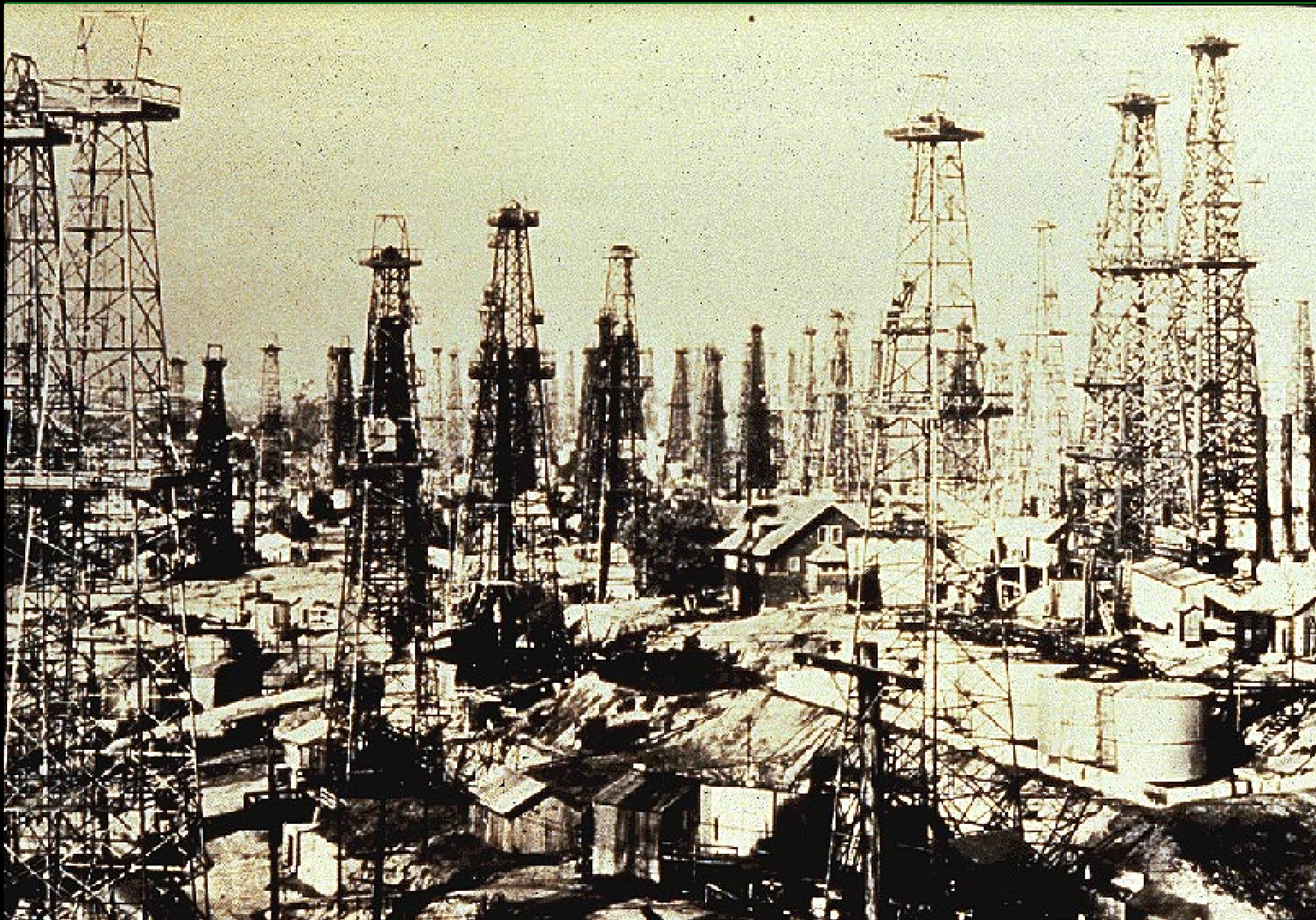
Fusion: Creating a Star on Earth

Produced by
General Atomics
in Conjunction with
Schools in the San Diego area

Why is Fusion Important?



Alternative Energy Sources

- Hydroelectric Power
- Wind
- Geothermal
- Solar

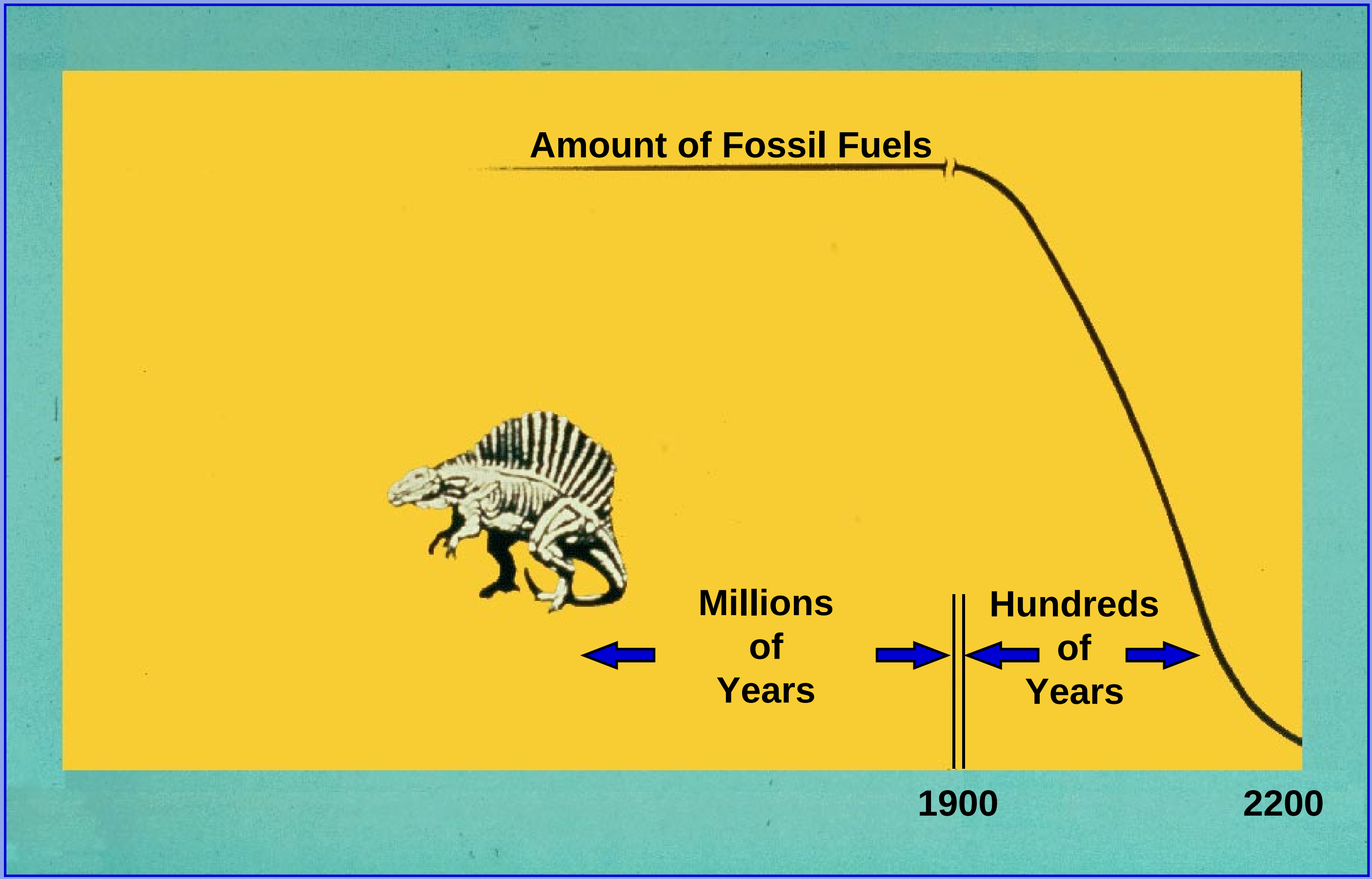
Fossil Fuel Energy Sources - Advantages and Disadvantages

	Advantages	Disadvantages
Coal	• Abundant	• Burns dirty • Causes acid rain and air pollution
Oil	• Flexible fuel source with many derivitives • Transportable	• Finite supply • Causes air pollution
Natural Gas	• Burns cleanly • Transportable	• Finite supply • Dangerous to handle

Energy Source
Advantages and Disadvantages

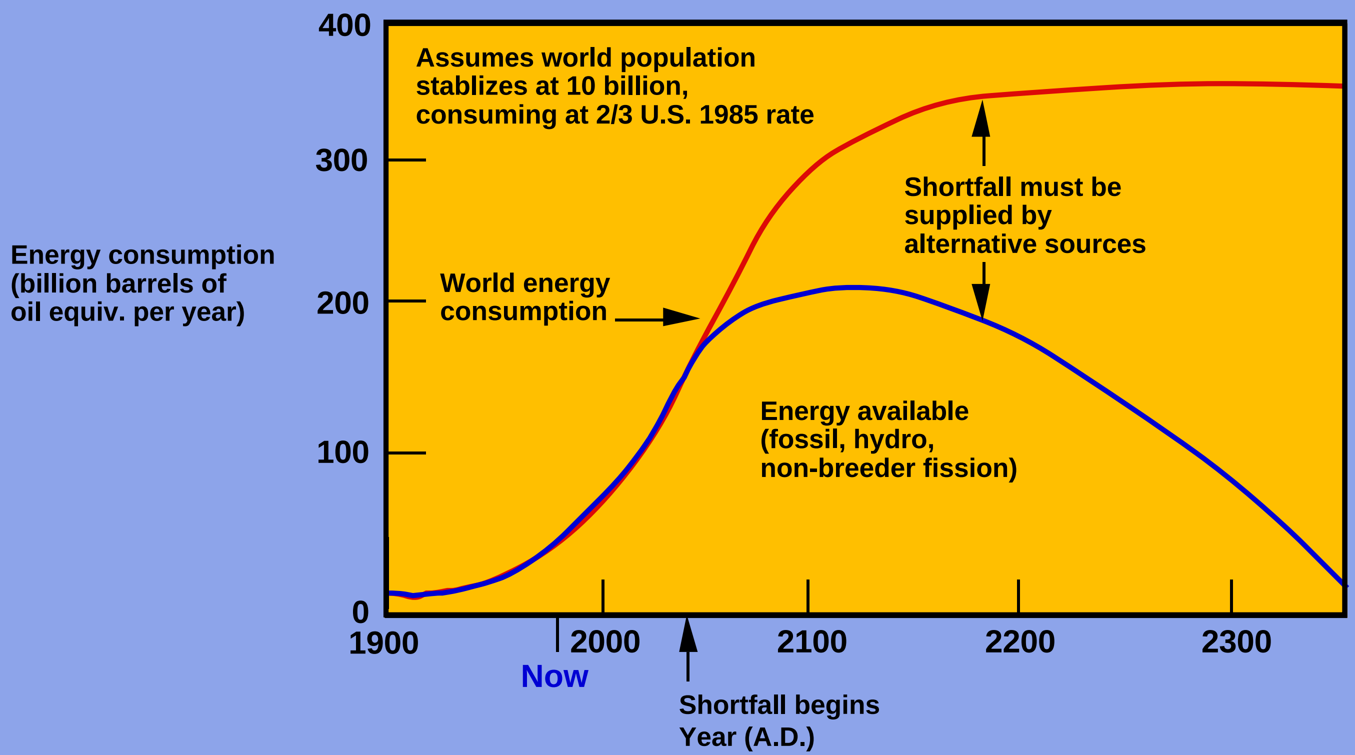
Energy Sources	Advantages	Disadvantages
Fission (Nuclear Power)	• Clean, no CO_2 • Does not produce immediate pollution	• Waste disposal is difficult • Safety concerns
Hydroelectric	• Clean, no CO_2	• Dam construction destroys habitats • Geographically limited
Wind	• Clean, no CO_2	• Huge numbers of windmills required for adequate power generation • Geographically limited
Geothermal	• Clean, no CO_2	• Geographically limited
Solar	• Clean, no CO_2	• Huge number of solar cells required for adequate power generation • Geographically limited

World Fossil Reserves



Fusion Energy

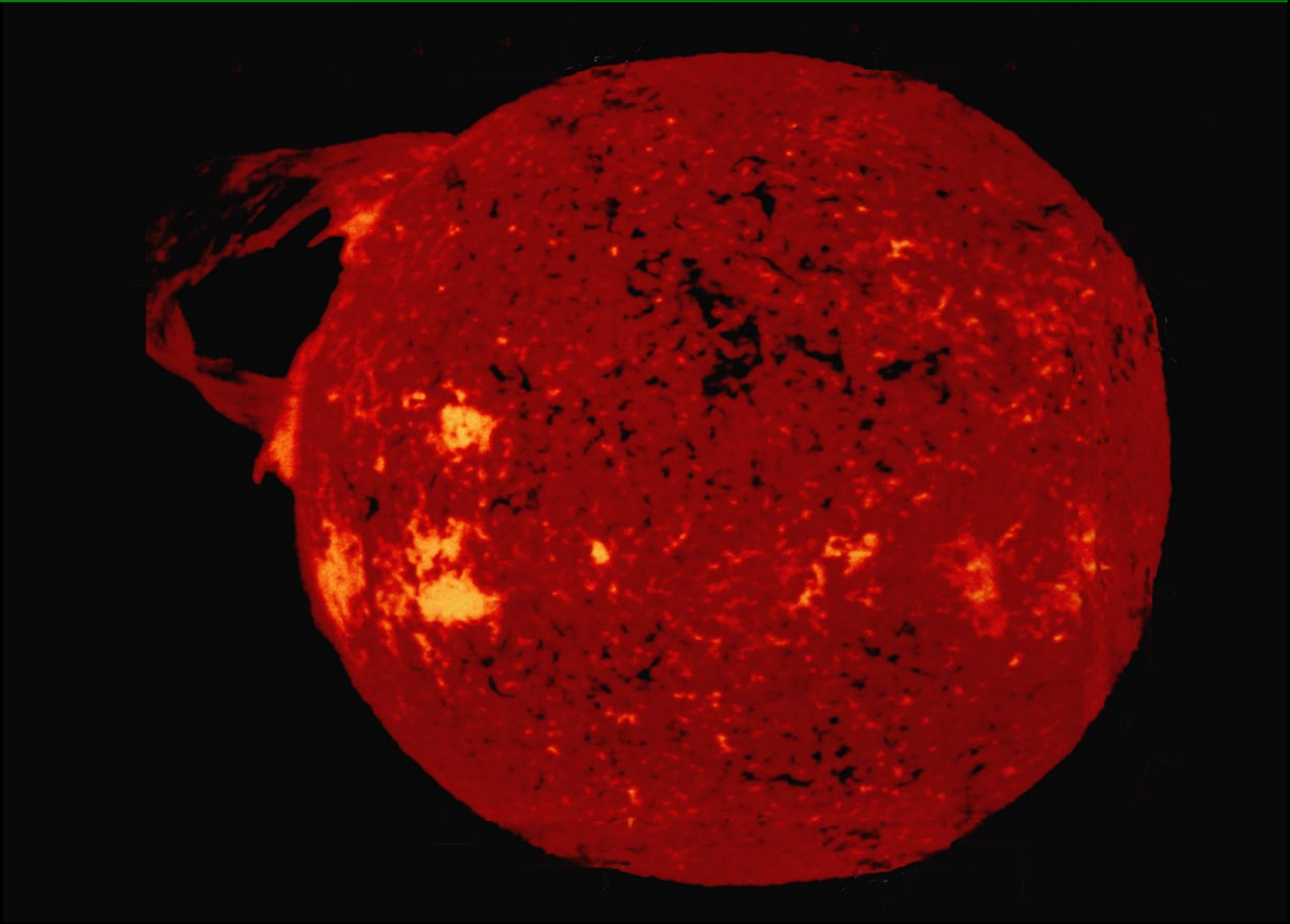
The fossil fuel era is almost over. If we continue to burn fossil fuels for energy, they will last only another few hundred years. At our present rate of use, experts predict a shortfall in less than fifty years.



