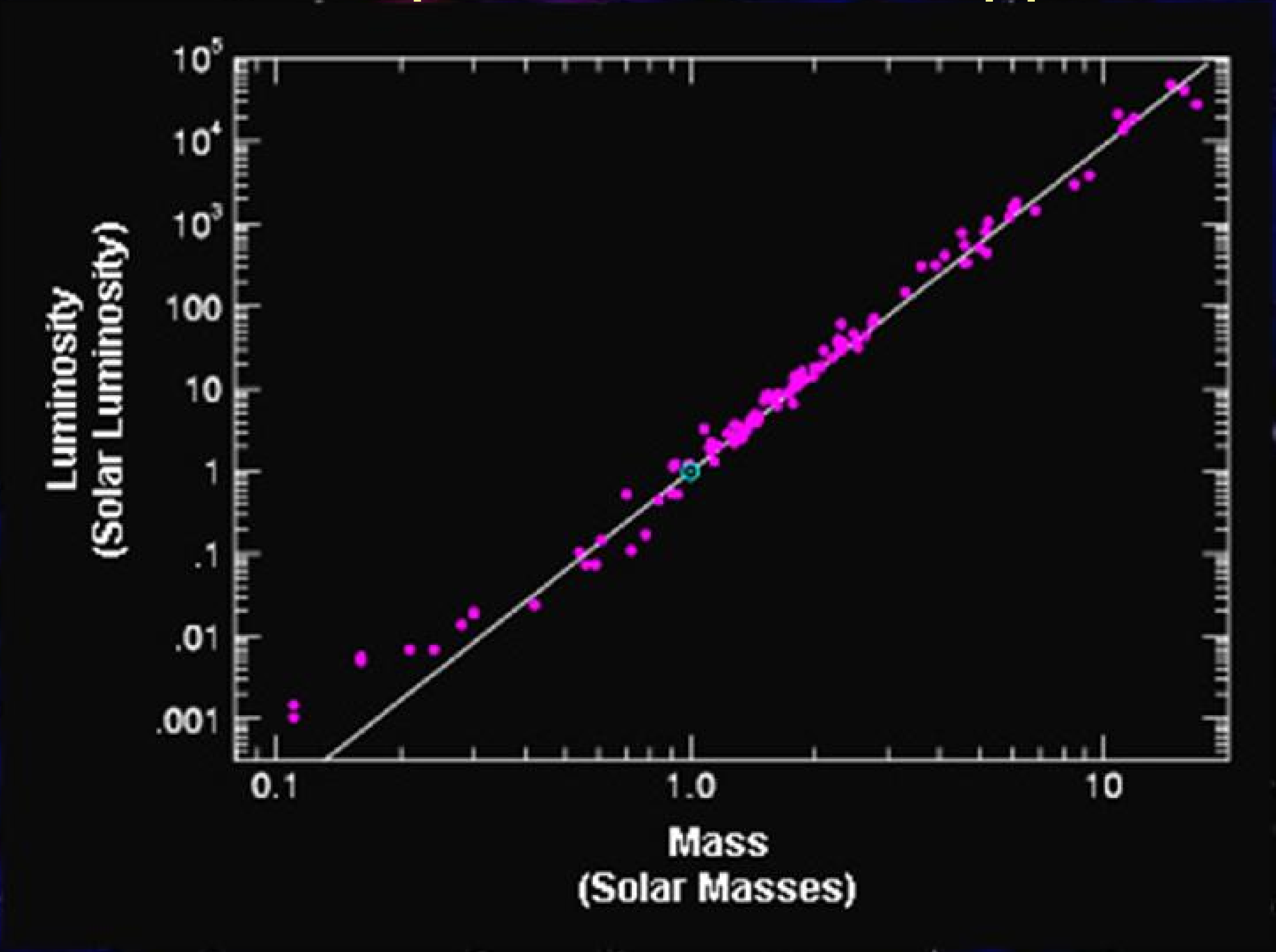
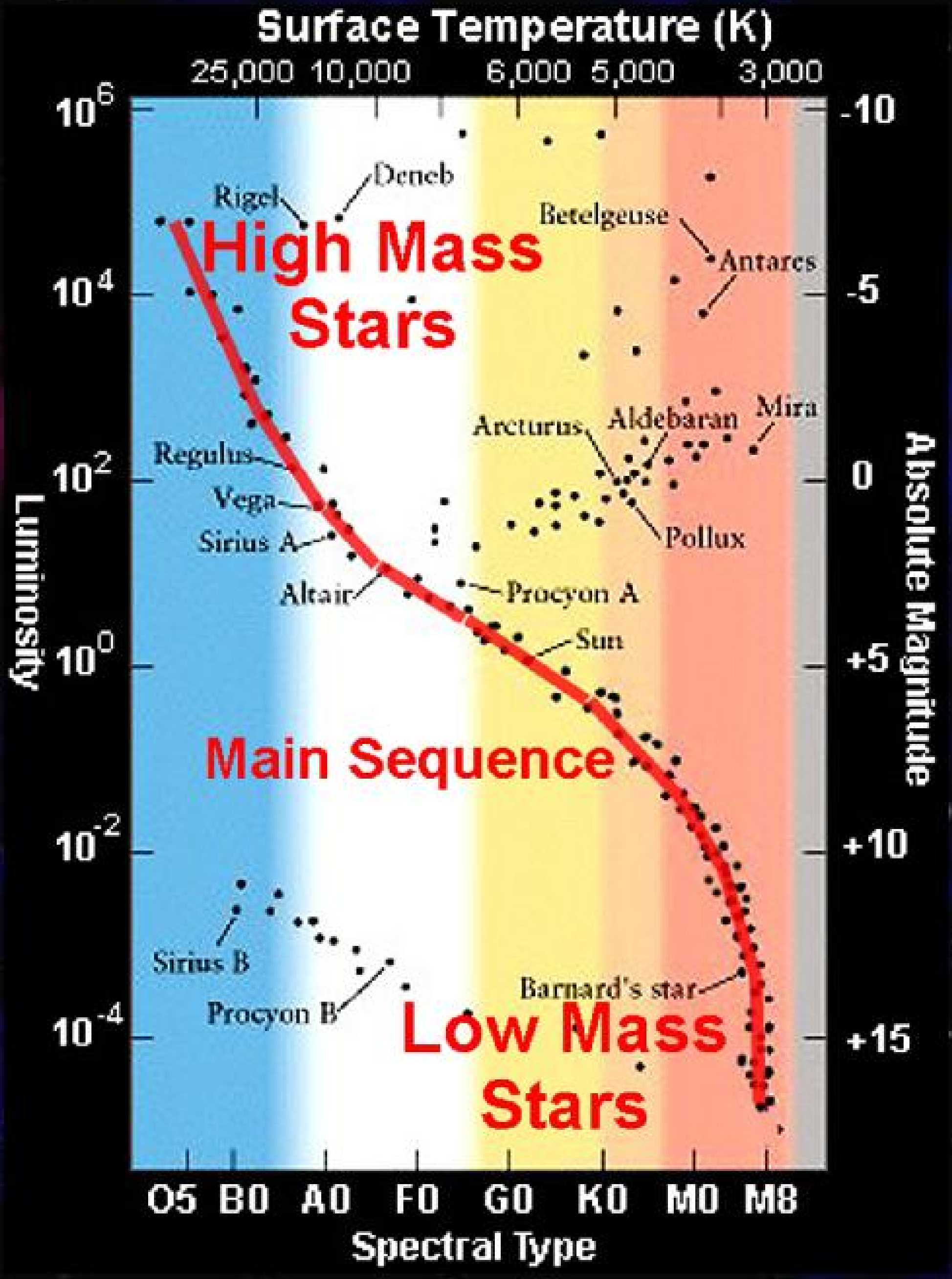
BINARY STARS

$$(m_1 + m_2) \propto \frac{d^3}{p^2} \qquad \frac{m_1}{m_2}$$

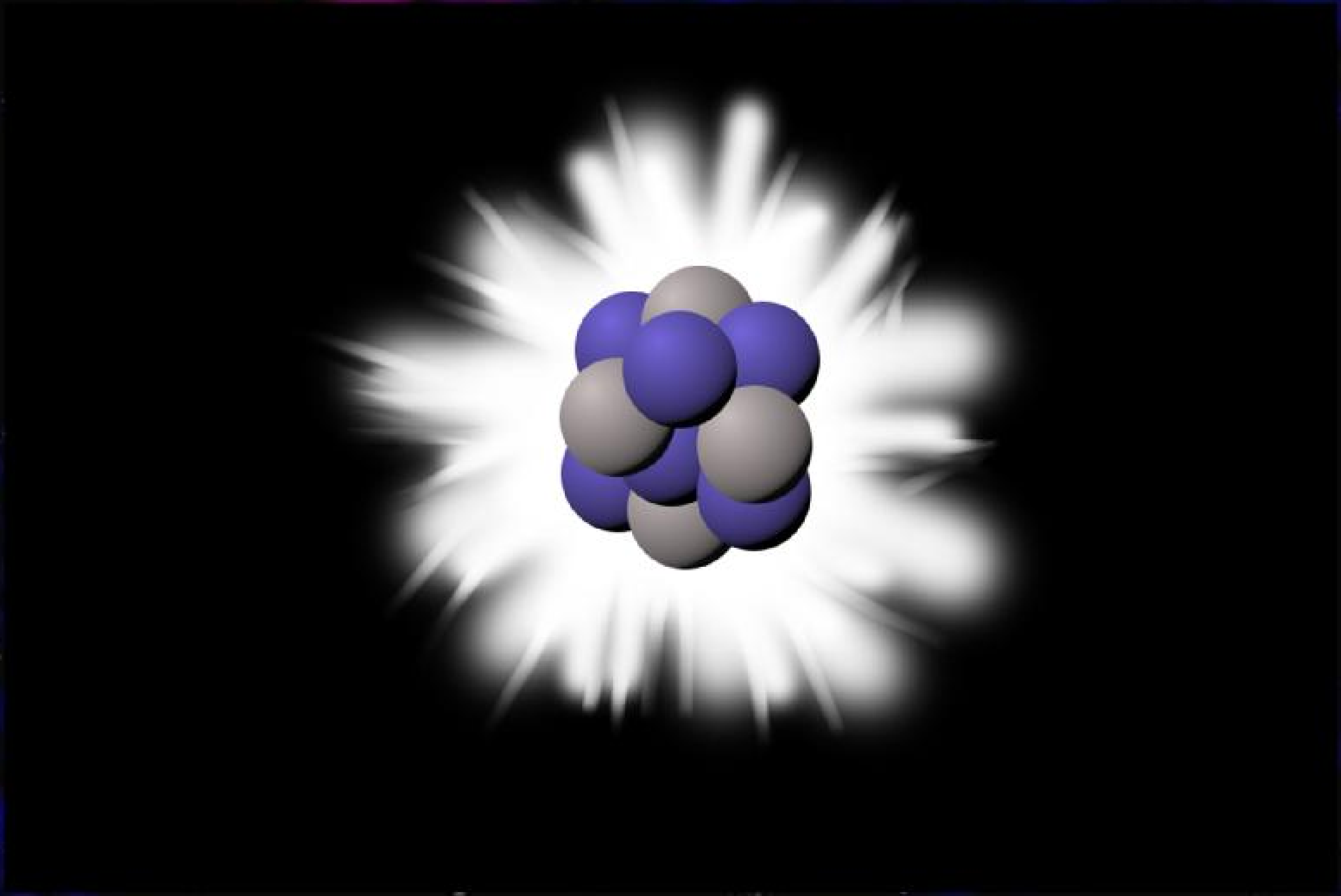
The masses of the individual stars can be calculated.

By gathering the masses of a large variety of stars in binary systems a fundamental relationship soon became apparent.



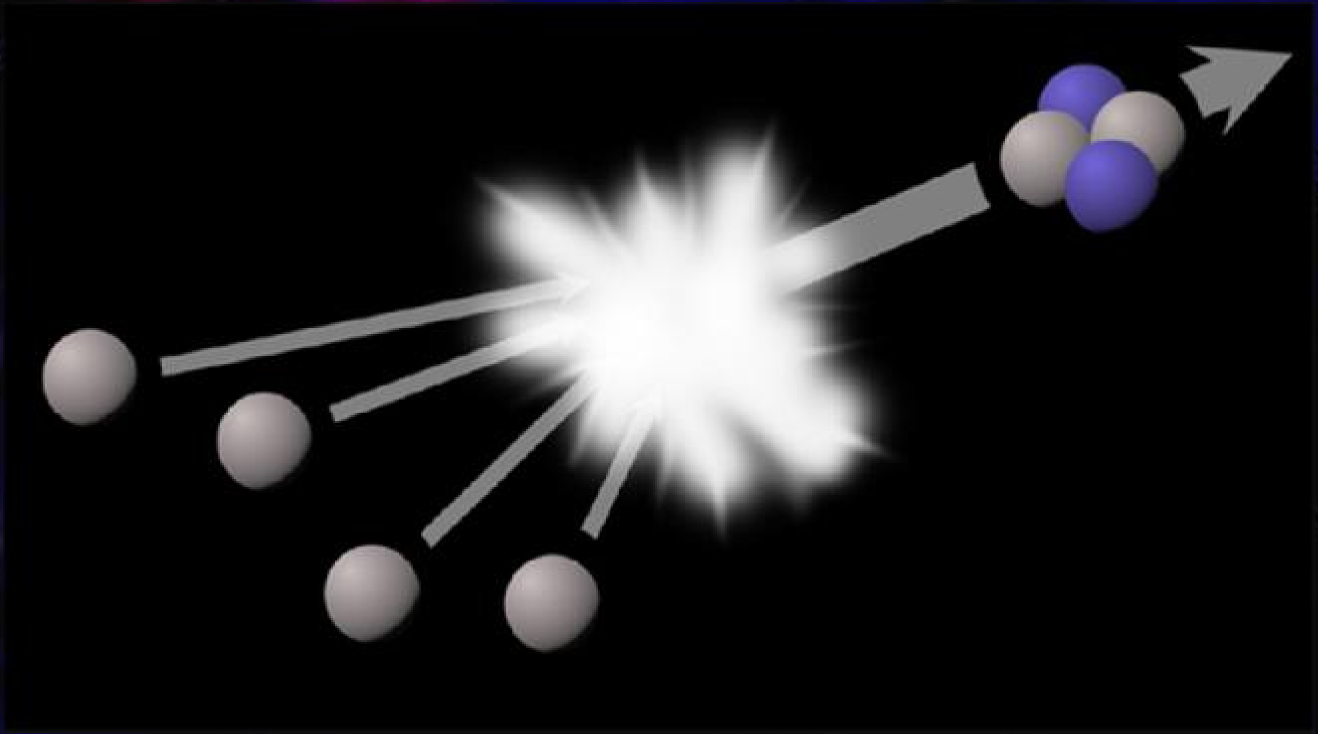

Surface Temperature (K)
25,000
10,000
6,000
5,000
3,000
Luminosity
10^6
10^4
10^2
10^0
10^{-2}
10^{-4}
Absolute Magnitude
-10
-5
0
+5
+10
+15
O5
B0
A0
F0
G0
K0
M0
M8
Spectral Type
High Mass Stars
Main Sequence
Low Mass Stars
Rigel
Deneb
Betelgeuse
Antares
Mira
Aldebaran
Arcturus
Pollux
Regulus
Vega
Sirius A
Altair
Procyon A
Sun
Sirius B
Procyon B
Barnard's star

Thermonuclear Fusion



Proton – Proton Cycle

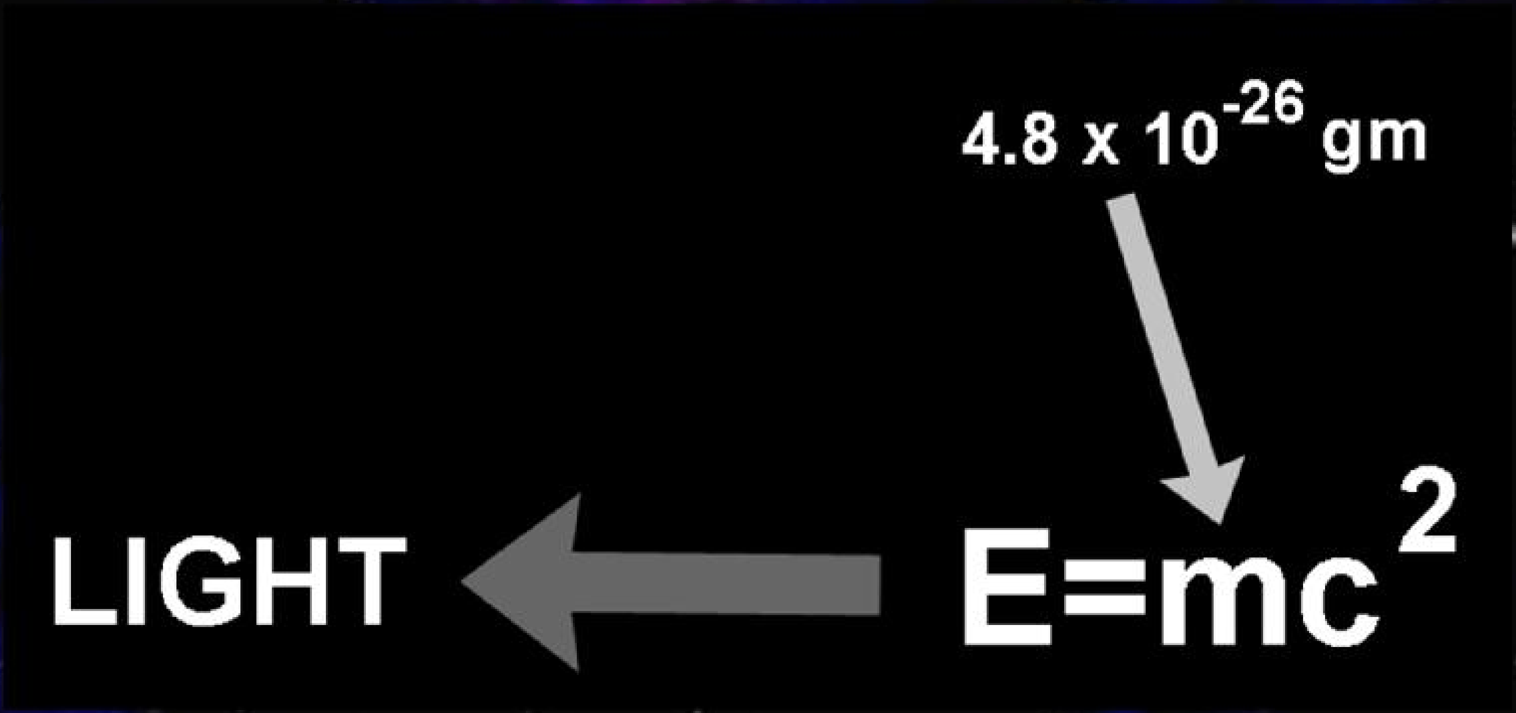
4H ® 1He + 2g



$$4H = 6.693 \times 10^{-24} \text{ gm}$$

$$-1He = 6.645 \times 10^{-24} \text{ gm}$$

Difference of 4.8×10^{-26} gm (0.7%)



Some incredible numbers...

The proton-proton cycle occurs

10^{38} times/second

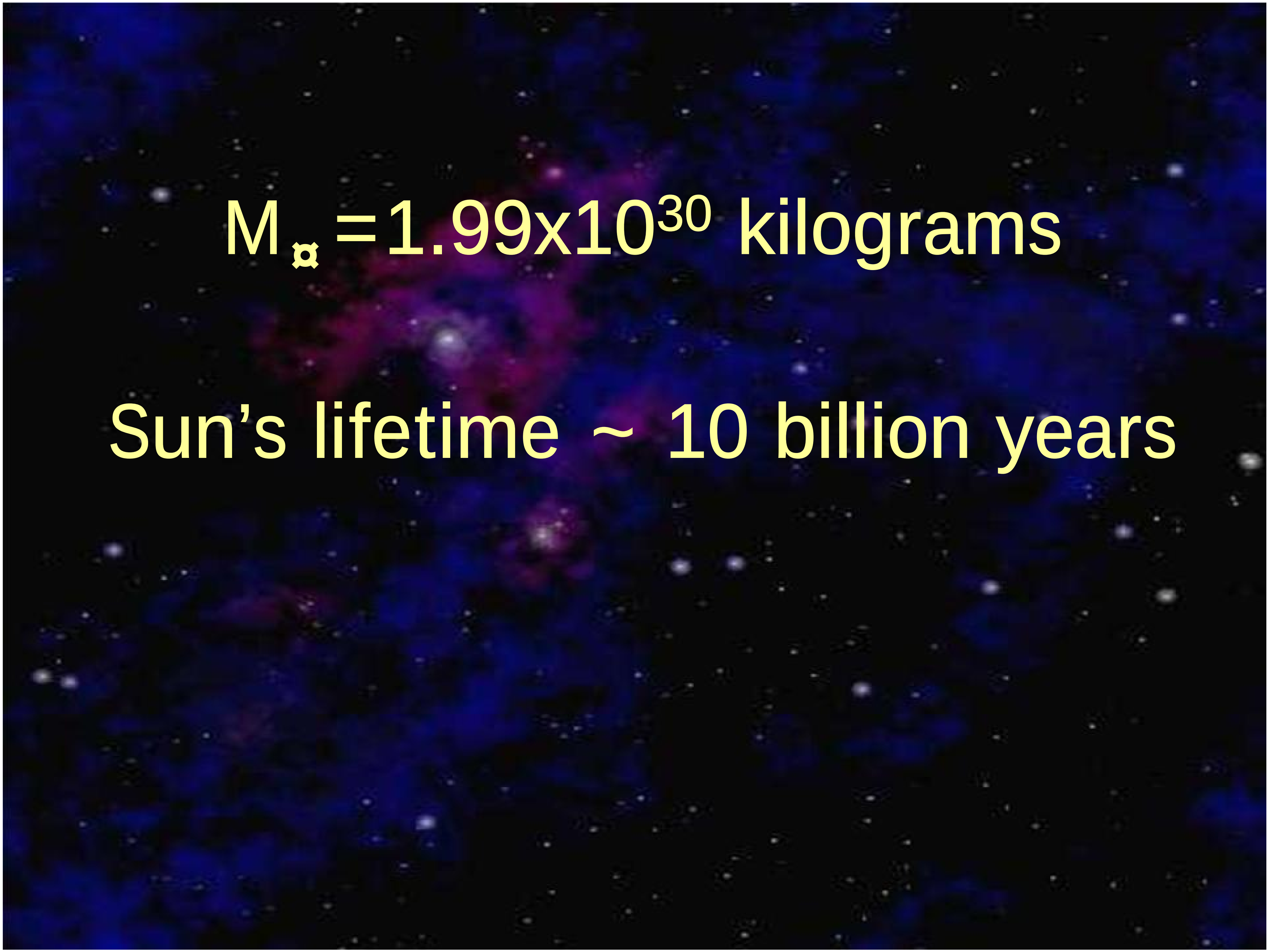
Each second:

