Turbulence (in plasmas)

Saskia Mordijck

What is turbulence?

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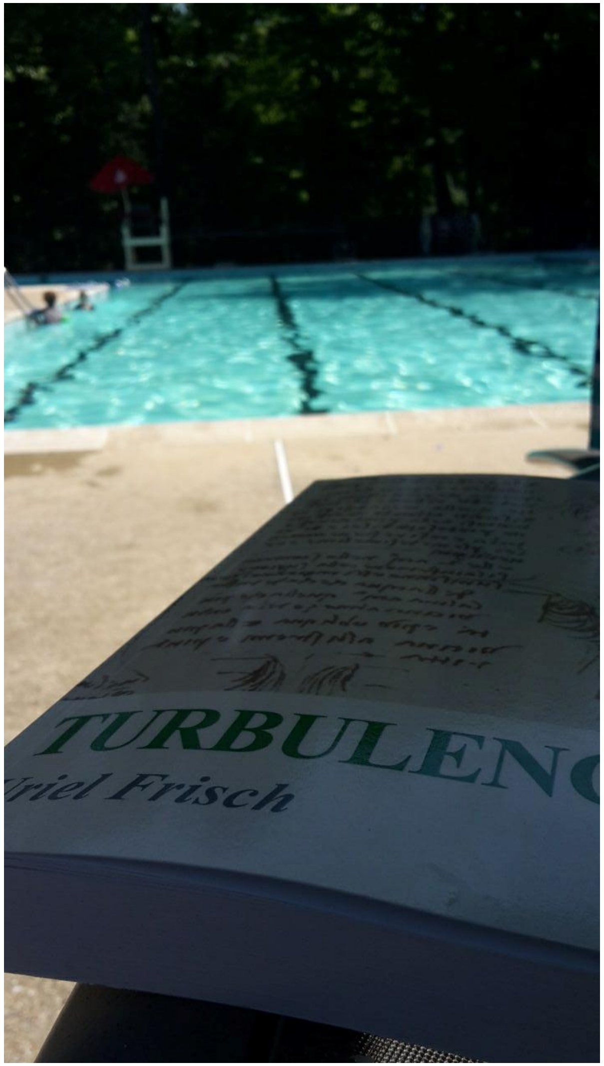
Wikipedia:

In fluid dynamics, turbulence or **turbulent flow** is any pattern of fluid motion characterized by **chaotic changes** in pressure and flow velocity. It is in contrast to a **laminar flow** regime, which occurs when a fluid flows in **parallel layers**, with **no disruption** between those layers.

What is turbulence?



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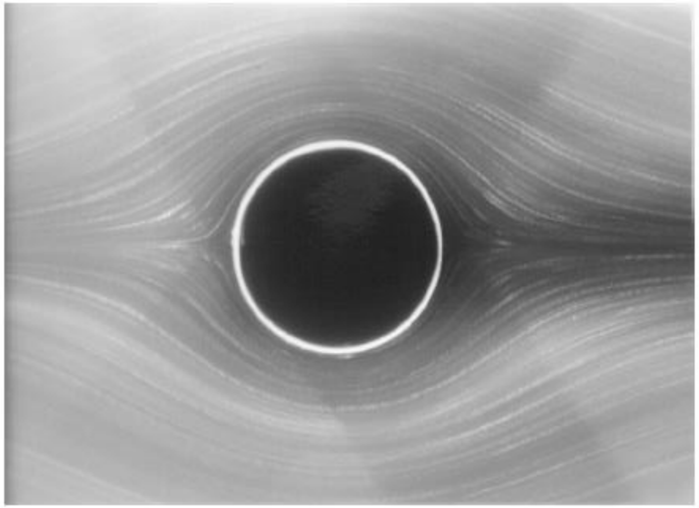
Turbulence is characterized by the breaking of symmetry



Very 'slow' flow is symmetric (R = 0.16):

All photographs by S. Taneda

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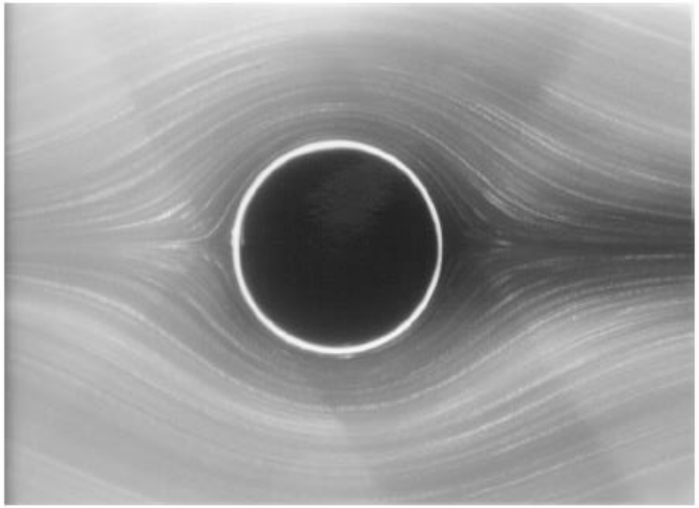

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Up - Down
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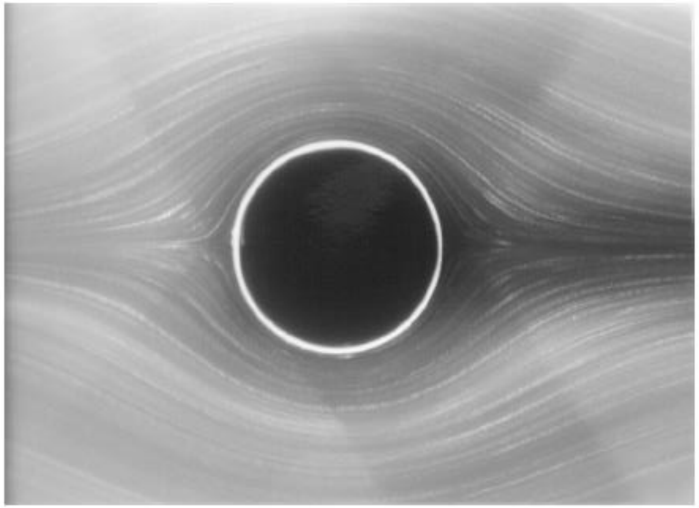

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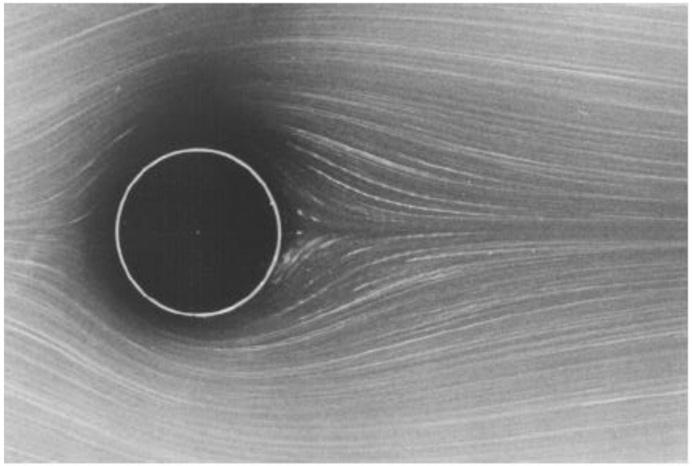

Very 'slow' flow is symmetric (R = 5.1):

Left – Right
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Time-translation
Space-translation (z-axis)

All photographs by S. Taneda

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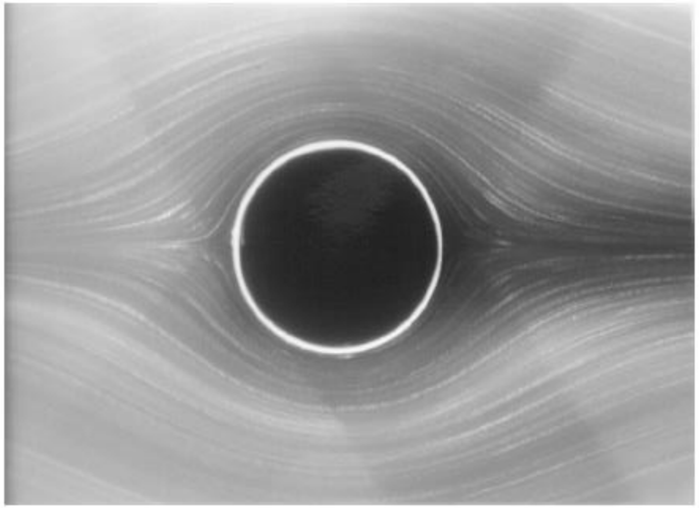

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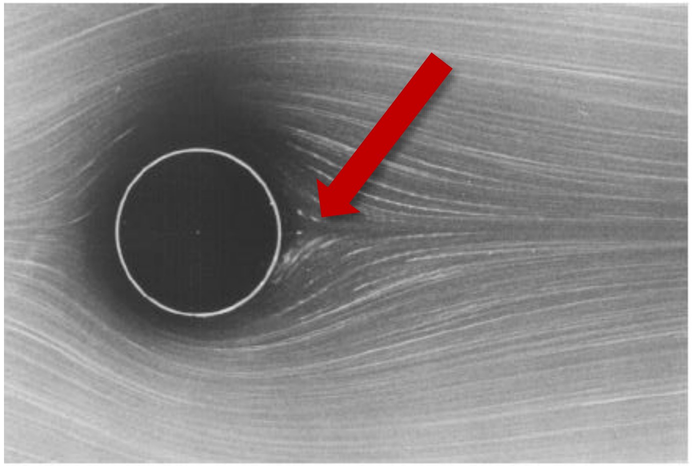

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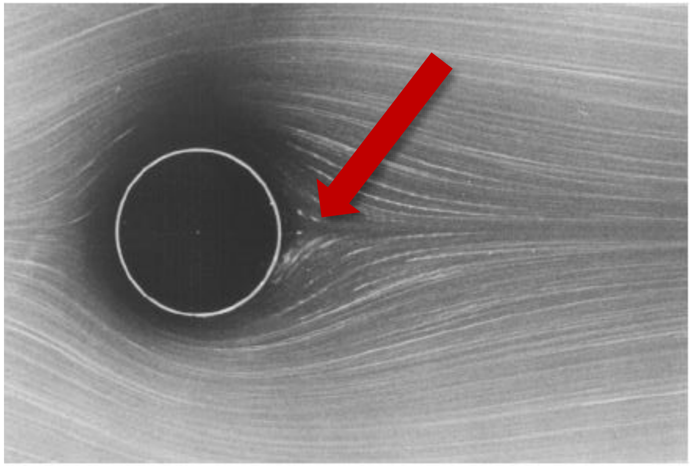
Turbulence is characterized by the breaking of symmetry

Navier-Stokes equation:

$$\frac{\partial \vec{\mathbf{v}}}{\partial t} + \vec{\mathbf{v}} \cdot \nabla \vec{\mathbf{v}} = -\frac{1}{\rho} \nabla p + \nu \nabla^2 \vec{\mathbf{v}}$$



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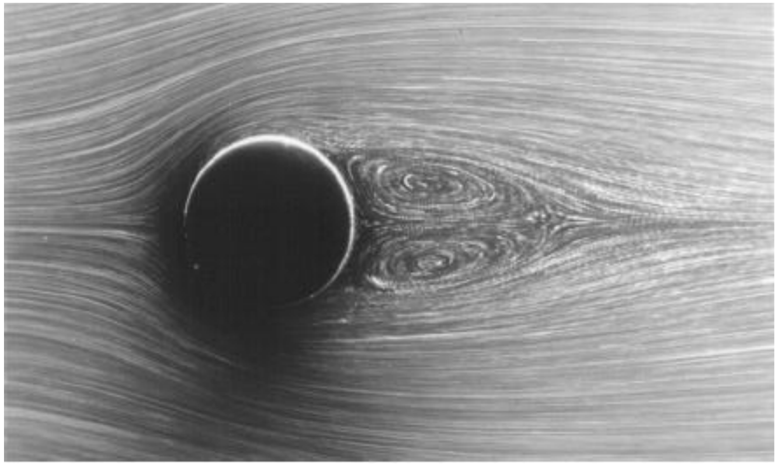

Very 'slow' flow is symmetric (R = 26):

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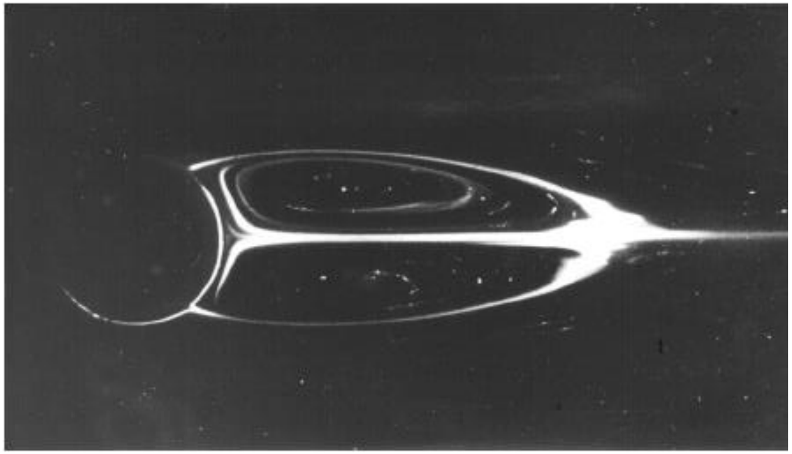
Turbulence is characterized by the breaking of symmetry



First real symmetry breaking (R = 40):

Left – Right : Breaks-Down
Up - Down
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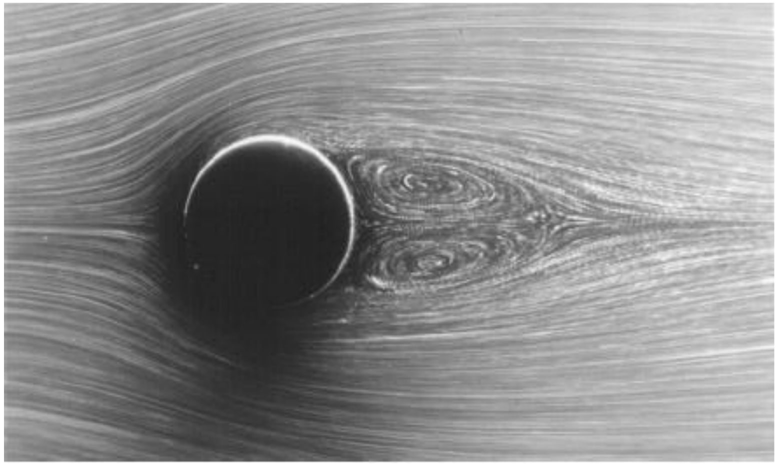

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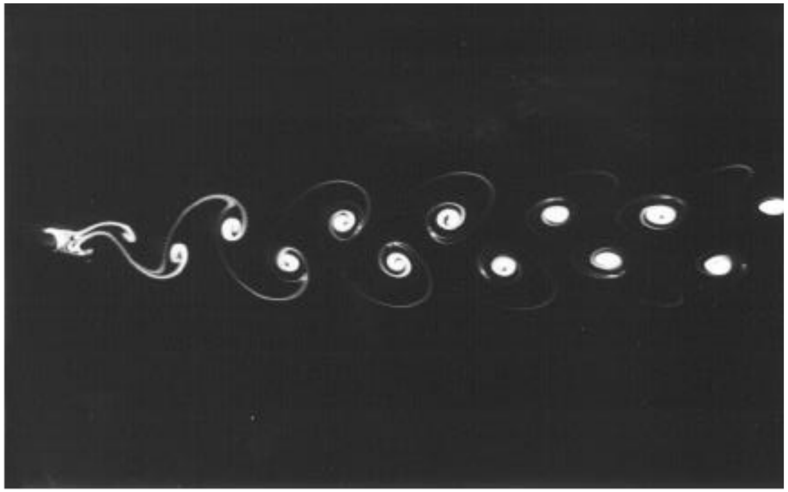

First real symmetry breaking (R = 105):

Left – Right : Breaks-Down
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Time-translation → Time-periodic
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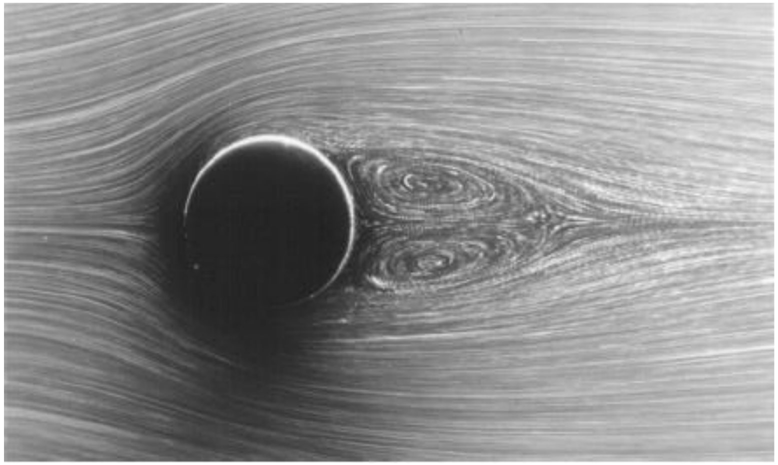

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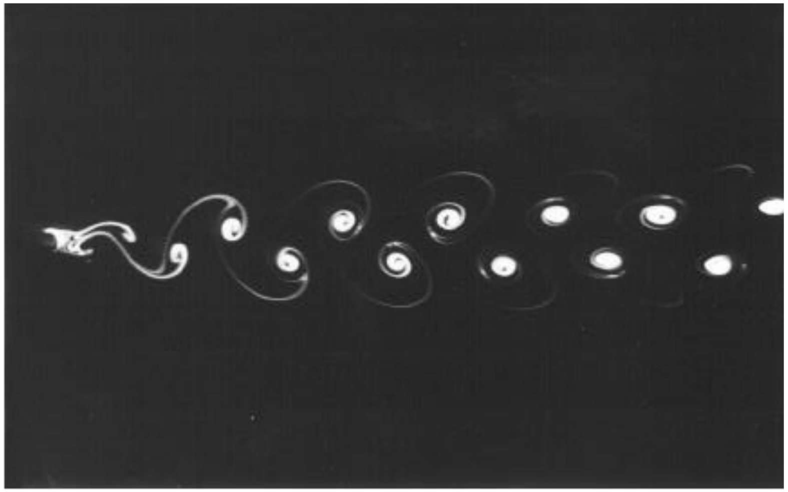

First real symmetry breaking (R = 105):

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Further increase of flow speed (R = 700):

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All photographs by S. Taneda

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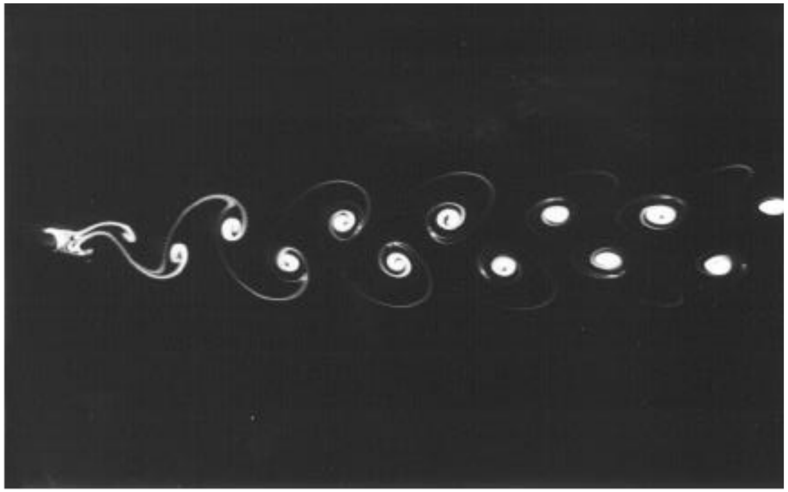

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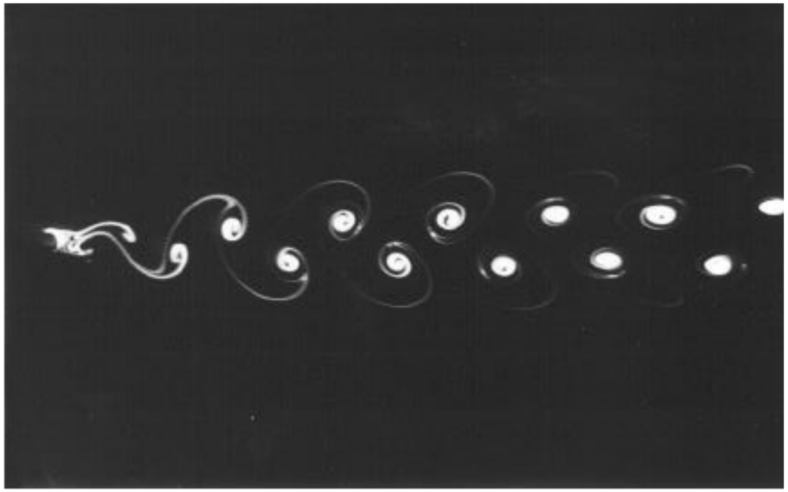

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Time-translation → Chaotic
Space-translation (z-axis) : Breaks-Down

All photographs by S. Taneda

Turbulence is characterized by the breaking of symmetry

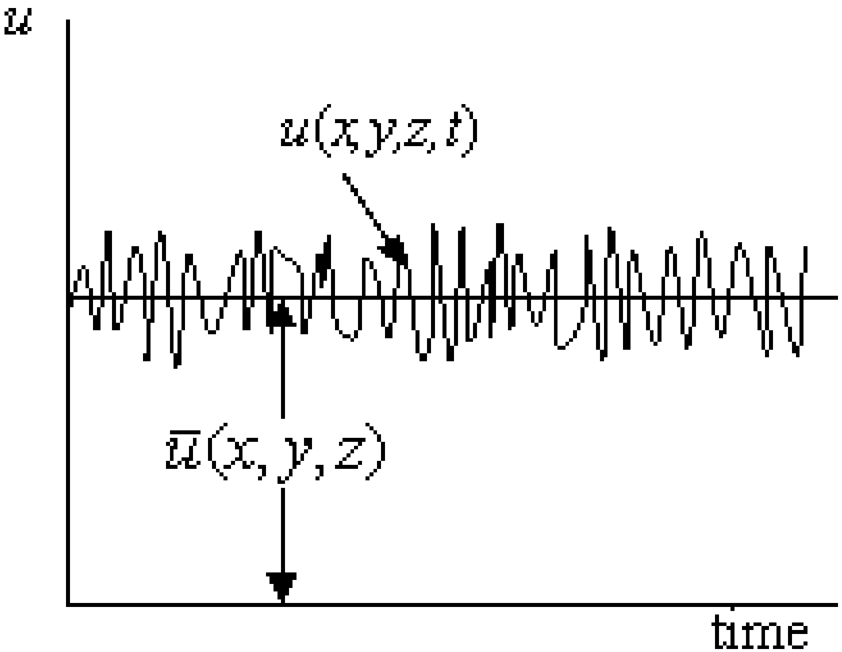
From deterministic to probabilistic system

Chaos only in the deterministic sense:

- Signals look disorganized
- Signals appear unpredictable

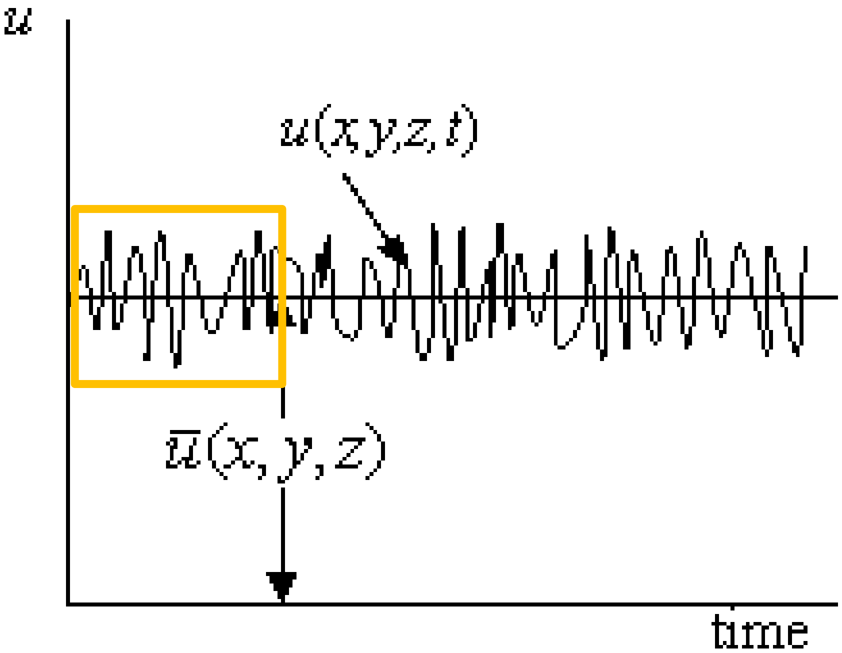
However some properties are reproducible

Fully developed 'steady-state' turbulence : average velocity remains constant



(a) steady mean flow

Fully developed 'steady-state' turbulence : construct a histogram for limited time-window



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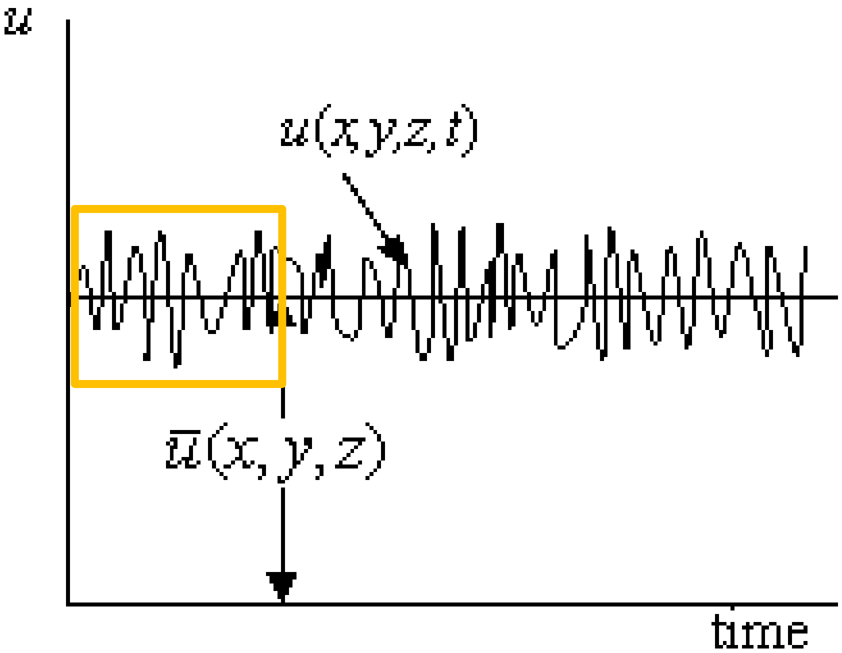

