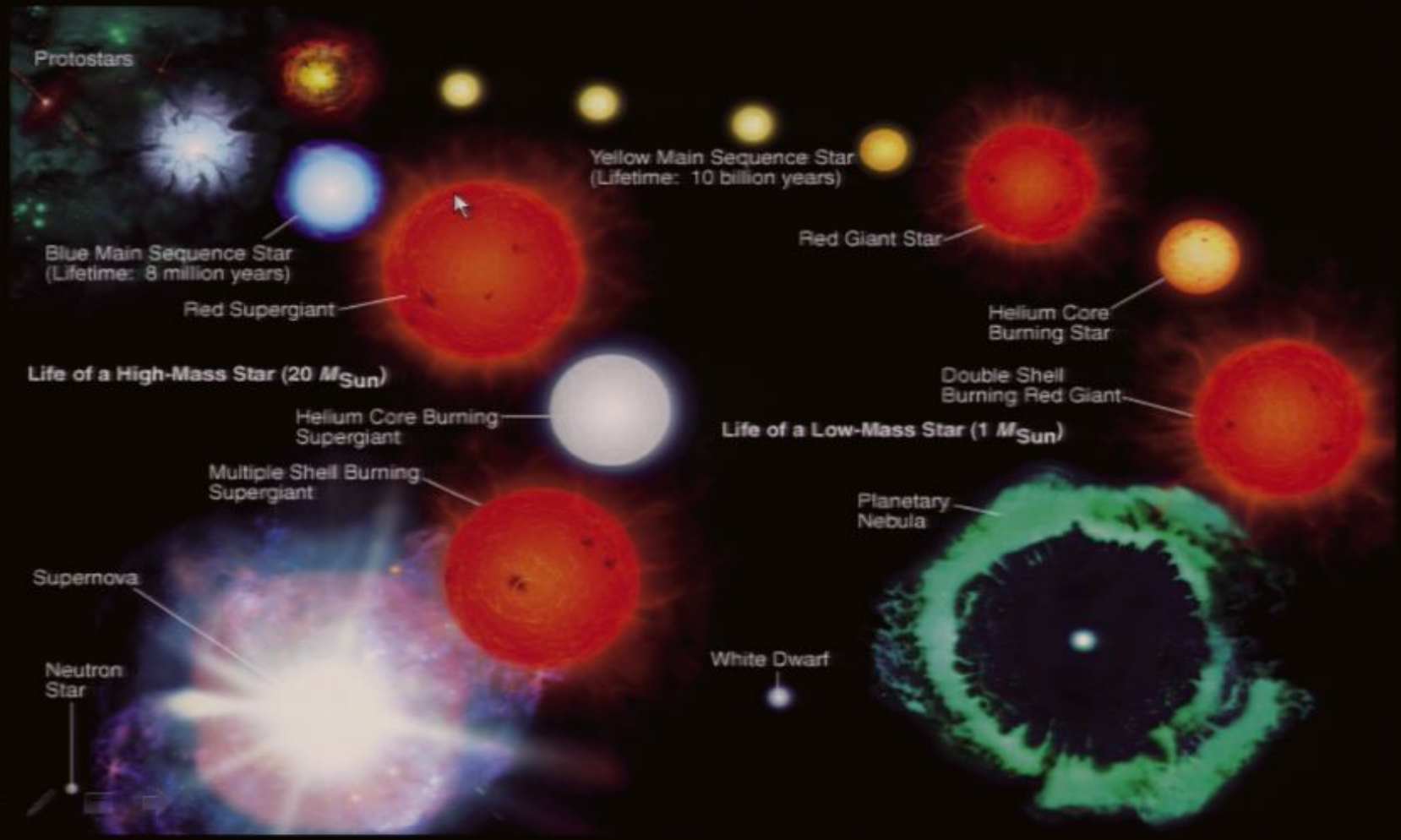
Title: General Relativity 4 - The Life Story of Stars

Date: Aug 01, 2006 10:45 AM

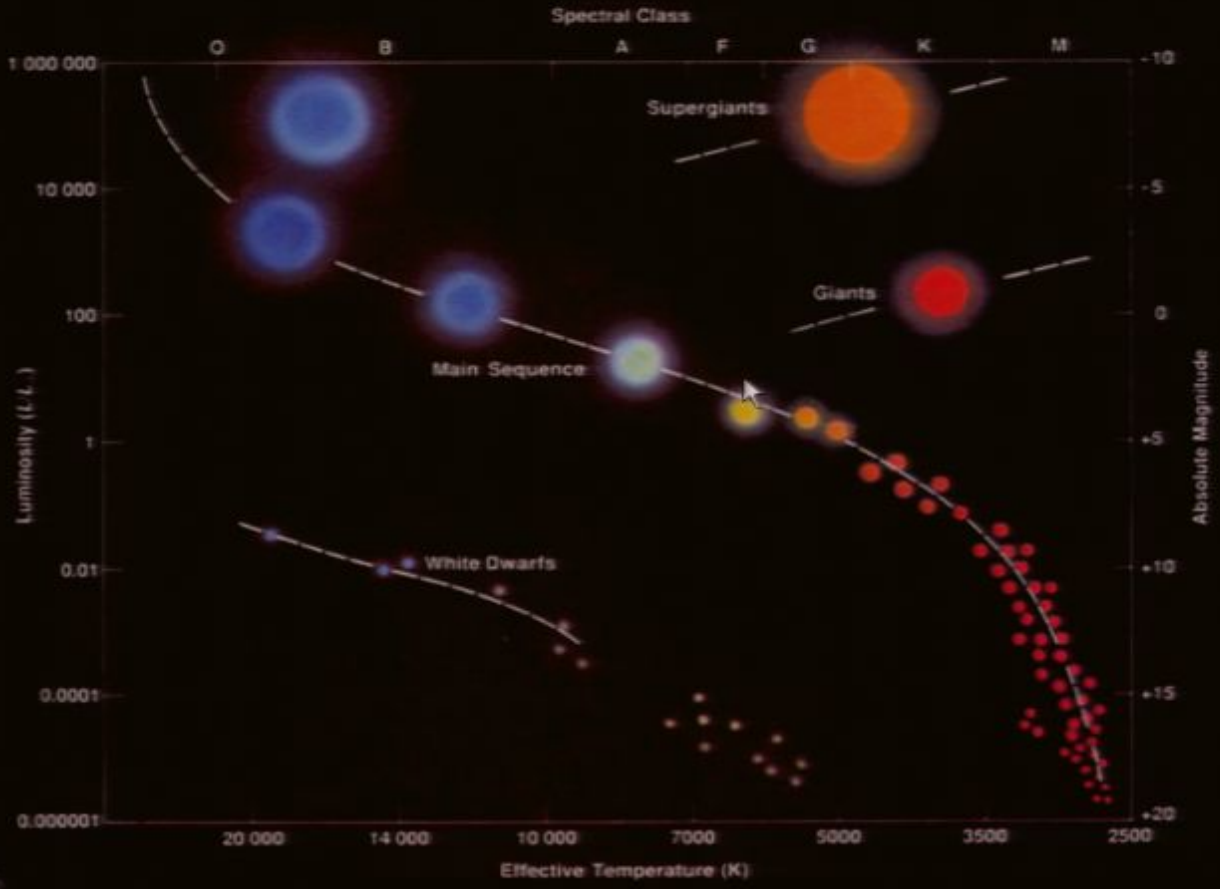
URL: http://pirsa.org/08080074

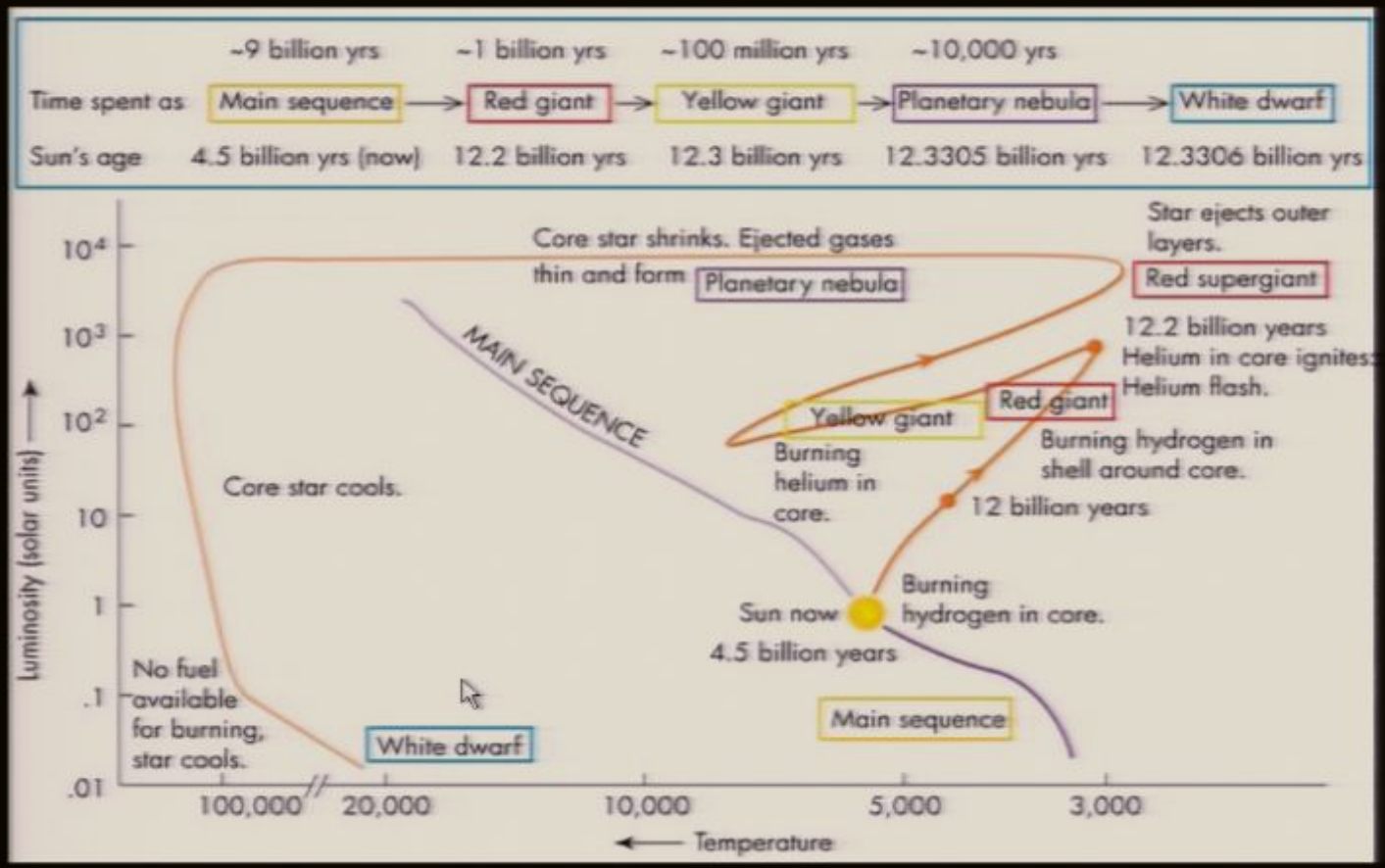
Abstract: The mathematical predictions made by scientists tell a story of the life and death of stars.
Learning Outcomes:
â€¢ How the Hertzsprung-Russel diagram describes the life cycle of stars.
â€¢ Depending on its mass, how a star ends its life as a white dwarf star, a neutron star, or a black hole, and where super novas fit in.
â€¢ How the mathematical predictions of white dwarf stars, super novas, and neutron stars are slowly verified by the advancement of the astronomical equipment used by astronomers.

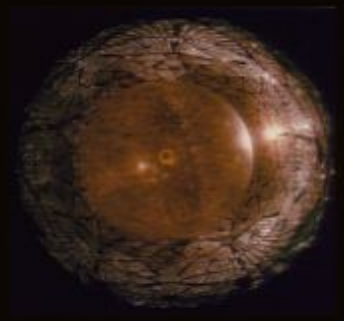
Life Cycle of Stars



Hertzsprung-Russel Diagram




~9 billion yrs
~1 billion yrs
~100 million yrs
~10,000 yrs
Time spent as
Main sequence
Red giant
Yellow giant
Planetary nebula
White dwarf
Sun's age
4.5 billion yrs (now)
12.2 billion yrs
12.3 billion yrs
12.3305 billion yrs
12.3306 billion yrs
Core star shrinks. Ejected gases thin and form
Planetary nebula
Star ejects outer layers.
Red supergiant
12.2 billion years
Helium in core ignites: Helium flash.
MAIN SEQUENCE
Yellow giant
Red giant
Burning helium in core.
Burning hydrogen in shell around core.
12 billion years
Core star cools.
Sun now
4.5 billion years
Burning hydrogen in core.
No fuel available for burning, star cools.
White dwarf
Main sequence
Luminosity (solar units)
10^4
10^3
10^2
10
1
.1
.01
100,000
20,000
10,000
5,000
3,000
Temperature



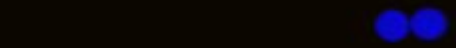
Stellar Energy

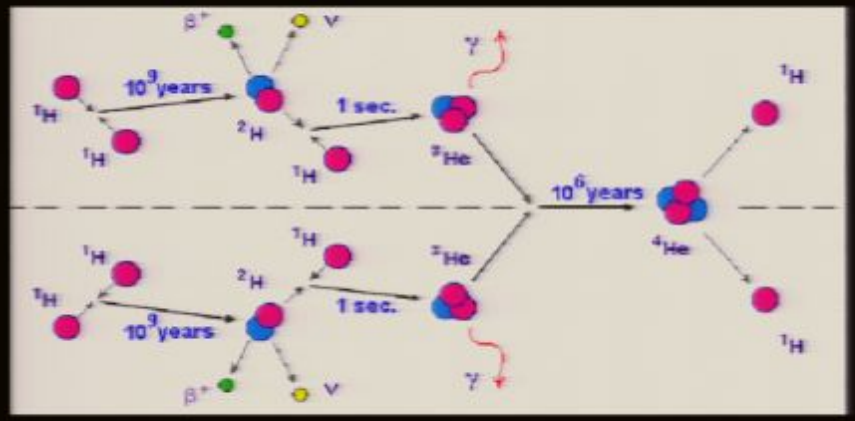
Proton-Proton Chain [4H→He + energy]

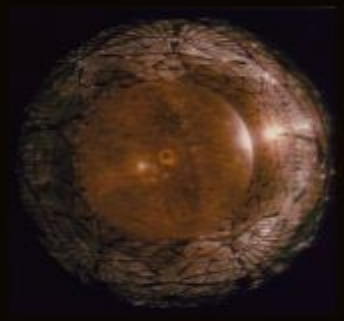
Two hydrogen nuclei merge to produce deuterium nucleus, a positron,and a neutrino. Add another hydrogen and you get helium 3 and a gamma photon (energy). Two Helium 3 merge and produce helium 4 and two Hydrogen nuclei.

Two 1H Atoms Combine

Neutron
Proton







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2He Is Formed

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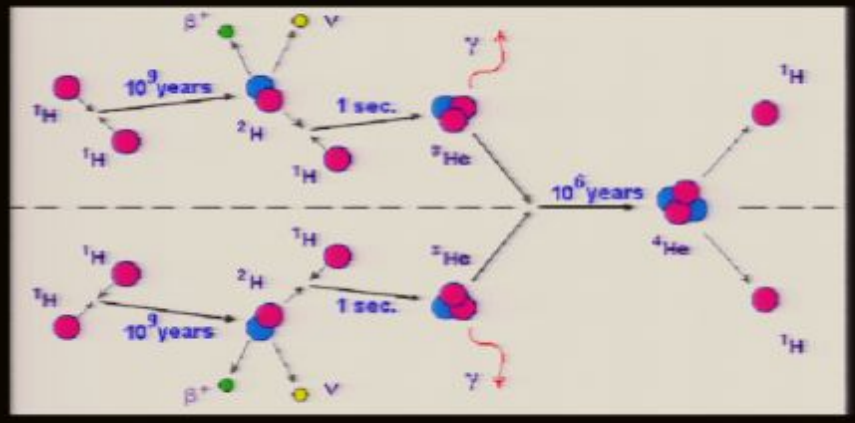
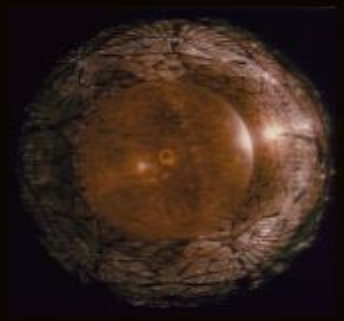
Proton





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Proton Decays Into A Neutron

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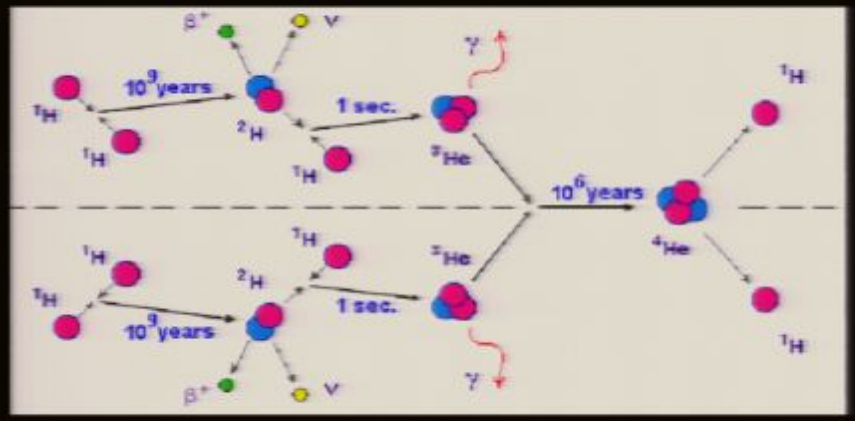

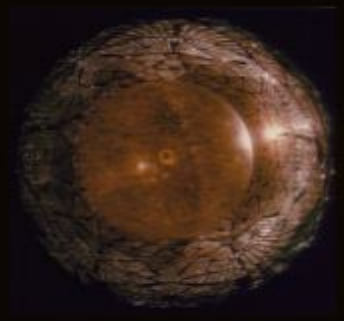

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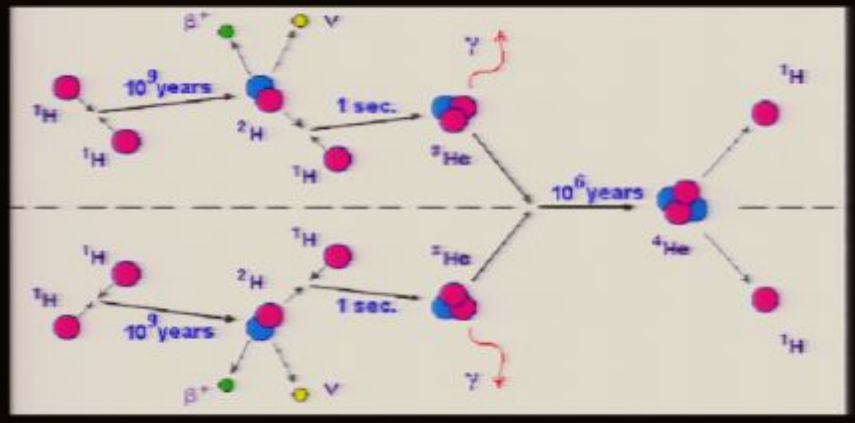
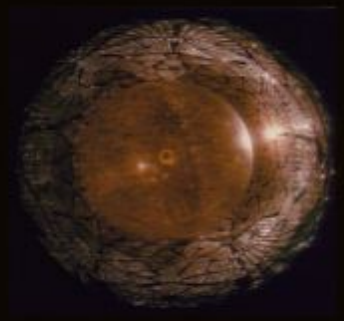
Stray 1H Fuses with 2H

Neutron
Proton

Positron
Neutrino





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3He Is Created

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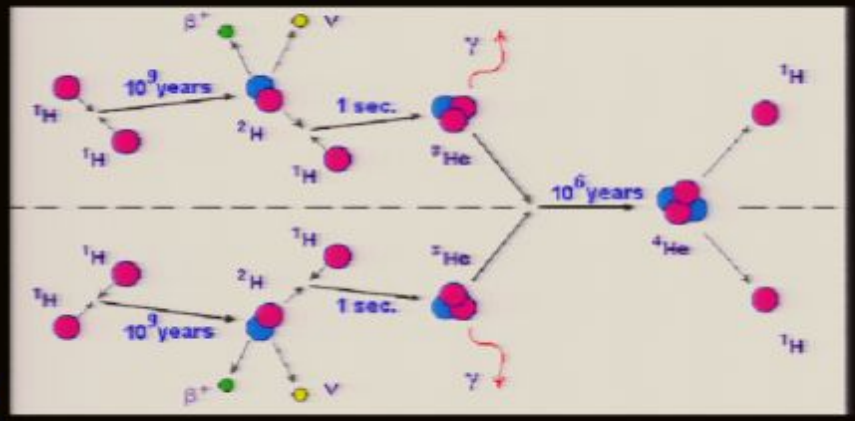
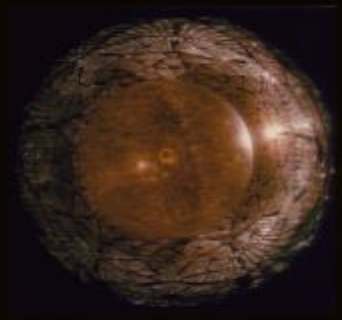
Proton





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Two 3He Fuse Together

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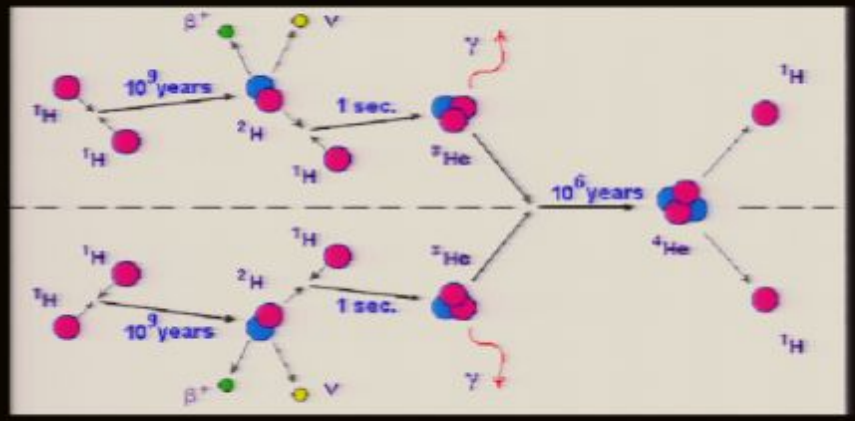

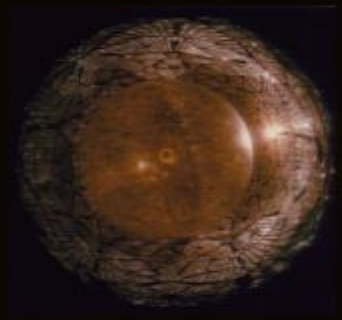

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Two 1H Atoms Released

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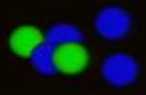

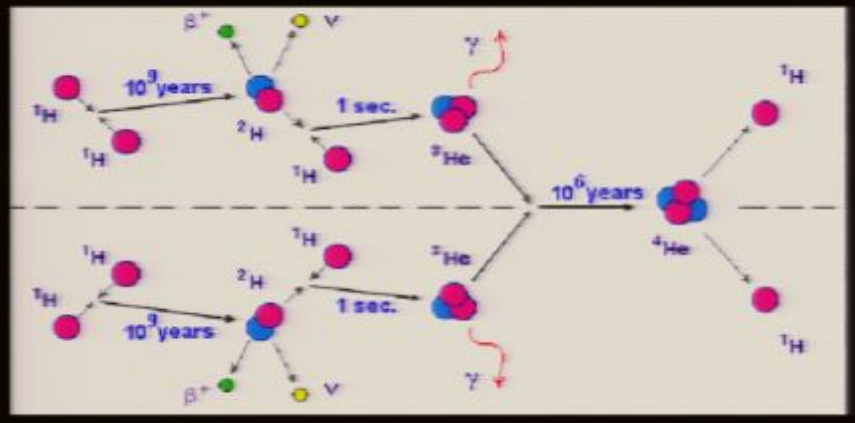

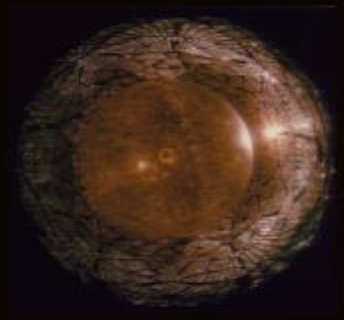

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4He Is Formed

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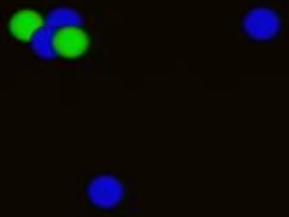

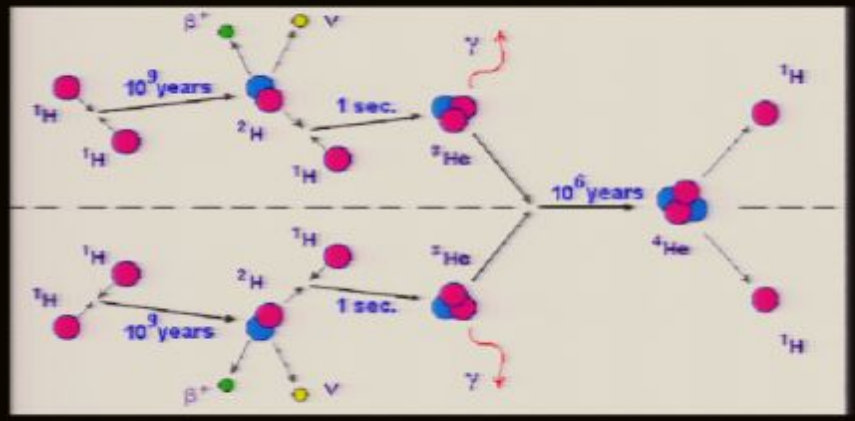

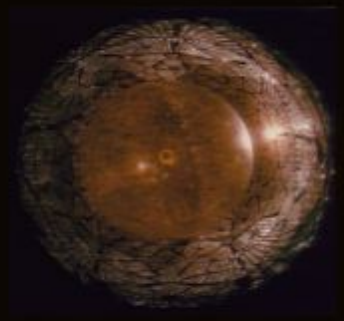

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Proton-Proton Reaction

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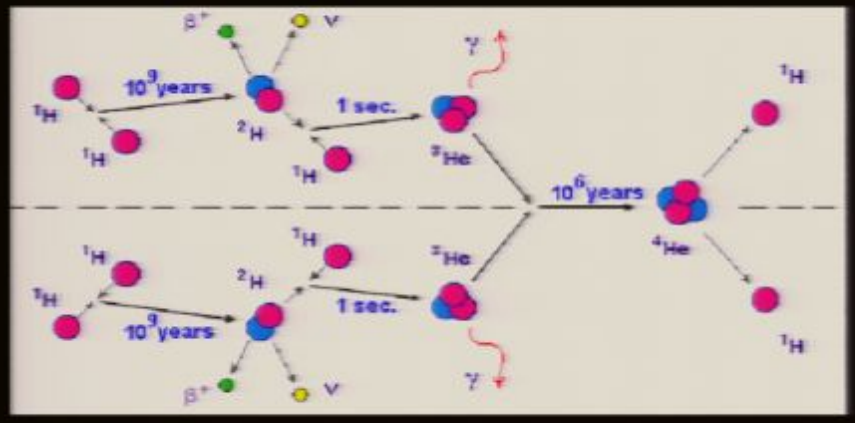

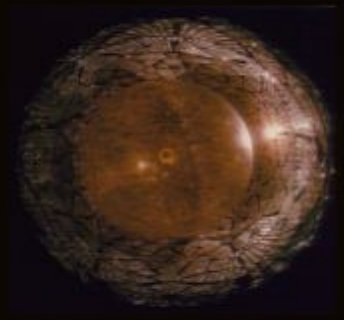

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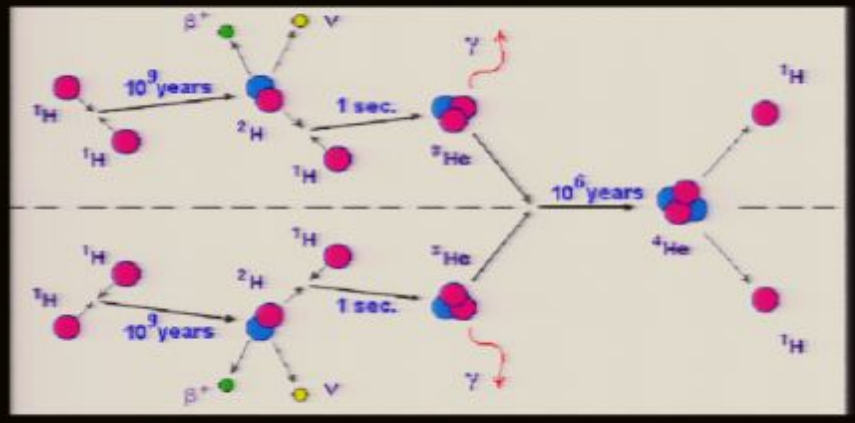

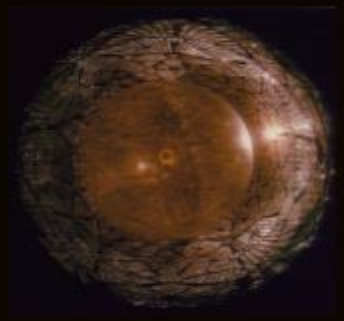

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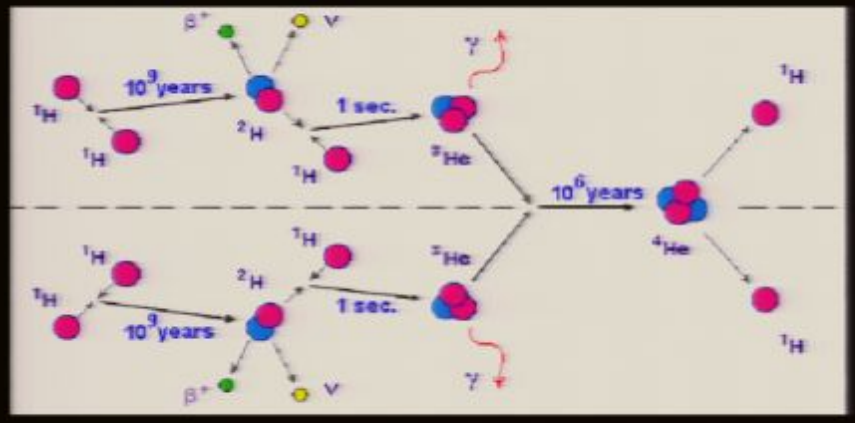

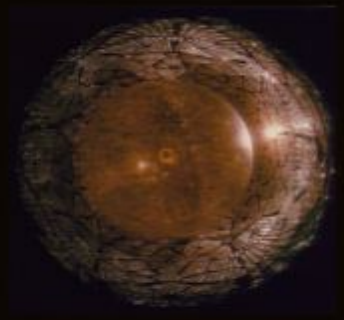

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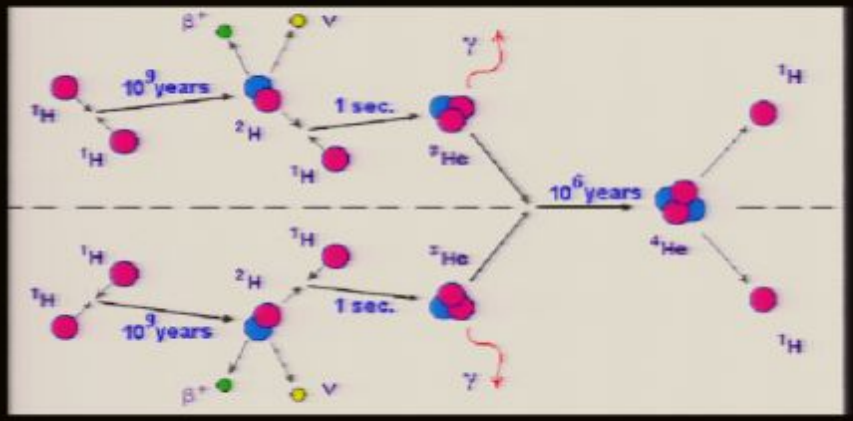

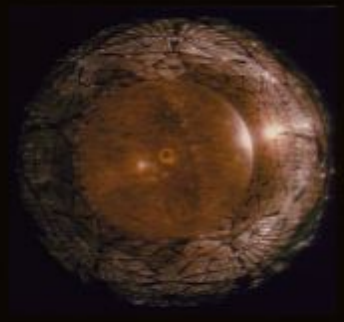

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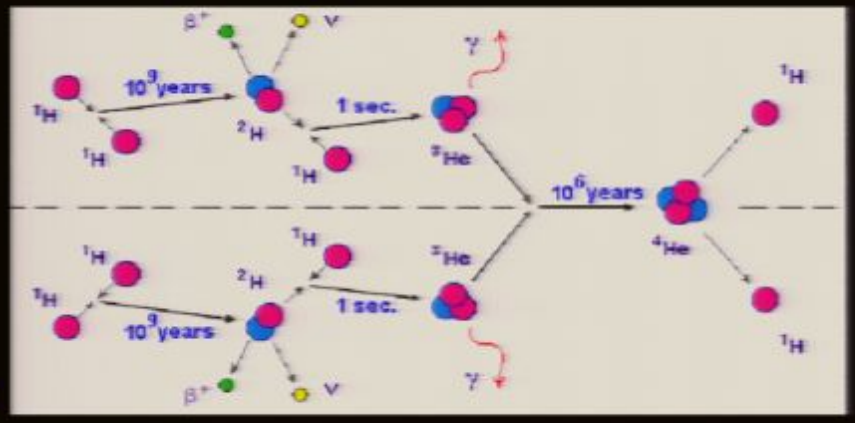
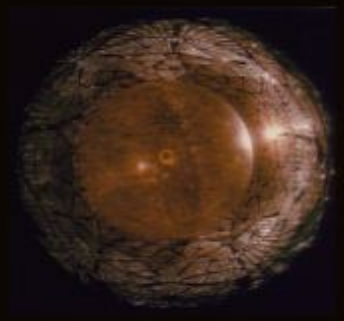
Stray 1H Fuses with 2H

Neutron
Proton

Positron
Neutrino





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3He Is Created

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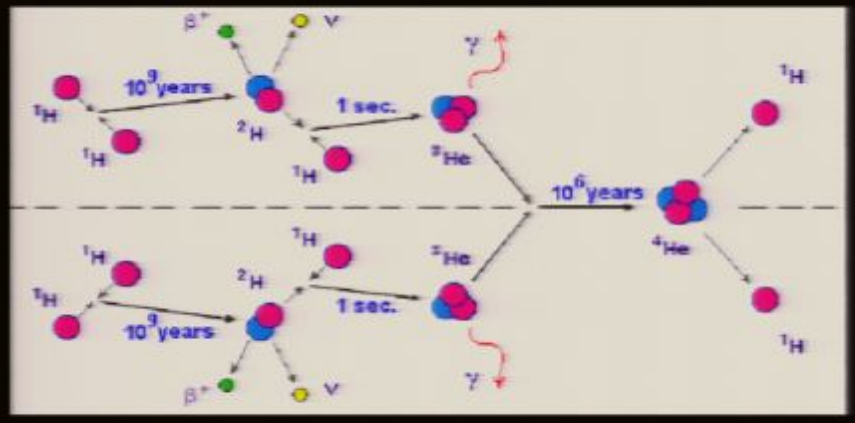

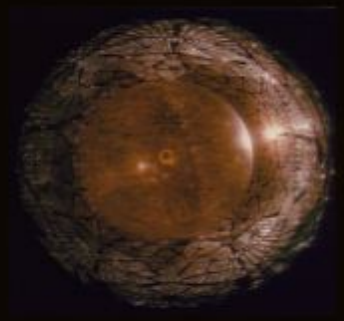

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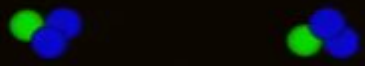

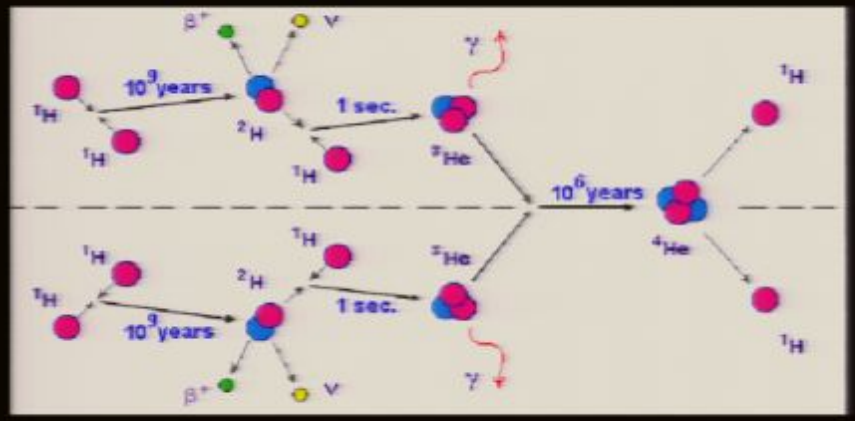

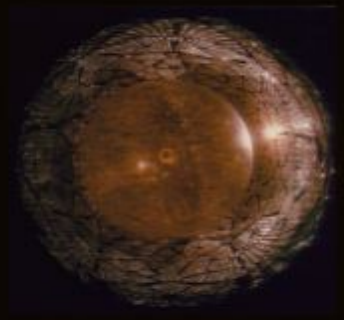

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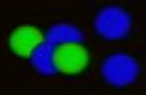