624 million tons of hydrogen

Fuses to become

620 million tons of helium

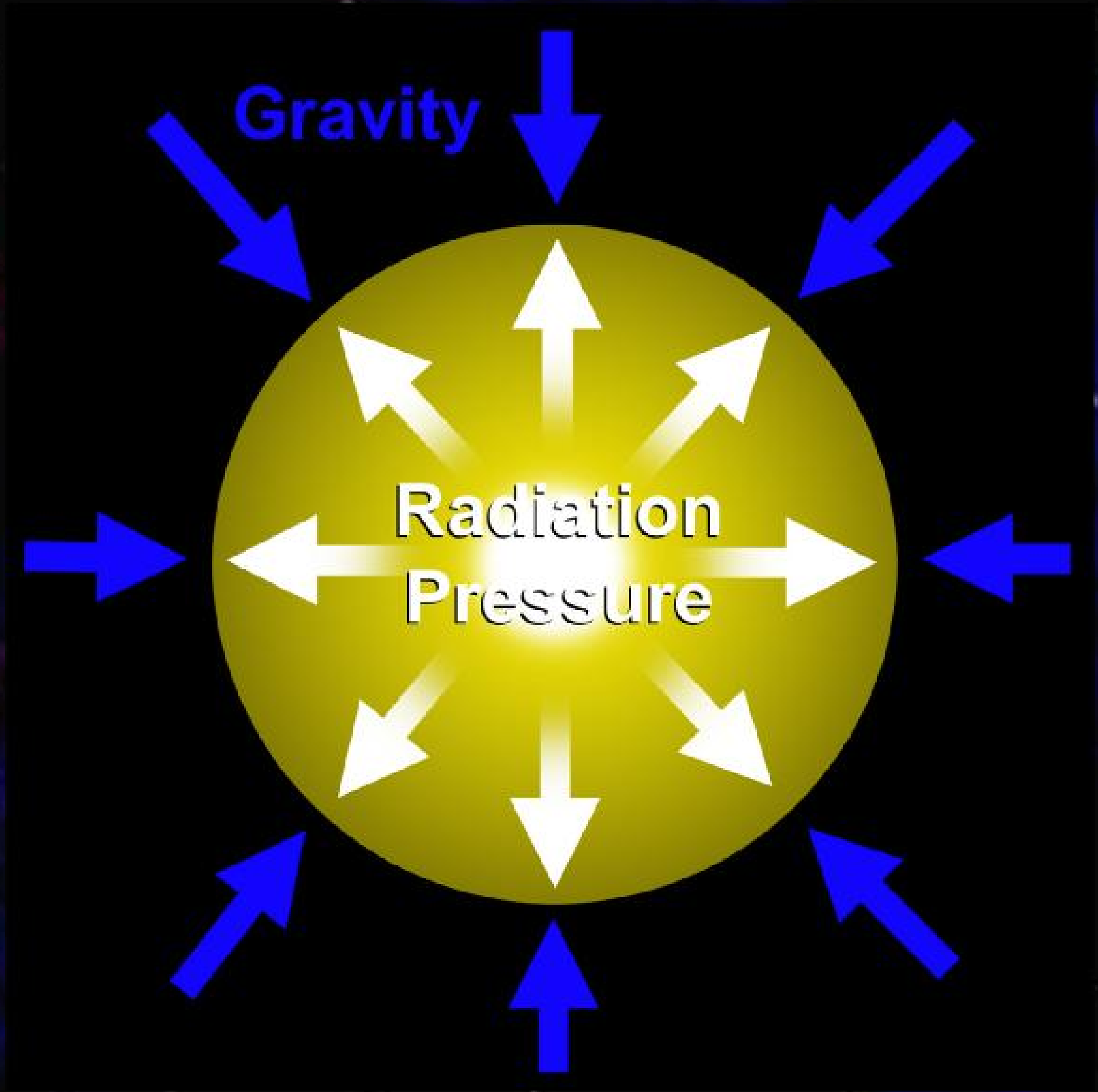
4 million tons of hydrogen becomes energy

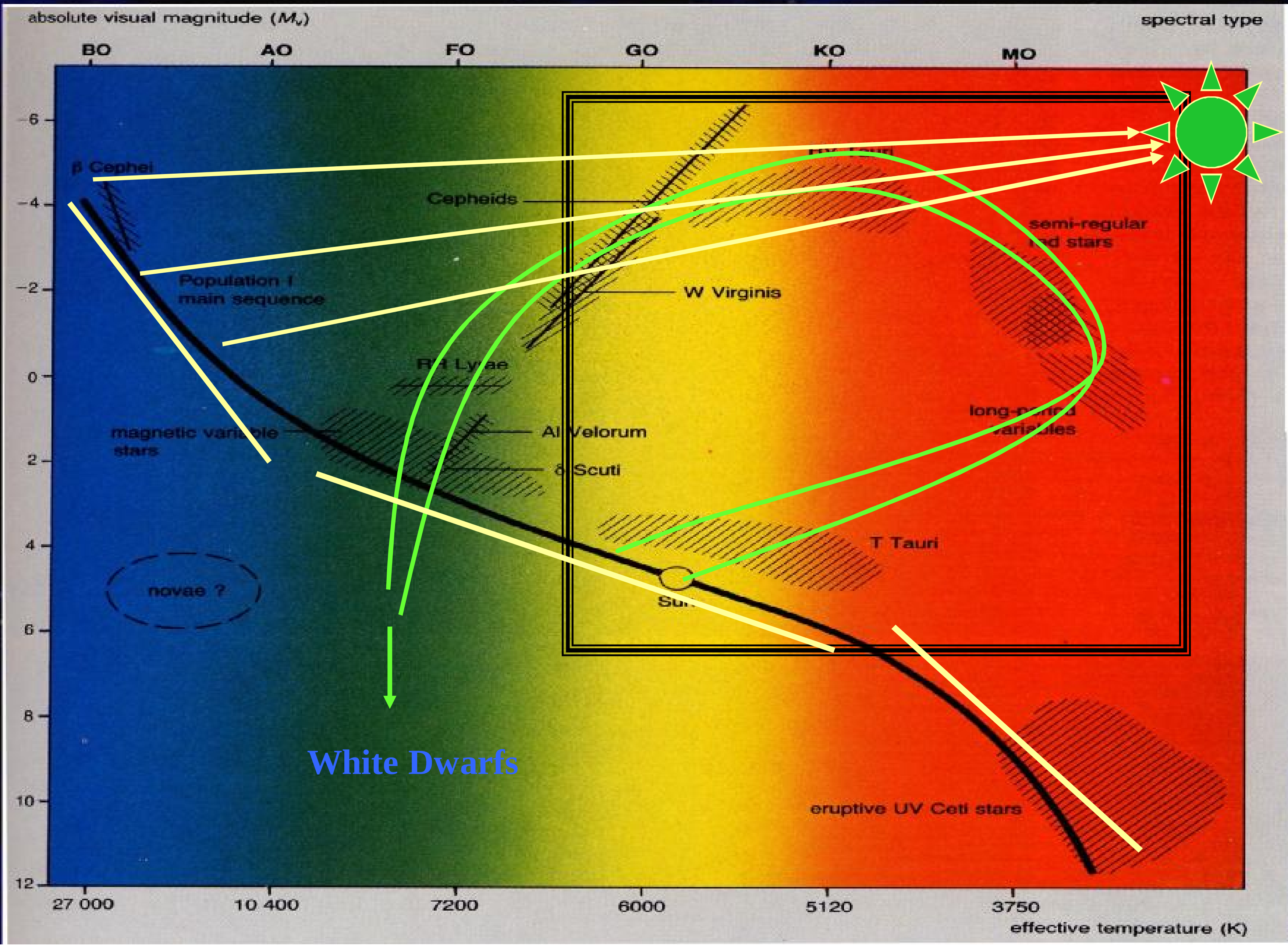


$M_{¤}=1.99x10^{30}$ kilograms

Sun’s lifetime ~ 10 billion years

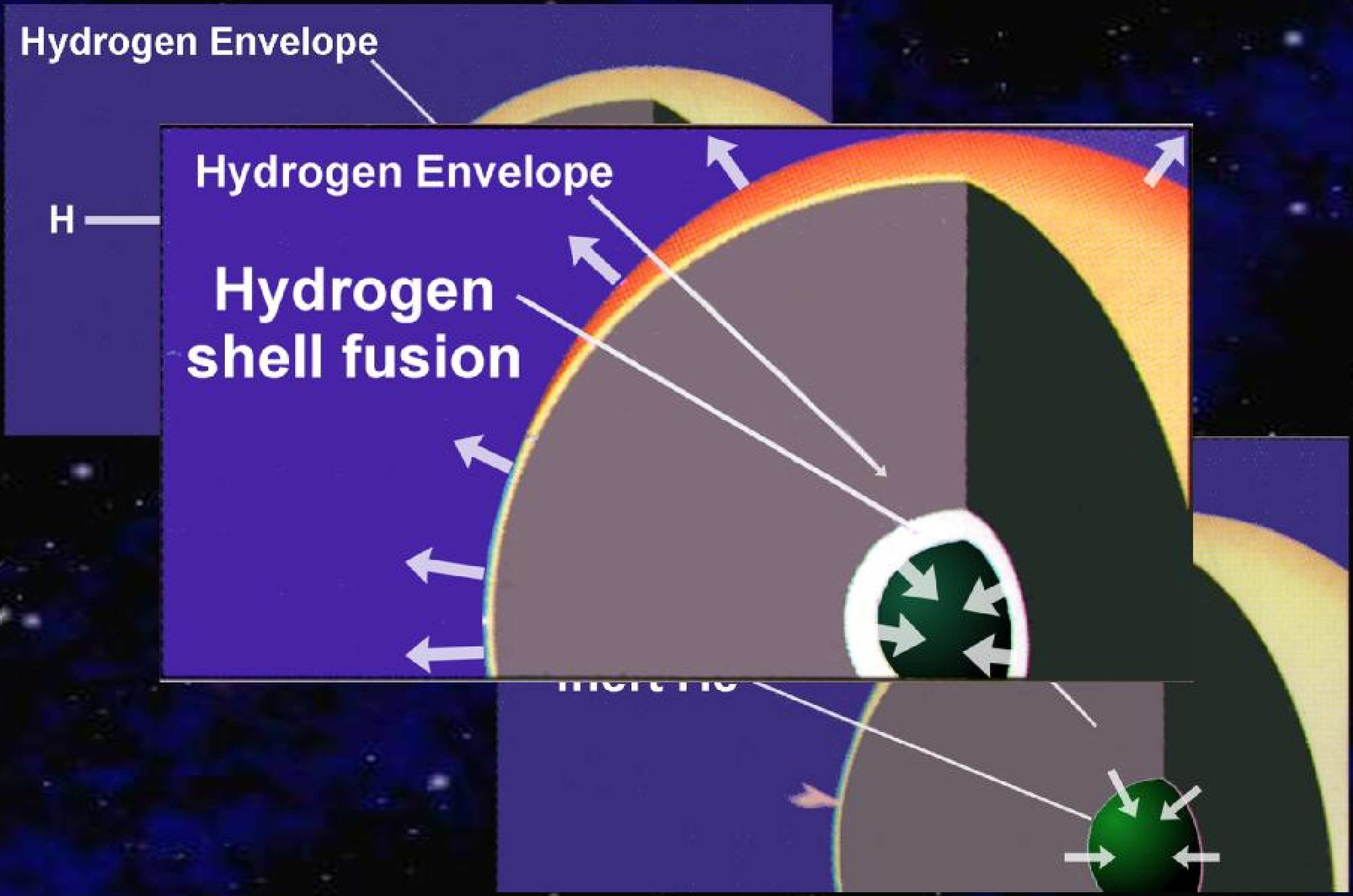
Hydrostatic Equilibrium

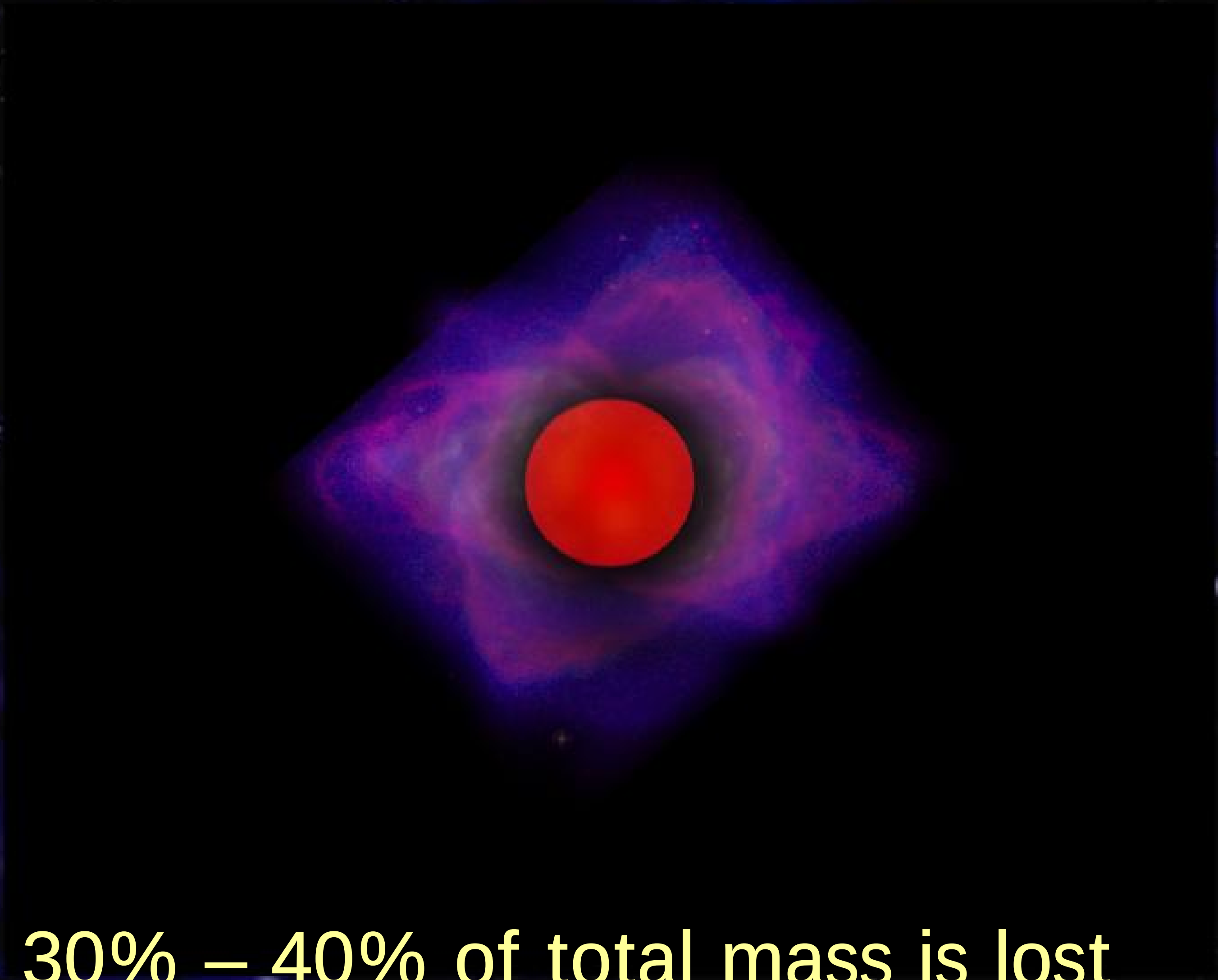




White Dwarfs

1. Low Mass Stars $M < 0.5\ M_{\odot}$

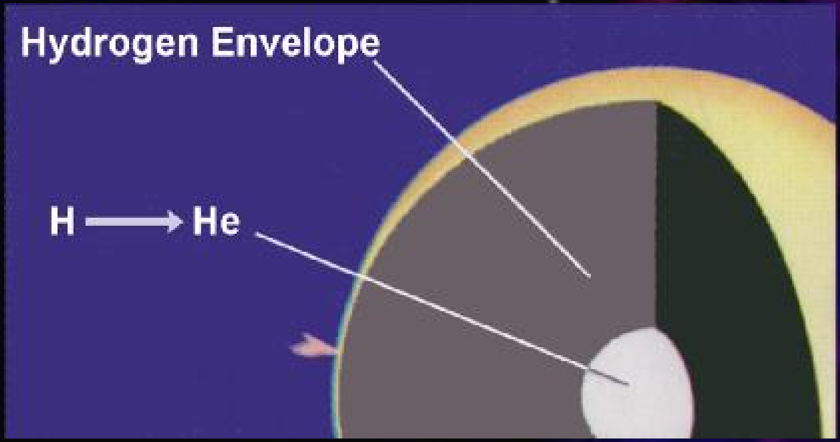


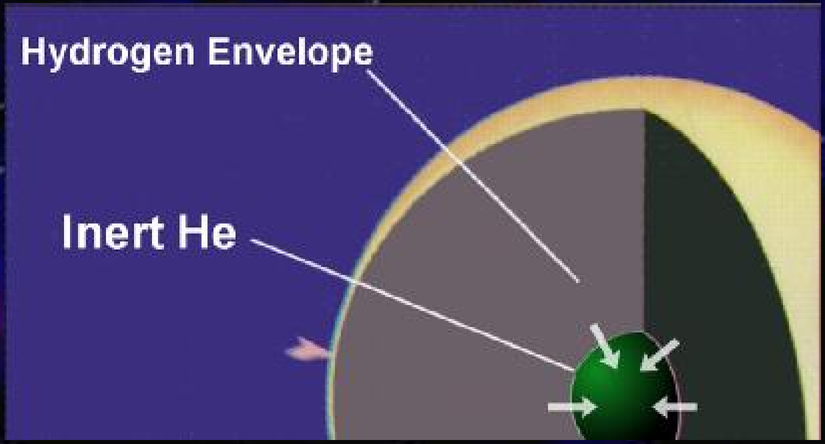


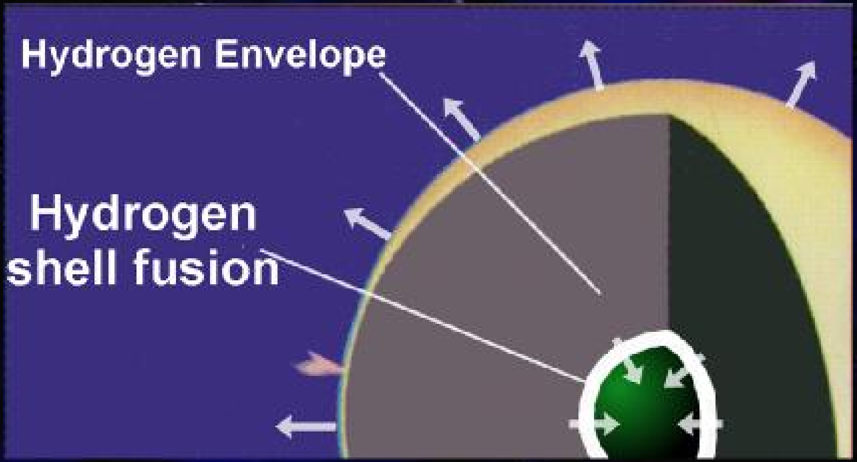
30% – 40% of total mass is lost

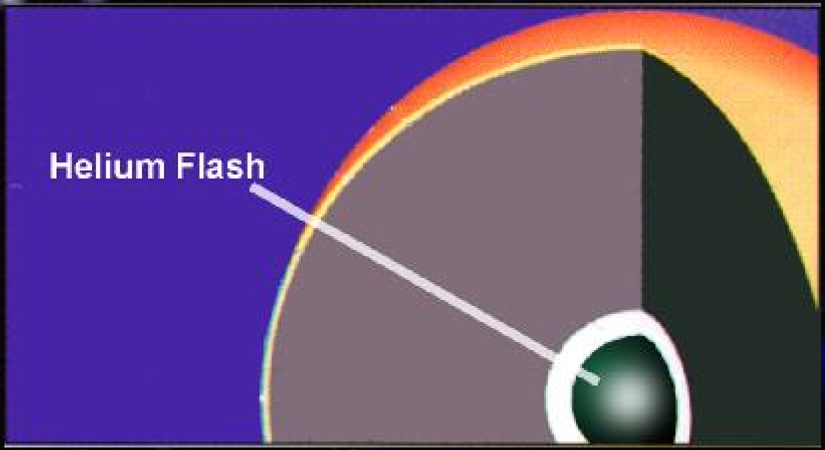
2. Intermediate Mass Stars

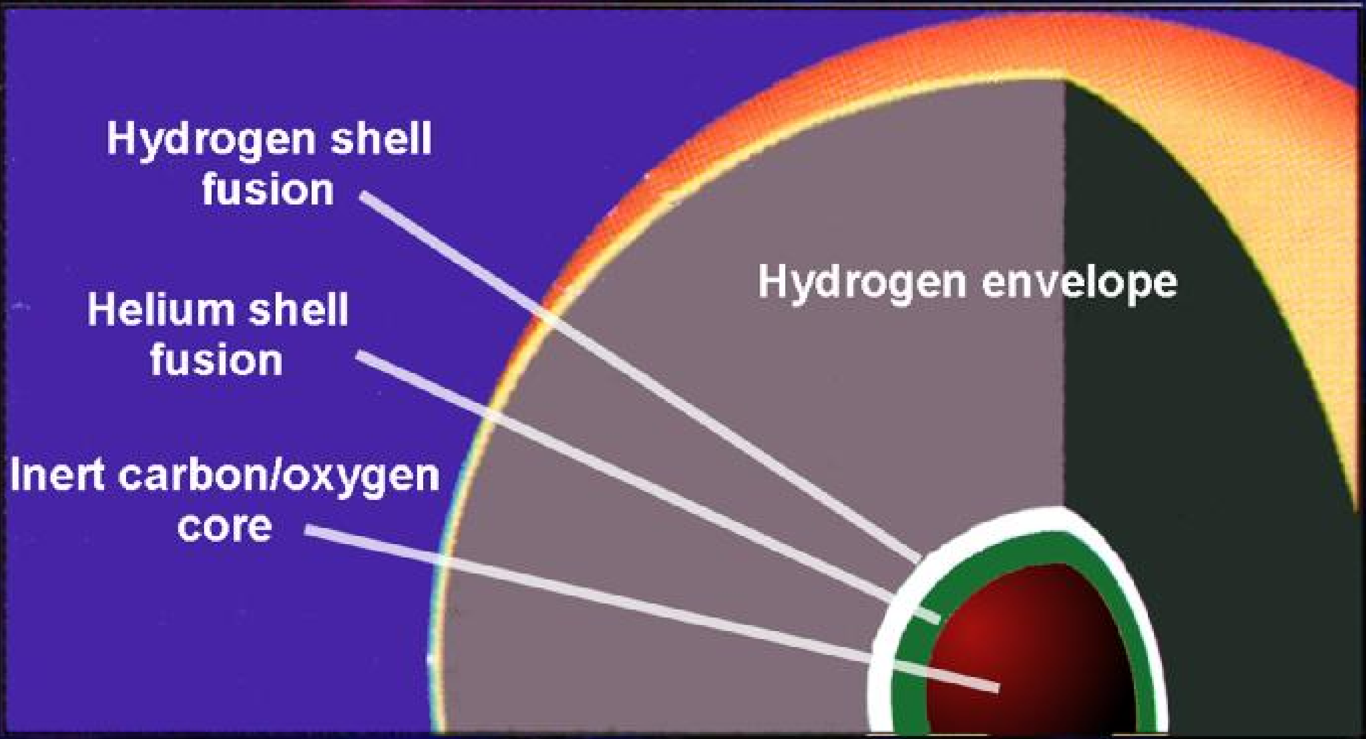
$0.5 < M_{\bullet} < 8$









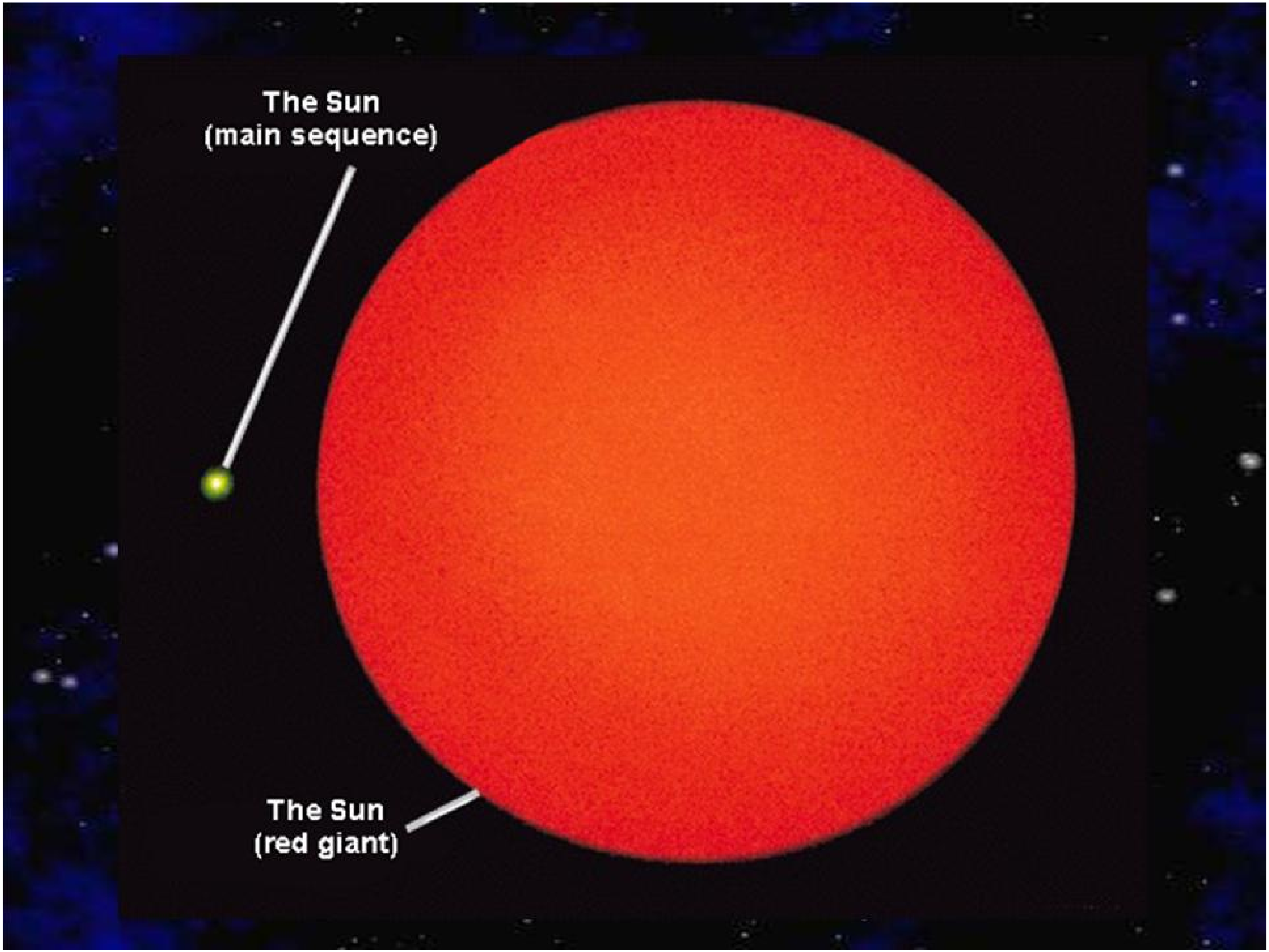


Hydrogen shell fusion

Helium shell fusion

Inert carbon/oxygen core

Hydrogen envelope


The Sun
(main sequence)
The Sun
(red giant)