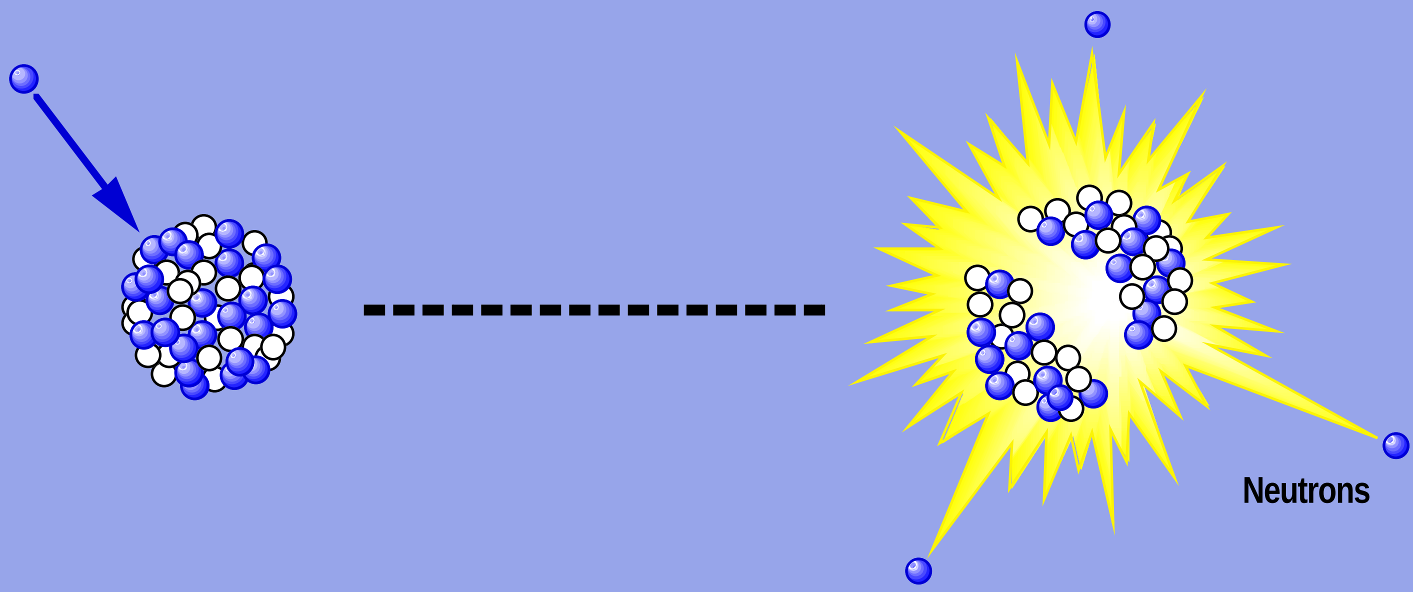
Fossil Fuel is Environmentally Costly

1000 MW electric plant

- It provides electricity for 1 million U.S. people (1.4 kW/person)
- We need at least 3 plants this size for San Diego
- We need at least 30 for California
- A coal plant this size consumes 8,600 tons of coal per day.
- This produces 32,000 tons of CO_2 per day
- This is 64 pounds of CO_2 for every American per day

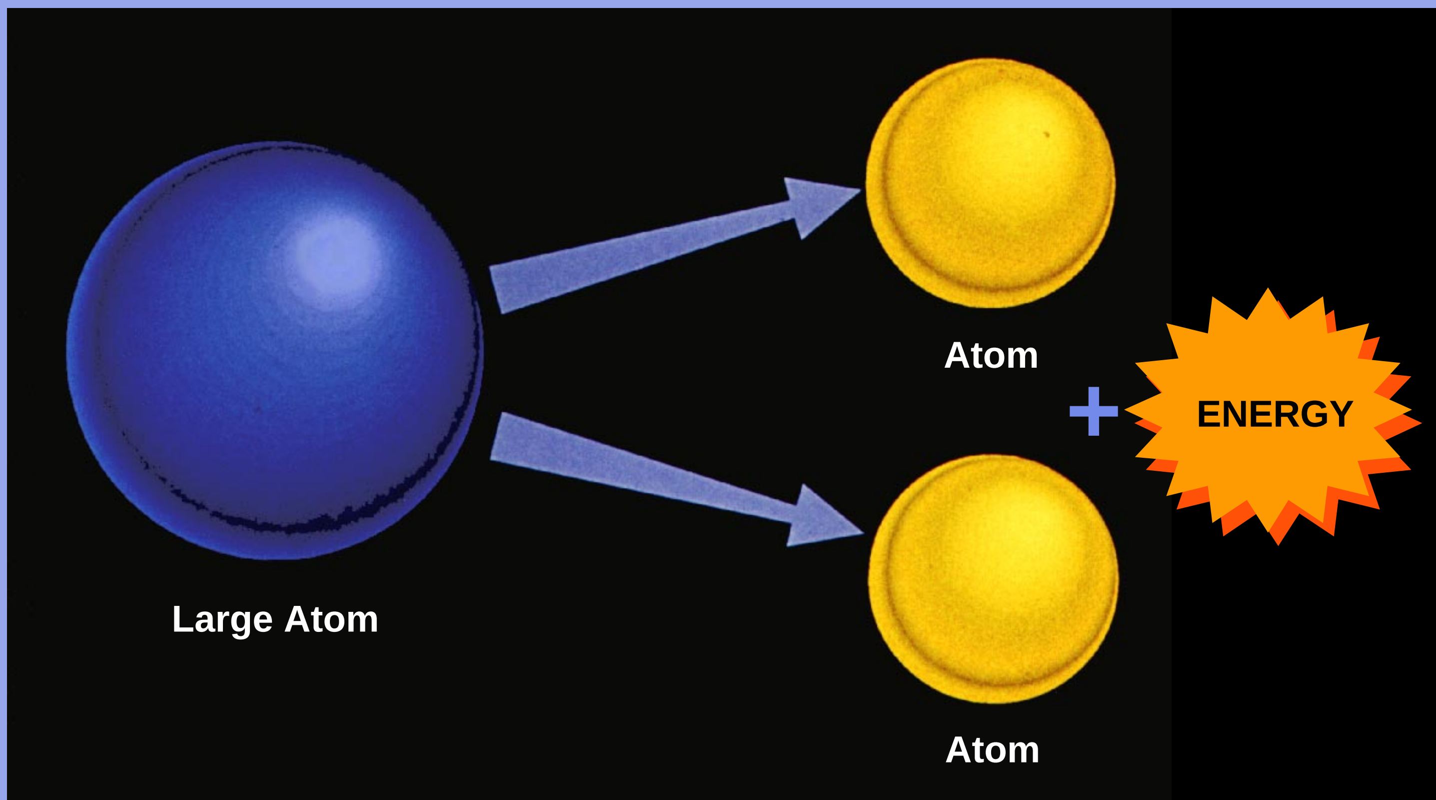


In a typical fission process used as a source of energy, a neutron strikes a uranium nucleus causing it to split into fragments. As in the fusion process, there is a difference in mass that is released as energy

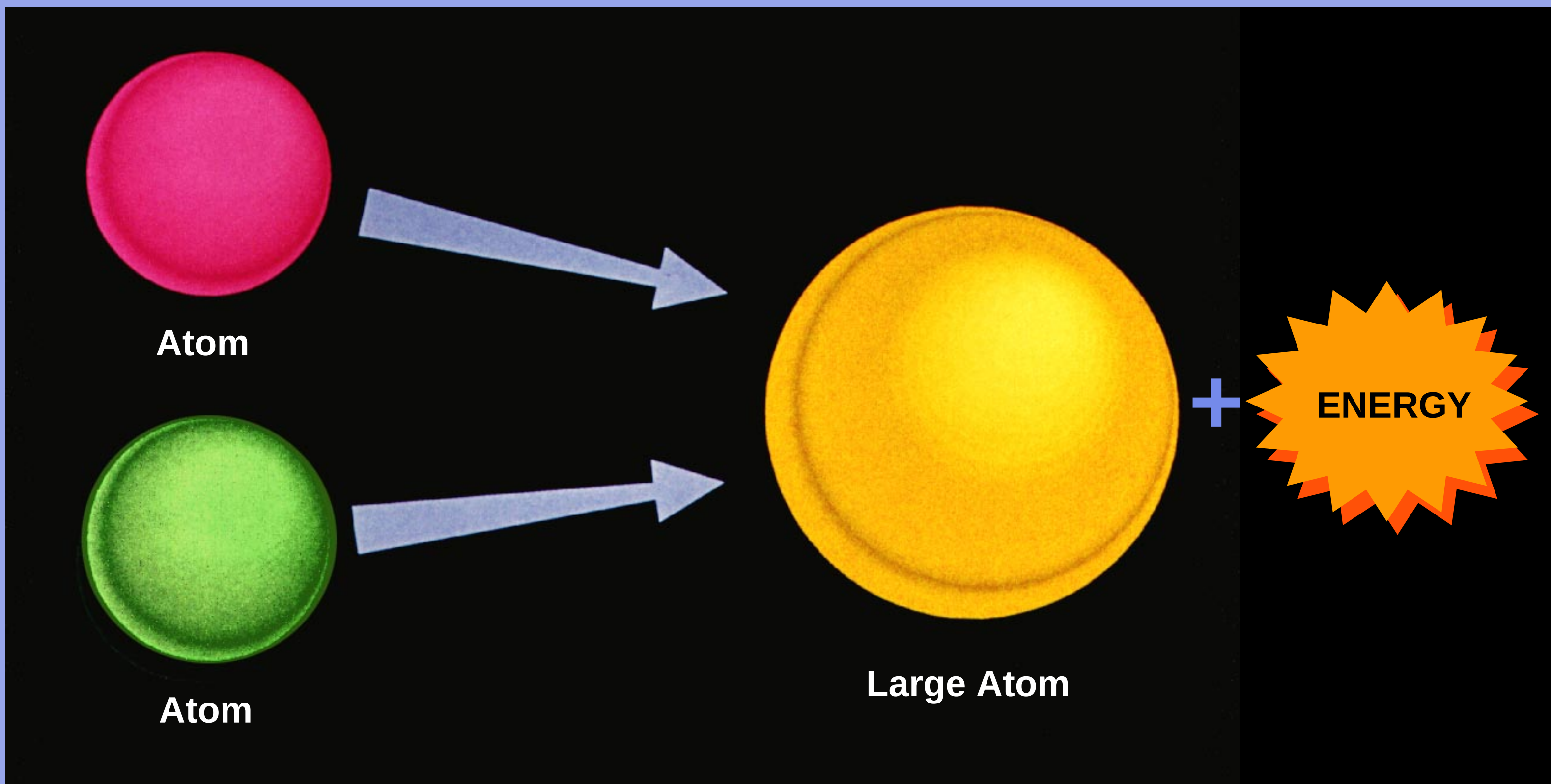


n+U → fission fragments + neutrons + energy

Fission



Fusion



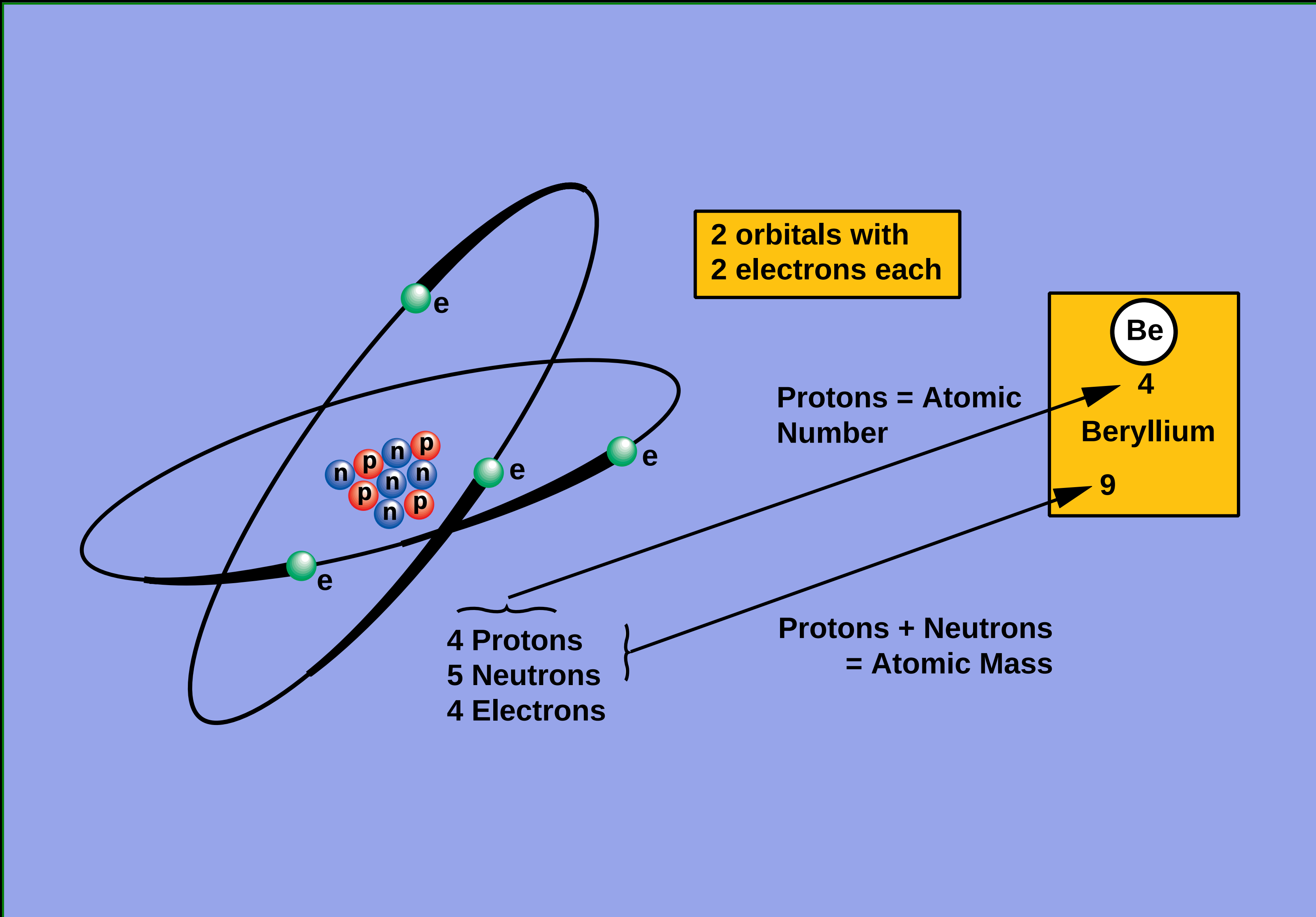
Fusion vs. Fission
Advantages and Disadvantages

Energy Sources	Advantages	Disadvantages
Fission (Nuclear Power)	• Clean, no CO_2 • Does not produce immediate pollution	• Waste disposal is difficult • Safety concerns
Fusion	• Inexhaustible supply of water-the fuel of fusion • Fuel is accessible worldwide • Clean • Fusion reactors are inherently safe, they cannot explode or overheat	• Huge research and development costs • Reactor vessel core becomes radioactive

Comparison of Long-Term Energy Sources

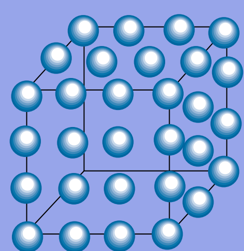
	Resources	Environment	Safety	Cost
Coal	Large	Very Dirty	Good	Moderate
Today's Fission	Small	Waste Concerns	Active Control	Moderate
Advanced Fission	Large	Waste Concerns	Passive	Moderate to High
Solar	Infinite	Very Clean	Excellent	High
Fusion	Infinite	Clean	Inherent	?

