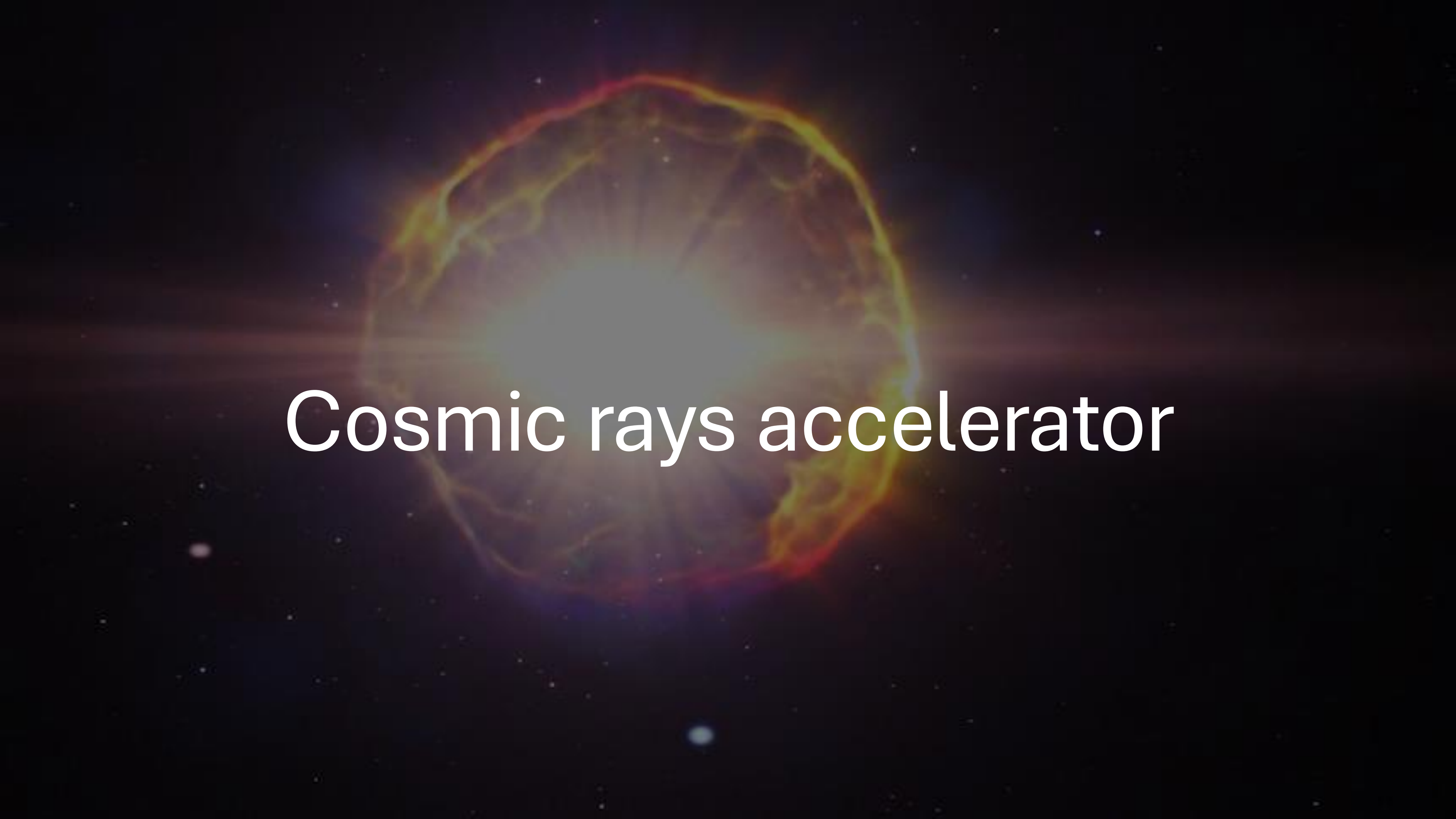
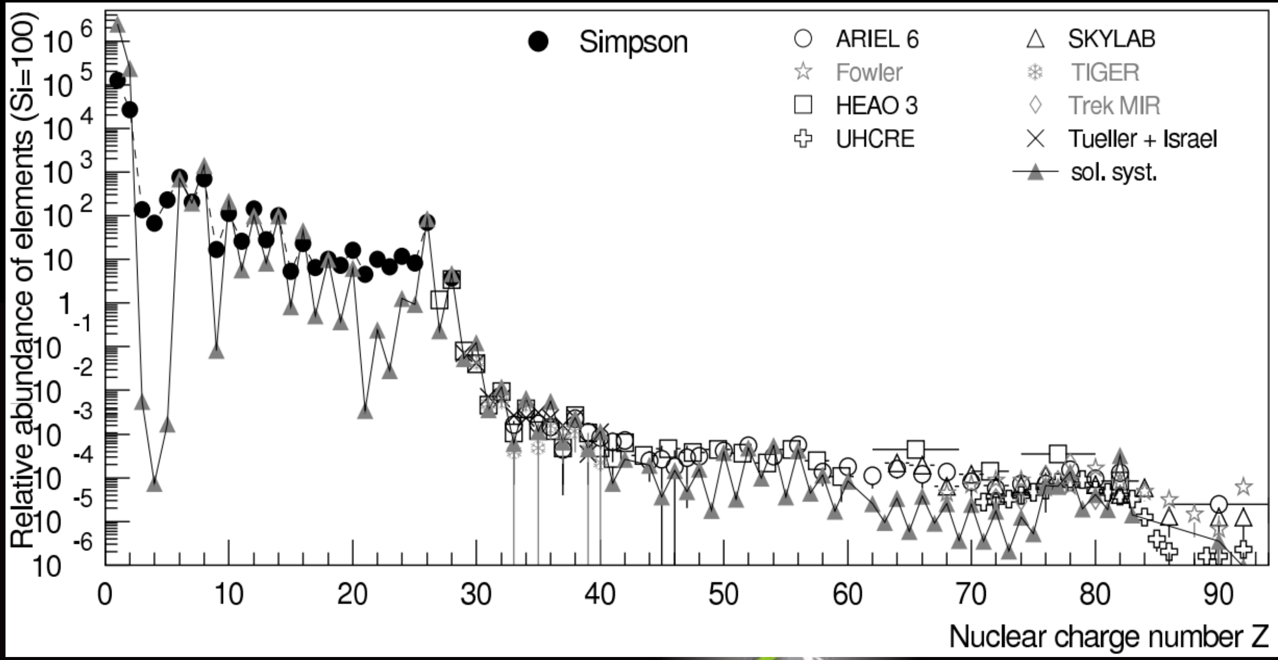
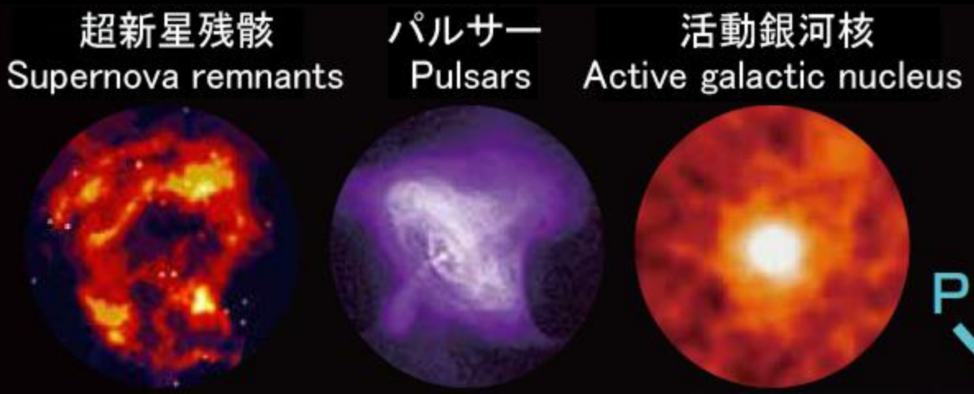
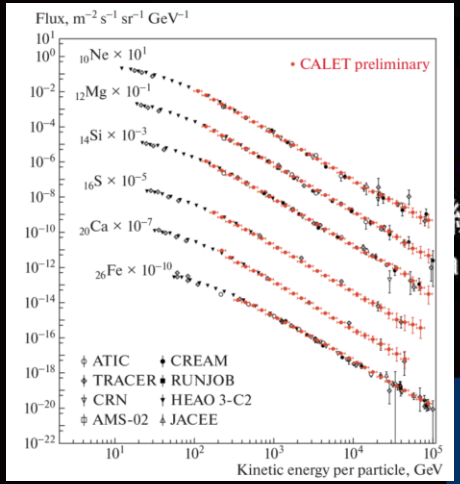
Cosmic rays accelerator