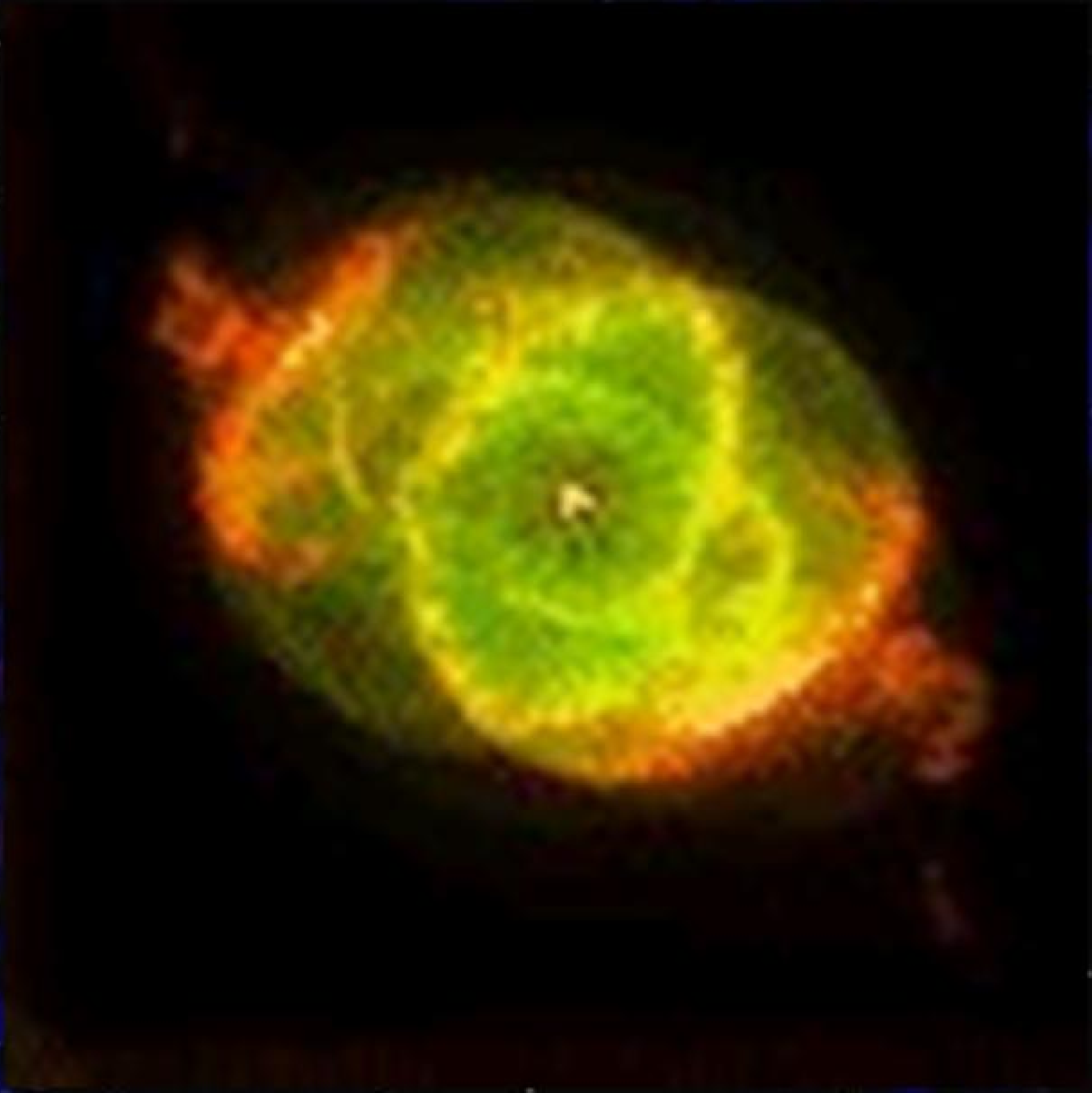
Planetary Nebula

(has nothing to do with planets!!)

Hourglass Nebula · MyCn18

Hubble Space Telescope · WFPC2

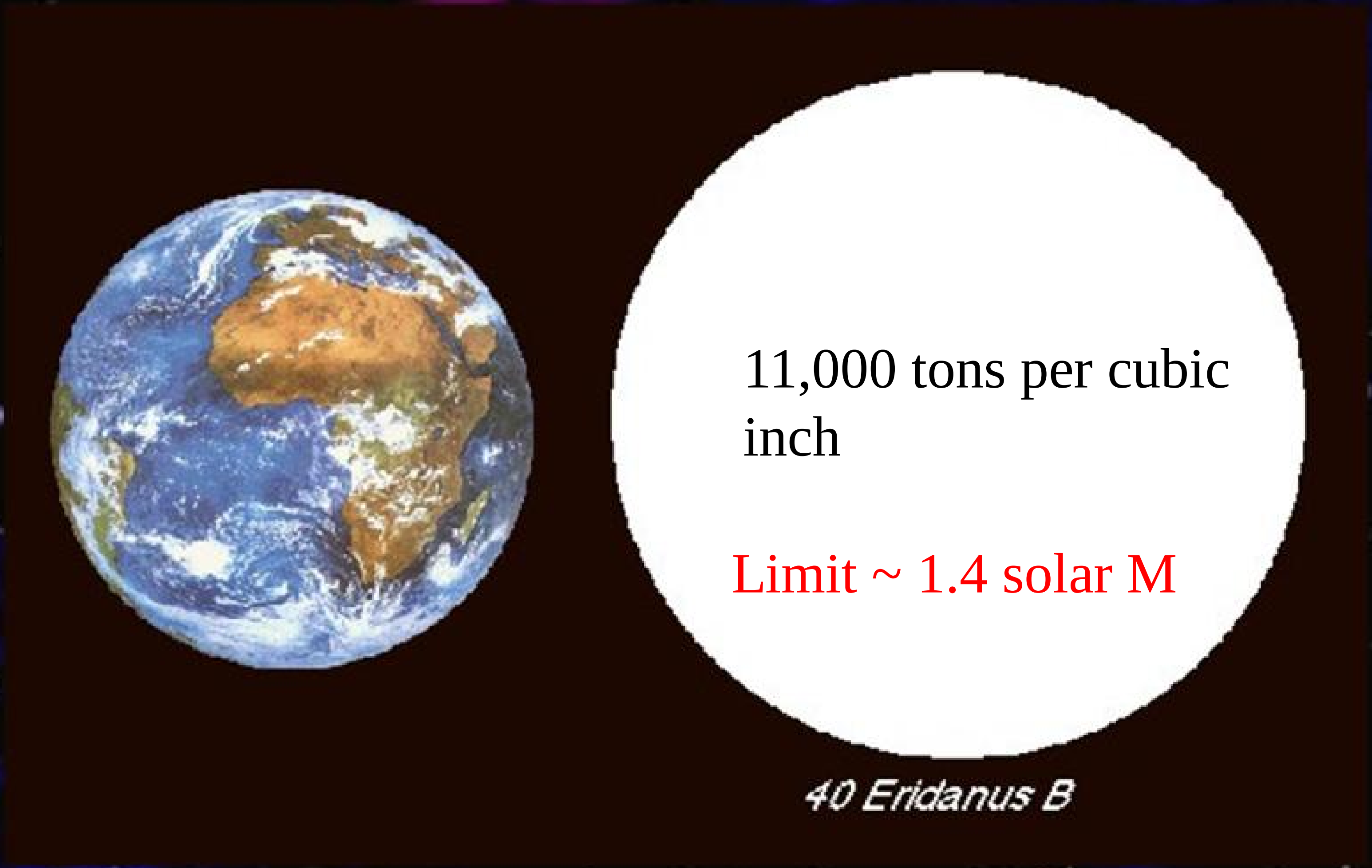
PRC96-07 · ST ScI OPO · January 16, 1996 · R. Sahai and J. Trauger (JPL), WFPC2 Science Team, NASA



White Dwarf Stars

- Composed mostly of carbon
- Surface temperatures of 50,000 K or more
- ***NO*** internal energy source
- Earth sized
- Mass is that of remnant stellar core
- VERY DENSE!

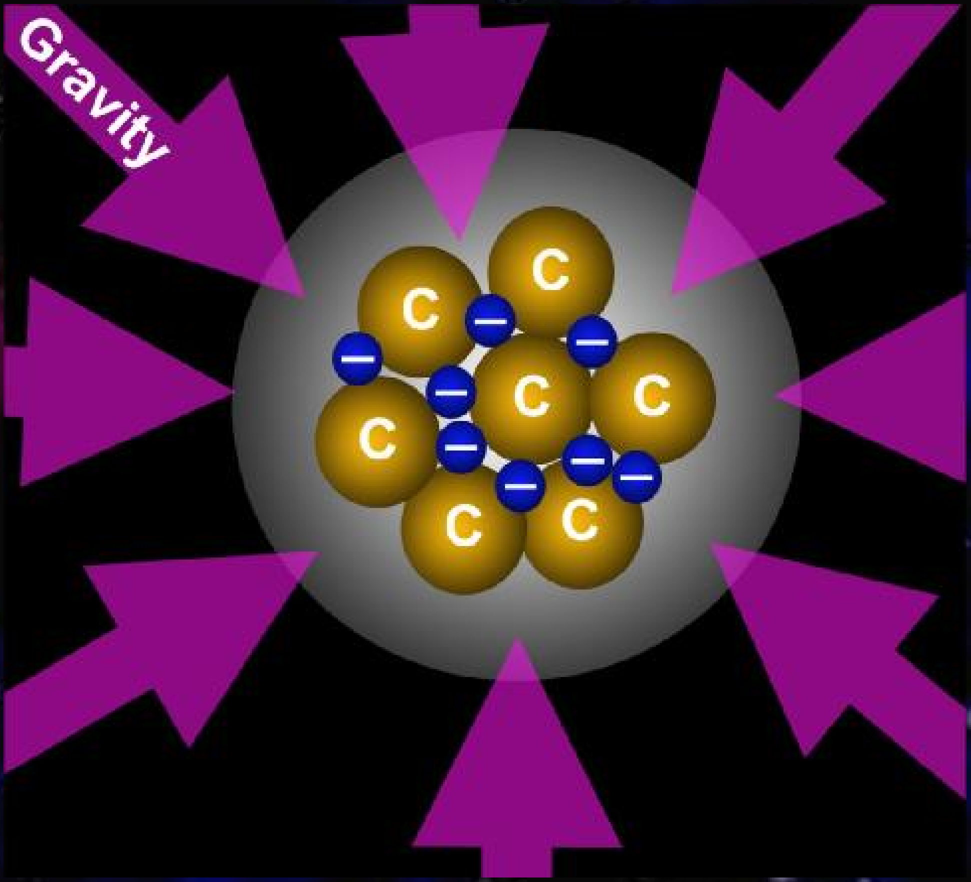
White Dwarf Star



11,000 tons per cubic inch

Limit ~ 1.4 solar M

The electrons did!



Electrons have a limit to how tightly they can be packed together

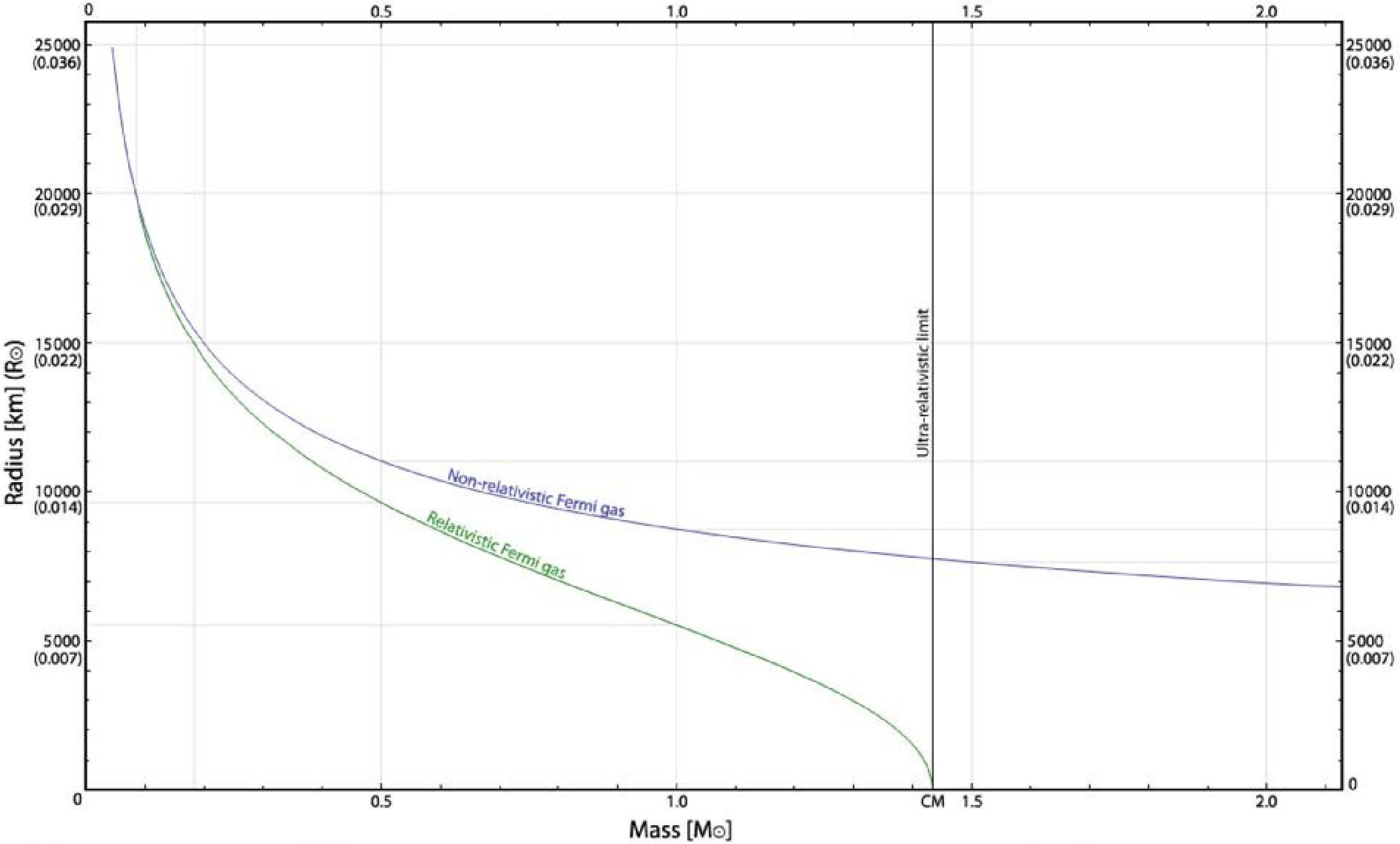
“ELECTRON DEGENERACY PRESSURE”

BUT! Electron Degeneracy Pressure
has its limits

Gravity can overwhelm the electrons
if the mass is high enough..

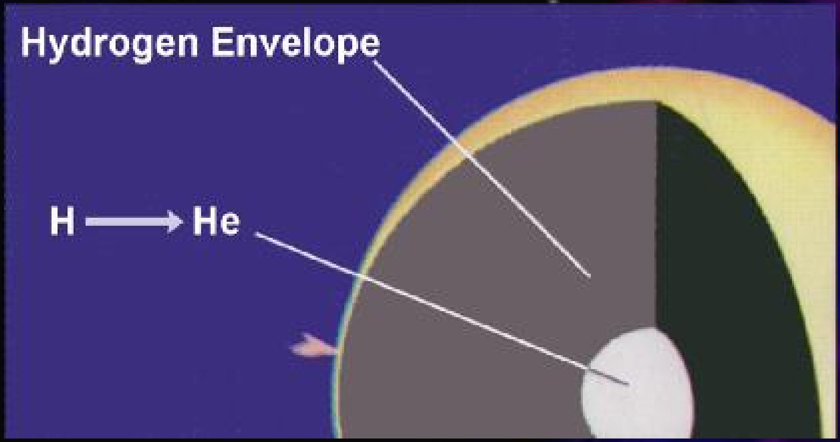
$$\mathbf{M < 1.4\ M_{\bullet}}$$

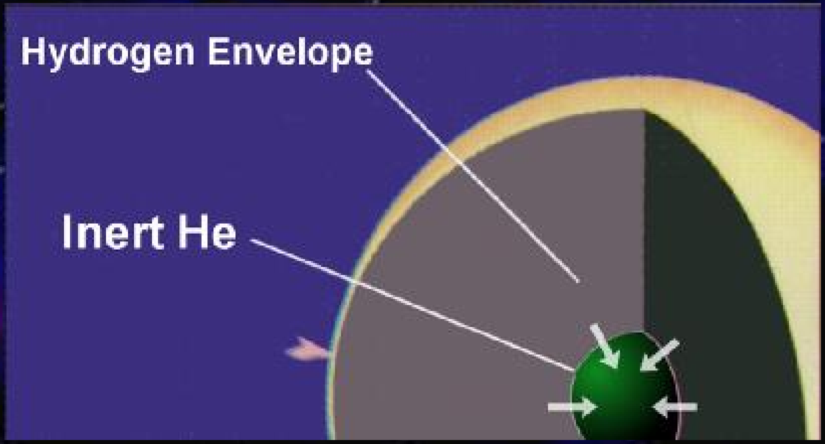
Chandrasekhar Limit

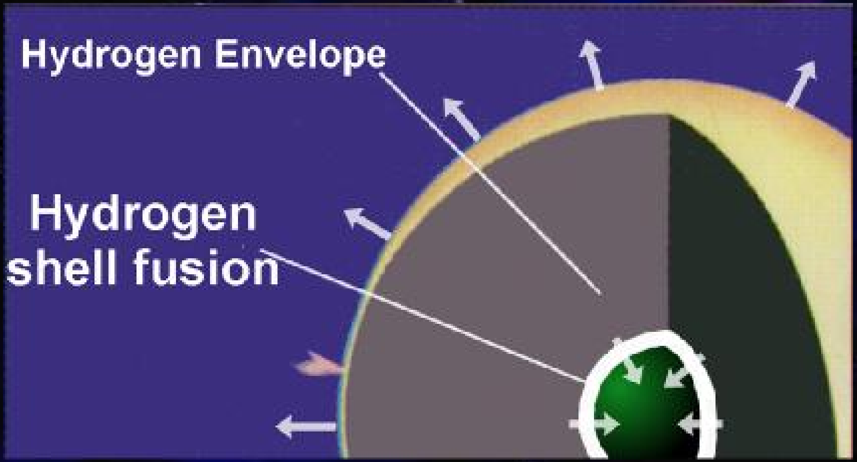

0
0.5
1.0
1.5
2.0
25000 (0.036)
20000 (0.029)
15000 (0.022)
10000 (0.014)
5000 (0.007)
0
Radius [km] (R☉)
Ultra-relativistic limit
Non-relativistic Fermi gas
Relativistic Fermi gas
0
0.5
1.0
CM
1.5
2.0
Mass [M☉]

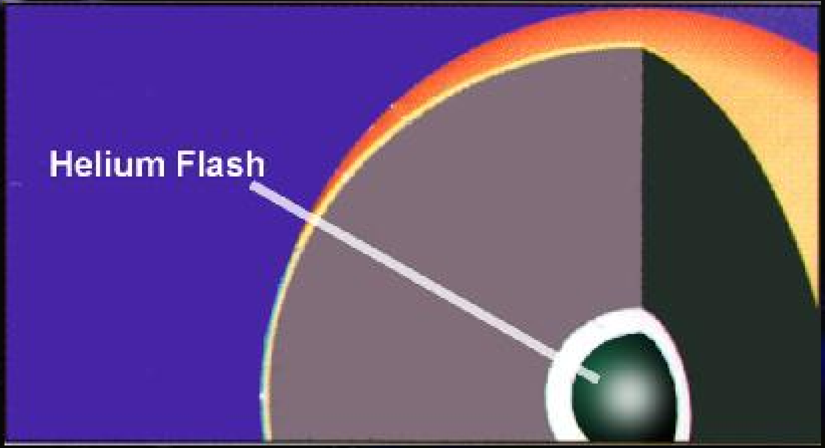
What happens if the core of the star that remains is GREATER than the Chandrasekhar Limit?