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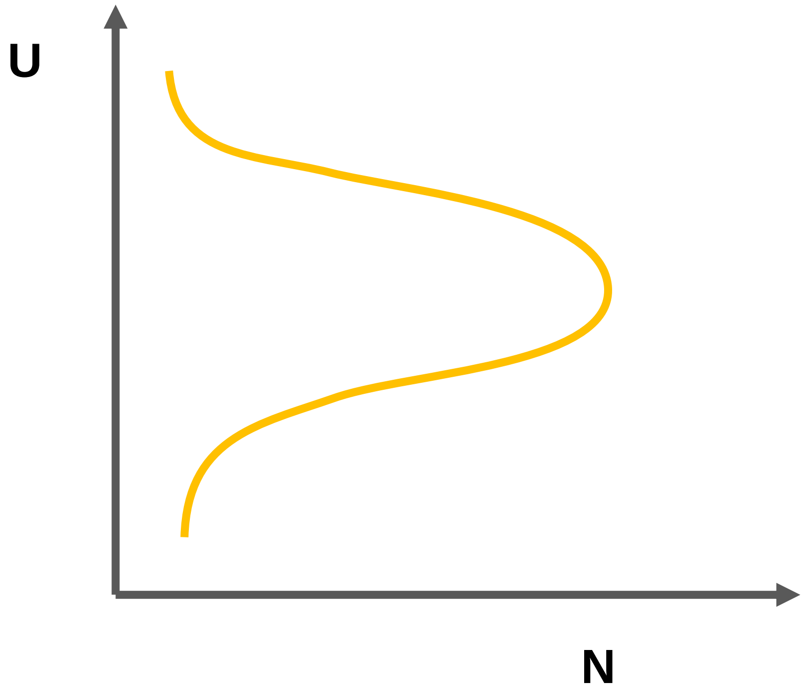
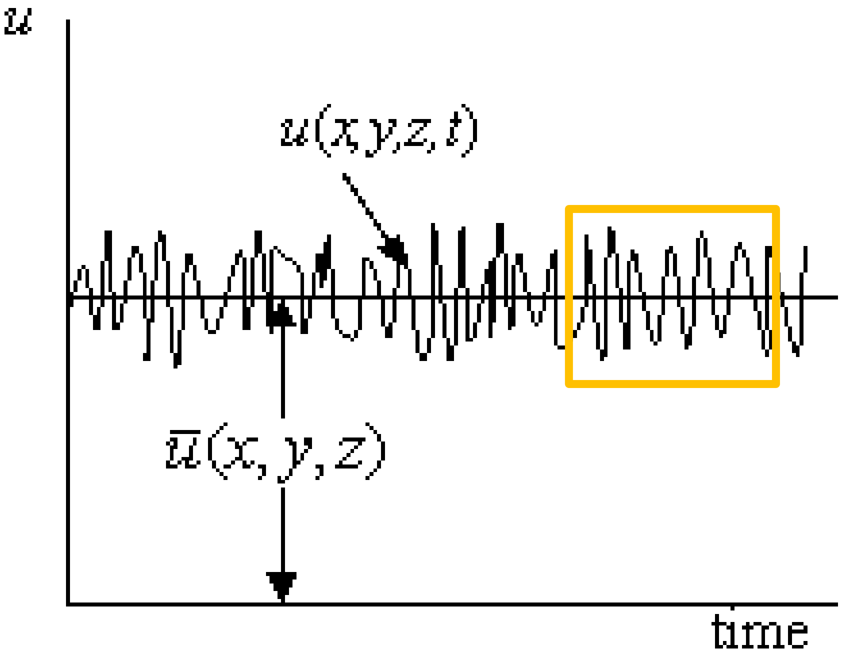


Fully developed ‘steady-state’ turbulence : while ‘raw’ signal changes with time the statistics are constant



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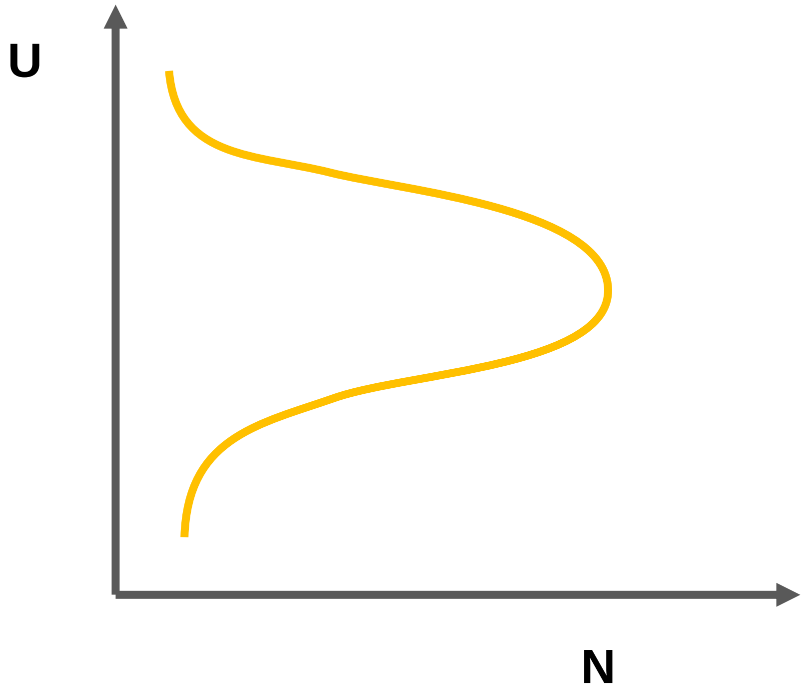
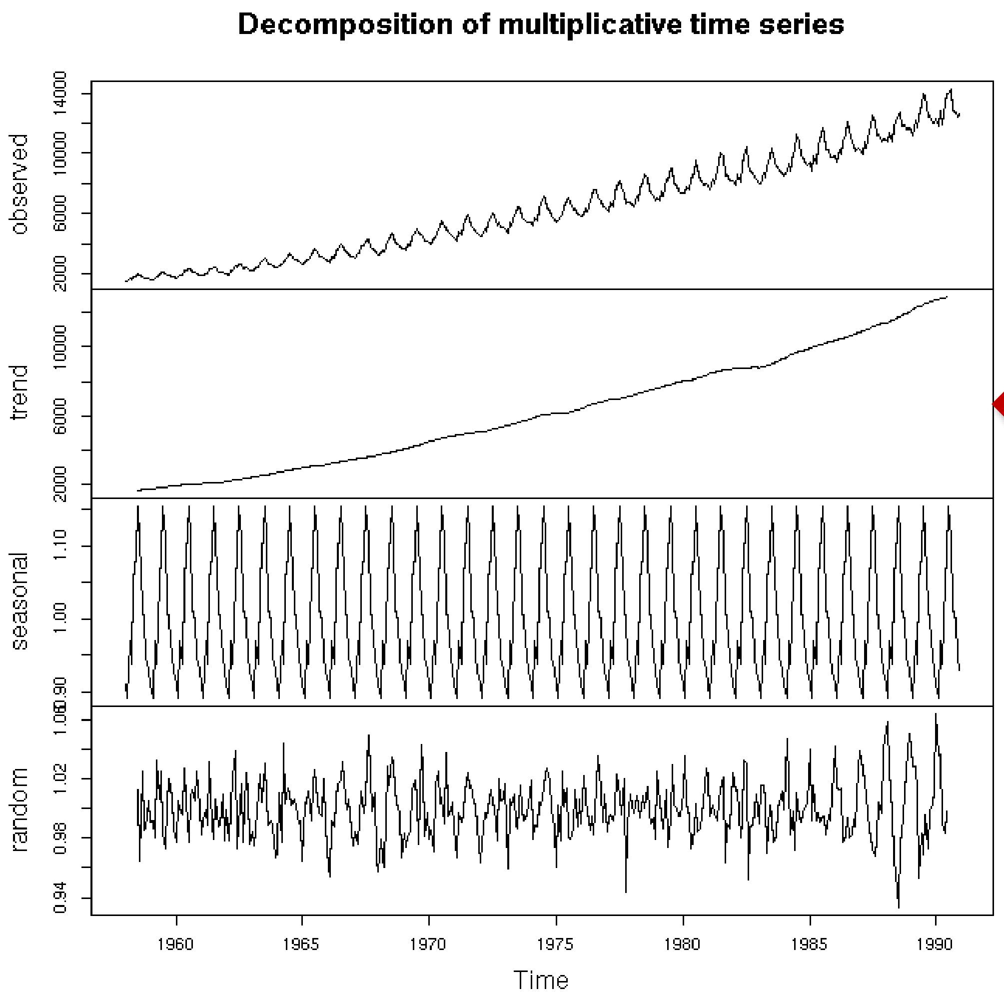
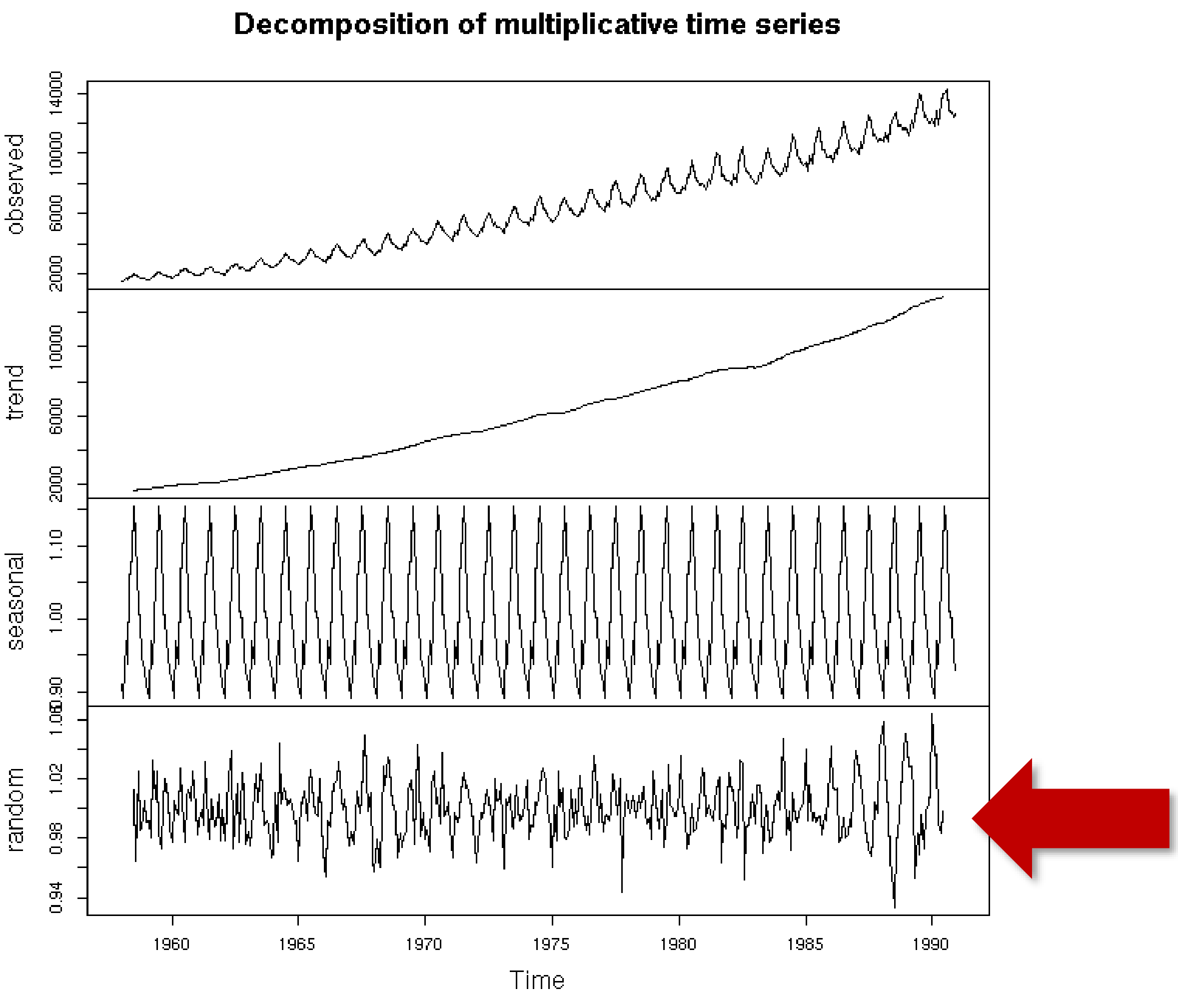


We can extract different scales by ‘filtering’



Mean change

We can extract different scales by 'filtering'



Random or 'small' scale

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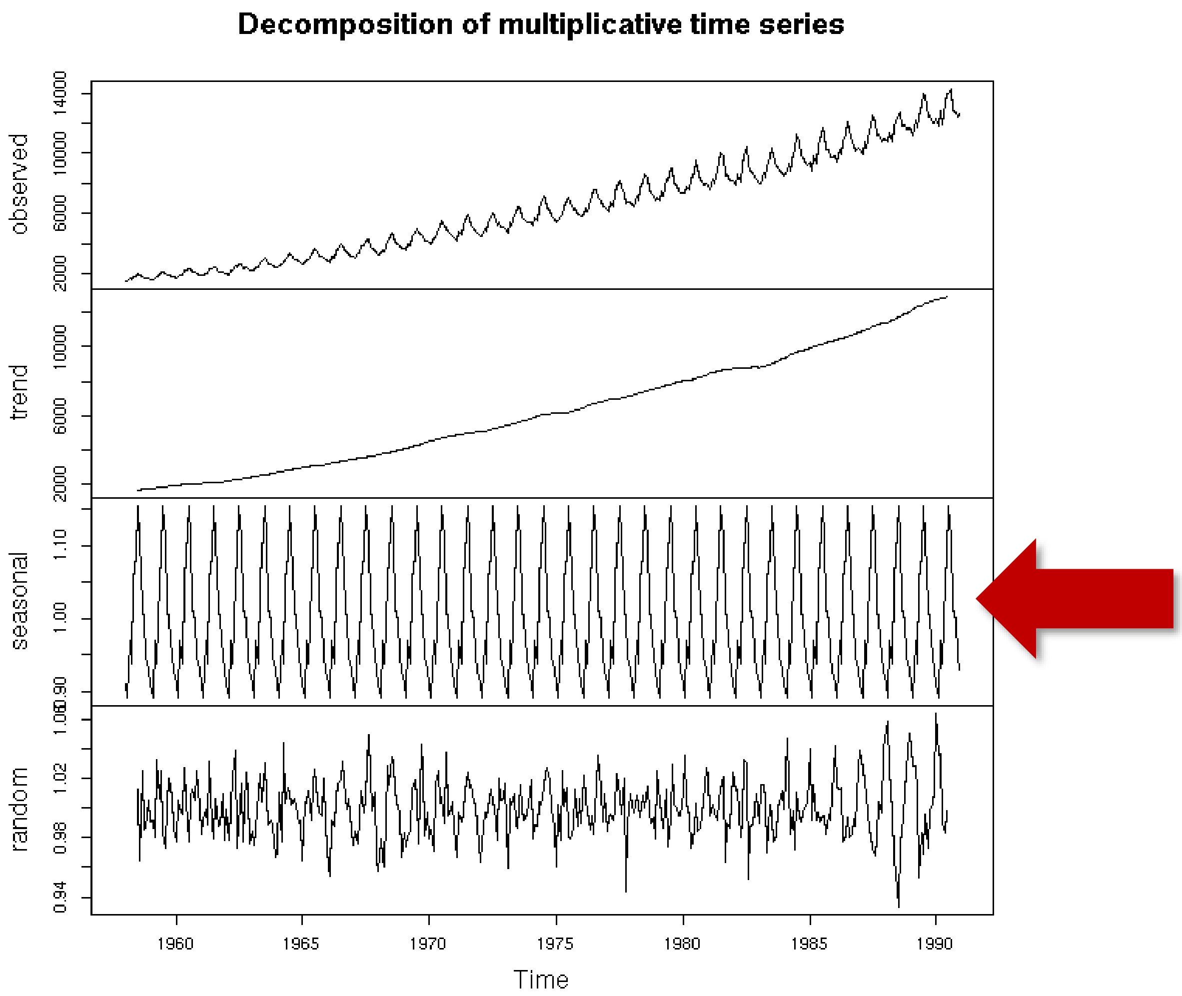
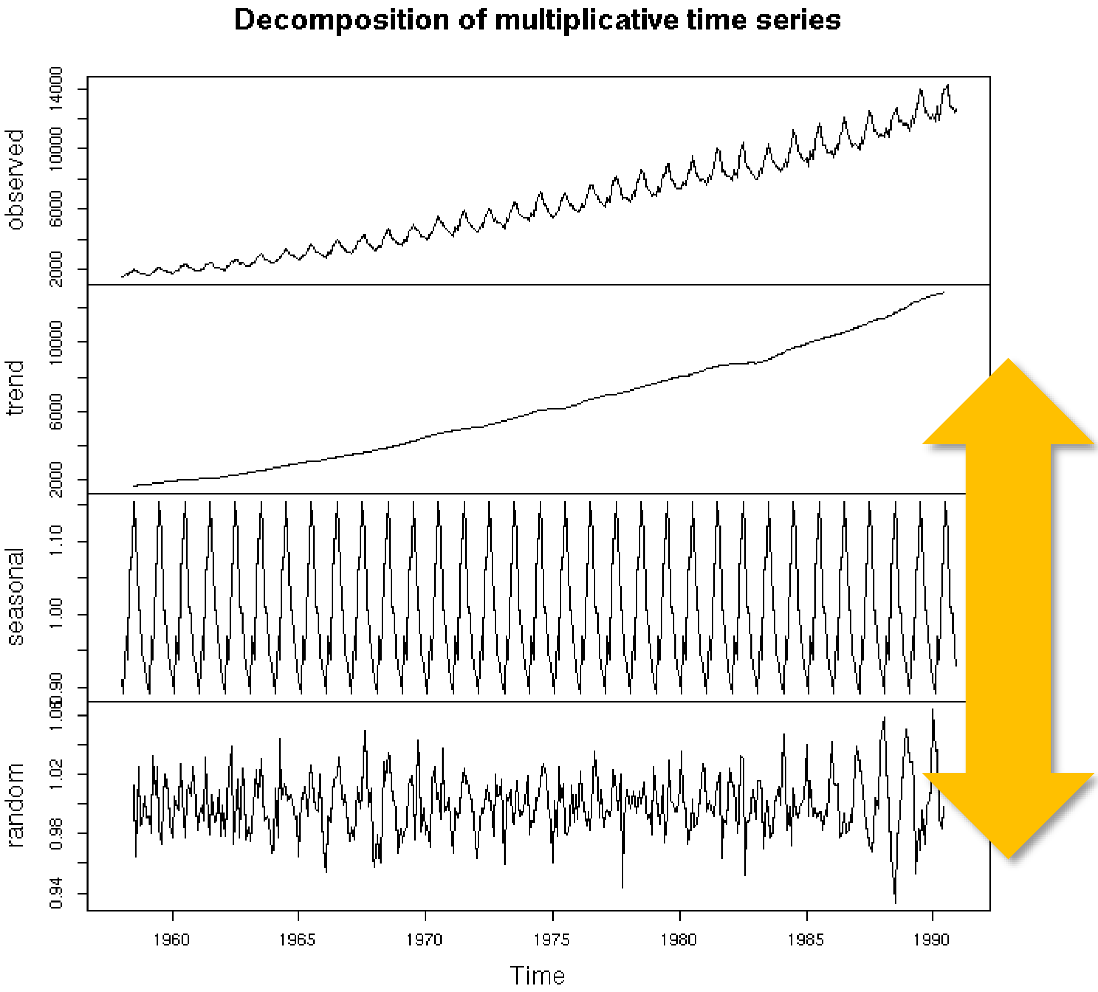


Meso-scale

All these scales interact with each other – thus making the problem non-linear



These scales can exchange energy with each other

All these scales interact with each other – thus making the problem non-linear

Source: Wikipedia

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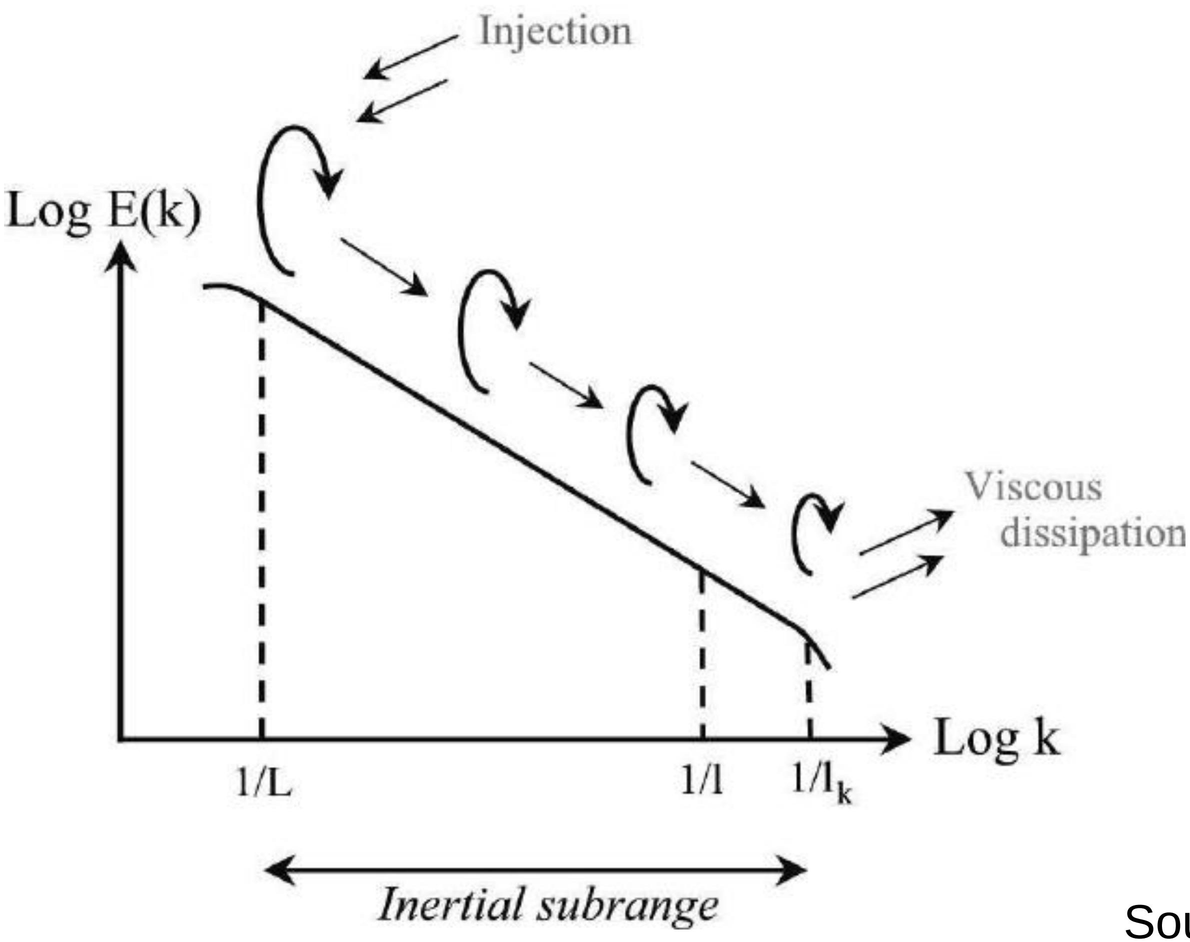
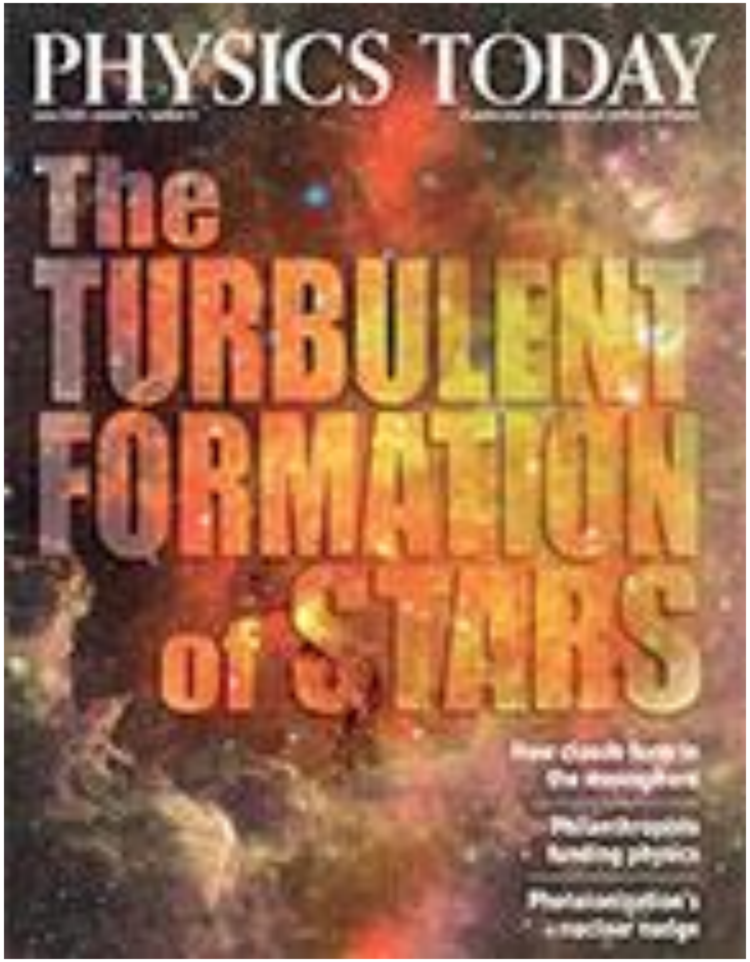


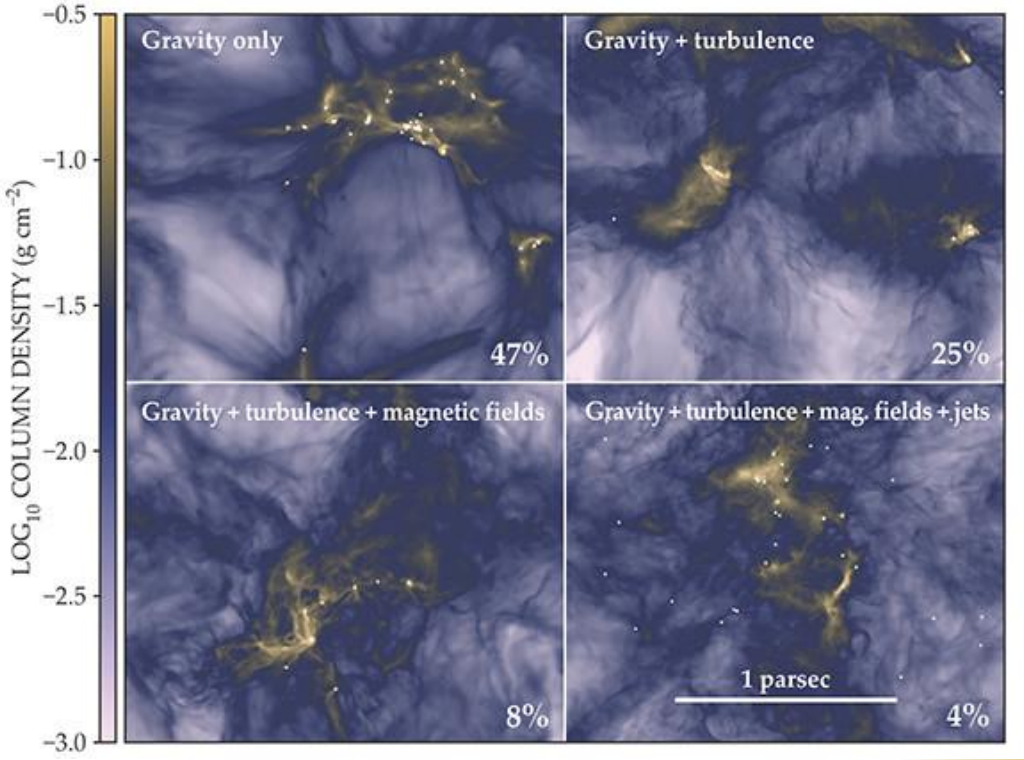
Source: Wikipedia

So are plasmas turbulent?

