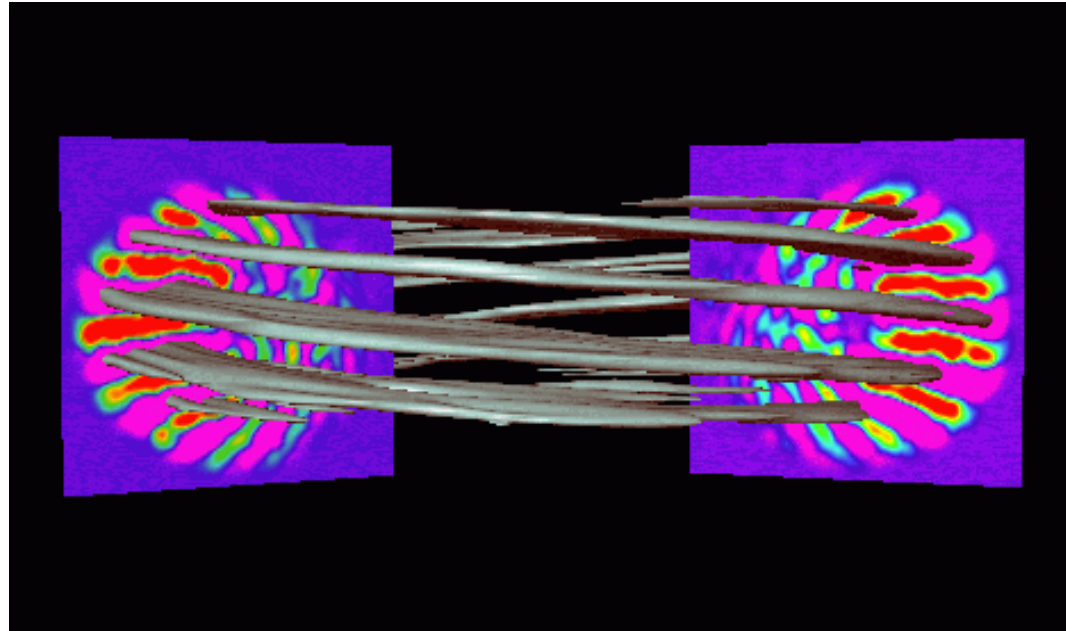


# Turbulence and Transport

## *The Secrets of Magnetic Confinement*



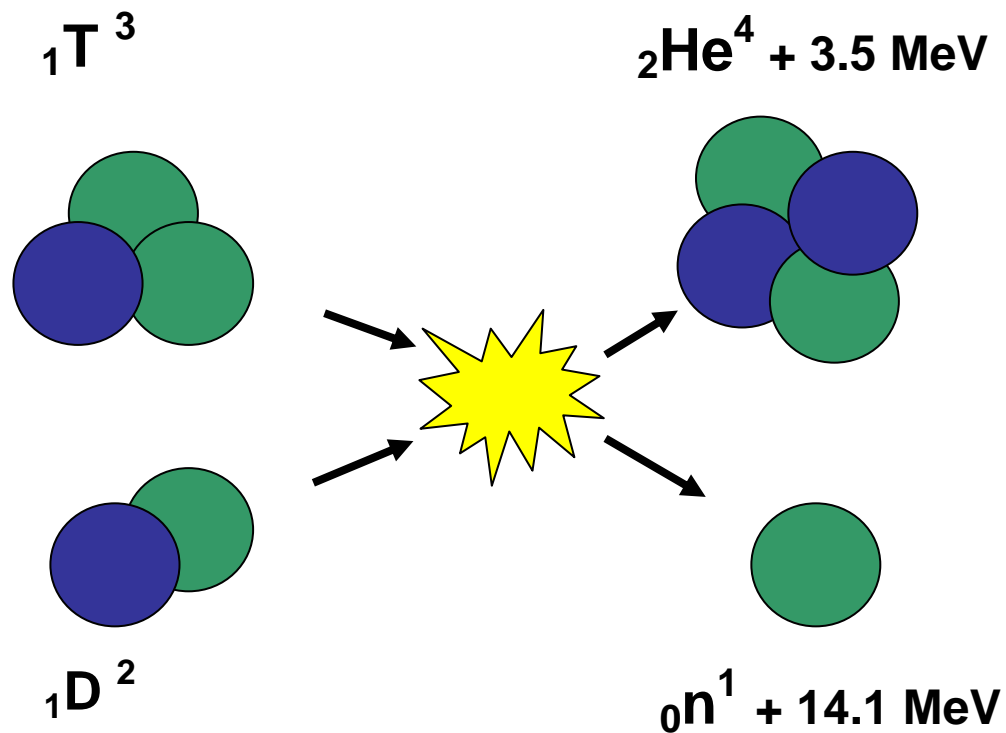
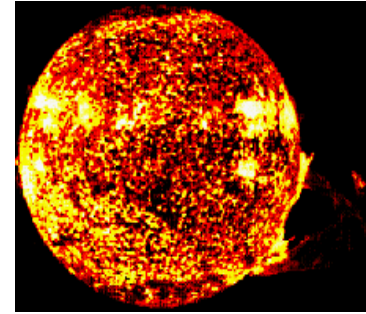
Presented by Martin Greenwald

MIT Plasma Science & Fusion Center

IAP – January 2005



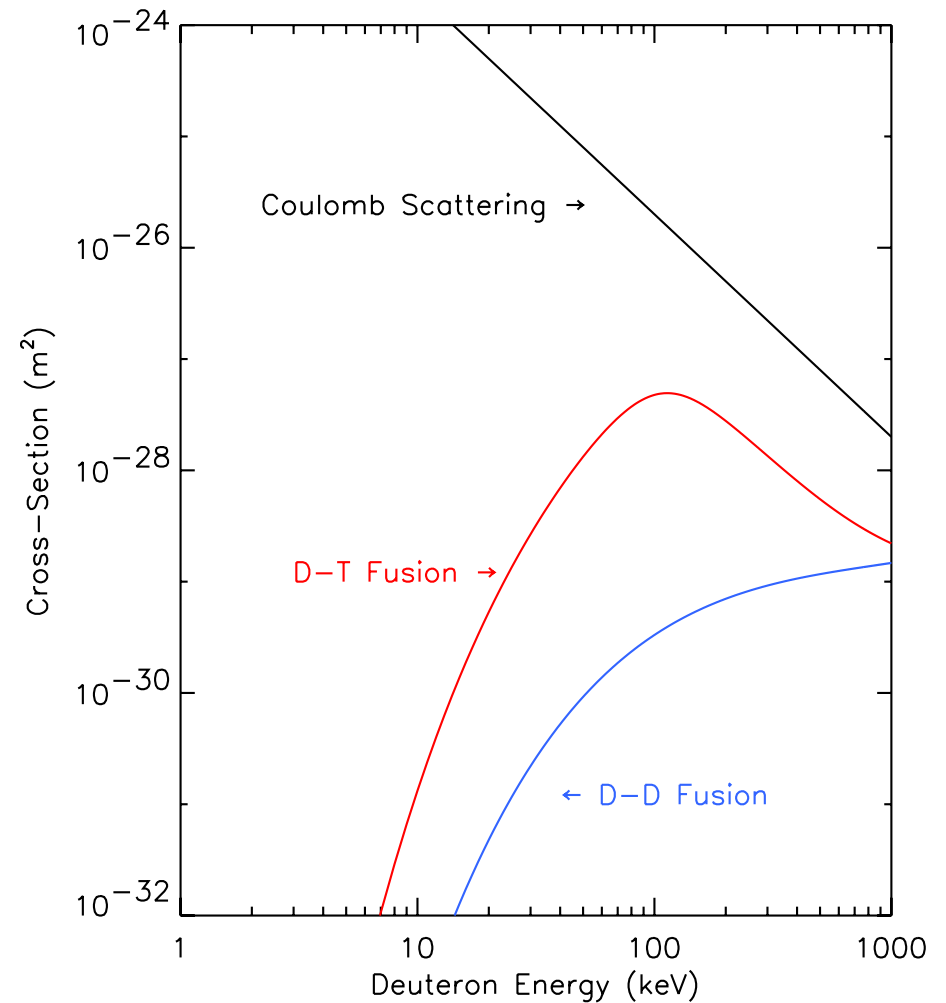
# FUSION REACTIONS POWER THE STARS AND PRODUCE THE ELEMENTS OF THE PERIODIC TABLE



- For 50 years, scientists and engineers at laboratories around the world have been working to exploit the fusion reaction as a practical energy source.
- The promise is for an environmentally friendly method for generating electricity with an inexhaustible fuel supply.

# THE CURVES OF THE FUSION REACTION AND FOR ELASTIC SCATTERING LEAD US DIRECTLY TO THE STUDY OF **CONFINED PLASMAS**

- Even at the optimum energy, the nuclei are much more likely to scatter elastically than to fuse
- Nuclei must be **confined** for many interaction times.
- Multiple scatterings thermalize the constituent particles.
- At the energies involved (10-100 keV), matter becomes fully ionized  $\Rightarrow$  **plasma**.



**(1keV  $\Leftrightarrow$  11,600 °K)**

# 90% OF THE (VISIBLE) UNIVERSE IS MADE OF PLASMA

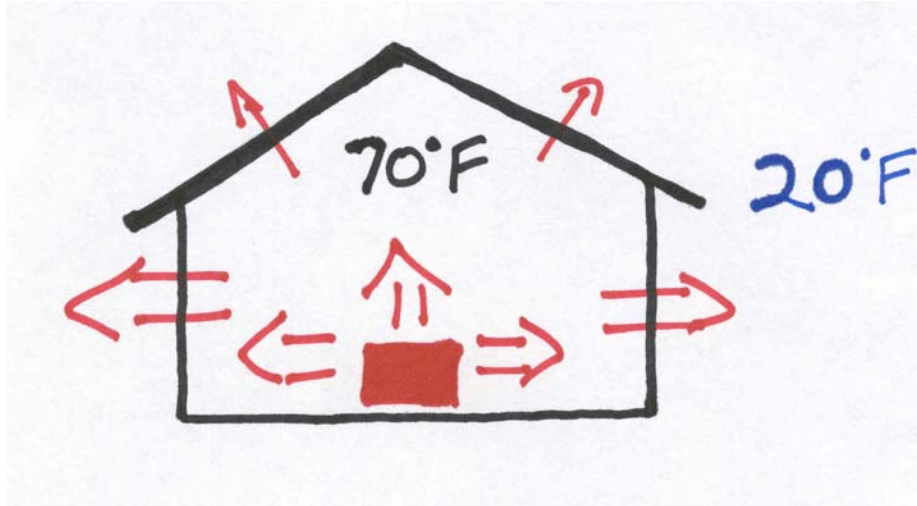
---



# WHAT PRECISELY DO WE MEAN BY THE TERM “CONFINEMENT” ?

---

An appropriate analogy for January in Boston: Heating a building



Define energy confinement as

$$\tau_E(\text{sec}) \equiv \frac{\text{Total stored energy (Joules)}}{\text{Heating rate (Watts)}}$$

- Our goal is to get to the required temperature with the least amount of heating power  $\Rightarrow$  Improve thermal insulation.

