Title: General Relativity - Part 2

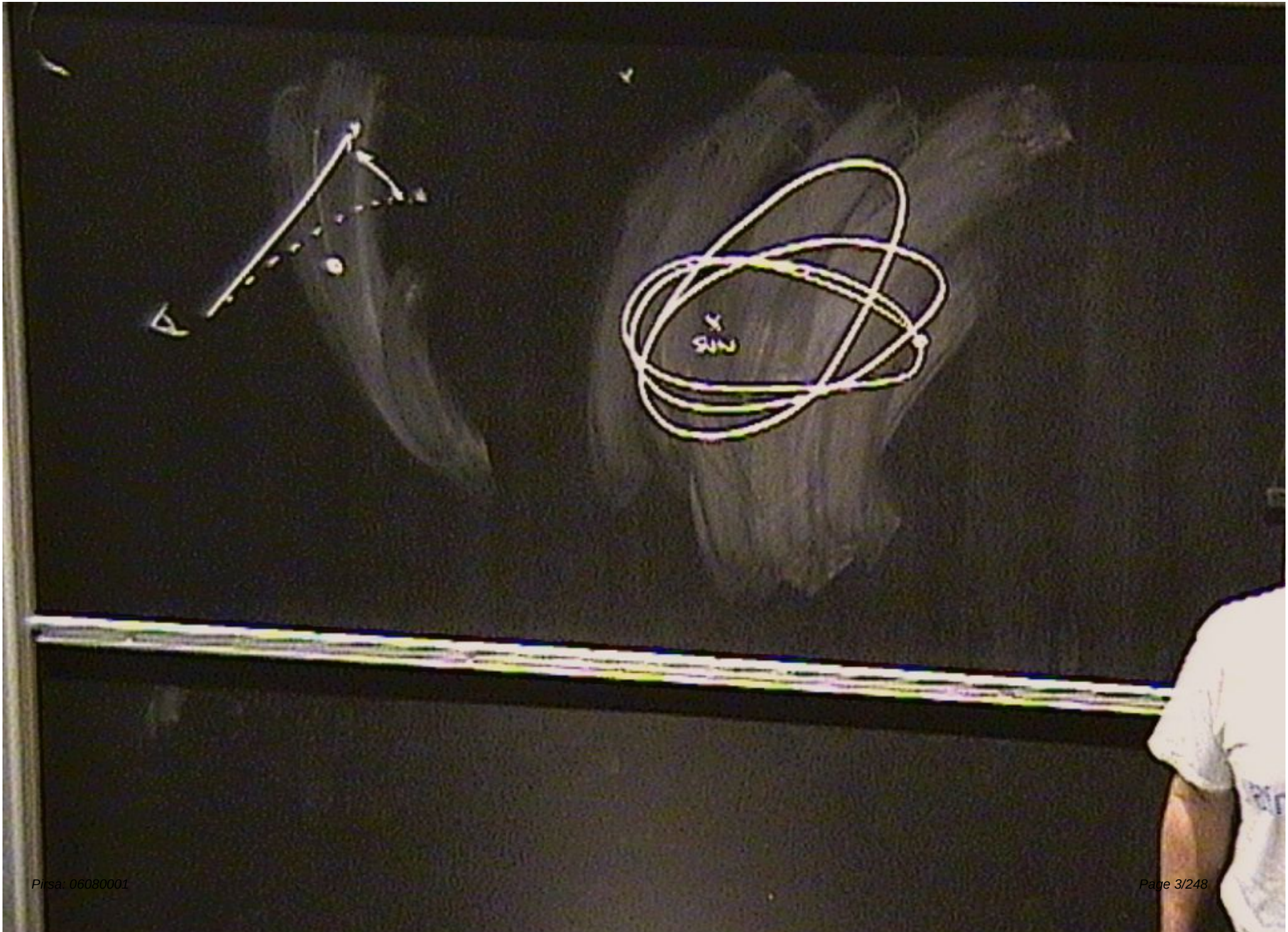
Date: Aug 01, 2006 10:45 AM

URL: http://pirsa.org/06080001

Abstract:

1919 Verification

The final proof: the small red line shows how far the position of the star has been shifted by the Sun's gravity.



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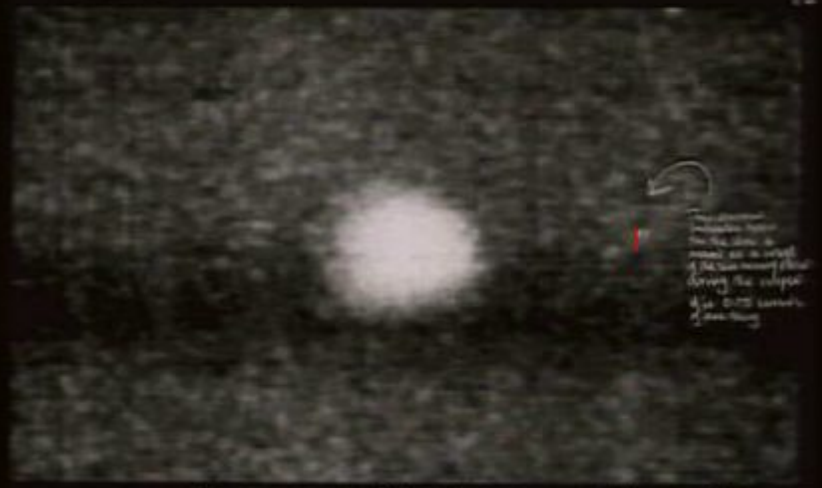

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General Relativity Test (1976)

65
Excess Time Delay, Microseconds

Distance > 37 km

General Relativity Test (1976)

79
Excess Time Delay, Microseconds

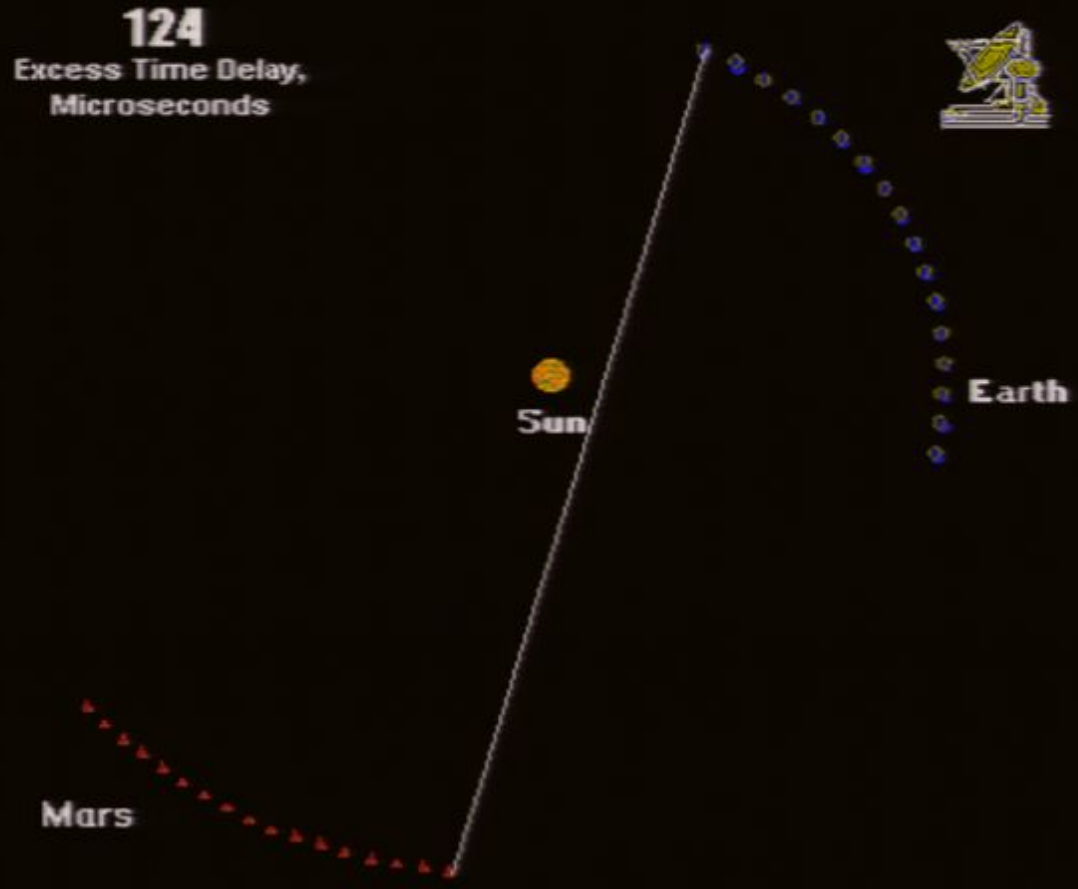
Distance > 37 km

General Relativity Test (1976)

96
Excess Time Delay, Microseconds

Distance > 37 km

General Relativity Test (1976)



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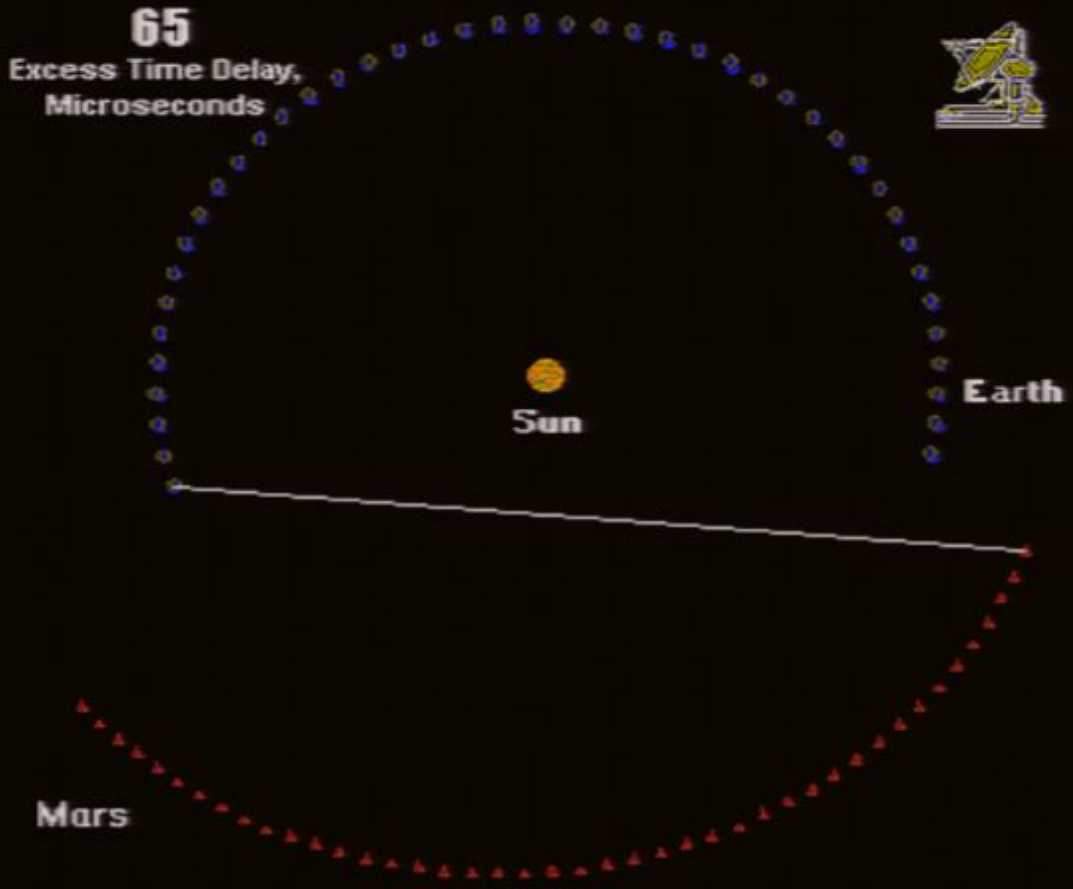

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General Relativity Test (1976)

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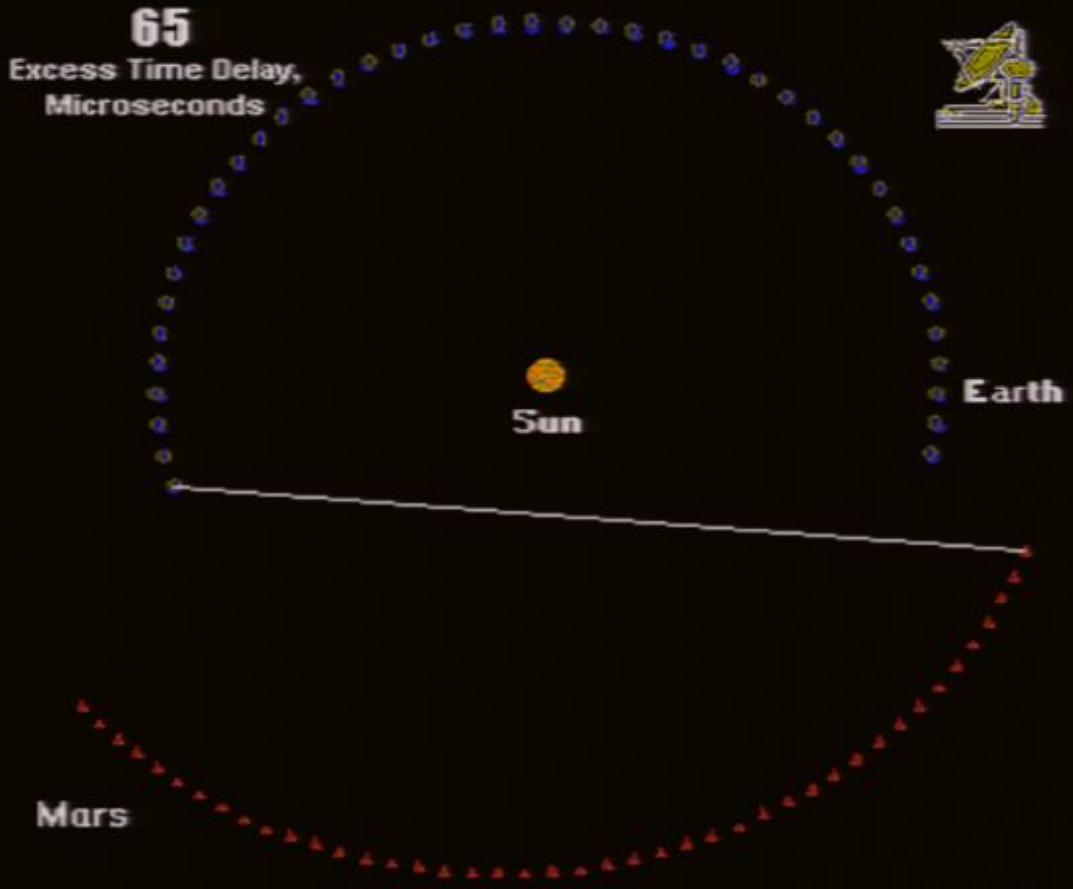

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General Relativity Test (1976)

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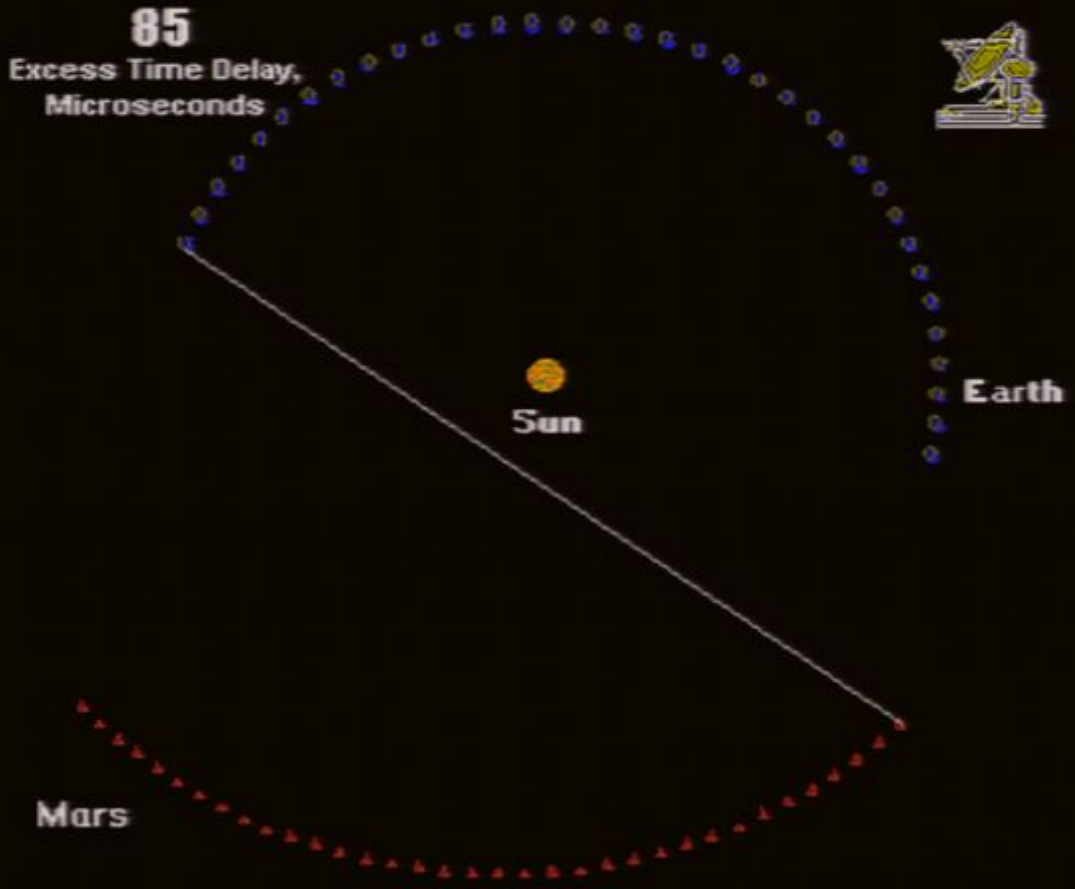

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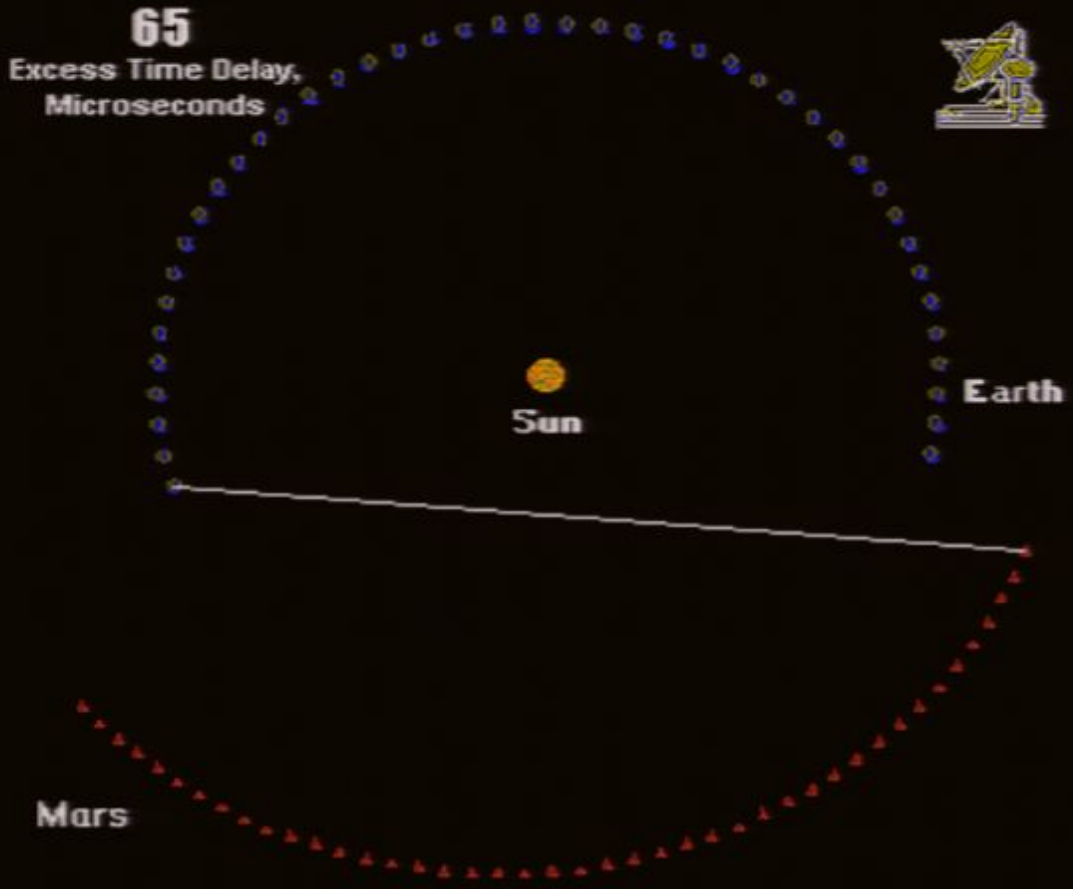
General Relativity Test (1976)



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Karl Schwarzschild (1876-1916)

Calculation of Schwarzschild radius

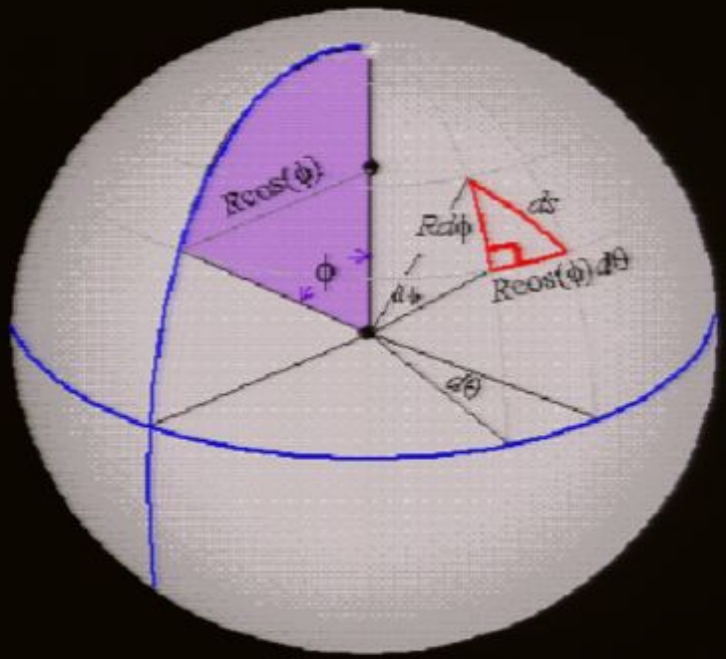
- ***In 1916 Karl Schwarzschild discovers a solution of the Einstein field equation, which describes a nonspinning, uncharged spherical body.***
- ***Did this when serving in the German Army on the Russion front of World War I***
- ***Only required a few days to solve equation and describe spacetime curvature.***
- ***Einstein presented solution on behalf of Shwarzschild to the Academy of Sciences.***
- ***Schwarzchild was killed 4 months later.***

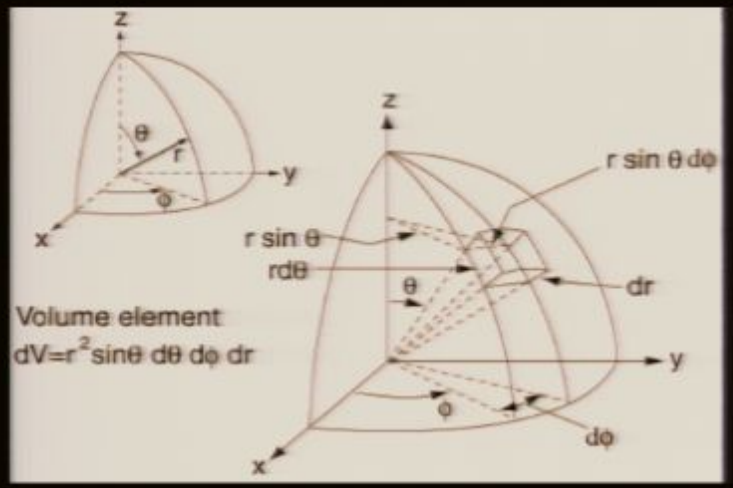
The Schwarzschild Radius

$$ds^2 = -\left(1-\frac{r_s}{r}\right)c^2dt^2 + \frac{dr^2}{\left(1-\frac{r_s}{r}\right)} + r^2\left(d\theta^2 + \sin^2(\theta)\,d\phi^2\right)$$

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

r, θ, ϕ *are the polar coordinates*





Schwarzschild Metric

Schwarzschild Metric

$\tau^2 = t^2 - s^2$ ⟸ *Timelike Spacetime Metric*

Schwarzschild Metric

$$d\tau^2 = dt^2 - dx^2 - dy^2$$ ⟸ *2D flat Spacetime in Cartesian*

Is the square of the wristwatch time between two events as marked by x, y, t

Schwarzschild Metric

$$(d\tau)^2 = (dt)^2 - (dr)^2 - (r d\phi)^2$$ ⟸ *2D flat Spacetime in Polar*

Schwarzschild Metric

$$d\tau^2 = \left(1 - \frac{r_s}{r}\right) c^2 dt^2 - \frac{dr^2}{\left(1 - \frac{r_s}{r}\right)} - r^2 d\phi^2$$

⟸ *Curvature added, now Schwarzschild timelike Spacetime Metric*

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

Schwarzschild Metric

$$d\sigma^2 = -\left(1-\frac{2M}{r}\right)dt^2 + \frac{dr^2}{\left(1-\frac{2M}{r}\right)} + r^2 d\phi^2$$

The metric describes the shape of spacetime outside of matter. Once you hit matter, be it some gas, a star, a planet, or a rock, this metric no longer applies.

You can see that, if r = 2M, dt term would be zero. That is to say that at the event horizon there would be no change in time. Makes sense; you can look at the event horizon as being the place where time "stops." The dr factor deals with how close to something you are. You'll notice that it "blows up" when r = 2M.

Schwarzschild Metric

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Spacelike Fo

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⟸ *Spacelike Form*

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⟸ *Spacelike Form*

$$d\tau^2 = \left(1-\frac{2M}{r}\right)dt^2 - \frac{dr^2}{\left(1-\frac{2M}{r}\right)} - r^2 d\phi^2$$

Timelike Form

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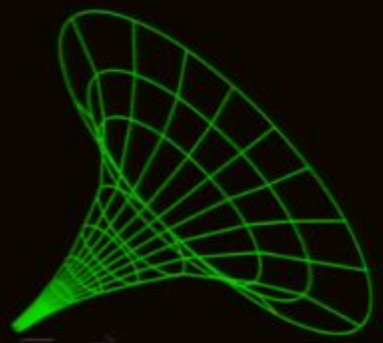
Schwarzchild radii for different objects

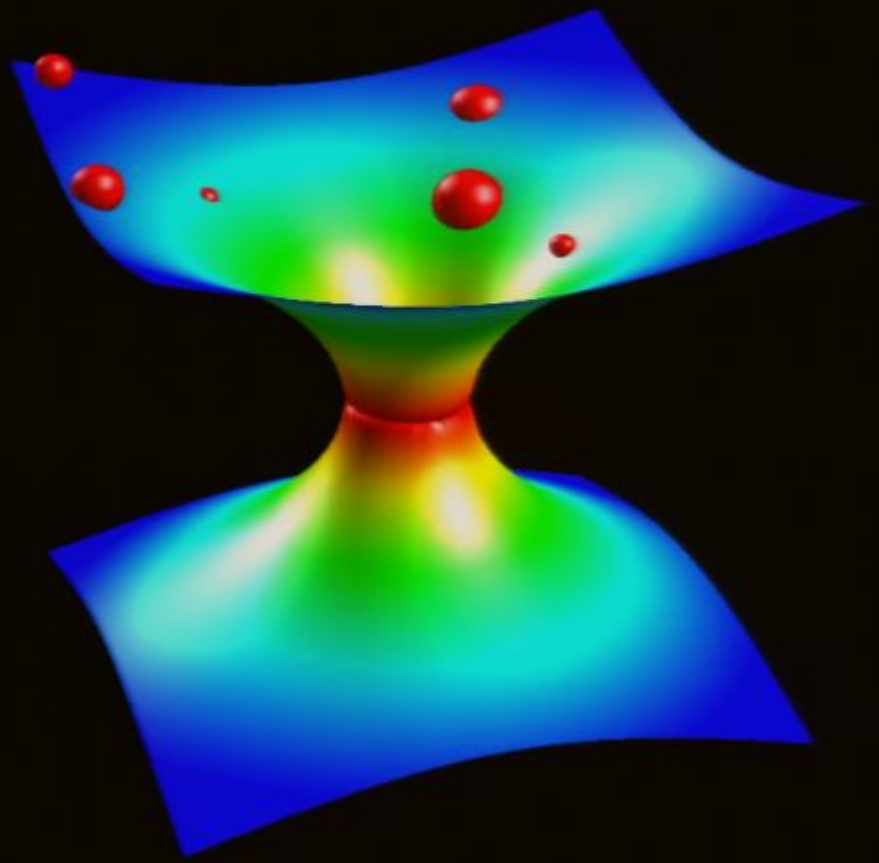
Object	Mass	R_S
Atom	10^{-26} kg	10^{-51} cm
Human Being	70 kg	10^{-23} cm
Earth	6.0×10^{24} kg	0.89 cm
Sun	2.0×10^{30} kg	3.0 km
Galaxy	$10^{11}\ M_S$	10^{-2} l.y.
Universe (if closed)	$10^{23}\ M_S$	10^{10} l.y.

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

Embedding Diagram

Emphasis on Spatial rather than temporal interpretations

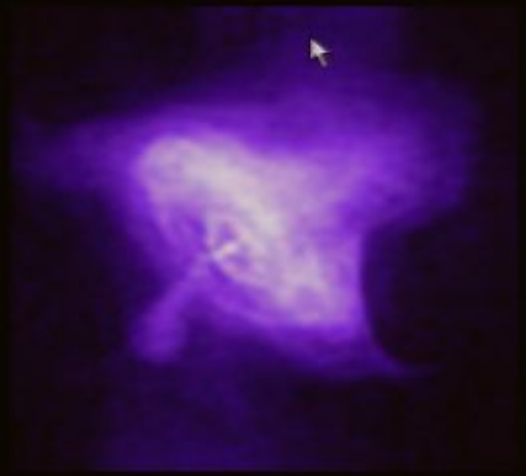




Sir Arthur Eddington

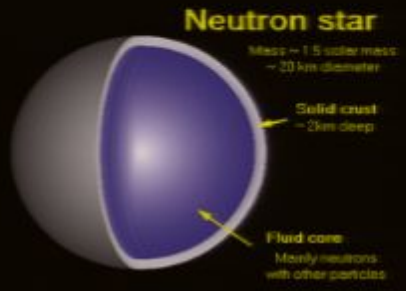
- 1926 Book – The internal constitution of the Stars
- Early proponent of Einstein's Theory of General Relativity (next to Einstein best expert on General Relativity)
- Poses the mystery of white dwarfs and attacks the reality of black holes predicted by Schwarzschild.
- Believed White Dwarf was last state in a stars life (rock Star)
- Paradox with White Dwarf

Subrahmanyan Chandrasekhar

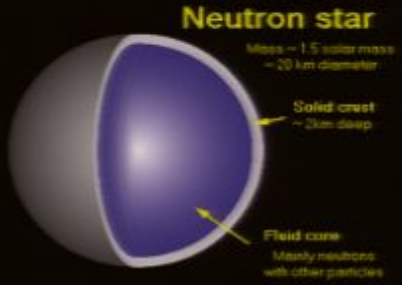


- *Idolized Eddington, resolved Eddington;s paradox*
- *In 1930 he showed that there is a maximum mass for White Dwarfs*
- *1935 Eddington attacks his work. "Chandra" left the field of Blackholes until 1970's*
- *Nobel Prize in Physics 1983*

Walter Baade and Fritz Zwicky



- *Identifies the process of a supernovae, predicted that this collapse strips the atoms of their electrons, packing the nuclei together as a neutron star .*
- *Neutron stars would not be verified observably until 1968.*
- *Identified the galaxies associated with cosmic radio sources.*
- *Still something was missing that took a star from fusion to supernovae.*

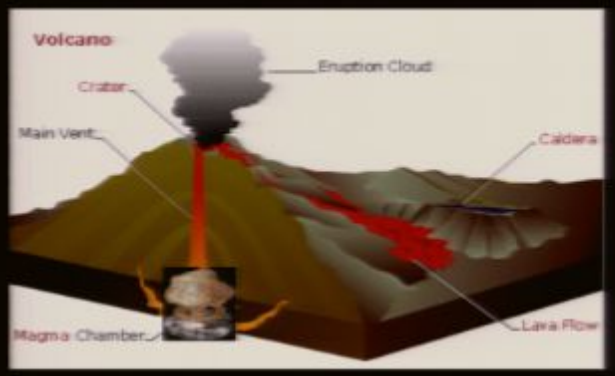


Robert J. Oppenheimer

- *Showed that there is a maximum mass for a neutron star from 1.5 to about 3 solar masses (1938).*
- *In a highly idealized calculation, showed that an imploding star forms a black hole.*
- *Led the American atomic bomb project.*
- *Which provided the opportunity to experimentally verify and test theories (too expensive for the universities) and the development of the atomic bombs which mimic the power source for the sun to come up with the mathematics and understanding of stellar mechanics*
- *Major battle with Wheeler.*

Yakov Zel'dovich

- *Soviet counterpart to Oppenheimer.*
- *Developed the theory of nuclear chain reactions. (1939)*
- *Lead theorist on USSR atomic bomb (1945)*
- *Creates black hole research team (1962).*
- *Super massive black holes power Quasars (1960's).*



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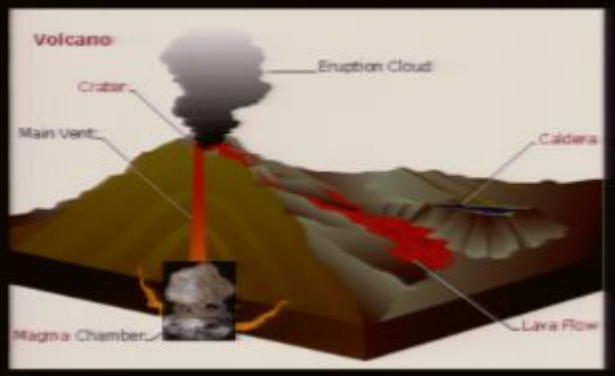

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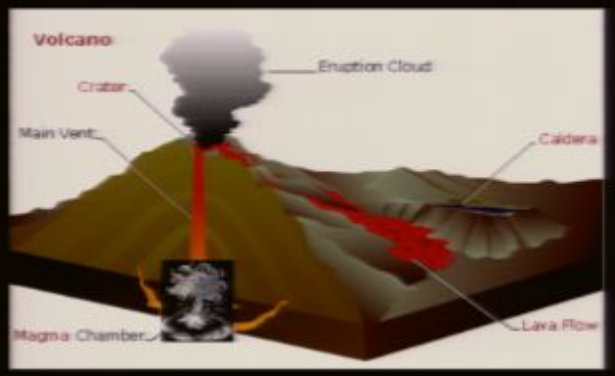

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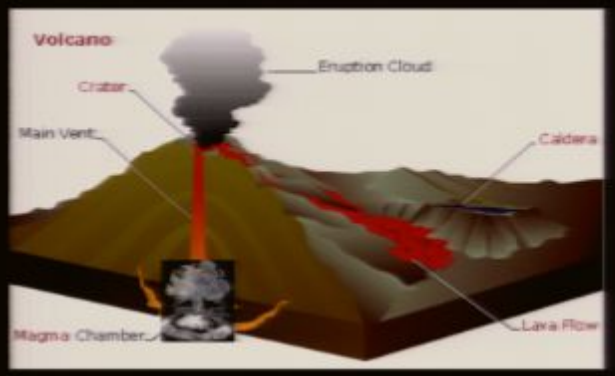

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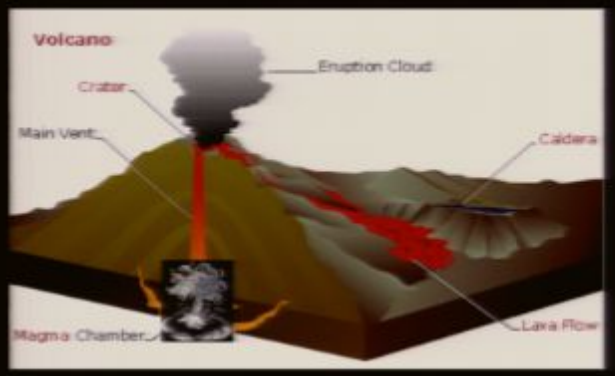

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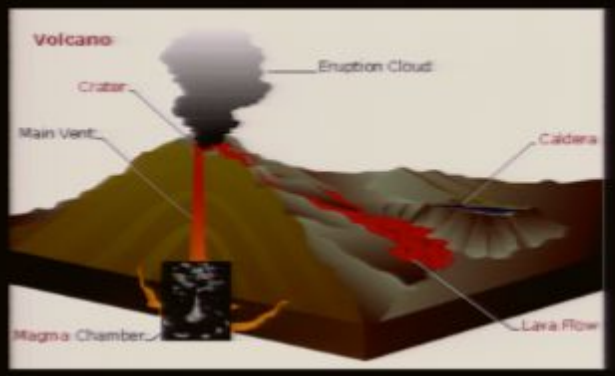

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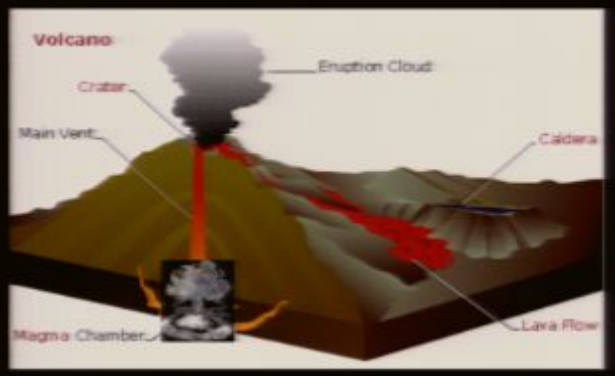

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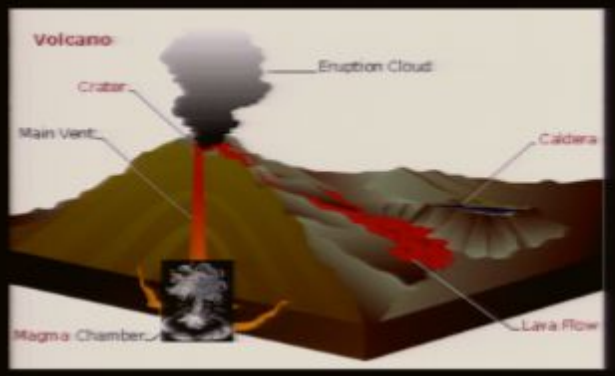

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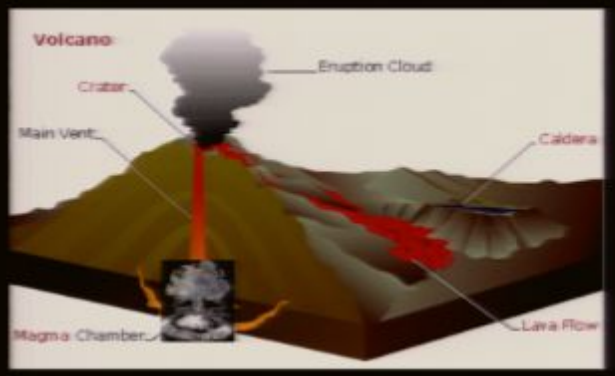

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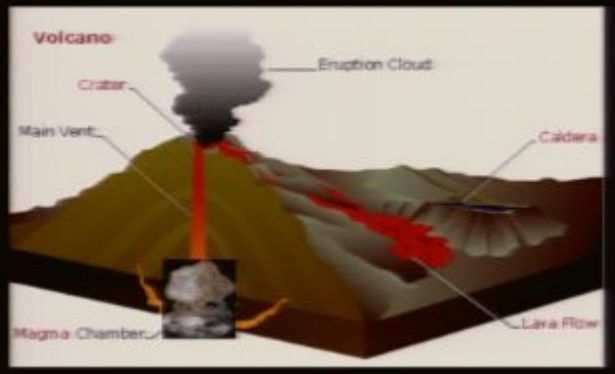

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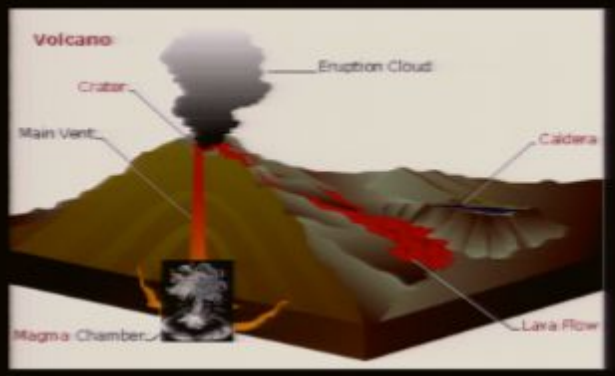

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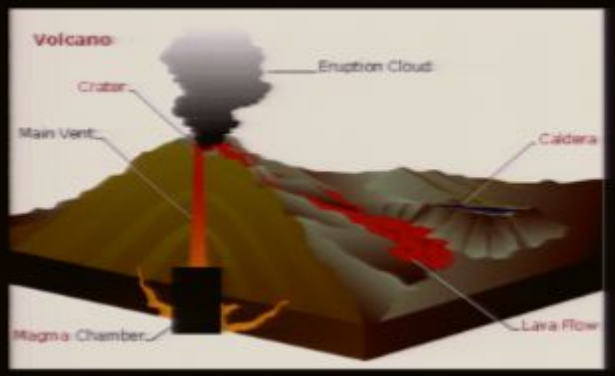

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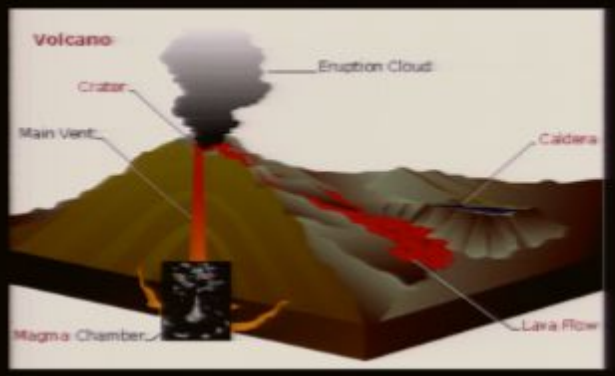

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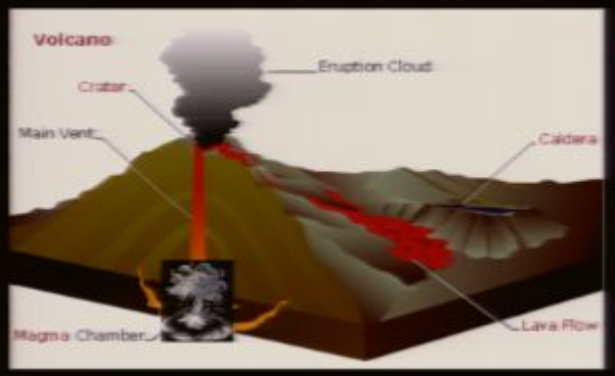

