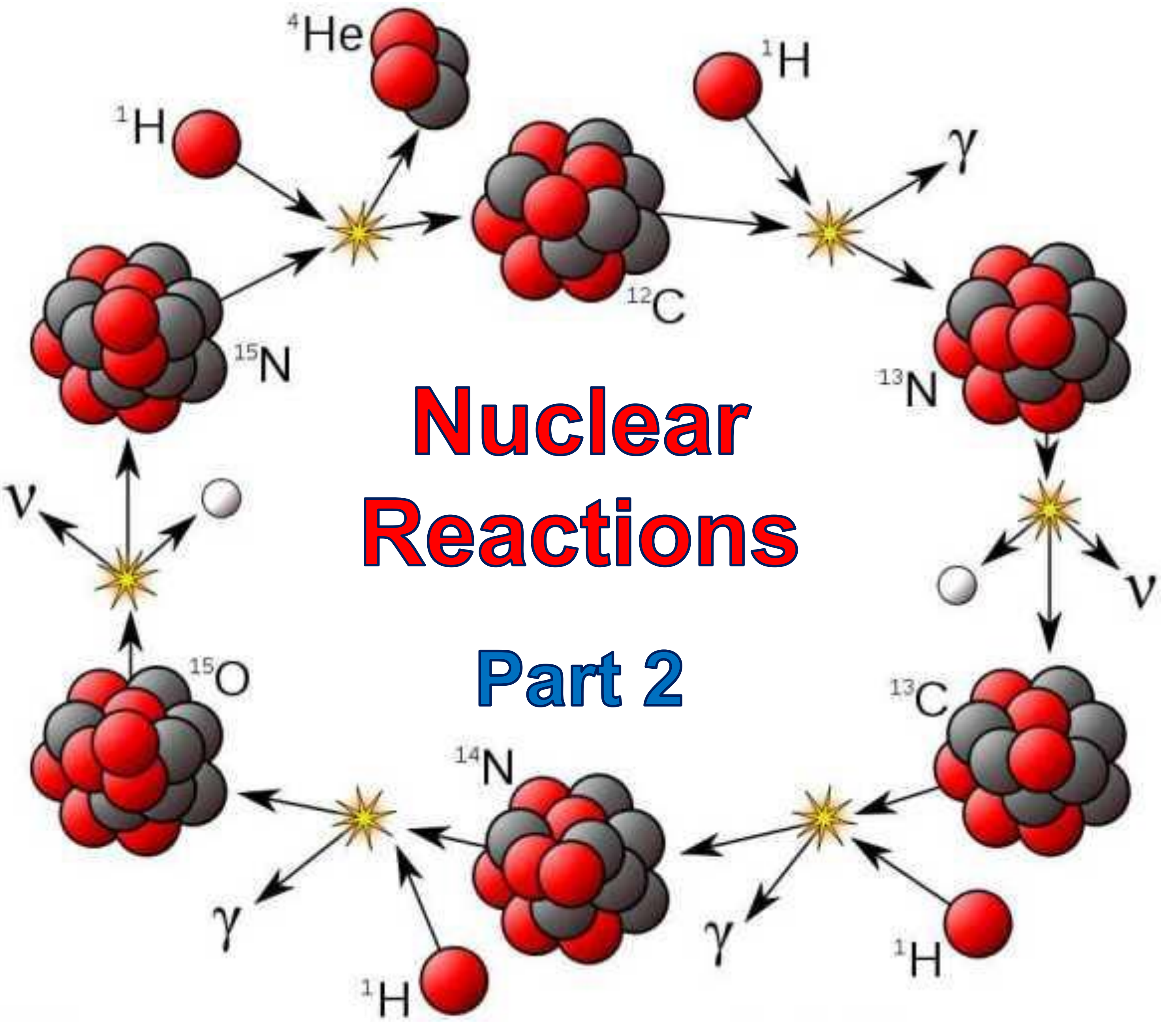
Nuclear Reactions

Part 2



Three Types of Nuclear Reactions

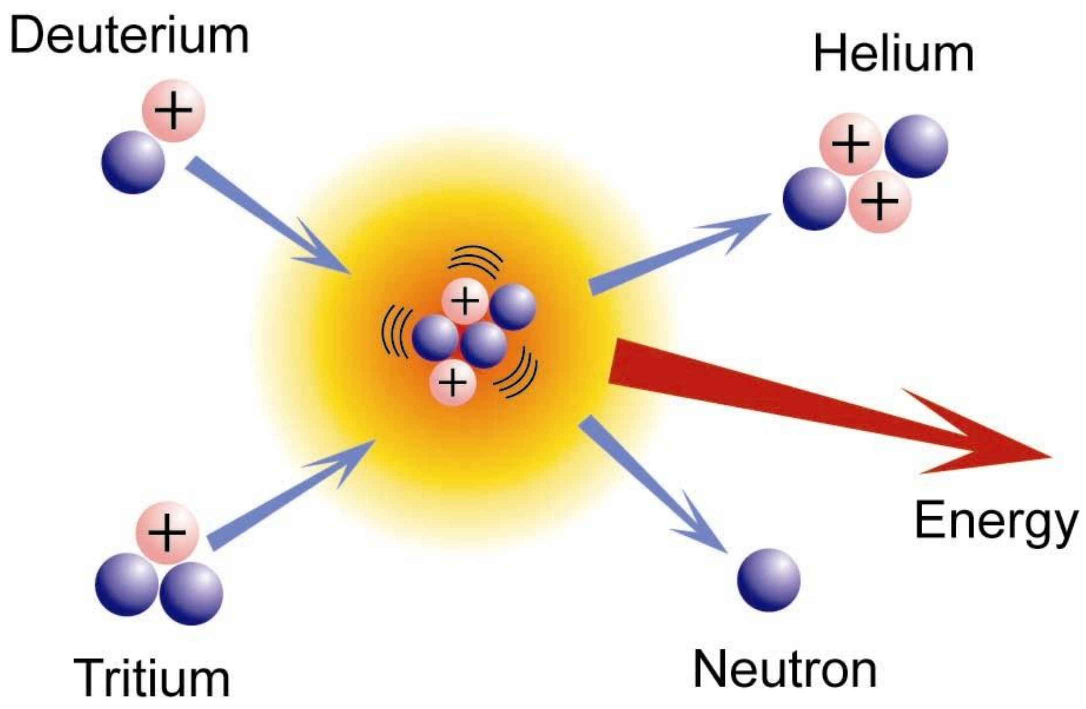
1. **Radioactive decay** – an unstable nucleus spontaneously emits a small particle of radiation to become a **different isotope** of the same element or a **different element** (such process is called ***transmutation***).

2. **Nuclear Fusion** – the **joining** of two atoms to form a larger one.

