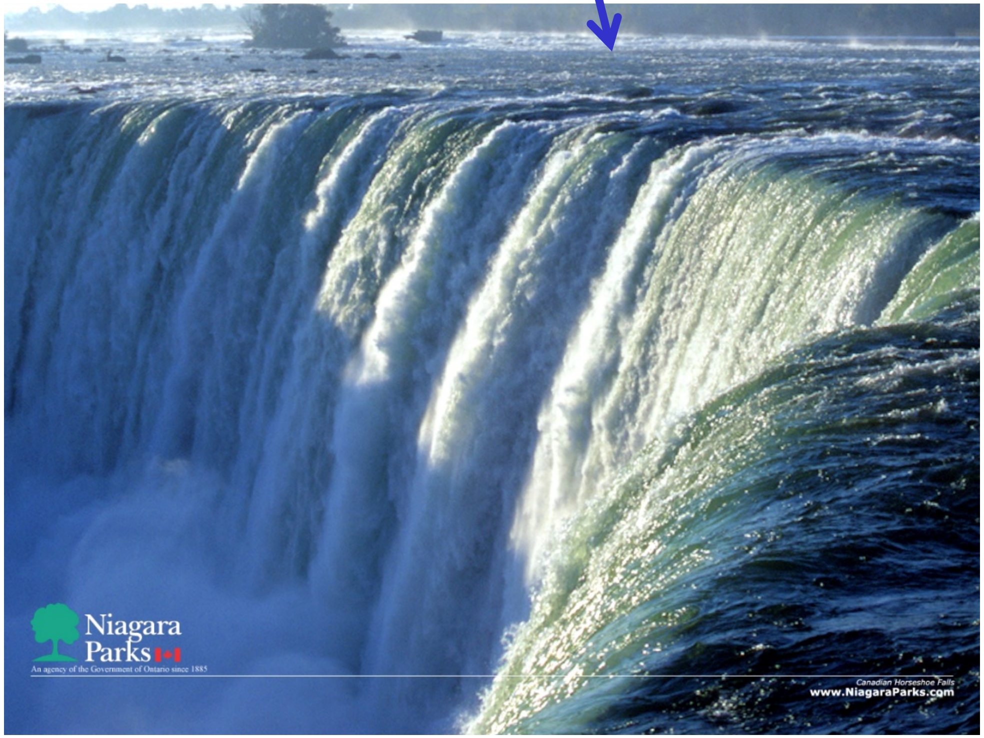
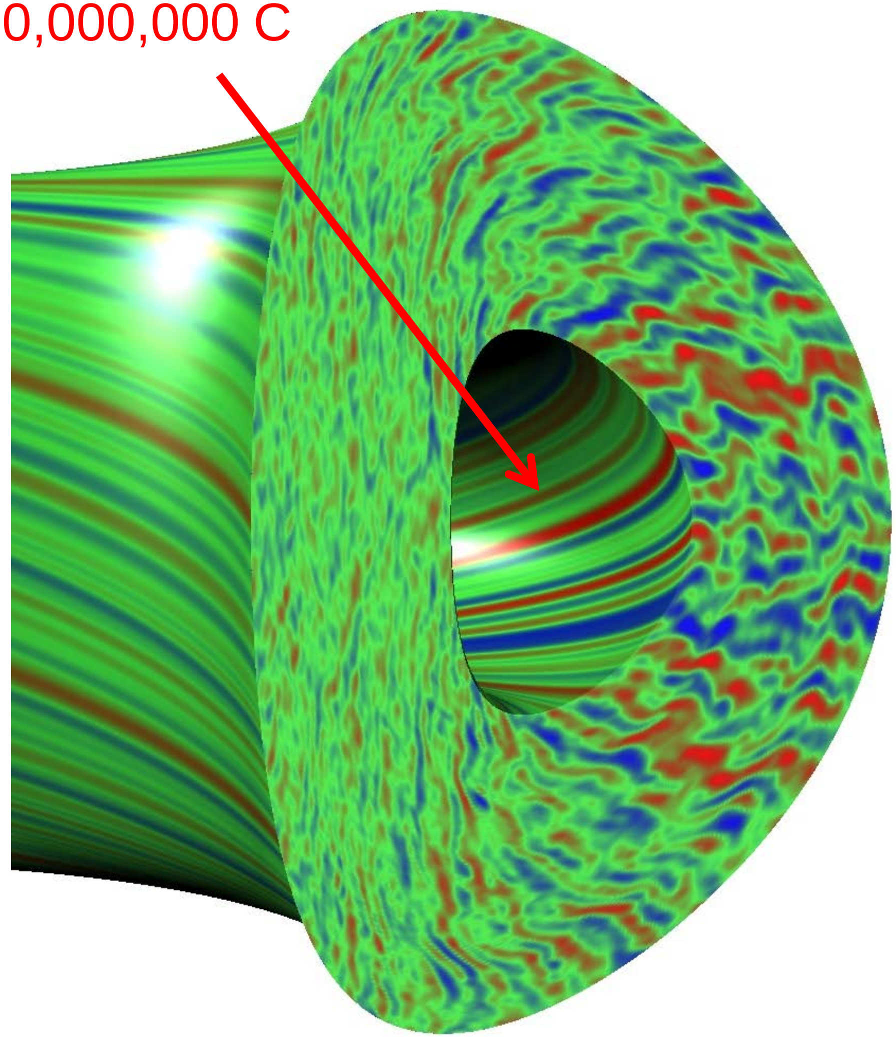
Understanding and controlling turbulence at 100 million degrees

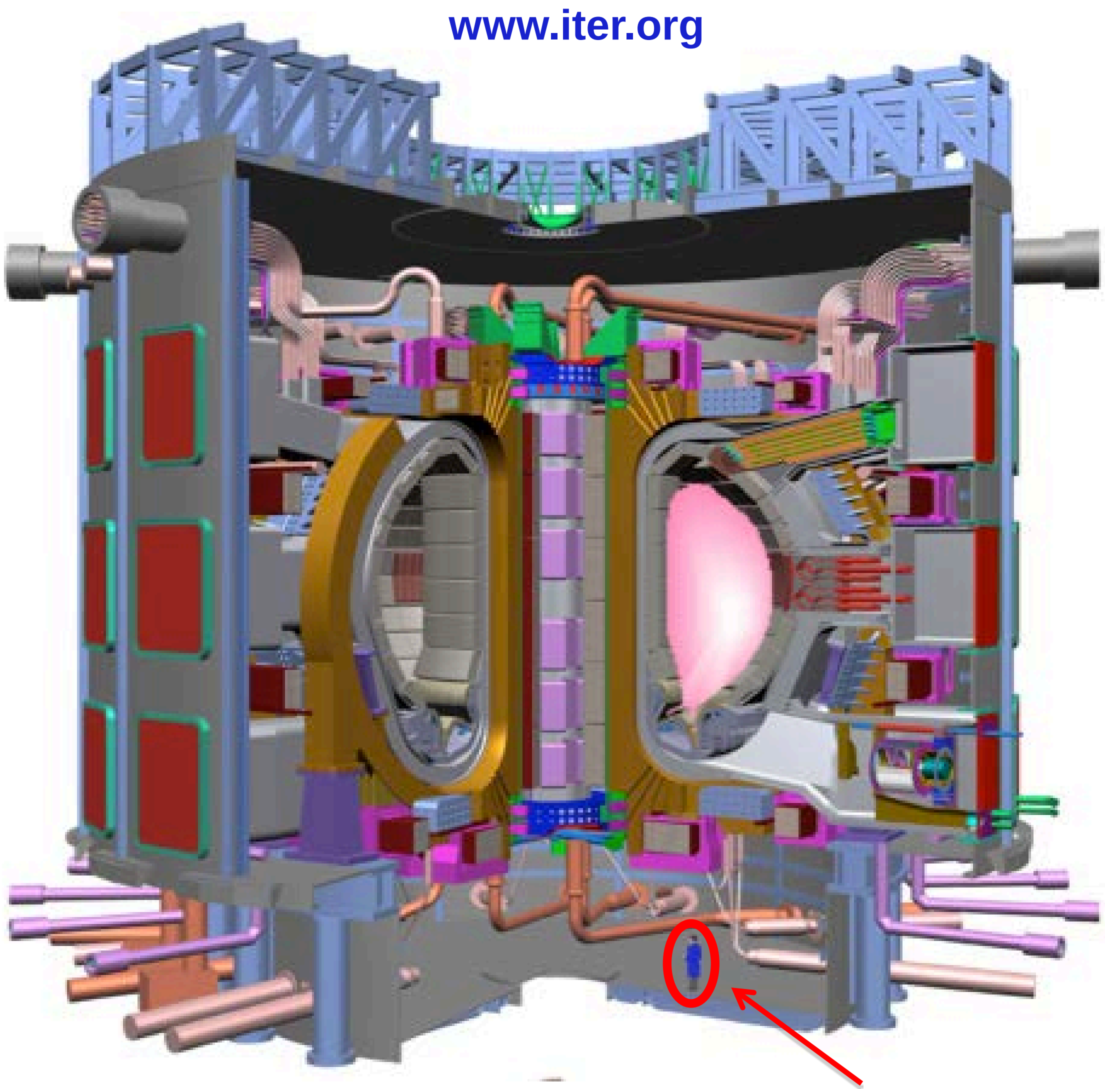
300 C



100,000,000 C



Next step for fusion research is ITER



Goal: deliver ten times the power (500 MW) it consumes (50 MW)

→**large “fusion gain”**

So why is ITER so big?

Need sufficient confinement to maximize fusion gain

Fusion power ~ $(\text{pressure})^2 \times$ volume

Fusion gain

$$\boxed{Q = \frac{P_{\text{fusion}}}{P_{\text{heat}}} \sim \text{pressure} \times \text{confinement time}}$$

$\Rightarrow$ Maximize confinement time

$$\boxed{\text{confinement time} \sim \frac{\text{pressure} \times \text{volume}}{\text{heat loss}}}$$

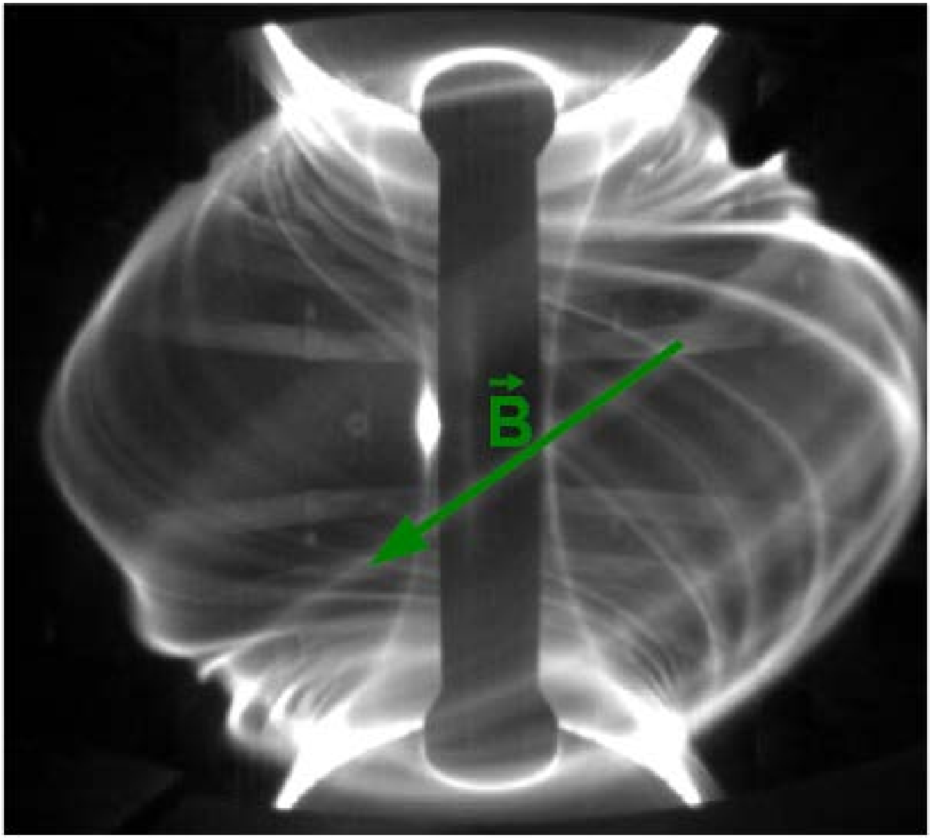
Easiest (conservative) solution – make it big (confinement~V), but…

Increasing volume → larger device = $$$

Better to minimize power required (heat losses) to maintain pressure

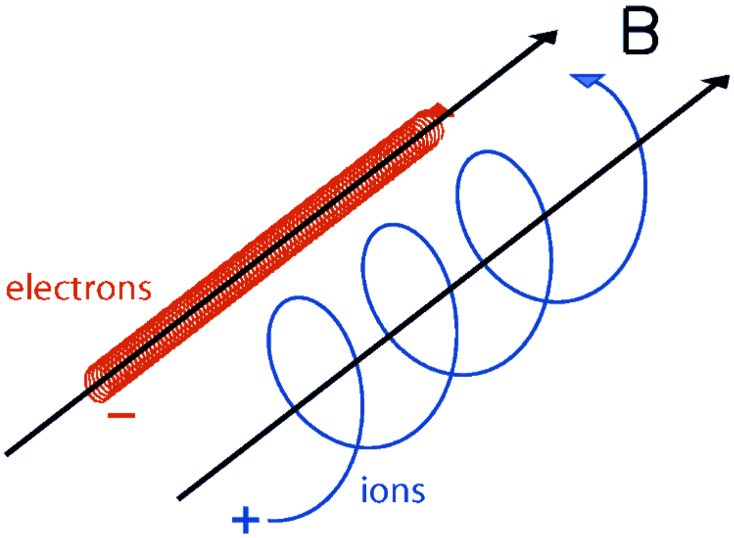
Strong magnetic fields provide confinement

