Introduction to Nuclear and Particle Physics

Nuclear fusion

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Binding energy

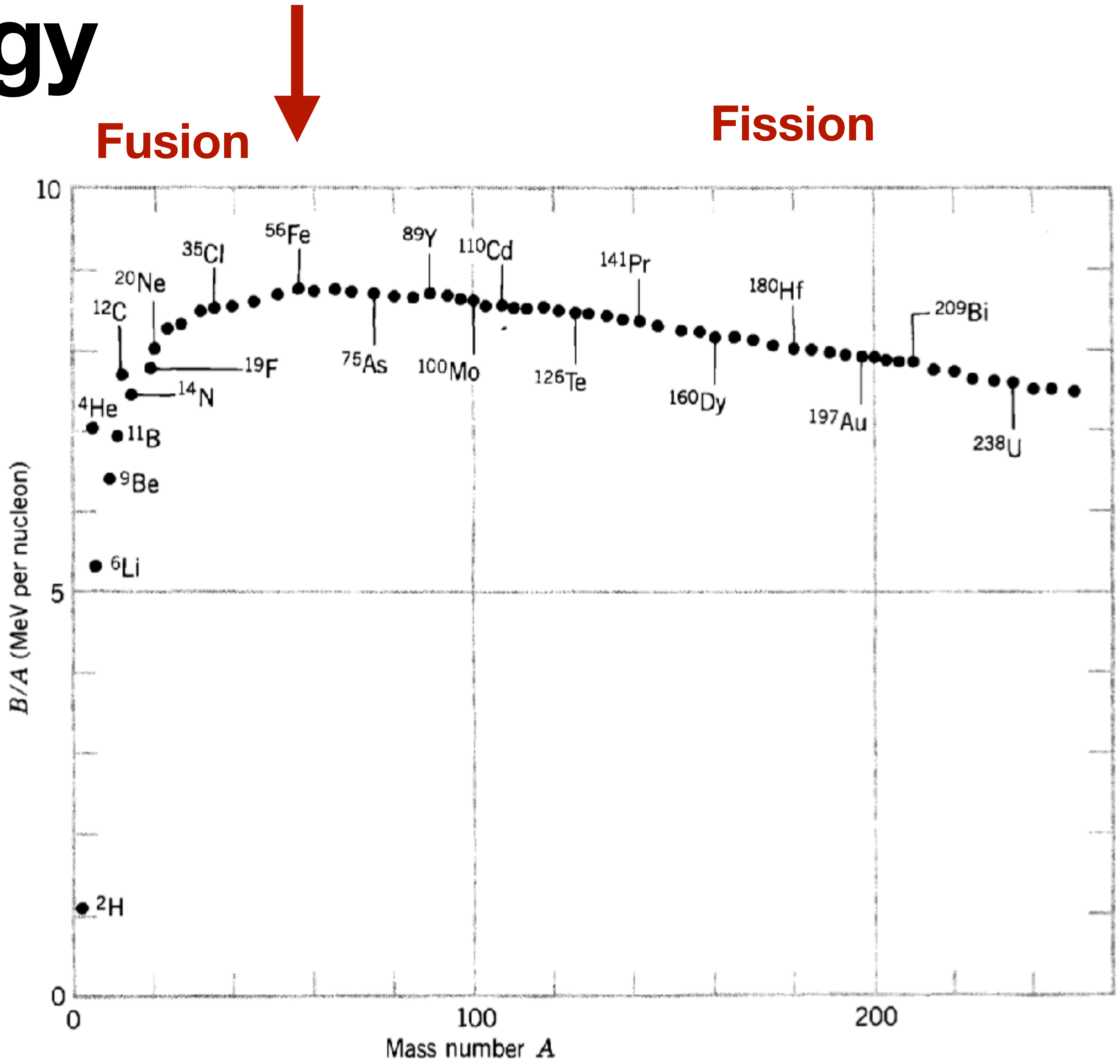


Figure 3.16 The binding energy per nucleon.

Nuclear fusion

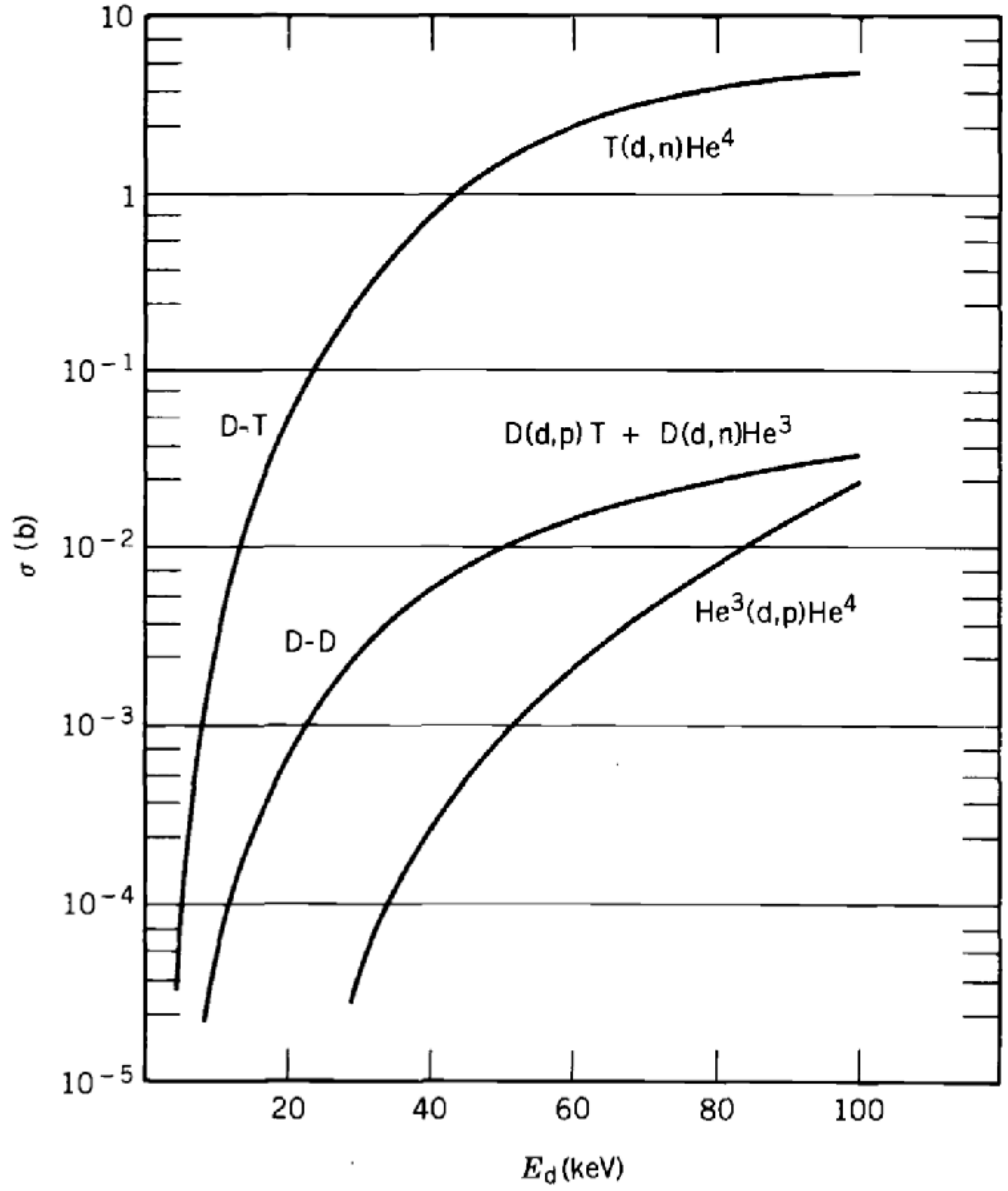


Figure 14.1 Cross sections for fusion reactions.

Nuclear fusion

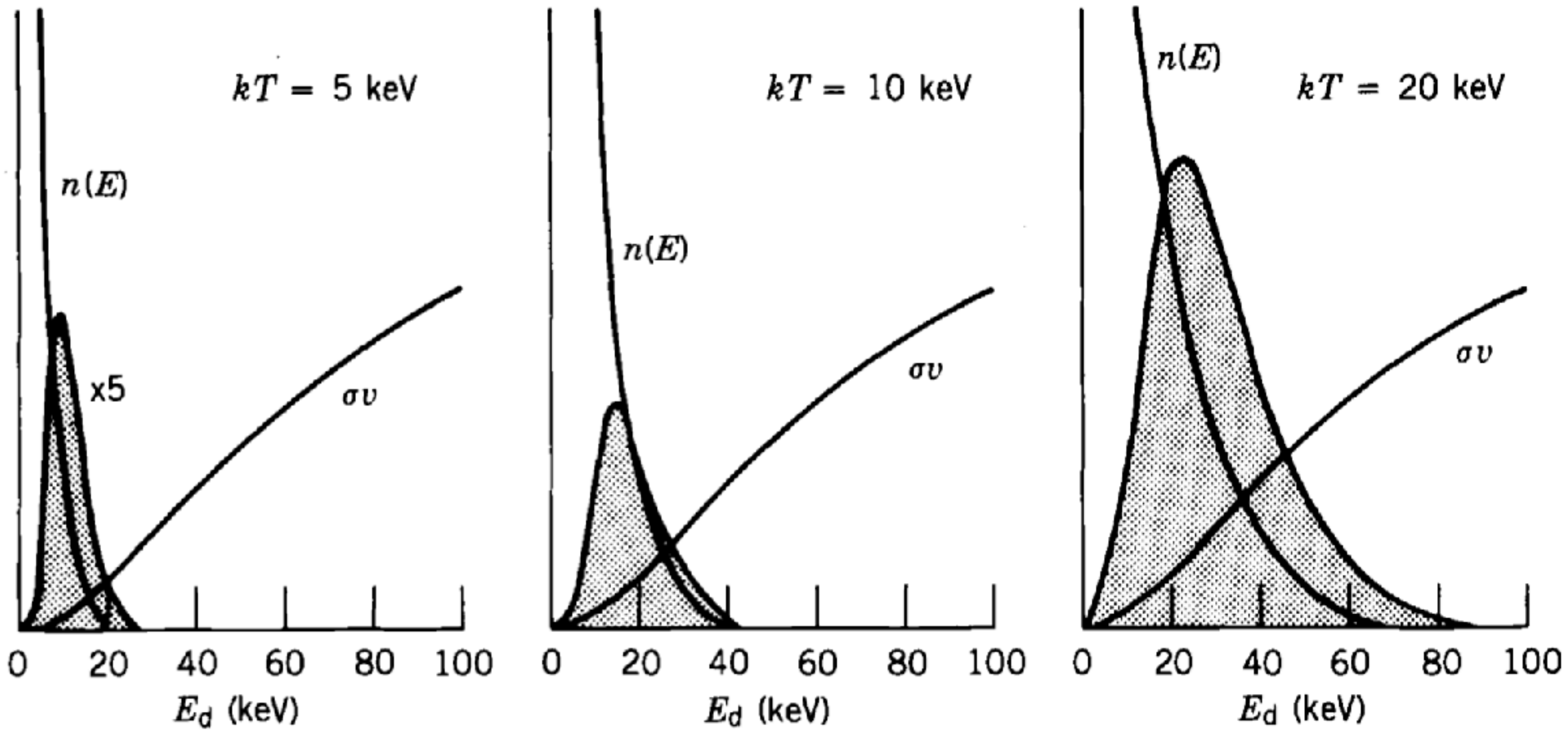


Figure 14.2 Folding of the product σv with a Maxwell-Boltzmann energy distribution at temperatures corresponding to $kT = 5$, 10, and 20 keV. The curve $n(E)$ shows the Maxwell-Boltzmann distribution, proportional to $E^{1/2}\exp(-E/kT)$; the curve $n(E)$ falls to zero at low energies, which is not shown in the graphs. The shaded area shows the product. Note the great increase in shaded area with kT, corresponding to an increase of $\langle \sigma v \rangle$ as is shown in Figure 14.3. The deuteron energy E_d is one-half of the total center-of-mass reaction energy E.

