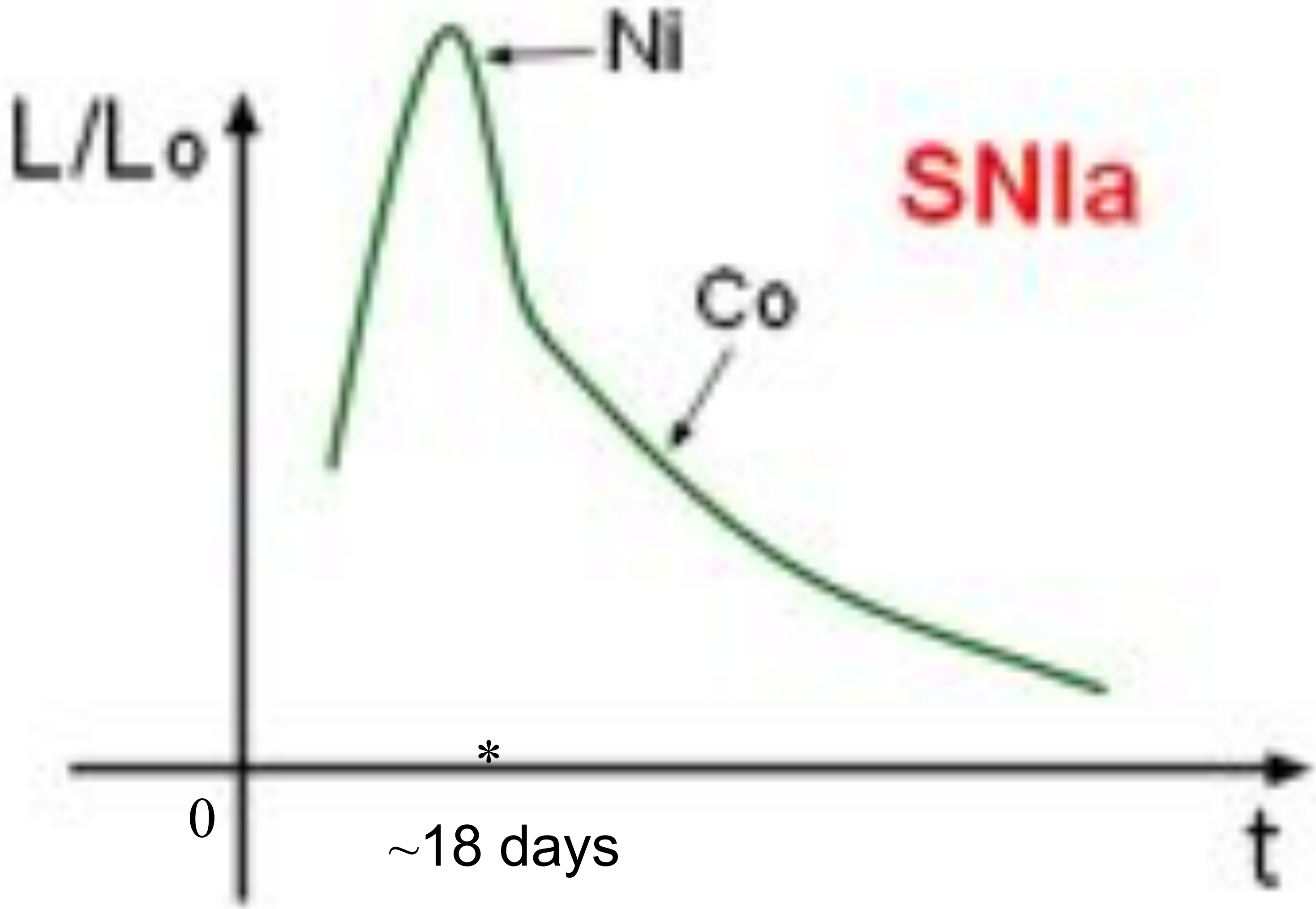
Type I Supernovae

- Type I supernovae lack hydrogen and thus have no plateau stage. The shock break out is also much fainter and shorter in wavelength (x-rays)

- The Type I supernova light curve is thus powered at all times by the decay of radioactive ^{56}Ni and ^{56}Co.

- Type I supernovae are segregated into several classes: Type Ia, Ib, and Ic depending upon special features in their spectra (Si II, He I) and where they are found.

- Type Ib and Ic are also the death of a massive star but one that has lost its envelope – most of the time to a binary companion. Type IIp and Ib/c are found in star forming regions


Ni
L/Lo
SNIa
Co
*
0
~18 days
t

Type Ia Supernovae

- Type Ia supernovae are **not** found in star forming regions. They show no preference for spiral arms and can occur in elliptical galaxies where the star formation rate is very low

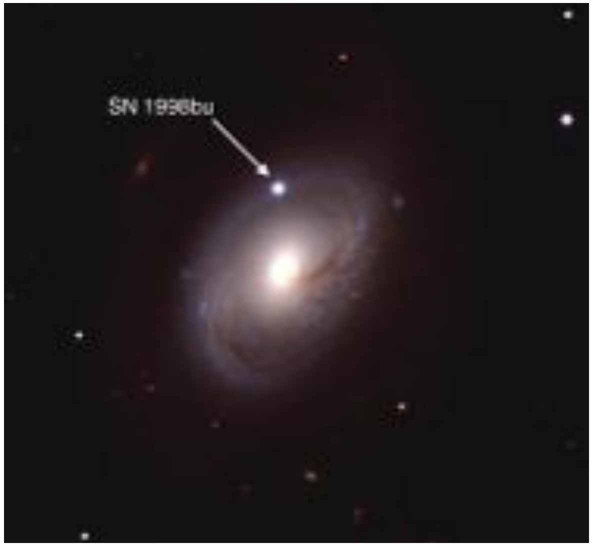
- While the progenitor stars of many 10 Type II supernovae have been seen before they exploded (e.g. 1987A), no progenitor of a SN Ia has ever been identified. They must be very faint

- Type Ia supernovae are brighter than any other class. Type I supernovae in general are bright a shorter time than SN IIp (weeks rather than months)

- Neutron stars and black holes may be produced by Type Ib and Ic supernovae, but never by Type Ia.

SN 1998aq

SN 1998dh



SN 1998bu

SN 1994D

Type Ia supernovae are the biggest thermonuclear explosions in the universe.

Thirty billion, billion, billion megatons.

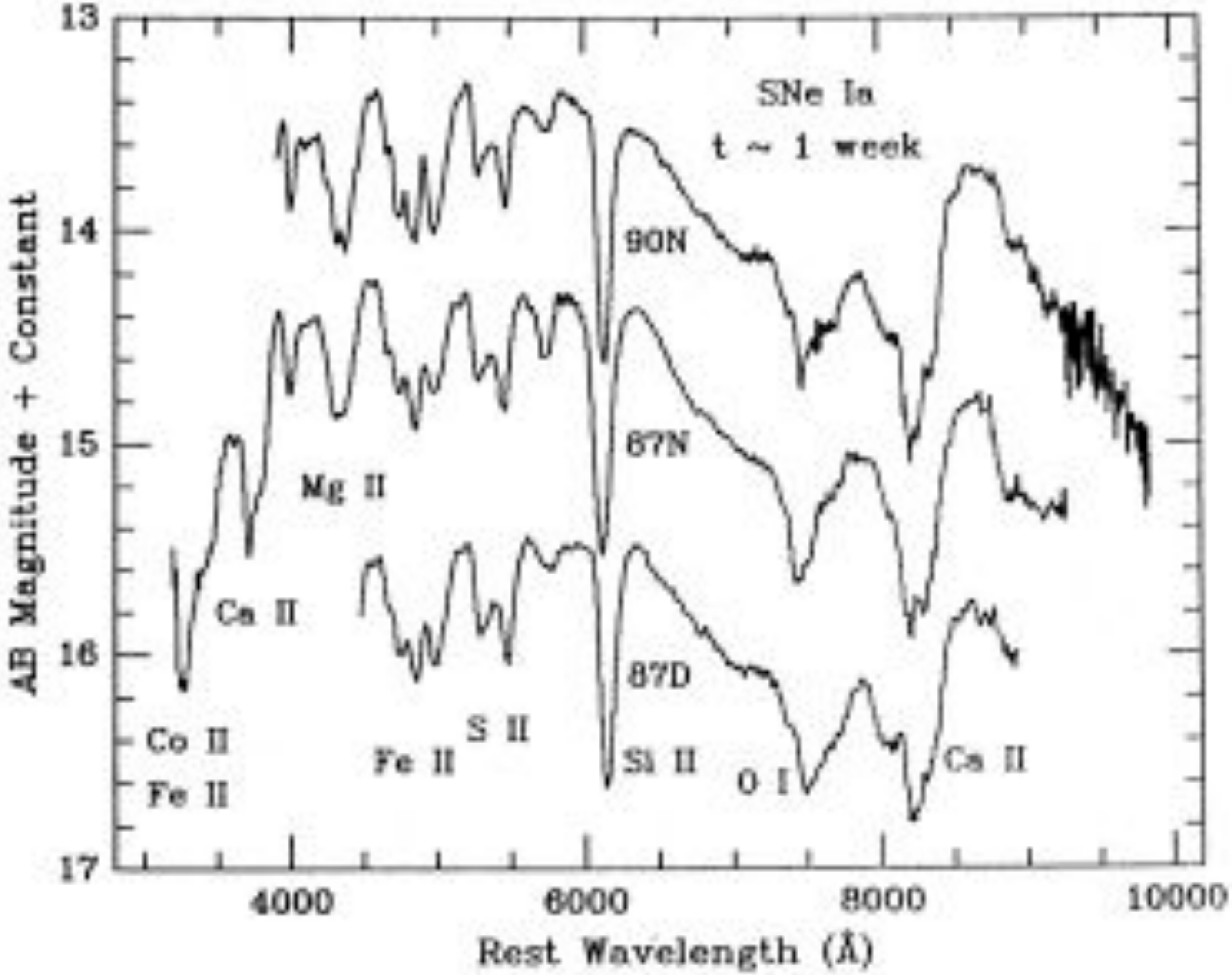
For several weeks their luminosity rivals that of a large galaxy.