MAST tokamak (UK)



Ions and electrons follow small radius orbits

B = 5 Tesla
T = 100 million C



ρ_{ion}~3 mm
$\rho_{electron}$~0.05 mm

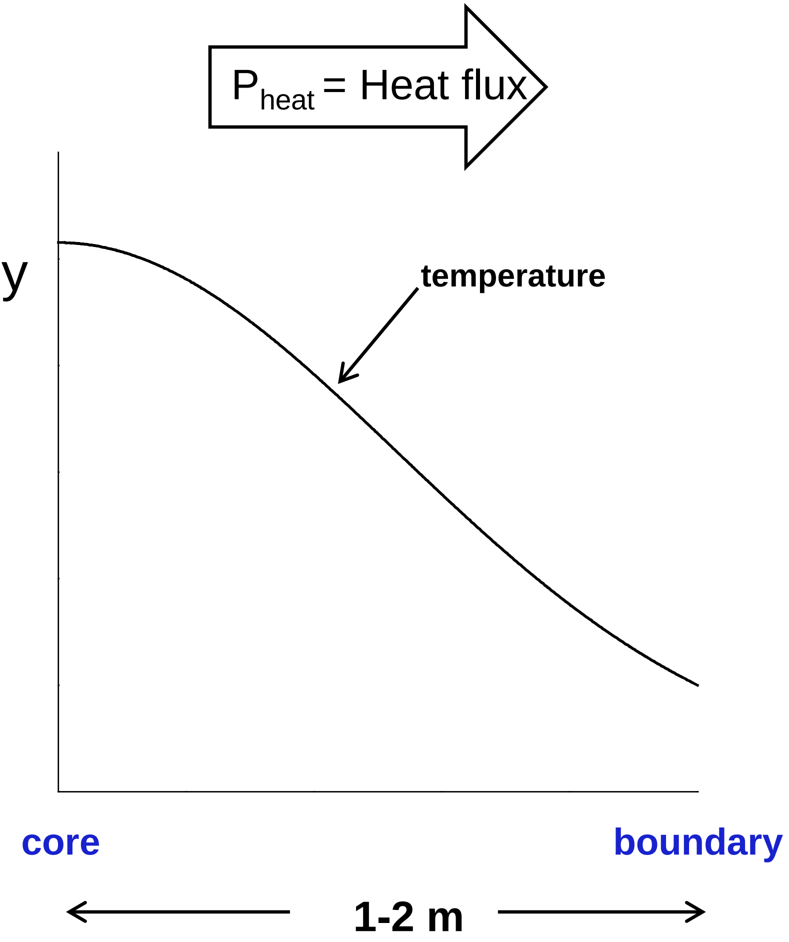
<<

1-2 meter device size

Diffusion by collisions will try to relax gradients

$$\text{heat flux} \sim D_{\text{collisions}} \times (T_{\text{hot}} - T_{\text{cold}})$$

$$D_{\text{collisions}} \sim (\text{step size})^2 \times \text{collision frequency}$$



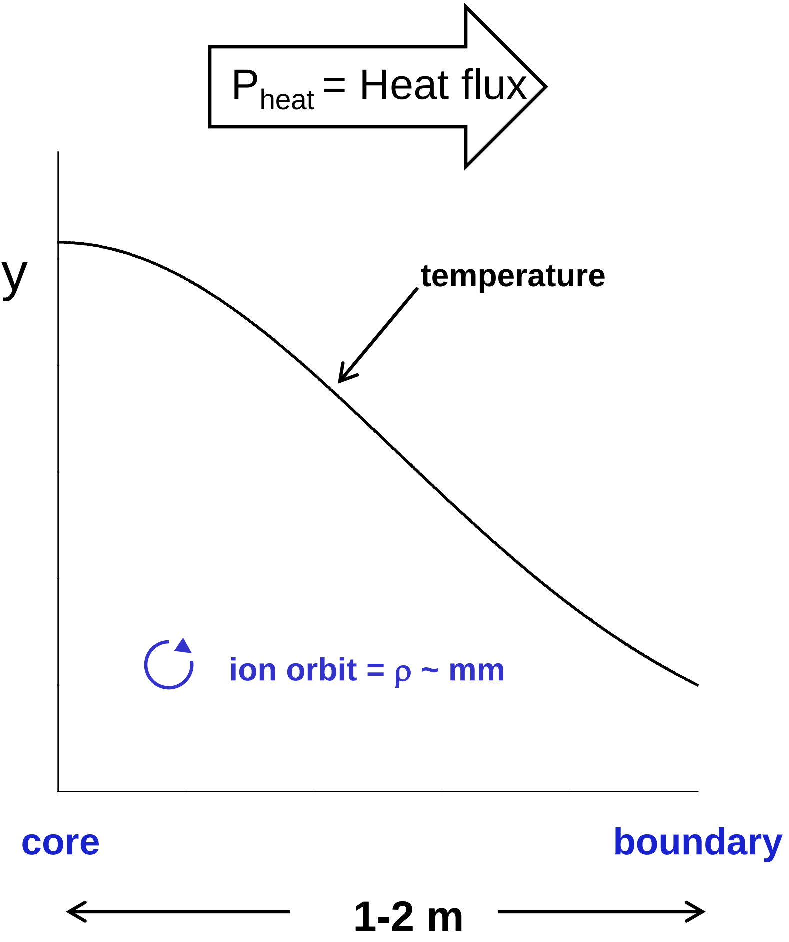
Diffusion by collisions will try to relax gradients

heat flux ~ $D_{\text{collisions}} \times (T_{\text{hot}} - T_{\text{cold}})$

$D_{\text{collisions}}$ ~ (step size)^2 × collision frequency

step size ~ particle orbits ~ mm

collision frequency ~ kHz



P_{heat} = Heat flux

Diffusion by collisions will try to relax gradients

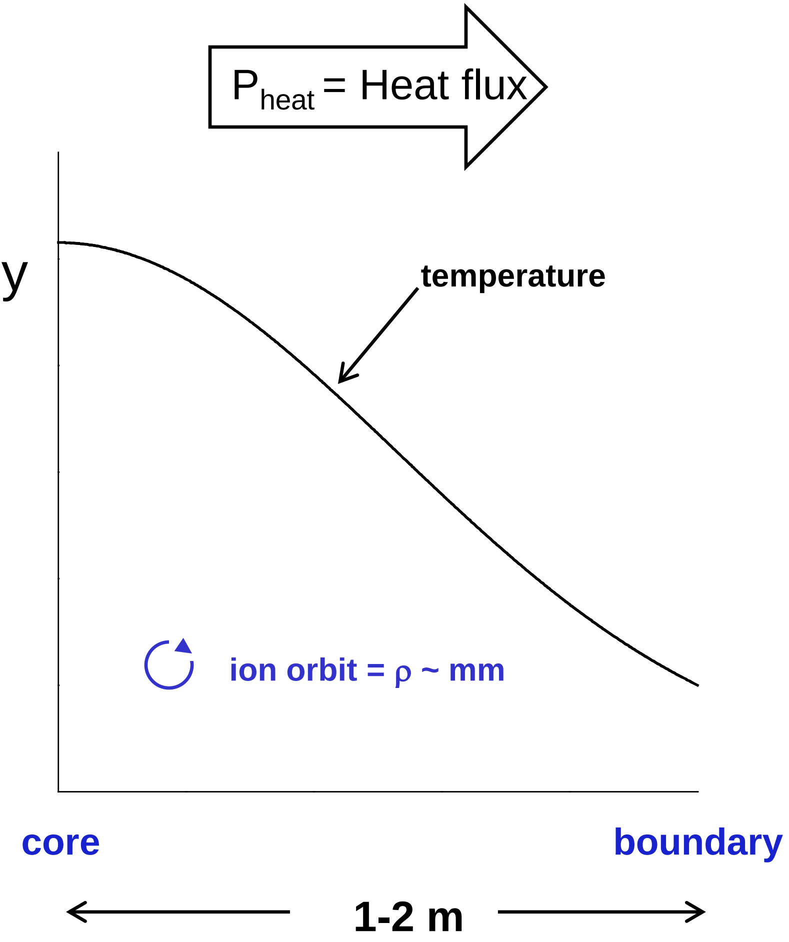
heat flux ~ $D_{\text{collisions}} \times (T_{\text{hot}} - T_{\text{cold}})$

$D_{\text{collisions}}$ ~ (step size)^2 × collision frequency

step size ~ particle orbits ~ mm

collision frequency ~ kHz

$$\boxed{\text{confinement time} \sim \frac{1}{D_{\text{collisions}}}}$$



Collisional confinement time estimate ~ 100 s

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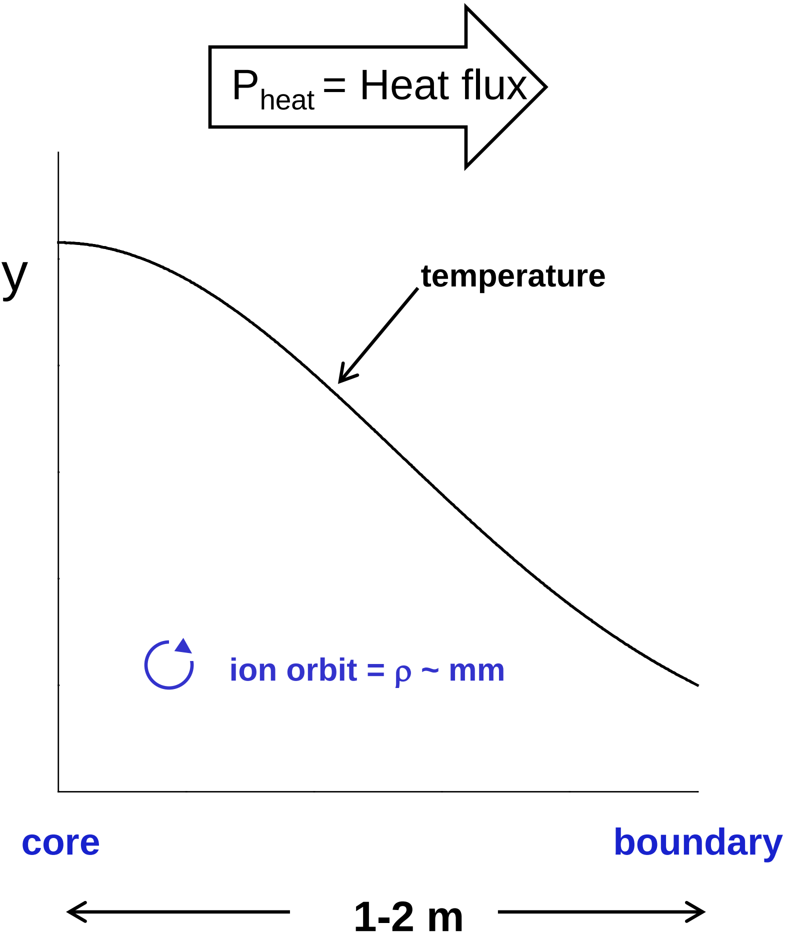
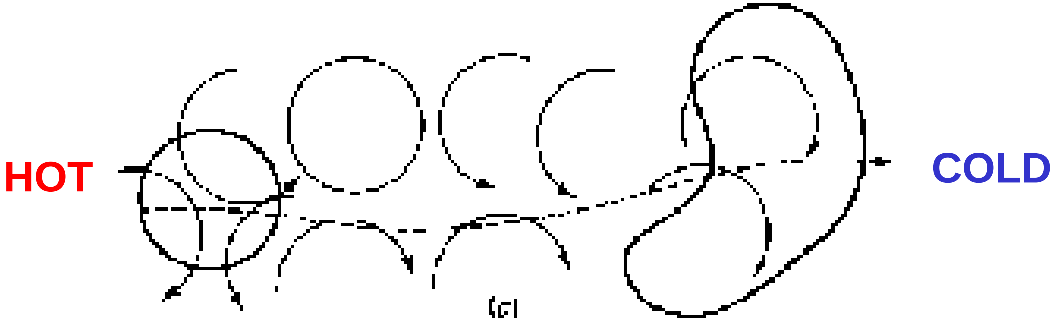


Collisional confinement time estimate ~ 100 s

Experimental confinement time ~ 0.1 s

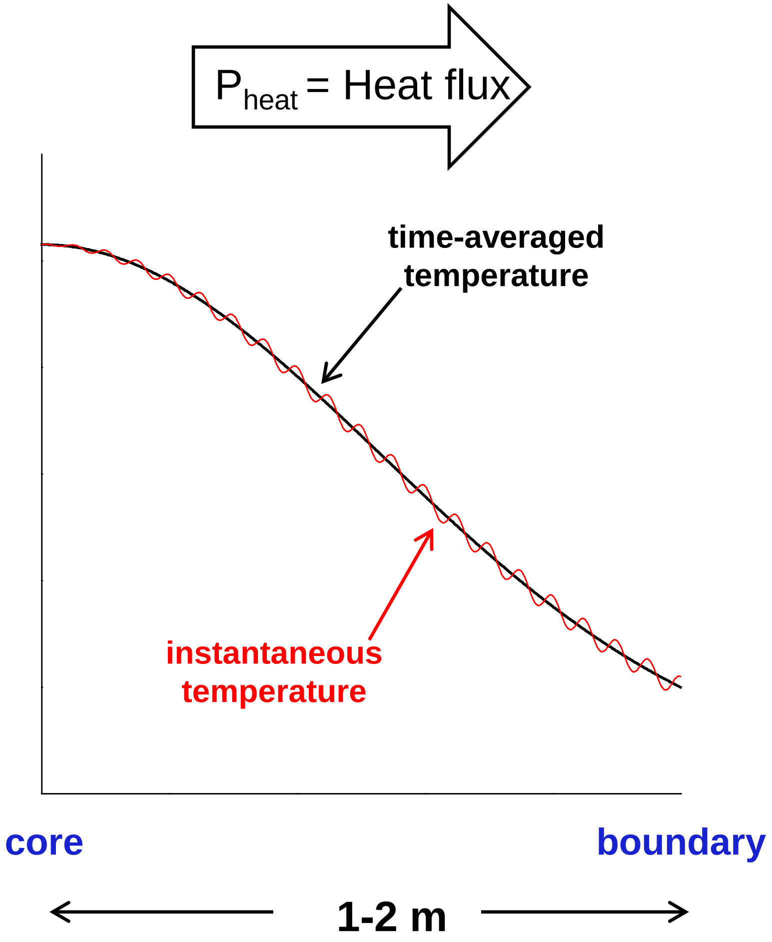
Increasing gradients eventually cause small scale instability → turbulence



