Supernovae:
from Stellar Evolution to Cosmology

Lesson d

Supernova Progenitors

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HR diagram

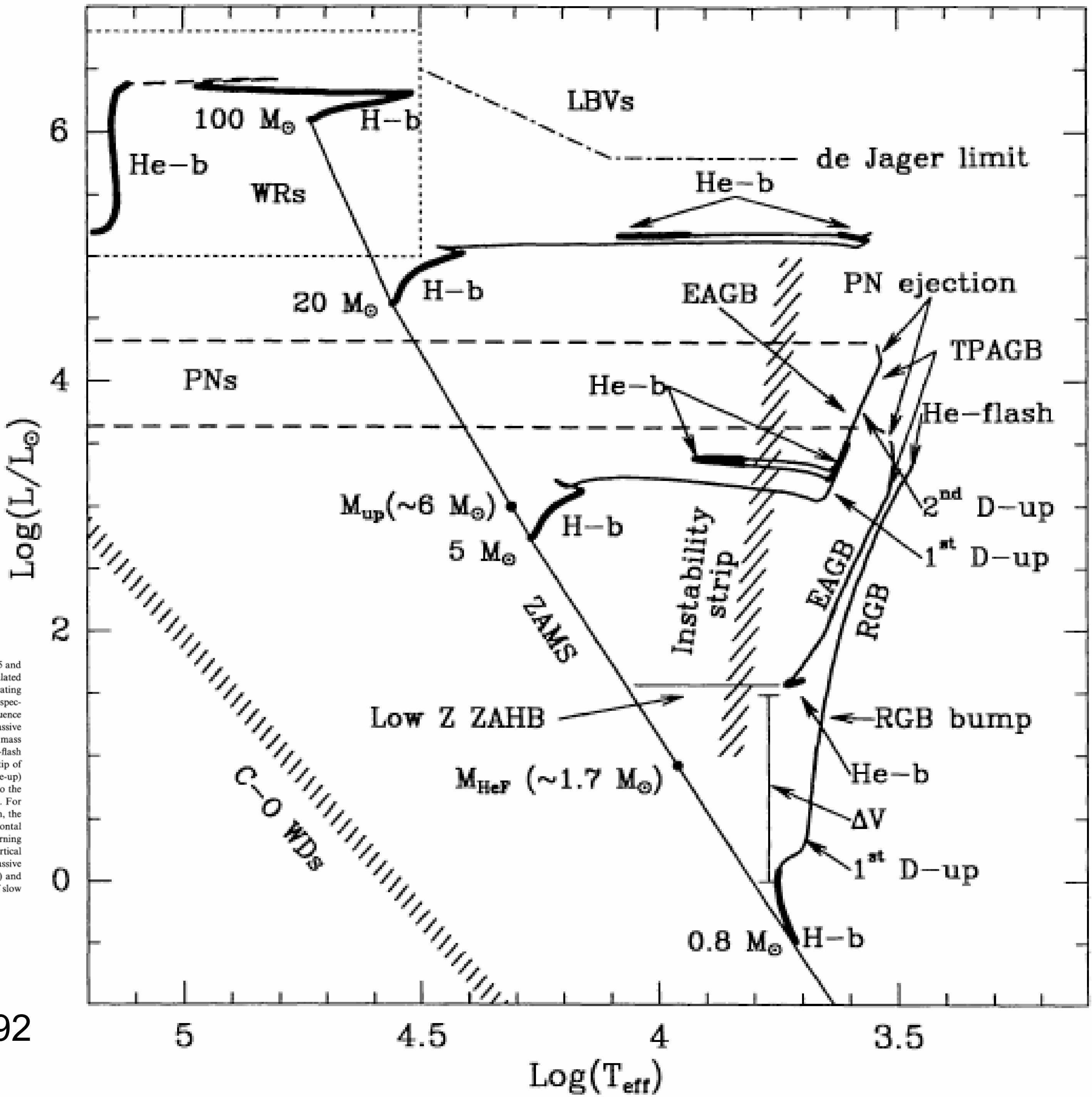


Figure 1 The evolutionary paths in the HRD of model stars of composition $Y = 0.25$ and $Z = 0.008$ and of initial mass $0.8M_\odot$, $5M_\odot$, $20M_\odot$, and $100M_\odot$. The models are calculated with the overshoot scheme for central convection. M_{HeF} and M_{up} are the masses separating low-mass stars from intermediate-mass stars, and the latter from the massive ones, respectively. For low- and intermediate-mass stars the tracks go from the zero-age main sequence (ZAMS) to the end of the asymptotic giant branch (AGB) phase, whereas for the massive stars they reach the stage of C-ignition in the core. Massive stars include the effect of mass loss by stellar wind. H-b and He-b stand for core H- and He-burning, respectively. He-flash indicates the stage of violent ignition of central He-burning in low-mass stars at the tip of the red giant branch (RGB). The main episodes of external mixing (1st and 2nd dredge-up) are indicated by 1st D-up and 2nd D-up, respectively. The AGB phase is separated into the early stages (EAGB) and thermally pulsing regime (TPAGB) of the He-burning shell. For low- and intermediate-mass stars we show the stage of planetary nebula (PN) ejection, the region where PN stars are observed, and the white dwarf (WD) cooling sequence. A horizontal line indicates the locus of the zero-age horizontal branch (ZAHB)—core He-burning models—of low-mass stars with composition typical of globular clusters. The shaded vertical band shows the instability strip of Cepheid and RR Lyrae stars. In the region of massive stars, we show the de Jager limit, the location of the blue luminous variables (LBVs) and Wolf-Rayet stars (WRs). Finally, the thick portions of the tracks indicate the stages of slow evolution, where the majority of stars are observed.

Chiosi et al. 1992

SN Ia summary

- *fairly* **homogeneous**
- **show O,Mg,S,Si,Ca near maximum, Fe at late phases**
- **no hydrogen**
- **no radio or X-ray emission**
- **occur in all type of galaxies (E included)**
- **in spirals, not strongly associated with HII regions**

⇒ **Old population, H-less, low M/En, similar one eachother**

➔ thermonuclear disruption of CO WDs which accreted their mass up to the Chandrasekhar limit via mass transfer from a companion in binary systems

3 possible scenarios:

- Single Degenarate (SD)
- Double Degenerate (DD)
- Sub-Chandra

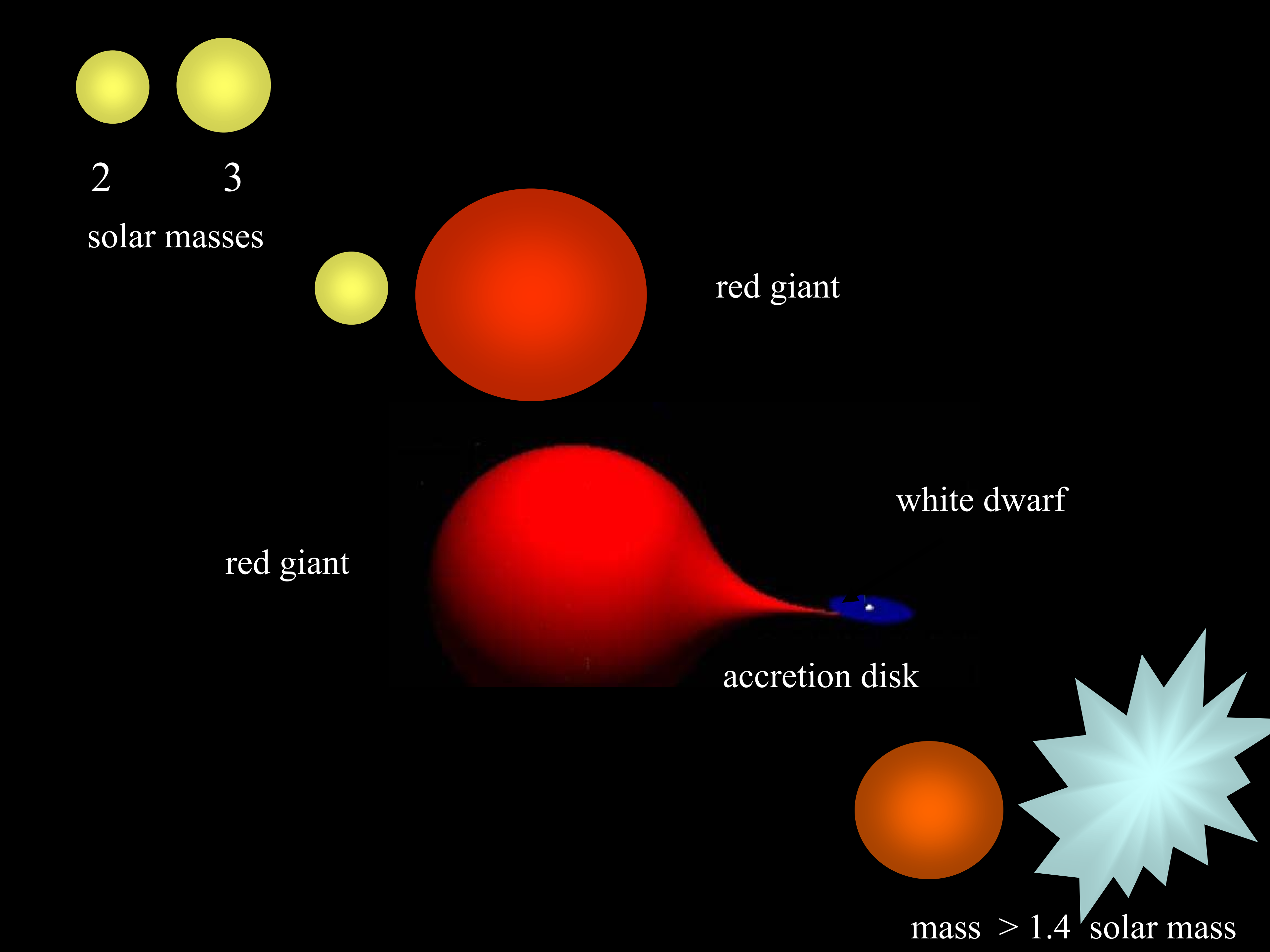
White Dwarfs

- final stage of stars $M<8M_\odot$
- dead stars (no nuclear burning)
- $T \sim 10^5\ ^oK$
- Cooling ➔ dark matter
- Mass $< M_{CH} \sim 1.4M_\odot$
- Radius~6000 km
- Density$\sim 10^6$ gr/cm^3

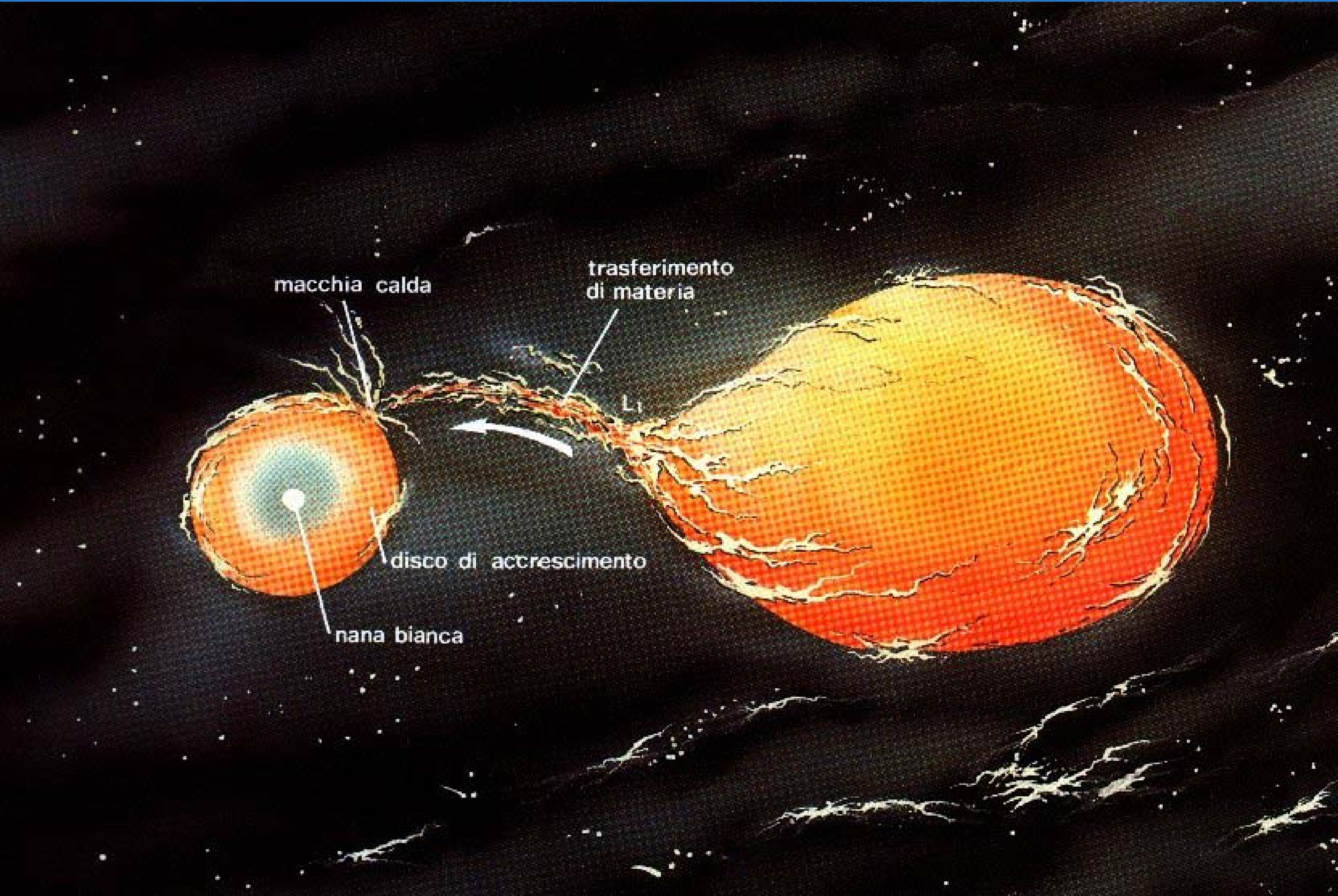
- In a binary system ➔ rejuvanated via H (or He) accretion

Single Degenerate (SD)

- Most popular
- WD + normal star with H-rich envelope in close system as result of Common Envelope phase
- companion fills the Roche lobe
- accreted H undergoes nuclear burning on the surface of the WD
- H is first converted into He and then into a CO mixture
- M(WD) ↑ approaching M_{CH}
- Degenerate C ignition at center
- Accretion rate required: $dM/dt \sim 10^{-8}$ to $10^{-6}\ M_{\odot}/yr$


2
3
solar masses
red giant
white dwarf
red giant
accretion disk
mass > 1.4 solar mass

An artistic view



Accretion from companion can occur in 3 different evolutionary phases:

a) at the end of the central H burning phase

$dM/dt \sim 10^{-9}$ to 10^{-8} $M_{\odot}$/yr

b) during the RGB phase

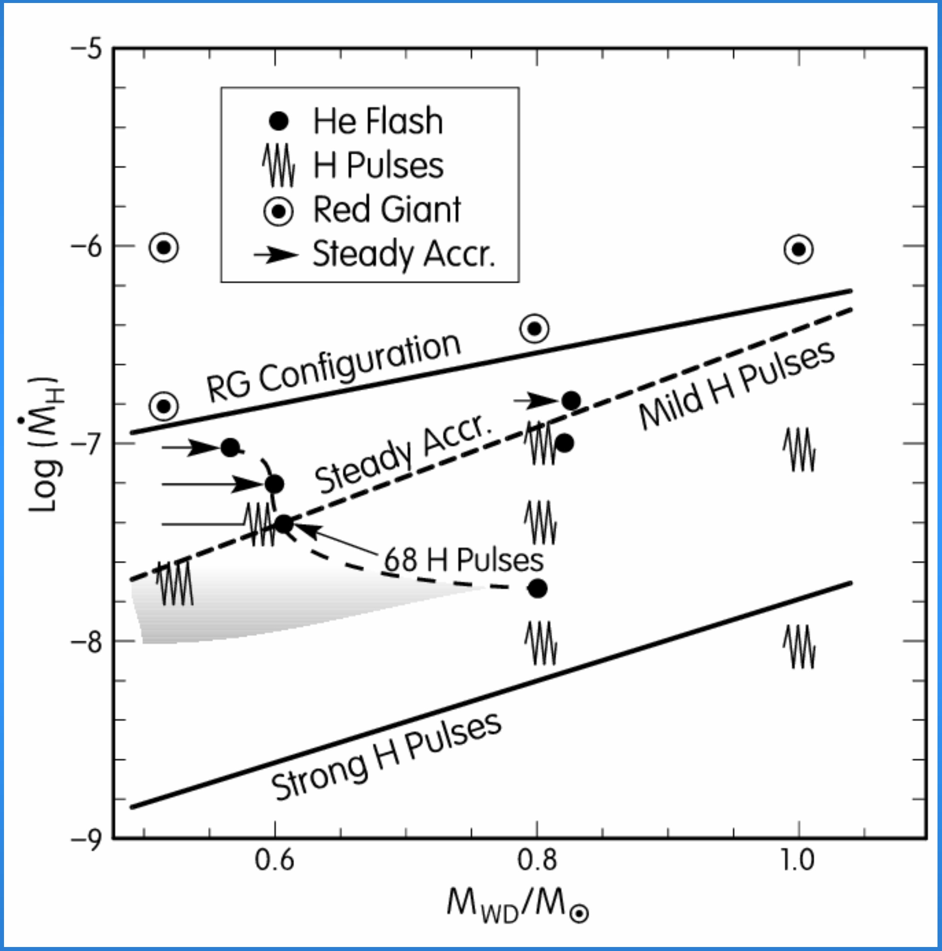
dM/dt very high

c) during the AGB phase

Major problem is dM/dt:

- dM/dt >1 to 3 10^{-7} $M_\odot$ yr-1 WD expands, fill Roche lobe, stops accretion
- 3 10^{-7}>dM/dt>5$10^{-8}$ Steady Accretion (H converted into He at the same rate at which is transferred) ➔ He piled up ➔ He flash ➔ expansion to giant dimensions ➔ CE ➔ mass loss
- Around 5 10^{-8} He ingnites mild-degenerate
- Around 1 10^{-8} He can ignite and produce SN with wrong nucleosynthesis
- 1 10^{-9} (circa)> Mdot, strong H-flashes ➔ Nova-like events, secular mass reduction of WD

Tornambe' & Piersanti 2005



Double Degenerate (DD)

- 2 CO WDs with M1+M2 ~ M_{Ch} as consequence of CE episodes
- orbital separation is small enough (A~1Rsun) ➔merging via GW emission in t < Hubble time
- less massive WD, overfills its own Roche Lobe, undergoes dynamical mass transfer, it completely disrupts forming a thick accretion disk around the companion
- CO rich matter is **directly** accreted onto the WD (➔ no flash driven instabilities)
- dM/dt is very high ➔ off-center ignition of CO burning ➔ O-Ne-Mg WD which can (core) collapse

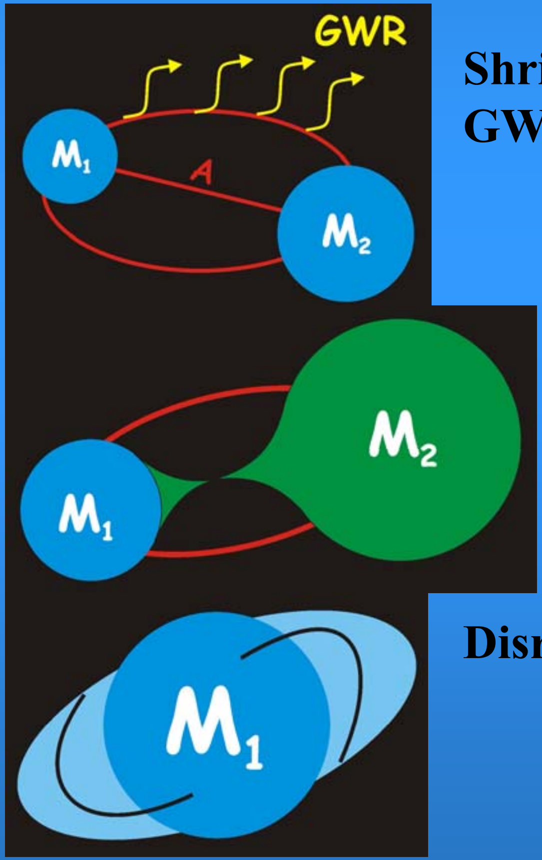
DD schematic evolution

(courtesy of Tornambe' & Piersanti)

$M_1 + M_2 > M_{ch}$

$A \sim 1\text{-}10\ R_0$

$t_{mer} < t_{Hubble}$



Shrinkage of the orbits due to GWR Emission

Dynamical mass transfer from M_2 to M_1

Disruption of M_2 and formation of an Accretion Disk

Rotation is way out

Tornambe' & Piersanti 2005

- WD rotate very slowly (in general)
- But in DD rotation is determined by the synchronization of the orbits in the binary system, on very short time scale
- 2 WDs becomes fast rotators (**$\omega 1=\omega 2= \omega_{merge}$=0.177 rad/s)**
- Models show that rotation acts as the tuning mechanism of the accretion process
- it is possible to obtain SN explosion for WDs in the mass range 1.4 - 1.5 $M_{\odot}$ or larger
- Such a spread in the final value of M(WD) could be responsible of the SNIa diversity

Sub-Chandra

- Sub-Chandra mass WD accretes mass from companion
- If 10^{-8} >Mdot>10^{-9} $M_{\odot}$/yr He-flash is enough to ignite off-center He-detonation which can ignite central C detonation
- Low mass

After ignition what ??

- Burning incenerites material into Fe-group elements
- Flame propagates outward with several instabilities (thermal, Rayleigh-Taylor, Landau-Darrius, Kelvin-Helmoltz)
- Behind flame burning of C, Ne, O, Si
- Outcome f(ρ): high ρ ➔ Fe-group (Ni), low ρ ➔ Ca, Ar, S, Si

Detonation or deflagration ?

- Deflagration (subsonic). Allows expansion of the WD. W7 model ($v=1/5\ v_{sound}$) in agreement with observations.
- Detonation (supersonic). Increased Ni production and distribution ok for some peculiar object (e.g. 1991T)
- Delayed-Detonation. Early deflagration expands the WD → transition to detonantion at 1-3 10^{-7} gr/cm^{-3} → possible to adjust the desired composition changing the transition ρ

