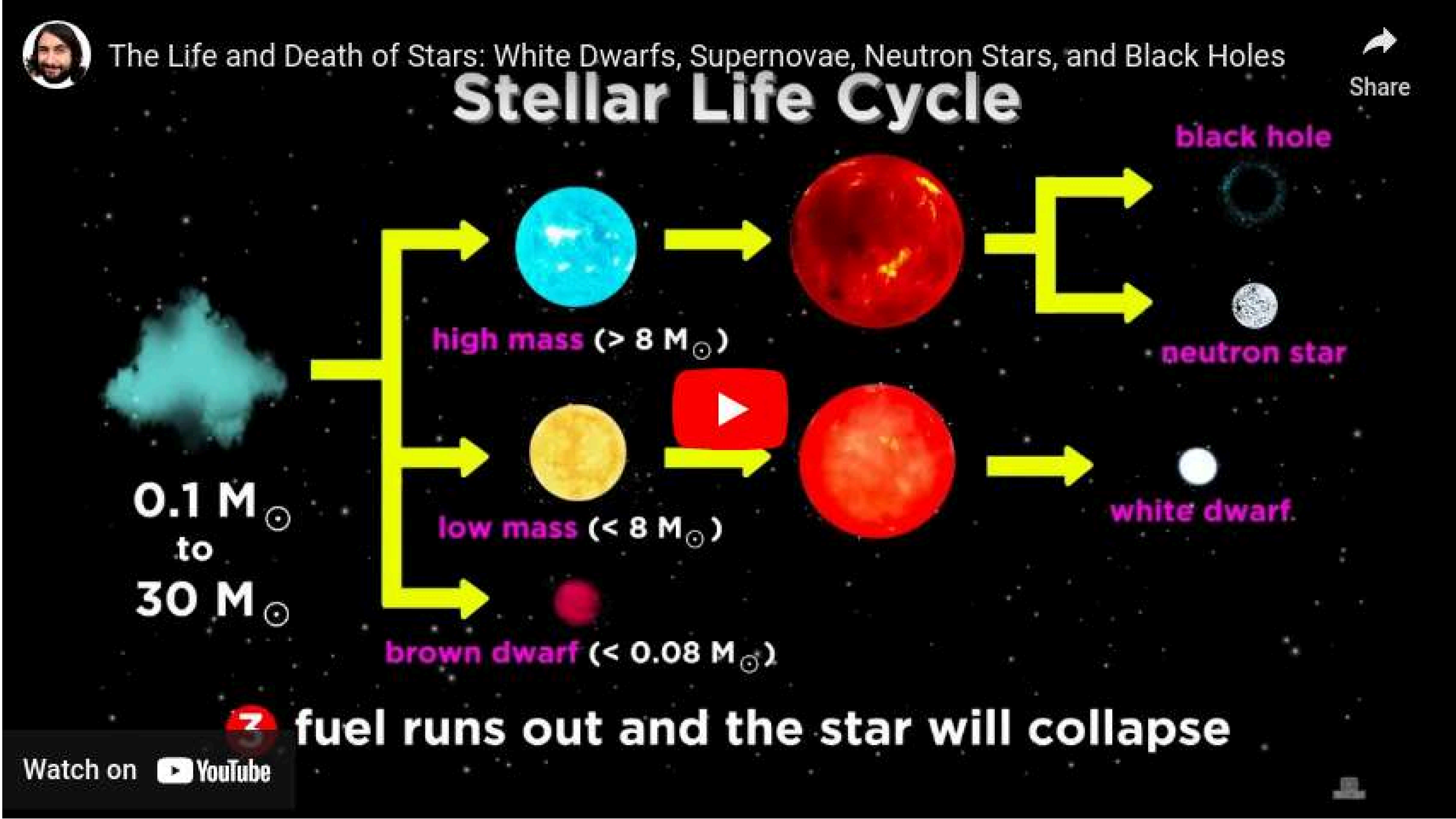
SOLAR MYSTERIES

WINTER PROJECTS 2024



The Life and Death of Stars: White Dwarfs, Supernovae, Neutron Stars, and Black Holes
Share
Stellar Life Cycle
black hole
neutron star
high mass (> 8 M☉)
low mass (< 8 M☉)
white dwarf
brown dwarf (< 0.08 M☉)
0.1 M☉
to
30 M☉
fuel runs out and the star will collapse
Watch on YouTube

Evolution of stars

- When we talk about stellar evolution we mean on changes that occur in stars as they consume "fuel" , since their birth through their long life, and until they die.
- Understanding the evolution of stars help astronomers to understand:

- The nature and future fate of our Sun.
- The origin of our solar system.
- How we compare our solar system with other planetary systems
- If there could be life elsewhere in the universe.

The Ring Nebula, a dying star.
Source: NASA

The Hertzsprung-Russell diagram

There is an order in the properties of stars!

- The Hertzsprung-Russell (HR) diagram, shows the power (brightness) as a function of temperature (spectral class); the ordinate "absolute magnitude" is a logarithmic measure of power.

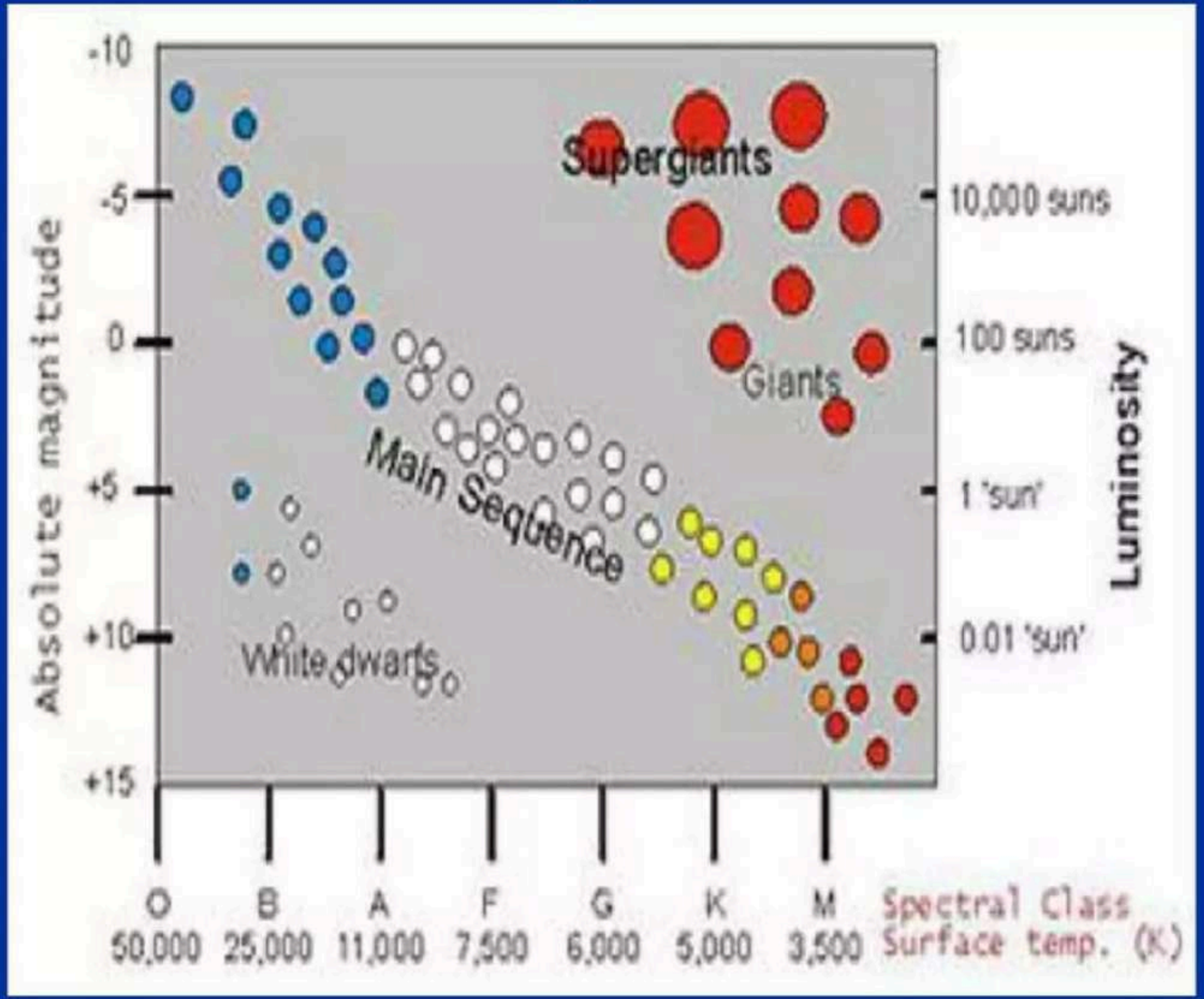
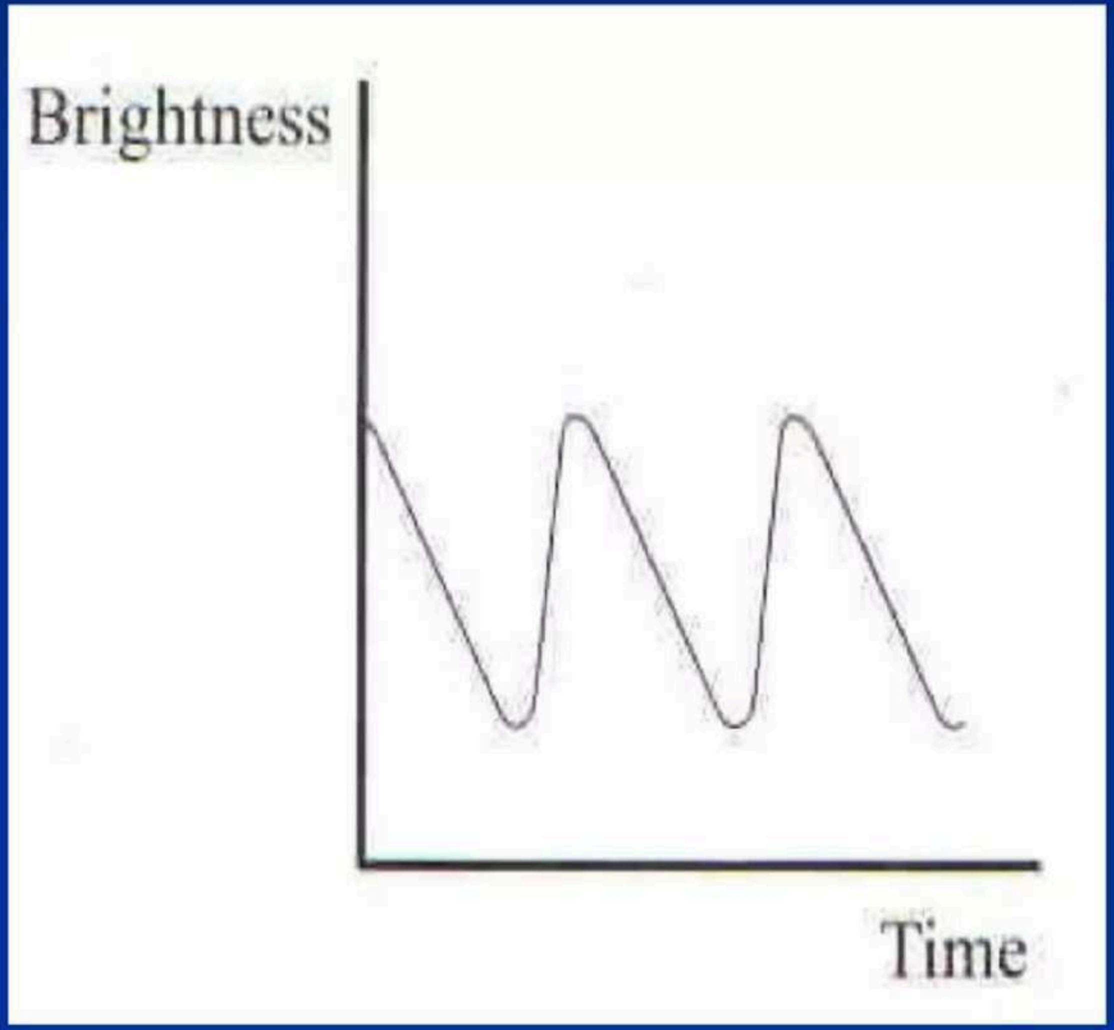


Diagram HR Source: NASA

- Most of the stars lie on the "main sequence": massive stars are hot and have high power (top left), while the small stars have lower masses, are cold and have low power (bottom right)
- The giant stars lie on the top-right part of the diagram, while the white dwarfs are on the bottom-left

Variable Stars



Light curve: a graph of brightness vs. time.

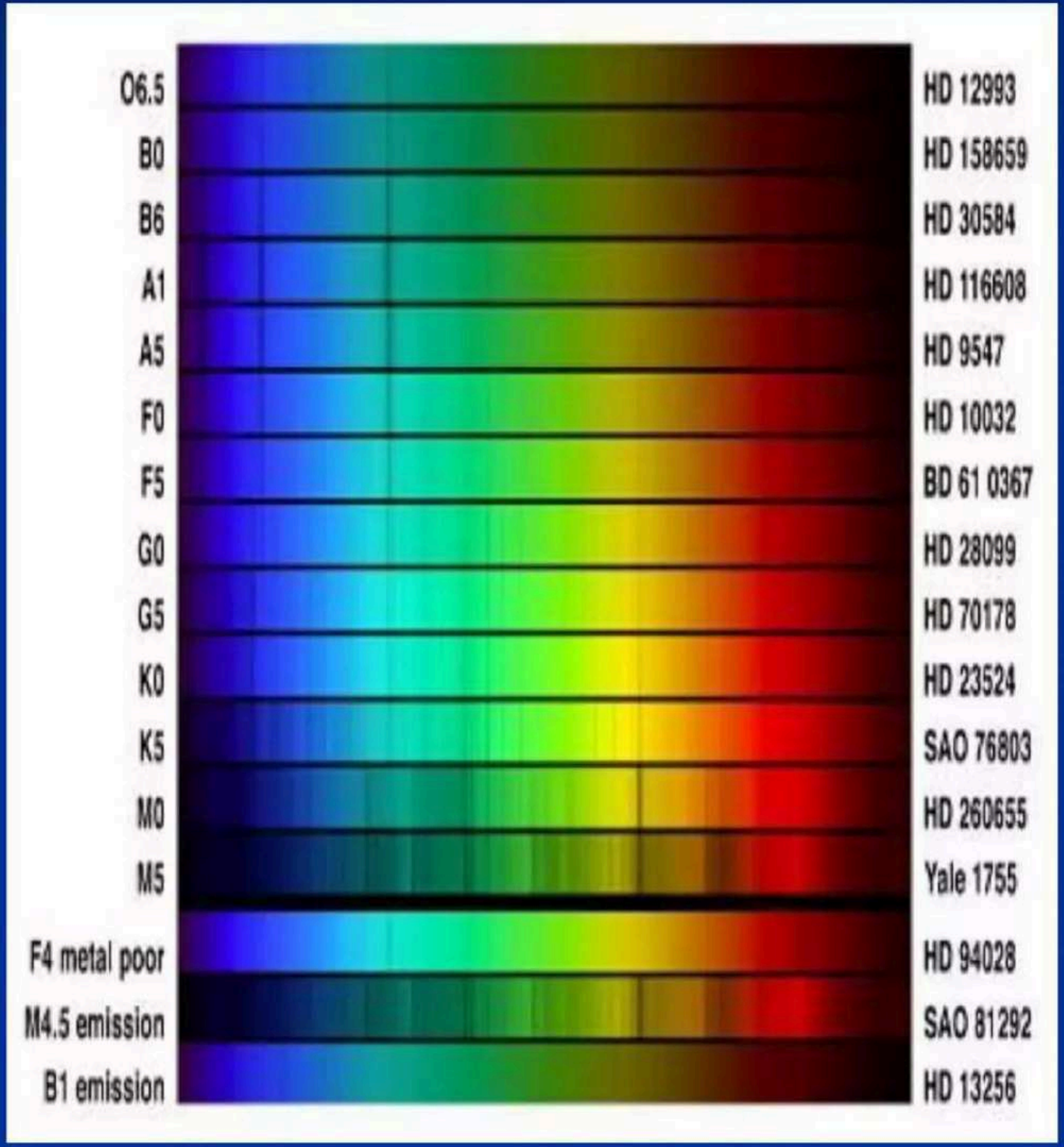
- Variable stars are stars that change their brightness with time
- Most of the stars are variable; can vary because they vibrate, shine brightly, erupt or explode, or are eclipsed by a companion star or planet
- Variable stars provide important information about the stellar nature and evolution

Properties of stars – distant suns and how astronomers measure them – important!

Orion Constellation.
Source: Hubble, ESA, Akira Fujii

- **Distance:** from the parallax, or from the apparent brightness if the power is known.
- **Power:** from the distance and apparent brightness
- **Surface temperature:** From the color or spectrum
- **Radio:** From the power and surface temperature
- **Mass:** Using the observations of binary stars
- **Chemical composition:** from stellar spectra

The spectra of the stars:
starlight, decomposed into colors



- **Astronomers learn about astronomical sources by studying the light that they emit**
- **The spectrum provides information on the composition, temperature, and other properties of stars**

Left: the first 13 spectra of stars with different surface temperatures (the highest on top); the last three spectra were taken from stars with peculiar properties

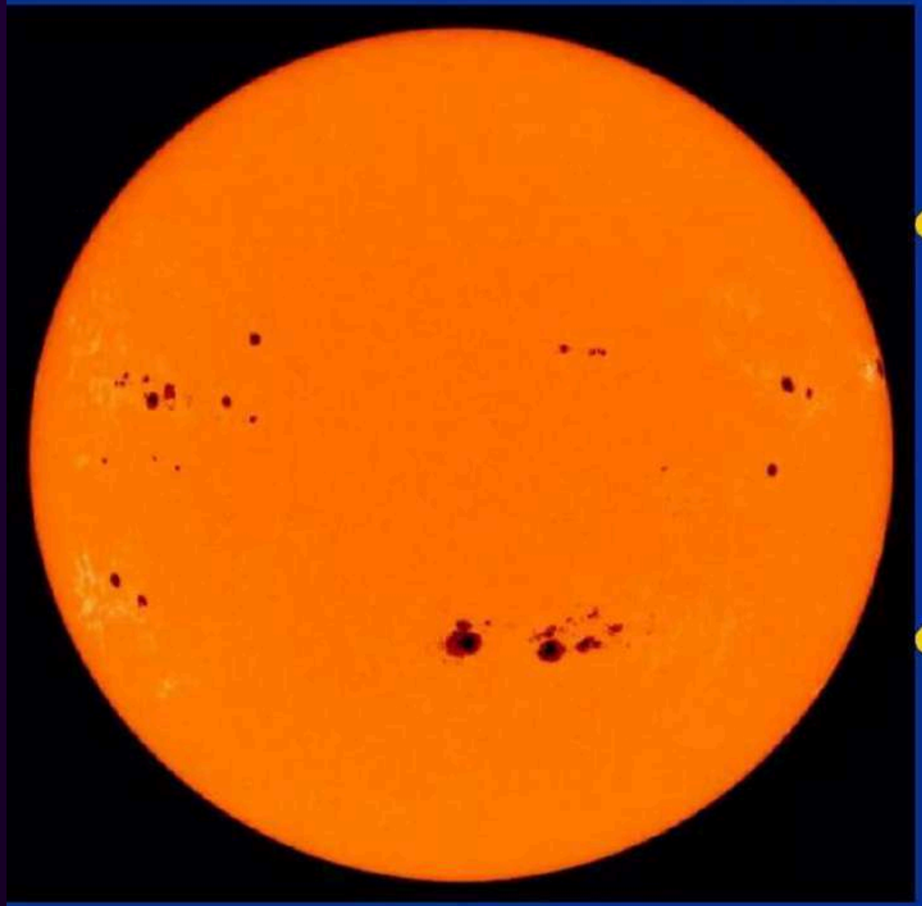
Stellar Spectra
Source: US National Optical Astronomy Observatory

What are the Sun and stars made of?

Abundances of chemical elements in the Cosmos: birdseed H (90%), rice He (8%), beans C, N, and O and a few of all the other elements (2%).

- Using spectroscopy and other techniques, astronomers can identify the “prime materials” that stars are made of
- Hydrogen (H) and helium (He) are the most abundant elements, and were formed with the formation of universe
- Heavier elements are million or billion times less abundant. They were formed inside the stars through thermonuclear reactions

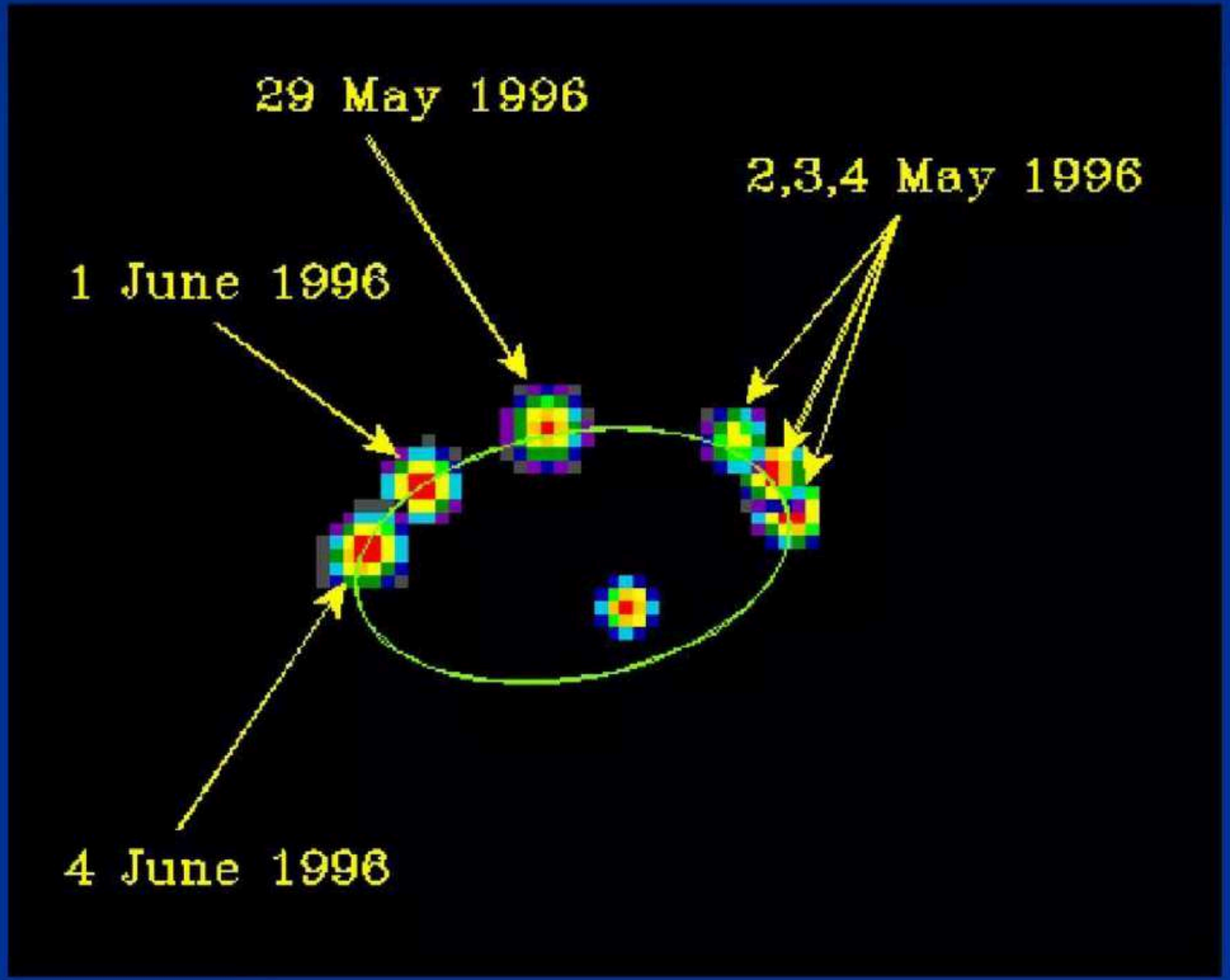
Properties of the Sun: the nearest star
and how astronomers measure them – important!