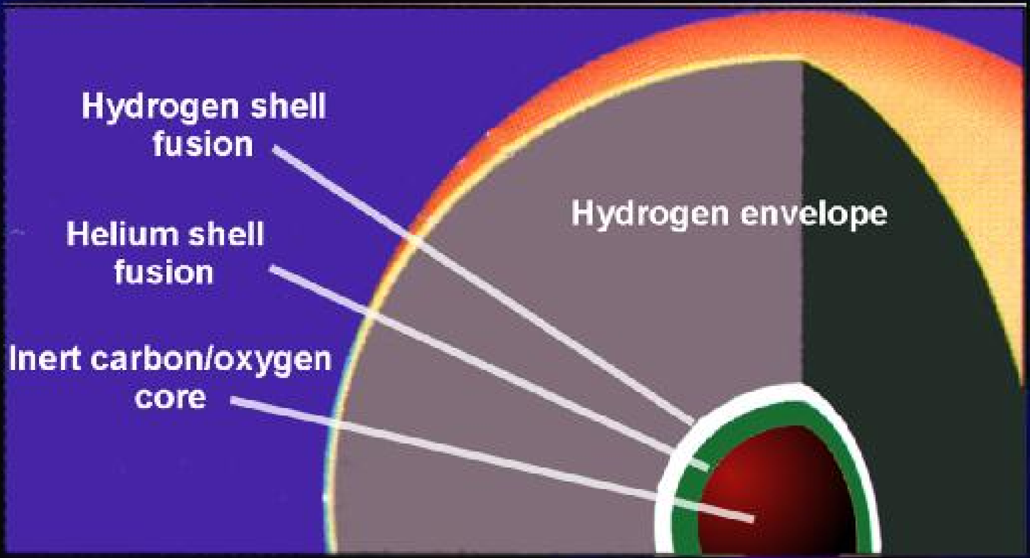
3. High Mass Stars $M_{\bullet} > 8$









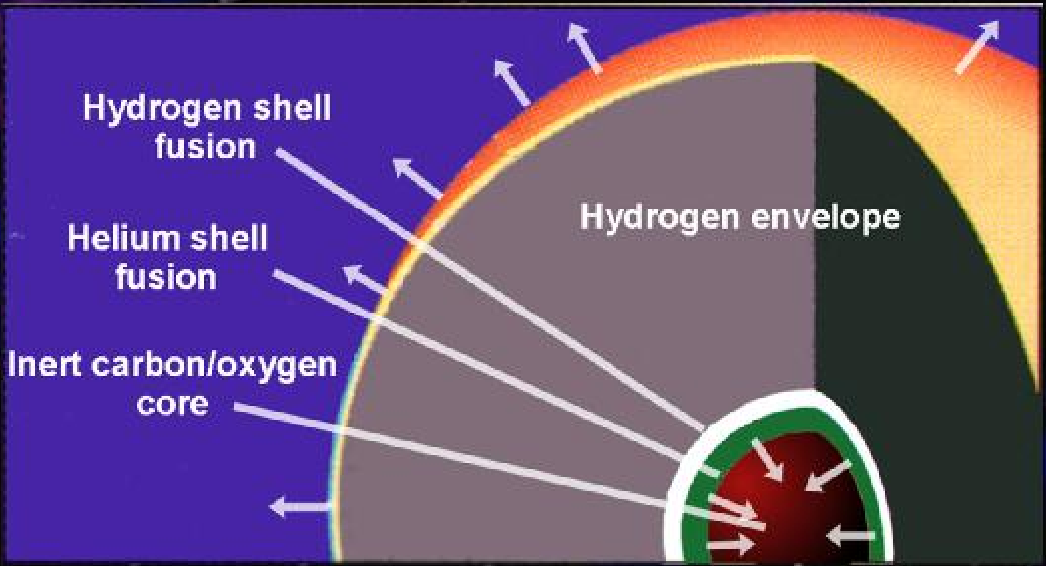


Hydrogen shell fusion

Helium shell fusion

Inert carbon/oxygen core

Hydrogen envelope



Hydrogen shell fusion

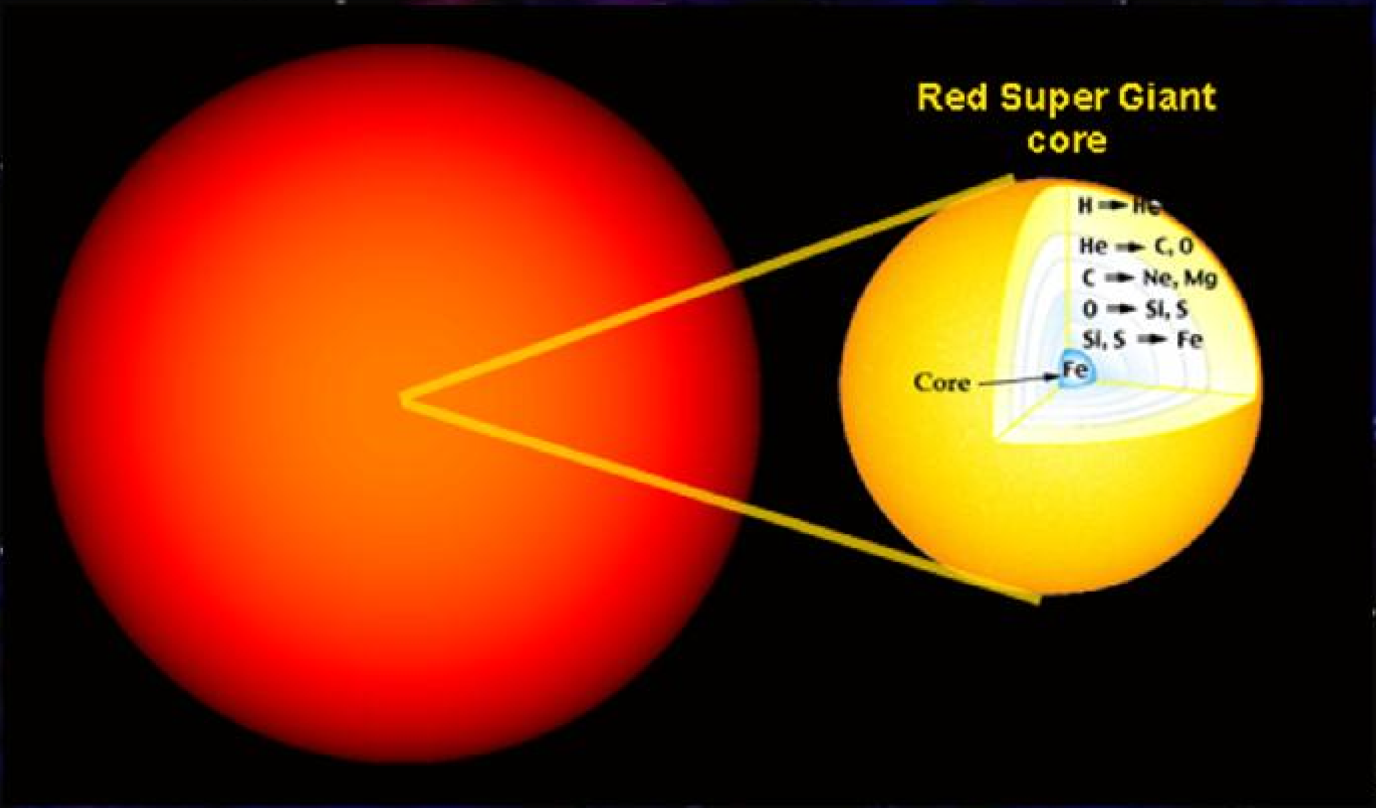
Helium shell fusion

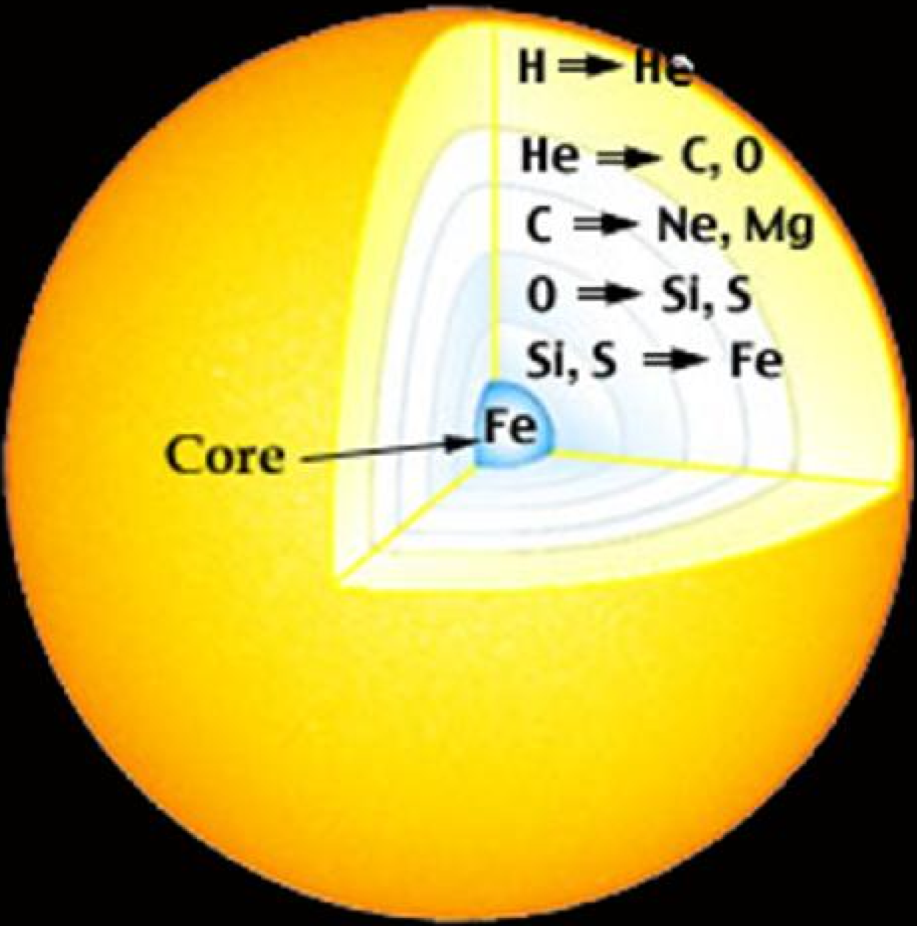
Inert carbon/oxygen core

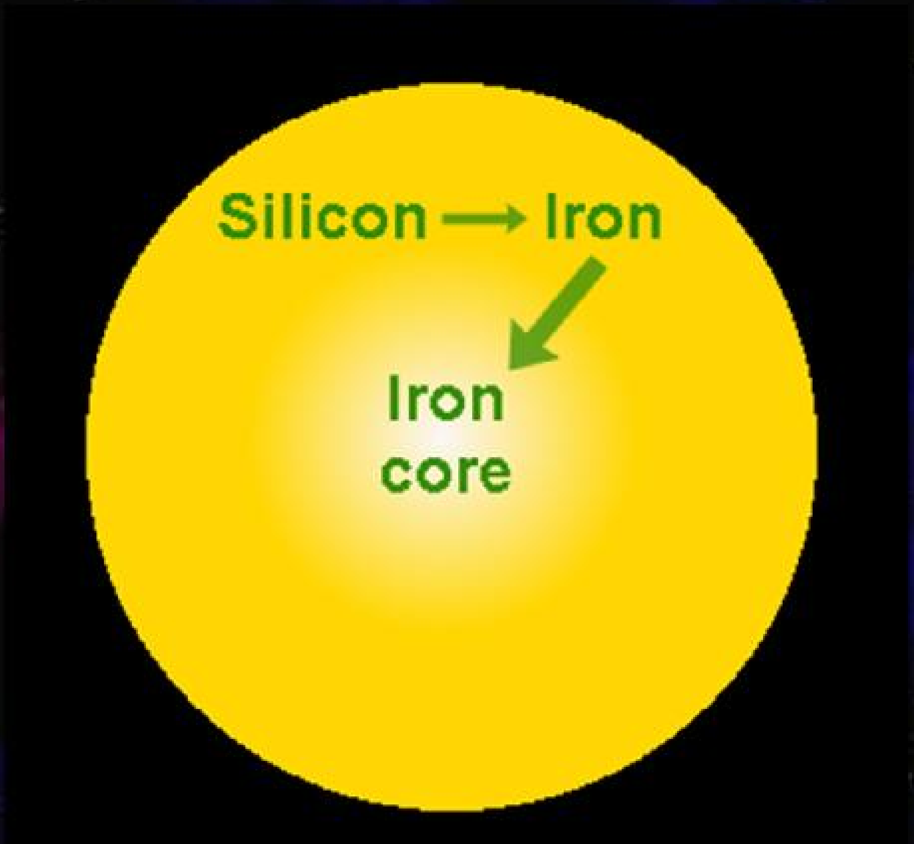
Hydrogen envelope

25 $M_\odot$ star

Element	Temperature	Duration
Hydrogen	4×10^7 K	7×10^6 yrs
Helium	2×10^8 K	5×10^5 yrs
Carbon	6×10^8 K	600 yrs
Neon	1.2×10^9 K	1 year
Oxygen	1.5×10^9 K	months
Silicon	2.7×10^9 K	days
Iron	none!	hours


Red Super Giant
core
H → He
He → C, O
C → Ne, Mg
O → Si, S
Si, S → Fe
Core
Fe

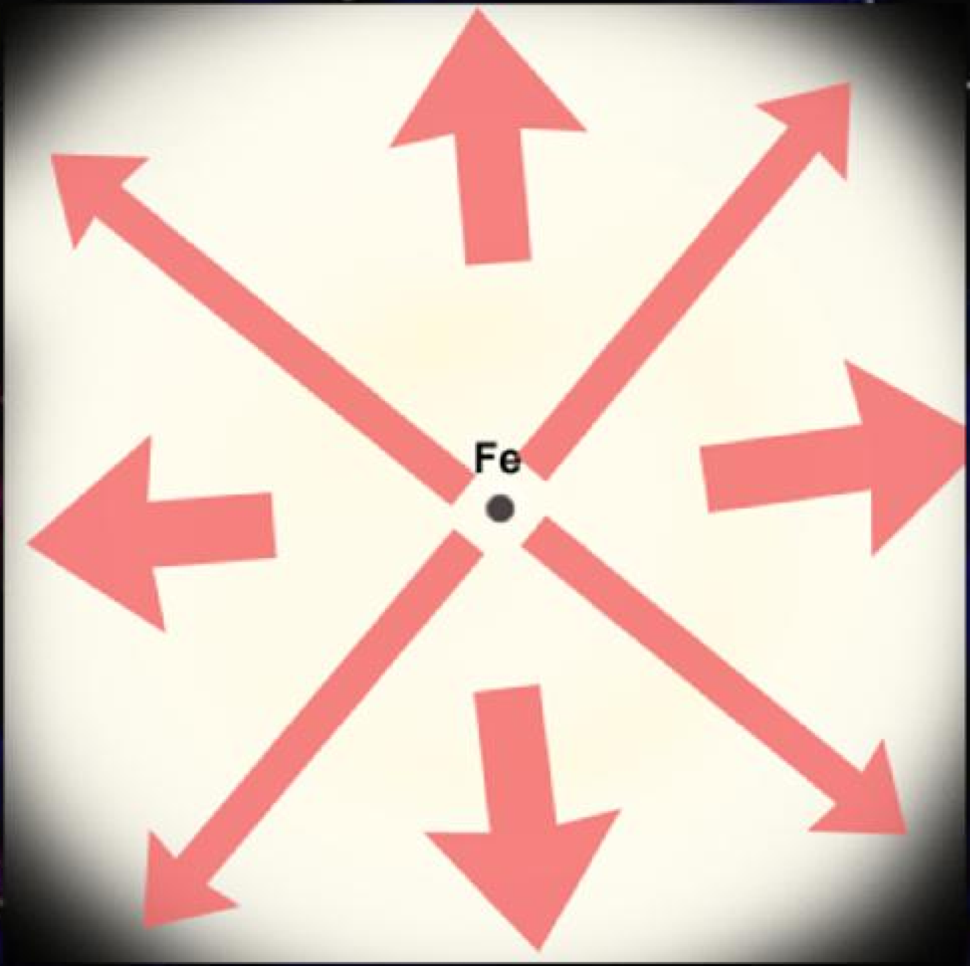

H ⇒ He
He ⇒ C, O
C ⇒ Ne, Mg
O ⇒ Si, S
Si, S ⇒ Fe
Fe
Core



Iron core < 1.4M.

Continual silicon fusion increases mass of core

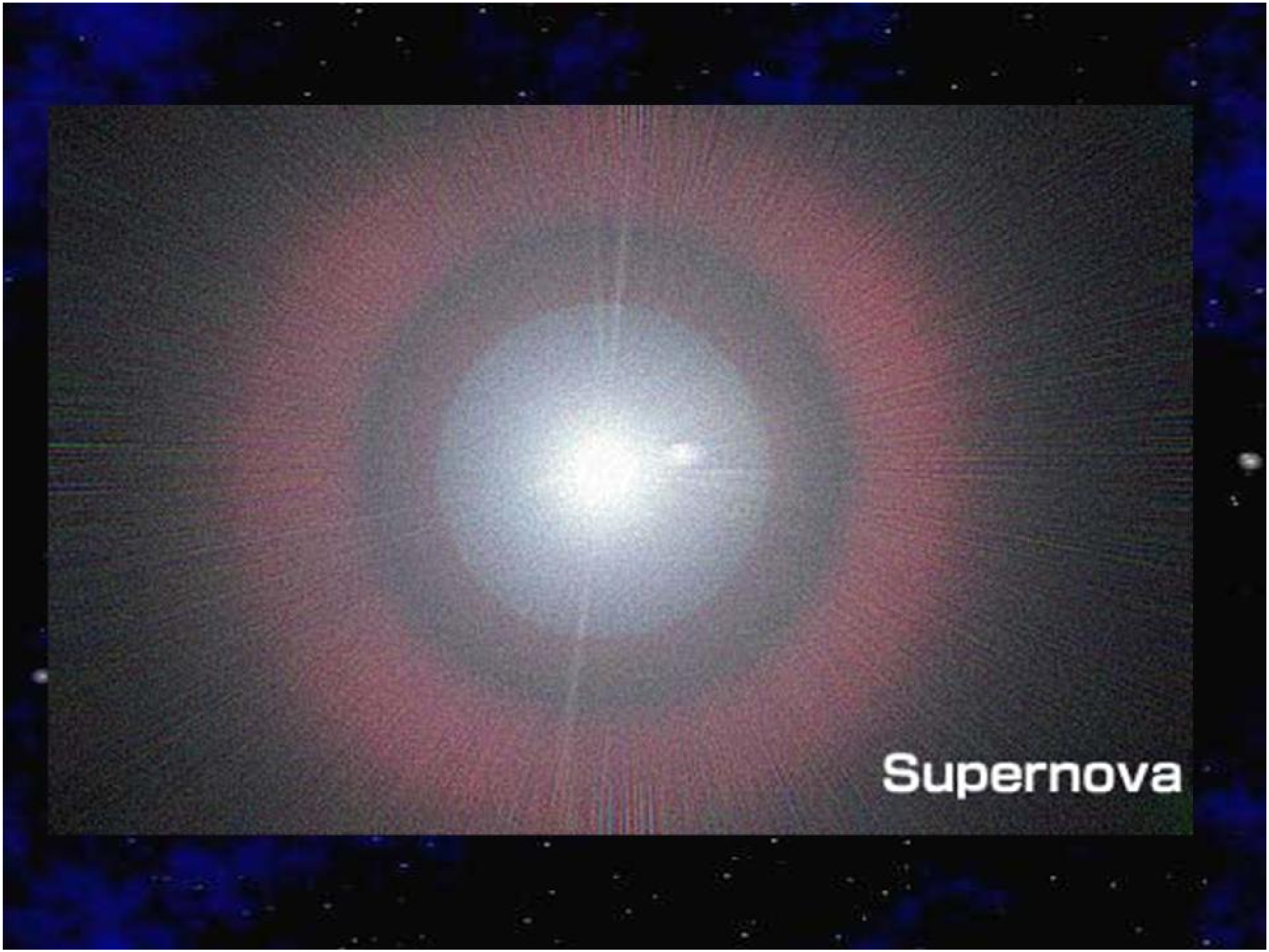
Eventually Iron core = 1.4M.



Iron core > $1.4M_{\odot}$

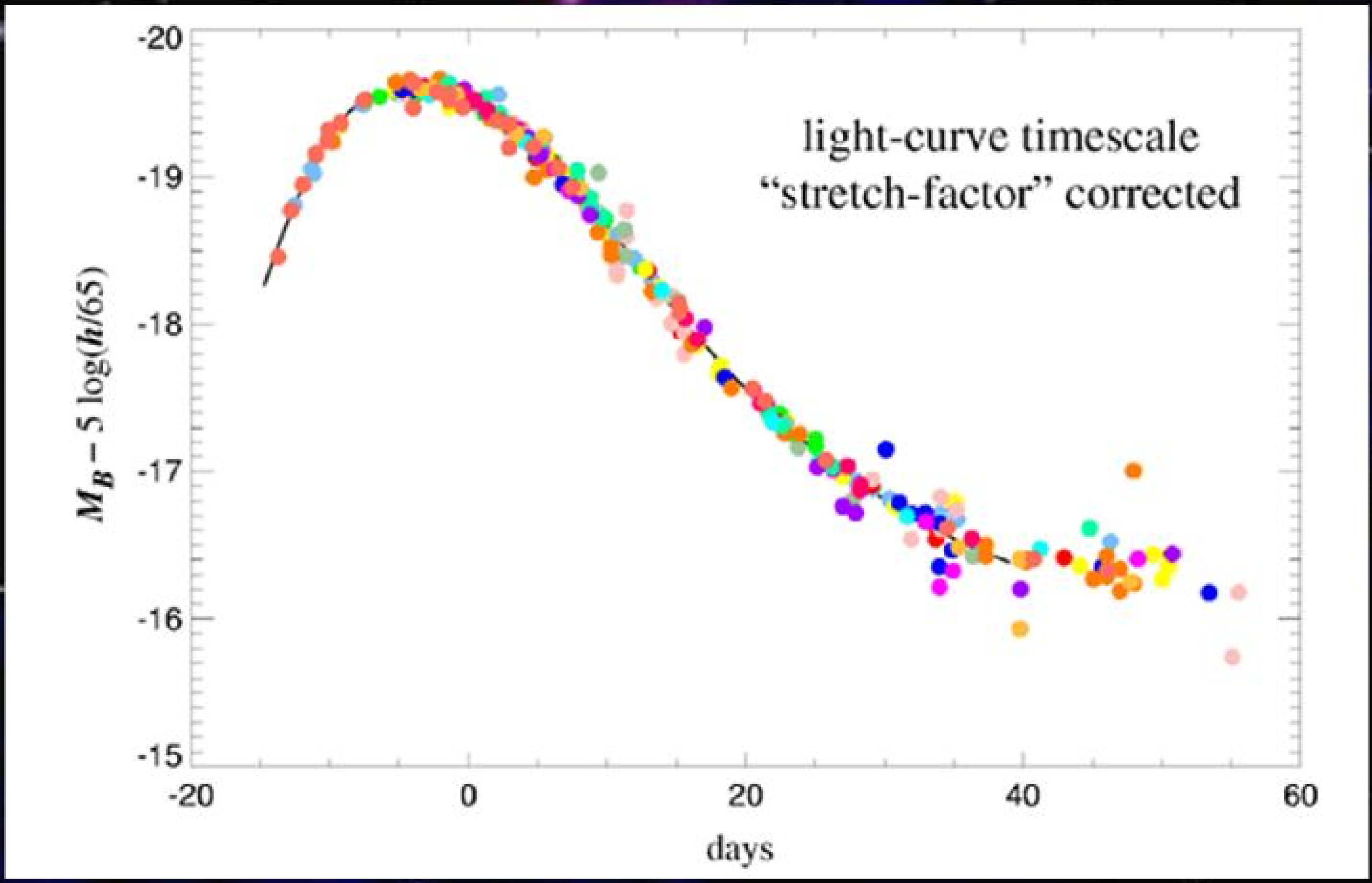
Iron core cannot support itself against gravity

Iron core collapses...

