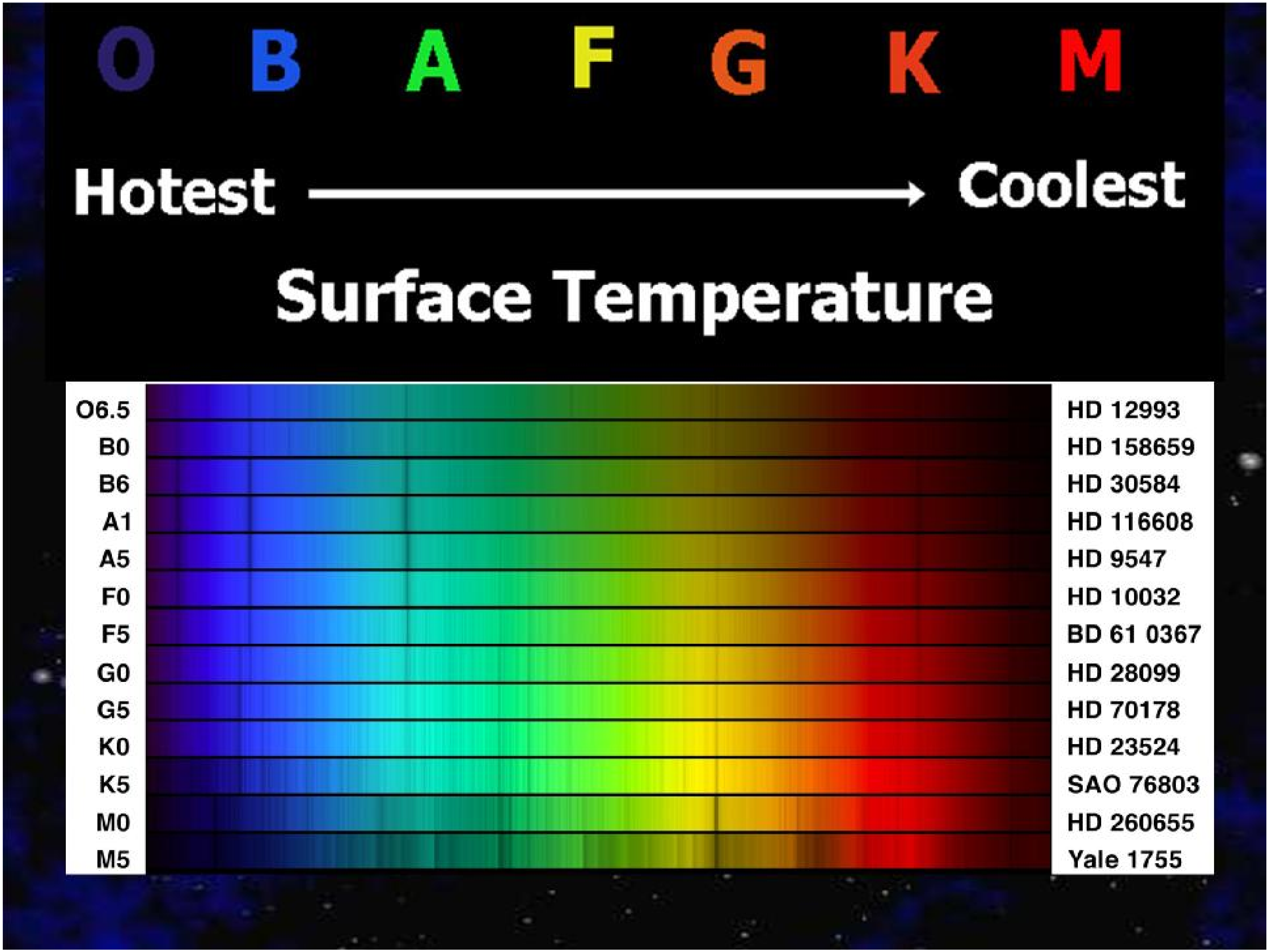
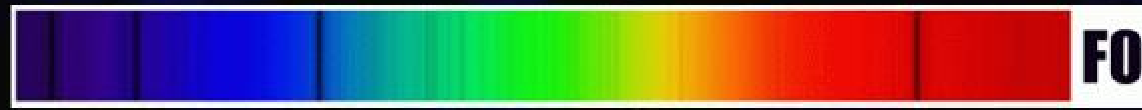
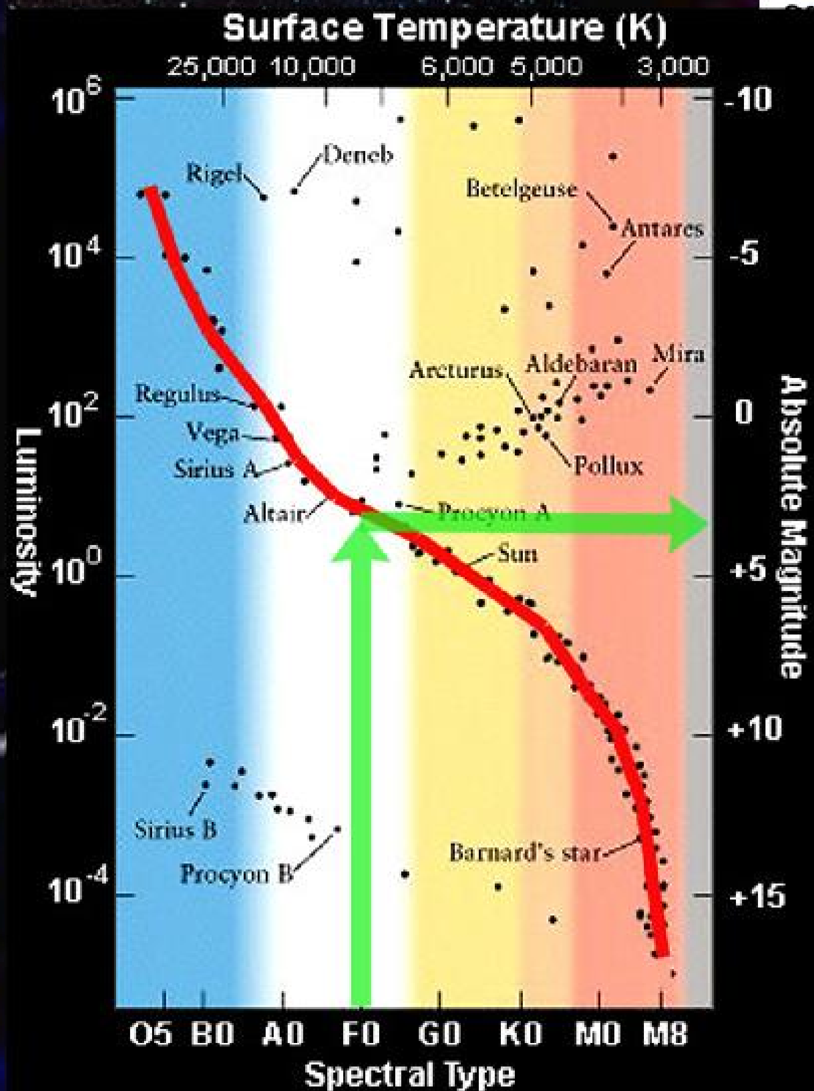
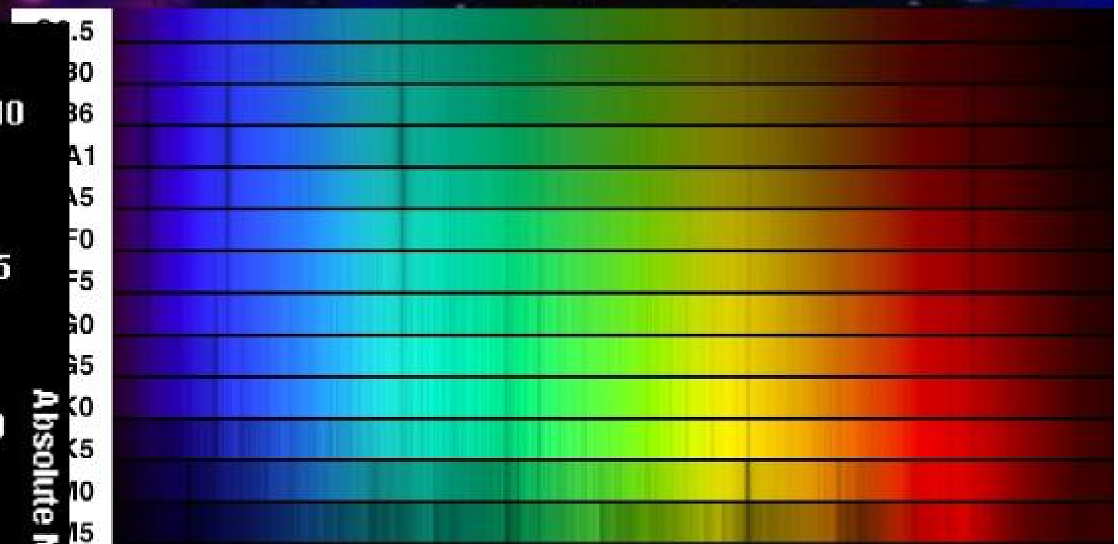

O B A F G K M
Hotest
Coolest
Surface Temperature
O6.5
B0
B6
A1
A5
F0
F5
G0
G5
K0
K5
M0
M5
HD 12993
HD 158659
HD 30584
HD 116608
HD 9547
HD 10032
BD 61 0367
HD 28099
HD 70178
HD 23524
SAO 76803
HD 260655
Yale 1755







$$m - M = 5\log d - 5$$

Spectroscopic Parallax

Temperature – Radius – Luminosity Relationship

$$L = 4pR^2sT^4$$

L = luminosity of the star

R = radius of the star

T = surface temperature of the star

π,σ = constants

Luminosity Classes

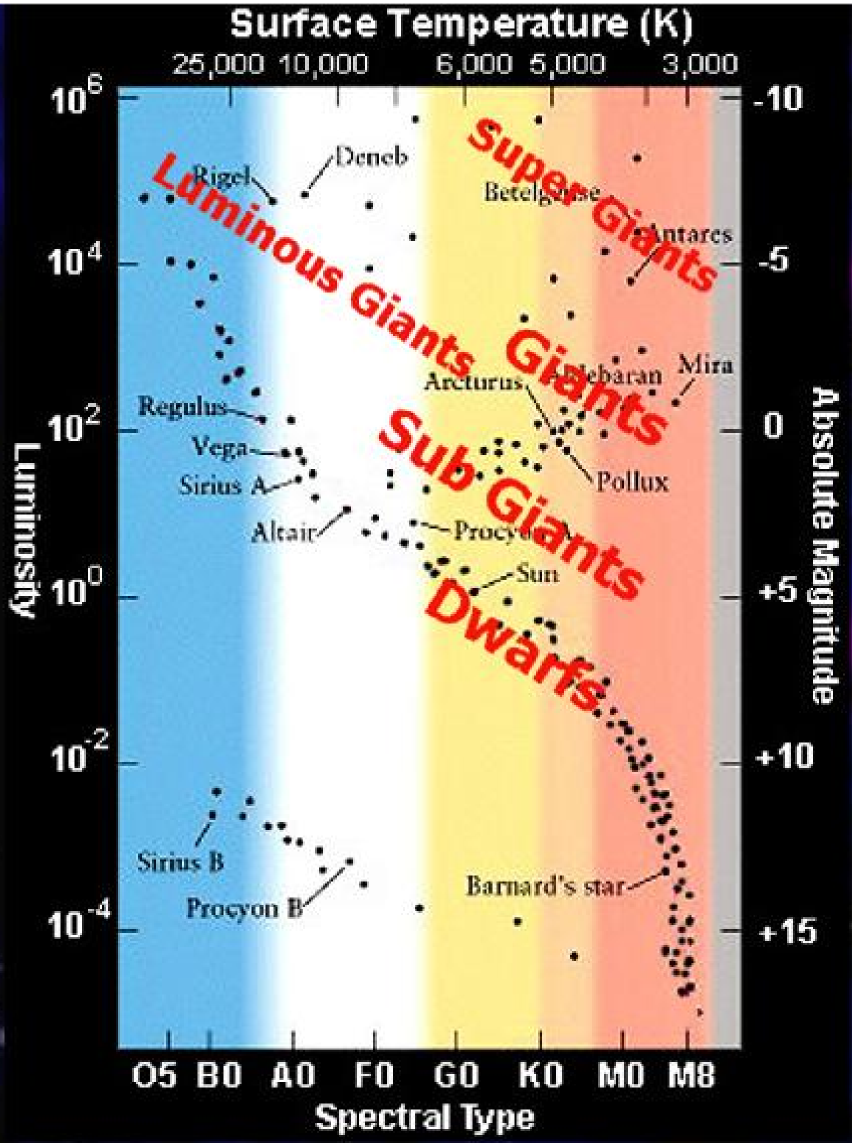
I	Super Giants
II	Luminous Giants
III	Giants
IV	Sub Giants
V	Dwarfs

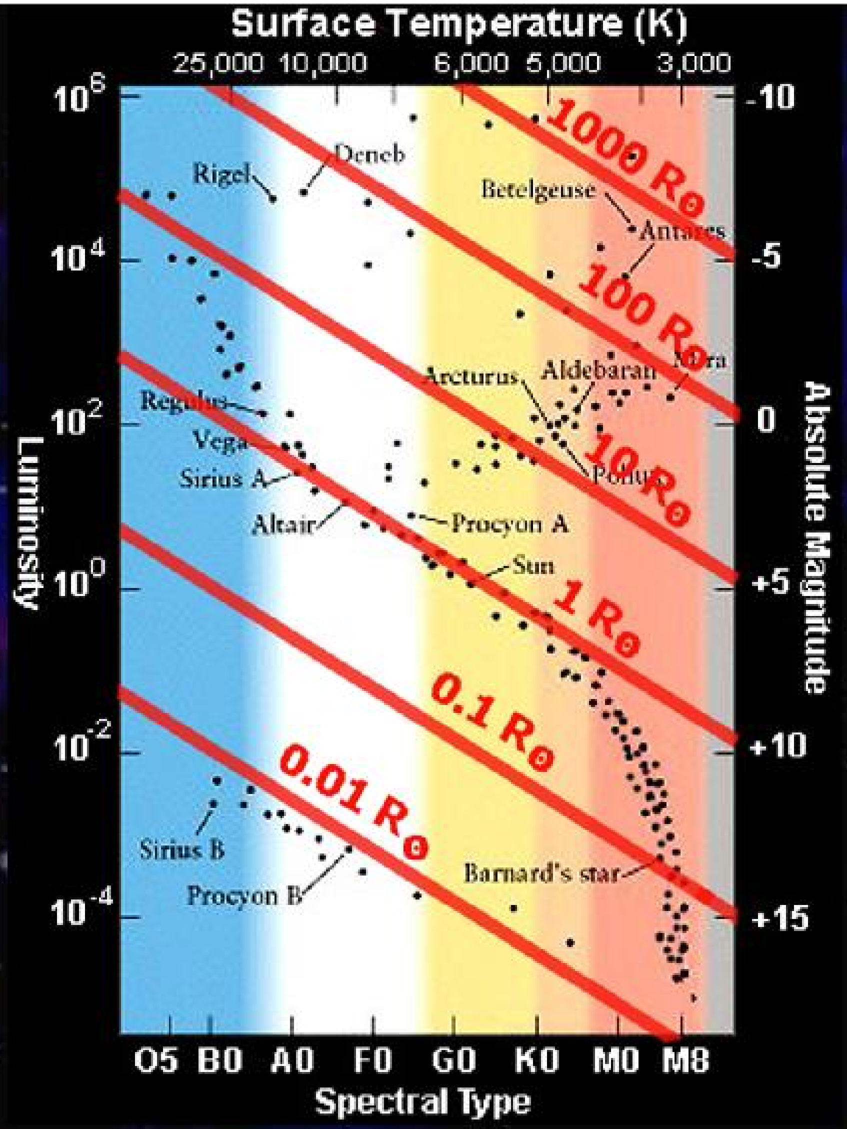
The Sun is a Dwarf…

So finally, stars can be classified...

By spectral type (OBAFGKM)

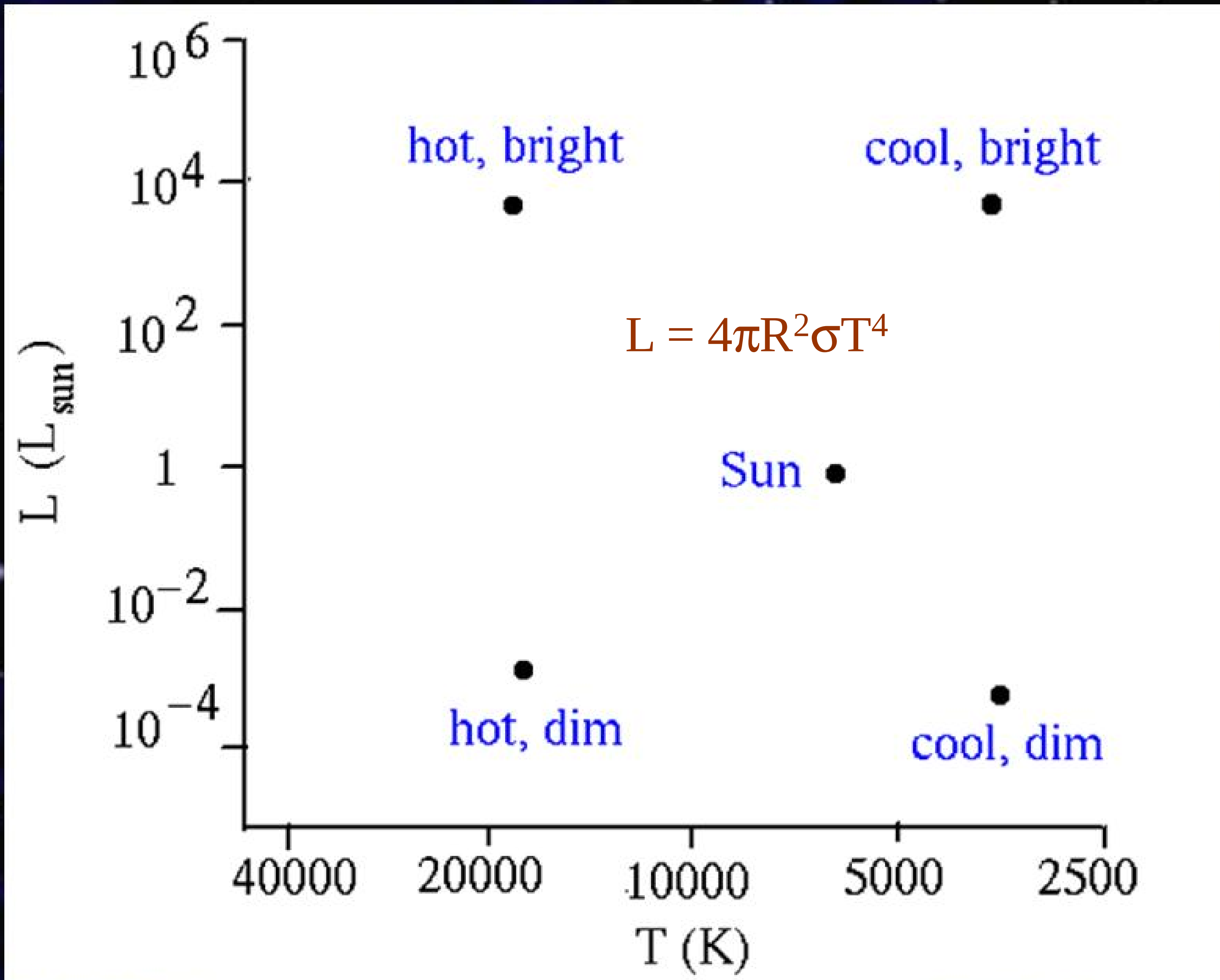
Luminosity class (I,II,III,IV,V)



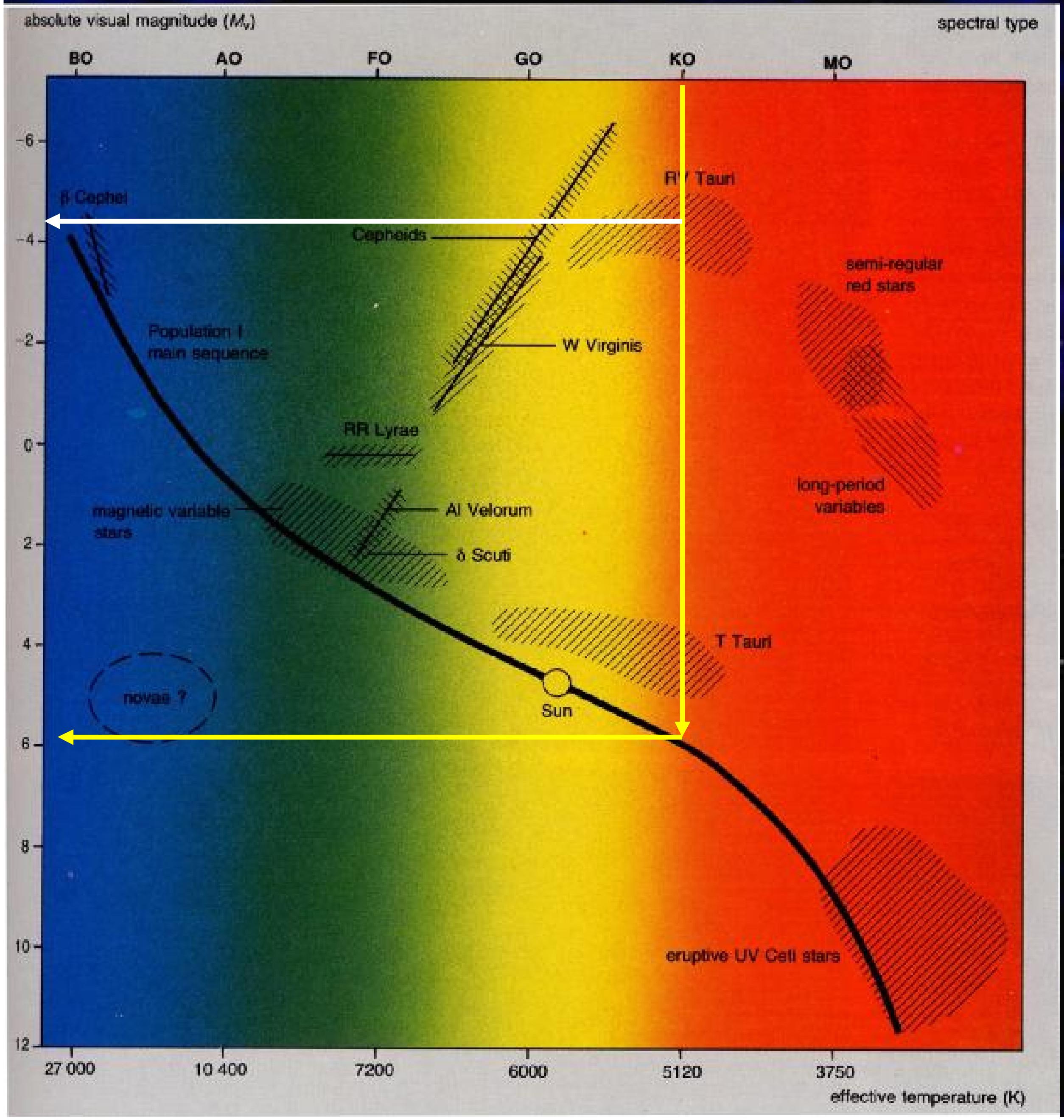


Betelgeuse: M1 I

Sun: G2 V


hot, bright
cool, bright
L = 4πR²σT⁴
Sun
hot, dim
cool, dim
L (L_sun)
10^6
10^4
10^2
1
10^−2
10^−4
40000
20000
10000
5000
2500
T (K)

The Art of Spectroscopic Parallax



1) Measure spectral type
2) Measure m_v
3) Determine luminosity class
4) Place on HR diagram
5) Read Mv

