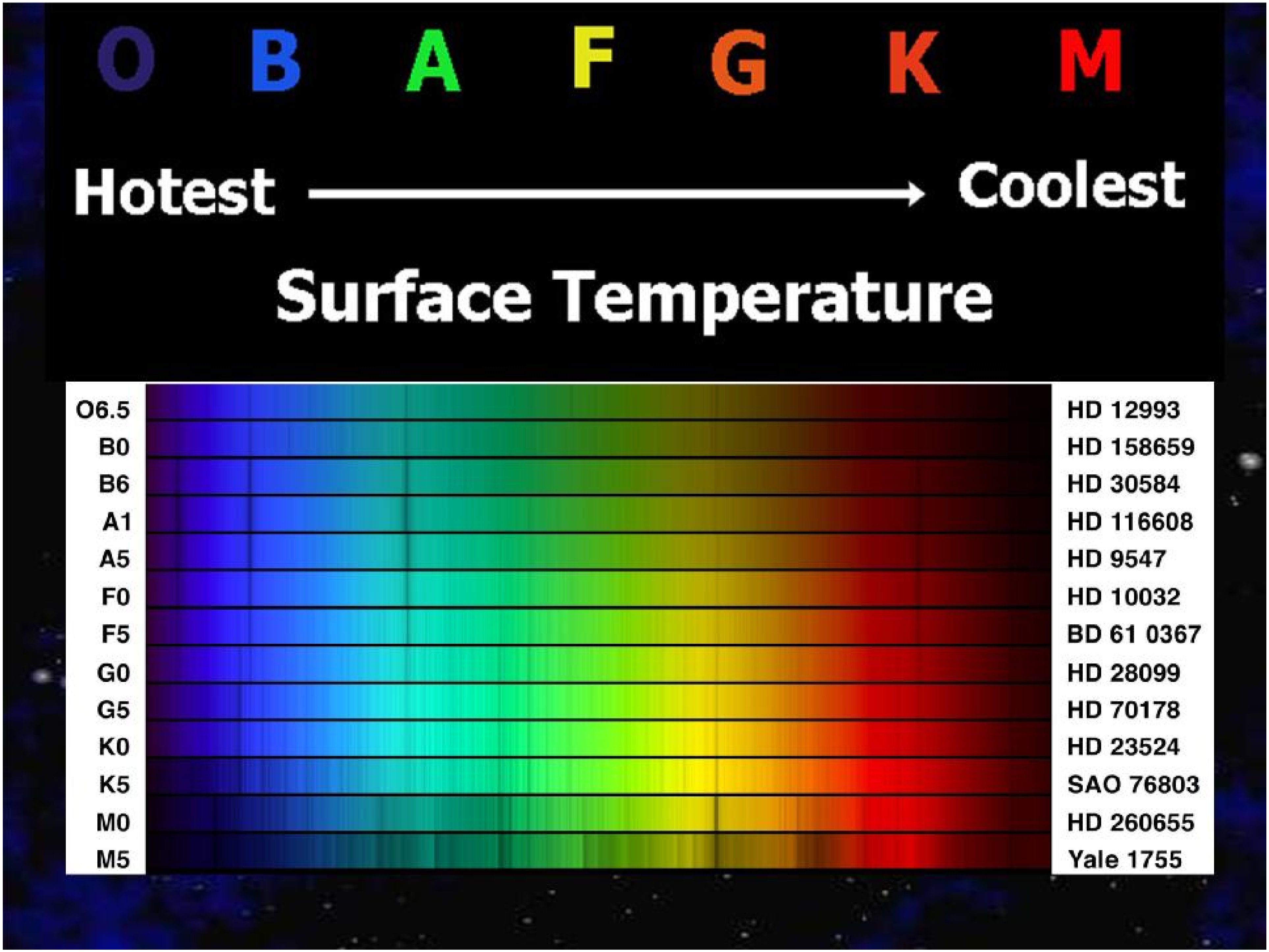
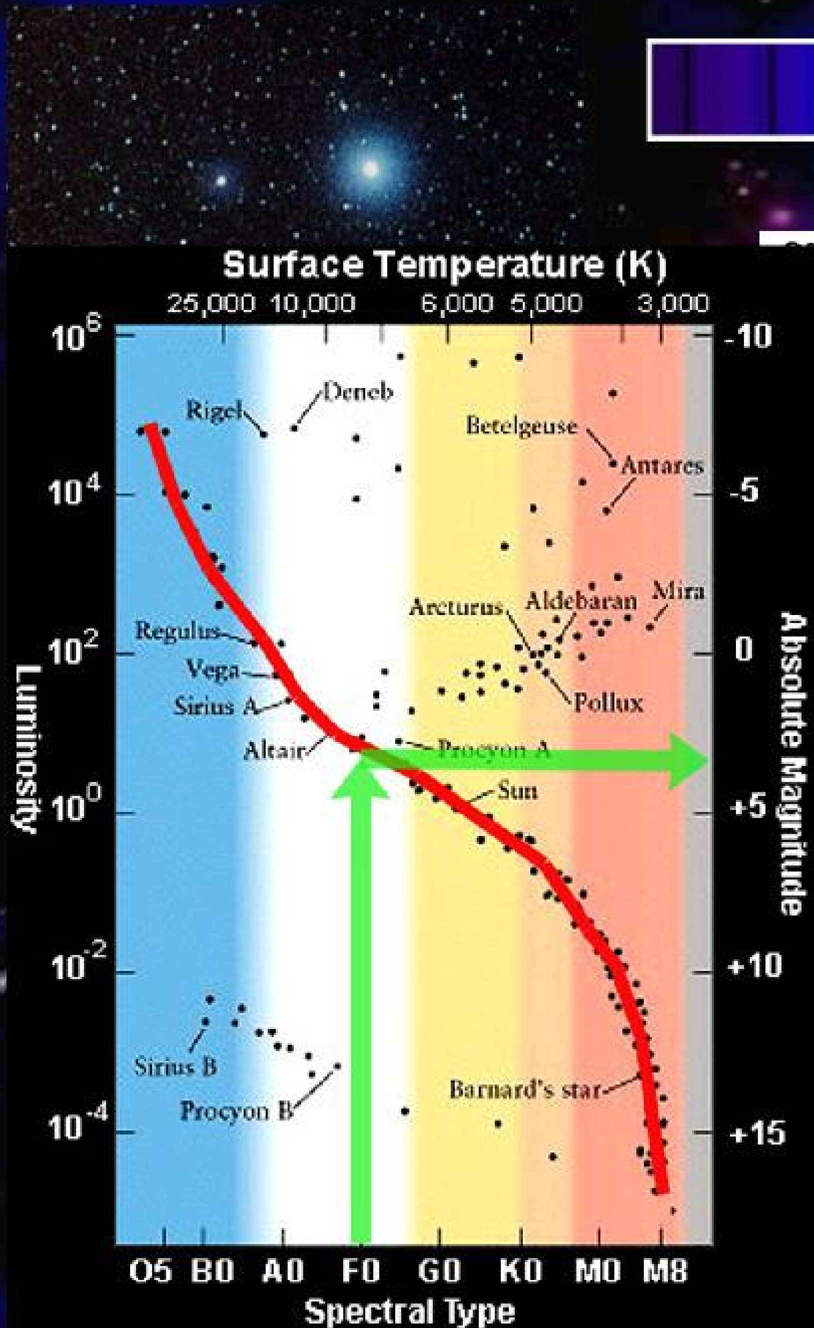
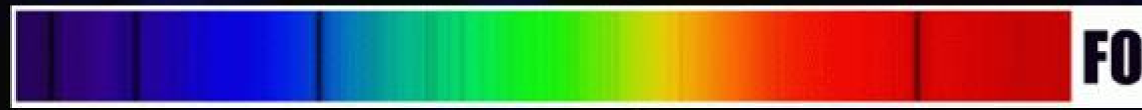
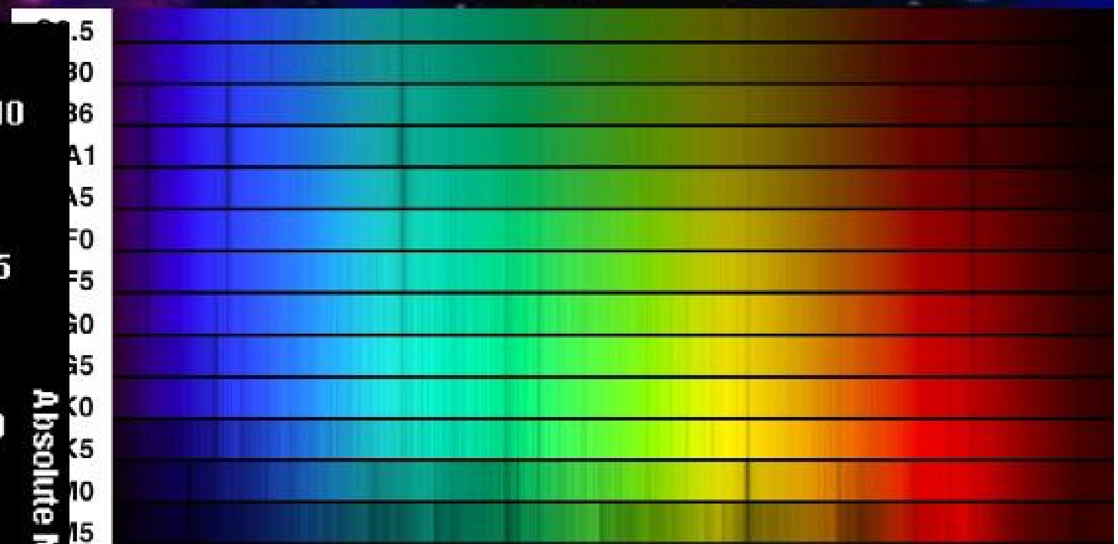

O B A F G K M
Hotest
Coolest
Surface Temperature
O6.5
B0
B6
A1
A5
F0
F5
G0
G5
K0
K5
M0
M5
HD 12993
HD 158659
HD 30584
HD 116608
HD 9547
HD 10032
BD 61 0367
HD 28099
HD 70178
HD 23524
SAO 76803
HD 260655
Yale 1755







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

Spectroscopic Parallax

Temperature – Radius – Luminosity Relationship

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

L = luminosity of the star

R = radius of the star

T = surface temperature of the star

π,σ = constants

Luminosity Classes

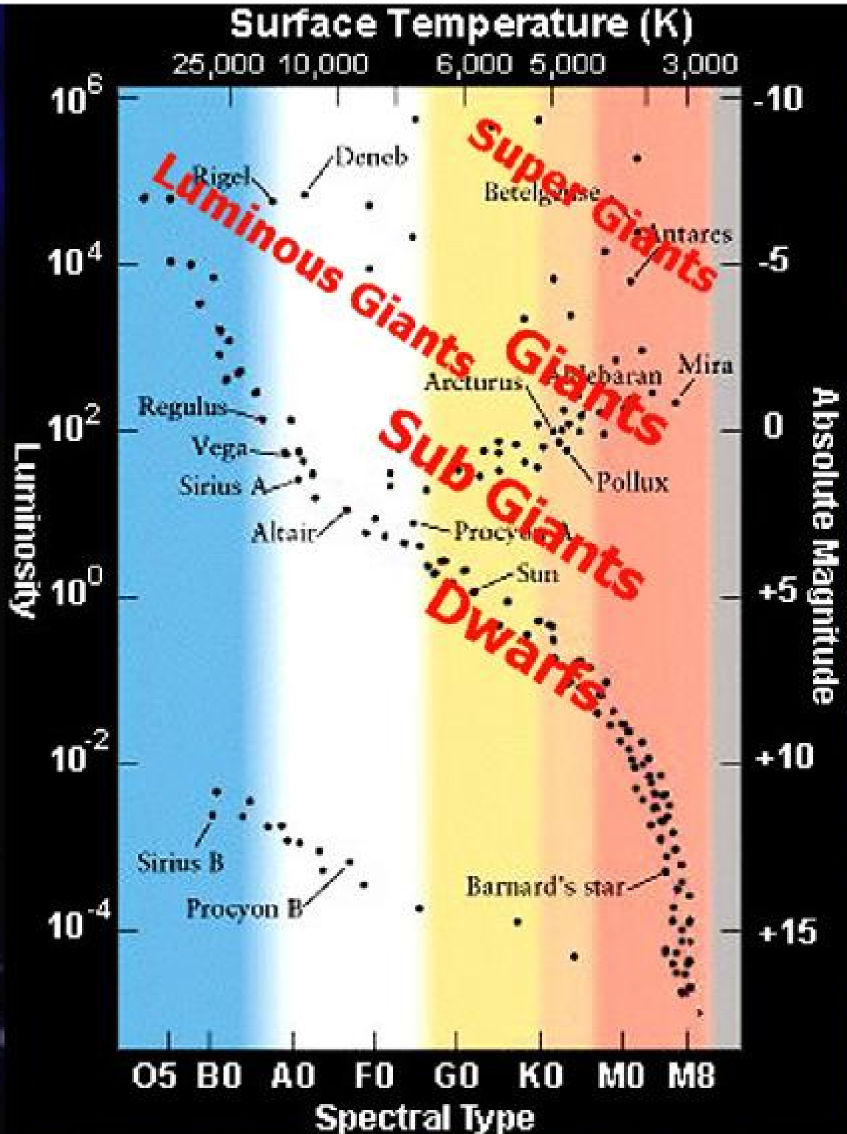
- I Super Giants
- II Luminous Giants
- III Giants
- IV Sub Giants
- V Dwarfs

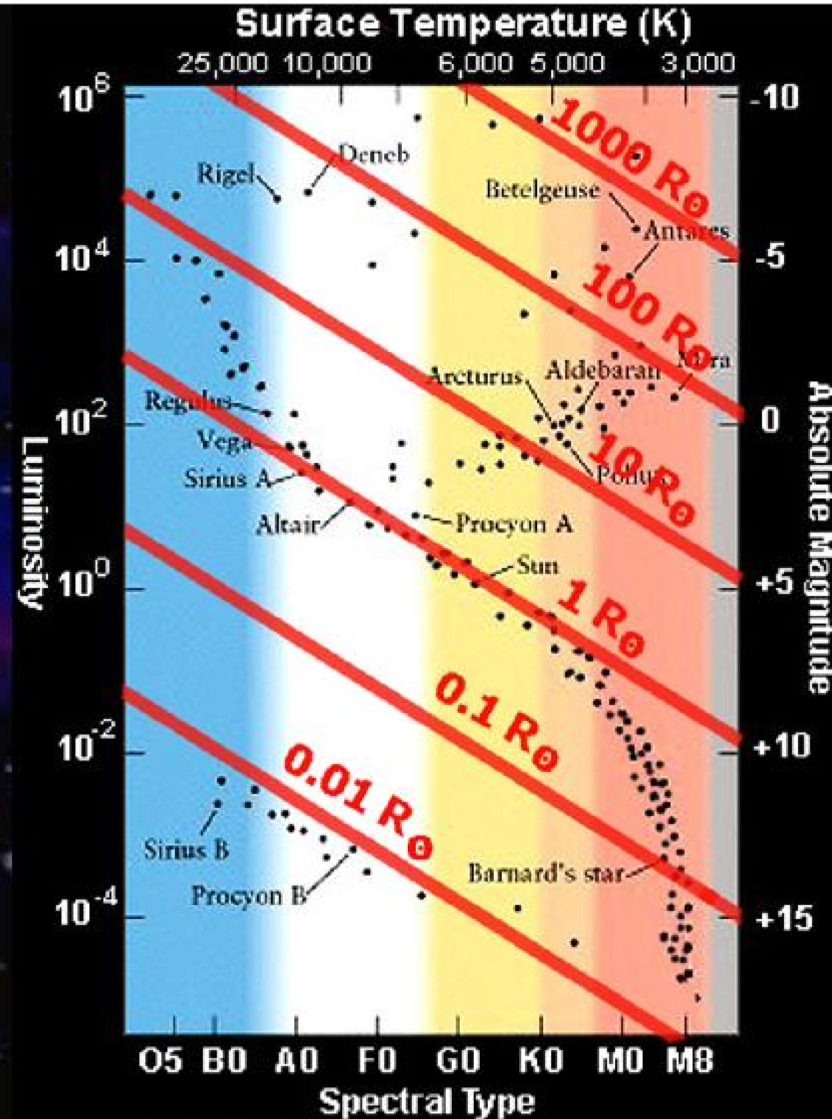
The Sun is a Dwarf…

So finally, stars can be classified...

By spectral type (OBAFGKM)

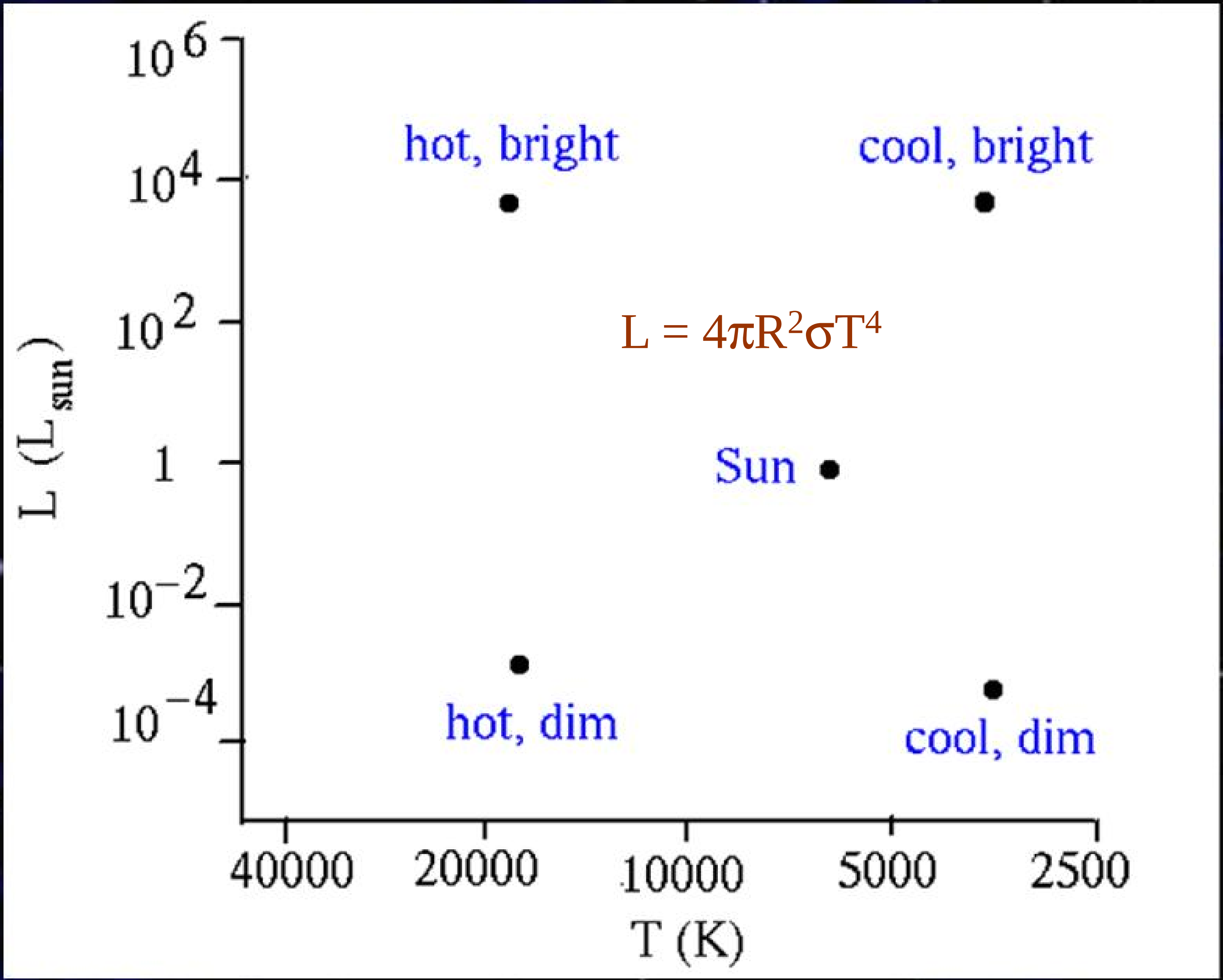
Luminosity class (I,II,III,IV,V)





Betelgeuse: M1 I

Sun: G2 V



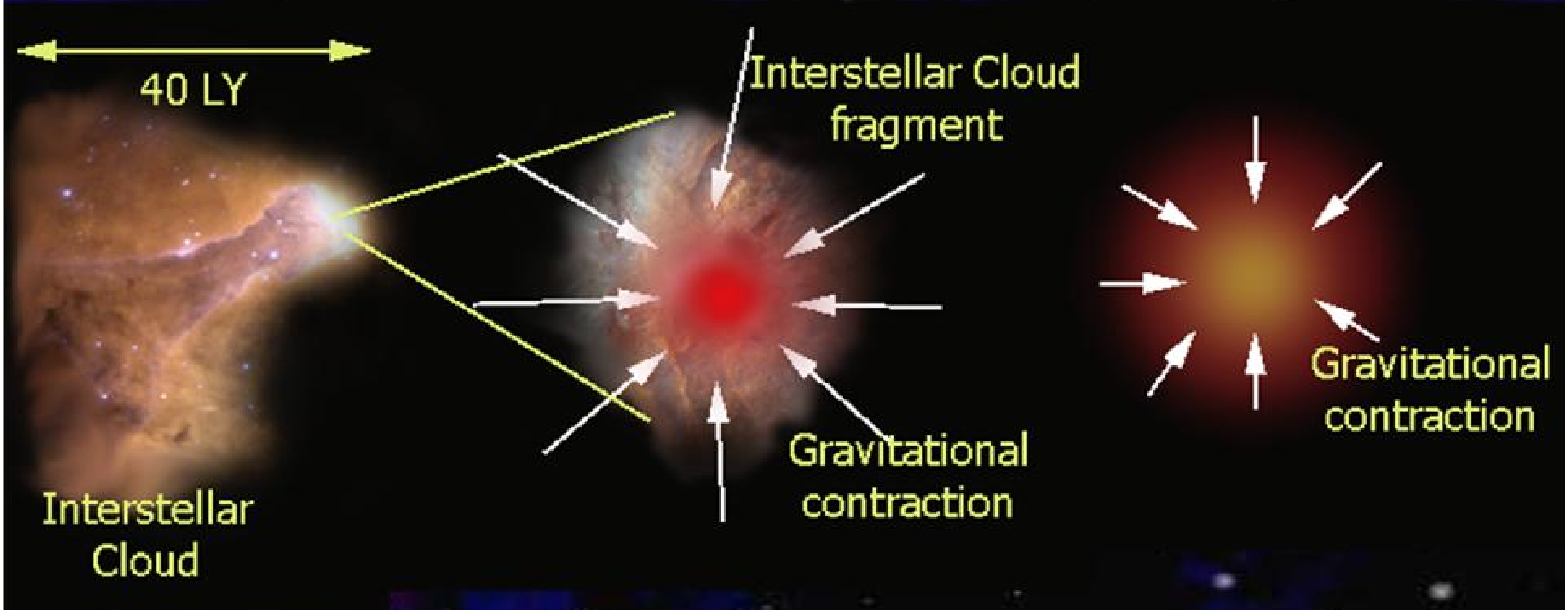
hot, bright
cool, bright
L = 4πR²σT⁴
Sun
hot, dim
cool, dim
L (L_sun)
10^6
10^4
10^2
1
10^-2
10^-4
40000
20000
10000
5000
2500
T (K)

STELLAR FORMATION

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

GRAVITATIONAL CONTRACTION

Stellar Birth



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

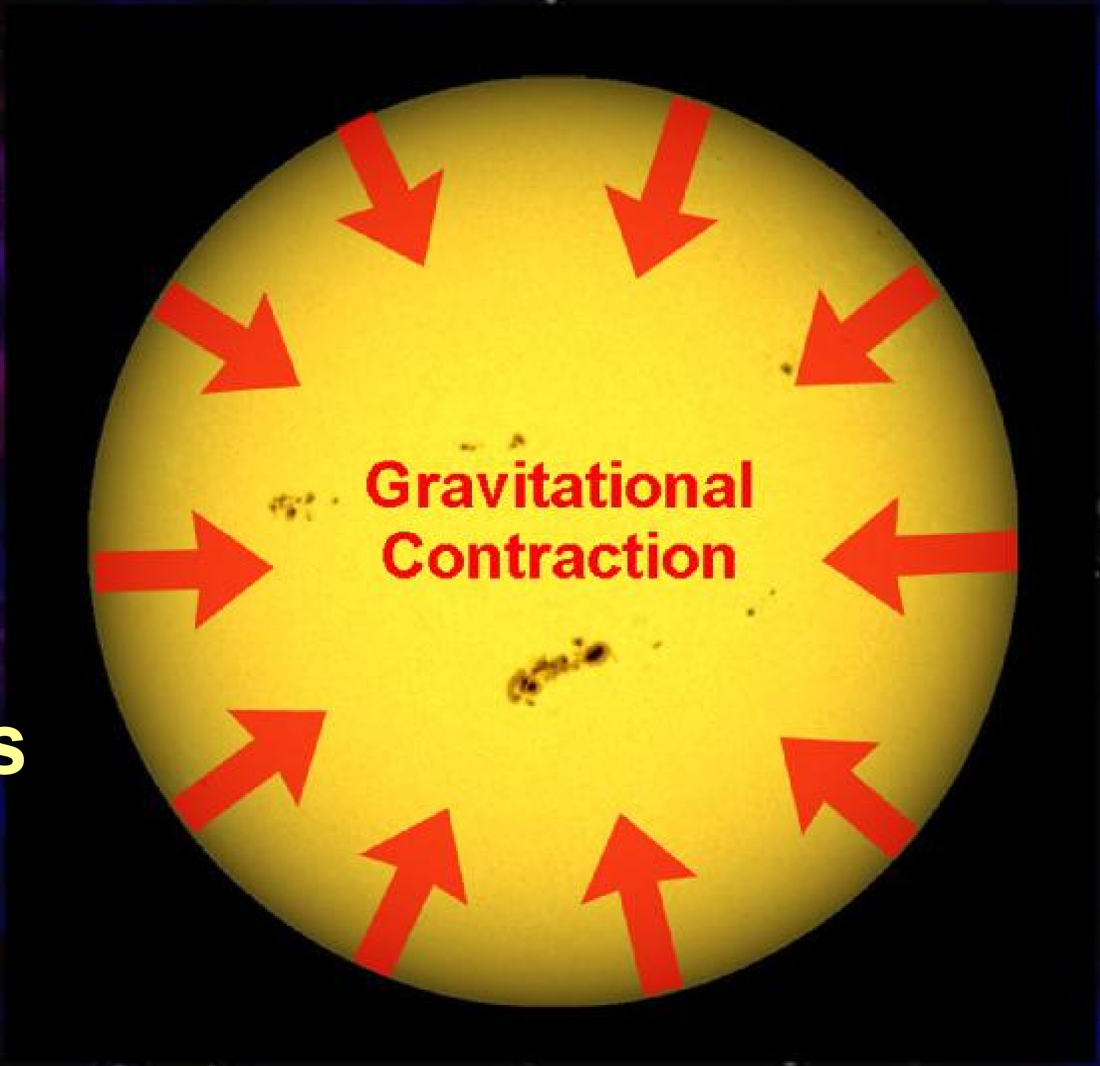
Chemical Burning (coal, wood, gas)

3,000 years

Gravitational Contraction

40 meters/year

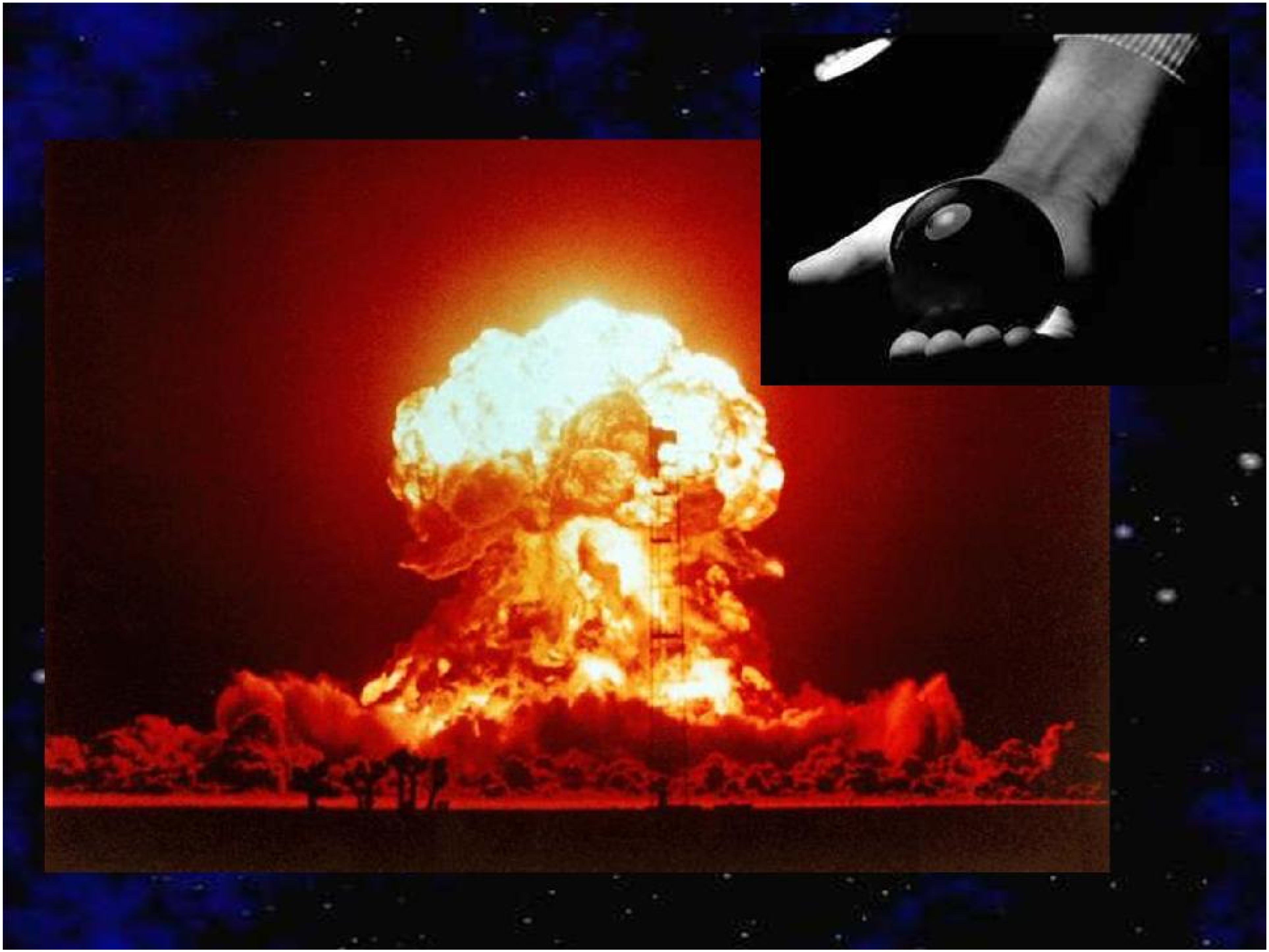
50 million years

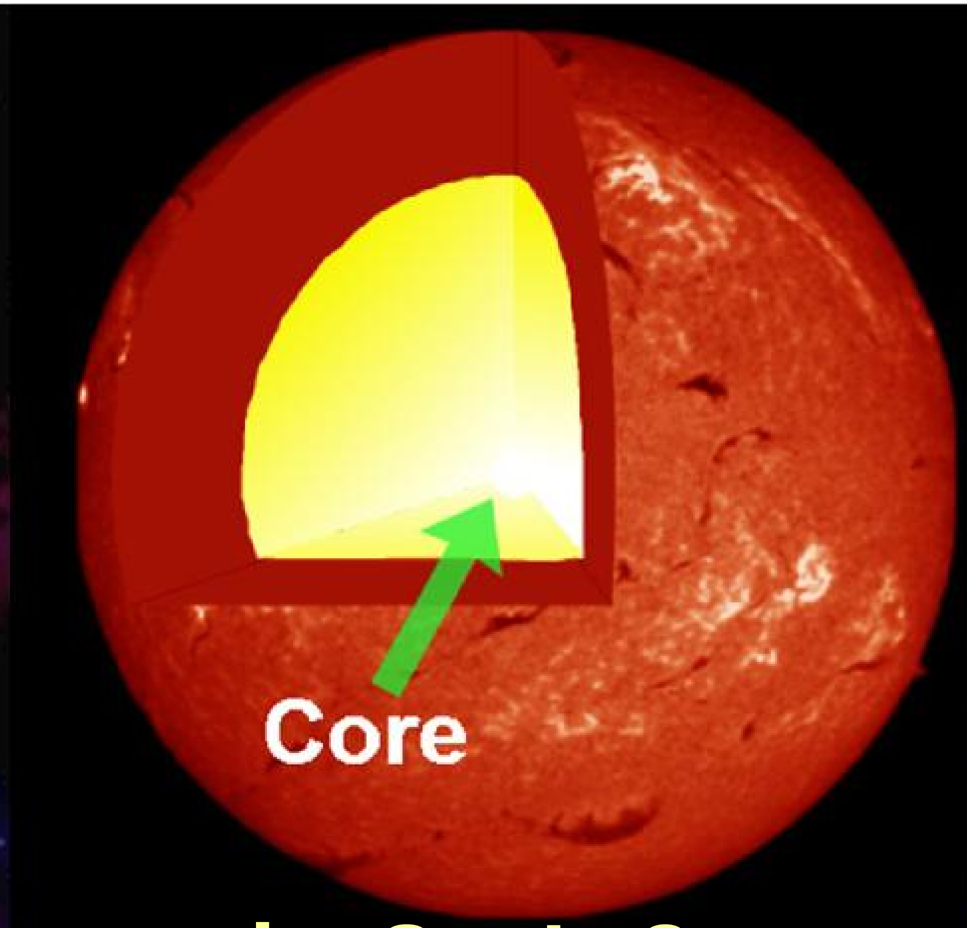


Albert Einstein (1879-1955)

$$E = mc^2$$

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



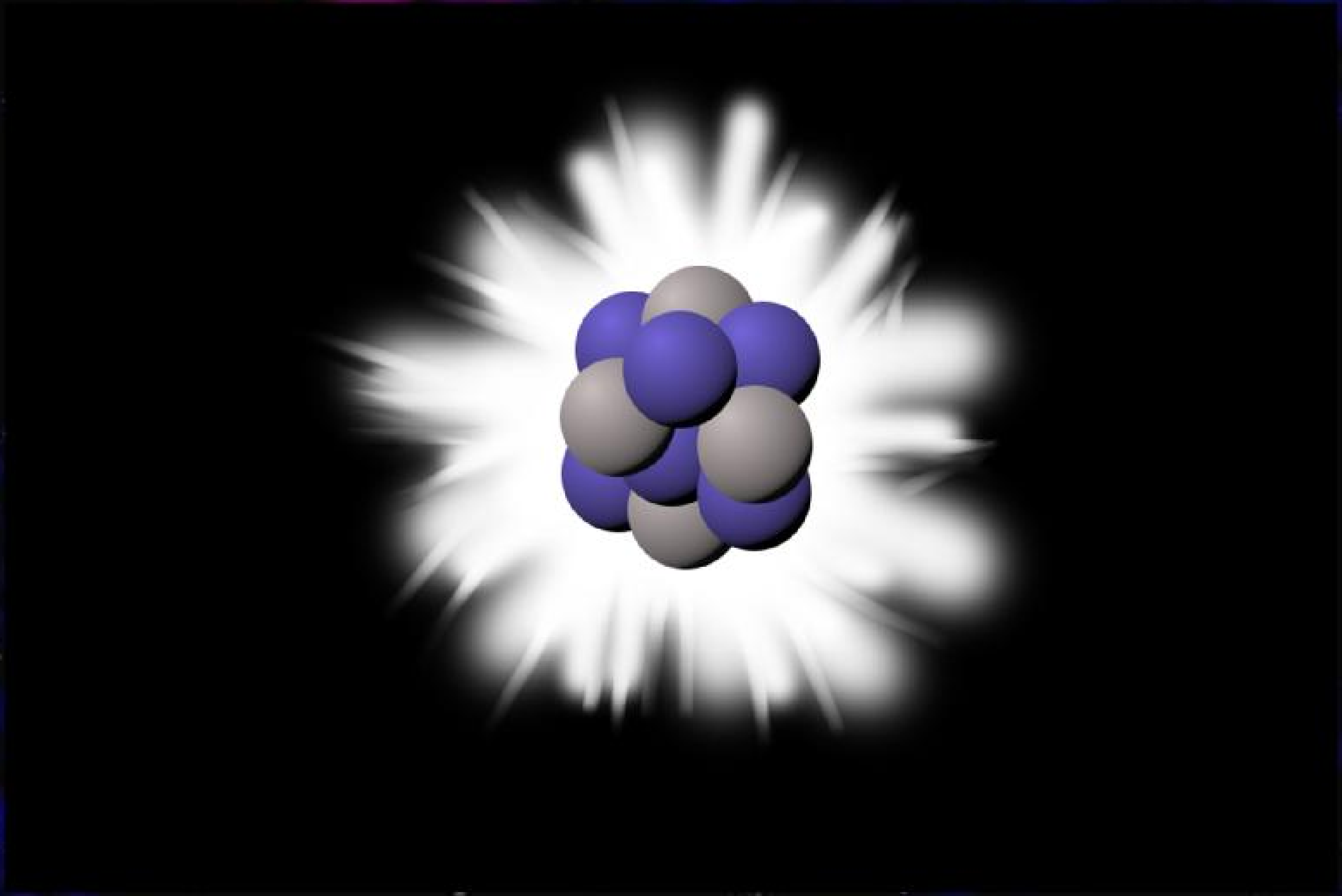


Conditions at the Sun's Core:

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

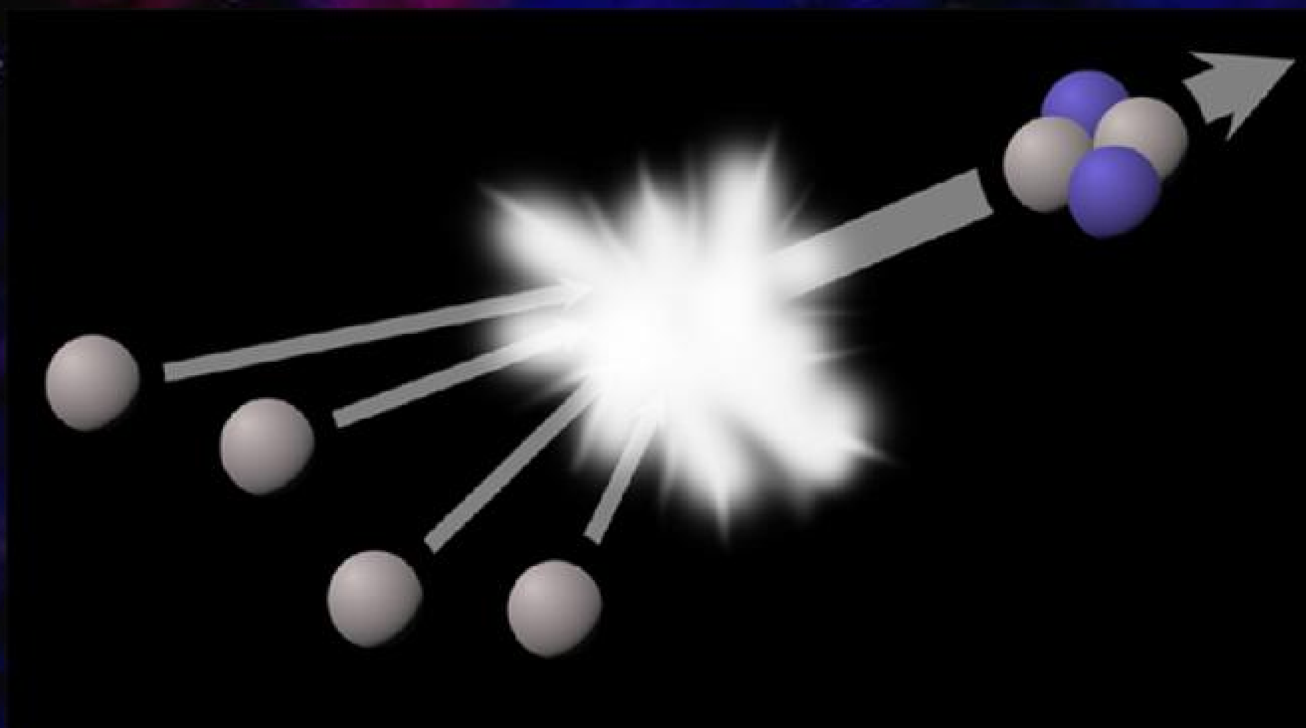
Core Pressure: 3 trillion pounds/in^2

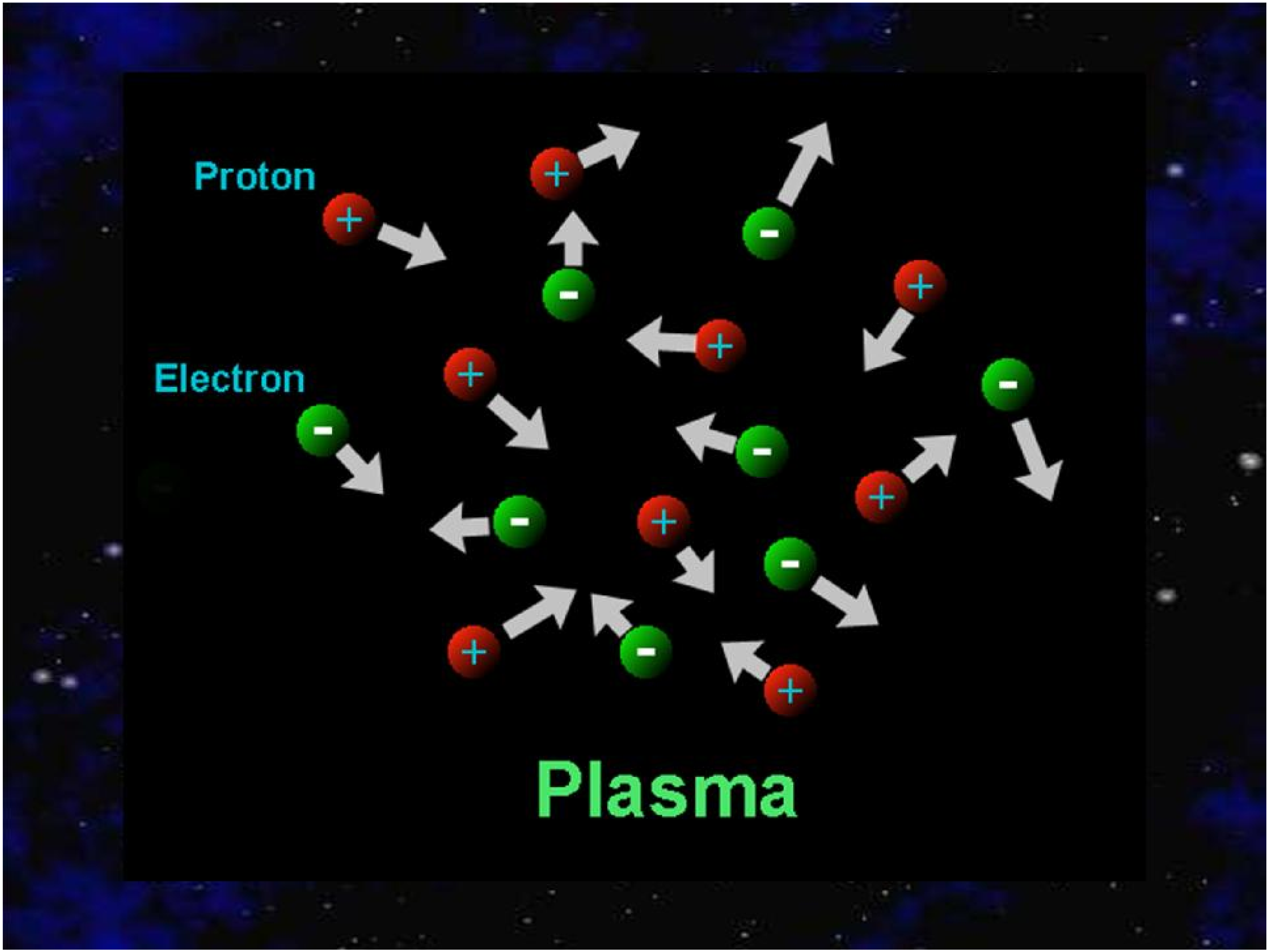
Thermonuclear Fusion



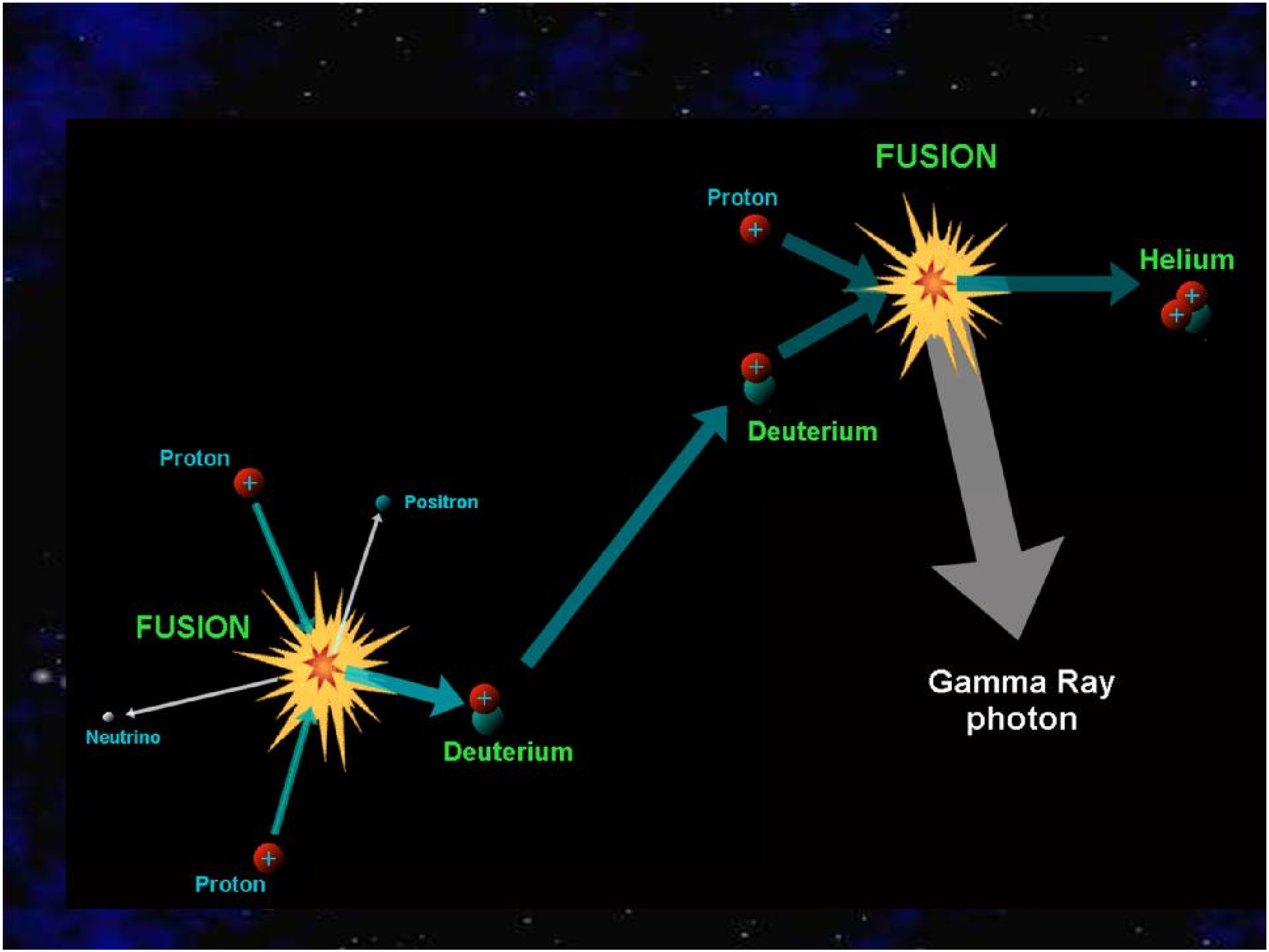
Proton – Proton Cycle

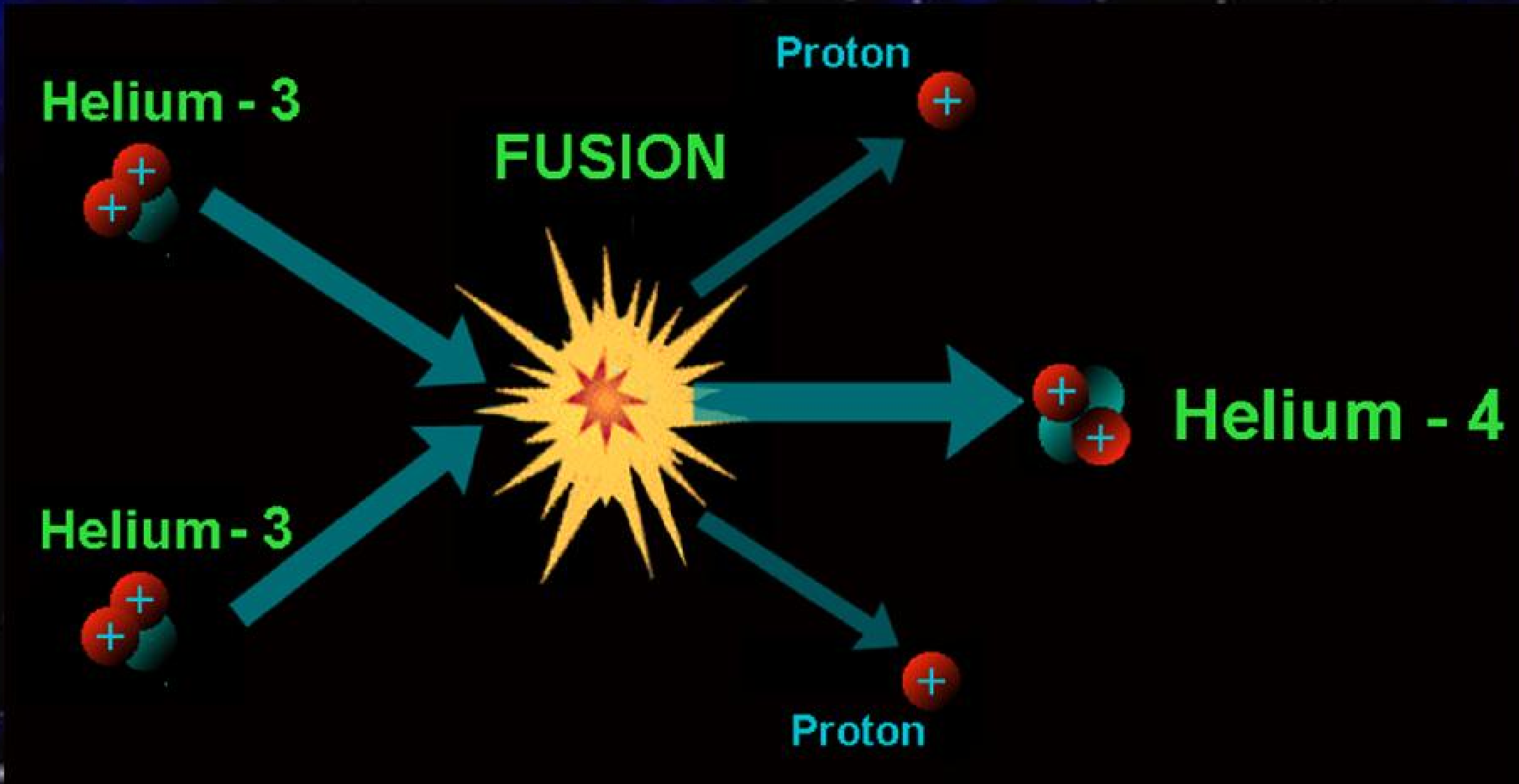
4H ® 1He + 2g



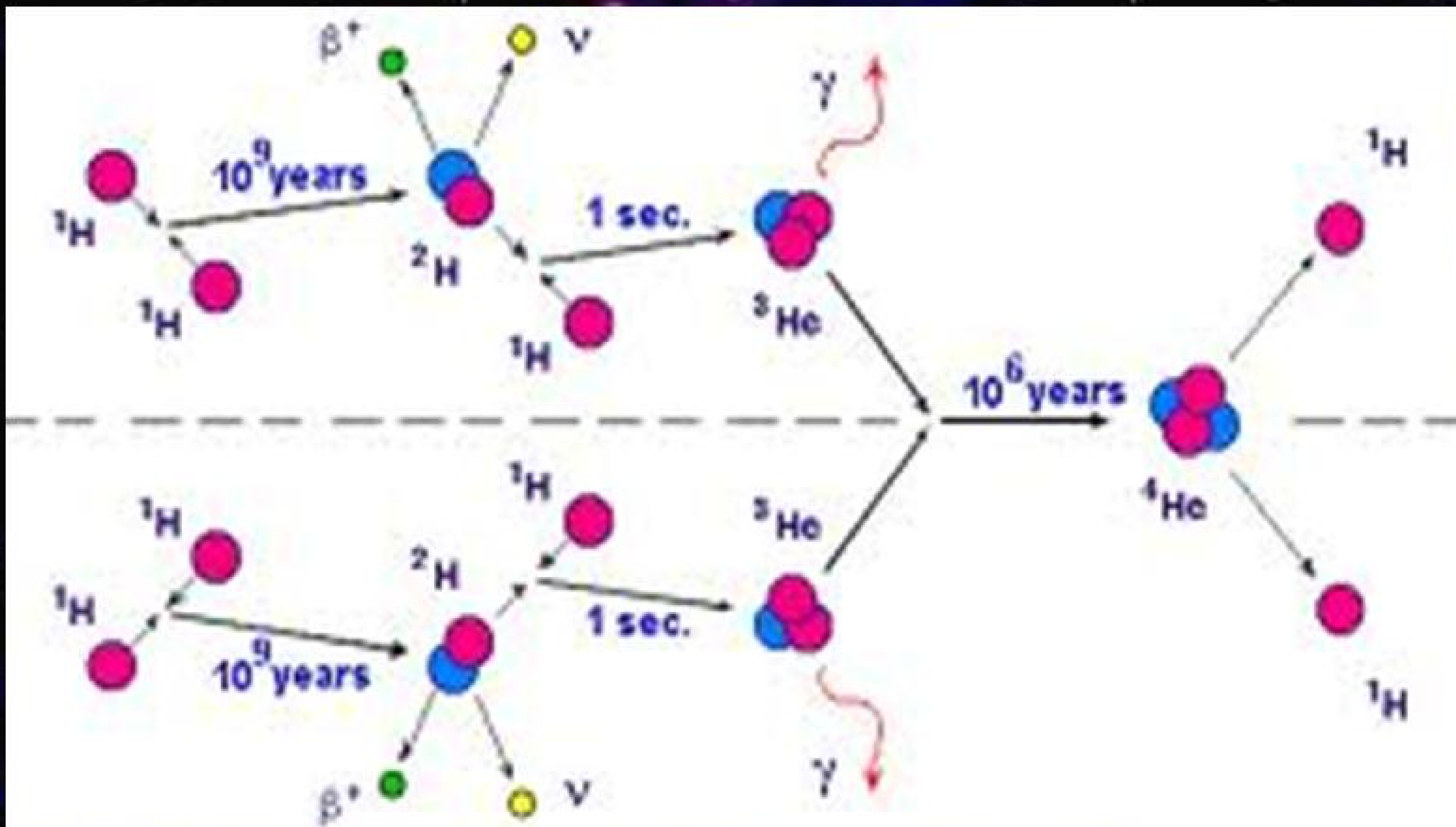

Proton
Electron
Plasma

www.spacetelescope.org


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

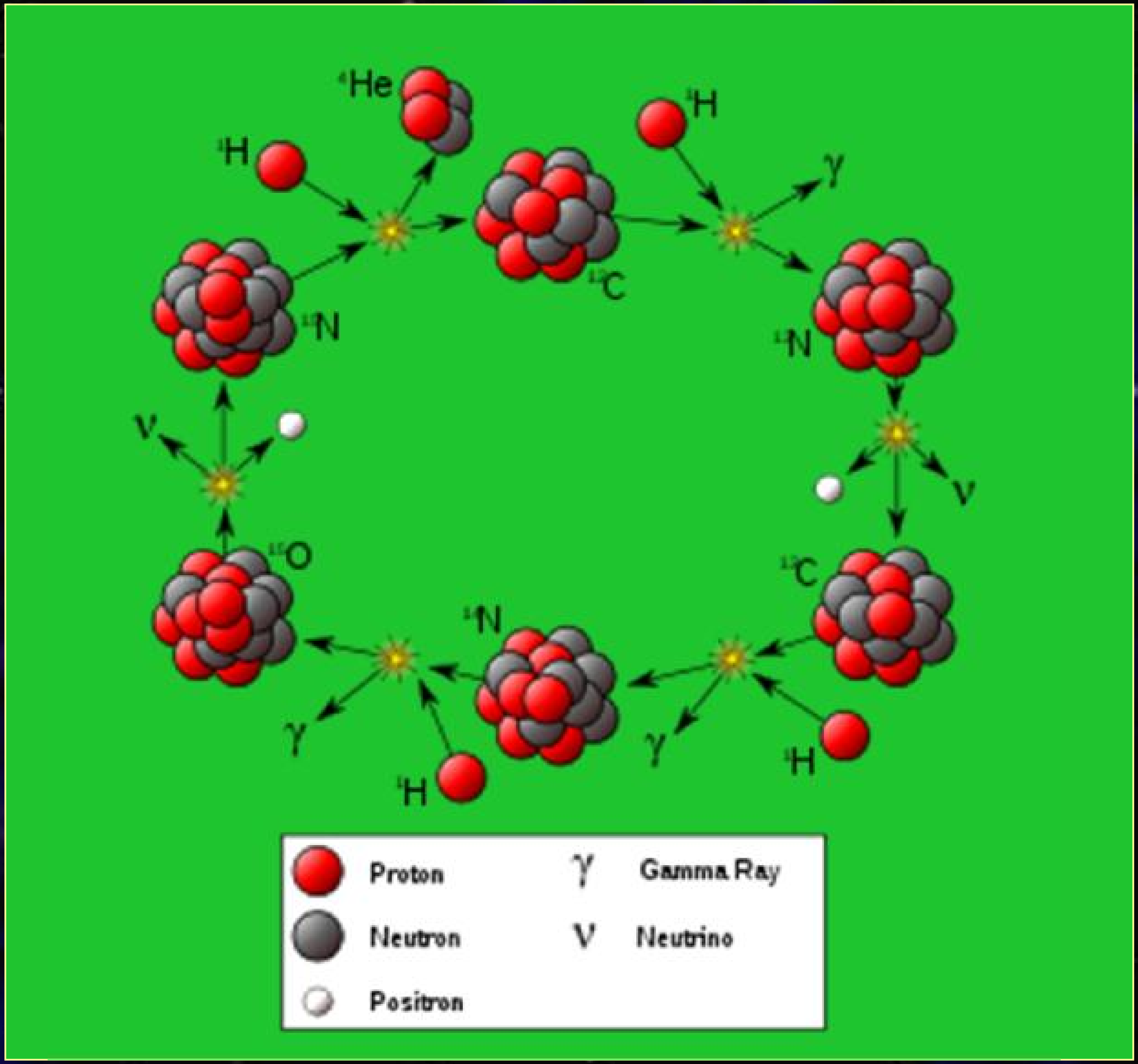


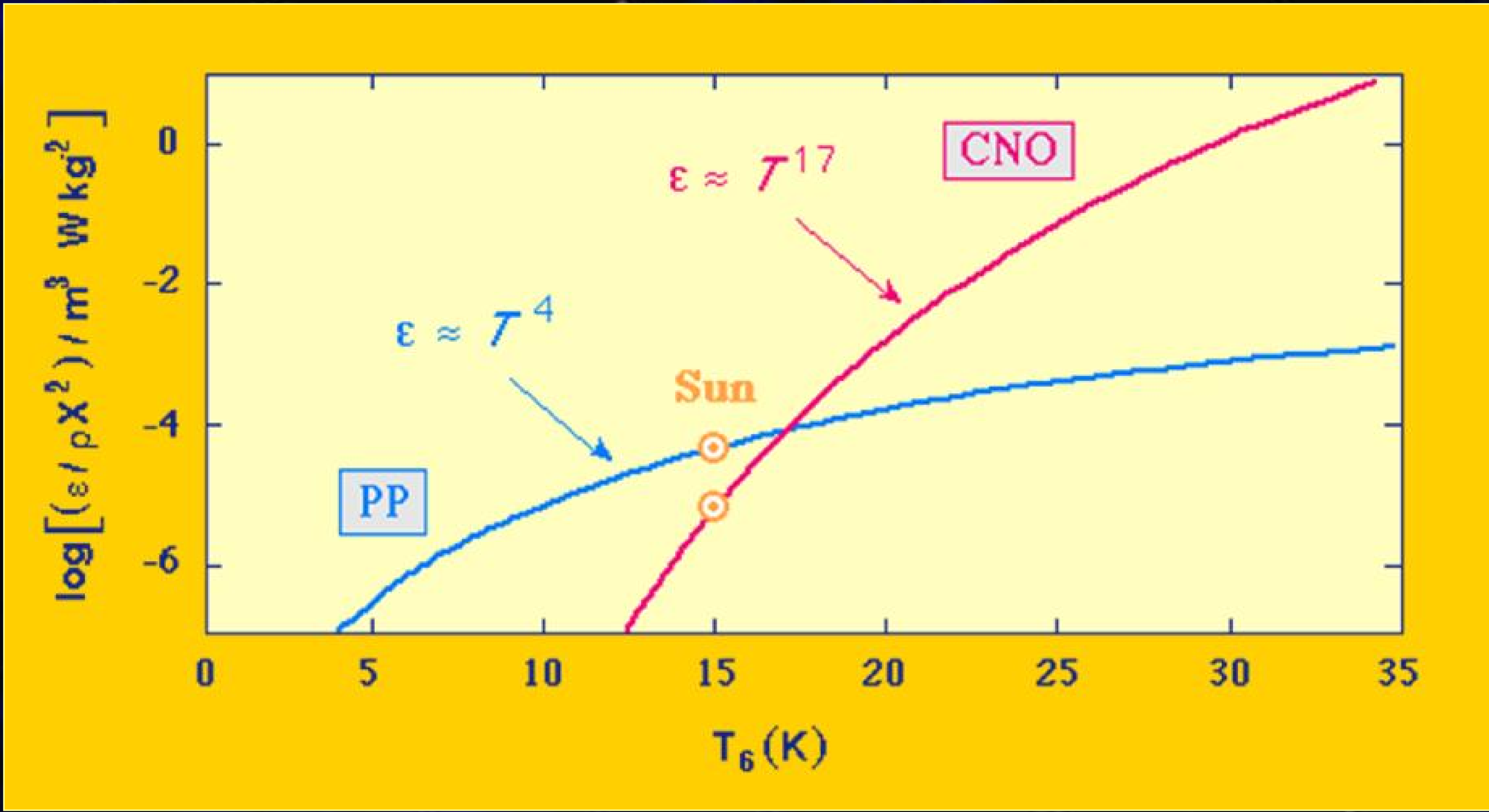
NUCLEOSYNTHESIS



β^+
ν
^1H
^1H
10^9 years
^2H
^1H
1 sec.
γ
^3He
10^6 years
^4He
^1H
^1H
^1H
^1H
^2H
^1H
10^9 years
1 sec.
^3He
γ
β^+
ν

Carbon-Nitrogen-Oxygen Cycle (CNO Cycle)



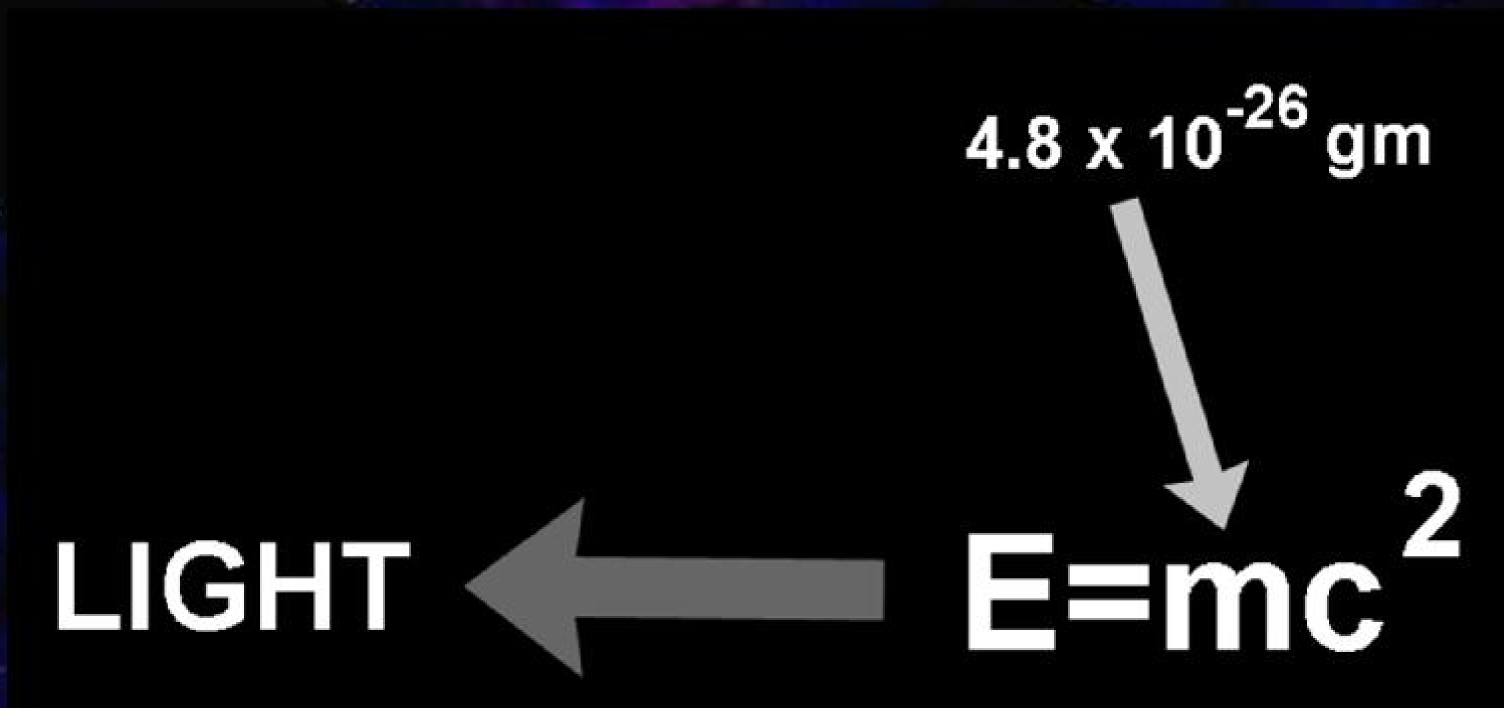


log[(ε / ρX²) / m³ W kg⁻²]
0
-2
-4
-6
0
5
10
15
20
25
30
35
T6 (K)
CNO
ε ≈ T17
ε ≈ T4
Sun
PP

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

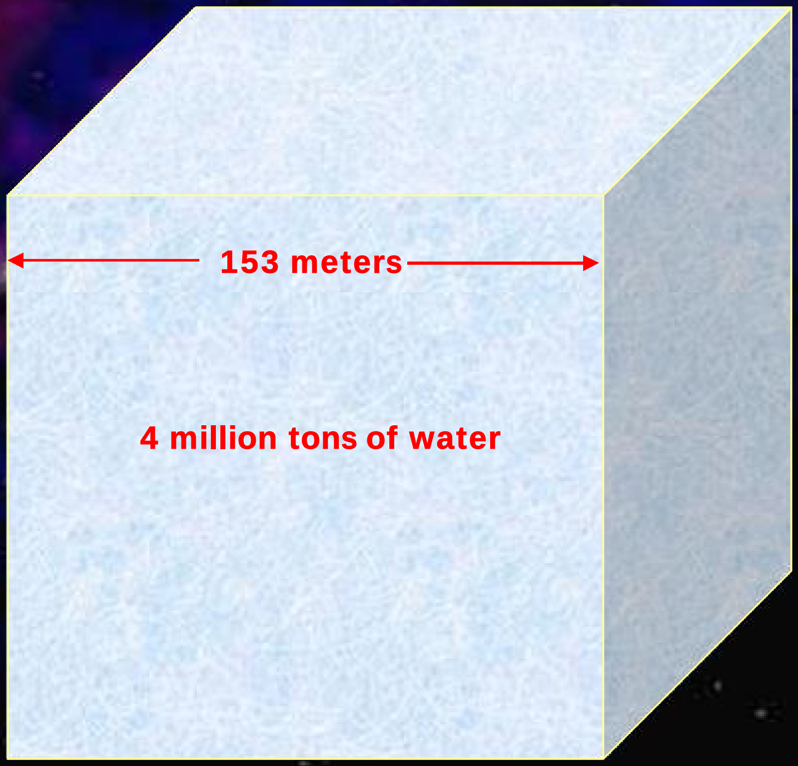
624 million tons of hydrogen

Fuses to become

620 million tons of helium

4 million tons of hydrogen becomes energy

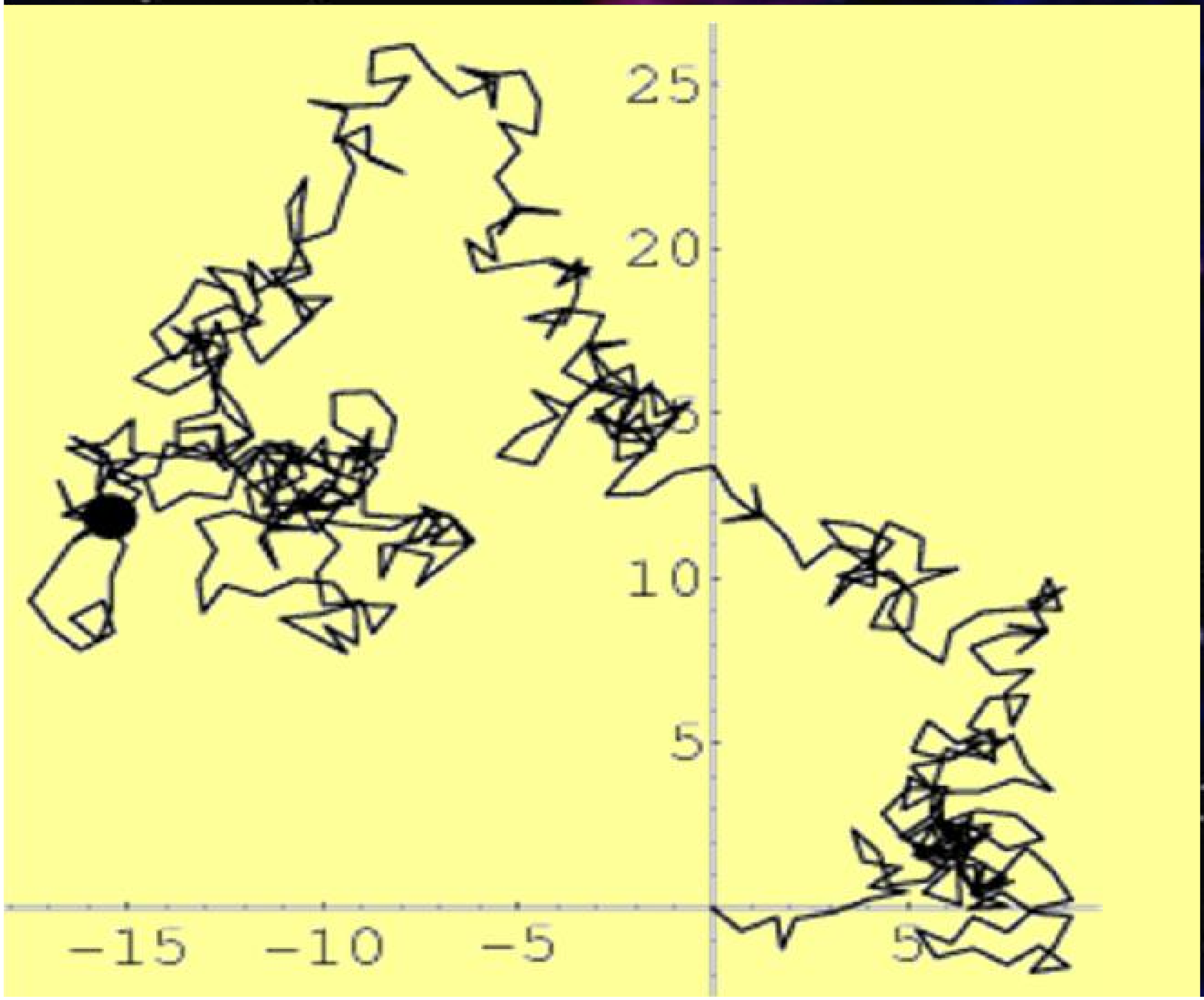
4 million tons of matter becomes energy



$M_{¤}=1.99x10^{30}$ kilograms

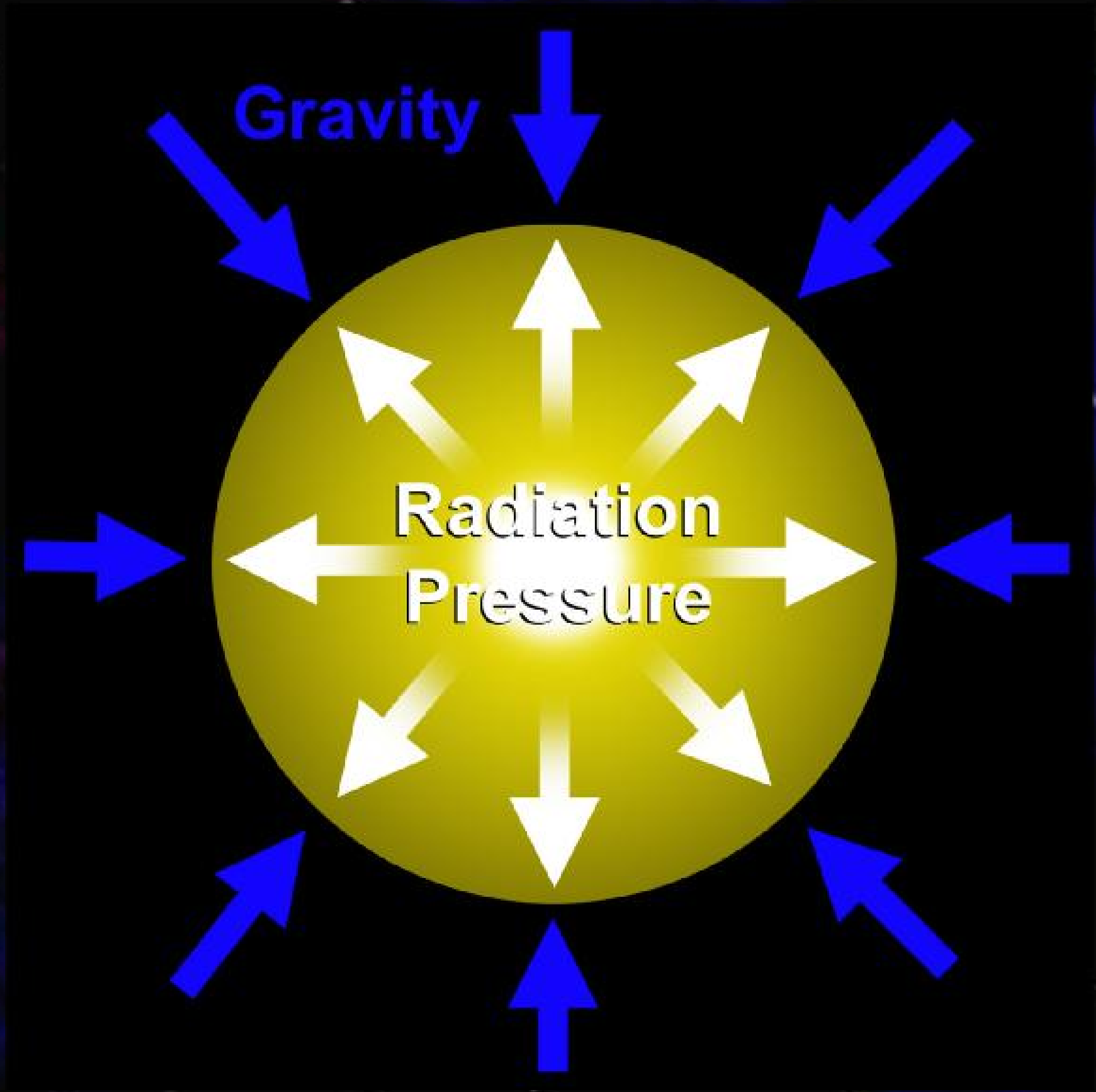
Sun’s lifetime ~ 10 billion years

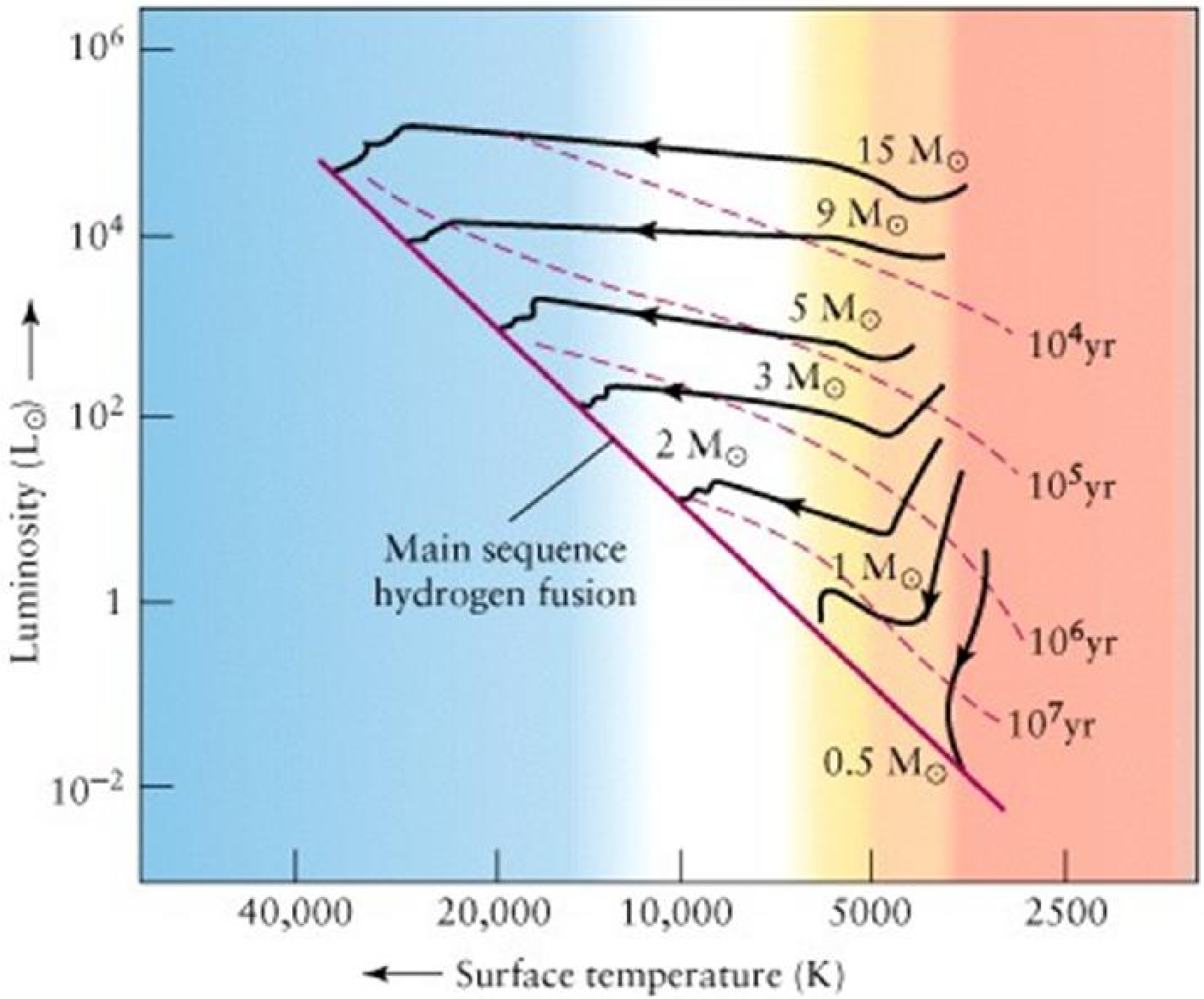
Radiation Escape from the Core – The drunken Random Walk



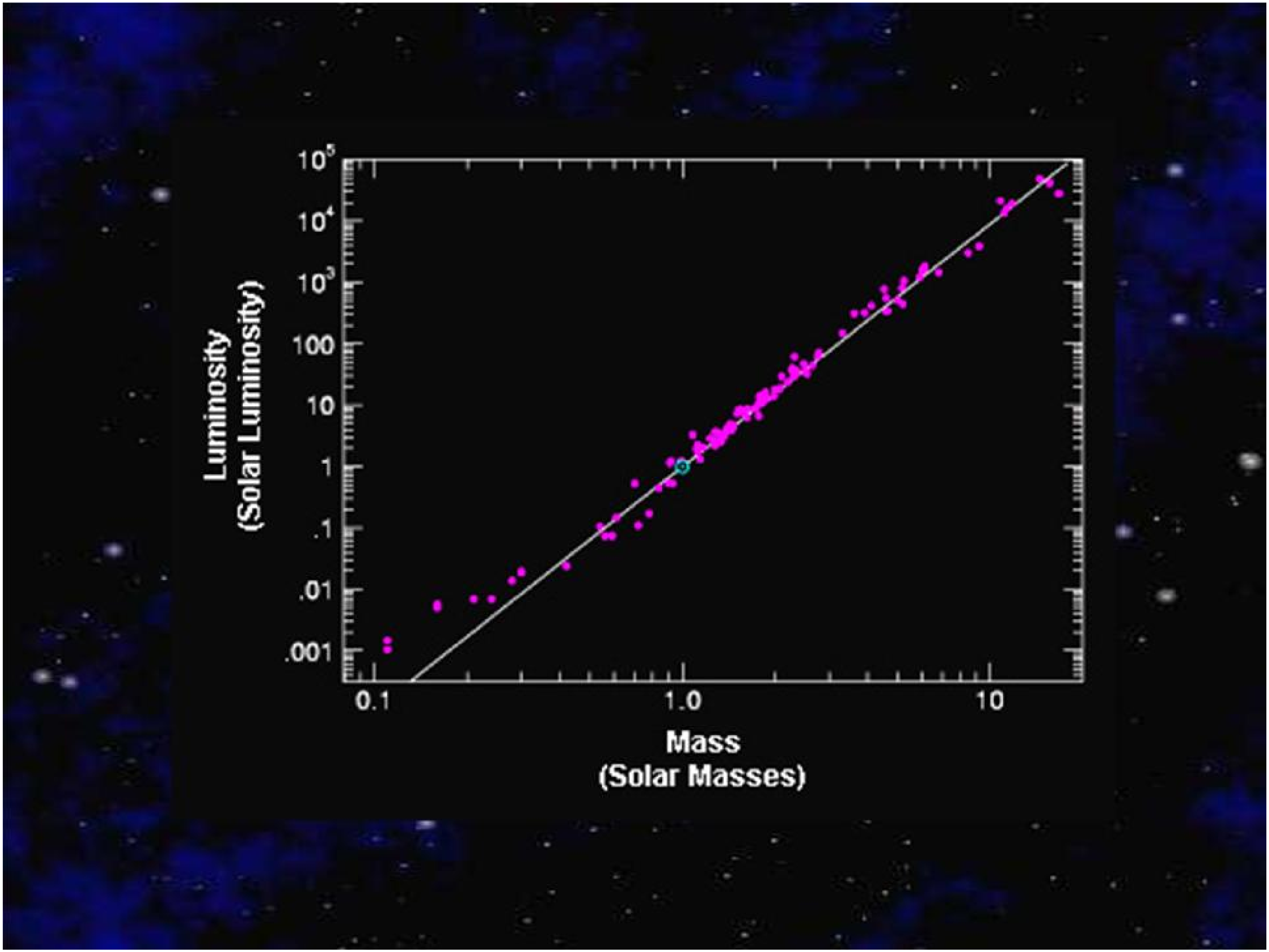
$D = (d/l)^2$

Hydrostatic Equilibrium





Luminosity ($L_\odot$)
10^6
10^4
10^2
1
10^{-2}
15 $M_\odot$
9 $M_\odot$
5 $M_\odot$
3 $M_\odot$
2 $M_\odot$
1 $M_\odot$
0.5 $M_\odot$
10^4yr
10^5yr
10^6yr
10^7yr
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
10³
10⁴
10⁵

Main Sequence Lifetime

15 M. _ 10^7 years

0.5 M. _ $3x10^{10}$ years

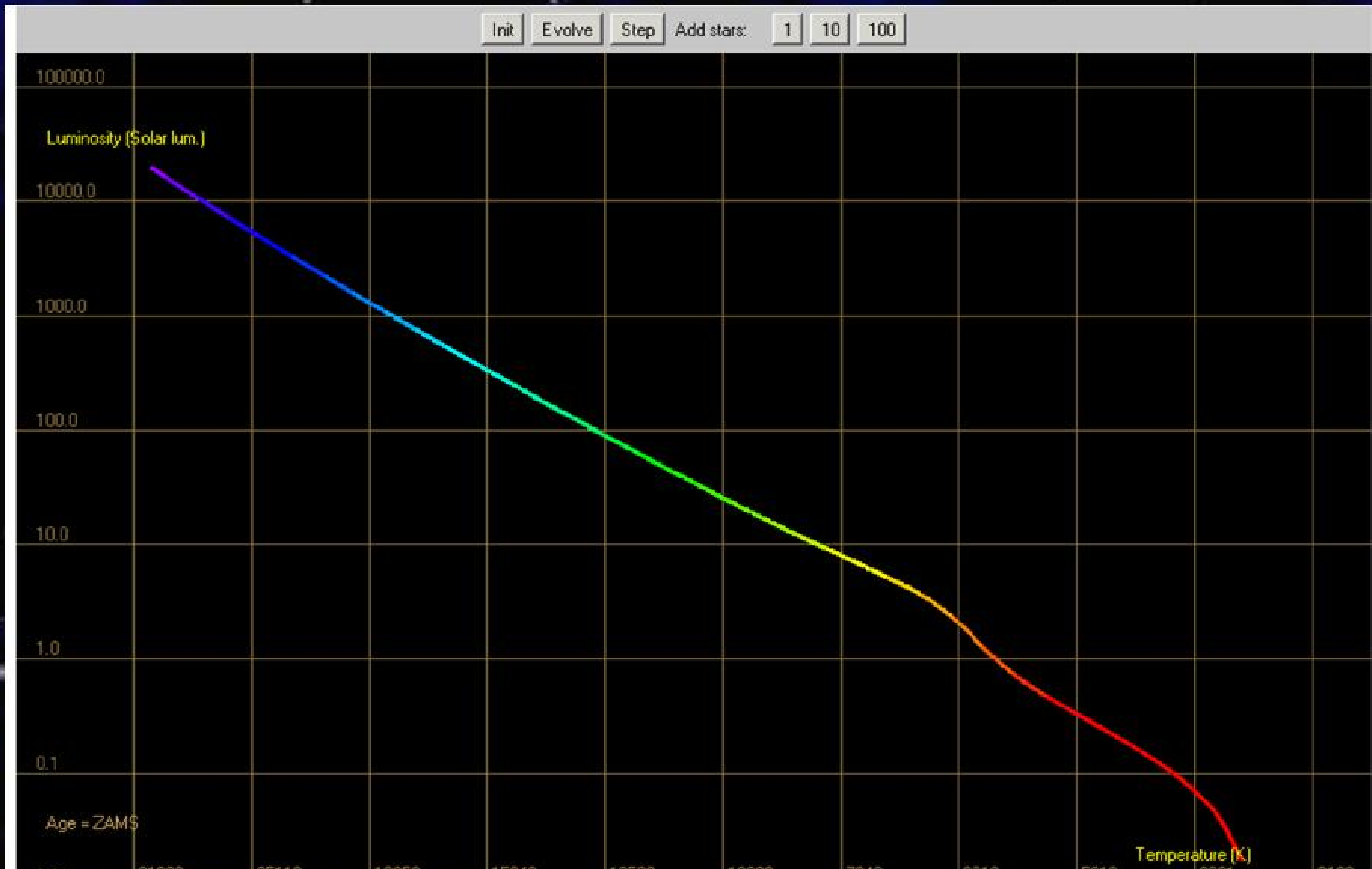
Why does a more massive star live a shorter lifetime?

Fuel consumption!

