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# Science of fusion energy

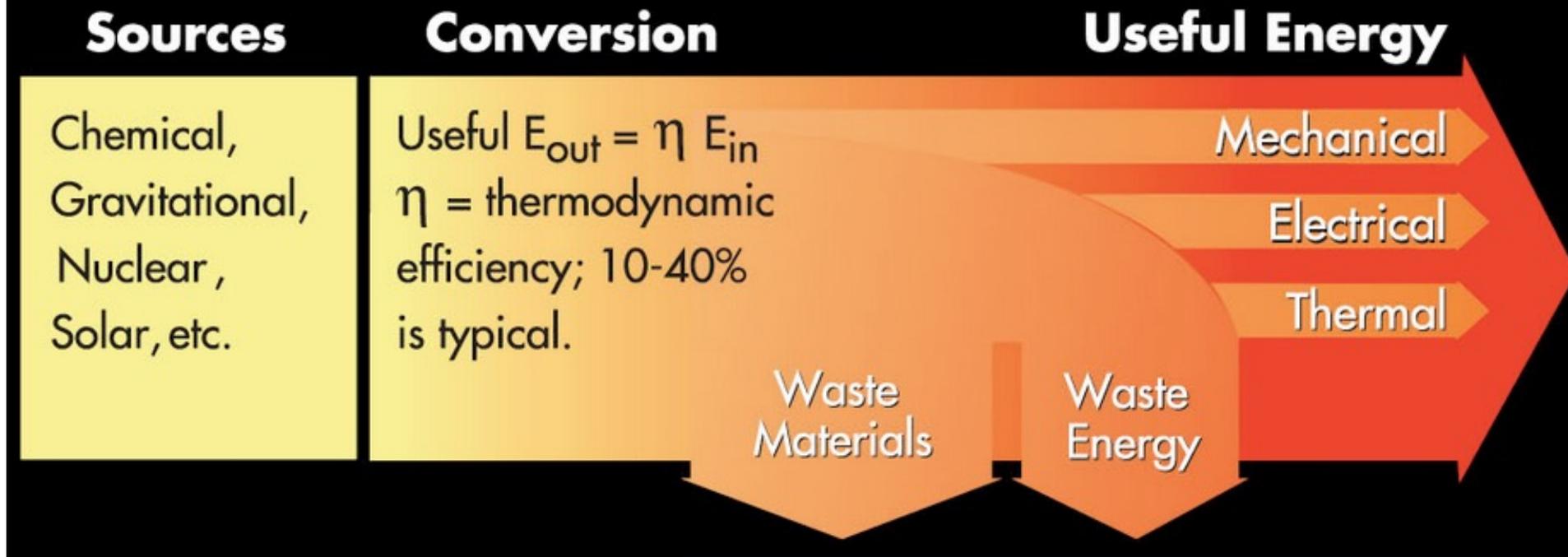
- Basic introduction
- Minimal math
  - $E = mc^2$ 
    - main formula behind fission and fusion
  - Unit conversion
    - Important to understand the scales involved
- Those with science/engineering backgrounds can see the references for more technical information

# General overview of energy conversion

## ENERGY SOURCES & CONVERSIONS

### AN OVERVIEW OF ENERGY CONVERSION PROCESSES ...

Energy can take on many forms, and various processes convert one form into another. While total energy always remains the same, most conversion processes reduce useful energy.



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# General overview of energy conversion

## ENERGY SOURCES & CONVERSIONS

### AN OVERVIEW OF ENERGY CONVERSION PROCESSES

Energy can take on many forms, but the total energy always remains constant.

#### Sources

Chemical,  
Gravitational,  
Nuclear,  
Solar, etc.

Think about goals for a useful energy source:

- High efficiency
- Abundant, easily obtained sources
- Waste materials
  - Minimize amount of waste and any negative impact on humans and environment

While

is typical.

