Star in a Jar

Prospects for Fusion Power in the 21st Century

A need for alternative energy sources

- **Peak oil production predicted in 10-20 years.**
- **Coal supply is extensive, but…**
  - **Concern about carbon emission and climate change.**
- **World population growth is concentrated in the developing world… where *per capita* energy demand is also increasing.**

The promise of fusion

- **Vast fuel supply**
- **No carbon emission**
- **Much less radioactive waste (with much shorter half-lives) than nuclear fission**
- **No risk of catastrophic accidents**

Chemical vs. *Nuclear* reactions

- *Chemical* reactions: rearrange atoms in molecules

  Example: methane combustion

$$CH_4 + 2O_2 \Rightarrow CO_2 + 2H_2O + \text{energy}$$

- *Nuclear* reactions: rearrange protons and neutrons to make new elements

  Example: FISSION reaction

$$n + {}^{235}U \Rightarrow {}^{141}Ba + {}^{92}Kr + 3n + \text{energy}$$

- The alchemists' dreams come true!

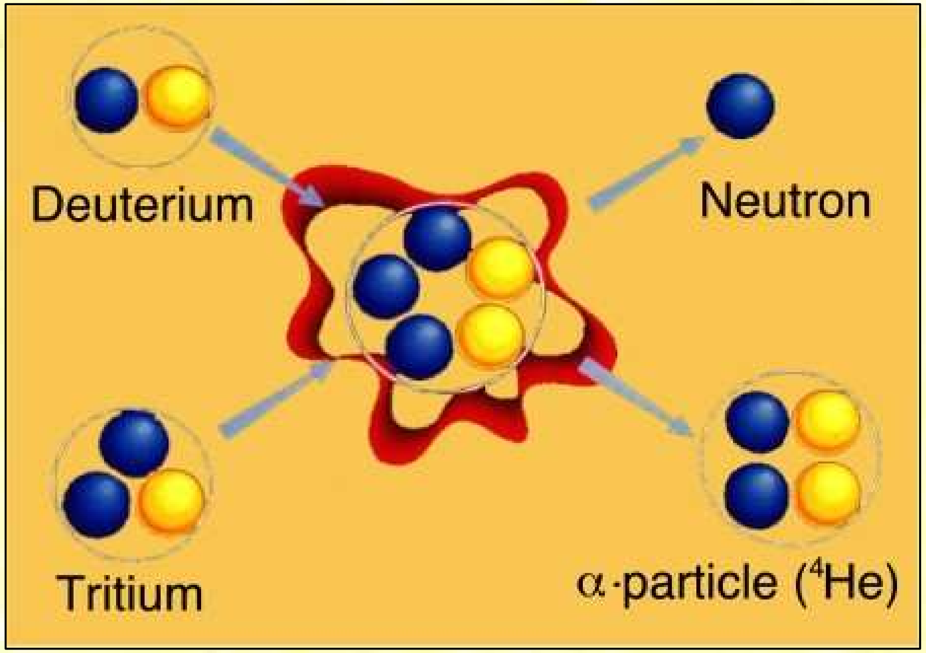
Fusion is a *nuclear* reaction

Light nuclei are combined to form heavier nuclei, releasing energy.