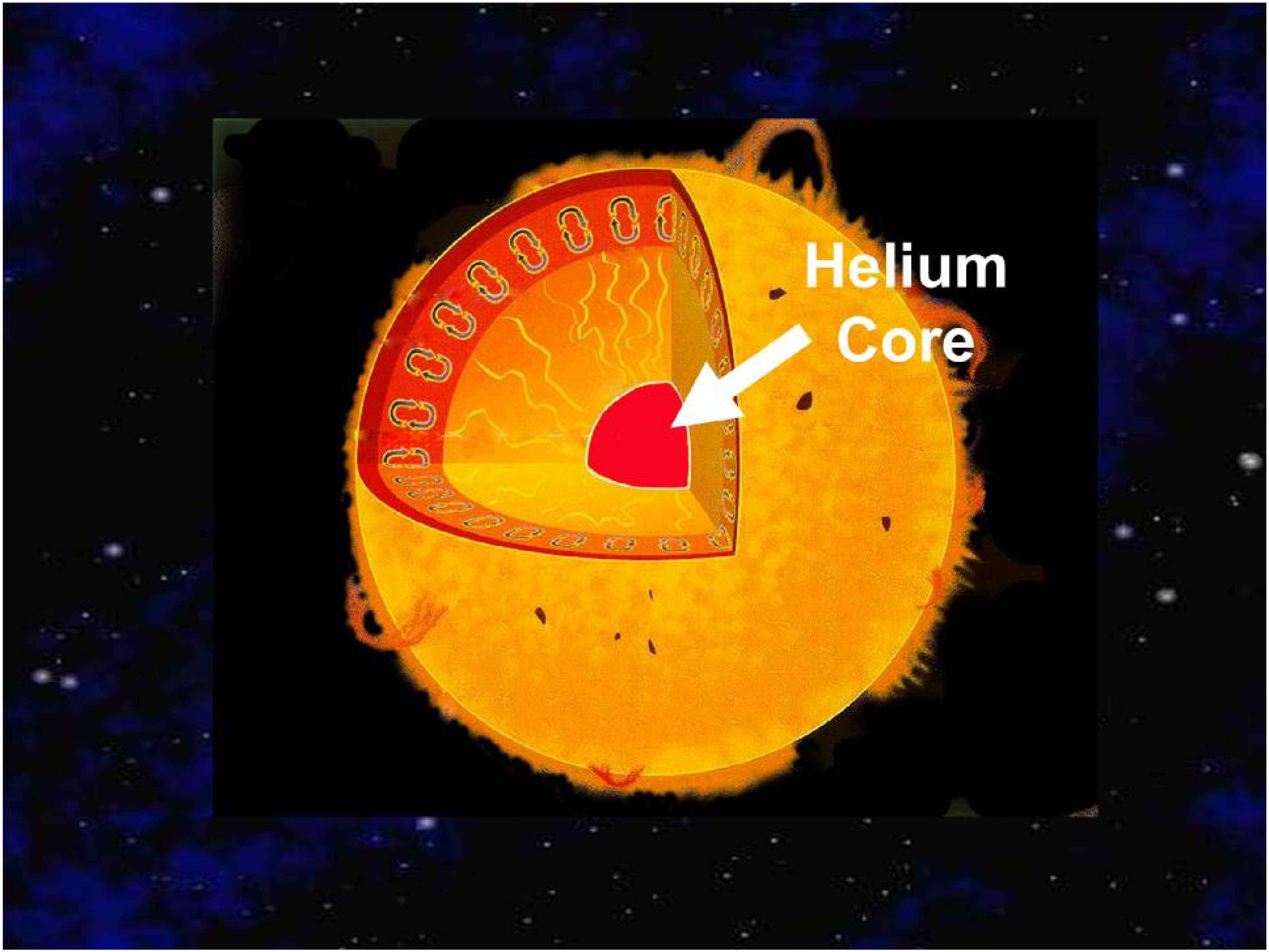
15 M. _ 10^7-10^8 K

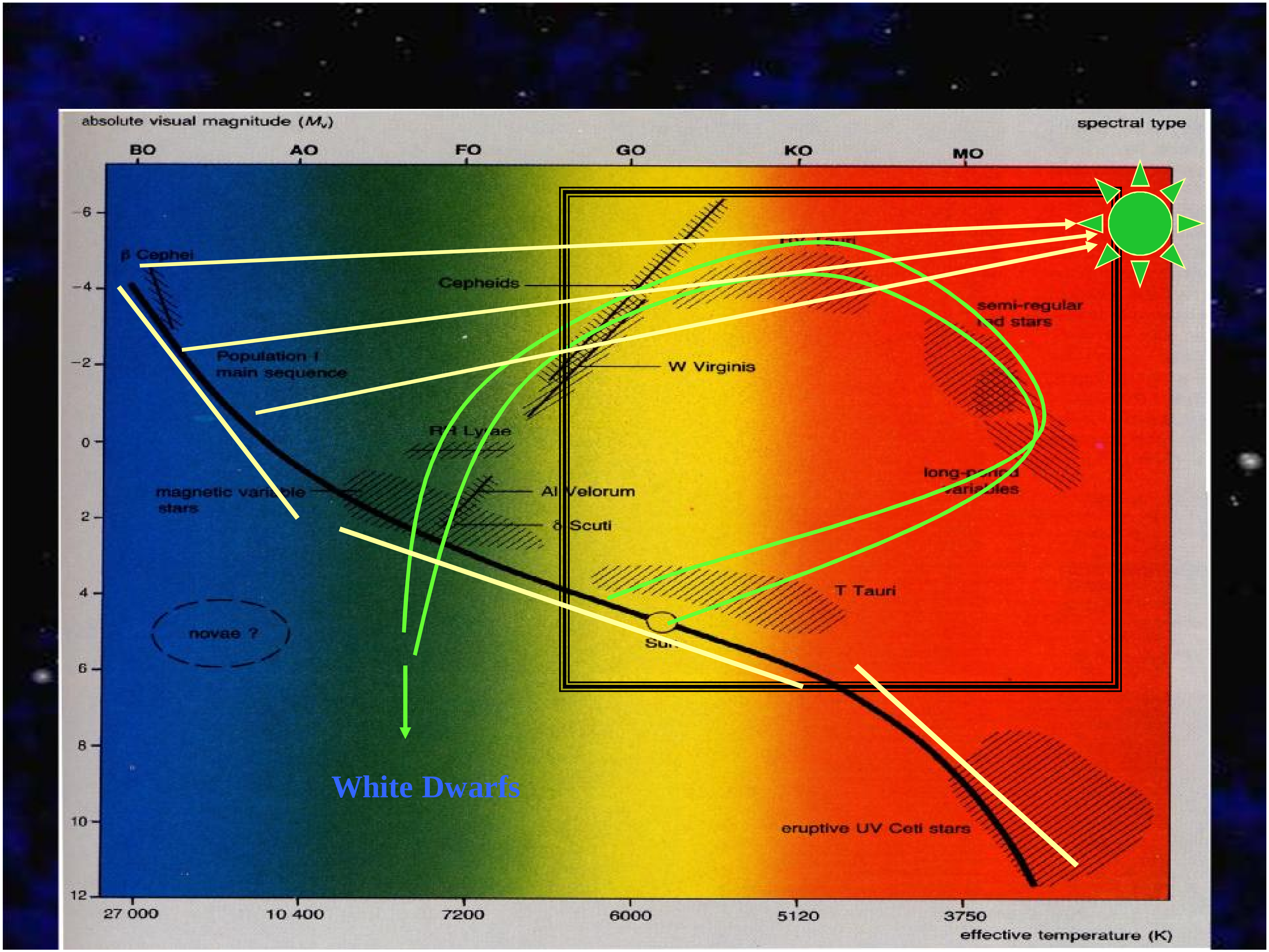
0.5 M. _ 10^6's K

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



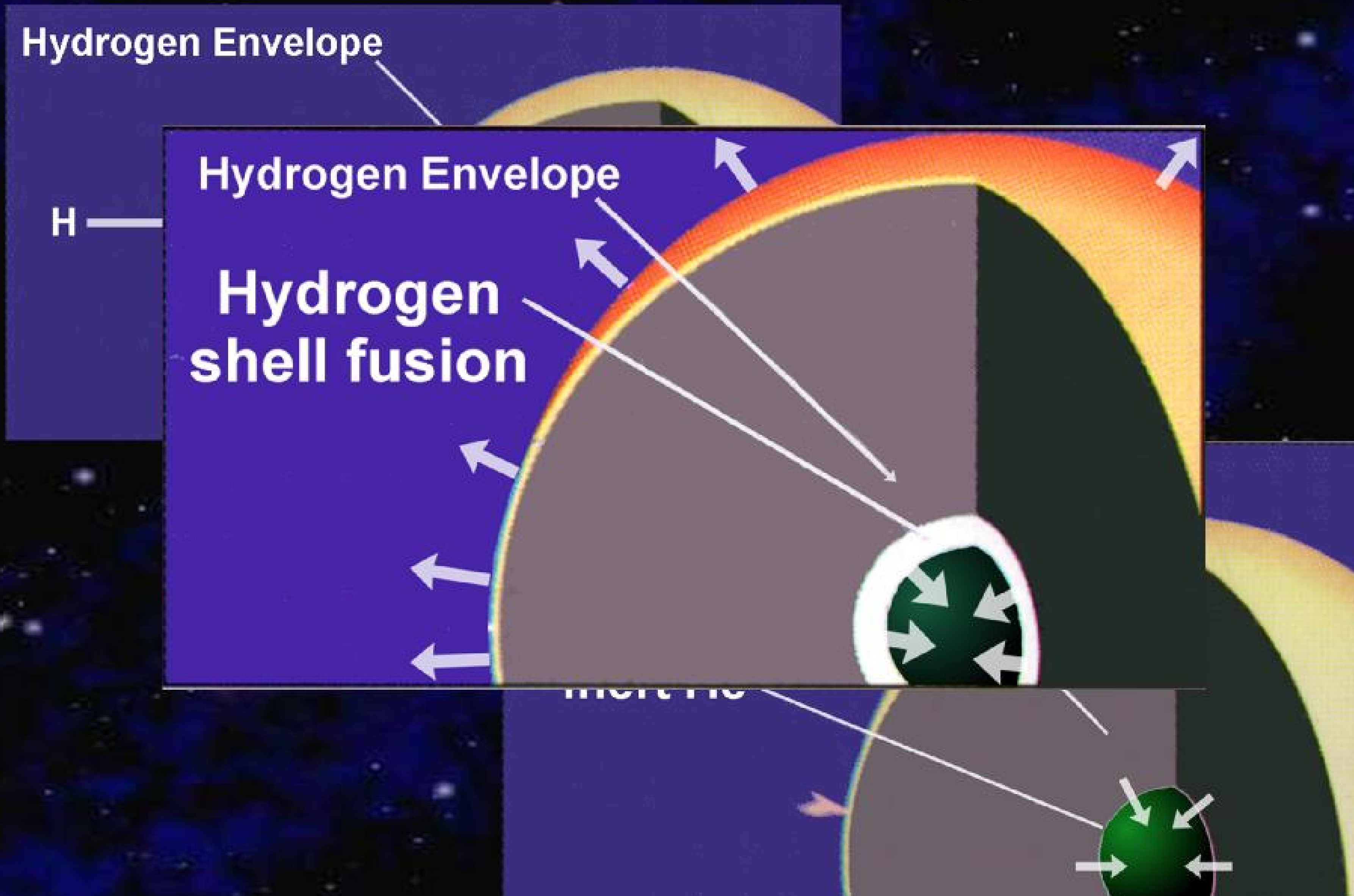
Init
Evolve
Step
Add stars:
1
10
100
100000.0
Luminosity (Solar lum.)
10000.0
1000.0
100.0
10.0
1.0
0.1
Age = ZAMS
Temperature (K)

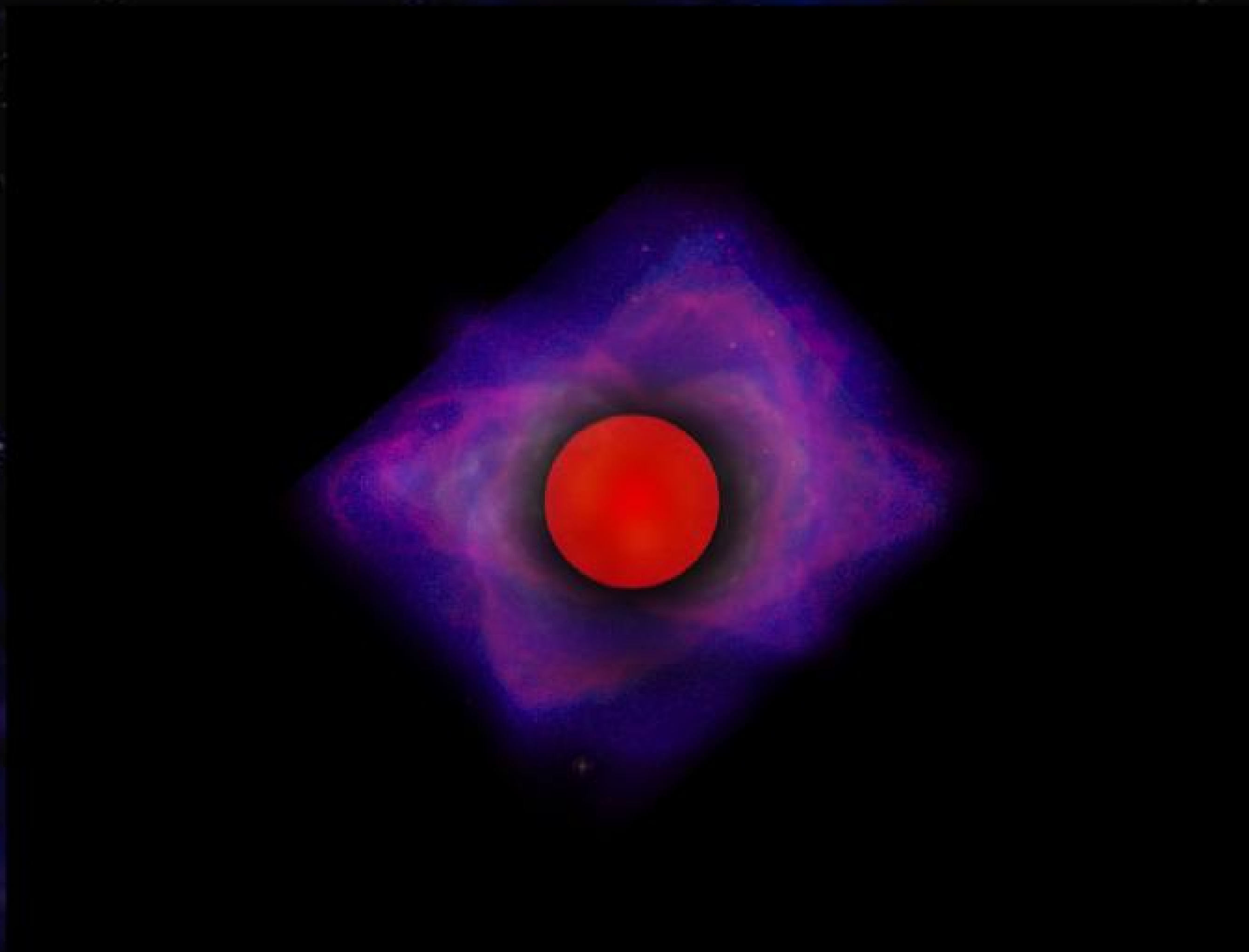

Helium
Core



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 red stars
Population I main sequence
W Virginis
RR Lyrae
magnetic variable stars
Al Velorum
δ Scuti
T Tauri
novae ?
Sun
White Dwarfs
eruptive UV Ceti stars
27 000
10 400
7200
6000
5120
3750
effective temperature (K)

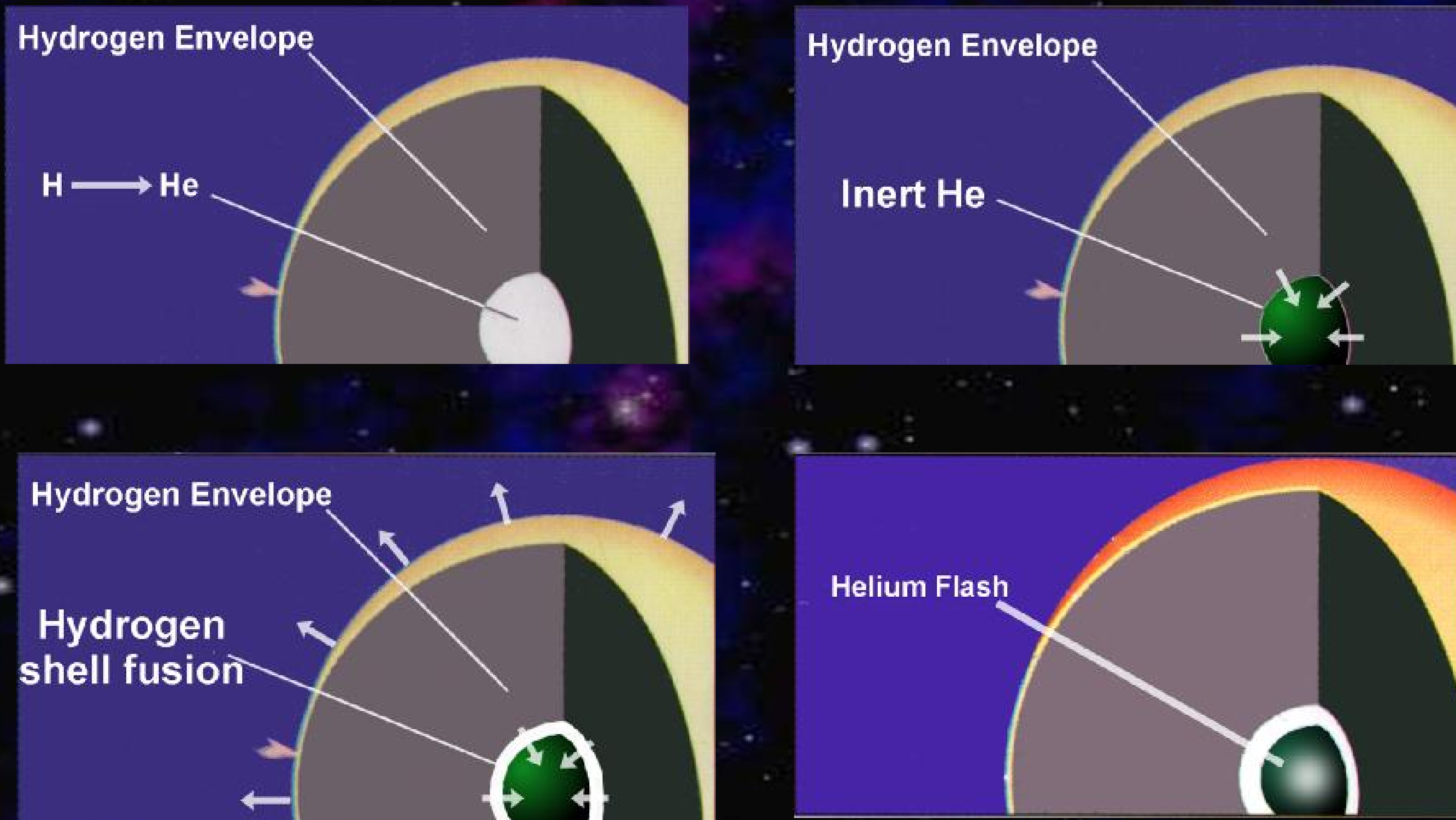
1. Low Mass Stars $M < 0.5 M_{\odot}$

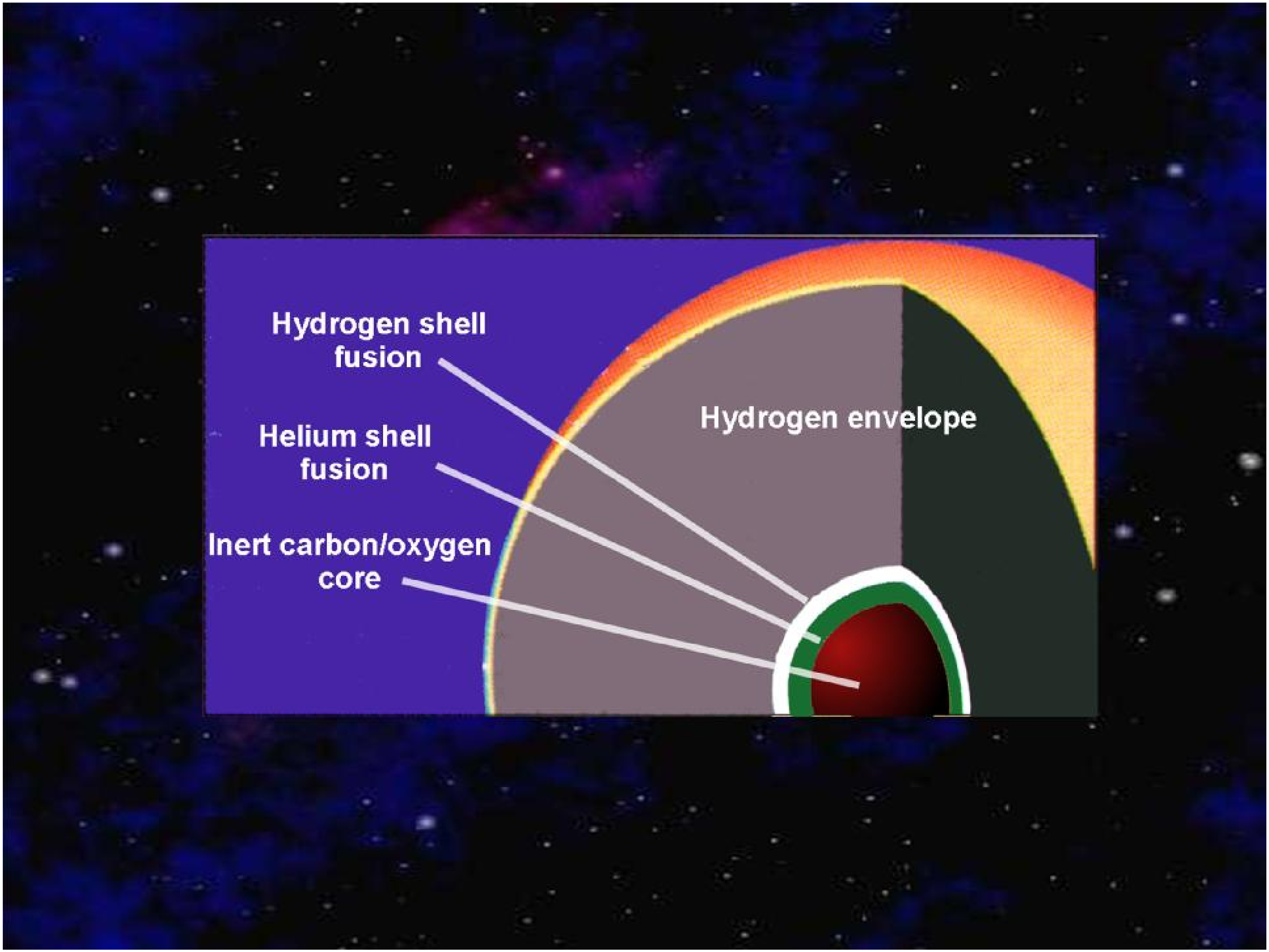


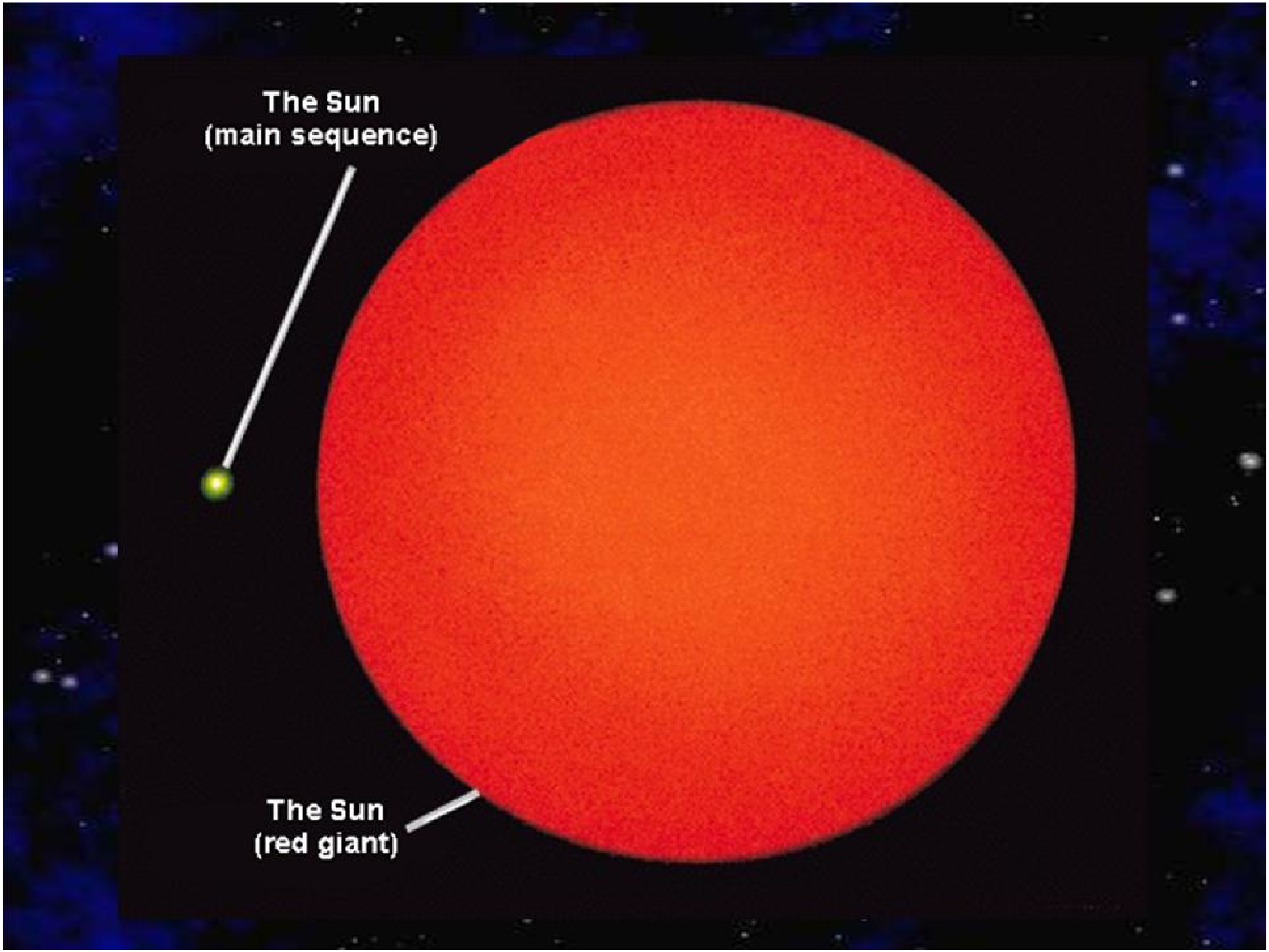


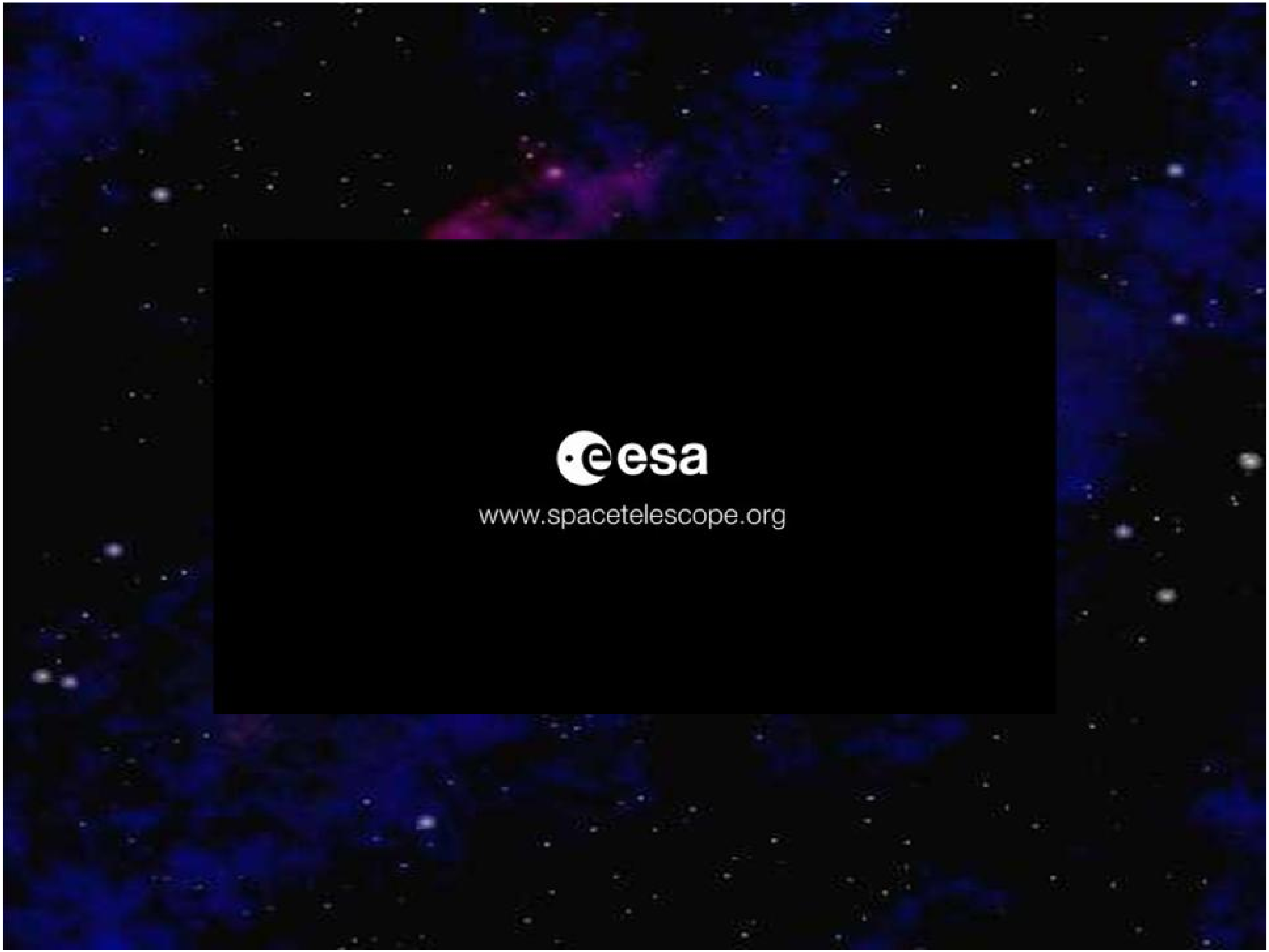
30% – 40% of total mass is lost

2. Intermediate Mass Stars
0.5 < M



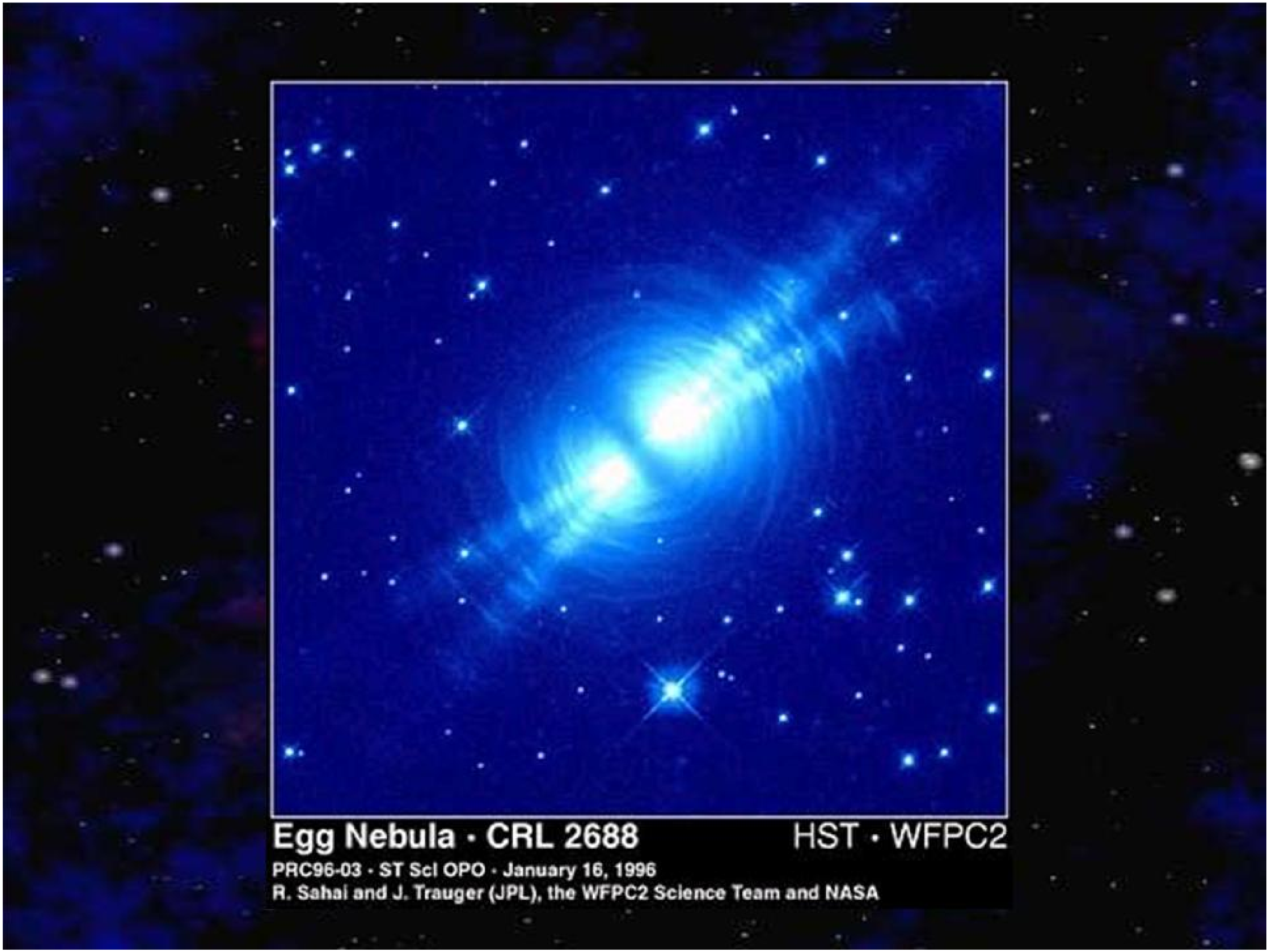

Hydrogen shell fusion
Helium shell fusion
Inert carbon/oxygen core
Hydrogen envelope

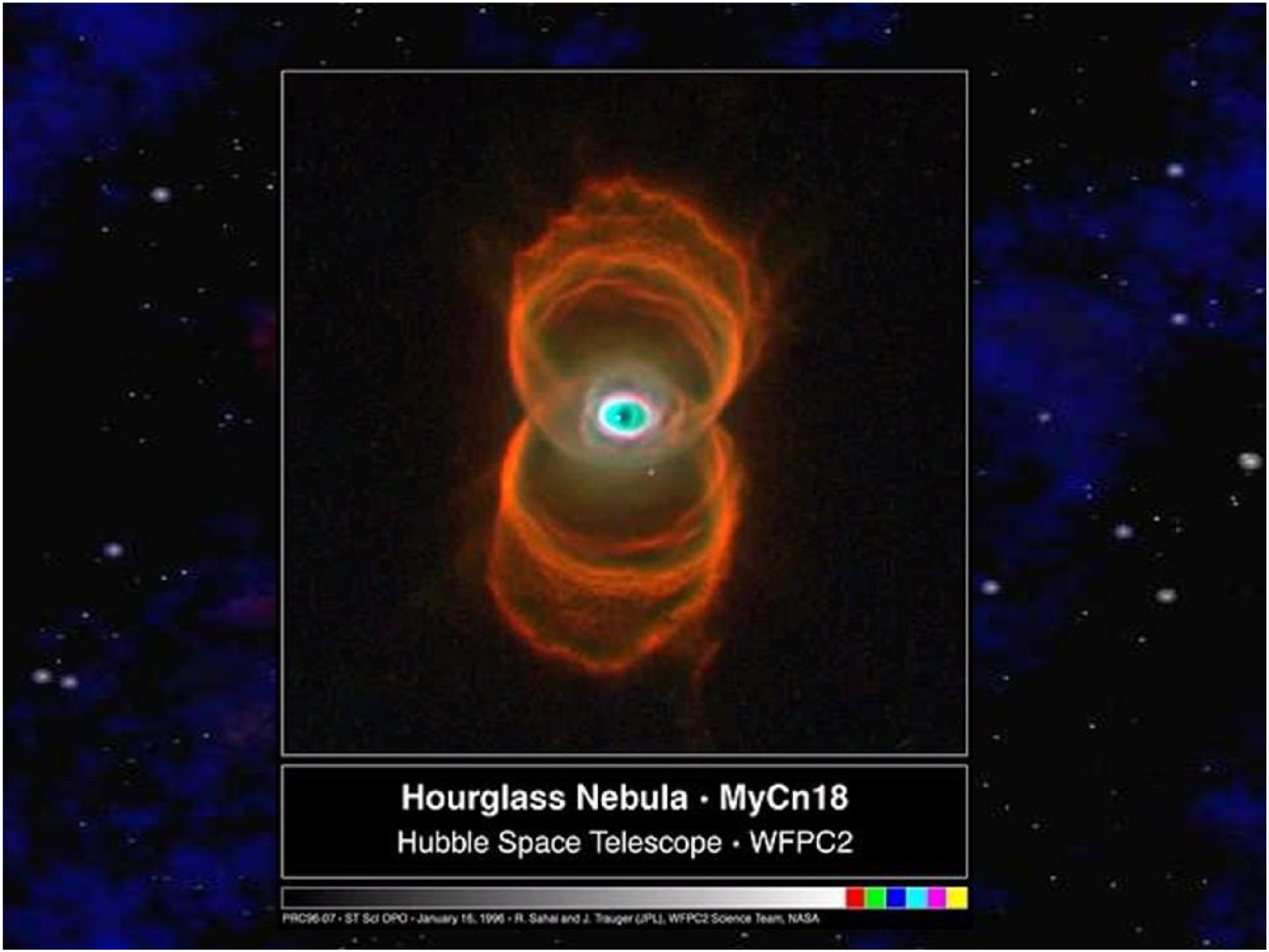

The Sun
(main sequence)
The Sun
(red giant)

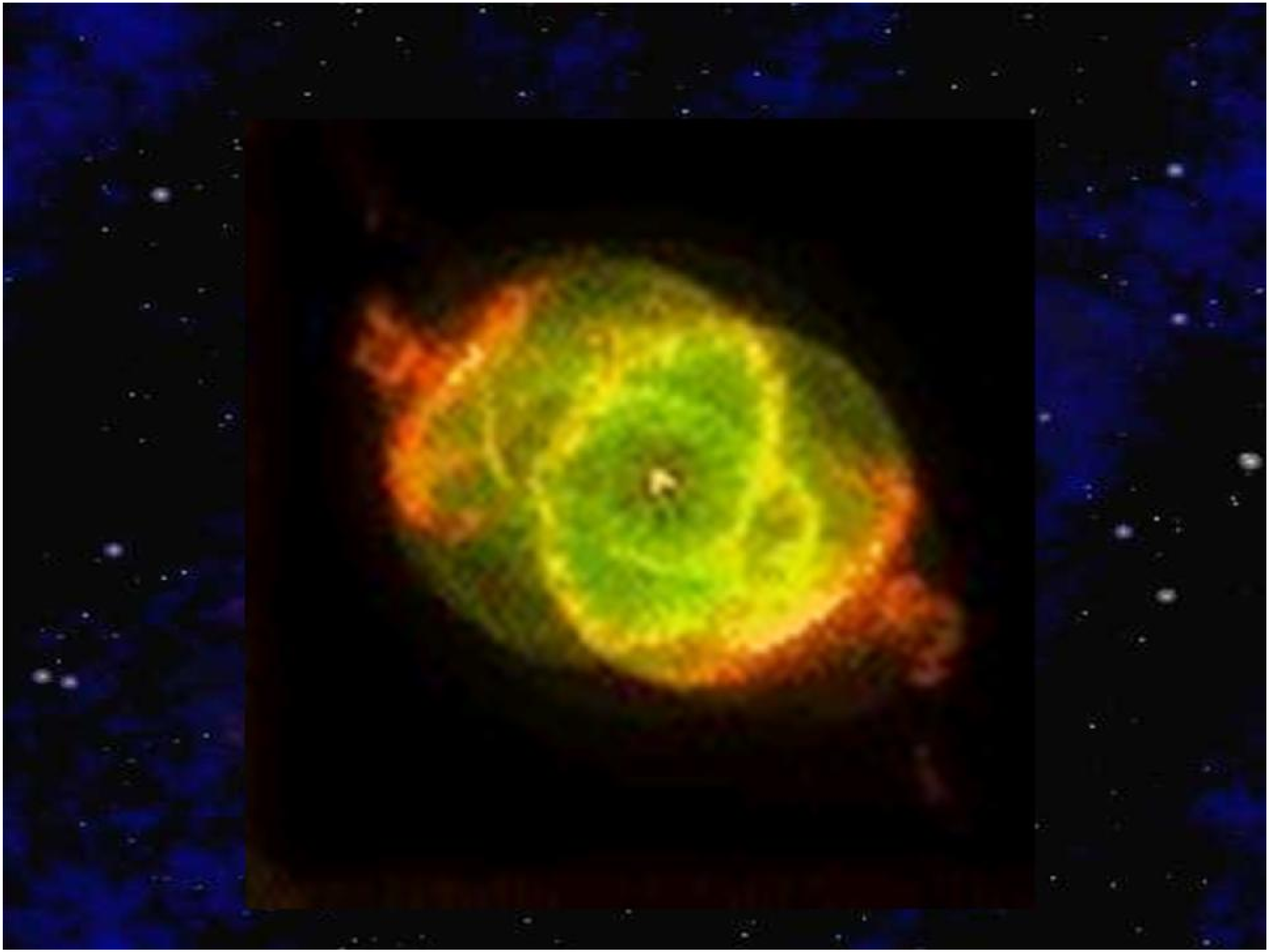

www.spacetelescope.org

Planetary Nebula

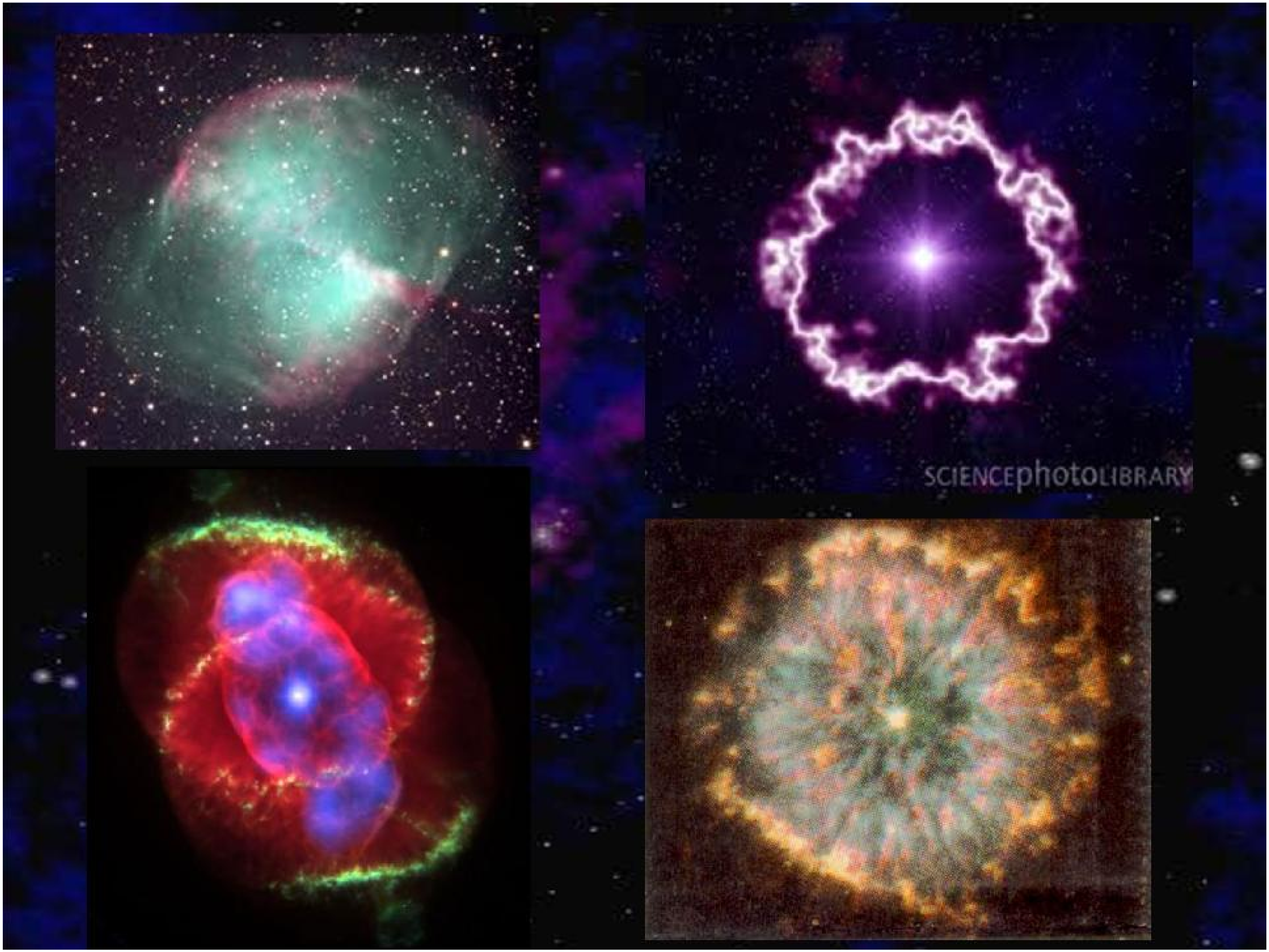
(has nothing to do with planets!!)

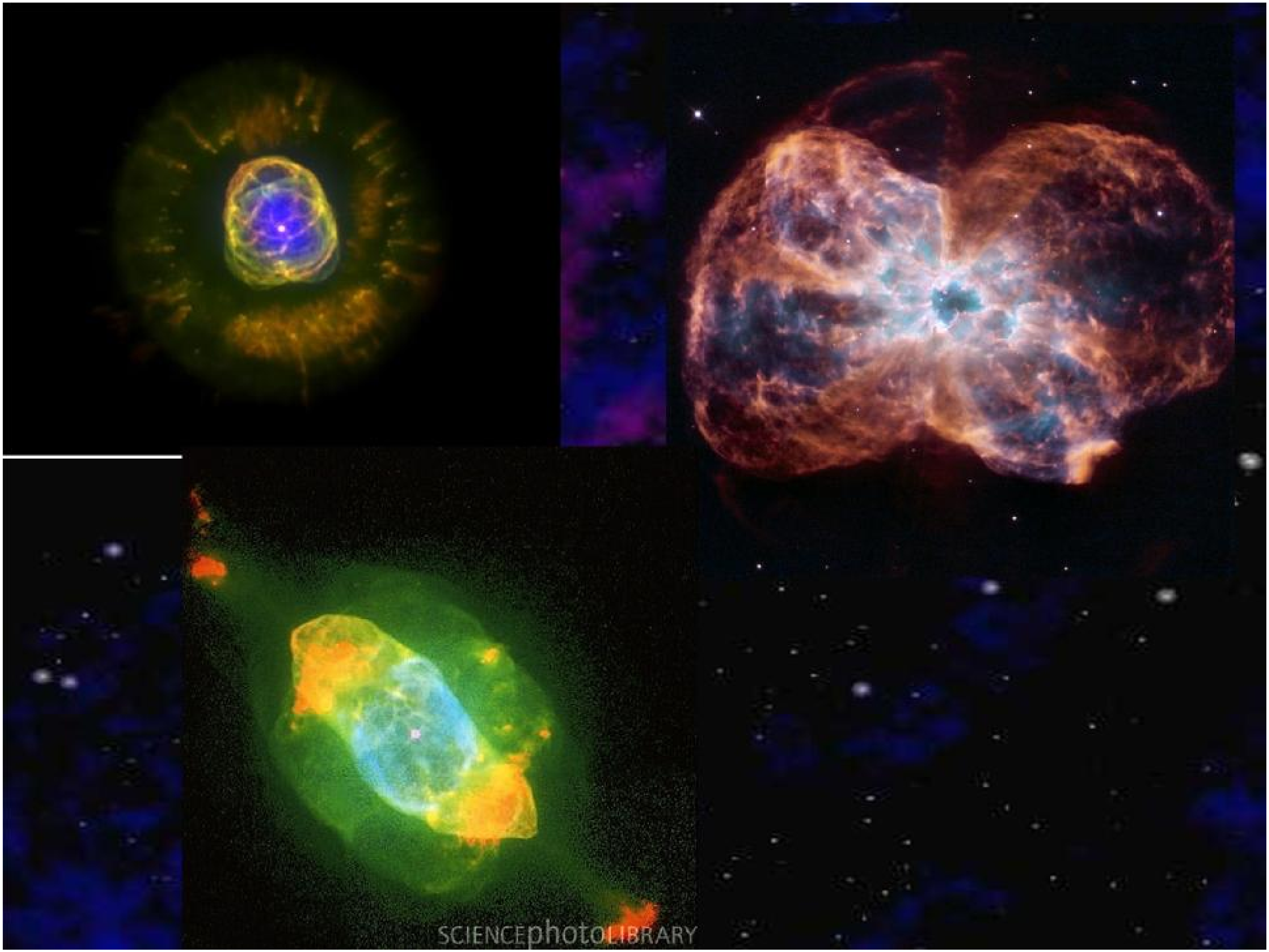

Egg Nebula · CRL 2688
HST · WFPC2
PRC96-03 · ST ScI OPO · January 16, 1996
R. Sahai and J. Trauger (JPL), the WFPC2 Science Team and NASA

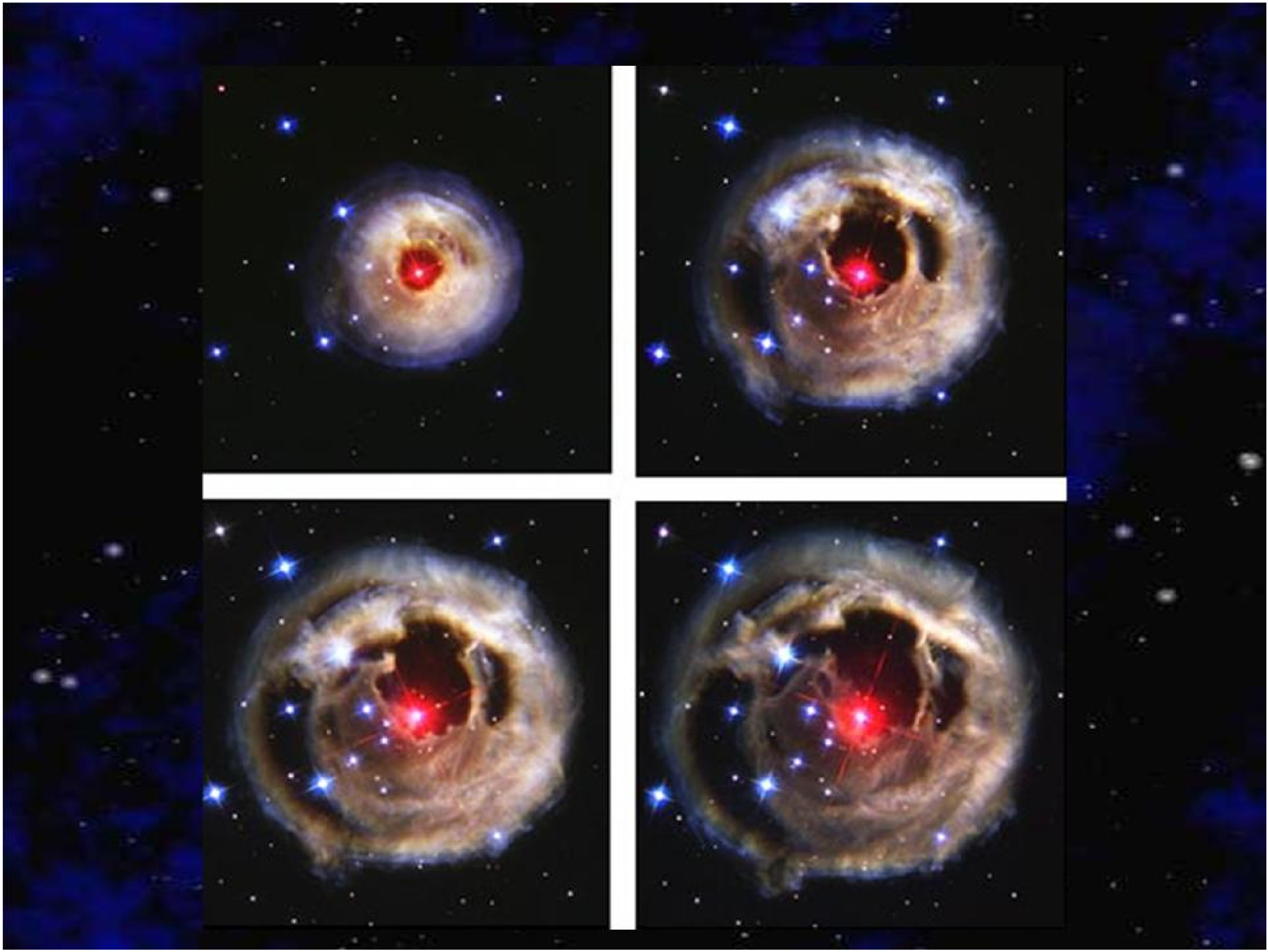

Hourglass Nebula · MyCn18
Hubble Space Telescope · WFPC2
PRC96-07 · ST ScI OPO · January 16, 1996 · R. Sahai and J. Trauger (JPL), WFPC2 Science Team, NASA

