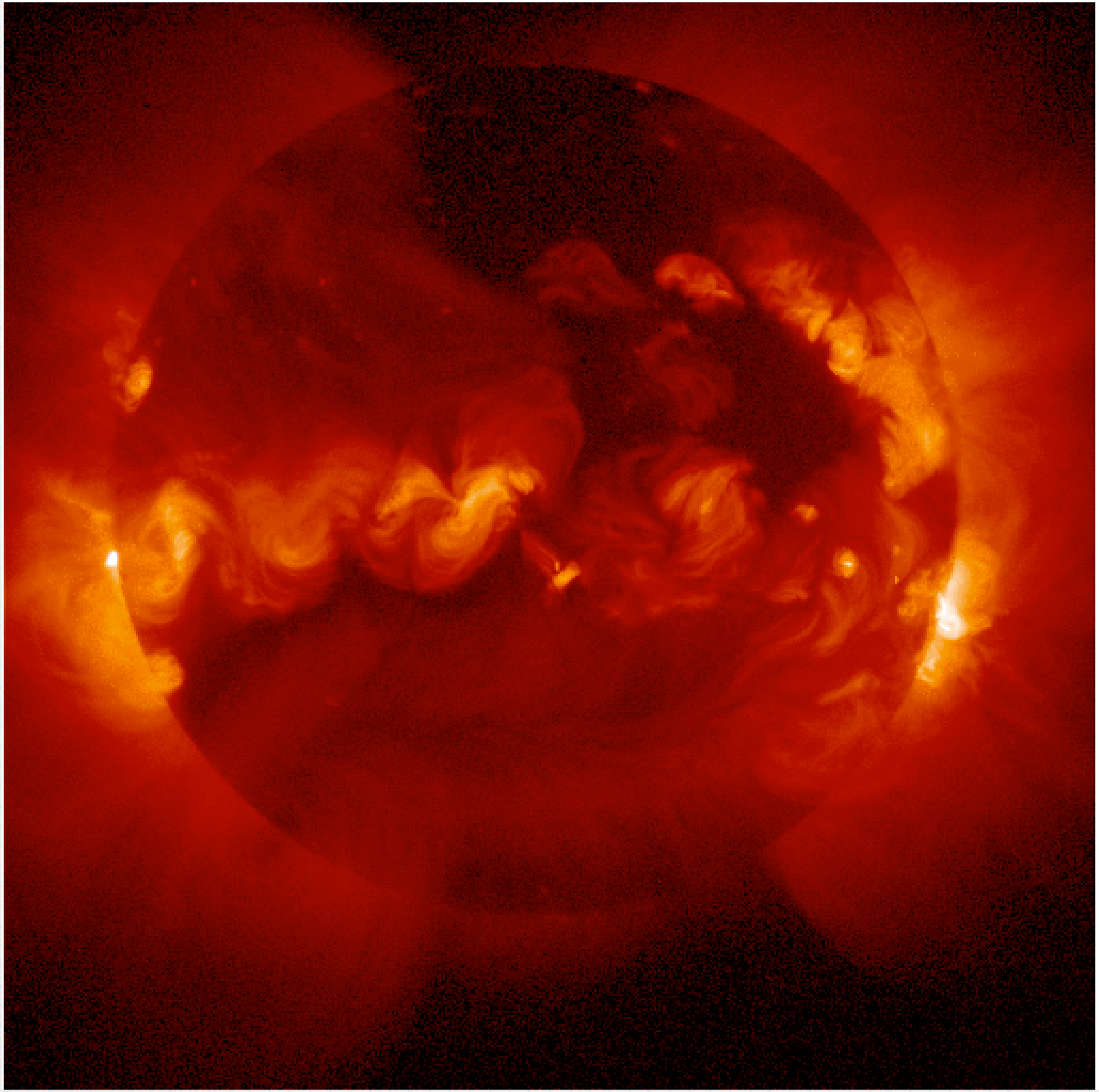
Creating a Star on the Earth

The challenge of fusion energy

Thanks to colleagues at Institute for Fusion Studies (UT), Princeton Plasma Physics Laboratory, MIT Plasma Science and Fusion Center, and General Atomics for advice and graphics.

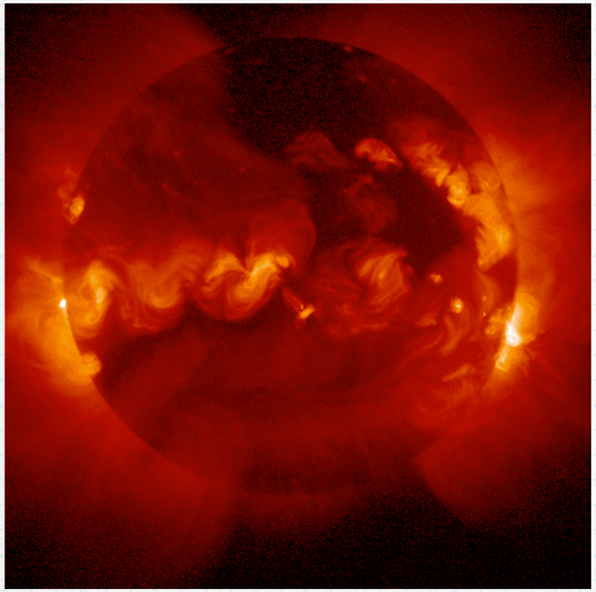
Thanks to SOHO web site for pictures of sun.

Fusion research is funded by the US Department of Energy



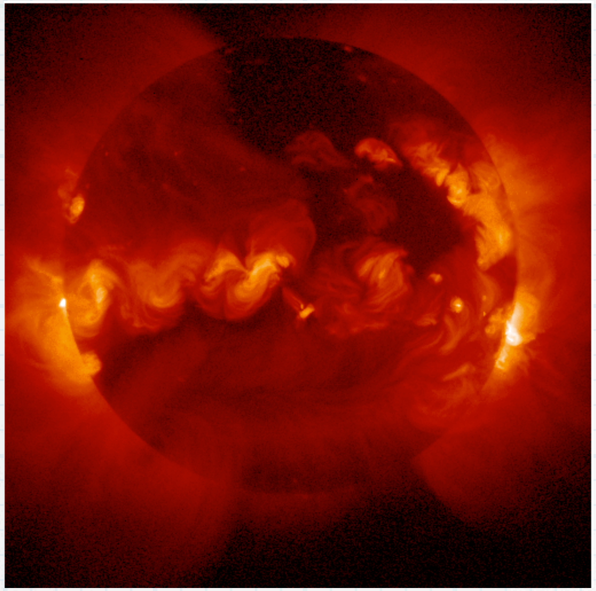
What are we looking at?

Why do we care?



We are looking at...

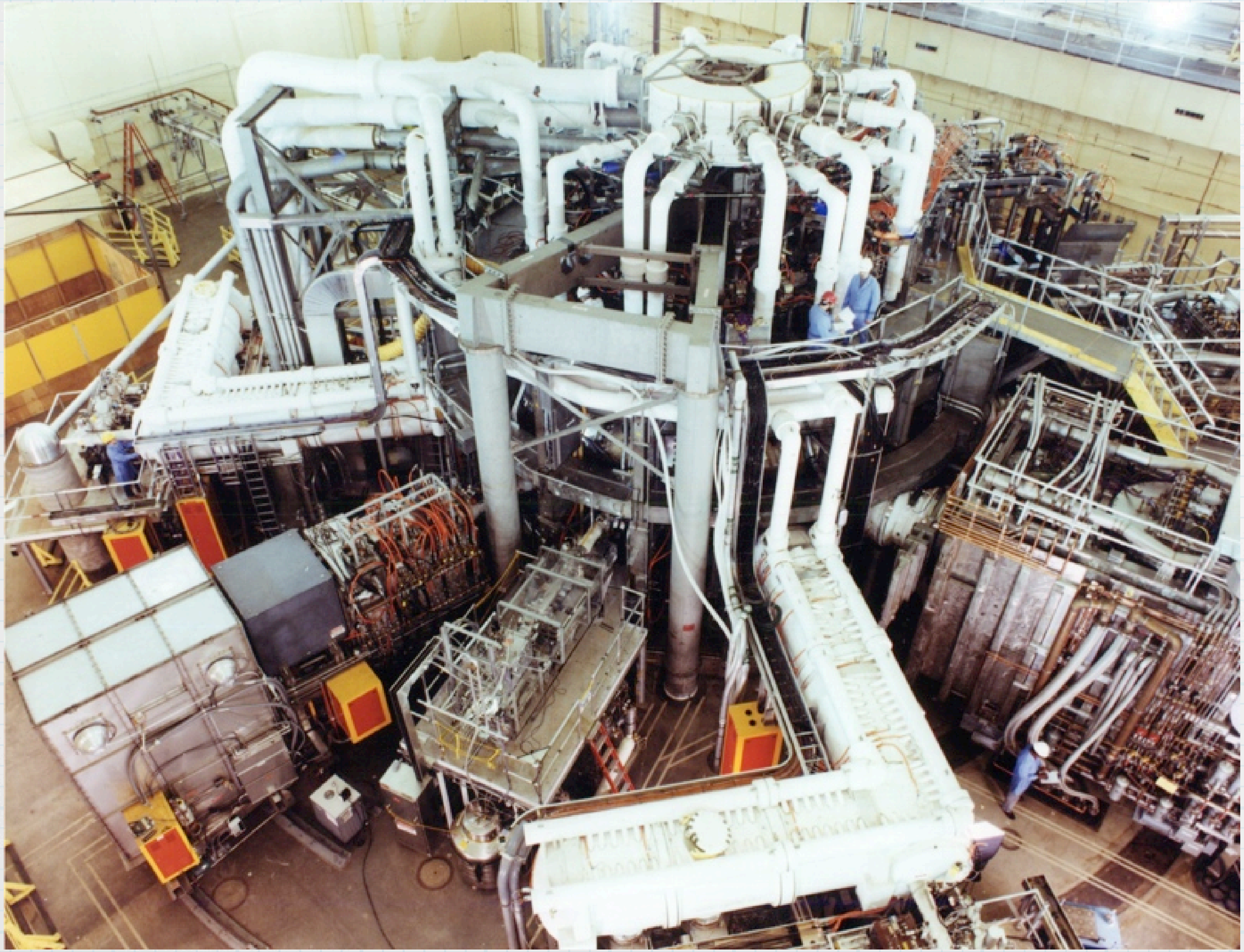
1. A hot plasma,
2. Held together ("confined") by gravity,
3. Powered by nuclear fusion.



We care (because its interesting and) because...