Nuclear fusion

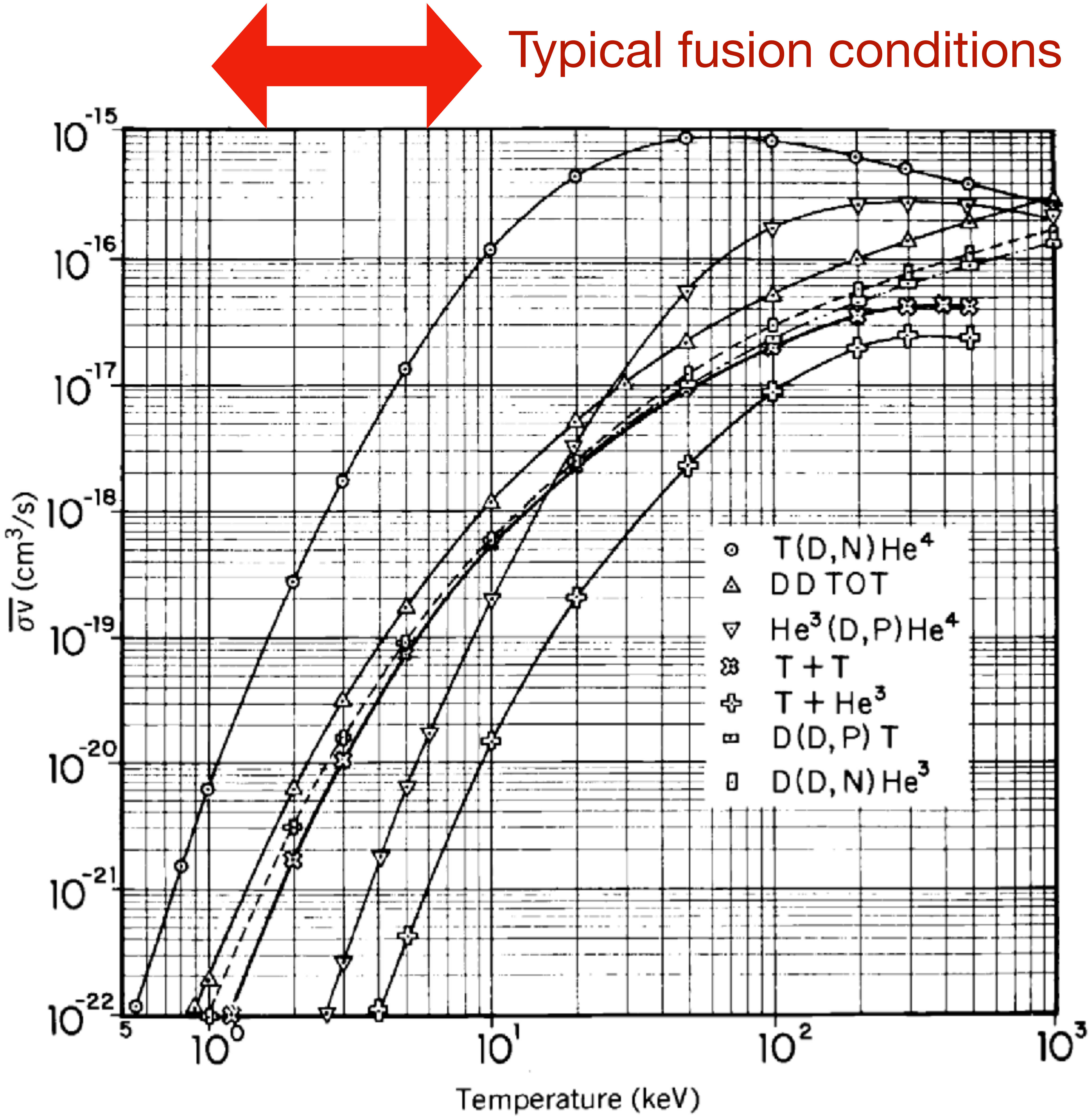
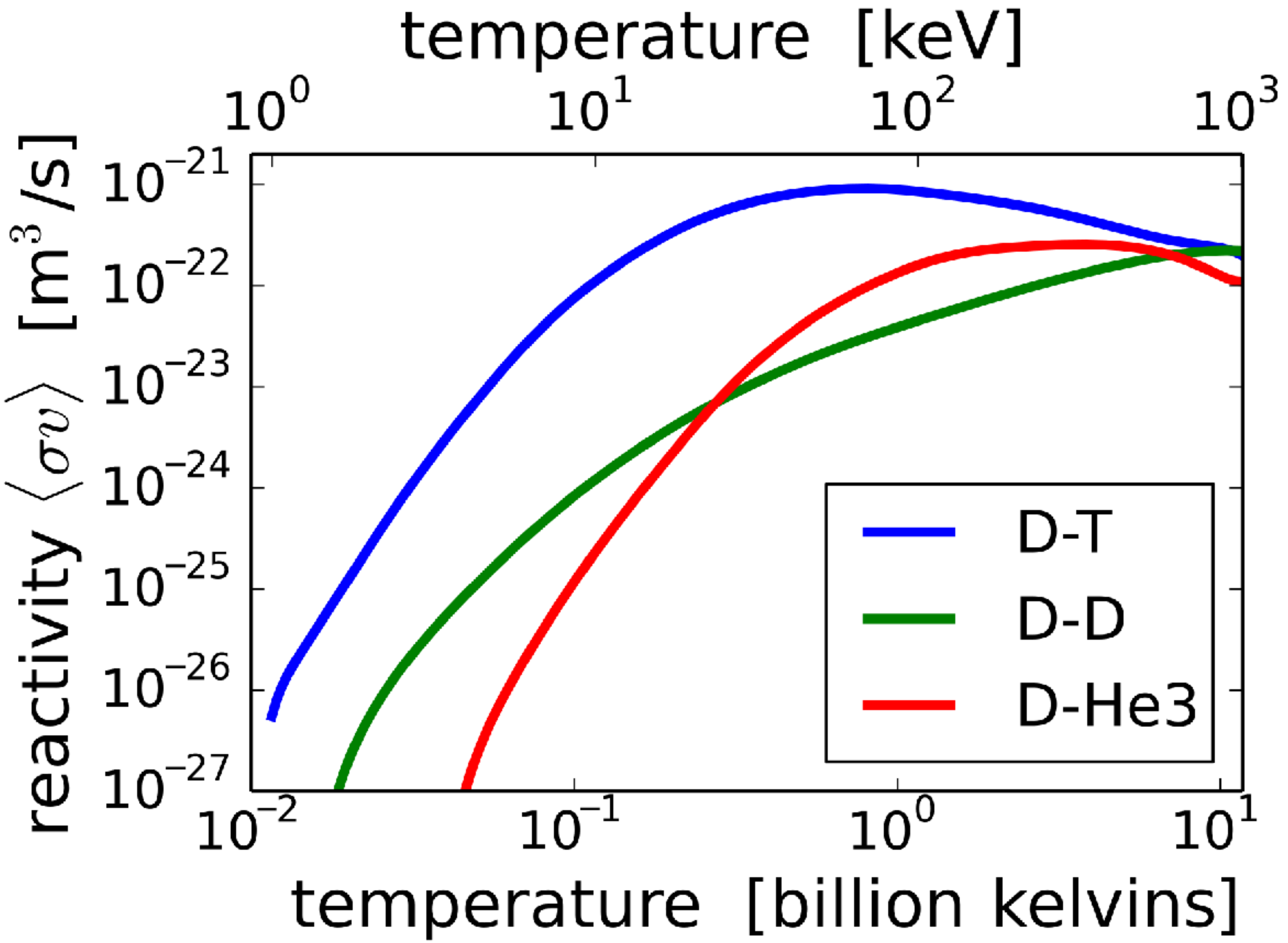


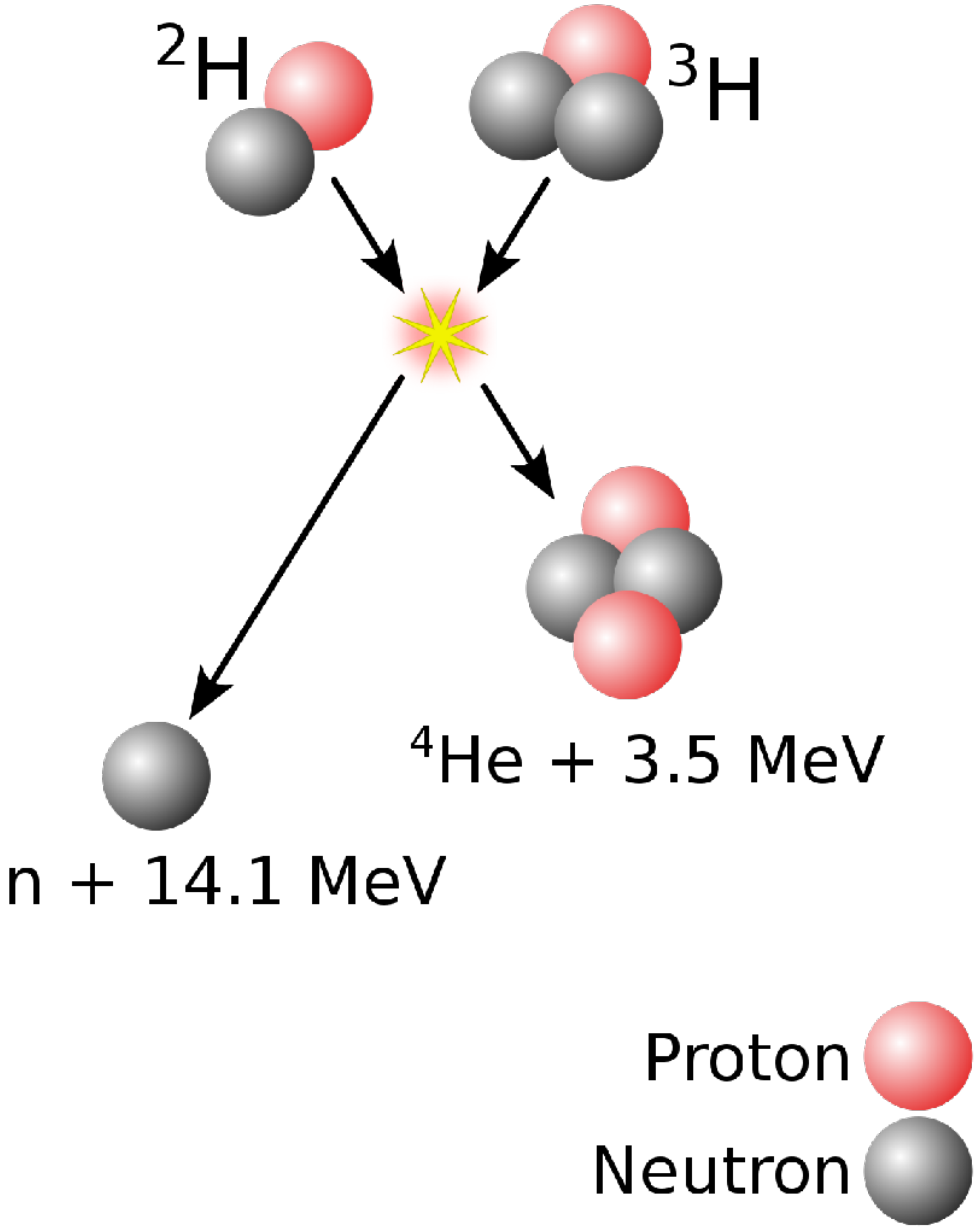
Figure 14.3 Values of σv averaged over a Maxwell-Boltzmann energy distribution for various fusion reactions. From D. Keefe, *Ann. Rev. Nucl. Particle Sci.* **32**, 391 (1982).

