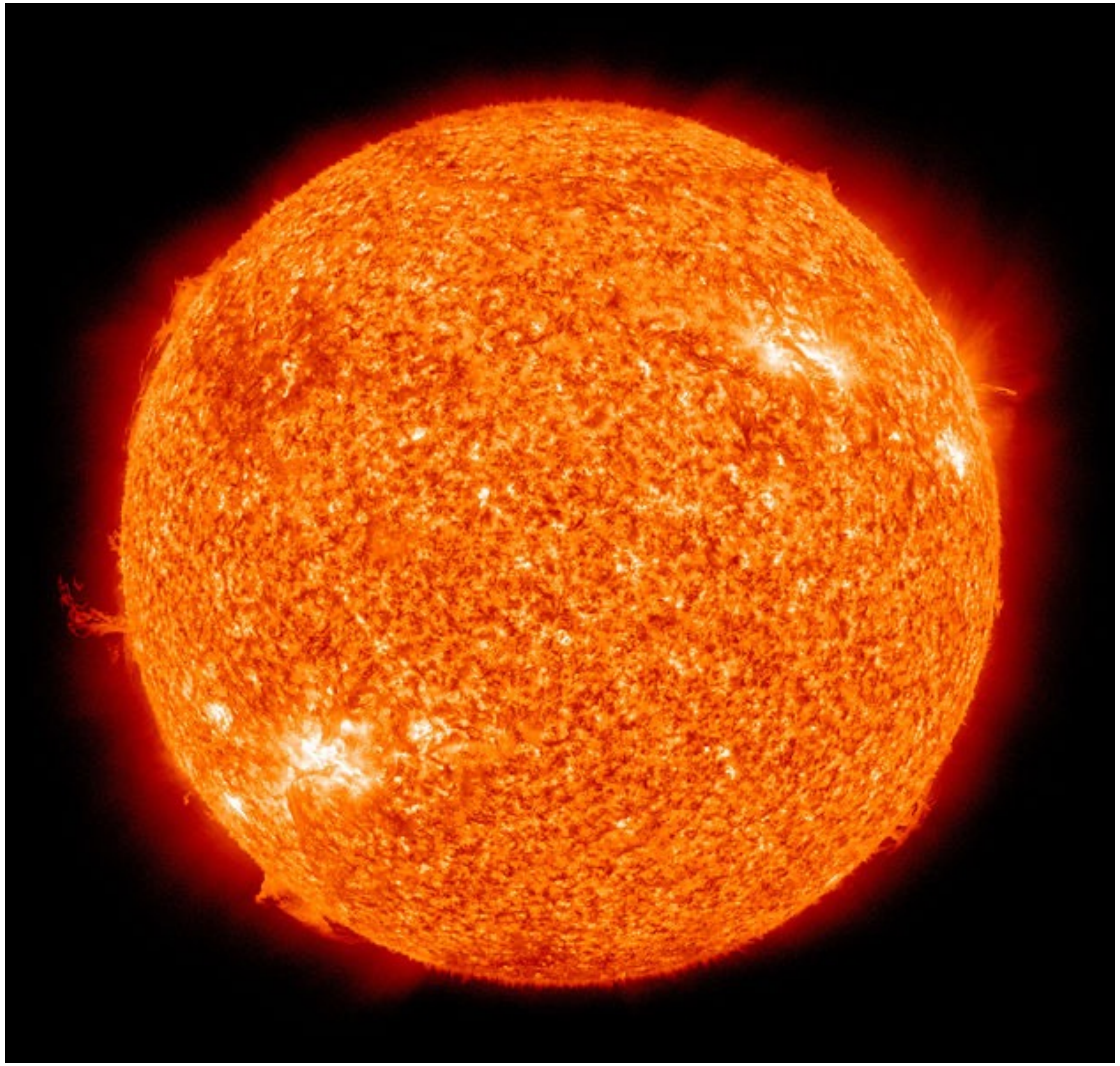


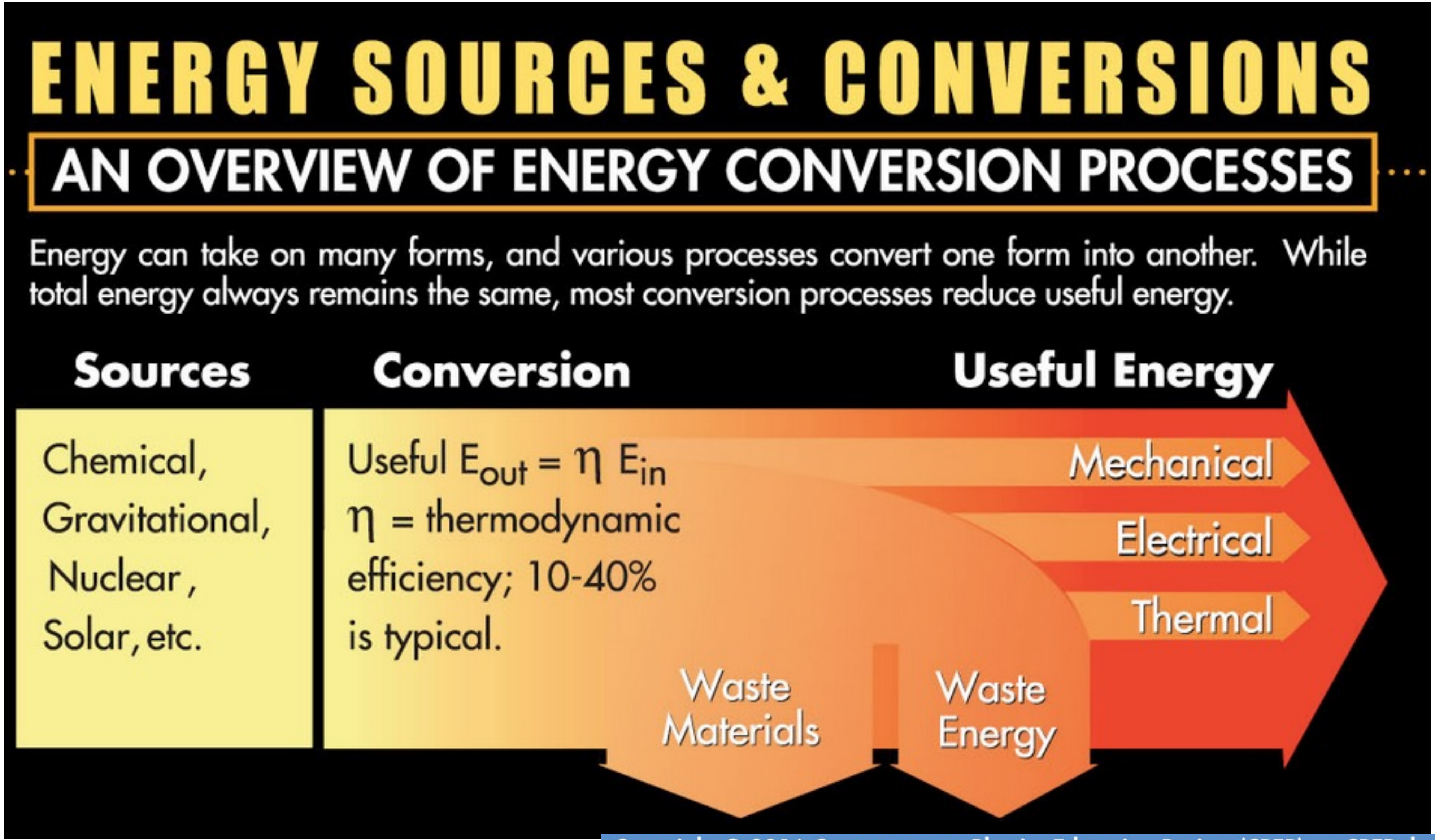
- Prof. Darien Wood
- Department of Physics
- Northeastern University

Science of fusion energy