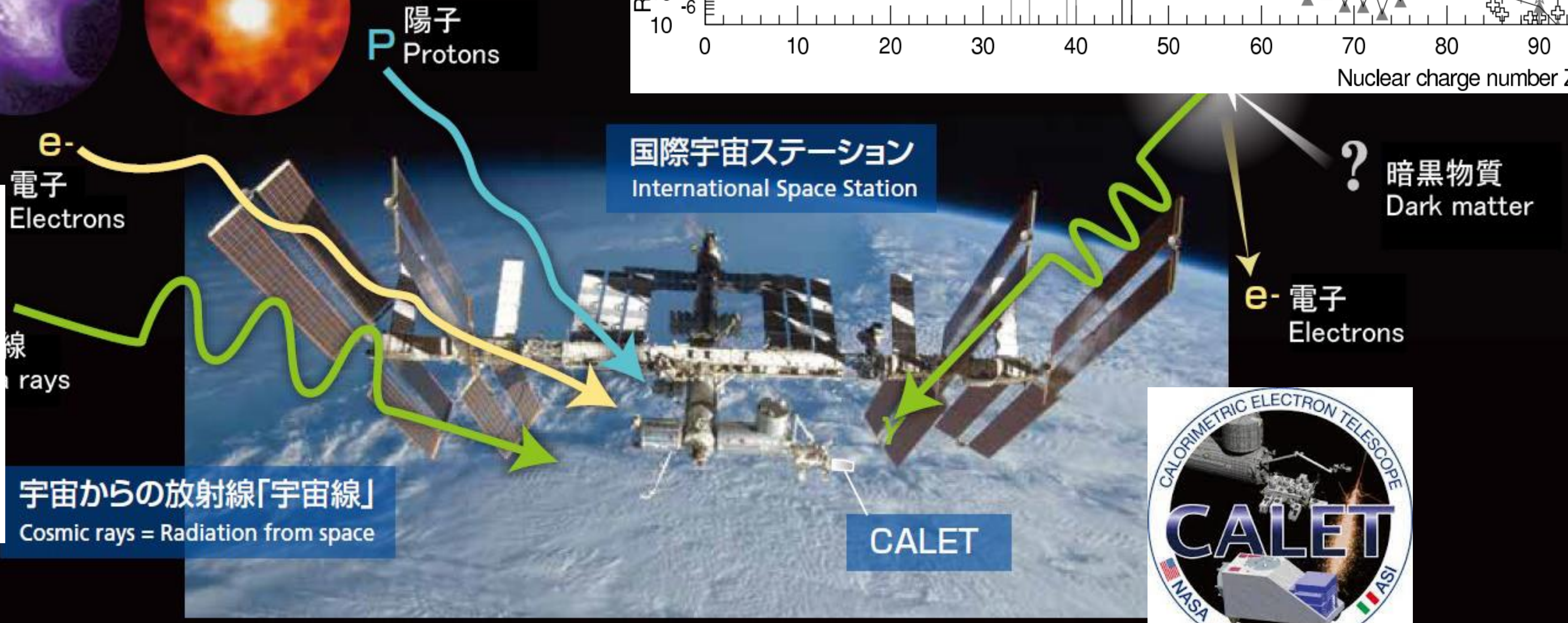


Cosmic rays observation









Stars

- Self-gravitating gaseous systems at hydrostatic equilibrium.
- An equilibrium in which the gravitational force is balanced by the radiative pressure.

Hydrostatic equilibrium

$$\rho \frac{\delta^2 r}{\delta t^2} = -\frac{\delta P}{\delta r} - \frac{G M \rho}{r^2}$$

- Thanks to the hydrostatic equilibrium equation and perfect gas law, some quantities of a star can be determined.
  - $\frac{P_C - P_{Ext}}{R} = \frac{G M \rho}{R^2} \Rightarrow \begin{cases} P_C \simeq 2 \cdot 10^{14} \text{N m}^{-2} \\ T_C \simeq 10^7 \text{K} \end{cases}$
  - $\tau_{ff} = \sqrt{\frac{R^3}{GM}} \simeq 1/2h$

Virial theorem

- How the gravitational force is balanced with the radiative pressure during stellar evolution

$$\cancel{\rho\frac{\delta^2 r}{\delta t^2}} = -\frac{\delta P}{\delta r} - \frac{GM\rho}{r^2} \qquad -2U = -\int_0^R 3\underbrace{nk_BT}_{P}4\pi r^2 dr = \int_0^R \left(-\frac{GM_r}{r}\right)4\pi r^2\rho dr = \Omega$$

- Virial theorem:

$$\begin{cases} 2U + \Omega = 0 \\ E = \Omega + U \end{cases} \Rightarrow \begin{cases} U = -\frac{1}{2}|\Omega| \\ E = -\frac{1}{2}|\Omega| \end{cases}$$

- For a gaseous system:

$$\begin{cases} \gamma = \frac{c_p}{c_v} \\ E = \frac{3\gamma-4}{3(\gamma-1)}\Omega = -(3\gamma-4)U \end{cases}$$

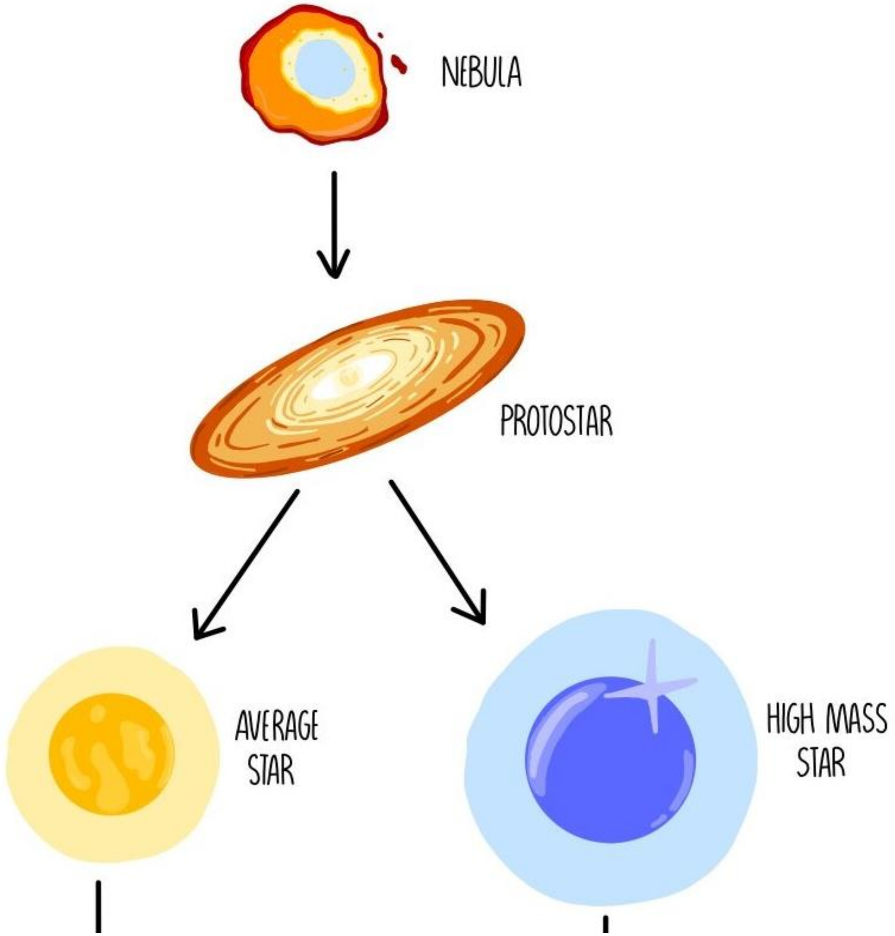
Star evolution without nuclear reactions

- From the virial theorem conclusions applied to a star.

$$\begin{cases} \gamma = \frac{5}{3} \\ E = \frac{1}{2}\Omega = -U \end{cases} \qquad L > 0 \Rightarrow E \searrow \rightarrow \dot{\Omega} \searrow \rightarrow \dot{U} \nearrow$$

- Lifetime of a star described by Kelvin (1862) and Helmotz (1854):

$$\tau_{KH} \sim \frac{\frac{1}{2}|\Omega|}{L} \sim 10^7\,\mathrm{yr}$$



Nuclear fusion process

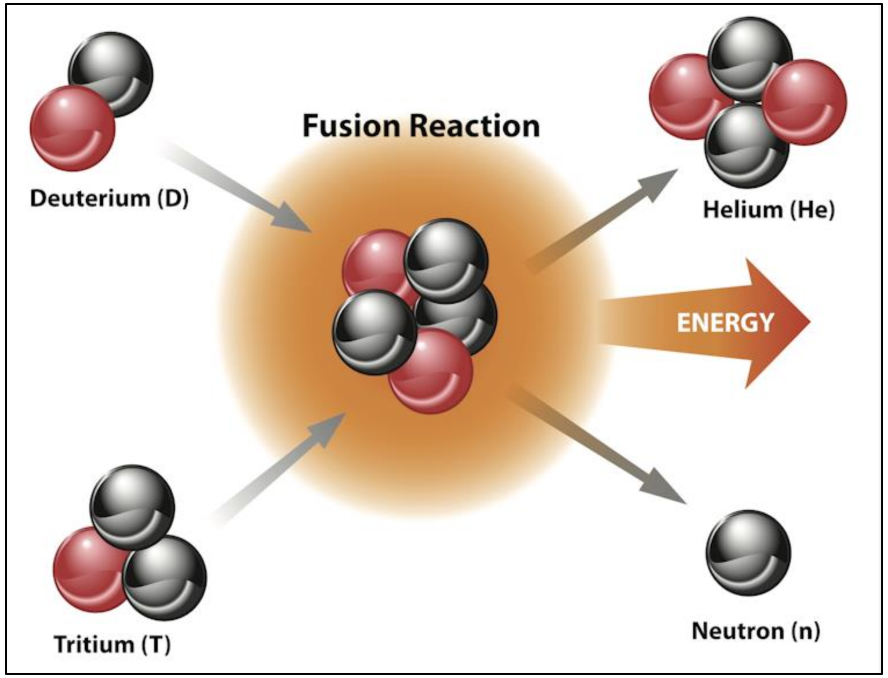
- After the discovery of the nuclear reactions, Eddinghton (1920) suggests that, to justify the lifetime of a star, nuclear reactions (NR) have to happen inside the inner core of the star.

