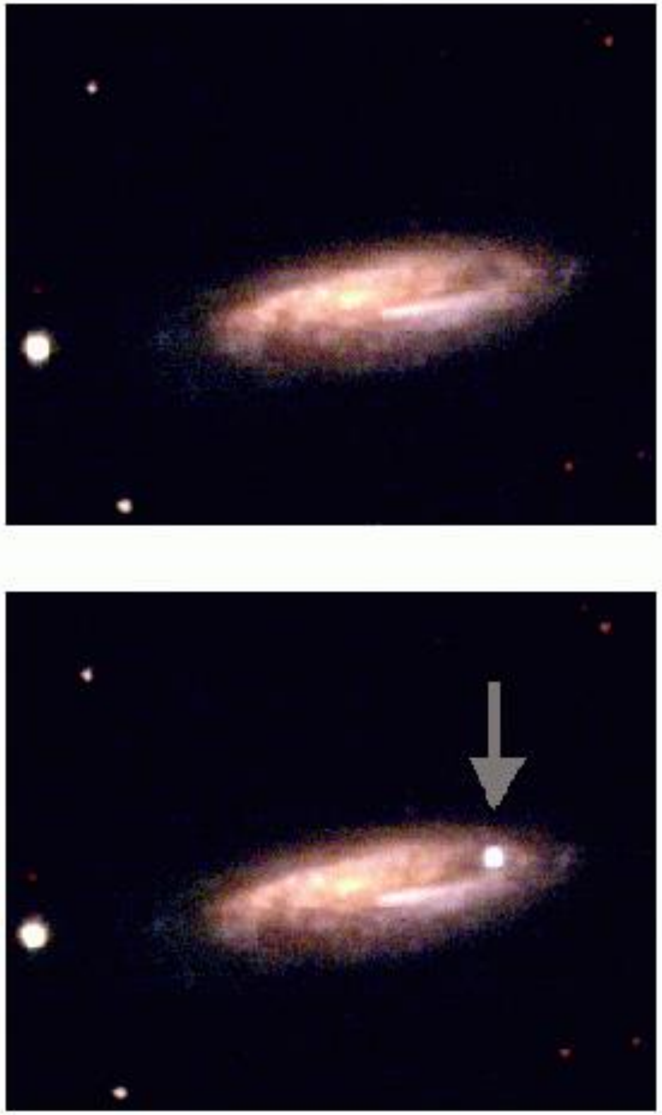
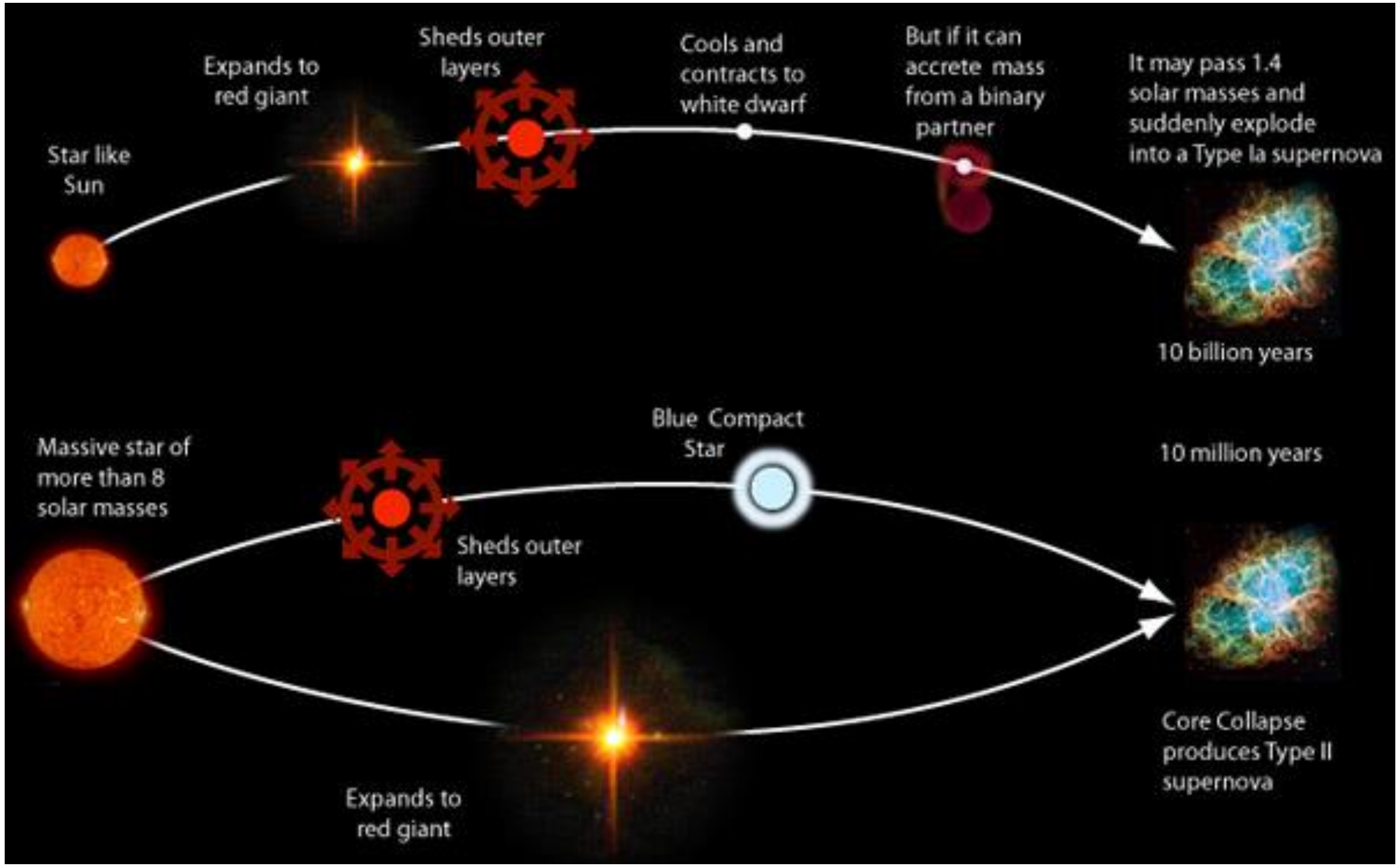
Supernovae



Possible evolutionary paths

- Core collapse
- Thermonuclear runaway



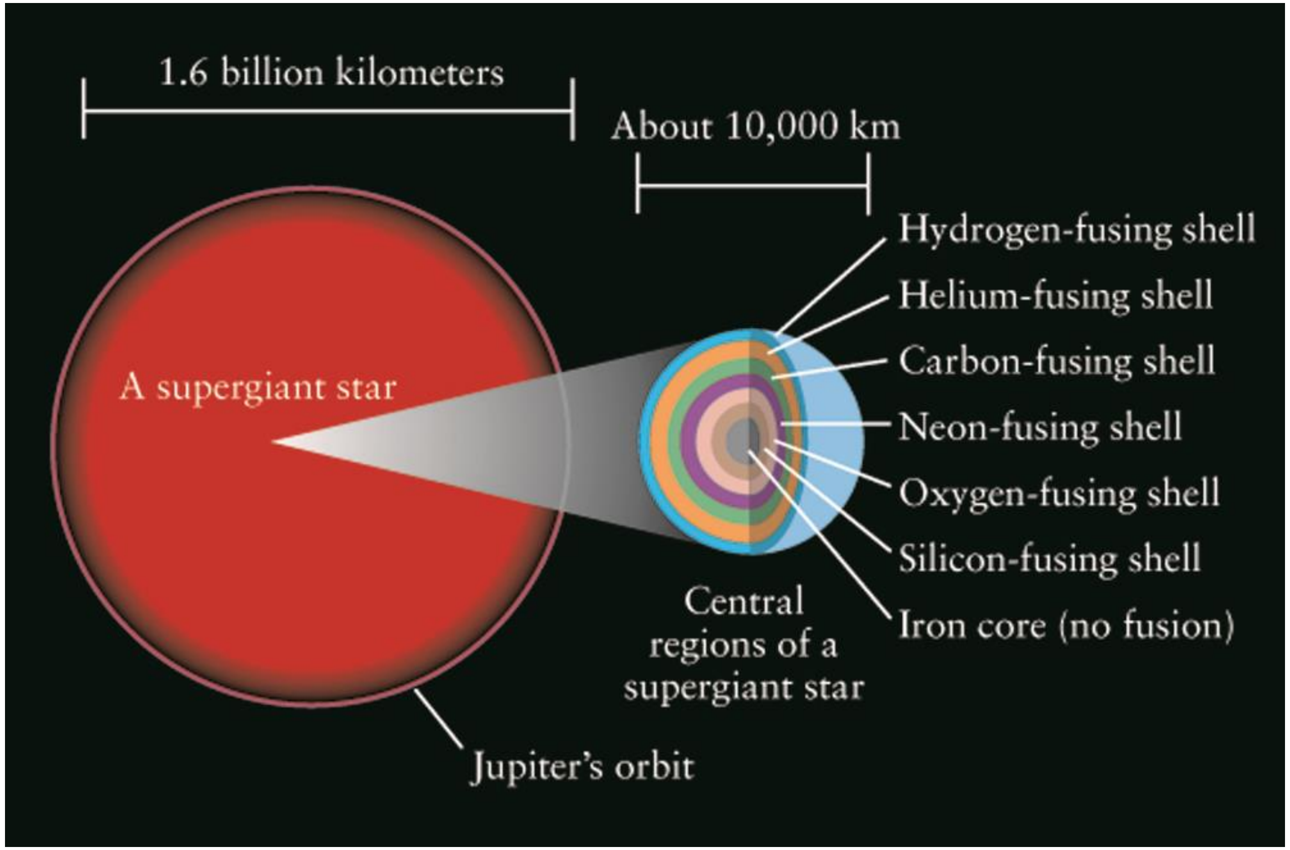
http://hyperphysics.phy-astr.gsu.edu/hbase/astro/snovcn.html

Evolution of an Intermediate-mass (8 to 25 $M_\odot$) or High-mass ($>$25 $M_\odot$) Star

☐ Core size ~ Earth

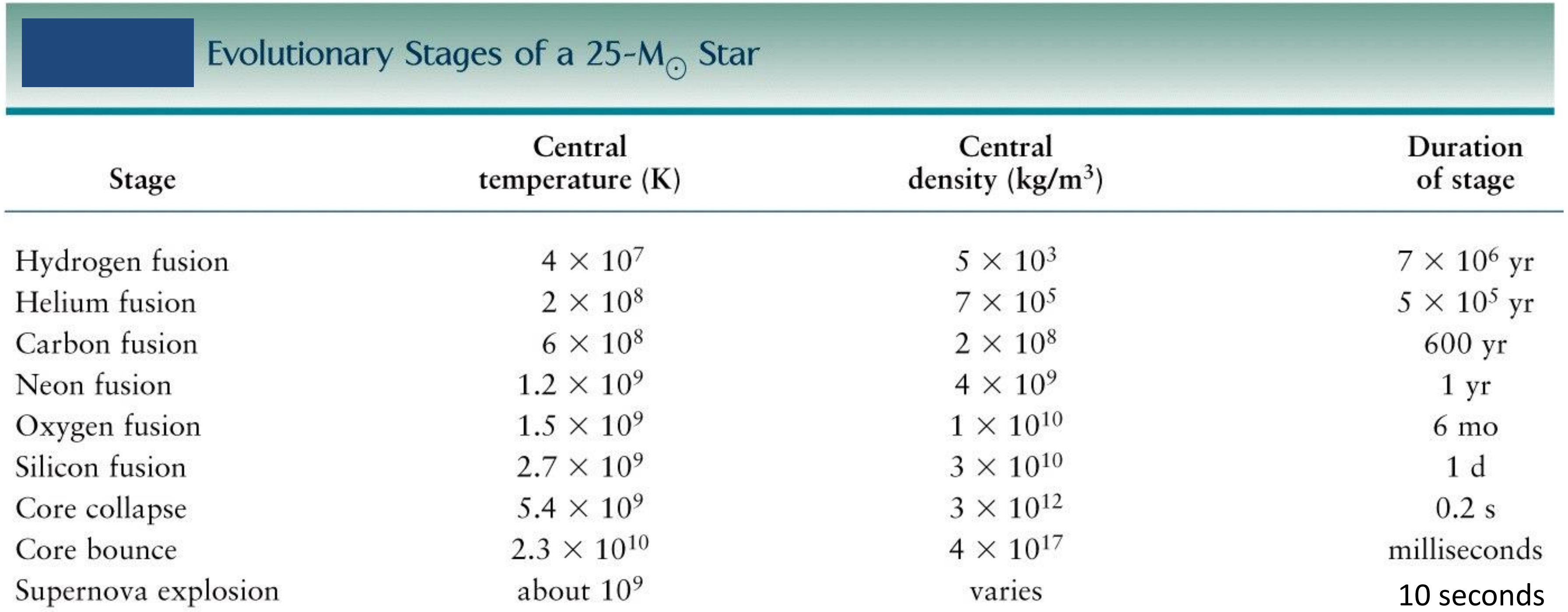
☐ Layers of nuclear reactions (cf an onion)

☐ Envelope as a supergiant, with the diameter comparable to the Jupiter's orbit



Each subsequent reaction proceeds ever faster; silicon → iron

An iron nucleus most compact between protons and neutrons
→ further fusion does not release energy
➔ iron core collapses (D∼3000 km, collapses in 0.1 s)



Evolutionary Stages of a $25\text{-}M_\odot$ Star

Stage	Central temperature (K)	Central density (kg/m^3)	Duration of stage
Hydrogen fusion	4×10^7	5×10^3	7×10^6 yr
Helium fusion	2×10^8	7×10^5	5×10^5 yr
Carbon fusion	6×10^8	2×10^8	600 yr
Neon fusion	1.2×10^9	4×10^9	1 yr
Oxygen fusion	1.5×10^9	1×10^{10}	6 mo
Silicon fusion	2.7×10^9	3×10^{10}	1 d
Core collapse	5.4×10^9	3×10^{12}	0.2 s
Core bounce	2.3×10^{10}	4×10^{17}	milliseconds
Supernova explosion	about 10^9	varies	10 seconds

Iron core collapse → 5 billion K → **photodisintegration** by energetic gamma rays

The star spends millions of years on the main sequence, synthesizing simple nuclei such as H and He to iron, then takes less than a second to disintegrate back to protons, neutrons and electrons.

Density of the core ↗↗, reaching 4×10^{17} kg/m^3 (cf density of a nucleus) in < 1 s → even the electron degenerate pressure cannot support the core → $e^- + \ p^+ \rightarrow \ n^o + \nu$

Core supported by neutron degenerate pressure
→ **neutron star**

Core bounces → **supernova explosion** + **supernova remnant**

Evolution of A Binary System

- Both stars of a few solar masses
- More massive component → RG → transfers and loses mass → a hot WD
- Secondary → RG → fills the Roche lobe → transfers mass to the hot WD via an accreting disk
- Accreted material compressed and heated, and if $T > 10^7$ K → CNO takes place at the base of the accreted layer (even with a thermonuclear runaway if the material is degenerate

➔A nova explosion

If accretion onto a C-O WD → core mass > M_{Ch}=1.4 $M_\odot$
→ Catastrophic collapse + C burning ➔ a Type Ia supernova

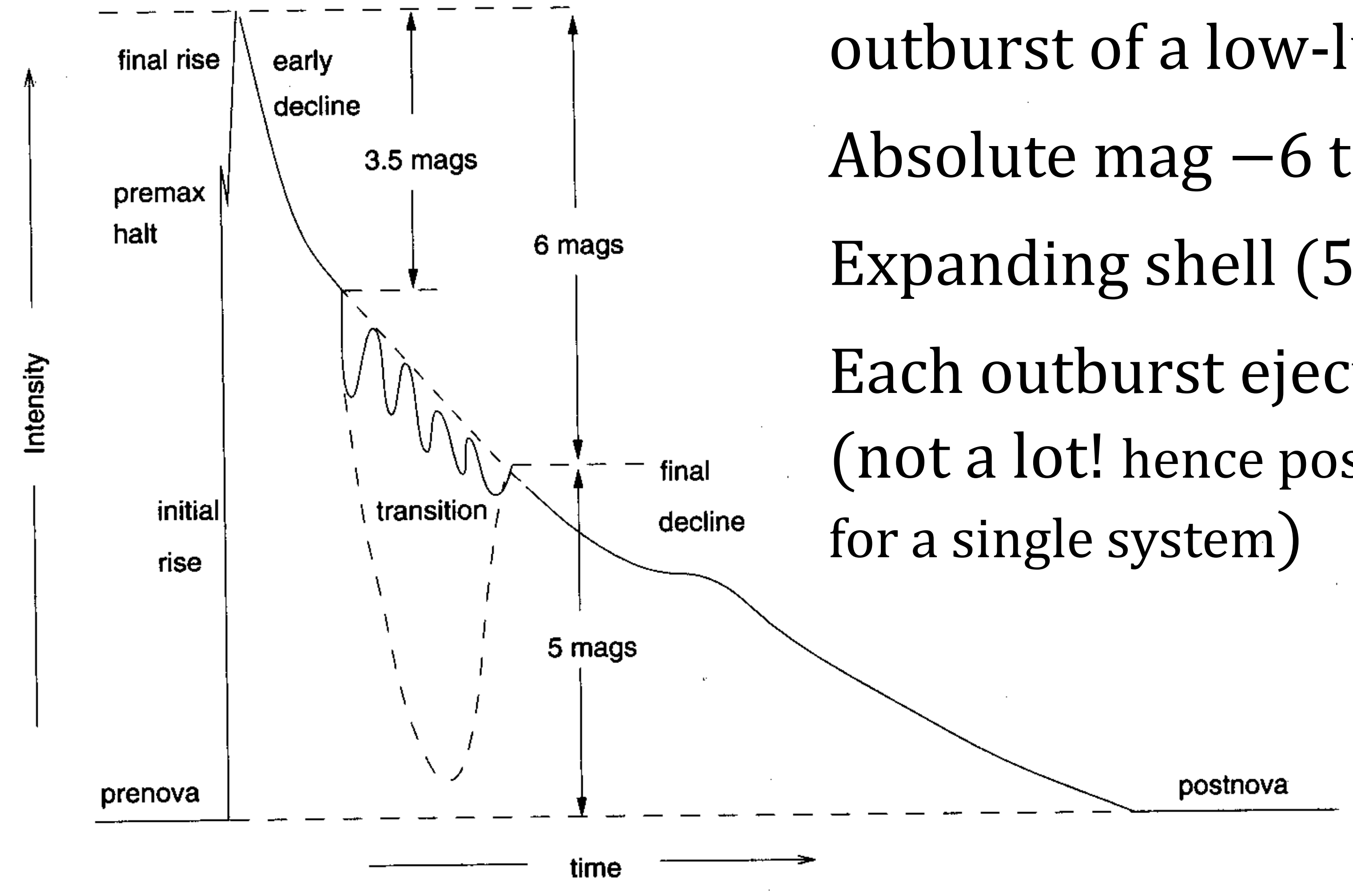


Fig. 7.10. Schematic light curve for a typical nova; the time axis is arbitrary and not to scale.

"A nova is a transient, possibly recurring, outburst of a low-luminosity star."

Absolute mag -6 to -9

Expanding shell $(500-2000)$ km/s

Each outburst ejects $10^{-4}-10^{-6}\ \mathrm{M}_{\odot}$ (not a lot! hence possible recurrent events for a single system)

Padmanabhan II

Accreting Binary Systems

A semi-detached binary system with the primary being a WD: (in increasing L)

- ✓ **dwarf nova**
- ✓ **classical nova**
- ✓ **type Ia supernova**

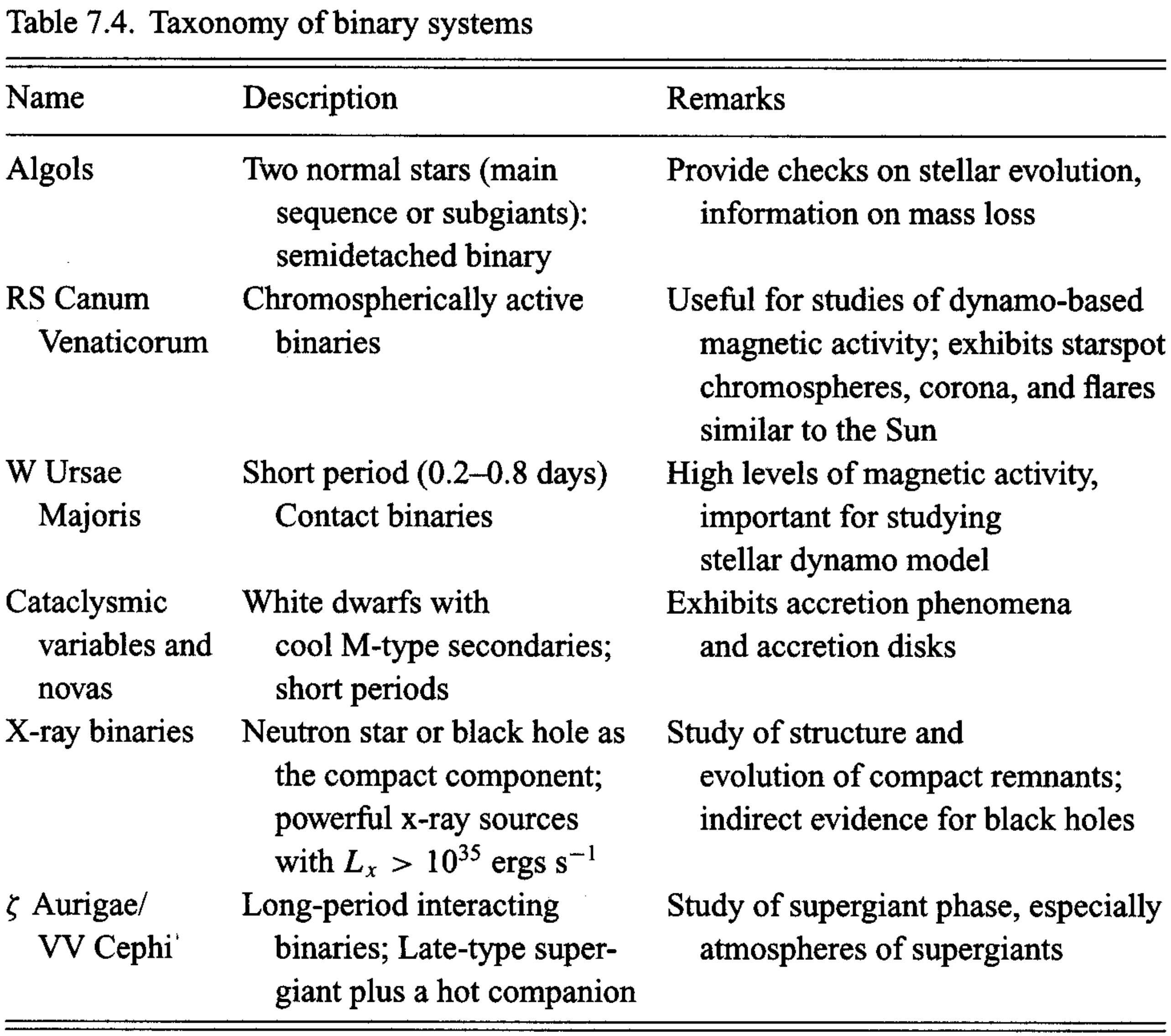
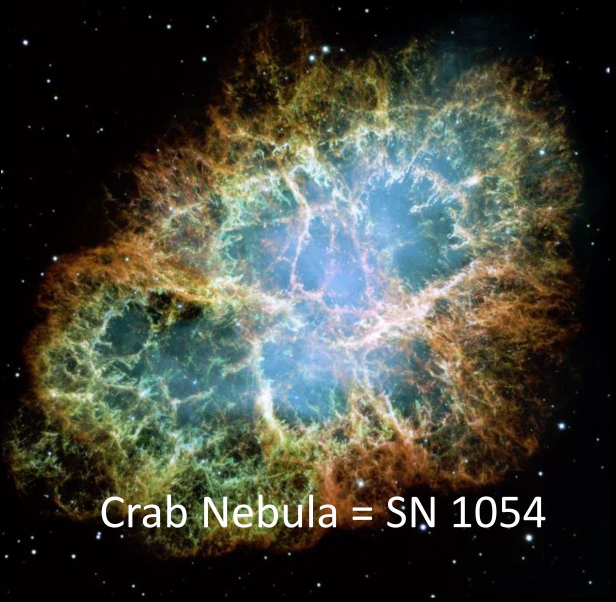
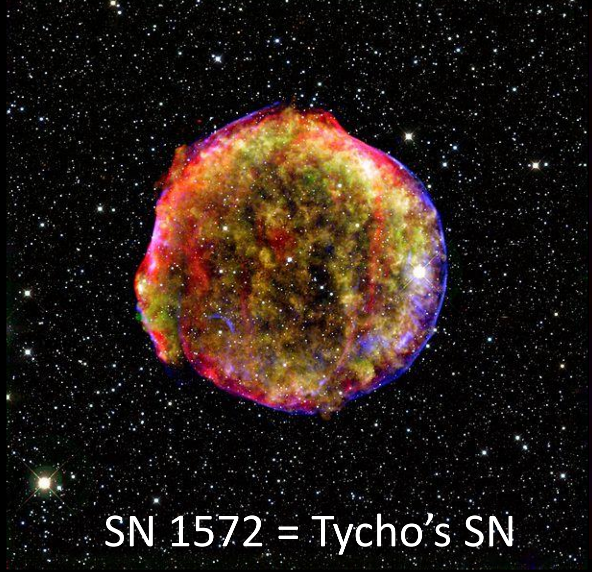