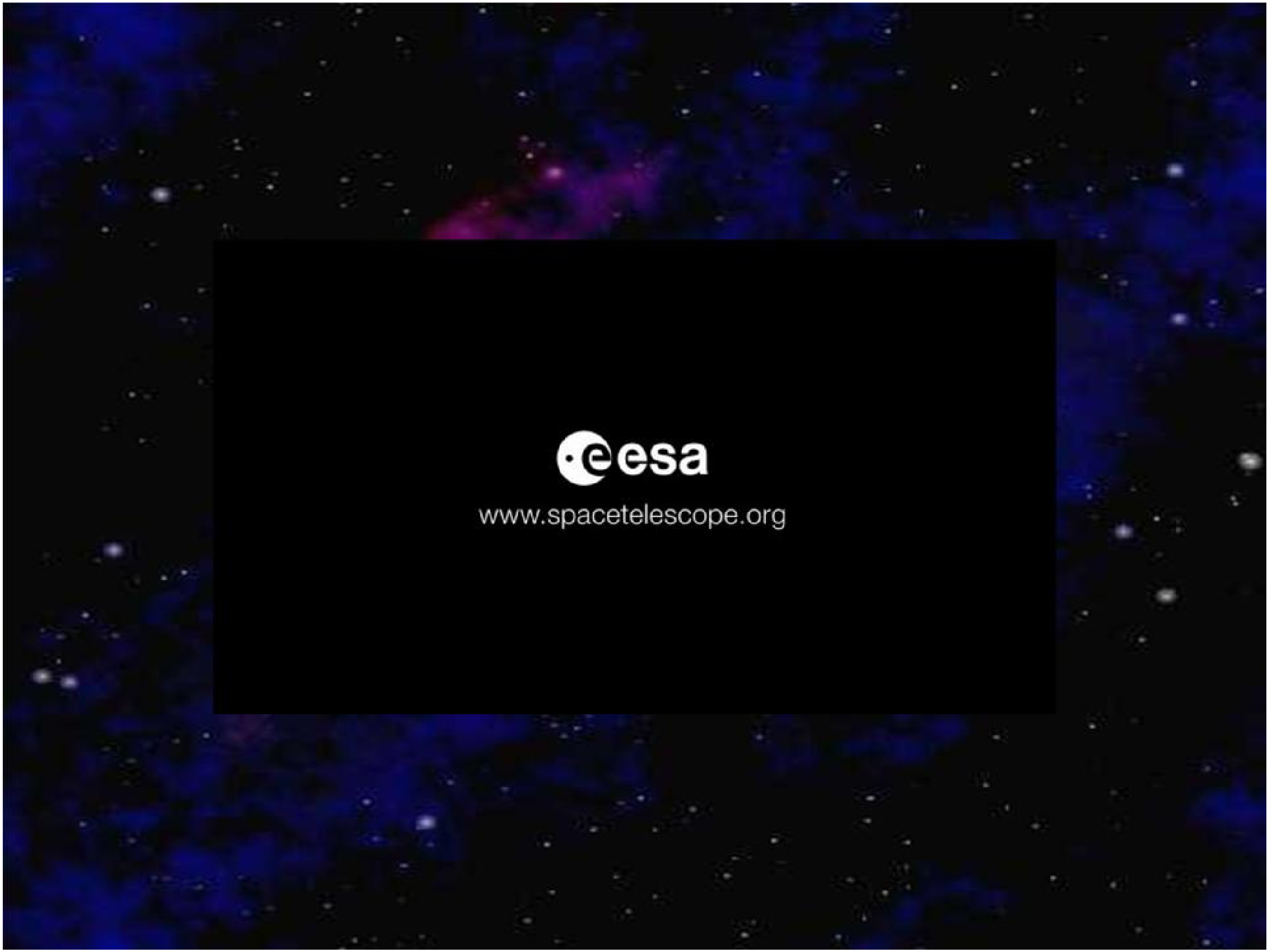


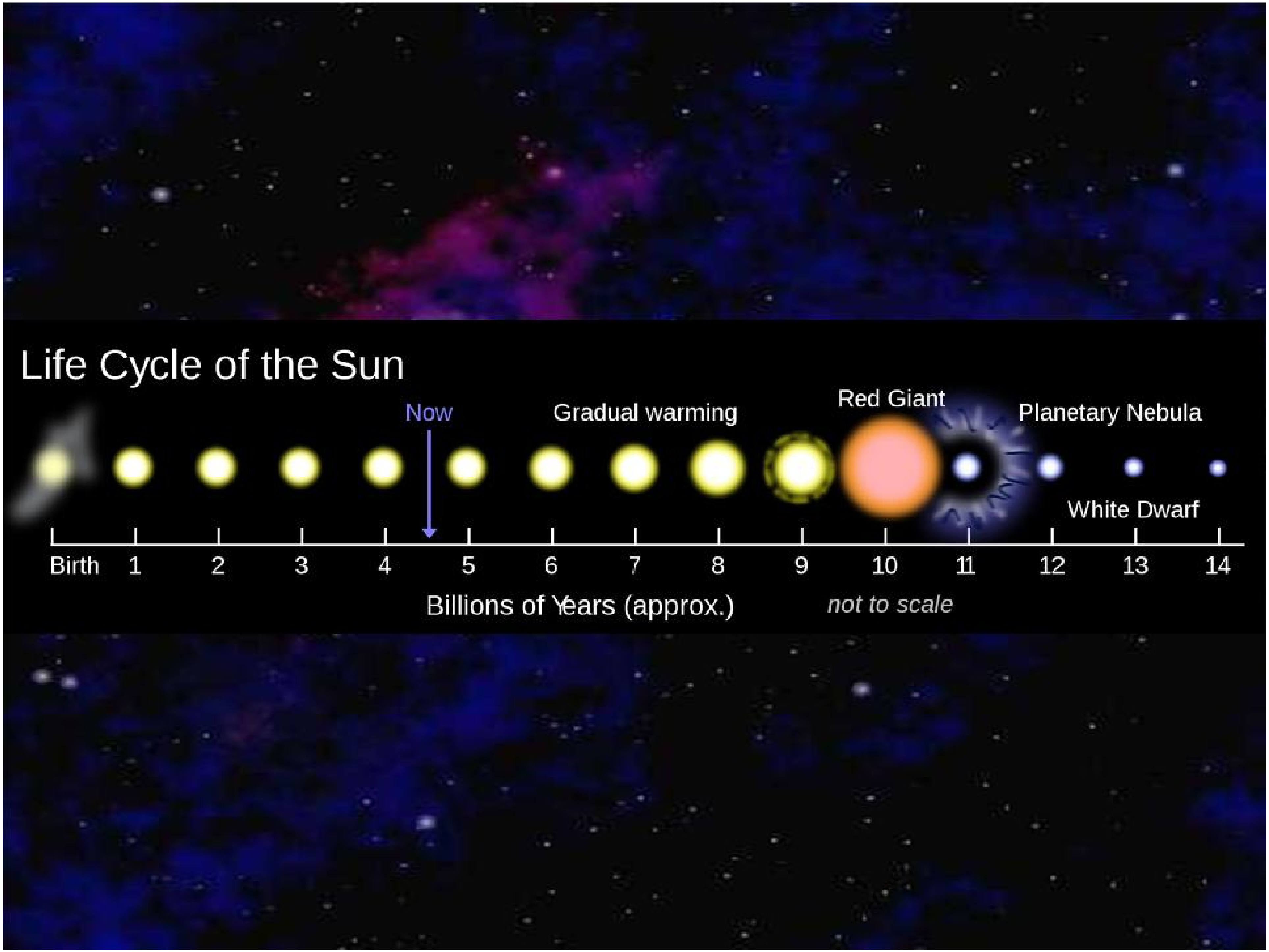
www.spacetelescope.org

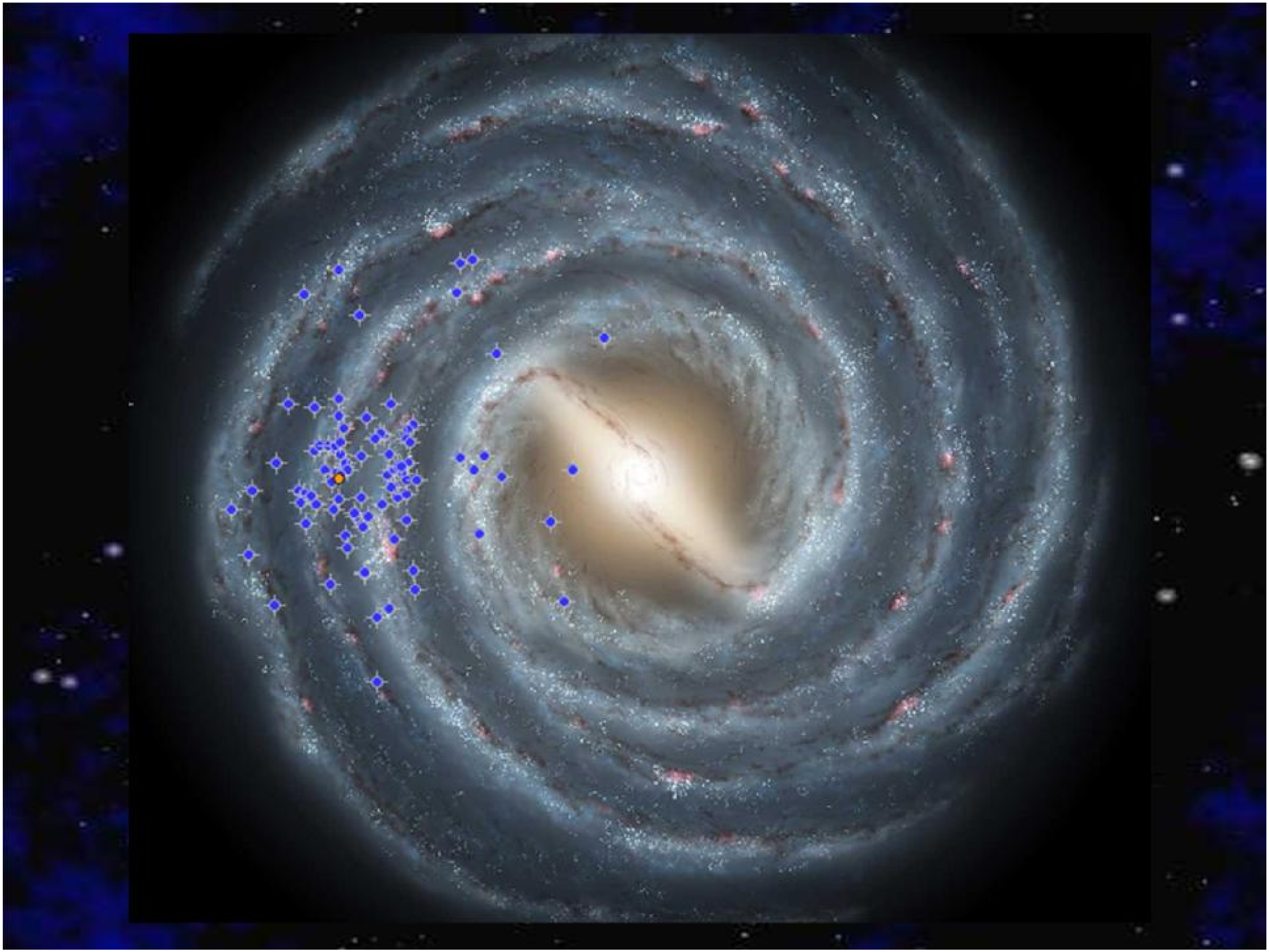

SCIENCEphotoLIBRARY

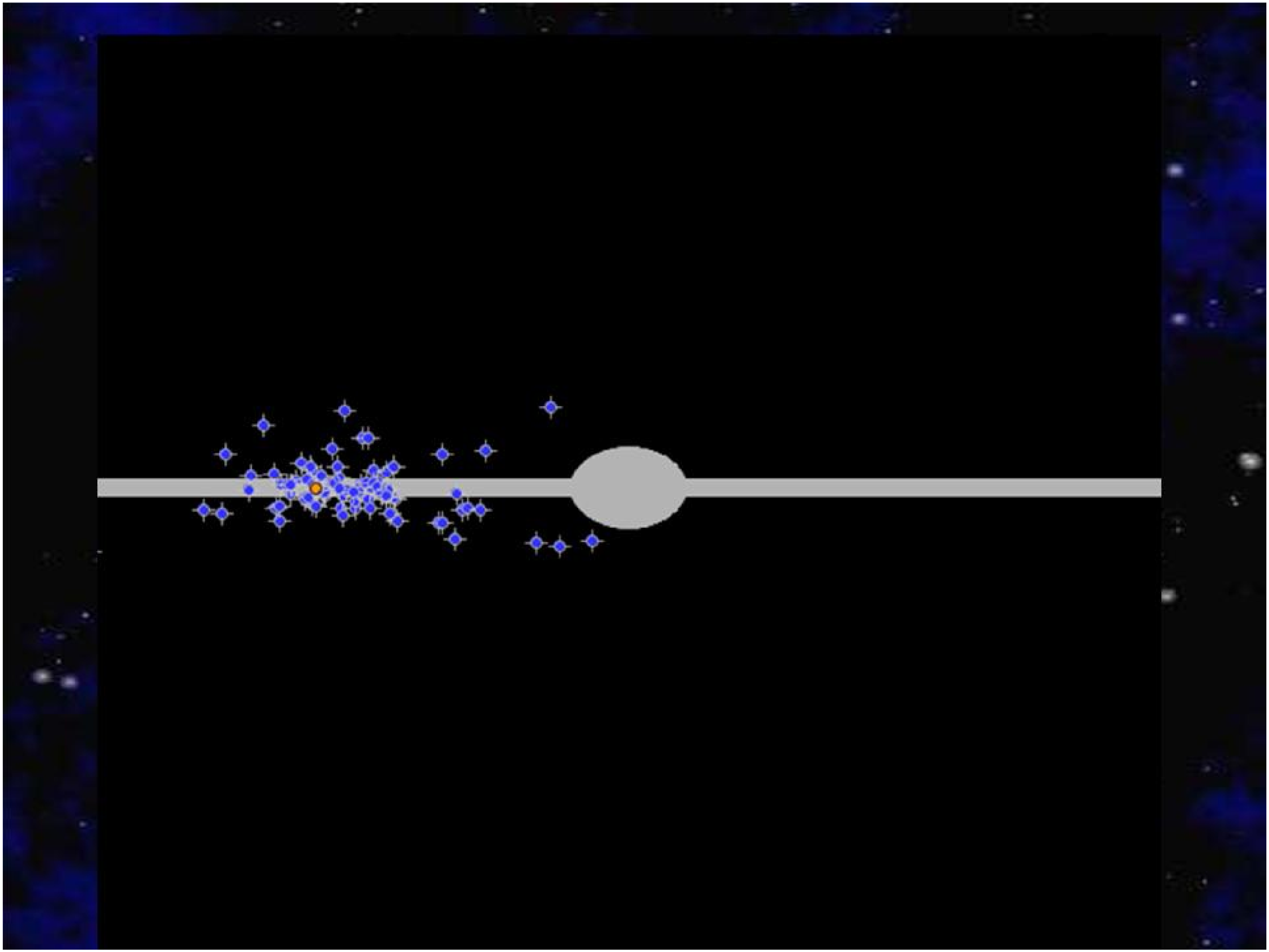

SCIENCEphotoLIBRARY




esa
www.spacetelescope.org


Life Cycle of the Sun
Now
Gradual warming
Red Giant
Planetary Nebula
White Dwarf
Birth
1
2
3
4
5
6
7
8
9
10
11
12
13
14
Billions of Years (approx.)
not to scale

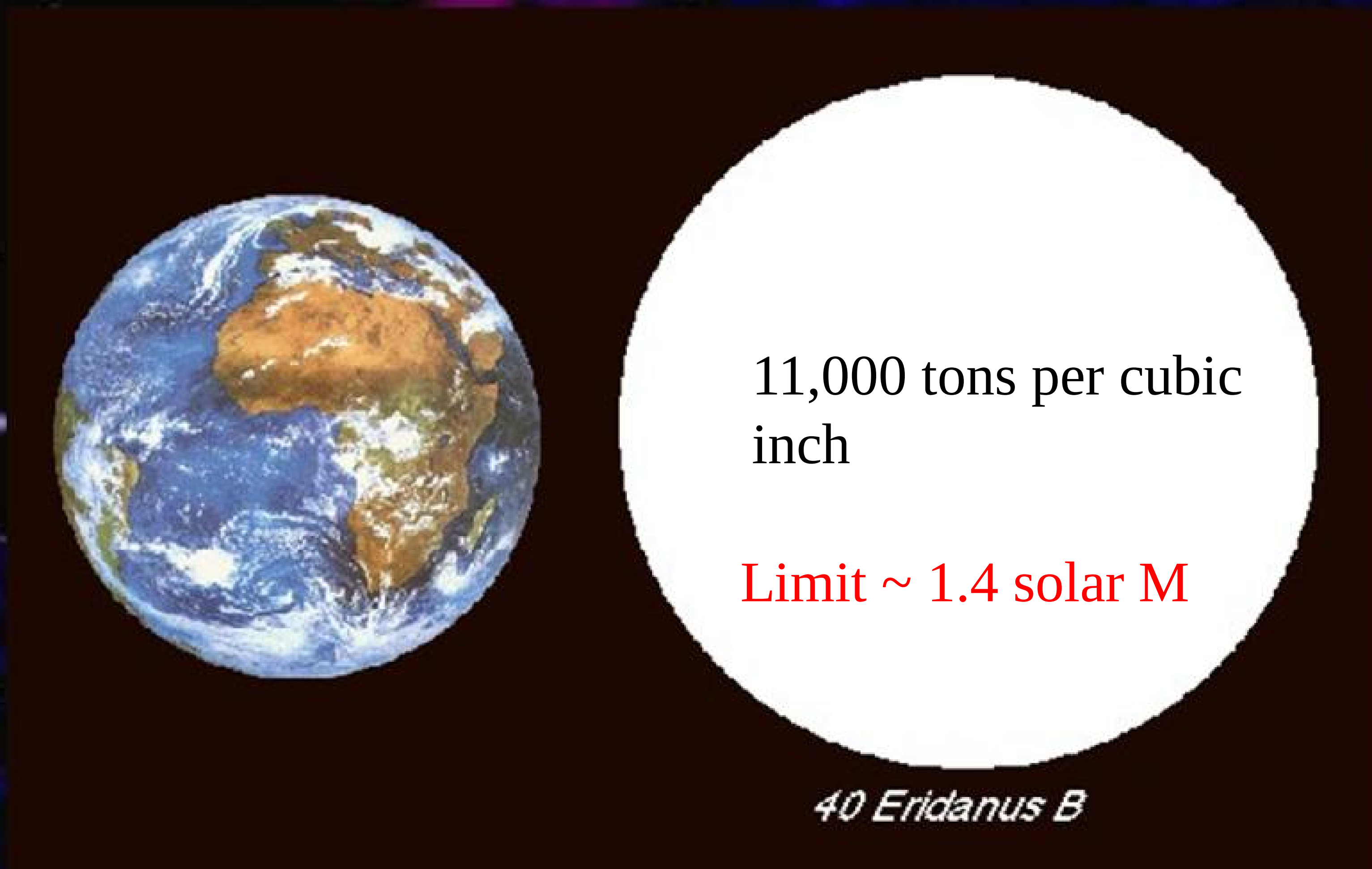


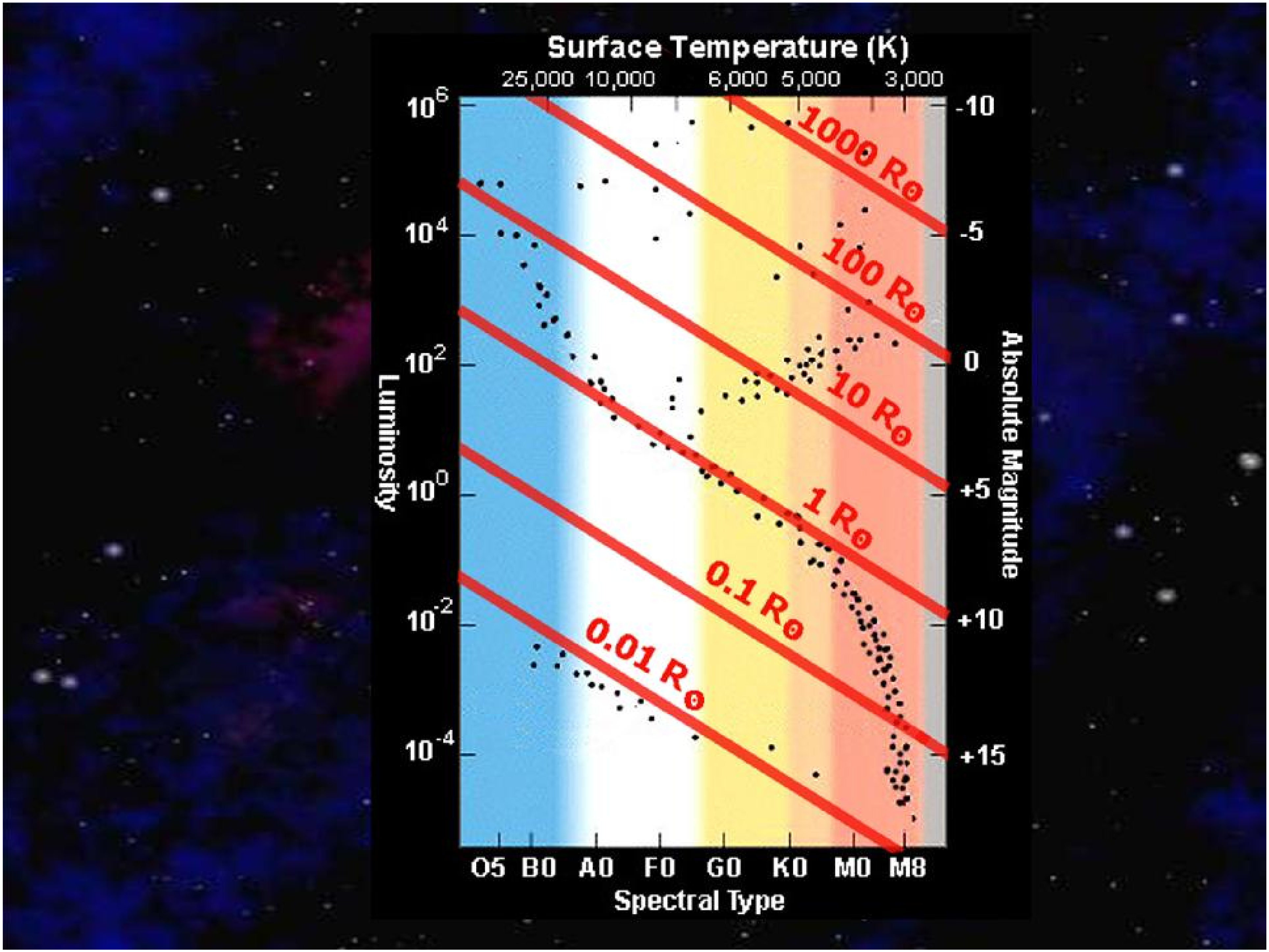


White Dwarf Stars

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

White Dwarf Star

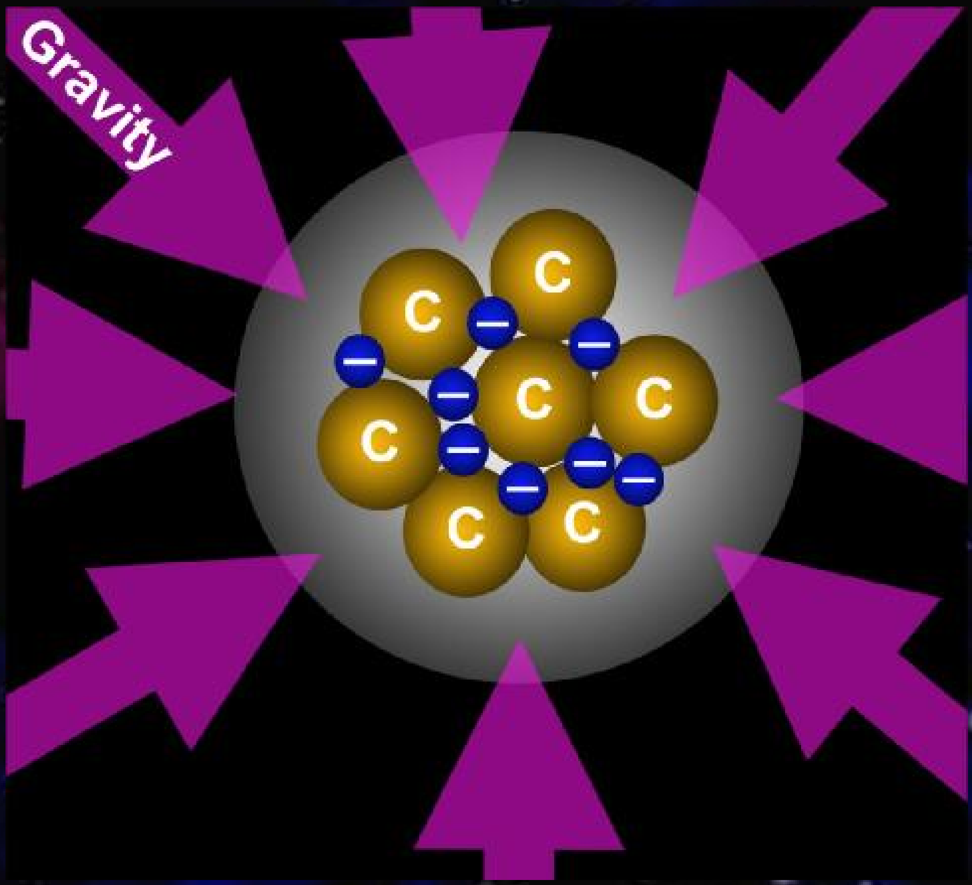




Surface Temperature (K)
25,000 10,000 6,000 5,000 3,000
Luminosity
10^6
10^4
10^2
10^0
10^{-2}
10^{-4}
Absolute Magnitude
-10
-5
0
+5
+10
+15
1000 R☉
100 R☉
10 R☉
1 R☉
0.1 R☉
0.01 R☉
O5 B0 A0 F0 G0 K0 M0 M8
Spectral Type

What stopped the gravitational collapse of the white dwarf?

The electrons did!



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

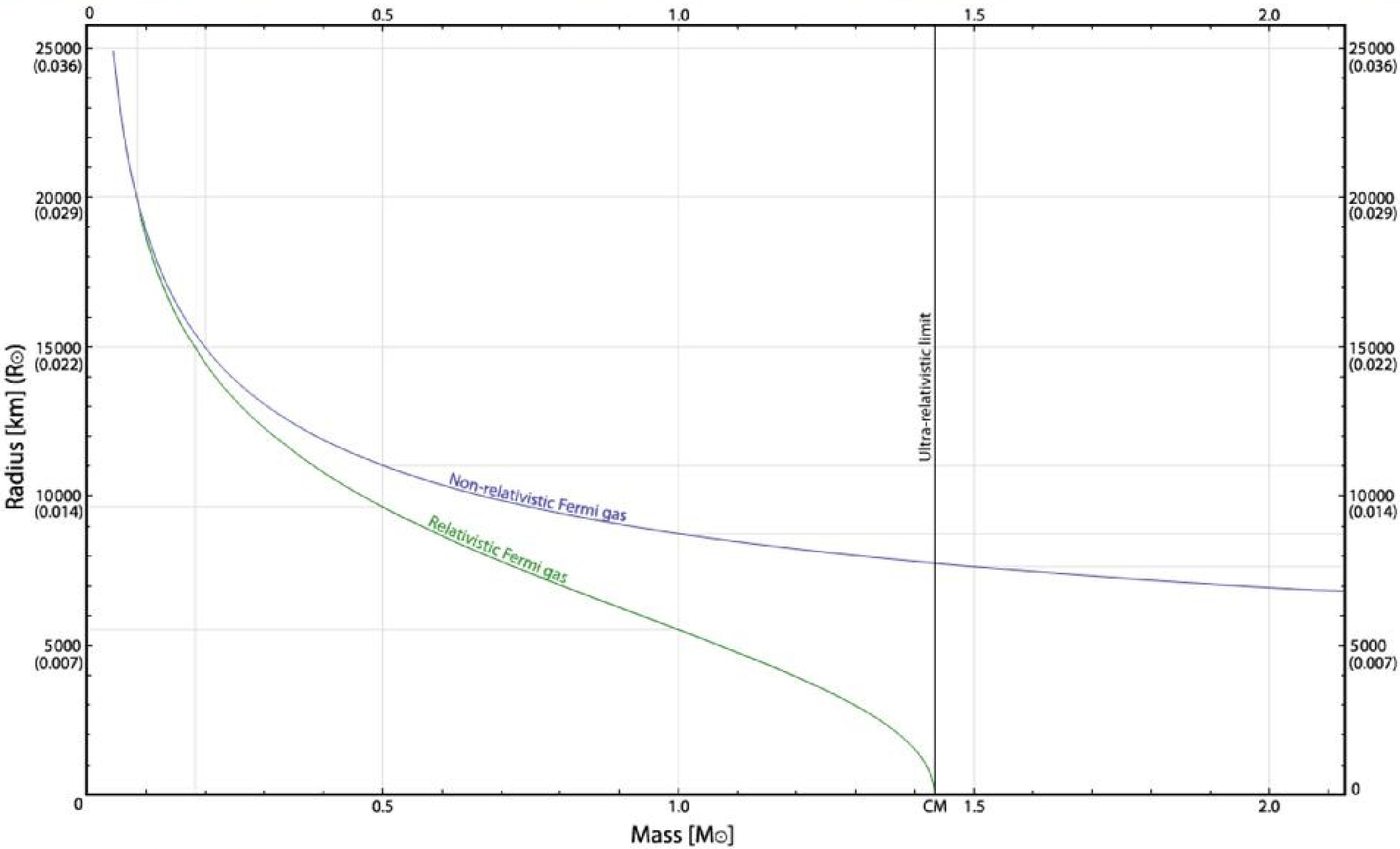
“ELECTRON DEGENERACY PRESSURE”

BUT! Electron Degeneracy Pressure has its limits

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

$$M < 1.4\ M_{\odot}$$

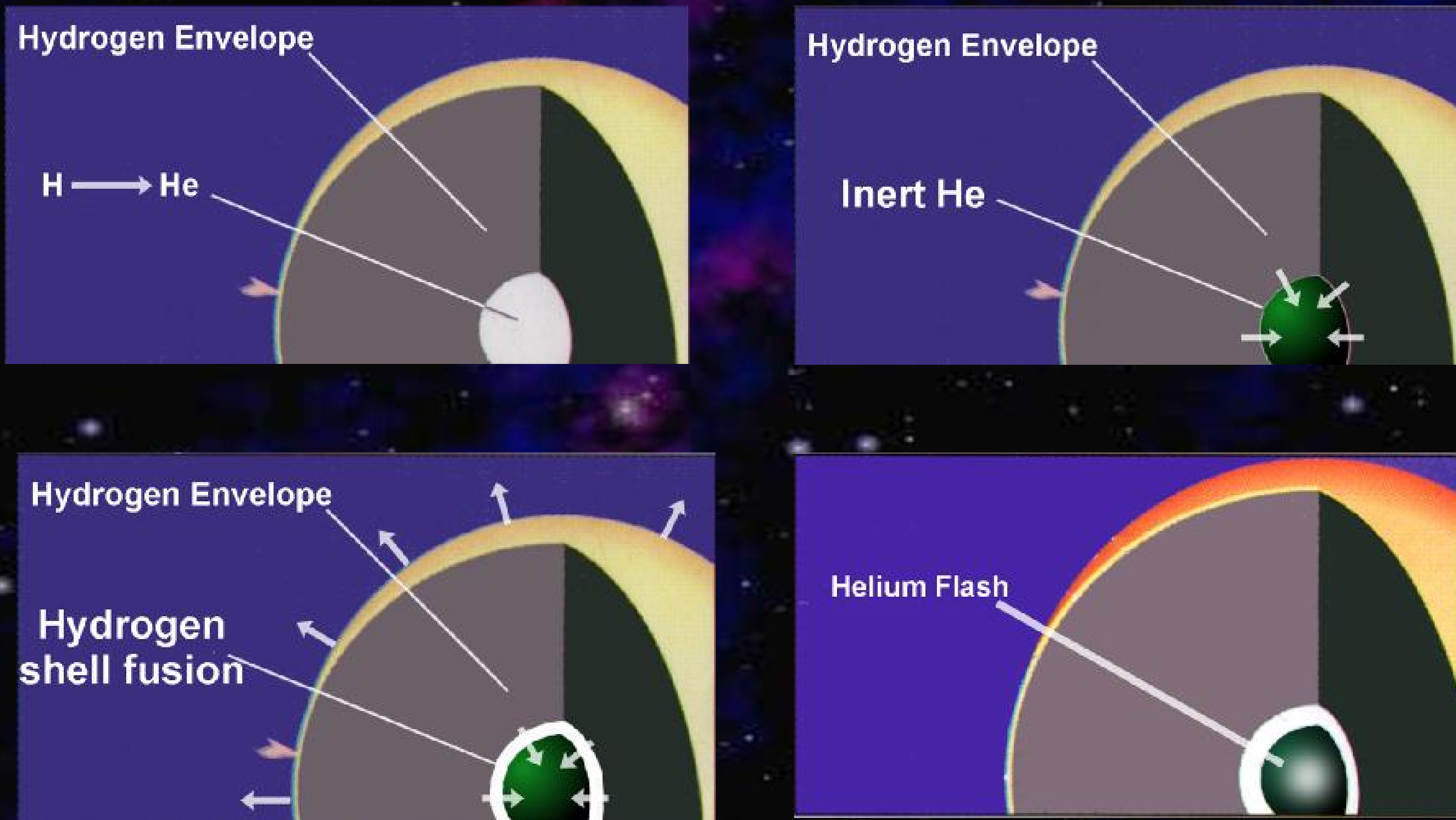
Chandrasekhar Limit

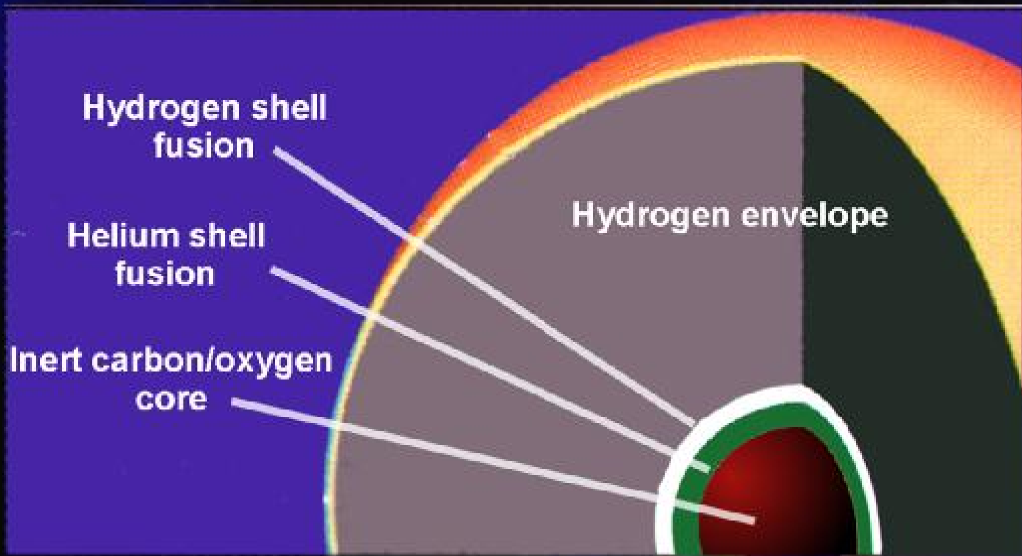


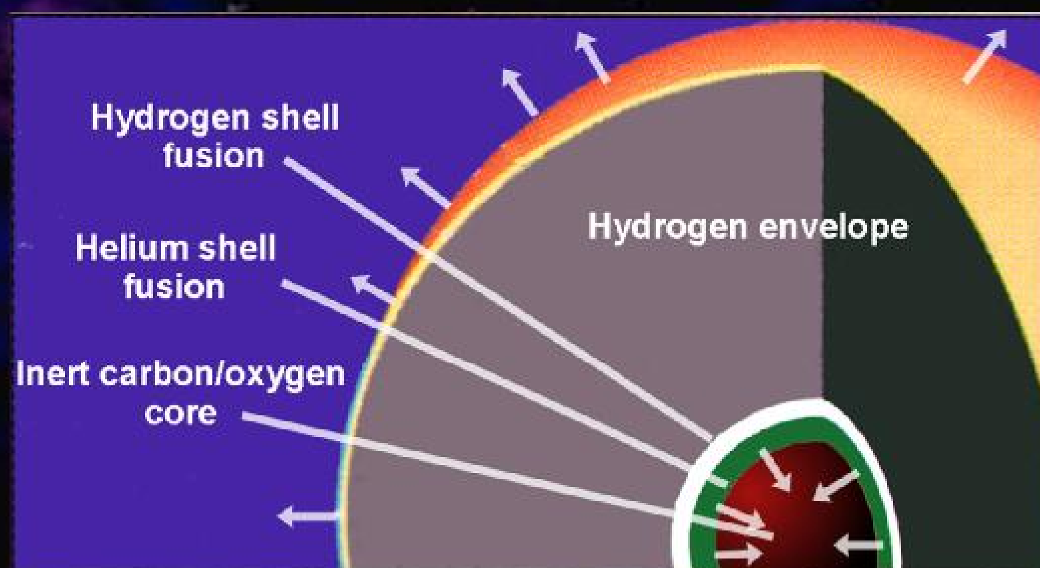
Radius [km] (R⊙)
Mass [M⊙]
Non-relativistic Fermi gas
Relativistic Fermi gas
Ultra-relativistic limit
CM
25000 (0.036)
20000 (0.029)
15000 (0.022)
10000 (0.014)
5000 (0.007)
0
0.5
1.0
1.5
2.0

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

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

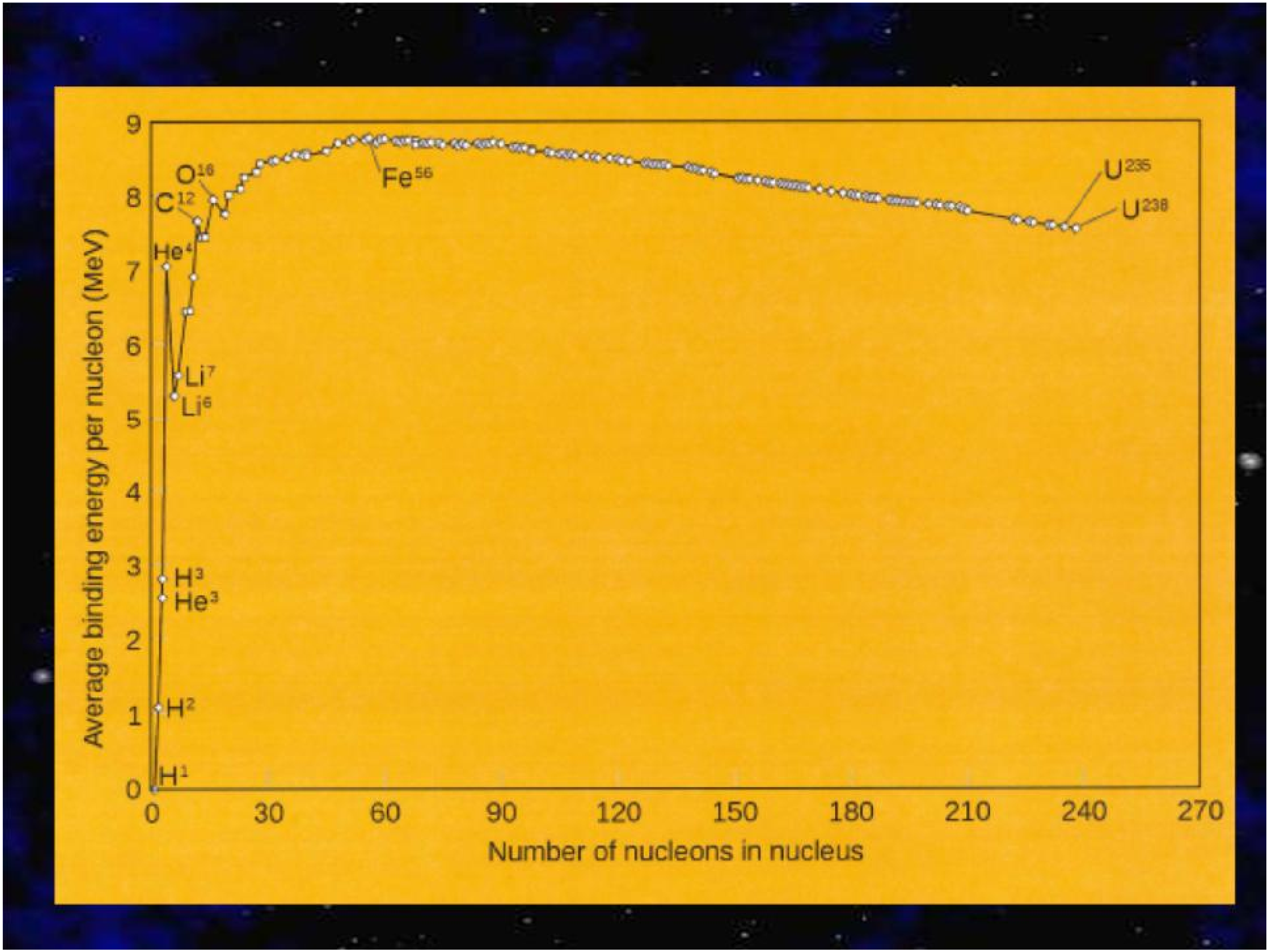



Hydrogen shell
fusion
Helium shell
fusion
Inert carbon/oxygen
core
Hydrogen envelope

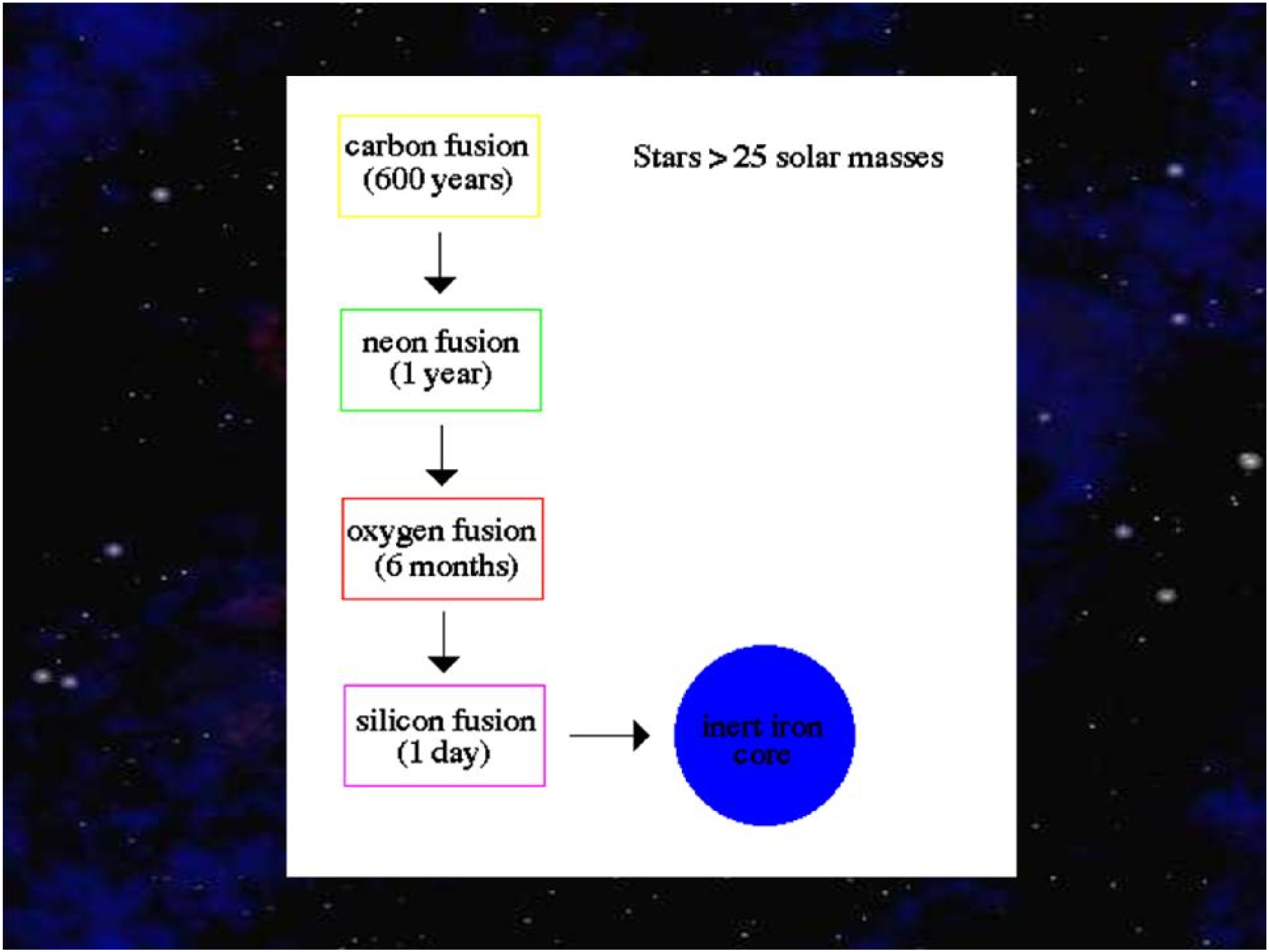

Hydrogen shell
fusion
Helium shell
fusion
Inert carbon/oxygen
core
Hydrogen envelope

