Formation of Stars and Planets

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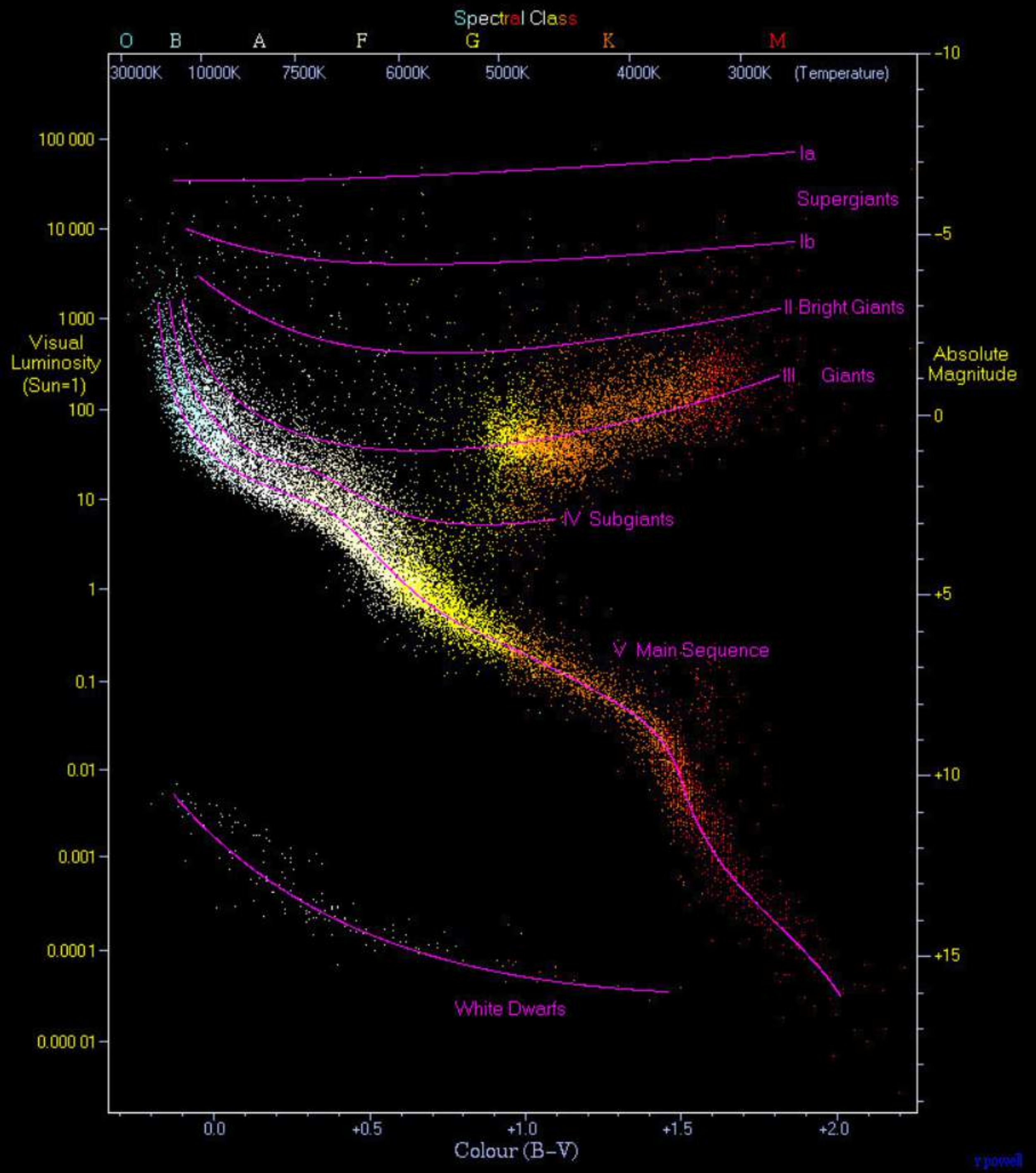
23.06.2020

Stellar Evolution

of low and massive stars

Credit: ESO/S. Steinhöfel



Spectral Class
O
B
A
F
G
K
M
30000K
10000K
7500K
6000K
5000K
4000K
3000K
(Temperature)
Visual Luminosity (Sun=1)
100 000
10 000
1000
100
10
1
0.1
0.01
0.001
0.0001
0.000 01
Absolute Magnitude
-10
-5
0
+5
+10
+15
Ia
Supergiants
Ib
II Bright Giants
III Giants
IV Subgiants
V Main Sequence
White Dwarfs
0.0
+0.5
+1.0
+1.5
+2.0
Colour (B−V)
r powell

How long do stars stay on the Main Sequence?

- Stars spend most of their lives on the Main Sequence and fuse H to He

- Lifetime depends on birth mass:

$$\tau_{MS} = \frac{E_{nuclear}}{L} \propto \frac{M}{M^3} = M^{-2}$$

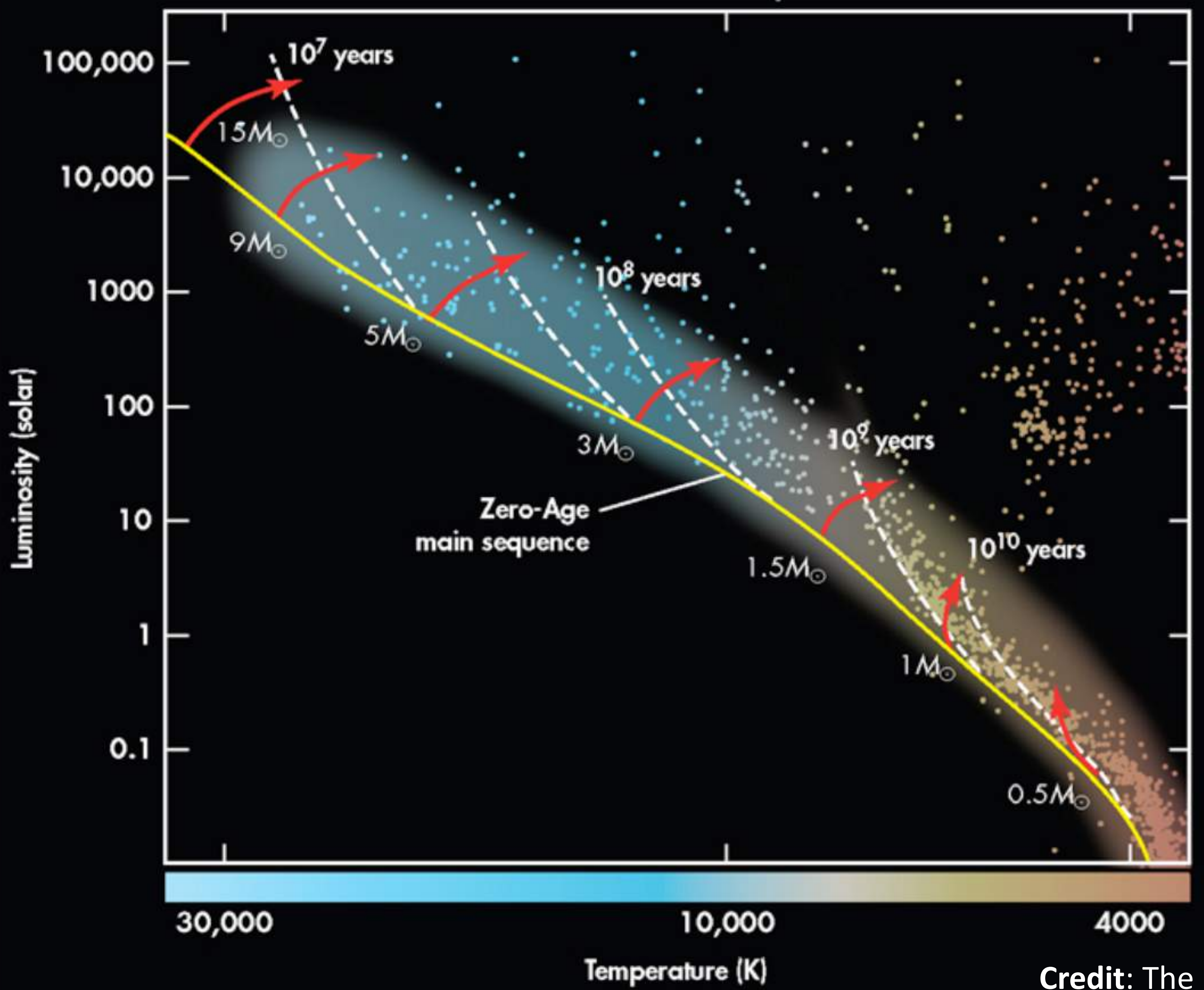
Mass-Luminosity-Relation:

$$L \sim M^3$$

→ larger mass results in shorter lifetime on MS

Mass/M$_\odot$	MS lifetime (yrs)
0,10	$2 \cdot 10^{12}$
0,50	$2 \cdot 10^{11}$
0,75	$3 \cdot 10^{10}$
1,0	$1 \cdot 10^{10}$
1,5	$2 \cdot 10^{9}$
3	$2 \cdot 10^{8}$
5	$7 \cdot 10^{7}$
10	$2 \cdot 10^{7}$
15	$1 \cdot 10^{7}$
25	$7 \cdot 10^{6}$
60	$3{,}4 \cdot 10^{6}$

Lifetime on Main Sequence as a function of mass



Credit: The McGraw-Hill Company

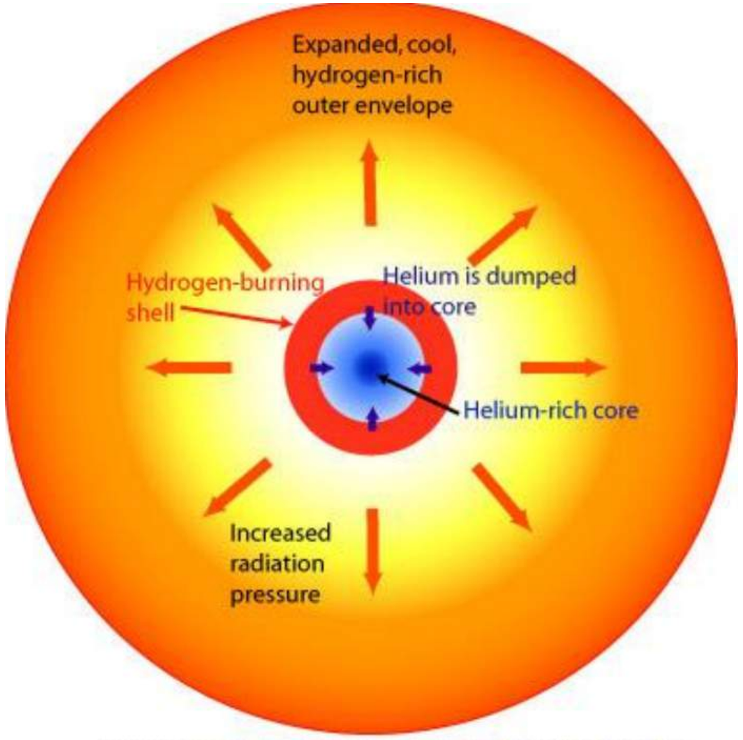
Low Mass Evolution for $M > 8\ M_\odot$

- Hydrogen in the core is exhausted
  → energy production via pp cycle stops

- T high enough for H shell burning
  → Helium core grows
  → HRD: star moves to right (cooler T)

- When reaching the Chandrasekhar limit the He-core contracts
  → the envelope expands and the star cools down
  → **Sub Giant Branch (SGB)**

