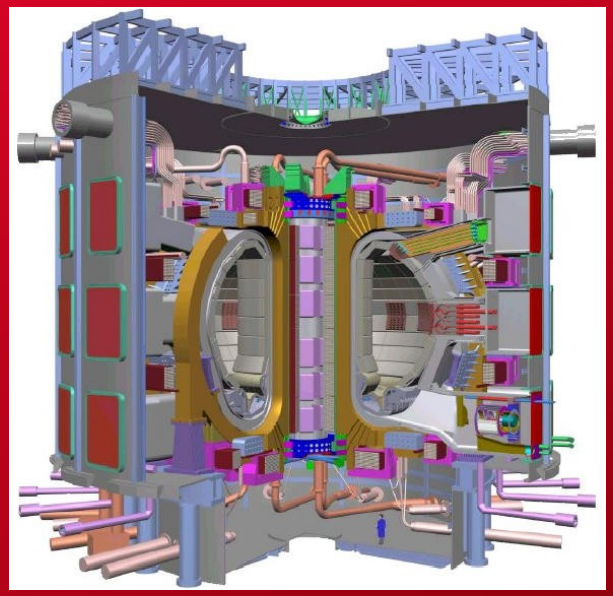
DE LA RECHERCHE À L'INDUSTRIE



# Stepping to burning plasmas and peaceful use of nuclear fusion: ITER Challenges


Philippe GHENDRIH
Directeur de Recherche du CEA
Collaboration
M2P2 / Aix-Marseille Université
EUROfusion


www.cea.fr

**Physics:**

**Nuclear Physics** *OK*

**Statistical physics & thermodynamics** *ongoing research*

**Complex systems** *ongoing research*

# ¿What is a plasma?

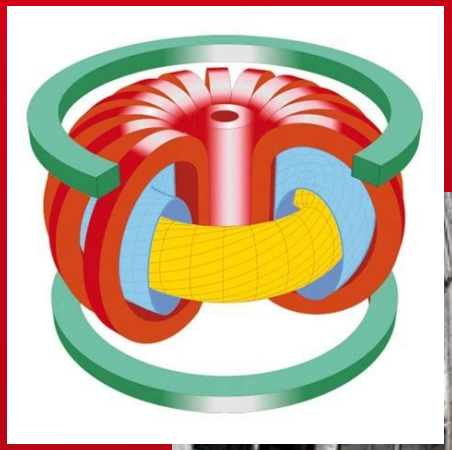
# ¿What is a tokamak?

# ITER = heat engine

## source: nuclear fusion

## losses: turbulent transport

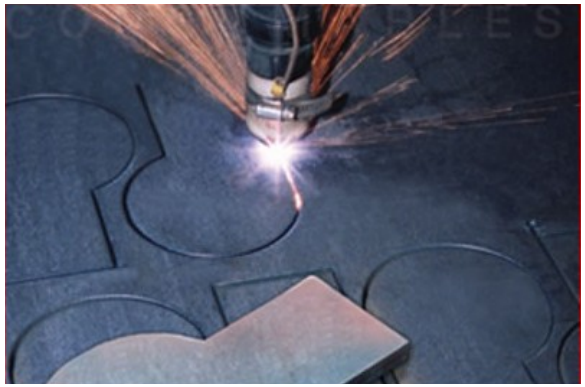
## open system: tokamak



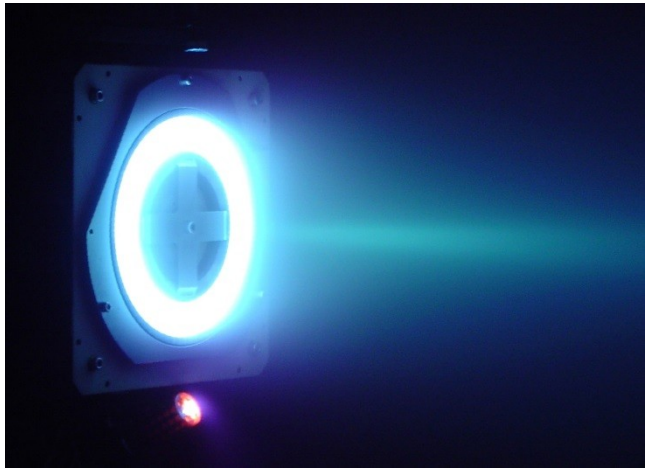
# Plasma: ionised state of matter

1928 : Langmuir
(electronics)

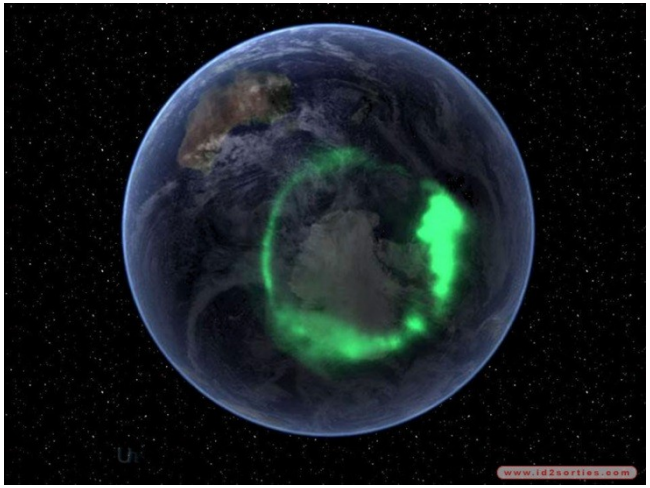
Cold plasmas
(industrial use)



Space Propulsion

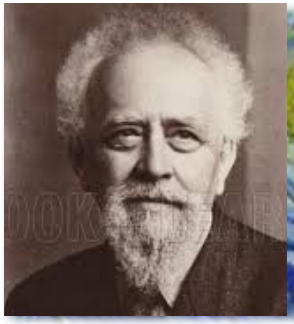


Telecommunication



*plasma = 99 % known matter in the universe*

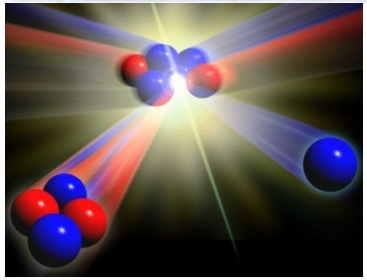
# Fusion = Nuclear Heat Engine



## ITER & Fusion Energy

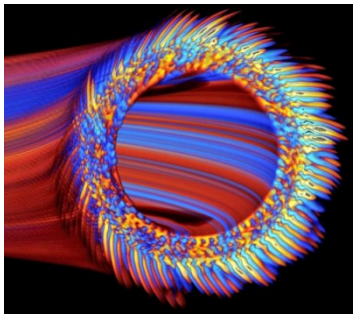
A scientific dream

*(started with Jean Perrin, about 1913)*



## What is nuclear in fusion?

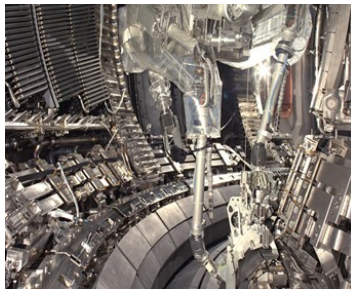
Tough engineering!



## Burning core plasma

Turbulence & Heat Transport

Simulations & big data



## Controlling Heat Exhaust

Ageing & Life time of wall components

# Why? What & how? When?

## Fusion Energy … the energy of the sun!

A **hot** topic of the **cold** war!