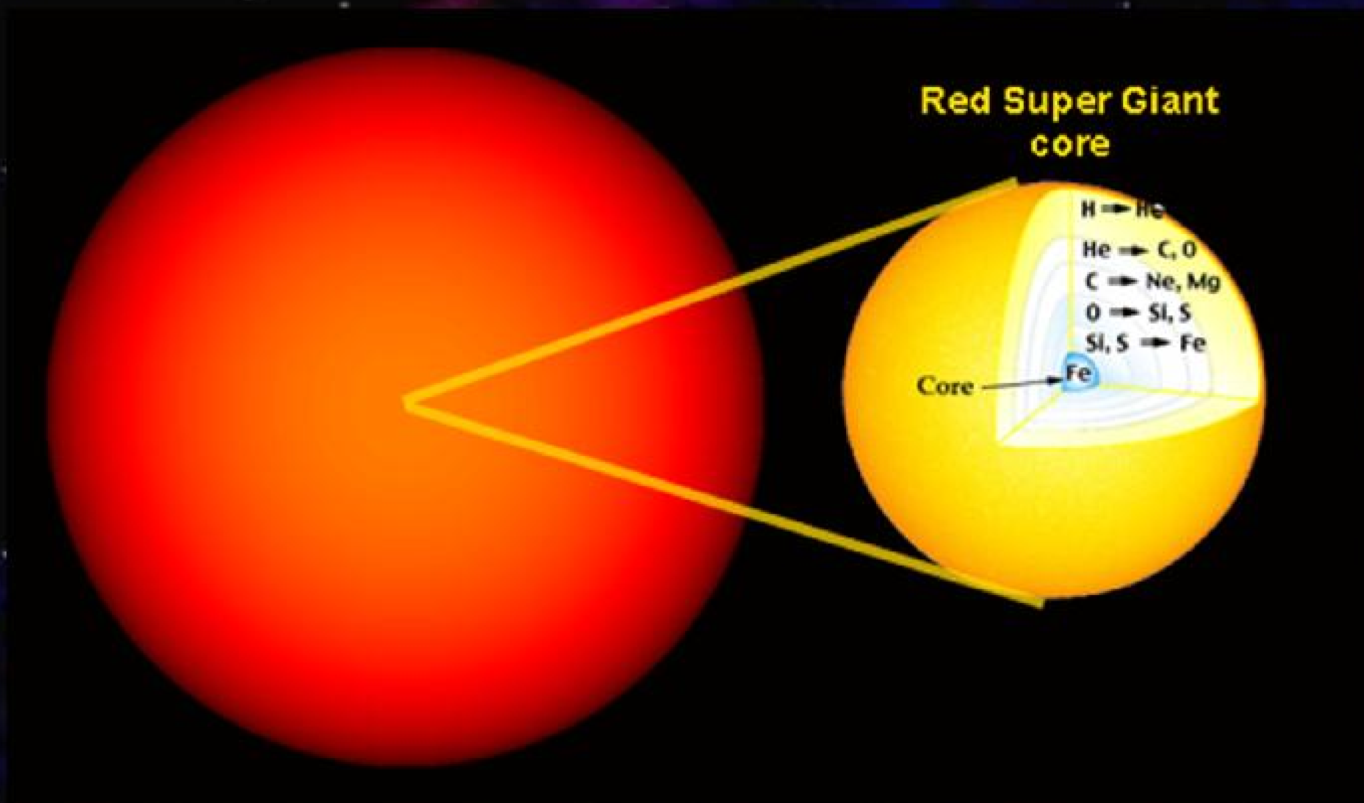
25 $M_\odot$ star

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

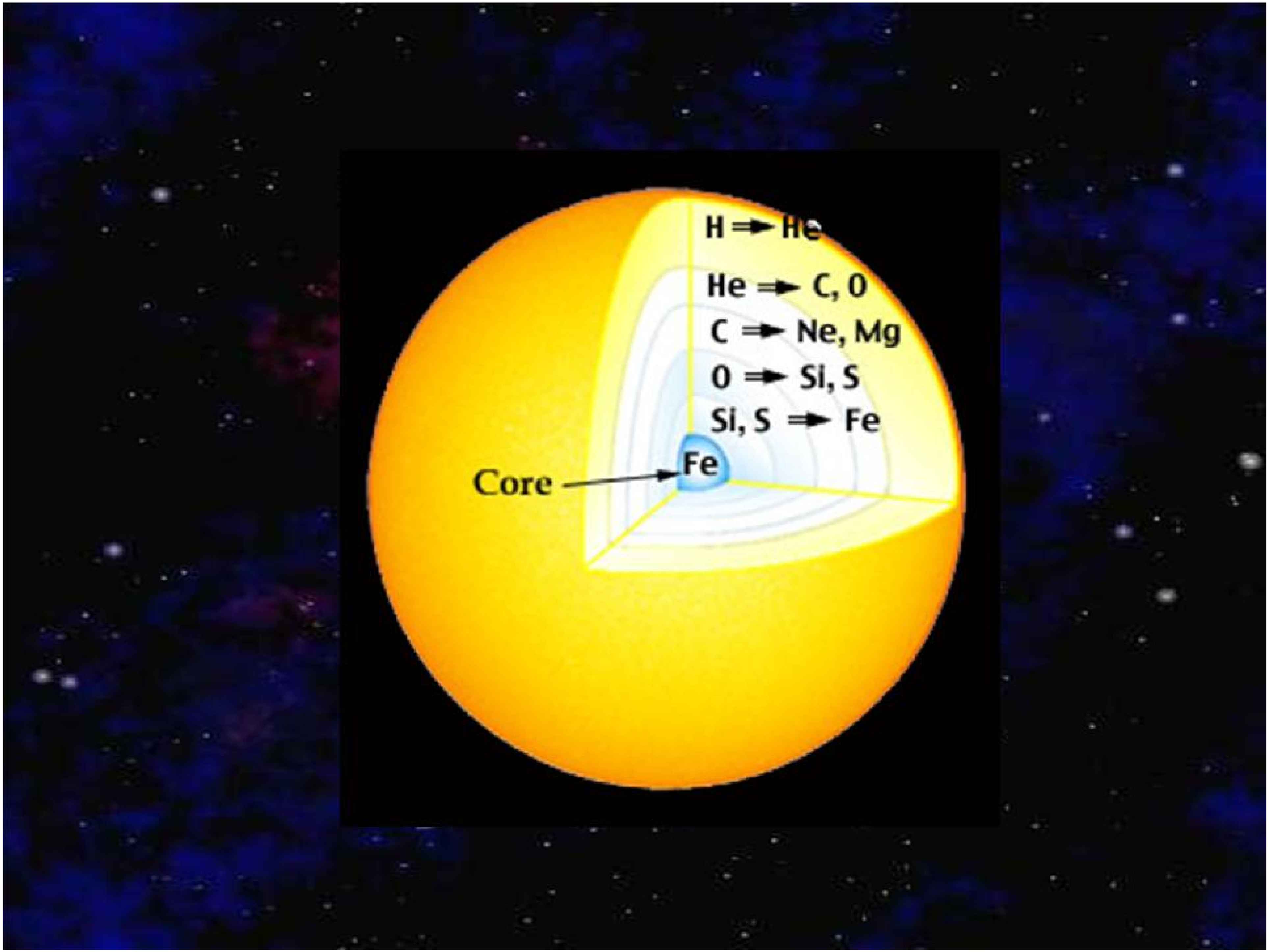


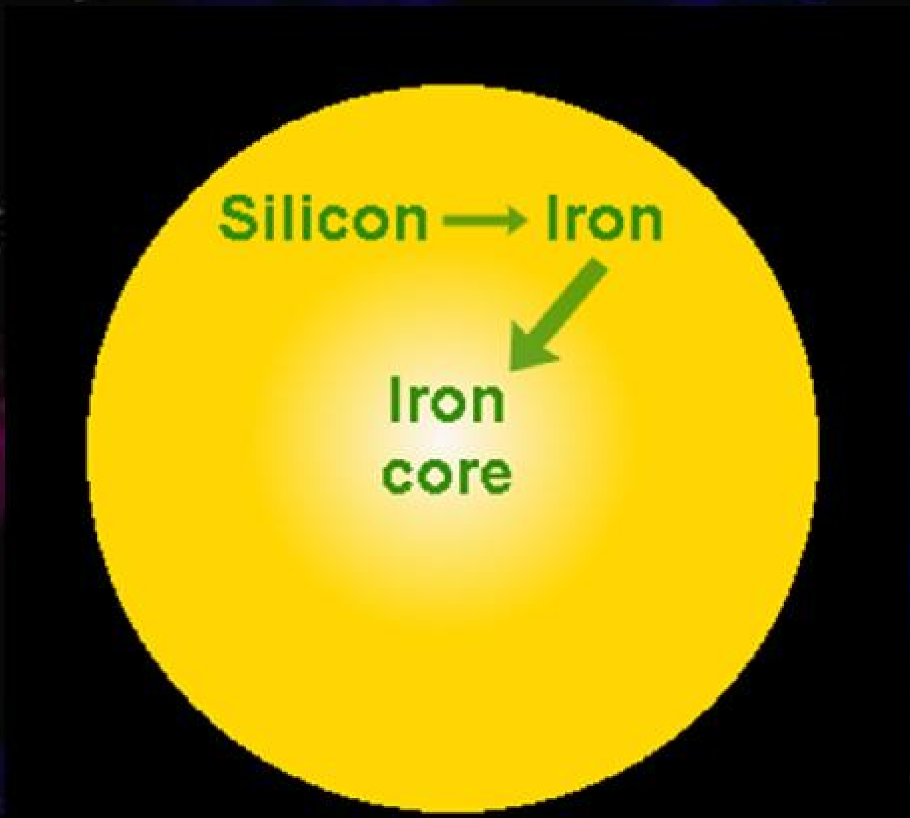
Average binding energy per nucleon (MeV)
Number of nucleons in nucleus
0
1
2
3
4
5
6
7
8
9
0
30
60
90
120
150
180
210
240
270
H1
H2
H3
He3
He4
Li6
Li7
C12
O16
Fe56
U235
U238


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

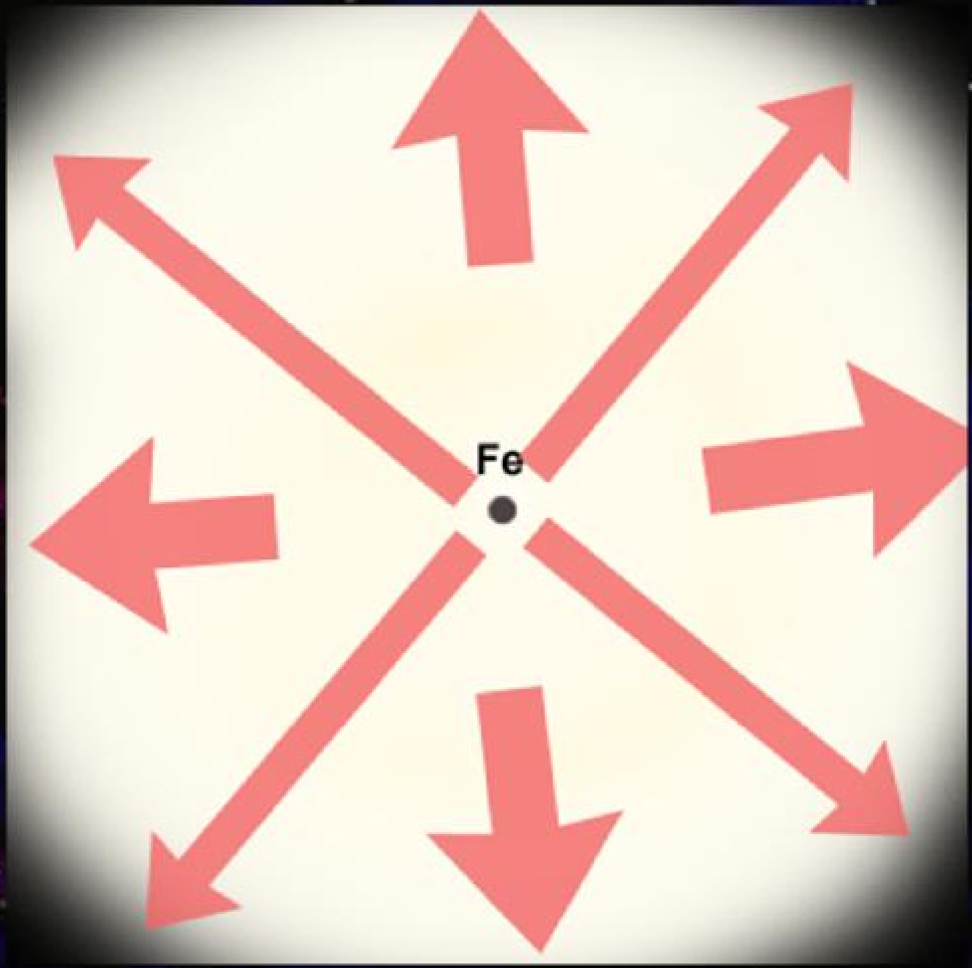

H → He
He → C, O
C → Ne, Mg
O → Si, S
Si, S → Fe
Fe
Core



Iron core < $1.4M_{\odot}$

Continual silicon fusion increases mass of core

Eventually Iron core = $1.4M_{\odot}$



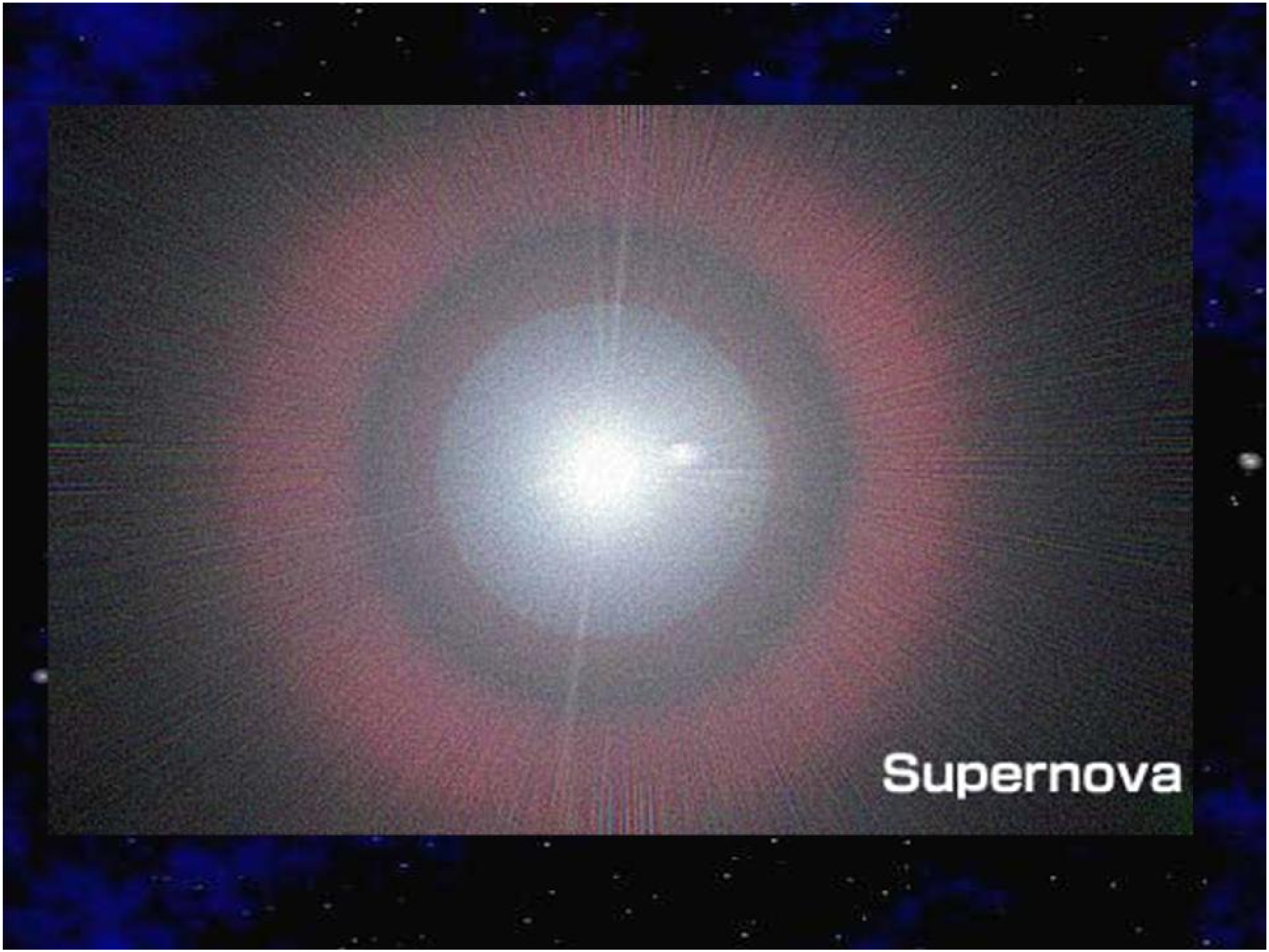
Iron core > 1.4M$_\odot$

Iron core cannot support itself against gravity

Iron core collapses...

esa

www.spacetelescope.org


Supernova

Supernova 1987a

Energy Considerations from a Supernova Explosion

Three releases of energy:

1. Electromagnetic (light)	1x
2. Kinetic energy of exploding material	100x
3. Neutrino escape	10000x

Energy Considerations from a Supernova Explosion

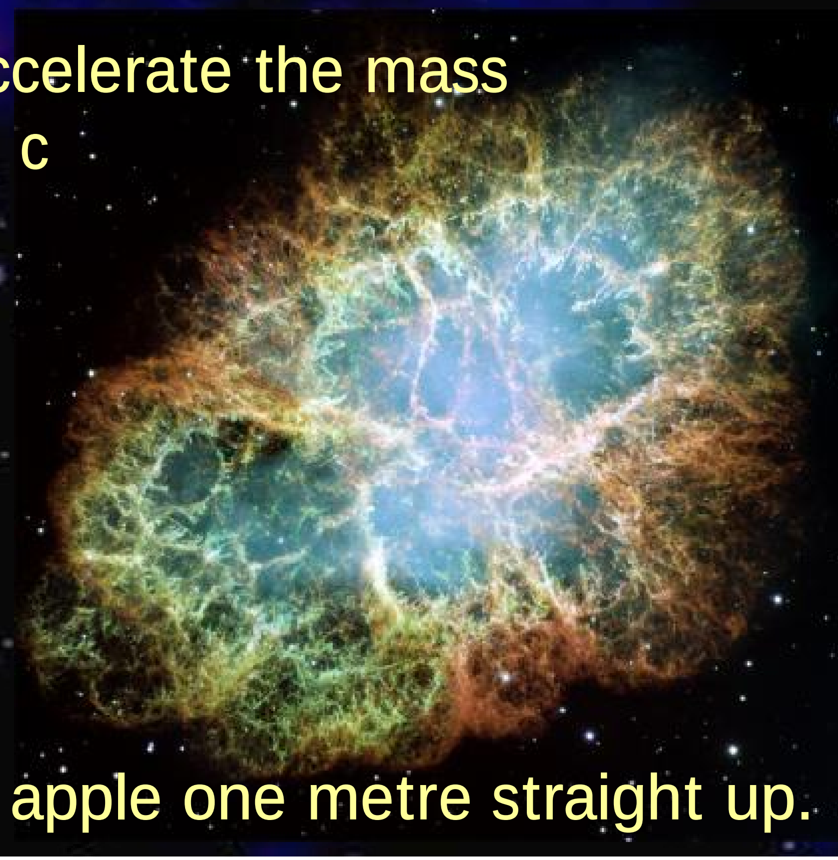
For a brief time a supernova explosion will out shine an entire galaxy in electromagnetic energy

Supernova 1987a

Energy Considerations from a Supernova Explosion

Kinetic energy: 100x the EM energy:

10^{47} Joules*, enough energy to accelerate the mass of the sun to 3.3% speed of light, c



*the energy required to lift a small apple one metre straight up.

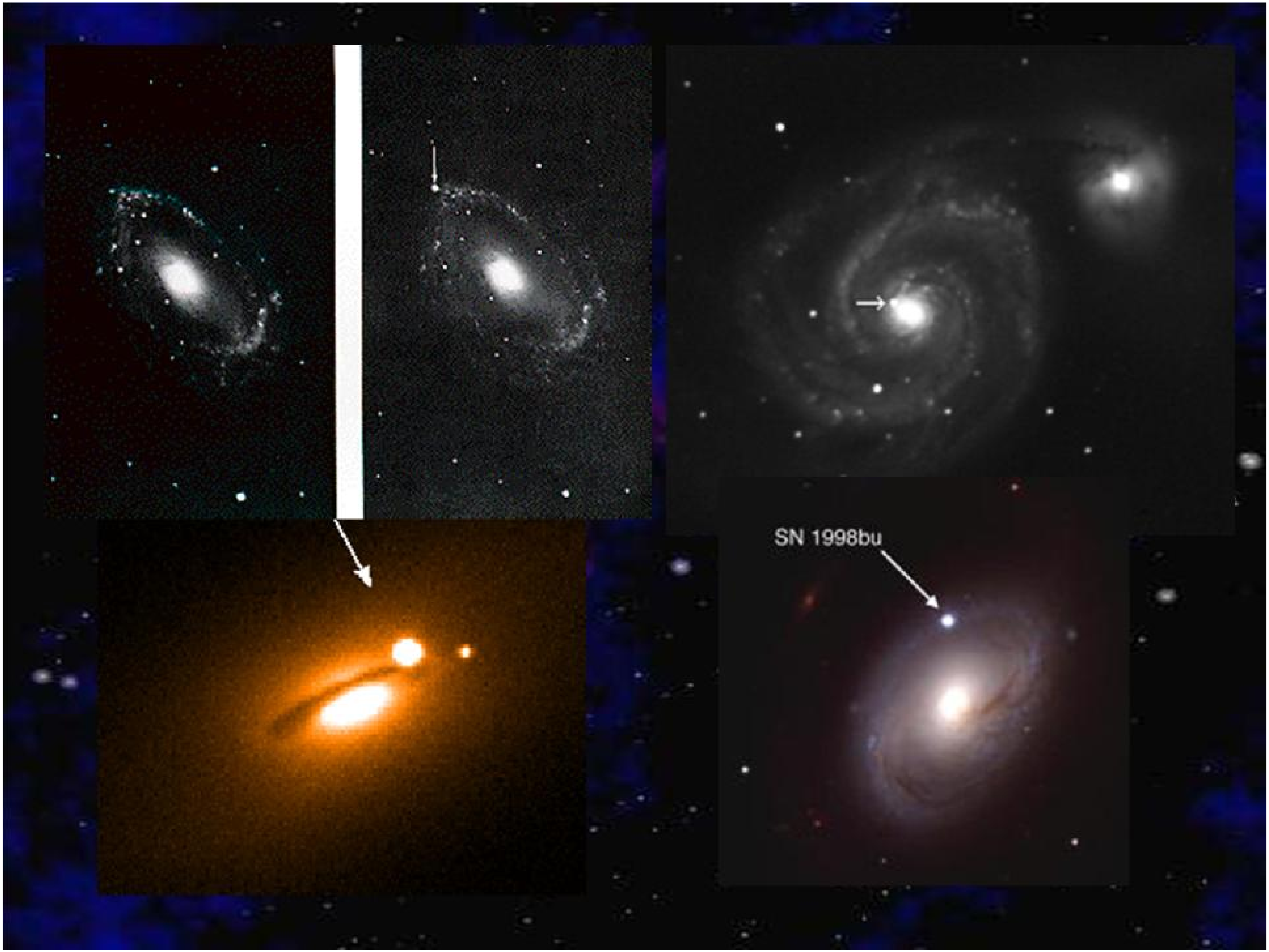
Energy Considerations from a Supernova Explosion

- Neutrinos: chargeless, very small or massless, weakly interacting particle
- Produced by nuclear reactions
- As fuels at carbon and beyond burn in core of high mass star, their release goes up dramatically, cooling the core
- Pass through light years of lead and not interact
- 10^{10} pass through every cm^2 of your body every second

Neutrino release: 10000x the EM energy:

10^{49} Joules, enough energy to accelerate the mass of the sun to 99% speed of light, c

April 1, 1993


SN 1998bu

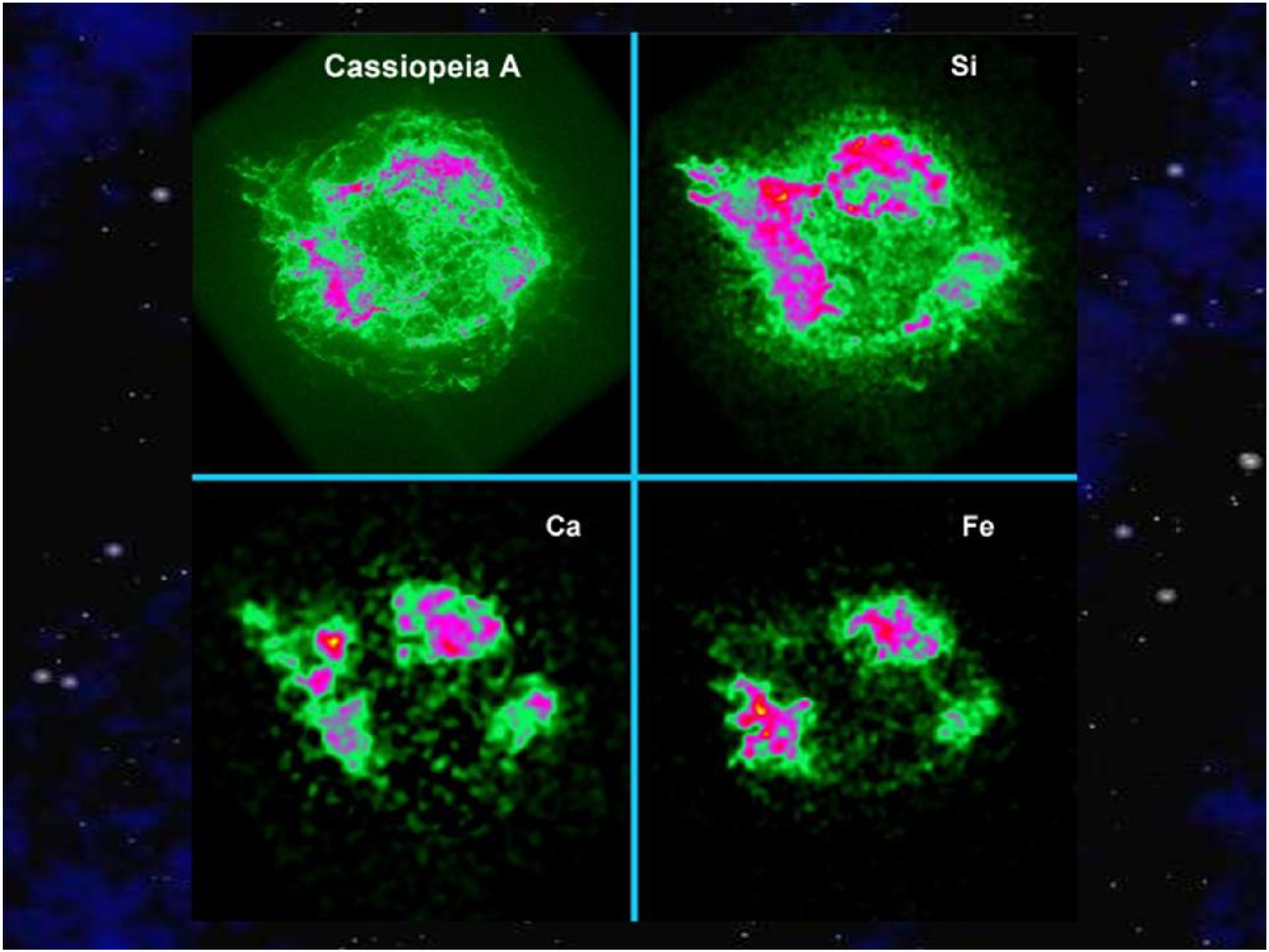
Supernova Remnants

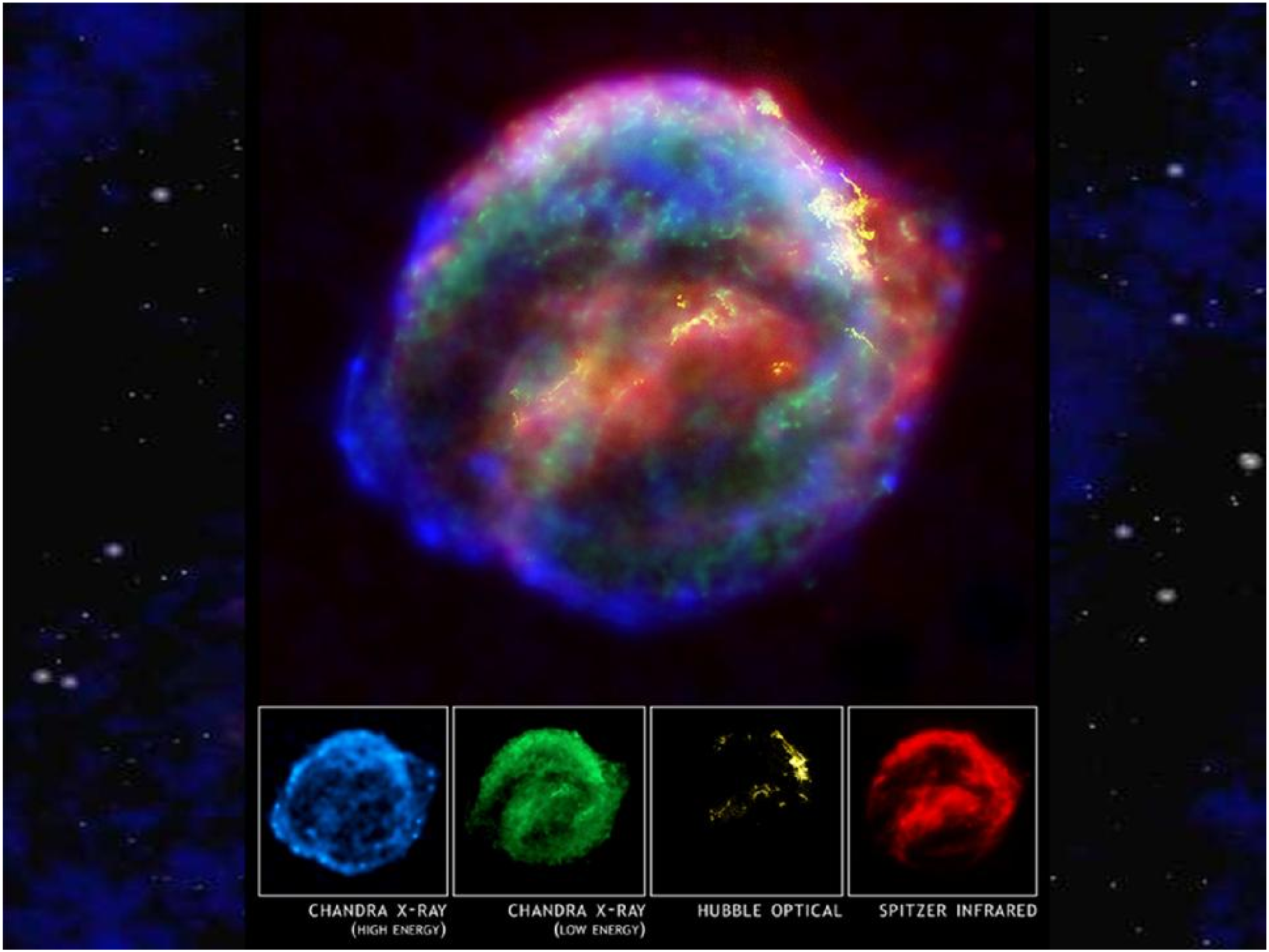
Supernova Remnants

Supernova Remnants

Supernova Remnants

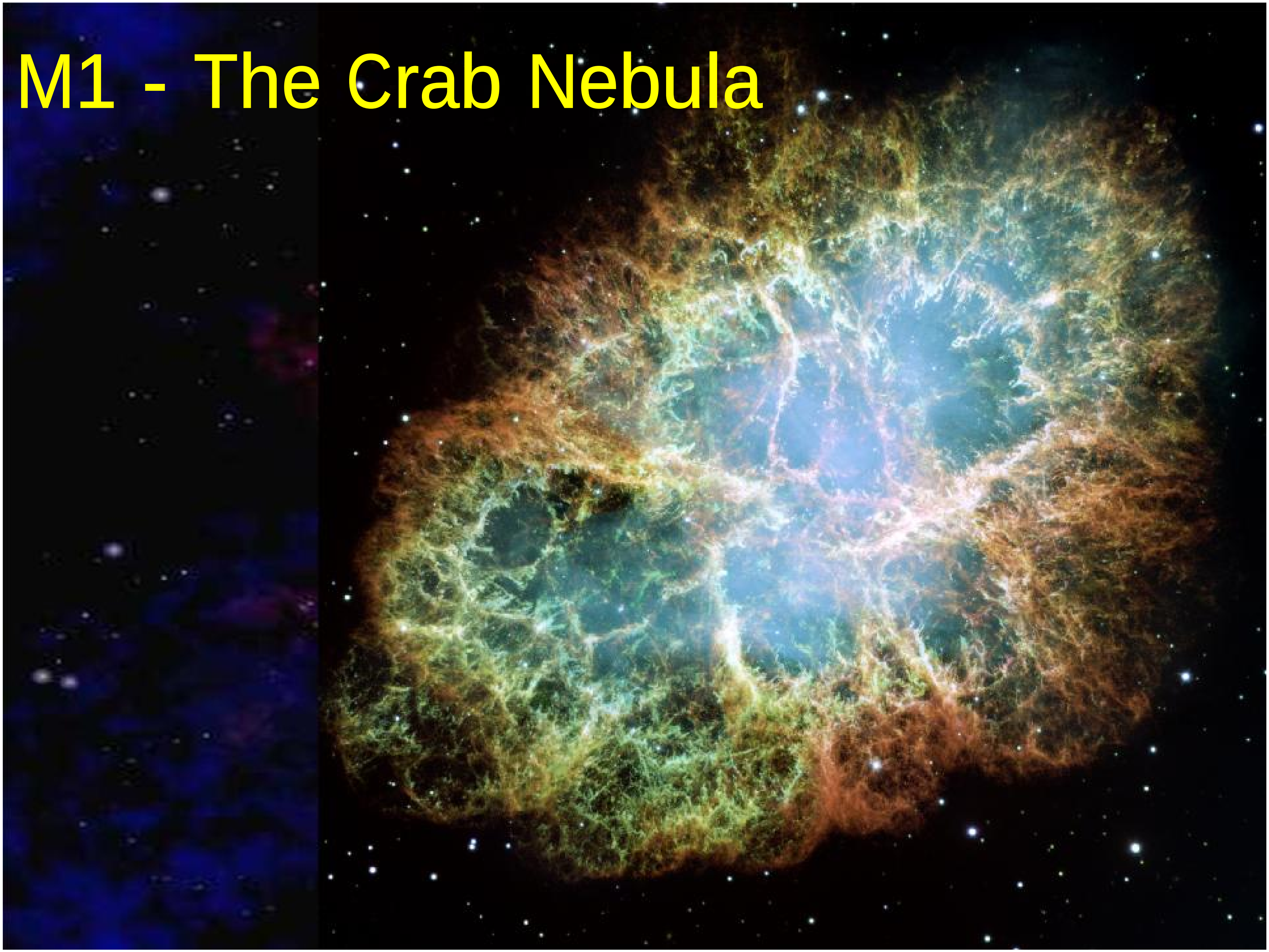
Supernova Remnants


Cassiopeia A
Si
Ca
Fe


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

July, 1054 A.D.

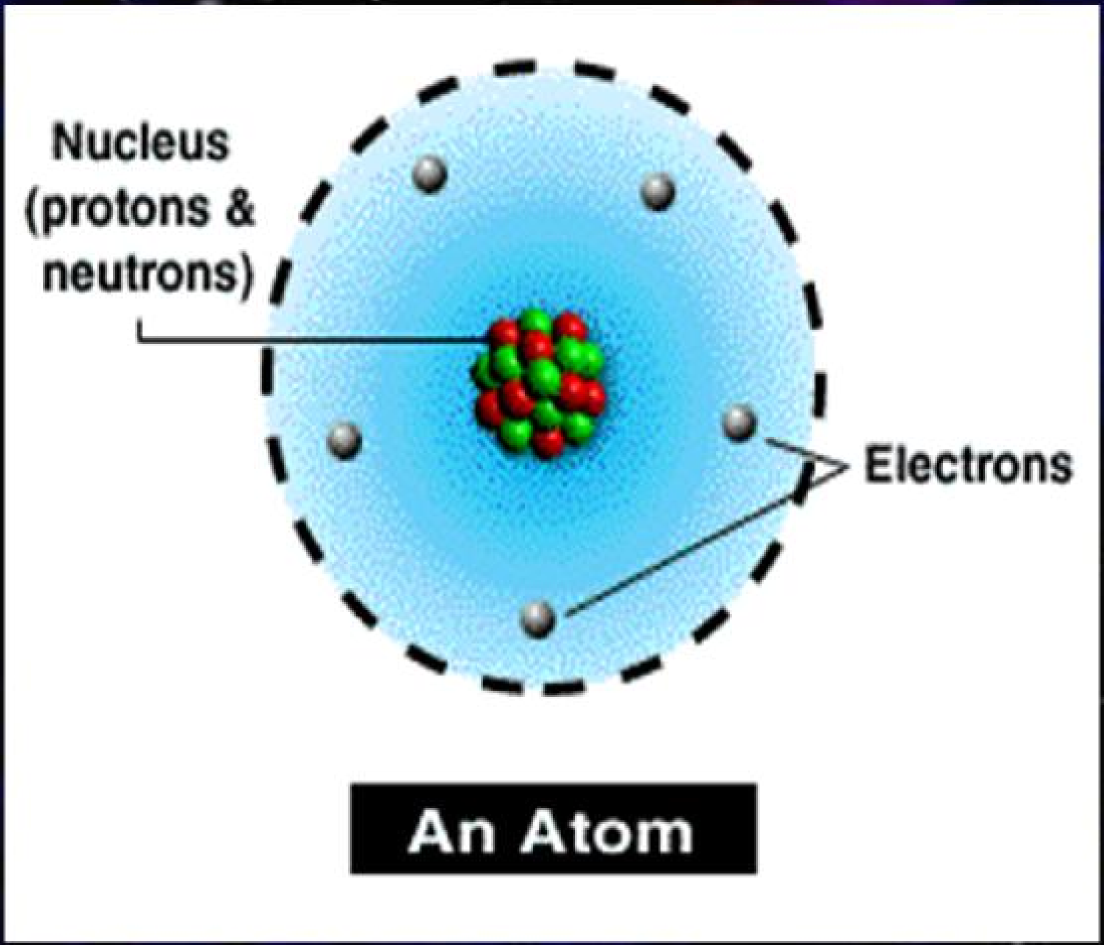
M1 - The Crab Nebula




Crab Nebula

Synthesis of the Elements

1	2 IIA 2A	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 IIIA 3A	14 IVA 4A	15 VA 5A	16 VIA 6A	17 VIIA 7A	2
1 H 1.008																	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											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)



Protons: + charge
determines chemistry

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

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

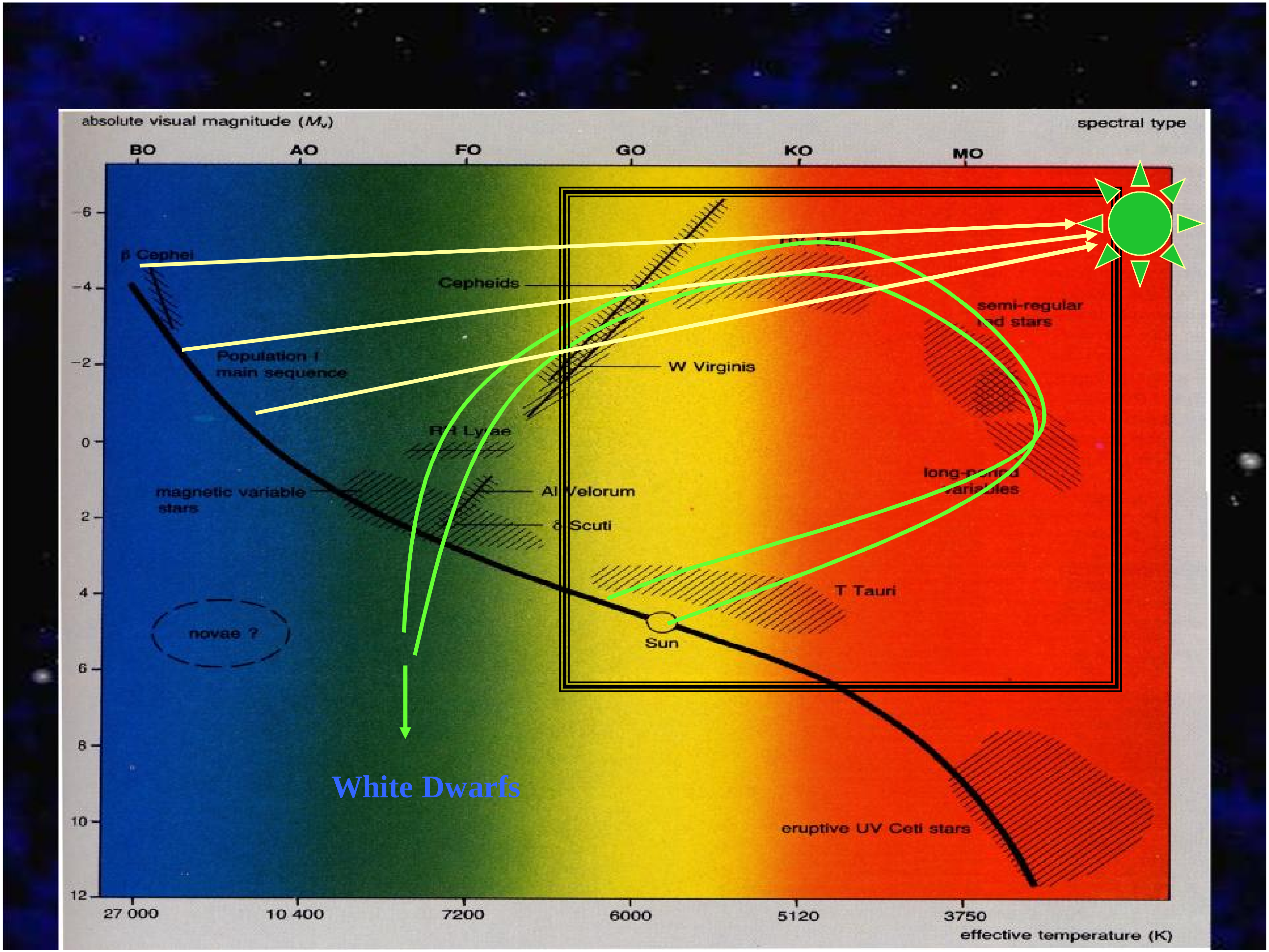
Isotopes of the elements

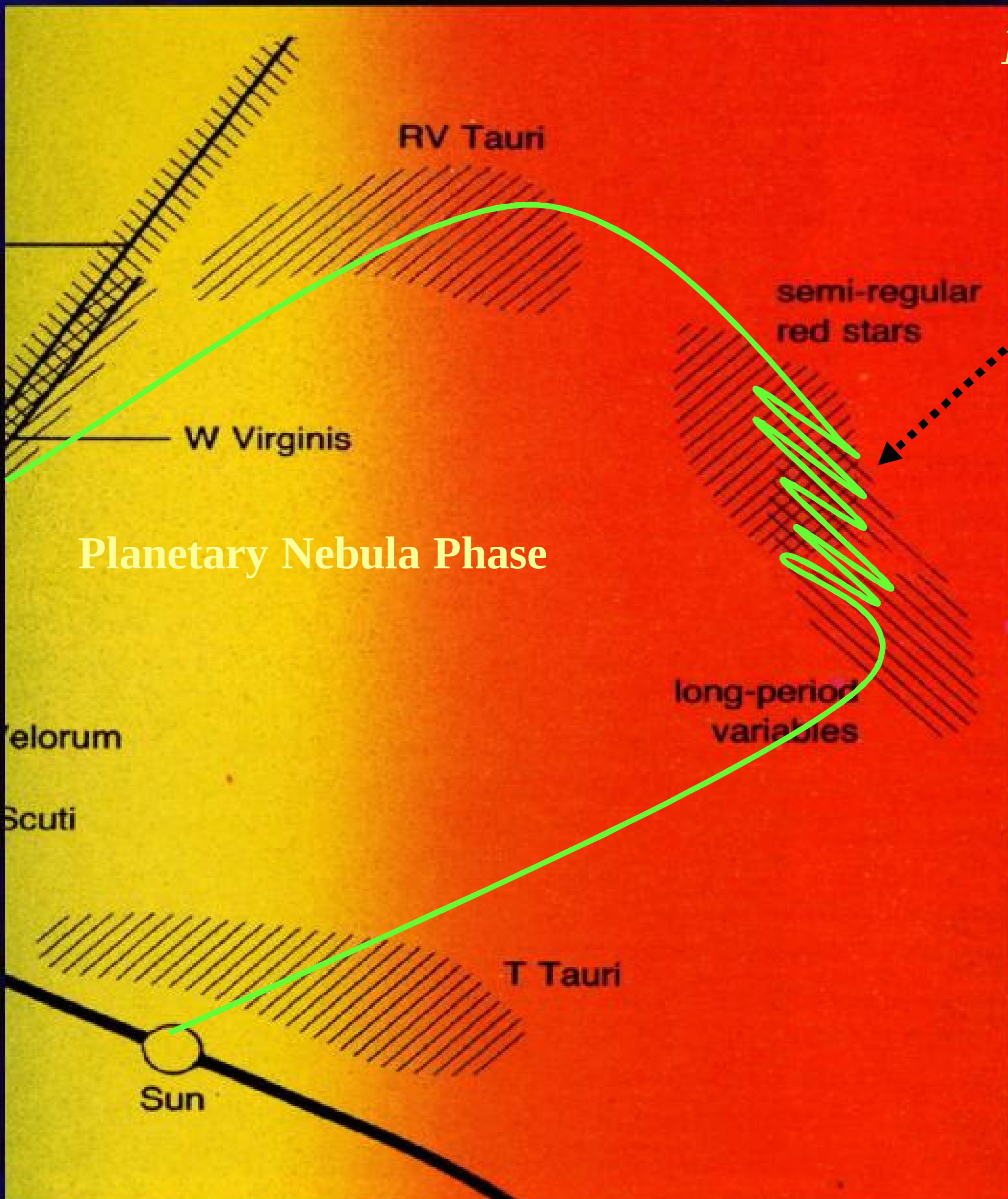
^{12}C = 6 protons + 6 neutrons

^{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


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 red stars
Population I main sequence
W Virginis
RR Lyrae
magnetic variable stars
AI Velorum
δ Scuti
long-period variables
T Tauri
novae ?
Sun
White Dwarfs
eruptive UV Ceti stars
27 000
10 400
7200
6000
5120
3750
effective temperature (K)



Death of a Star, Birth of the Elements

C and S Stars: Thermal Pulse Phase

1) He → ^{12}C
2) ^{12}C → ^{13}C
3) ^{13}C + He → ^{16}O + n
   ^{22}Ne + *He* → ^{25}Mg + n
4) n + {Fe, Ni, Co…} → *s-elements*