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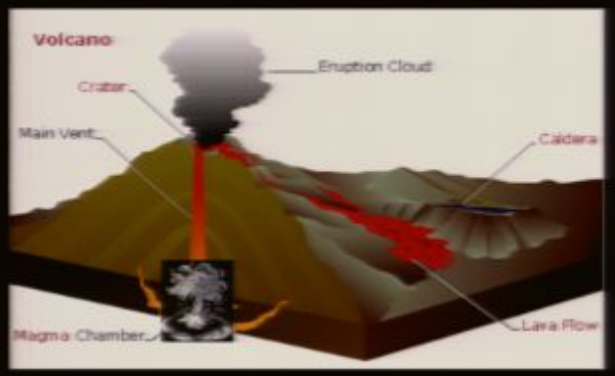
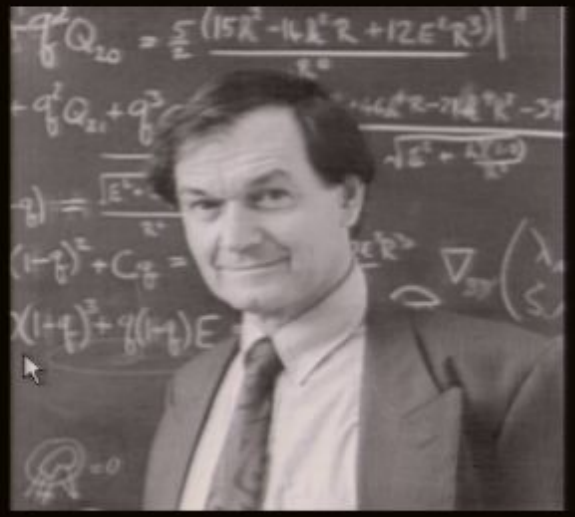


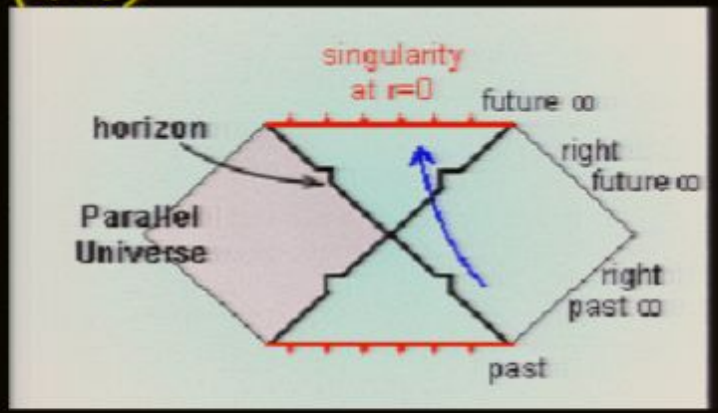
John Wheeler

- *With Bohr develops the theory of nuclear fission.*
- *Completes a catalog cold, dead stars firming up evidence of destiny of dead stars. (1957)*
- *Major battle with Oppenheimer about existence of black holes. (1957)*
- *Retracted argument and became the leading proponent of black hole. (1960)*
- *Coined the phrase "Black Hole" (1967).*
- *Coined the phrase "a Black Hole has no hair" (1968).*

Roger Penrose



- *Speculated black holes loose their hair by radiating it away.*
- *Discovered that spinning black holes store energy in space outside their horizon (1969).*
- *Discovered surface area of black holes must increase.*
- *Proved that black holes must have singularities at their core (1964).*
- *Proposed cosmic censorship conjecture (1969).*



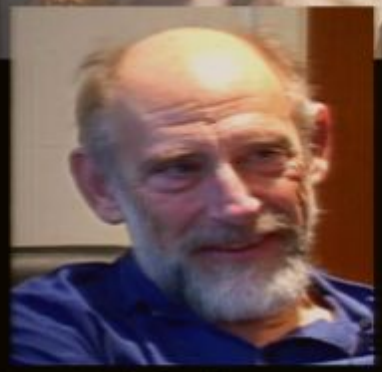
Topology

The Blackhole Stars Today

Hawking

Bekenstein

Thorne

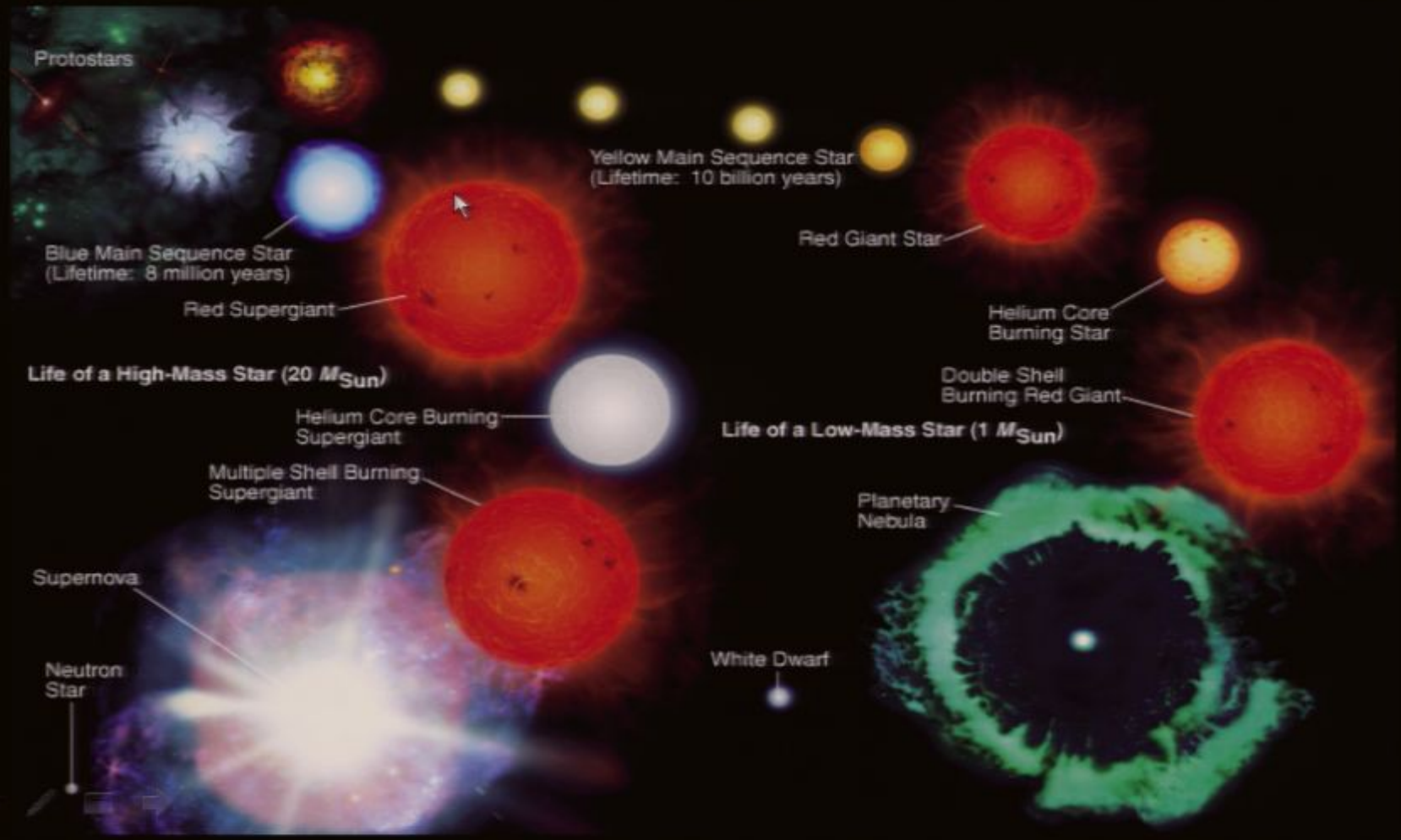


Susskind

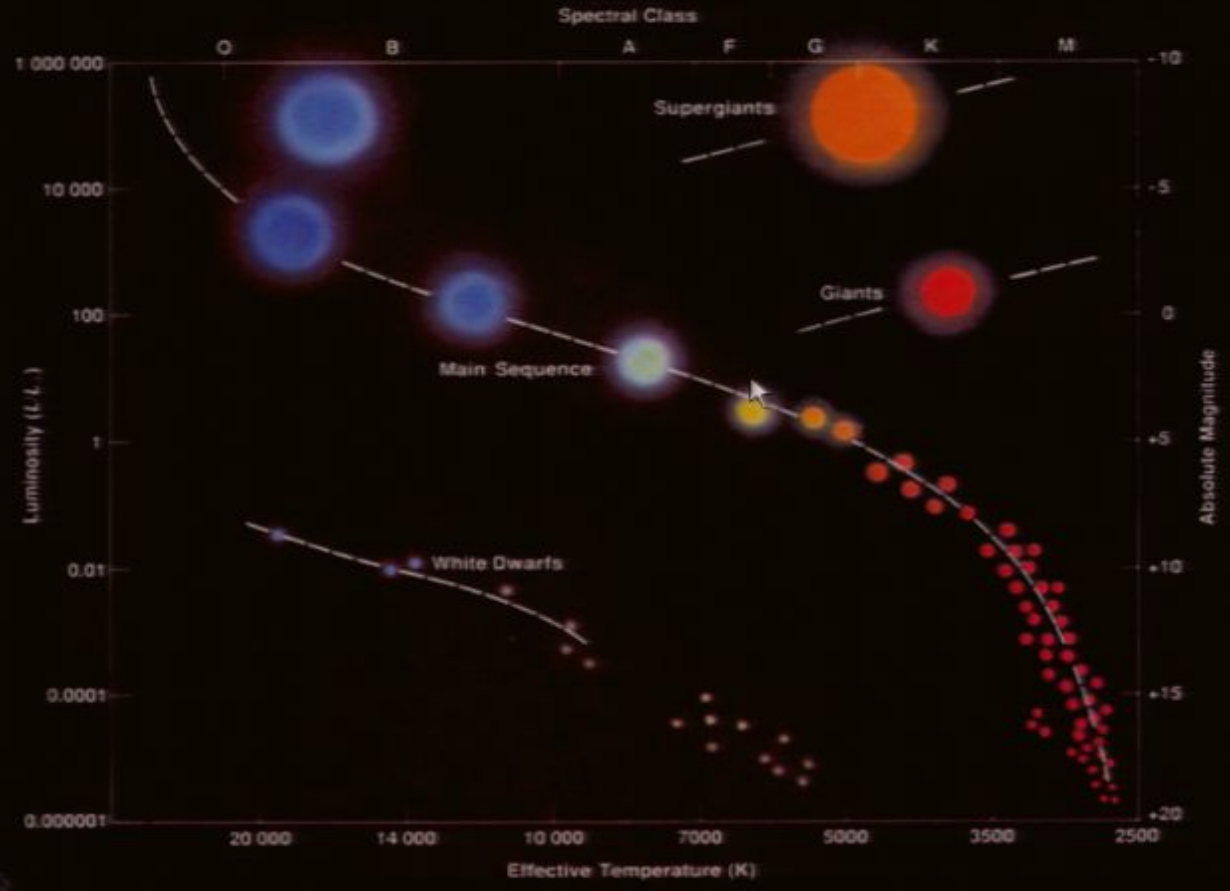
Werner Israel

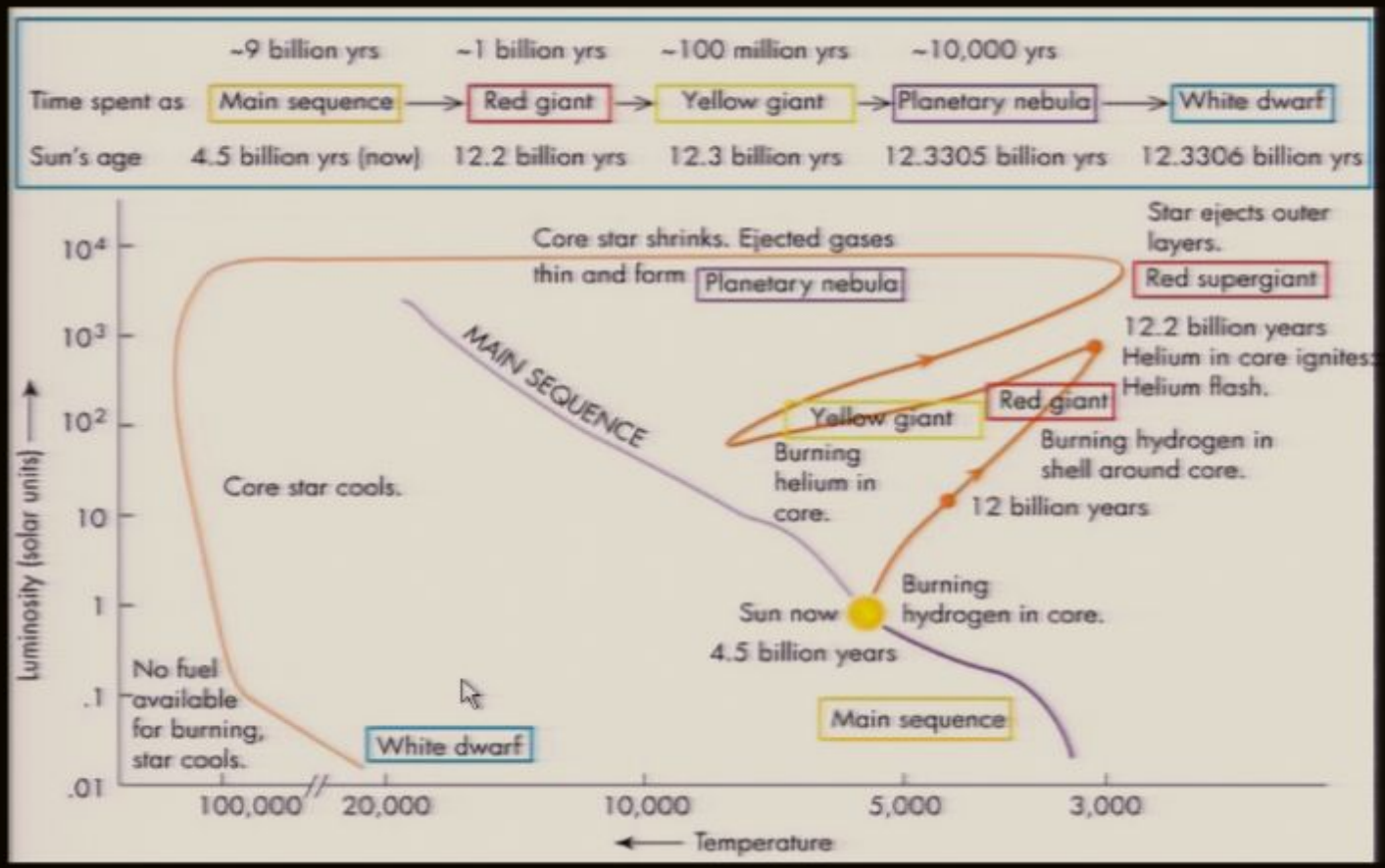
Robert Wald

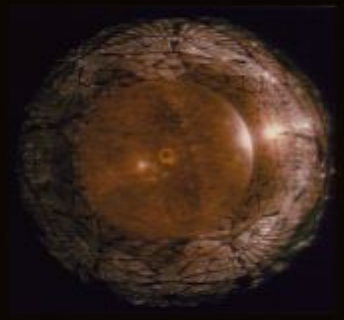
Life Cycle of Stars



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
Luminosity (solar units)
10^4
10^3
10^2
10
1
.1
.01
Core star shrinks. Ejected gases thin and form
Planetary nebula
Star ejects outer layers.
Red supergiant
MAIN SEQUENCE
12.2 billion years
Helium in core ignites: Helium flash.
Red giant
Yellow 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
100,000
20,000
10,000
5,000
3,000
Temperature



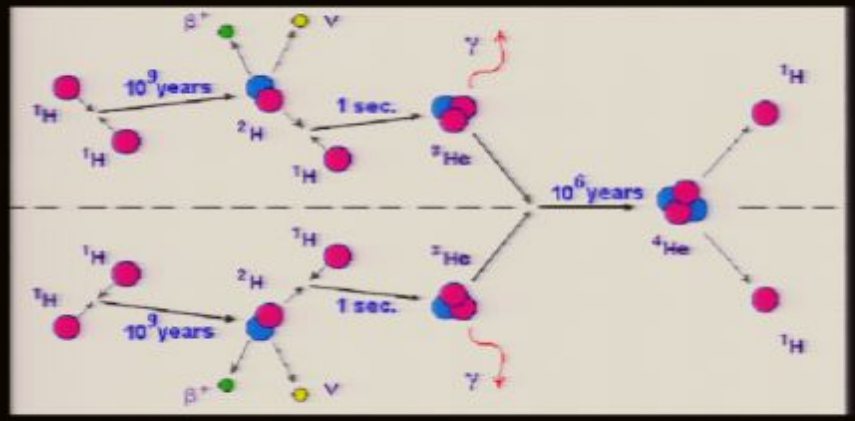
Stellar Energy

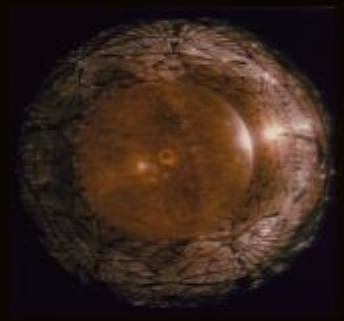
Proton-Proton Chain [4H→He + energy]

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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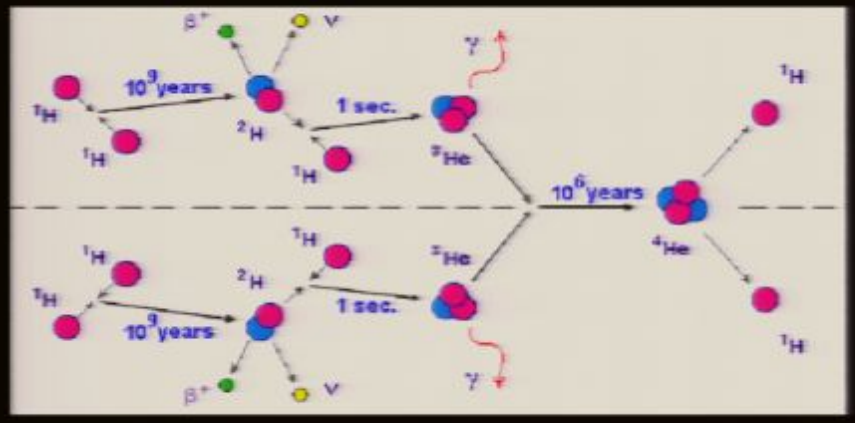
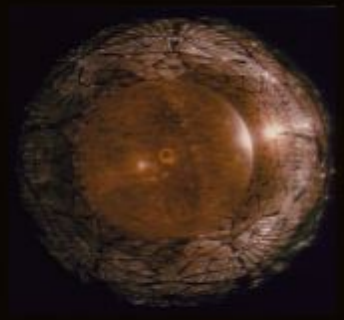
2He Is Formed

● = Neutron
● = Proton





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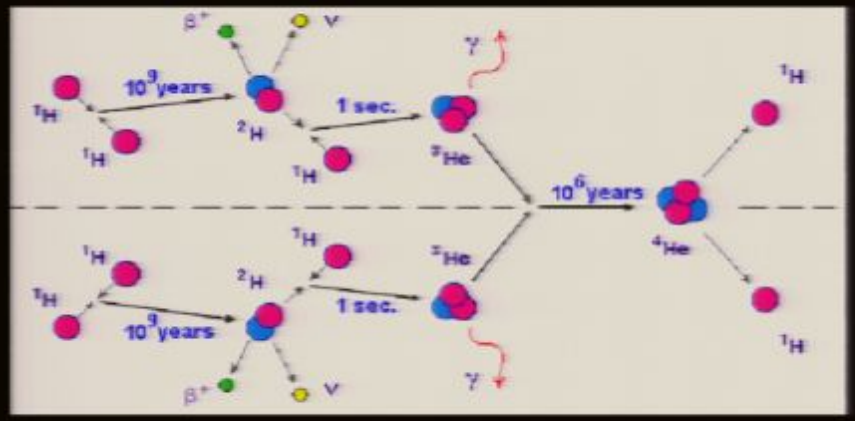
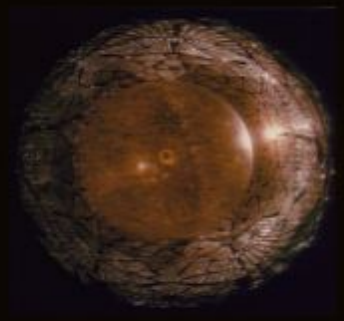
Proton





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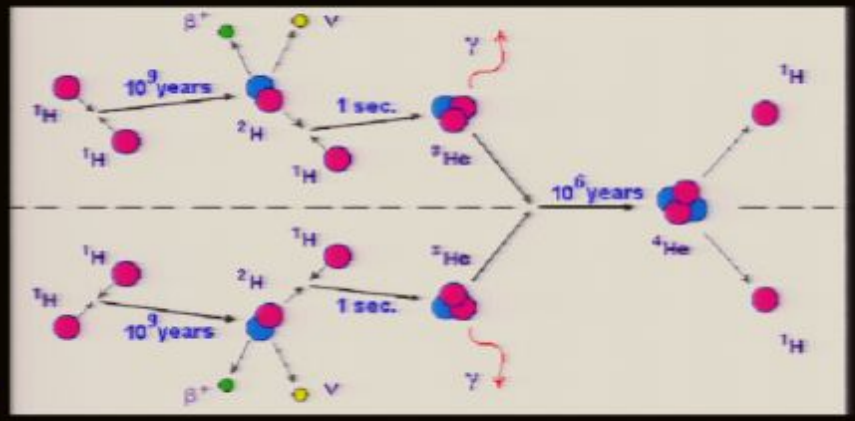
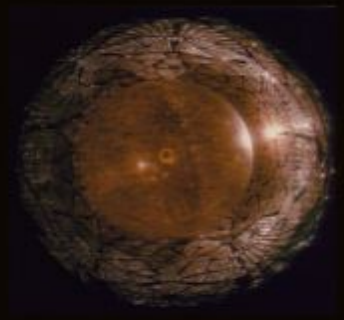
Stray 1H Fuses with 2H

Neutron
Proton

Positron
Neutrino





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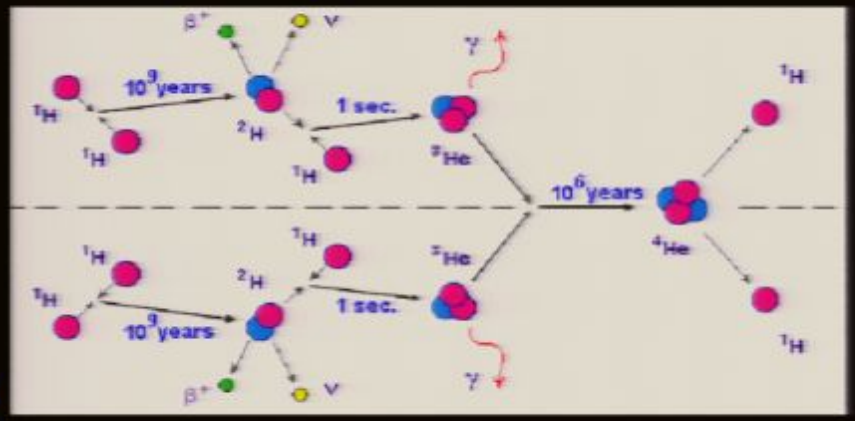
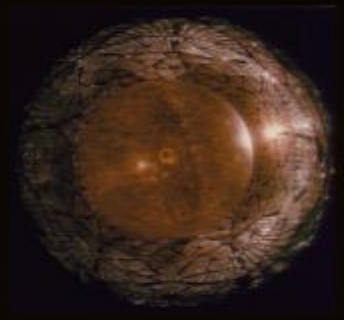
3He Is Created

Neutron
Proton





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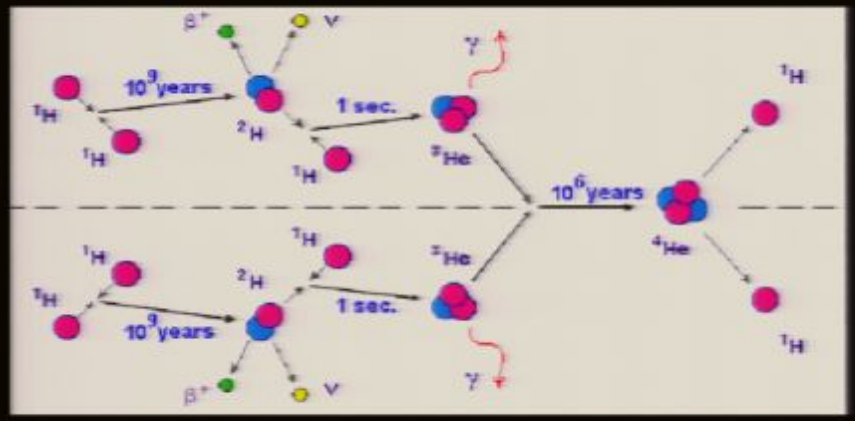
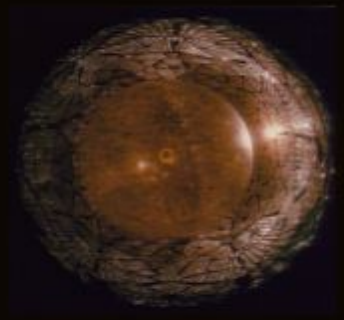
Two 3He Fuse Together

Neutron
Proton





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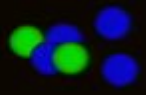
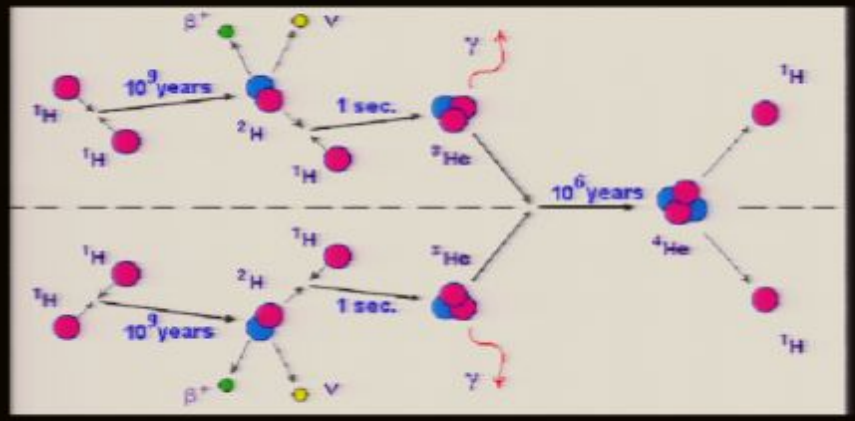
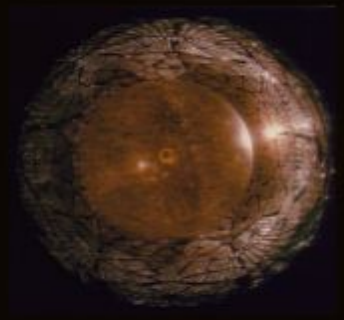
Neutron
Proton







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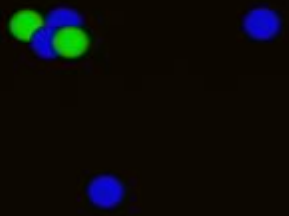

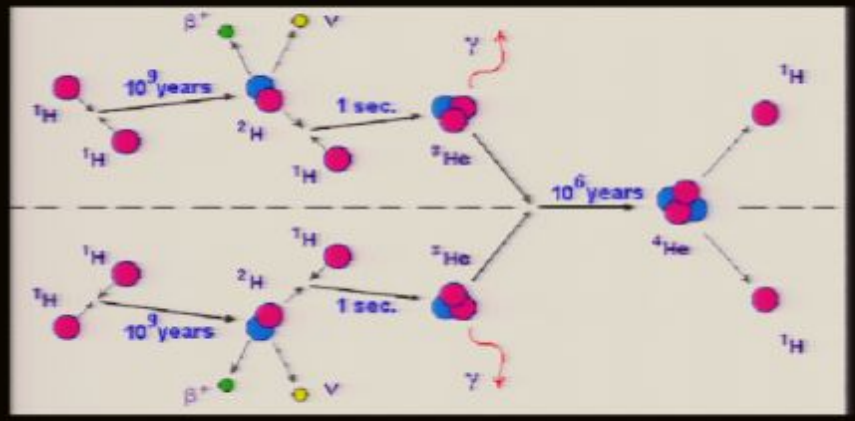

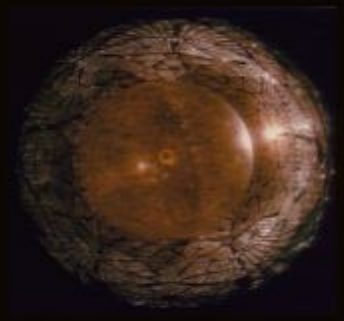

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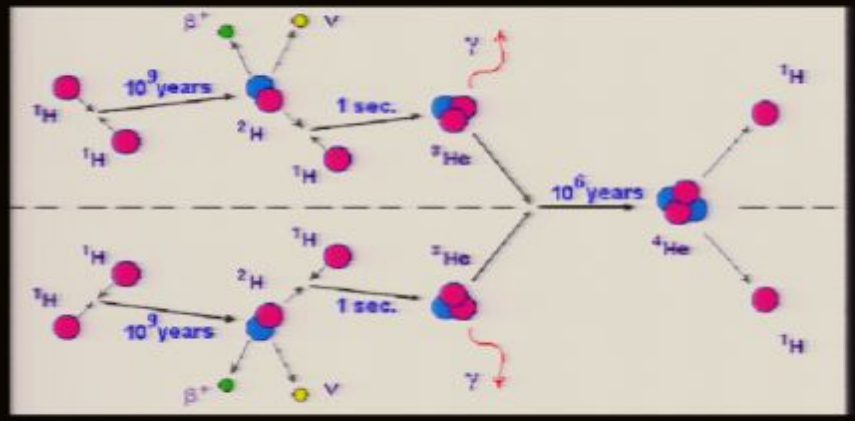
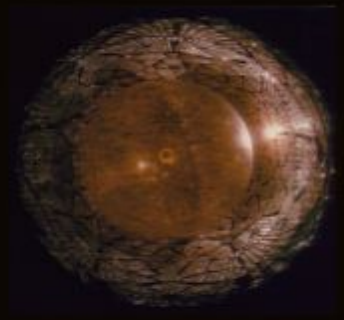
Proton-Proton Reaction

Neutron
Proton





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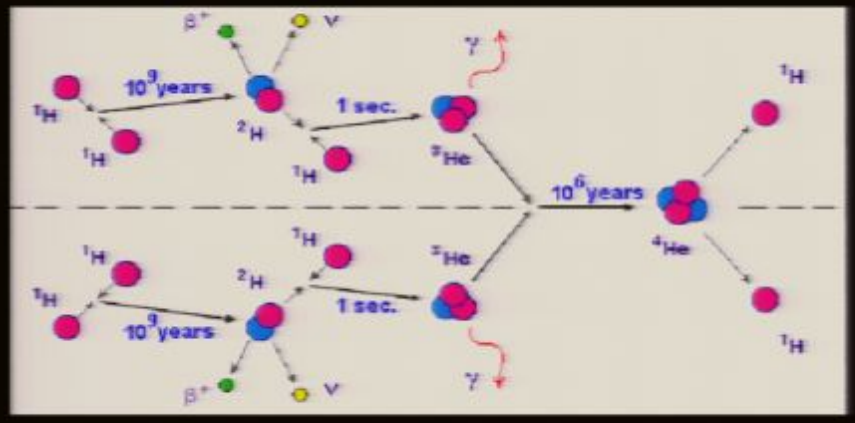

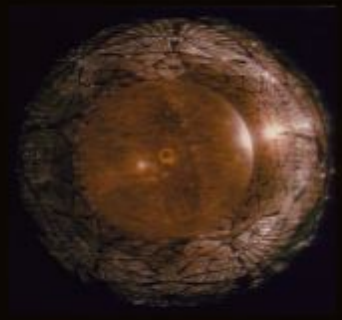

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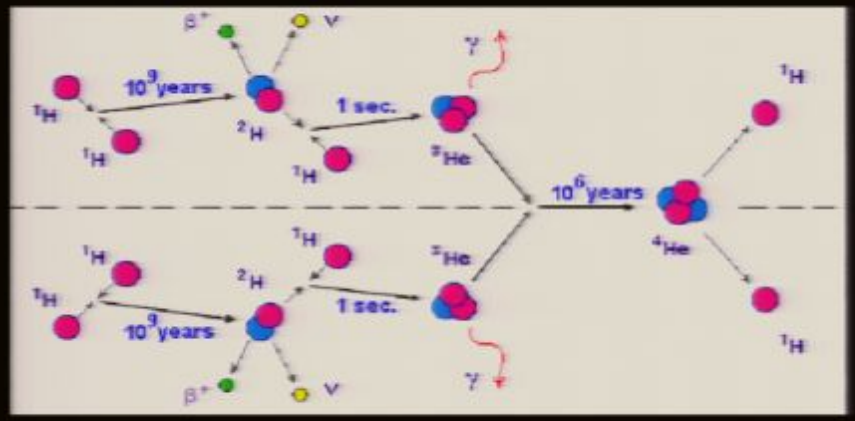

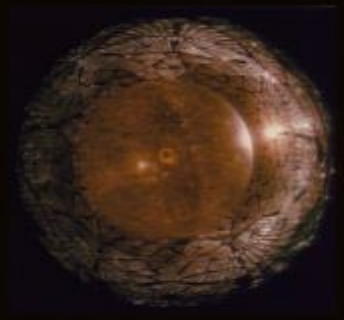

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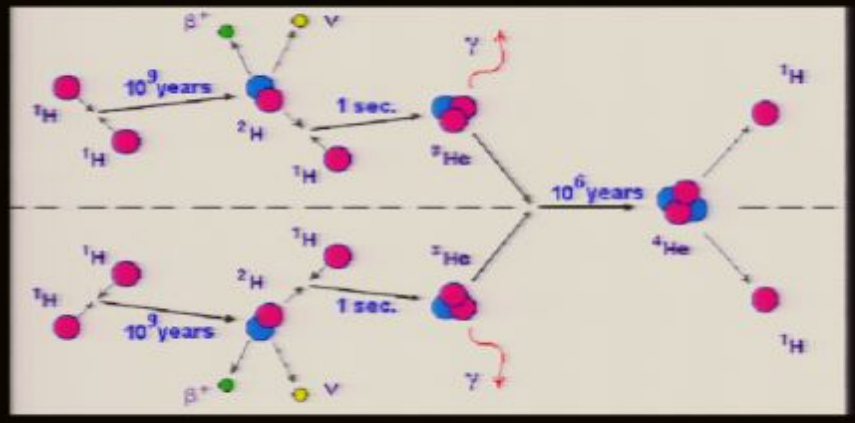

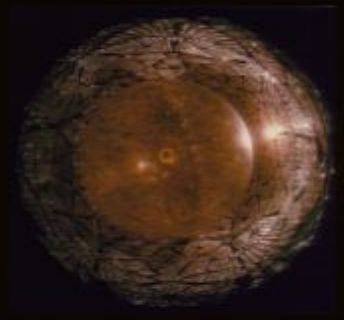

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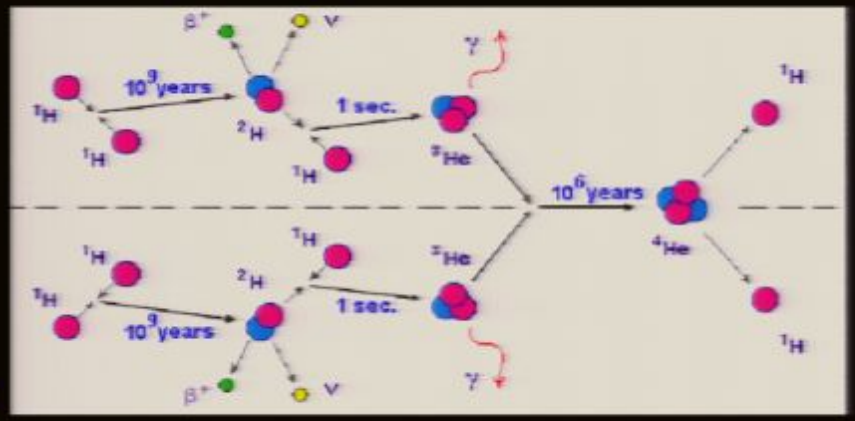
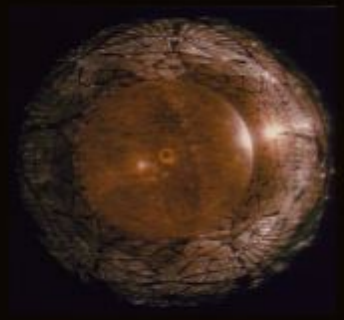
Neutron
Proton

Positron
Neutrino





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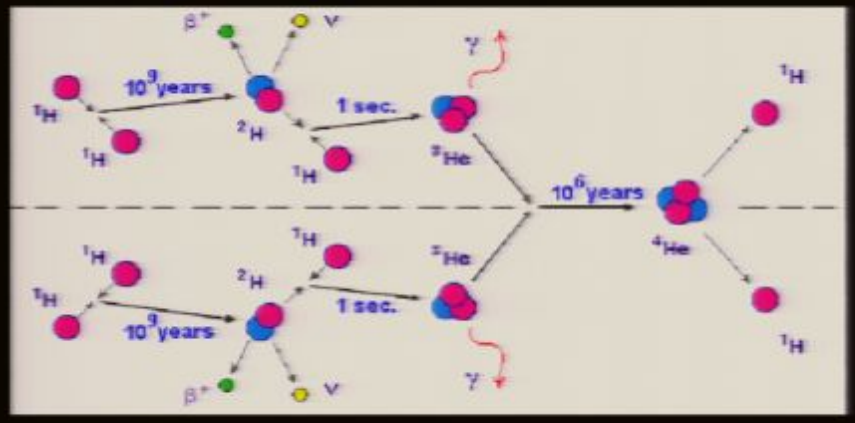

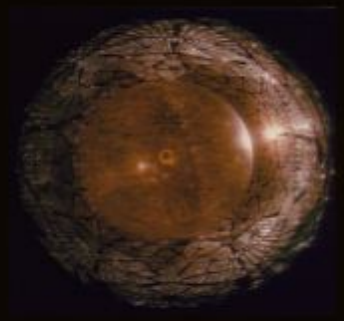

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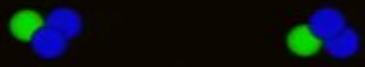

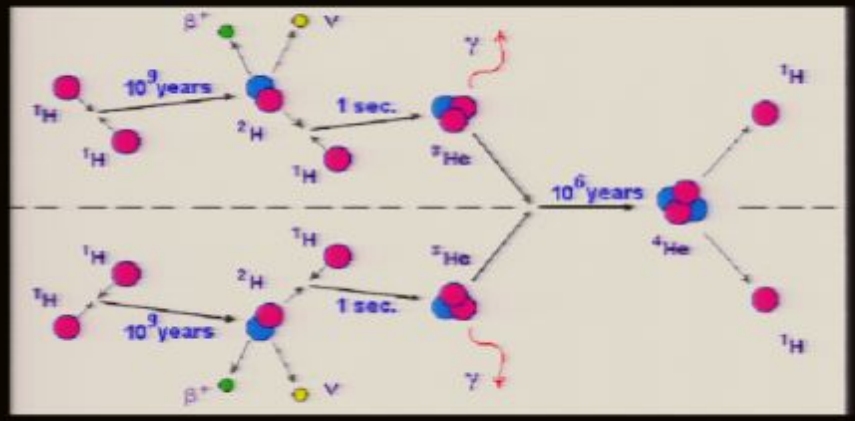

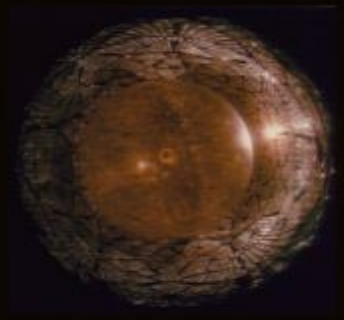

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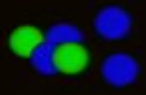

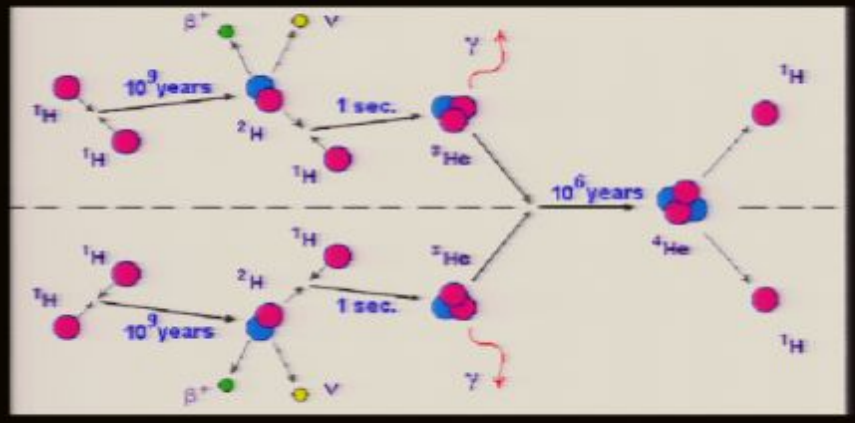

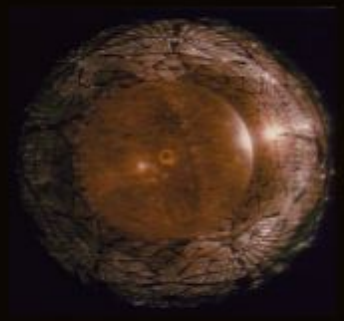

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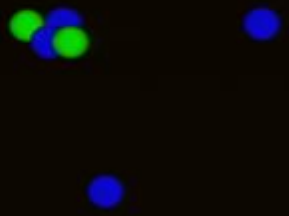

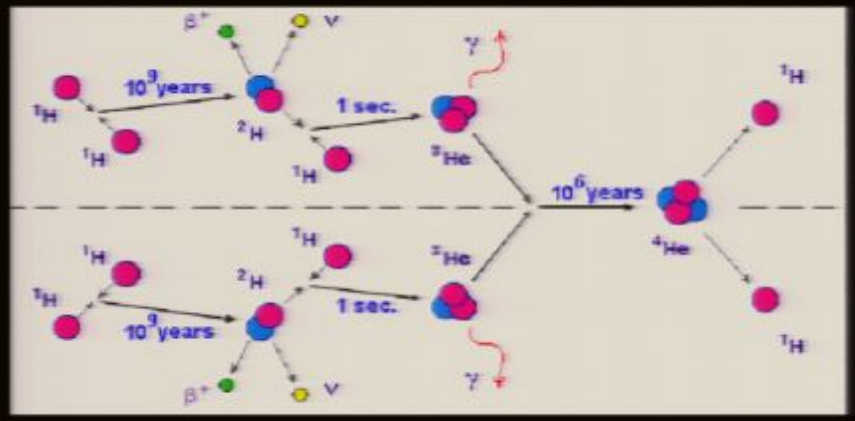

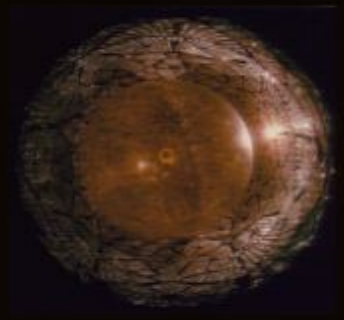

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Proton-Proton Reaction

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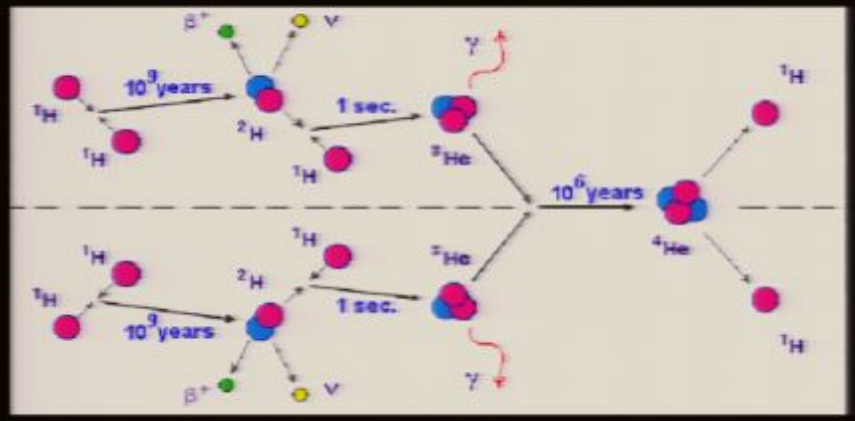