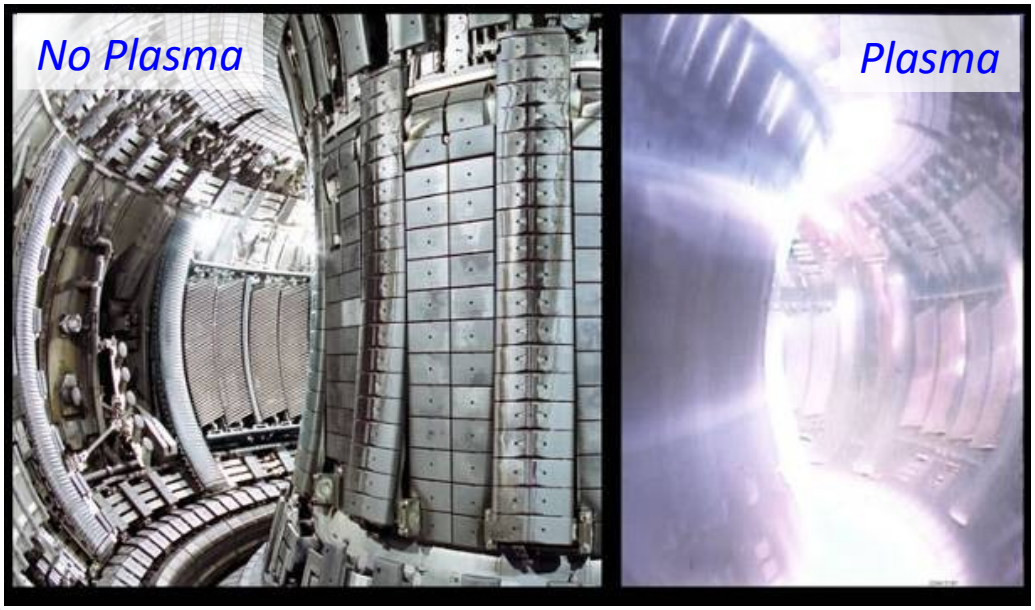
## Plasma at $10^8$ K

Confinement!

Insulator =

## Magnetic field

## ⇒ TOKAMAK

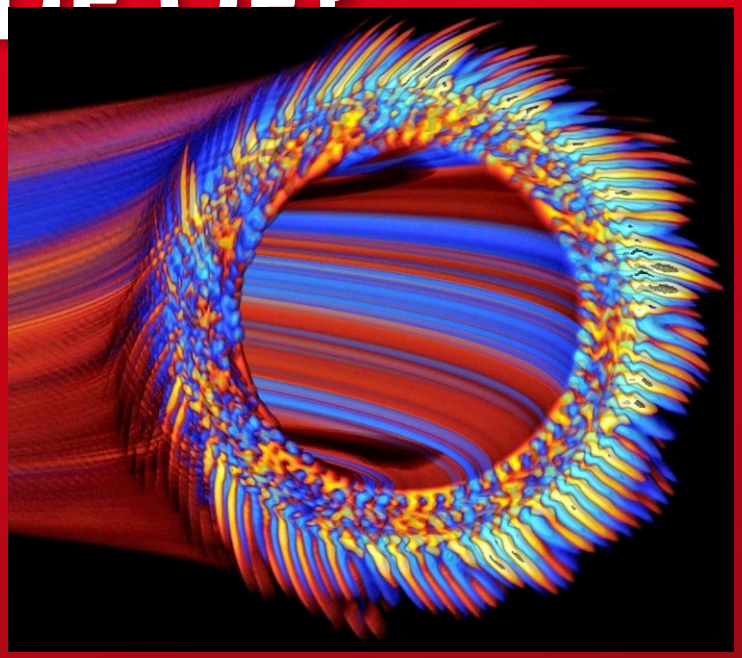


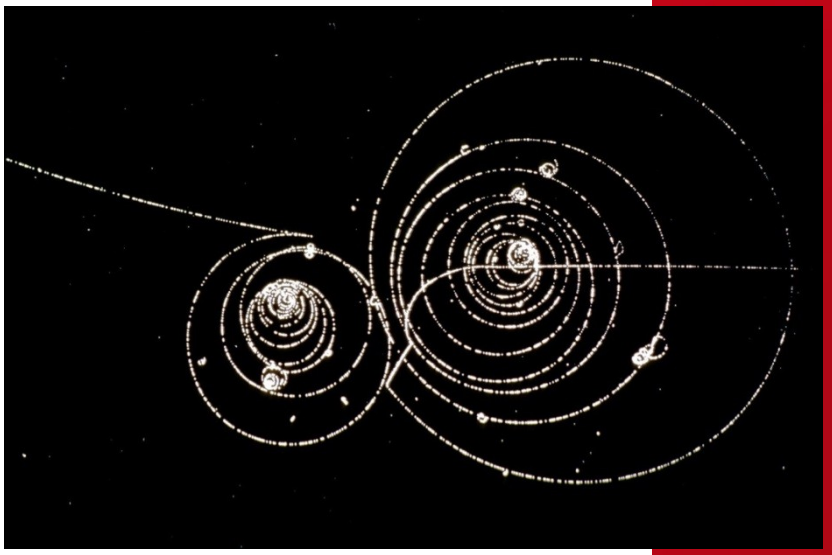

*JET European Tokamak*

## ITER … to operate burning plasmas!

1985→2005→2025-2035…

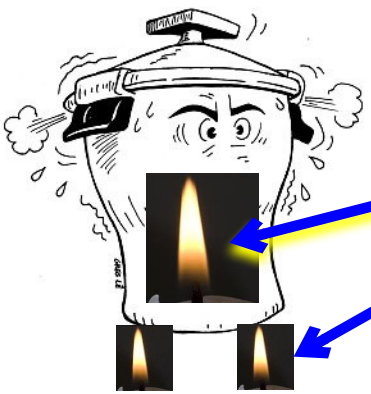
# WHAT IS FUSION ENERGY RESEARCH MADE OF?





Plasma
&
Large magnetic fields

# Fusion in 2 equations



$$\partial_t W = S - \frac{W}{\tau_E}$$

**Internal energy balance interne 0-D**

phenomenological

$\tau_E$ **perimental input**

$$\partial_t f_a + \dot{x}\,\nabla_x f_a + \dot{v}\,\nabla_v f_a = \varepsilon S_a$$