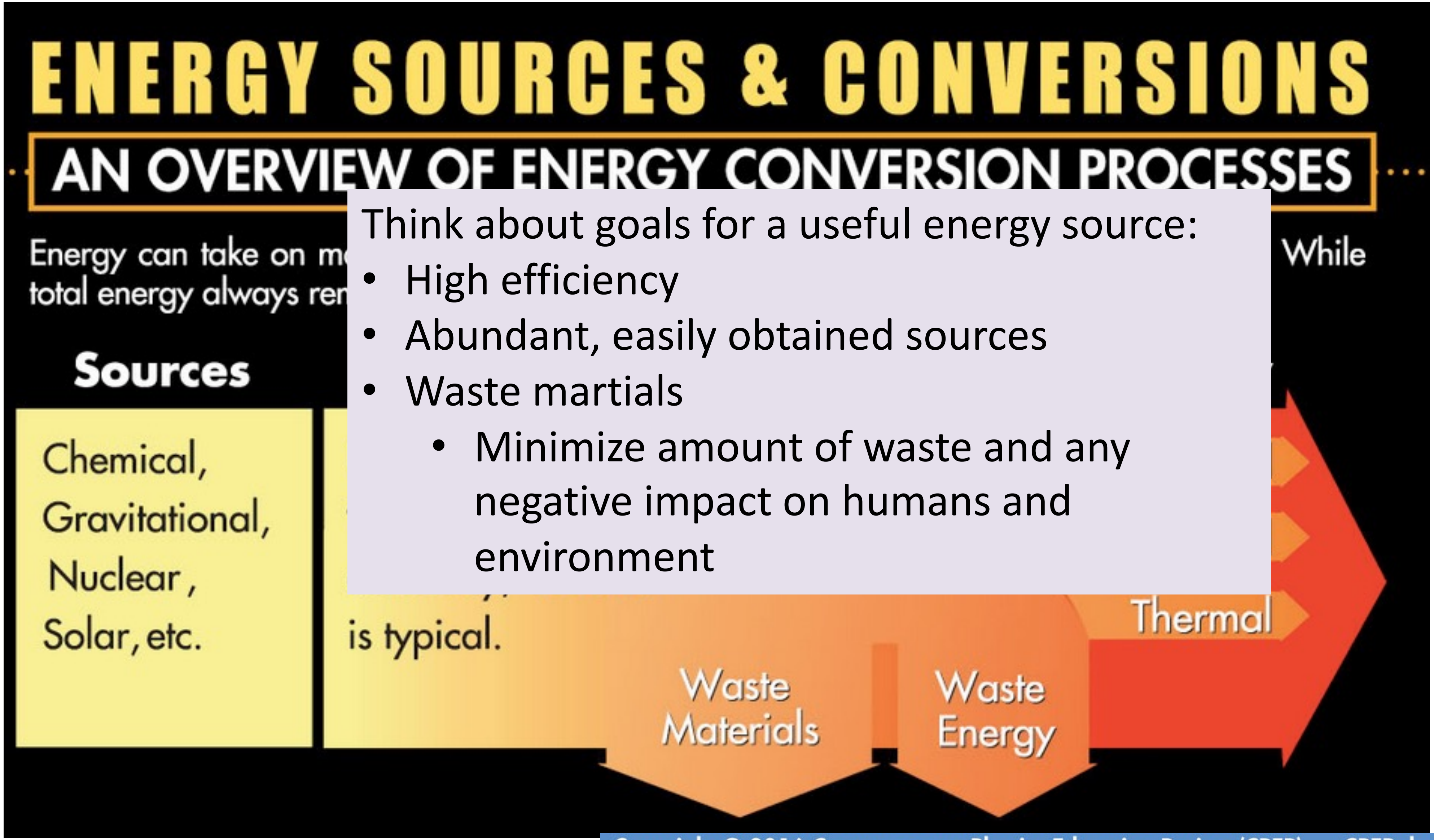
- Basic introduction
- Minimal math
  - $E = mc^2$
    - main formula behind fission and fusion
  - Unit conversion
    - Important to understand the scales involved