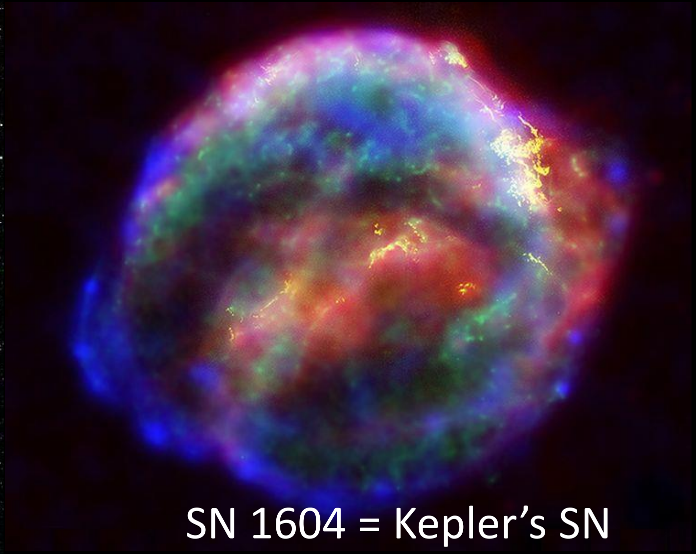
Table 7.4. Taxonomy of binary systems

Name	Description	Remarks
Algols	Two normal stars (main sequence or subgiants): semidetached binary	Provide checks on stellar evolution, information on mass loss
RS Canum Venaticorum	Chromospherically active binaries	Useful for studies of dynamo-based magnetic activity; exhibits starspot chromospheres, corona, and flares similar to the Sun
W Ursae Majoris	Short period (0.2–0.8 days) Contact binaries	High levels of magnetic activity, important for studying stellar dynamo model
Cataclysmic variables and novas	White dwarfs with cool M-type secondaries; short periods	Exhibits accretion phenomena and accretion disks
X-ray binaries	Neutron star or black hole as the compact component; powerful x-ray sources with $L_x > 10^{35}$ ergs s^{-1}	Study of structure and evolution of compact remnants; indirect evidence for black holes
ζ Aurigae/ VV Cephi	Long-period interacting binaries; Late-type supergiant plus a hot companion	Study of supergiant phase, especially atmospheres of supergiants

Padmanabhan II


Crab Nebula = SN 1054


SN 1572 = Tycho’s SN


SN 1604 = Kepler’s SN


N63A in LMC


W49B SNR

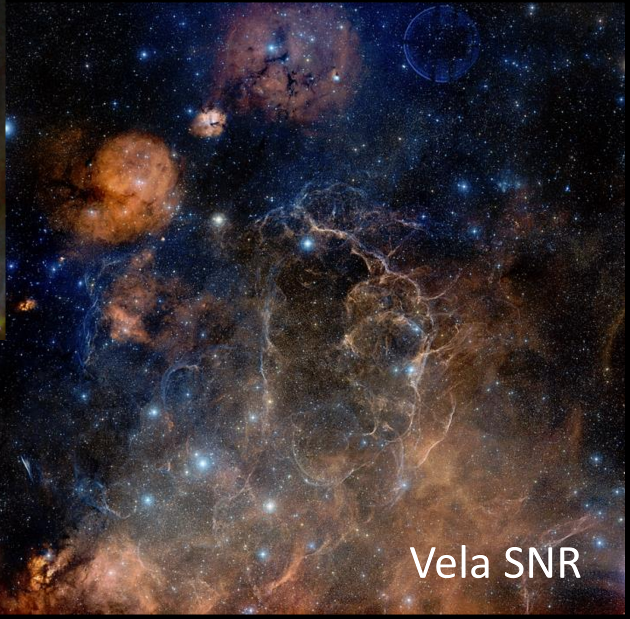
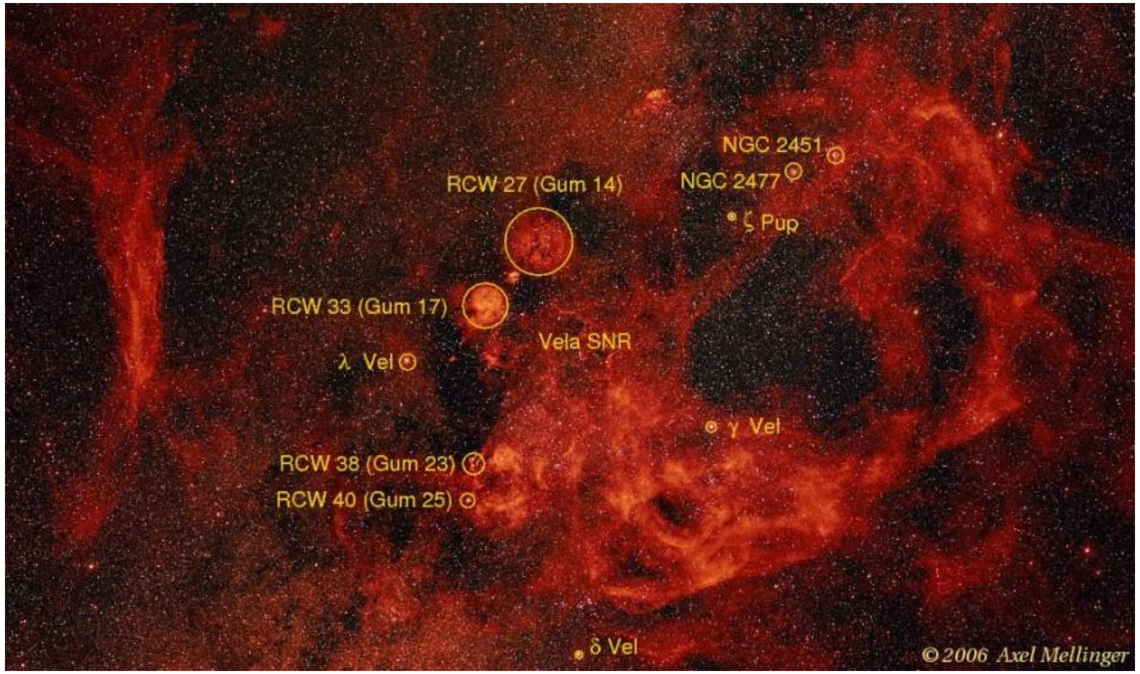

Vela SNR

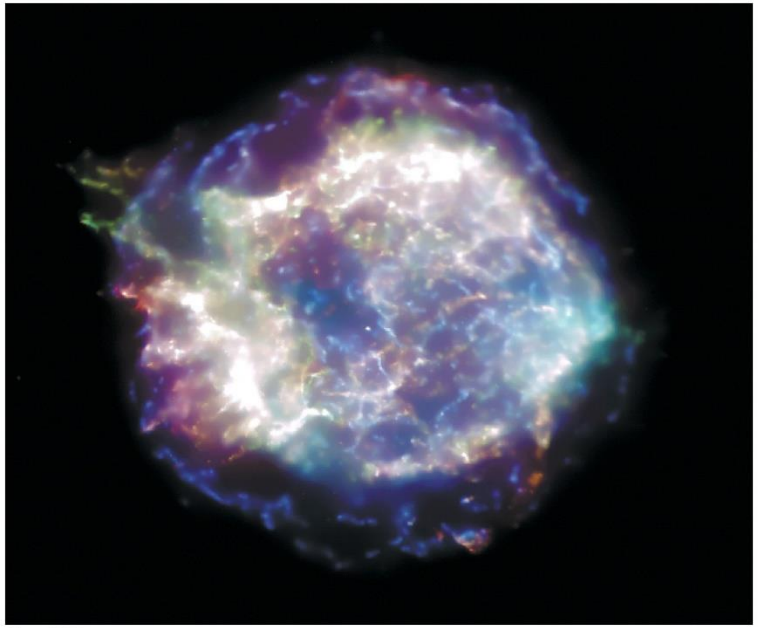
Figure 13-11
Discovering the Universe, Seventh Ed
© 2006 W. H. Freeman and Company

Gum Nebula is the largest SNR in the sky, originated from a supernova explosion perhaps a Myr ago.

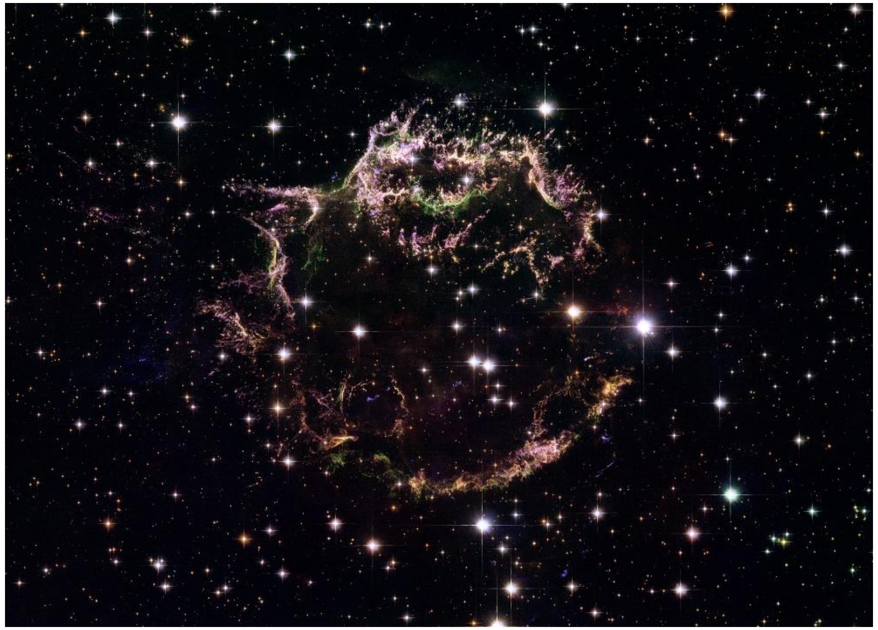


Gum Nebula has a angular extent > 40 deg → linear size more than 2300 ly across → The closest part from Earth ~300 ly

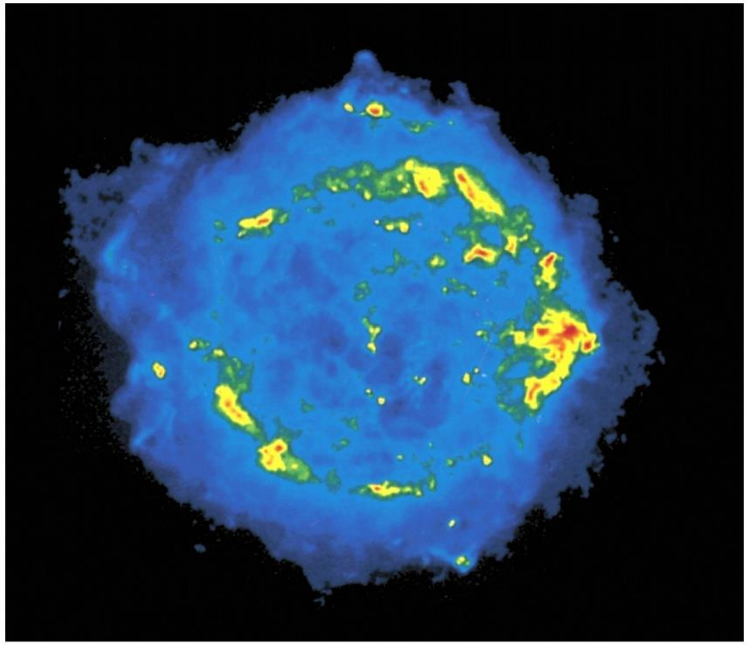
Cassiopeia A SNR is 3.4 kpc from us. The explosion should have been seen 300 years ago, but was not recorded.



X rays



Visible
(HST)

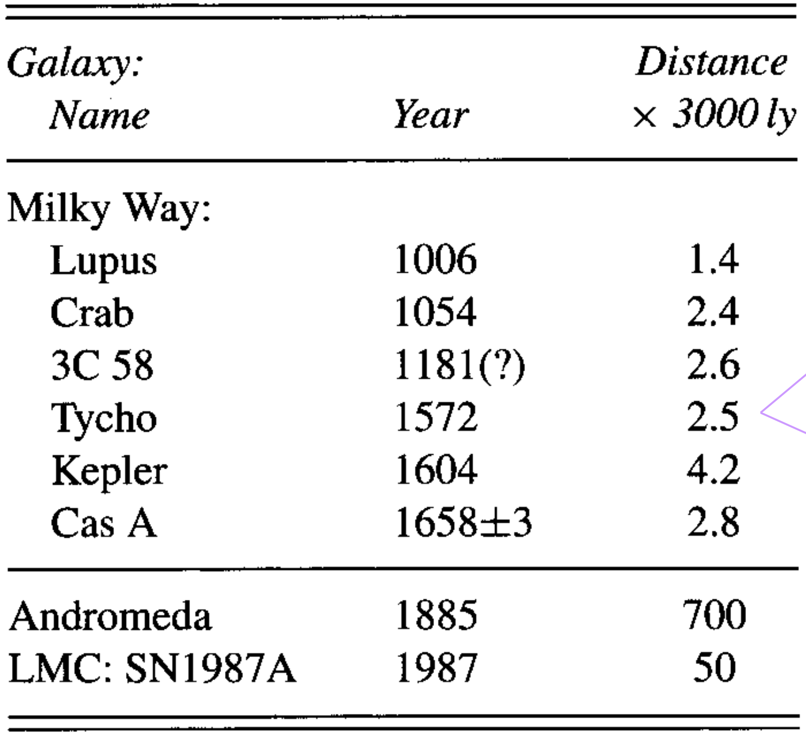


Radio

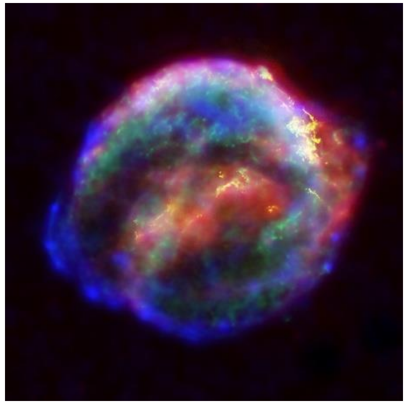
Supernovae in History

- OB association in Scorpius-Centaurus
  Solar system within 150 ly 2 Myr ago; should have experienced SN explosions

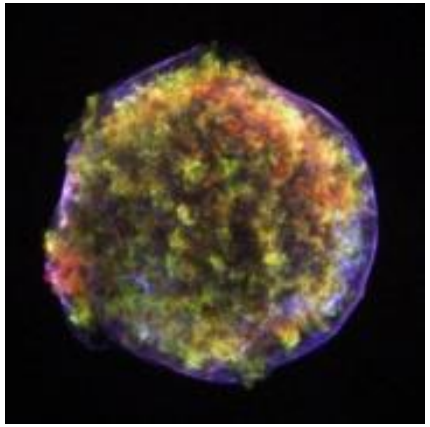
Table 10.1 Historical supernovae



Galaxy: *Name*	*Year*	*Distance* × *3000 ly*
Milky Way:		
Lupus	1006	1.4
Crab	1054	2.4
3C 58	1181(?)	2.6
Tycho	1572	2.5
Kepler	1604	4.2
Cas A	1658±3	2.8
Andromeda	1885	700
LMC: SN1987A	1987	50



Chandra SN1604



Chandra SN1572

Crab Nebula (in Taurus)

SN clearly recorded in AD1054 by Chinese astronomers
→ “Chinese supernova”

西元1054年七月（宋仁宗至和元年五月）金牛座超新星爆炸，據記載最明亮時相當於太白（金）星的光芒，長達23天在白天可見，直到1056年四月（宋嘉祐元年三月）肉眼才看不見。

天關客星

凡十一日没三年三月乙巳出東南方大中祥符四年正月丁丑見南斗魁前天禧五年四月丙辰出軒轅前星西北大如桃速行經軒轅大星入太微垣掩右執法犯次將歷屛星西北凡七十五日入濁没明道元年六月乙巳出東北方近濁有芒彗至丁巳凡十三日没至和元年五月己丑出天關東南可數寸歲餘稍没熙寧二年六月丙辰出箕度中至七月丁卯犯箕乃散三年十一月丁未出天囷元祐六年十一月辛亥出參度中犯掩側星壬子犯九游星十二月癸酉入奎至七年三月辛亥乃散紹興八年五月守婁

宋史志卷九

The Expanding Crab Nebula
1973 to 2001

SN 1987A

First observed 24 Feb, 1987

not quite SN II

preSN progenitor observed and sp. classified

Sanduleak -69 202

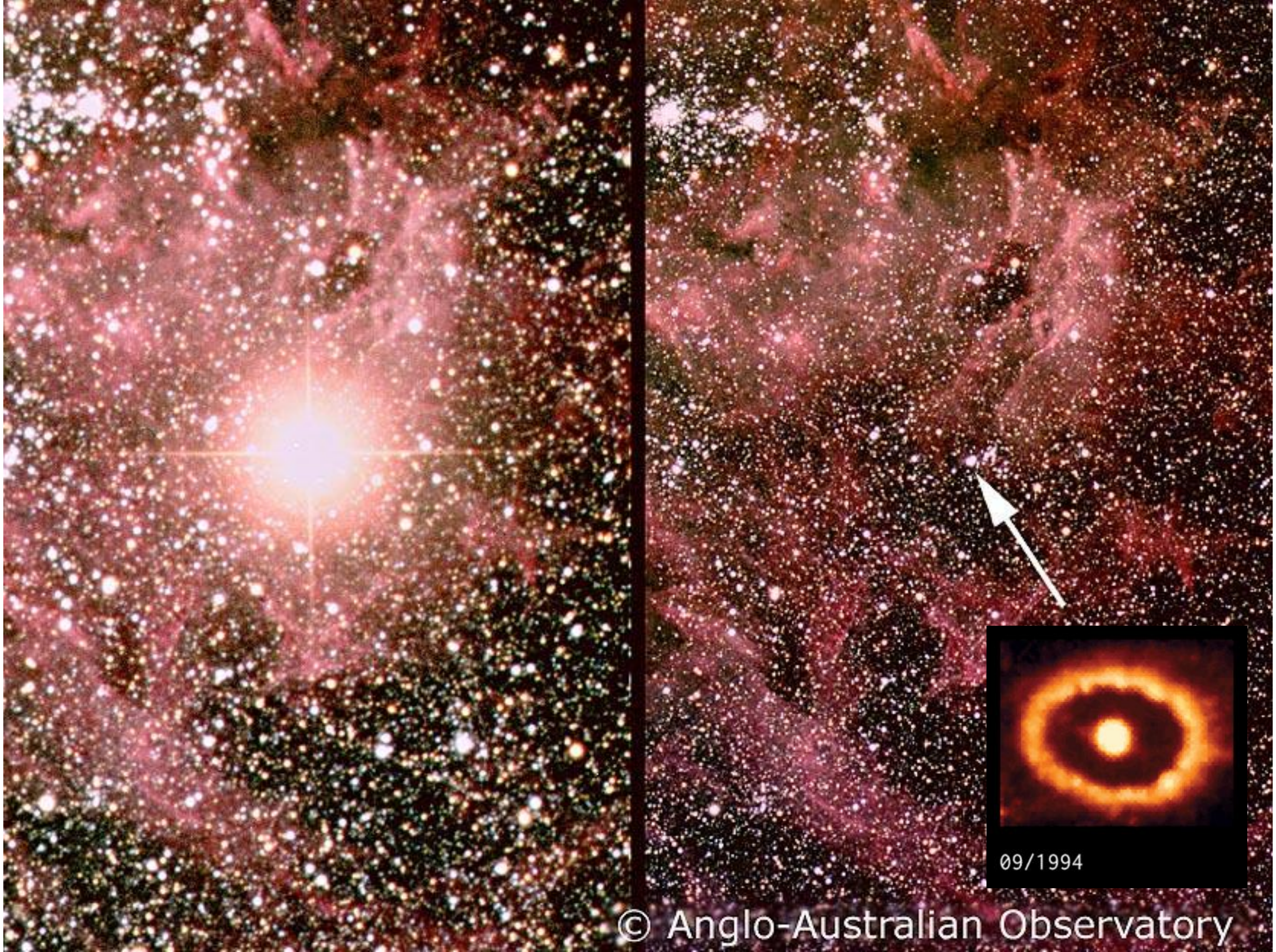
Sp: B 3 I

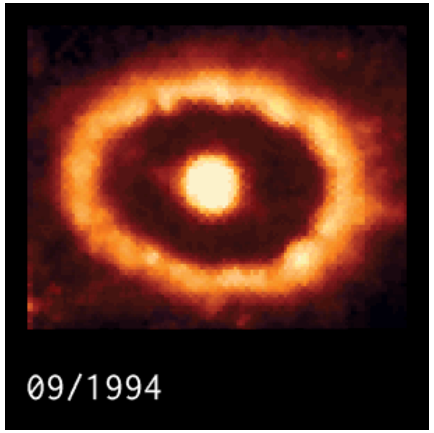
$L \sim 1.1 \times 10^5 L_\odot$; $T_{eff} \sim 16{,}000$ K

($M \sim 16\text{-}22\ M_\odot$)