3. **Nuclear Fission** – the **splitting** of an atom into two smaller atoms.

Our today's focus

Nuclear Fusion



- The fusion of two nuclei with masses lower than iron generally releases energy, while the fusion of nuclei heavier than iron absorbs energy.

Fusion is the process that powers active stars.

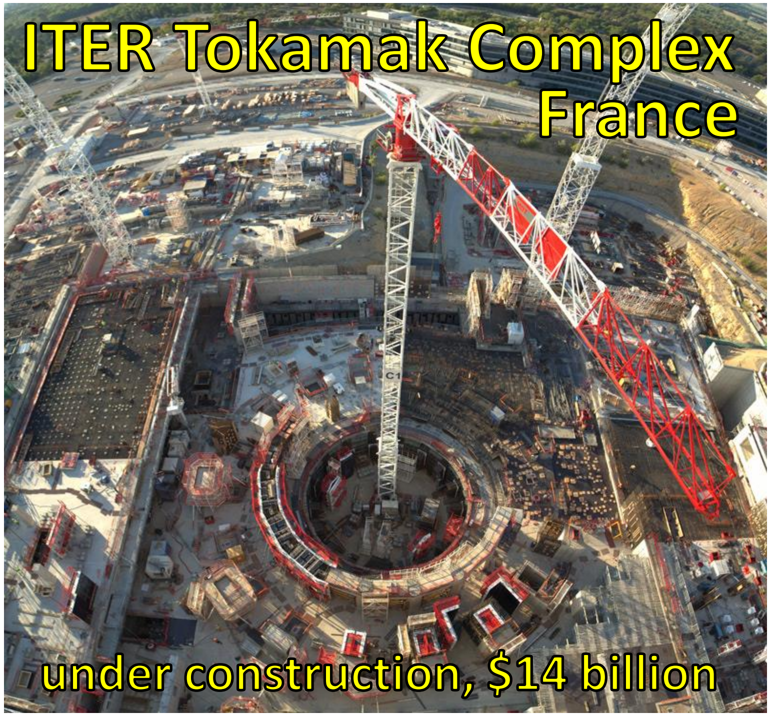
- **Fusion reactions have the greatest energy density, that is energy per unit of mass, than any known process (nuclear fission or chemical reactions).**

