Magnetic confinement in plasma physics

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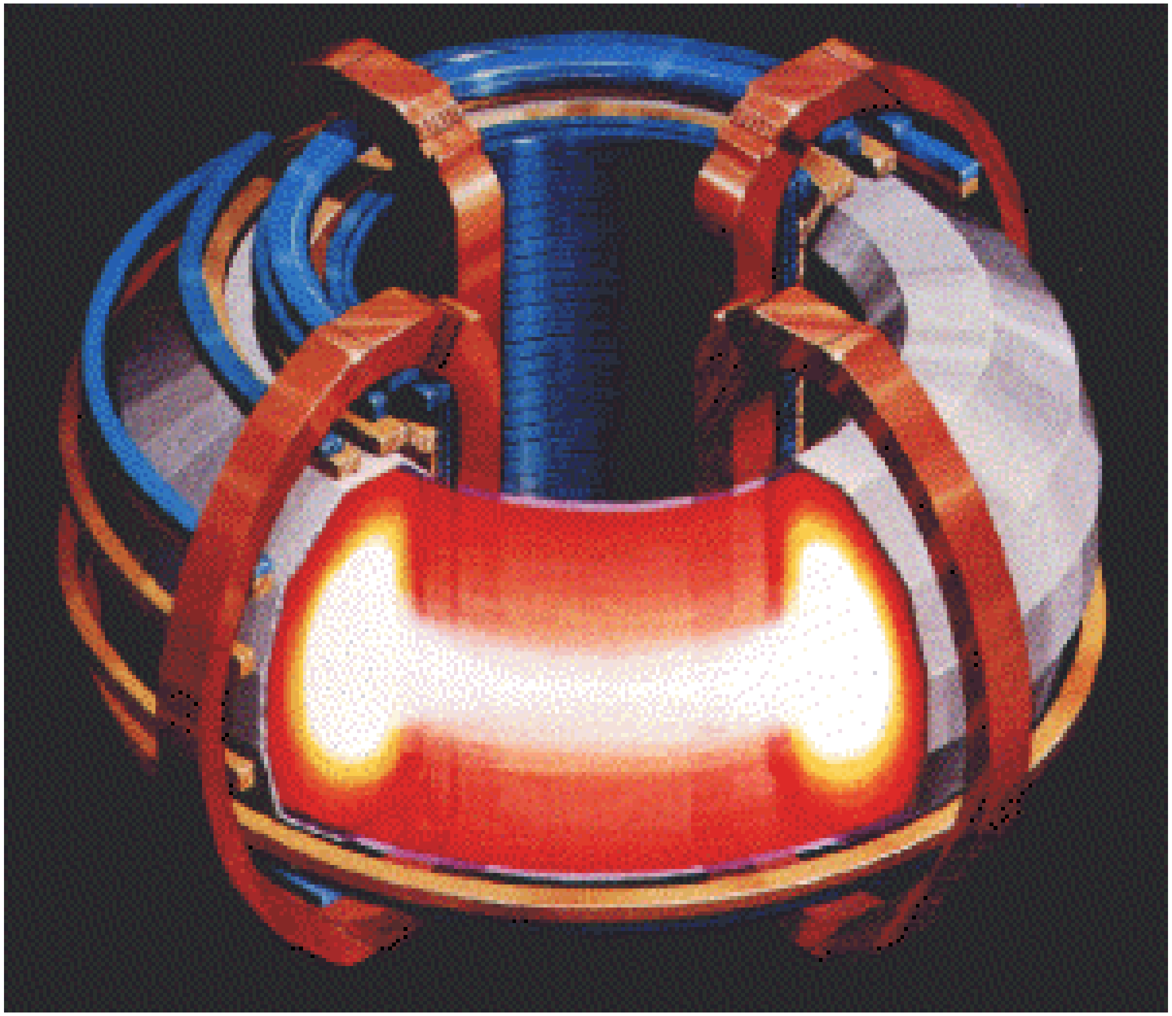
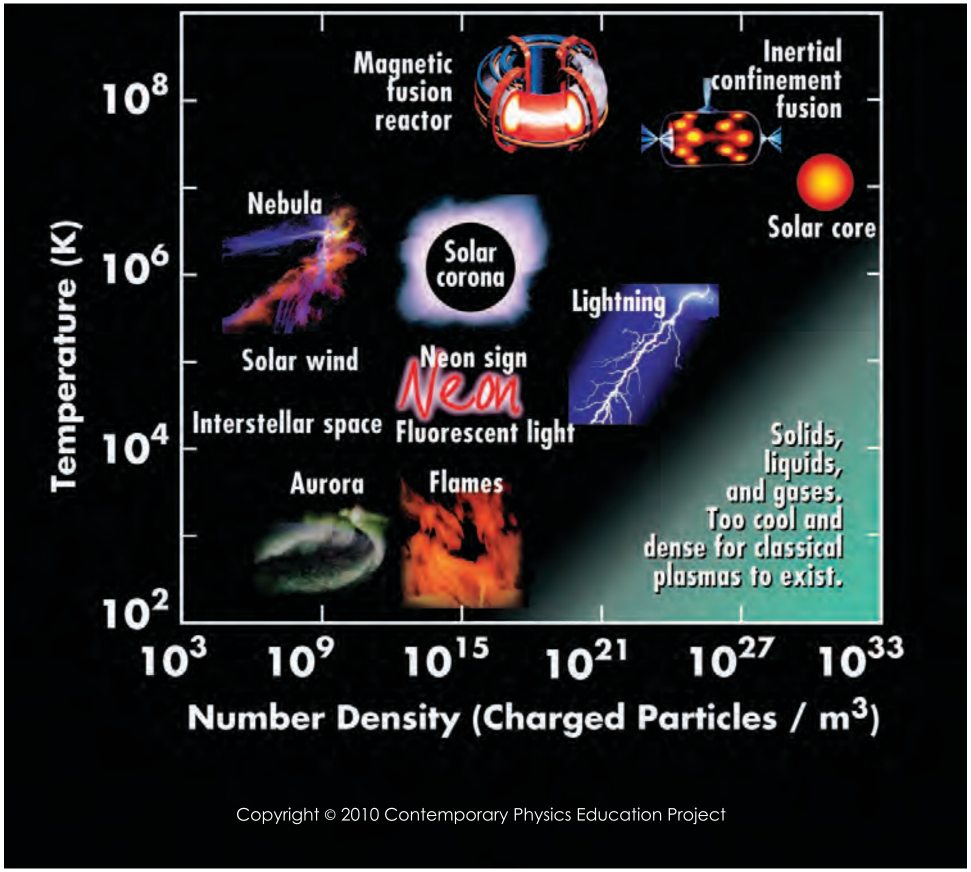
Controlled fusion electric power is a main goal of magnetic confinement physics



Plasma physics

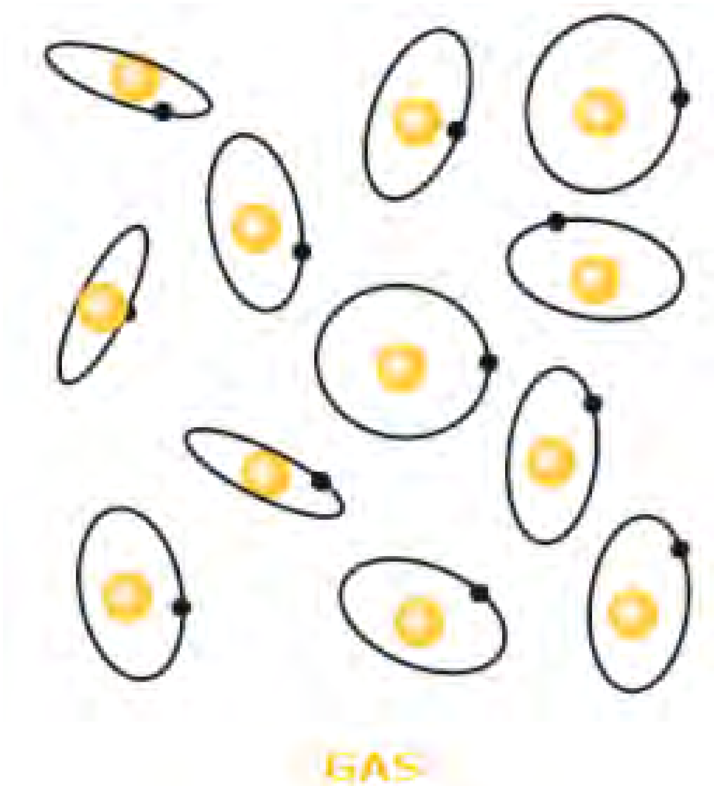
- Largely classical physics of ionized gases
- Important in basic science, astrophysics, industry, and controlled fusion research
- Fluid or particle models with many degrees of freedom and varied geometries
- Nonlinear dynamical coupling across different scales, collective particle motions, waves, symmetry-breaking, emergent phenomena, self-organization, . . .
- Scientific progress often driven by laboratory experiments and astronomical observations ahead of theory and numerical calculations

Plasma phenomena occur in many contexts



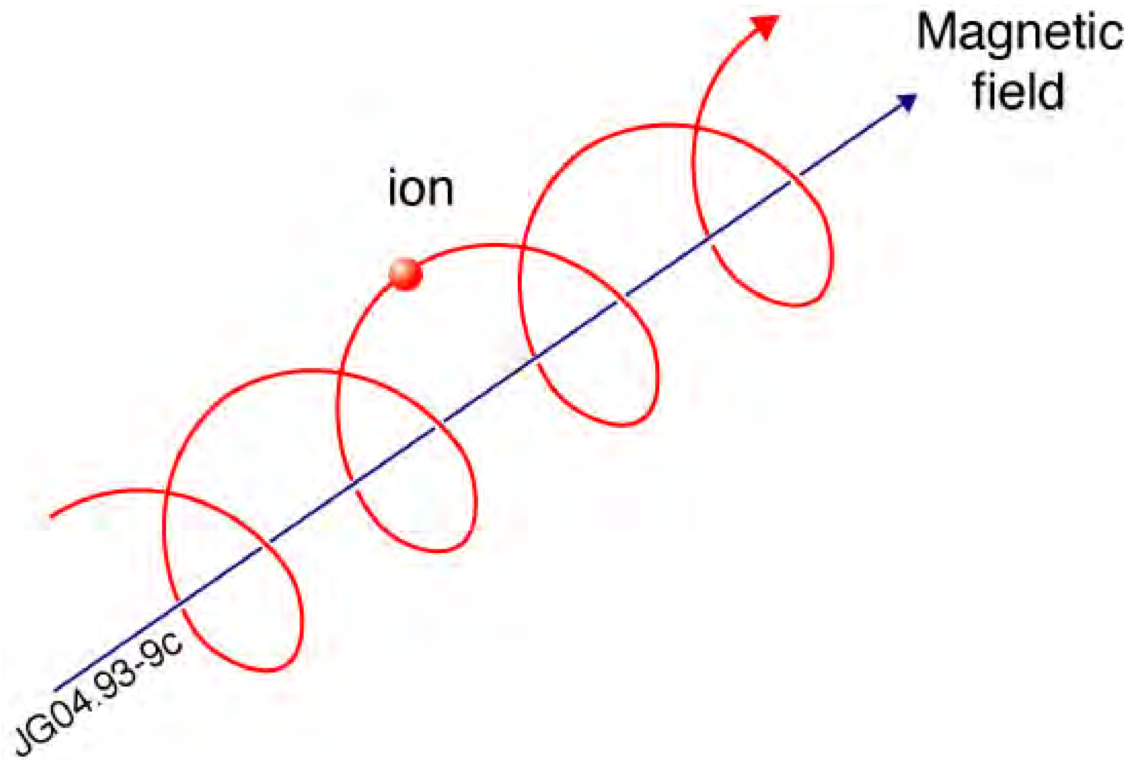
- Large ranges of temperature, density, distance, time, magnetic field . . .
- Almost all visible matter in the universe is in a plasma state

Plasmas are ionized gases



- Free charges in a plasma can respond to electromagnetic fields and carry electric currents