Nuclear fusion

- The fusion reaction rate increases rapidly with temperature until it maximizes and then gradually drops off.
- The DT rate peaks at a lower temperature (about 70 keV, or 800 million kelvin) and at a higher value than other reactions commonly considered for fusion energy.



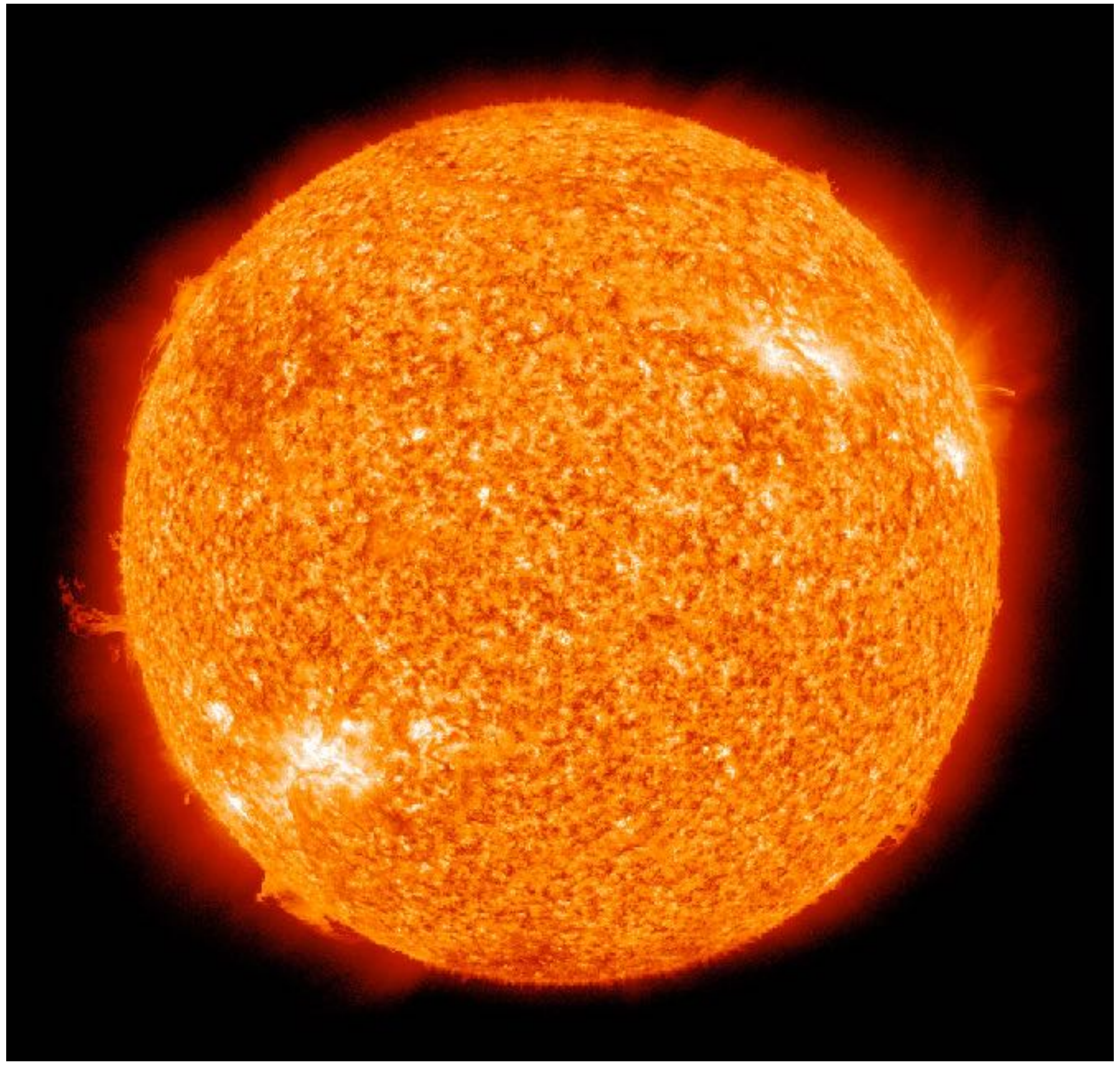
Nuclear fusion

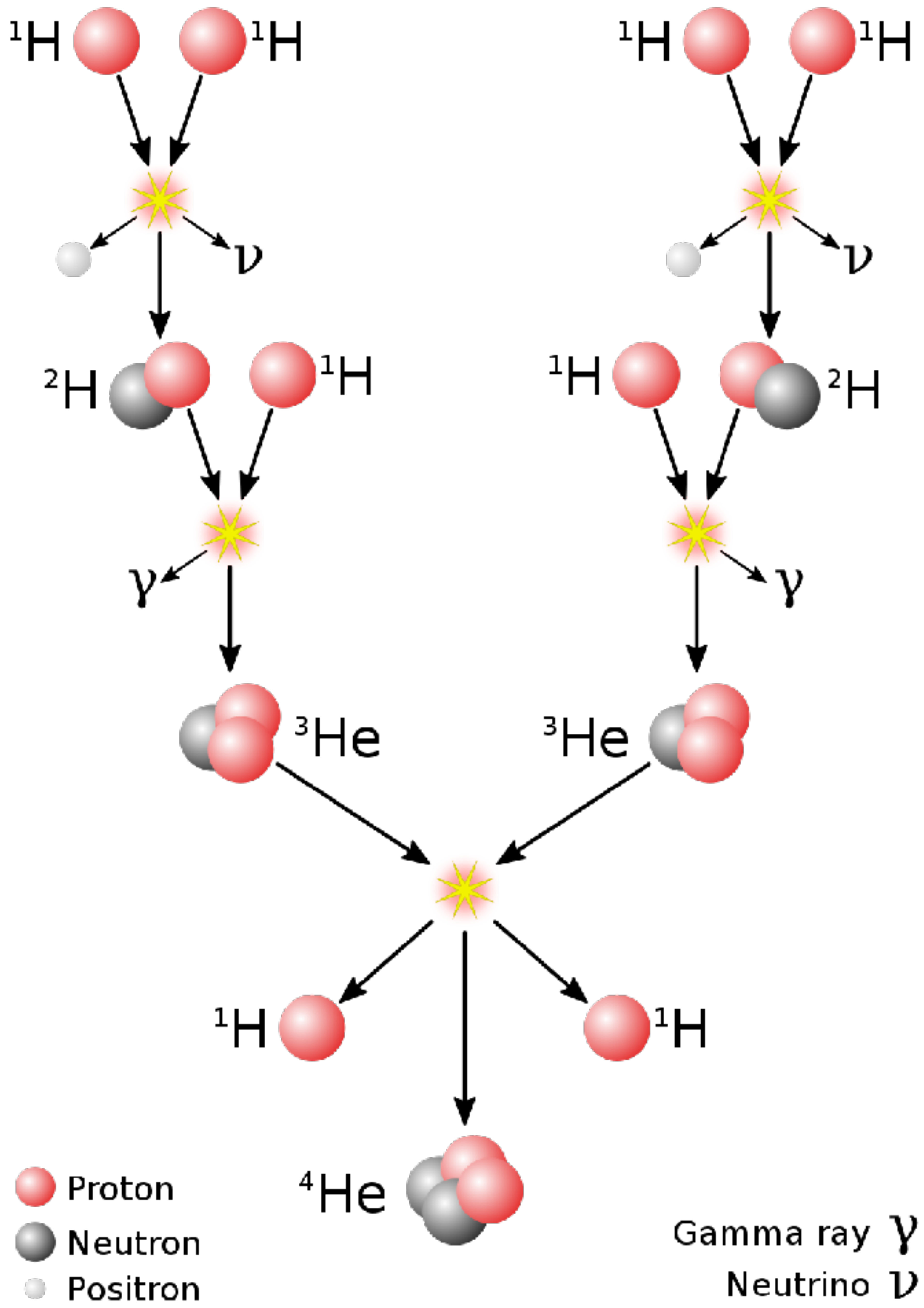


Fusion of **deuterium with tritium** creating ^4He, freeing a neutron, and releasing 17.59 MeV as kinetic energy of the products.

p-p chain

The proton–proton chain reaction, branch I, dominates in **stars the size of the Sun or smaller.**