So are plasmas turbulent? YES !!

How turbulence affects star formation

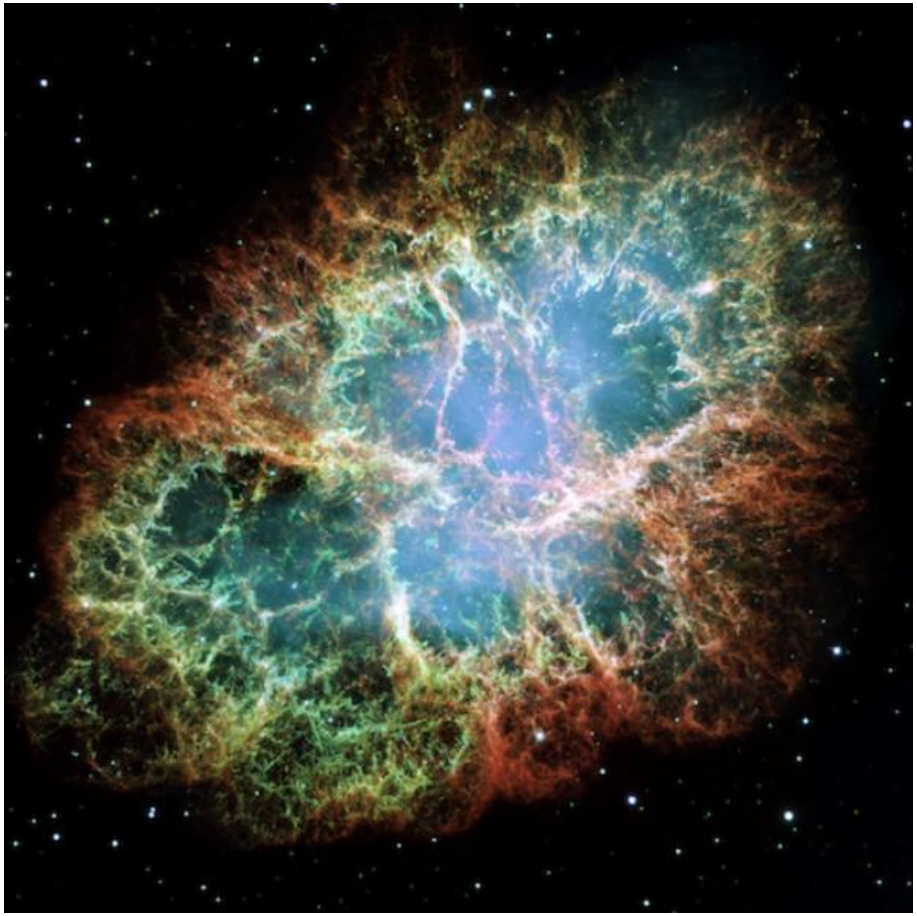




Source: Physics Today June 2018

So are plasmas turbulent? **YES !!**
Astrophysical examples

Highly turbulent supernova remnant
Crab nebula

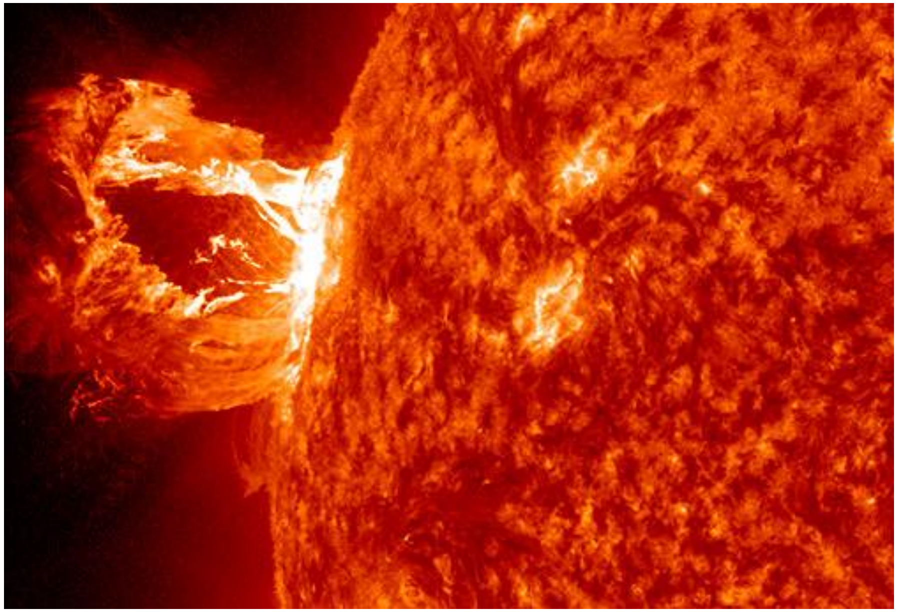


Accretion disks require plasma turbulence to explain energy release in hot disks

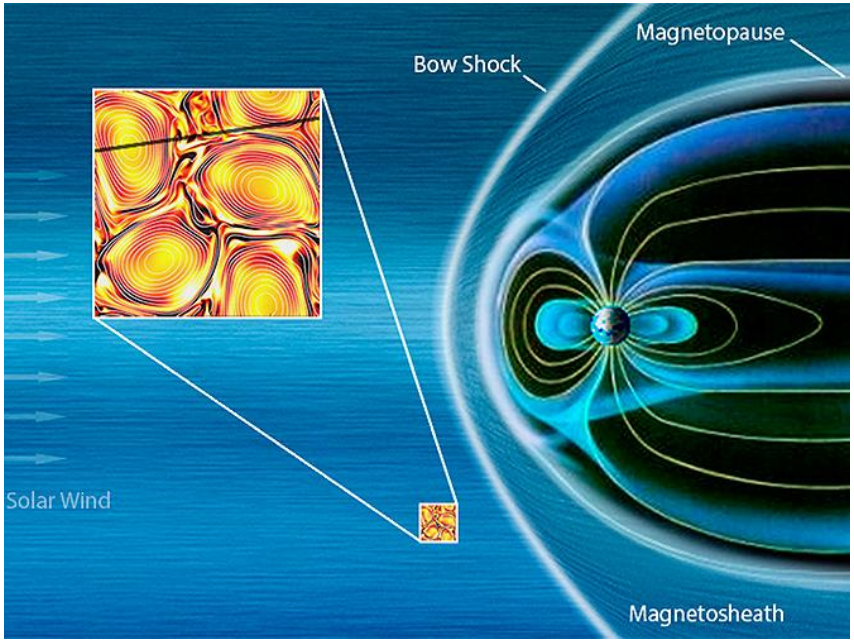
Sources: NASA and Gauss Center for supercomputing

So are plasmas turbulent? YES !!
Solar Physics

Sun is one turbulent ball of fusing plasma



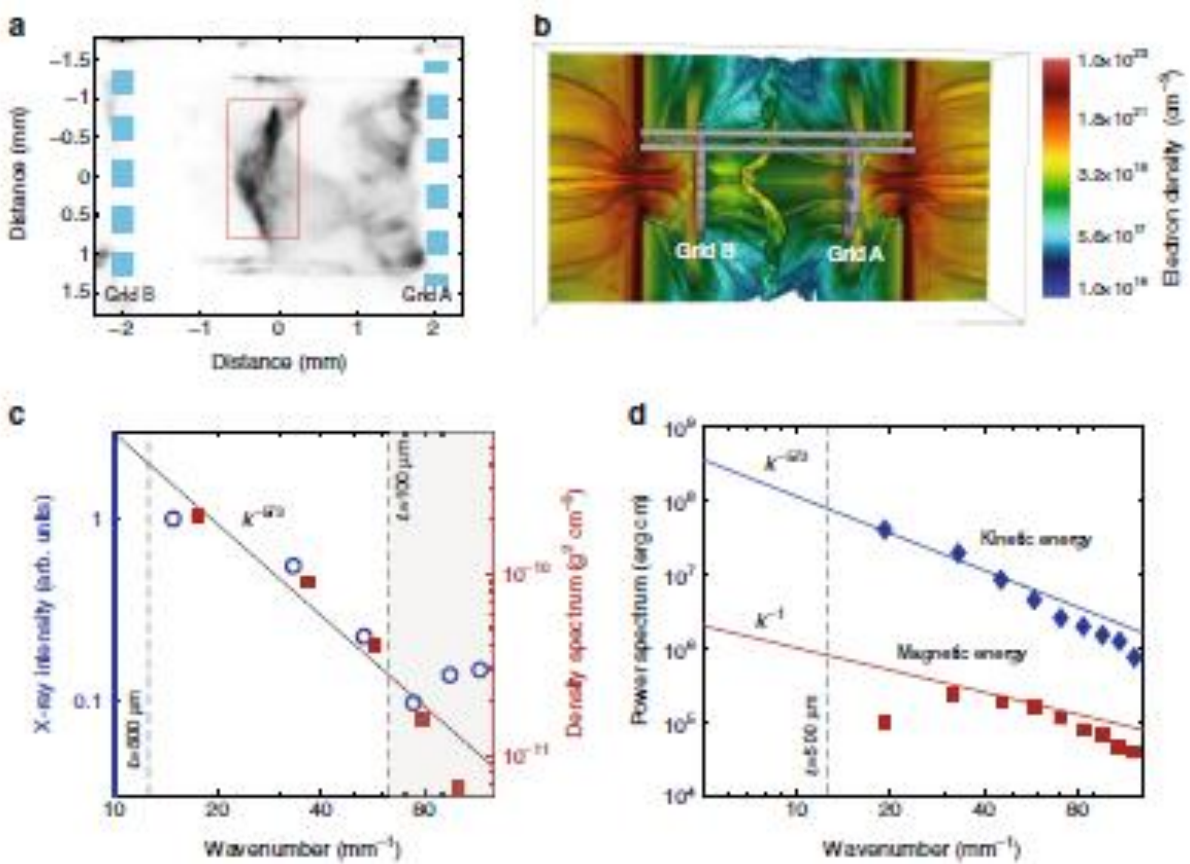
Turbulence might explain 'heating' of the solar wind



Sources: NASA

So are plasmas turbulent? YES !!
Inertial confinement

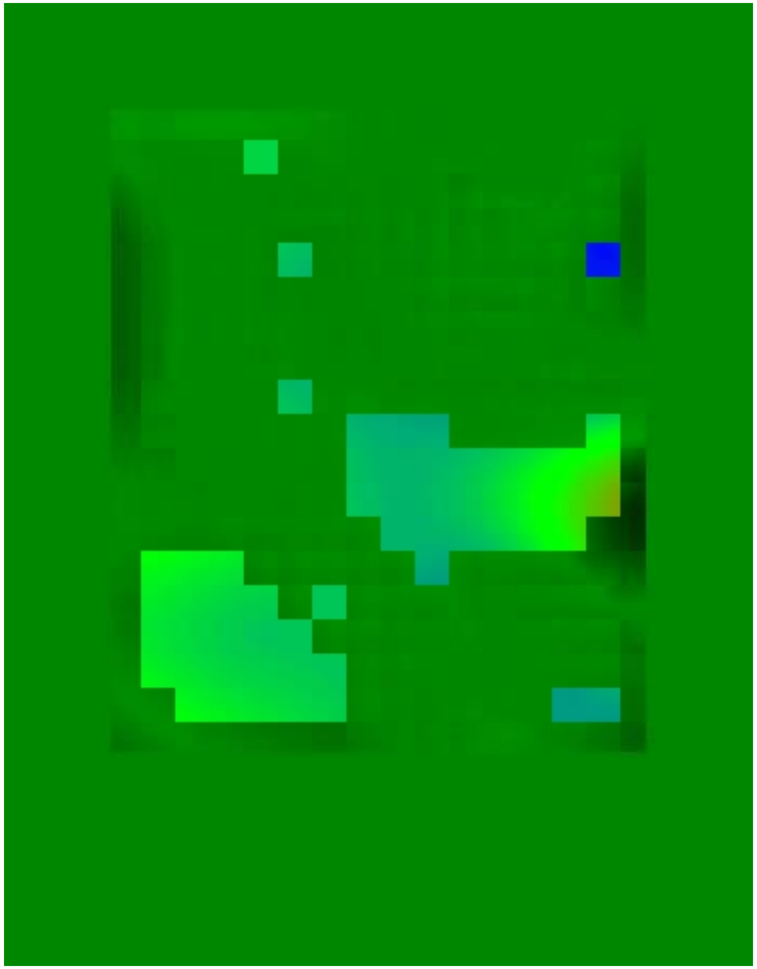
Using lasers to show how turbulence in plasmas can enhance magnetic fields



Sources: Tzefarcos et al. Nature
Shared by C. Kuranz

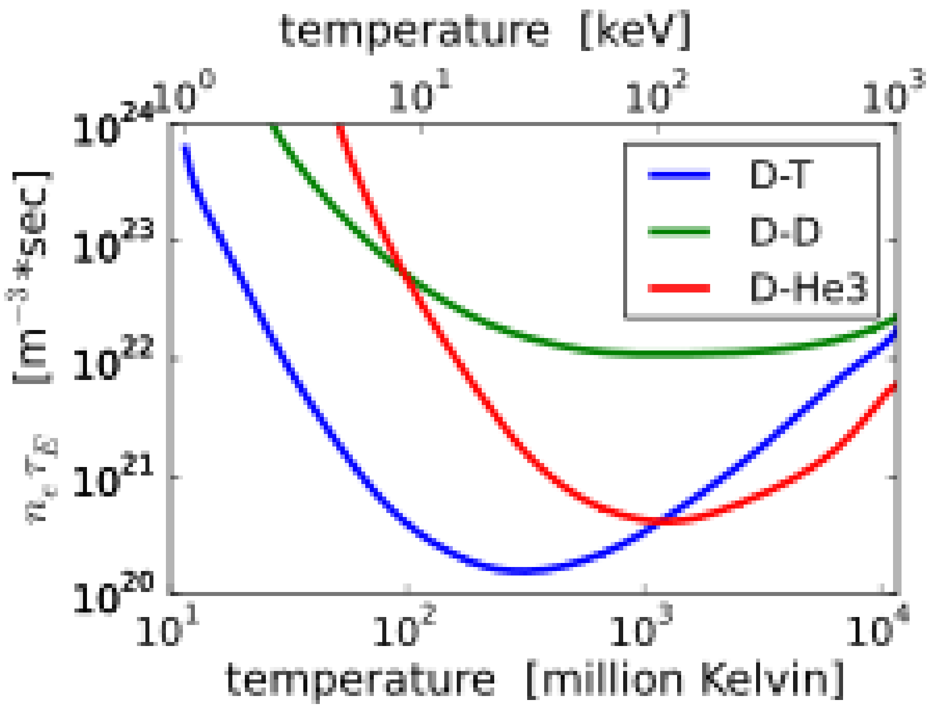
So are plasmas turbulent? YES !!

Magnetic Confined Plasmas

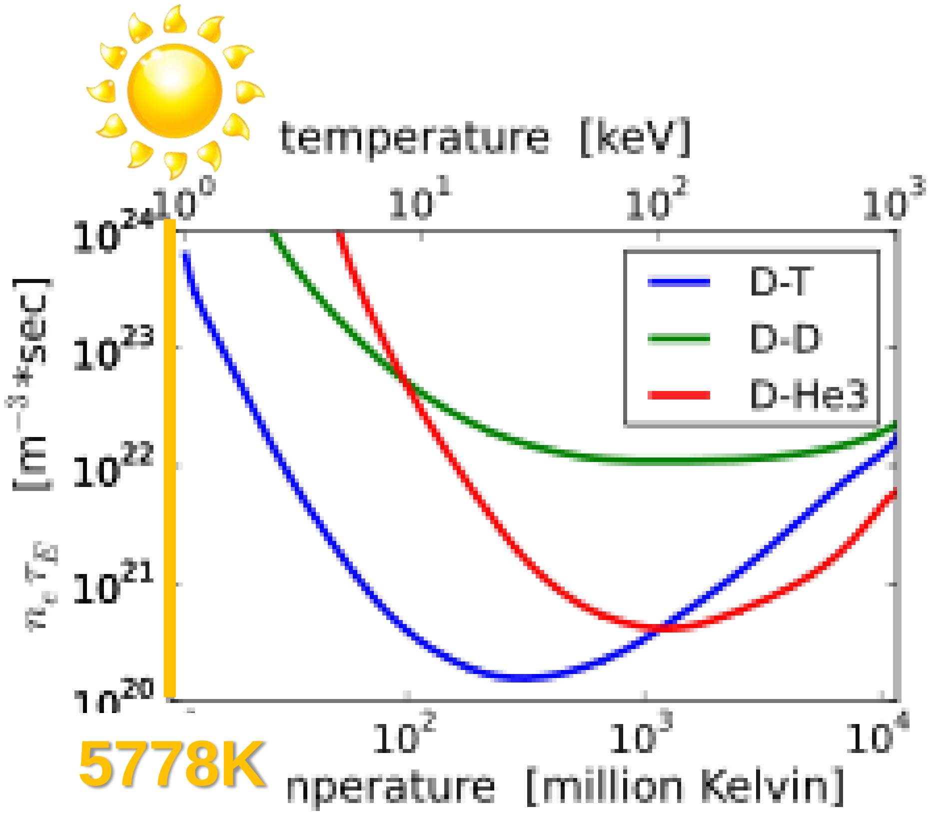


Sources: G.R. McKee (DIII-D tokamak)

Turbulence determines confinement and thus whether we achieve 'ignition' in a Tokamak



The Lawson criterion determines whether we achieve ‘ignition’



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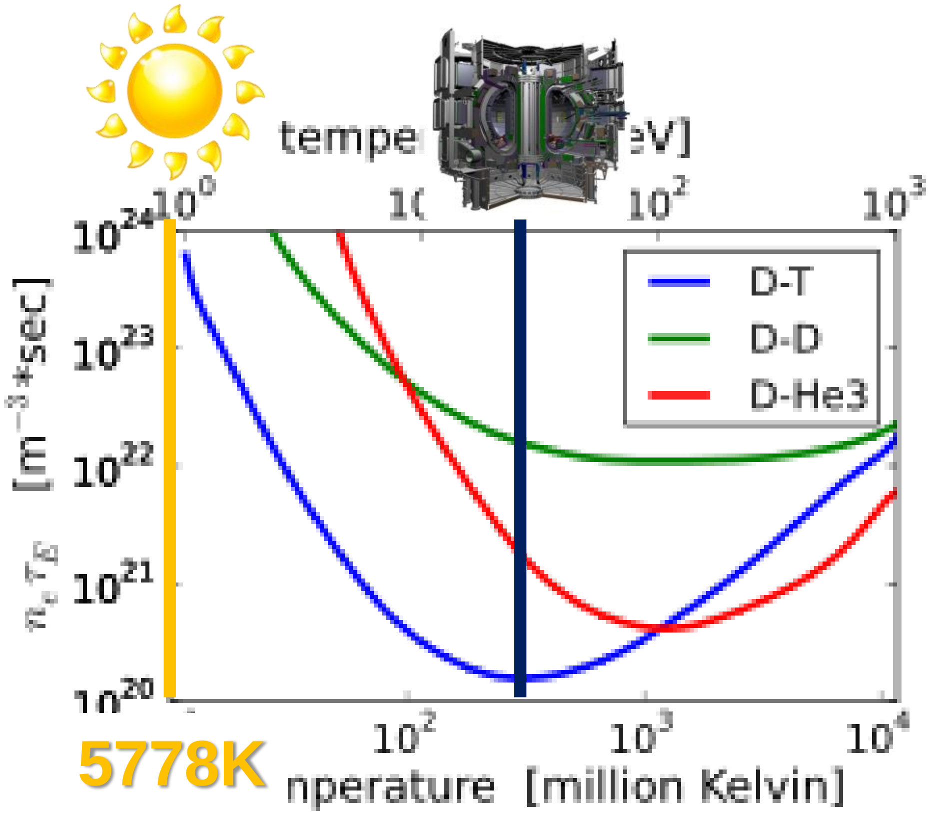

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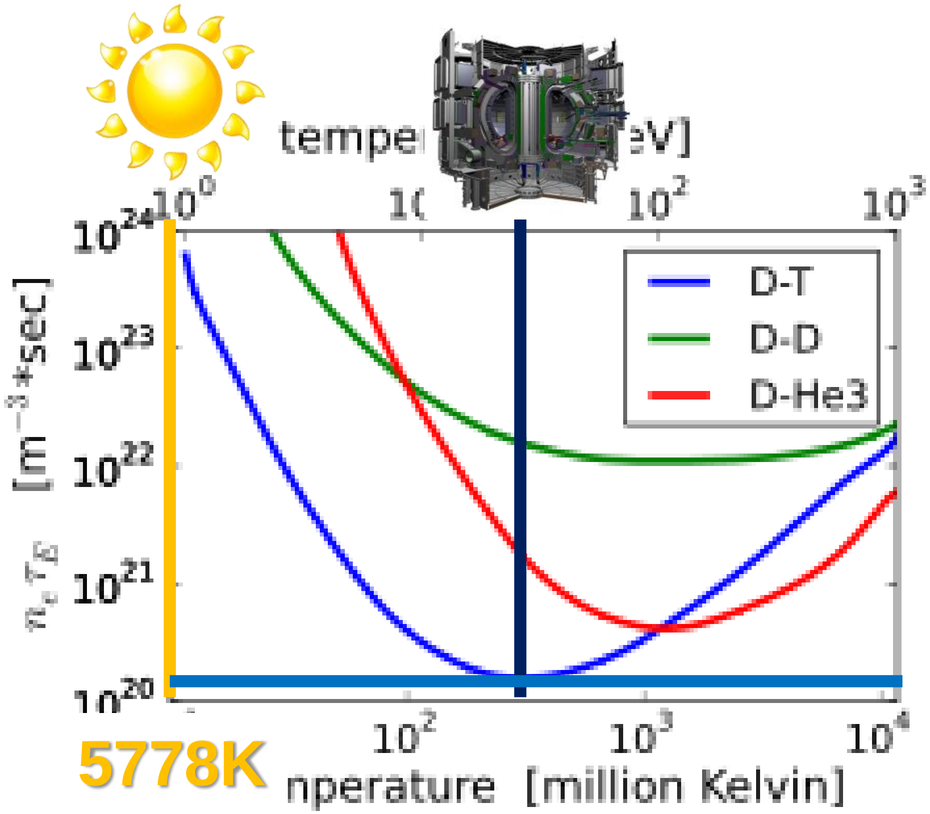

To reach ignition using DT:

τ_e ~ 10^{-1} on DIII-D

n_e ~ 10^{21} on DIII-D

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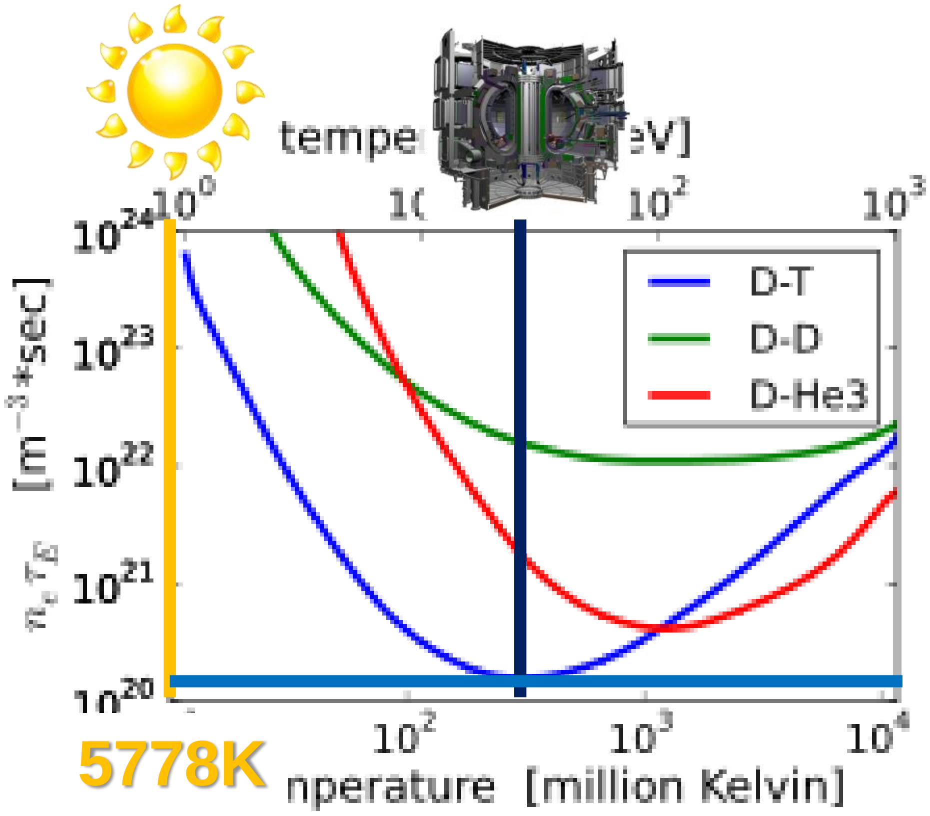

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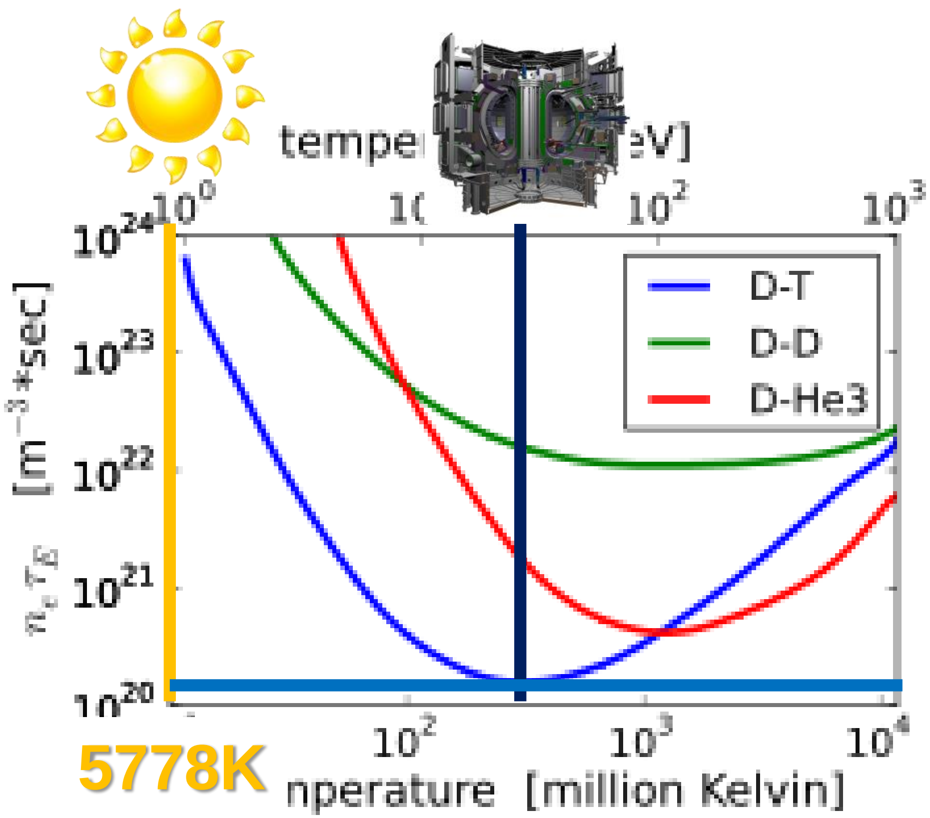