- Those with science/engineering backgrounds can see the references for more technical information

General overview of energy conversion



General overview of energy conversion



Think about goals for a useful energy source:

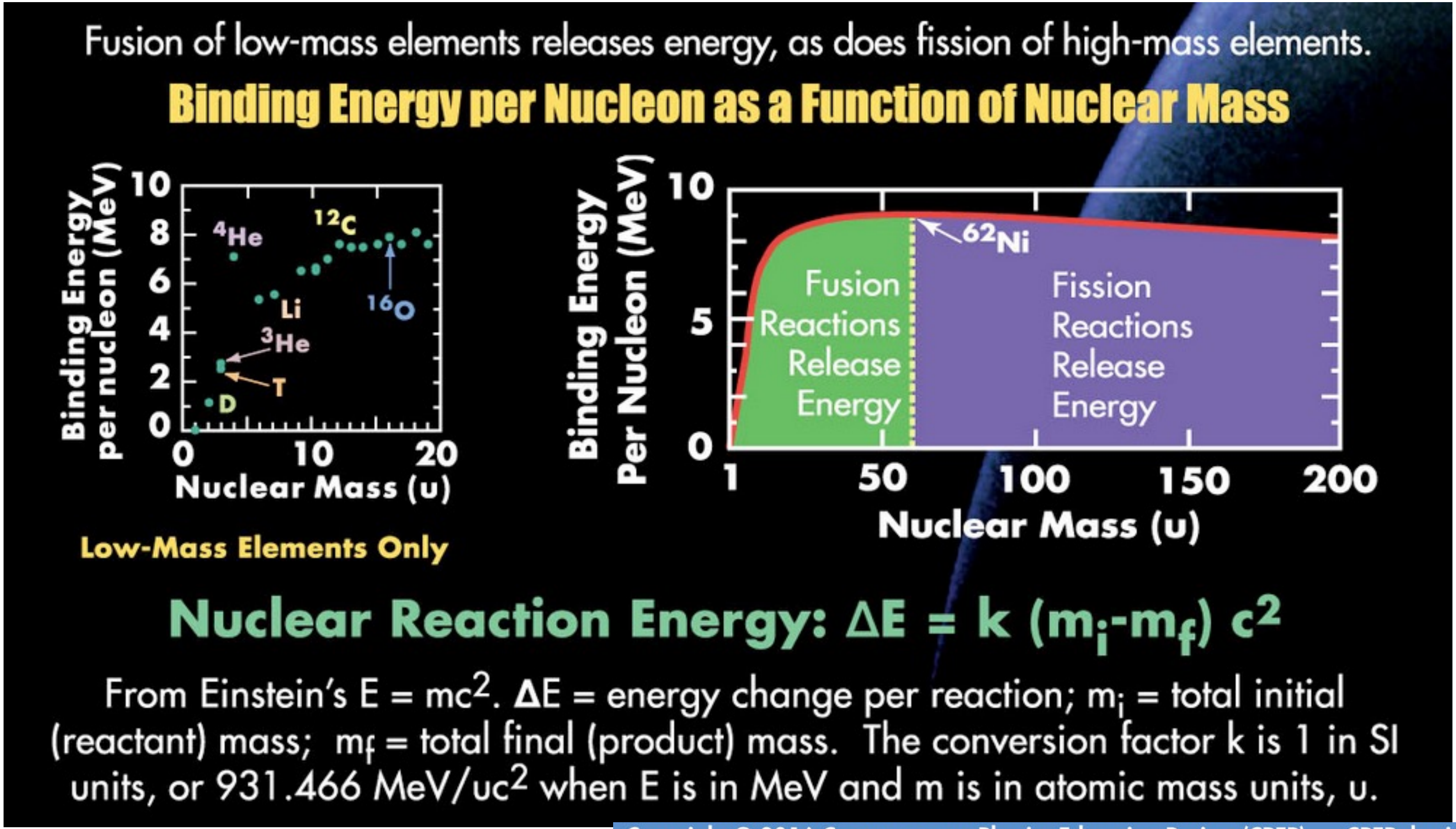
- High efficiency
- Abundant, easily obtained sources
- Waste martials
  - Minimize amount of waste and any negative impact on humans and environment