SN Ia - Observational facts

- Very bright, regular events, peak $L \sim 10^{43}$ erg s^{-1}
- Associated with an old stellar population (found in ellipticals, no clear association with spiral arms when in spiral galaxies)
- No hydrogen in spectra; strong lines of Si, Ca, Fe
- Total kinetic energy $\sim 10^{51}$ erg (nothing left behind)
- Higher speed, less frequent than Type II

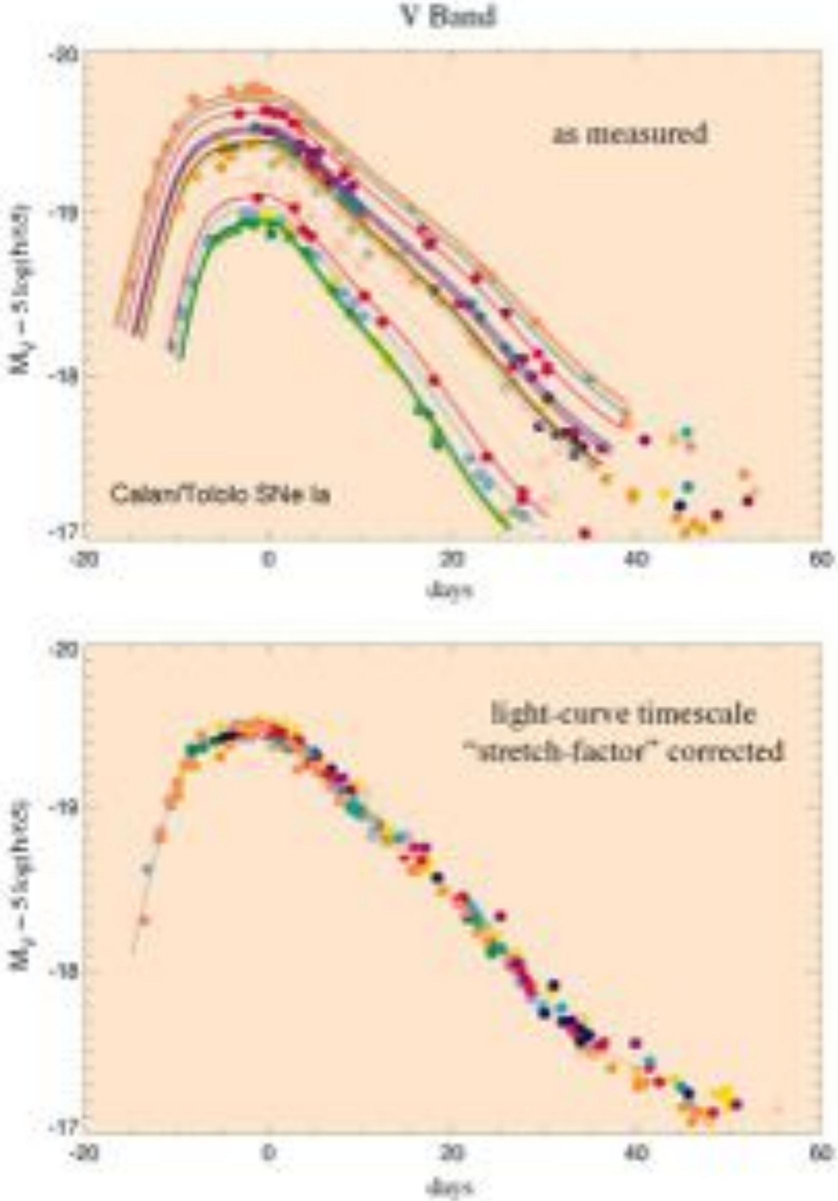
SN 1994D

Spectra are similar from event to event



Spectra of three Type Ia supernovae near peak light – courtesy Alex Filippenko

Useful standard candles



The Phillips Relation
(post 1993)

Broader = Brighter

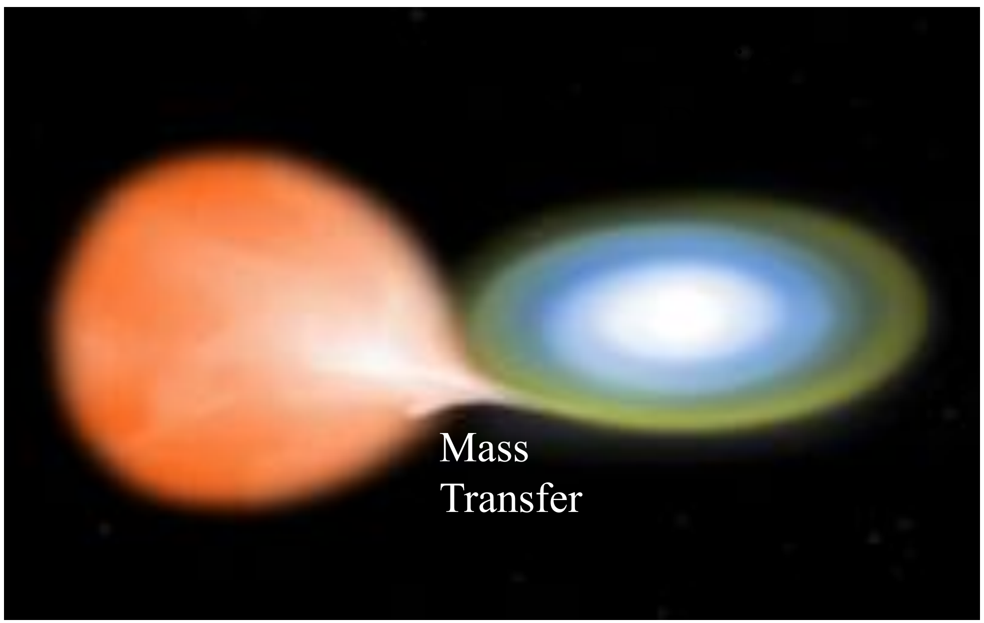
Possible Type Ia Supernovae in Our Galaxy

SN	D(kpc)	m_V
185	1.2+-0.2	-8+-2
1006	1.4+-0.3	-9+-1
1572	2.5+-0.5	-4.0+-0.3
1604	4.2+-0.8	-4.3+-0.3

Expected rate in the Milky Way Galaxy about 1 every 200 years, but dozens are found in other galaxies every year. About one SN Ia occurs per decade closer than 5 Mpc. SN 2014J was at 3.5 Mpc and was extensively studied. ^{56}Co decay lines were recently detected from SN 2014J.

Leading Models

All models are based upon the thermonuclear explosion of a carbon-oxygen white dwarf star accreting mass from a companion star in a binary. (Hoyle and Fowler, 1960).



Explains:

- Lack of H in spectrum
- Association with old population
- Regularity
- Large production of ^{56}Ni and a light curve dominated by radioactivity.

Unfortunately there are several paths to instability

- *Single Degenerate models*

1) A CO – white dwarf accretes from a non-degenerate companion grows to almost the Chandrasekhar mass and ignites a carbon runaway near its center

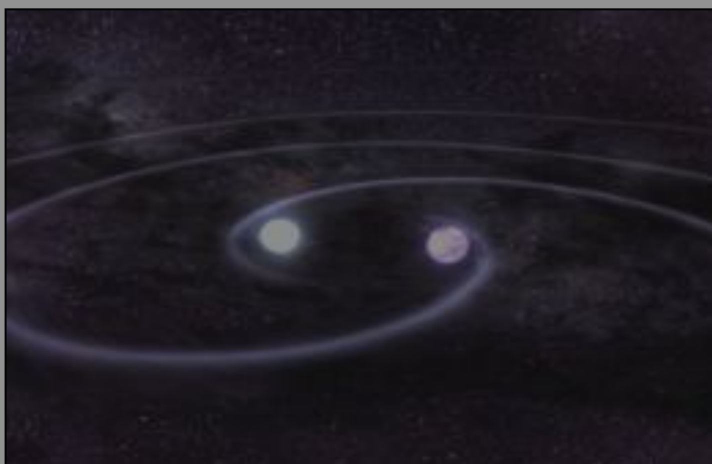
2) The sub-MCh model = similar to 1) but the accretion rate is lower and a layer of degenerate helium of about 0.1 M_O accumulates on the surface of WD from 0.9 to 1.1 M_O. A runaway in the helium leads to its detonation and triggers a detonation in the carbon core as well

- *Double Degenerate models*

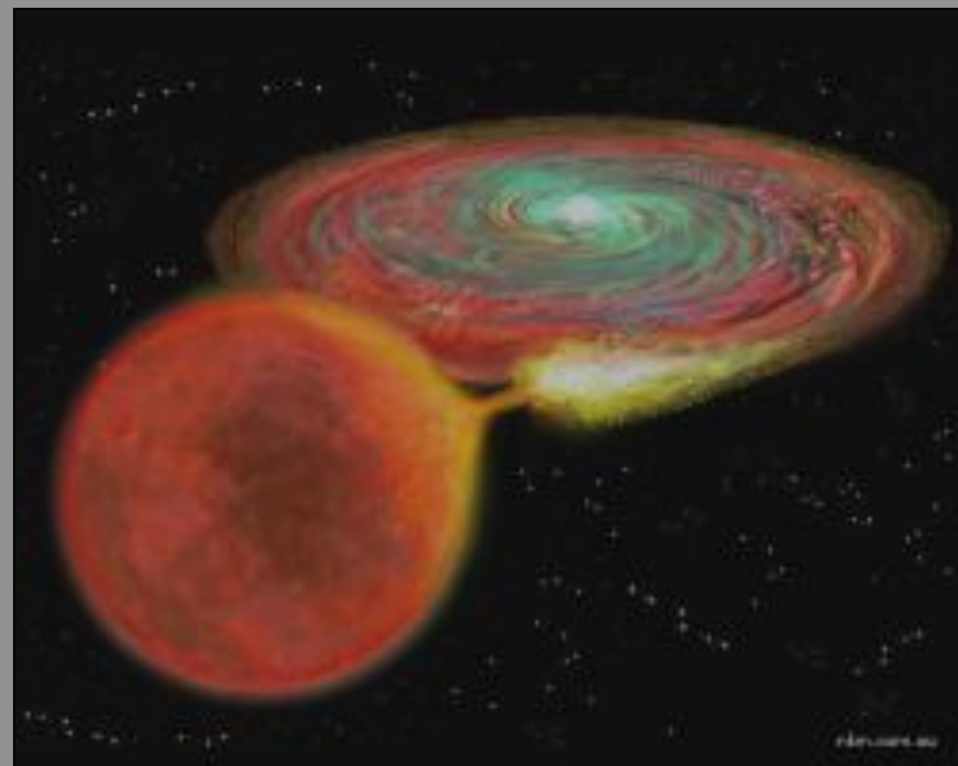
3) Two white dwarfs in a binary system merge because of gravitational radiation. During the merger, compression and/or shear lead to the detonation of one or both white dwarfs

