# Magnetic confinement fusion: science that’s hotter than a Kardashian Instagram post*

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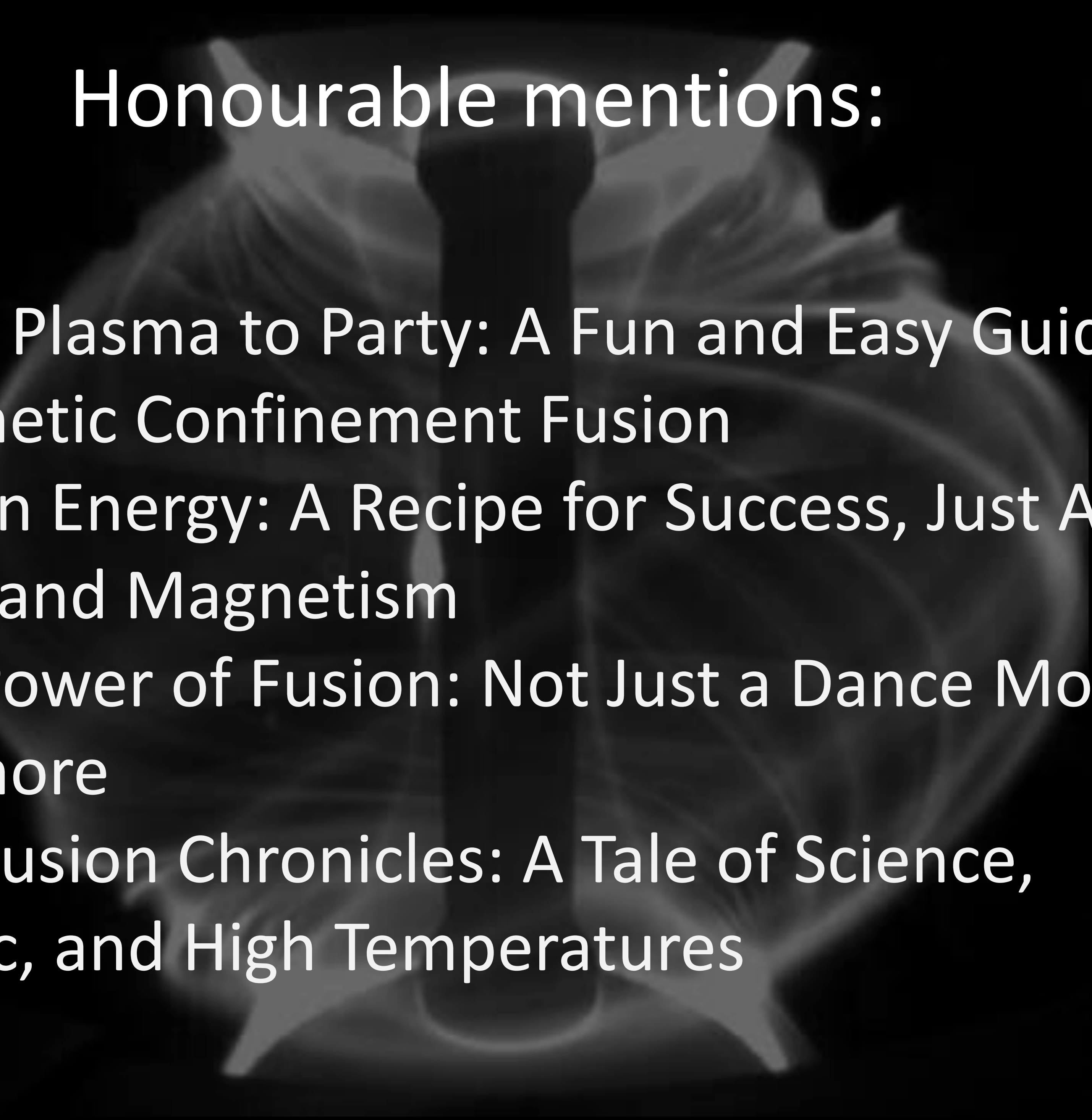
*Thanks to ChatGPT

# Honourable mentions:



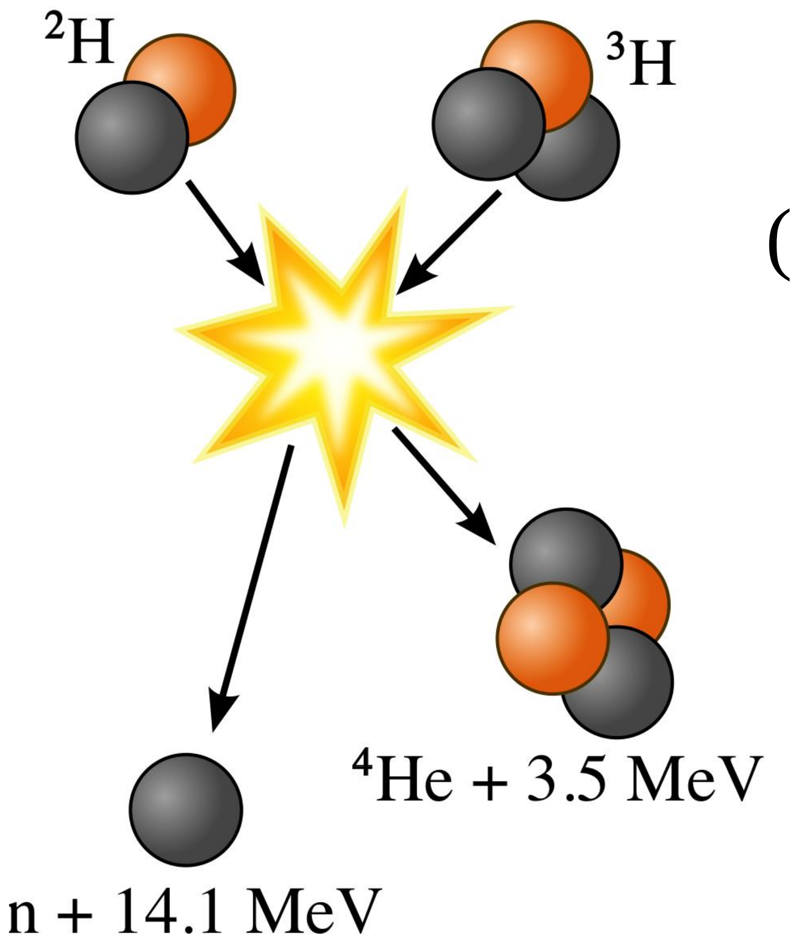
- From Plasma to Party: A Fun and Easy Guide to Magnetic Confinement Fusion
- Fusion Energy: A Recipe for Success, Just Add Heat and Magnetism
- The Power of Fusion: Not Just a Dance Move Anymore
- The Fusion Chronicles: A Tale of Science, Magic, and High Temperatures

# Most energy on Earth comes from fusion

Credit: Diyana Dimitrova/shutterstock.com

Credit: Chris Lim, wikipedia

# The fusion reaction



https://en.wikipedia.org/wiki/Nuclear_fusion

$$E = mc^2$$

$$(m_D + m_T)c^2 = (m_a + m_n)c^2 + 17.6 MeV$$

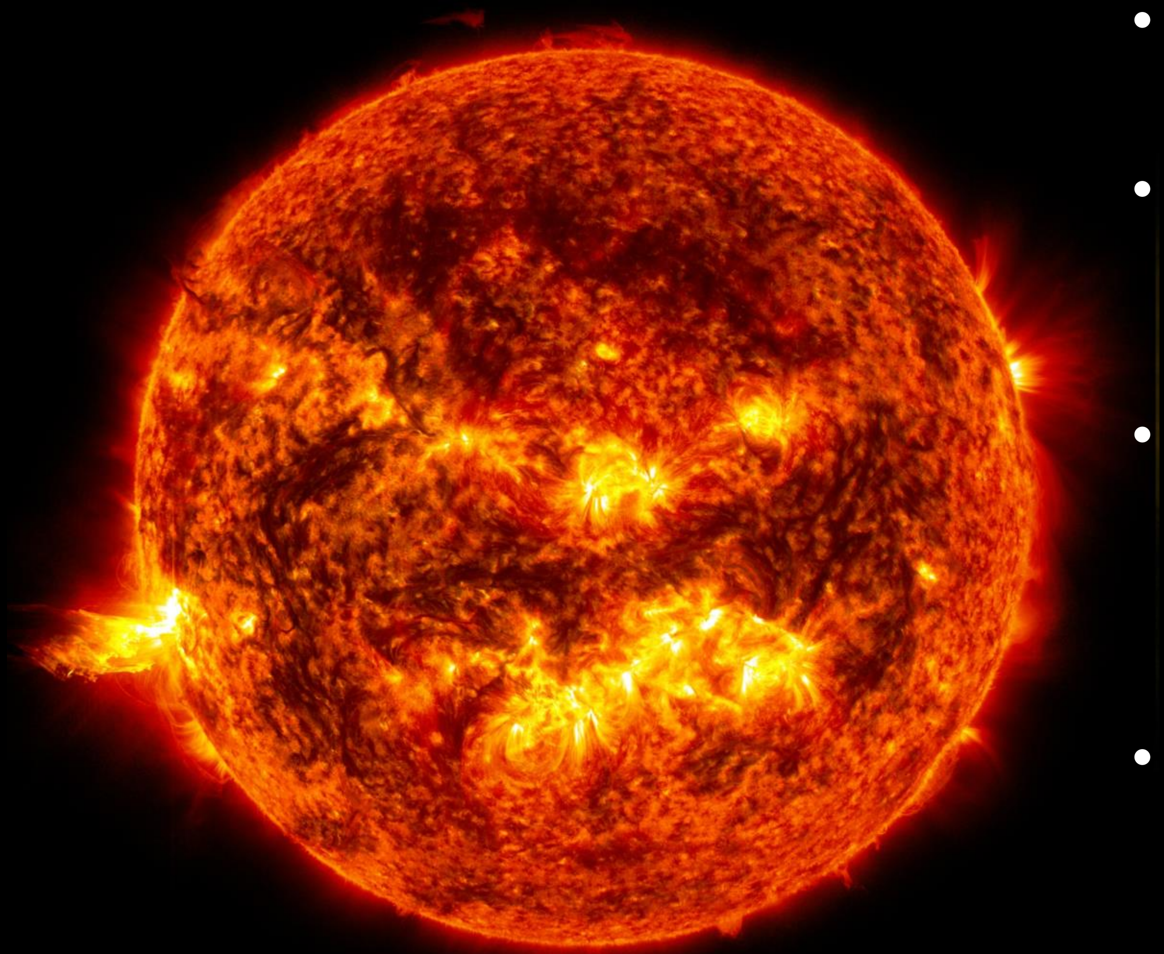
$10^7$ times energy released
by gas combustion!

Caveat: must breed Tritium

$$n + {}^6_3Li \rightarrow T + a + 4.784 MeV$$

Limited by Lithium supply ~20k yrs

# Controlled thermonuclear fusion



- **Must overcome Coulomb barrier to fuse nuclei**
- **Thermonuclear fusion imparts necessary energy via thermal energy**
- **Need about 100 Million degrees Celsius to get significant fusion reaction rate (hotter than Sun)**
- **Must find way to initially heat hydrogenic nuclei and must insulate long enough that fusion is self-sustaining**

# Magnetic confinement fusion

© Carol Sexton Art

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# 1 gram H at 100M° for 1 second

Power out = $\boldsymbol{\frac{nT}{\tau_E}}$ = fusion power in = $\boldsymbol{S_{fusion}(n,T)}$

$$\mathcal{S}_{\mathrm{fusion}} = n^2 \left\langle \sigma v \right\rangle E_{\mathrm{fusion}}$$

Fusion cross section peaks at T ~ 100M degrees

Macroscopic stability → $n \sim 10^{20}/\mathrm{m}^3$

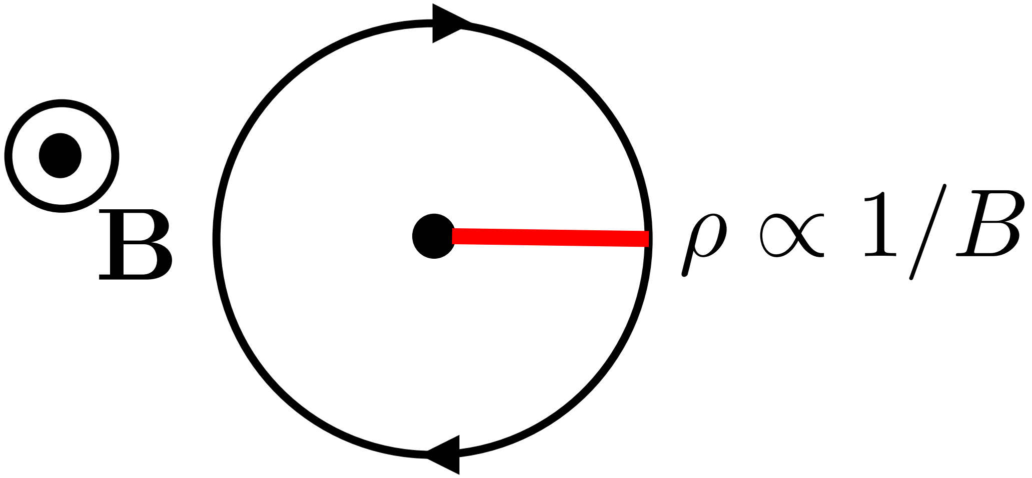
Microscopic stability → $V \sim 1\, m^3$

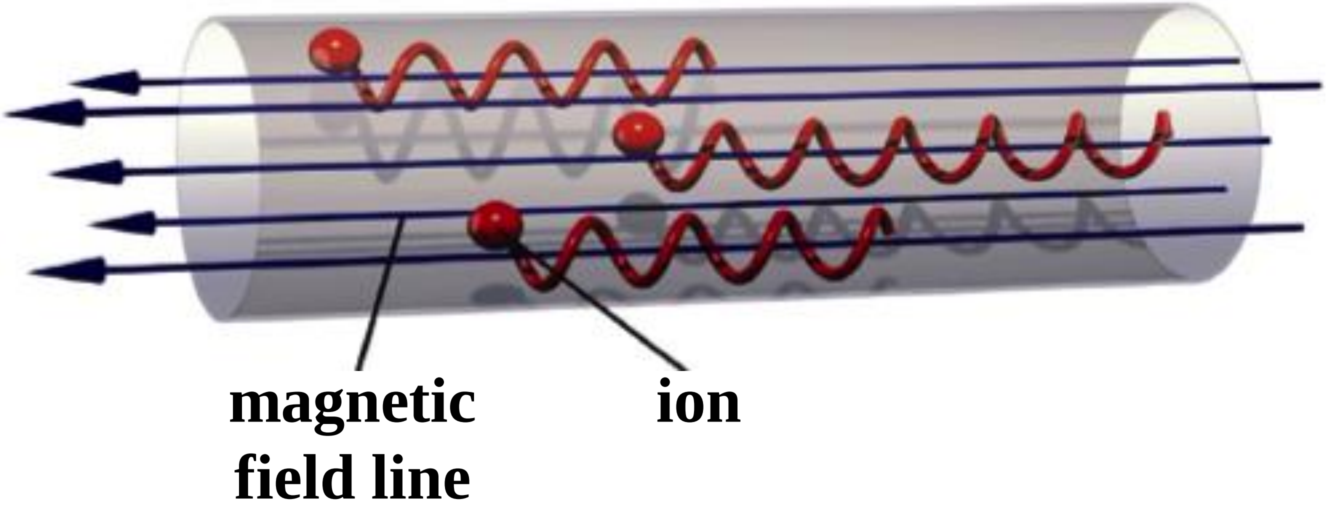
Solve for required confinement time → $\tau_E \sim 1s$