Comparison of different processes of energy generation

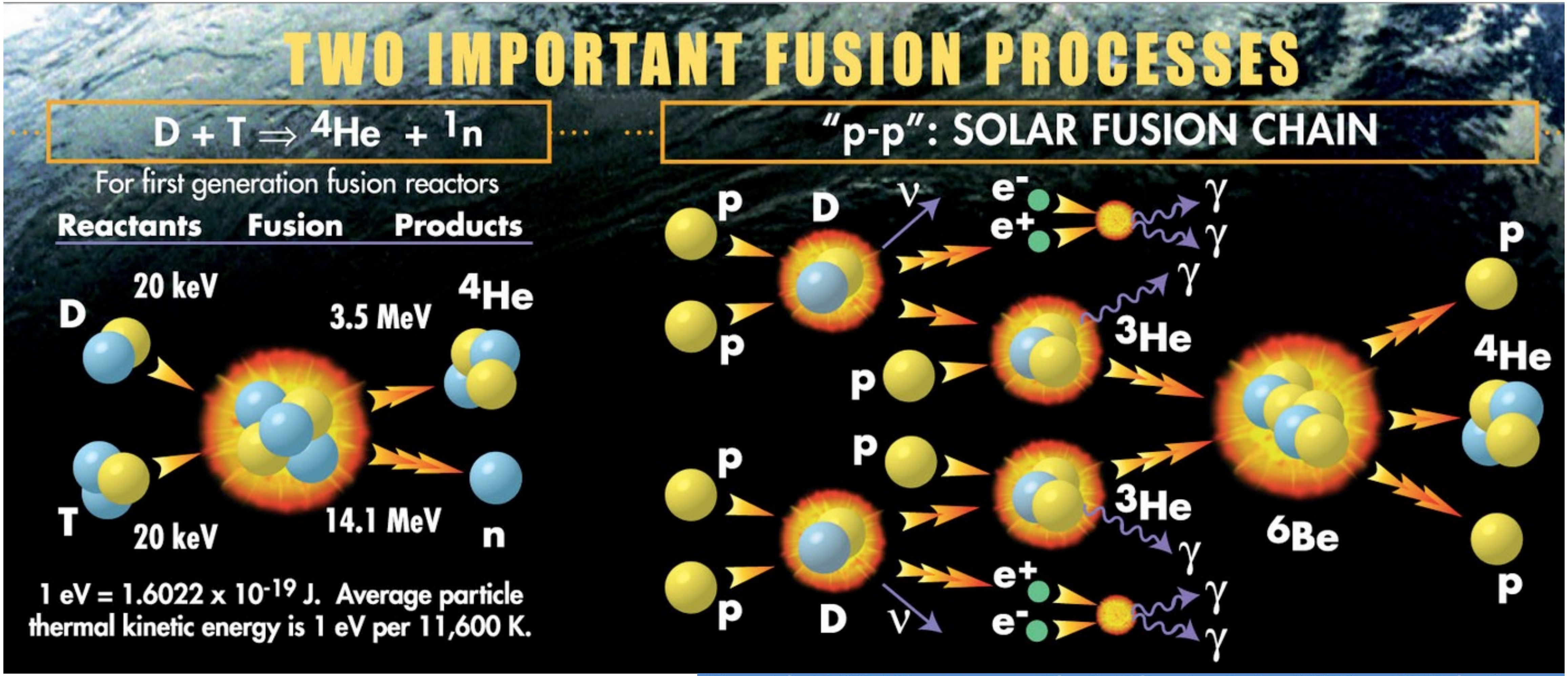
Physical Parameters of Energy-Releasing Reactions

Reaction Type:	Chemical	Fission	Fusion
Sample Reaction	$C + O_2 \Rightarrow CO_2$	$^{1}n + {}^{235}U \Rightarrow {}^{143}Ba + {}^{91}Kr + 2\,{}^{1}n$	$D\,(^{2}H) + T\,(^{3}H) \Rightarrow {}^{4}He + {}^{1}n$
Typical Inputs (to Power Plant)	Coal and Air	UO_2 (3% ^{235}U + 97% ^{238}U)	Deuterium and Lithium
Typical Temp. (K)	1000	1000	100,000,000
Energy Released per kg Fuel (J/kg)	3.3×10^{7}	2.1×10^{12}	3.4×10^{14}

A little bit of nuclear physics…

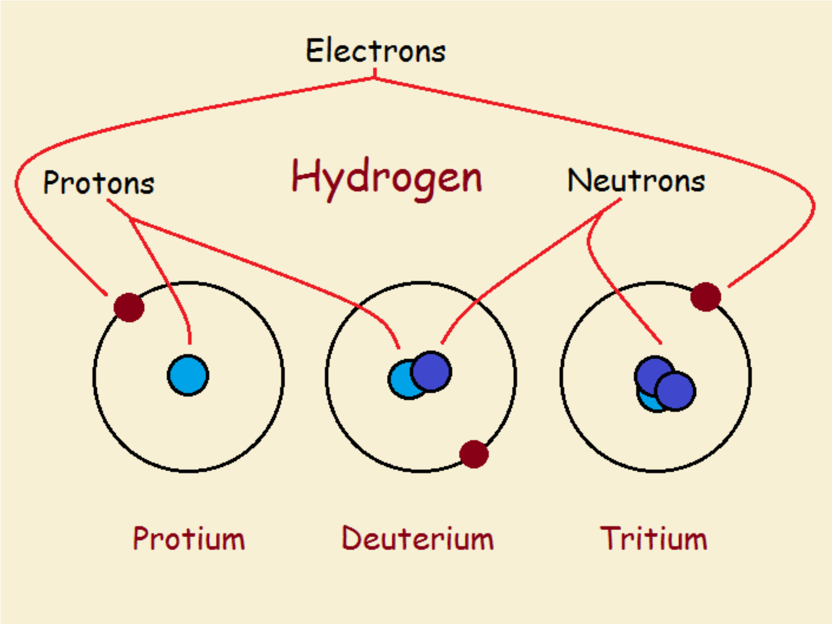


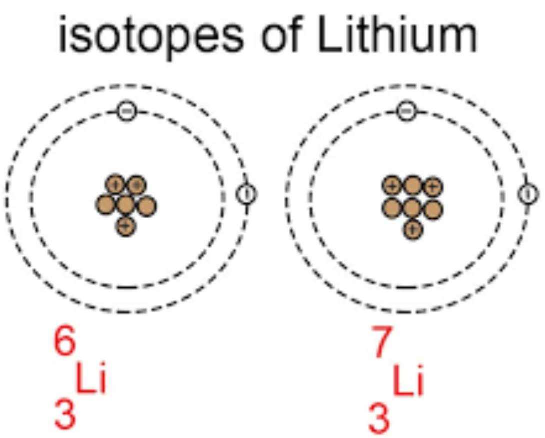
D-T process (man-made fusion) vs p-p (Sun)