Opposite of nuclear fission

Heavy hydrogen: 1 of every 6500 H Atoms is deuterium

Really heavy hydrogen: produced in a nuclear reaction using *lithium*



Much of the energy comes out in hot neutrons … source of radioactive waste

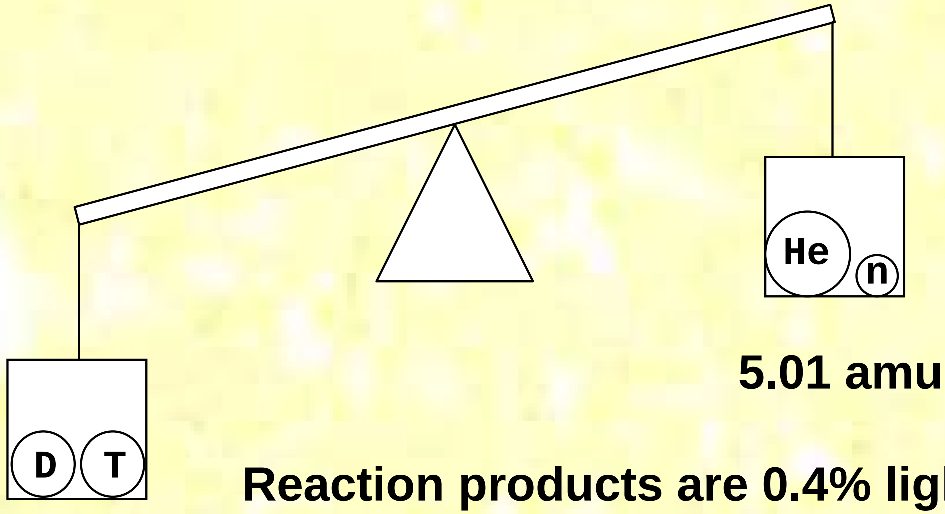
Helium "ash" is benign

Yellow = proton Blue = neutron

Image source: www.iter.org

Einstein’s most famous equation

- **Converting mass to energy ($E = mc^2$)**



Reaction products are 0.4% lighter than reactants

5.03 amu

- **Energy concentration:**

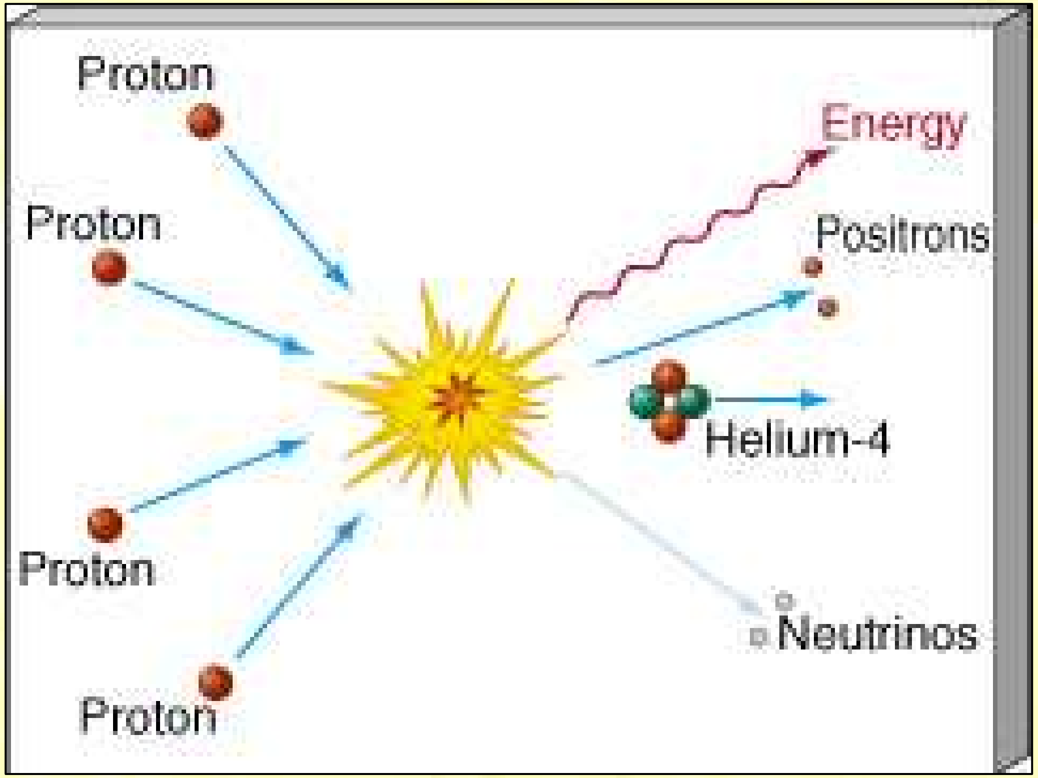
D-T: 360,000,000,000 J/g

methane: 56,000 J/g

Nuclear energy is millions of times more concentrated than chemical energy

Does fusion really happen?

- **Fusion is STARPOWER!**

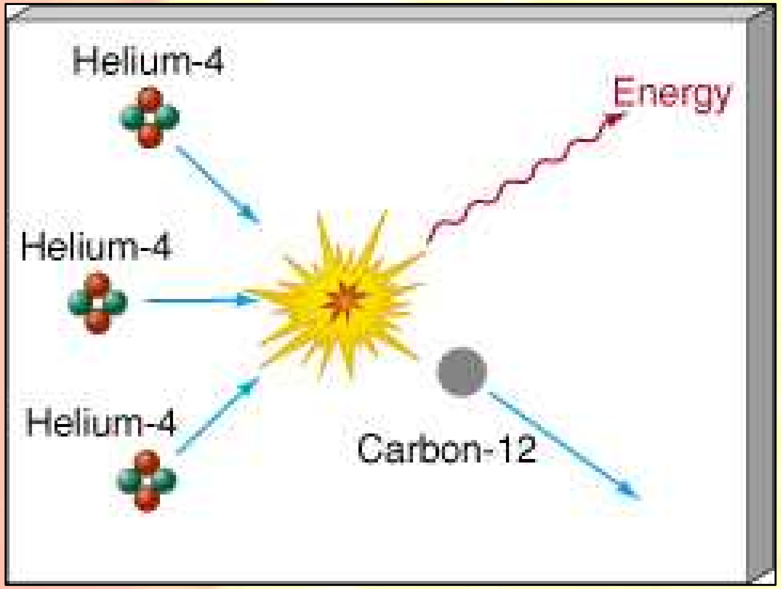


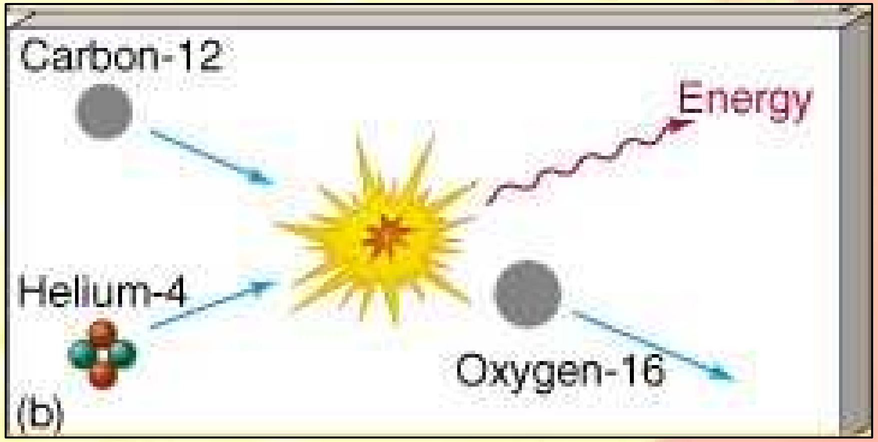
Proton-proton chain is the dominant energy producing reaction in the sun.

Image source: Astronomy Today, by Chaisson and McMillan (Prentice Hall 2002)

We are made of stardust!

- Hydrogen and helium were the original elements in the universe.
- Stars have cooked up everything else.





Triple alpha process

Image source: Astronomy Today, by Chaisson and McMillan (Prentice Hall 2002)

Humans have made fusion happen explosively

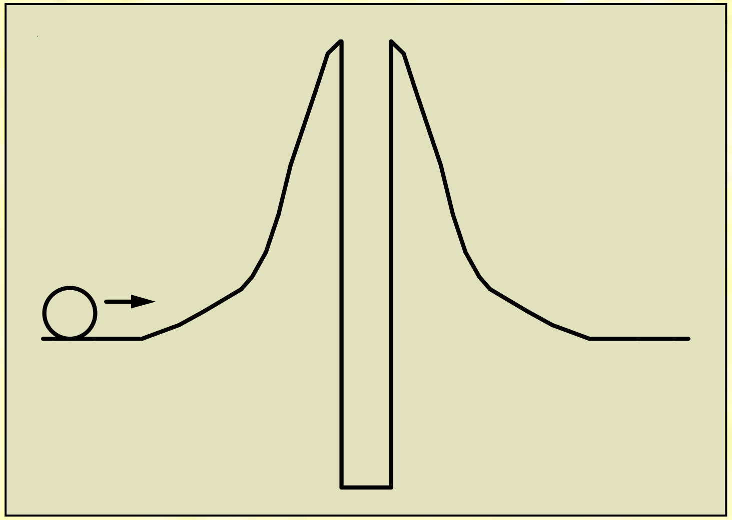
- The hydrogen bomb is a fusion bomb

- Fusion is also observed and measured in accelerator experiments.

Image source: www.michaellight.net

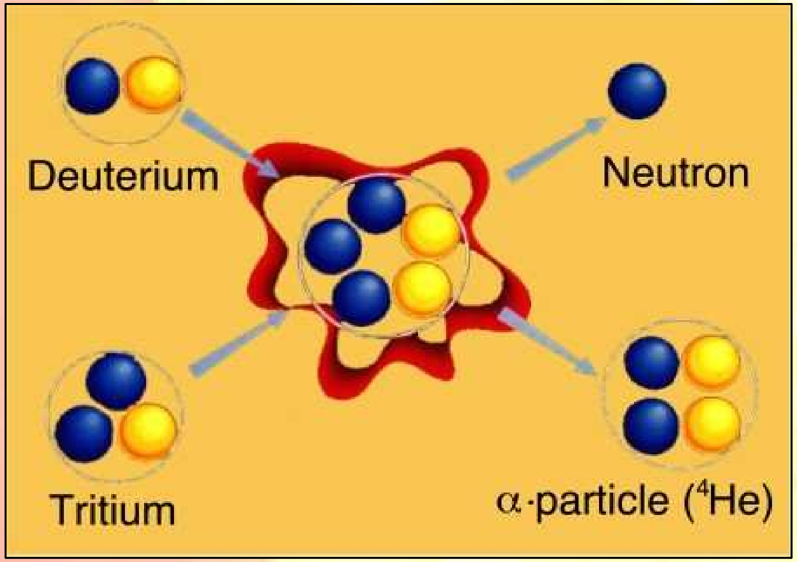
Why doesn't fusion happen easily?

