Structure and Evolution of Stars

Lecture 20: Supernovae, Core Collapse and Remnant Properties (#1)

- Maximum ZAMS mass for formation of a White Dwarf
- Observations of Supernovae – supernovae types from spectra
- Core Collapse Supernovae
  - Photodisintegration
  - Electron Capture or Neutronisation
  - Supernovae Energetics
  - Neutrino Emission and SN1987A
  - Estimate mean-free-path of neutrinos at nuclear densities

Core Collapse Supernovae and Exotic Remnants

• White dwarfs are extreme in terms of their densities but the physical properties are relatively well understood.

• Stars with ZAMS masses in range 0.1-10M_{sun} believed to result in white dwarf remnants, Helium composition for low-mass stars with no Helium ignition on giant branch and Carbon+Oxygen composition for stars that ignite Helium on the giant branch

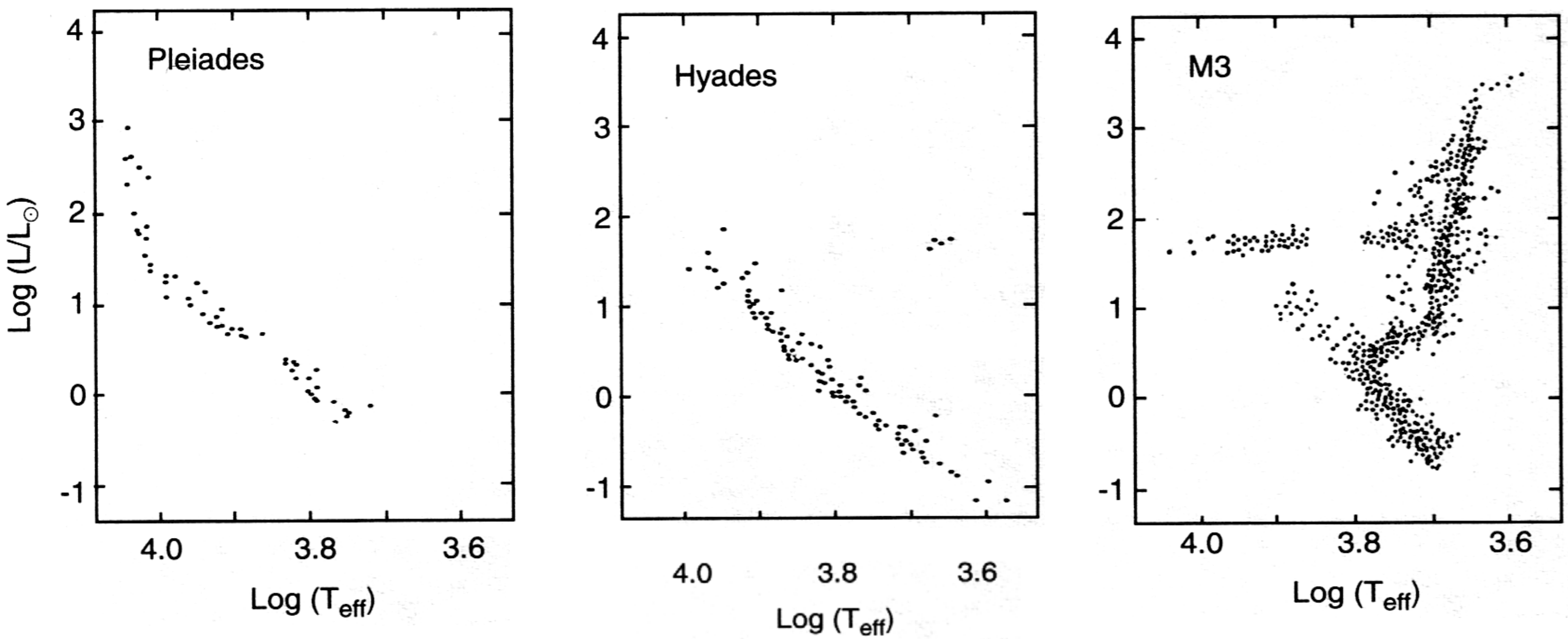
• The upper mass limit is not well determined but is believed to lie in the range ~8-11M_{sun}

• How can the mass limit be more tightly constrained via observations?

• From the upper end, new studies of supernovae progenitors, as in *Star of the Week* #2, now making progress

• From the lower end, use observations of young stellar clusters, looking for presence of white dwarfs as a function of main sequence turnoff mass