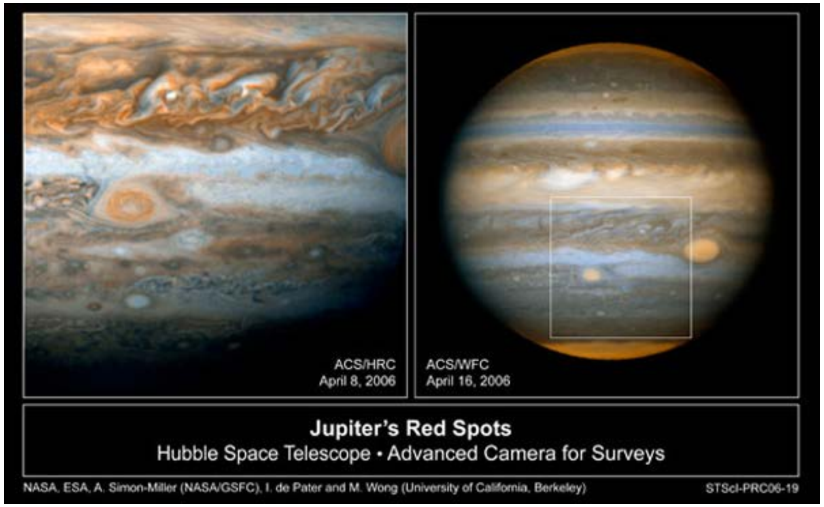
- Turbulent “eddies” → random velocity fluctuations mix hot and cold

- Can be small size, small amplitude (<1%)

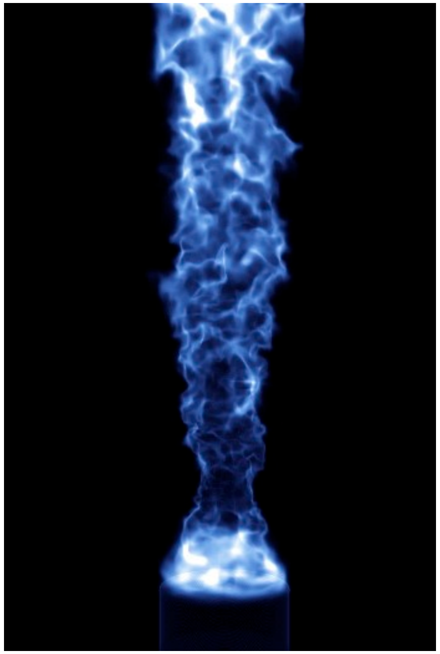
But still effective at transport



Turbulence found throughout the universe - not surprising to find it in tokamaks



Steve Morr

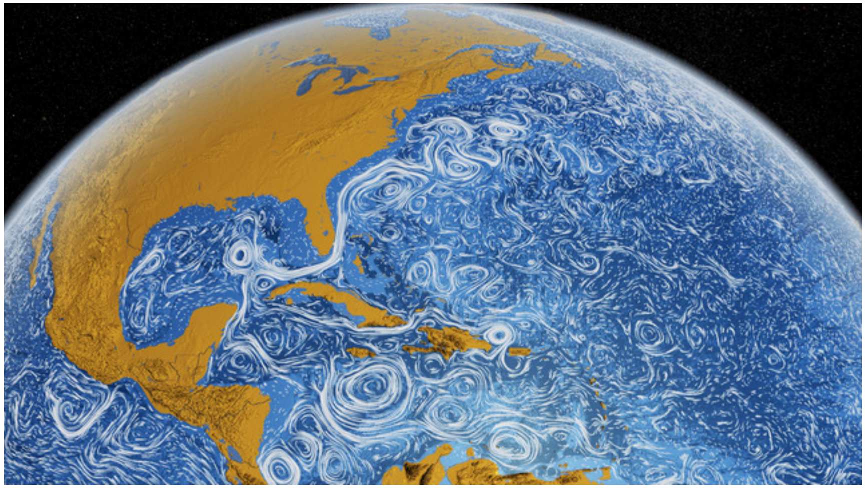


Universität Duisburg-Essen

- Seemingly random or chaotic flows
  - Deterministic yet unpredictable (e.g. daily weather)
  - Understand through statistical approach (e.g. climate)
- Exists at multiple length & time scales
  - Energy at large scales
  - Dissipated by friction/viscosity at small scales
- Leads to enhanced mixing & transport

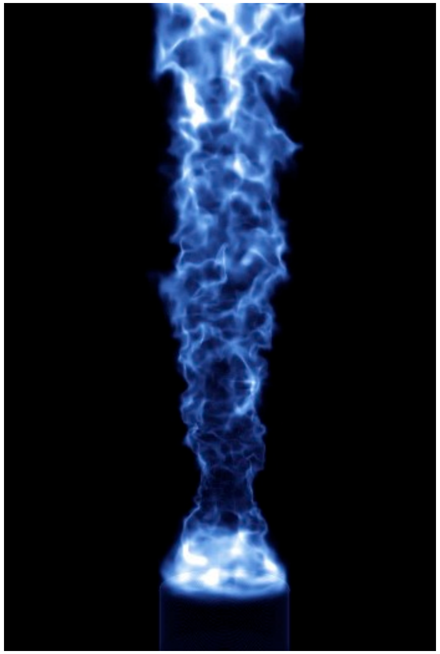
  ⇒ **Why we're interested in magnetic fusion**

Turbulence found throughout the universe - not surprising to find it in tokamaks



NASA

Steve Morr



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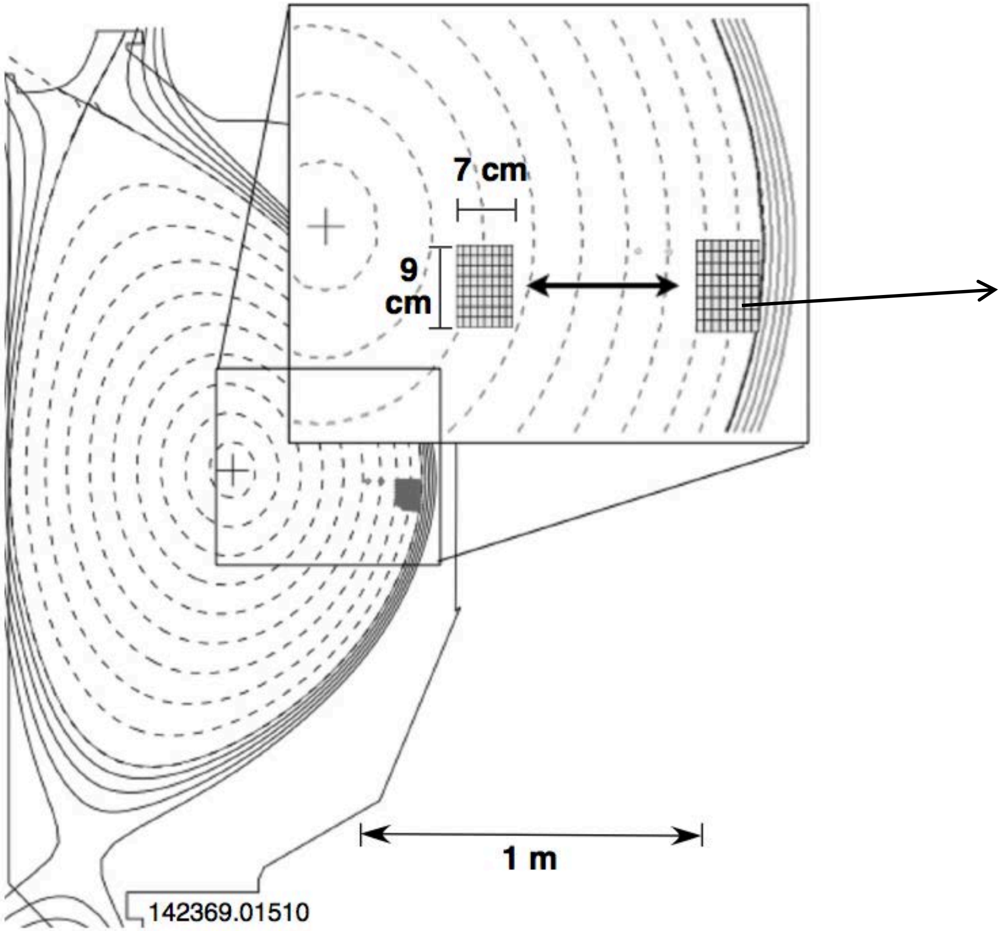
  $\Rightarrow$ **Why we’re interested in magnetic fusion**

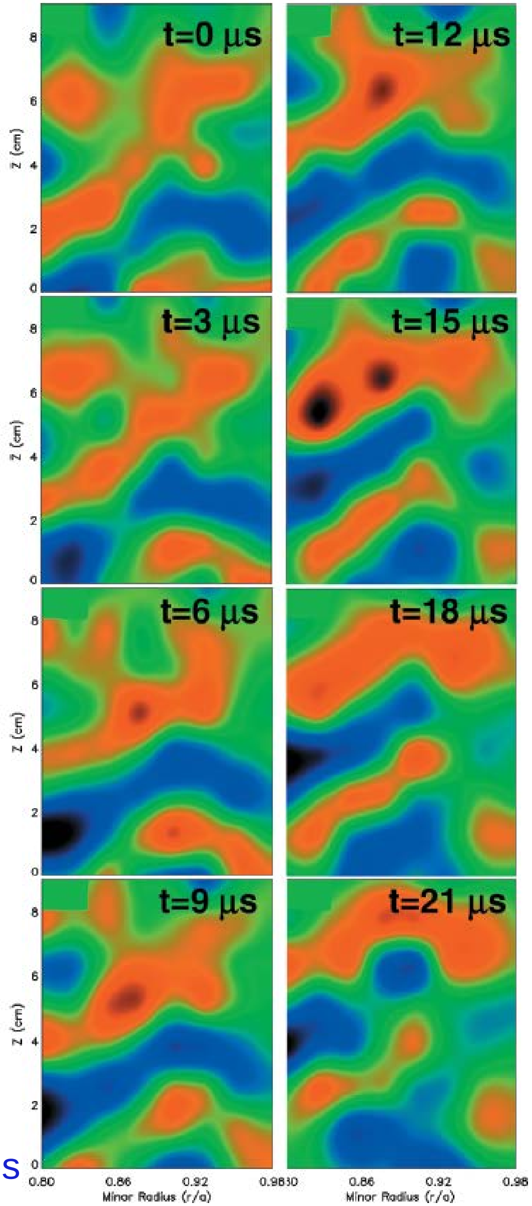
The Great Wave off Kanagawa, Hokusai (1831)

Spectroscopic imaging provides a 2D picture of turbulence in tokamaks: cm spatial scales, μs time scales, <1% amplitude

- Utilize interaction of neutral atoms with charged particles to measure density

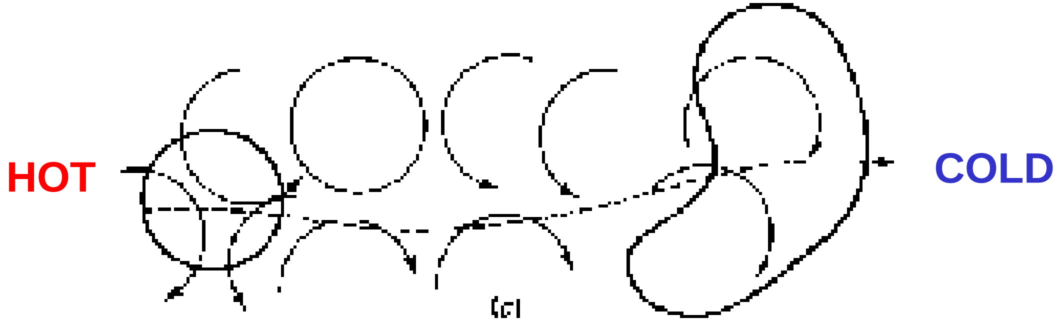
DIII-D tokamak (General Atomics)