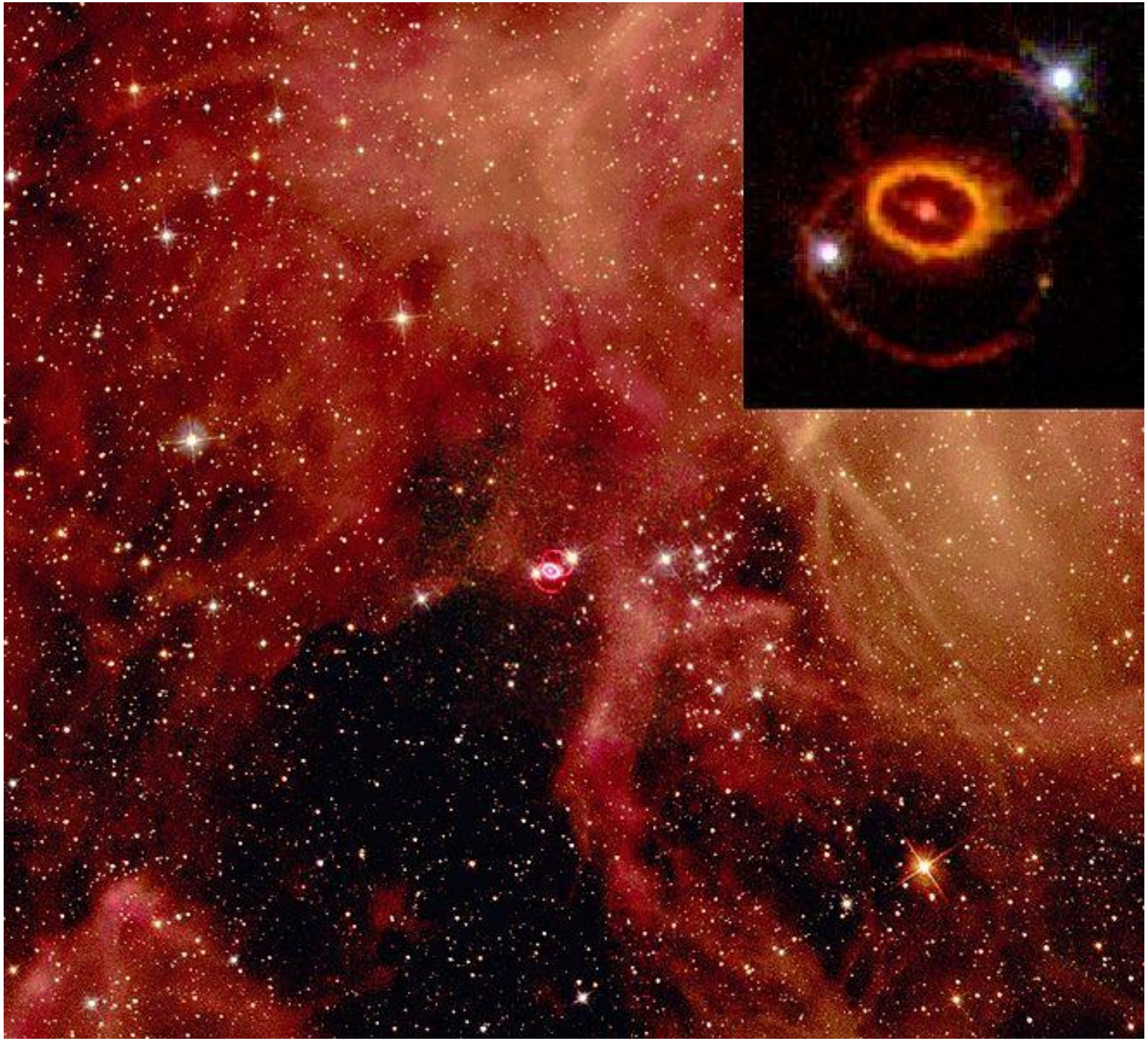
Pop I but metal-poor

Neutrino events (kamiokande) detected
hours before SN visible


09/1994



09/1994



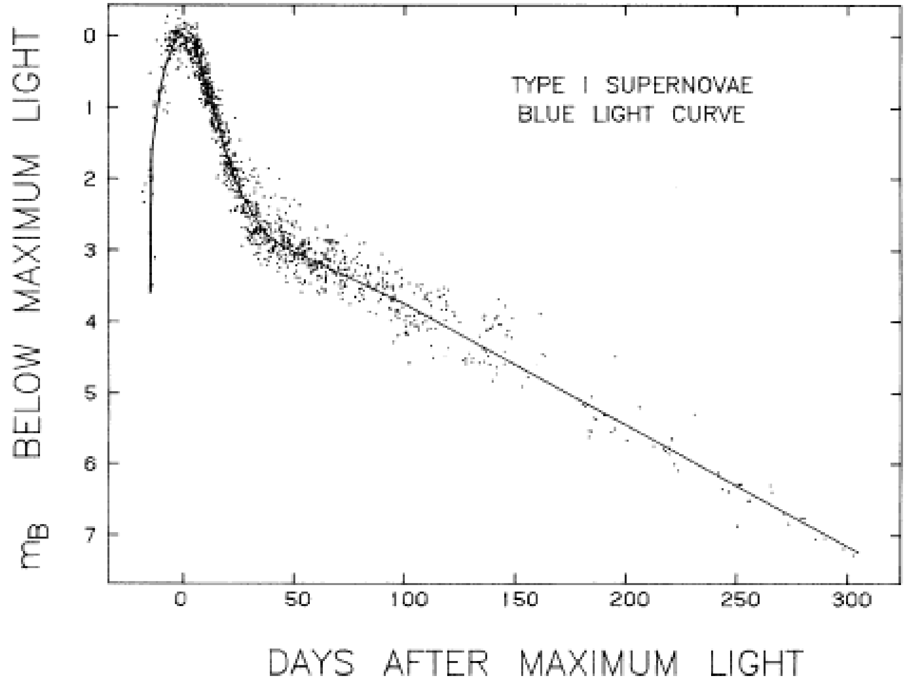
Supernova classification

Divided into two types based on spectra

Type I – with no H lines

- Further classification based also on spectra:
  - ✓ Ia – strong Si line
  - ✓ Ib – no H or Si line, but have He lines
  - ✓ Ic – no Si, He or H lines
- Ia found in all types of galaxies

  ➔ associated with white dwarfs in binary systems



Doggett and Branch (1985)
Astron. J., **90**, 2303

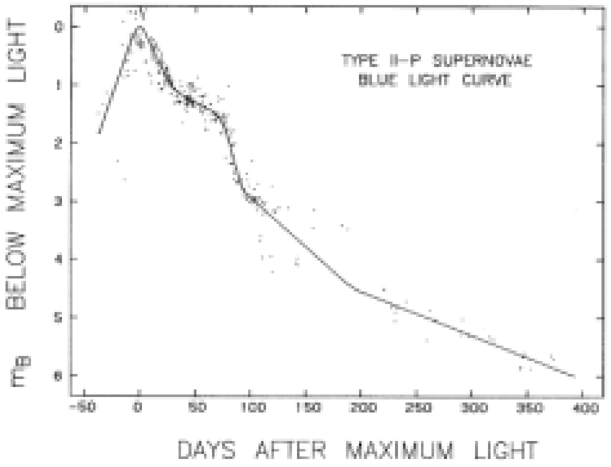
Supernova classification II

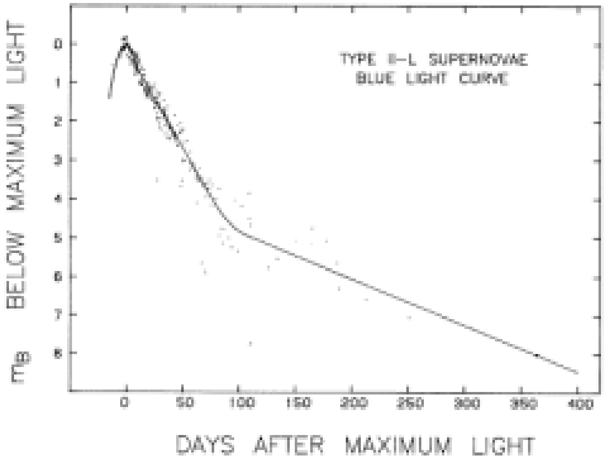
Type II – with H lines

Further classification based on light curve

✓ II P – flat ‘plateau’ in LC
✓ II L - linear light curve

- Type II, Ib, Ic found only in spiral arms of spiral galaxies (i.e. regions of recent star formation) ➔ massive stars
  Core collapse supernovae with mass loss in Ib and Ic





Doggett and Branch (1985)
Astron. J., **90**, 2303

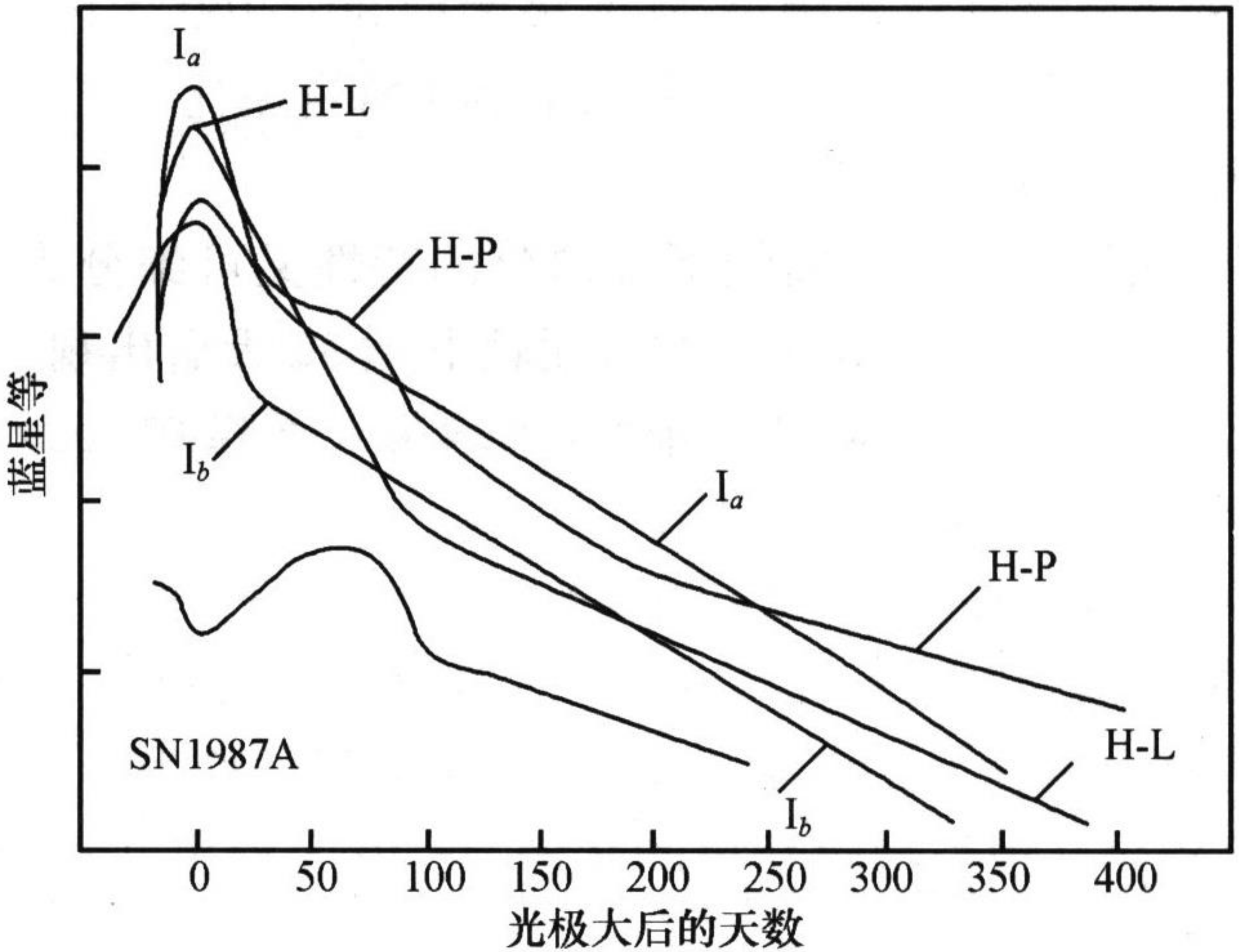
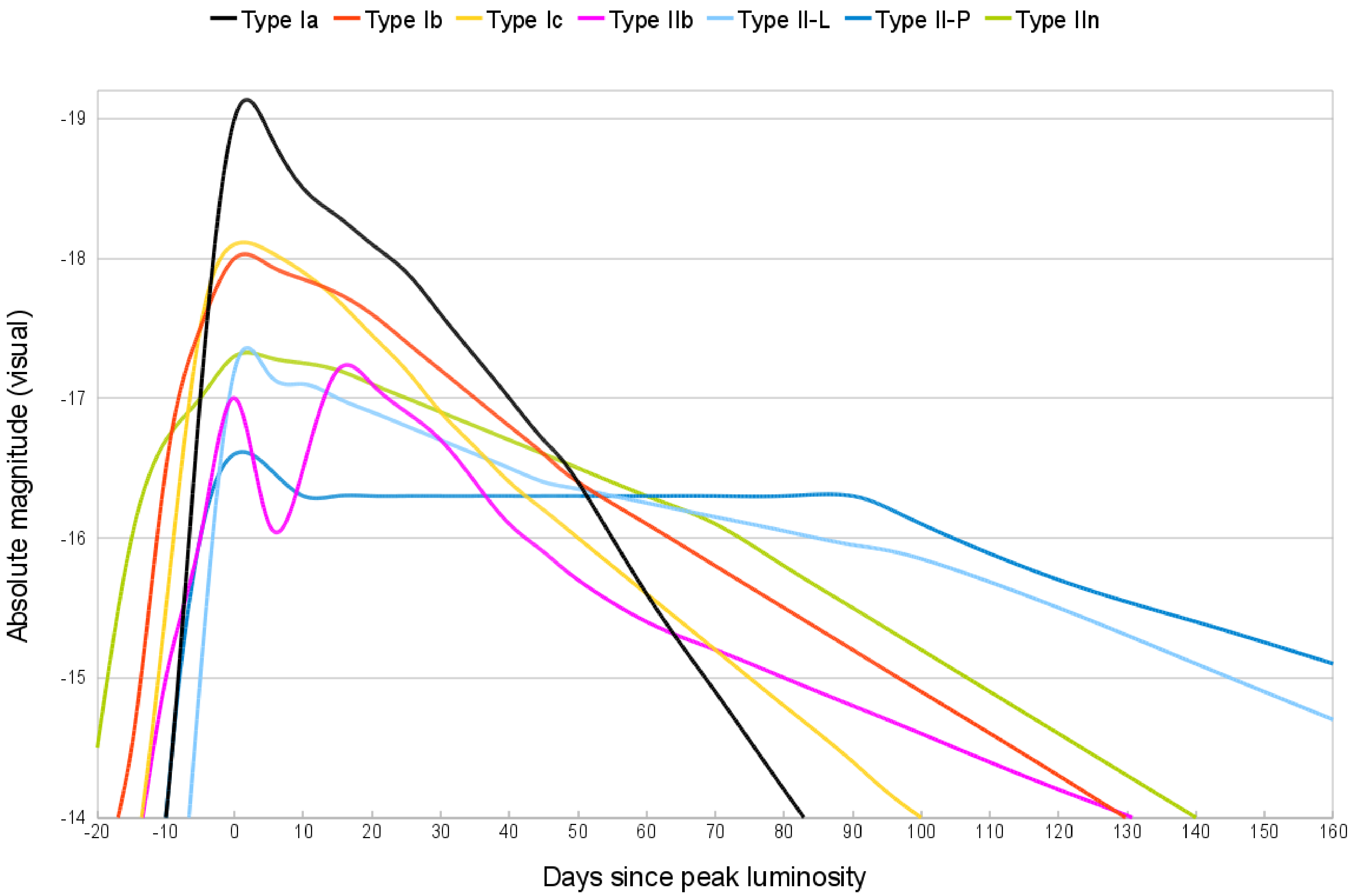
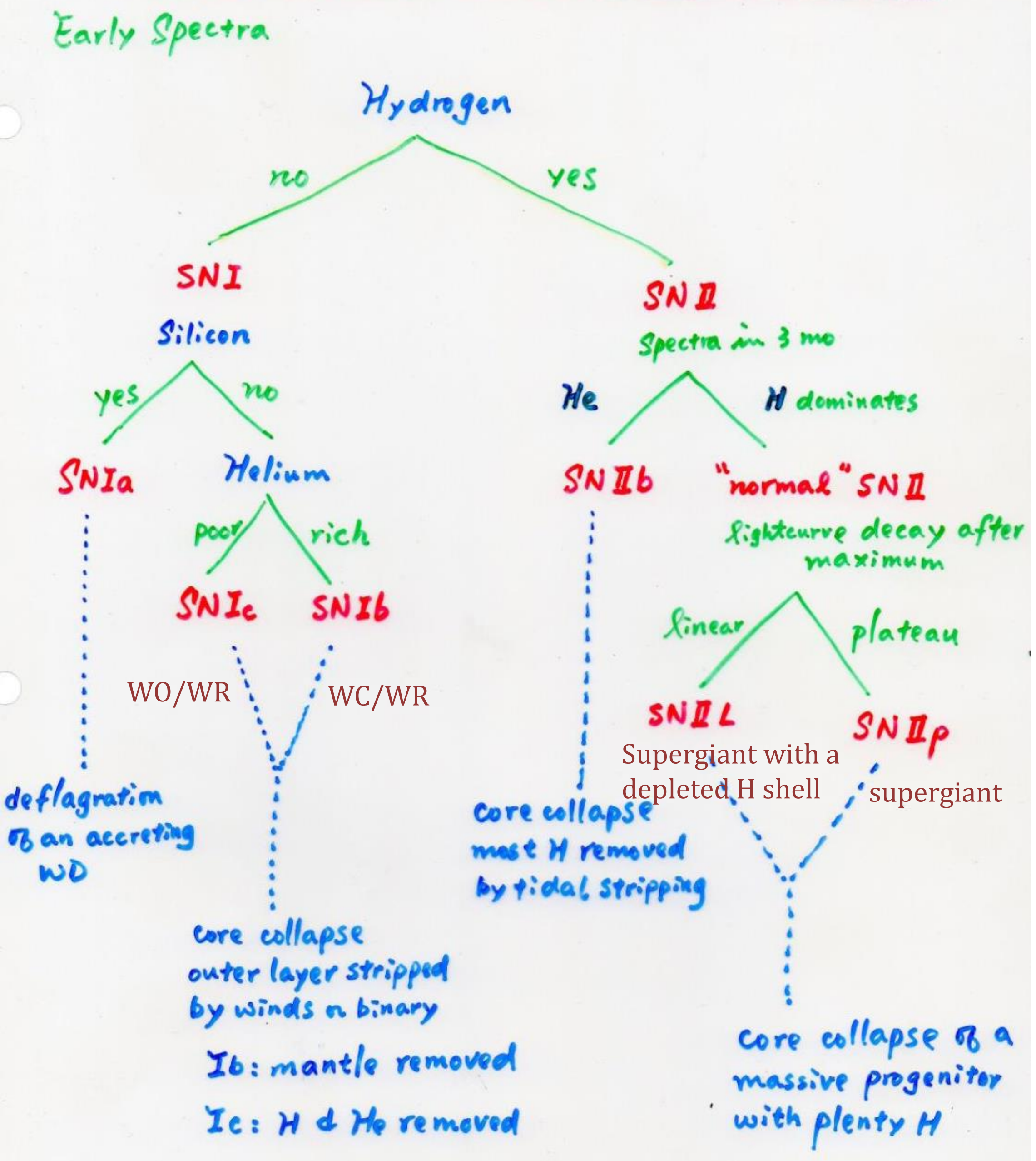


图 10.8　几种类型超新星的光变曲线(Wheeler, Harkness, 1992)

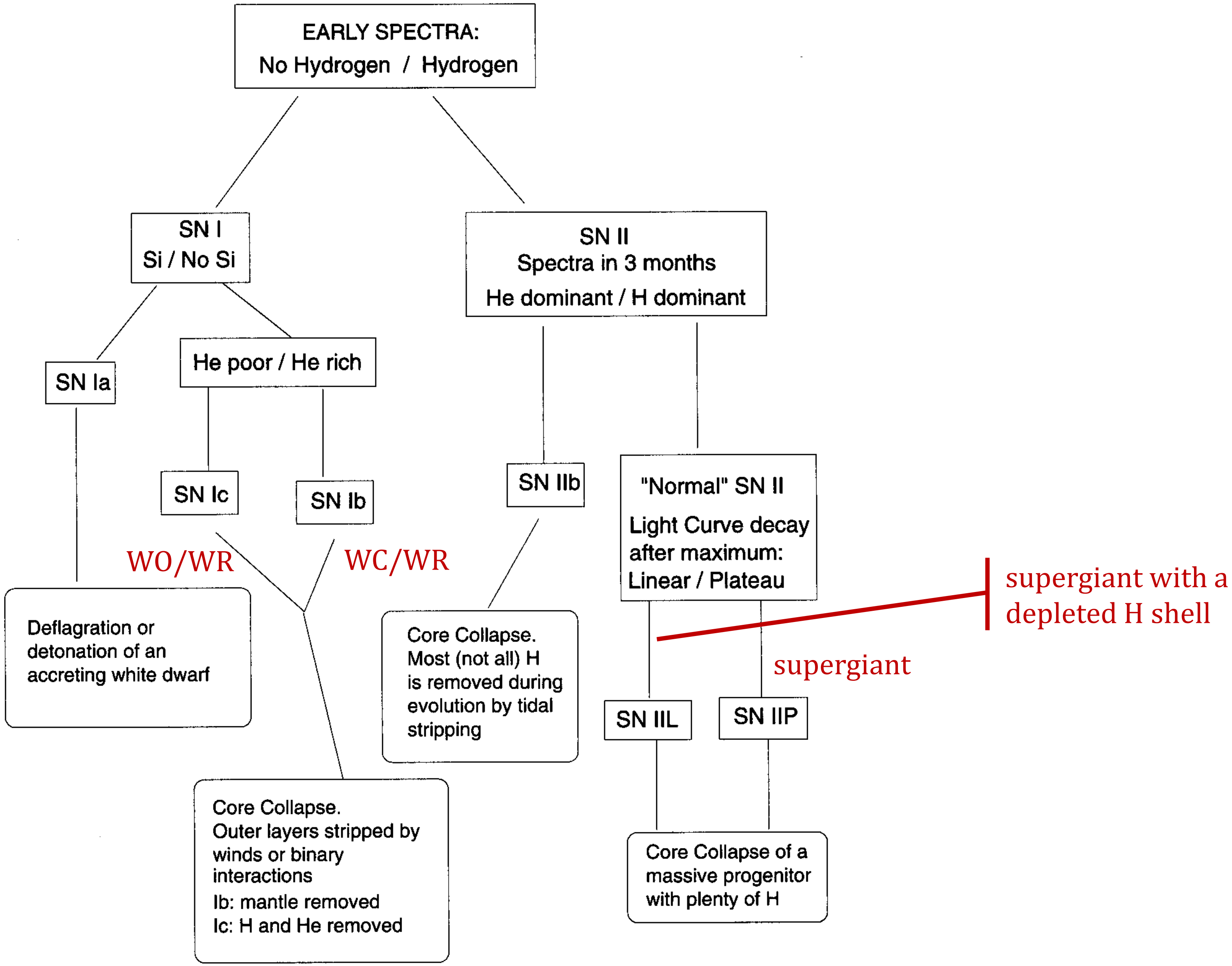


http://upload.wikimedia.org/wikipedia/commons/e/e0/Comparative_supernova_type_light_curves.png

Observational Classification of Supernovae



Padmanabhan II



EARLY SPECTRA:
No Hydrogen / Hydrogen

SN I
Si / No Si

SN Ia

Deflagration or detonation of an accreting white dwarf

He poor / He rich

SN Ic

SN Ib

WO/WR

WC/WR

Core Collapse.
Outer layers stripped by winds or binary interactions
Ib: mantle removed
Ic: H and He removed

SN II
Spectra in 3 months
He dominant / H dominant

SN IIb

Core Collapse.
Most (not all) H is removed during evolution by tidal stripping

"Normal" SN II
Light Curve decay after maximum:
Linear / Plateau

supergiant with a depleted H shell

supergiant

SN IIL

SN IIP

Core Collapse of a massive progenitor with plenty of H

Fig. 7.12. Observational classification of supernovas (SNs).