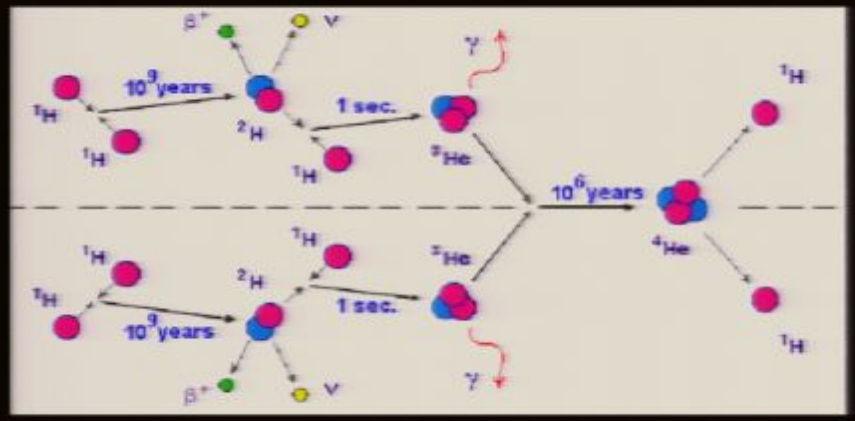

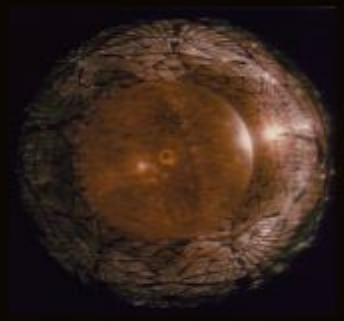

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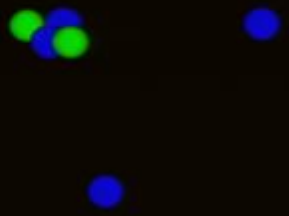

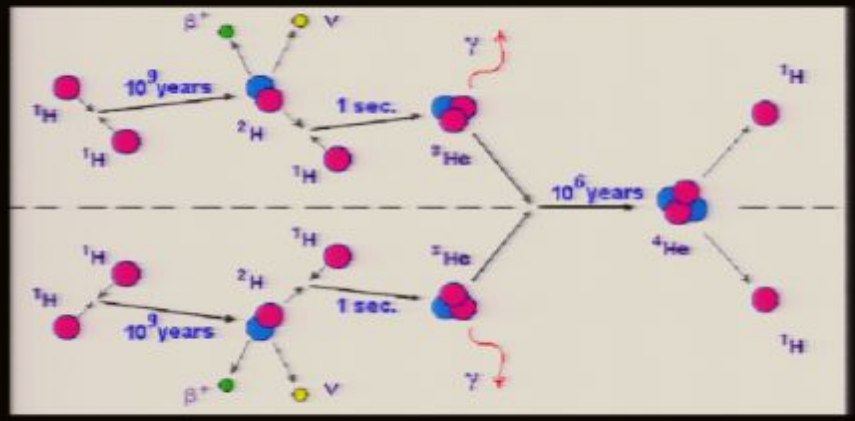

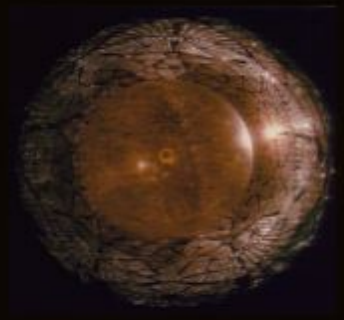

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Proton-Proton Reaction

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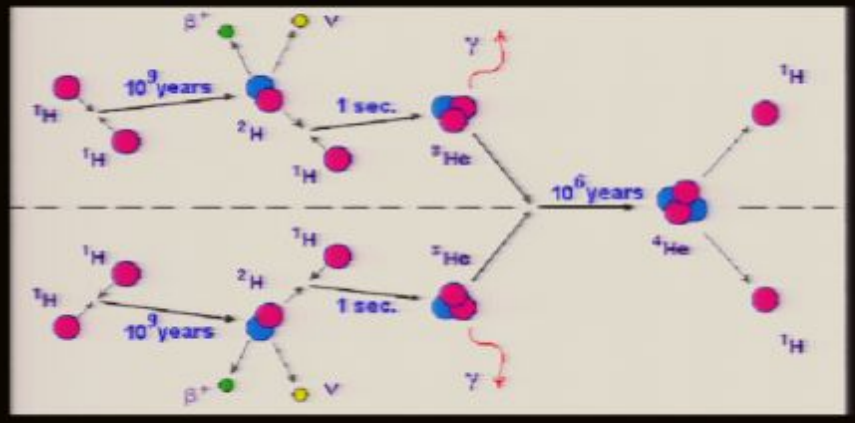

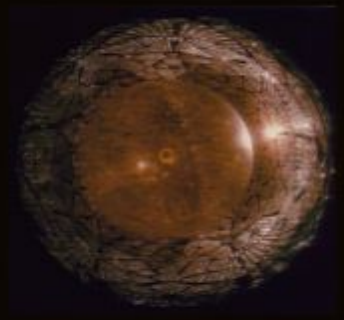

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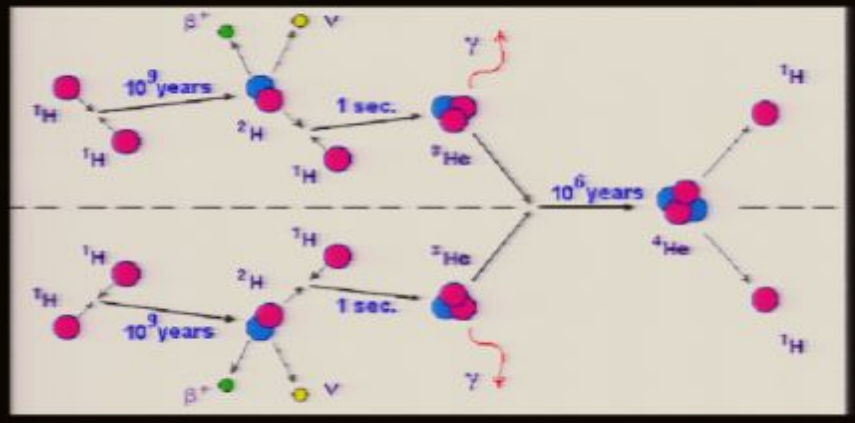

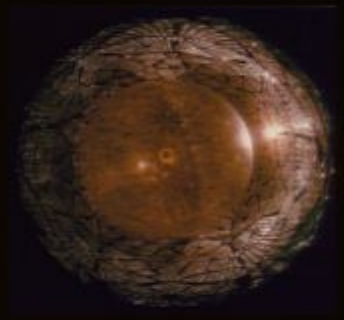

Stellar Energy

Proton-Proton Chain [4H→He + energy]

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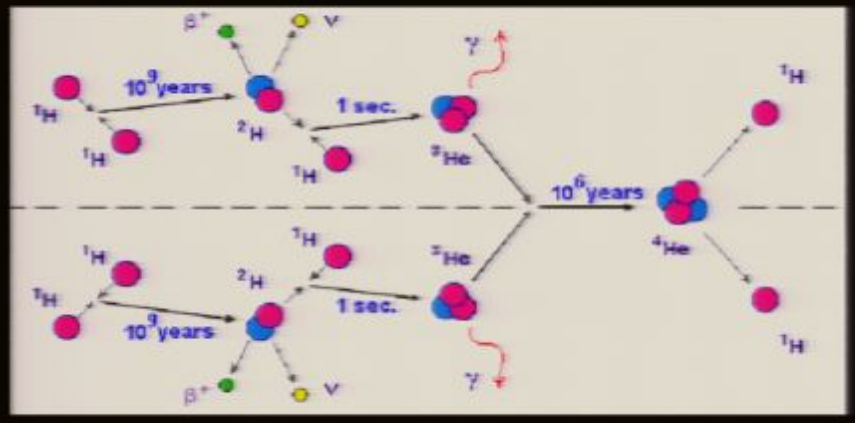
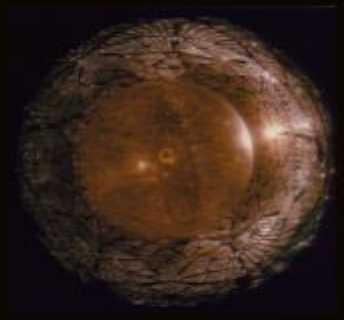
2He Is Formed

● = Neutron
● = Proton





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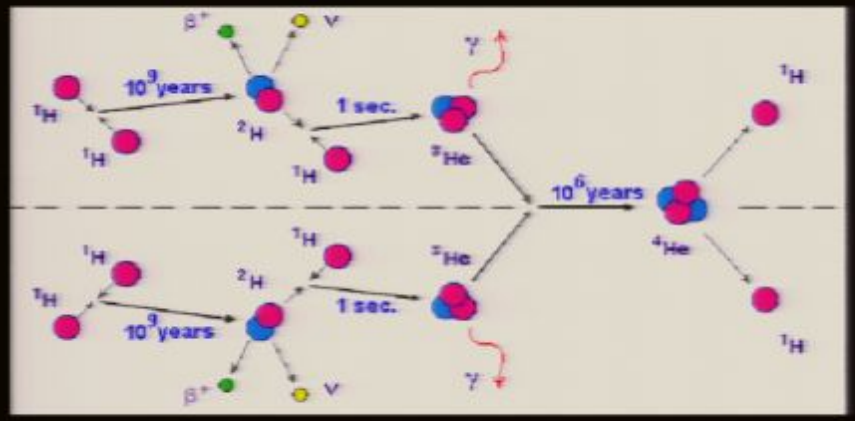
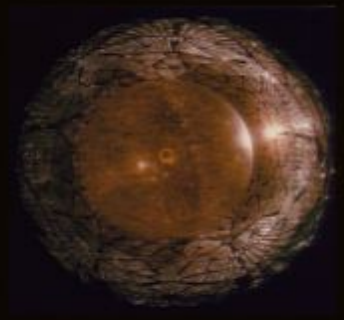
Neutron
Proton





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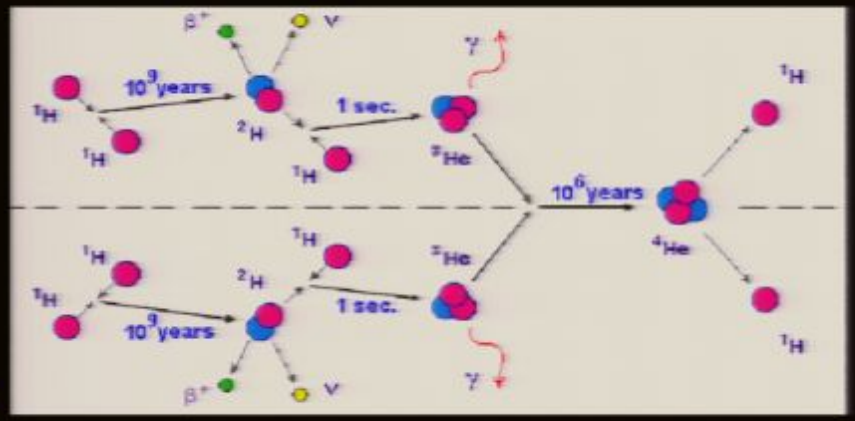
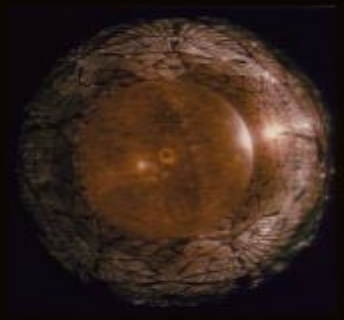
Stray 1H Fuses with 2H

Neutron
Proton

Positron
Neutrino





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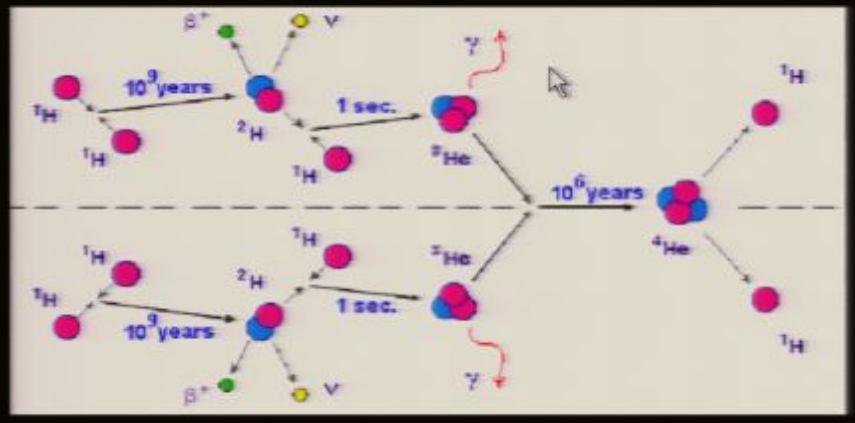
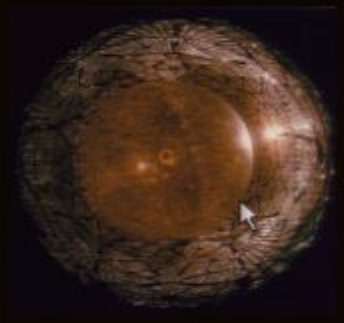
3He Is Created

Neutron
Proton





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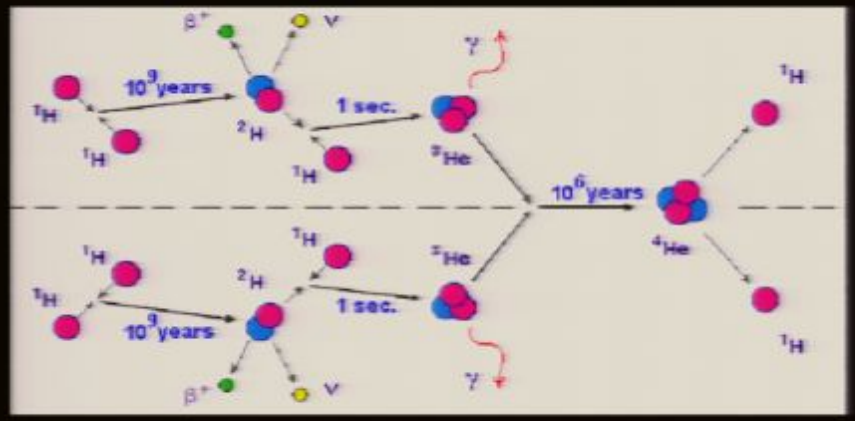
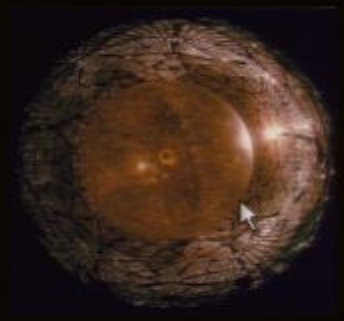
Two 3He Fuse Together

Neutron
Proton





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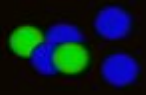
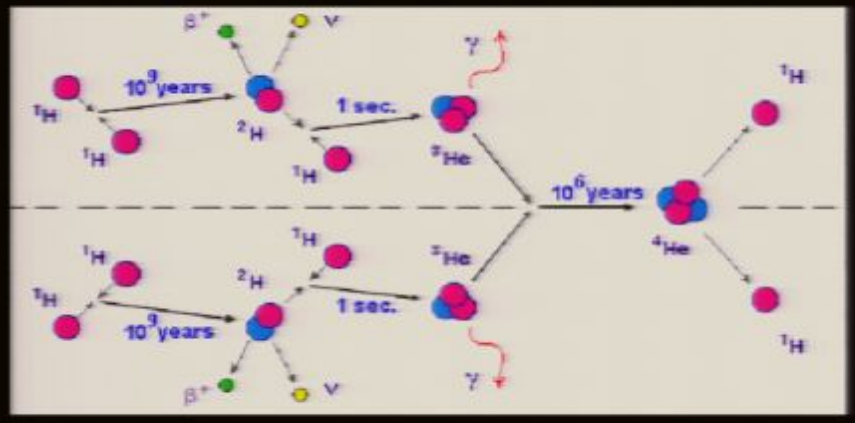
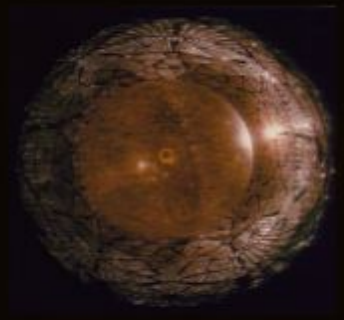
Two 1H Atoms Released

Neutron
Proton







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4He Is Formed

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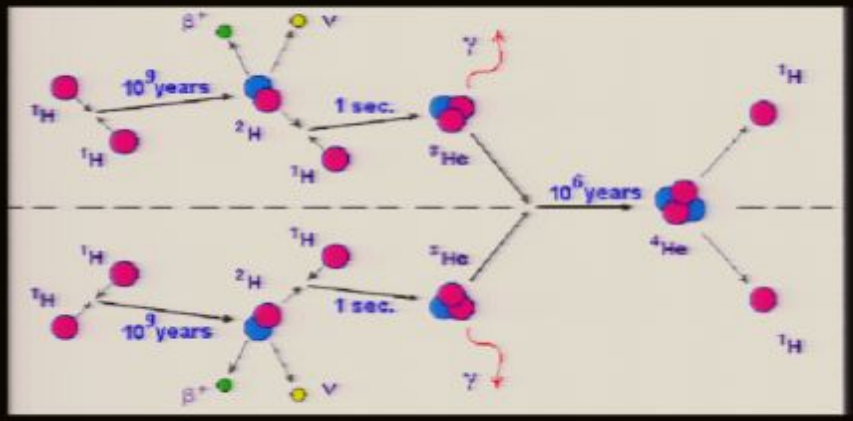
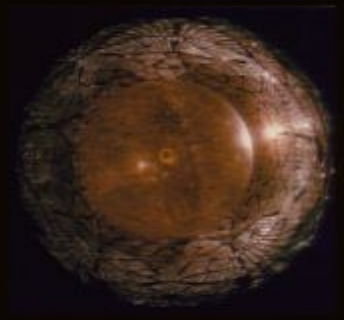
Proton





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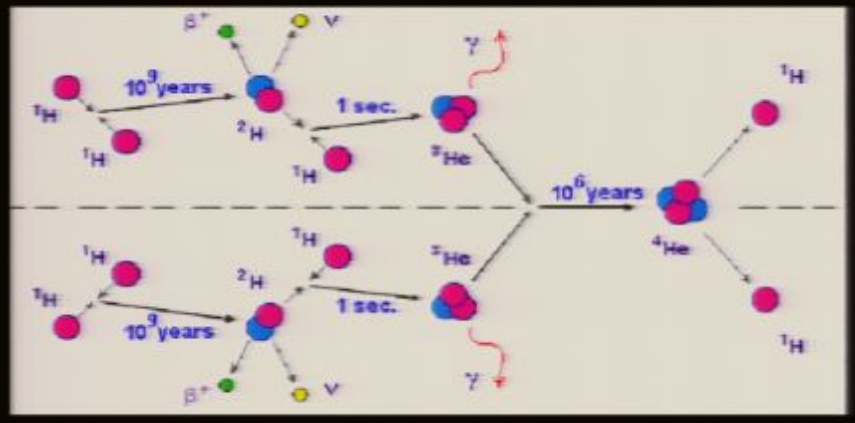
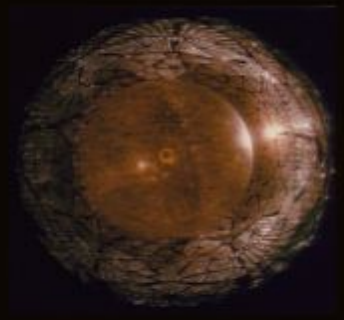
Proton-Proton Reaction

Neutron
Proton





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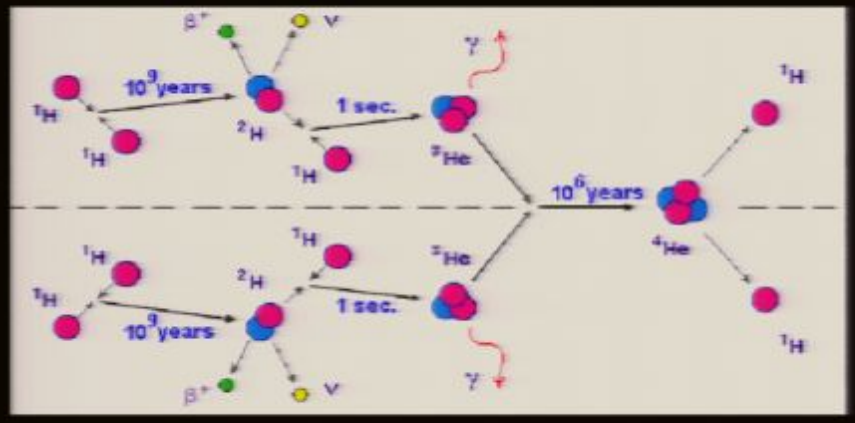
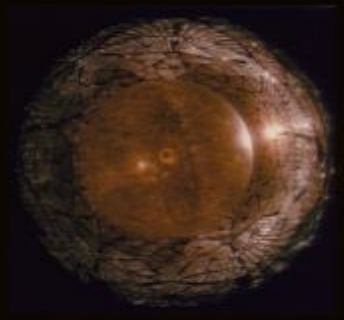
Two 1H Atoms Combine

Neutron
Proton





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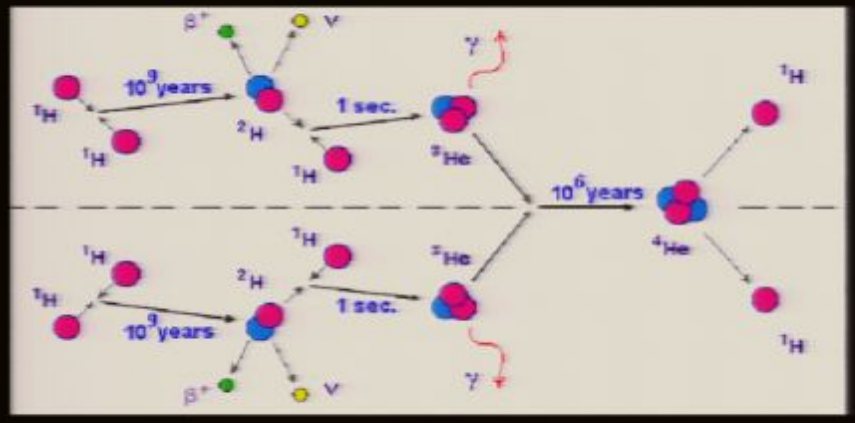

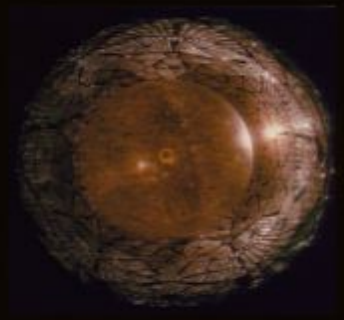

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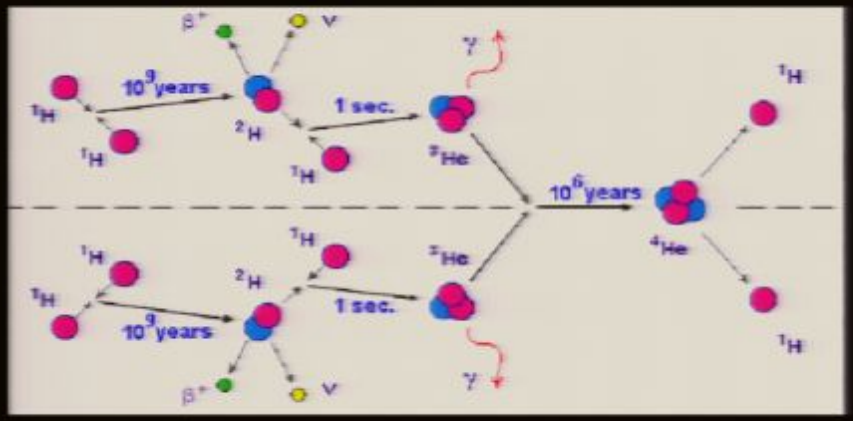
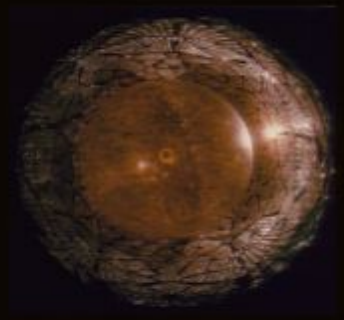
Neutron
Proton





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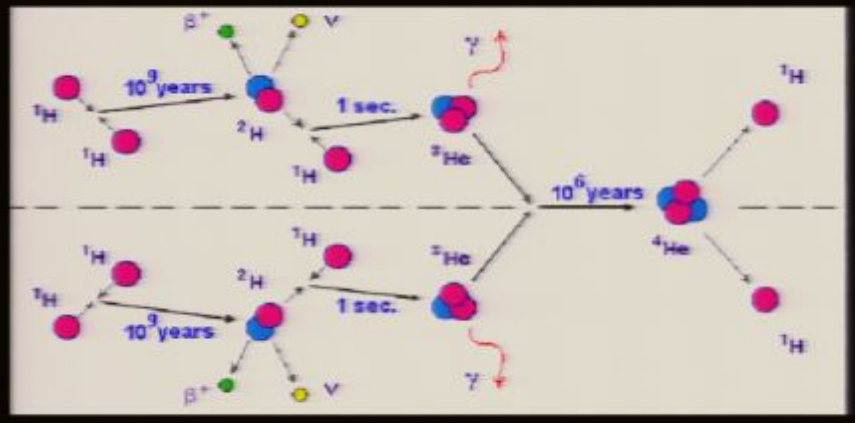
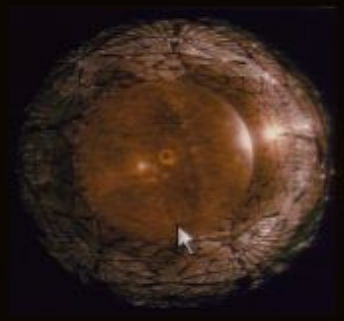
Stray 1H Fuses with 2H

Neutron
Proton

Positron
Neutrino





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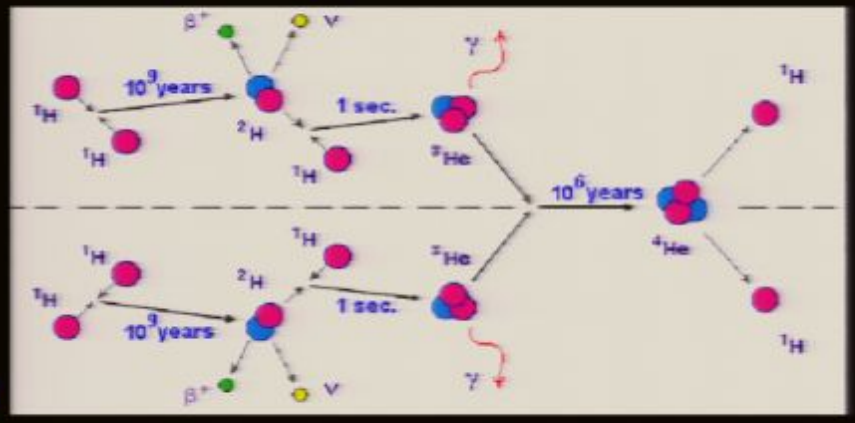
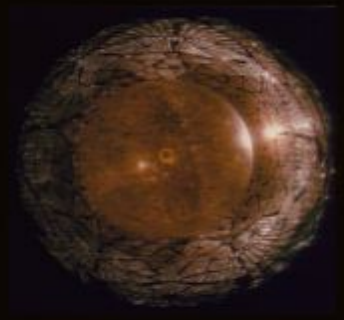
3He Is Created

Neutron
Proton





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Two 3He Fuse Together

Neutron
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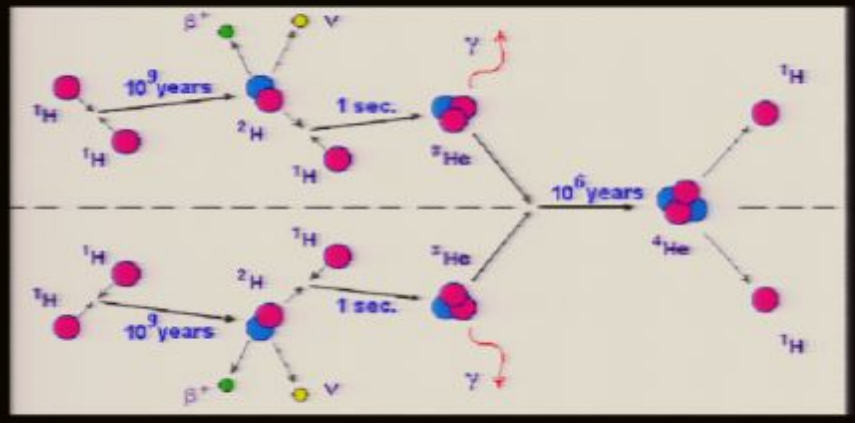

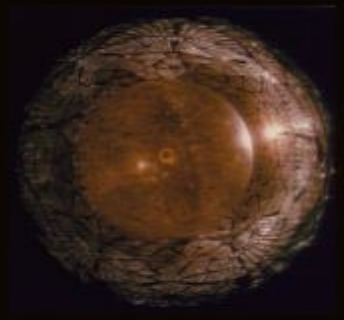

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Two 1H Atoms Released

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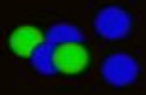
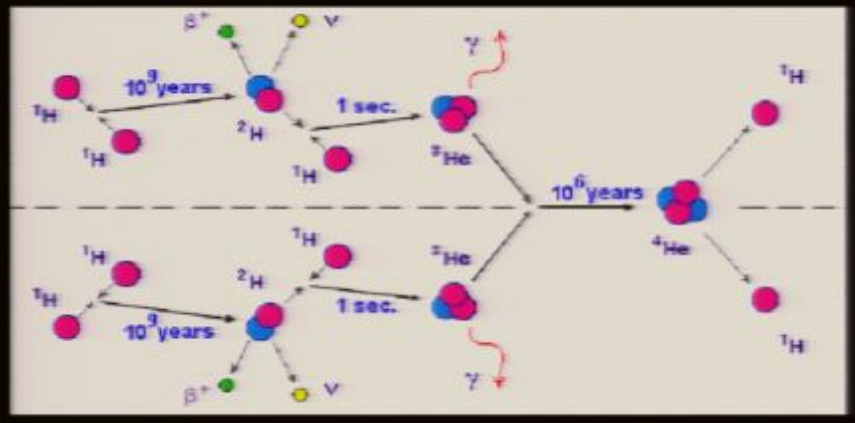
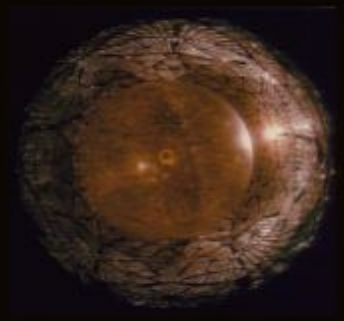
Proton







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4He Is Formed

Neutron
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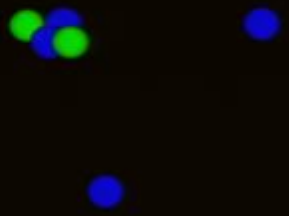

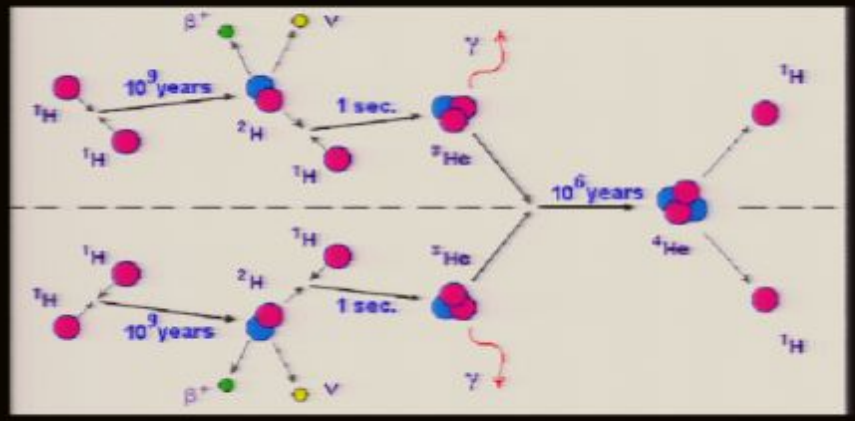

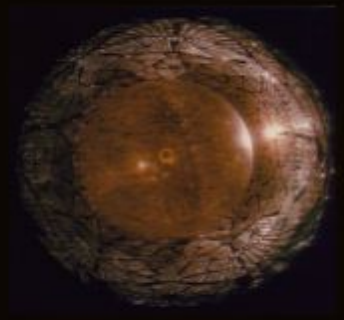

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Proton-Proton Reaction

Neutron
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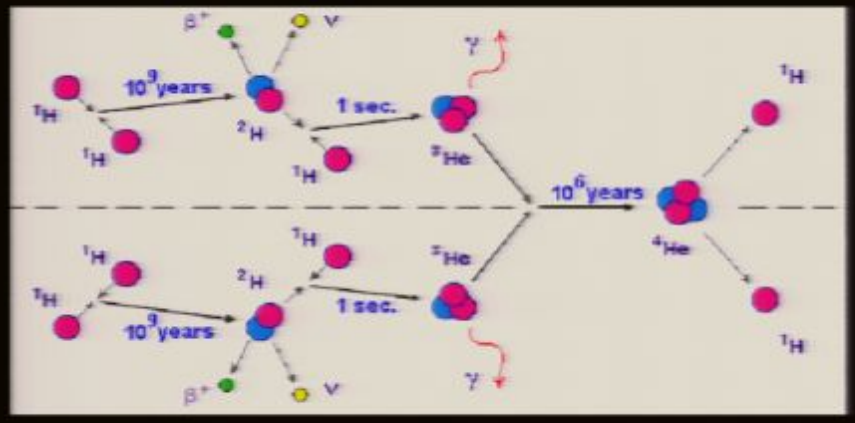

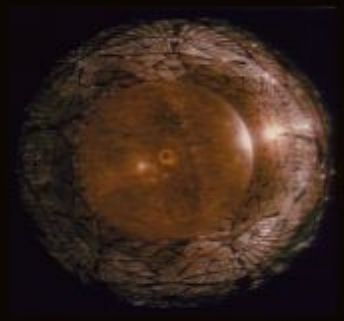

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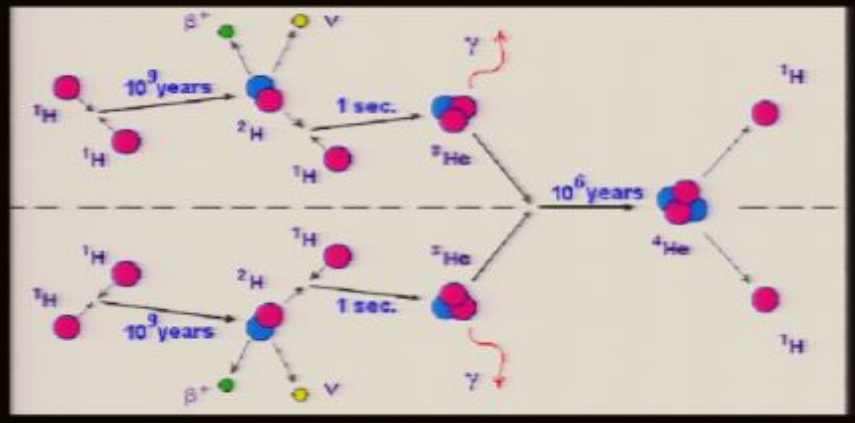

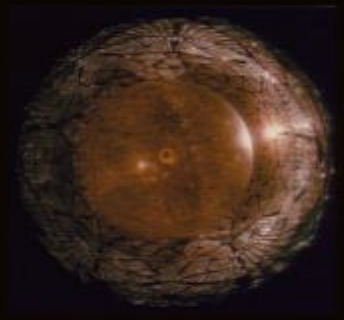

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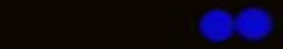

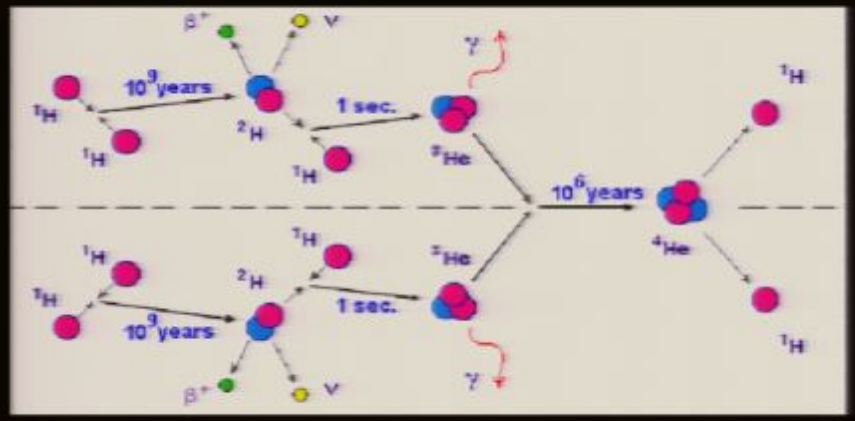

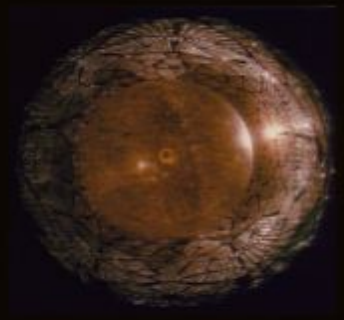

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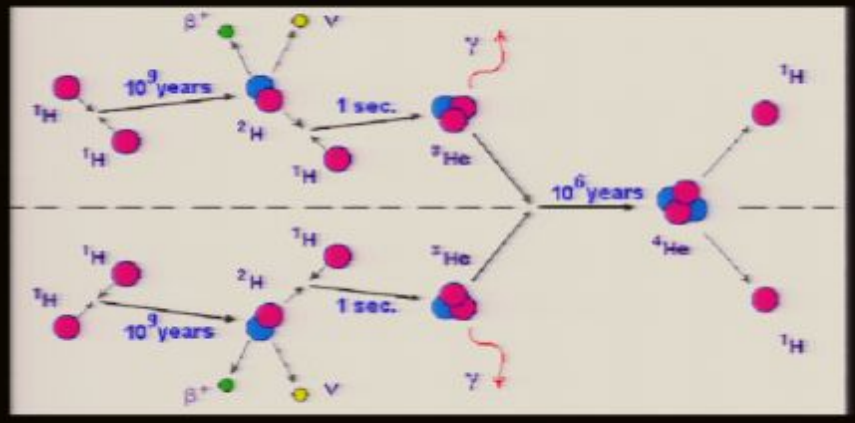