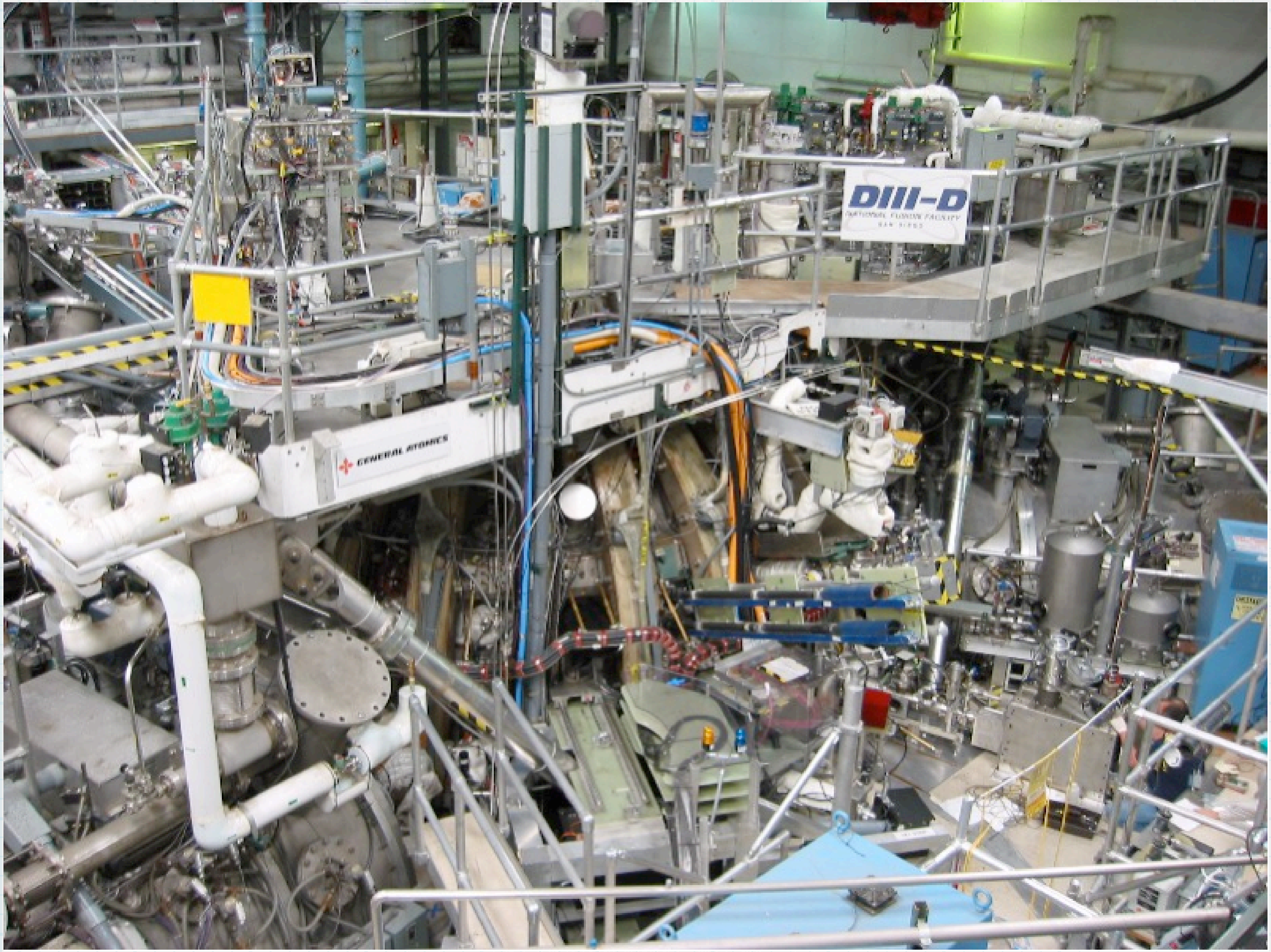
- Exploding global demand for electric power
- Unacceptable climate change from fossil fuels
- Potentially copious, benign energy source: an earthbound star

Some laboratory stars:



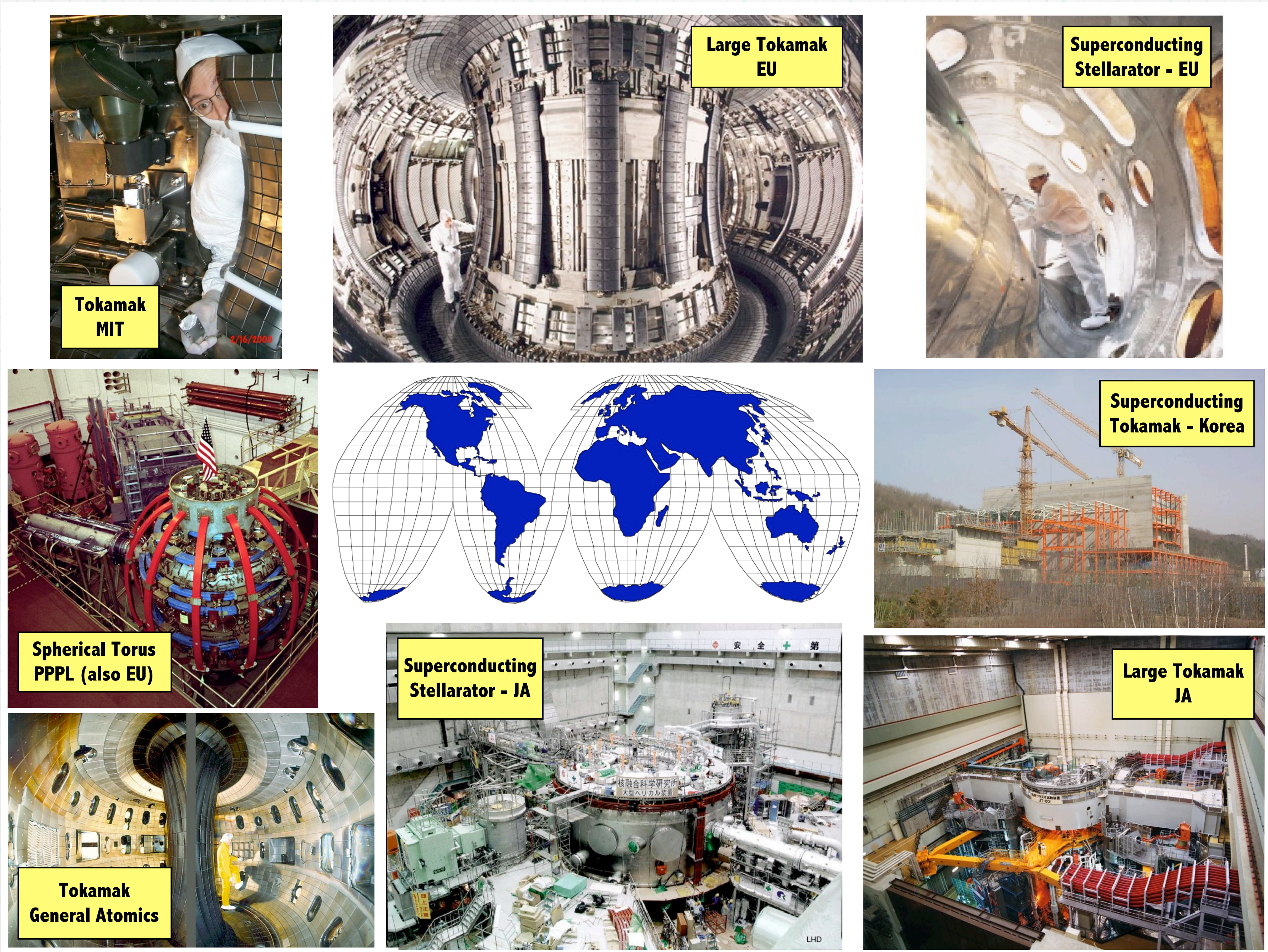
TFTR device at Princeton

Break-even fusion energy production, 1994.



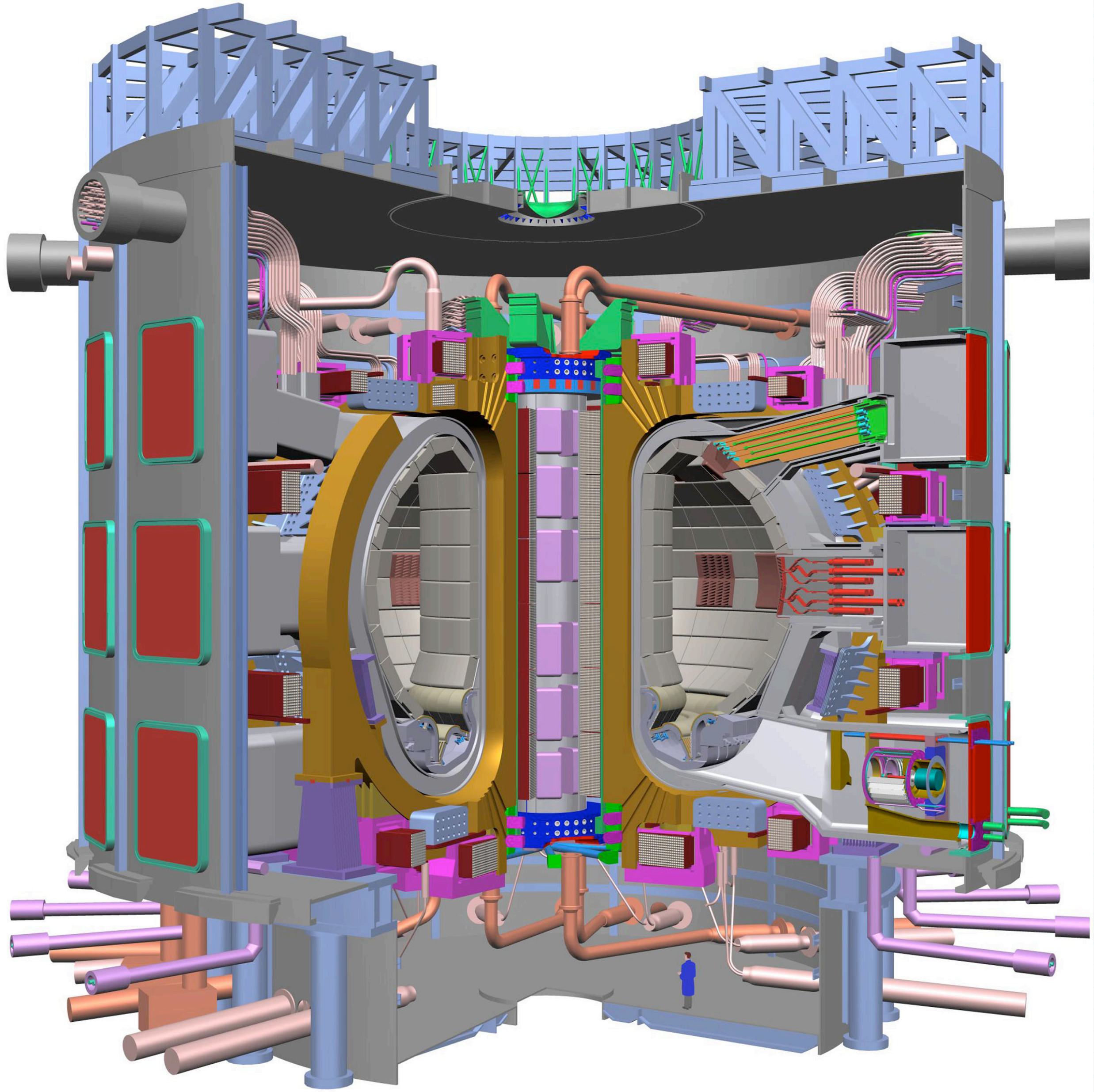
DIII-D toroidal device (tokamak) at General Atomics

Toroidal proliferation: samples



ITER ("The Way")

Joint project of EU, Japan, Russia, US, China, Korea, India



Construction begins in 2008, in France

Outline of talk

- What is fusion, and how does it provide energy?
- What is plasma, and why does it matter?
- Why are all these devices toroidal (doughnut-shaped)?
- Why bother?