Chrandrasekhar-limit: $1{,}4\ M_\odot$



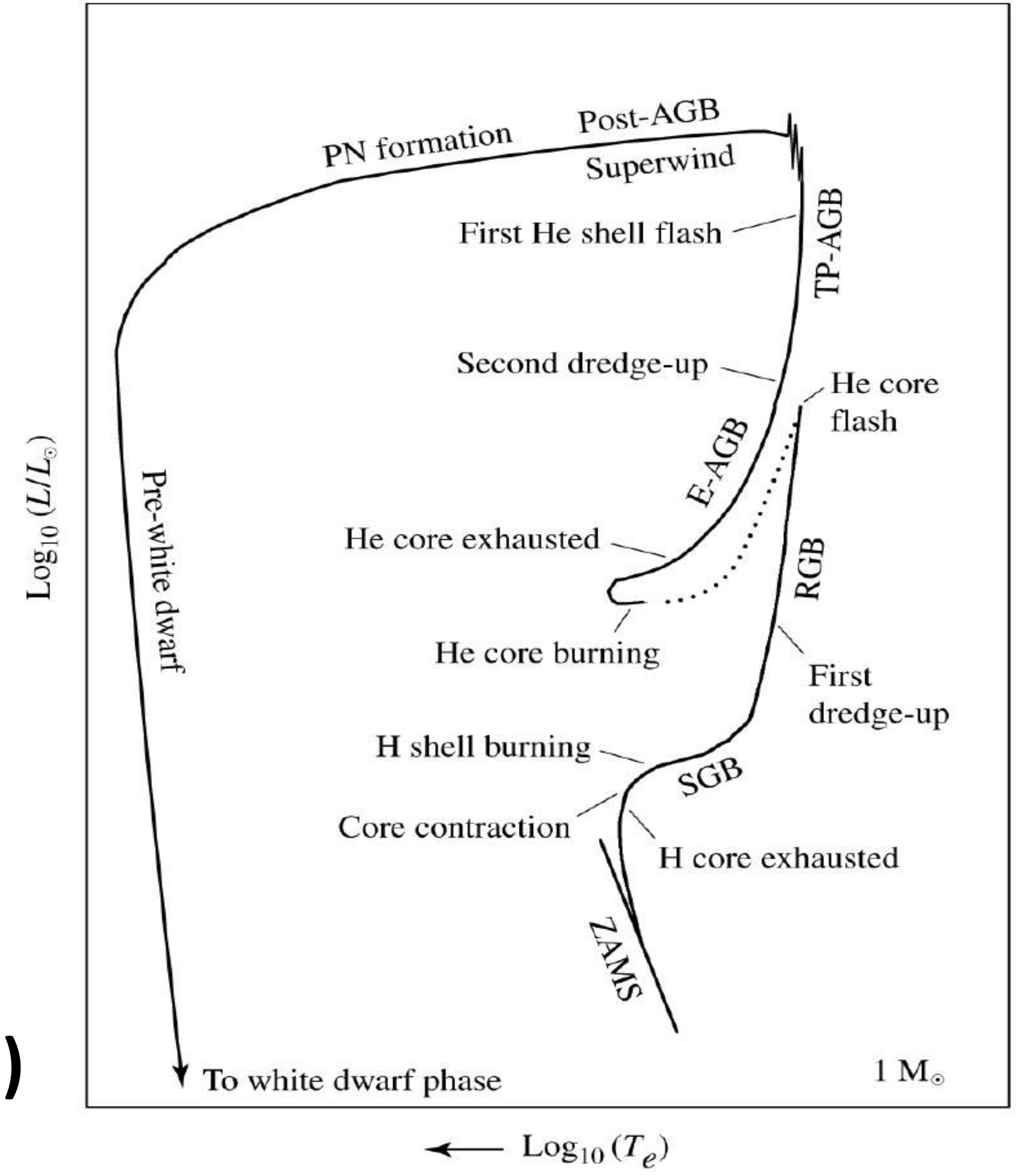
Low Mass Evolution for $\mathrm{M} > 8\ \mathrm{M}_{\odot}$

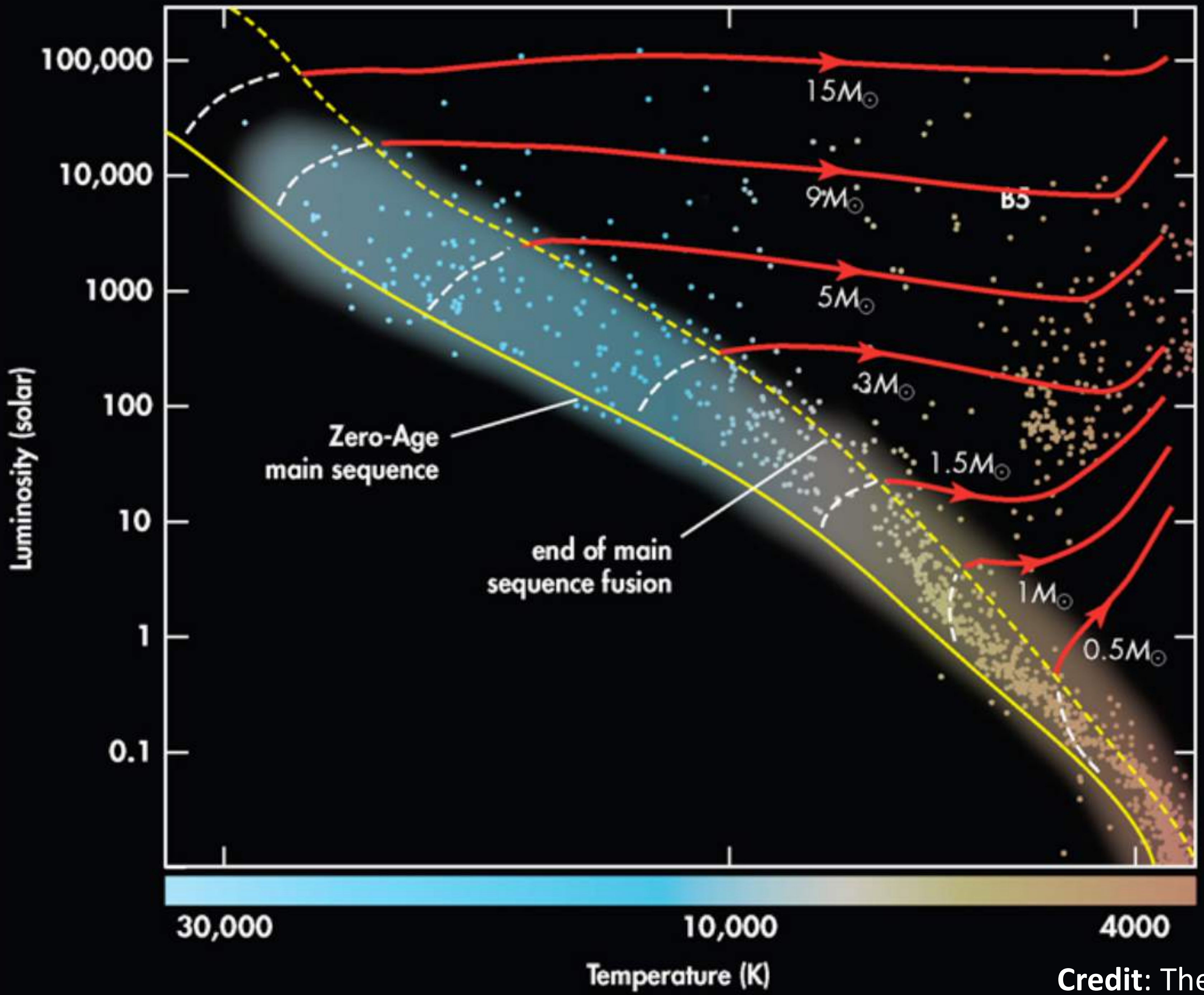
- $T \sim 5000\ K$: opacity of the envelope increase
  → Convection sets in
  → Luminosity increases dramatically

- Core continues to collapse
  → L and P in shell increases
  → outer layers become convective

- Star is not longer in hydrostatic equilibrium
  → envelope expands and cools down

- HRD: star moves up the **Red Giant Branch (RGB)**

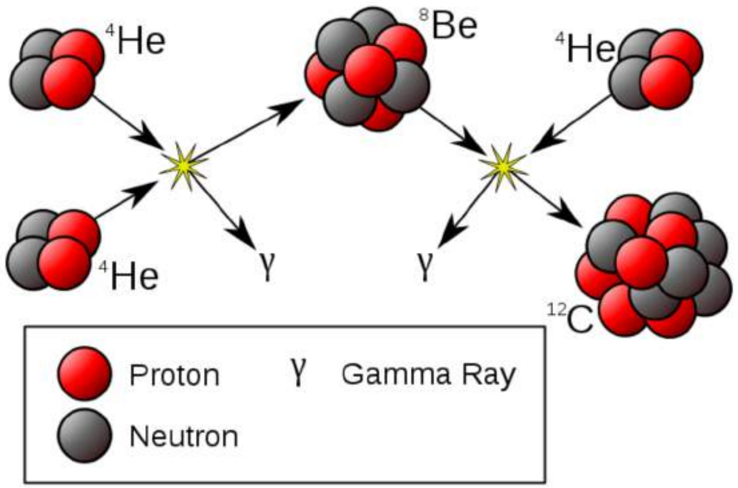




Credit: The McGraw-Hill Company

When does Helium ignition start?

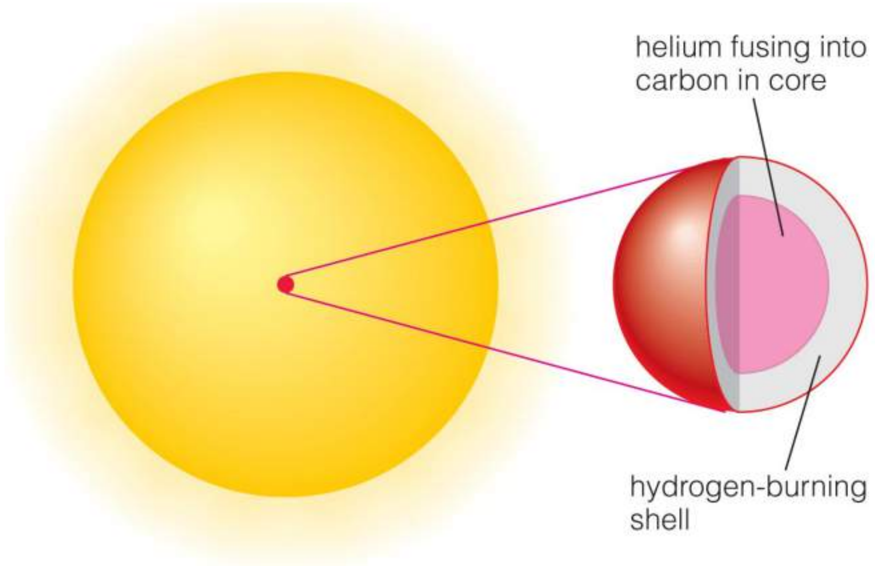
- End of RGB: T_{core} is high enough for triple-α process
  → core must be degenerate for high densities



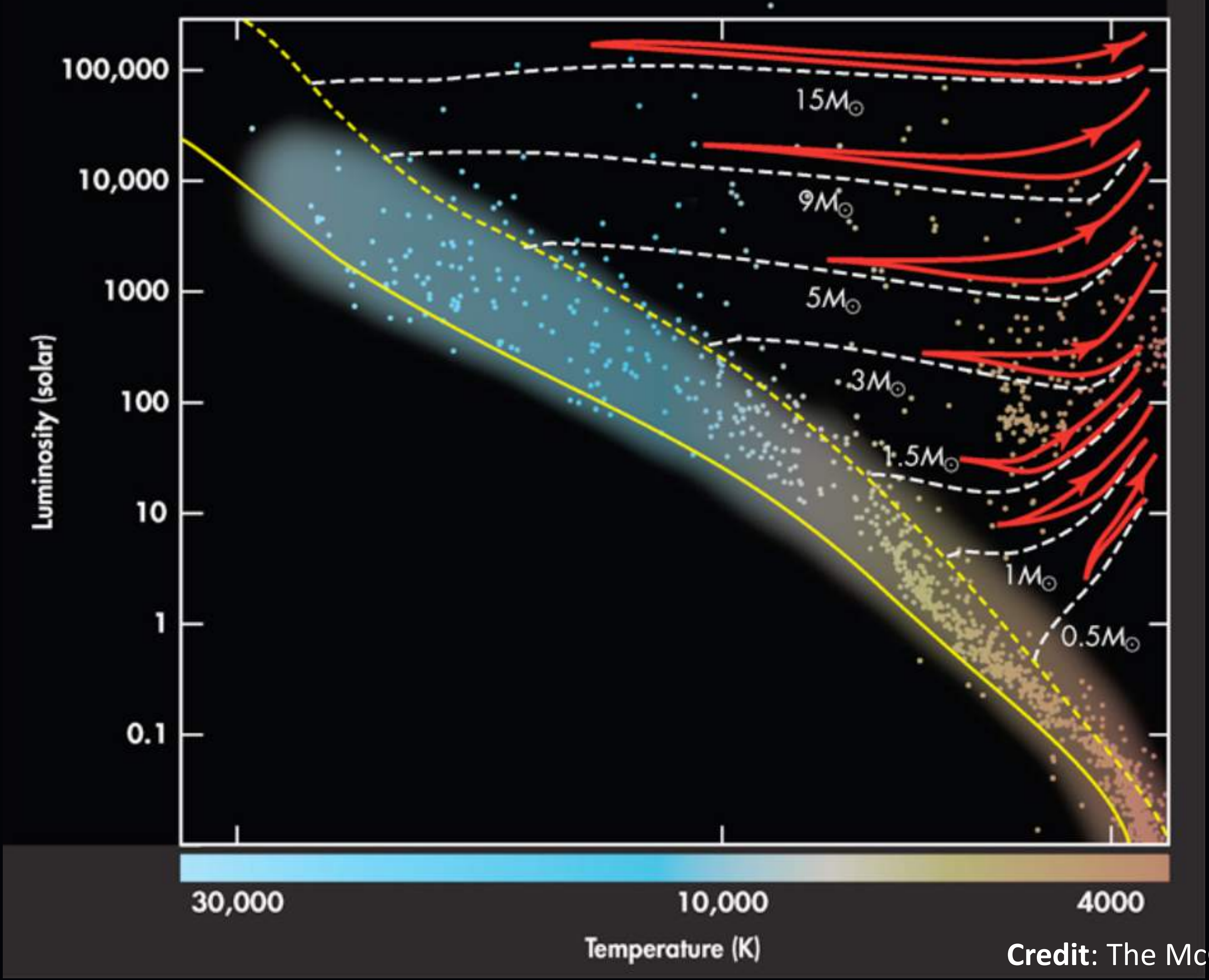
- Nuclear runaway: **Helium flash**
  → energy removes electron degeneracy