# FUSION REQUIRES HIGH CONFINEMENT, DENSITY AND TEMPERATURE IN A PARTICULAR COMBINATION: THE LAWSON CRITERION

---

*Fusion Power =  $n_D n_T \cdot \text{Rate per ion} \cdot \text{Energy per reaction}$*

*Fusion Power  $\propto n^2 F(T)$*

*Loss Power = Confinement Loss + Radiation Loss*

*Loss Power =  $\frac{3nT}{\tau_E} + n^2 R(T)$*

In steady state, Fusion Power = Loss Power    **(Scientific Breakeven)**

$$n^2 F(T) = \frac{3nT}{\tau_E} + n^2 R(T)$$

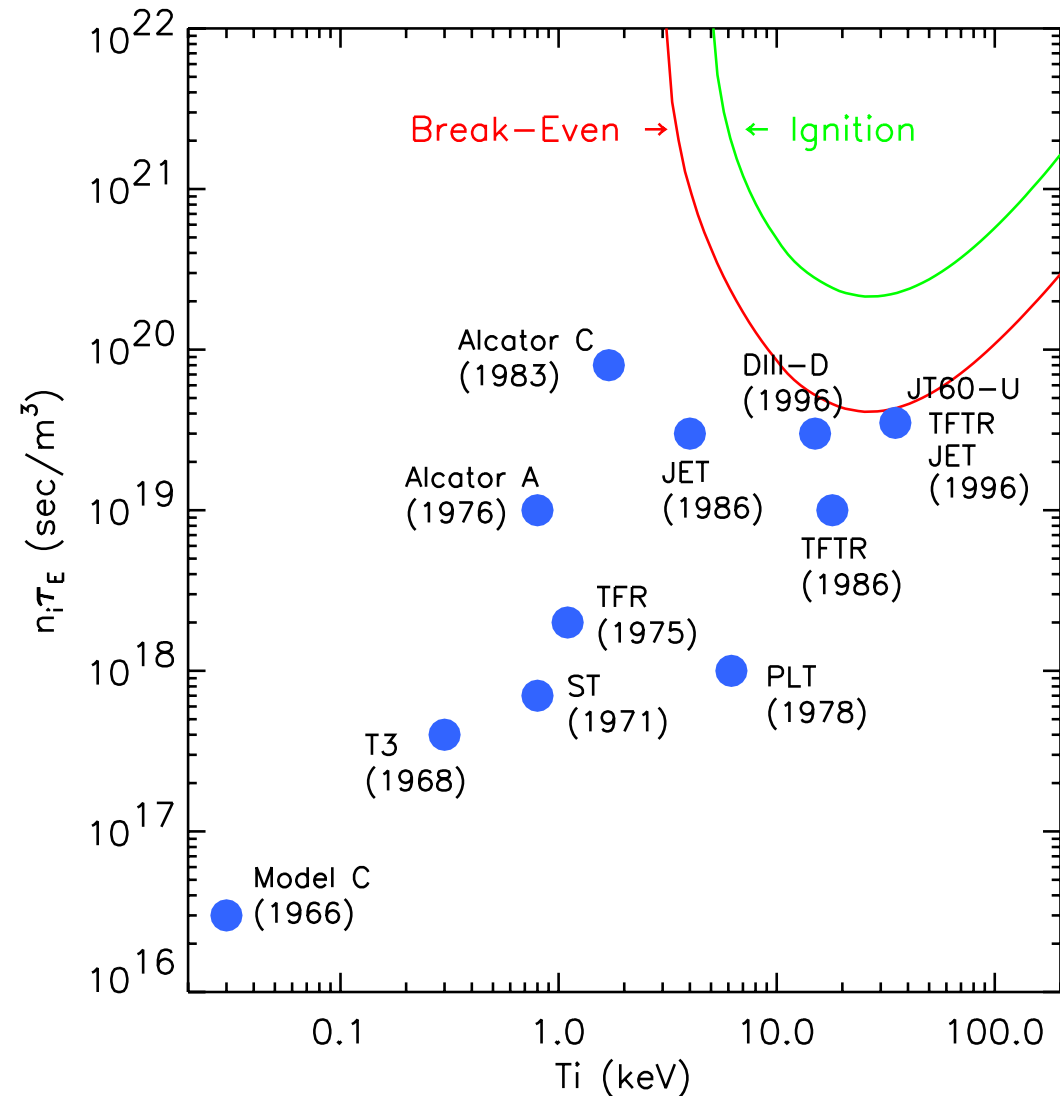
$$n\tau_E F(T) = 3T + n\tau_E R(T)$$

$$n\tau_E = \frac{3T}{F(T) - R(T)} = G(T)$$

- This is a quantitative statement of the requirements for good confinement **and** high temperature.

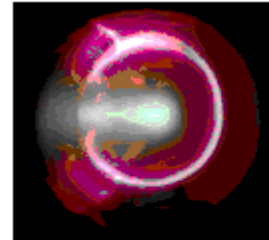
# PROGRESS HAS BEEN DRAMATIC

- Over the last 35 years fusion yield has increased by about  $10^7$ . **A doubling time of about 18 months!**
- We have roughly another factor of 100 in performance to go.
- We also need to go from pulses to steady state.



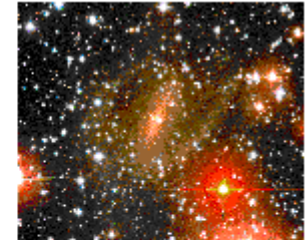
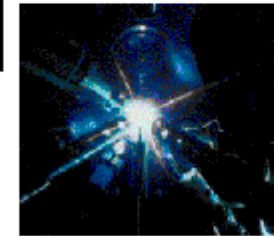
# How Do WE Do IT?

---



Magnetic  
Confinement

Inertial  
Confinement



Gravity

## 1 Gravitational Confinement

- In a deep gravitational well, even fast particles are trapped
- Works well for stars
- Who can afford to build a star?

## 2 Inertial Confinement

- Heat and compress plasma to ignite plasma before constituents fly apart.
- Works for the H-bomb
- “Micro” explosions to be tested with NIF (Defense Program).

## 3 Magnetic Confinement

- Takes advantage of the motion of charged particles in a magnetic field.

# MAGNETIC CONFINEMENT

Gyro-radius

$$\rho = \frac{mv_{\perp}}{qB} \propto \frac{\sqrt{mT}}{B}$$

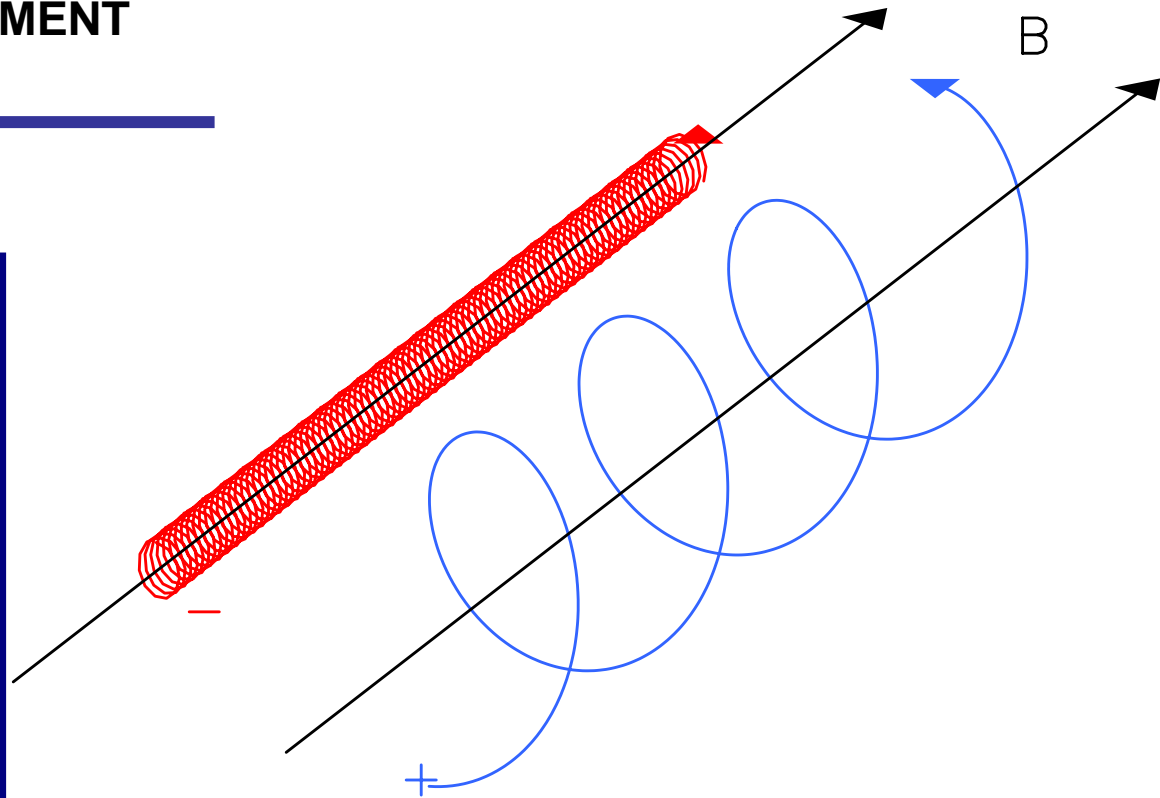
Gyro-frequency

$$\omega_c = \frac{eB}{m}$$

At  $B = 5 \text{ T}$ ,  $10 \text{ keV}$

$\rho_e = 0.067 \text{ mm}$

$\rho_i = 2.9 \text{ mm}$



**Ionized particles are deflected by the Lorentz force and bent into circular orbits.**

- **THAT'S THE BASIC PRINCIPLE**
- **BUT SURELY THERE MUST BE MORE TO THE STORY**
- **CONFINEMENT ISN'T PERFECT**
- **SO, HOW DOES ENERGY GET TRANSPORTED IN A  
MAGNETICALLY CONFINED PLASMA?**