HR-diagrams for 3 stellar clusters of very different ages

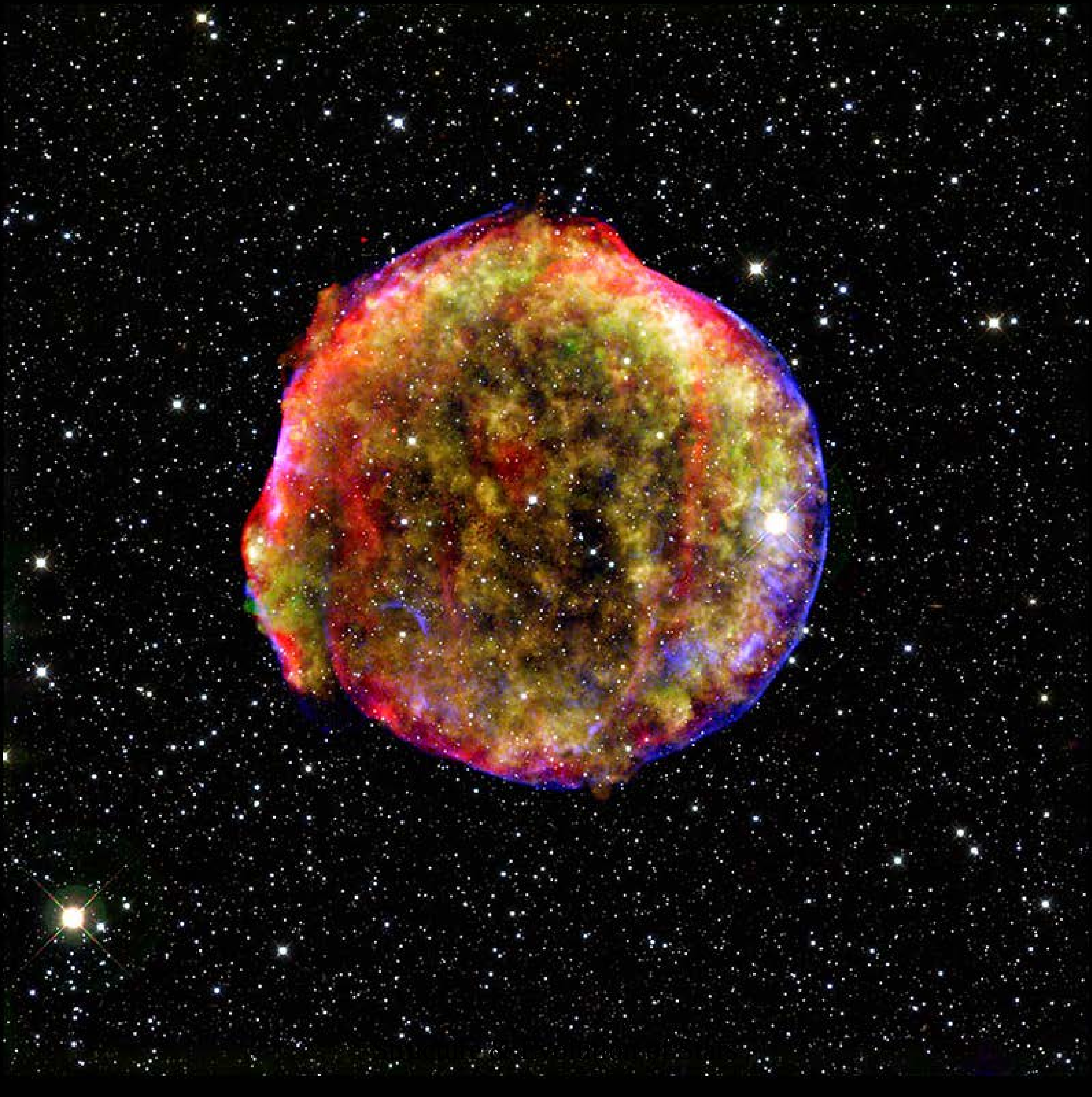


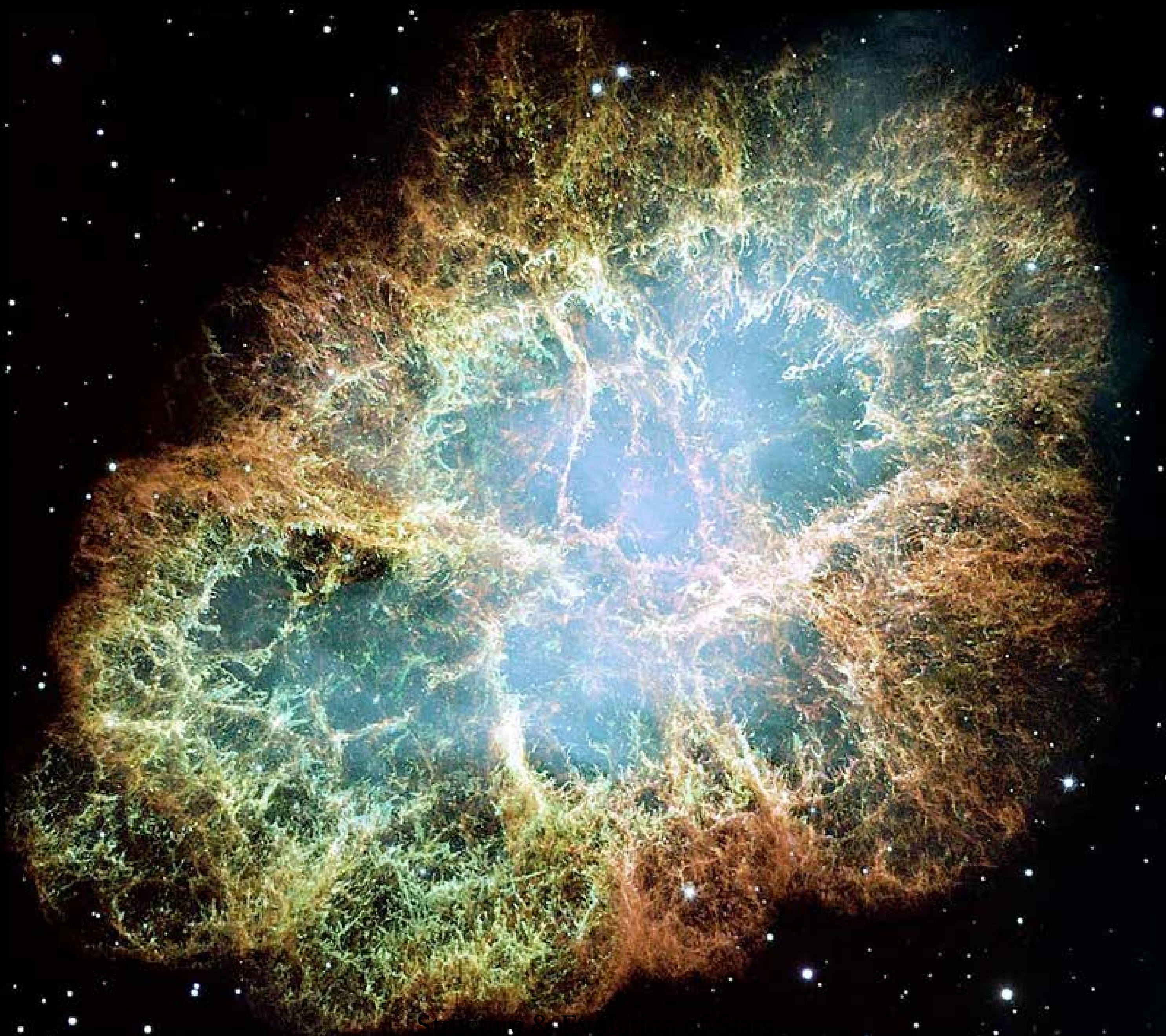
Radically different morphology of HR-diagrams as a function of age. An "isochrone" describes location of stars of fixed age in HR-diagram. (M3 $\approx 11 \times 10^9$yr; Hyades $\approx 6 \times 10^8$yr)


2005ed
2005ef
2005ei
2005ez
2005fa
2005fd
2005ff
2005fv
2005gj
2005hc
2005ij
2005ir
2005js
2005ku
2005lk
2006fs
2006gf
2006hr
2006hx
2006jz
2006kd
2006ne
2006nz
2006ob
2007jh
2007jt
2007jw
2007la
2007lr
2007mi
2007mn
2007ol
2007om
2007pd
2007rs
2007sn

Table 16.1. Historical supernovae.

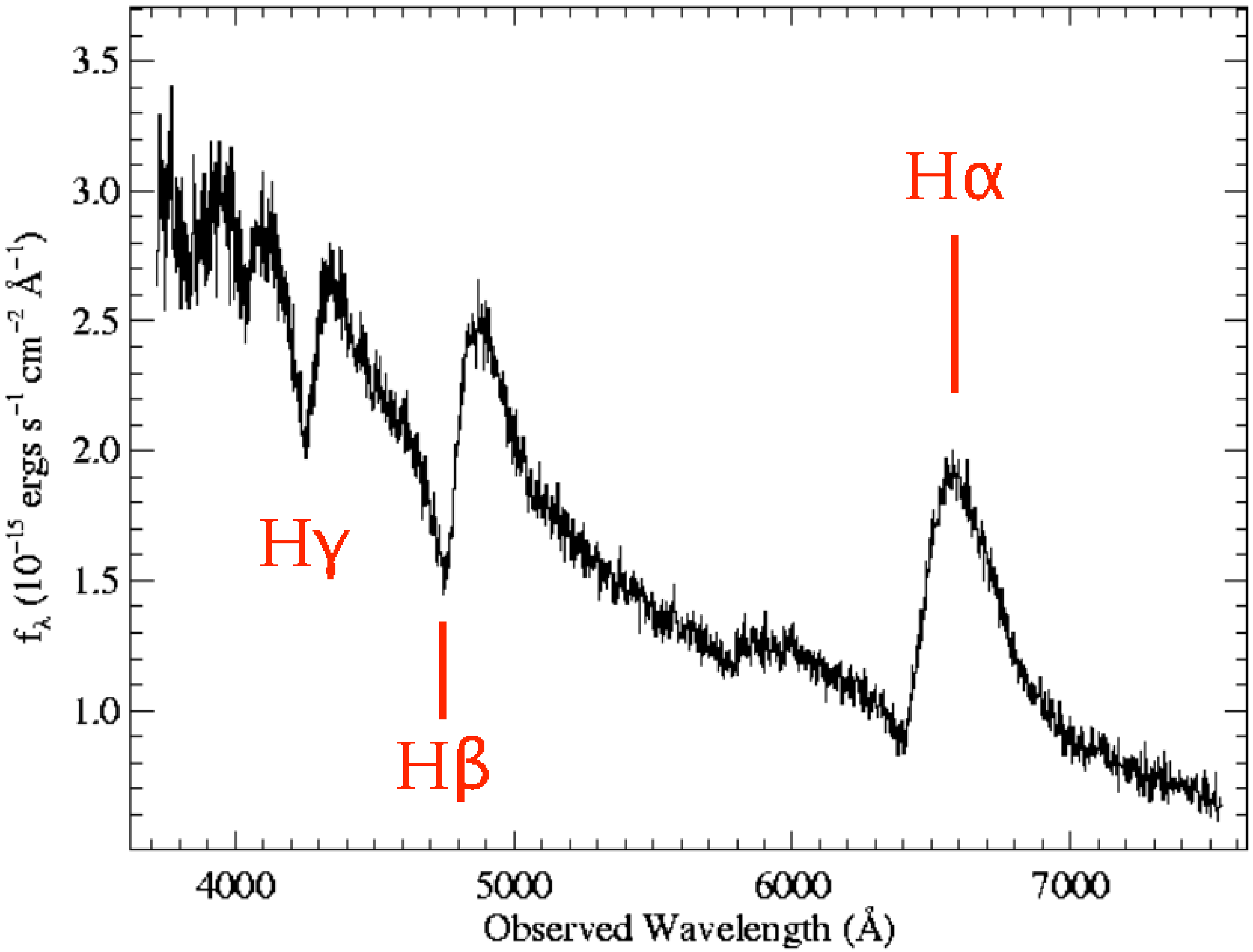
year (AD)	V (peak)	SN remnant	SN type	compact object
185	−2	RCW 86	Ia?	–
386		?	?	
393	−3	?	?	
1006	−9	PKS 1459-41	Ia?	–
1054	−6	Crab nebula	II	NS (pulsar)
1181	−1	3C 58	II	NS (pulsar)
1572	−4	'Tycho'	Ia	–
1604	−3	'Kepler'	Ia?	–
~1667	$\gtrsim +6$	Cas A	IIb	NS