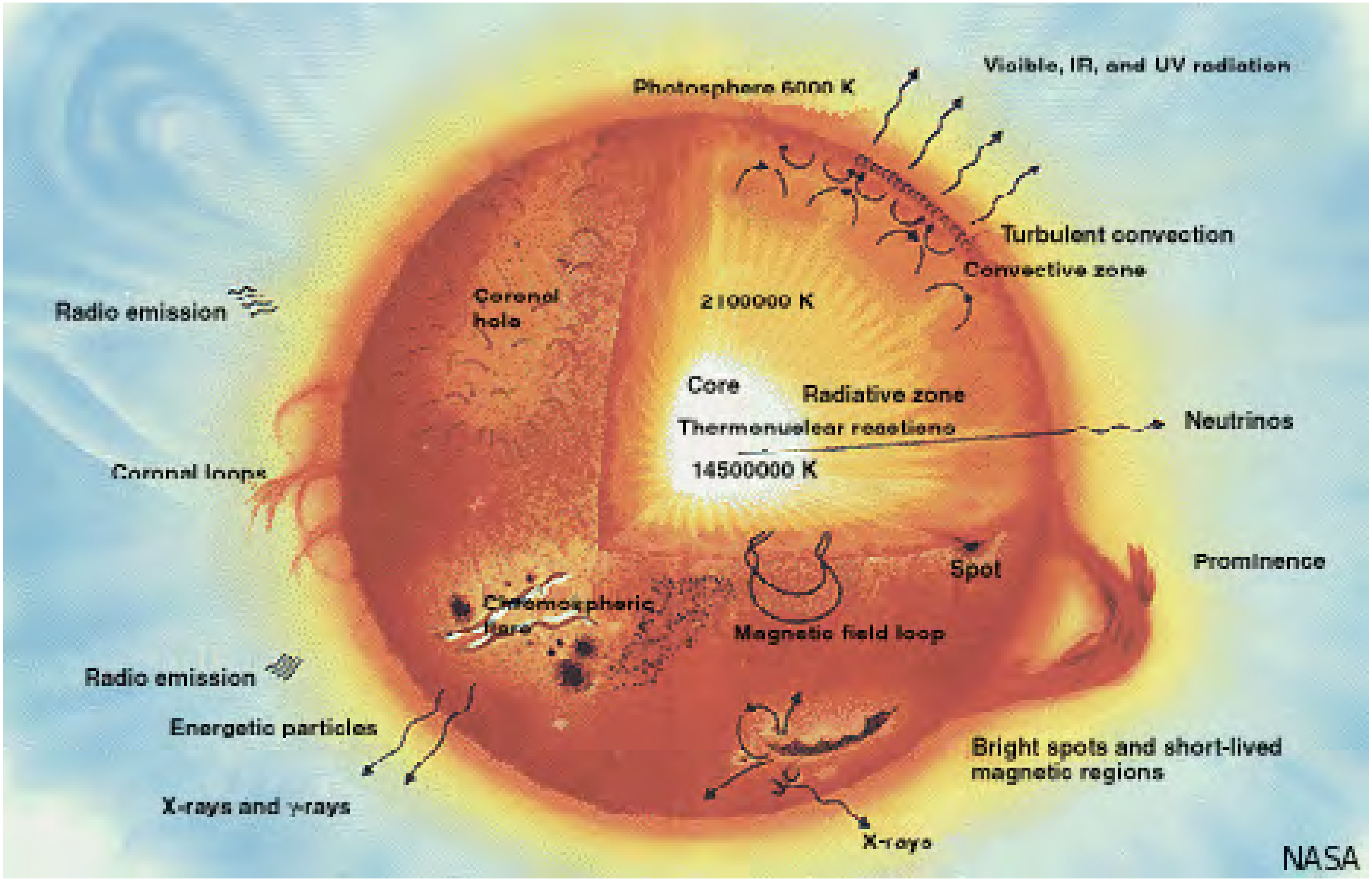
Due to Lorentz qv$\times$B force, particles undergo helical cyclotron motion around magnetic field lines



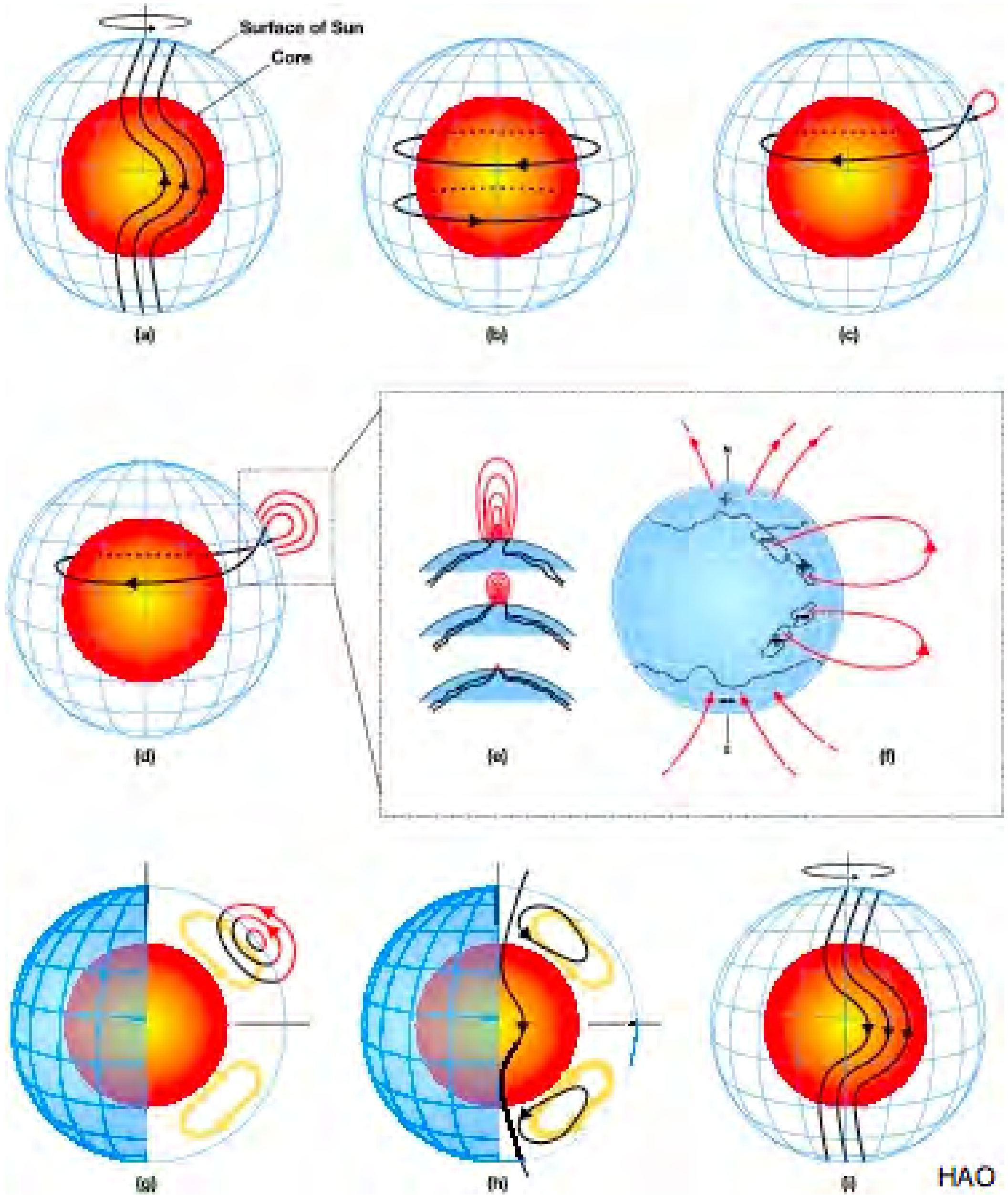
- We say plasma is tied to field lines, which have magnetic tension and pressure

- In plasmas with high electrical conductivity, magnetic field behaves as if field lines were frozen into the moving plasma fluid

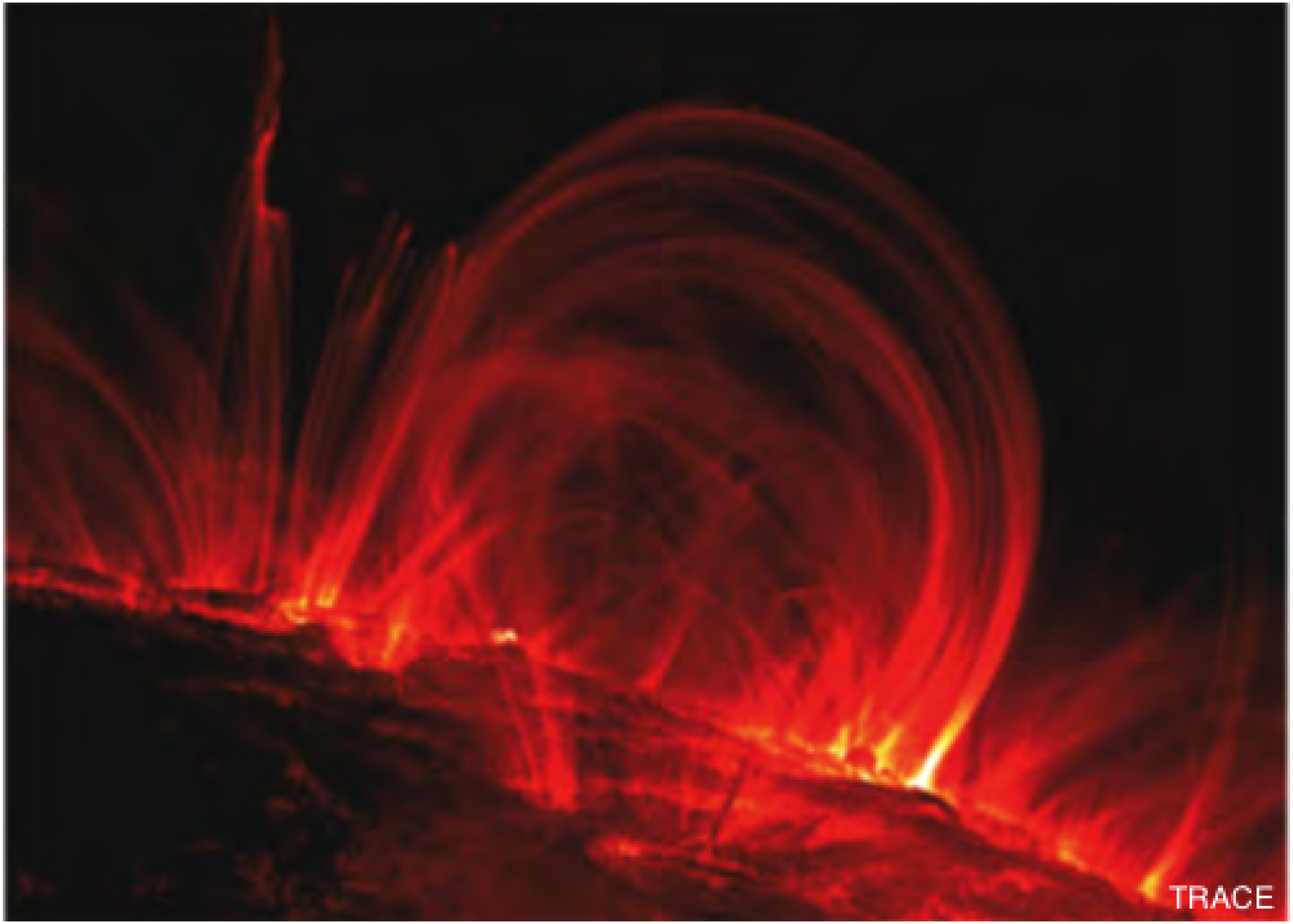
The Sun is a gravitationally confined fusion plasma



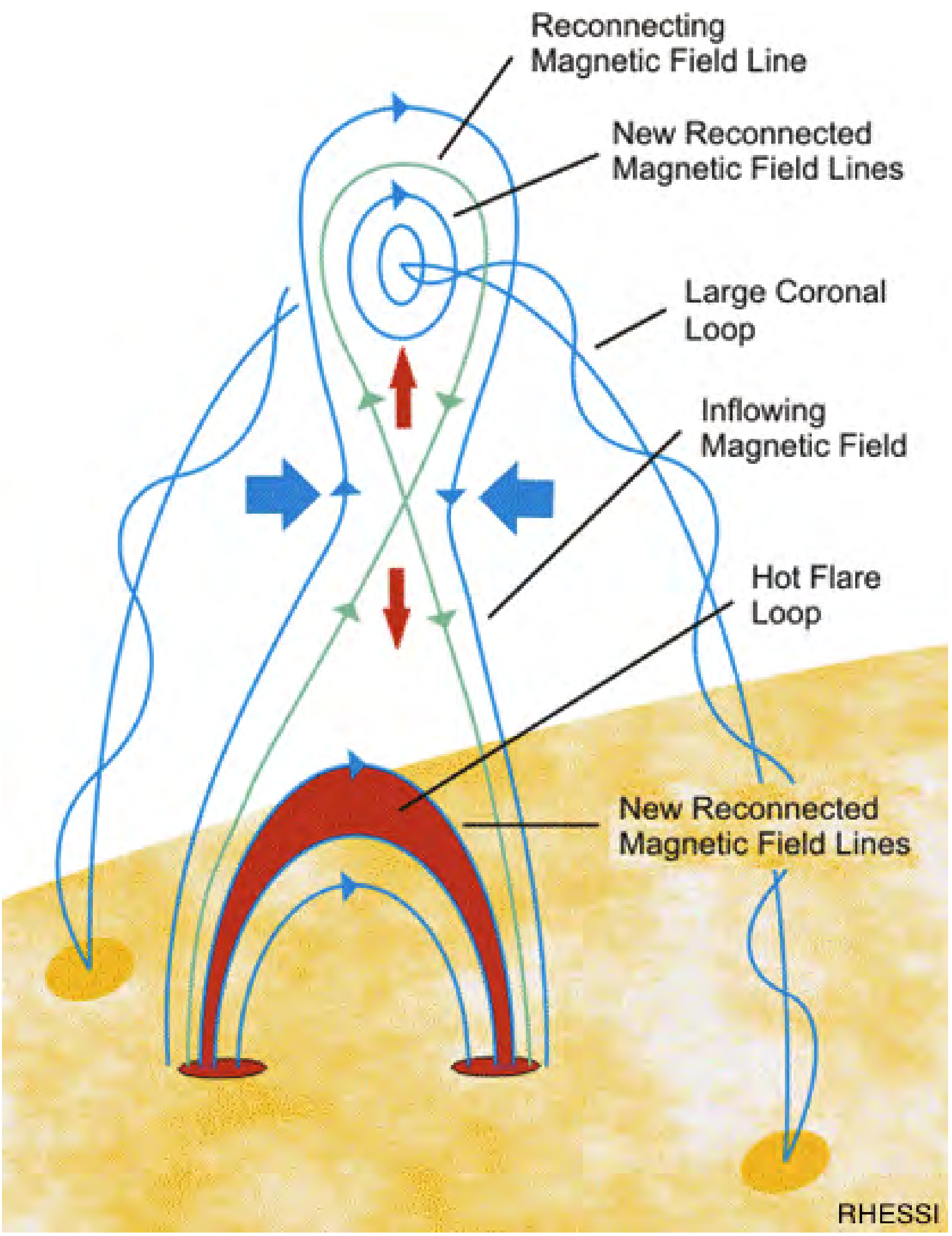
Plasma flows generate the solar dynamo magnetic field