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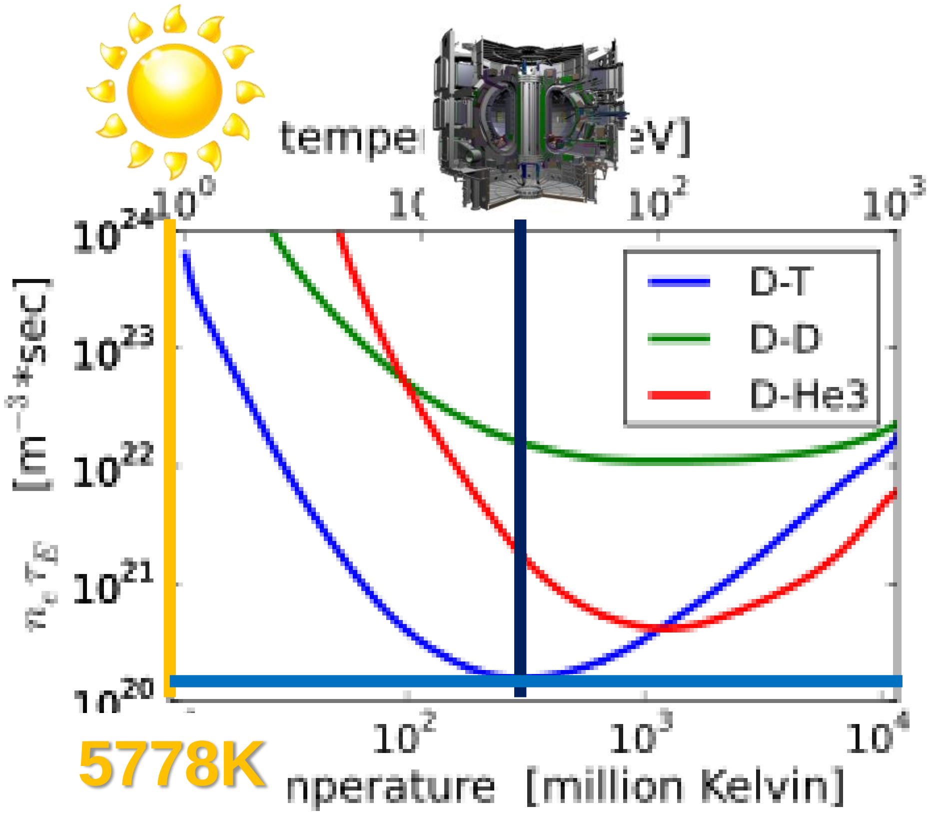

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$n_e \sim 10^{19\text{-}20}$ on ITER

DD experiments now:

$\tau_e \sim 0.25$ on DIII-D

$n_e \sim 1\text{x}10^{20}$ on DIII-D

$Q_{DT} \sim 0.6$

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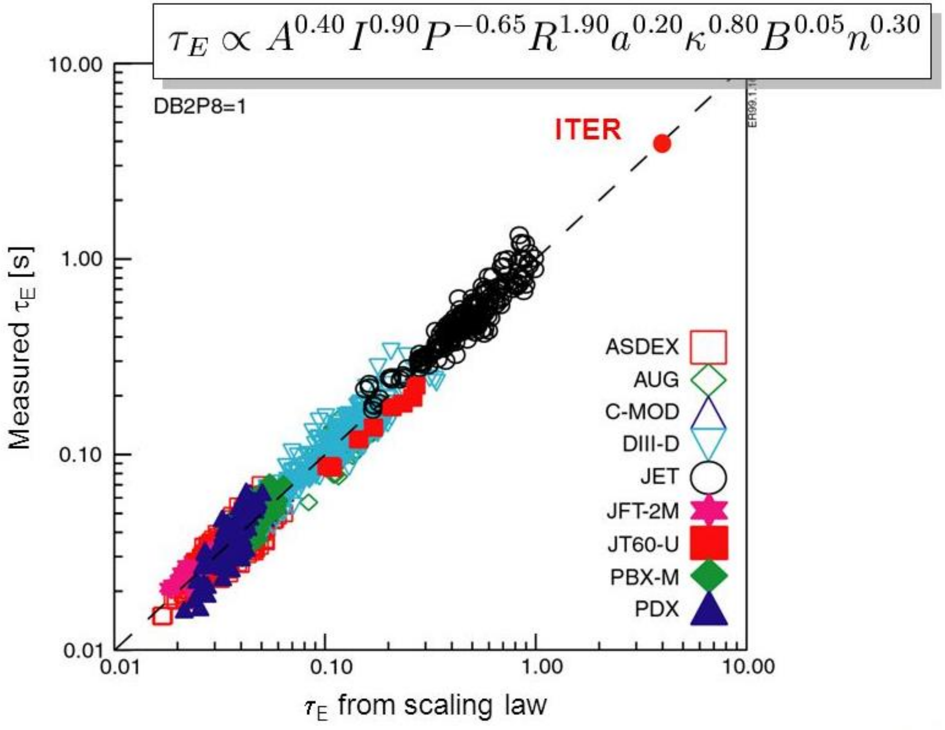

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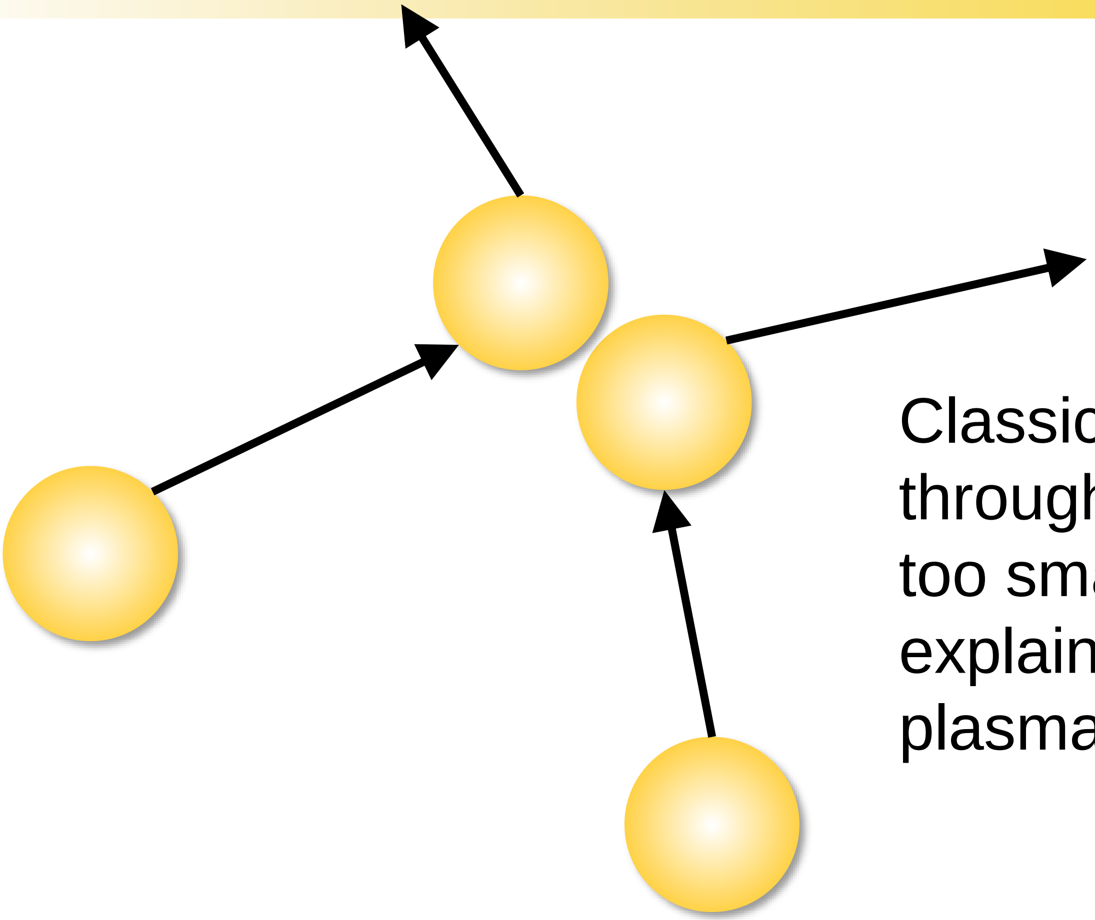
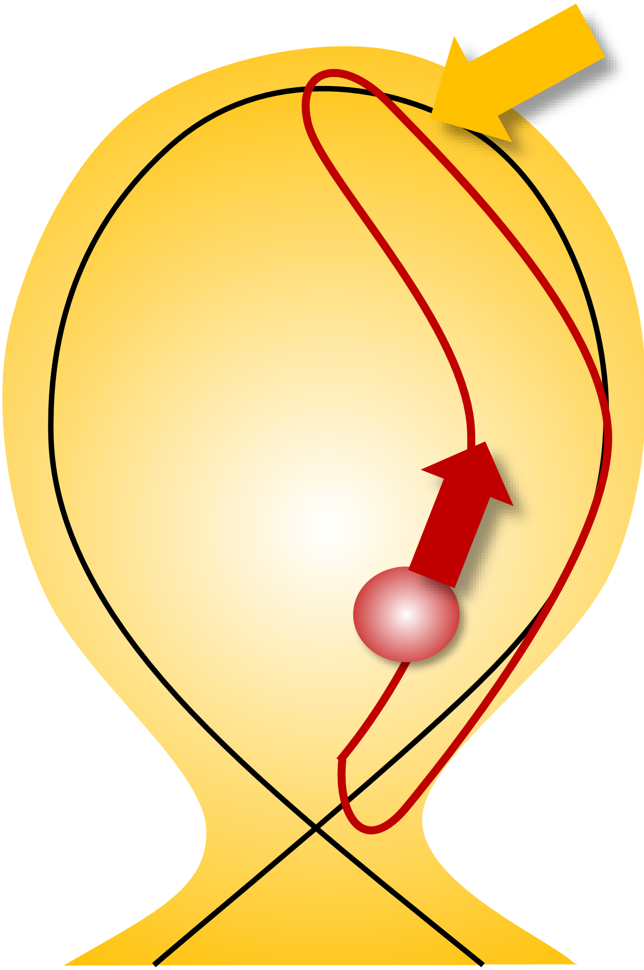
Transport in a plasma is predominantly turbulent



Classical transport through collisions only is too small ($\sim 10^{-2}$) to explain transport in a plasma

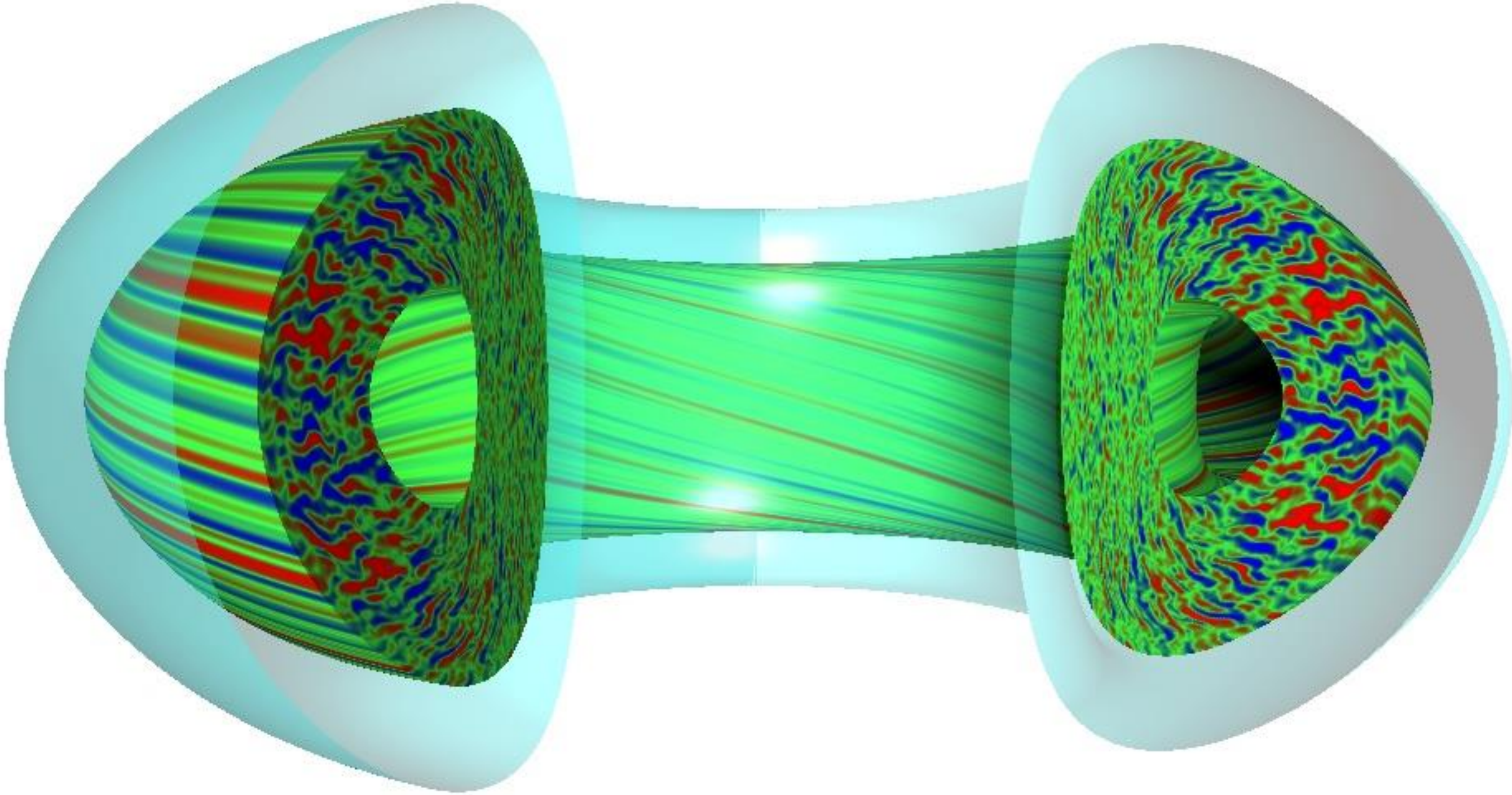
Transport in a plasma is predominantly turbulent



Particle bounces back, like in magnetic mirror. Collisions make it move from it’s path resulting in banana orbit and eventually outward transport

Neo-Classical transport through collisions only is too small (~10^{-1}) to explain transport in a plasma

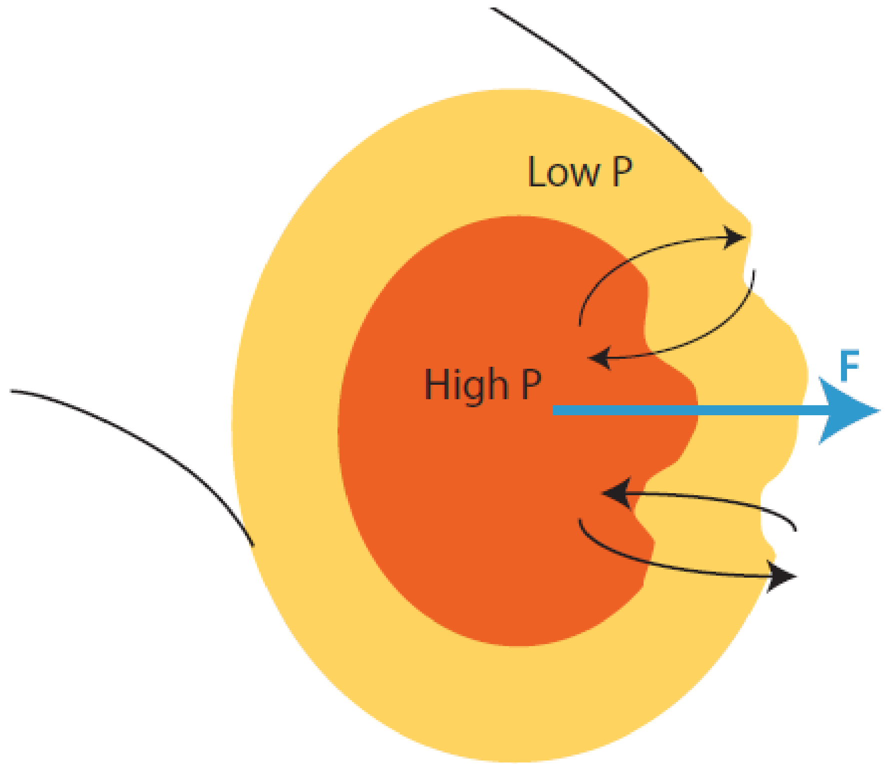
Turbulence is driven by gradients. These gradients provide the drive for the growth of turbulent eddies



DIII-D theory group
General Atomics

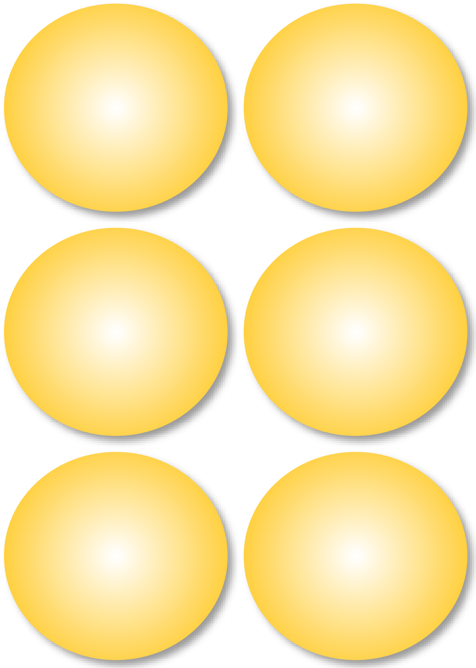
Instabilities such as 'heavy' on 'light' or temperature gradients drive turbulence

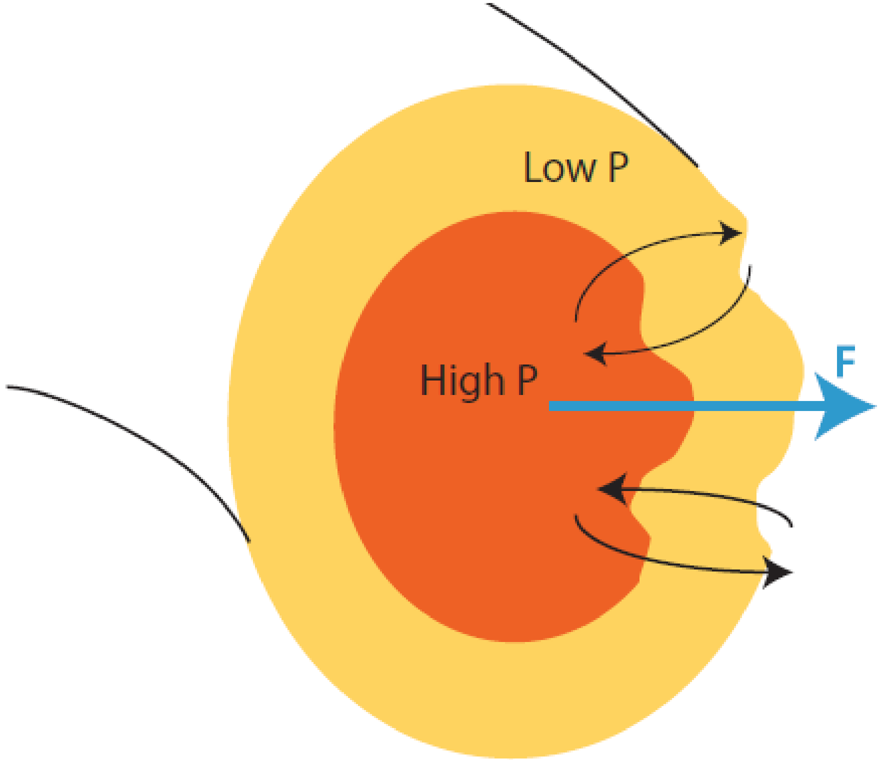
Gravity (un)stabilizes



Magnetic field (un)stabilizes

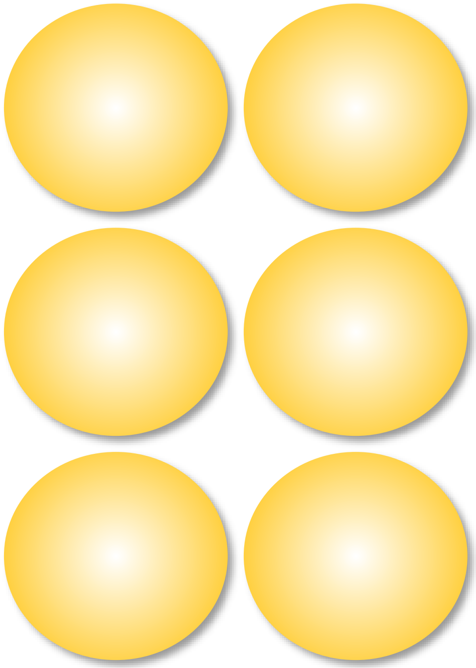
We can characterize the turbulence by 'eddies' of various sizes/shapes

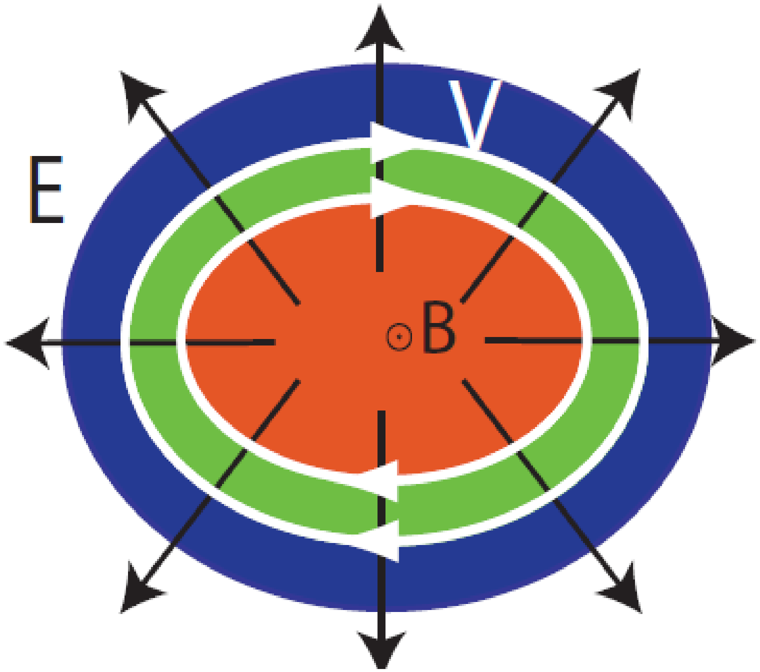




Magnetic field stabilizes

These eddies create an E-Field, which in combination with the B-field results in ‘circulation’



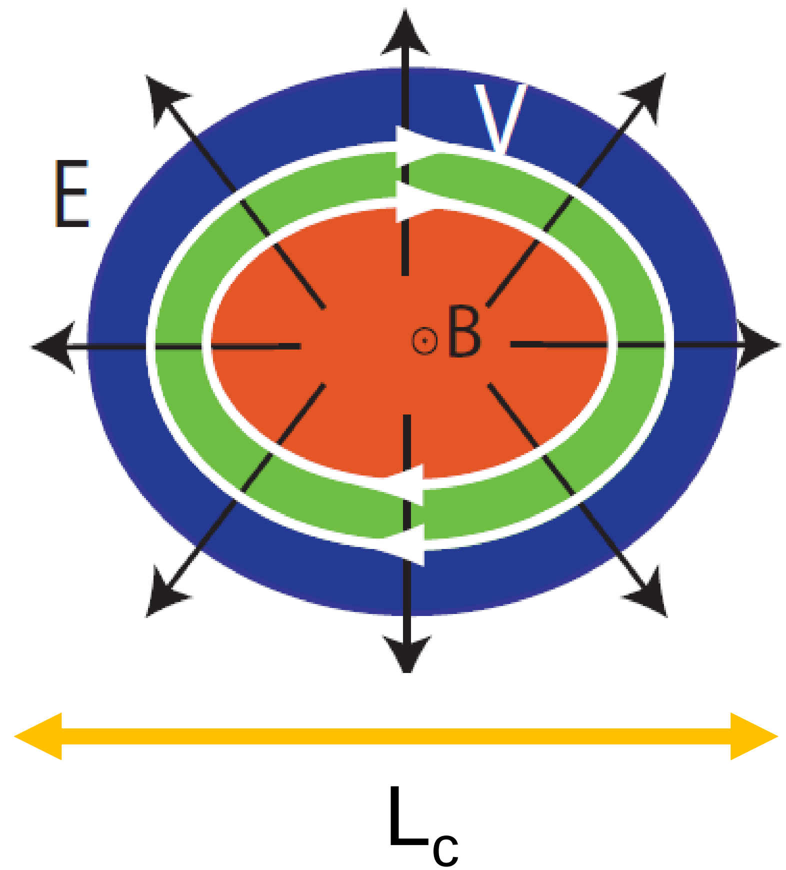


Diffusion increases as the temperature increases thus limiting/regulating the temperature gradients

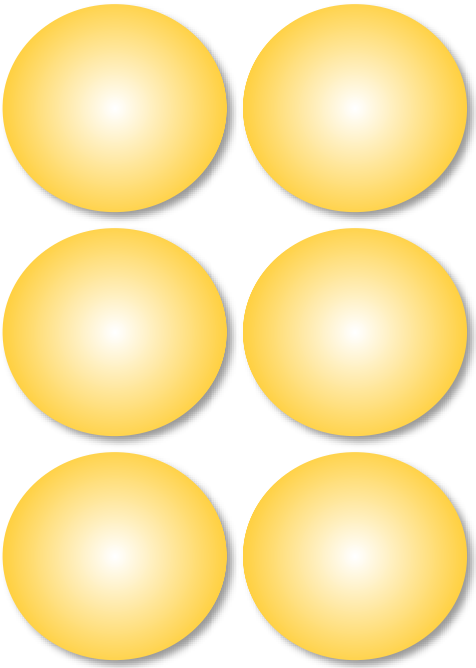
$$D \sim \frac{(\Delta x)^2}{\Delta t} \sim \frac{L_c^2}{\tau_c}$$