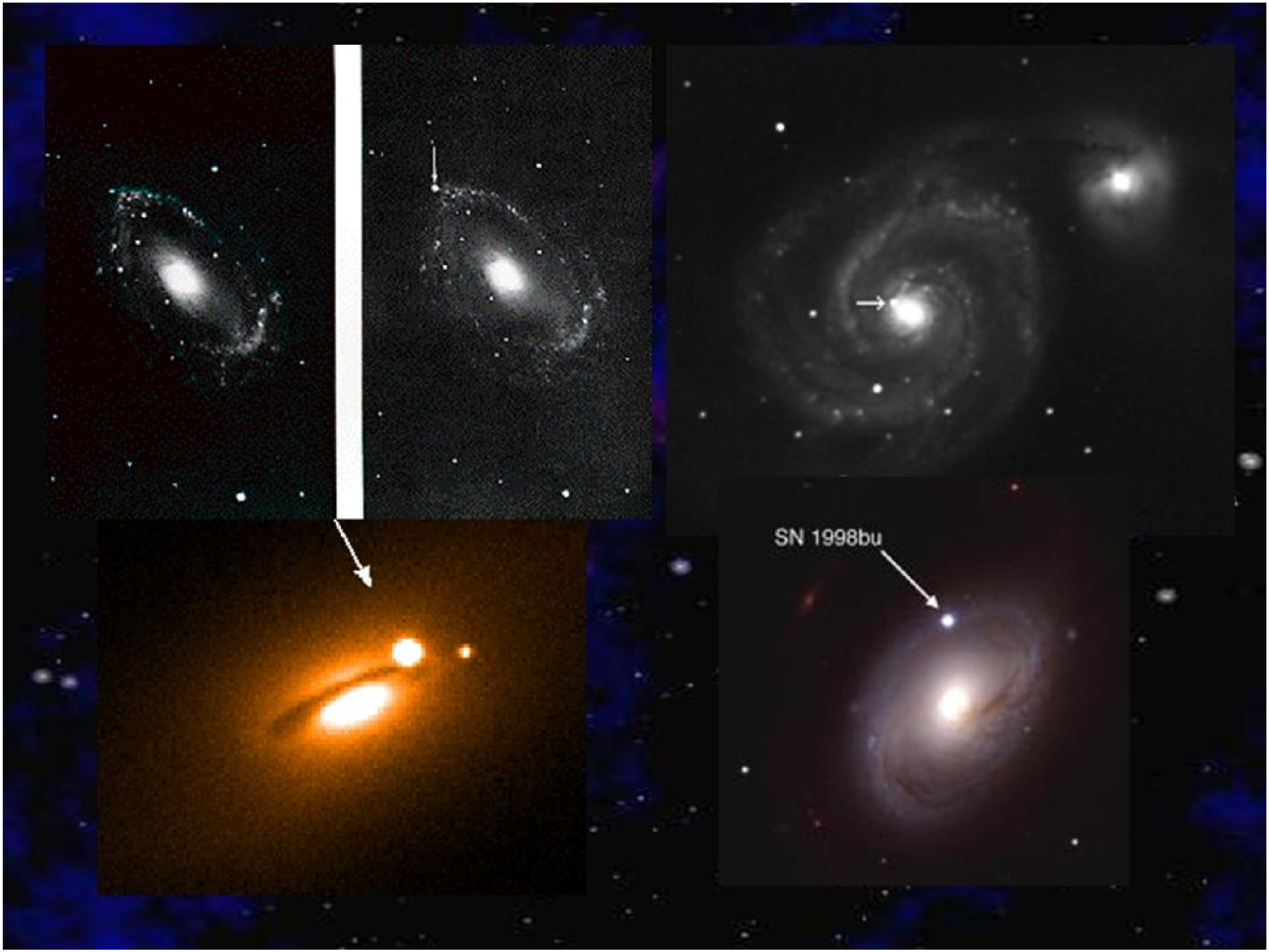


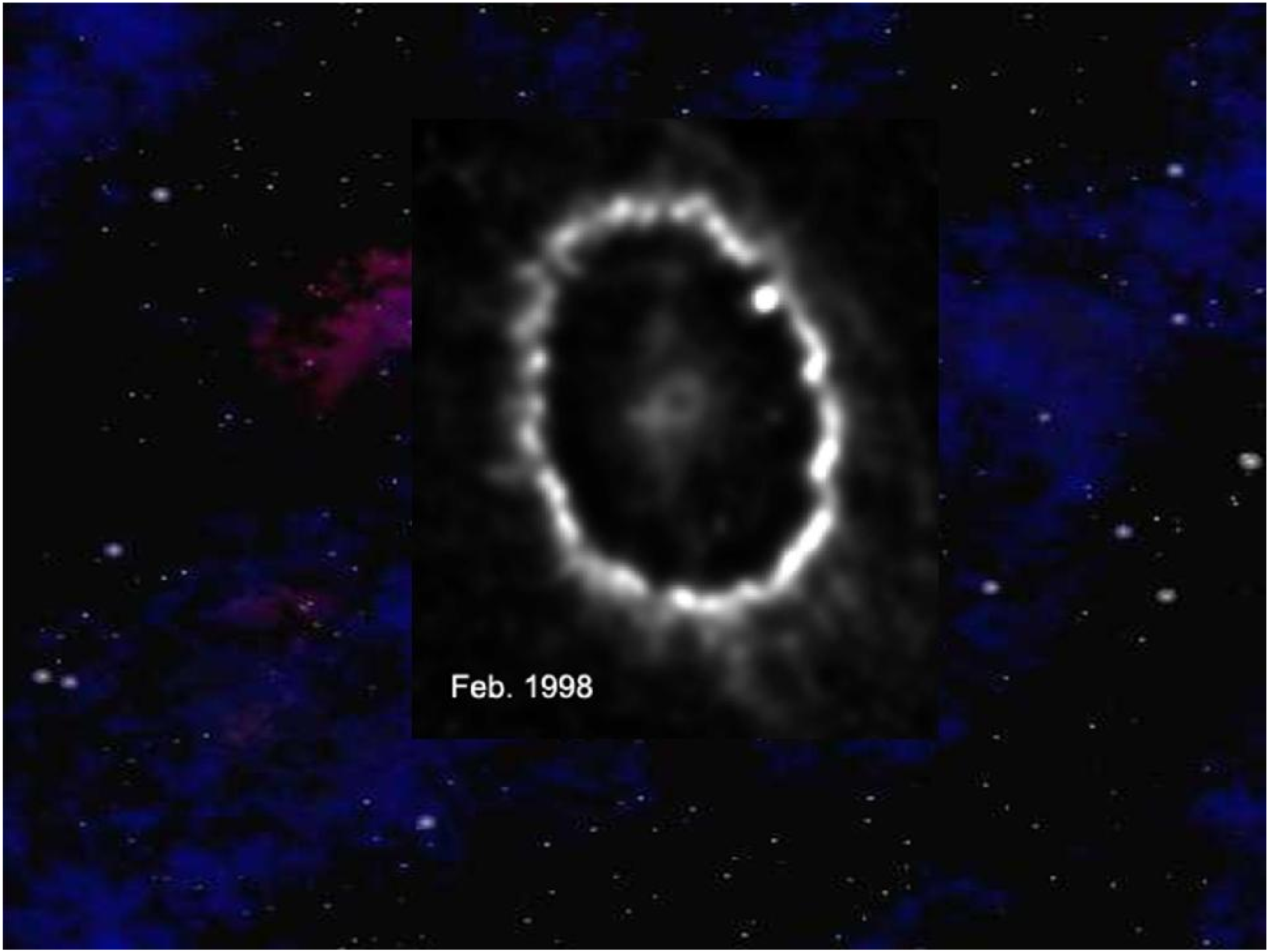
Supernova

Supernova 1987a


light-curve timescale
“stretch-factor” corrected
$M_B - 5\log(h/65)$
-20
-19
-18
-17
-16
-15
-20
0
20
40
60
days

April 1, 1993


SN 1998bu


Feb. 1998

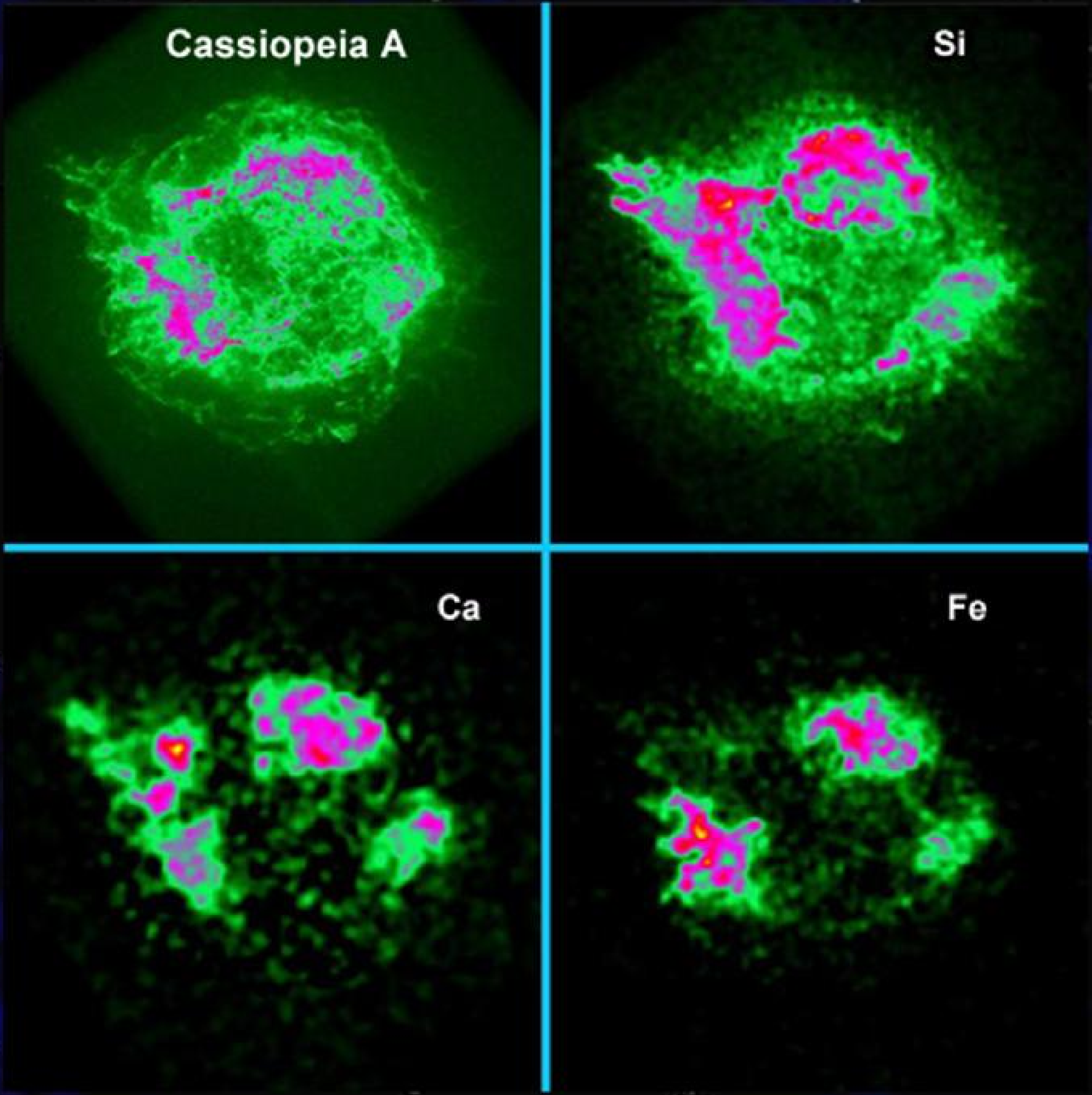
Supernova Remnants

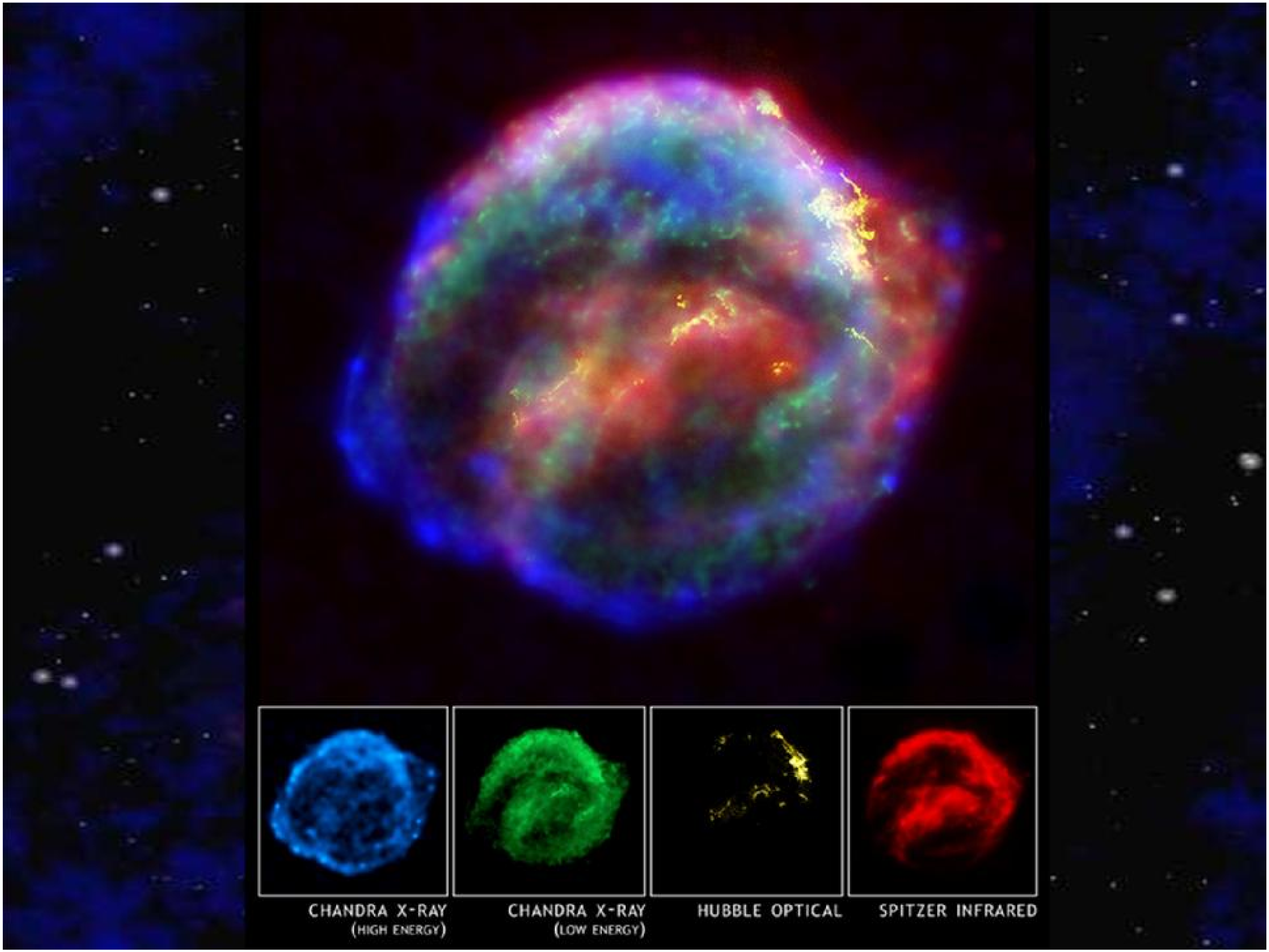
Supernova Remnants

Supernova Remnants

Supernova Remnants

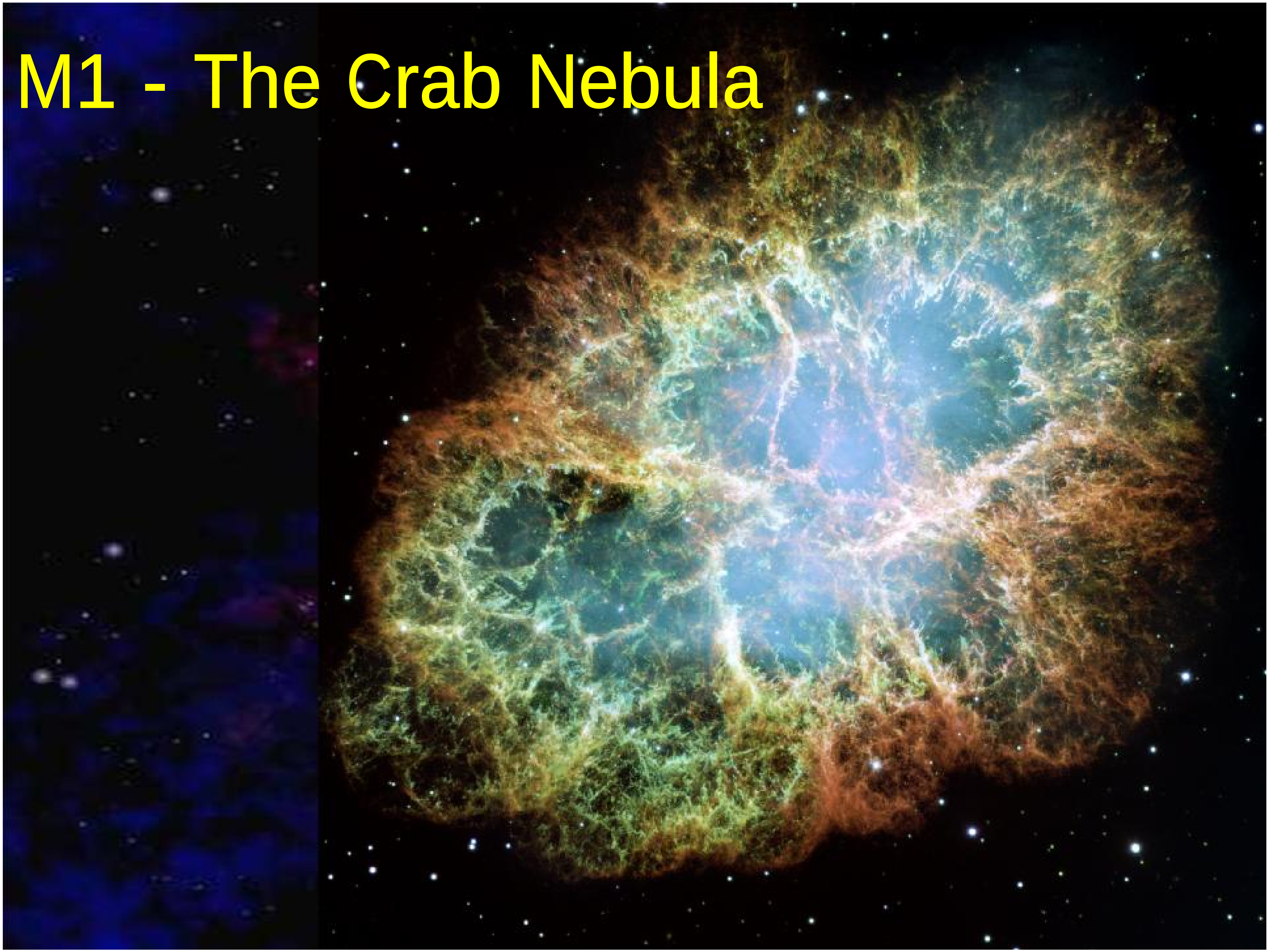
Supernova Remnants


Cassiopeia A
Si
Ca
Fe


CHANDRA X-RAY
(HIGH ENERGY)
CHANDRA X-RAY
(LOW ENERGY)
HUBBLE OPTICAL
SPITZER INFRARED

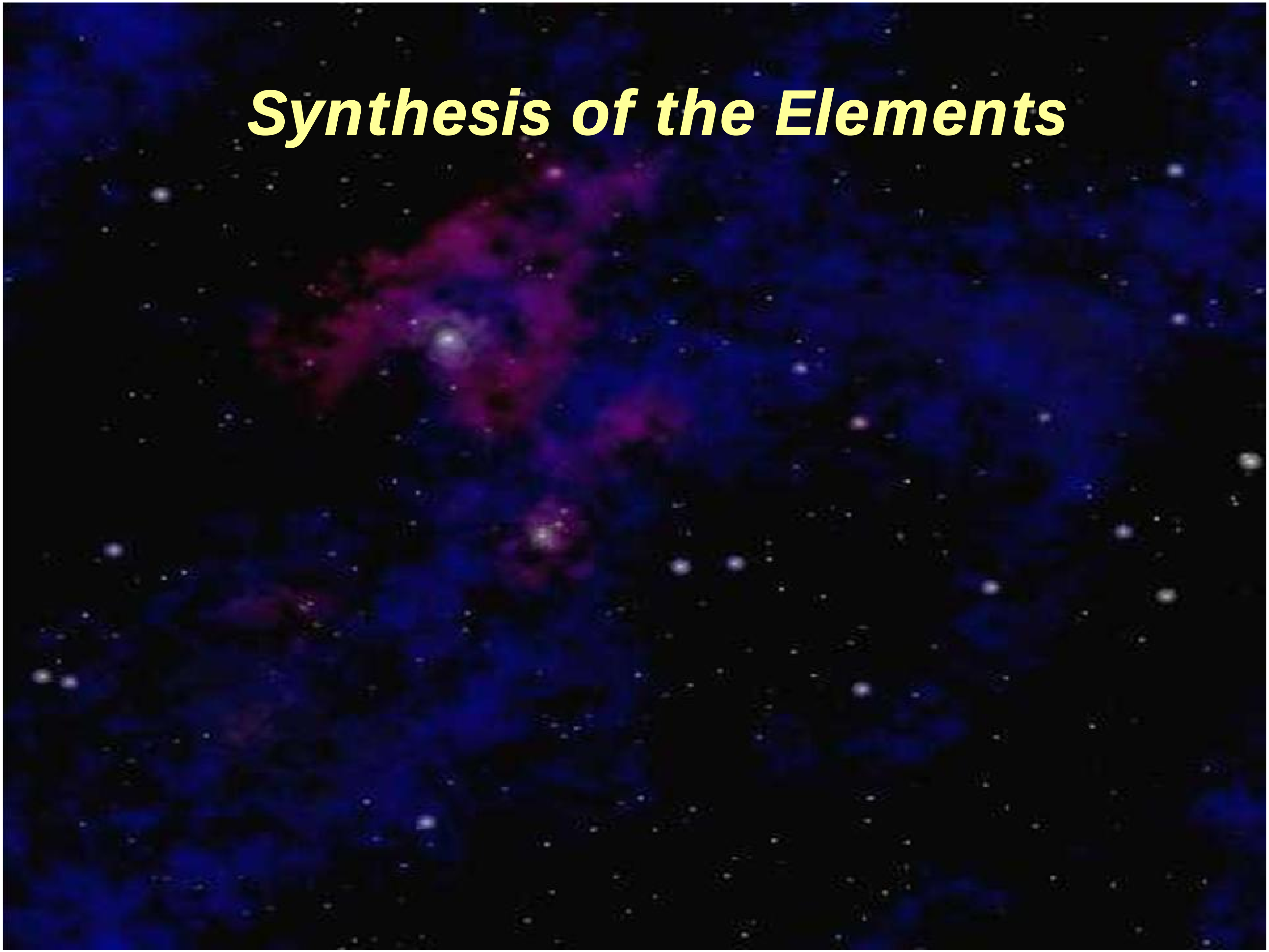
July, 1054 A.D.