- He core burning and H shell burning

- Star starts to fuse He to C in its core
  → Lifetime as red giant ~ 10% of MS lifetime



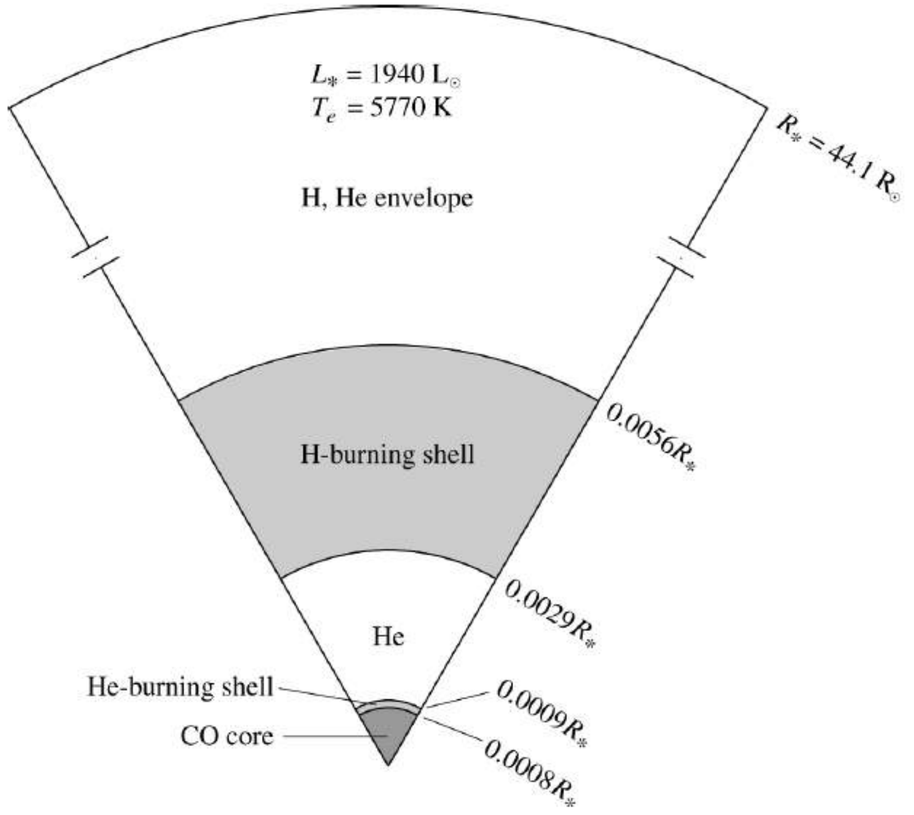
Credit: Pearson Education Inc.



Credit: The McGraw-Hill Company

Late Burning Phase for $\mathrm{M} < 8\ \mathrm{M}_{\odot}$

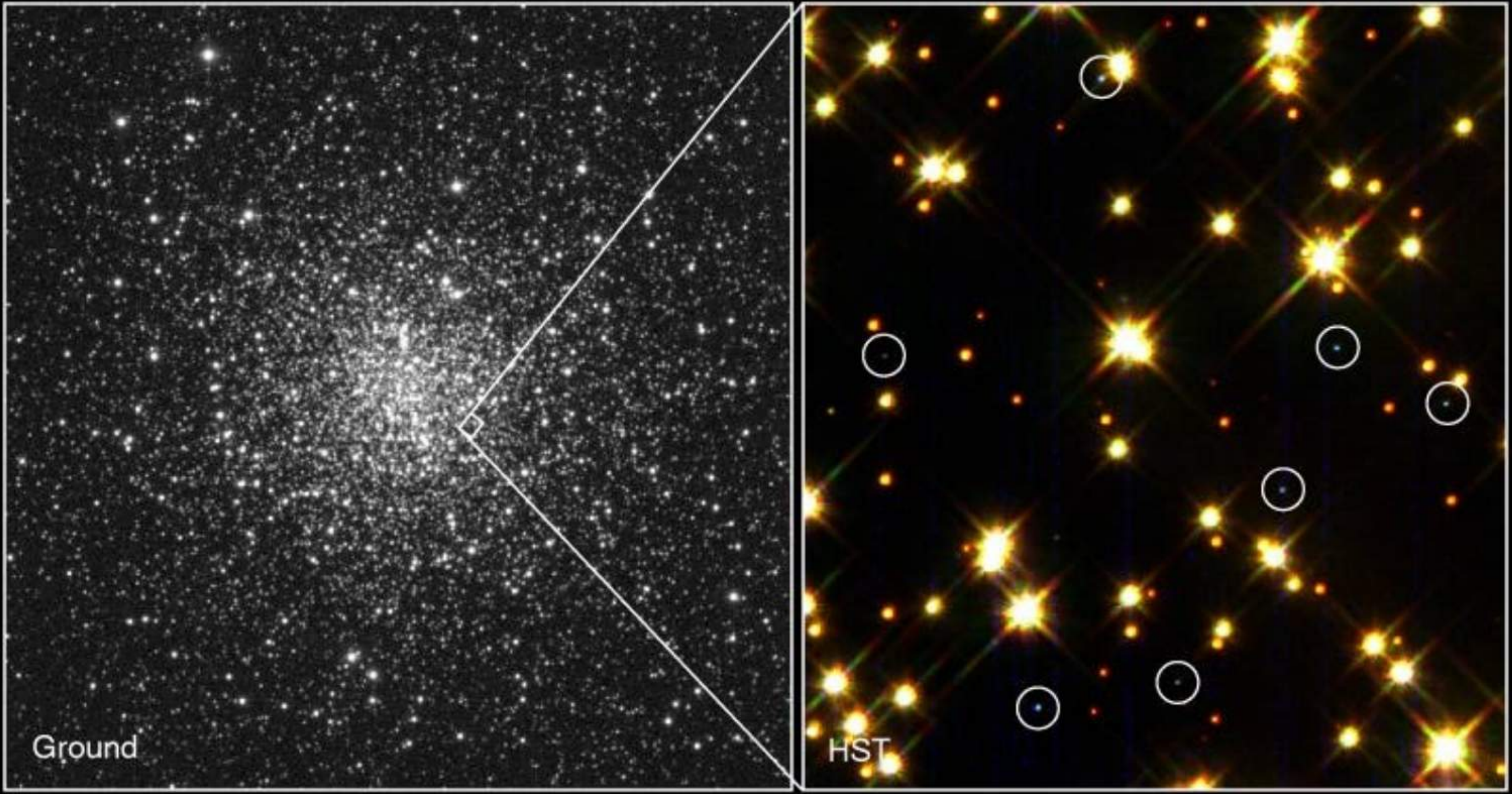
- Core runs out of He, it stops producing energy
  → begins to collapse again
- Inert C core, He and H shell burning
- Star moves up the **Asymptotic Giant Branch (AGB)**
- Shell burning occurs not simultaneously
  → changing thermal pulses
  → outer layers of the star are ejected
- Mass loss increases, until the entire envelope is ejected



Final Stage for Low Mass Stars with $\mathrm{M} < 8\ \mathrm{M}_{\odot}$

- Star is not massive enough to ignite C core
- Ejected shells with hot exposed cores
  $\rightarrow$ **planetary nebula phase**
- C/O white dwarf remains
- Some stars at the higher end of this phase can burn C
  $\rightarrow$ O Ne Mg white dwarfs

Phase $1\ M_{\odot}$	τ (yrs)
Main Sequence	$9 \cdot 10^9$
Subgiant	$3 \cdot 10^9$
Red giant	$1 \cdot 10^9$
AGB evolution	$\sim 5 \cdot 10^6$
PN	$\sim 1 \cdot 10^5$
WD cooling	$> 8 \cdot 10^9$



White Dwarf Stars in M4

HST · WFPC2

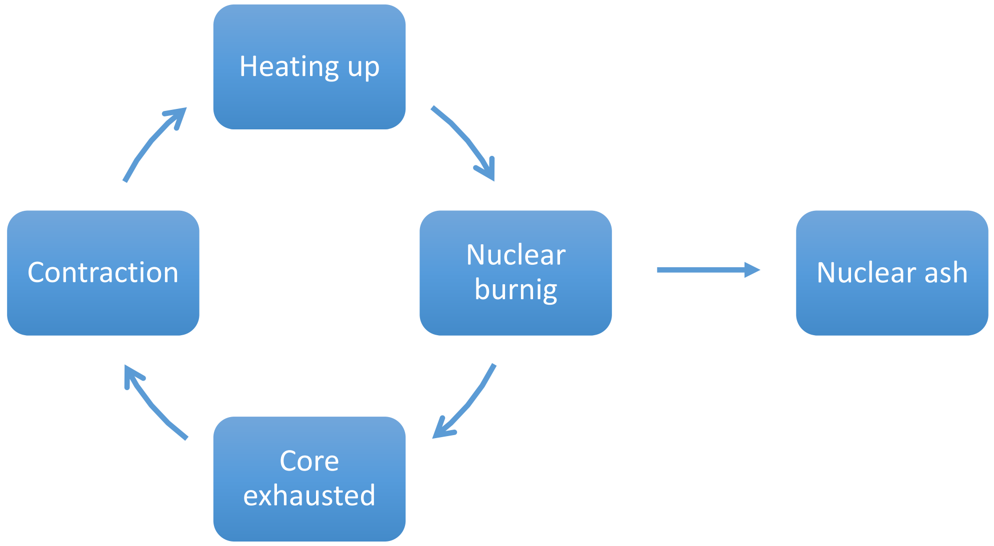
PRC95-32 · ST ScI OPO · August 28, 1995 · H. Bond (ST ScI), NASA

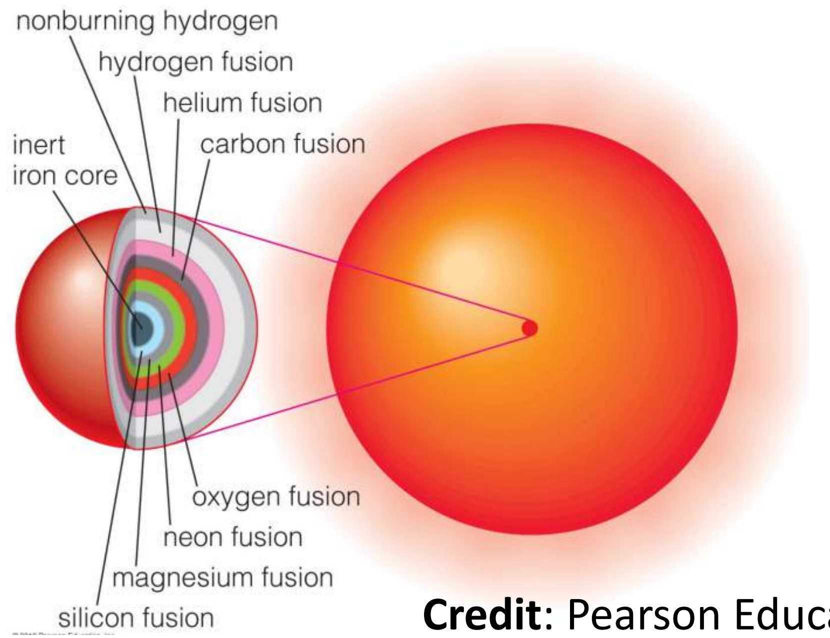
High Mass Evolution for $M > \sim 8\, M_\odot$