So Why Aren't Fusion Power Plants Here Now?

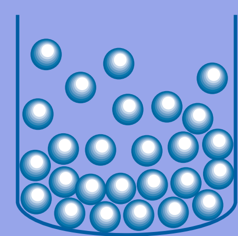

2 orbitals with
2 electrons each
Be
4
Beryllium
9
Protons = Atomic
Number
n
p
n
p
n
p
n
p
n
e
e
e
e
4 Protons
5 Neutrons
4 Electrons
Protons + Neutrons
= Atomic Mass

Fusion Energy

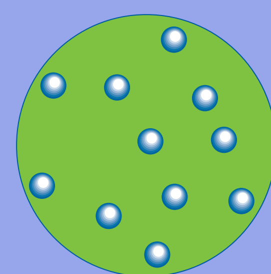
Plasma is sometimes referred to as the fourth state of matter



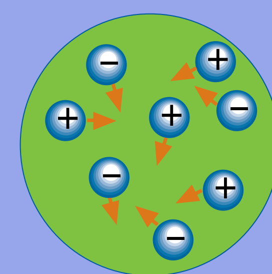
Cold
Solid:Ice



Warm
Liquid: Water



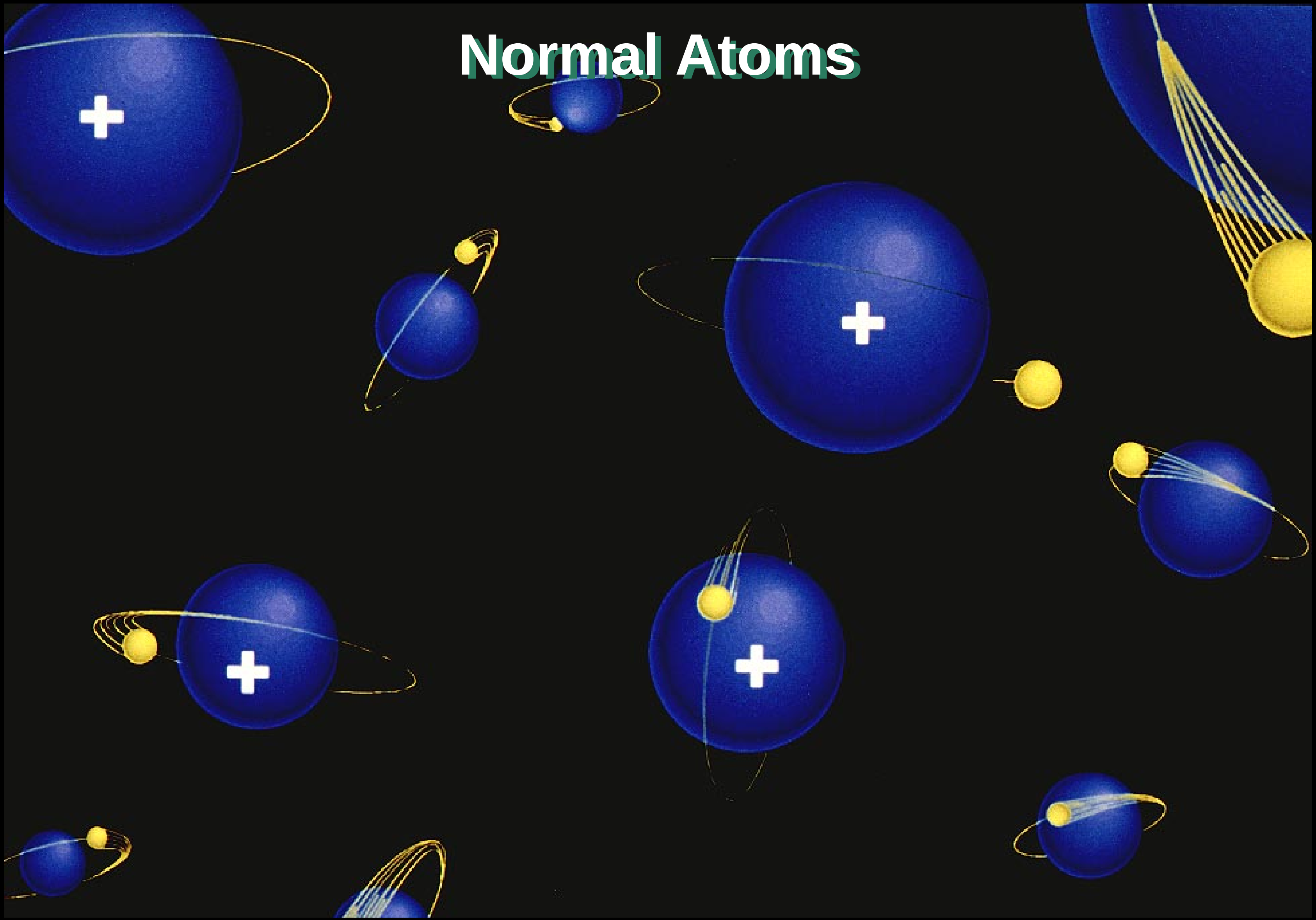
Hot
Gas: Steam

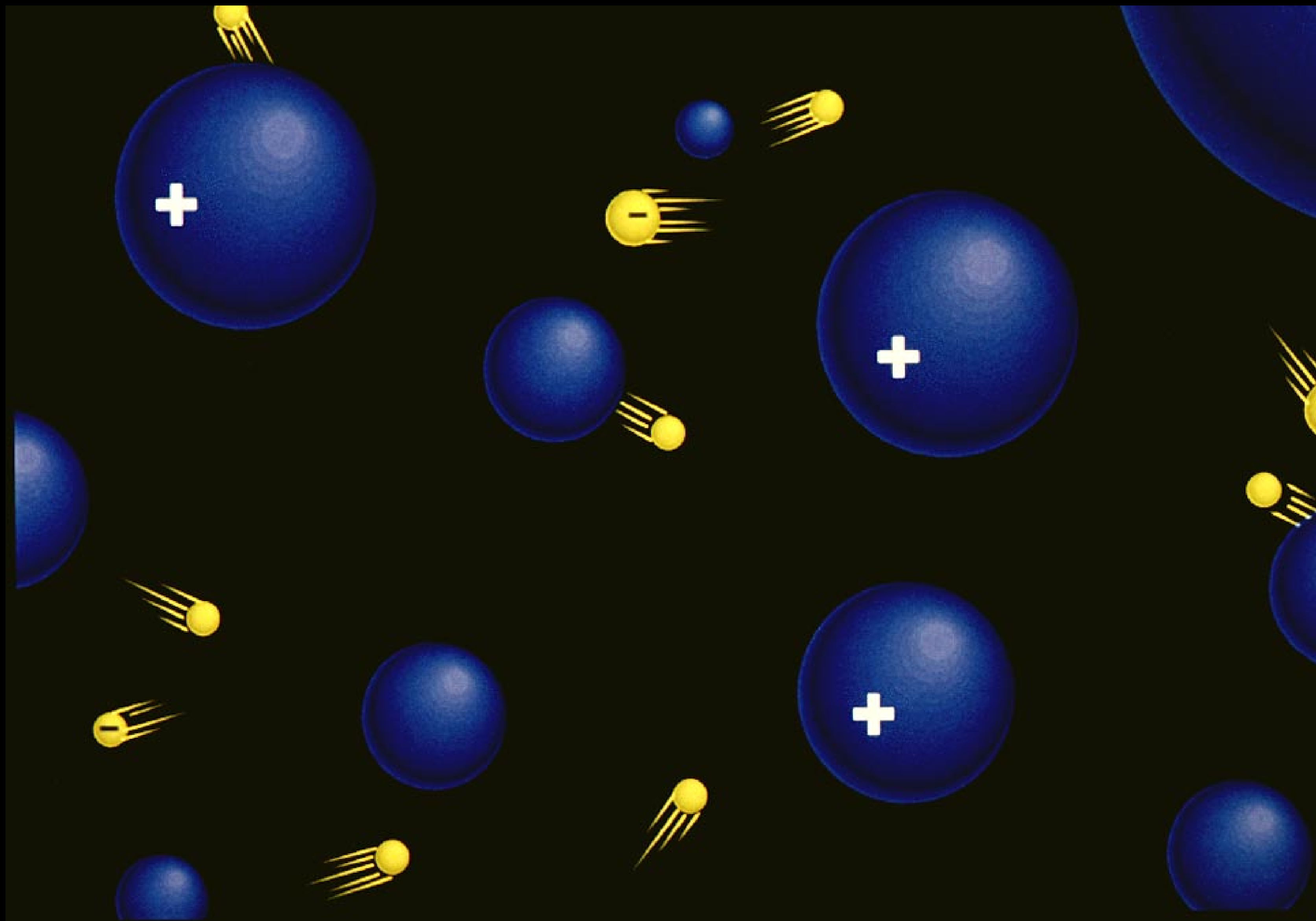


Hotter
Plasma

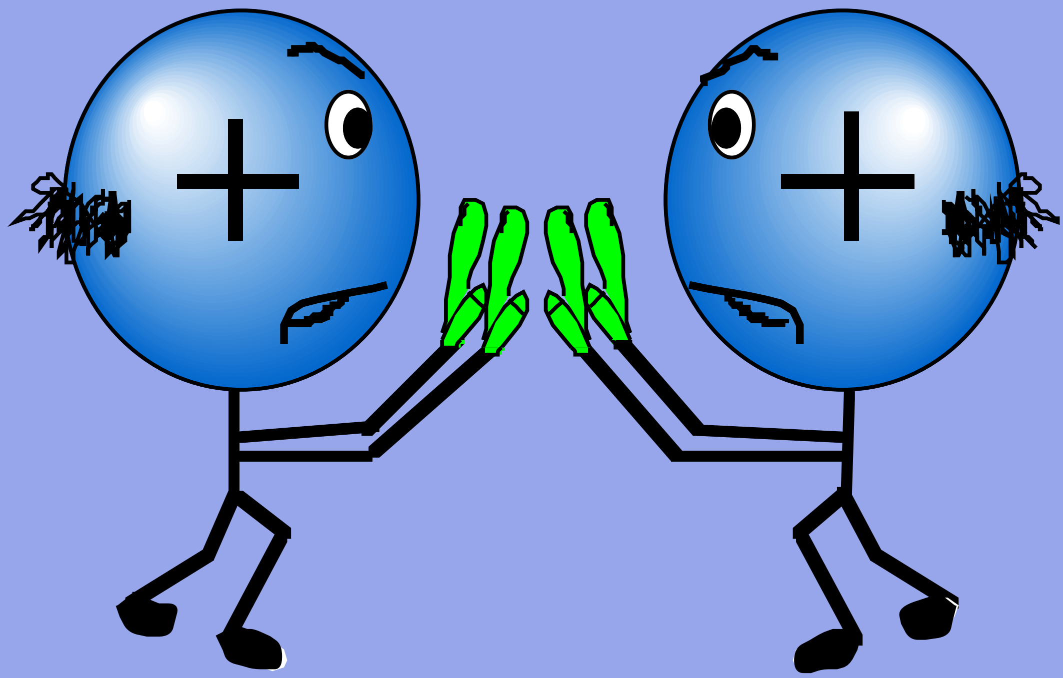
Plasma Makes up The Sun & Stars

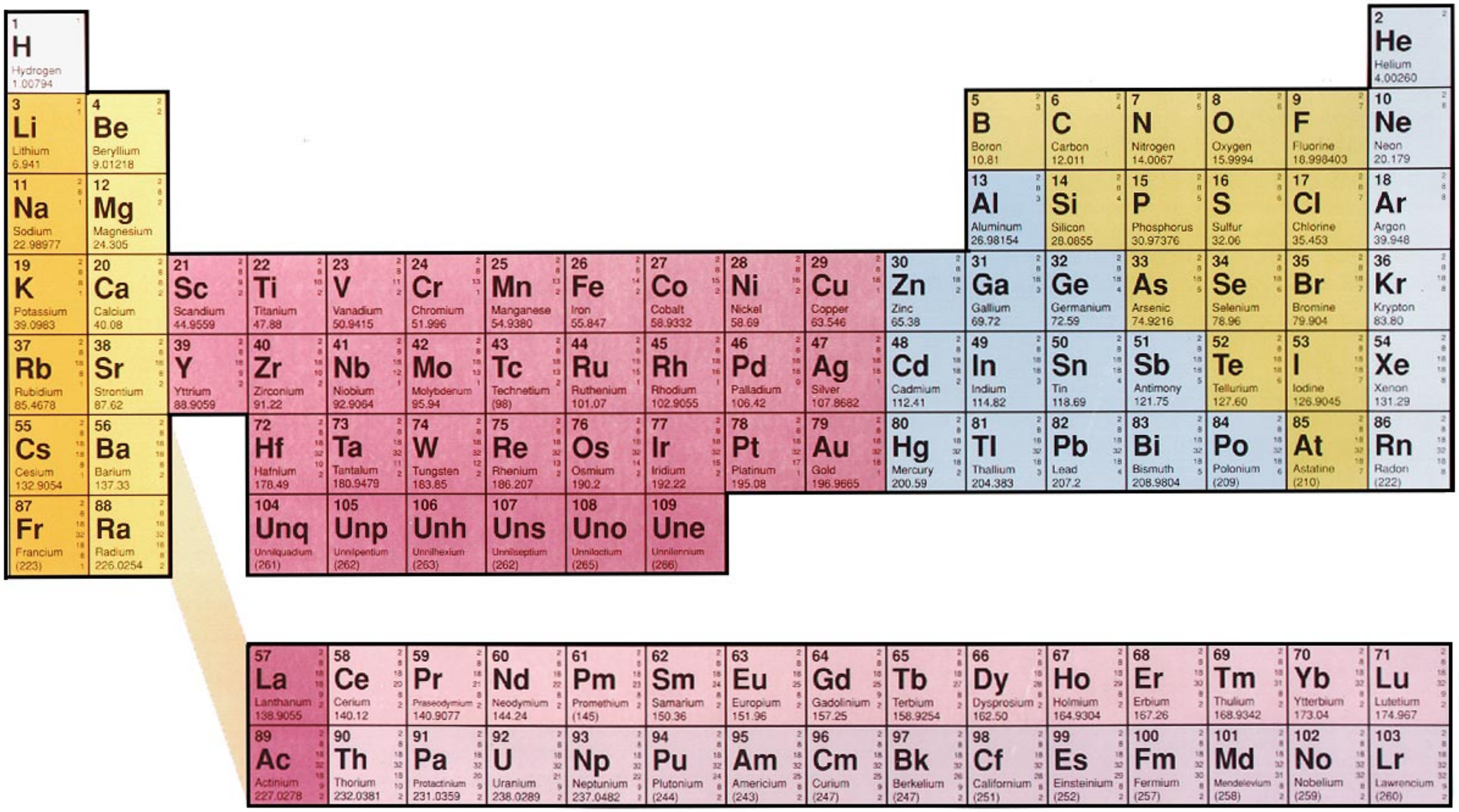
Normal Atoms



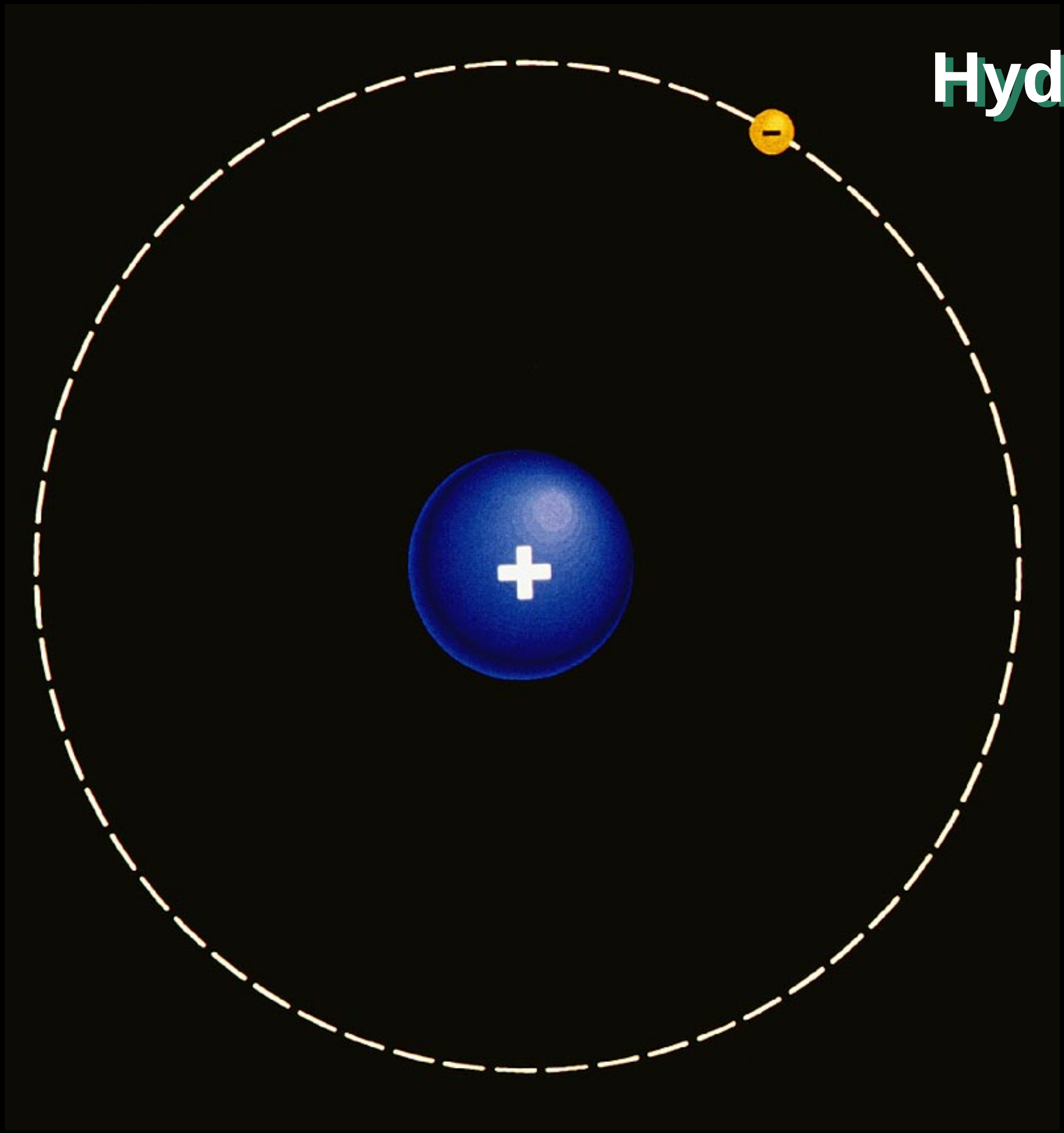


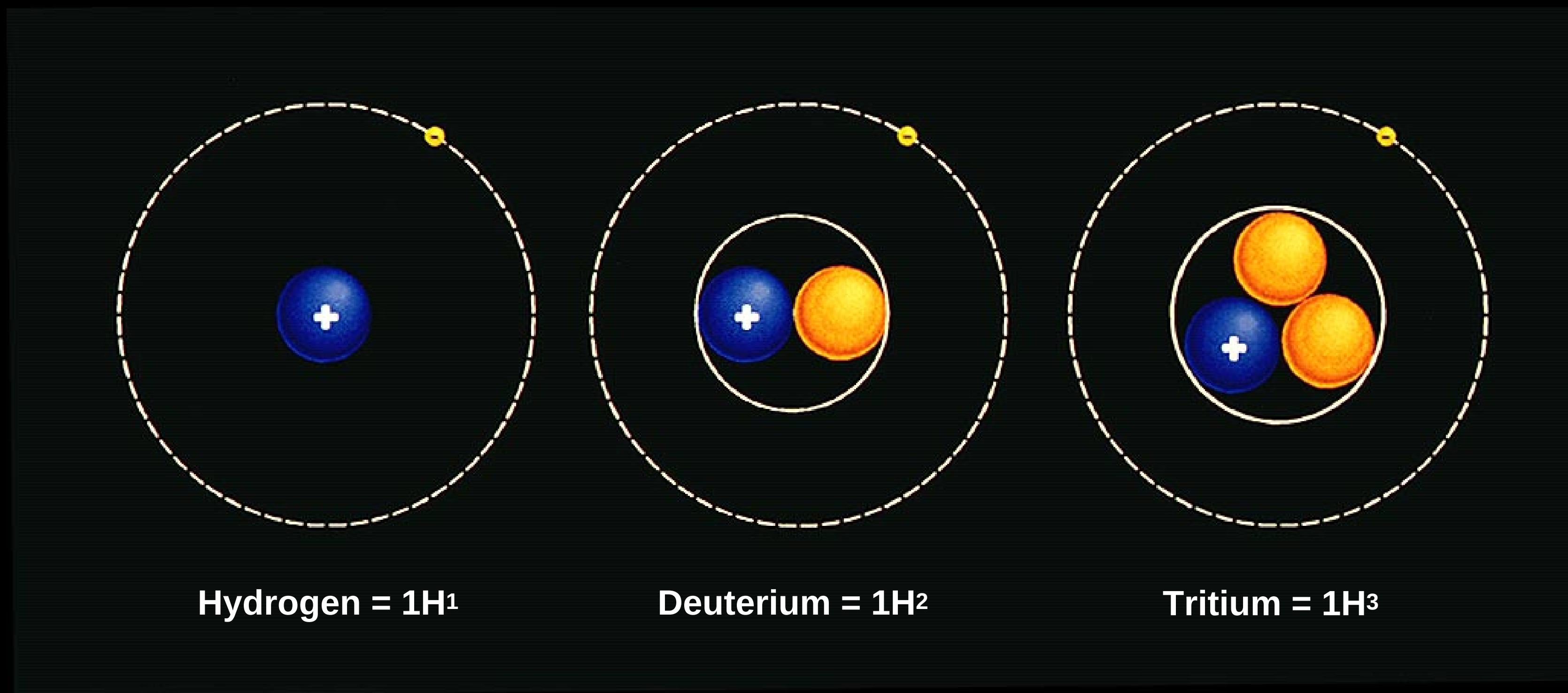
Like Charges Repel




1 H Hydrogen 1.00794
2 He Helium 4.00260
3 Li Lithium 6.941
4 Be Beryllium 9.01218
5 B Boron 10.81
6 C Carbon 12.011
7 N Nitrogen 14.0067
8 O Oxygen 15.9994
9 F Fluorine 18.998403
10 Ne Neon 20.179
11 Na Sodium 22.98977
12 Mg Magnesium 24.305
13 Al Aluminum 26.98154
14 Si Silicon 28.0855
15 P Phosphorus 30.97376
16 S Sulfur 32.06
17 Cl Chlorine 35.453
18 Ar Argon 39.948
19 K Potassium 39.0983
20 Ca Calcium 40.08
21 Sc Scandium 44.9559
22 Ti Titanium 47.88
23 V Vanadium 50.9415
24 Cr Chromium 51.996
25 Mn Manganese 54.9380
26 Fe Iron 55.847
27 Co Cobalt 58.9332
28 Ni Nickel 58.69
29 Cu Copper 63.546
30 Zn Zinc 65.38
31 Ga Gallium 69.72
32 Ge Germanium 72.59
33 As Arsenic 74.9216
34 Se Selenium 78.96
35 Br Bromine 79.904
36 Kr Krypton 83.80
37 Rb Rubidium 85.4678
38 Sr Strontium 87.62
39 Y Yttrium 88.9059
40 Zr Zirconium 91.22
41 Nb Niobium 92.9064
42 Mo Molybdenum 95.94
43 Tc Technetium (98)
44 Ru Ruthenium 101.07
45 Rh Rhodium 102.9055
46 Pd Palladium 106.42
47 Ag Silver 107.8682
48 Cd Cadmium 112.41
49 In Indium 114.82
50 Sn Tin 118.69
51 Sb Antimony 121.75
52 Te Tellurium 127.60
53 I Iodine 126.9045
54 Xe Xenon 131.29