Example: Record spectrum of star and find it is K0 V type

Read off Mv

Determine visual mag, m_v

$$m - M = 5 \log d - 5$$

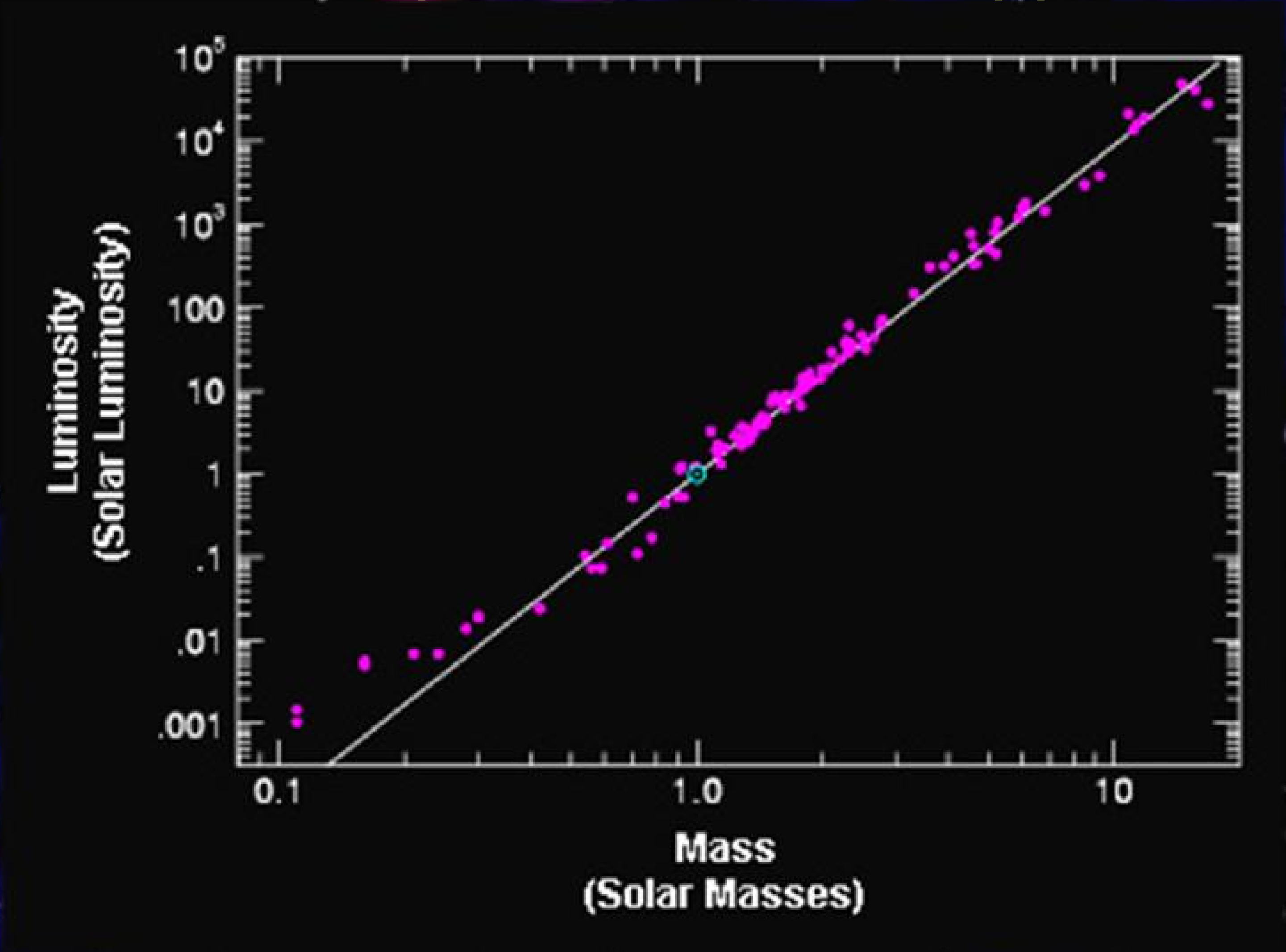
100 fold error in d

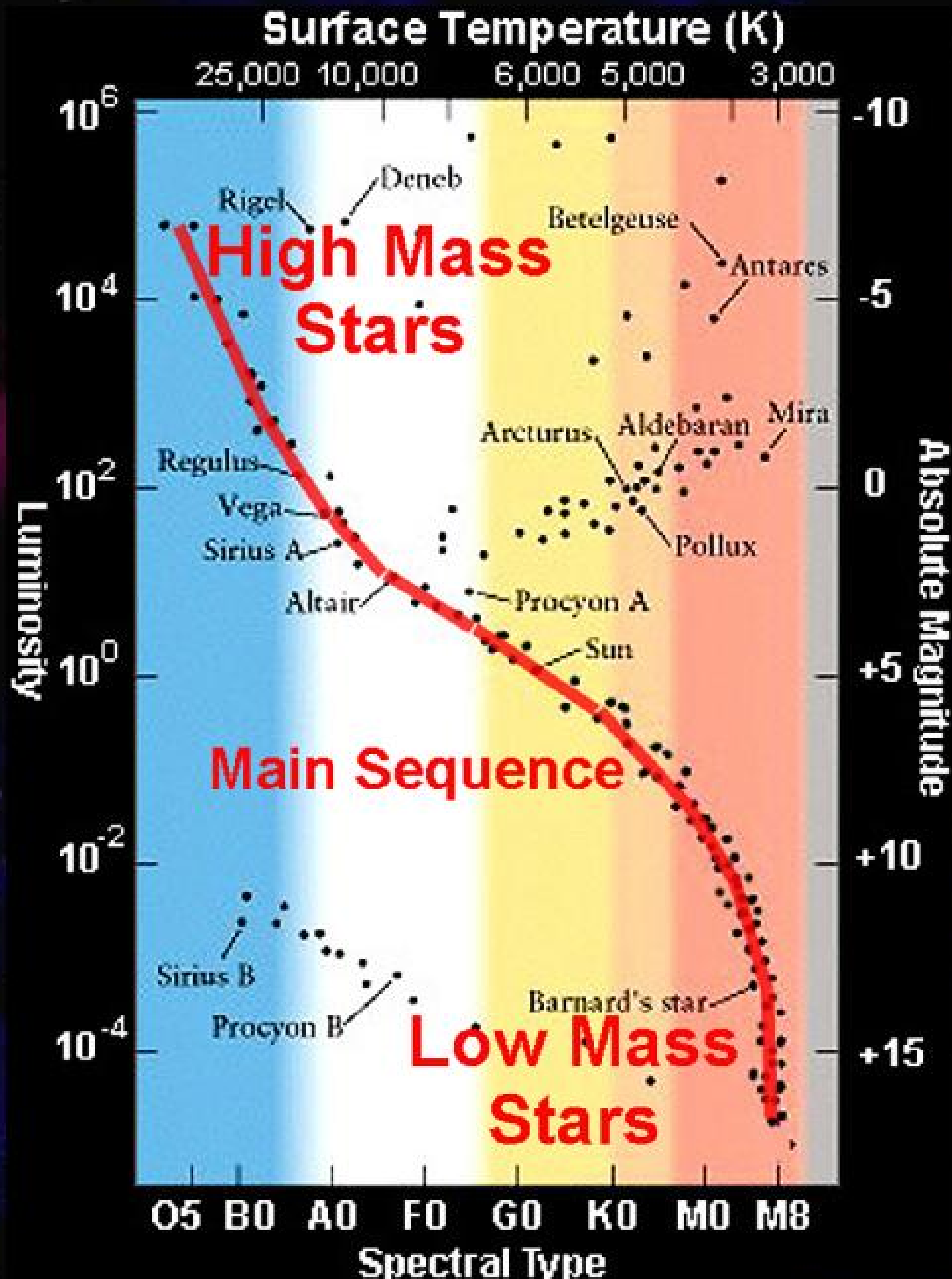
BINARY STARS

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

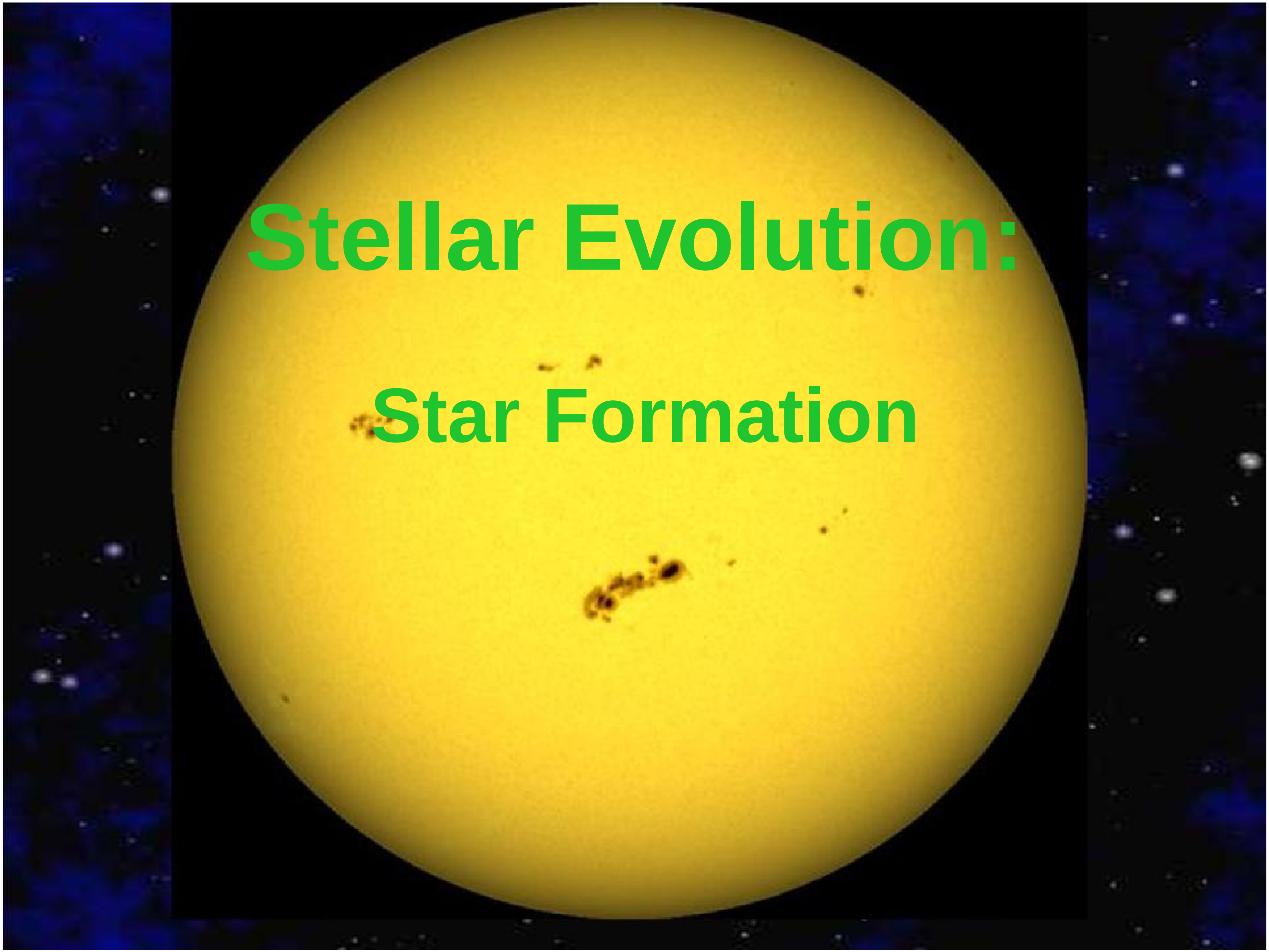
The masses of the individual stars can be calculated.

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


Stellar Evolution:
Star Formation

What are the stars made out of?

The Sun is composed of:

element	by #	by mass
Hydrogen	92%	73%
Helium	7.8%	25%
all others	0.2%	2%

Carbon, nitrogen, oxygen, neon, magnesium, silicon, sulfur, iron...

The Interstellar Medium (ISM)

Composed of gas and dust

ALMOST **a perfect vacuum!**

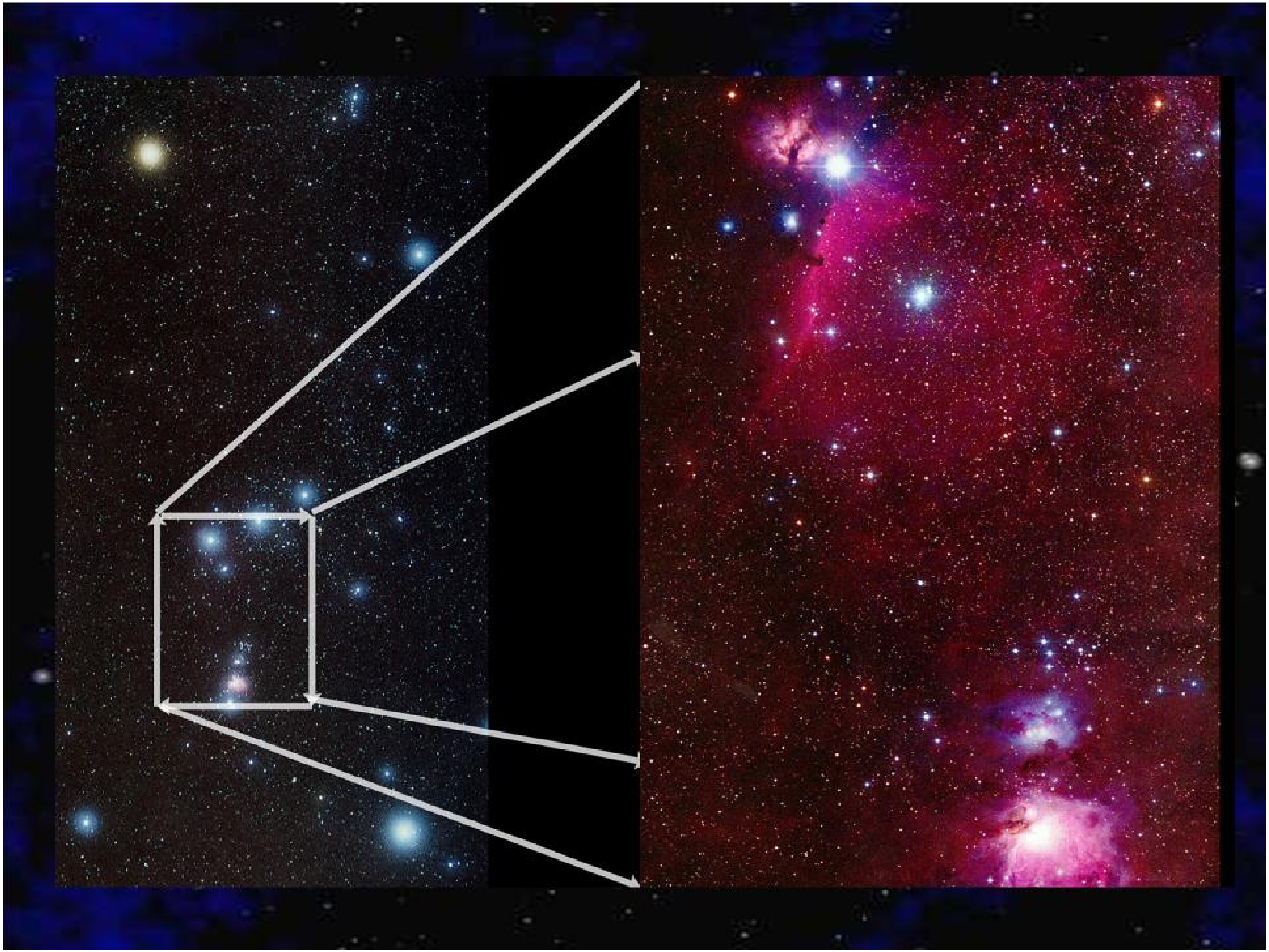
Gas:

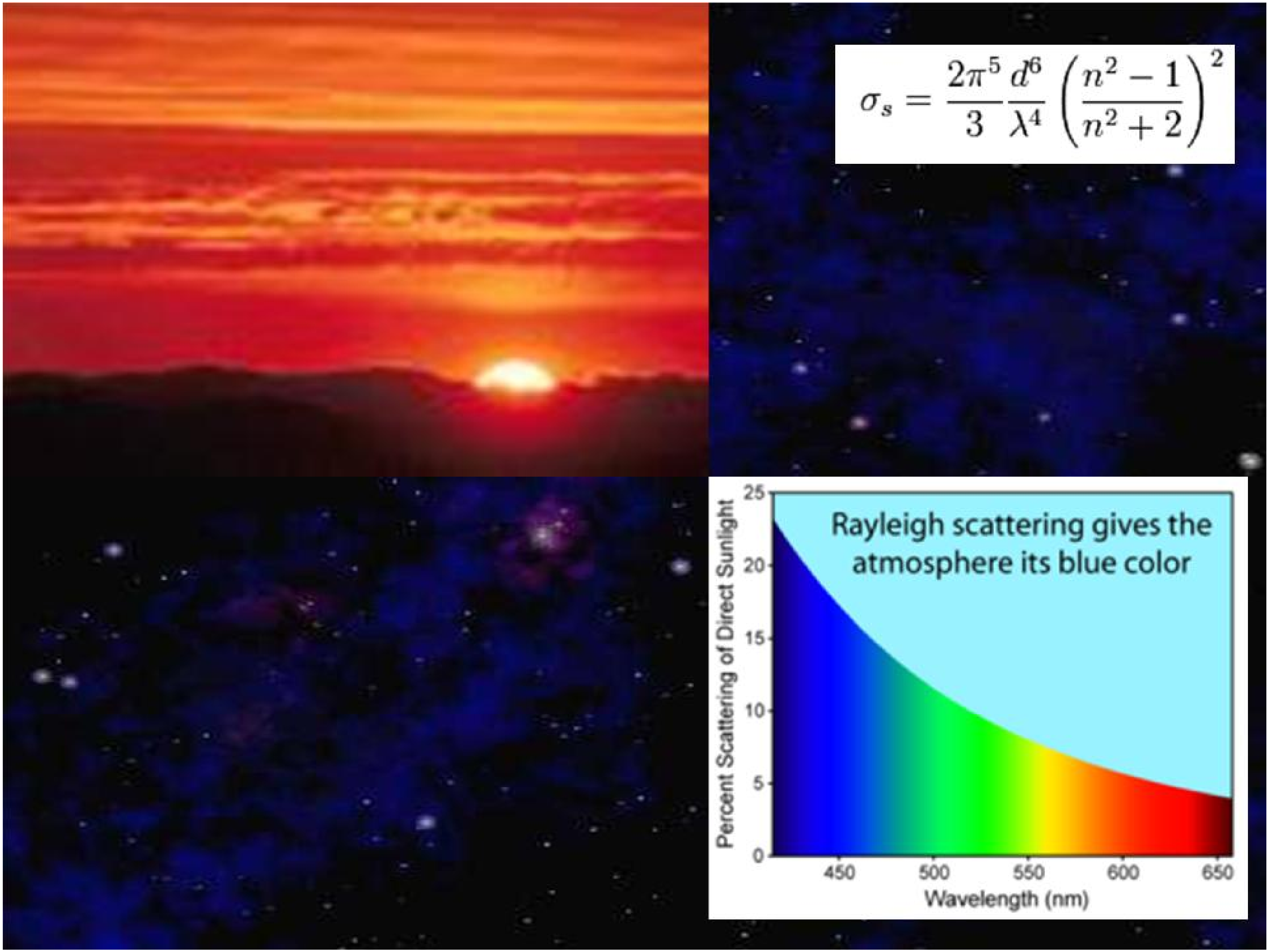
- 99% of the ISM
- 1 atom/cm^3 (if spread out uniformly)

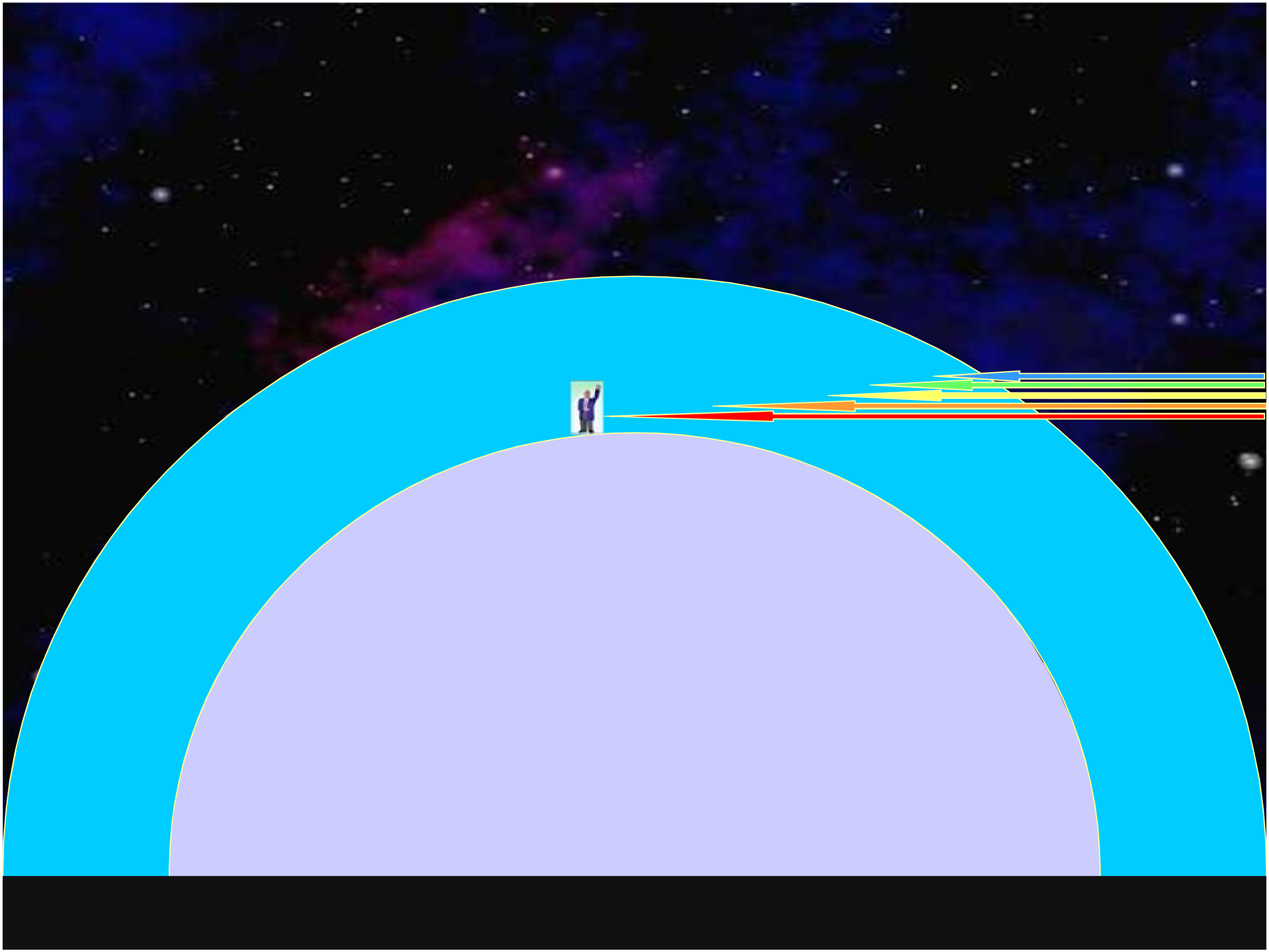
The Interstellar Medium

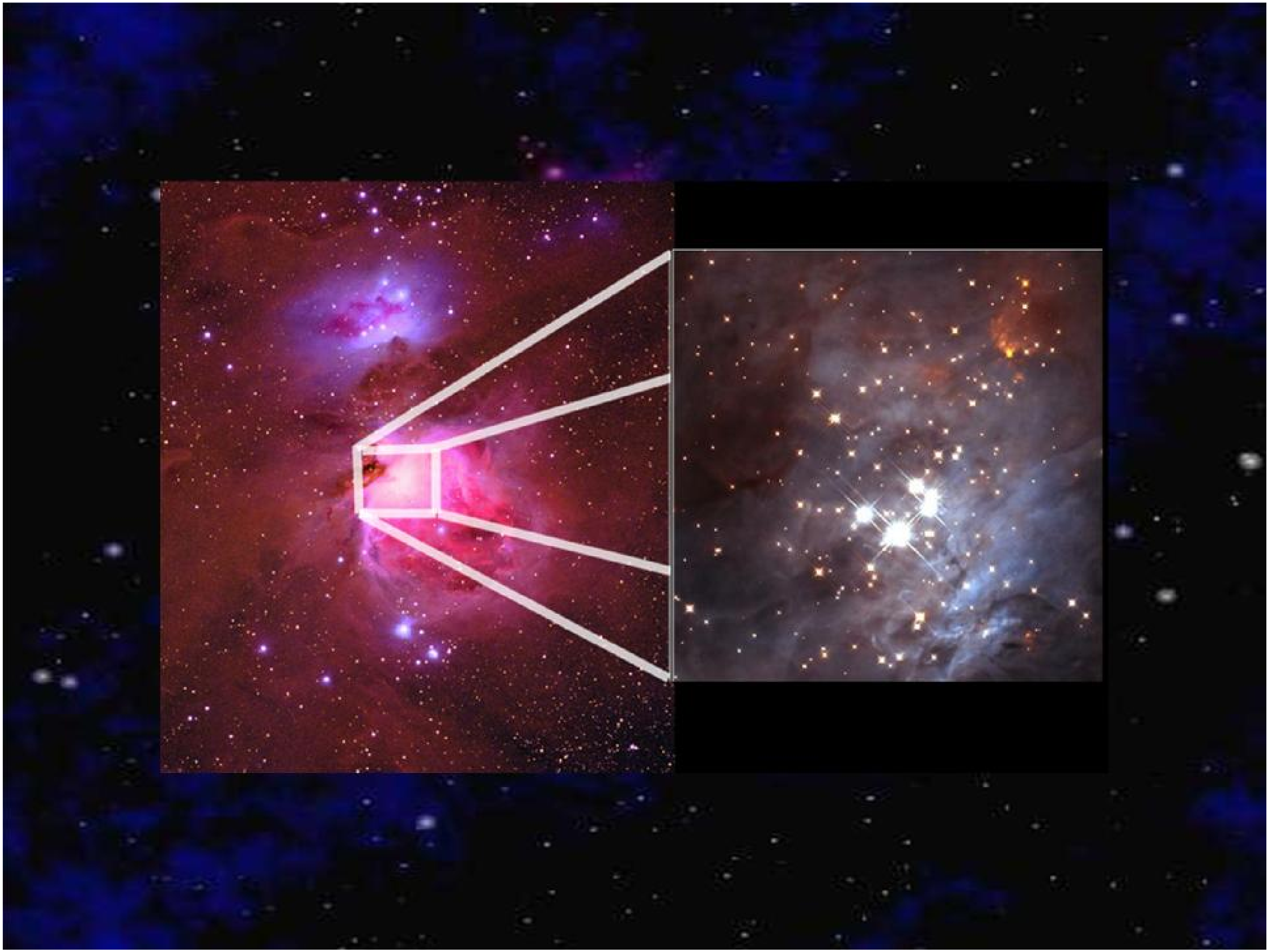
Dust:

- 1% of the ISM
- 1 dust grain per 10 cm^3

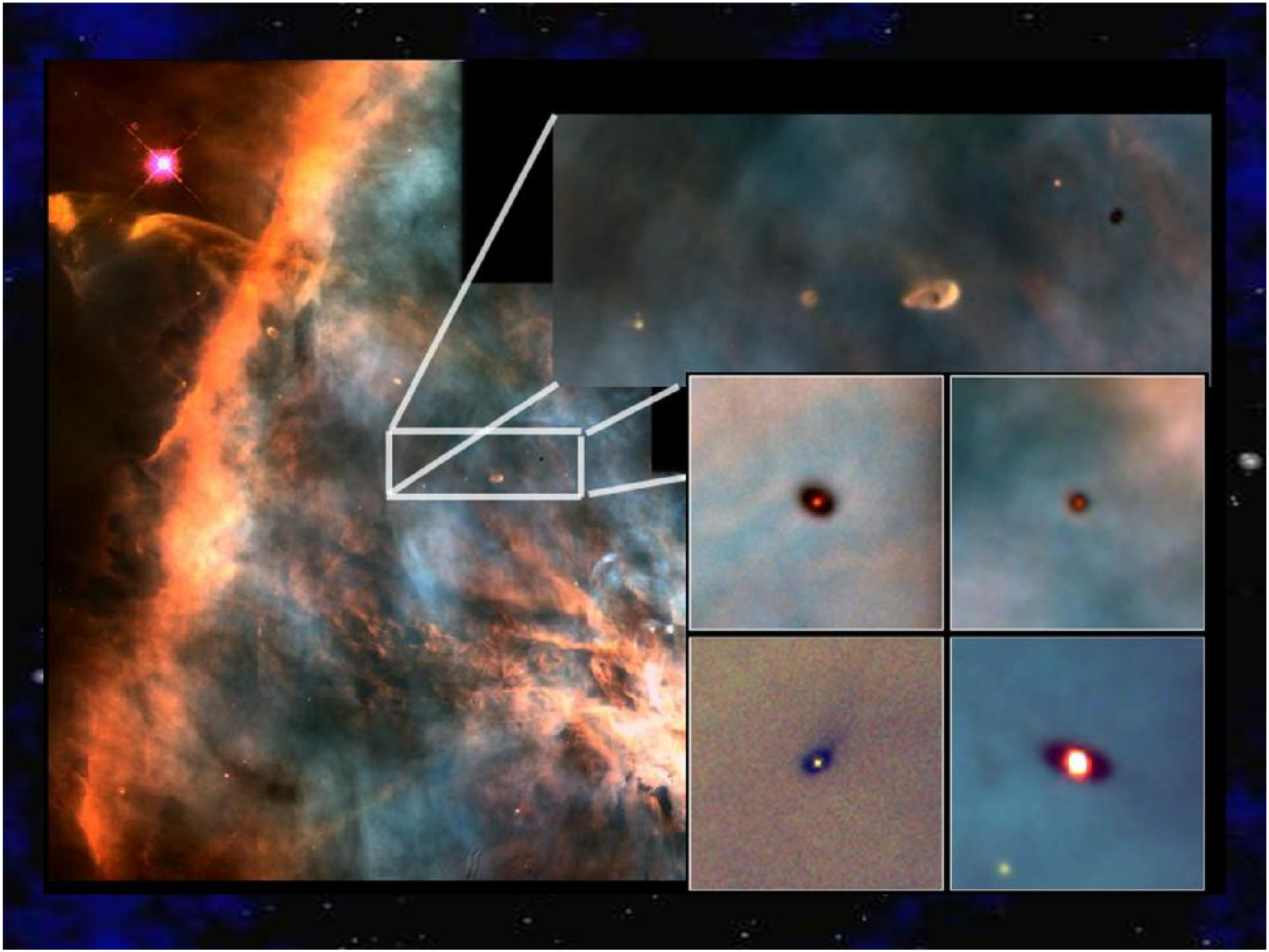



$\sigma_s = \frac{2\pi^5}{3}\frac{d^6}{\lambda^4}\left(\frac{n^2-1}{n^2+2}\right)^2$
Rayleigh scattering gives the atmosphere its blue color
Percent Scattering of Direct Sunlight
0
5
10
15
20
25
450
500
550
600
650
Wavelength (nm)





[redacted]

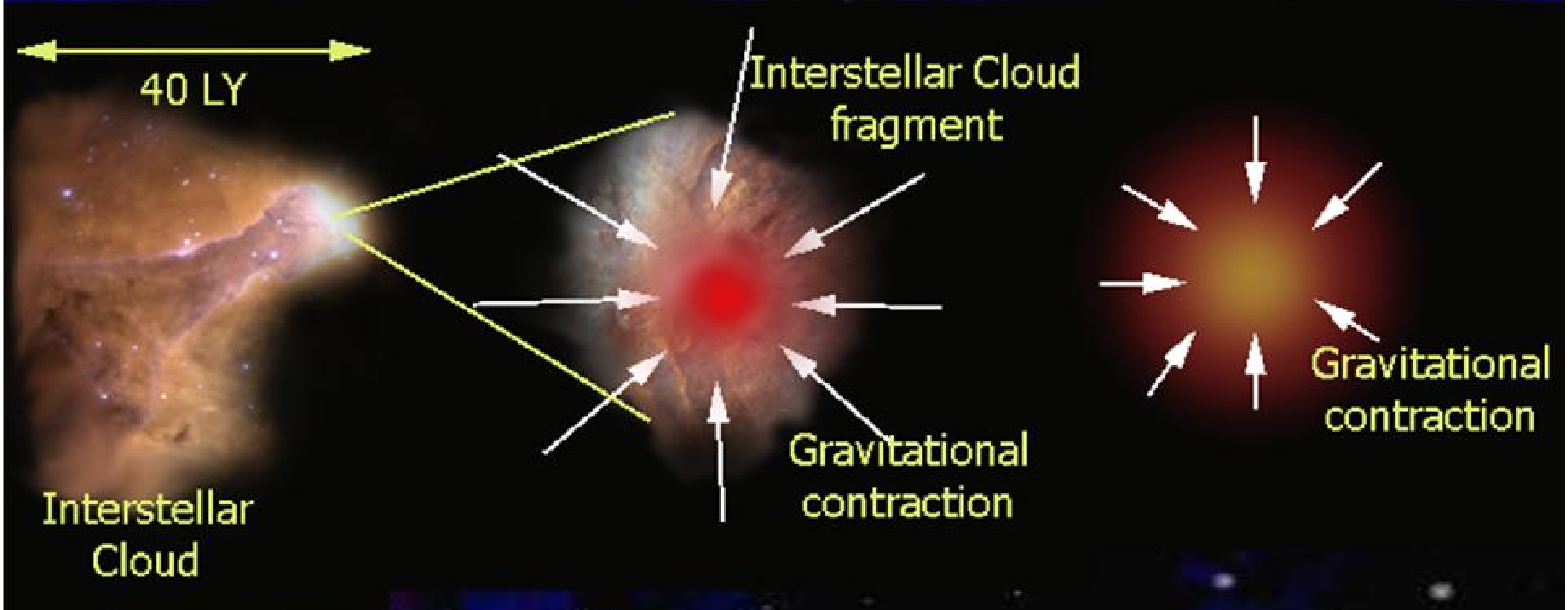


STELLAR FORMATION

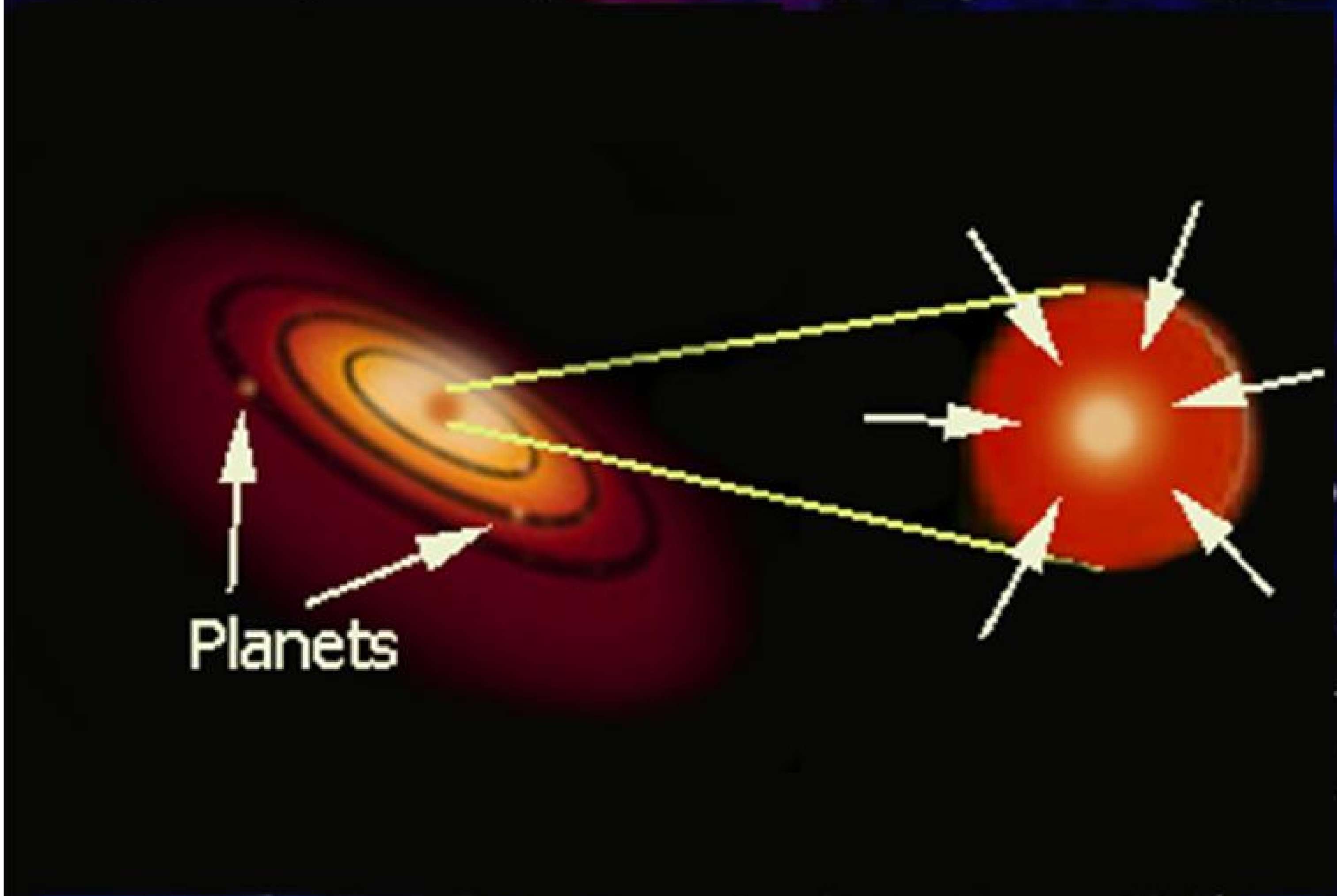
Gas Pressure		Gravity
Outward	<	Inward
(temperature)		(mass of cloud)