# How to heat the plasma hotter than the sun

# Basic concept of magnetic confinement

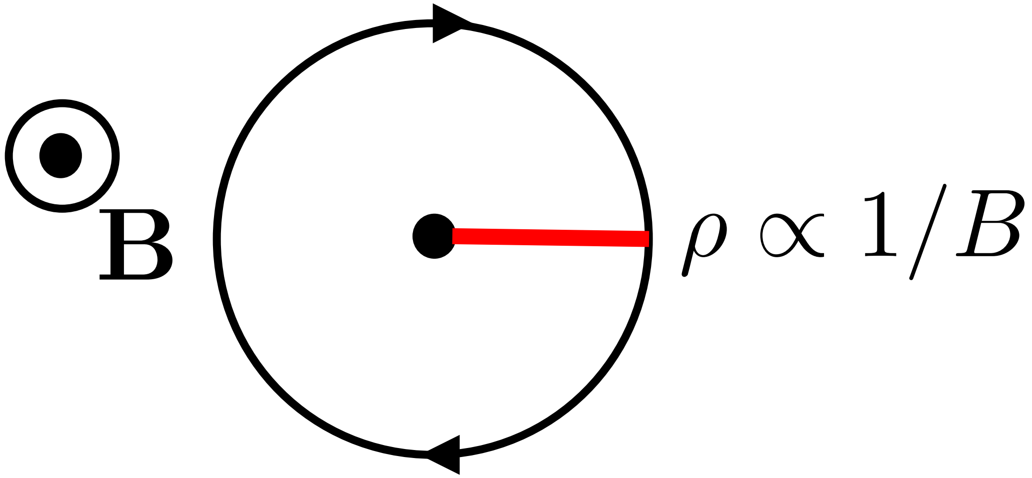
$$\mathbf{F} = \frac{e}{c}\mathbf{v} \times \mathbf{B}$$

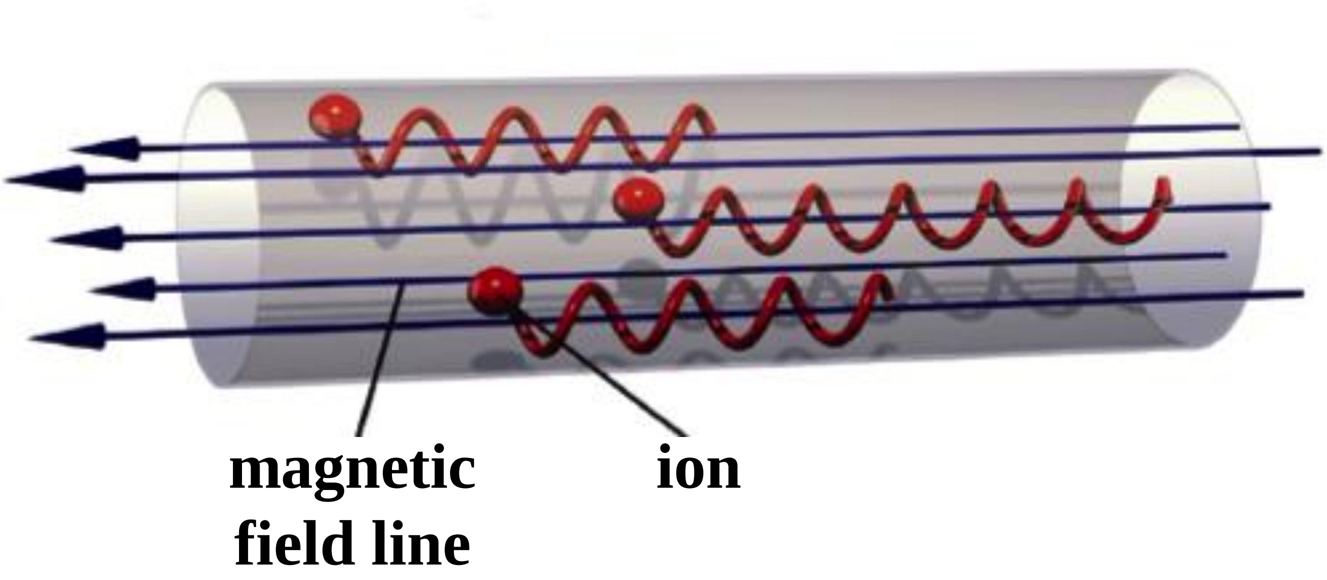




# Stronger field = better confinement

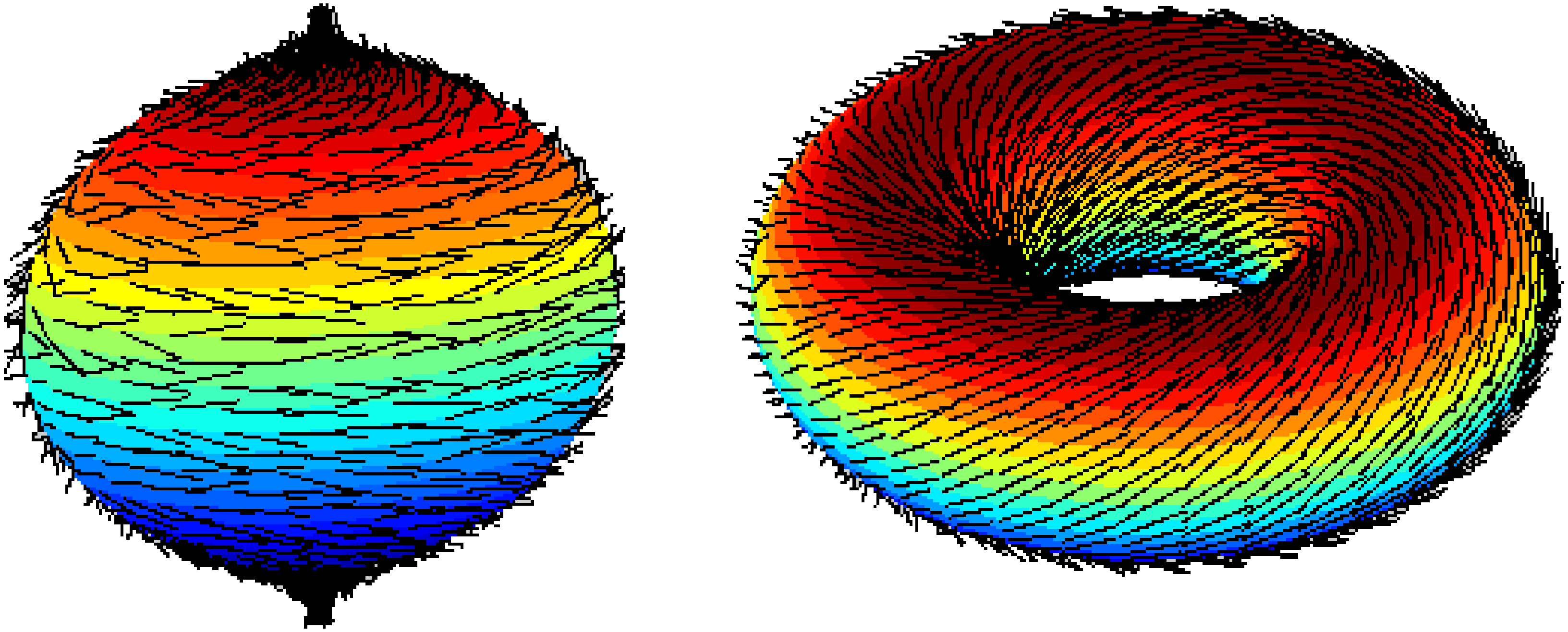
$$\mathbf{F} = \frac{e}{c}\mathbf{v} \times \mathbf{B}$$





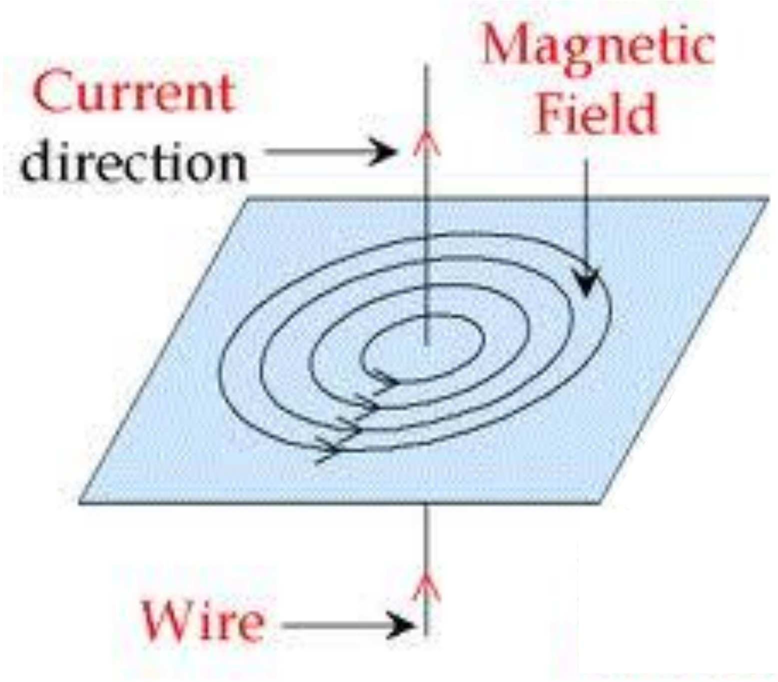
# Why magnetic fusion devices look like doughnuts

- ‘Hairy ball theorem’ → confined trajectories of vector field possible only for torii

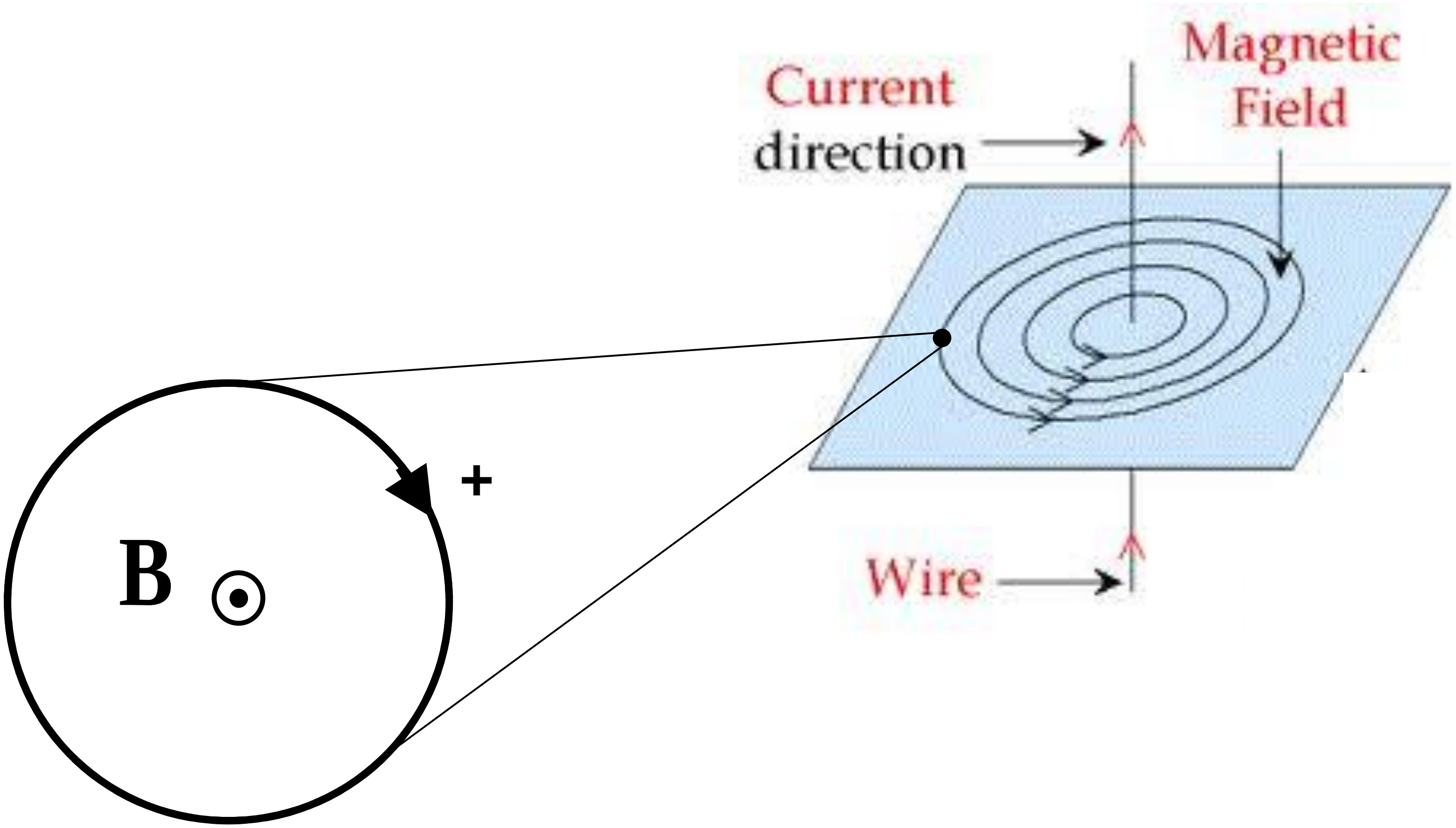


# Confined field line trajectory

- Simplest idea is circles:

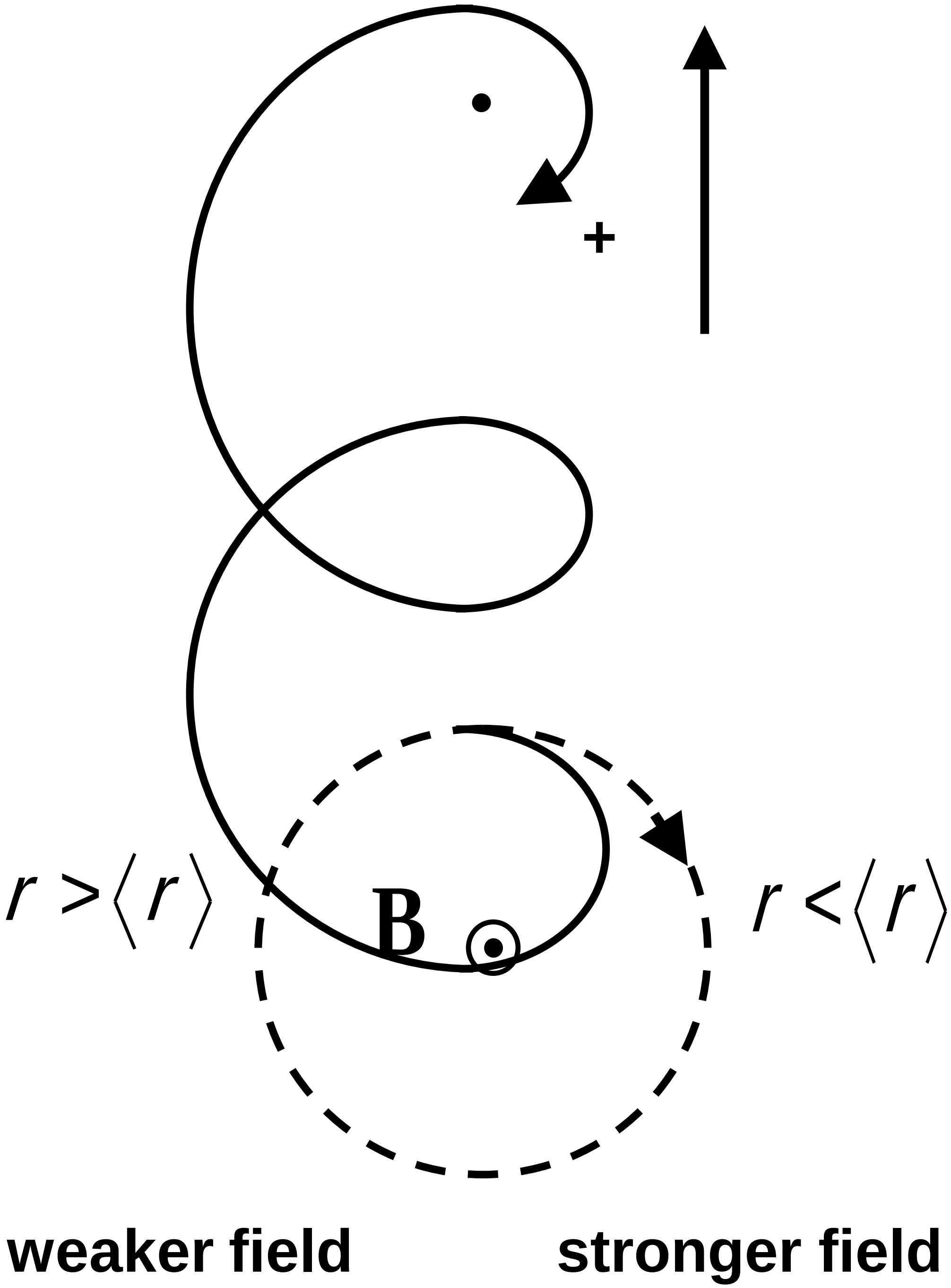


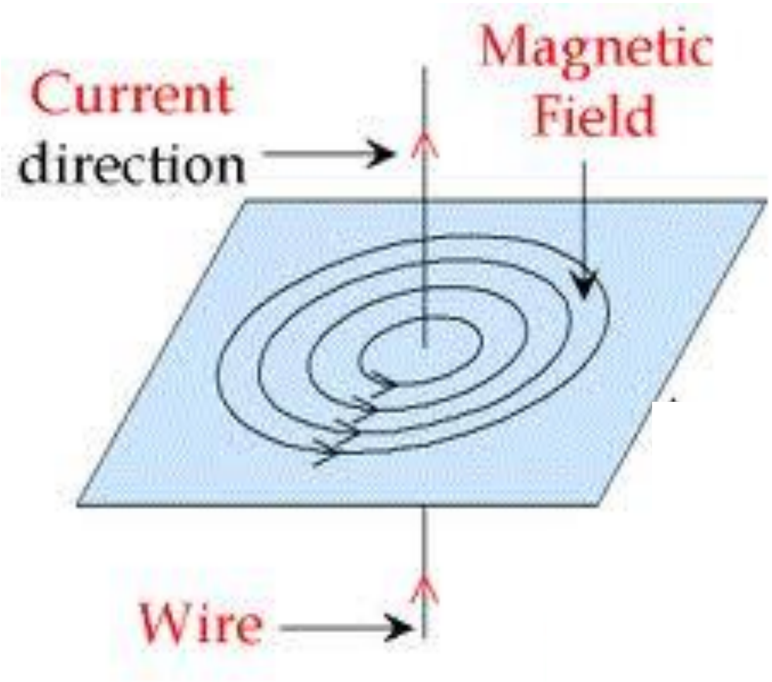
$$B = \frac{m_0 I}{2pR}$$



**weaker field** **stronger field**

$$\rho \propto 1/B$$





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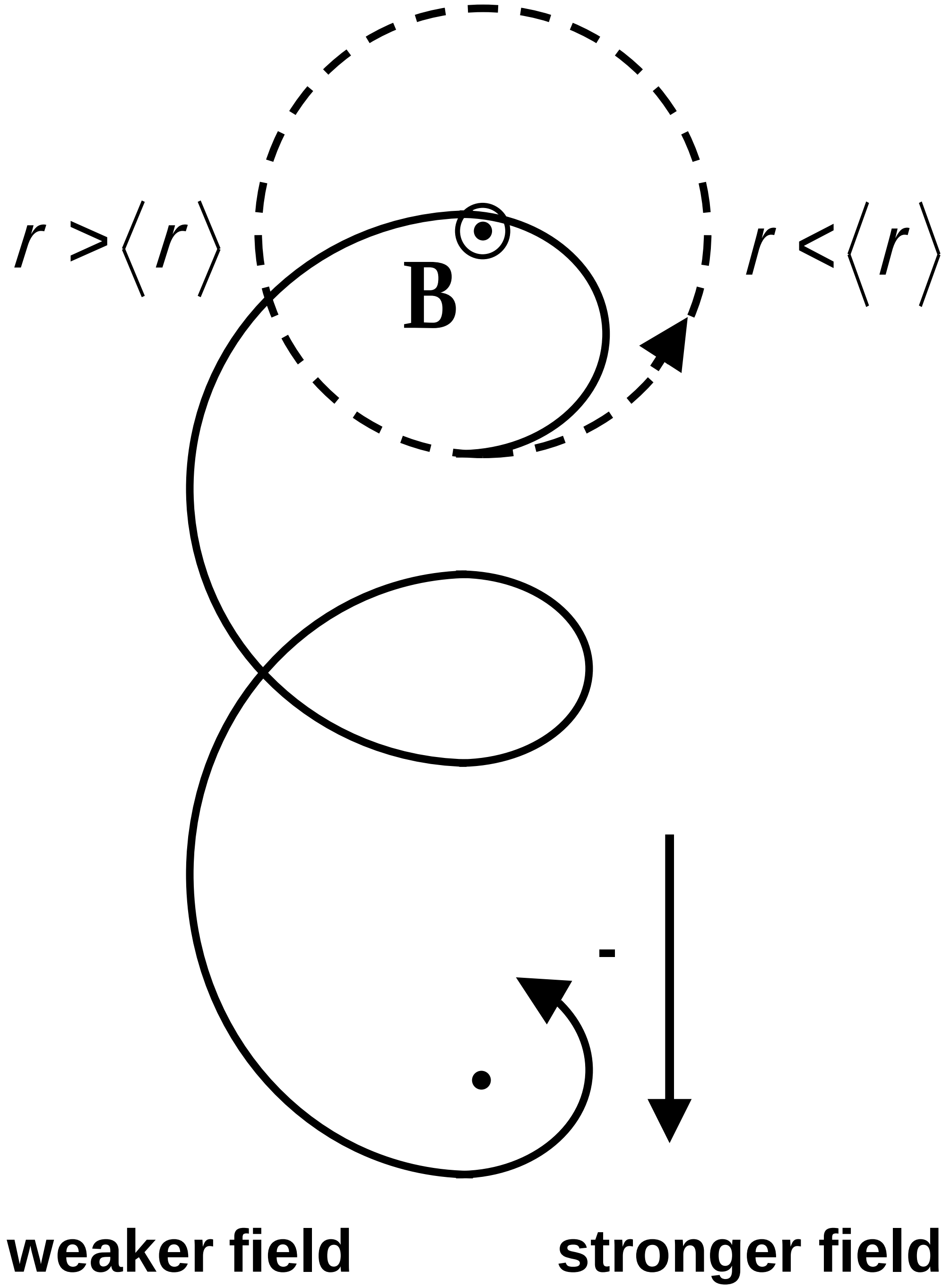
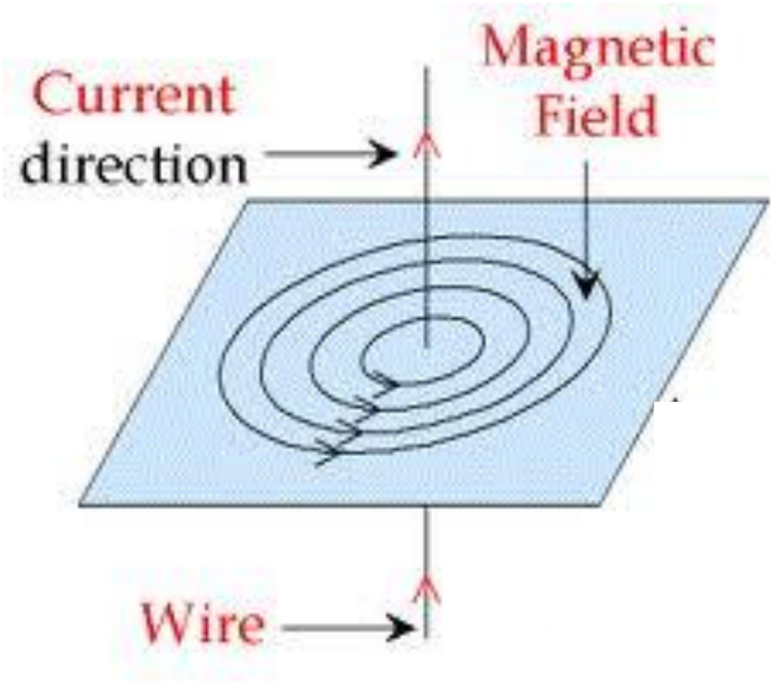
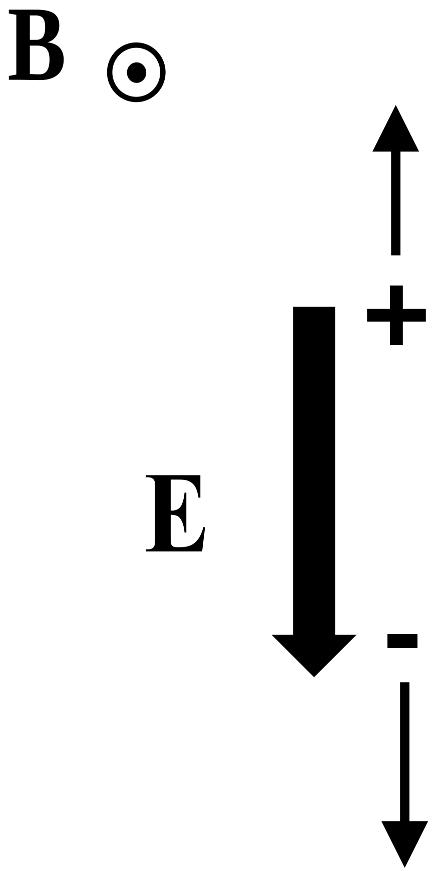
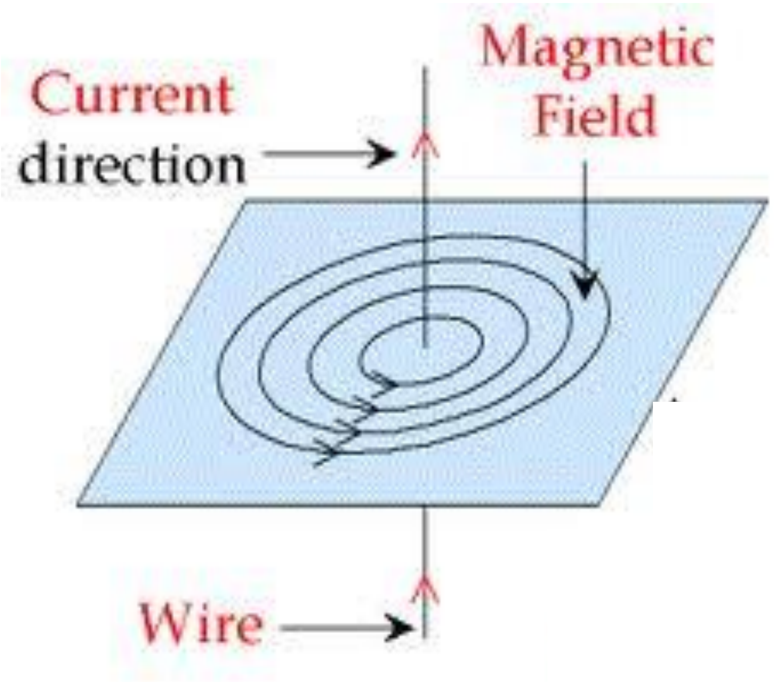