55 Cs Cesium 132.9054
56 Ba Barium 137.33
72 Hf Hafnium 178.49
73 Ta Tantalum 180.9479
74 W Tungsten 183.85
75 Re Rhenium 186.207
76 Os Osmium 190.2
77 Ir Iridium 192.22
78 Pt Platinum 195.08
79 Au Gold 196.9665
80 Hg Mercury 200.59
81 Tl Thallium 204.383
82 Pb Lead 207.2
83 Bi Bismuth 208.9804
84 Po Polonium (209)
85 At Astatine (210)
86 Rn Radon (222)
87 Fr Francium (223)
88 Ra Radium 226.0254
104 Unq Unnilquadium (261)
105 Unp Unnilpentium (262)
106 Unh Unnilhexium (263)
107 Uns Unnilseptium (262)
108 Uno Unniloctium (265)
109 Une Unnilennium (266)
57 La Lanthanum 138.9055
58 Ce Cerium 140.12
59 Pr Praseodymium 140.9077
60 Nd Neodymium 144.24
61 Pm Promethium (145)
62 Sm Samarium 150.36
63 Eu Europium 151.96
64 Gd Gadolinium 157.25
65 Tb Terbium 158.9254
66 Dy Dysprosium 162.50
67 Ho Holmium 164.9304
68 Er Erbium 167.26
69 Tm Thulium 168.9342
70 Yb Ytterbium 173.04
71 Lu Lutetium 174.967
89 Ac Actinium 227.0278
90 Th Thorium 232.0381
91 Pa Protactinium 231.0359
92 U Uranium 238.0289
93 Np Neptunium 237.0482
94 Pu Plutonium (244)
95 Am Americium (243)
96 Cm Curium (247)
97 Bk Berkelium (247)
98 Cf Californium (251)
99 Es Einsteinium (252)
100 Fm Fermium (257)
101 Md Mendelevium (258)
102 No Nobelium (259)
103 Lr Lawrencium (260)

Hydrogen





$_1H^1$ $_1H^2$ $_1H^3$

Thermonuclear Reactions in the Sun

$_1H^1 + {}_1H^1 \rightarrow {}_1H^2 + {}_1e^0$

In the first reaction, 2 protons combine to form deuterium and a positron. One of the protons is converted into a neutron and a positon

proton → neutron
proton → positron

$_1H^2 + {}_1H^1 \rightarrow {}_2He^3 +$ (gamma) radiation

In the 2nd reaction a proton + deuterium unite to form the light isotope of helium, $_2He^3$

$_2He^3 + {}_2He^3 \rightarrow {}_2He^4 + {}_1H^1 + {}_1H^1$

The first two reactions must occur twice for the 3rd reaction to occur

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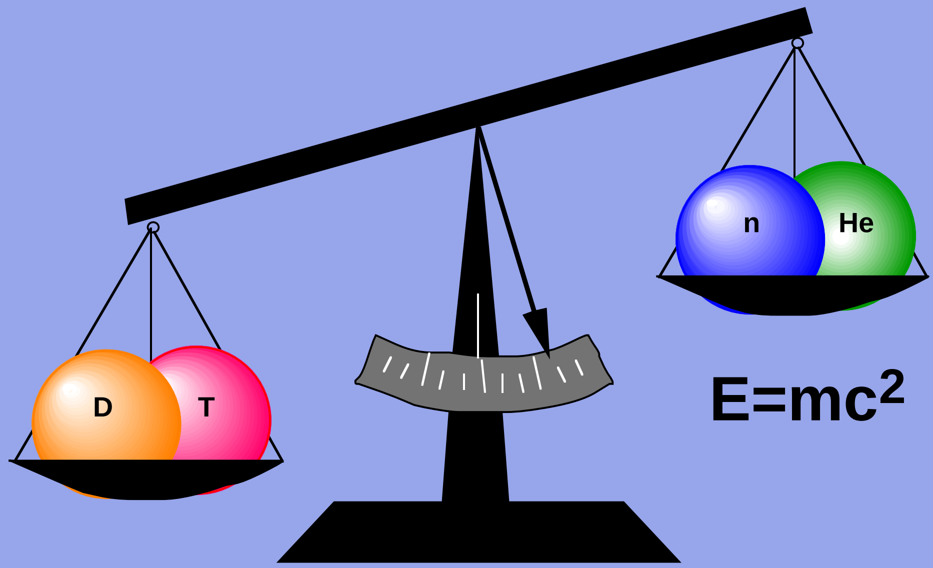
Summary of Solar Fusion Reactions