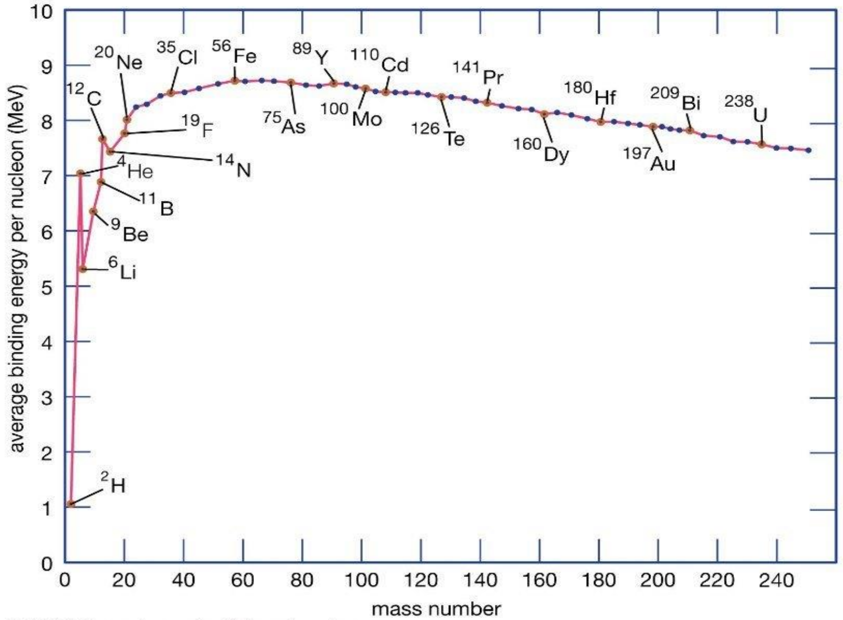
- Energy is released during NR:

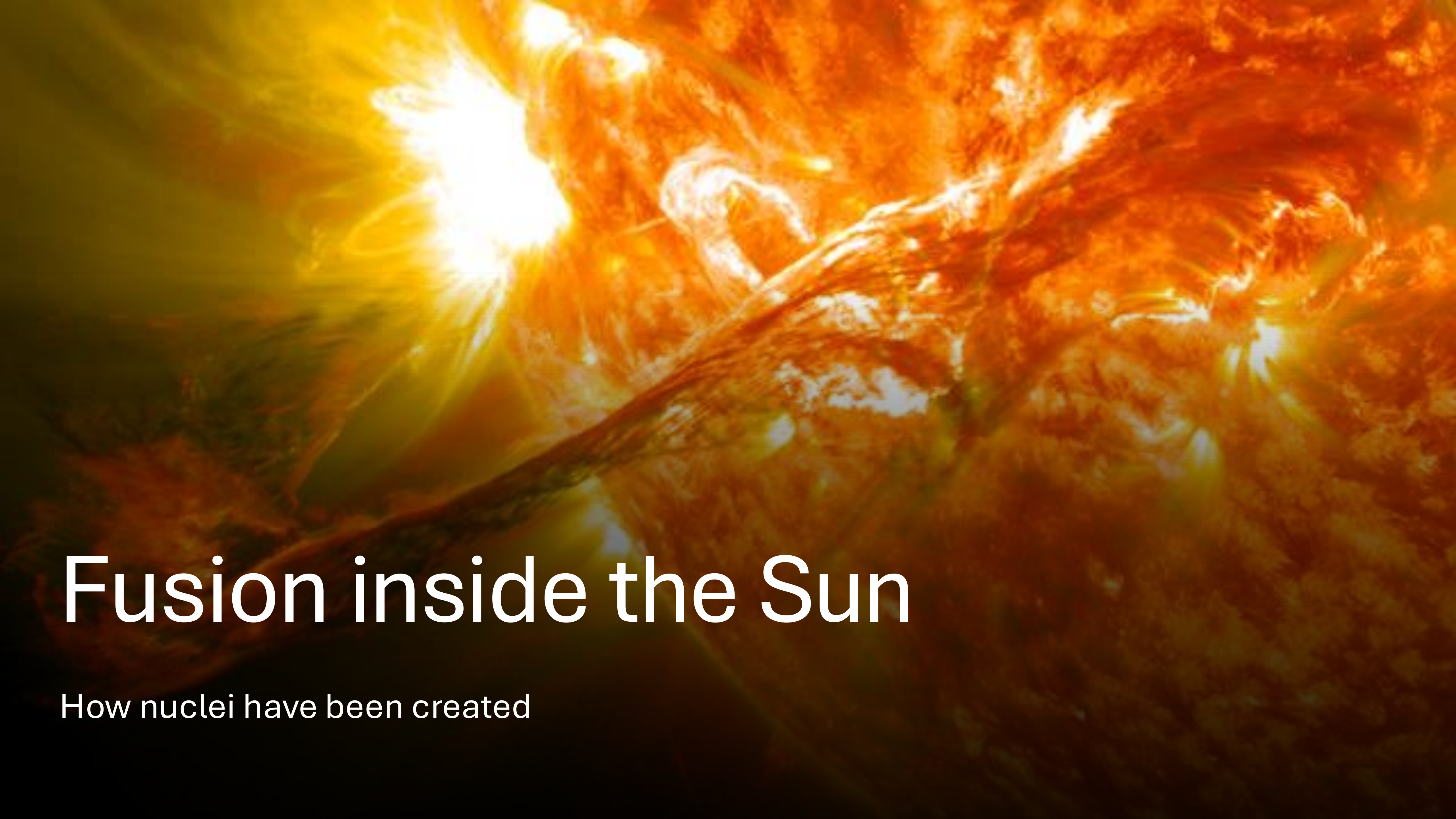
$$A + B \rightarrow C + E[\mathrm{MeV}]$$

$$E_B = [Zm_p + (A - Z)m_n - m_{nuc}]c^2$$

- Lifetime with NR: $\tau_{nuc} \sim \dfrac{0.007Mc^2}{L} \sim 10^{11}\ \mathrm{yr}$