GRAVITATIONAL CONTRACTION

Stellar Birth

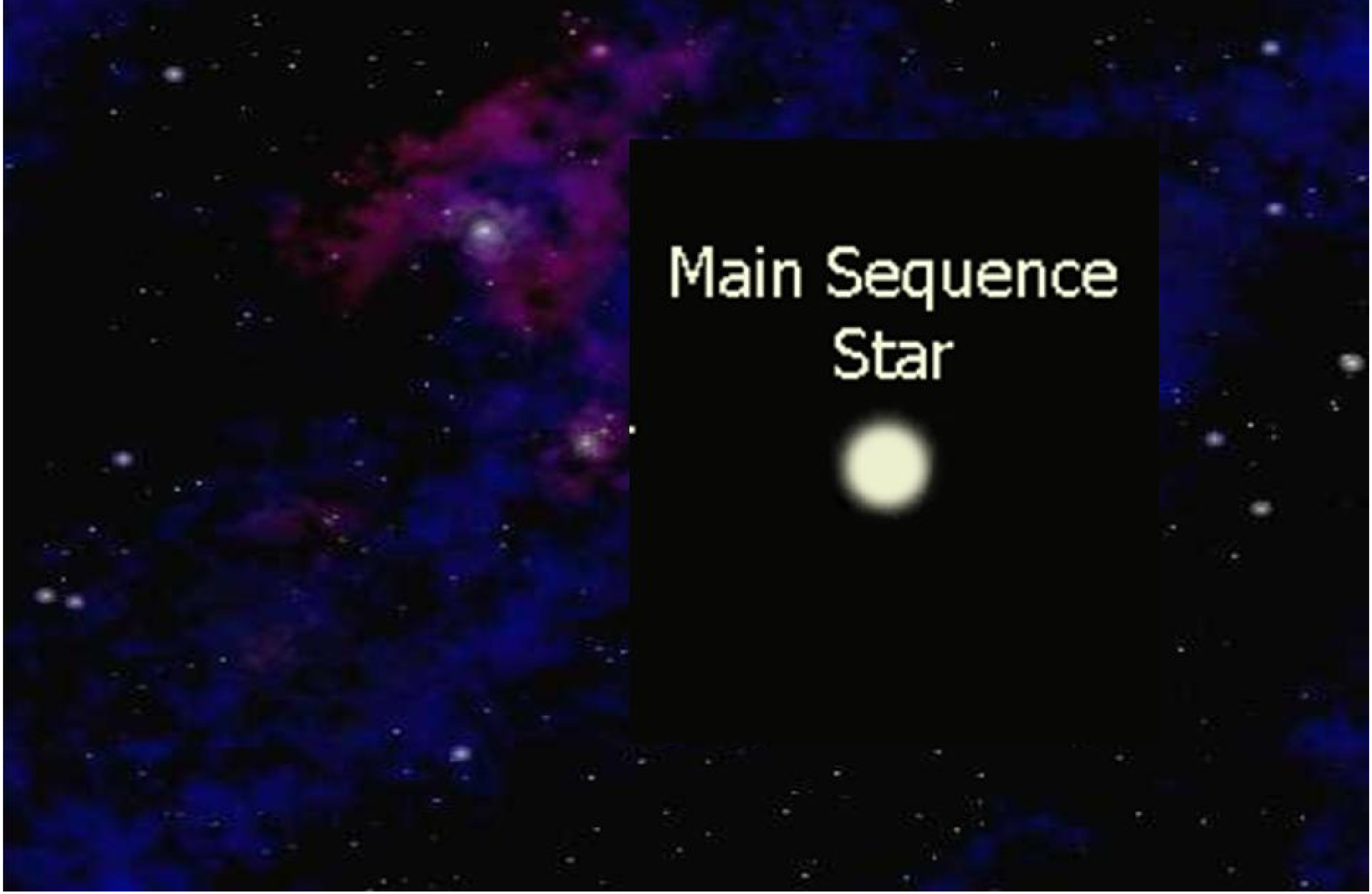


Stellar Birth



Stellar Birth

Stellar Birth



The Pleiades Cluster

What is the source of the Sun's energy?

Recall the Sun's Luminosity:

390,000,000,000,000,000,000,000,000 watts

$$Duration = \frac{Amount \quad of \quad fuel}{Rate \quad of \quad consumption}$$

Historical attempts to explain energy production

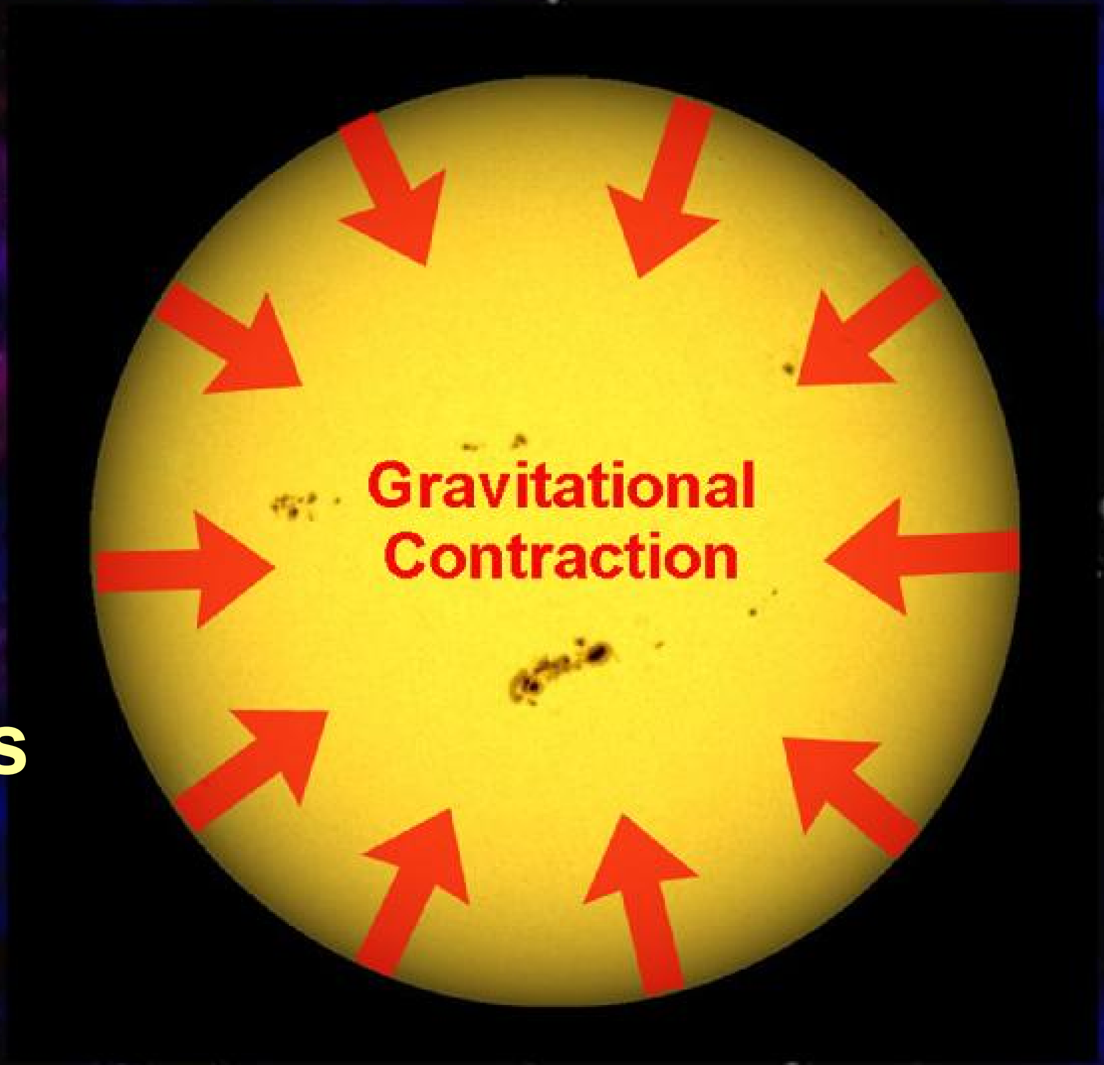
Chemical Burning (coal, wood, gas)

3,000 years

Gravitational Contraction

40 meters/year

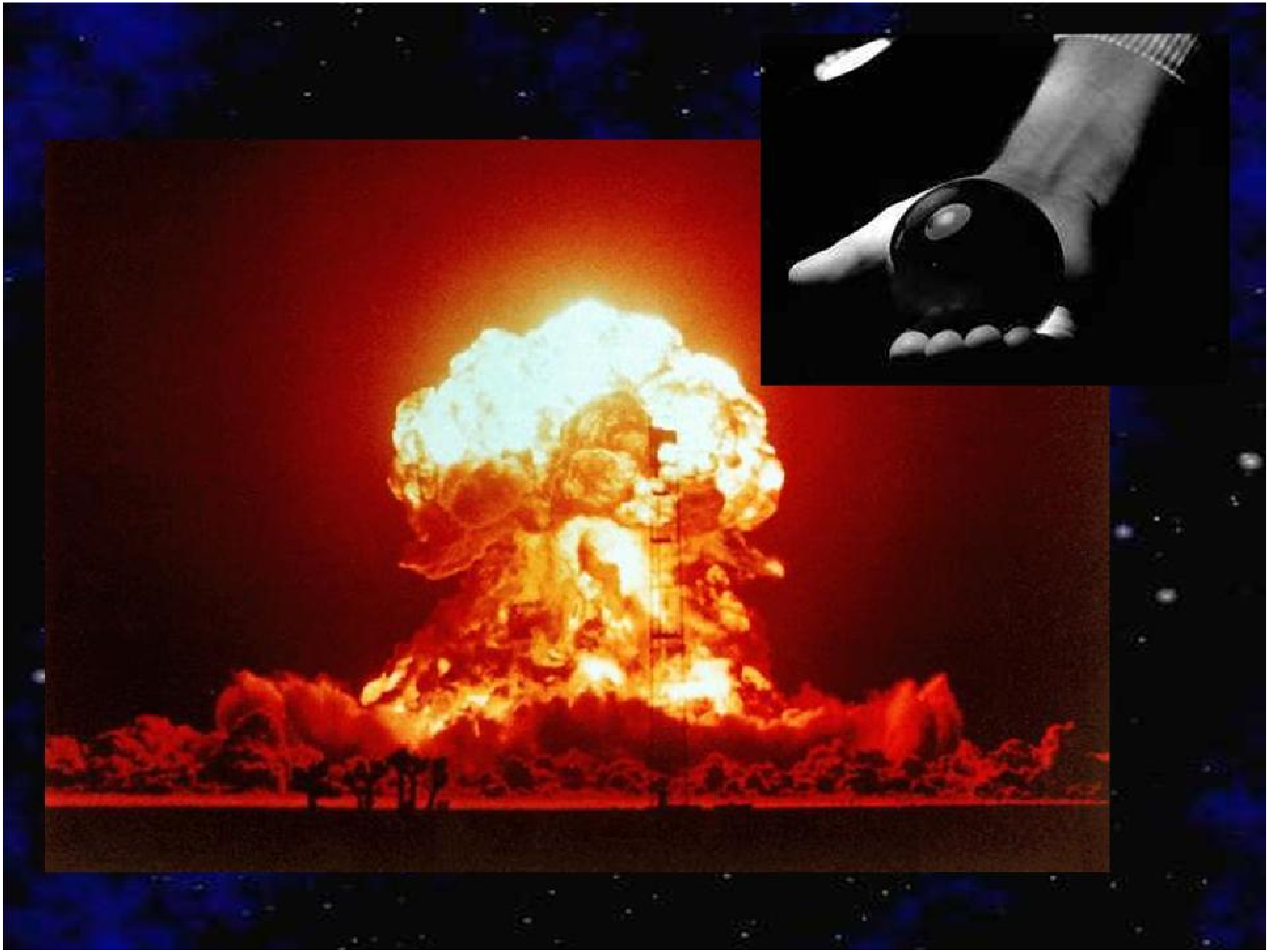
50 million years

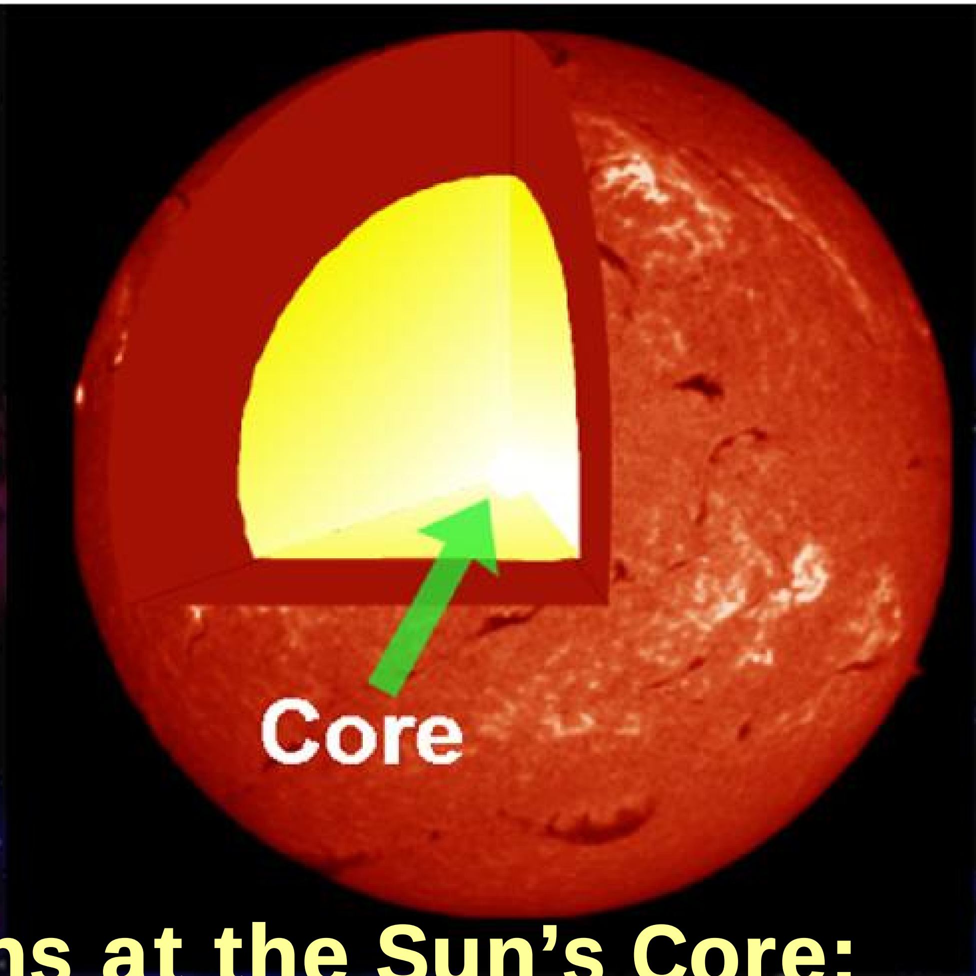


Albert Einstein (1879-1955)

$$E = mc^2$$

- Mass and Energy are equivalent
- A small amount of mass yields a large amount of energy



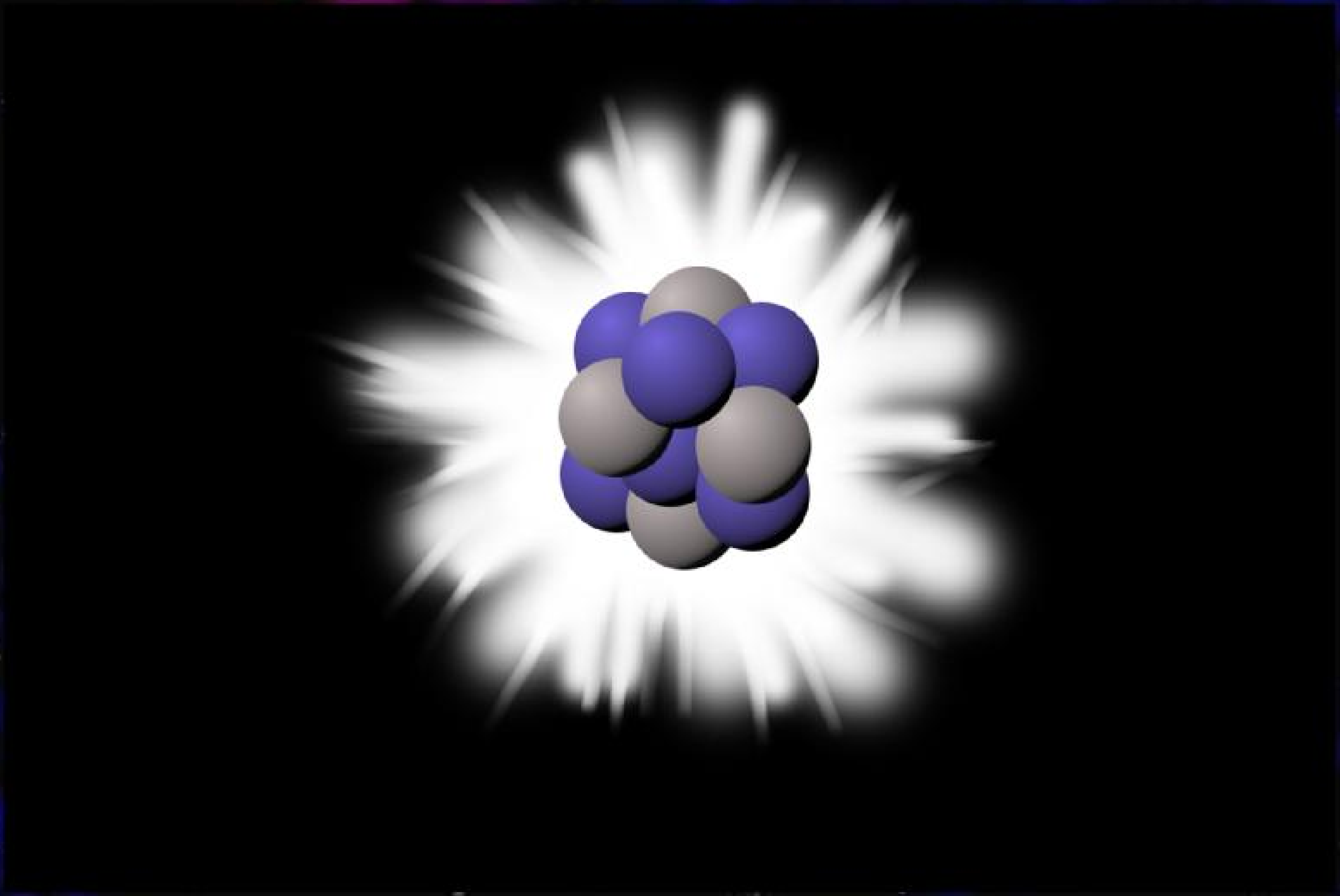


Conditions at the Sun's Core:

Core Temp: 15,000,000 K (27,000,000 °F)