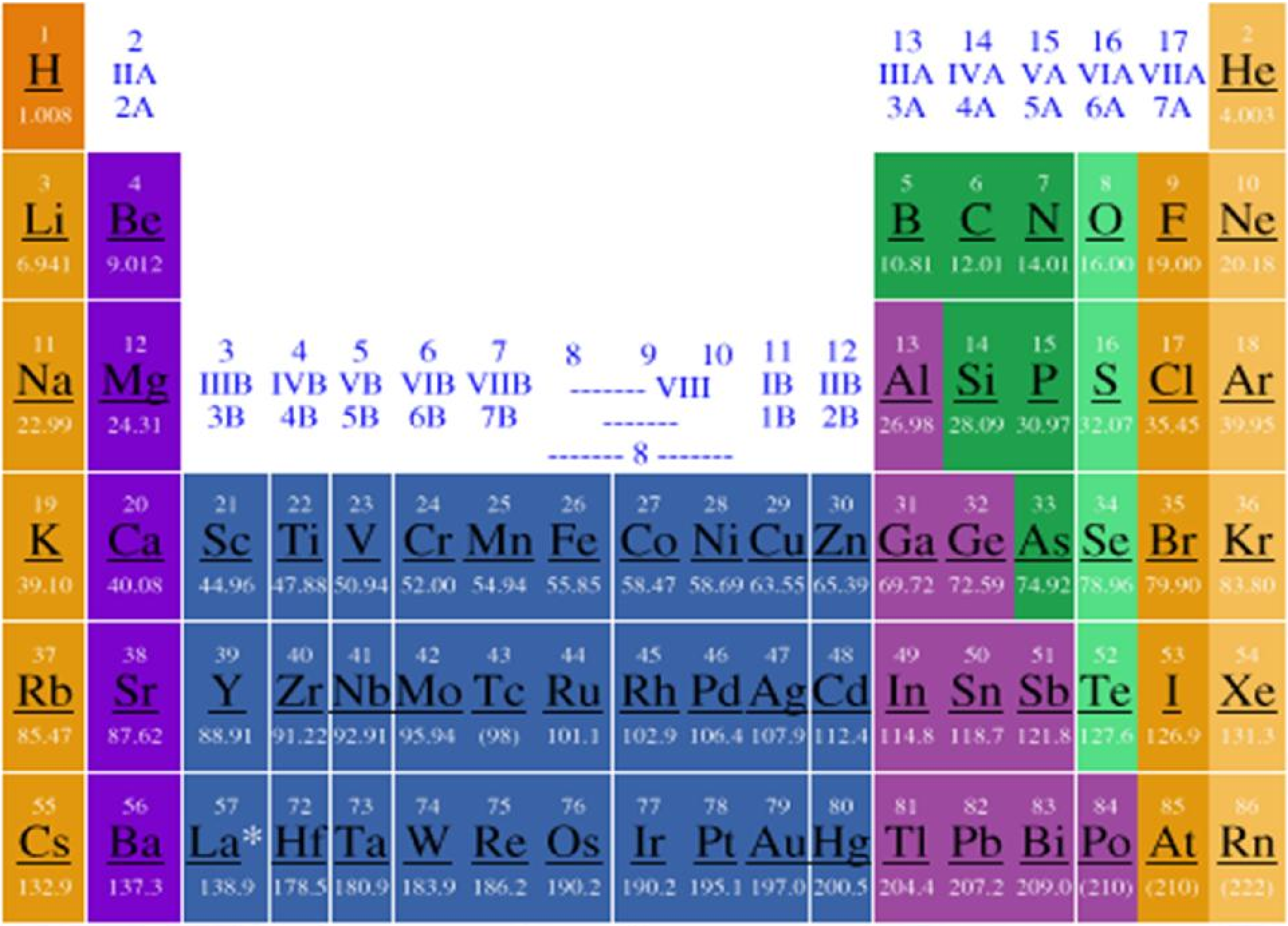
M1 - The Crab Nebula



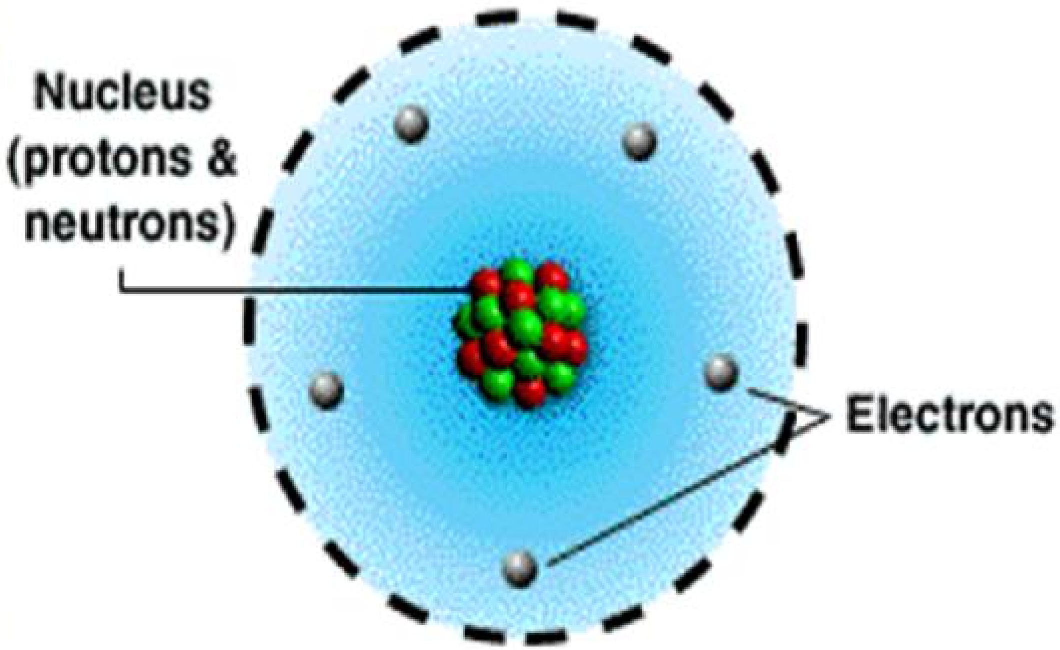
Crab Nebula

Synthesis of the Elements





1 H 1.008	2 IIA 2A											13 IIIA 3A	14 IVA 4A	15 VA 5A	16 VIA 6A	17 VIIA 7A	2 He 4.003
3 Li 6.941	4 Be 9.012											5 B 10.81	6 C 12.01	7 N 14.01	8 O 16.00	9 F 19.00	10 Ne 20.18
11 Na 22.99	12 Mg 24.31	3 IIIB 3B	4 IVB 4B	5 VB 5B	6 VIB 6B	7 VIIB 7B	8	9 ------- VIII ------- ------- 8 -------	10	11 IB 1B	12 IIB 2B	13 Al 26.98	14 Si 28.09	15 P 30.97	16 S 32.07	17 Cl 35.45	18 Ar 39.95
19 K 39.10	20 Ca 40.08	21 Sc 44.96	22 Ti 47.88	23 V 50.94	24 Cr 52.00	25 Mn 54.94	26 Fe 55.85	27 Co 58.47	28 Ni 58.69	29 Cu 63.55	30 Zn 65.39	31 Ga 69.72	32 Ge 72.59	33 As 74.92	34 Se 78.96	35 Br 79.90	36 Kr 83.80
37 Rb 85.47	38 Sr 87.62	39 Y 88.91	40 Zr 91.22	41 Nb 92.91	42 Mo 95.94	43 Tc (98)	44 Ru 101.1	45 Rh 102.9	46 Pd 106.4	47 Ag 107.9	48 Cd 112.4	49 In 114.8	50 Sn 118.7	51 Sb 121.8	52 Te 127.6	53 I 126.9	54 Xe 131.3
55 Cs 132.9	56 Ba 137.3	57 La* 138.9	72 Hf 178.5	73 Ta 180.9	74 W 183.9	75 Re 186.2	76 Os 190.2	77 Ir 190.2	78 Pt 195.1	79 Au 197.0	80 Hg 200.5	81 Tl 204.4	82 Pb 207.2	83 Bi 209.0	84 Po (210)	85 At (210)	86 Rn (222)



An Atom

Protons: + charge
determines chemistry

Neutrons: no charge
adds stability..to a degree
adds mass

Electrons: - charge
interacts with rest of world interacts with light

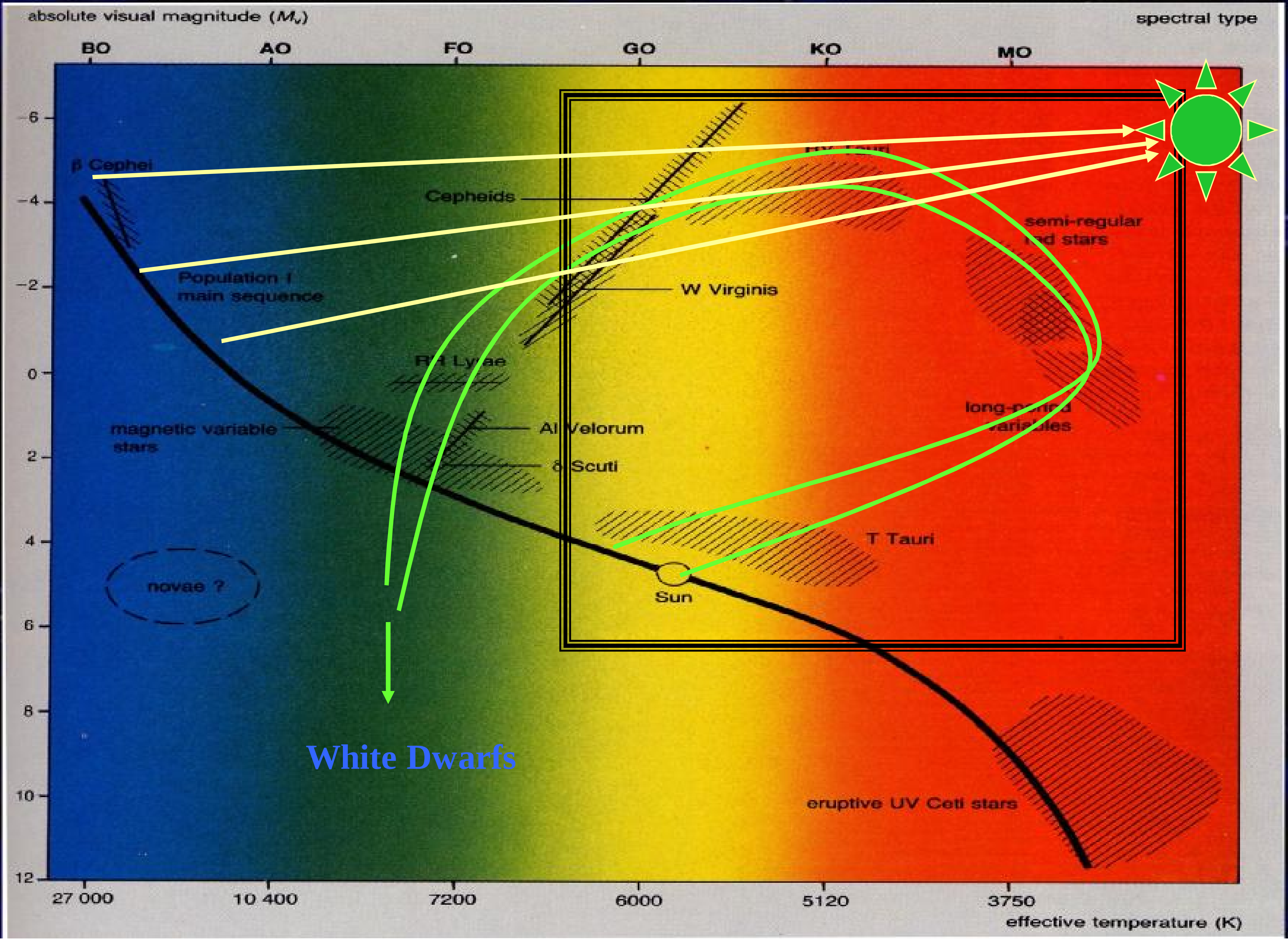
Isotopes of the elements

^{12}C = 6 protons + 6 neutrons

^{13}C = 6 protons + 7 neutrons

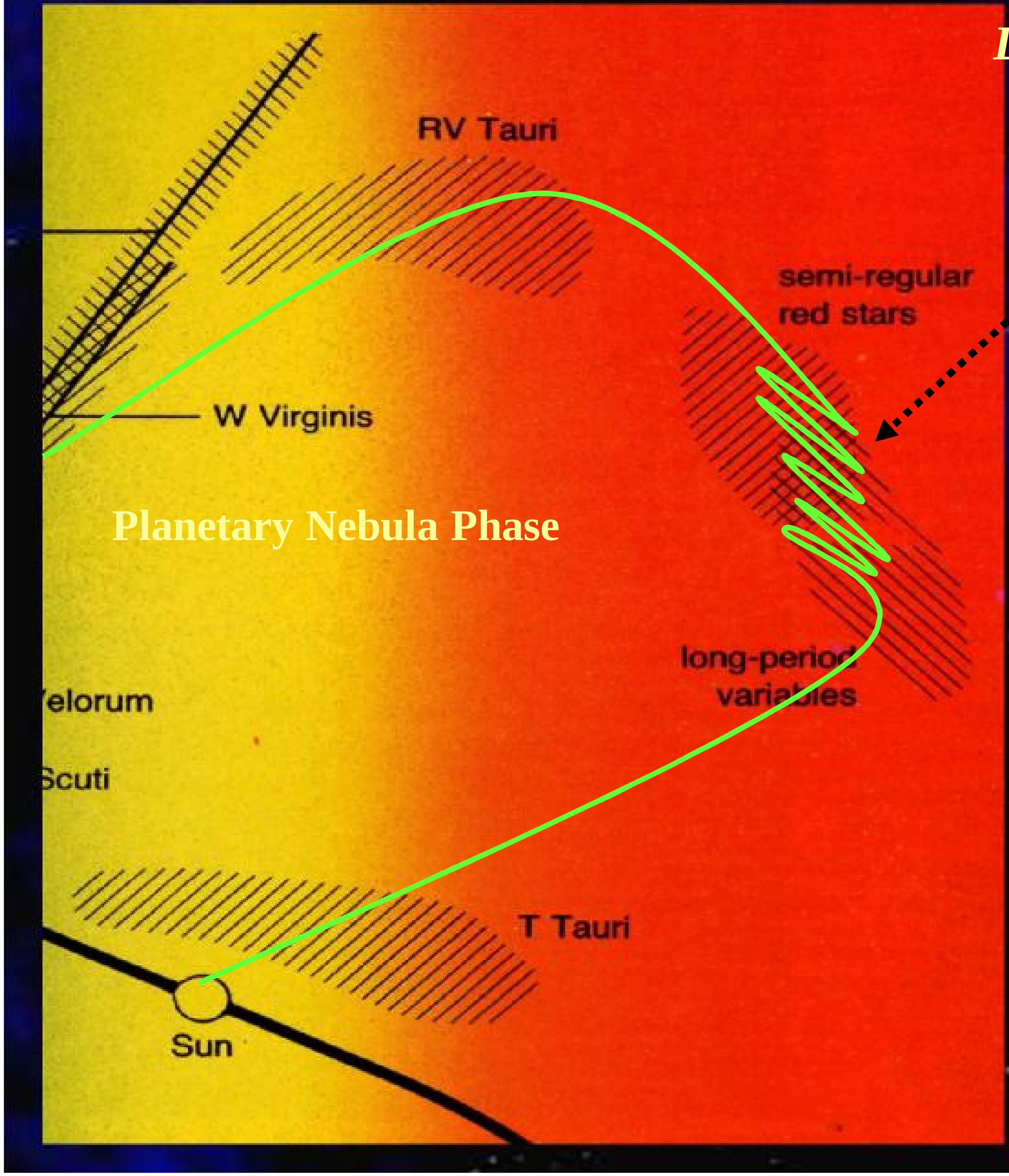
^{14}C = 6 protons + 8 neutrons, unstable $t_{1/2}$ = ~6000 years

^{15}C = 6 protons + 9 neutrons, unstable $t_{1/2}$ = ~12 years



White Dwarfs

Death of a Star, Birth of the Elements



Planetary Nebula Phase

C and S Stars: Thermal Pulse Phase

1) $\text{He} \longrightarrow {}^{12}\text{C}$
2) ${}^{12}\text{C} \longrightarrow {}^{13}\text{C}$
3) ${}^{13}\text{C} + \text{He} \longrightarrow {}^{16}\text{O} + n$
$\quad {}^{22}Ne + He \longrightarrow {}^{25}Mg + n$
4) $n + \{\text{Fe, Ni, Co}\ldots\} \longrightarrow$
s-elements

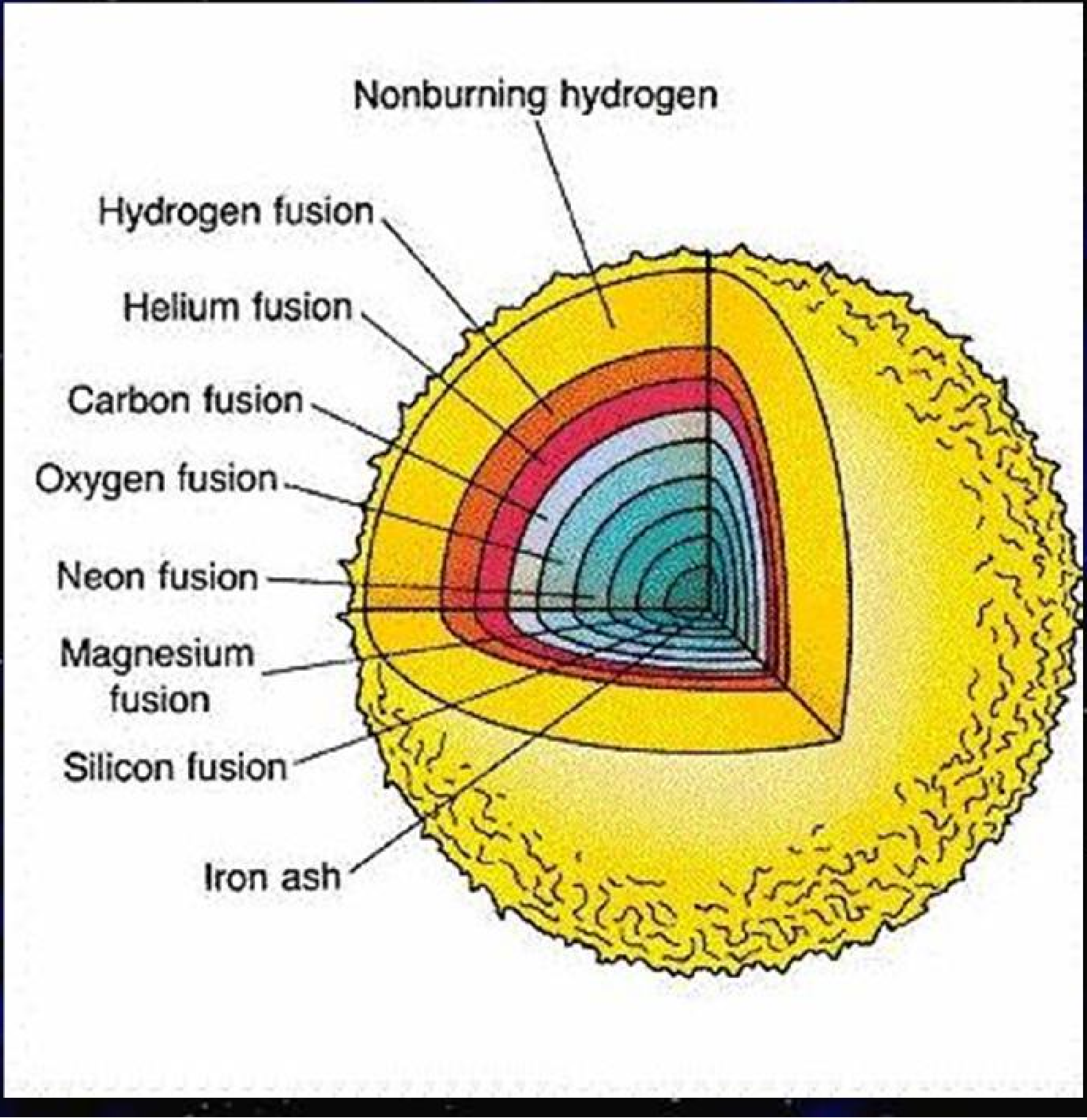
Total lifetime in TP: ~100,000 years
Total TP: ~15-20
Slow Neutron Capture Synthesis of heavy elements: >Fe
Between TP: Dredge Up Period

Historical

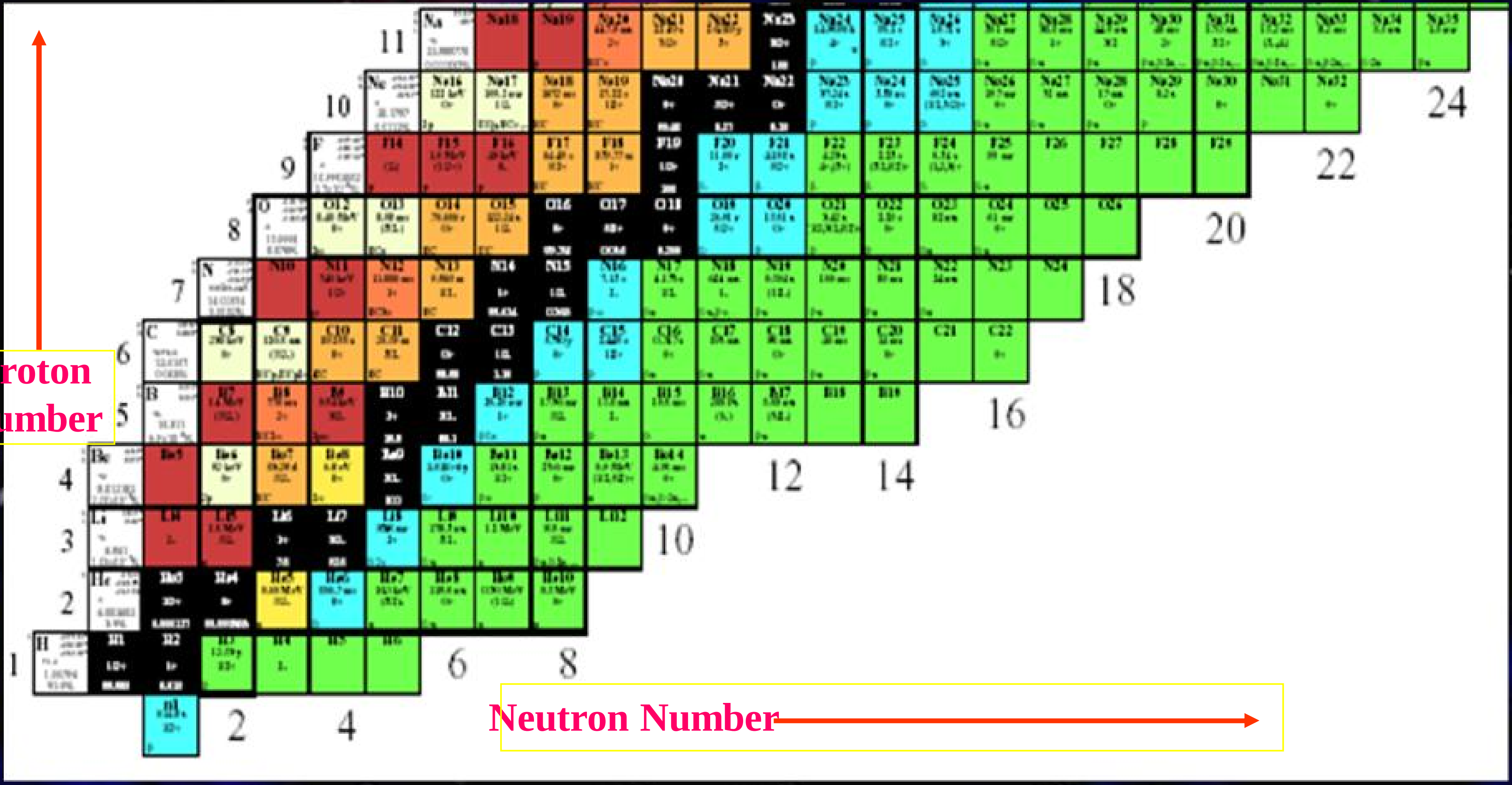
- 1930’s Hans Bethe discovers mechanisms by which stars shine - fusion of hydrogen to helium primary energy source
- In the 1940’s and early 1950’s as Big Bang picture for origin of Universe was developing – elements cooked up early in expansion
- Early 1950’s this started to give way to the stars being the most likely place

  Fred Hoyle, Cambridge
  William Fowler, Cal Tech
  Geoffrey Burbidge
  Margarate Burbidge

- The seminal observation was detection of technetium in atmospheres of old (>several 10^9 years) stars


Nonburning hydrogen
Hydrogen fusion
Helium fusion
Carbon fusion
Oxygen fusion
Neon fusion
Magnesium fusion
Silicon fusion
Iron ash