Thermonuclear Fusion

- **In order to fuse, two nuclei must be brought close enough together (*confinement requirement*) so the electrostatic repulsion can be overcome by the attractive nuclear force which is stronger at close distances.**
- **If the matter is sufficiently heated (*plasma state*), the <u>thermonuclear fusion</u> reaction may occur due to collisions between the particles of extreme thermal kinetic energies.**
- **<u>Laboratory fusion</u> of hydrogen isotopes was first accomplished by Mark Oliphant in <u>1932</u> based on transmutation experiments by Ernest Rutherford.**
    - **Nuclear <u>fusion on a large scale in an explosion</u> was first carried out on November 1, 1952, in the *Ivy Mike* hydrogen bomb test on an island in the Pacific Ocean.**

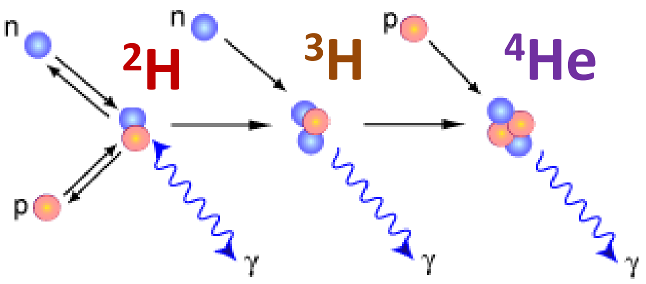
The Future: Fusion Energy?

- **International research into developing controlled self-sustained thermonuclear fusion (seen as a means of producing large scale cleaner energy) has been ongoing for more than 60 years; it still remains a challenge as reactions are extremely delicate.**
- **The main question is how to sustain (that is, *keep continuously*) the plasma …the current record for the longest sustained plasma is just 6 minutes and 30 seconds, achieved in 2003.**



Nucleosynthesis

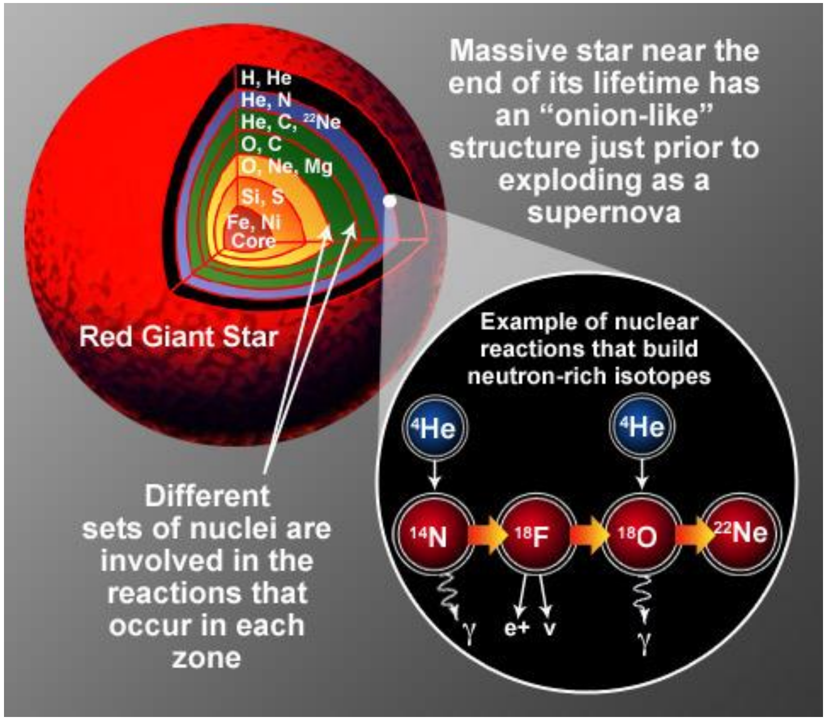
Nucleosynthesis is the natural process that creates new atomic nuclei from pre-existing nucleons, primarily protons and neutrons:



- **Big Bang nucleosynthesis**: the first nuclei, hydrogen and helium, were formed about *three minutes* after the Big Bang.