Fusion energy

Start with a basic principle: energy is conserved in every process. In that case...

1. How can energy be created? (Why is there an energy industry?)

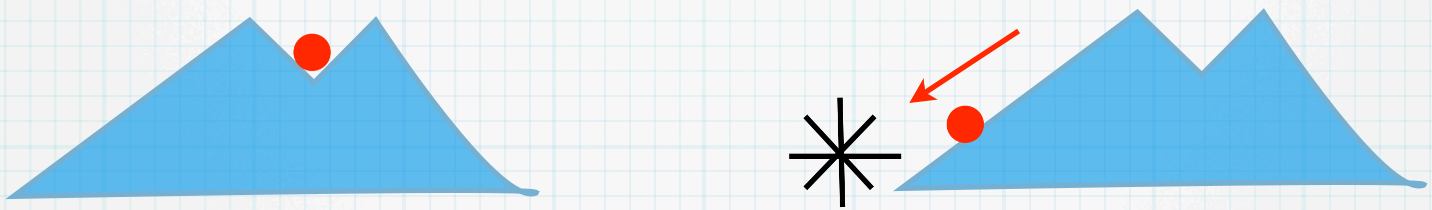
2. How can energy be used up? (Why is there an energy crisis?)

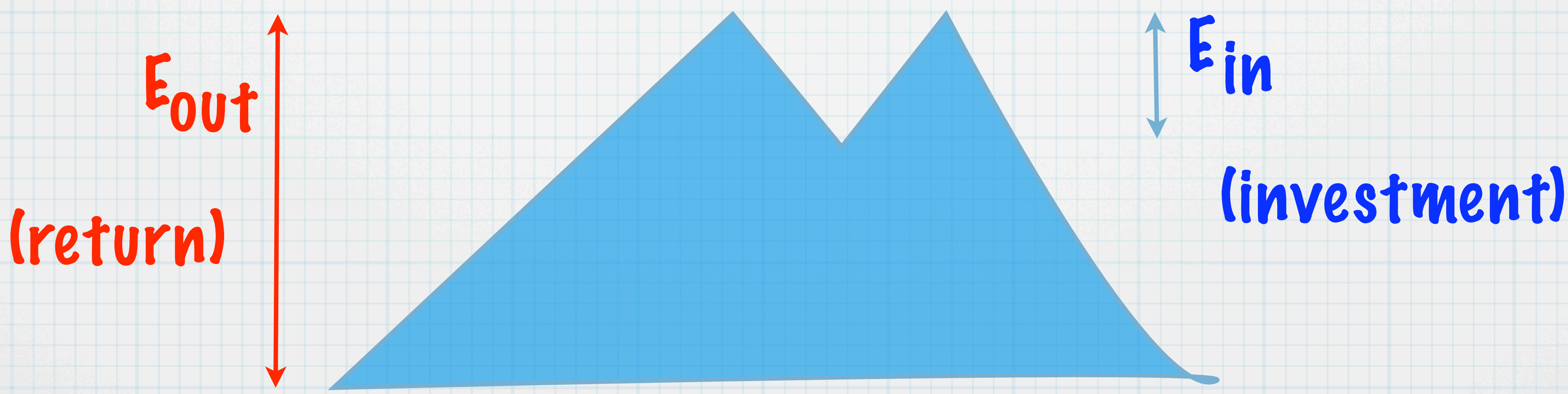
Answers:

1. Energy is not created, but found---in the form of **fuel**.

2. Energy is not destroyed, but dissipated---**dispersed** into useless heat.

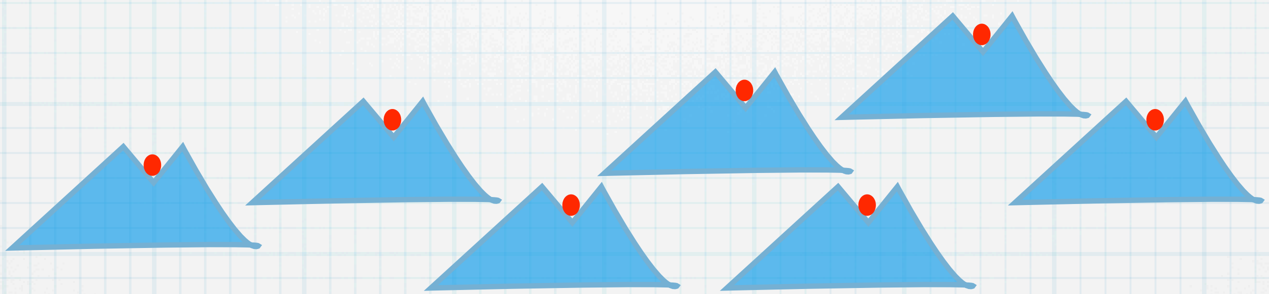
A theorist's view of fuel





Fuel must be concentrated

Part of the E_{out} from one reaction becomes E_{in} for other reactions: the "fire" is maintained.



But fire goes out if fuel is too broadly dispersed.

Where does fuel come from?

Fossil fuels: the sun (photosynthesis)