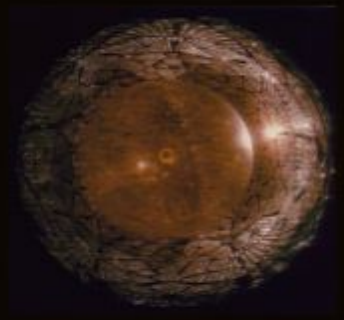

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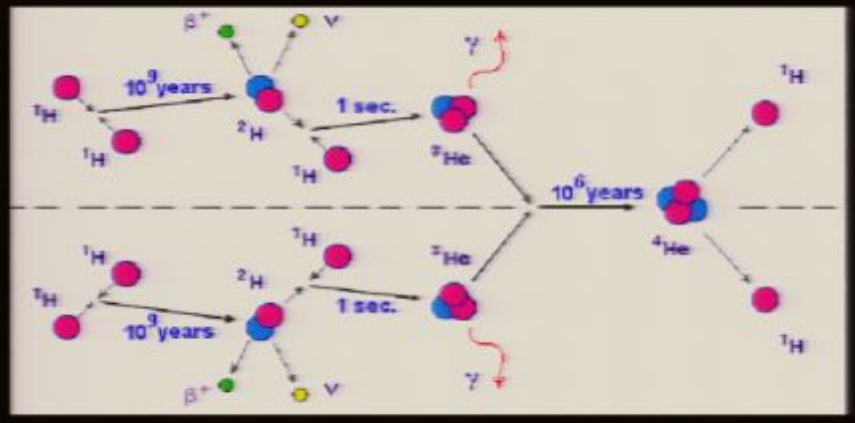

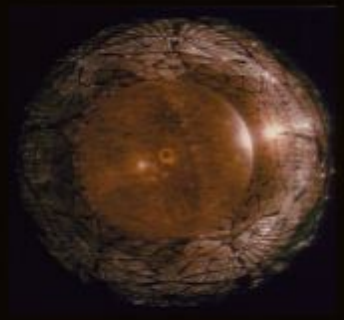

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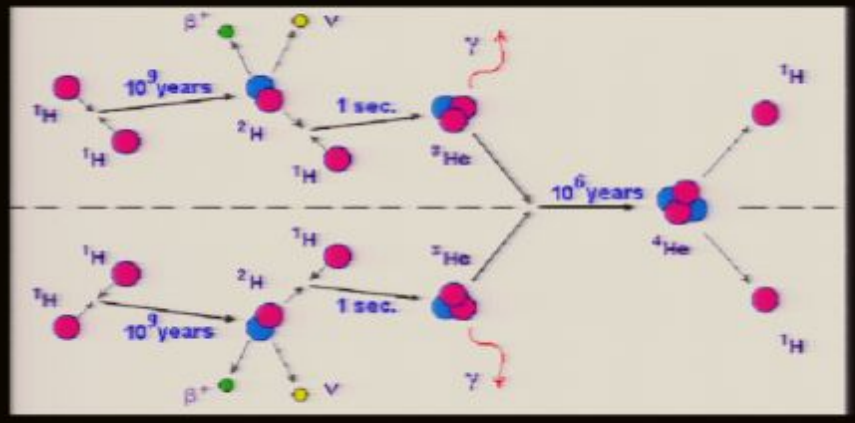

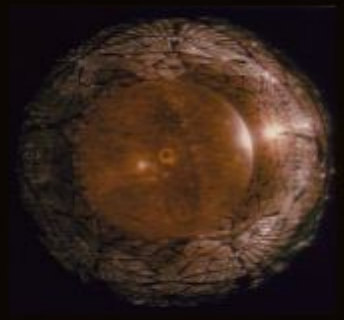

Stellar Energy

Proton-Proton Chain [4H→He + energy]

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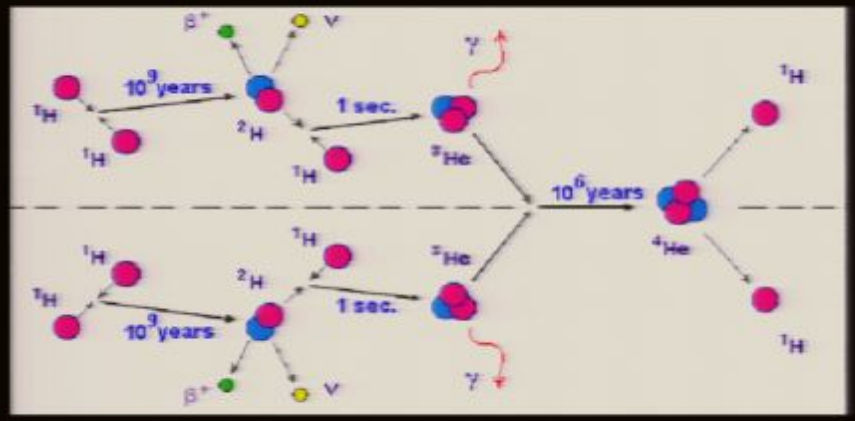
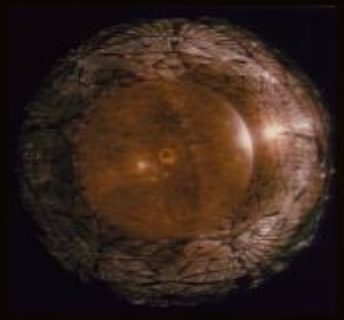
Proton Decays Into A Neutron

Neutron
Proton





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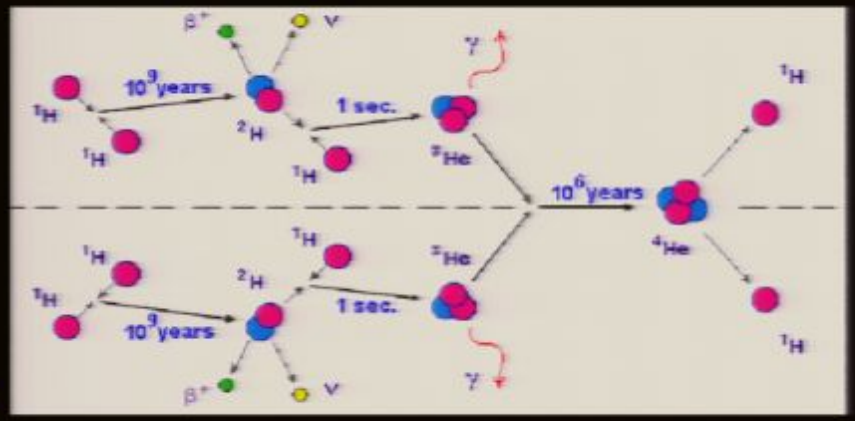
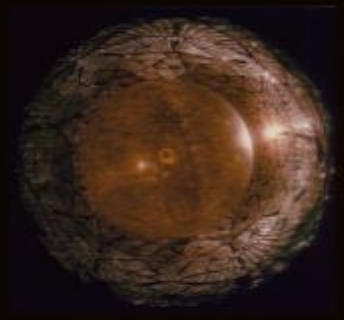
Stray 1H Fuses with 2H

Neutron
Proton

Positron
Neutrino





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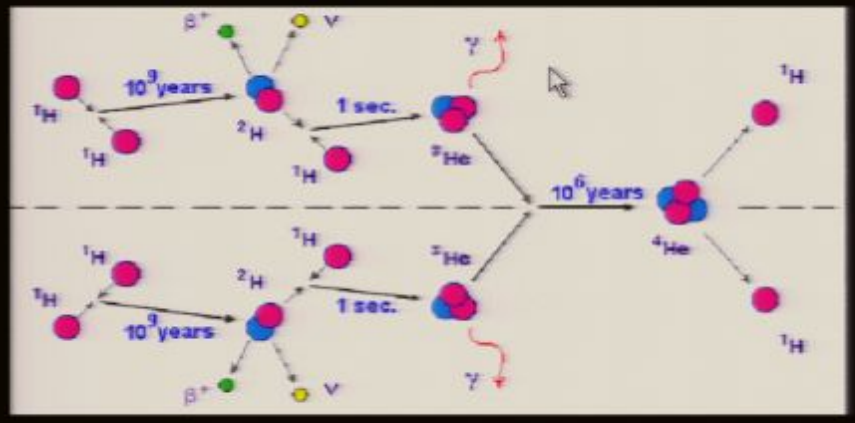
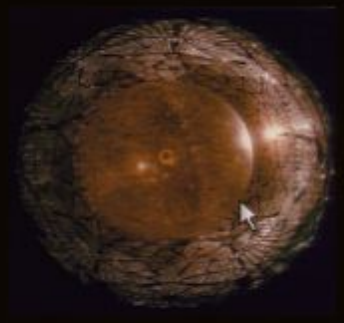
3He Is Created

Neutron
Proton





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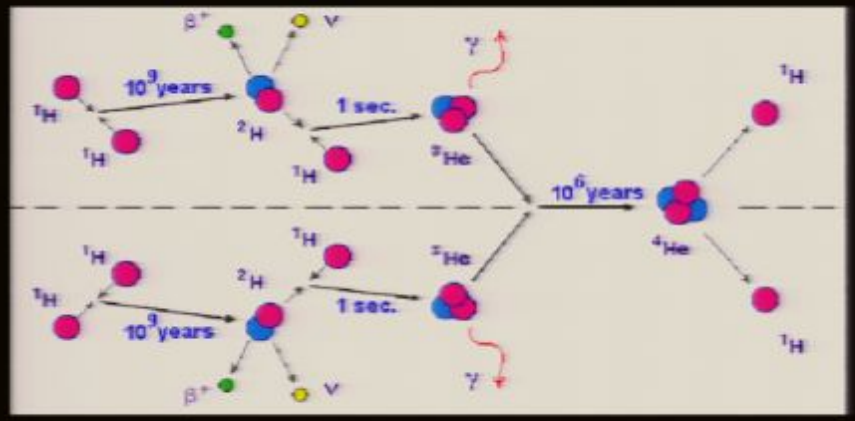
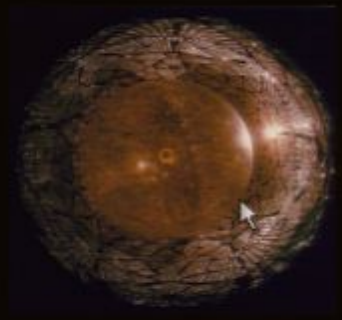
Two 3He Fuse Together

Neutron
Proton





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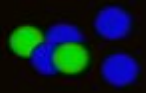
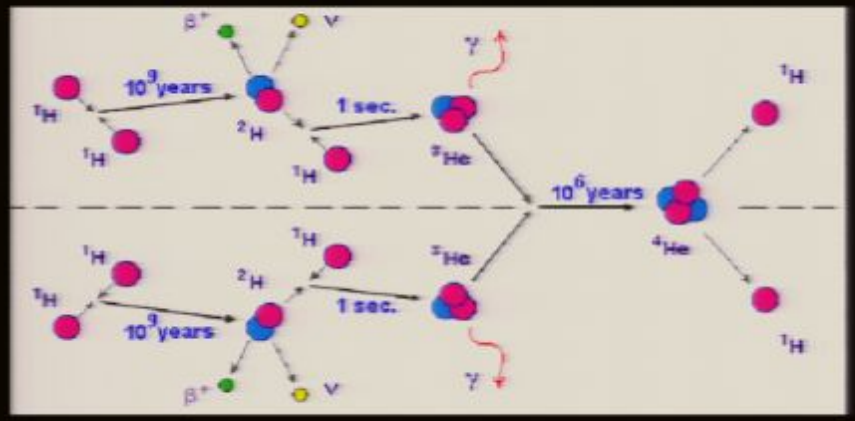
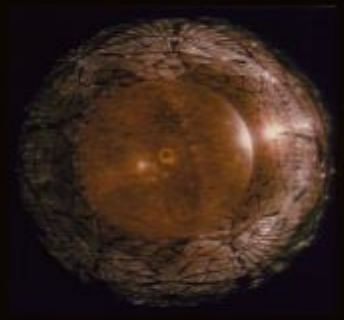
Two 1H Atoms Released

Neutron
Proton







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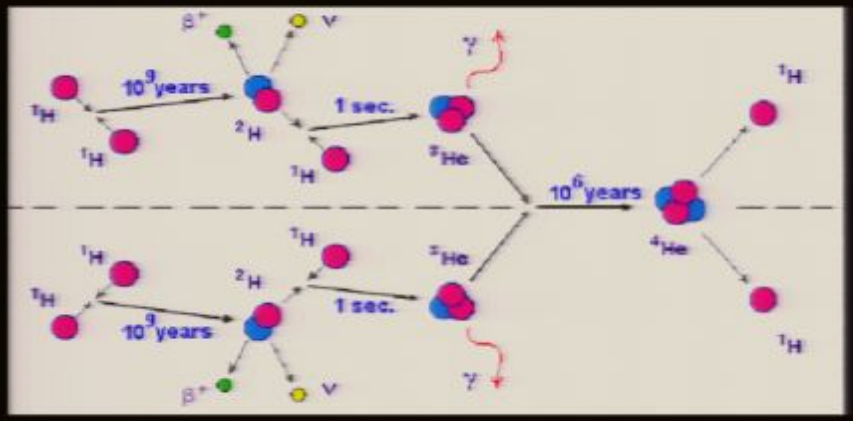
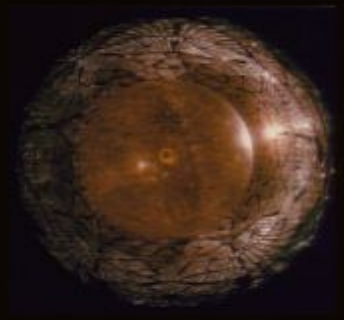
4He Is Formed

Neutron
Proton





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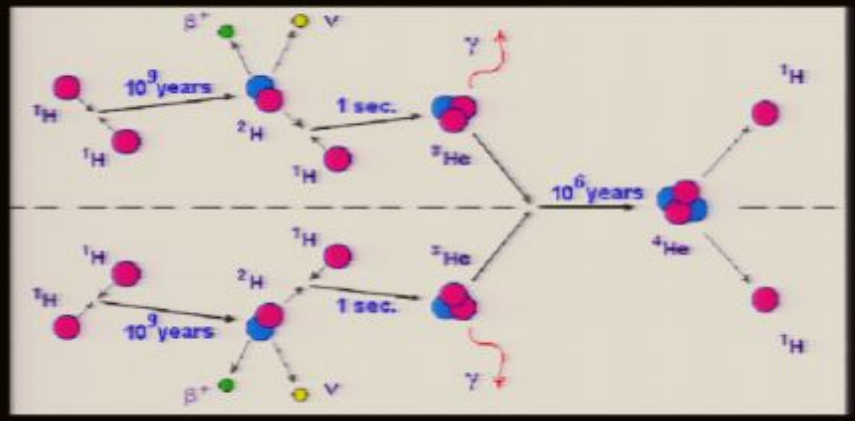
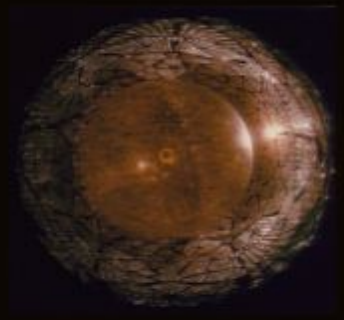
Proton-Proton Reaction

Neutron
Proton





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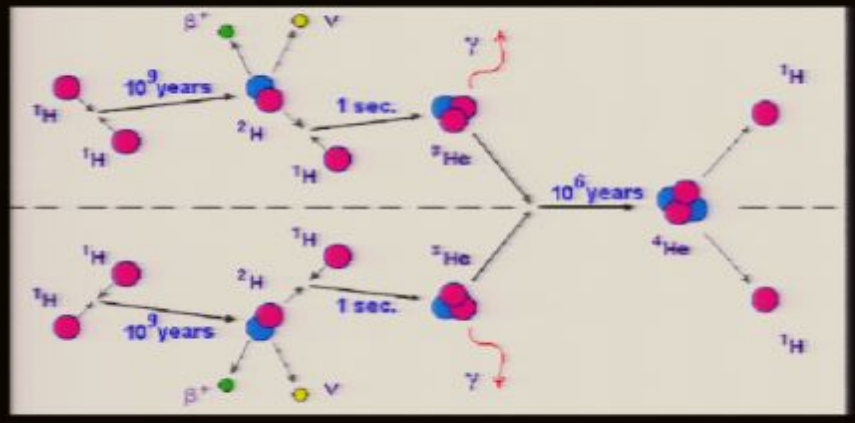
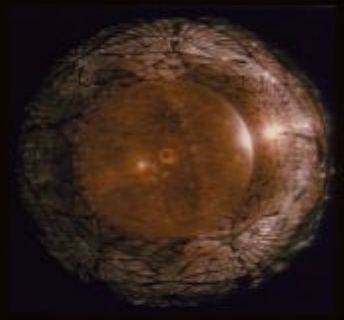
Two 1H Atoms Combine

Neutron
Proton





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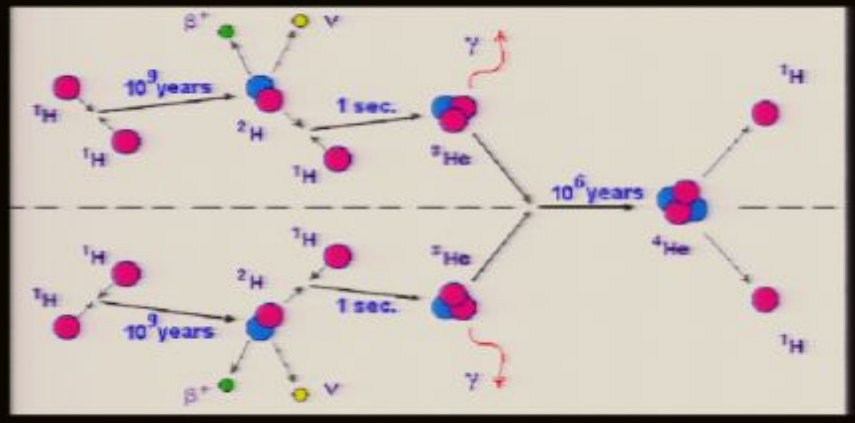
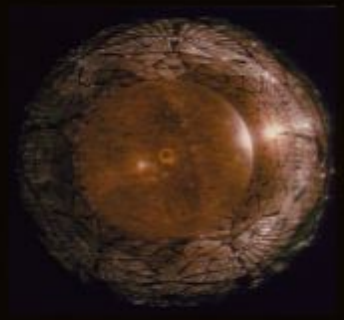
2He Is Formed

Neutron
Proton





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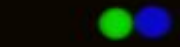
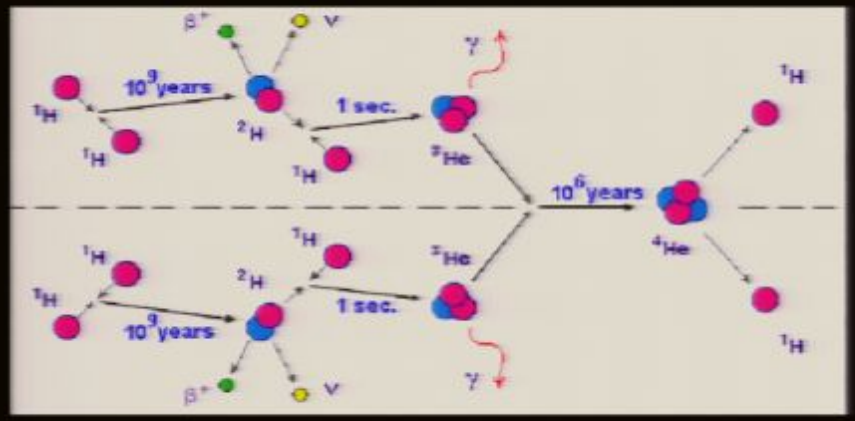
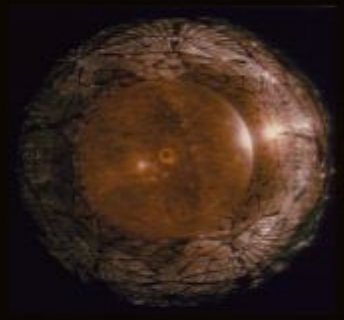
Neutron
Proton







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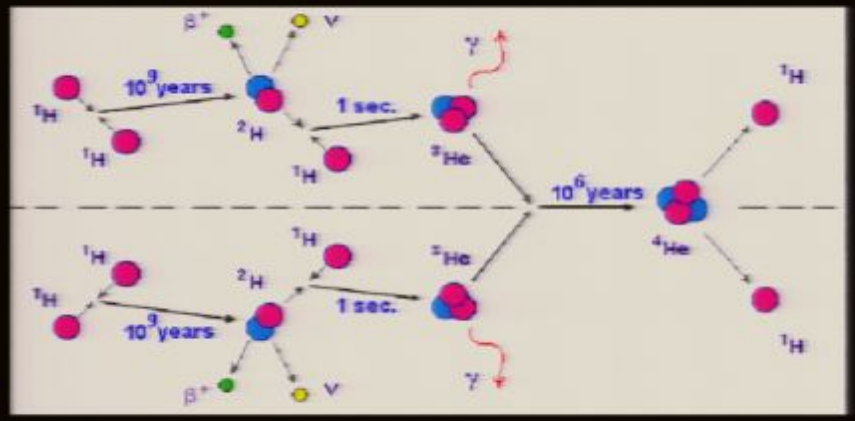
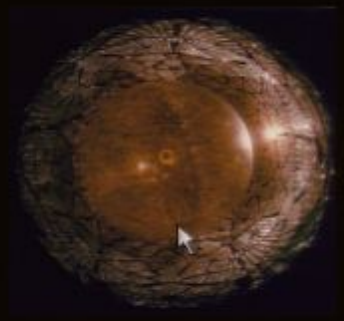
Stray 1H Fuses with 2H

Neutron
Proton

Positron

Neutrino





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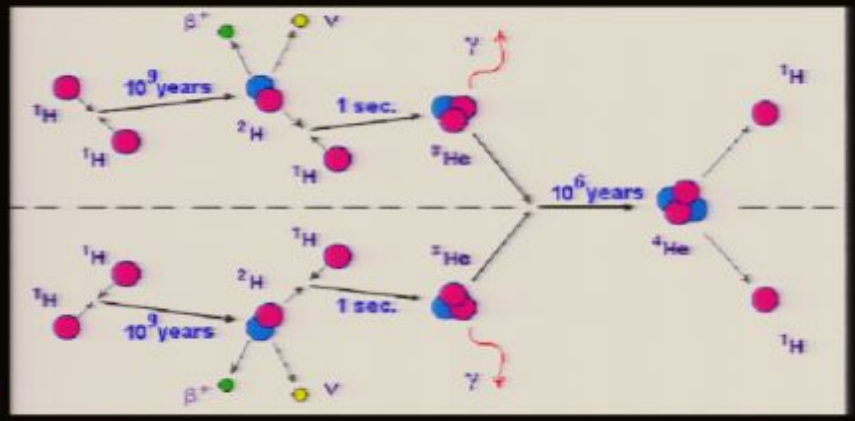
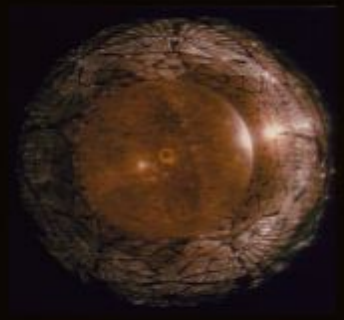
3He Is Created

Neutron
Proton





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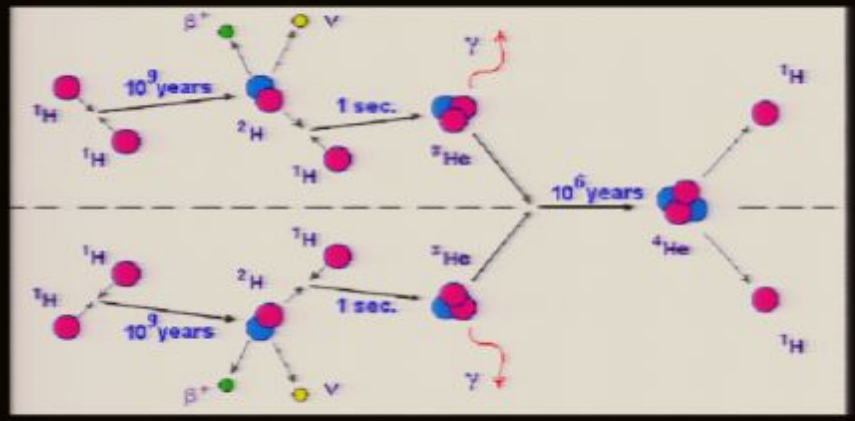
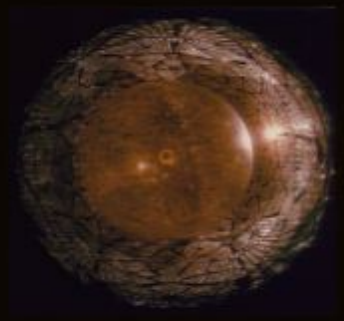
Two 3He Fuse Together

Neutron
Proton





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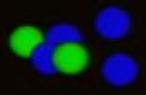
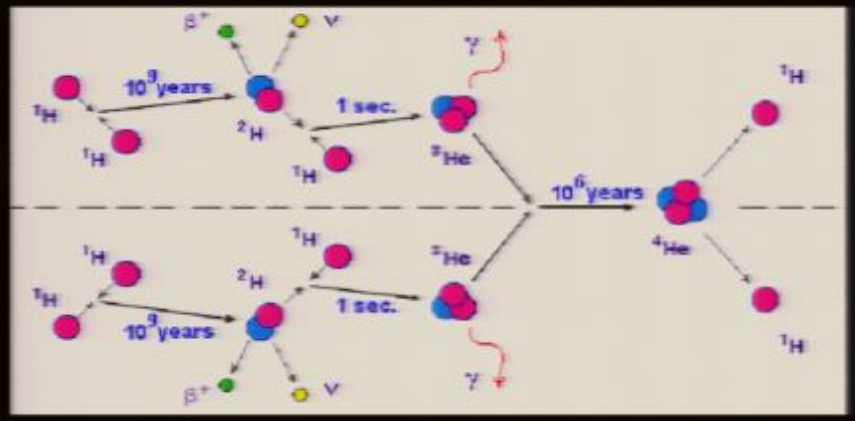
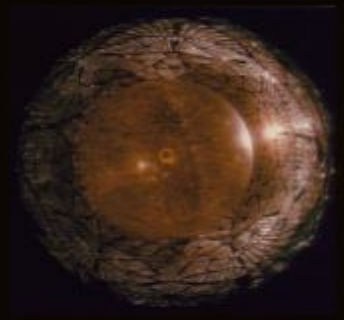
Two 1H Atoms Released

Neutron
Proton







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4He Is Formed

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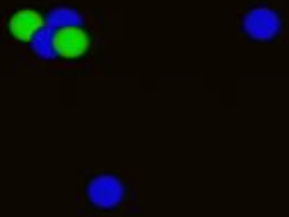

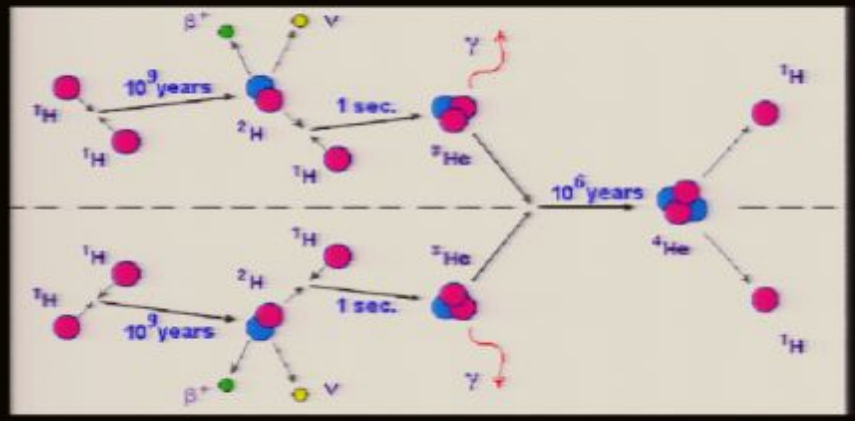

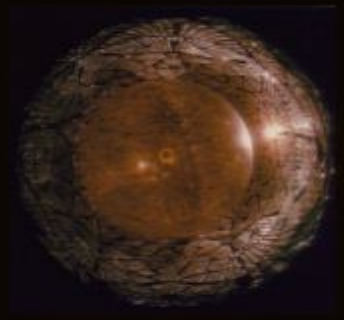

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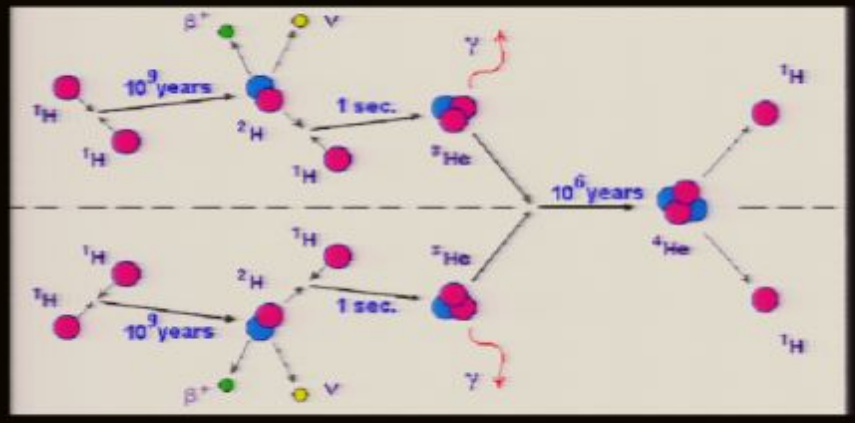
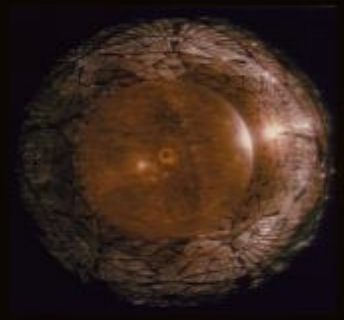
Proton-Proton Reaction

Neutron
Proton





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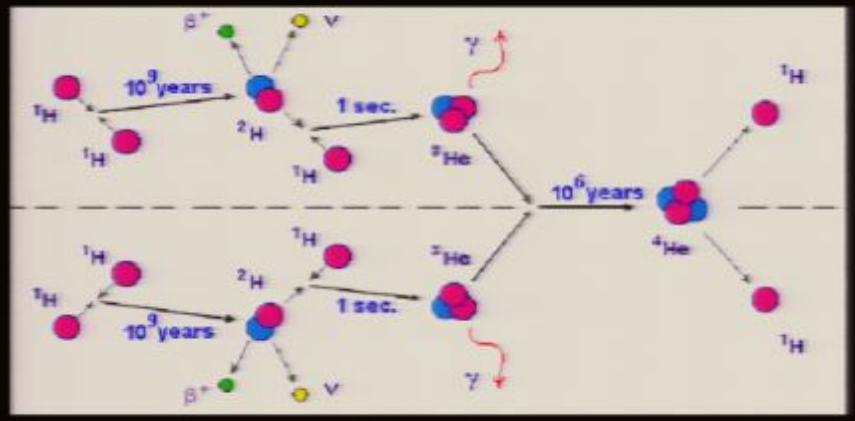
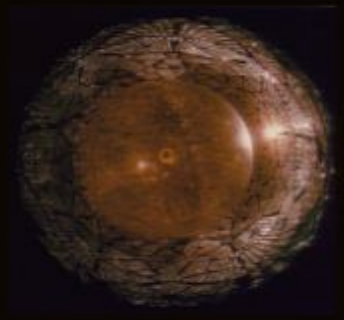
Two 1H Atoms Combine

Neutron
Proton





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2He Is Formed

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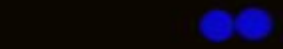

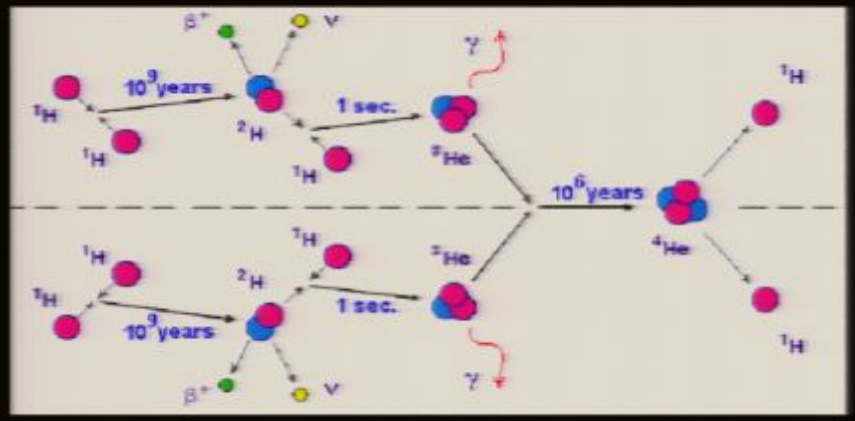

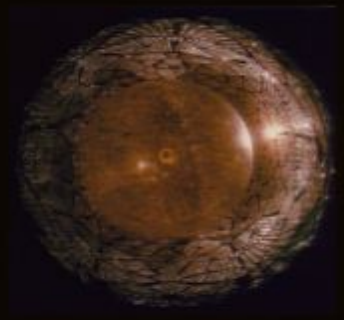

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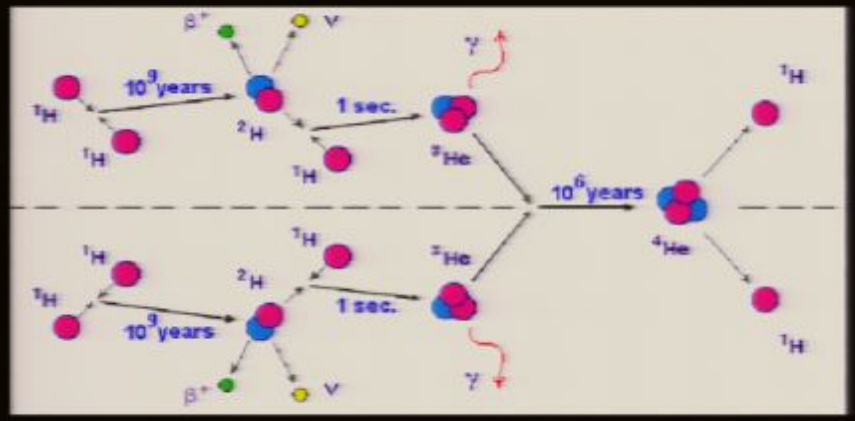
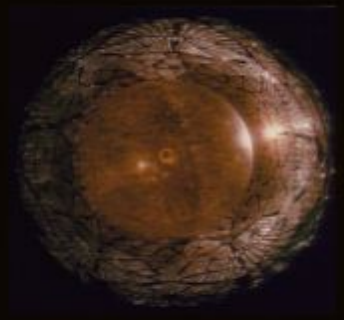
Neutron
Proton





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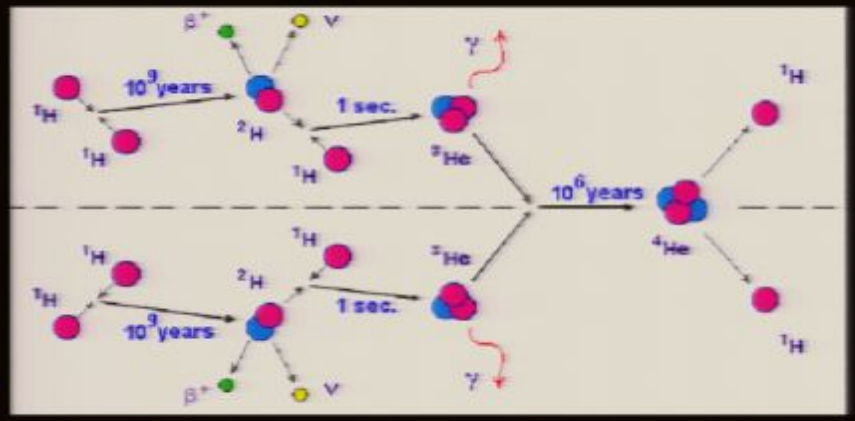
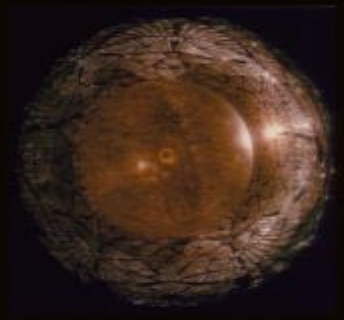
Stray 1H Fuses with 2H

Neutron
Proton

Positron
Neutrino





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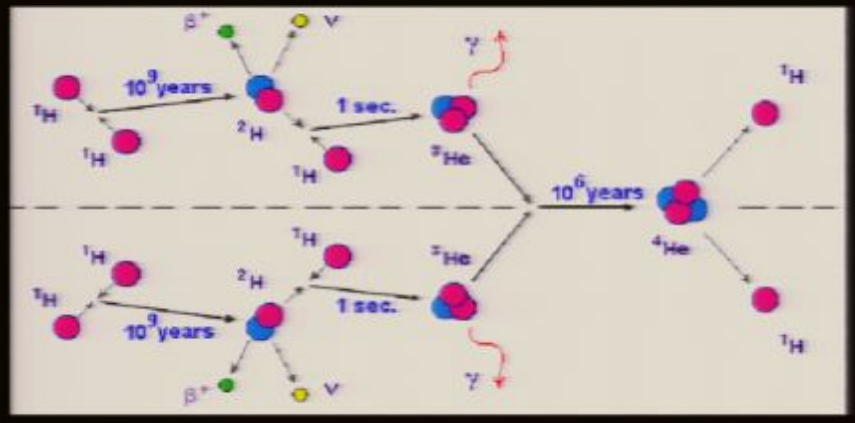
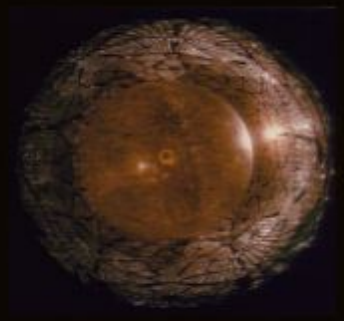
3He Is Created

Neutron
Proton





Stellar Energy

Proton-Proton Chain [4H→He + energy]

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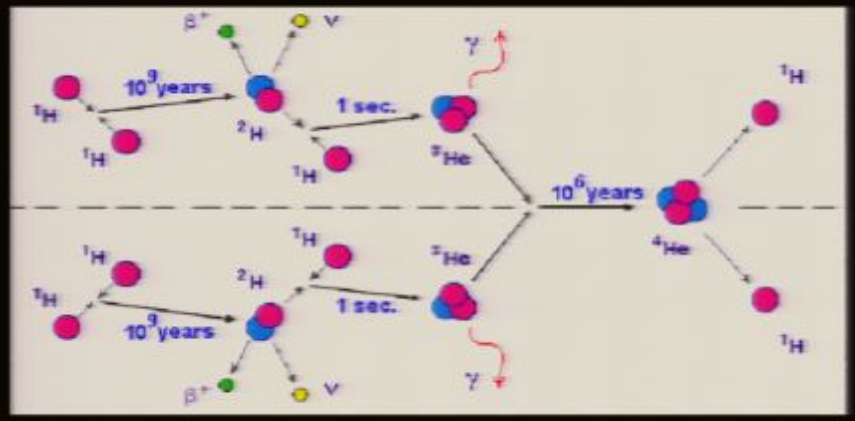
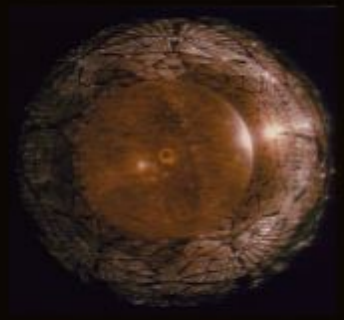
Two 3He Fuse Together

Neutron
Proton





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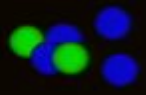
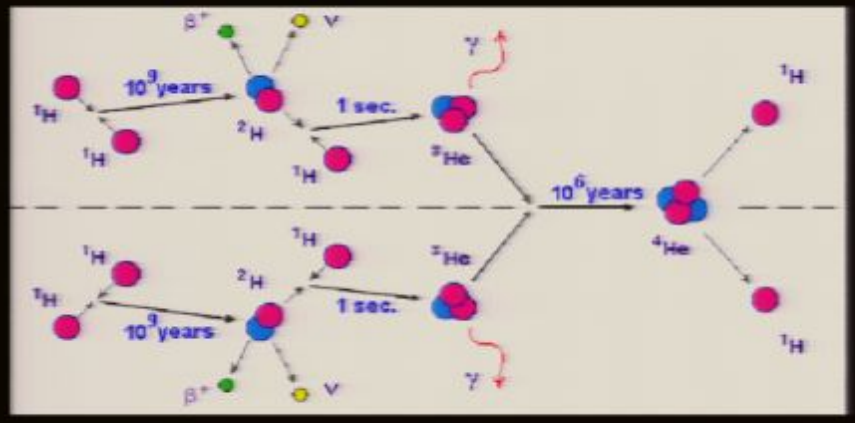
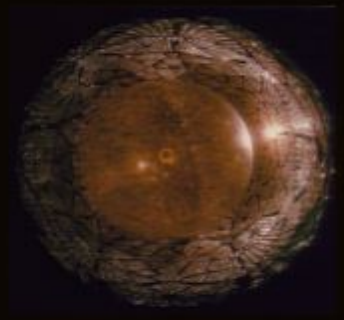
Two 1H Atoms Released

Neutron
Proton







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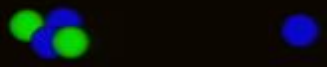
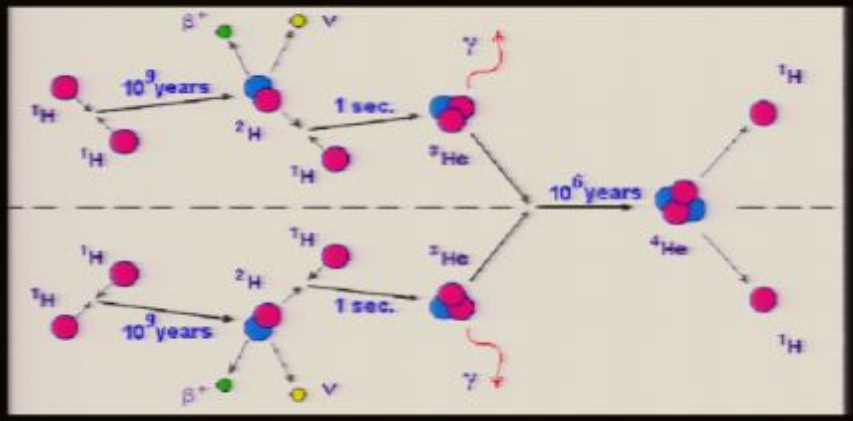
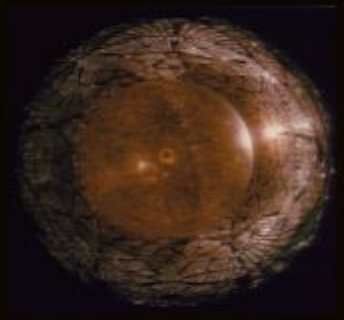
4He Is Formed