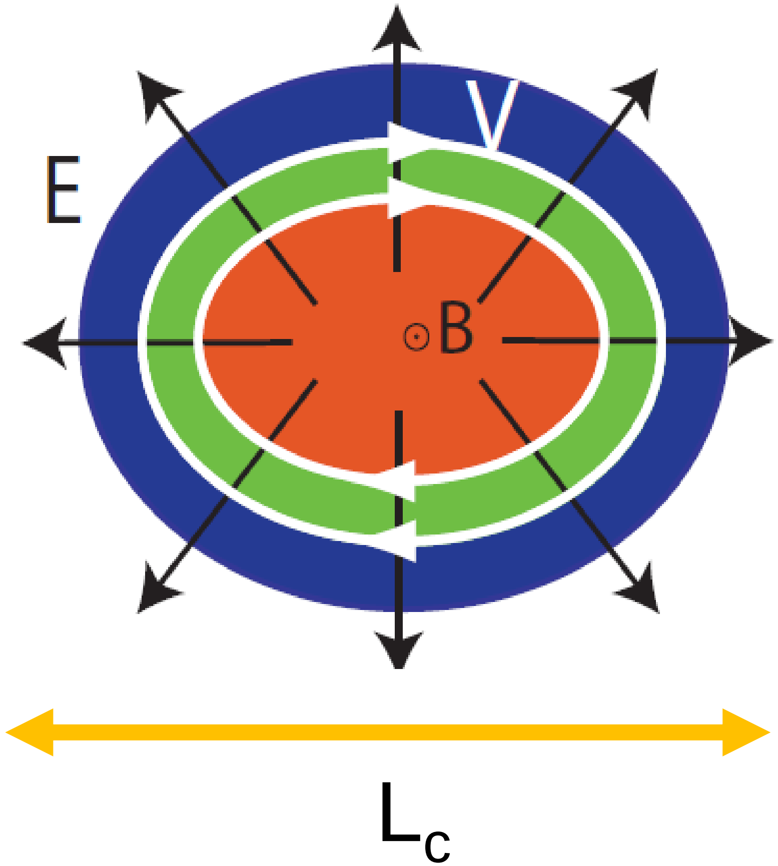
$$\tau_c \sim \frac{L_c}{v} \qquad v \sim \frac{E}{B} \sim \frac{\phi}{L_c}\frac{1}{B}$$

$$\boxed{D \sim \frac{\phi}{B} \sim \frac{T}{B}}$$

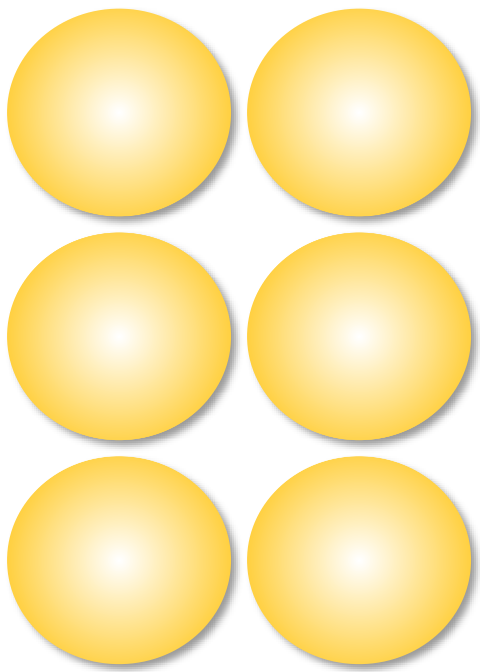


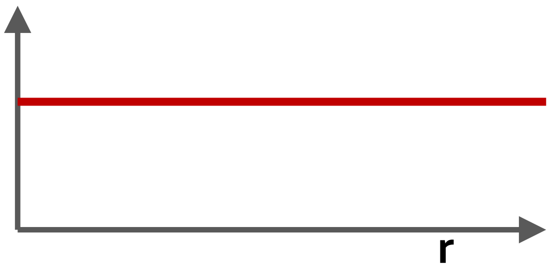
So controlling the ‘size’ and ‘correlation time’ of these blobs allows us to ‘control’ confinement

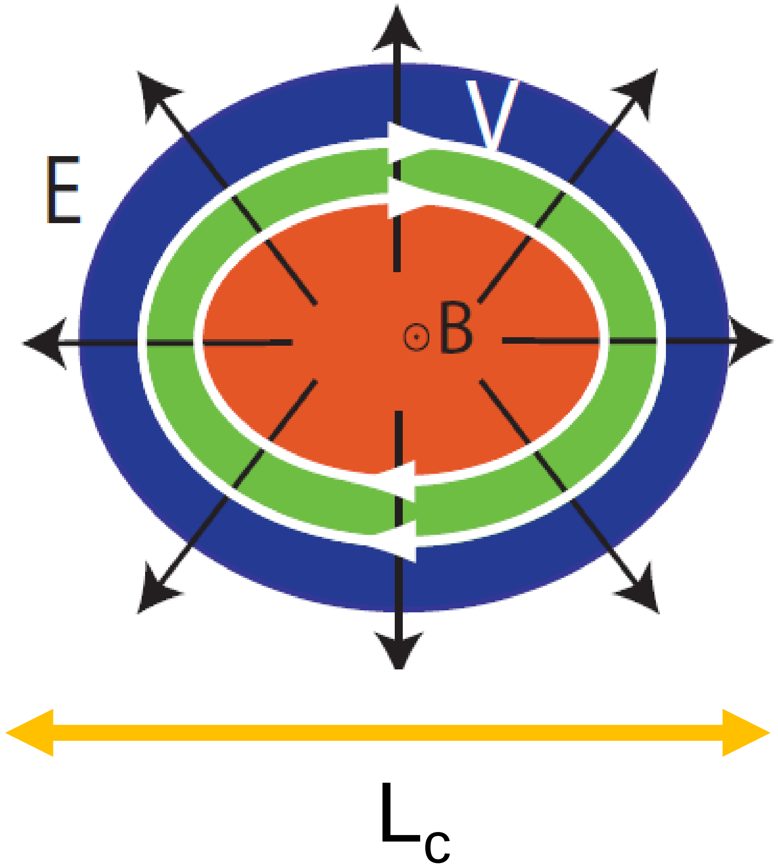




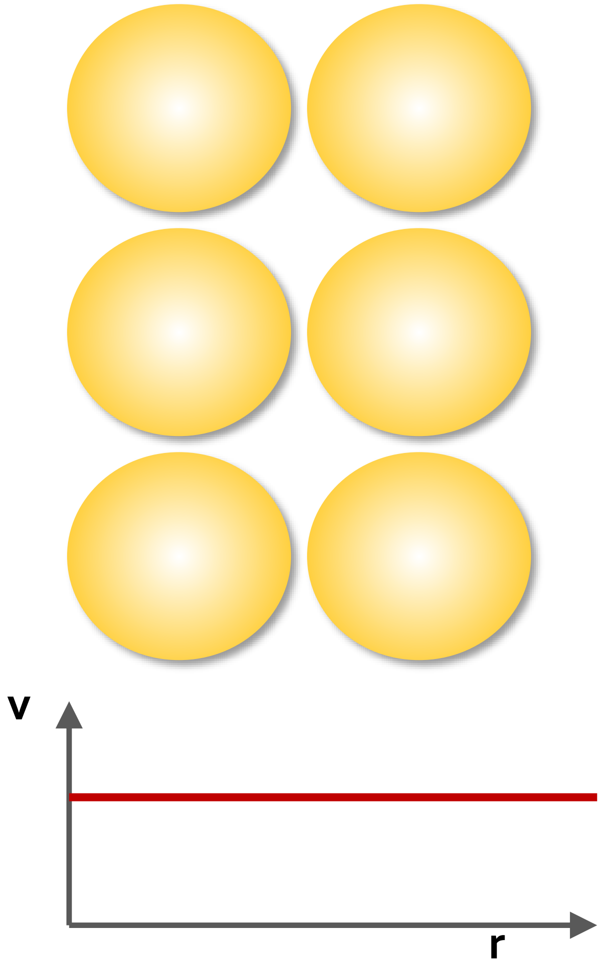
These eddies ‘live’ in a ‘background’ flow

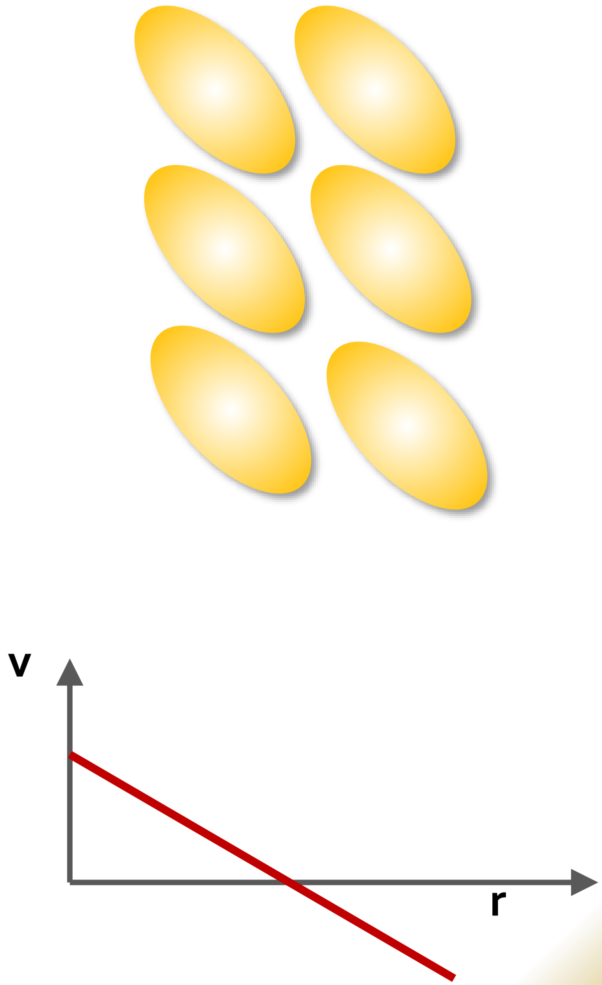






By changing the 'background flow' we can tilt and eventually break these eddies





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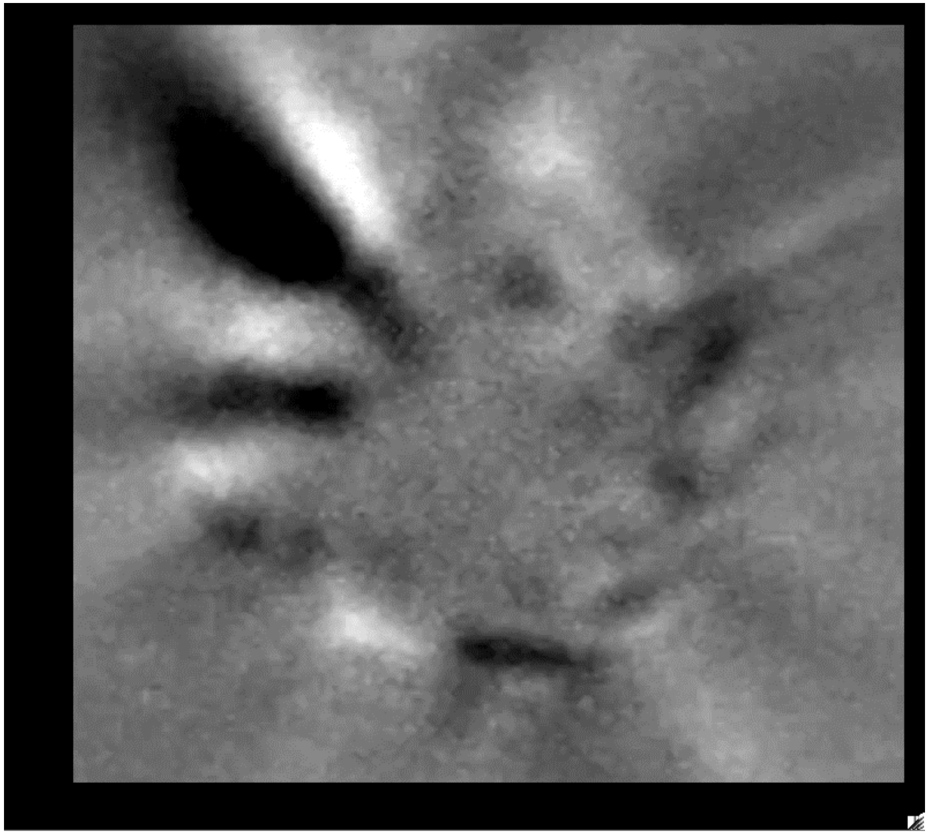
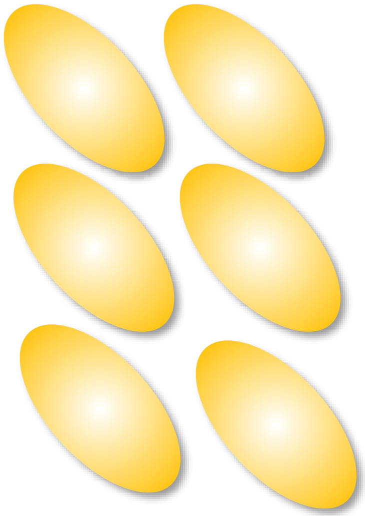
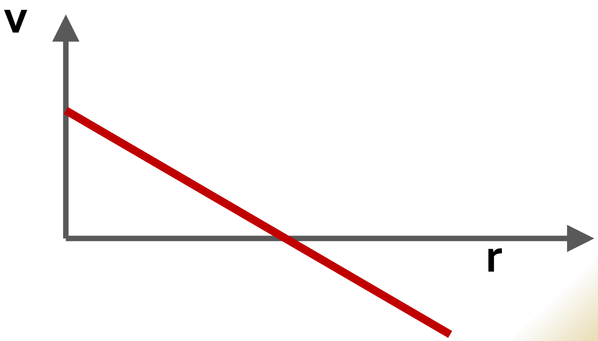




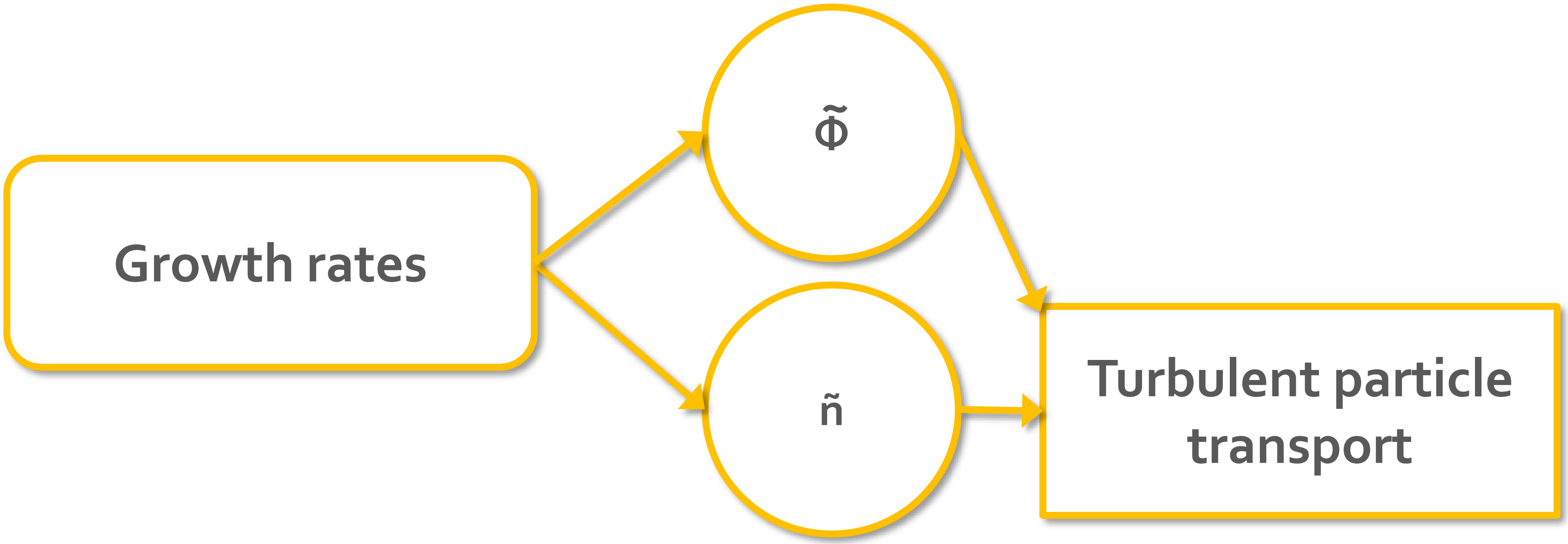


Turbulent transport is affected by gradients that drive fluctuations, the shear that suppresses them

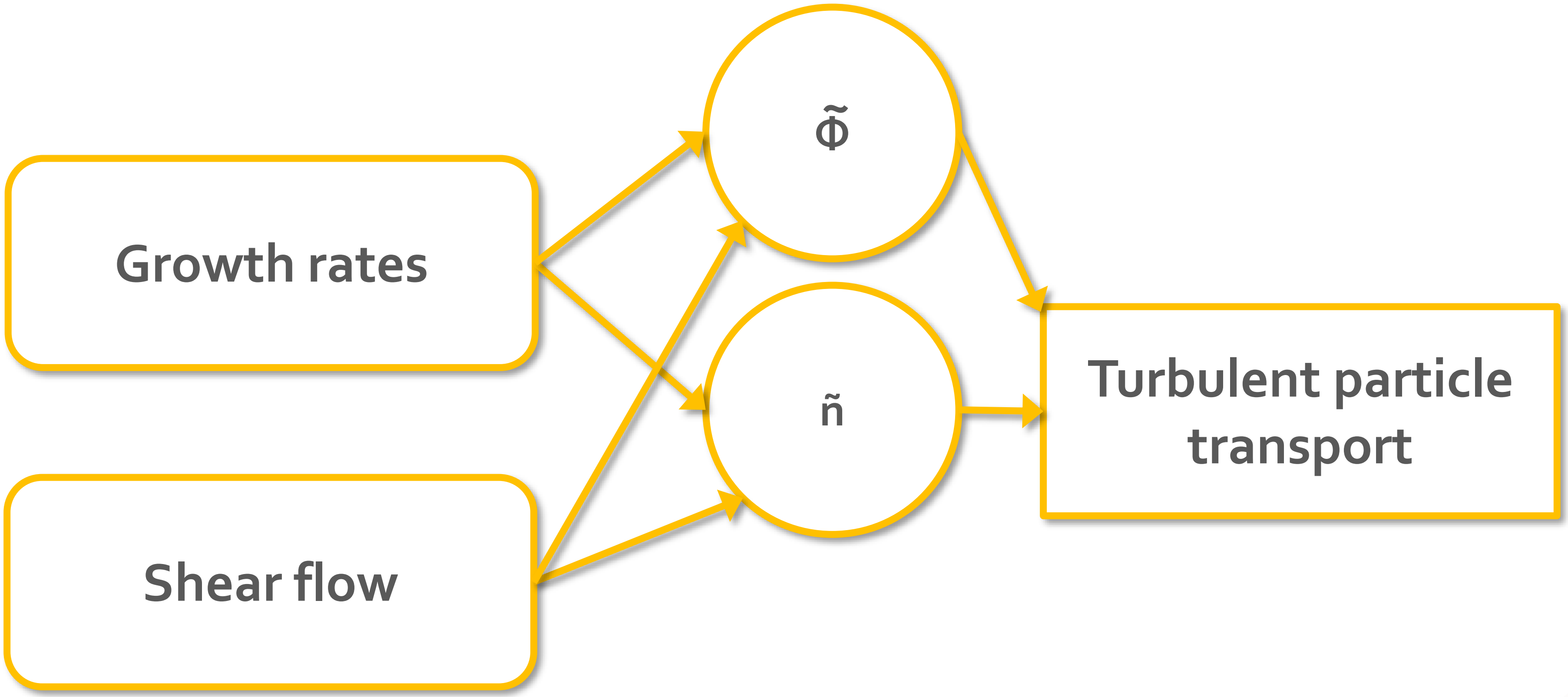
Growth rates

Turbulent particle transport

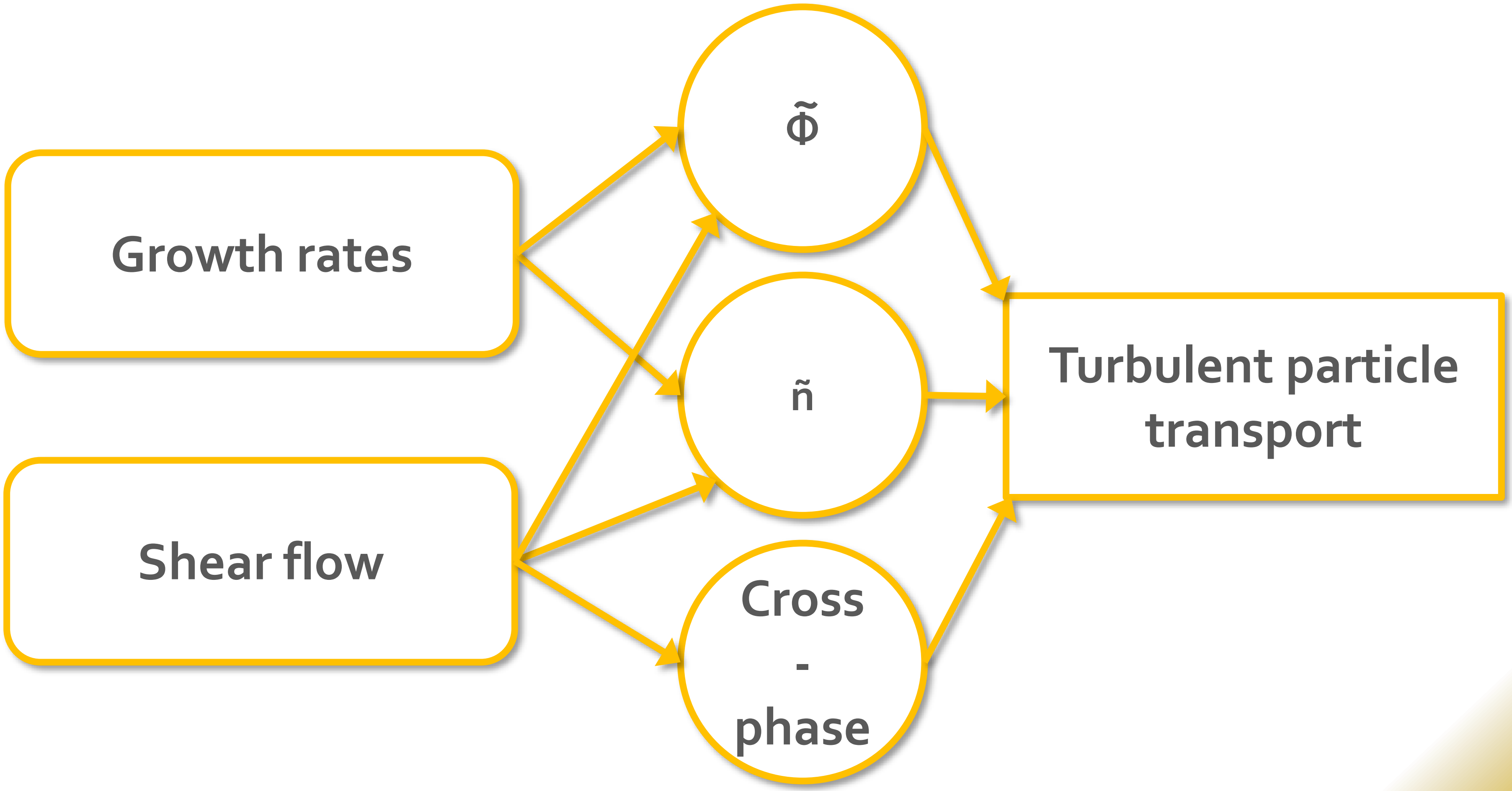
Turbulent transport is affected by gradients that drive fluctuations, the shear that suppresses them



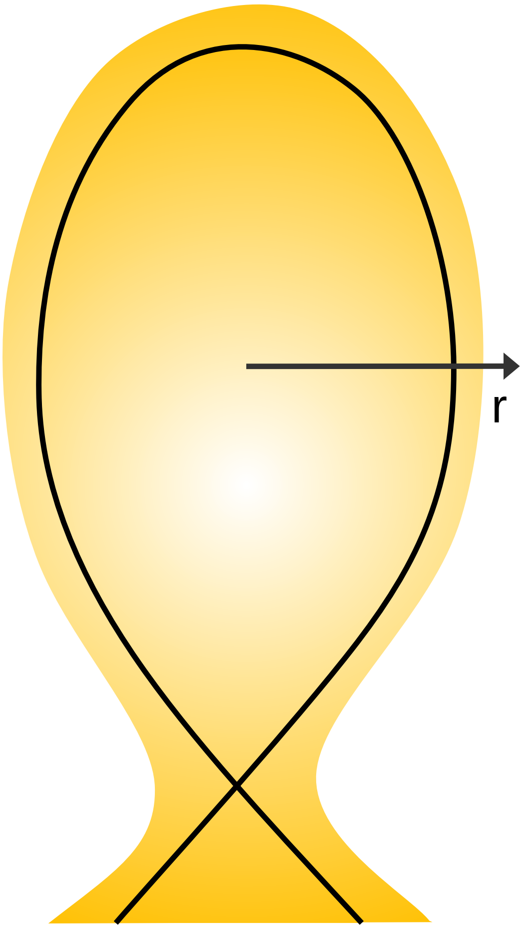
Turbulent transport is affected by gradients that drive fluctuations, the shear that suppresses them

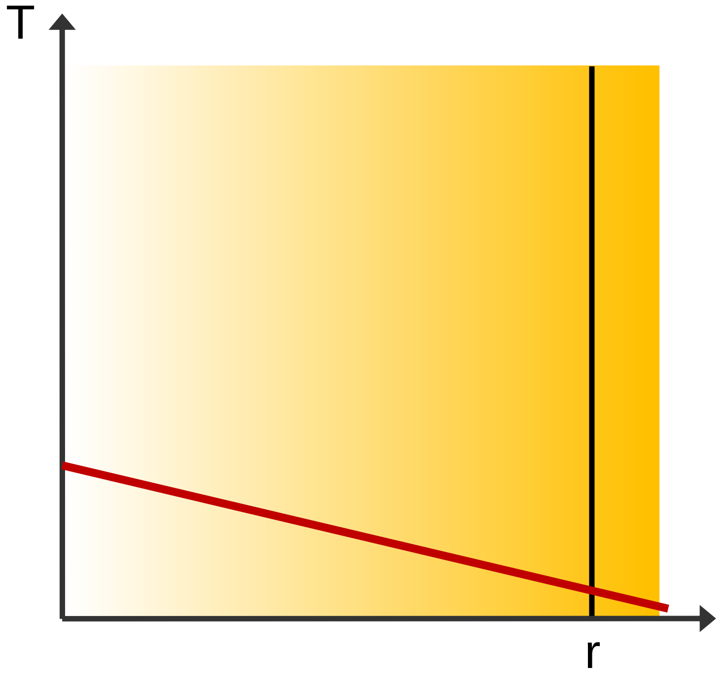


Turbulent transport is affected by gradients that drive fluctuations, the shear that suppresses them