SN Ia Progenitor Systems

explosions of carbon/oxygen white dwarf stars

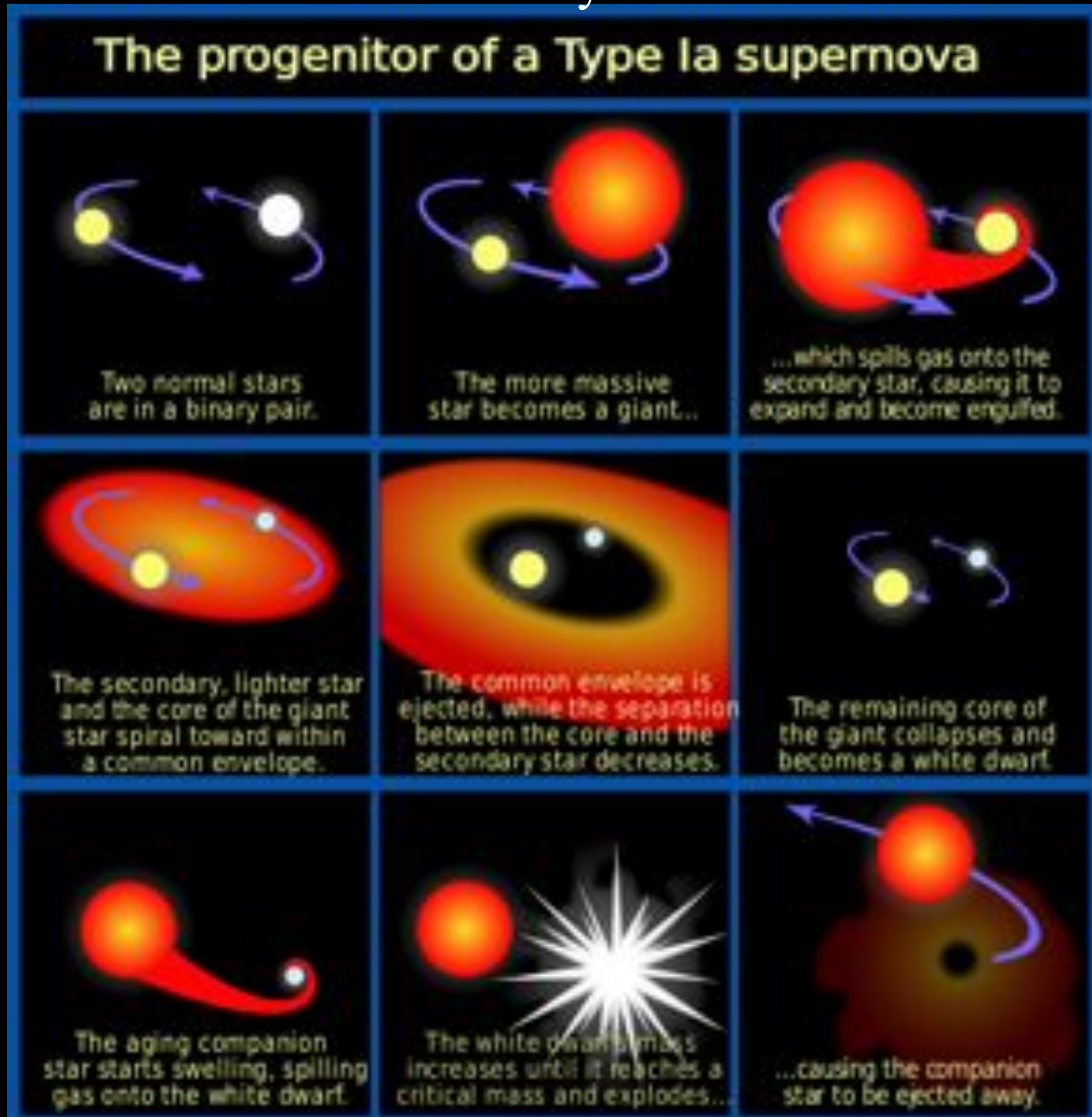


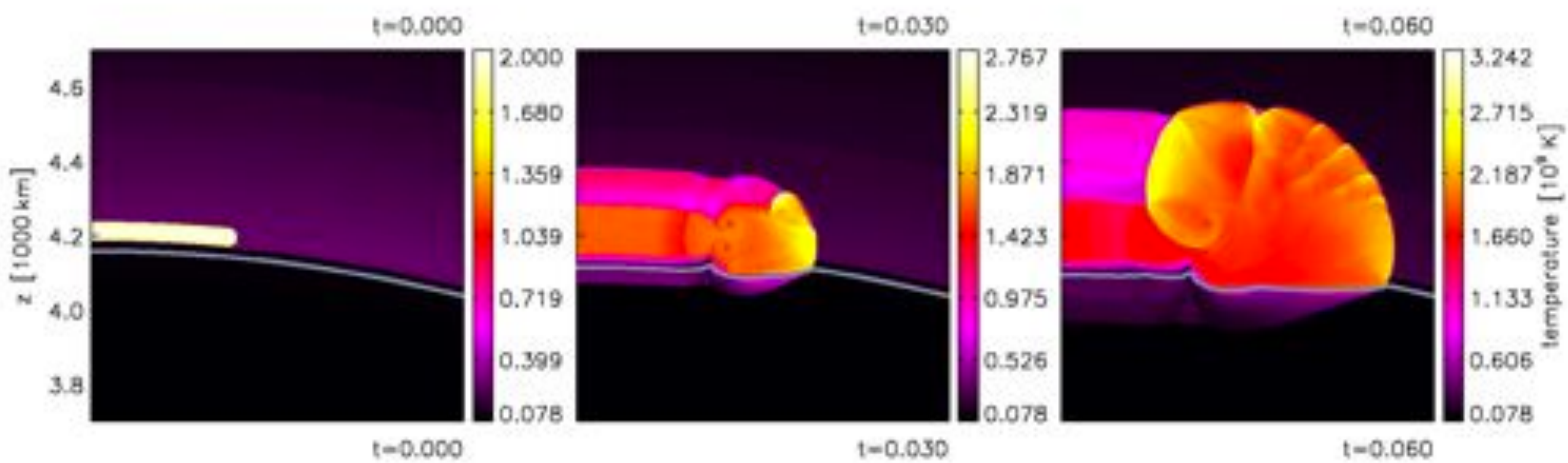
merging double white dwarf binary

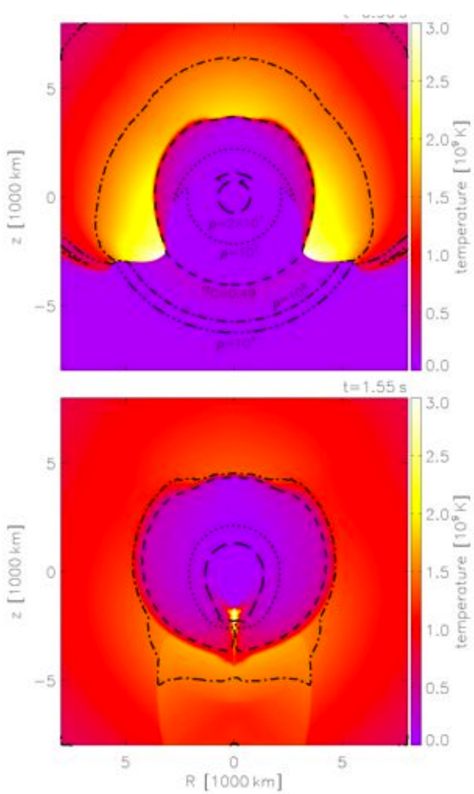


accreting white dwarf

Evolutionary scenario



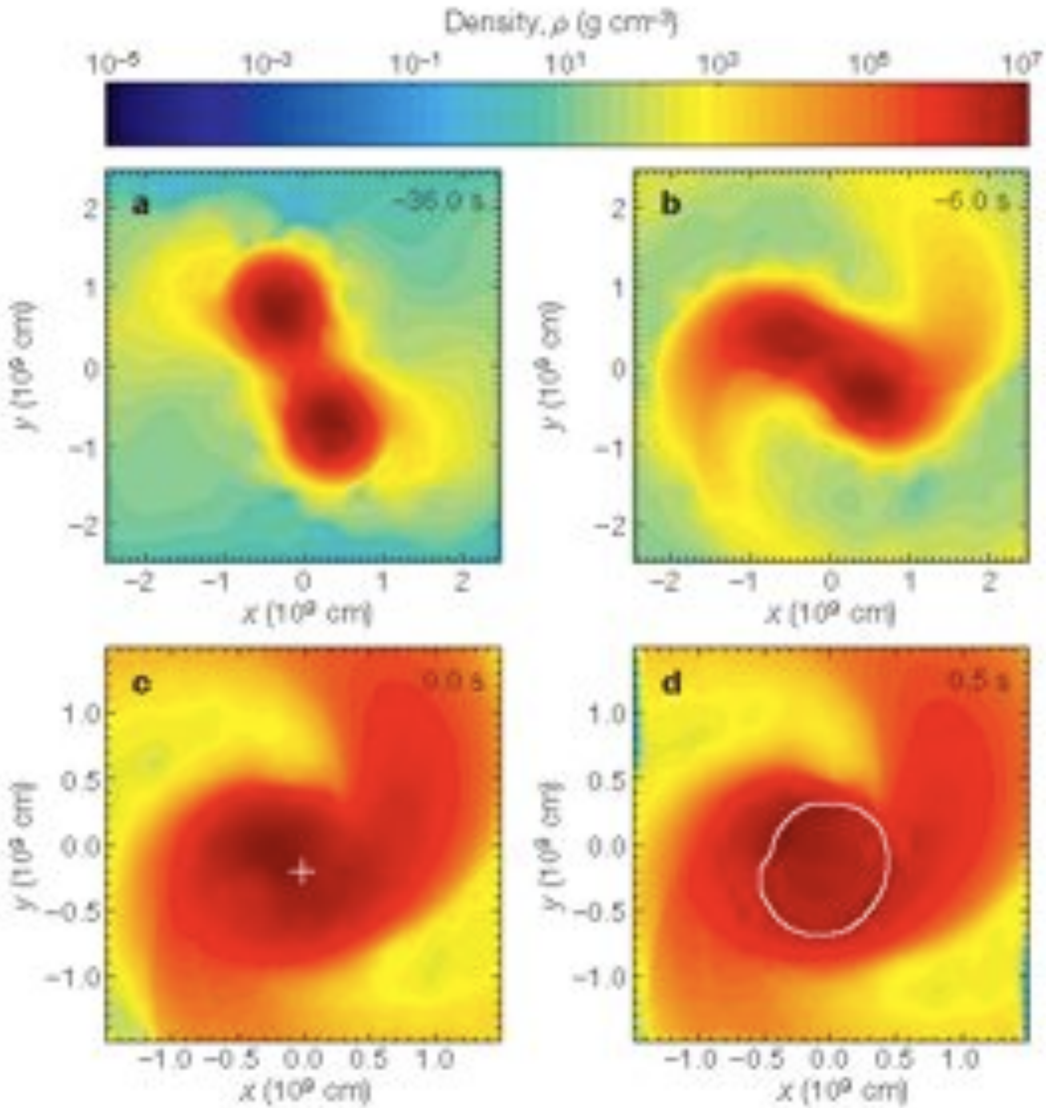


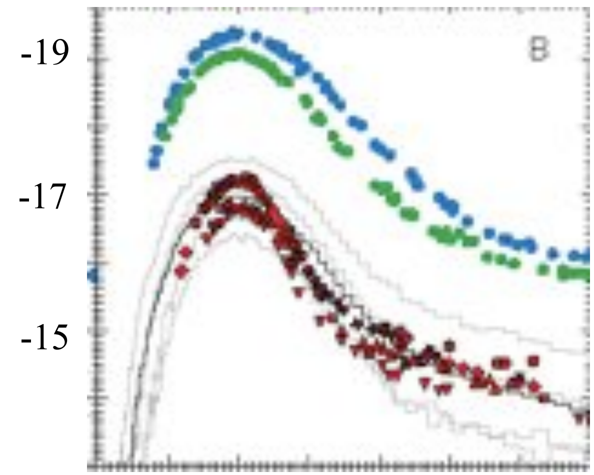


Sub-Chandrasekhar mass Model

0.045 $M_\odot$ of helium atop a 1.0 $M_\odot$ carbon--oxygen white dwarf.A runaway in the helium intiates a lateral detonation which goes *a*round the CO core compressing and heating it, causing it to detonate as well. Produces 0.64 $M_\odot$ of ^{56}Ni (Woosley and Kasen 2011; Moll and Woosley 2013)