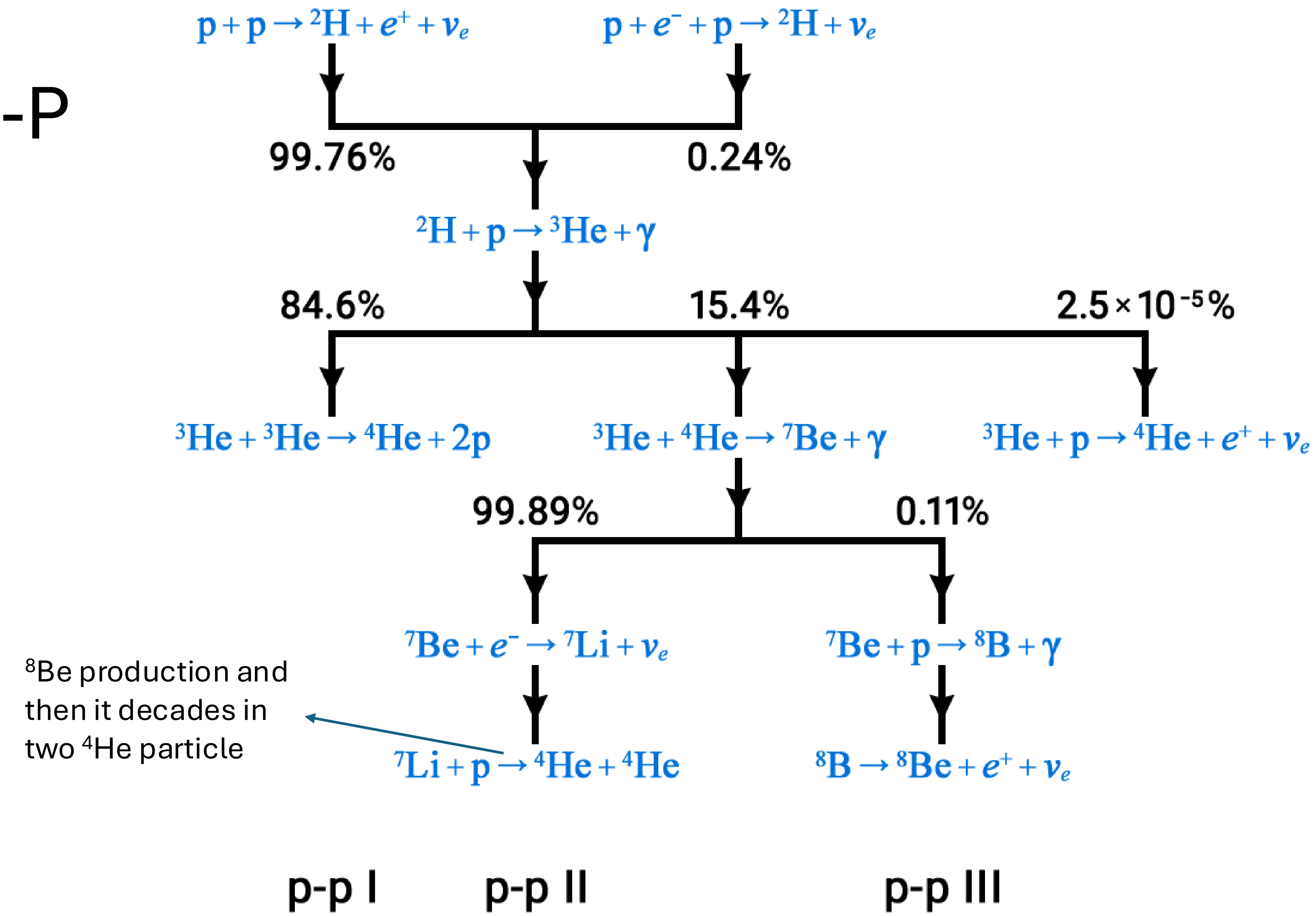




Fusion inside the Sun

How nuclei have been created

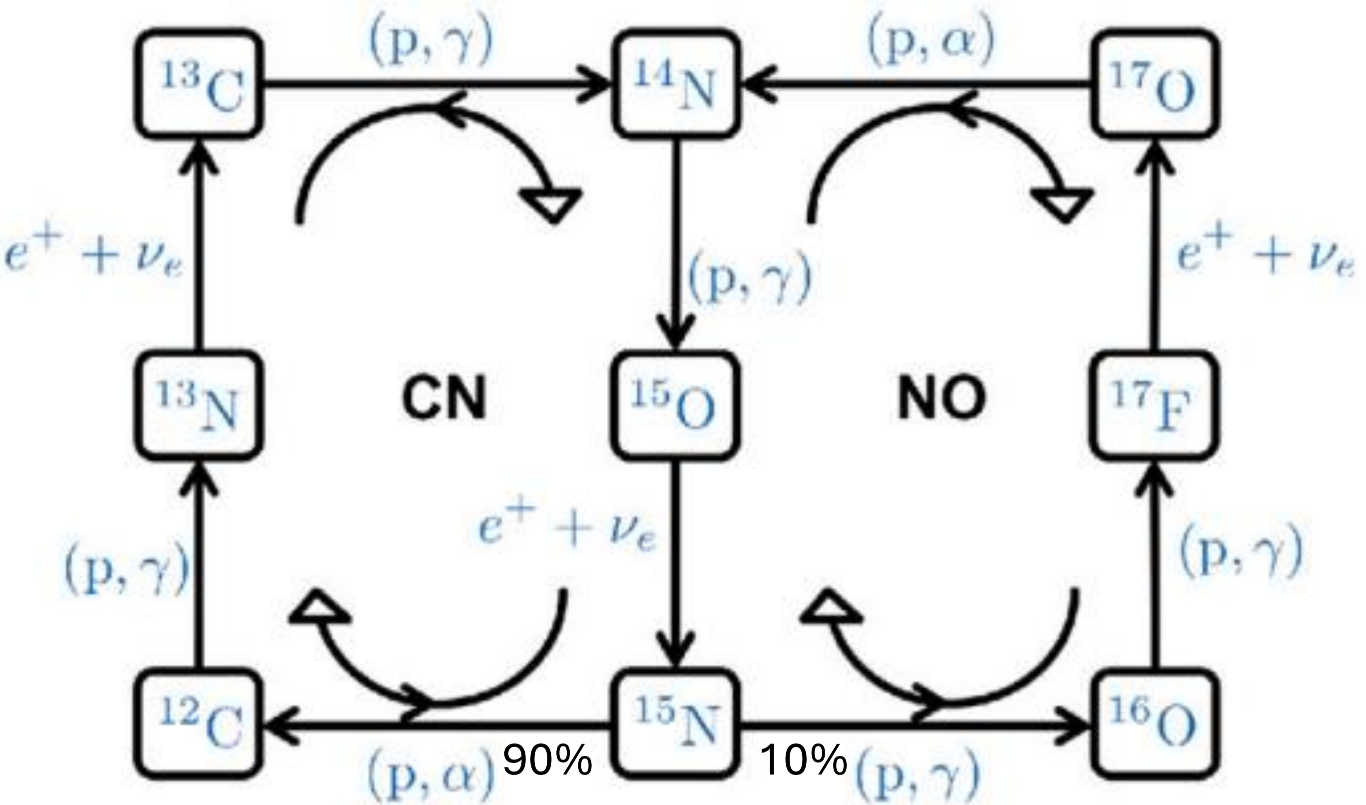
Ciclo P-P

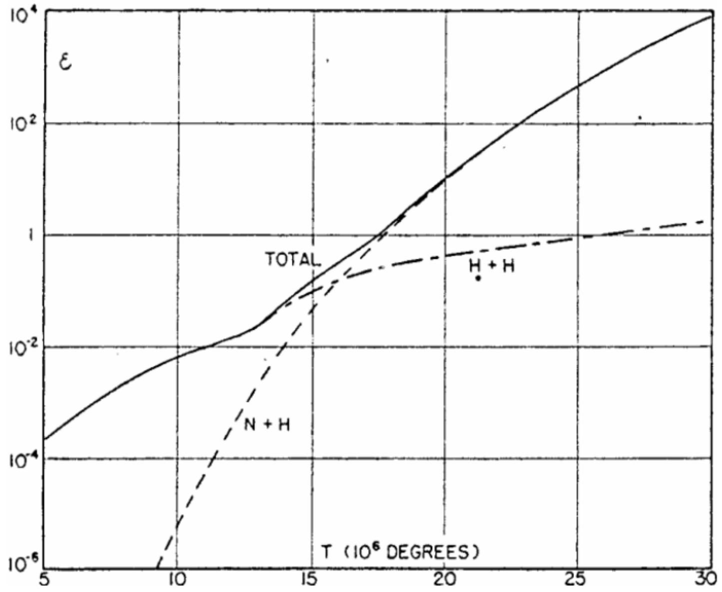


$p + p \rightarrow {}^{2}H + e^{+} + \nu_e$
$p + e^{-} + p \rightarrow {}^{2}H + \nu_e$
99.76%
0.24%
${}^{2}H + p \rightarrow {}^{3}He + \gamma$
84.6%
15.4%
2.5×10^{-5}%
${}^{3}He + {}^{3}He \rightarrow {}^{4}He + 2p$
${}^{3}He + {}^{4}He \rightarrow {}^{7}Be + \gamma$
${}^{3}He + p \rightarrow {}^{4}He + e^{+} + \nu_e$
99.89%
0.11%
${}^{7}Be + e^{-} \rightarrow {}^{7}Li + \nu_e$
${}^{7}Be + p \rightarrow {}^{8}B + \gamma$
^{8}Be production and then it decades in two ^{4}He particle
${}^{7}Li + p \rightarrow {}^{4}He + {}^{4}He$
${}^{8}B \rightarrow {}^{8}Be + e^{+} + \nu_e$
p-p I
p-p II
p-p III

CN-NO cycle

- Carbon and Oxygen nuclei are used as catalyst.
- It is impossible to create nuclei with A less than 20 with odd number of nucleons.
- Cycles ignite efficiency depend differently on the temperature.