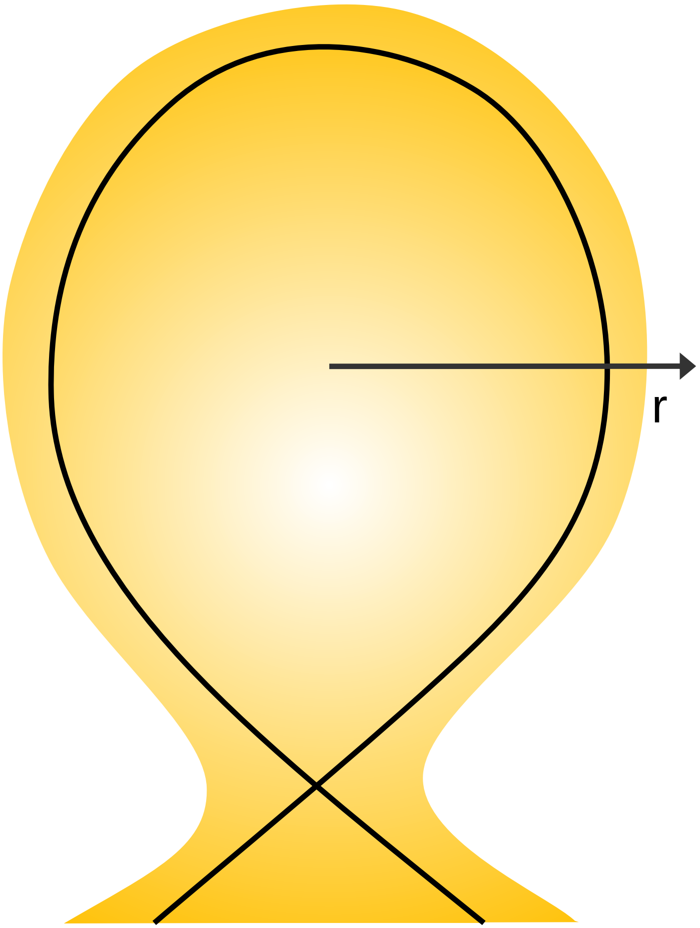


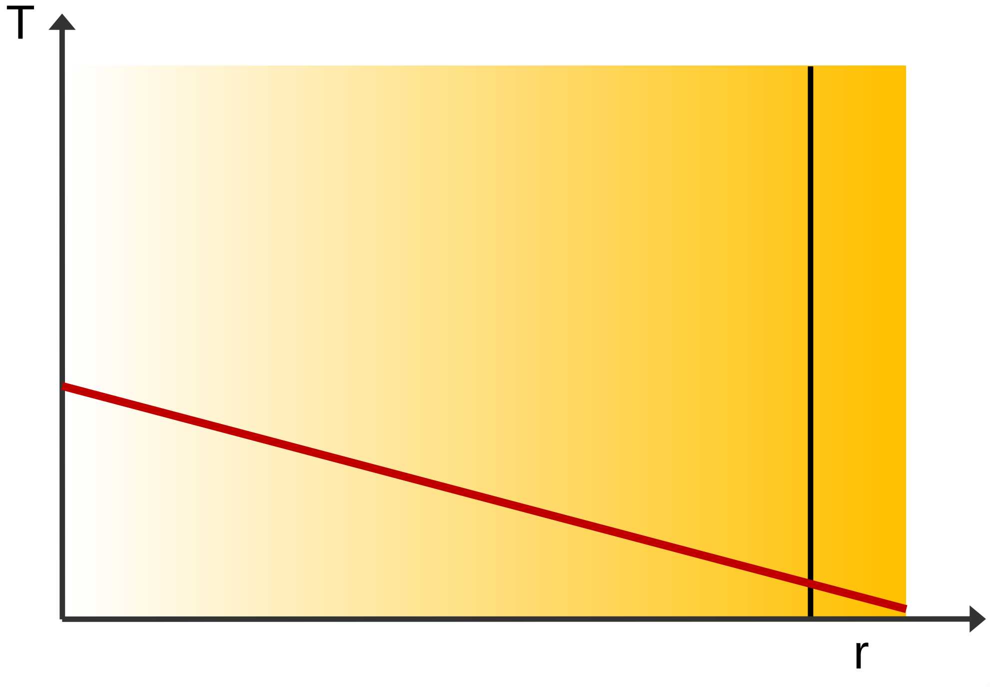
Originally, confinement was limited and profiles were stiff (i.e. gradient was limited)



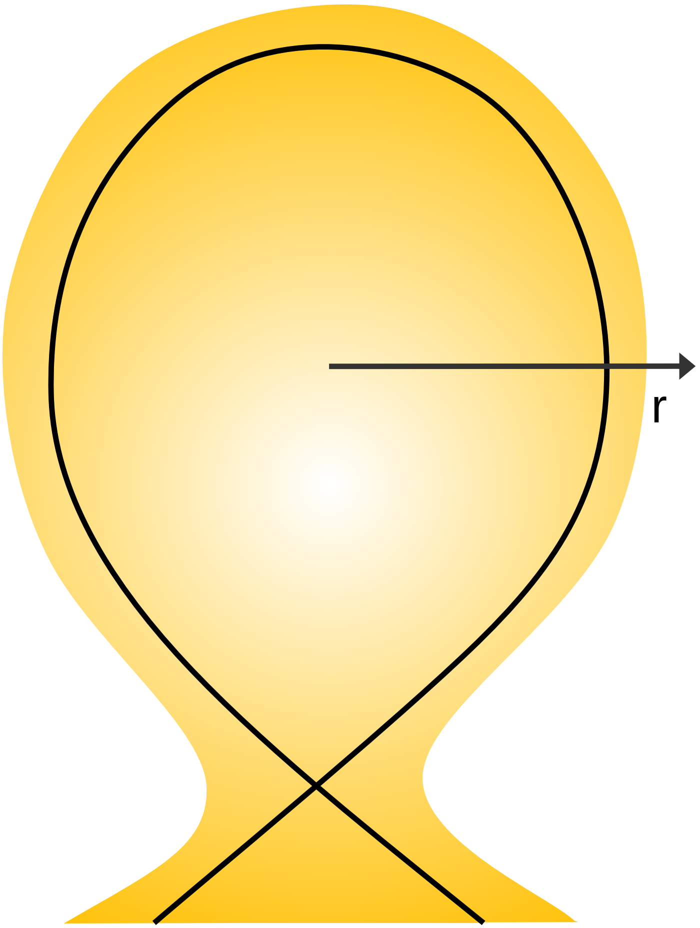


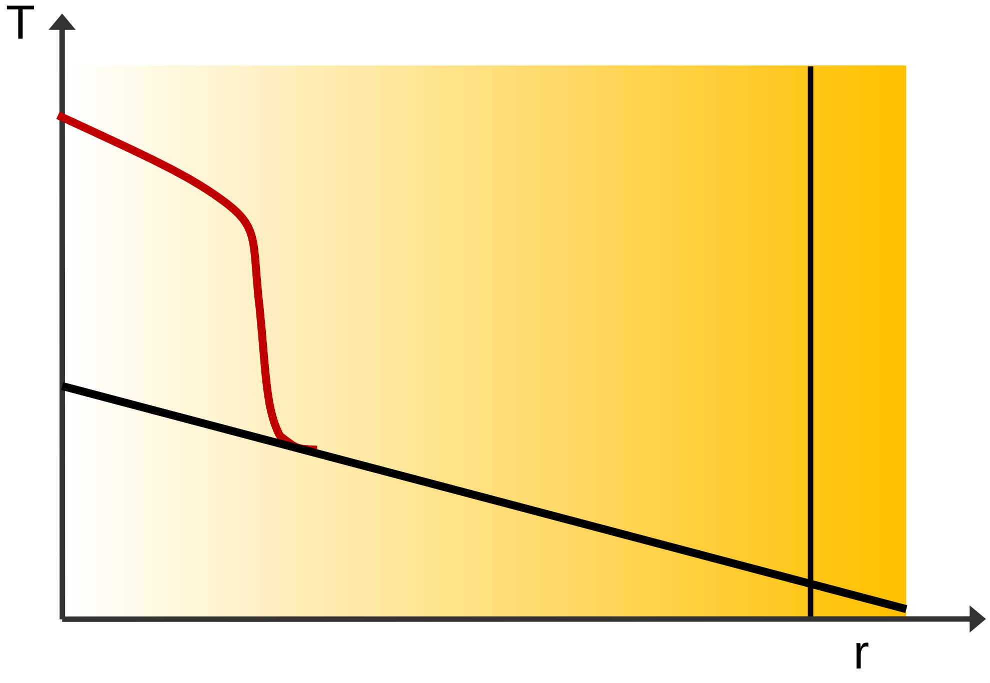
So to raise the temperature, the radius of the device has to increase



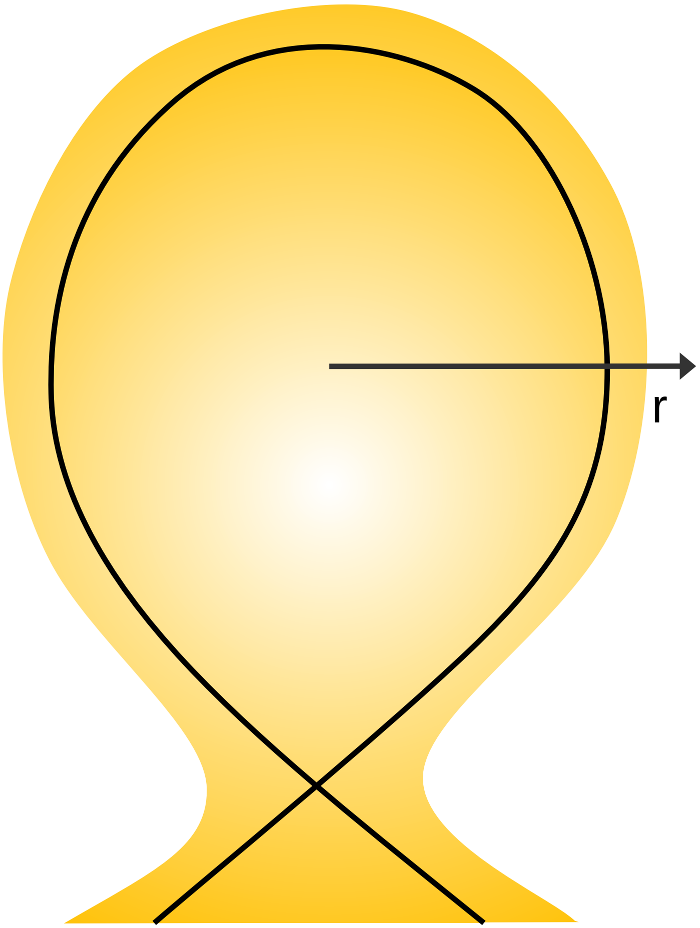


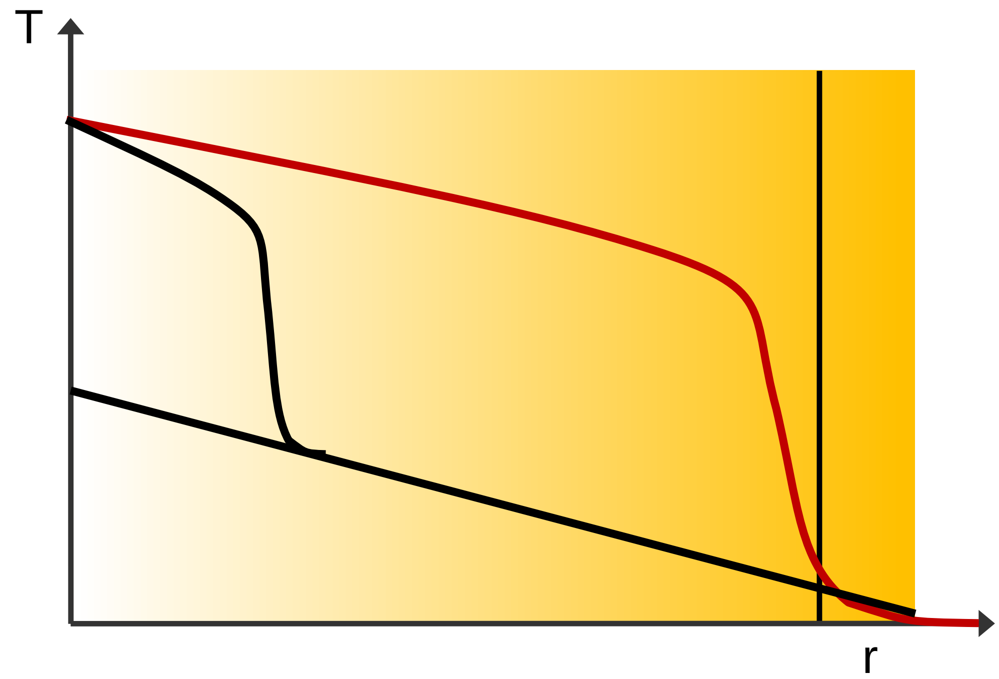
The other option is to 'break' the stiffness in the profiles : creation of Transport Barrier



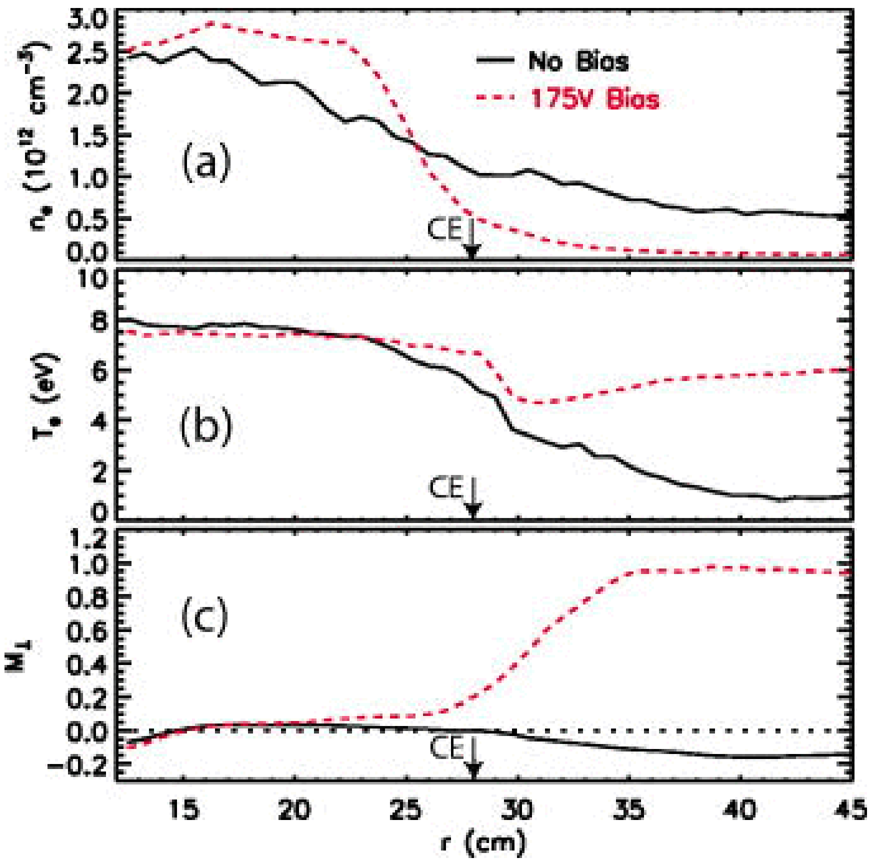


Even better is when the transport barrier is at the plasma edge, which results in a larger volume at fusion conditions





LAPD: Linear machine that shows how introduction of shear flow reduces outward transport



T. Carter et al. Phys. Plasmas 16, 012304 (2009)

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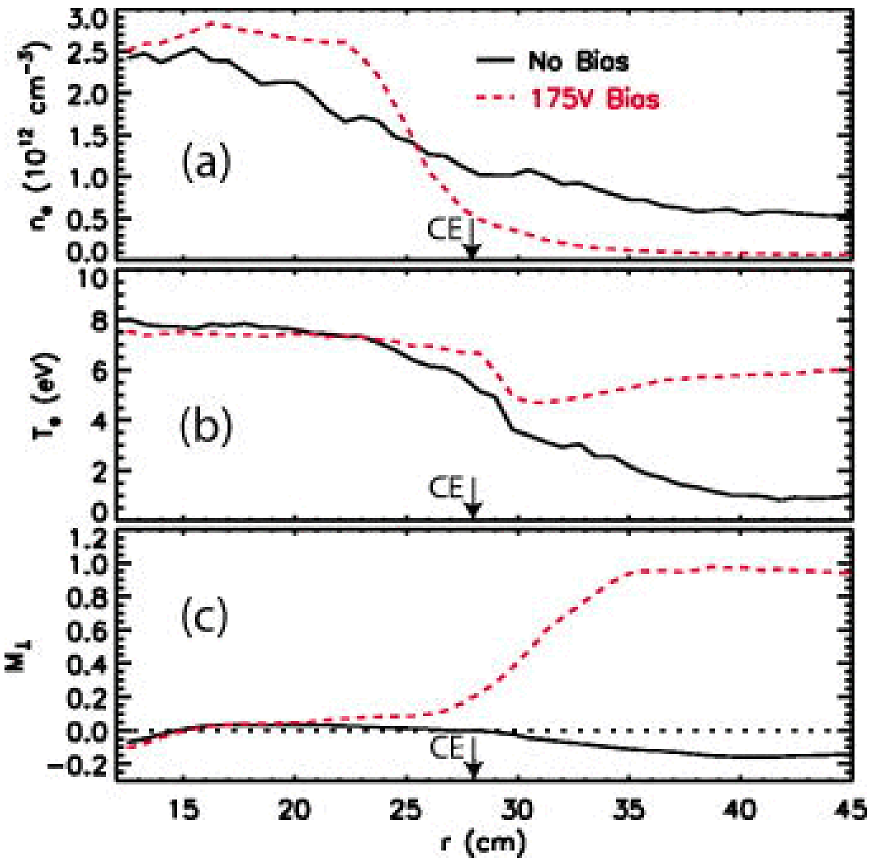

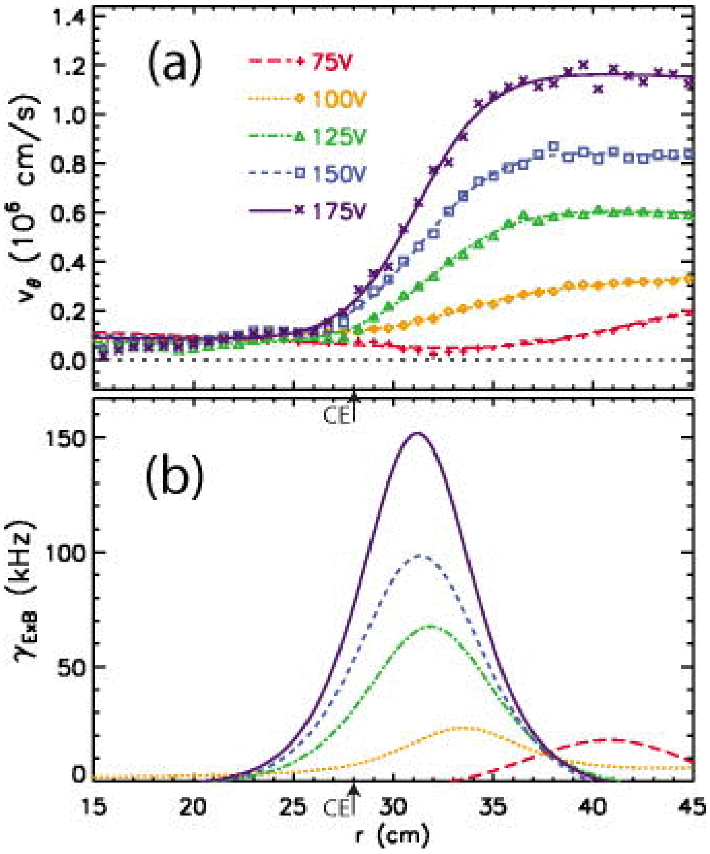

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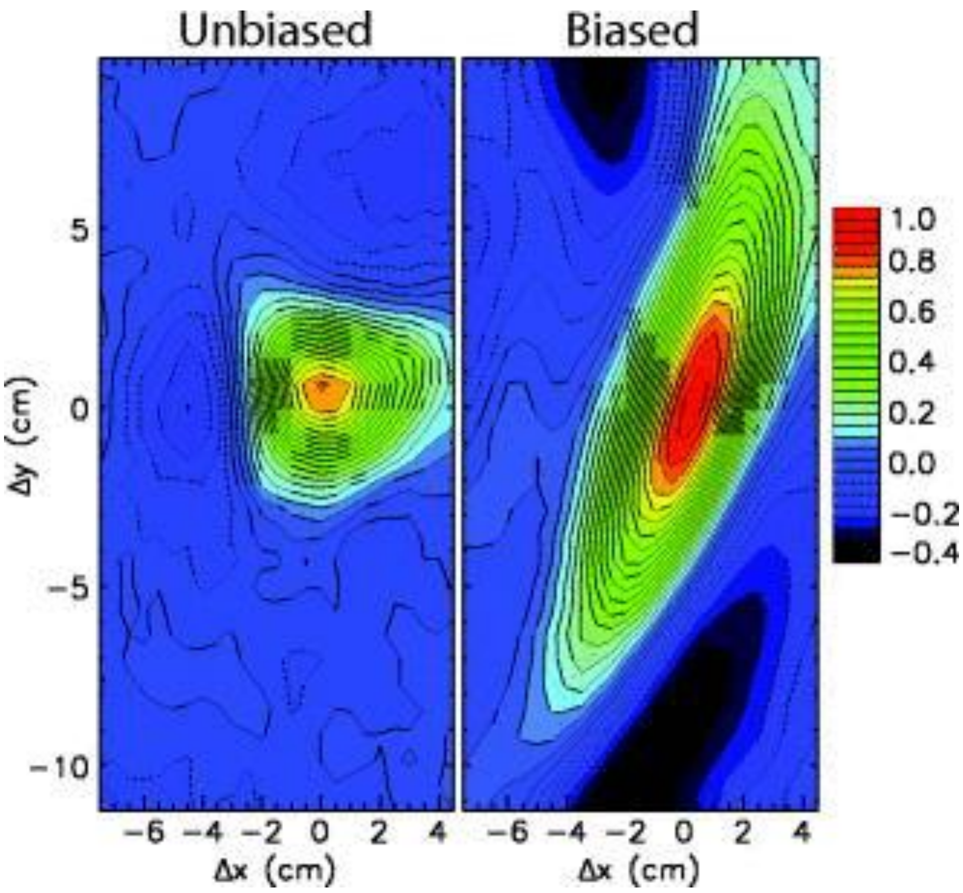

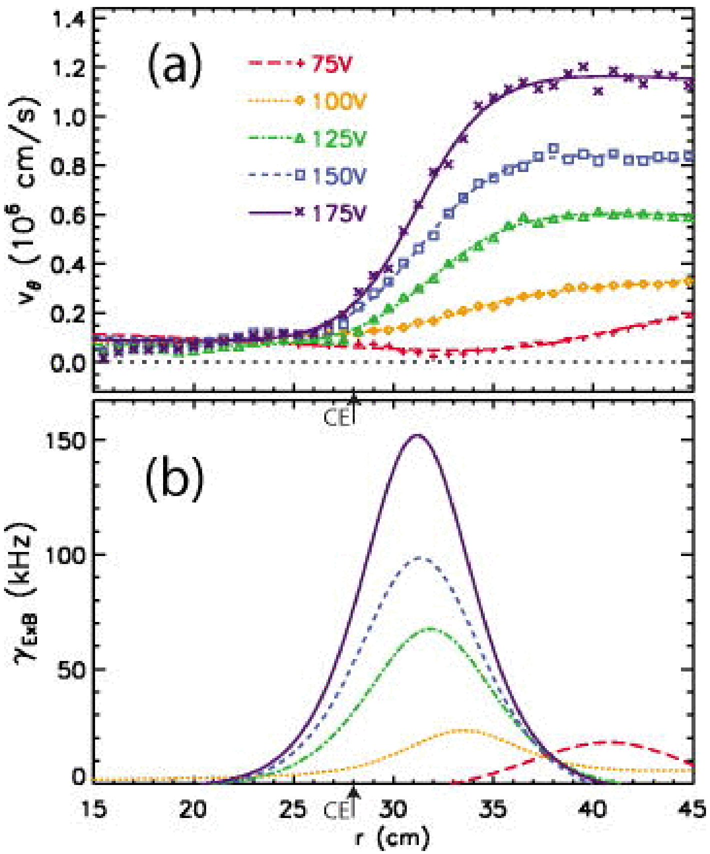

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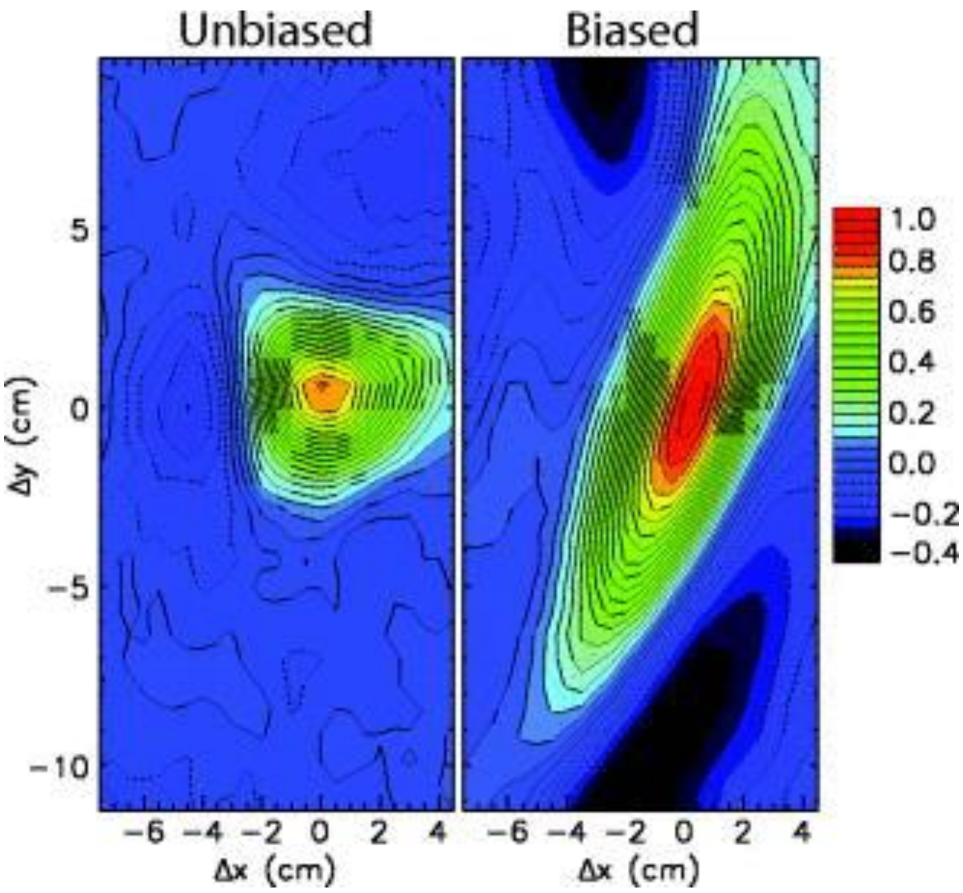