The Sun.
Source: NASA SOHO Satellite

- **Distance: 1.5×10^{11} m,** reflecting radar waves from Mercury and Venus
- **Mass: 2×10^{30} kg,** measuring the movement of the planets that rotate around the Sun
- **Diameter: 1.4×10^{9} m,** from the apparent diameter (angle) of the Sun and its distance
- **Power: 4×10^{26} W,** from the distance and the measured power from Earth
- **Chemical composition:** 98% hydrogen and helium, studying its spectrum.

Binary stars (double) and multiple



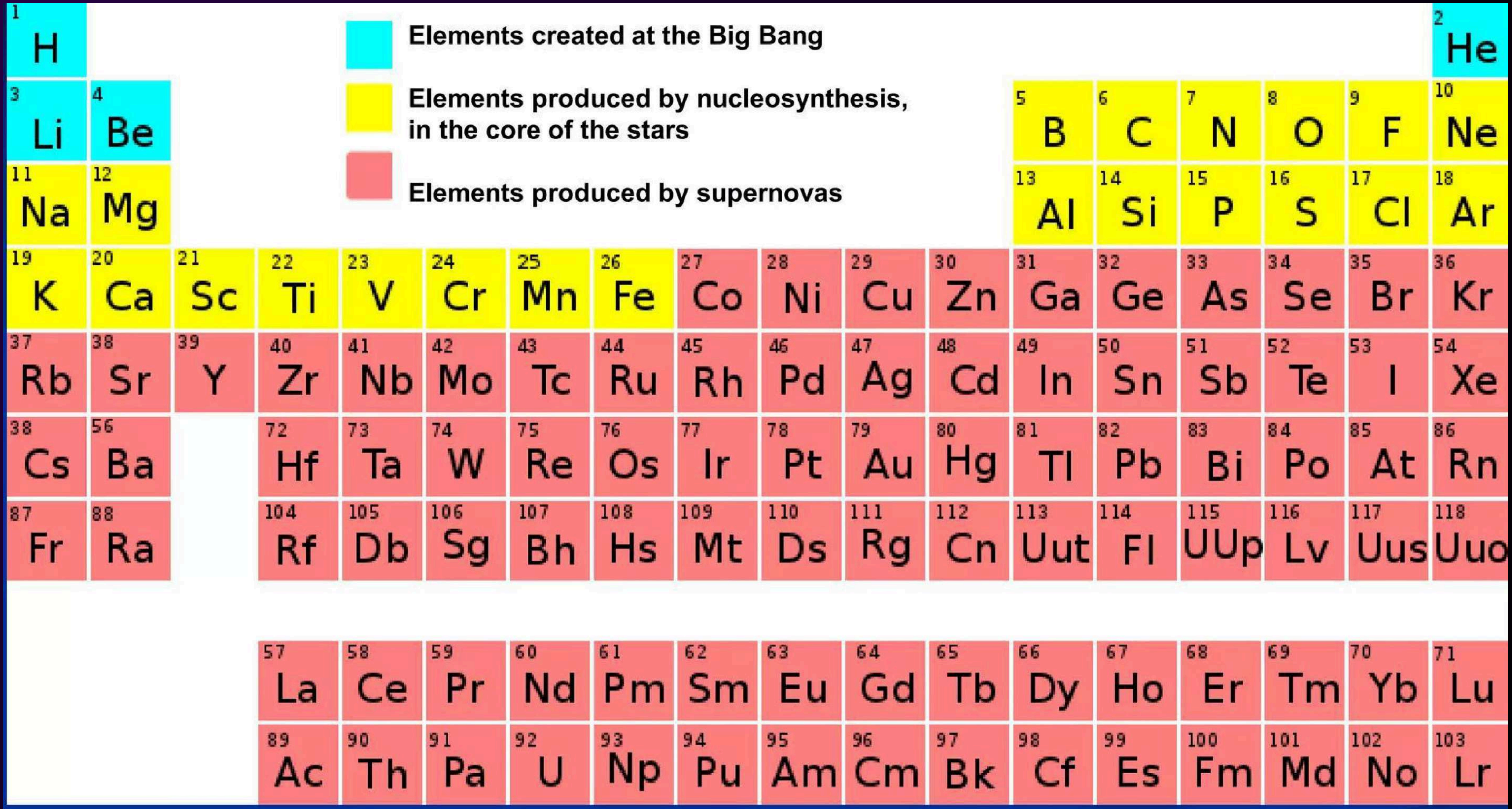
Orbital movement of Mizar, in Osa Major.
Source: NPOI Group, USNO, NRL

- Binary stars are pairs of stars that are close together due to gravity, and orbit around themselves. They can be visible directly (as in the image on the left), or detected by their spectra, or an eclipse between the stars.
- They are the most important tool to measure the masses of stars
- Multiple stars are three or more stars that are bonded together due to gravity

Star clusters
"Experiments of nature"

Open Cluster The Pleiades.
Source: Mount Wilson Observatory

- Star clusters are groups of stars that are close each other due to gravity, and move all together through the space
- They were formed at the same time and place, the same material, and are at the same distance, only differ in the mass
- Clusters are samples of stars with different masses but with the same age


Elements created at the Big Bang
Elements produced by nucleosynthesis, in the core of the stars
Elements produced by supernovas
1 H
2 He
3 Li 4 Be
5 B 6 C 7 N 8 O 9 F 10 Ne
11 Na 12 Mg
13 Al 14 Si 15 P 16 S 17 Cl 18 Ar
19 K 20 Ca 21 Sc 22 Ti 23 V 24 Cr 25 Mn 26 Fe 27 Co 28 Ni 29 Cu 30 Zn 31 Ga 32 Ge 33 As 34 Se 35 Br 36 Kr
37 Rb 38 Sr 39 Y 40 Zr 41 Nb 42 Mo 43 Tc 44 Ru 45 Rh 46 Pd 47 Ag 48 Cd 49 In 50 Sn 51 Sb 52 Te 53 I 54 Xe
38 Cs 56 Ba 72 Hf 73 Ta 74 W 75 Re 76 Os 77 Ir 78 Pt 79 Au 80 Hg 81 Tl 82 Pb 83 Bi 84 Po 85 At 86 Rn
87 Fr 88 Ra 104 Rf 105 Db 106 Sg 107 Bh 108 Hs 109 Mt 110 Ds 111 Rg 112 Cn 113 Uut 114 Fl 115 UUp 116 Lv 117 Uus 118 Uuo
57 La 58 Ce 59 Pr 60 Nd 61 Pm 62 Sm 63 Eu 64 Gd 65 Tb 66 Dy 67 Ho 68 Er 69 Tm 70 Yb 71 Lu
89 Ac 90 Th 91 Pa 92 U 93 Np 94 Pu 95 Am 96 Cm 97 Bk 98 Cf 99 Es 100 Fm 101 Md 102 No 103 Lr

The laws of the structure of the stars

- Inside the star, as we go deeper, the pressure increases due to the weight of upper layers.
- According to the laws of gases, temperature and density increase as the pressure increases.
- The energy will flow from the inside hotter part to the outside colder part by radiation and convection.
- If the energy flows out of the star, the star will cool - unless more energy is created inside.
- *The stars are governed by these simple and universal laws of physics*

Example: Why the Sun does not collapse or contract?

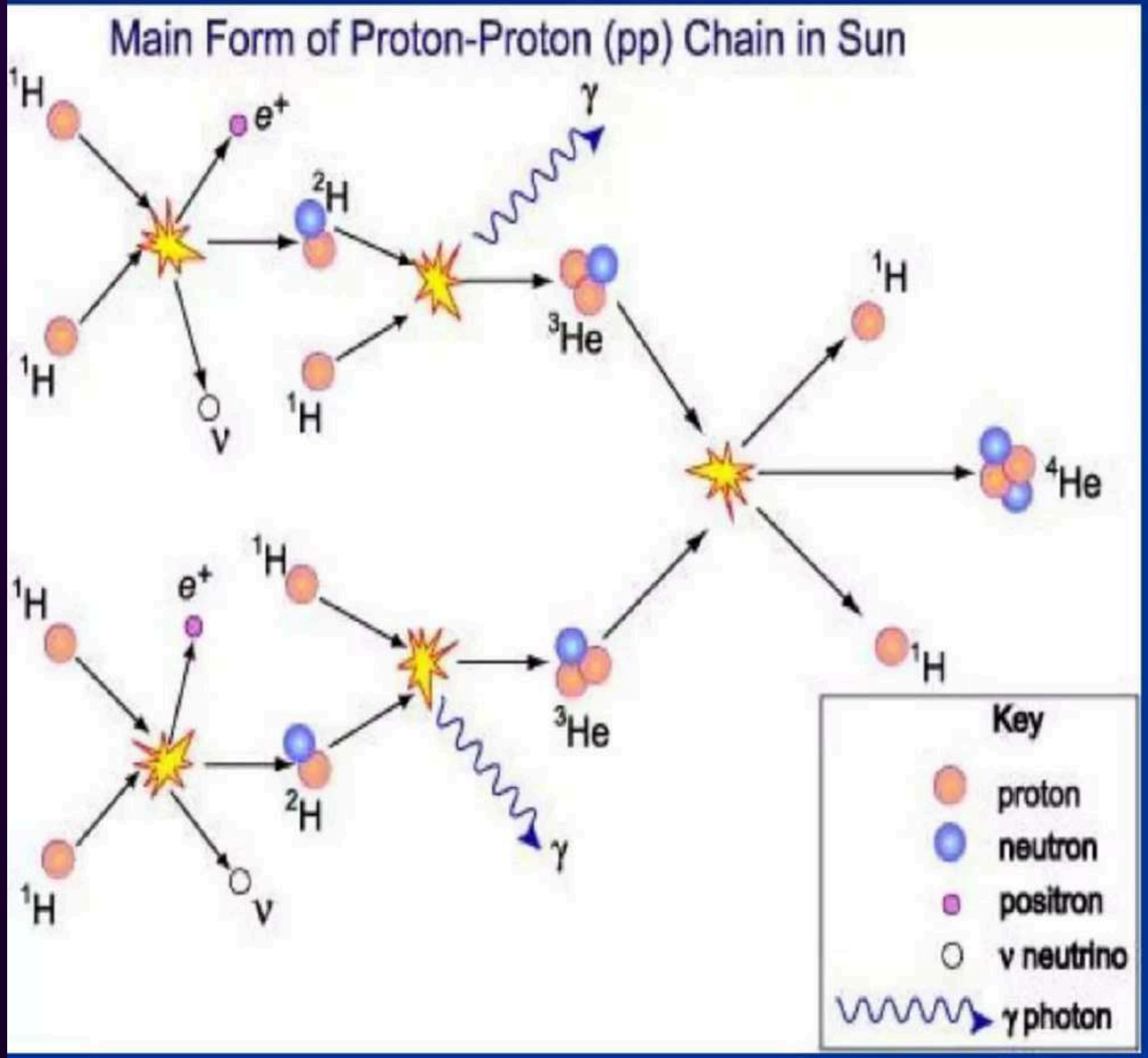
- Inflate a balloon as shown on the left
- The atmospheric pressure is "pushing" the balloon inward. It does not shrink because the gas pressure is "pushing" the balloon outward.
- Inside the Sun, gravity, pushing the material inward, is balanced by the gas pressure.

The energy source of the Sun and stars

- Chemical combustion of gas, oil or carbon?
  This process is so inefficient that bring energy to the Sun for only a few thousand years
- Slow gravitational contraction?
  This could bring energy to the Sun during millions of years, but the Sun is billions years old
- Radioactivity (nuclear fission)?
  Radioactive isotopes are almost non-existent inside the Sun and stars
- **Nuclear fusion of light elements into heavier ones?**
  Yes! This is a very efficient process, and light elements such as hydrogen and helium represent 98% of the Sun and stars

Proton-Proton chain

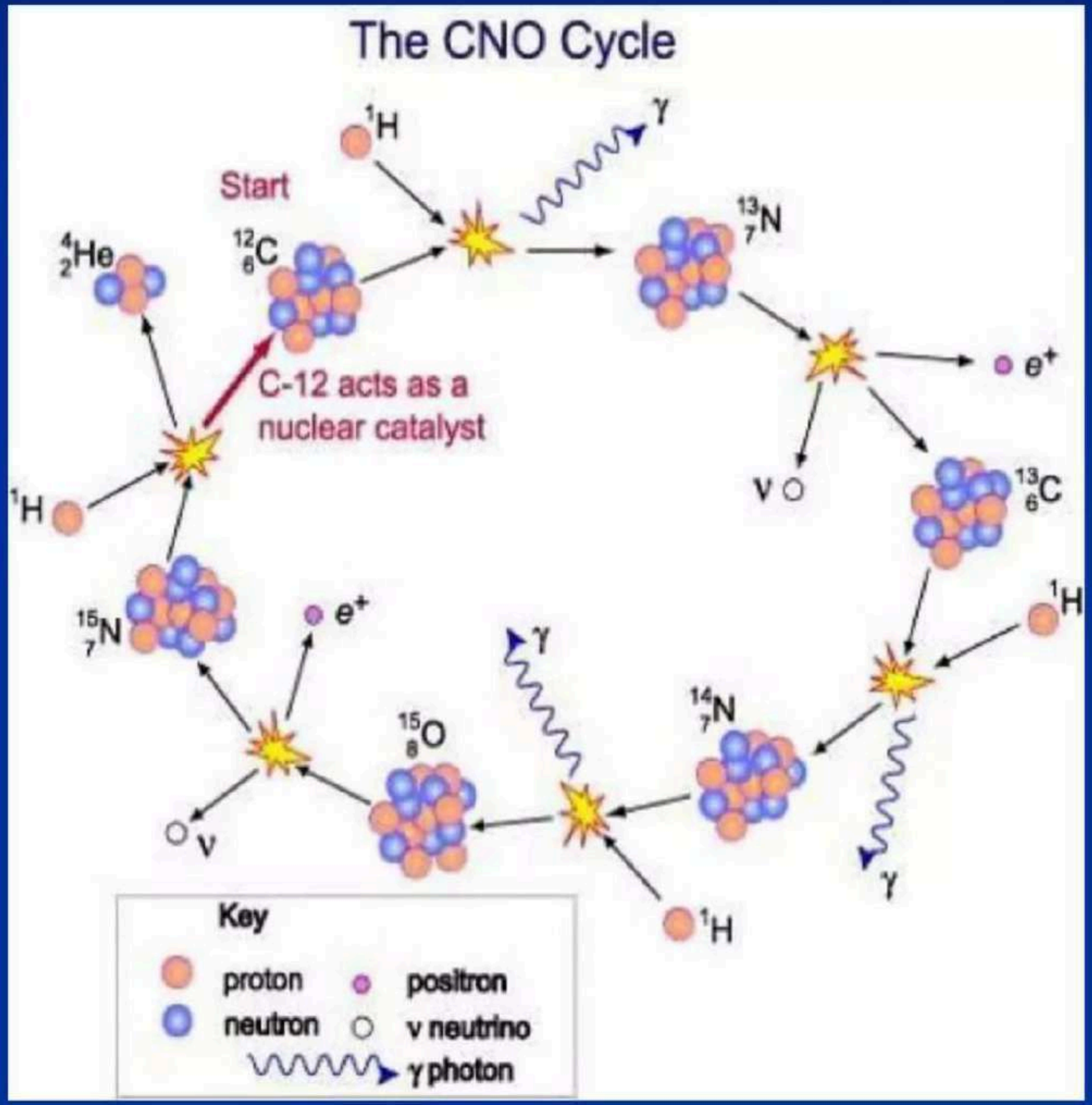
is the main process of fusion in the Sun



Proton-proton cycle
Source: Australia National Telescope Facility

- At high temperatures and densities, in stars like our Sun, protons (in red) overcome the electrostatic repulsion between them, and form ^2H (deuterium) and neutrino (ν)
- Later, another proton is coupled with deuterium to form ^3He
- Later, the ^3He nuclei are coupled with each other to form a ^4He nucleus, releasing two protons.
- Result: 4 protons together to form helium and energy (gamma-rays and kinetic energy)

The carbon – nitrogen - oxygen cycle



CNO cycle
Source: Australia National Telescope Facility

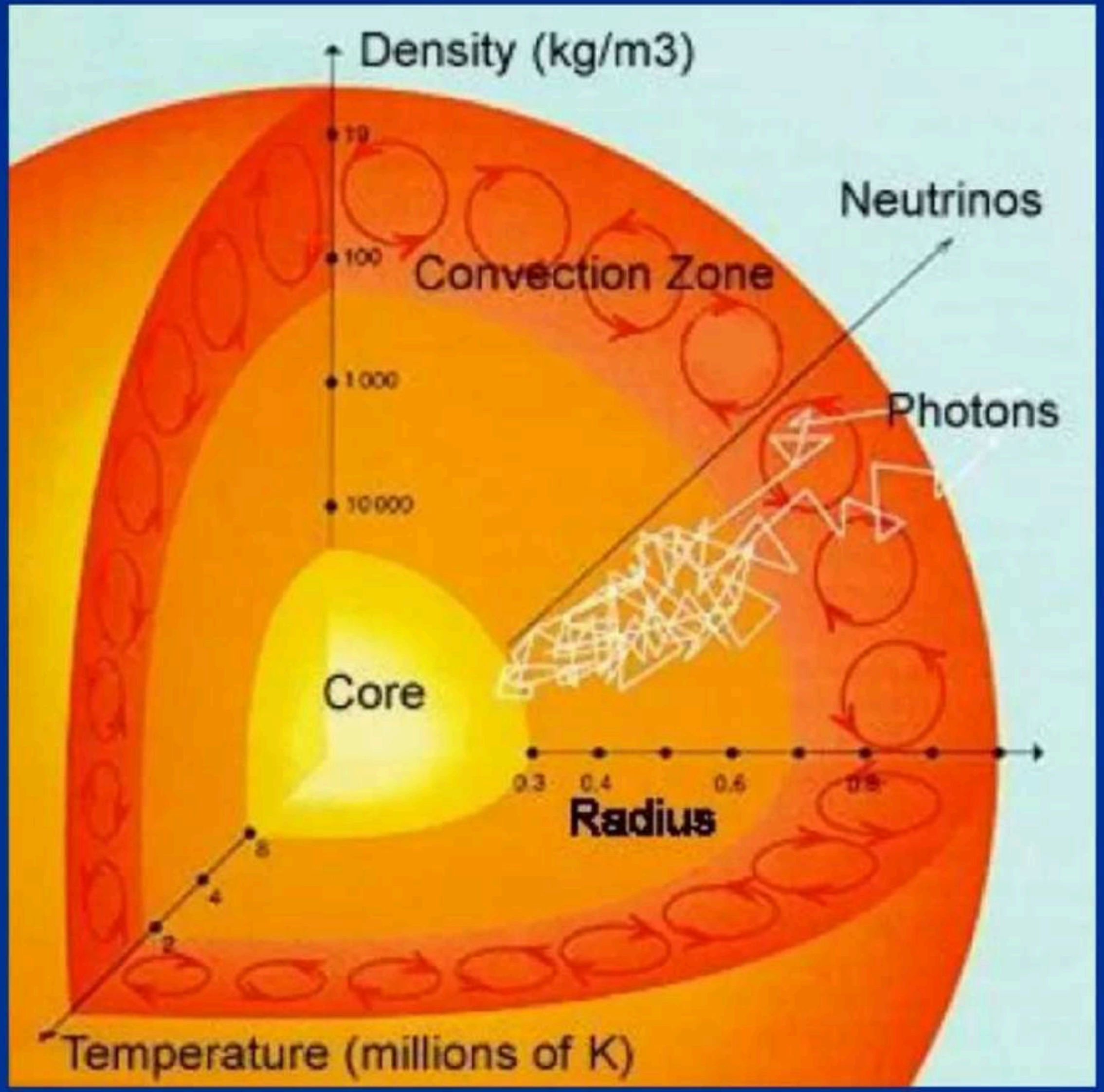
- In massive stars, with very hot nucleus, protons (red) can collide with a ^{12}C (carbon) nucleus (top left)
- This begins a circular sequence of reactions in which finally four protons fuse to form a helium nucleus (top left)
- A ^{12}C nucleus is recovered again at the end of the cycle, therefore it is not created nor destroyed; it acts as a nuclear catalyst

Making stellar "models"

- The laws that describe the stellar structure are expressed in equations, and are resolved by means of a computer
- The computer calculates the temperature, density, pressure, and the power at each point of the Sun or the star. This is called a model
- In the center of the Sun, the density is 150 times higher than the water density, and the temperature is ~15,000,000 K!