Merging White Dwarfs



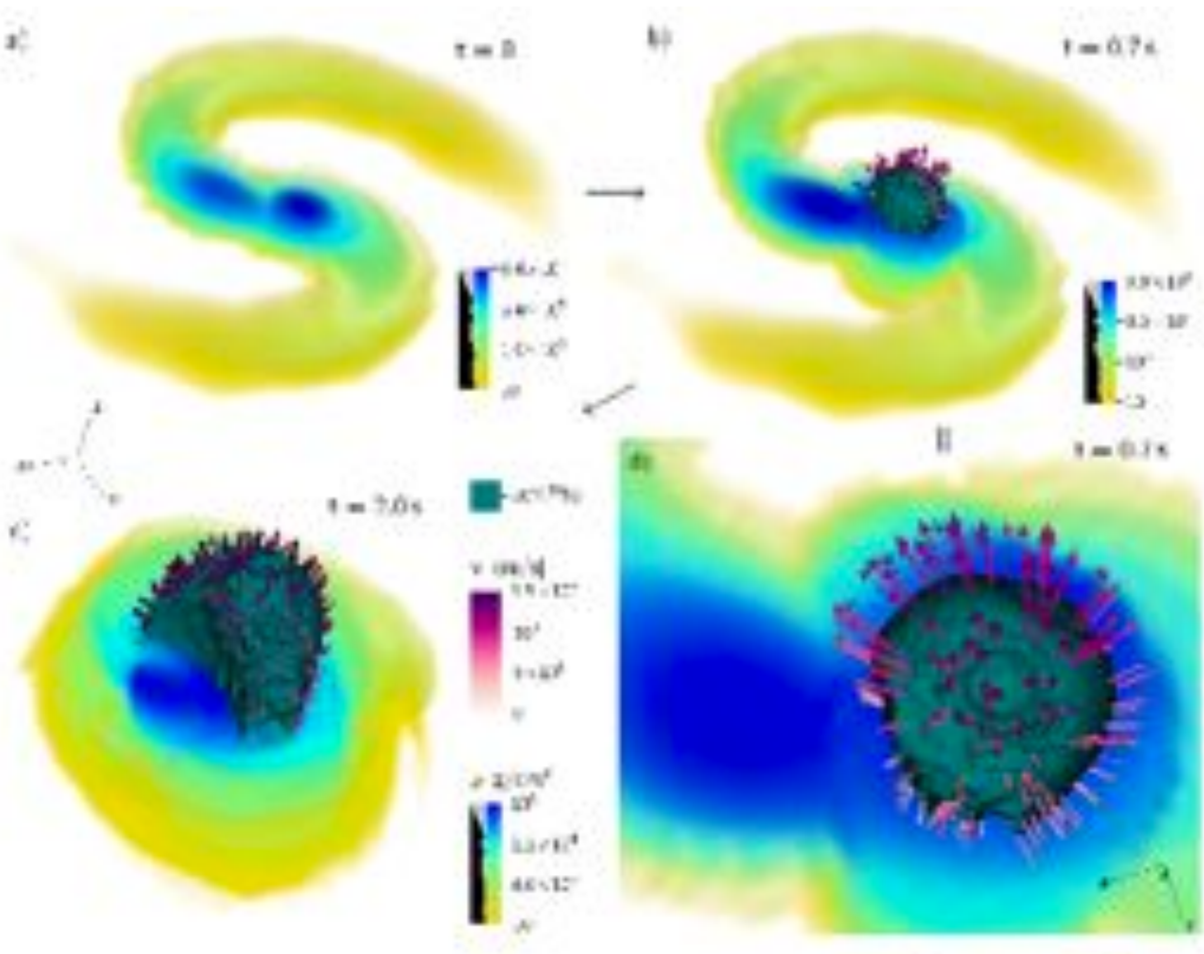


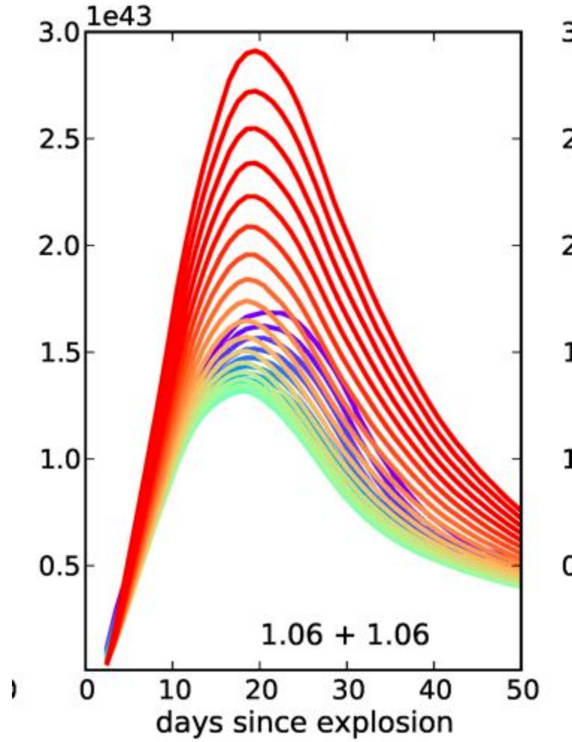
0.9 + 0.9 solar mass WD still make subluminous event

1.1 + 0.9 can make a more typical SN Ia like 2011fe (Roepke et al 2012, ApJL, 750, L19)

Moll, Raskin, Kasen and Woosley, 2013

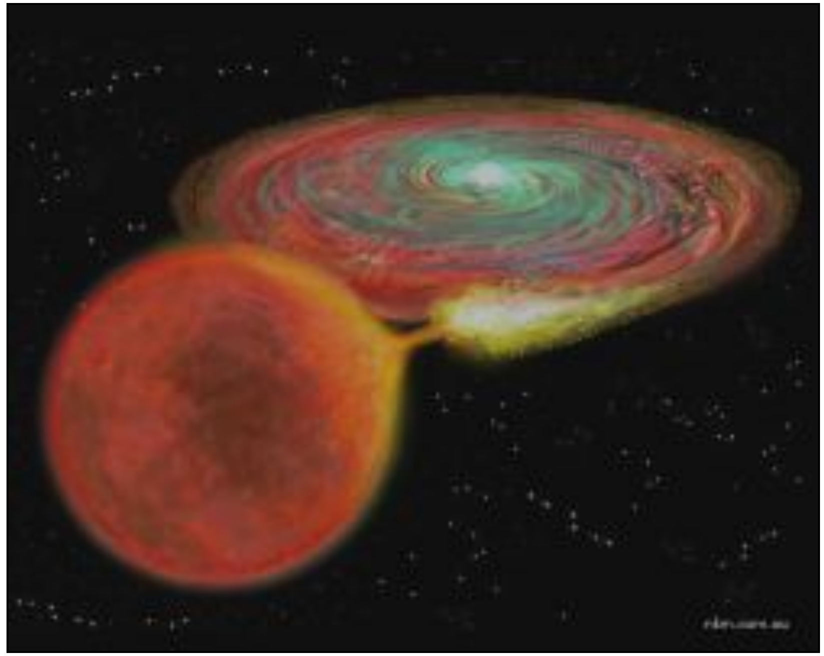
$1.06\ M_\odot + 1.06\ M_\odot$





$0.86\ M_0$ of ^{56}Ni
Light curve highly angle dependent

Chandrasekhar Mass Model

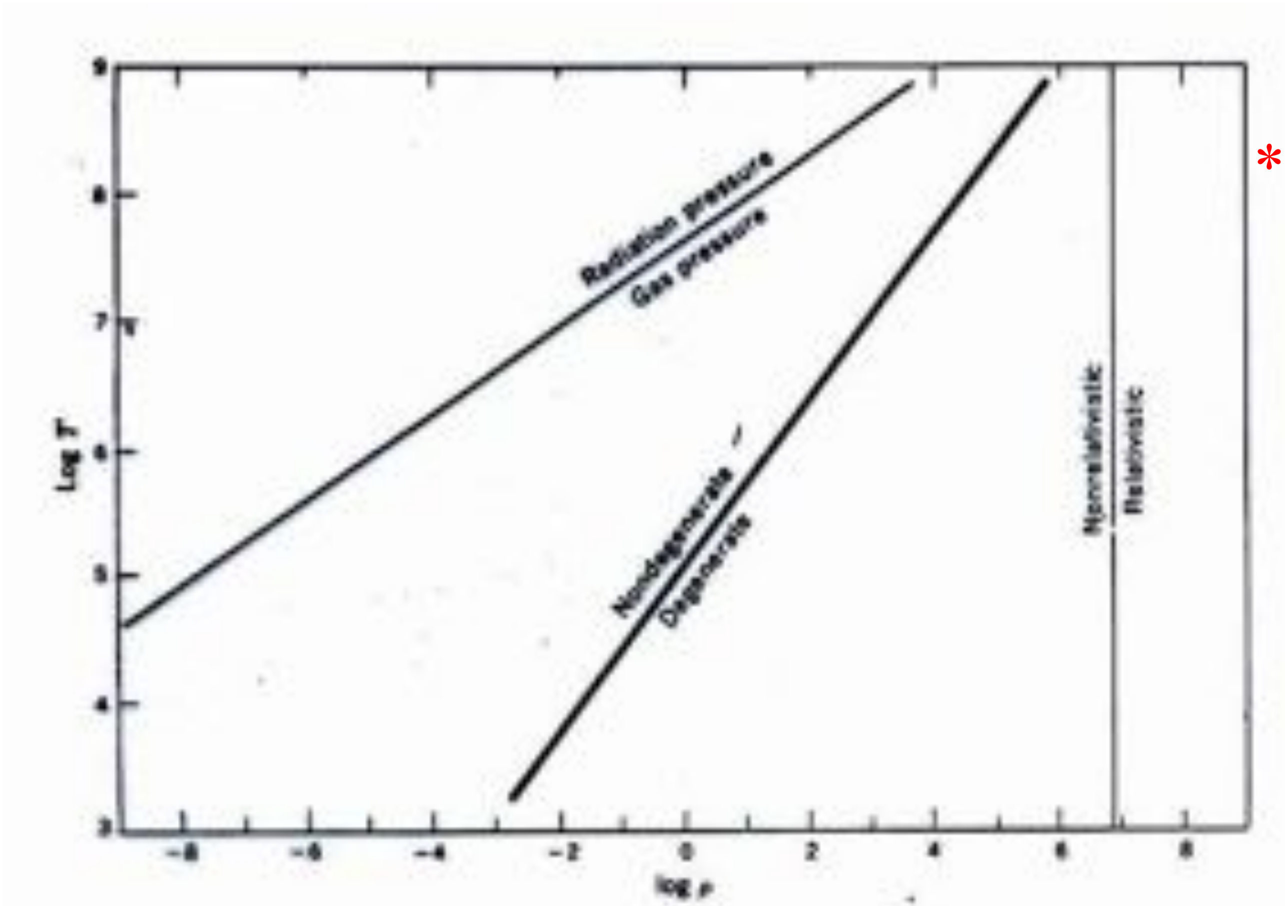


In order for the white dwarf to grow and reach the Chandrasekhar Mass the accretion rate must be relatively high (to avoid the nova instability). This must be maintained for millions of years.