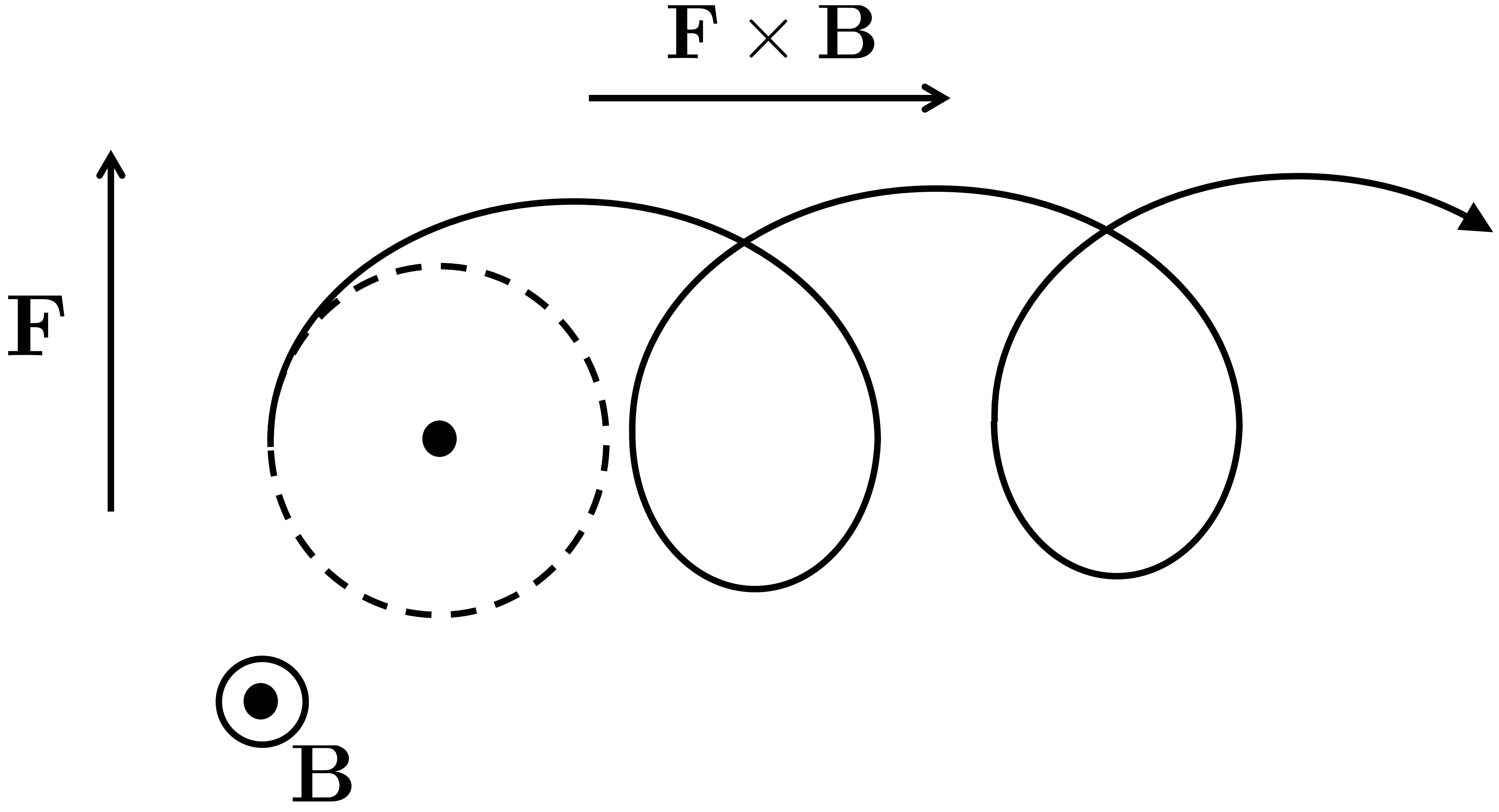
$$\rho \propto 1/B$$

# Charge separation gives electric field

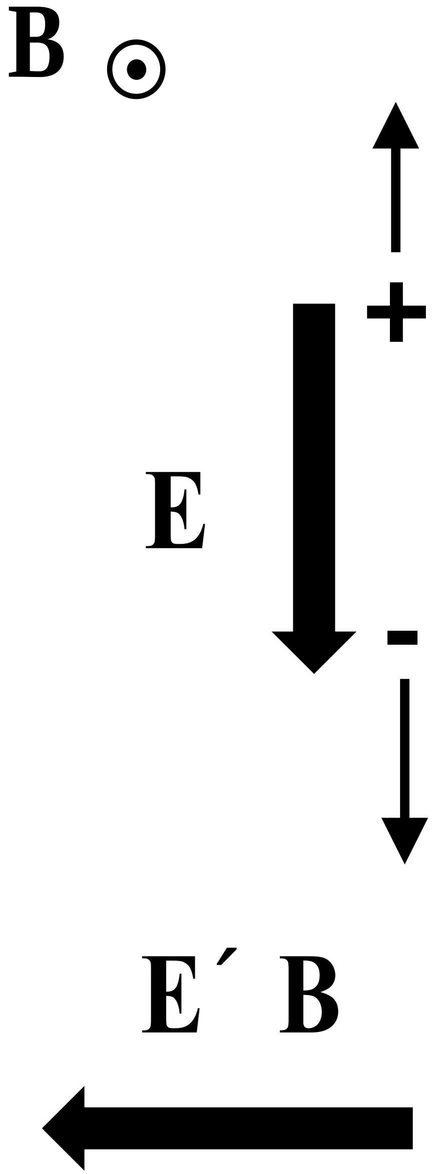


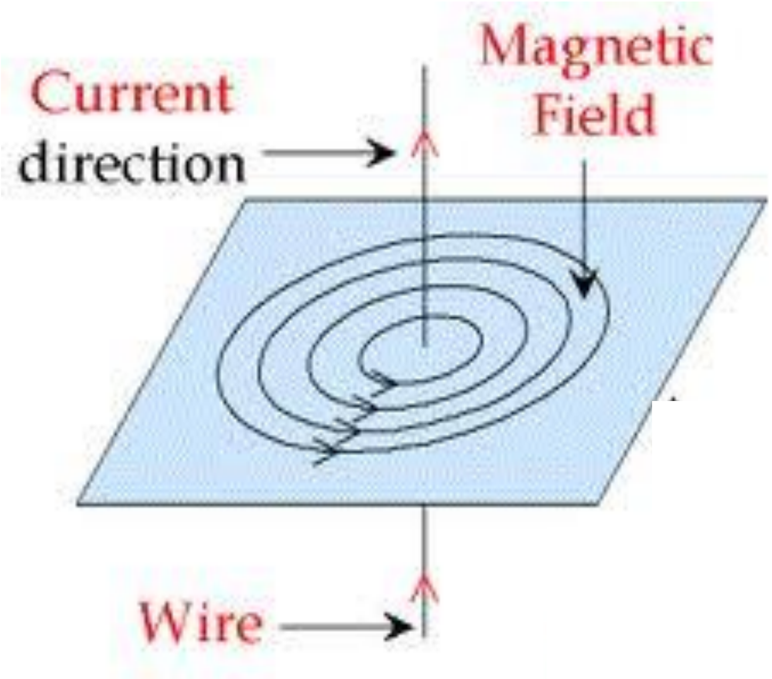


# Magnetised plasma is different

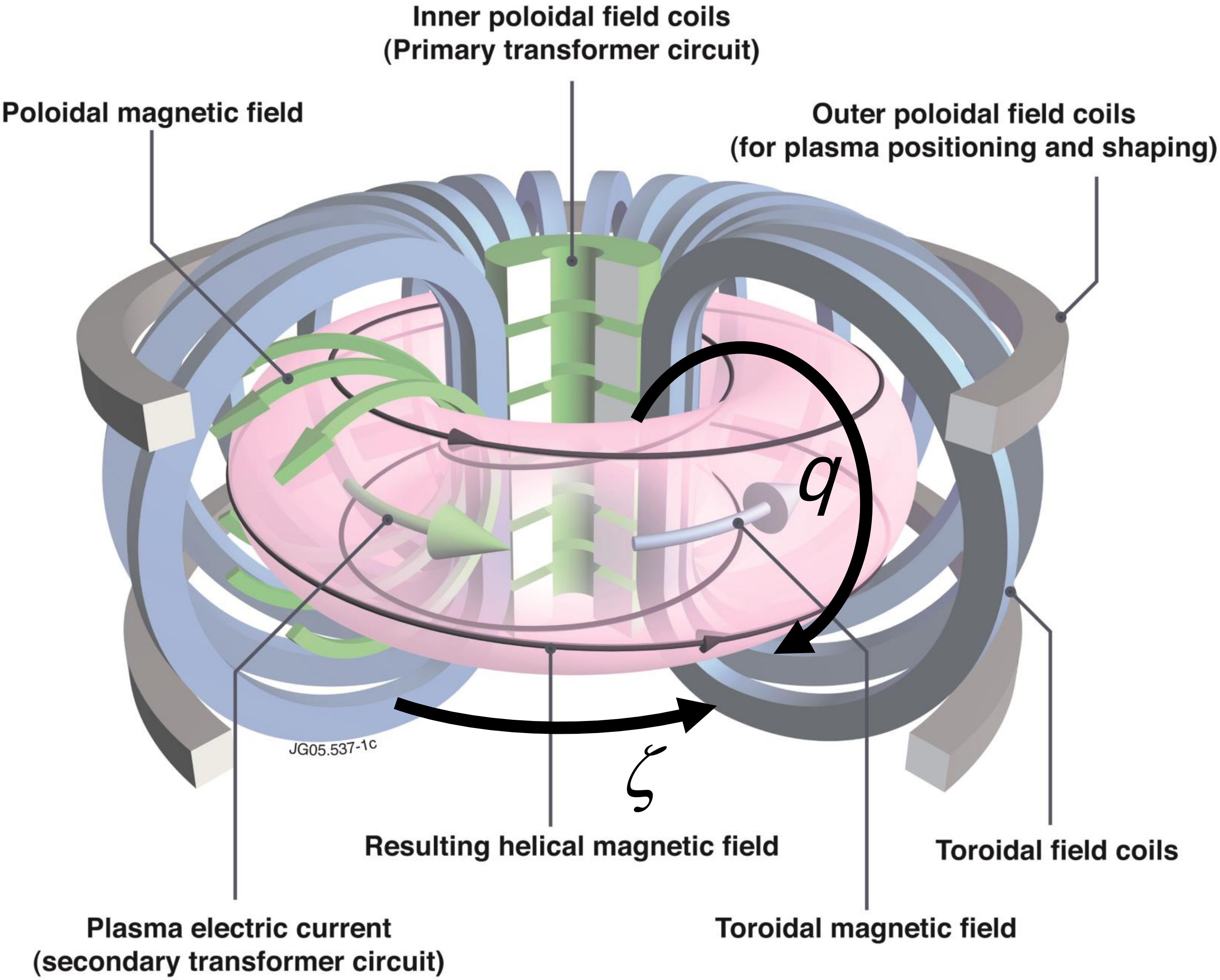


# The simplest doughnut does not work





# The solution? Add a twist



Inner poloidal field coils
(Primary transformer circuit)

Poloidal magnetic field

Outer poloidal field coils
(for plasma positioning and shaping)

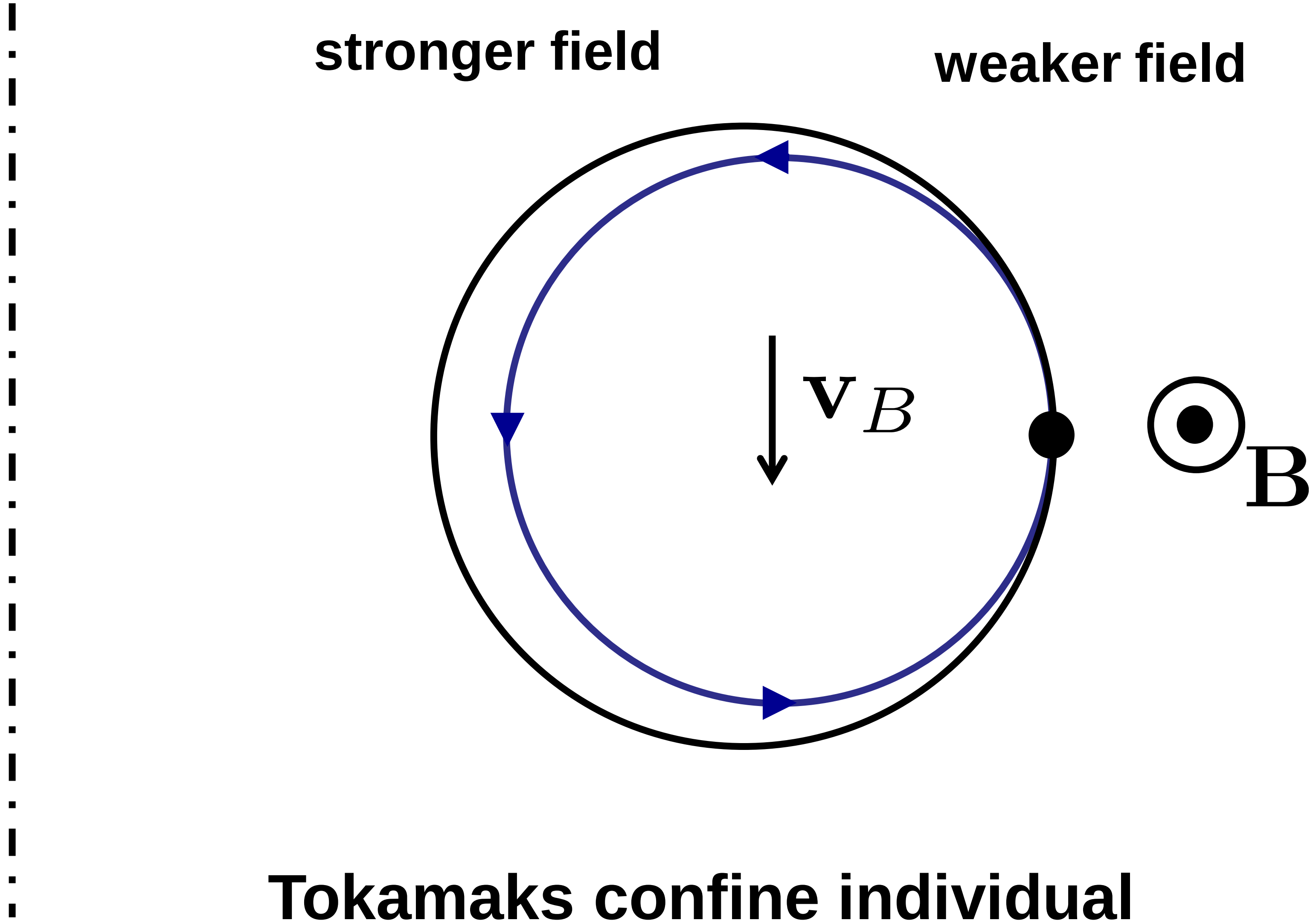
Resulting helical magnetic field

Toroidal field coils

Plasma electric current
(secondary transformer circuit)