- **Positively charged nuclei repel each other *electrically*.**
- ***Strong* force is attractive at very close distances.**
- **Analogy: rolling ball into well at the top of a hill.**



Why heavy hydrogen?

- D-T reaction is easiest
- Required temperature:
  About 100 million ℃
  (200 million ℉)



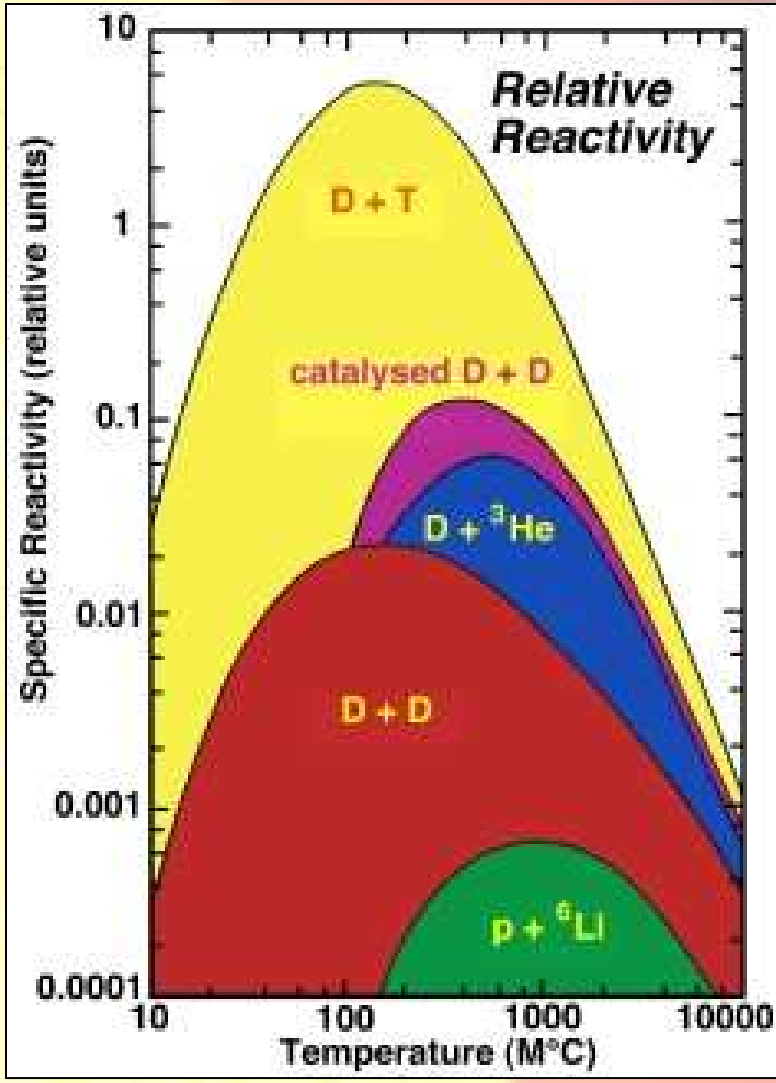


Image source: www.iter.org

Plasma Physics

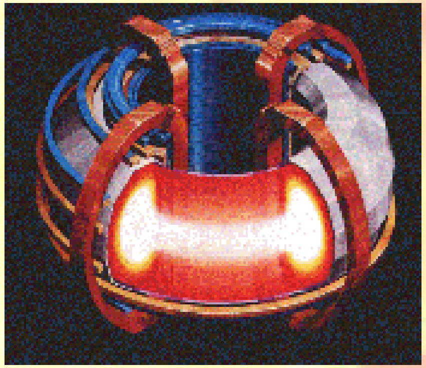
- **At 100 million ℃ collisions between atoms knock off electrons creating PLASMA.**

- **Examples of plasma:**
  - **Lightning bolt**
  - **Fluorescent light bulbs**
  - **Ionosphere → aurorae**
  - **Stars**
  - **Fusion experiments**
  - **Silicon chip manufacturing**
  - **Flat screen plasma TVs**
  - ***NOT BLOOD***

Image source: Astronomy Today, by Chaisson and McMillan (Prentice Hall 2002)

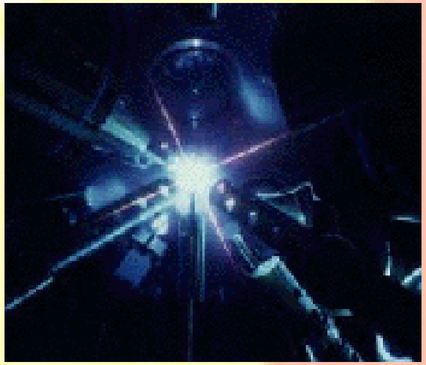
Strategies for Achieving Controlled Fusion Reactions

- **Magnetic Confinement**



  - **Strong magnetic field insulates hot plasma from cool vessel.**
  - **Heat plasma with particle beams, radio waves and high currents (mega-amps).**

- **Inertial Confinement**



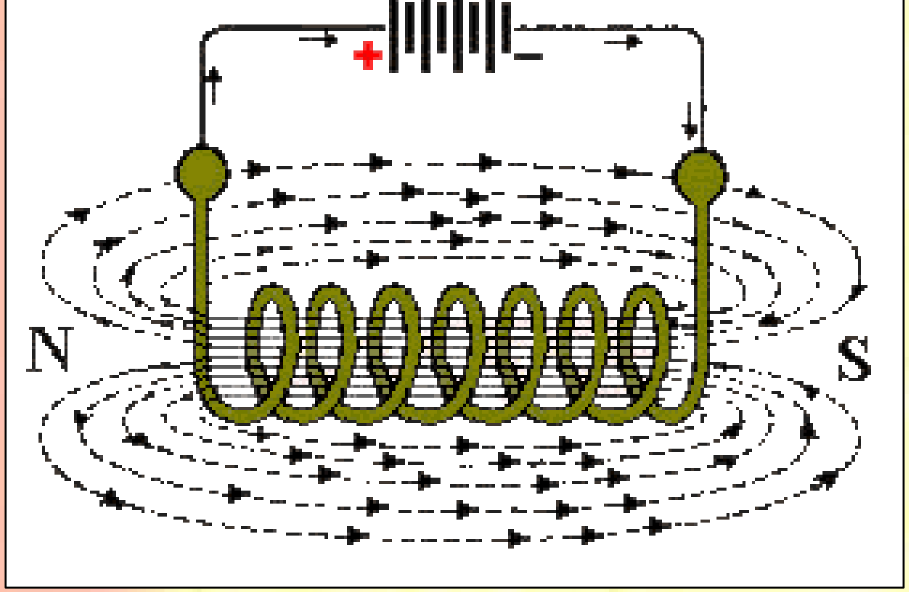
  - **Mini-H-bomb**
  - **Implode tiny fuel capsule with particle or laser beams.**