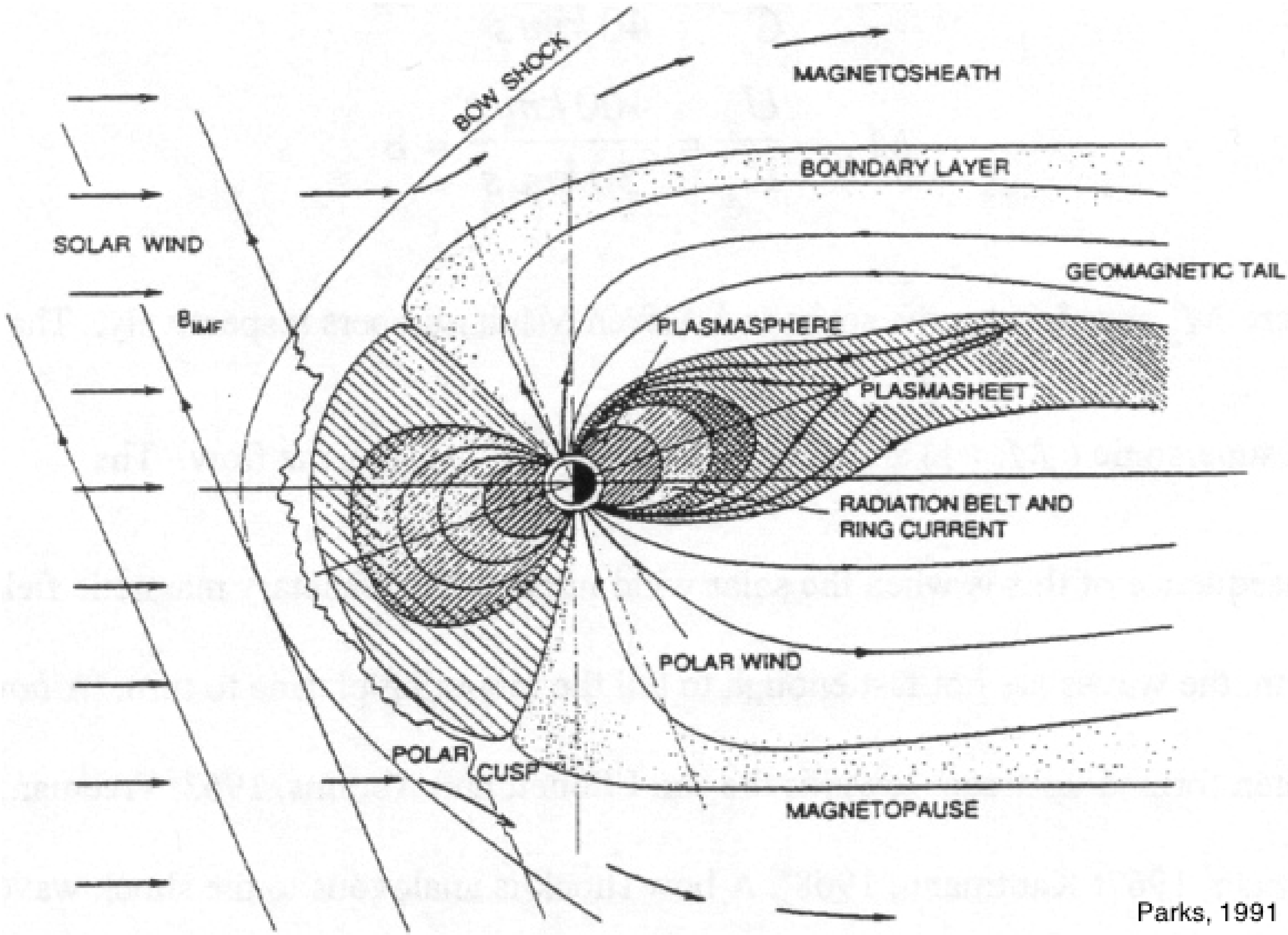
Coronal loops magnetically confine plasma



Solar flares as magnetic reconnection events



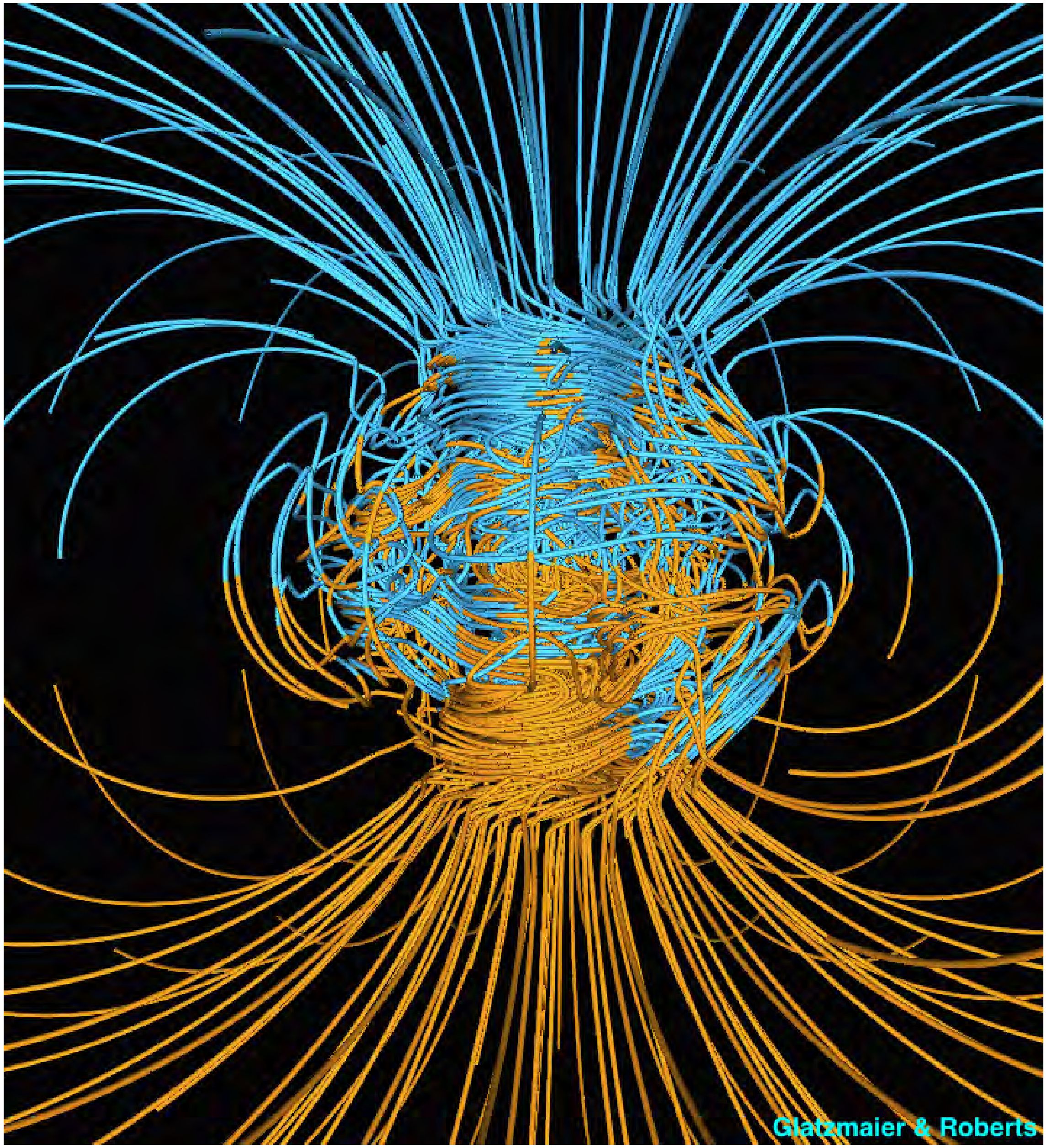
Earth's magnetosphere blocks incoming solar wind