P + P → D + e^+ + Energy

D + P → $_2He^3$ + gamma radiation + Energy

$_2He^3$ + $_2He^3$ → $_2He^4$ + P + P + Energy

But the Potential Payoff is Enormous



$E=mc^2$

- The fraction of mass “lost” is just 38 parts out of 10,000
- Nevertheless, the fusion energy released from just 1 gram of DT equals the energy from about 2400 gallons of oil

$E = mc^2$

Einstein's equation that equates energy and mass

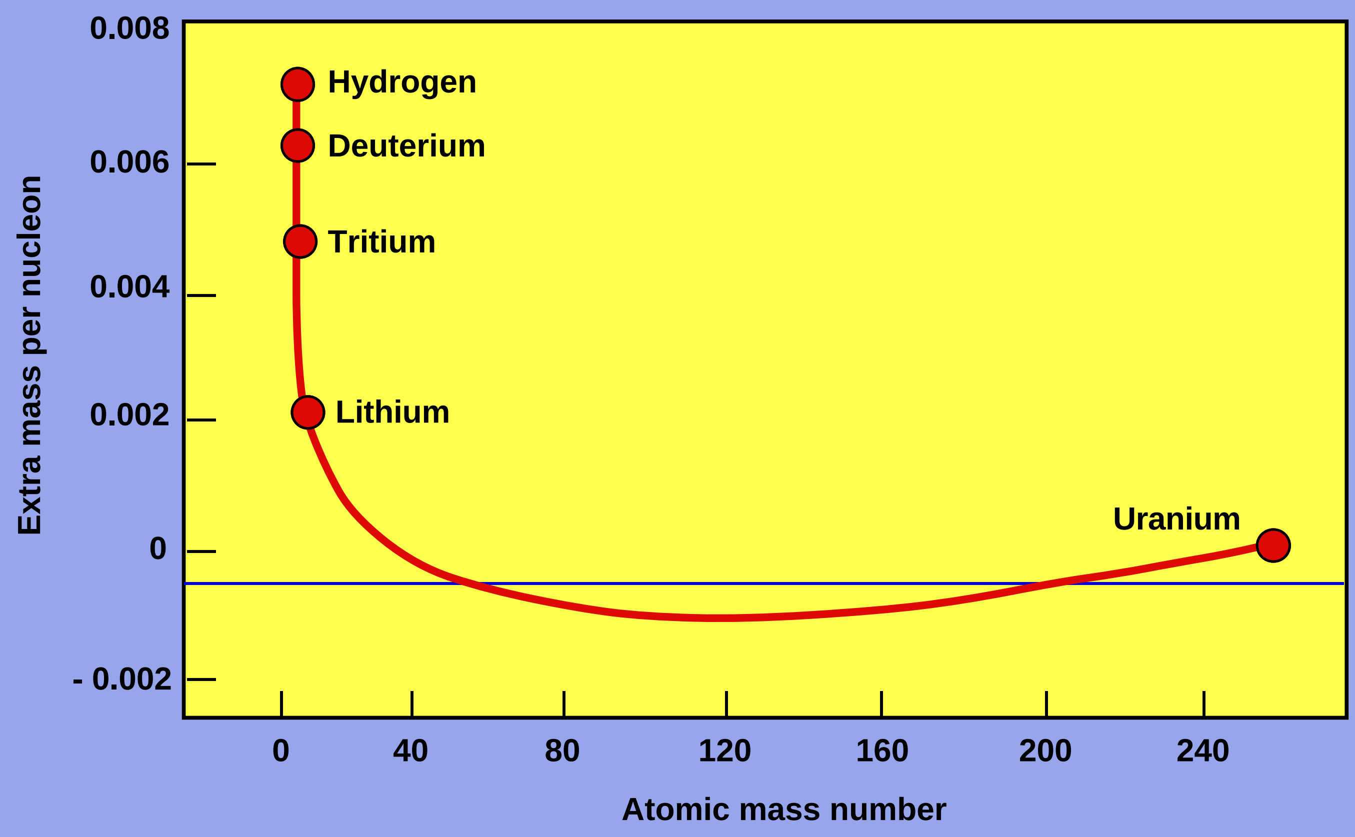
E = Energy
m = Mass
c = Speed of Light (3×10^8 m/sec)

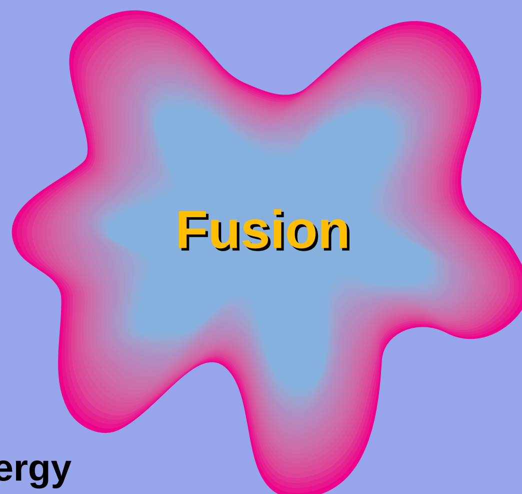
Example:
If a 1 gram raisin was converted completely into energy

$$E = 1 \text{ gram} \times c^2$$
$$= (10^{-3} \text{ kg})(3 \times 10^8 \text{ m/sec})^2$$
$$= 9 \times 10^{13} \text{ joules}$$

This would be equivalent to 10,000 tons of TNT!

Energy Release $E = mc^2$



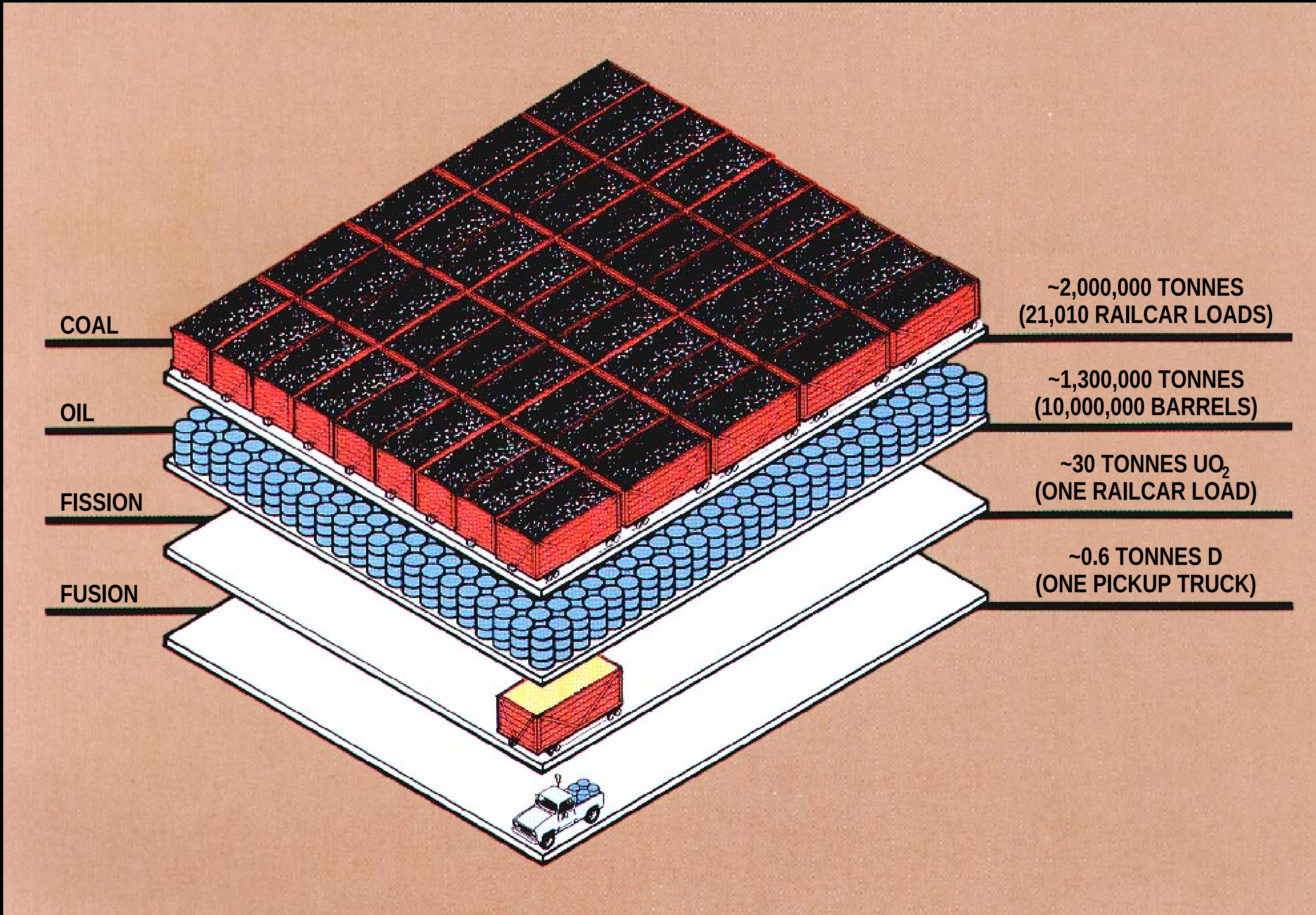


Energy Input

We give kinetic energy (temperature) to hydrogen

Energy Output

We get back 2000 times more energy than we put in


COAL
OIL
FISSION
FUSION
~2,000,000 TONNES
(21,010 RAILCAR LOADS)
~1,300,000 TONNES
(10,000,000 BARRELS)
~30 TONNES UO_2
(ONE RAILCAR LOAD)
~0.6 TONNES D
(ONE PICKUP TRUCK)