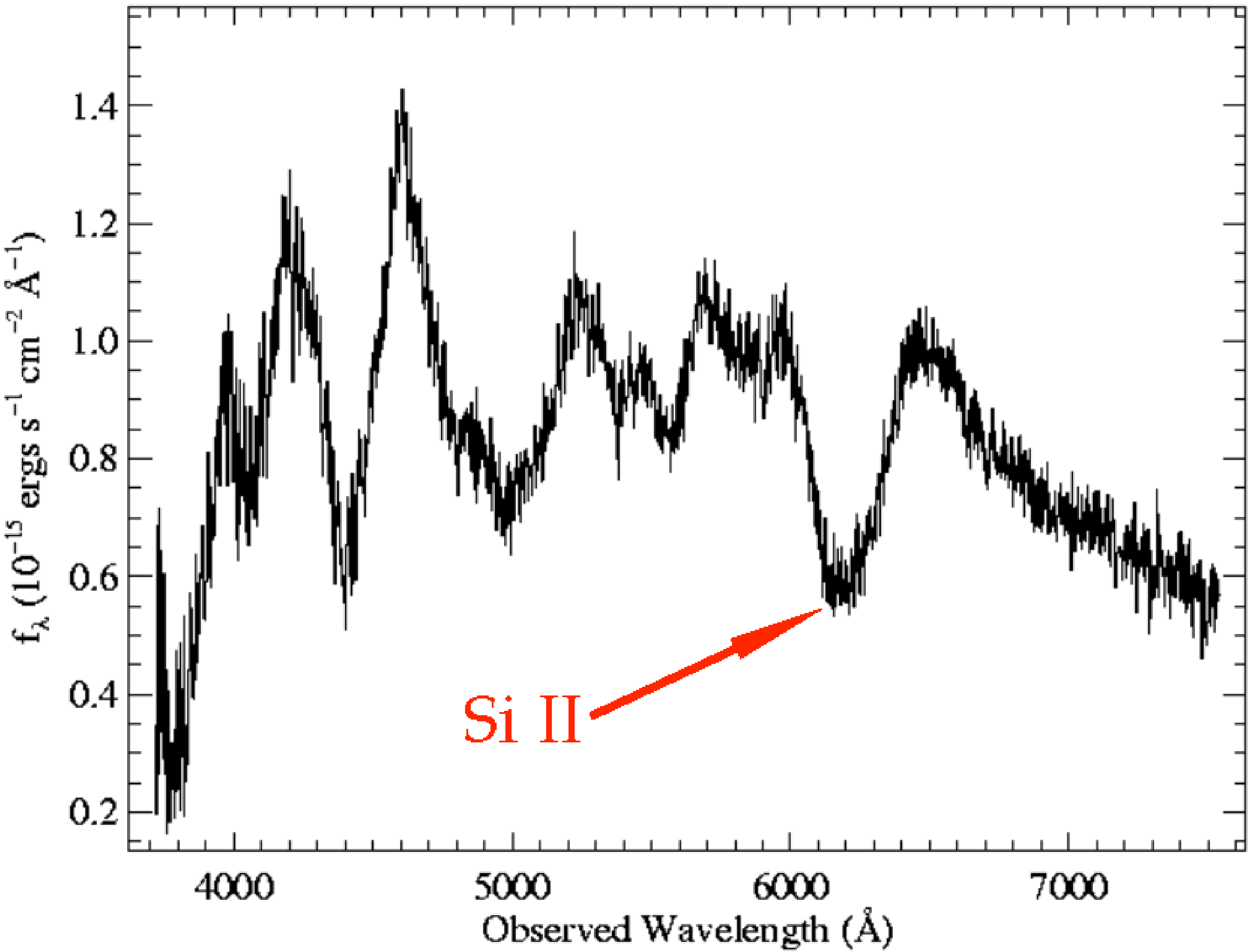


Structure & Evolution of Stars

Type II SN 2001cm



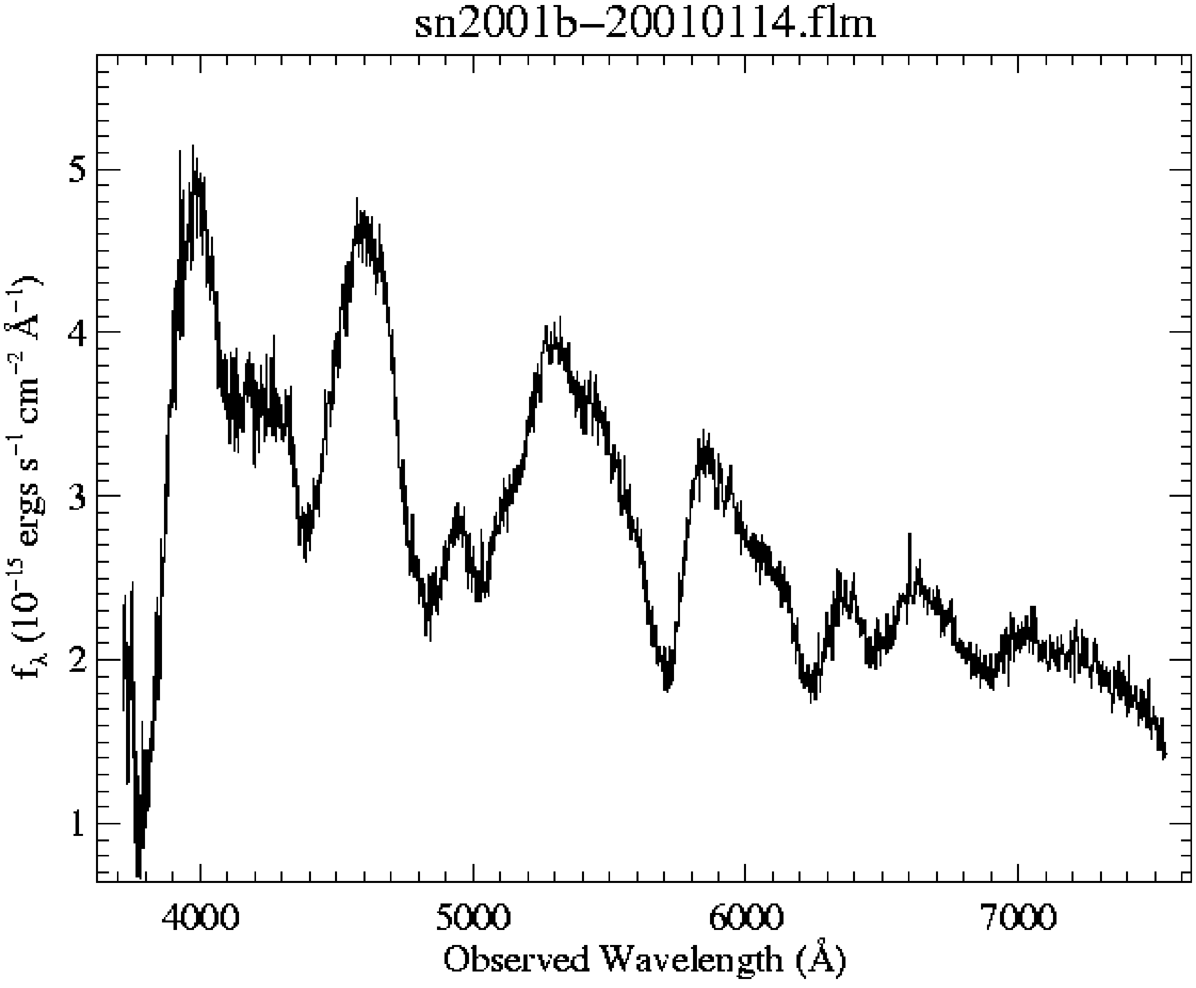
Type Ia SN 2001N

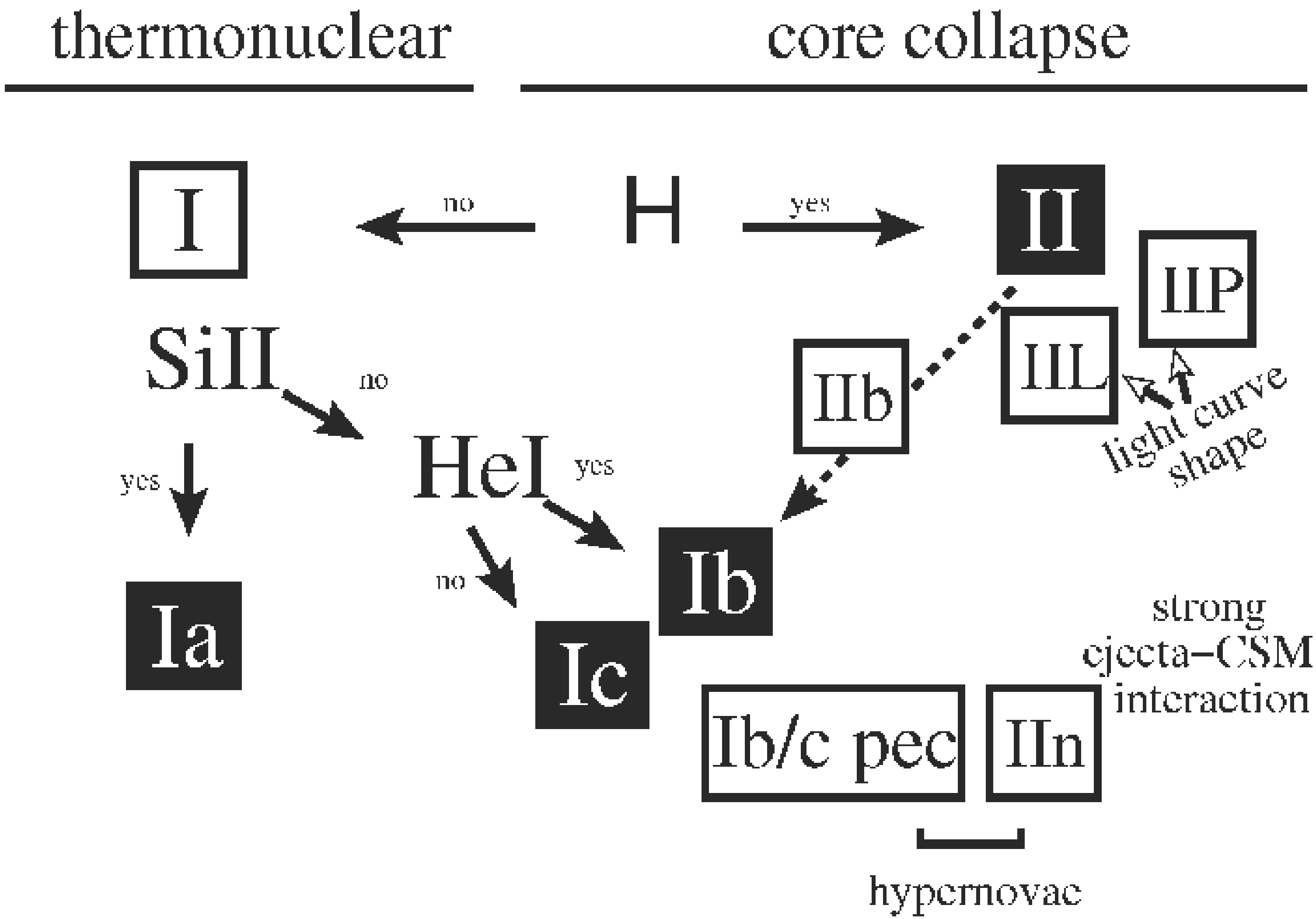


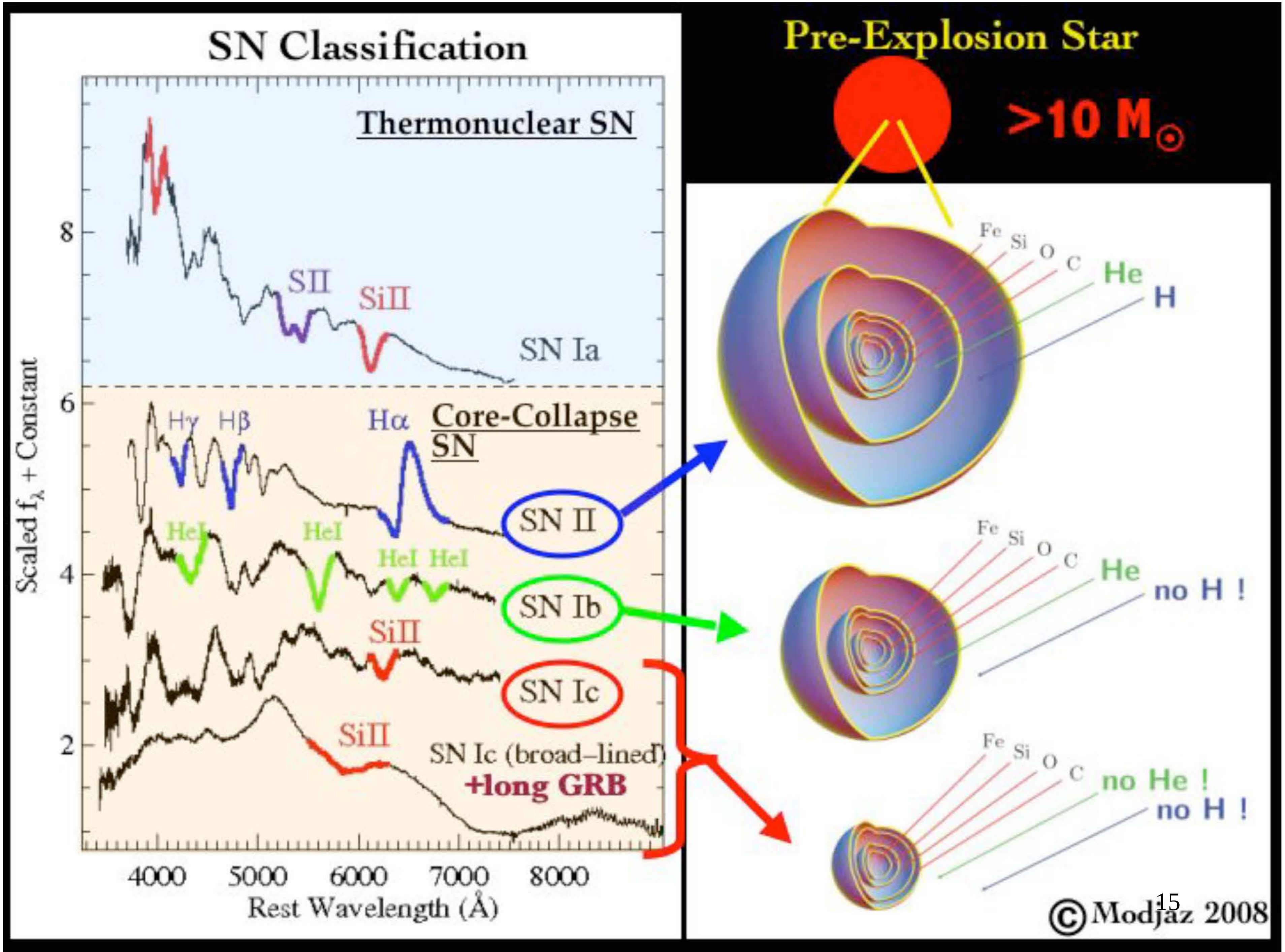
• SN2001B

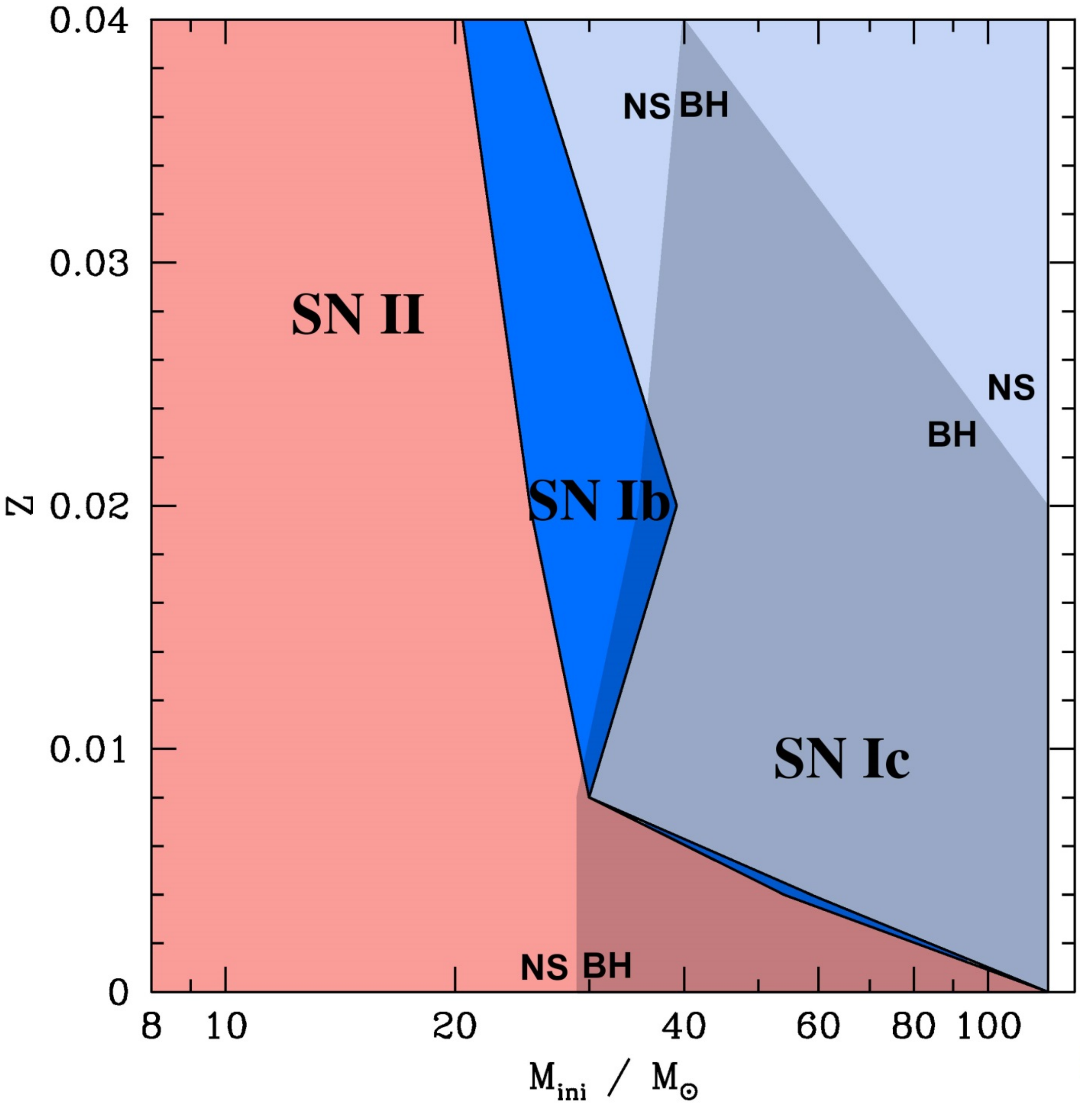
Type Ib – no Hydrogen lines but believed to result from core collapse

What type of star might produce a spectrum with little Hydrogen evident?




thermonuclear
core collapse
I
no
H
yes
II
IIP
SiII
IIL
IIb
no
light curve
shape
yes
HeI
yes
no
Ib
Ia
Ic
strong
ejecta–CSM
interaction
Ib/c pec
IIn
hypernovae


SN Classification
Thermonuclear SN
SII
SiII
SN Ia
Core-Collapse SN
Hγ
Hβ
Hα
SN II
HeI
HeI
HeI
HeI
SN Ib
SiII
SN Ic
SiII
SN Ic (broad-lined)
+long GRB
Scaled f$_\lambda$ + Constant
Rest Wavelength (Å)
Pre-Explosion Star
>10 M$_\odot$
Fe
Si
O
C
He
H
no H !
no He !
© Modjaz 2008



Different supernovae as a function of initial stellar mass and the metallicity.