**Kinetic Equation 6-D = evolution of** $f_a$

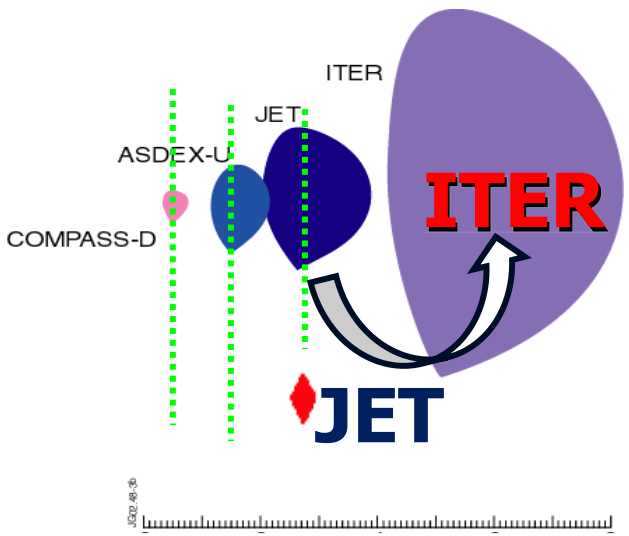
distribution function for species *a*

**Fundamental Equation:** determine $\tau_E$ **theoretical output**

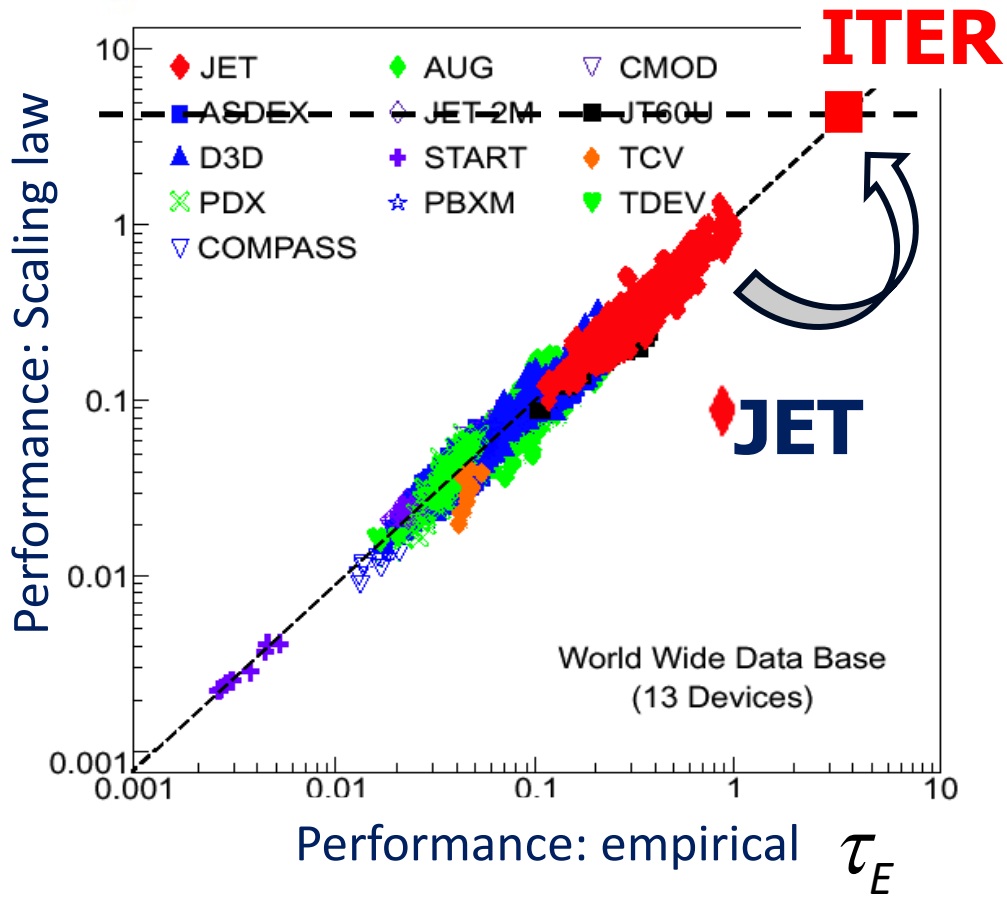
(energy confinement time)

# Go big / experimental evidence

$$\tau_{E,th}^{IPB\,98(y,2)} = 0.05621\, I_p^{0.93} B_T^{0.15} P^{-0.69} n_e^{0.41} M^{0.19} R^{1.97}$$




**size = cost…** *$ = political*

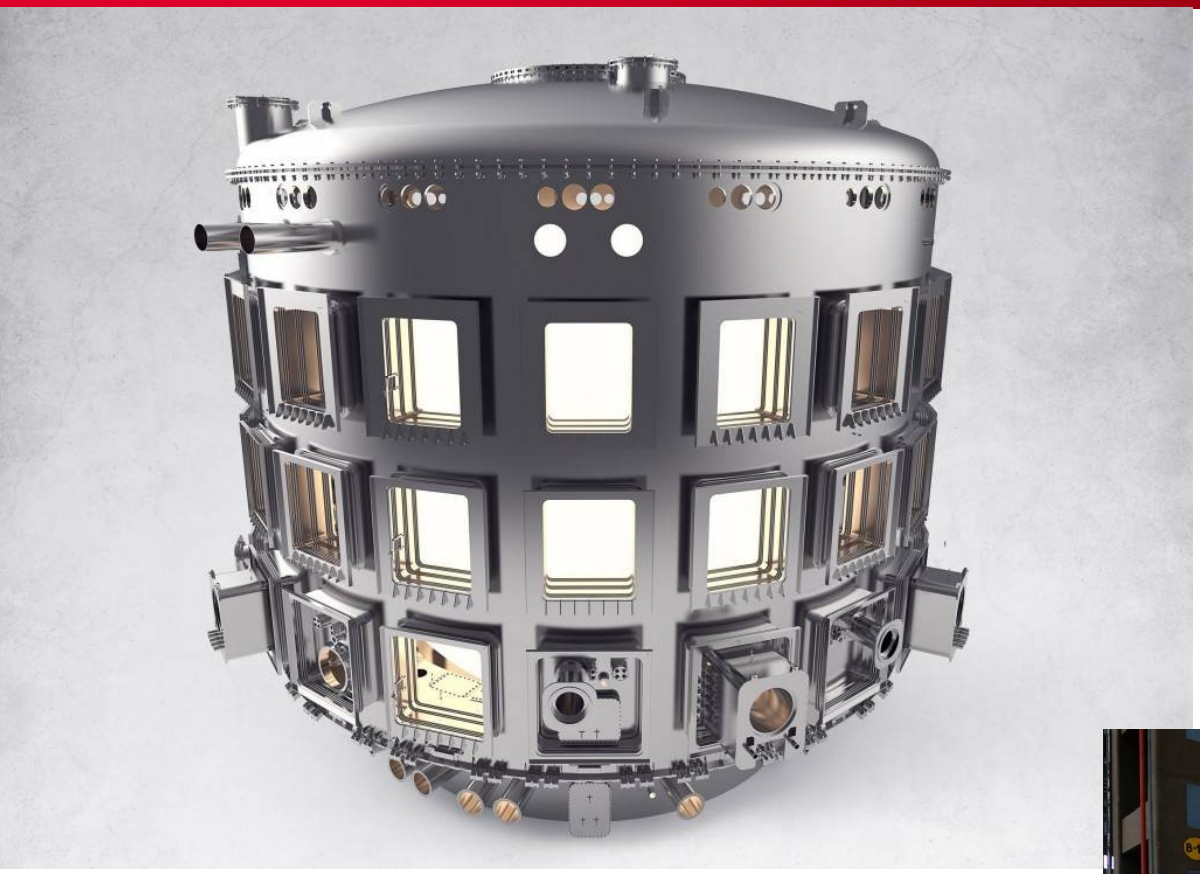



Many open questions:

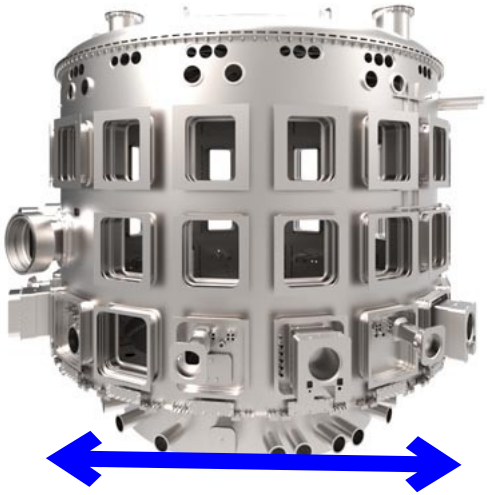
- Uncertainty =
  small device weight? Scatter?
- Data selection