In the interior of the Sun

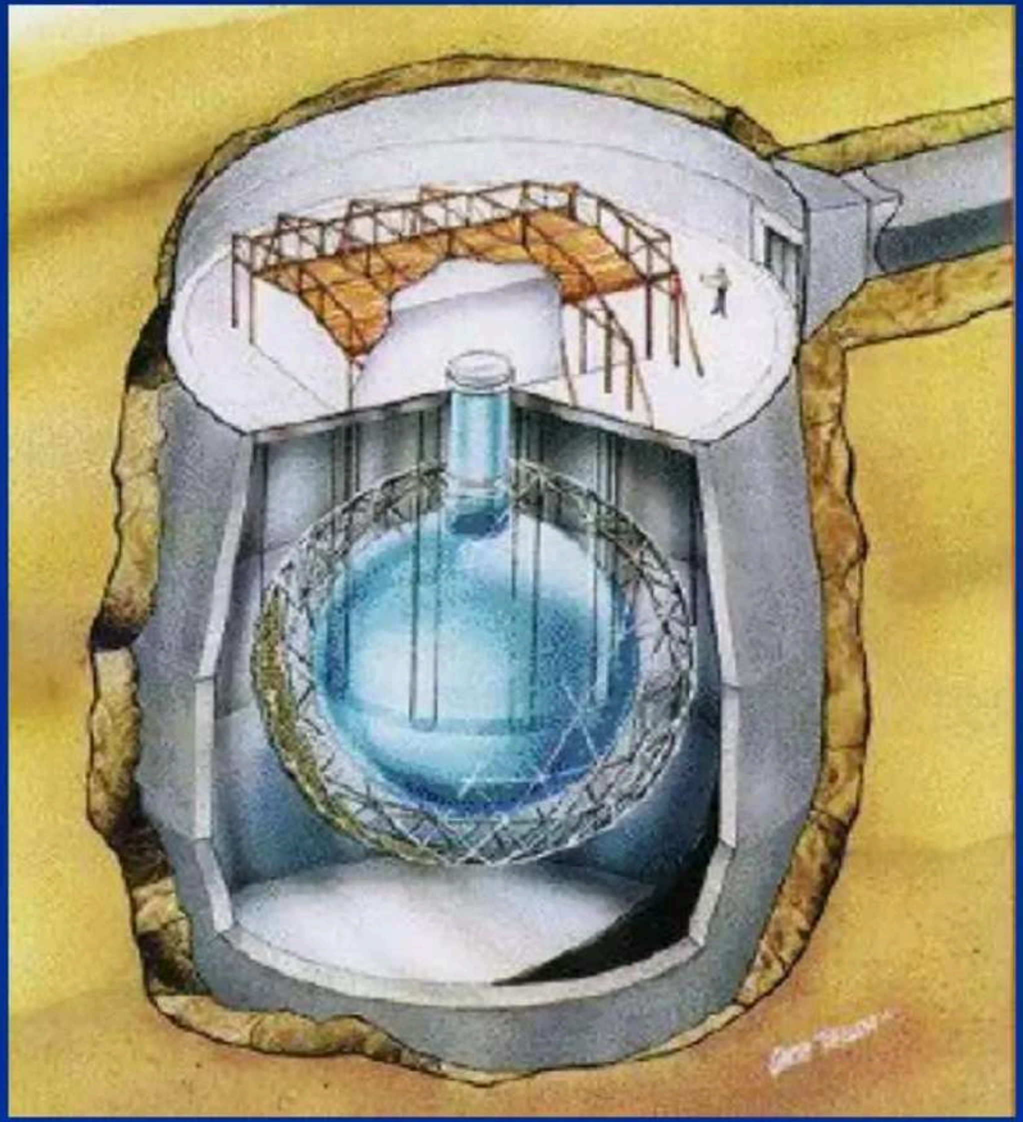
Based on a "model" of the Sun made with computer



Solar model
Source: Institute of Theoretical Physics, University of Oslo

- Inside the hot core, nuclear reactions produce energy by fusing hydrogen into helium
- In the radiative zone, above the nucleus, the energy flows outward through the mechanism of radiation
- In the convective zone, between the radiative area and the surface area, the energy flows outward by convection
- The photosphere, on the surface, is the layer where the star becomes transparent

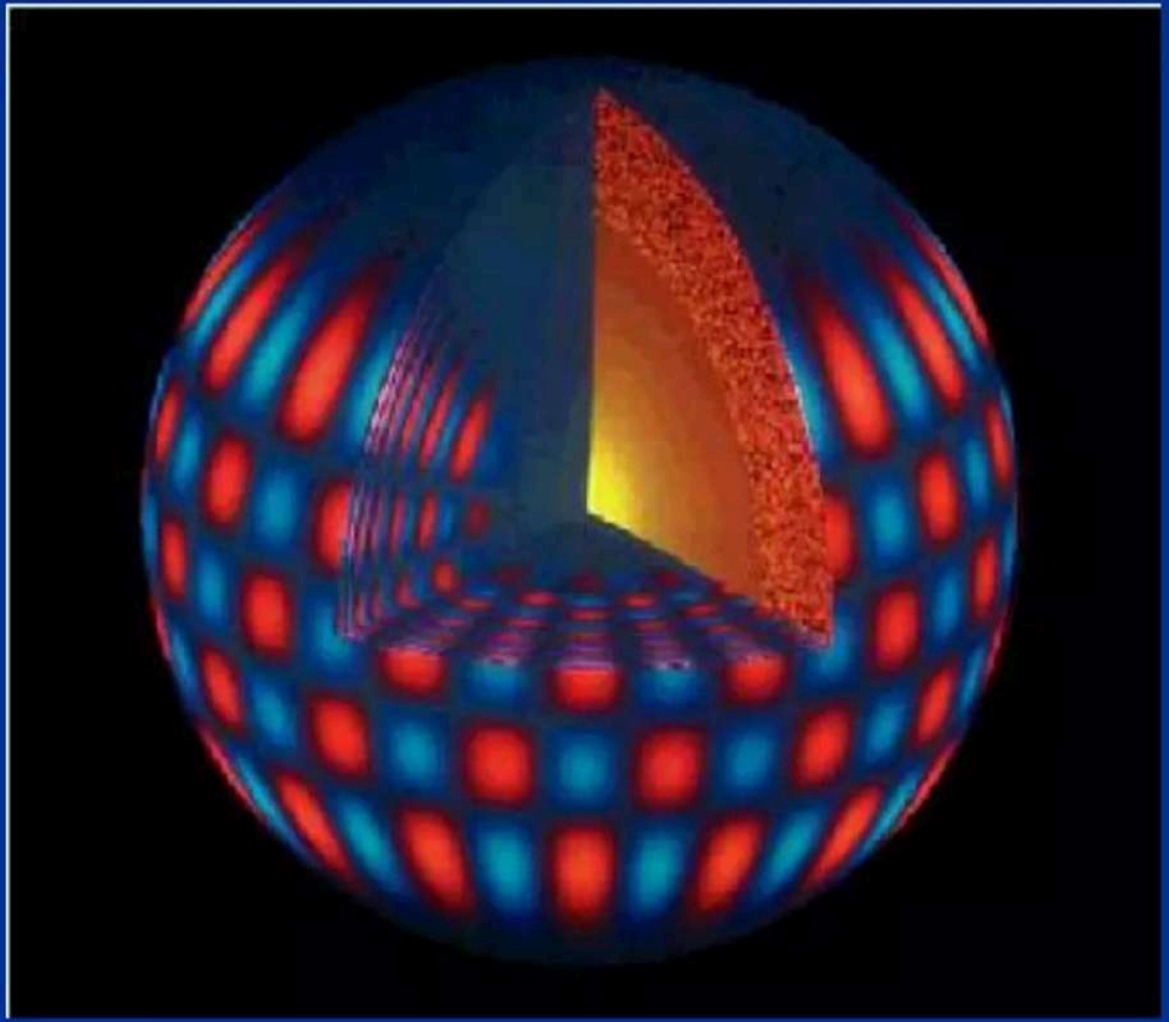
Testing the solar neutrino model



Observatory of neutrino, Sudbury
Source: Sudbury Neutrino Observatory

- Nuclear fusion reactions produce elementary particles called neutrinos.
- They have very low mass, and rarely interact with matter.
- Their mass was detected and measured thanks to special observatories, such as the Sudbury Neutrino Observatory (left). The results are consistent with the predictions obtained in models

Testing helioseismological model



Artistic conception of the solar vibration. Source: US National Optical Astronomy Observatory

- The Sun vibrates gently in thousands of ways (patterns). One of them is shown in the image on the left
- These vibrations can be observed and we can use them to deduce the internal structure of the Sun, testing therefore the existing models of Sun's structure. This process is known as helioseismology
- Similar vibrations can be observed in other stars: astroseismology

Duration of the stellar lives

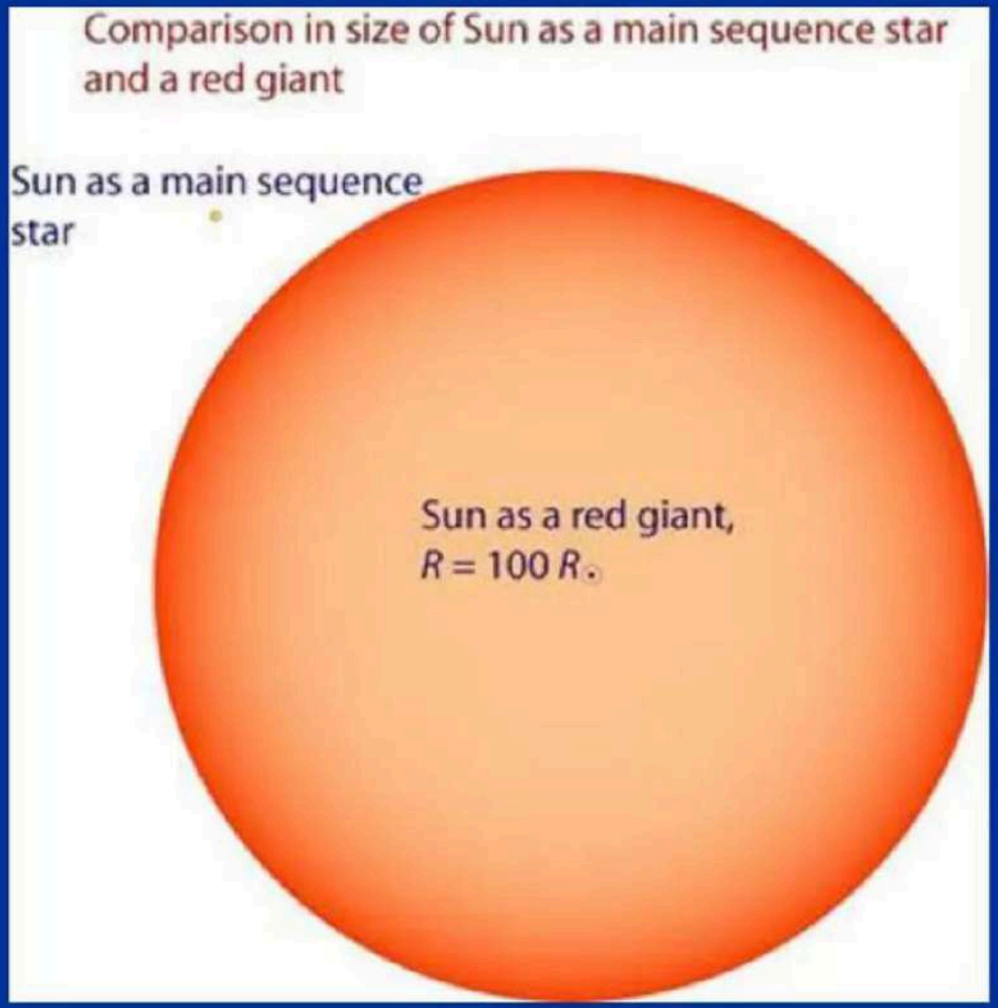
- The duration of the life of a star depends on how much nuclear fuel (hydrogen) it has, and how fast consumes it (power)
- The stars less massive than our Sun are the most common. They have less fuel, but much smaller powers, so they have longer lives
- The stars more massive than the Sun are less common. They have more fuel, but powers much higher, therefore have shorter lives

How astronomers learn about stellar evolution?

- Observing the stars in various stages of their lives, and putting them in a sequence of logical evolution.
- Making models using computers, using the laws of physics, and accounting the changes in the composition of the stars that occur due to nuclear fusion.
- Studying the stellar clusters and/or groups of stars with different masses, but with the same age.
- Studying the fast and strange phases in stellar lives (e.g. supernovae and novae).
- Through the study of variable pulsating stars, measuring the slow changes in the period of pulsation caused by their evolution.

The evolution of Sun-like stars

- The Sun-like star does not change much during the first ~90% of its life, as far as it has enough fuel (hydrogen) to continue with thermonuclear reactions. We call it a main sequence star.



Comparison of size: Sun - red giant
Source: Australia National Telescope Facility

- When its fuel, hydrogen, exhausts, it expands into a red giant star.
- Inside the core, the temperatures can increase enough to start to produce the energy through the fusion of helium into carbon.
- When the helium fuel is exhausted, the star again swells into even bigger red giant, hundreds of times bigger than the Sun

The death of Sun-like stars

Helix Planetary Nebula.
Source: NASA

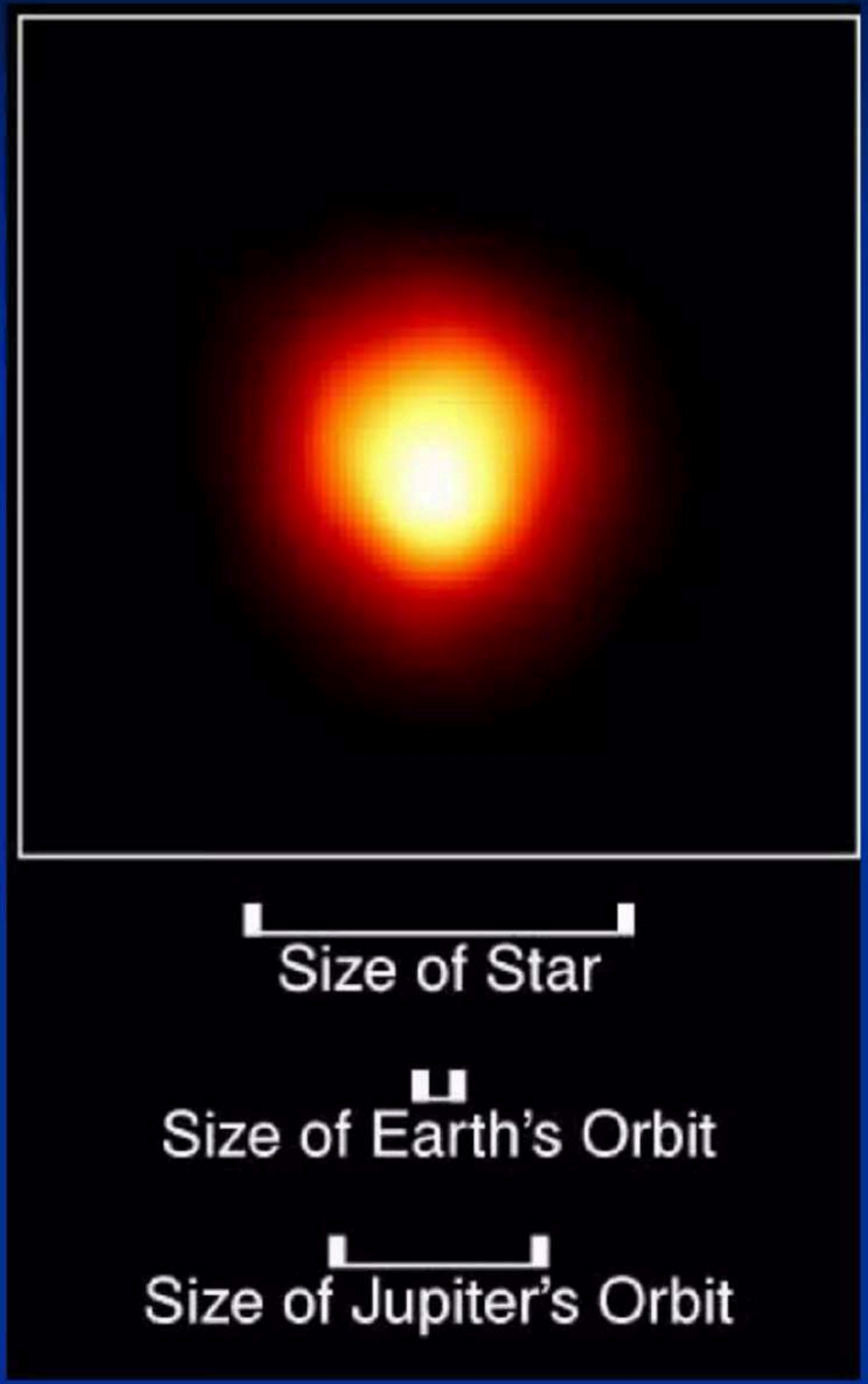
- When the star becomes a red giant, it starts to pulsate (vibrate). We call it Mira star.
- The pulsation causes the separation of the outer layers of the star, producing a beautiful planetary nebula (on the left)
- The core of the star is a dwarf, dense, white, small, and without fuel

White dwarf

The white dwarf companion (below) of Sirius (above). Source NASA

- A white dwarf presents a dead core of a Sun-like stars.
- A white dwarf star has a mass similar to the Sun, a volume similar to the Earth, and a density million times greater than that of the water.
- In a white dwarf, the centripetal gravitational force is balanced by the external quantum pressure of the electrons in its interior.
- Many nearby stars, including Sirius (left) and Procyon, have white dwarf companions.

The evolution of a massive star



Betelgeuse.
Source: NASA/ESA/HST

- Massive stars are rare, powerful and consume their fuel very quickly - in a few million years.
- When they spent their fuel, they swell and become red supergiant stars
- Their core is very hot, enough to produce heavy elements as iron .
- Betelgeuse (left), in Orion constellation, is a bright red supergiant. It is much larger than the Earth's orbit

The death of a massive star

The Crab nebula, the remnant of an explosion of supernovae observed in 1054 AD. Source: NASA

- When the core of a massive star becomes mainly made of iron, it has no more nuclear fuel to continue with fusion and can no longer remain hot.
- Gravity crushes the nucleus in a neutron star, releasing enormous amounts of gravitational energy, and leading the star to an explosion of a supernova (left).
- Supernovae produce elements heavier than iron, and expel these and other elements into the space, which will become part of new stars, planets and life

Neutron stars

Pulsar, neutron star in the heart of the Crab Nebula The rotational energy that emits energized Nebula.
Source: NASA/ESA/HST

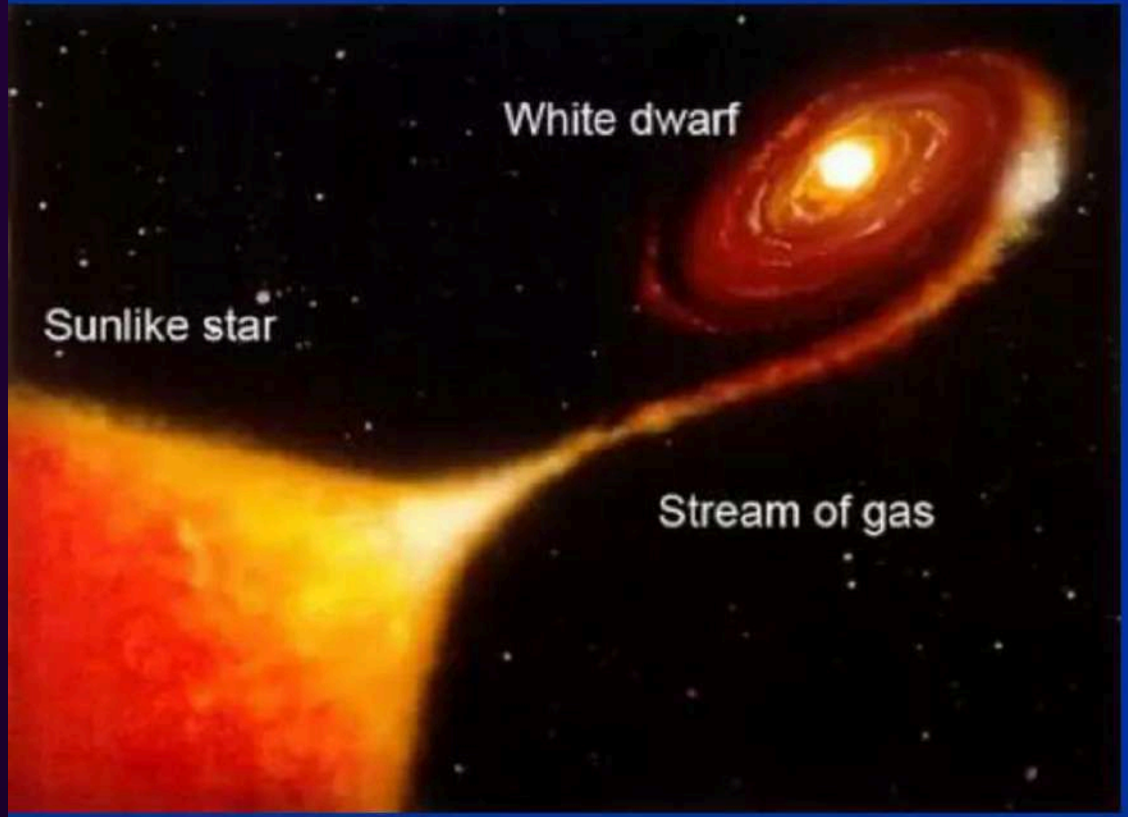
- The stellar cores with masses between 1.5 and 3 times the mass of the Sun collapse and become neutron stars at the end of the life of the star.
- They have diameters of about 10 km and densities trillions of times bigger than water.
- They are made of neutrons and more exotic particles.
- Young neutron stars rotate rapidly and emit regular pulses of radiation in radio, and are known as pulsars.

Black holes

Artistic conception of Cygnus X-1, a visible star (left) with a black hole (right) in a center of accretion disk. Source: NASA.

- A black hole is an astronomical object whose gravity is so strong that nothing can escape from it, not even light.
- The nuclei of the uncommon massive stars (more than 30 times the mass of the Sun) become black holes when their fuel runs out.
- One way of black hole detection: when a visible star is orbiting around them (left).