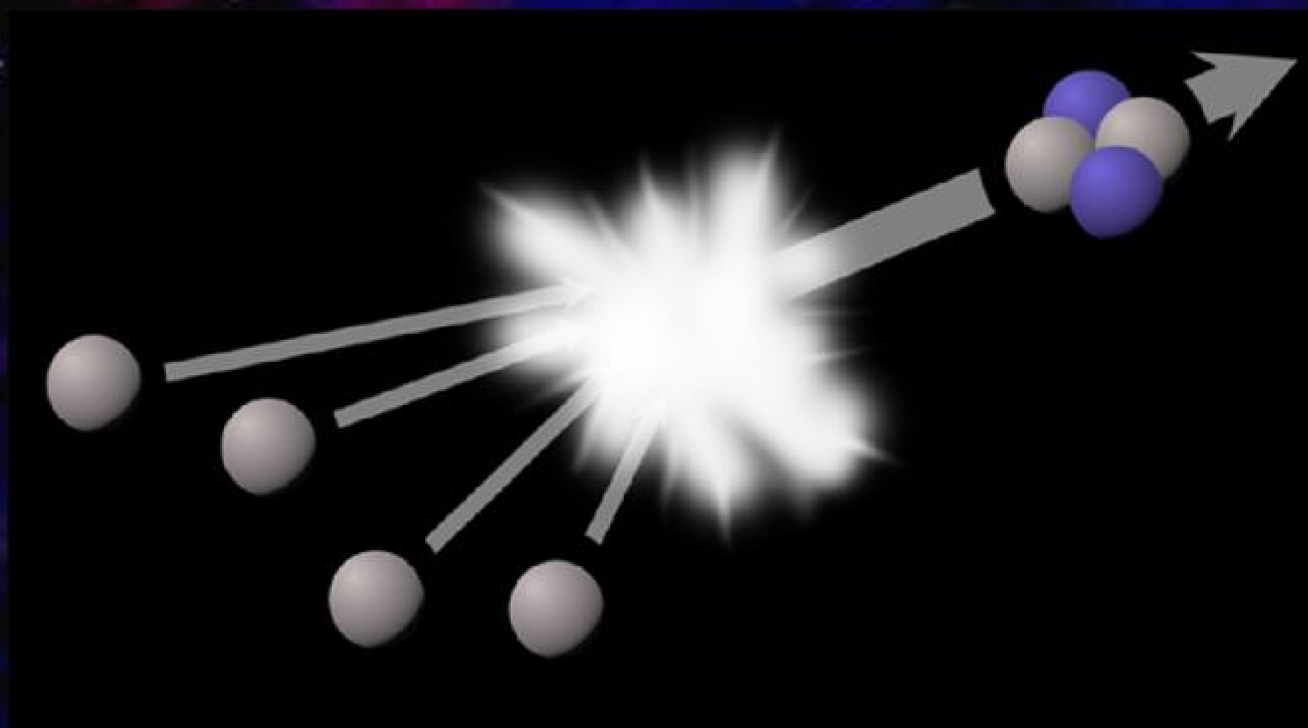
Core Pressure: 3 trillion pounds/in^2

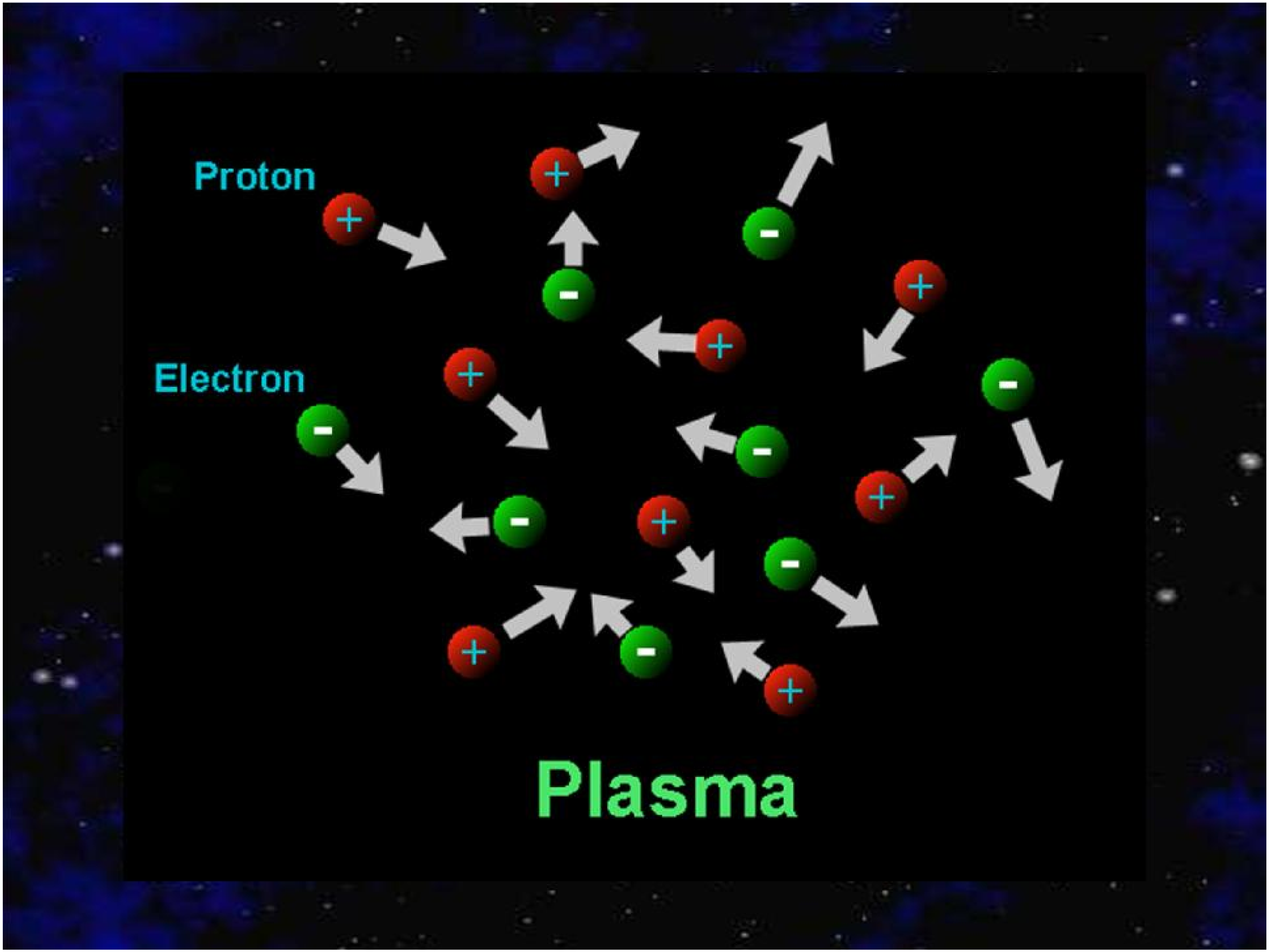
Thermonuclear Fusion



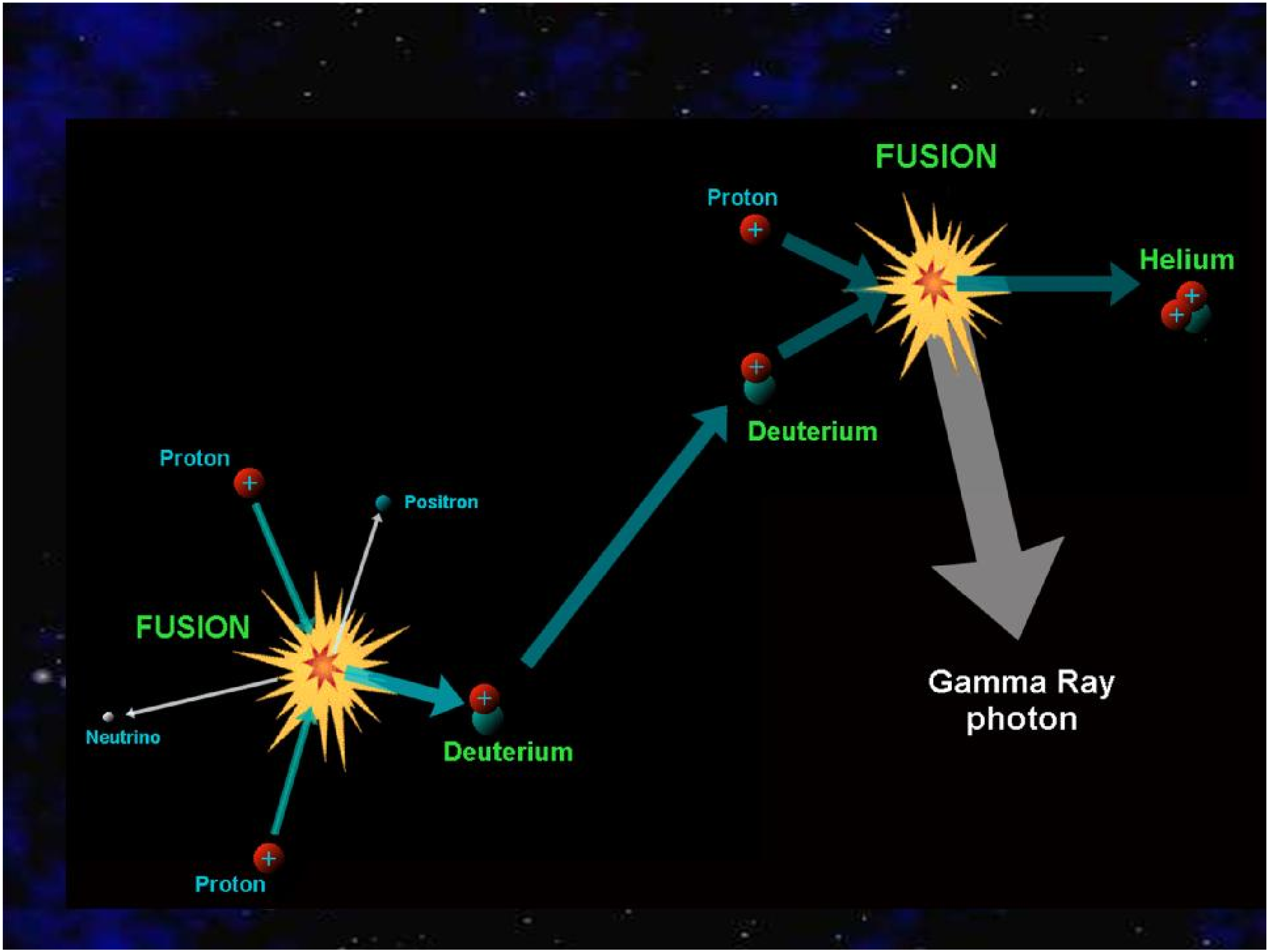
Proton – Proton Cycle

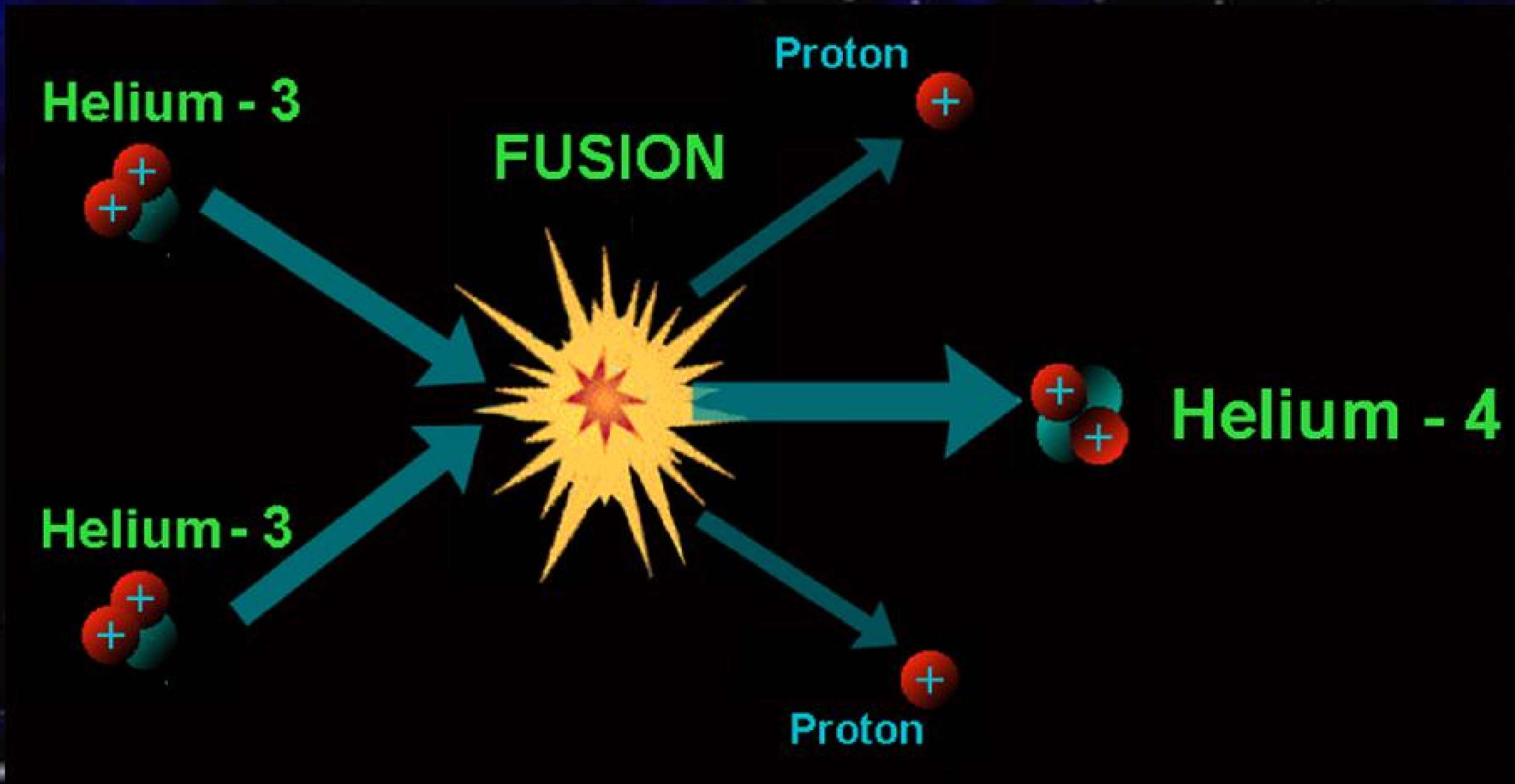
4H ® 1He + 2g



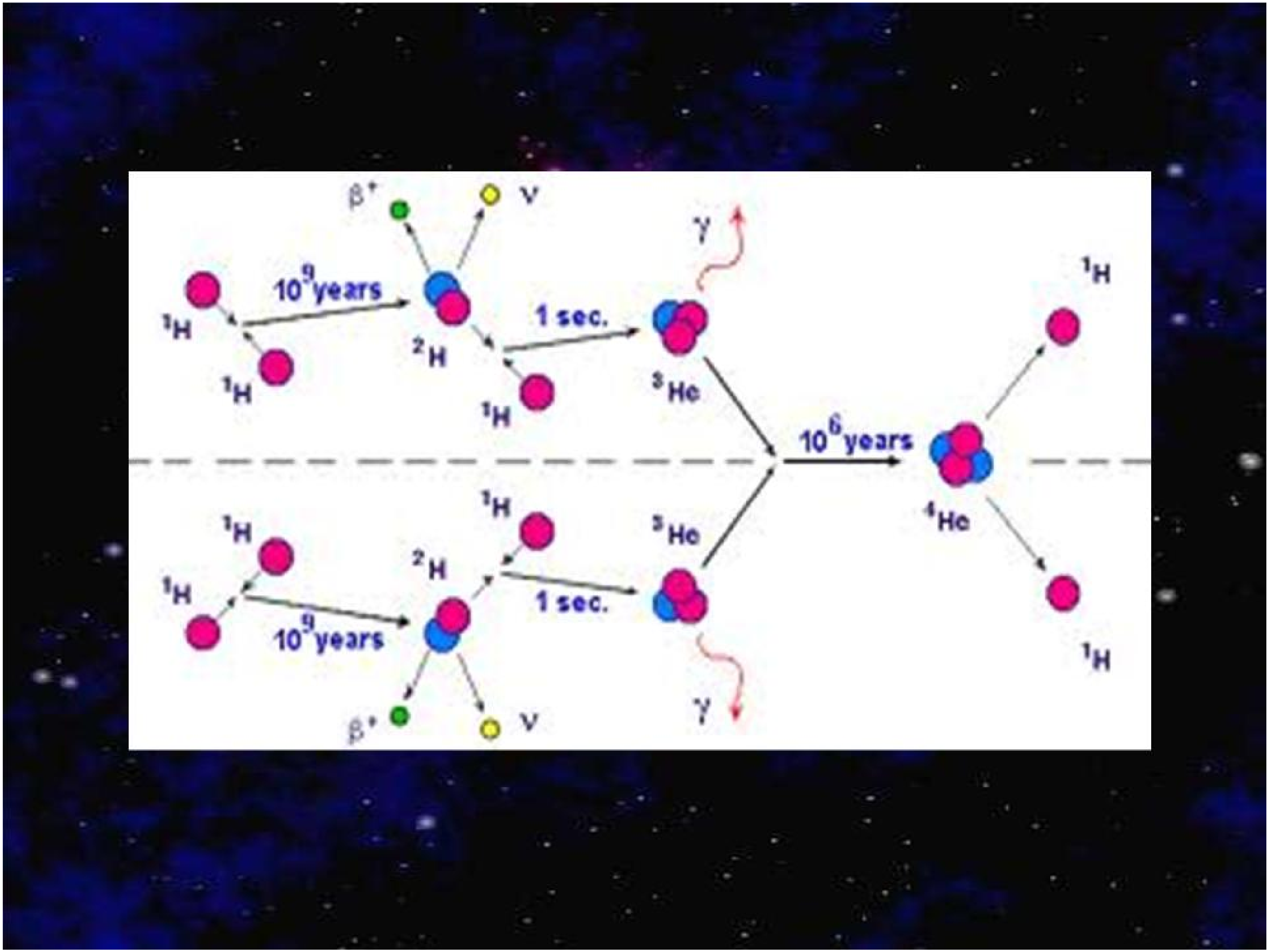

Proton
Electron
Plasma

www.spacetelescope.org

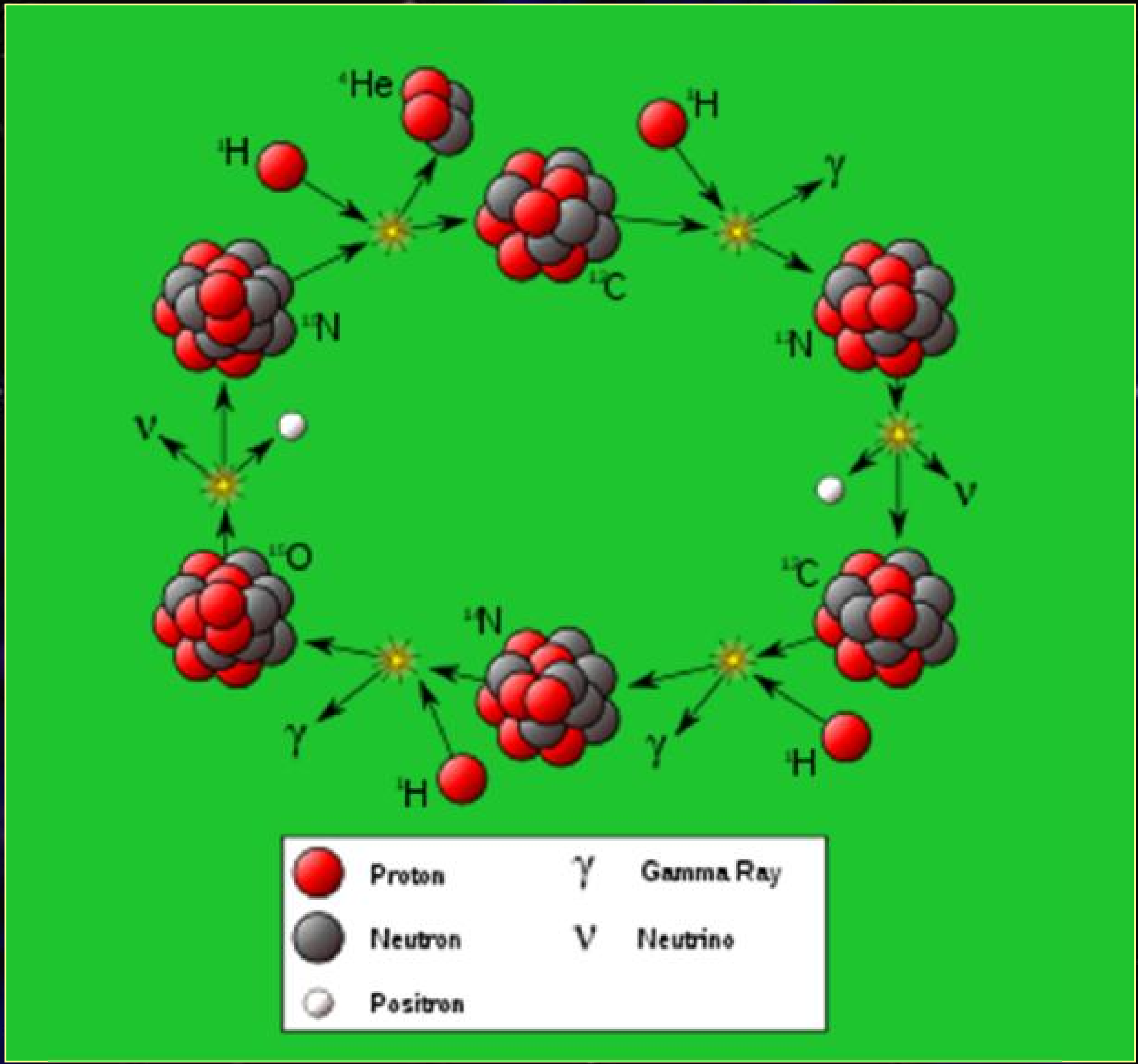

FUSION
Proton
Helium
Deuterium
Proton
Positron
FUSION
Gamma Ray
photon
Neutrino
Deuterium
Proton

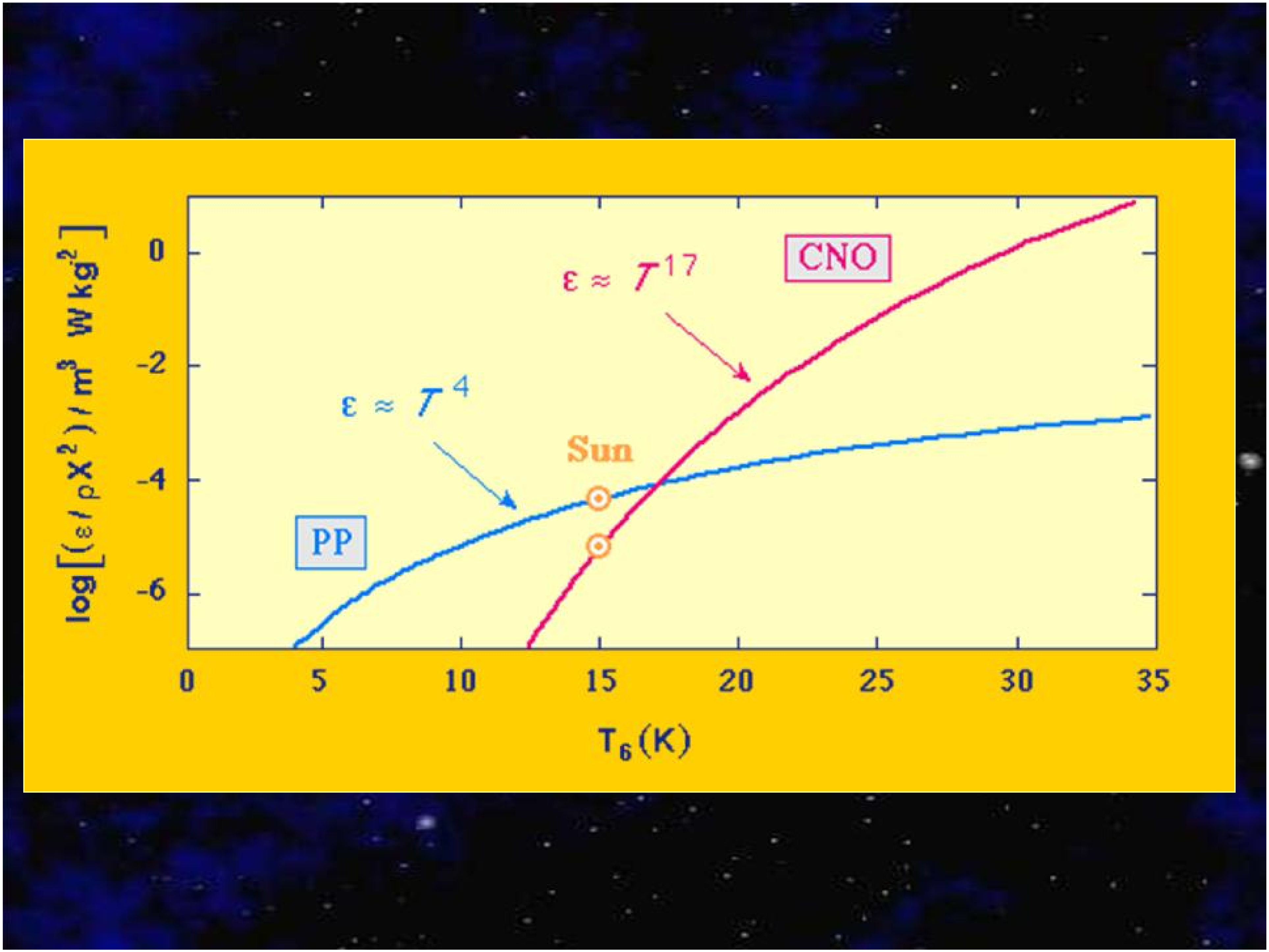


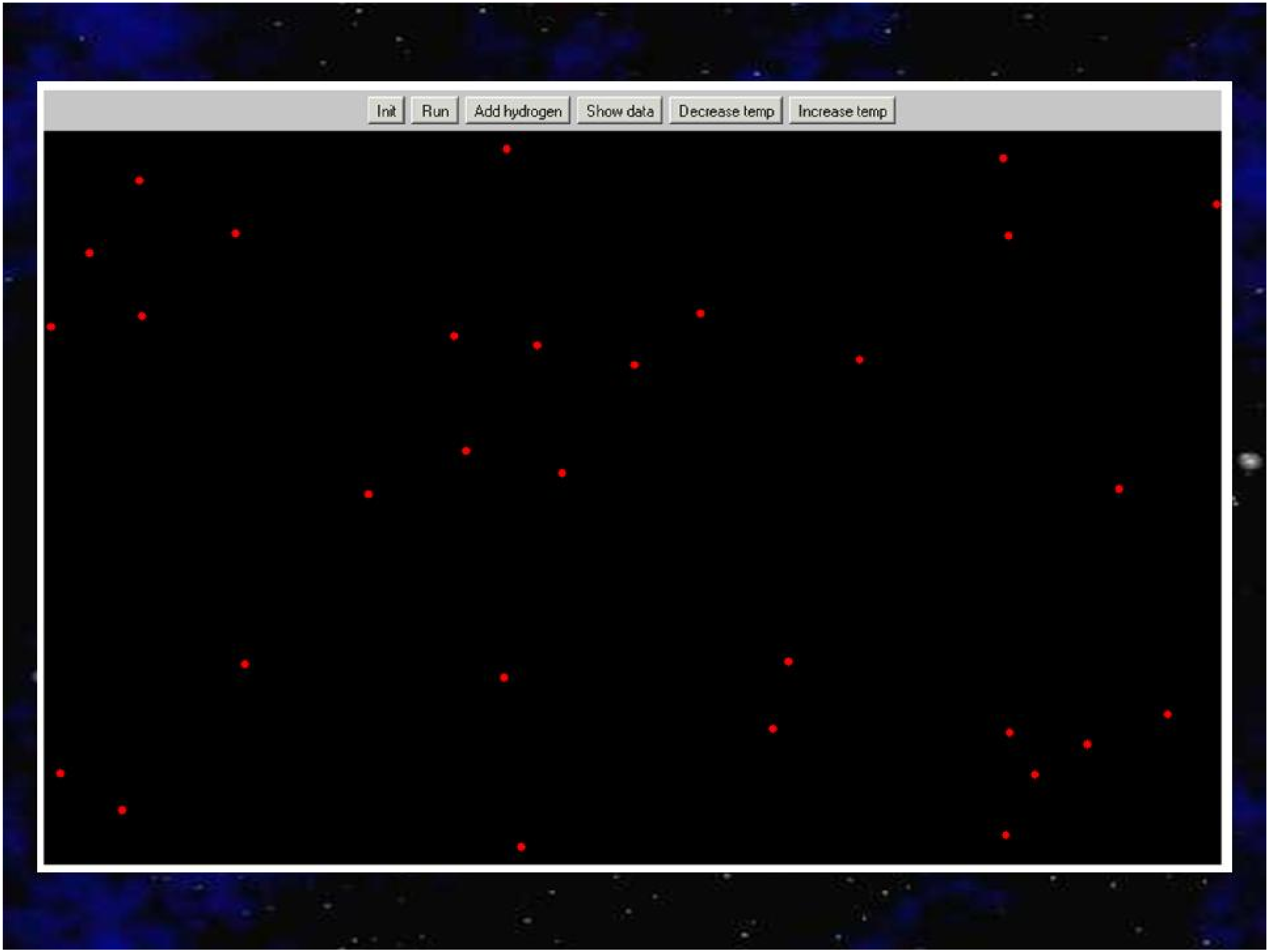
NUCLEOSYNTHESIS


β+
ν
γ
1H
10⁹years
2H
1 sec.
3He
10⁶years
4He
1H
2H
1H
10⁹years
1 sec.
3He
γ
β+
ν

Carbon-Nitrogen-Oxygen Cycle (CNO Cycle)



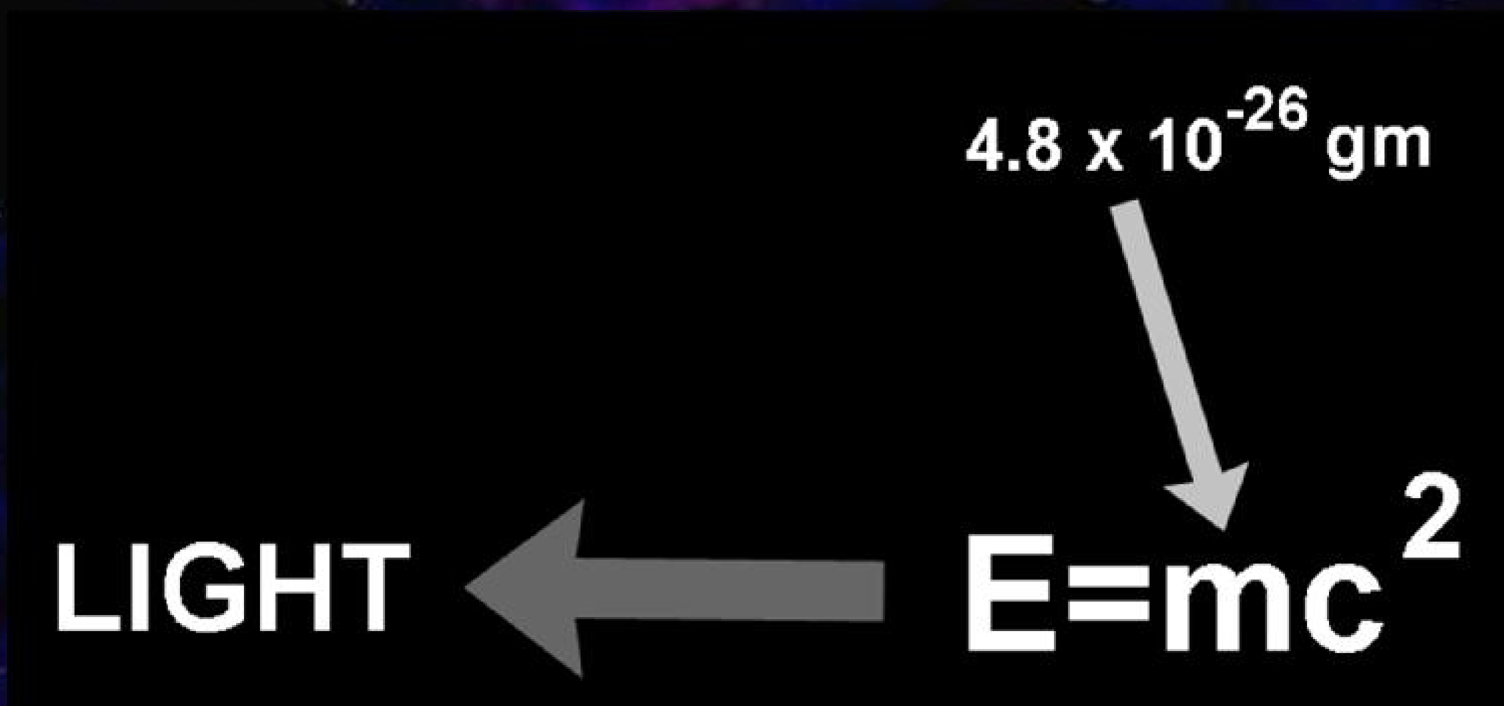

log[(ε/ρX²)/m³ W kg⁻²]
0
-2
-4
-6
CNO
ε ≈ T^17
ε ≈ T^4
Sun
PP
0
5
10
15
20
25
30
35
T6(K)


Init
Run
Add hydrogen
Show data
Decrease temp
Increase temp

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

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

Difference of 4.8×10^{-26} gm (0.7%)



Some incredible numbers...

The proton-proton cycle occurs

10^{38} times/second

Each second:

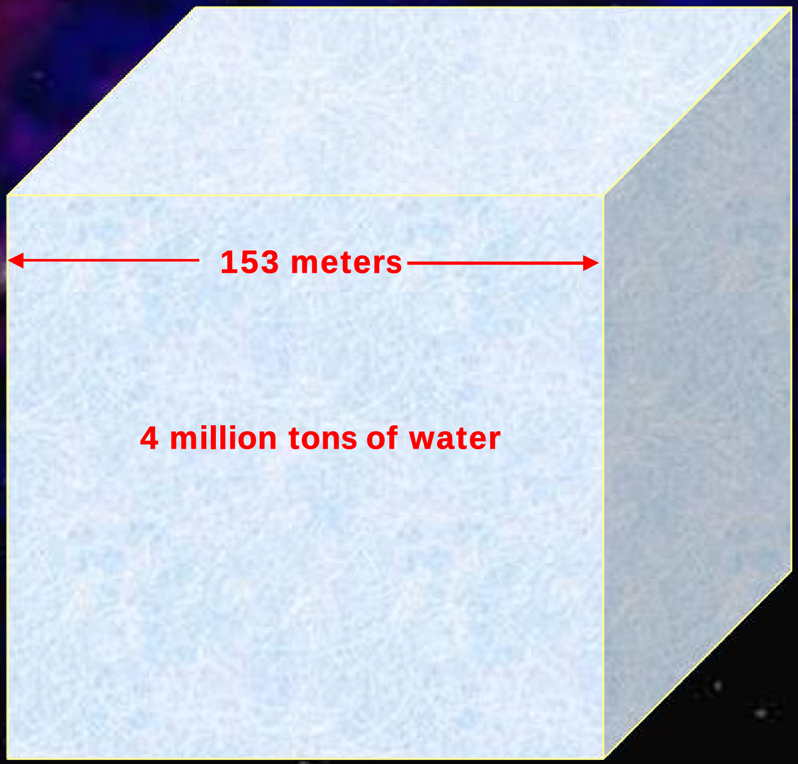
624 million tons of hydrogen

Fuses to become

620 million tons of helium

4 million tons of matter becomes energy

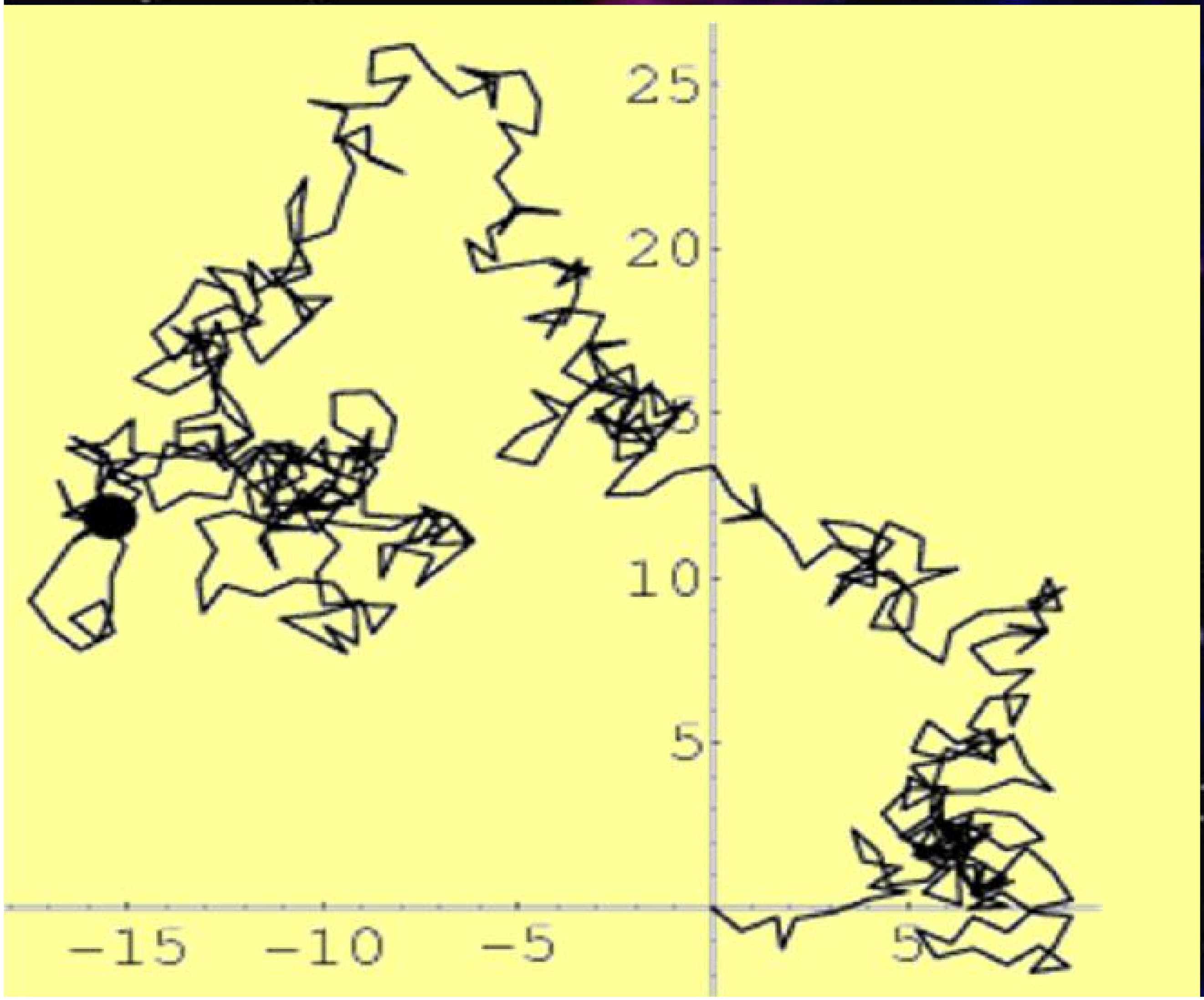
4 million tons of matter becomes energy



$M_{\text{¤}}=1.99\text{x}10^{30}$ kilograms

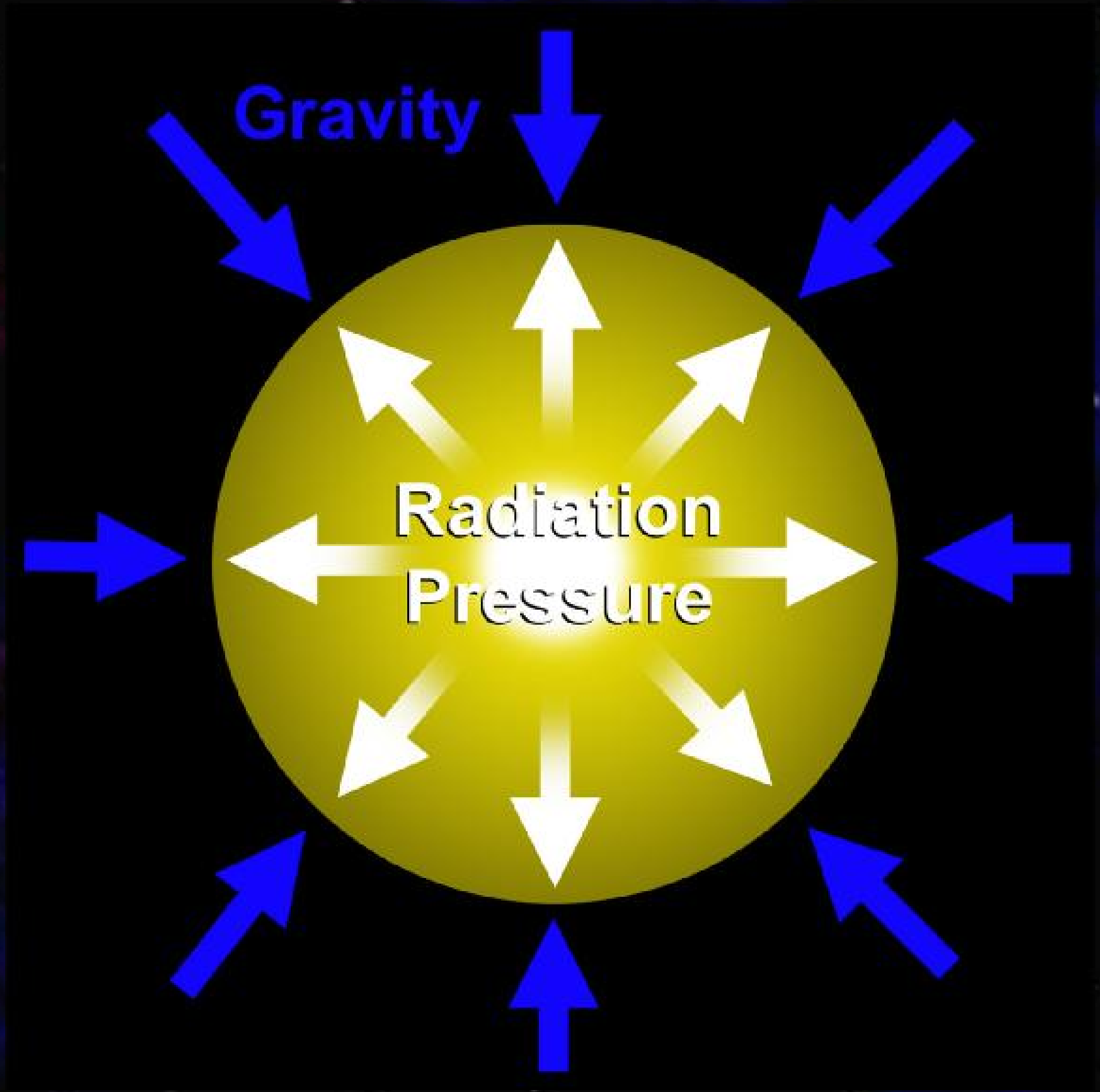
Sun’s lifetime ~ 10 billion years

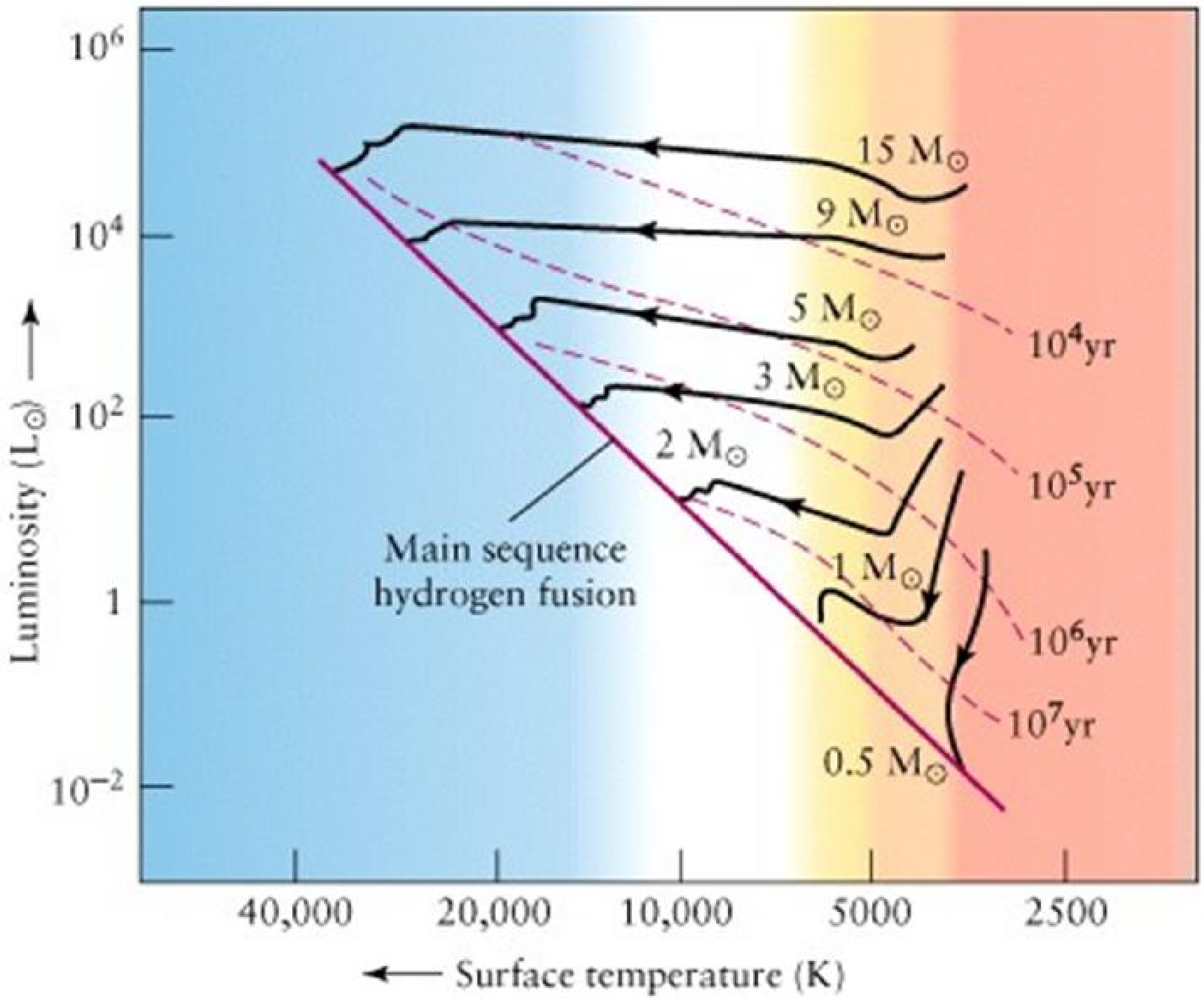
Radiation Escape from the Core – The drunken Random Walk



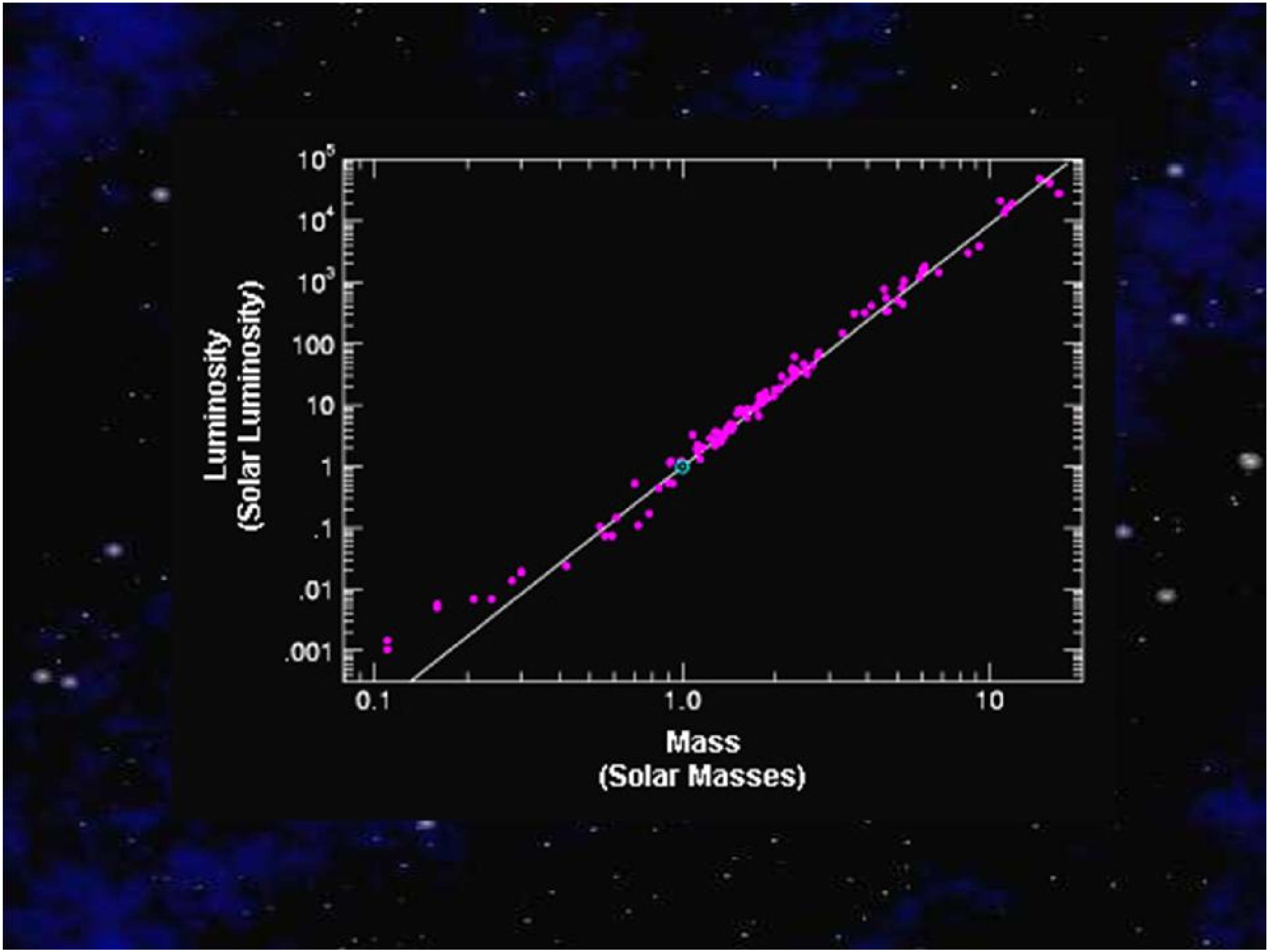
$D = (d/l)^2$

Hydrostatic Equilibrium





10⁶
10⁴
10²
1
10⁻²
Luminosity (L⊙) ⟶
15 M⊙
9 M⊙
5 M⊙
3 M⊙
2 M⊙
1 M⊙
0.5 M⊙
10⁴yr
10⁵yr
10⁶yr
10⁷yr
Main sequence
hydrogen fusion
40,000
20,000
10,000
5000
2500
⟵ Surface temperature (K)



Luminosity
(Solar Luminosity)
Mass
(Solar Masses)
0.1
1.0
10
.001
.01
.1
1
10
100
10^3
10^4
10^5

Main Sequence Lifetime

15 M• _ 10^7 years

0.5 M• _ $3x10^{10}$ years

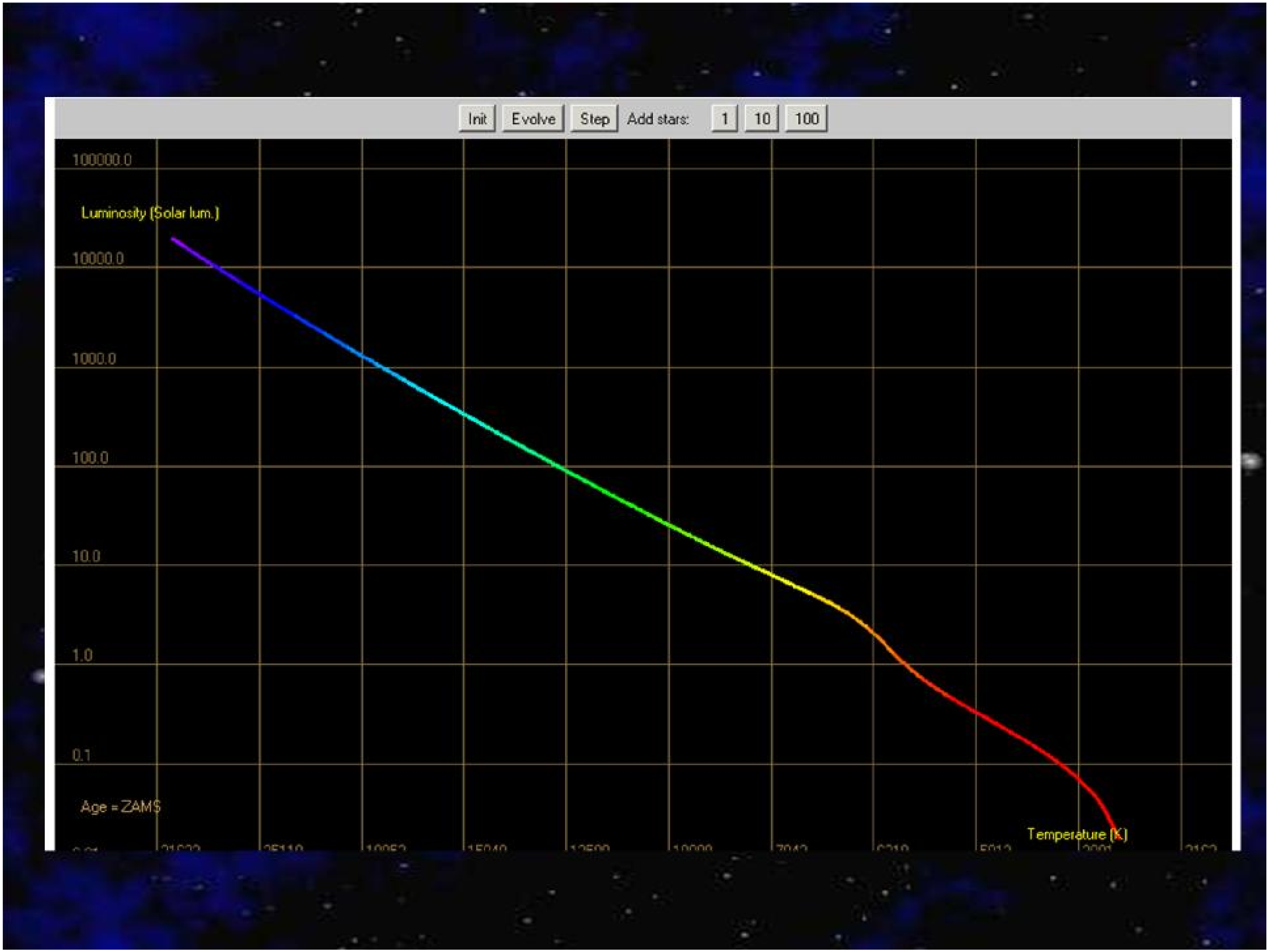
Why does a more massive star live a shorter lifetime?

Fuel consumption!

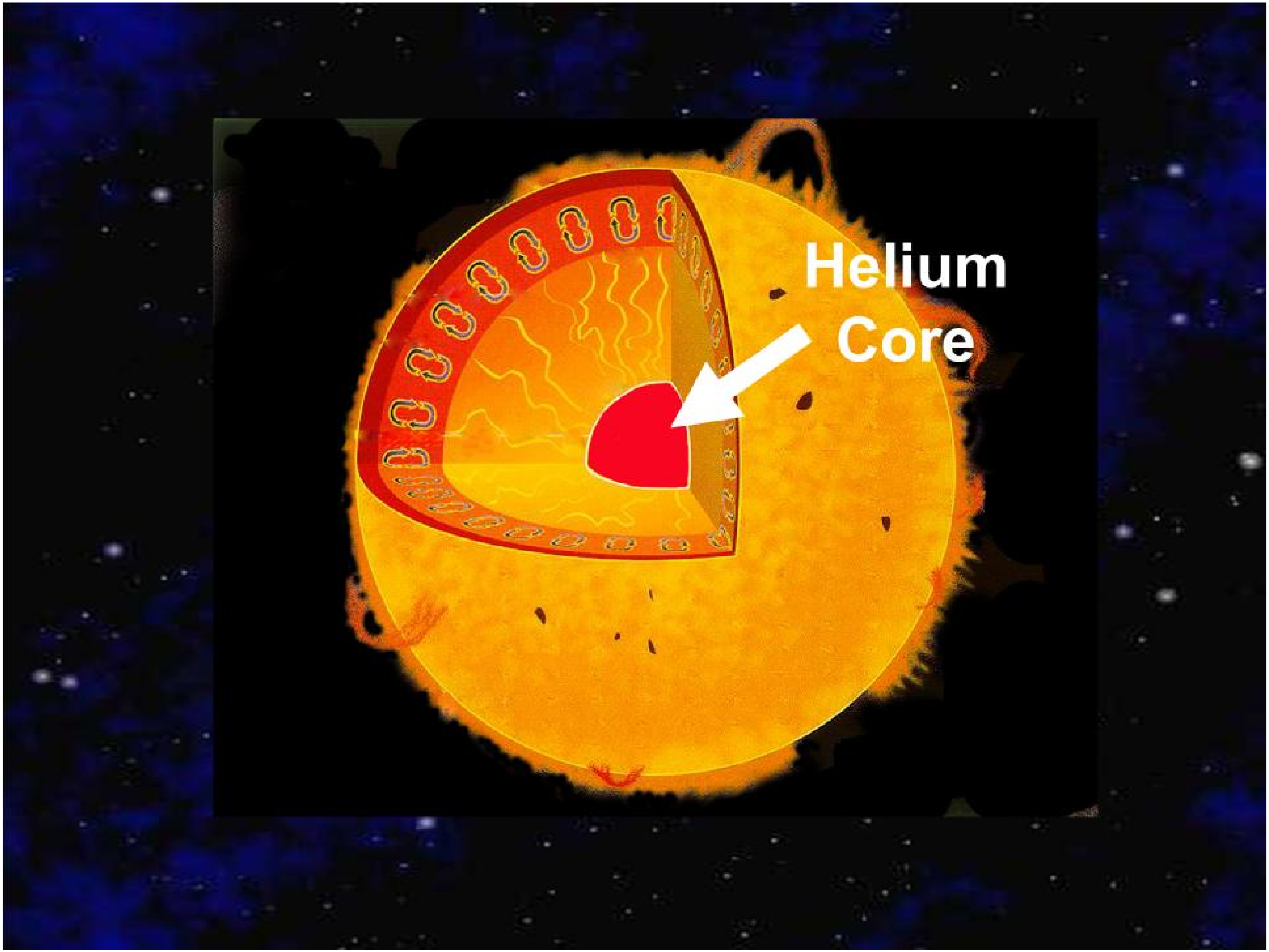
15 M• _ 10^7-10^8 K

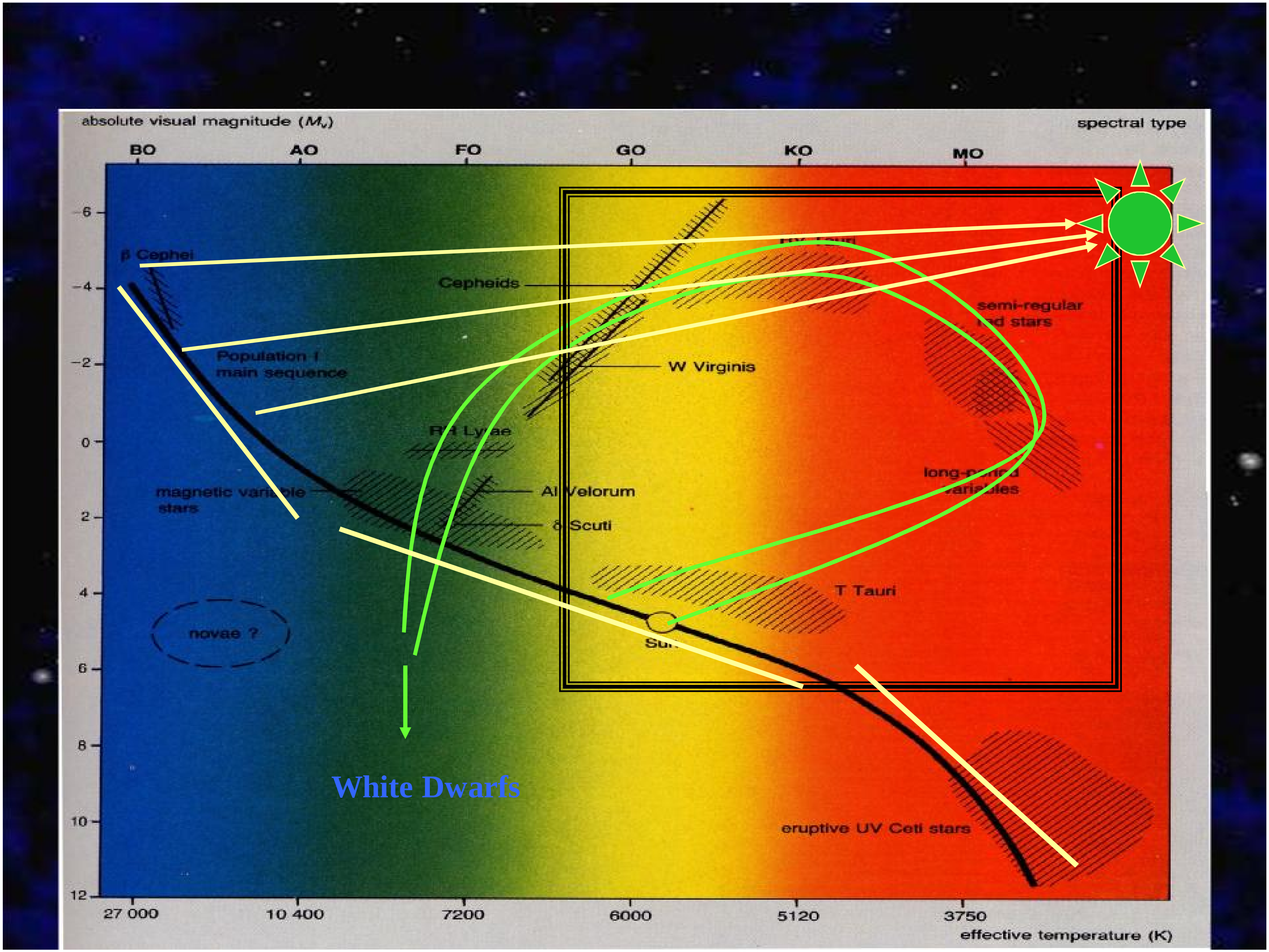
0.5 M• _ 10^6's K

Lifetime of star on MS α $1/M^3 = M^{-3}$



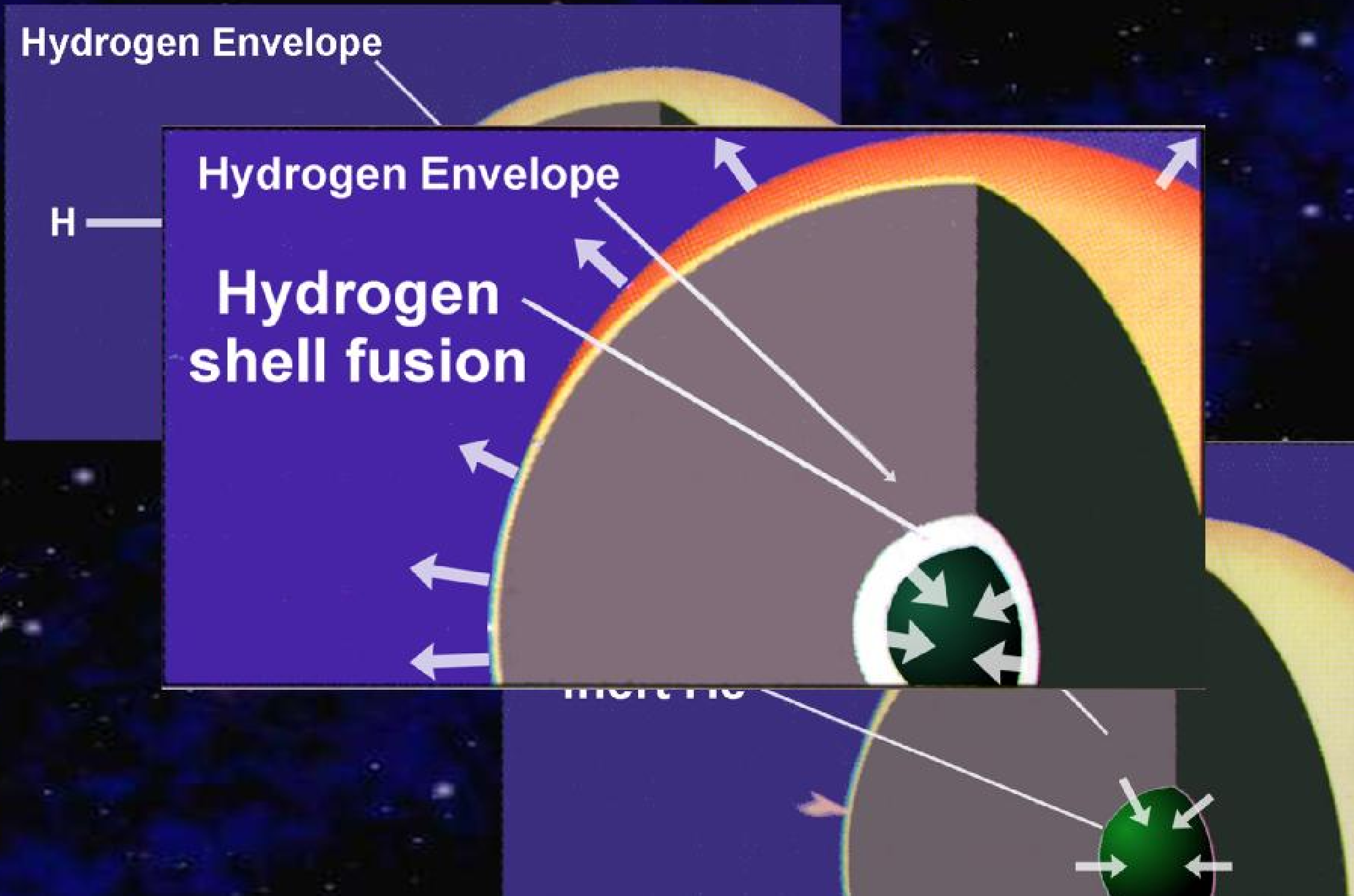
Init
Evolve
Step
Add stars:
1
10
100
100000.0
Luminosity (Solar lum.)
10000.0
1000.0
100.0
10.0
1.0
0.1
Age = ZAMS
Temperature (K)