**Performance = size = cost**

# Cryostat: a monster



16,000 m³ @ 4,5 K

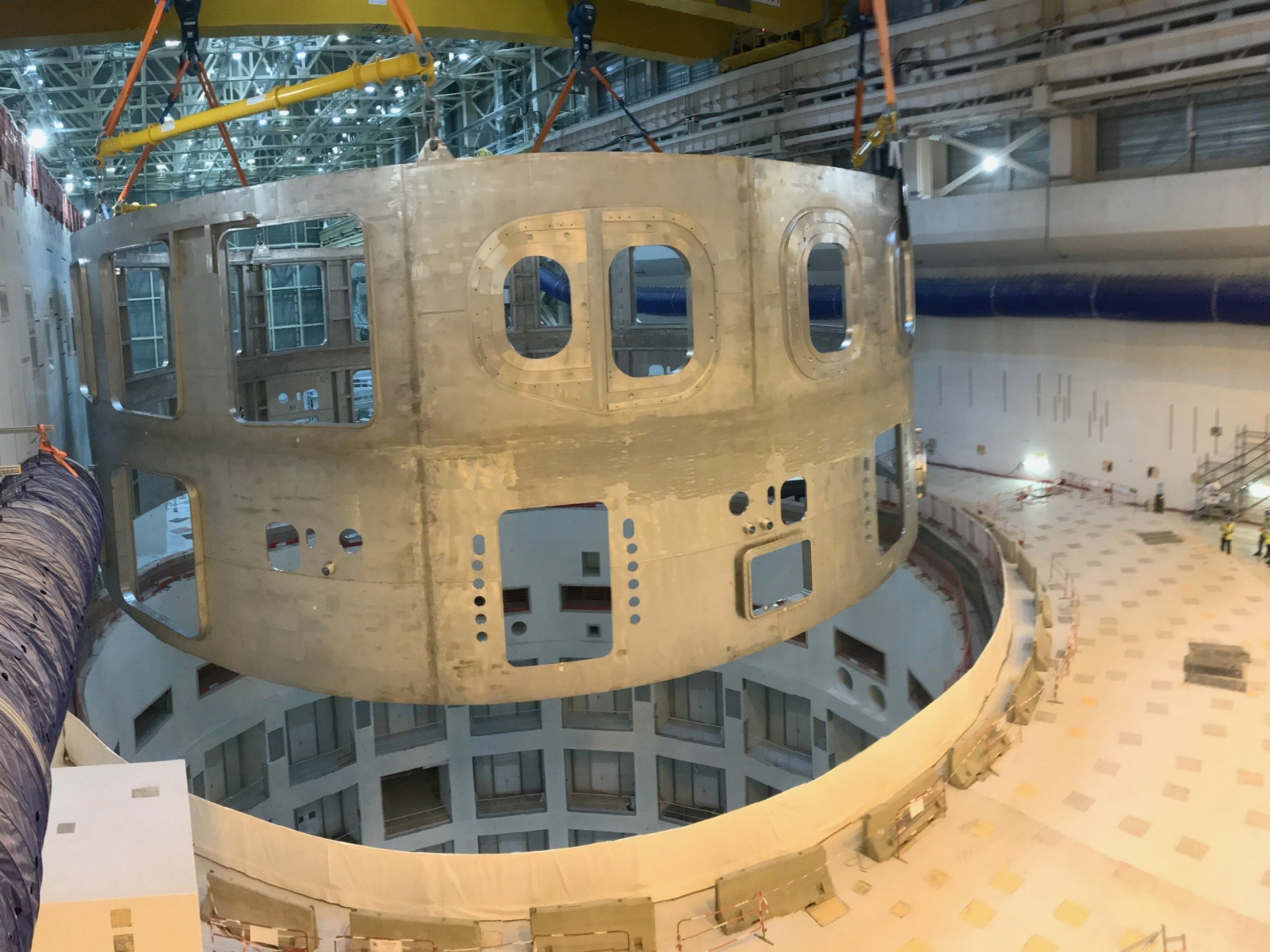


30 m 3,850 tons

**steel making**

here in India

**Multi-task component**

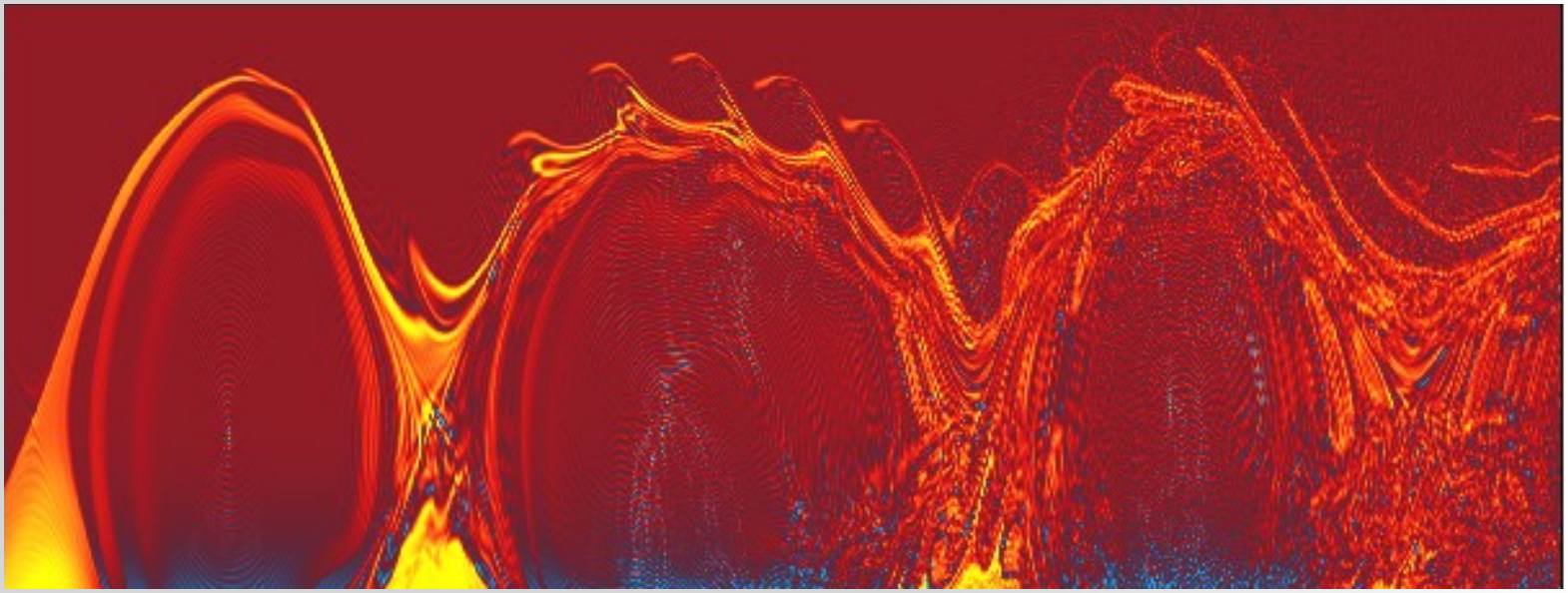


iter

china eu india japan korea russia usa

# ITER ORGANIZATION PROGRESS IN PICTURES 2020

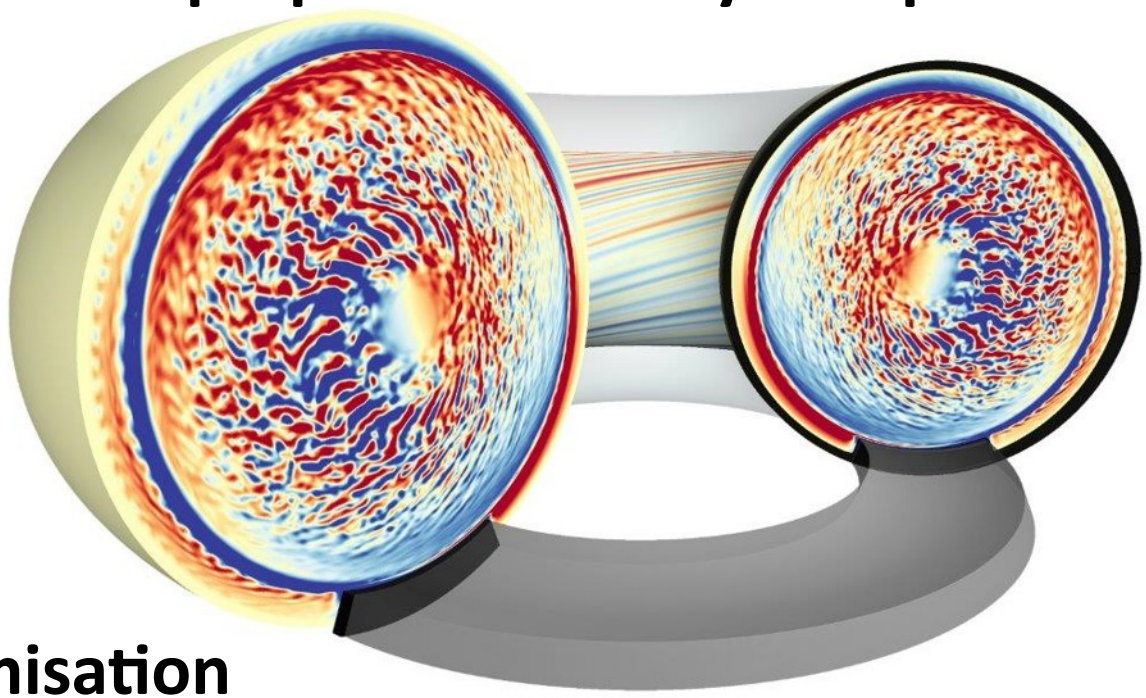
# Numerical simulations & research: simulations for fusion