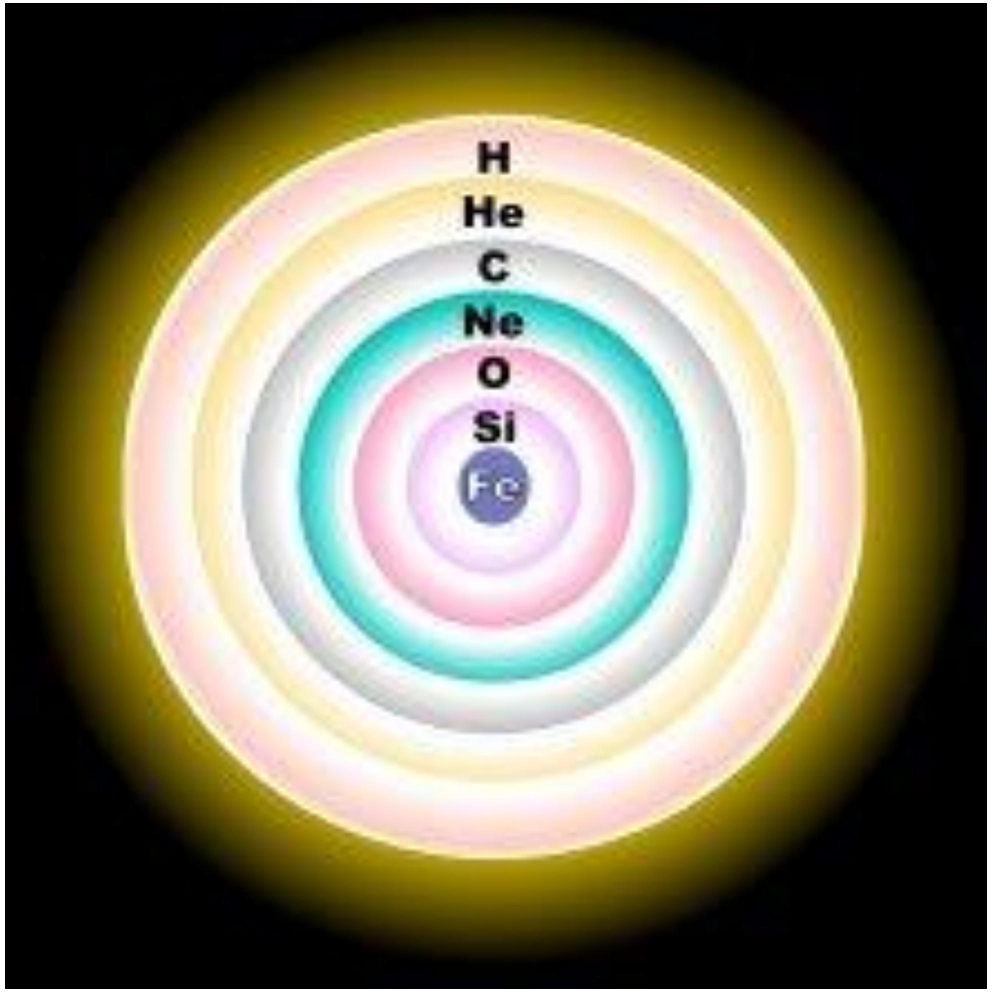
Helium burning

- After the end of the hydrogen burning a star evolves following again the virial theorem until the helium burning is ignited.
- Nuclei with mass A=5 or A=8 are instable.
- The only process to burn the helium creating ^{12}C is the 3-α.
- The 3-α is a resonance process that "starts" at a temperature of 10^8k.

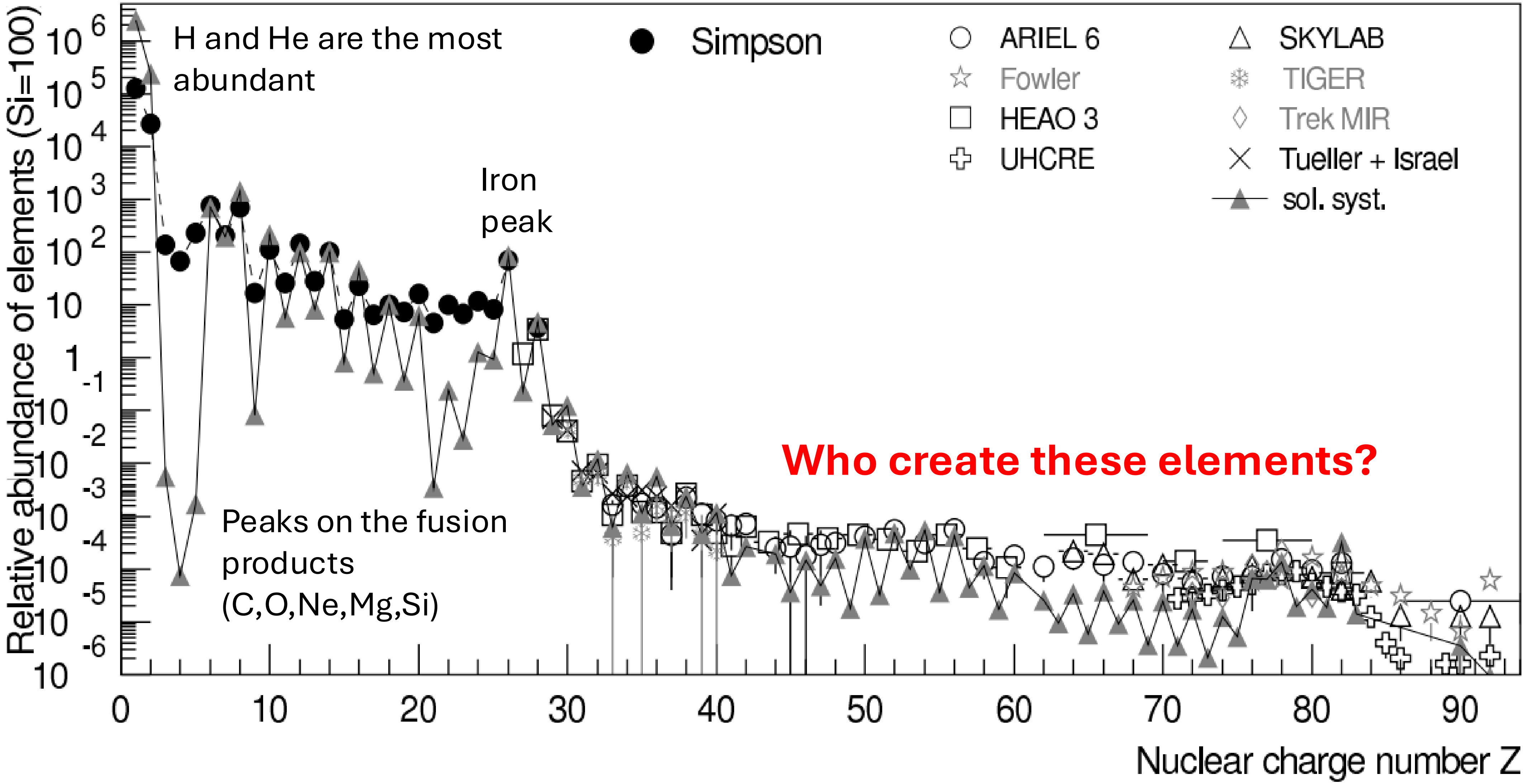
$$^4He +^4 He +^4 He \rightarrow^8 Be +^4 He \rightarrow^{12} C + \gamma$$

Heavier nuclei fusion

- The heavier nuclei fusion involves a lot of different process. A single nucleus can interact with p, α, n, photon or decay.
- The burning chain since the core of a star is full of iron
    - Carbon burning (T>0.8-1x10^9k)
    - Neon burning (T>1.5x10^9k)
    - Oxygen burning (T>2x10^9k)
    - Silicon burning (T>2.5-3x10^9k)
- More hotter is the star less time is recquired to end the burning phase.



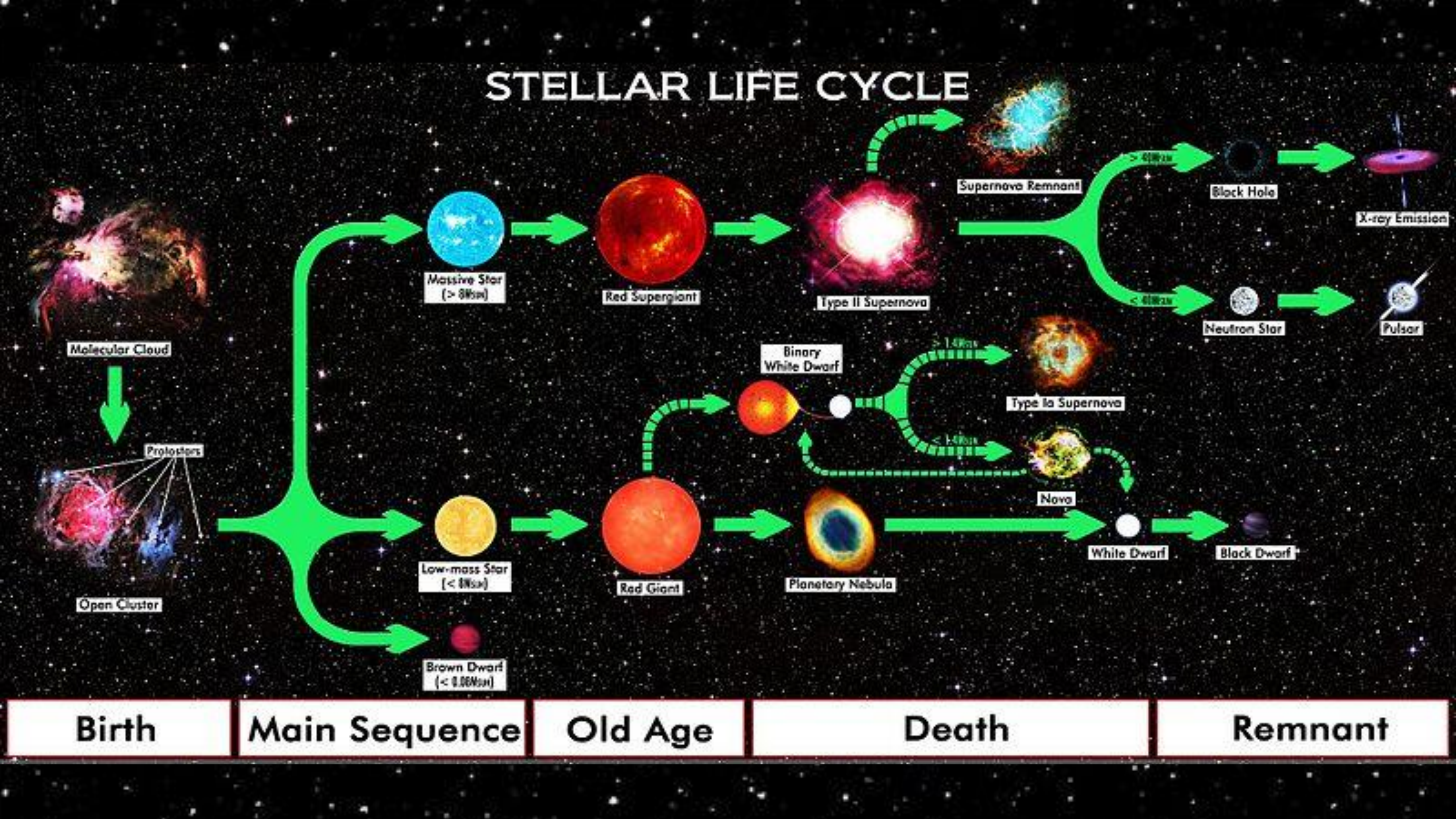
Abundaces



Relative abundance of elements (Si=100)
H and He are the most abundant
Simpson
ARIEL 6
Fowler
HEAO 3
UHCRE
SKYLAB
TIGER
Trek MIR
Tueller + Israel
sol. syst.
Iron peak
Peaks on the fusion products (C,O,Ne,Mg,Si)
Who create these elements?
Nuclear charge number Z