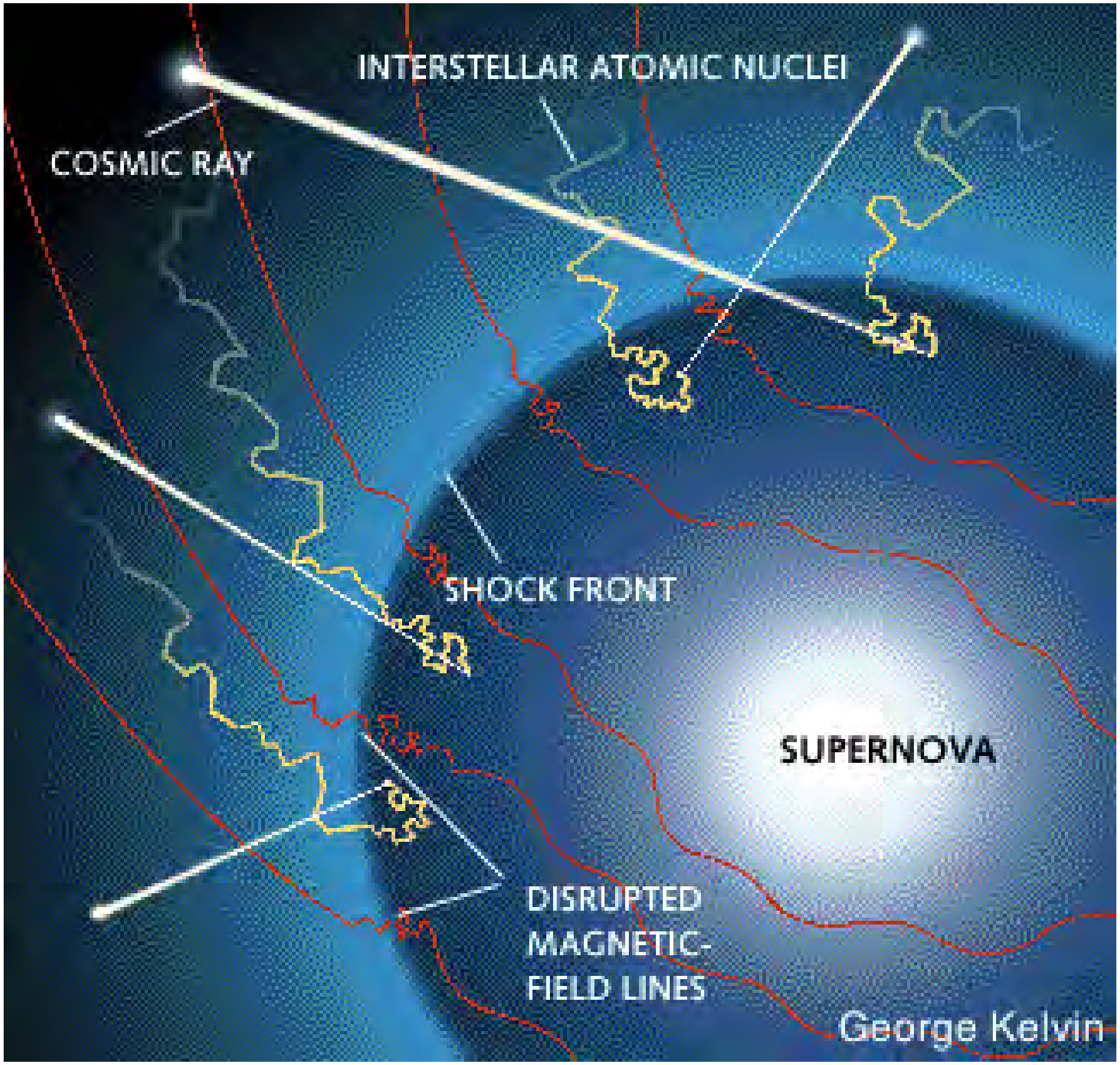
Parks, 1991

Trapped energetic particles produce aurora borealis

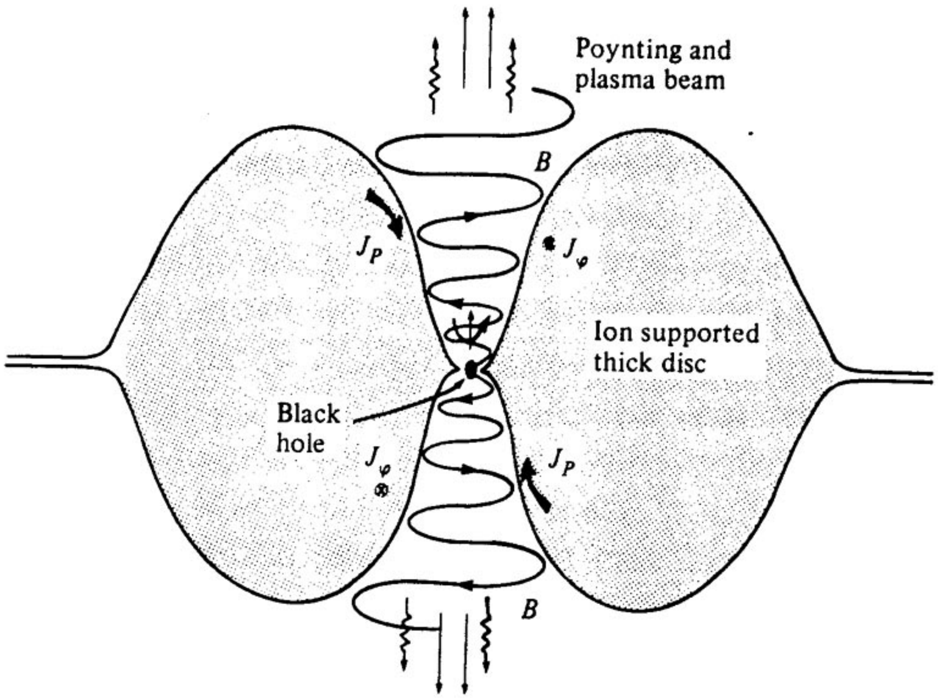
Liquid metal flows generate the Earth's dynamo magnetic field

