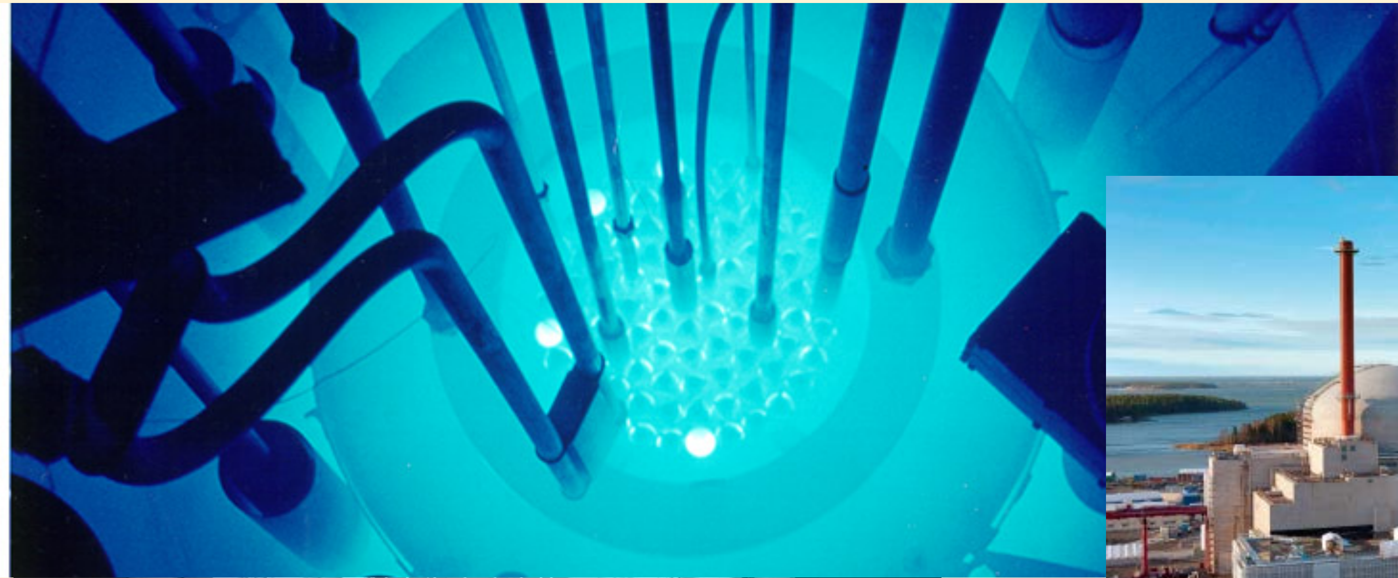
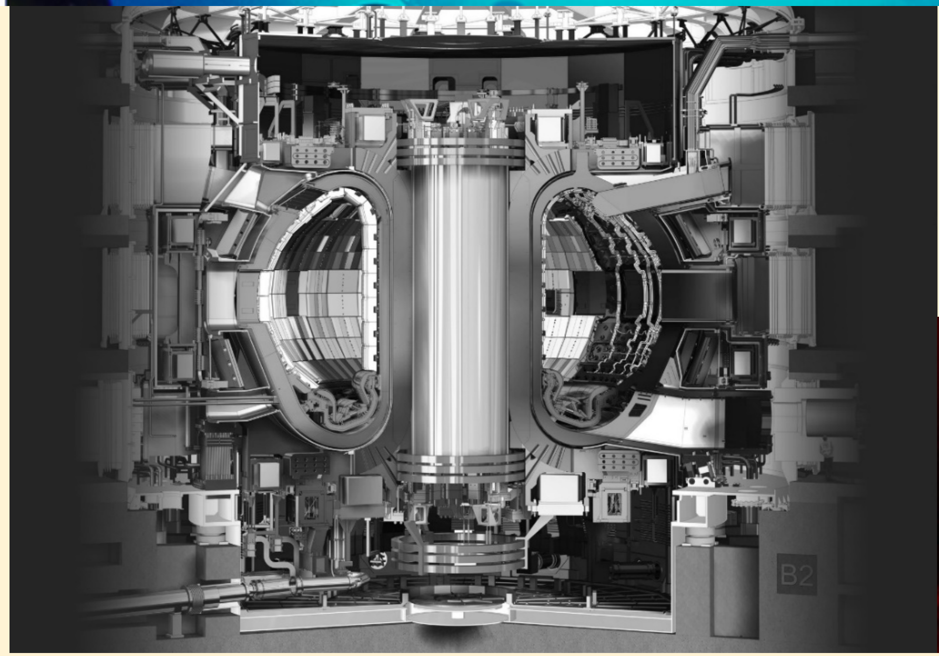
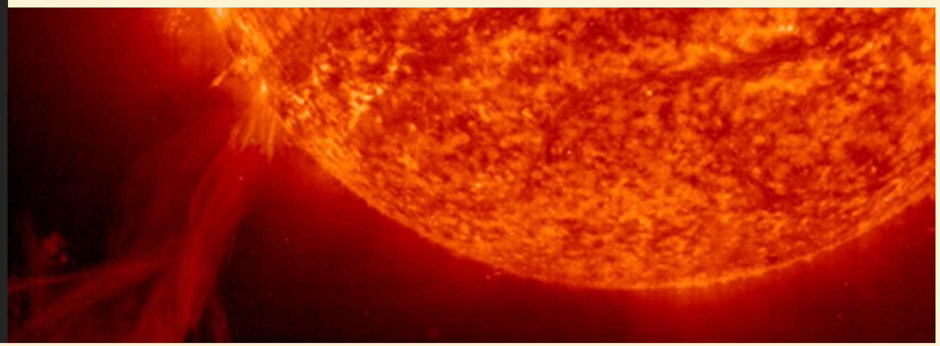
Nuclear Energy from Fission and Fusion: an overview







Marco Ripani
INFN Genova

What is energy?

We are familiar with situations where we consume energ

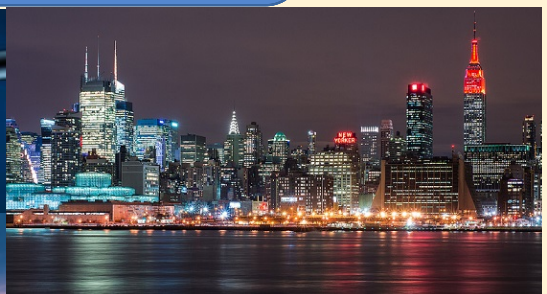
…or others in which energy is
stored in some form

The forms of energy

Mechanical→Kinetic(*)

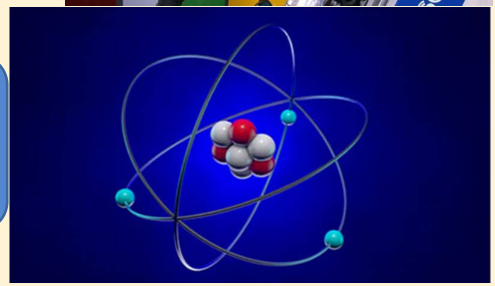
Mechanical→Potential

Electromagnetic



Chemical (Potential)

Nuclear (Potential)



(*) kinetic energy = energy of motion

Energy transforms

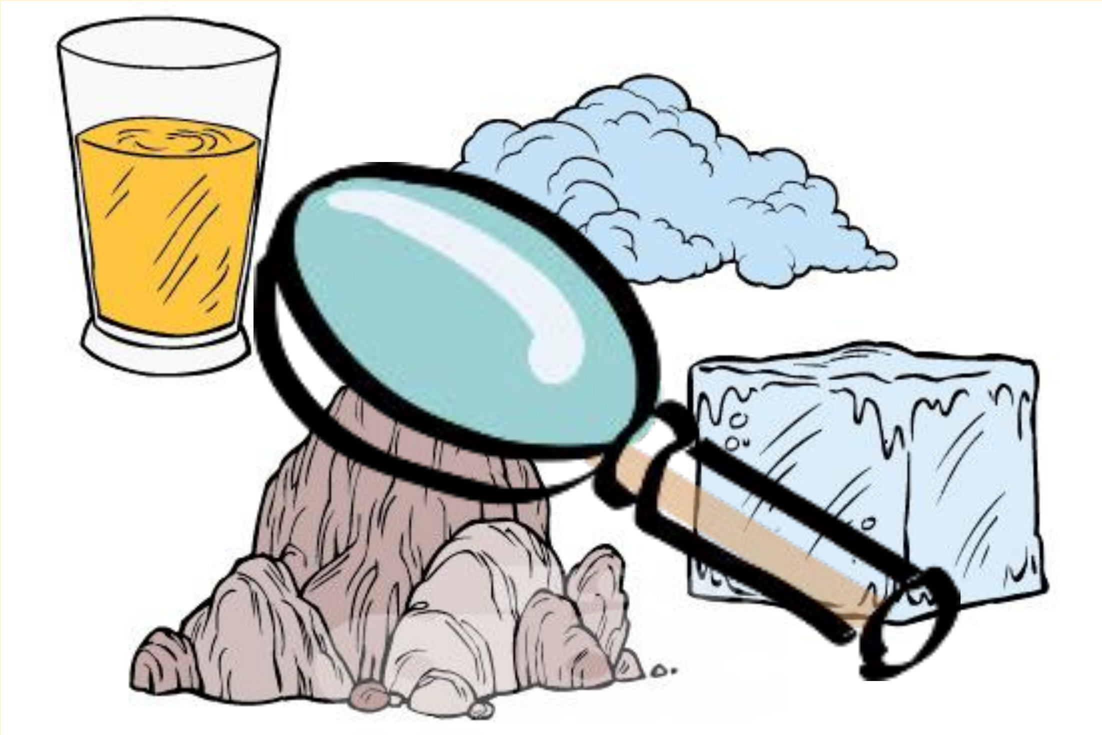
From potential to kinetic…

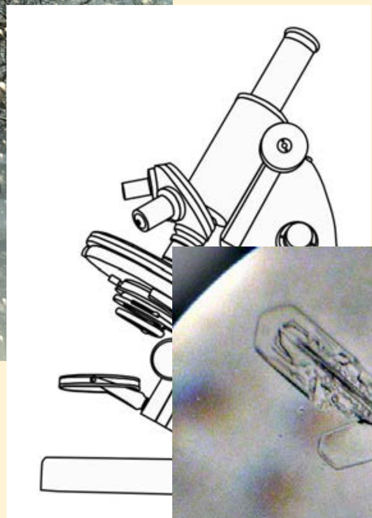
From chemical to kinetic (or mechanical) …

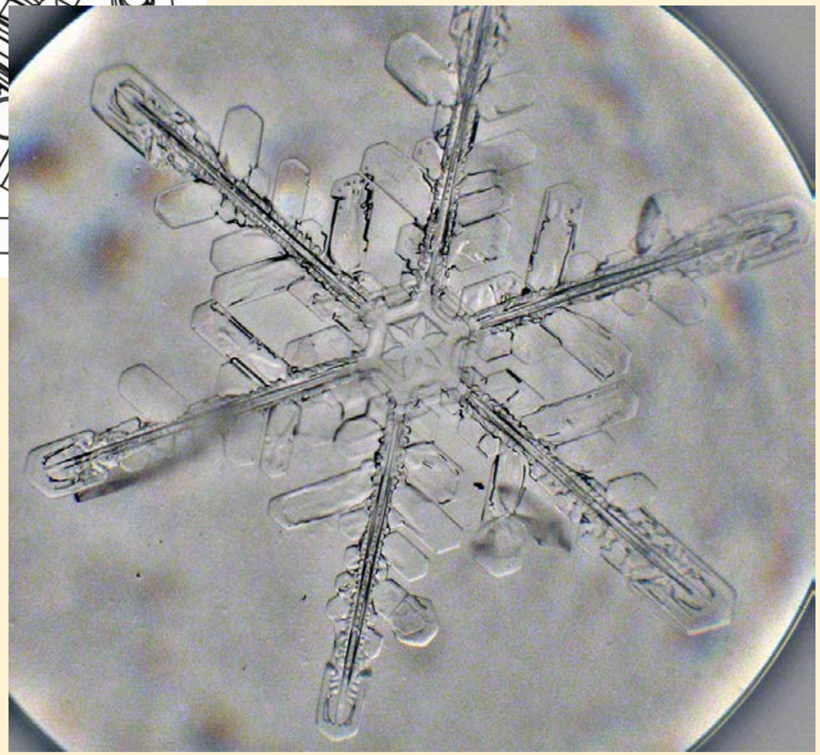
From chemical to kinetic (or mechanical) and electromagnetic (light)

…

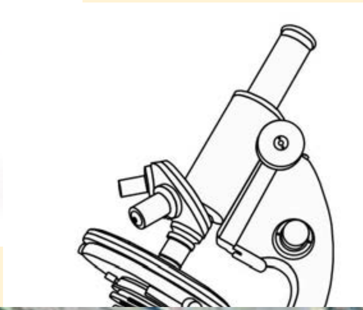
Matter under a magnifying glass

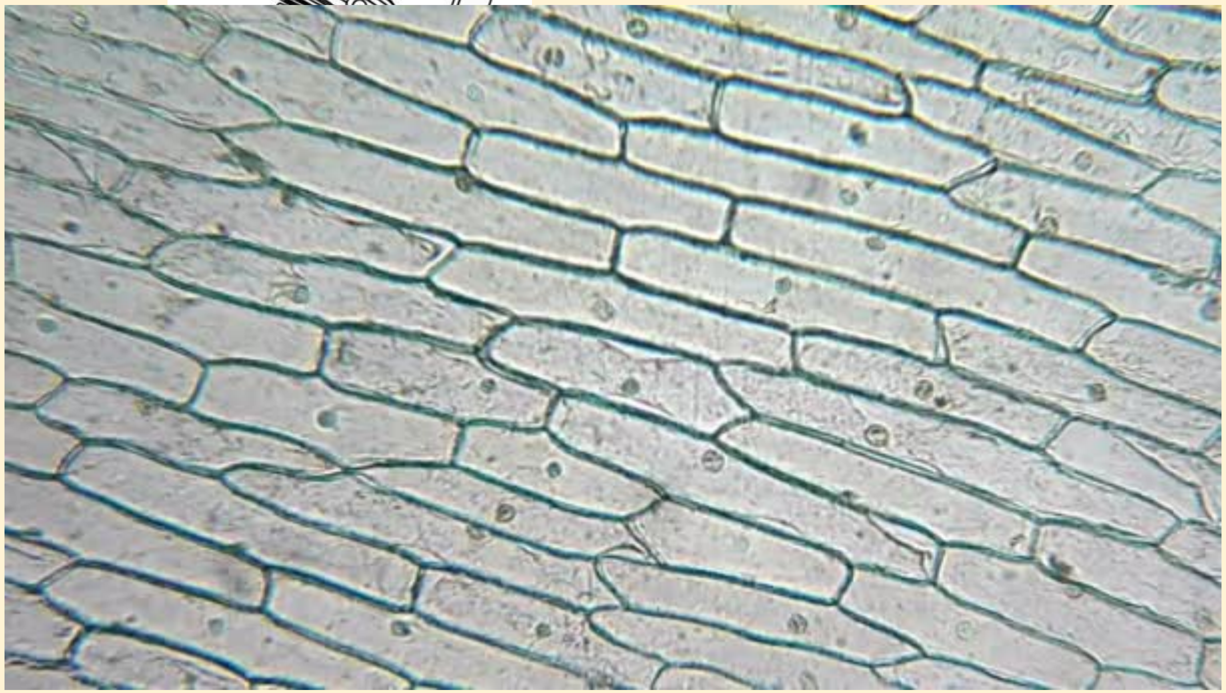






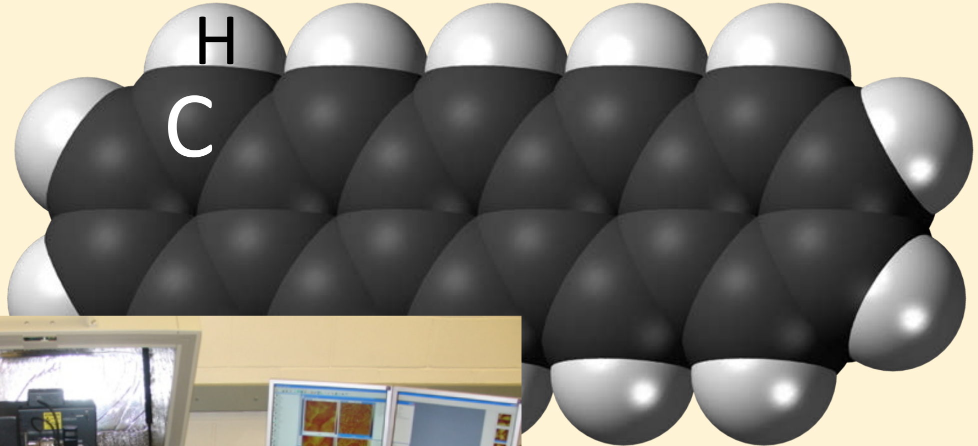
Snowflake
(from about 0,1 mm to a few mm)

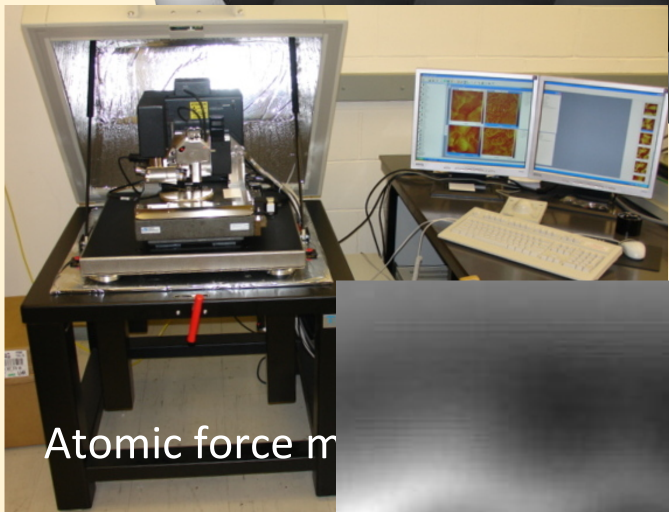


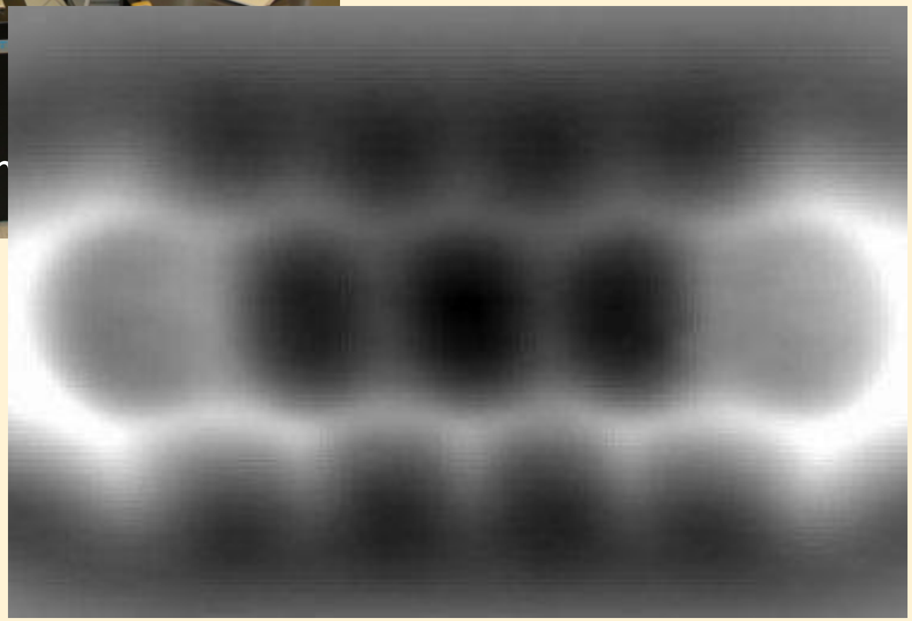


Onion cells
(about 0,01 mm)