# Simulations for ITER

**Scarce and difficult measurements + reduced margin**

- **simulations for tokamak operation**
- **simulations to prepare and analyse experiments**



**ITER = optimisation**

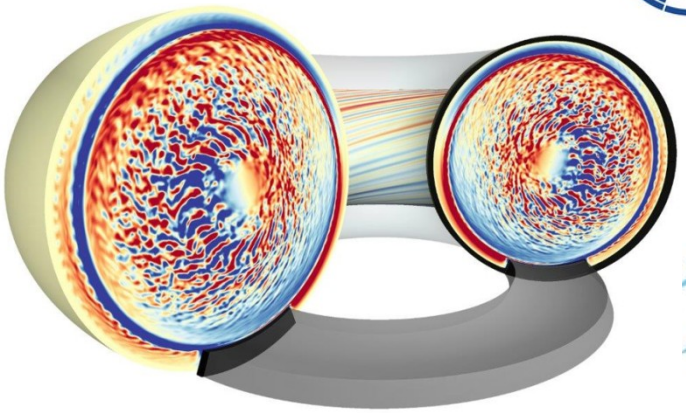
- **simulations to complete experimental evidence**
- **simulations to improve our understanding**

# Moving grounds

**Computing power: example GYSELA code**

**$10^{13}$** degrees of freedom **x $10^{6}$** time steps (petascale $10^{15}$ / s)

**100 Mhcpu / year = 32 768** cores (test up to 458 752)

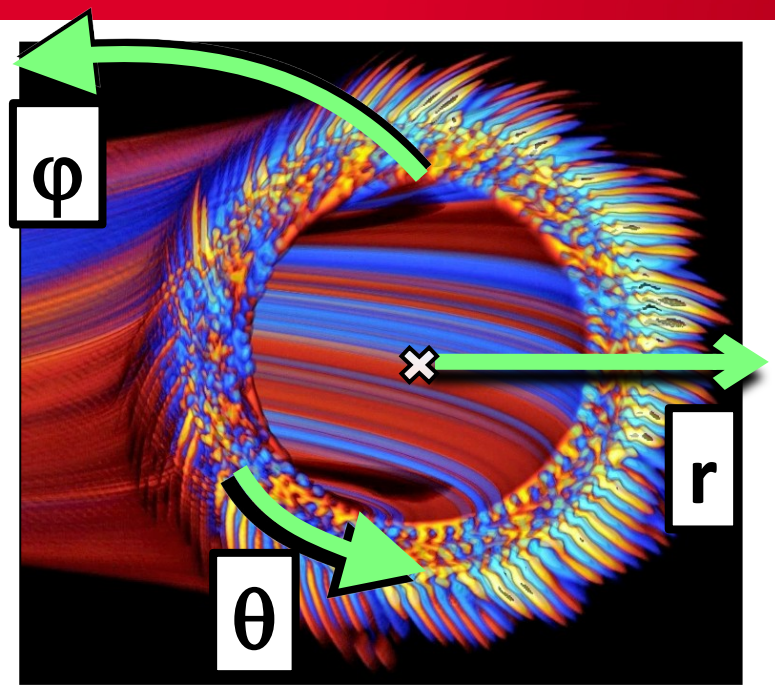


**Big data / Machine Learning = data**

**Chain of models:** complexity to simplicity

**Still physics** ⇒ new connection to experiments

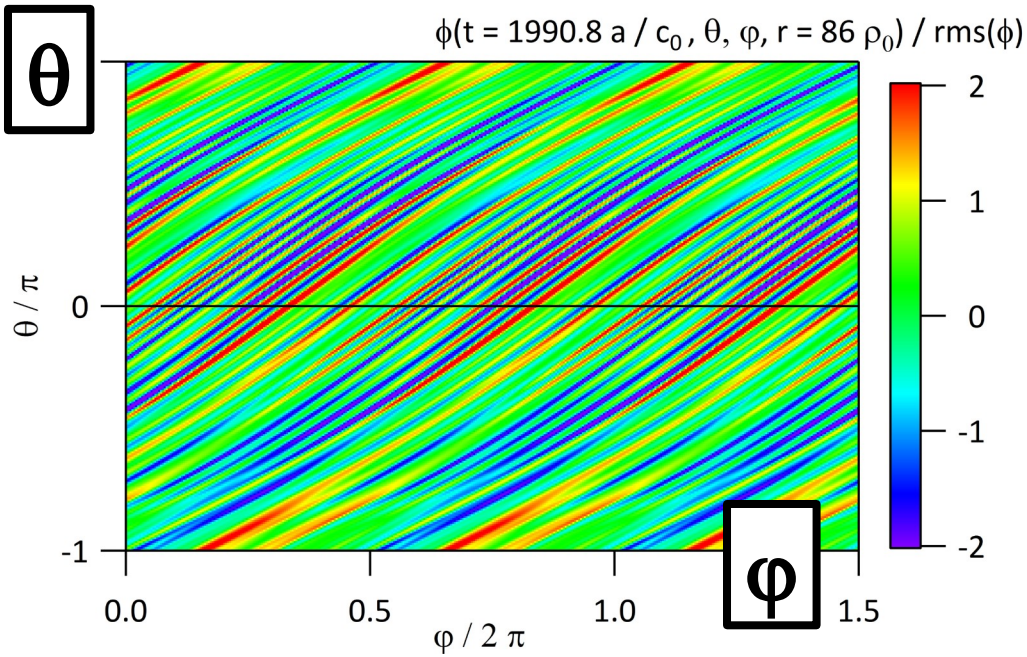
# A guide to toroidal geometry



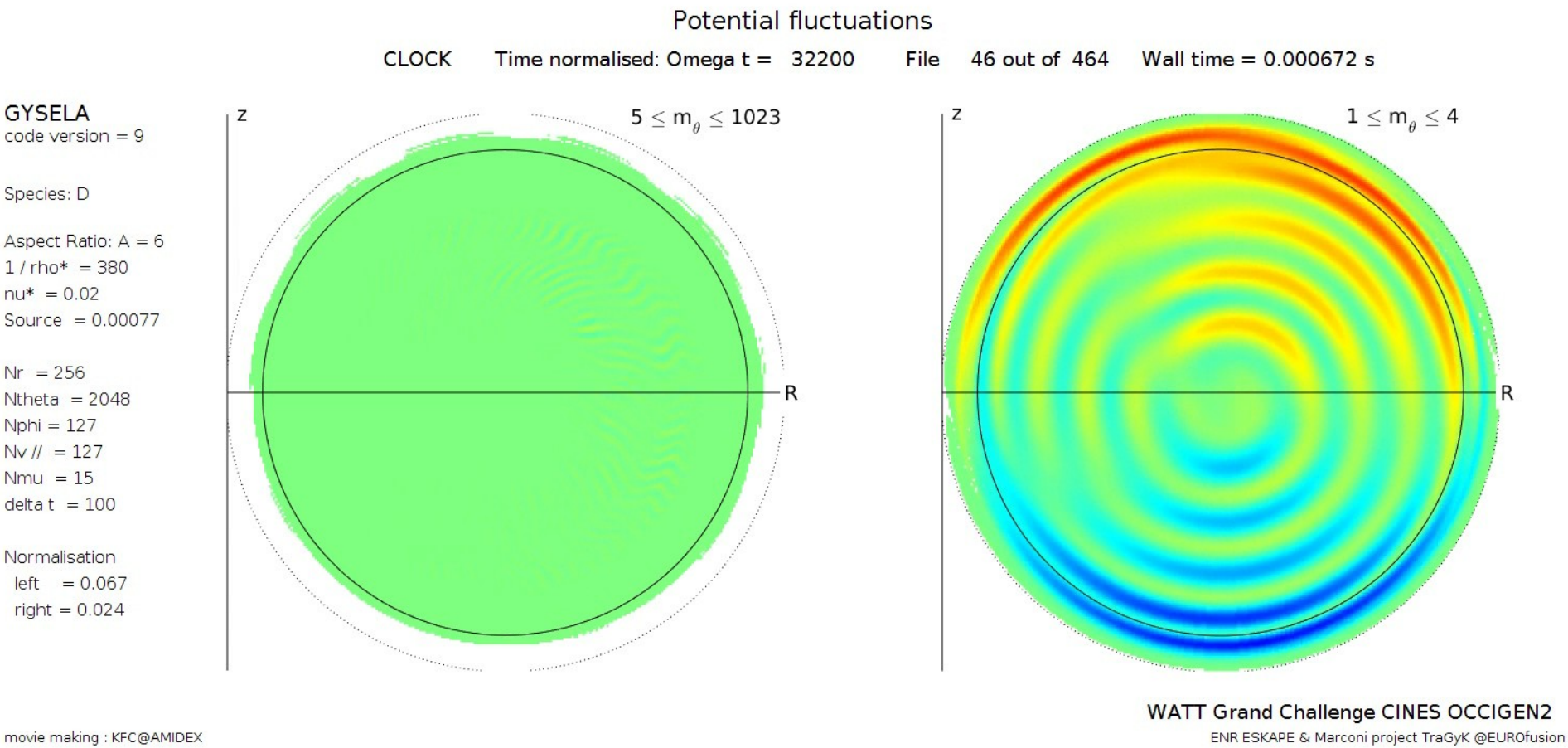

Torus

2 angles + radial coordinate = r

filament structure ≈ quasi 2D



# Steady-state & global

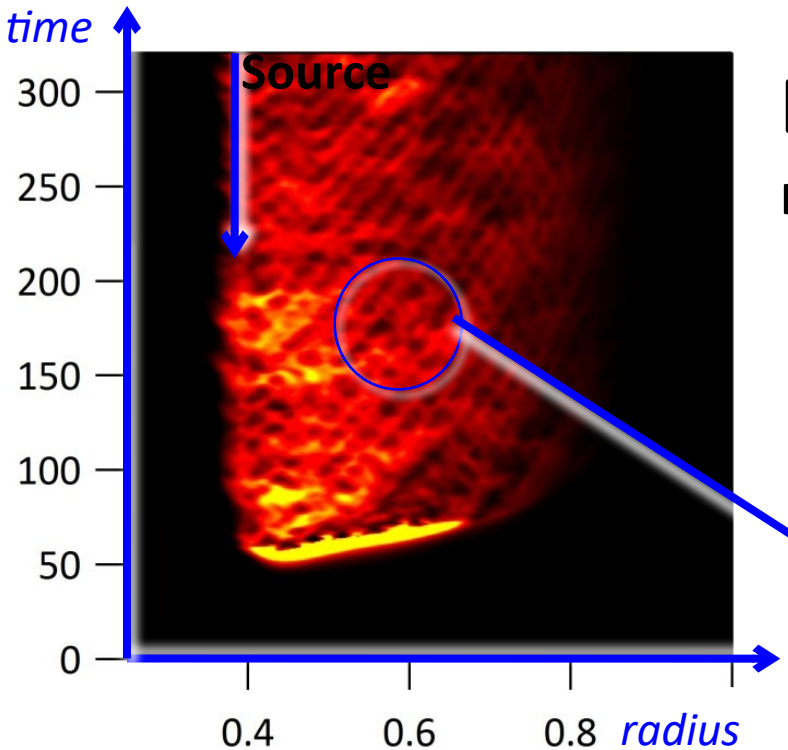