Image source: http://fusedweb.pppl.gov/

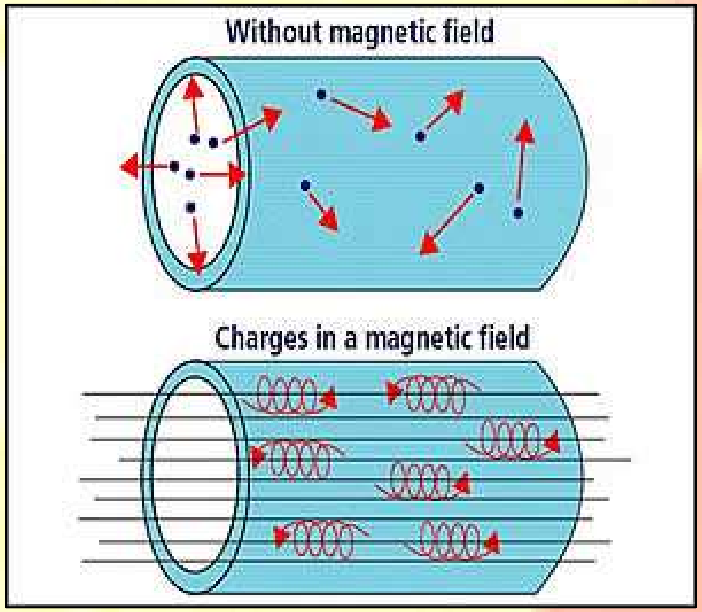
Magnetic Confinement Fusion

• Magnetic fields are created by electric current loops (coils).

SOLENOID



•Charged particles move in helical orbits around magnetic field, but stream freely along the field



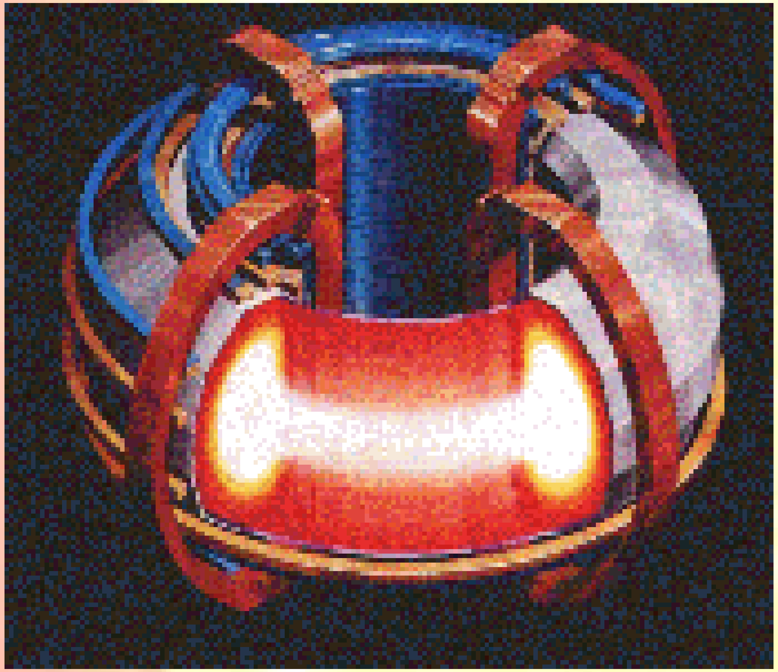
• Magnetic field keeps charged particles from moving radially,
• But… what about the ends?

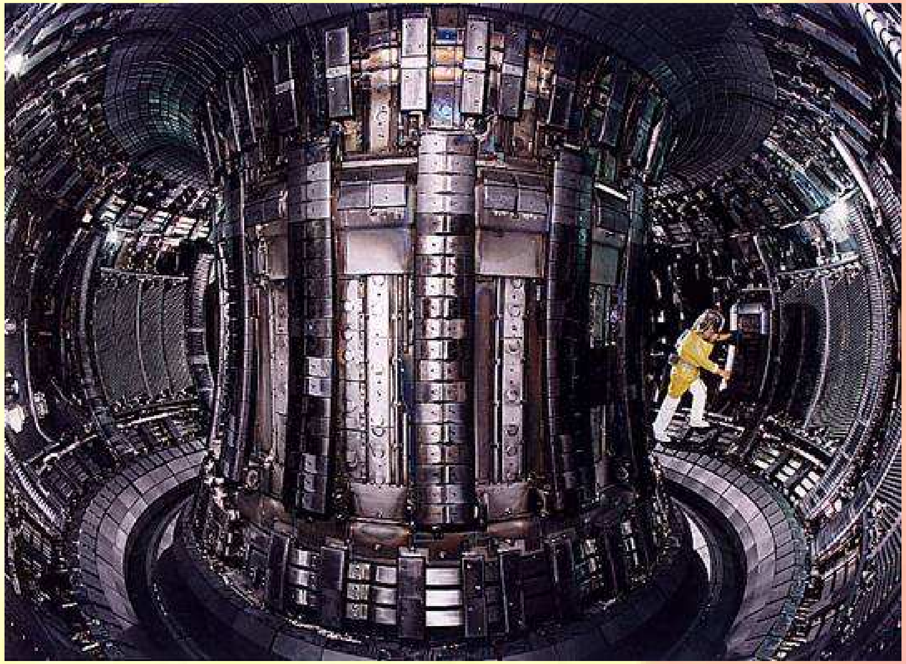
Image source: www.physics.mcmaster.ca/~macdougj/pics/solenoid.gif

Image source: www.jet.efda.org/pages/content/fusion3.html

The Tokamak

- Bend solenoid into a torus (doughnut).
- Magnetic field bites its own tail.