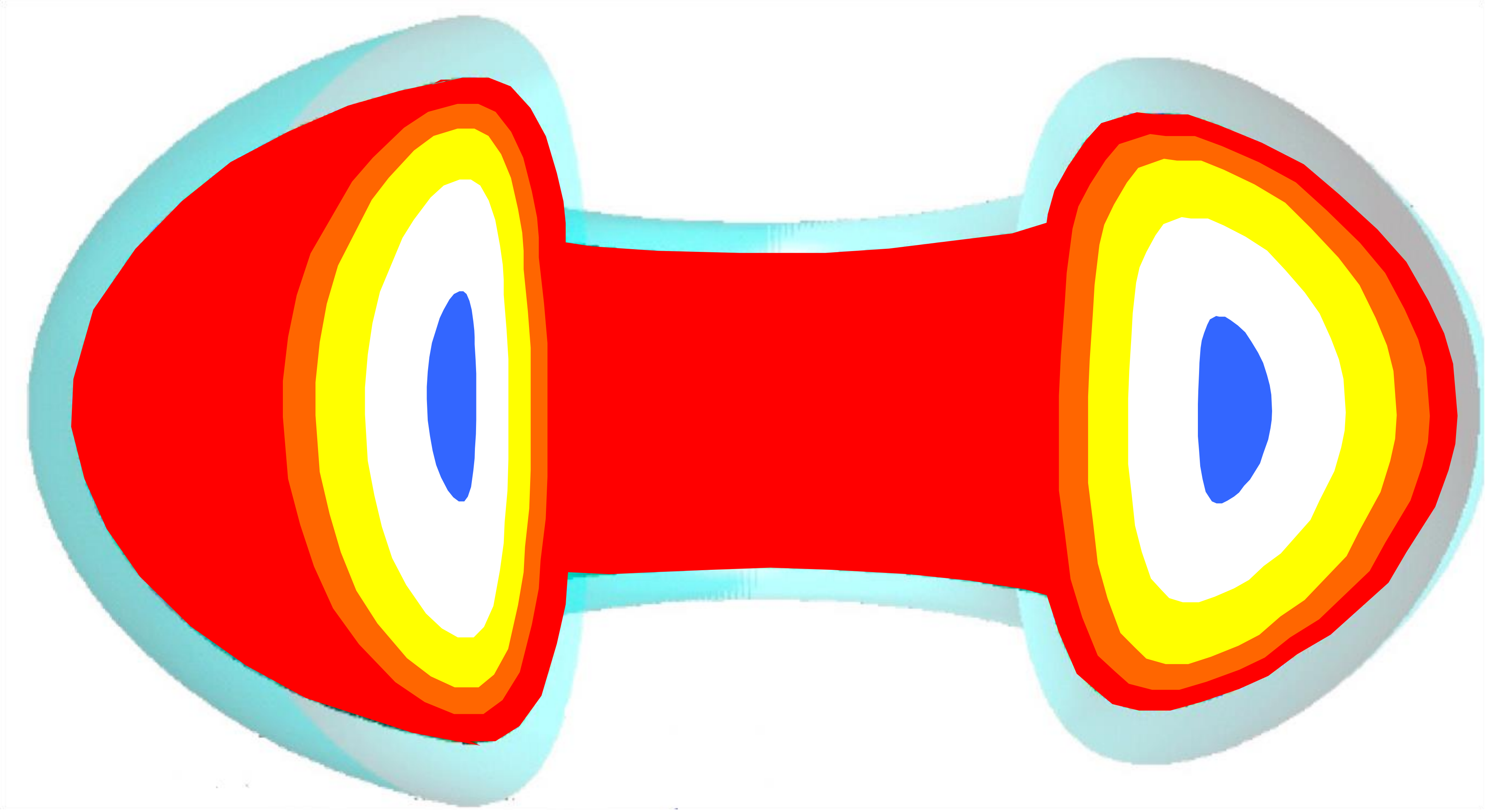
Toroidal magnetic field

# Magnetic drifts close, so no net drift



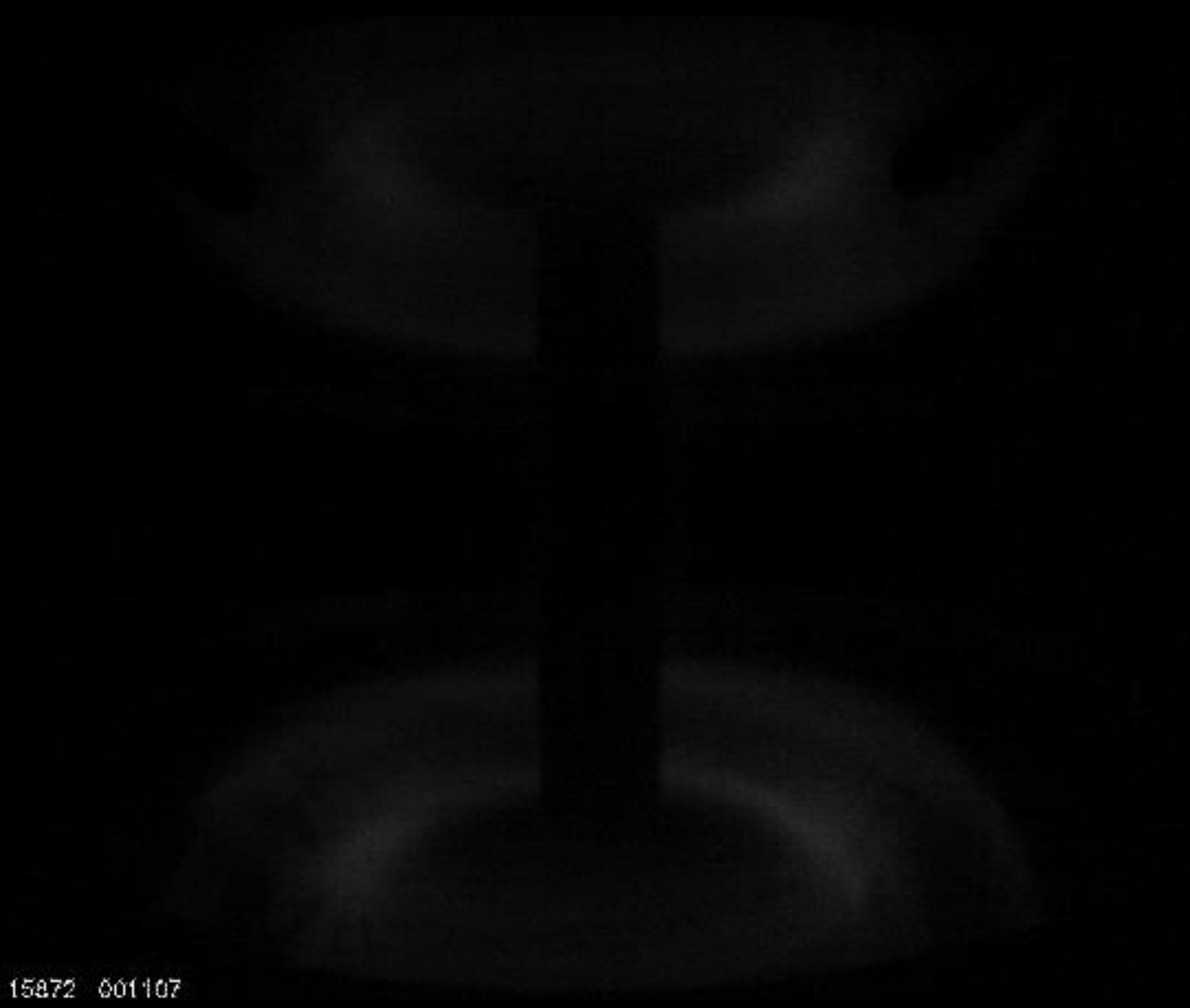
**Tokamaks confine individual charged particles!**

# Magnetic confinement on toroidal surfaces



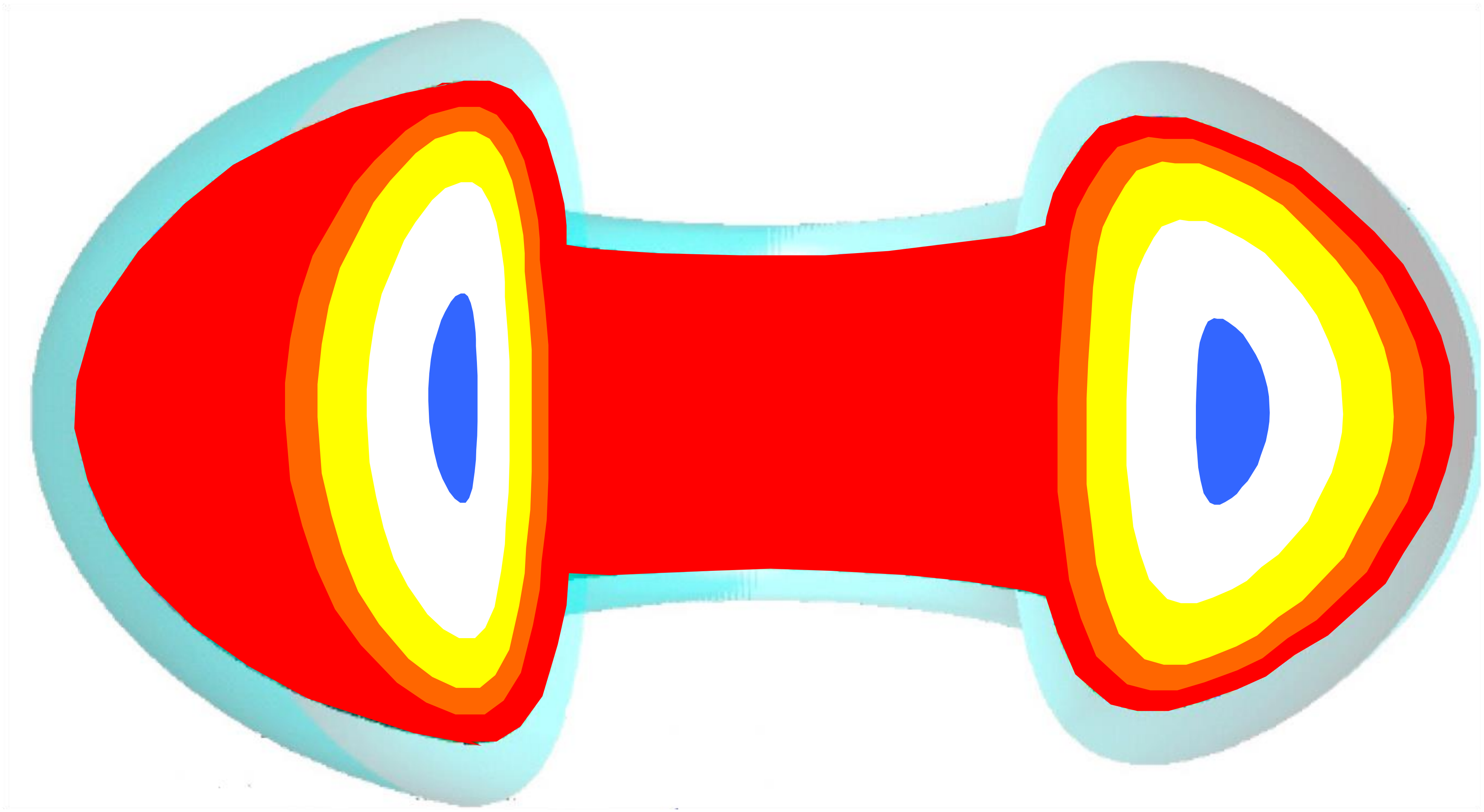
**Nested contours of constant pressure/density/temperature**

# Challenges and opportunities ahead



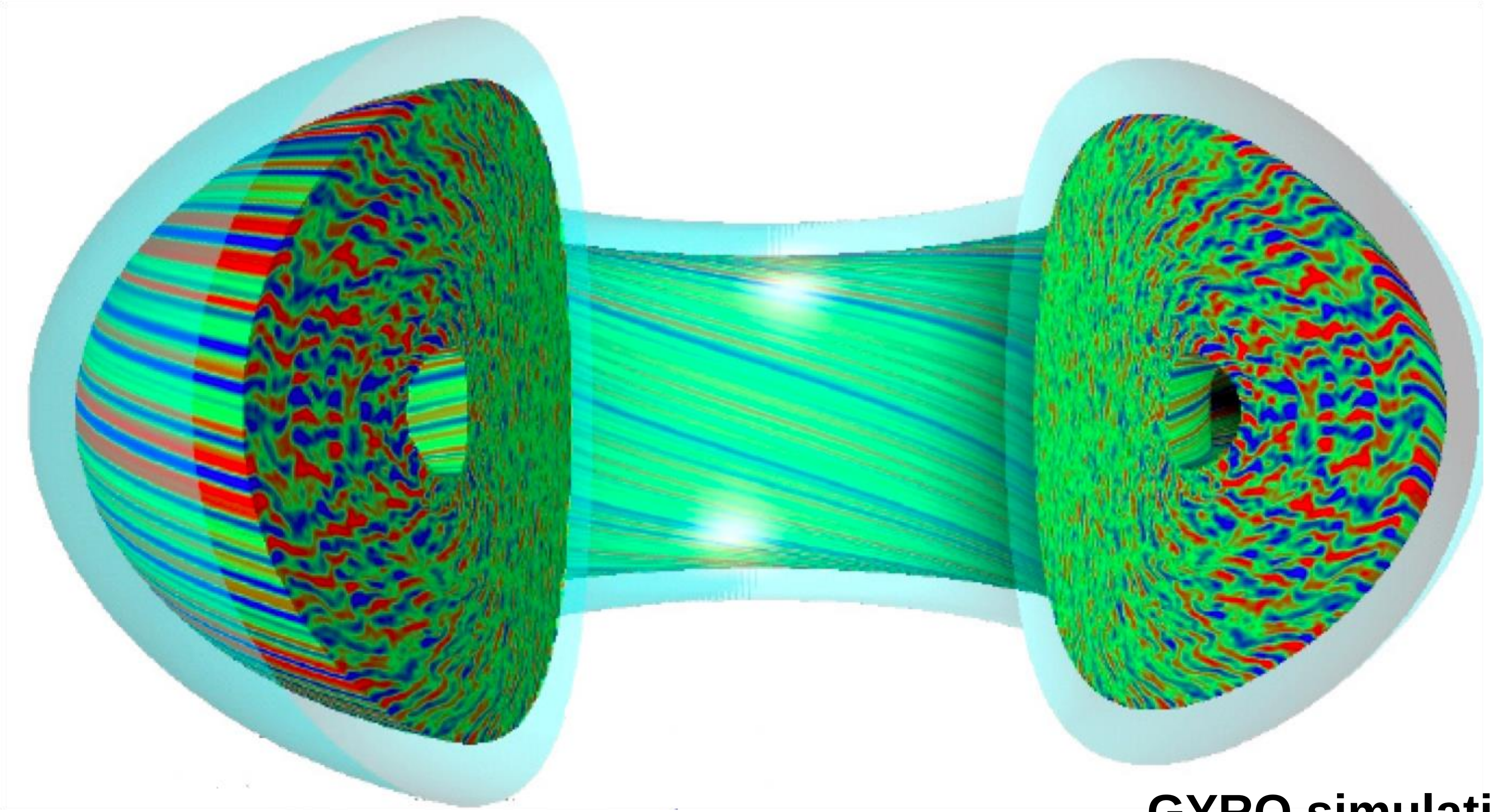
Fast camera image of MAST plasma

# Magnetic confinement on toroidal surfaces



**Nested contours of constant pressure/density/temperature**

# Magnetic confinement on toroidal surfaces…almost



**GYRO simulation**

**Turbulent density fluctuations**

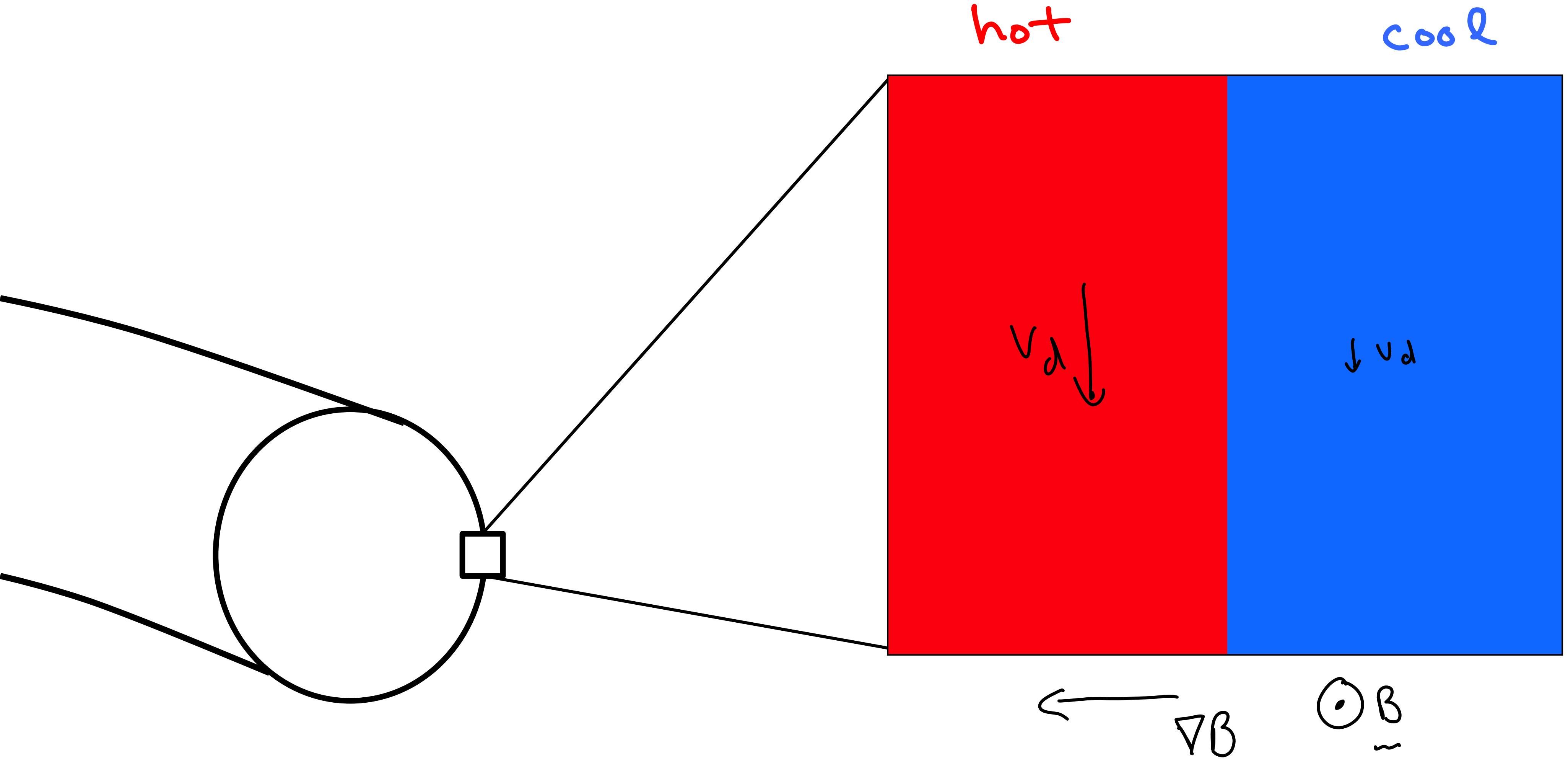
# Words of encouragement

Sir Horace Lamb
(1904)