# COLLISIONS CAN DRIVE DIFFUSION – HEAT CONDUCTION

- Elastic collisions cause particles to move off field lines; energy is transferred (transported) in these collisions too.
- The process resembles a random walk with a step of size  $\Delta x$  taken every  $\Delta t$  seconds.

$$\text{Diffusion Coefficient} \equiv D = \frac{\Delta x^2}{\Delta t}$$

$$\Delta t = \frac{1}{\nu}; \quad \nu \equiv \text{collision frequency}$$

Characteristic relaxation time for a diffusive process,  $\tau \propto \frac{L^2}{D}$

**For a magnetic fusion  
plasma:**

$$\Delta x = \rho_i = 0.003 \text{ m}$$

$$D \sim 10^{-3} \text{ m}^2/\text{sec}$$

$$L = \text{plasma radius} \sim 1 \text{ meter,}$$

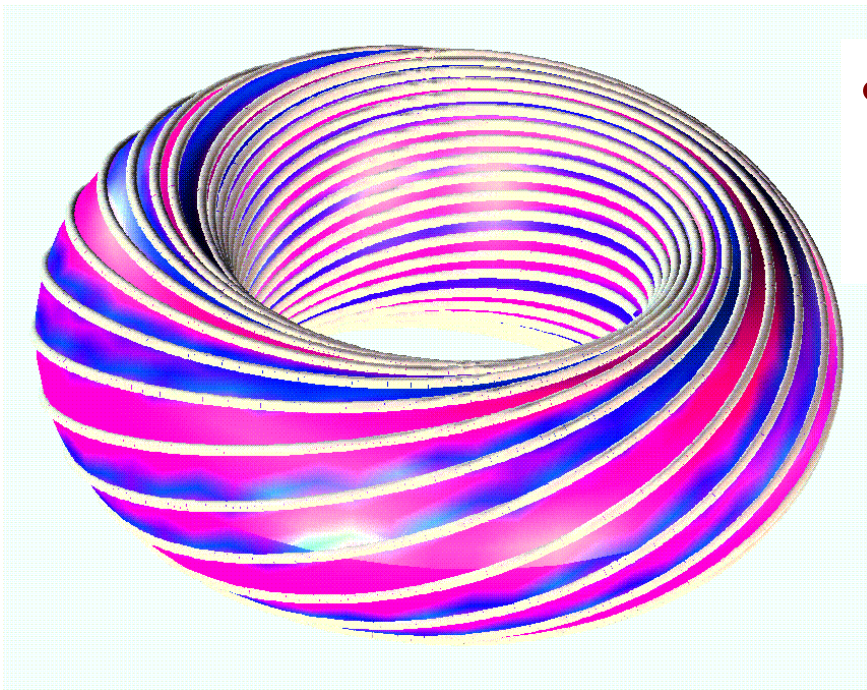
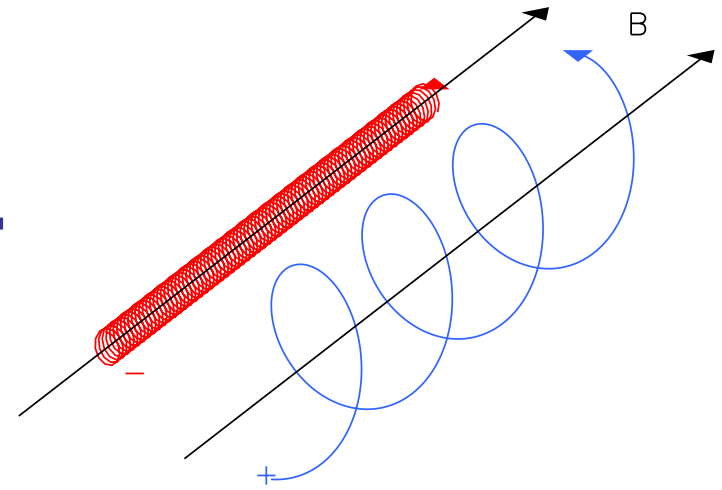
$$\tau \sim 1000 \text{ sec}$$

**(more than good enough)**

For an unmagnetized plasma,  $\Delta x = \text{mean-free-path} \sim 10 \text{ km} !!$

**IN THE SIMPLE EXAMPLE SHOWN,  
THERE IS NO CONFINEMENT AT ALL  
PARALLEL TO THE MAGNETIC FIELD.**

---



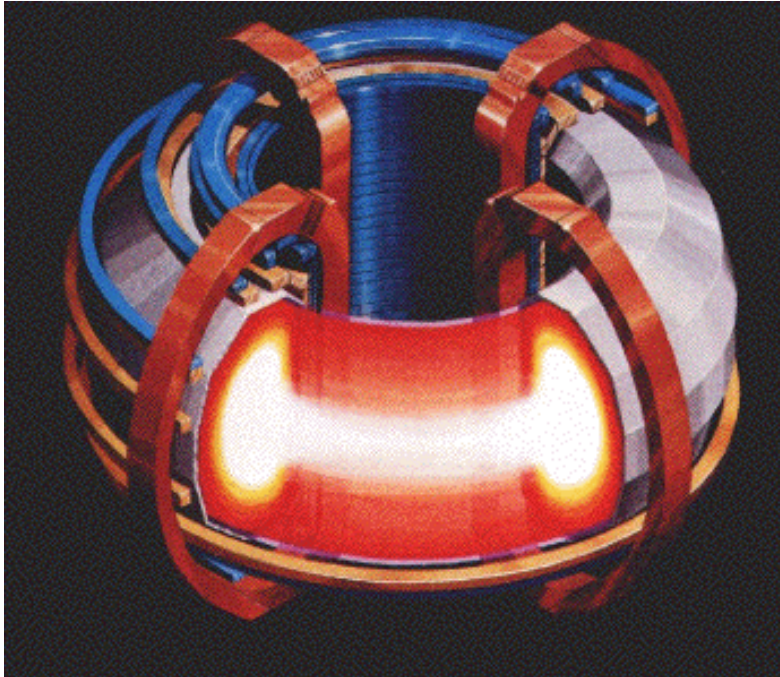
- For a practical device, the end losses must be eliminated

**Voila! Eliminate the ends.**

The resulting shape is a torus

# MOST FUSION EXPERIMENTS START HERE: WITH TOROIDAL PLASMAS.

---

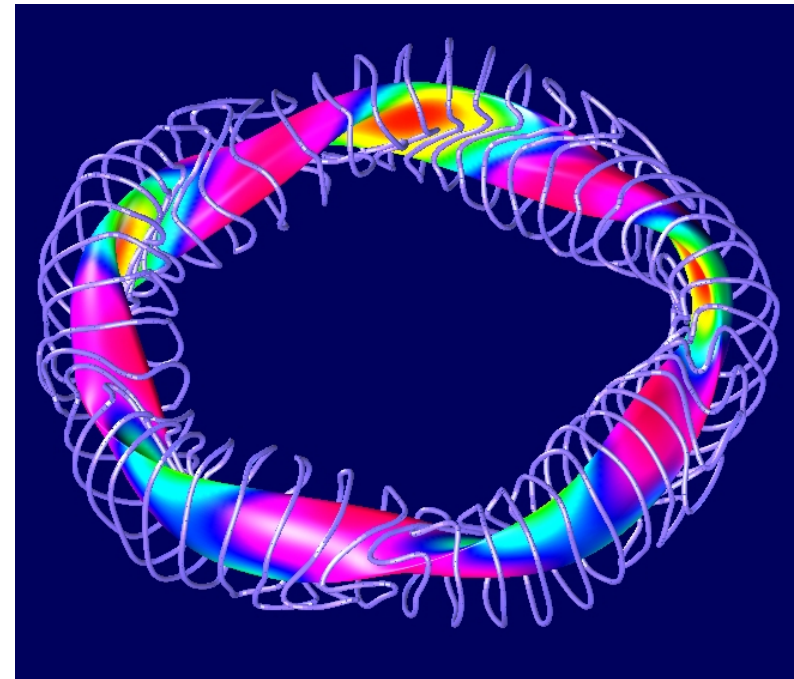


## **Tokamak**

*(toroidalnaya kamera  
magitnaya katushka)*

## **Stellarator - Wendelstein 7AX**

*(Under construction in  
Greifswald Germany)*



- In Toroidal devices, plasma is confined by *Poloidal* magnetic fields

# COLLISIONAL TRANSPORT IS LARGER IN A TOROIDAL DEVICE

Ions and electrons drift off of magnetic field lines due to:

**Magnetic Field Curvature**

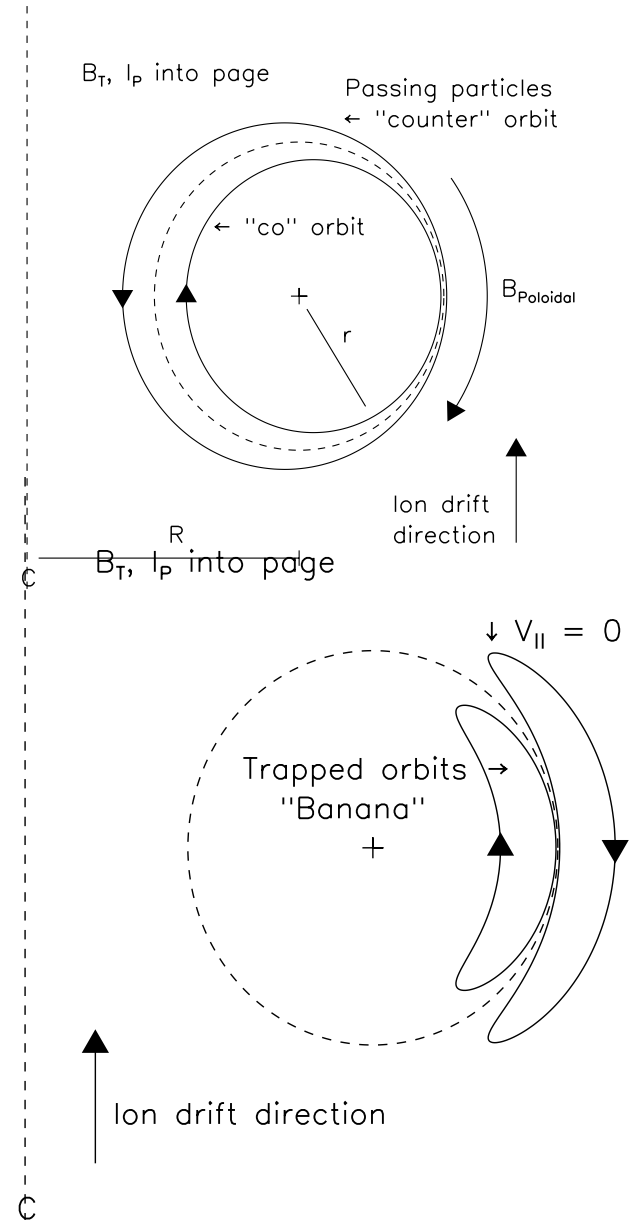
$$V_D = \frac{mV_{\parallel}^2}{qBR}$$

**Magnetic Field Gradients**

$$V_D = \frac{mV_{\perp}^2}{qB^2} \nabla B$$

**Electric Fields**

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



# COLLISIONAL TRANSPORT IN A TORUS VS ANOMALOUS TRANSPORT

---

- $\Delta x \sim 20 \text{ mm}$
- $D \sim 5 \times 10^{-2} \text{ m}^2/\text{sec}$
- For a plasma about 1 meter in radius:
- $\tau \sim 20 \text{ sec}$  (still more than enough)
- We could live easily with classical conductive losses, **even with the toroidal effects.**

- **In experiments, losses are typically much higher.**
- The search for source of these anomalous losses has been an important part of controlled fusion research .
- It presents one of the most challenging problems of classical physics.

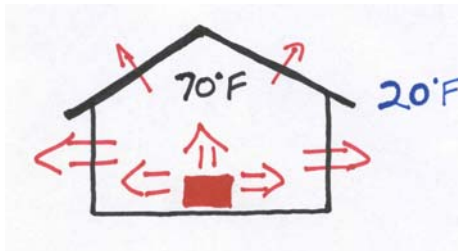
# **Transport and Turbulence**

# CONVECTION – USUALLY DOMINATES HEAT TRANSFER IN FLUIDS

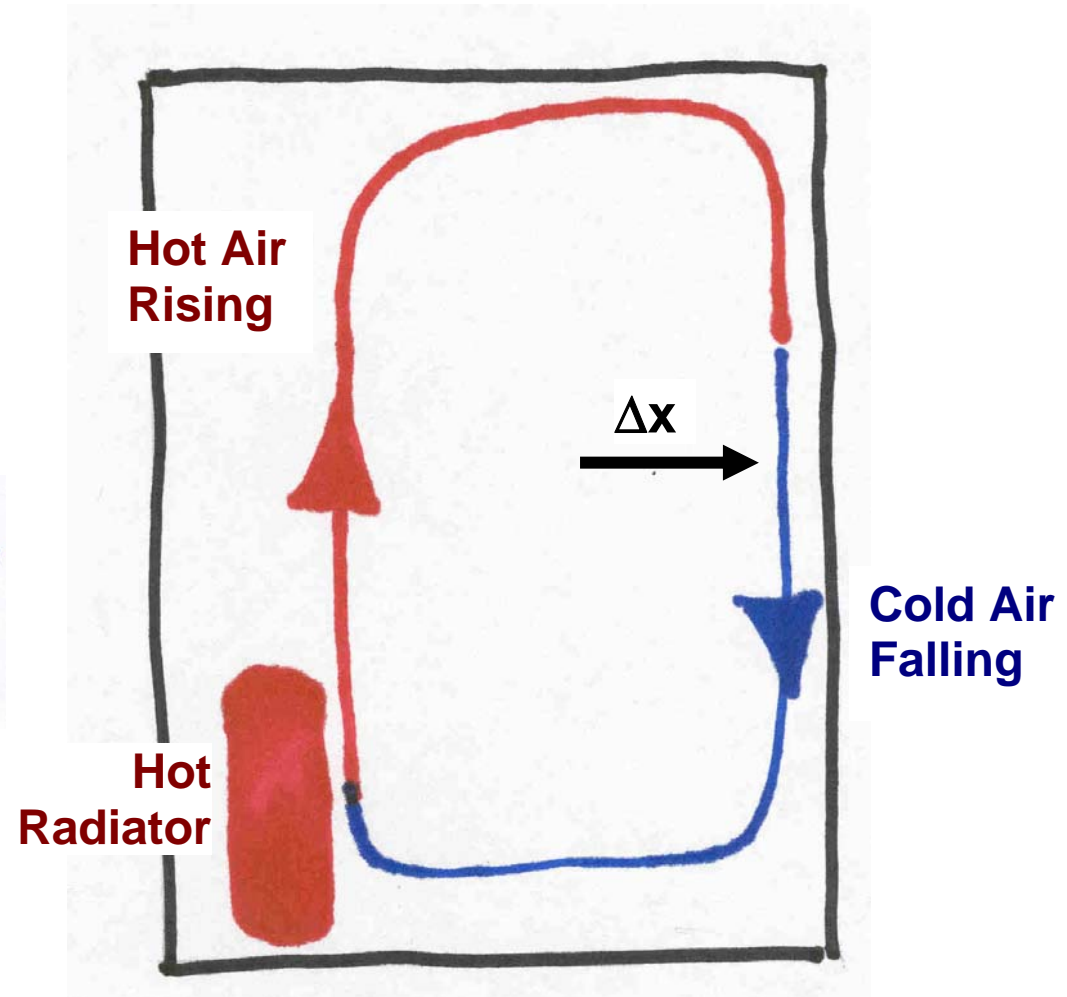
Air is a very poor heat conductor: theoretically 10,000 x worse than a typical solid.

Q: So why do we wear coats, why insulate our houses???

A: Convection



- The **only** purpose of insulation (down/fiberglass) is to break up convection currents
- Makes the convection process less efficient at carrying heat.



## ROUGH ESTIMATE OF TRANSPORT CAUSED BY CONVECTION

---

Using random walk approximation

Step size =  $\Delta x$  = size of convective eddy

Time per step =  $\Delta t$  = circulation time  $\cong$  growth time for convective flow

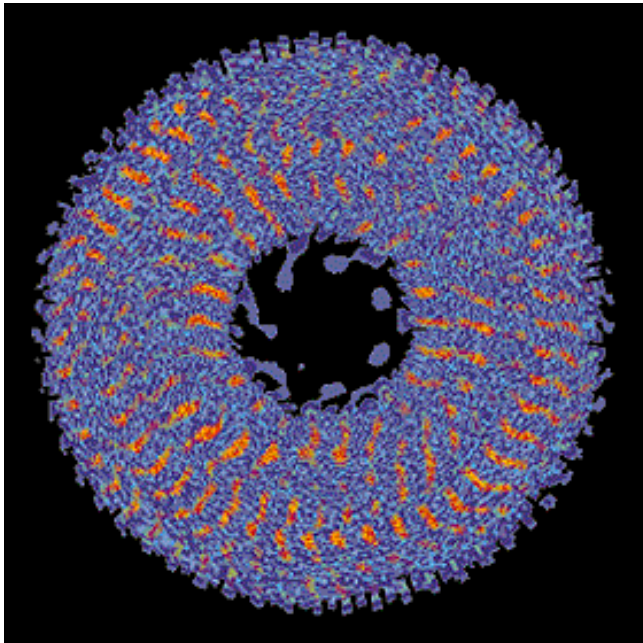
$$\text{Effective Diffusion Coefficient} \equiv D = \frac{\Delta x^2}{\Delta t} = \frac{\gamma}{k^2}$$

where  $k \propto \frac{1}{\Delta x}$  and  $\gamma$  = growth rate

Insulation works by making  $\Delta x$  small !!

# WHERE DOES CONVECTION COME FROM IN PLASMAS??

- Plasmas support all sorts of wavelike motion
- The system is not in equilibrium (pressure gradients)
- Waves can tap free energy in temperature and density gradients.