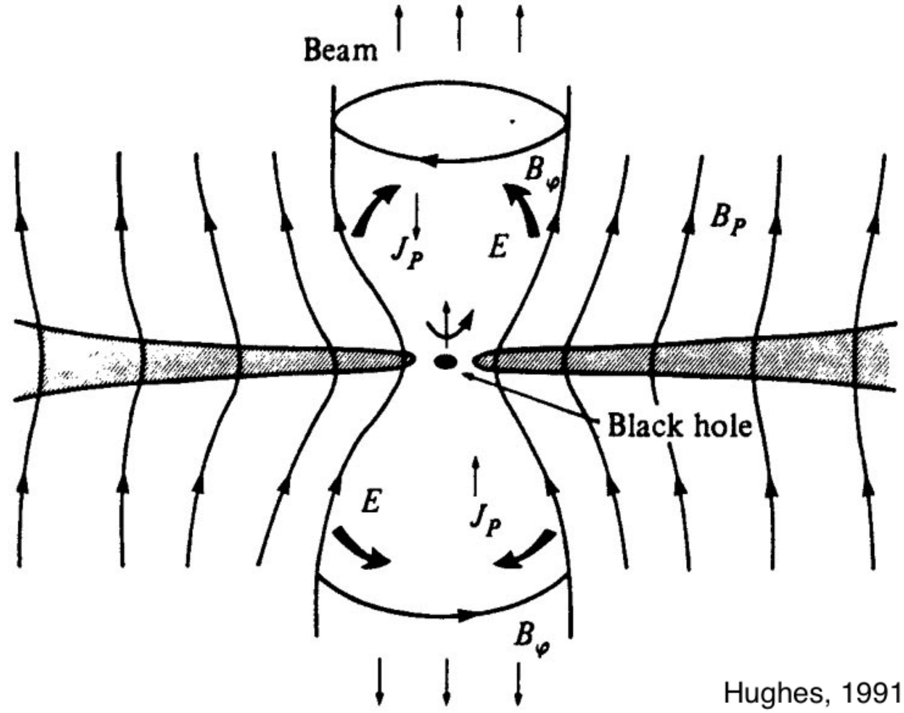


Generation and acceleration of cosmic rays



Black hole accretion disks and X-ray jets

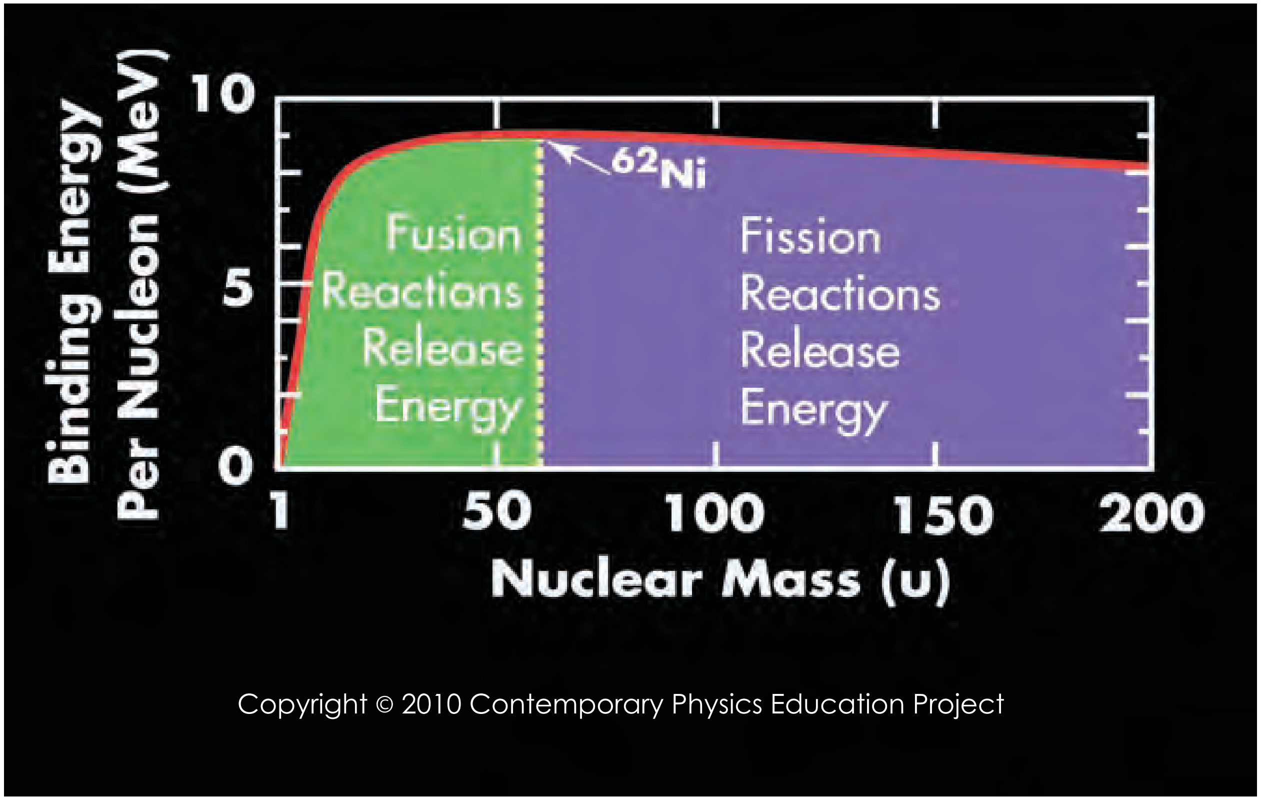




Hughes, 1991

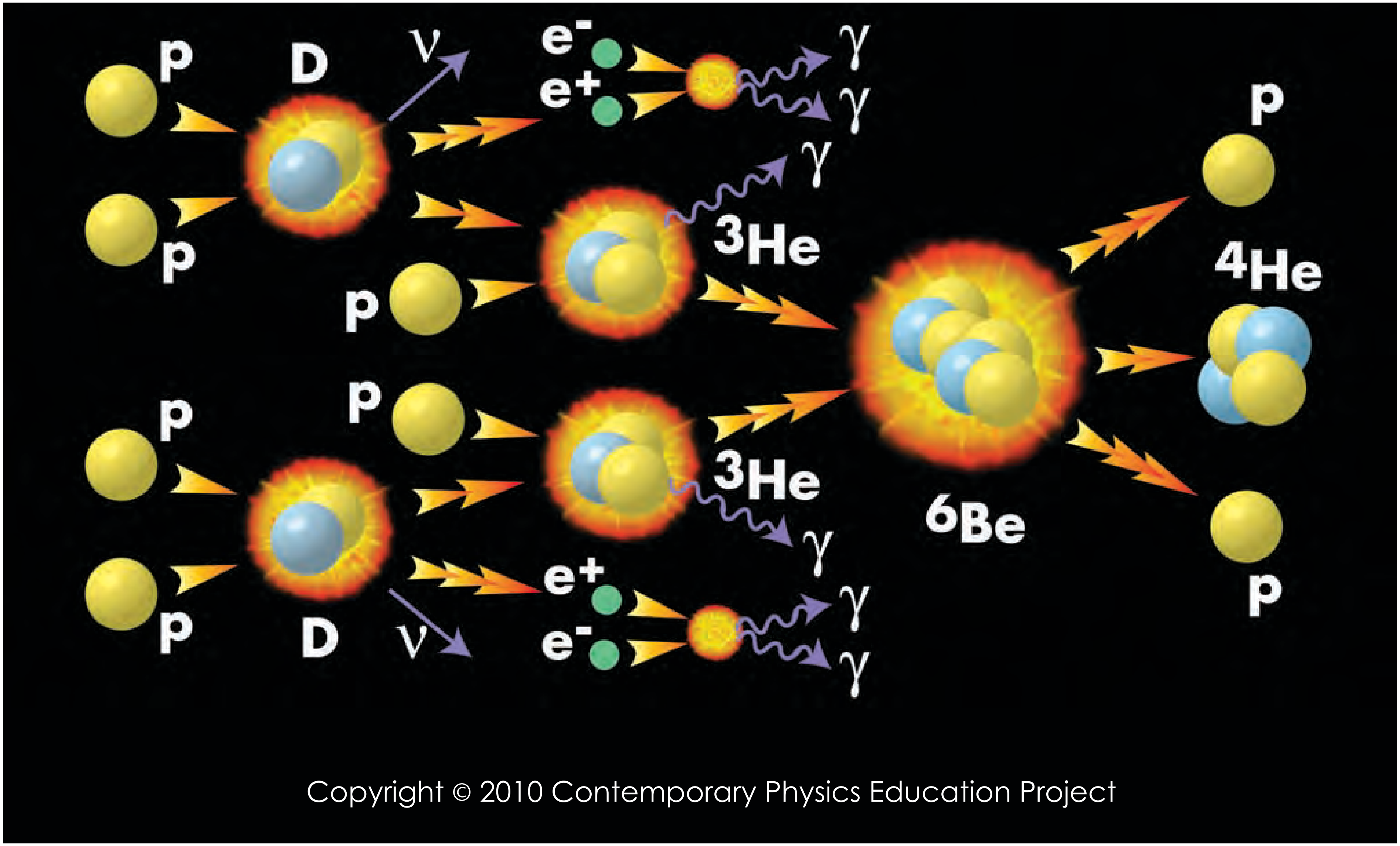
Fusion

Nuclear reactions can release binding energy of strong nuclear force

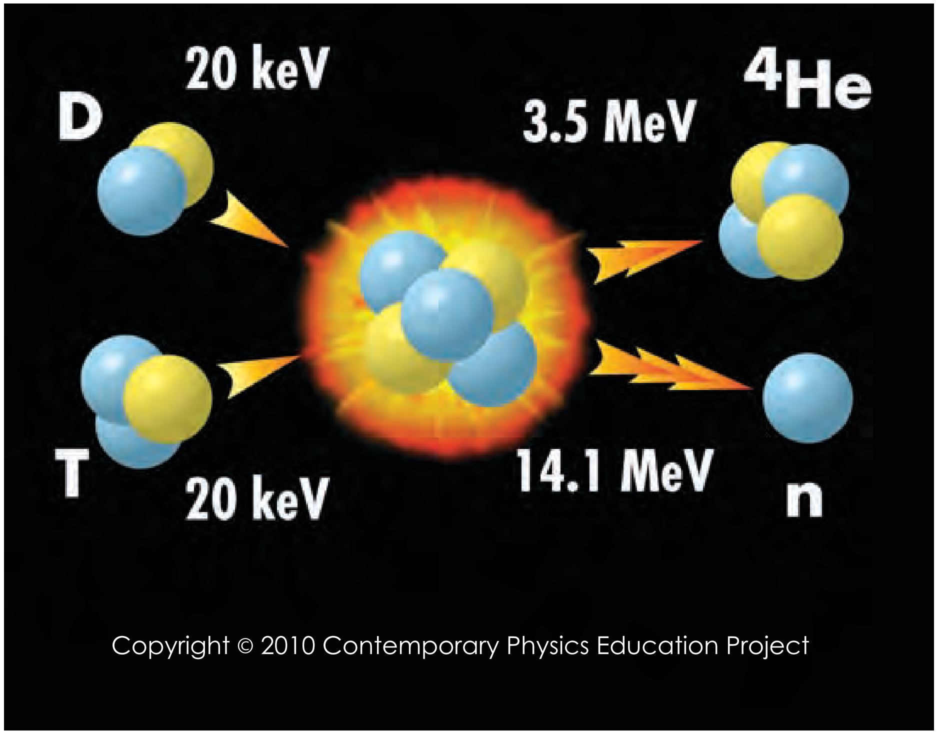


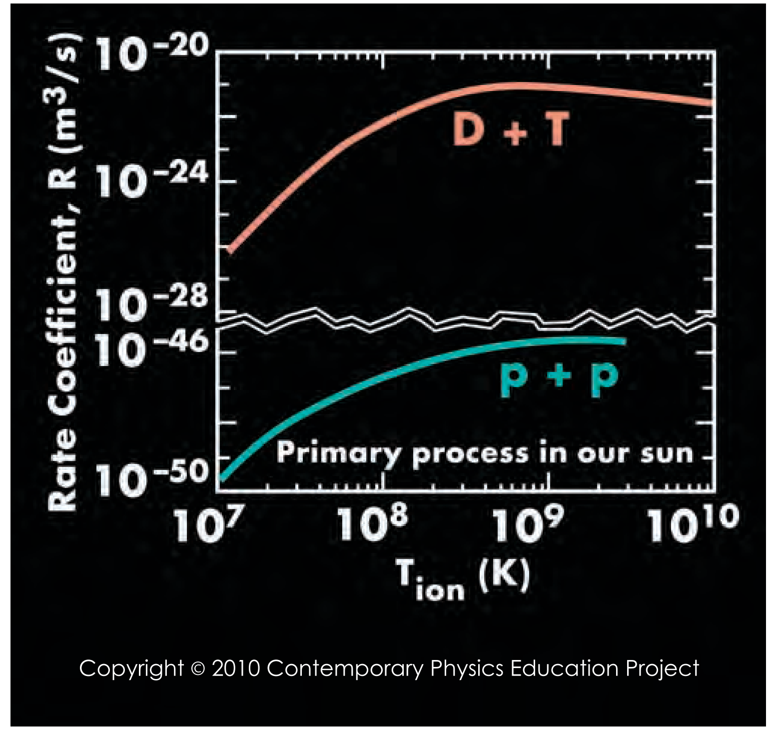
- Fusion is joining and fission is splitting nuclei
- Energy scale is MeV as opposed to eV for chemical reactions
- Note energy unit 1 eV $\sim 10^4$ K temperature unit

Solar fusion burns hydrogen, i.e. protons, to release energy, with helium ash



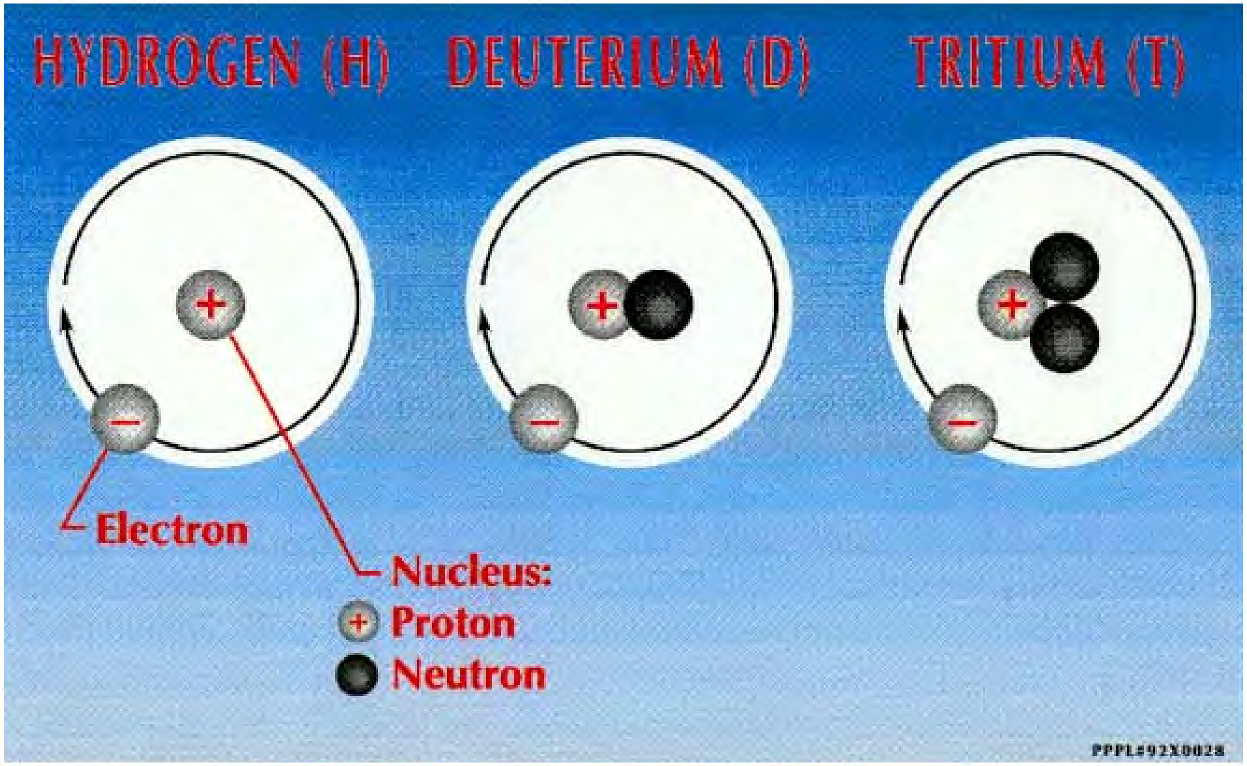
DT is the most feasible type of fusion for us





- At a given temperature, its reaction rate is much higher than that for the solar fusion reaction
- Still, it is very difficult to reach thermal speeds such that impact parameters are small enough for attractive nuclear force to overcome electrostatic repulsion

Isotopes of hydrogen

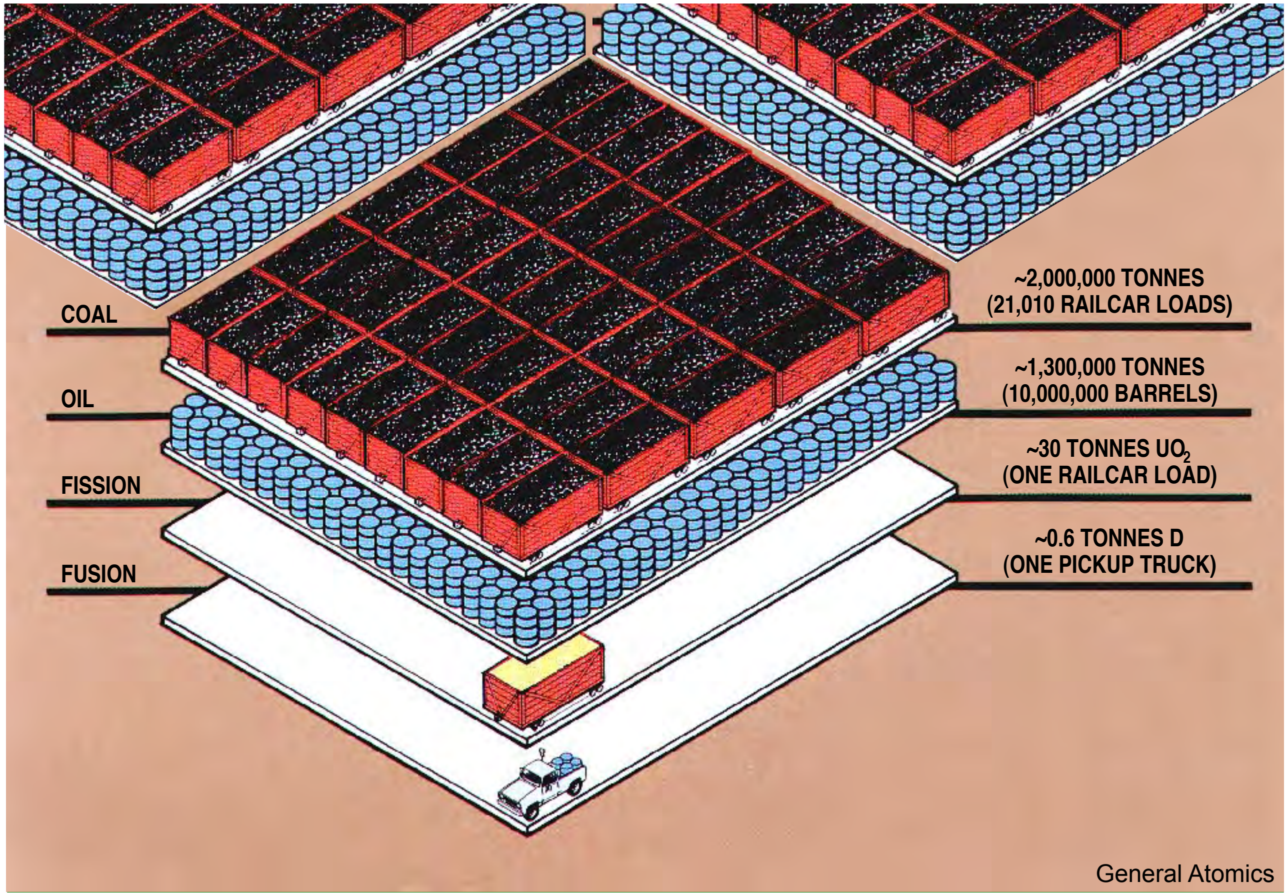


Hydrogen (H) 99.985% of natural hydrogen, in water

Deuterium (D) 0.015% of natural hydrogen

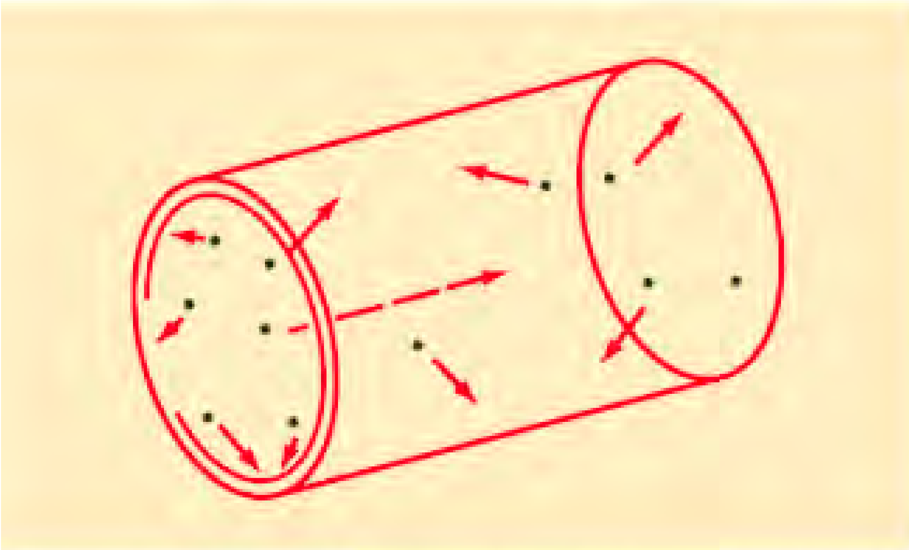
Tritium (T) 12 year half-life, so needs to be bred from Li, which is plentiful in seawater

With world energy demand expected to increase significantly, main advantage of fusion is its fuel supply

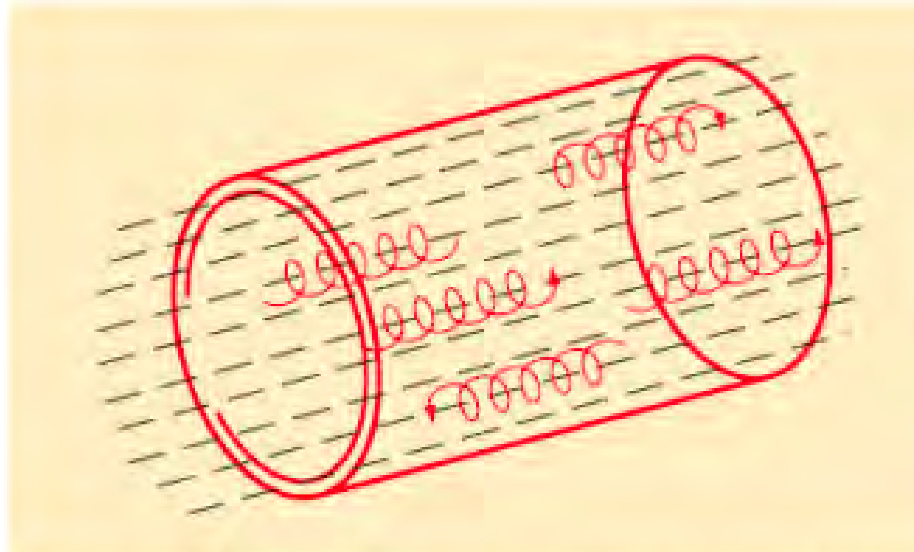


- Relatively small amount needed for 1 GWe power plant for 1 year
- Thousands of years' supply vs. a few hundred (?) for fossil fuels

Magnetic confinement is the main concept being pursued



Motion of charged particles without magnetic field.