A pentacene sample…





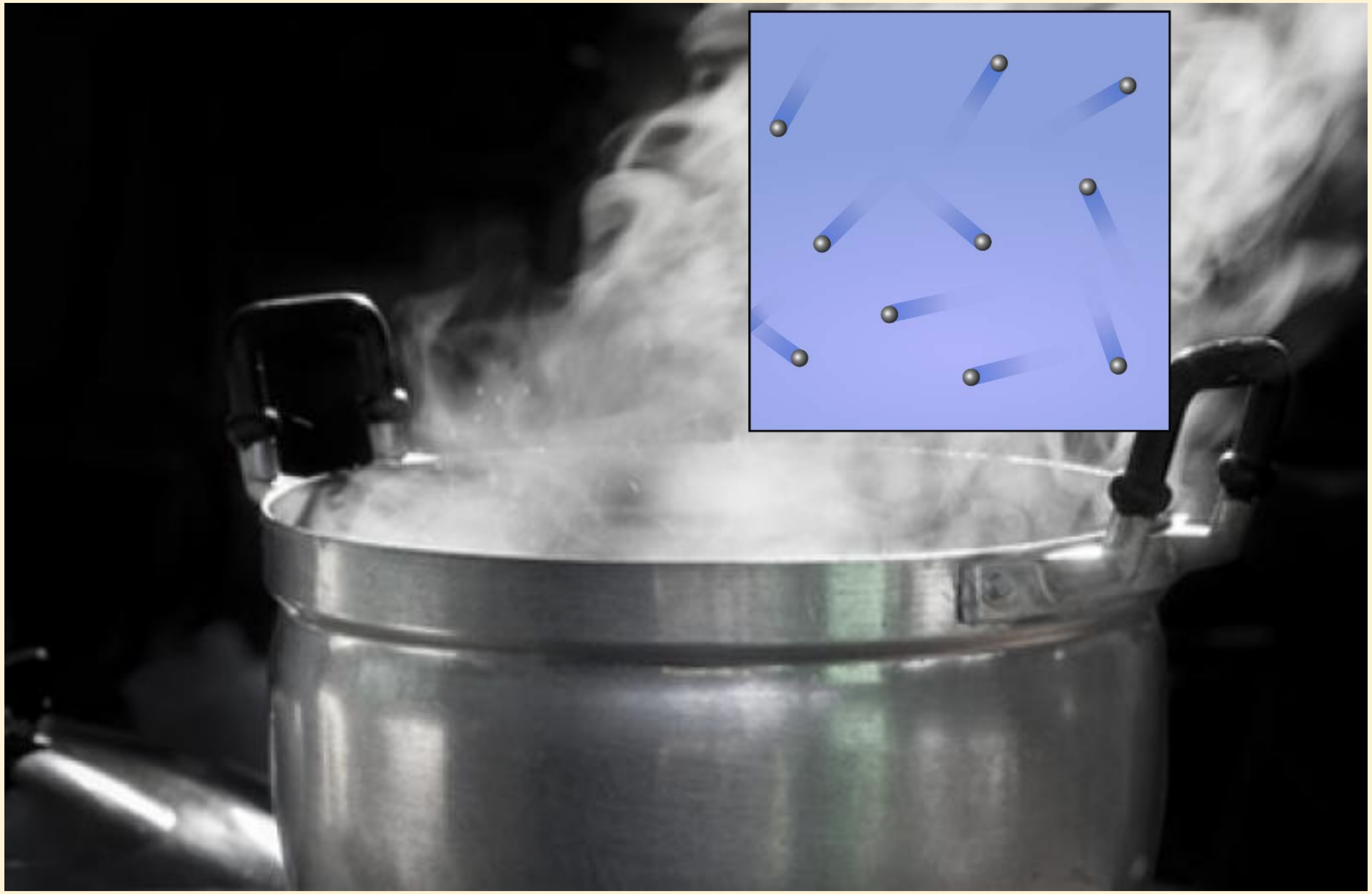


Pentacene atoms
(0,00000012-0,00000017 mm –
a fraction of a millionth of a mm)

Atoms are very many…

In one liter of water there are 33 million billion billion molecules

Heat

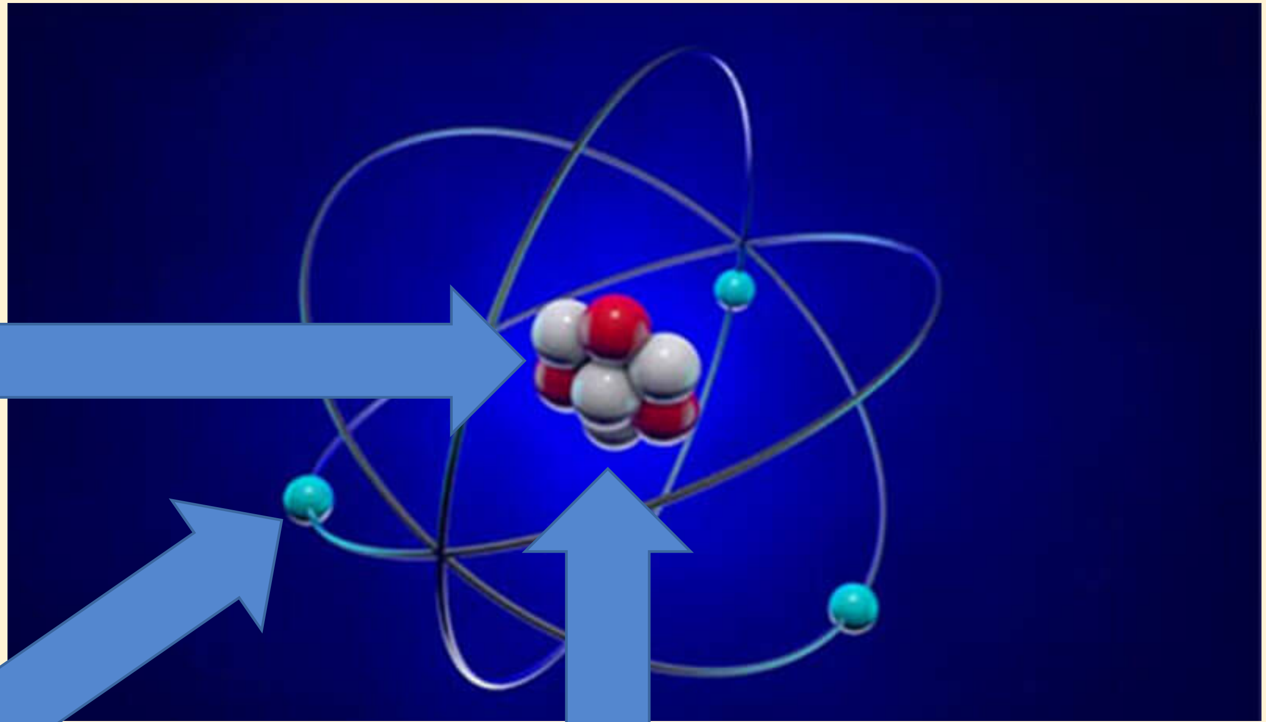


Water molecules in steam move and hit each other at a very high speed, about 500 meters per second (1,800 km/hour)

Heat is nothing but mechanical (kinetic) energy

The atom

at if we were able to see even smaller things?



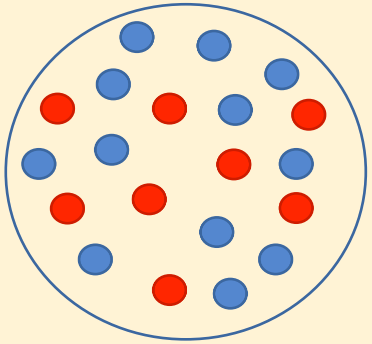
Atomic nucleus
(about 0,000000000001 mm – one thousandth of a billionth of a mm)

"Orbiting" around are the electrons (negative electric charge)

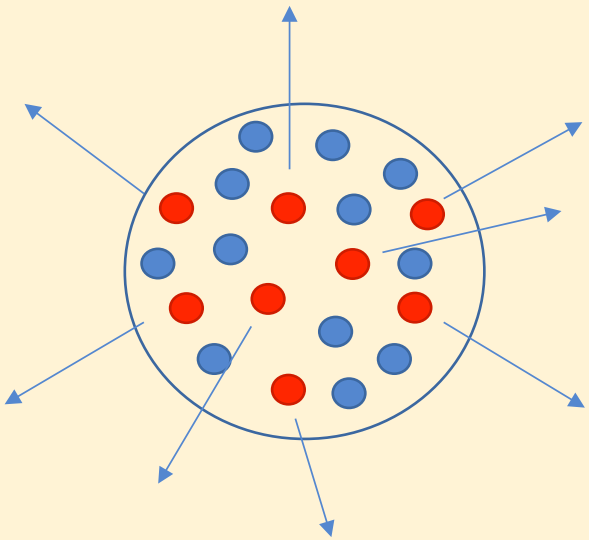
Composed of protons (positive electric charge) and neutrons (no electric charge)
Simplest atom: Hydrogen → just one proton and no neutrons

The figure does not show the correct proportions: the nucleus is 100,000 times smaller than the atom!

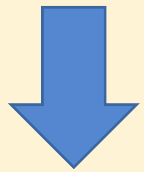
The atomic nucleus



- Protons (positive electric charge)
- Neutrons (no electric charge)



Electric charges with the same sign repel each other



Neutrons act as the "glue" that holds the nucleus together
(it's called «strong nuclear force»)

The larger the nucleus, the more neutrons it needs

r example, Oxygen has 8 protons and 8 neutrons

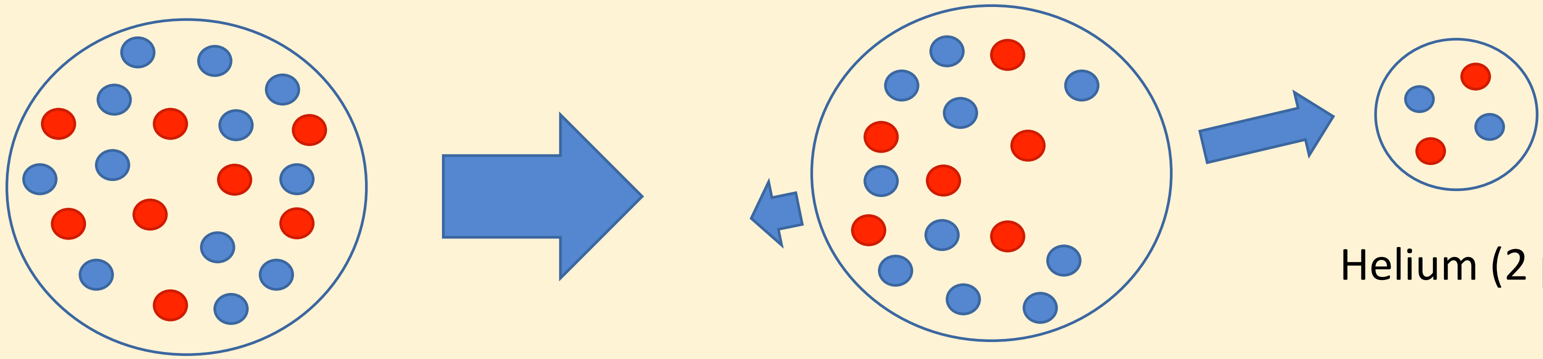
nost abundant type of Lead in nature has 82 protons and 126 neutrons

But there is also Lead with 124 and 125 neutrons → "isotopes“ → same chemical properties, different nuclei

Radioactivity

Certain atomic nuclei are «unstable», that is, they tend to break up, <u>releasing</u>

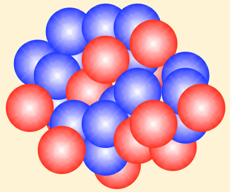
Alpha (α) decay



Helium (2 p

Uranium 238 (92 protons, 146 neutrons)   Thorium 234 (90 protons, 144 neutrons)

Elements and isotopes



There are many nuclear species

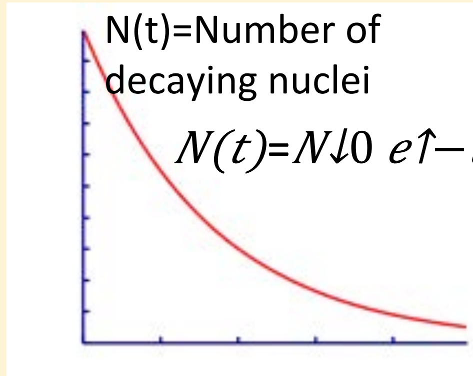
They are classified with two numbers:

Z = number of protons, which determines the chemistry

A = total number of nucleons (protons + neutrons)

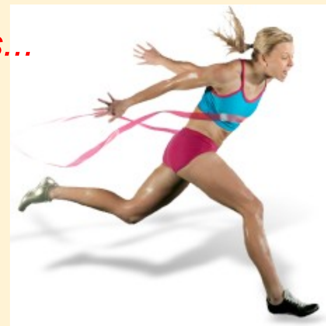
- *each nuclear species is uniquely determined by its A and Z*
- *about 1700 known (A,Z) combinations (species)*
- *about 300 stable (minimum energy: equilibrium)*
- *the rest: radioactive (unstable)*

Each radioactive substance ha *characteristic time $T_{1/2}$* in whic radioactivity is halved.



tim

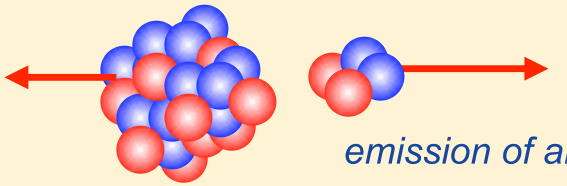
Some species decay in seconds...



...others in million (or even billion

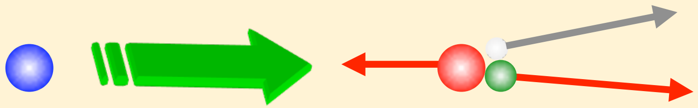
The three main types of radioactivity

alpha



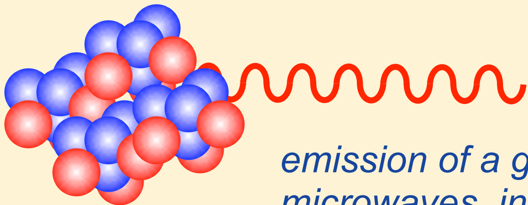
emission of an alpha particle (= helium nucleus)

beta



a neutron transforms into a proton (or a nucleus with N neutrons and Z protons transforms into a nucleus with N-1 neutrons and Z+1 protons, emitting an electron (beta particle) and an antineutrino

gamma

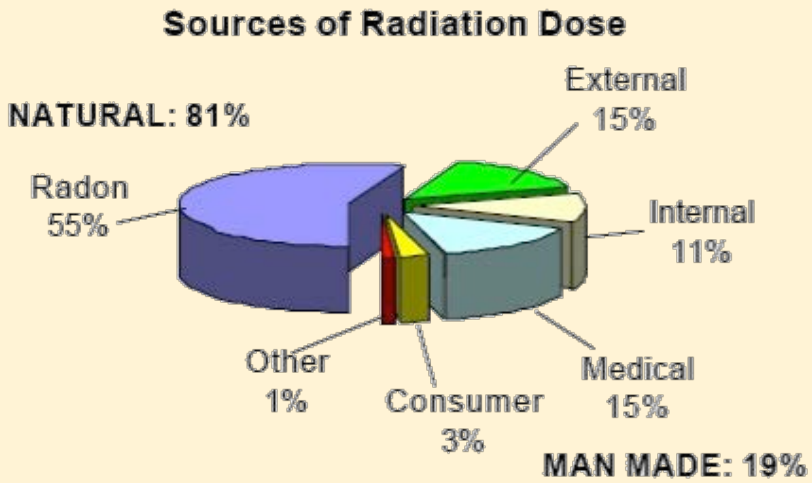


emission of a gamma ray (=photon, such as radio waves, microwaves, infrared, visible, ultraviolet, X-rays: the only difference is the wavelength or, if you prefer, the energy)

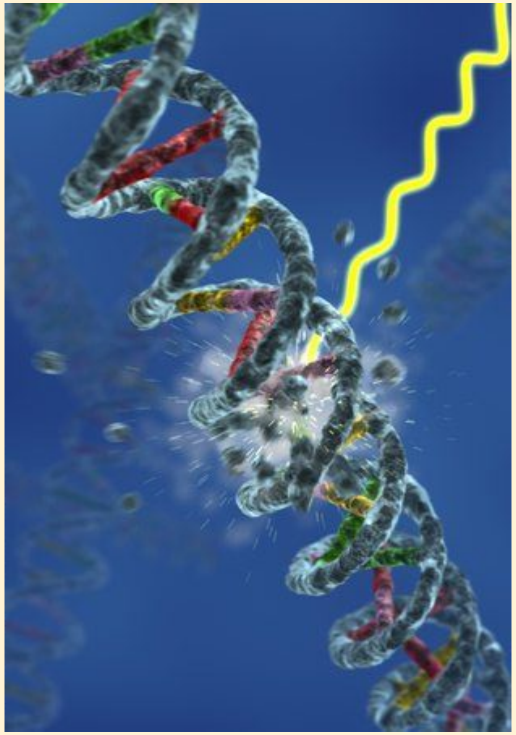
Very often, alpha and beta radiation lead to the formation of nuclei in excited states which decay by gamma radiation

Radiation is part of our everyday life on earth

Radiation around us



they can break DNA and cause mutations
probably plays a role in evolution



From the sky: about 30 neutrons and 120 cosmic rays pass through our body per second

From air: about 10 atoms per second (Radon, Polonium, Bismuth, Lead) disintegrate in the lungs releasing alpha, beta, gamma

From diet: about 4500 atoms per second (Potassium-40) disintegrate in our body, releasing beta and gamma; also, about 2 atoms per second of natural uranium release alpha

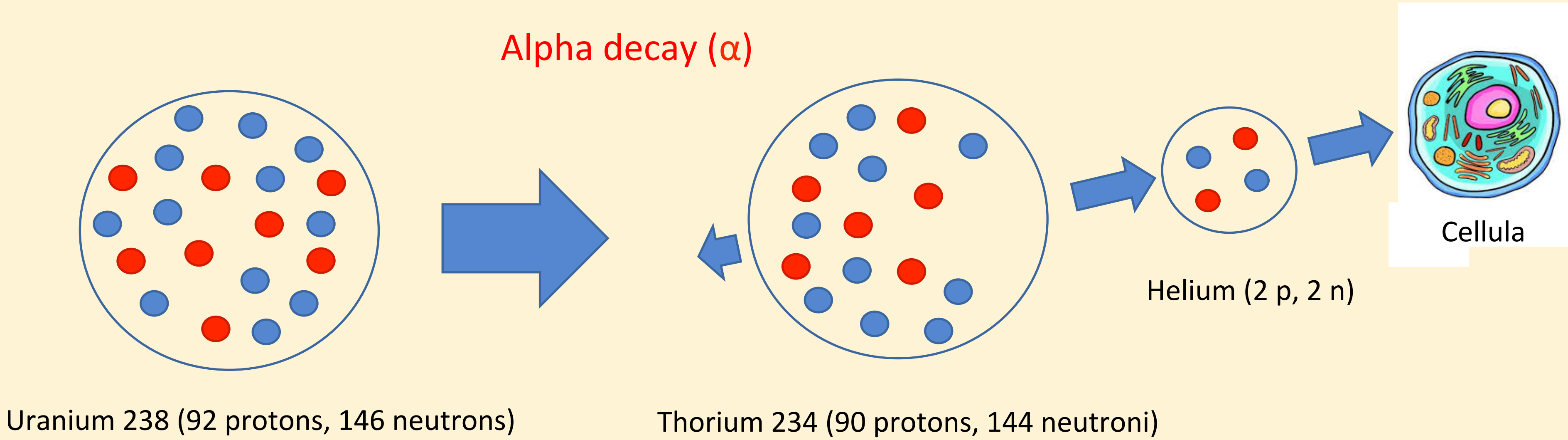
From the ground and buildings: about 56,000 gamma per second pass through our body

≈ 6000 decays per second of Potassio-40 (^{40}K) per m^3 of sea water

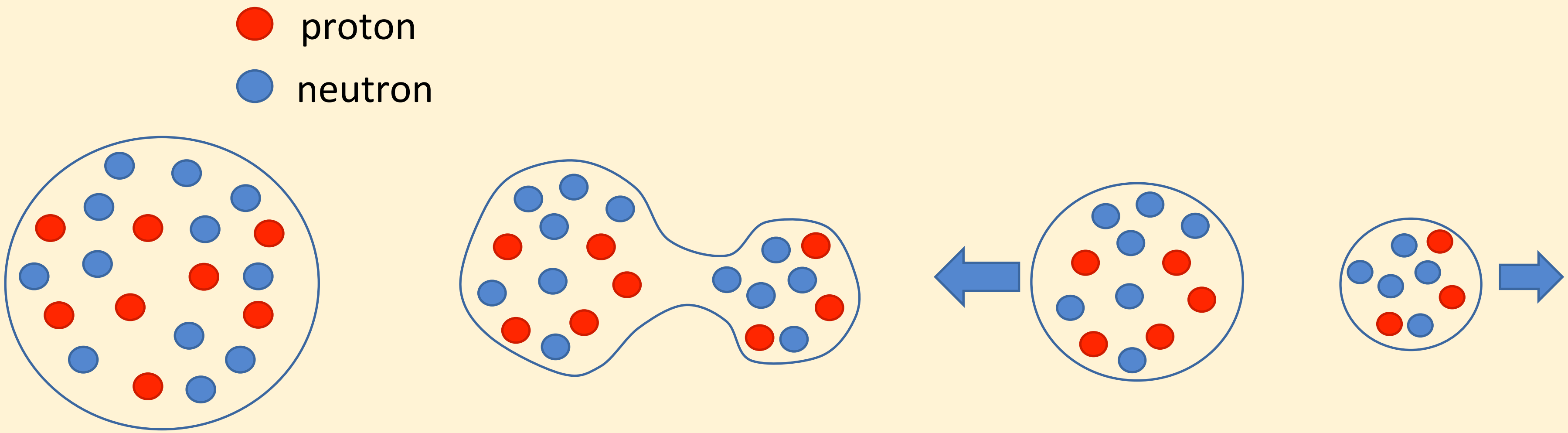
What are the biological effects of radioactivity ?