Waste  
Materials

Waste  
Energy

Thermal

# Comparison of different processes of energy generation

## Physical Parameters of Energy-Releasing Reactions

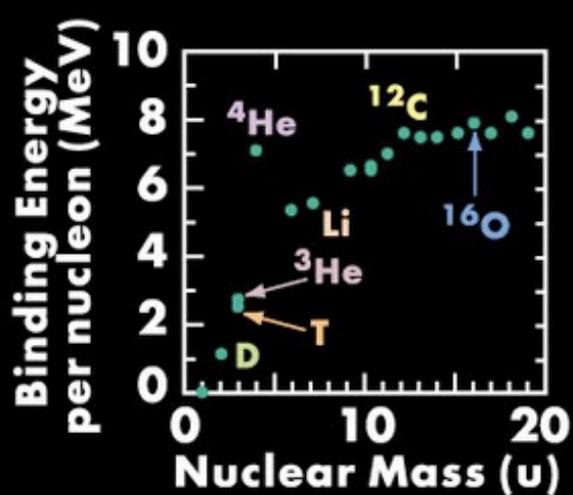
Reaction Type:	Chemical	Fission	Fusion
<b>Sample Reaction</b>	$C + O_2 \Rightarrow CO_2$	$^1_0n + ^{235}_{92}U \Rightarrow ^{143}_{56}Ba + ^{91}_{36}Kr + 2^1_0n$	$D (^2H) + T (^3H) \Rightarrow ^4He + ^1_0n$
<b>Typical Inputs (to Power Plant)</b>	Coal and Air	UO <sub>2</sub> (3% <sup>235</sup> U + 97% <sup>238</sup> U)	Deuterium and Lithium
<b>Typical Temp. (K)</b>	1000	1000	100,000,000
<b>Energy Released per kg Fuel (J/kg)</b>	$3.3 \times 10^7$	$2.1 \times 10^{12}$	$3.4 \times 10^{14}$

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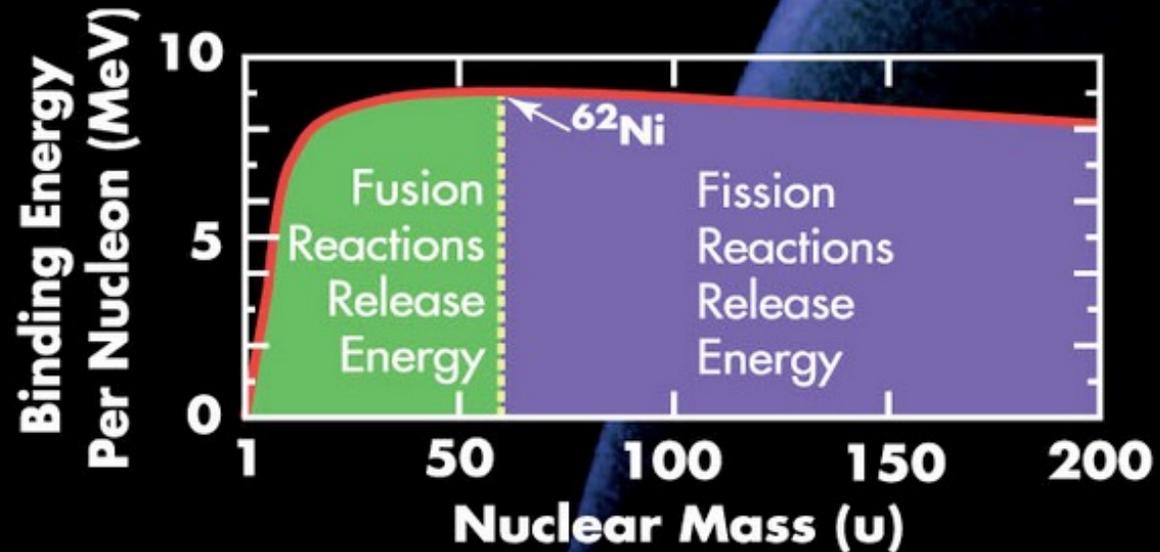
# A little bit of nuclear physics...

Fusion of low-mass elements releases energy, as does fission of high-mass elements.

## Binding Energy per Nucleon as a Function of Nuclear Mass



Low-Mass Elements Only



## Nuclear Reaction Energy: $\Delta E = k (m_i - m_f) c^2$

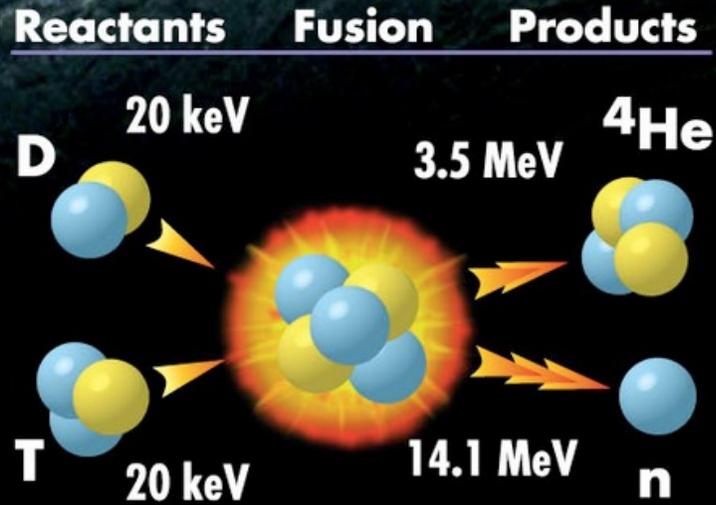
From Einstein's  $E = mc^2$ .  $\Delta E$  = energy change per reaction;  $m_i$  = total initial (reactant) mass;  $m_f$  = total final (product) mass. The conversion factor  $k$  is 1 in SI units, or  $931.466 \text{ MeV}/\text{uc}^2$  when  $E$  is in MeV and  $m$  is in atomic mass units,  $u$ .