Assumes that a supernova is produced even when a blackhole formed

Georgy et al. 2009

Core Collapse Supernovae and Exotic Remnants

• Above the maximum ZAMS mass for creation of a white dwarf remnant, stars run through the full nuclear burning spectrum up to the peak at Iron in the binding energy per nucleon
• Core of inert Fe grows as Silicon burning in shell deposits more Fe onto the core
• Lack of energy source within the core leads to contraction, with electron degeneracy pressure providing the resistance to gravity
• As mass of Fe core approaches the Chandrasekhar mass (about $1.4M_{sun}$ for composition of Fe) electron velocities become relativistic. Equation of state tending towards $P \propto \rho^{4/3}$

and core becomes unstable and will collapse on dynamical timescale

$$\text{Density } \rho \approx 10^{12}\,\text{kgm}^{-3} \Rightarrow \tau_{dyn} \approx \frac{1}{3\sqrt{G\rho}} \approx 10^{-2}\,\text{s}$$

Core Collapse: Photodisintegration

• Stability of the core is undermined by photodisintegration of the nuclei

• As the density increases the temperature of the core rises and the photon energies reach point where photodisintegration occurs:

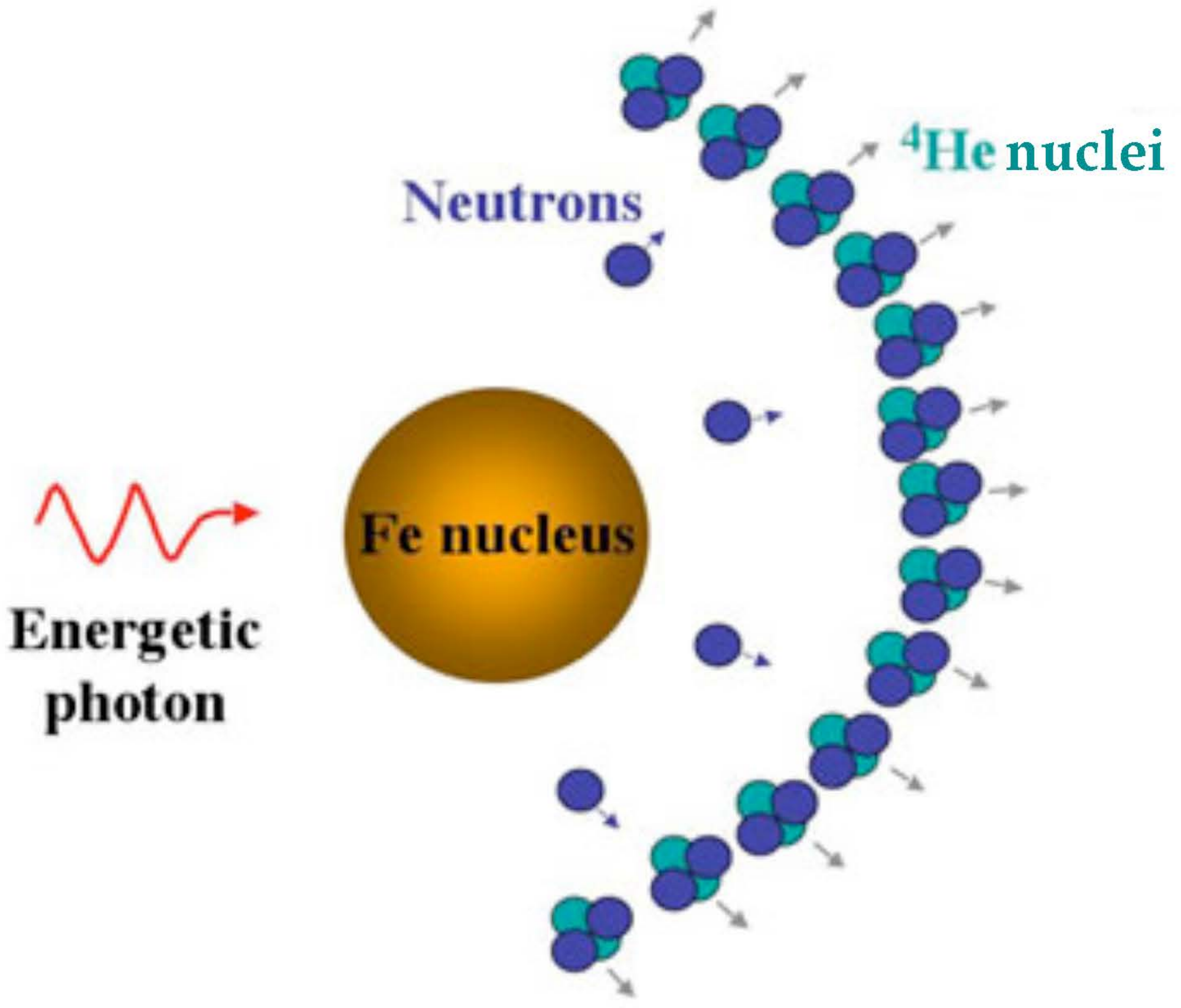
$$\gamma + {}^{56}_{26}\mathrm{Fe} \rightarrow 13\,{}^{4}_{2}\mathrm{He} + 4n$$

• Reaction absorbs energy, 124.4MeV per Fe nucleus. 1kg of Fe into He requires 2×10^{14}J, equivalent 50kilotons of TNT!

• At even higher temperature Helium photodisintegration occurs:

$$\gamma + {}^{4}_{2}\mathrm{He} \rightarrow {}^{1}_{1}\mathrm{H} + {}^{1}_{1}\mathrm{H} + 2n$$

• For a 1.4M_{sun} core, 4×10^{44}J (Fe→He), 1 $\times10^{45}$J (He→H), equivalent to the output of the Sun over 10^{10}yr. Photodisintegration effectively reverses nucleosynthesis!



Neutrons
^{4}He nuclei
Fe nucleus
Energetic photon

Core Collapse: Electron Capture

• Under normal circumstances, neutrons are unstable, with a short half-life of 615s, the decay resulting in a proton, an electron and an anti-neutrino:

$$n \rightarrow {}^{1}_{1}\mathrm{H} + e + \overline{\nu}$$

• Energy of electron =1.3MeV but in the fully degenerate core all the available energy states for the electrons are full (Lecture 8) well above 1.3MeV and the decay cannot occur