Biological effects of radioactivity

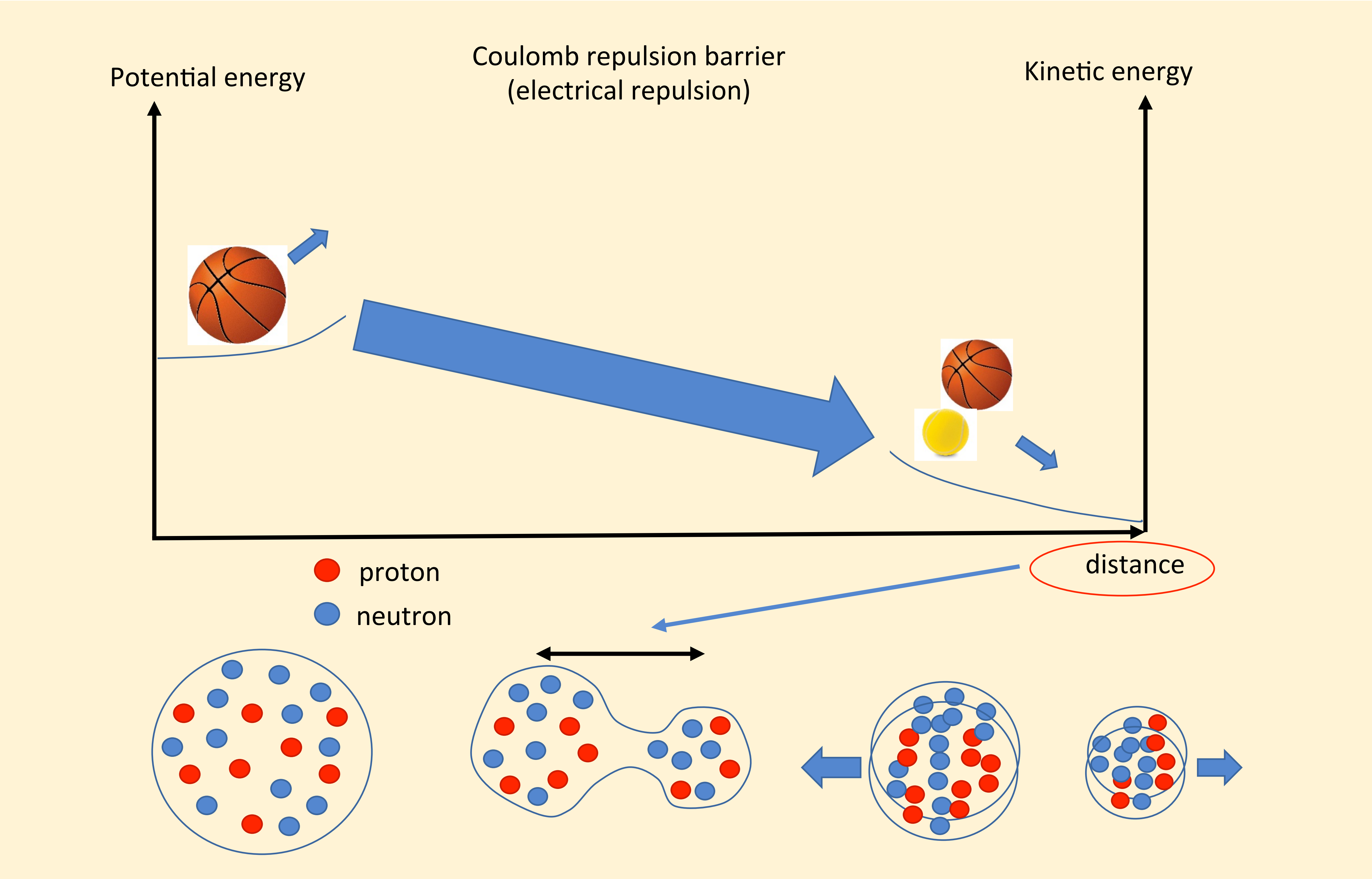
Radioactivity can be dangerous to the environment and humans due to cell damage (by *direct exposure* or by *inhalation or ingestion*)



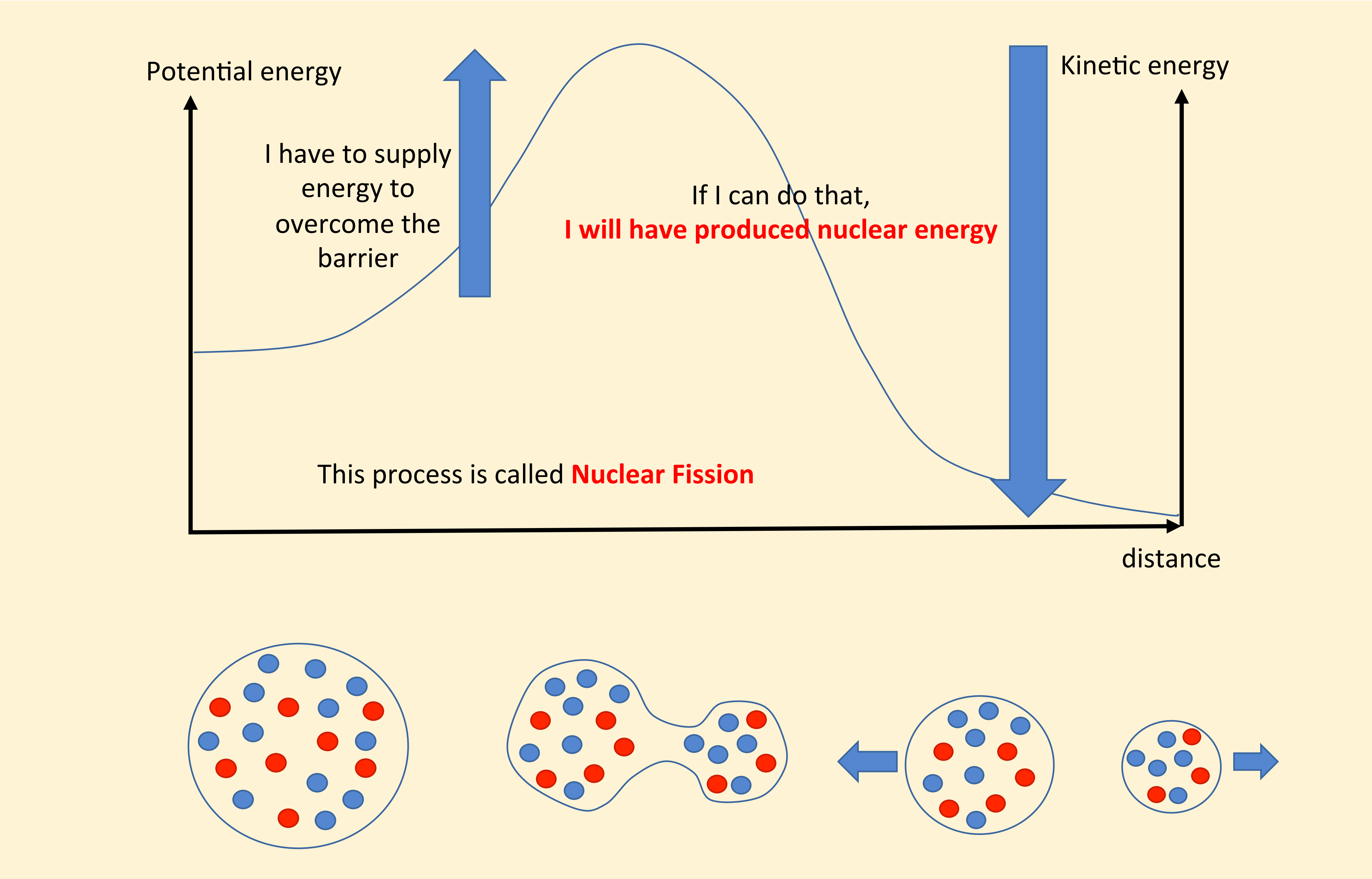
Is it possible to break up a nucleus ?



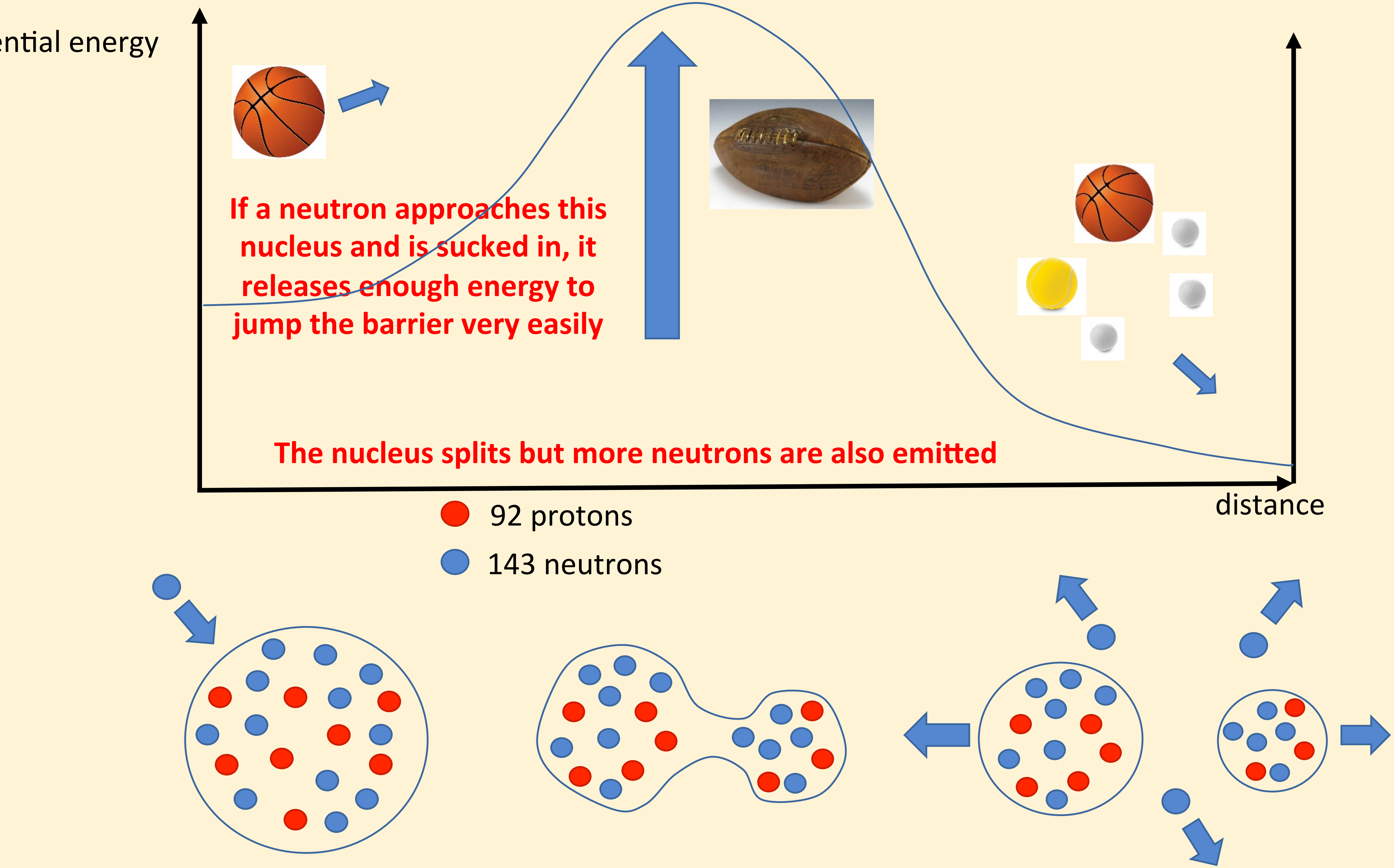
- ✓ Some (radioactive) nuclei can split on their own, but many do not (stable) or do so with difficulty
- ✓ We suppose that a certain force must be applied
- ✓ Put another way, you will need to supply a certain amount of energy



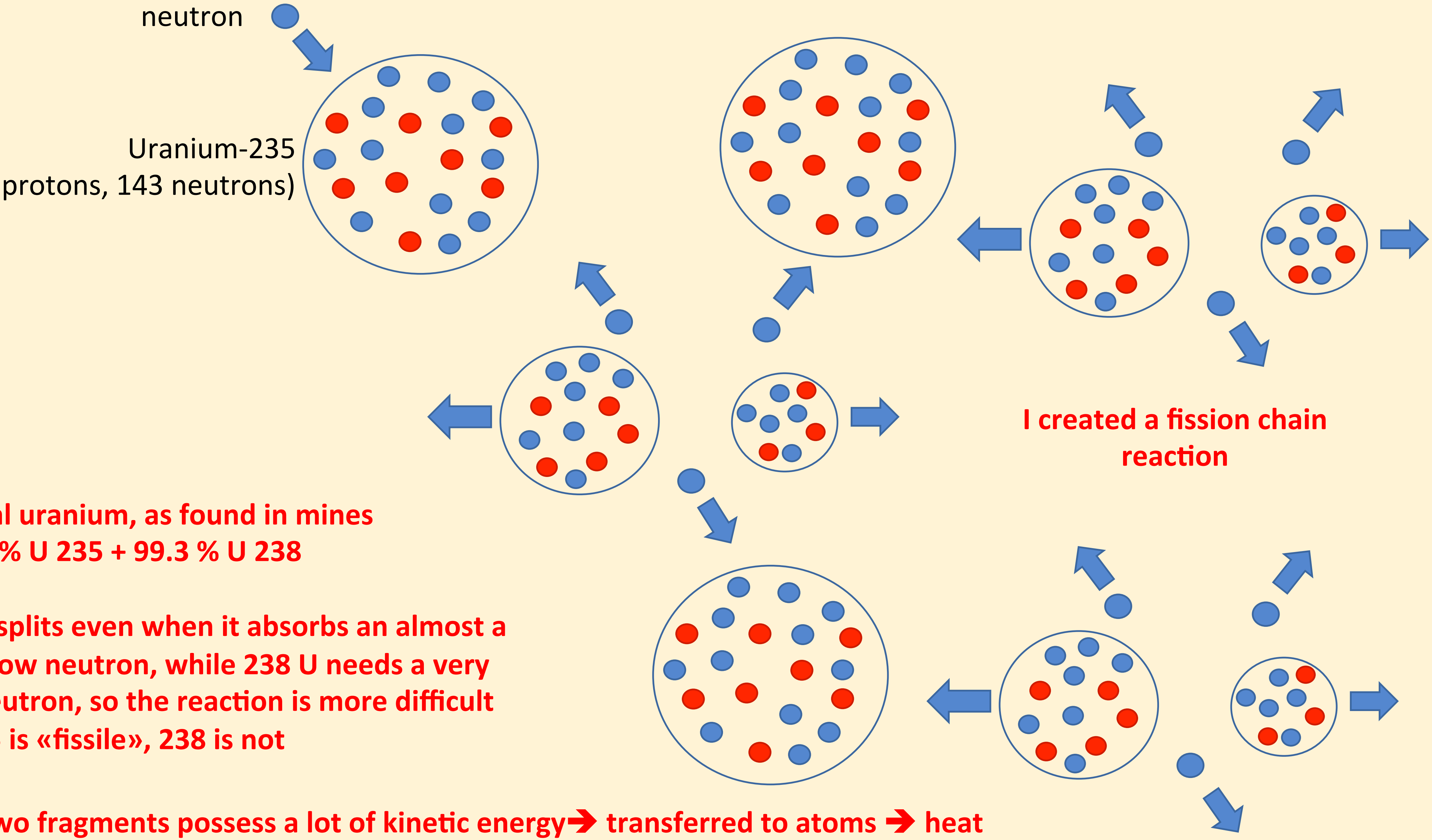
Coulomb repulsion barrier
(electrical repulsion)
Potential energy
Kinetic energy
distance
proton
neutron


Potential energy
I have to supply energy to overcome the barrier
If I can do that,
I will have produced nuclear energy
Kinetic energy
This process is called Nuclear Fission
distance

A special case, Uranium 235



Nuclear fission



I created a fission chain reaction

l uranium, as found in mines
% U 235 + 99.3 % U 238

splits even when it absorbs an almost a
ow neutron, while 238 U needs a very
utron, so the reaction is more difficult
is «fissile», 238 is not

wo fragments possess a lot of kinetic energy→ transferred to atoms → heat

How much energy is produced ? And what are the reaction products ?