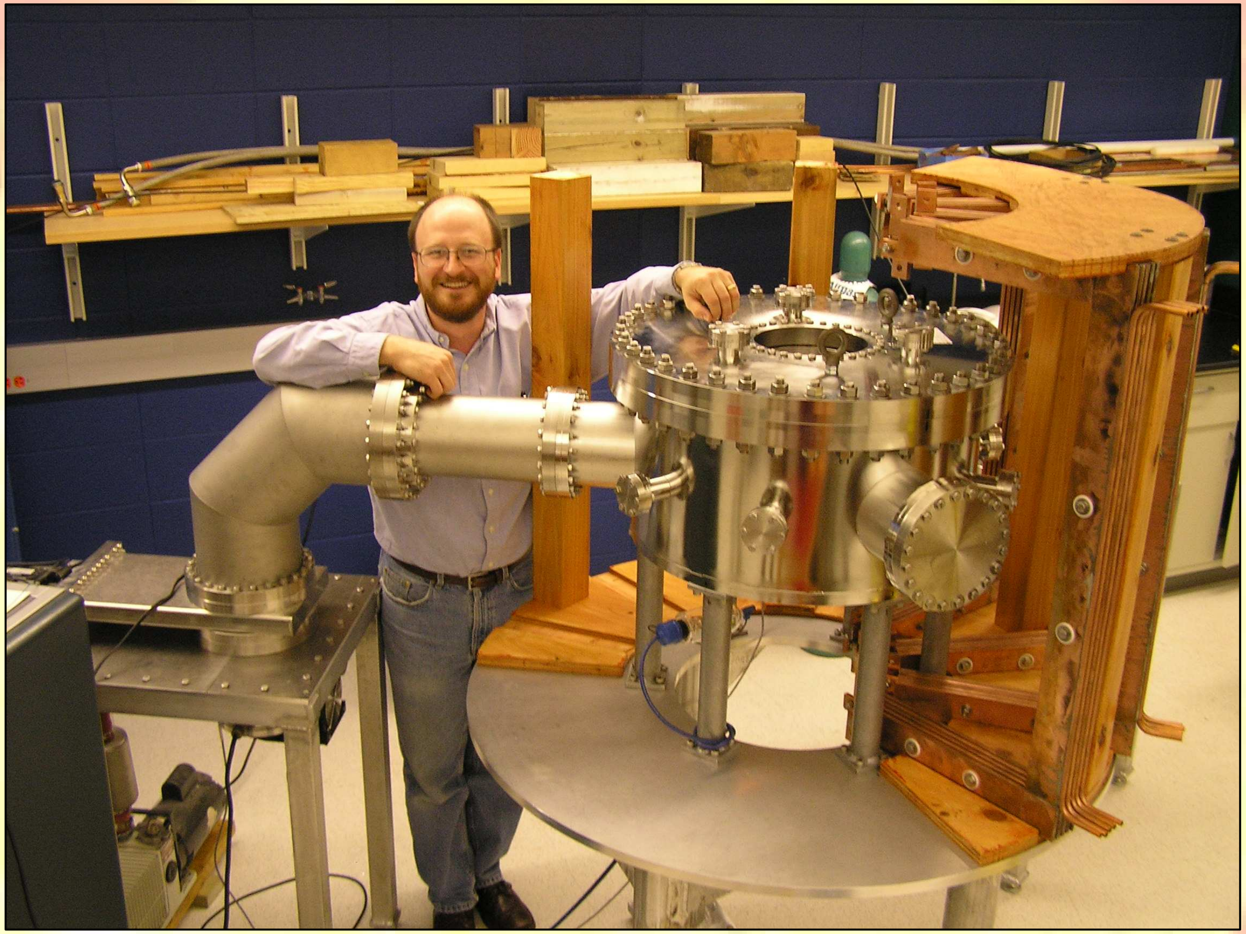


Joint European Torus (JET), Culham, UK

Image source: http://fusedweb.pppl.gov/

Image source: www.jet.efda.org

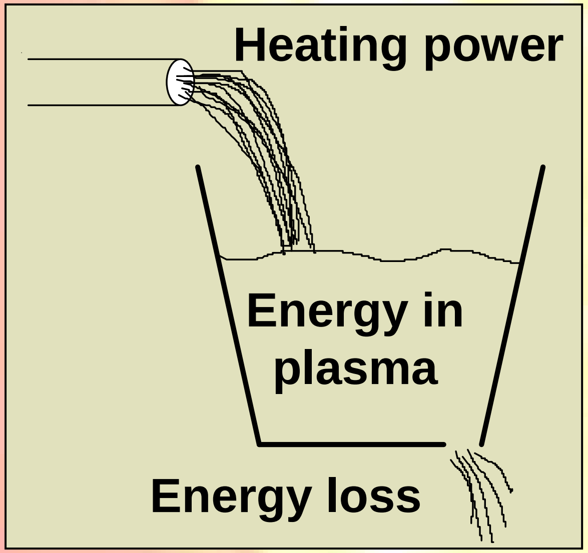
Toroidal particle traps make interesting physics experiments!



Lawrence Non-neutral Torus II

Assessing fusion performance

1. **Temperature: ~100-200 million ℃**
2. **High Density: more fusion power**
3. **Long Energy Confinement Time**
   - **Analogy: filling a leaky bucket**



$$\text{Water confinement time} = \frac{\text{Amount in bucket}}{\text{Leak rate}}$$

$$\text{Energy confinement time} = \frac{\text{Thermal energy in plasma}}{\text{Energy loss rate}}$$

Improving fusion performance

• **Open the spigot – increase heating power**

• **Fix the leaks – understand the physics of plasma *transport***

• **Fusion plasma physics = understanding instabilities that lead to turbulence and enhanced energy loss.**