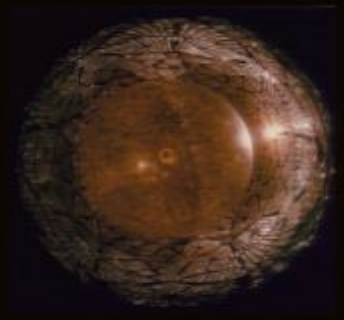

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Neutron
Proton

Positron
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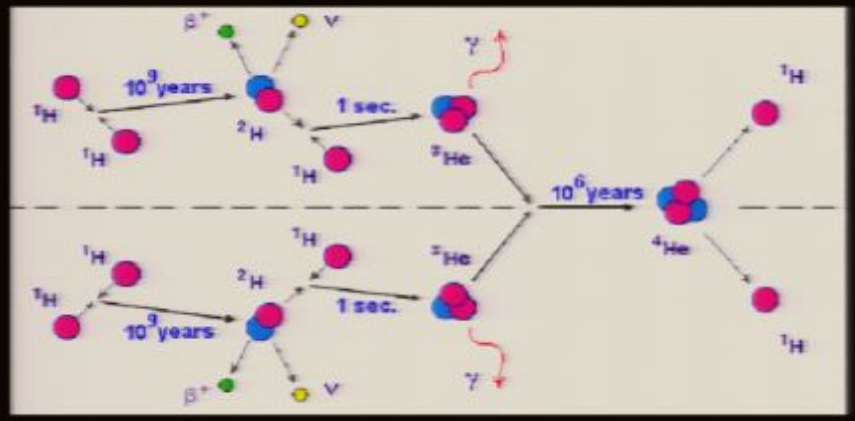

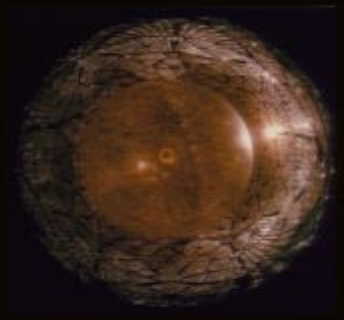

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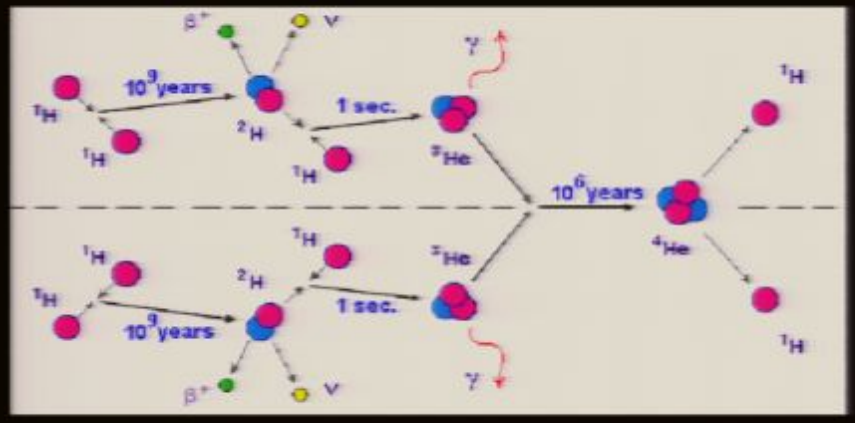
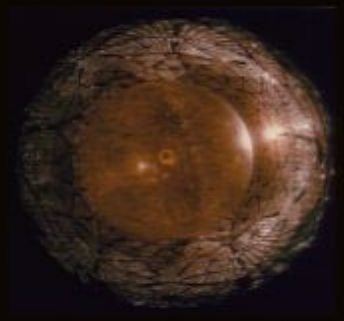
Proton





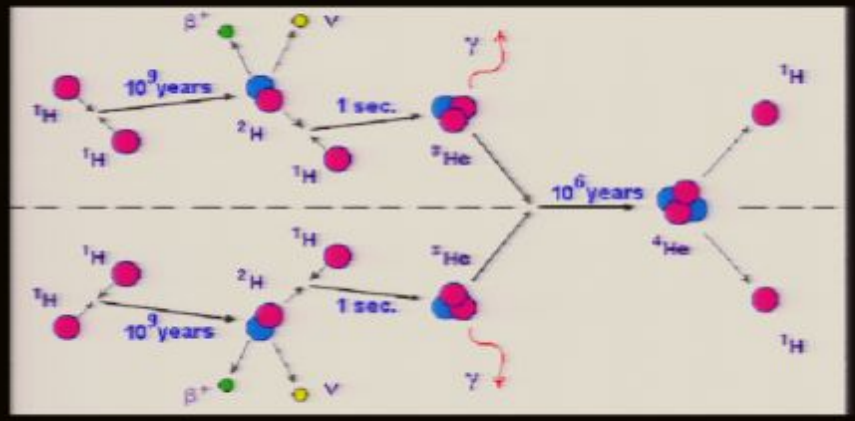
Stellar Energy

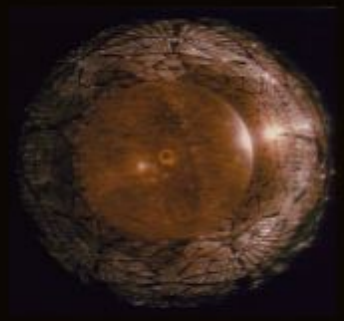
Proton-Proton Chain [4H→He + energy]

Two hydrogen nuclei merge to produce deuterium nucleus, a positron,and a neutrino. Add another hydrogen and you get helium 3 and a gamma photon (energy). Two Helium 3 merge and produce helium 4 and two Hydrogen nuclei.

Two 3He Fuse Together

Neutron
Proton





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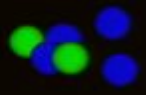
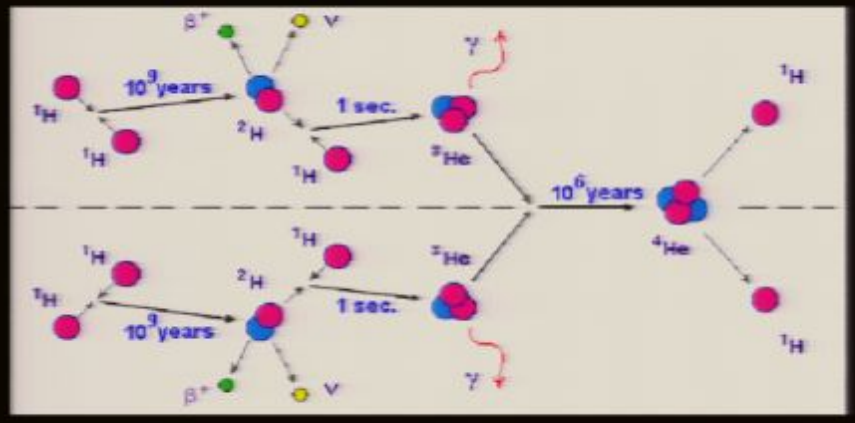
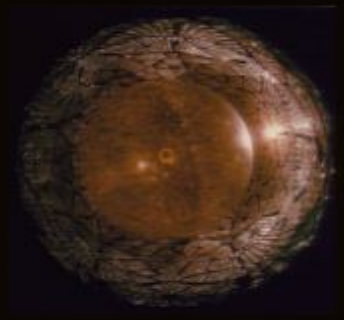
Two 1H Atoms Released

Neutron
Proton







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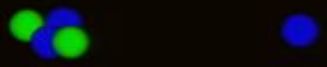
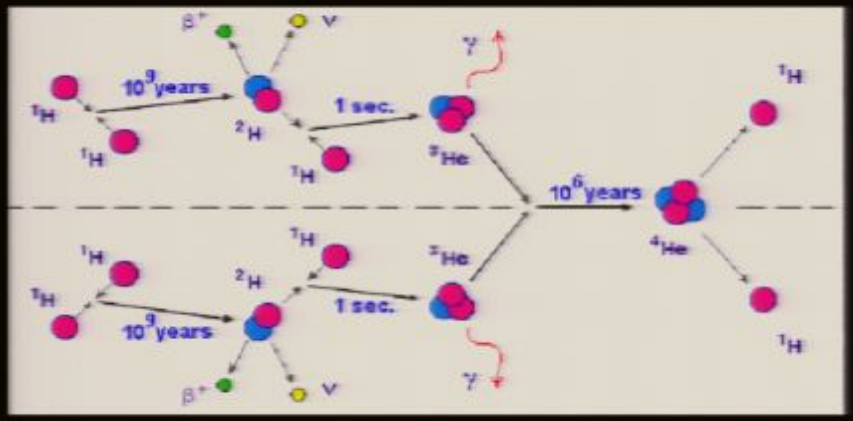
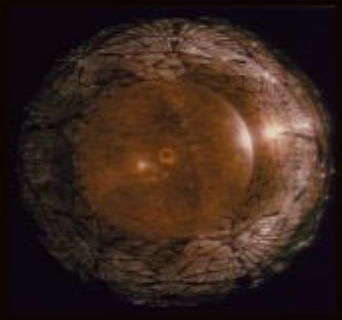
4He Is Formed

= Neutron
= Proton







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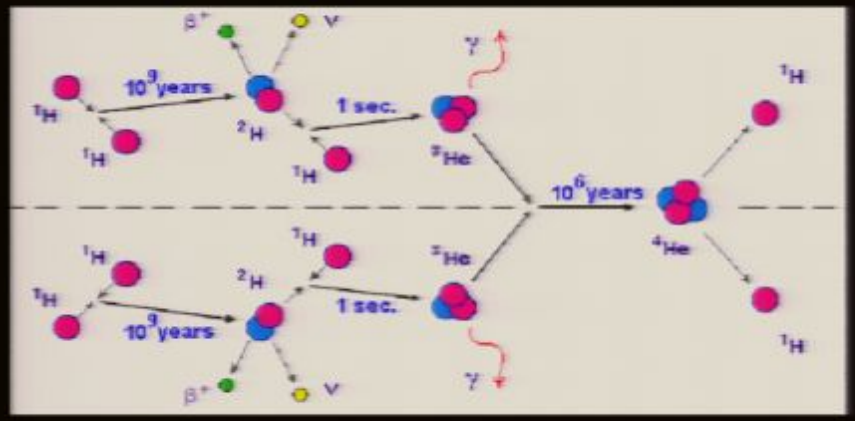
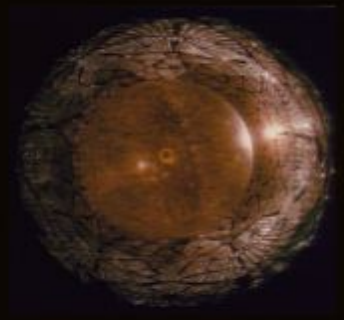
Proton-Proton Reaction

Neutron
Proton





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Two 1H Atoms Combine

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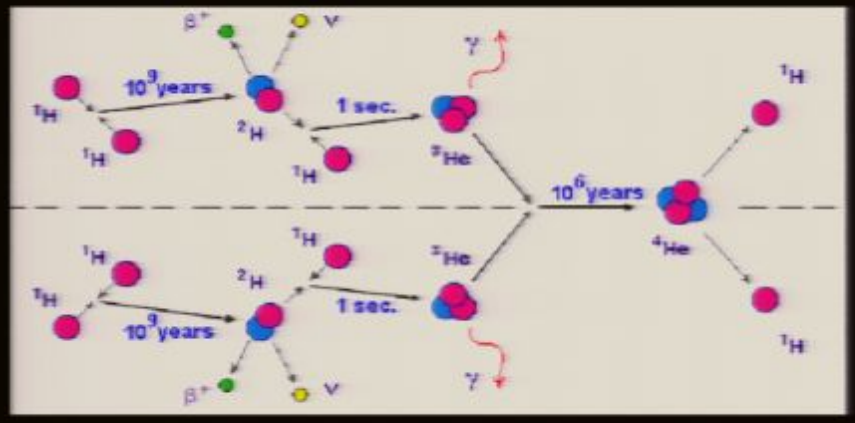
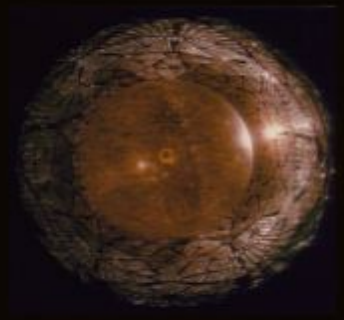
Proton





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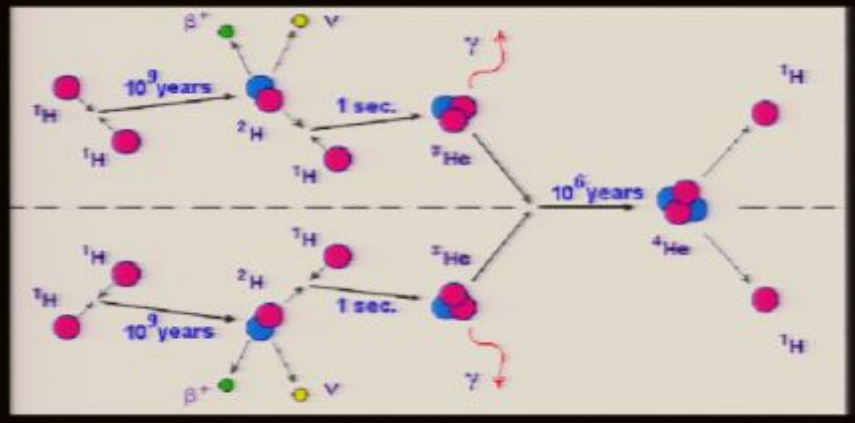
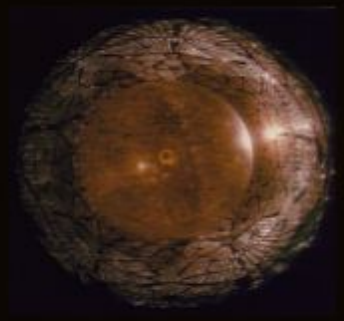
2He Is Formed

● = Neutron
● = Proton





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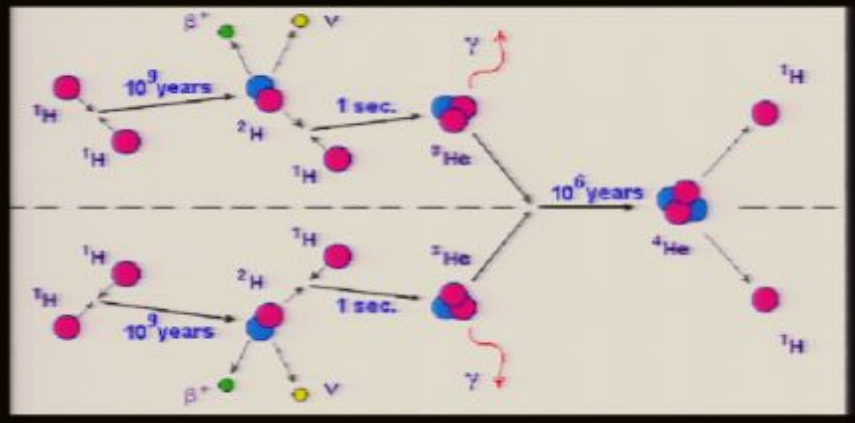
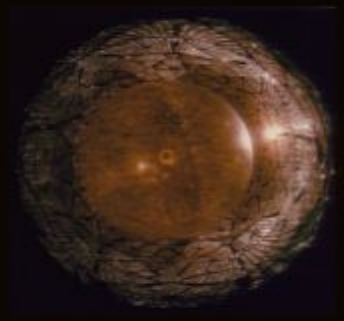
Proton Decays Into A Neutron

= Neutron
= Proton





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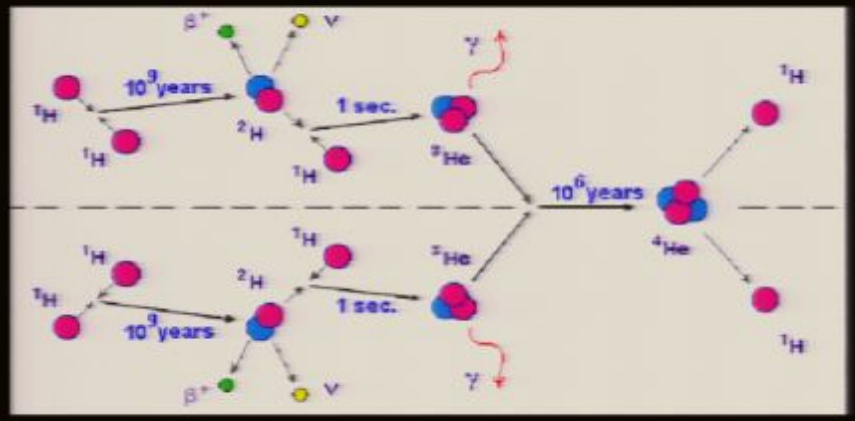
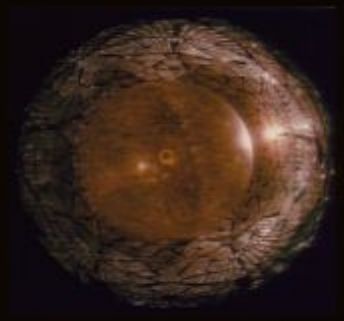
Stray 1H Fuses with 2H

Neutron
Proton

Positron

Neutrino





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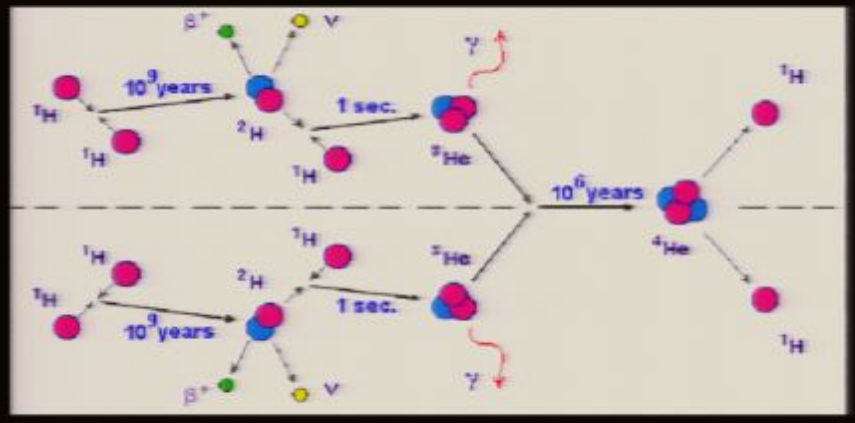
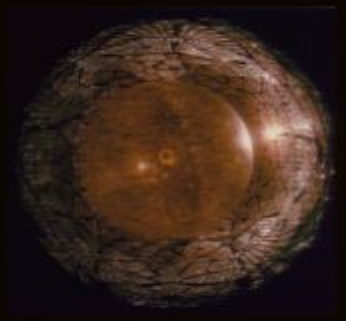
3He Is Created

Neutron
Proton





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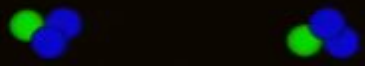
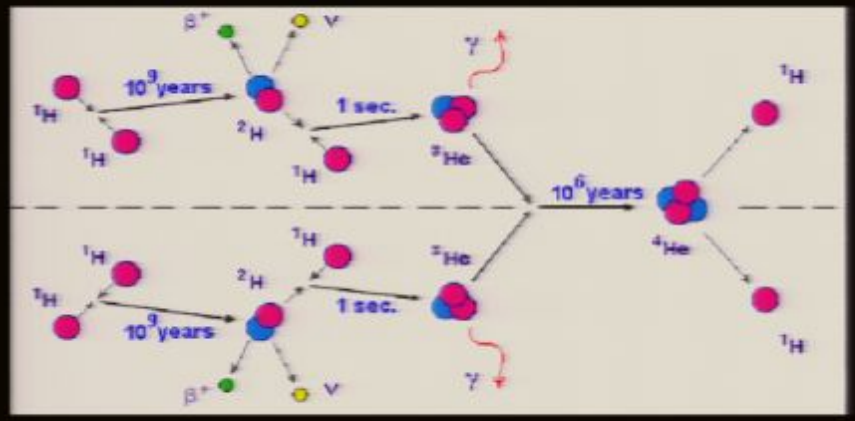
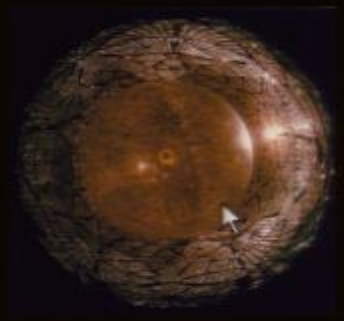
Two 3He Fuse Together

Neutron
Proton







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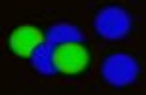
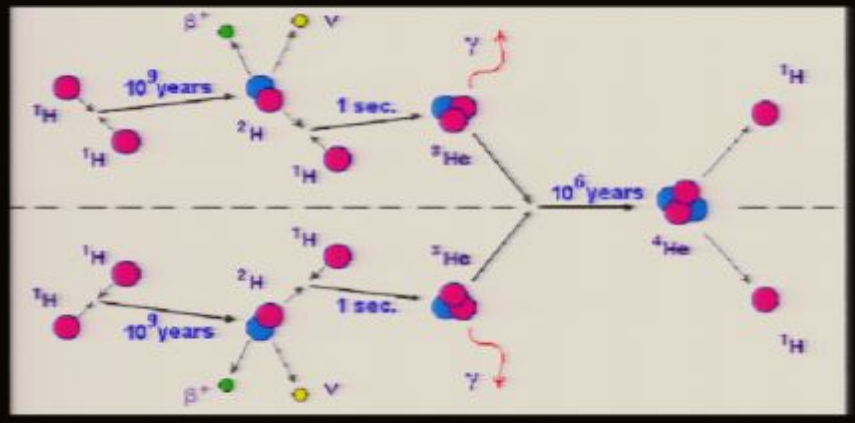
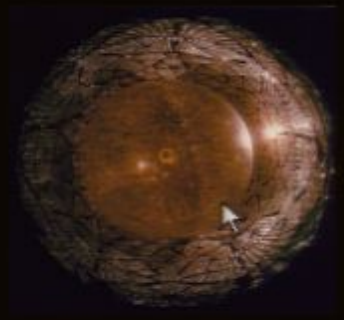
Two 1H Atoms Released

Neutron
Proton







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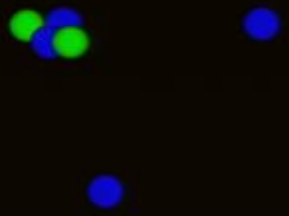
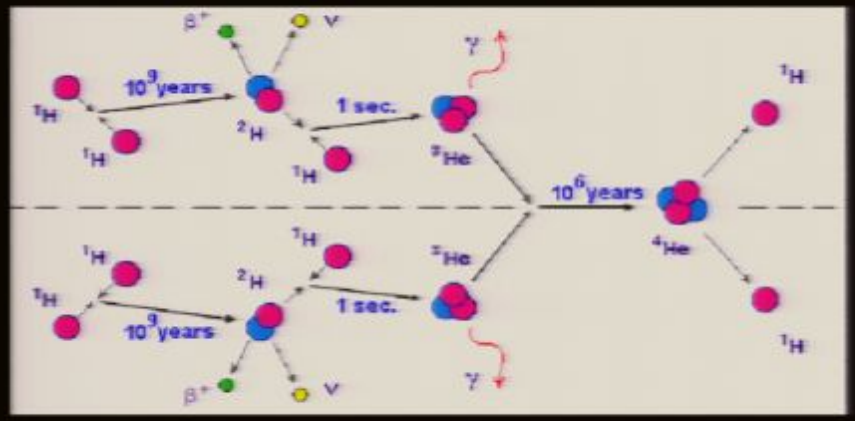
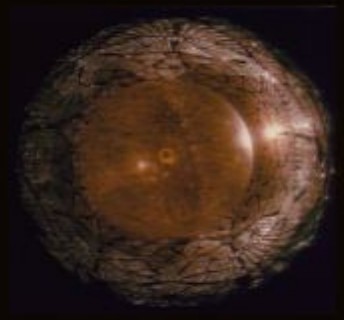
4He Is Formed

Neutron
Proton







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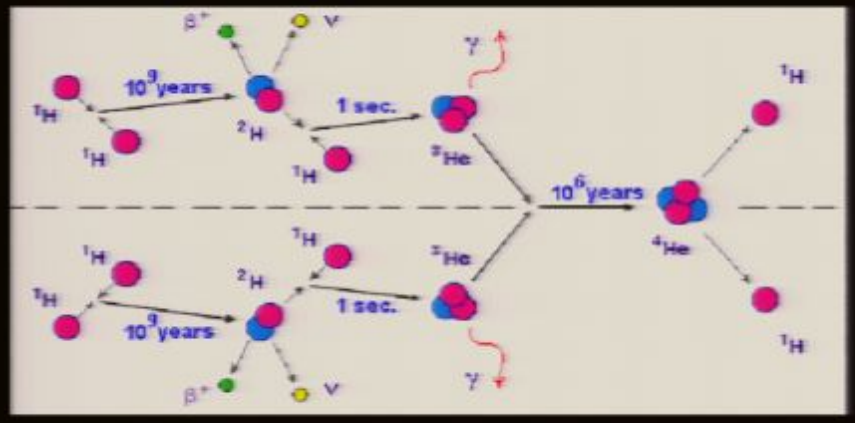
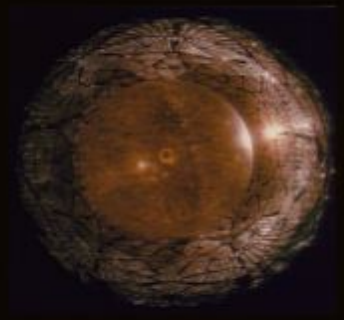
Proton-Proton Reaction

Neutron
Proton





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Two 1H Atoms Combine

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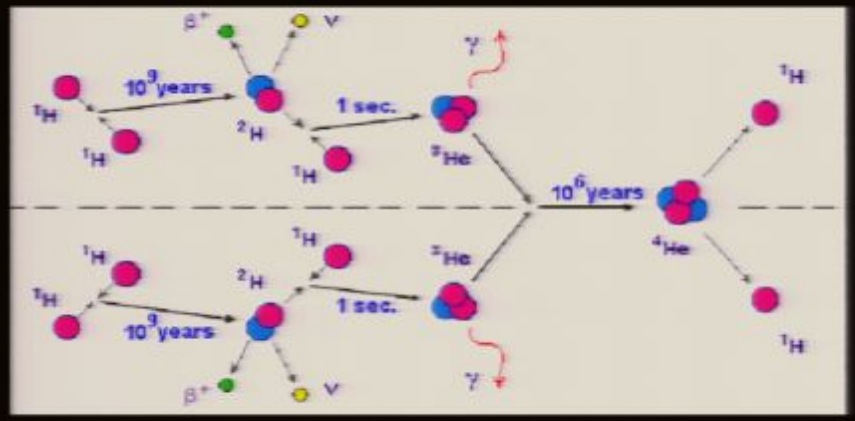

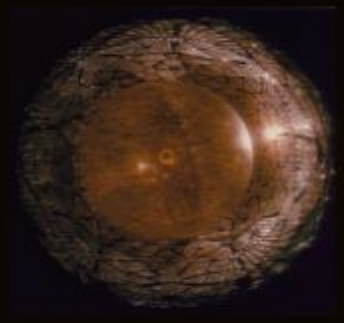

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2He Is Formed

Neutron
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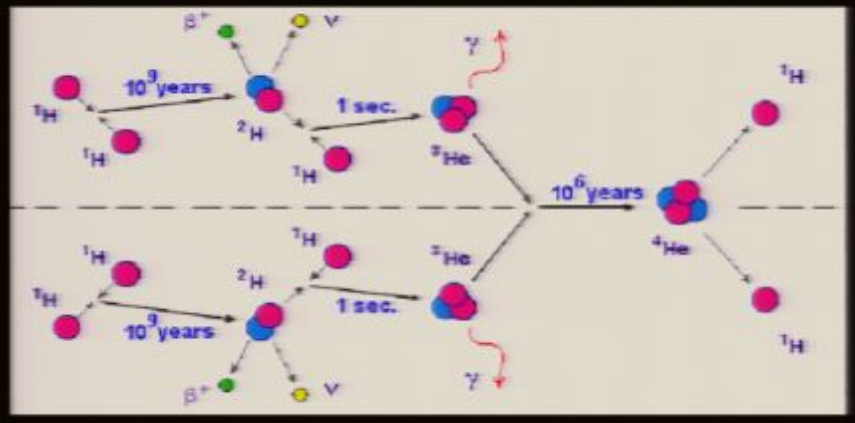

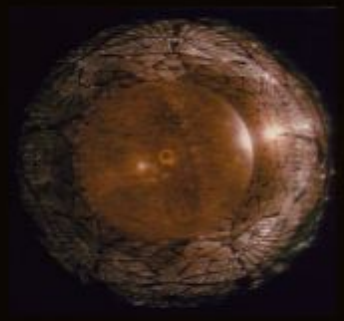

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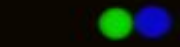
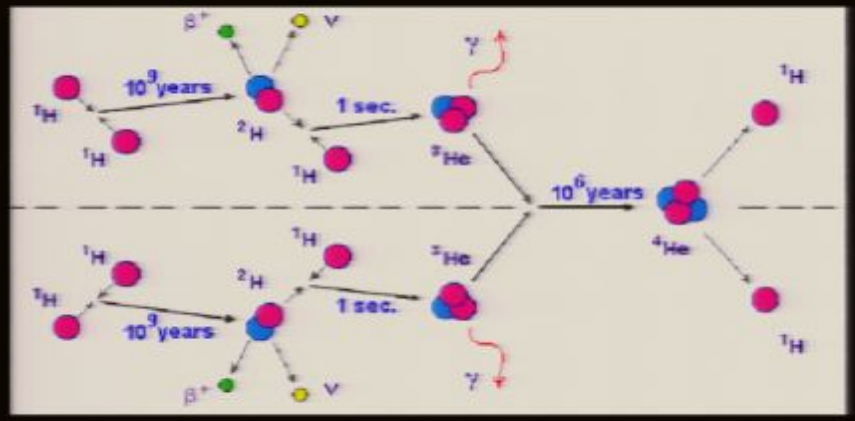
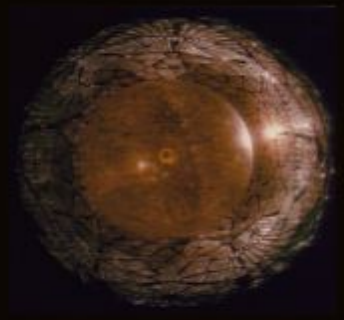
Neutron
Proton







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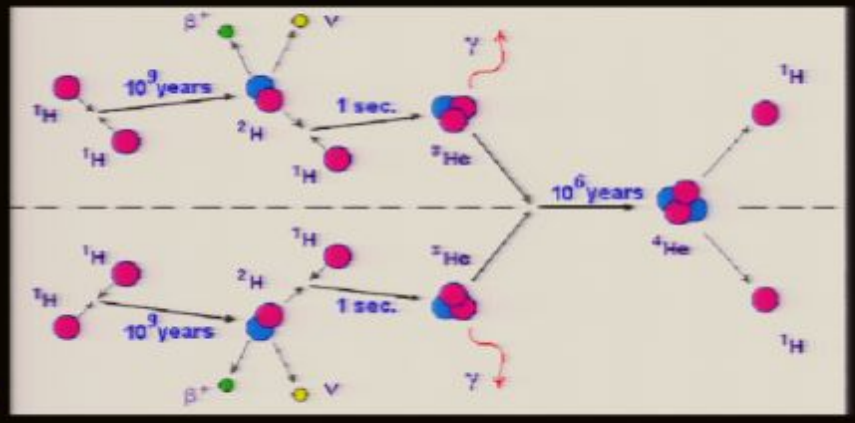
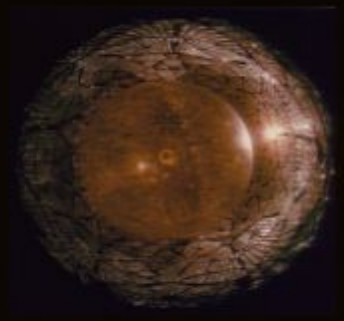
Stray 1H Fuses with 2H

Neutron
Proton

Positron
Neutrino





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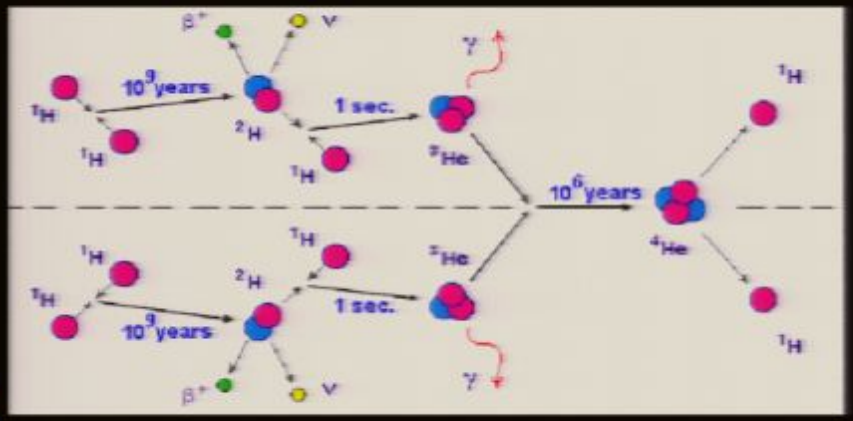

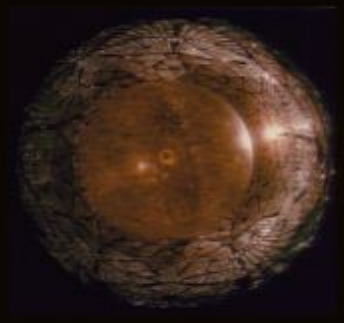

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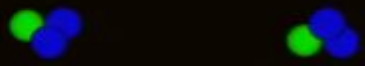
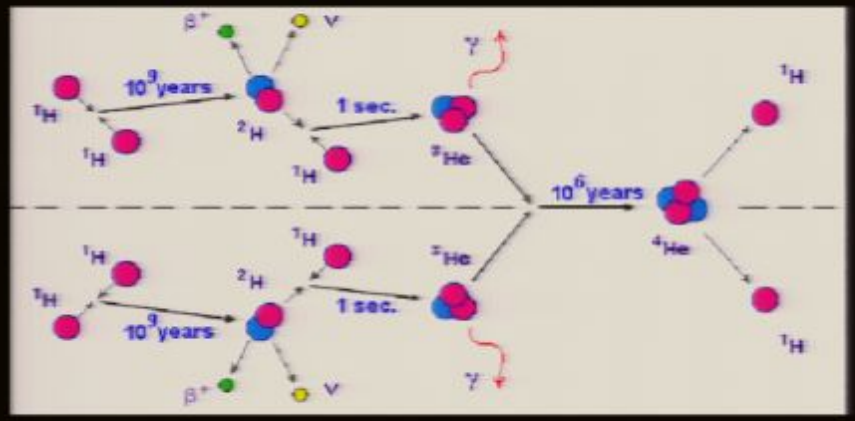
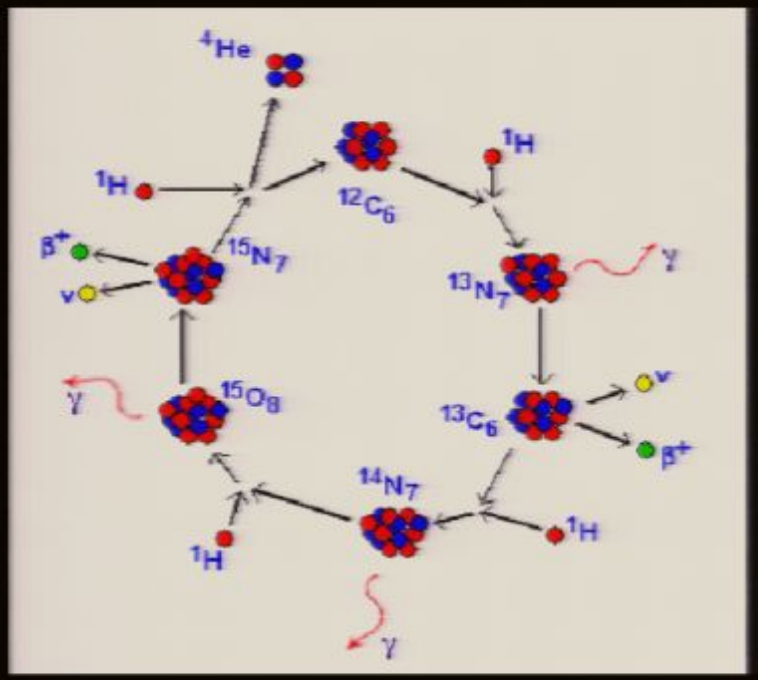
Proton





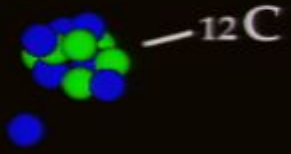
CNO Cycle

- *The higher the temperature, the more important the production of energy from the CNO.*
- *For stars less than 1 solar mass proton-proton cycle dominates.*