The mass of the two fragments plus the mass of the neutrons makes a little less than the mass of the initial uranium nucleus ➔ about a thousandth of the mass of the nucleus has been transformed into energy, according to Einstein's famous relationship

$$E = m c^2$$

This energy is shared among

- **Kinetic energy of the two fragments**
- **Kinetic energy of the 2-3 emitted neutrons**
- **Gamma rays (electromagnetic energy)**
- **neutrinos** (practically massless particles that pass through matter as if it were transparent)

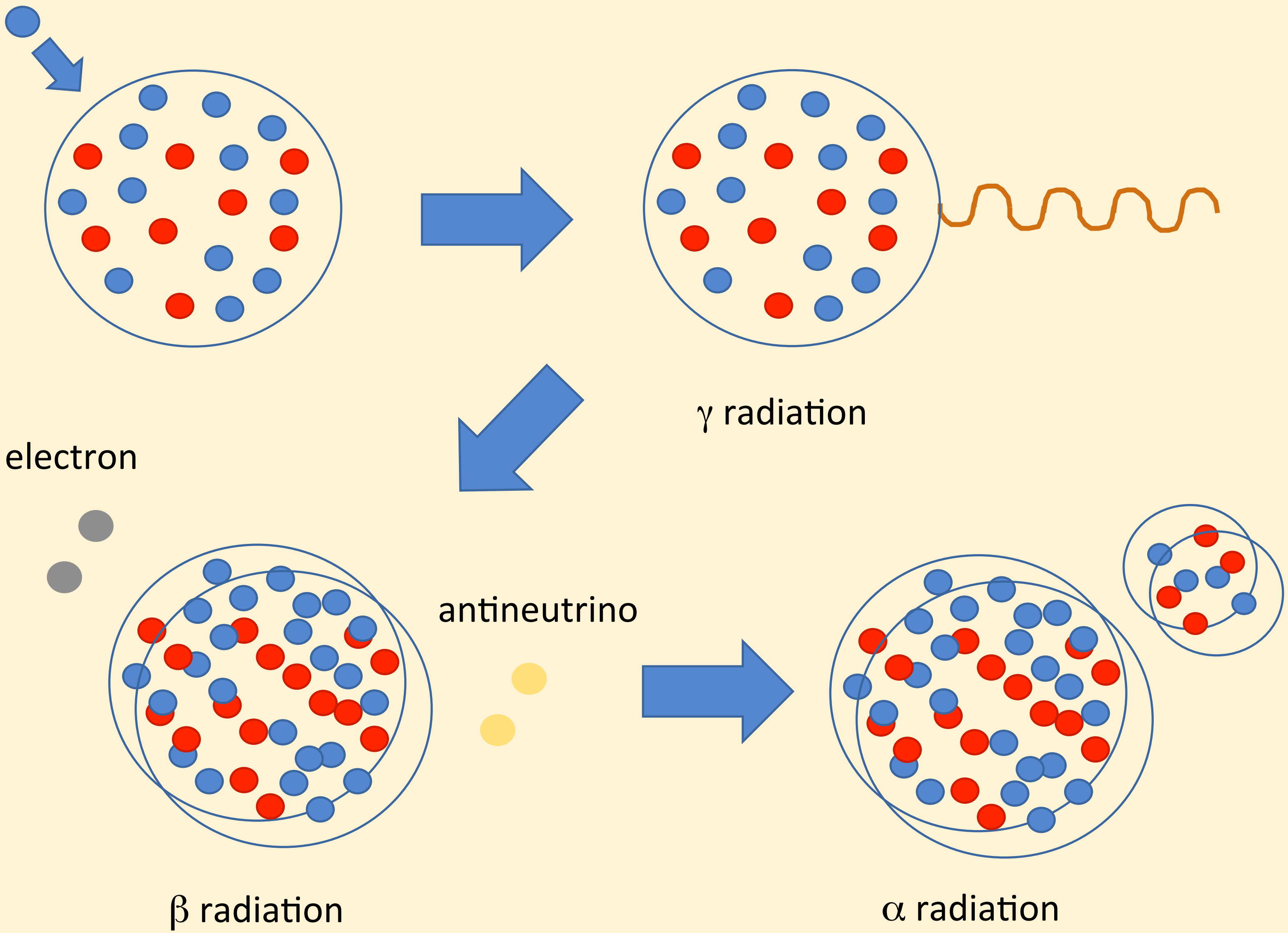
The biggest part of the energy released by the fission process **is converted into heat**

Fission provides 20 to 50 million times more energy than a chemical reaction

With 1 gram of U-235, about 7,000 washing machines run for an hour

The same job would require almost 3 tons of coal

Neutron radiative capture



Nuclear energy and radioactive products

vo nuclei resulting from fission are called **«fragments or fission products»** → most of them are **radioactive**

ermore, we have seen that it is Uranium 235 that produces fission. **Uranium 238** instead, with high probability absor utron, giving rise to a **transformation chain that produces heavier elements, including Plutonium** (that doesn't exi e)

ver, plutonium can also give rise to fission, so it can be used as fuel

materials of the plant, subjected to the intense flux of neutrons, can also become radioactive *(activation)*

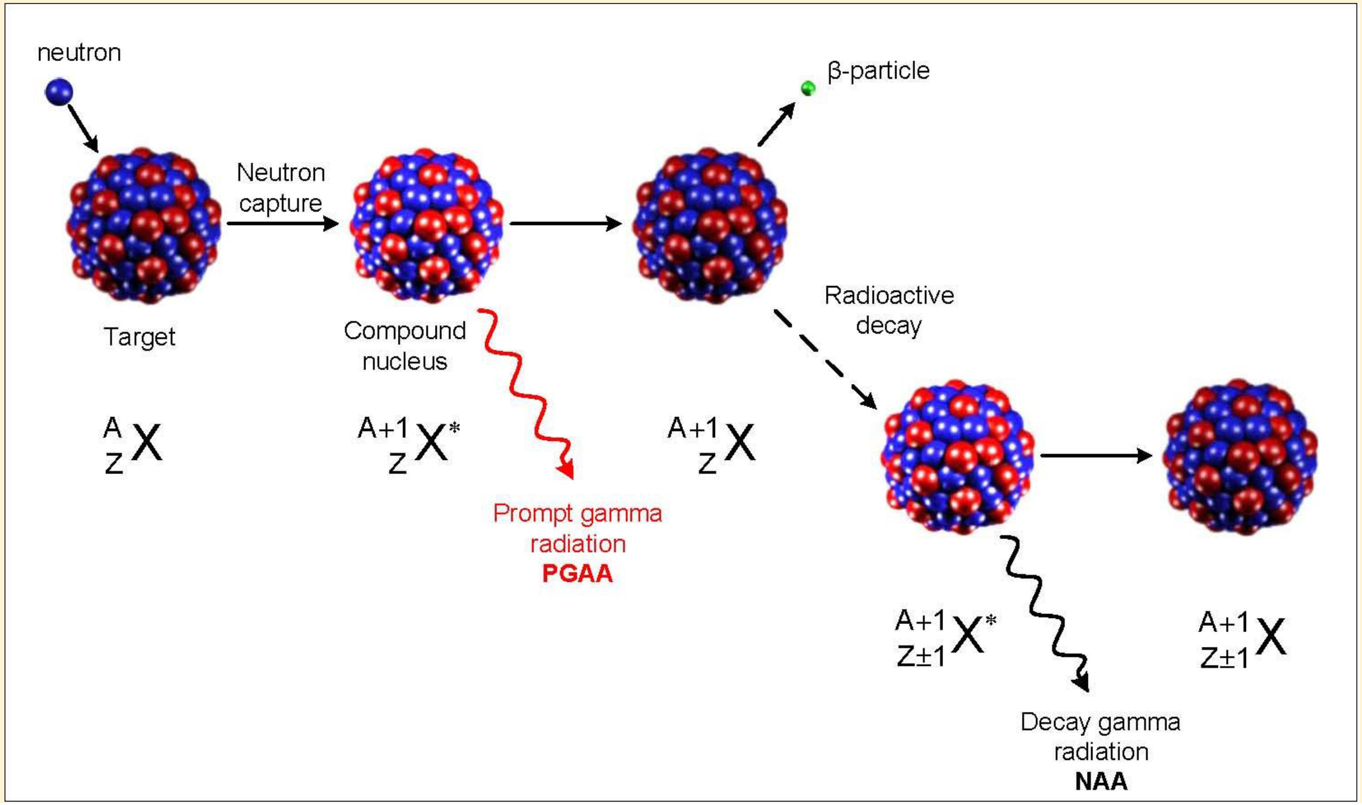
Plutonium production from Uranium

→ $^{239}U + \gamma \rightarrow {}^{239}Np + \beta$ + anti-$\nu \rightarrow$ **^{239}Pu** $+ \beta$ + anti-ν

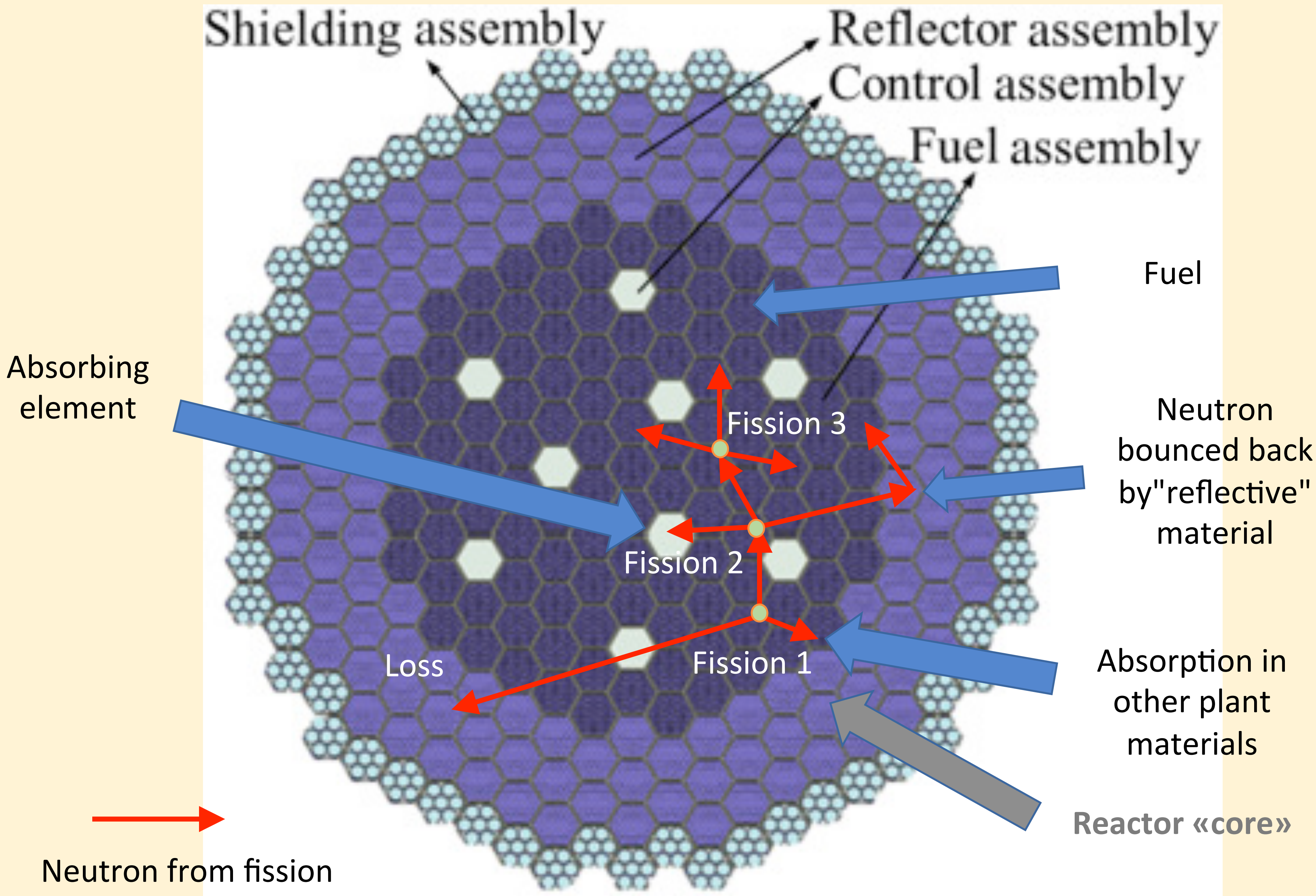
ements (*Transuranics: elements heavier than Uranium)* ng in Nature are formed beyond Plutonium: the so-*nor Actinides* (Americium, Curium, etc.), typically with lives → they make handling and disposing of spent e challenging