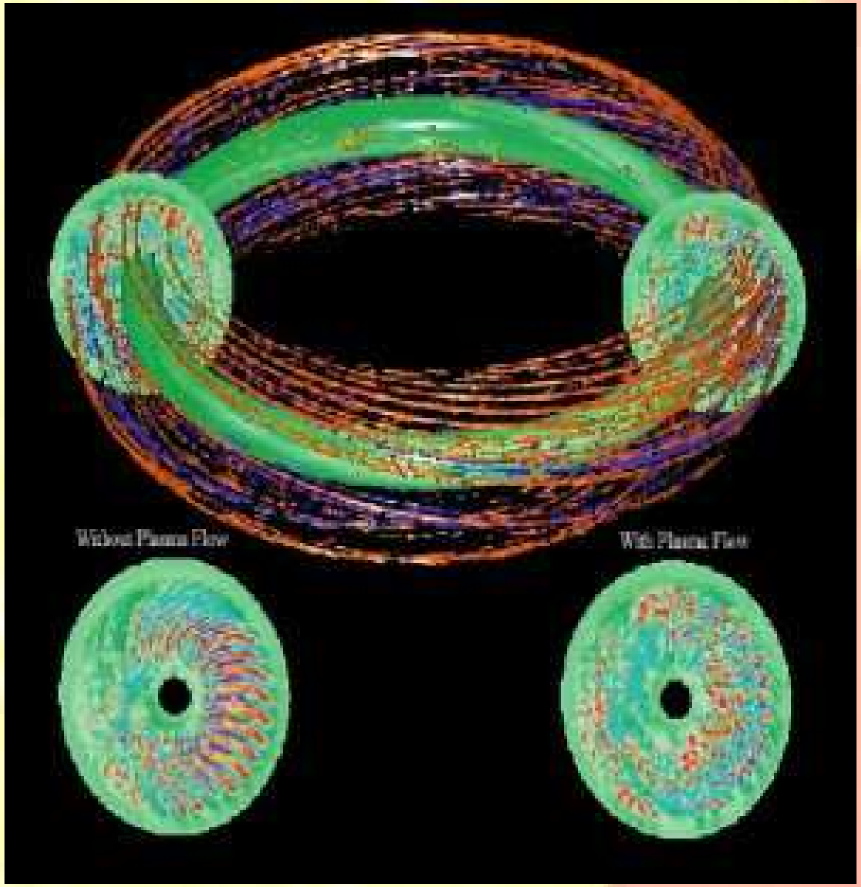


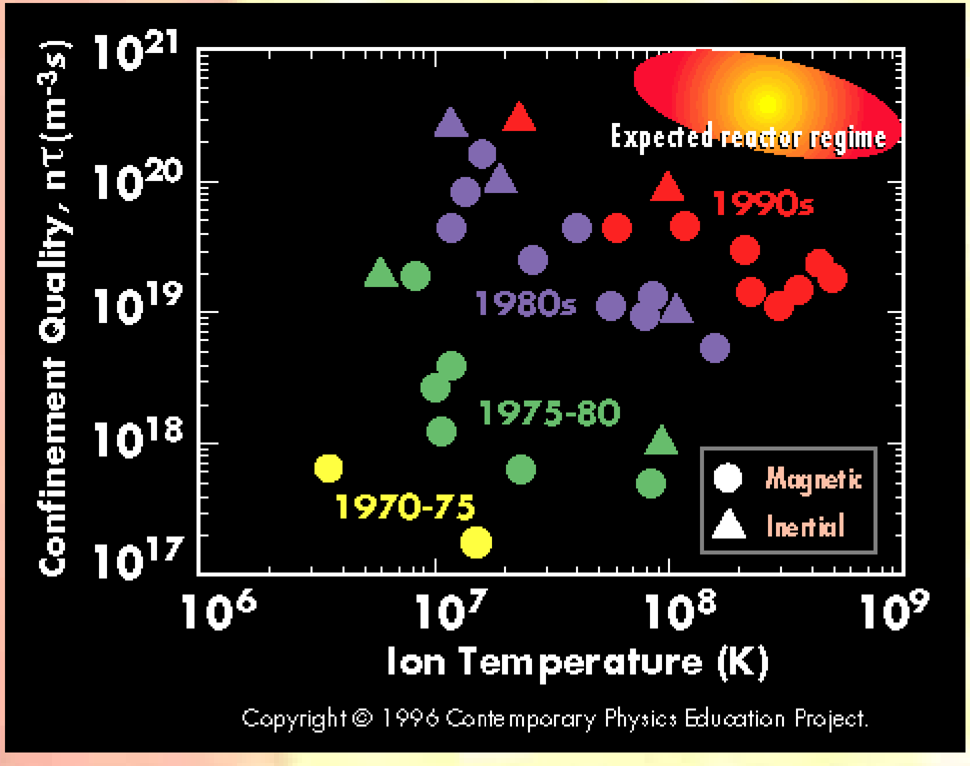
Image source: www.er.doe.gov/Sub/Accomplishments/Decades_Discovery/59.html

The Goals: Breakeven and Ignition

- **Breakeven: Heating power = Fusion power**
  - **Major scientific accomplishment, but not good enough for generating electricity**
- **Ignition: self-heated plasma**
  - **Fusion power maintains plasma temperature**
  - **A self-filling bucket!**

Progress toward reactor conditions

Remarkable progress has been achieved!



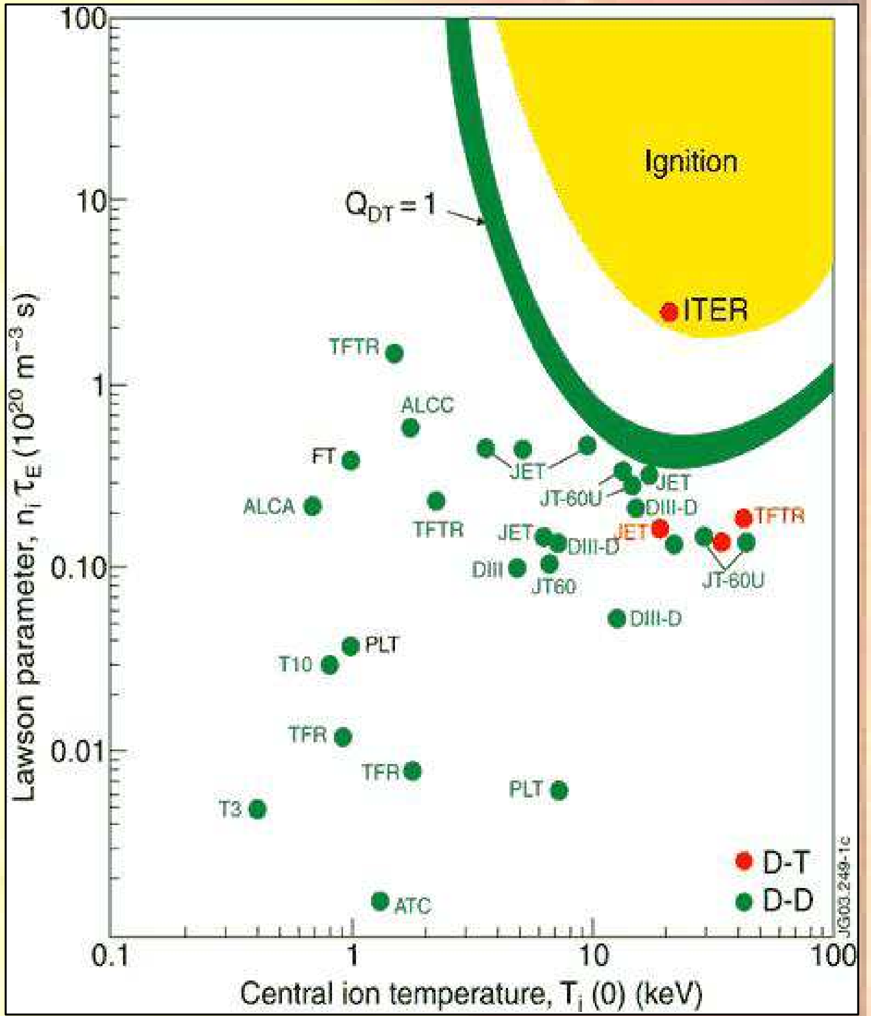


Image source: www.jet.efda.org/documents/presentations/borba.pdf

The next step in magnetic confinement fusion: ITER

• **1985 Geneva summit (Reagan and Gorbachev)**

• **ITER means "the way" in Latin (International Thermonuclear Experimental Reactor)**

•Superconducting coils: 5.3 Tesla
•Plasma current: 15 mega amps
•Plasma pressure: 2.5 atmospheres
•Plasma temperature: 150 million ℃
•Fusion power: 500 MW for 400 s
•High confidence that ignition can be reached!