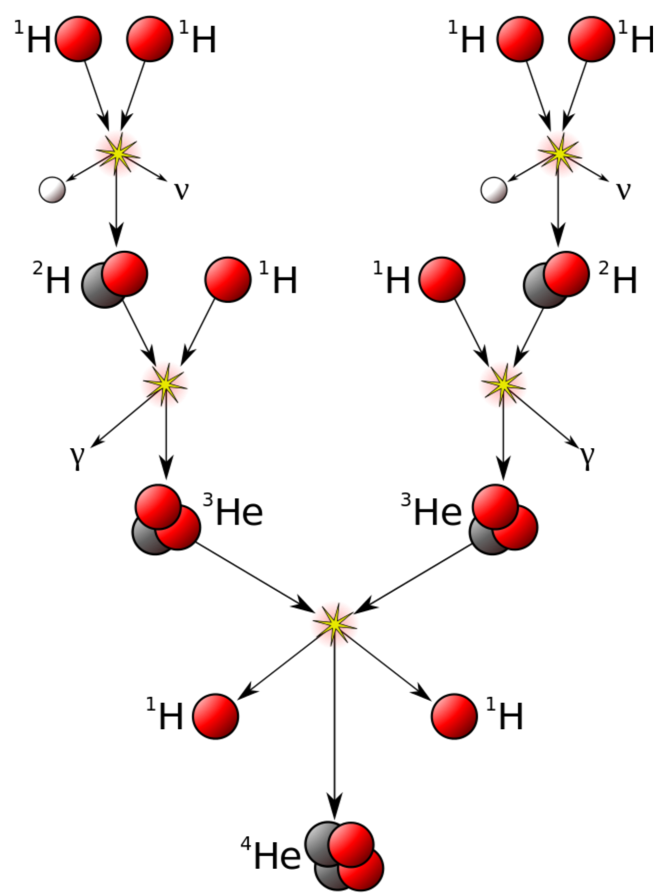
- **Stellar nucleosynthesis**: with the formation of stars, heavier nuclei were created from hydrogen and helium, a process that continues today; the heaviest element produced by fusion in a normal star is iron.

- **Supernova nucleosynthesis**: production of elements from iron to uranium occurs *within seconds* in a supernova explosion.

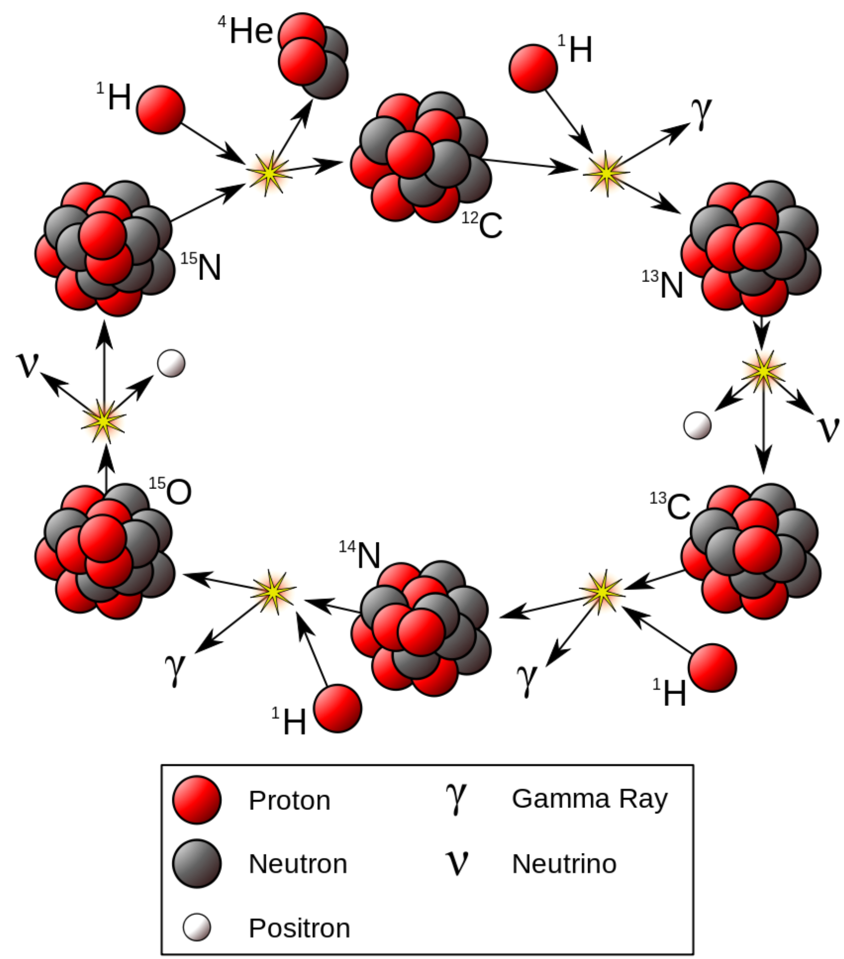


Stellar Nucleosynthesis

The [proton-proton chain](#) dominates in stars ***the size of the Sun or smaller***.