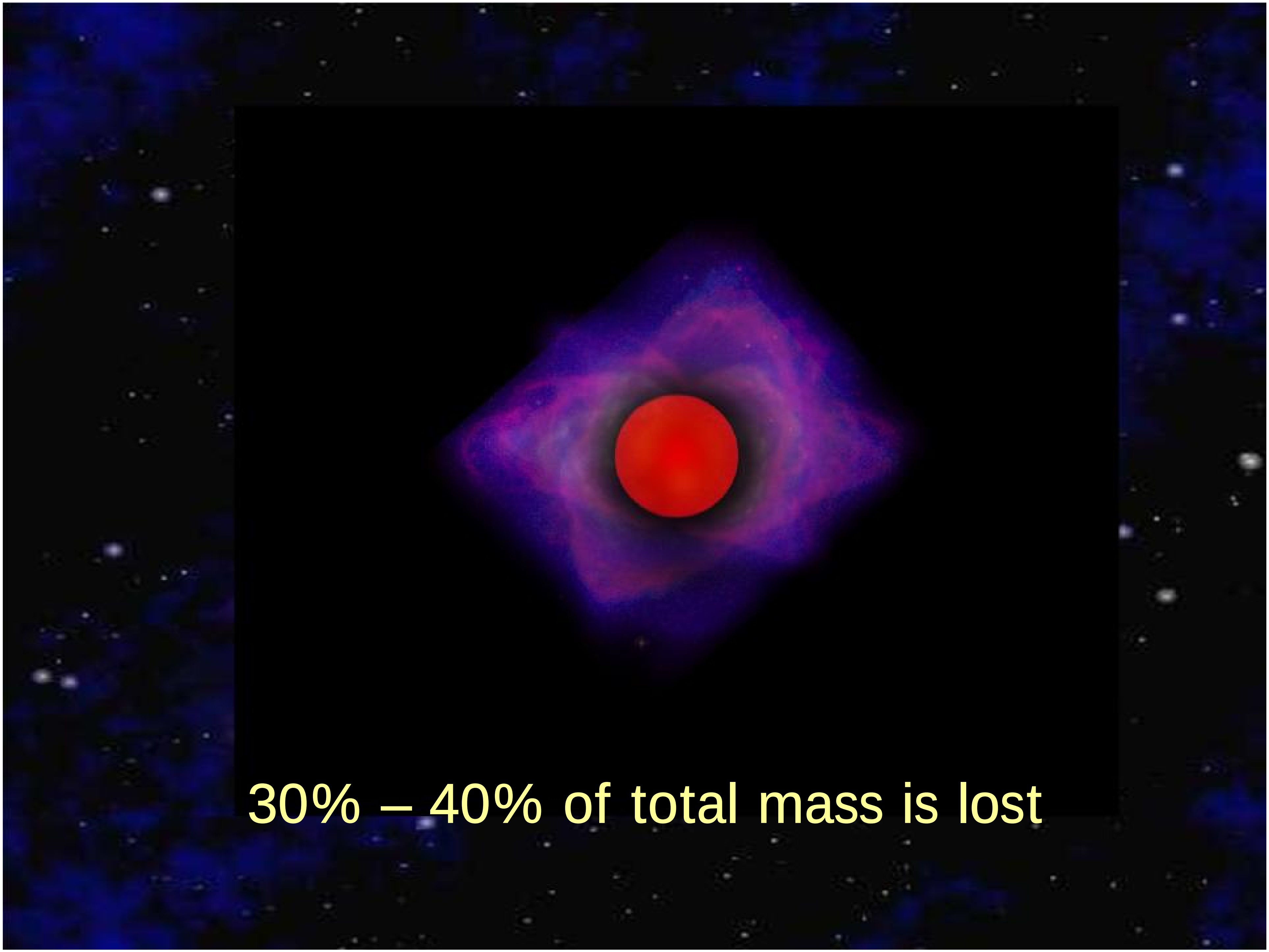

Helium
Core



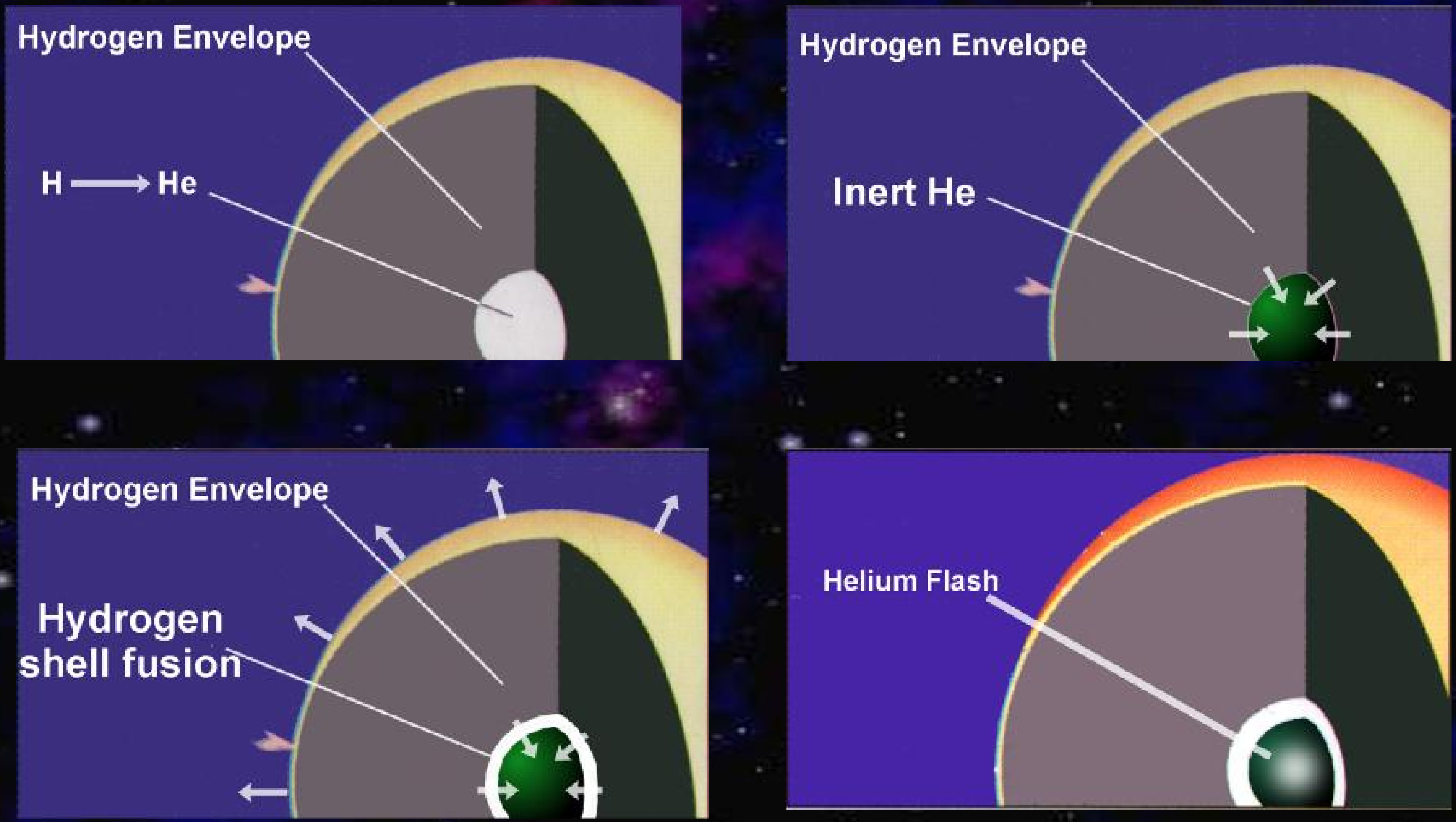
absolute visual magnitude (M_v)
spectral type
BO
AO
FO
GO
KO
MO
-6
-4
-2
0
2
4
6
8
10
12
β Cephei
Cepheids
semi-regular
W Virginis
Population I
main sequence
RR Lyrae
magnetic variable
stars
Al Velorum
δ Scuti
T Tauri
novae ?
Sun
eruptive UV Ceti stars
White Dwarfs
27 000
10 400
7200
6000
5120
3750
effective temperature (K)

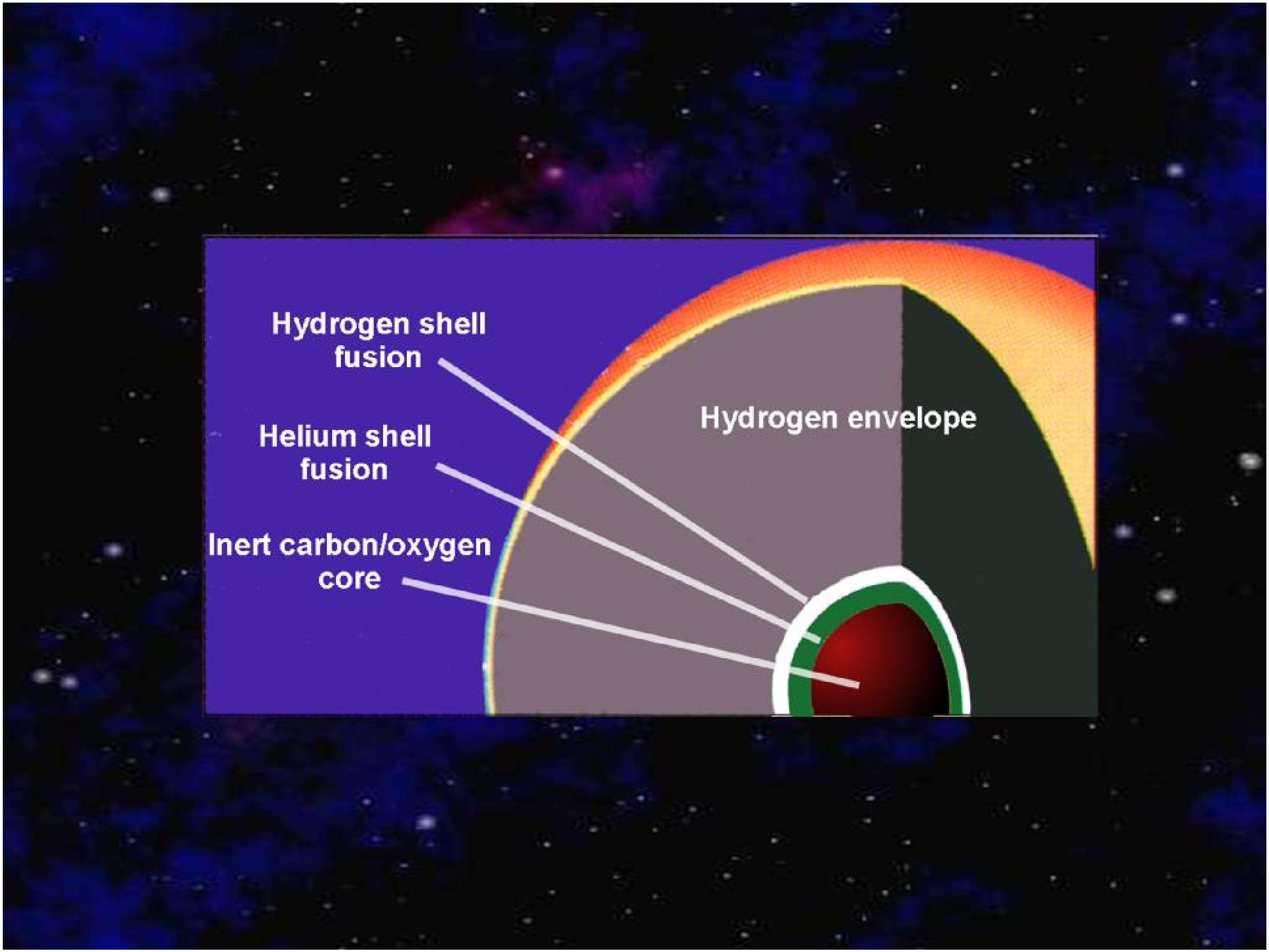
1. Low Mass Stars M < 0.5 M$_\odot$

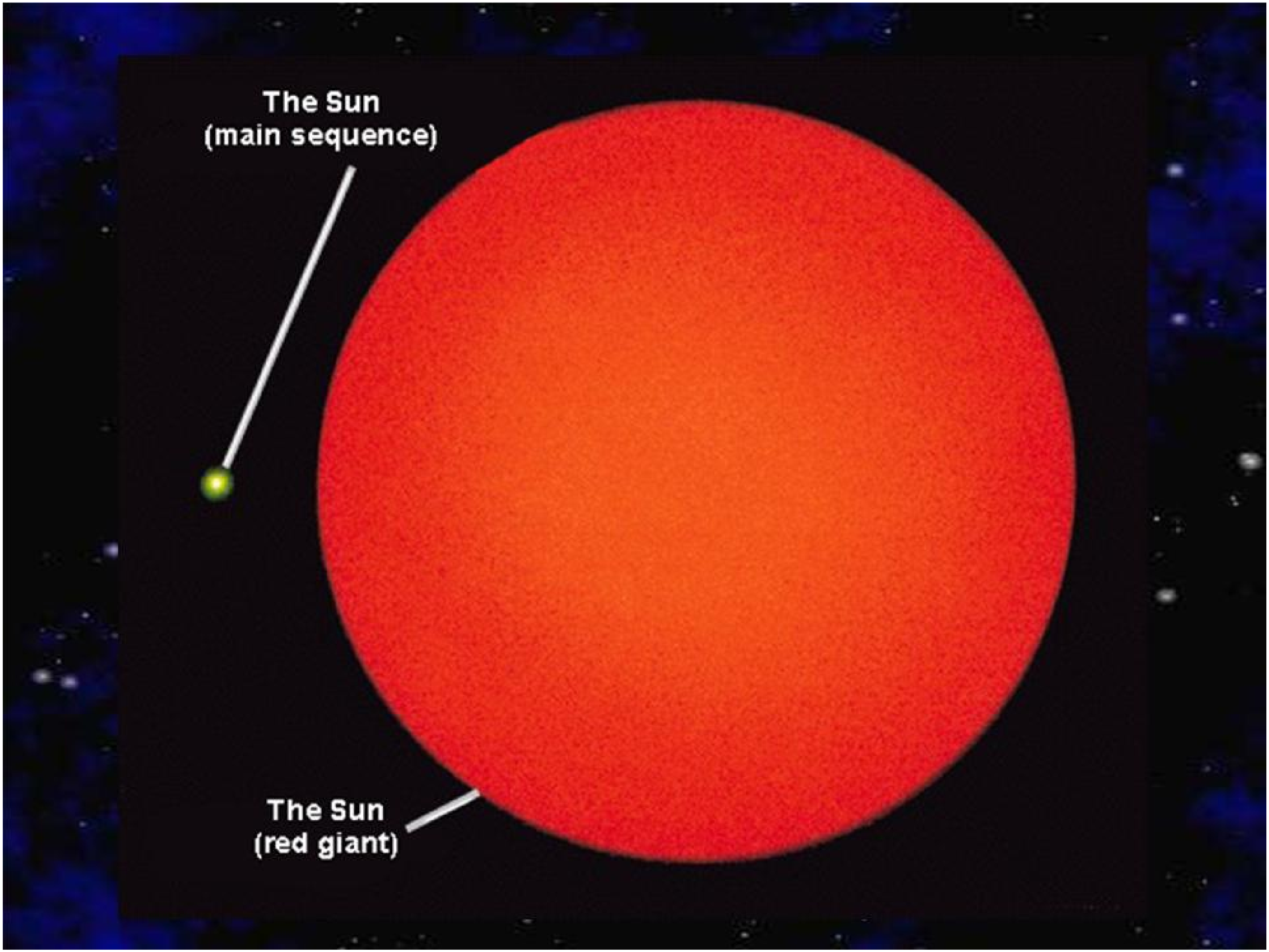



30% – 40% of total mass is lost

2. Intermediate Mass Stars
0.5 < M$_\odot$ < 8




Hydrogen shell fusion
Helium shell fusion
Inert carbon/oxygen core
Hydrogen envelope


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

esa

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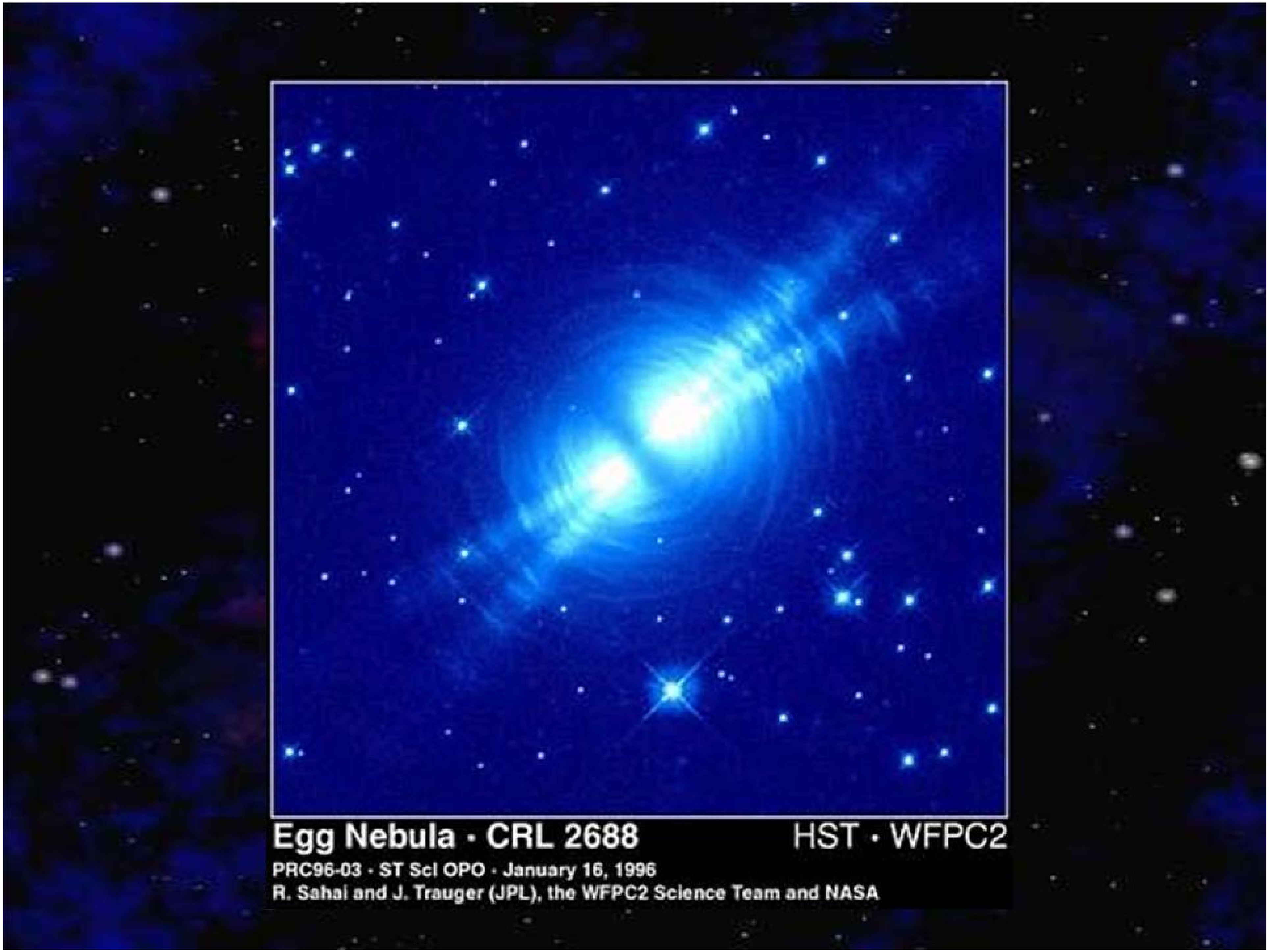
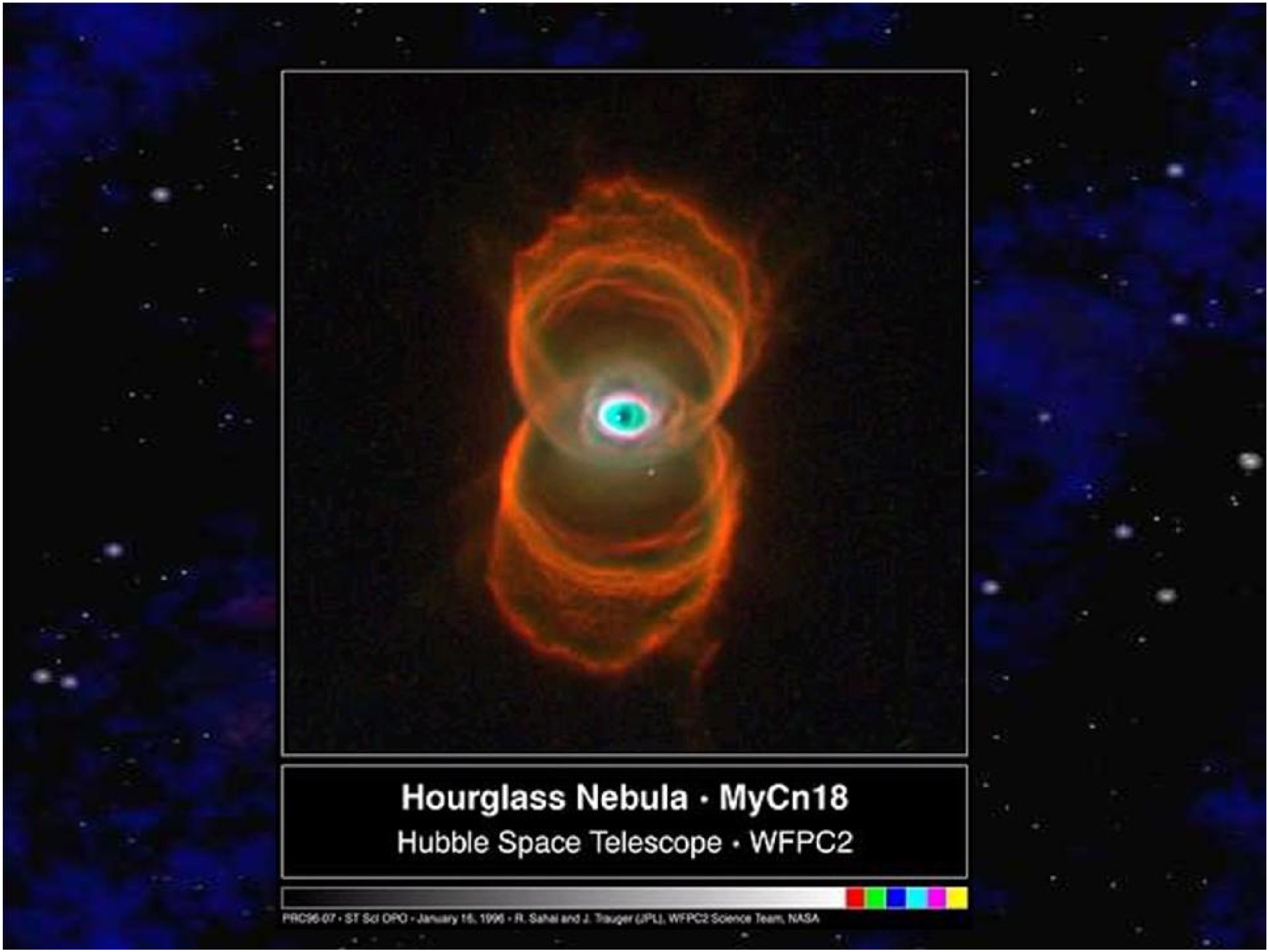
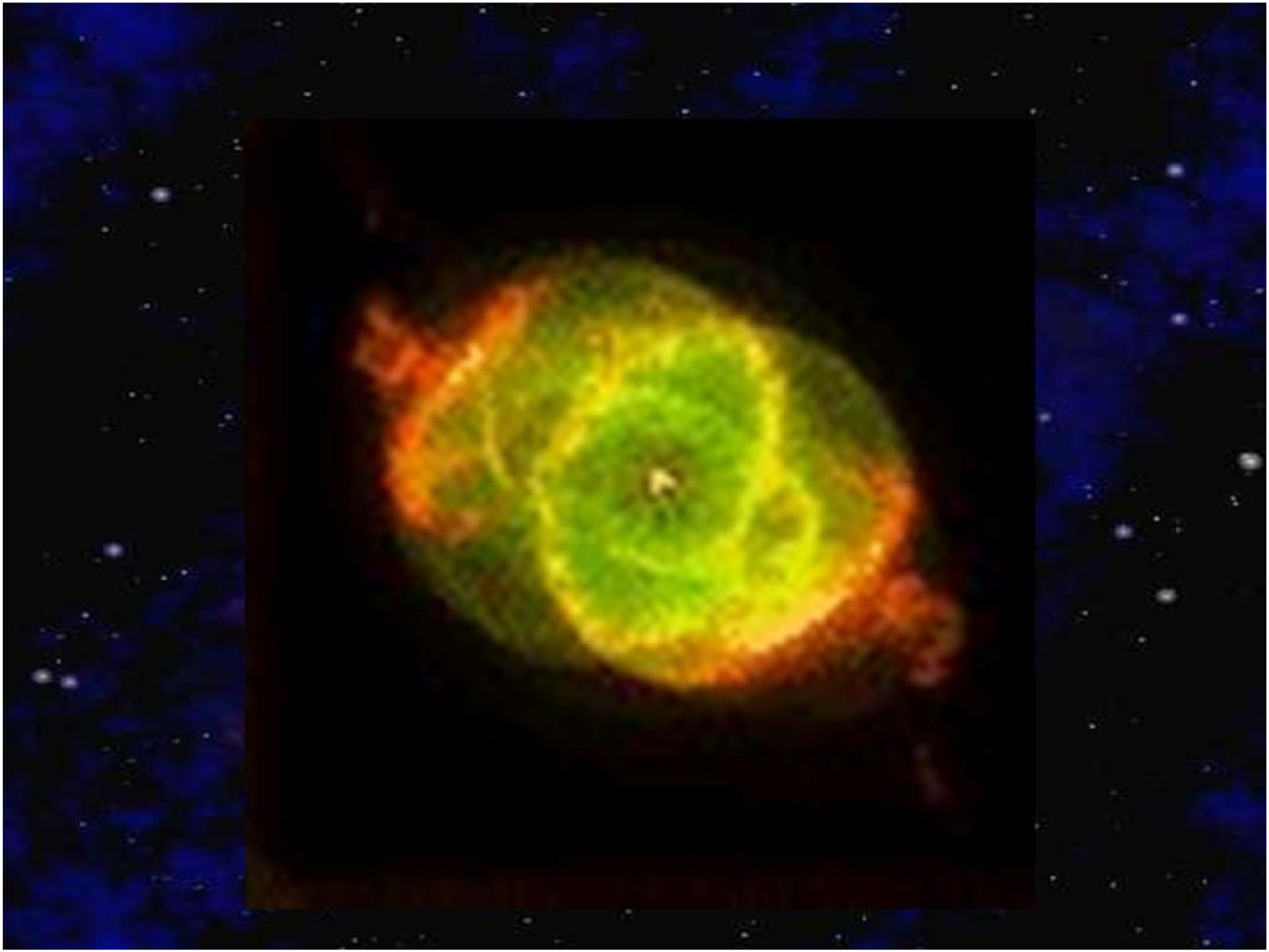
Planetary Nebula

(has nothing to do with planets!!)


Egg Nebula · CRL 2688
HST · WFPC2
PRC96-03 · ST ScI OPO · January 16, 1996
R. Sahai and J. Trauger (JPL), the WFPC2 Science Team and NASA