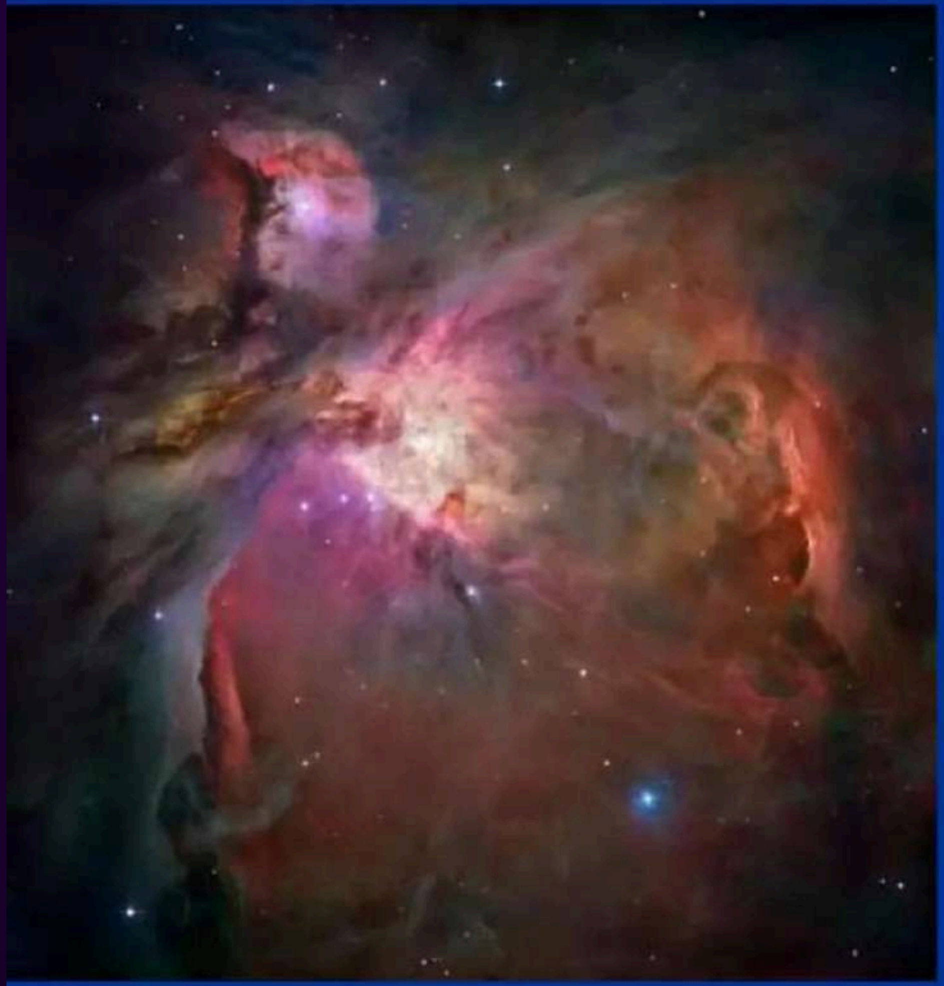
Special cases of variable stars



A pair of normal star (left) and
a white dwarf star with an accretion disc
stealing gas from the companion (right).
Source: NASA

- Many stellar remnants - white dwarfs, black holes or neutron stars - have a normal visible star orbiting around it.
- If the gas from the normal star falls to the stellar remnant, the accretion disk can be formed around it (left).
- When gas falls on the stellar remnant, it can burst, erupt, or explode, which we call a cataclysmic variable star

The birth of stars



Orion Nebula
Source: NASA

- Stars are formed inside the molecular clouds (nebulae), made of cold gas and dust.
- Interstellar dust and gas is about 10% of the matter in our Galaxy.
- The young stars can generally be found inside or near the nebula from which they arose.
- The closest and clear example of a star formation region is the Orion nebula (left), around 1500 light years away from us.

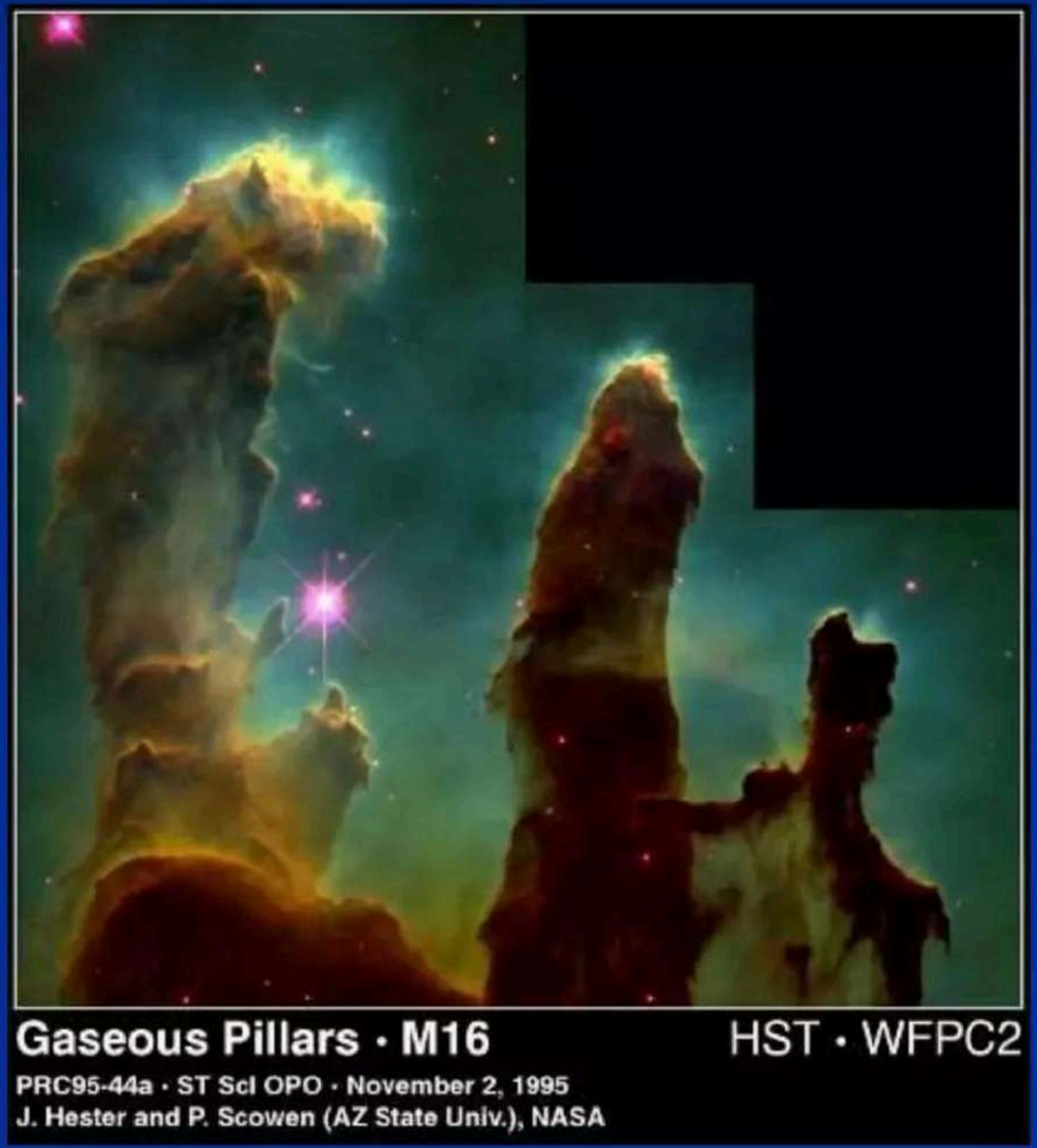
Interstellar gas

The gas between the stars

The Orion nebula. The gas is energized by ultraviolet light from the stars in the nebula. Source: NASA

- The interstellar gas (atoms or molecules) can be activated by ultraviolet light coming from a nearby star, producing an emission nebula (left).
- Cold gas between the stars, produces radio waves that can be detected by radio telescopes.
- 98% of the interstellar gas is made of hydrogen and helium

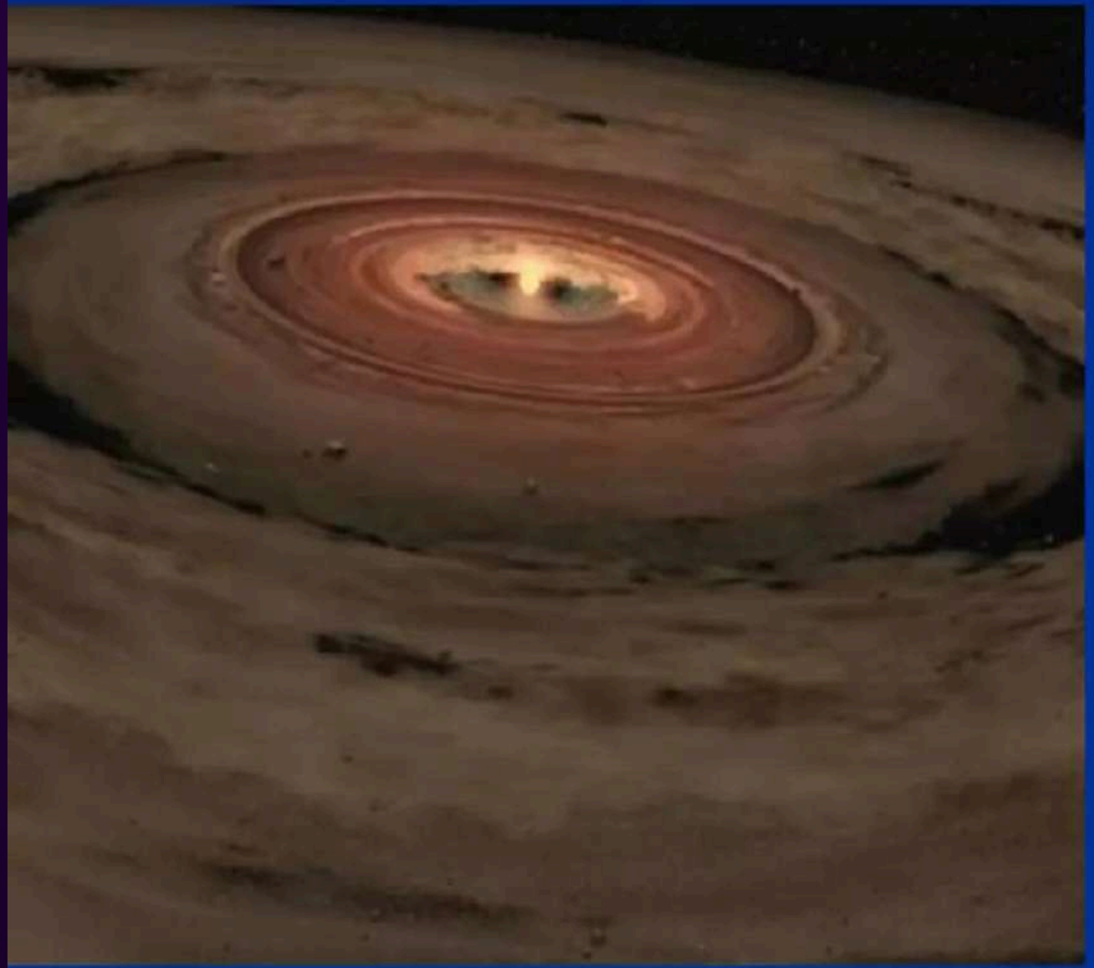
Interstellar dust
Dust between the stars



M16
Soruce: NASA/ESA/HST

- Interstellar dust near the bright stars can be detected in the visible part of spectra
- Dust can block the light from the stars and gas behind (left). The stars are formed in these clouds.
- Only 1% of the material between the stars is dust. The dust particles are a few hundred nm in size, and are mostly silicates or graphite

Star formation

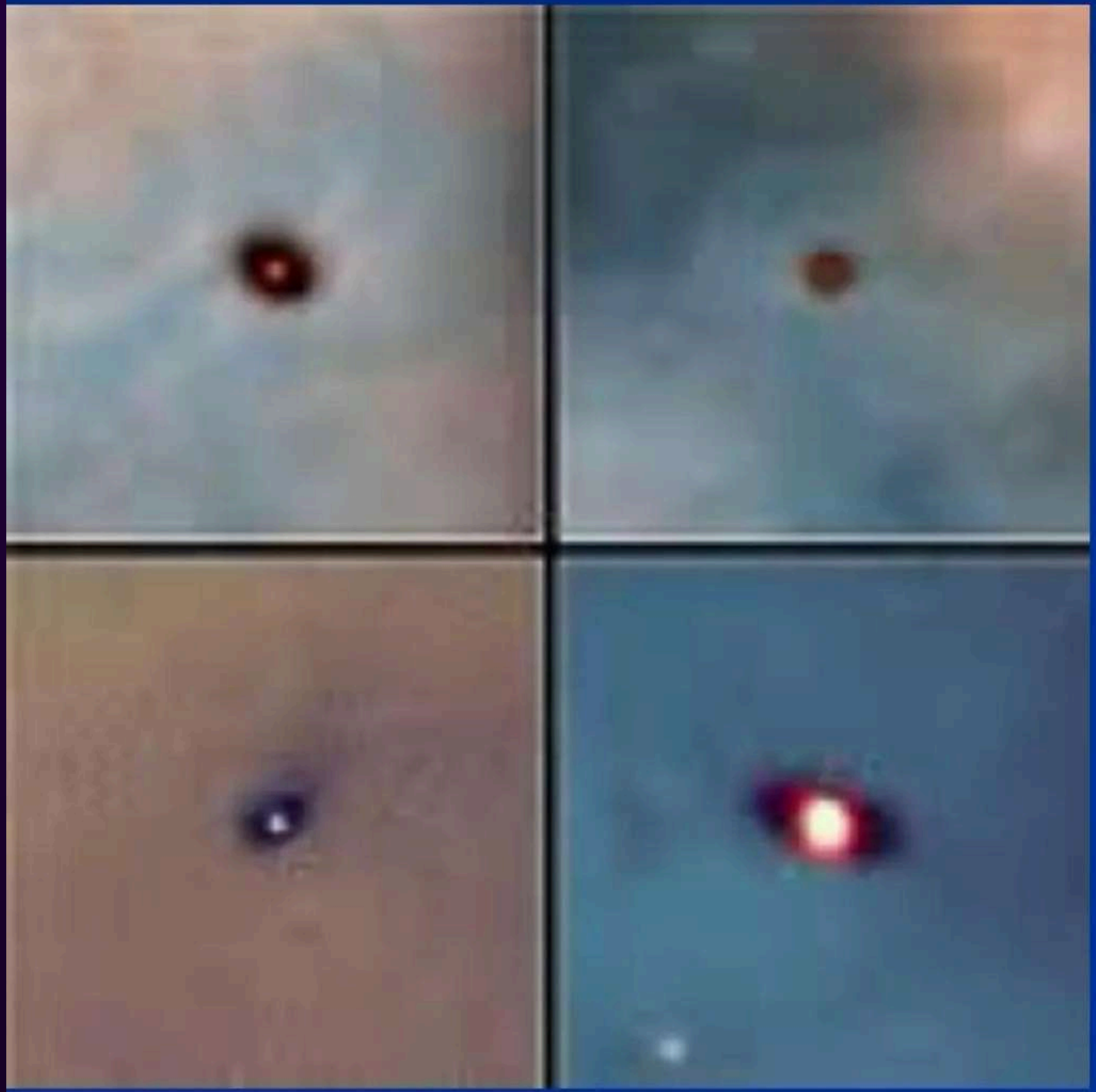


Artistic conception of a planetary system in the formation process.
Source: NASA

- The stars are formed inside the parts of a nebula called nuclei, which are dense or compressed.
- Gravity is responsible for attraction of nuclei.
- The conservation of angular momentum increases the rotation of the nuclei, which become flattened and finally convert into the discs.
- Stars are formed in the center of disks. The planets are formed in the colder, outer parts of the disk.

Protoplanetary disks: Proplyds

Planetary systems in the process of formation

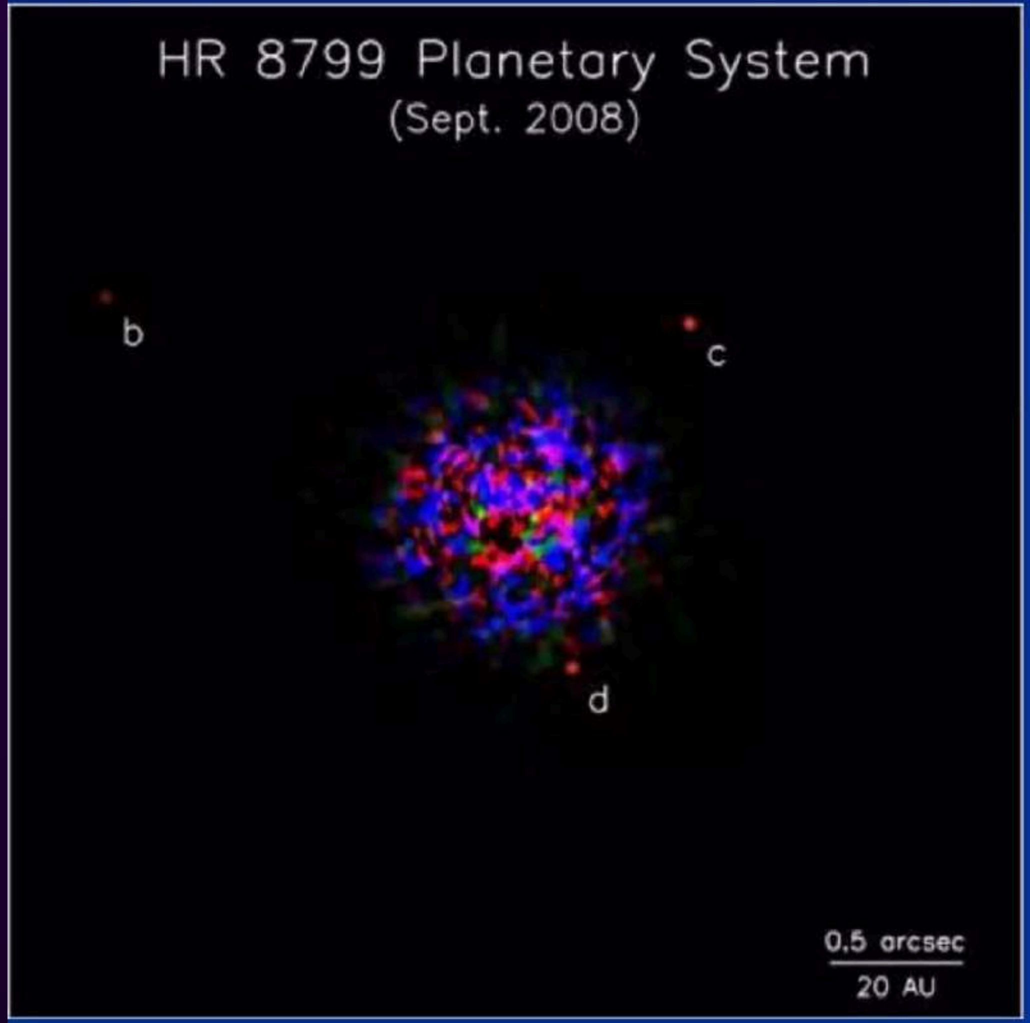


Proplyds
Source: NASA/ESA/HST

- Protoplanetary disks have been observed in the Orion nebula (left)
- The star can hardly be visible in the center of the disc.
- The disk of dust blocked the light that is behind.
- These and other observations provide a direct evidence of the formation of planetary systems.

Exoplanets = extrasolar planets

Planets around other stars



System exoplanet HR 8799
Source: C. Marois et al., NRC Canada

- The exoplanets are usually discovered and studied through gravitational effect they have on the star, or through the light dimming of its star if transit occur.
- Very few have been directly captured (left).
- Unlike the planets in our Solar System, many exoplanets are huge and very close to its star. This allows the astronomers to modify/correct their theories how planetary systems formg.

Final considerations

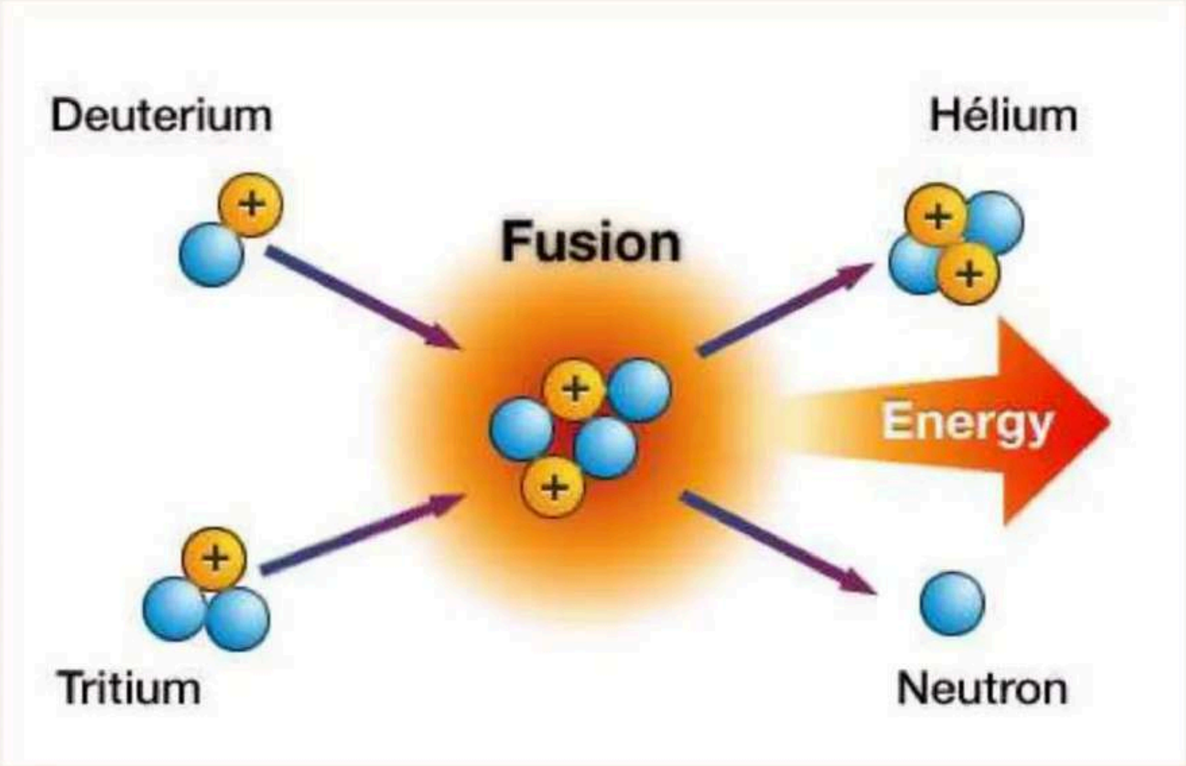
- "Gravity drives the formation, life and death of stars" [Professor R.L. Bishop]
- The birth of a star explains the origin of our Solar System and other planetary systems.
- The life of the star explains the energy source that makes life on Earth possible.
- The life and death of the stars produce chemical elements heavier than hydrogen, that stars, planets and life are made of.
- During the death of a star, gravity produces the strangest objects in the universe: white dwarfs, neutron stars and black holes.