Stray 1H Absorbed Into 12C, Forming 13N

● — Neutron ● — Proton



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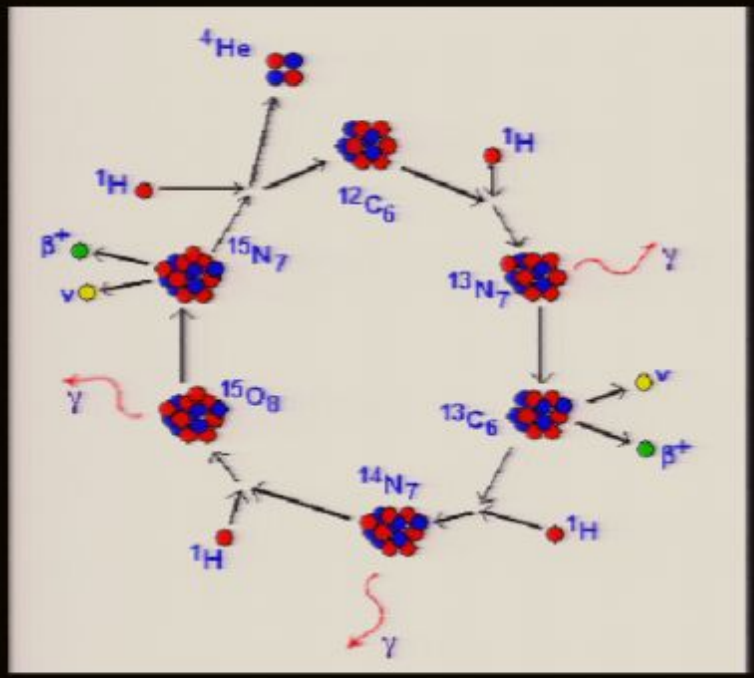
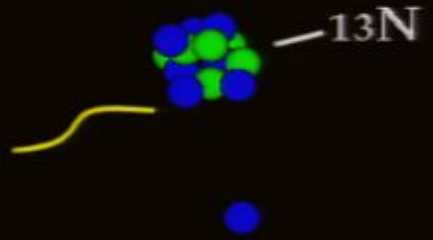


Gamma Ray Released

Neutron — Proton



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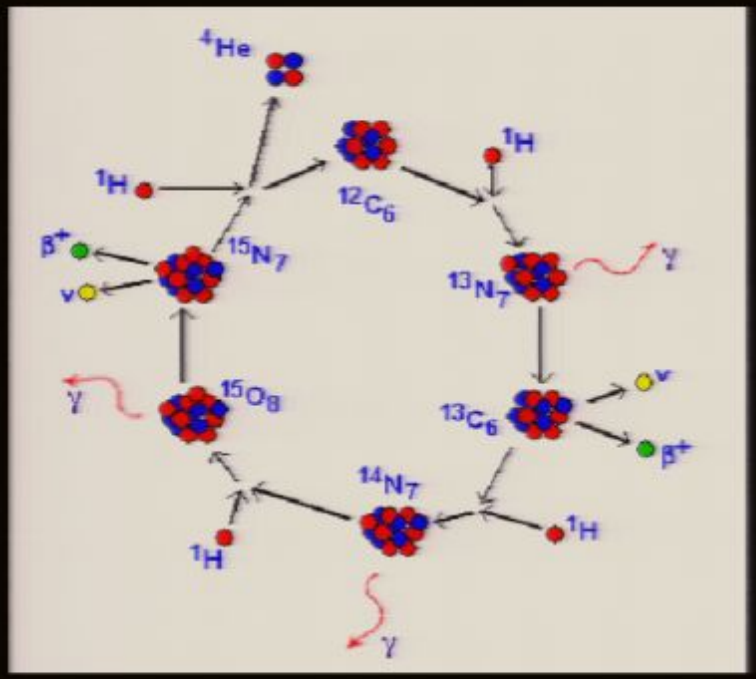
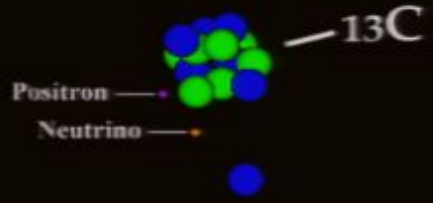


13N ß+ Decays Into 13C

Neutron — Proton



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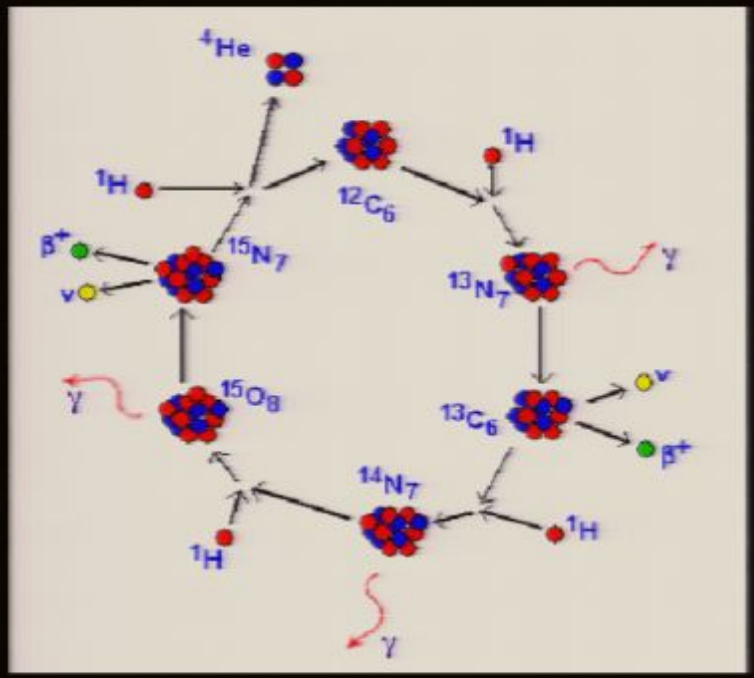
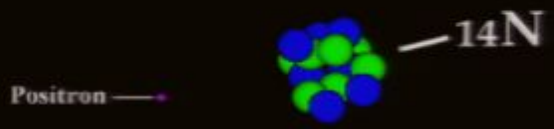


Stray 1H Absorbed Into 12C, Forming 14N

Neutron — Proton



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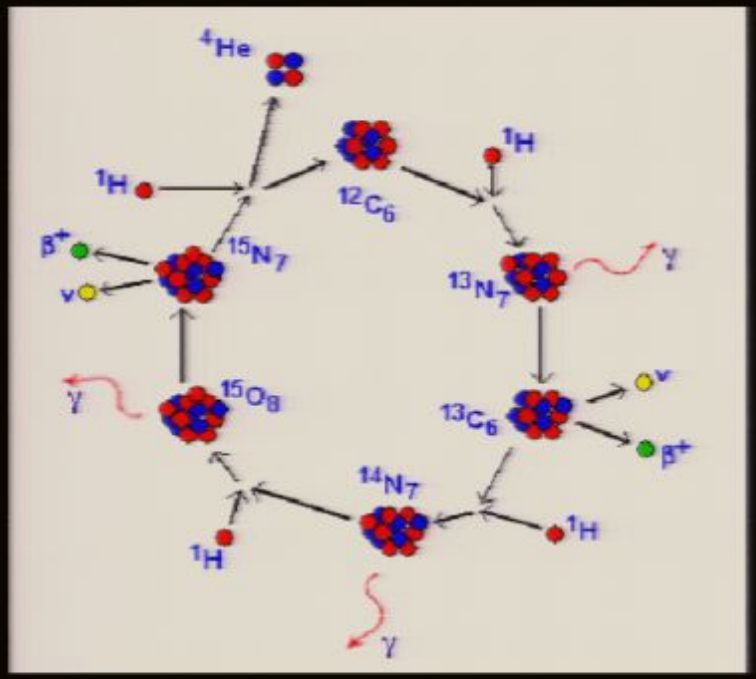
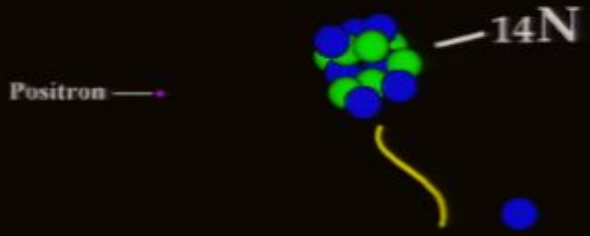


Gamma Ray Released

Neutron — Proton



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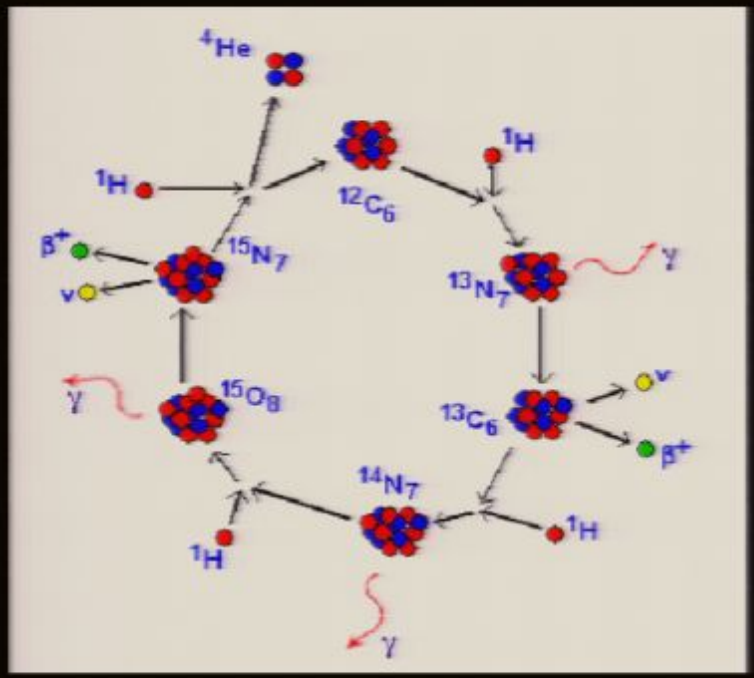

Stray 1H Absorbed Into 14N, Forming 15O

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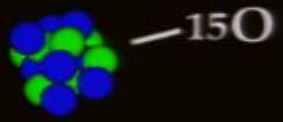

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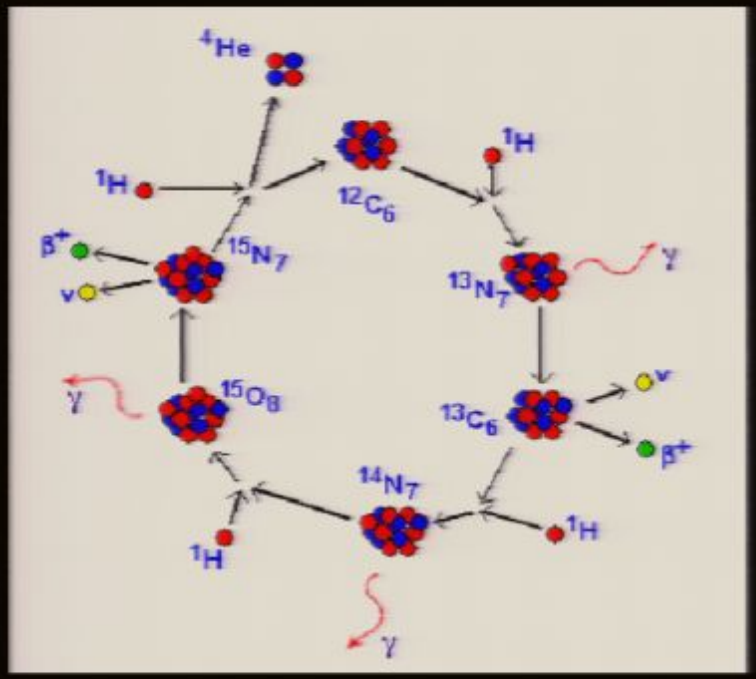

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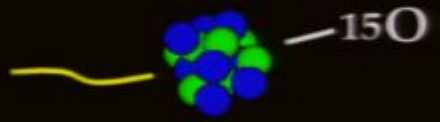
Neutron — Proton



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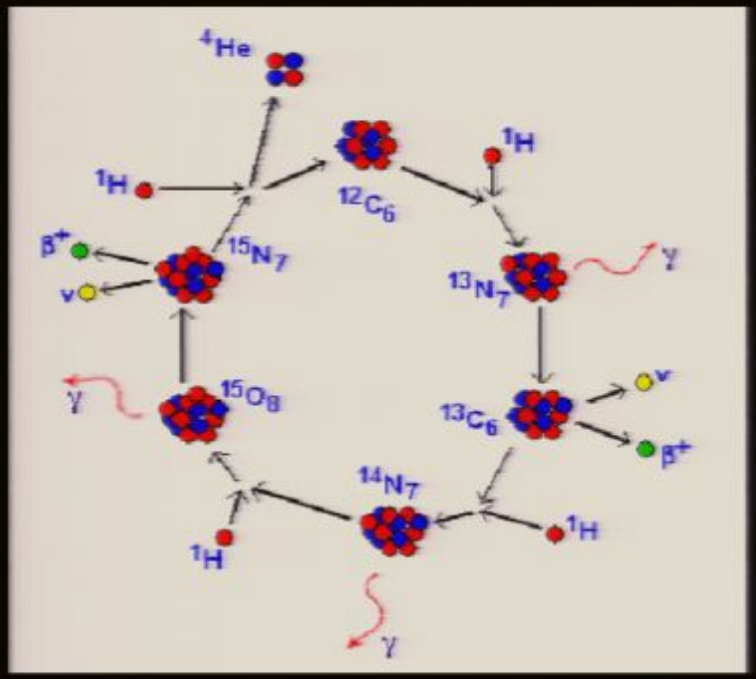
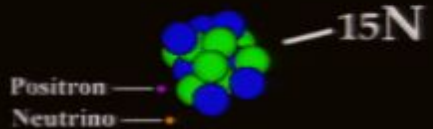


15O ß+ Decays Into 15N

Neutron — Proton



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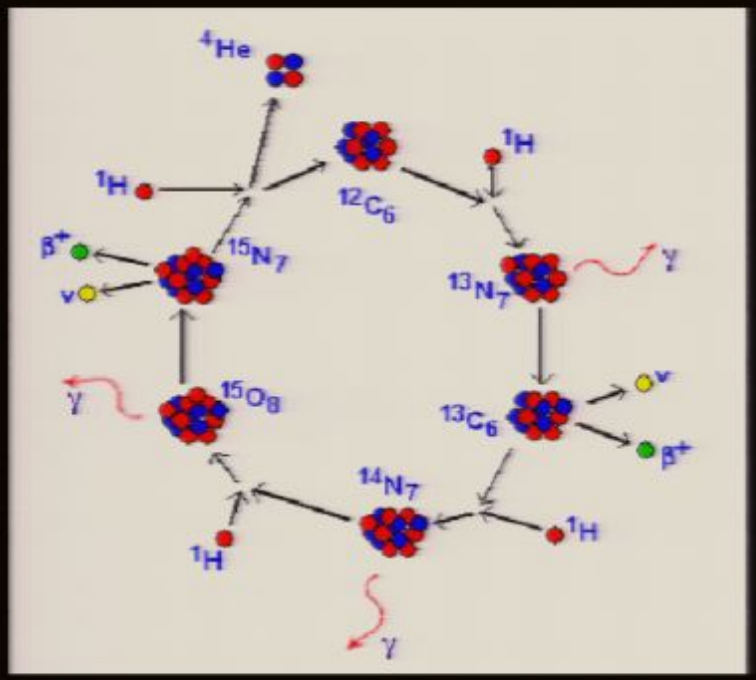
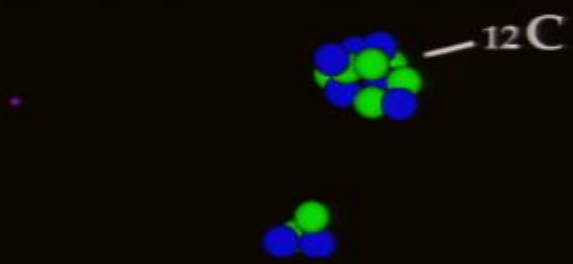


Alpha Particle Released, and 12C Remains

Neutron — Proton



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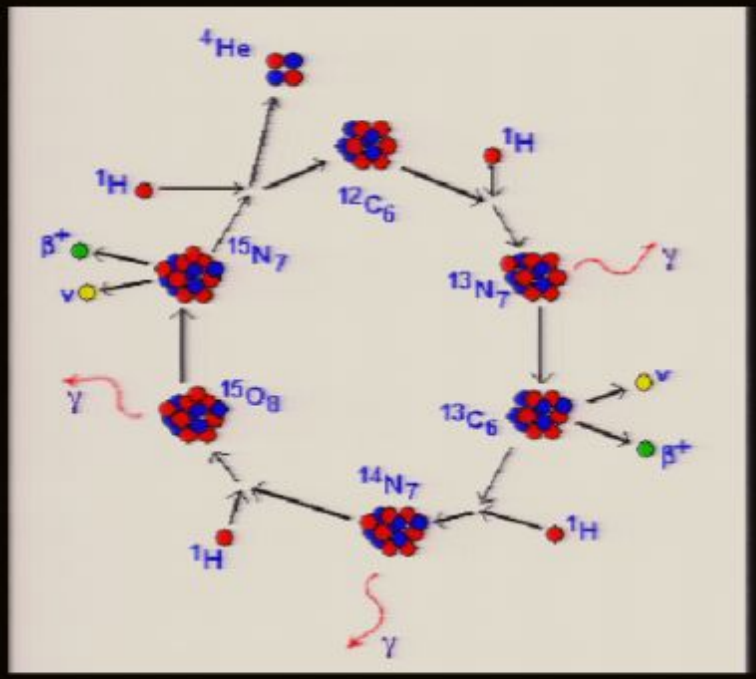

Carbon-Nitrogen-Oxygen (CNO) Cycle

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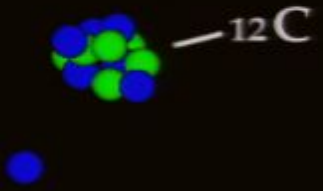

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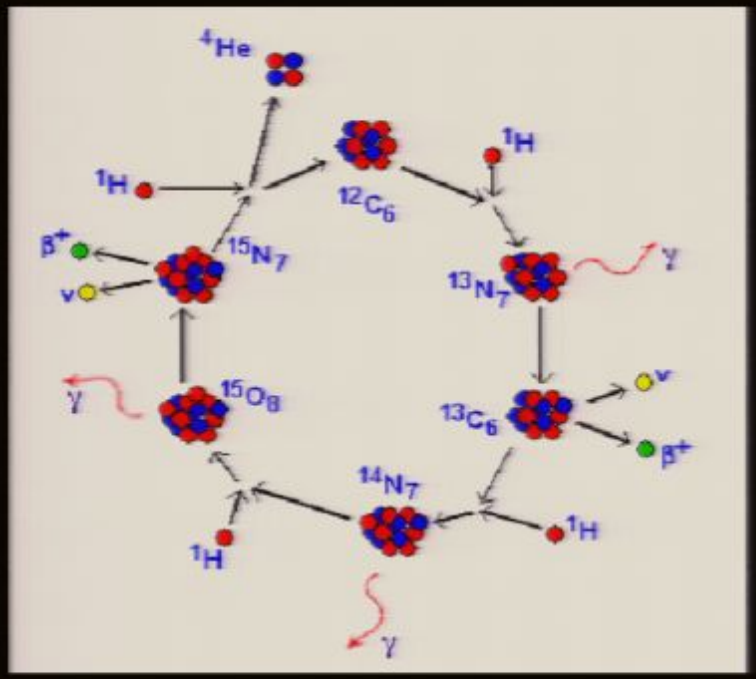

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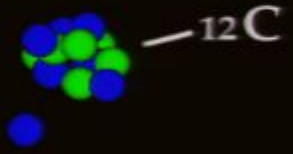

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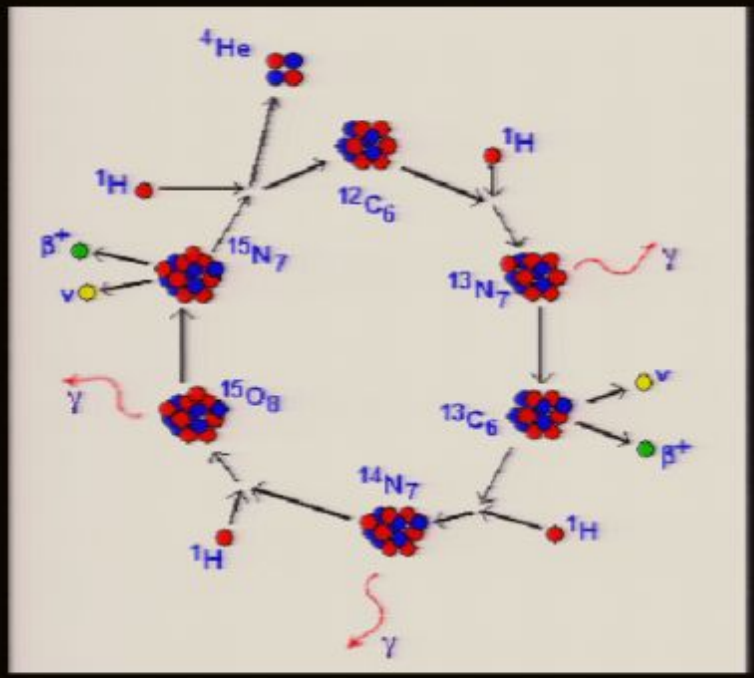
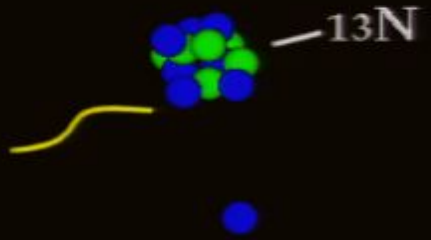


Gamma Ray Released

Neutron — Proton



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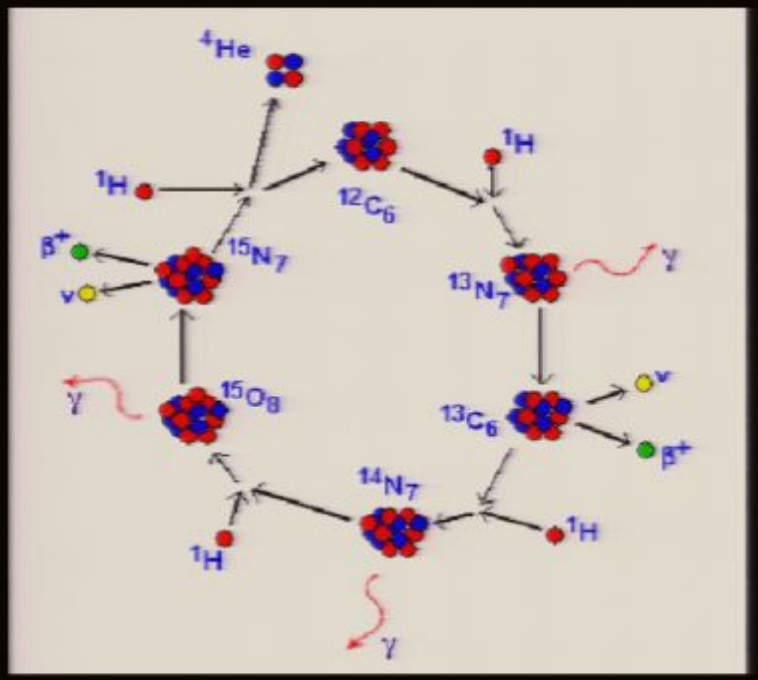
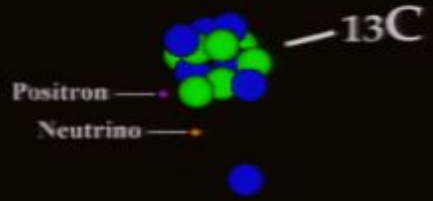


^{13}N ß$^+$ Decays Into ^{13}C

Neutron — Proton



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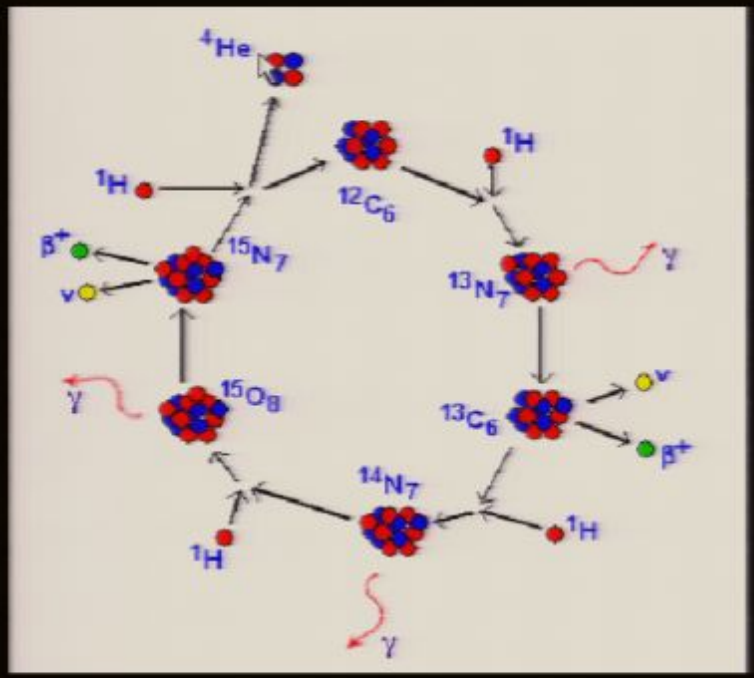

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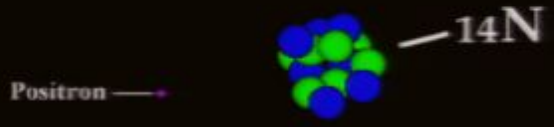
Neutron — Proton



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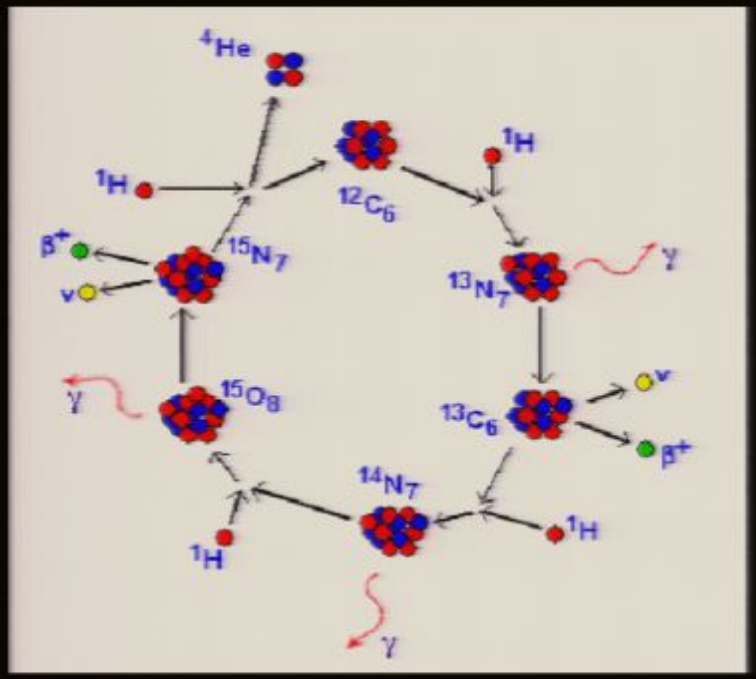
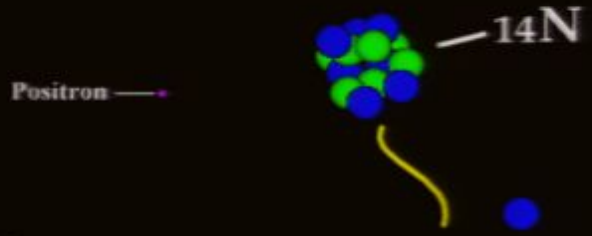


Gamma Ray Released

Neutron — Proton



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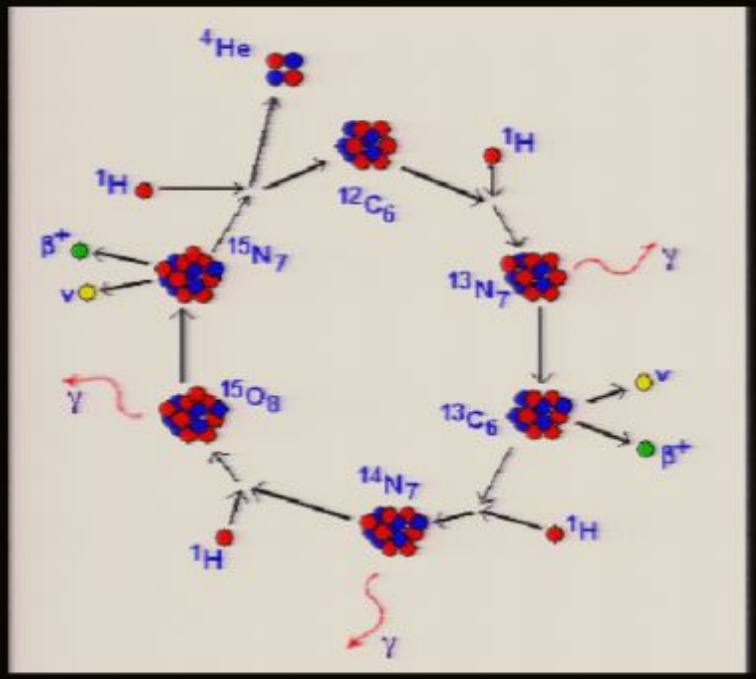

Stray 1H Absorbed Into 14N, Forming 15O

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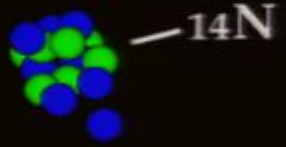

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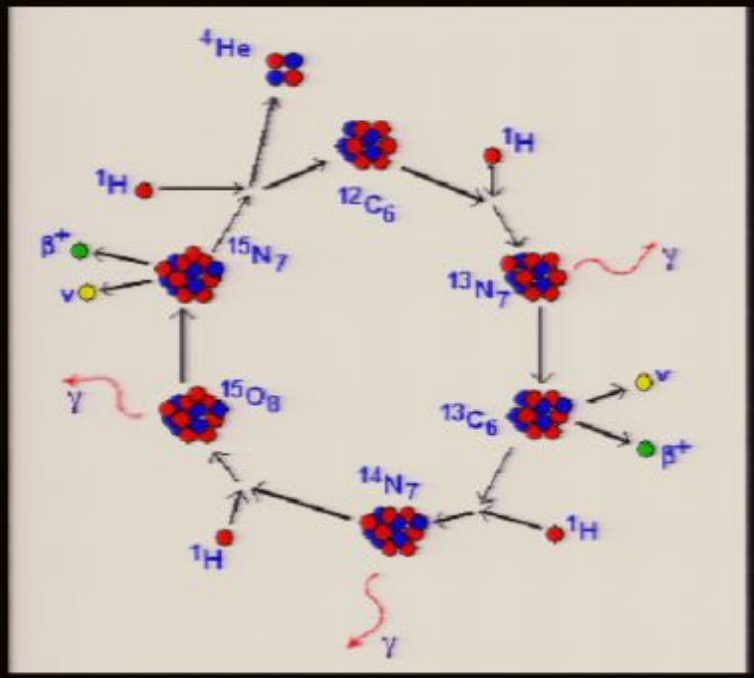

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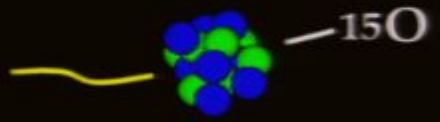

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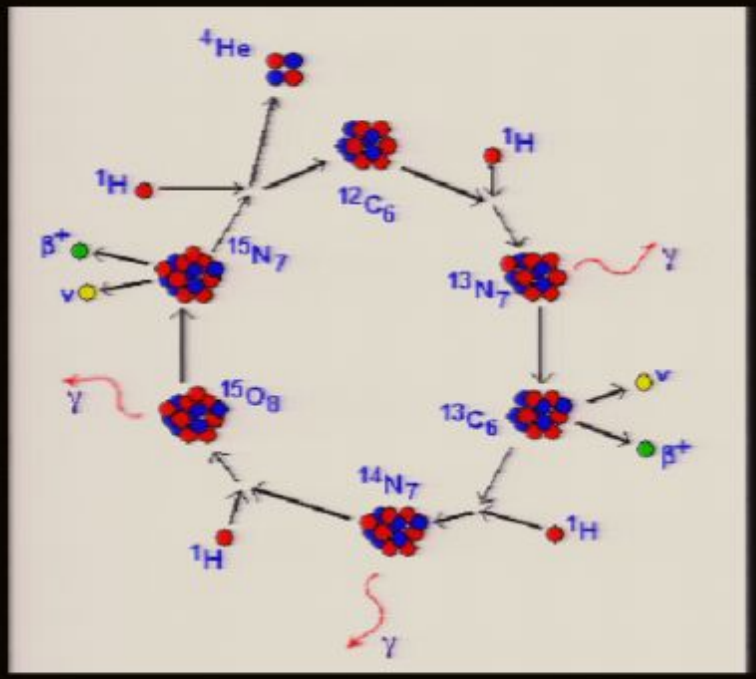

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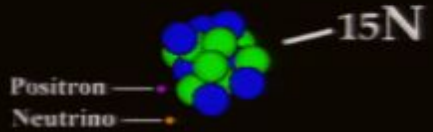

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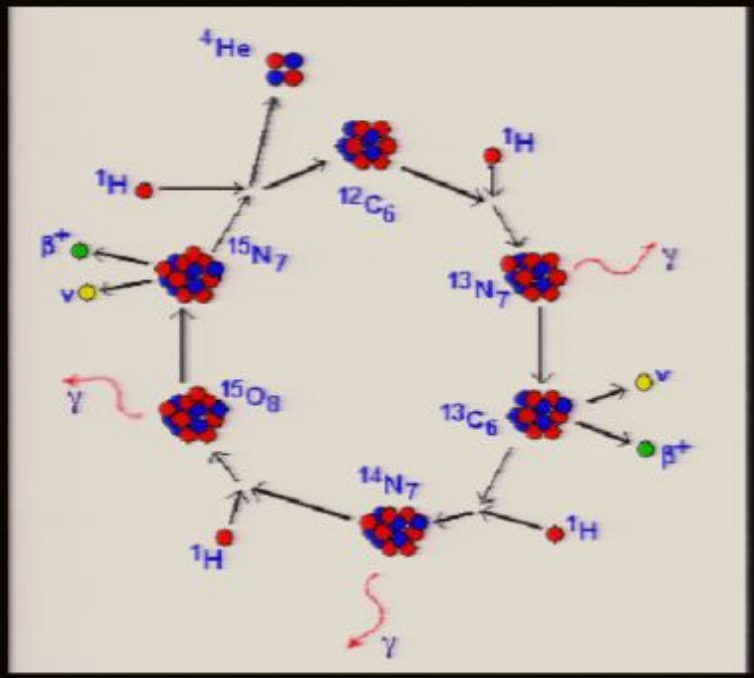

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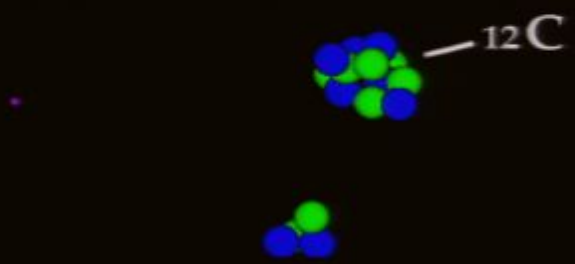

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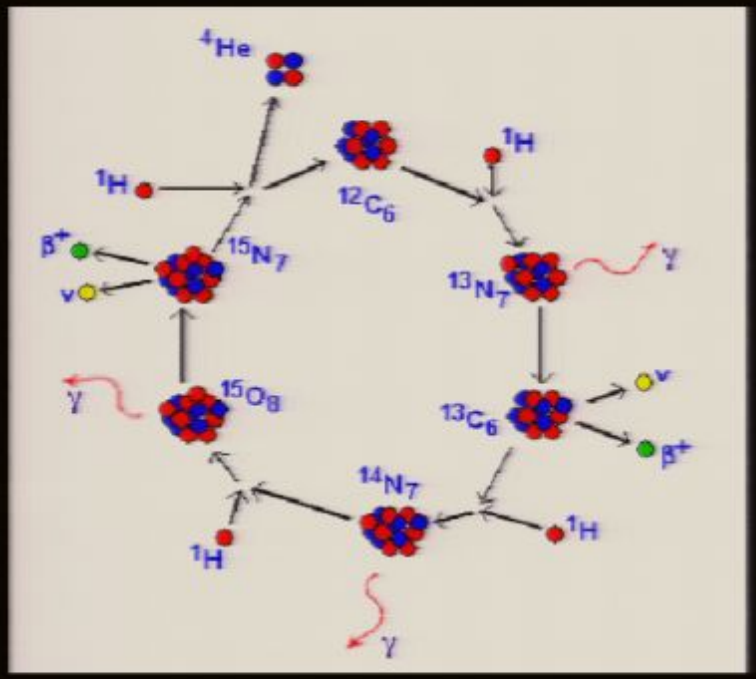

Carbon-Nitrogen-Oxygen (CNO) Cycle

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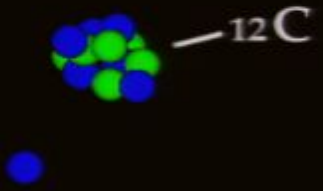
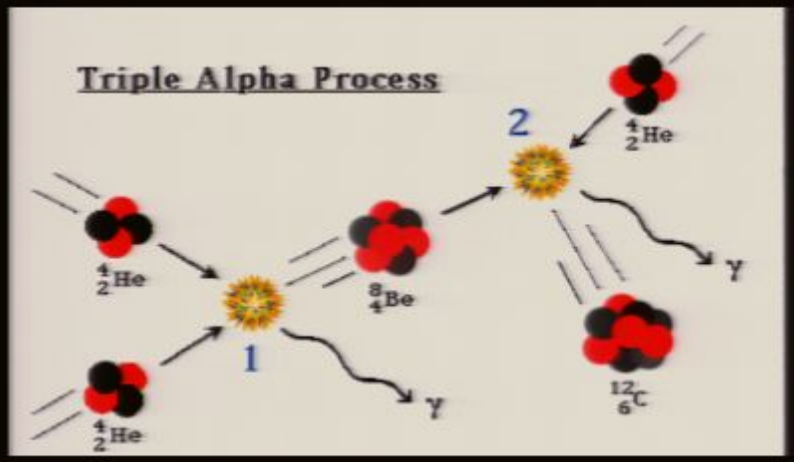


Beyond Helium

As Hydrogen is exhausted in the core of the star, Helium nuclei merge to create Beryllium with again fuses with another Helium nucleus to give Carbon and then to Oxygen then to Silicon until we finally end up with Iron.