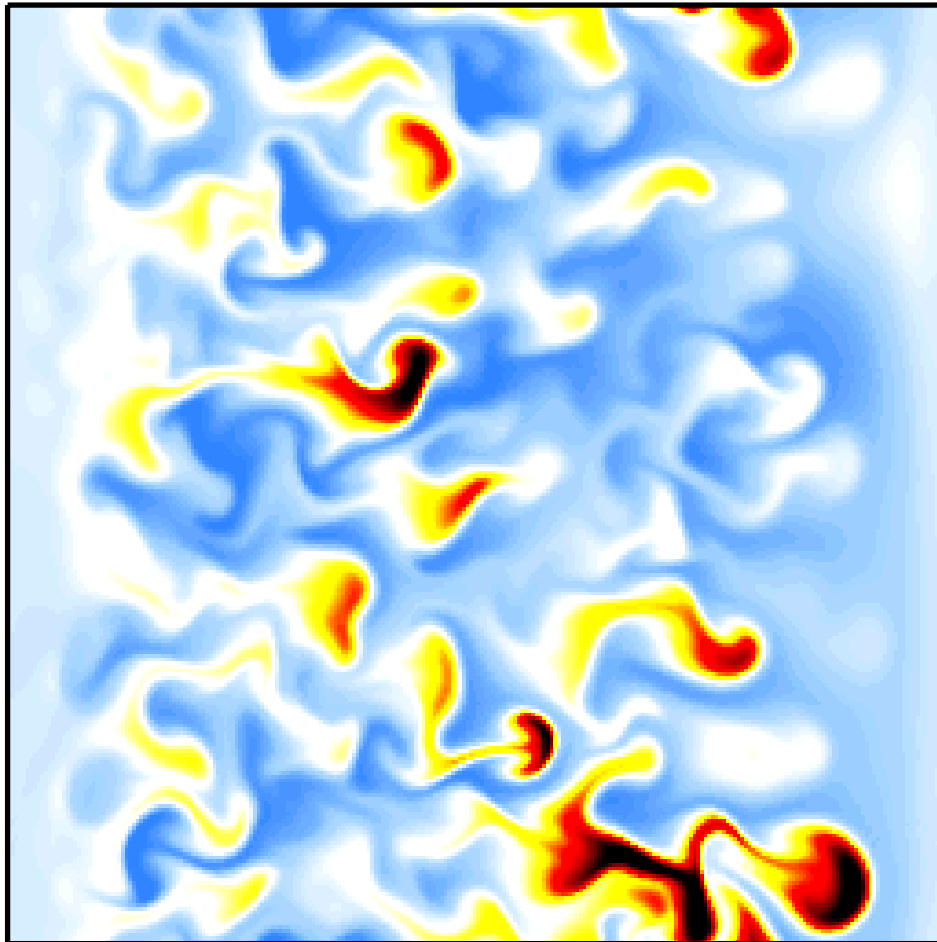


## Drift Waves and Sound Waves

- Believed to be responsible for turbulent transport in our experiments.
- Electric and magnetic properties of plasma differentiate them from types of waves we are more familiar with.
- Family of waves with wavelengths running from  $\rho_e$  to  $\rho_i$ .
- Frequencies  $\sim \omega_{*e} \sim 100\text{s kHz}$

# TURBULENCE IS THE RESULT OF NONLINEAR PROCESSES IN THE PLASMA

---

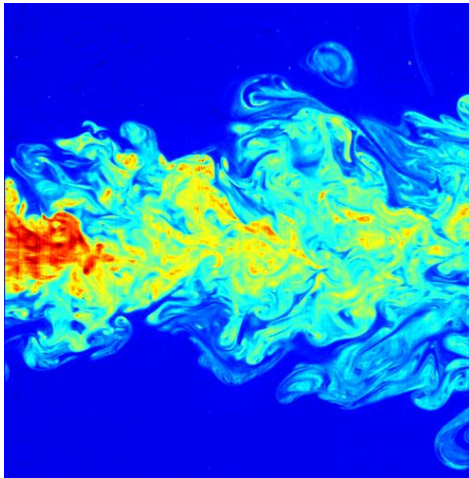


- As the plasma waves grow, they modify the medium in which they propagate.
- This non-linear interaction leads to chaos and turbulence

# TURBULENCE IS A UBIQUITOUS PHENOMENON IN NATURE

---

- It is generated as a spontaneous way of releasing the free energy associated with flows or gradients in fluids (or fluid-like matter).
- Requires some degree of nonlinearity and dissipation in the system.
- It breaks the symmetry of the physical system and involves multiple time and space scales.
- Many, many examples.....

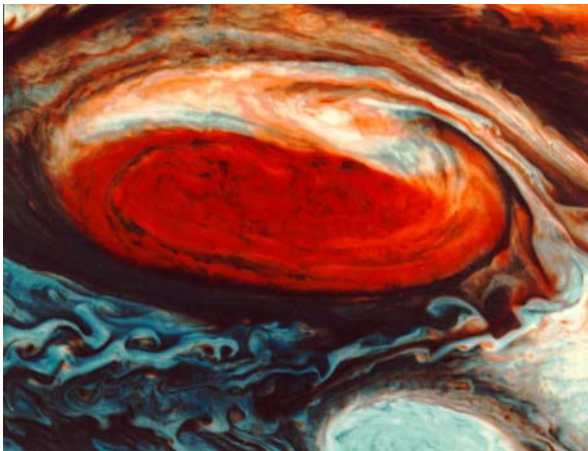
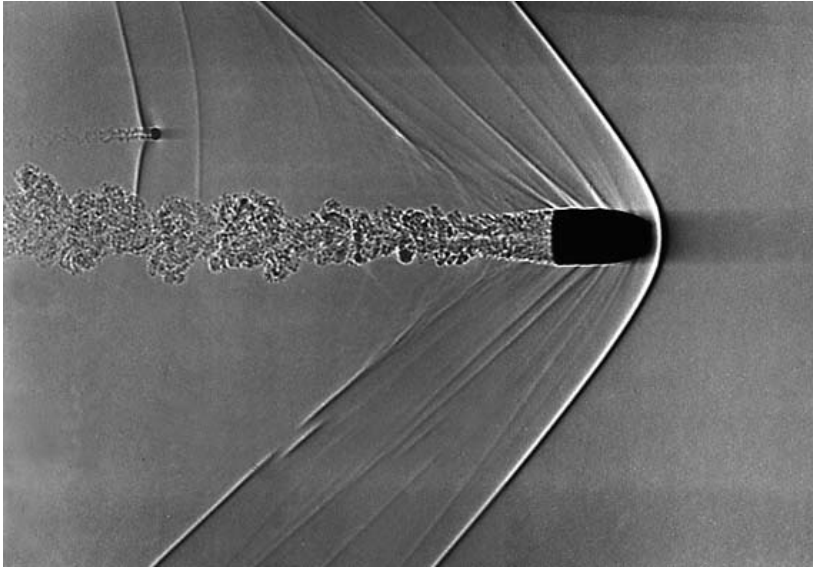


**Turbulence is a  
Grand challenge  
of physics**



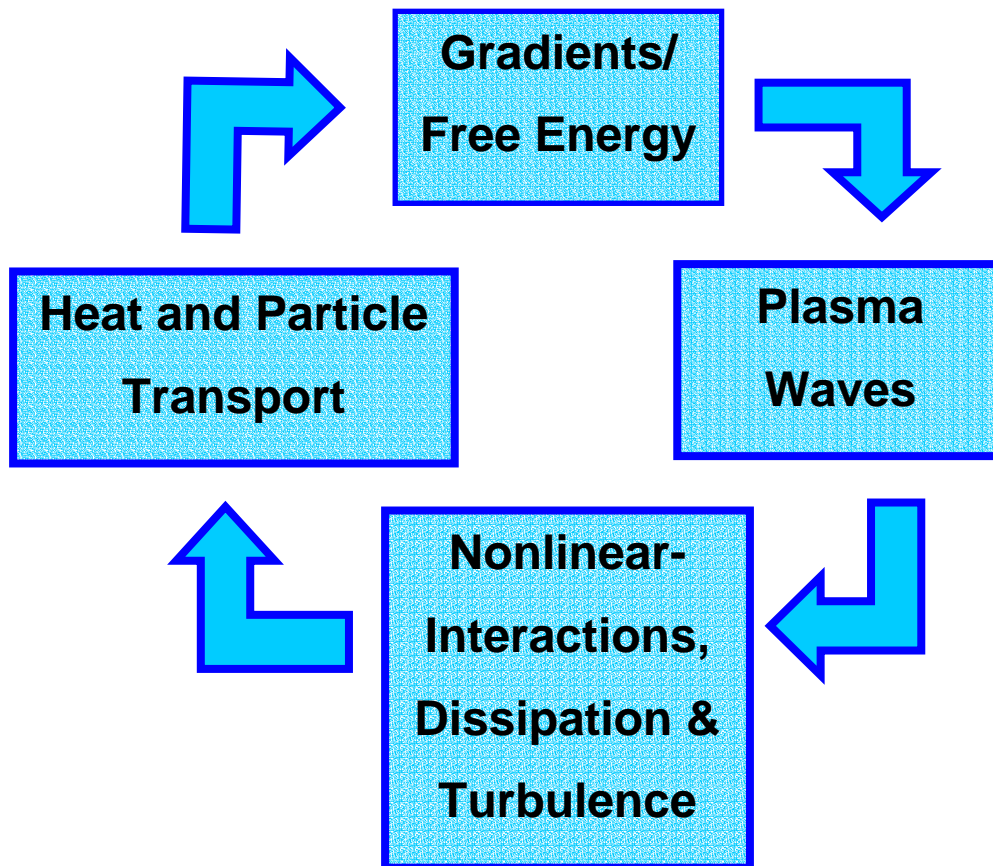
# TURBULENCE OCCURS OVER A WIDE RANGE OF SCALES