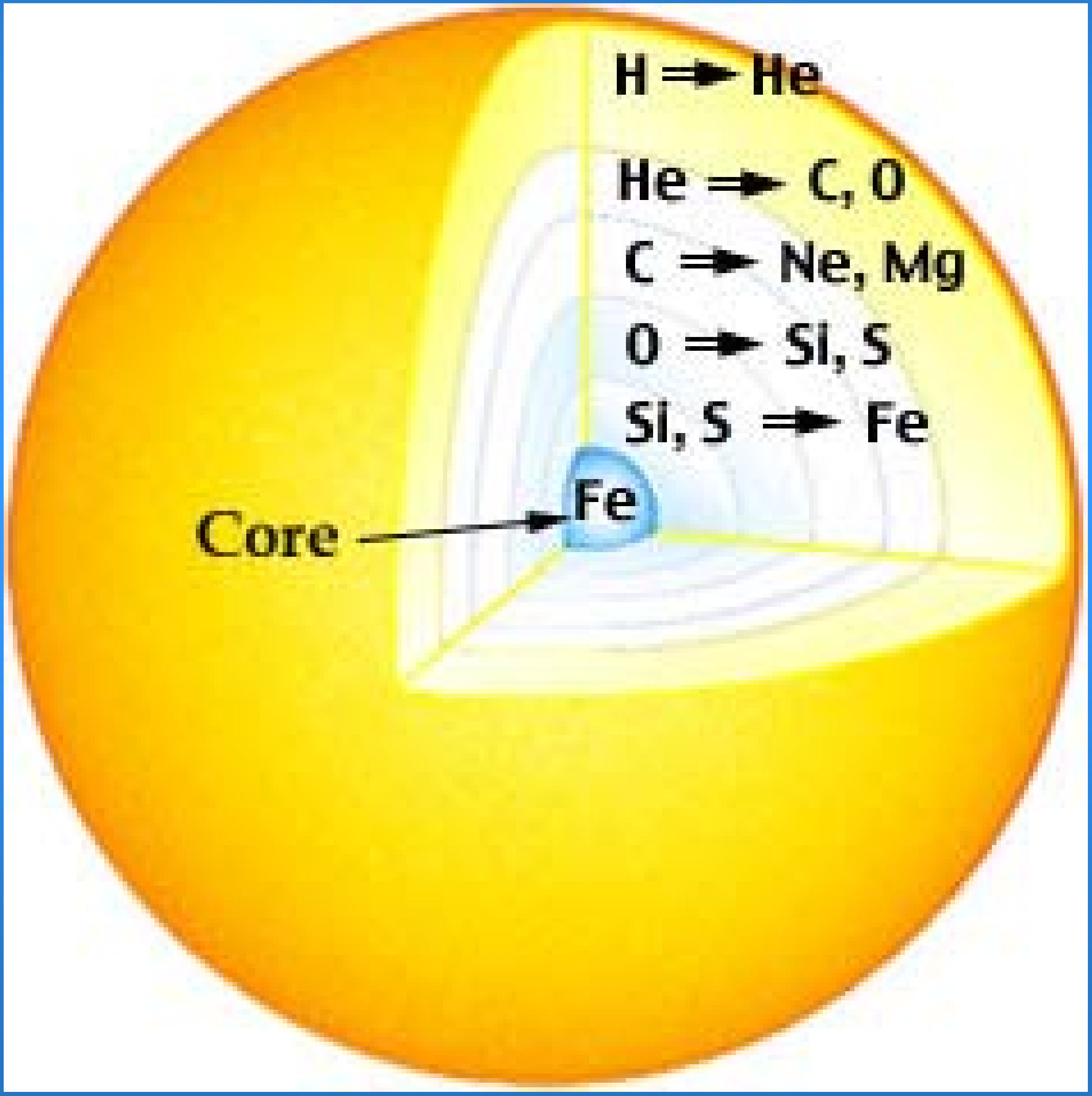
Still open. Need for more observations

Core collapse SNe summary

- ***NOT*** **homogeneous**
- **show H, He, O, Ca ……**
- **from small to huge radio and X-ray emission**
- **occur only (!!) in spiral galaxies and are associated with star forming regions**
- **leave collapsed remnant (NS or BH) [Crab]**
- **emit neutrinos and *gravitational waves***

→ Young massive progenitors in various configurations

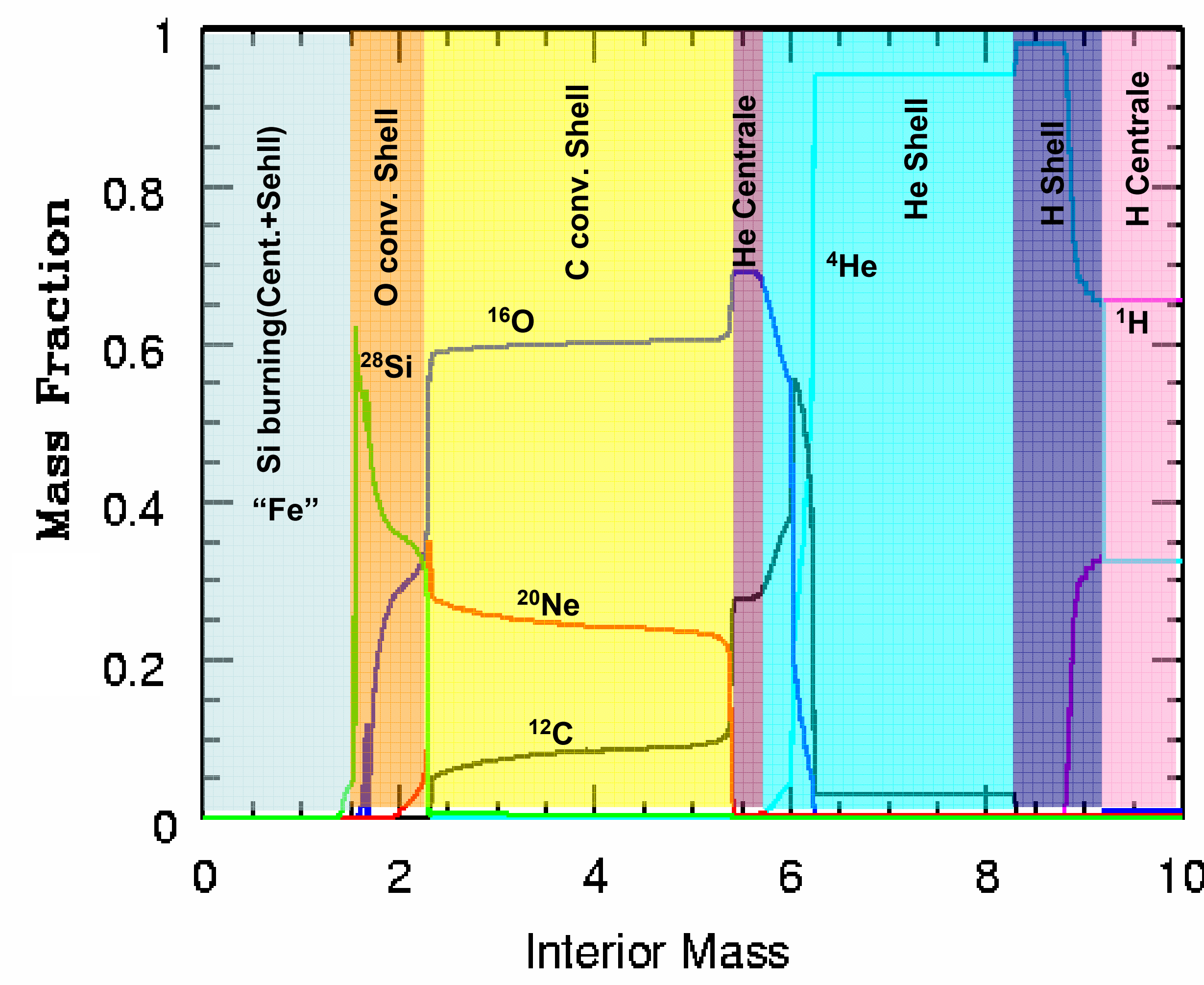
Massive stars final structure



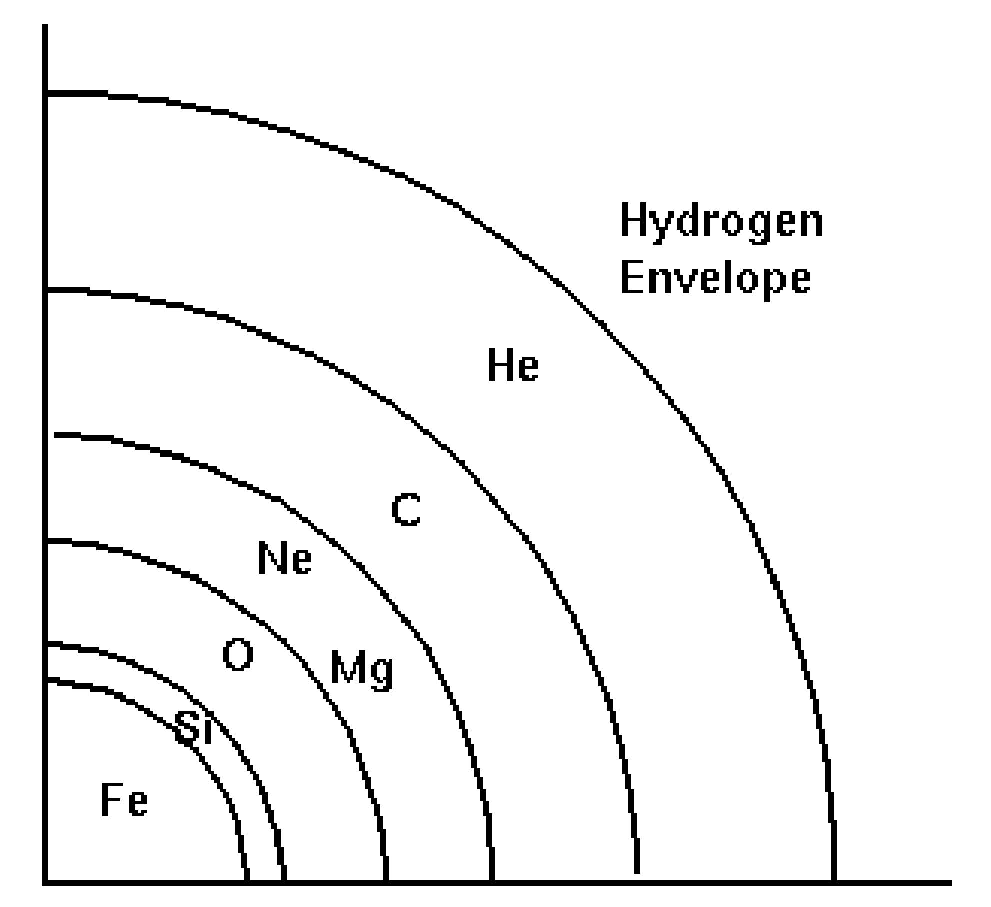
Pre-SN structure: chemical composition

Limongi

Burning Site	Main Products
Si Burning	^{54}Fe, ^{56}Fe, ^{55}Fe, ^{58}Ni, ^{53}Mn
O Conv. Shell	^{28}Si, ^{32}S, ^{36}Ar, ^{40}Ca, ^{34}S, ^{38}Ar
C Conv. Shell	^{20}Ne, ^{23}Na, ^{24}Mg,^{25}Mg, ^{27}Al + *s*-process
He Central	^{16}O, ^{12}C + *s*-process
He Shell	^{16}O, ^{12}C
H Central+Shell	^{14}N, ^{13}C, ^{17}O