Padmanabhan II

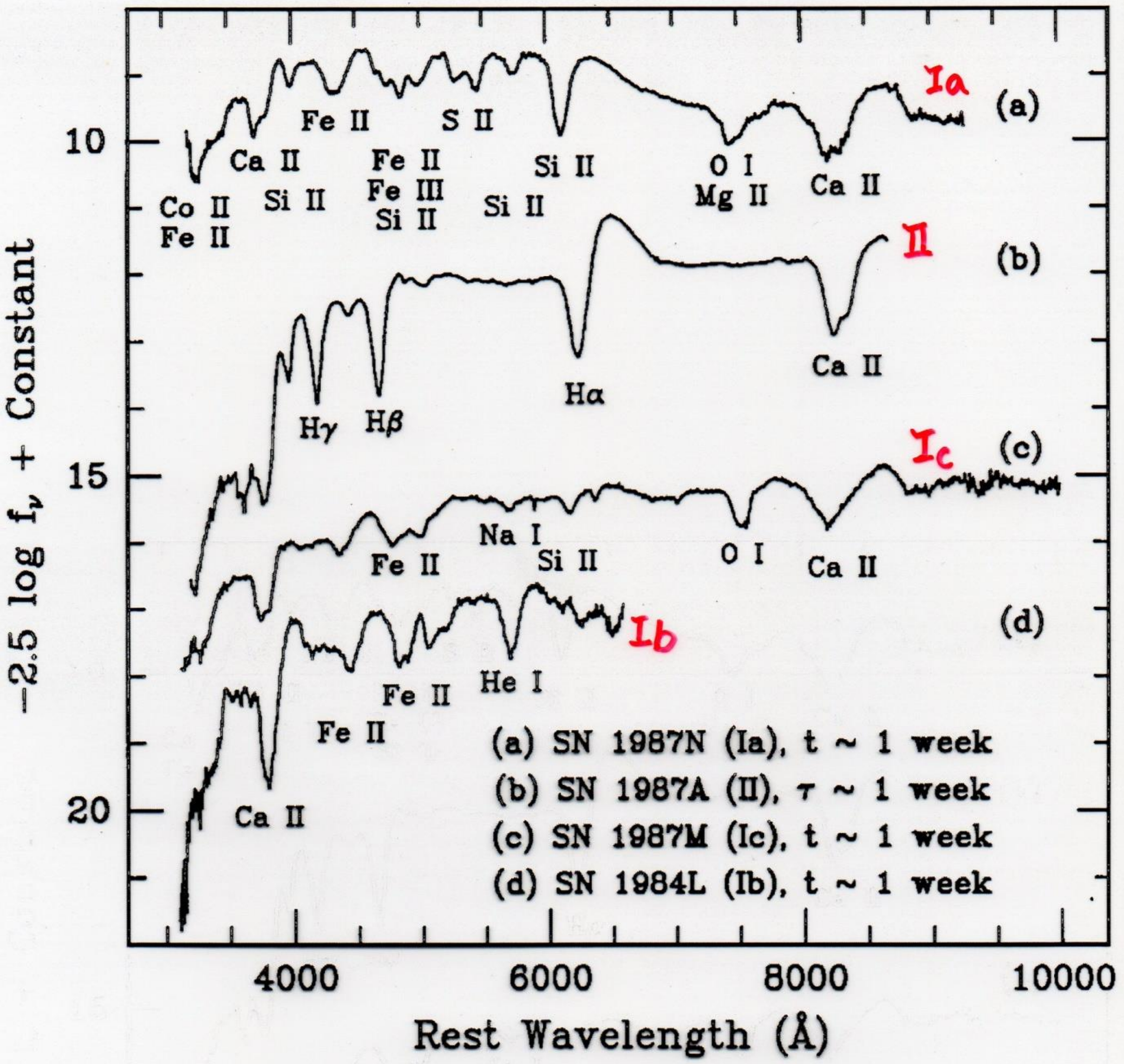


Figure 1 Spectra of SNe, showing early-time distinctions between the four major types and subtypes. The parent galaxies and their redshifts (kilometers per second) are as follows: SN 1987N (NGC 7606; 2171), SN 1987A (LMC; 291), SN 1987M (NGC 2715; 1339), and SN 1984L (NGC 991; 1532). In this review, the variables t and τ represent time after observed B-band maximum and time after core collapse, respectively. The ordinate units are essentially "AB magnitudes" as defined by Oke & Gunn (1983).

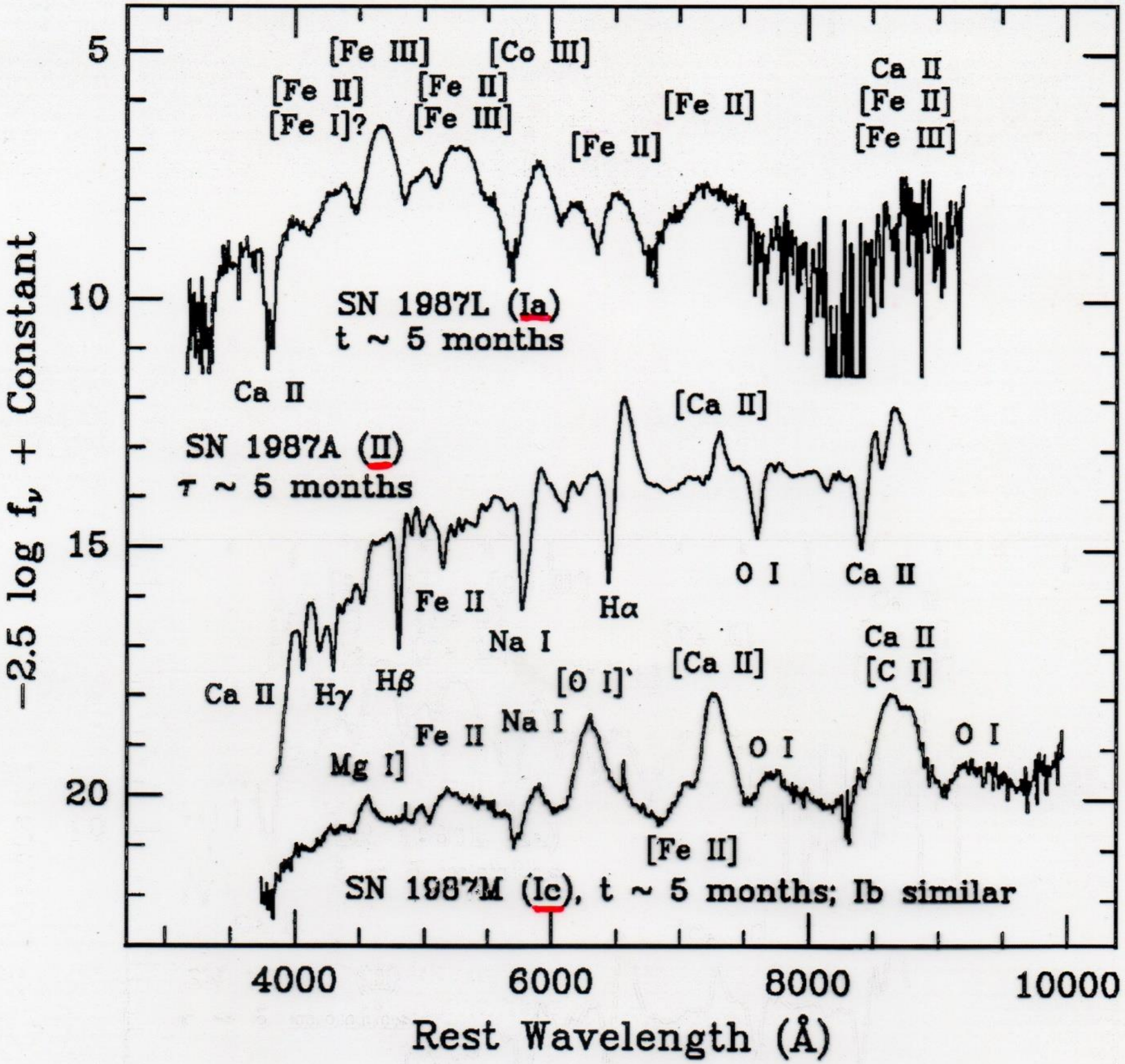


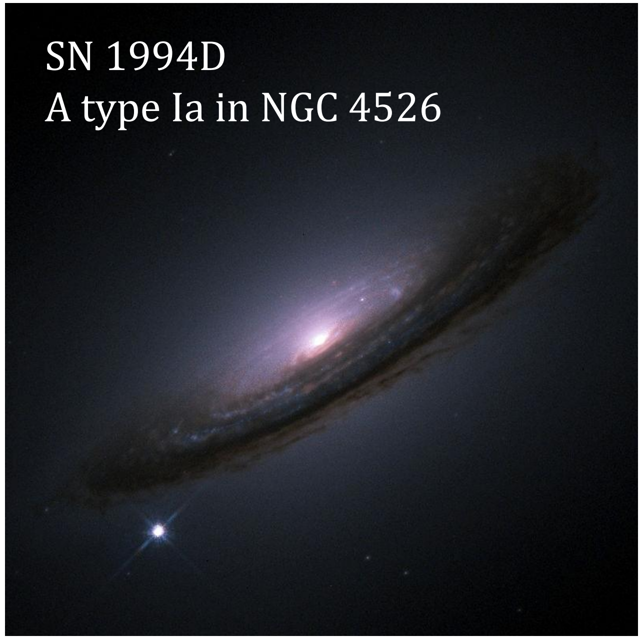
Figure 2 Spectra of SNe, showing late-time distinctions between various types and subtypes. Notation is the same as in Figure 1. The parent galaxy of SN 1987L is NGC 2336 ($cz = 2206$ km s^{-1}); others are listed in the caption of Figure 1. At even later phases, SN 1987A was dominated by strong emission lines of Hα, [O I], [Ca II], and the Ca II near-IR triplet, with only a weak continuum.

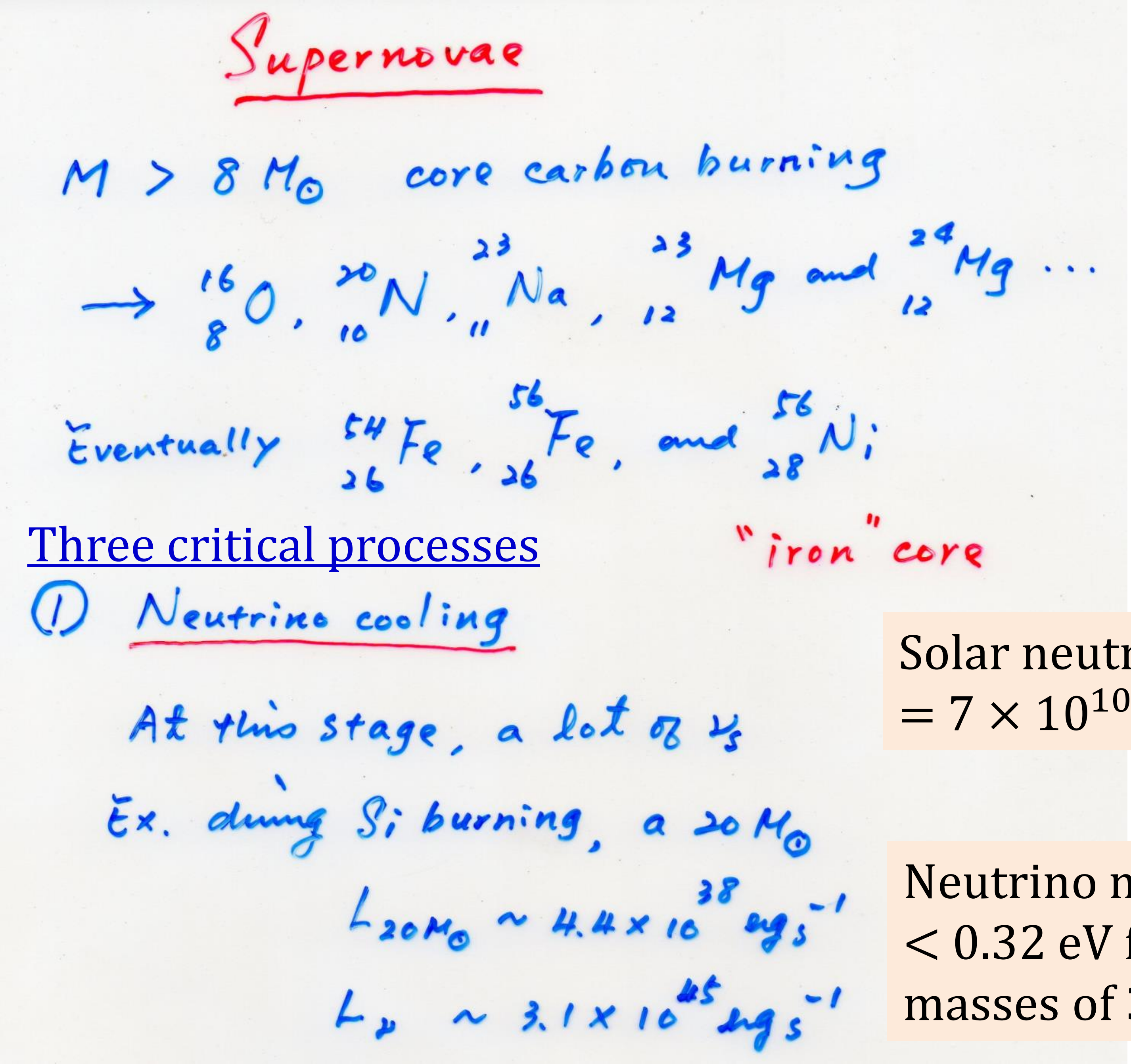
Elements observed in SN I spectra

subclass	~ maximum	~ 6 months
SNIa	O, Mg, Si, S, Ca, Fe	Fe, Co
SNIb	O, Ca, Fe	O, Ca, Mg
SNIc	He, Fe, Ca	O, Mg

Hansen + Kawaler

- The energy source of the type Ia supernovae comes from nuclear fusion. The explosion produces various radioactive isotopes , e.g., nickel becomes cobalt.
- So far, a few thousands SNe have been detected in external galaxies.
- Applying the statistics, the Milky Way should have occurred one type Ia SN every 36 years, and
  one type II SN every 44 years.
- Each century, therefore, we should have seen about 5 supernovae. So, what happened?
- Which is most likely the next? In the solar neighborhood?


SN 1994D
A type Ia in NGC 4526



Supernovae

$M > 8\,M_\odot$ core carbon burning

$\rightarrow {}^{16}_{8}O,\ {}^{20}_{10}N,\ {}^{23}_{11}Na,\ {}^{23}_{12}Mg$ and ${}^{24}_{12}Mg$ …

Eventually ${}^{54}_{26}Fe,\ {}^{56}_{26}Fe$, and ${}^{56}_{28}Ni$

"iron" core

Three critical processes

① Neutrino cooling

At this stage, a lot of ν's

Ex. during Si burning, a $20\,M_\odot$

$L_{20M_\odot} \sim 4.4 \times 10^{38}$ erg s^{-1}

$L_\nu \sim 3.1 \times 10^{45}$ erg s^{-1}

Solar neutrino flux
$= 7 \times 10^{10}$ /cm^2/s

Neutrino mass
< 0.32 eV for the sum of masses of 3 known flavors

② Photodisintegration

Energetic photons disintegrate iron nuclei into α particles and protons

吸热

This is an endothermic process; i.e. takes energy away and lowers pressure support at the core

$$^{56}Fe + \gamma \rightarrow 13\,^{4}He + 4n$$

$$^{4}He + \gamma \rightarrow 2p^{+} + 2n$$

3. Neutronization

possible inverse β decay $p^+ + e^- \to n^0 + \nu$

$\downarrow$

$n_e \downarrow \Rightarrow P_{deg} \downarrow$

ν escape $\Rightarrow$ cooling

$\Rightarrow$ A rapid collapse of the core

放熱

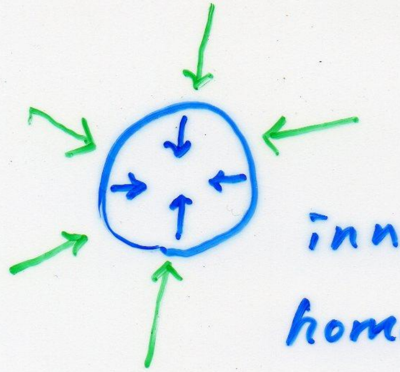
Note exothermic

releasing energy

Outer core/mantle

collapses supersonically (free fall)

$v \sim 70,000 \, km \, s^{-1}$



inner core collape

homologously (infall speed ∝ distance to center)

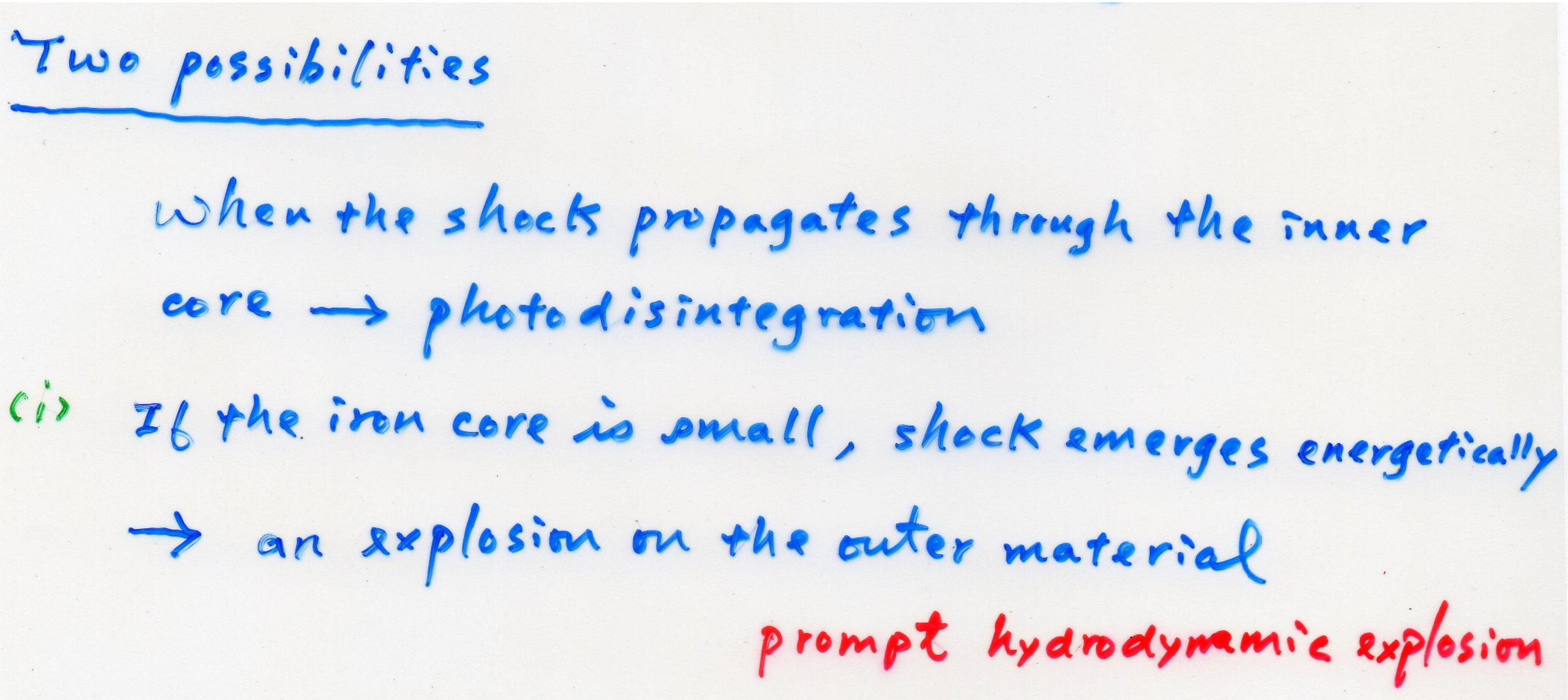
subsonically

Inner core collapses until $\rho_c \sim 8 \times 10^{14} \, g \, cm^{-3}$

This is 3 × $\rho_{nucleus}$ → nuclear reactions produce rupulsive force

(cannot "squeeze" anymore)

This sends an outgoing pressure wave through the infalling material



Two possibilities

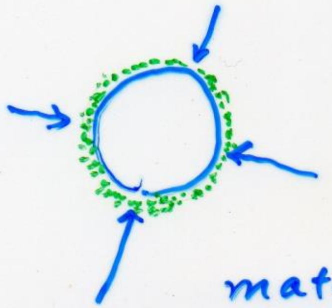
when the shock propagates through the inner core → photodisintegration

(i) If the iron core is small, shock emerges energetically → an explosion on the outer material

prompt hydrodynamic explosion

This can explain the explosion of MS stars with 8~12 $M_\odot$, ending with a core < 1.2 $M_\odot$. But the progenitor of SN1987A had 20 $M_\odot$ → need an alternative mechanism to explain more massive SNe

(ii) If the core is massive, inner shock stalls



$\rho_{crit} > 1.5 \times 10^{11}\,g\,cm^{-3}$

accretion shock

cf protostars

material becomes so dense that even νs cannot escape → formation of a neutrino sphere

cf photosphere of a star

when $\rho > \rho_{crit}$ $\tau^{\nu}_{diff} > \tau_{free fall}$

This deposits some energy to the inner shock

→ explosion

delayed-explosion mechanism

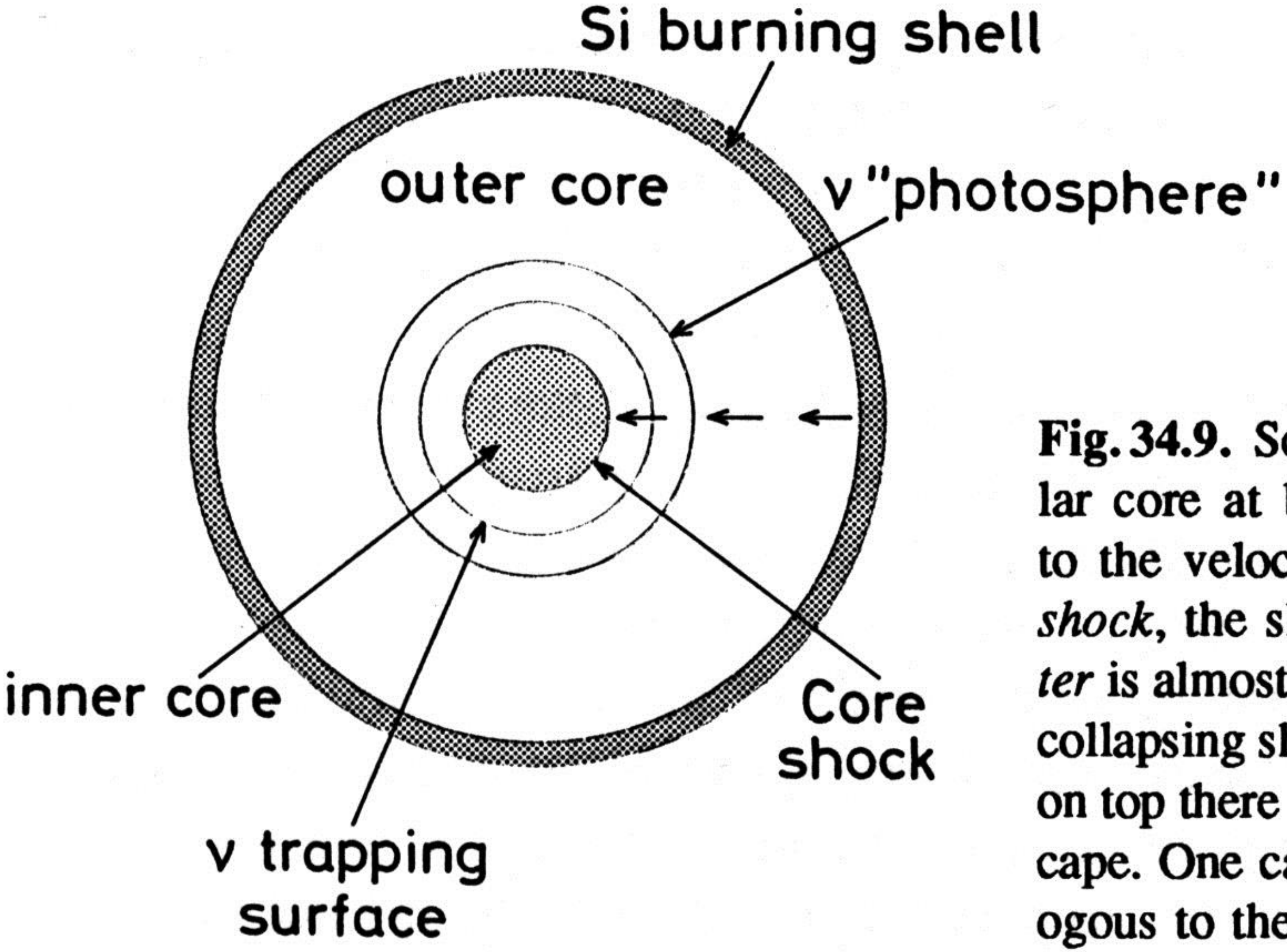


Fig. 34.9. Schematic picture of a collapsing stellar core at bounce. The short arrows correspond to the velocity field. At the sphere labelled *core shock*, the shock is formed inside which the *matter* is almost at rest. Above the shock there is a still collapsing shell in which neutrinos are trapped. But on top there is a shell from which neutrinos can escape. One can define a neutrino photosphere analogous to the photosphere in a stellar atmosphere

Total kinetic energy of outgoing shock

$E_{kin} \sim 10^{51}$ ergs

(This is only 1% of the energy in energy)
neutrinos

→ outer material expands & becomes optically thin

⇒ SN explosion, releasing $\sim 10^{49}$ ergs
in photons

with $L_{peak} \sim 10^{43}$ ergs s^{-1} $\sim 10^{9} L_{\odot}$

c.f $L_{Milky Way}$

Roughly if original mass $< 25 M_\odot$; can be supported neutron pressure; may survive the explosion → a neutron star

If $M > 25 M_\odot$ → collapse to a black hole

Neutrino Trapping

Mean free path $\lambda = 1/n\sigma$

cross section $\sigma = \sigma_0 \varepsilon^2$

For neutrinos, $\sigma_0 \sim 2 \times 10^{-44}$ [cm^2]

ε = relative energy in unit of e^- rest mass

In lead $\rho = 11.34$ g cm^{-3}, $A = 208$

A neutrino of 1 MeV, or $\varepsilon = 2$, $\lambda \sim 3.8 \times 10^{20}$ cm

~ 380 ly

In a collapsing stellar core

$$\rho \sim 4 \times 10^{14} \text{ g cm}^{-3}$$

Neutrinos have ~ 150 MeV, or $\varepsilon \sim 300$

$$\rightarrow \lambda = 2.2 \text{ cm}$$

So if $R \sim 10$ km, the mean free time, or

diffusion time $\tau \sim 5$ s

Supernova Observations

$L_{peak} \sim 10^{9} - 10^{10} L_{\odot}$

Time before peak (rising time) ~ 2 wks

Shell expansion $v \sim 5\text{-}10 \times 10^{3}\ \mathrm{km\,s^{-1}}$

supernova remnant (SNR)

lasting ~ 10^{3} yrs

$$E_{total} \sim 10^{51} - 10^{53}\ \mathrm{ergs} = \underbrace{E_{photons}}_{\text{usually minor } (\sim 1\%)} + \underbrace{E_{neutrinos}}_{\text{predominant}} + E_{kinetic}$$

cooling core → a neutron star

$\rho \sim 10^{14}\ \mathrm{g\,cm^{-3}}$, $M \sim M_{\odot}$

- 1932 Chadwick discovered the neutron.
- Landau thought neutron stars might exist.
- 1934 Baade & Zwicky suggested neutron stars as remnants of supernova explosions.
- 1939 Oppenheimer & Volkoff proposed the first model for neutron stars, with estimates of masses and sizes.
- 1967 Hewish & Bell discovered the pulsar.
- Gold & Pacini proposed pulsars as fast spinning, highly magnetized neutron stars.