---



# TRANSPORT/TURBULENCE FEEDBACK LOOP

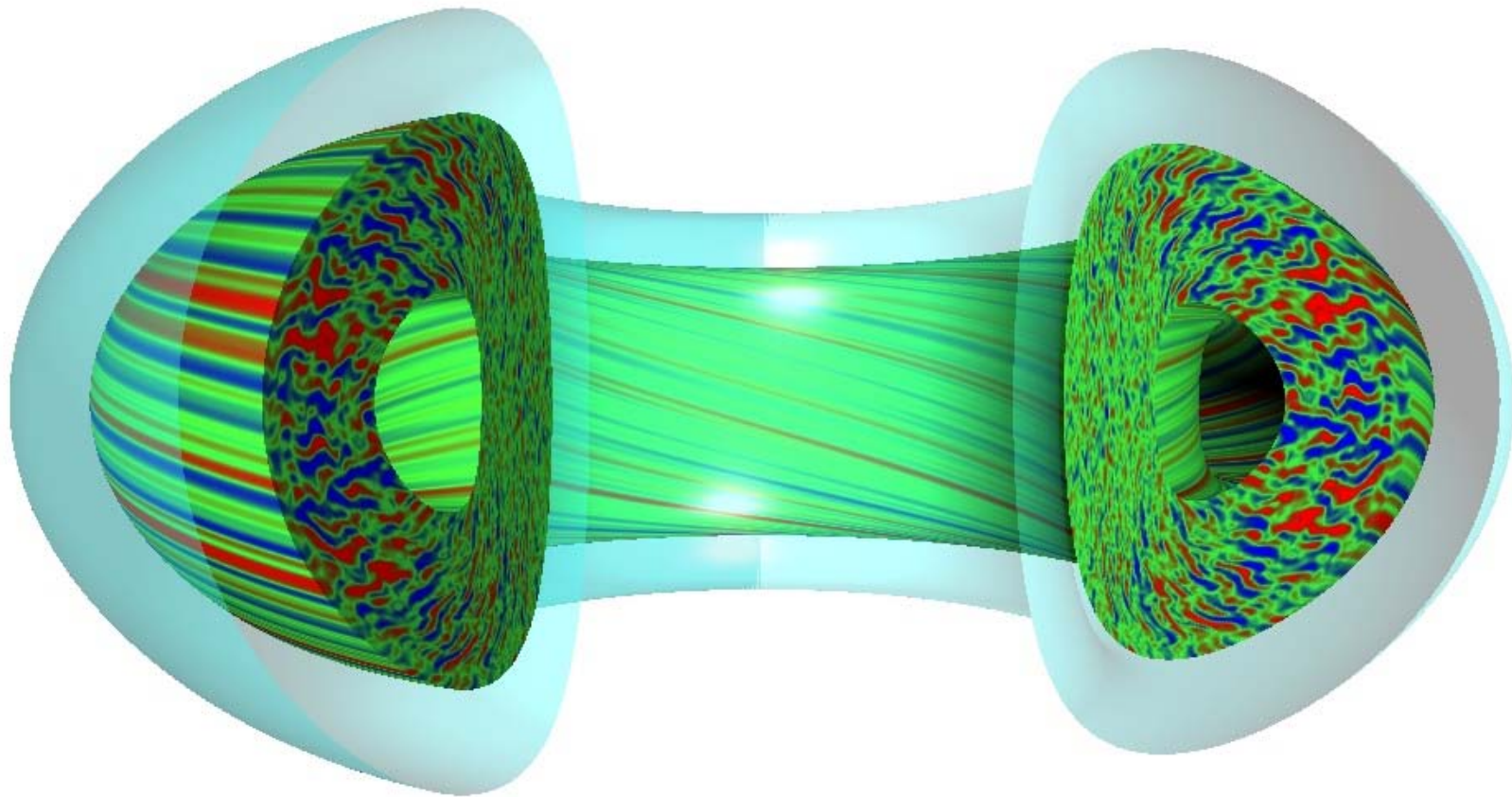
---



- Turbulence is driven by the free energy residing in plasma gradients
- Increases transport above collisional levels.
- Modifies gradients
- And so forth til a steady state is reached.

# PLASMA TURBULENCE AND TRANSPORT CAN BE SIMULATED BY LARGE COMPUTER CODES

---

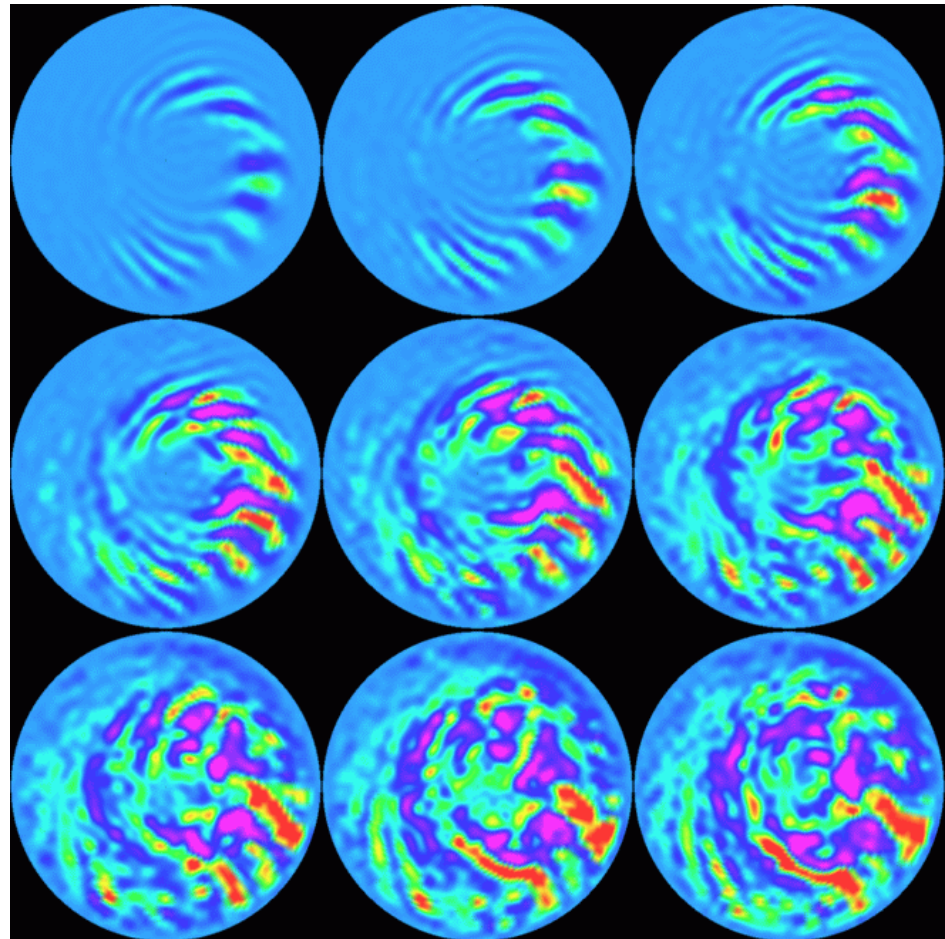


In magnetized plasmas, turbulence features are small in cross section, but extend along the magnetic field lines.

# IN COMPUTER SIMULATIONS, TURBULENCE CAN BE SEEN GROWING FROM LINEAR INSTABILITIES (UNSTABLE WAVES).

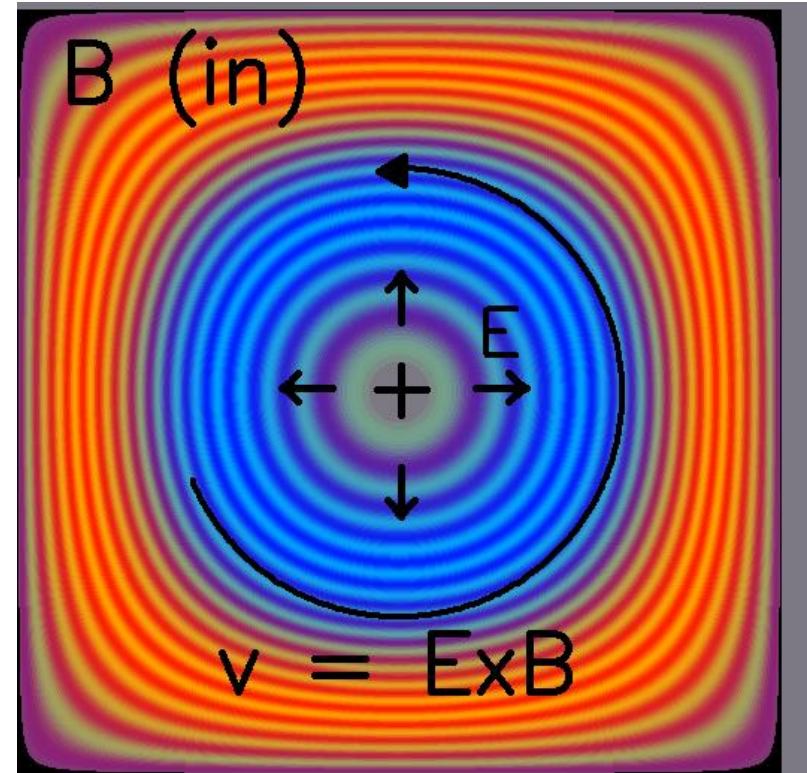
---

- Different colors represent regions of high or low plasma density
- The "free" motion along field lines lead to fluctuations that have very long wavelengths in that direction
- Most of the variation is perpendicular to the field