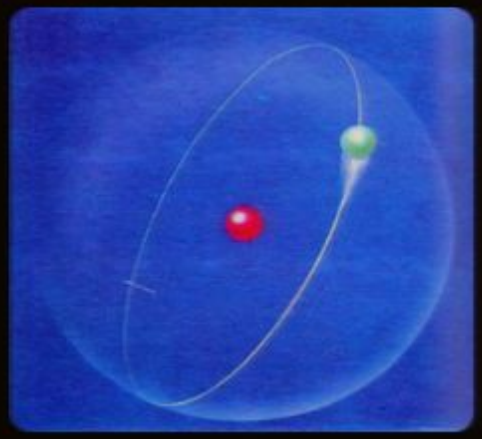


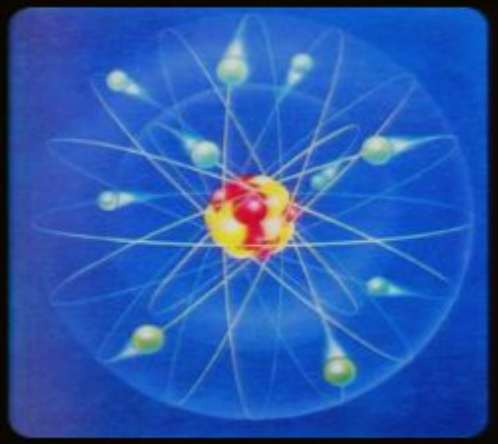
Pressure balance in a star

Pressure balance in a star

thermal pressure = force of gravity

Model of an Atom





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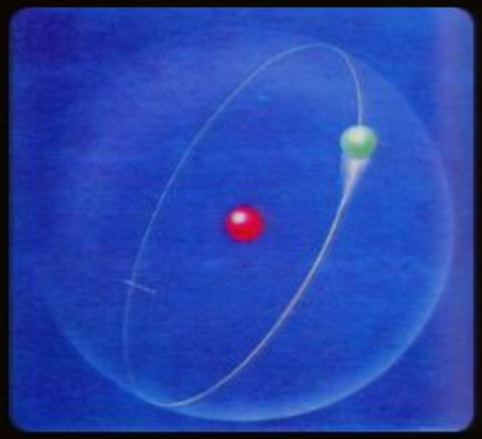
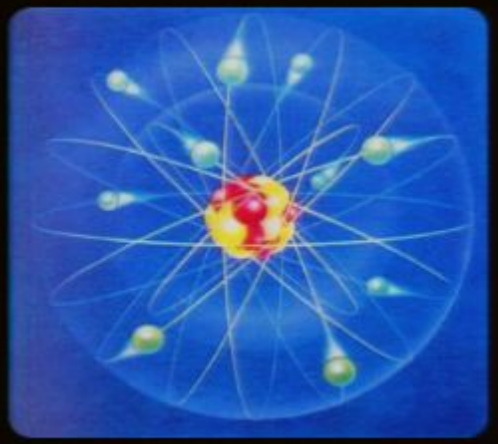




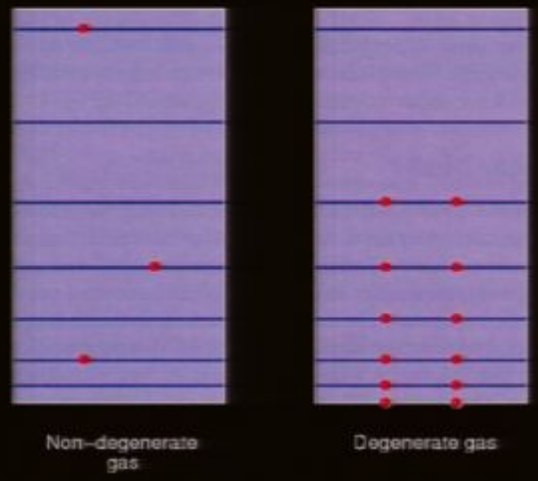
... an atom consists of mainly empty space ...

Electron Degeneracy Pressure

$$R = N_e^{\frac{2}{3}} \frac{h^2}{8Gm_e m_p M}$$

- Pauli Exclusion Principle:
  No two electrons (fermions) can occupy the same position in space at the same time doing the same thing.
- Electrons are packed side by side in a white dwarf
- This prevents it from collapsing any further

Calculate pressure



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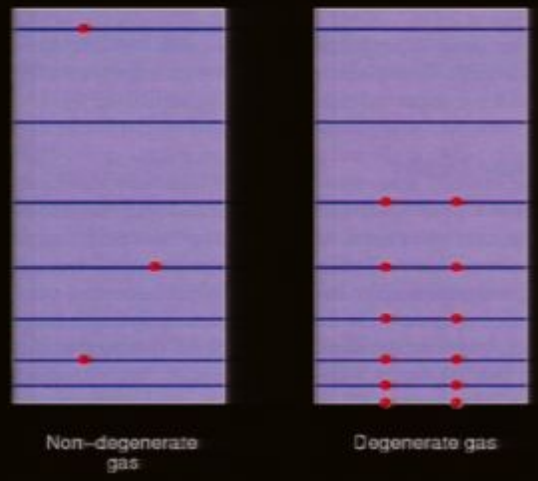

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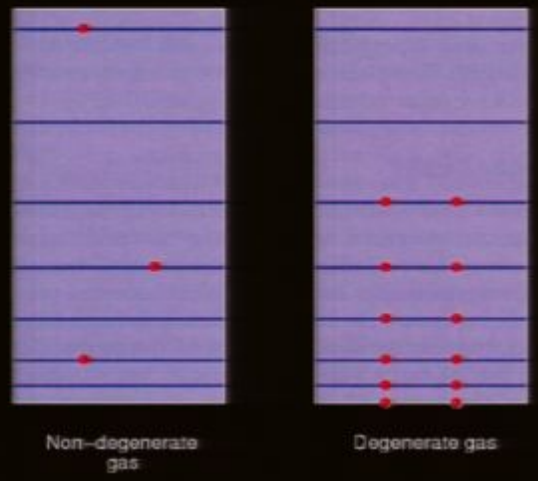

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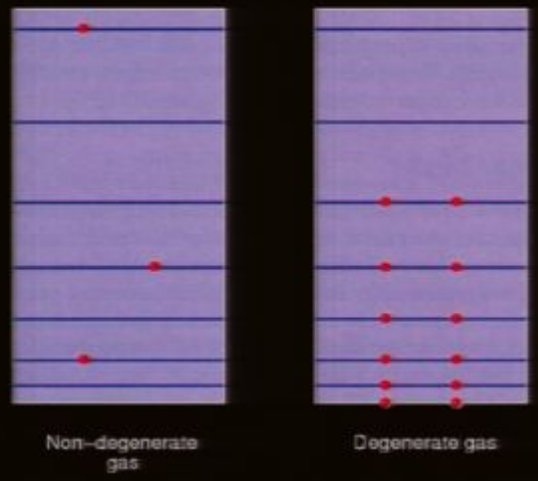

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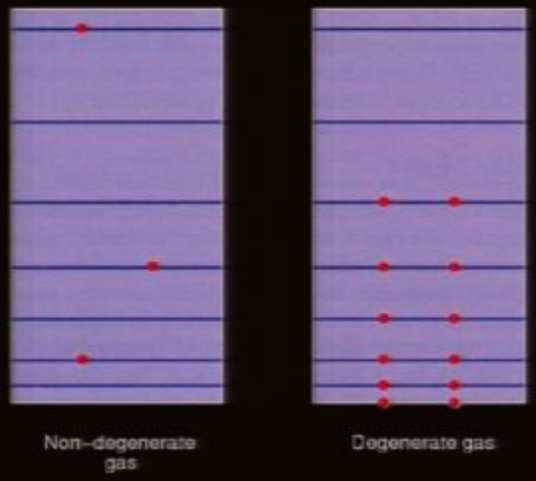


Electron Degeneracy Pressure

$$R = N_e^{\frac{2}{3}} \frac{h^2}{8Gm_e m_p M}$$

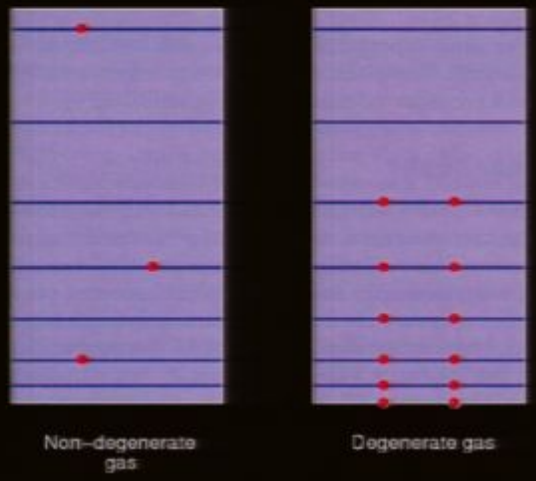
$$h = 6.6261 \times 10^{-34}$$

$$G = 6.6726 \times 10^{-11}$$

$$m_e = 9.1094 \times 10^{-31}$$

$$m_p = 1.6726 \times 10^{-27}$$

$$M = 1.989 \times 10^{30}$$

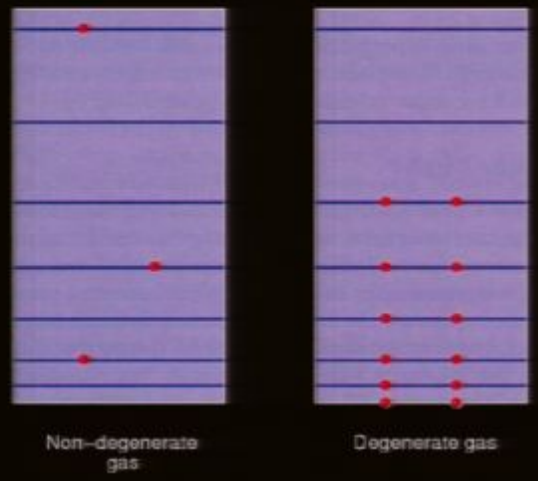


Electron Degeneracy Pressure

$$R = N_e^{\frac{2}{3}} \frac{h^2}{8Gm_e m_p M}$$

$$\left(5.95 \times 10^{56}\right)^{\frac{2}{3}}$$

$$2.7 \times 10^{-31}\, m$$



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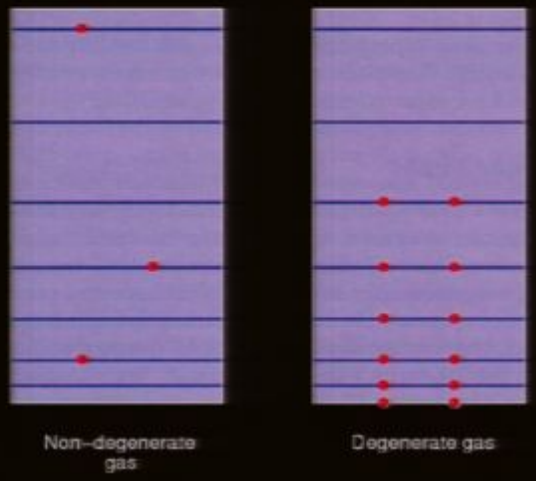
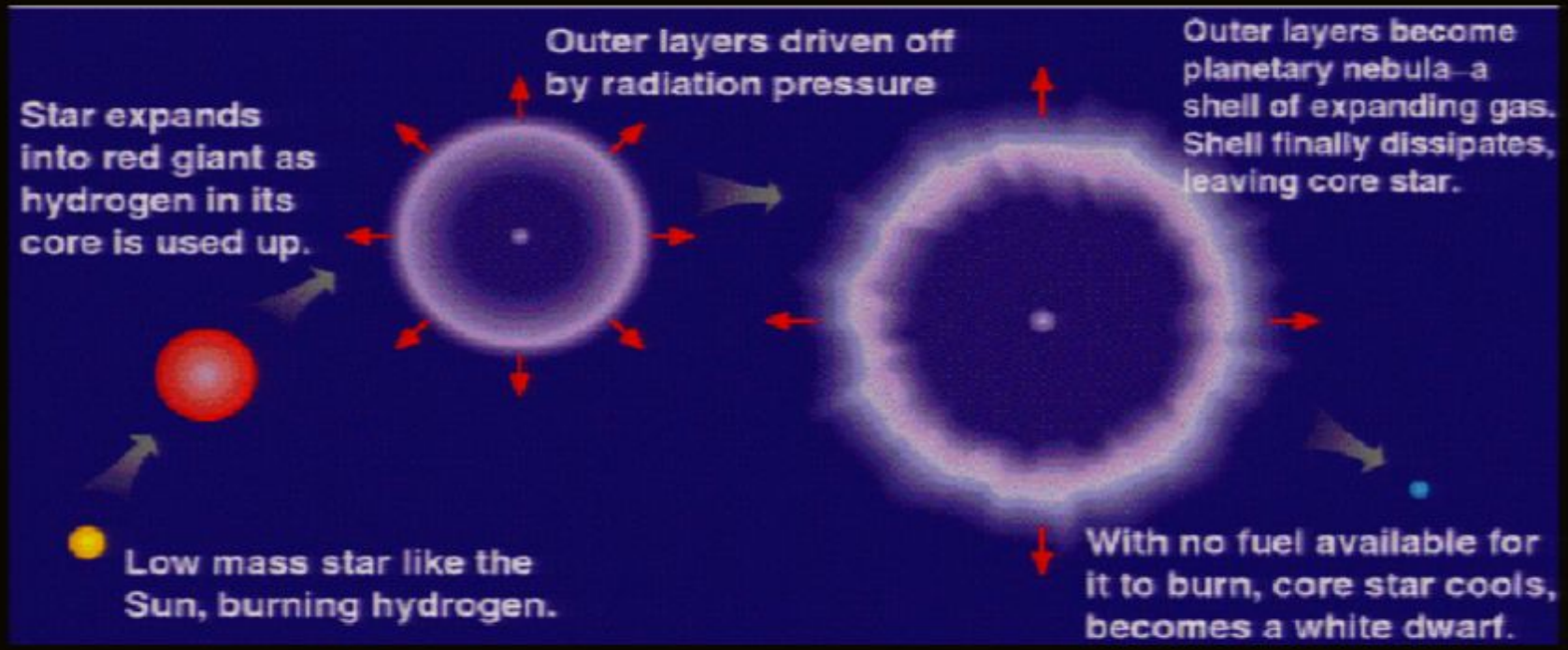
$$10^7\,m$$



Path to being a White Dwarf



7 solar mass star now reduced to about 20% of its original mass

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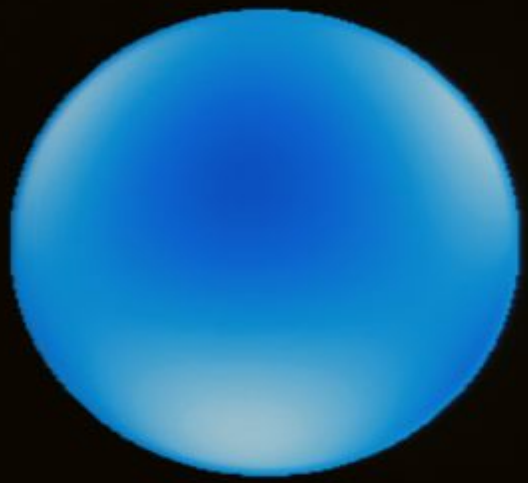

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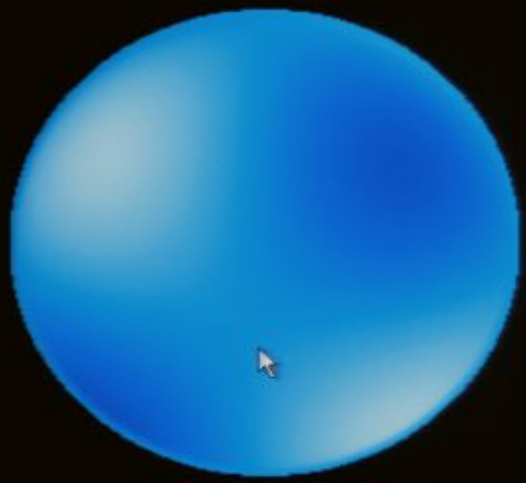

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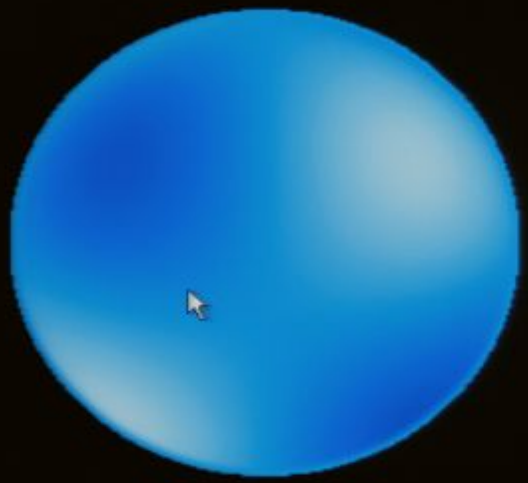
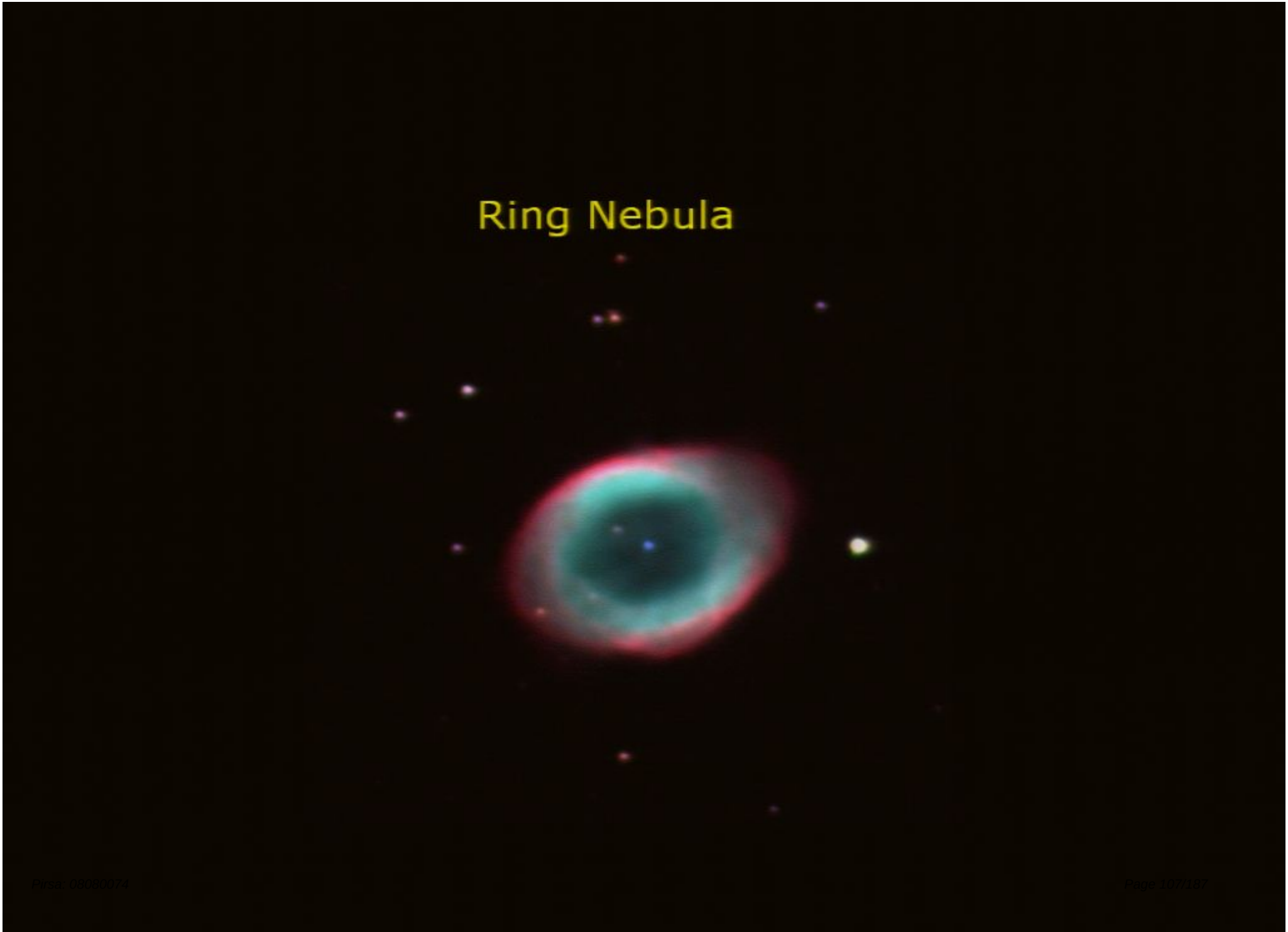
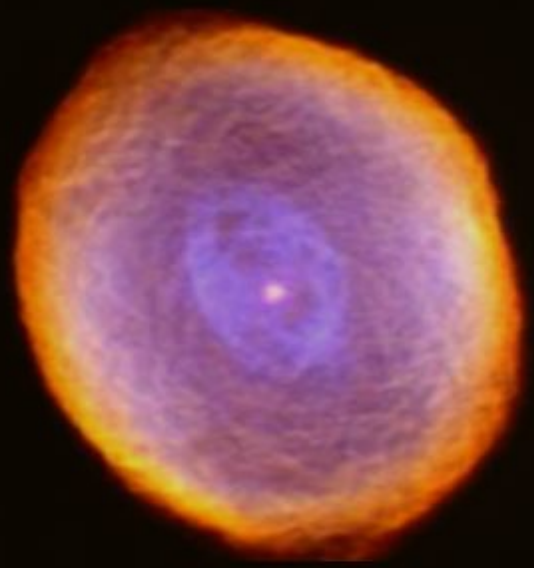


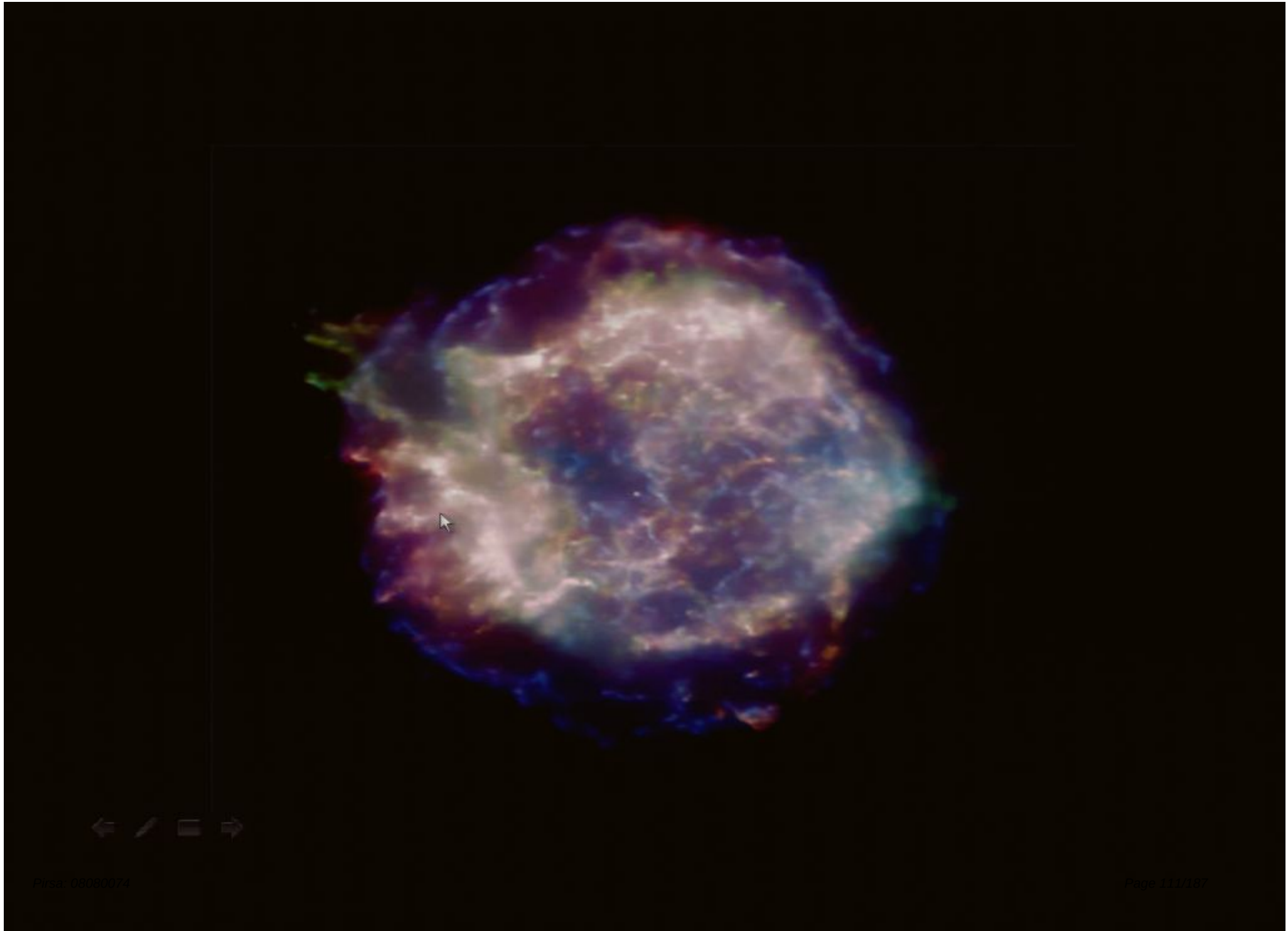

Ring Nebula


Ring Nebula

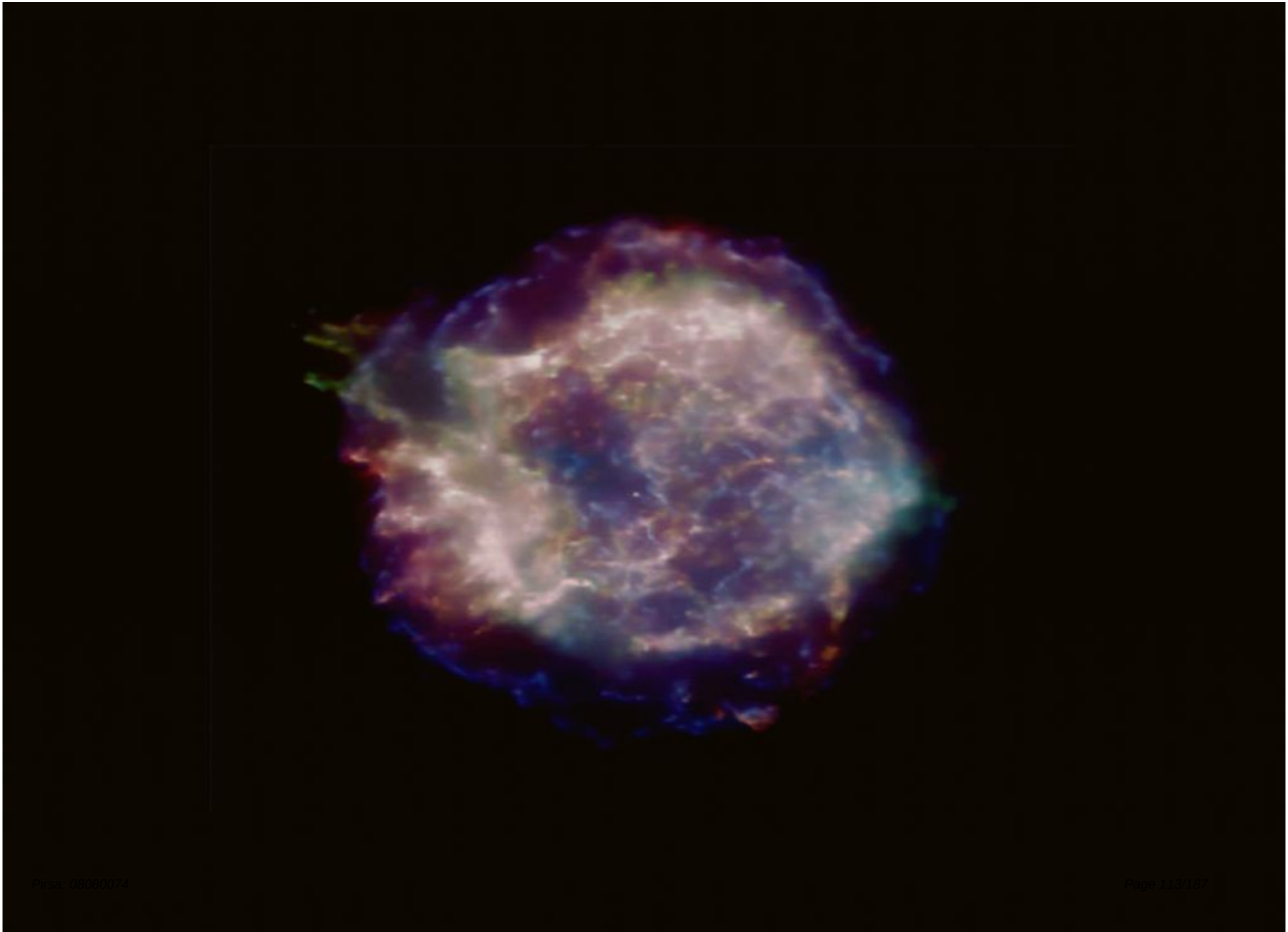
Cat’s eye nebula

Spirograph Nebula





Eskimo Nebula



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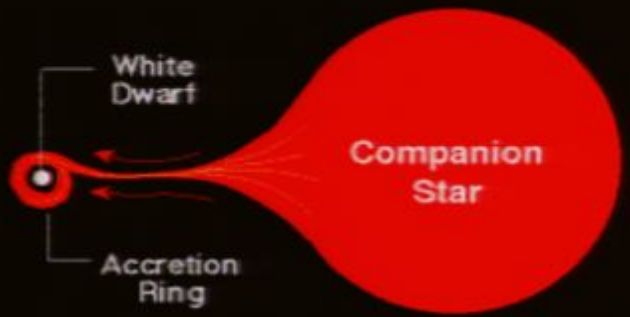
- Above this, even electron degeneracy pressure cannot counterbalance gravity
- What is the fate of a star more massive than this?

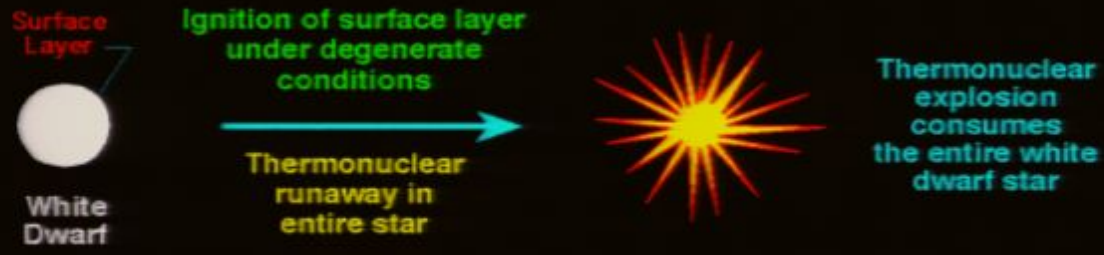
Supernova Remnant

- In the death of a high-mass star (<40 solar mass), the core is converted to neutrons and collapses catastrophically.
- The collapse and rebound creates a supernova.
- But what happens to the neutrons already at the very center of the core?
- The central core is left behind as a small, dense, sphere of neutrons → a neutron star.

Type 1a Super Nova



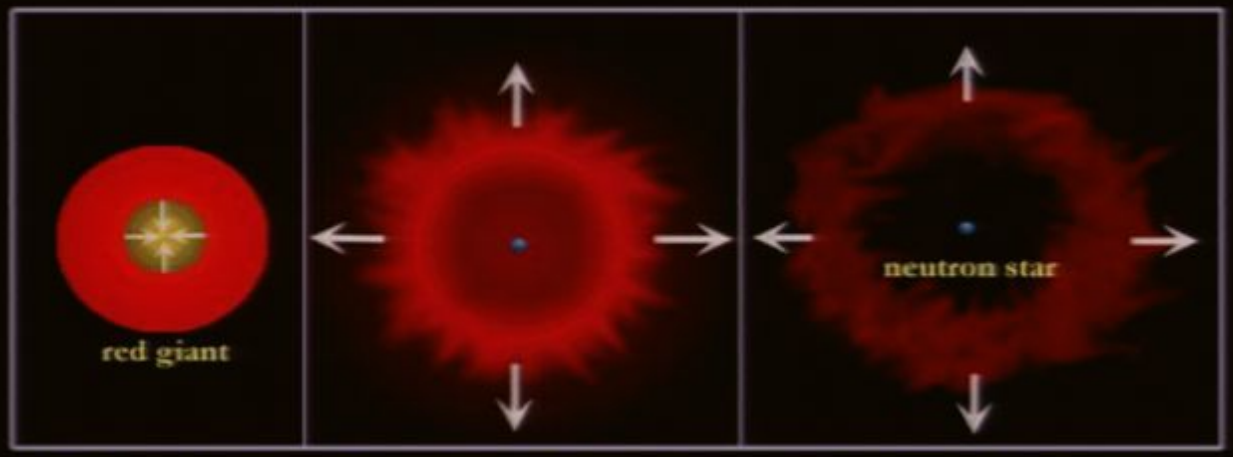
Thin hydrogen surface layer accumulated on white dwarf through accretion ring



Not of interest to black hole cosmologists, but type 1a's are great yard sticks in determining distances

Type II Supernovae: Birth of a neutron star

- *The core survives and is prevented from collapsing any further by neutron degeneracy pressure*
- *These are what we are interested in.*



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- Temperature 1 million degrees and cooling.
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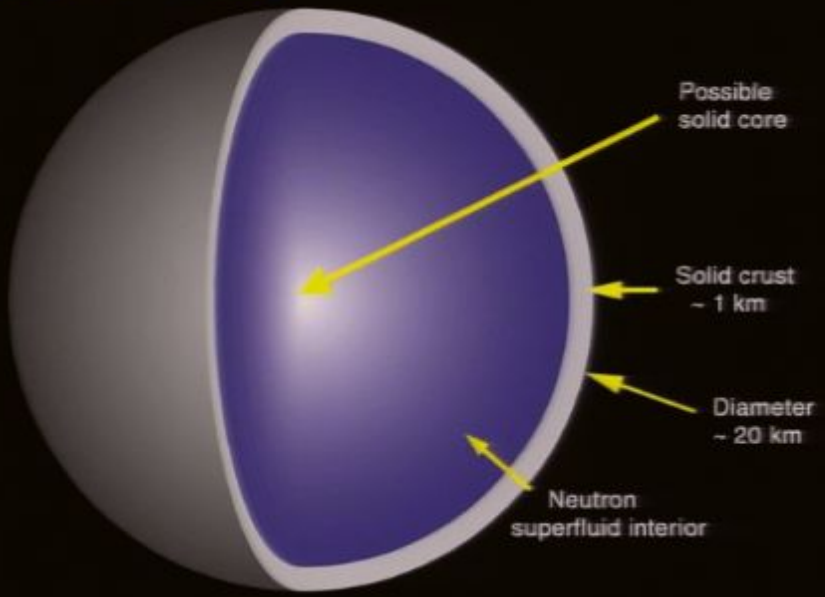

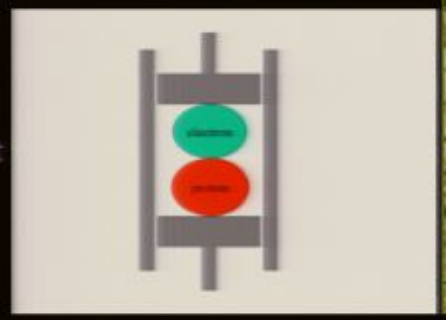

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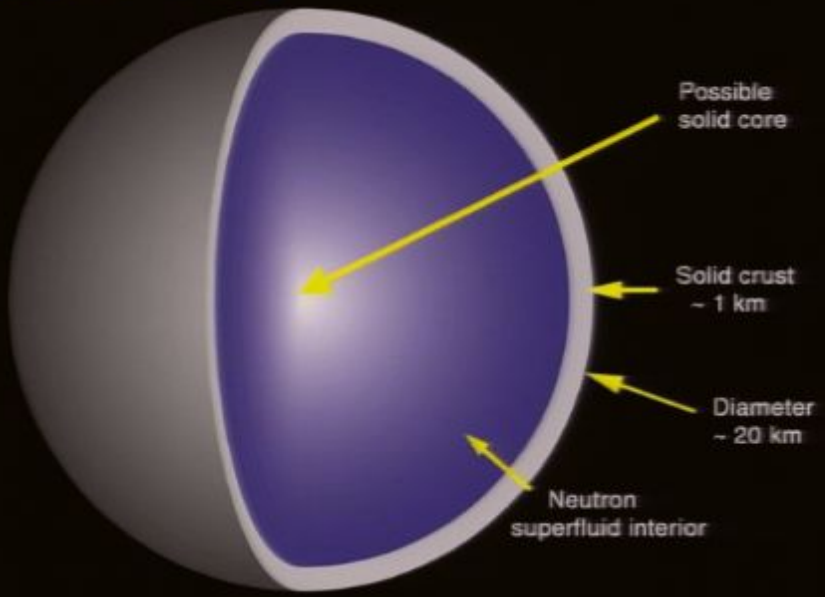

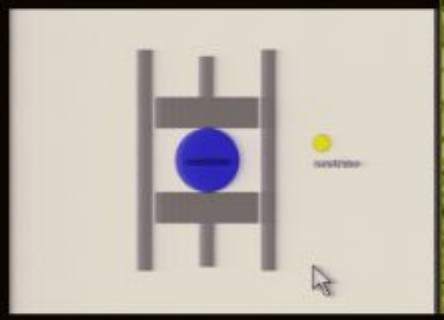

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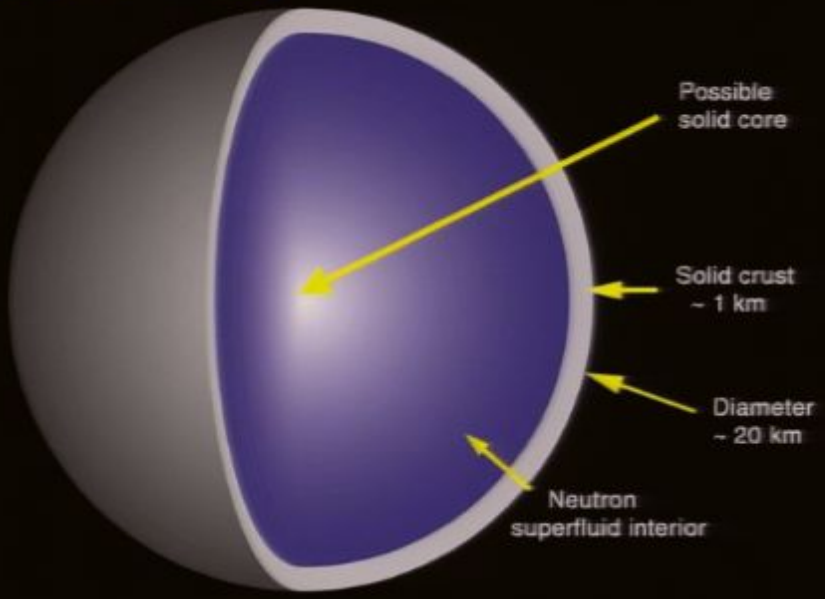