$$\dot{M} \sim 10^{-7}\, M_{sun} / yr$$

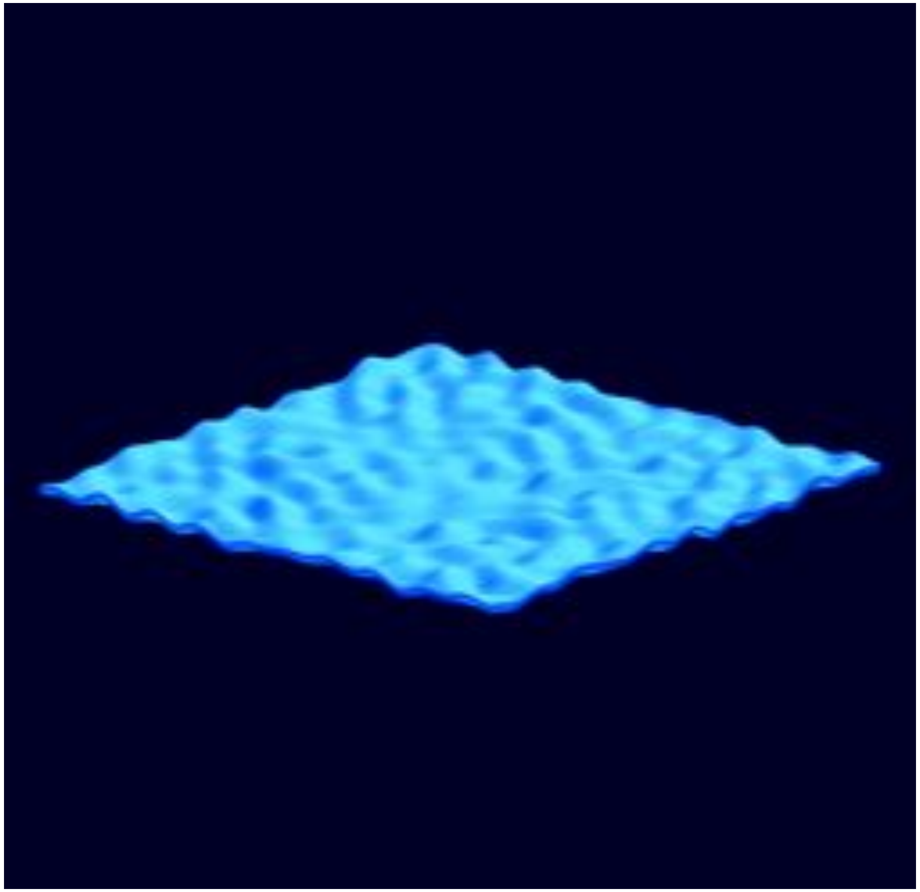
Ignition occurs carbon fusion in the center of the white dwarf begin to generate energy faster than convection and neutrino losses can carry it away.

$M \approx 1.38\, M_{\odot} \qquad \text{As } \rho \rightarrow 2\,x 10^{9} \text{ gm cm}^{-3};\ \mathrm{T} \approx 3\,x 10^{8} \text{ K}$

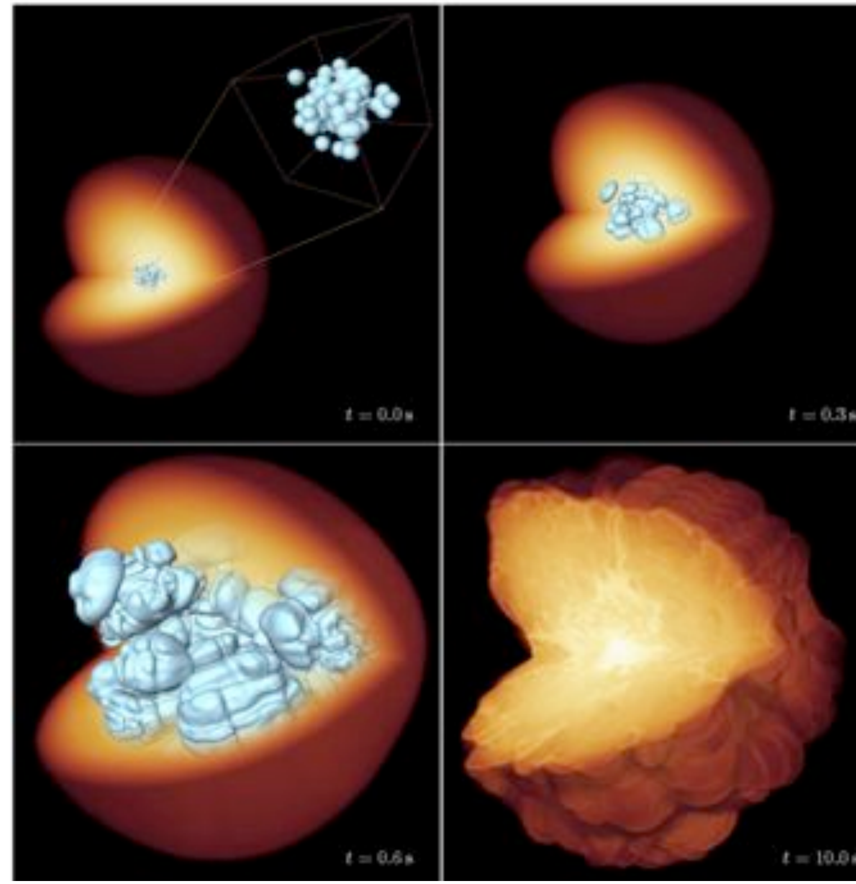


Explosion preceded by about a century of convection. The convection is asymmetric