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

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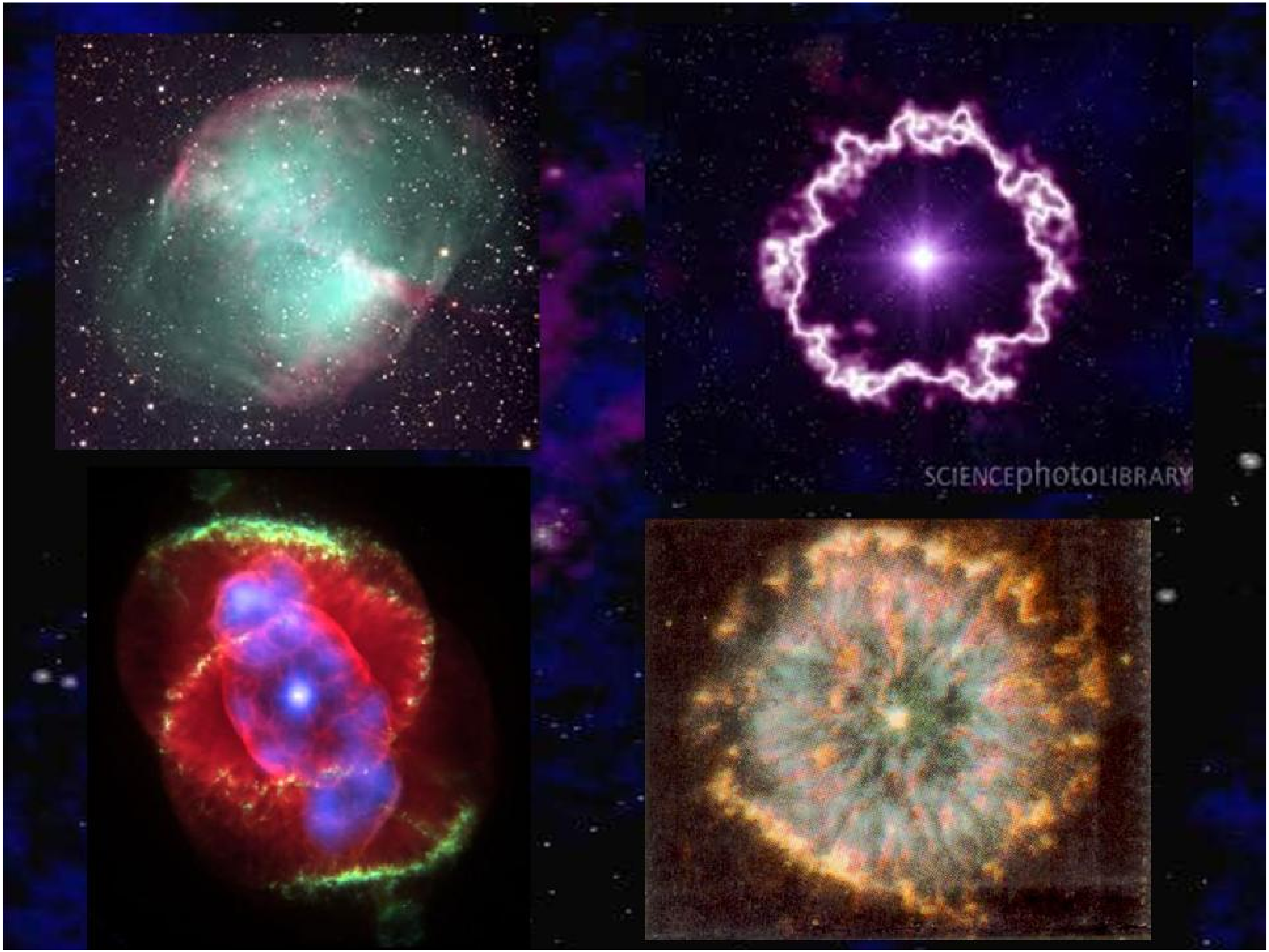
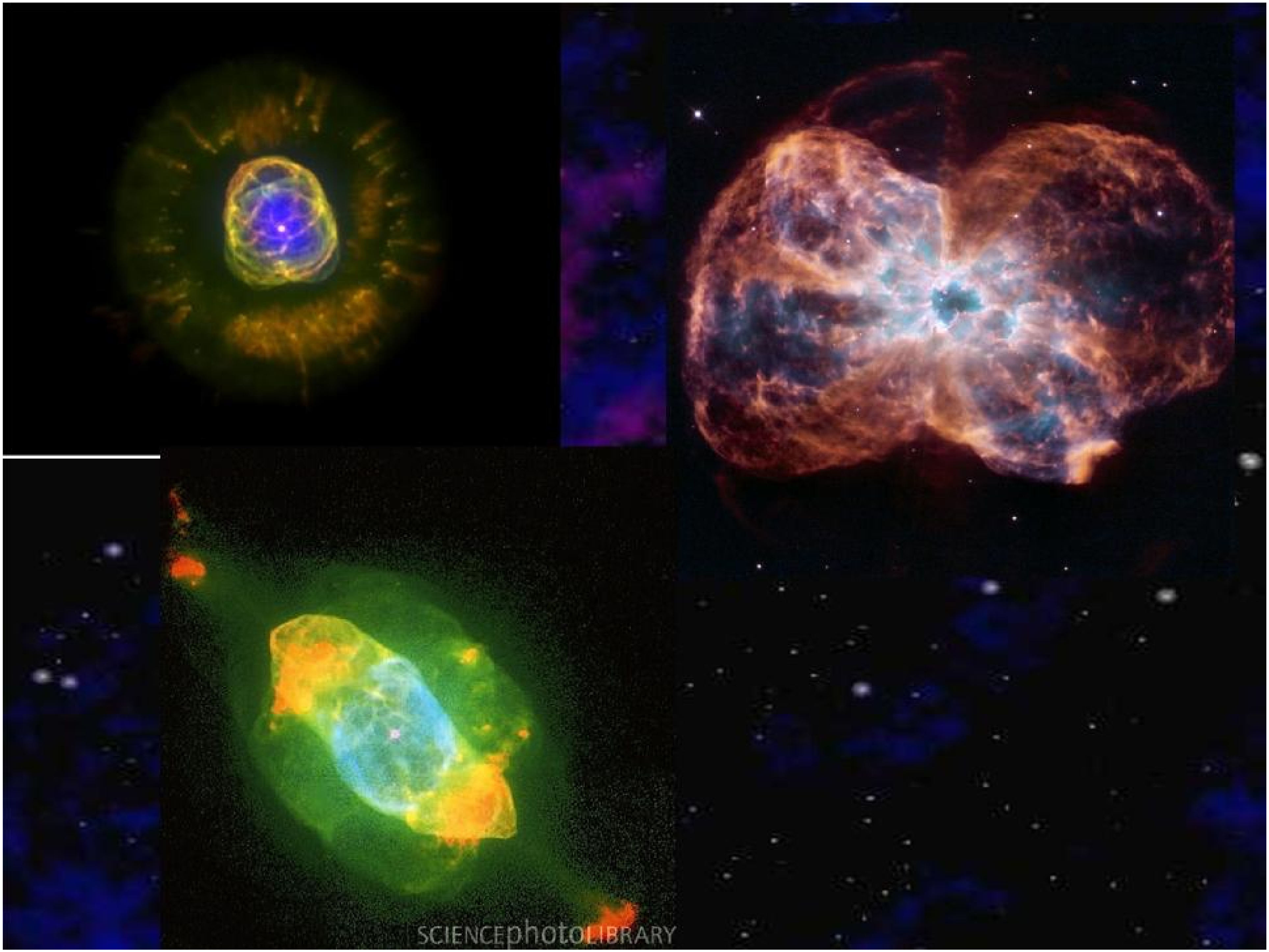
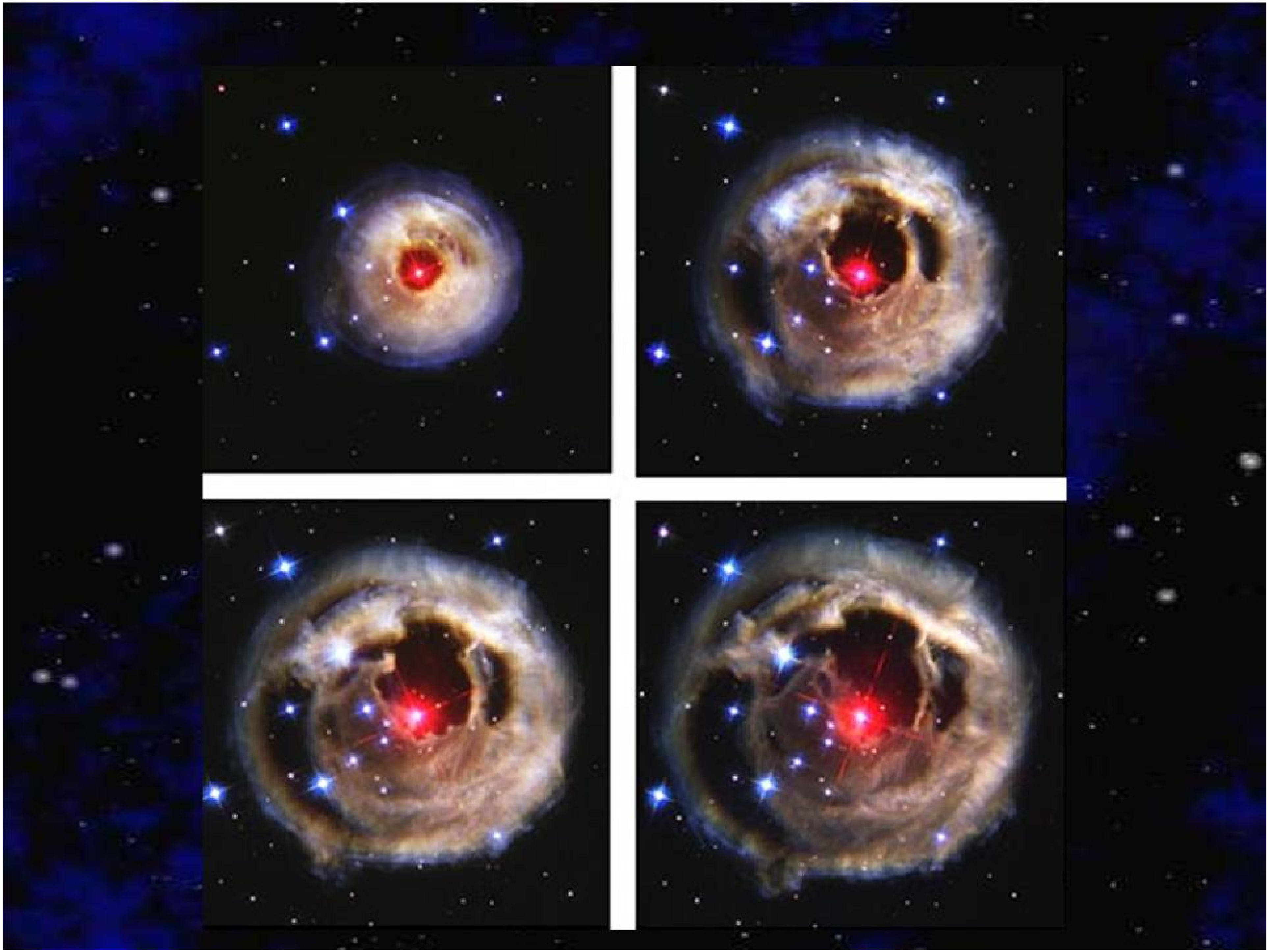
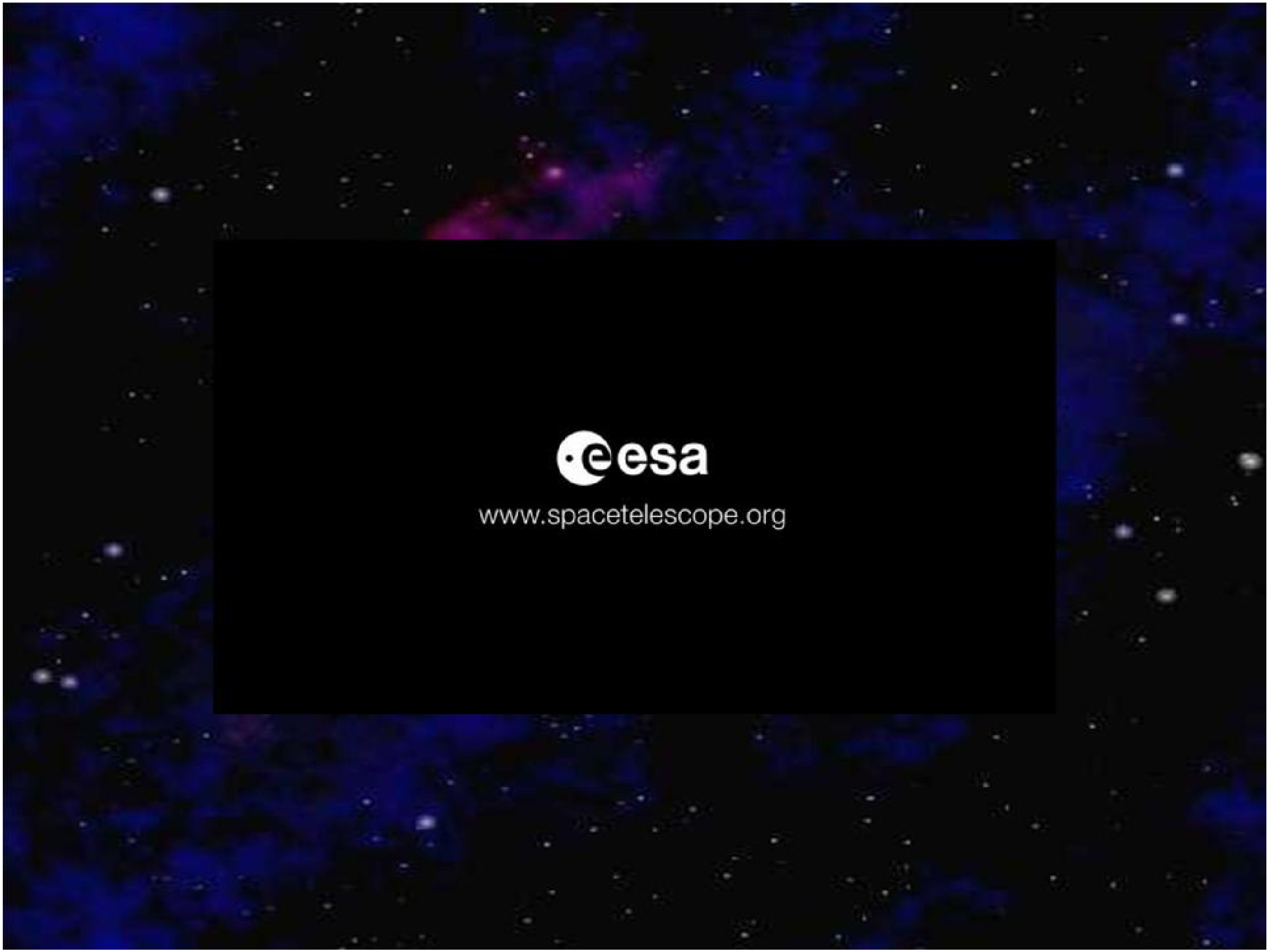

SCIENCEphotoLIBRARY


SCIENCEphotoLIBRARY




esa
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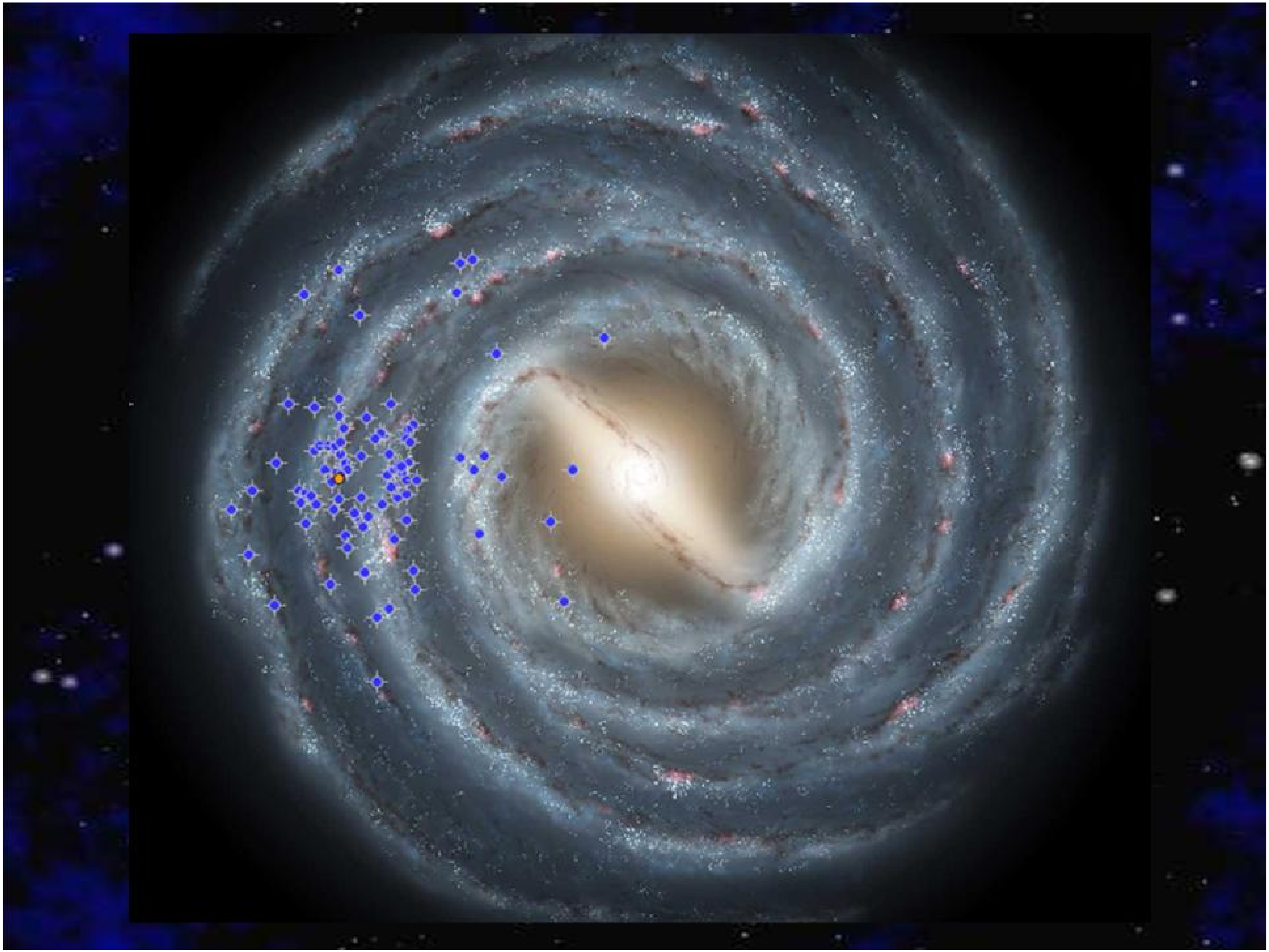
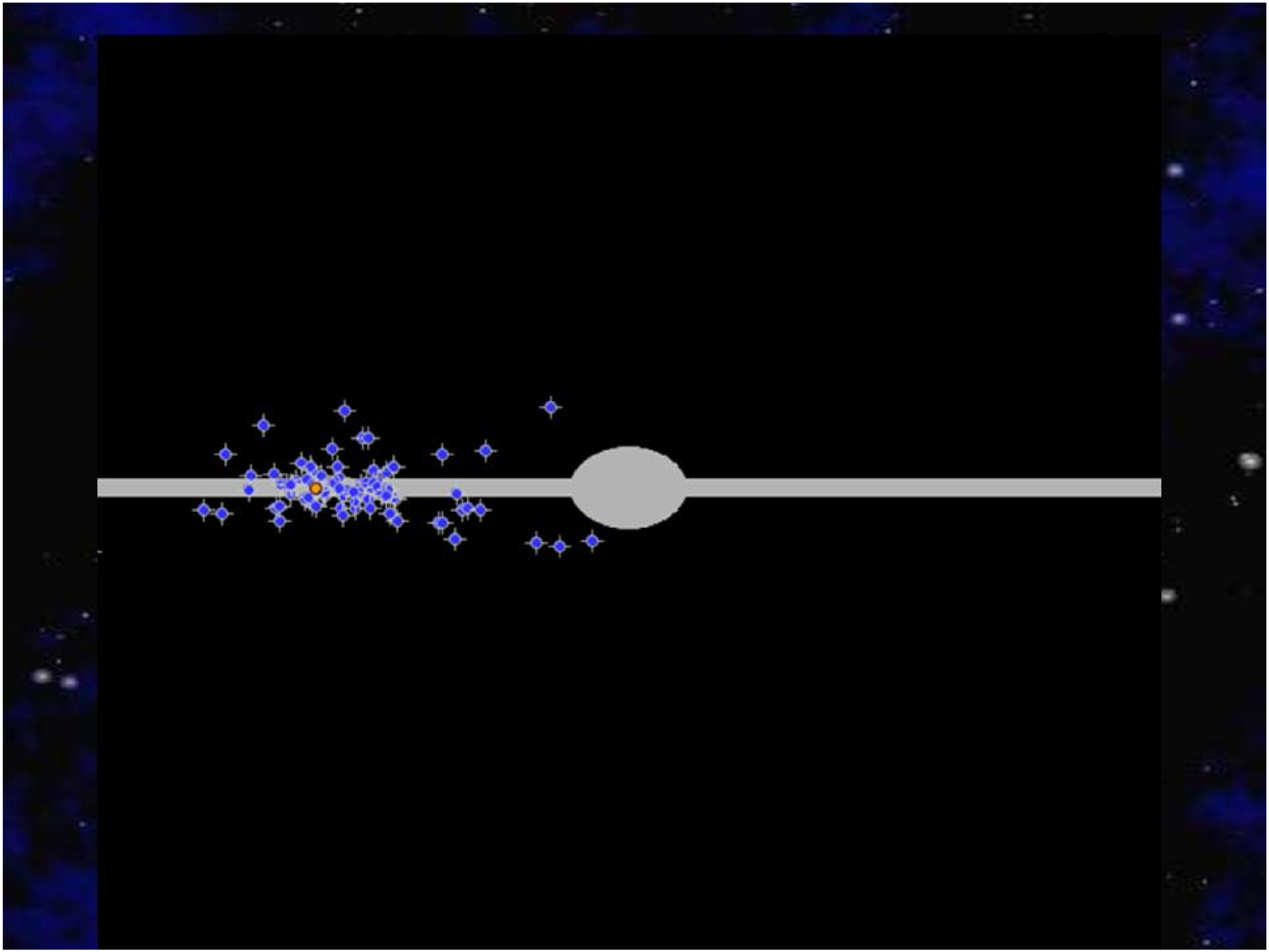
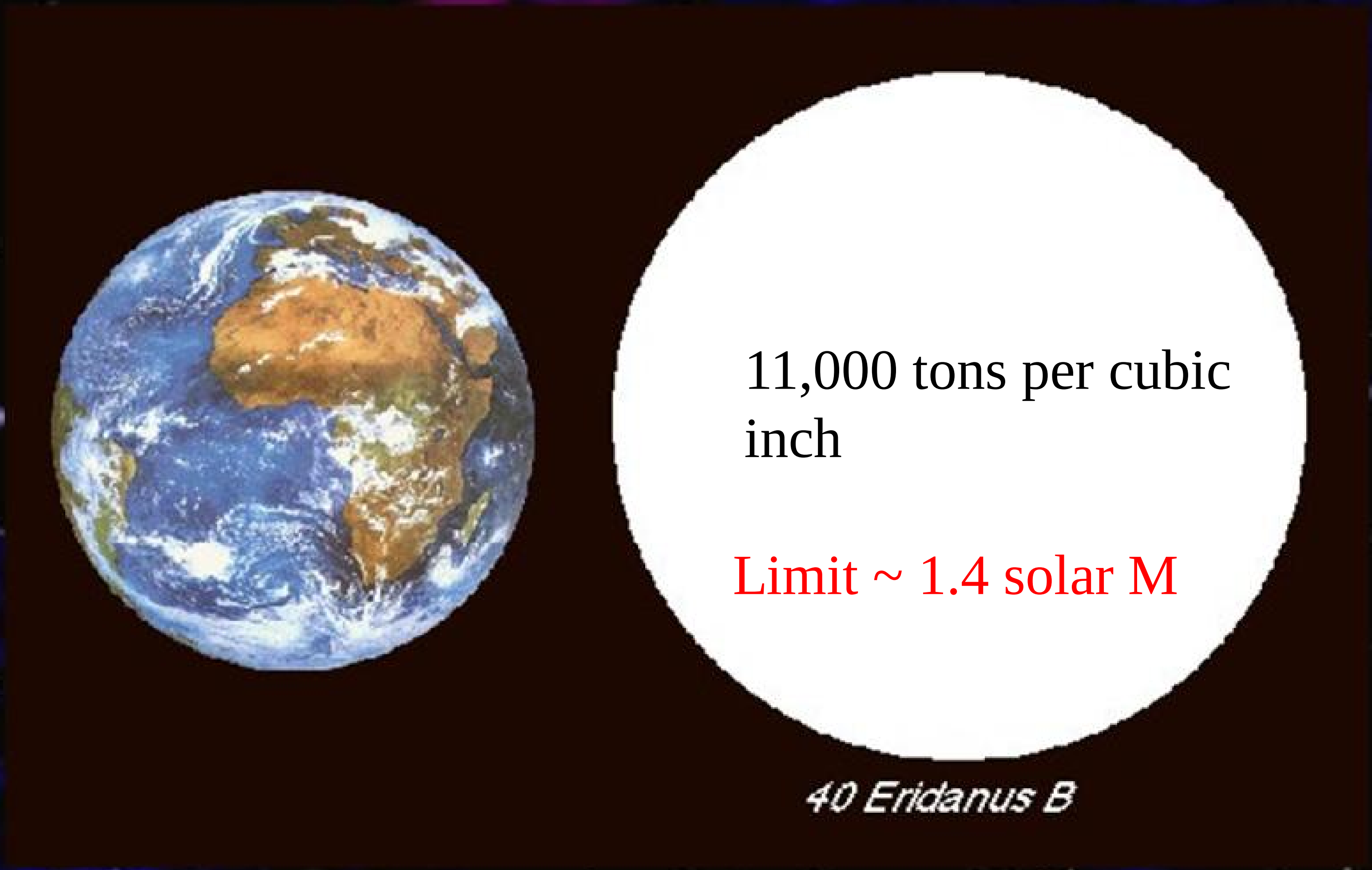




White Dwarf Stars

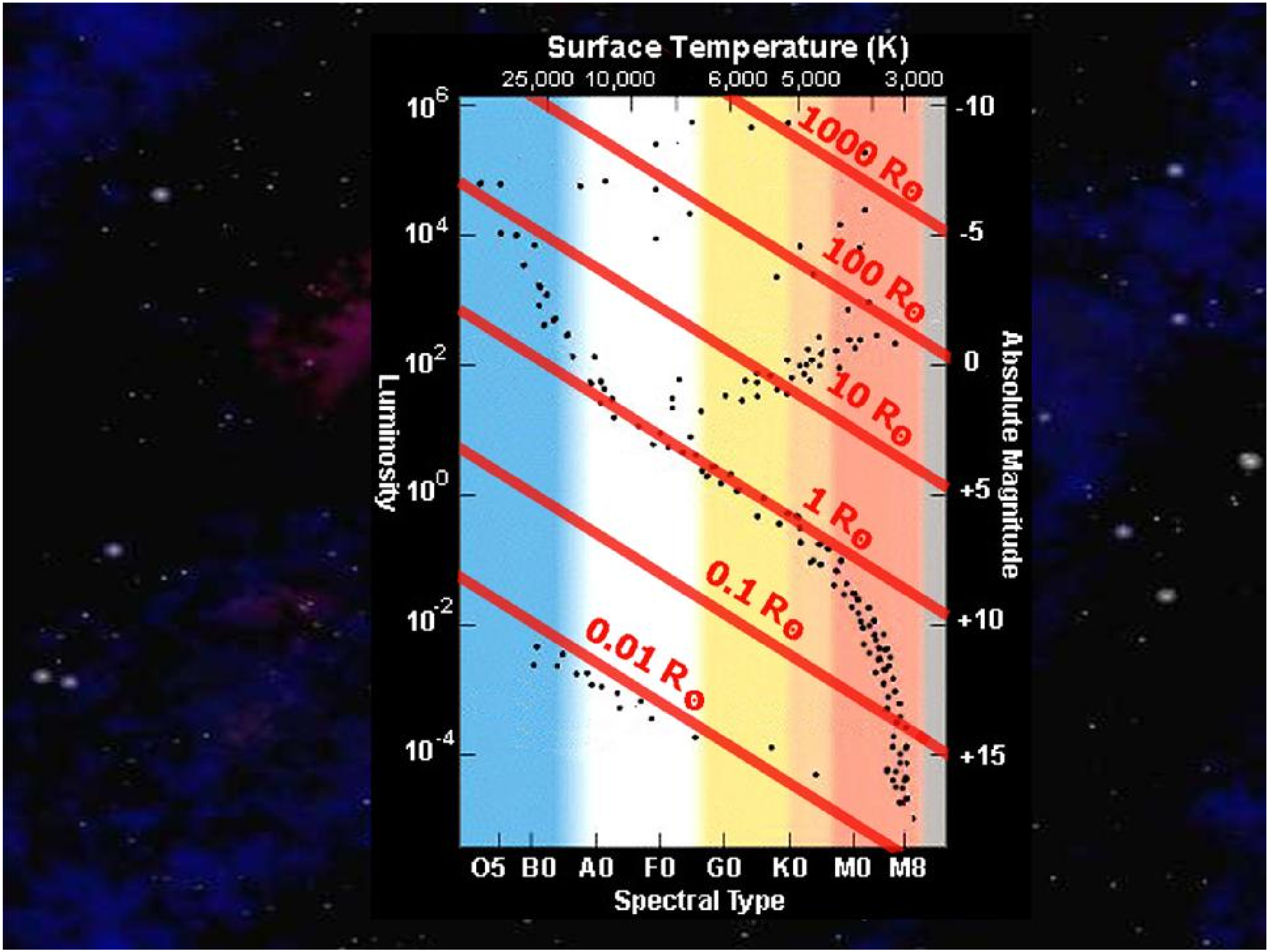
- Composed mostly of carbon
- Surface temperatures of 50,000 K or more
- ***NO*** internal energy source
- Earth sized
- Mass is that of remnant stellar core
- VERY DENSE!

White Dwarf Star



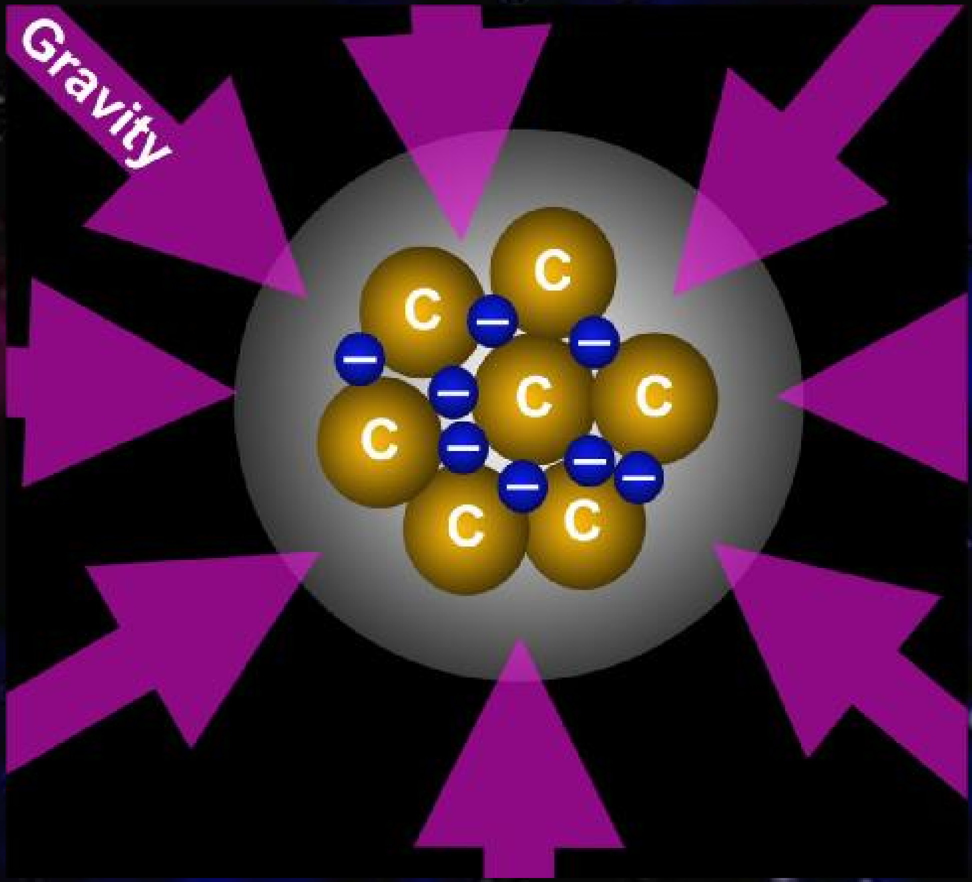
11,000 tons per cubic inch

Limit ~ 1.4 solar M


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
1000 $R_\odot$
100 $R_\odot$
10 $R_\odot$
1 $R_\odot$
0.1 $R_\odot$
0.01 $R_\odot$
O5 B0 A0 F0 G0 K0 M0 M8
Spectral Type

What stopped the gravitational collapse of the white dwarf?

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

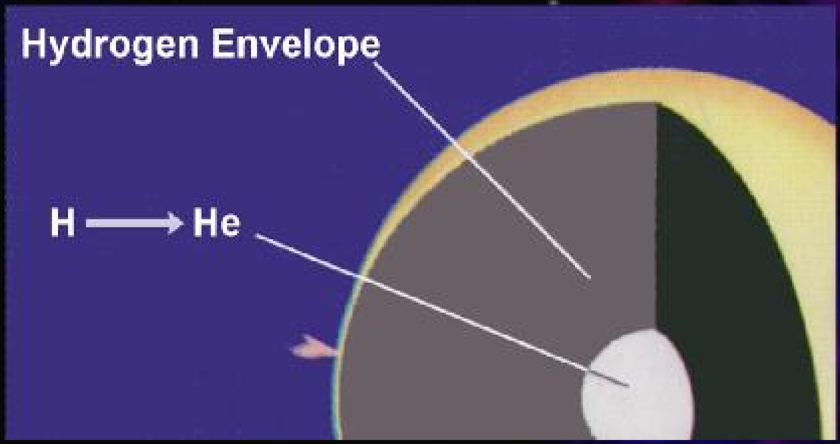
Gravity can overwhelm the electrons if the mass is high enough..

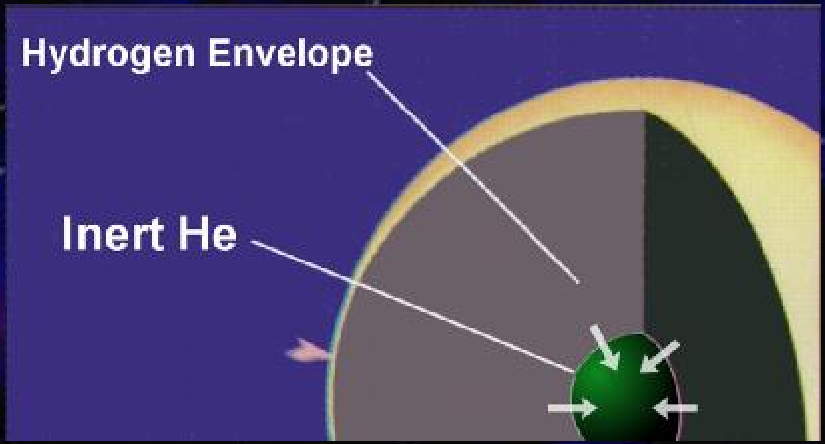
$M < 1.4\ M_{\odot}$

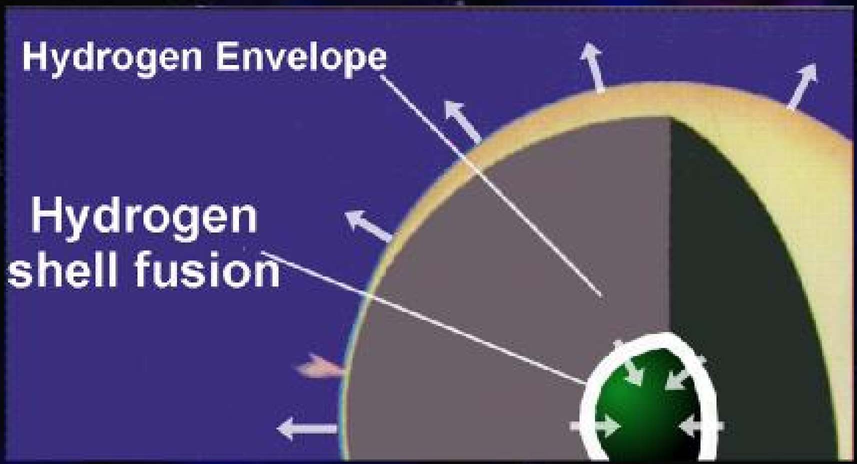
Chandrasekhar Limit

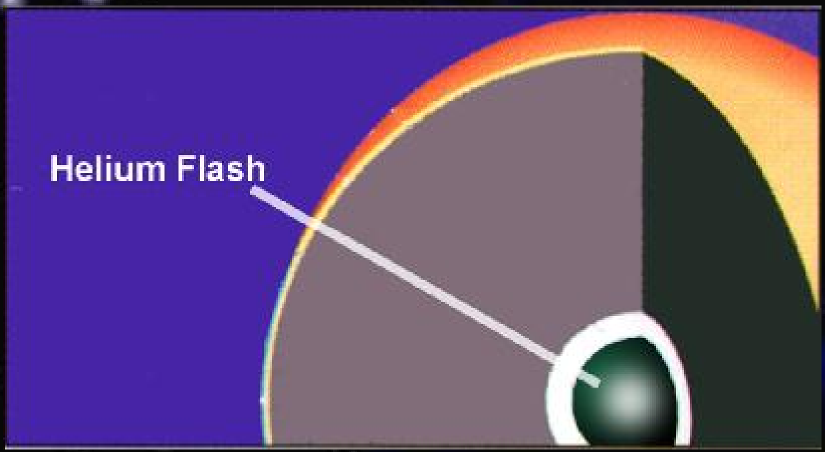
What happens if the core of the star that remains is GREATER than the Chandrasekhar Limit?