End of a star

Cosmic ray emission

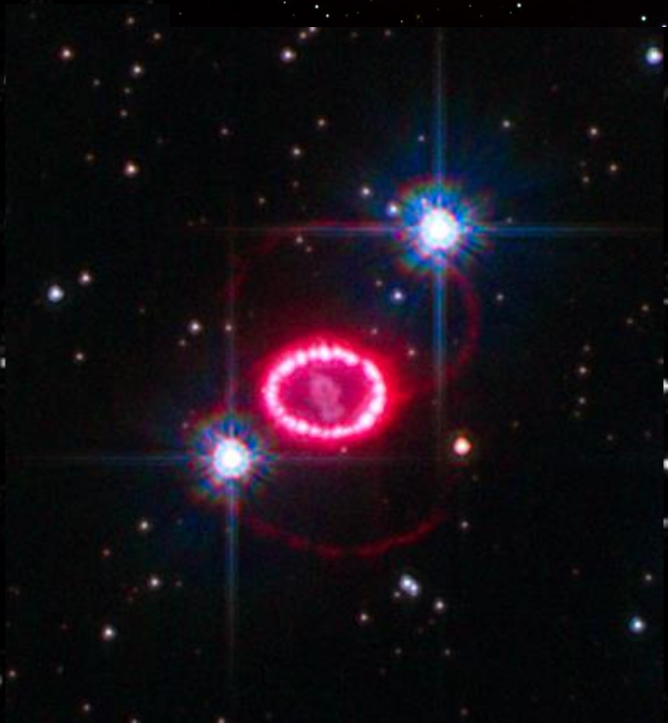

STELLAR LIFE CYCLE
Molecular Cloud
Protostars
Open Cluster
Massive Star
Low-mass Star
Brown Dwarf
Red Supergiant
Red Giant
Type II Supernova
Supernova Remnant
Black Hole
X-ray Emission
Neutron Star
Pulsar
Binary White Dwarf
Type Ia Supernova
Nova
Planetary Nebula
White Dwarf
Black Dwarf
Birth
Main Sequence
Old Age
Death
Remnant

Nuclei heavier than Iron, Supernova II

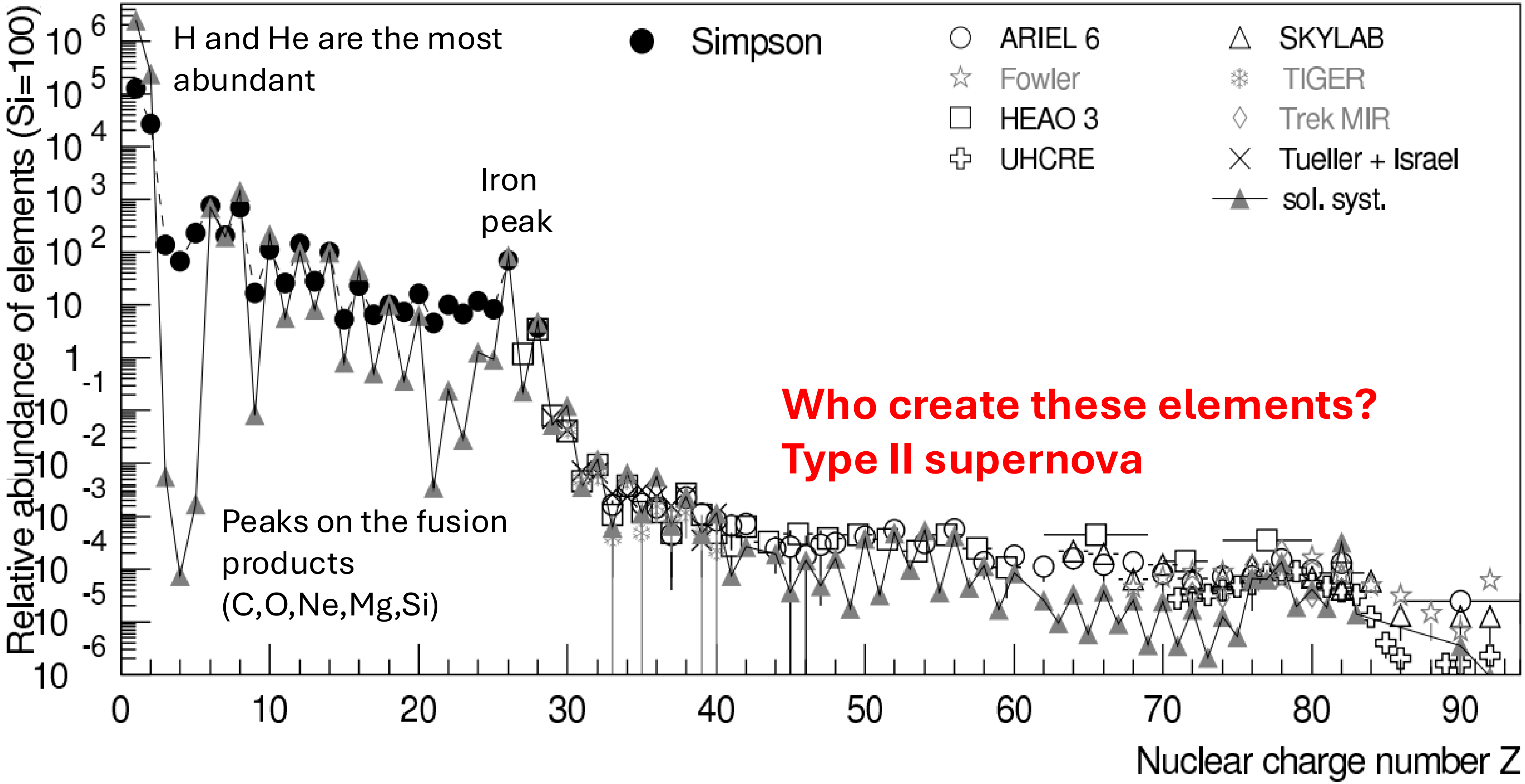
- Only under the extreme conditions reached during a supernova explosion an electron can combine with a proton

$$p + e^- \longrightarrow n + v$$

- The neutron interact with iron nuclei forming an A+1 nucleus
- After the B- decay a nucleus with mass A has become a nucleus with mass A+1 and charge Z+1