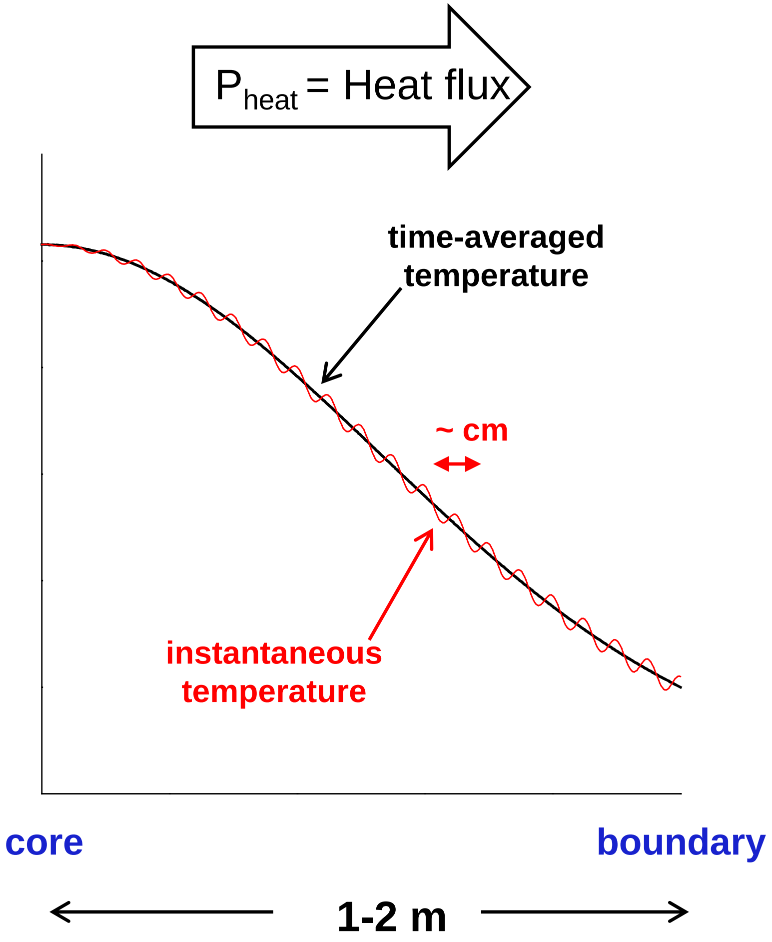
Movies at: https://fusion.gat.com/global/BESMovies

Rough estimate of turbulent diffusivity indicates it's a plausible explanation for confinement



- $D_{\text{turbulence}}$ ~ (step size)^2 × "collision frequency"

  step size ~ 5-7 particle orbits ~ cm's
  "collision frequency" ~ 100 kHz



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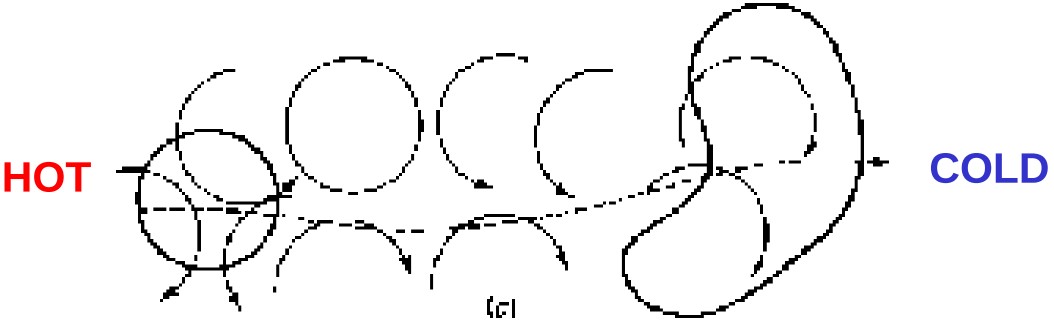
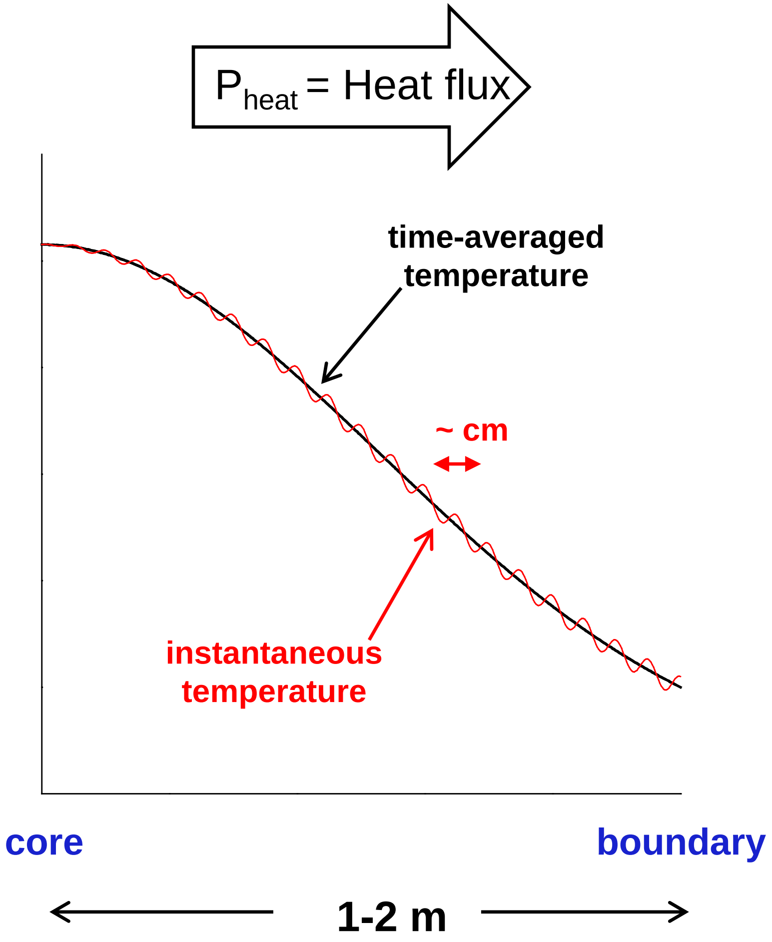


- $D_{\text{turbulence}}$ ~ (step size)^2 × "collision frequency"

step size ~ 5-7 particle orbits ~ cm's
"collision frequency" ~ 100 kHz

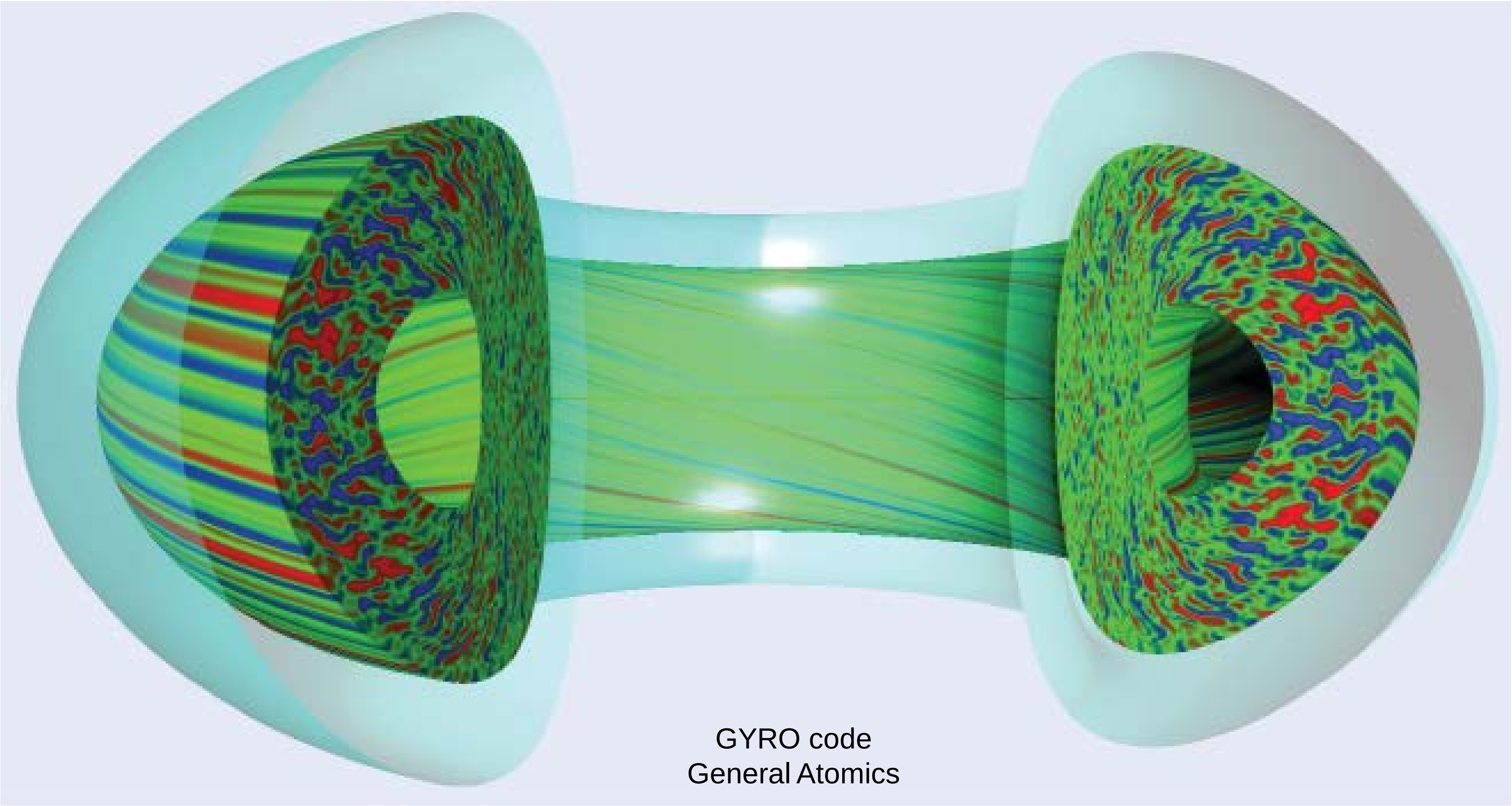
$$\boxed{\text{confinement time} \sim \frac{1}{D_{\text{turbulence}}}}$$



Turbulence confinement time estimate ~ 0.1 s
Experimental confinement time ~ 0.1 s

Interpretation aided by theory and nonlinear simulations

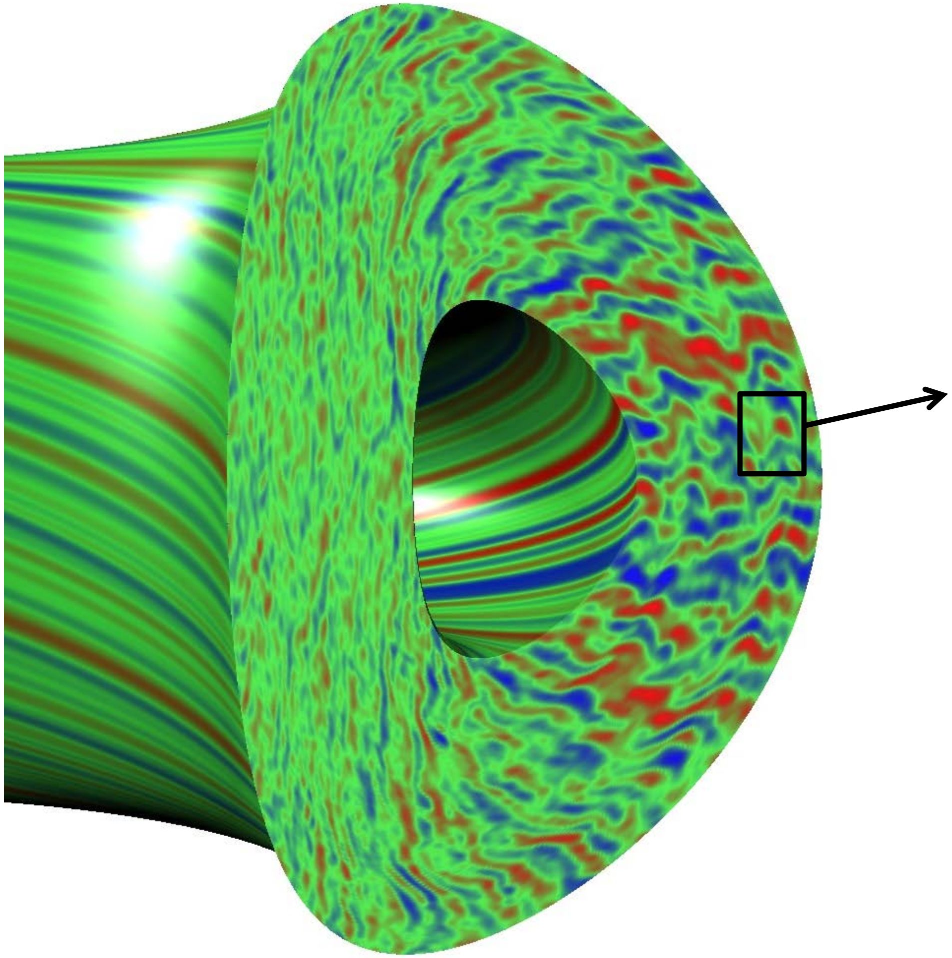
- State-of-the-art kinetic codes, 3D space + 2D particle motion
- Self-consistent electric and magnetic fields (Maxwell’s equations)
  - 100’s millions of grid points, or 10’s billions of particle markers
  - Millions of cpu-hours, exploiting up to 200,000 cpu’s



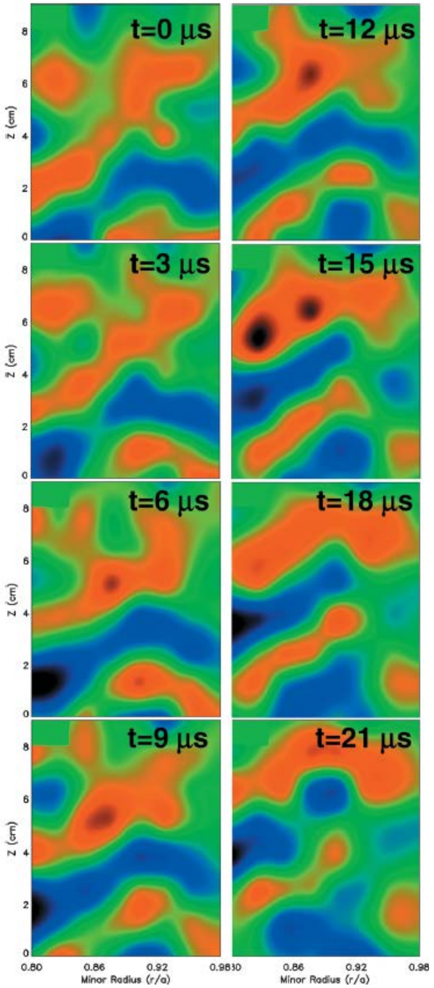
GYRO code
General Atomics

Physically realistic nonlinear turbulence simulations now capable of reproducing measured behavior