Fission fuels: nucleosynthesis in stars and supernovae

Fusion fuels: big-bang nucleosynthesis

Two basic facts about fusion fuel

1. Energy output E_{out} is huge

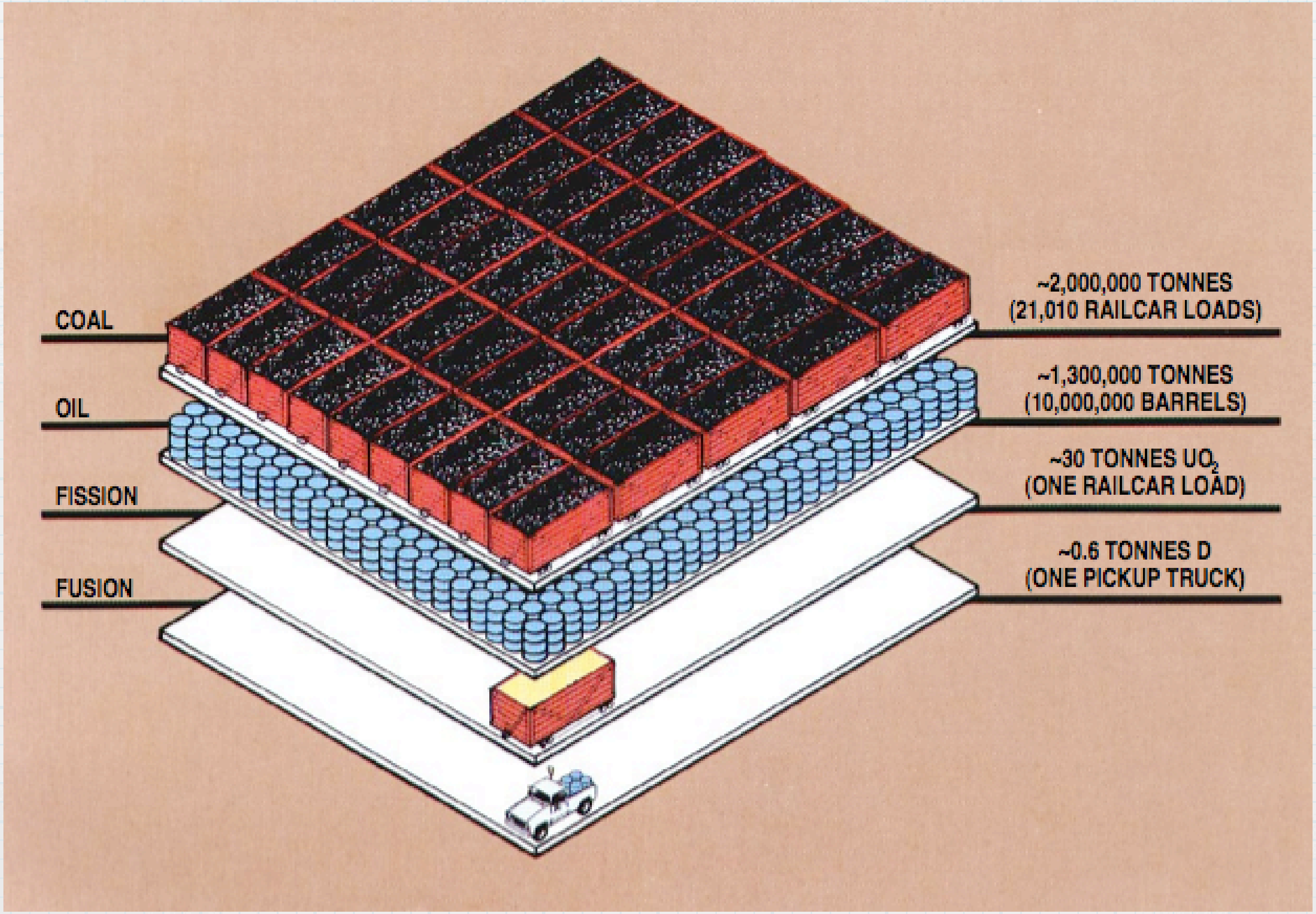
$$E_{out} \approx 450 \times E_{in}$$

→ fusion energy could have global importance

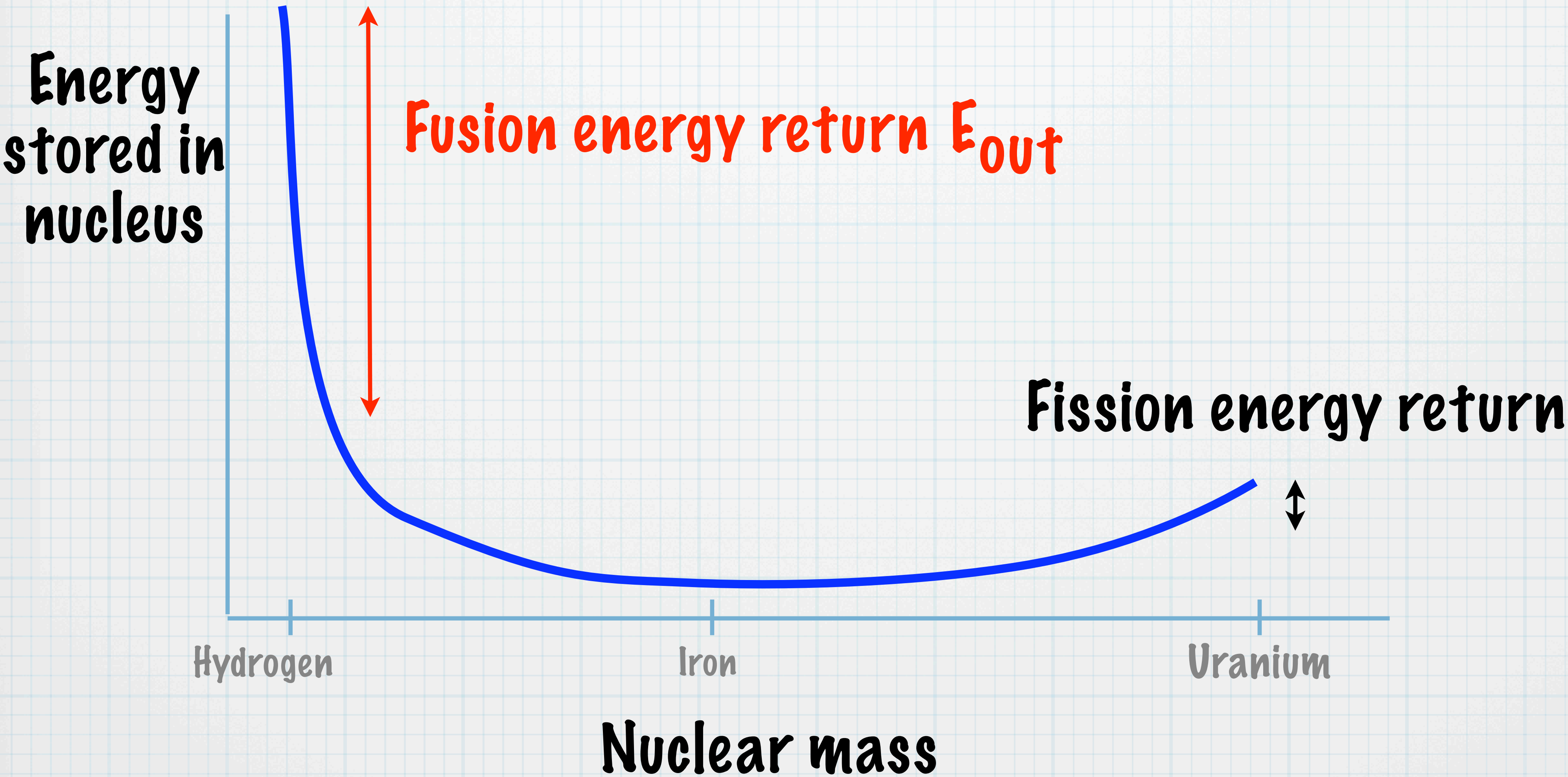
2. Required energy input E_{in} is also huge

→ releasing fusion energy isn't easy

Because E_{out} is large...



E_{out} is large because...



D-T fusion

-easiest fusion reaction uses isotopes of hydrogen: deuterium (D) and tritium (T)

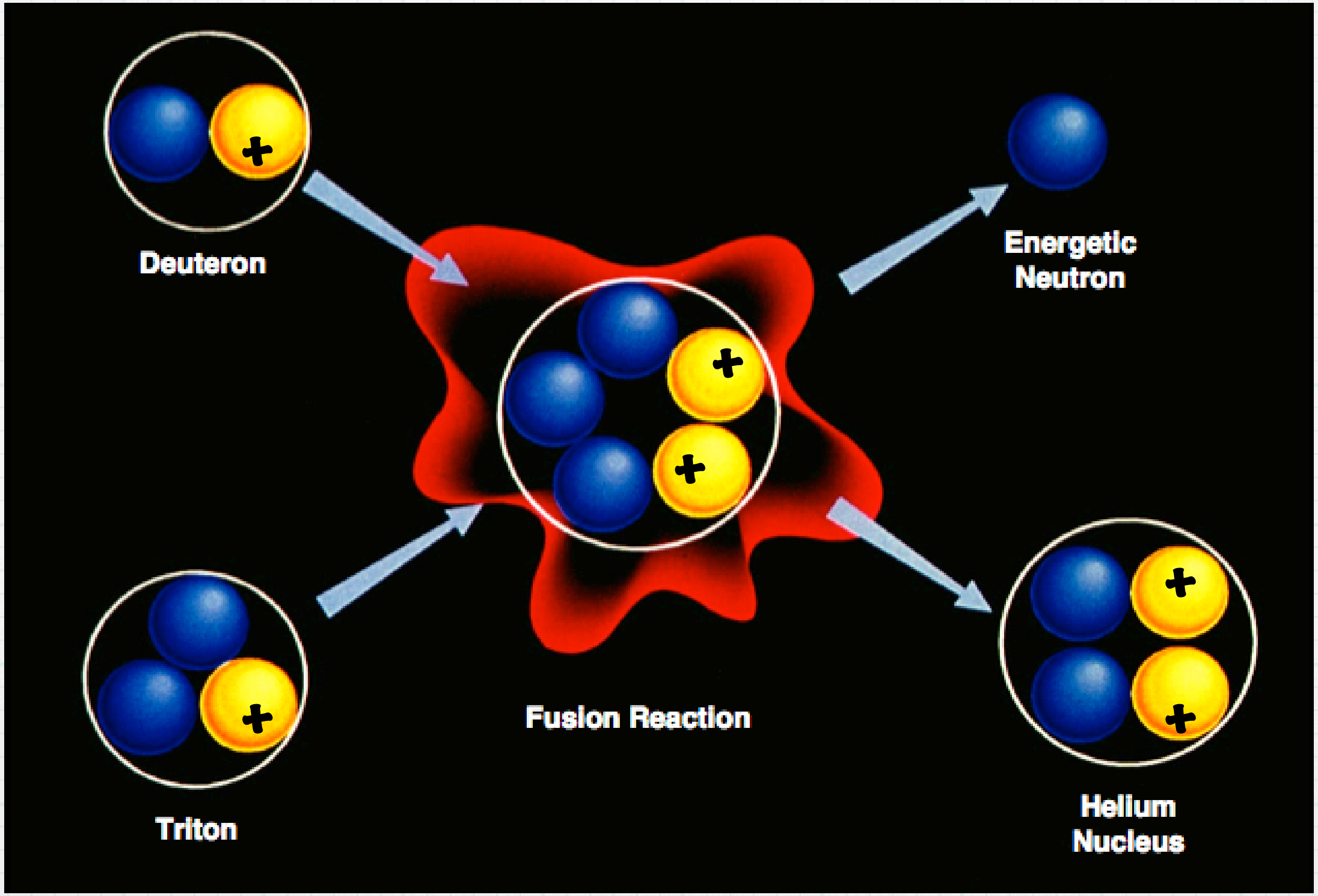
$$D + T \rightarrow He + n$$

-D is plentiful in sea water; T can be manufactured from lithium (also plentiful)

$$Li + n \rightarrow T + He$$

-He (helium) is harmless---even useful!

Why is E_{in} large?



$$D + T \rightarrow He + n$$

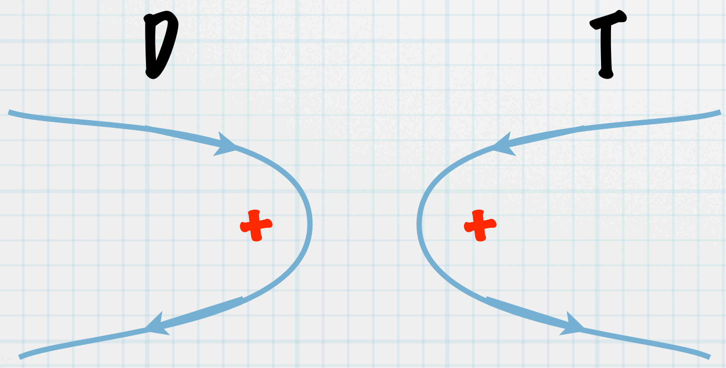
But note that both fusing particles have positive charge...

Two forces between nuclei

1. Nuclear force is strongly attractive, but has very short range

2. Electric force is repulsive, with long range

Repulsion of like charges → "Coulomb barrier"



Only very fast nuclei can overcome barrier

To fuse, nuclei must collide at high speed: hot nuclear stew

For useful reaction rate, 100 million degrees (hotter than sun).

At even much lower temperatures, atomic electrons and break free from their nuclei: gas becomes plasma---a gas of charged particles

Plasma is "4th state of matter": stars, lightning, fluorescent lights...

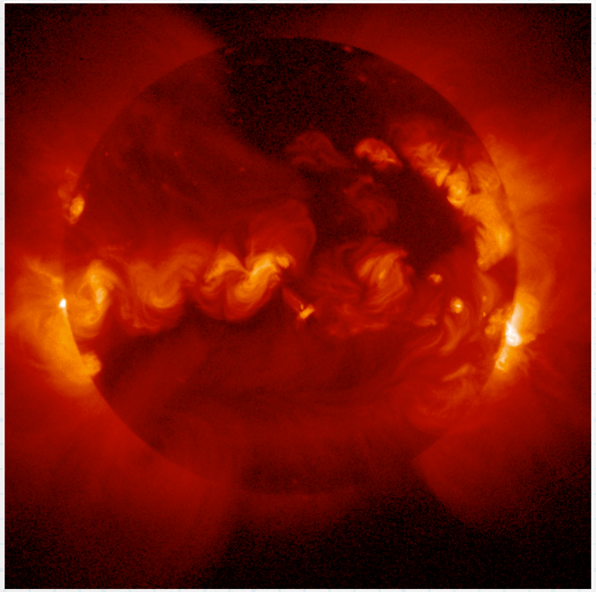
Plasma physics

- Most of the universe is plasma: stars, nebulae, magnetosphere, interstellar space...
- Untamed matter: fierce interaction with electromagnetic fields
- Although basic forces understood, predicting plasma behavior is hard--a long-standing scientific challenge

Plasma physics applies to...