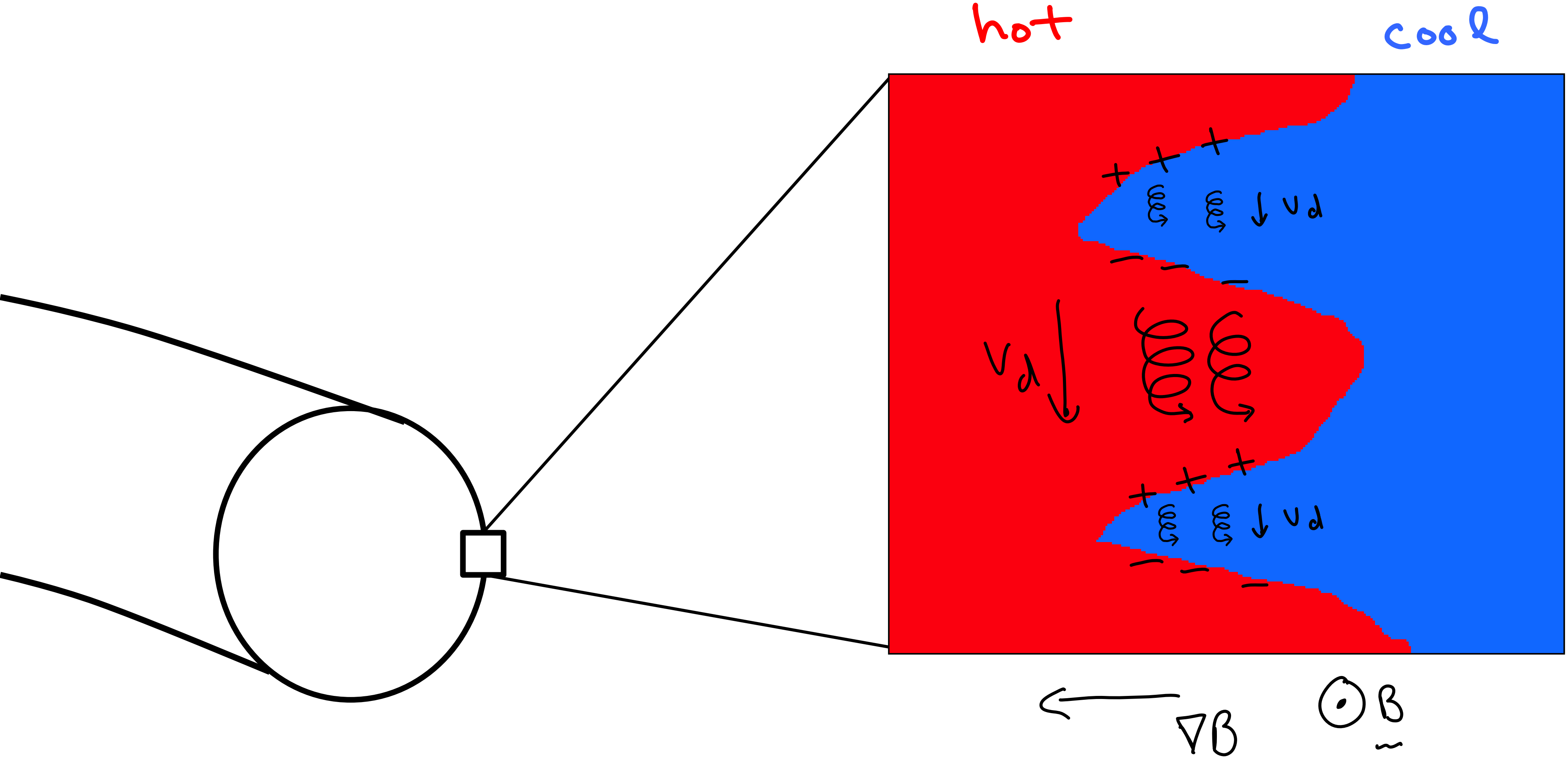
“When I meet God, I am going to ask him two questions: Why relativity? And why turbulence? I really believe he will have an answer for the first.”

Werner Heisenberg (1933),
German Federal Archives

# What drives the turbulence?

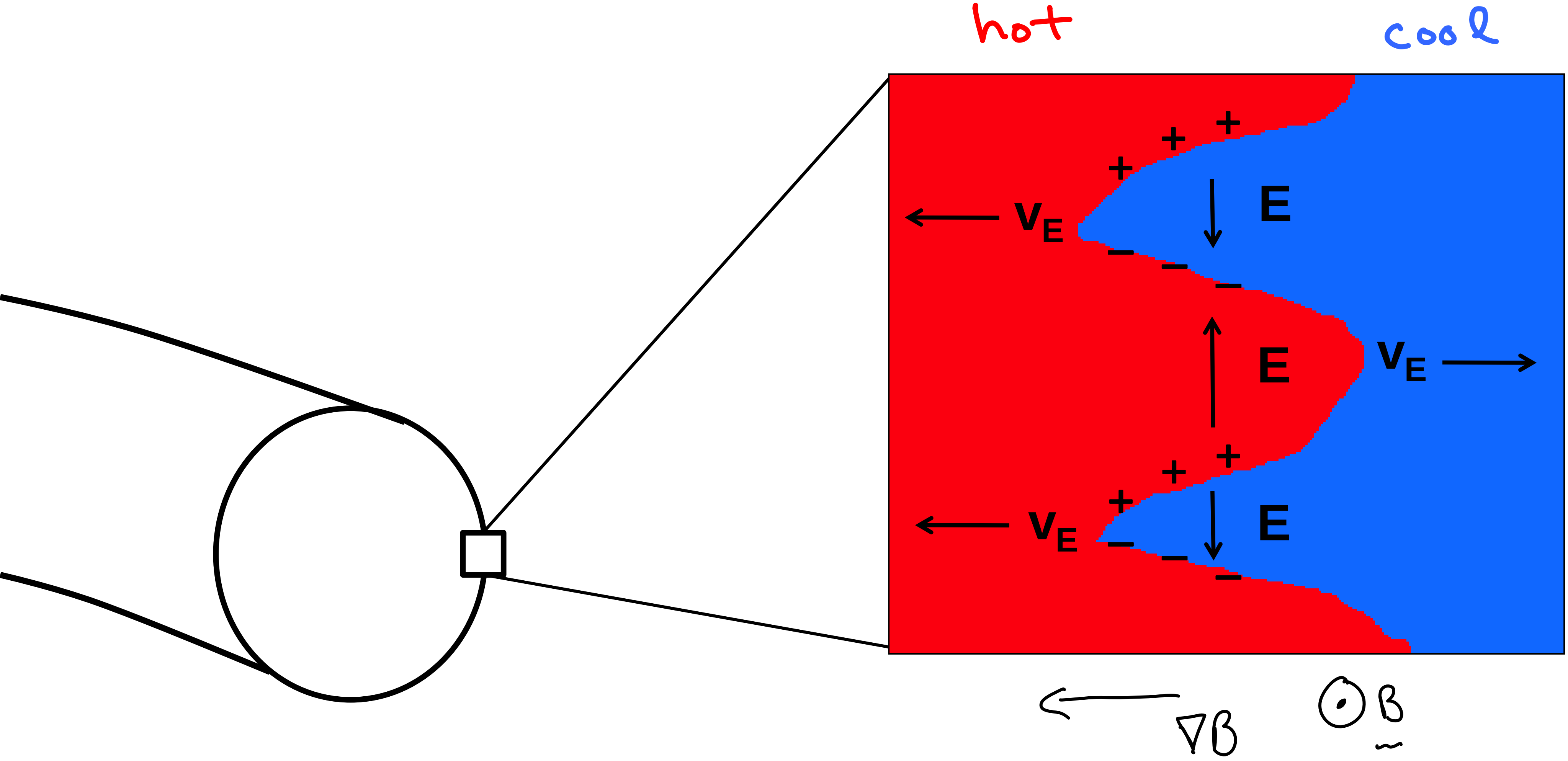


# What drives the turbulence?



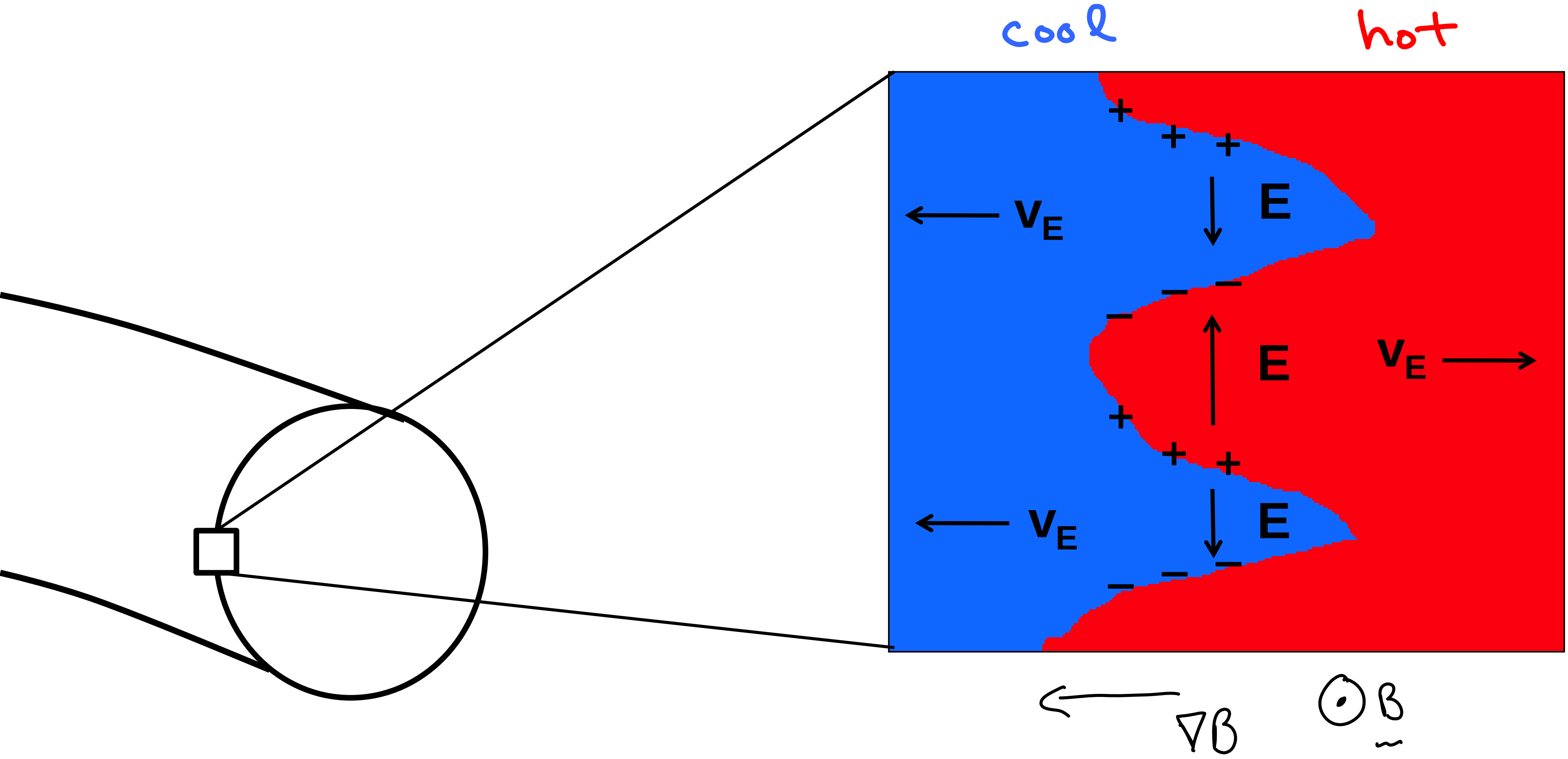
# What drives the turbulence?

$$\mathbf{v_E} = \frac{c}{B^2}\mathbf{E} \times \mathbf{B}$$

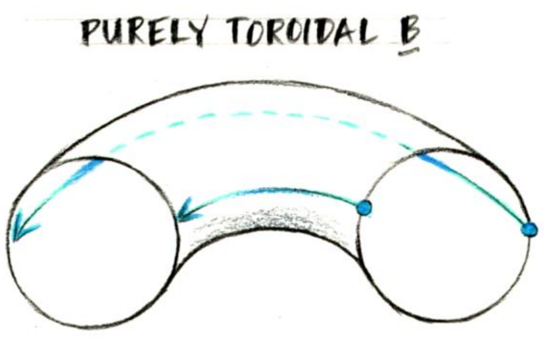


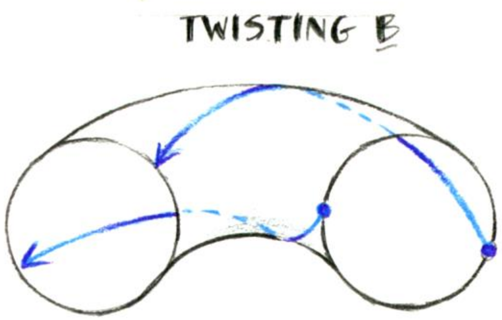
# No drive on inside

$$\mathbf{v_E} = \frac{c}{B^2}\mathbf{E} \times \mathbf{B}$$



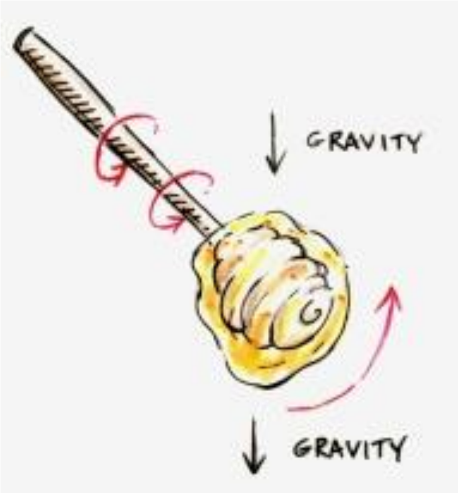
# Competition gives critical gradient





**Unstable**

**Stable**

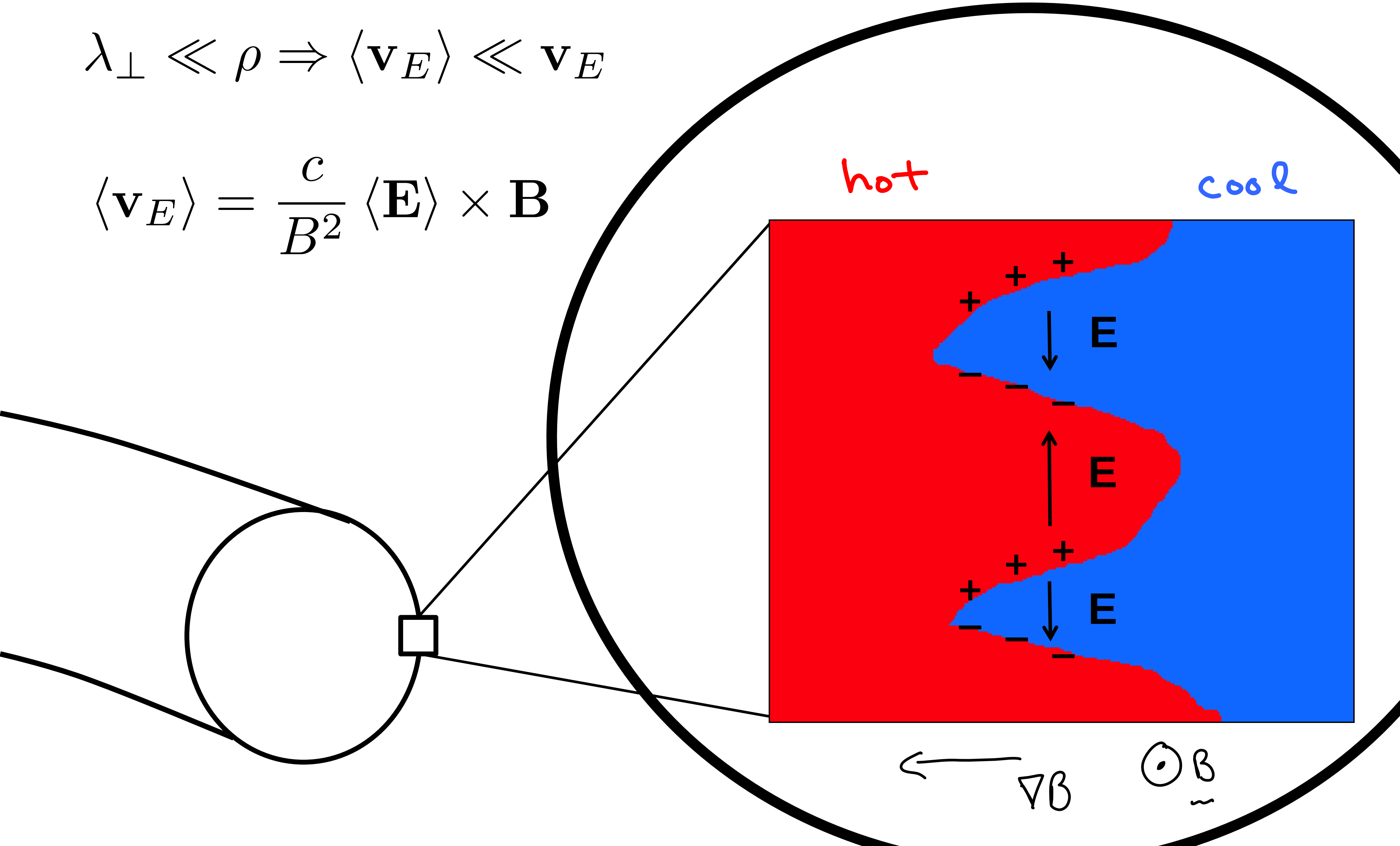


**No turbulence below some critical temperature gradient**

# Eddy size is gyro-radius

$$\lambda_\perp \ll \rho \Rightarrow \langle \mathbf{v}_E \rangle \ll \mathbf{v}_E$$

$$\langle \mathbf{v}_E \rangle = \frac{c}{B^2} \langle \mathbf{E} \rangle \times \mathbf{B}$$