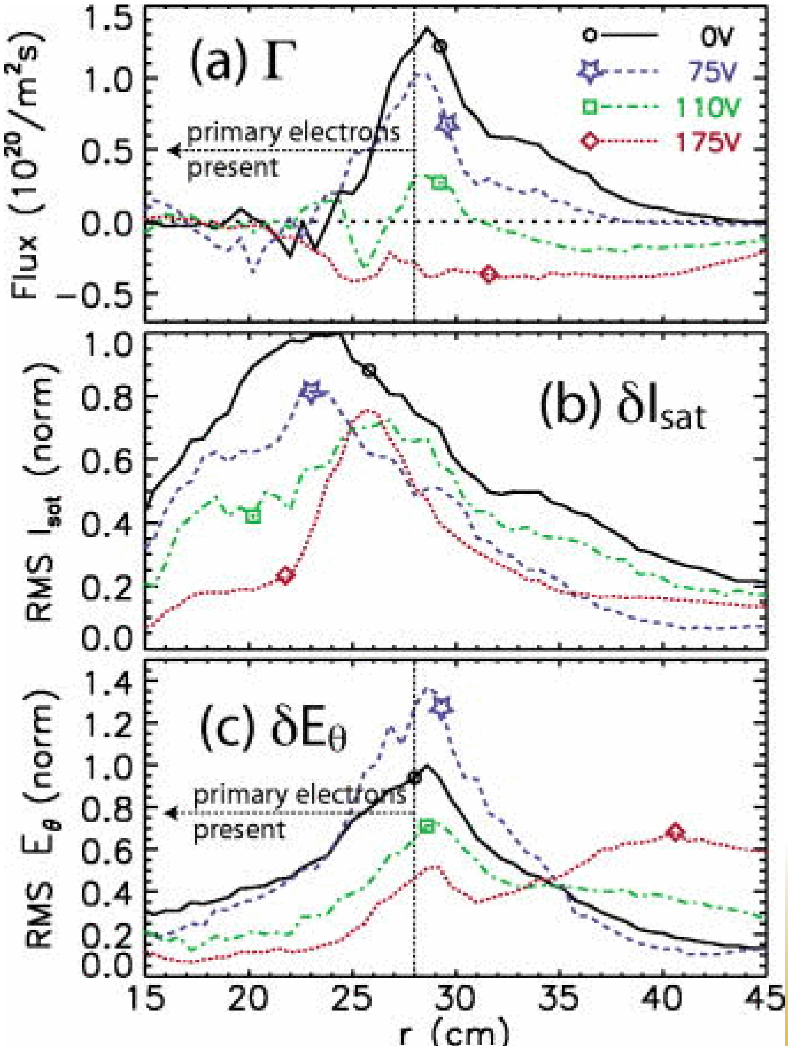

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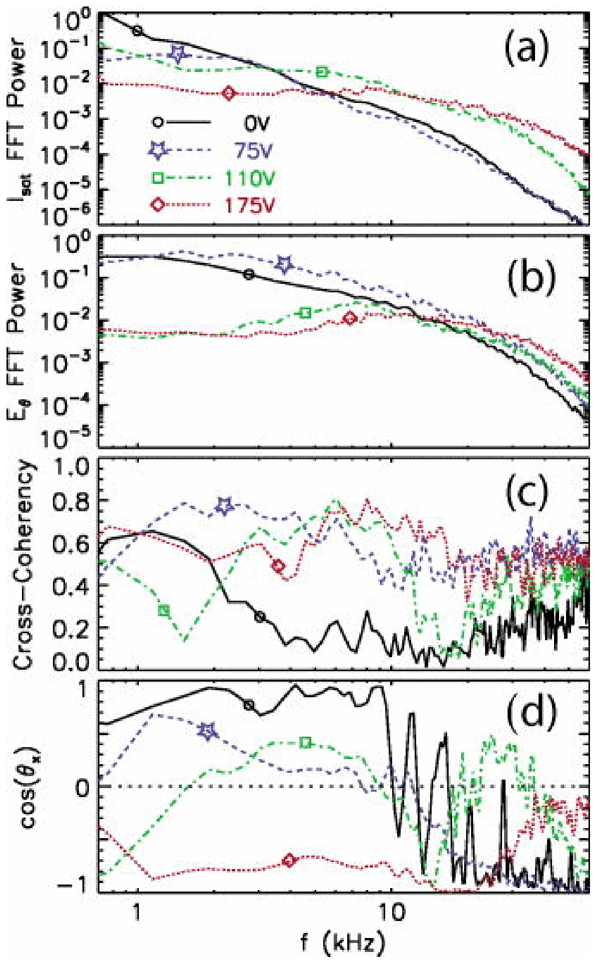
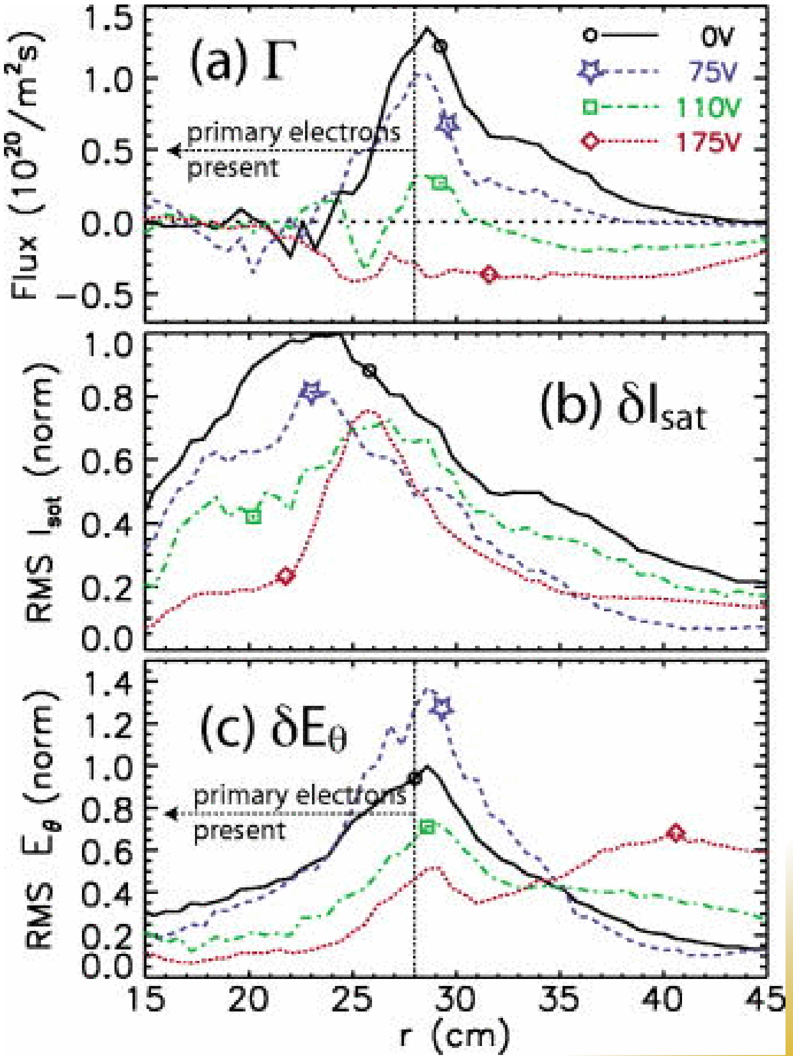
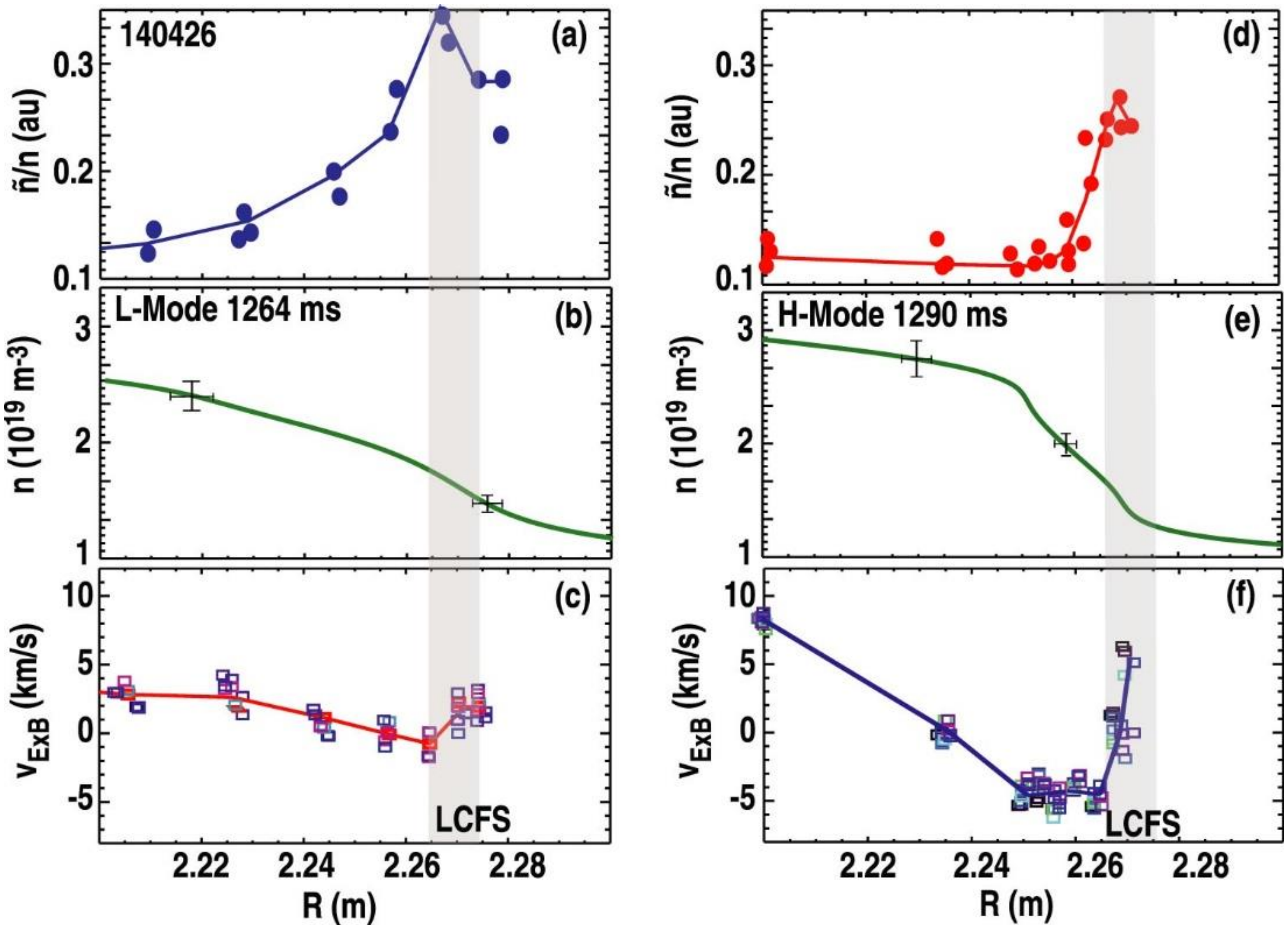




T. Carter et al. Phys. Plasmas 16, 012304 (2009)

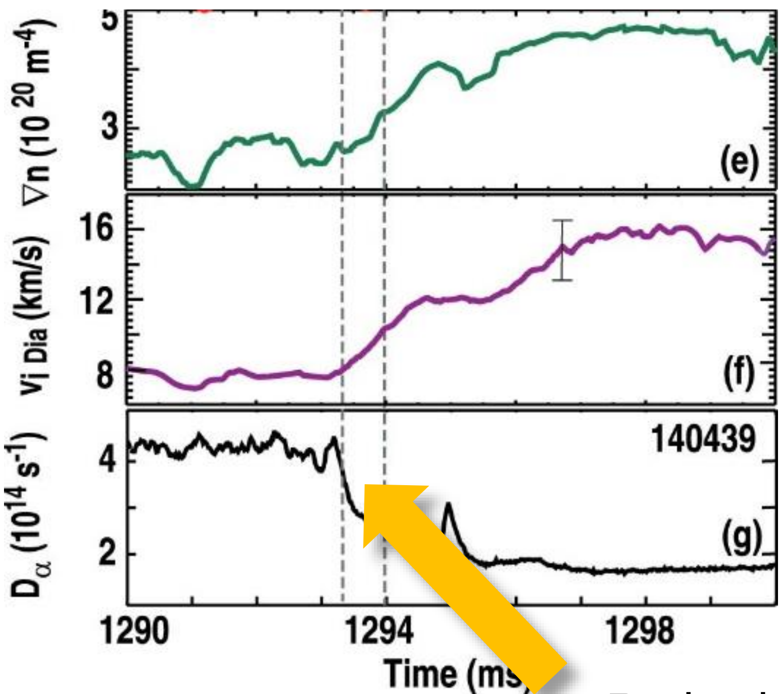
An increase in power triggers the formation of a barrier at the plasma edge in a tokamak



L. Schmitz et al 2014 NF 54 073012

In a Tokamak, a similar bifurcation can be observed. This results in an important improvement in confinement

Increase in injected power, triggers reduction in transport



Reduction in neutral recycling in divertor is used as t=0

L. Schmitz et al 2014 NF 54 073012

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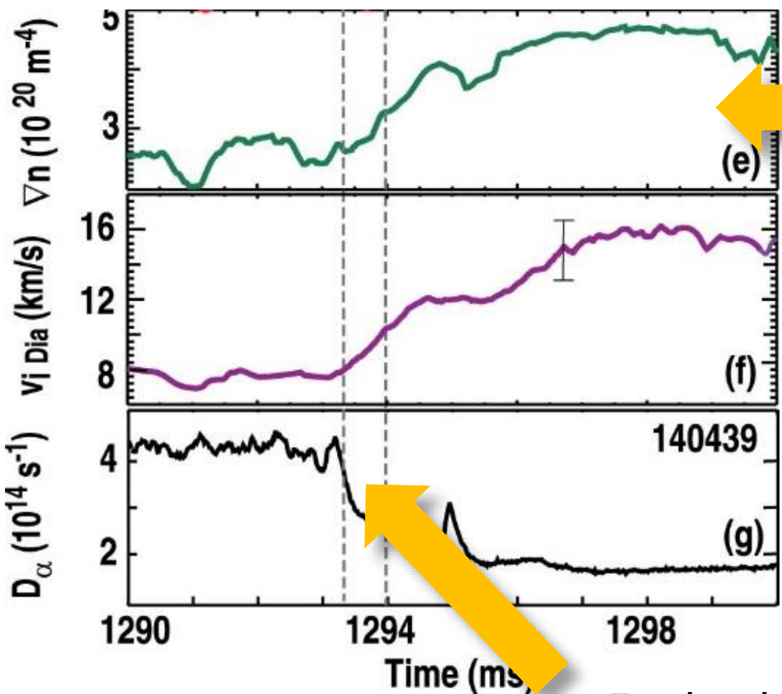

The density gradient steepens

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L. Schmitz et al 2014 NF 54 073012

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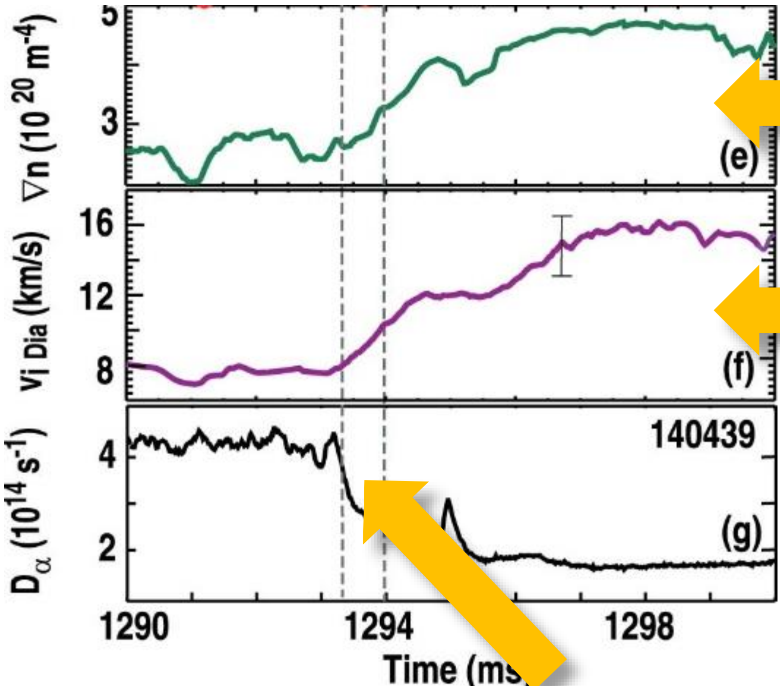


The density gradient steepens

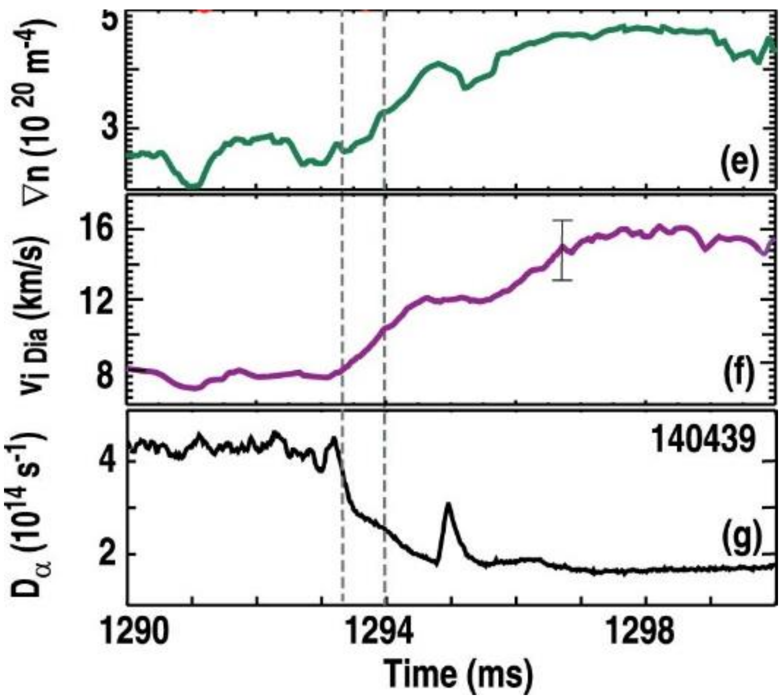
The diamagnetic component of the v_{ExB} increases

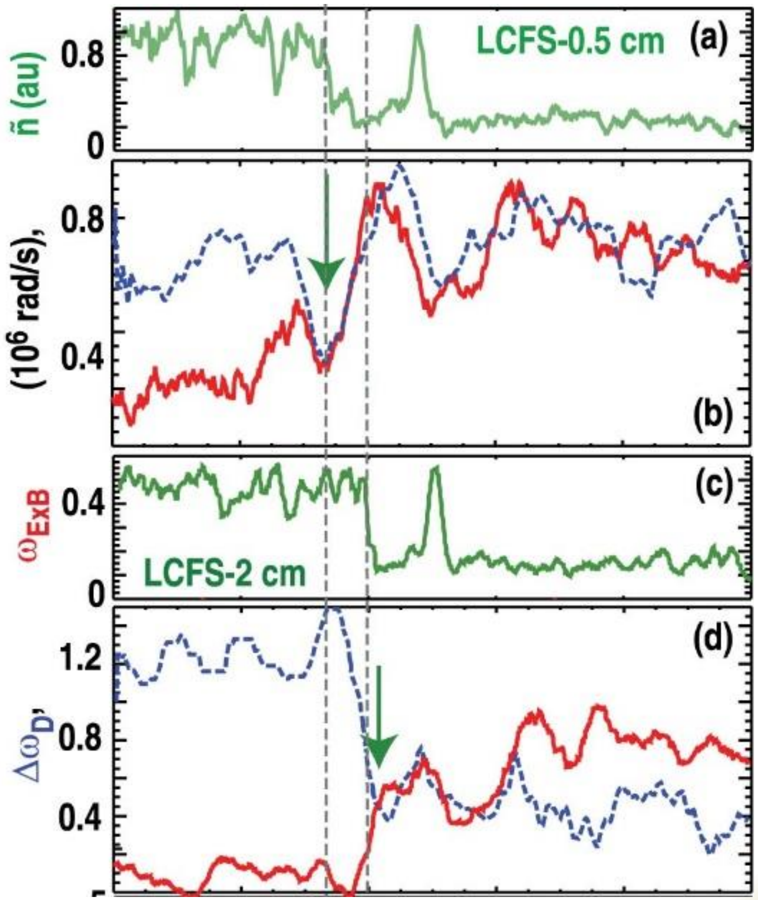
$$\bar{v}_{i\theta} = \frac{E_r}{B_\phi} - \frac{\nabla p_i}{eB_\phi n_i} + \bar{v}_{i\phi}\frac{B_\theta}{B_\phi}$$

Reduction in neutral recycling in divertor is used as t=0

L. Schmitz et al 2014 NF 54 073012

At the L- to H-mode transition, first the density fluctuations at the edge are reduced, when the shear >= decorrelation of fluctuations





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We can slow down the L- to H-mode transition to better understand the underlying dynamics

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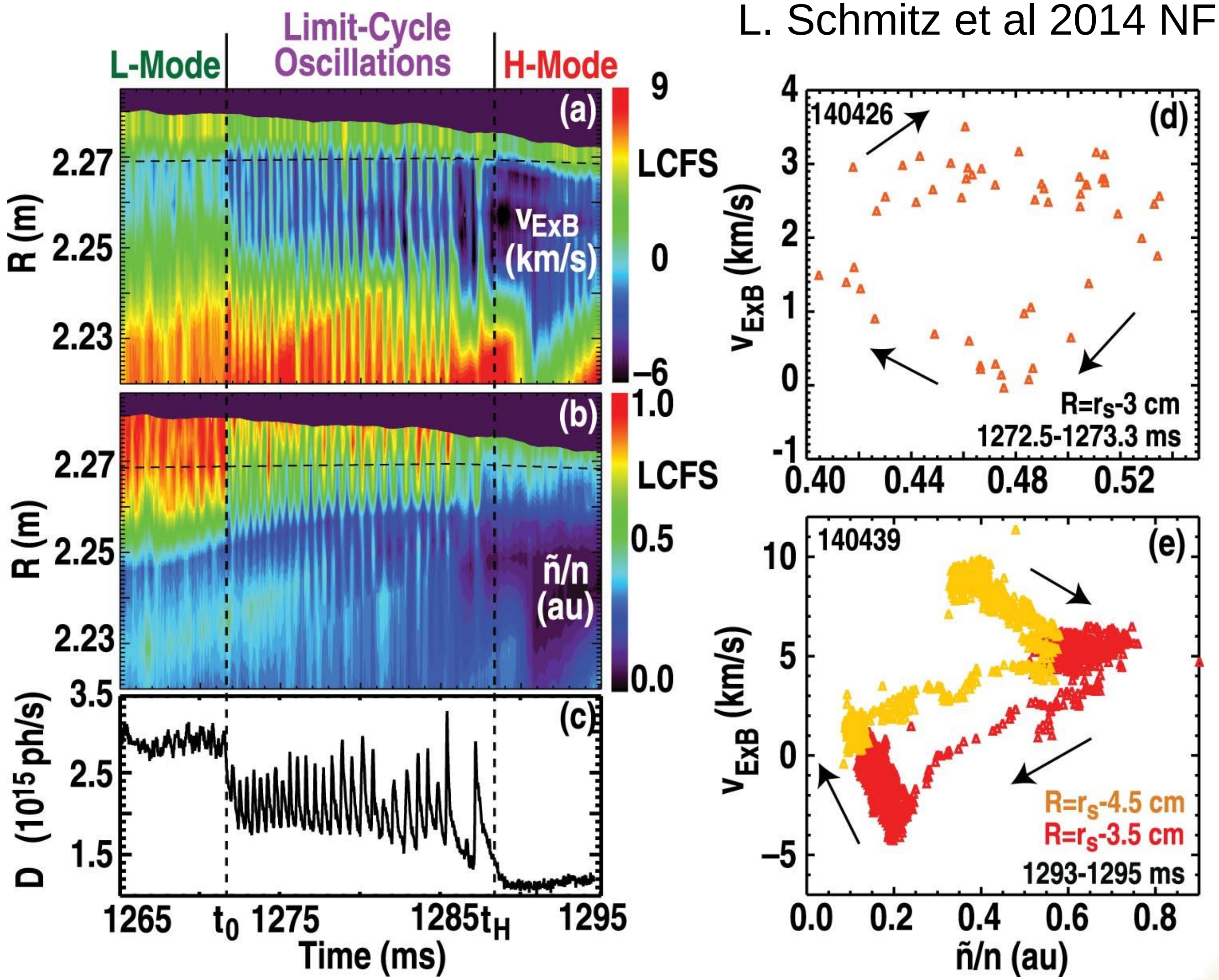
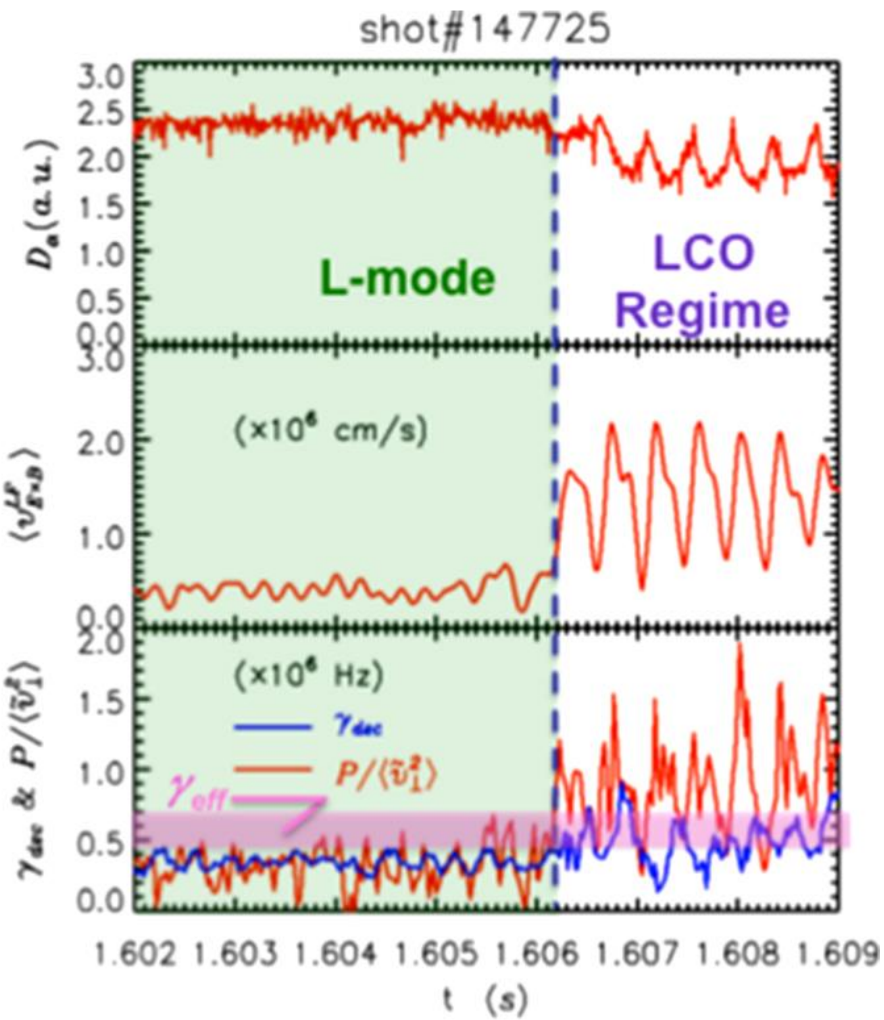


Evidence of how the energy transfer changes to predominantly to the flow at LCO transition



G.R. Tynan et al 2013 NF 53 073053

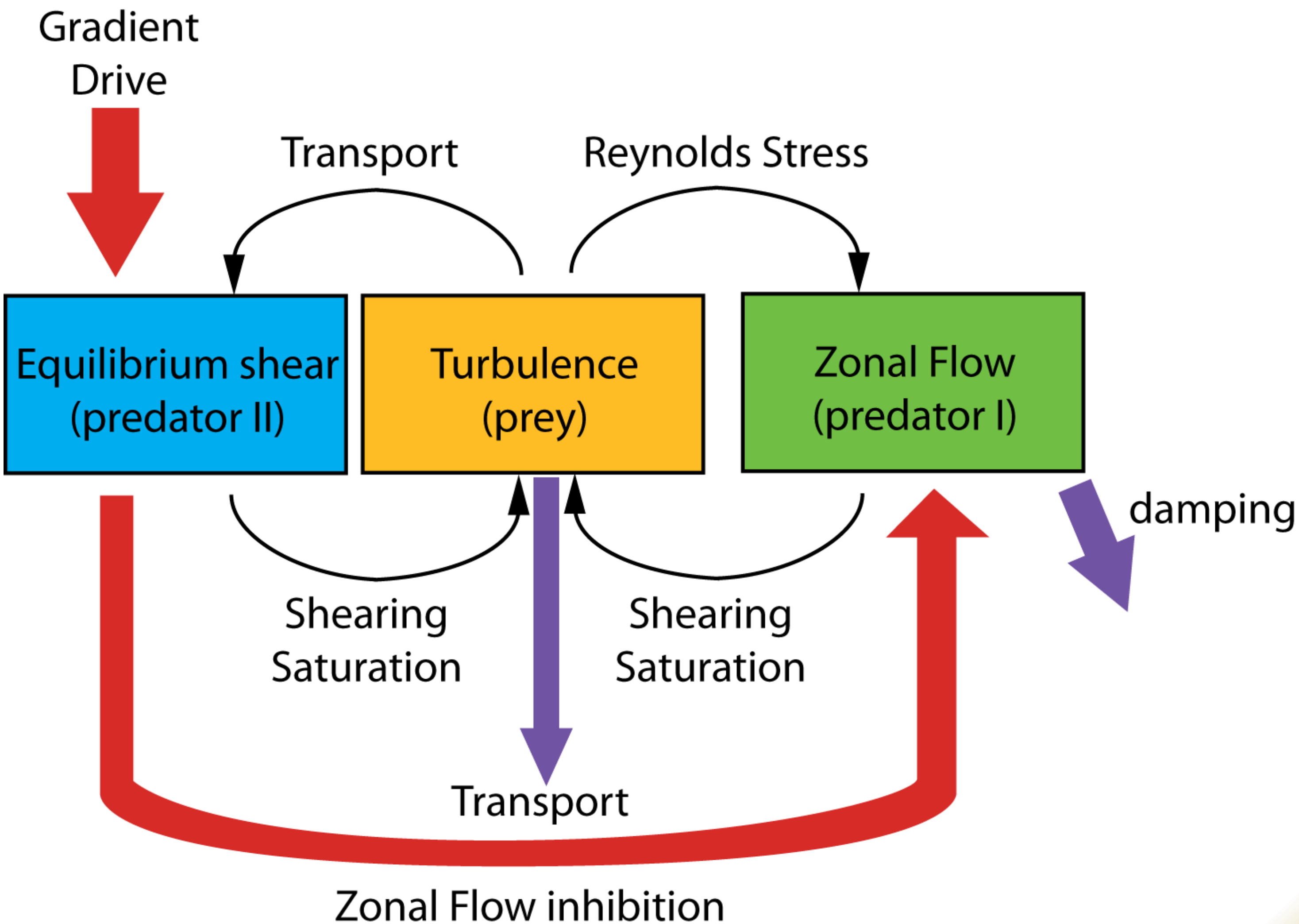
Before transition energy is dissipated to 'mean' flow and turbulence.