*WATT: Grand challenge OCCIGEN2 (8 Million CPU hours)*

- self-organised turbulence: avalanches + staircase (= large scale)
- SOL corrugated boundary

# Turbulent Heat Transport

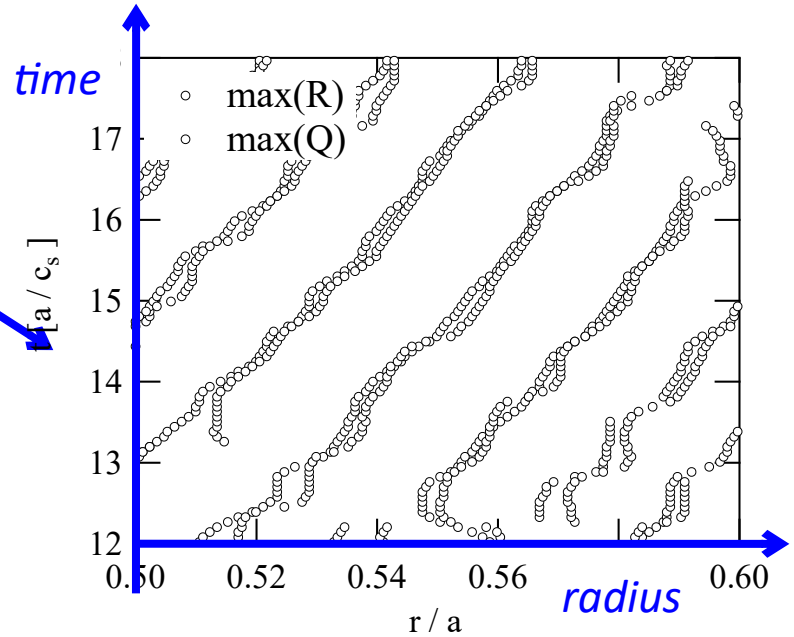
$\phi$ **Turbulent electric potential $\Rightarrow$ Turbulent heat flux**




## Ballistic transport events

**more avalanche-like (SOC)**

**than Fourier-like heat transport**



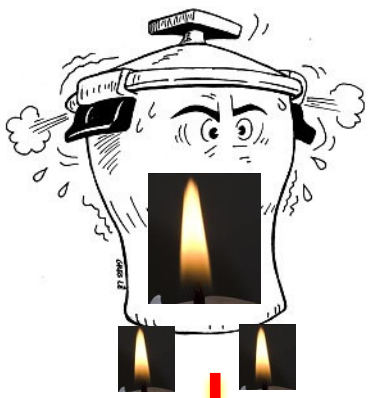

**Q Heat flux**

**interplay with momentum**

**R Reynolds stress $\Rightarrow$ transport barriers**

# heat sink = High Tech wall

$P_\alpha + P_{add} \rightarrow$ **heat outflux on wall / plasma wall interaction**



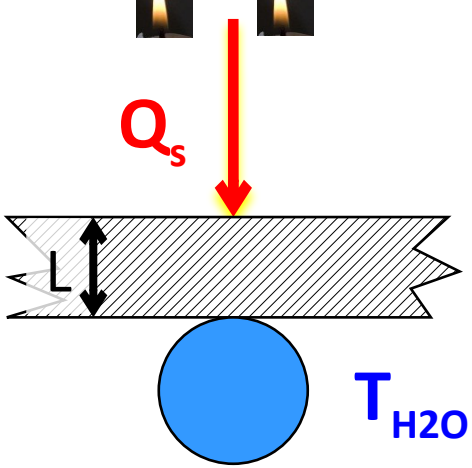
$P_\alpha + P_{add} \approx 150\ MW$

**+ Boundary layer:** *= physics: turbulent transport*

**confinement loss in // direction**

**heat channel surface ≈** *0.15 m²*

**peak heat flux $Q_{//}$ = 3 GW / m²**




$T_{H2O}$ **=150 °C**

**Technology $Q_s$** = 10 MW/m²

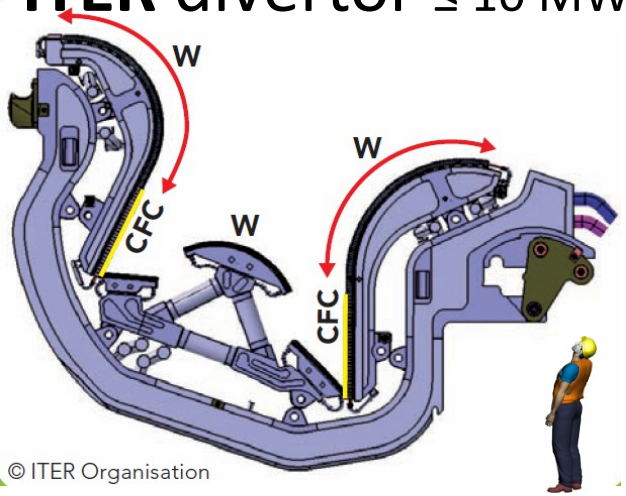
(sun surface ≈ 80 MW /m²)