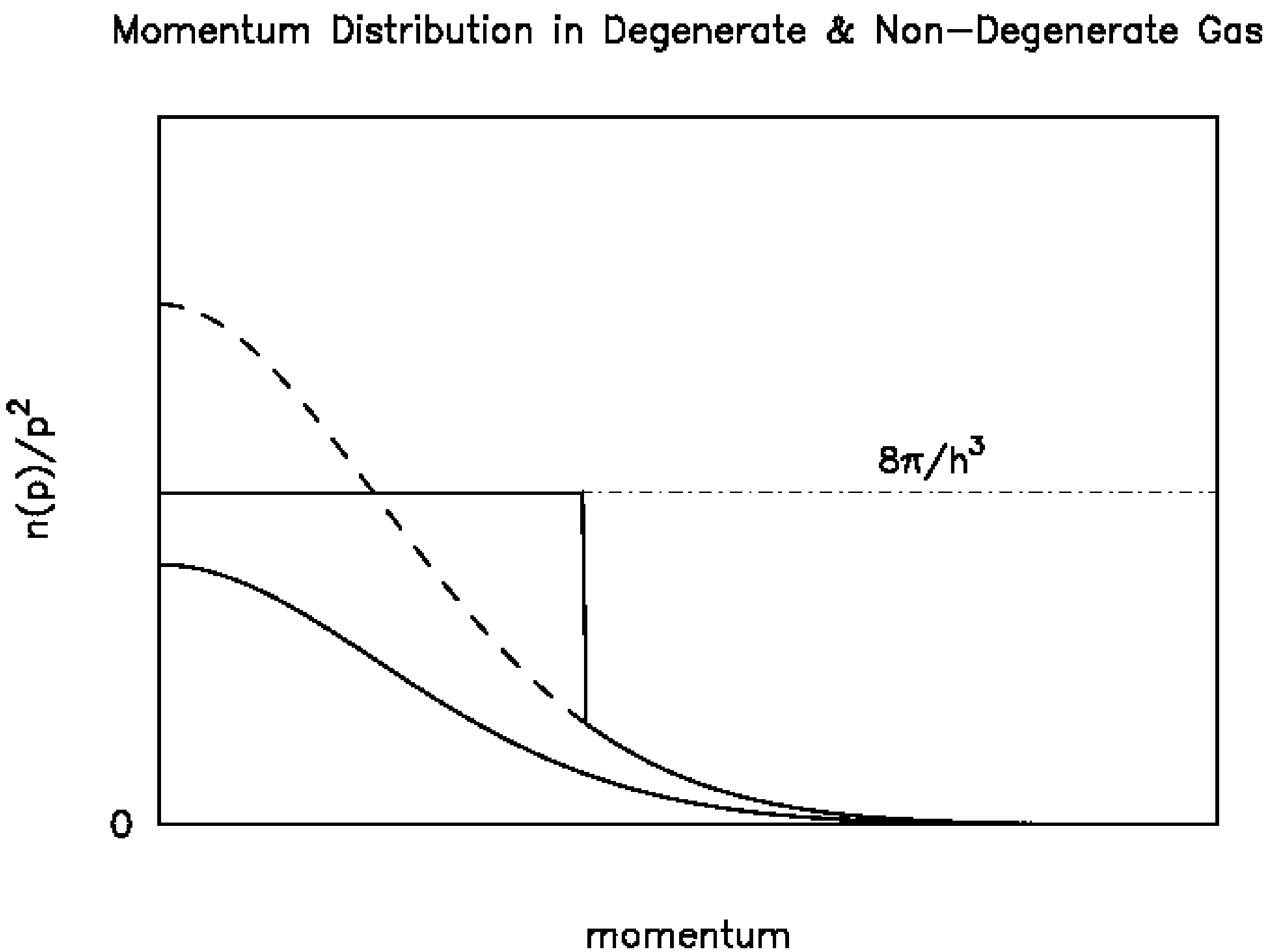
• Large electron energies mean that the reverse process can occur with 3.7MeV electrons:

$$e + {}^{1}_{1}\mathrm{H} \rightarrow n + \nu$$

also

$$e + {}^{56}_{26}\mathrm{Fe} \rightarrow {}^{56}_{25}\mathrm{Mn} + \nu$$

• This **neutronisation** continues with subsequent *e*-capture to give Cr



Momentum Distribution in Degenerate & Non–Degenerate Gas
n(p)/p^2
8π/h^3
0
momentum

Core Collapse: Electron Capture

• The effect of the neutronisation is to remove electrons from the core, causing the core to collapse as resistance to gravity reduced
• Electron capture reactions also produce neutrinos, which have very low cross-section for interaction with matter even at the core densities
• Neutrinos escape from the core, free-streaming for $\rho < 10^{14}$kgm^{-3}, removing more energy, exacerbating the predicament of the core
• An Fe-core with the Chandrasekhar-mass contains $\sim 10^{57}$ electrons, each of which leads to creation of a neutrino during electron capture. With an average energy of 10MeV per neutrino, the energy lost from the core is:

$$E_{capt} \approx 10^{57} \times (10 \times 1.6 \times 10^{-13}) = 1.6 \times 10^{45}\,\mathrm{J}$$

• Core collapses on timescale of 10^{-3}s

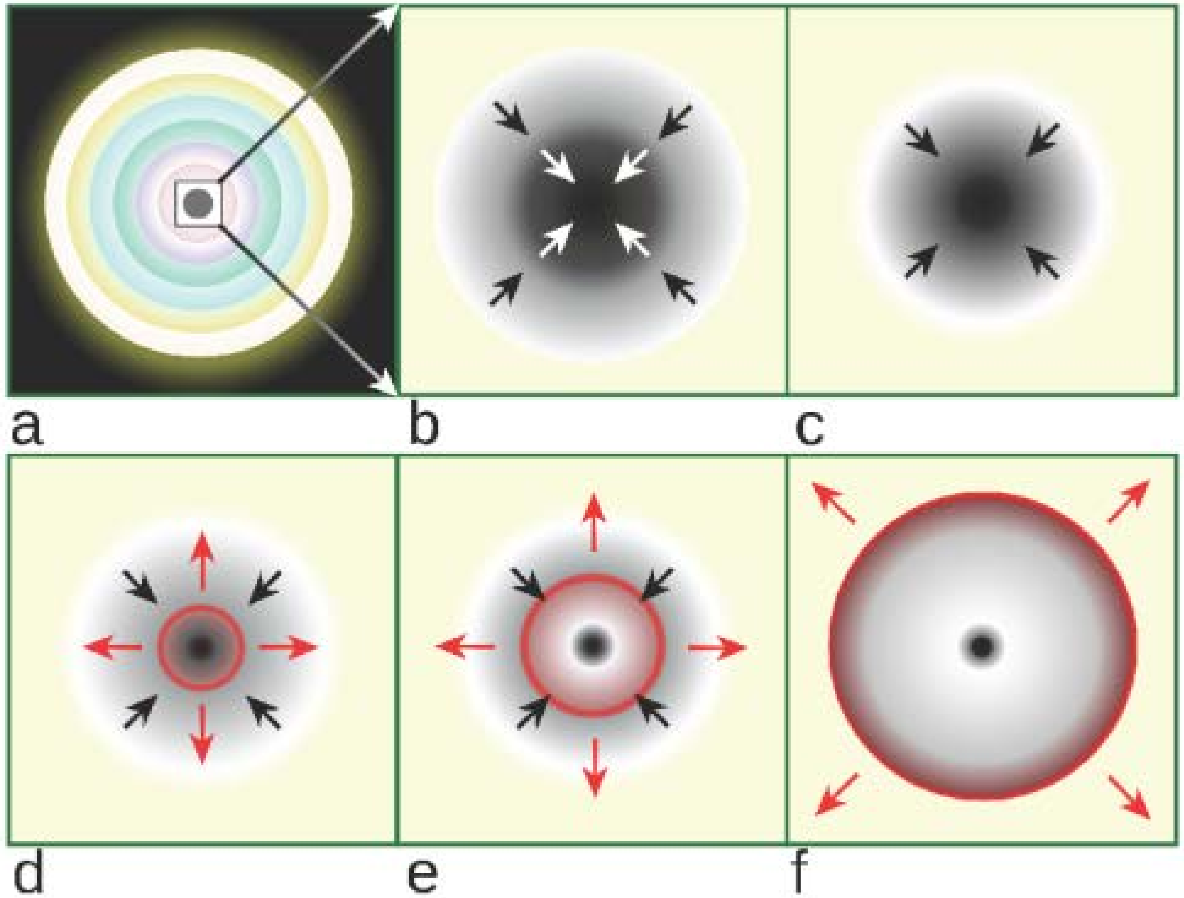


Figure 16.8: Within a massive, evolved star (a) the onion-layered shells of elements undergo fusion, forming an iron core. (b) Unable to generate energy by further fusion, the iron core starts to collapse. The inner part of the core is compressed into neutrons (c), causing infalling material to bounce (d) and form an outward-propagating shock front (red). The shock starts to stall (e), but it is re-invigorated by a process that may include neutrino interaction. The surrounding material is blasted away (f), leaving only a degenerate remnant.

Core Collapse: Energetics

• Collapse continues until halted by the neutrons packed sufficiently close that the object has nuclear density, $\rho \approx 10^{18}\,\mathrm{kgm}^{-3}$, with pressure deriving from the degeneracy pressure of the neutrons (c.f. electrons for white dwarfs)