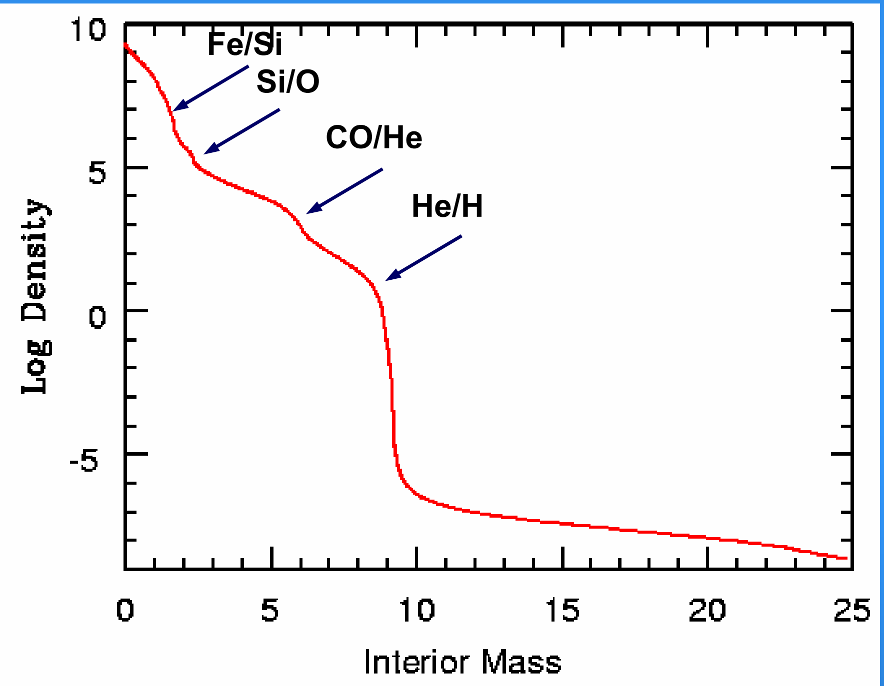


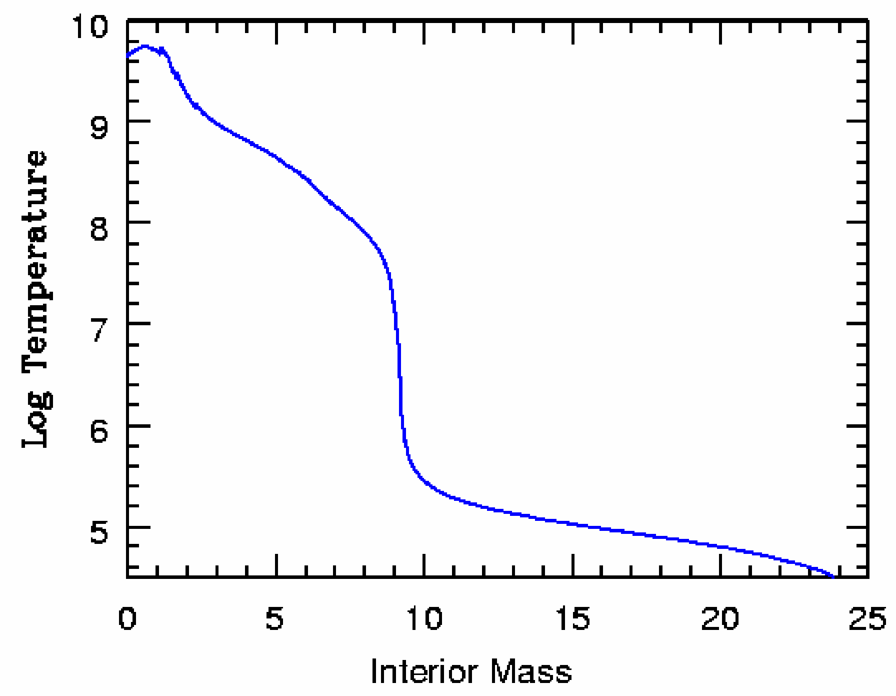
Evolution of a 25 M_o Star



Fuel	Temperature	Density (gm/cc)	Time (yrs)	Sample reaction
Hydrogen	4×10^7	5	7×10^6	CNO cycle
Helium	2×10^8	700	5×10^5	Triple Alpha
Carbon	6×10^8	2×10^5	600	$^{12}C + ^{12}C \rightarrow ^{20}Ne + ^4He$
Neon	1.2×10^9	4×10^6	1	$^{20}Ne + ^4He \rightarrow ^{16}O + 2\ ^4He$
Oxygen	1.5×10^9	10^7	0.5	$^{16}O + ^{16}O \rightarrow ^{28}Si + ^4He$
Silicon	2.7×10^9	3×10^7	1 day	Si --> Fe

Pre-SN structure





Limongi

Binding Energy

Einstein's equation $E = m c^2$

Proton: $mc^2 = 938.3$MeV

Neutron: $mc^2 = 939.5$MeV

sum = 1877.8MeV

Deuteron: $mc^2 = 1875.6$MeV

Difference is Binding energy, 2.2MeV

In general for a given nucleus:

$$\mathbf{Eb = (Z \times mH + N \times mn - m_{isotope}) \times 931.5\ MeV/amu}$$

Eb = binding energy, in MeV

Z = number of protons

mH = mass of a hydrogen atom (1.007825 atomic mass units, or **amu**)

N = number of neutrons

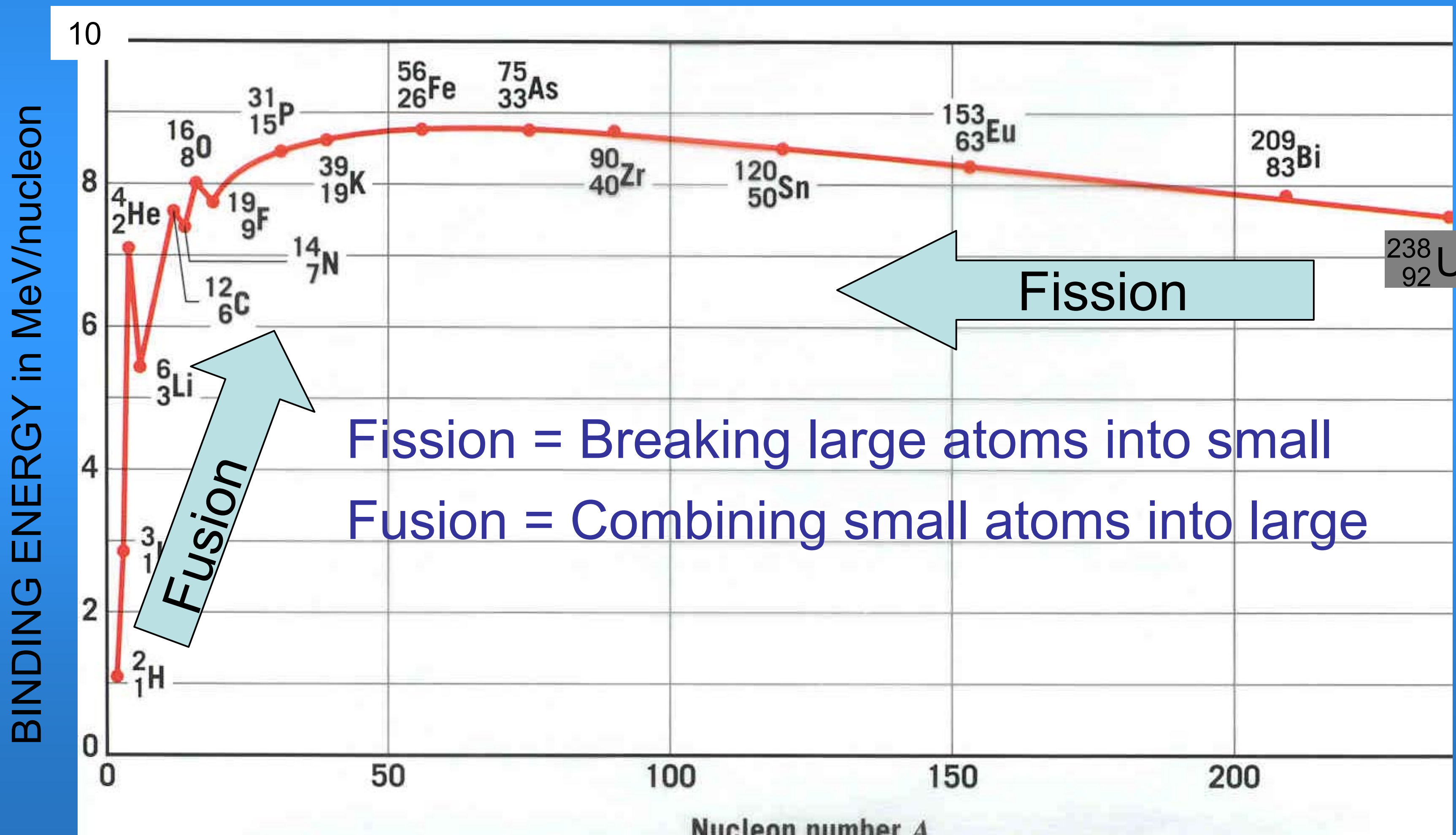
mn = mass of a neutron (1.008664904 amu)