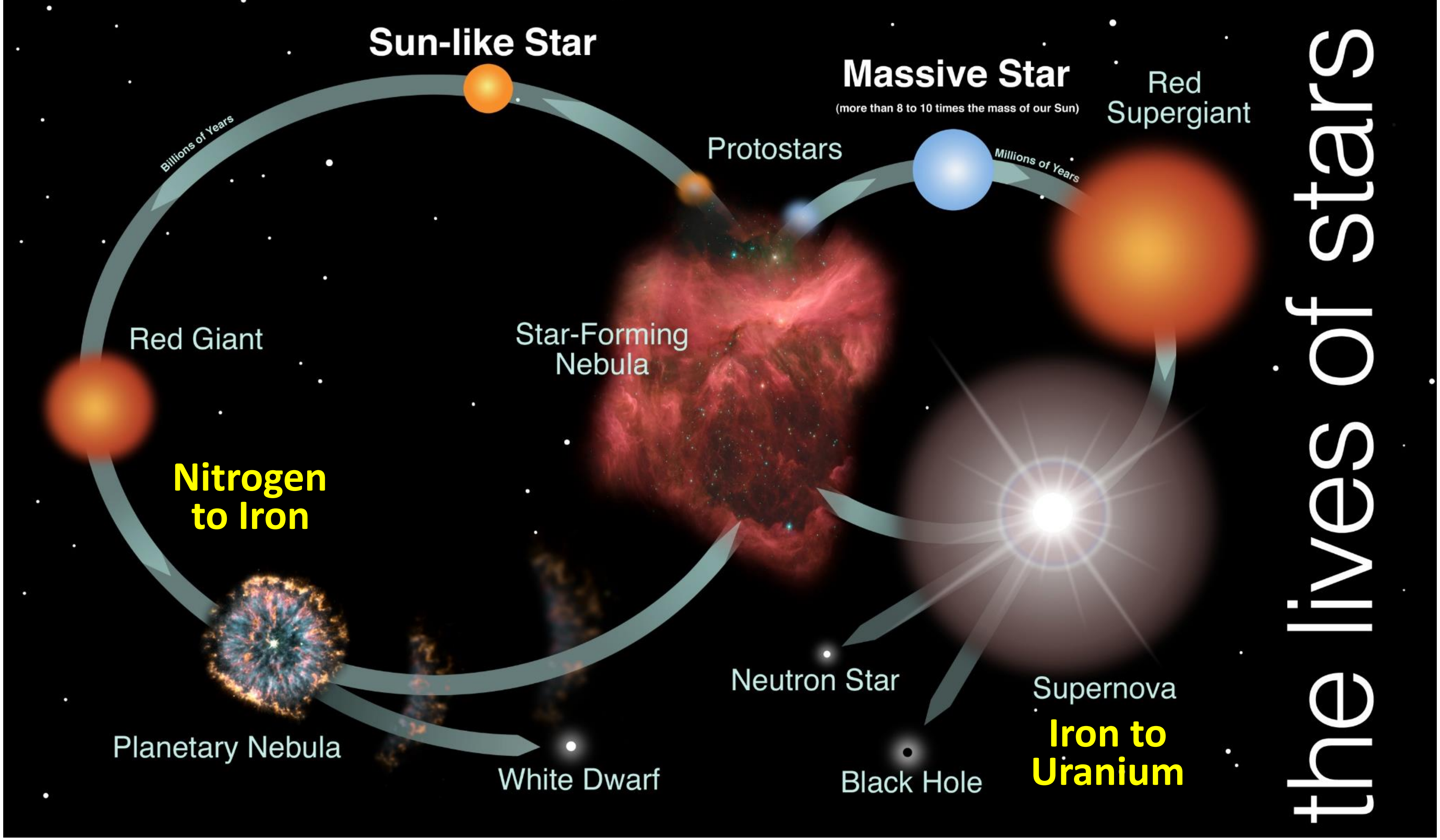
The [CNO cycle](#) dominates in stars ***heavier than the Sun***.