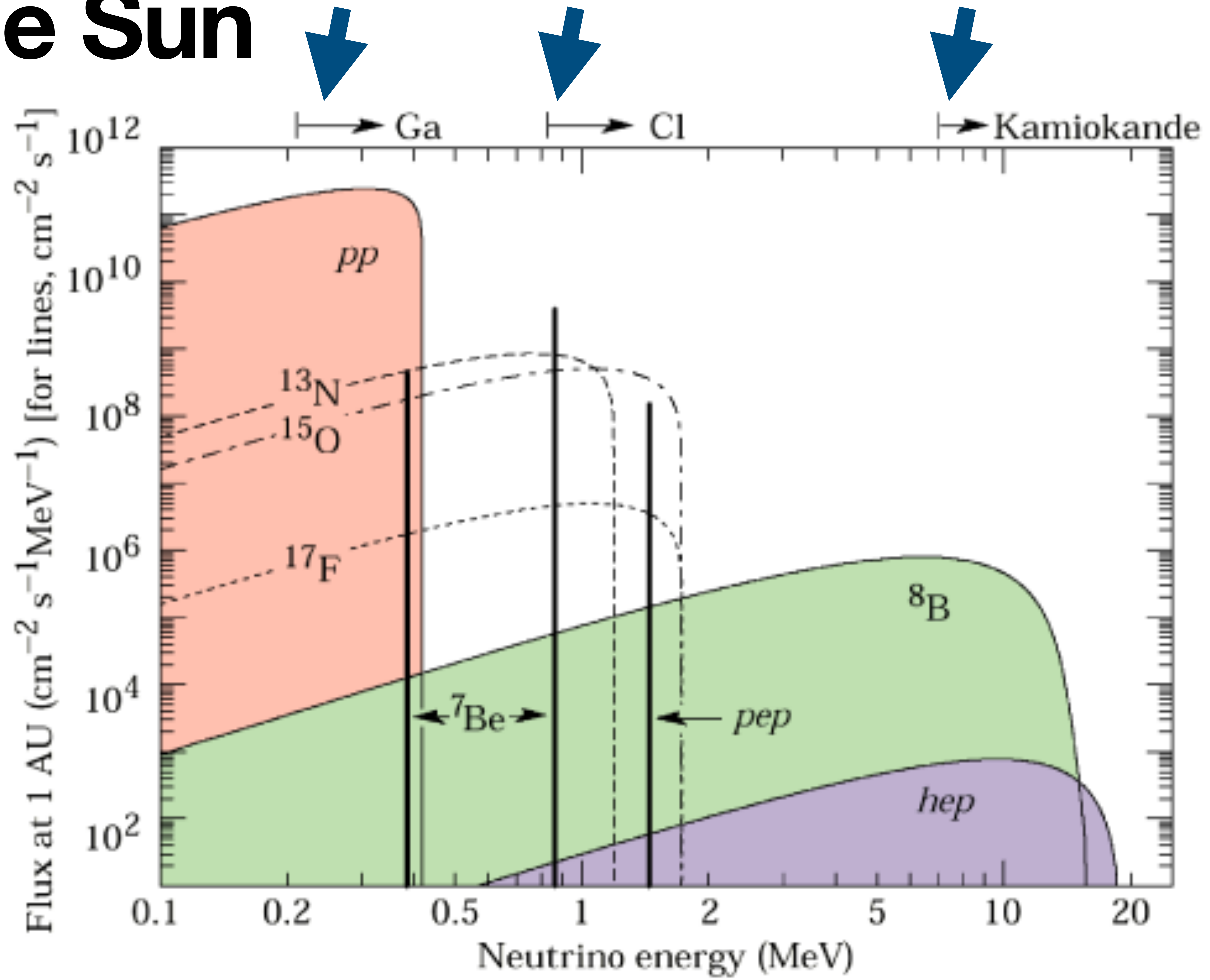




Neutrinos from the Sun

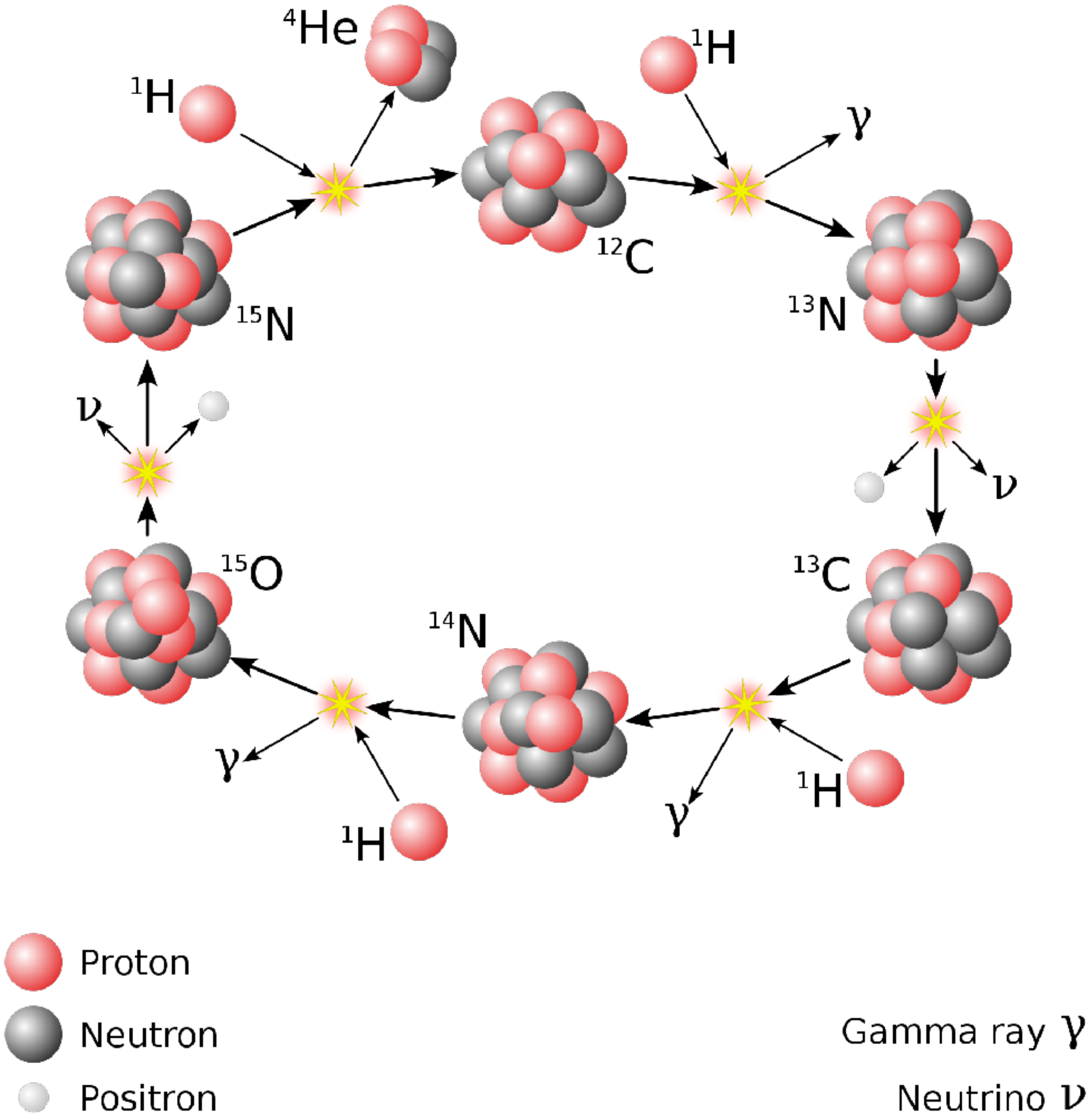
The fusion processes in the Sun can produce neutrinos with different energies.
The plot illustrates the **energy spectrum of the Solar neutrinos** based on **Solar models**.

Detection range of neutrino experiments



https://neutrino-history.in2p3.fr/solar-neutrinos/

CNO cycle

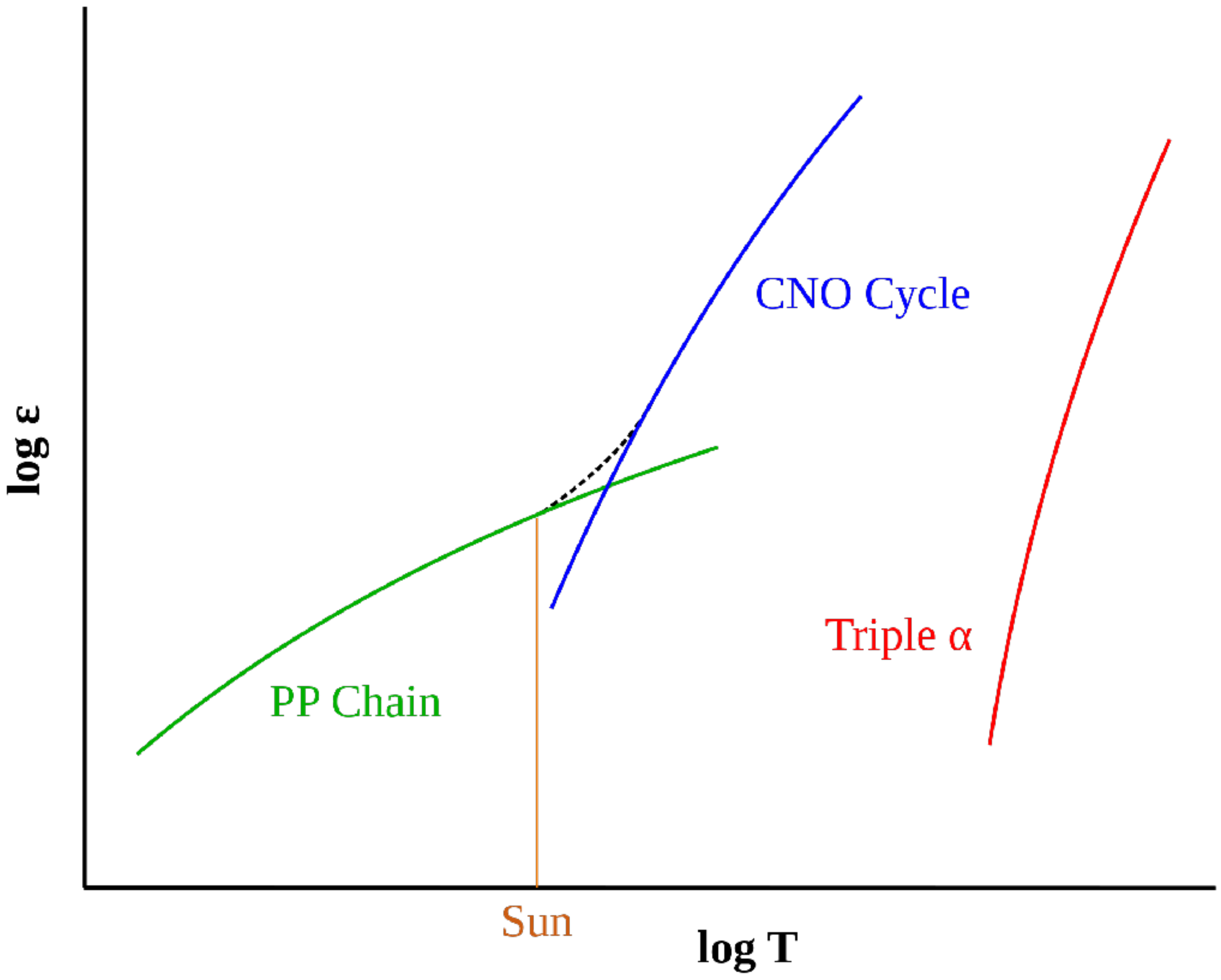


The CNO cycle dominates in stars **heavier than the Sun.**

Stellar fusion

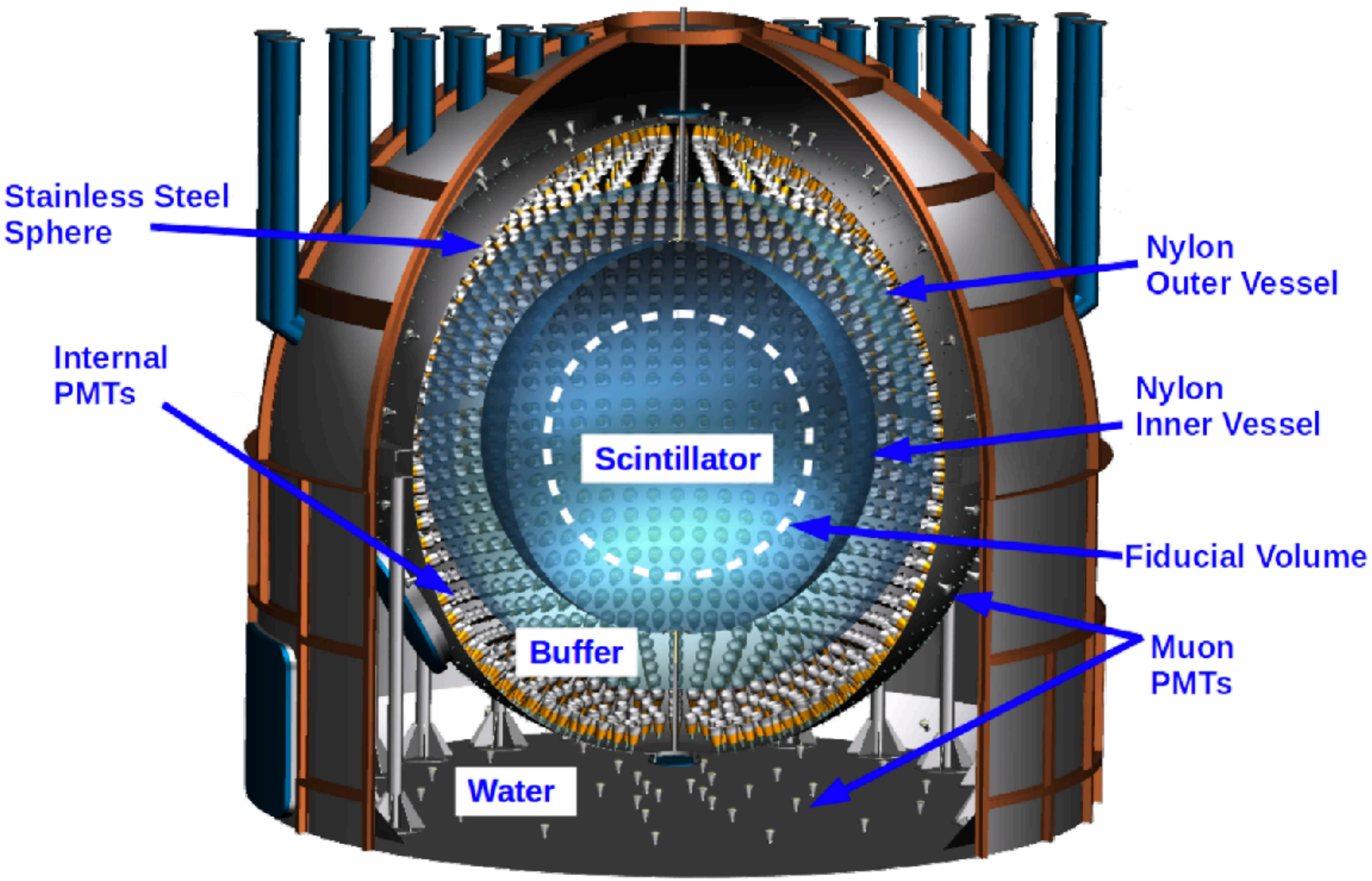
Temperature dependence and relative energy output of fusion chains.