misotope = actual mass of the isotope

931.5 Mev/amu = the conversion factor to convert mass into energy, in units of MeV

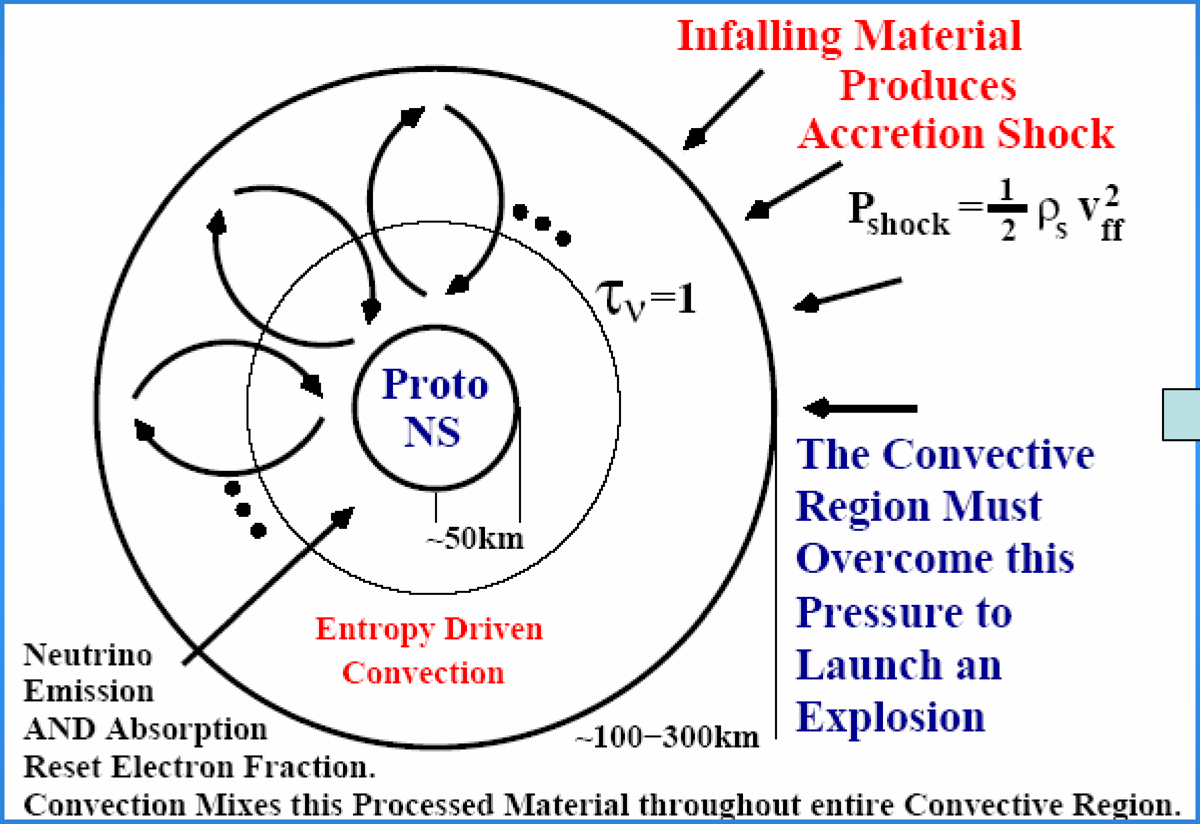
Binding Energy

Fe has the highest energy/nucleon ratio



Fission = Breaking large atoms into small

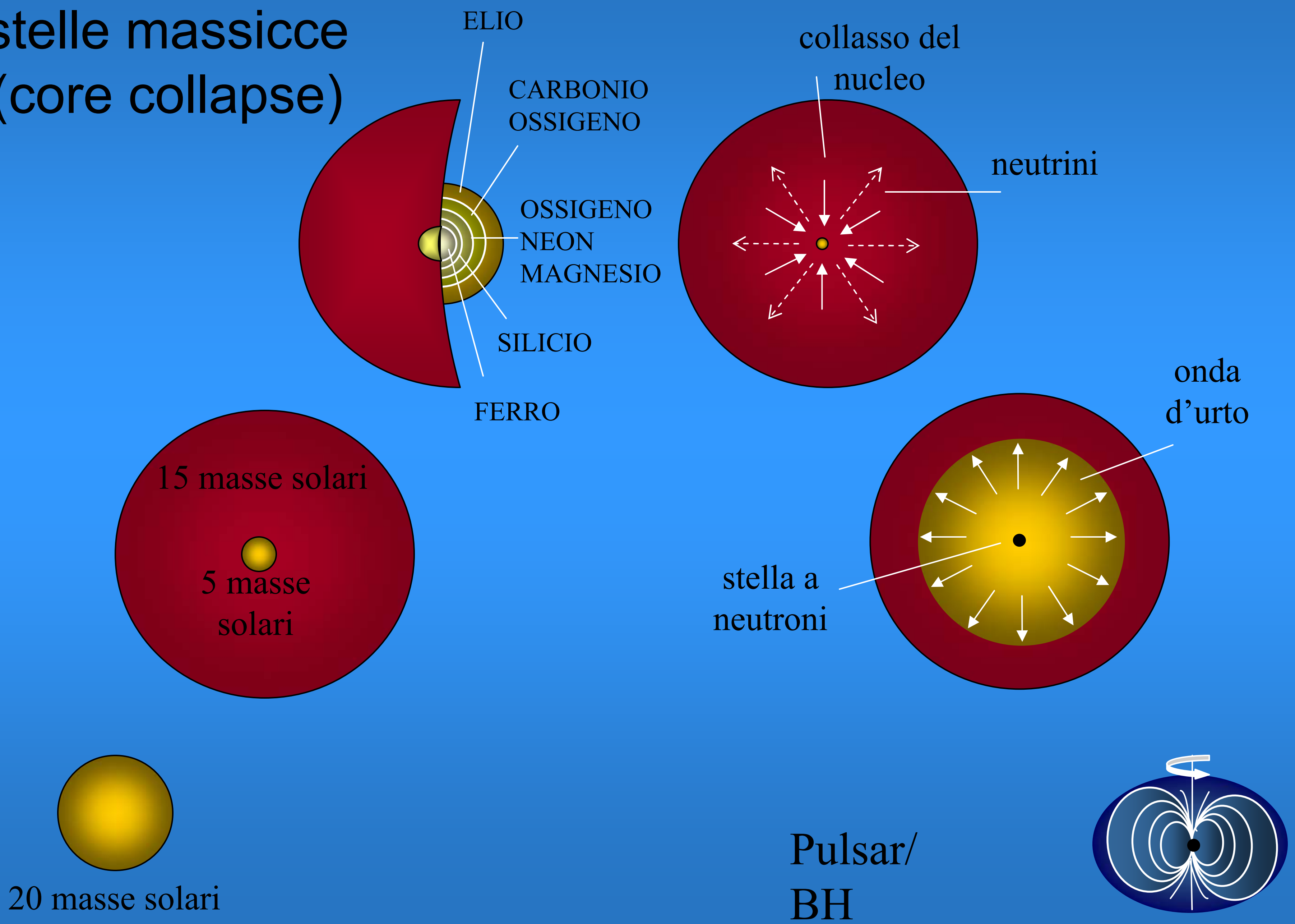
Fusion = Combining small atoms into large neutronization