- Structure of stars, planetary atmospheres, most of astrophysics
- Creation of magnetic fields in earth and sun, sunspots, Van Allen belts...
- Various industrial processes, including computer chip manufacture
- New technologies for light, Plasma TV's...
- Novel space-craft propulsion systems
- ...and fusion research!

Two plasmas:



A hot plasma, confined by gravity: long lifetime.

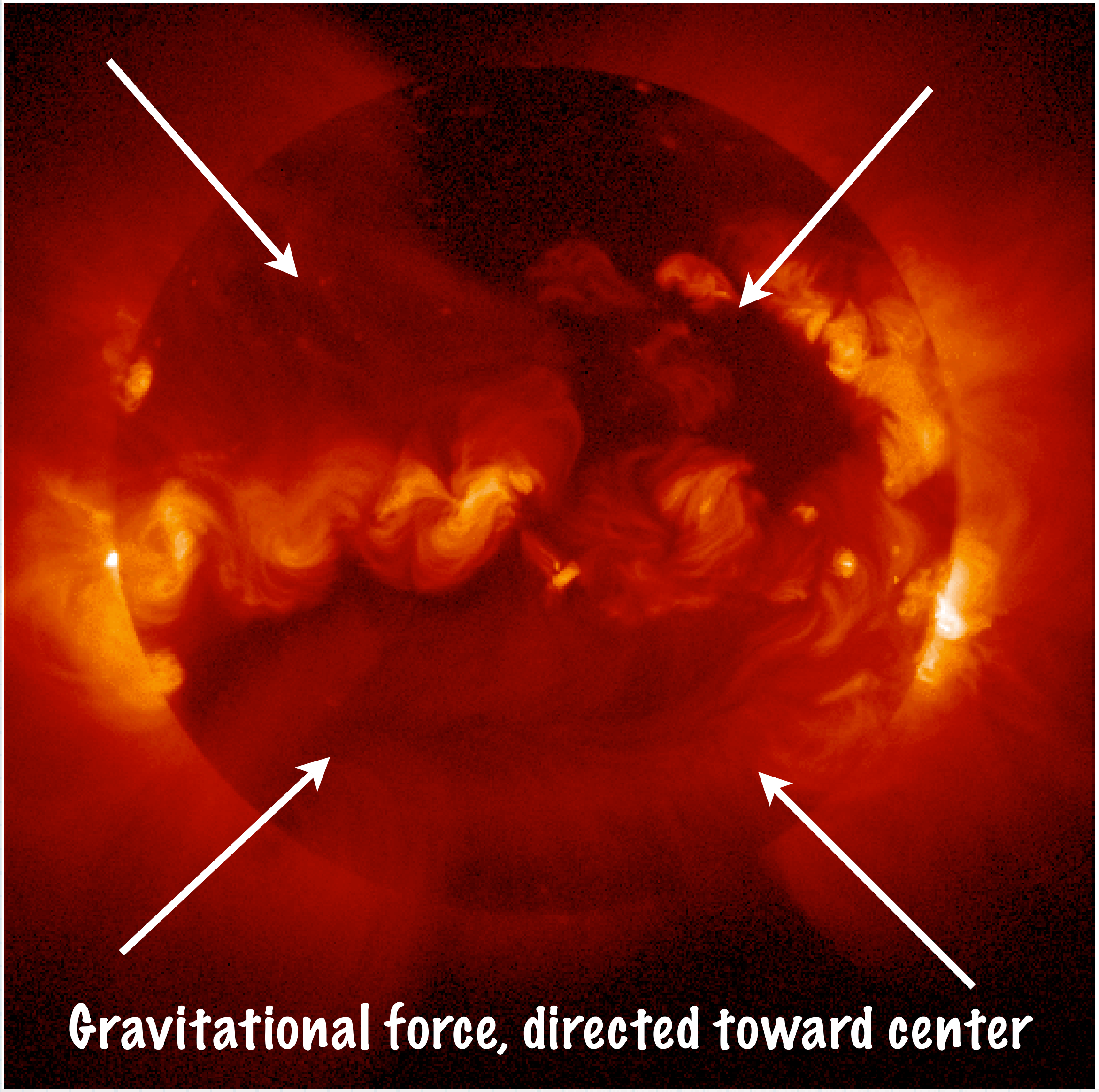
A cooler plasma, not confined: very short lifetime.

Unconfined plasmas disperse and quench.

Plasma confinement

Cool plasma is easy to confine

But fusion plasma cannot survive contact with any wall: heat loss quenches plasma (only minor damage to wall).



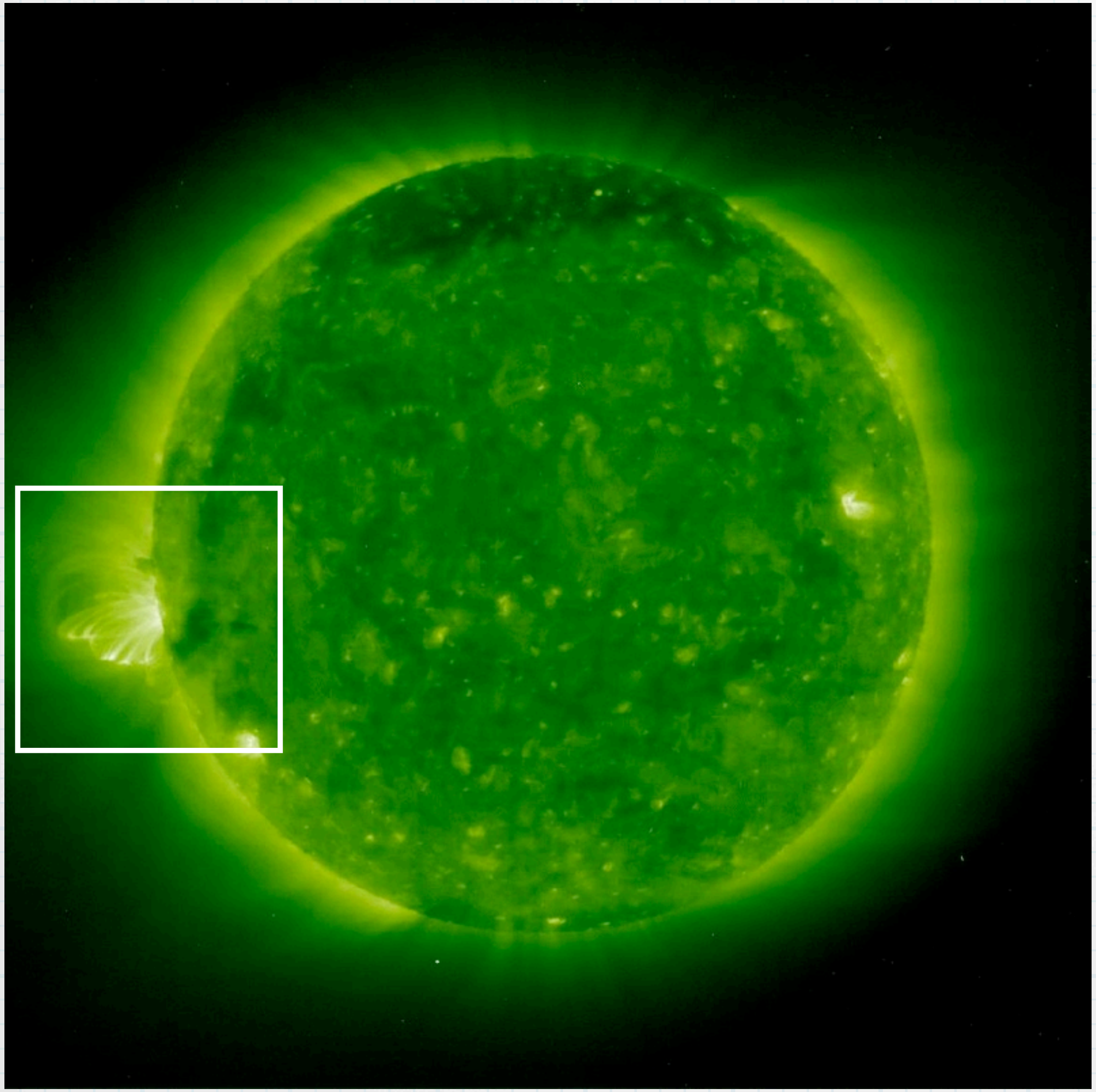
Solar plasma confinement:

Gravity holds plasma together, allowing fusion

But gravitational force is proportional to mass:

Solar confinement works because sun is large and massive

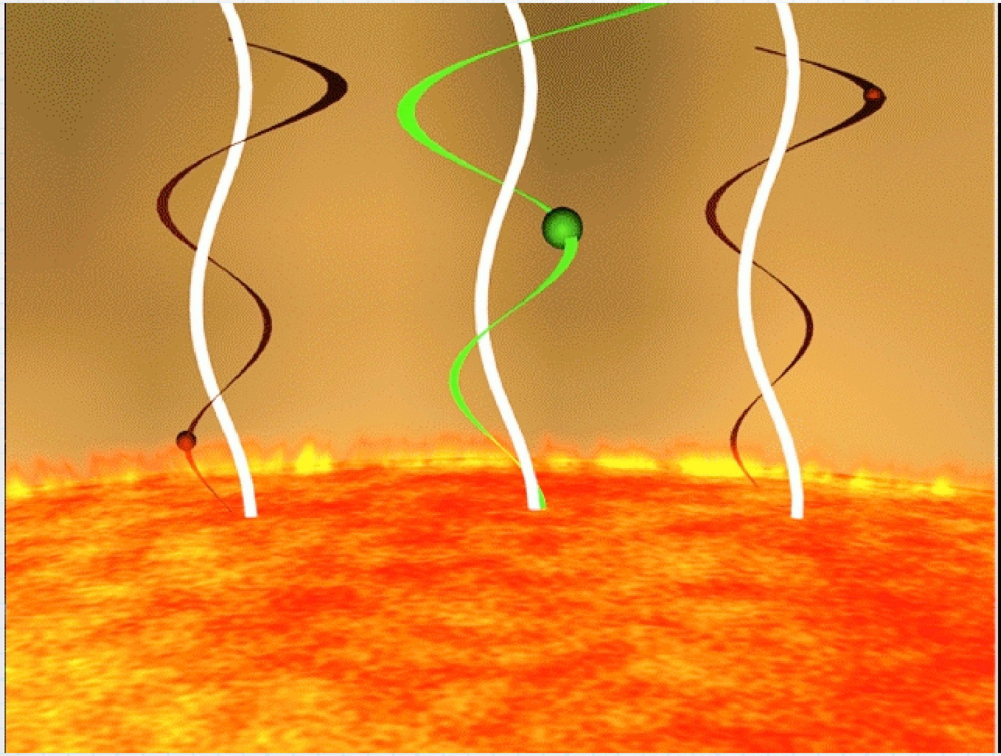
Solar corona: a different sort of confinement