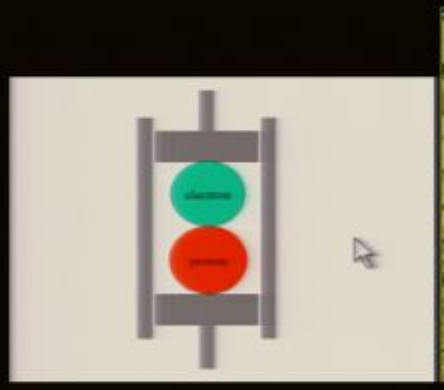

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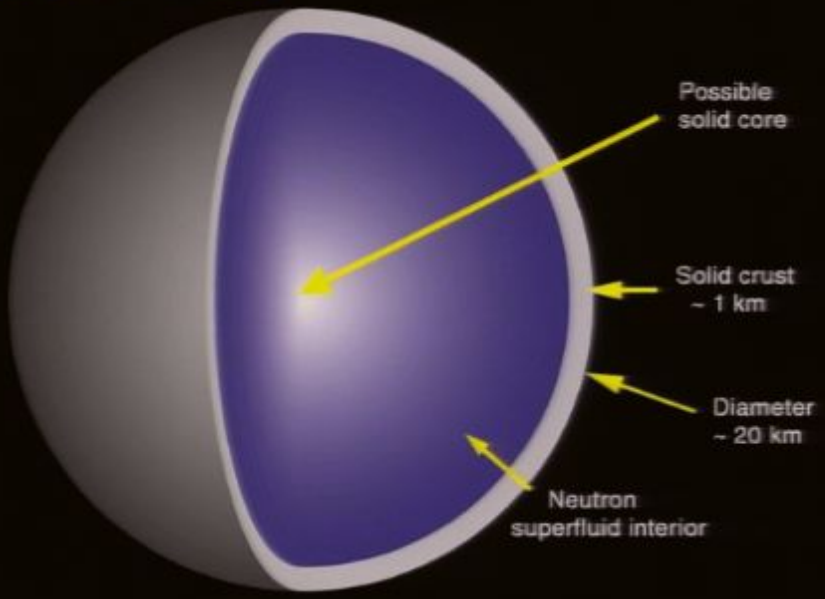

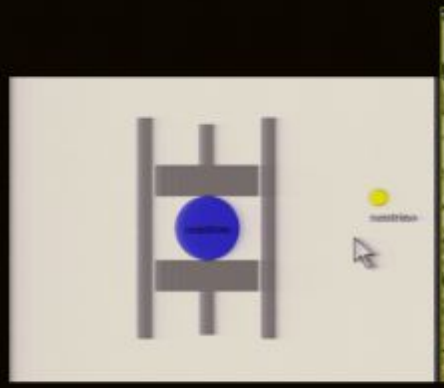

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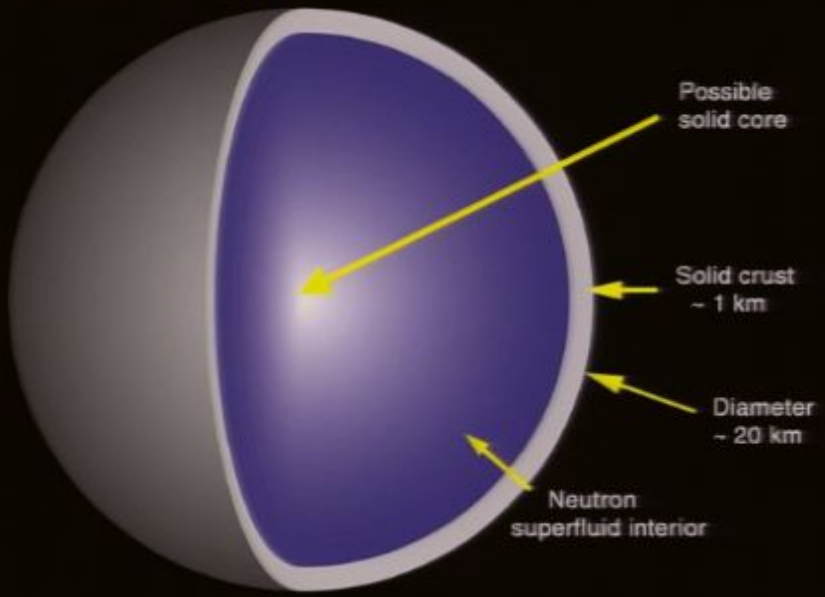

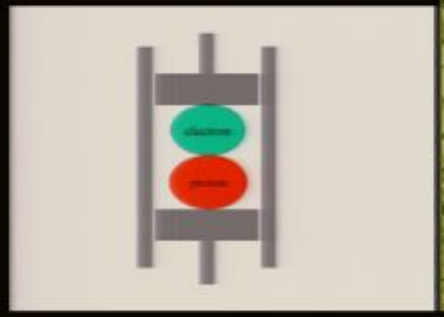

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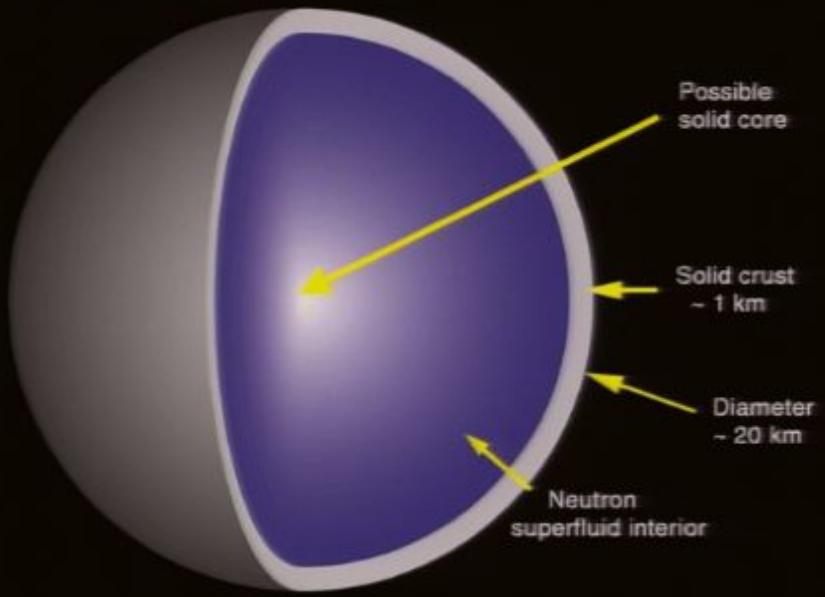

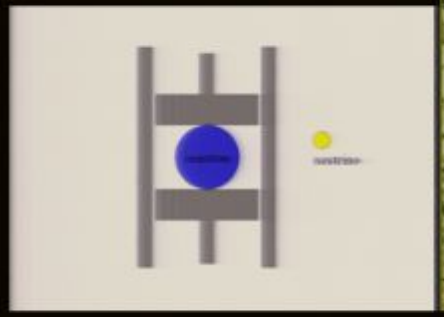

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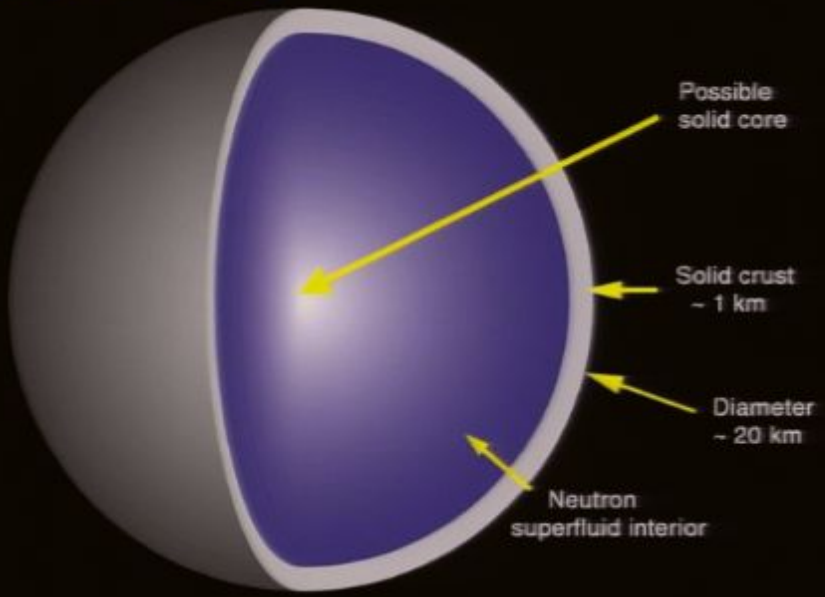

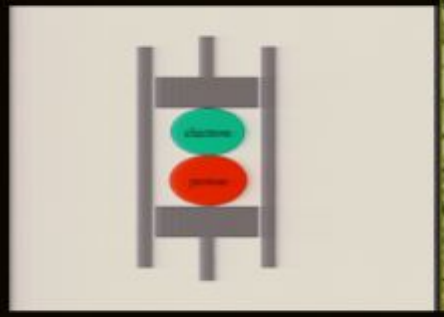

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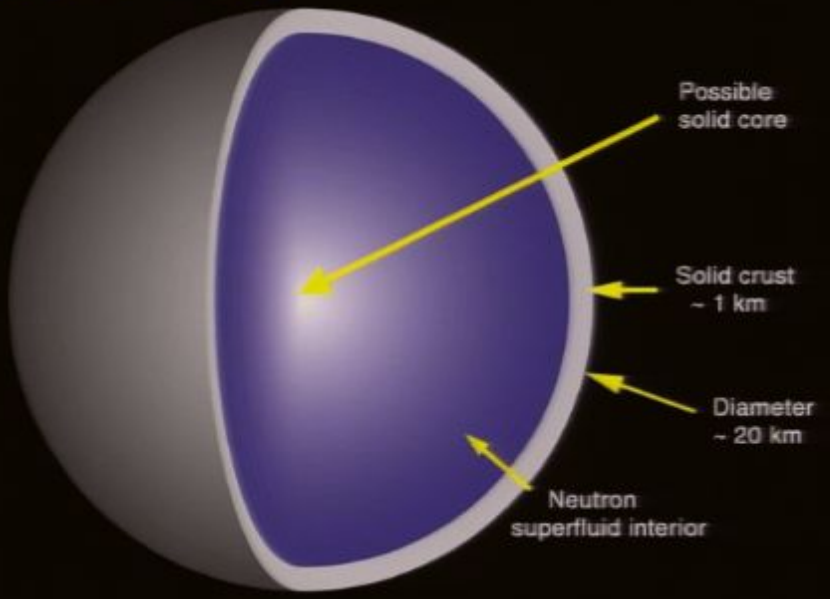

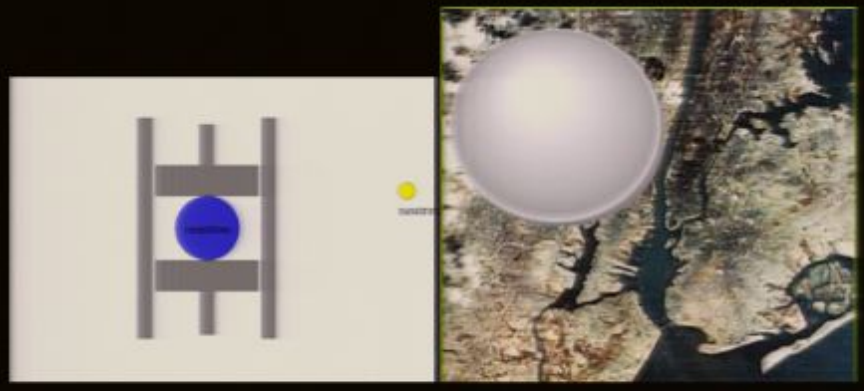

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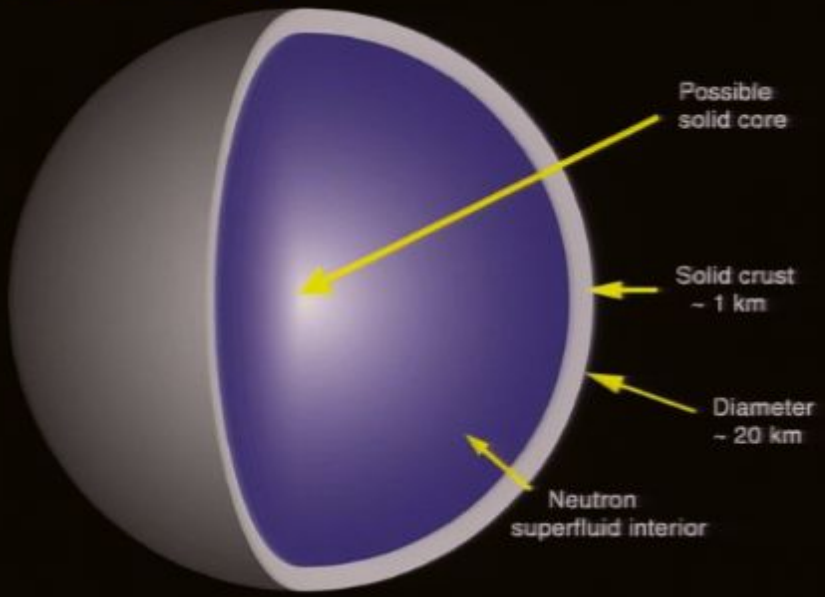

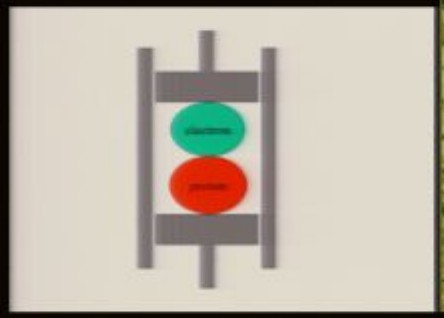

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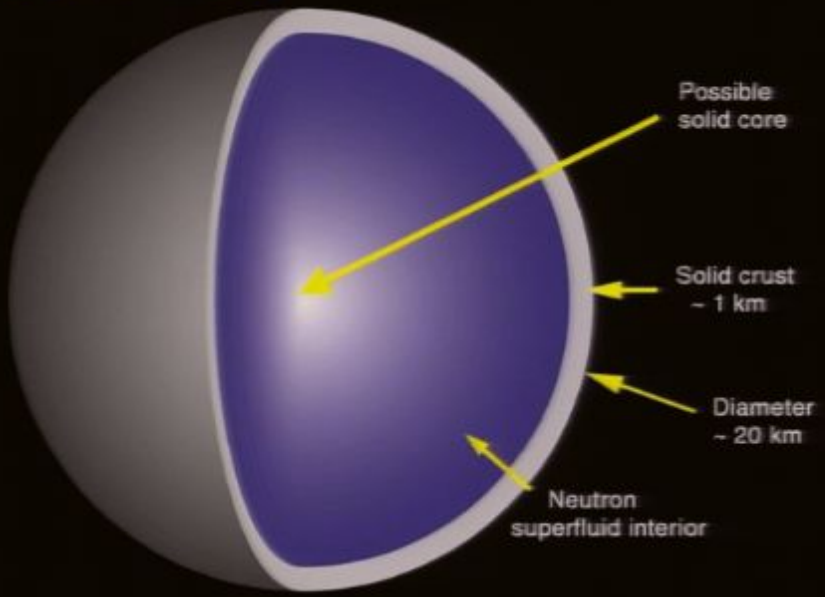

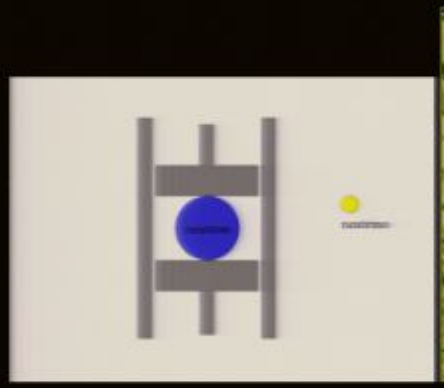

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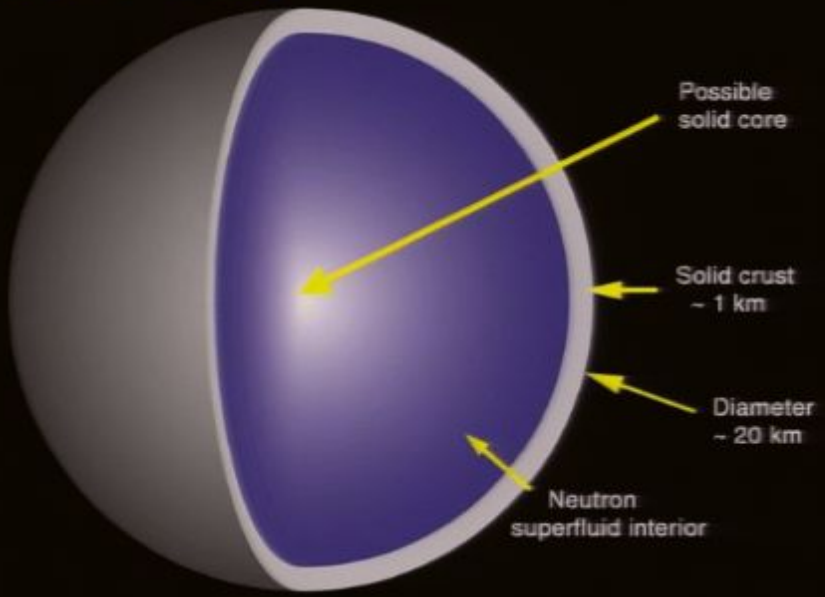

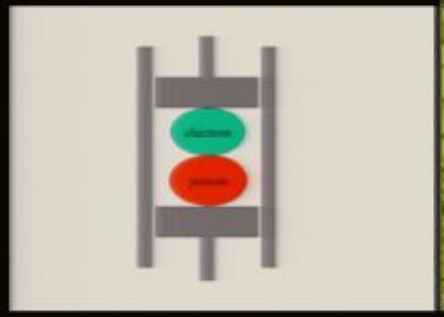

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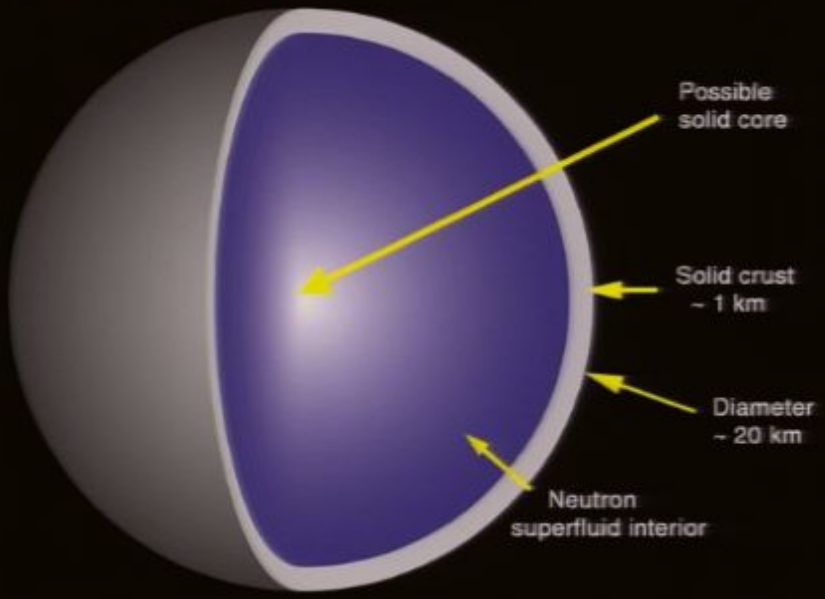

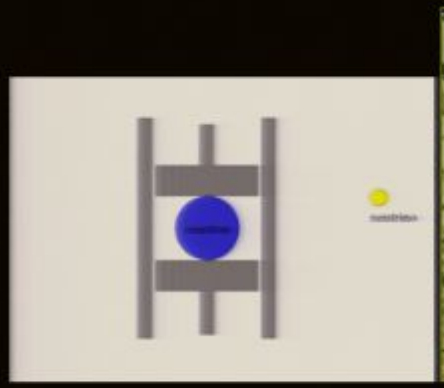

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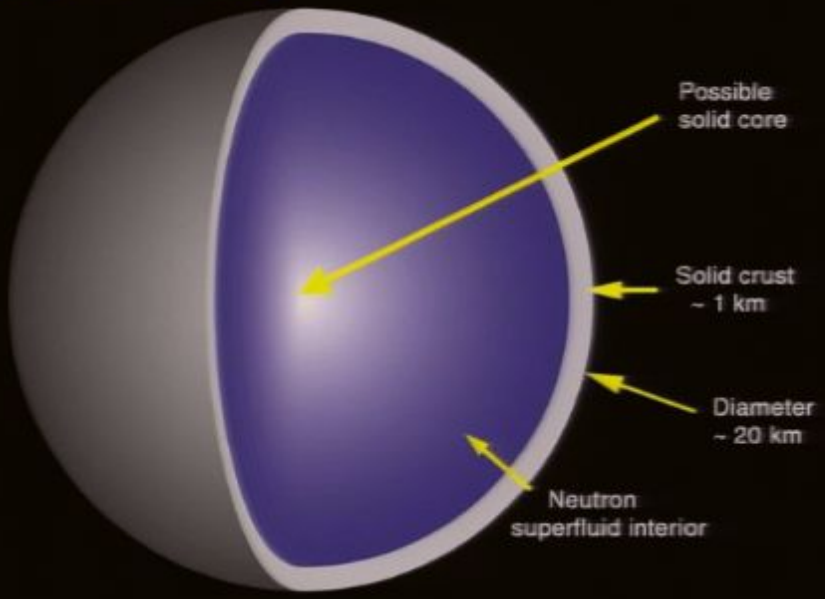

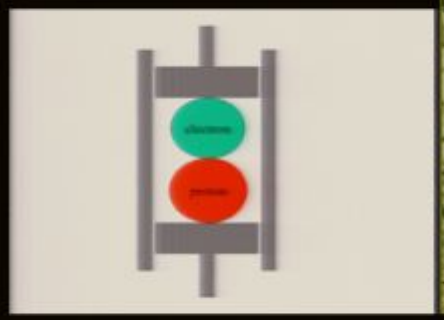

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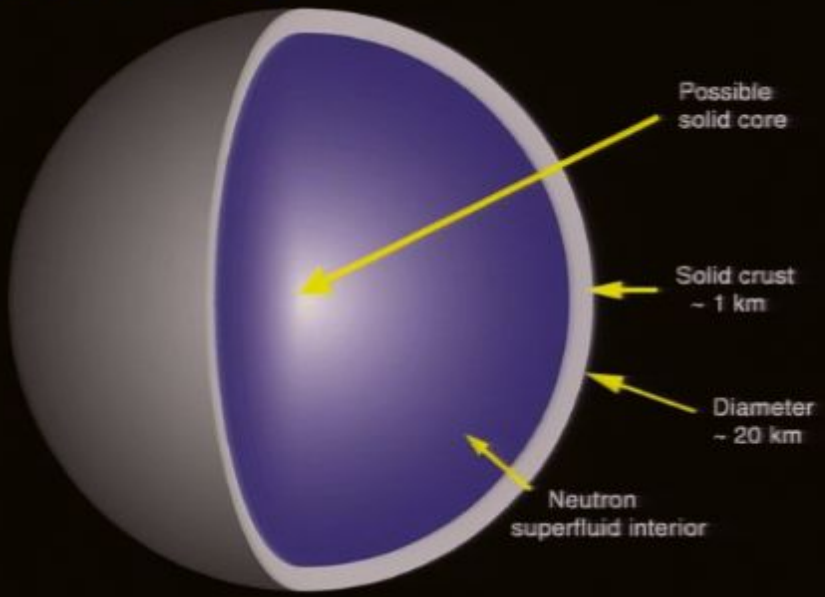

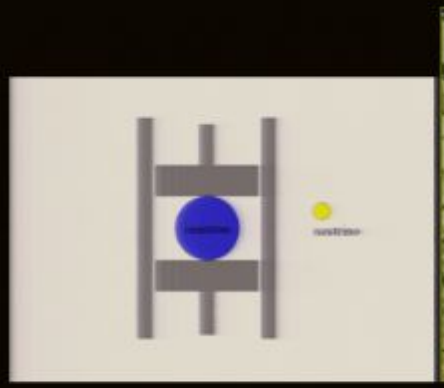

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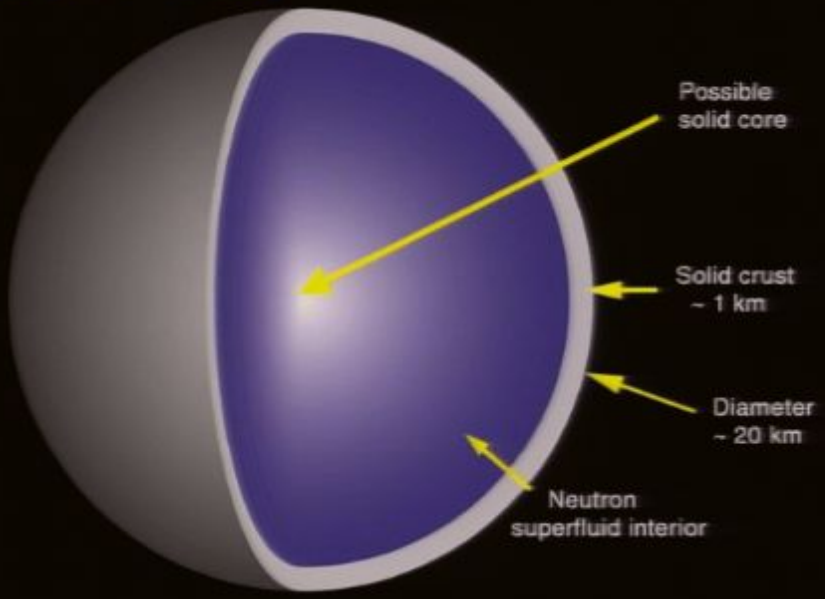

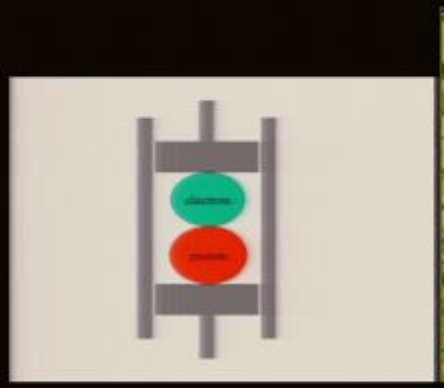

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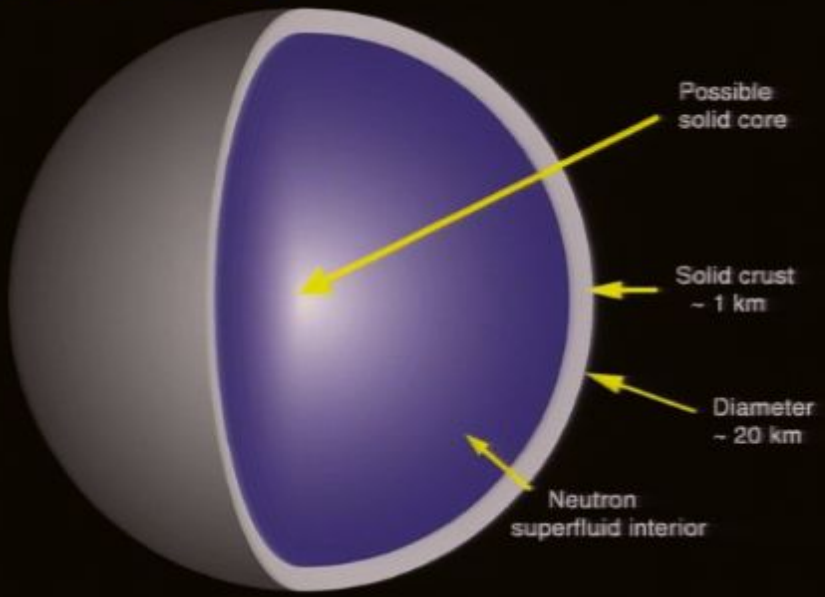

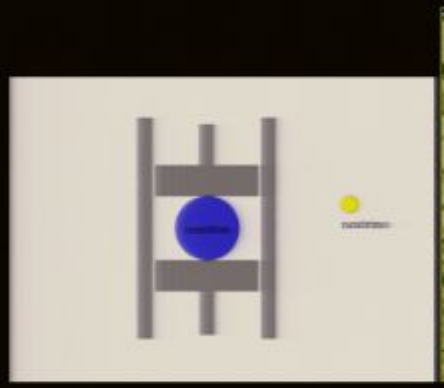

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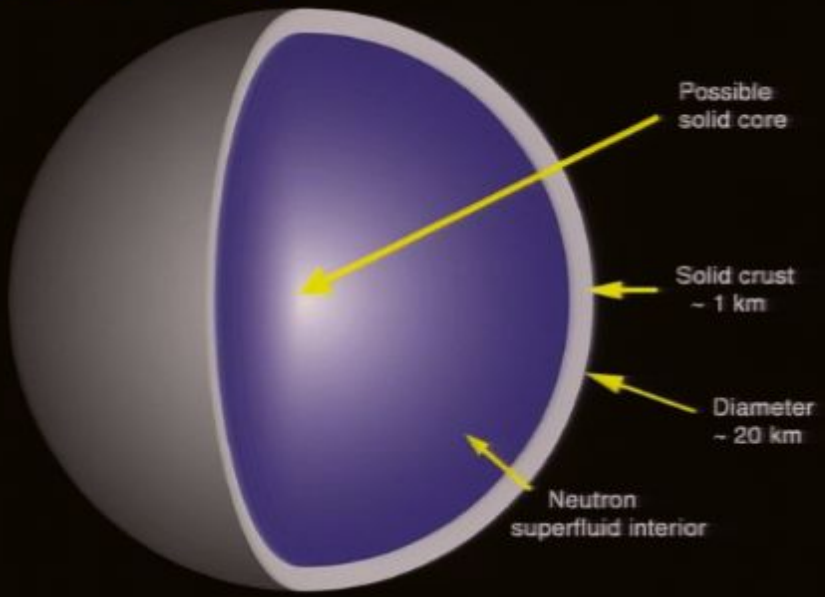

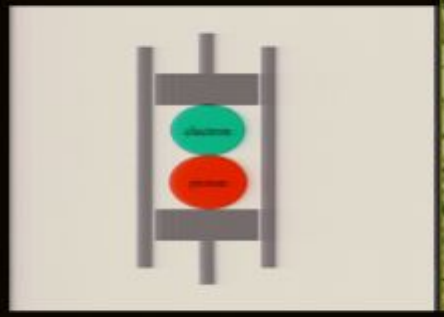

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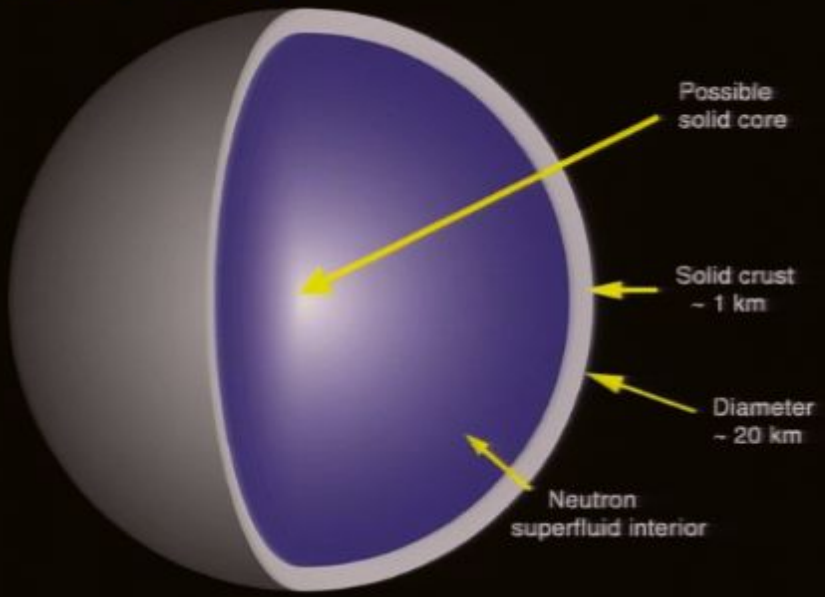

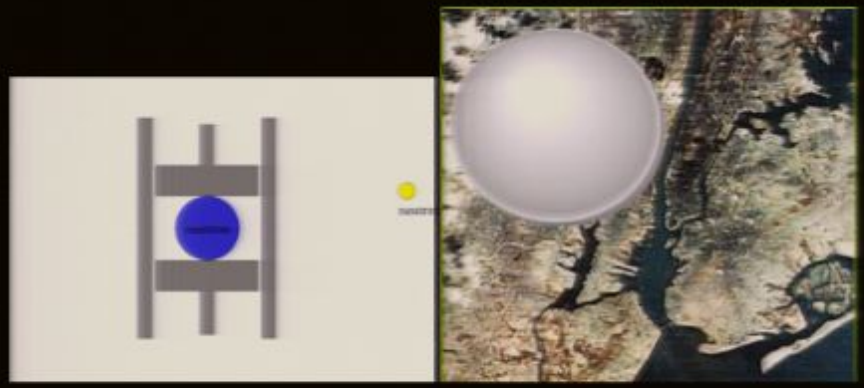

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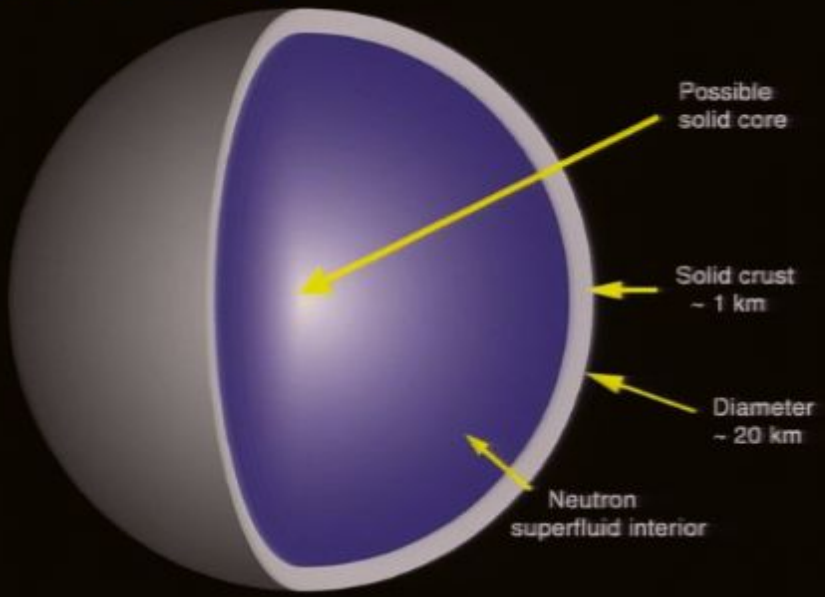

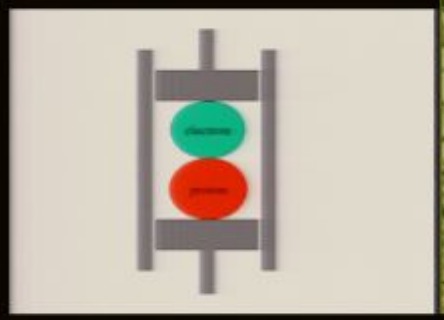

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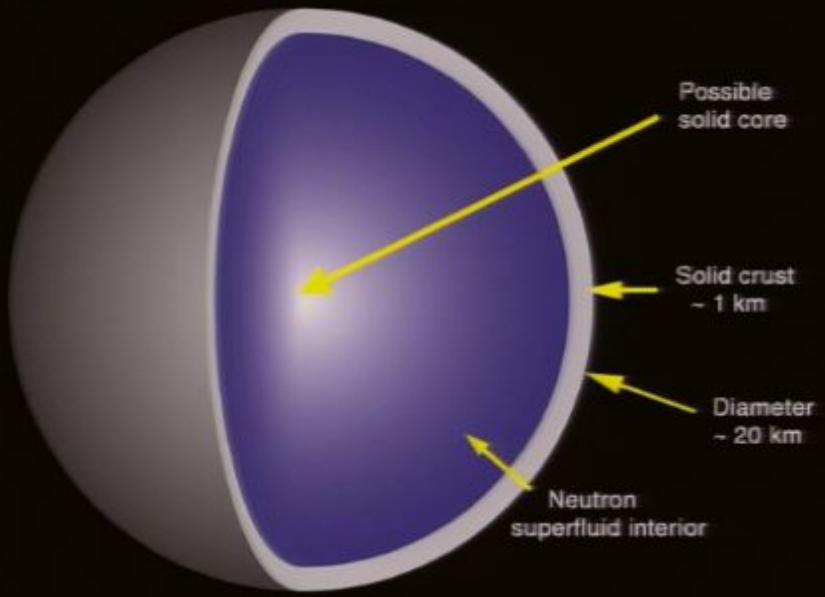