explosion

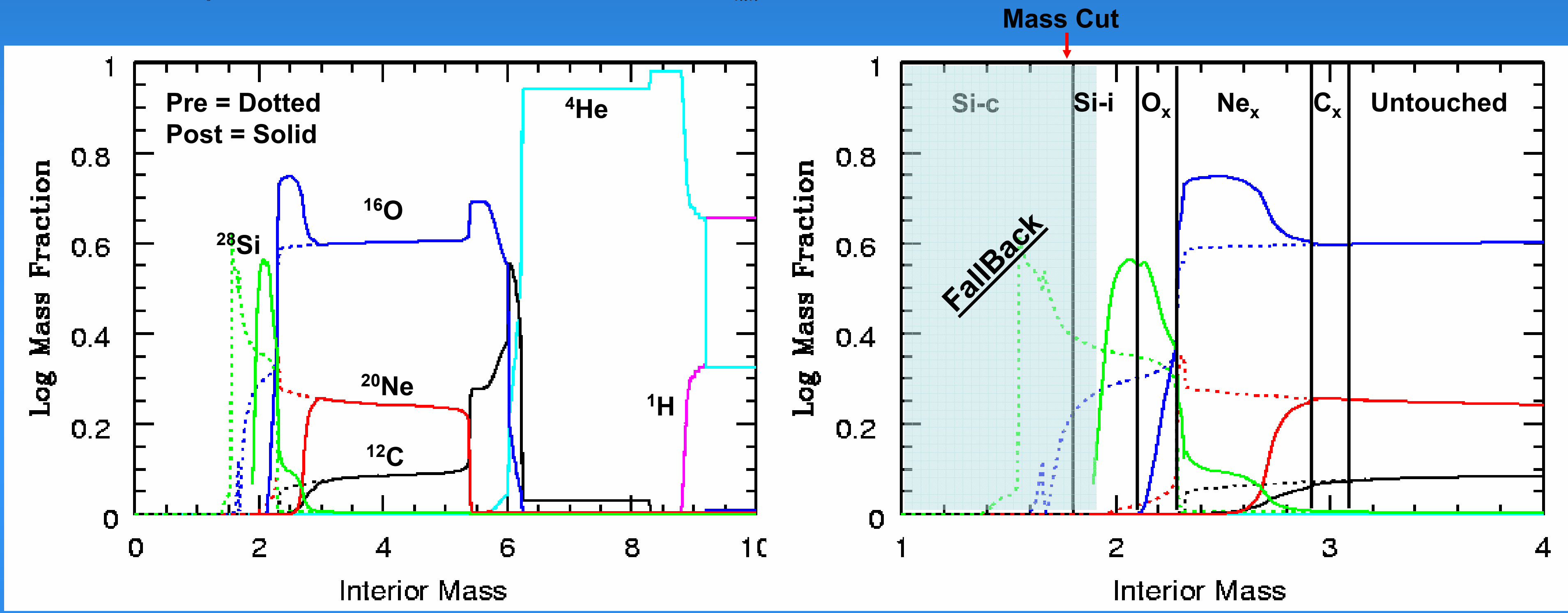
1% E

Supernovae da stelle massicce (core collapse)

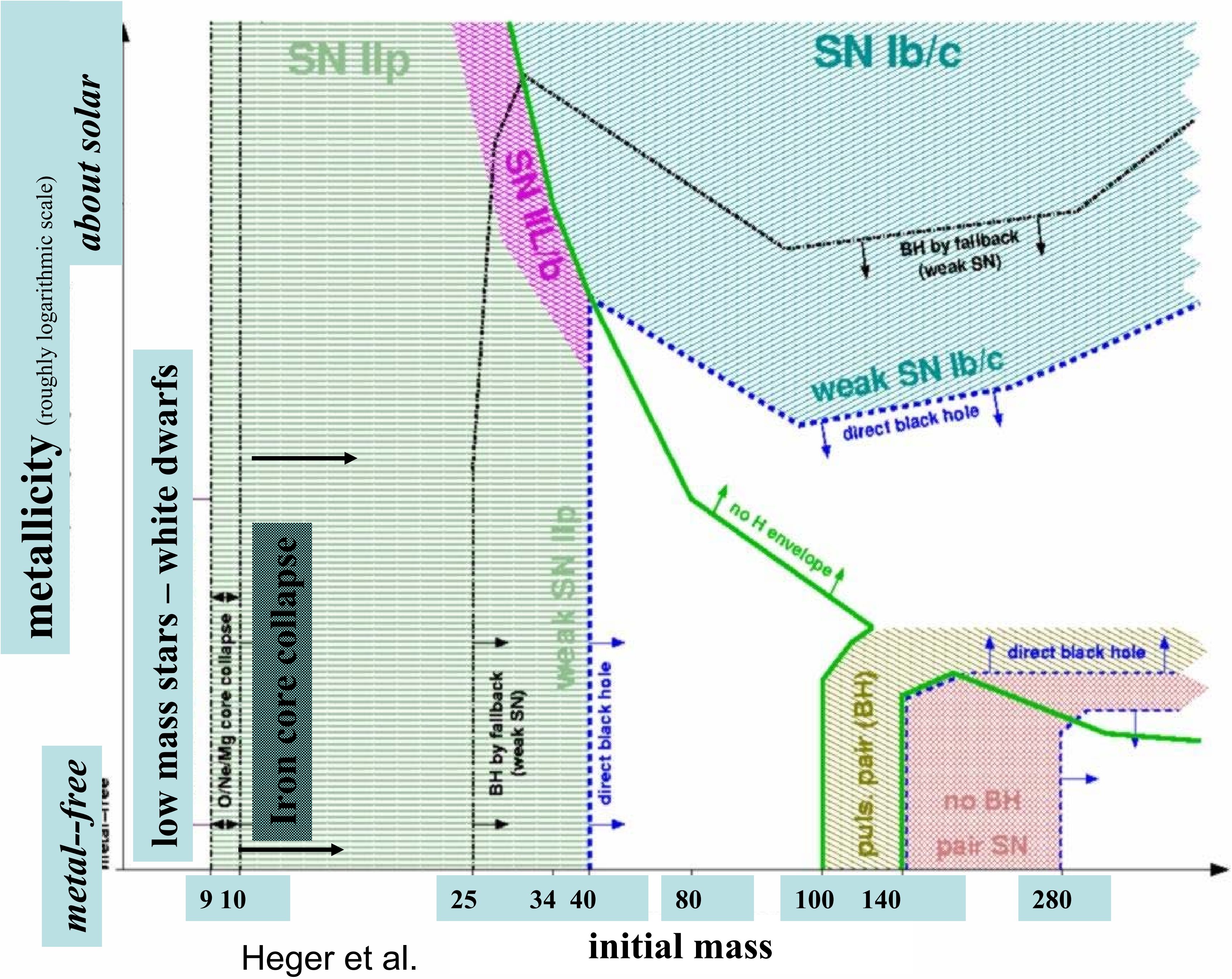


Explosive burning and chemical composition

Case: v_0=1.5550 10^9 cm/s M_{cut}=1.89 $M_\odot$ E_{kin}=1.144 foe



- Explosion affects only the innermost ~3.1 $M_\odot$
- Above the chemical composition remains unchanged
- Fall-back oft the explosive complete Si burning zone and part of the incomplete explosive Si



metallicity (roughly logarithmic scale)
about solar
metal–free
low mass stars – white dwarfs
Iron core collapse
O/Ne/Mg core collapse
SN IIp
SN IIL/b
SN Ib/c
BH by fallback (weak SN)
weak SN IIp
direct black hole
weak SN Ib/c
no H envelope
puls. pair (BH)
no BH
pair SN
9 10
25
34 40
80
100 140
280
initial mass
Heger et al.