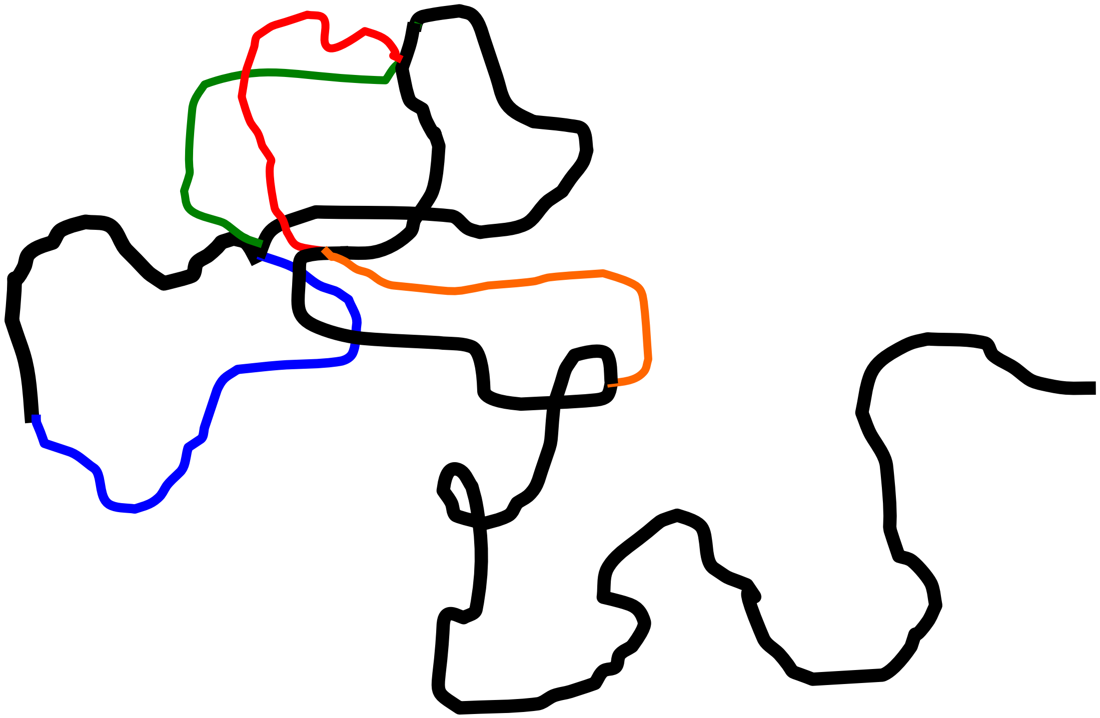


# DIII-D Shot 121717

## GYRO Simulation

## Cray X1E, 256 MSPs

# Turbulence and random walks

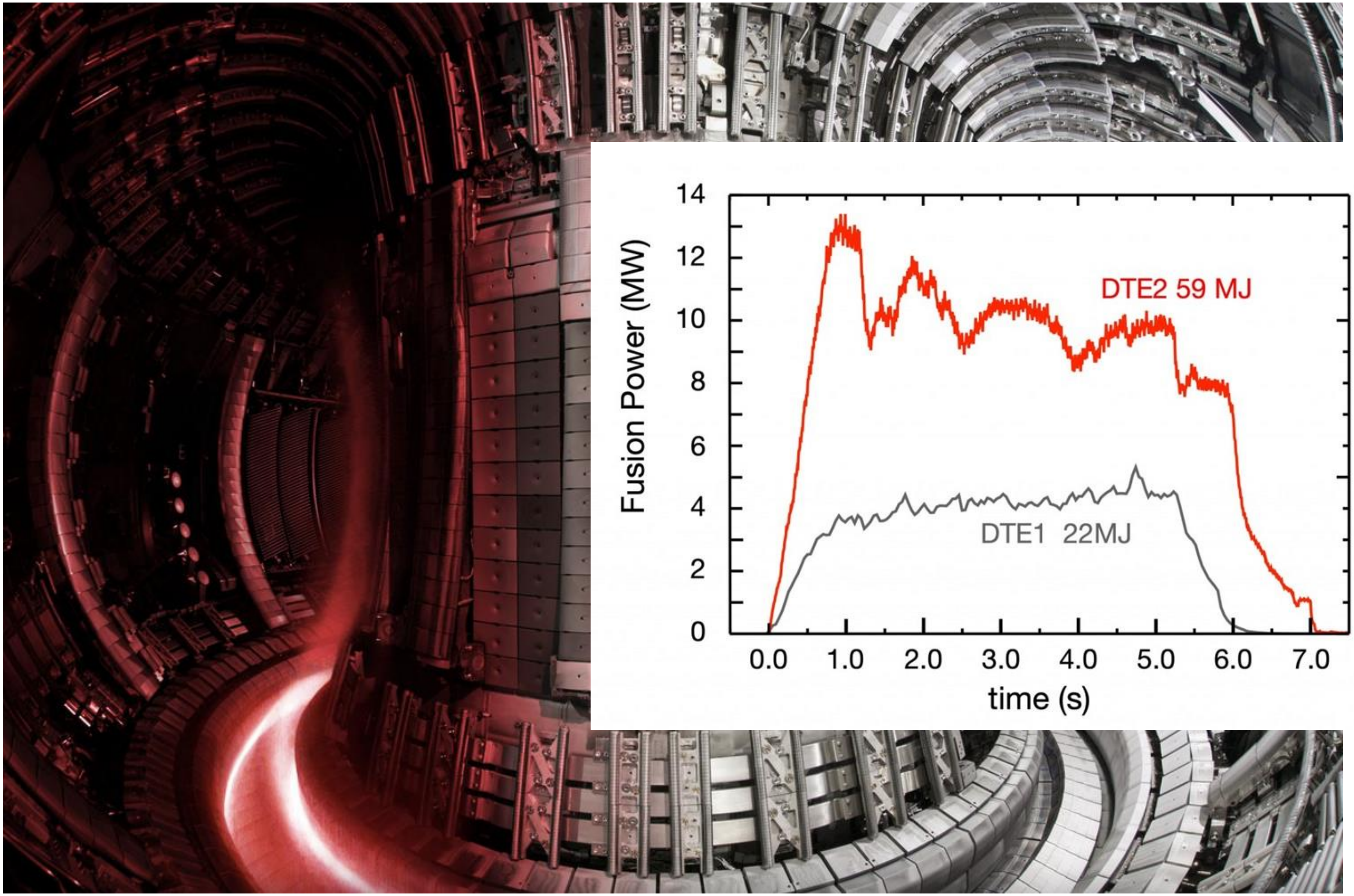


**Random walk: (time to move move distance L) =**
**(time per step) x (L/d) steps**

**L = system size, d = gyroradius, time per step = turbulence time**

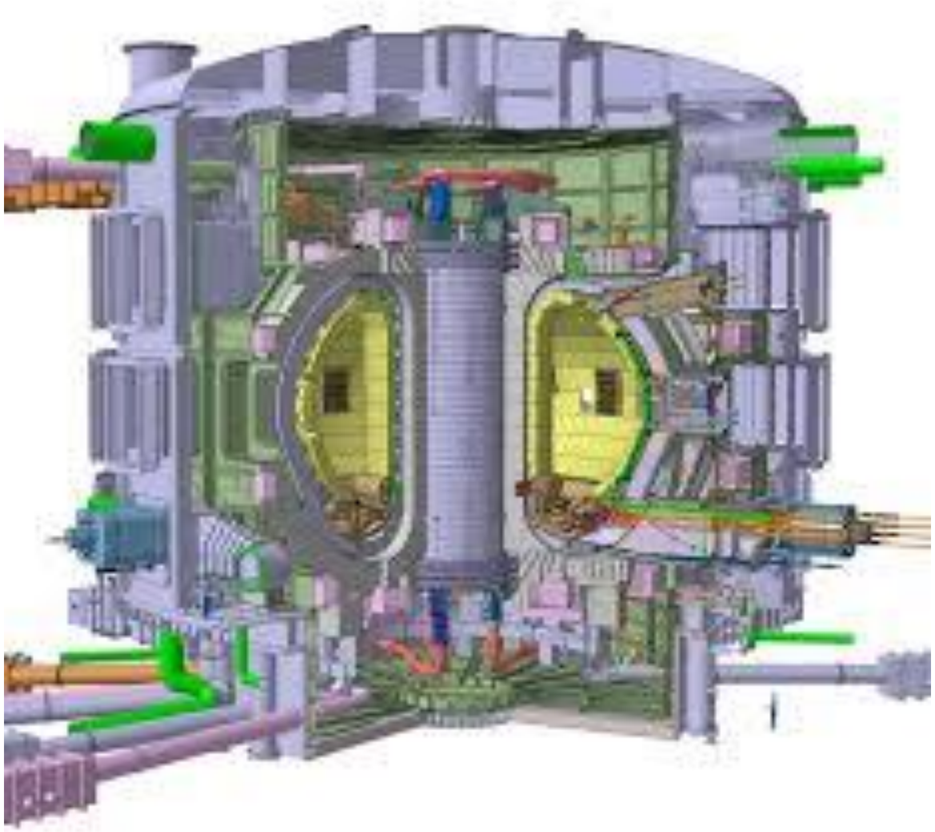
$$\longrightarrow \tau_E \sim 1\ \mathrm{s}$$

# We are close to the required confinement time, but not there yet



# Different reactor approaches

- Make the plasma volume bigger
  - Pros: Achieve fusion temperatures without exceeding critical gradient that drives instability
  - Cons: bigger = more expensive; high heat loads on walls



**ITER**

# ITER first plasma 2026

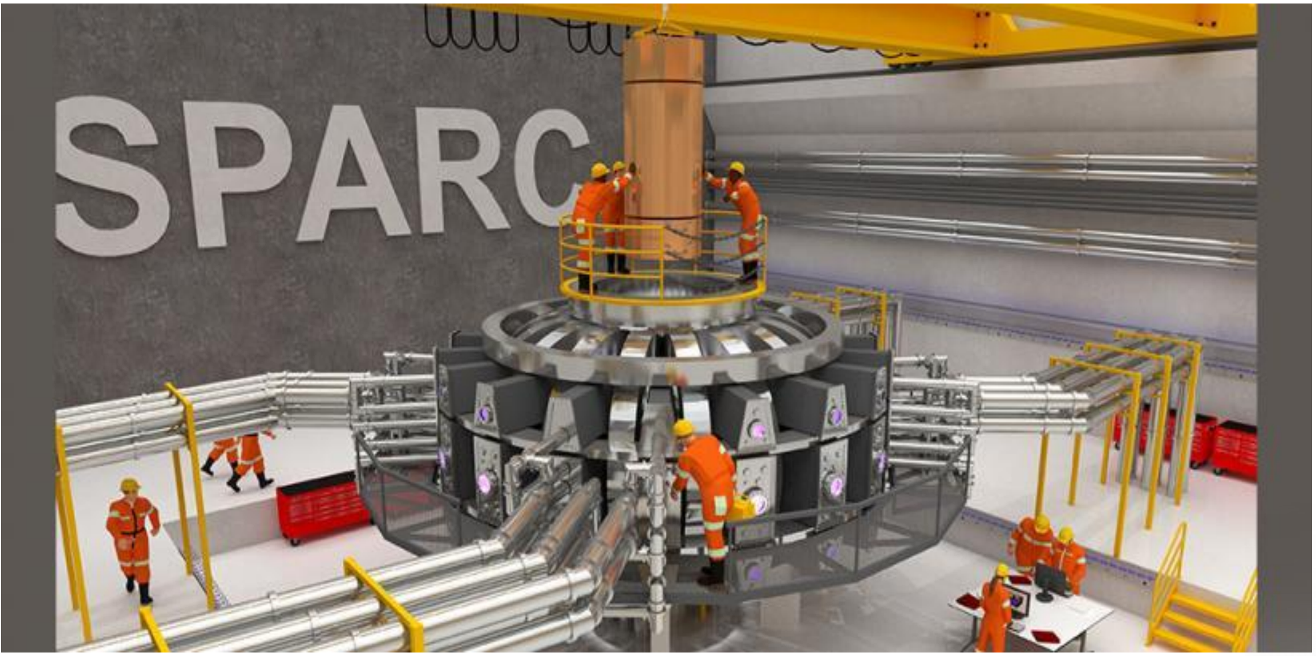
Largest scientific experiment ever built

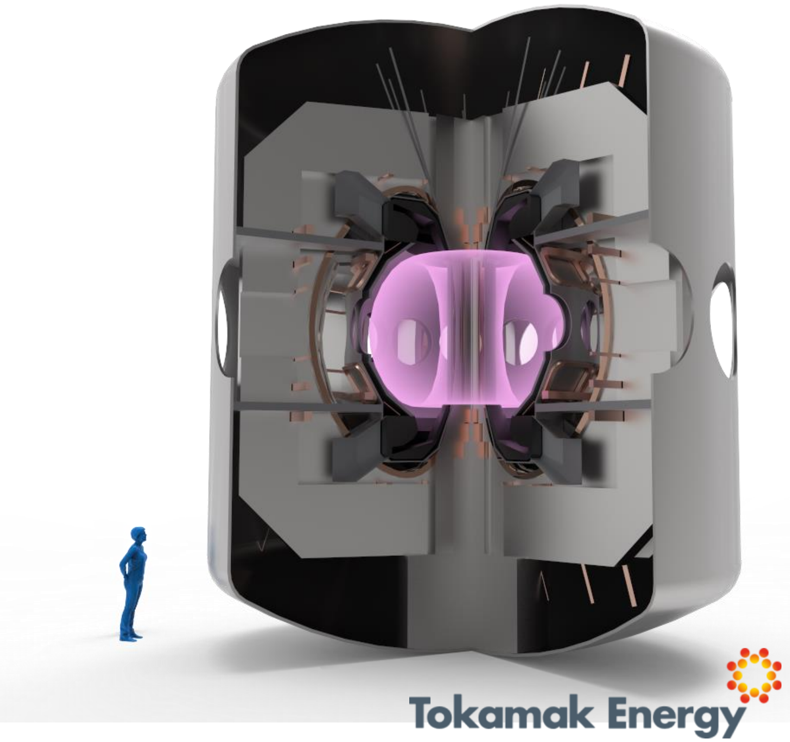
Construction towards 1st plasma is 73% complete