- Collapsing He core reaches T for triple-α process
  → He burning begins when core is not-degenerate (lower density)
  → no helium flash

- He burning stops when core is converted to C and O
  → core begins to collapse and He burning shell ignites outside the core

- This pattern of core ignition and shell ignition continues
  → lead to a „onion-skin“ layering of nuclei



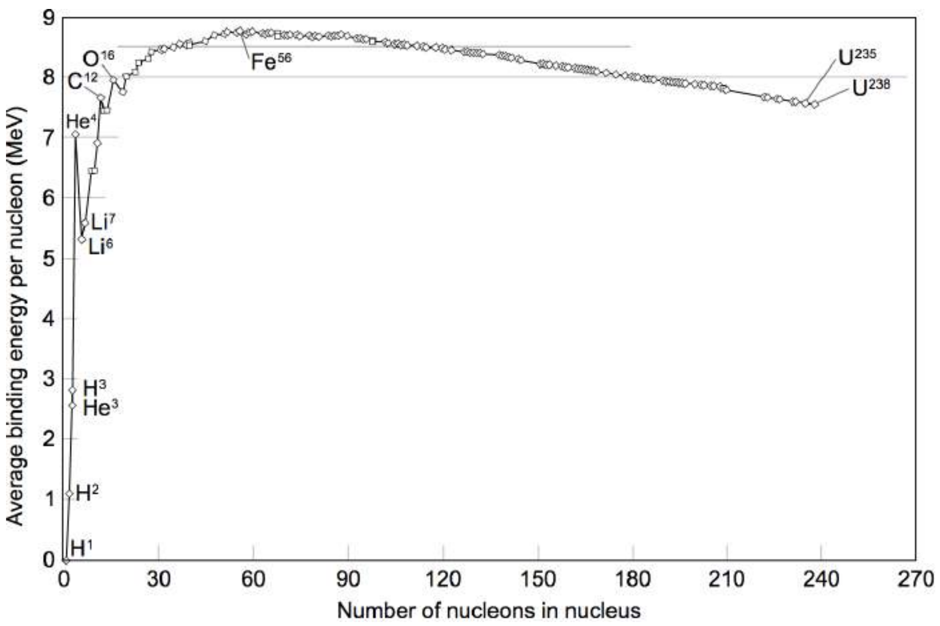


Credit: Pearson Education Inc.

Later Burning Phases

- Heavier elements are built up until Fe core is formed
  → The core is surrounded by a series of shells at lower T and lower ρ

- Nucleosynthesis of elements above He is less efficient
  → the reactions occur at greater rates so radiation pressure can balance gravity

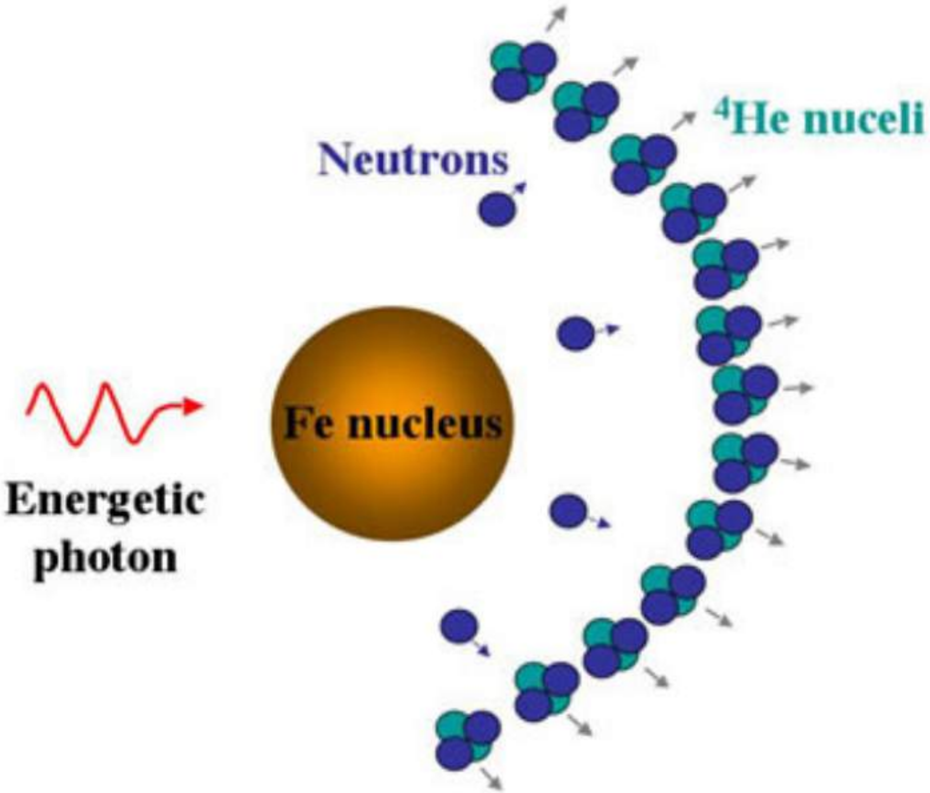


Phase	Required Temperature [K]	$15\ M_\odot$ τ [yrs]	$25\ M_\odot$ τ [yrs]
Hydrogen (MS)	$4 \cdot 10^7$	$10 \cdot 10^6$	$7 \cdot 10^6$
Helium	$2 \cdot 10^8$	$2 \cdot 10^6$	$5 \cdot 10^5$
Carbon	$6 \cdot 10^8$	2000	600
Neon	$1{,}2 \cdot 10^9$	$0{,}7$	1
Oxygen	$1{,}5 \cdot 10^9$	$2{,}6$	$0{,}5$
Silicon	$2{,}7 \cdot 10^9$	$5 \cdot 10^{-2}$	$3 \cdot 10^{-3}$

Core Collapse!

- Fe-core reaches $1{,}4\ M_\odot$ (Chandrasekhar-limit) → degeneracy pressure can no longer resist its own gravity
- Collapse begins → Temperature rises, but Fe can‘t fuse
- Fe nuclei breaks down because of **photodesintegration**
- Inverse β-decay occurs, requires 1,3 MeV for each reaction

$$p + e^- \rightarrow n + \nu_e$$

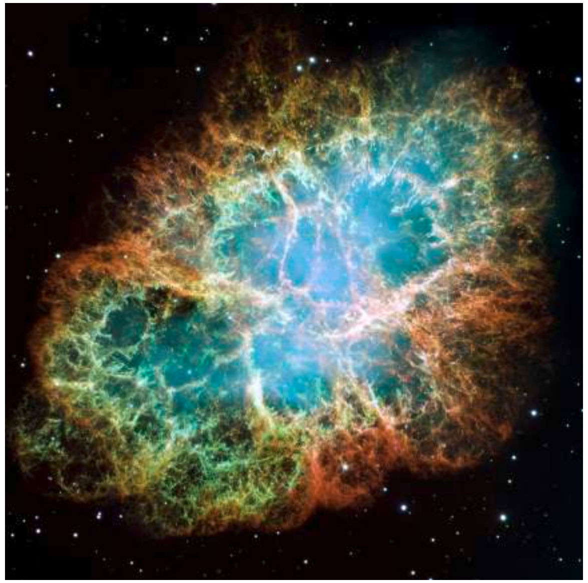


Credit: Swinburne University of Technology

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

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

Supernova



- Core collapses from under the rest of the star
  → outer layers start to fall inwards and hit surface of core
- Outer layers „bounce“ of and are again ejected out
  → creates shock wave which pushes back the envelope
- shock wave smashes outward through the star – v ~ 0,1c
  → explosive nuclear fusion takes place behind the shock (r-process)
  → shock heats and expands the layers of the star
- The light increases as the surface area of the ball of gas increases

Neutron Star or Black Hole?

NS with $M < 3\ M_{\odot}$:

- Neutron degeneracy sets in → resists gravitational pressure

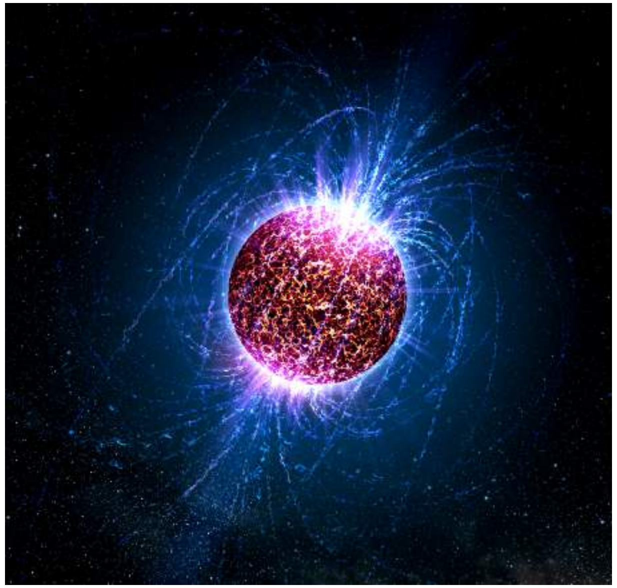
- Whole core is like one giant atomic nucleus
  → Neutron star has been born

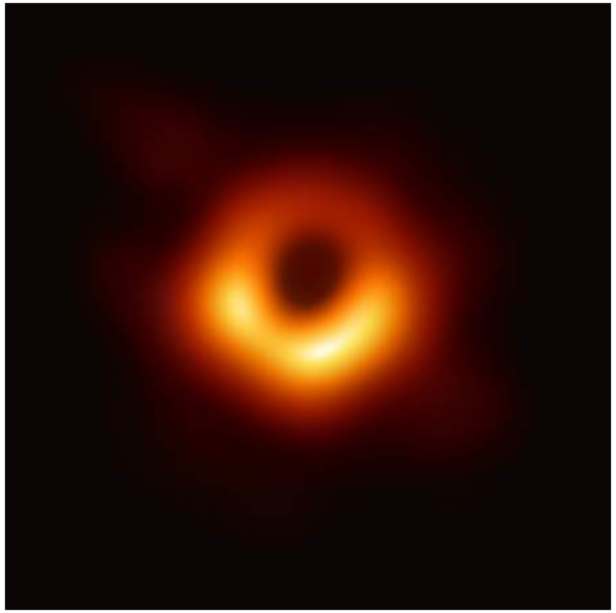
NS with $M > 3\ M_{\odot}$:

- Mass of NS reaches Tolman–Oppenheimer–Volkoff limit
  → corresponding to the Chandrasekhar mass