Motion of charged particles with magnetic field.

- Magnetic fields to confine thermonuclear plasma, isolating it from much colder solid walls of vacuum vessel

Interesting fusion reactions

- DT fuel cycle with T breeding
  - $D + T \to n + {}^{4}He + 17.6$ MeV
  - $n + {}^{6}Li \to T + {}^{4}He + 4.8$ MeV
  - $n + {}^{7}Li + 2.5\ \text{MeV} \to n + T + {}^{4}He$

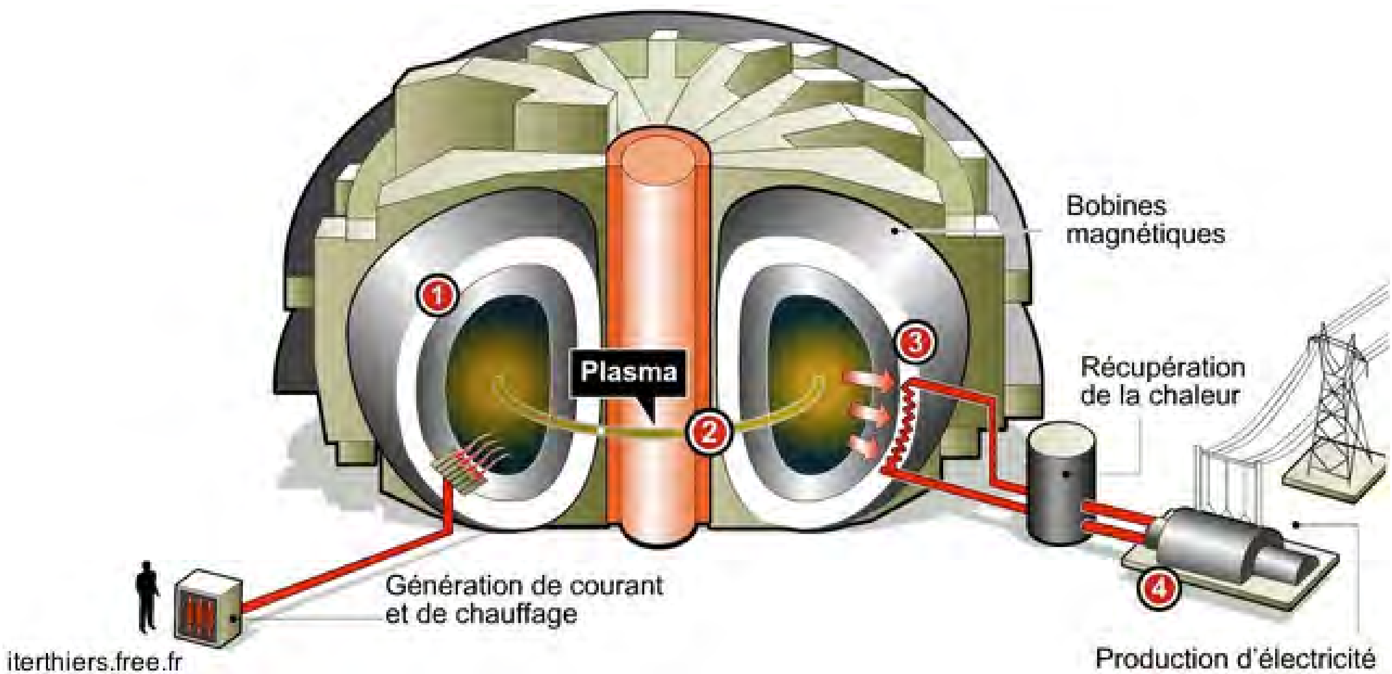
- Advanced fusion can be aneutronic, but reaction rates are lower and peak at higher temperatures
  - $$\begin{aligned} D + D &\to n + {}^{3}He + 3.3\ \text{MeV} \\ &\to H + T + 4.0\ \text{MeV} \end{aligned}$$
  - $D + {}^{3}He \to H + {}^{4}He + 18.4$ MeV
  - $H + {}^{11}B \to 3\,{}^{4}He + 8.7$ MeV

Criterion for magnetic confinement DT fusion ignition, or burning plasma

- $\mathrm{D} + \mathrm{T} \rightarrow \mathrm{n}$ (14.1 MeV) $+\ ^4\mathrm{He}$ (3.5 MeV)
  - Uncharged neutrons (n) carry 4/5 of fusion output power out of the plasma, where it can be converted into electric power
  - Remaining confined, charged alpha particles (^{4}He) allow 1/5 of the fusion output power to heat the plasma, so that in principle the input power could be removed
  - Thus, for ignition, $P_{\mathrm{fusion}}/P_{\mathrm{input}} \equiv Q \geq 5$

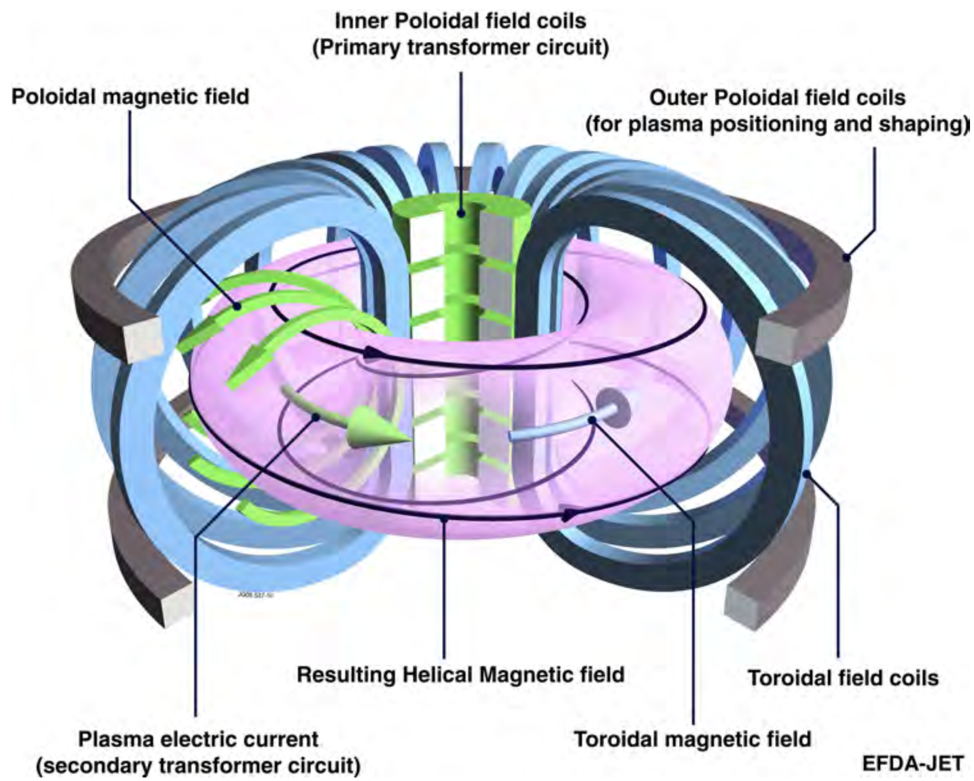
- Lawson criterion: $nT\tau_{\mathrm{E}} \gtrsim 5 \times 10^{21}$keV s/m$^3 \approx 8$ atm-s
  - Density $n \gtrsim 5 \times 10^{20}$/m^3 ($\sim 1/10^5$ that of Earth's atmosphere)
  - Temperature $T \gtrsim 10$ keV $\approx 10^8$ K ($\sim 10\times$ that of Sun's core)
  - Energy confinement time $\tau_{\mathrm{E}} \gtrsim 1$ s

What magnetic confinement fusion power would look like



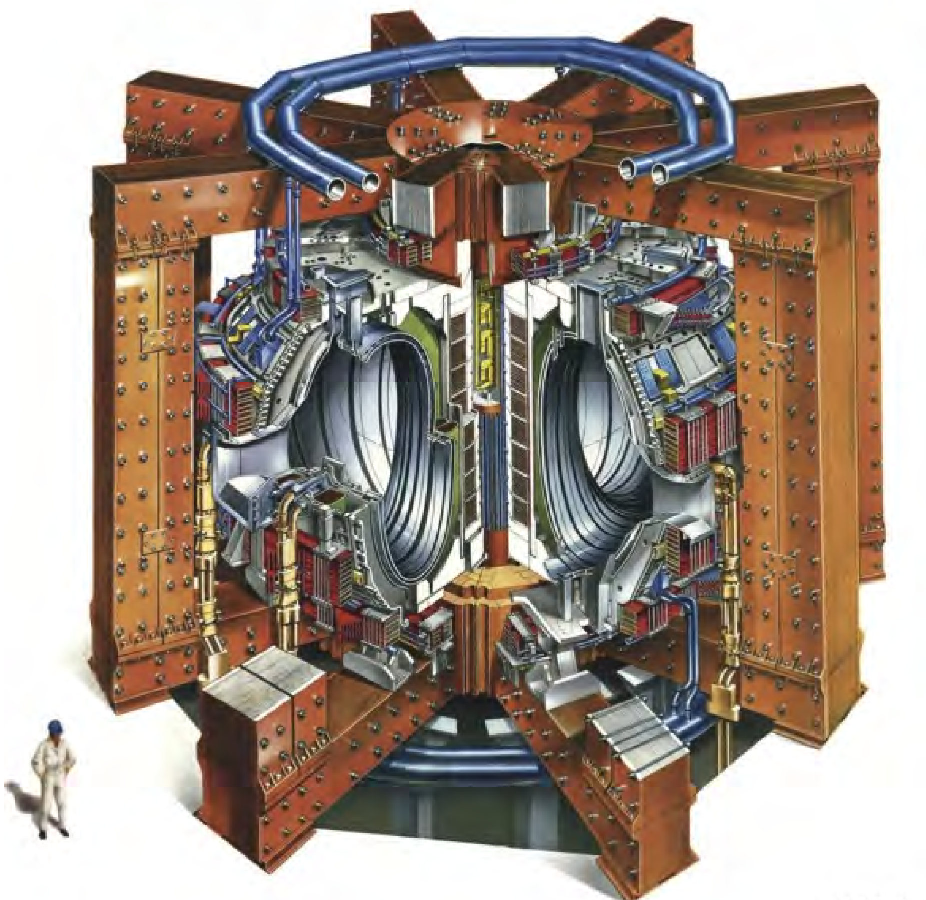
- Much less or zero danger of accidents associated with fission
- Helium ash is an inert gas
- DT neutron-activated vessel has much lower level of radioactivity than spent fission fuel, and technology may improve this
- Cost of electricity competitive with today's sources

Tokamaks are the most successful magnetic confinement concept

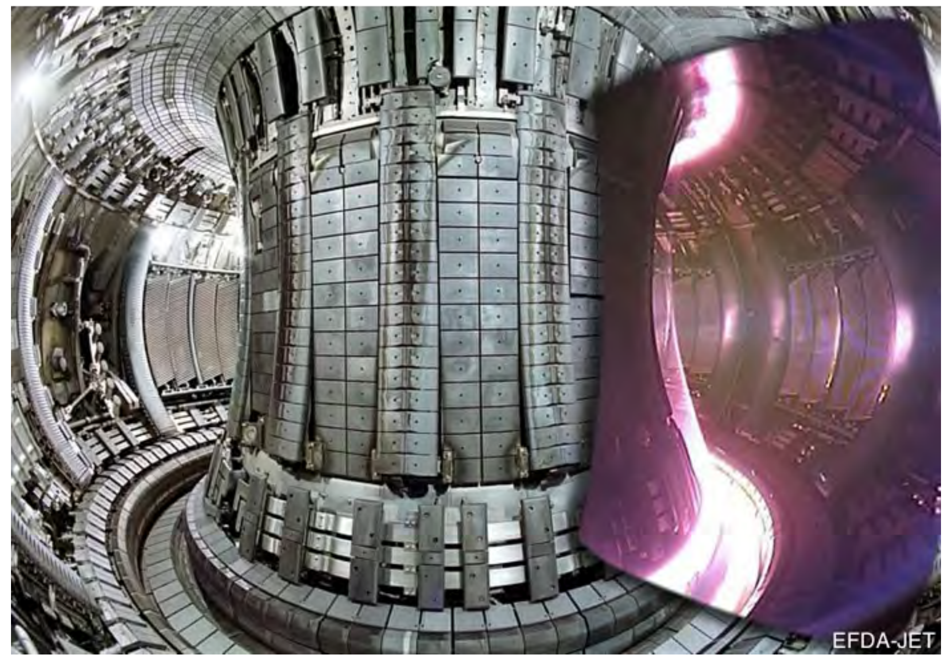


- Strong toroidal magnetic field to stabilize plasma fluctuations
- Toroidal plasma current generates confining poloidal field
- Plasma heated by its own current, microwaves, particle beams