Total energy input remains same at transition (gradients are still the same), but energy distribution changes

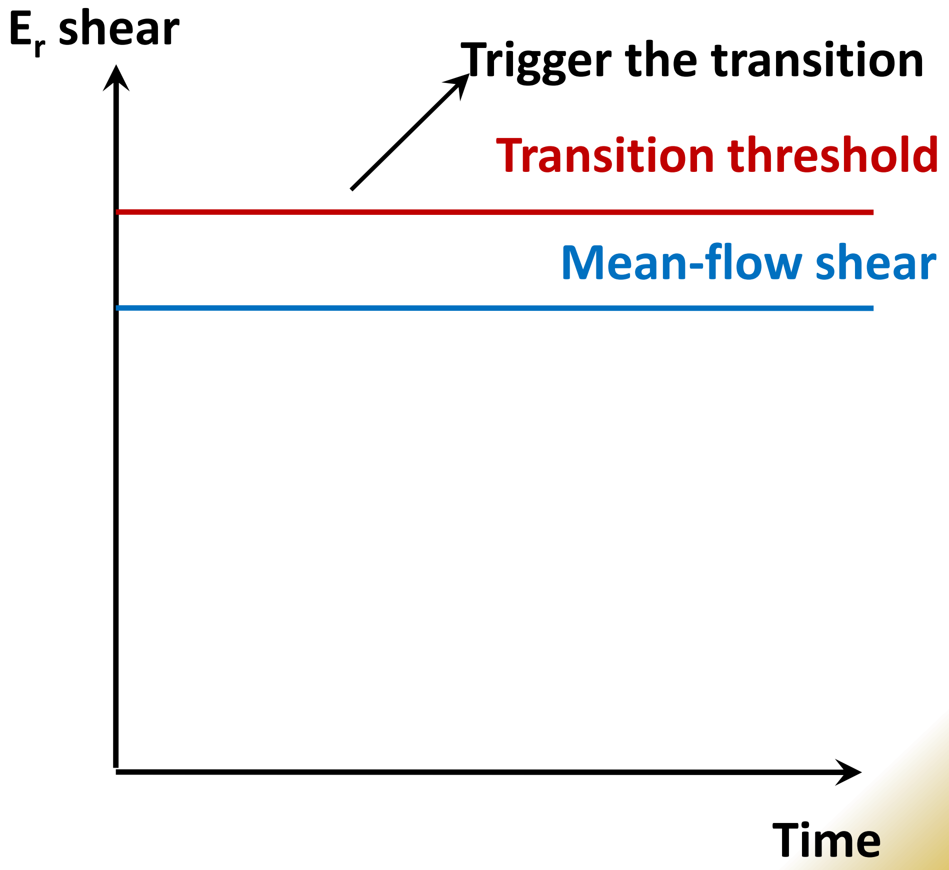
Energy transfer from turbulence into (mean) shear flow

Turbulence decorrelation rate in the plasma frame

Dynamics behind the suppression of turbulent transport at the plasma edge follows a predator prey model



Zonal Flows (or GAMs) are superimposed on the mean flow and can help trigger a transition



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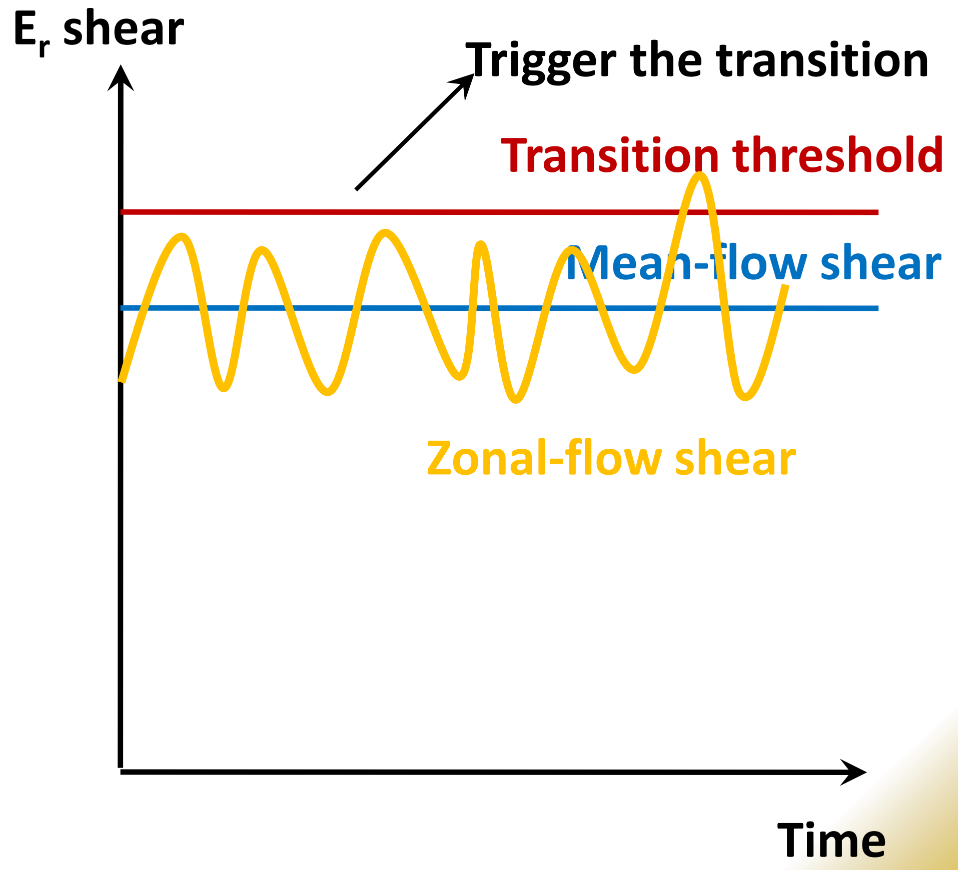
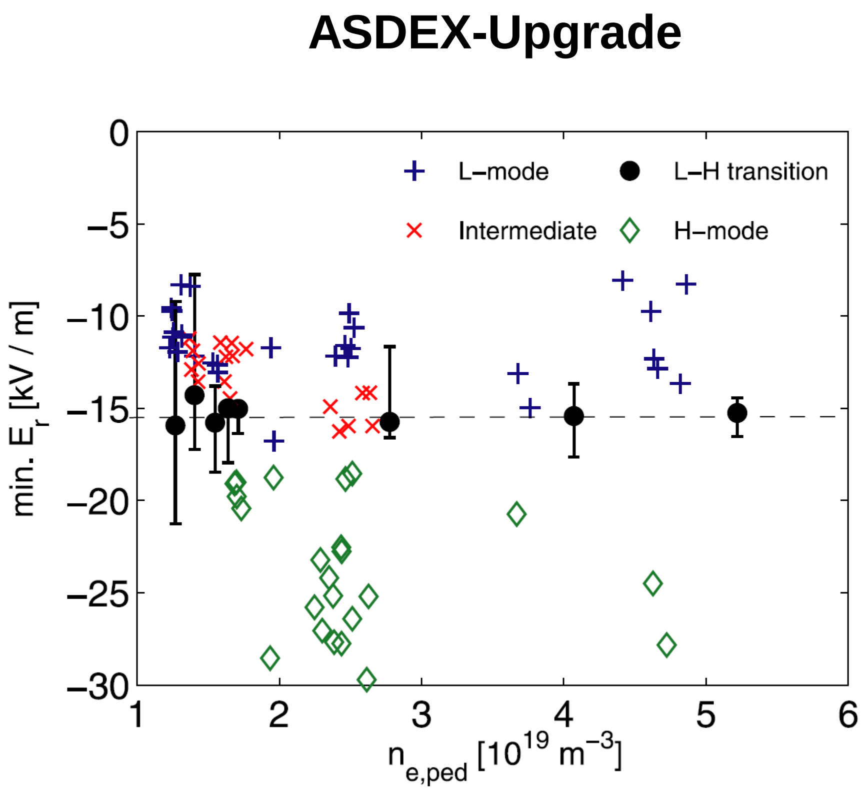
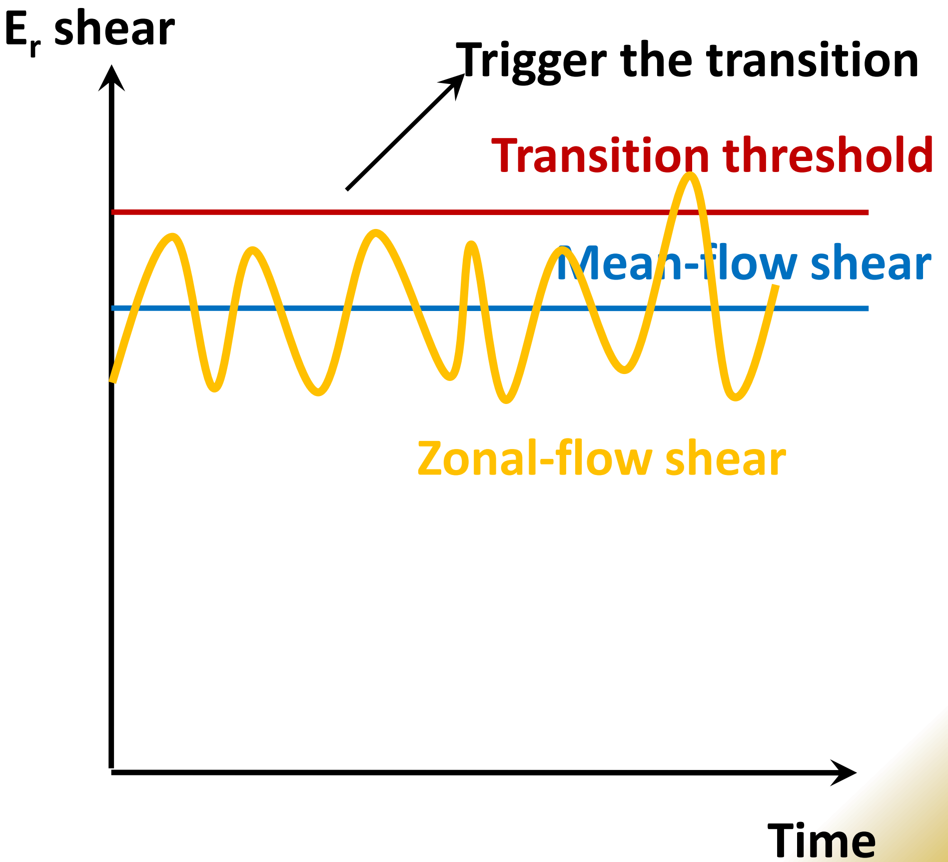


For example, there is no change in Er shear across different initial L-mode densities before LH-transition

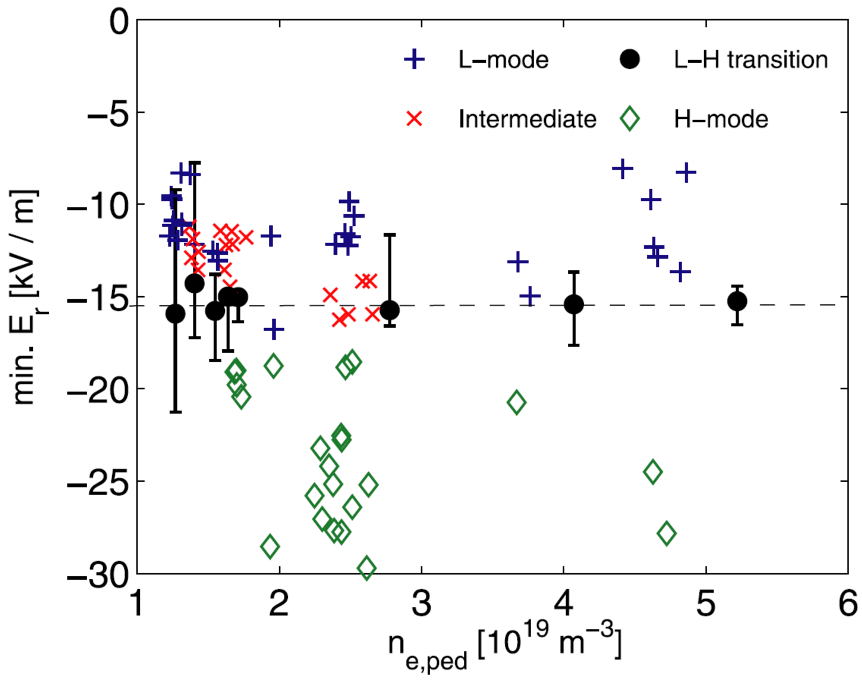


P. Sauter, et al. NF 52, 012001 (2012)



However, there is a strong density dependence on the amount of power needed for the L- to H-mode transition

ASDEX-Upgrade



P. Sauter, et al. NF 52, 012001 (2012)

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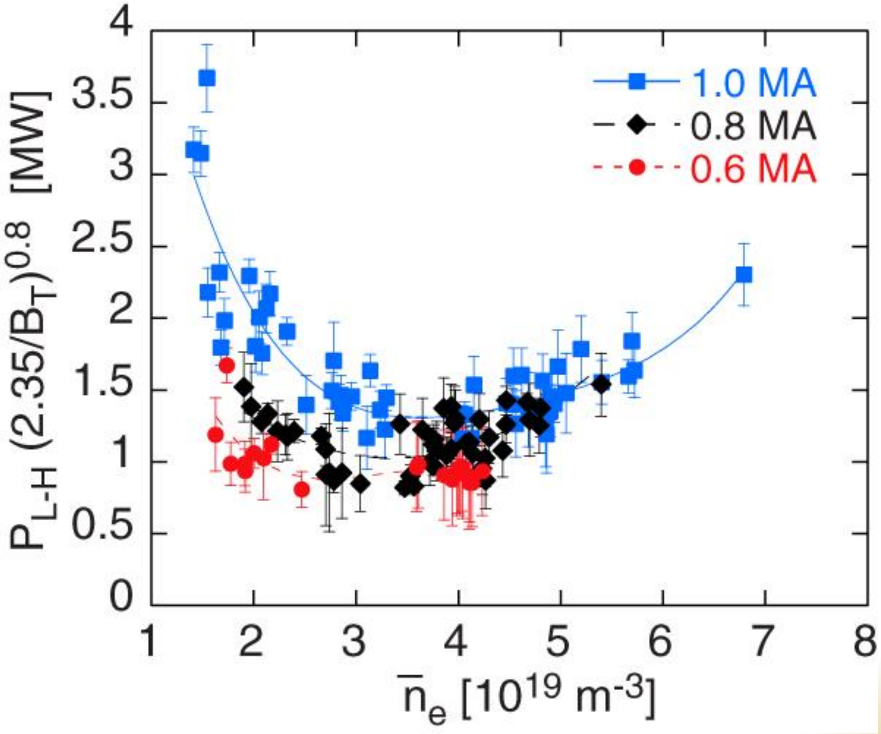
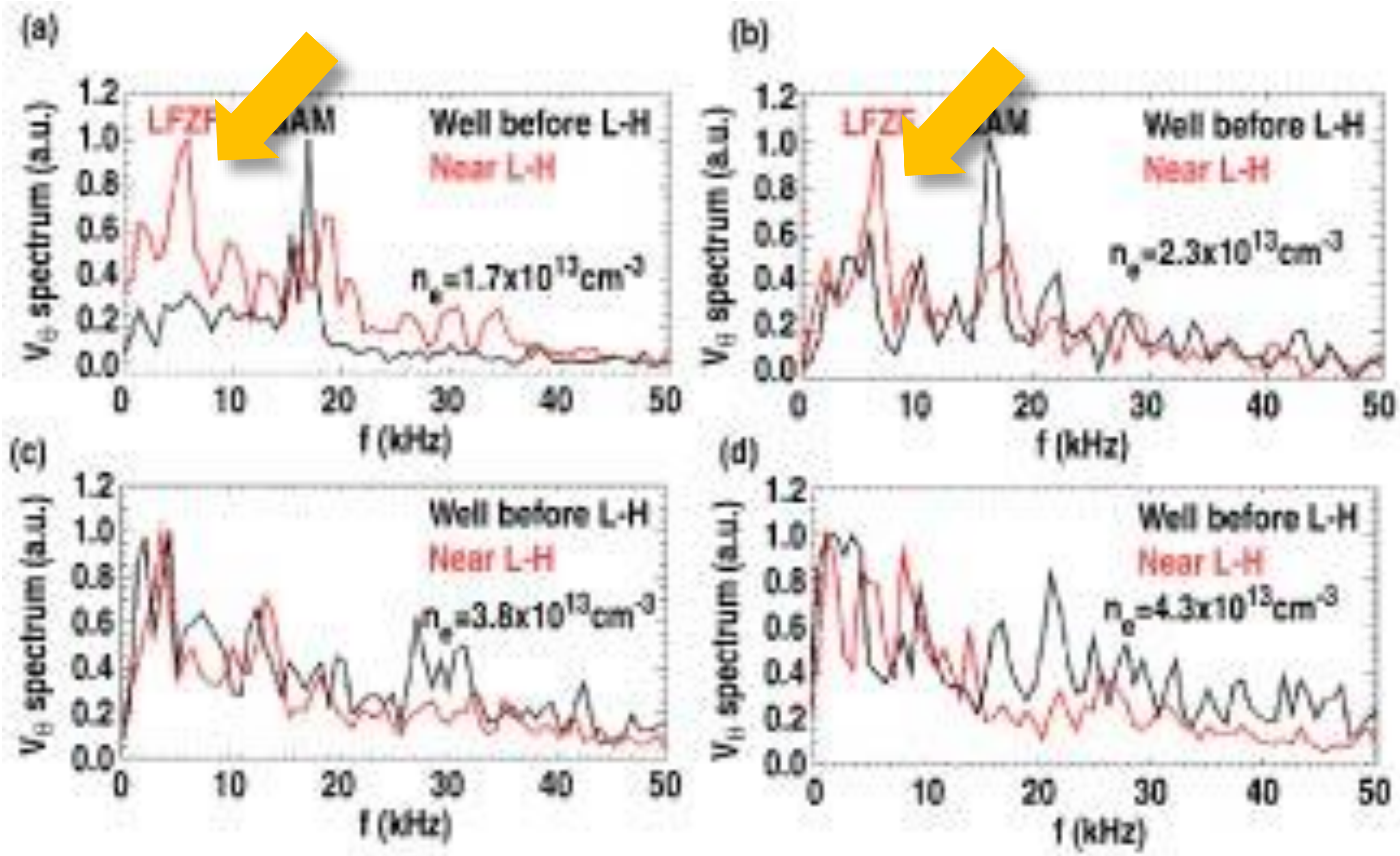


F. Ryter et al 2013 NF 53 113003

The influence on turbulence characteristics just before L-to H-mode transition show importance of ZF versus turbulence

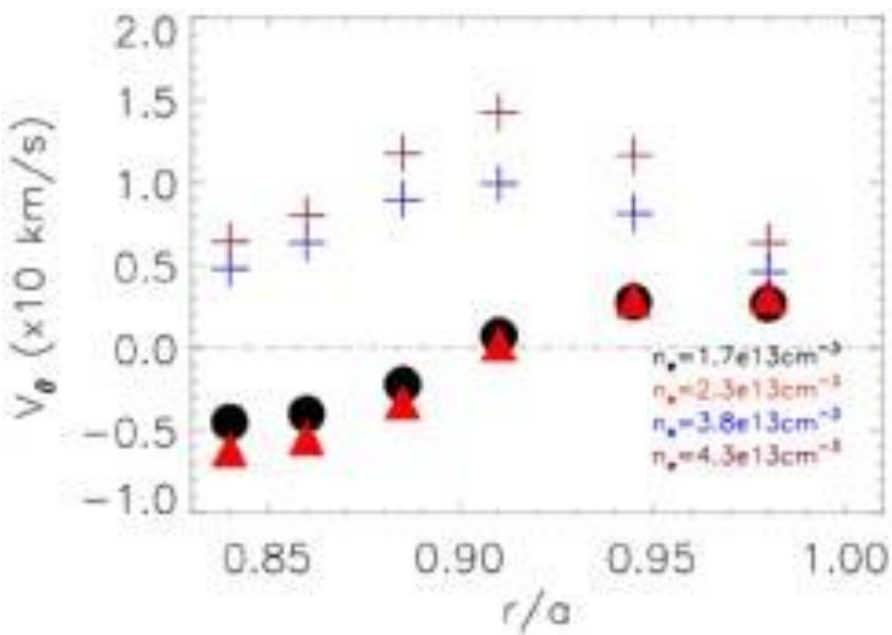
DIII-D



Z. Yan et al 2013 NF 53 113038

There is a clear difference in poloidal flow of the fluctuations (not mean flow) at low versus high density

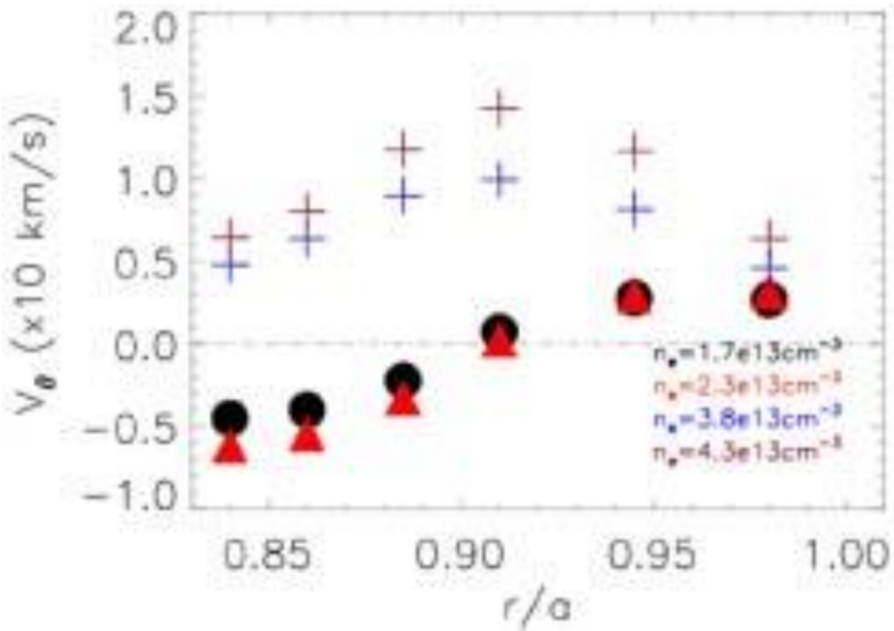
DIII-D in L-mode



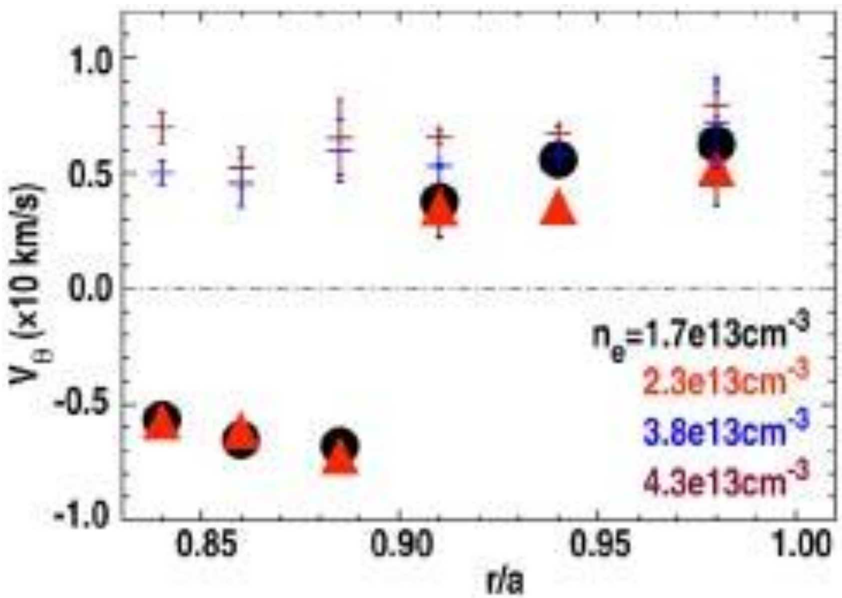
Z. Yan et al 2013 NF 53 113038

At low density, the ZFs provide the ability to cross the threshold before mean flow reaches threshold

DIII-D in L-mode



DIII-D at LH-transition



Z. Yan et al 2013 NF 53 113038

Turbulence in plasmas is everywhere

- Turbulence is the result of the breaking of symmetry
  - From deterministic to probabilistic system
- Energy in eddies can be transferred to eddies at different scales
- Plays an important role in achieving fusion energy
  - Flow shear can help reduce ‘leakage’