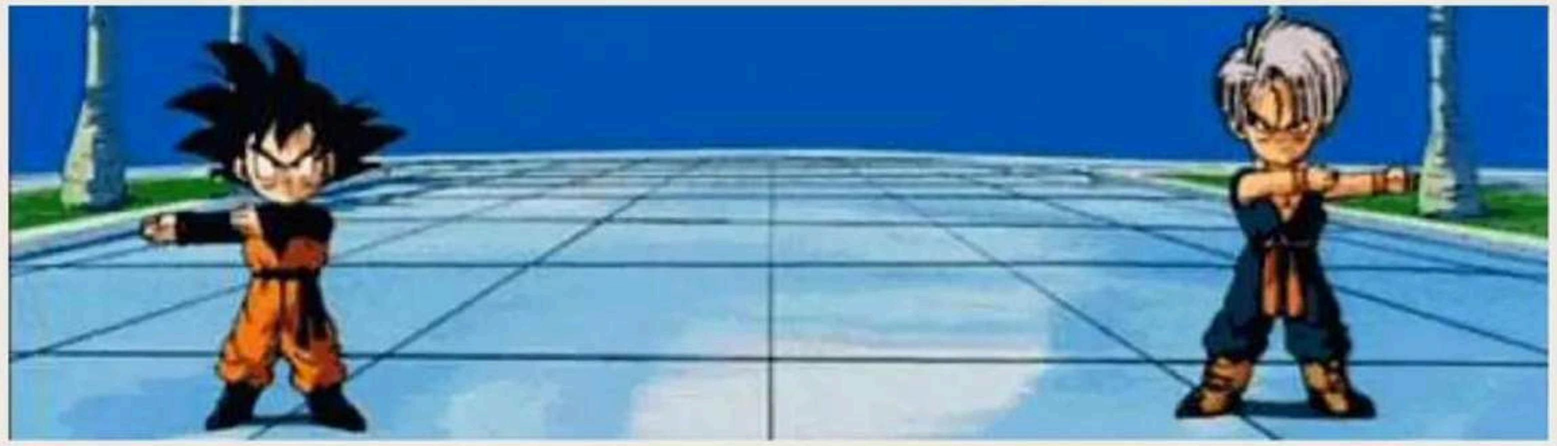
KEY TERMS

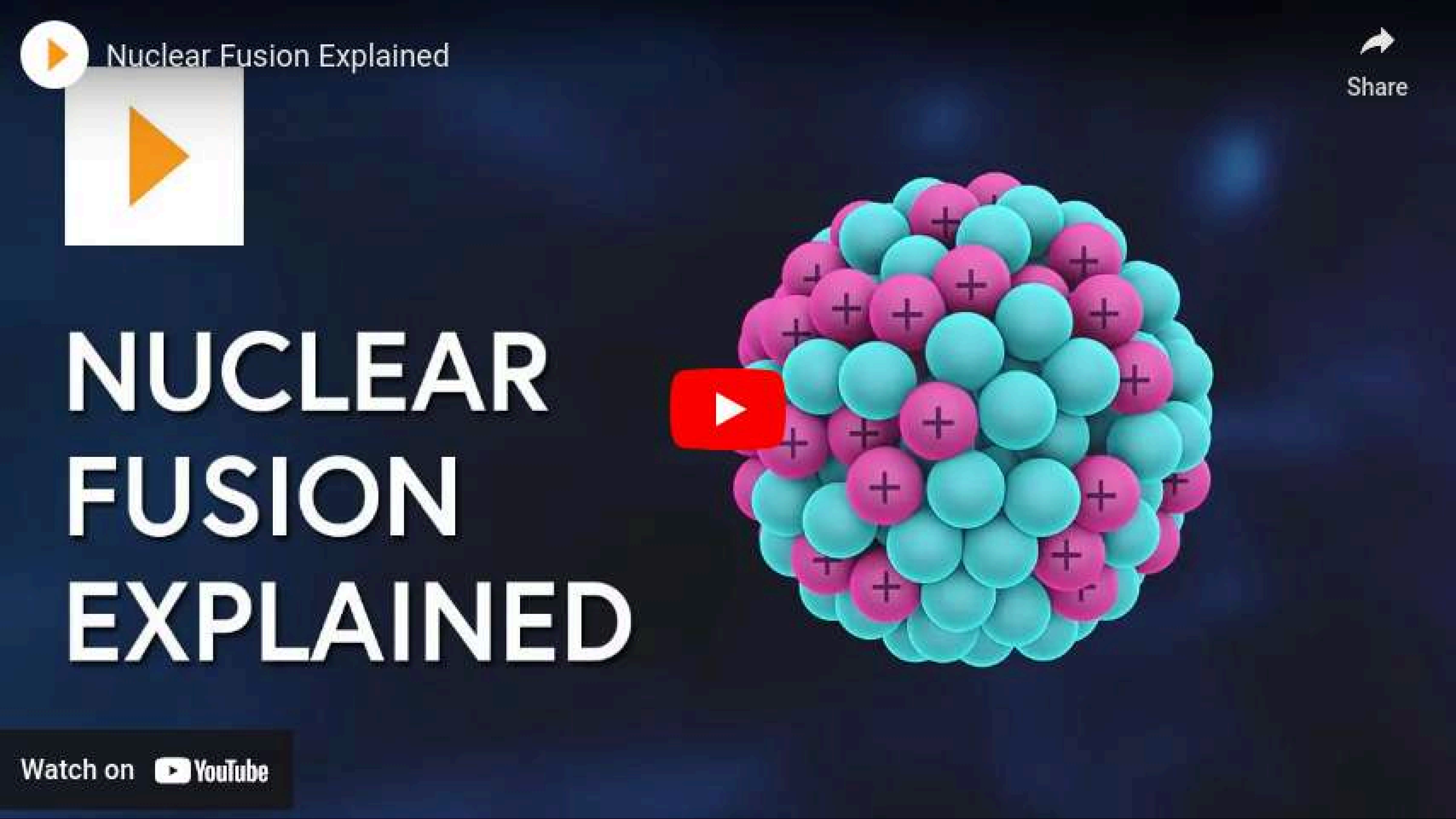
1) Fusion -
2) Isotope -
3) Stellar evolution -
4) Stellar nucleosynthesis -
5) Supernova nucleosynthesis -
6) Proton-proton chain reaction -
7) Triple alpha process nucleosynthesis -
8) Alpha ladder -
9) CNO cycle -
10) Main-sequence star -
11) Red giant -
12) Supernova explosion -
13) Supernova -
14) R-process -
15) S-process -

Fusion

→ is the combining of nuclei to form a bigger and heavier nucleus.

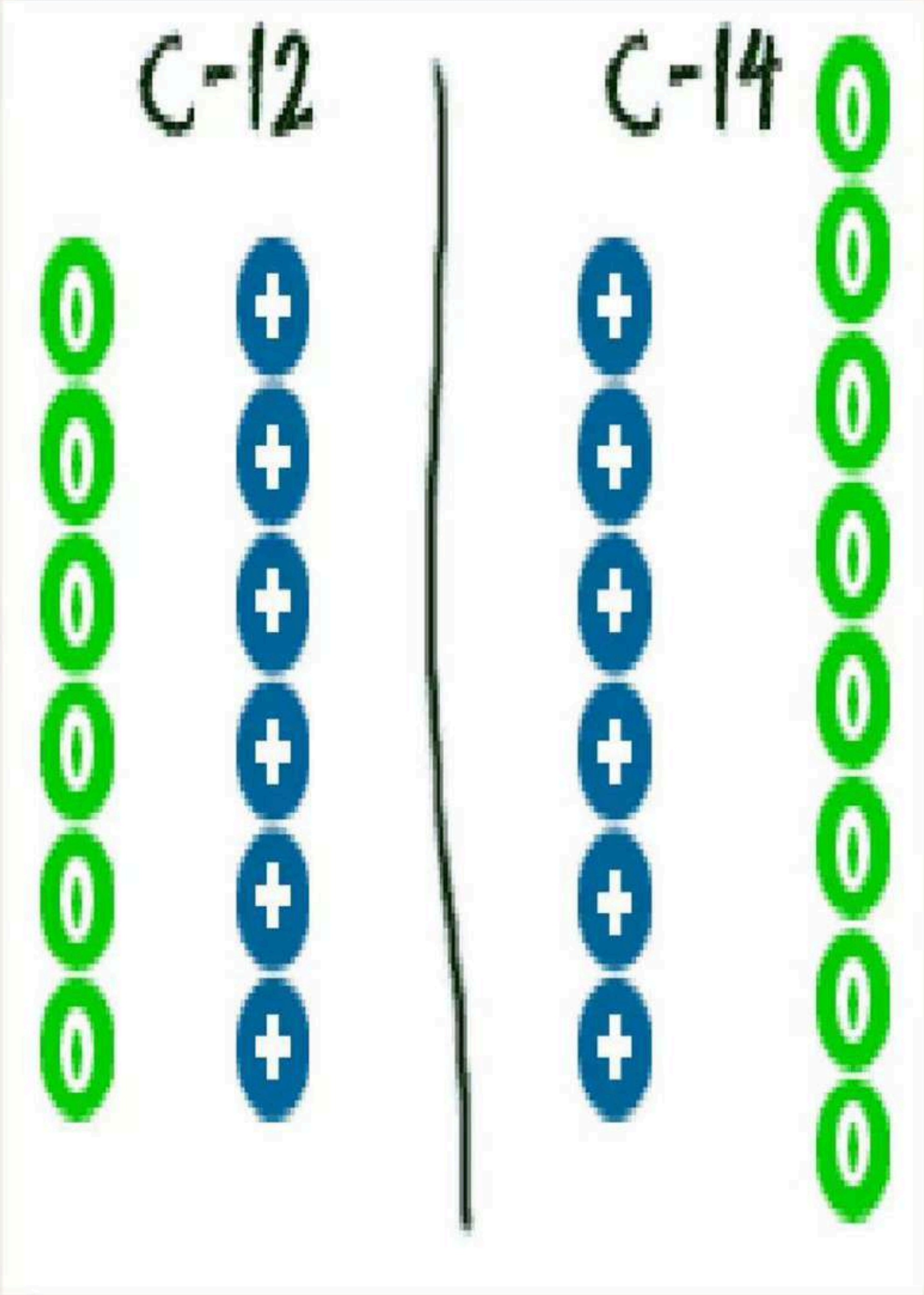





Nuclear Fusion Explained
Share
NUCLEAR
FUSION
EXPLAINED
Watch on YouTube

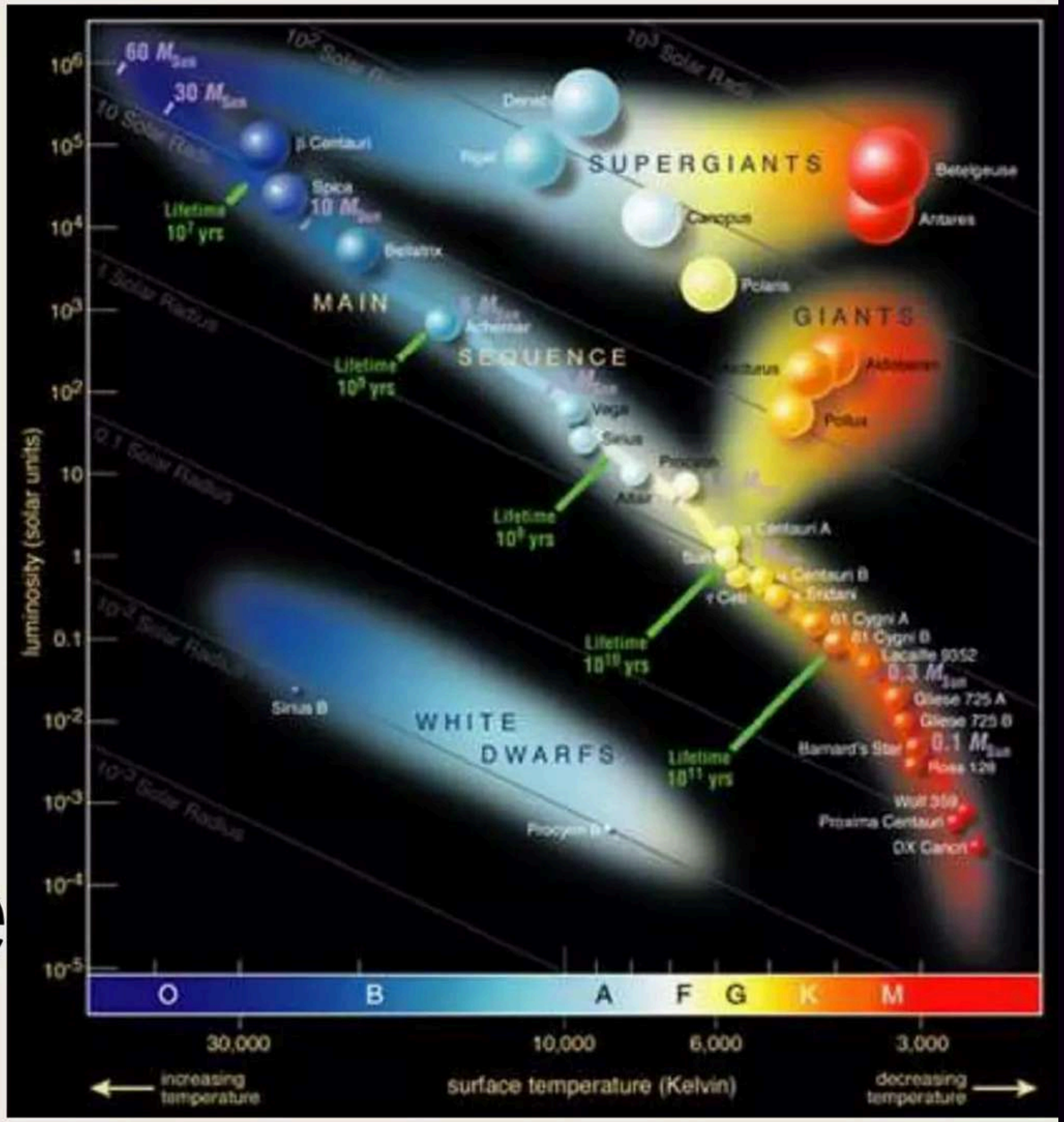
Isotope

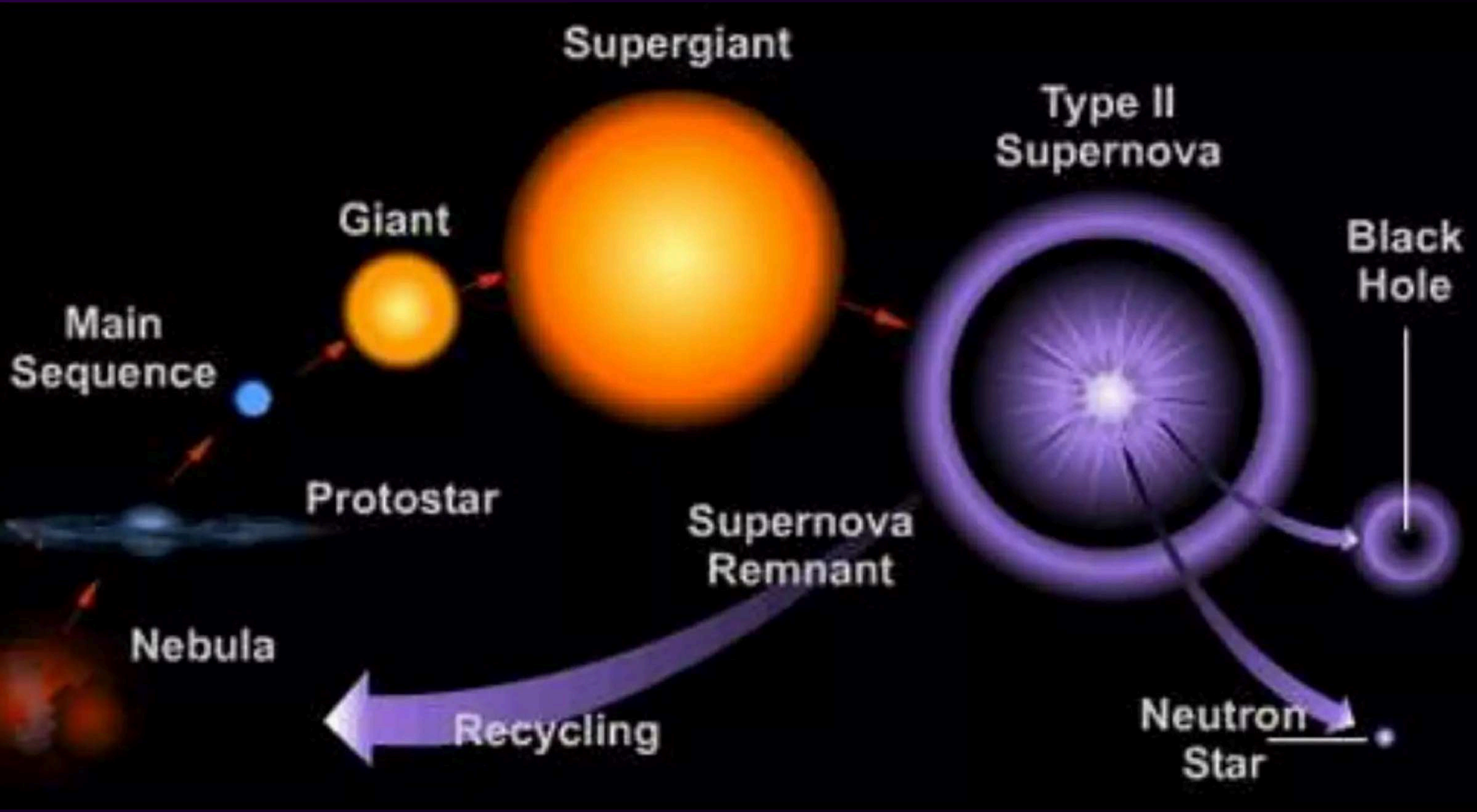
→ is a form of a chemical element whose atomic nucleus contains a specific number of neutrons, in addition to the number of protons that uniquely defines the element.



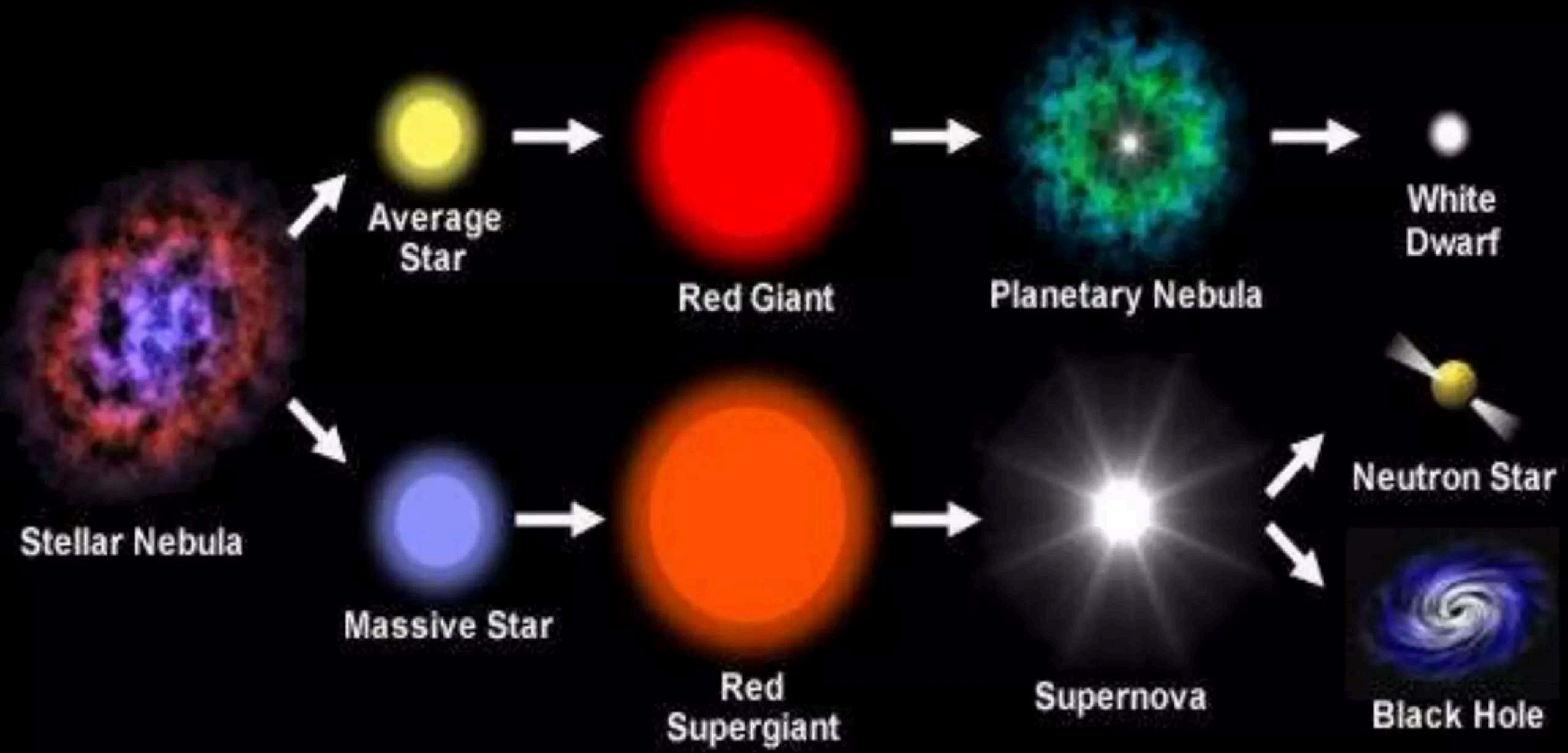
Stellar Evolution

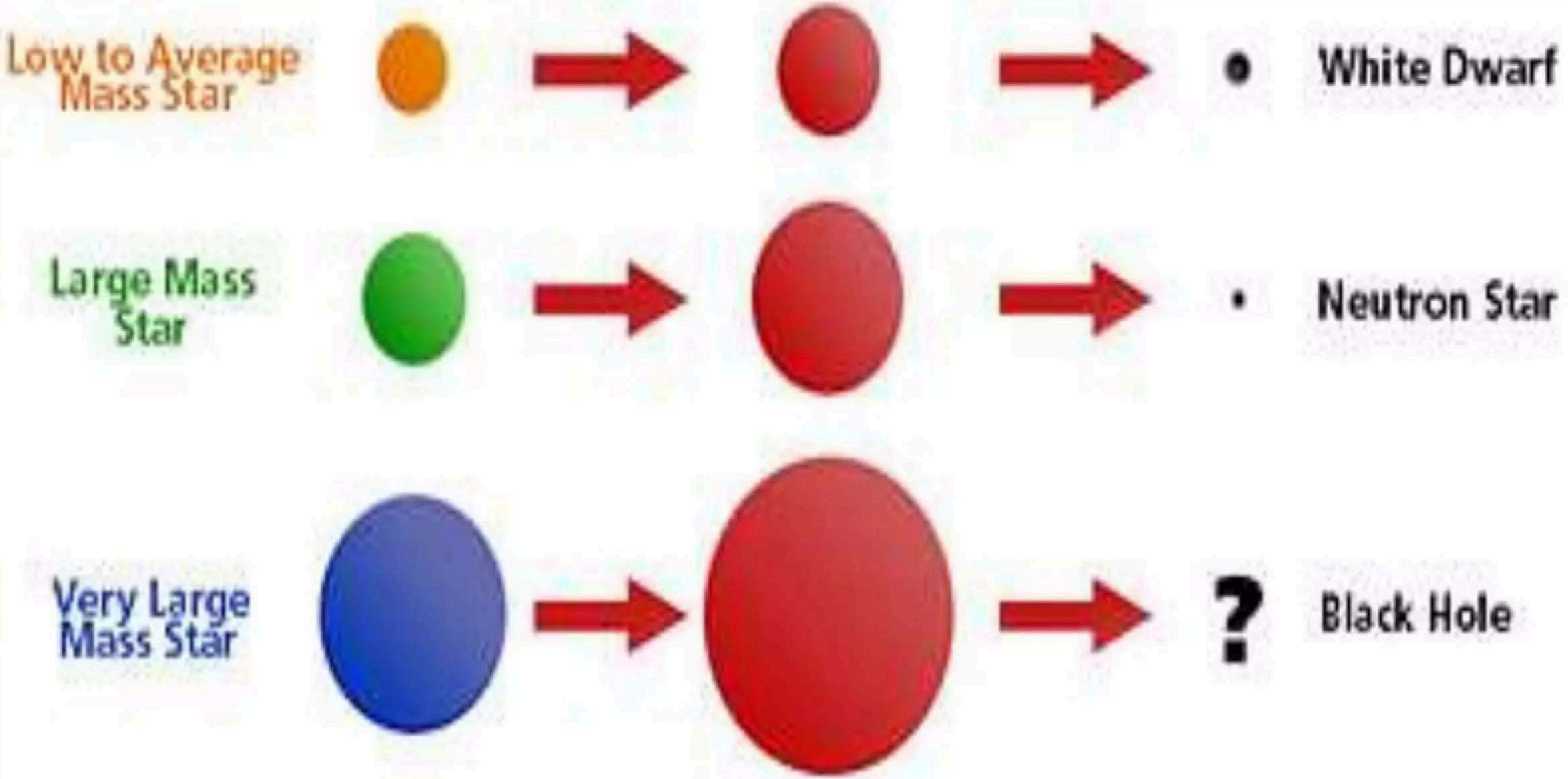
→ is the process by which a star changes over the course of time.