Mass limit of neutron degenerate stars uncertain because of uncertain EoS at $\rho > \rho_{\text{nuclear}}$, ranging from $0.7\,M_\odot$ for non-interacting neutrons

(Tolman-Oppenheimer-Volkoff limit)

up to $\sim 2.5\,M_\odot$

$R \sim 10\,\text{km}$

A pulsar
- $B \sim 10^{13}\,\text{G}$
- Spin down from periods $\sim$ ms

Some SNRs host no pulsars.

- not enough e^-, not strong enough $\vec{B}$?
- we are not in the 'lighthouse beam' ?
- neutron star destroyed completely
- neutron star 'kicked out'

some NSs (or pulsars) have space motion ~ 1000 km s^{-1}

Annu. Rev. Astron. Astrophys. 1992. 30: 359–89

TYPE Ia SUPERNOVAE AS STANDARD CANDLES

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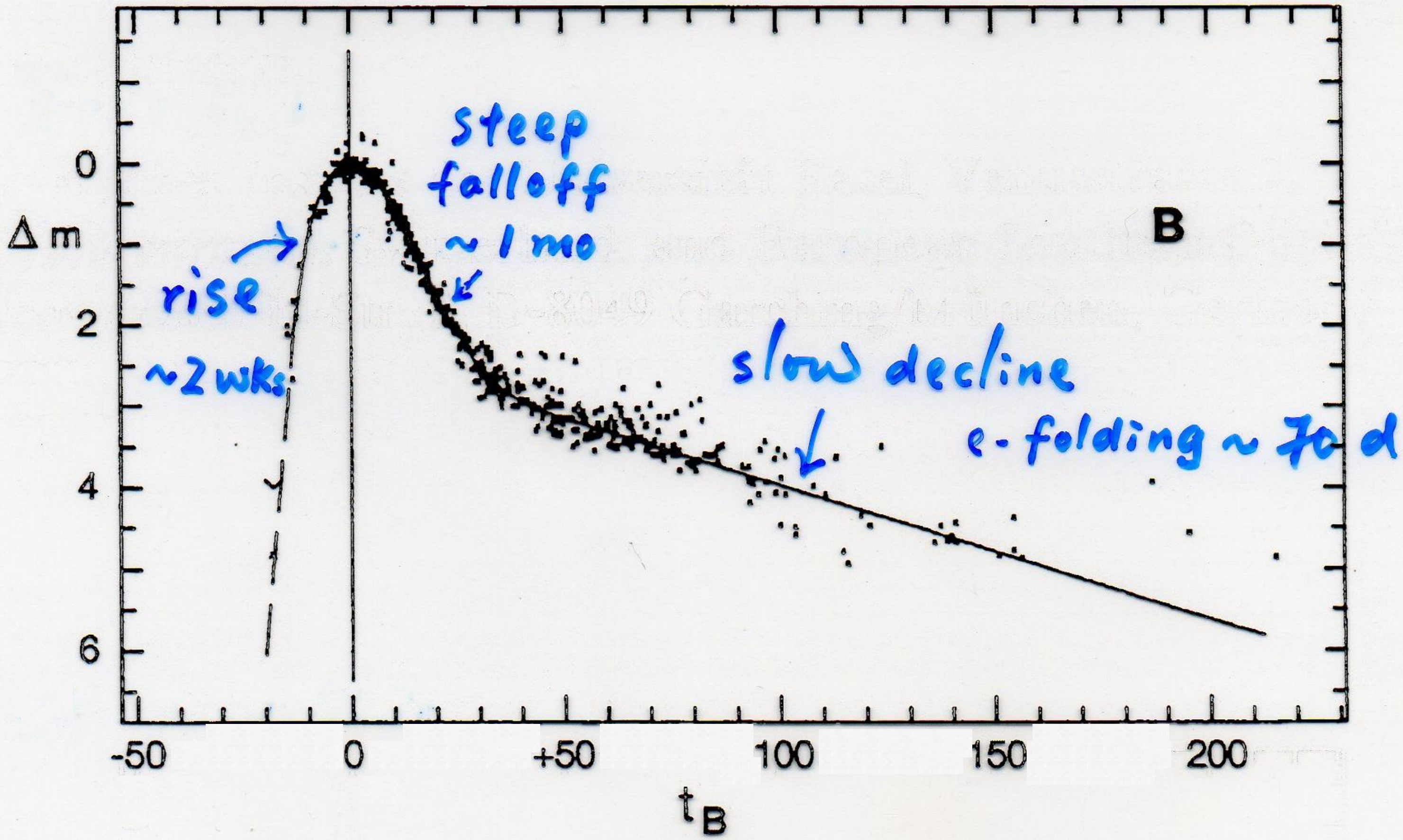


Figure 2 The standard B light curve (adapted from Cadonau 1987), based on observations of 22 SNe Ia.

Many sky survey projects, e.g., Pan-STARRS (PS), Palomar Transient Factory (PTF), Sky Mapper, Large Synoptic Survey Telescope (LSST), to catch SNe early on, for pre-SN characterization

Type I

No H in spectra

Located in spirals or ellipticals

If in spirals, usually **NOT** in arms

but some seen near H II regions or

arms → Ib

Ia **Standard model**

A WD close to Chandrasekhar limit

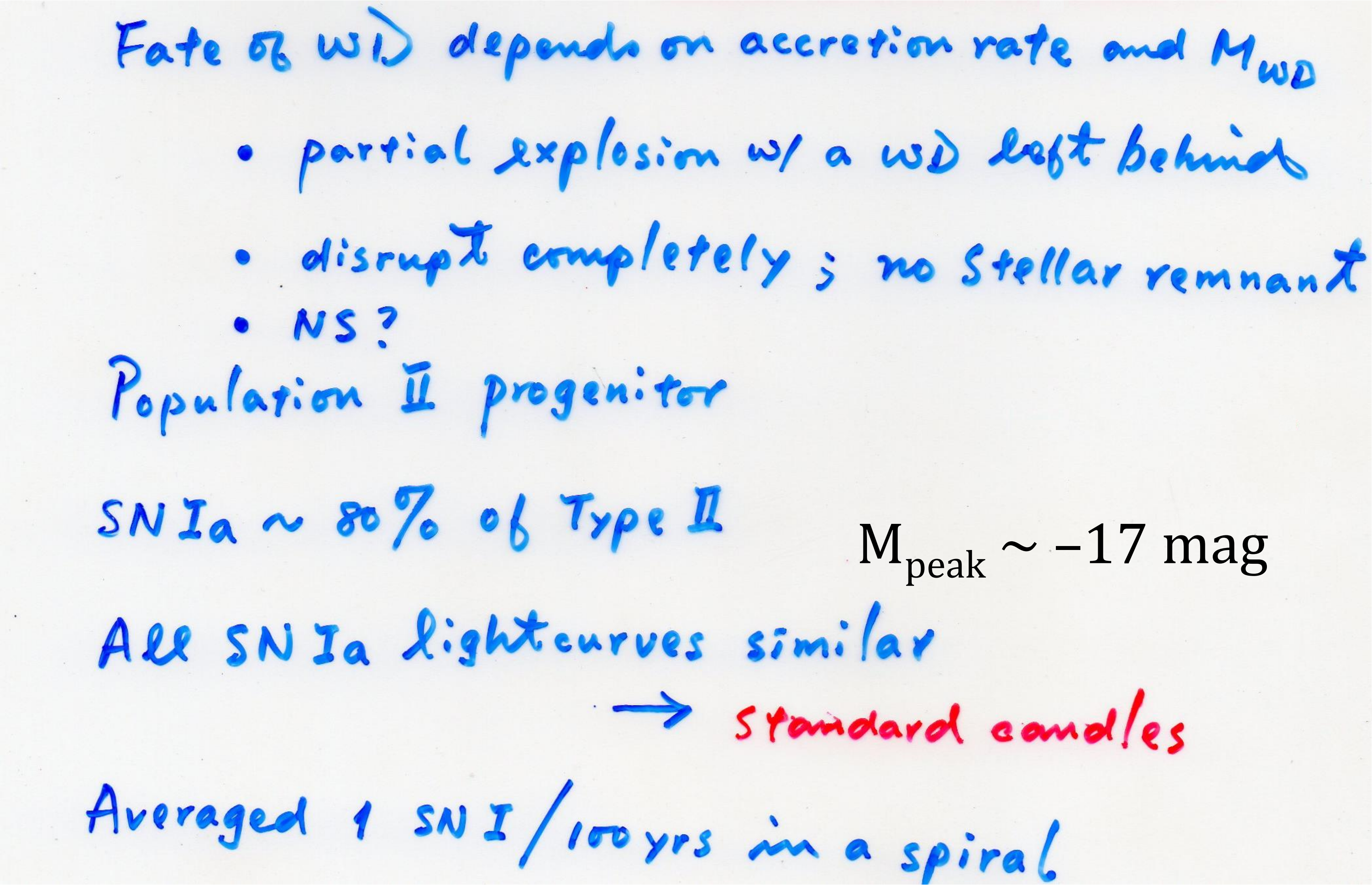
\+ a mass losing companion

→ accretion onto WD → $R_{WD} \downarrow$

→ T ↑. If heat not carried away

⇒ ignition of C, O, ...

thermonuclear explosion



Fate of WD depends on accretion rate and M_{WD}

- partial explosion w/ a WD left behind
- disrupt completely ; no Stellar remnant
- NS?

Population II progenitor

SN Ia ~ 80% of Type II

$M_{\text{peak}} \sim -17$ mag

All SN Ia lightcurves similar

→ standard candles

Averaged 1 SN I/100 yrs in a spiral

Type II $M_{\text{peak}} \sim -19$ mag

With hydrogen lines in spectra

Found in spiral arms or Irr.

If formed in the same arm

timescale $< 10^7$ yr $\Rightarrow M > 10 M_\odot$ progenitor

Standard model

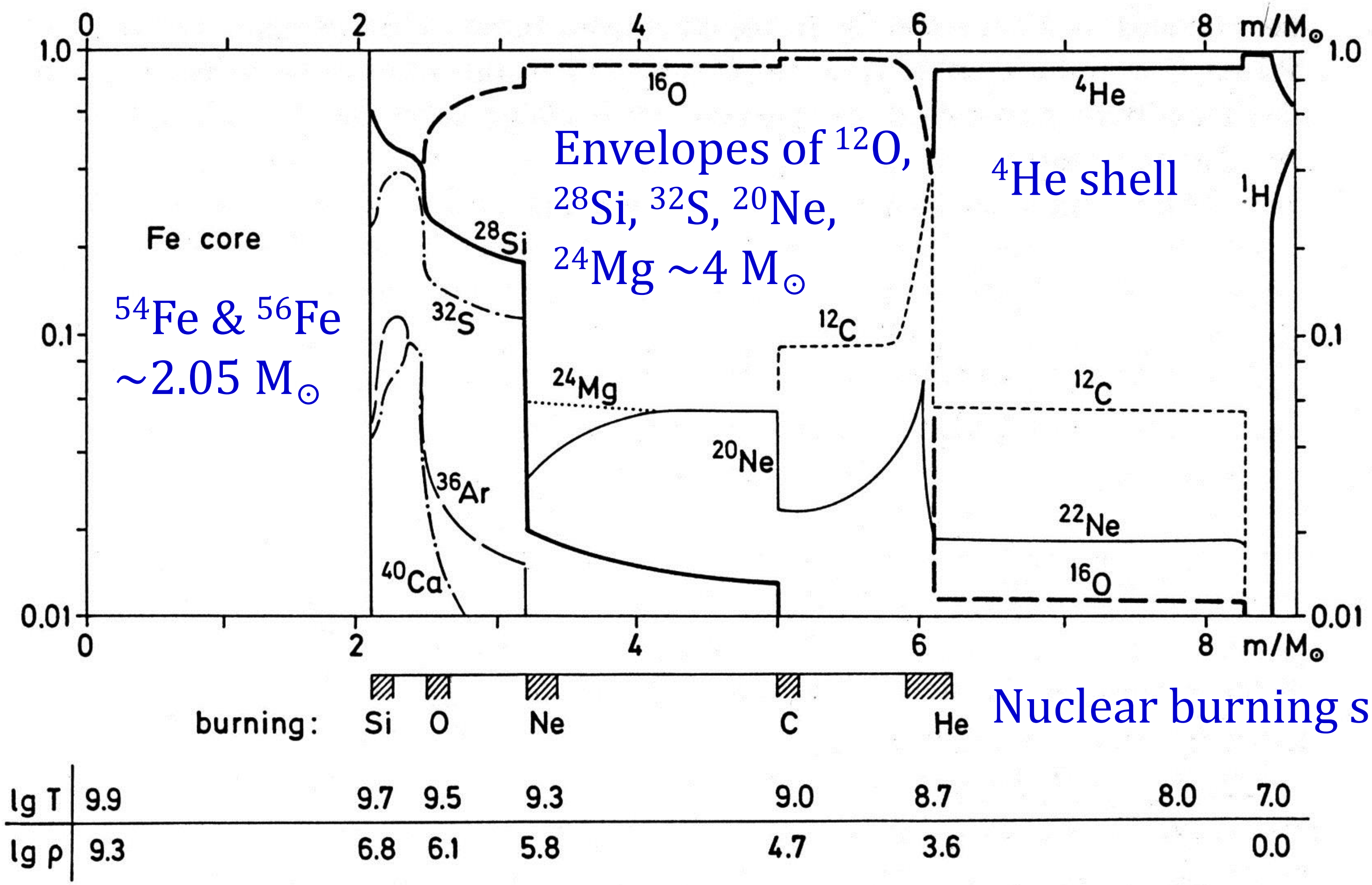
End of massive star evolution

gravitational collapse

Population I progenitor

Fate → NS, BH

Type II (core collapse) SN progenitors



^{54}Fe & ^{56}Fe ~2.05 $M_\odot$

Envelopes of ^{12}O, ^{28}Si, ^{32}S, ^{20}Ne, ^{24}Mg ~4 $M_\odot$

^{4}He shell

Nuclear burning shells

Fig. 34.7. The chemical composition in the interior of a highly evolved model of a $25M_\odot$ star of population I. The mass concentrations of a few important elements are plotted against the mass variable m. Below the abscissa the location of shell sources and typical values of temperature (in K) and density (in g cm^{-3}) are indicated. (After WOOSLEY, WEAVER, 1986)

Ann. Rev. Astron. Astrophys. 1986. 24 : 205–53

THE PHYSICS OF SUPERNOVA EXPLOSIONS[1]

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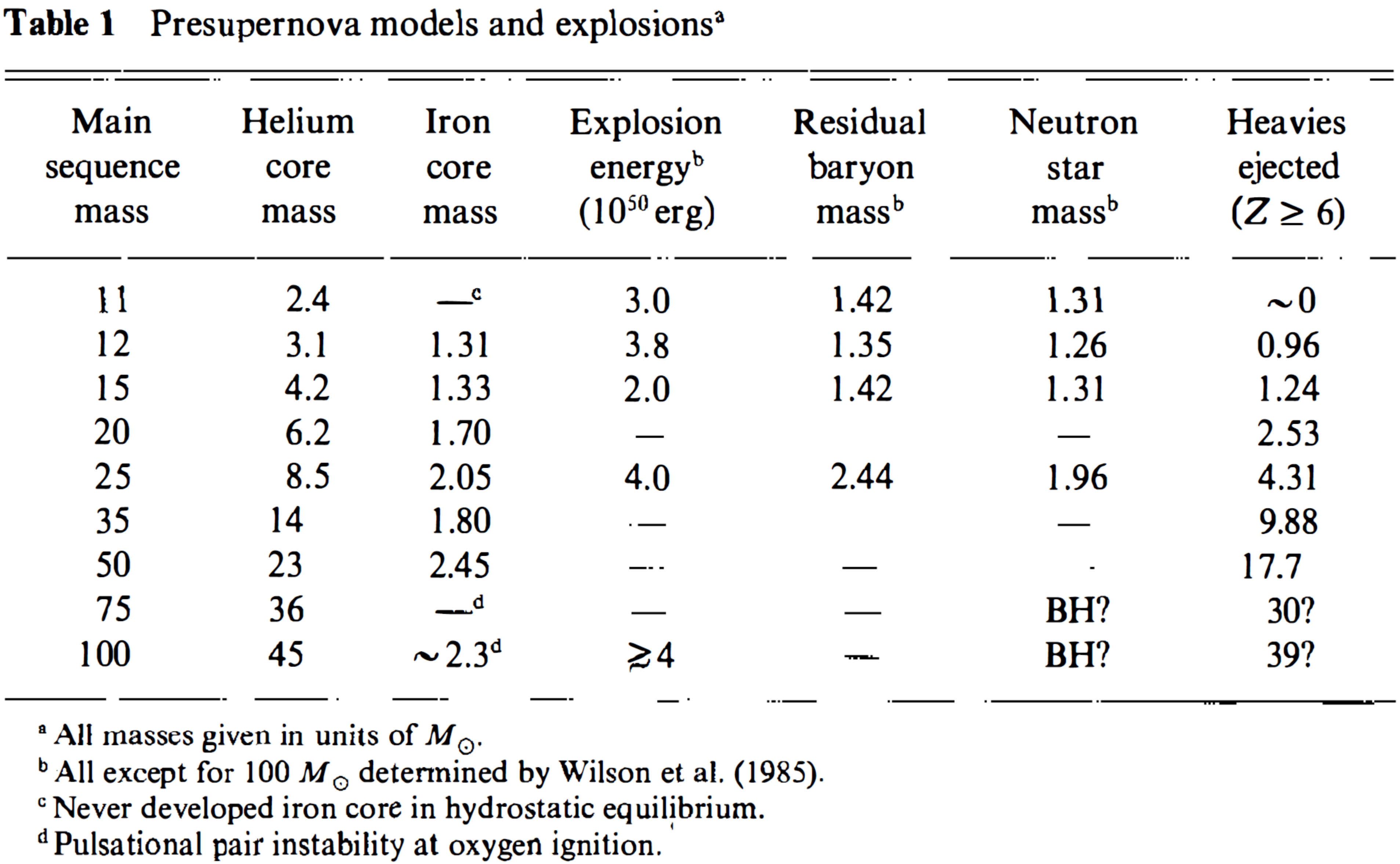


Table 1 Presupernova models and explosions[a]

Main sequence mass	Helium core mass	Iron core mass	Explosion energy[b] (10^{50} erg)	Residual baryon mass[b]	Neutron star mass[b]	Heavies ejected ($Z \geq 6$)
11	2.4	—[c]	3.0	1.42	1.31	~0
12	3.1	1.31	3.8	1.35	1.26	0.96
15	4.2	1.33	2.0	1.42	1.31	1.24
20	6.2	1.70	—		—	2.53
25	8.5	2.05	4.0	2.44	1.96	4.31
35	14	1.80	—		—	9.88
50	23	2.45	—	—		17.7
75	36	—[d]	—	—	BH?	30?
100	45	~2.3[d]	$\gtrsim 4$	—	BH?	39?

[a] All masses given in units of $M_\odot$.
[b] All except for 100 $M_\odot$ determined by Wilson et al. (1985).
[c] Never developed iron core in hydrostatic equilibrium.
[d] Pulsational pair instability at oxygen ignition.

Woosley & Weaver

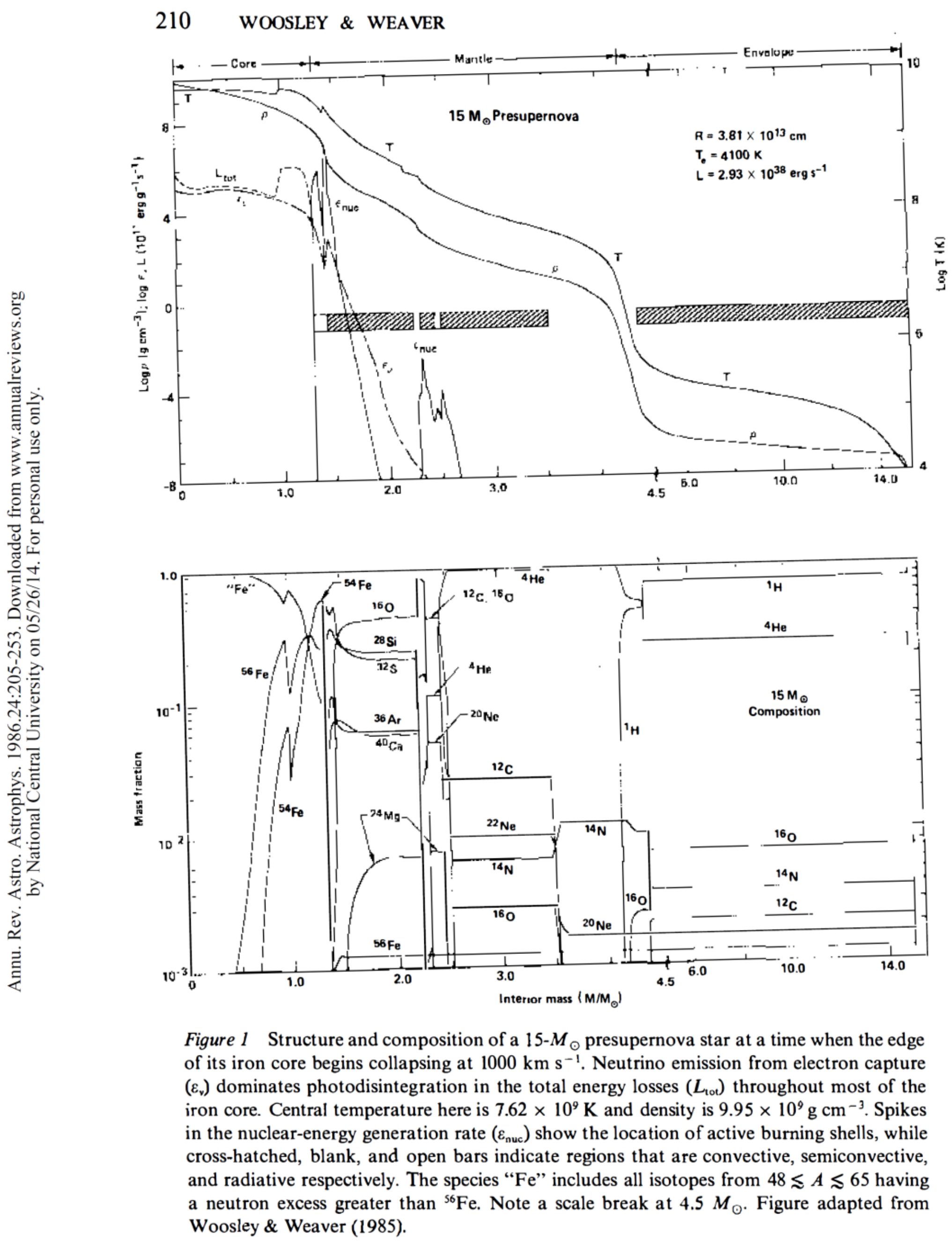


Figure 1 Structure and composition of a 15-$M_\odot$ presupernova star at a time when the edge of its iron core begins collapsing at 1000 km s^{-1}. Neutrino emission from electron capture (ε_ν) dominates photodisintegration in the total energy losses (L_{tot}) throughout most of the iron core. Central temperature here is 7.62 × 10^9 K and density is 9.95 × 10^9 g cm^{-3}. Spikes in the nuclear-energy generation rate (ε_{nuc}) show the location of active burning shells, while cross-hatched, blank, and open bars indicate regions that are convective, semiconvective, and radiative respectively. The species "Fe" includes all isotopes from 48 $\lesssim A \lesssim$ 65 having a neutron excess greater than ^{56}Fe. Note a scale break at 4.5 $M_\odot$. Figure adapted from Woosley & Weaver (1985).