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

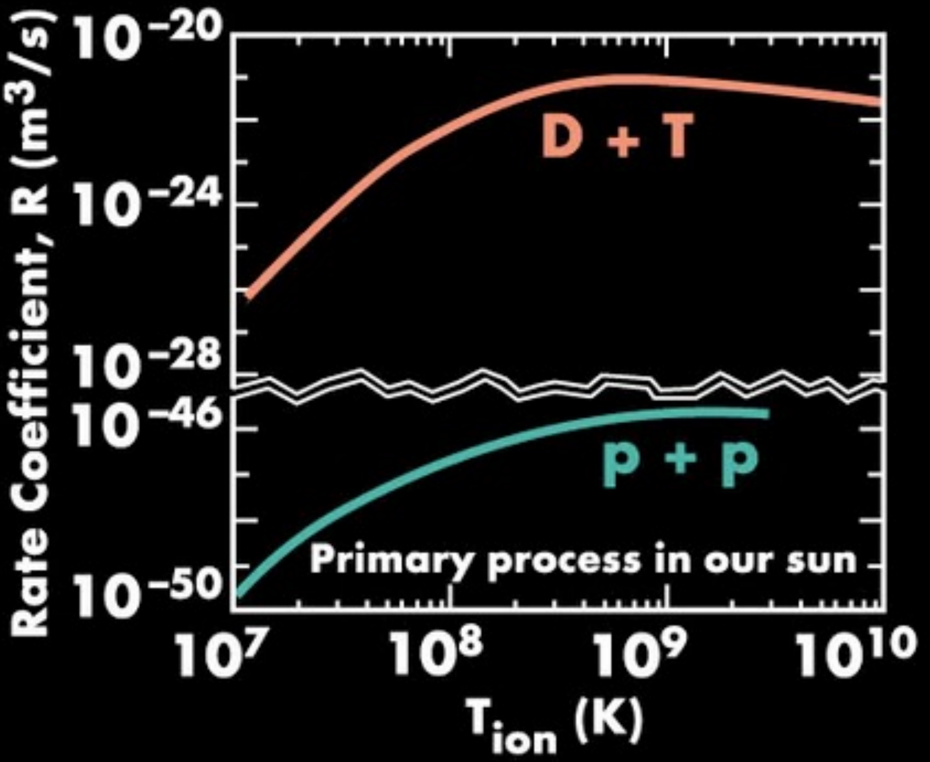
Useful Nuclear Masses

(The electron's mass is 0.000549 u.)