Supergiant
Type II
Supernova
Giant
Black
Hole
Main
Sequence
Protostar
Supernova
Remnant
Nebula
Recycling
Neutron
Star

Life Cycle of a Star

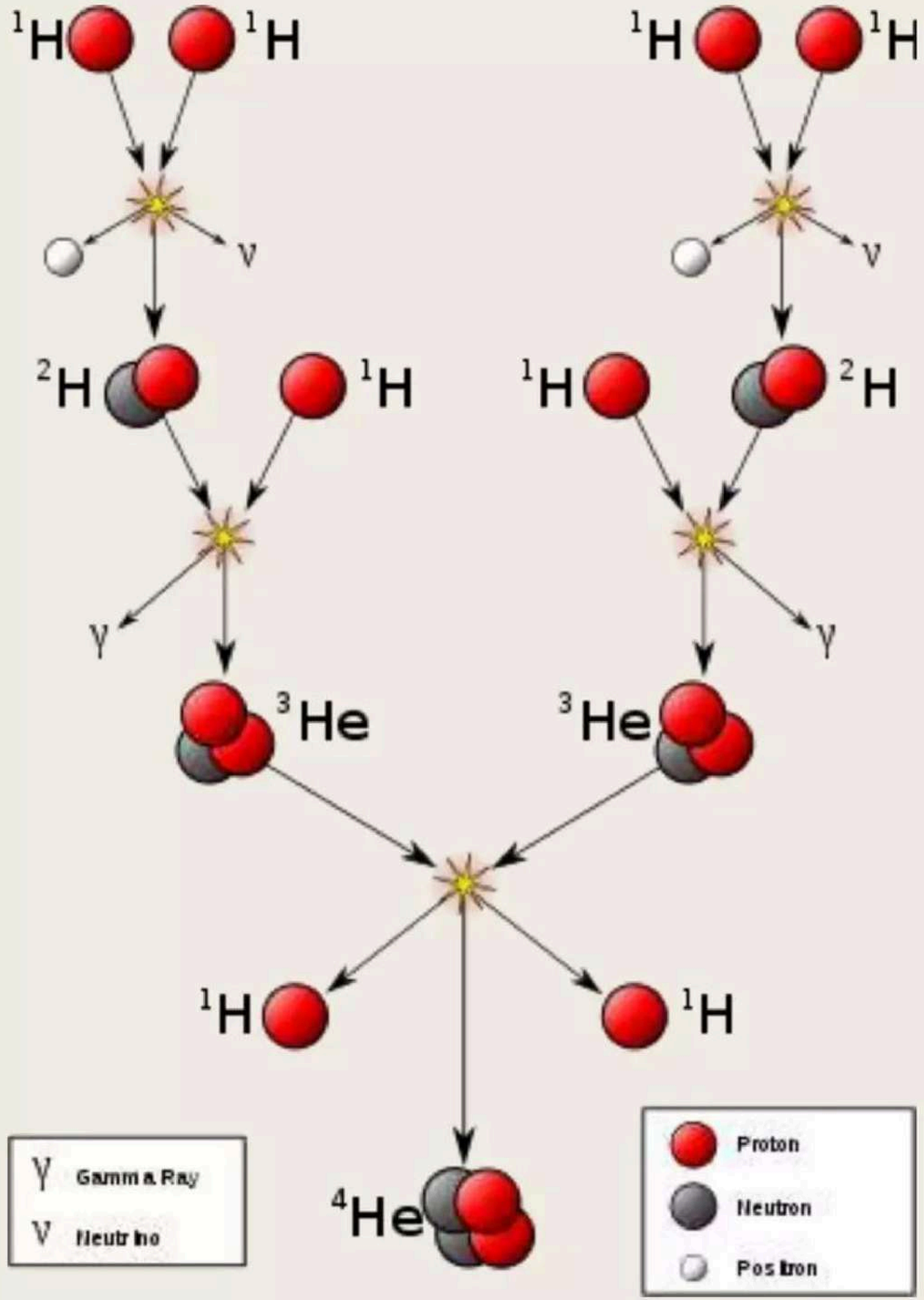




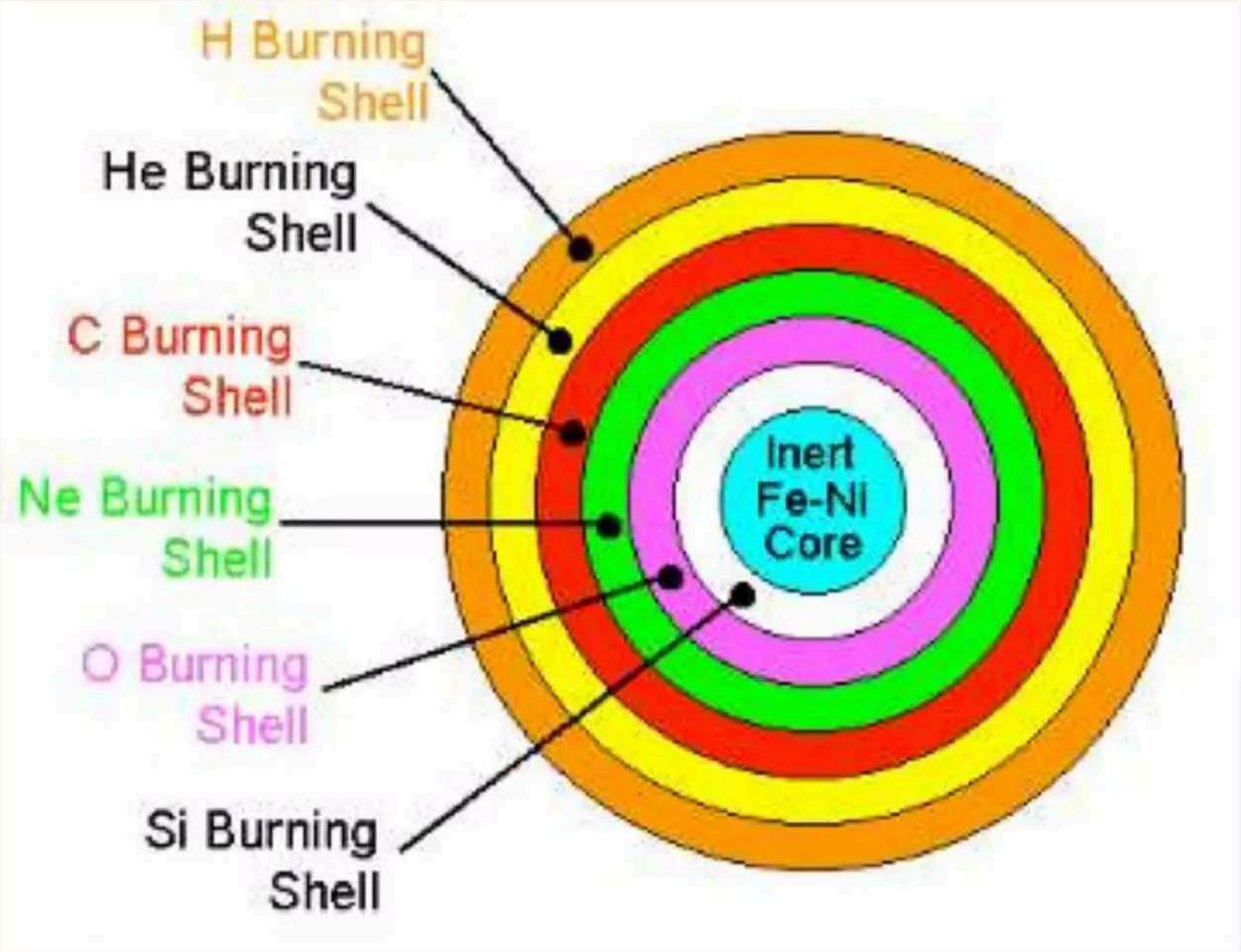
The fate of a star depends on its mass (size not to scale)

Stellar Nucleosynthesis

→ is the process by which the natural abundances of the chemical elements within stars vary due to nuclear fusion reactions in the cores and overlying mantles of stars.



^1H ^1H ^1H ^1H
ν ν
^2H ^1H ^1H ^2H
γ γ
^3He ^3He
^1H ^1H
^4He
γ Gamma Ray
ν Neutrino
Proton
Neutron
Positron

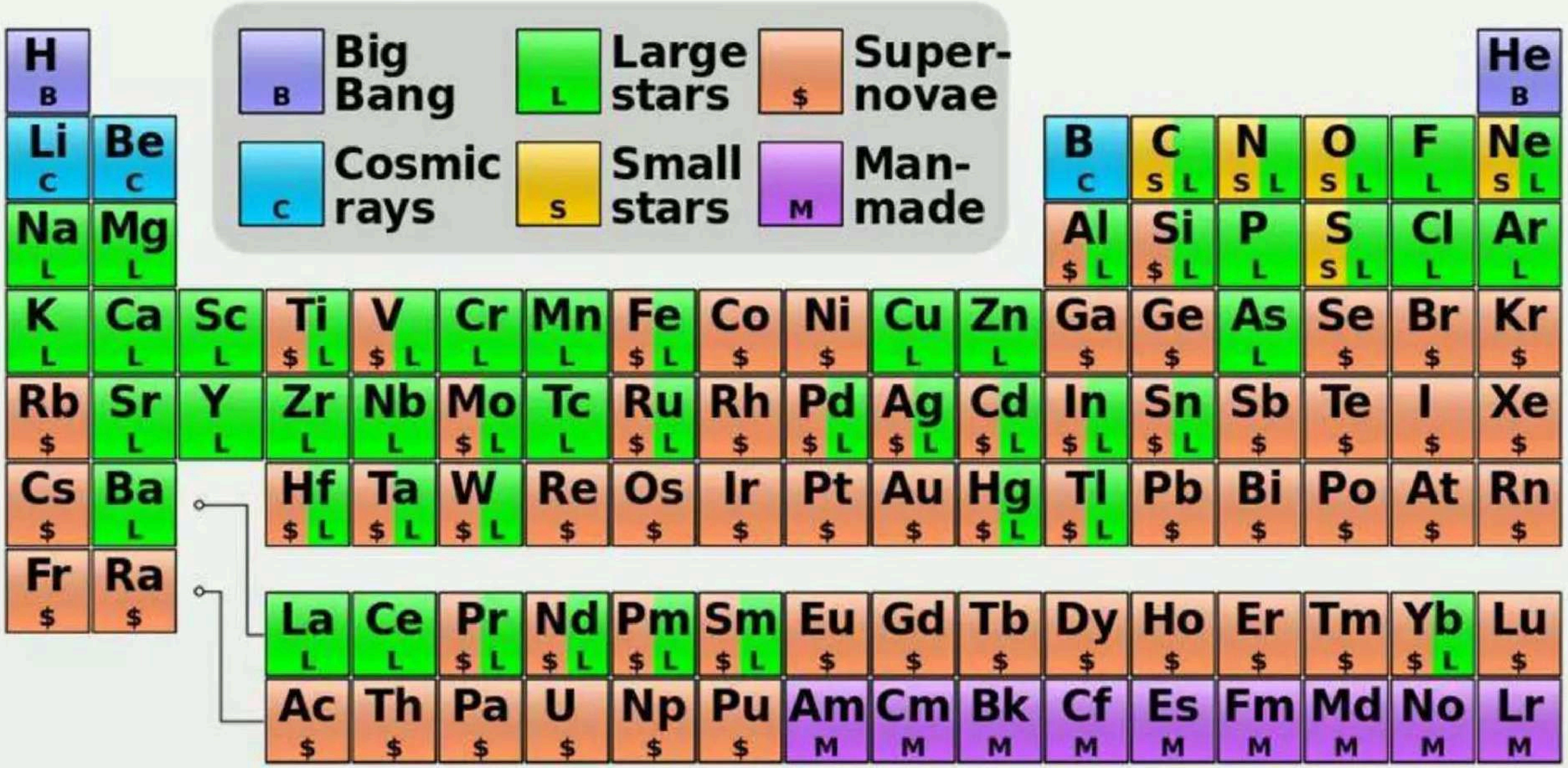


H Burning Shell
He Burning Shell
C Burning Shell
Ne Burning Shell
O Burning Shell
Si Burning Shell
Inert Fe-Ni Core

Supernova Nucleosynthesis

→ is a theory of the production of many different chemical elements in supernova explosions, first advanced by Fred Hoyle in 1954.

Supernova nucleosynthesis



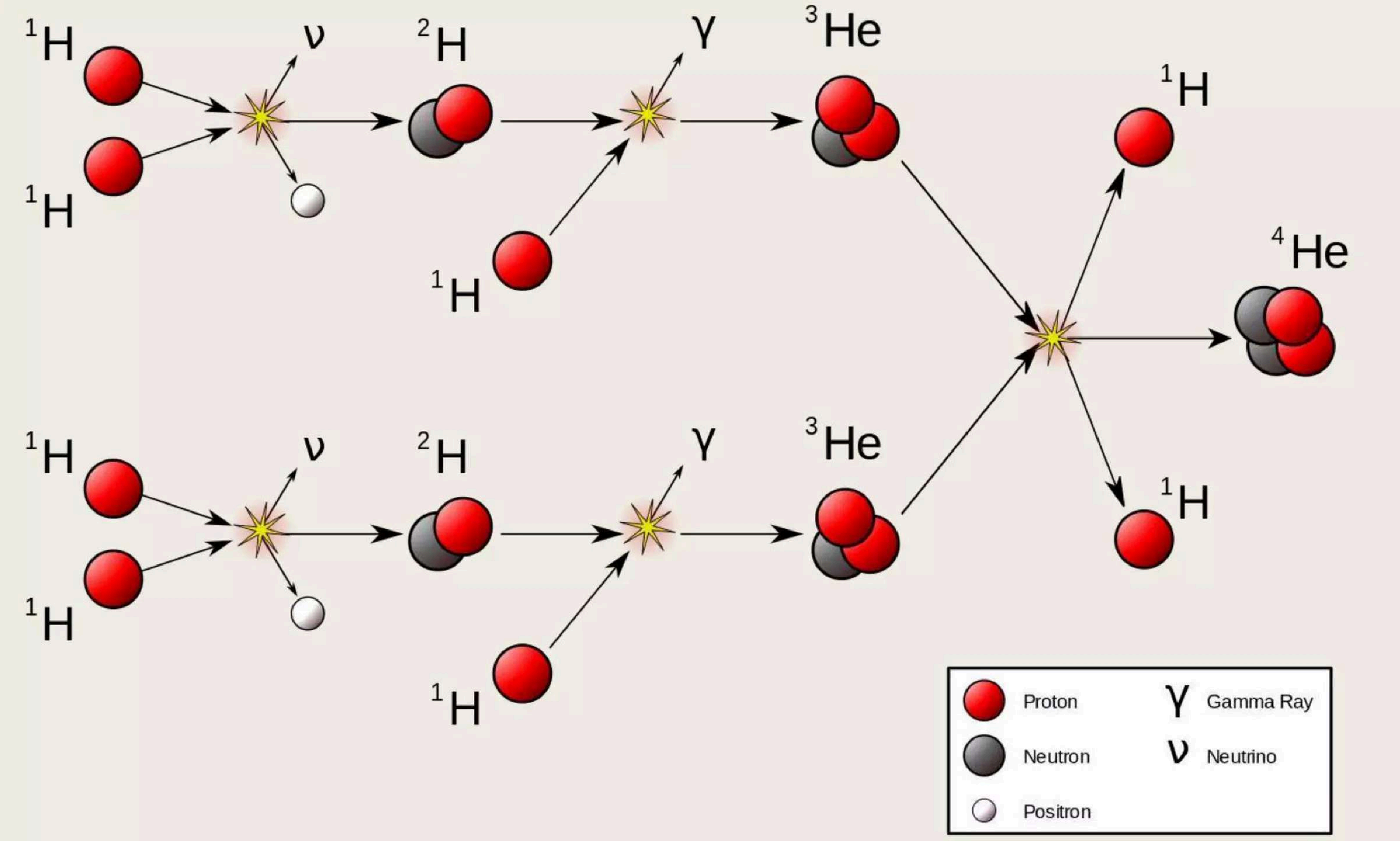
https://en.wikipedia.org/wiki/File:Nucleosynthesis_periodic_table.svg

Proton-proton chain reaction

→ is one of the two (known) sets of fusion reactions by which stars convert hydrogen to helium. It dominates in stars the size of the Sun or smaller.

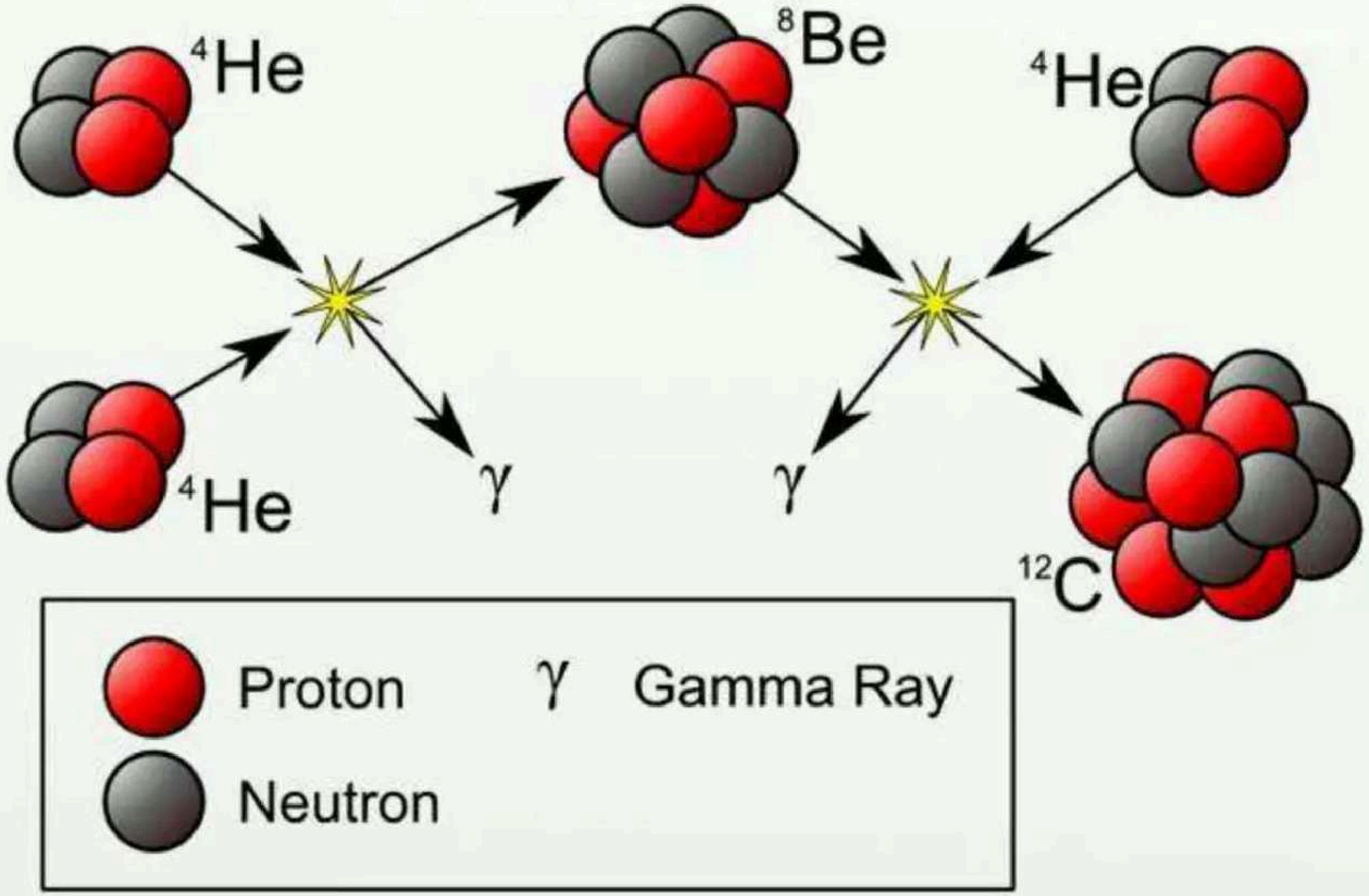
Triple alpha process nucleosynthesis

→ is a set of nuclear fusion reactions by which three helium-4 nuclei (alpha particles) are transformed into carbon.