This plot shows the rate of nuclear energy generation (ε) for a main sequence star as a function of temperature (T). The green curve shows the proton-proton cycle, blue is the CNO cycle and red is the triple-α process. The brown vertical line represents the core temperature of the Sun, demonstrating that the P-P chain is the primary source of energy generation. The dashed line joining the P-P curve to the CNO cycle represents the net energy generation rate of the combined nuclear hydrogen burning cycles. The slope of the curves shows the greater temperature sensitivity of the CNO cycle and triple-α process.



https://en.wikipedia.org/wiki/Stellar_nucleosynthesis

Neutrinos from the Sun



The Borexino detector in Italy
Has detected Solar neutrinos

https://www.nature.com/articles/s41586-020-2934-0

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Power generation

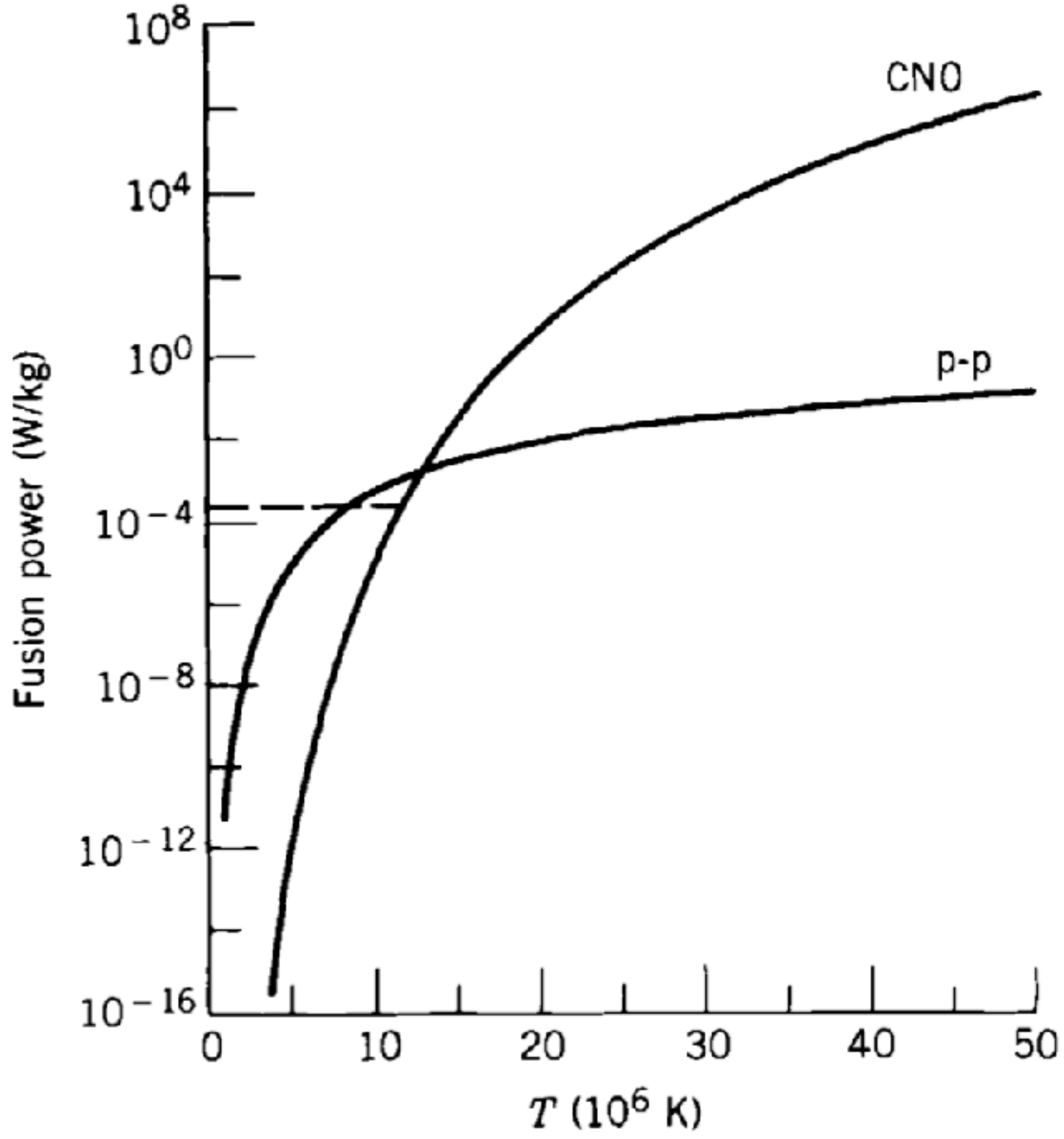
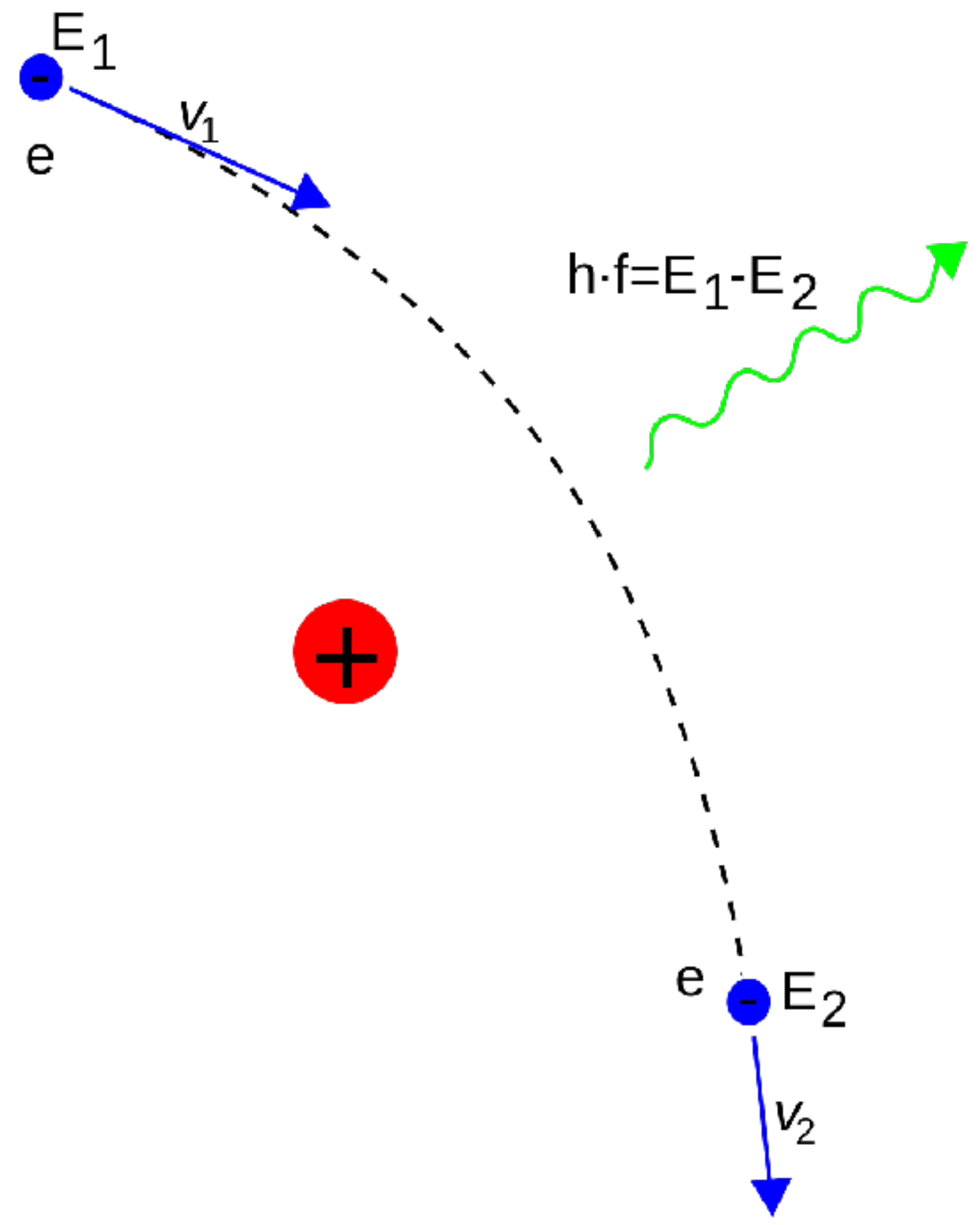


Figure 14.5 Power generation per unit mass of fuel for proton-proton and CNO processes. The dashed line indicates the sun's power of about 2×10^{-4} W / kg.

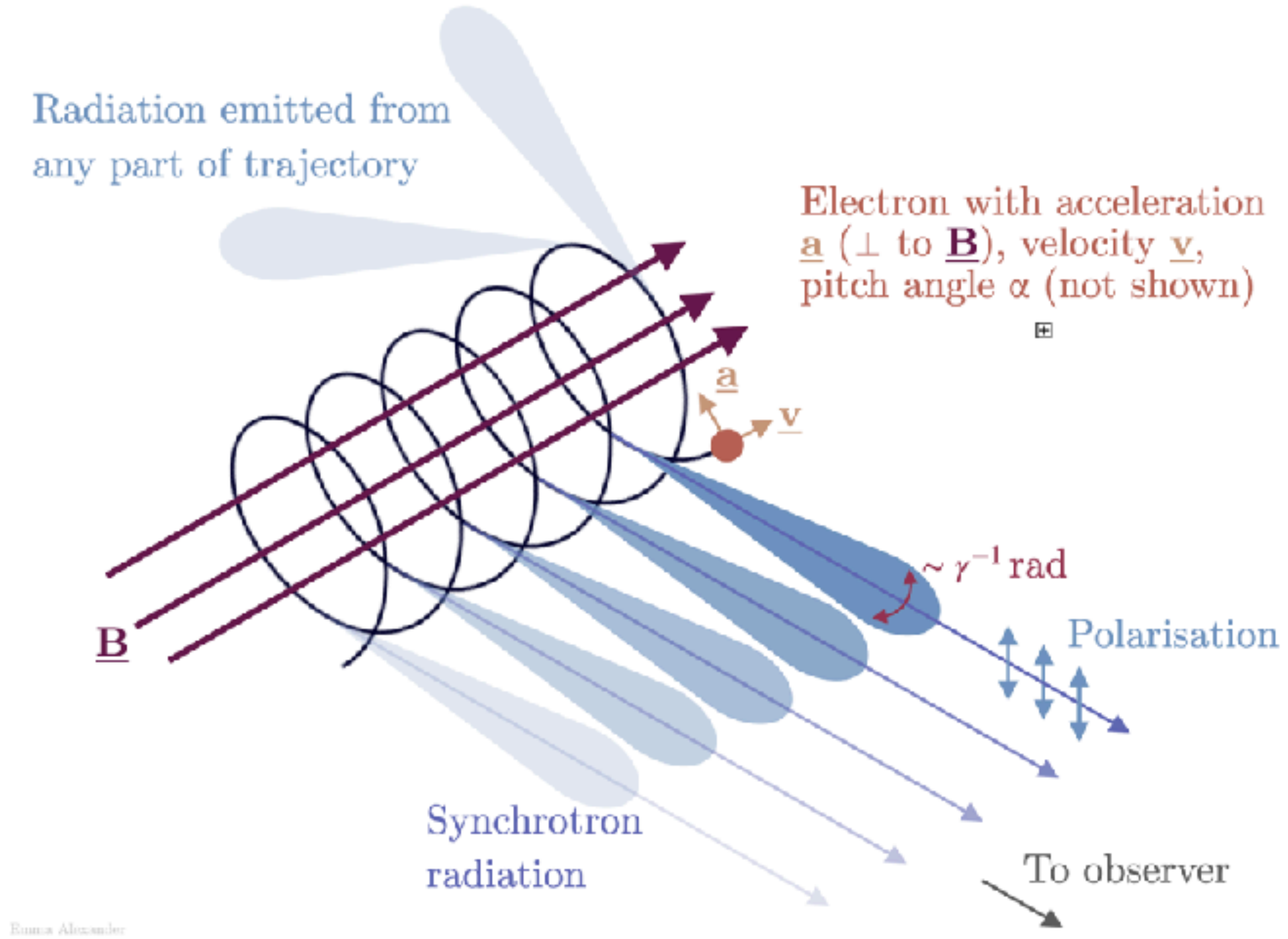
Bremsstrahlung

- A Bremsstrahlung, from bremsen "to brake" and Strahlung "radiation"; i.e., "braking radiation" or **"deceleration radiation"**, is electromagnetic radiation produced by the deceleration of a charged particle when deflected by another charged particle, typically an electron by an atomic nucleus.
- The moving particle loses kinetic energy, which is converted into radiation (i.e., photons), thus satisfying the law of conservation of energy.
- Bremsstrahlung has a continuous spectrum, which becomes more intense and whose peak intensity shifts toward higher frequencies as the change of the energy of the decelerated particles increases.