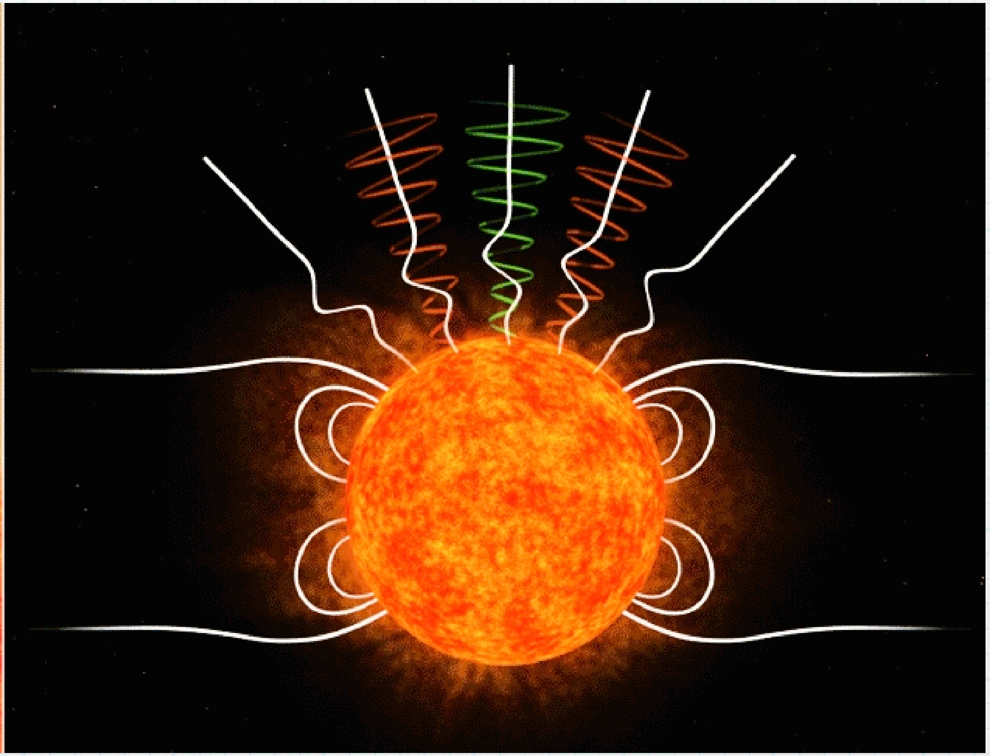


Filaments and loops reveal charged particles trapped on magnetic field lines

Magnetic force is independent of mass: acts equally on large and small scales

Magnetic force links plasma (charged particles) to “field lines”





Motion across field lines is tightly constrained; **but motion along field lines is not affected.** (“2-D confinement.”)

Key to magnetic confinement

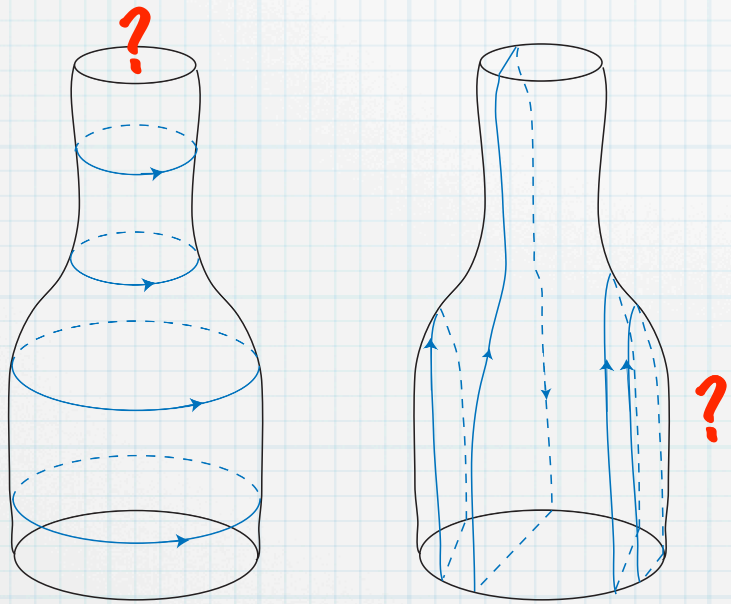
Suppose magnetic field lines lie on a surface, rather than wandering through some 3D volume.

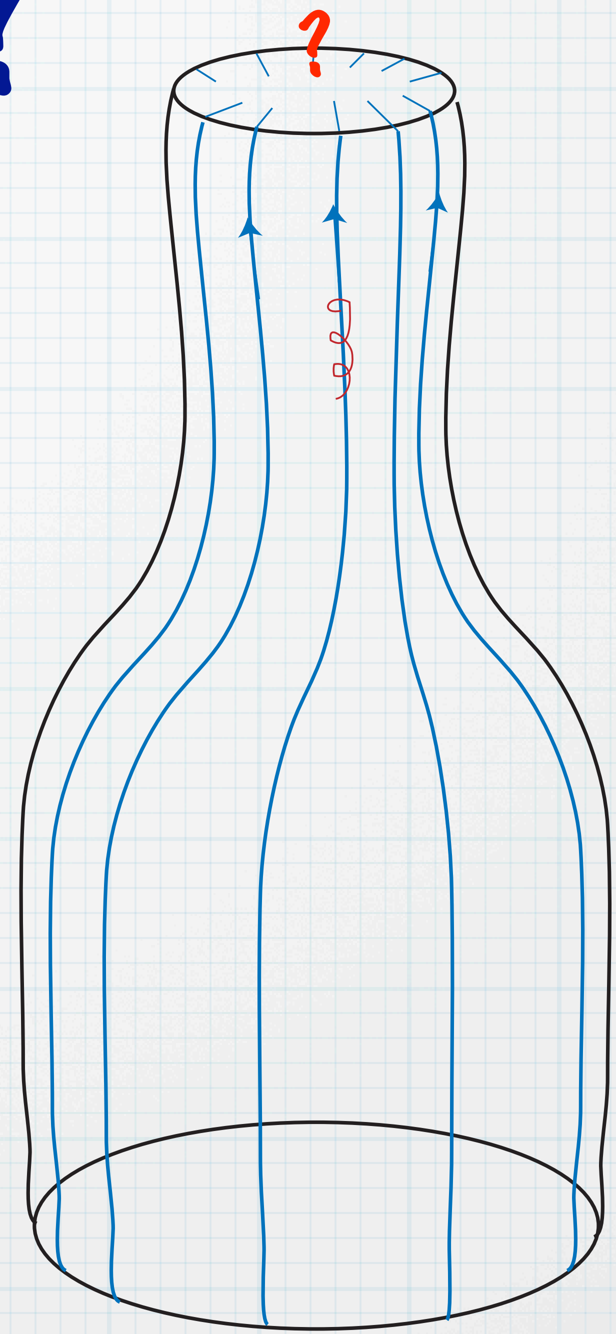
A surface covered by magnetic field lines is called a magnetic surface.

A closed magnetic surface will confine plasma.

Magnetic bottle?