Simulation



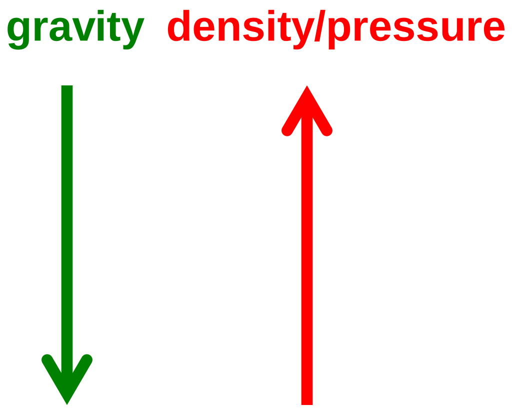
Experiment



Movies at: https://fusion.gat.com/theory/Gyromovies

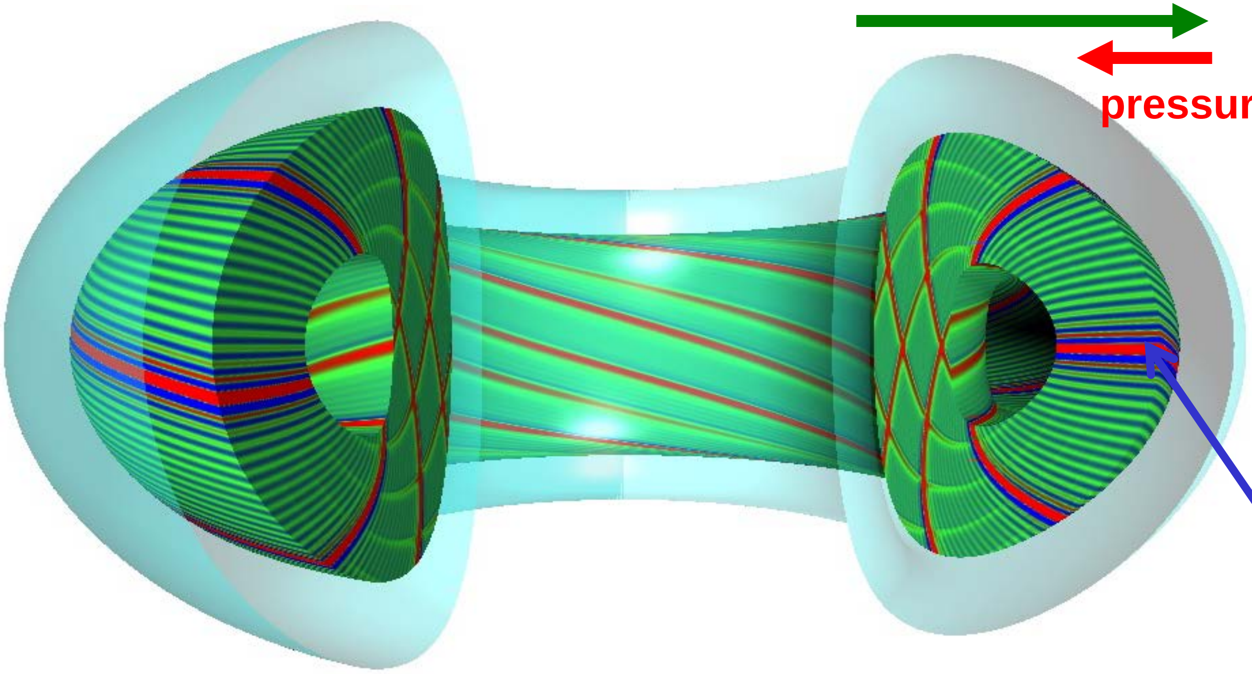
Analogy for turbulence in tokamaks - density gradient in the presence of gravity

- Higher density on top of lower density, with gravity acting downwards (Rayleigh-Taylor instability)
- Any small perturbation becomes unstable
- Convection mixes regions of different density



gravity **density/pressure**

Centrifugal force in toroidal field acts like an effective gravity



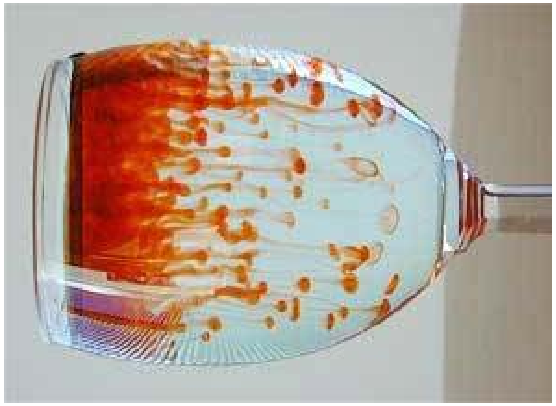
centrifugal force

→effective gravity

pressure

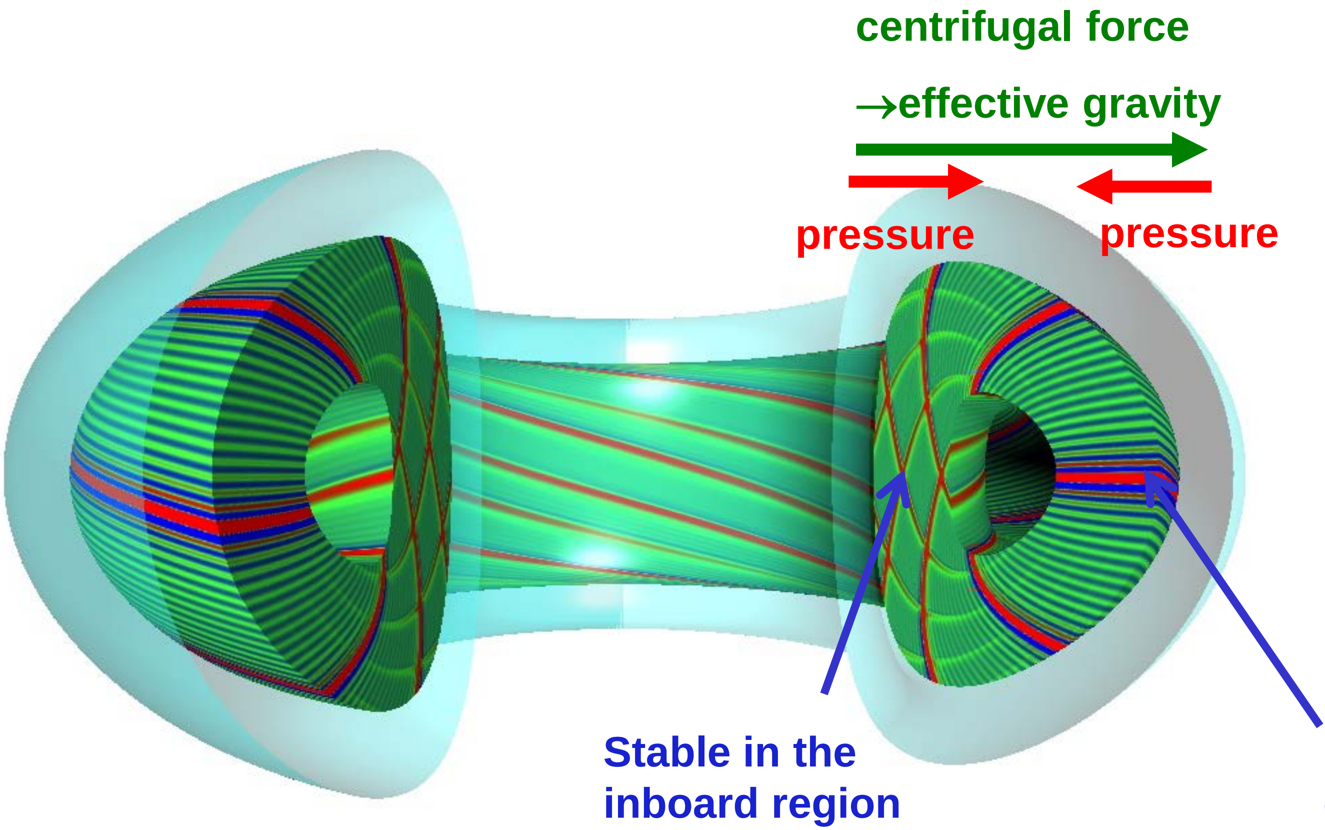
gravity

pressure



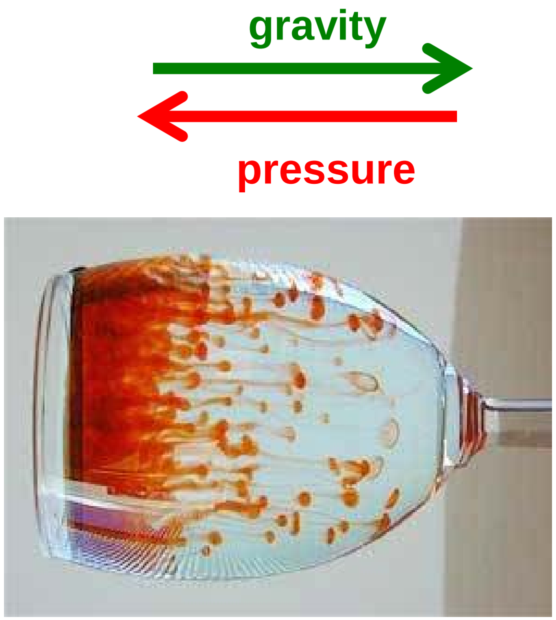
Unstable in the outboard region

Centrifugal force in toroidal field acts like an effective gravity



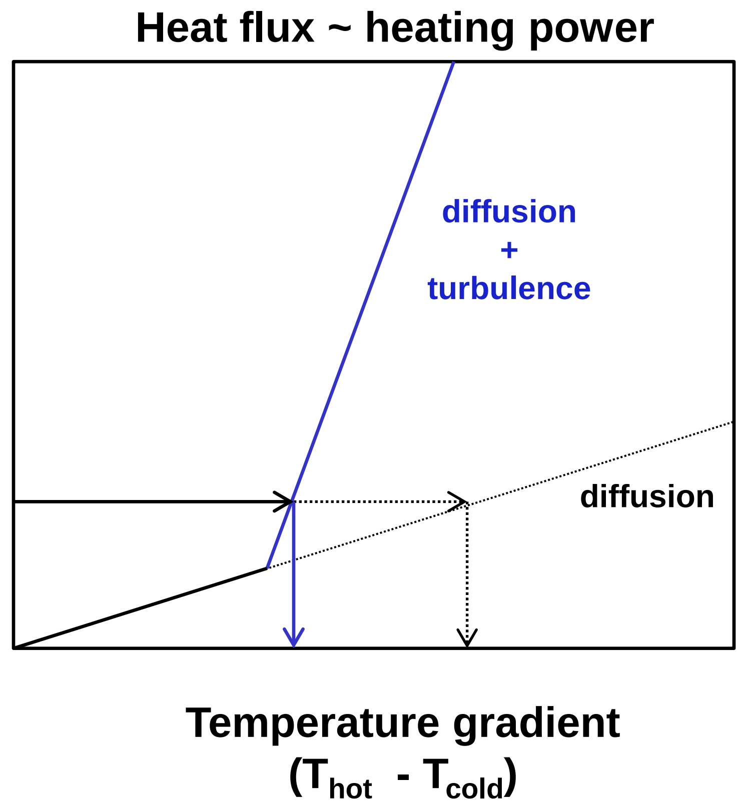
Stable in the inboard region

Unstable in the outboard region



Fast parallel dynamics + helical field lines provides stability → <u>gradient must surpass a threshold for instability</u>

Onset of turbulence reduces the achieved temperature that would have been present due only to diffusion