Abundant Energy From Sea Water

50 Cups Sea Water

2 Tons of Coal

or

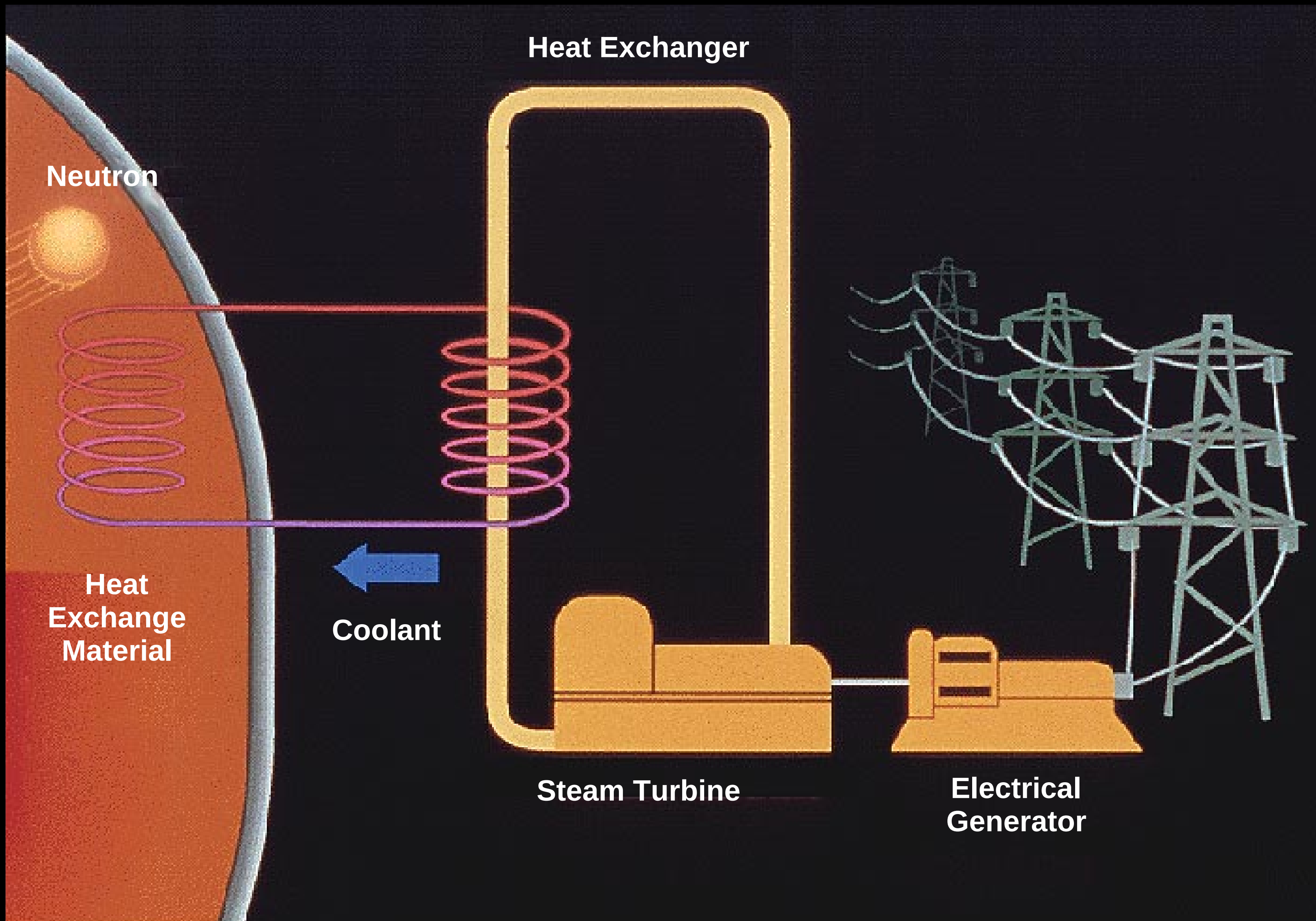
Thimble of ^{2}H (D)
Deuterium

20 Tons of Coal

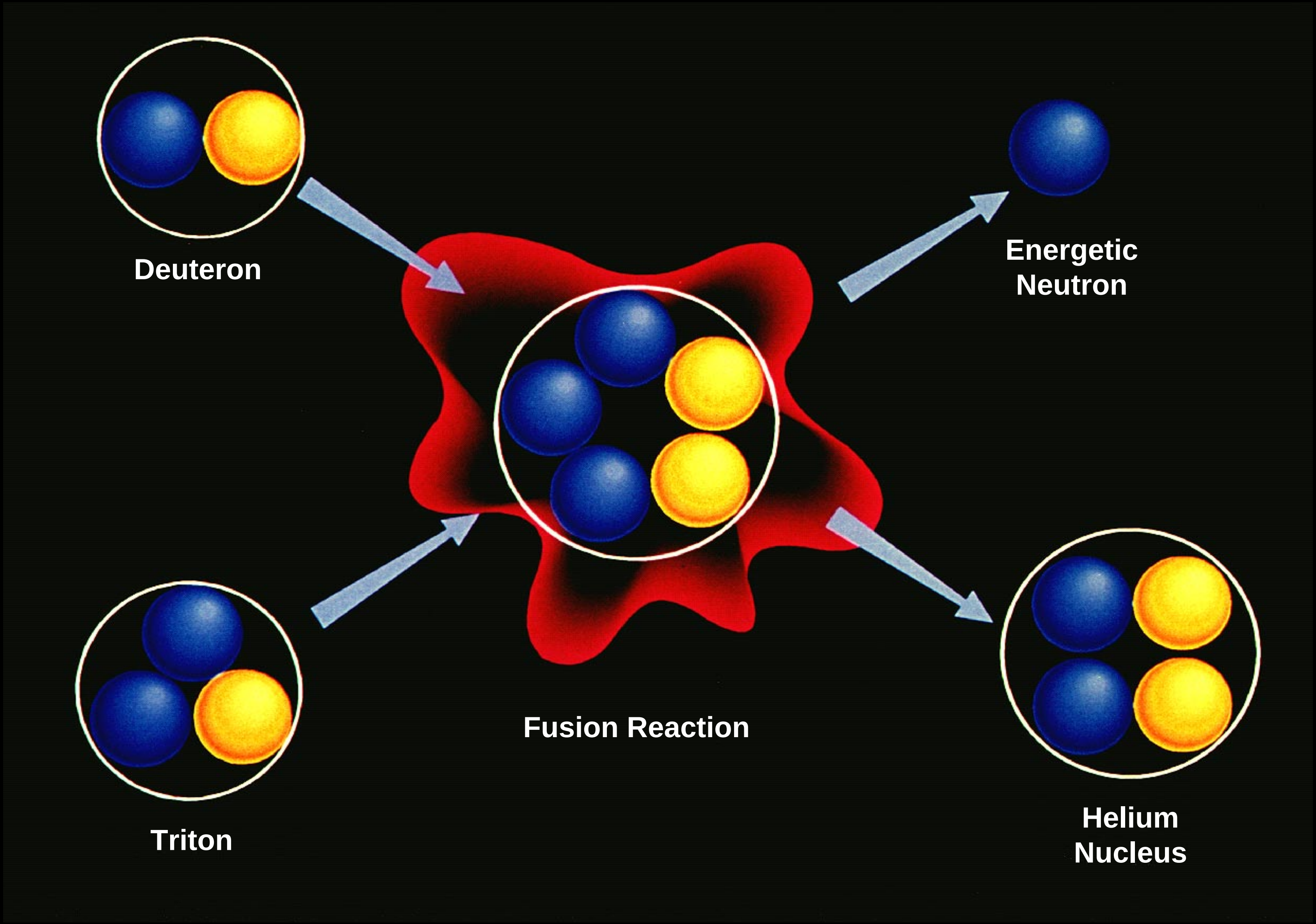
Reduced Waste Products

Power Source	Total Waste (cubic meters)	High-Level RAD Waste
Coal	10,000 (ashes)	0
Fission	440	120
Fusion:		
Today's Materials	2000	30
Advanced Materials	2000	0

1000 MW(e) Power Plant - 30 year Lifetime


Heat Exchanger
Neutron
Heat Exchange Material
Coolant
Steam Turbine
Electrical Generator

Reaction		Ignition Temperature		Output Energy
Fuel	Product	(millions of °C)	(keV)	(keV)
D + T	^4He + n	45	4	17,600
D + ^3He	^4He + p	350	30	18,300
D + D	^3He + n	400	35	~4,000
	T + p	400	35	~4,000


Deuteron
Energetic
Neutron
Fusion Reaction
Triton
Helium
Nucleus

Fusion Represents an Inexhaustible Energy Supply for Mankind

- Fusion fuels deuterium (D) and tritium (T) are hydrogen isotopes

- 3/4 oz. of heavy water has the same energy content as 13,000 gallons of oil for D-D reaction, or 32,000 gallons of oil for D-T reaction

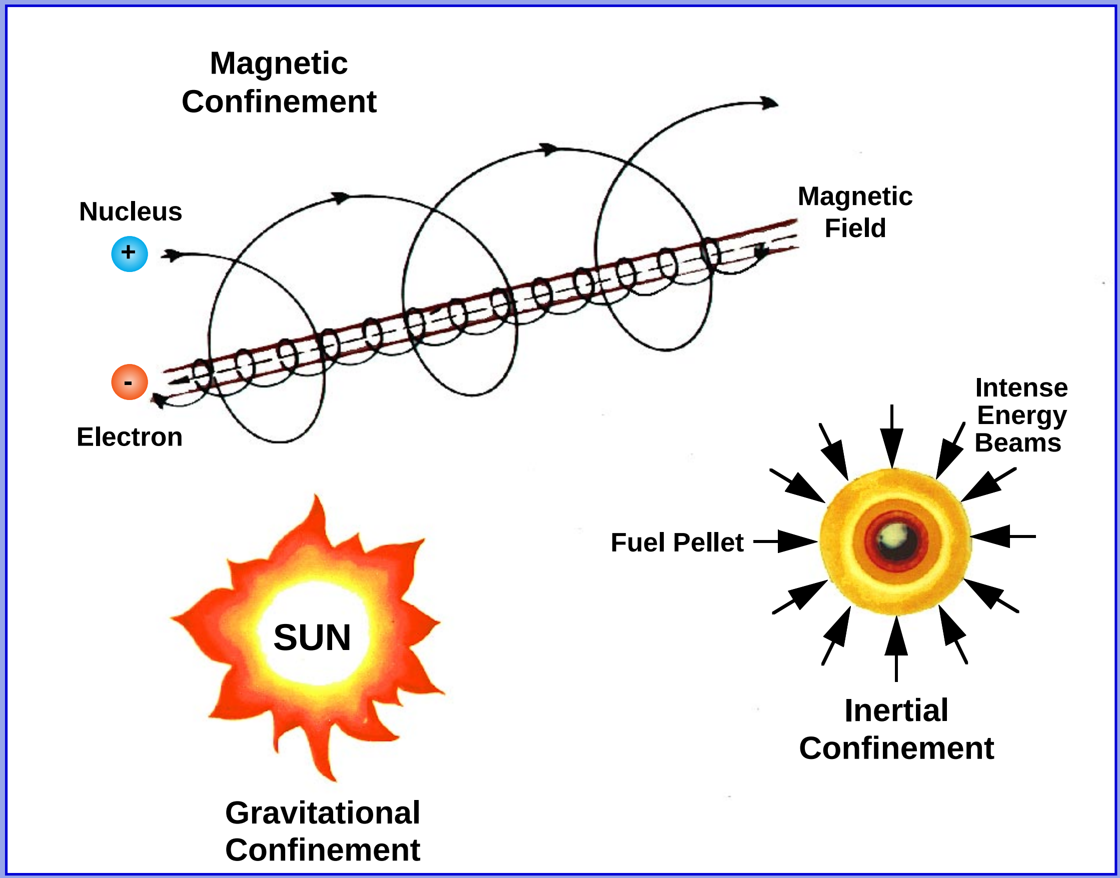
- Tritium is made from
  n + Li ⇨ T + He

- Lithium is plentiful both in the earth's crust and oceans

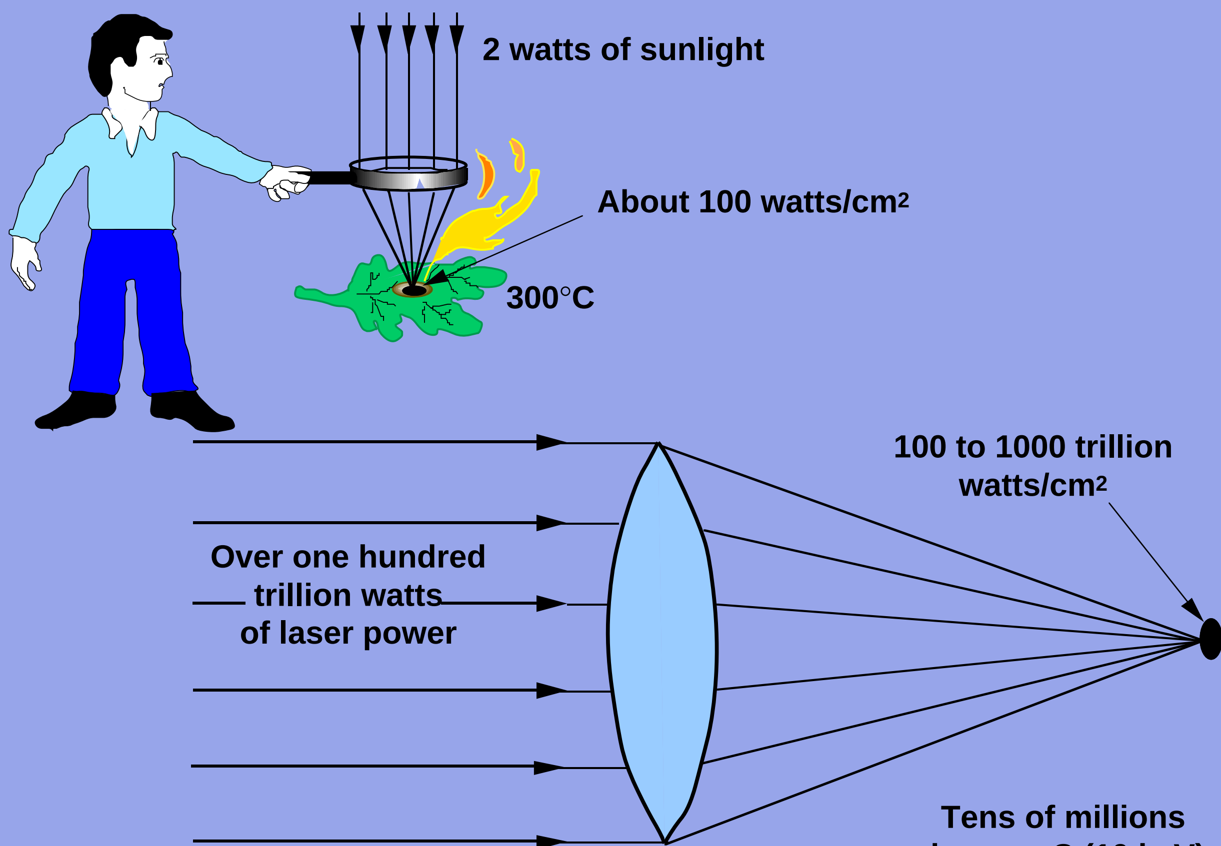
Methods to Heat Deuterium-Tritium Fuel

- Compressing the fuel
- Internal Electric Current
- Neutral Particles
- Microwaves
- Lasers

Fusion can be accomplished in Three Different Ways



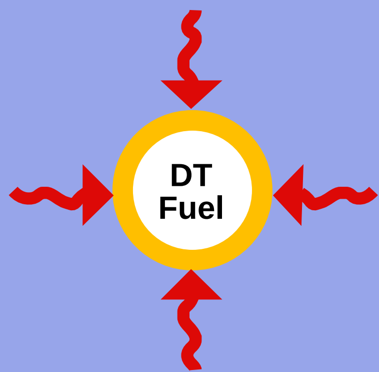
High Power Lasers can Deliver the Intensity Required for Fusion Ignition



Inertial Confinement Fusion Concept

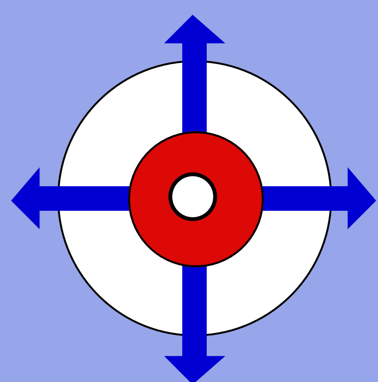
Our ultimate goal is to create a short lived, microminiature star which will release energy by thermonuclear fusion in the same manner that our sun and the stars produce energy.

Heating of ablator



Use high power laser to heat outer surface of pellet

Ablation and compression



Outward streaming ablator material produces an inward directed, rocket-like force that compresses the DT fuel

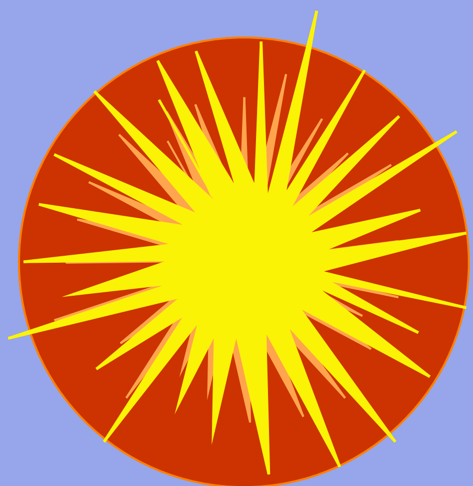
Inertial Confinement Fusion Concept

(continued)

Compression and heating

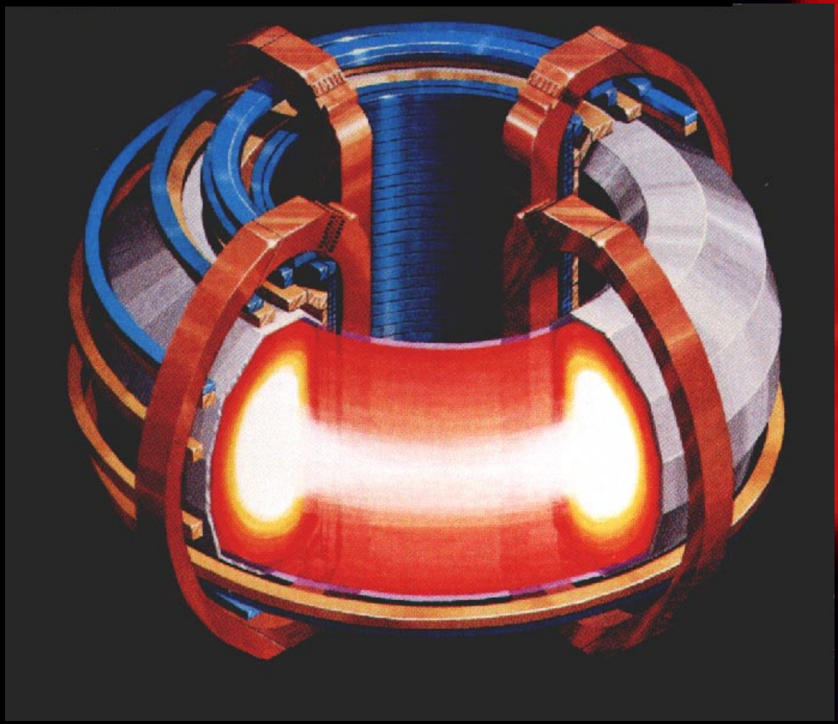
Careful tailoring of implosion produces compression to several 1000X and 100,000,000°C