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

* 1 u = 1.66054 x 10^{-27} kg = 931.466 MeV/c^2

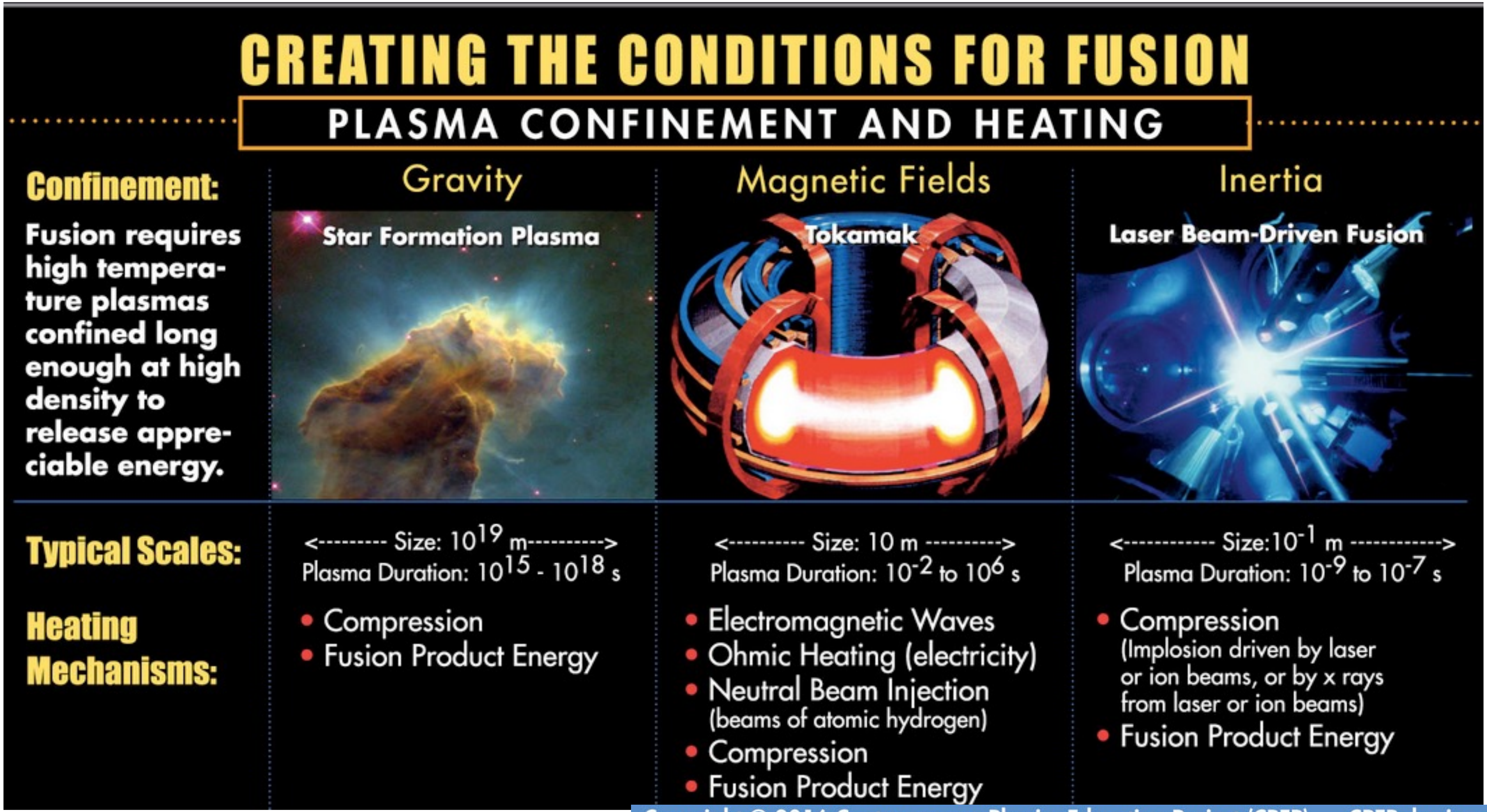
Fusion Rate Coefficients



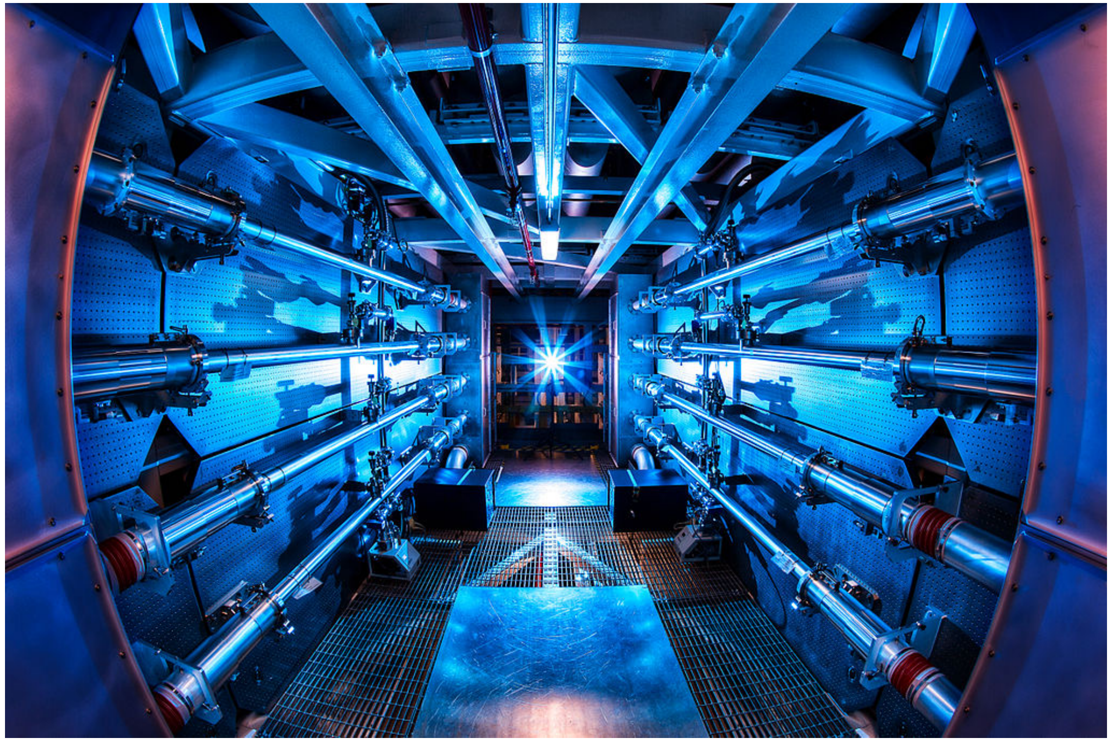
Plasma Fusion Reaction Rate Density = R n_1 n_2

n_1,n_2 = densities of reacting species (ions/m^3); R = Rate Coefficient (m^3/s).
Multiply by ΔE to get the fusion power density.