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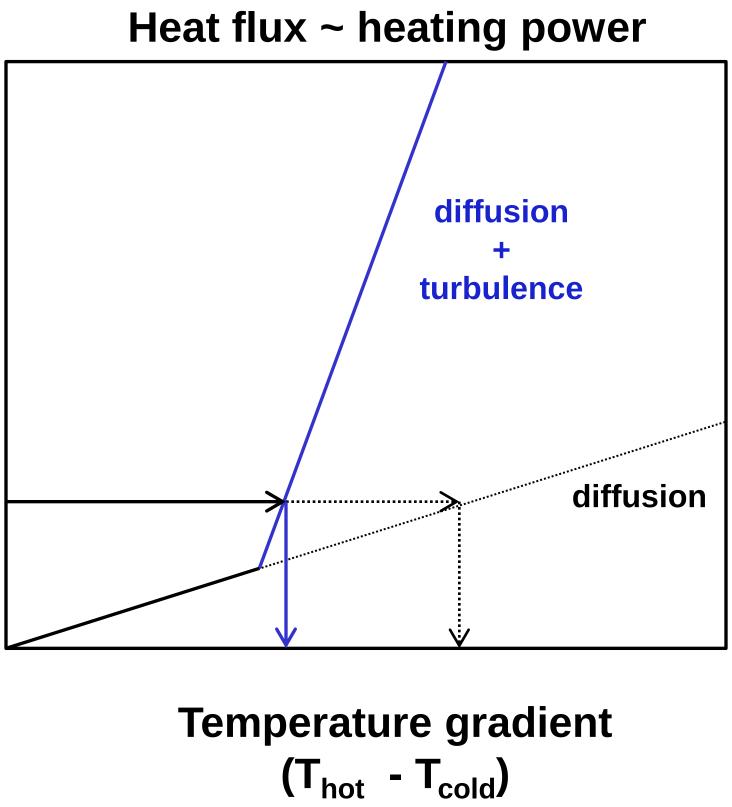
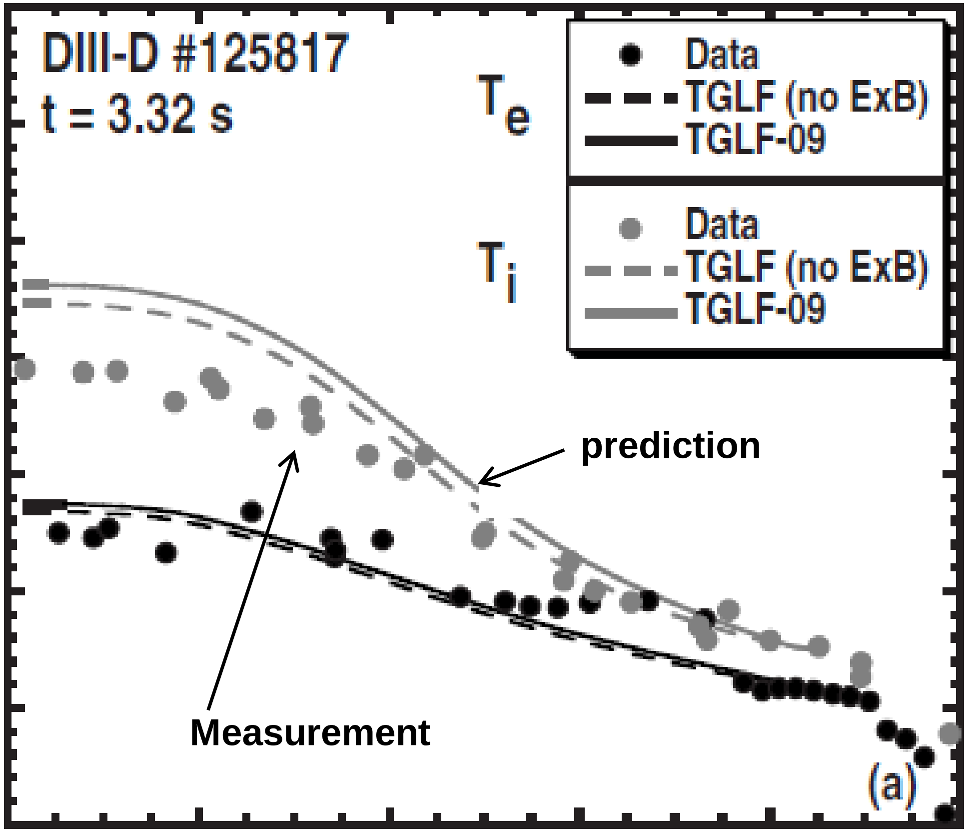


Analogous to convective transport when heating a fluid from below … boiling water (before the boiling)

Nonlinear simulations have improved quantitative predictive capability

Temperature



40 million C →

prediction

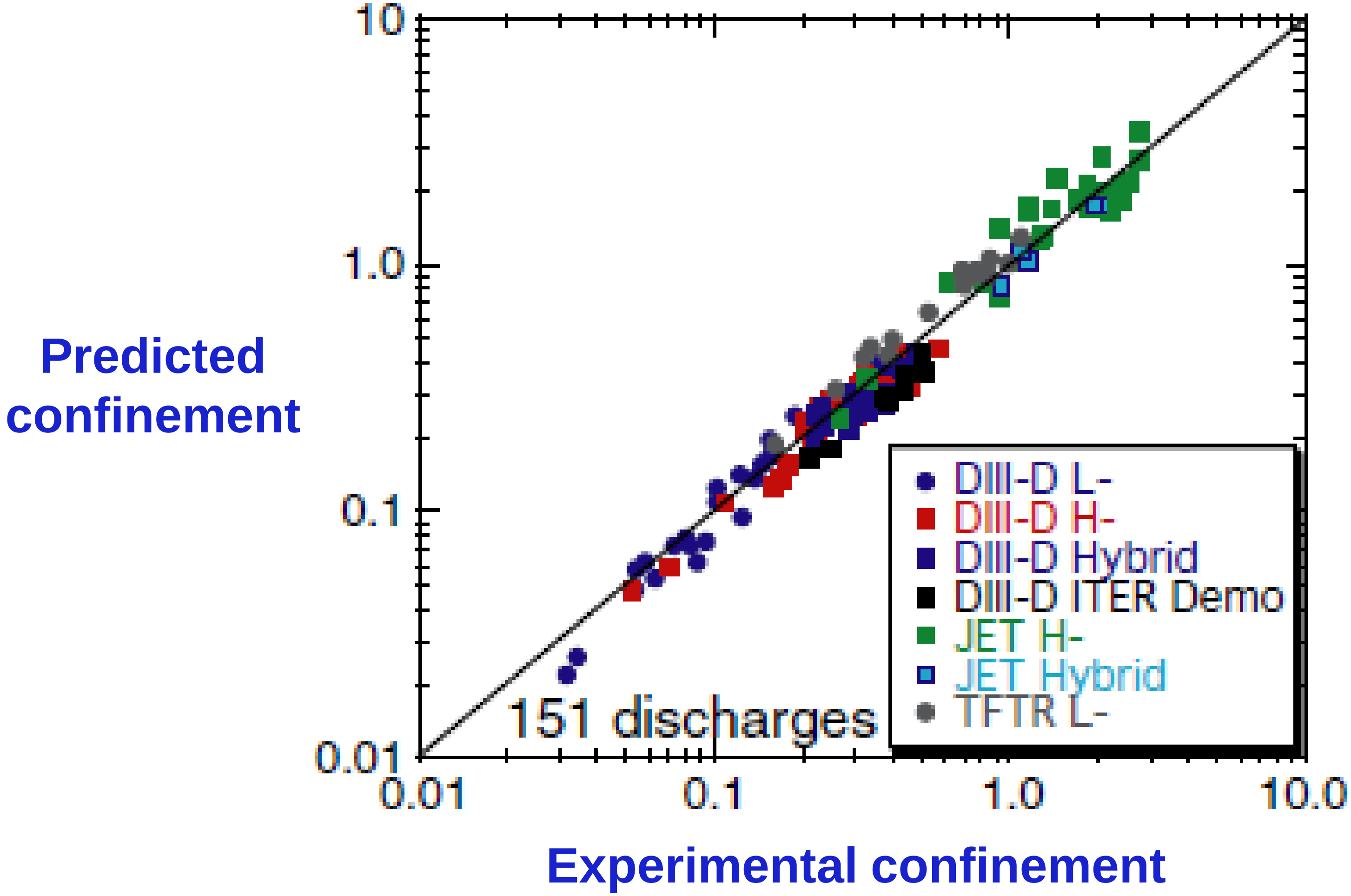
Measurement

core **boundary**

Kinsey, 2010

- Remember, predicting “climate” not “weather” – only concerned with statistical averages

Success in predicting confinement in multiple tokamaks around the world → confidence in ITER



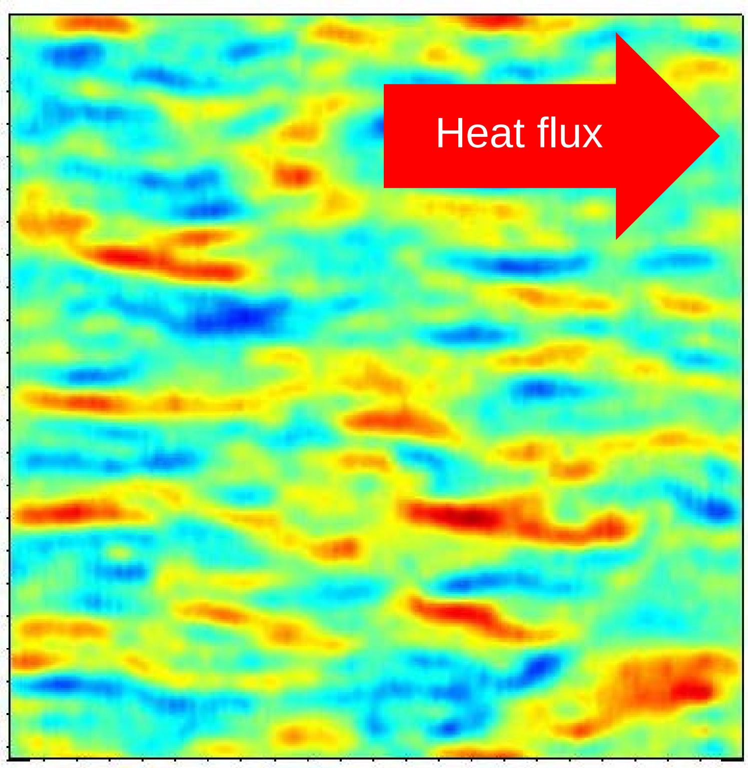
Kinsey, 2010

- **Considerable work remains to validate the kinetic physics responsible for turbulence, enabling more comprehensive predictions**

Equilibrium sheared flows can tear apart turbulent eddies, reduce turbulence → improve confinement

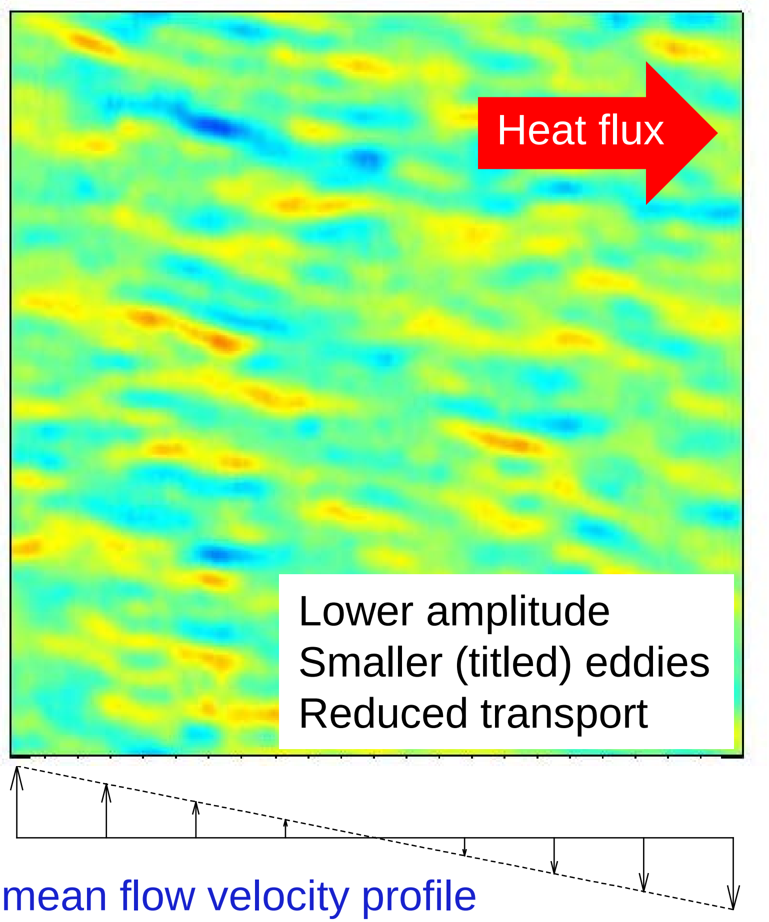
- Strong flows often present
- **Heat loss through ions no longer turbulent, collision dominated (good!)**

Snapshot of density without flow shear



100 ion radii
6,000 electron radii
~50 cm

Snapshot of density with flow shear



Lower amplitude
Smaller (titled) eddies
Reduced transport

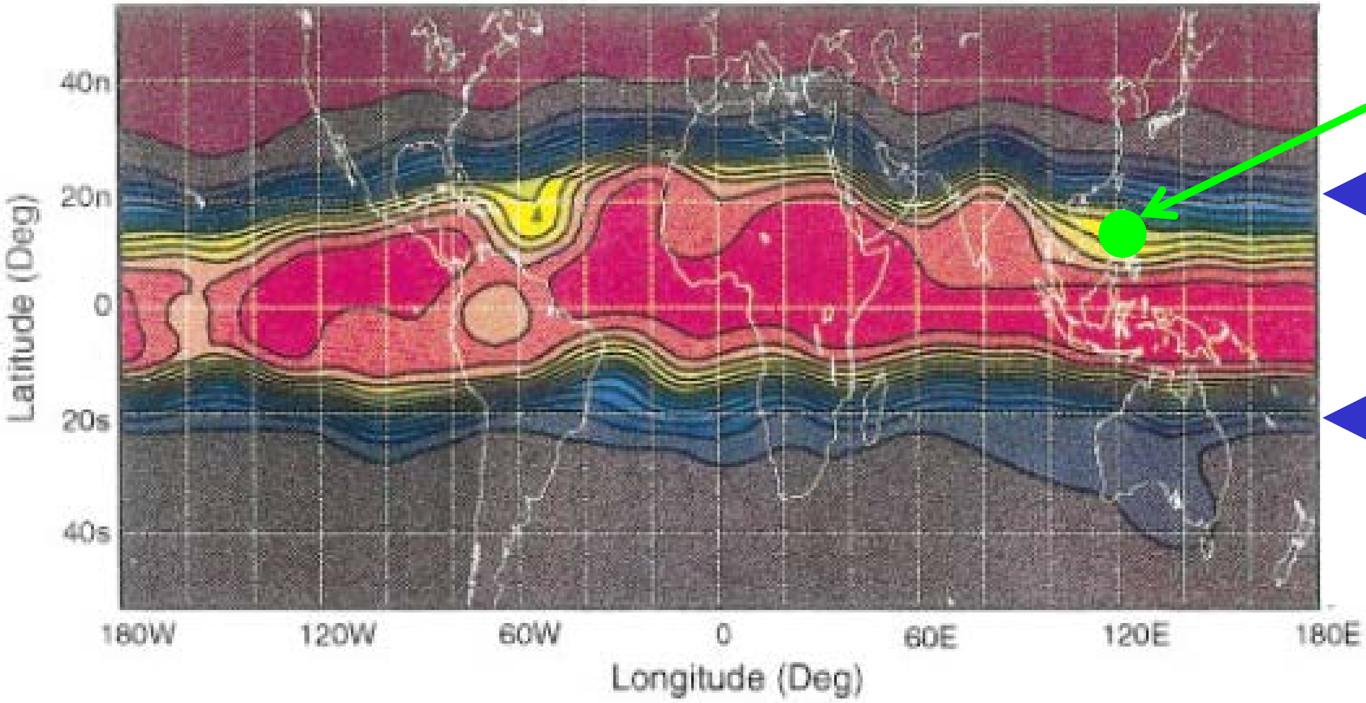
mean flow velocity profile

In neutral fluids, sheared flows are usually the source of free energy to drive turbulence