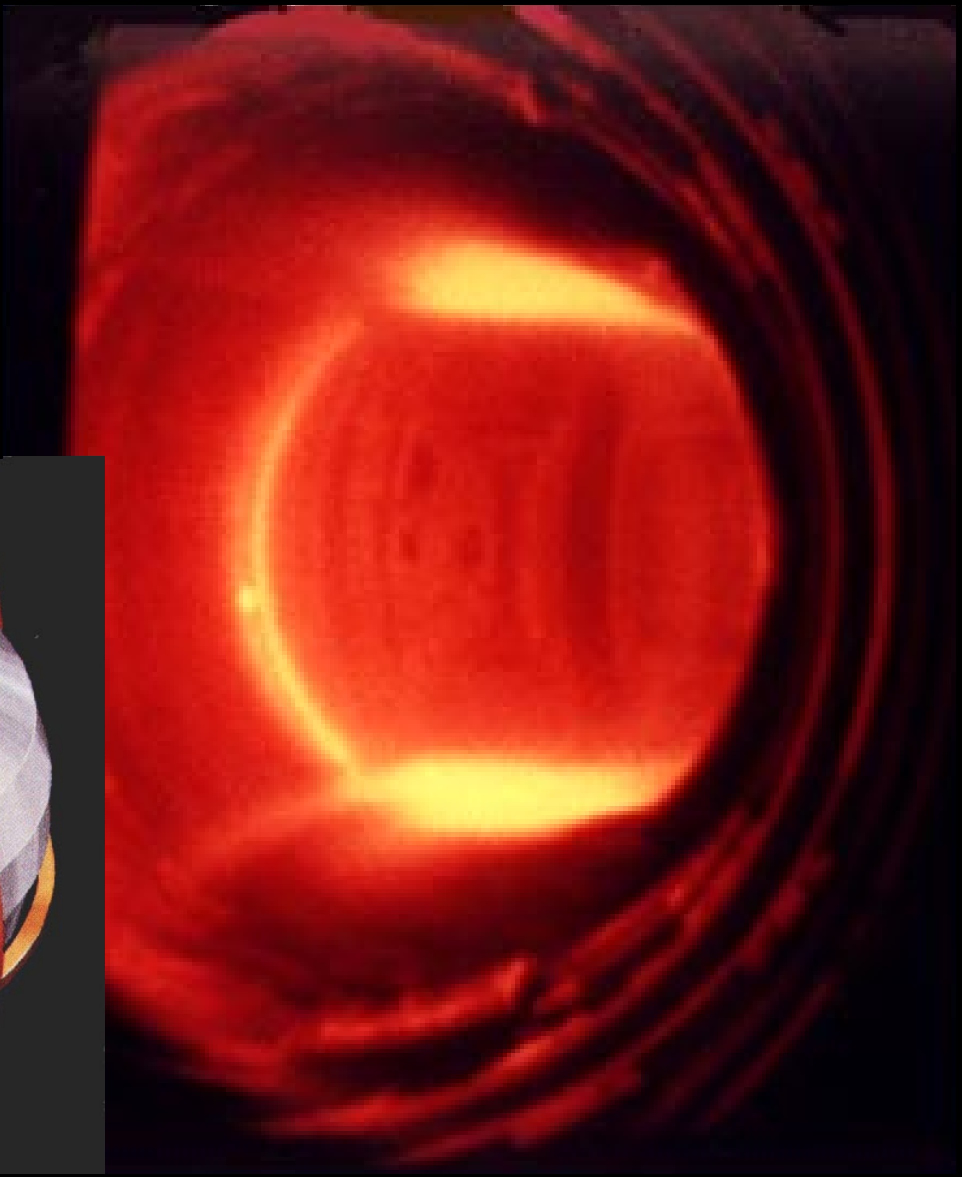
Ignition and Thermonuclear burn



Thermonuclear burn of the DT fuel will produce a fusion yield many times the input driver energy

Toroidal Magnetic Confinement of Plasma



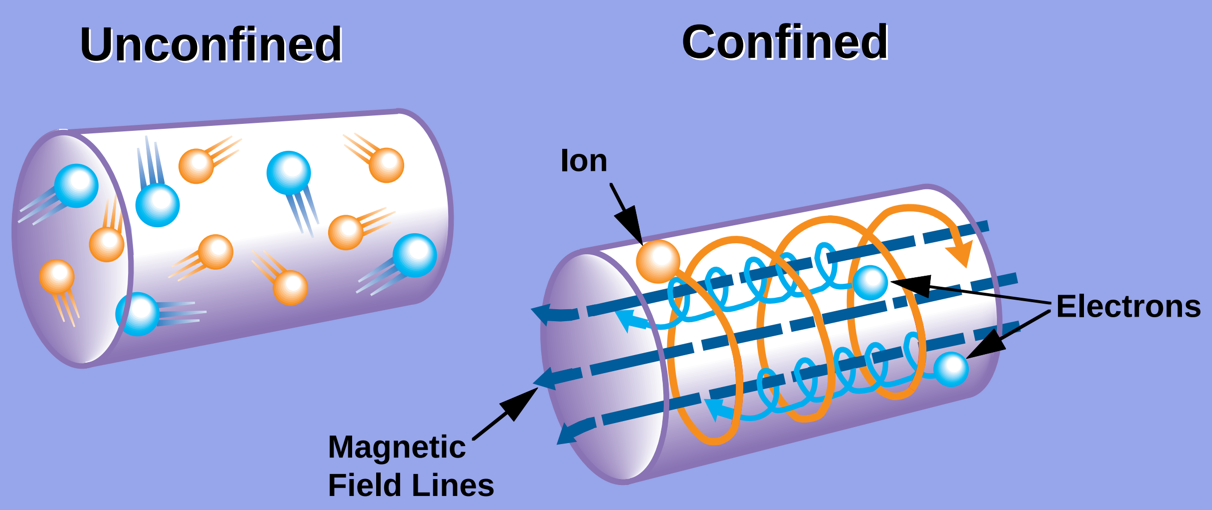


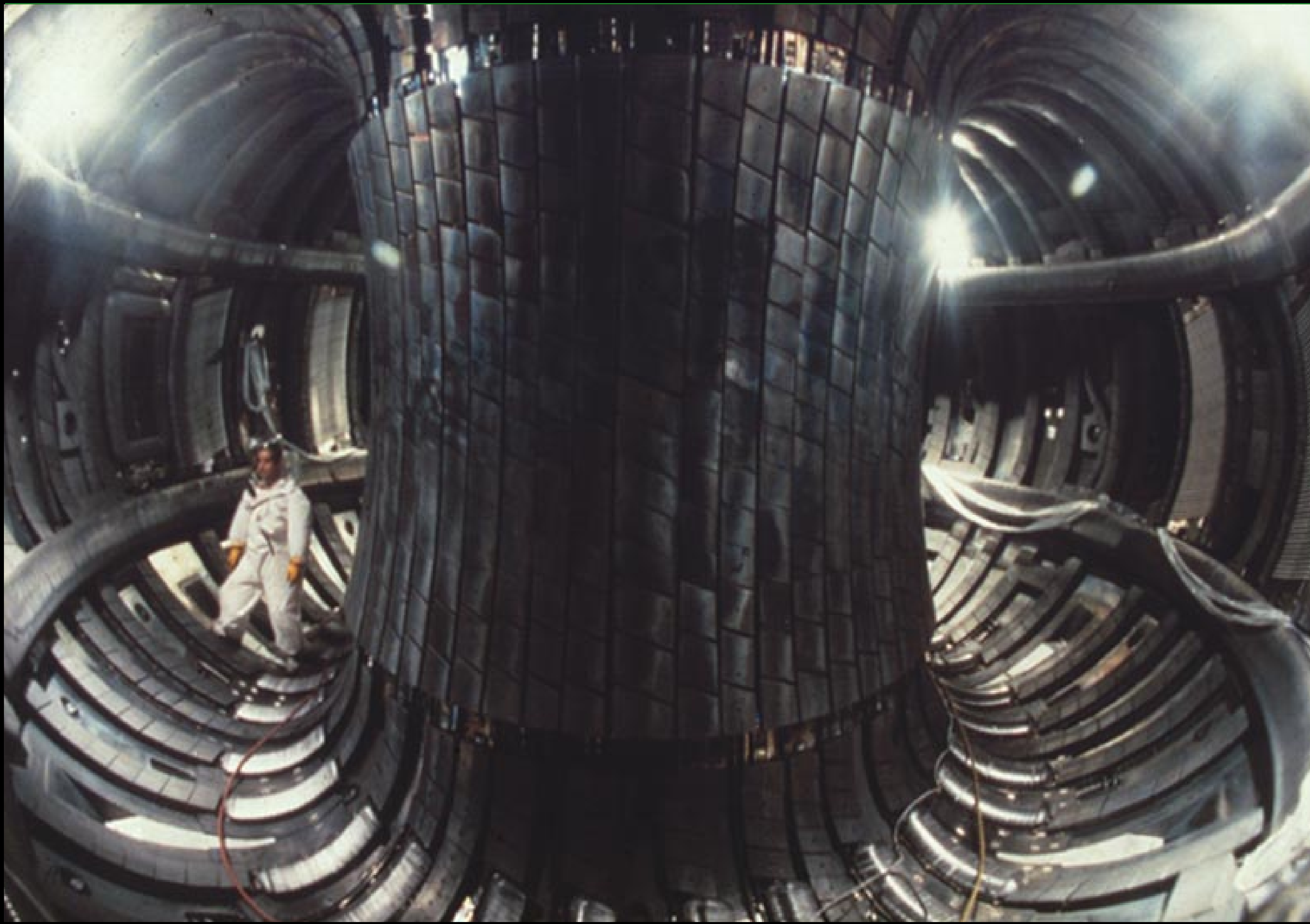
Typical Plasmas

	Density	Temperature	
	n_e (m^{-3})	T_e (eV)	°K
Interstellar	10^{+6}	1	10^4
Solar Corona	10^{12}	10^2	10^6
Thermonuclear	10^{20}	10^4	10^8
Laser	10^{26}	10^2	10^6
Air Density	10^{25}	1/40	294

Characteristics of a Plasma

- Particles are charged
- Conducts electricity
- Can be constrained magnetically


Unconfined
Confined
Ion
Electrons
Magnetic
Field Lines



Where are the Current Major Fusion Energy Research Projects?

List of Major Programs/Devices Worldwide

JET from the European Community

JT-60U in Japan

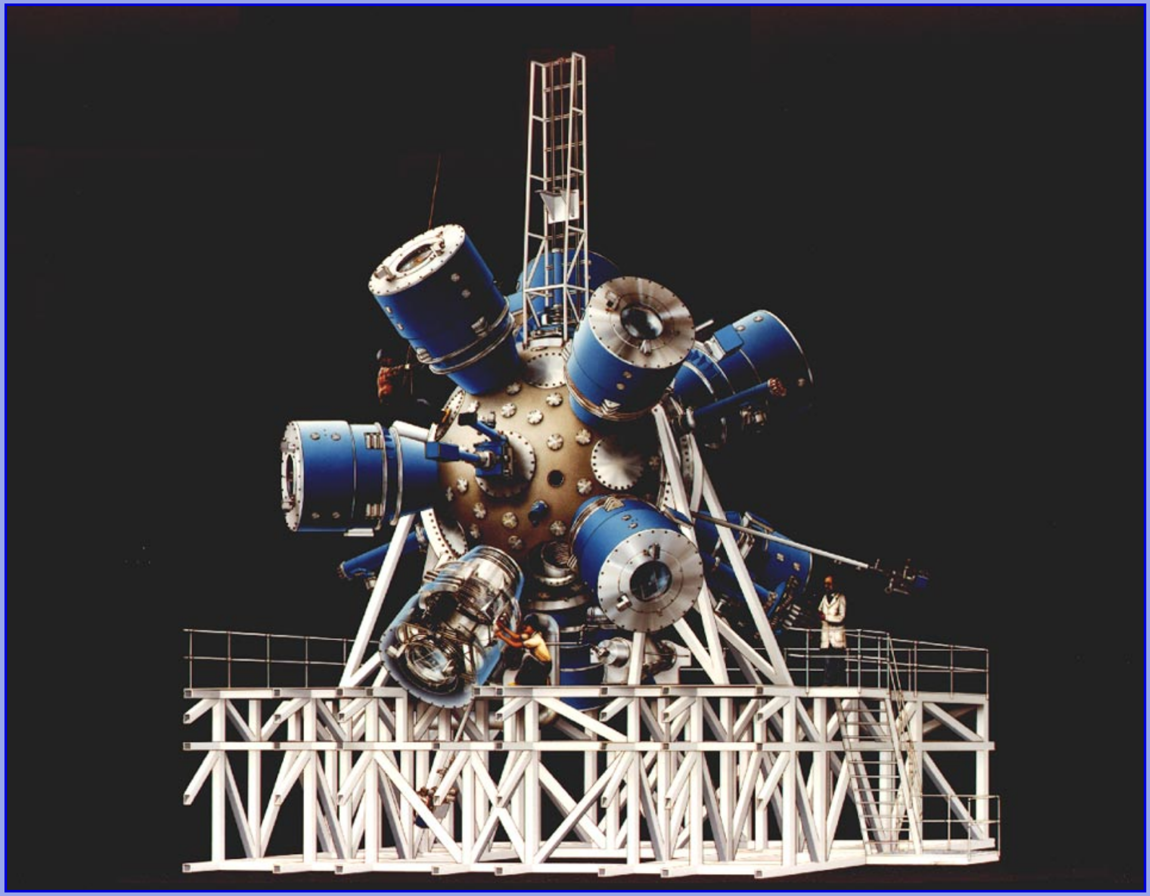
NOVA at Lawrence Livermore Labs in California