$T_s = T_{H2O} + L\ R_{th}\ Q_s$

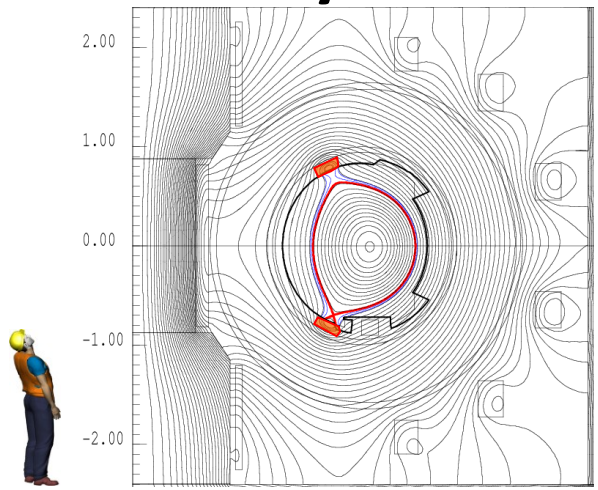
**L ≈ 5 - 7 mm**

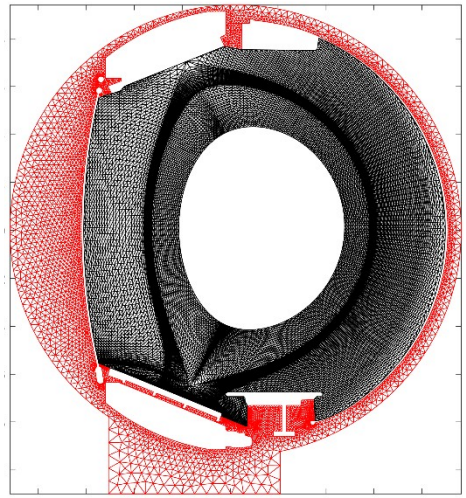
# just WEST of ITER

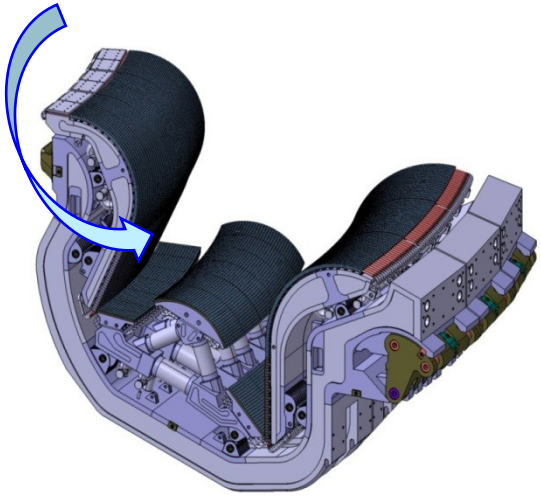
## ITER divertor ≤ 10 MW / m²

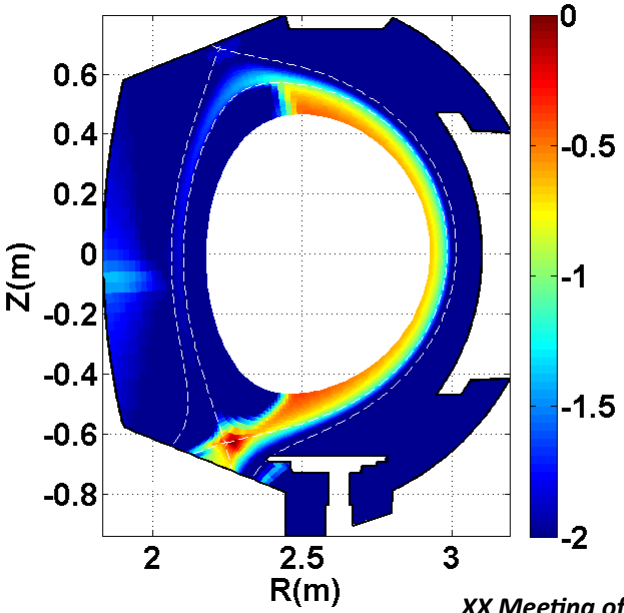


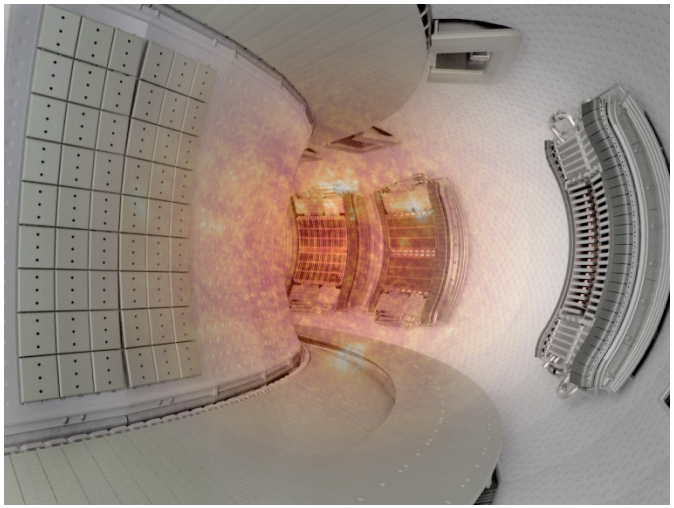

## Physics & technology for ITER



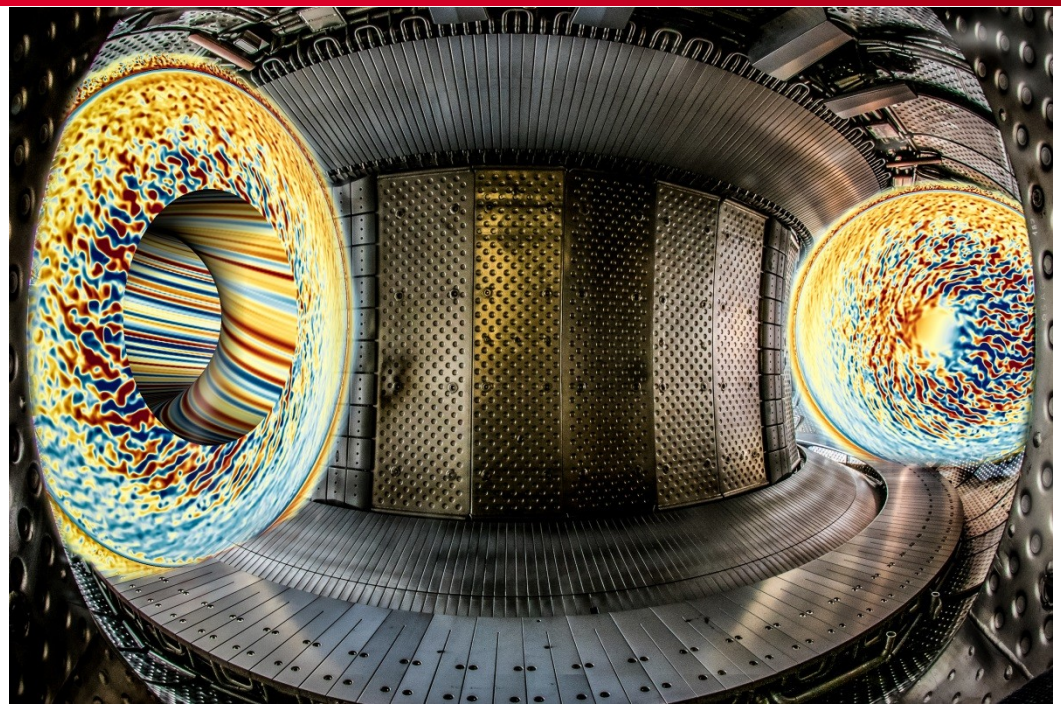







# Welcome to Fusion challenges!



**Science of complexity**
**"infinitely normal"**
**Large scale computing**

**Theory & simulation based research a new challenge!**

Exascale simulation = new research teams (exascale $10^{18}$ / s)
**theoretical physics + mathematics + computer science**