= Neutron
= Proton







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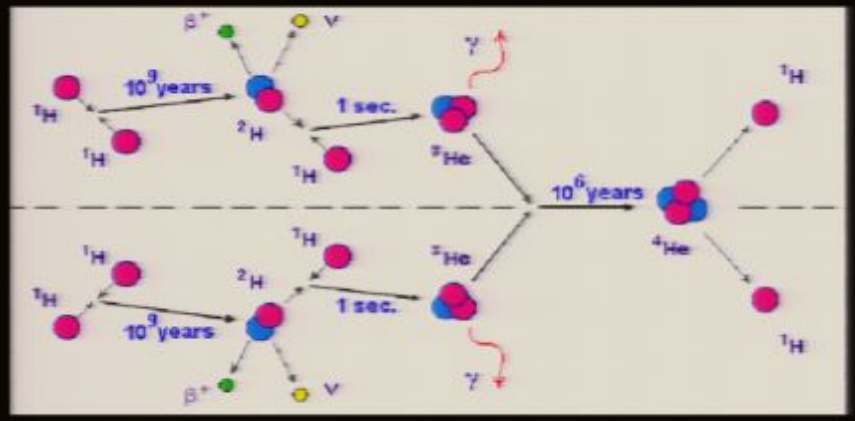
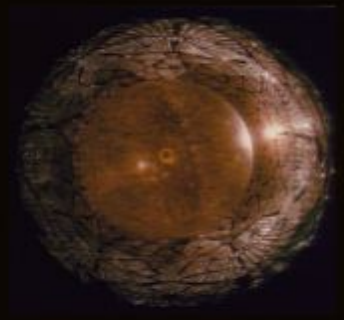
Proton-Proton Reaction

Neutron
Proton





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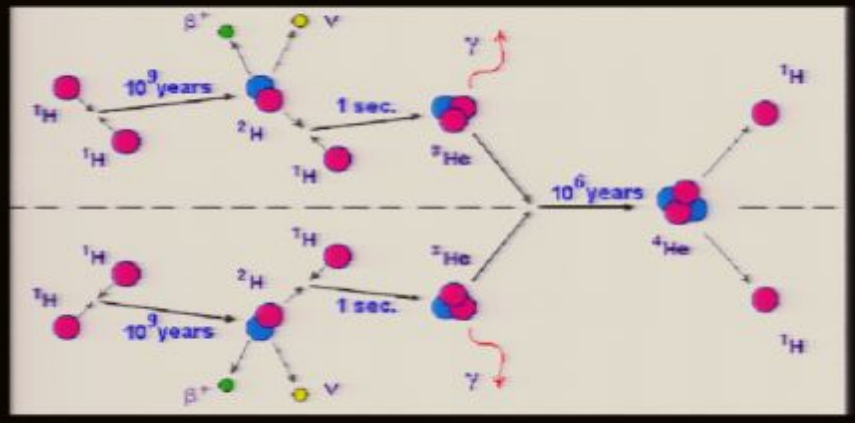
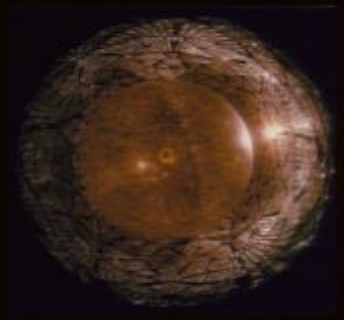
Proton





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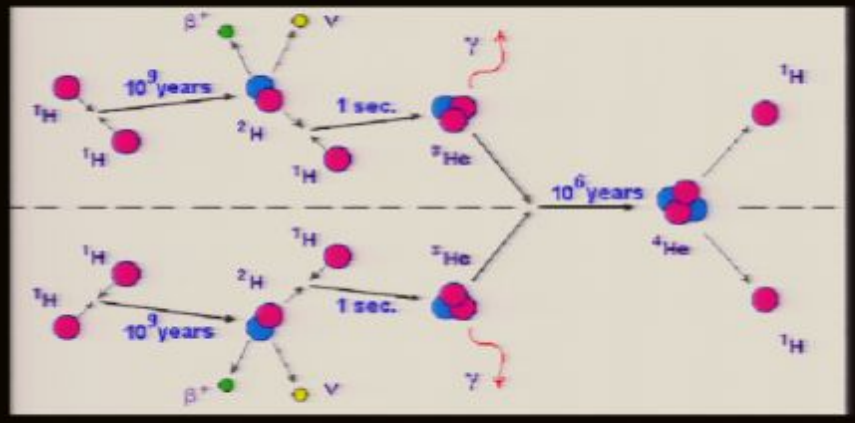
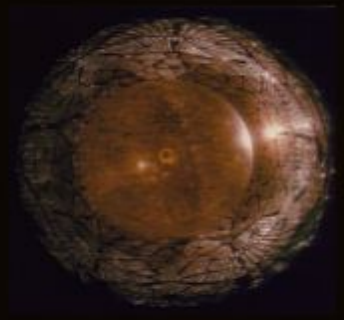
2He Is Formed

● = Neutron
● = Proton





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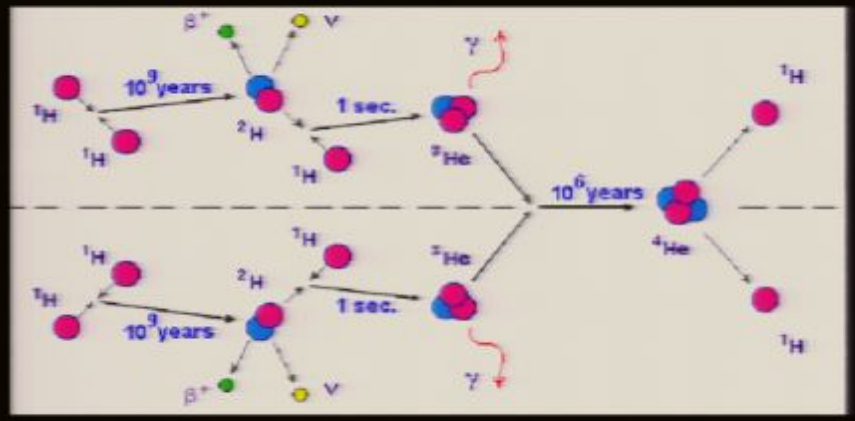
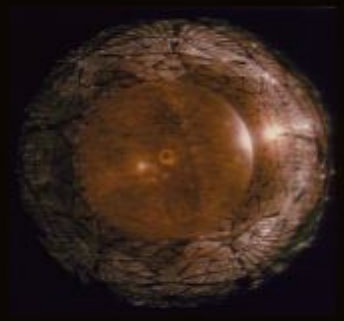
Neutron
Proton





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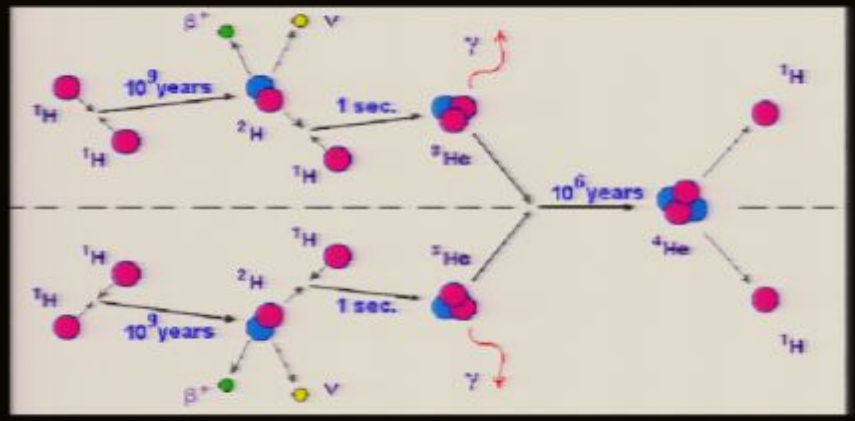
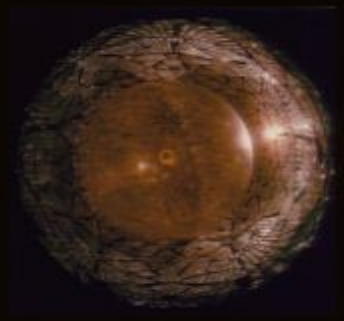
Stray 1H Fuses with 2H

Neutron
Proton

Positron

Neutrino





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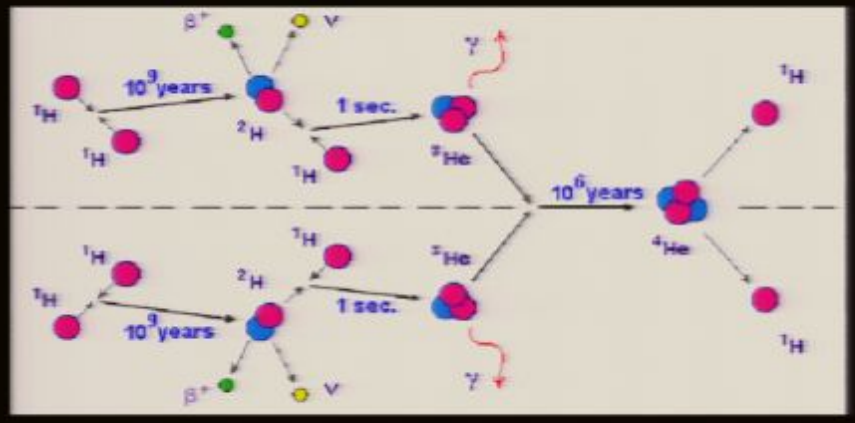
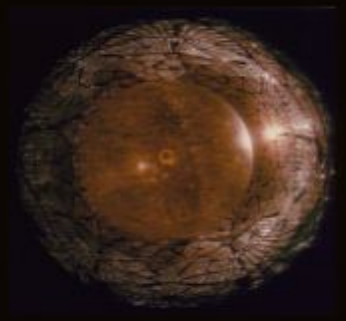
3He Is Created

Neutron
Proton





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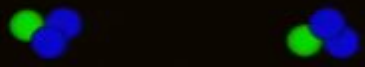
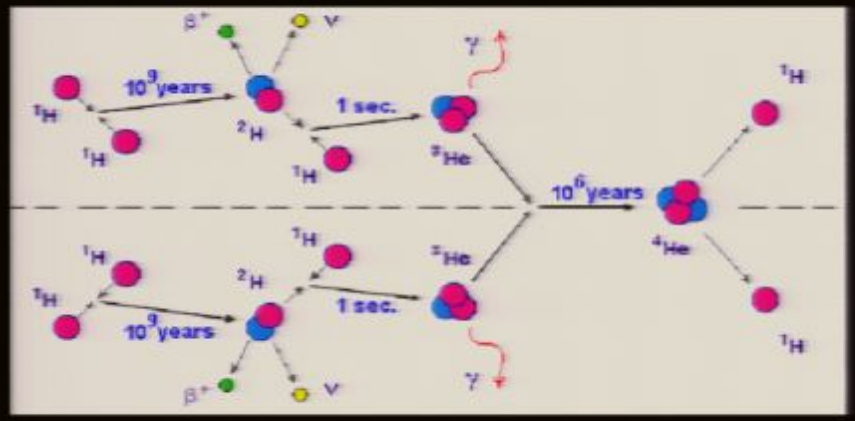
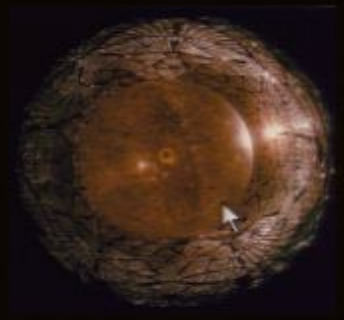
Neutron
Proton







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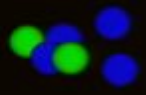
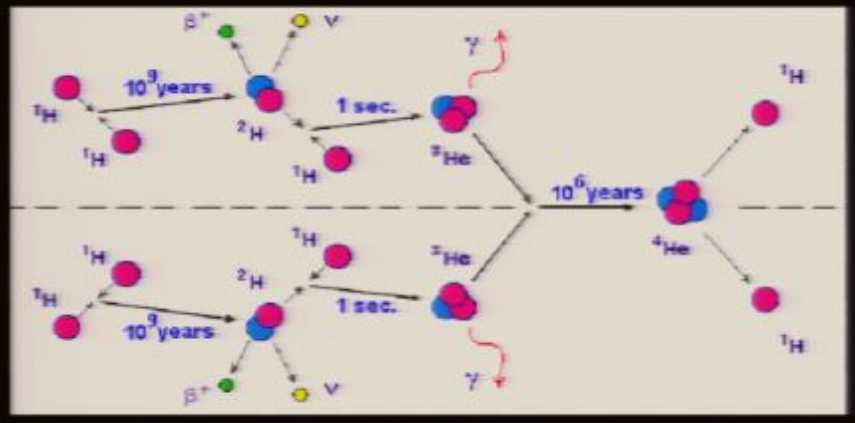
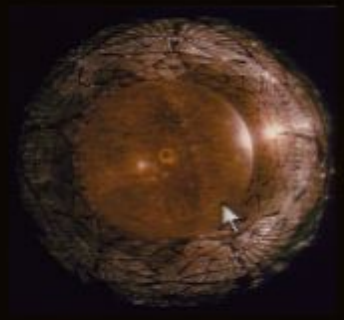
Two 1H Atoms Released

Neutron
Proton







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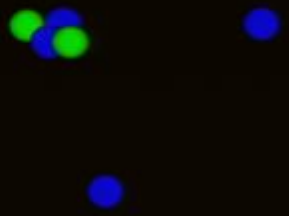

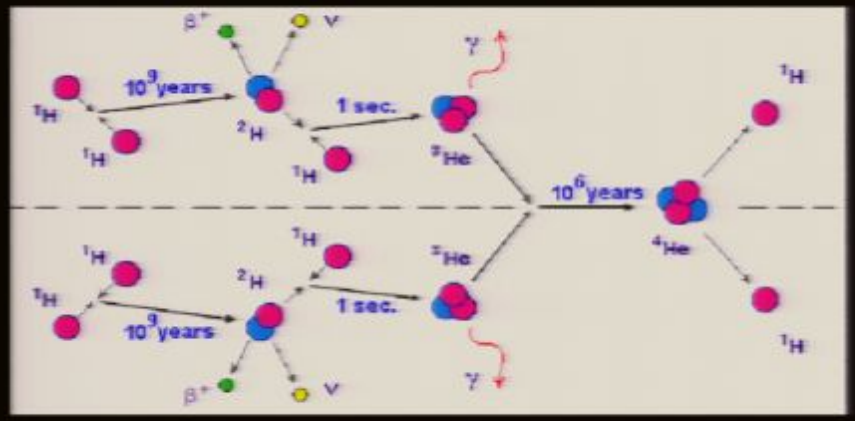

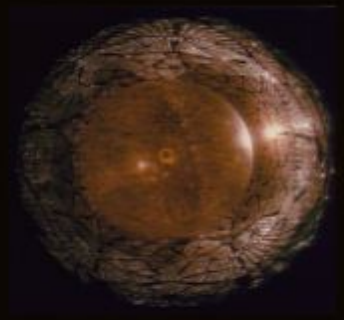

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Neutron
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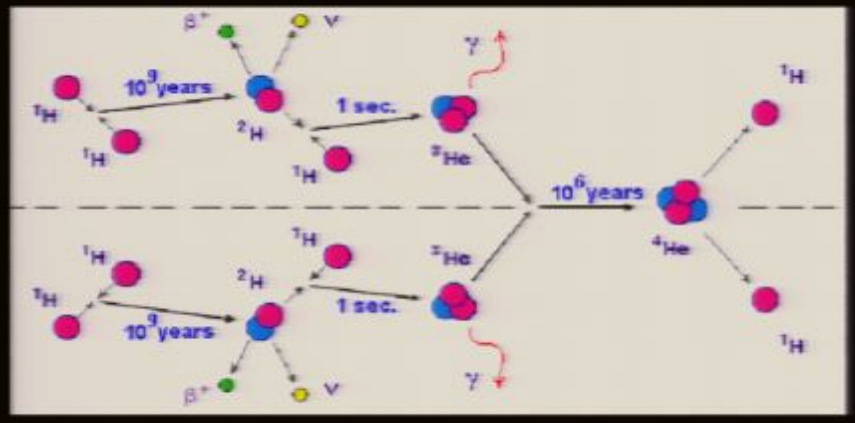

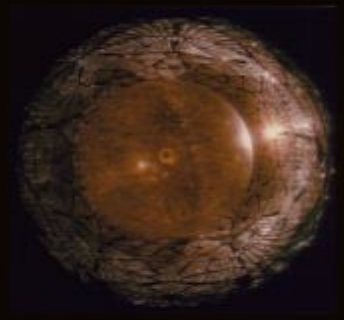

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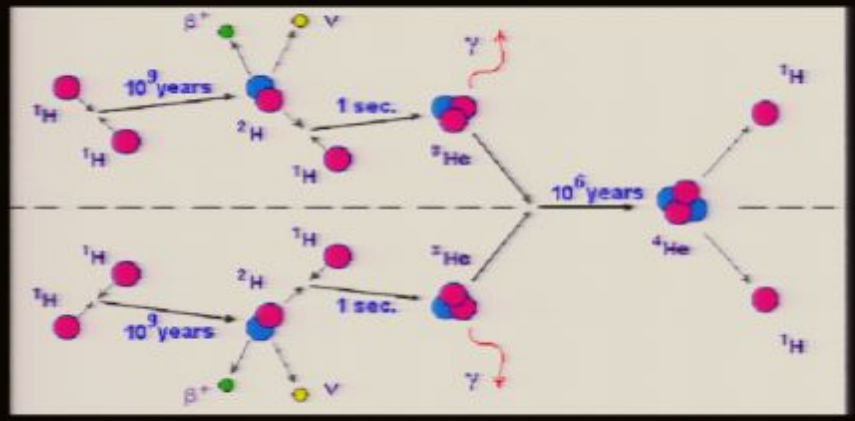

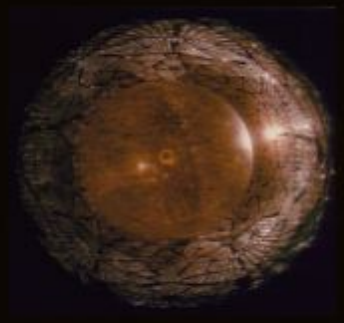

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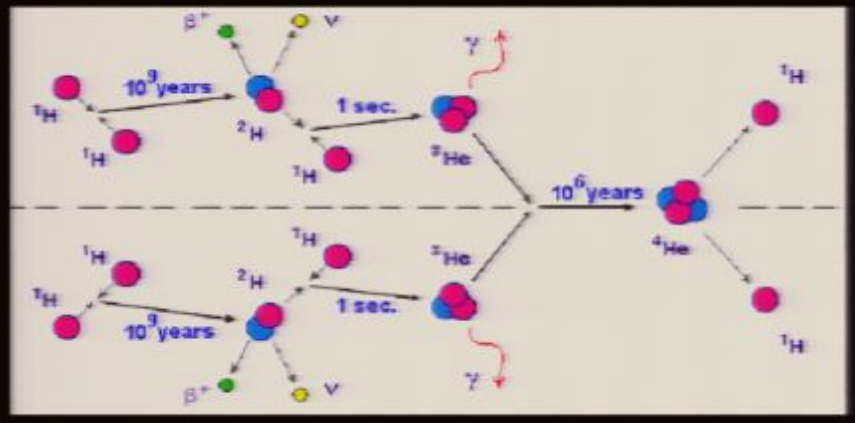

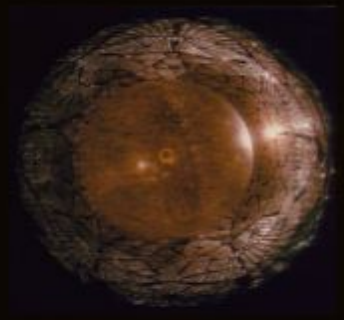

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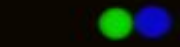
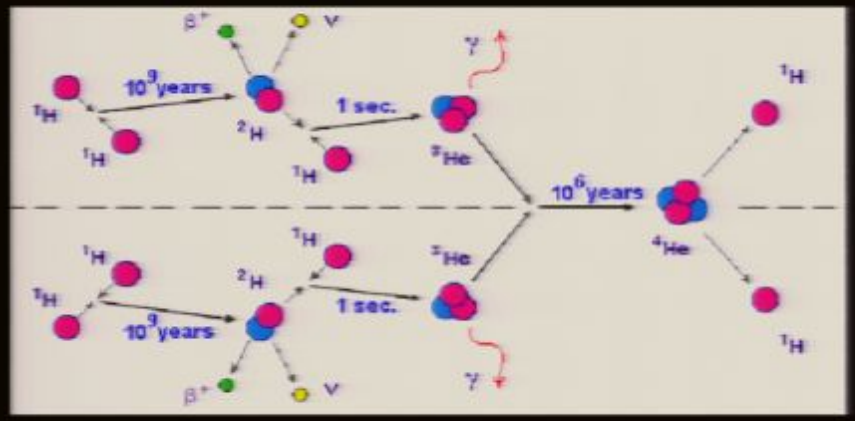
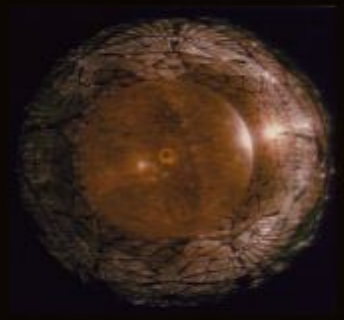
Neutron
Proton







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Neutron
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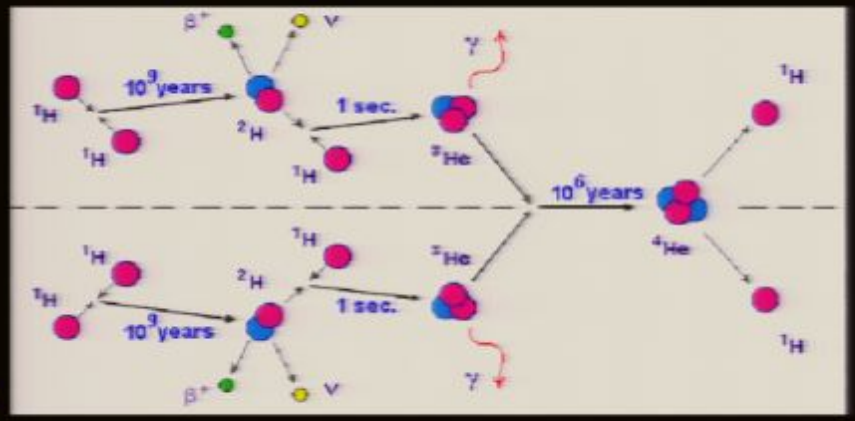
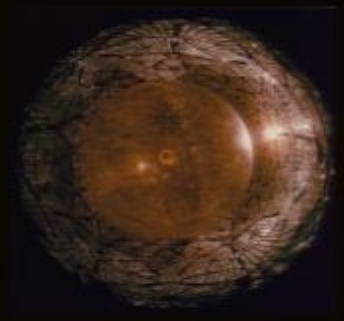
Positron
Neutrino





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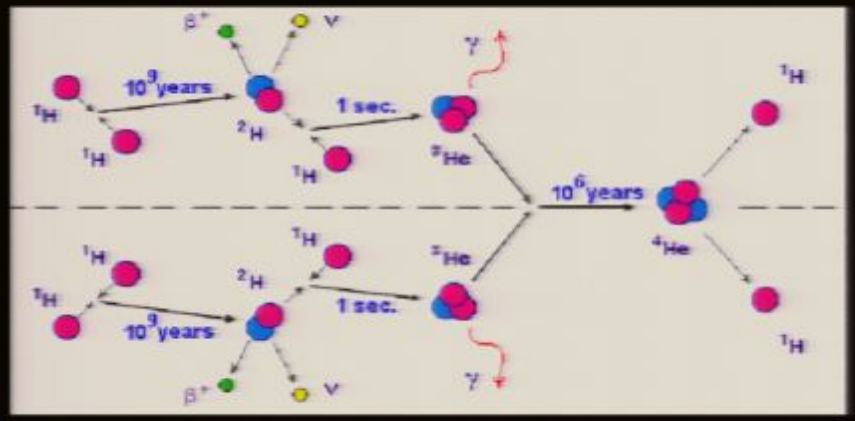

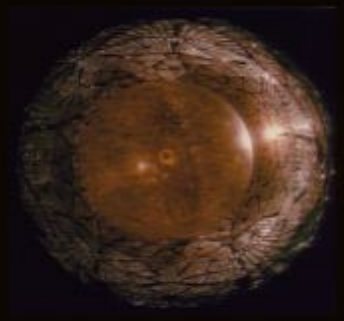

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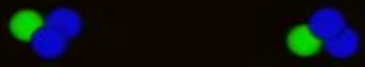
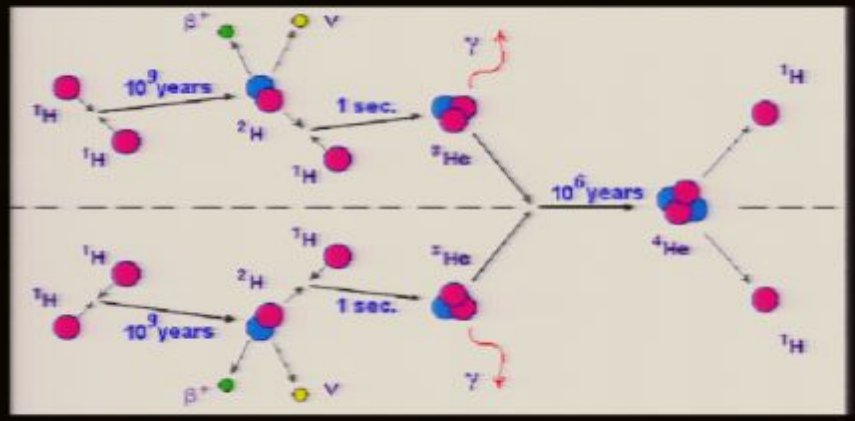
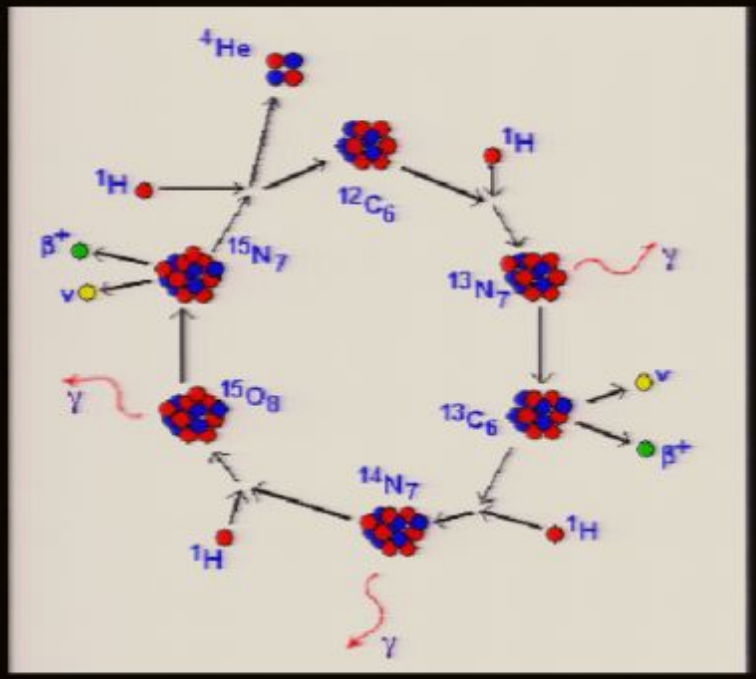




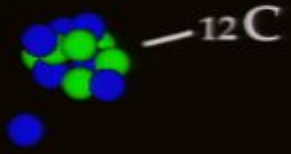
CNO Cycle

- *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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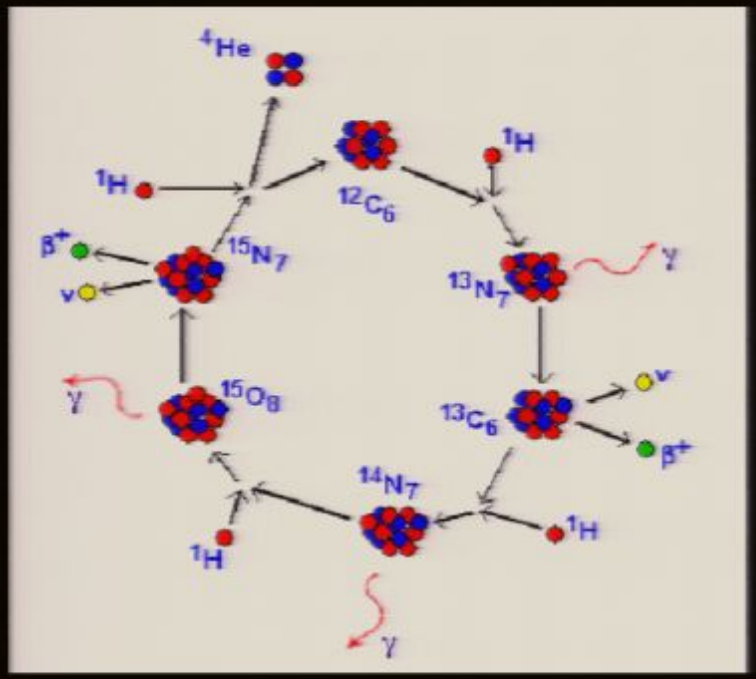
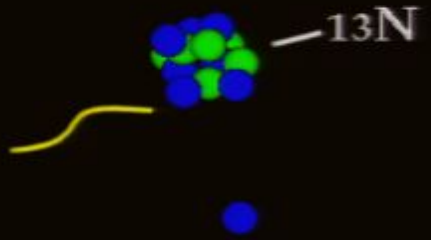


Gamma Ray Released

Neutron — Proton



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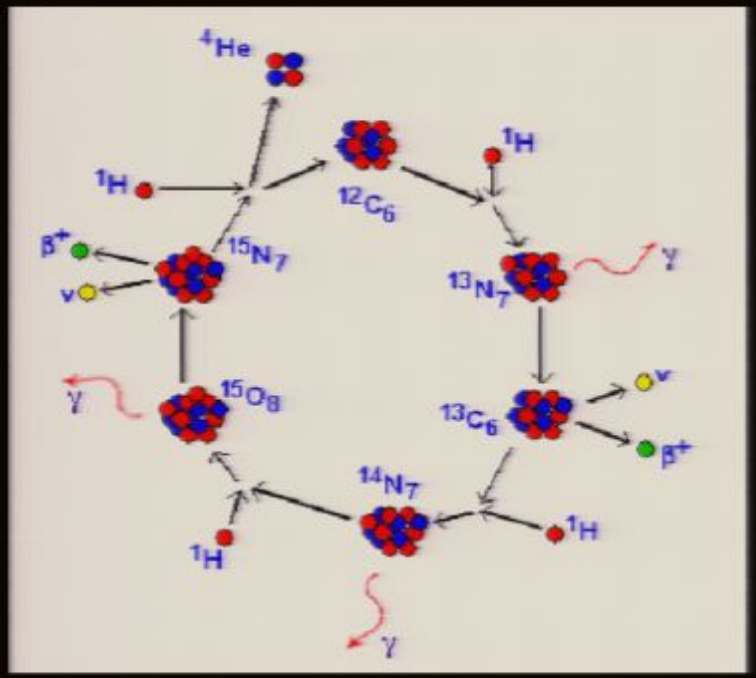
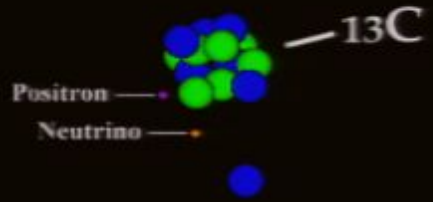


^{13}N ß$^+$ Decays Into ^{13}C

Neutron — Proton



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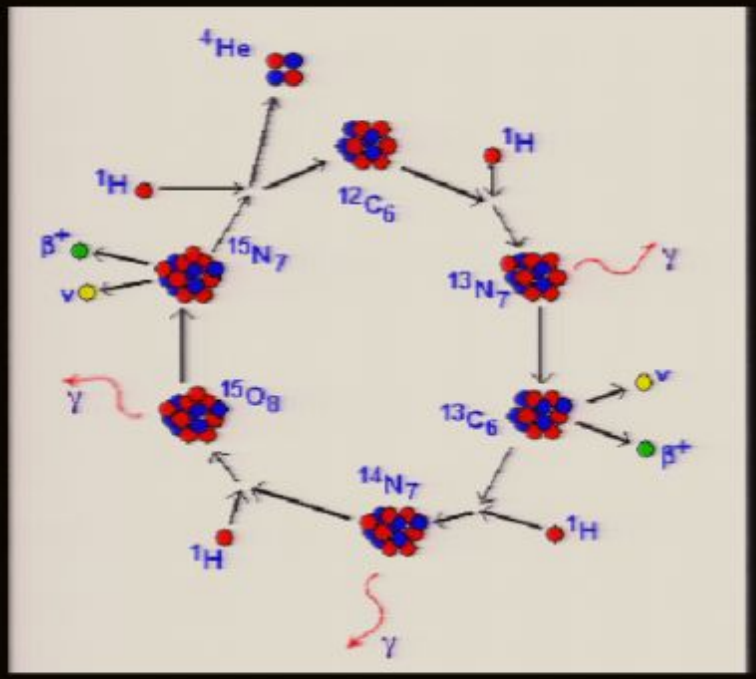
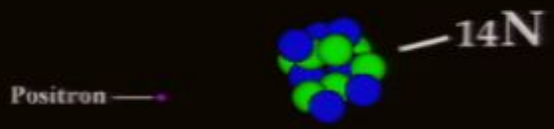


Stray 1H Absorbed Into 12C, Forming 14N

● — Neutron ● — Proton



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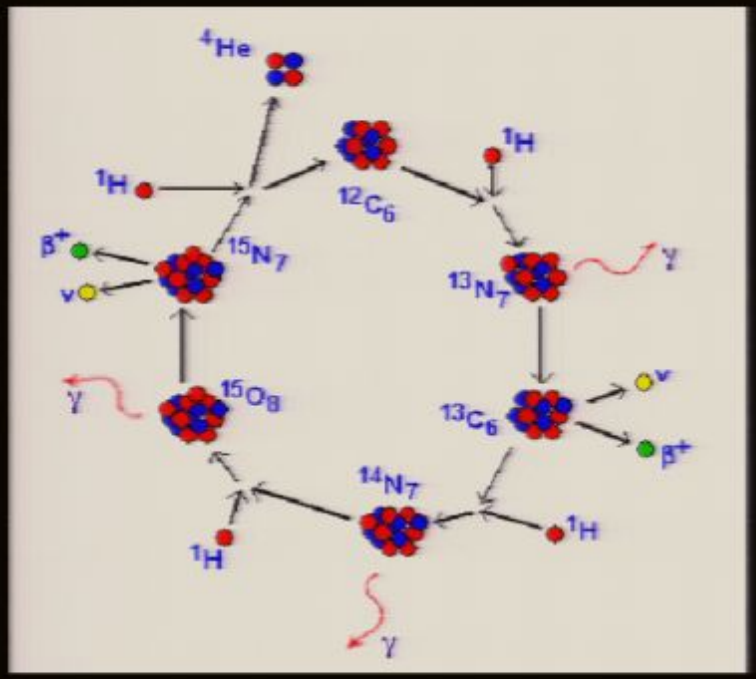
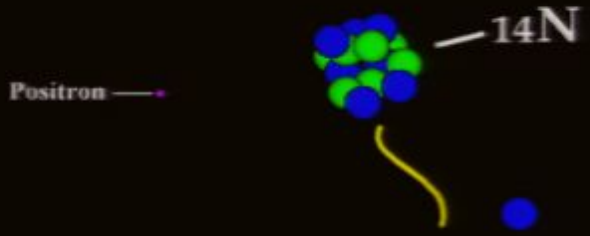


Gamma Ray Released

Neutron — Proton



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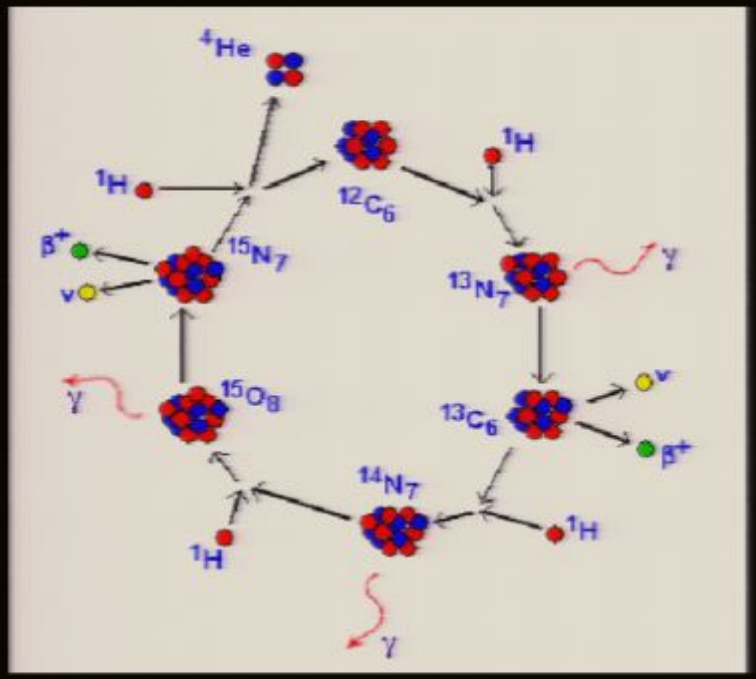
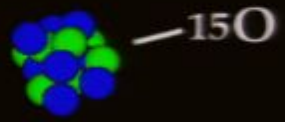


Stray 1H Absorbed Into 14N, Forming 15O

● — Neutron ● — Proton



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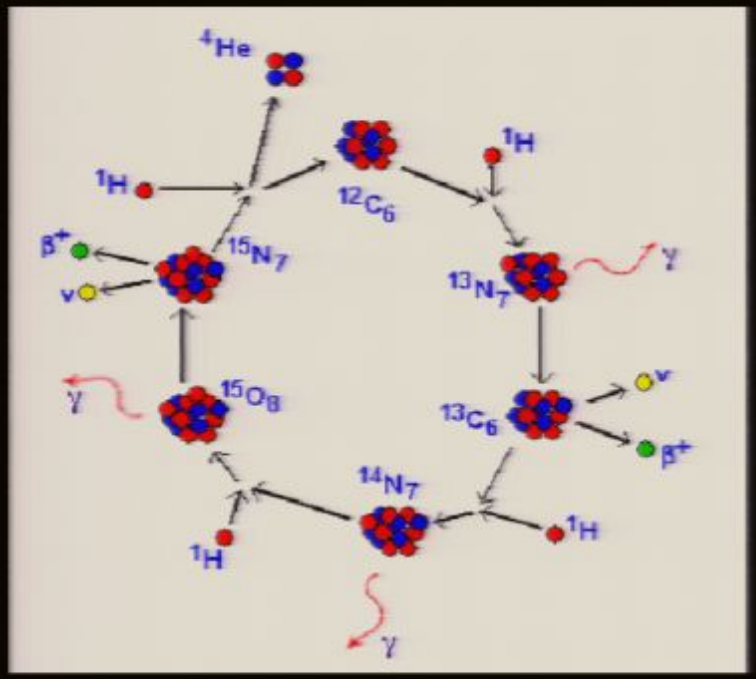
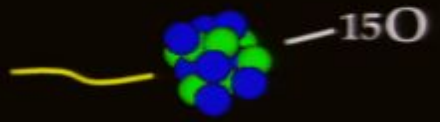


Gamma Ray Released

Neutron — Proton



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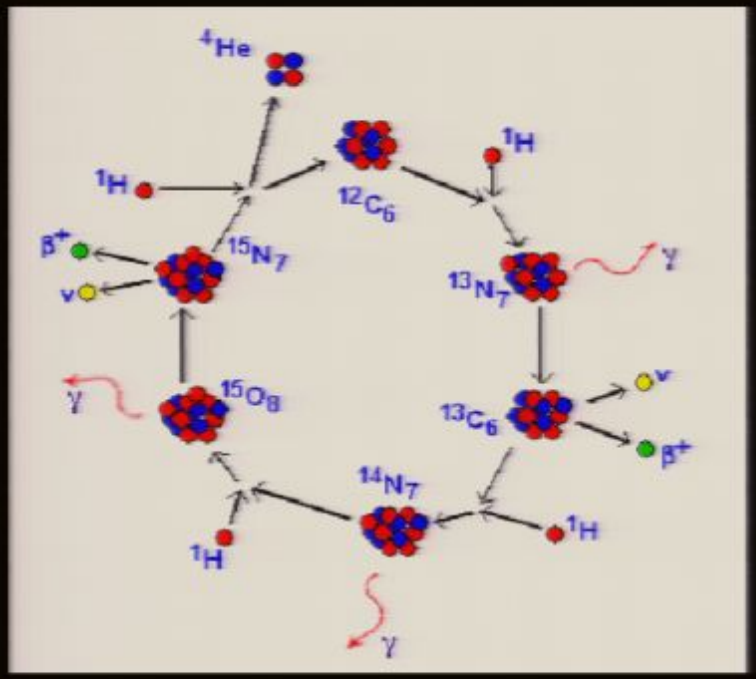
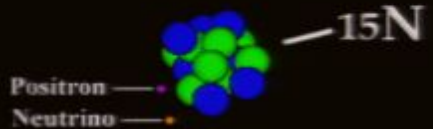


15O ß+ Decays Into 15N

Neutron — Proton



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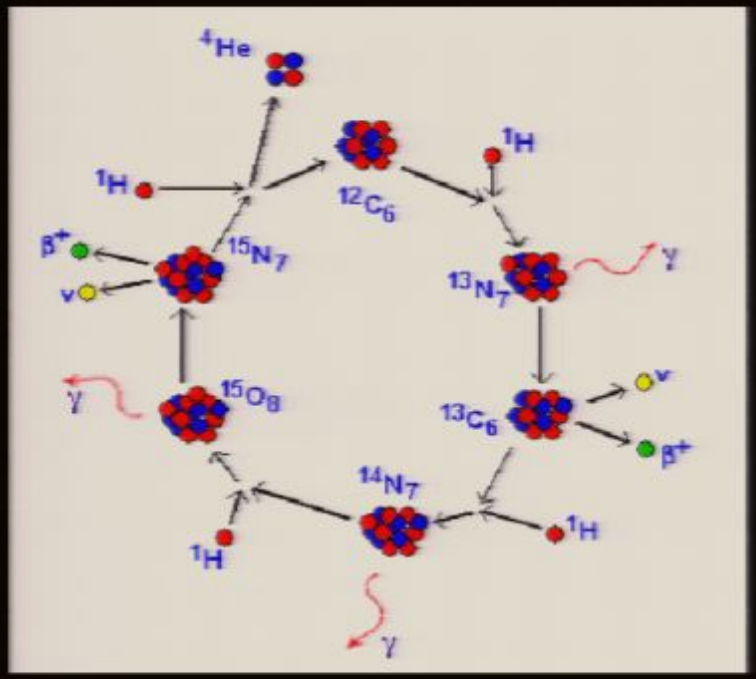
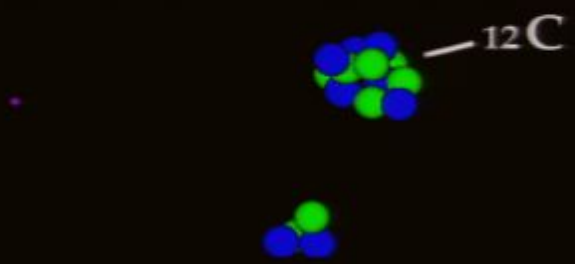