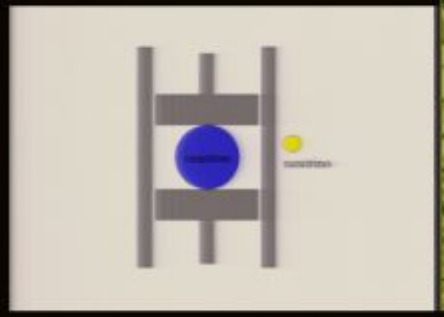

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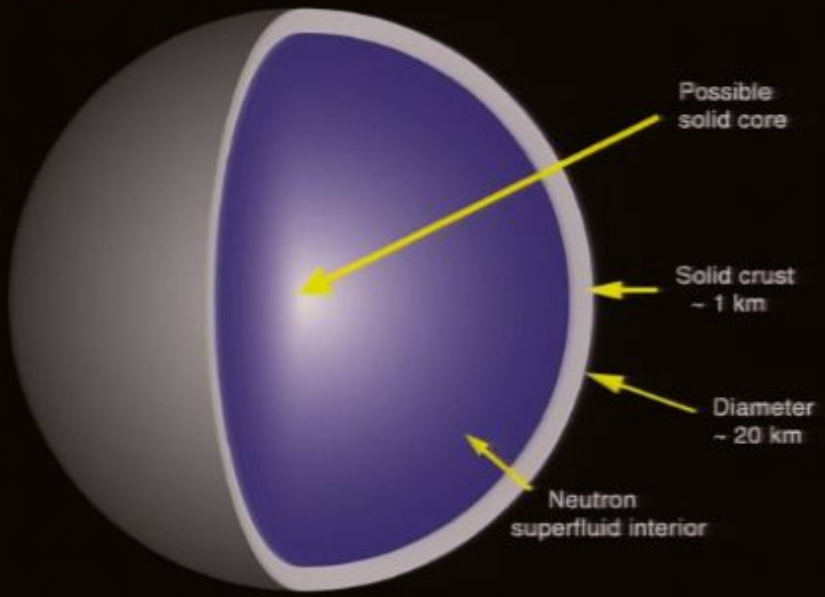

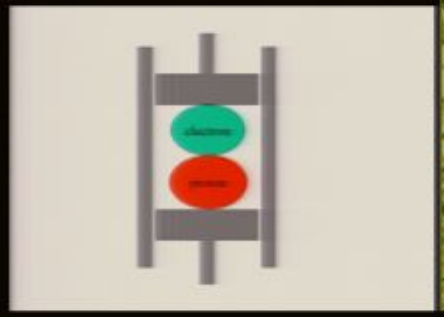

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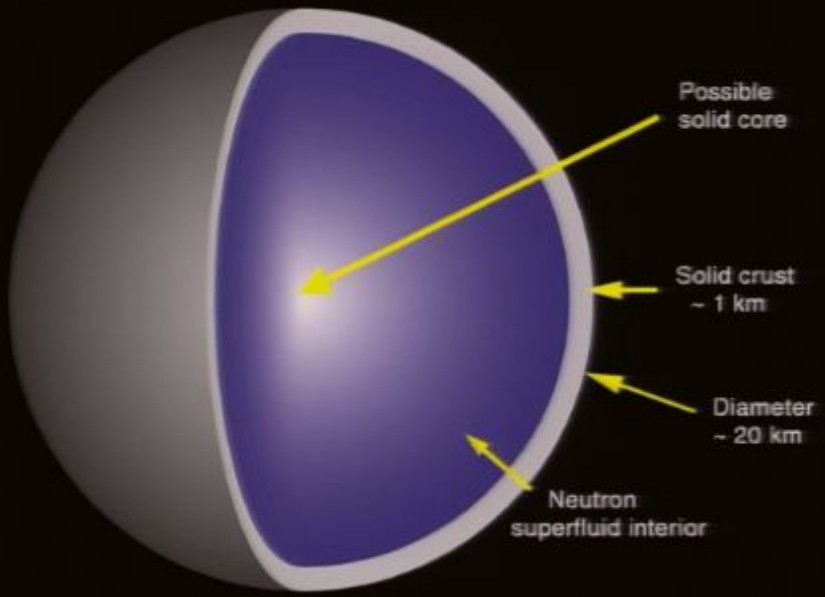

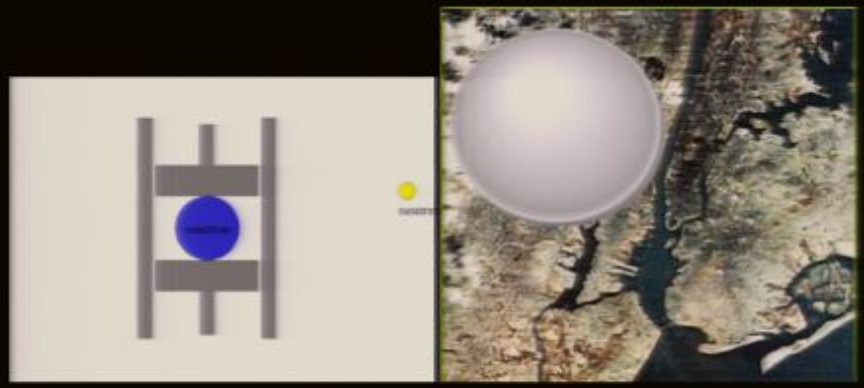

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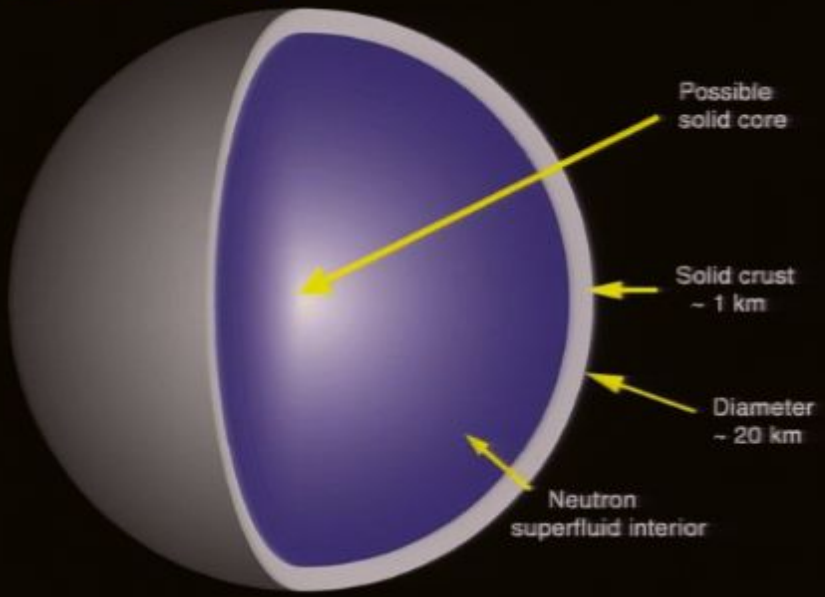

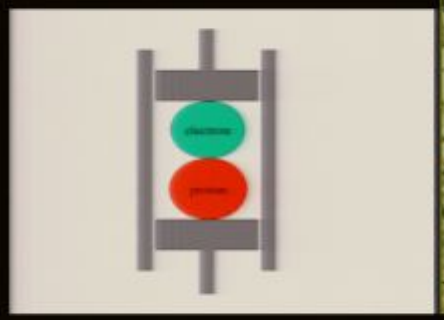

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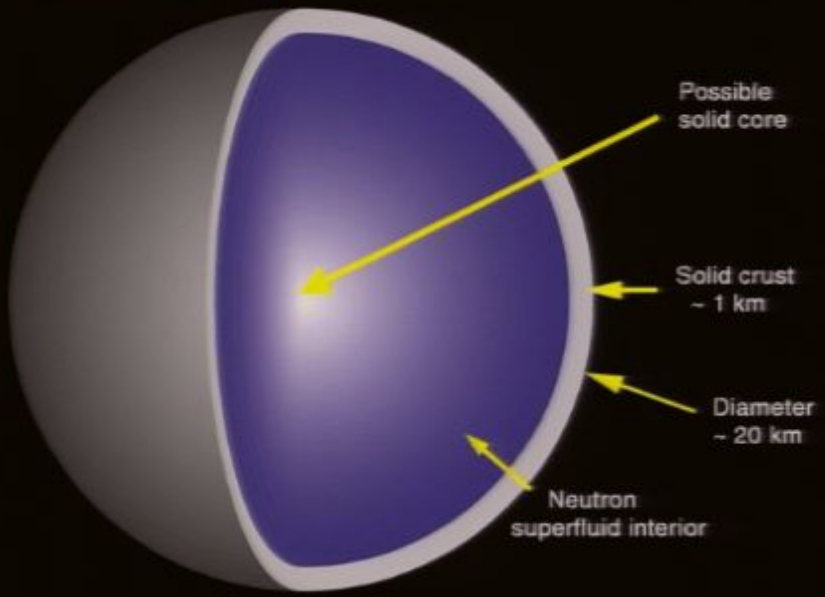

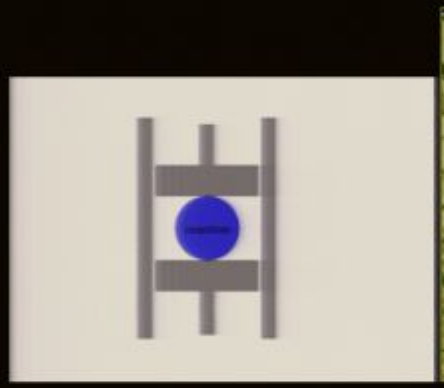

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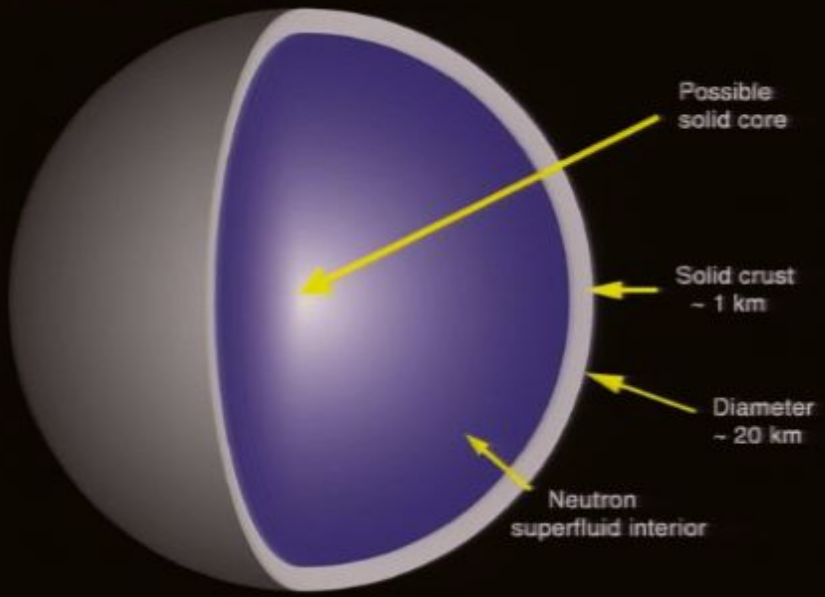

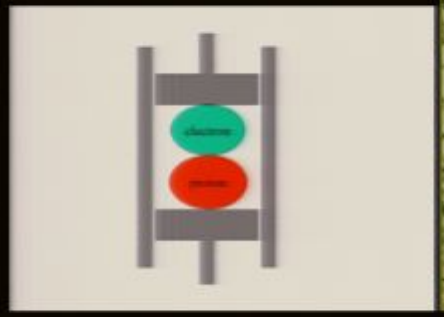

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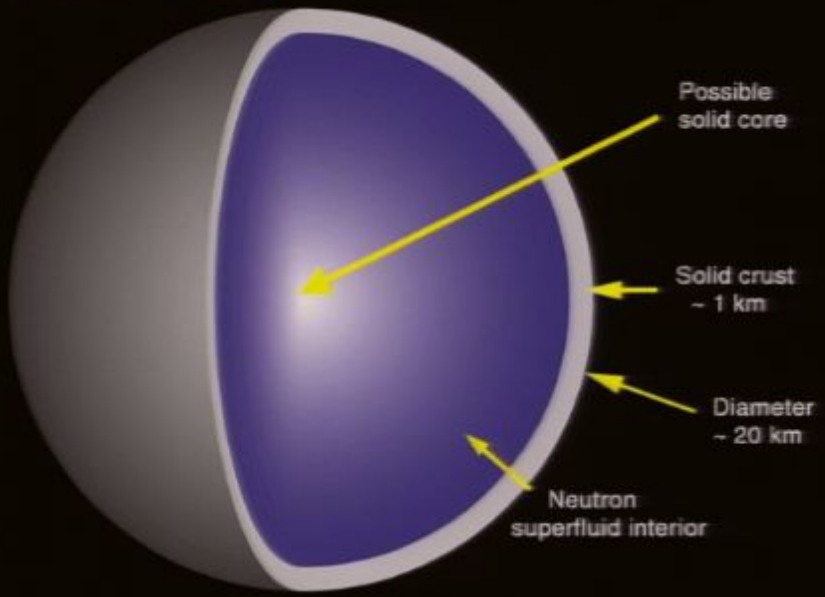

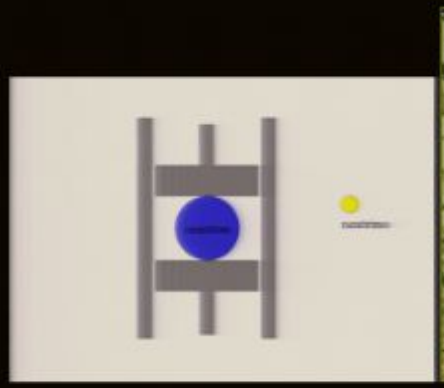

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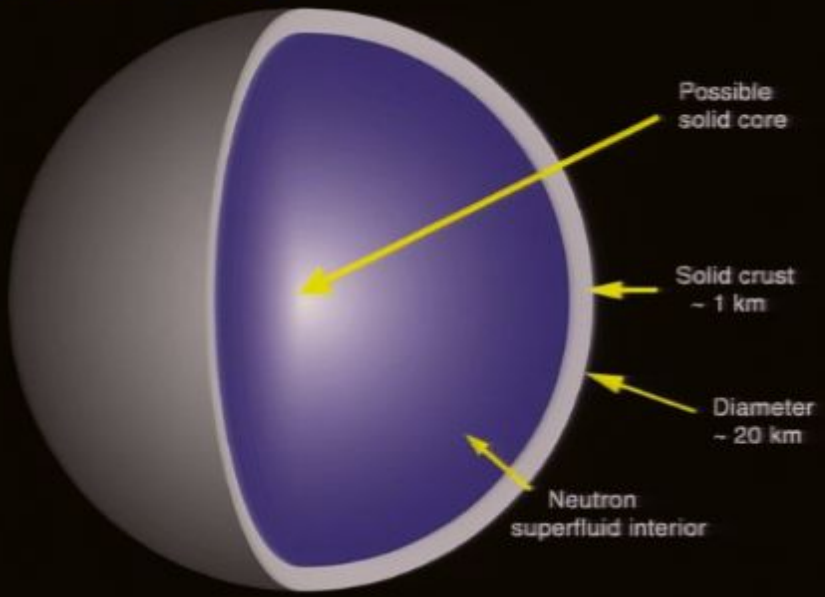

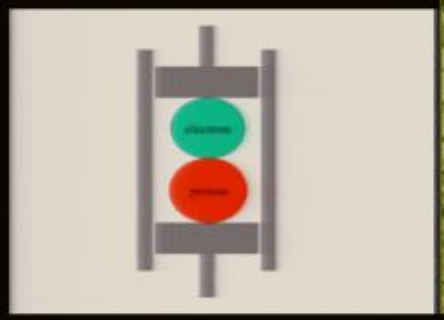

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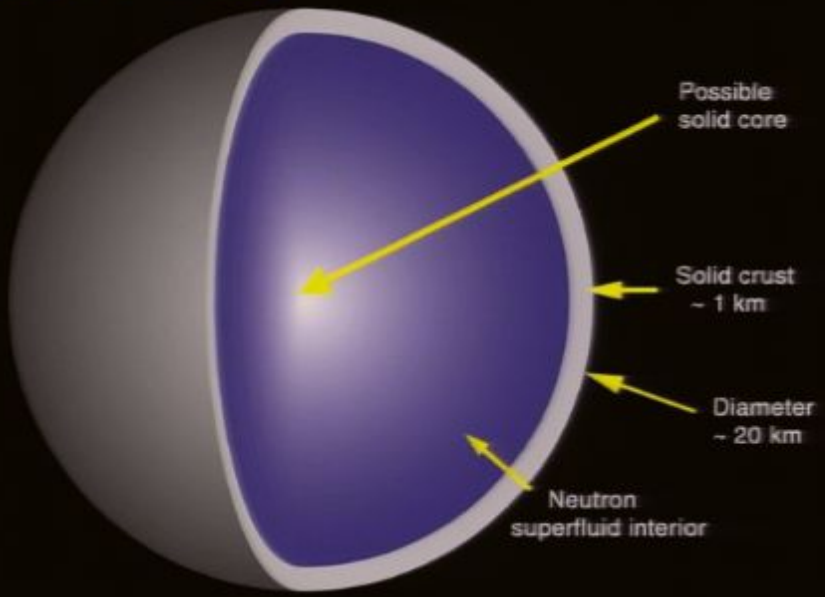

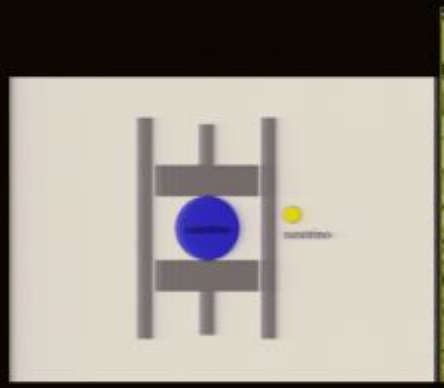

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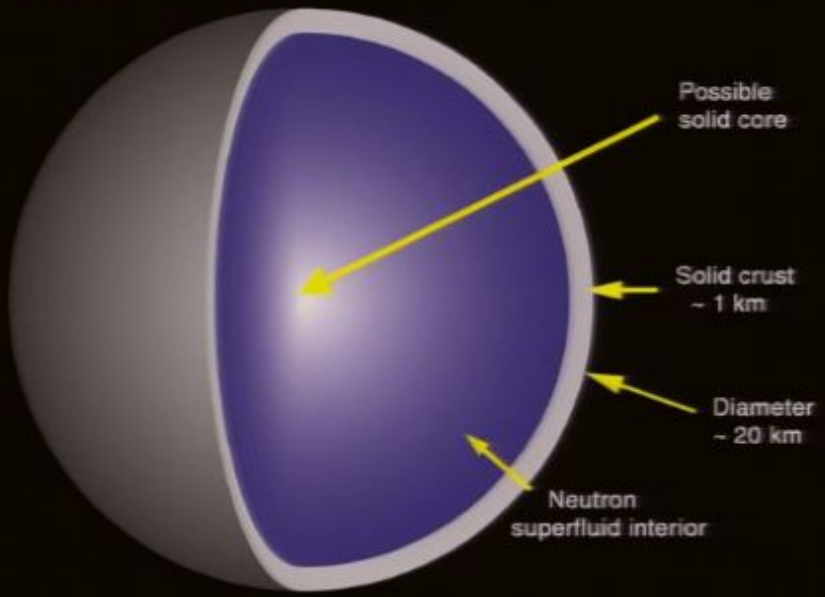

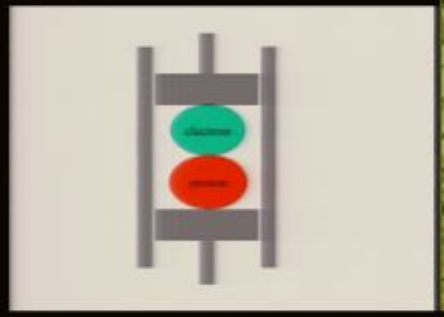

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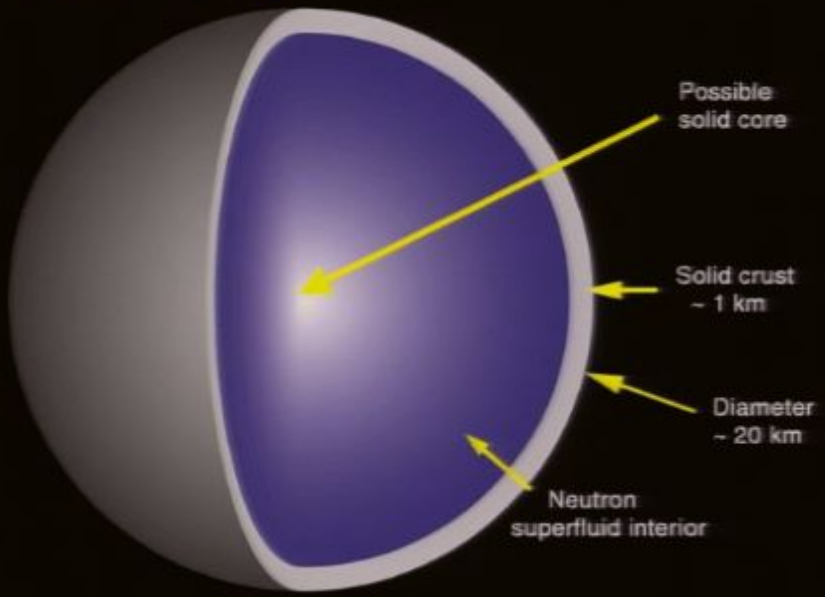

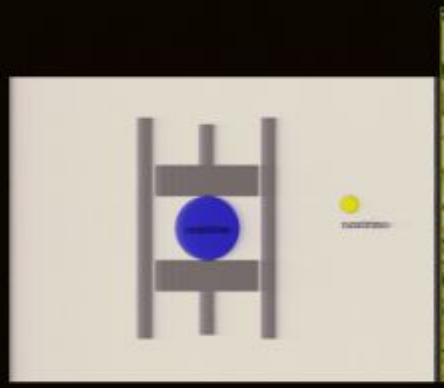

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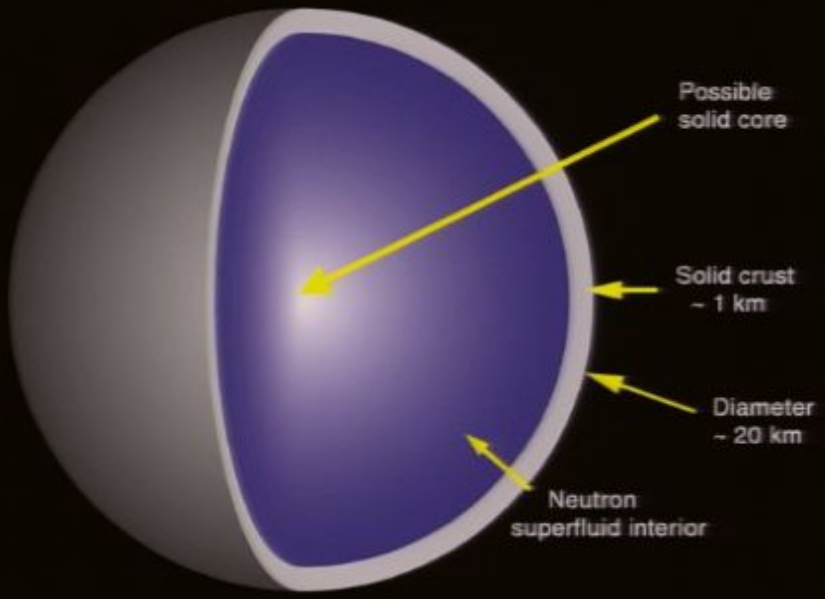

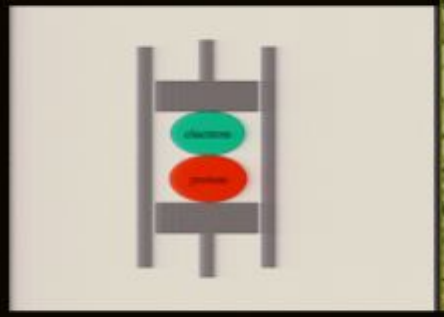

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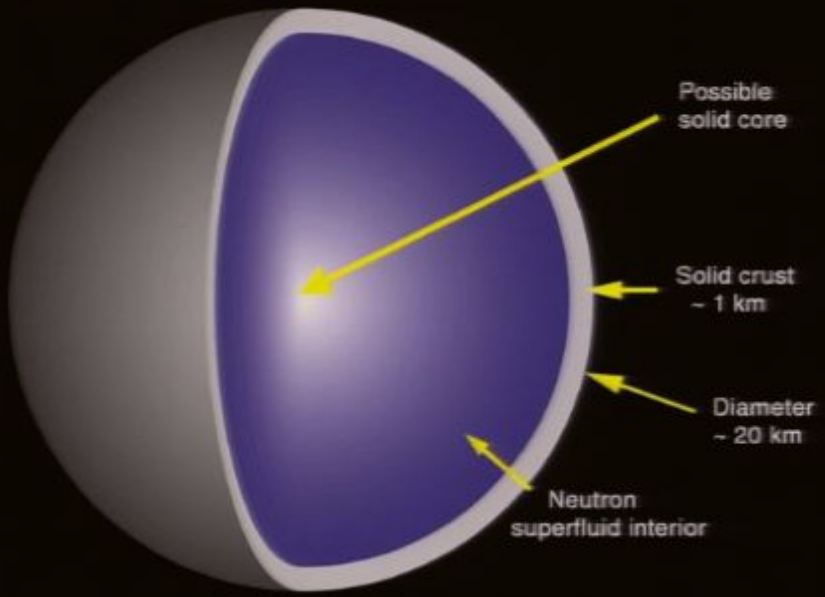

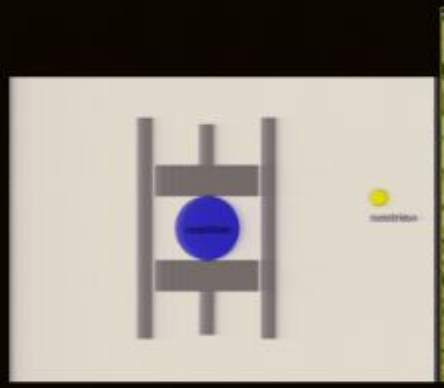

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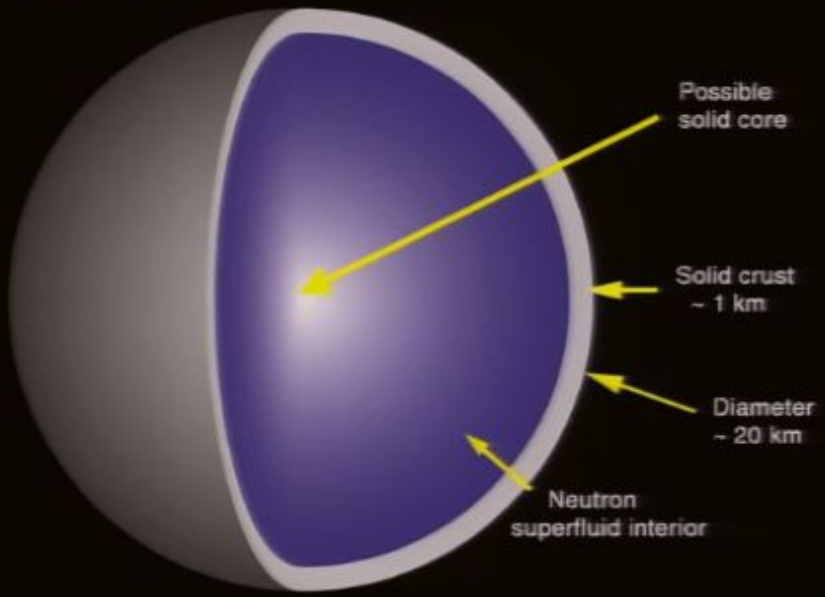

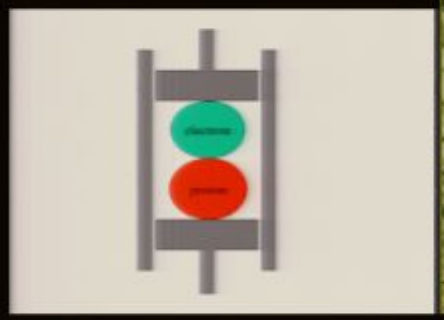

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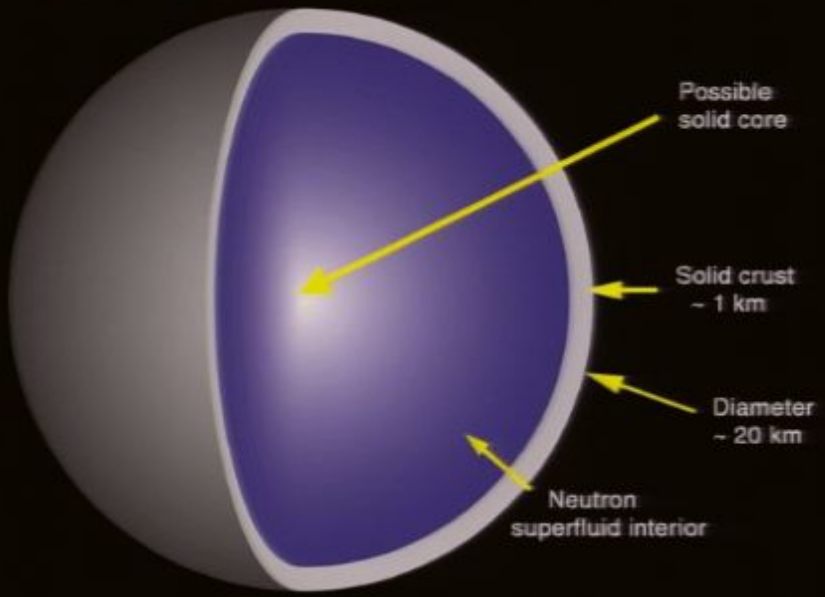

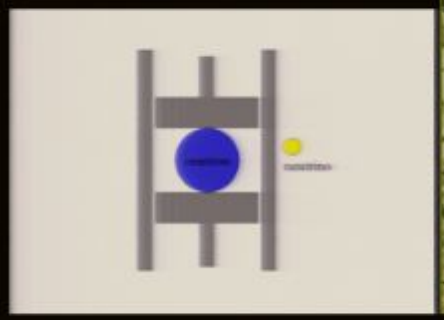

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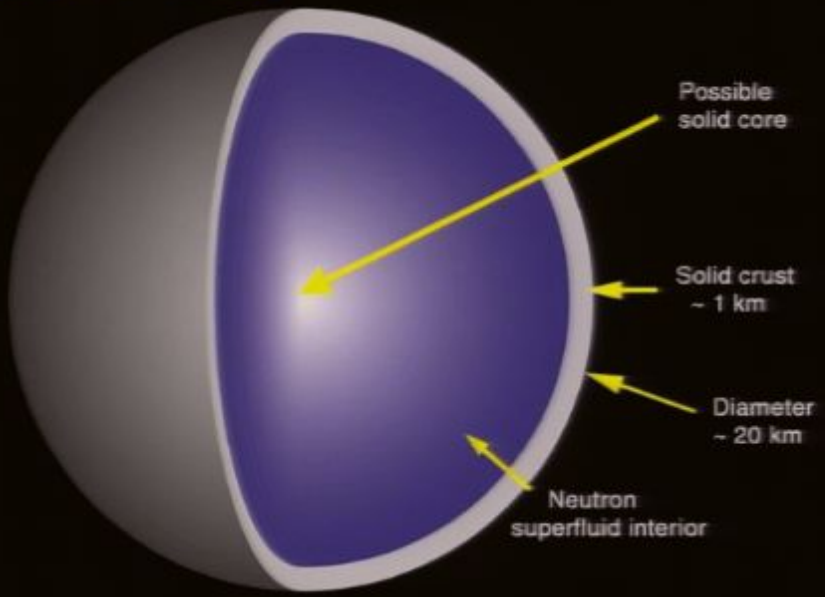

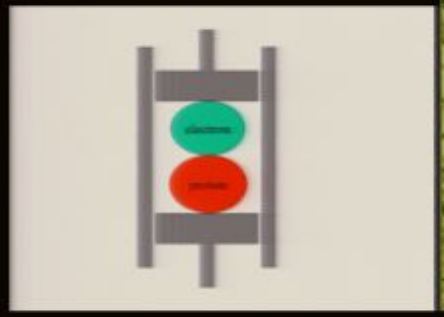

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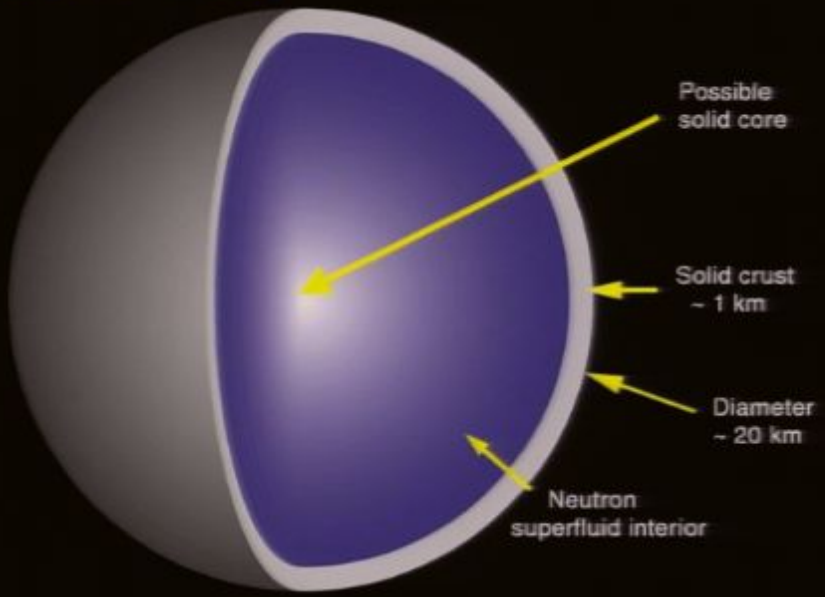

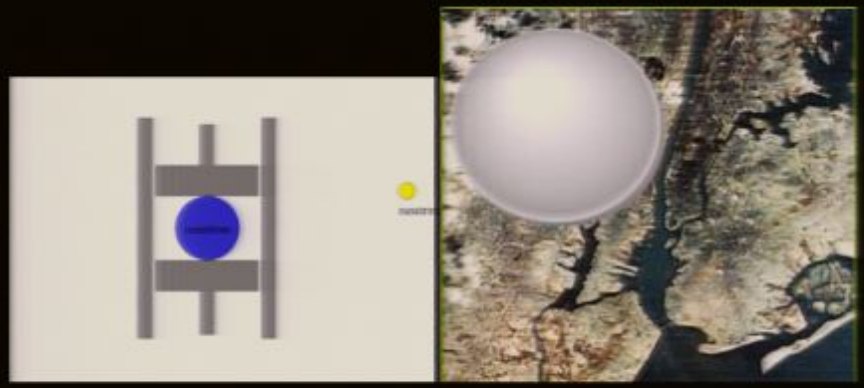

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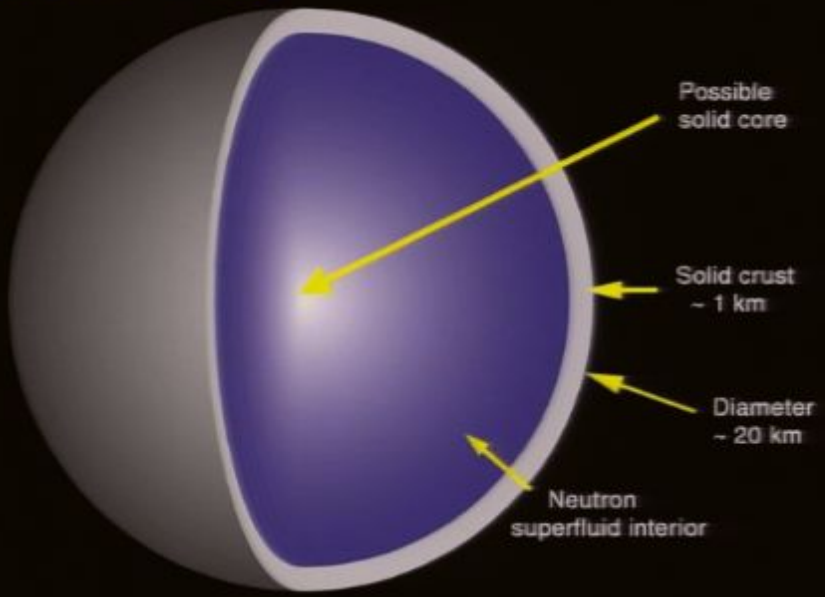

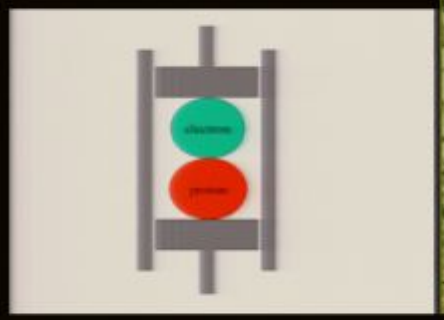

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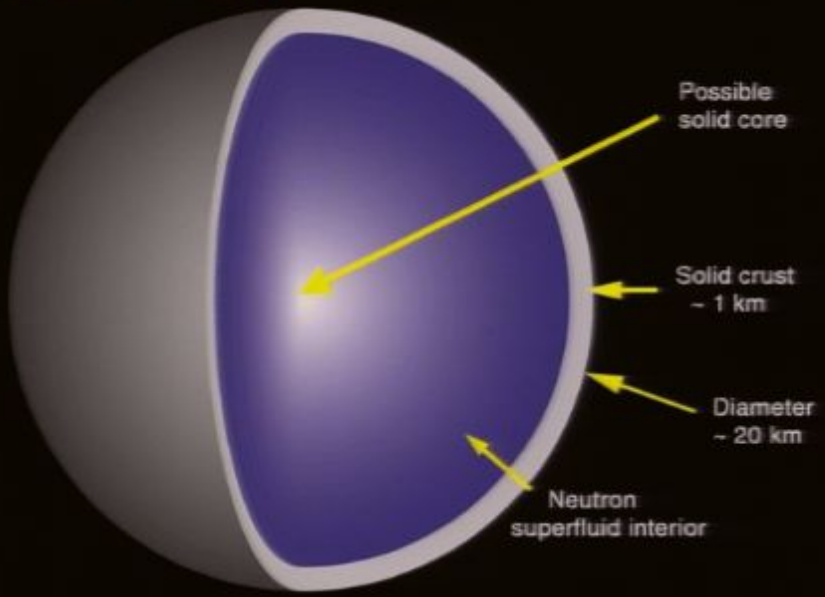