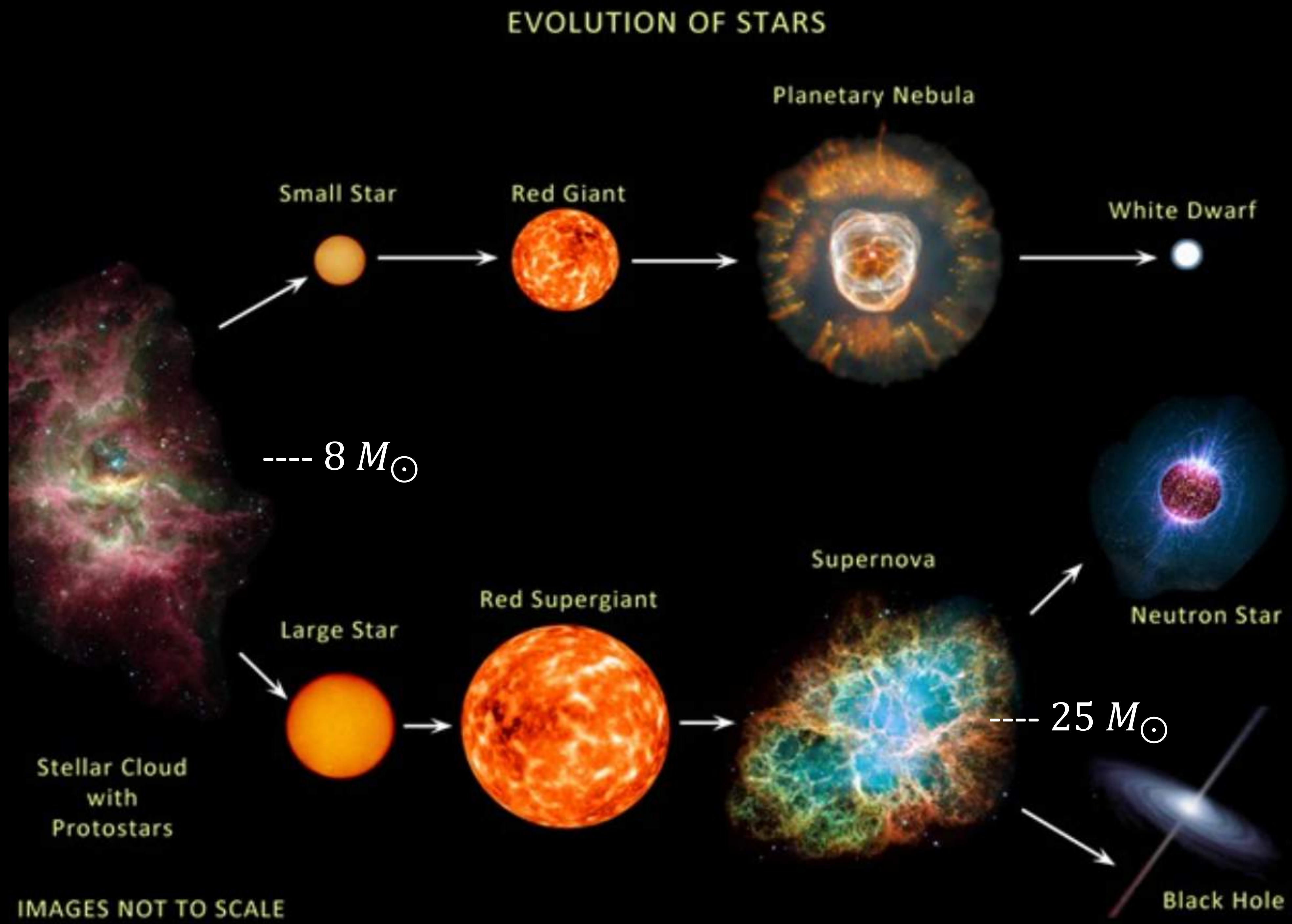
- neutron degeneracy pressure is unable to balance self-gravity

- Upper limit is less than $\sim 3\ M_{\odot}$
  → above this limit, NS will collapse to a black hole

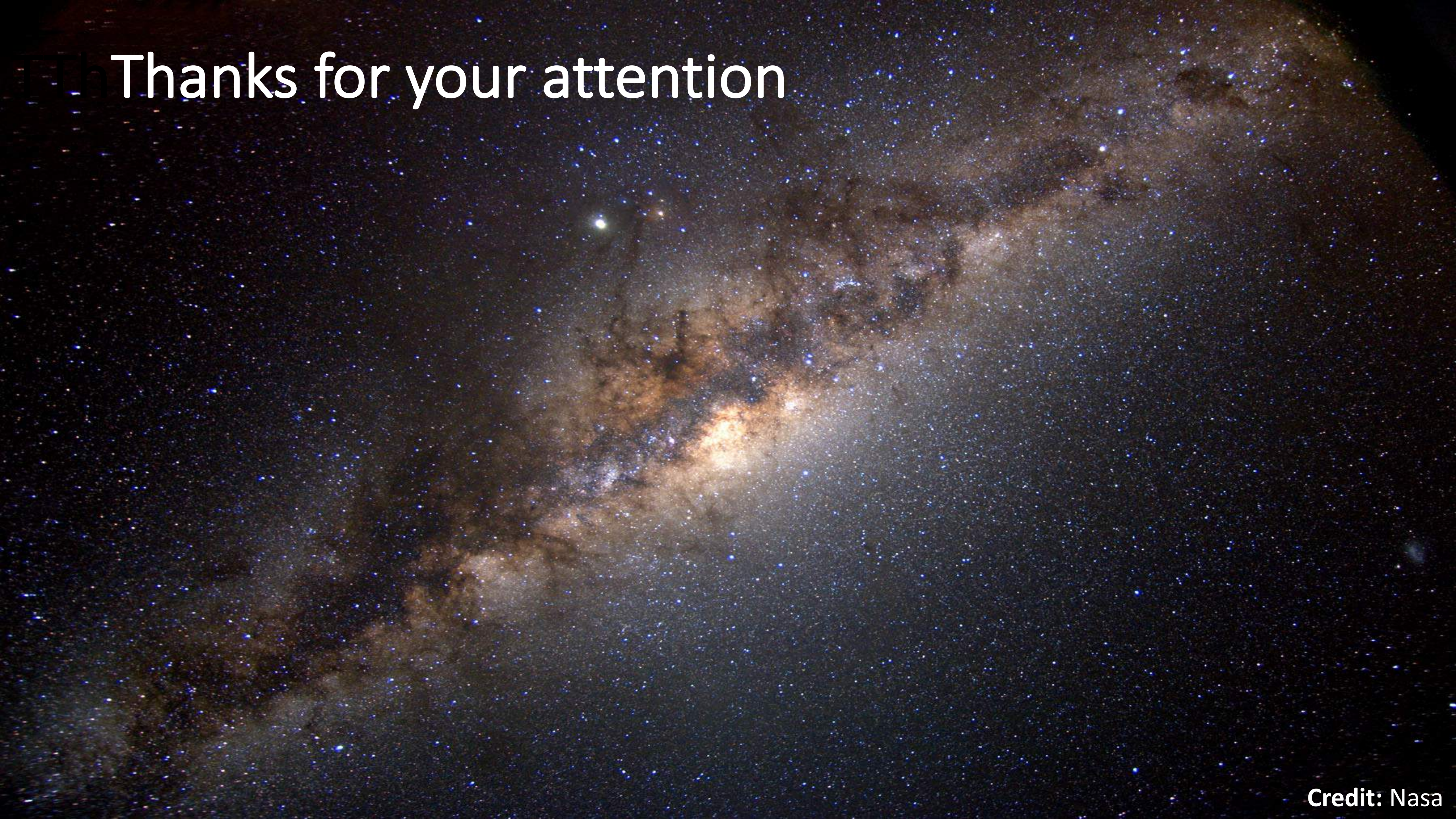




Credit: EHT Collaboration


EVOLUTION OF STARS
Planetary Nebula
Small Star
Red Giant
White Dwarf
---- $8\ M_{\odot}$
Supernova
Red Supergiant
Large Star
Neutron Star
---- $25\ M_{\odot}$
Stellar Cloud with Protostars
IMAGES NOT TO SCALE
Black Hole