The Explosion - Burning and Propagation

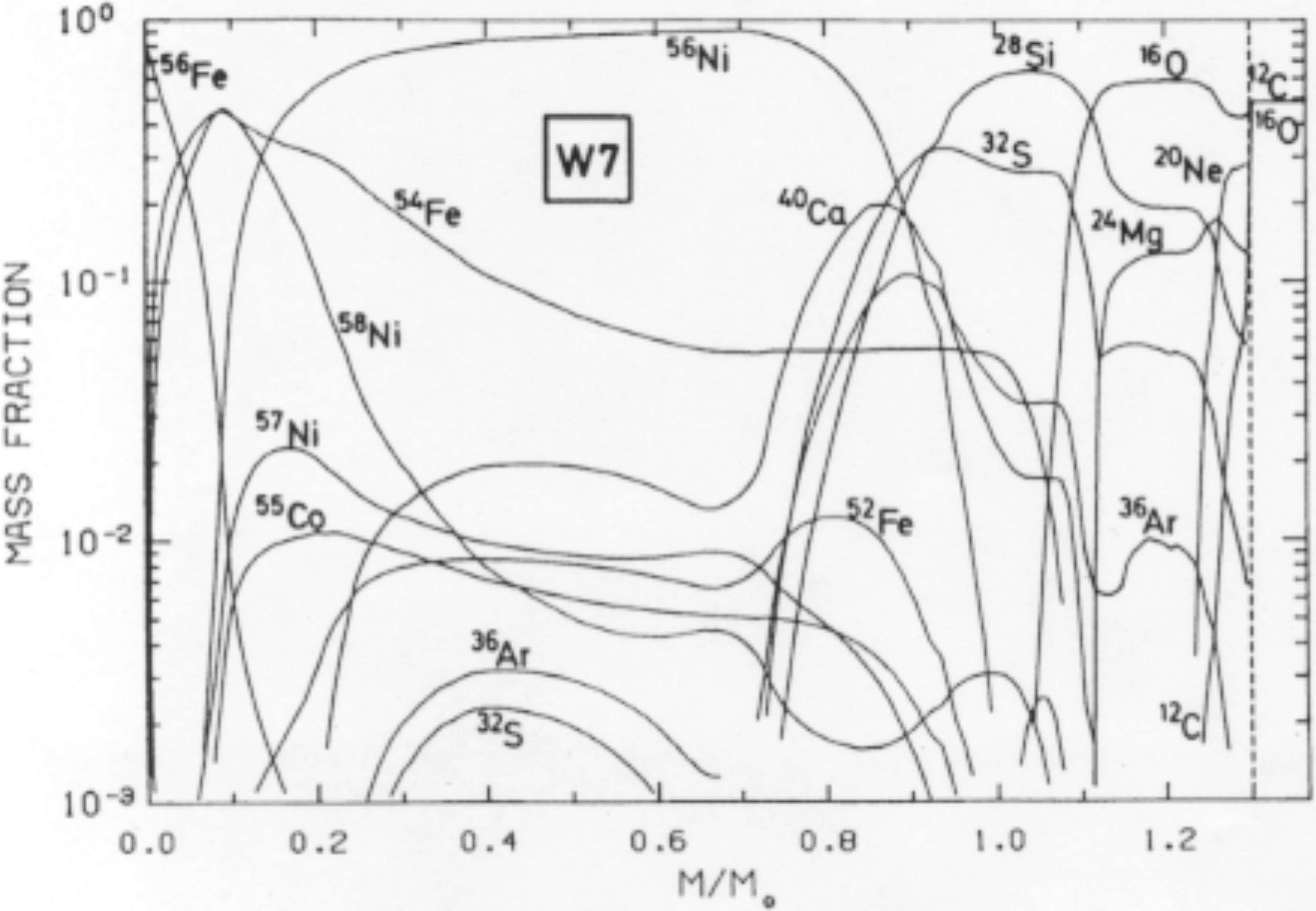


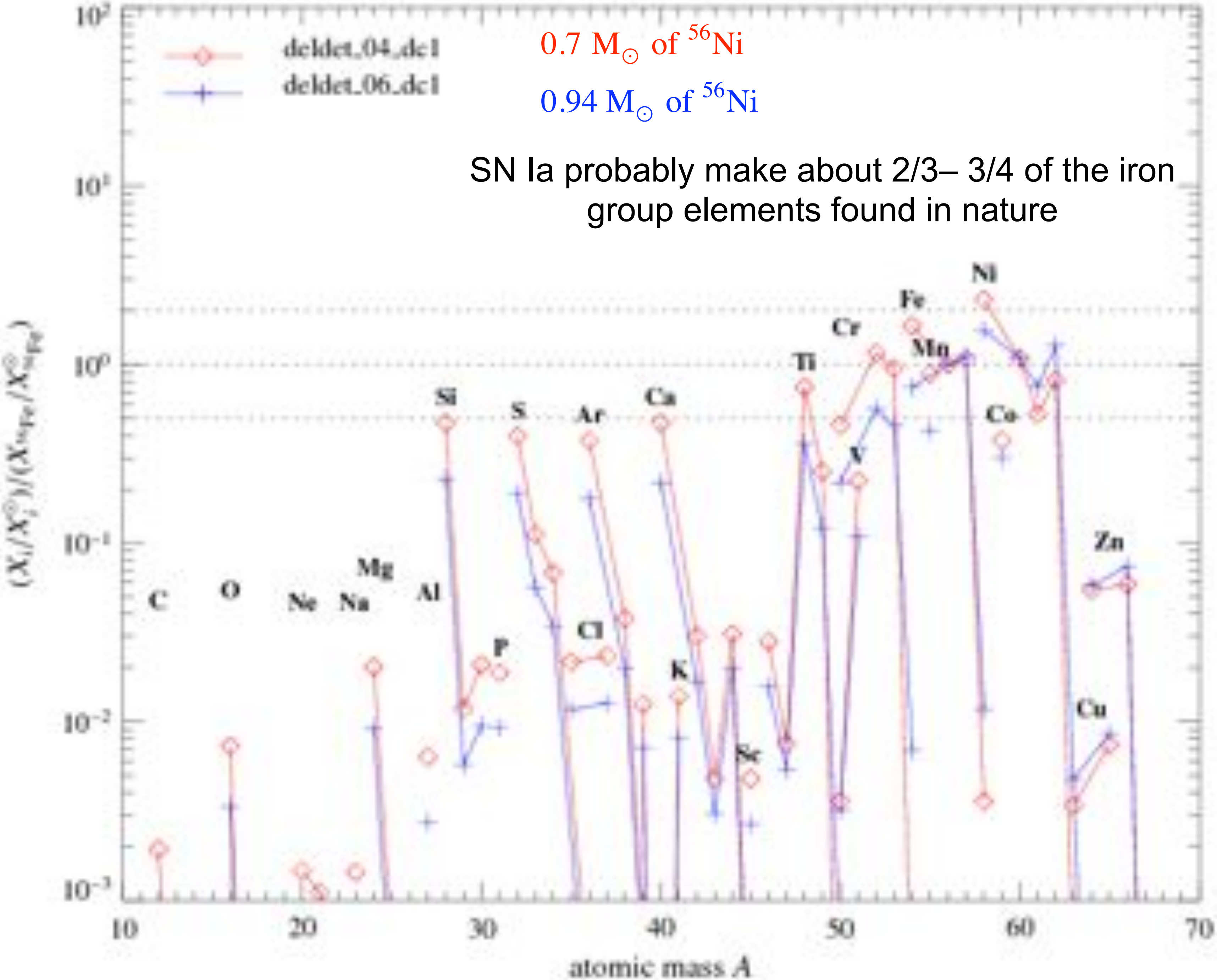
Zingale et al. (2005)



Roepke and Hillebrandt (2007)

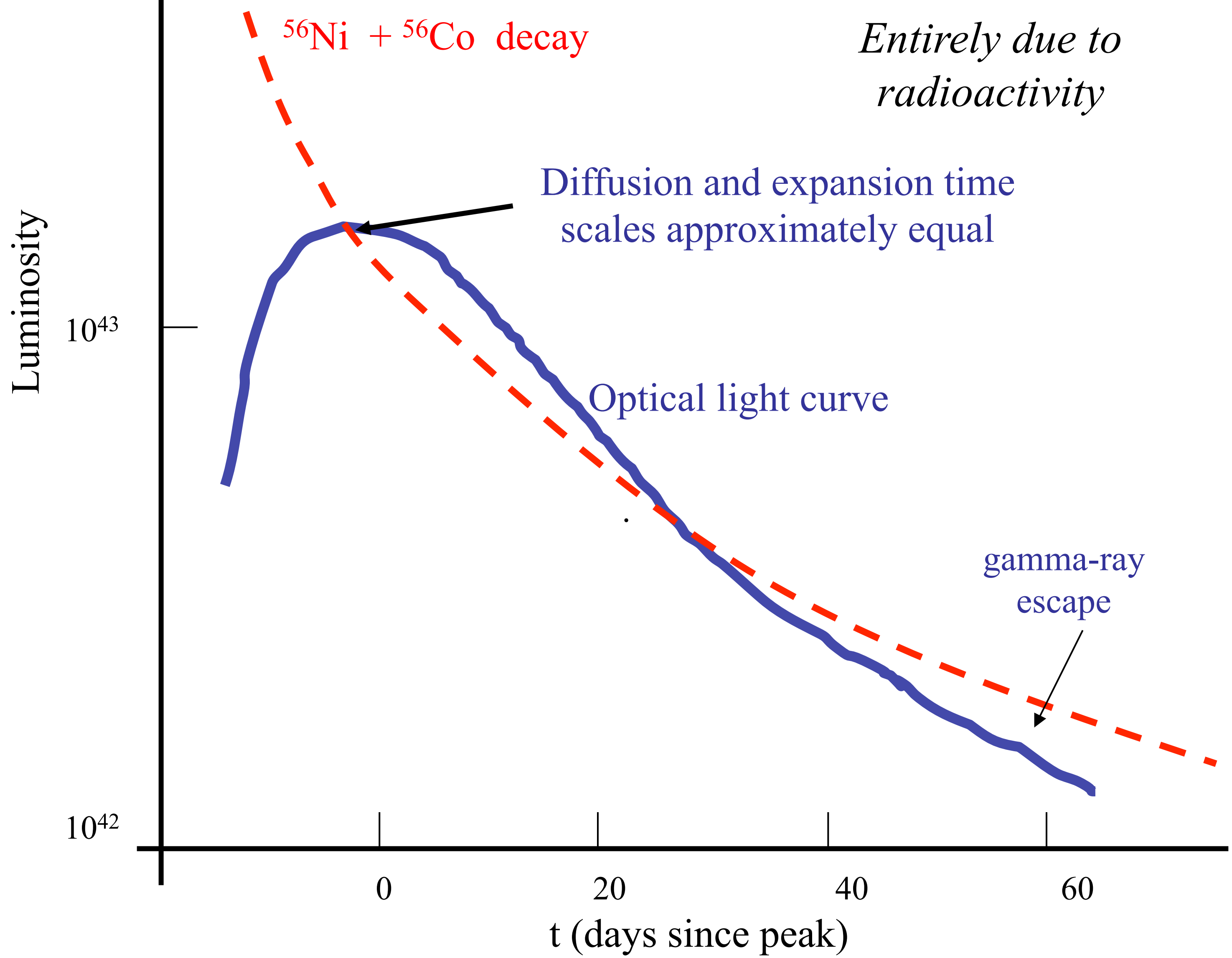

Size (km) : 5342.16
Time (s) : 0.0120128


W7
56Fe
56Ni
28Si
16O
12C
16O
20Ne
32S
40Ca
54Fe
24Mg
58Ni
57Ni
55Co
52Fe
36Ar
36Ar
32S
12C
MASS FRACTION
10^0
10^-1
10^-2
10^-3
0.0
0.2
0.4
0.6
0.8
1.0
1.2
M/M⊙



deldet_04_dc1
deldet_06_dc1
0.7 M☉ of 56Ni
0.94 M☉ of 56Ni
SN Ia probably make about 2/3– 3/4 of the iron group elements found in nature
C
O
Ne
Na
Mg
Al
Si
P
S
Cl
Ar
K
Ca
Sc
Ti
V
Cr
Mn
Fe
Co
Ni
Cu
Zn
10
20
30
40
50
60
70
atomic mass A

Qualitative Type Ia Supernova Light Curve



Radioactivity

$$^{56}\mathrm{Ni} + \mathrm{e}^- \rightarrow {}^{56}\mathrm{Co} + \nu \qquad \tau_{1/2} = 6.1\ \mathrm{days}$$

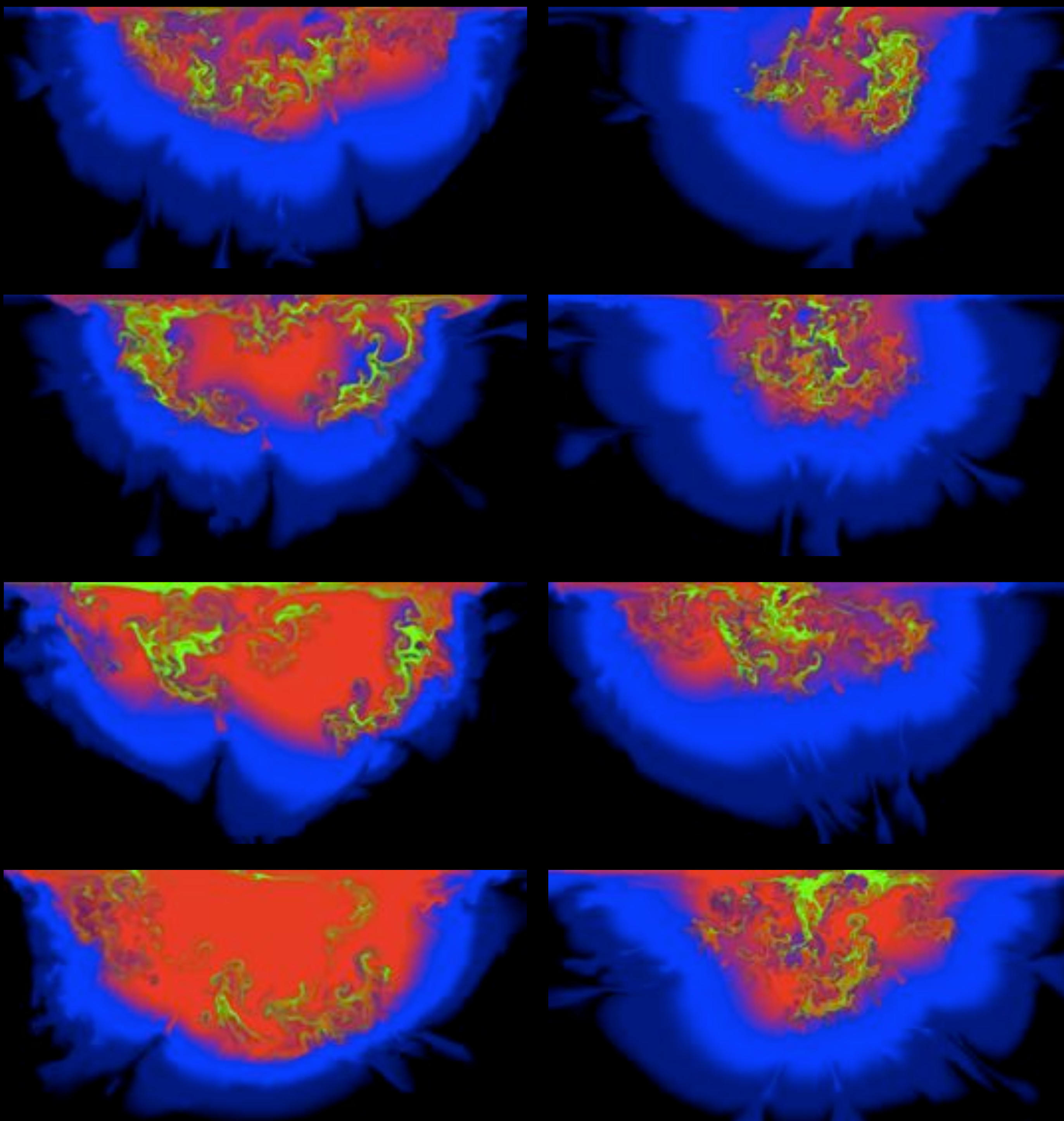
q = 3.0 x 10^{16} erg/gm

$$^{56}\mathrm{Co} + \mathrm{e}^- \rightarrow {}^{56}\mathrm{Fe} + \nu \qquad \tau_{1/2} = 77.1\ \mathrm{days}$$