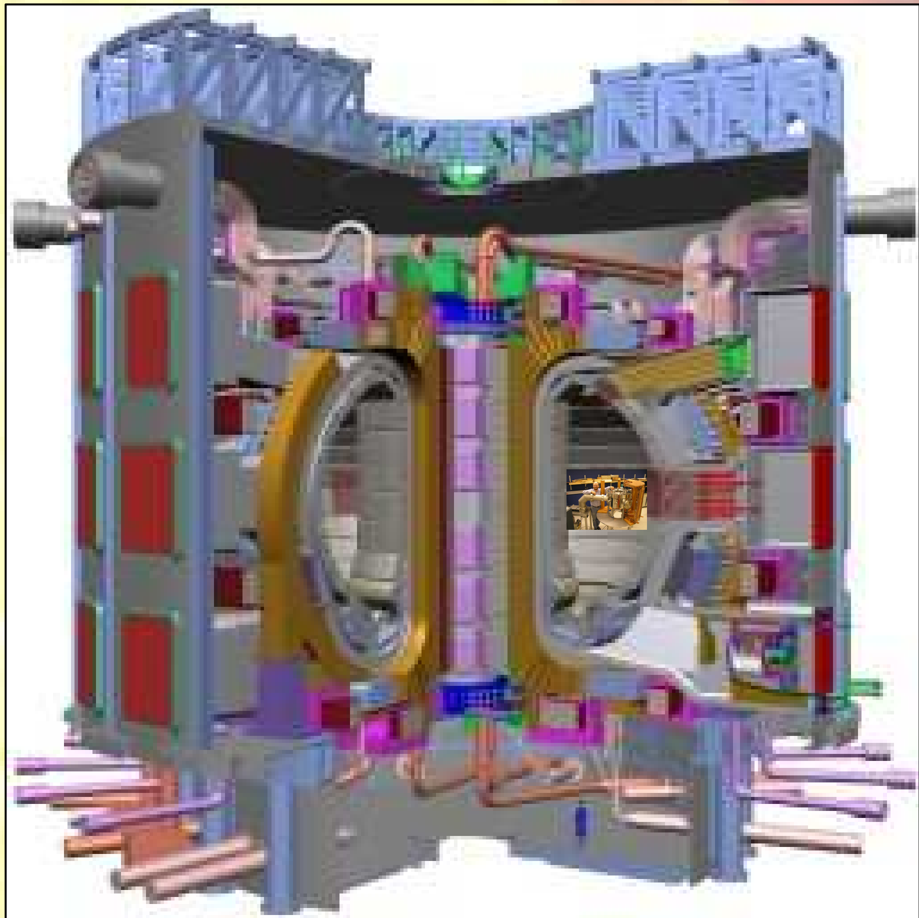


Image source: www.iter.org

ITER site has been chosen

- **Cadarache, France (near Aix en Provence)**

- **Collaborators: European Union, Japan,** Russia, USA, China, S. Korea, India, Switzerland

- **Operational in 2016**

- **Construction cost: $2 - 5 billion**

- **Operational lifetime: 20 years**

Image sources: www.iter.org and travel.yahoo.com

Magnetic Confinement Fusion Beyond ITER?

- **Demonstration power plant(s)**

- **Prototype power plant(s)**

- **Practical and economically competitive power plants**

- **Timescale: ????**

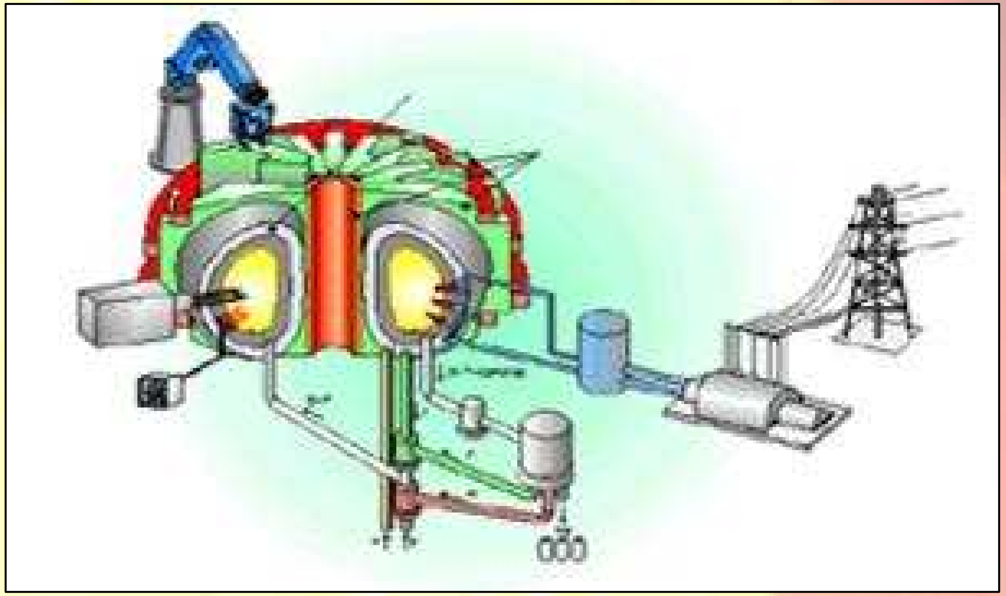
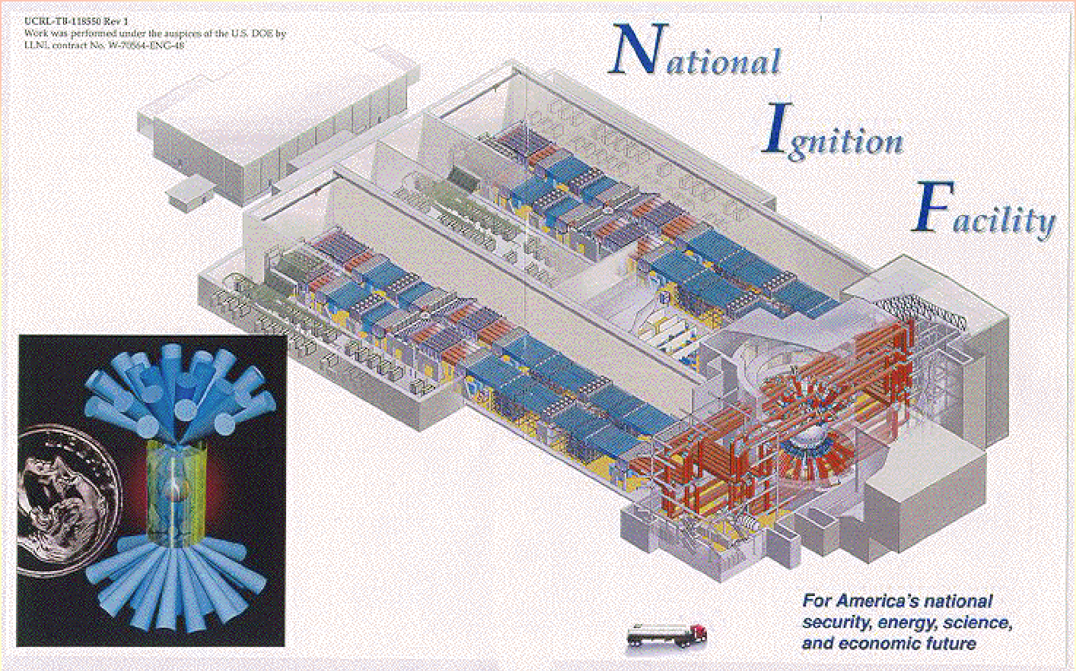