TFTR at PPPL in Princeton, New Jersey

DIII-D at General Atomics in San Diego, CA

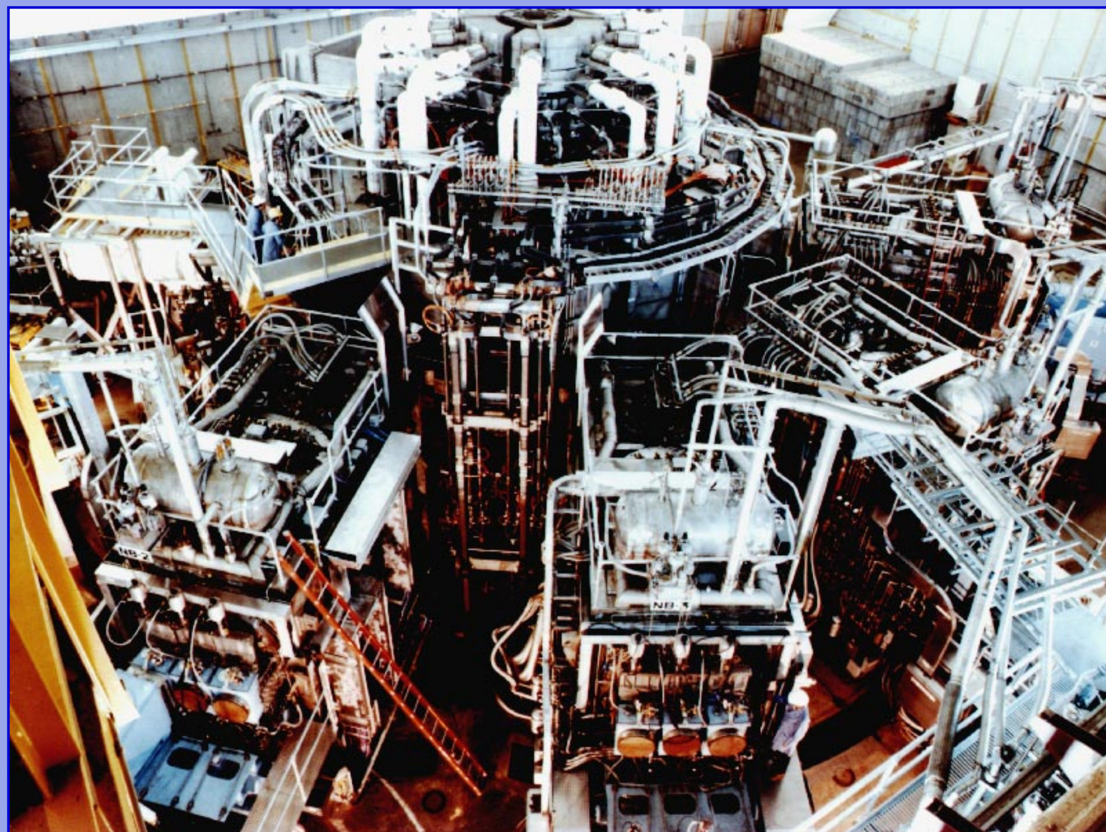
NOVA Machine Used Inertial Confinement

(Has Not Proved as Successful as Magnetic Confinement)



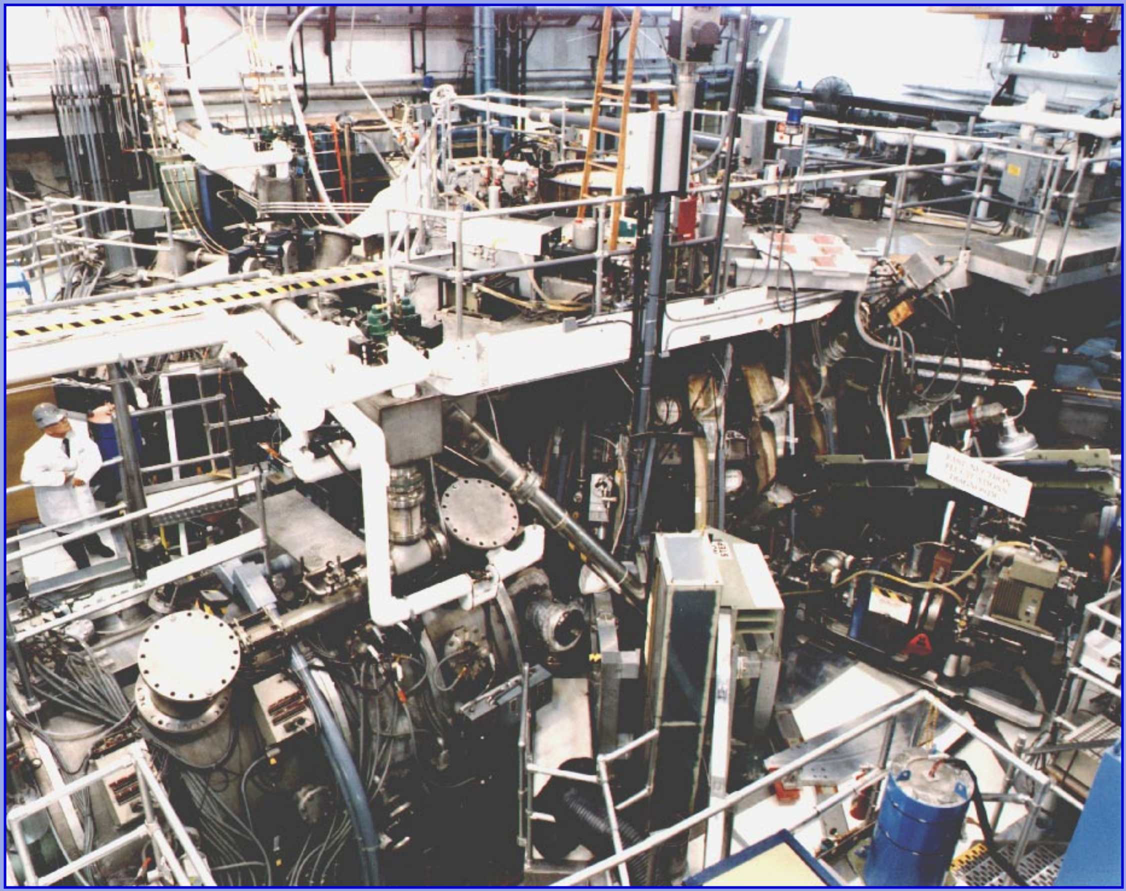
TFTR is located at PPPL

Princeton, New Jersey



DIII-D is Located at General Atomics

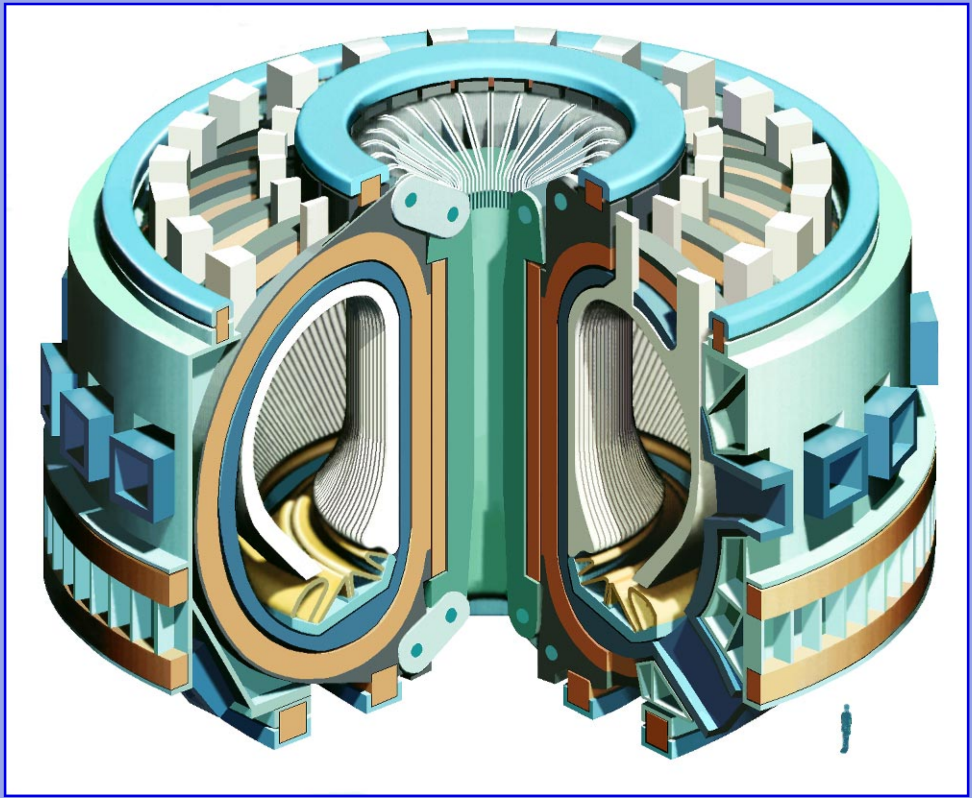
San Diego, CA



ITER
(International Thermonuclear Experimental Reactor)

- Cooperative effort by Europe, Japan, U.S. and Russia
- Conceptual Design Activity completed
- Engineering Design Activity is underway
  - Three sites: San Diego, U.S.A., Garching, Germany and Naka, Japan
  - Detailed engineering and protoype testing
  - Cost of $300 M per party over 6 years
- Decision to proceed with construction will be made in 1995

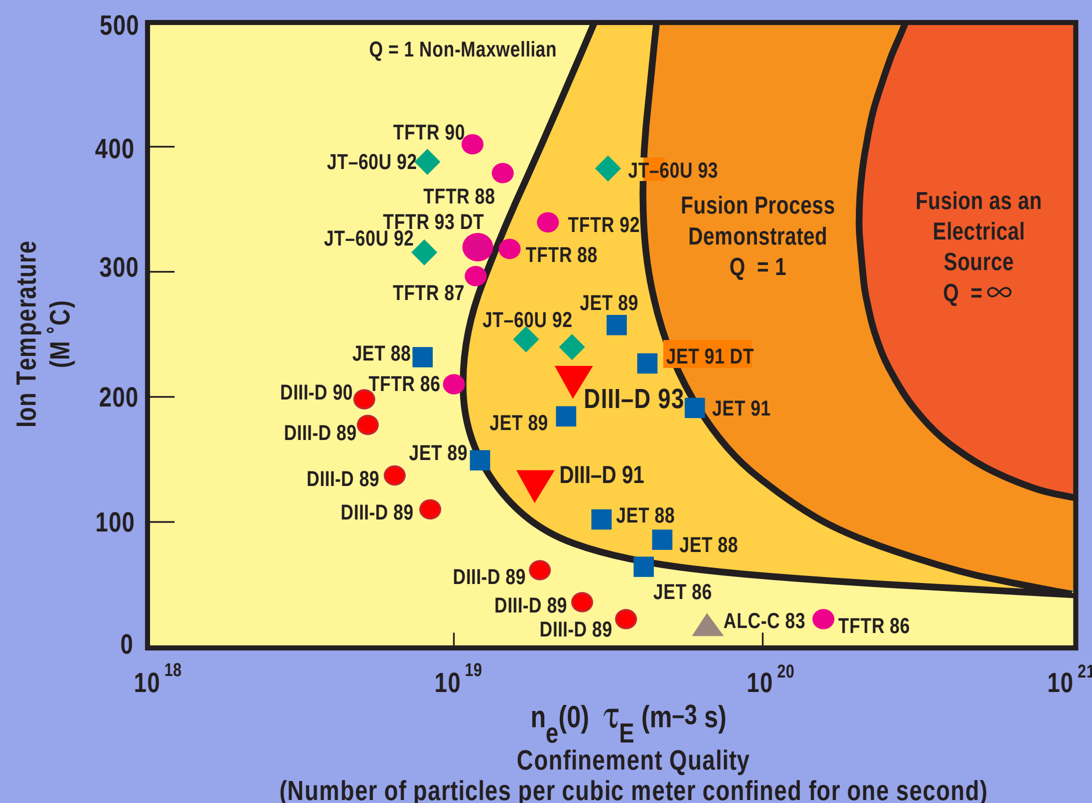
ITER
(International Thermonuclear Experimental Reactor)



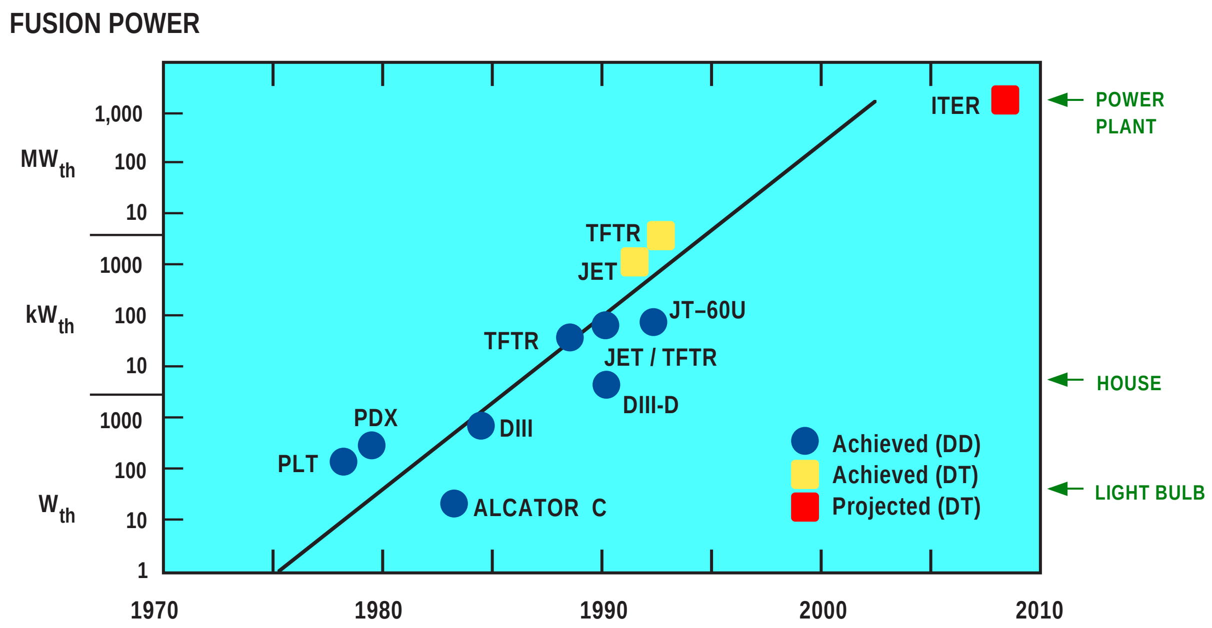
30 meters diameter
30 meters tall

ITER

Fusion Experiments Now Approach Ignition Conditions



What Progress Has Been Made in Magnetic Fusion?



PLT	Princeton Large Tokamak	TFTR	Princeton Plasma Physics Laboratory
PDX	Princeton Divertor Experiment	ALCATOR C	Massachusetts Institute of Technology
JET	Joint European Torus	ITER	International Thermonuclear Experimental Reactor
DIII & DIII-D	General Atomics Tokamak Experiments	JT–60U	Japanese Tokamak Experiment

World Energy Resources Indicate New Sources of Clean Energy Must be Found

ANNUAL USE	**0.3 Q/year**
Oil	13
Fossil	80
Uranium	9,000
Lithium	7,600
Deuterium	16,000,000

In units of Q or 10^{18} BTU