Ways of obtaining the necessary temperature and density



Inertial Confinement



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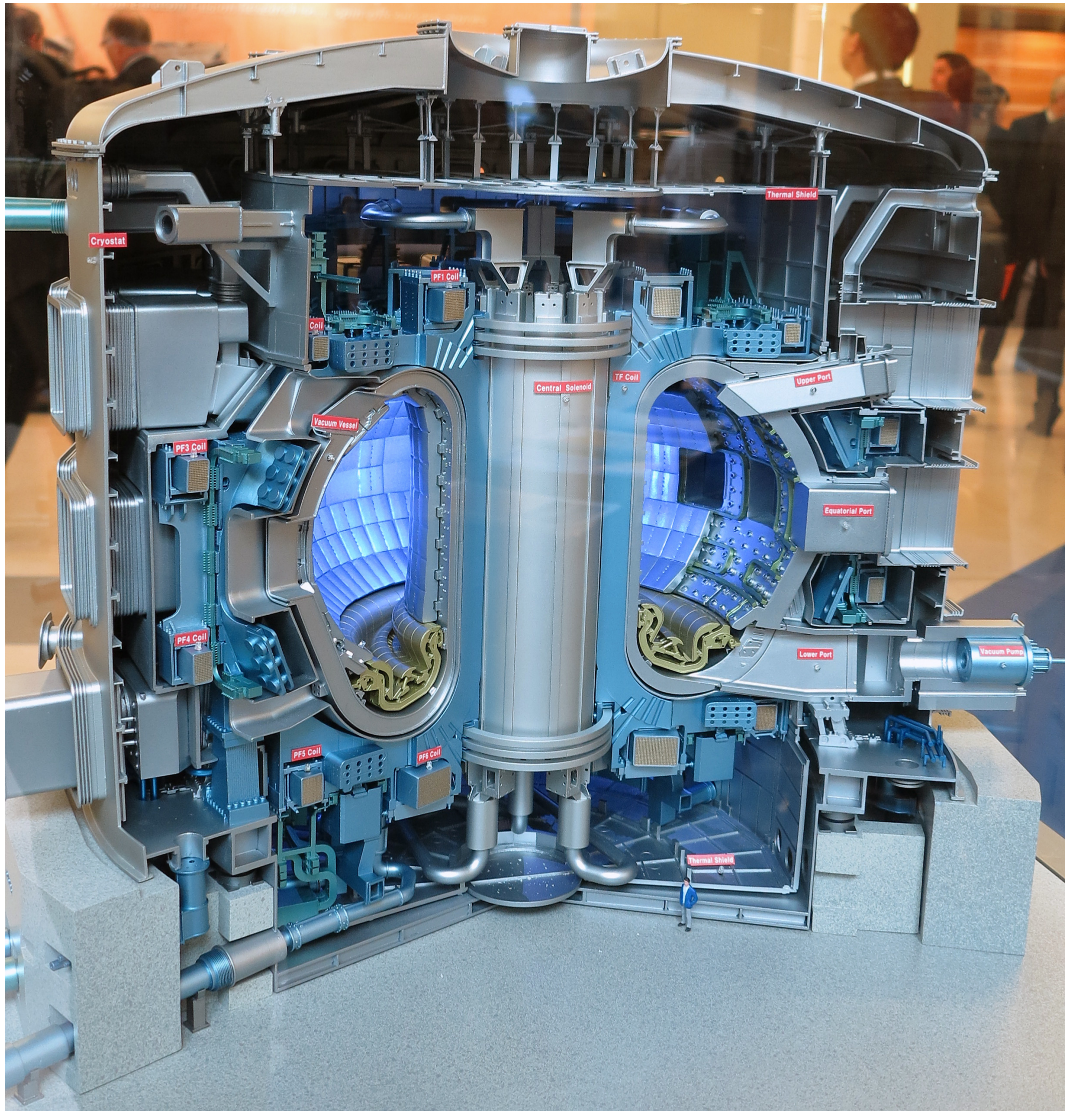
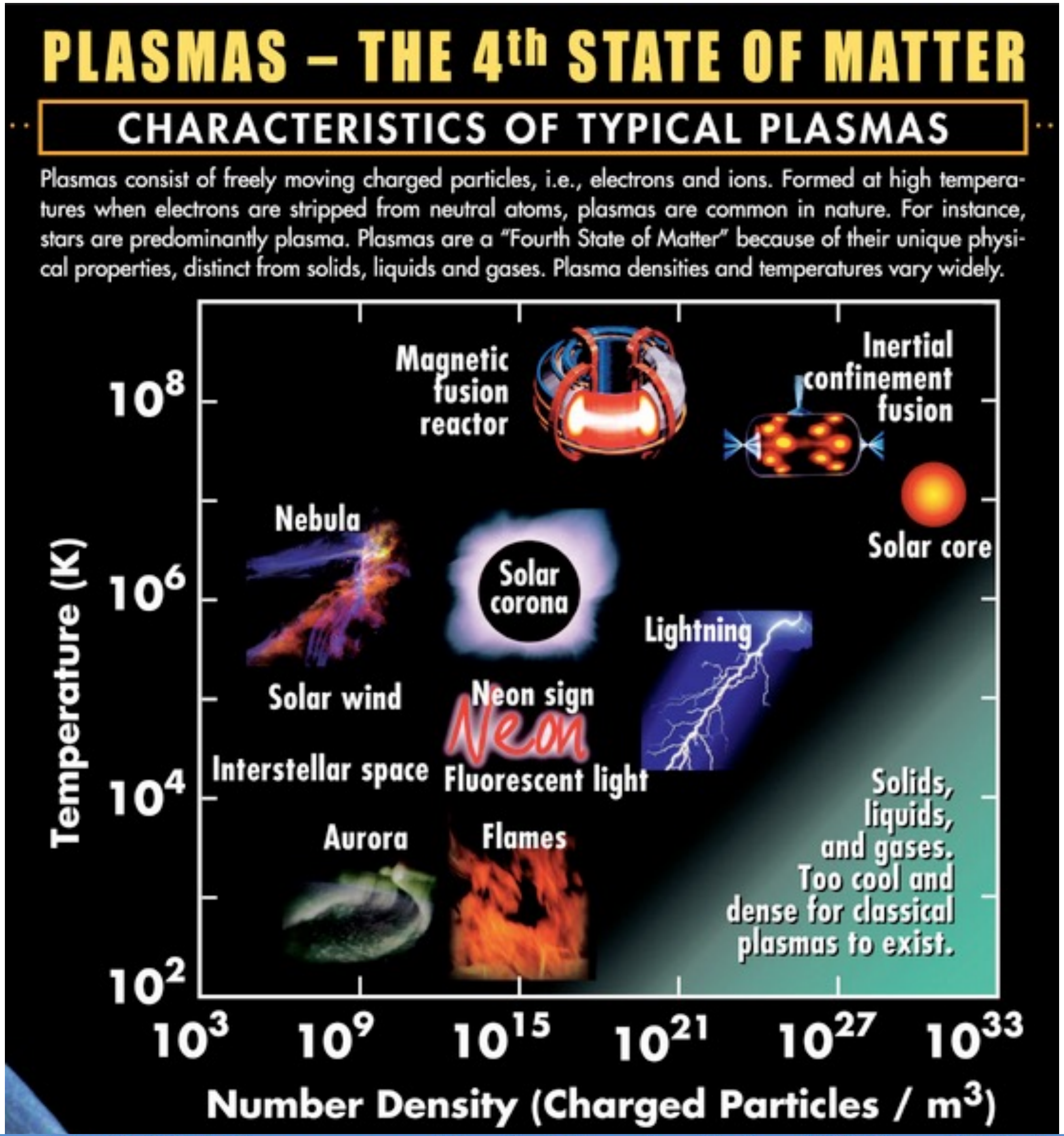
- Simple description:
  - Make a pellet of deuterium and tritium
  - Blast it with high-powered lasers from all directions to make short-lived plasma
- Most advanced Facility
  - **National Ignition Facility (NIF)**, located at the Lawrence Livermore National Laboratory, California