Stellar Recycling

5 minutes after the Big Bang: 75% H and 25% He.

<u>10 billion years</u> of nucleosynthesis: 98% H and He combined, <u>2% complex elements</u>.



Nuclear fusion can fulfill…

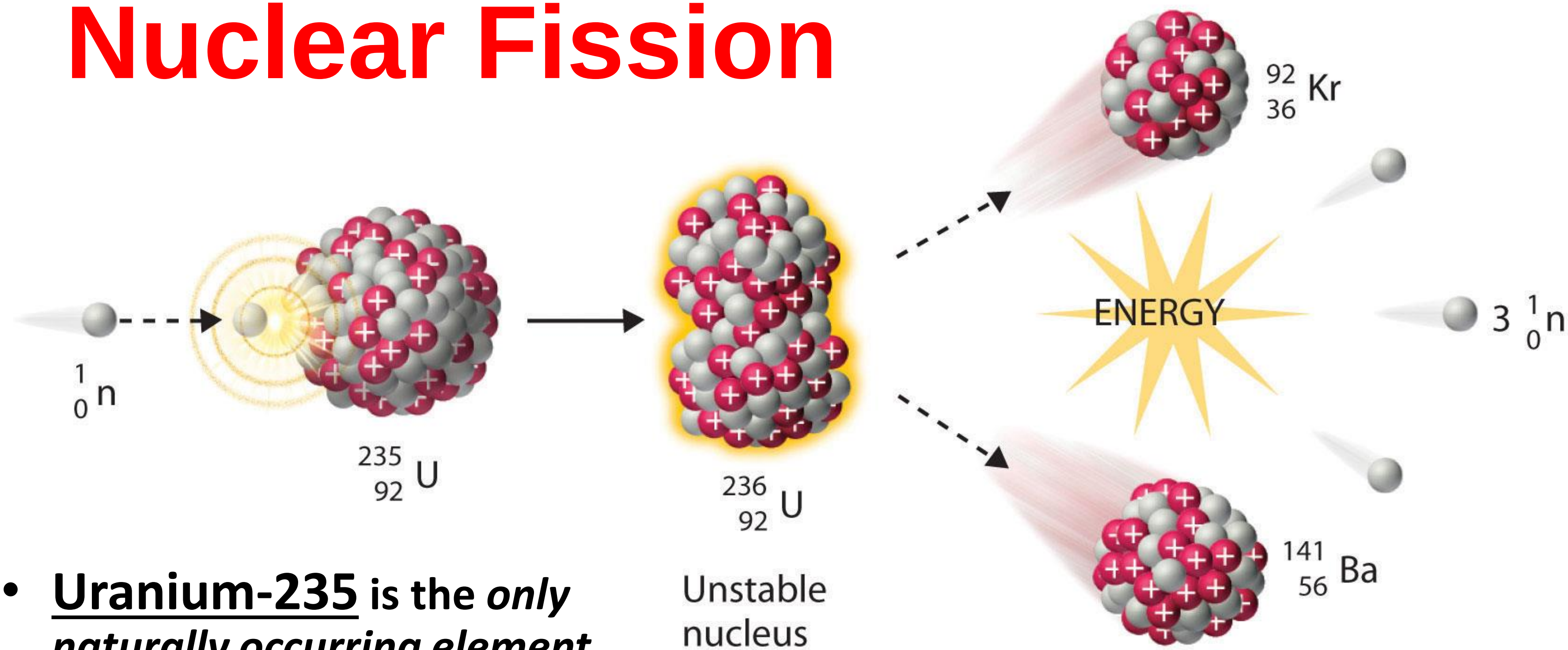
…the ancient dream of the alchemists ☺

Gold can be produced by slamming isotopes of hydrogen nuclei called deuterium into platinum:

$$H^2 + Pt^{196} \rightarrow Au^{197} + \text{neutron}$$

The catch is that gold produced in this manner would be much more expensive than gold mined from the Earth…