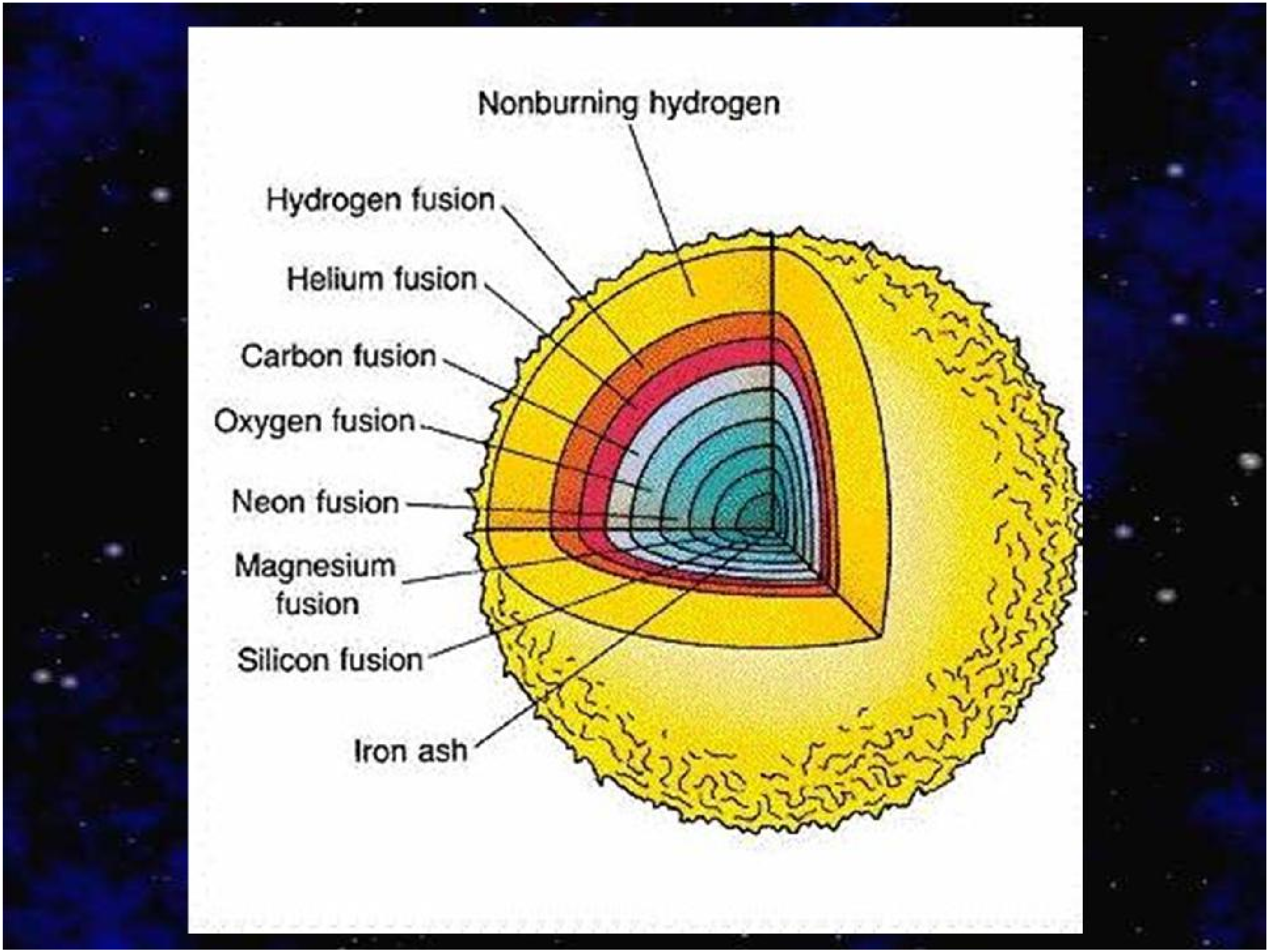
Total lifetime in TP: ~100,000 years
Total TP: ~15-20
Slow Neutron Capture Synthesis of heavy elements: >Fe
Between TP: Dredge Up Period

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

Energy Production in Stars

Main Sequence

4H $\longrightarrow$ He

0.7% of mass converted to energy by $E = mc^2$

Off main sequence

He $\longrightarrow$ C, O, Ne

C, O, Ne $\longrightarrow$ Si, P, S

Si, S, P $\longrightarrow$ Fe, Co, Ni

Much lower energy obtained from these reactions

End of line, most stable nuclei

The problem: Synthesis of Carbon-12

4H ⟶ He

He + H ⟶ [Li] ⟶ He + H

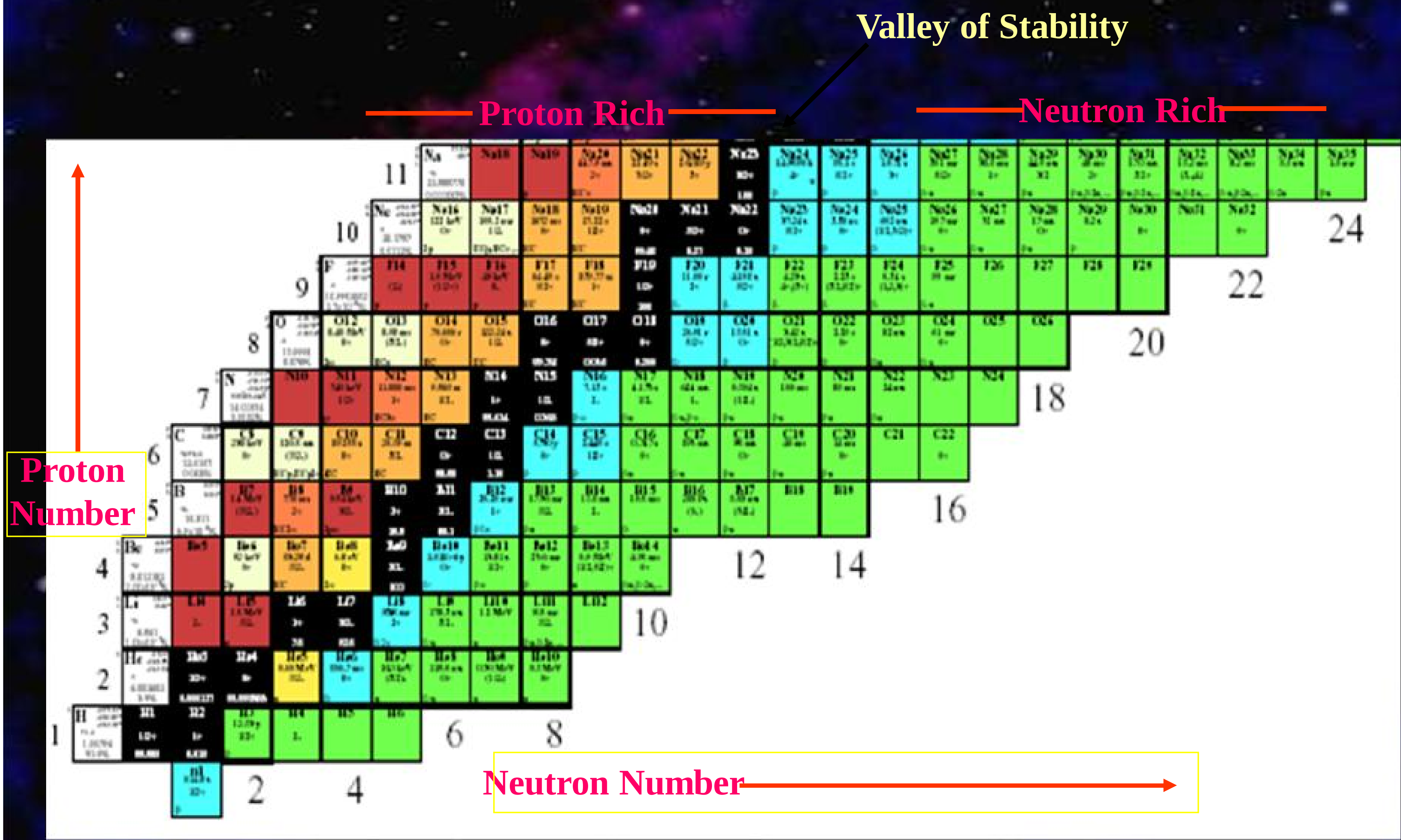
He + He ⟶ [Be] ⟶ He + He

He + He + He ⟶ $[^{12}C]^*$ —fast⟶ 3He   Triple alpha Process

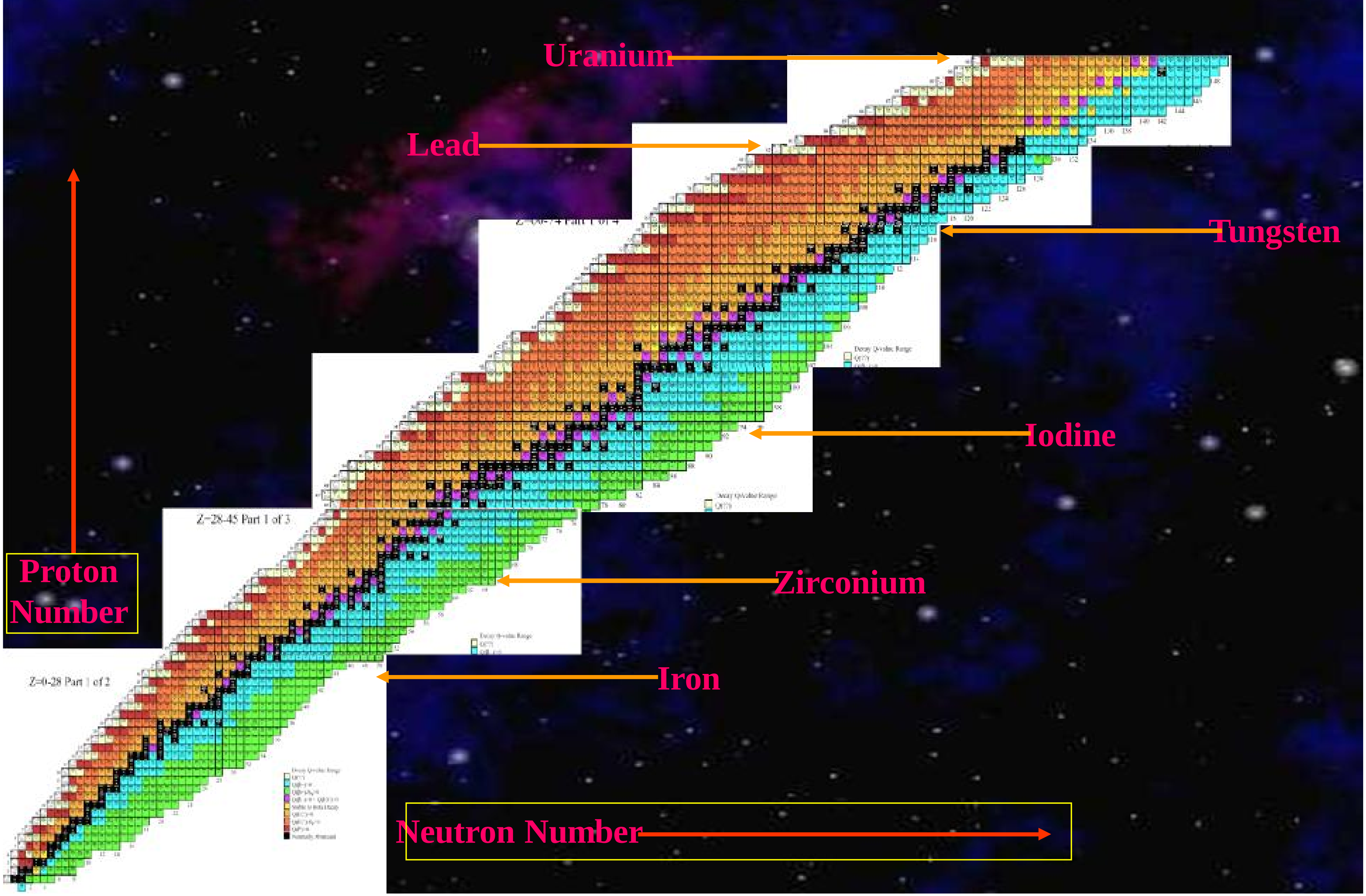
$[^{12}C]^*$ —slow⟶ ^{12}C + gamma ray

Fred Hoyle solved this

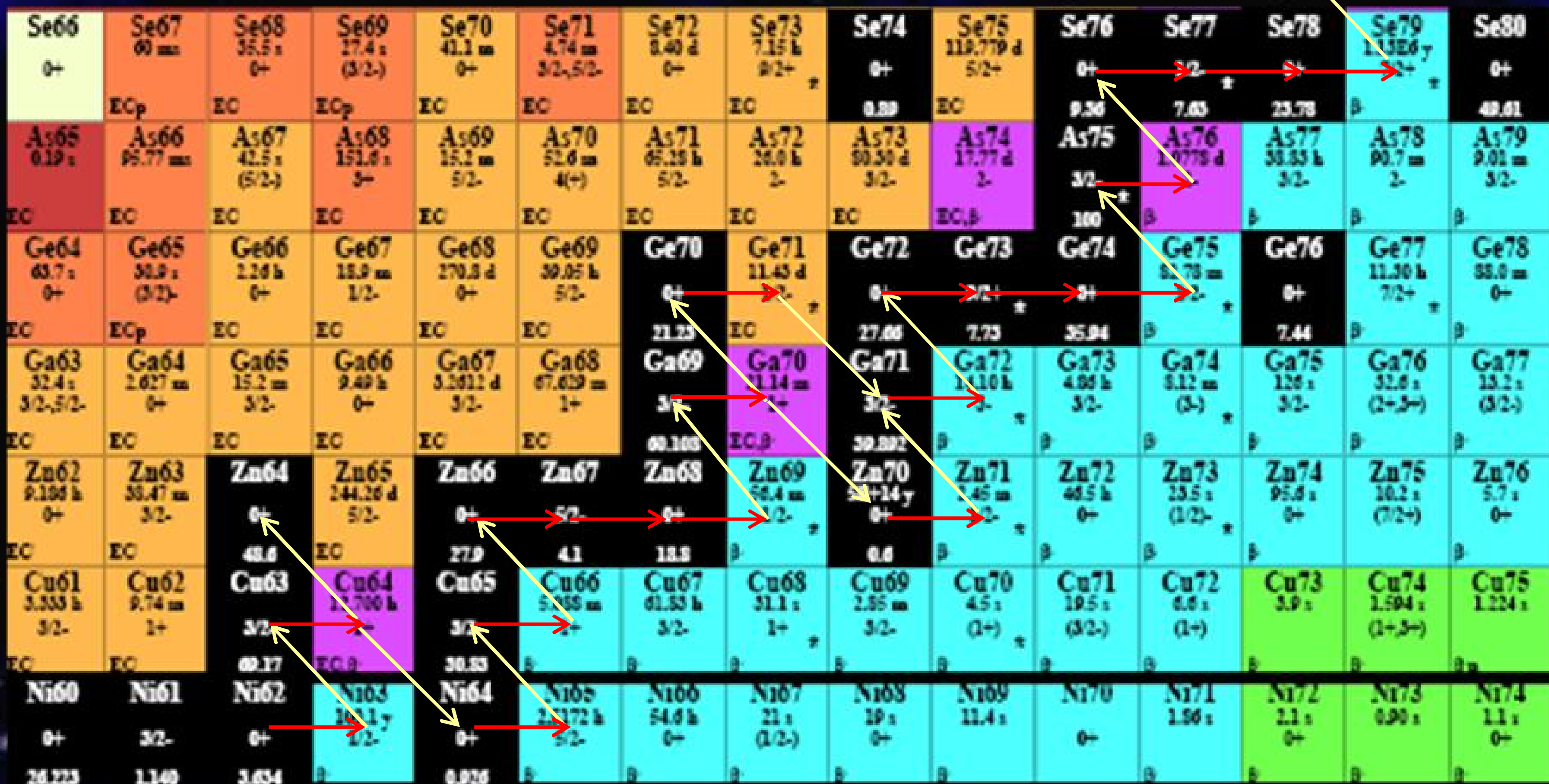
The 3rd Dimension of the Periodic Table



The 3rd Dimension of the Periodic Table



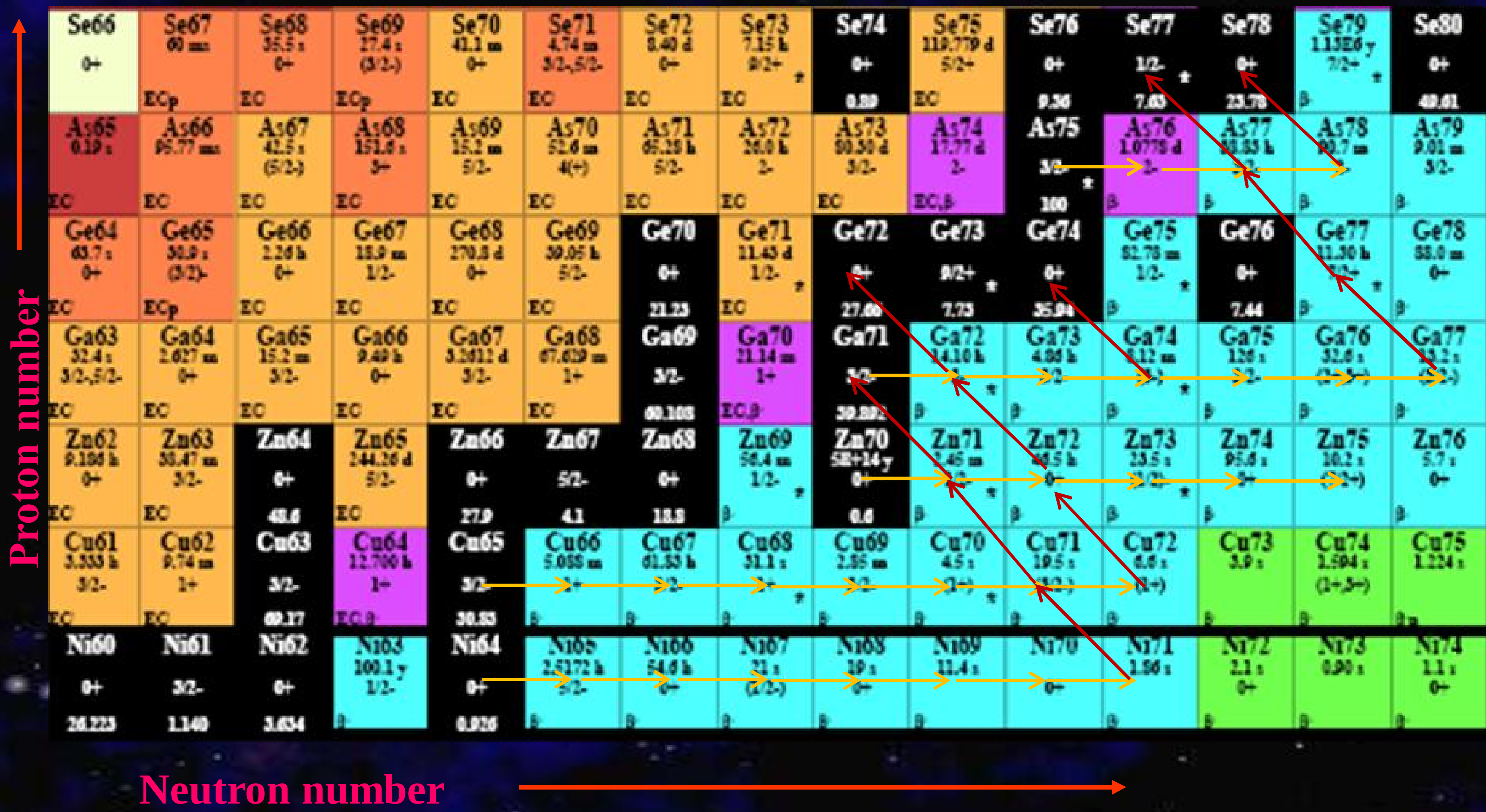
Nucleosynthesis in Stars by s-process (slow neutron capture)



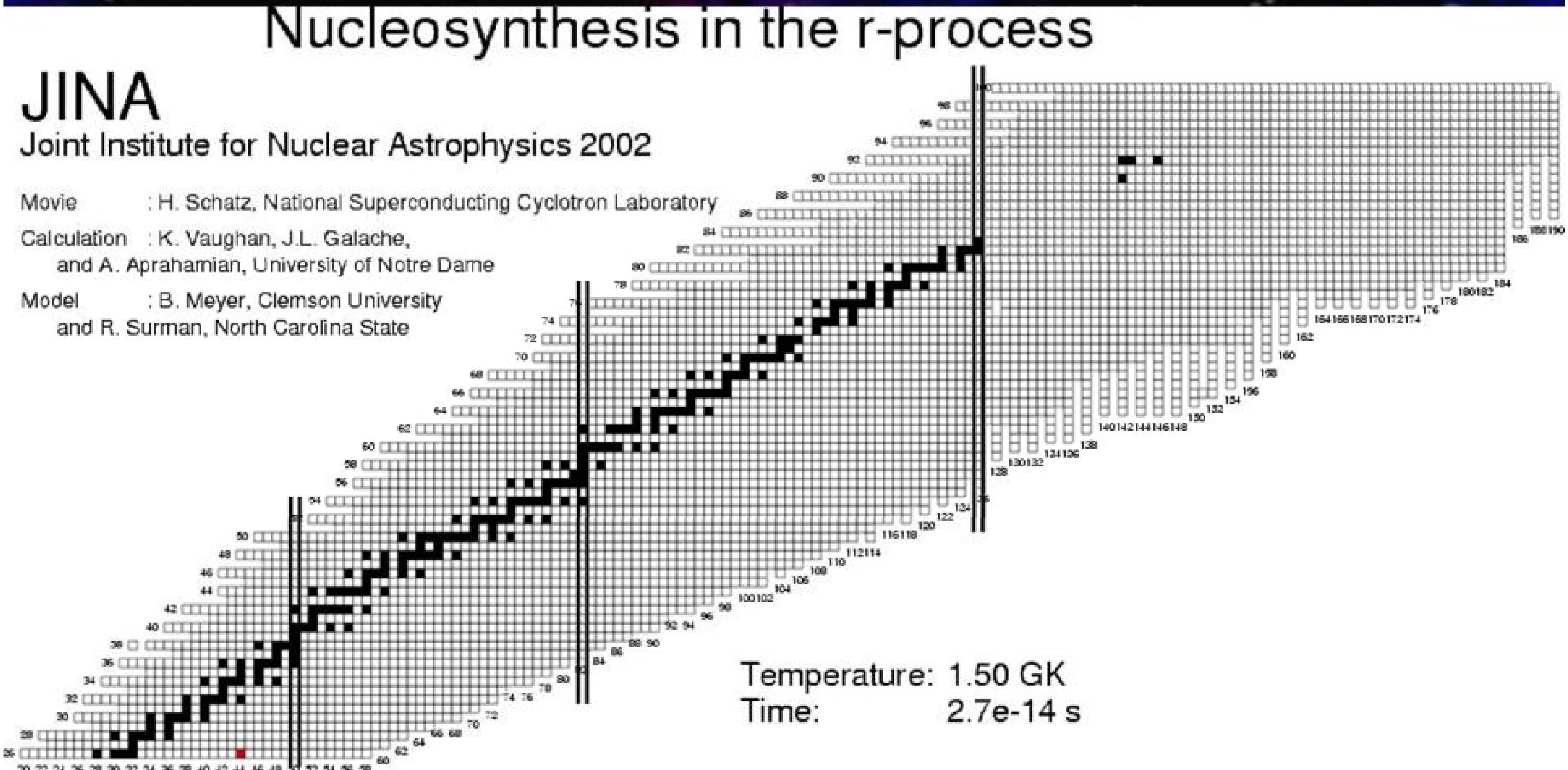
Proton number

Neutron number

Nucleosynthesis in Stars by r-process (Rapid neutron capture)



Nucleosynthesis in Stars by r-process (Rapid neutron capture)



B²FH

REVIEWS OF MODERN PHYSICS

VOLUME 29, NUMBER 4 — OCTOBER, 1957

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

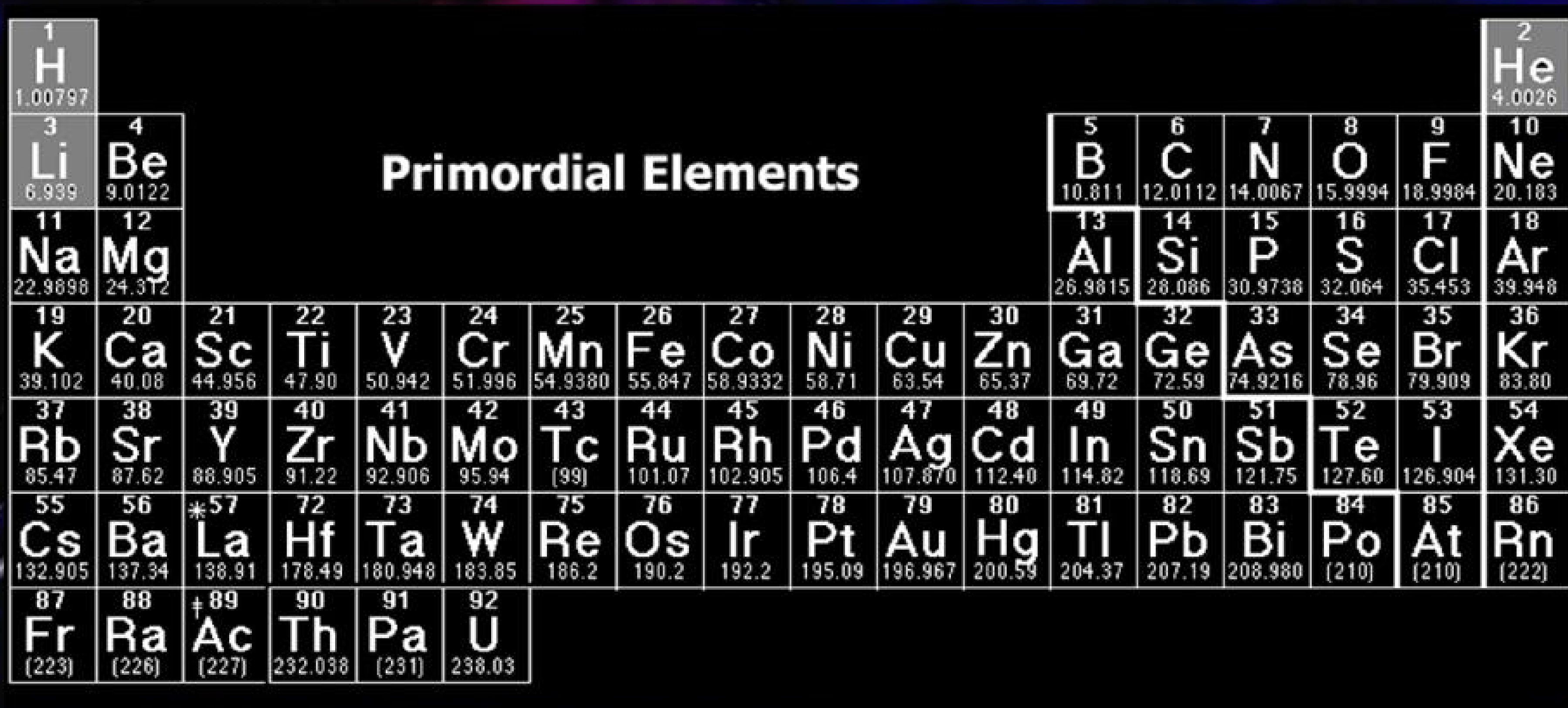
"It is the stars, The stars above us, govern our conditions";
(*King Lear*, Act IV, Scene 3)

but perhaps

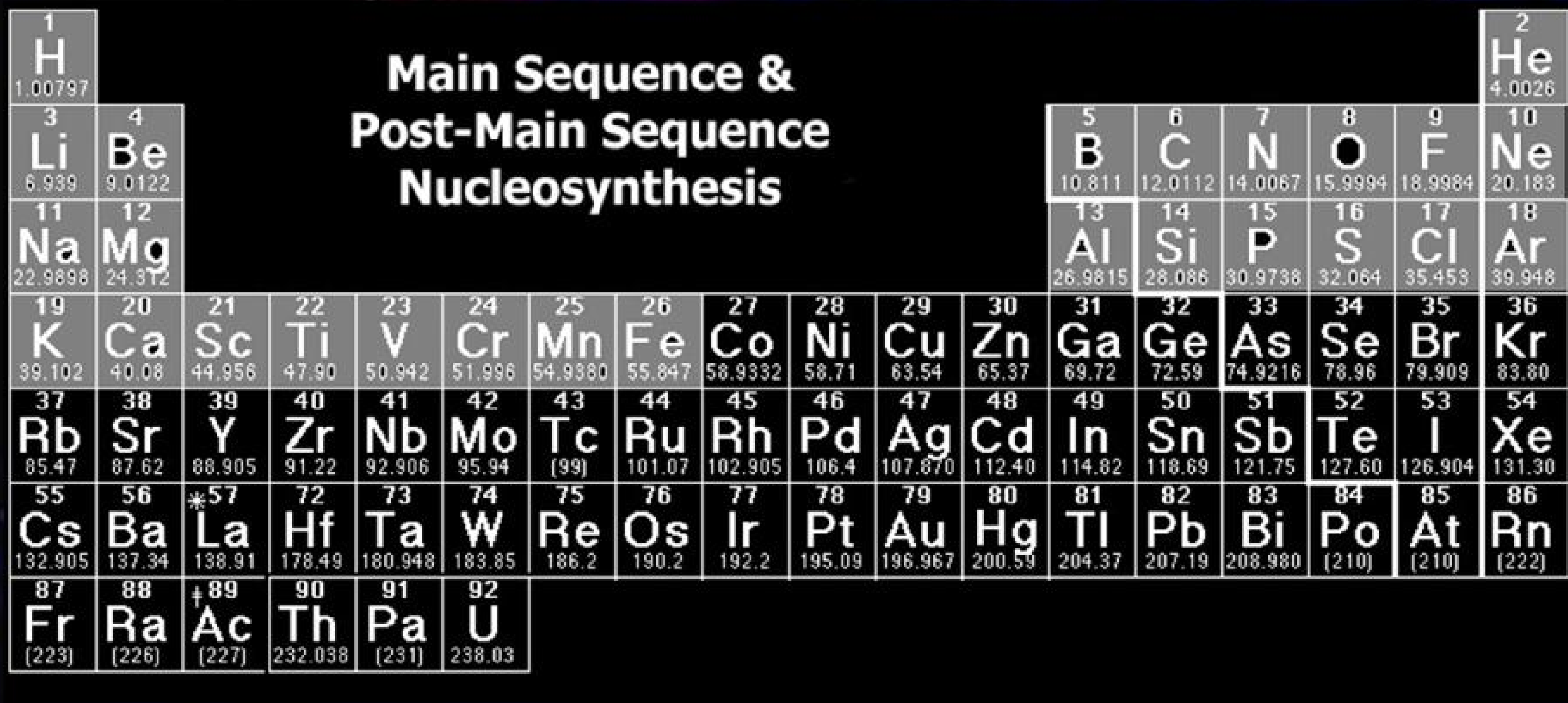
"The fault, dear Brutus, is not in our stars, But in ourselves,"
(*Julius Caesar*, Act I, Scene 2)

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)

Big Bang Nucleosynthesis



Stellar Evolution



Nucleosynthesis of elements heavier than iron

S-Process

- Occurs in post-main sequence giants
- Creation of stable nuclei up through ^{208}Pb (lead) and ^{209}Bi (bismuth)
- Neutron Capture

^{13}C + ^{4}He **à** ^{16}O + neutron

If iron “seed” nuclei are available then:

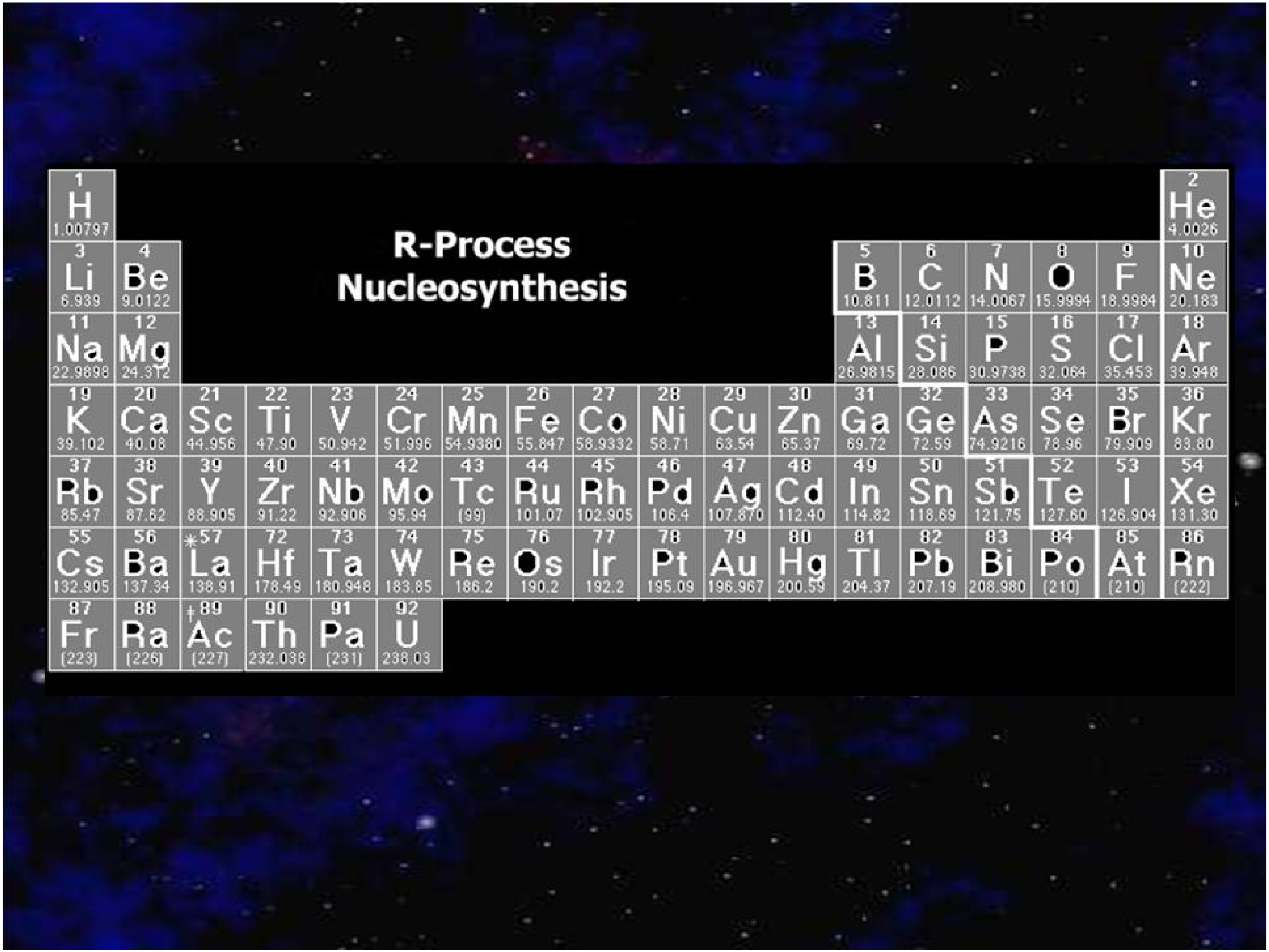
^{56}Fe + n **à** ^{57}Fe + n **à** ^{58}Fe +n **à** ^{59}Fe + n **à** ^{59}Co

S-Process Nucleosynthesis

1 H 1.00797																	2 He 4.0026
3 Li 6.939	4 Be 9.0122											5 B 10.811	6 C 12.0112	7 N 14.0067	8 O 15.9994	9 F 18.9984	10 Ne 20.183
11 Na 22.9898	12 Mg 24.312											13 Al 26.9815	14 Si 28.086	15 P 30.9738	16 S 32.064	17 Cl 35.453	18 Ar 39.948
19 K 39.102	20 Ca 40.08	21 Sc 44.956	22 Ti 47.90	23 V 50.942	24 Cr 51.996	25 Mn 54.9380	26 Fe 55.847	27 Co 58.9332	28 Ni 58.71	29 Cu 63.54	30 Zn 65.37	31 Ga 69.72	32 Ge 72.59	33 As 74.9216	34 Se 78.96	35 Br 79.909	36 Kr 83.80
37 Rb 85.47	38 Sr 87.62	39 Y 88.905	40 Zr 91.22	41 Nb 92.906	42 Mo 95.94	43 Tc (99)	44 Ru 101.07	45 Rh 102.905	46 Pd 106.4	47 Ag 107.870	48 Cd 112.40	49 In 114.82	50 Sn 118.69	51 Sb 121.75	52 Te 127.60	53 I 126.904	54 Xe 131.30
55 Cs 132.905	56 Ba 137.34	*57 La 138.91	72 Hf 178.49	73 Ta 180.948	74 W 183.85	75 Re 186.2	76 Os 190.2	77 Ir 192.2	78 Pt 195.09	79 Au 196.967	80 Hg 200.59	81 Tl 204.37	82 Pb 207.19	83 Bi 208.980	84 Po (210)	85 At (210)	86 Rn (222)
87 Fr (223)	88 Ra (226)	†89 Ac (227)	90 Th 232.038	91 Pa (231)	92 U 238.03												

R-Process

- Creates the heaviest (neutron rich) elements
- Involves creation of highly unstable nuclei
- Very rapid neutron capture helps create stable nuclei
- Requires very high temperatures and high “neutron flux”
- Supernovae environment


R-Process Nucleosynthesis
1 H 1.00797
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4 Be 9.0122
5 B 10.811
6 C 12.0112
7 N 14.0067
8 O 15.9994
9 F 18.9984
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11 Na 22.9898
12 Mg 24.312
13 Al 26.9815
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15 P 30.9738
16 S 32.064
17 Cl 35.453
18 Ar 39.948
19 K 39.102
20 Ca 40.08
21 Sc 44.956
22 Ti 47.90
23 V 50.942
24 Cr 51.996
25 Mn 54.9380
26 Fe 55.847
27 Co 58.9332
28 Ni 58.71
29 Cu 63.54
30 Zn 65.37
31 Ga 69.72
32 Ge 72.59
33 As 74.9216
34 Se 78.96
35 Br 79.909
36 Kr 83.80
37 Rb 85.47
38 Sr 87.62
39 Y 88.905
40 Zr 91.22
41 Nb 92.906
42 Mo 95.94
43 Tc (99)
44 Ru 101.07
45 Rh 102.905
46 Pd 106.4
47 Ag 107.870
48 Cd 112.40
49 In 114.82
50 Sn 118.69
51 Sb 121.75
52 Te 127.60
53 I 126.904
54 Xe 131.30
55 Cs 132.905
56 Ba 137.34
*57 La 138.91
72 Hf 178.49
73 Ta 180.948
74 W 183.85
75 Re 186.2
76 Os 190.2
77 Ir 192.2
78 Pt 195.09
79 Au 196.967
80 Hg 200.59
81 Tl 204.37
82 Pb 207.19
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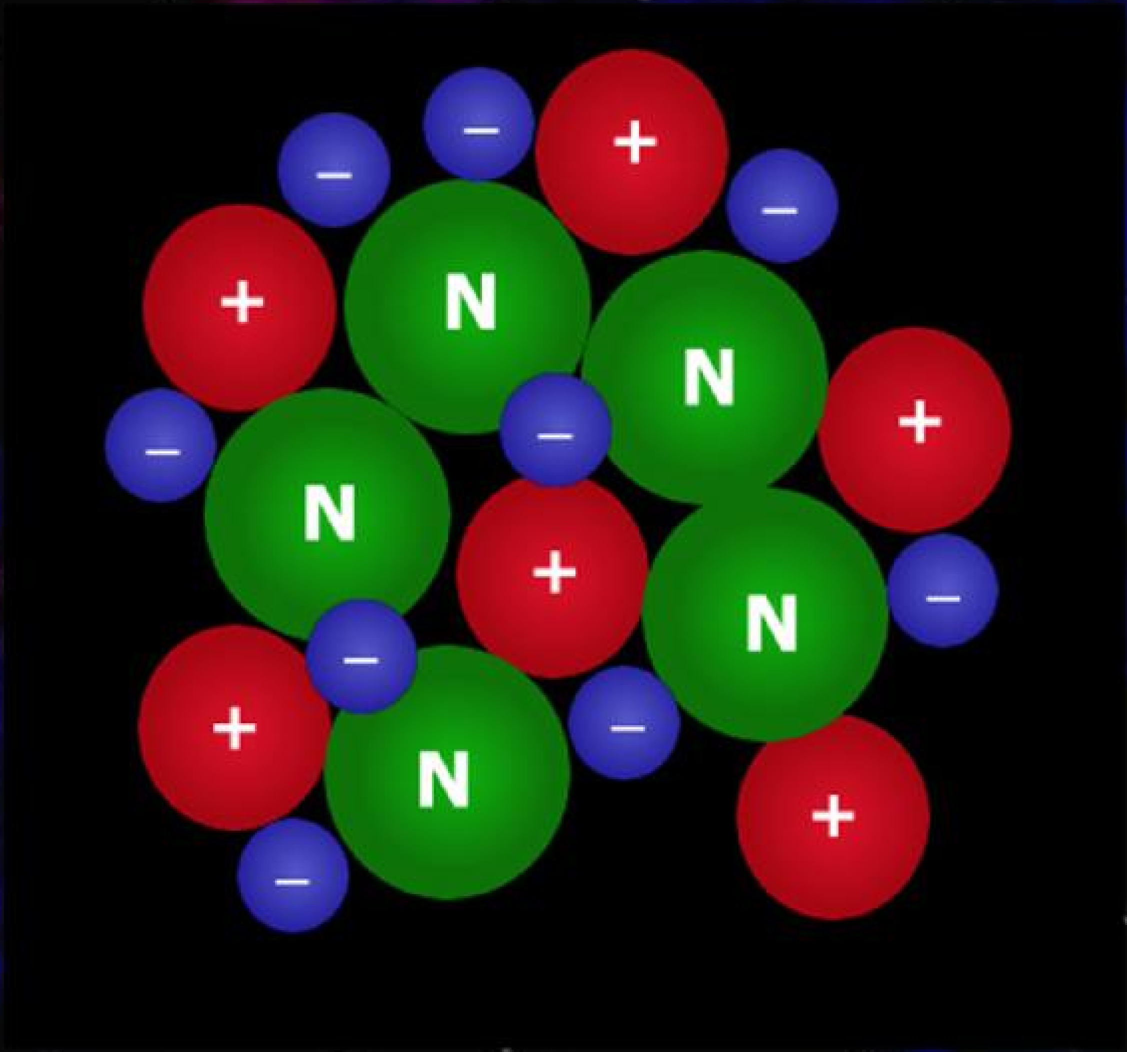
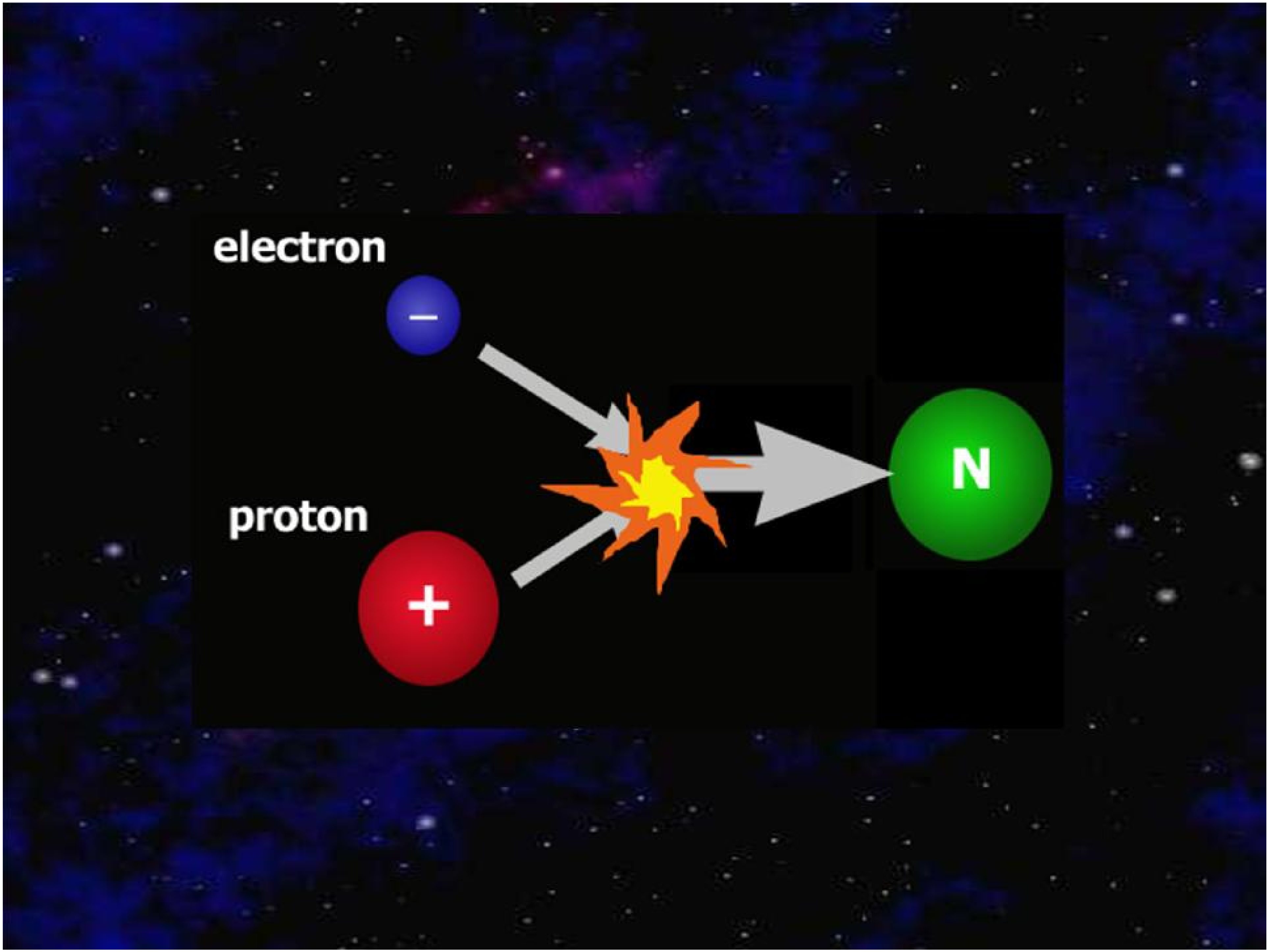
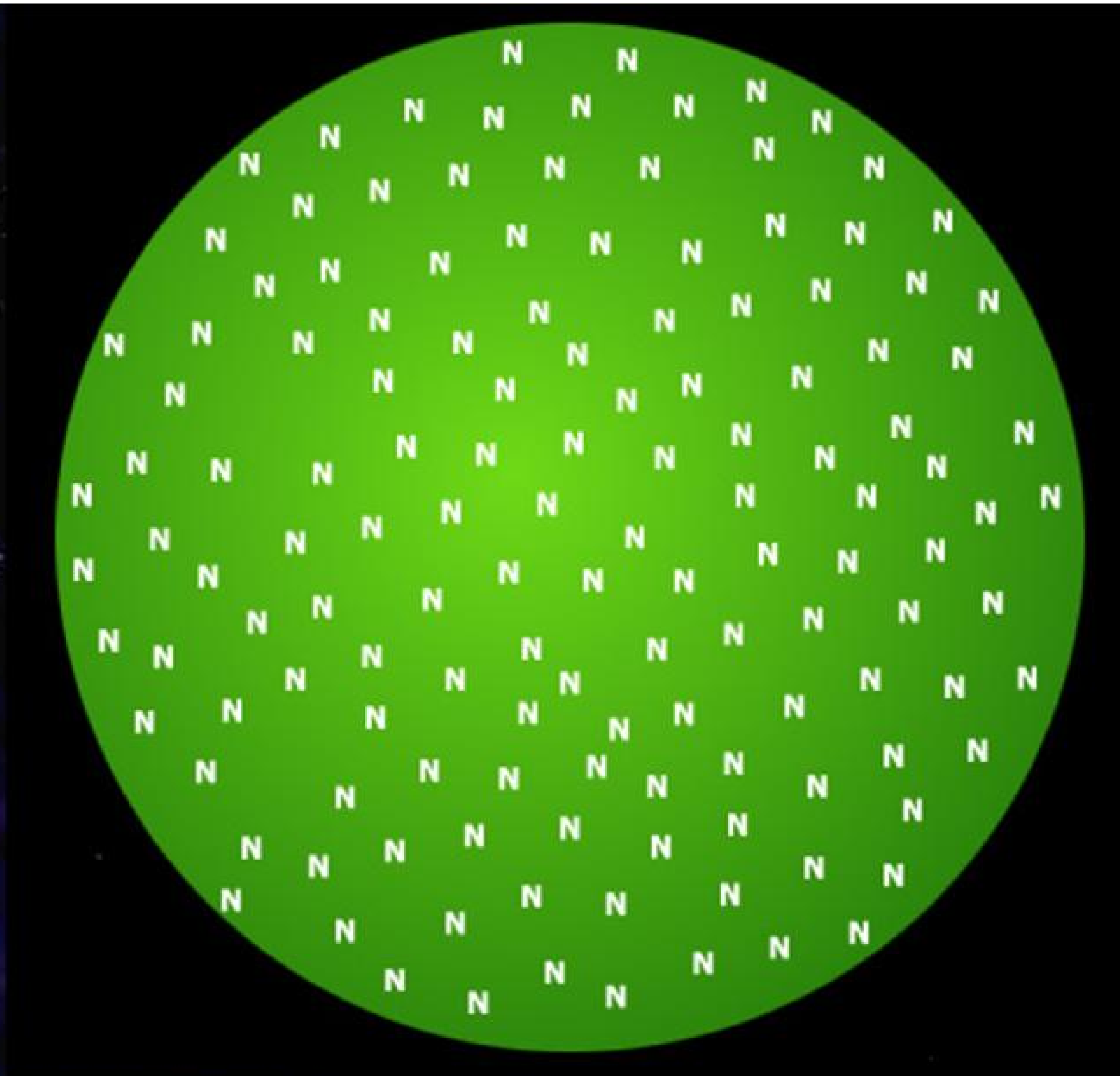
84 Po (210)
85 At (210)
86 Rn (222)
87 Fr (223)
88 Ra (226)
†89 Ac (227)
90 Th 232.038
91 Pa (231)
92 U 238.03

NEUTRON STARS

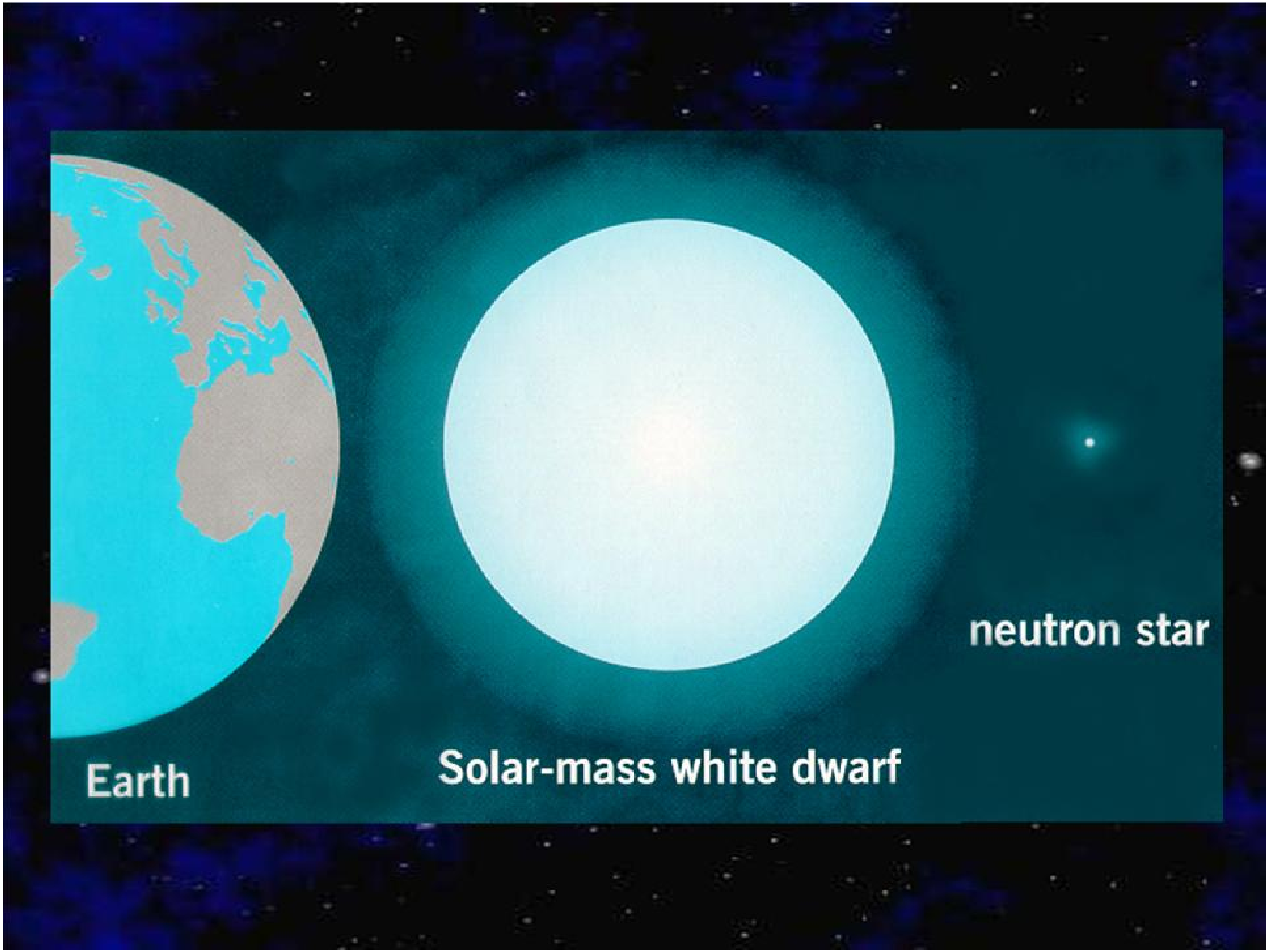
What happened to the iron core after the supernova?