- Thin (quasi-2D) atmosphere in axisymmetric geometry of rotating planets similar to tokamak plasma turbulence

- Stratospheric ash from Mt. Pinatubo eruption (1991) spread rapidly around equator, **but confined in latitude by flow shear**

Aerosol concentration



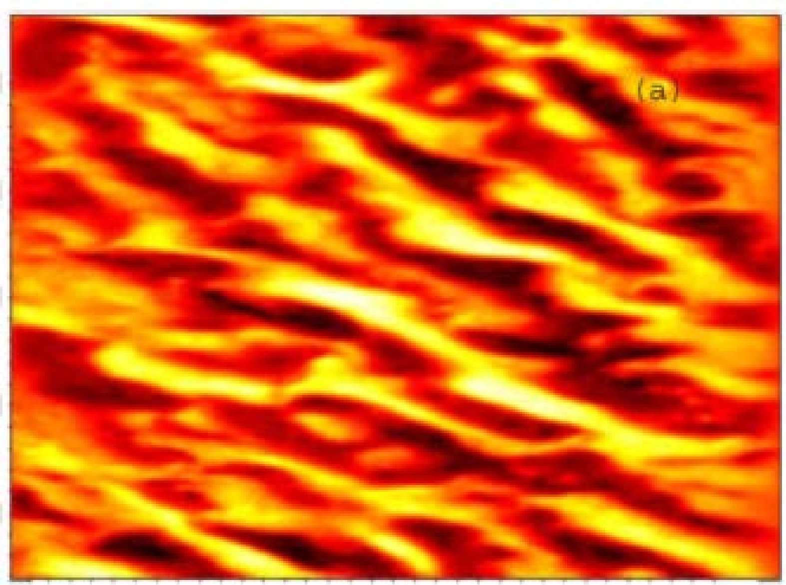
Large shear in stratospheric equatorial jet

(Trepte, 1993)

Flow shear reduces turbulence at ion (cm) scales, electron (mm) scale turbulence remains

- Still provides heat loss → **plug one leaky hole, another one opens!**

density fluctuations



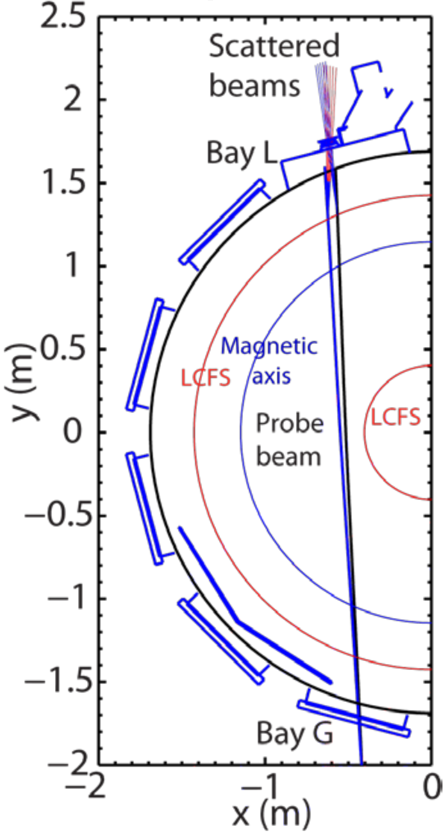
6 ion radii
360 electron radii
~2 cm

Flow shear reduces turbulence at ion (cm) scales, electron (mm) scale turbulence remains

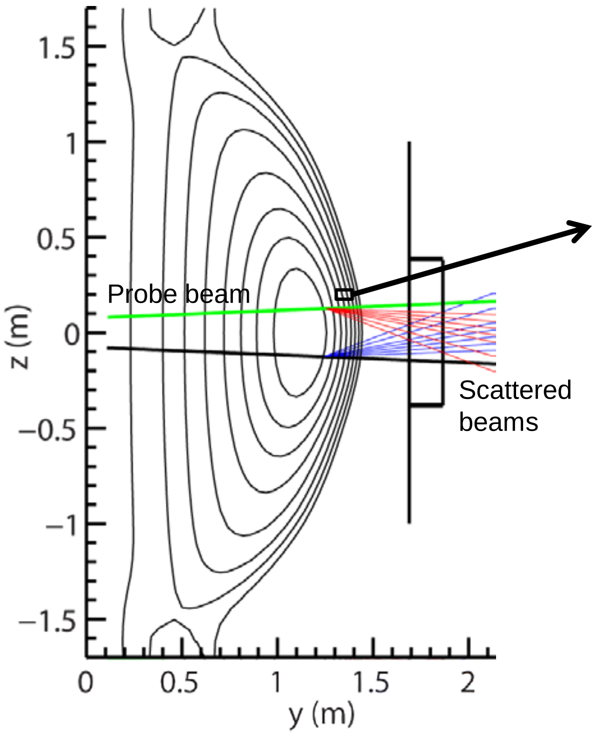
- Still provides heat loss → **plug one leaky hole, another one opens!**

NSTX tokamak (PPPL)

Top View

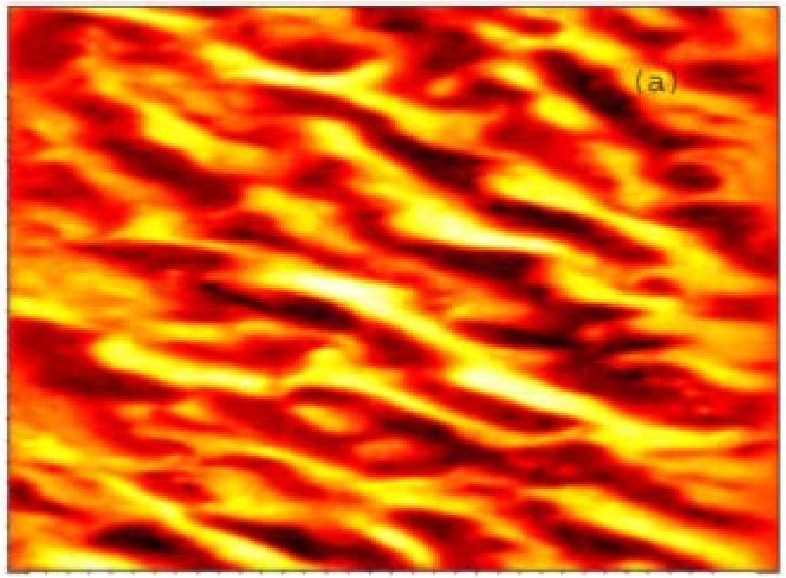


Side View



UC-Davis

density fluctuations



6 ion radii

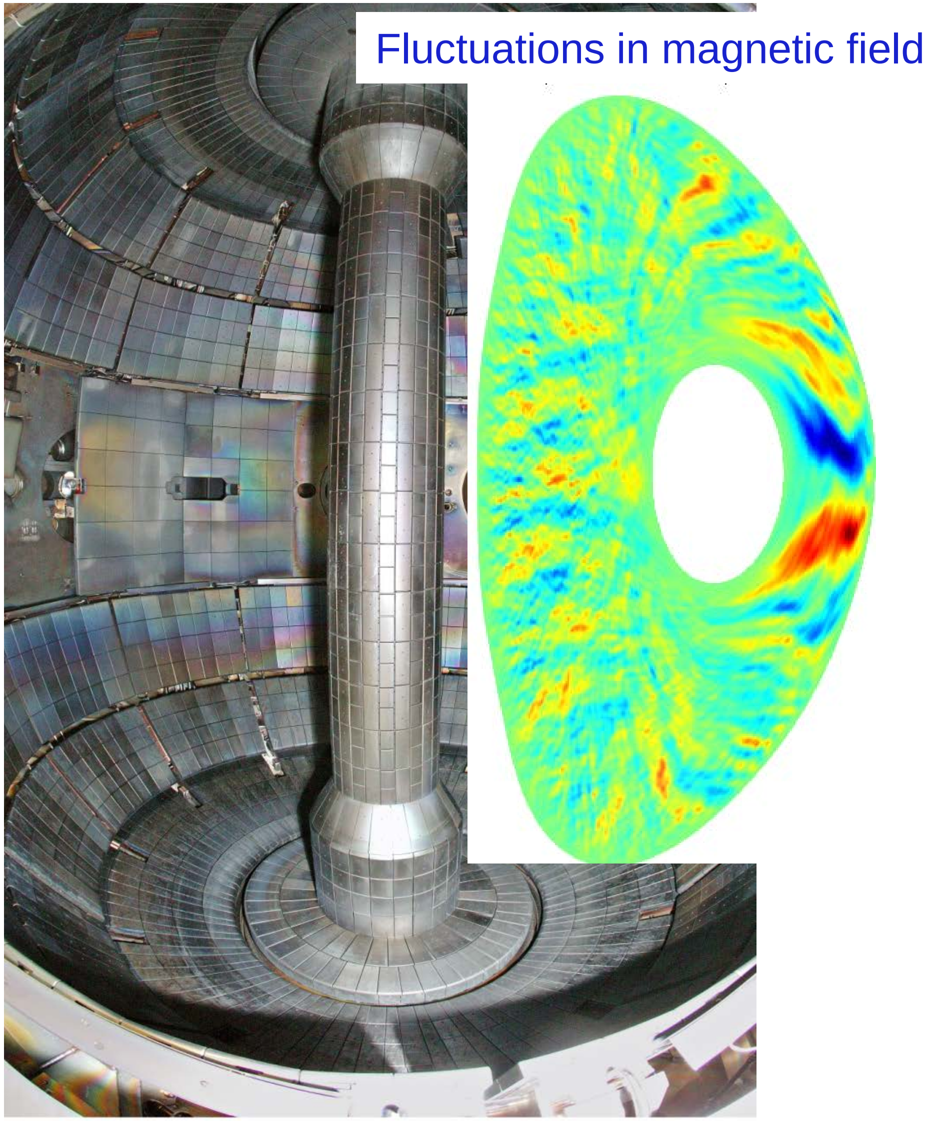
360 electron radii

~2 cm

- Challenge to diagnosis even smaller fluctuations – e.g. microwave scattering

At high pressure, magnetic turbulence becomes important → another leaky hole to plug!

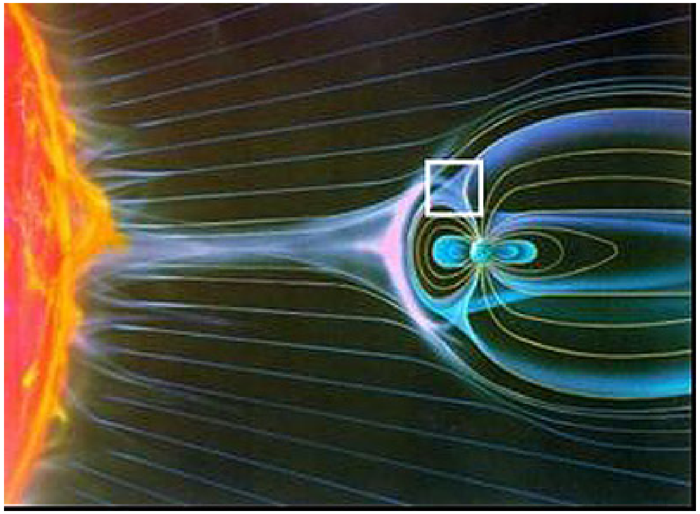
NSTX (PPPL)



- Can we optimize pressure & flow shear to reduce all “flavors” of turbulence?
- **NSTX presently undergoing an upgrade (stronger magnetic field, heating power) to test these predictions (late 2014)**
- <u>Open challenge</u>- measure internal magnetic fluctuations

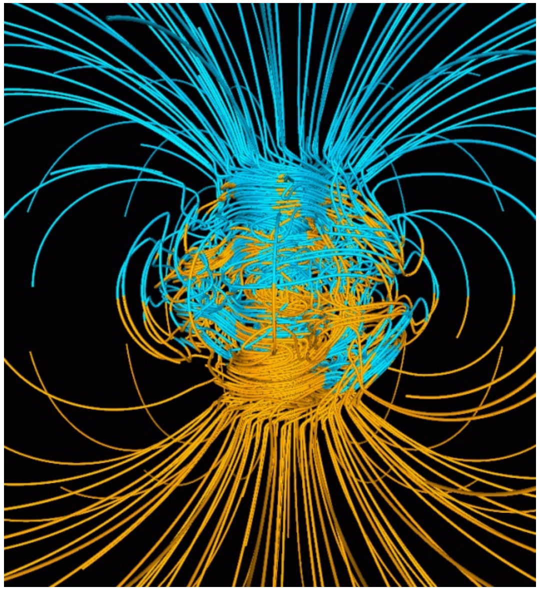
Turbulence plays a role in other plasmas throughout the universe, many possible areas of overlap