Woosley & Weaver

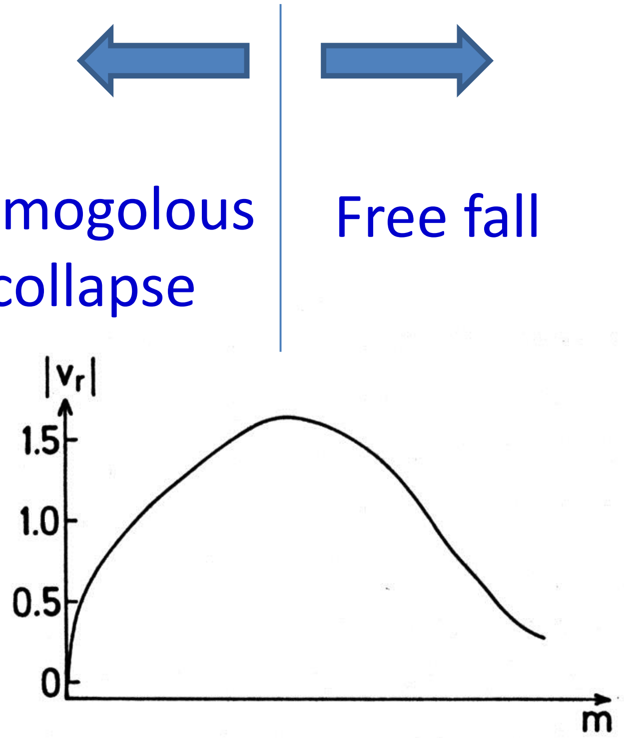
◆ Core collapse in free-fall,
$\tau_{\mathrm{ff}} \approx (G\overline{\rho})^{-1/2} \approx 1$ ms, if $\rho = 10^{10}$ g cm^{-3}

◆ Central density and pressure ↑↑ and becomes subsonic;
outer material remains free-fall and supersonic.

◆ Transition zone = constant speed, force free, relativistic
electron degenerate pressure balances gravy
→ Chandrasekhar limit

◆ Inside $\mathbf{M}_{\mathrm{ch}}$, $\rho \approx 2.3 \times 10^{14}$ g cm^{-3} (nuclear),
strong force; material incompressible; neutron degeneracy
Outside $\mathbf{M}_{\mathrm{ch}}$ → supersonic accretion

→ Shock wave and bounce


Homogolous collapse

Free fall

Fig. 34.8. Schematic picture of the velocity distribution in a collapsing stellar core originally of $1.4 M_\odot$ after numerical calculations (VAN RIPER, 1978). Note the two regimes: on the left $|v_r|$ (in units of 10^9 cm s^{-1}) increases in the outward direction. It corresponds to a (roughly) homologously collapsing part, while on the right $|v_r|$ decreases with m. This corresponds to the free-fall regime

Energy released in a core collapse

$R: R_{WD}(0.01 R_\odot) \longrightarrow R_{NS}(10\ \mathrm{km})$

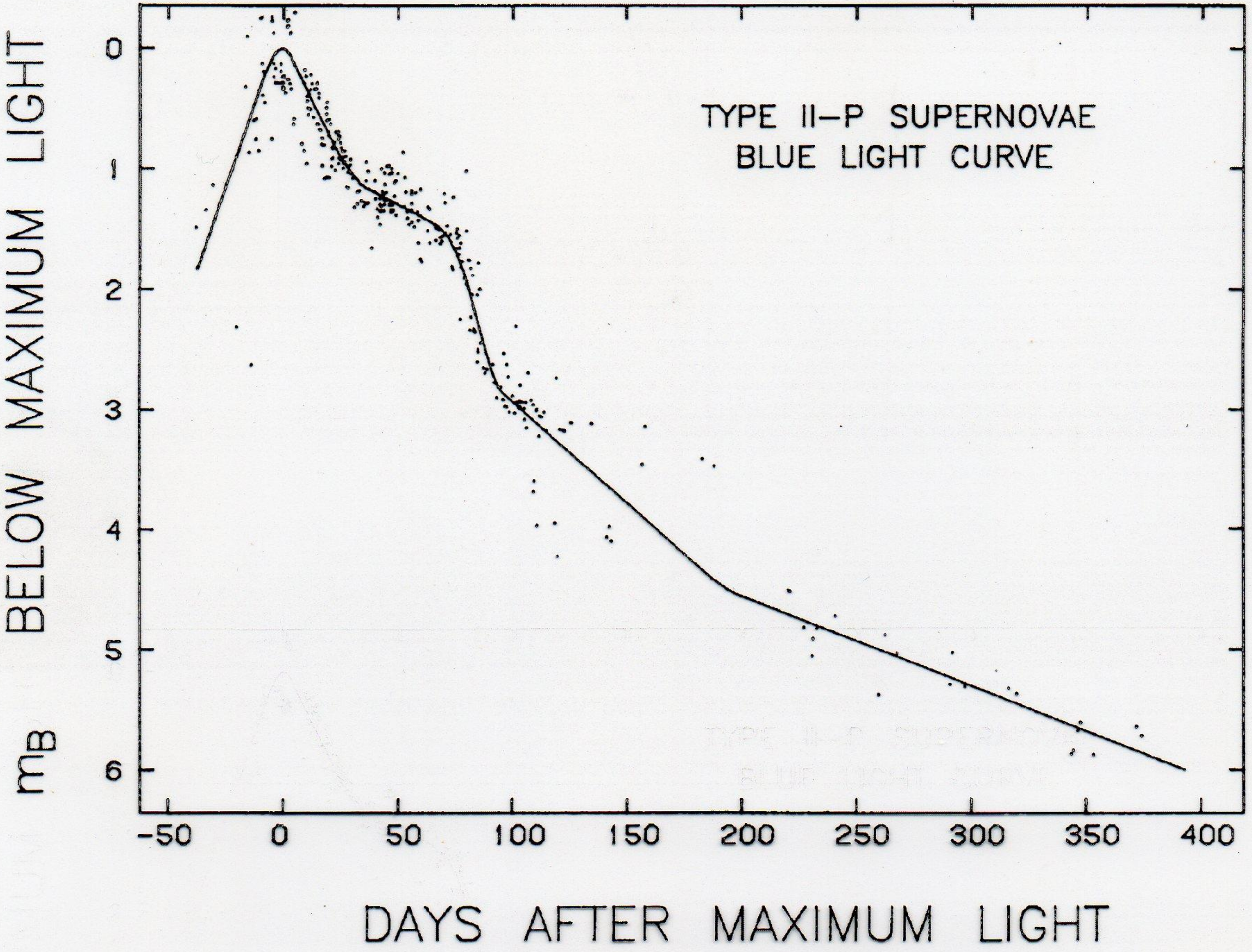
$\Delta E_{grav} \sim \frac{G M_\odot^2}{R_{NS}} \sim 3 \times 10^{53}$ ergs

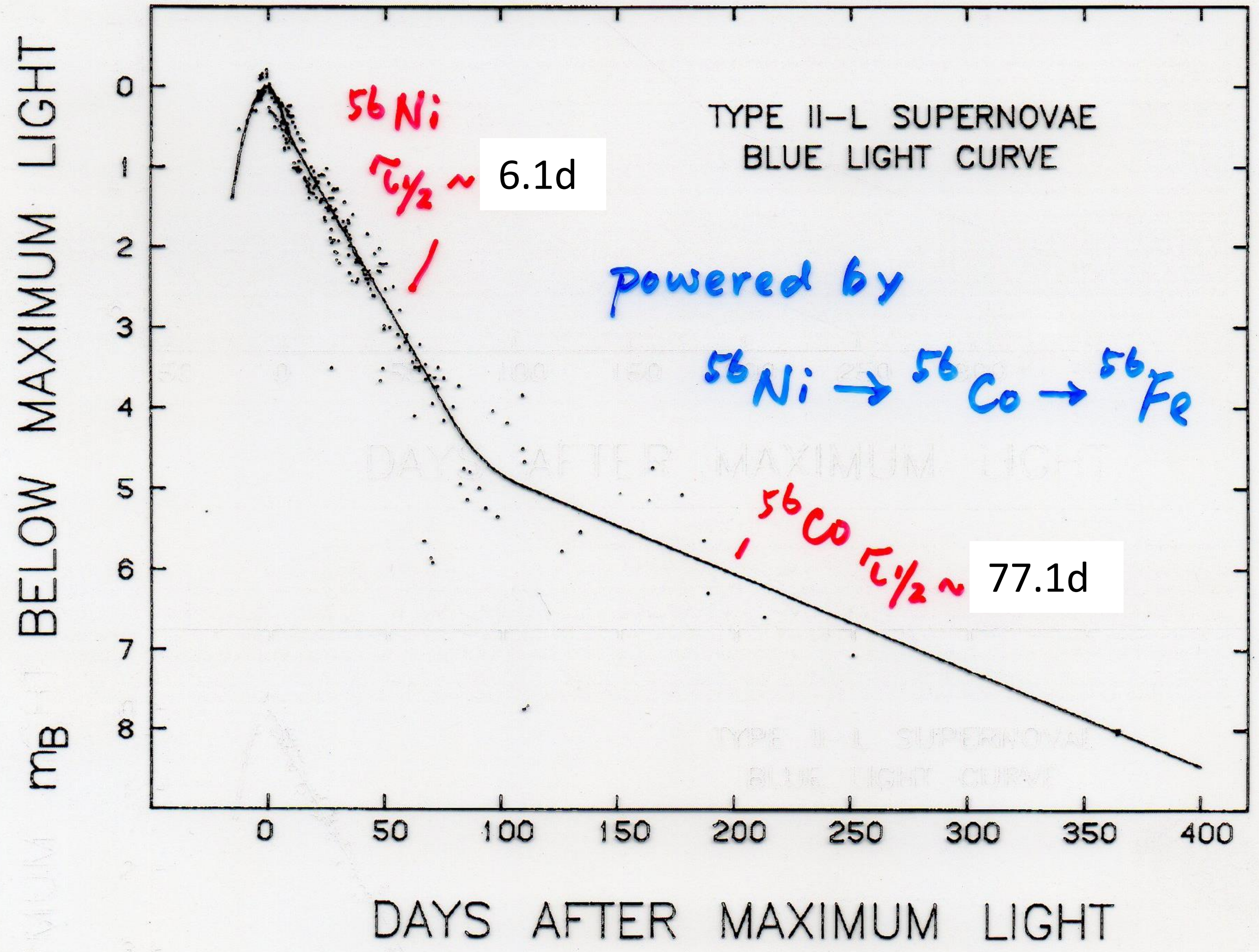
10% used up by nuclear processes

rest to radiation and ejecting material

$\downarrow$

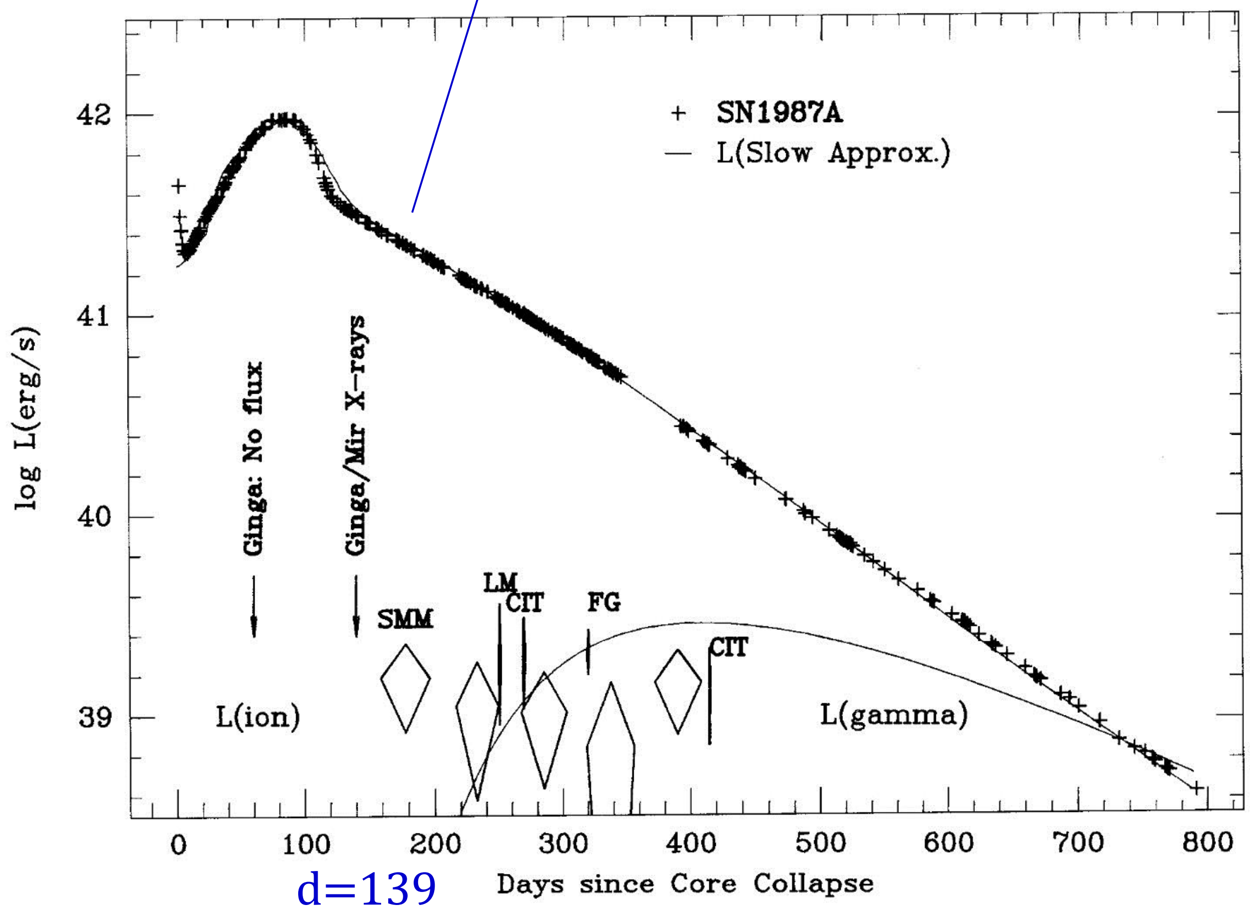
(luminosity & neutrinos)


TYPE II–P SUPERNOVAE
BLUE LIGHT CURVE
m_B BELOW MAXIMUM LIGHT
0
1
2
3
4
5
6
-50
0
50
100
150
200
250
300
350
400
DAYS AFTER MAXIMUM LIGHT



Doggert + Branch (1985
AJ. 90, 2303

UVOIR light curve



d=139
x-rays

d=178
γ-ray

Arnett

Evidence of synthesis of heavy elements in 1987A

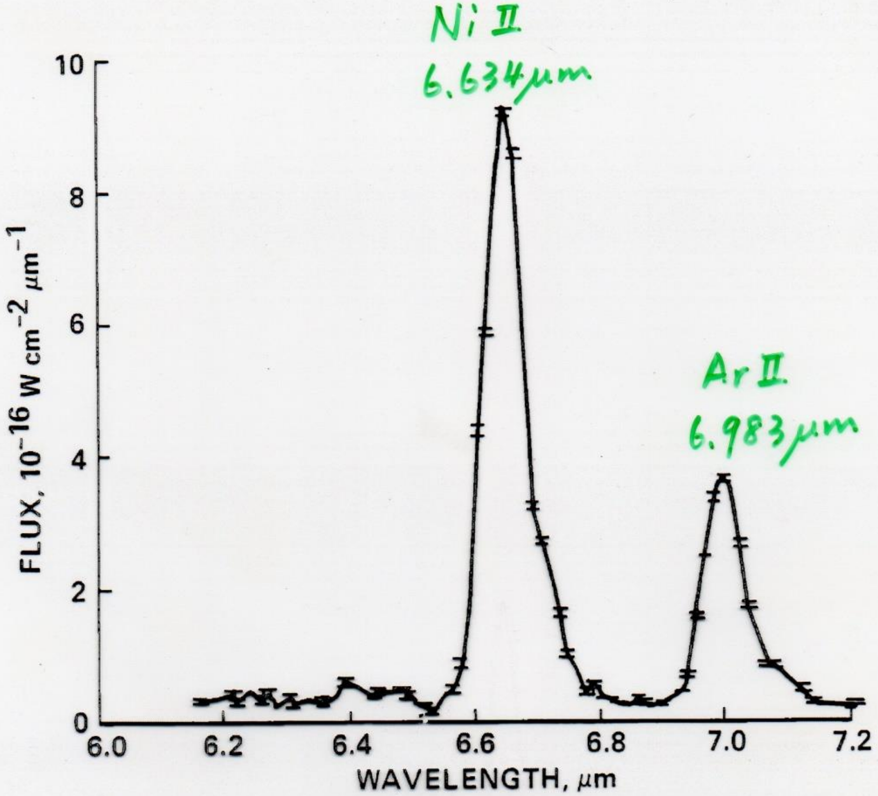


FIG. 1.—Spectrum of SN 1987A. The 1 σ error bars are typically $\pm 5 \times 10^{-18}$ W cm^{-2} µm^{-1}. The flux calibration star was α Bootis.

by Kuiper Airborne Observatory
in 1988 April

Witteborn + 1989
ApJL, 338, L9

◆ During a type II SN explosion, the neutron star reaches $T \approx\ 10^{11} \sim 10^{12}$ K, but cools down quickly by neutrinos, to $T \approx\ 10^{9}$ K in a day, 10^{8} K in 100 years.

◆ This is cold, $kT \approx 10$ keV
cf. Fermi energy ($\rho \approx 10^{14}$ g cm^{-3}), $\varepsilon_F \approx 1000$ MeV,
so $T_{\text{neutron star}} \rightarrow 0$, and all electrons, protons, and neutrons are at the lowest energy states.

◆ Neutron beta decay process, $n \rightarrow p +\ e^- + \overline{\nu_e}$, does not take place, because the resultant electron and neutrino are not energetic enough (energy difference between n and p)

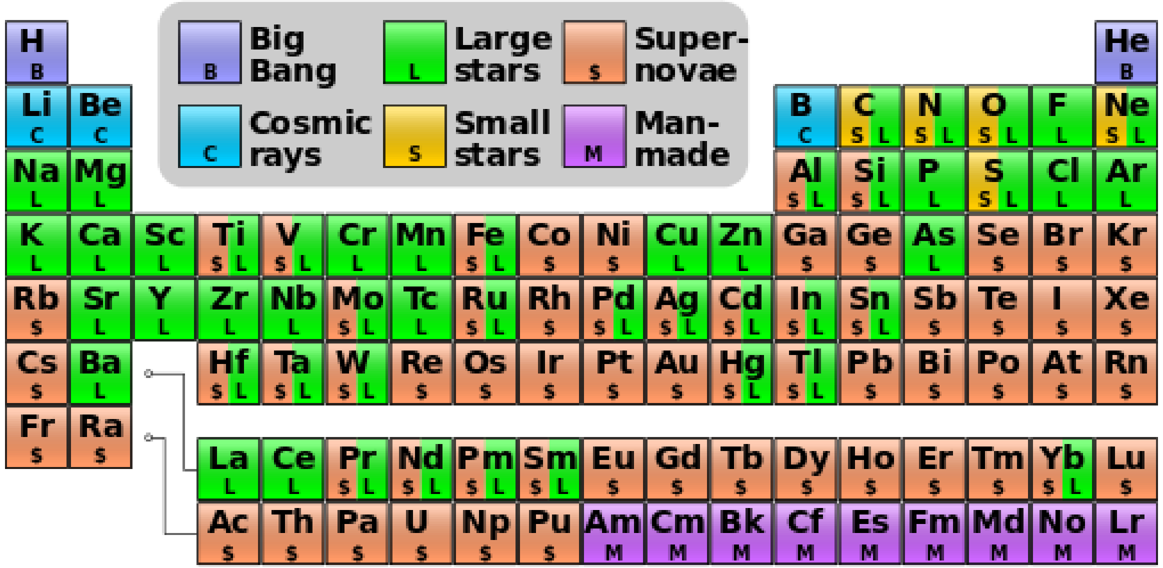
◆ But inverse beta decay $p +\ e^- \rightarrow n +\ \nu_e$ OK

➔ All neutrons

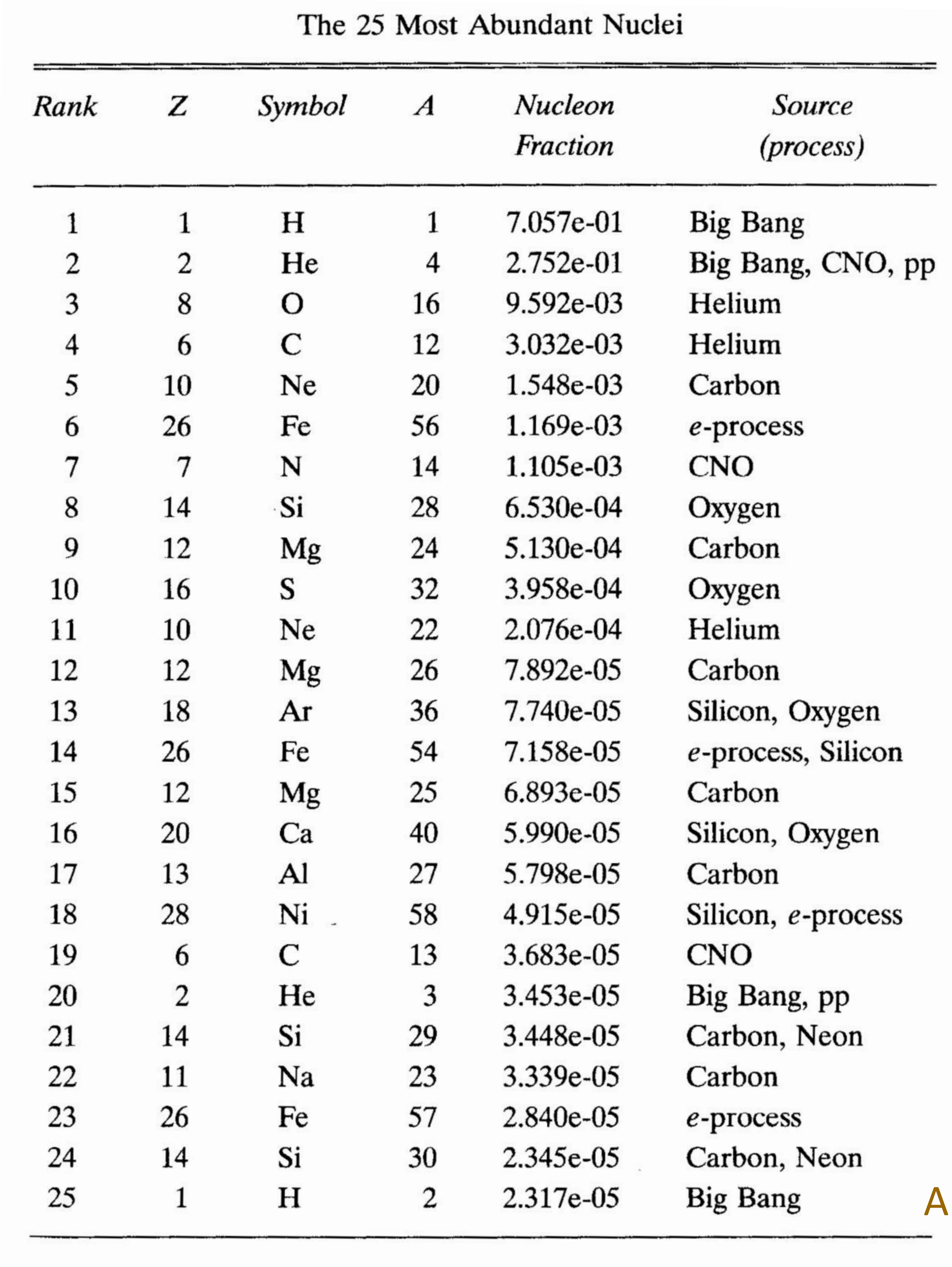
- So far thousands of SNe have been detected in external galaxies.
- In the Milky Way, a type Ia SN is expected every 36 years, and a type II SN is expected every 44 years. Then each century should see about 5 SNe.