JET experiment in Culham, England the world's largest tokamak



EFDA-JET



Fusion progress has been rapid

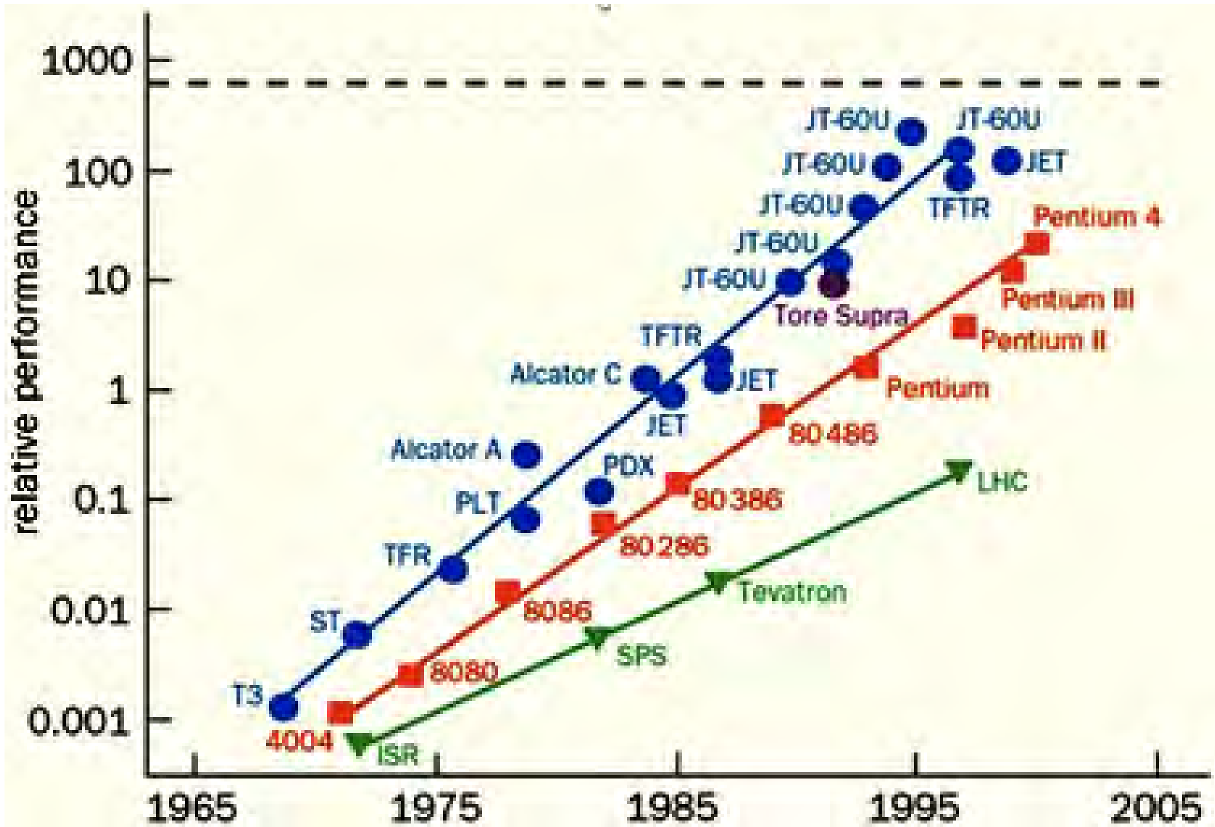
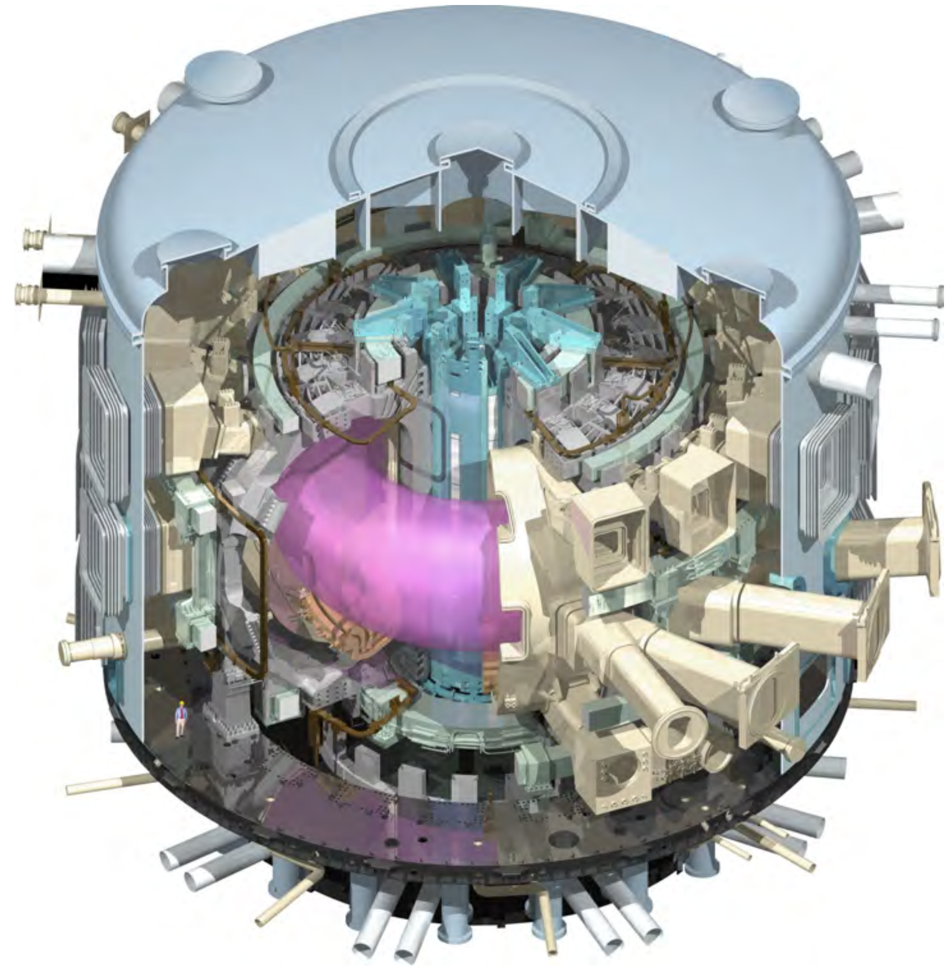


Figure 2: Progress of tokamak based fusion research compared to development of semiconductor chips and particle accelerators. (Picture courtesy J.B. Lister, CRPP-EPFL, Lausanne, Switzerland) iter-india.org

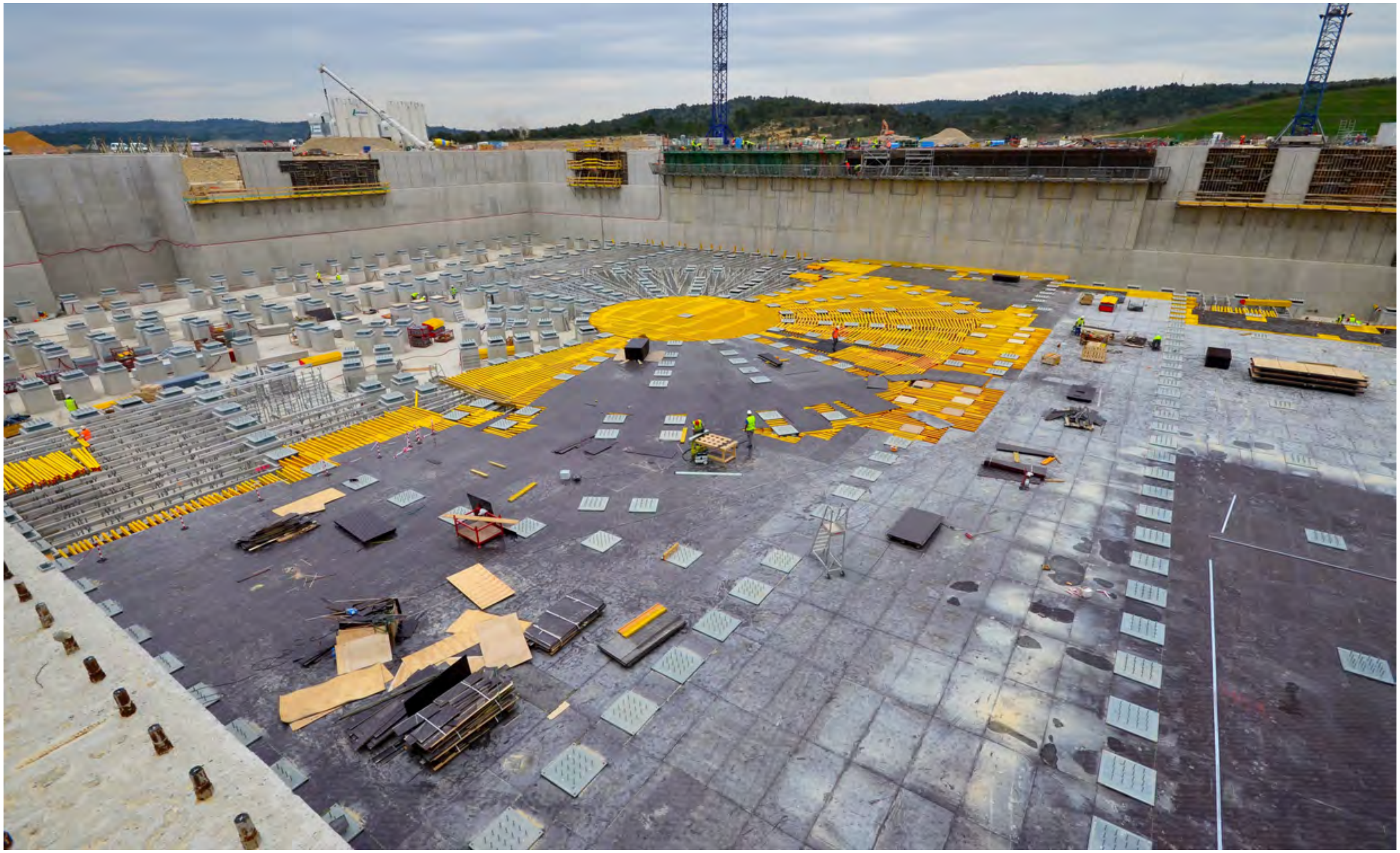
- Dotted line shows $nT\tau_{\mathrm{E}}$ for burning plasma

The ITER tokamak experiment is to be the first magnetic confinement device to achieve burning plasma

- Goal is $Q = 10$
  - $P_{\text{fusion}} = 500$ MW
  - $P_{\text{input}} = 50$ MW
- Originally proposed in 1985, the ITER collaboration now comprises China, the EU, India, Japan, Korea, Russia, and the USA