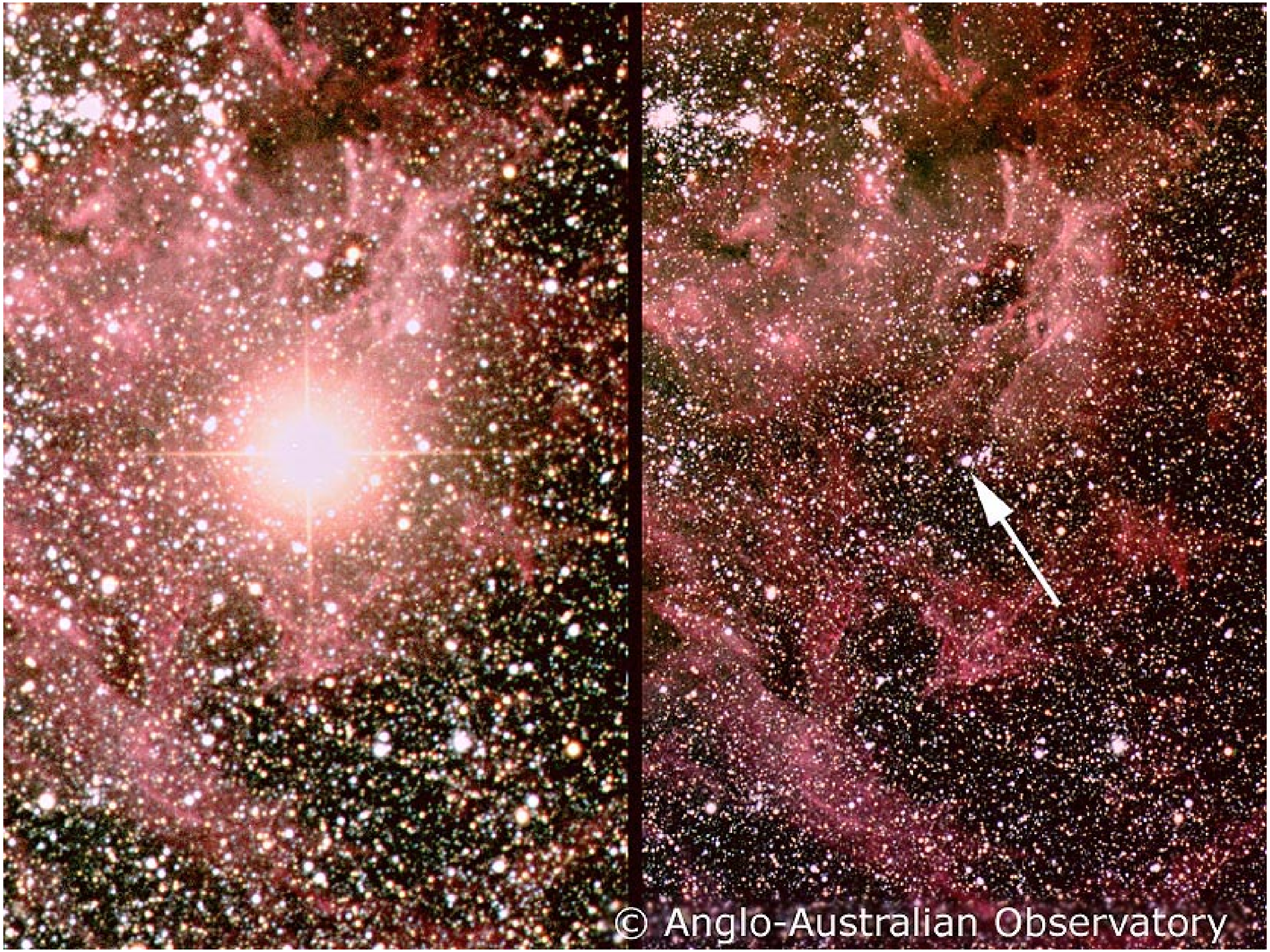
• Enormous amount of gravitational PE liberated during collapse:

$$\Delta E_{grav} \approx -GM_c^2\left(\frac{1}{R_c} - \frac{1}{R_{ns}}\right)$$

$$\approx \frac{GM_c^2}{R_{ns}} \approx 3\times 10^{46}\,\mathrm{J}$$

• Compare to amount required to reverse the fusion of H to Fe:

$$\Delta E_{nuc} \approx 7\mathrm{MeV}\,\frac{M_c}{m_H} \approx 2\times 10^{45}\,\mathrm{J}$$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Core Collapse: Energetics

• Manifestation of collapse is a supernova with observed luminosity for characteristic time:

$$L_{SN} \approx 3\times10^{10}\,\mathrm{L_{sun}} \approx 10^{37}\,\mathrm{J}; \quad \tau_{SN} \approx 1\mathrm{yr}$$

$$\Delta E_{rad} \approx L_{SN}\tau_{SN} \approx 3\times10^{44}\,\mathrm{J}$$

• Energy required to unbind the stellar envelope:

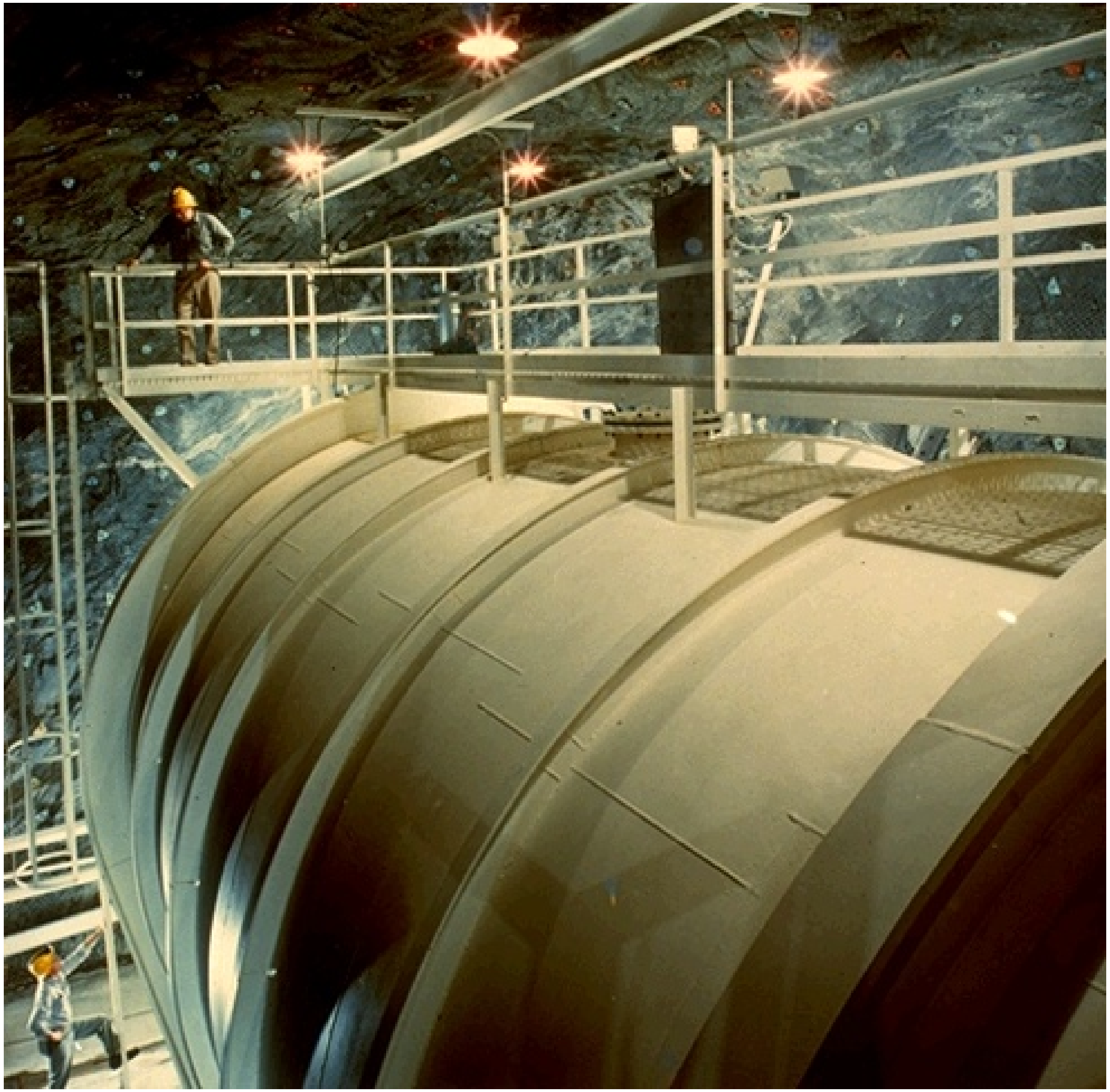
$$\Delta E_{bind} \approx \frac{GM_c(M - M_c)}{R_c} \approx 5\times10^{44}\,\mathrm{J}$$

• Energy required to accelerate envelope to expansion velocities of 10000kms^{-1}:

$$\Delta E_{kinetic} \approx 0.5(M - M_c)v_{\mathrm{exp}}^2 \approx 10^{45}\,\mathrm{J}$$

Core Collapse: Energetics

• Combined energy required to explain all manifestations of core collapse in a supernova amounts to <10% of the energy available from the collapse of the core to neutron star dimensions
• Prediction of the model is that the bulk of the energy leaves the core in the form of neutrinos (neutrino produced for every elecron and proton combining to produce a neutron via a weak interaction)
• Predicted number of neutrinos at the Earth due to the core collapse that produced SN1987A ~10^{13}m^{-2}!
• Neutrino detectors were operational in South Dakota and Japan
• US detector sits 1500m below ground, consisting of tank of 600 tons of cleaning fluid (C_2Cl_4) in an abandoned gold mine
• Small probability a rare isotope of Chlorine absorbs a neutrino to produce a rare isotope of Argon, the presence of which can be measured via radioactive decay
• Total of 20 neutrinos detected in two detectors!