^1H
ν
^2H
γ
^3He
^1H
^1H
^1H
^4He
^1H
ν
^2H
γ
^3He
^1H
^1H
^1H
Proton
γ Gamma Ray
Neutron
ν Neutrino
Positron

Triple-alpha process



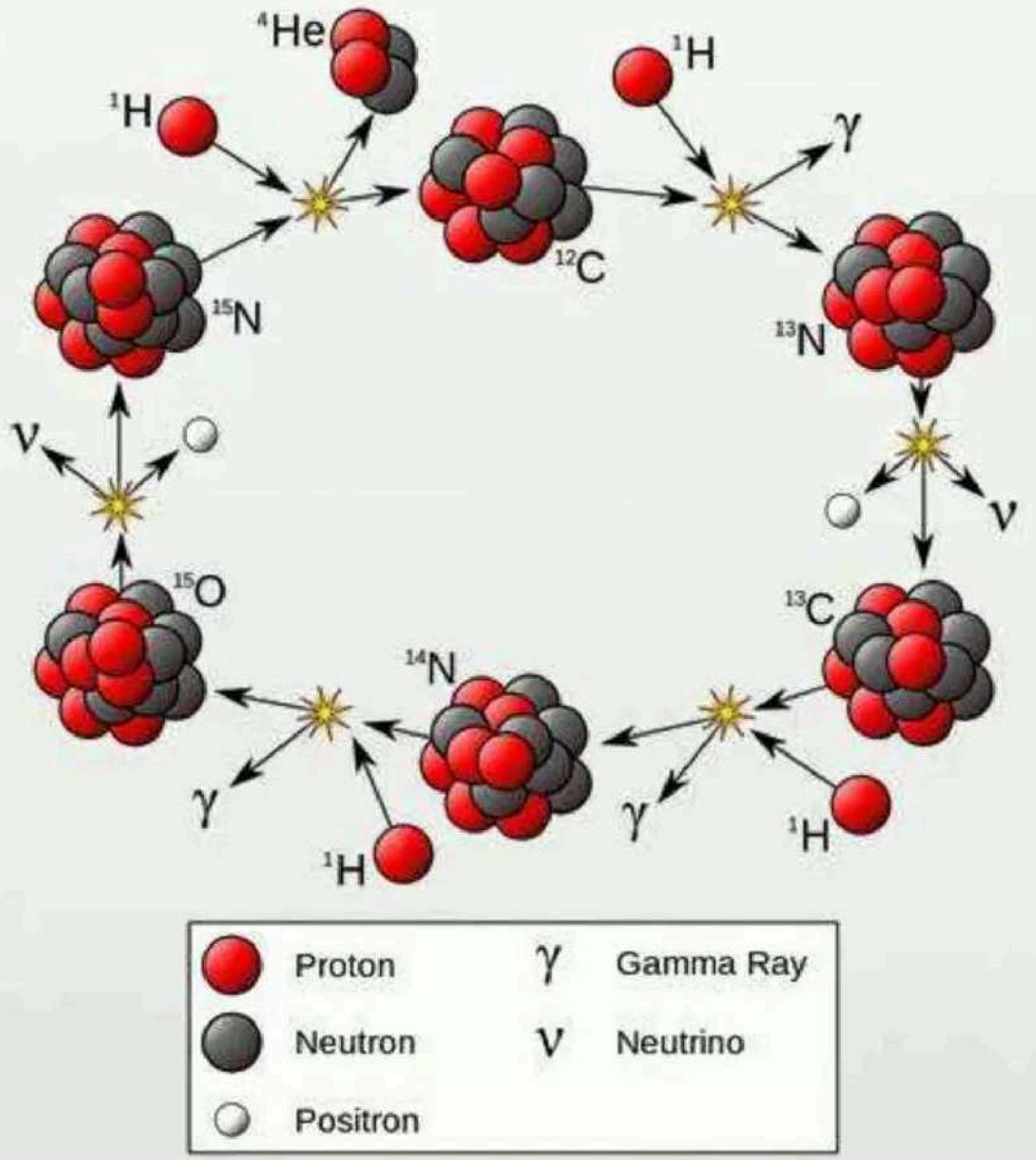
https://en.wikipedia.org/wiki/File:Triple-Alpha_Process.png

CNO Cycle

→ (for carbon–nitrogen–oxygen) is one of the two known sets of fusion reactions by which stars convert hydrogen to helium.

→ It is a catalytic cycle.

CNO cycle

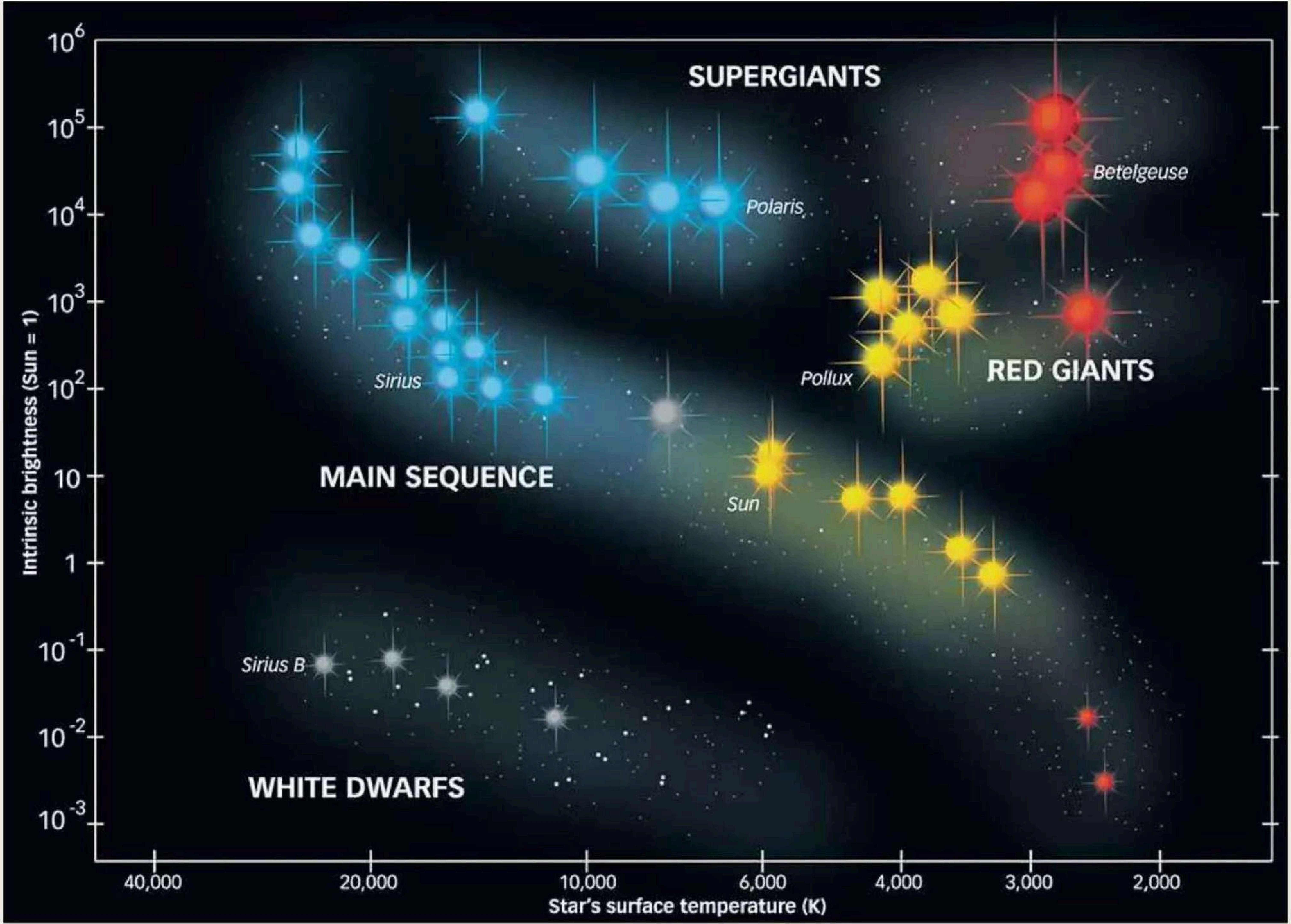


https://en.wikipedia.org/wiki/File:CNO_Cycle.svg

Alpha ladder/process

→ is one of two classes of nuclear fusion reactions by which stars convert helium into heavier elements, the other being the triple-alpha process.

$$
\begin{array}{ll}
{}^{12}_{6}\mathrm{C} + {}^{4}_{2}\mathrm{He} \longrightarrow {}^{16}_{8}\mathrm{O} + \gamma & E = 7.16\ \mathrm{MeV} \\
{}^{16}_{8}\mathrm{O} + {}^{4}_{2}\mathrm{He} \longrightarrow {}^{20}_{10}\mathrm{Ne} + \gamma & E = 4.73\ \mathrm{MeV} \\
{}^{20}_{10}\mathrm{Ne} + {}^{4}_{2}\mathrm{He} \longrightarrow {}^{24}_{12}\mathrm{Mg} + \gamma & E = 9.32\ \mathrm{MeV} \\
{}^{24}_{12}\mathrm{Mg} + {}^{4}_{2}\mathrm{He} \longrightarrow {}^{28}_{14}\mathrm{Si} + \gamma & E = 9.98\ \mathrm{MeV} \\
{}^{28}_{14}\mathrm{Si} + {}^{4}_{2}\mathrm{He} \longrightarrow {}^{32}_{16}\mathrm{S} + \gamma & E = 6.95\ \mathrm{MeV} \\
{}^{32}_{16}\mathrm{S} + {}^{4}_{2}\mathrm{He} \longrightarrow {}^{36}_{18}\mathrm{Ar} + \gamma & E = 6.64\ \mathrm{MeV} \\
{}^{36}_{18}\mathrm{Ar} + {}^{4}_{2}\mathrm{He} \longrightarrow {}^{40}_{20}\mathrm{Ca} + \gamma & E = 7.04\ \mathrm{MeV} \\
{}^{40}_{20}\mathrm{Ca} + {}^{4}_{2}\mathrm{He} \longrightarrow {}^{44}_{22}\mathrm{Ti} + \gamma & E = 5.13\ \mathrm{MeV} \\
{}^{44}_{22}\mathrm{Ti} + {}^{4}_{2}\mathrm{He} \longrightarrow {}^{48}_{24}\mathrm{Cr} + \gamma & E = 7.70\ \mathrm{MeV} \\
{}^{48}_{24}\mathrm{Cr} + {}^{4}_{2}\mathrm{He} \longrightarrow {}^{52}_{26}\mathrm{Fe} + \gamma & E = 7.94\ \mathrm{MeV} \\
{}^{52}_{26}\mathrm{Fe} + {}^{4}_{2}\mathrm{He} \longrightarrow {}^{56}_{28}\mathrm{Ni} + \gamma & E = 8.00\ \mathrm{MeV}
\end{array}
$$



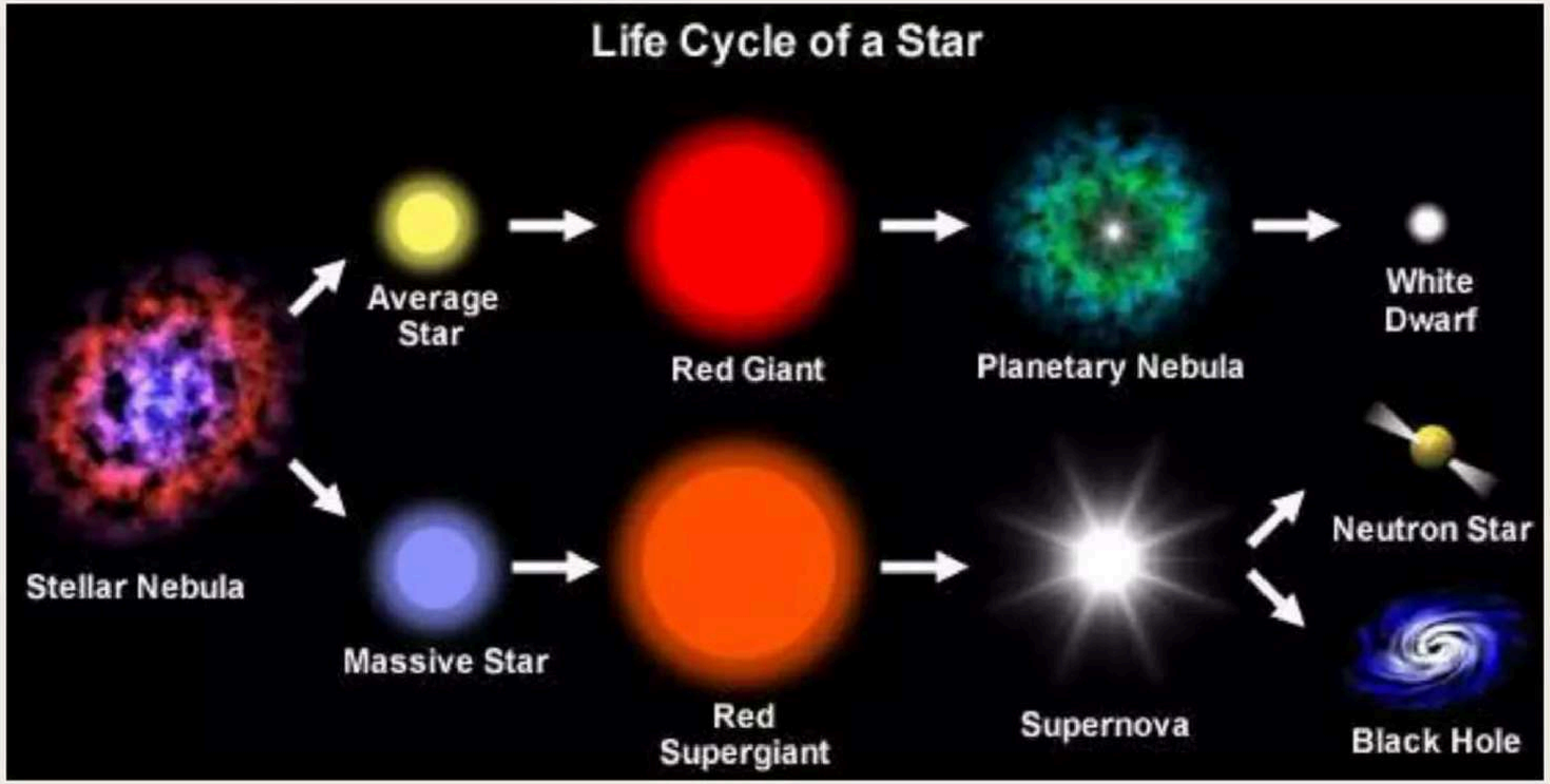
SUPERGIANTS
Betelgeuse
Polaris
Pollux
RED GIANTS
Sirius
MAIN SEQUENCE
Sun
Sirius B
WHITE DWARFS
Intrinsic brightness (Sun = 1)
10^6
10^5
10^4
10^3
10^2
10
1
10^-1
10^-2
10^-3
40,000
20,000
10,000
6,000
4,000
3,000
2,000
Star's surface temperature (K)

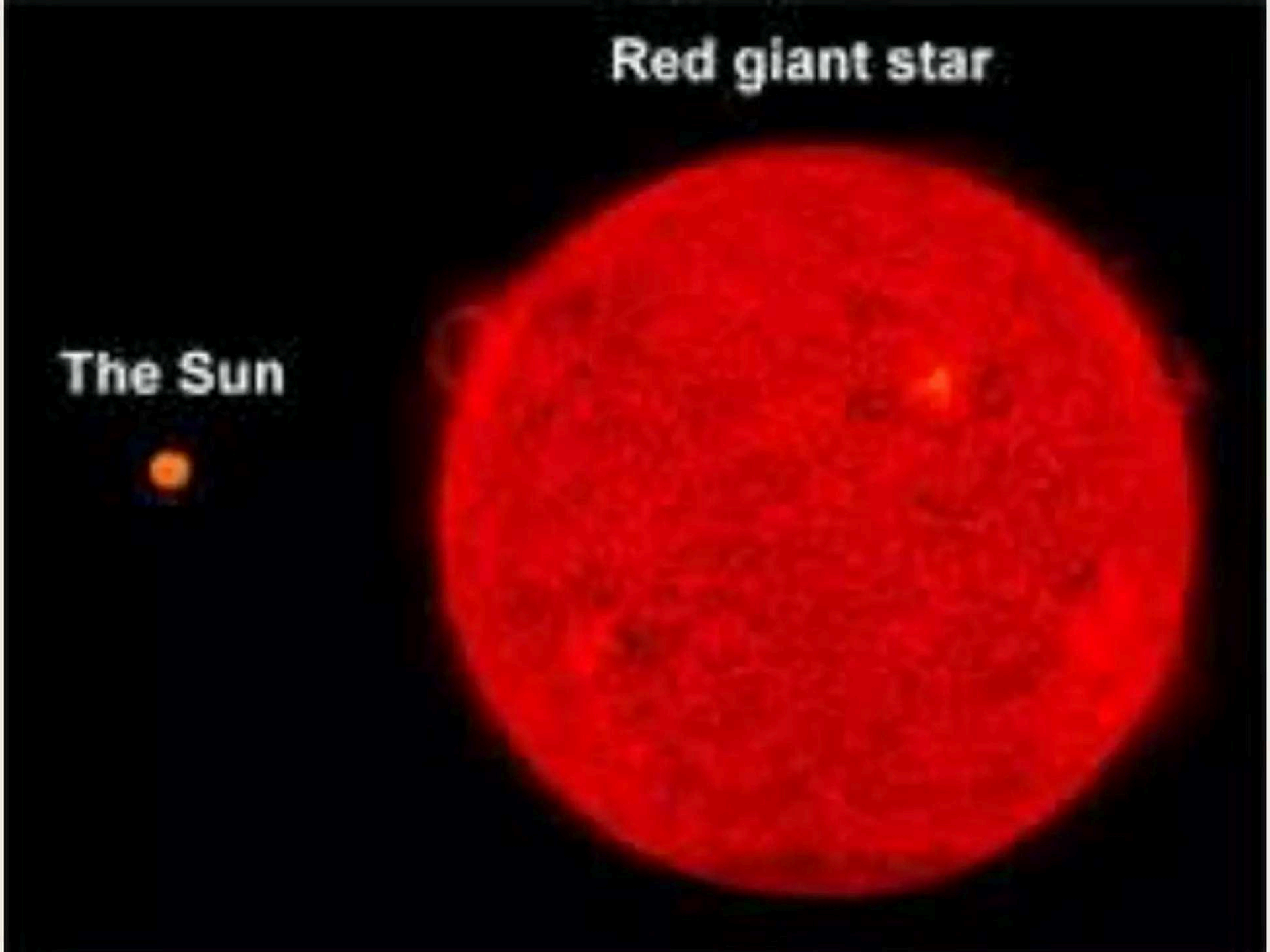
Main-Sequence Star

→ is any star that is fusing hydrogen in its core and has a stable balance of outward pressure from core nuclear fusion and gravitational forces pushing inward.

Red Giant Star

→ is a dying star in the last stages of stellar evolution.