An arbitrary surface **cannot** be covered with smooth field lines

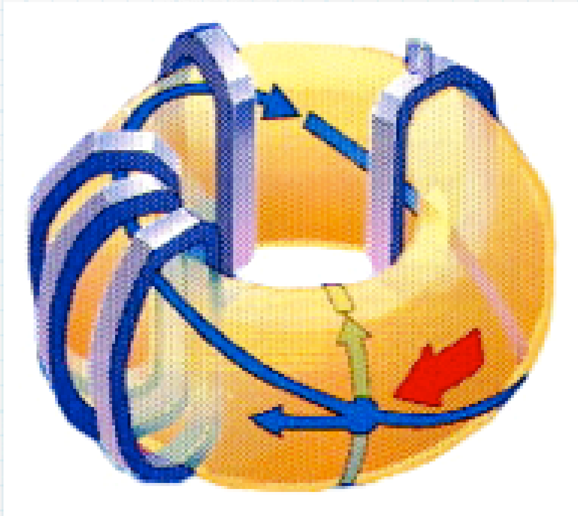




Either singular point, or null point, somewhere on surface

Closed magnetic surface must be toroidal

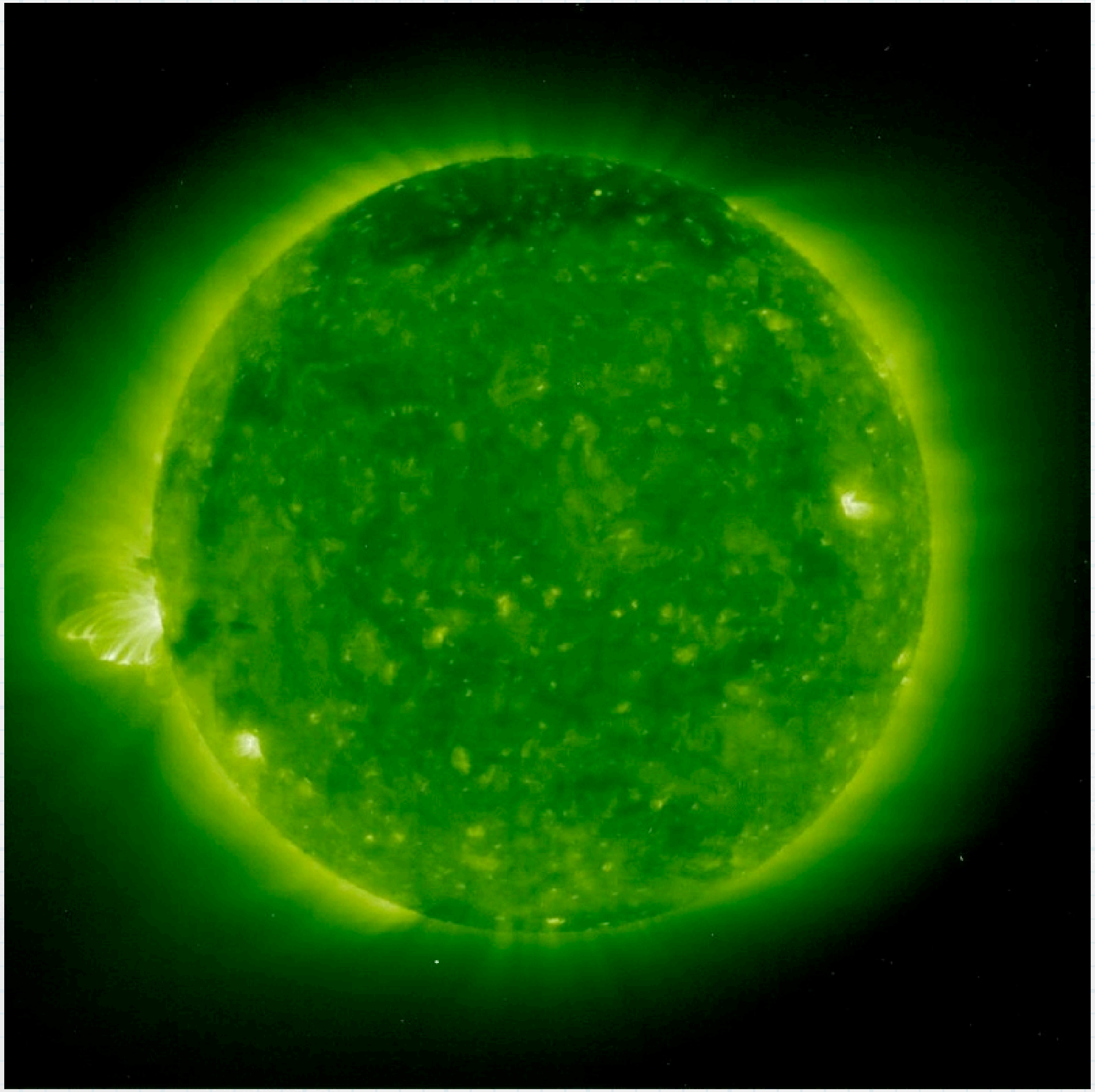
Krispy Kreme



Tokamak

No ends to cap: field lines cover surface

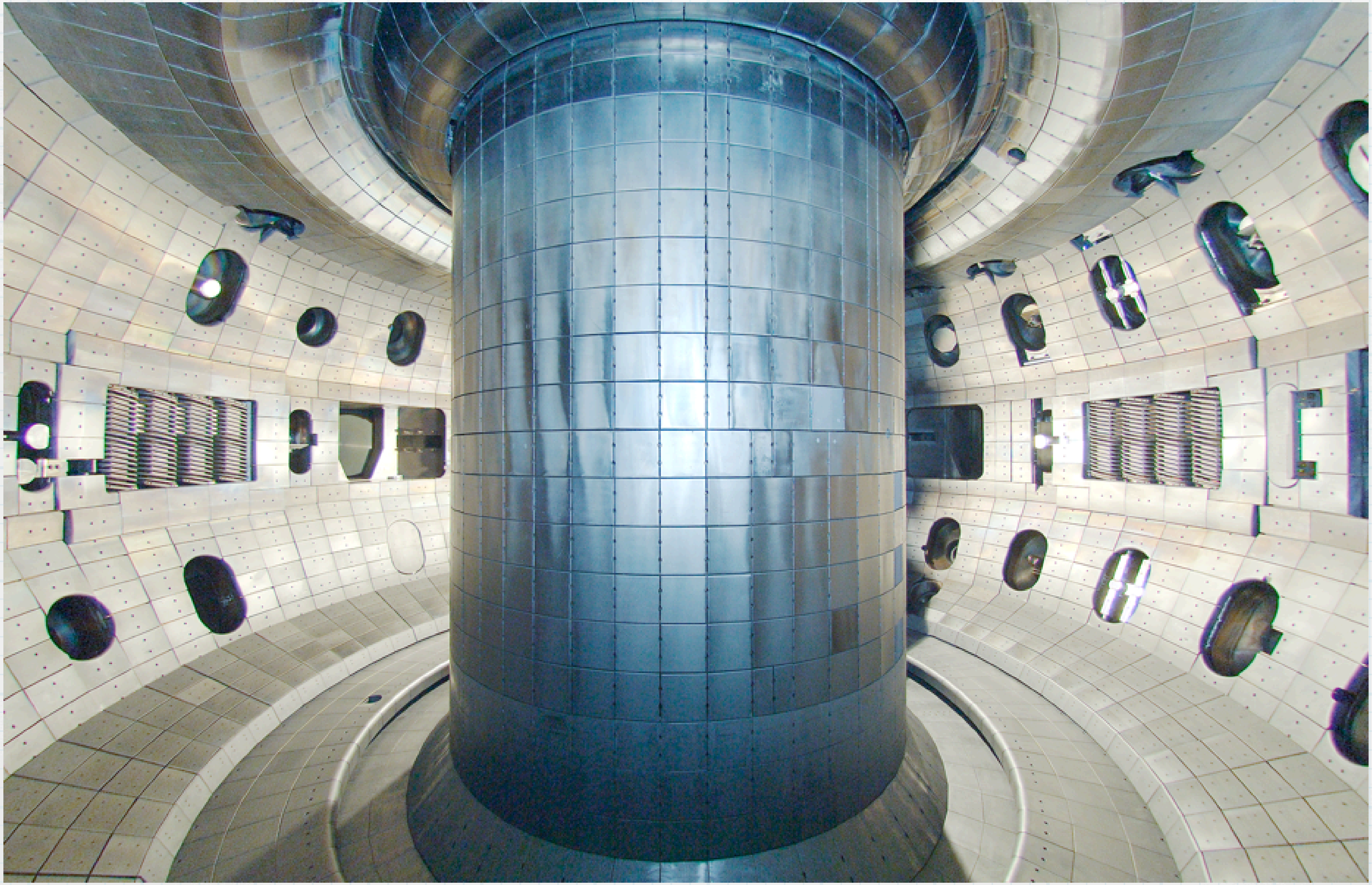
Summarize: confinement and topology



Gravity → sphere

Magnetism → torus

Tokamak interior



Recall D-T reaction

$$D + T \rightarrow He + n$$

The neutron (n), being neutral, escapes reactor and heats confining vessel. This heat produces steam and then electricity, as in other power plants.

The helium nucleus (He), being charged, remains confined. Its energy helps to keep plasma hot (providing E_{in}), sustaining reaction.

Not quite so simple...

- Confinement is the main thing, not the only thing
- Tokamaks are the main approach to confinement, not the only approach
- Tokamak confinement is not perfect...only good enough

Confinement is the main thing, not the only thing...

Equilibrium must be stable
-historically, the hardest puzzle

Plasma must be heated (energy investment)
-induction heating, plus microwave heating

Fuel must be supplied
-breeding tritium is an engineering challenge

Etc.

Tokamaks are not the only approach...

Toroids that are not tokamaks: not symmetric about central axis (e.g., stellarator)

Non-toroidal configurations: attempts to stopper the bottle (magnetic mirror)

"Inertial confinement:" laser-compressed fusion firecrackers (NIF)

Magnetic confinement is not perfect

- Collisions between particles cause occasional jumps between neighboring field lines

  → gradual loss of particle and heat

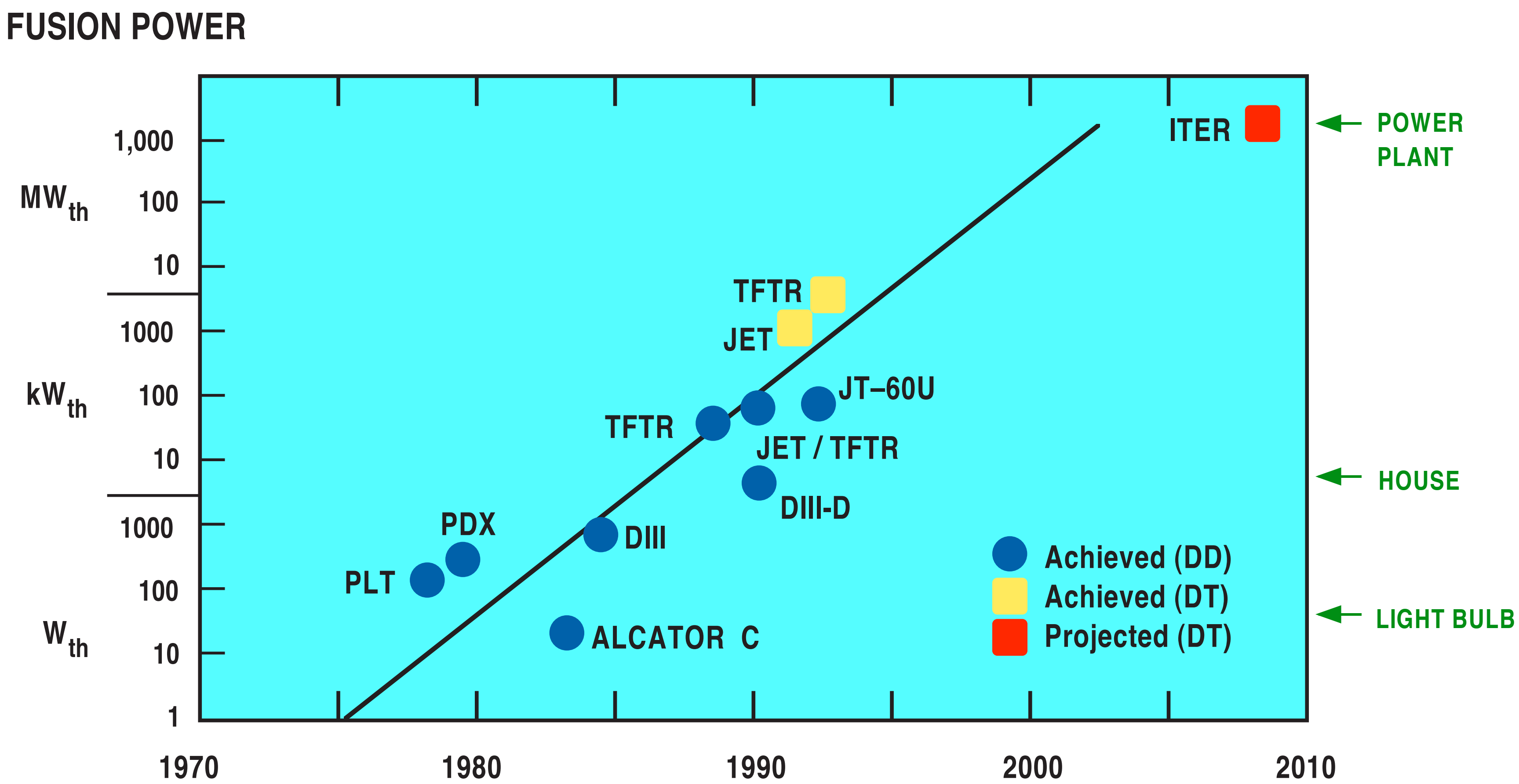
- Magnetic curvature (inter alia) causes slow drifts of particles off field lines

  → enhanced losses

- Residual instabilities cause fluctuating electric fields

  → more serious turbulent heat loss

Yet tokamaks work:



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

Recall outline:

- ✔What is fusion?
- ✔What is plasma, and why does it matter?
- ✔Why are all these devices toroidal?
- Why bother?