Thanks for your attention



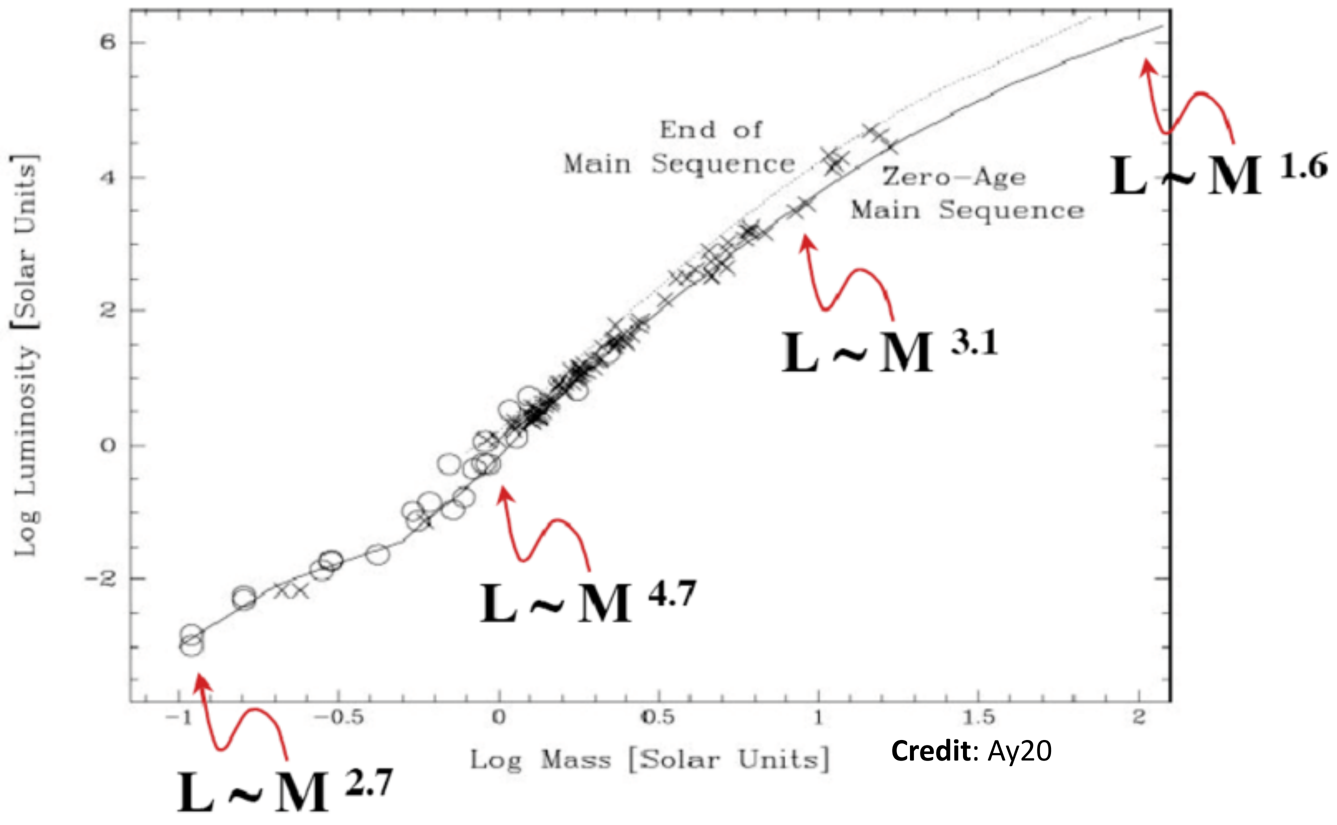
Credit: Nasa

Additional Material

Credit: Nasa, ESA, Hubble-SM4-ERO-Team

Main Sequence Mass-Luminosity Relation

- For MS stars a direct relationship between mass M and luminosity L is observed



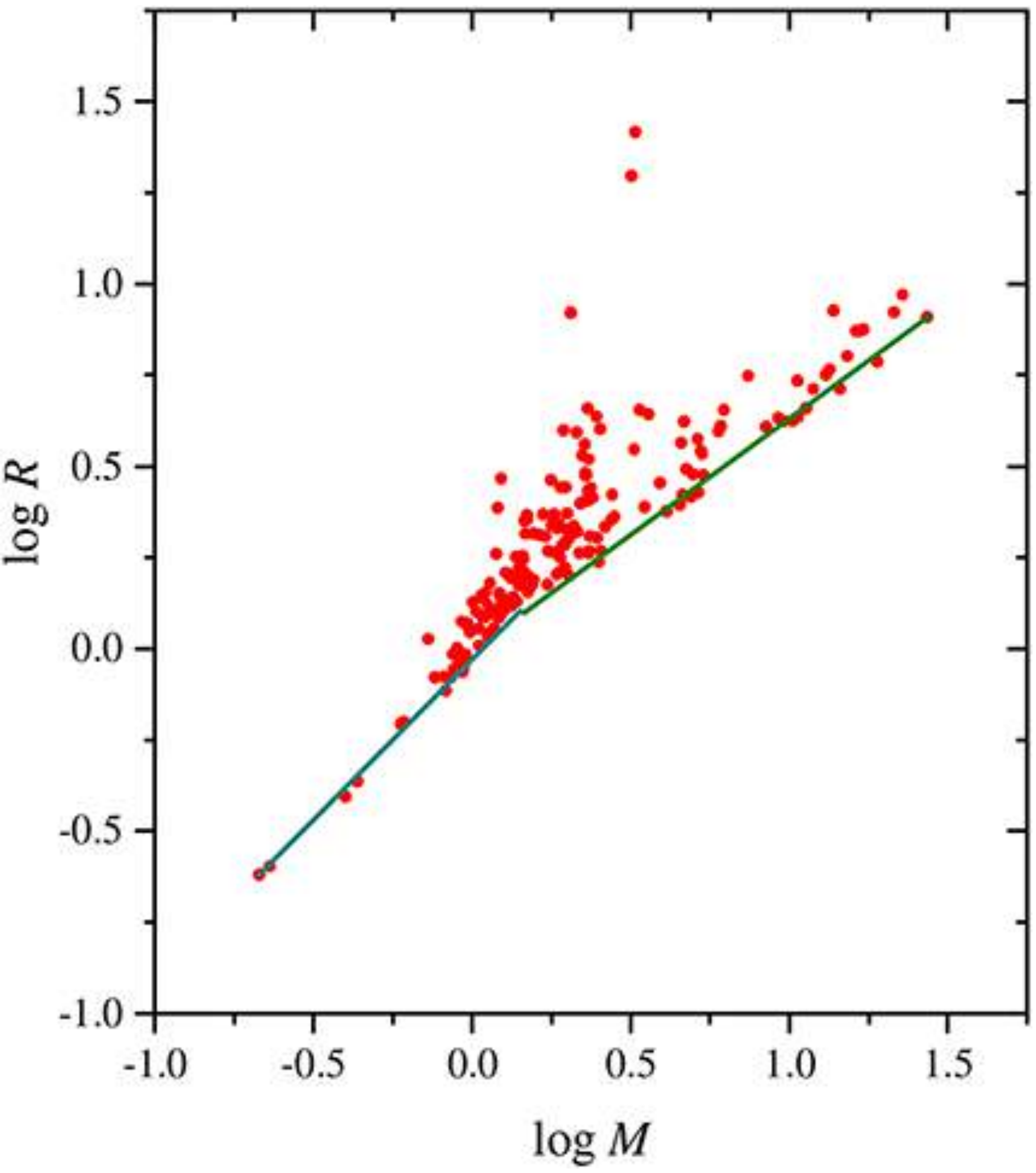
Credit: Ay20

$$L \sim M^{\alpha}$$

Mass, $M_{\odot}$	Exponent, α
100	1,6
10	3,1
1	4,1
0,1	2,7

- it is possible to estimate the mass of a star by the observed luminosity

Main Sequence Mass-Radius Relation



- fairly tight for stars with $M < 0.9\ M_{\odot}$, but large at higher mass because of stellar evolution on the Main Sequence

$$R \propto M^{\alpha}$$

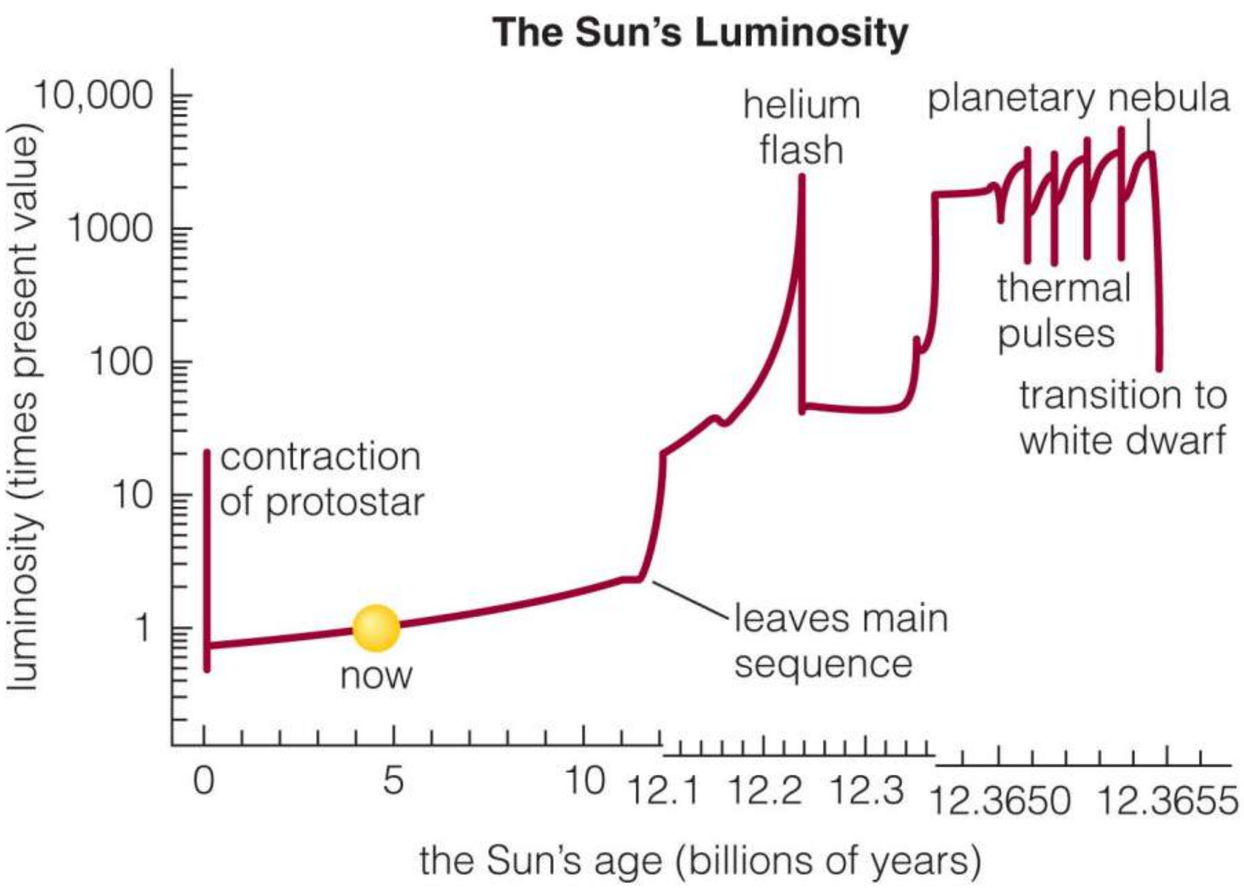
Mass, $M_{\odot}$	Exponent, α
$0{,}2 - 1{,}4$	0,9
$1{,}4 - 30$	0,6