# D-T process (man-made fusion) vs p-p (Sun)

## TWO IMPORTANT FUSION PROCESSES

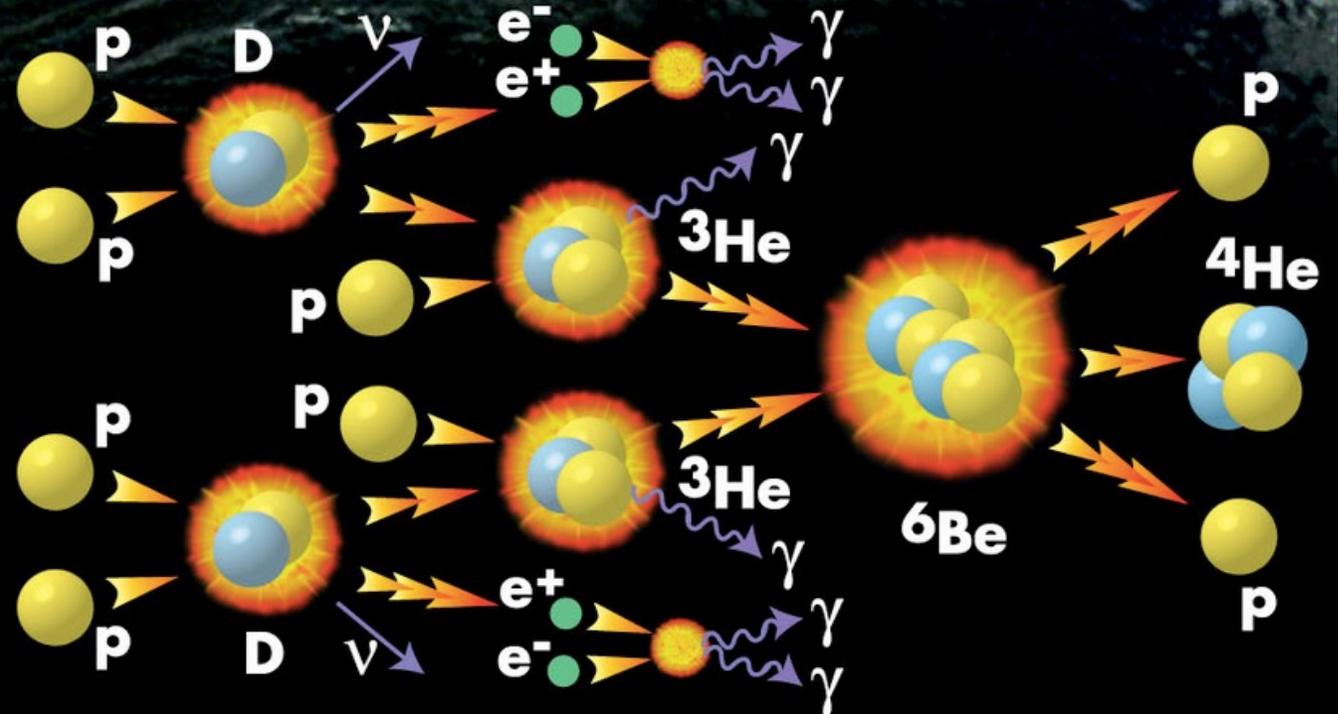


For first generation fusion reactors



1 eV =  $1.6022 \times 10^{-19}$  J. Average particle thermal kinetic energy is 1 eV per 11,600 K.