Fossil fuels

Coal, oil and natural gas now supply 80% of global energy needs

Two problems:

1. depletion of oil and gas

   -only coal, the dirtiest fuel of all, will be available in long term

2. climate change

   -from dirt and greenhouse gas: global filth and global warming

A true crisis

- World energy use will double by 2045
- Continued reliance on fossil fuel is certain to cause unacceptable climate change
- Serious R&D program needed to find alternative sources. Present research investment is pitifully small ($3 trillion world energy market)

Alternatives to coal

The usual suspects: improved efficiency, renewables, wind, solar, fission....

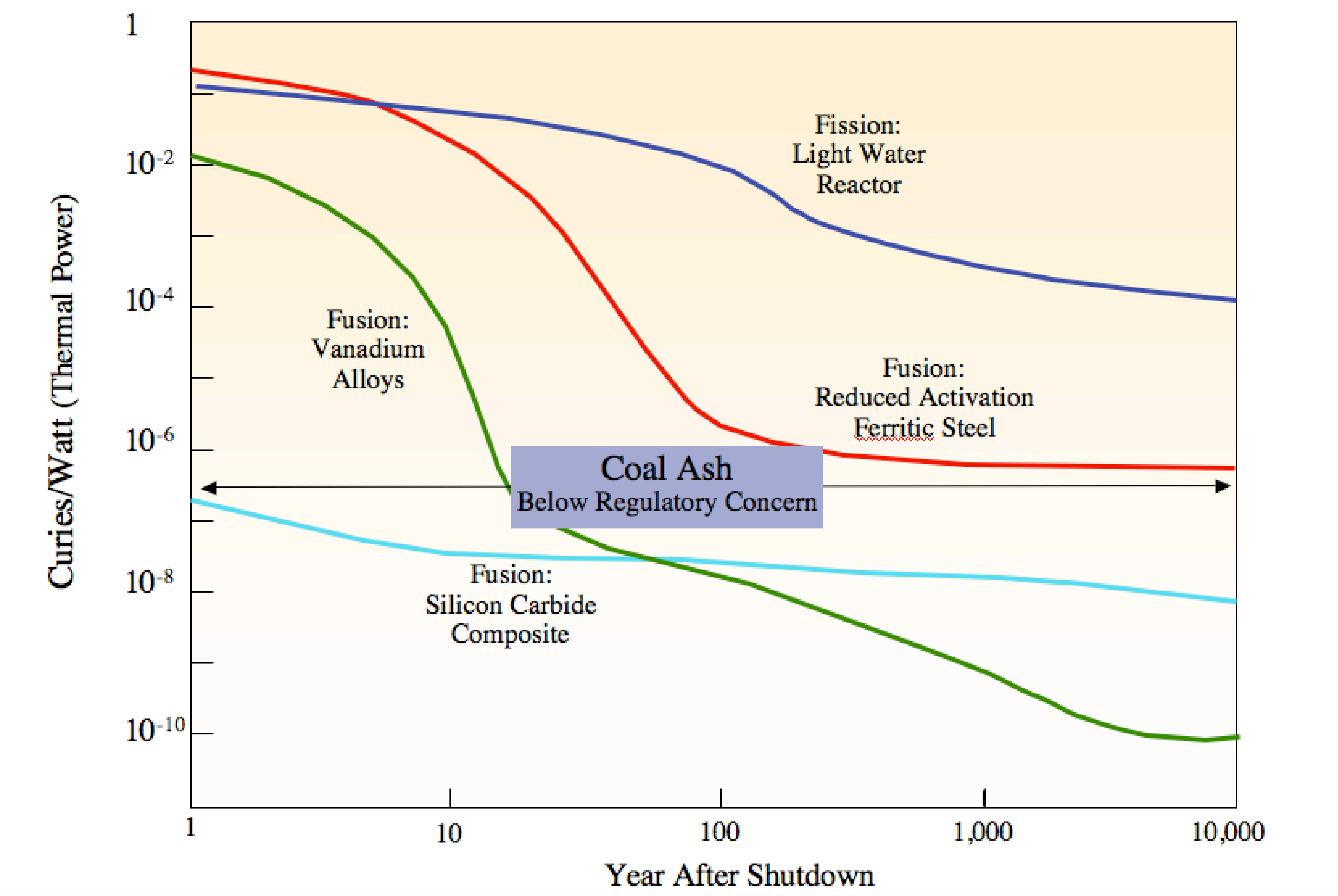
All should be pursued, but

- list is too short, given magnitude of problem
- not all items on list seem capable of meeting large fraction of predicted demand

Fusion power

- worldwide availability of low-cost fuel, billion-year supply
- no greenhouse-gas production, no smog, no acid rain
- no possibility of runaway reaction or meltdown
- no proliferation threat: not a credible bomb factory
- only short-lived radioactive wastes (from neutron bombardment of vessel material)

Radioactivity from fusion power plant



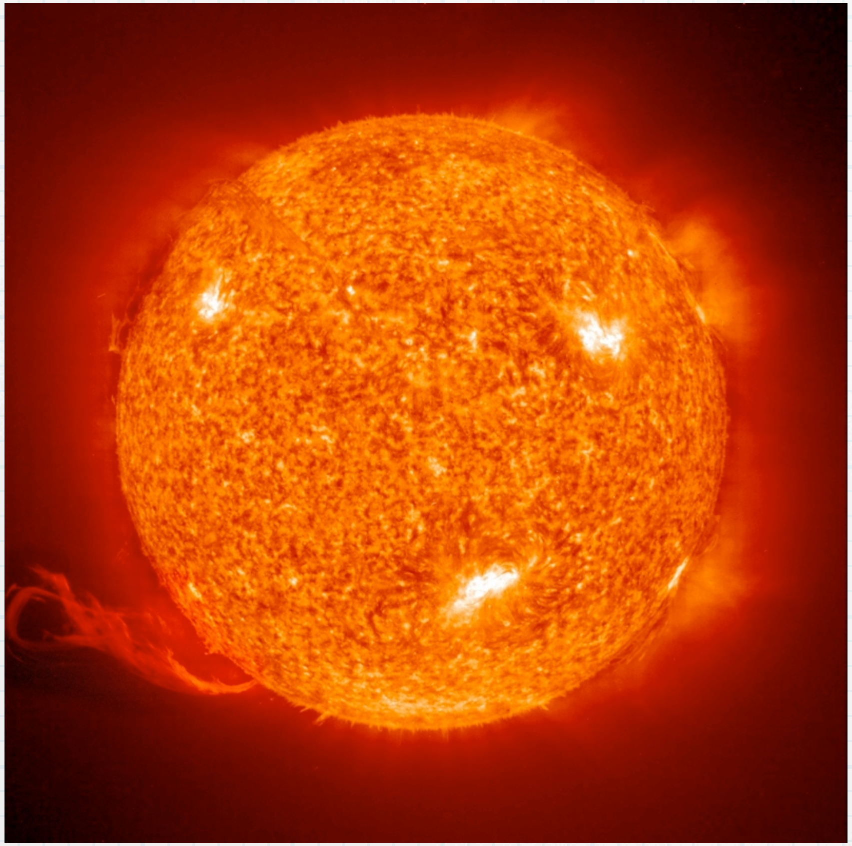
What's wrong with fusion power?

- large power plant
  - might power a city, never a car
- expensive
  - costly development path: no table-top stars (plant cost appears comparable to coal-burning plant with same output)
- complicated
  - high maintenance?
- there aren't any fusion power plants!

Why are tokamaks so large?

- Device size determined by required fusion temperature, and by rate of heat loss (surface to volume ratio)
- Heat loss rate determined by plasma turbulence
- Turbulence driven by temperature gradient ("residual instabilities")

Turbulent heat loss:



Hot plasma bubbles up from interior

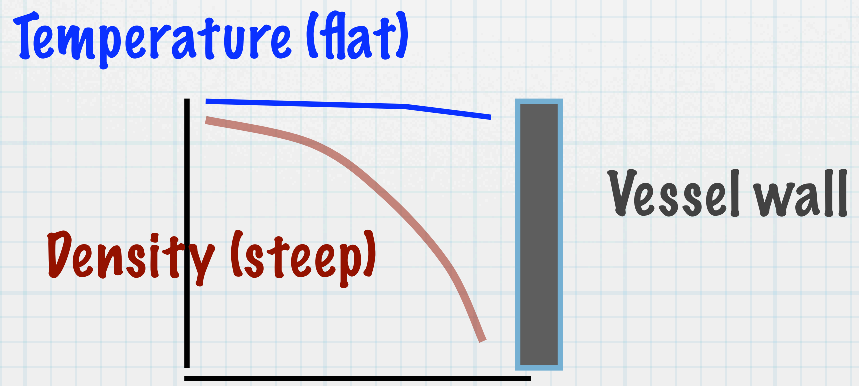
No surprise...

Smaller tokamaks?

A focus of present US research: "advanced tokamak"

For example, differential plasma rotation can break turbulent eddies, reducing heat loss. This effect is striking in experiments and reasonably well understood.

A more speculative approach: flat temperature profile (with density fall-off to avoid heat loss to wall) would remove drive for turbulence:



Summary: logic of an earth-bound star

Everything wants to be iron

→ nuclear energy source, fission or fusion

Fusion requires close encounters, despite electric repulsion

→ need for hot nuclei

→ plasma state

Plasmas are prevalent and interesting

Summary concluded

- Earthbound scale requires
  magnetic confinement, which requires
  toroidal magnetic surfaces.
- Major challenges remain in the realization fusion power, but
- Fusion's potential advantages place it among a small, critically important group of alternative energy sources.