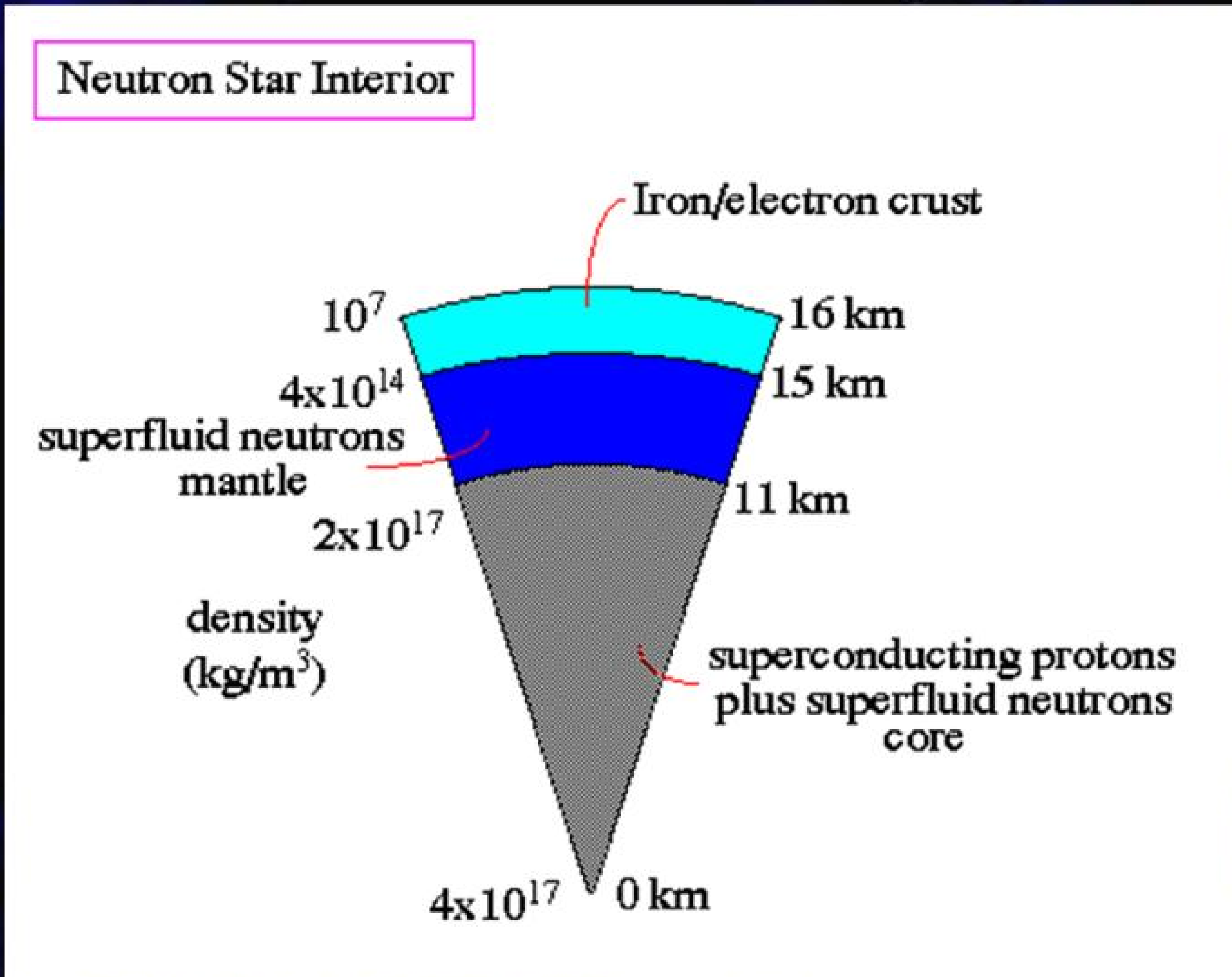



electron
–
proton
+
N



NEUTRON STAR

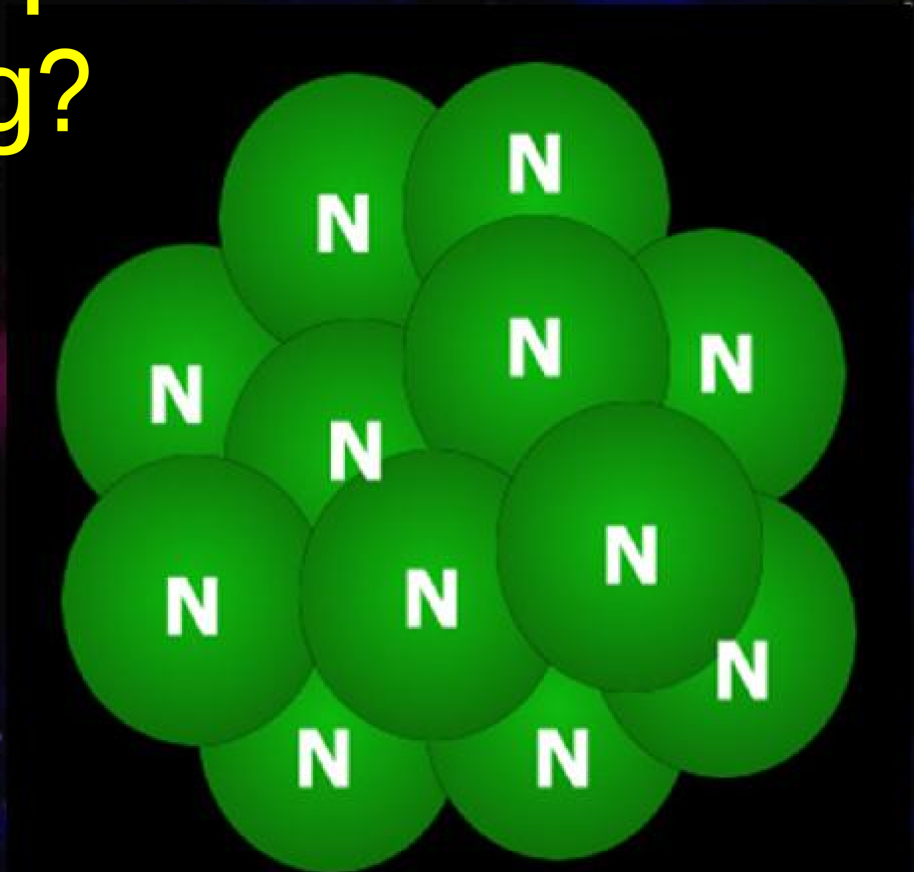

neutron star
Earth
Solar-mass white dwarf



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

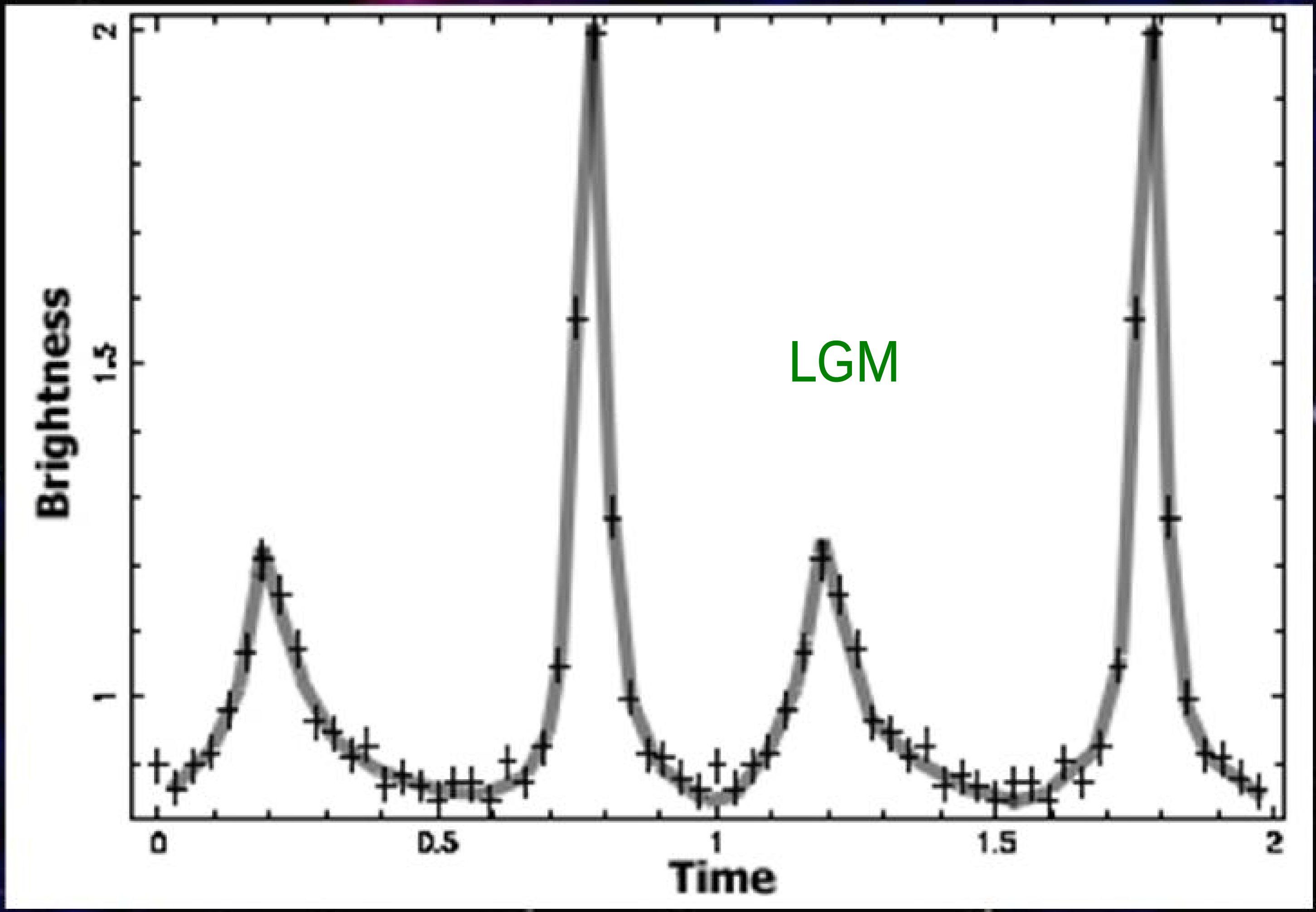
Chandrasekhar Limit for neutron stars

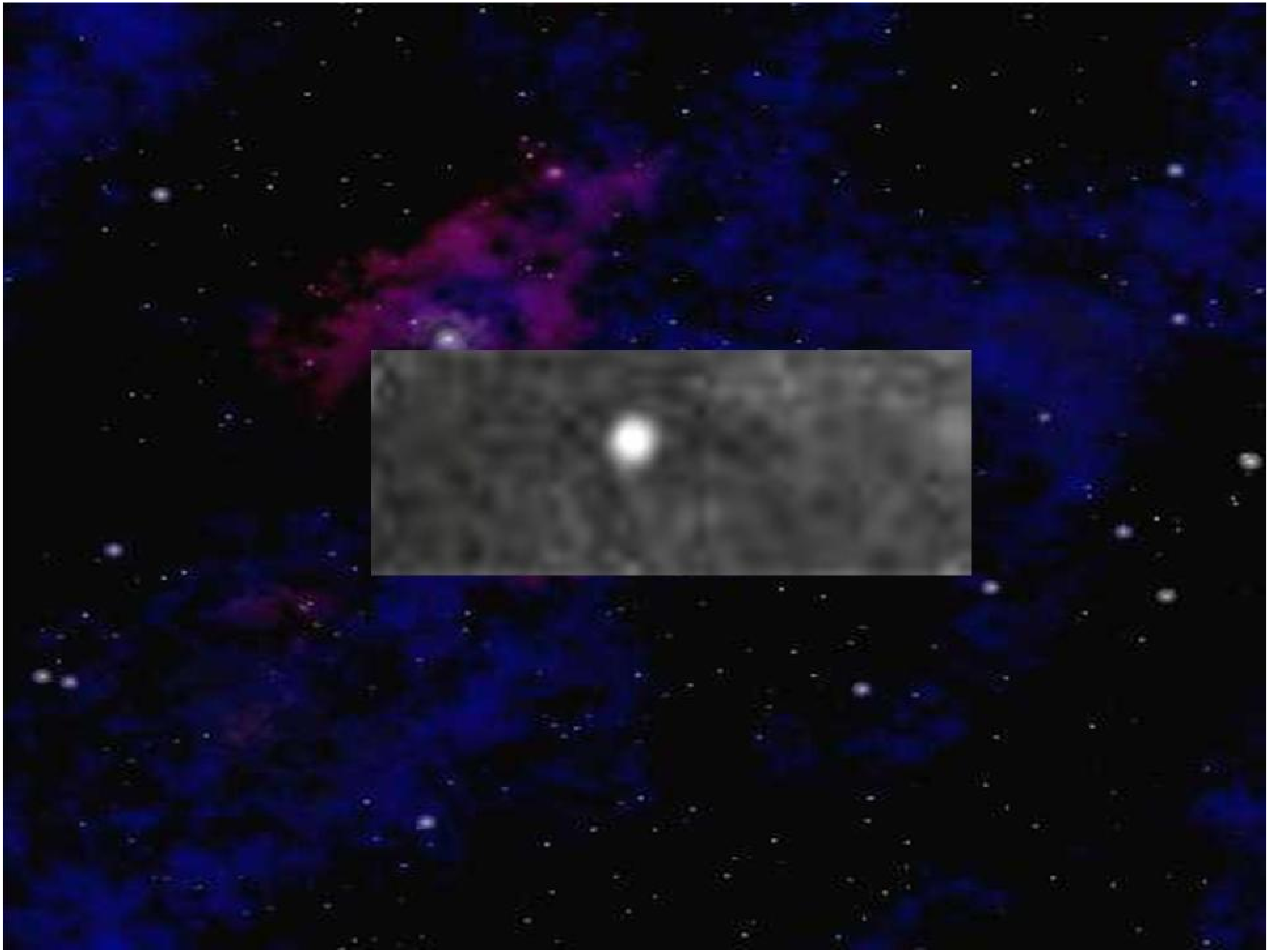
$$M < 3.0\ M_{\odot}$$

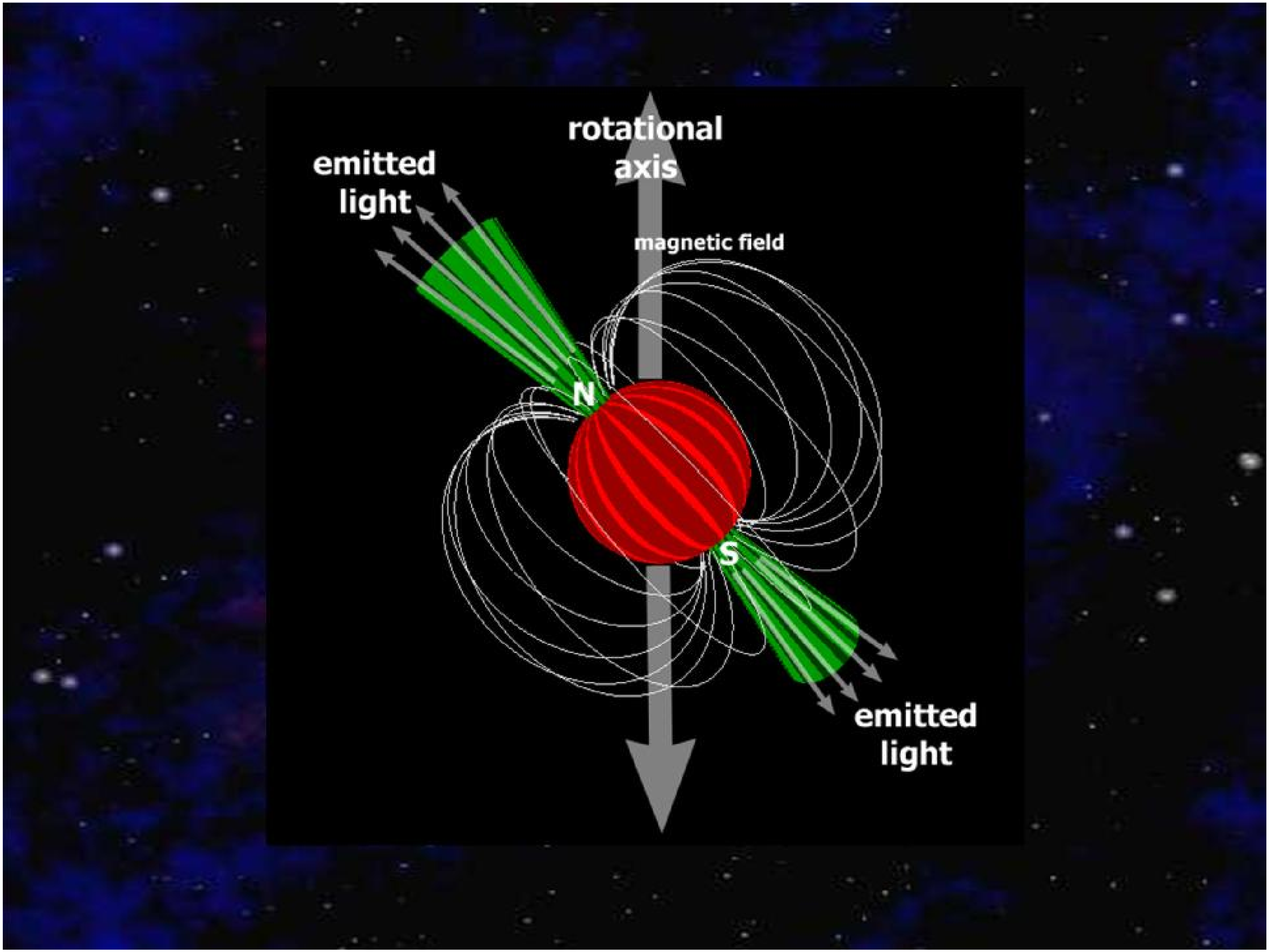
How do we know that neutron stars actually exist?

- First theorized in the 1930's
- First discovered in 1967

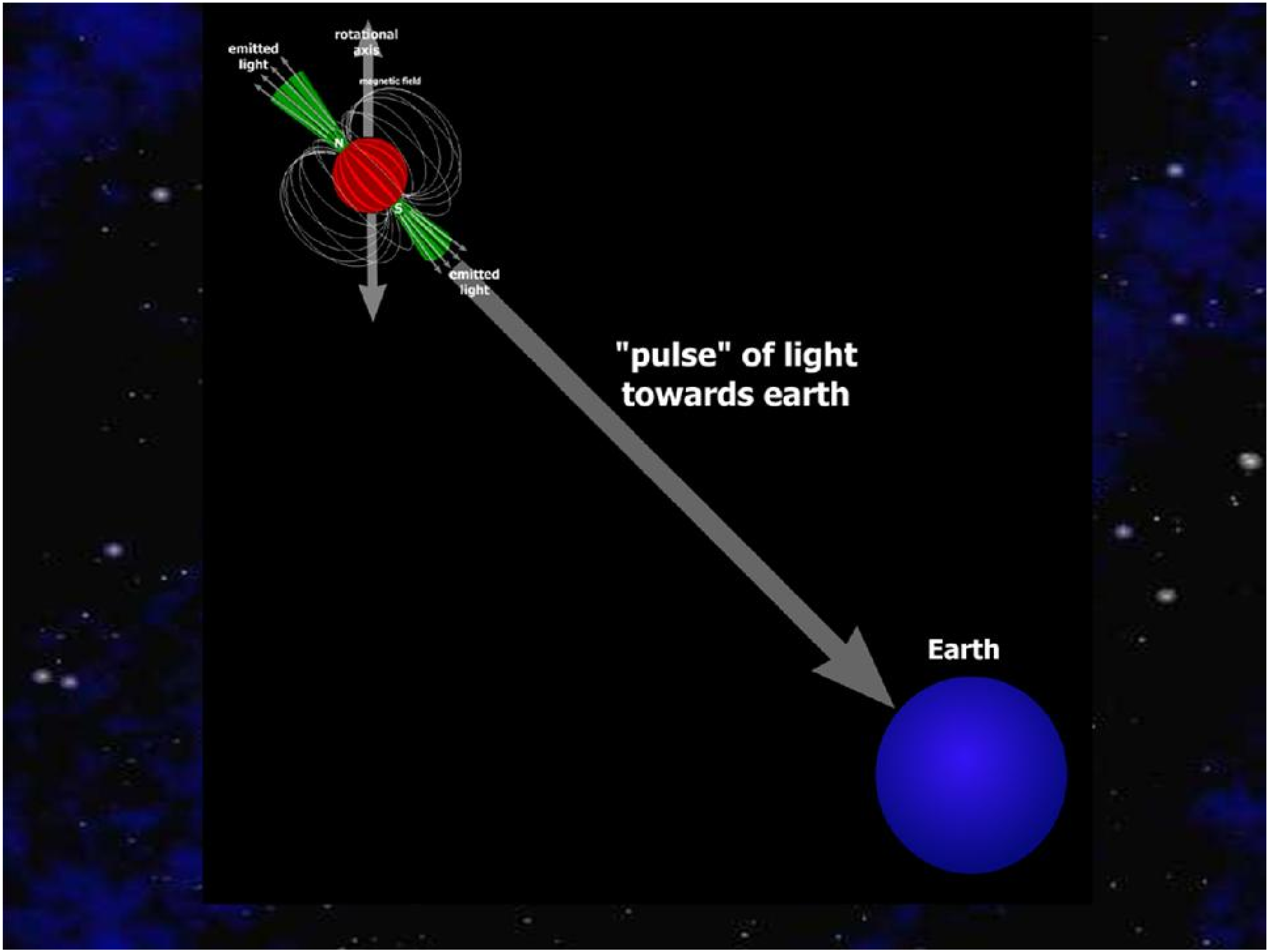
"pulsed" energy every 1.34 seconds

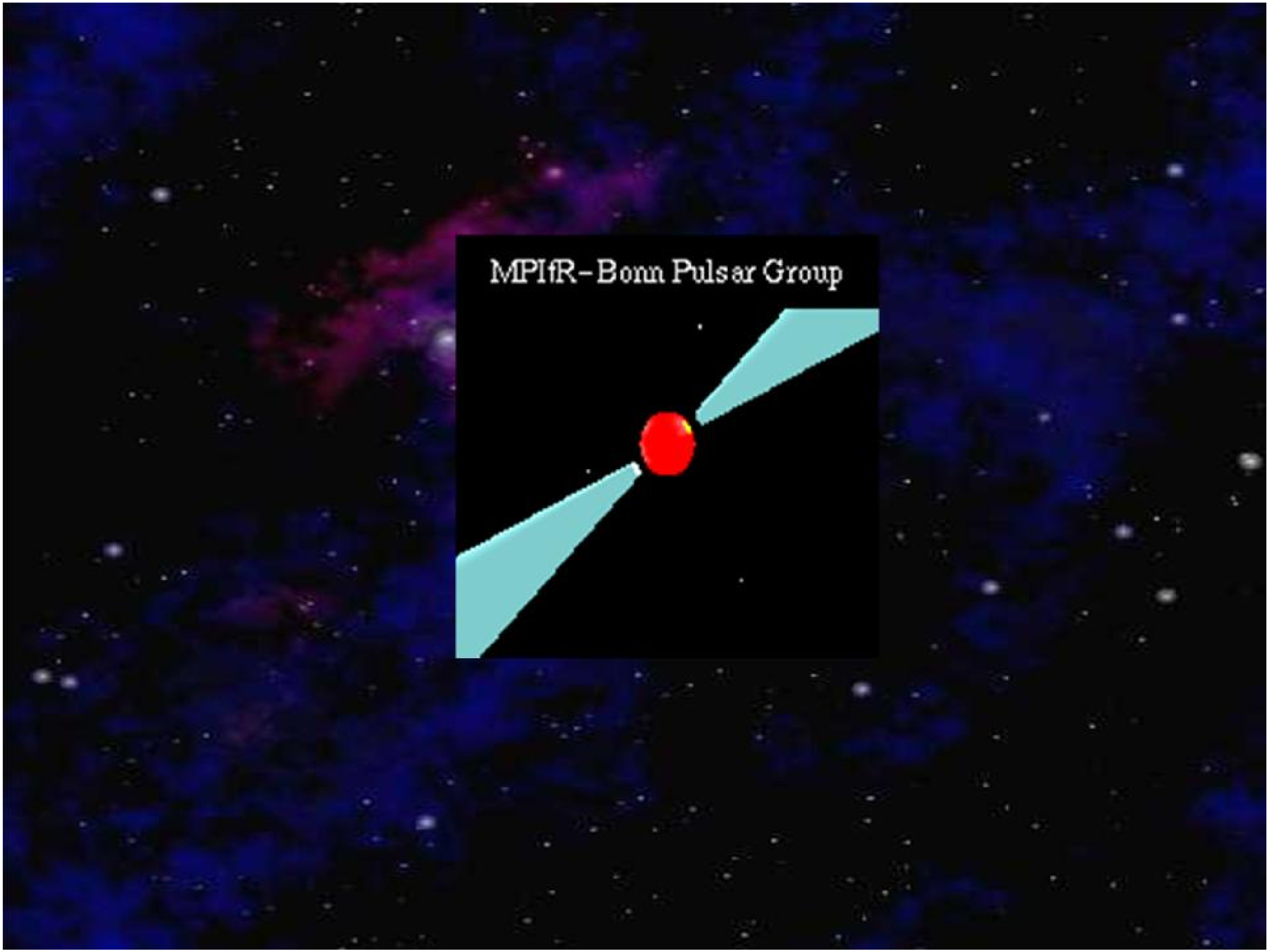





rotational
axis
emitted
light
magnetic field
N
S
emitted
light

Conservation of Angular Momentum


emitted
light
rotational
axis
magnetic field
N
S
emitted
light
"pulse" of light
towards earth
Earth


MPIfR-Bonn Pulsar Group

esa

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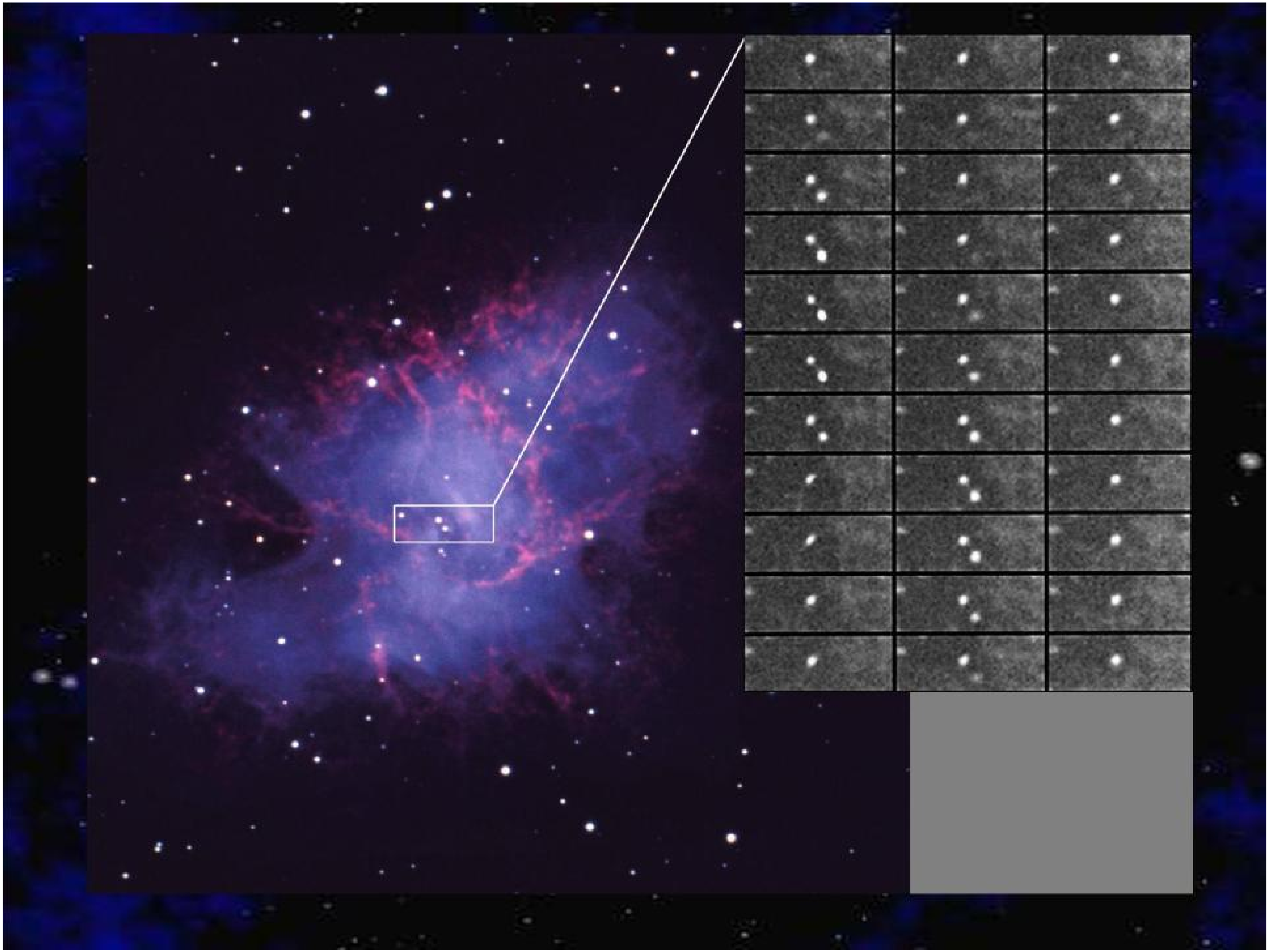
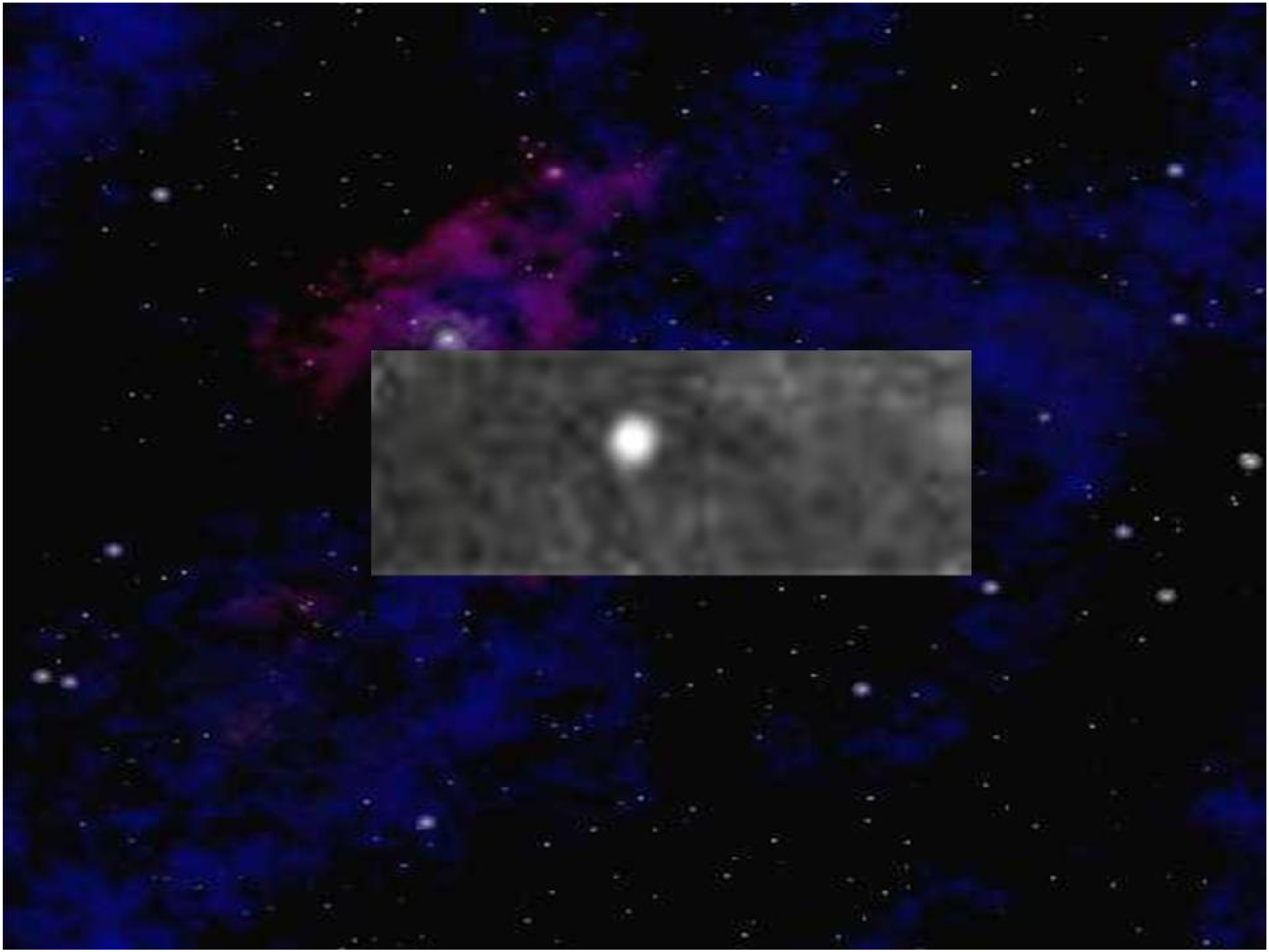
Rapidly rotating neutron star

-or-

PULSAR

The Crab Nebula





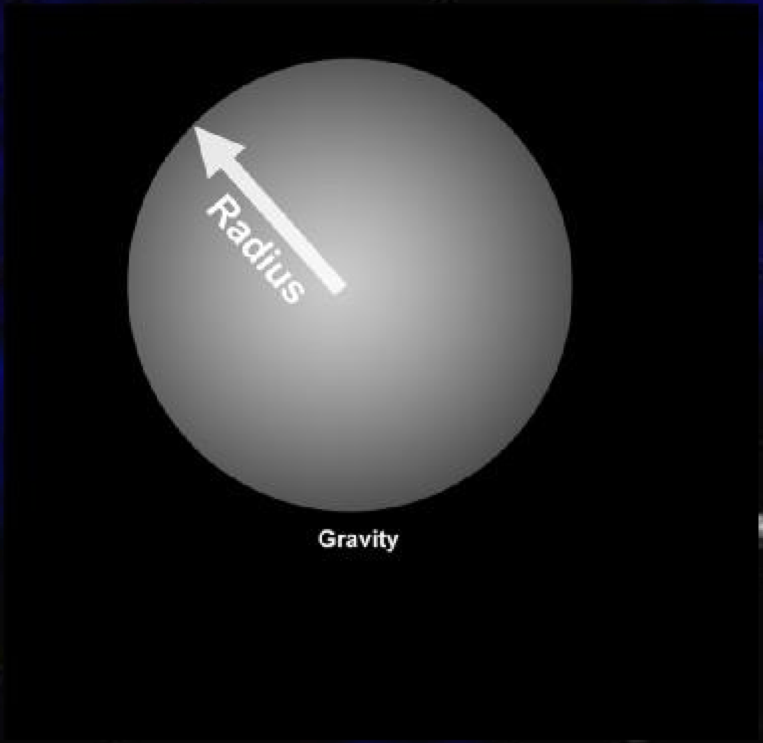
The Crab Pulsar

What if the iron core > $3.0M_{\odot}$

- Degeneracy pressure is overcome by gravity
- The core continues to shrink producing NO HEAT.
- No force in nature can stop the collapse

ESCAPE VELOCITY

$$V_{esc} = \sqrt{\frac{2GM}{R}}$$



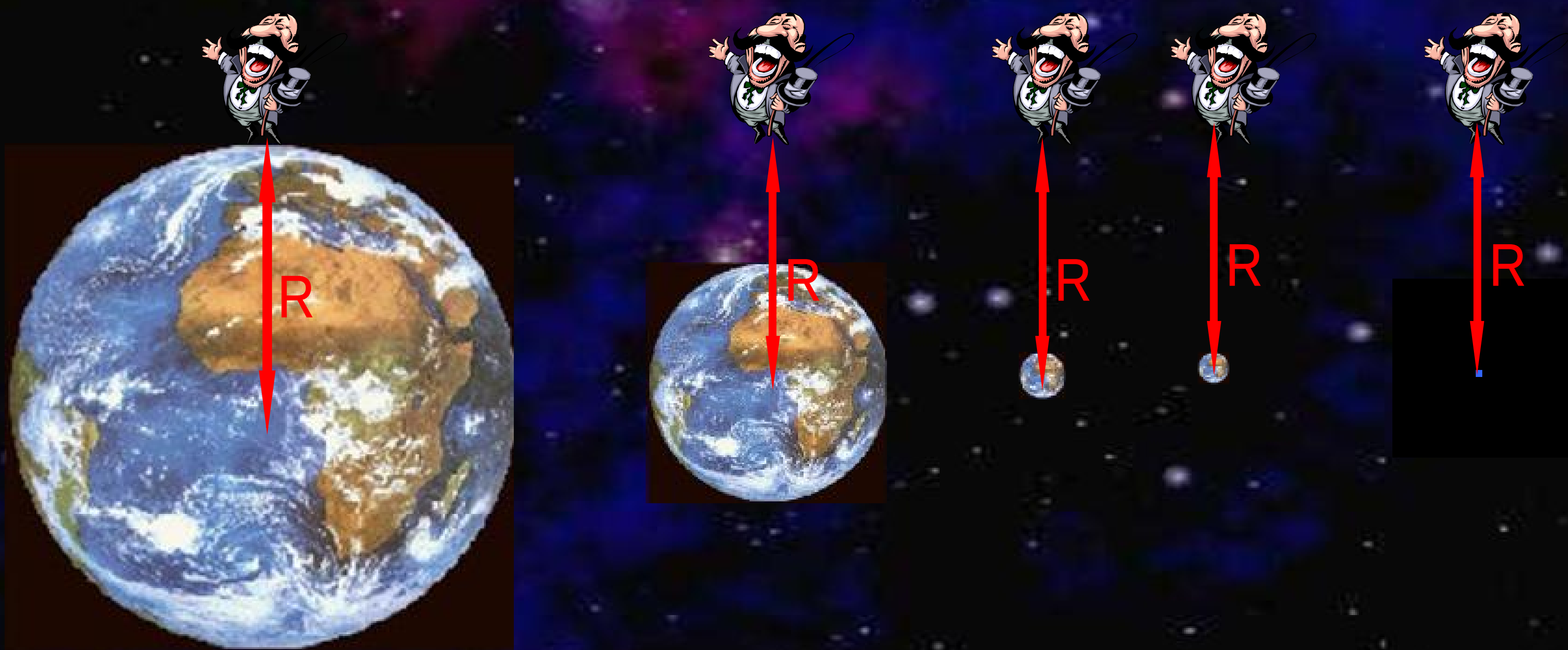
G = Universal Gravitational Constant

M = Mass of the gravitating body

R = Radius of the gravitating body

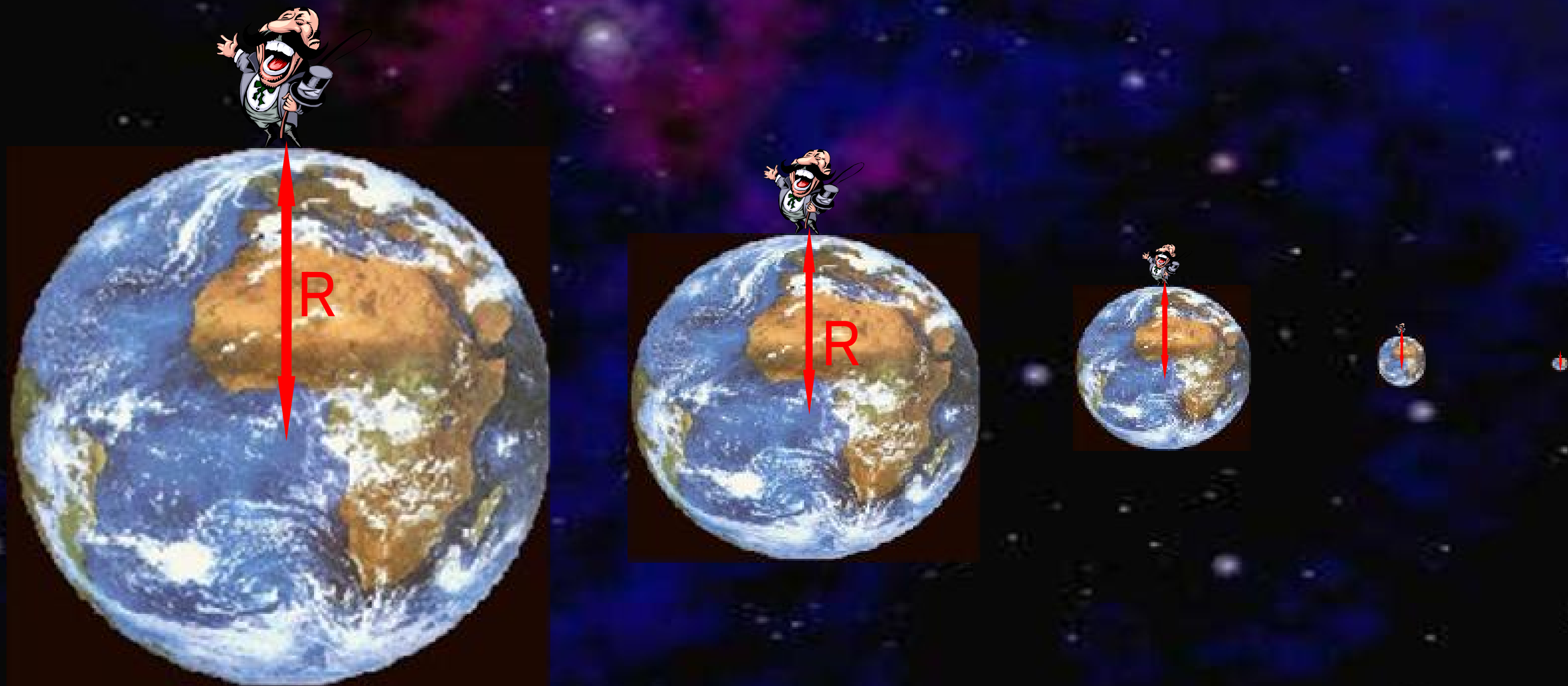
$$V_{esc} = \sqrt{\frac{2GM}{R}}$$

$$F = \frac{Gm_1 m_2}{r^2}$$



$$V_{esc} = \sqrt{\frac{2GM}{R}}$$

$$F = \frac{Gm_1 m_2}{r^2}$$



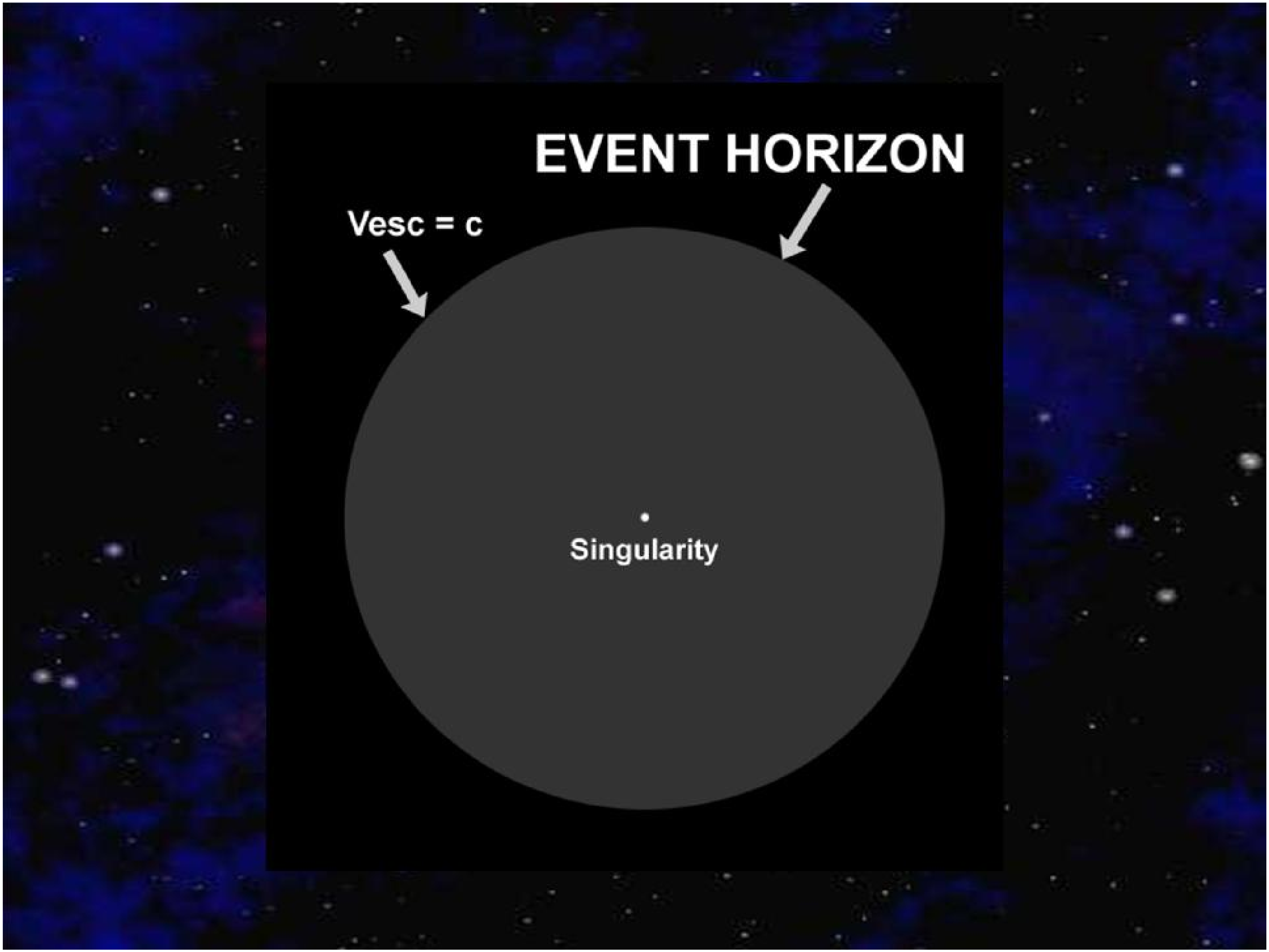
Soon the escape velocity is

greater than the speed of light!