Notable Historical supernovae in the Milky Way			
SN 1006	Lupus	Ia	–7.5 mag, brightest in history
SN 1054	Taurus	II	Chinese SN; Crab Nebula as the SNR
SN 1572	Cassiopeia	Ia	Tycho’s Nova
SN 1604	Ophiuchus	Ia	Kepler’s Star
SN 1680	Cassiopeia	IIb	Not observed, Cas A as the SNR

Solar System Abundances



https://en.wikipedia.org/wiki/R-process#/media/File:Nucleosynthesis_periodic_table.svg



The 25 Most Abundant Nuclei

Rank	*Z*	*Symbol*	*A*	*Nucleon Fraction*	*Source (process)*
1	1	H	1	7.057e-01	Big Bang
2	2	He	4	2.752e-01	Big Bang, CNO, pp
3	8	O	16	9.592e-03	Helium
4	6	C	12	3.032e-03	Helium
5	10	Ne	20	1.548e-03	Carbon
6	26	Fe	56	1.169e-03	*e*-process
7	7	N	14	1.105e-03	CNO
8	14	Si	28	6.530e-04	Oxygen
9	12	Mg	24	5.130e-04	Carbon
10	16	S	32	3.958e-04	Oxygen
11	10	Ne	22	2.076e-04	Helium
12	12	Mg	26	7.892e-05	Carbon
13	18	Ar	36	7.740e-05	Silicon, Oxygen
14	26	Fe	54	7.158e-05	*e*-process, Silicon
15	12	Mg	25	6.893e-05	Carbon
16	20	Ca	40	5.990e-05	Silicon, Oxygen
17	13	Al	27	5.798e-05	Carbon
18	28	Ni	58	4.915e-05	Silicon, *e*-process
19	6	C	13	3.683e-05	CNO
20	2	He	3	3.453e-05	Big Bang, pp
21	14	Si	29	3.448e-05	Carbon, Neon
22	11	Na	23	3.339e-05	Carbon
23	26	Fe	57	2.840e-05	*e*-process
24	14	Si	30	2.345e-05	Carbon, Neon
25	1	H	2	2.317e-05	Big Bang

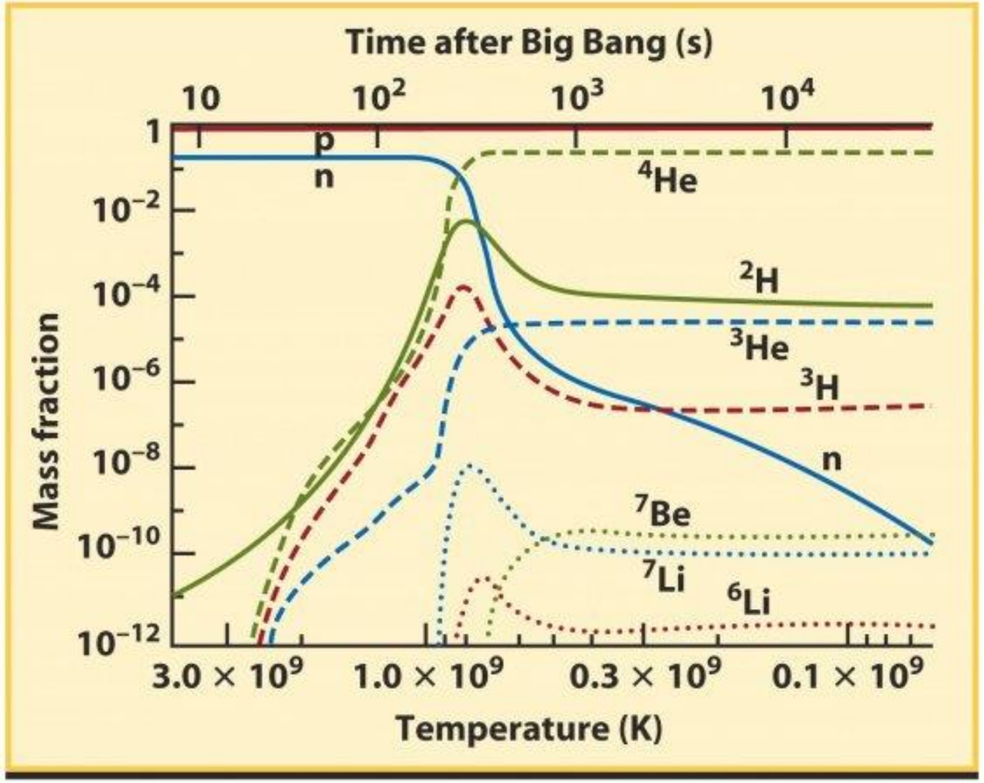
Arnett

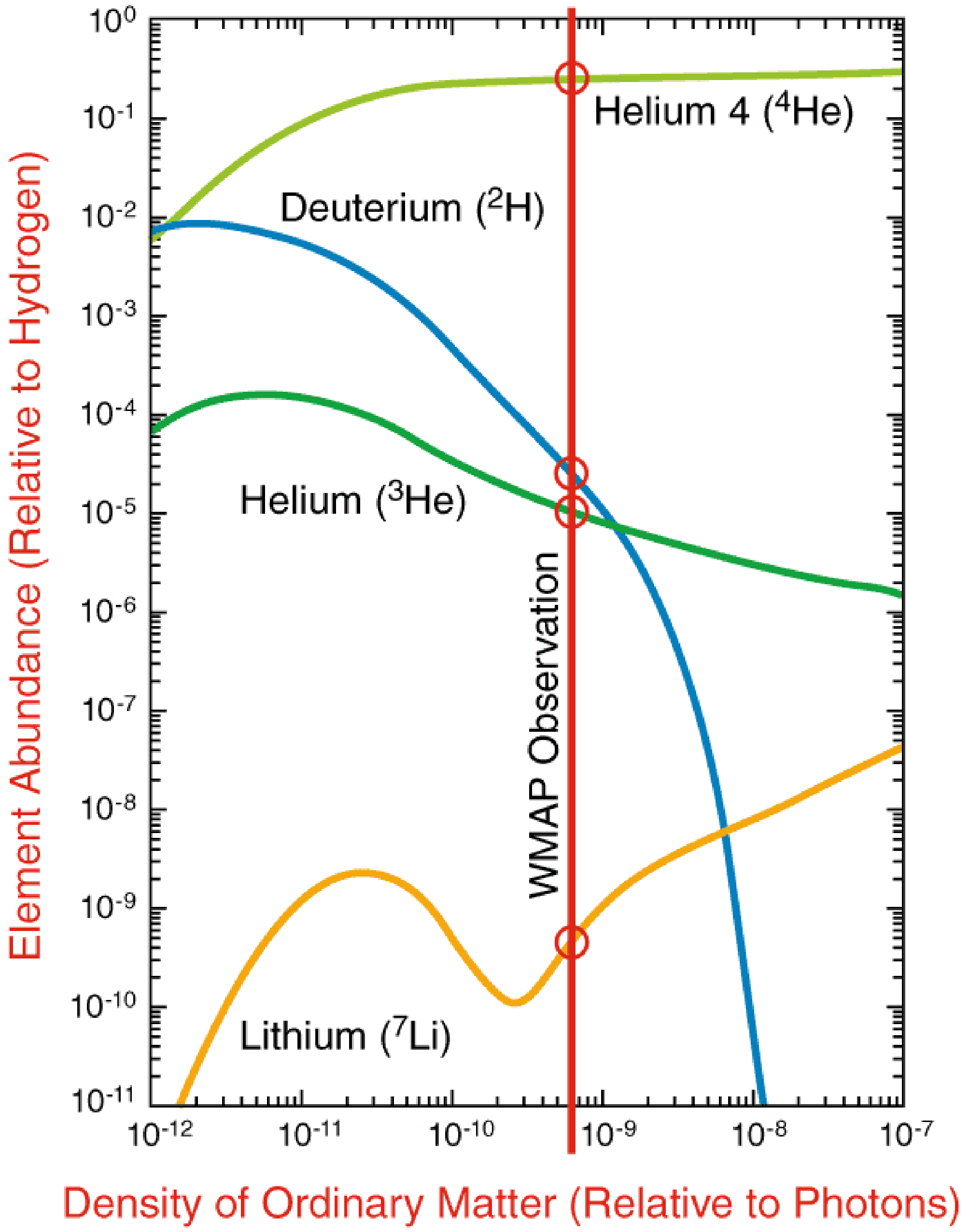
Prediction:

✓ $[\,^4\mathrm{He/H}] \approx 0.25$ → obs OK

✓ $[\mathrm{D/H}]$, $[\,^4\mathrm{He/H}]$, , $[\,^3\mathrm{He/H}]$, $[\mathrm{Li/H}]$ density dependent → obs all same densities

WMAP (CMB) obs → consistent result

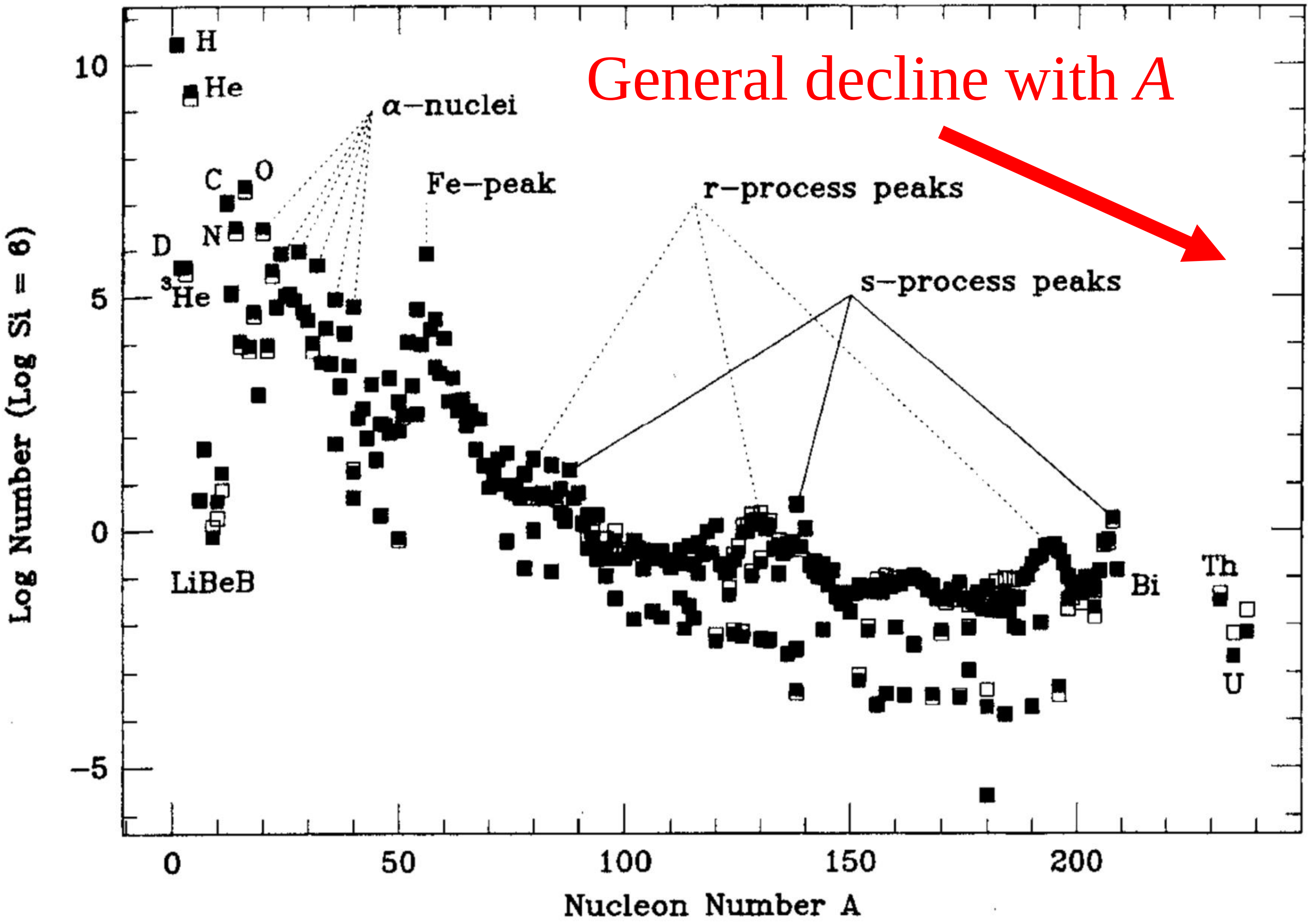




NASA/WMAP Science Team
WMAP101087

Element Abundance graphs: Steigman, Encyclopedia of Astronomy and Astrophysics (Institute of Physics) December, 2000

Solar System Abundances



General decline with *A*

Z ↑, Coulomb barrier
↑ ↑ for charged
particle reactions
→ elements produced
by neutron capture

Different symbols from different compilations

Arnett

Cosmic abundance and stellar/galaxy evolution (Burbidge, E. M., Burbidge, G. R., Fowler, W. A., & Hoyle, F. (1957)

Big Bang → H:He=10:1

Stellar Interior

10^7 K → p-p, CNO (fusing proton, in a proton rich or neutron poor gas) **(p process)**

10^8 K → triple-alpha to C → continue to fuse α particles → mass number multiples of 4 by fusing **(α process)**

4×10^9 K → nuclear equilibrium → V, Cr, Mn and elements of the iron group **(e process)**

Explosive events

Neutron capture rapidly (compared to the competing β decays) → neutron-rich isotopes **(r process)**
e, g., the radioactive elements ^{235}U, ^{238}U, at the expense of the iron group

Neutron capture slowly (compared to the competing β decays) → neutron-rich isotopes **(s process)**

Valleys at *A*=5 to 15 (LiBeB) and *A*~ 45 (Sc=scandium)

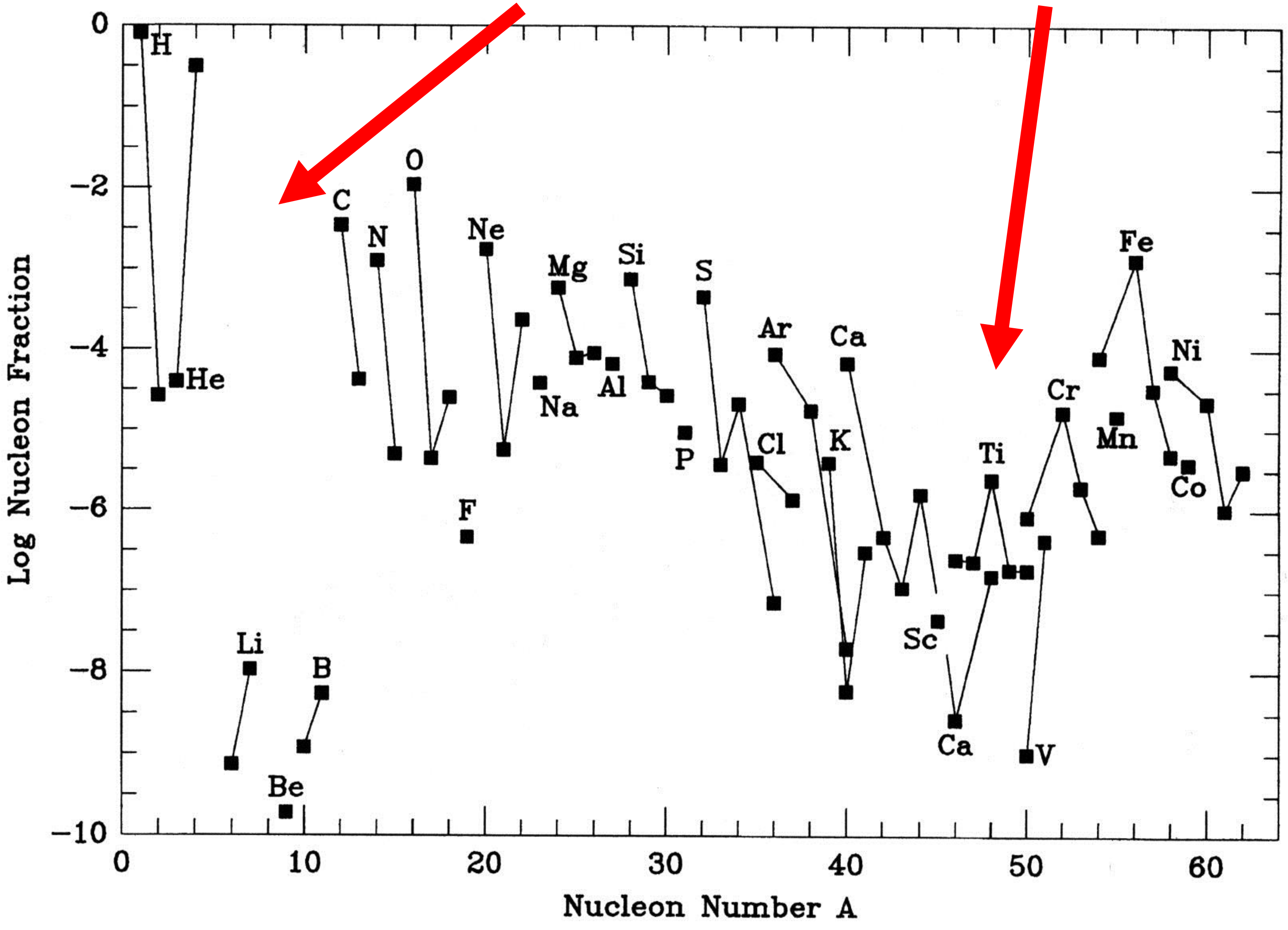


Fig. 2.2. Abundance ($A = 1, 64$)

Isotopes connected by lines.

Arnett

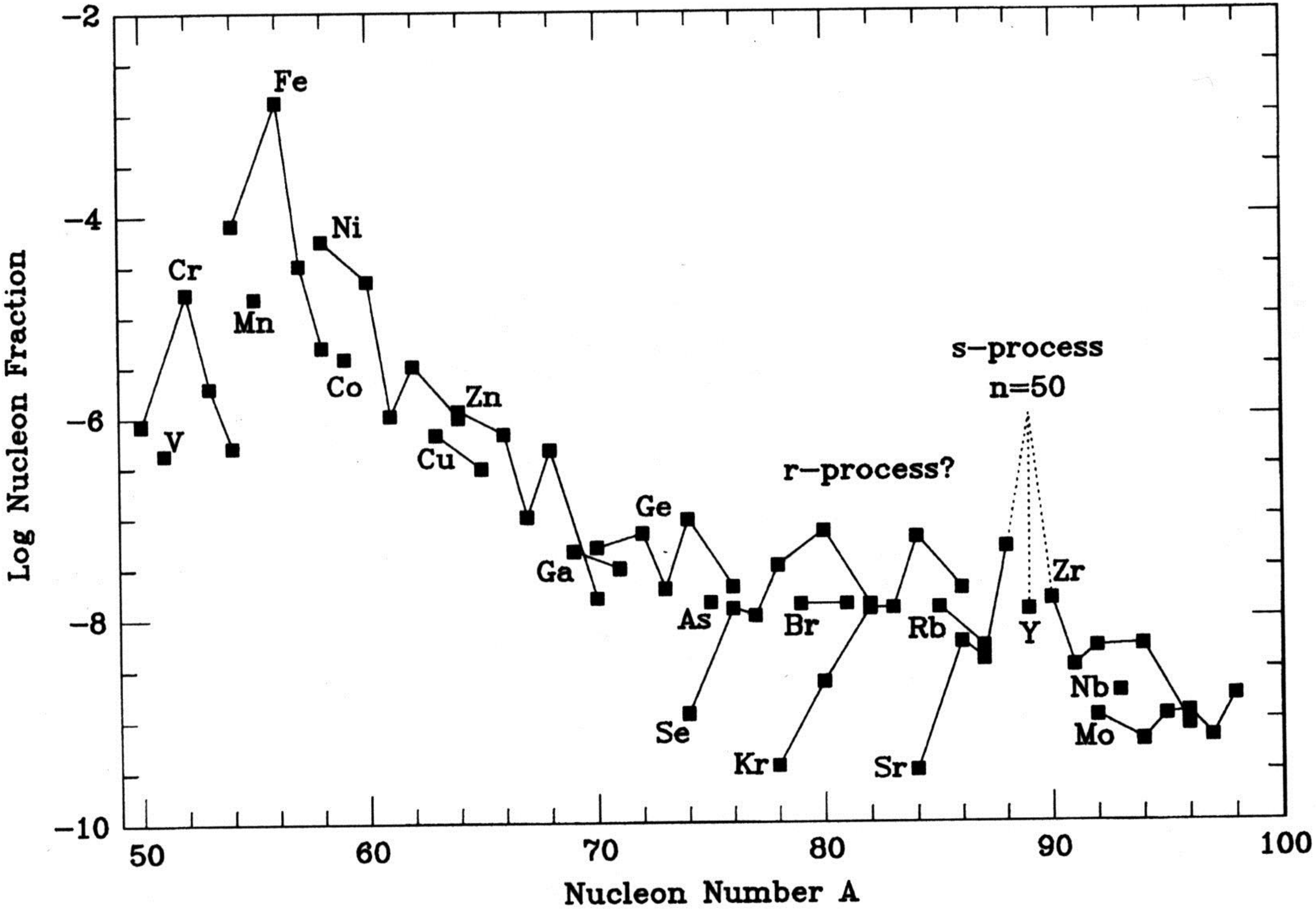


Fig. 2.3. Abundance ($A = 50, 100$)

- Other than H and He, the rest (‘metals’) is rare

  ∵ penetration prob. between positively charged nuclei has
  an exponential dependence $(Z_1 Z_2)$
  e.g., O + O → 64 times stronger than in H + H

- Even *A* nuclei are favored; especially for even-even elements, i.e., even *Z* and even *N*.

- $Z = N$ → **α particle nuclei** e.g., ^{12}C, ^{16}O, ^{20}Ne, ^{24}Mg, ^{28}Si, ^{32}S, ^{36}Al, ^{40}Ca

- First odd-*A* element is ^{25}Mg; placed the 15th

- Among the top, only ^{14}N is not even-even.