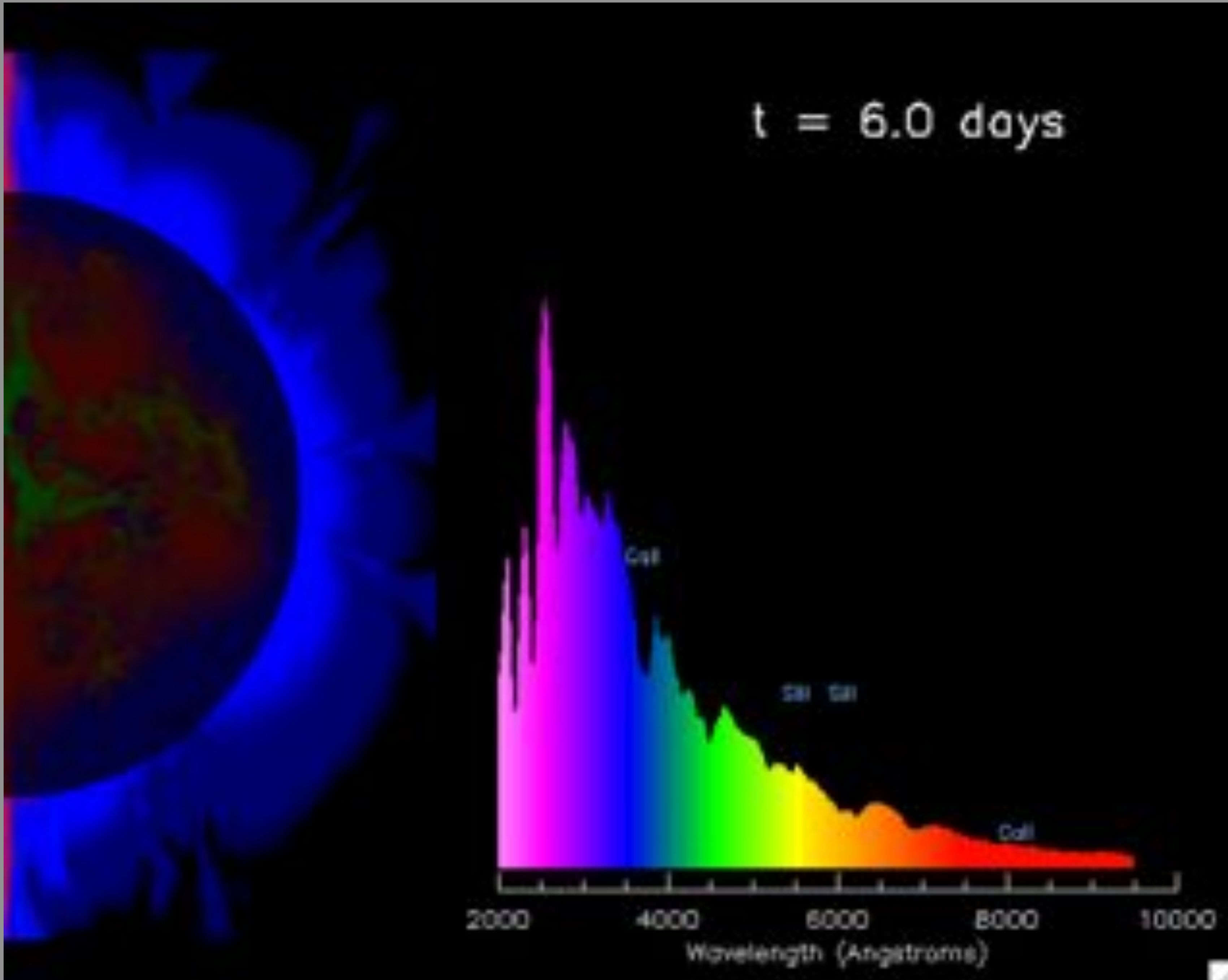
q = 6.4 x 10^{16} erg/gm

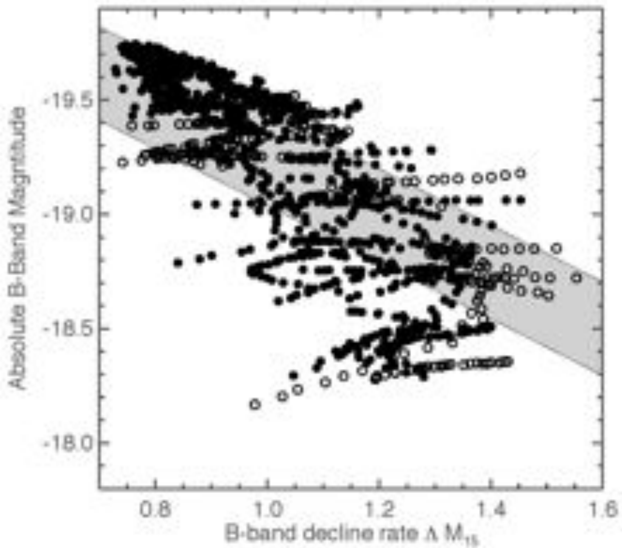
0.6 solar masses of radioactive Ni and Co can thus provide 1.1 x 10^{50} erg at late times after adiabatic expansion is essentially over.

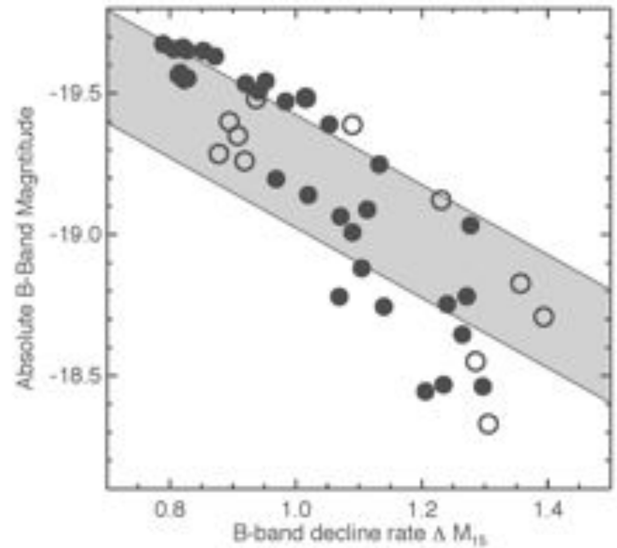
strong deflagration
weak detonation



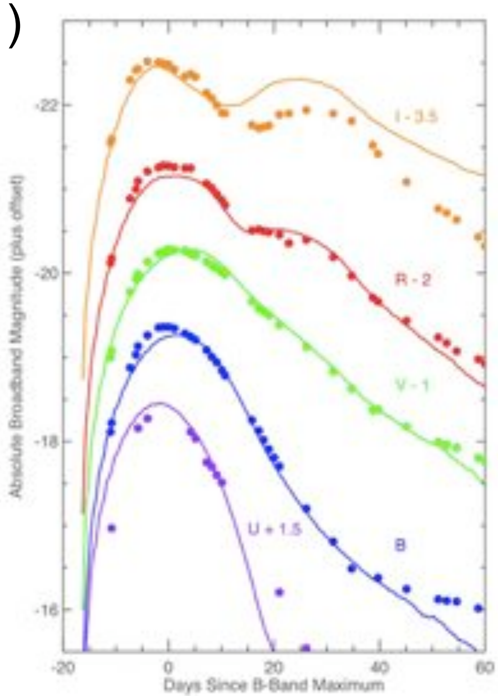
weak deflagration
strong detonation

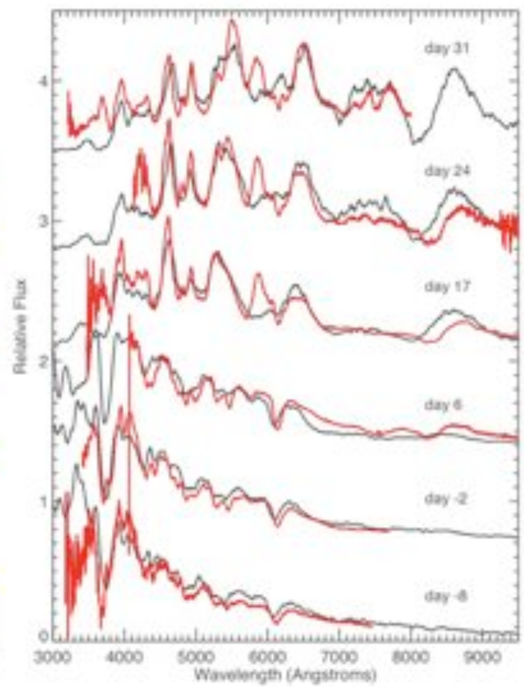

t = 6.0 days
CaII
SiII SiII
CaII
2000
4000
6000
8000
10000
Wavelength (Angstroms)





Kasen, Roepke,
and Woosley (2011)





SN 2003 du
vs
Model

Supernova - Summary

Type Ia

- No hydrogen
- Thermonuclear explosion of a white dwarf star
- No bound remnant
- $\sim 10^{51}$ erg kinetic energy
- $v \sim 5{,}000 - 30{,}000$ km s^{-1}
- No neutrino burst
- $E_{optical} \sim 10^{49}$ erg
- $L_{peak} \sim 10^{43}$ erg s^{-1} for 2 weeks
- Radioactive peak and tail (^{56}Ni, ^{56}Co)
- 1/200 yr in our Galaxy
- Makes about 2/3 of the iron in the Galaxy

Type II

- Hydrogen in spectrum
- $M > 8$ solar masses
- Iron core collapses to a neutron star or black hole
- $\sim 10^{51}$ erg kinetic energy
- $v \sim 2{,}000 - 30{,}000$ km s^{-1}
- Neutrino burst $\sim 3 \times 10^{53}$ erg
- $E_{optical} \sim 10^{49}$ erg
- $L_{peak} \sim 3 \times 10^{42}$ erg s^{-1} for about 3 months (varies from event to event)
- Radioactive tail (^{56}Co)
- 2/100 yr in our Galaxy
- Makes about 1/3 iron and all the oxygen plus many other elements

There are also Type Ib and Ic supernovae that share many of the properties of Type II but have no hydrogen in their spectra

Supernovae - Statistics

- There have been 6 supernovae visible to the unaided eye in the last 1000 years. The last one before SN 1987A was Kepler's supernova in 1604. This was about 2.5 kpc away and reached a magnitude of -2.5. The brightest supernova in history was SN 1006 which reached magnitude -8 to -10, as bright a a quarter moon.