Abundaces

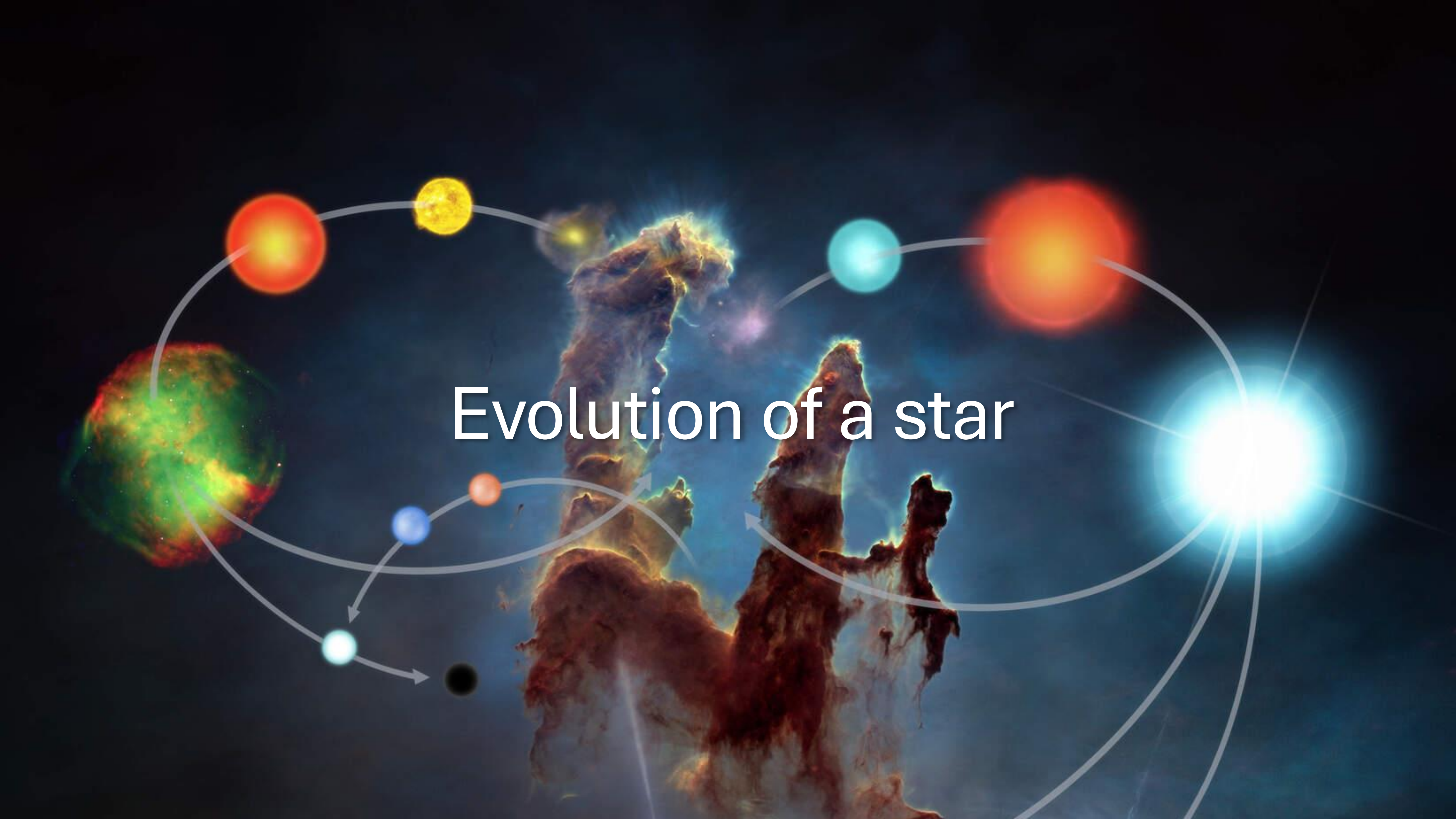


Relative abundance of elements (Si=100)
Nuclear charge number Z
H and He are the most abundant
Simpson
ARIEL 6
Fowler
HEAO 3
UHCRE
SKYLAB
TIGER
Trek MIR
Tueller + Israel
sol. syst.
Iron peak
Peaks on the fusion products (C,O,Ne,Mg,Si)
Who create these elements?
Type II supernova

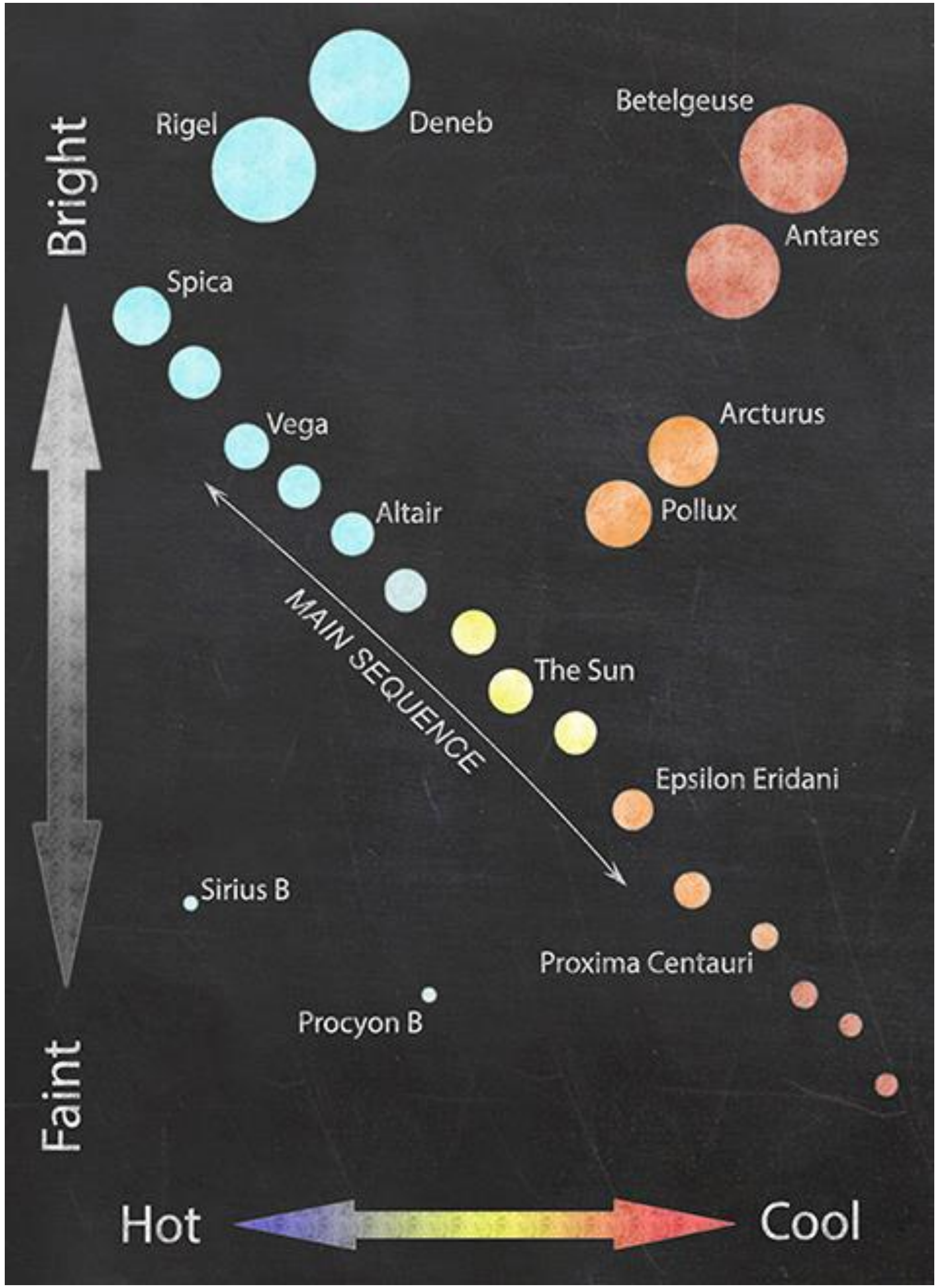
Spare slides

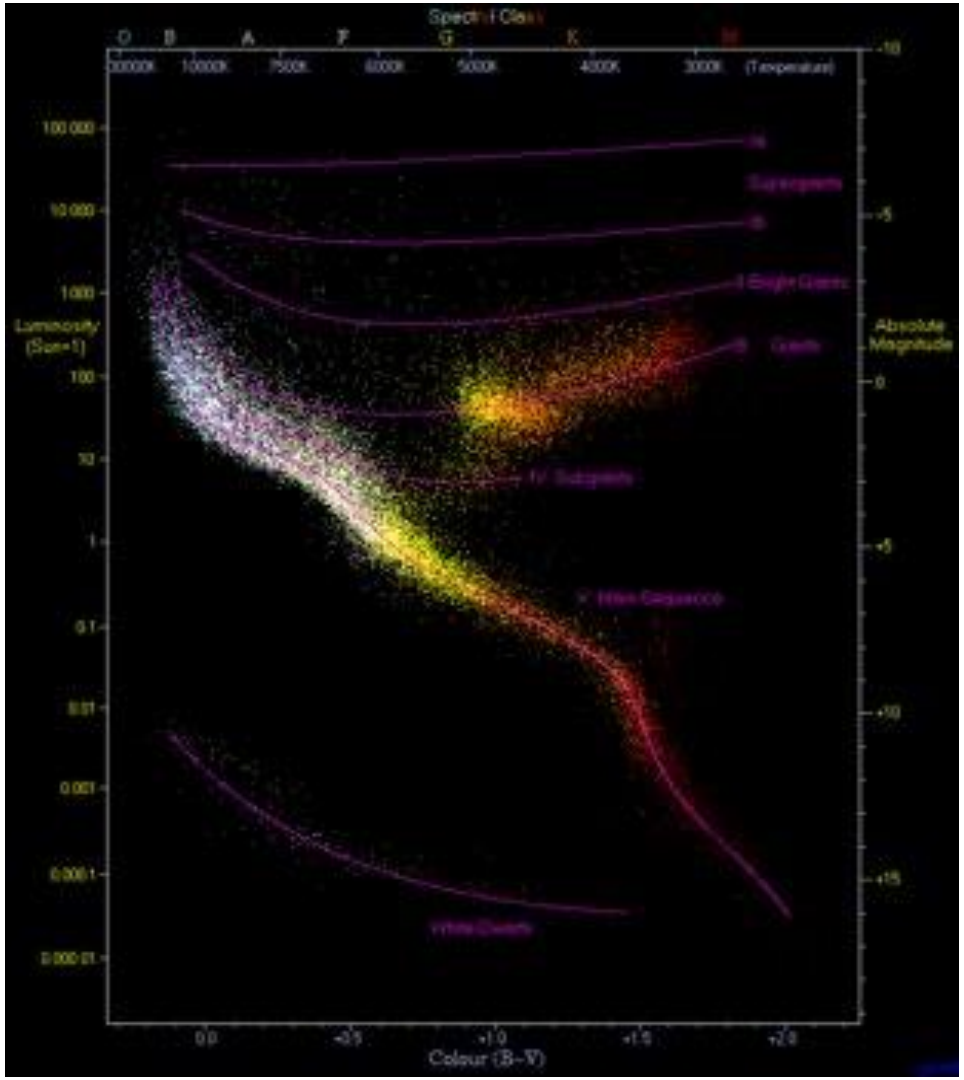
In realtà è più qualcosa che non entrava nella presentazione