Alpha Particle Released, and 12C Remains

Neutron — Proton



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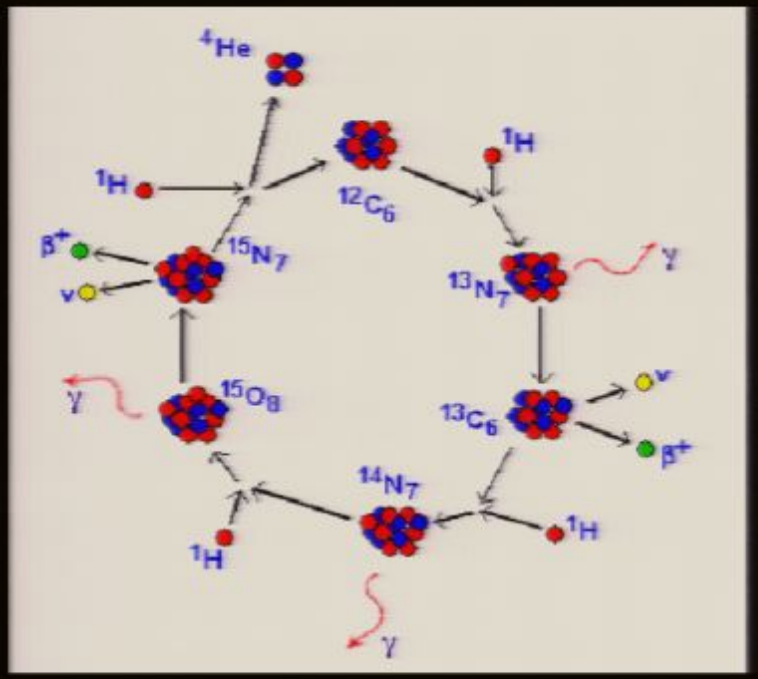
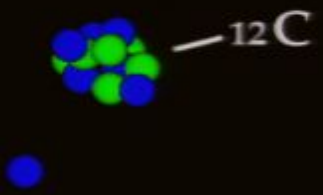


Carbon-Nitrogen-Oxygen (CNO) Cycle

● — Neutron ● — Proton



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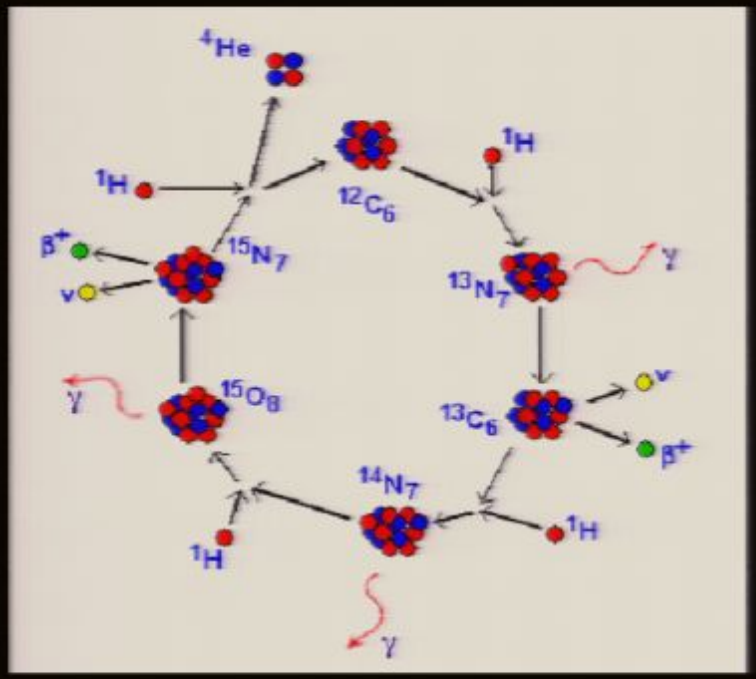
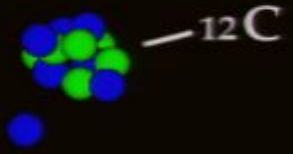


Stray 1H Absorbed Into 12C, Forming 13N

● — Neutron ● — Proton



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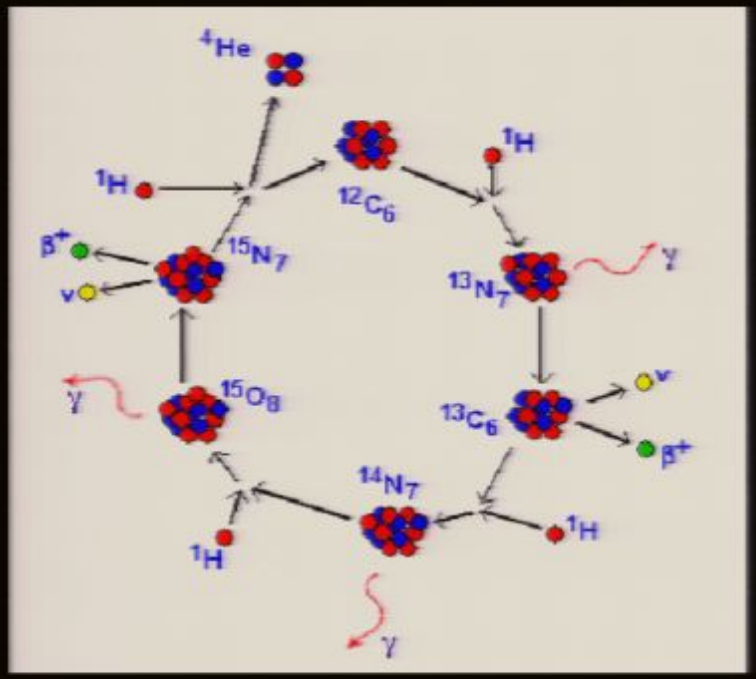
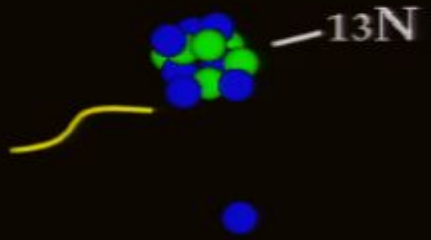


Gamma Ray Released

Neutron — Proton



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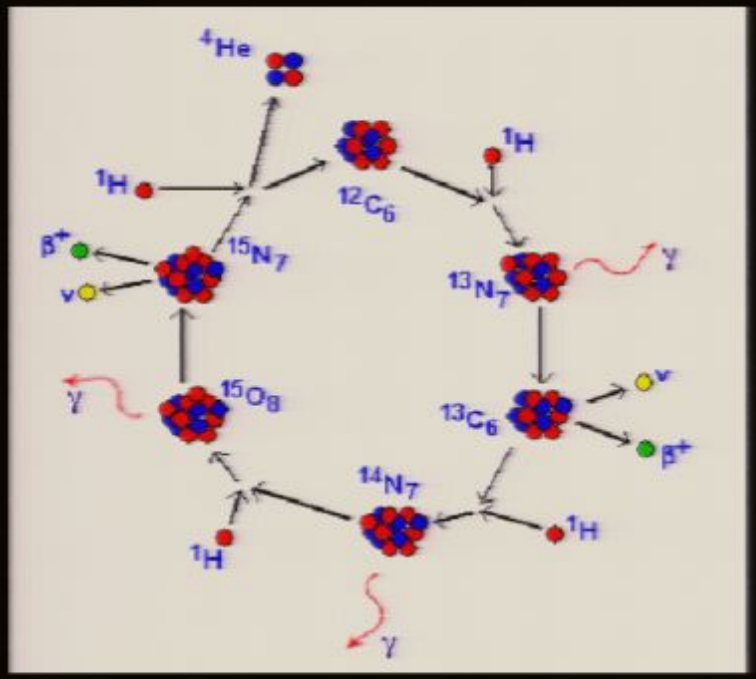
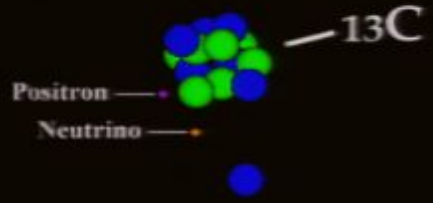


^{13}N ß$^+$ Decays Into ^{13}C

● — Neutron ● — Proton



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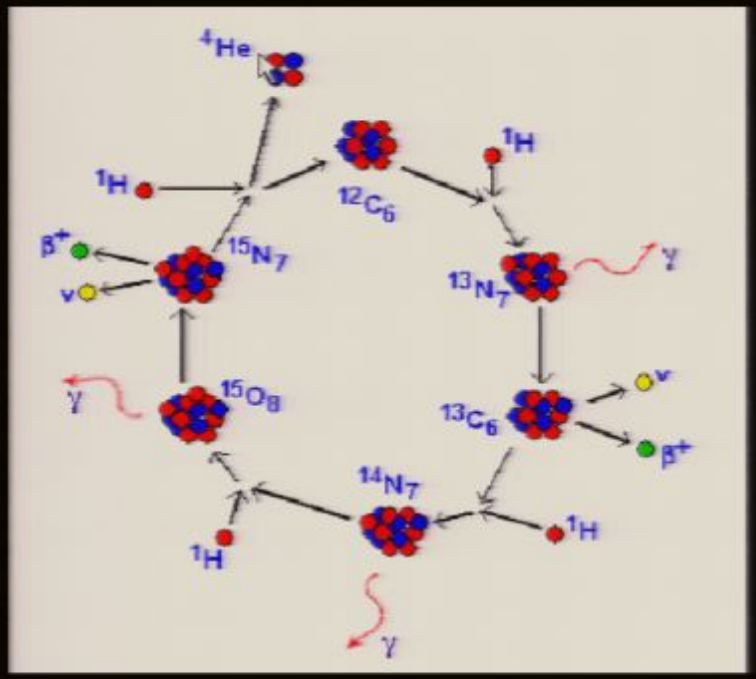
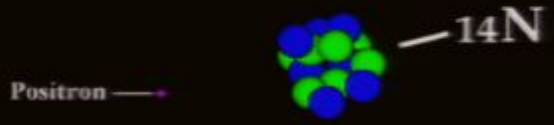


Stray 1H Absorbed Into 12C, Forming 14N

● — Neutron ● — Proton



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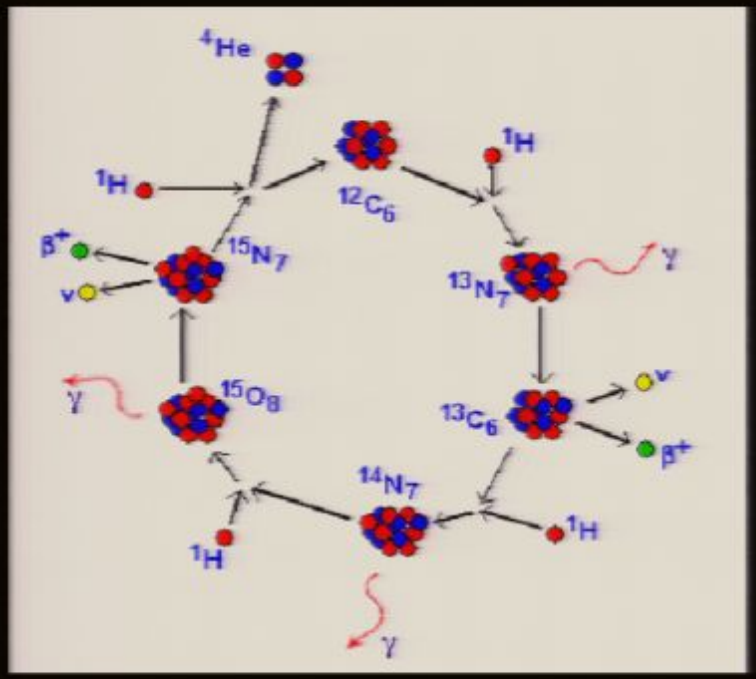
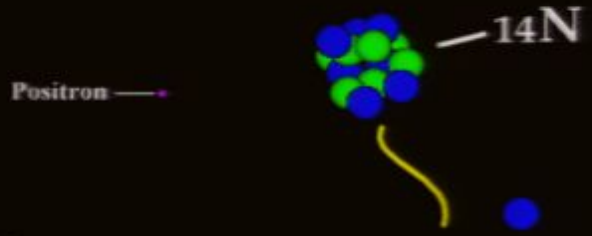


Gamma Ray Released

Neutron — Proton



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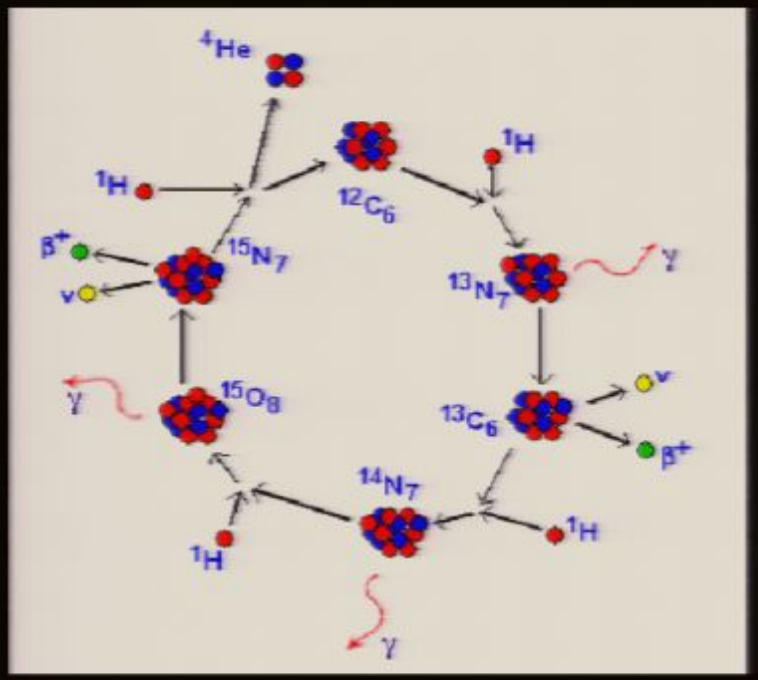

Stray 1H Absorbed Into 14N, Forming 15O

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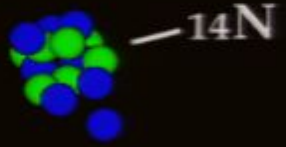

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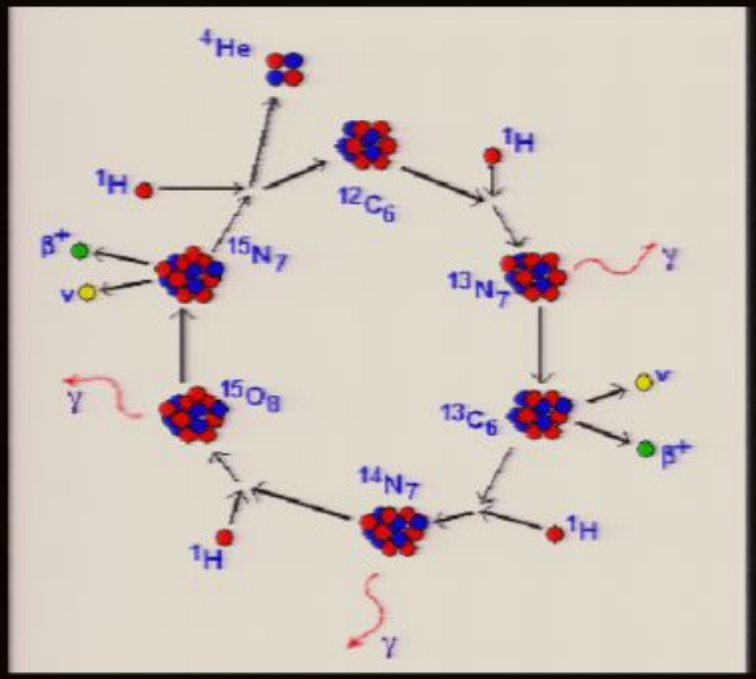

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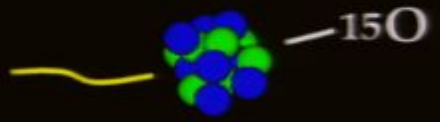

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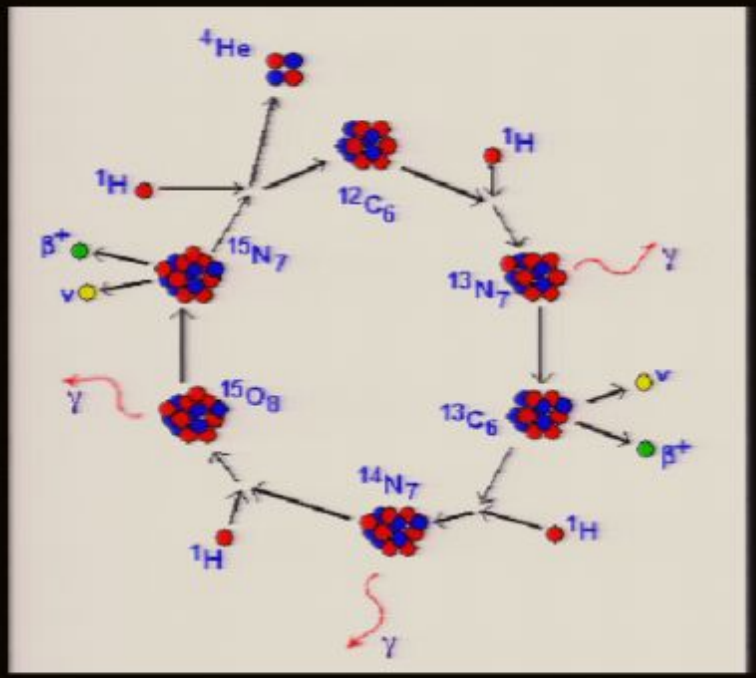

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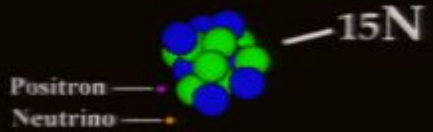
Neutron — Proton



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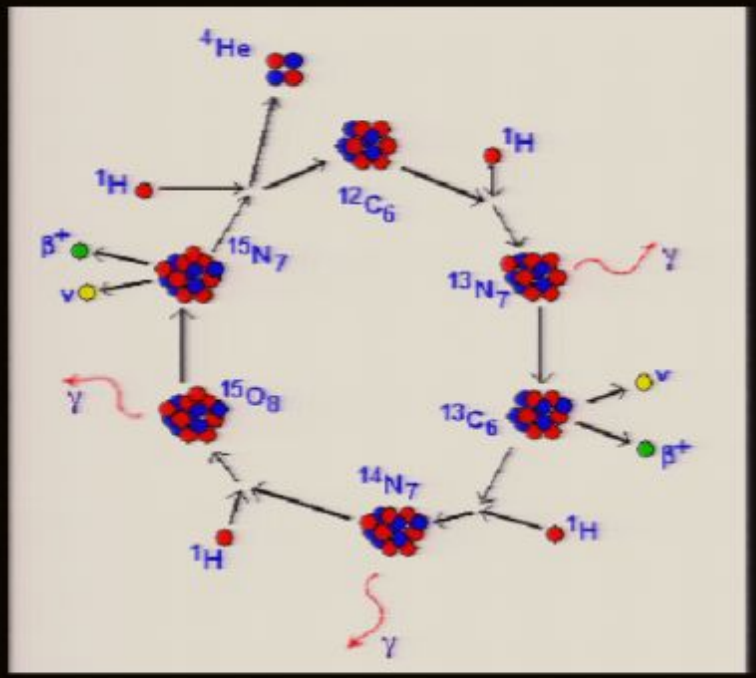

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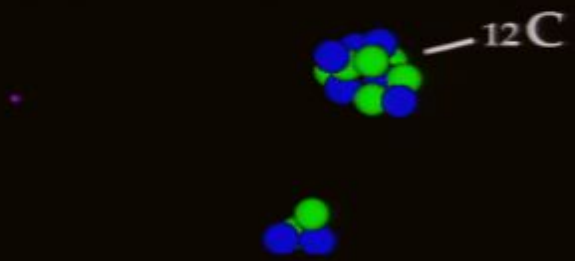

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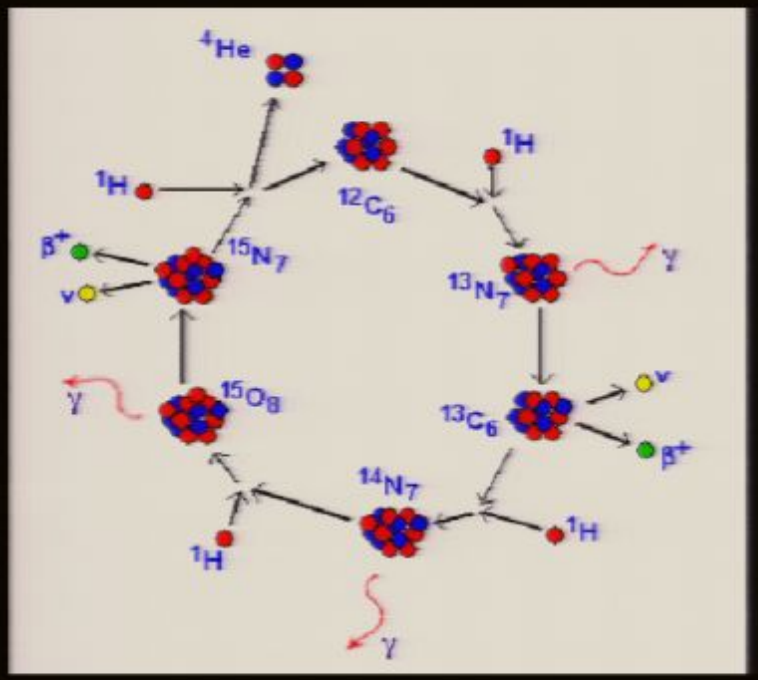

Carbon-Nitrogen-Oxygen (CNO) Cycle

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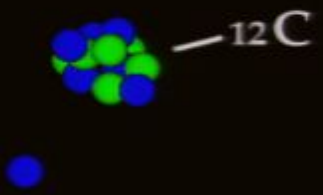
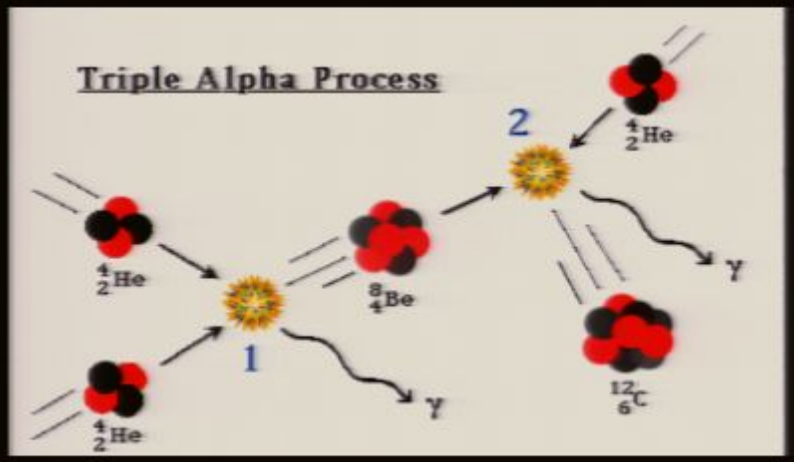


Beyond Helium

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.

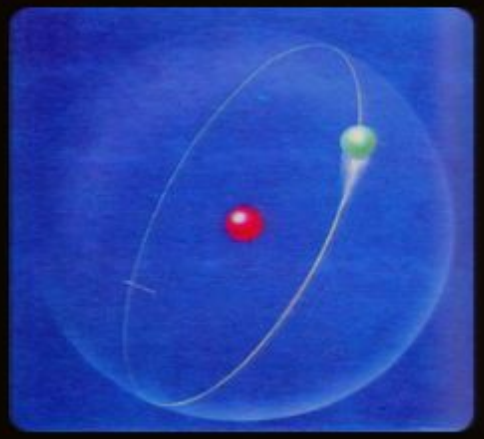


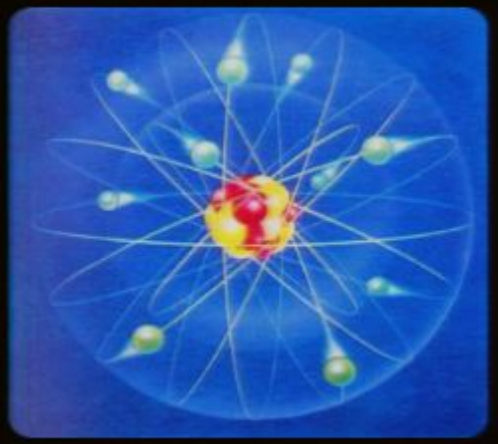
Pressure balance in a star

Pressure balance in a star

thermal pressure = force of gravity

Model of an Atom





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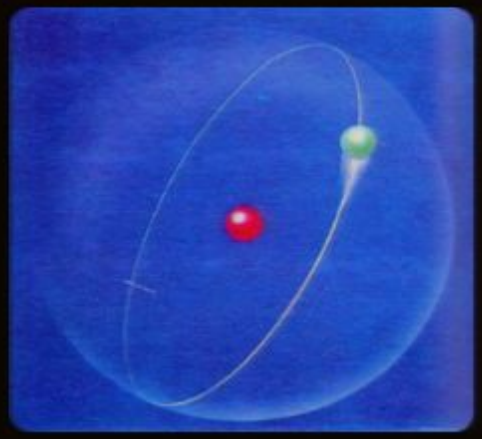
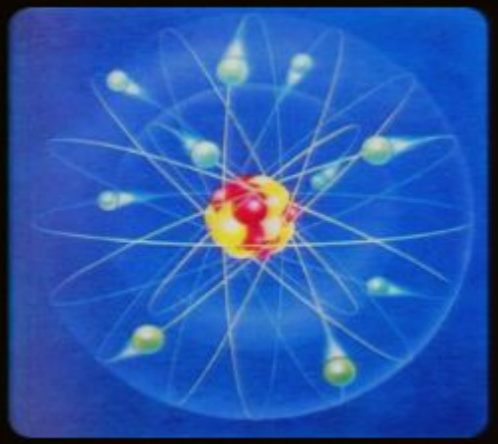




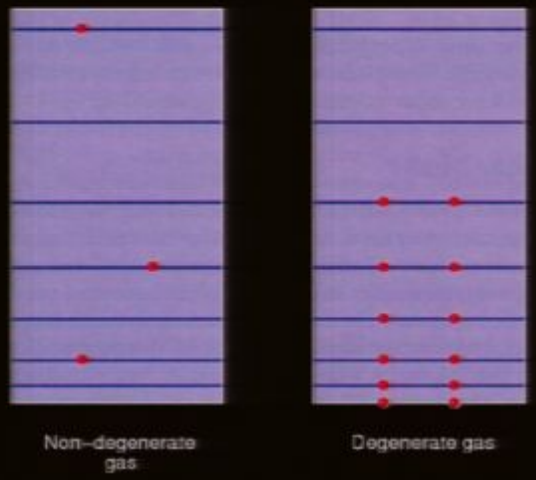
... an atom consists of mainly empty space ...

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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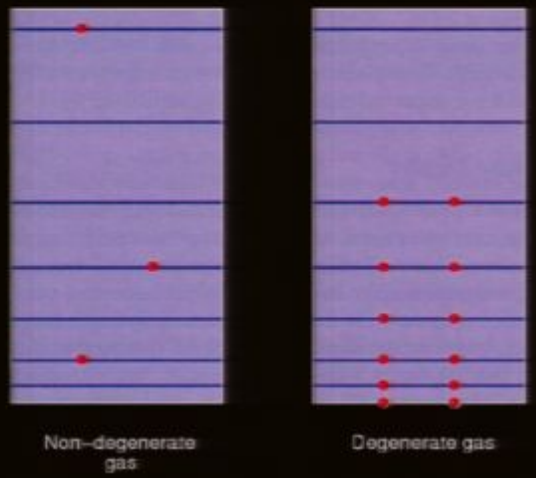

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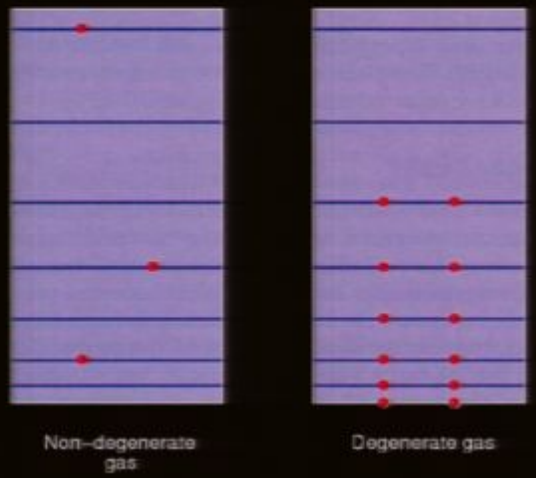

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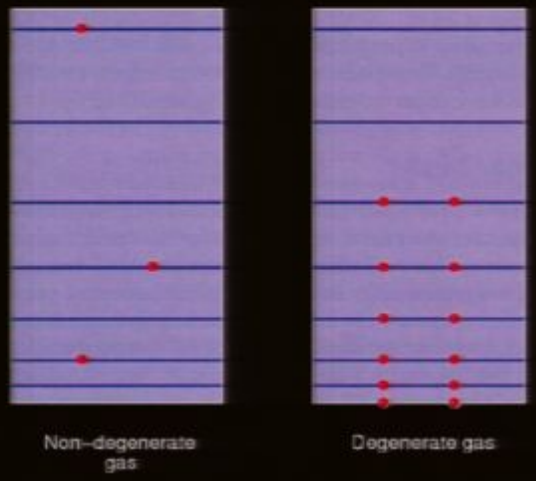

Calculate Pressure

Electron Degeneracy Pressure

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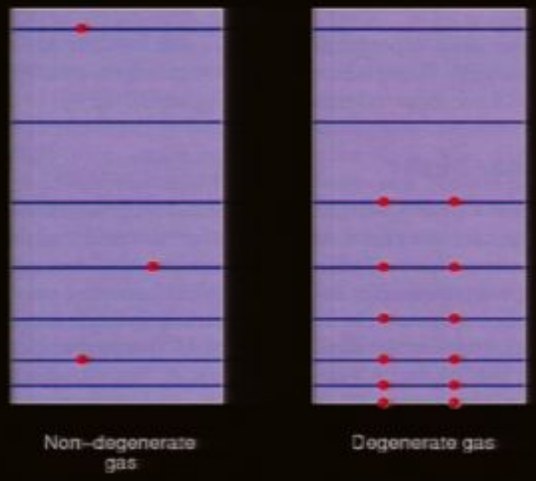


Electron Degeneracy Pressure

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

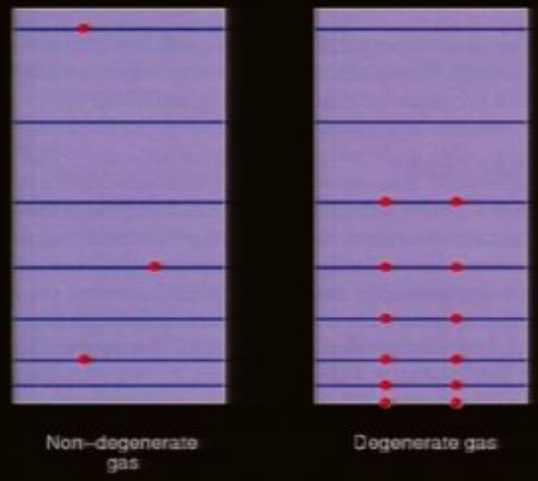
$$h = 6.6261 \times 10^{-34}$$

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

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

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

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

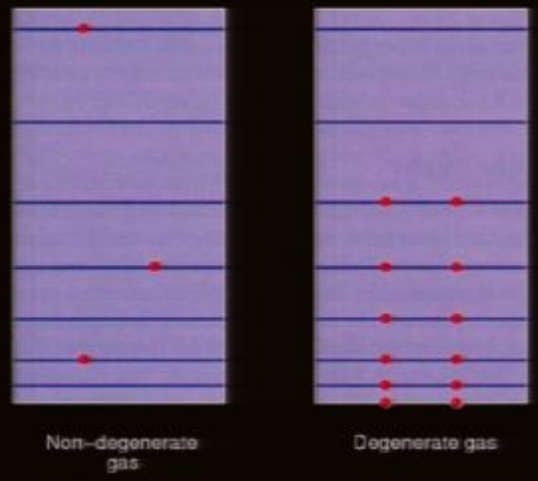


Electron Degeneracy Pressure

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

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

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



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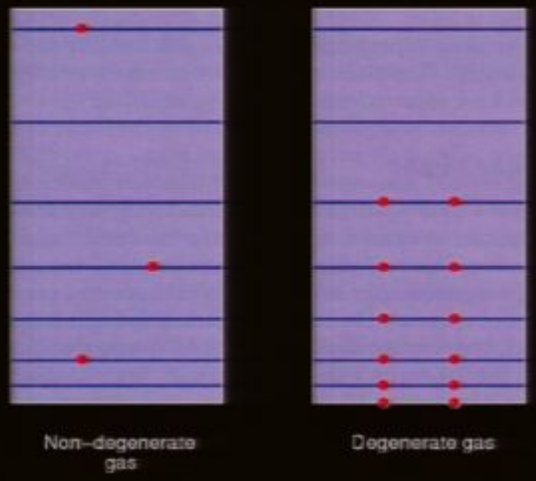
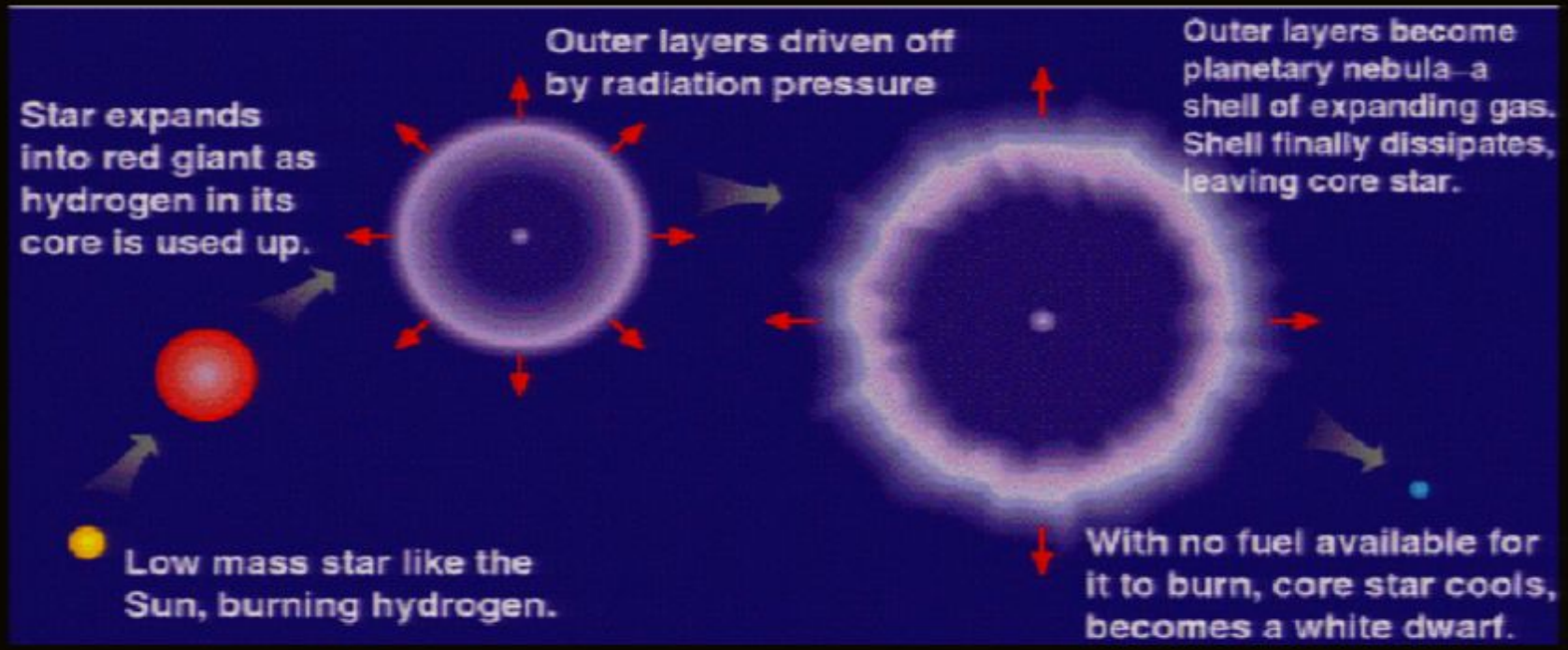
$$2.7\times10^{-31}\,m$$

$$10^7\,m$$



Path to being a White Dwarf



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

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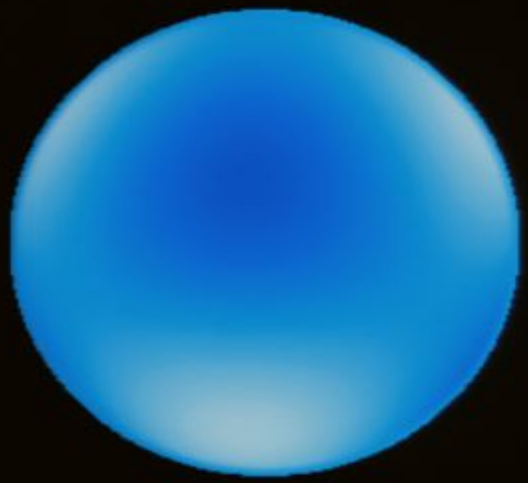

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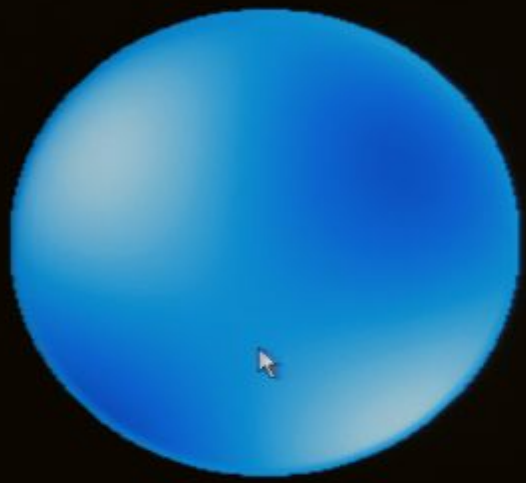

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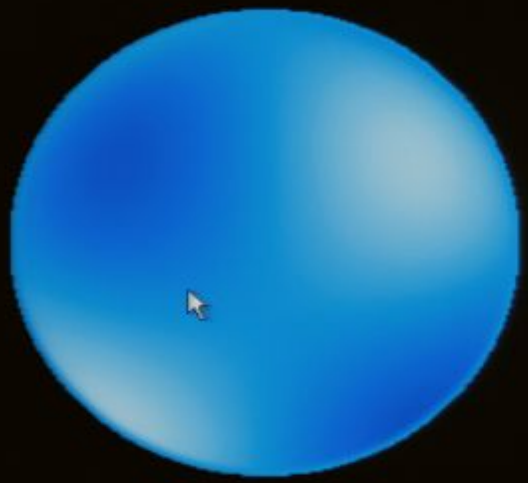
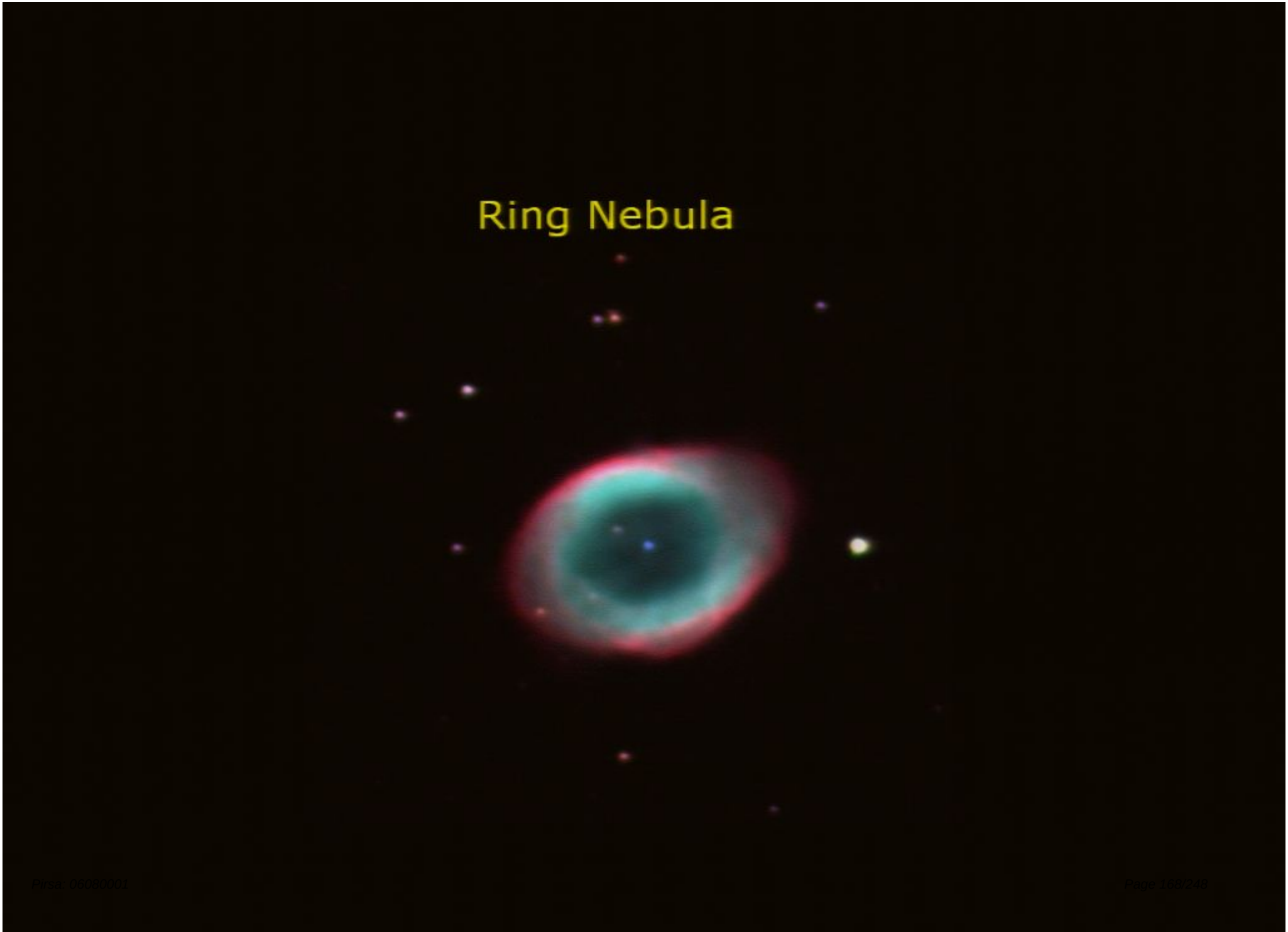
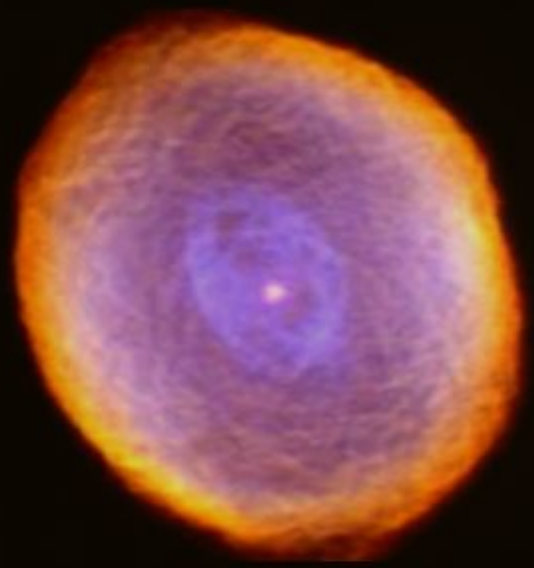