- About two Type II supernovae are thought to occur in our galaxy every century and about one Type Ia every other century. Most have gone undetected.

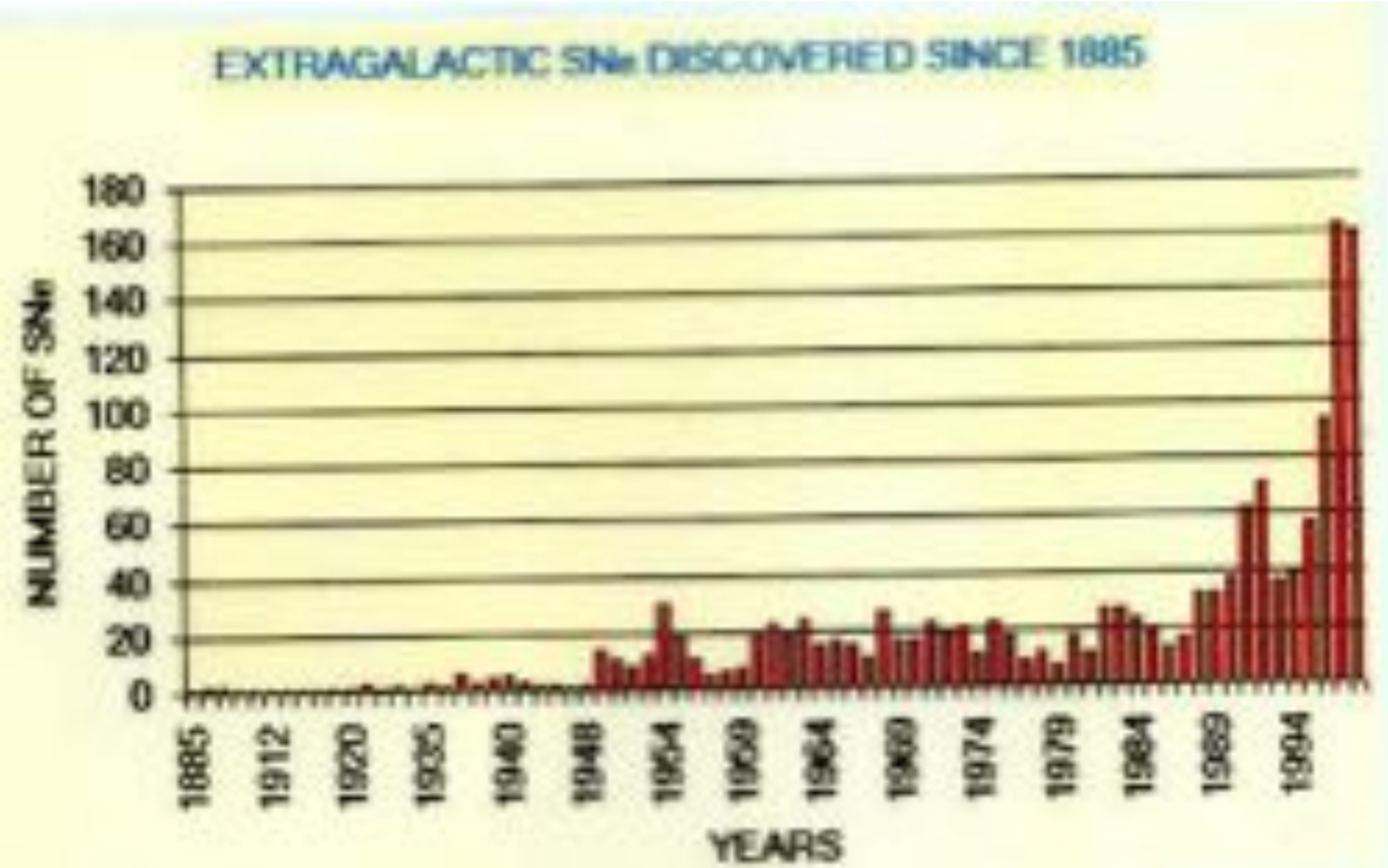
- We see many more supernovae – hundreds each year – in other galaxies

Year	Report	Status
185 A.D.	Chinese	Identification in doubt (Chin and Huang 1994)
386	Chinese	unknown
393	Chinese	unknown
1006	China, Japan, Korea, Arab lands, Europe	Identified with radio SNR
1054	China, Japan	Crab Nebula
1181	China, Japan	Possible identification with radio SNR 3C58
1572	Europe (Tycho Brahe), China, Japan	Tycho's remnant
1604	Europe (Kepler), China, Japan, Korea	Kepler's remnant

Historical Supernovae*

Explosion Date (AD)	Maximum Apparent Visual Magnitude, V (mag)	Time Visible to Unaided Eye (months)	Galactic Coordinates	Remnant Name	Distance (kpc)	Remnant Diameter (pc)
185	−8.0	20	G 315.4−02.3	RCW 86	3.	35.0
386**	+1.5	3	G 11.2−00.3		≥ 5.	≥ 6.0
393	0.0	8	G 348.5+00.1	CTB 37A	10.4	24.0
			or G 348.7+00.3	CTB 37B	10.4	24.0
1006	−9.5	> 24	G 327.6+14.6	PKS 1459−41	1.0	8.8
1054	−5.0	22	G 184.6−05.8	Crab Nebula, 3C 144	2.0	2.9
1181	0.0	6	G 130.7+03.1	3C 58	2.6	5.3
1572	−4.0	16	G 120.1+01.4	Tycho, 3C 10	2.3	5.4
1604	−3.0	12	G 4.5+06.8	Kepler, 3C 358	4.4	3.8

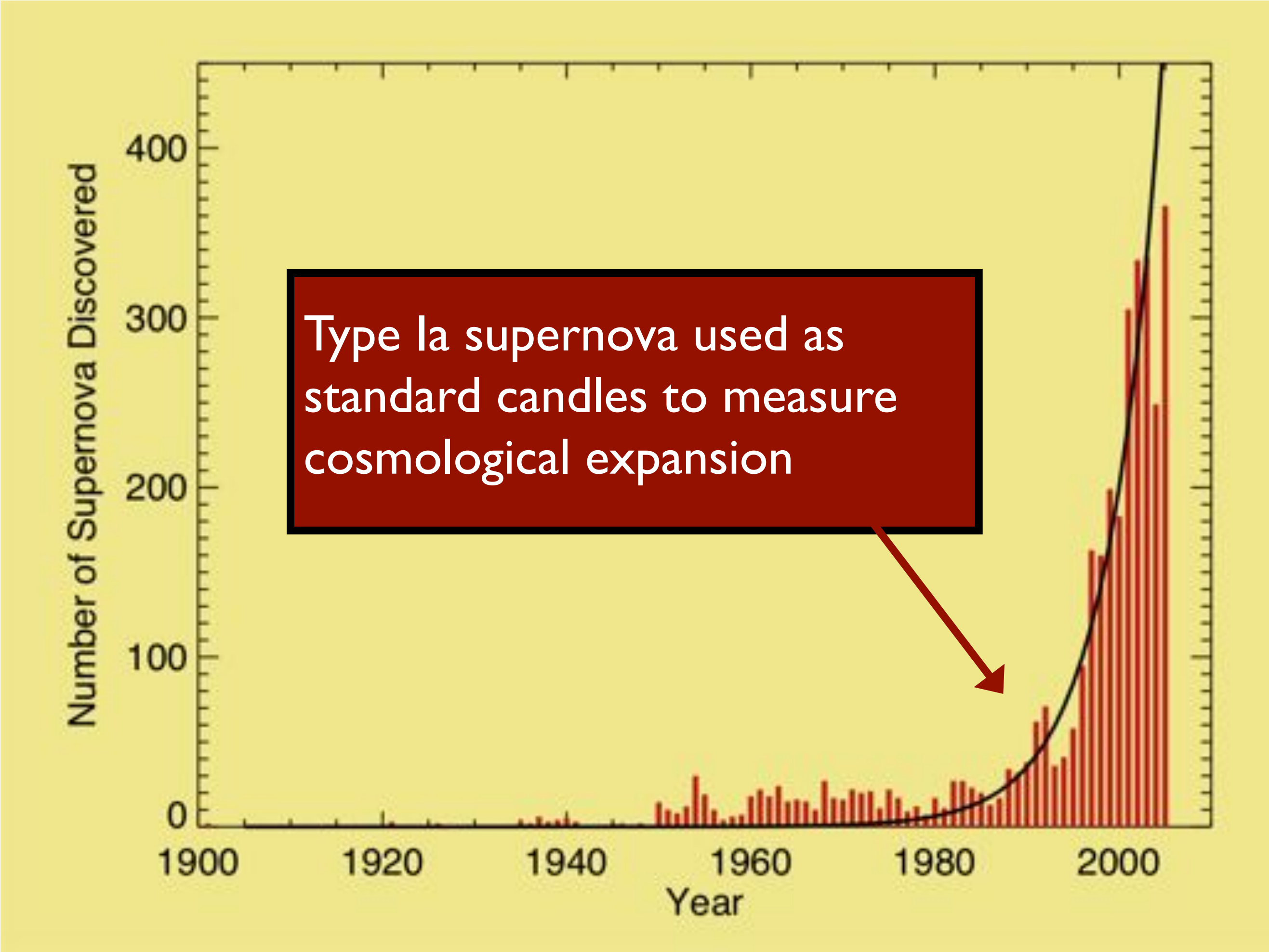
1680 Casseopeia-A



EXTRAGALACTIC SNe DISCOVERED SINCE 1885
NUMBER OF SNe
180
160
140
120
100
80
60
40
20
0
1885
1912
1920
1935
1940
1948
1954
1959
1964
1969
1974
1979
1984
1989
1994
YEARS

Supernova Discovery History

Asiago Catalog (all supernova types)



Supernova Discovery Future

Rough predictions and promises…