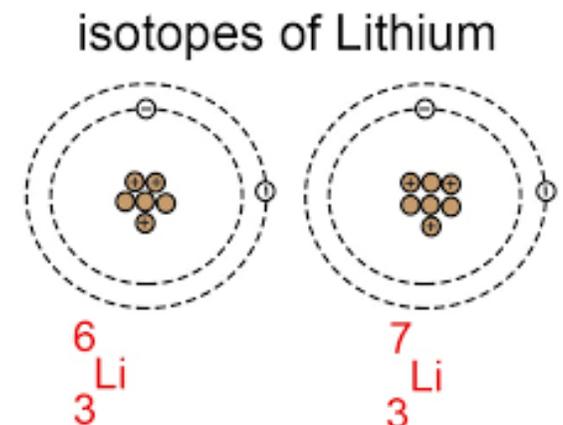
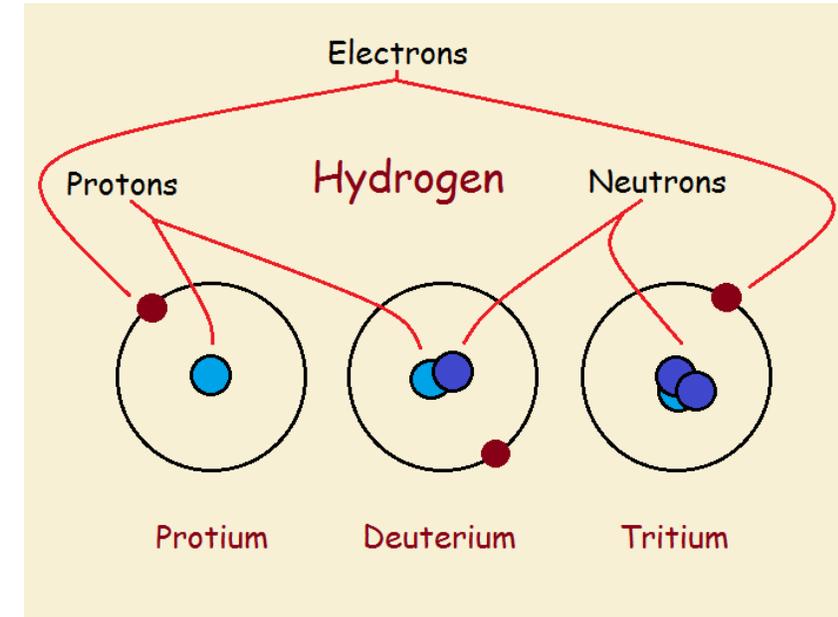
## "p-p": SOLAR FUSION CHAIN



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# Fuel for fusion

- Deuterium
  - Stable, harmless isotope of hydrogen (one proton+one neutron)
  - Can be distilled from all forms of water
    - E.g. 33 grams of deuterium in each cubic meter of sea water
- Tritium
  - Unstable isotope of hydrogen (one proton + two neutrons)
    - Half-life: 12.5 years
    - Used to be used to make glowing watch dials
  - Too rare in nature to get needed quantities
  - Can be created by bombarding Lithium with neutrons
    - Neutrons can come from the fusion reactor itself, so you really just need to supply Lithium
- Lithium
  - Metal (Used in batteries as well), found in rocks, brine, seawater
  - A 1-GW reactor would require 500 kg of Li per year



For practical energy generation, you need a large reaction rate

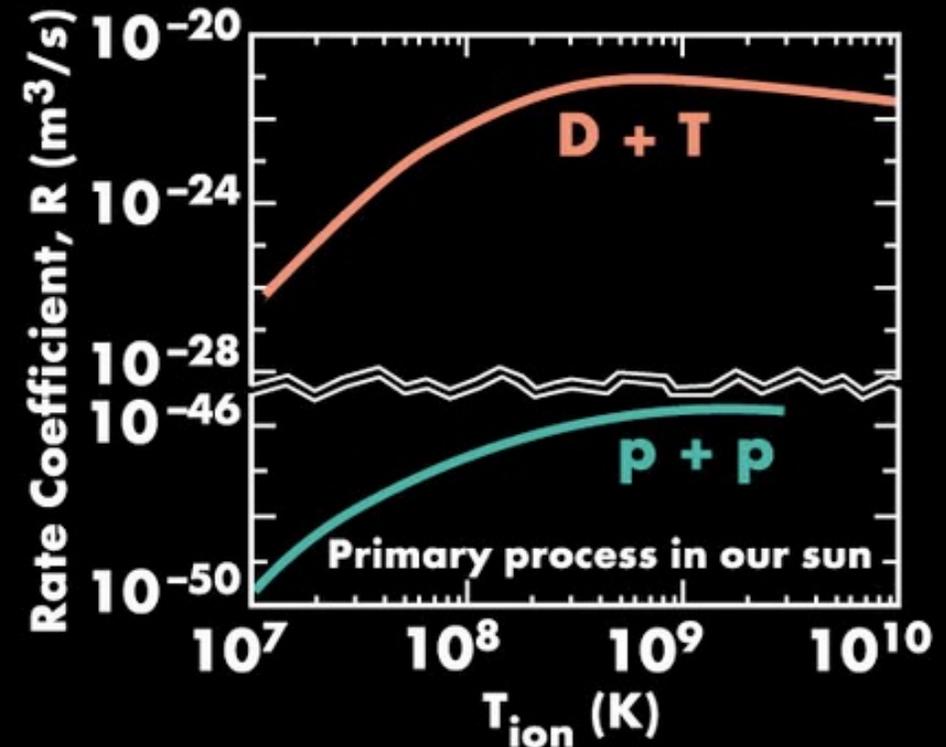
## Useful Nuclear Masses

(The electron's mass is 0.000549 u.)