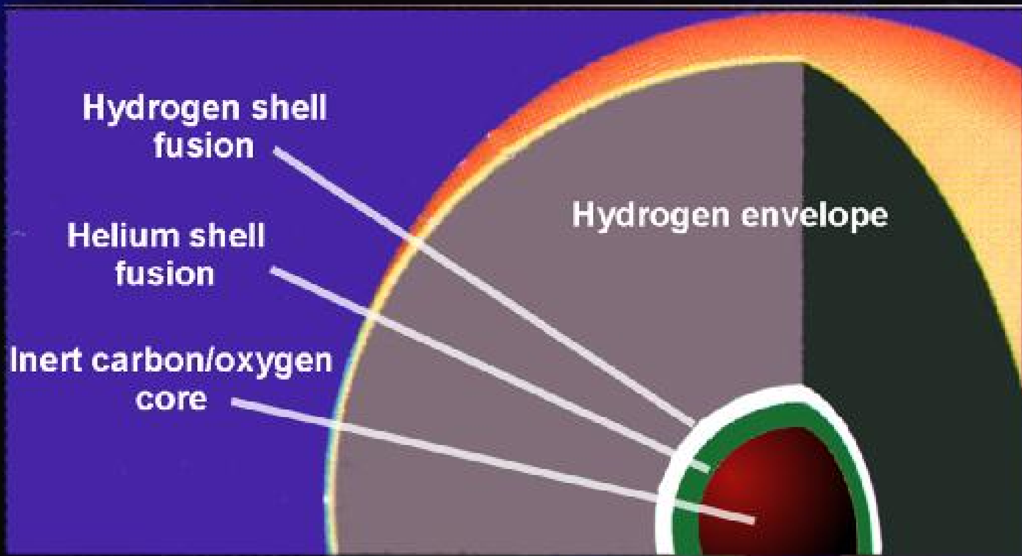
3. High Mass Stars $M_{\odot} > 8$

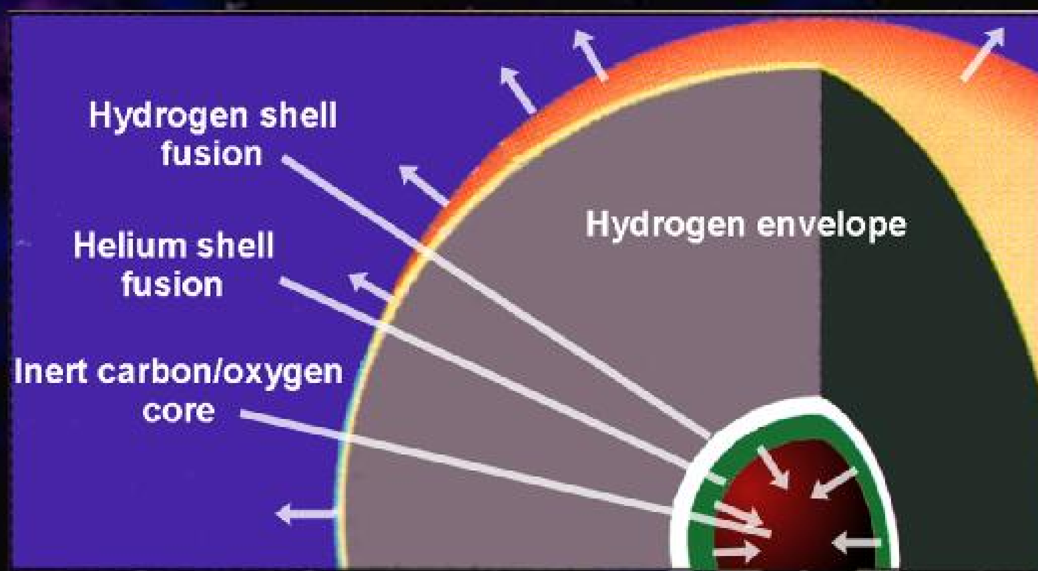






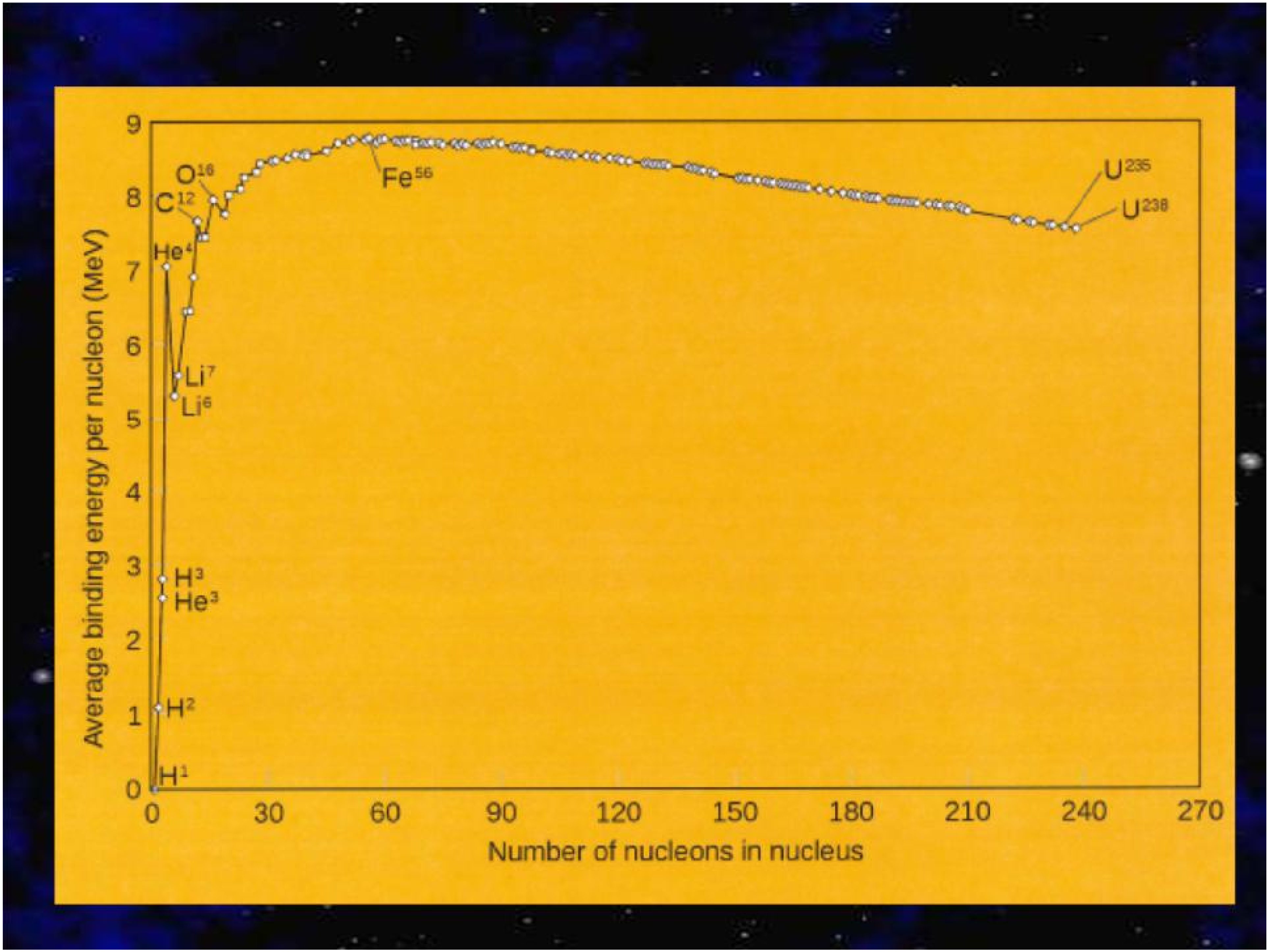



Hydrogen shell fusion
Helium shell fusion
Inert carbon/oxygen core
Hydrogen envelope

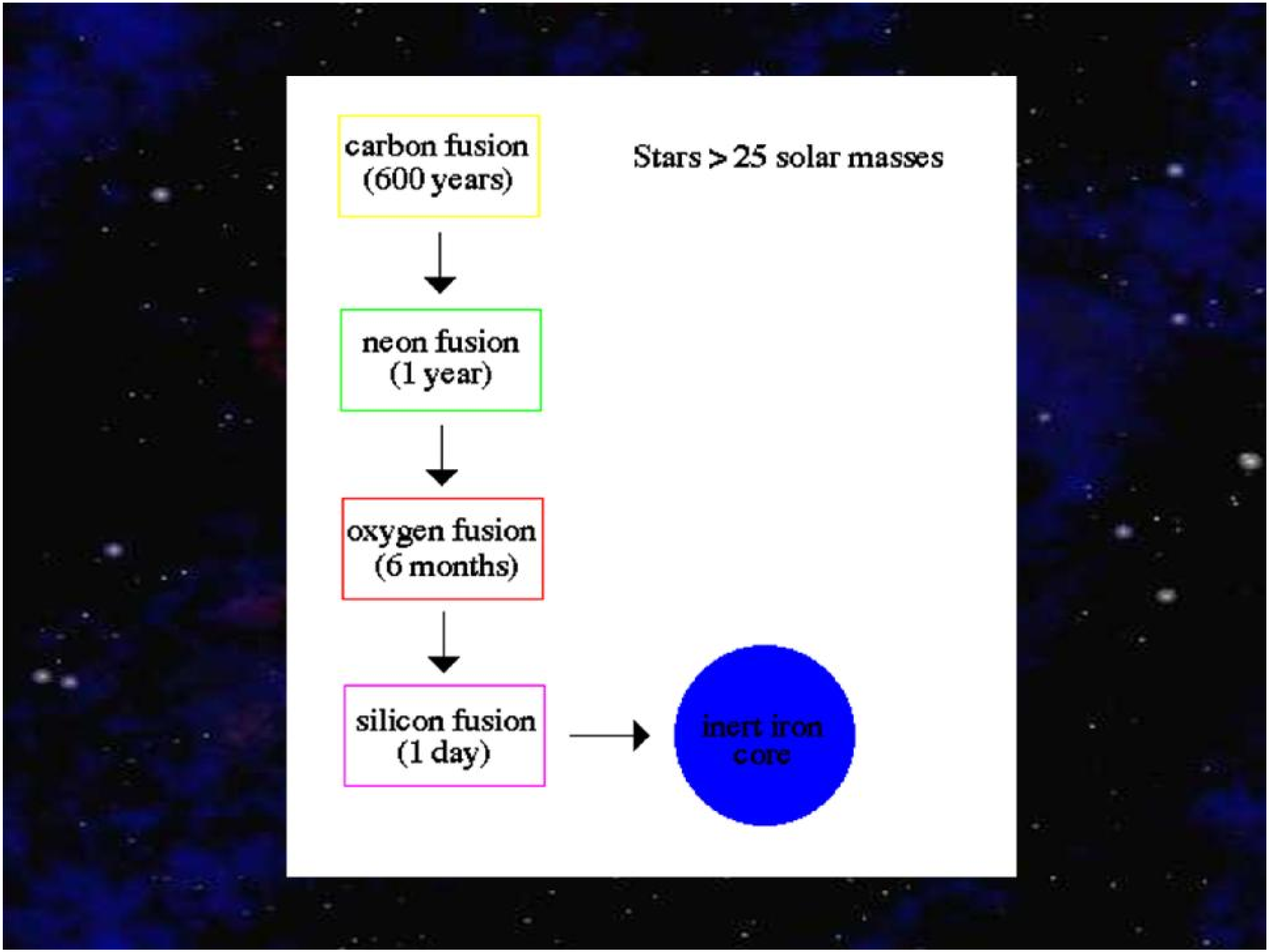

Hydrogen shell fusion
Helium shell fusion
Inert carbon/oxygen core
Hydrogen envelope

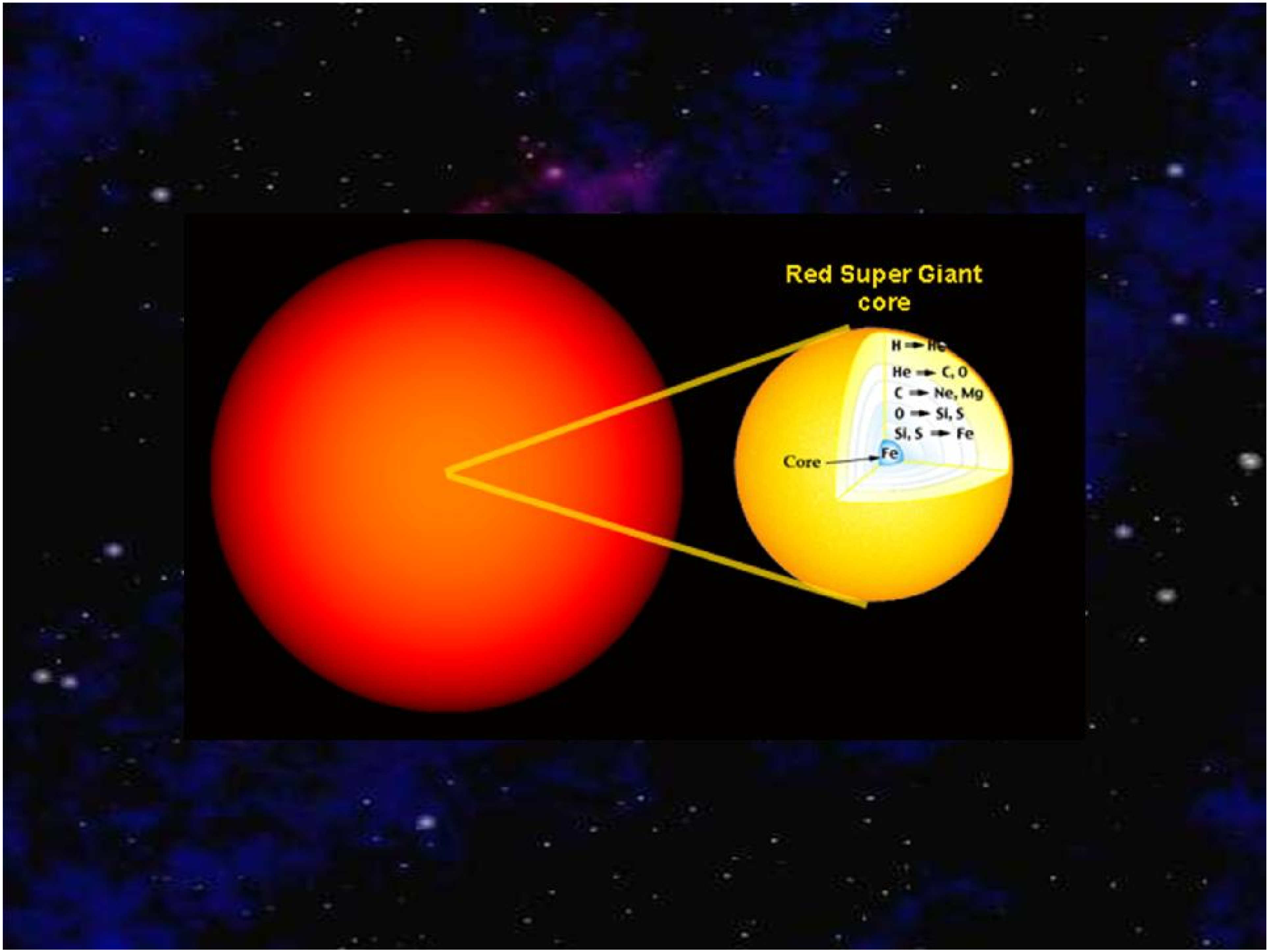
25 $M_\odot$ star

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

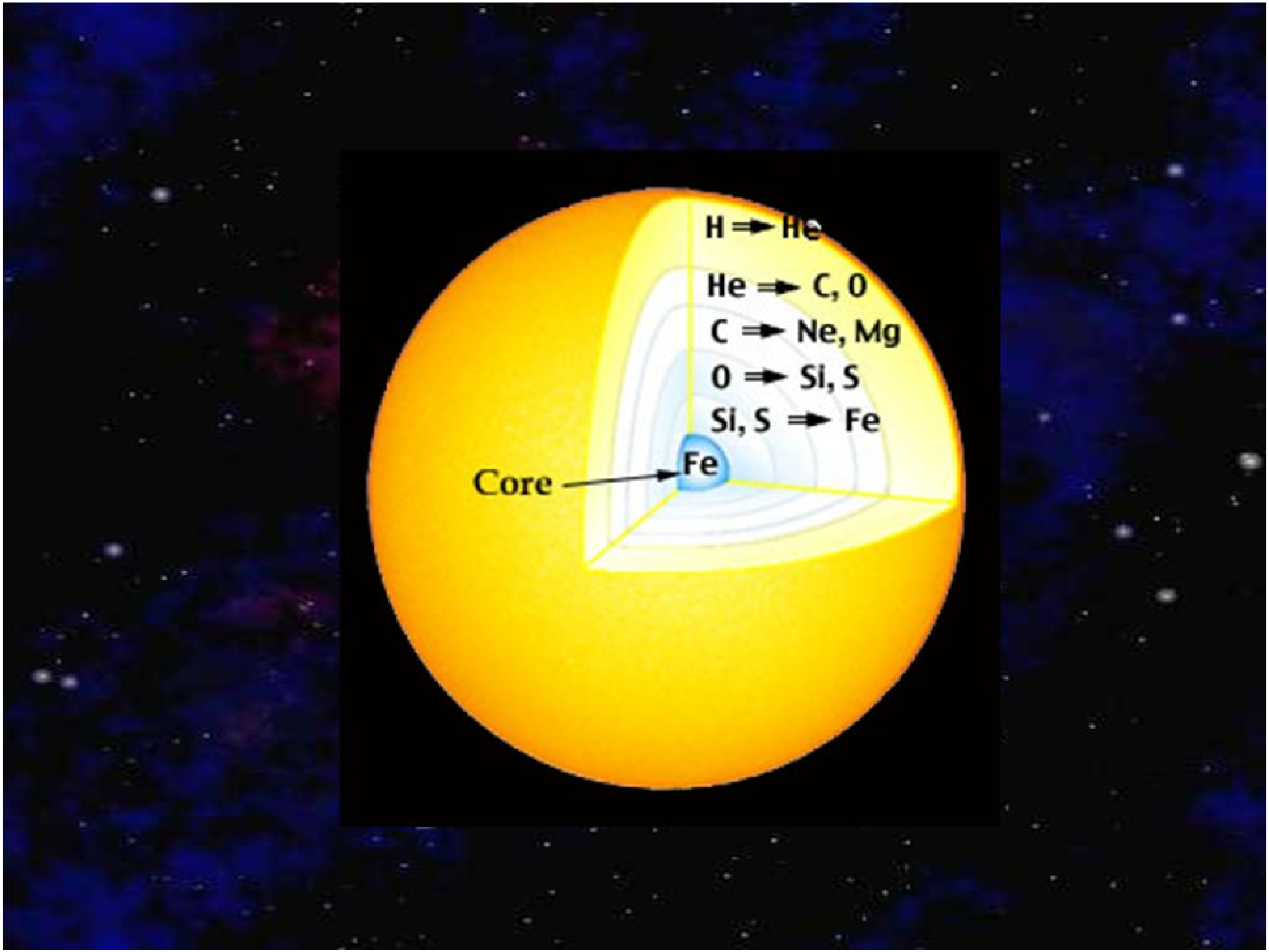


Average binding energy per nucleon (MeV)
Number of nucleons in nucleus
0
1
2
3
4
5
6
7
8
9
0
30
60
90
120
150
180
210
240
270
H1
H2
H3
He3
He4
Li6
Li7
C12
O16
Fe56
U235
U238


carbon fusion
(600 years)
Stars > 25 solar masses
neon fusion
(1 year)
oxygen fusion
(6 months)
silicon fusion
(1 day)
inert iron
core



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


H → He
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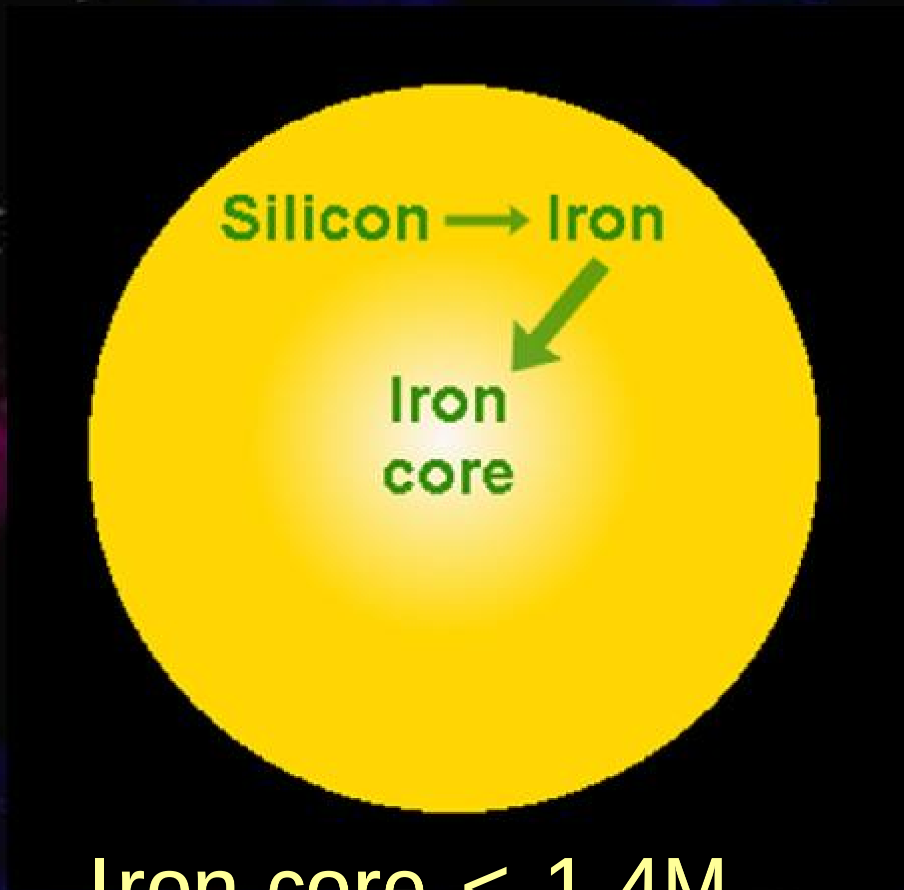
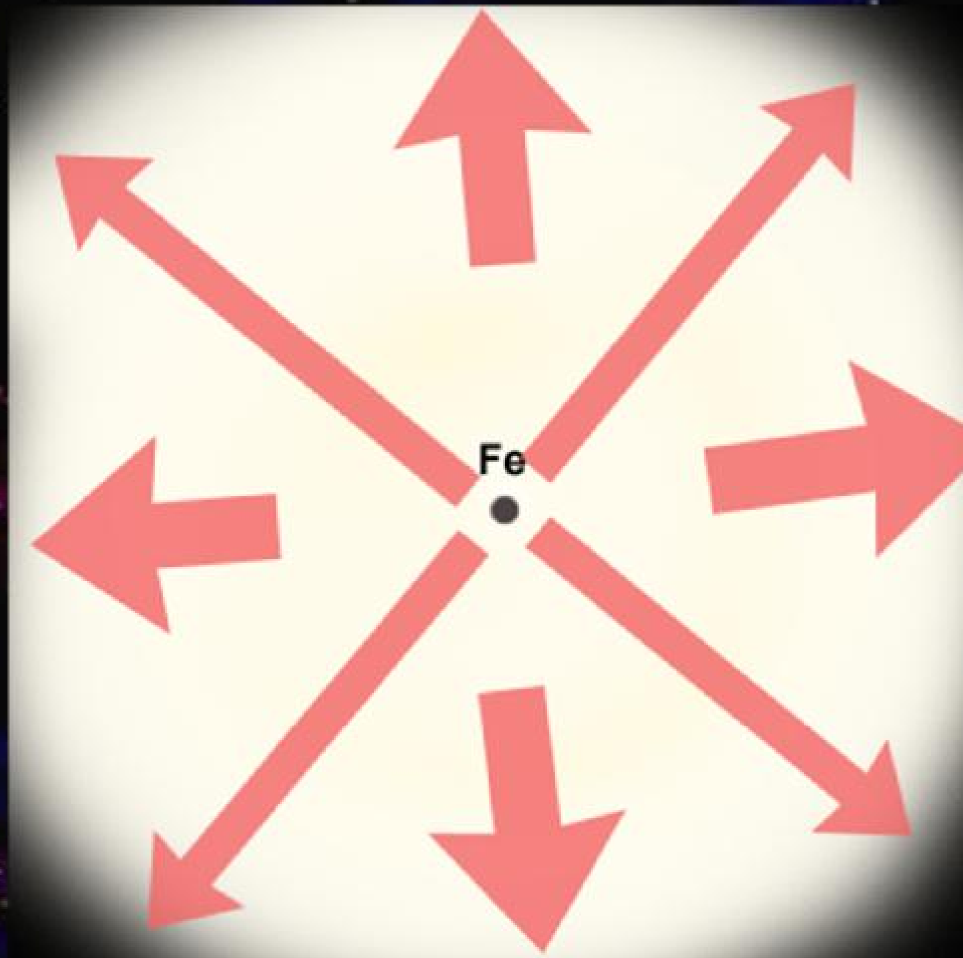
Core



Iron core < 1.4M.

Continual silicon fusion increases mass of core

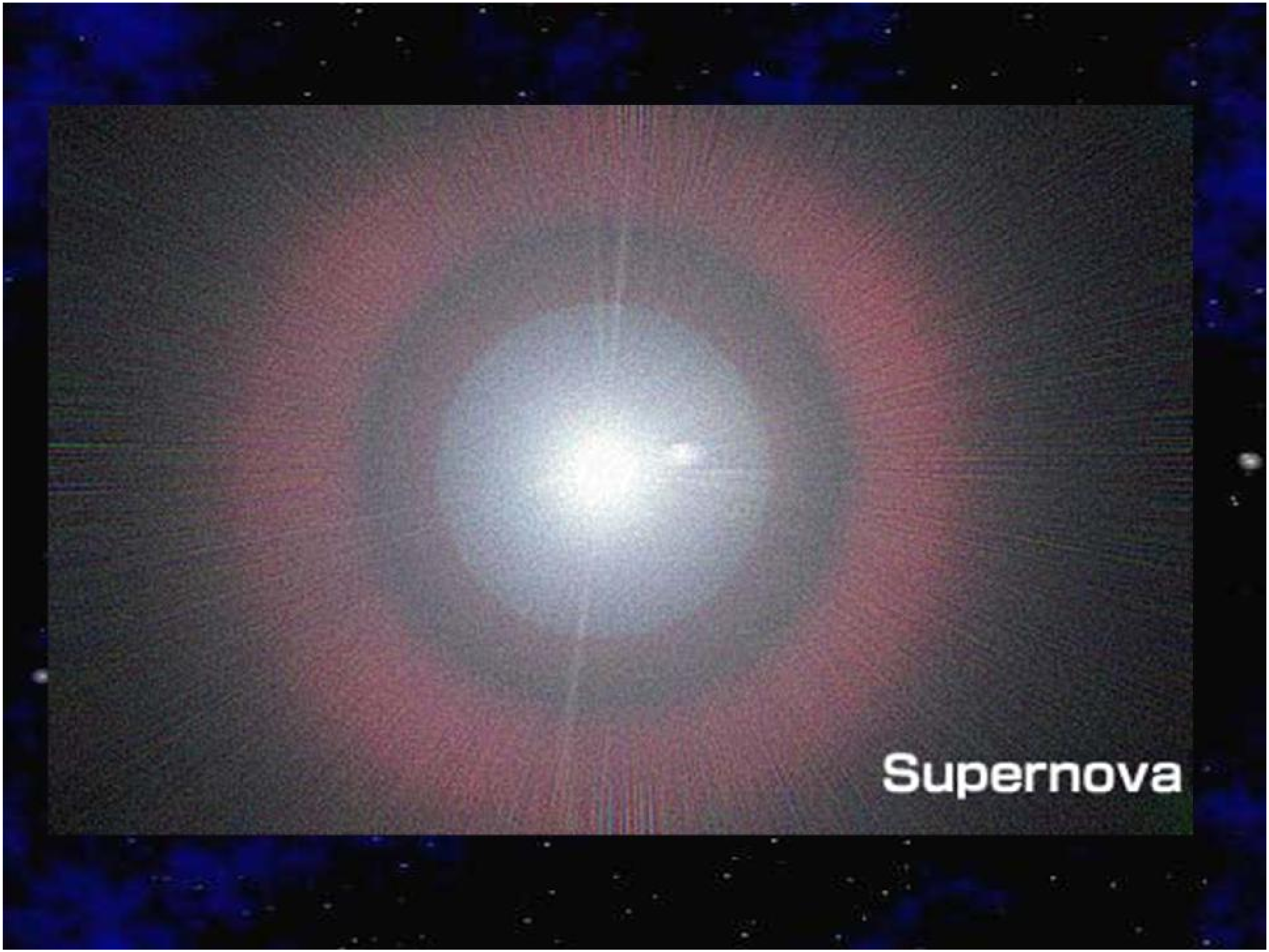
Eventually Iron core = 1.4M.



Iron core > $1.4M_{\odot}$

Iron core cannot support itself against gravity

Iron core collapses...


Supernova

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