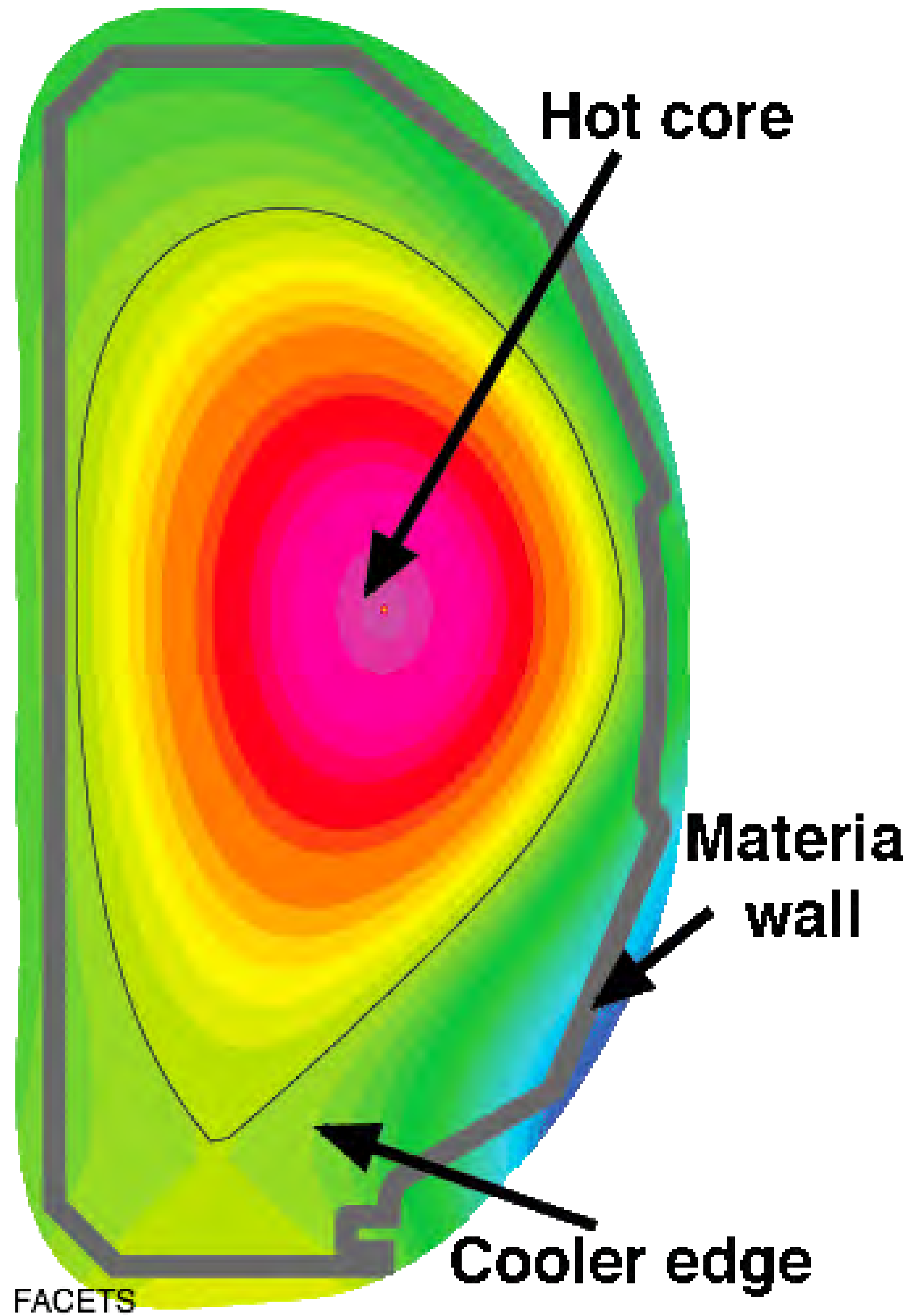
ITER is under construction in Cadarache, southern France



- First plasmas in $\sim$ 2020, burning plasmas some years later
- Demonstration reactor could follow in some decades

Magnetic fusion science addresses many interrelated issues

- Equilibrium: $\mathbf{J} \times \mathbf{B} = \nabla p$
- Instabilities and fluctuations
- Magnetic stochasticity
- Turbulent heat and particle transport
- Thermal pressure limits and particle density limits
- Burning plasma dynamics
- Plasma disruption events: Few GJ stored magnetic energy dissipated in a few ms
- First wall: ~ 50 MW/m^2 heat loads and 14 MeV neutron fluxes onto reactor vessel



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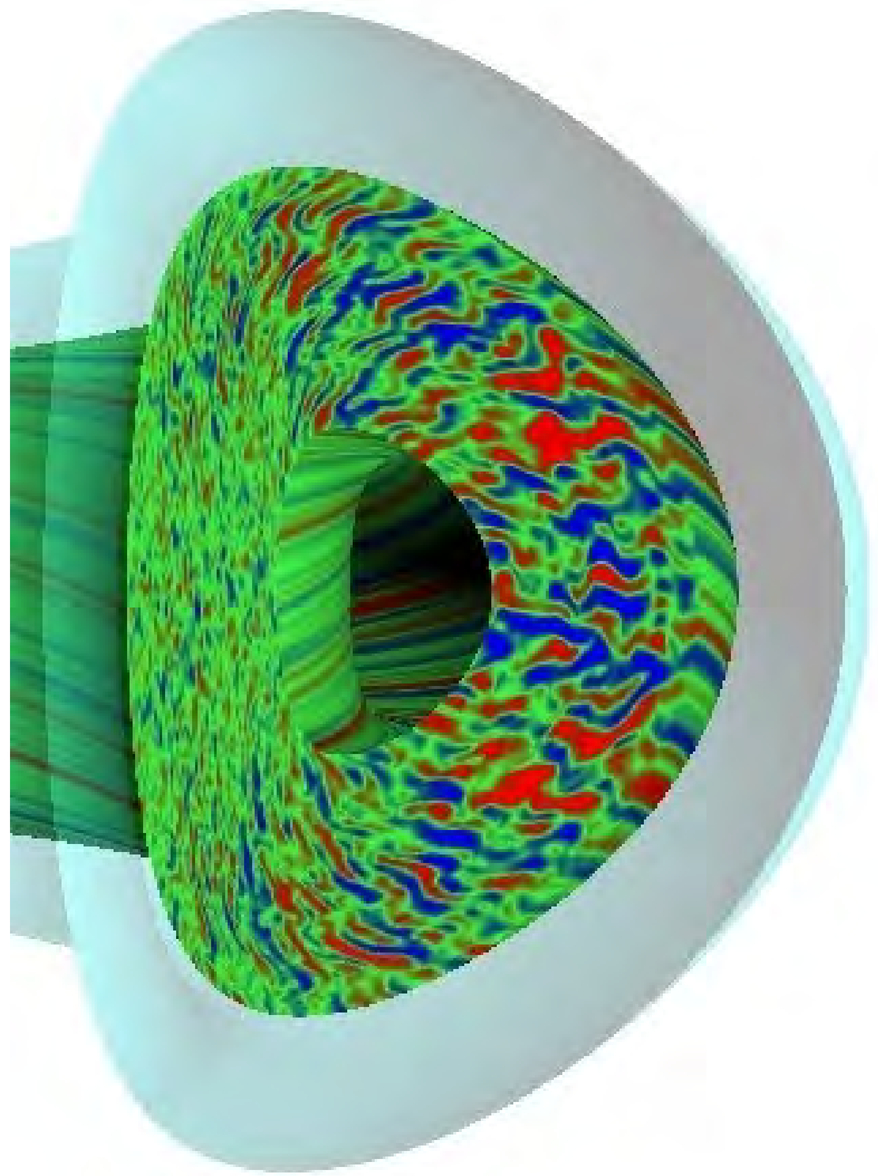

Candy, Waltz

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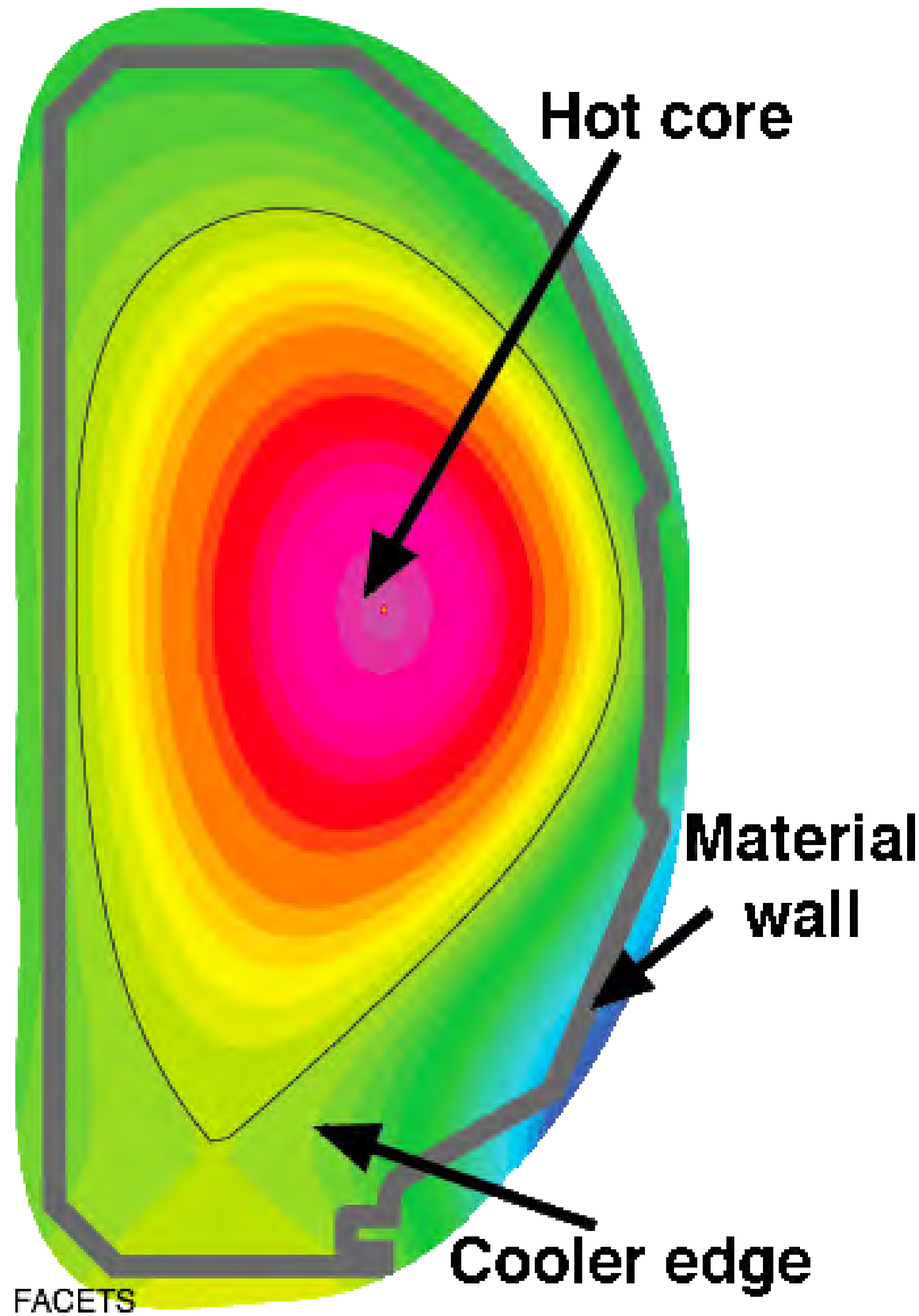
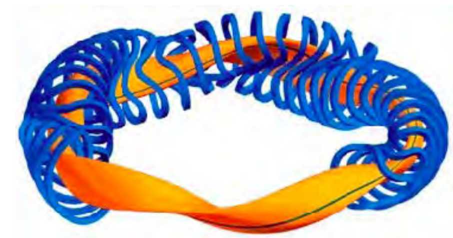
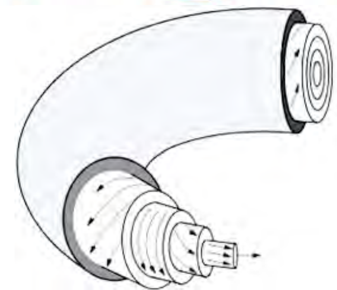


Experiments on alternative toroidal concepts help optimize fusion and explore physics of magnetized plasmas

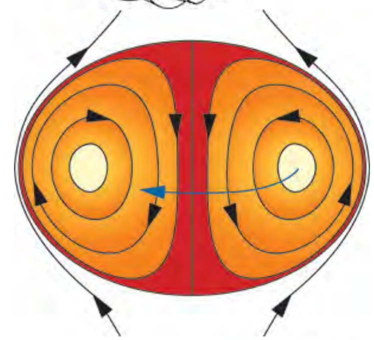
Stellarator Imposed helical field
for more quiescent plasmas
lacking net current



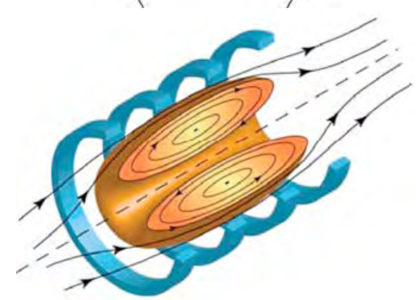
Reversed-field pinch (RFP)
Highly sheared field to confine
higher thermal pressures for
the same field strength



Spheromak Highly sheared field
with simplified structure
lacking center column



Field-reversed configuration (FRC)
Zero toroidal magnetic field
for very high thermal pressure
relative to field strength



UW–Madison is strong in plasma physics

- Experiments

  Madison Symmetric Torus (MST) reversed-field pinch

  Madison Dynamo Experiment (MDE) propeller-driven liquid sodium

  Rotating Wall Machine (RWM) plasma stability experiment

  Plasma-Couette Experiment (PCX) flows relevant to accretion disks

  Madison Plasma Dynamo Experiment (MPDX) driven by JxB forces

  Pegasus tokamak in the EP department

  Helically Symmetric Experiment (HSX) stellarator in the ECE department

- Theory centers

  Center for Plasma Theory and Computation (CPTC) multiple UW departments

  Center for Magnetic Self Organization (CMSO) multi-institutional, established by the National Science Foundation

  Center for Momentum Transport and Flow Organization (CMTFO) multi-institutional, sponsored by the Department of Energy

Summary

- Plasma physics applies to phenomena throughout the universe
- Magnetic confinement research is an application of plasma physics to the goal of controlled fusion electric power
- Experiments to produce burning plasmas are planned for the near future

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