- Mass-Radius Relation implies that

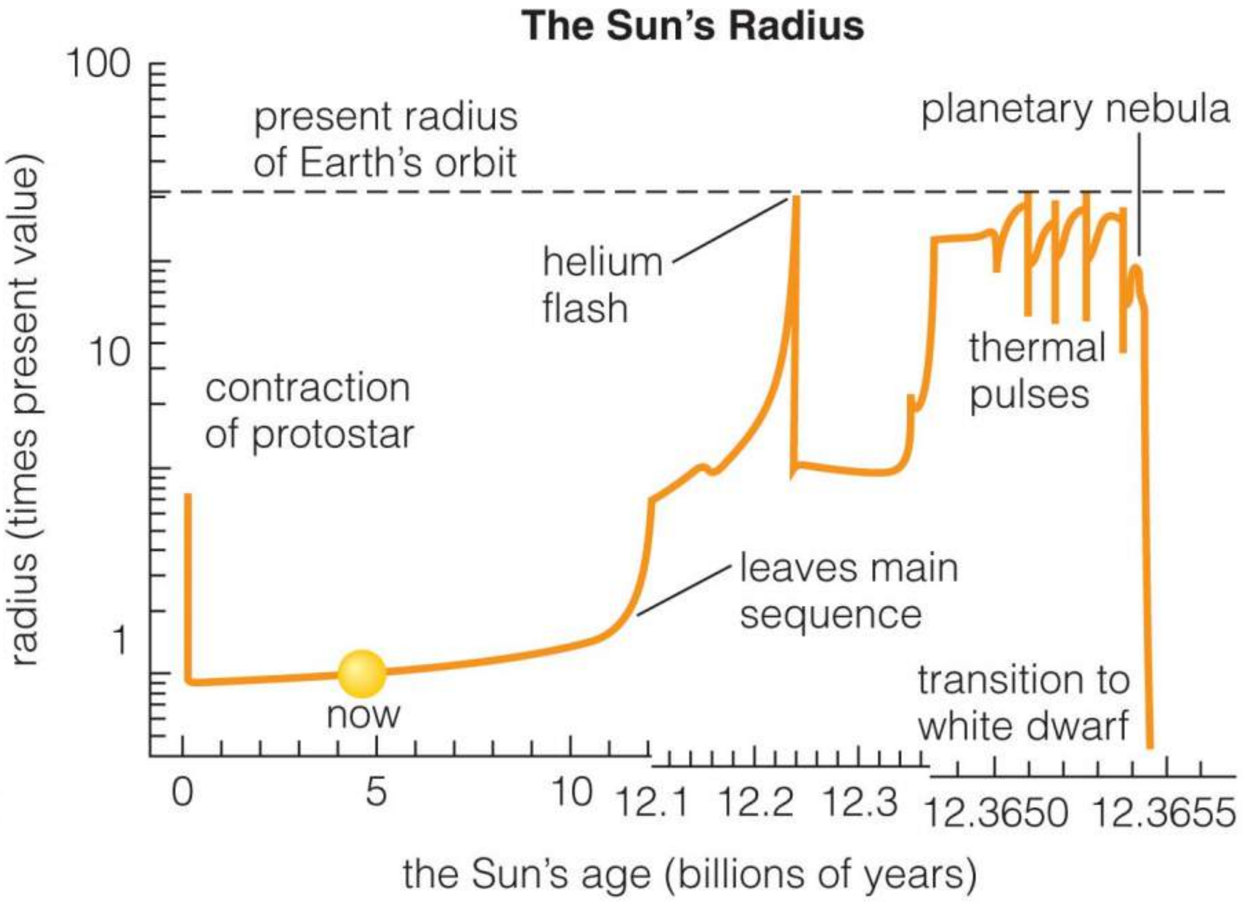
$$\bar{\rho} \propto M^{1-3\alpha}$$

→ stars are less dense with increasing mass

Comparison of Luminosity and Radius to the Lifetime of the Sun

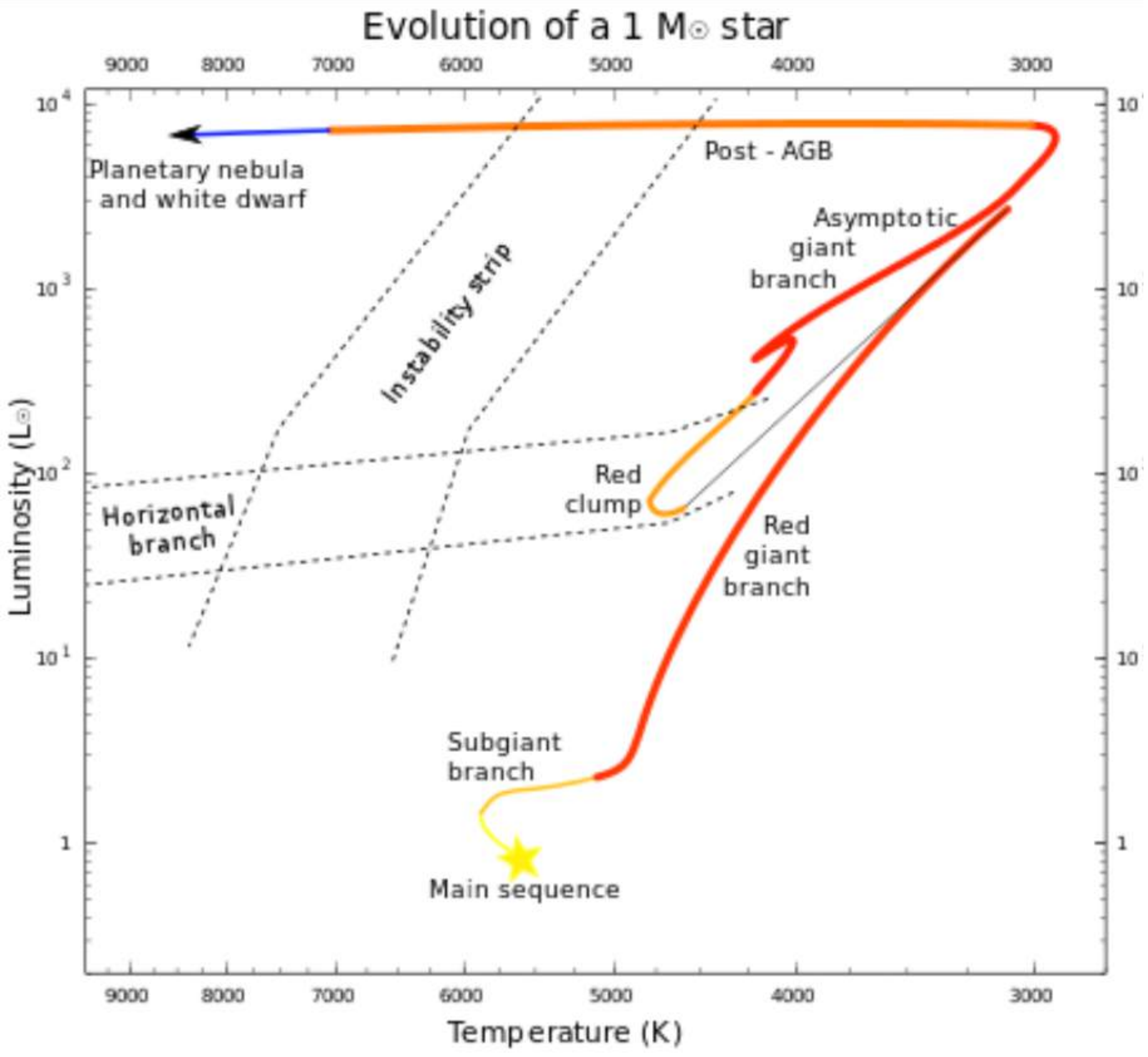


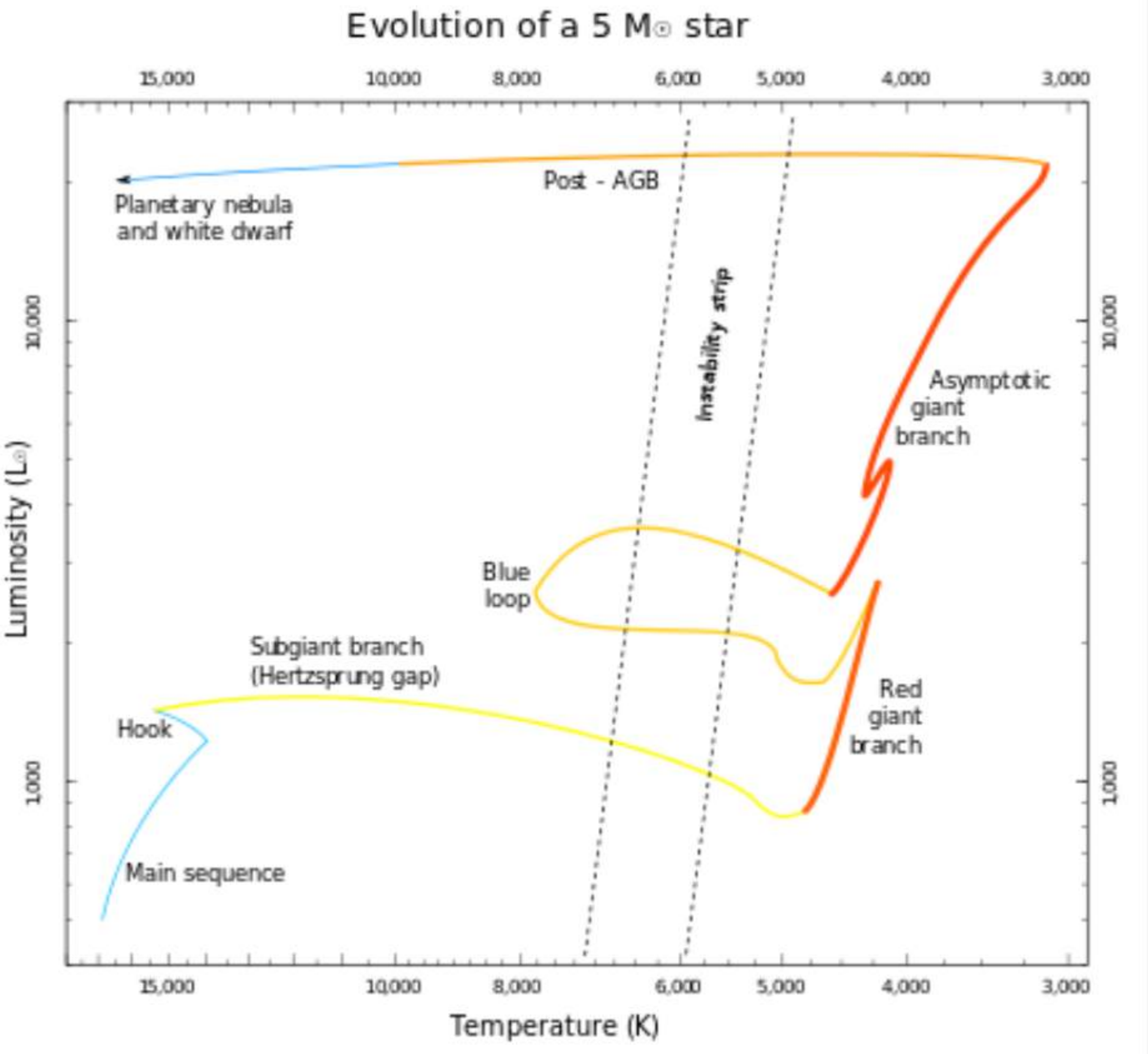
a Changes in the Sun's luminosity over time.



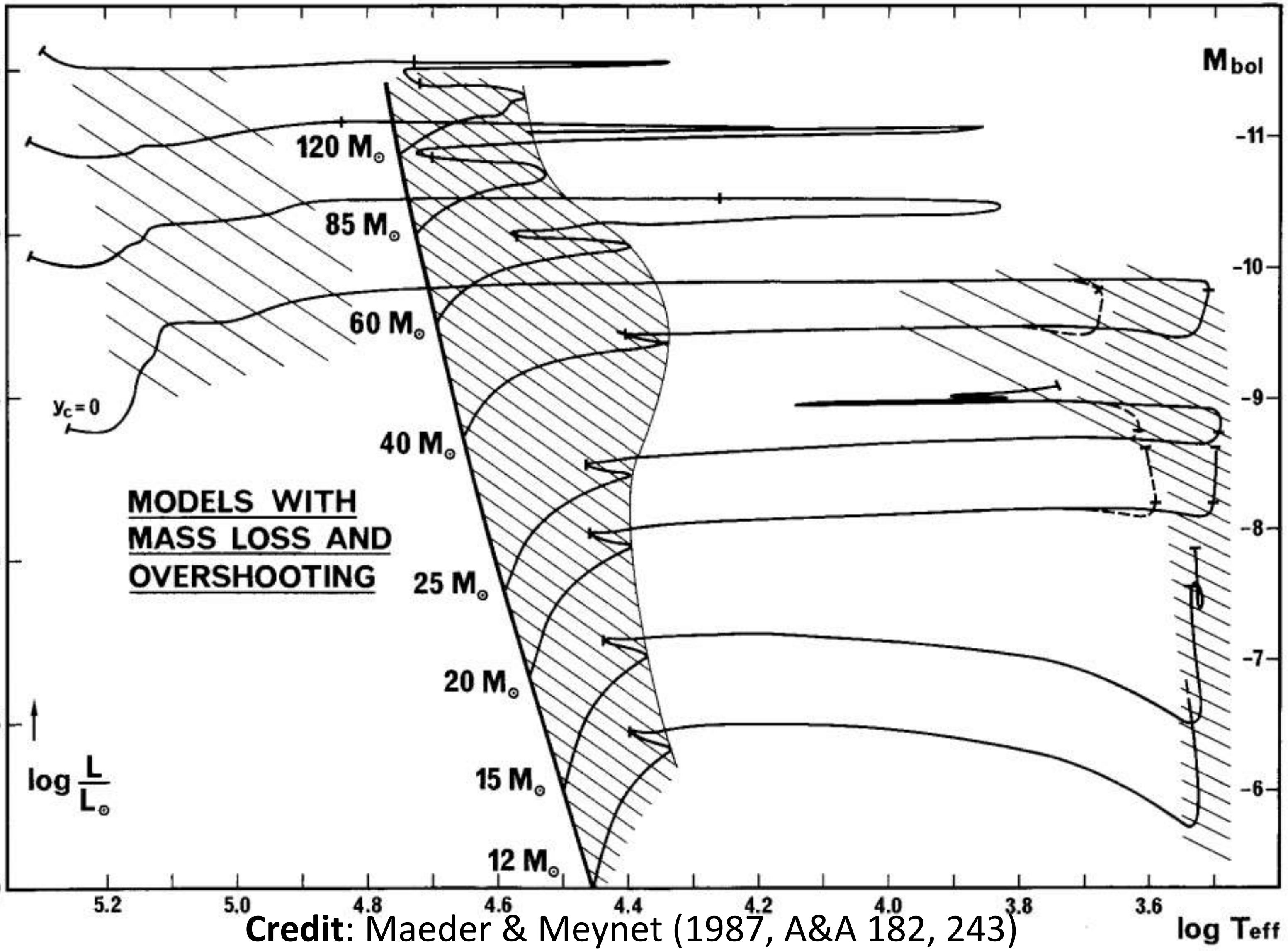
b Changes in the Sun's radius over time.

Comparison of Stellar Evolution for Low and Intermediate Mass Stars





Stellar Evolution for High Mass Stars

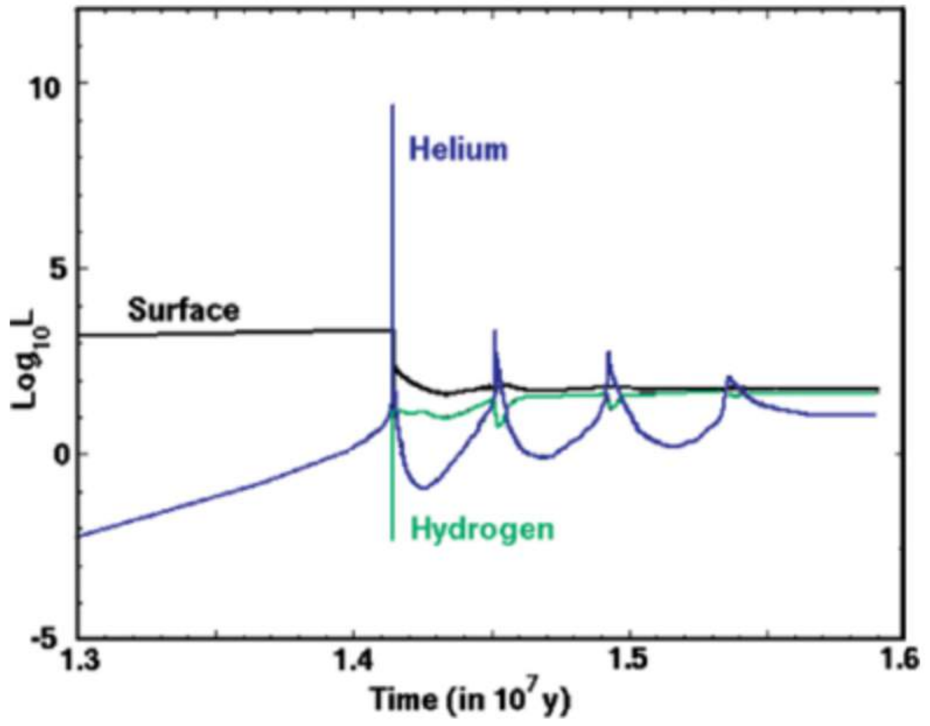


Credit: Maeder & Meynet (1987, A&A 182, 243)

The shaded regions correspond to long-lived evolution phases on the Main Sequence and during He core burning

Helium Flash for $M < 2\ M_{\odot}$

- stars undergo He core flash instead of regular He burning
  → cores of low mass stars are more dense than of those high mass stars