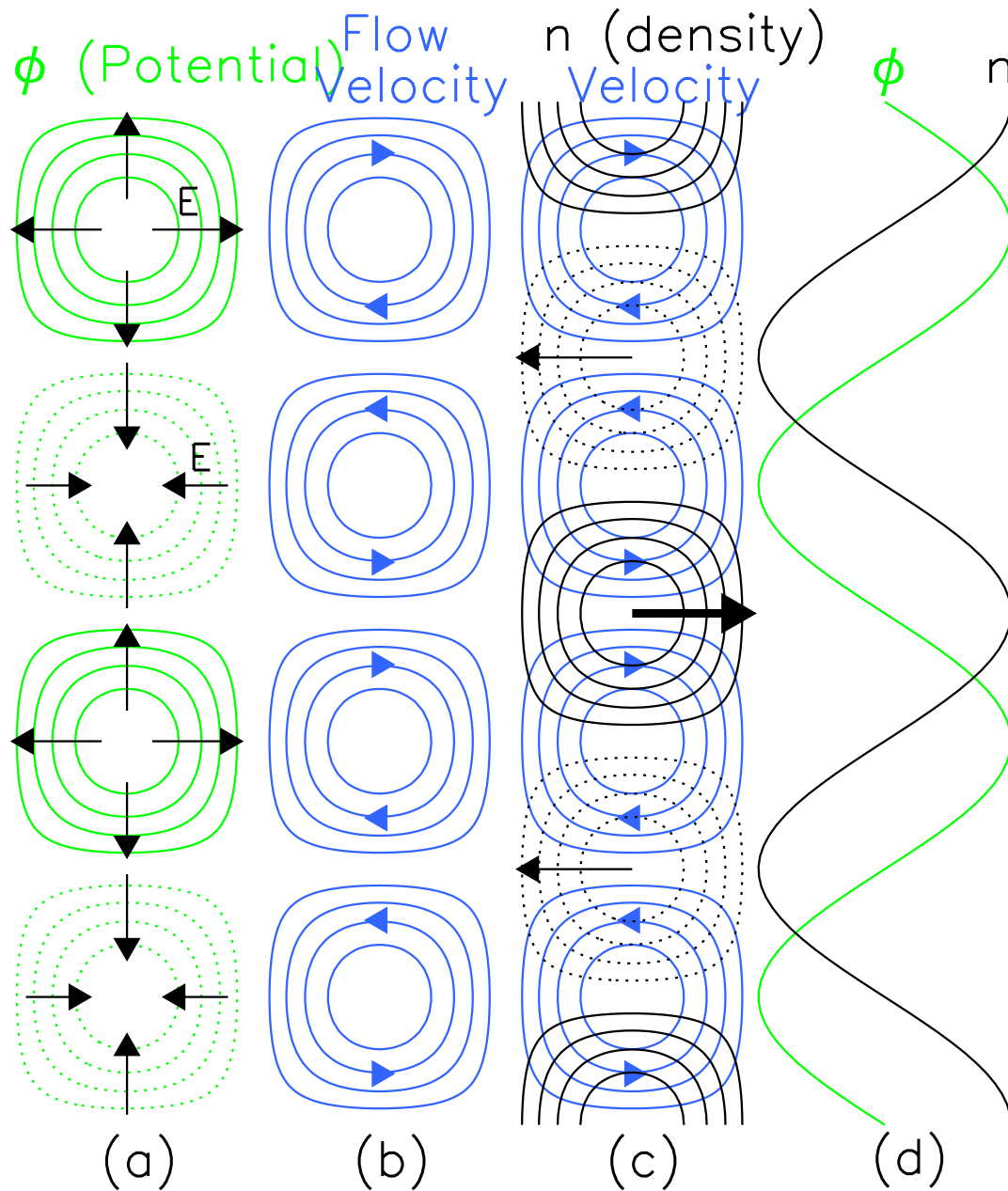


## LETS LOOK AT THE PROCESS IN DETAIL

- The waves that seem to cause the most transport are a little like ordinary sound waves but.....
- They have an important electric component
- That is, the electrons, being lighter, move faster and separate slightly from the ions
- The result are localized regions of excess + and - charge, + and - potential



The  $E \times B$  drift causes the plasma to whirl around regions of high or low potential.

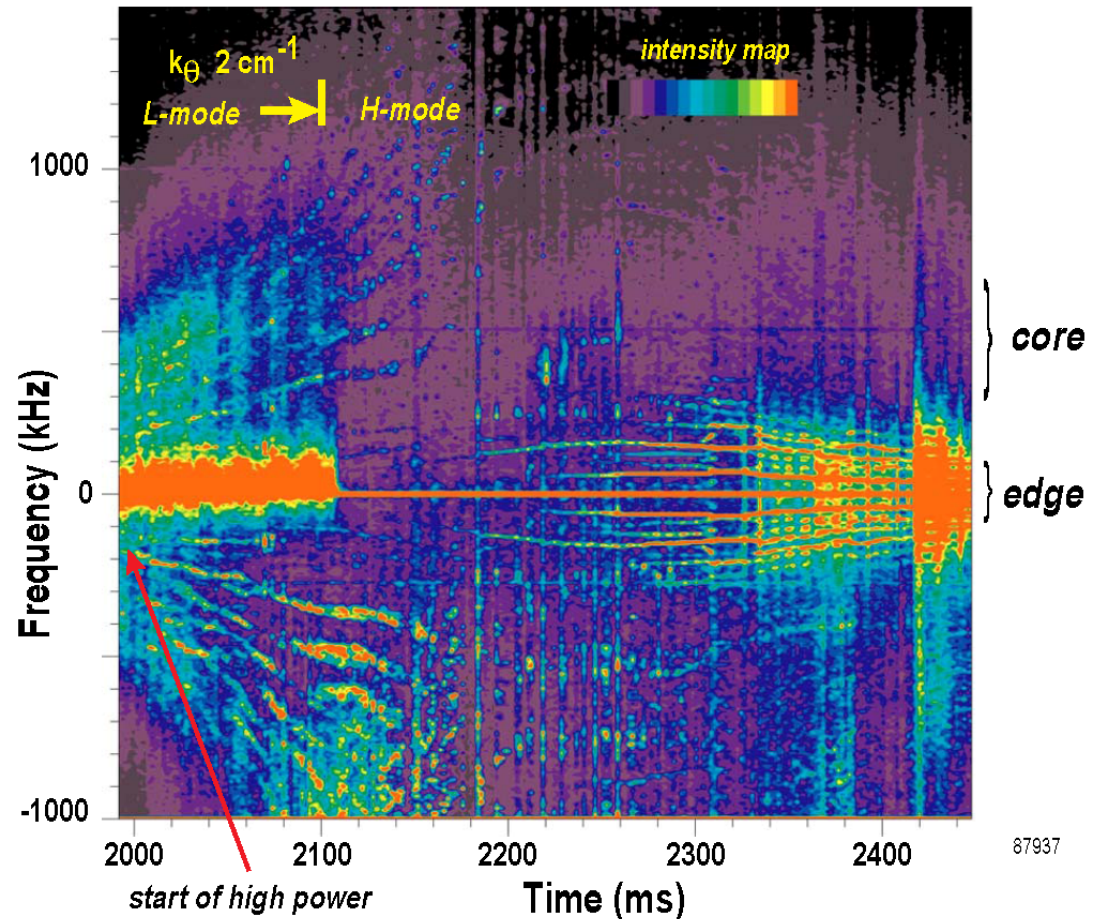


**Transport depends  
 on the size of the  
 fluctuations and  
 their relative phase**

# HOW CAN WE REDUCE TURBULENCE AND THE TRANSPORT THAT IT CAUSES?

- Experiments have found several regimes with dramatically improved confinement:
- Reducing the basic turbulence drives certainly helps.
- Theory suggests that another route is through **self-organized** flows.