Magnetic Confinement

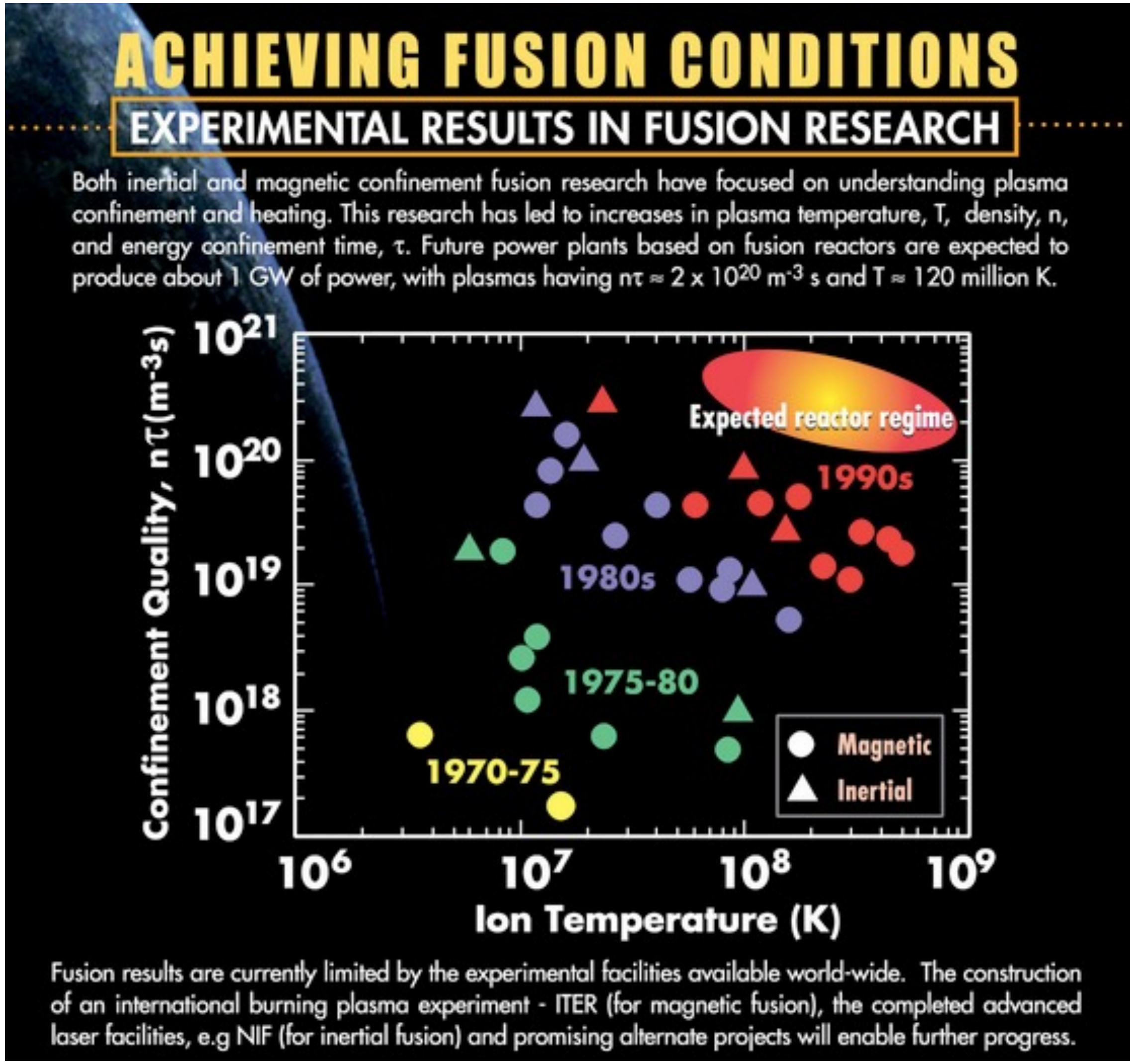
- Use magnetic fields to confine the plasma while it is heated with electromagnetic waves
- Geometry: torus (Tokamak)
- Largest example under construction: ITER in Saint-Paul-lès-Durance, France



Plasma


PLASMAS – THE 4th 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.
Magnetic fusion reactor
Inertial confinement fusion
Solar core
Nebula
Solar corona
Lightning
Solar wind
Neon sign
Interstellar space
Fluorescent light
Aurora
Flames
Solids, liquids, and gases. Too cool and dense for classical plasmas to exist.
Temperature (K)
10^8
10^6
10^4
10^2
10^3
10^9
10^15
10^21
10^27
10^33
Number Density (Charged Particles / m^3)

Experimental challenge – confinement conditions



- Goal for ITER:
  - Demonstrate a Q-factor of 10
  - Q = (energy out)/(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)