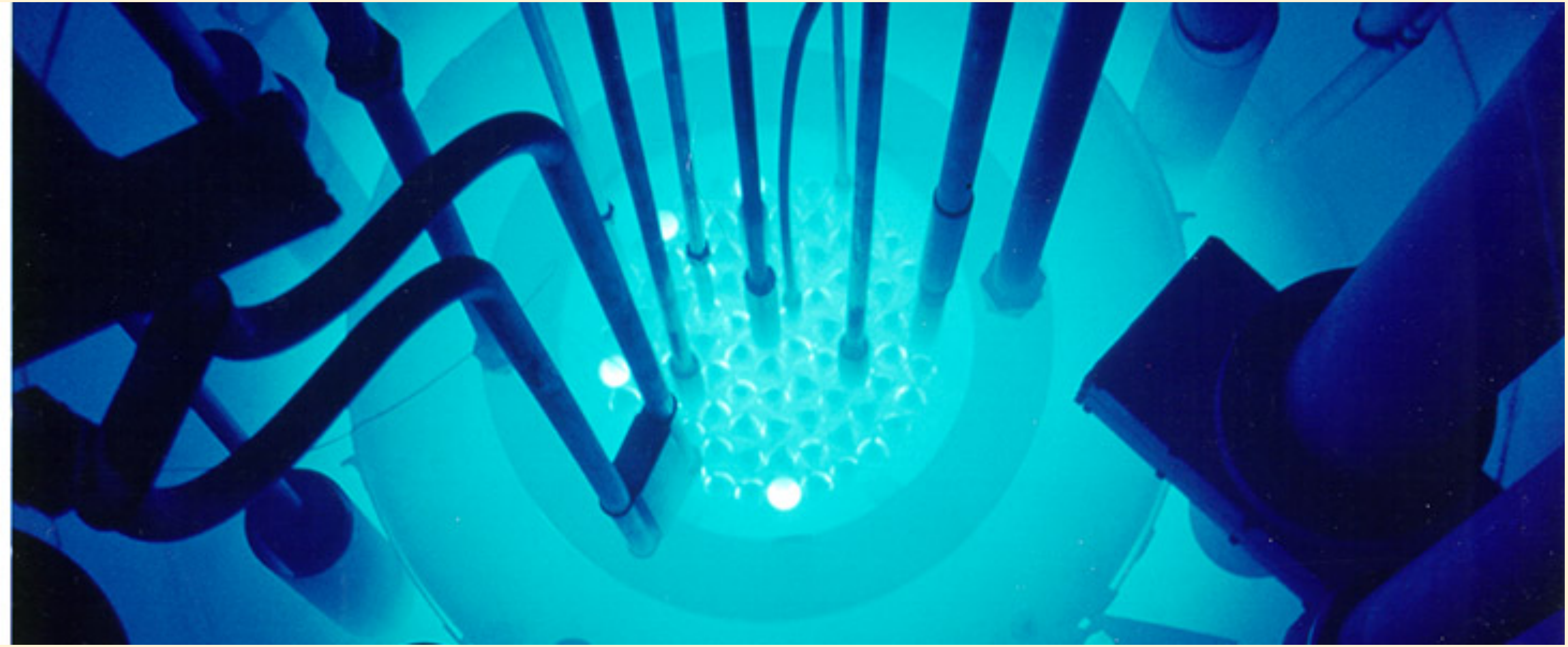
e: ^{60}Co production in steel

→ **^{60}Co** $+ \gamma \rightarrow {}^{60}Ni + \beta$ + anti-ν

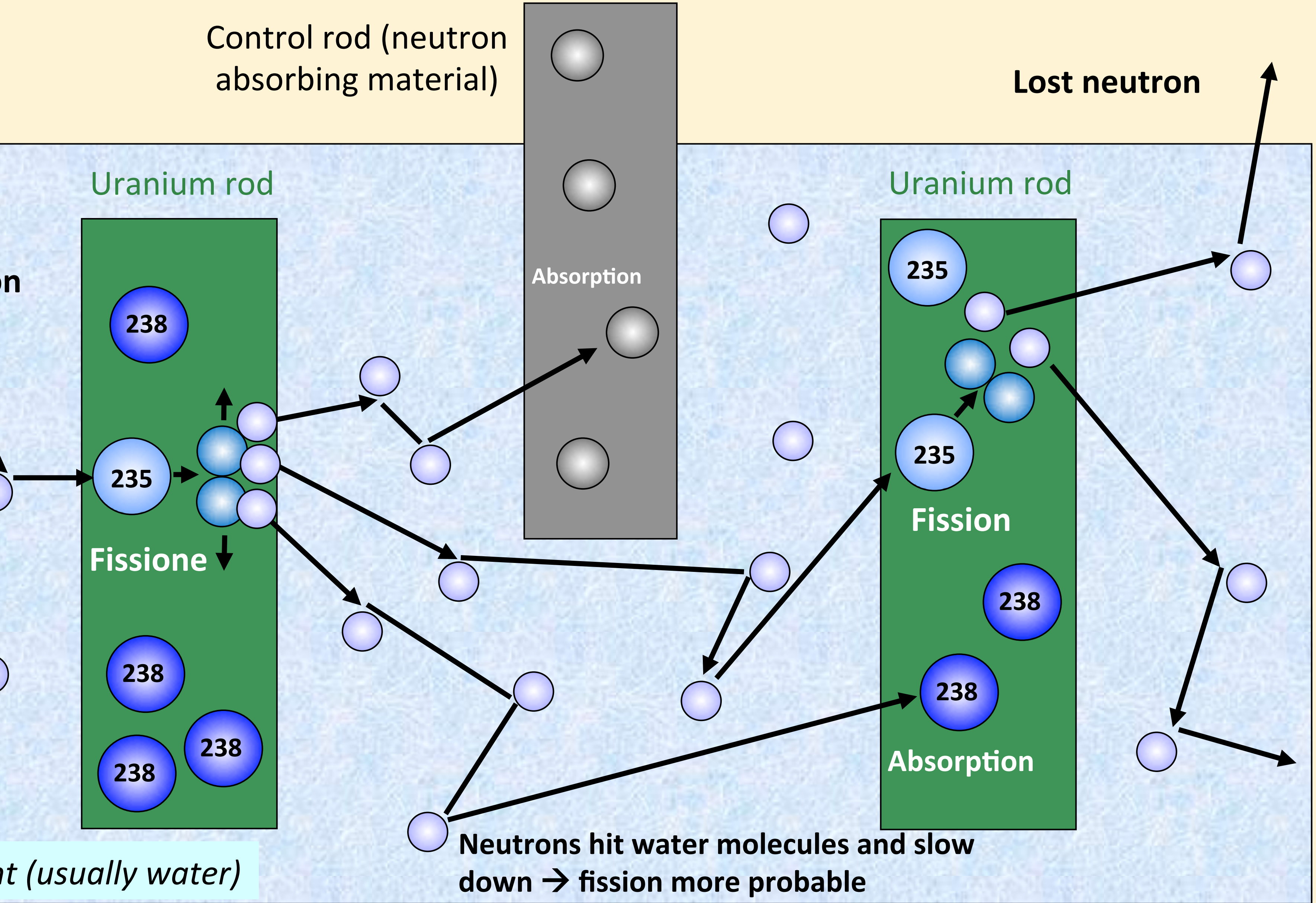


How it is built in practice



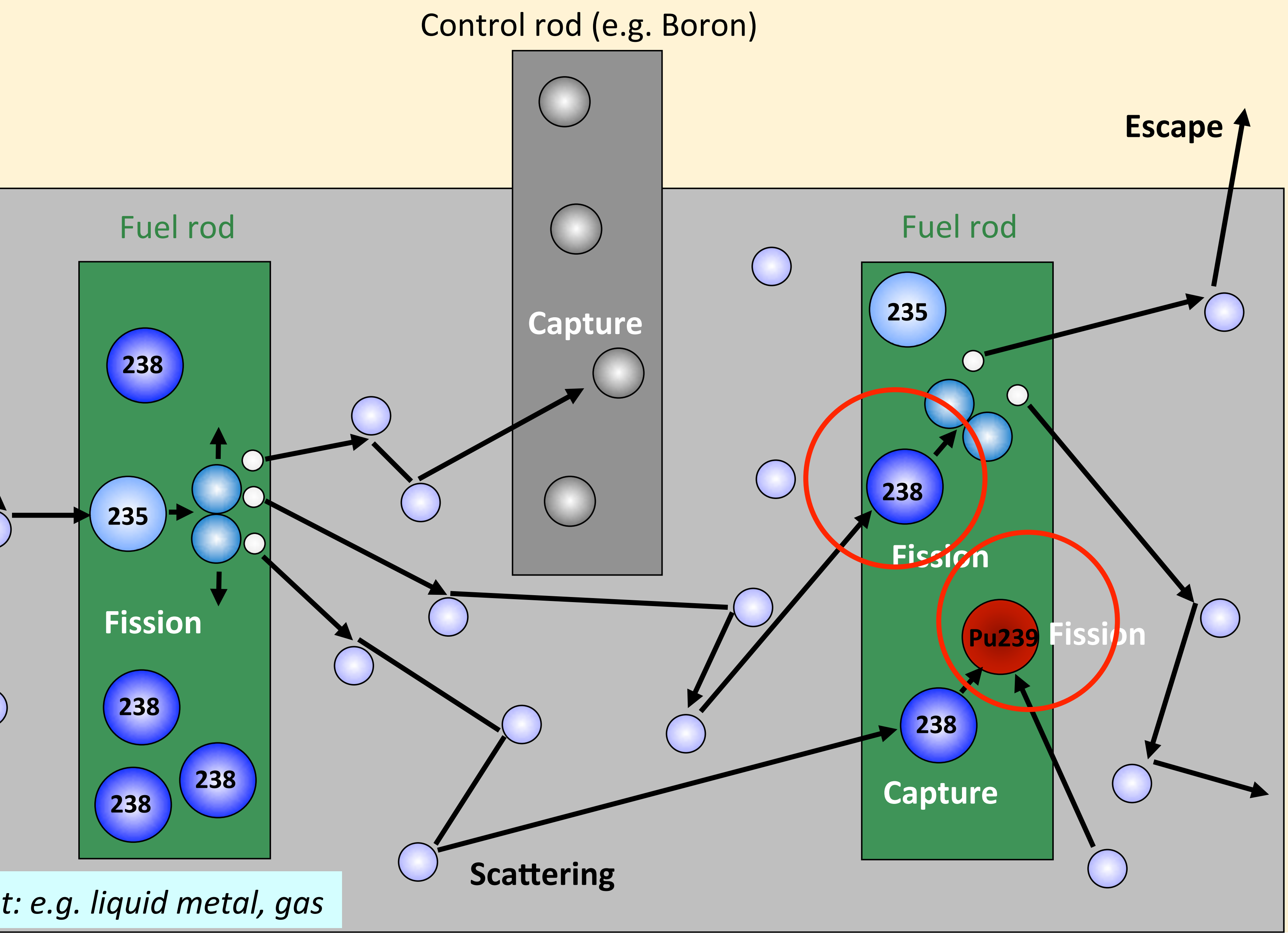


The“termal” reactor



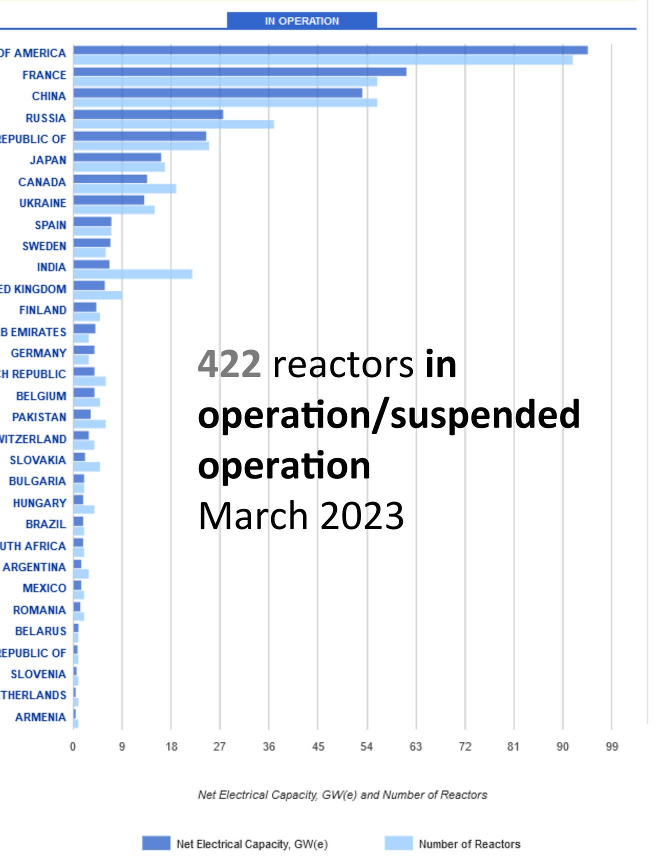
In the thermal reactor, neutrons are slowed d... to have maximum bur... of fissile Uranium 235

The fast reactor

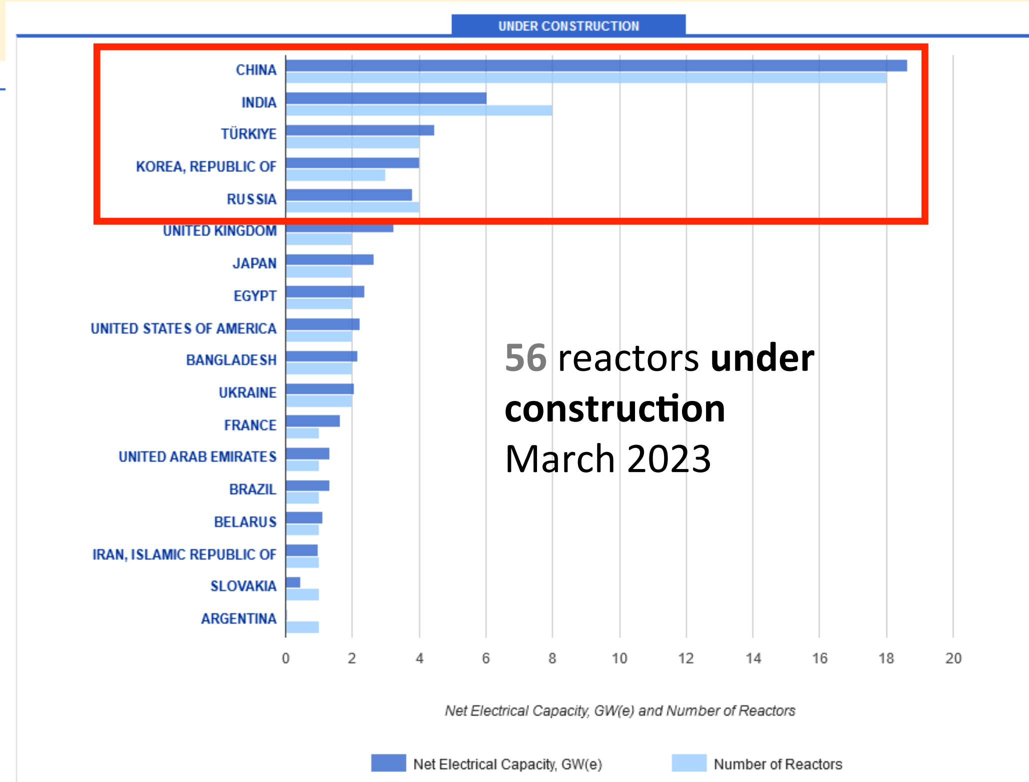


In the fast reactor, neutrons are not slowe down → possibility to produce and burn mor Plutonium and also to other radioactive nucle beyond Plutonium for by neutron capture

Nuclear fission energy in the world

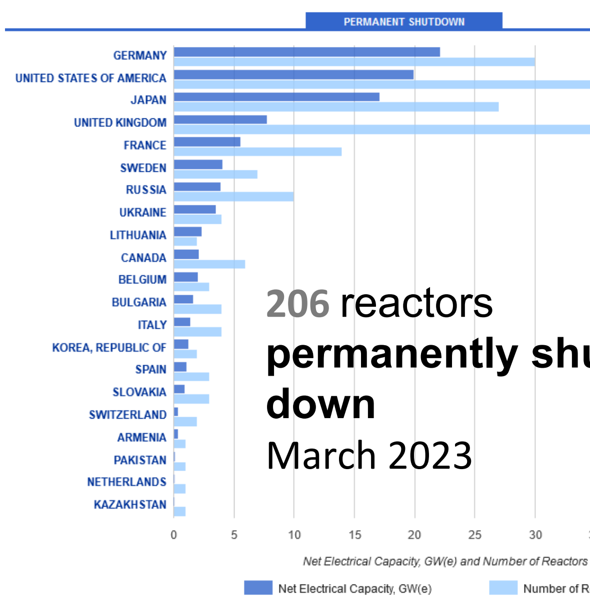


422 reactors **in operation/suspended operation**
March 2023



56 reactors **under construction**
March 2023

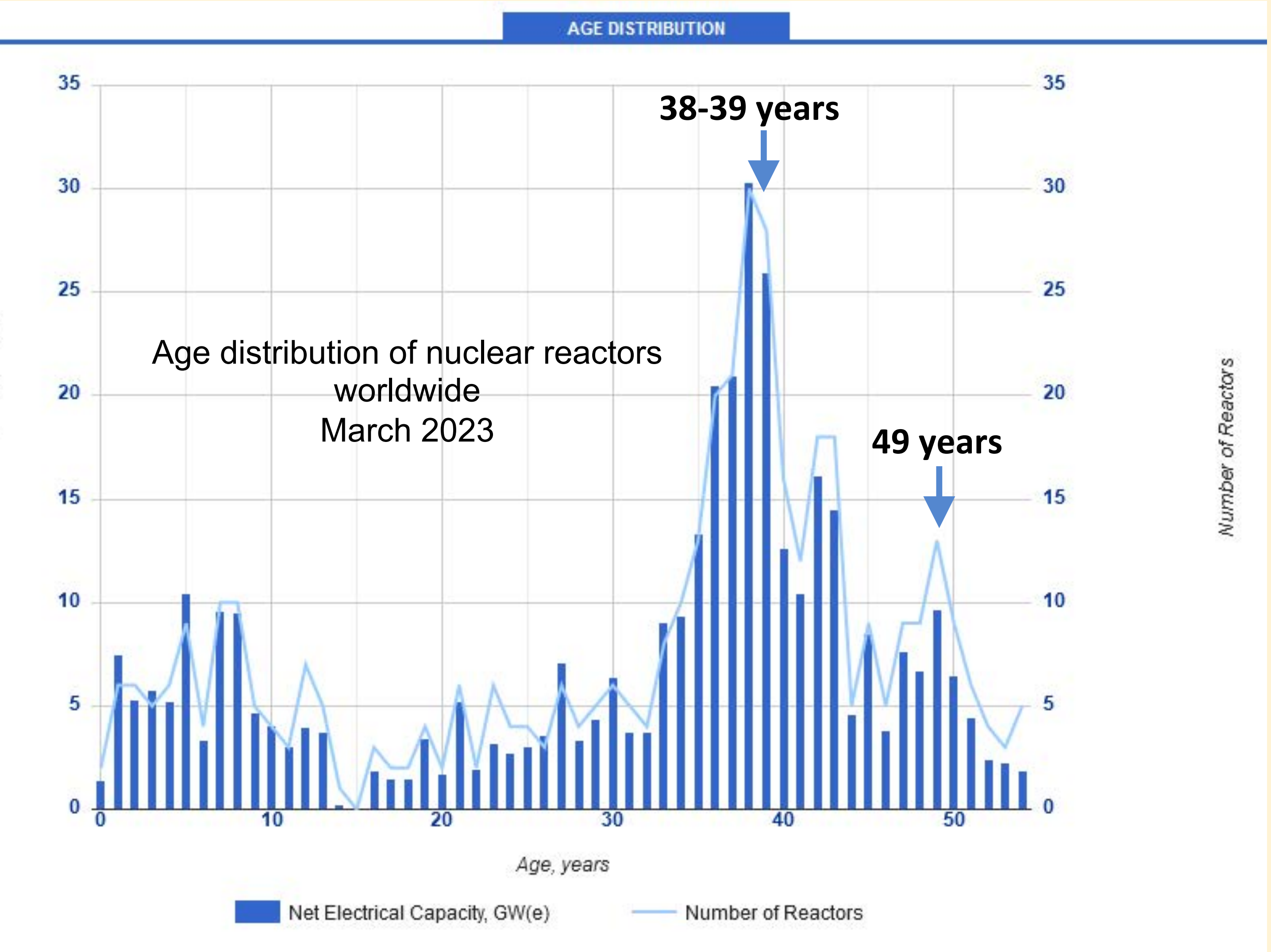
Source:
[IAEA Power Reactor Informatic System (PRIS)]



206 reactors **permanently shu down**
March 2023

- ***5%*** *total world primary energy*
- ***10%*** *world electricity*
- ***18%*** *electricity in OECD countries (**25%** in EU)*
- ***33%*** *«low carbon» electricity*
- *Energy source with the least GHG production (together with hydro and wind)*
- *24-7 availability (back up for «Intermittent Renewables»)*

Nuclear fission energy in the world



Source:
[IAEA Power Reactor Informatio
System (PRIS)]

The typical life span of a plant is 40-60 y

Many are being decommissioned or wil decommissioned

BUT, in the current situation, many cou are reconsidering license extensions…

CNBC News

CLEAN ENERGY

California lawmakers vote to extend Diablo Canyon nuclear plant operations as state battles energy emergency

PUBLISHED THU, SEP 1 2022•9:28 AM EDT

Catherine Clifford
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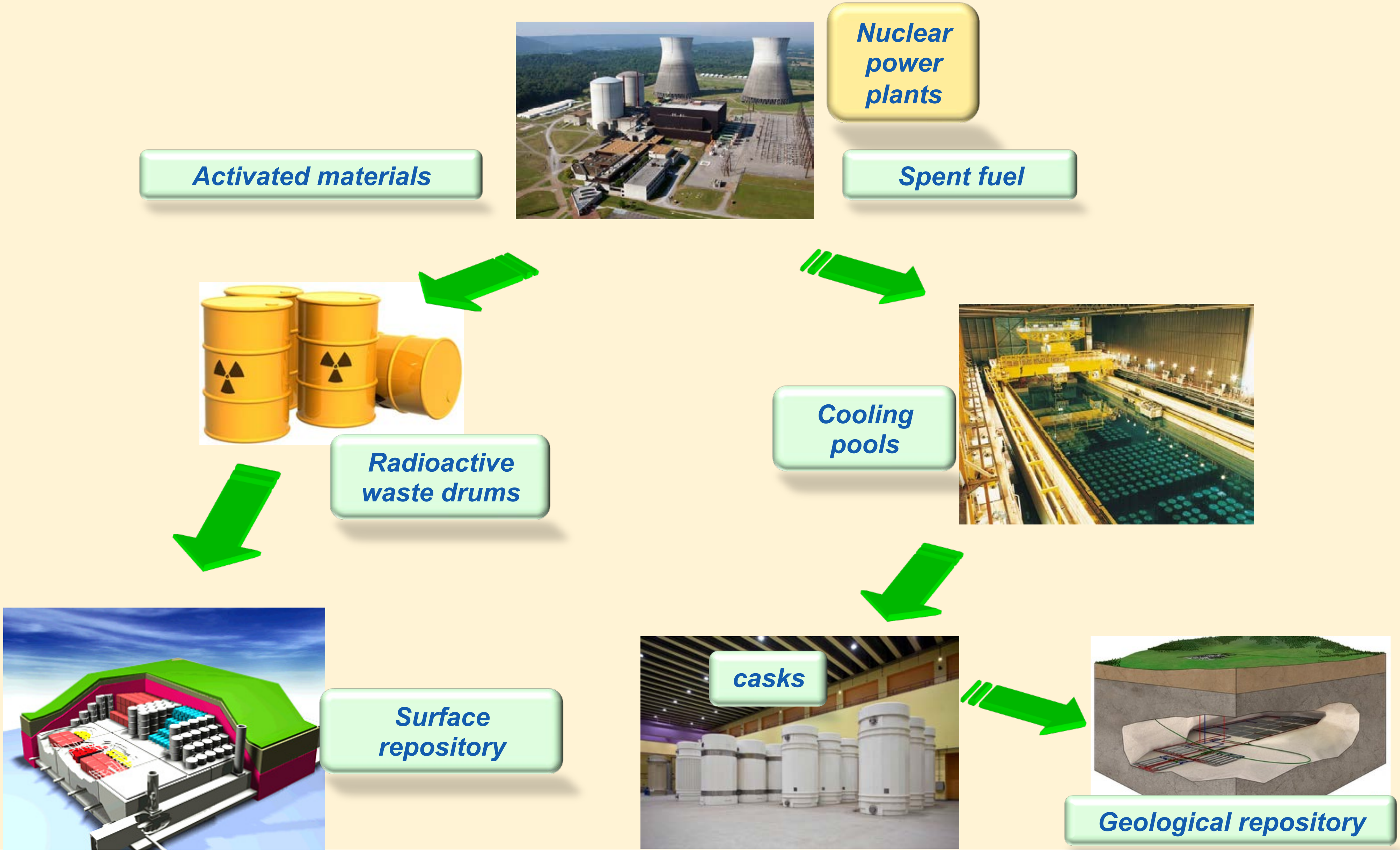
KEY POINTS

- In a late night, last-minute vote, California lawmakers approved a measure to give the state the option to keep its last remaining nuclear power plant operating for another five years, contingent on, among other things, the utility operating the power plant getting access to federal funding.
- The decision is a reversal of a previous decision to shut the power plant down and comes amid an energy crunch in the state.

Aerial view of the Diablo Canyon, the only operational nuclear plant left in California, is viewed in these aerial photos taken on December 1, 2021, near Avila Beach, California. Set on 1,000 acres of scenic coastal property just north and west of Avila Beach, the controversial power plant operated by Pacific Gas & Electric (PG&E) was commissioned in 1985.