Contour Plot of Scattered Fluctuation Spectra Evolution

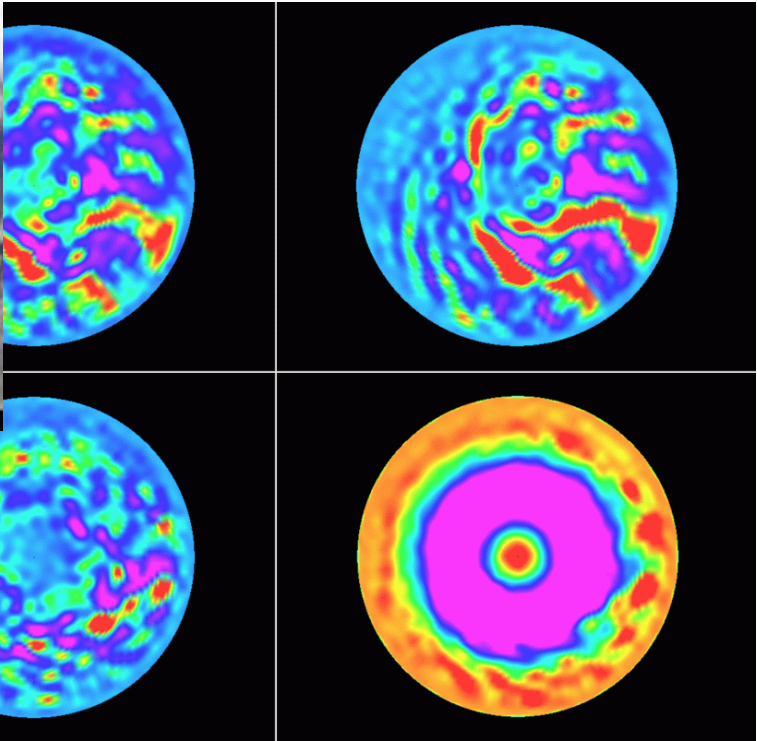


# SELF ORGANIZATION: OUT OF CHAOS, NONLINEAR SYSTEMS CAN CREATE LARGE ORGANIZED STRUCTURES

---

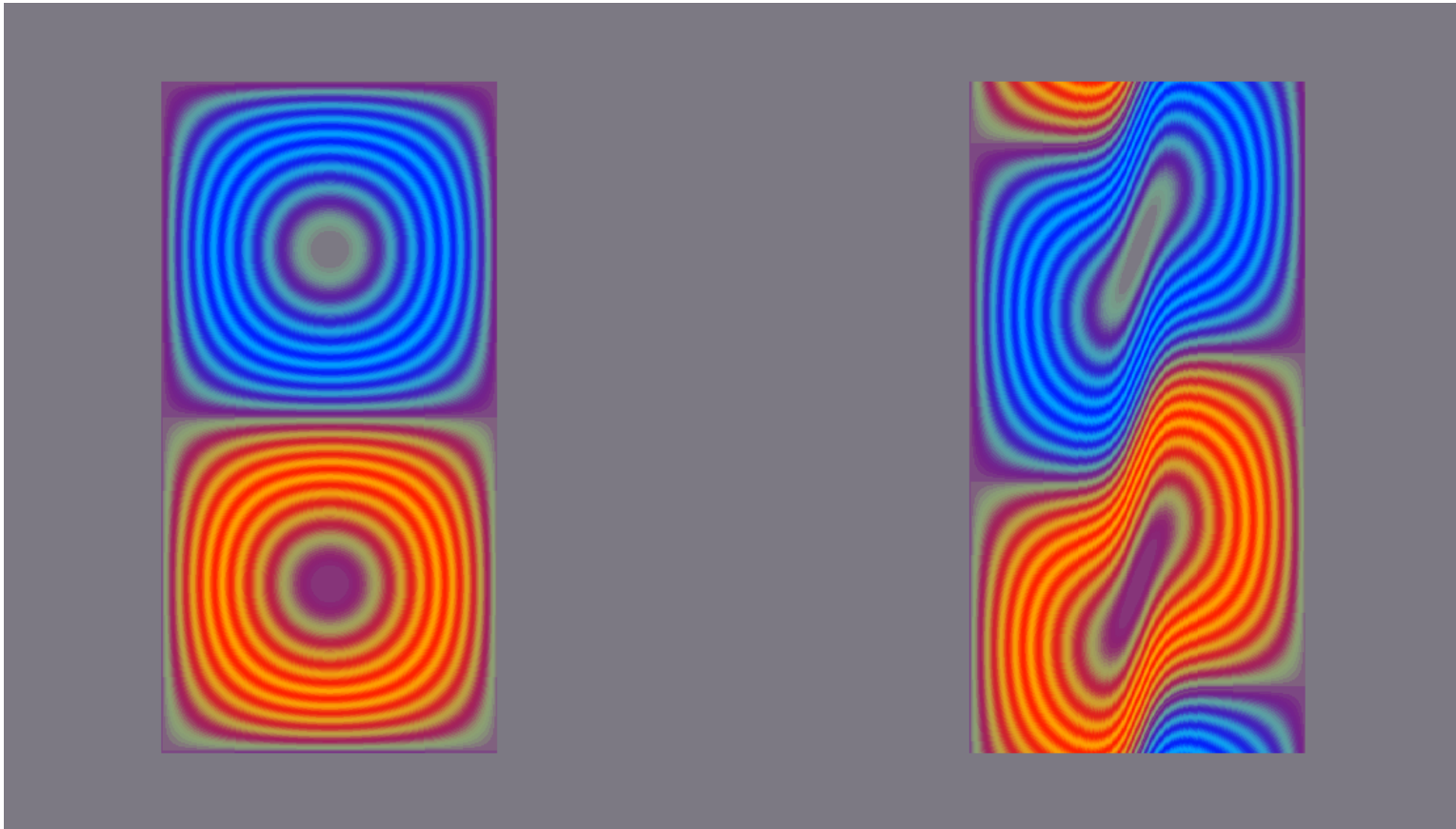


253 UTC SeaWiFS Project/WASA/GSFC and ORBIMAGE



# COHERENT FLOWS CAN “SHEAR” TURBULENT EDDYS AND REDUCE TRANSPORT

---



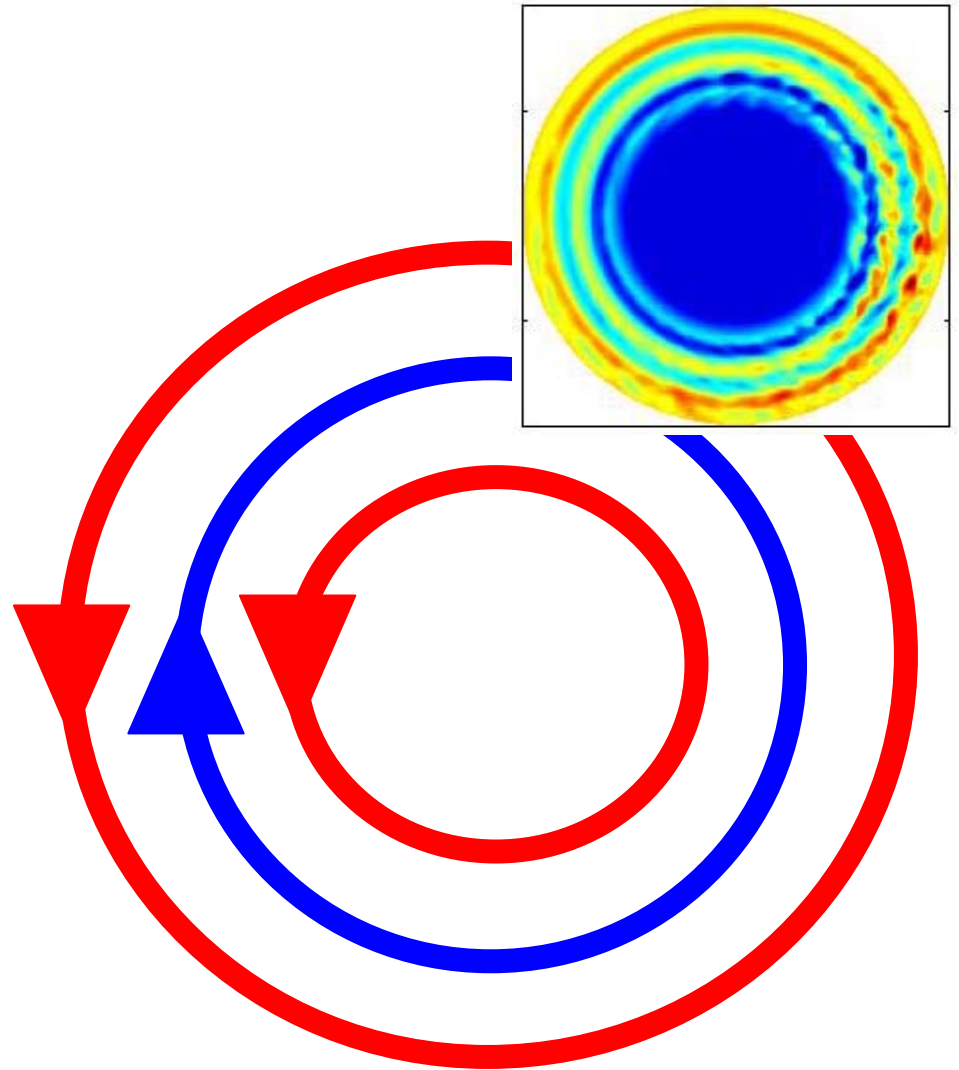
Remember: small turbulent eddies = lower levels of transport

# STABILIZING FLOWS CAN BE LARGE SCALE AND PERSISTENT OR SMALLER SCALE AND INTERMITTENT – ZONAL FLOWS

---

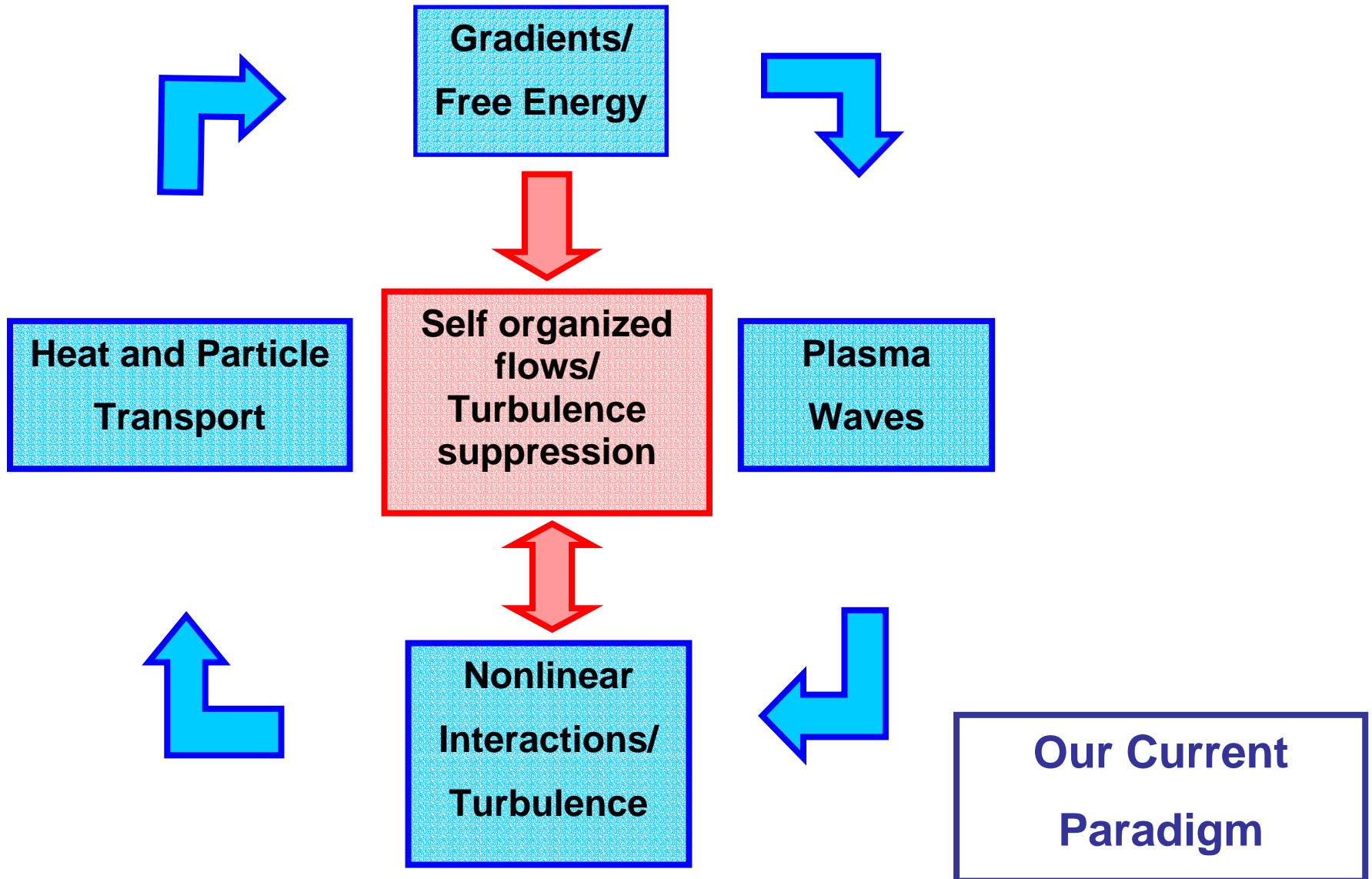
Zonal flows are part of the plasma turbulence but:

- Do not correspond to linear instability.
- Only driven by turbulence.
- Steal energy from the turbulence.
- Lower the amplitude and reduce the size of turbulent eddies.
- Do not drive radial transport – only involve motion along the magnetic field



# BOTH TYPES OF FLOWS CAN INTERVENE IN THE TRANSPORT/TURBULENCE FEEDBACK LOOP

---



## SO WHERE ARE WE?

---

- We have a reasonable understanding of energy transport driven by ion-scale turbulence
- We can reduce turbulent transport – sometimes to collisional levels.
- We understand some of the mechanisms which lead to enhanced confinement.
  
- We have a much less complete picture of how particle and momentum transport (viscosity) work.
- We are only beginning to study mechanisms for electron transport

# SUMMARY

---

- Controlled fusion has the potential to provide virtually unlimited energy **if** we can solve the associated technical problems
- Confinement of heat and particles is one of the foremost of these problems
- In experiments, heat and particle transport are mostly driven by turbulence
- Great progress has been made in understanding the nature of this turbulence and the means to reduce it.

**Much work remains to be done: the problem of turbulent transport is among the greatest challenges in physics**