Nuclear Fission



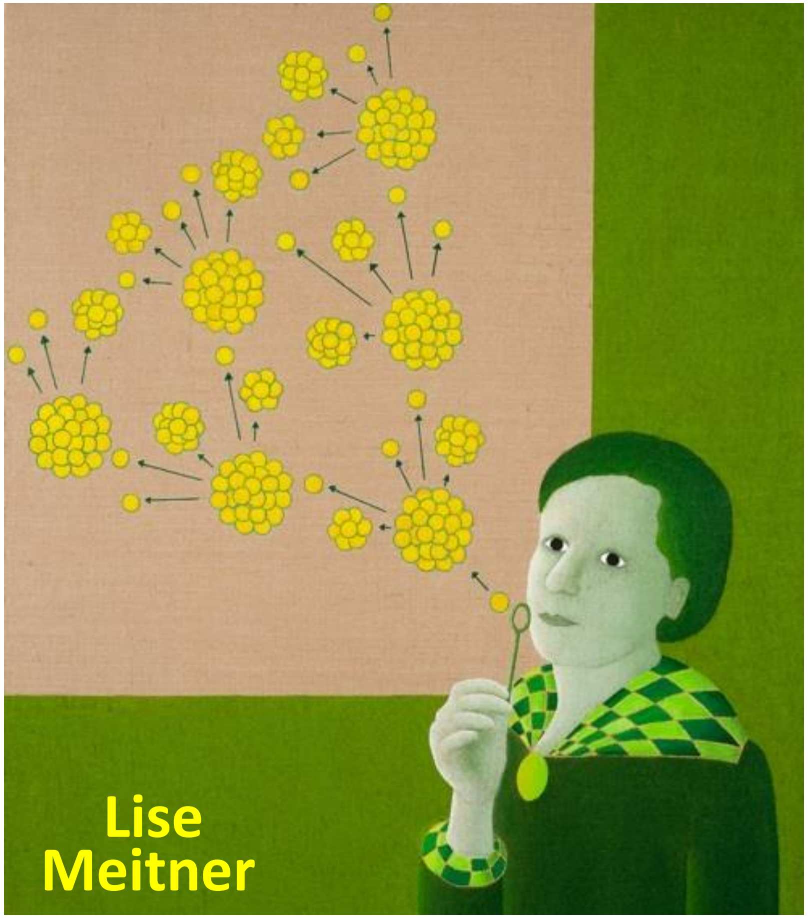
- **<u>Uranium-235</u> is the *only naturally occurring element* that undergoes fission.**
- **<u>Nuclear fission</u> was discovered by Otto Hahn and Fritz Strassmann in 1938 and explained theoretically by Lise Meitner and Otto Robert Frisch in 1939.**
- **The most energetic process known, typical fission events release ~100 million times more energy for each reaction than most chemical oxidation reactions (such as burning coal).**

Nuclear energy used in power plants comes from fission.

Fission Chain Reaction

A <u>chain reaction</u> is a sequence of reactions where a reactive product or by-product causes additional reactions to take place, leading to a <u>self-amplifying chain of events</u>.