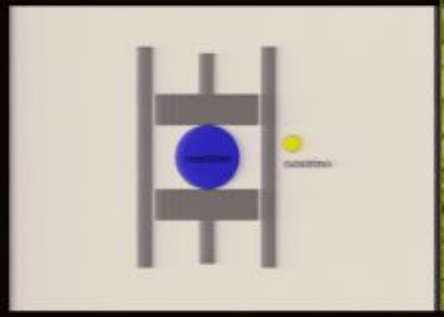

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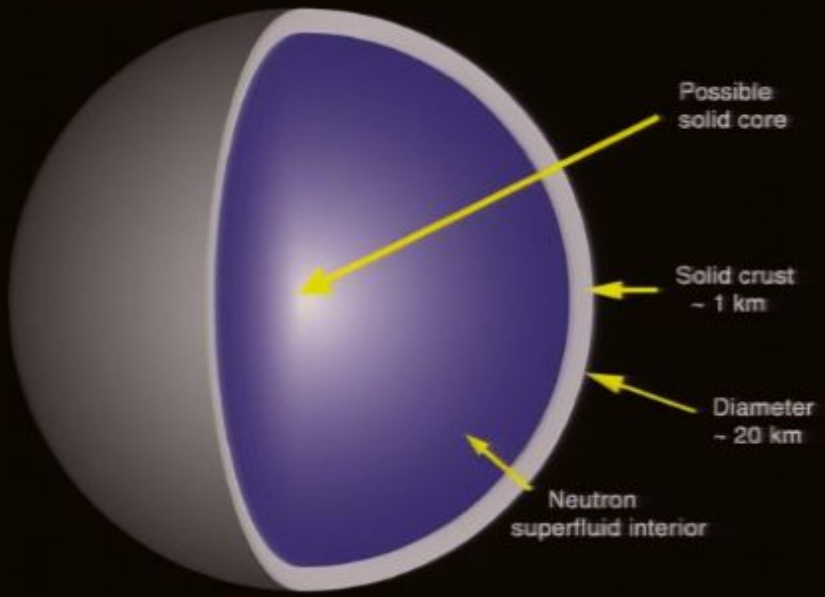

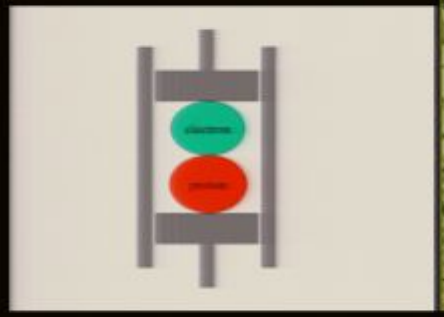

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- A giant ball of neutrons.
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- Temperature 1 million degrees and cooling.
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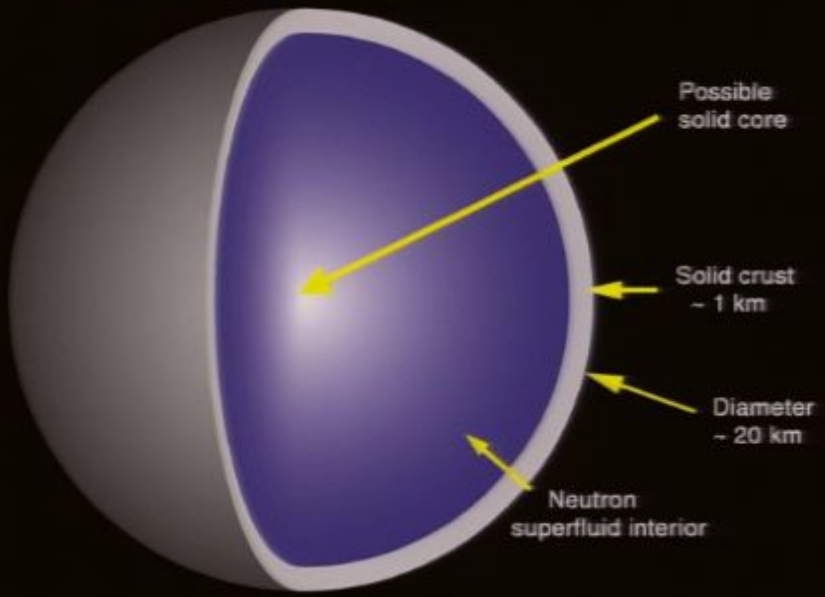

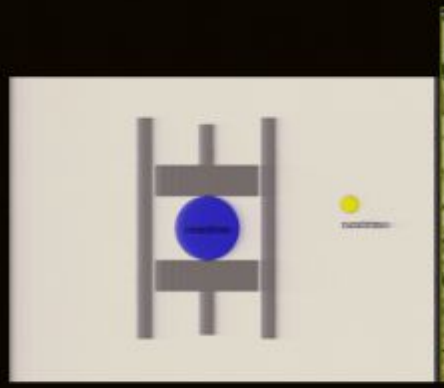

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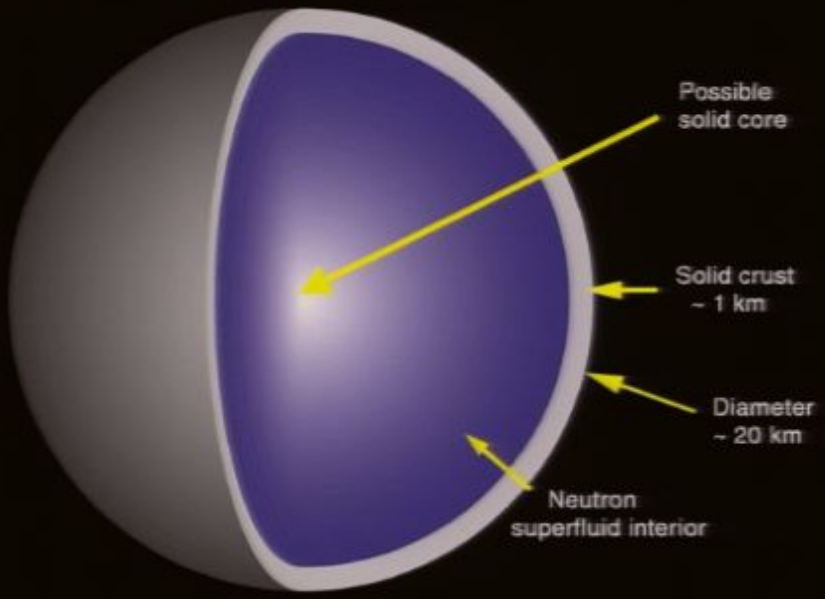

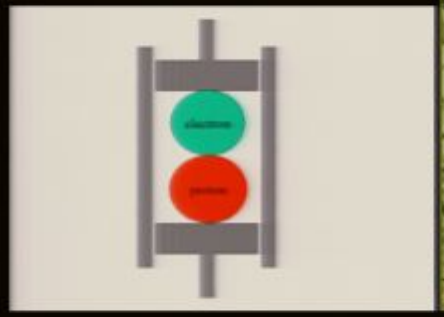

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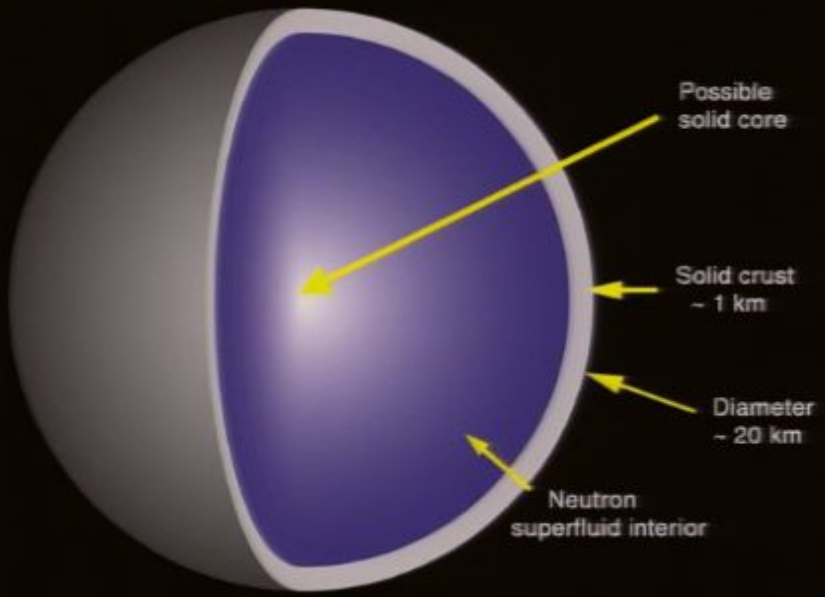

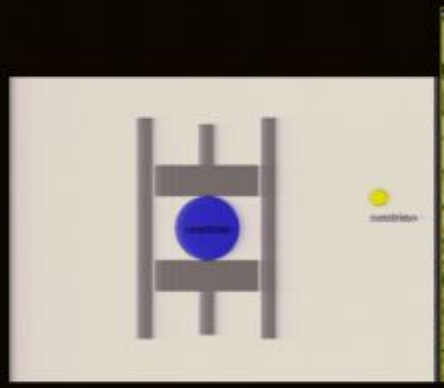

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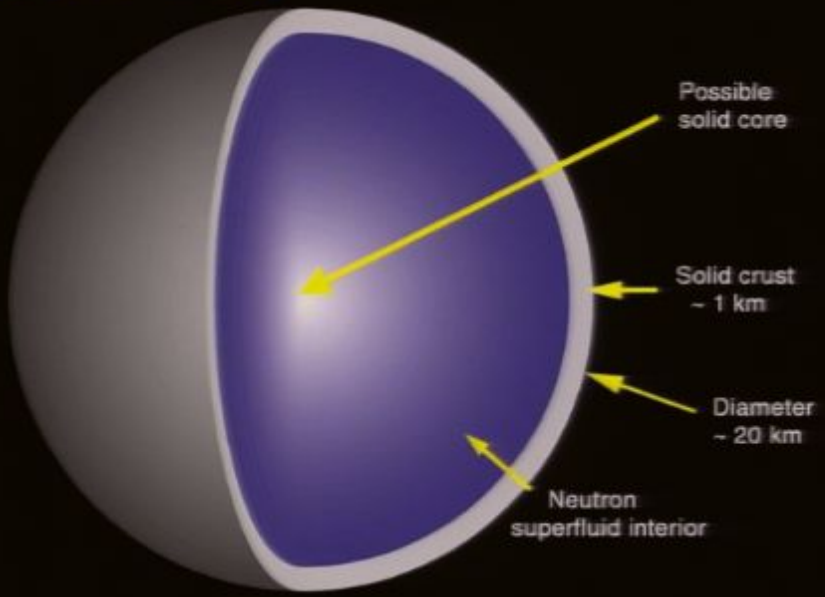

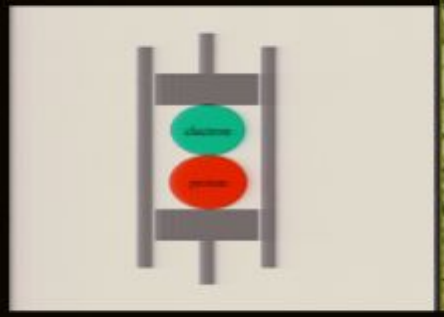

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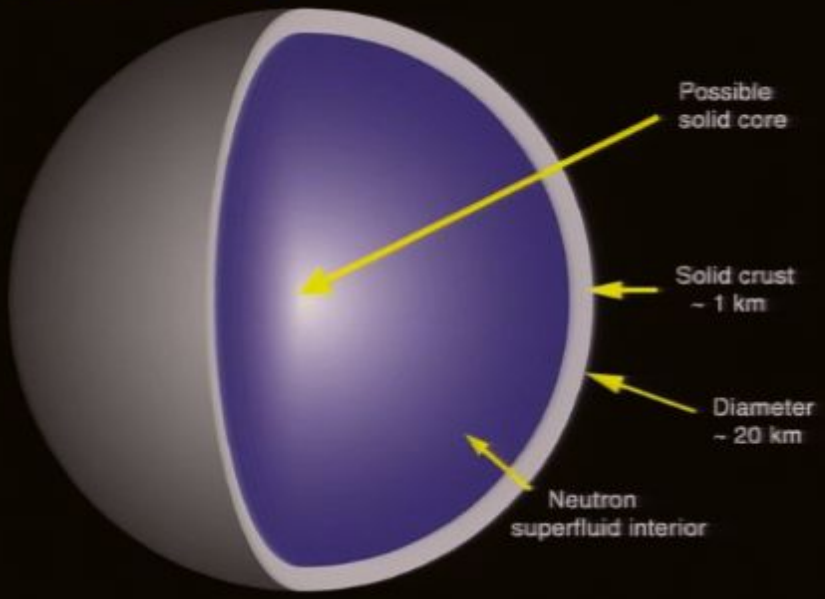

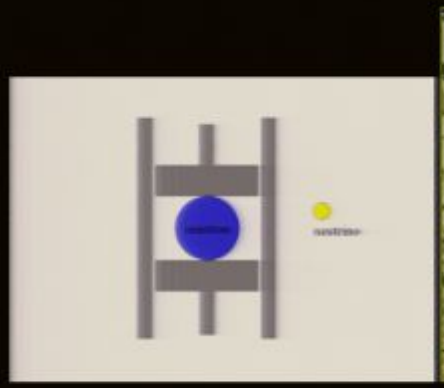

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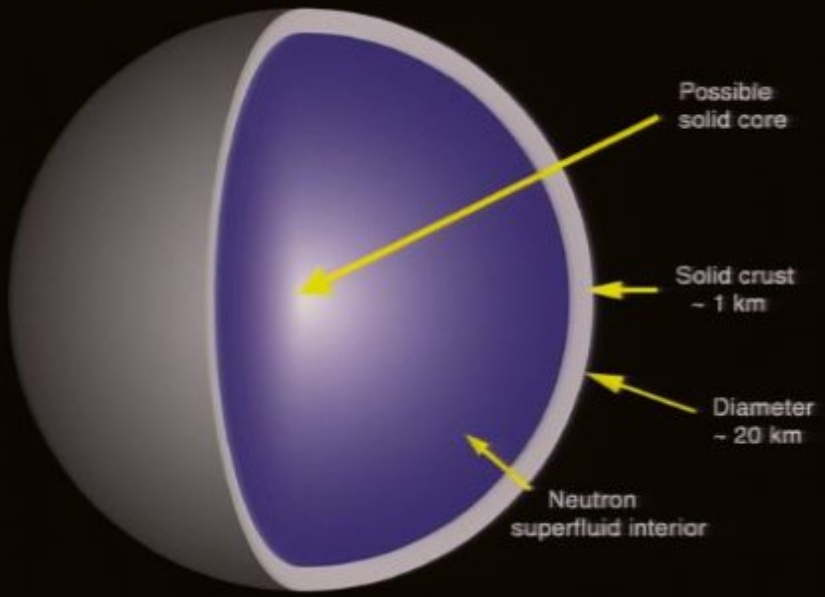
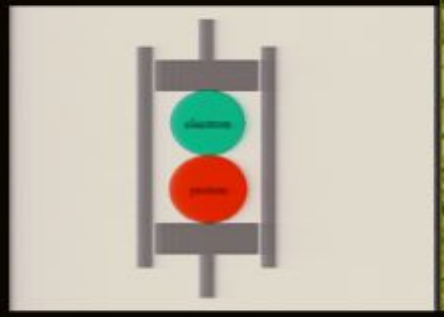
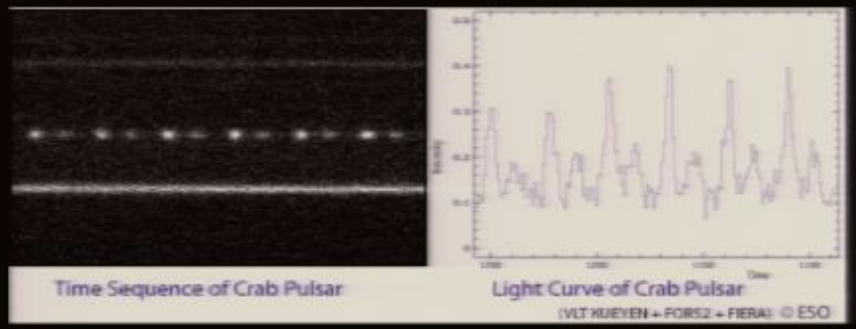
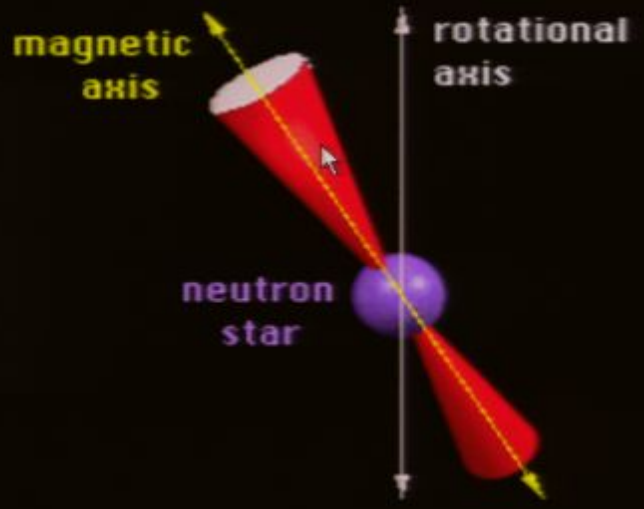




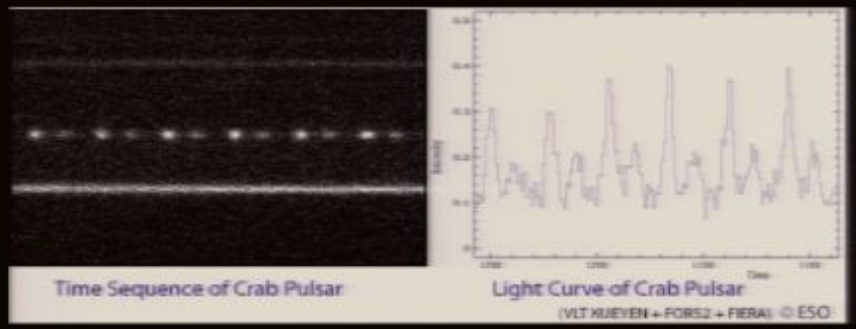
Pulsars

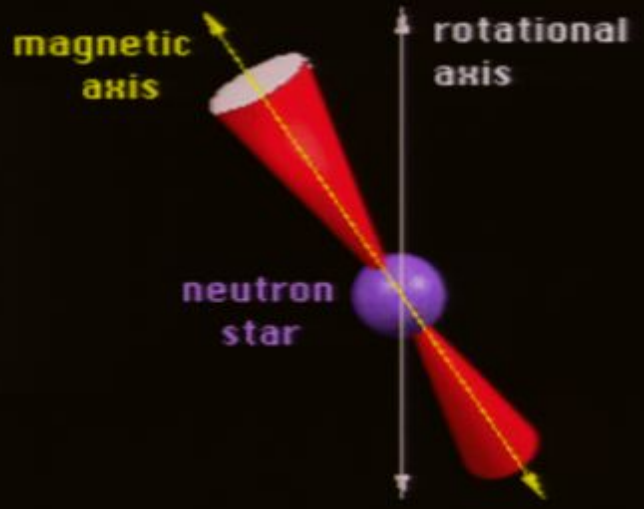

Time Sequence of Crab Pulsar
Light Curve of Crab Pulsar
(VLT KUEYEN + FORS2 + FIERA) © ESO


magnetic axis
rotational axis
neutron star

Pulsars

- Discovered by Bell and Hewish in 1968





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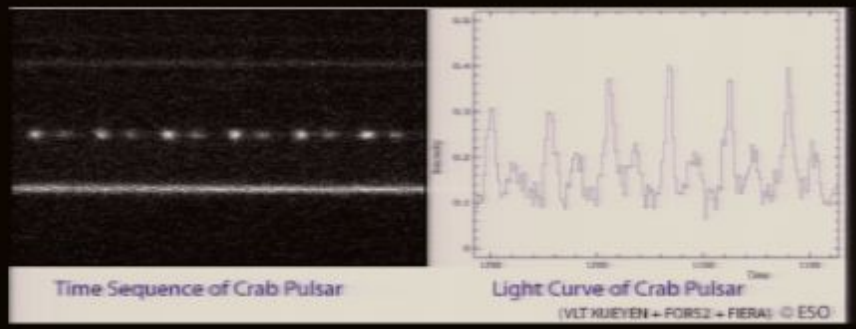

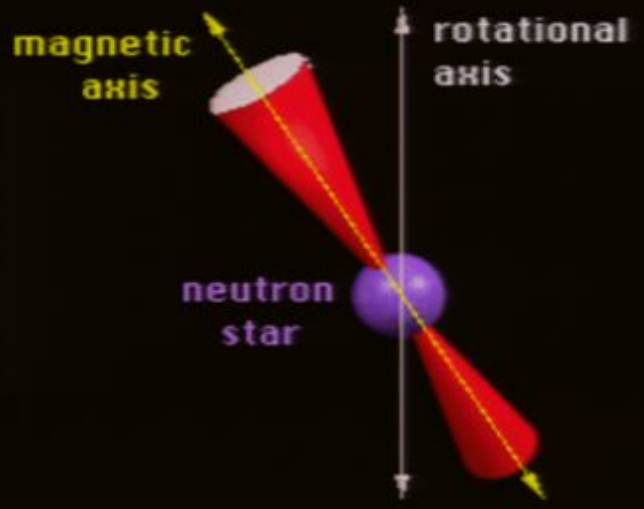

Pulsars

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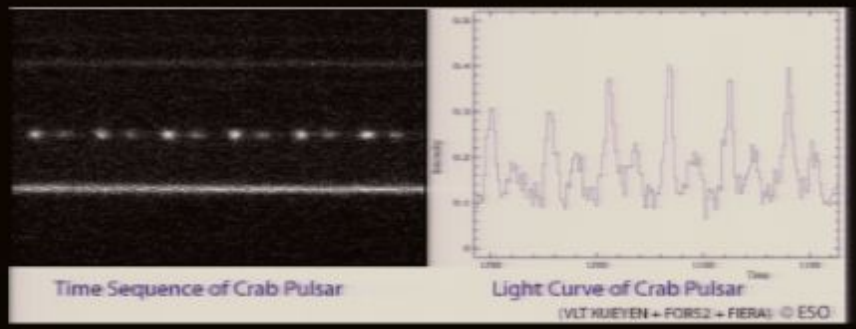
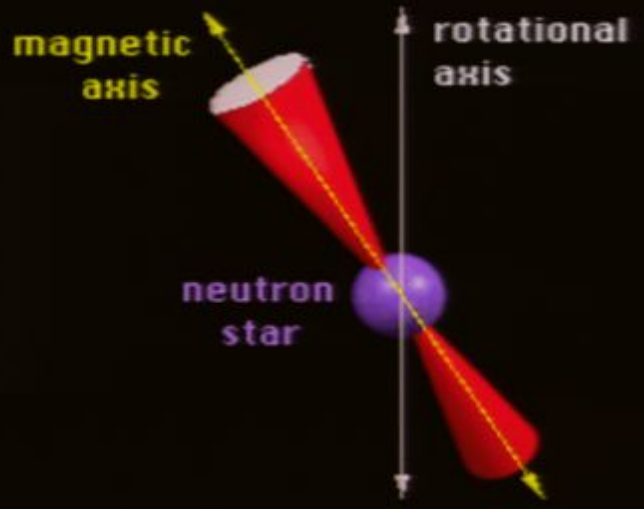
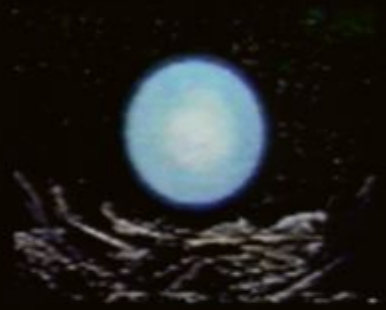
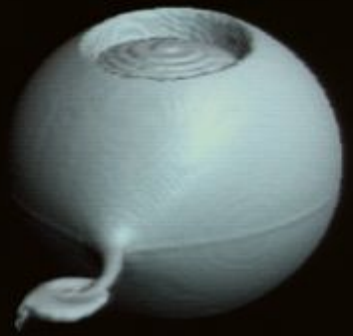
- Now known to be spinning neutron stars





Supernova





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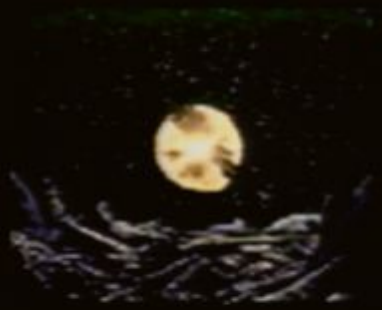

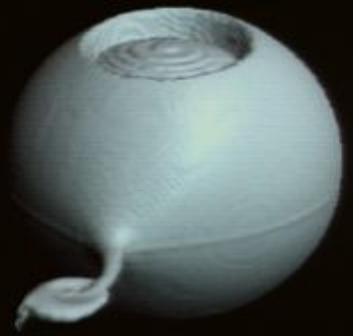

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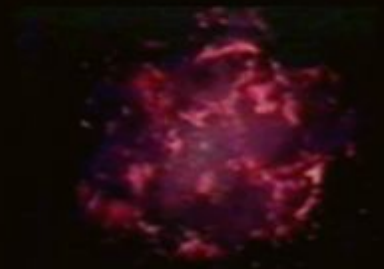

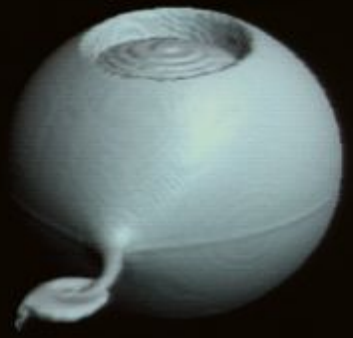

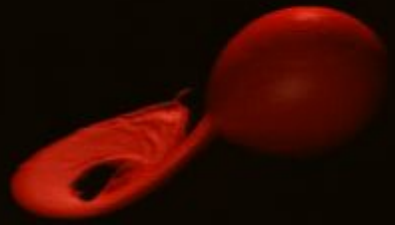

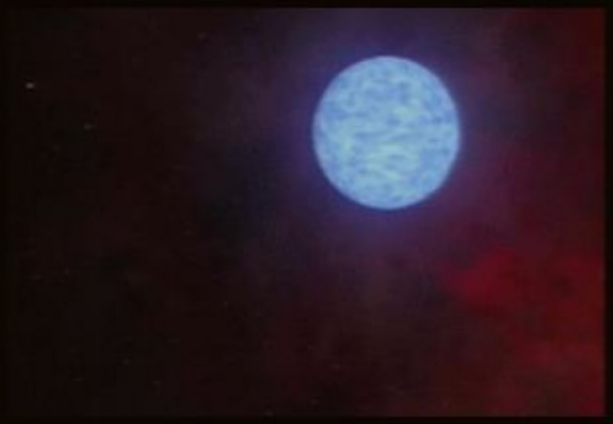

Crab Nebula Pulsar

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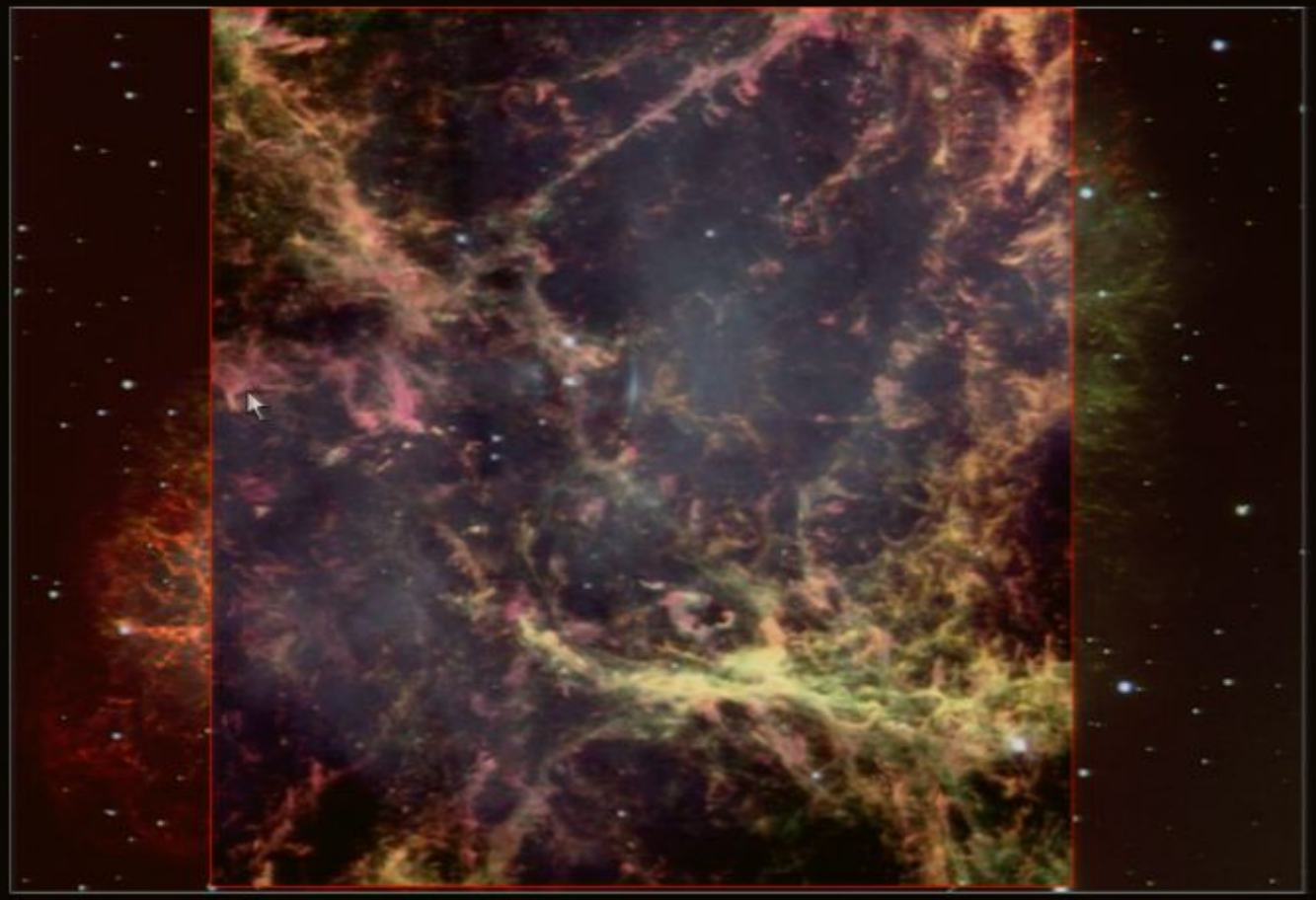

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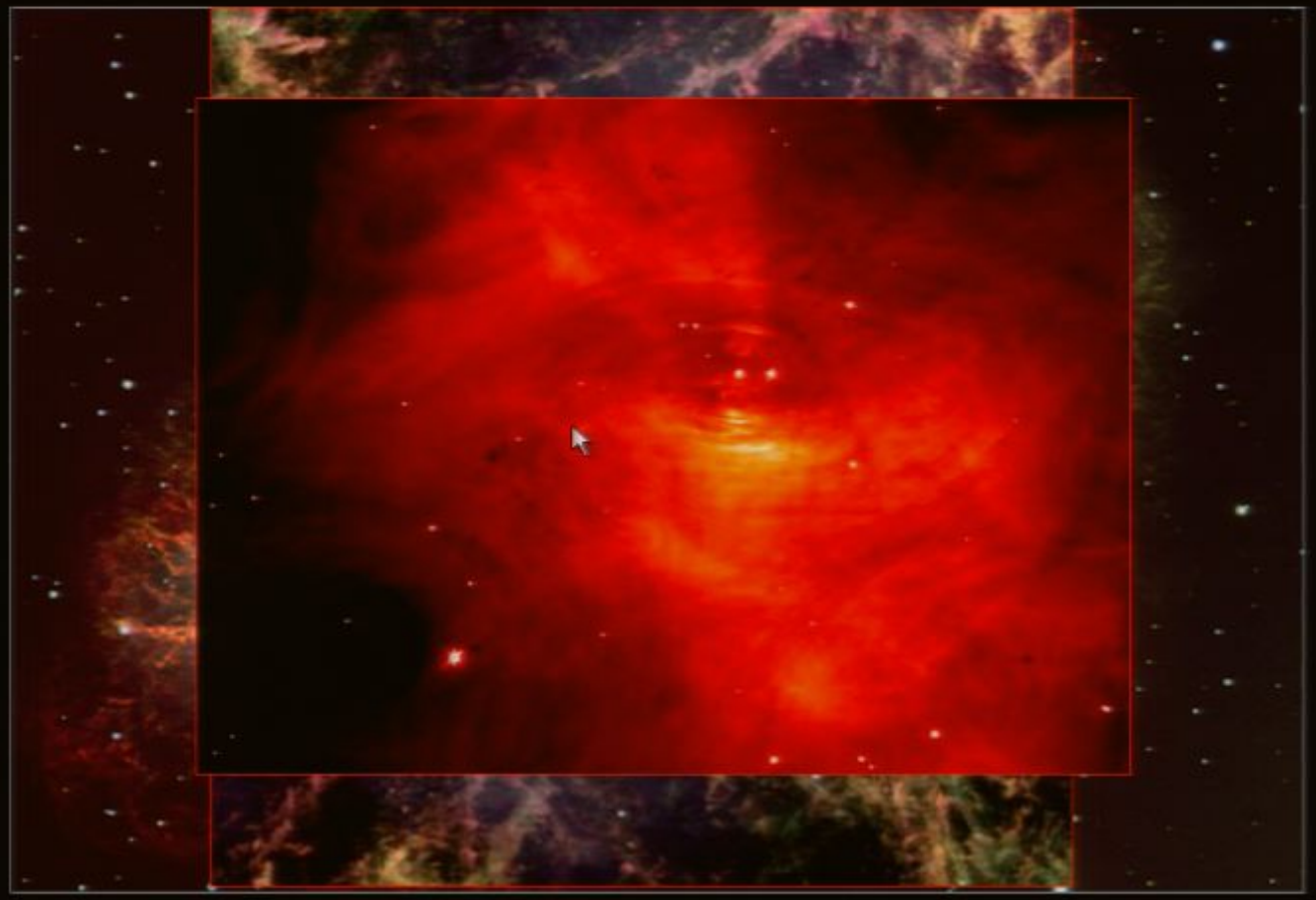

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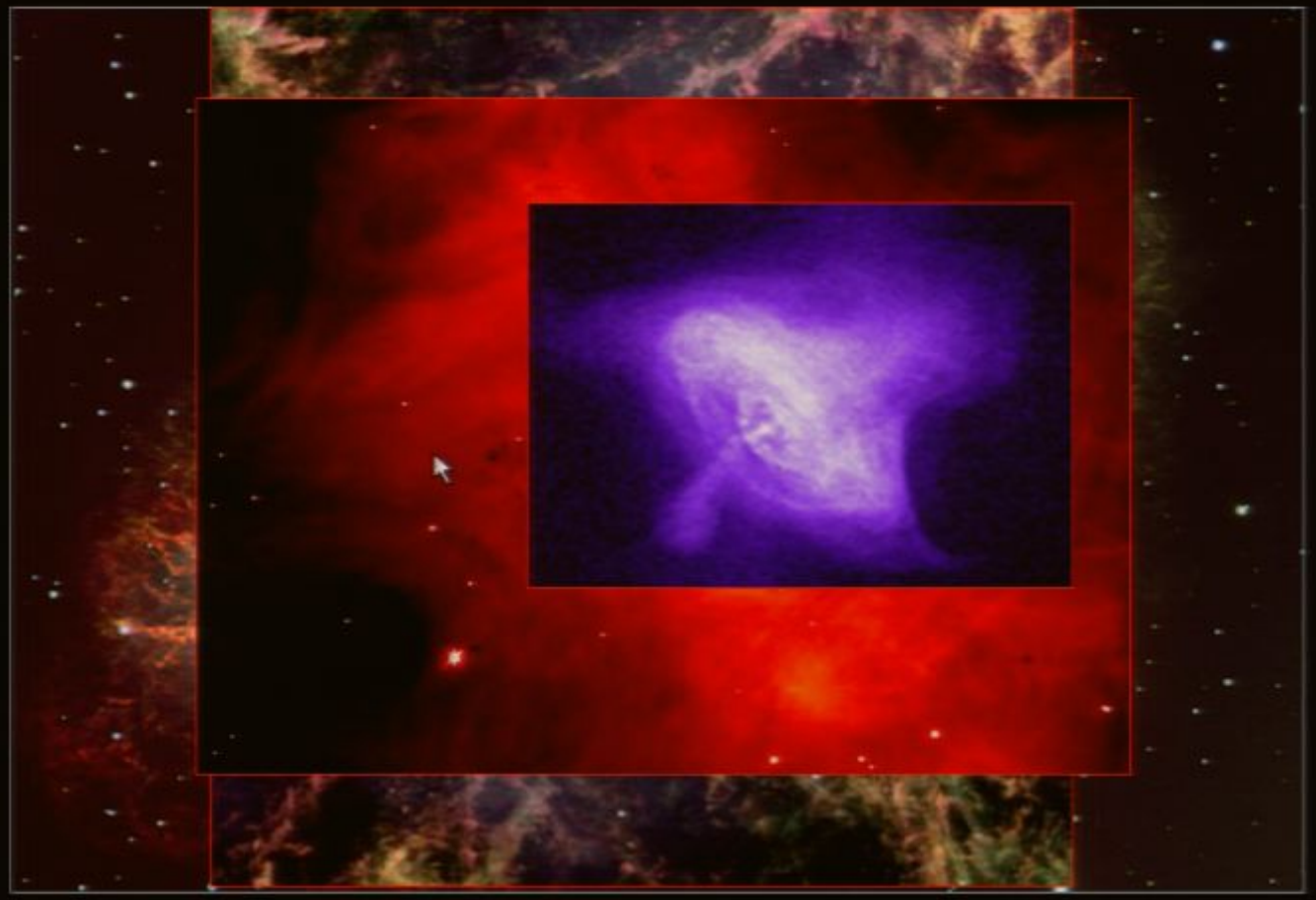

Mass

- Low mass stars
  - Less than 8 $M_\odot$ on Main Sequence
  - Become White Dwarf (< 1.4 $M_\odot$)
    - Electron Degeneracy Pressure
- High Mass Stars
  - Less than 40 $M_\odot$ on Main Sequence
  - Become Neutron Stars (1.4 $M_\odot$ < M <3 $M_\odot$)
    - Neutron Degeneracy

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- What if the escape velocity is faster than light?

Black Hole

- The star collapses to form a Black Hole.