Direct observation of SN progenitors CC-SNe

- So far: SN1987A, 1993J
- High-res HST+ 8m-class telescopes preimaging → new CC-SN progenitors
- Reconstruction of SED and /or location on HR diagram

Progenitor of SN 2005cs in M51

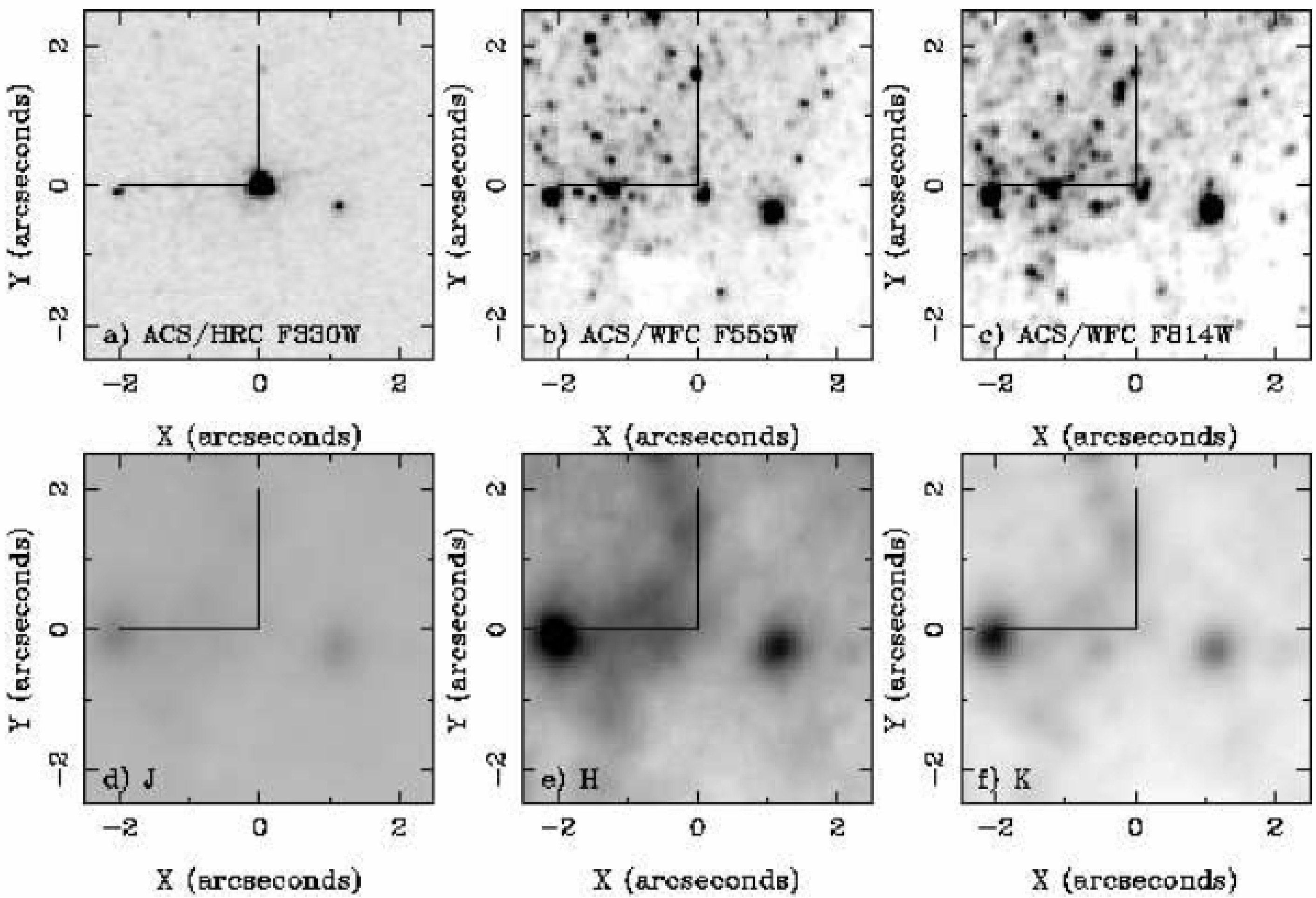


Figure 1. Pre- and post-explosion images of the site of SN 2005cs in M51. a) Post-explosion ACS/HRC F330W image of SN 2005cs, the cross hairs indicate the centre of the PSF. b) Pre-explosion ACS/WFC F555W image, in which the progenitor is not detected to $m_{F555W} = 25$ at 5σ. c) Pre-explosion ACS/WFC F814W image, the progenitor is detected in this image, indicated by the cross hairs, with $m_{F814W} = 23.26$. d) Pre-explosion Gemini J-band image. e) Pre-explosion Gemini NIRI H-band image. f) Pre-explosion Gemini H-band image. The images are aligned to the reference ACS/WFC F555W image (panel b), such that North is up and East is left.

Maund et al. 2005

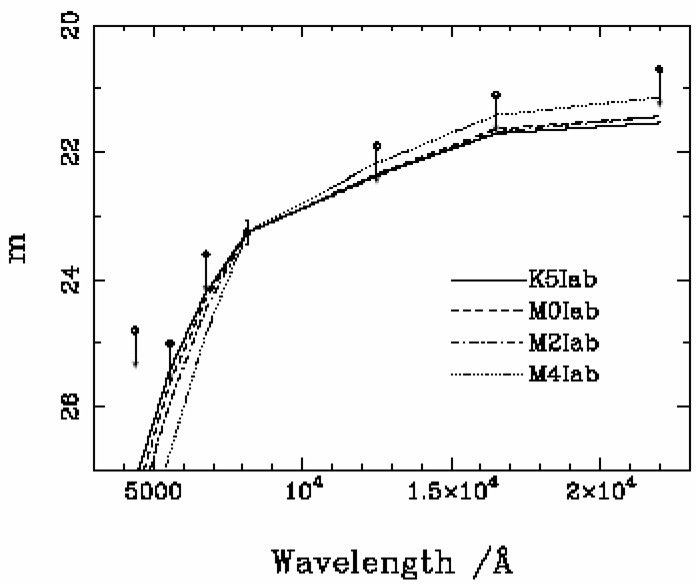


Figure 2. The spectral energy distribution of the progenitor is constrained by the I-band detection, and the upper limits in $VRJHK$. The star cannot have been bluer than a mid K-type, or it would have been detected in the V and R bands. The colours of the K5Ia-M4Iab supergiants where taken from Elias et al. (1985), and scaled to I=23.26 with appropriate reddening as discussed in the text.

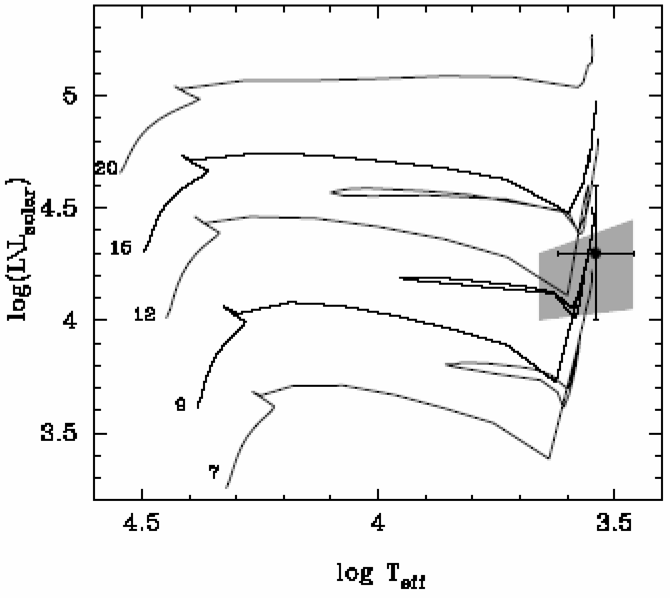


Figure 3. The position of the progenitor of SN2005cs is restricted to lie in the grey shaded region. The evolutionary tracks are the non-rotating models from the Geneva group (Meynet et al. 1994) and the point with the error bar is the position of the progenitor of SN 2003gd which was another low mass red supergiant progenitor.

likely initial mass for the star was in the range $M_{ZAMS} = 9^{+3}_{-2} M_{\odot}$. This adds to the emerging argument that all type II-P supernovae lie in the low to moderate mass range of red supergiants.

Progenitor scenario

Single star

M_0	8 - 10 $M_\odot$	10 - 30 $M_\odot$	> 30 $M_\odot$
Core	0/Ne/Mg core collapse	--------------- Fe core collapse	--------------
R_0	10^{14} cm	10^{12} - 10^{15} cm	10^{11} cm
M_{ej}	2 $M_\odot$	7 - 15 $M_\odot$	5 $M_\odot$
M_H	1 $M_\odot$	5 - 10 $M_\odot$	0
M_{Ni}	-------------------------	0.1 $M_\odot$	--------------------------------
	IIL	**87A --- IIP --- 83K**	**Ib**

Binary system

	WD+MS	WD+WD	WD+MS	MS+MS
M_0	0.7 + 2 $M_\odot$	0.7 + 0.7	1.3 + 2 $M_\odot$	5-15 + 5-15 $M_\odot$
expl.	off-center He	CO detonation		Fe core collapse
M_{Ni}	0.1 $M_\odot$	0.4-0.8 $M_\odot$		0.1 $M_\odot$
	faint-Ia	**Ia**		**Ib - Ic - IIb - IIL -IIn**