George Rose | Getty Images News | Getty Images

Radioactive waste production (from fission)

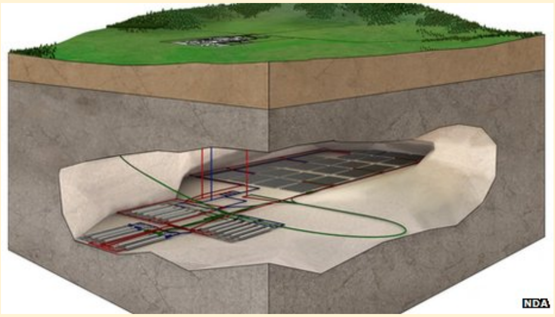


w much nuclear waste is there? And what to do with

In **one year**, a **typical high power reactor** produces **about 1200 kg of radioactive substances** in the fuel, of which 400 kg are radioactive for long periods, from a few hundred to a few hundred thousand years → they must be kept isolated

Therefore, the **used fuel rods must be stored in safety for very long periods**
when the plant is dismantled, the other activated materials must also be kept in isolation

ome countries are already using or are planning to use **underground epositories**, to store the spent fuel and other highly activated omponents, and then close the access to the repository, letting the adioactivity run out on its own → after about 200,000 years the naterial is no longer dangerous



However, **it is also possible to partially recycle the spent fuel** → it can be treated to extract Uranium and Plutonium to be used a second time

What about accidents

The operation of the reactor creates radioactive substances, both in the fuel and in the surrounding materials → these substances **must not** end up in the environment

Chernobyl, Soviet Union, 1986

Fukushima, Japan, 2011

Safety measures are therefore fundamental and there is continuous research and development to improve them

How long will U resources last ?

s an example, **fuel fabrication** for a big nuclear power plant with **1000 1We production**, requires about **160 tons natural U per year**

→ In the **current scheme** with about 450 reactors and **369 GWe capacity**, conventional" (cheap) **reserves would last for another 80 years** (maybe ss if average reactor power will increase)

→ Should nuclear power increase as in some of the above scenarios, we hould think about (more expensive) resources like phosphates (doable) or from sea water (still under study)

→ **Switching to fast reactors/Thorium cycle would increase vailability to a few 100/few 1000 years**

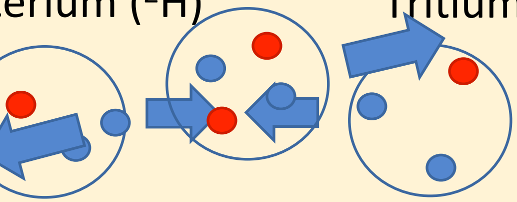
	million tons uranium
Australia	1.14
Kazakhstan	0.82
Canada	0.44
USA	0.34
South Africa	0.34
Namibia	0.28
Brazil	0.28
Russian Federation	0.17
Uzbekistan	0.12
World total (conventional reserves in the ground)	4.7
Phosphate deposits	22
Seawater	4 500

Lifetime of uranium resources (in years) for current reactor technology and future fast neutron systems (based on 2006 uranium reserves and nuclear electricity generation rate)

	Identified resources	Total conventional resources	Total conventional and unconventional resources
Present reactor technology	100	300	700
Fast neutron reactor systems	> 3 000	> 9 000	> 21 000

Source: OECD/NEA, Nuclear Energy Outlook, 2008

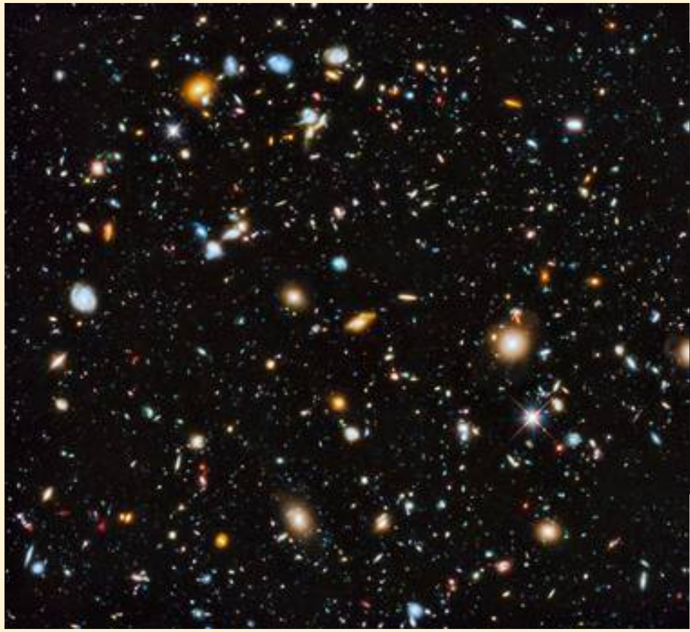
Nuclear Fusion

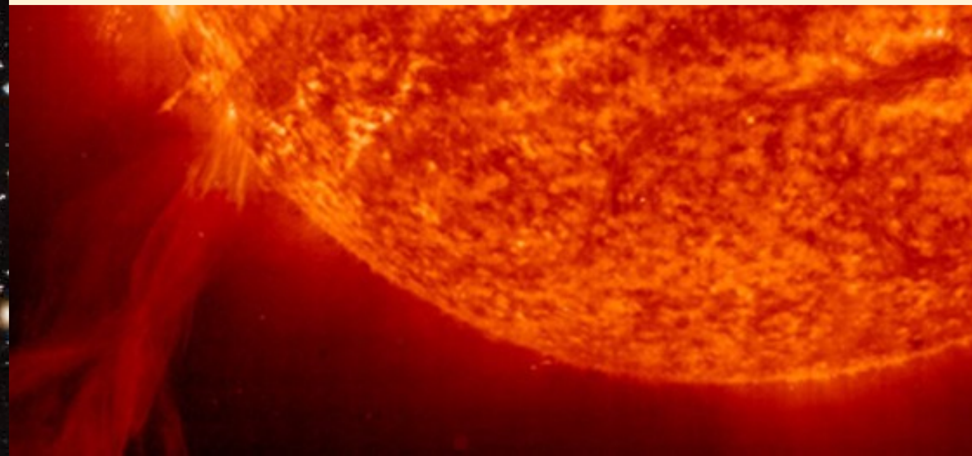


This is called Nuclear Fusion: it is the mechanism at work in stars
(actually, not with D-T, the Sun works mainly with p+p→D+e^++ν)

eutrons have about 14 MeV ic energy ➔ transferred to r around the apparatus ➔

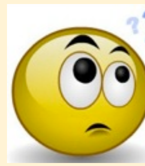
m nuclei have about 3 MeV ey give some contribution to ng the plasma



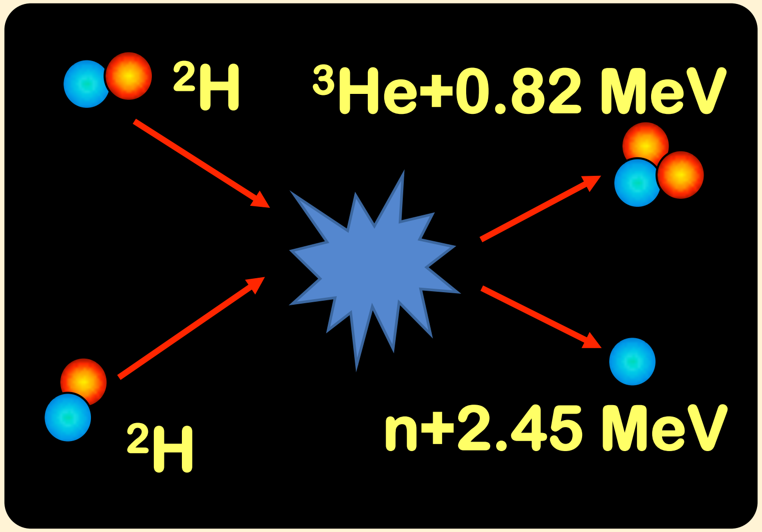


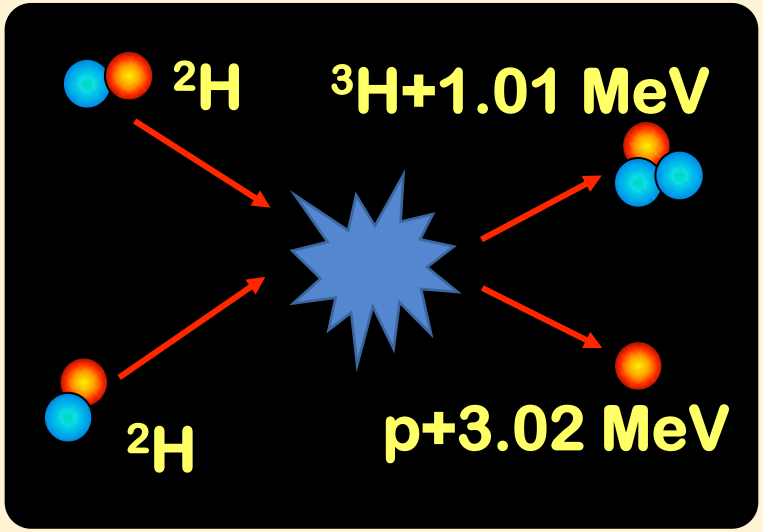
Fusion does not produce *directly* radioactive fragments
(but Tritium is radioactive and neutrons activate structural materials)
→ It provides cleaner energy with respect to Fission

ntly we do not know how to build reactors capable of maintaining a stable regime for long enough

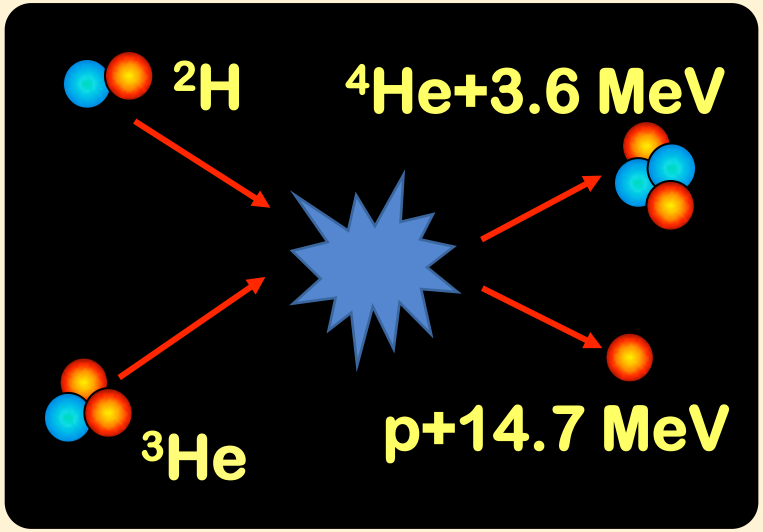


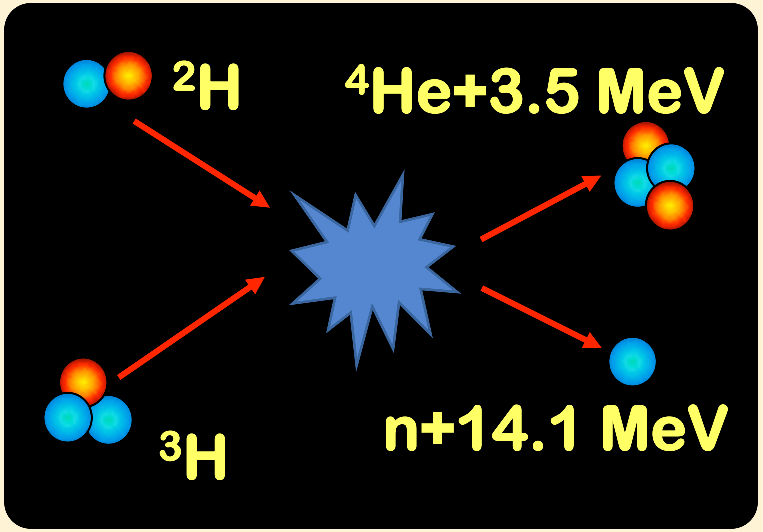
Ongoing research (JET, ITER, DEMO) is long term





Q-value is sum of energy acquired by final nuclei → energy released in exoergic reactions

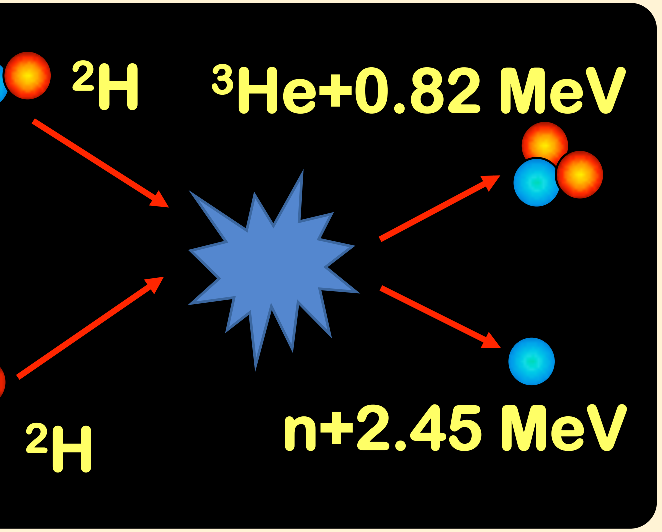


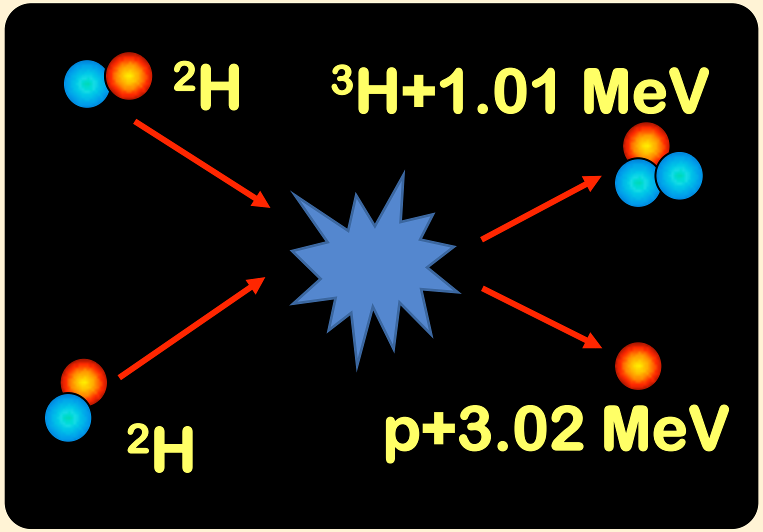


Deuterium-Tritium (50 % mix)

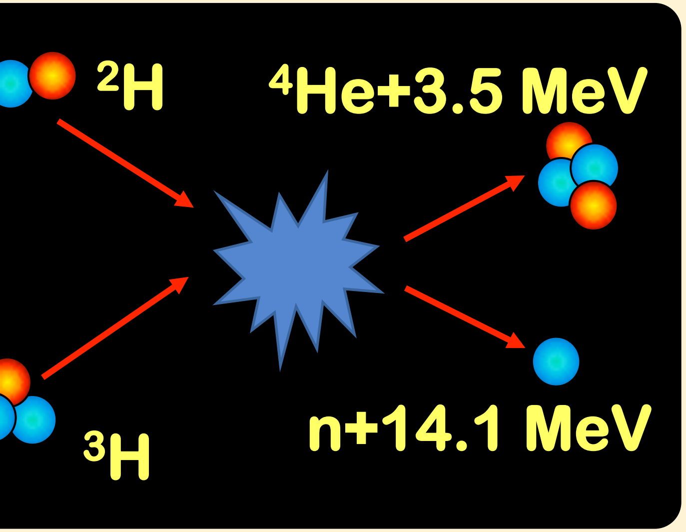
has maximum probability to occur

Fusion reaction candidates



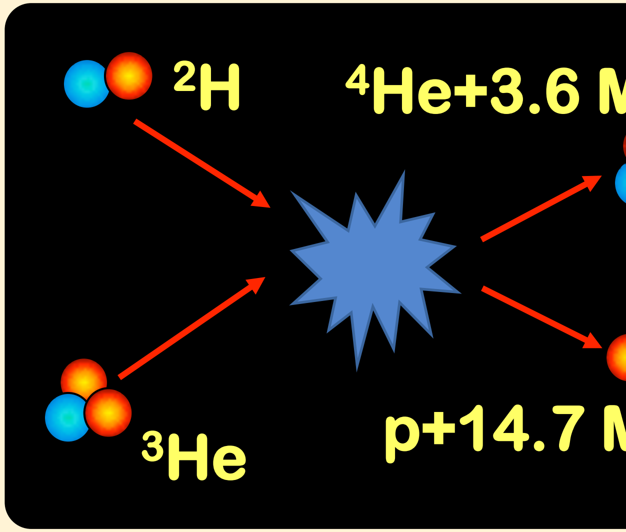


Q-value is sum of energy acquired by final nuclei → energy released in exoergic reactions



Deuterium-Tritium

has maximum probability to occur at the conditions that we can be able to reach in our fusion plants and provides a significant amount of energy

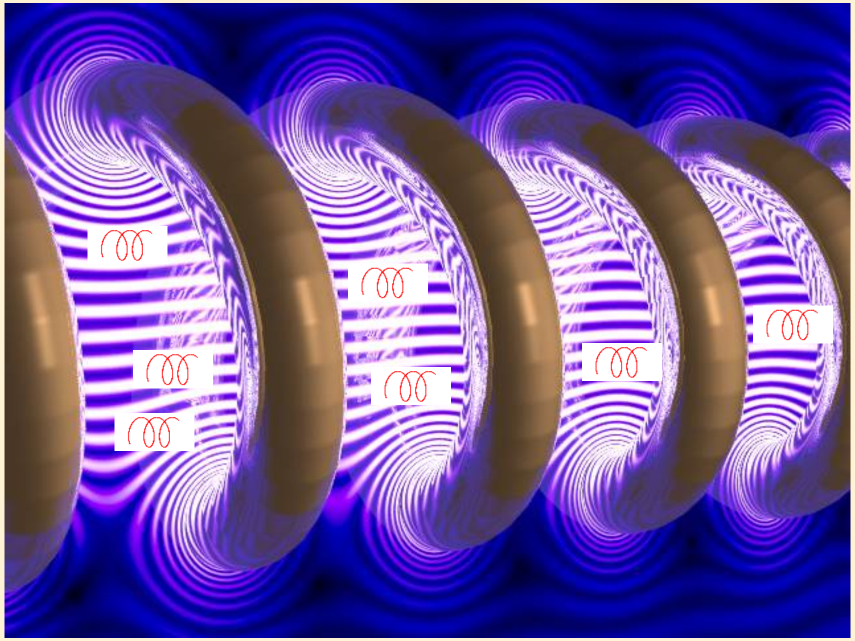


Conditions for Fusion

o make fusion happen, **Coulomb repulsion between (positive) nuclei has to be overcome → necessary to reach VE high temperatures** → Deuterium-Tritium gas mixture must be heated to several million degrees

At such high temperatures, a **plasma** is created → **a gas of electrons and nuclei (ions) moving independently**

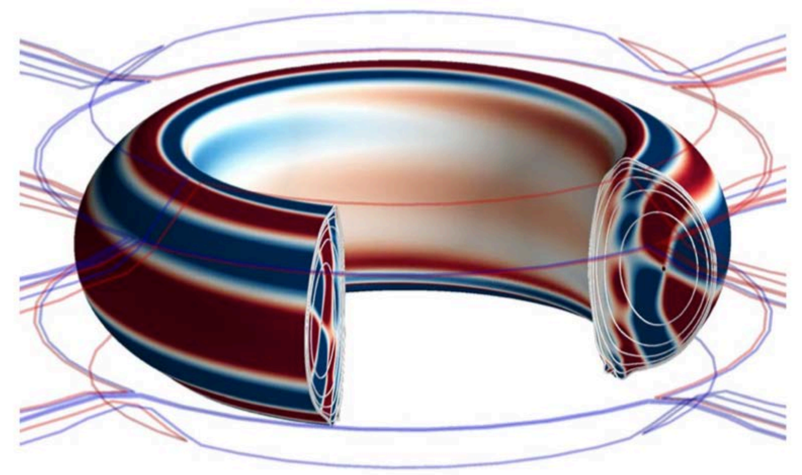
The plasma is so hot that it must be trapped (confined) such as to avoid touching the reactor walls → Confinement is achieved through magnetic fields