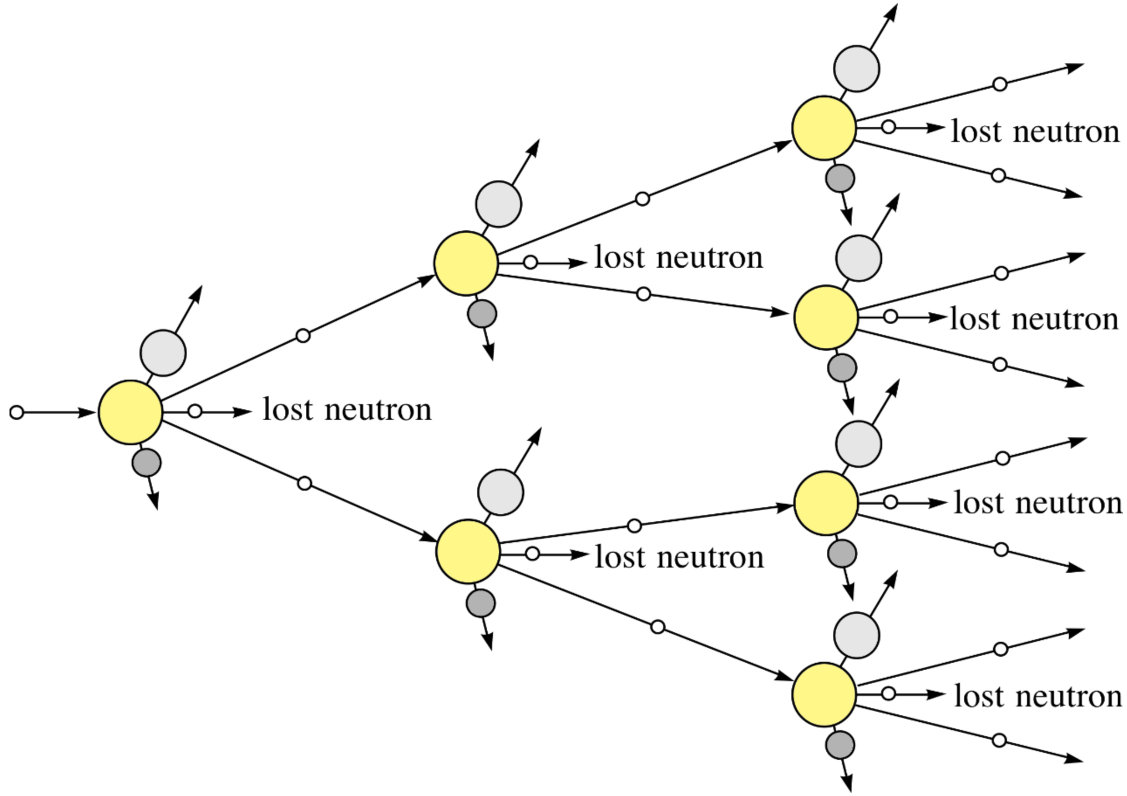
- **When an atom (such as Uranium-235) undergoes nuclear fission, a few neutrons are ejected from the reaction. These free neutrons will then interact with the surrounding medium, and if more fuel is present, some may be absorbed and cause more fissions - the cycle repeats to give a <u>reaction that is self-sustaining</u>.**
- **A <u>critical mass</u> is the smallest amount of fissile material needed for a sustained nuclear chain reaction. It depends upon <u>nuclear properties of the material</u>, its <u>density</u>, <u>shape</u>, degree of enrichment, <u>purity</u>, <u>temperature</u>, and <u>surroundings</u>.**



Fission Chain Reaction Rate

self-amplifying

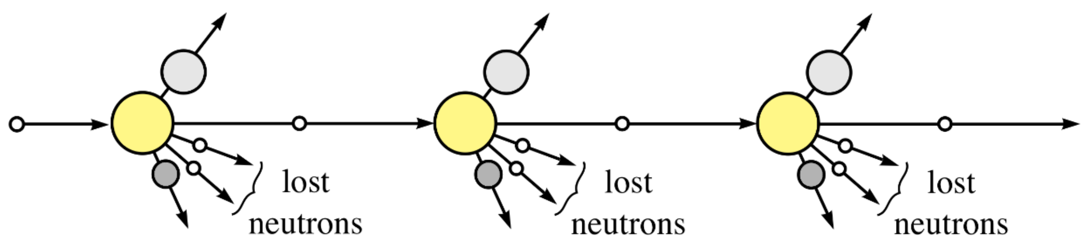
Two to three new neutrons produce fission at each step; the reaction is self-perpetuating with uncontrolled (explosive) release of energy.



VS

self-sustaining

On average, just one new neutron will produce fission at each step; this will lead to a steady release of energy.



Explosive vs Controlled

Nuclear weapons

are specifically engineered to produce a reaction that is so fast and intense it cannot be controlled after it has started and leads to an explosive energy release.

Nuclear weapons employ high purity, highly enriched fuel:

>85% U-235

or

>95% Pu-239

Nuclear power plants

operate by precisely controlling the rate at which nuclear reactions occur.

The fuel for a nuclear fission reactor usually consists of a low-enriched oxide material:

3-5% Uranium-235

Natural Fission Reactor

<u>Natural nuclear fission reactor</u> is a rich uranium deposit where self-sustaining nuclear chain fission reactions have naturally occurred in the past:

- existence predicted in 1956 by Paul Kazuo Kuroda
- discovered in 1972 by French physicist Francis Perrin

- **<u>Location</u>** – Oklo, Gabon, Africa (consists of 17 sites), the only one in the world found so far.
- **<u>Evidence</u>** – anomalous uranium isotope content, showing loss of Uranium-235.
- **<u>Timing</u>** - reactions took place approximately 1.7 billion years ago, and ran for a few hundred thousand years.
- **<u>Power</u>** - averaging 100 kW of thermal power during that time.