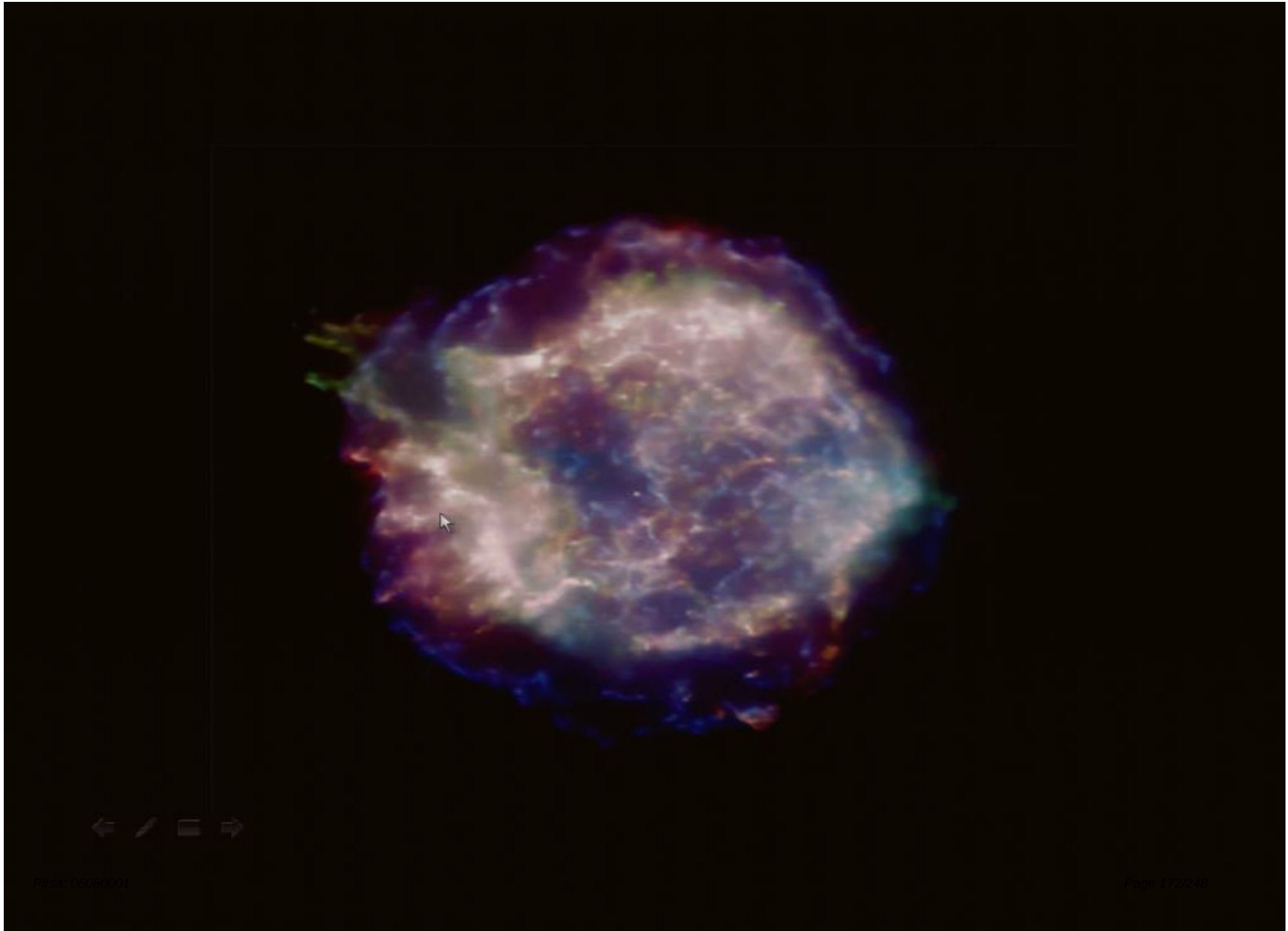

Ring Nebula


Ring Nebula

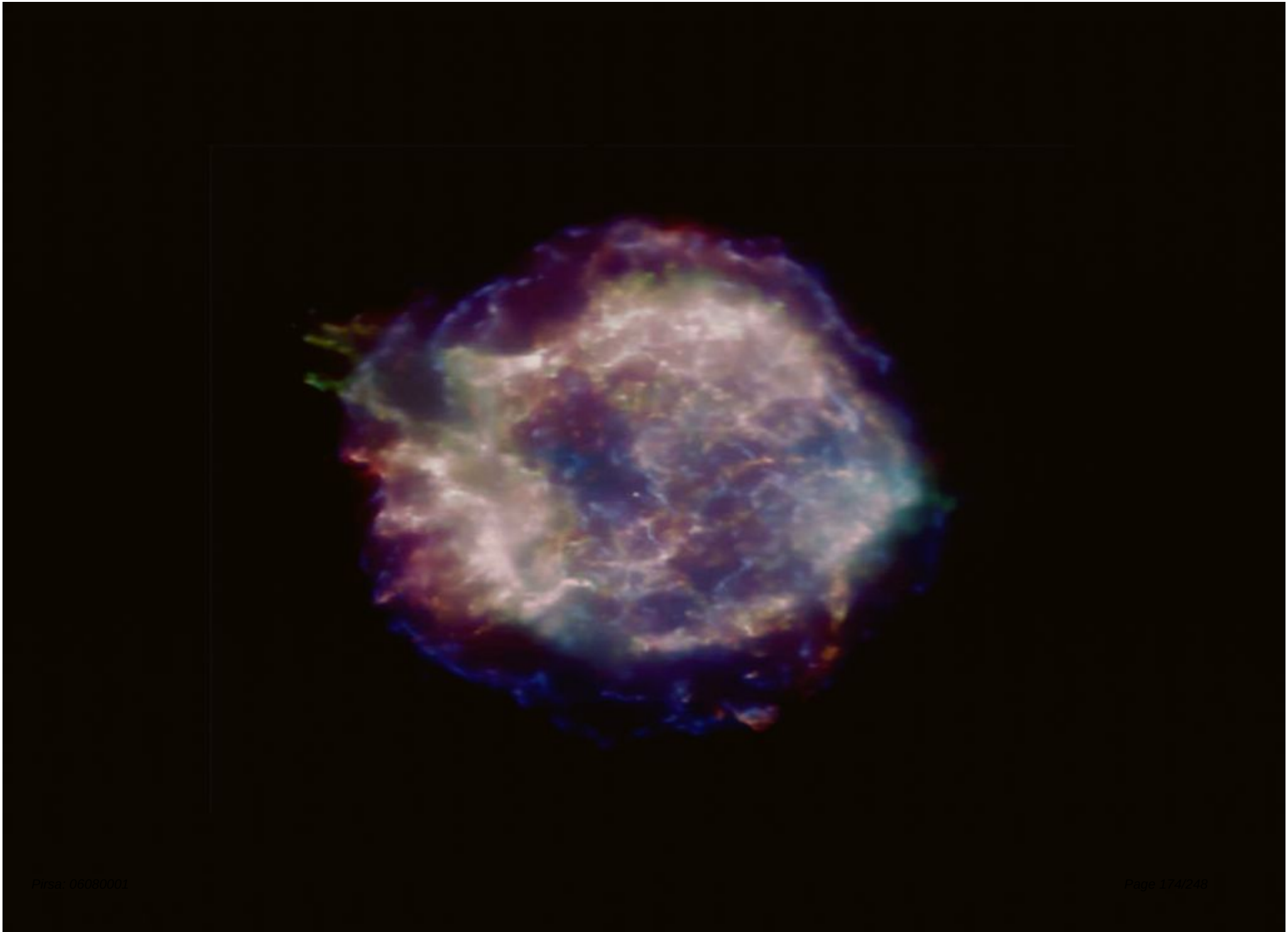
Cat's eye nebula

Spirograph Nebula





Eskimo Nebula



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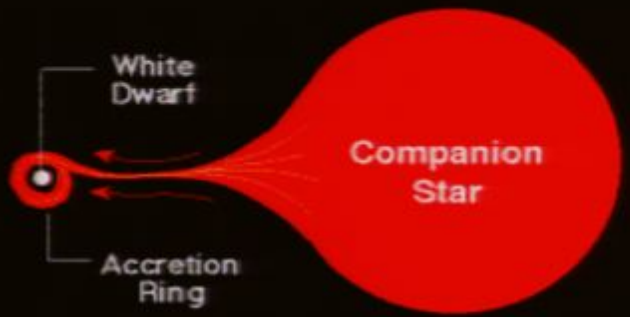
- Above this, even electron degeneracy pressure cannot counterbalance gravity
- What is the fate of a star more massive than this?

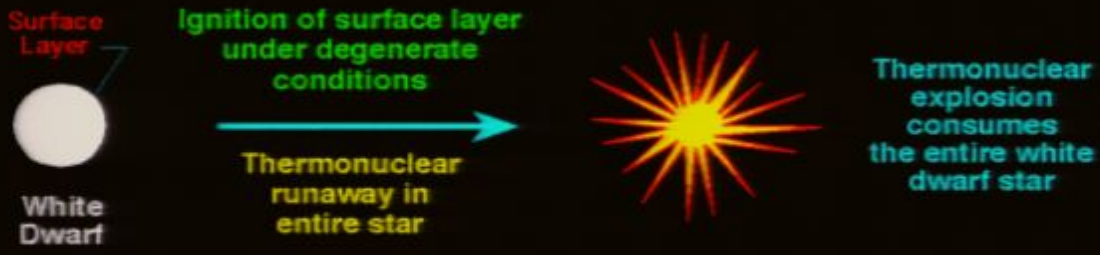
Supernova Remnant

- 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



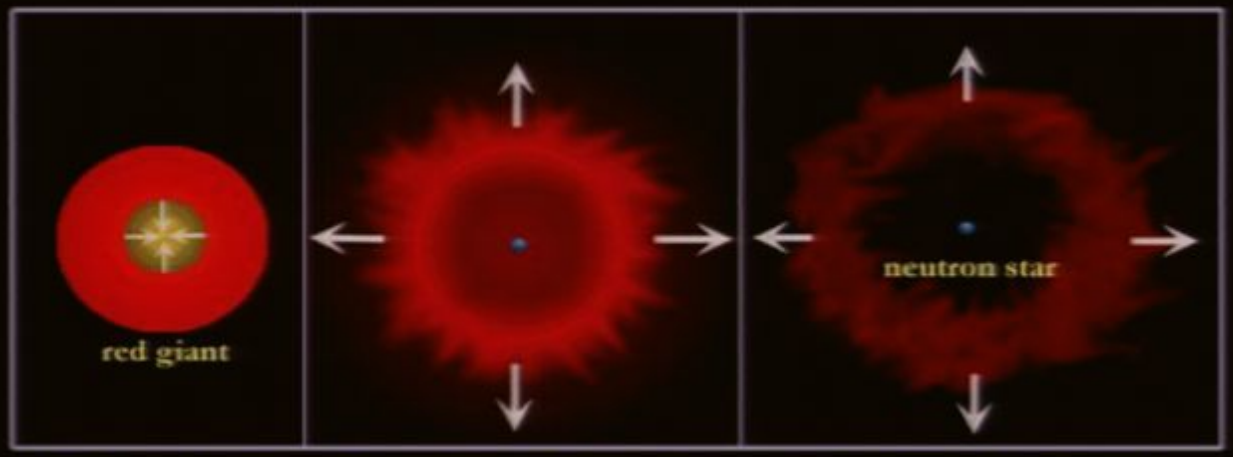
Thin hydrogen surface layer accumulated on white dwarf through accretion ring



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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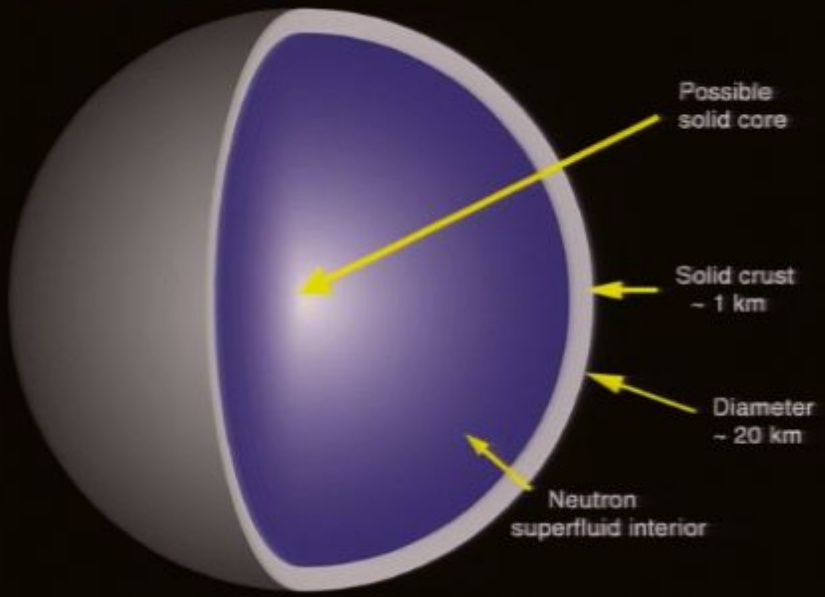

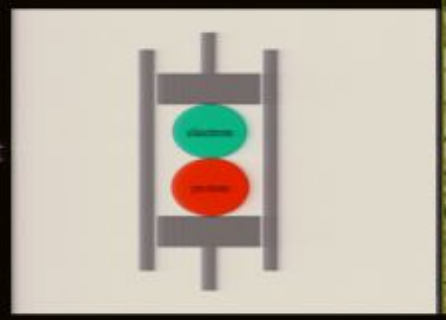

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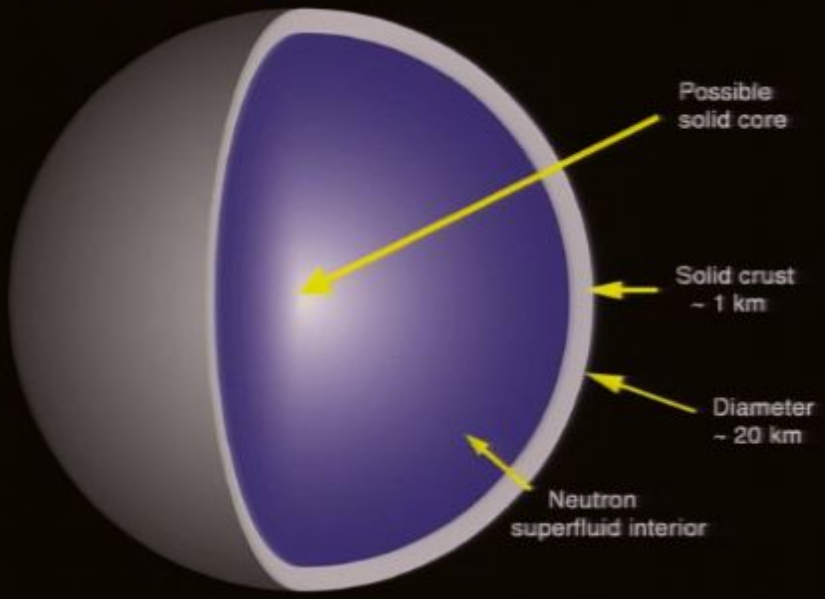

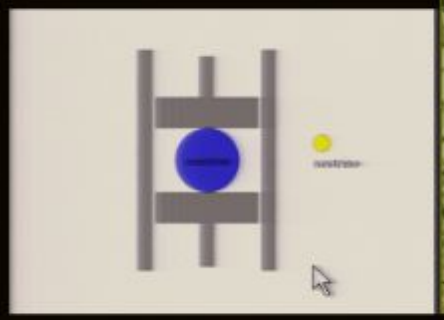

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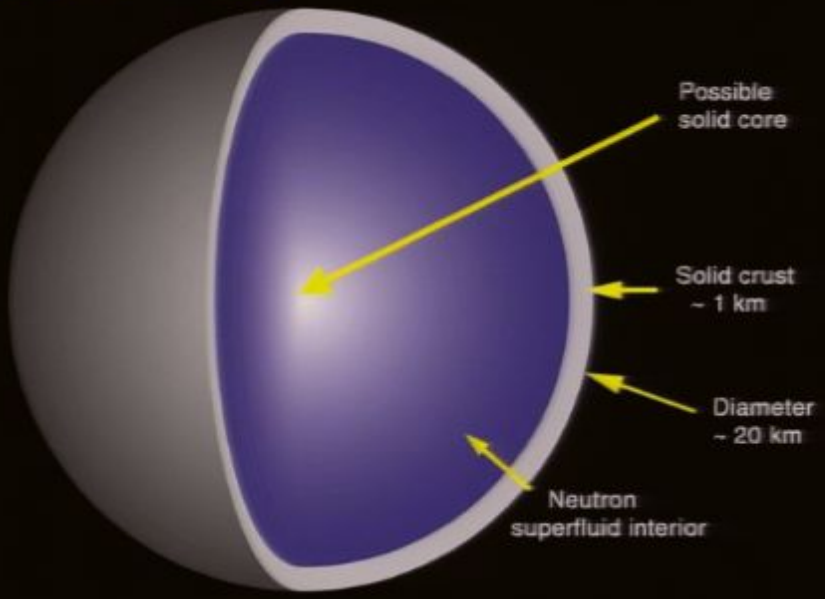

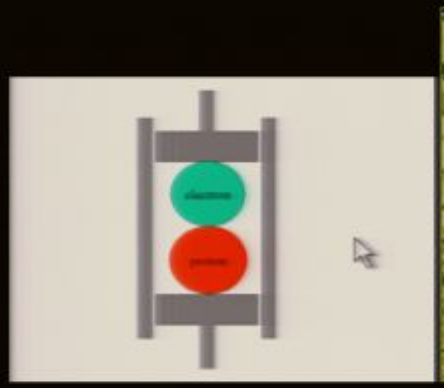

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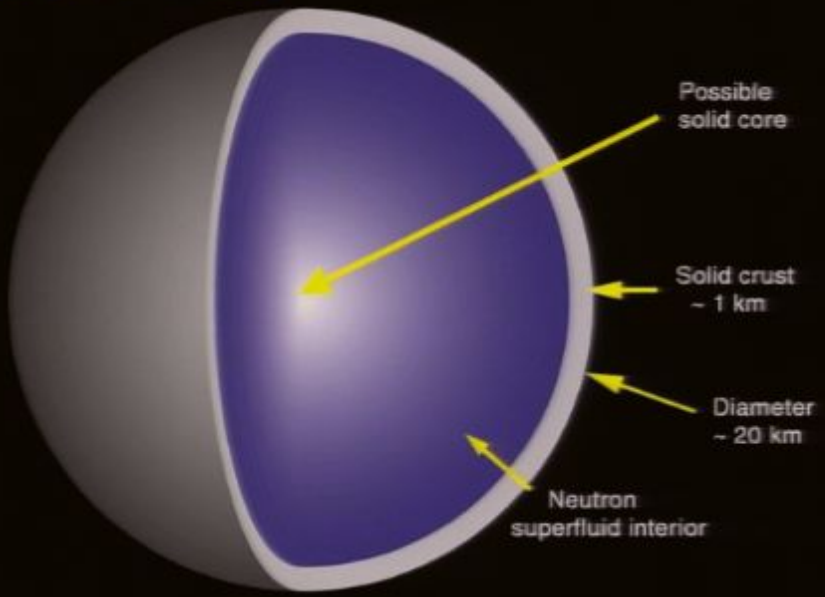

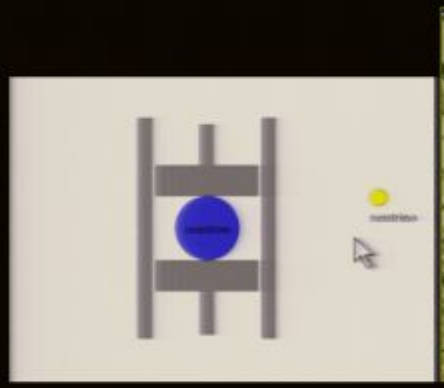

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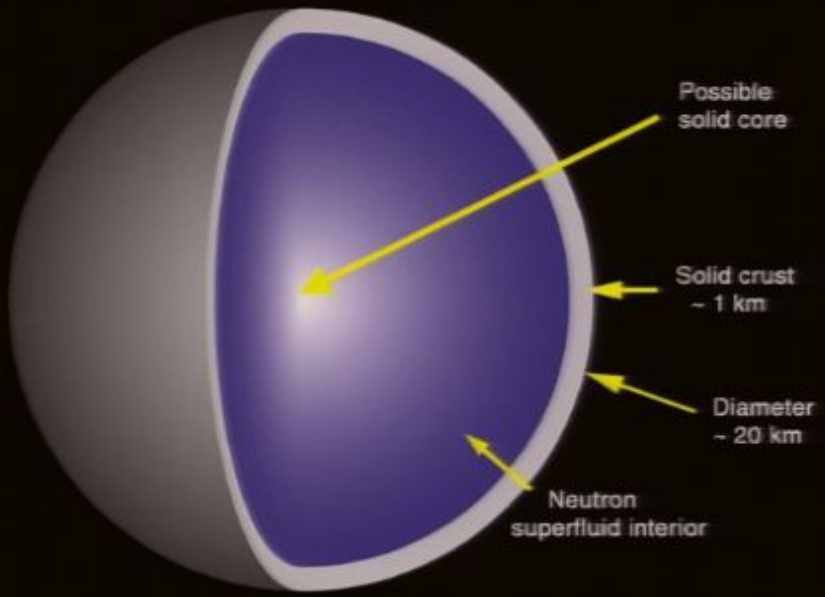

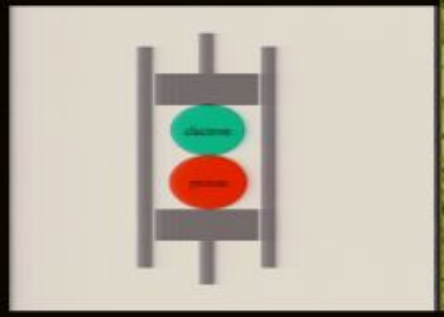

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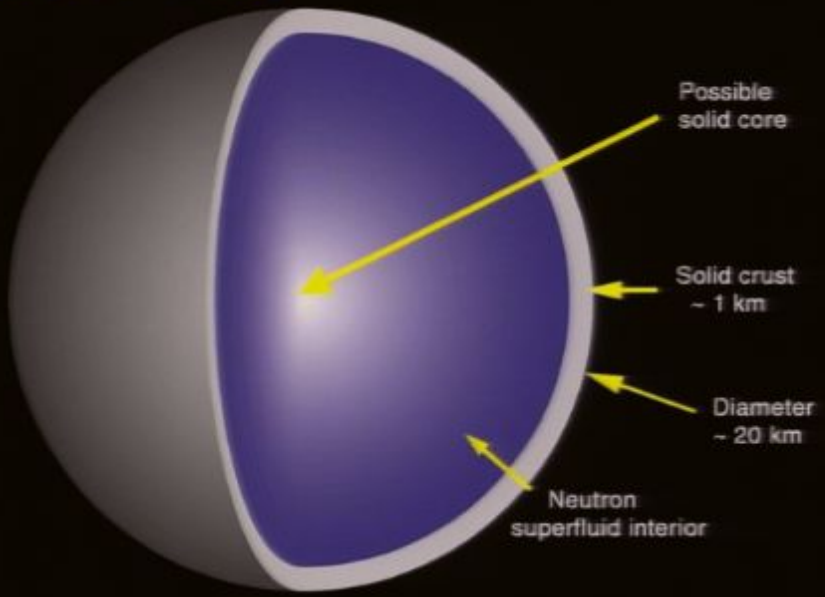

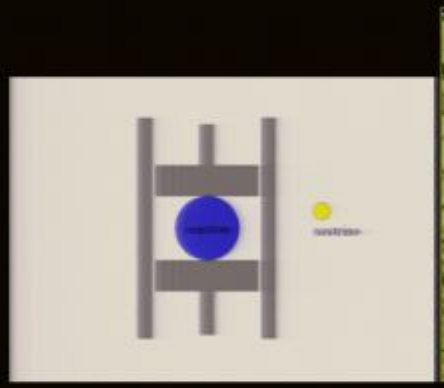

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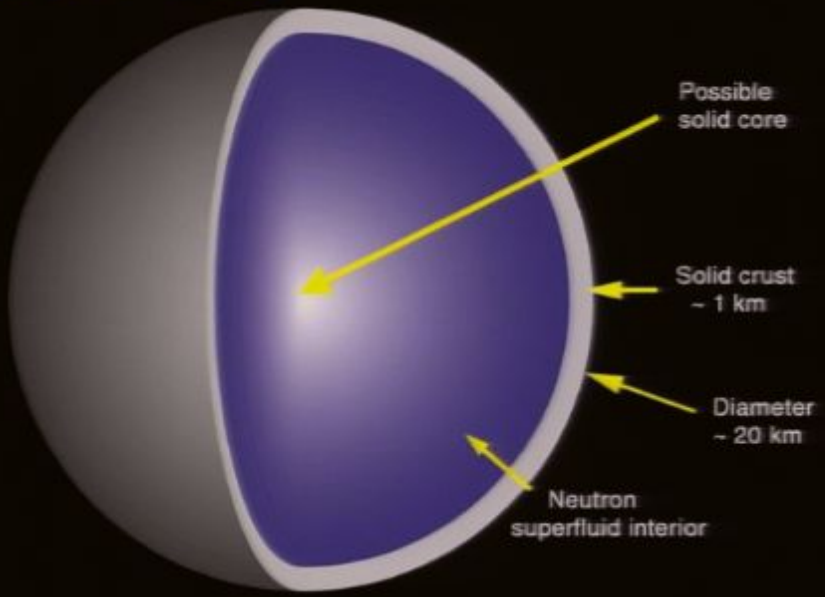

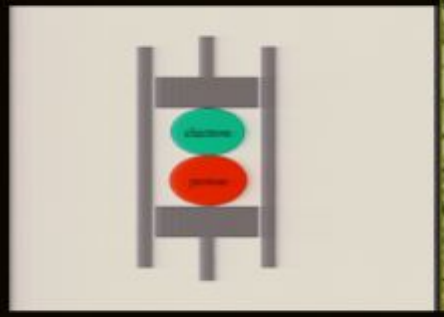

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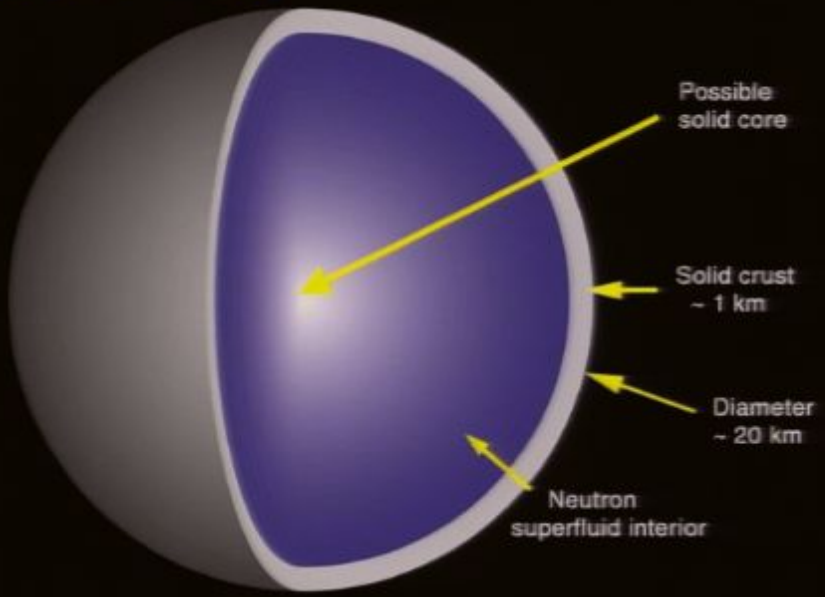

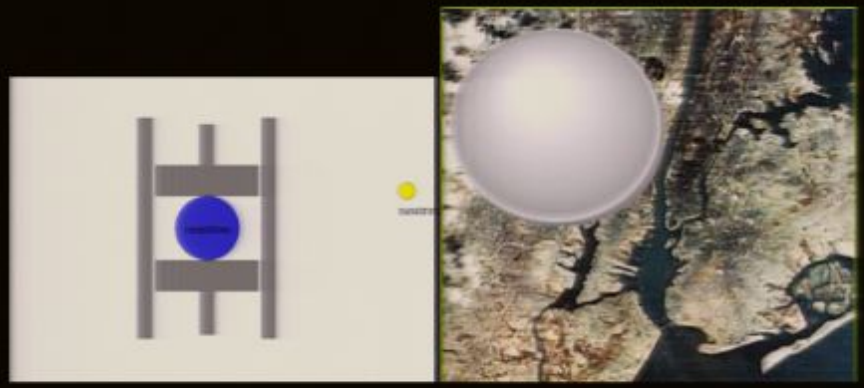

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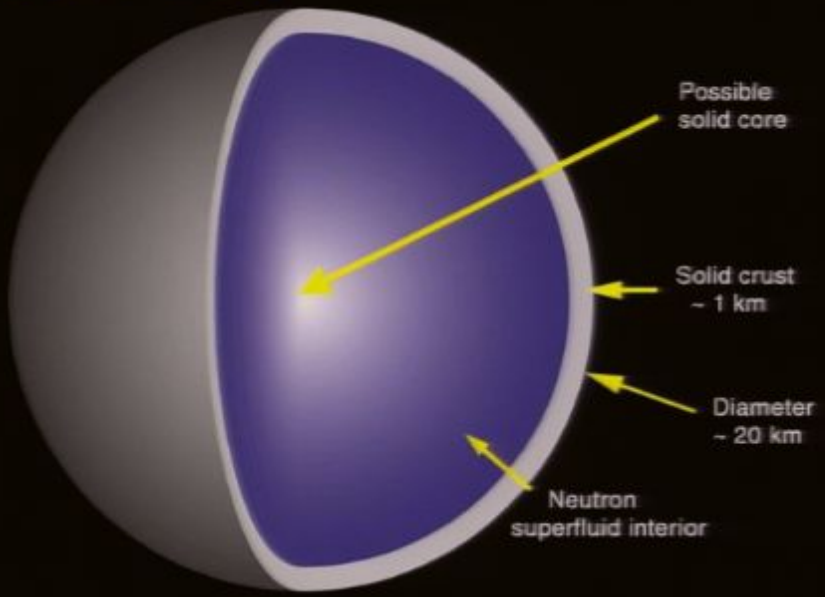

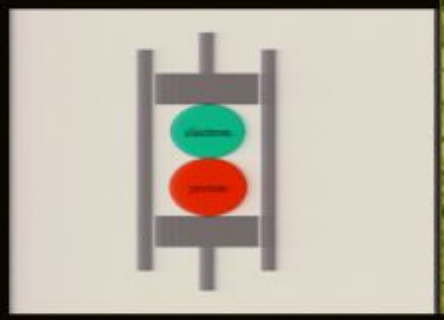

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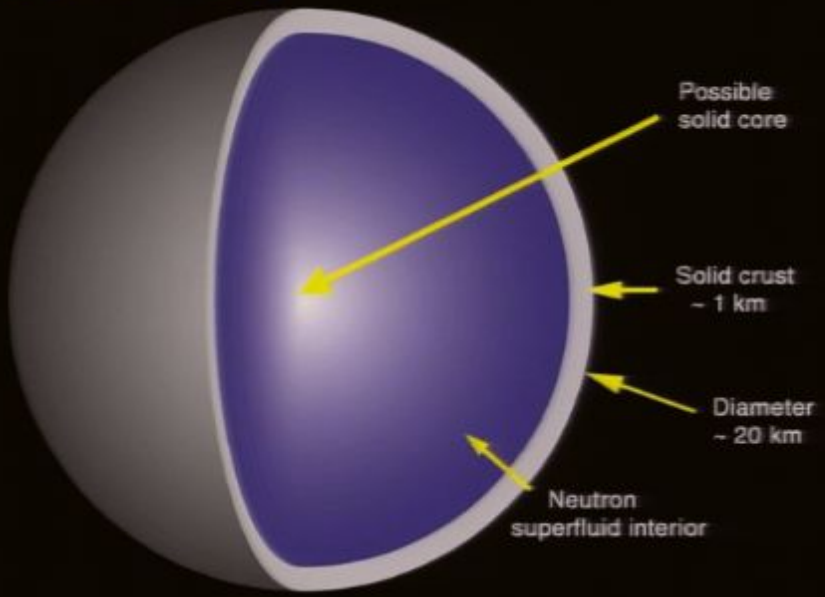

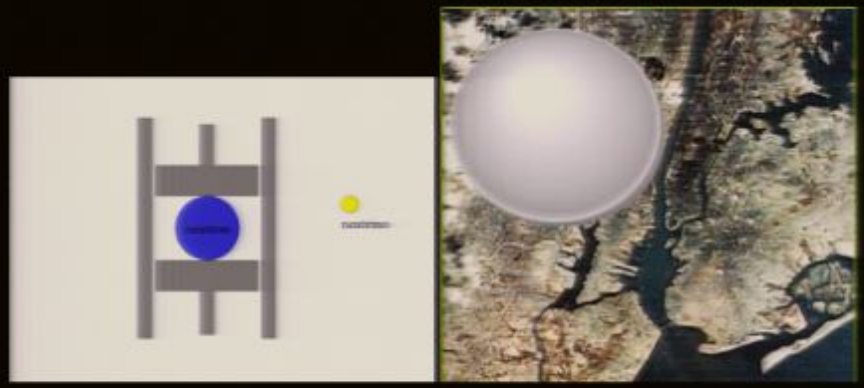

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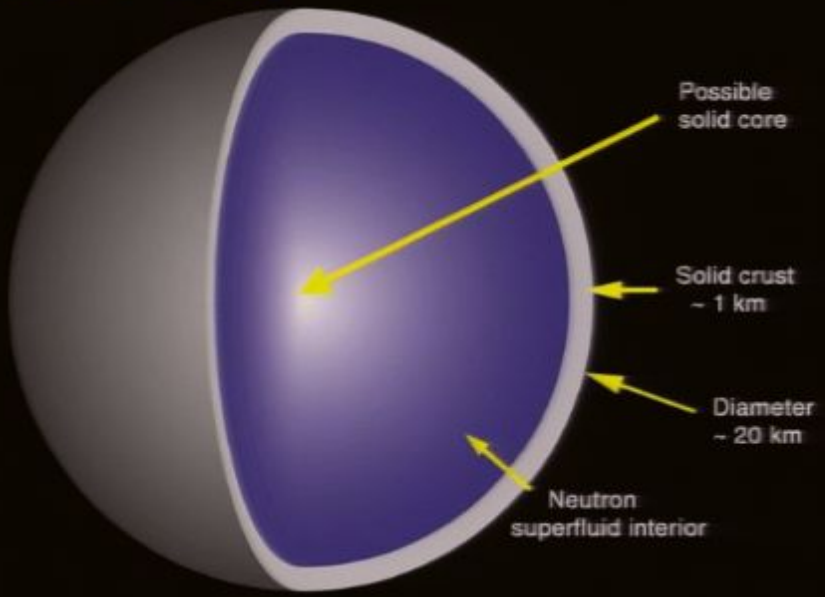

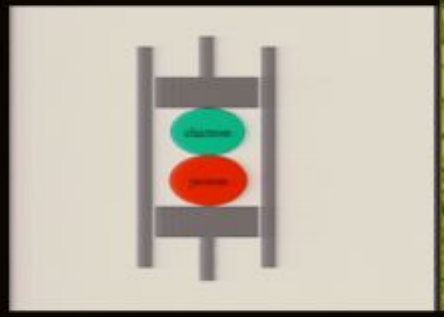

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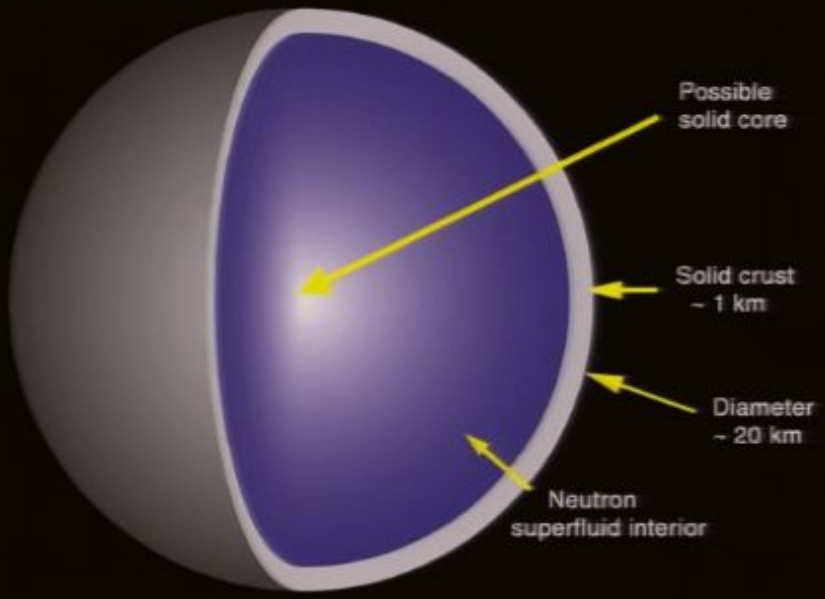

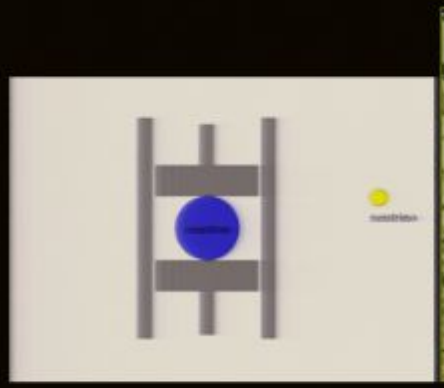

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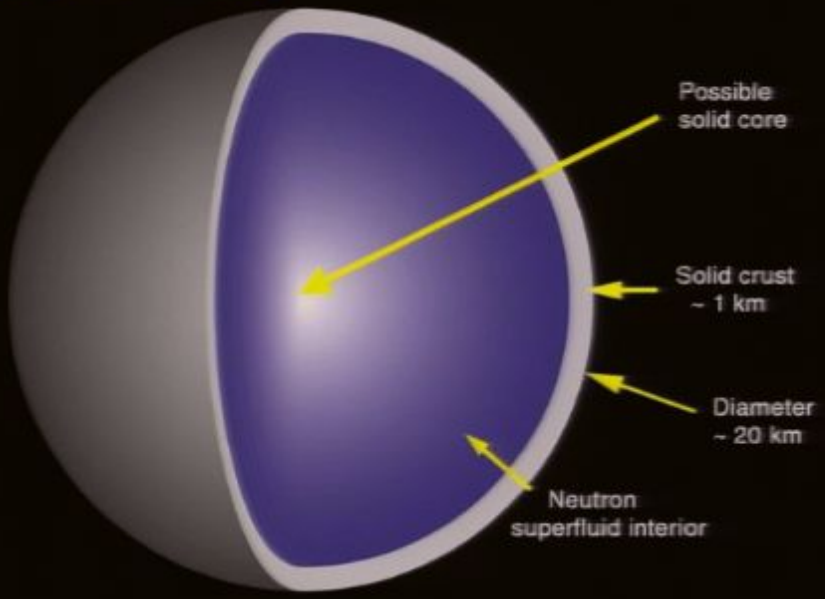

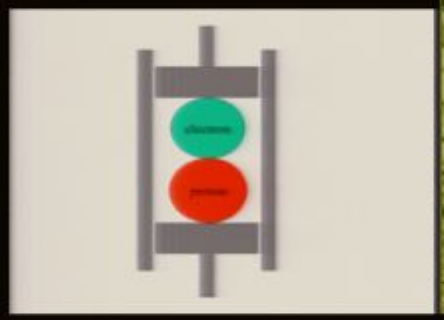

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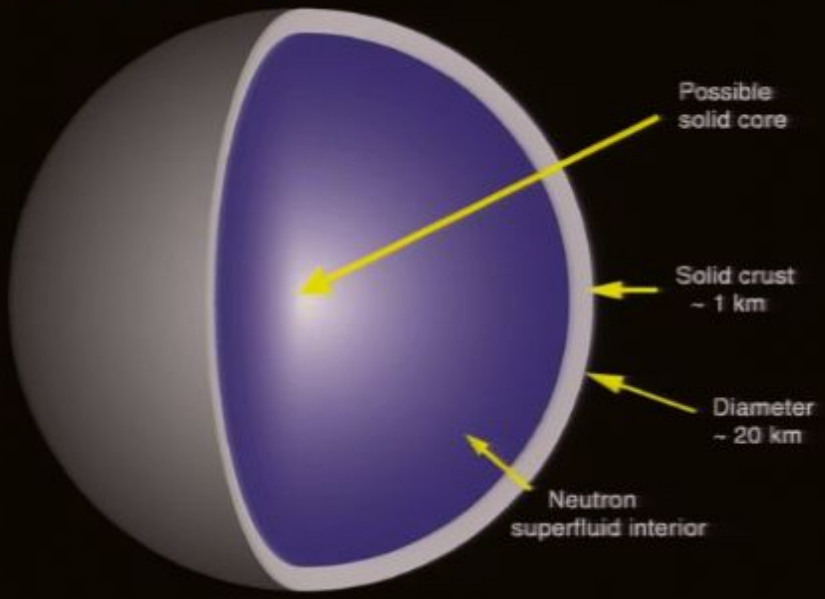

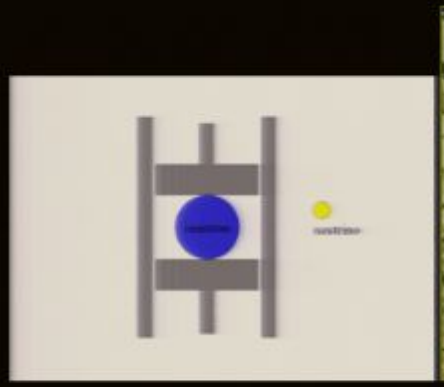

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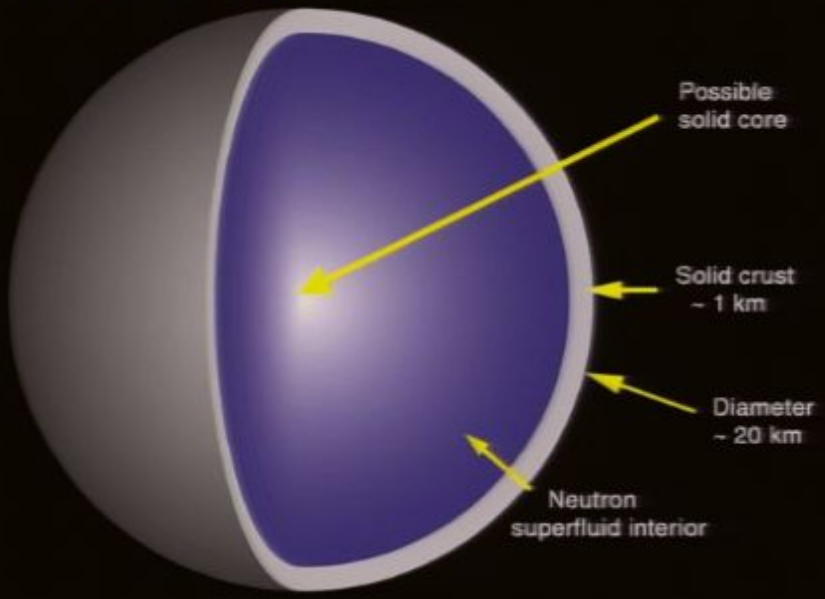