- Magnetosphere around earth
- Solar atmosphere, solar wind



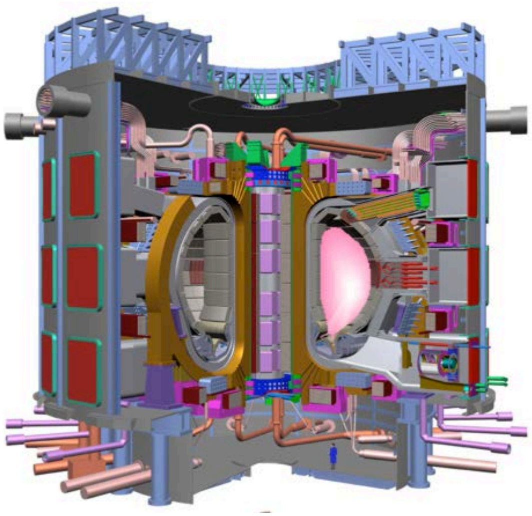
European Space Agency

- Accretion disks around black holes
- Origin of planetary, stellar and cosmic magnetic fields
- Plasma arcs, plasma processing
- Magnetic dynamo in earth's core

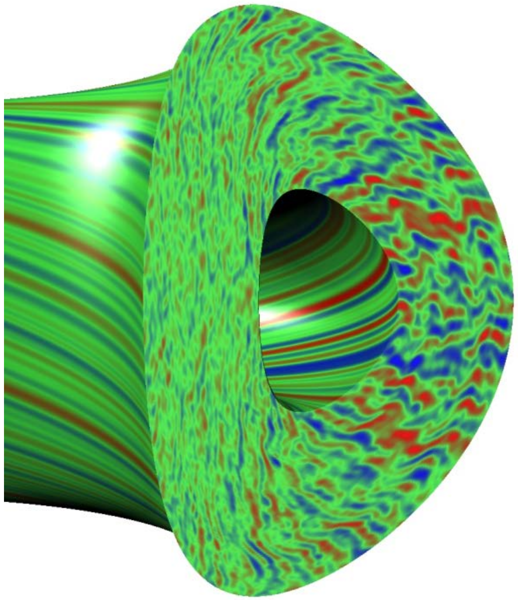


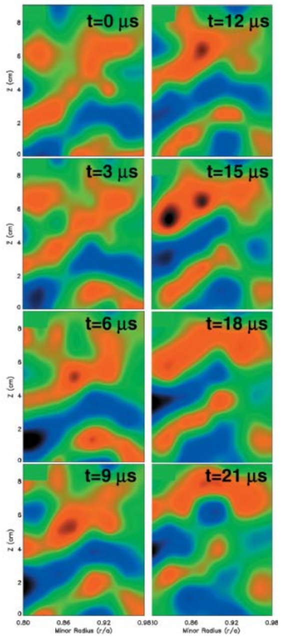
(G. A. Glatzmaier/Los Alamos National Lab)

With our present understanding of turbulent transport, confident ITER will demonstrate ~500 MW fusion power



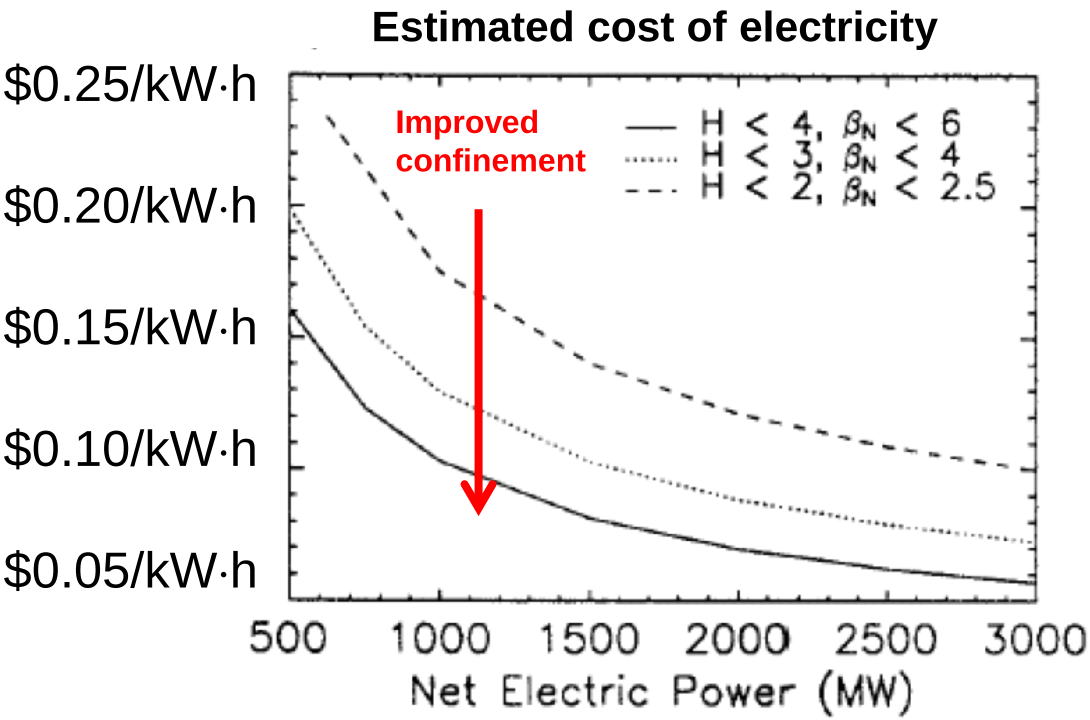
- But ITER is big = $$$
- **Frontier is to optimize confinement utilizing new physics understanding, innovative diagnostics and simulations**
- Will eventually have to cope with exhausting power to plasma facing components – Hartwig, next talk





Thank you!

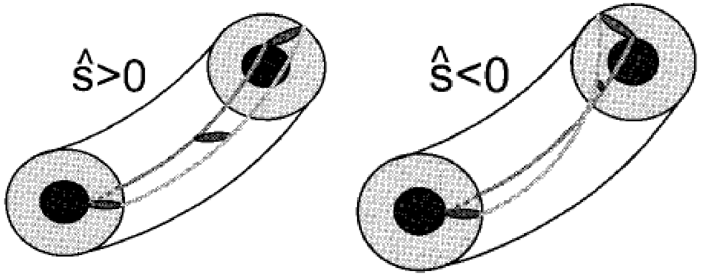
Improved confinement means more fusion power for a smaller device = lower Cost of Electricity (COE)



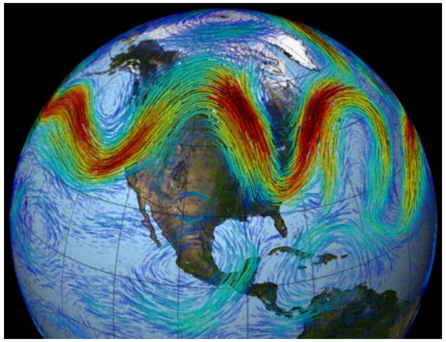
Galambos, 1995

- Caveats: more fusion power for a given device size = more power on plasma facing components – not obvious how to cope with (Hartwig, next talk…)

In addition to flow shear, similar improvements achieved due to other mechanisms



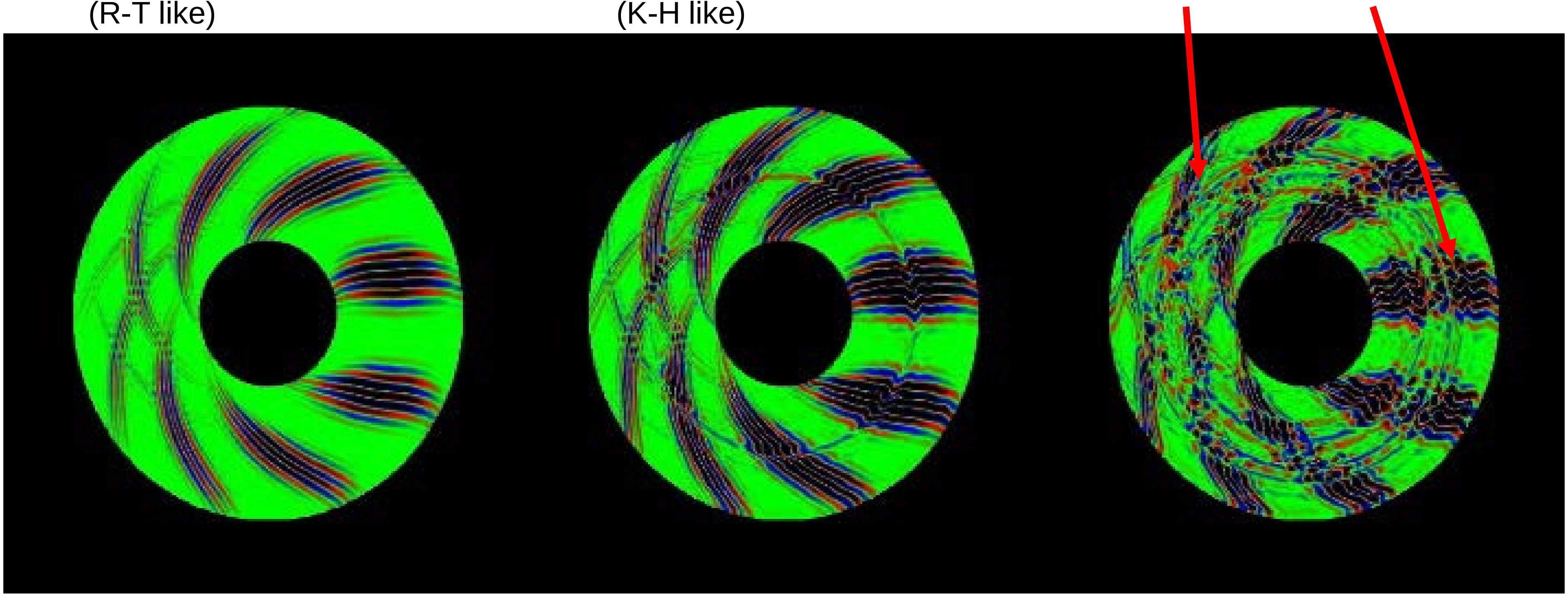
- Magnetic topology/shaping
  - Exploit helical field lines + fast parallel motion to twist eddies apart


NASA

- Self-driven “zonal flows”
  - Turbulence drives benign zonal flows that act as self-regulating energy sink
  - Analogous to jet stream

- Presence of high energy ions can reduce turbulence
  - Favorable for ITER and reactors with fusion produced high energy α’s (Helium nuclei)

Self-generated “zonal flows” impact saturation of turbulence and overall transport



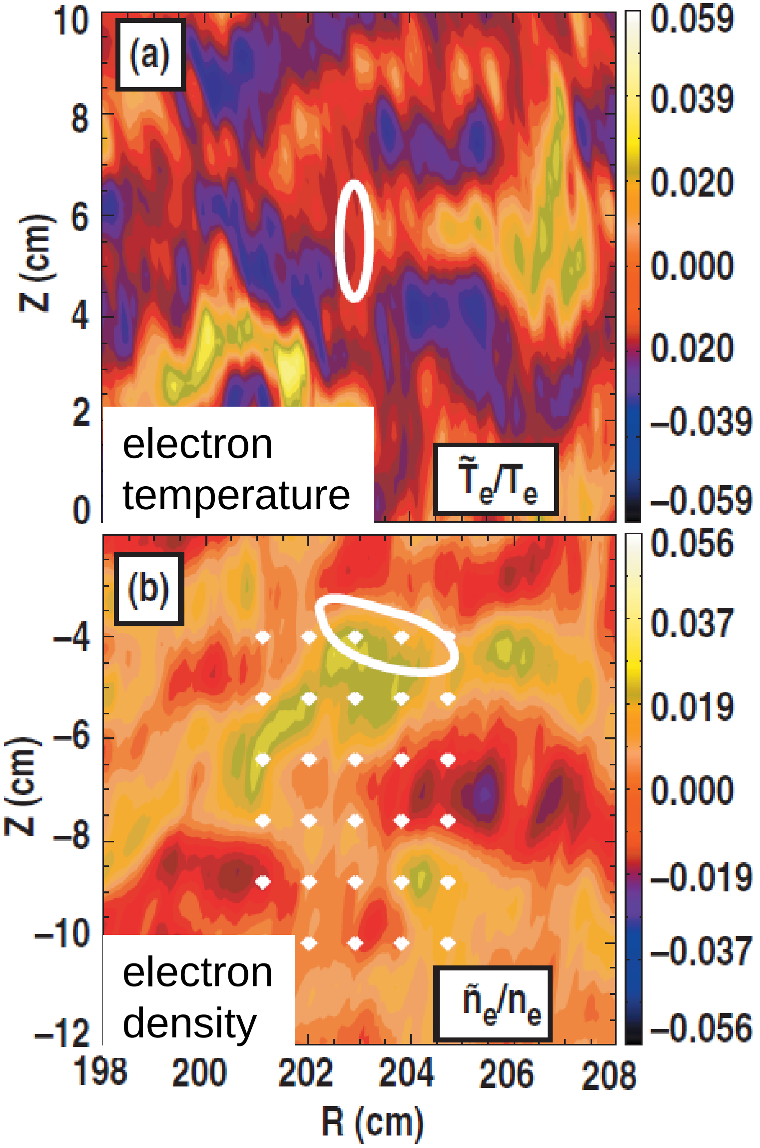
Late linear stage demonstrates structure of fastest growing modes (R-T like)

Large shear flows from primary instabilities cause zonal flows to develop (K-H like)

Zonal flows develop uniformly on flux surfaces, with narrow radial extent

More sensitive tests of underlying physics required to constrain simulation validity

Simulation results



- **Breakthrough in *simultaneously* measuring density & temperature**

(DIII-D, White 2010)

Phase between density & temperature