Synchrotron radiation

- **Synchrotron radiation is the electromagnetic radiation emitted when relativistic charged particles are subject to an acceleration perpendicular to their velocity**. It is produced naturally by fast electrons moving through magnetic fields. The radiation produced in this way has a characteristic polarization and the frequencies generated can range over a large portion of the electromagnetic spectrum.
- Synchrotron radiation is similar to bremsstrahlung radiation, which is emitted by a charged particle when the acceleration is parallel to the direction of motion.
- The **general term for radiation emitted by particles in a magnetic field is gyromagnetic radiation**, for which synchrotron radiation is the ultra-relativistic special case. Radiation emitted by charged particles moving non-relativistically in a magnetic field is called cyclotron emission. For particles in the mildly relativistic range (≈85% of the speed of light), the emission is termed gyro-synchrotron radiation.



https://en.wikipedia.org/wiki/Synchrotron_radiation

Confinement

The major division is between magnetic confinement and inertial confinement.

In **magnetic confinement**, the tendency of the hot plasma to expand is counteracted by the Lorentz force between currents in the plasma and magnetic fields produced by external coils. The particle densities tend to be in the range of 10^{18} to 10^{22} m^{-3} and the linear dimensions in the range of 0.1 to 10 m. The particle and energy confinement times may range from under a millisecond to over a second, but the configuration itself is often maintained through input of particles, energy, and current for times that are hundreds or thousands of times longer. Some concepts are capable of maintaining a plasma indefinitely.

In contrast, with **inertial confinement**, there is nothing to counteract the expansion of the plasma. The confinement time is simply the time it takes the plasma pressure to overcome the inertia of the particles, hence the name. The densities tend to be in the range of 10^{31} to 10^{33} m^{-3} and the plasma radius in the range of 1 to 100 micrometers. These conditions are obtained by irradiating a millimeter-sized solid pellet with a nanosecond laser or ion pulse. The outer layer of the pellet is ablated, providing a reaction force that compresses the central 10% of the fuel by a factor of 10 or 20 to 10^3 or 10^4 times solid density. These microplasmas disperse in a time measured in nanoseconds. For a fusion power reactor, a repetition rate of several per second will be needed.

https://en.wikipedia.org/wiki/List_of_fusion_experiments

Magnetic confinement

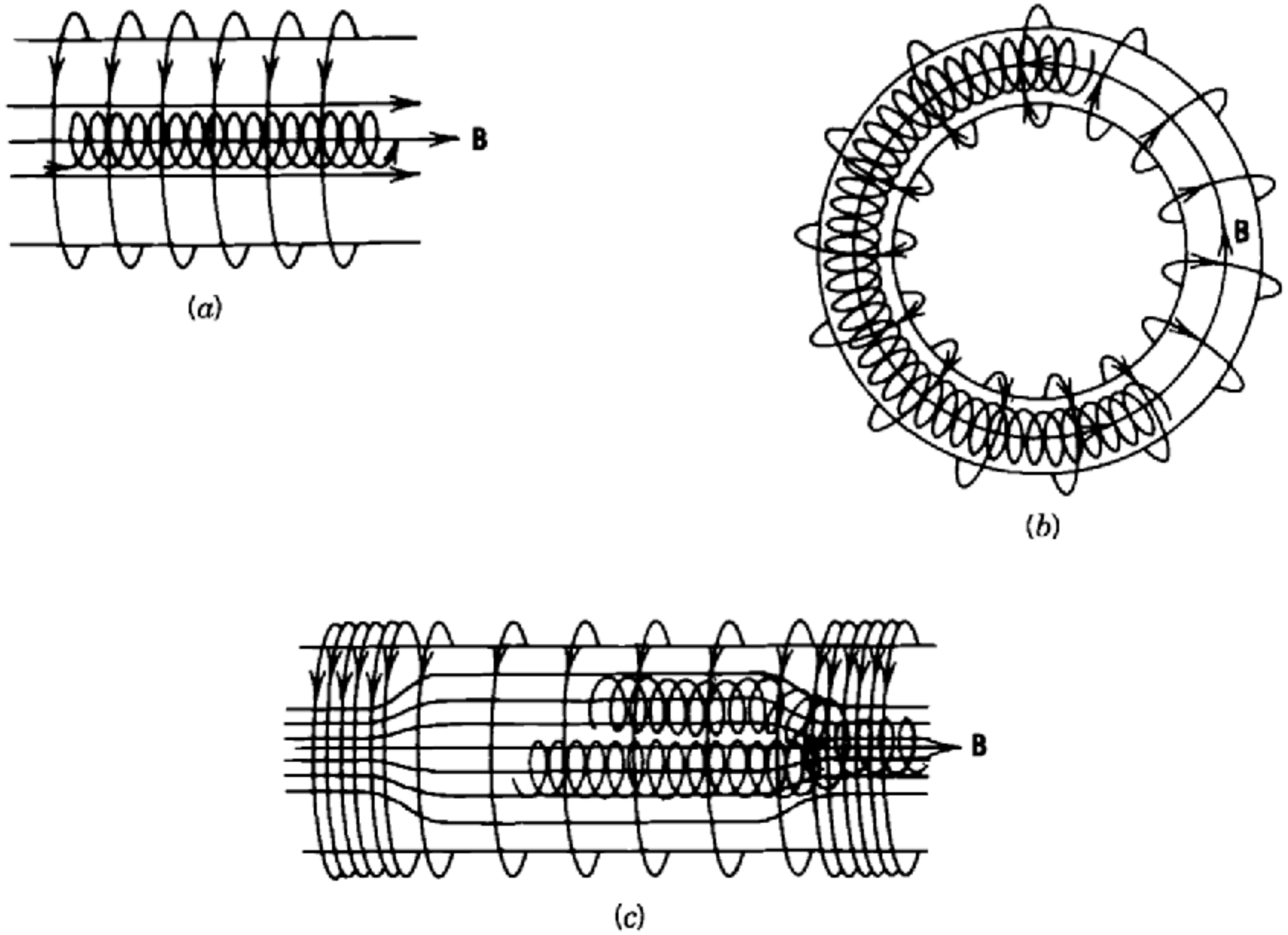
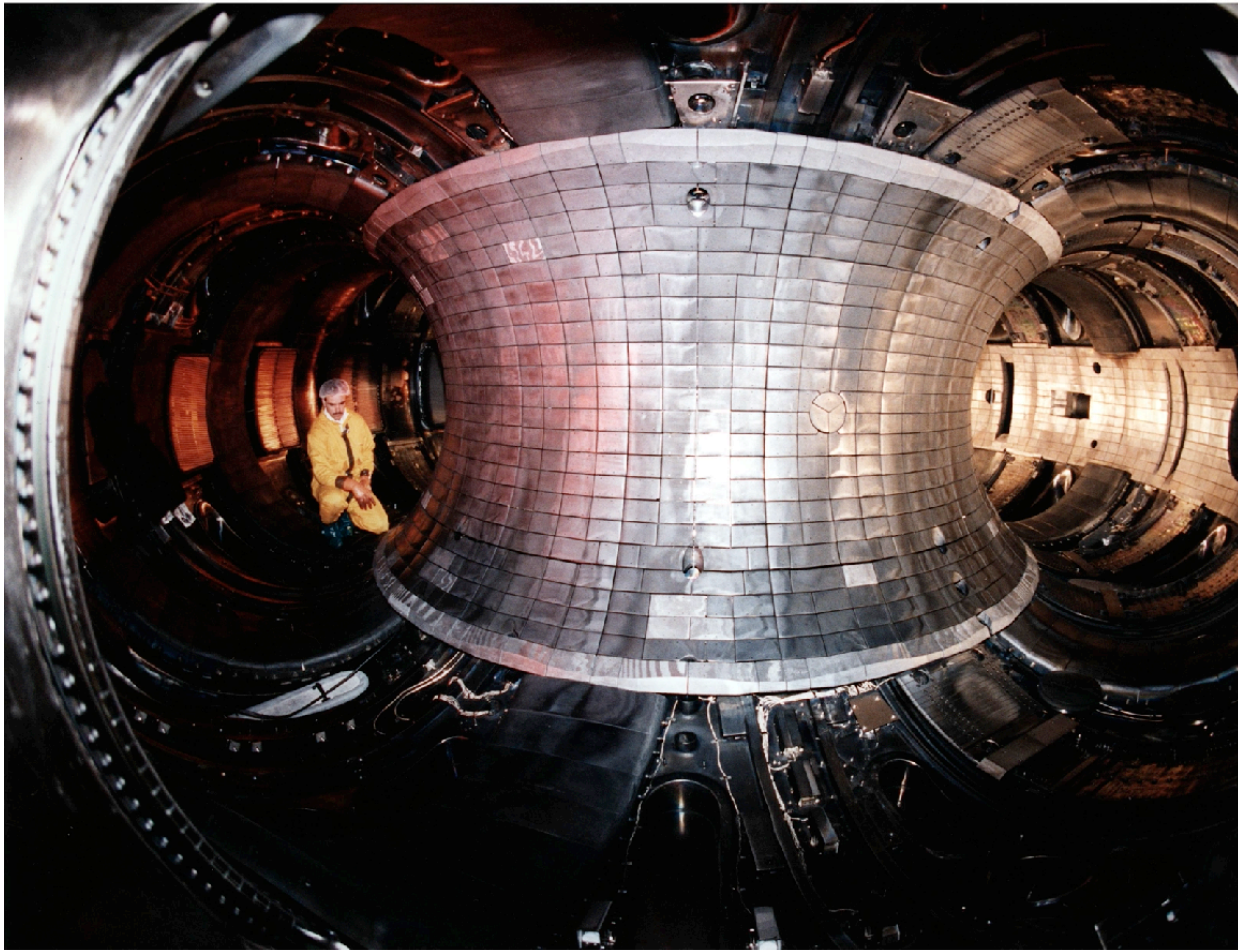


Figure 14.8 (*a*) Confinement by uniform axial magnetic field. The field ***B*** is established by the large current-carrying coils. The particles spiral about ***B***. (*b*) In a toroidal geometry, the particles follow the magnetic field lines as they spiral, but there is a gradual drift toward the outer wall. (*c*) In a magnetic mirror, the particles again follow the field lines, but are reflected from the high-field region.