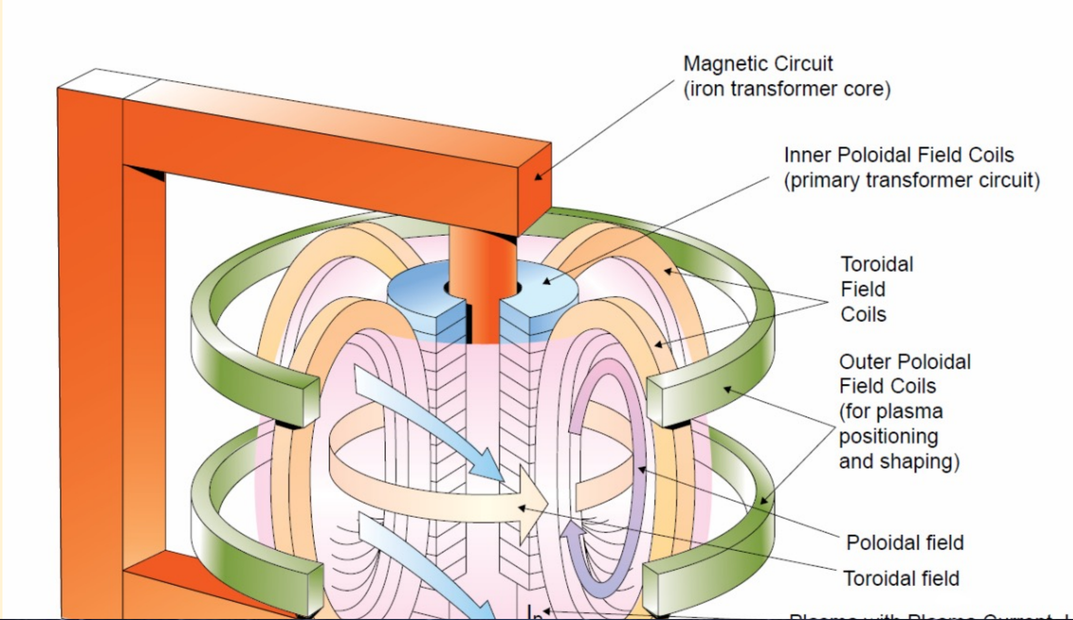


or the mixture can be compressed by using high power lasers («inertial» fusion)

The (magnetic) fusion reactor

a doughnut-shaped device works better *(tokamak)*





TOKAMAK

токамак, an acronym of either:

"**то**роидальная **ка**мера с **ма**гнитными **к**атушками"

(***to****roidal'naya* ***ka****mera s* ***ma****gnitnymi* ***k****atushkami*)

toroidal chamber with magnetic coils

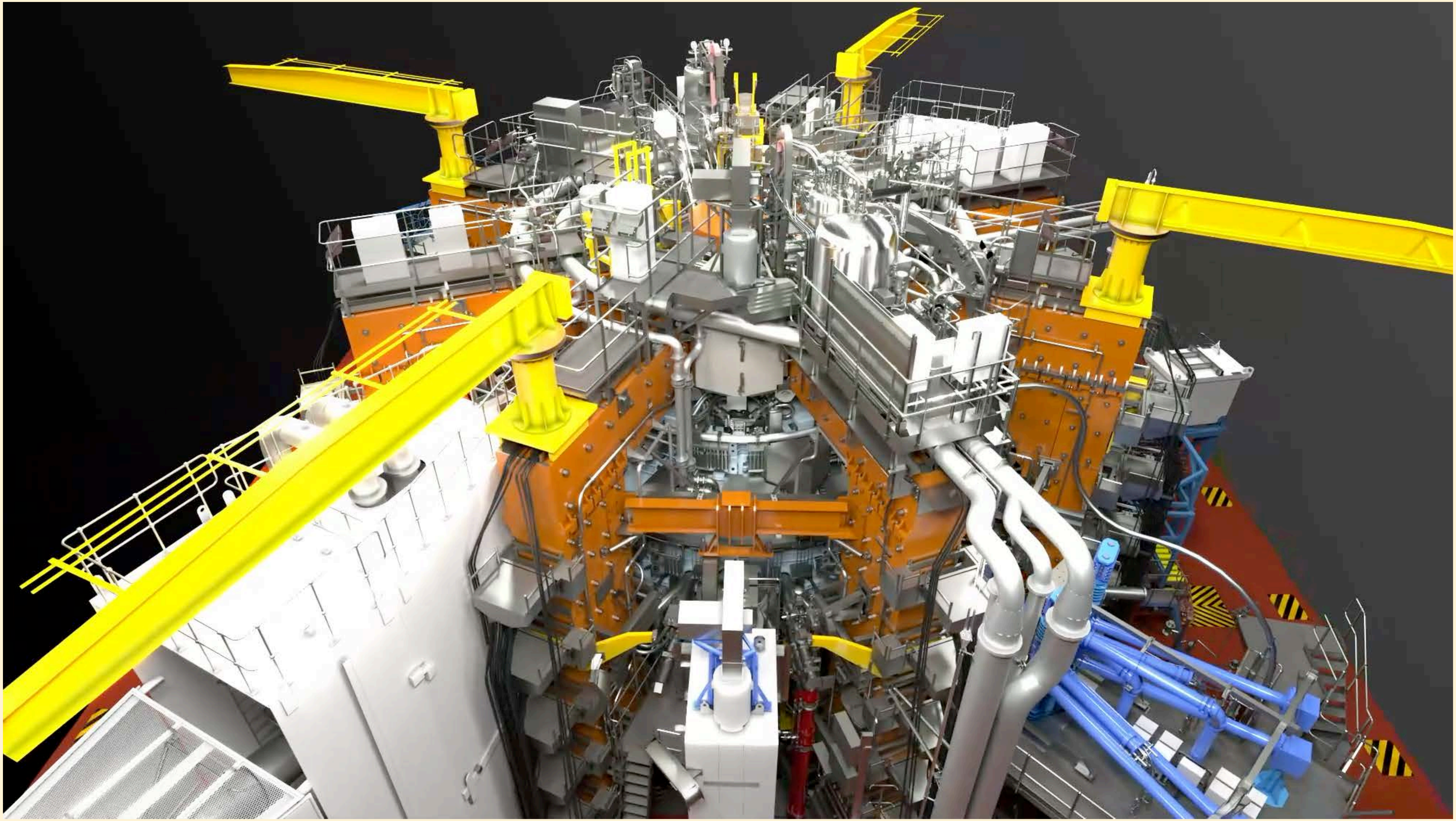
or

"**то**роидальная **кам**ера с **ак**сиальным магнитным полем"

(***to****roidal'naya* ***kam****era s* ***ak****sial'nym magnitnym polem*)

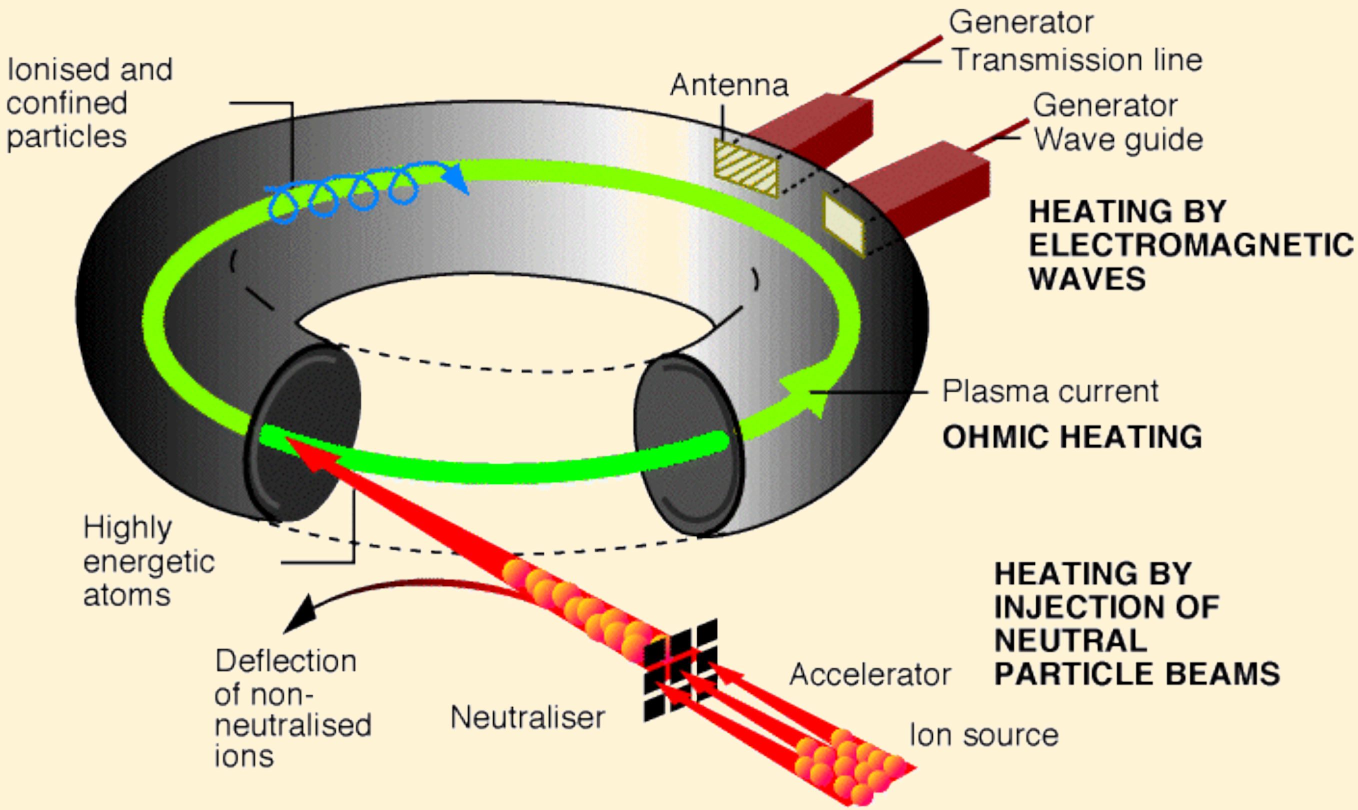
toroidal chamber with axial magnetic field

And here is a real one…



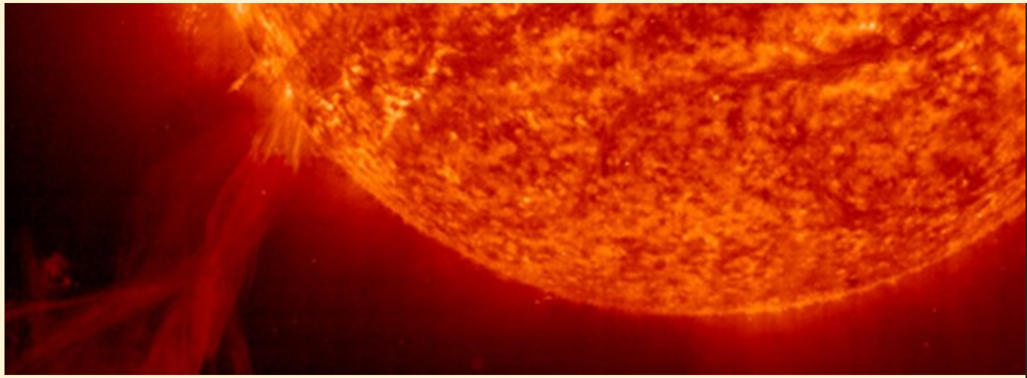
Heating the plasma

T_{plasma} in the tokamaks: **~100-150x10^6 degree** to trigger fusion D + T → ^{4}He + n (*)
Plasms heating is obtained essentially by **Ohm effect (but at lower temperatures as plasma resistance decreases with temperature), RadioFrequency (electron and ion Cyclotron Resonance) and injection of neutral atoms** (Neutral Beam Injectors, NBI)

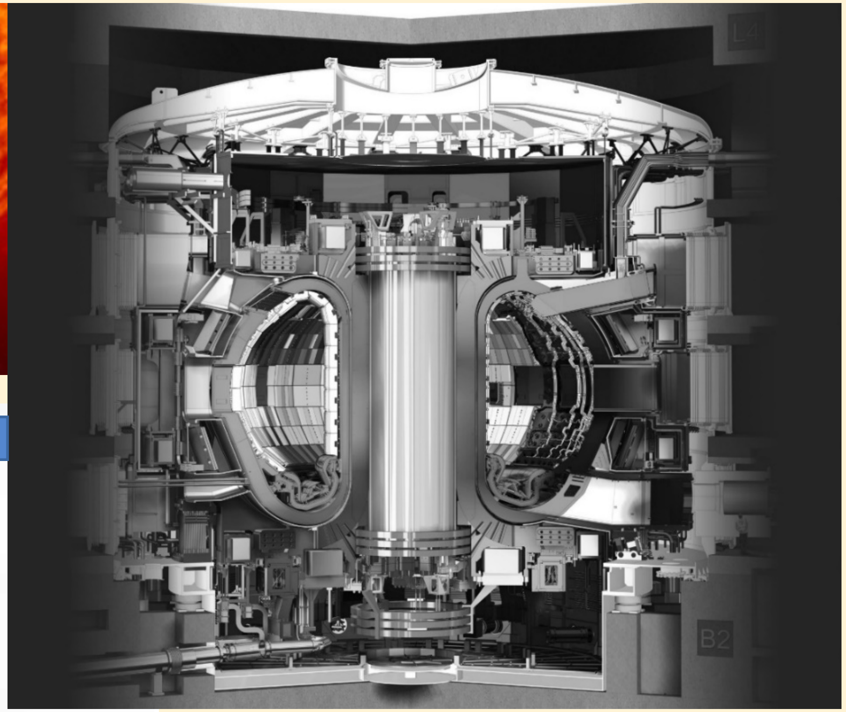


hinese Experimental Advanced Superconducting Tokamak (EAST) established a new world record in 2021 by reaching a plasma tempe
n degrees for 101 seconds and 160 million degrees for 20 seconds

The fusion roadmap



DEMO



ITER

Current roadmap for ITER…

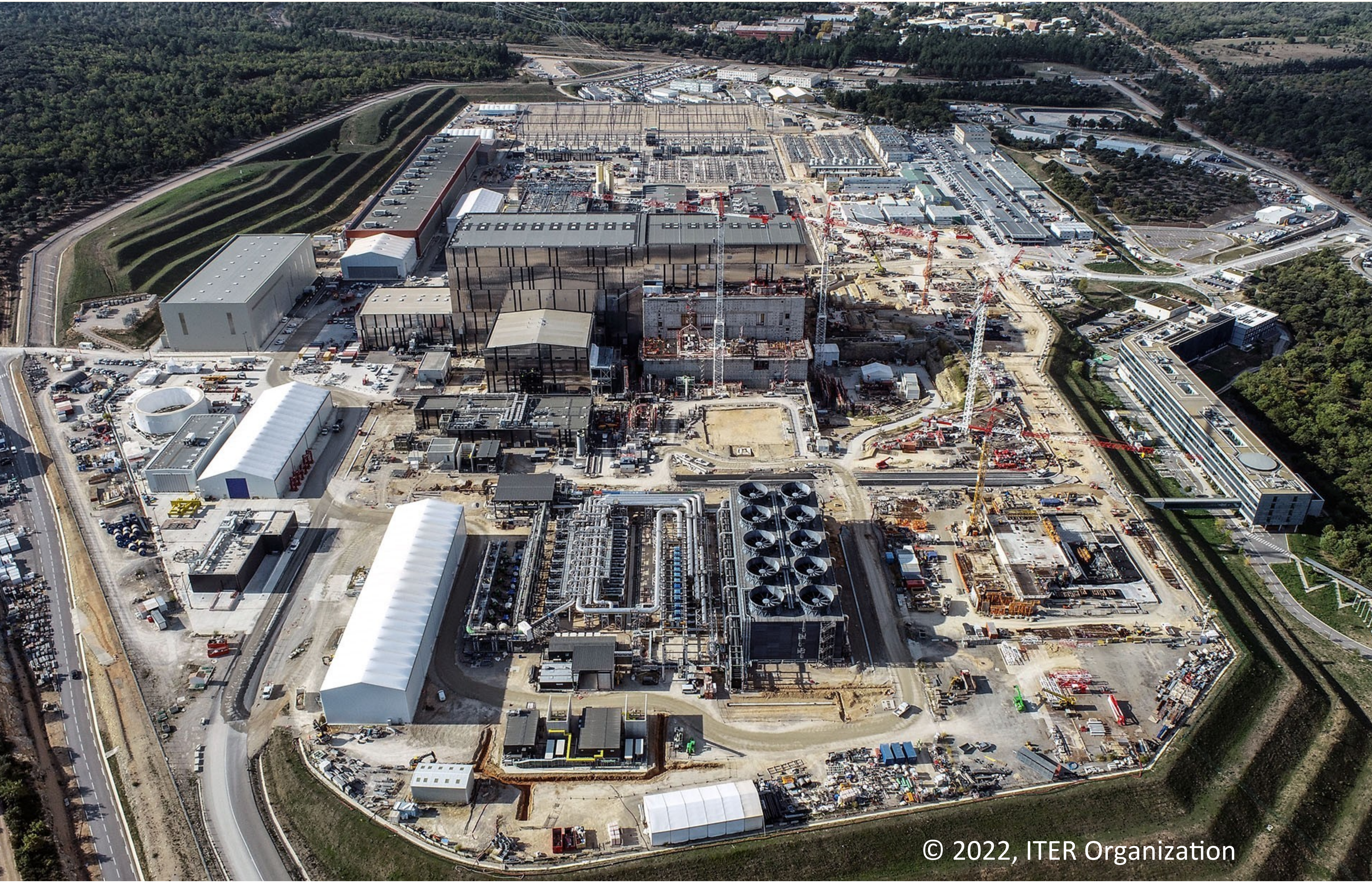
PAUL-LEZ-DURANCE, France (16 June 2016)

oncluding a two year effort by the ITER Organization and the seven Domestic Agencies to establish a new baseline schedule, the ITER Council h
ndorsed the updated Integrated **Schedule for the ITER Project**, which identifies the date of **First Plasma as December 2025** (now revised to 2025-203

One of ITER's goals is to get 10 times more fusion energy than the energy used to heat the plasma

…and for DEMO

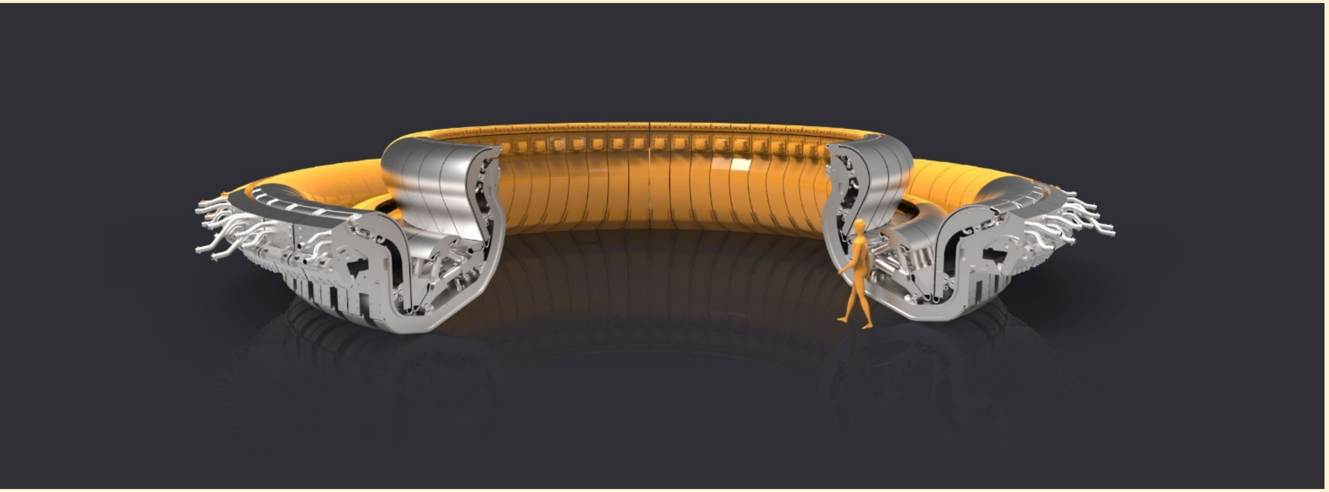
the European strategy **DEMO** is the only step between ITER and a commercial fusion power plant.
o meet the goal of **fusion electricity demonstration by 2050**, **DEMO construction** has to **begin in the early 2030s** at the latest, to allow the **start of**
peration in the early 2040s