Label	Species	Mass (u*)
n ( ${}^1_0\text{n}$ )	neutron	1.008665
p ( ${}^1_1\text{H}$ )	proton	1.007276
D ( ${}^2_1\text{H}$ )	deuteron	2.013553
T ( ${}^3_1\text{H}$ )	triton	3.015500
${}^3\text{He}$	helium-3	3.014932
$\alpha$ ( ${}^4_2\text{He}$ )	helium-4	4.001506

\* 1 u =  $1.66054 \times 10^{-27}$  kg = 931.466 MeV/c<sup>2</sup>

## Fusion Rate Coefficients



**Plasma Fusion Reaction Rate Density =  $R n_1 n_2$**

$n_1, n_2$  = densities of reacting species (ions/m<sup>3</sup>);  $R$  = Rate Coefficient (m<sup>3</sup>/s).

Multiply by  $\Delta E$  to get the fusion power density.

# Ways of obtaining the necessary temperature and density

## CREATING THE CONDITIONS FOR FUSION PLASMA CONFINEMENT AND HEATING

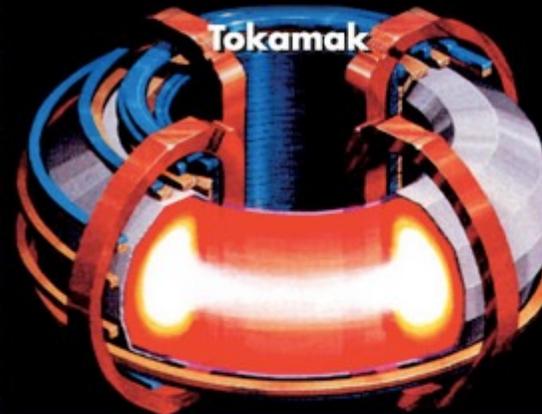
### Confinement:

Fusion requires high temperature plasmas confined long enough at high density to release appreciable energy.