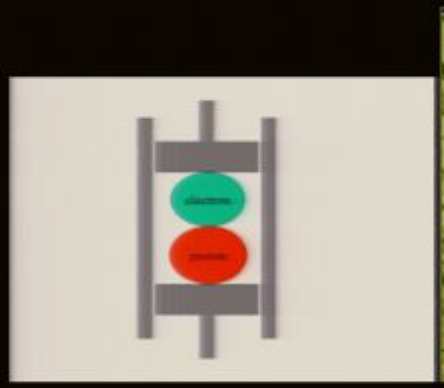

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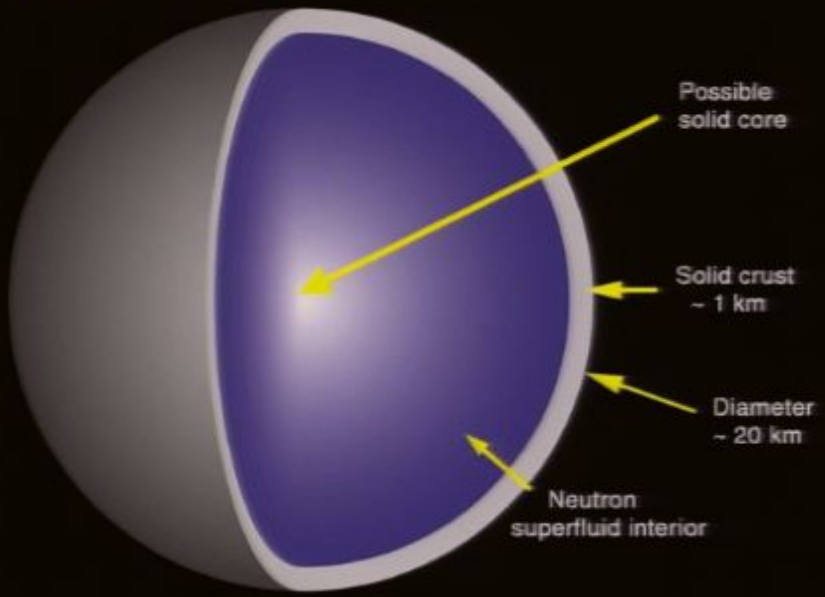

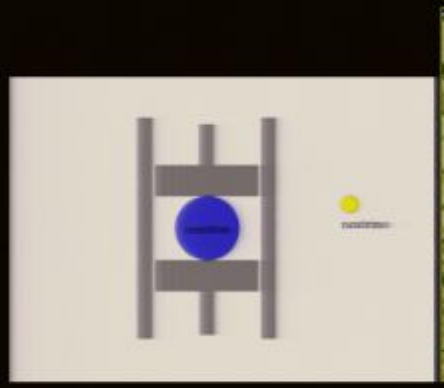

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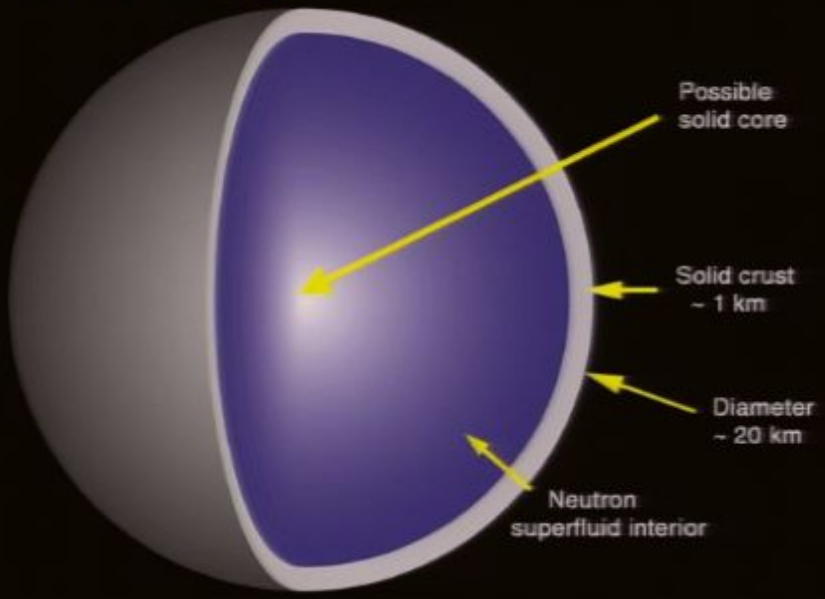

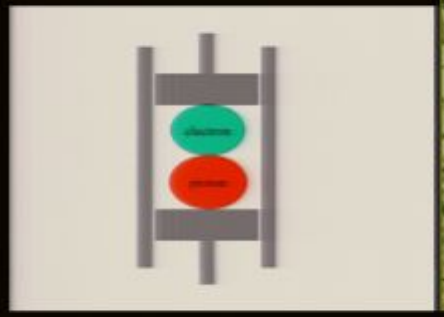

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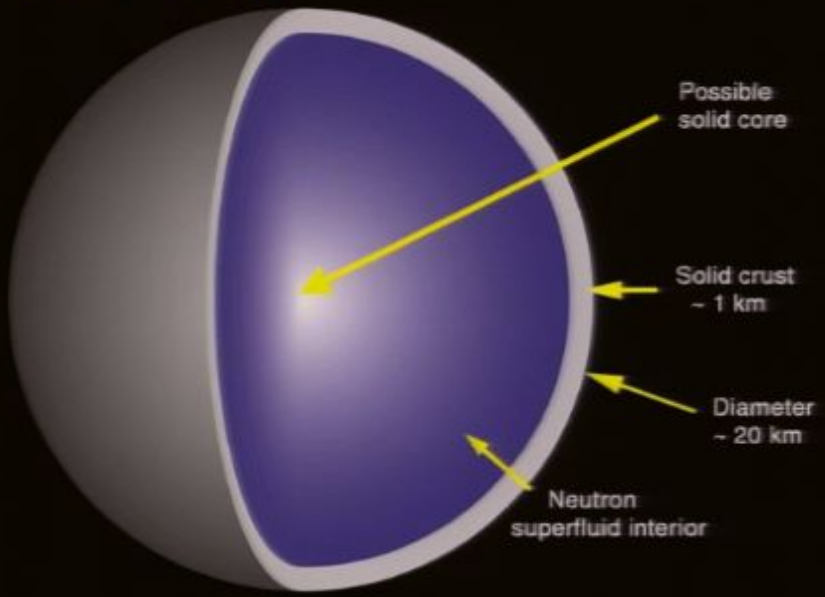

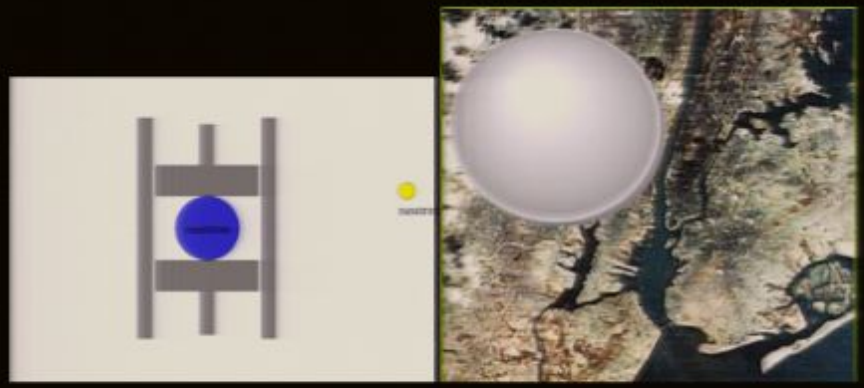

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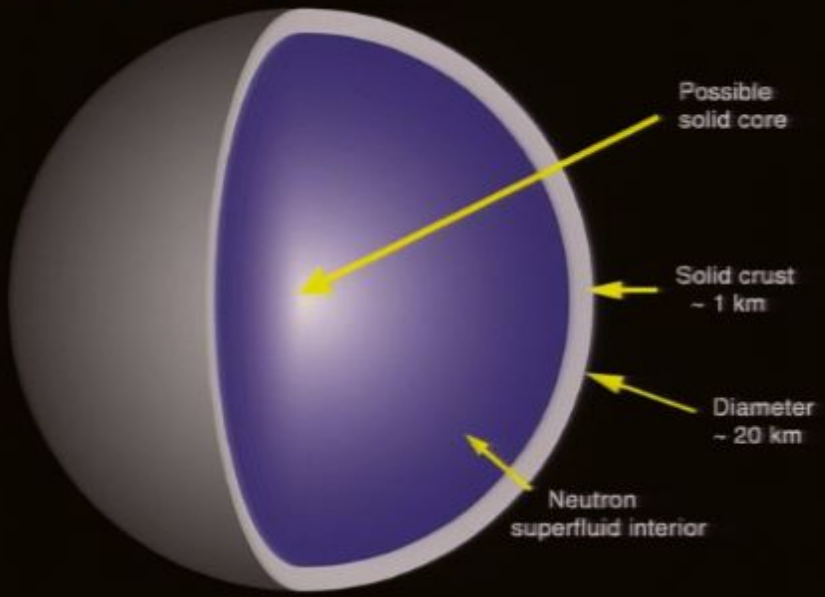

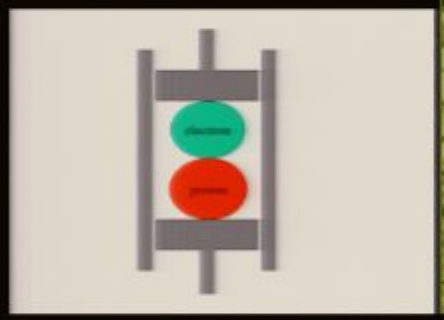

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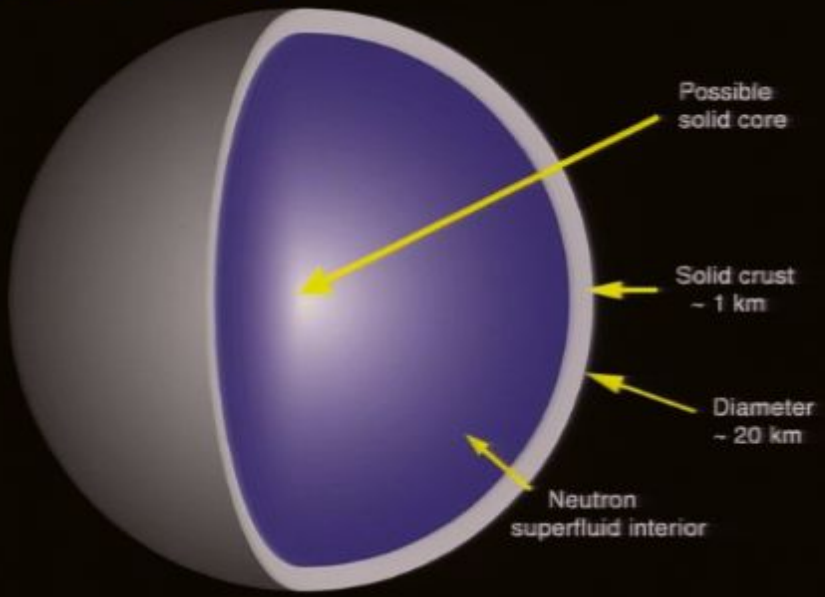

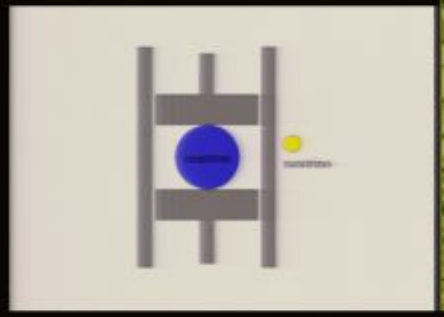

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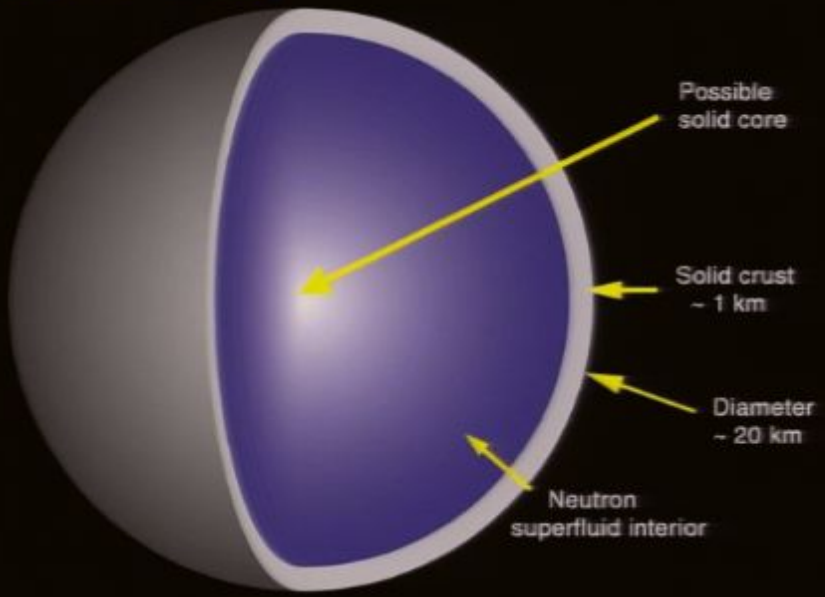

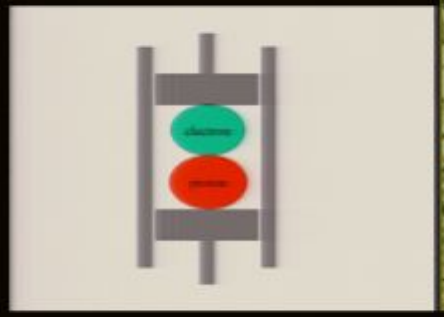

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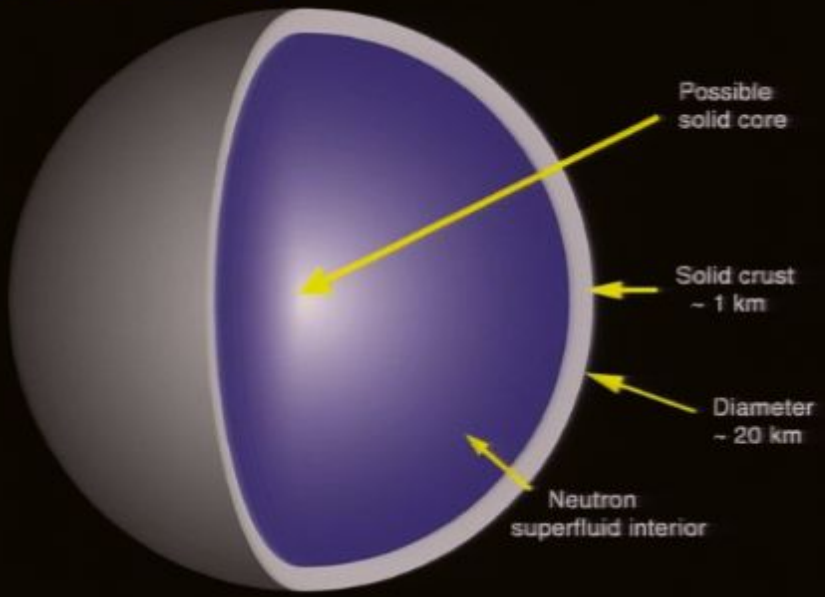

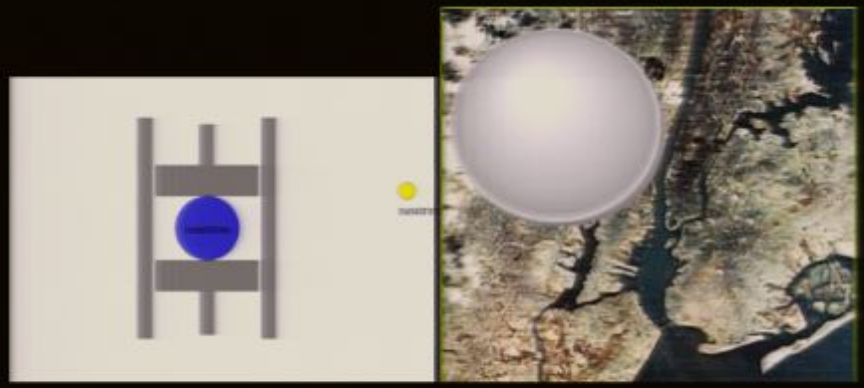

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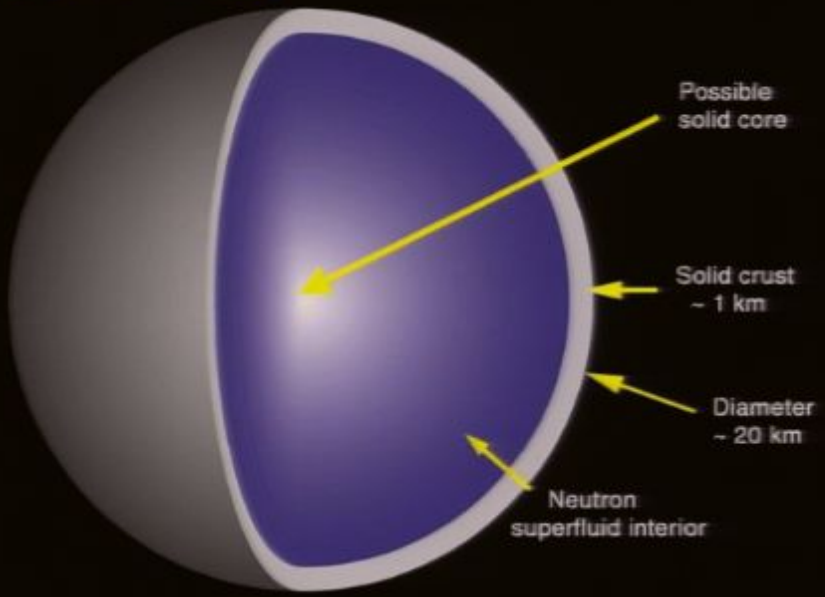

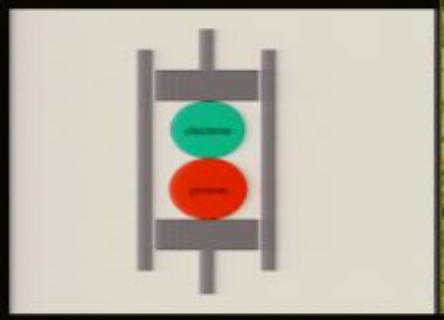

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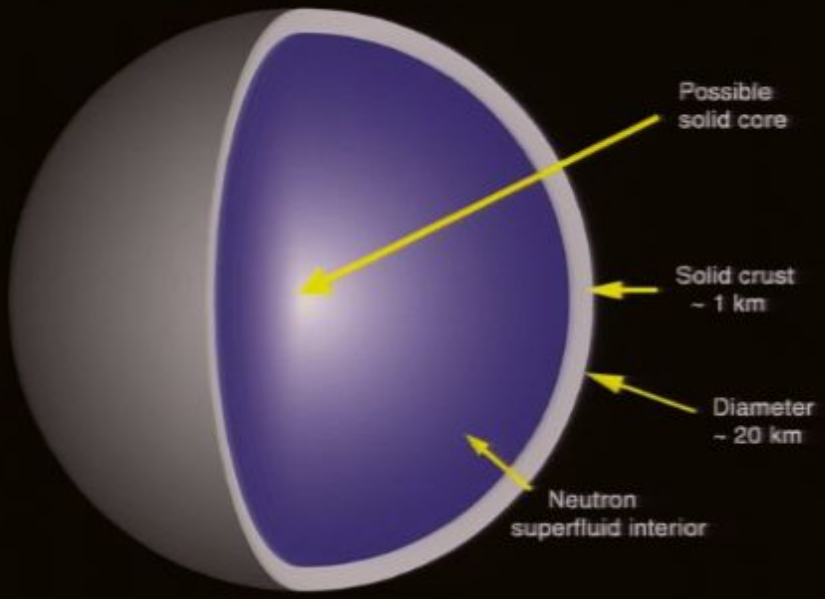

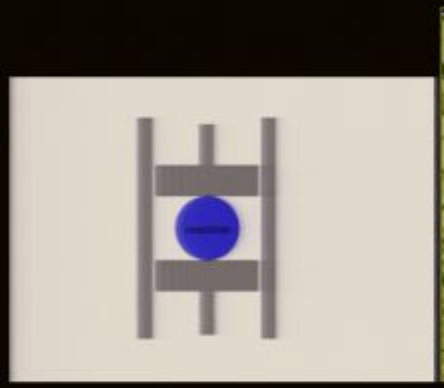

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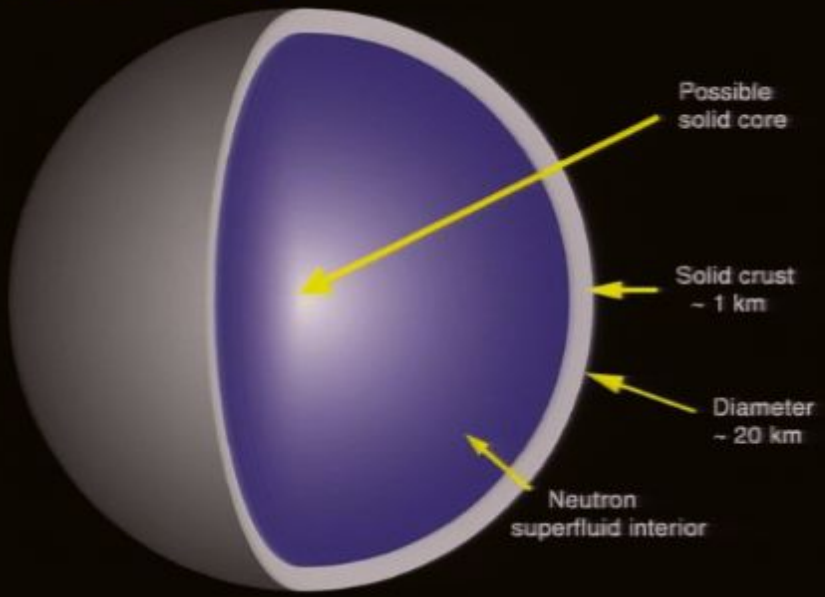

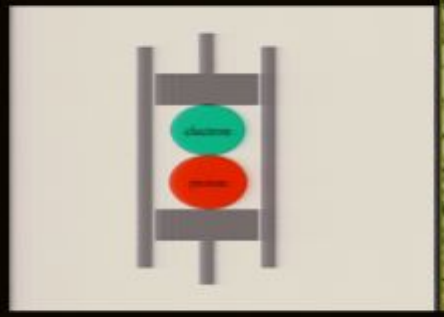

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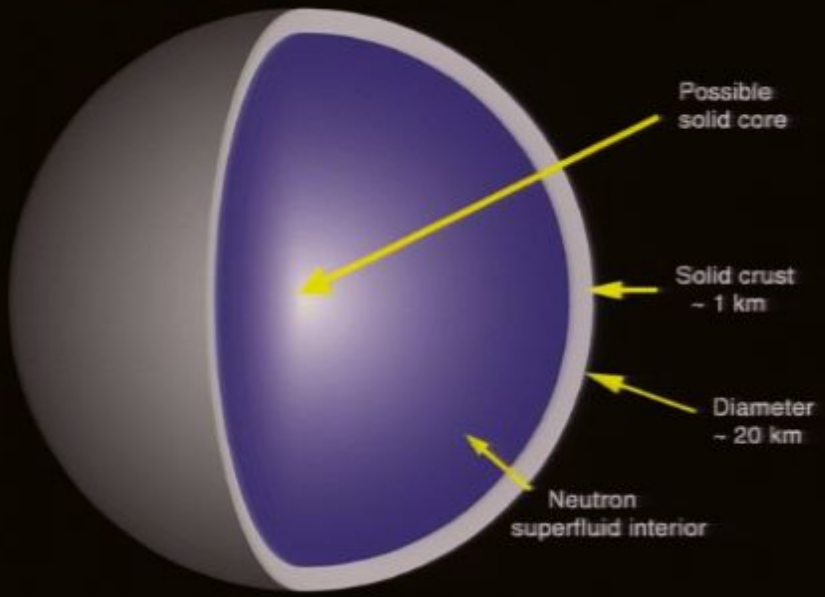

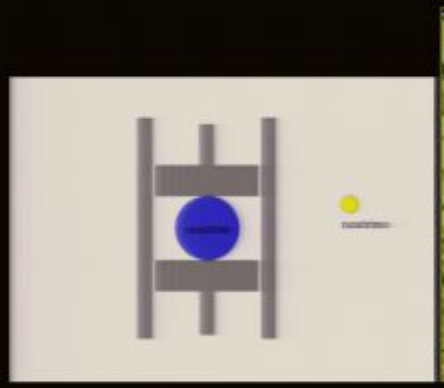

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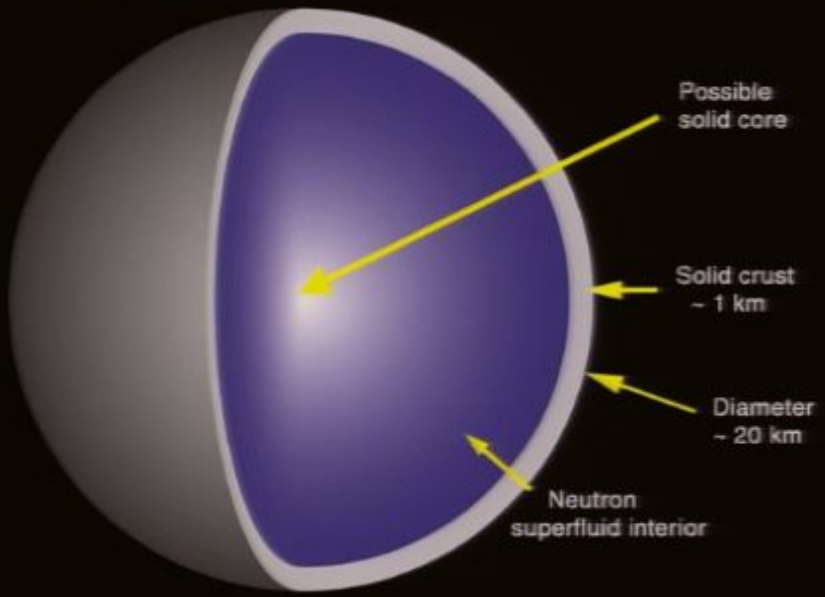

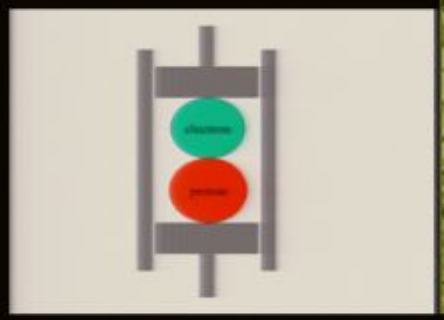

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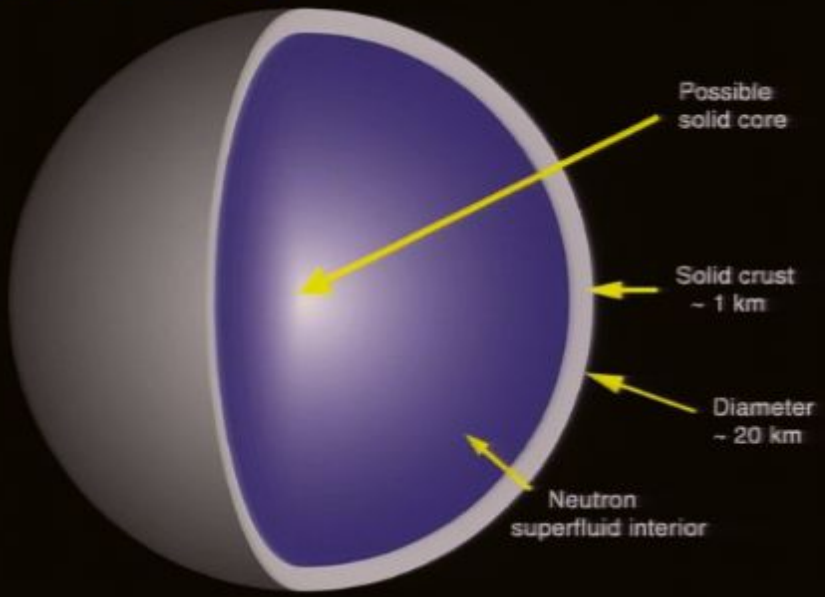

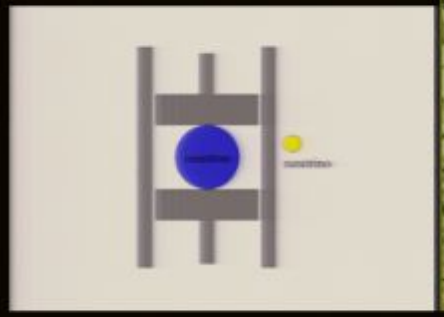

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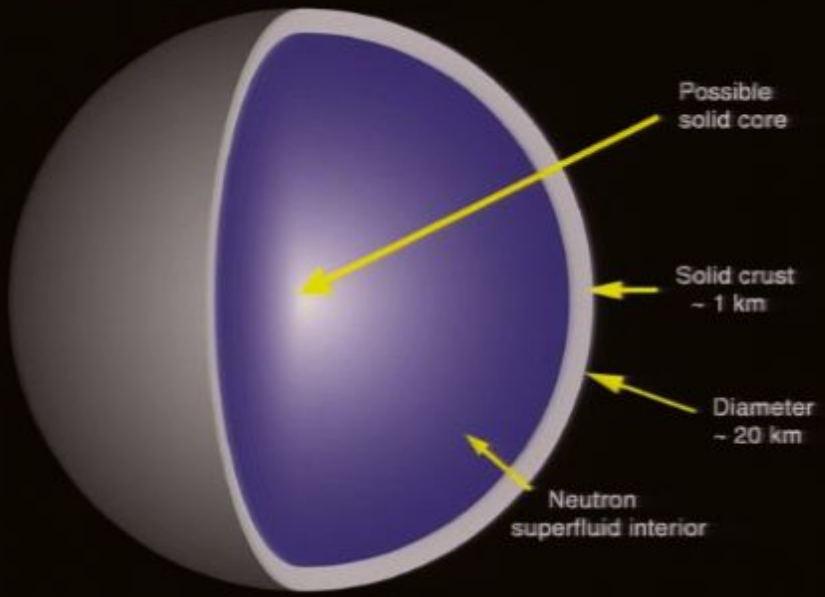

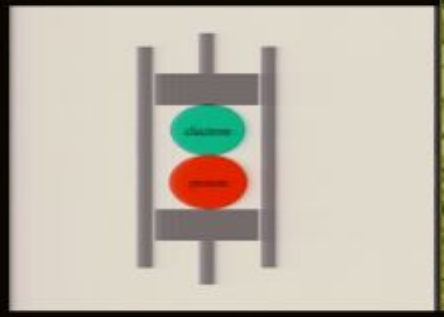

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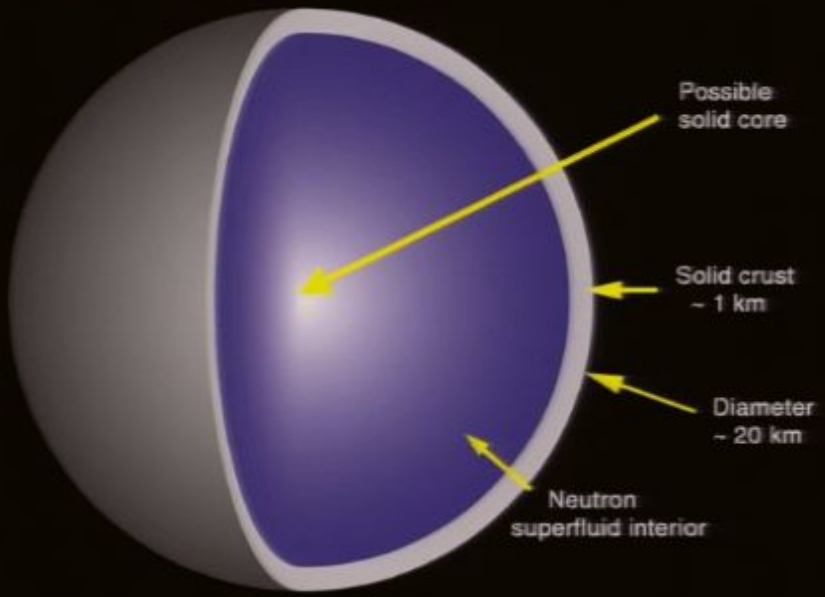

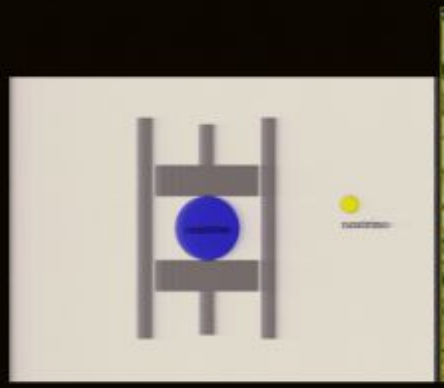

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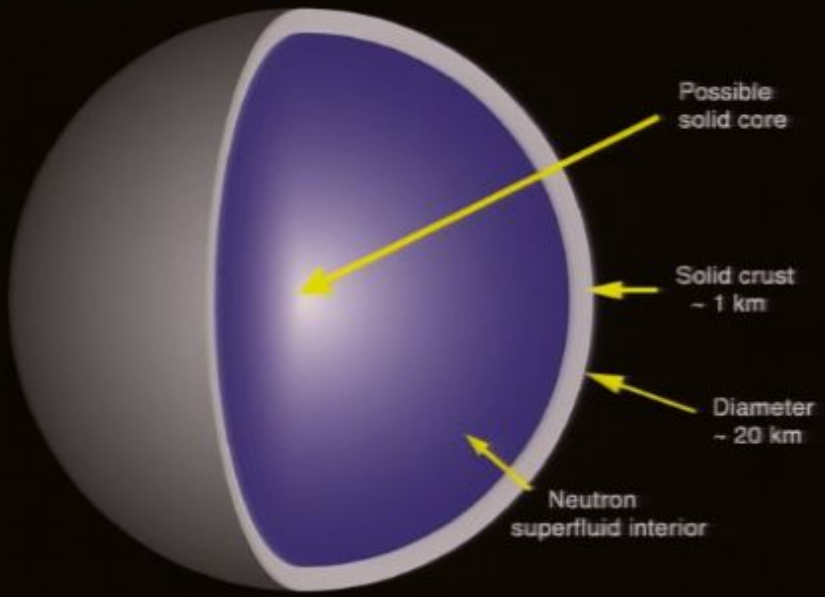

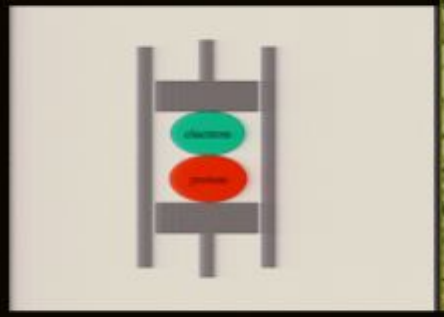

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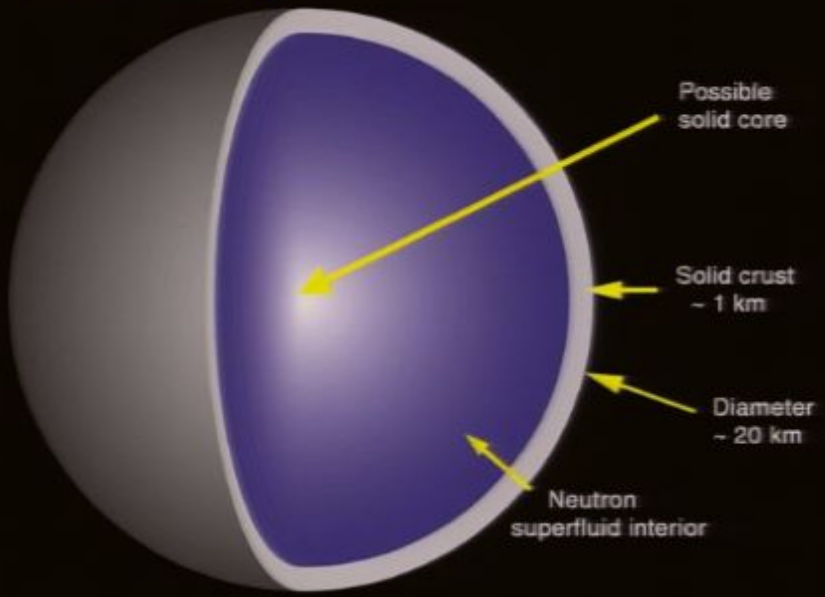

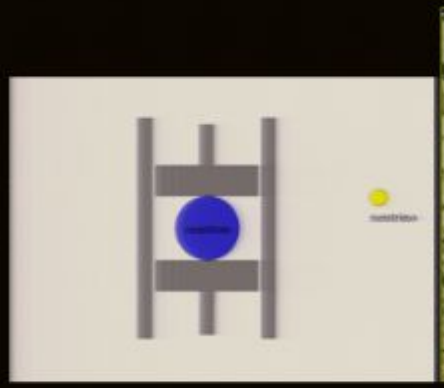

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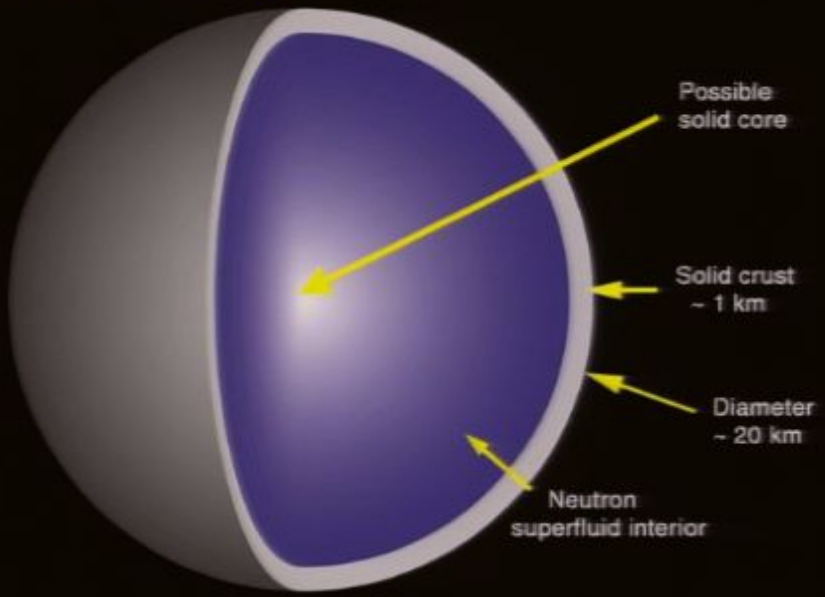

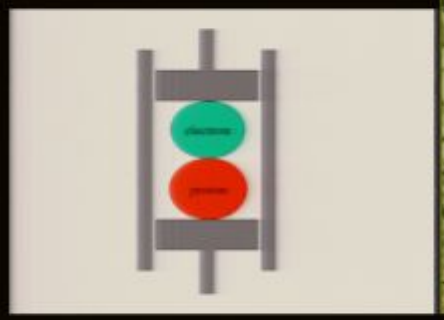

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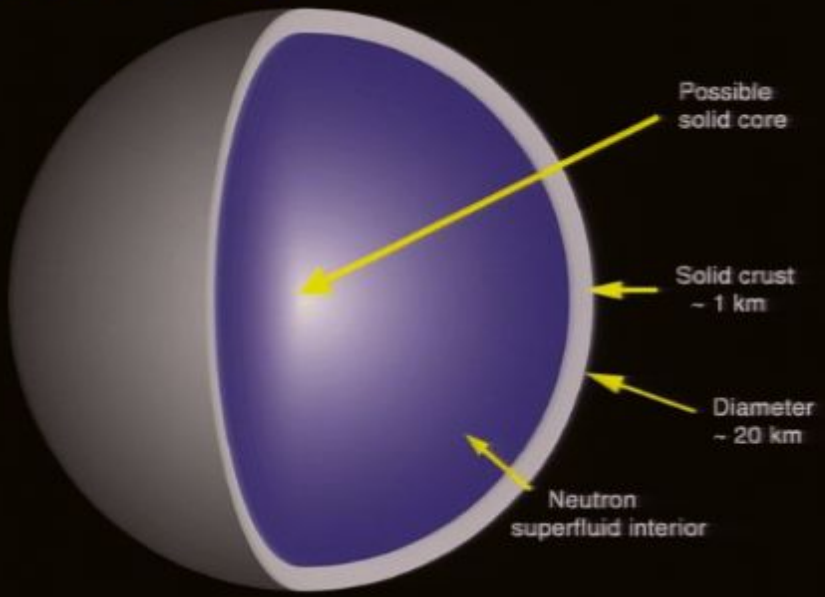

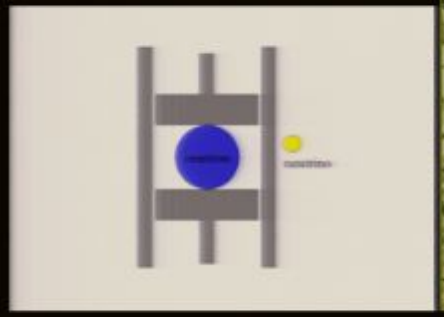

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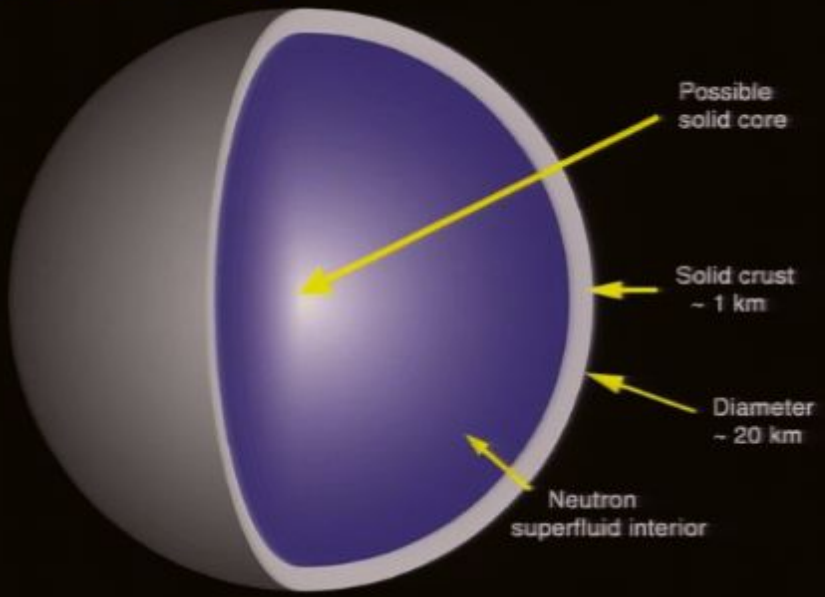

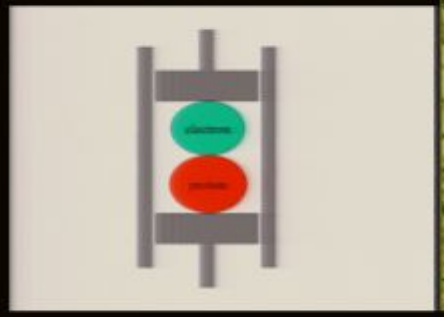

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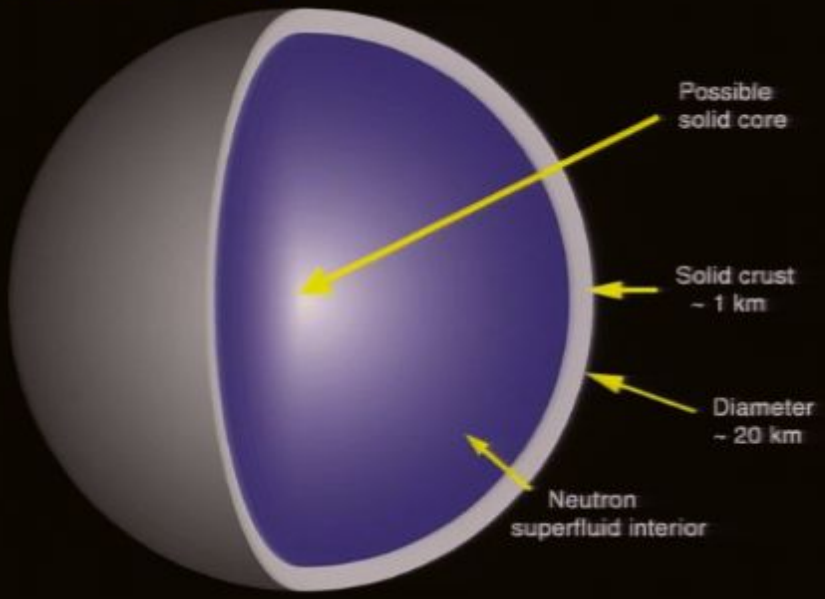