Requirement: **reduced models = key to knowledge & teaching**

**Master computing science**

# Summary

***Strong need for simulations :***

***fundamental & reduced models***

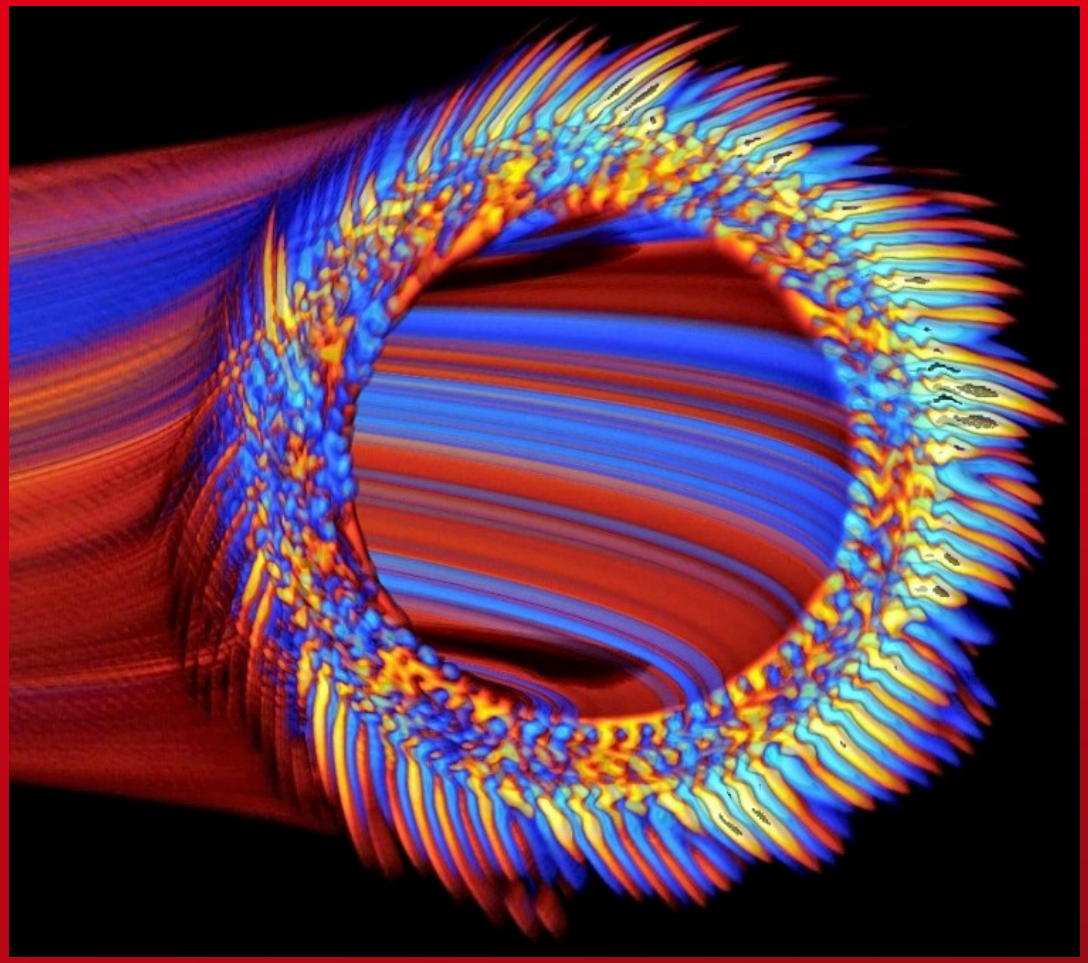
***New research & innovation paths***

***Links:***

Here! (UNI)
aparedesc@uni.edu.pe
M2P2 (ECM-AMU)
eric.serre@univ-amu.fr
IRFM-CEA Cadarache
guido.ciraolo@cea.fr

http ://irfm.cea.fr/

https://www.iter.org



Commissariat à l'énergie atomique et aux énergies alternatives
Centre de Cadarache | 13108 Saint Paul Lez Durance Cedex
T. +33 (0)4 42 25 46 59 | F. +33 (0)4 42 25 64 21

DSM
IRFM
SIPP

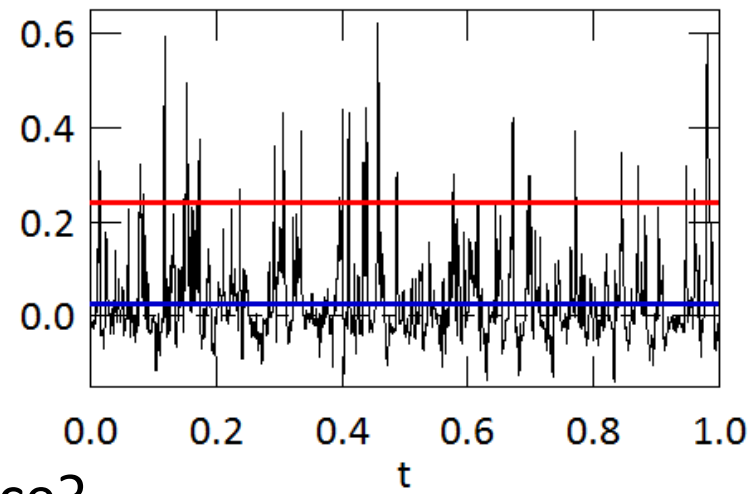
Etablissement public à caractère industriel et commercial | RCS Paris B 775 685 019

# Flux driven, free $\nabla_\perp n$

## Particle flux

avalanche transport

near ballistic

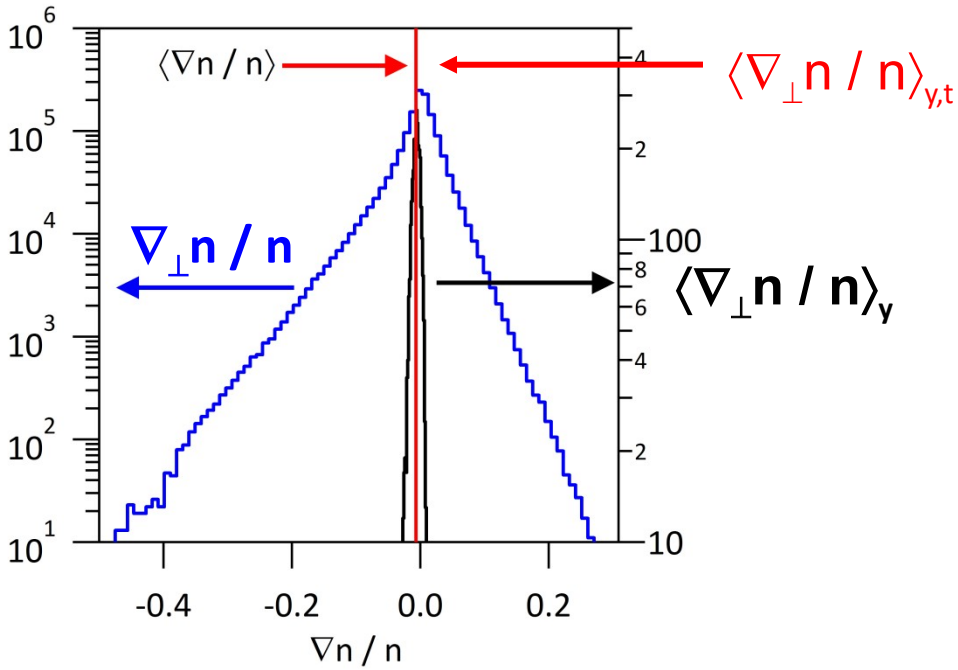



## intermittent transport

Paris commuting: 2 $10^6$ /day

Population growth: 150 / day

thermodynamical force?




Histogram $\nabla_\perp n / n$

Histogram $\langle \nabla_\perp n / n \rangle_y$

$\langle \nabla_\perp n / n \rangle_{y,t}$