© 2022, ITER Organization

ITER: assembly in progress

The inside of
the cryostat
with the
nstallation of
he first sector
of the torus
(11.5.2022)

The ITER divertor



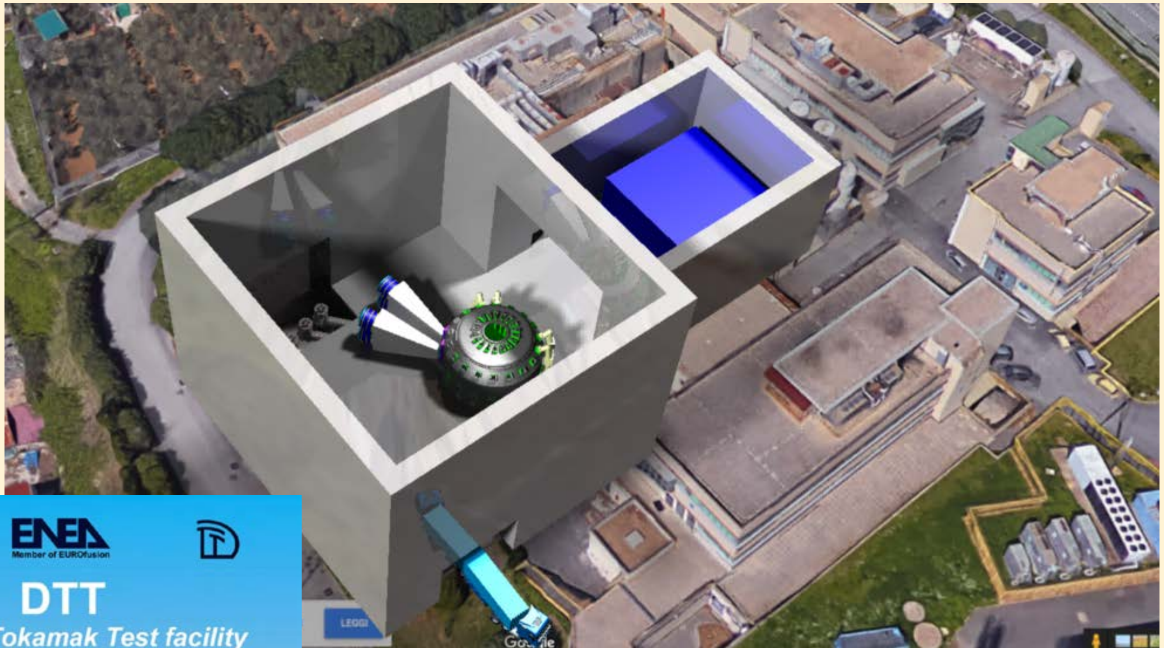
- Divertor: the fusion «exhaust», it absorbs gases that escape confinement and contaminants that accumulate during the fusion process

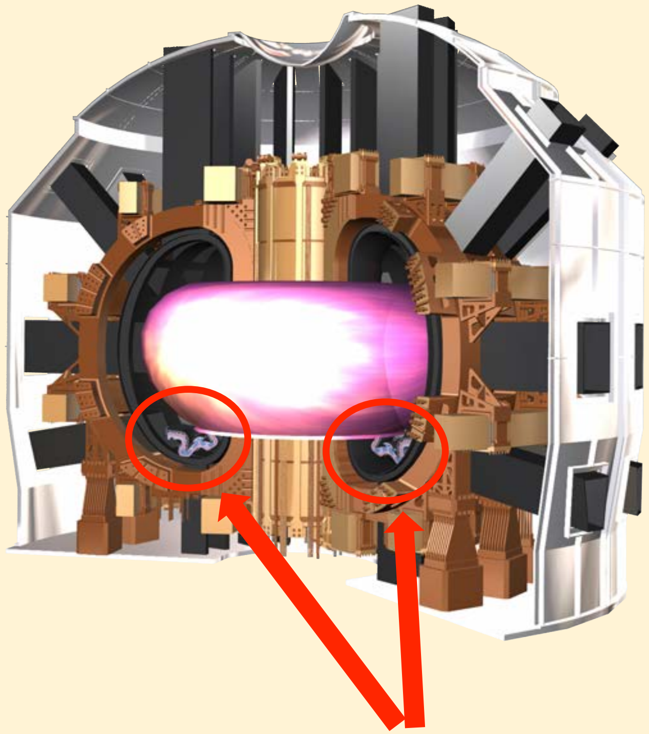
- Situated **at the bottom of the vacuum vessel**
- **Extracts heat and ash produced by the fusion reaction**, minimizes plasma contamination, and protects the surrounding walls from thermal loads

As the high-energy plasma particles strike the targets, their kinetic energy is transformed into heat and the heat is removed by active water cooling

Source: http://www.iter.org

The Divertor Tokamak Test (DTT) project in Frascati

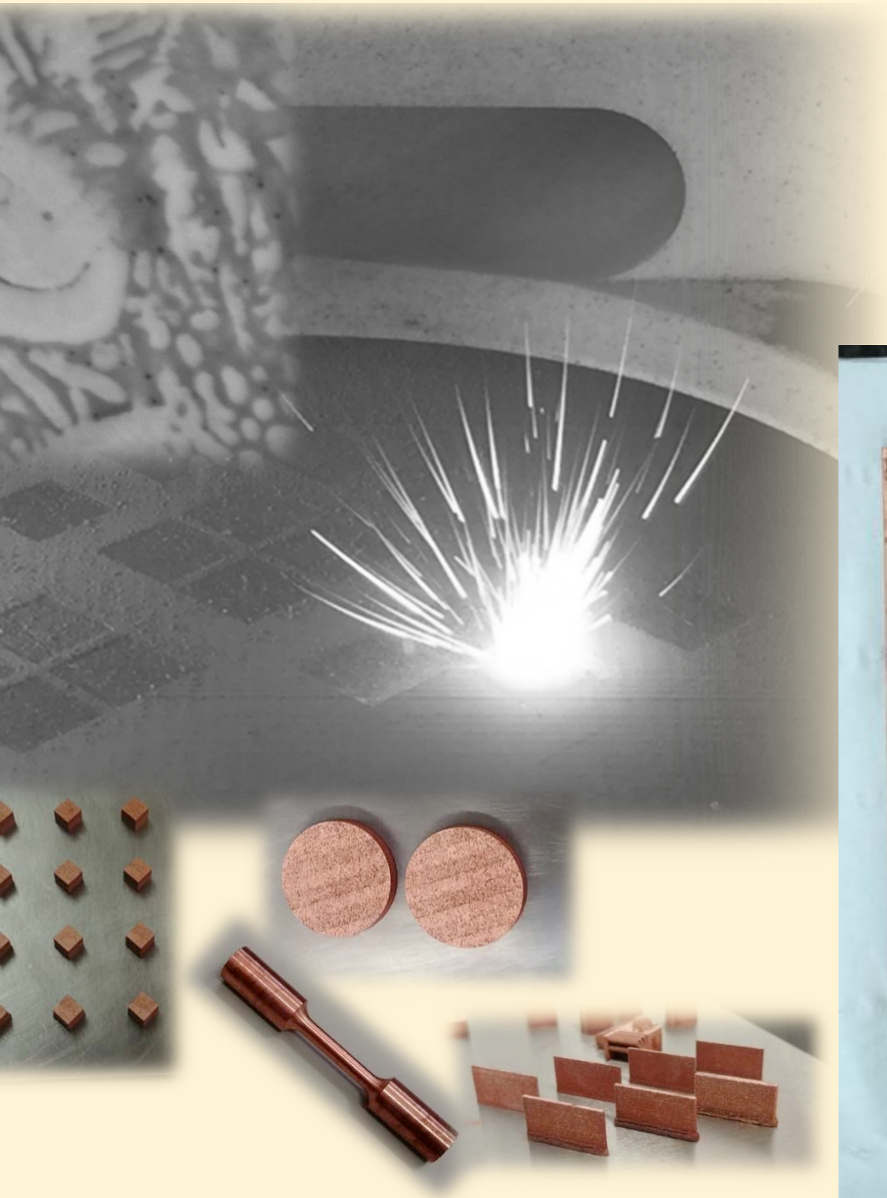




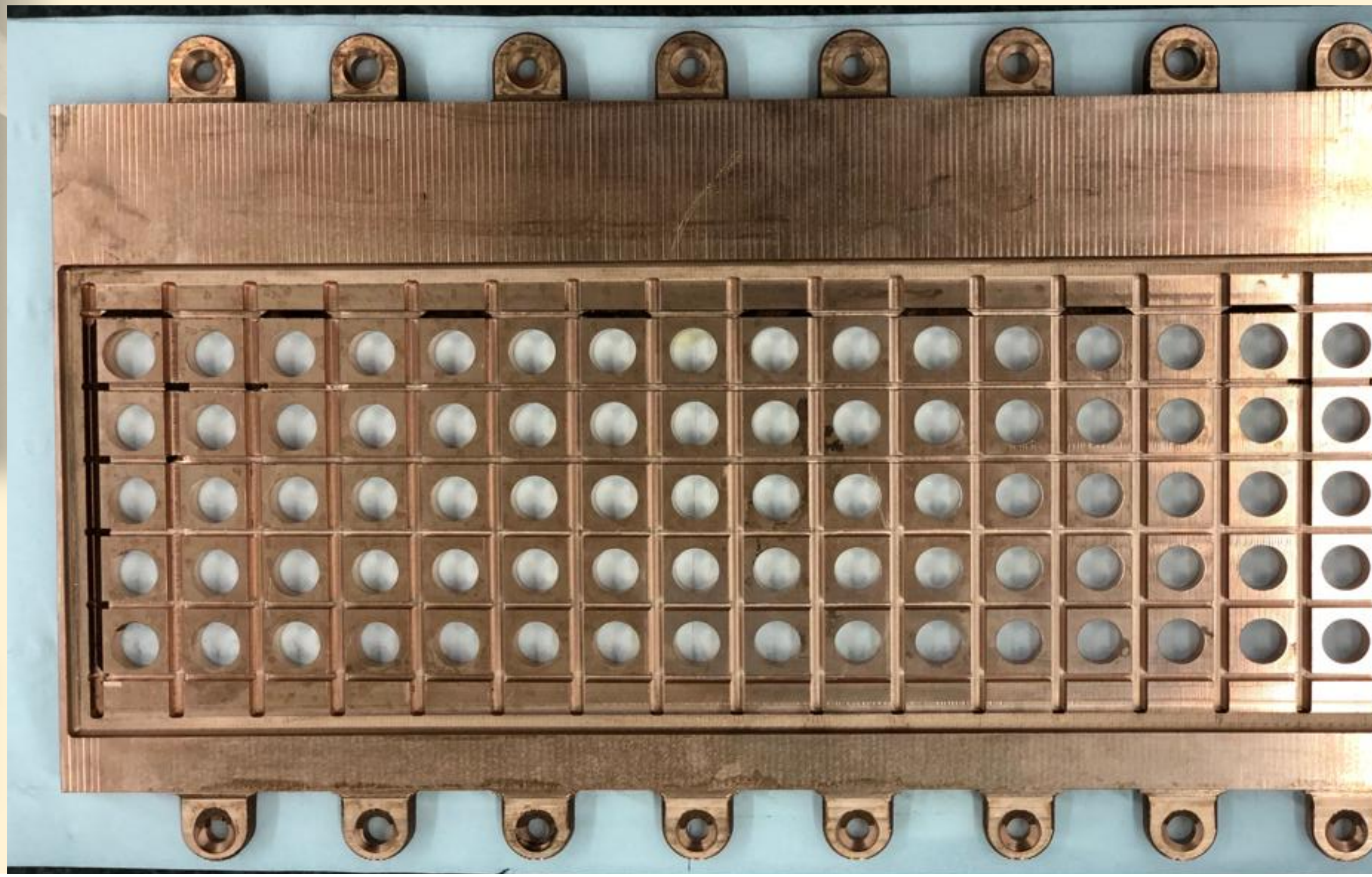
- Goal: test different options for the **DEMO divertor**

- ITER will use a "traditional" approach which may not work in DEMO
- in addition to the divertor, various possible solutions suitable for DEMO can be studied at D

New technologies: additive manufacturing (3D printing)



Prototype accelerator grids for DTT Neutral Beam Injector, 3D-printed in Copper-Chrome-Zirconium allo



Where is the fusion fuel coming from ?

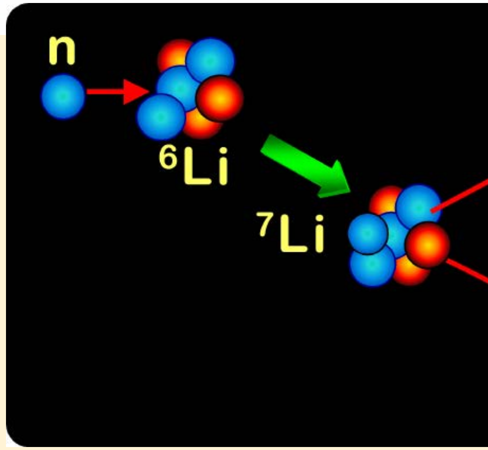
**euterium can be extracted from seawater in virtually boundless
antities
the contrary, the supply of available tritium is limited, estimated
rrently at 20 Kg**

ritium can be produced by **neutrons interacting with a lithium-rich
ket**

will procure tritium for its expected 20-year lifetime from the global
tory

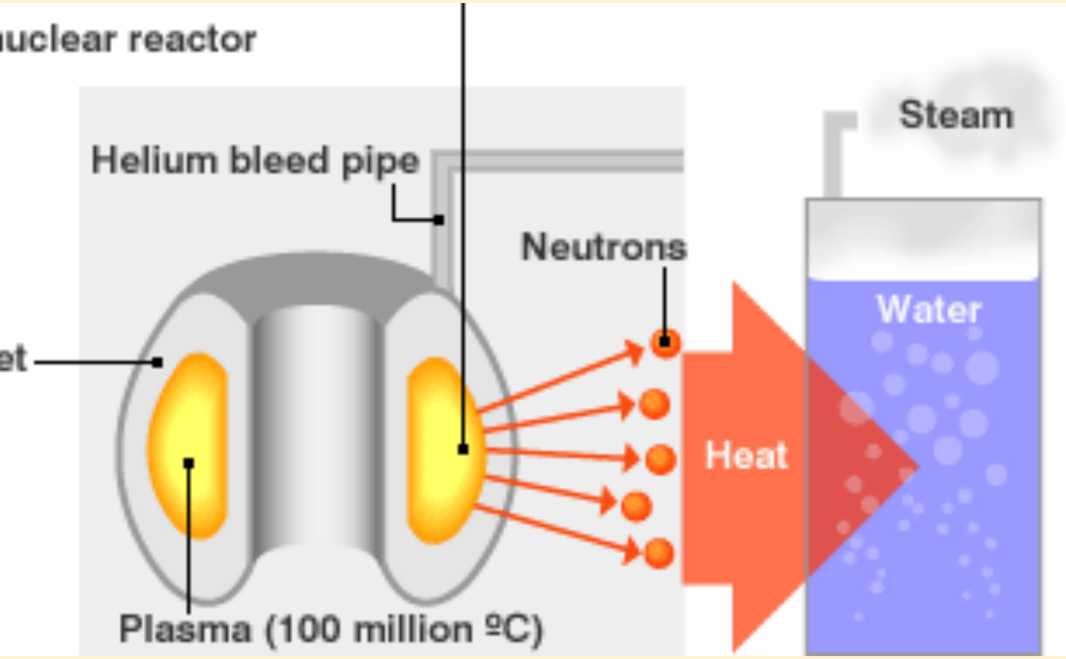
or **DEMO**, **about 300 g of tritium will be required per day to
uce 800 MW of electrical power** → **tritium breeding** essential

will provide a unique **opportunity to test mockups of breeding
kets**, called Test Blanket Modules (TBM), in a real fusion
onment. Within these test blankets, viable techniques for ensuring
m breeding self-sufficiency will be explored



Source: http://www.iter.org

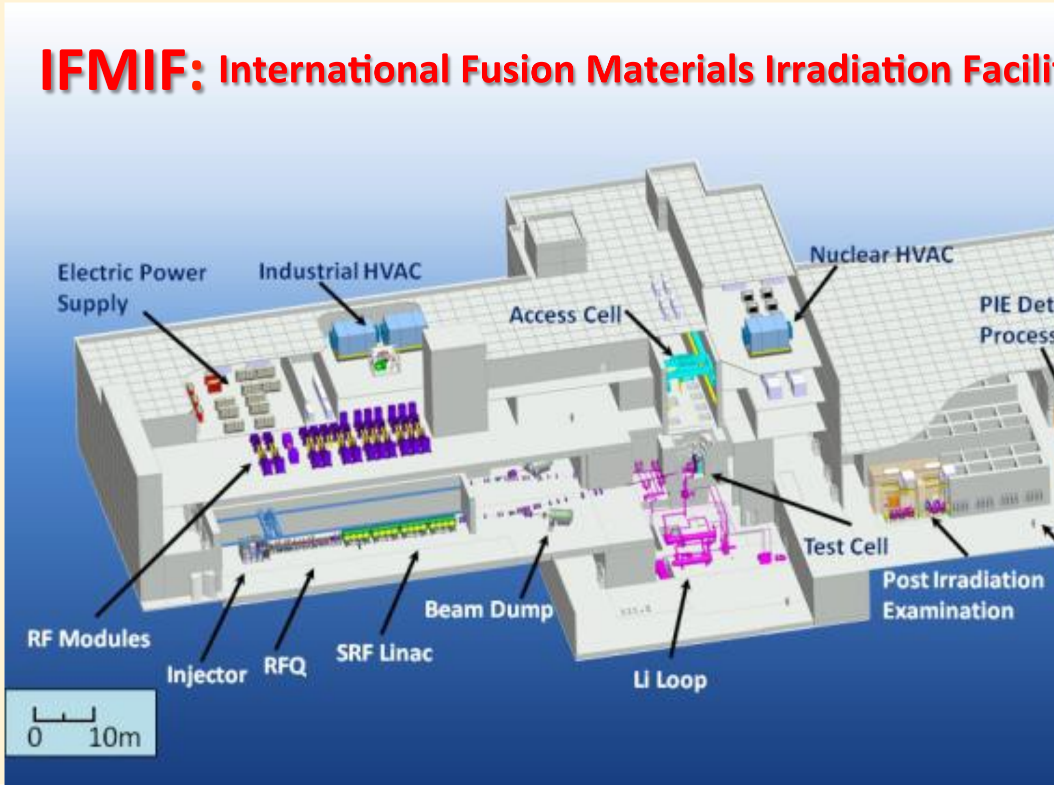
The challenge of materials



Reactor materials are subjected to a great deal o stress (neutron bombardment) → it is necessary test them

IMFIF project foresees a powerful deuteron accelerator uterons, 40 MeV and 125 mA → 5 MW beam power !) → ineering Validation stage (EVEDA) going on at Rokkasho, an, with the goal to reach 9 MeV, 125 mA

deuterons will hit a liquid lithium target, producing trons with intensity and energy spectrum similar to that of fusion reactor, allowing to test certain materials (e.g. es of steel)



Summary

- **Radioactivity is a natural phenomenon** and radioactive materials have been around us forever

- **Nuclear energy will still be one of the sources of low-emission «baseload» in many countries** (including several new ones) **for several years** (and not only baseload, see small-scale reactors…)

- **There are solutions for the safe management of nuclear waste** → they are also important for sectors other than energy (for instance, disposal of waste from the past and medical and industrial waste)

- **Fusion plants are at the center of a very intense experimental research program** and could become a **new source of energy around 2050**

- **The fusion research program involves several challenges that require the development of many technologies**, with a significant impact on industry