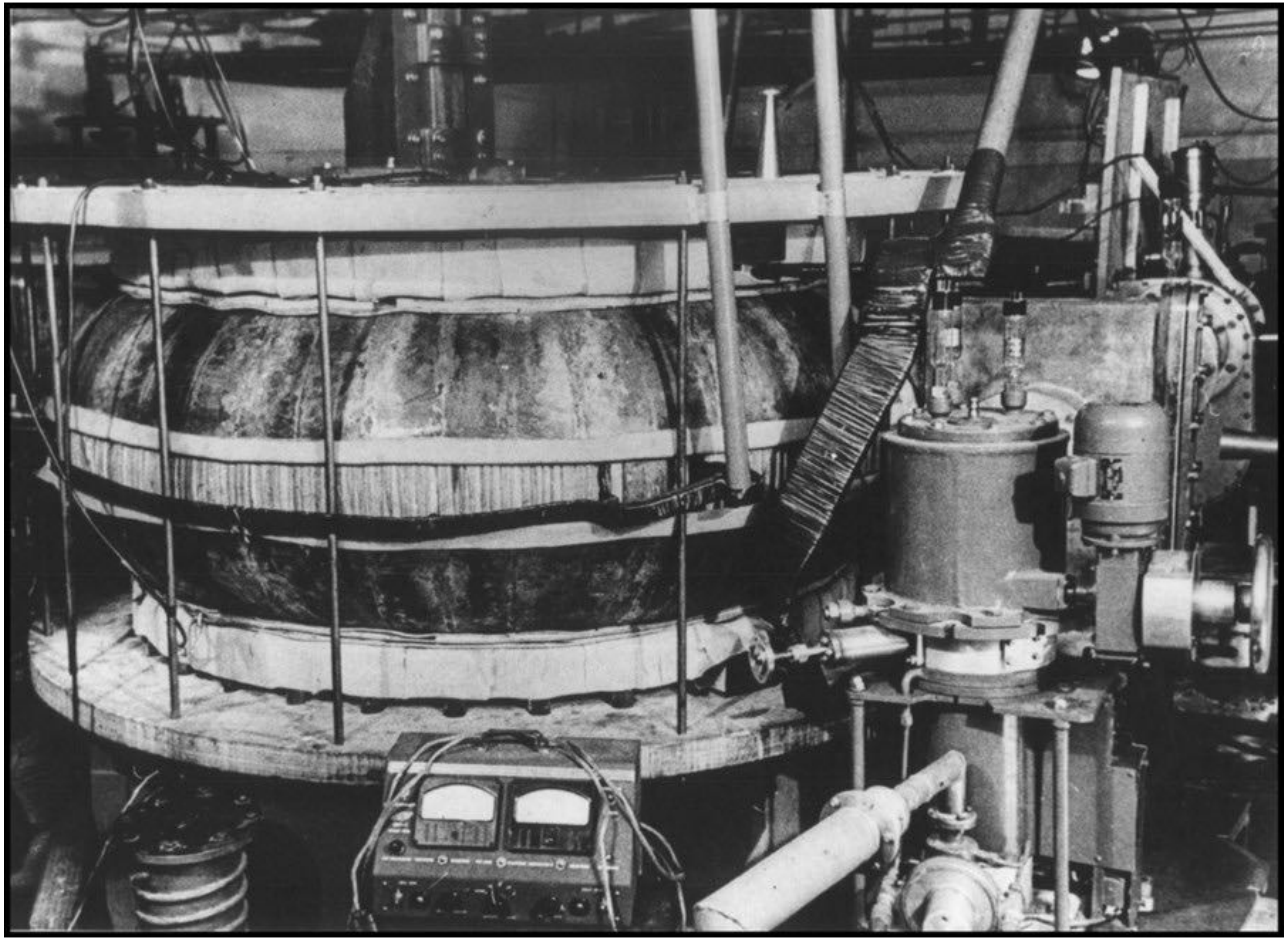
Magnetic confinement

Plasma chamber of TFTR, used for magnetic confinement fusion experiments, which produced 11 MW of fusion power in 1994
TFTR (Tokamak Fusion Test Reactor) at Princeton University



Magnetic confinement

The world's first tokamak device: the Russian T1 Tokamak at the Kurchatov Institute in Moscow. Plasmas in the range of 0.4 cubic metres were produced in its copper vacuum vessel.
Constructed in 1957



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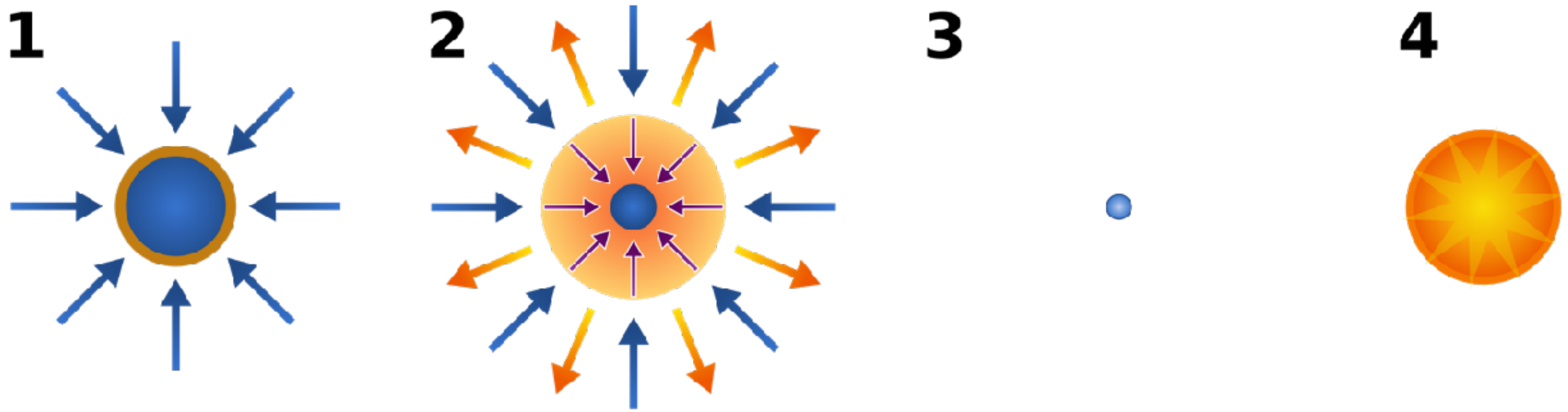
Inertial confinement



Schematic of the stages of inertial confinement fusion using lasers. The blue arrows represent radiation; orange is blowoff; yellow is inwardly transported thermal energy.

1. Laser beams or **laser-produced X-rays rapidly heat the surface** of the fusion target, forming a surrounding plasma envelope.
2. **Fuel is compressed** by the rocket-like blowoff of the hot surface material.
3. During the final part of the capsule implosion, the fuel core reaches 20 times the density of lead and ignites at 100,000,000 ˚C.
4. **Thermonuclear burn spreads rapidly** through the compressed fuel, yielding many times the input energy.

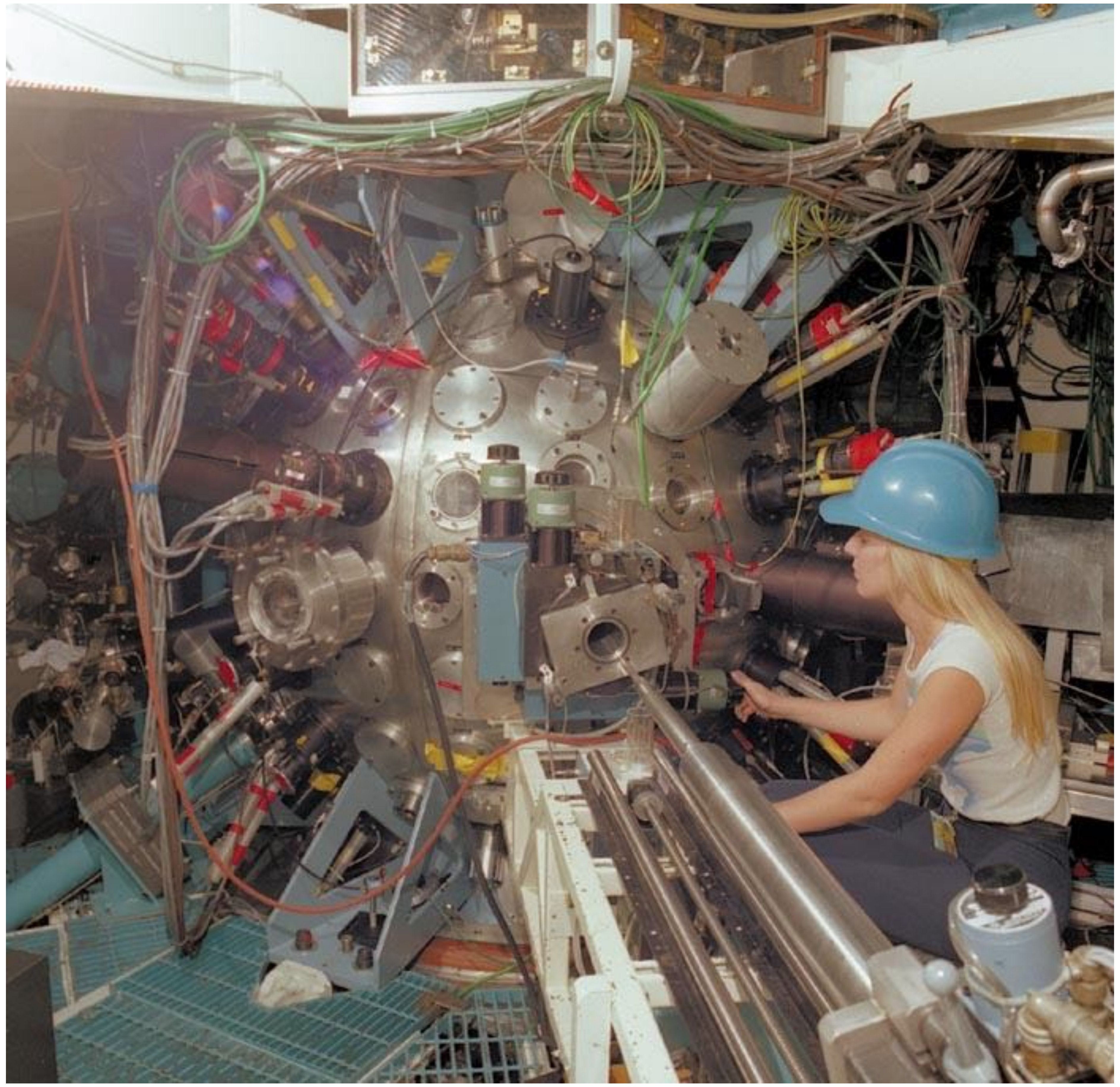
https://en.wikipedia.org/wiki/Inertial_confinement_fusion

Inertial confinement

Inertial confinement - experiments

Target chamber of the Shiva laser, used for inertial confinement fusion experiments from 1978 until decommissioned in 1981.