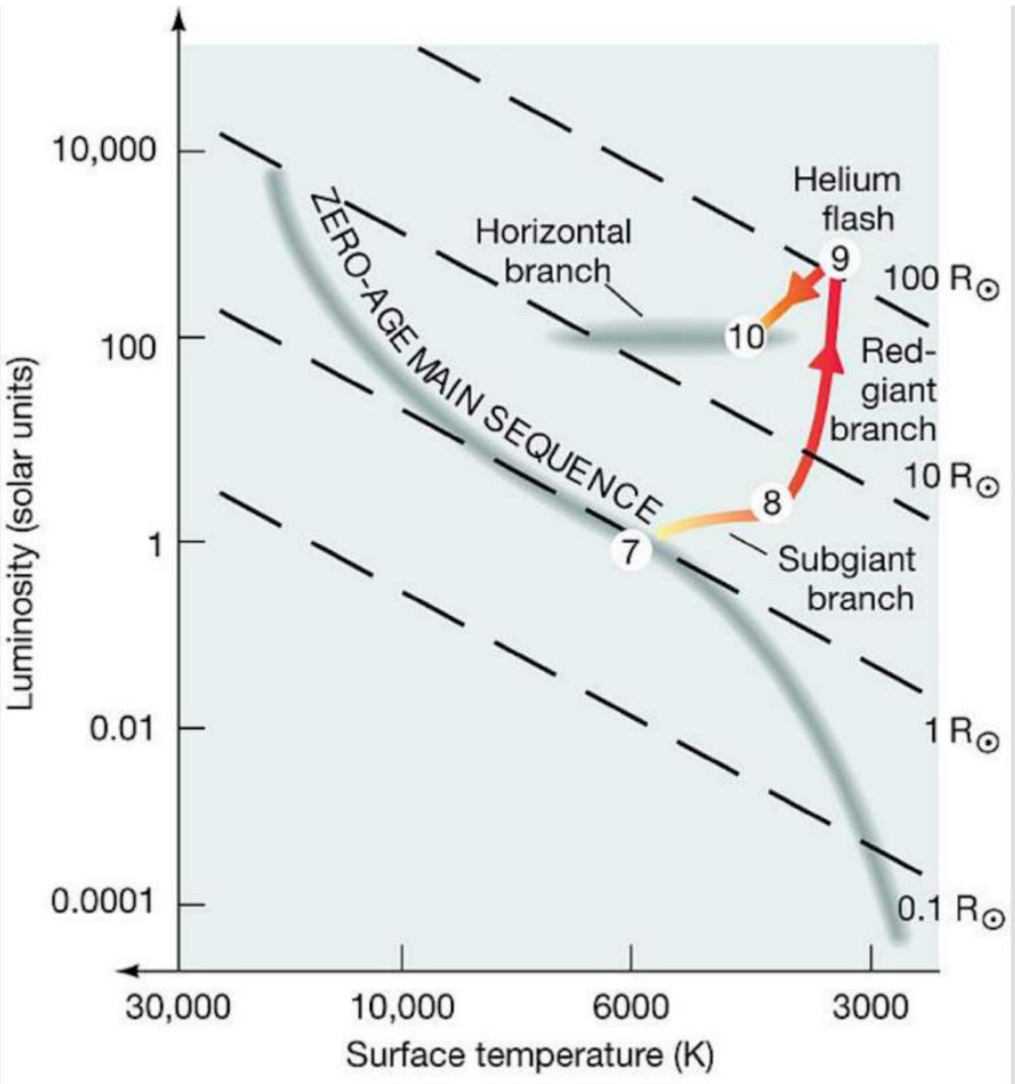


- Contracted Core is so dense that it cannot be described as an ideal gas
  → degenerate gas, in which P is only depending on ρ but not on T

- When triple-α process starts He ignites as thermonuclear runaway
  → rising T does not raise P and does not cause an expansion of the burning zone

Helium Flash for $M < 2\,M_\odot$

- mechanism of hydrostatic burning is not working anymore and He burning proceeds quickly to high T
- Very high T lift the degeneracy of the gas and its equation-of-state becomes T dependent again very suddenly
- This causes an explosive expansion of the outer core, also ejecting the outer layers of the star as a planetary nebula
  → mass loss because of He flash



Later Burning Phases for $M > \sim 8\ M_{\odot}$

- C/O core has shrunk → core temperature increases → C burning ignites at $T \sim 6 \cdot 10^8$ K

$$^{12}\mathrm{C} + {}^{12}\mathrm{C} \rightarrow \begin{Bmatrix} ^{20}\mathrm{Ne} + {}^{4}\mathrm{He} \\ ^{23}\mathrm{Na} + \mathrm{p} \end{Bmatrix}$$

- Neon burning follows (not O!) at $T \sim 1{,}2 \cdot 10^9$ K → photodegradation occurs for the first time and leads to the formation of heavier nuclei

$$^{20}\mathrm{Ne} + \gamma \rightarrow {}^{16}\mathrm{O} + {}^{4}\mathrm{He}$$
$$^{20}\mathrm{Ne} + {}^{4}\mathrm{He} \rightarrow {}^{24}\mathrm{Mg} + \gamma$$

Later Burning Phases for $M > \sim 8\, M_\odot$

- O burning occurs when tempature reaches $T \sim 1{,}5 \cdot 10^9$ K

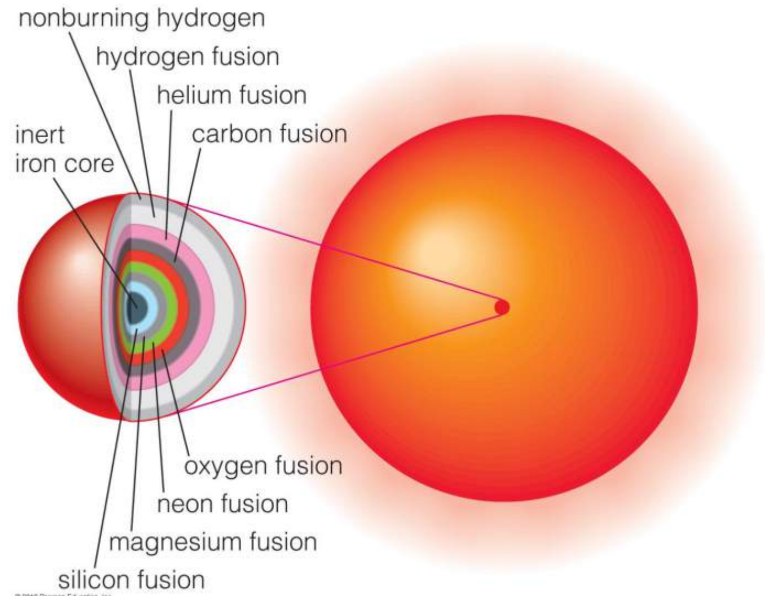
$$^{16}\mathrm{O} + {}^{16}\mathrm{O} \rightarrow {}^{28}\mathrm{Si} + {}^{4}\mathrm{He}$$

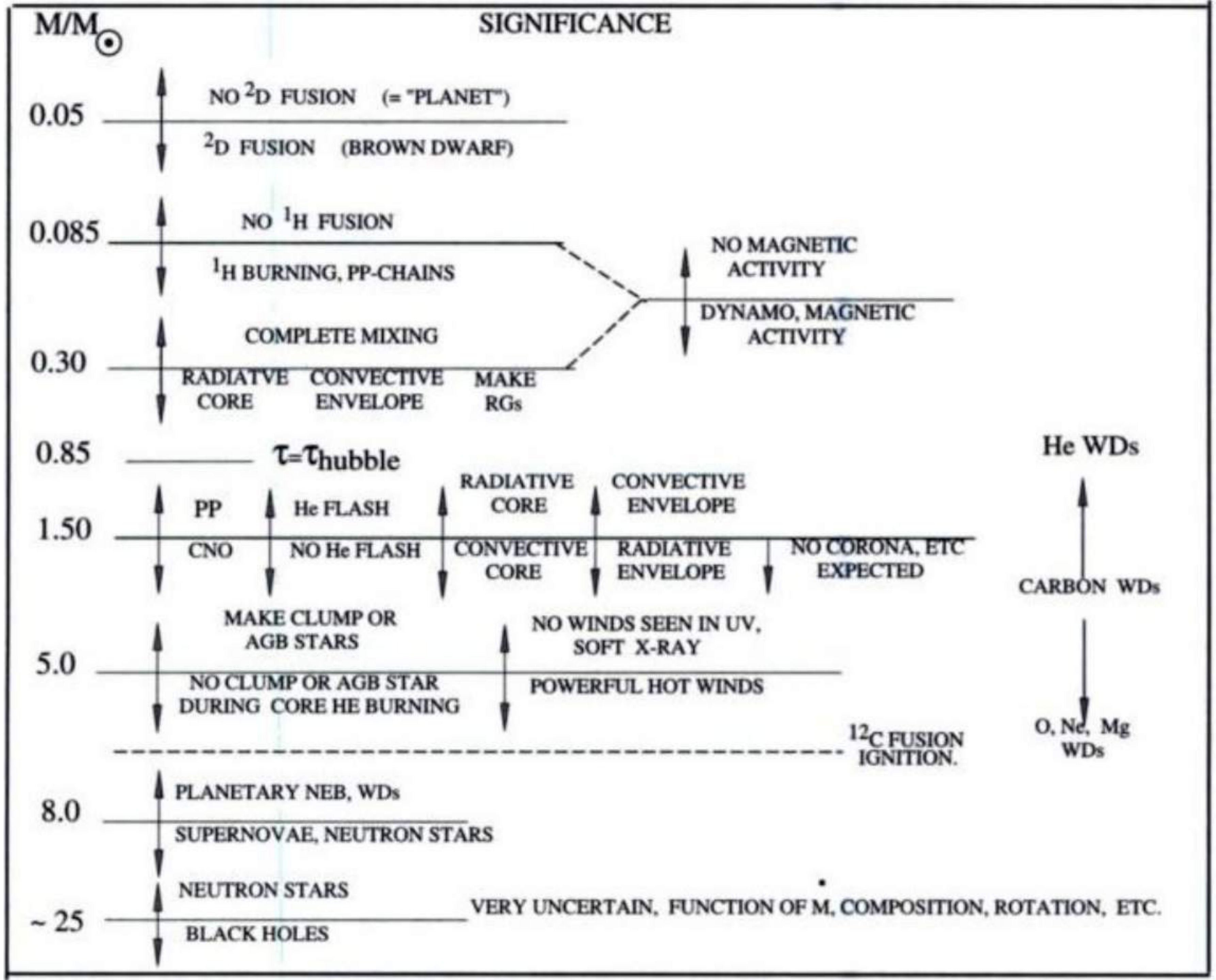
- $^{4}\mathrm{He}$ nuclei build up heavier nuclei by successive capture reactions

$$^{4}\mathrm{He} + \left\{ \begin{array}{c} ^{28}\mathrm{Si} \rightarrow {}^{32}\mathrm{S} + \gamma \\ ^{32}\mathrm{S} \rightarrow {}^{36}\mathrm{Ar} + \gamma \\ ^{36}\mathrm{Ar} \rightarrow {}^{40}\mathrm{Ca} + \gamma \end{array} \right\} \text{and so on...}$$

- Advanced burning phases lead to a „onion-skin“ layering of nuclei

- Inert Fe/Ni core has formed




M/M⊙
SIGNIFICANCE
0.05
NO 2D FUSION (= "PLANET")
2D FUSION (BROWN DWARF)
0.085
NO 1H FUSION
1H BURNING, PP-CHAINS
NO MAGNETIC ACTIVITY
DYNAMO, MAGNETIC ACTIVITY
COMPLETE MIXING
0.30
RADIATVE CORE
CONVECTIVE ENVELOPE
MAKE RGs
0.85
τ=τhubble
He WDs
RADIATIVE CORE
CONVECTIVE ENVELOPE
PP
He FLASH
1.50
CNO
NO He FLASH
CONVECTIVE CORE
RADIATIVE ENVELOPE
NO CORONA, ETC EXPECTED
CARBON WDs
MAKE CLUMP OR AGB STARS
NO WINDS SEEN IN UV, SOFT X-RAY
5.0
NO CLUMP OR AGB STAR DURING CORE HE BURNING
POWERFUL HOT WINDS
12C FUSION IGNITION.
O, Ne, Mg WDs
PLANETARY NEB, WDs
8.0
SUPERNOVAE, NEUTRON STARS
NEUTRON STARS
~ 25
BLACK HOLES
VERY UNCERTAIN, FUNCTION OF M, COMPOSITION, ROTATION, ETC.