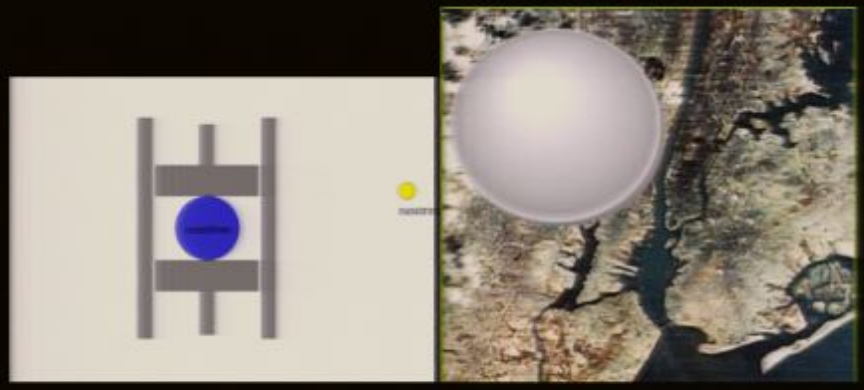

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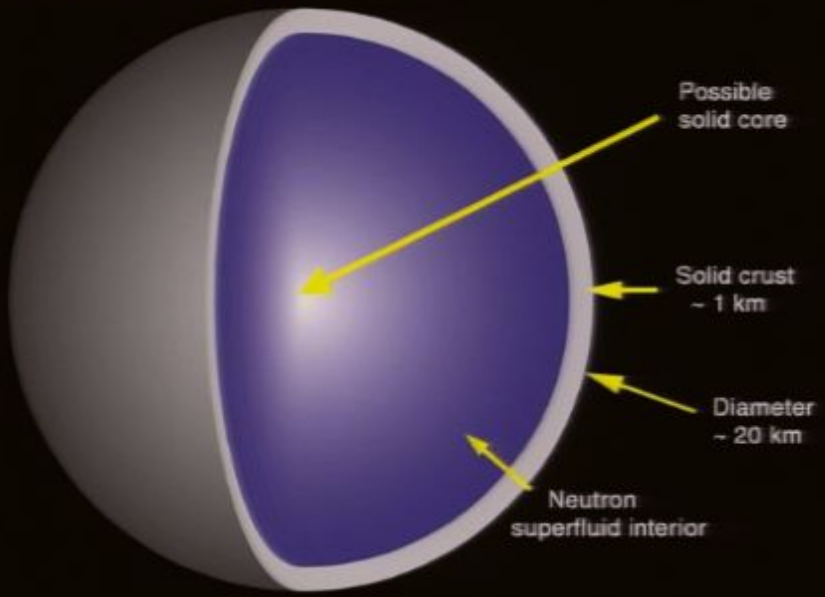

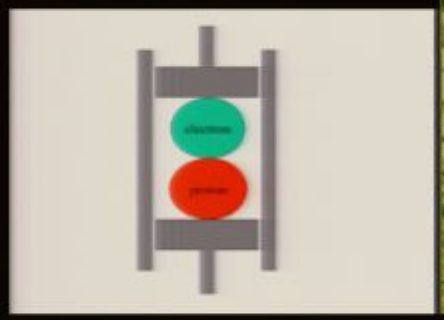

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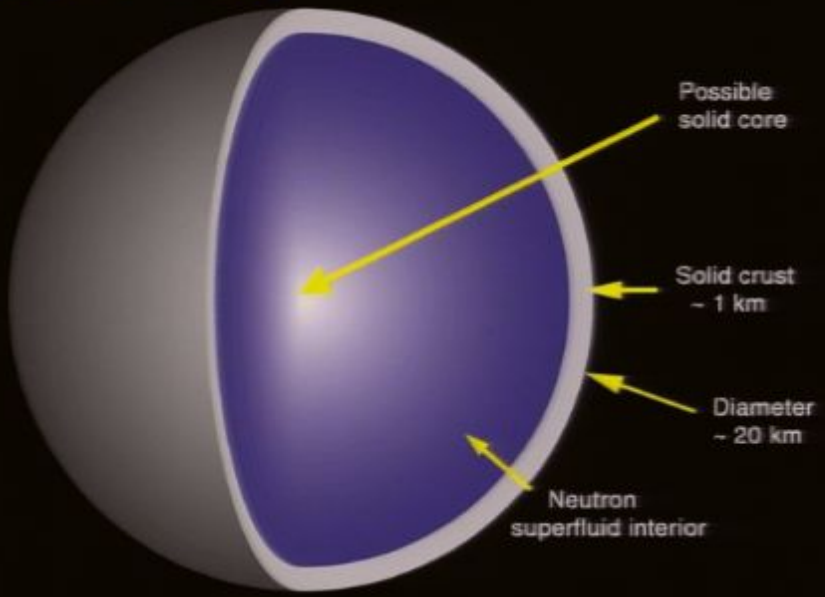

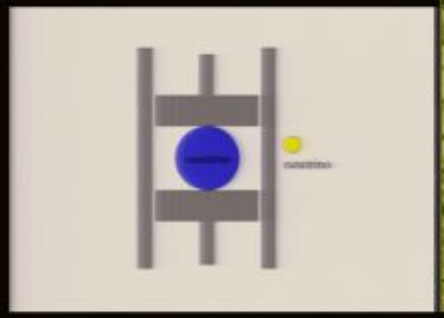

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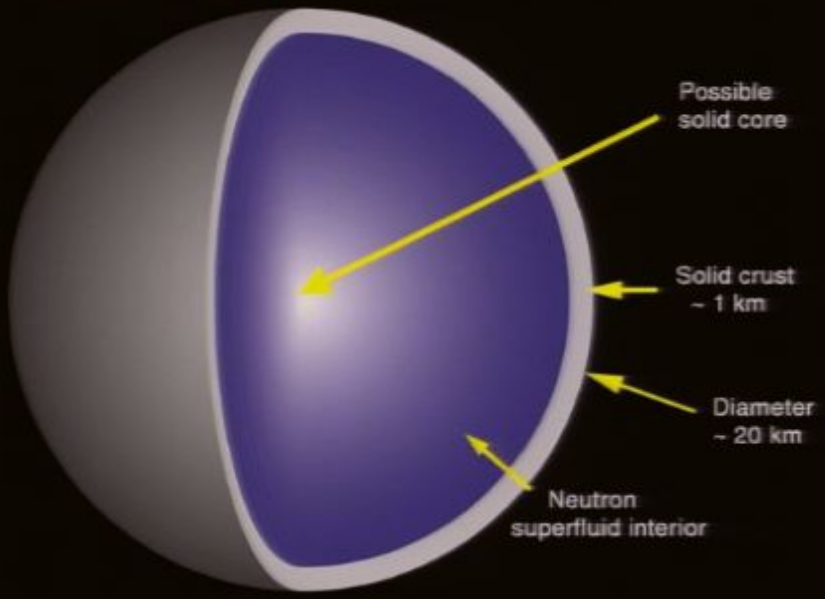

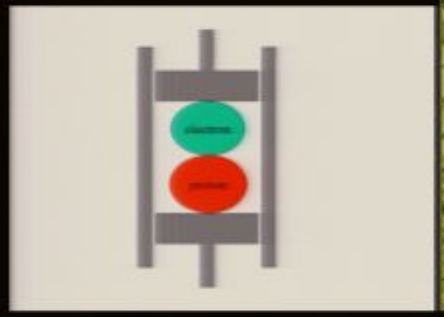

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- A giant ball of neutrons.
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  - A sugar cube of this matter weighs 400 billion tons
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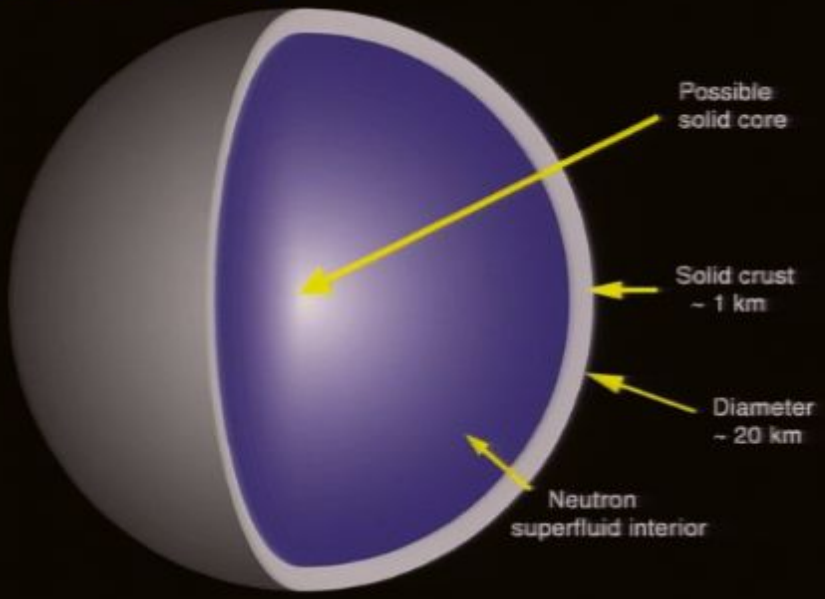

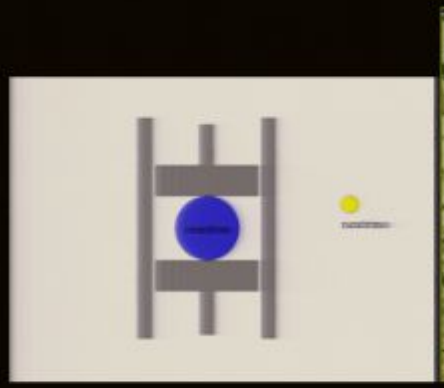

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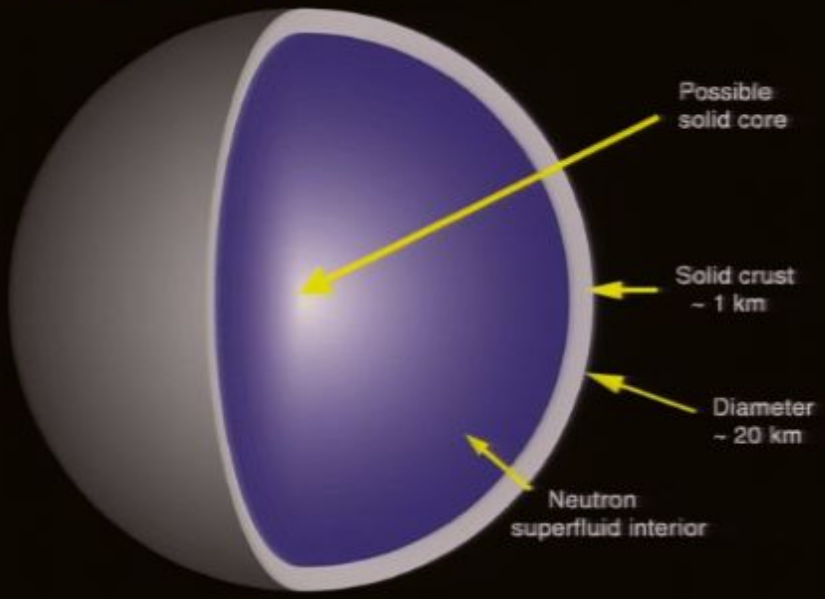

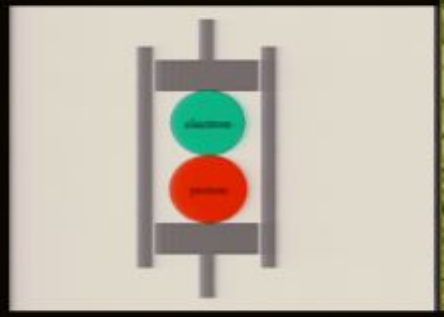

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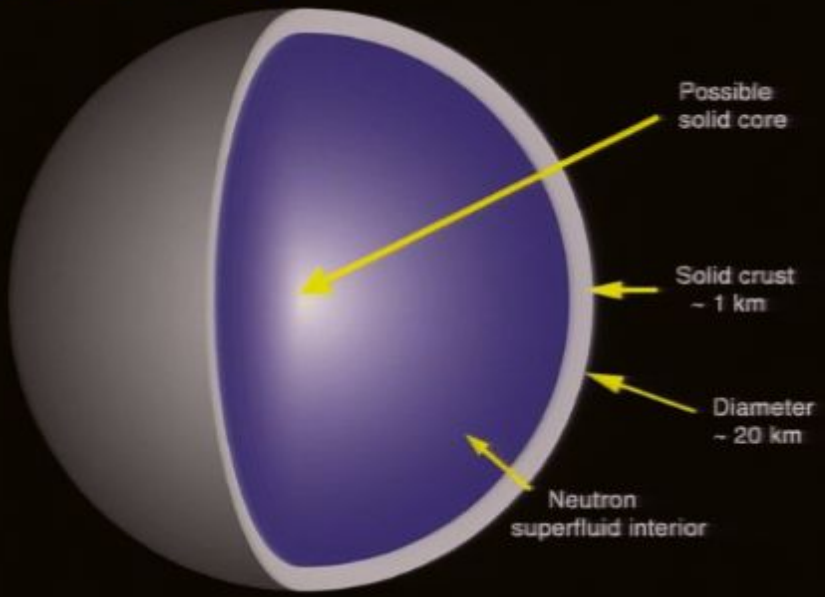

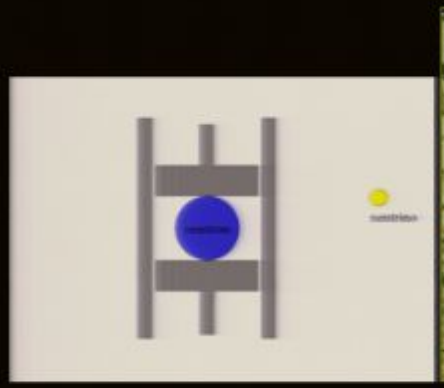

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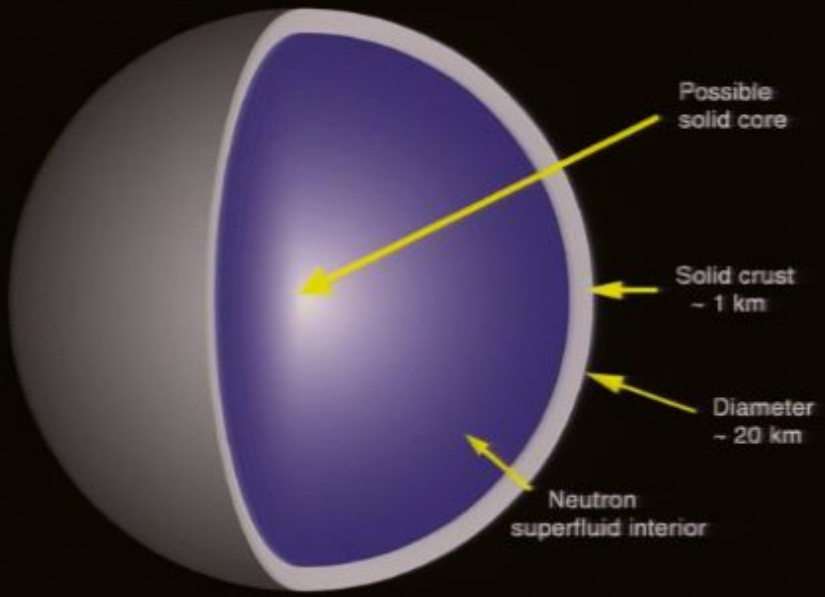

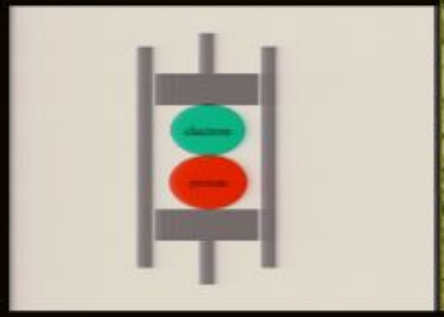

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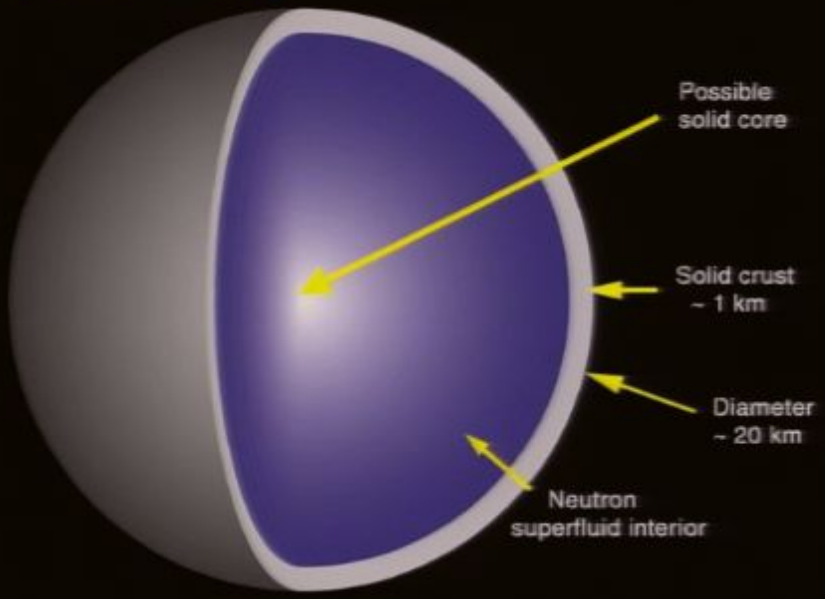

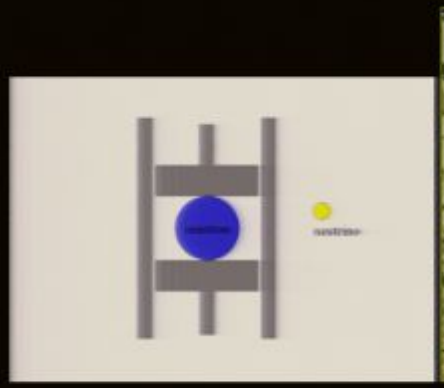

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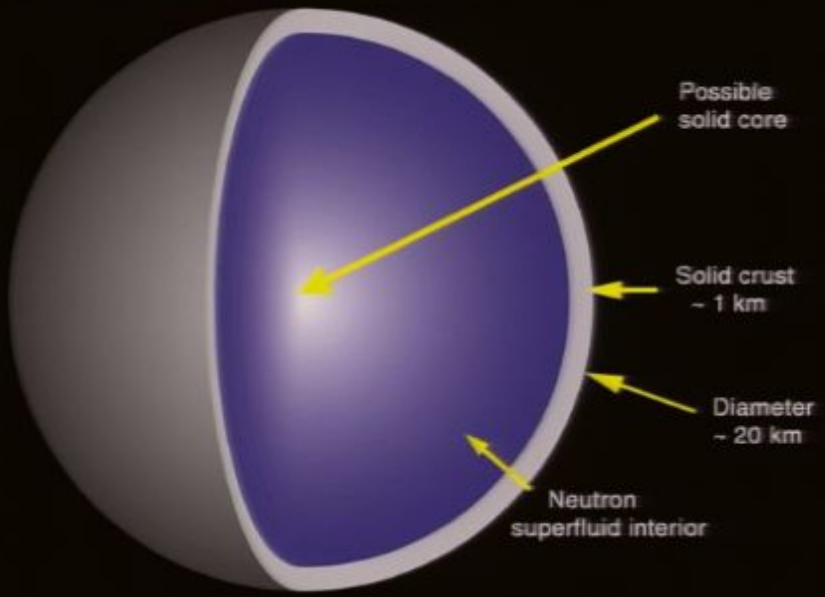
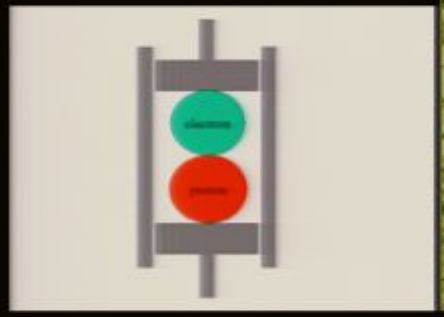
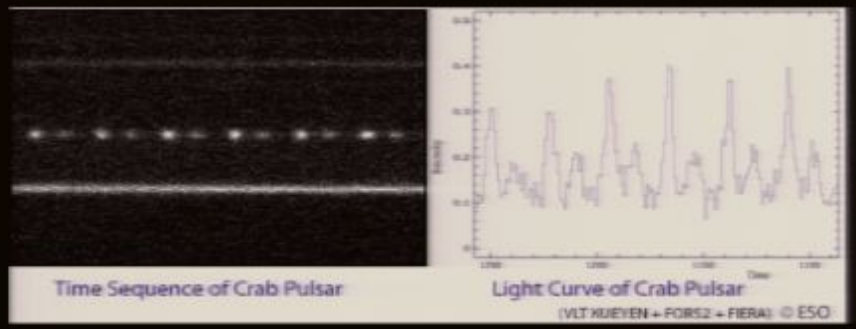
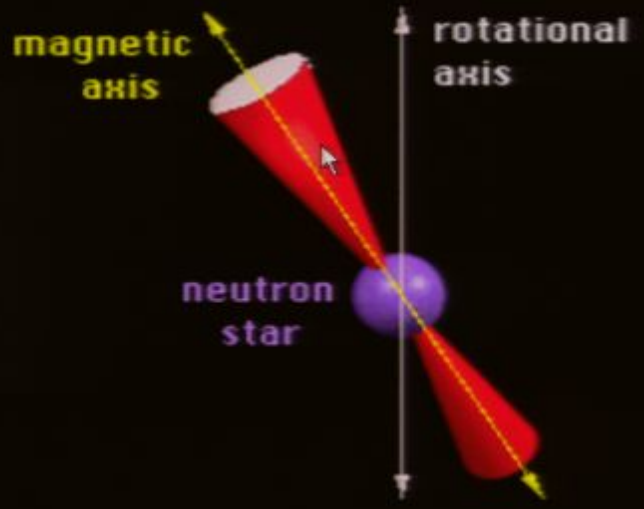




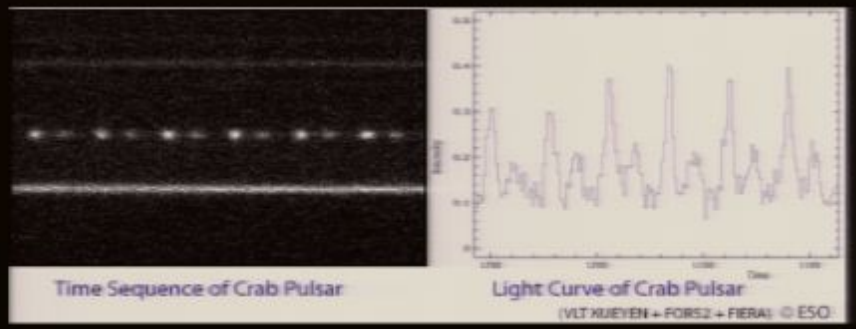
Pulsars

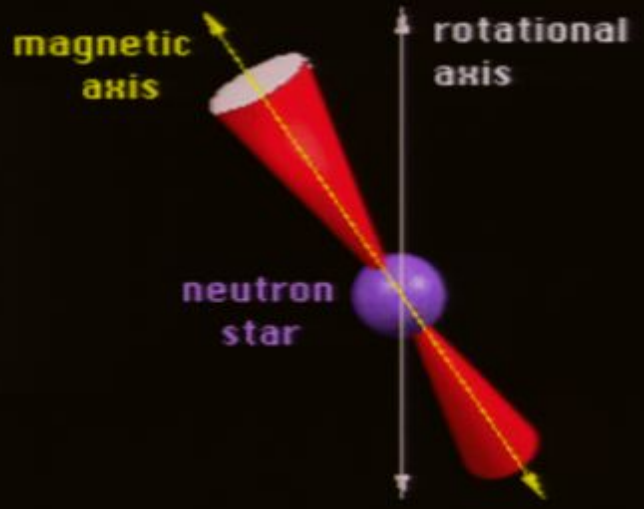

Time Sequence of Crab Pulsar
Light Curve of Crab Pulsar
(VLT KUEYEN + FORS2 + FIERA) © ESO


magnetic axis
rotational axis
neutron star

Pulsars

- Discovered by Bell and Hewish in 1968





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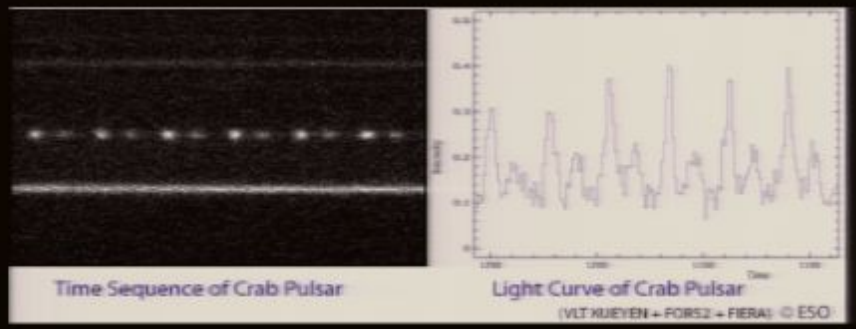
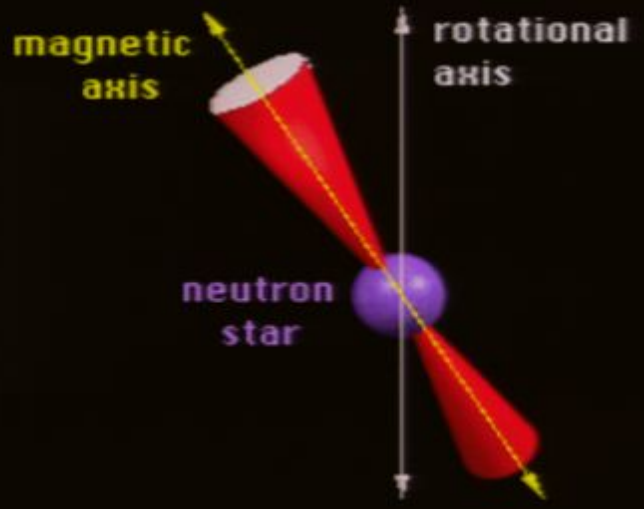
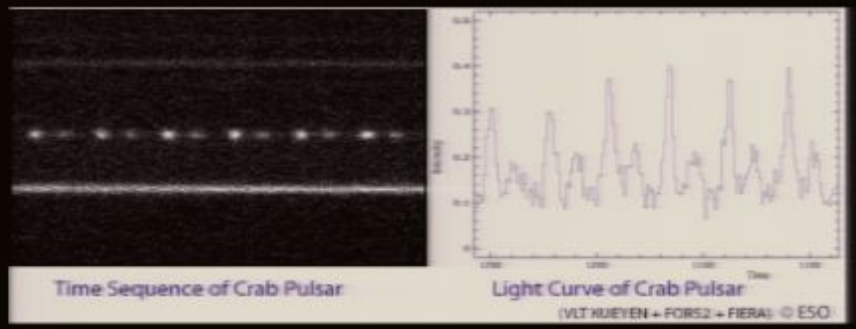
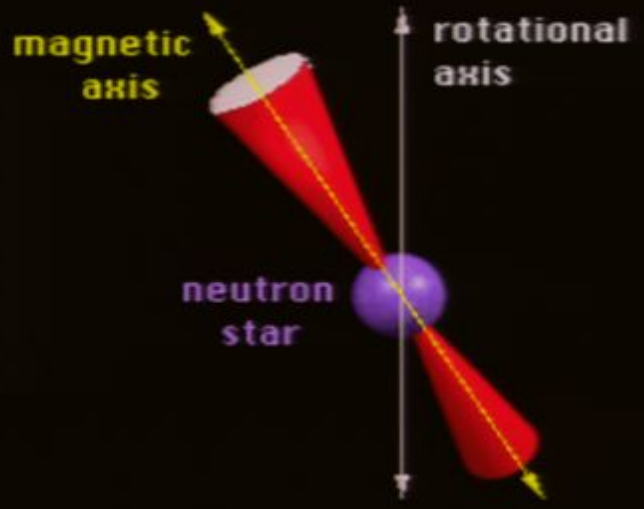




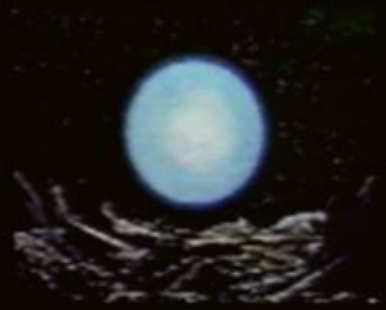
Pulsars

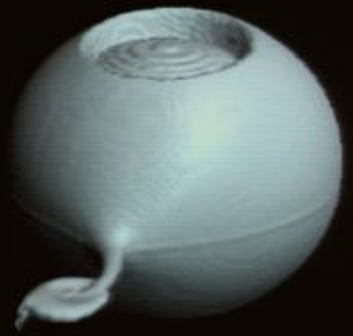
- Discovered by Bell and Hewish in 1968
- Stands for pulsating stars, since they emit regular pulses
- Now known to be spinning neutron stars





Supernova





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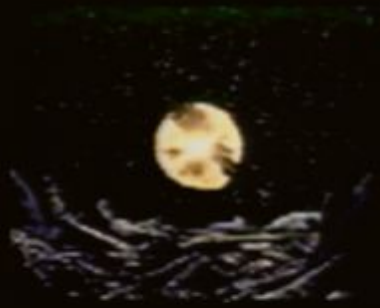

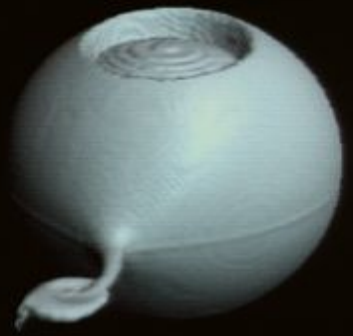

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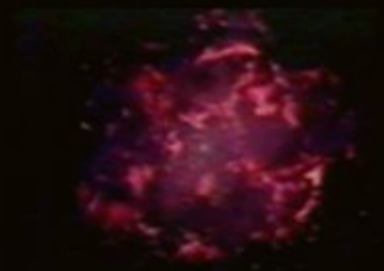

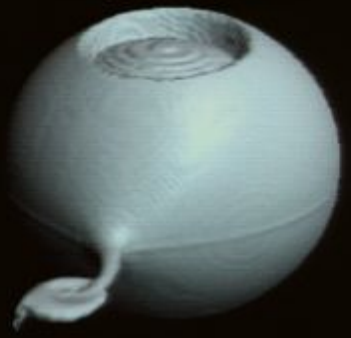

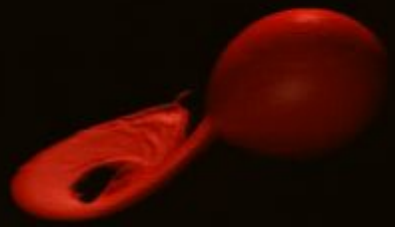

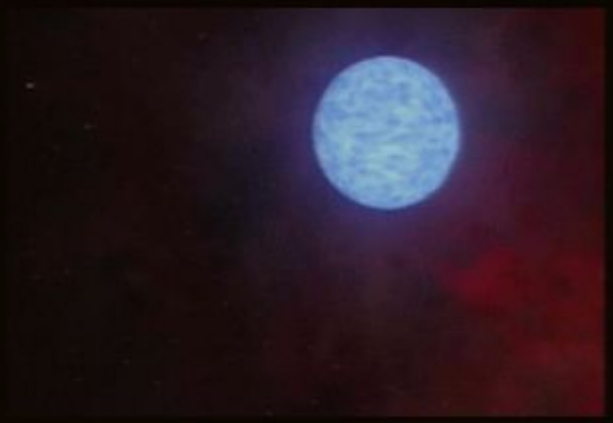

Crab Nebula Pulsar

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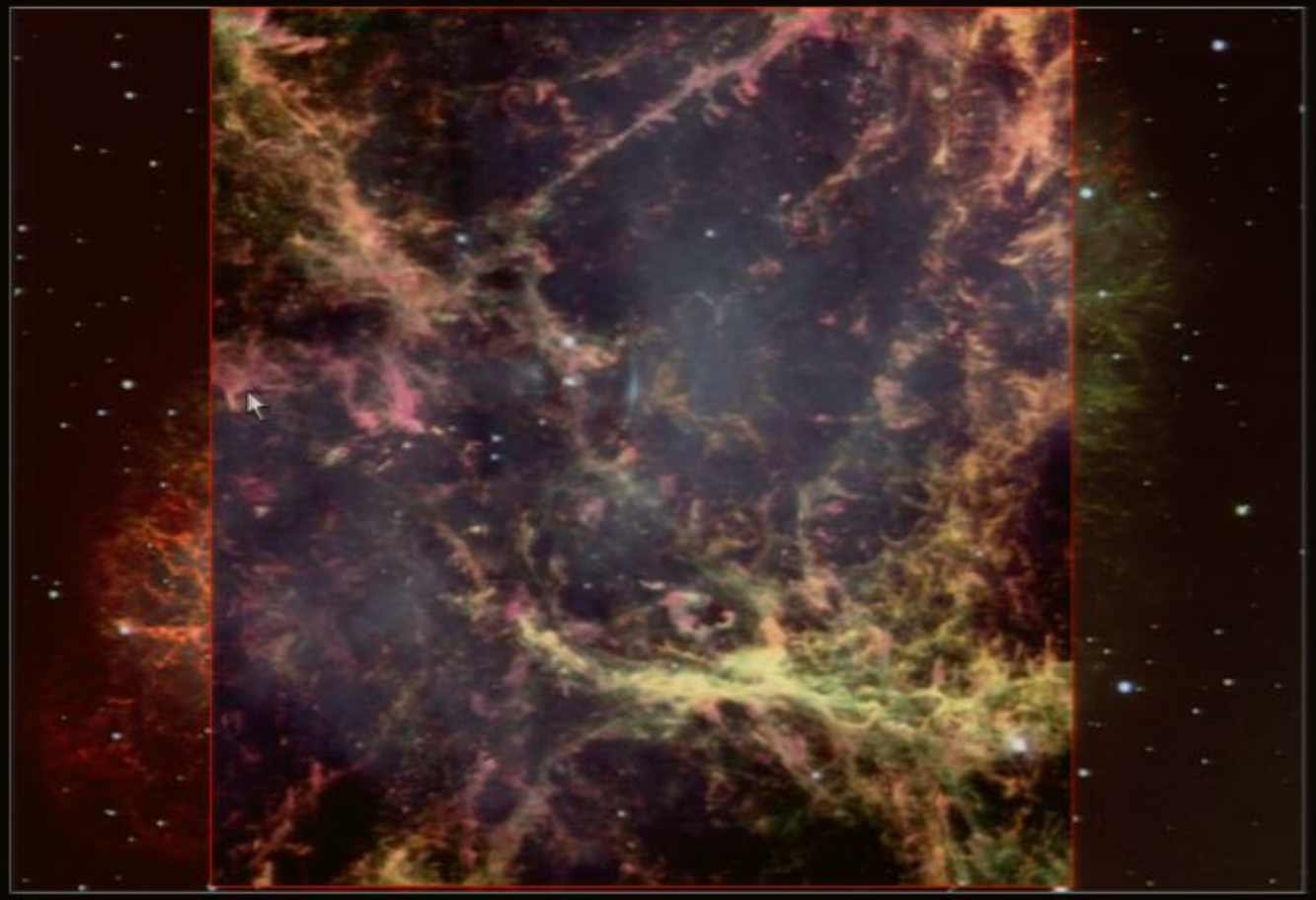

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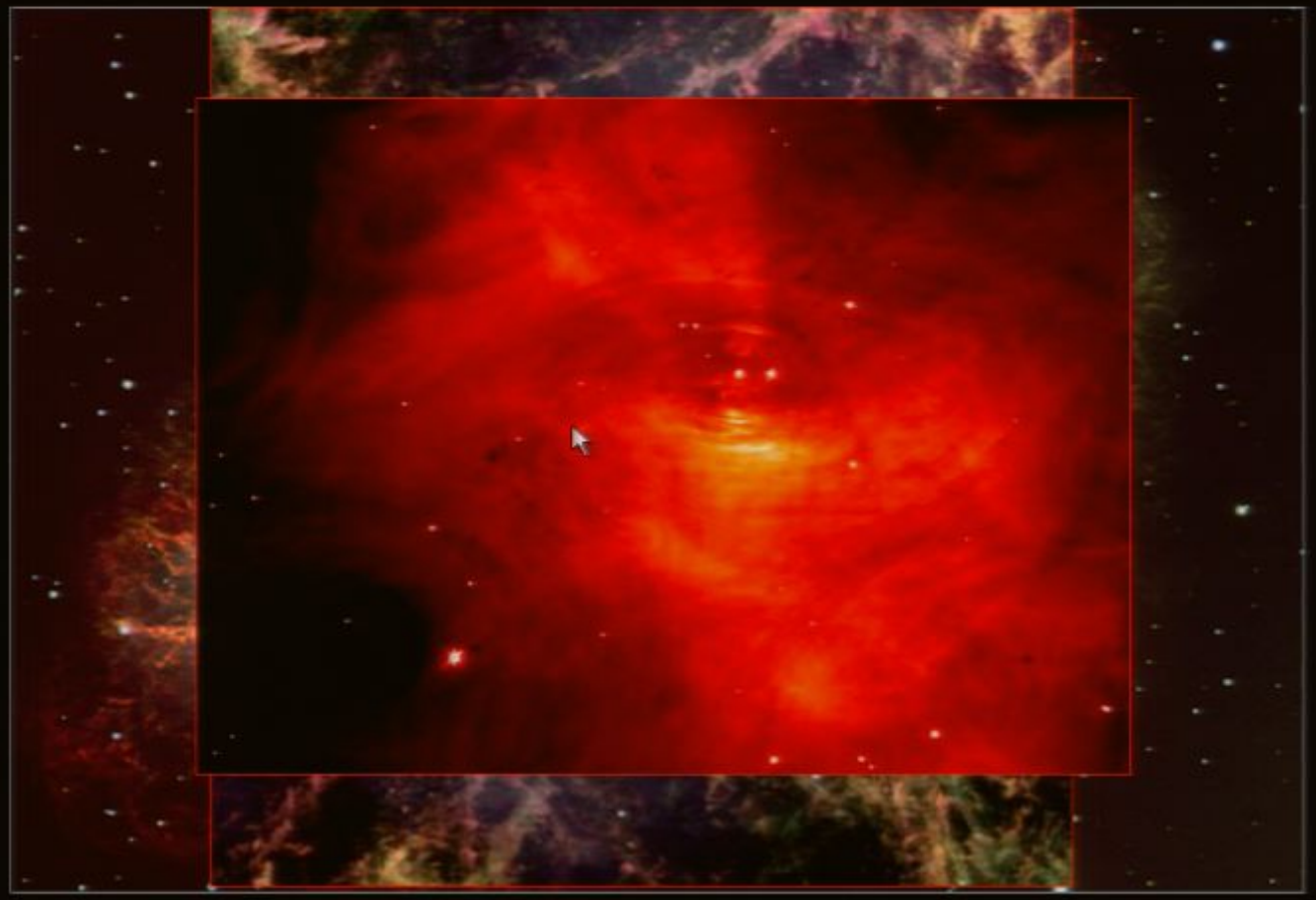

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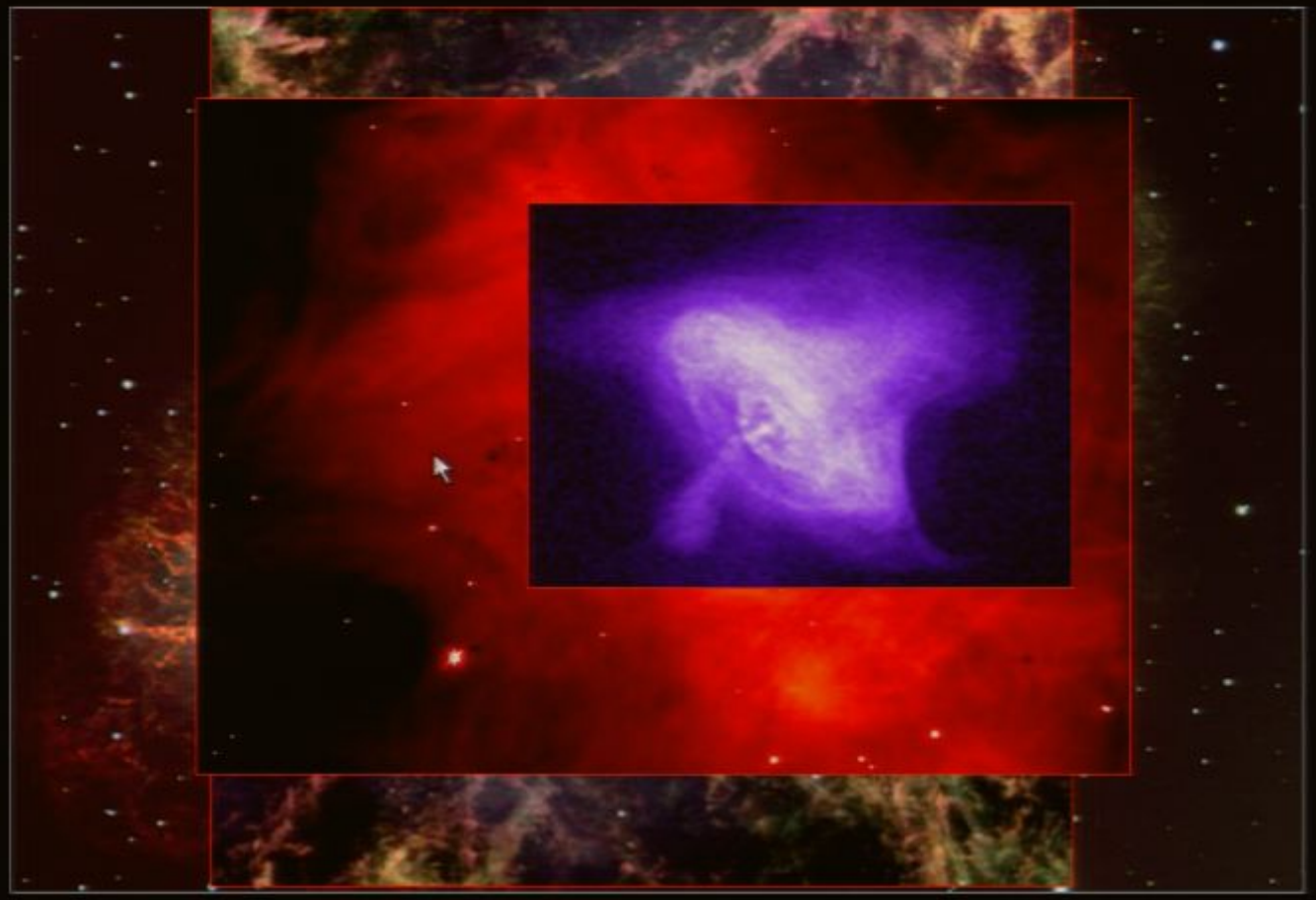

Mass

- 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

What Next

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- What if the escape velocity is faster than light?

Black Hole

- The star collapses to form a Black Hole.