Built at the Lawrence Livermore National Laboratory

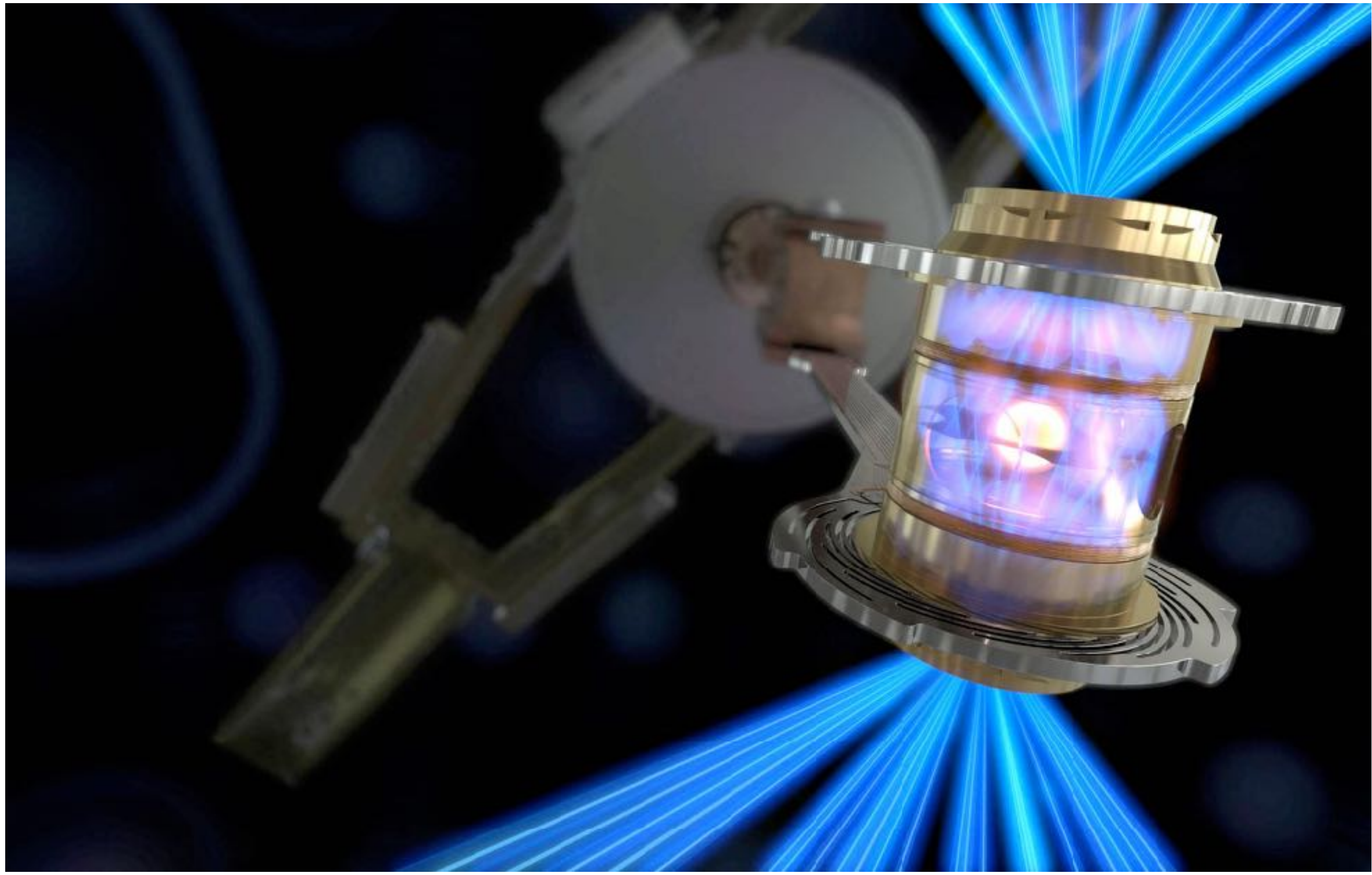


https://en.wikipedia.org/wiki/List_of_fusion_experiments

US National Ignition Facility

Inertial confinement - experiments

National Ignition Facility's **laser** energy is converted into x-rays inside the hohlraum, which then **compress a fuel capsule until it implodes,** creating a high temperature plasma, at Lawrence Livermore National Laboratory federal research facility in Livermore, California.



https://www.japantimes.co.jp/news/2022/12/14/world/science-health-world/lawrence-livermore-labs-nuclear-fusion/

Inertial confinement

Inertial confinement - experimer

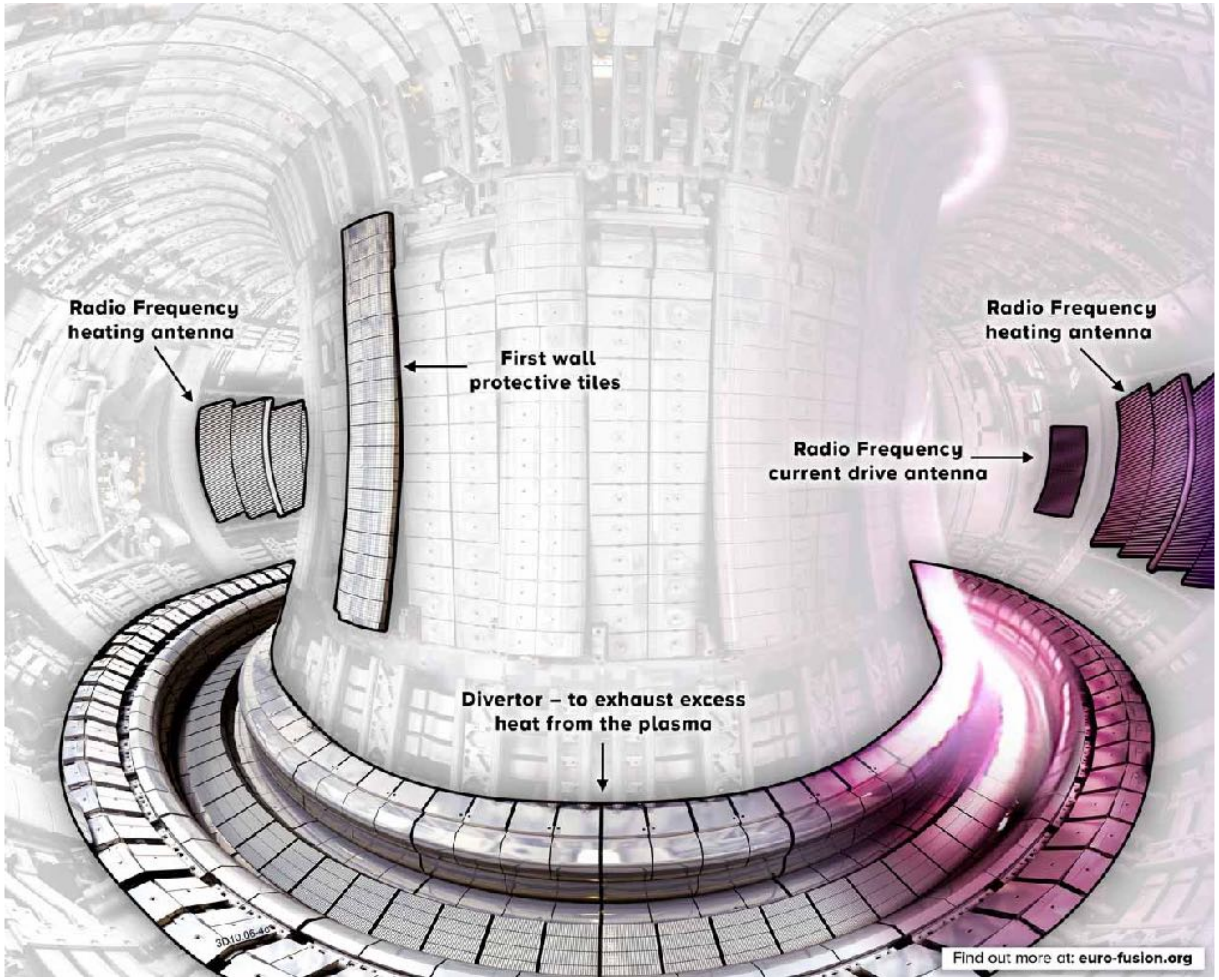
Image showing the arrangement of the later versions of the MEF or LIFE.1 (Laser Inertial Fusion Energy) power plant. The grey boxes arranged in groups at the top and bottom (just visible, shaded) are the laser beam-in-a-box systems. Their light, in blue, shines through the optical system into the yellow colored target chamber in the center. The machinery on the left pumps liquid lithium or flibe into the target chamber walls to cool the reactor, extract energy for generation, and produce tritium.

https://en.wikipedia.org/wiki/List_of_fusion_experiments

Inside the tokamak of Jet

The tokamak uses powerful external magnetic fields to confine and control the hot plasma of fusion fuels in a ring-shaped container called a ‘torus’.

It was first developed in the Soviet Union in the 1960s. The name tokamak is the Russian abbreviation of: toroidal chamber with magnetic coils.

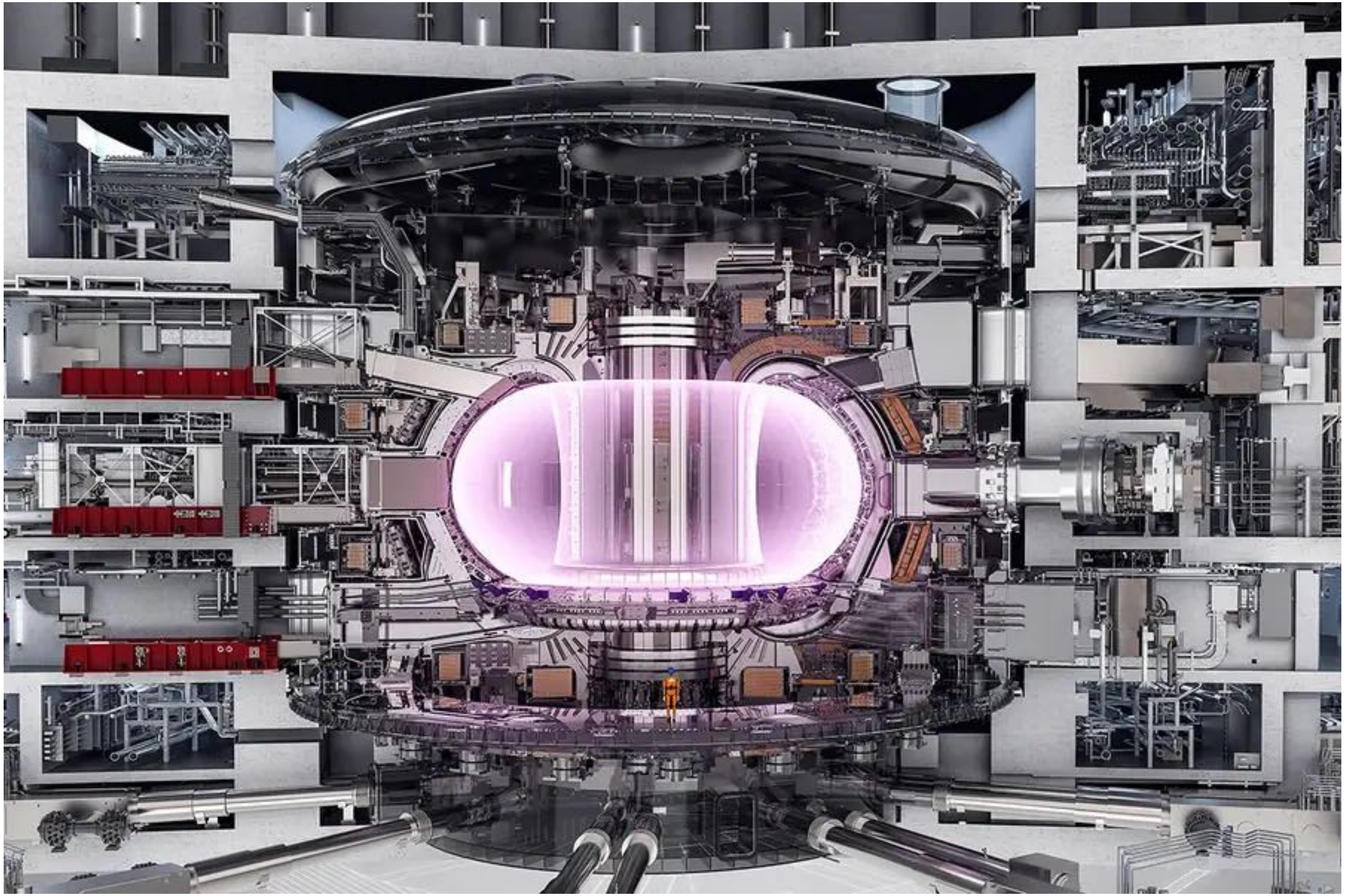


ITER under construction

ITER

CENTRAL SOLENOID

A tall electromagnet--the central solenoid--is at the heart of the ITER Tokamak. It both initiates plasma current and drives and shapes the plasma during operation. Image: https://www.iter.org/



https://www.newscientist.com/article/2280763-worlds-most-powerful-magnet-being-shipped-to-iter-fusion-reactor/

Nuclear Fusion