### Gravity



### Magnetic Fields



### Inertia



### Typical Scales:

Size:  $10^{19}$  m  
Plasma Duration:  $10^{15}$  -  $10^{18}$  s

Size: 10 m  
Plasma Duration:  $10^{-2}$  to  $10^6$  s

Size:  $10^{-1}$  m  
Plasma Duration:  $10^{-9}$  to  $10^{-7}$  s

### Heating Mechanisms:

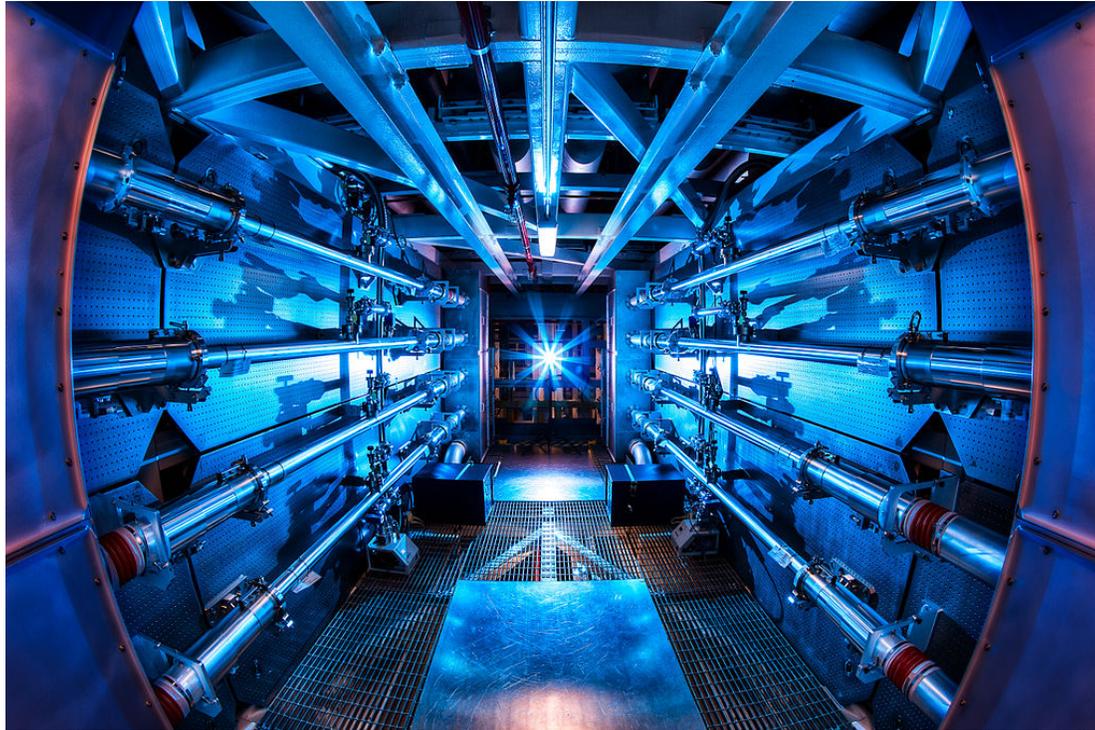
- Compression
- Fusion Product Energy

- Electromagnetic Waves
- Ohmic Heating (electricity)
- Neutral Beam Injection (beams of atomic hydrogen)
- Compression
- Fusion Product Energy

- Compression (Implosion driven by laser or ion beams, or by x rays from laser or ion beams)
- Fusion Product Energy

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# Inertial Confinement



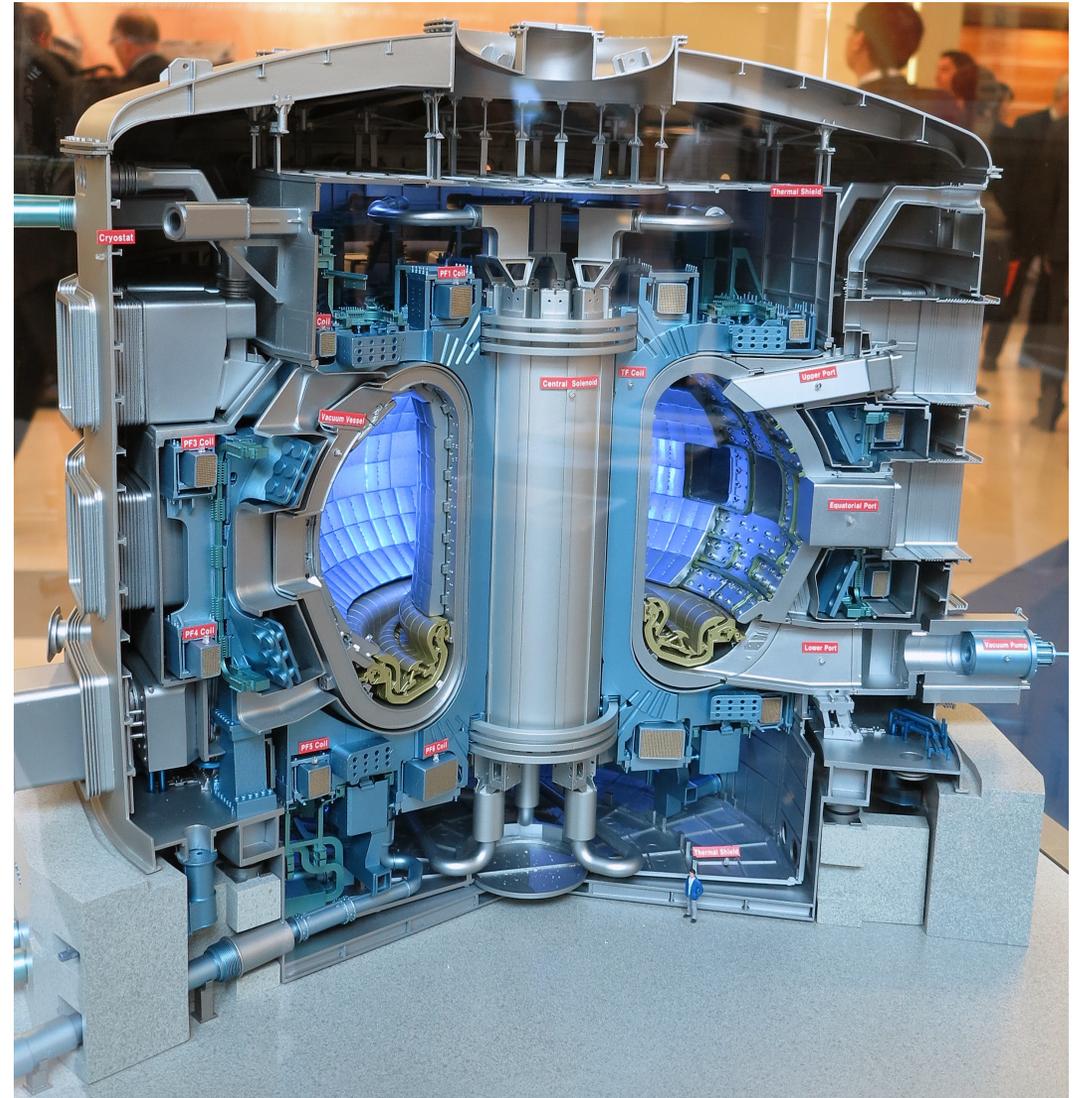
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- Simple description:
  - Make a pellet of deuterium and tritium
  - Blast it with high-powered lasers from all directions to make short-lived plasma
- Most advanced Facility
  - **National Ignition Facility (NIF)**, located at the Lawrence Livermore National Laboratory, California