May 2021

# Different reactor approaches

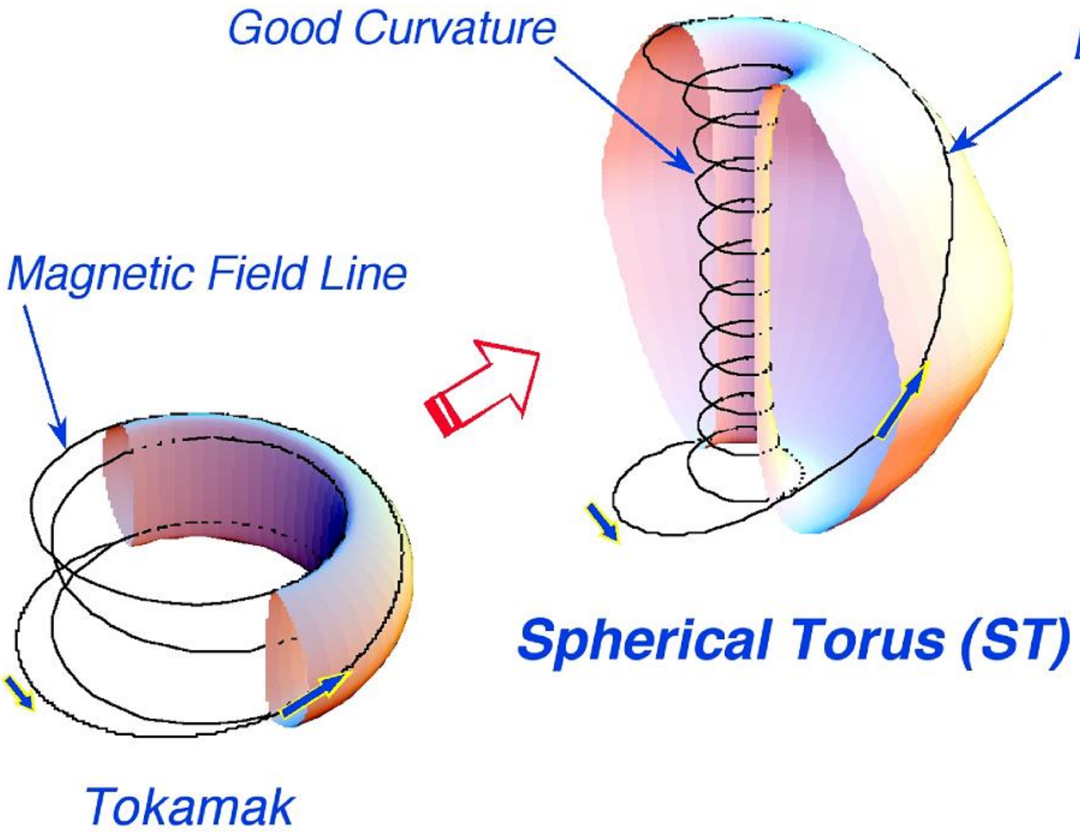
- Make the magnetic field stronger
  - Pro: increased confinement time (smaller eddies = smaller device = cheaper)
  - Con: technology in development; high stresses



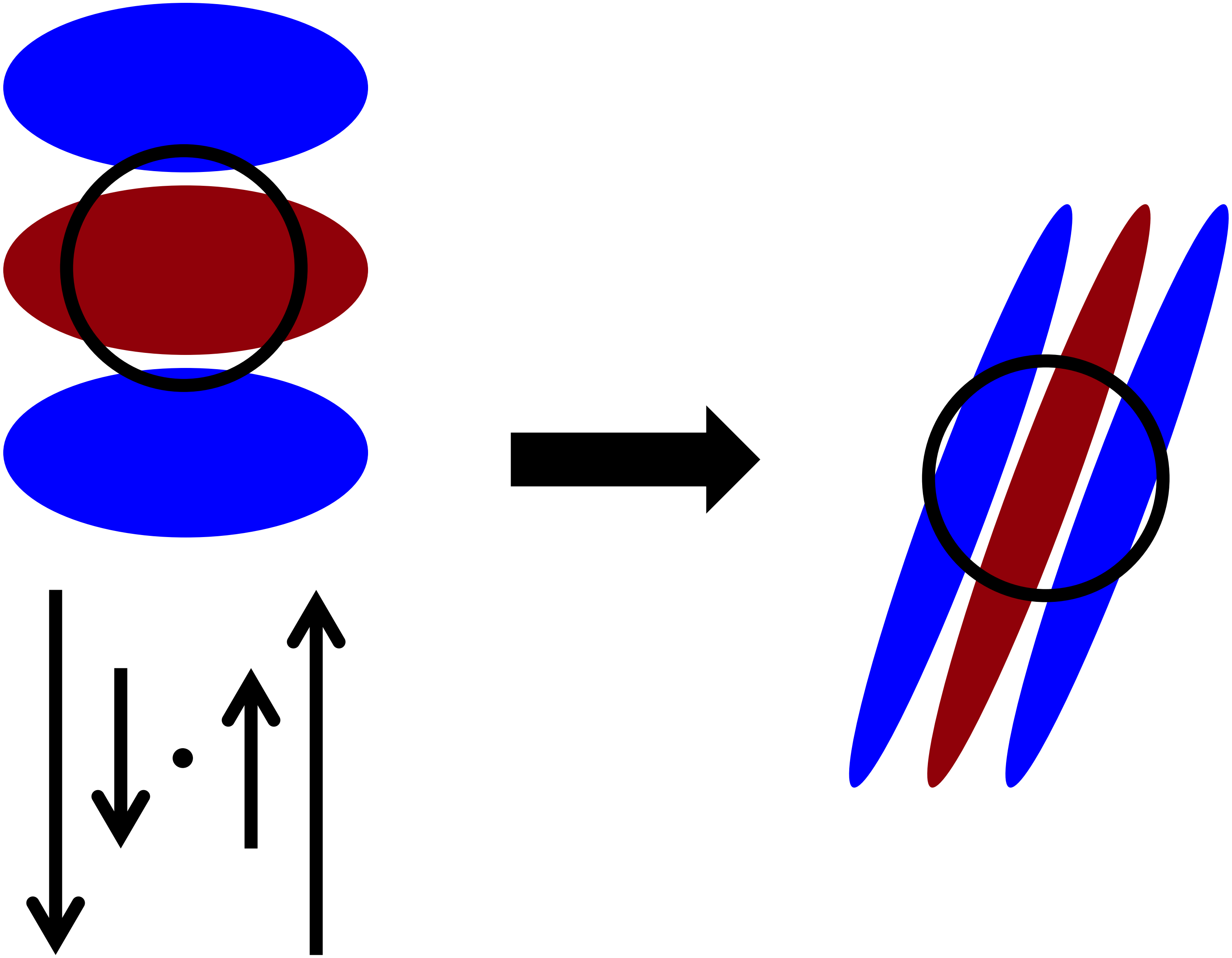


# Different reactor approaches

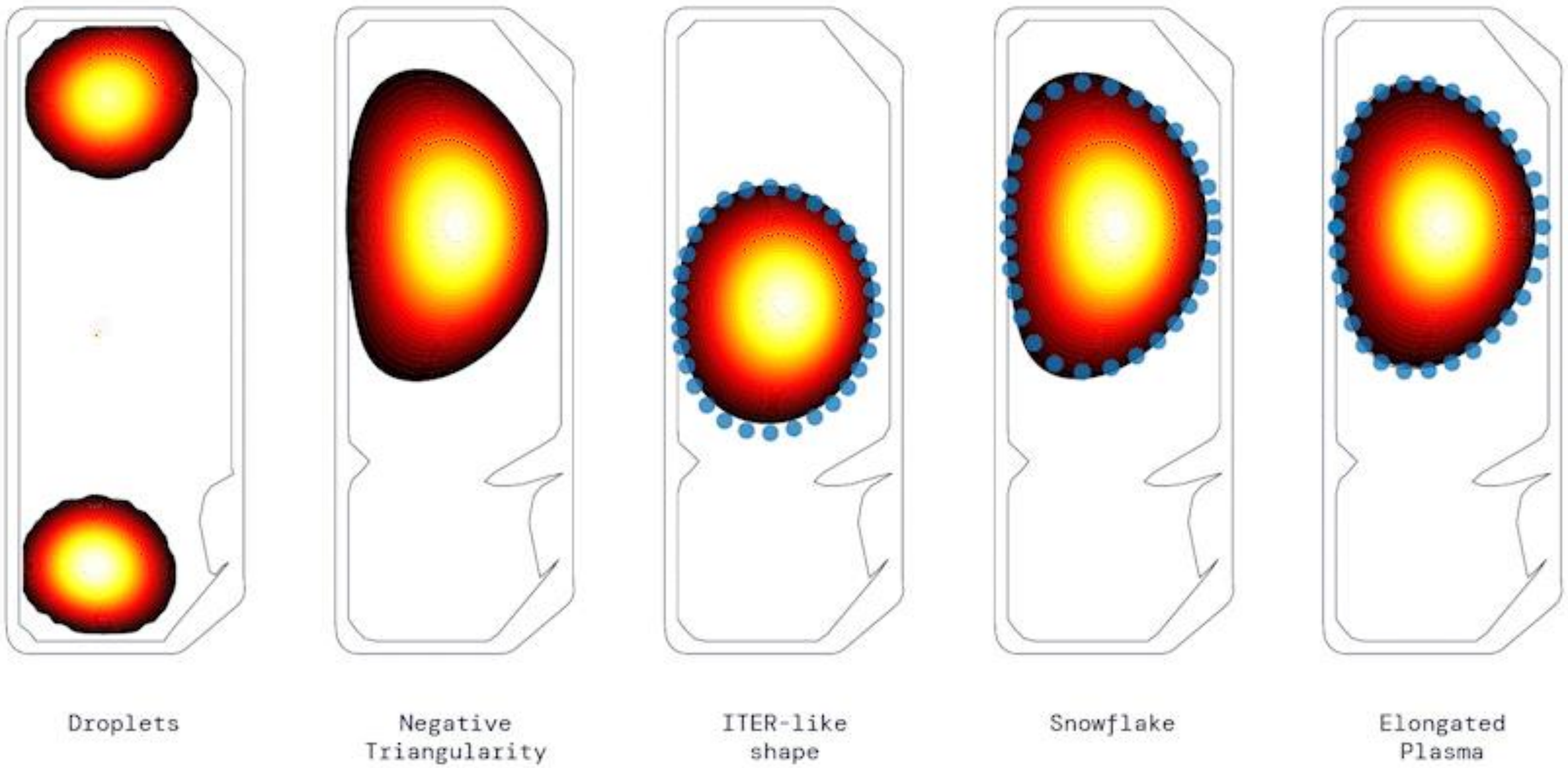
- Reduce the aspect ratio
  - Pro: cheaper, better stability/confinement
  - Con: engineering constraints (shielding + heat loads)



# Turbulence suppression via, e.g., flow shear

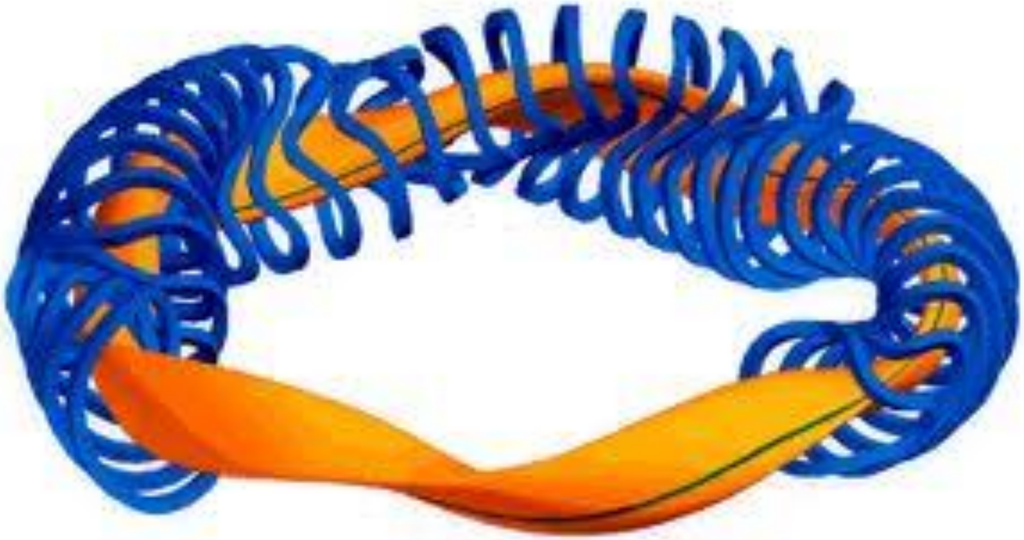


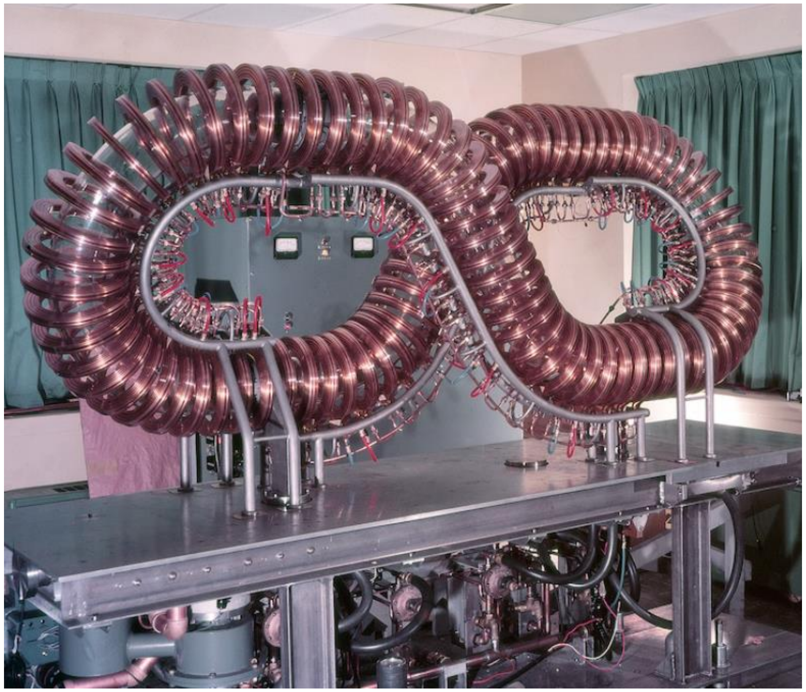
# Plasma control via machine learning



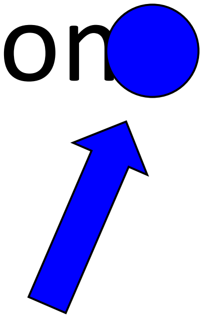
**Credit: DeepMind & SPC/EPFL**

# Steady state operation and the resurgence of stellarators





# Progress in magnetic confinement fusion



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