◆ Nuclei, like atoms, have a shell structure;
"**magic numbers**" of protons are particularly tightly bound, e.g., ^{4}He (Z=N=2), ^{16}O (Z=N=8)

◆ ^{56}Fe not even-even; most tightly bound is ^{56}Ni.
SN I and II light curves provide evidence that Ni → Co → Fe for *A*=56 ➔ Abundance peaks at ^{56}Fe

◆ For A > 60, via neutron capture
- ✓ **r-process**: rapid relative to beta-decay
- ✓ **s-process**: slow *nuclei already tightly bound → small cross section for neutron capture (slow compare to beta decays)*

(Burbidge, Burbidge, Fowler, & Hoyle; see Clayton)

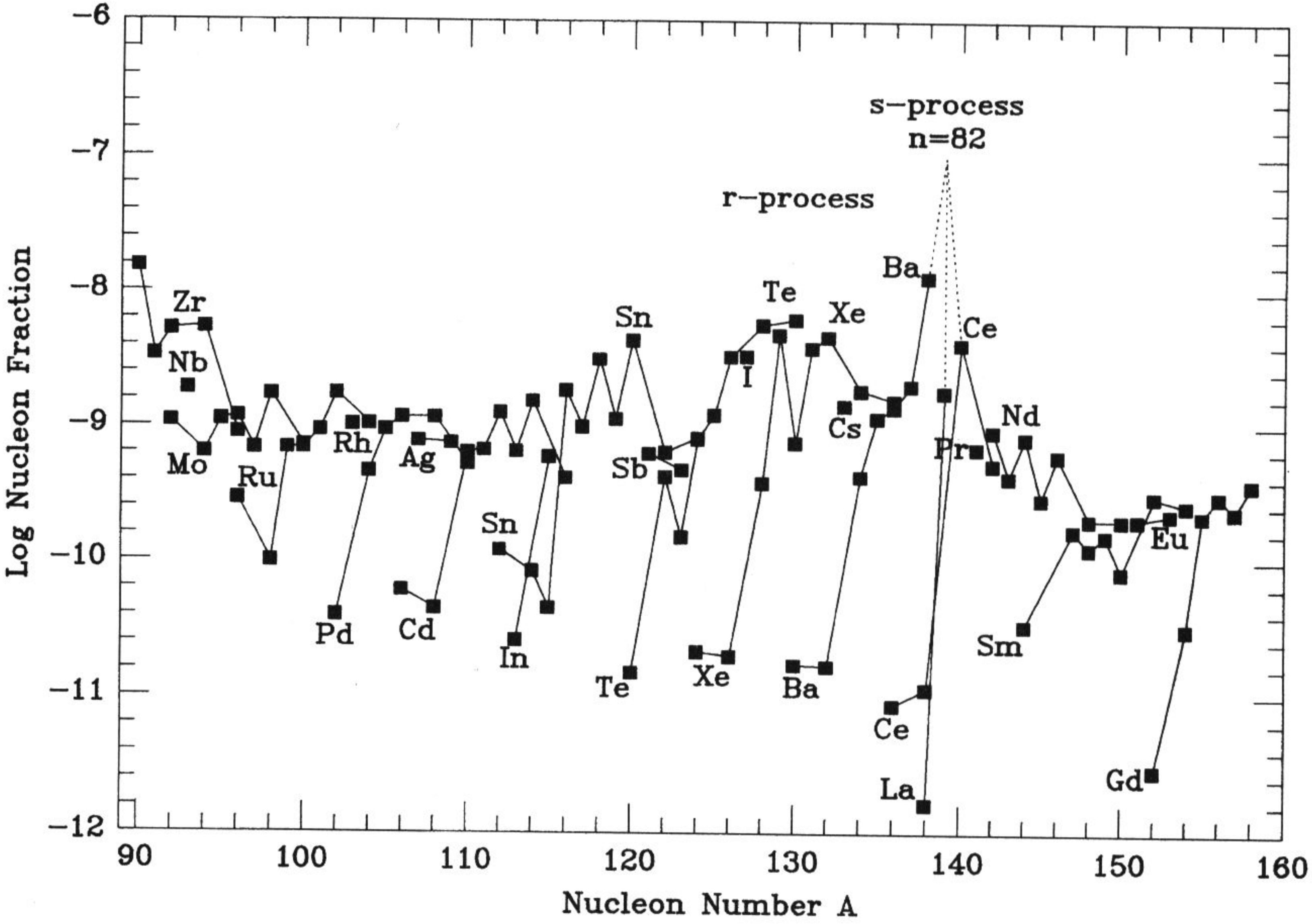


Fig. 2.4. Abundance ($A = 90$, 160)

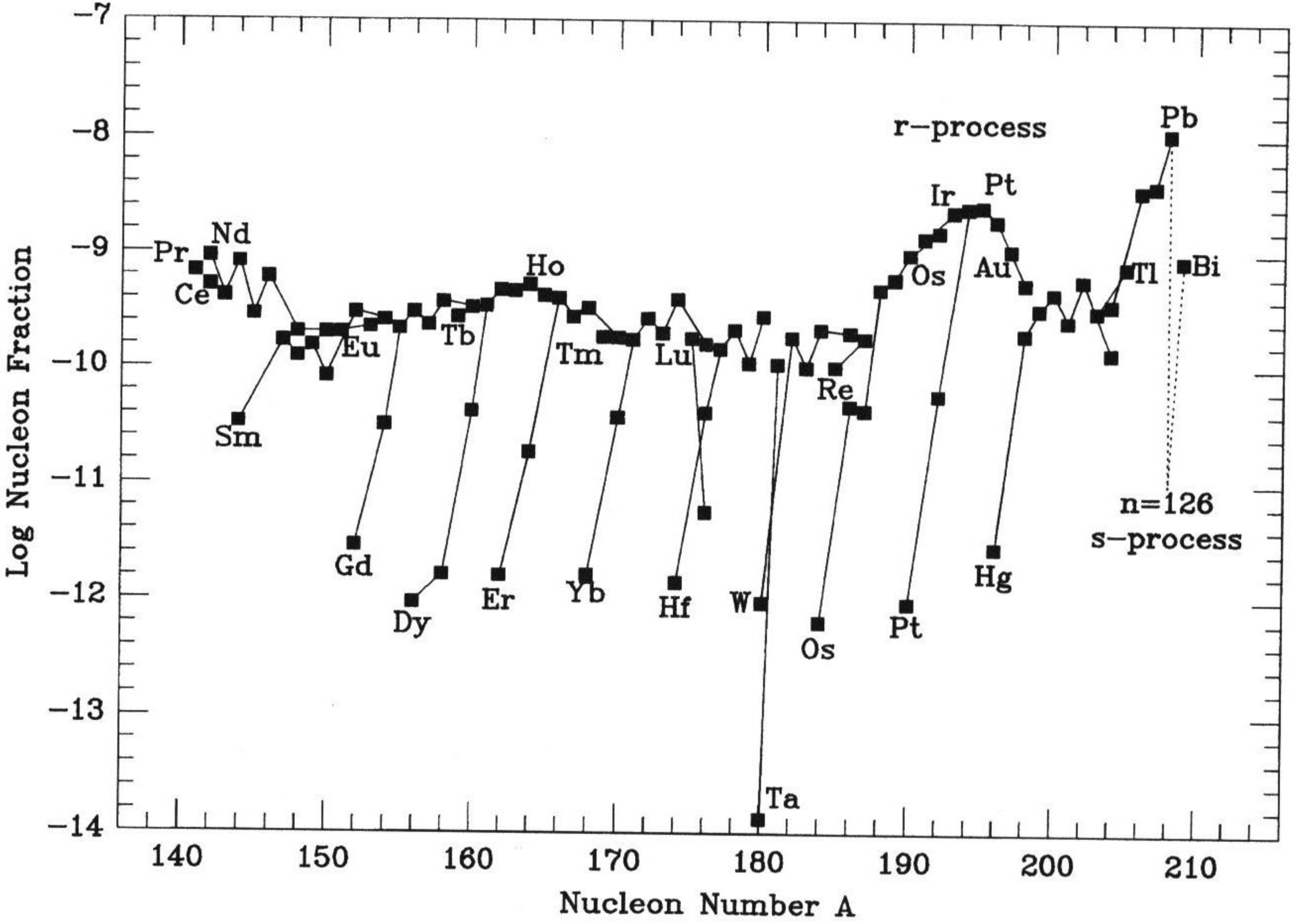
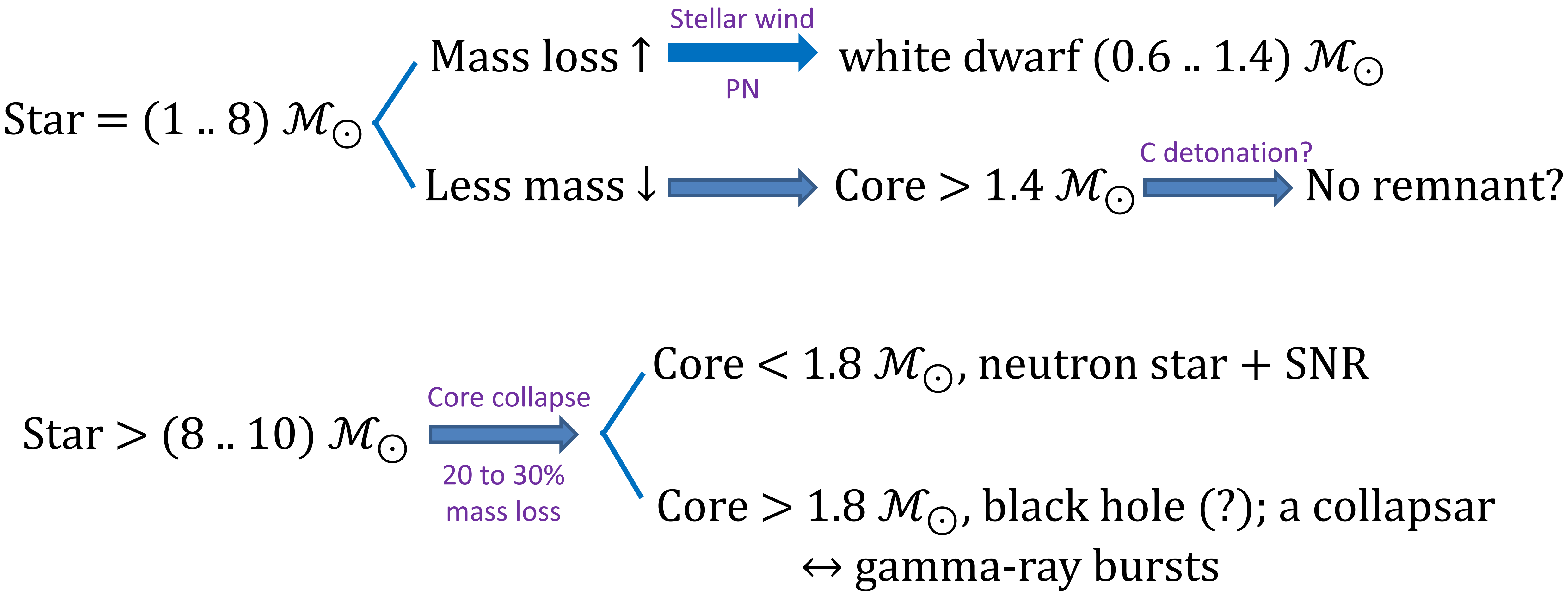


Fig. 2.5. Abundance ($A = 140$, 210)

Stellar Evolutionary Path



Star = (1 .. 8) $\mathcal{M}_\odot$

- Mass loss ↑ $\xrightarrow[\text{PN}]{\text{Stellar wind}}$ white dwarf (0.6 .. 1.4) $\mathcal{M}_\odot$
- Less mass ↓ $\longrightarrow$ Core > 1.4 $\mathcal{M}_\odot$ $\xrightarrow{\text{C detonation?}}$ No remnant?

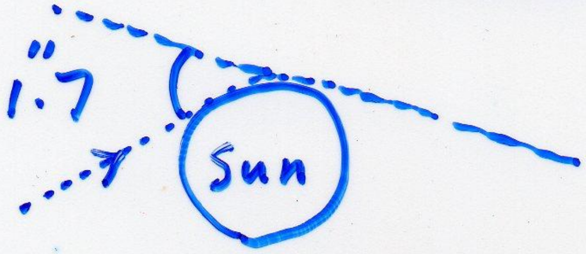
Star > (8 .. 10) $\mathcal{M}_\odot$ $\xrightarrow[\text{20 to 30\% mass loss}]{\text{Core collapse}}$

- Core < 1.8 $\mathcal{M}_\odot$, neutron star + SNR
- Core > 1.8 $\mathcal{M}_\odot$, black hole (?); a collapsar ↔ gamma-ray bursts

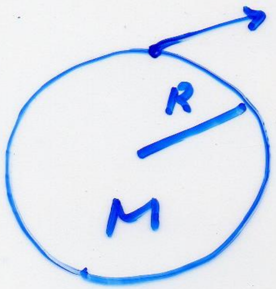
Black Holes predicted by General Relativity

Spacetime near a mass is warped

Total solar eclipse



A full treatment of a BH required GR. But for an electrically neutral, non-rotating BH, classical derivations give the same results as with the relativisitic approach.



$$v_{escape} = \sqrt{\frac{2GM}{R}} \equiv c$$

∴ Too much mass in a volume.

Scharzschild radius

$$\boxed{R_s = \frac{2GM}{c^2}} \simeq 3 \frac{M}{M_\odot} \text{ [km]}$$

∴ M ↑ , ρ_{BH} ↓↓

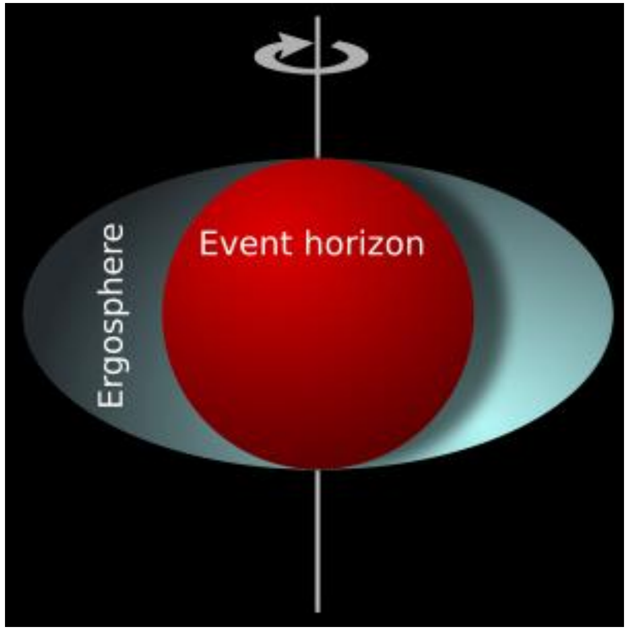
Surface of R_s = Event Horizon for uncharged, non-rotating BHs

Schwarzschild black hole

BH (M=10^8 sun), <u>average</u> density ~ water

	Nonrotating ($J = 0$)	Rotating ($J > 0$)
Uncharged ($Q = 0$)	Schwarzschild	Kerr
Charged ($Q \neq 0$)	Reissner-Nordström	Kerr-Newman

General BH metric, with M, J and Q = Kerr-Newman metric.



The two physical relevant surfaces of a Kerr black hole.

Table 1.4

Compact Objects in the Solar Neighborhood[a]

Object	Mass Range of Parent Star ($M_\odot$)	Integrated Galactic Birth Rate (yr^{-1})	Number Density (pc^{-3})	$\frac{\rho}{\rho_T}$	$\langle d \rangle$ (pc)
White dwarfs	1–4	0.16	1.5×10^{-2}	0.070	2.5
Neutron stars	4–10	0.021	2.0×10^{-3}	0.020	4.9
Black holes	> 10	0.0085	8.0×10^{-4}	0.22	6.7

[a] These values are obtained from Eqs. (1.3.17)–(1.3.21).

Note: Nearest known white dwarf: Sirius B, 2.7 pc. Nearest known neutron star: PSR 1929 + 10, 50 pc. Nearest known black hole candidate: Cygnus X-1, ~2 kpc.

Size of the Universe

13.7 billion yrs

$R_{observable} \sim 137 \times 10^{8} \times 10^{13}$ km

$\sim 1.4 \times 10^{23}$ km

$M_{obs} \sim 10^{11} M_\odot / \text{gal} \cdot 10^{12} \text{gal.}$ (+ dark matter + dark energy)

$\sim 10^{23} M_\odot$

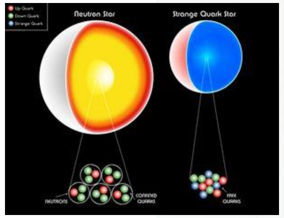
$$\left(R_s \sim 3 \frac{M}{M_\odot} [\text{km}] \right)$$

$R_{obs} \sim R_s$

The whole Universe is a BH!

Quark Stars / Strange Stars

hyperthetical type of stars composed of quark matter or strange matter



currently 6 "flavors" of quarks

up, down, strange, charm,
top, bottom

spin $1/2$

when a neutron star is further compressed

neutrons → break down to up and down quarks → break down strange quark

dark matter candidates ?

These highly mathematical & speculative

Some recent observations, e.g. in some SNe → existence of quark stars ?

Magnetars

A neutron star w/ an extremely strong $\vec{B}$

(10^{11} teslas or 10^{15} gauss)

Earth/Sun ~ 1 G

Ap/Bp ~ 10^3 G

WDs ~ 10^6 G

NSs ~ 10^{12} G

collapse → energy sources

(i) $\breve{E}_{grav} \sim 0.2\,Mc^2 \sim 10^{53.8}$ ergs

(ii) $\breve{E}_{rot} \sim \frac{1}{2} I \Omega^2 \sim 10^{52.7}$ ergs $I_{45}\,\Omega_4^2$

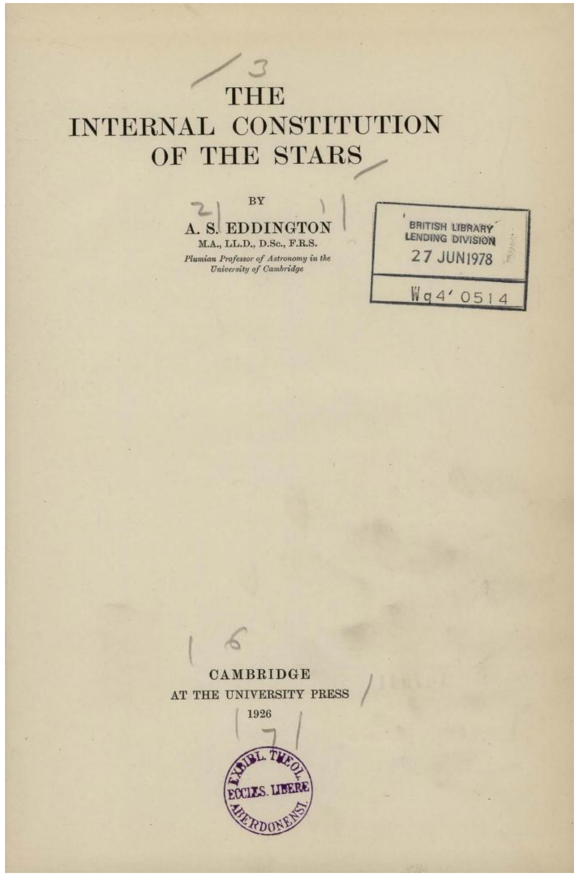
$\vec{B}$ links the fast spinning core to the outlying envelopes

magnetic breaking

$D \sim 20$ km ; spin : several times/s

Time spans short , $\lesssim 10^4$ yr

$\vec{B}$ decays



THE
INTERNAL CONSTITUTION
OF THE STARS

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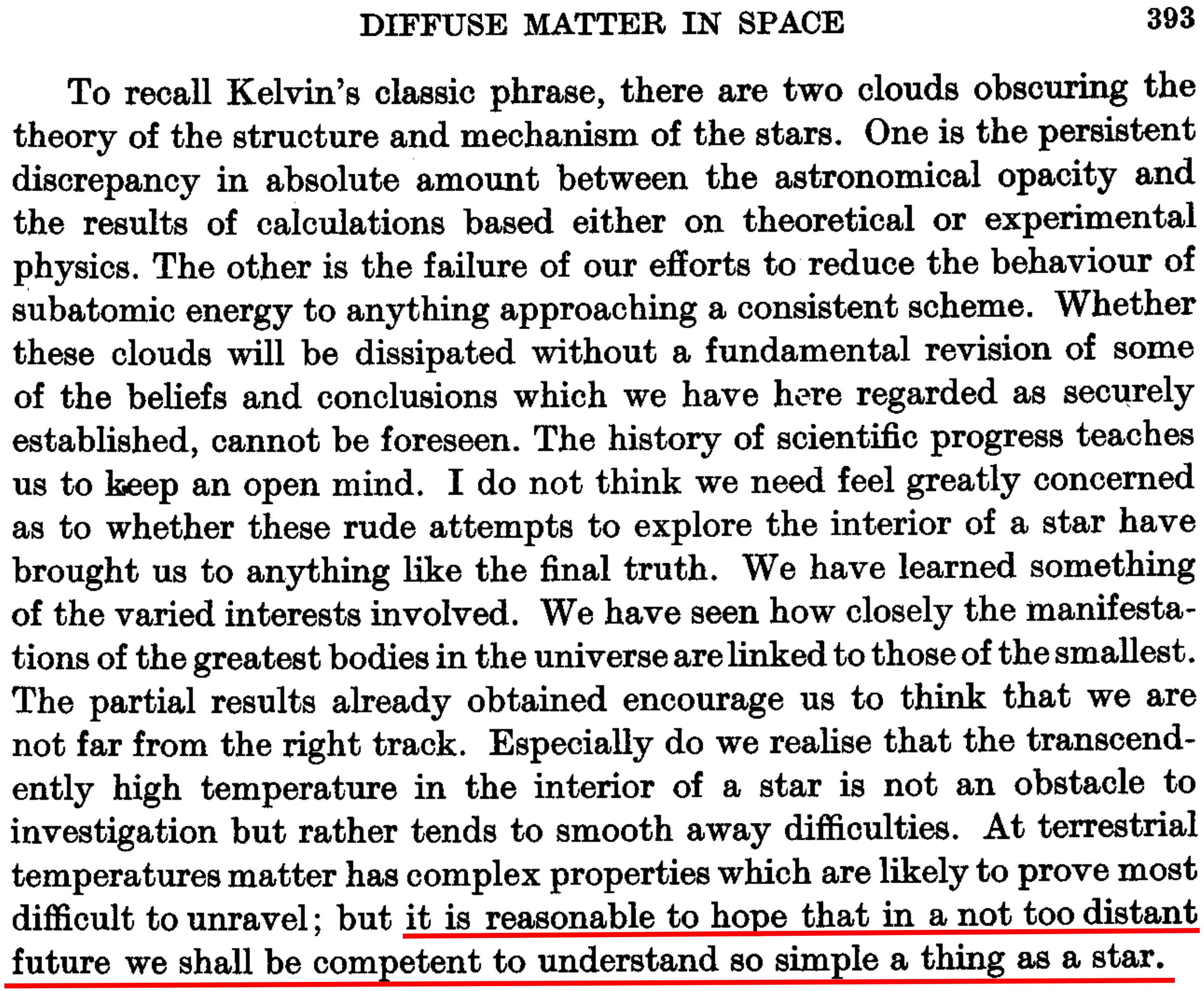
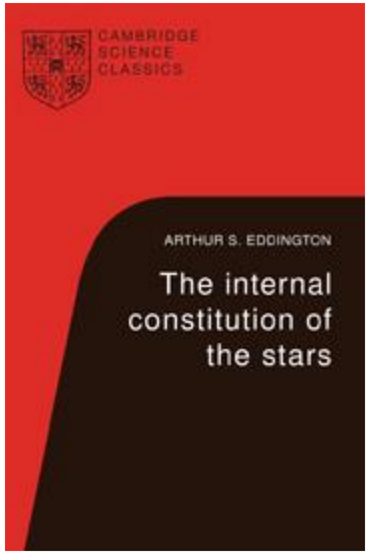


To recall Kelvin's classic phrase, there are two clouds obscuring the theory of the structure and mechanism of the stars. One is the persistent discrepancy in absolute amount between the astronomical opacity and the results of calculations based either on theoretical or experimental physics. The other is the failure of our efforts to reduce the behaviour of subatomic energy to anything approaching a consistent scheme. Whether these clouds will be dissipated without a fundamental revision of some of the beliefs and conclusions which we have here regarded as securely established, cannot be foreseen. The history of scientific progress teaches us to keep an open mind. I do not think we need feel greatly concerned as to whether these rude attempts to explore the interior of a star have brought us to anything like the final truth. We have learned something of the varied interests involved. We have seen how closely the manifestations of the greatest bodies in the universe are linked to those of the smallest. The partial results already obtained encourage us to think that we are not far from the right track. Especially do we realise that the transcendently high temperature in the interior of a star is not an obstacle to investigation but rather tends to smooth away difficulties. At terrestrial temperatures matter has complex properties which are likely to prove most difficult to unravel; but it is reasonable to hope that in a not too distant future we shall be competent to understand so simple a thing as a star.



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ARTHUR S. EDDINGTON

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