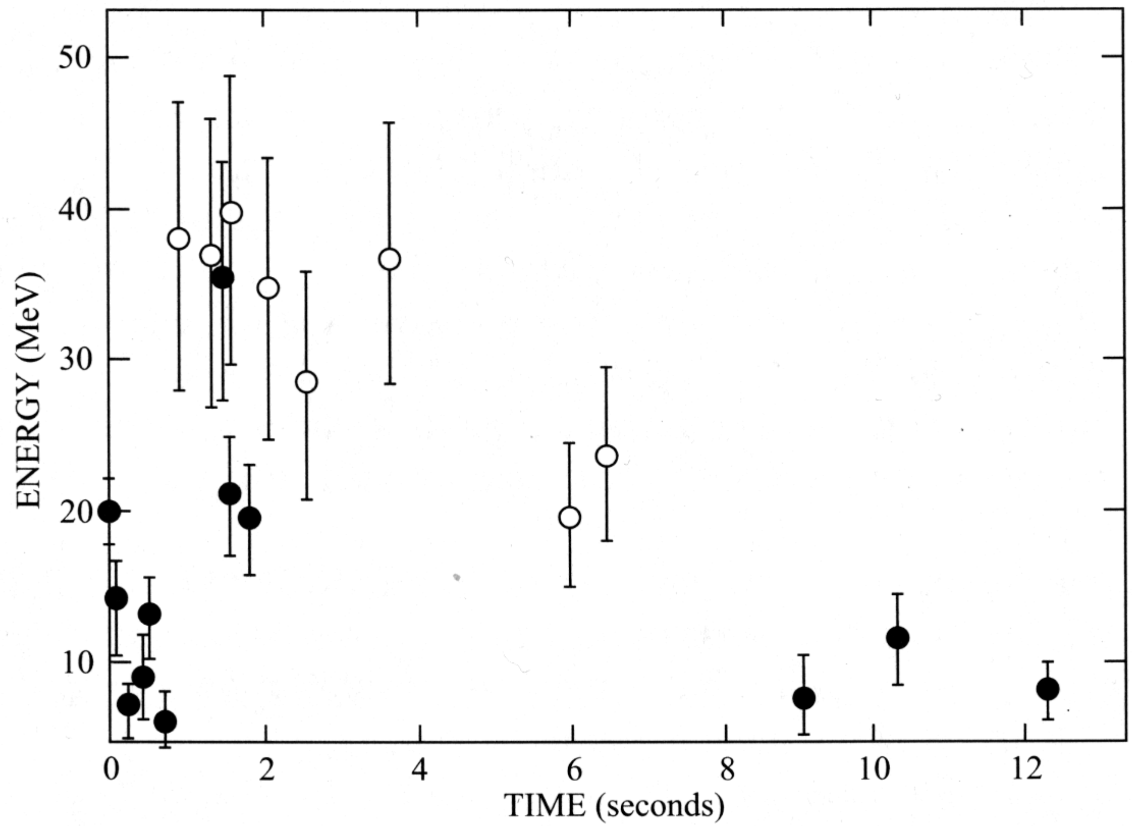


Fig. 6.3 Energy and time of arrival of neutrinos from the supernova SN1987A as registered by the Kamiokande II and IMB detectors. In all, 20 neutrinos were detected and the duration of the neutrino pulse was about 10 seconds

SN1987A: Neutrino Detection

• Energies of the neutrinos detected are consistent with the energy spectrum predicted from a blackbody-like source with $T \approx 5\times10^{10}$K

• Allowing for the efficiency (very, very low!) and the ability to detect only 1 of the 6 neutrino/anti-neutrino types, the observed number of neutrinos agrees with the prediction for the number of neutrinos liberated in the core of SN1987A

• Time of arrival of the neutrinos pre-dated the first optical radiation observed from SN1987A by hours. Why is this?

• The total time over which the neutrinos were observed was 12 s
• Can use the timescale for the arrival of the neutrinos to make estimates of important quantities describing interactions of neutrinos and matter at very high densities

SN1987A: Neutrino Detection

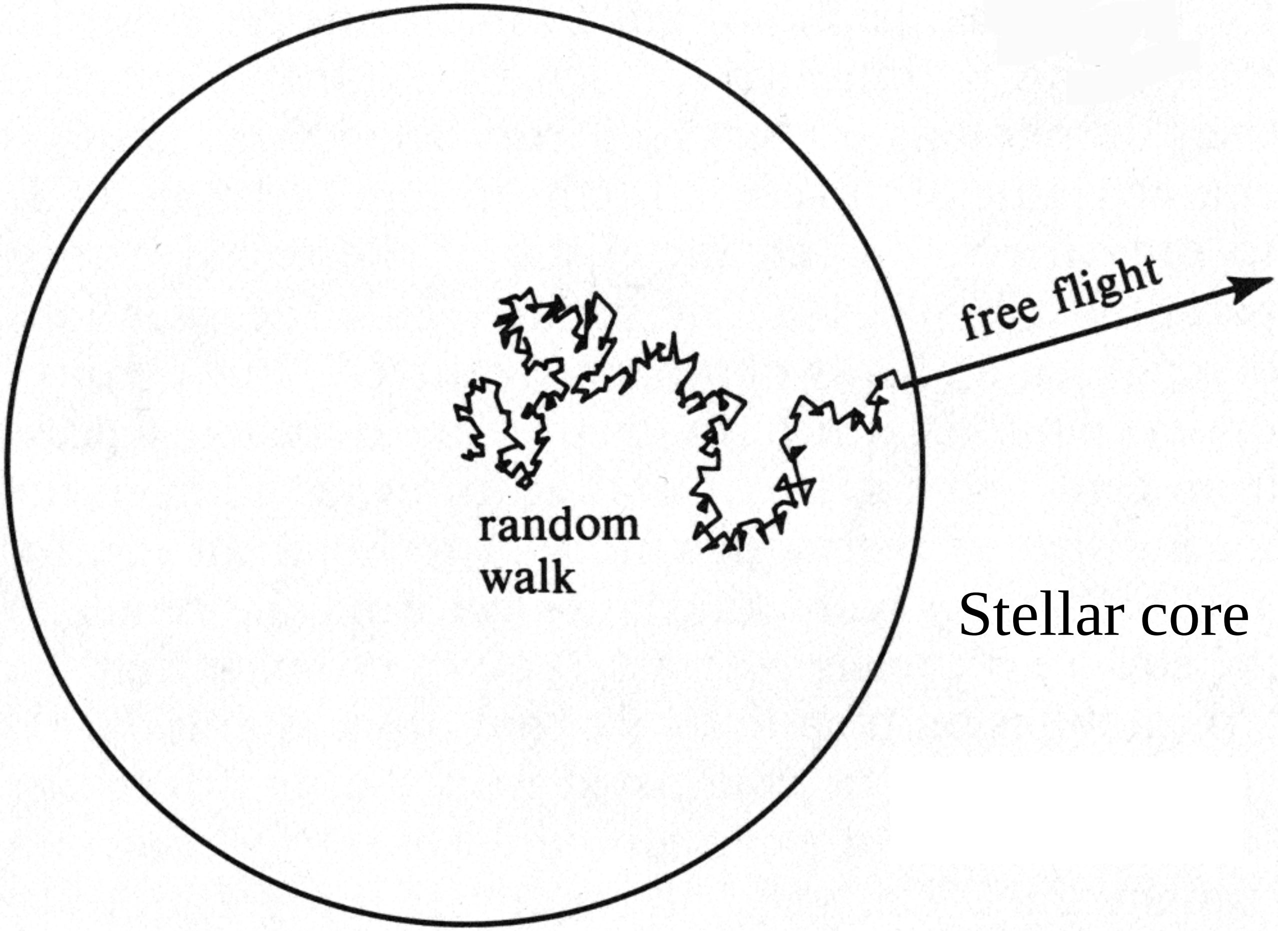
- Collapse timescale << 1s – not origin of extended time over which neutrinos were detected
- Crossing time of the core at velocity of light (R/c) at maximum 40km/300000kms^{-1} << 1s – not origin of Δt
- If neutrinos do not free-stream but possess mean-free-path ($<R$) then time taken to diffuse out from the core is larger than the crossing time by a factor R/l, where l=mfp of the neutrinos

- Taking estimate for spread in arrival times combined with idea of neutrinos random-walking out of neutron star with density $\rho \approx 10^{18}$kgm^{-3} obtain direct estimate of mean-free-path

$$\Delta t \approx \frac{R_{ns}^2}{lc} \approx 10\mathrm{s}$$

$$\Rightarrow l \approx 1\mathrm{m}$$

- Neutrino detection from SN1987A a major triumph for supernova core collapse models and physics



Stellar core

Lecture 20: Summary

- Maximum ZAMS mass for formation of a white dwarf can be deduced from observations of young clusters
- Supernova types from spectra – Type Ia, no Hydrogen evident, thermonuclear detonation. Core-collapse supernovae for Type II, with Hydrogen and Type Ib and Ic, without Hydrogen
- Importance of photodisintegration and electron capture (neutronisation) for collapse of inert Iron cores in massive stars, leading to creation of neutron star and supernova
- Energetics require a means to extract majority of gravitational energy released – neutrinos
- Observations of neutrino emission from SN1987A provided direct confirmation of model for core collapse and allowed estimate of the mean-free-path of neutrinos at nuclear densities

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