Evolution of a star



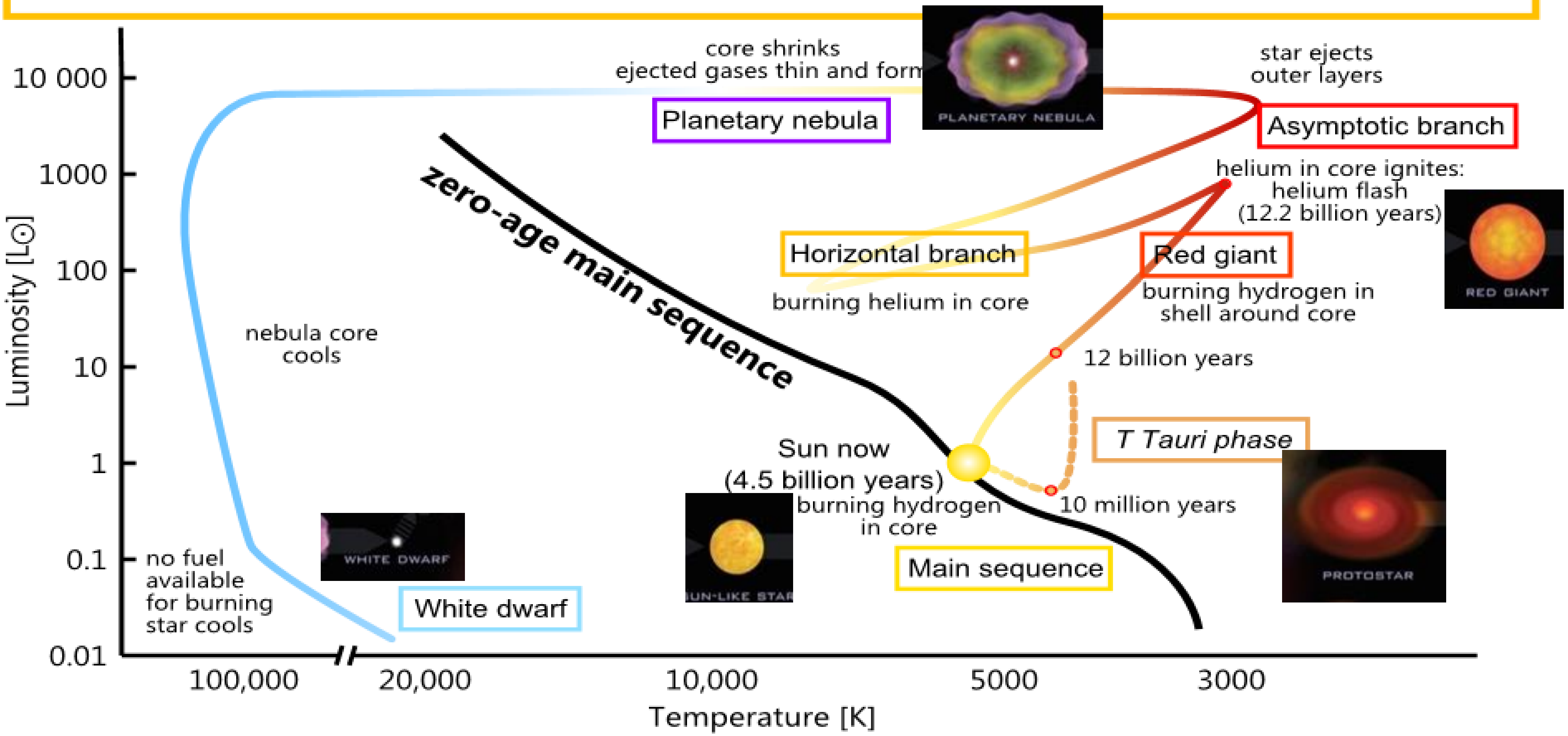
HR diagram


Bright
Faint
Rigel
Deneb
Betelgeuse
Antares
Spica
Vega
Altair
Arcturus
Pollux
MAIN SEQUENCE
The Sun
Epsilon Eridani
Sirius B
Proxima Centauri
Procyon B
Hot
Cool


O
B
A
F
G
K
M
Luminosity (Sun=1)
Absolute Magnitude
Main Sequence
White Dwarfs
Colour (B−V)
0.0
+0.5
+1.0
+1.5
+2.0

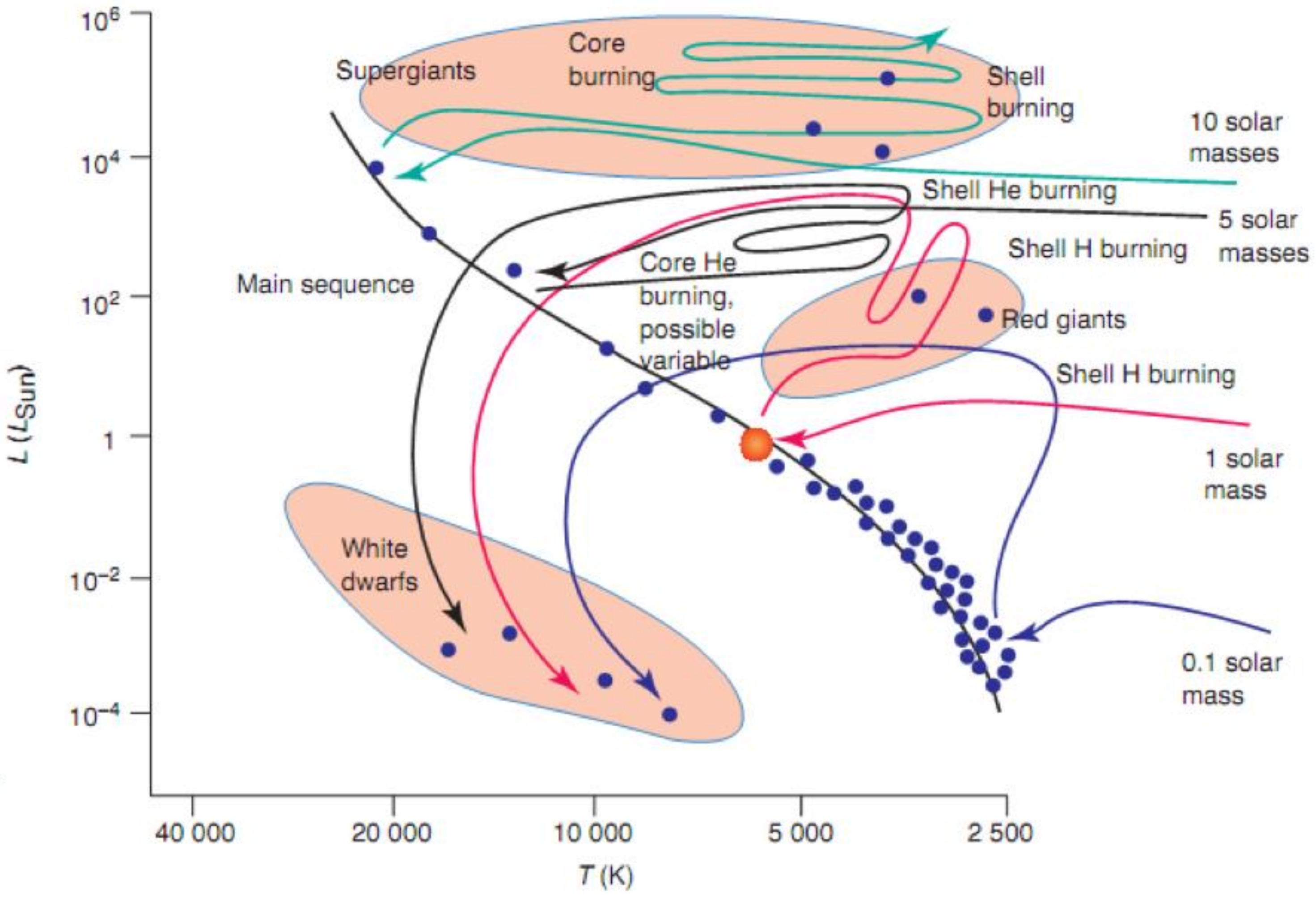
Evolution of a Sun-like star

	~9 Ga		~1 Ga		~100 Ma		~10 000 a		
Stage:	Main sequence	>	Red giant	>	Horizontal branch	>	Planetary nebula	>	White dwarf
Sun's age:	4.5 Ga (now)		12.2 Ga		12.3 Ga		12.3305 Ga		12.3306 Ga



Stars with mass less than 8 solar masses

- Different time spent in the main sequence.
- Higher mass allow the star to burn higher massive nuclei.
- Stellar wind emission doesn't justify the CR emission.



Supernova Ia, Tycho 1572