# Magnetic Confinement

- Use magnetic fields to confine the plasma while it is heated with electromagnetic waves
- Geometry: torus (Tokamak)
- Largest example under construction: ITER in Saint-Paul-lès-Durance, France

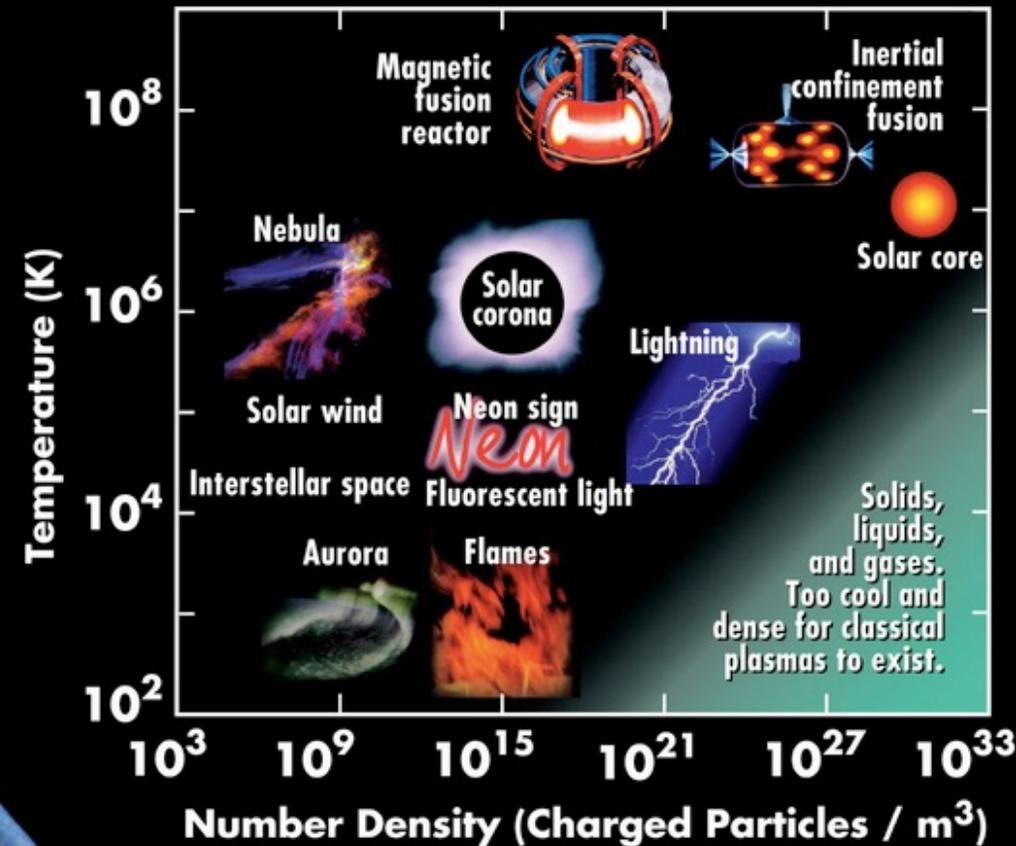


# Plasma

## PLASMAS – THE 4<sup>th</sup> STATE OF MATTER

### CHARACTERISTICS OF TYPICAL PLASMAS

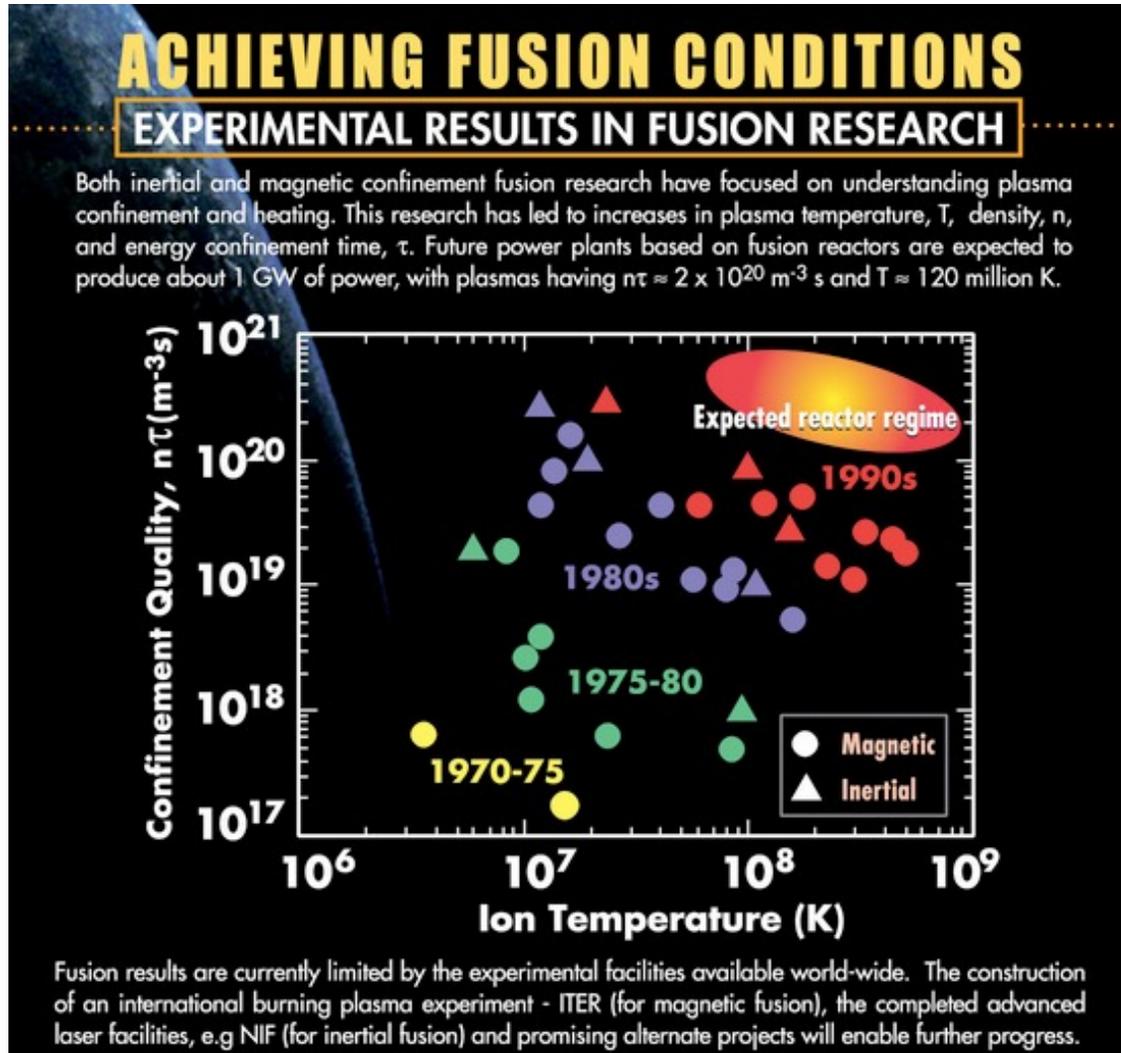
Plasmas consist of freely moving charged particles, i.e., electrons and ions. Formed at high temperatures when electrons are stripped from neutral atoms, plasmas are common in nature. For instance, stars are predominantly plasma. Plasmas are a "Fourth State of Matter" because of their unique physical properties, distinct from solids, liquids and gases. Plasma densities and temperatures vary widely.



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D. Wood, International Research Collaborations

# Experimental challenge – confinement conditions



- Goal for ITER:
  - Demonstrate a Q-factor of 10
  - $Q = (\text{energy out})/(\text{energy in})$

# A few remaining points

- Nuclear fission has a major drawback of producing tons of radioactive waste
  - Examples of isotopes in waste
    - Strontium-90 – half live 30 years
    - Cesium-137 - half life 30 years
    - Plutonium-239 - half-life of 24,000 years
- Fusion was products are:
  - Helium (harmless, can be released to atmosphere)
  - Neutrons (are absorbed in reactor material, but can activate/weaken the material)