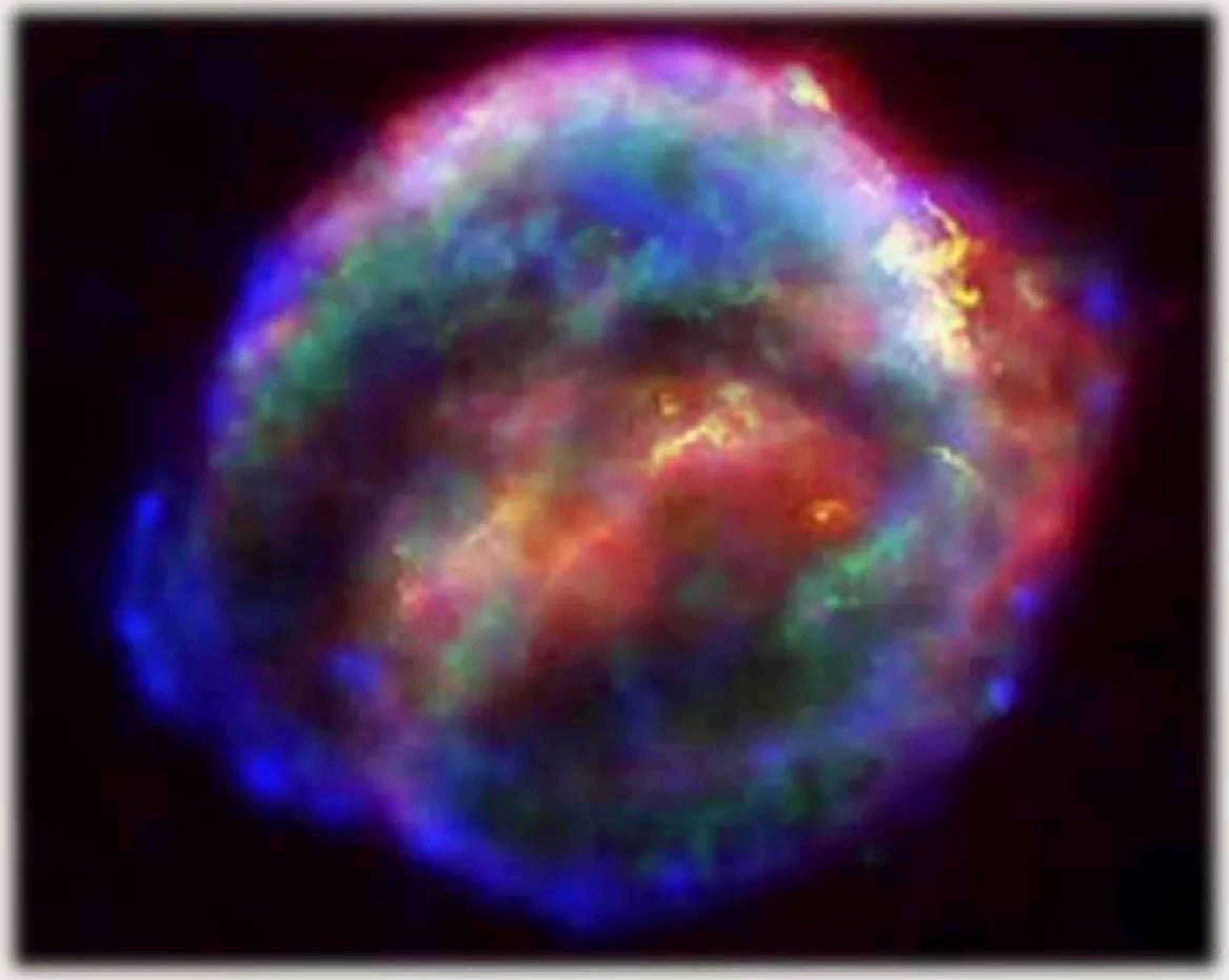


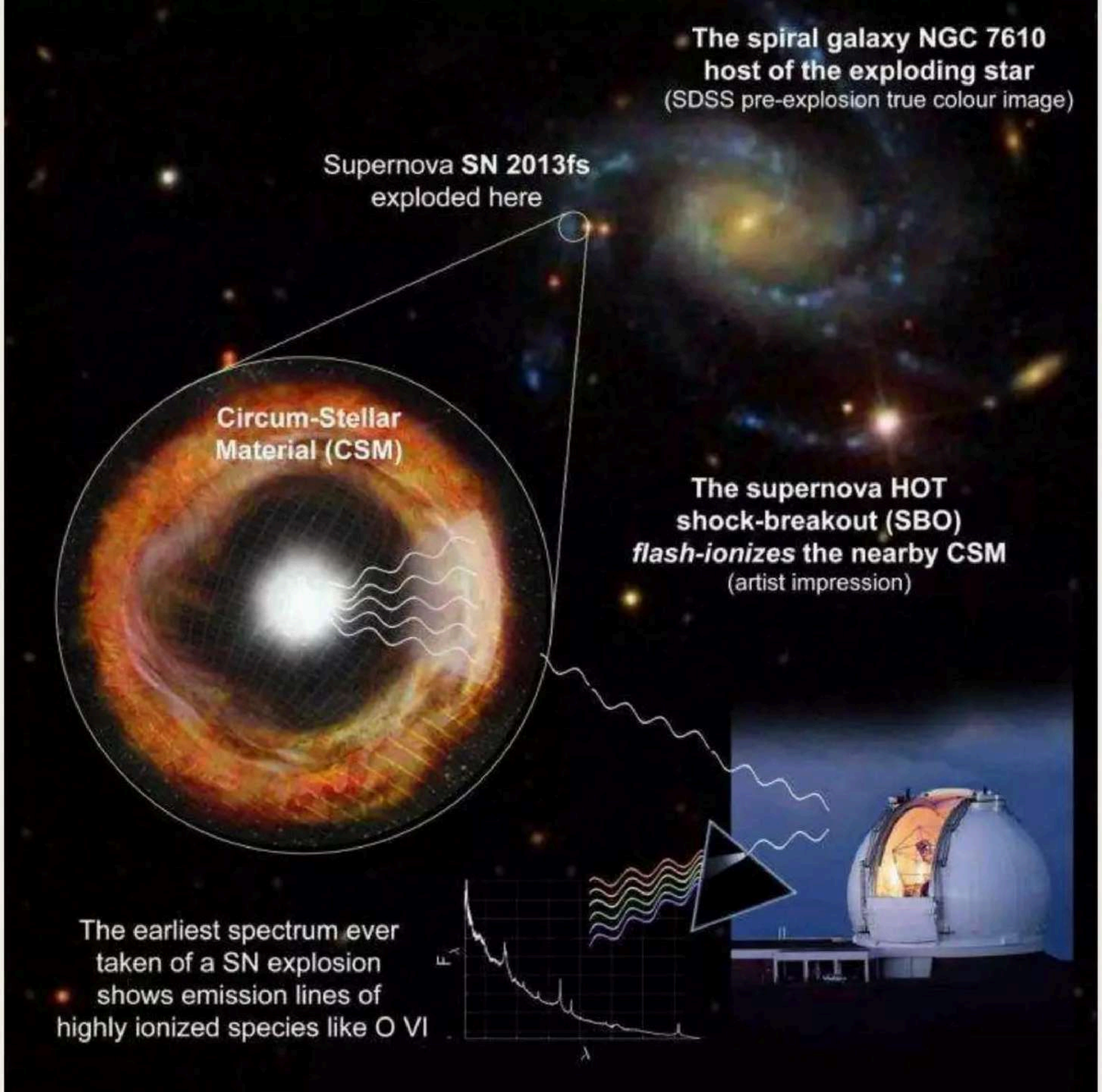

Red giant star
The Sun

Supernova

→ is the explosion of a star

→ the largest explosion that takes place in space.




The spiral galaxy NGC 7610
host of the exploding star
(SDSS pre-explosion true colour image)
Supernova SN 2013fs
exploded here
Circum-Stellar
Material (CSM)
The supernova HOT
shock-breakout (SBO)
flash-ionizes the nearby CSM
(artist impression)
The earliest spectrum ever
taken of a SN explosion
shows emission lines of
highly ionized species like O VI

R-process / Rapid neutron capture process

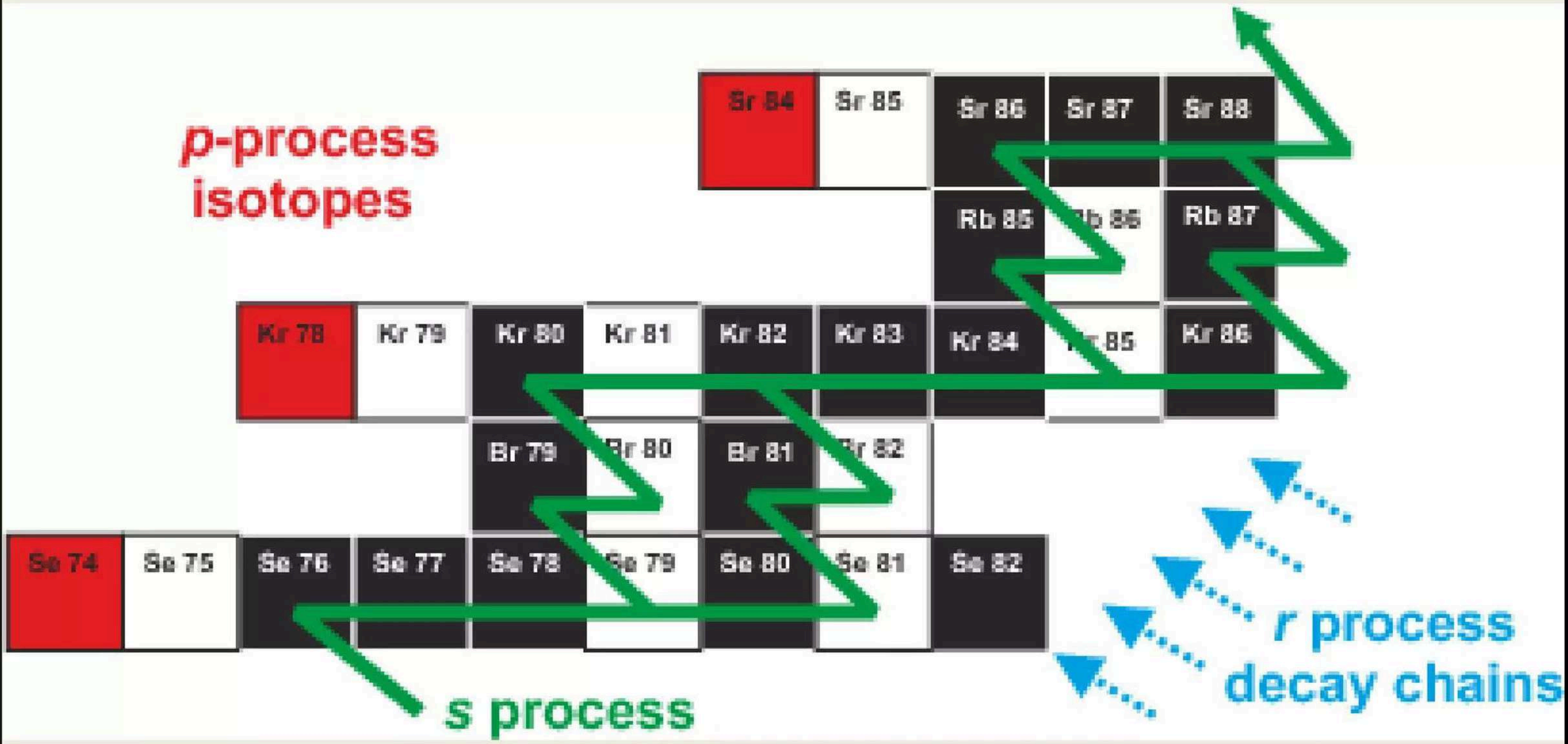
→ involves rapid capture of neutrons by the atom.

→ is a set of reactions in nuclear astrophysics that are responsible for the creation (nucleosynthesis) of approximately half the atomic nuclei heavier than iron.

S-process / Slow neutron capture process

→ involving slow neutron capture in red giants.

→ is a series of reactions in nuclear astrophysics which occur in stars, particularly AGB stars. It is responsible for the creation (nucleosynthesis) of approximately half the atomic nuclei heavier than iron.

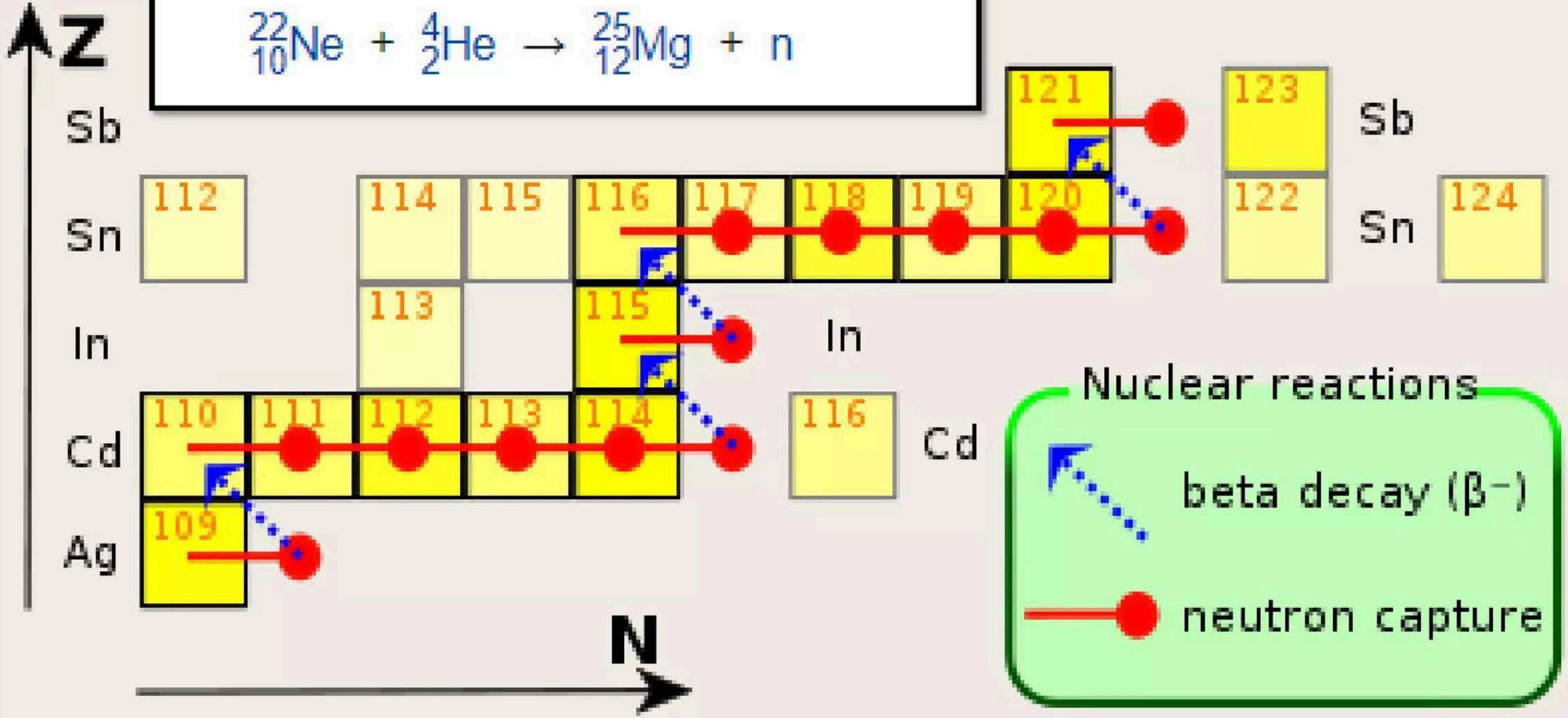


p-process isotopes
Sr 84
Sr 85
Sr 86
Sr 87
Sr 88
Rb 85
Rb 86
Rb 87
Kr 78
Kr 79
Kr 80
Kr 81
Kr 82
Kr 83
Kr 84
Kr 85
Kr 86
Br 79
Br 80
Br 81
Br 82
Se 74
Se 75
Se 76
Se 77
Se 78
Se 79
Se 80
Se 81
Se 82
s process
r process decay chains

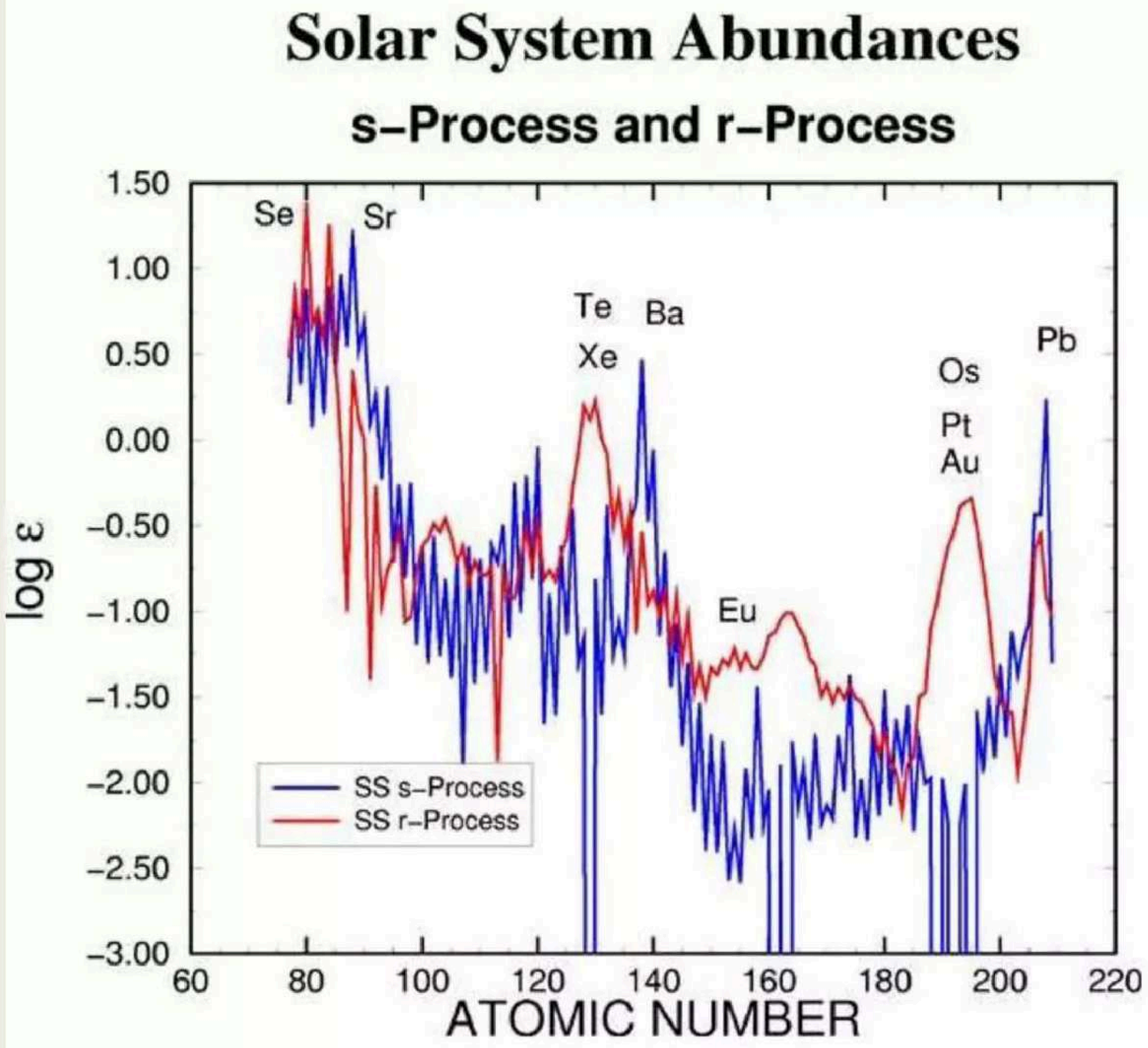
The main neutron source reactions are:

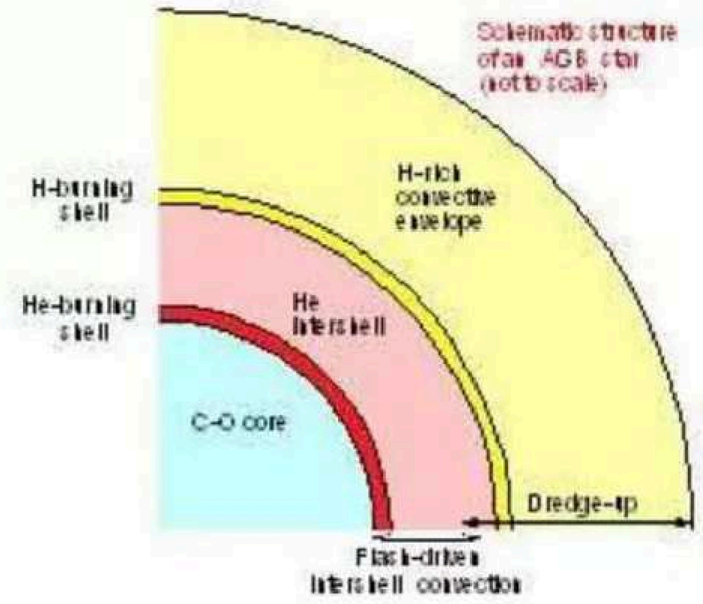
$$^{13}_{6}C + ^{4}_{2}He \rightarrow ^{16}_{8}O + n$$

$$^{22}_{10}Ne + ^{4}_{2}He \rightarrow ^{25}_{12}Mg + n$$



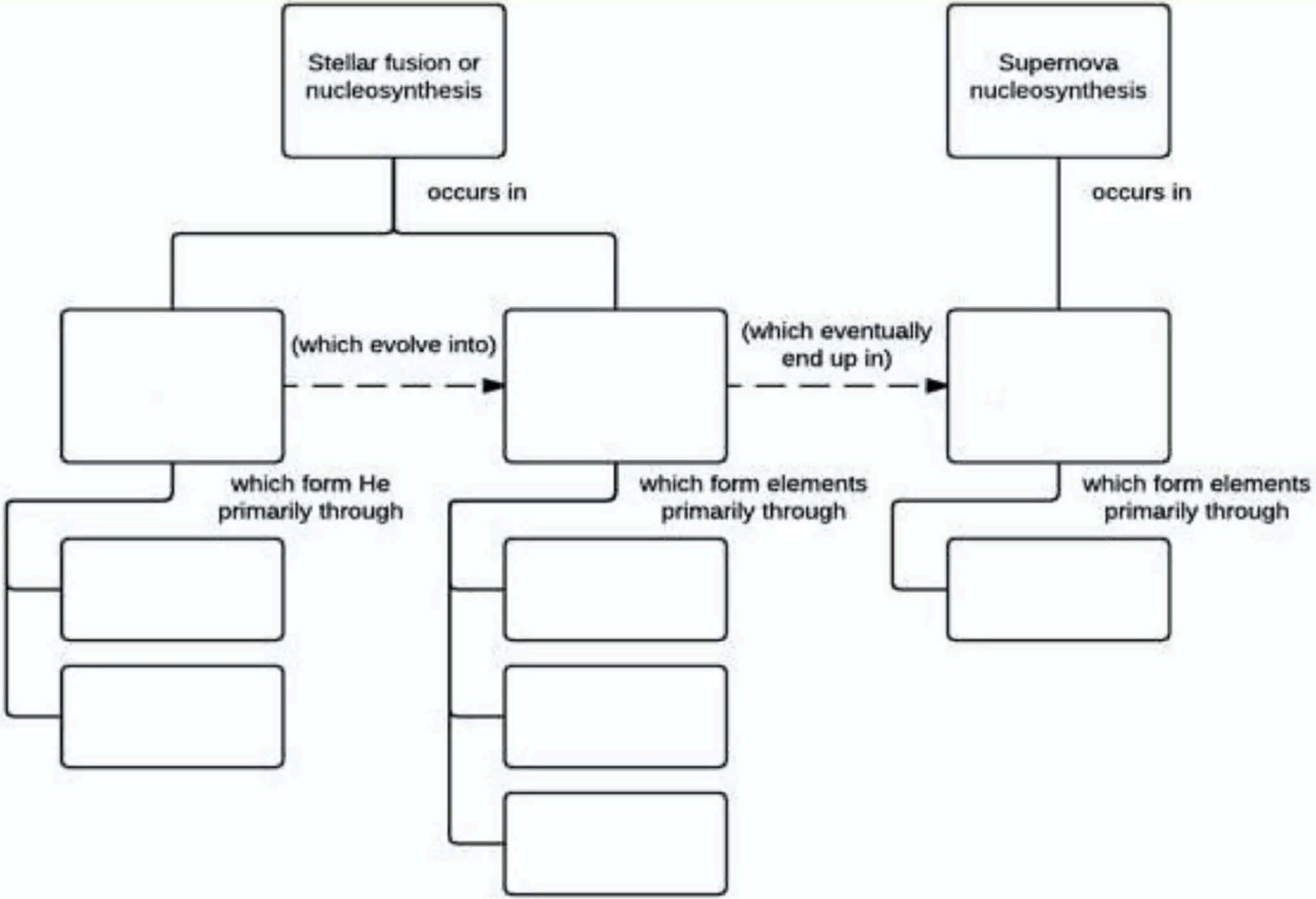
r-Process and s-Process Synthesis





s-process in red giants

r-process in supernovae


Stellar fusion or nucleosynthesis
occurs in
(which evolve into)
(which eventually end up in)
which form He primarily through
which form elements primarily through
Supernova nucleosynthesis
occurs in
which form elements primarily through

THANK YOU

FOR YOUR ATTENTION