Image source: http://evilprofessor.co.uk/uniwork/fusion/images/image019.jpg

Inertial Confinement Fusion



- Lawrence Livermore Lab (CA)
- 192 pulsed laser beams
- focused on BB sized fuel pellet
- total pulse energy: 1.8 million Joules
- construction complete in 2009

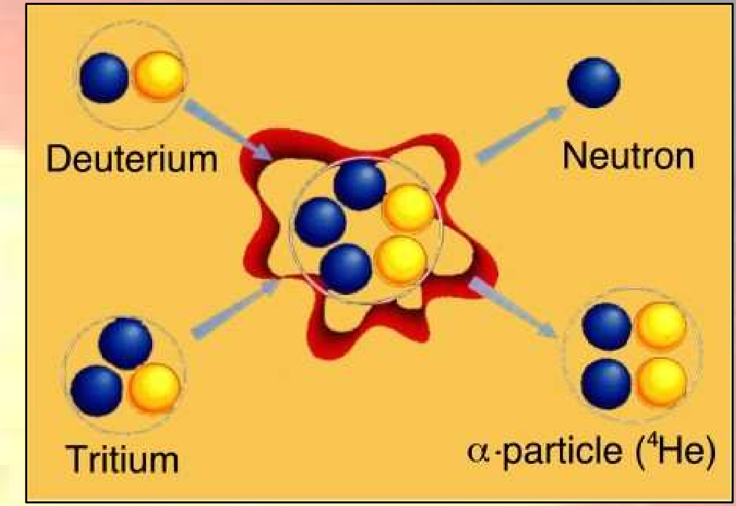
- Science:
  - fusion ignition physics
  - weapons physics without underground testing

Image source:http://alumnus.caltech.edu/~lsiegel/images/nif_mod.GIF

Fuel Supply

- Deuterium abundance: 1 out of every 6500 H atoms
- Tritium must be "bred" from lithium-6
  - $n + {}^{6}\mathrm{Li} \Rightarrow {}^{4}\mathrm{He} + \mathrm{T} + \mathrm{energy}$
  - neutrons from D-T fusion are captured in "blanket" to breed tritium and exchange energy with liquid lithium.
- Eventually go to D-D fusion process
  - 1 gallon of water = 200 gallons of gasoline

Waste and Safety



- **Nuclear waste:**
  - Primary reaction products:
    - Helium … benign
    - Neutrons … can "activate" surrounding materials
  - Choose vessel/blanket materials to minimize half-lives (100 years rather than thousands of years).
- **Safety:**
  - Very little fuel is in reactor at any time.
  - No chance of catastrophic explosion or "meltdown"

Conclusions

- Fusion is the process that powers the stars.
- If it can be made to work on earth the payoff is substantial
  - Vast fuel supply
  - No carbon emission
  - Safe and minimal radioactive waste
- It is hard to make work! –Turbulence
- Watch for news of ITER (2016) and NIF (2009)

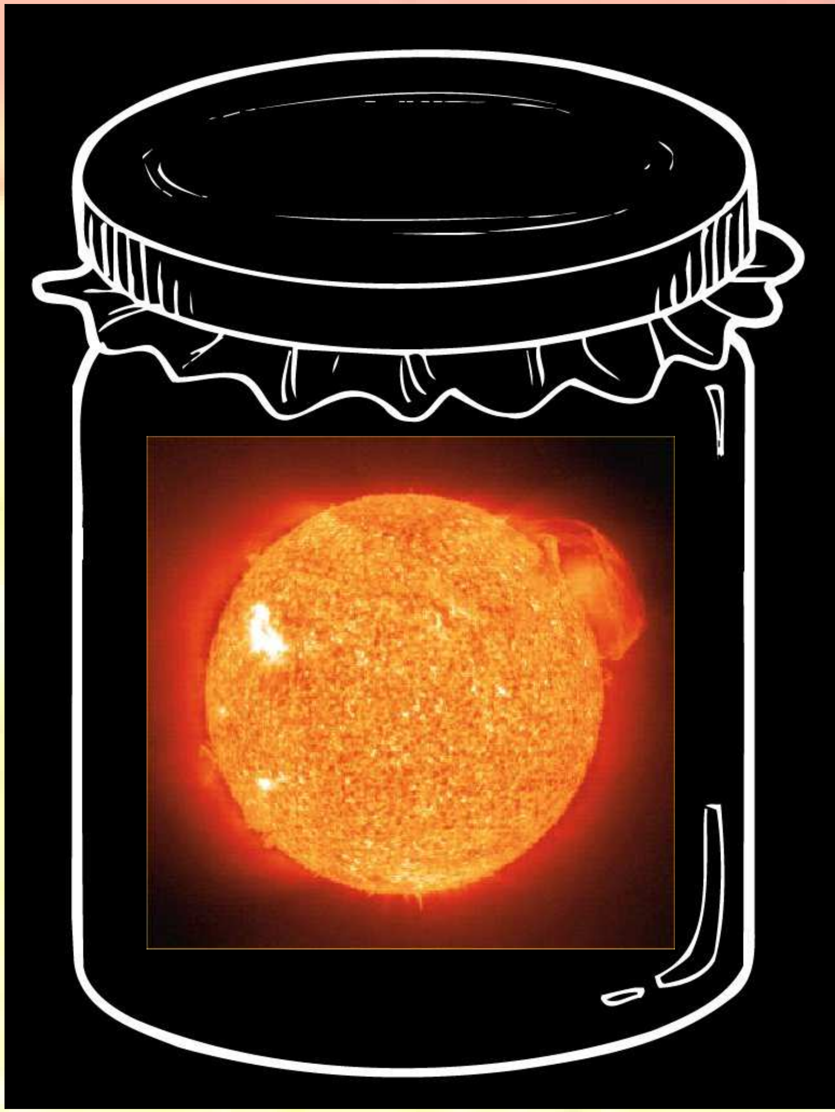


Image sources: www.unit5.org/pdatcr/Centers_Mathmats/Candy_jar/jar.jpg
Astronomy Today, by Chaisson and McMillan (Prentice Hall 2002)