The 3rd Dimension of the Periodic Table



Valley of Stability

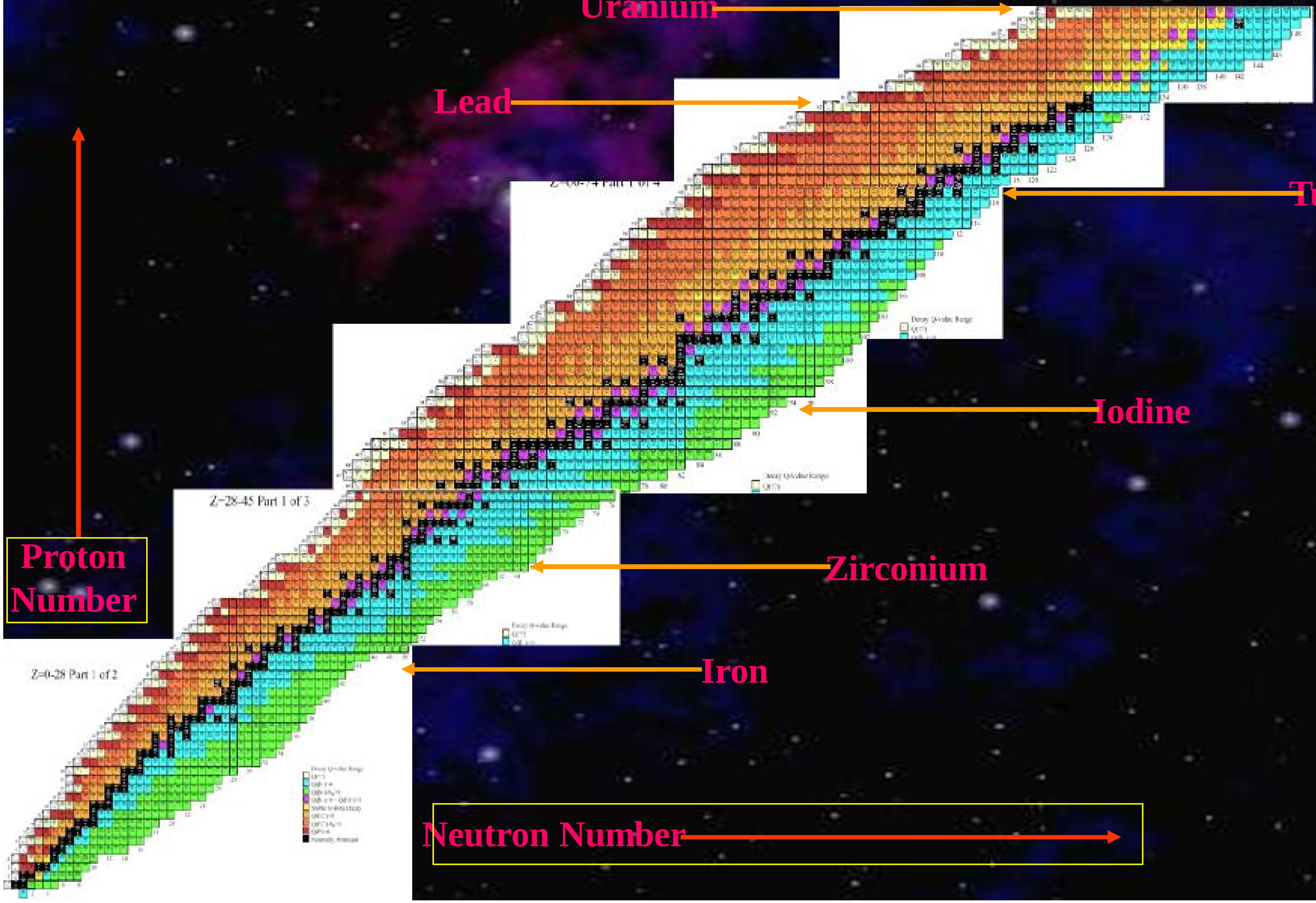
Proton Rich

Neutron Rich

Proton Number

Neutron Number

The 3rd Dimension of the Periodic Table



Uranium

Lead

Tungsten

Iodine

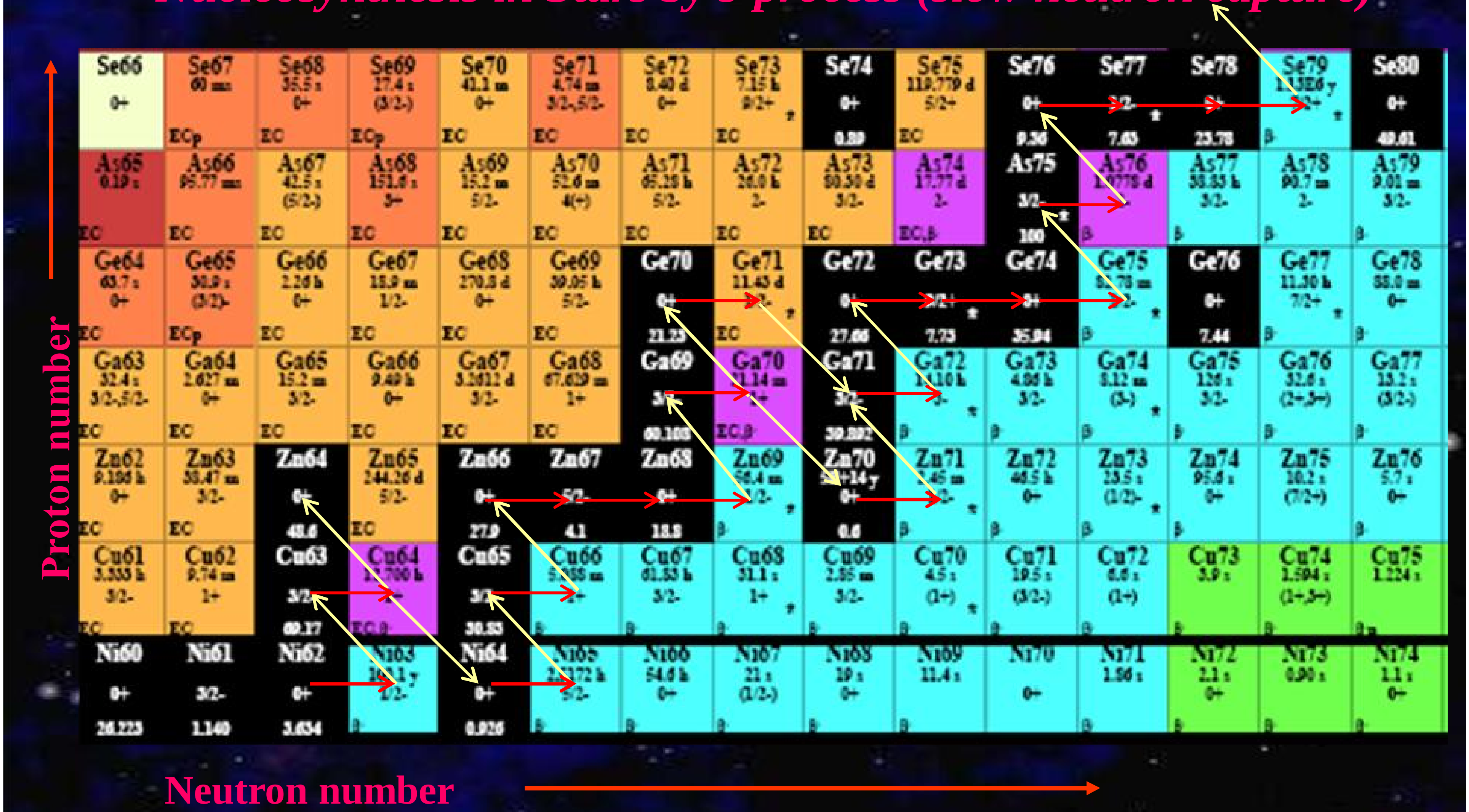
Zirconium

Iron

Proton Number

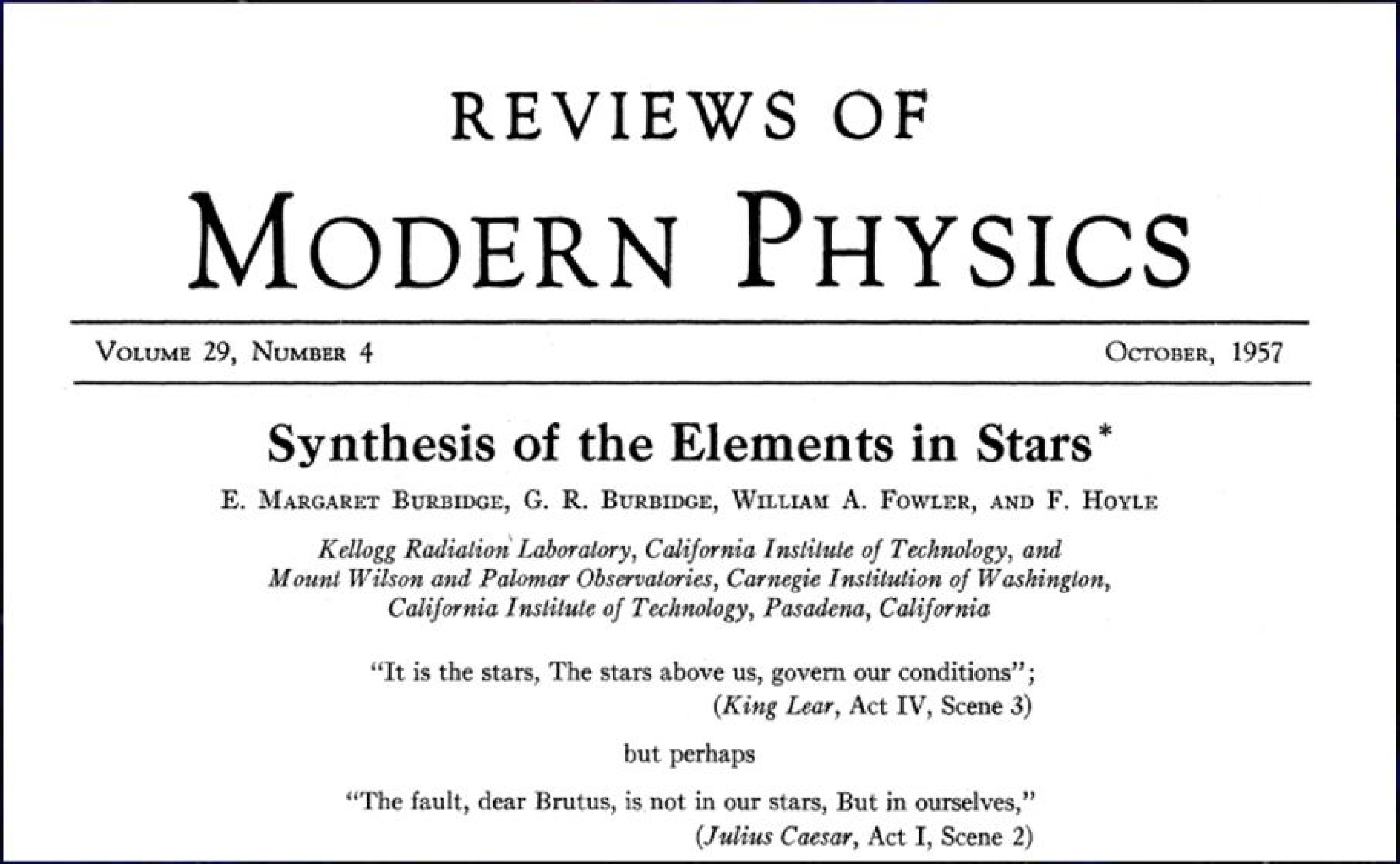
Neutron Number

Nucleosynthesis in Stars by s-process (slow neutron capture)



Se66 0+	Se67 60 ms ECp	Se68 35.5 s 0+ EC	Se69 27.4 s (3/2-) ECp	Se70 41.1 m 0+ EC	Se71 4.74 m 3/2-,5/2- EC	Se72 8.40 d 0+ EC	Se73 7.15 h 9/2+ * EC	Se74 0+ 0.89	Se75 119.779 d 5/2+ EC	Se76 0+ 9.36	Se77 1/2- * 7.63	Se78 0+ 23.78	Se79 1.13E6 y 7/2+ * β-	Se80 0+ 49.61
As65 0.19 s EC	As66 95.77 ms EC	As67 42.5 s (5/2-) EC	As68 151.6 s 3+ EC	As69 15.2 m 5/2- EC	As70 52.6 m 4(+) EC	As71 65.28 h 5/2- EC	As72 26.0 h 2- EC	As73 80.30 d 3/2- EC	As74 17.77 d 2- EC,β	As75 3/2- * 100	As76 1.0778 d 2- β-	As77 38.83 h 3/2- β-	As78 90.7 m 2- β-	As79 9.01 m 3/2- β-
Ge64 63.7 s 0+ EC	Ge65 30.9 s (3/2)- ECp	Ge66 2.26 h 0+ EC	Ge67 18.9 m 1/2- EC	Ge68 270.8 d 0+ EC	Ge69 39.05 h 5/2- EC	Ge70 0+ 21.23	Ge71 11.43 d 1/2- * EC	Ge72 0+ 27.66	Ge73 9/2+ * 7.73	Ge74 0+ 35.94	Ge75 82.78 m 1/2- * β-	Ge76 0+ 7.44	Ge77 11.30 h 7/2+ * β-	Ge78 88.0 m 0+ β-
Ga63 32.4 s 3/2-,5/2- EC	Ga64 2.627 m 0+ EC	Ga65 15.2 m 3/2- EC	Ga66 9.49 h 0+ EC	Ga67 3.2612 d 3/2- EC	Ga68 67.629 m 1+ EC	Ga69 3/2- 60.108	Ga70 21.14 m 1+ EC,β-	Ga71 3/2- 39.892	Ga72 14.10 h 3- * β-	Ga73 4.86 h 3/2- β-	Ga74 8.12 m (3-) * β-	Ga75 126 s 3/2- β-	Ga76 32.6 s (2+,3+) β-	Ga77 13.2 s (3/2-) β-
Zn62 9.186 h 0+ EC	Zn63 38.47 m 3/2- EC	Zn64 0+ 48.6	Zn65 244.26 d 5/2- EC	Zn66 0+ 27.9	Zn67 5/2- 4.1	Zn68 0+ 18.8	Zn69 56.4 m 1/2- * β-	Zn70 5E+14 y 0+ 0.6	Zn71 2.45 m 1/2- * β-	Zn72 46.5 h 0+ β-	Zn73 23.5 s (1/2)- * β-	Zn74 95.6 s 0+ β-	Zn75 10.2 s (7/2+) β-	Zn76 5.7 s 0+ β-
Cu61 3.333 h 3/2- EC	Cu62 9.74 m 1+ EC	Cu63 3/2- 69.17	Cu64 12.700 h 1+ EC,β	Cu65 3/2- 30.83	Cu66 5.088 m 1+ β-	Cu67 61.83 h 3/2- β-	Cu68 31.1 s 1+ * β-	Cu69 2.85 m 3/2- β-	Cu70 4.5 s (1+) * β-	Cu71 19.5 s (3/2-) β-	Cu72 6.6 s (1+) β-	Cu73 3.9 s β-	Cu74 1.594 s (1+,3+) β-	Cu75 1.224 s β-n
Ni60 0+ 26.223	Ni61 3/2- 1.140	Ni62 0+ 3.634	Ni63 100.1 y 1/2- β-	Ni64 0+ 0.926	Ni65 2.5172 h 5/2- β-	Ni66 54.6 h 0+ β-	Ni67 21 s (1/2-) β-	Ni68 19 s 0+ β-	Ni69 11.4 s β-	Ni70 0+ β-	Ni71 2.56 s β-	Ni72 2.1 s 0+ β-	Ni73 0.90 s β-	Ni74 1.1 s 0+ β-

B^{2}FH



REVIEWS OF
MODERN PHYSICS

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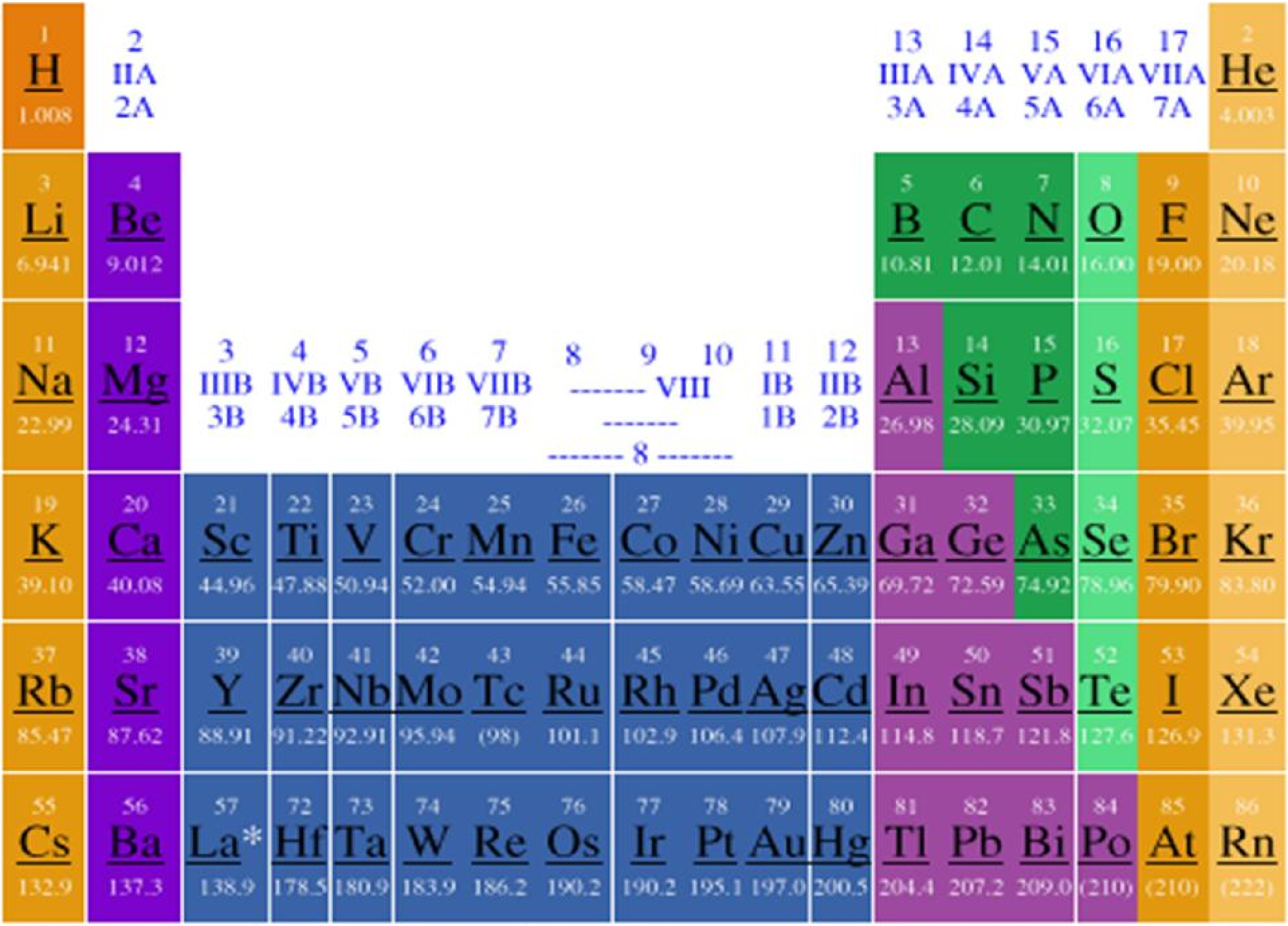
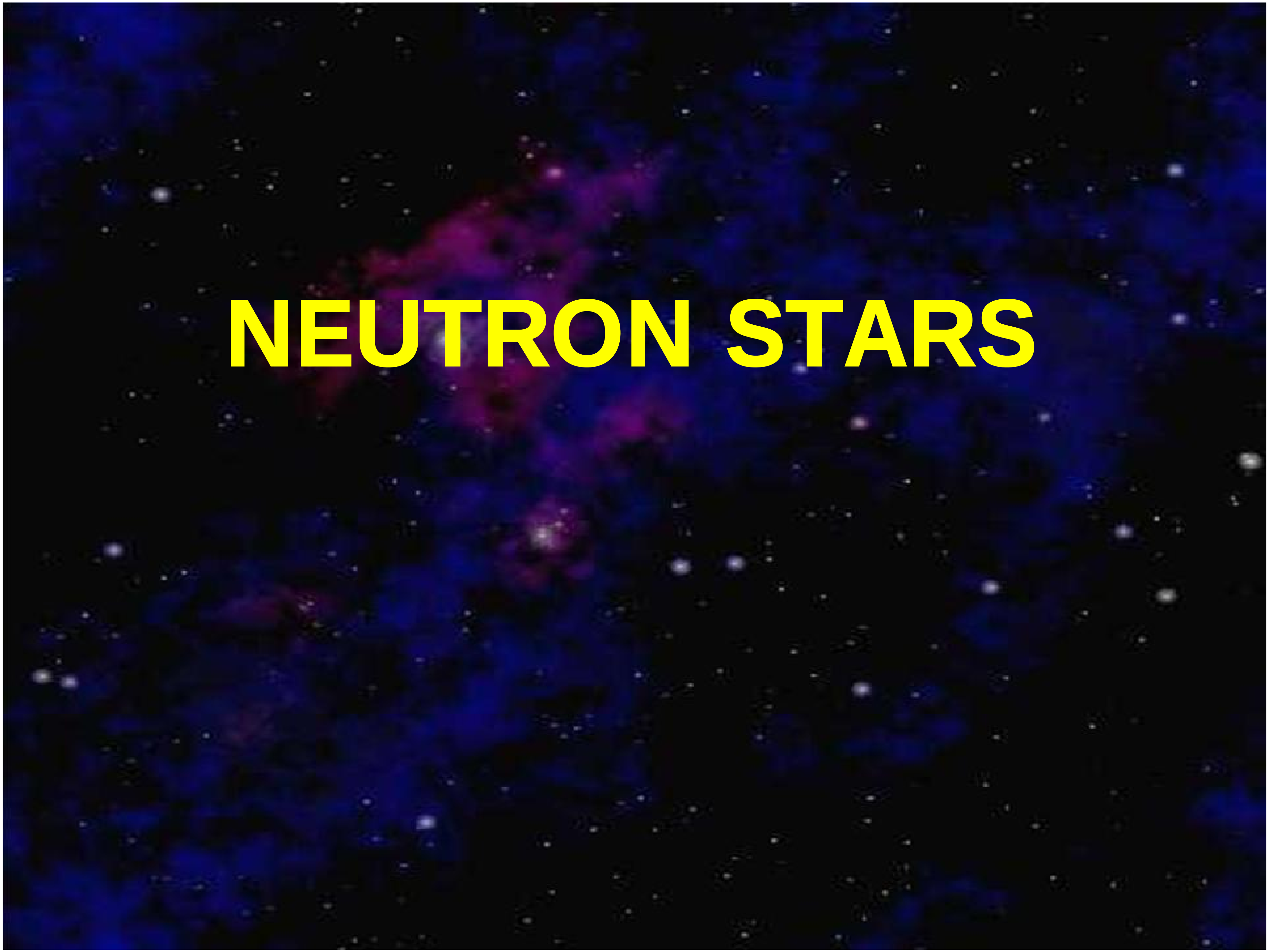
Synthesis of the Elements in Stars*

E. MARGARET BURBIDGE, G. R. BURBIDGE, WILLIAM A. FOWLER, AND F. HOYLE

Kellogg Radiation Laboratory, California Institute of Technology, and
Mount Wilson and Palomar Observatories, Carnegie Institution of Washington,
California Institute of Technology, Pasadena, California