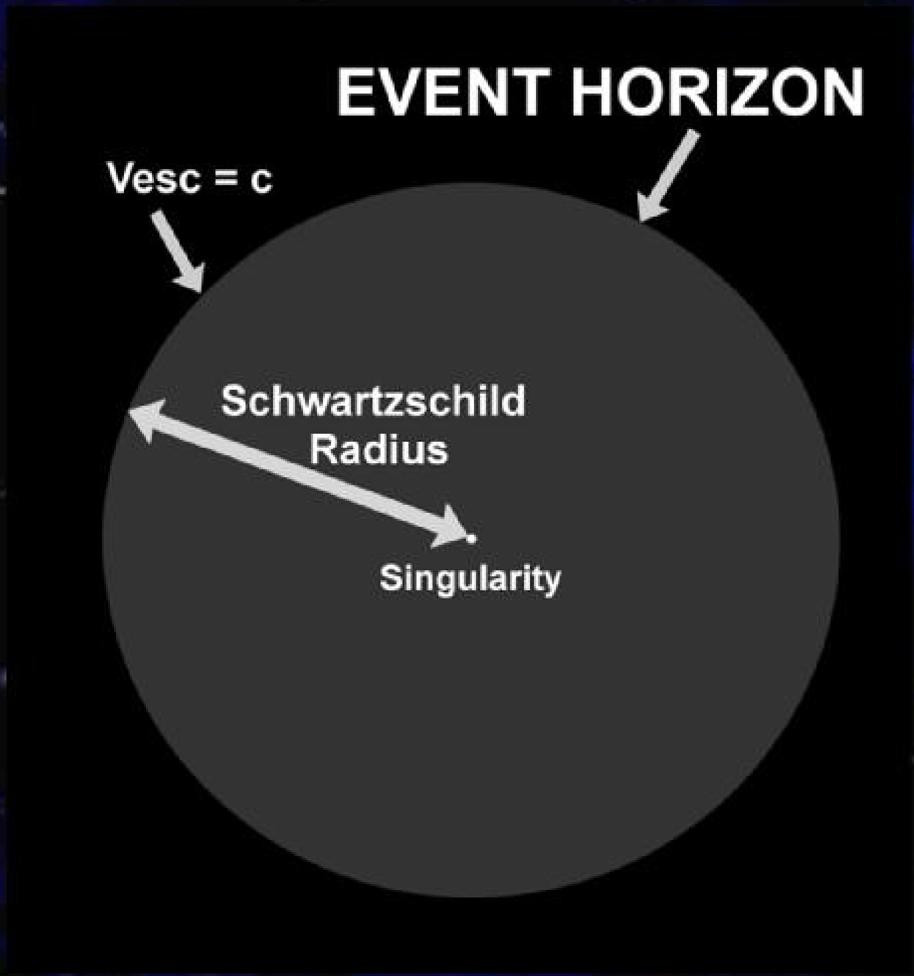
Radius = 0

Mass = mass of the original core

Singularity


EVENT HORIZON
Vesc = c
Singularity

Physical Properties of Black Holes



$$R = \frac{2GM}{c^2}$$

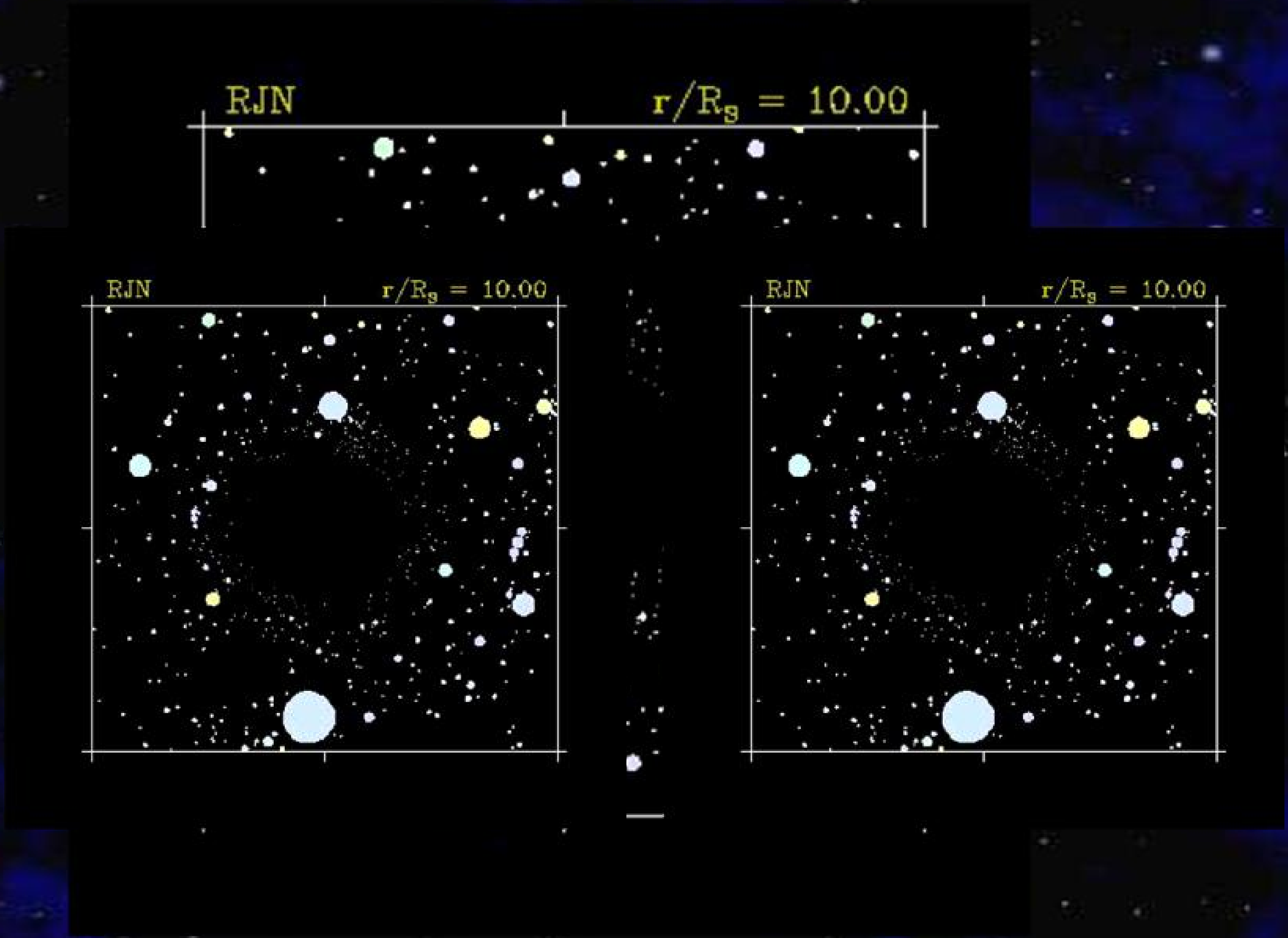
R = Schwartzschild Radius

Size of event horizon depends only on MASS

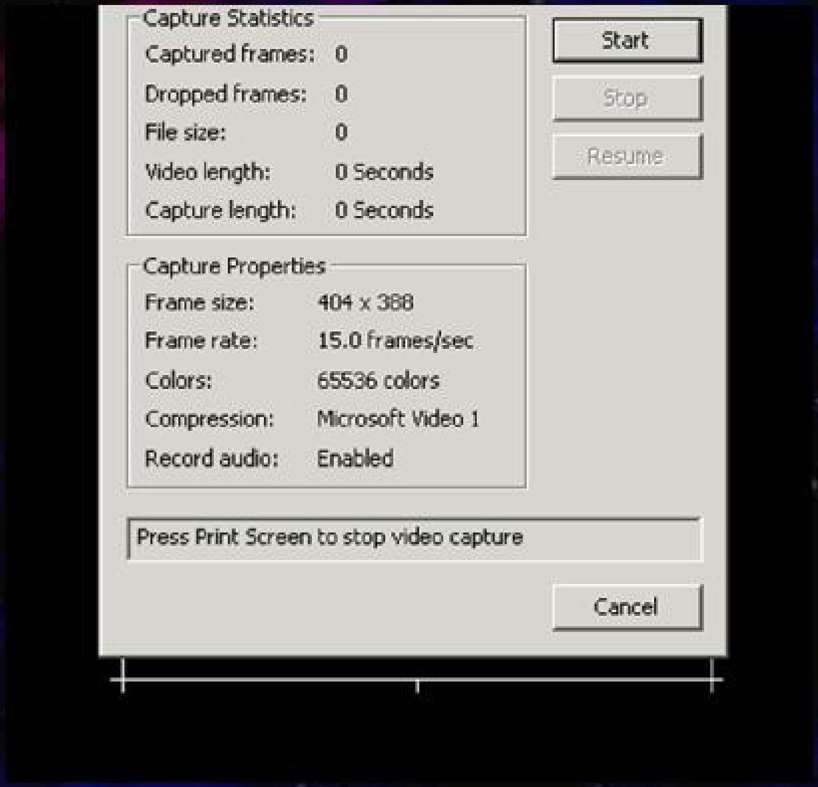
Mass bends space and time

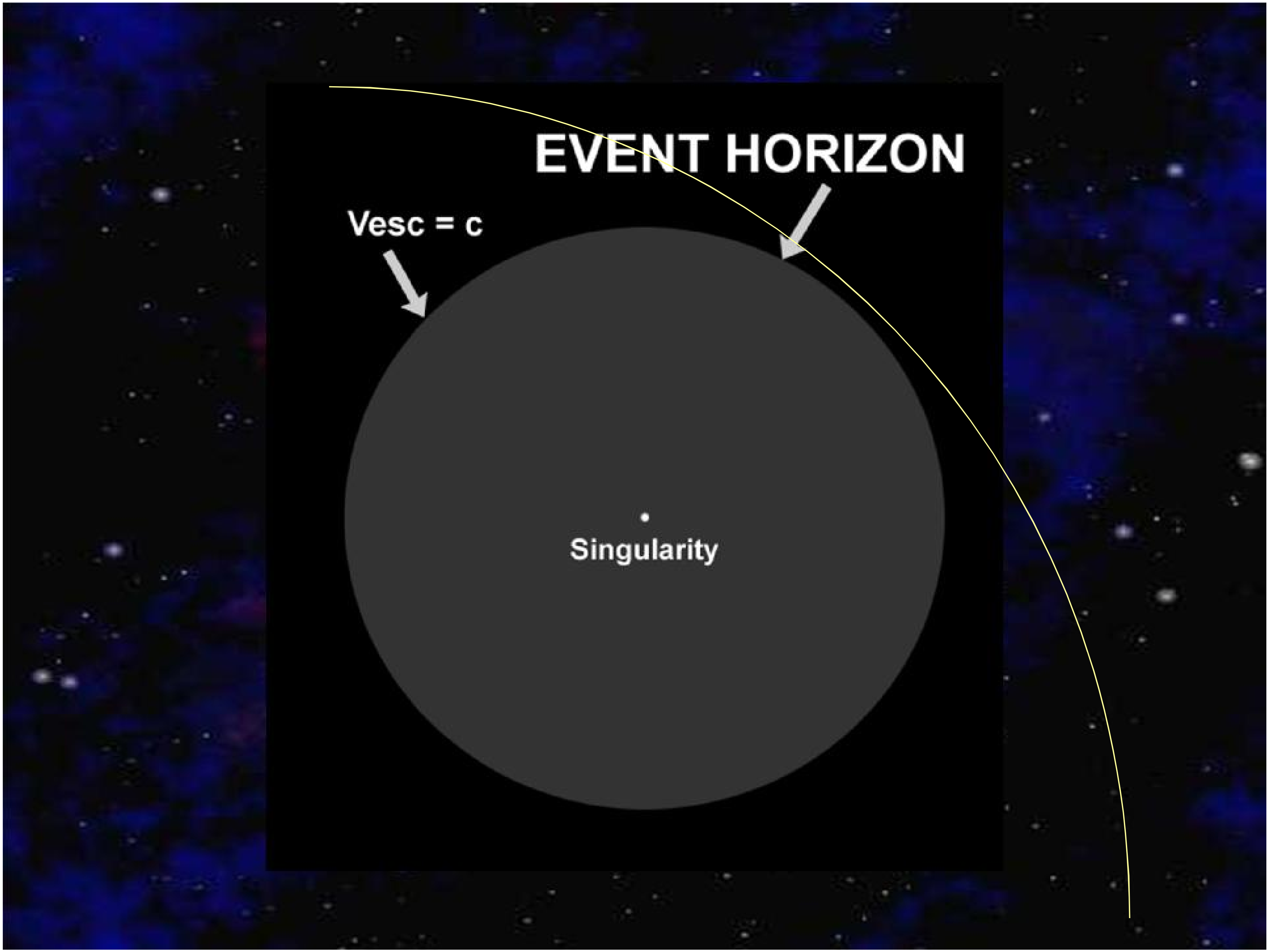
- very peculiar effects on time
- space becomes warped

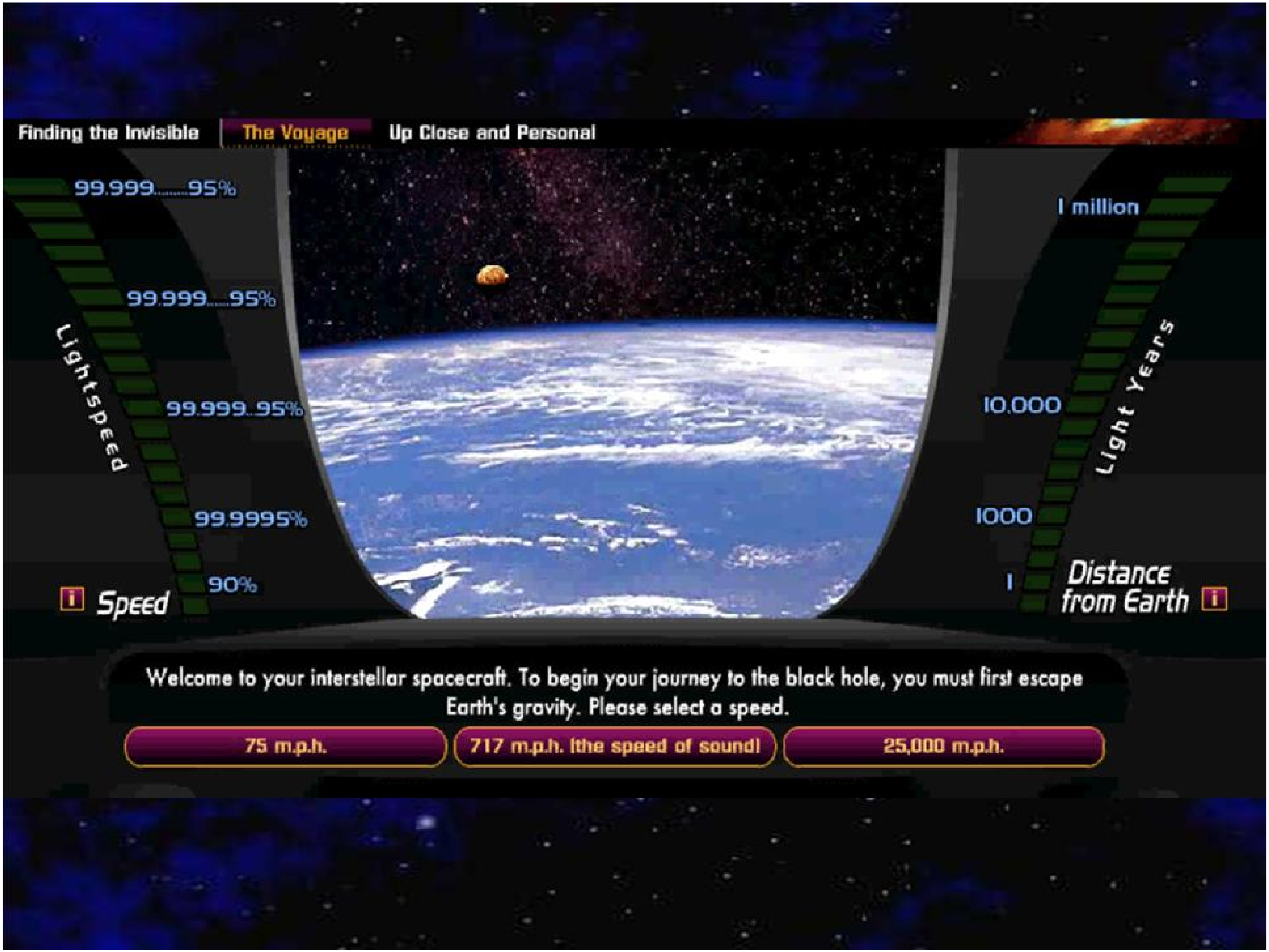
In orbit around a Black Hole



In orbit around a Black Hole at Event Horizon




EVENT HORIZON
Vesc = c
Singularity


Finding the Invisible
The Voyage
Up Close and Personal
99.999........95%
99.999.....95%
99.999..95%
99.9995%
90%
Lightspeed
Speed
1 million
10,000
1000
1
Light Years
Distance from Earth
Welcome to your interstellar spacecraft. To begin your journey to the black hole, you must first escape Earth's gravity. Please select a speed.
75 m.p.h.
717 m.p.h. (the speed of sound)
25,000 m.p.h.

Examples

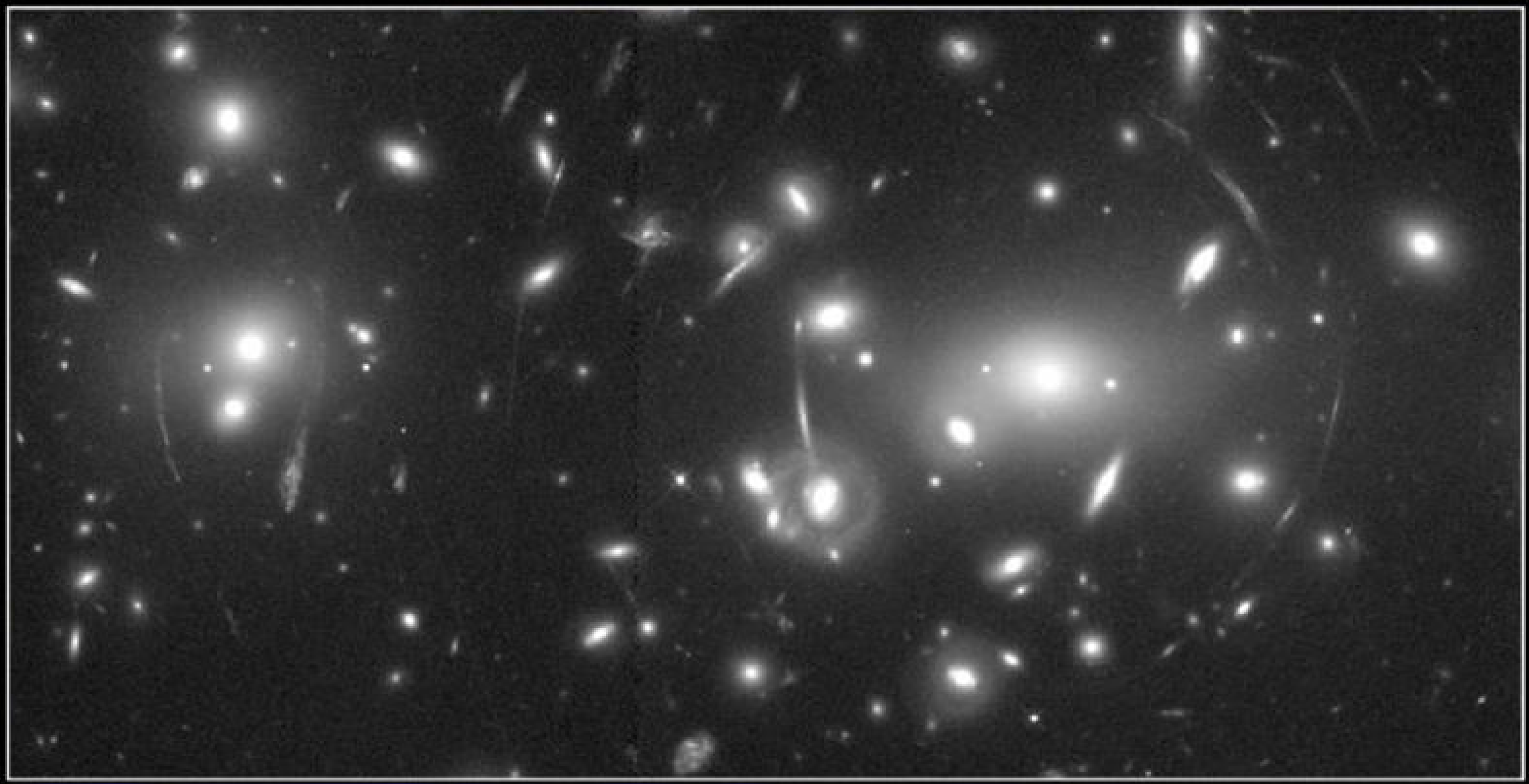
$M = 3\ M_{\odot}$ — $R_S = 9$km (5.4 mi)

$M = 1\ M_{\odot}$ — $R_S = 3$km (1.8 mi)

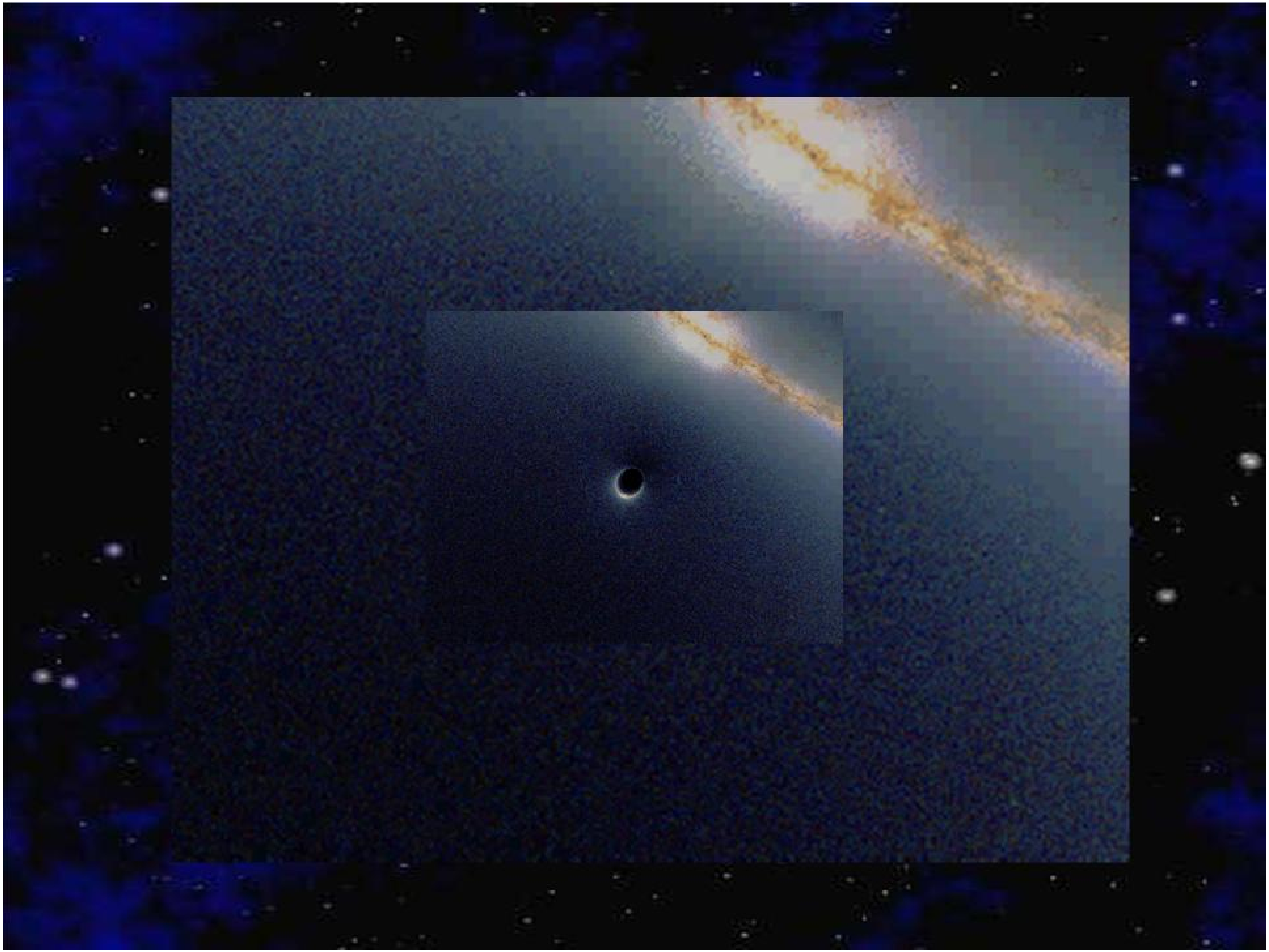
$M = 1\ M_{earth}$ — $R_S \sim 1$ cm

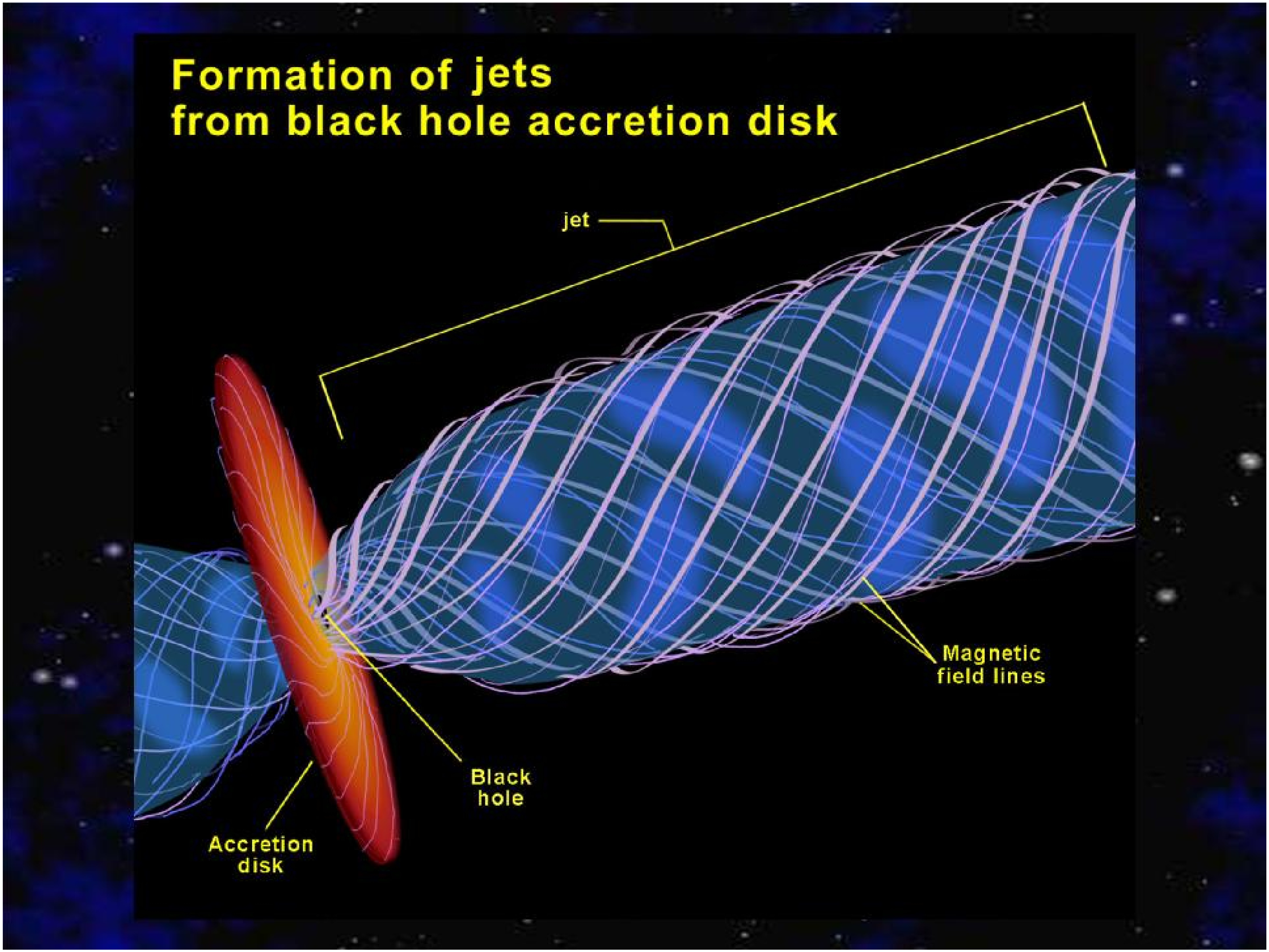
If we can’t see ‘em, how do we find ‘em?

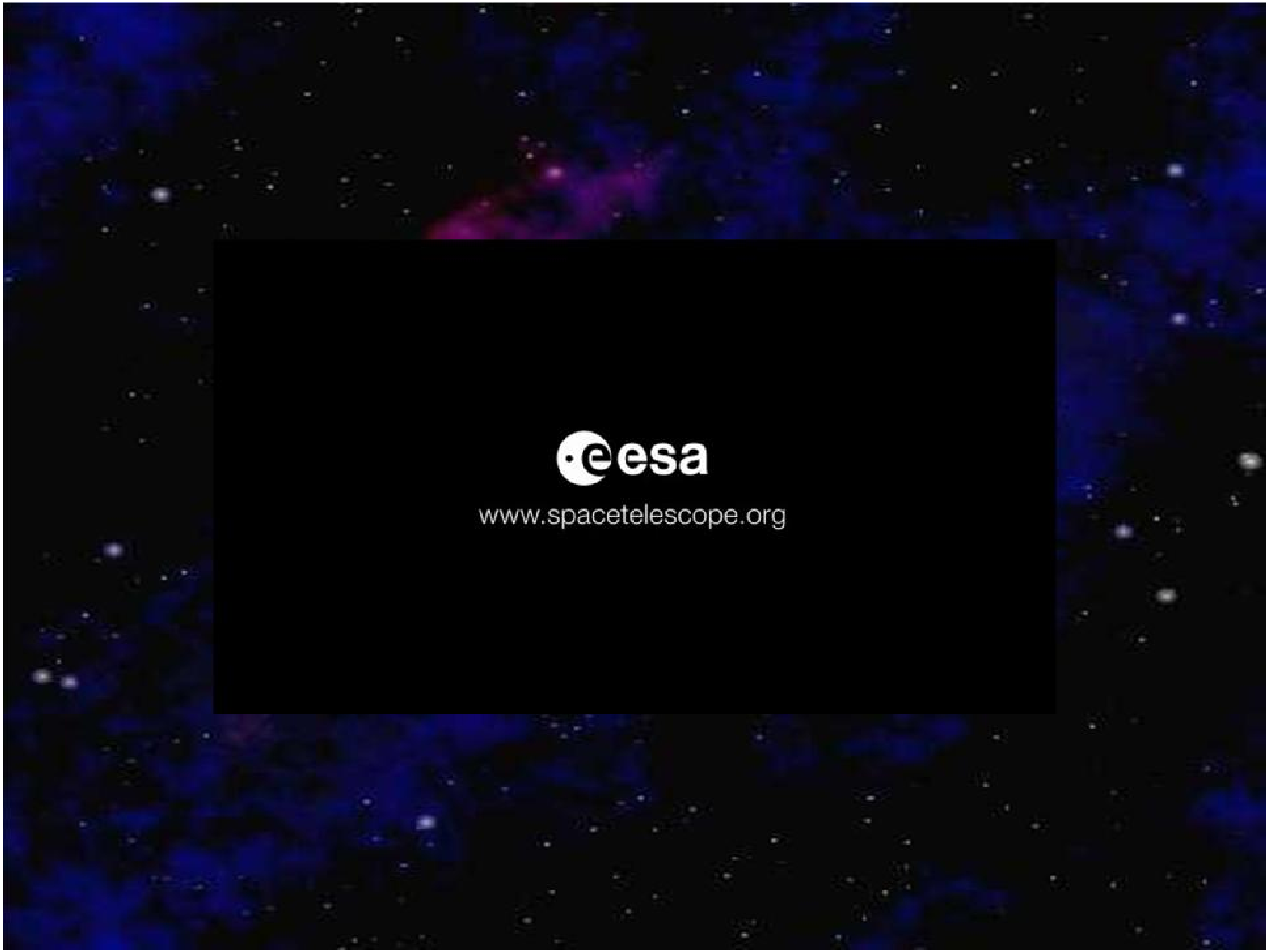
Solitary stellar mass black hole



Solitary stellar mass black hole




Formation of jets
from black hole accretion disk
jet
Magnetic
field lines
Black
hole
Accretion
disk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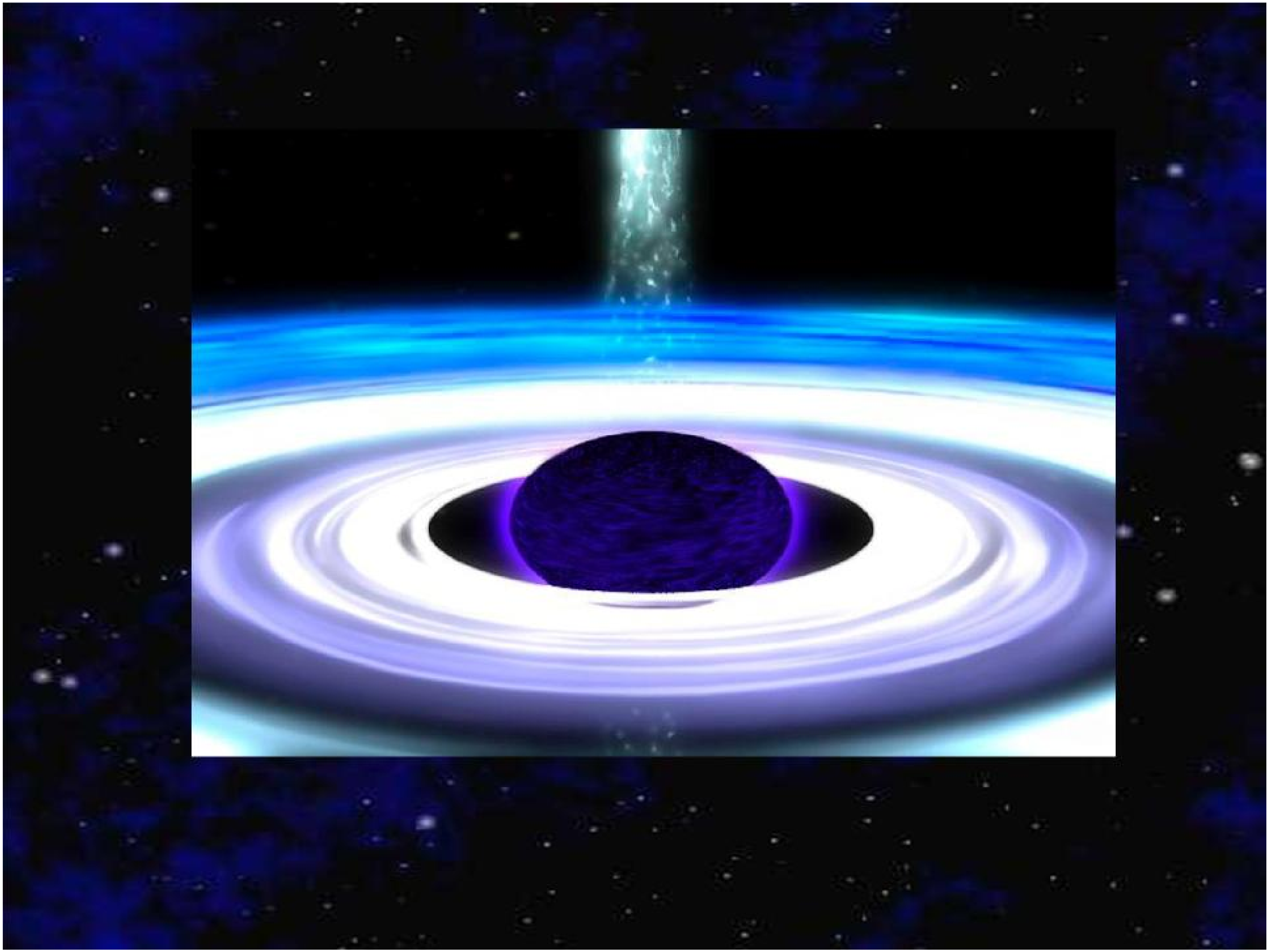

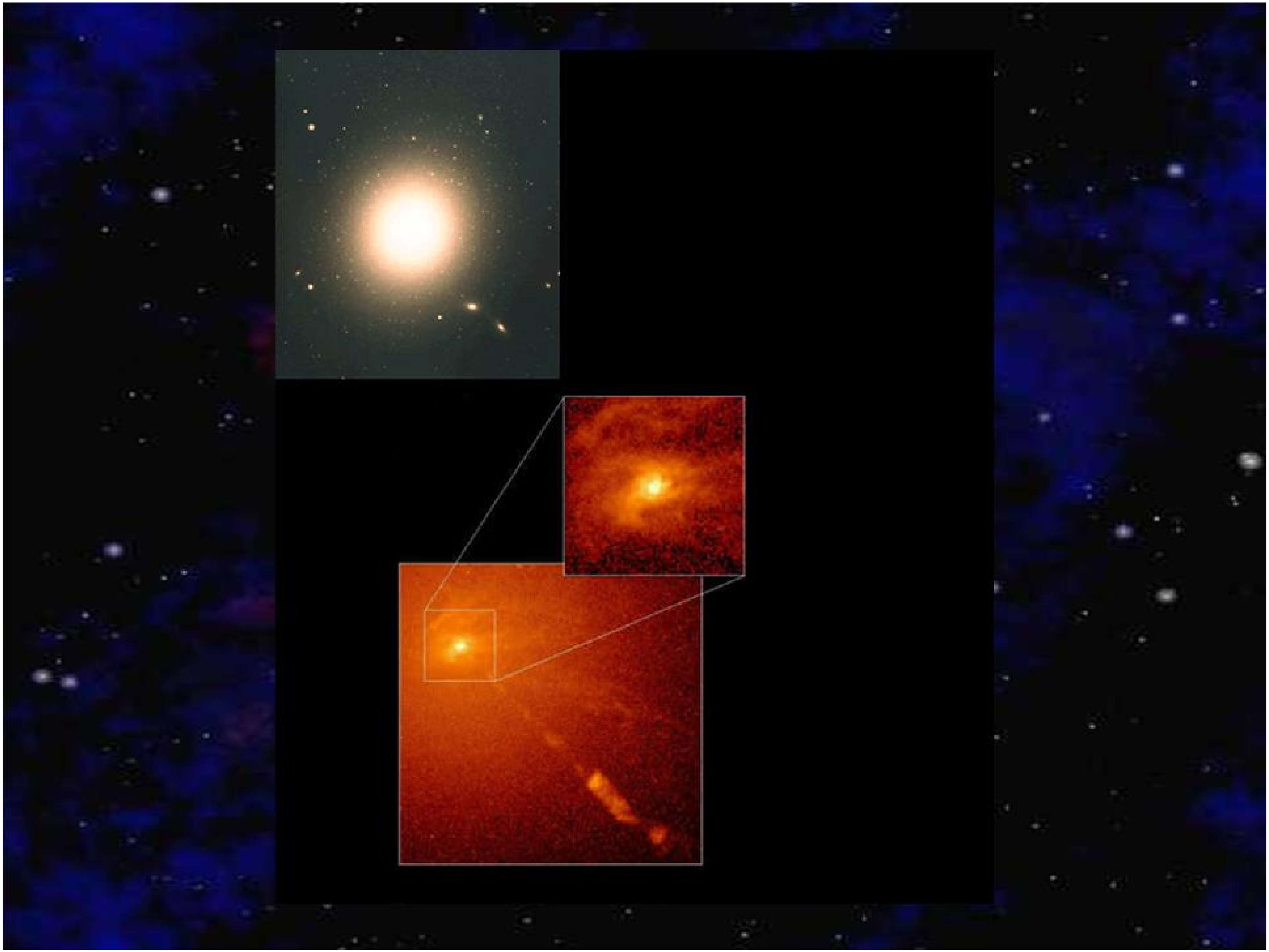

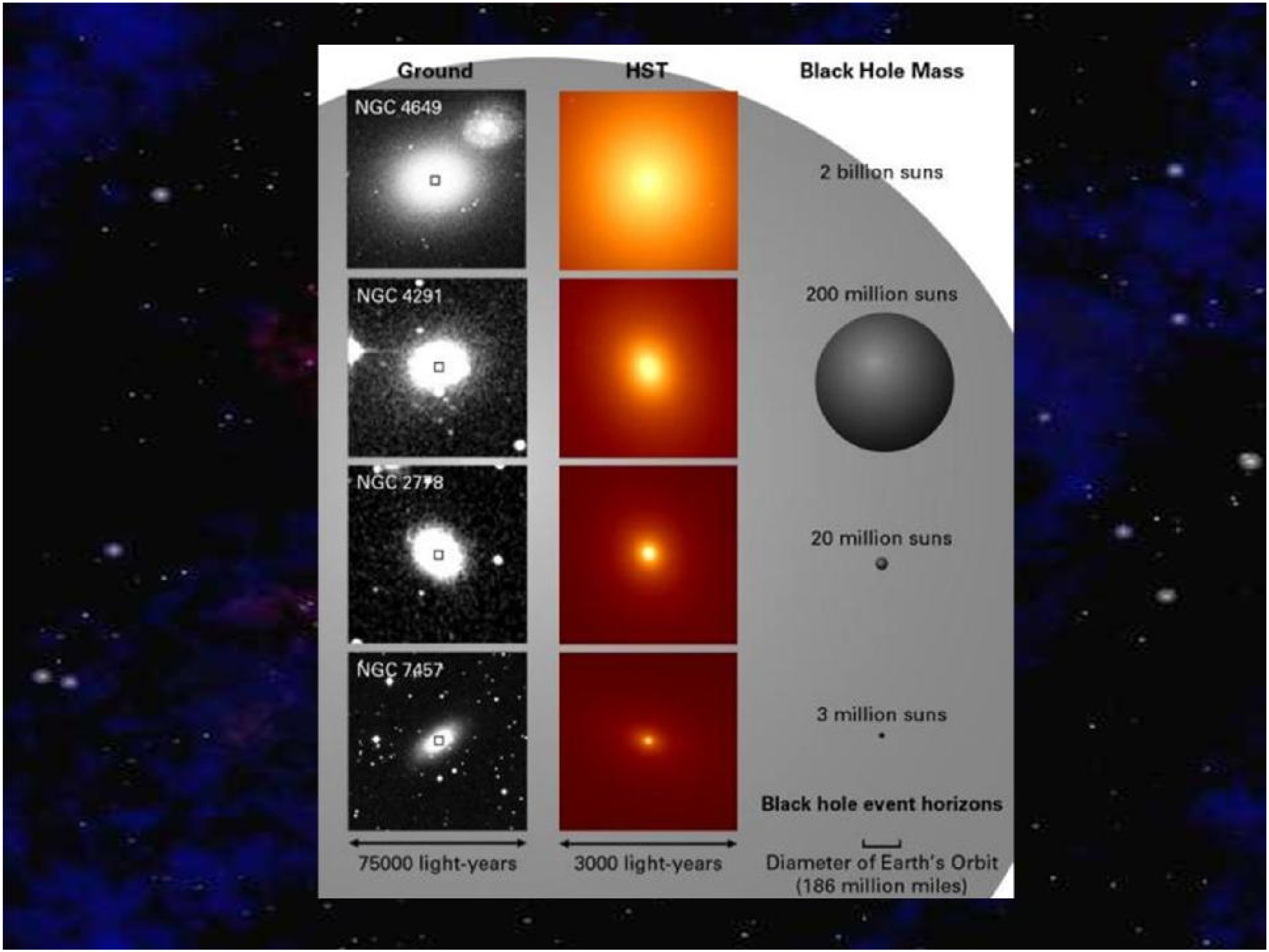

Ground
HST
Black Hole Mass
NGC 4649
2 billion suns
NGC 4291
200 million suns
NGC 2778
20 million suns
NGC 7457
3 million suns
Black hole event horizons
75000 light-years
3000 light-years
Diameter of Earth's Orbit
(186 million miles)