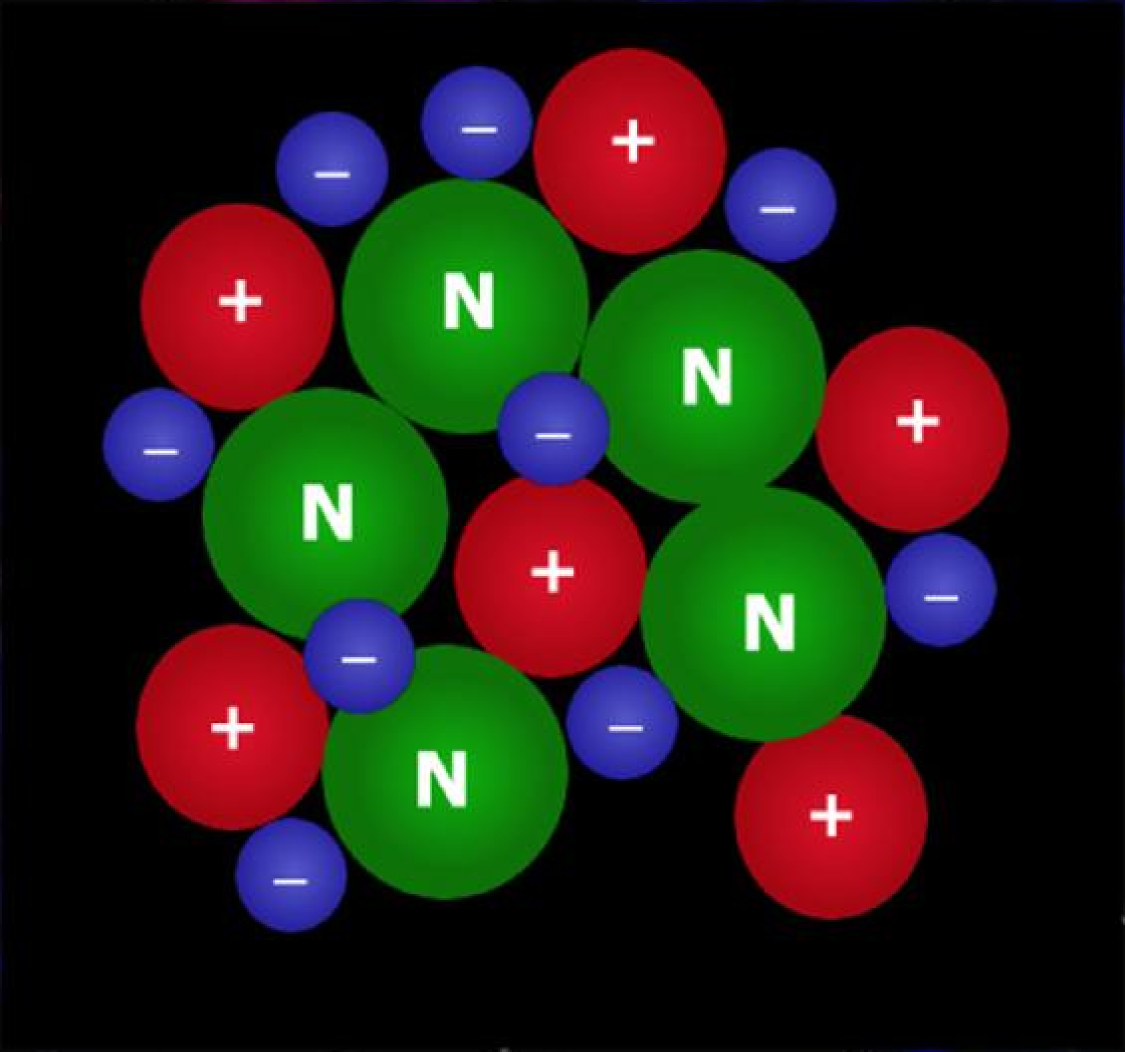
> "It is the stars, The stars above us, govern our conditions";
> (*King Lear*, Act IV, Scene 3)
>
> but perhaps
>
> "The fault, dear Brutus, is not in our stars, But in ourselves,"
> (*Julius Caesar*, Act I, Scene 2)

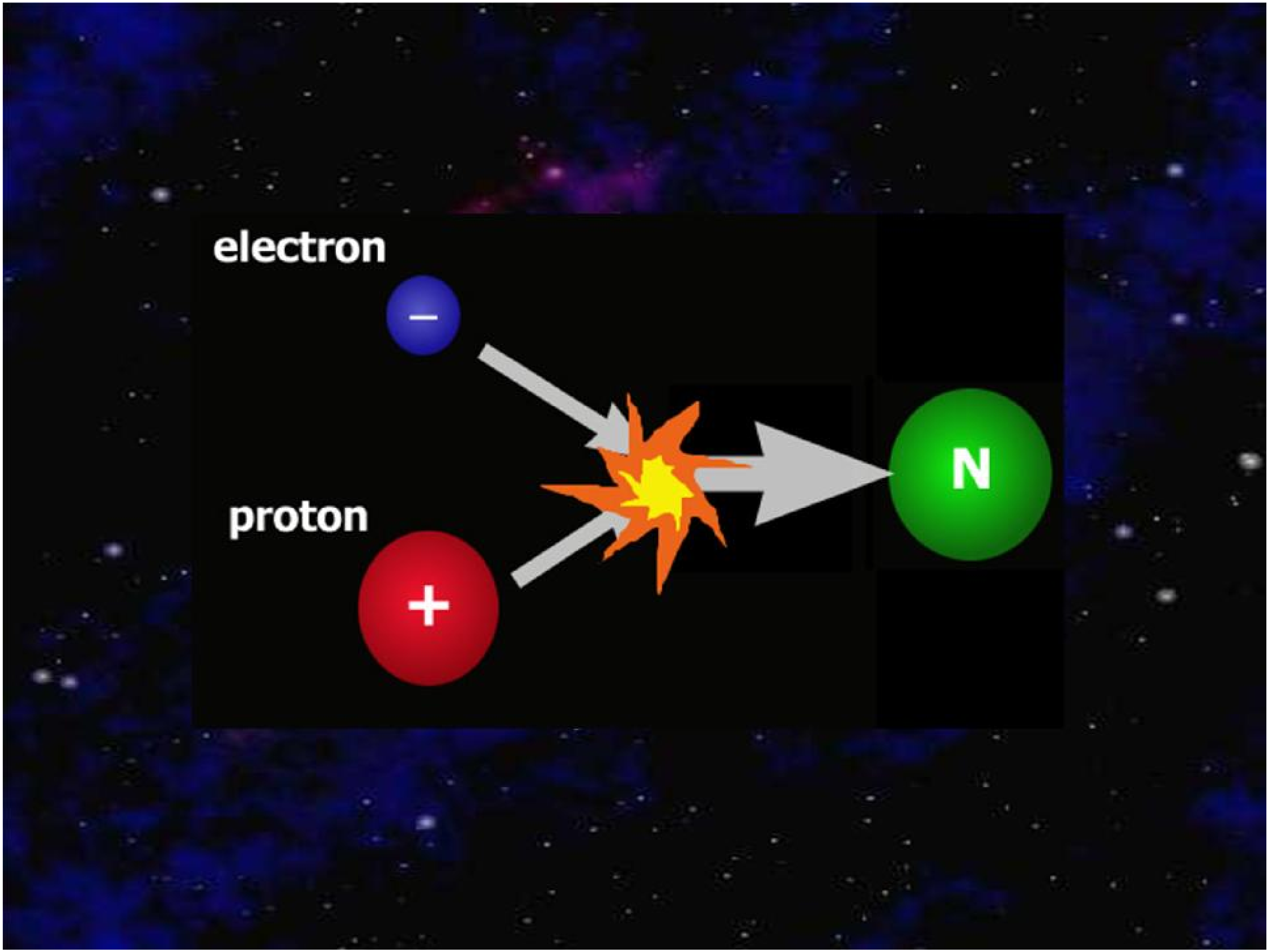


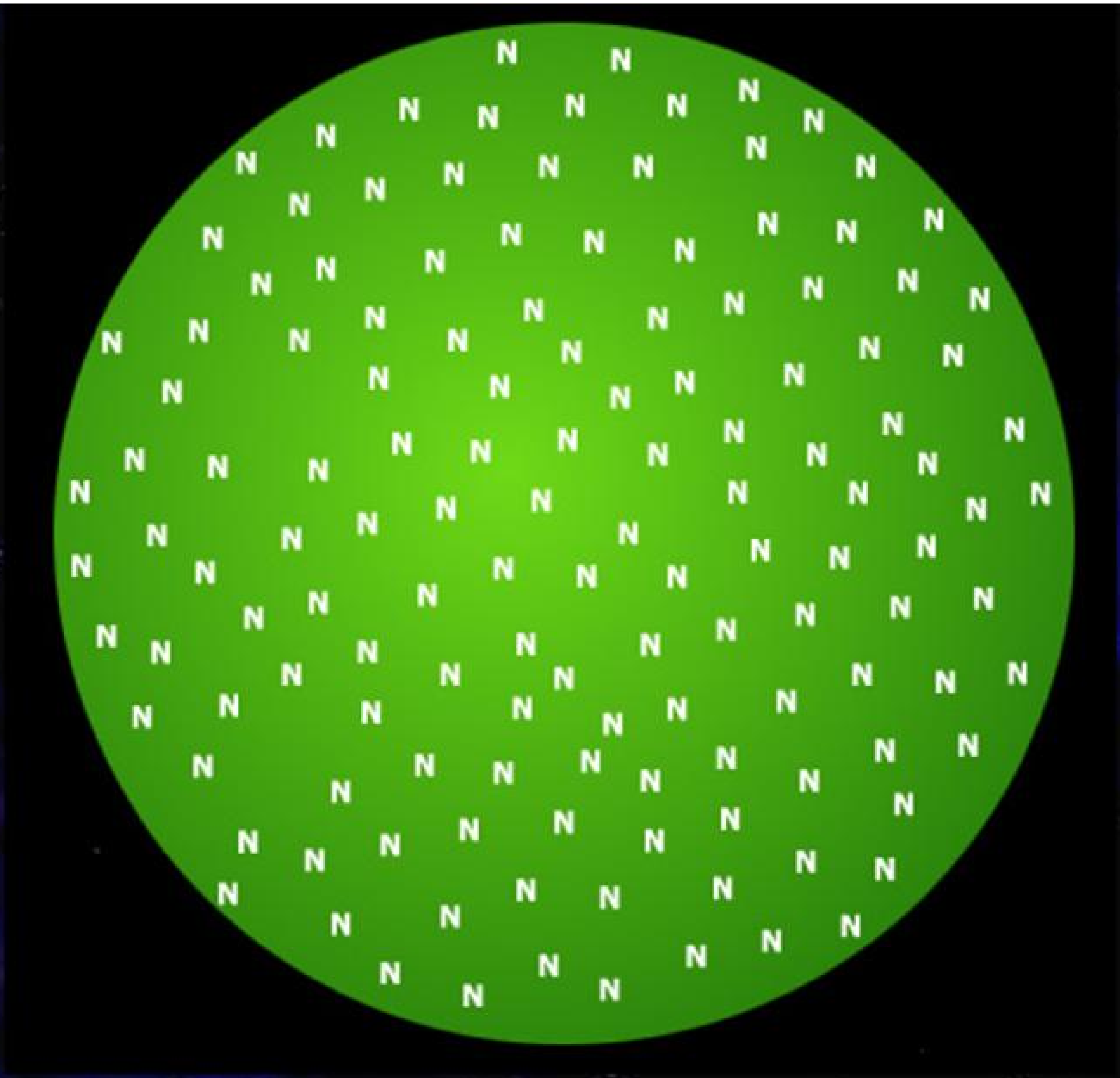


NEUTRON STARS

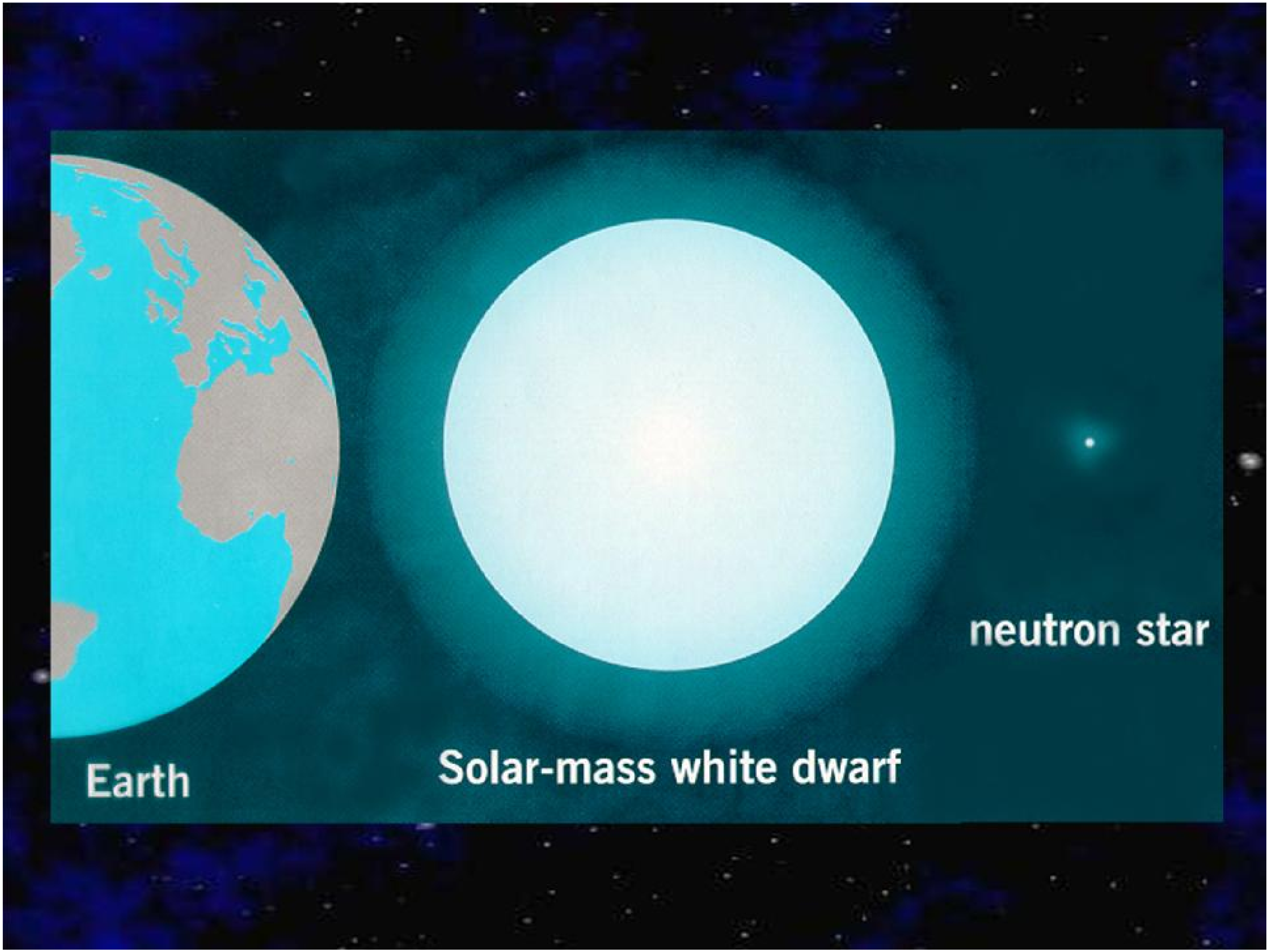
What happened to the iron core after the supernova?

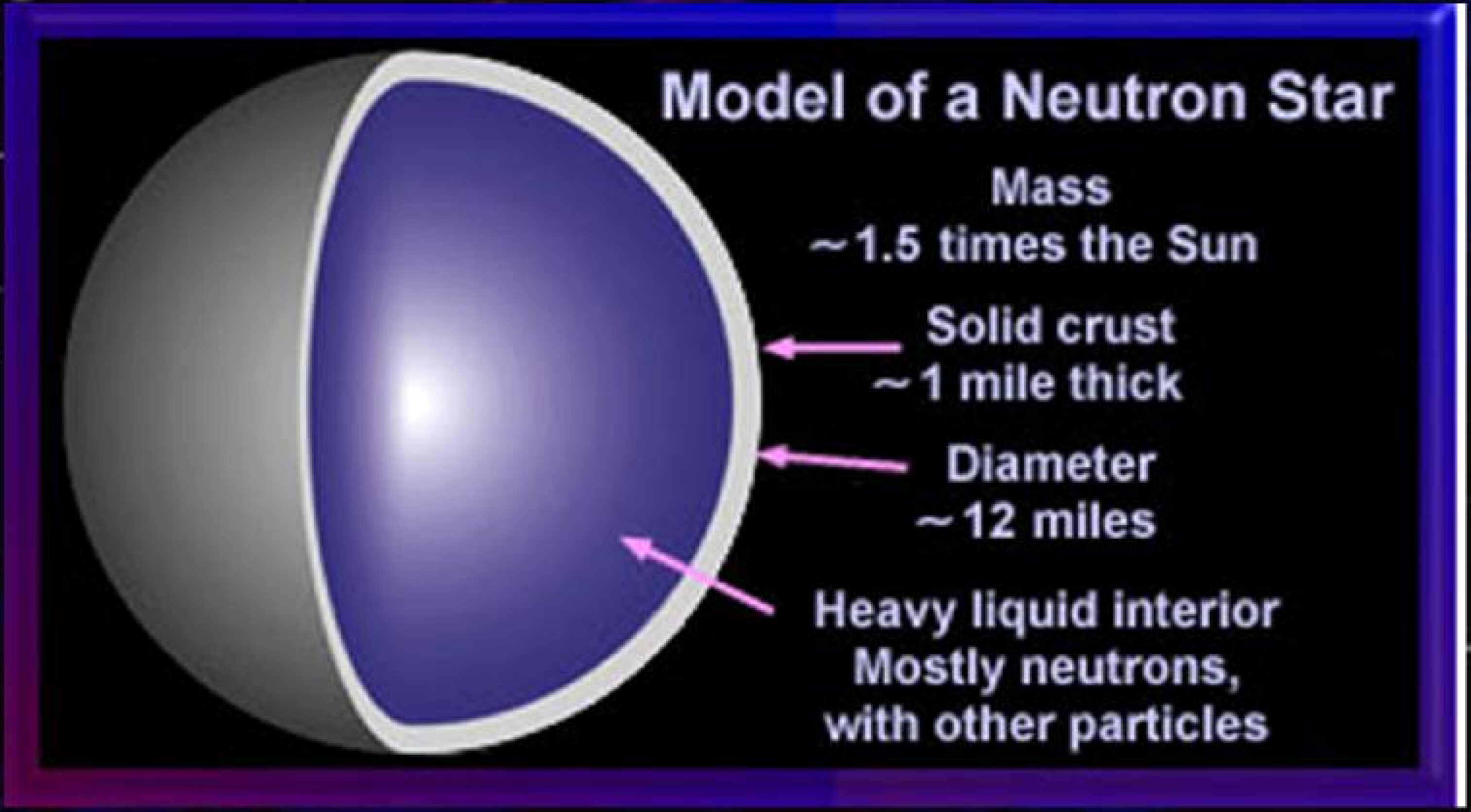



electron
–
proton
+
N



NEUTRON STAR


neutron star
Solar-mass white dwarf
Earth



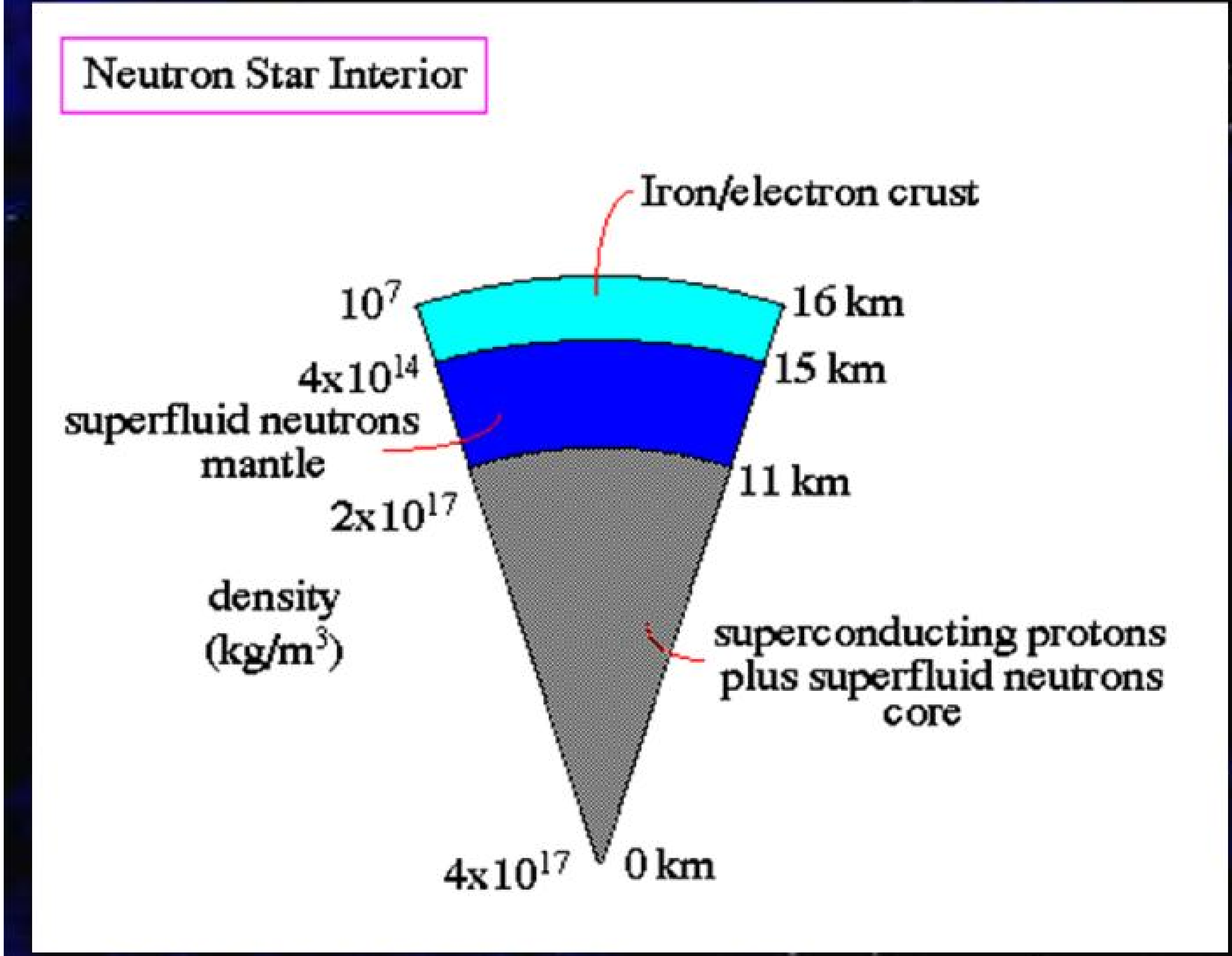
Model of a Neutron Star

Mass
~1.5 times the Sun

Solid crust
~1 mile thick

Diameter
~12 miles

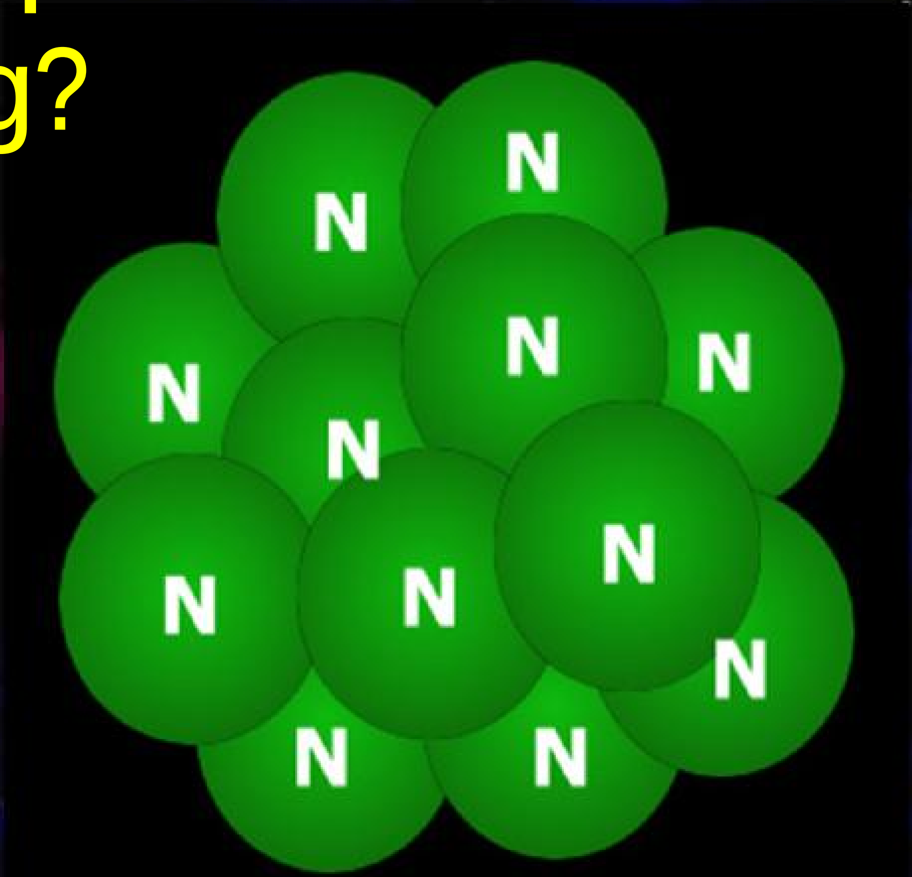
Heavy liquid interior
Mostly neutrons,
with other particles



220,000,000 tons per cubic inch

Limit ~ 3 solar M

What keeps the neutron star from collapsing?



NEUTRON DEGENERACY PRESSURE

Neutrons have a limit to how tightly they can be packed together

Chandrasekhar Limit for neutron stars

$$M < 3.0\ M_{\bullet}$$