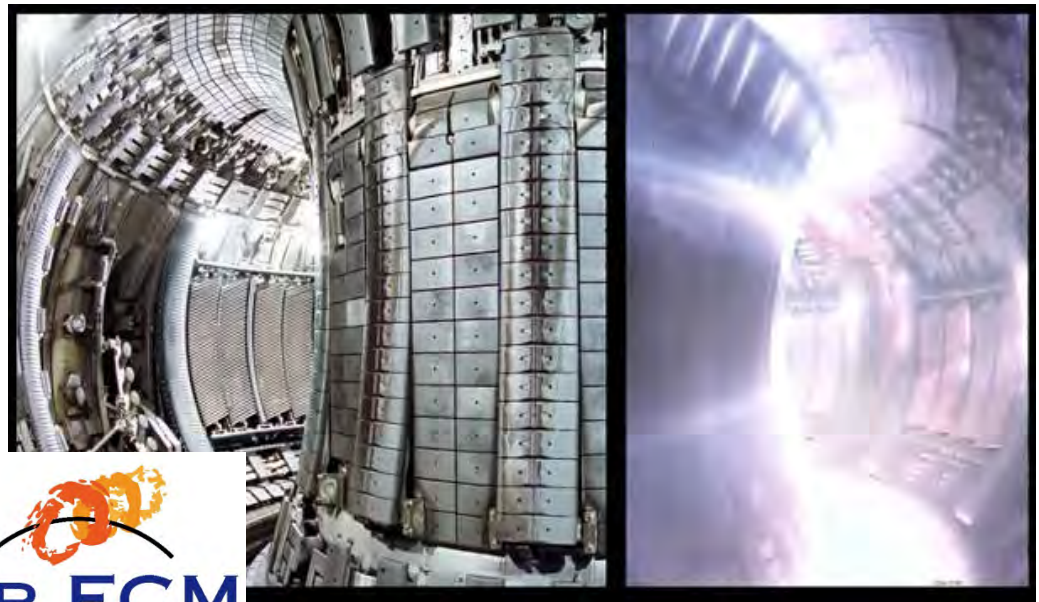
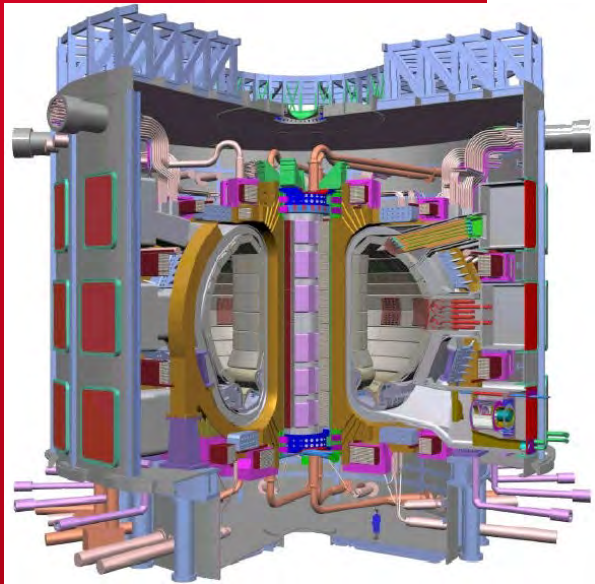


DE LA RECHERCHE À L'INDUSTRIE

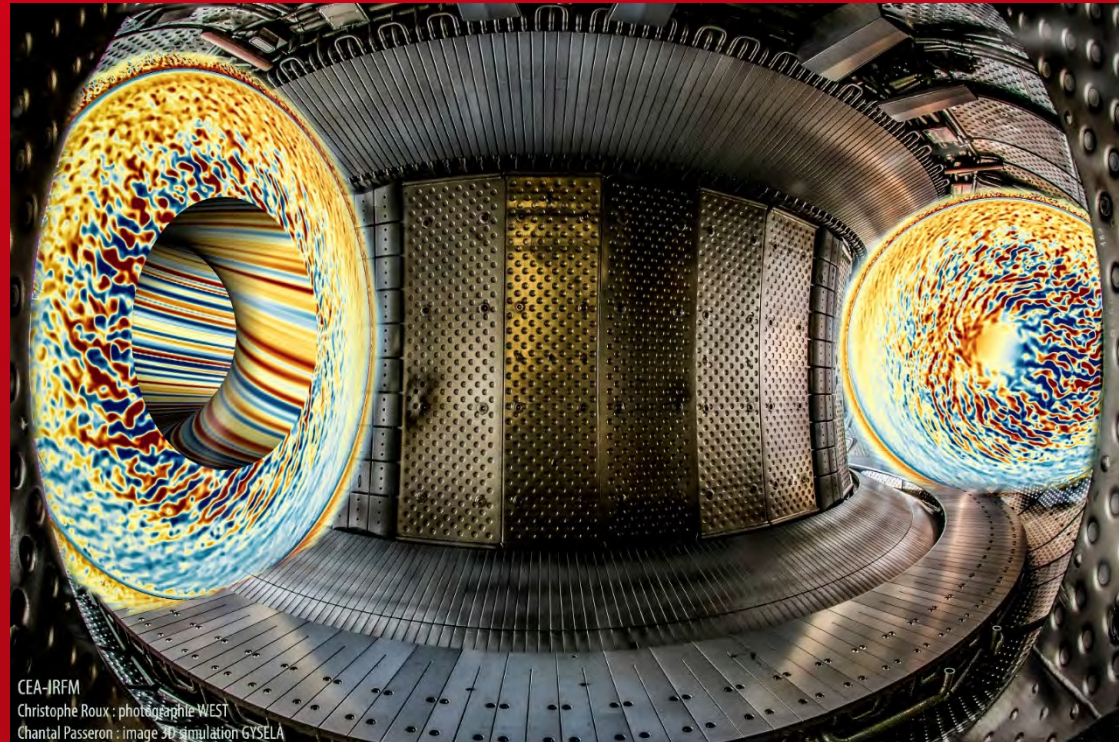


La FUSION par CONFINEMENT MAGNÉTIQUE le long CHEMIN du RÊVE à UNE RÉALISATION EXPÉRIMENTALE



SOMMAIRE II

- Déterminer le confinement
- *Turbulence plasma*
- *Statistiques cinétiques*
How is plasma special?
- *Gyrocinétique 5D*
- *Flux de chaleur à la paroi*





Triple produit : $n_e T_i \tau_E > \text{seuil}$

Lawson 1957

n_e densité (des électrons)

T_i énergie thermique des ions (D & T)

τ_E temps de confinement de l'énergie

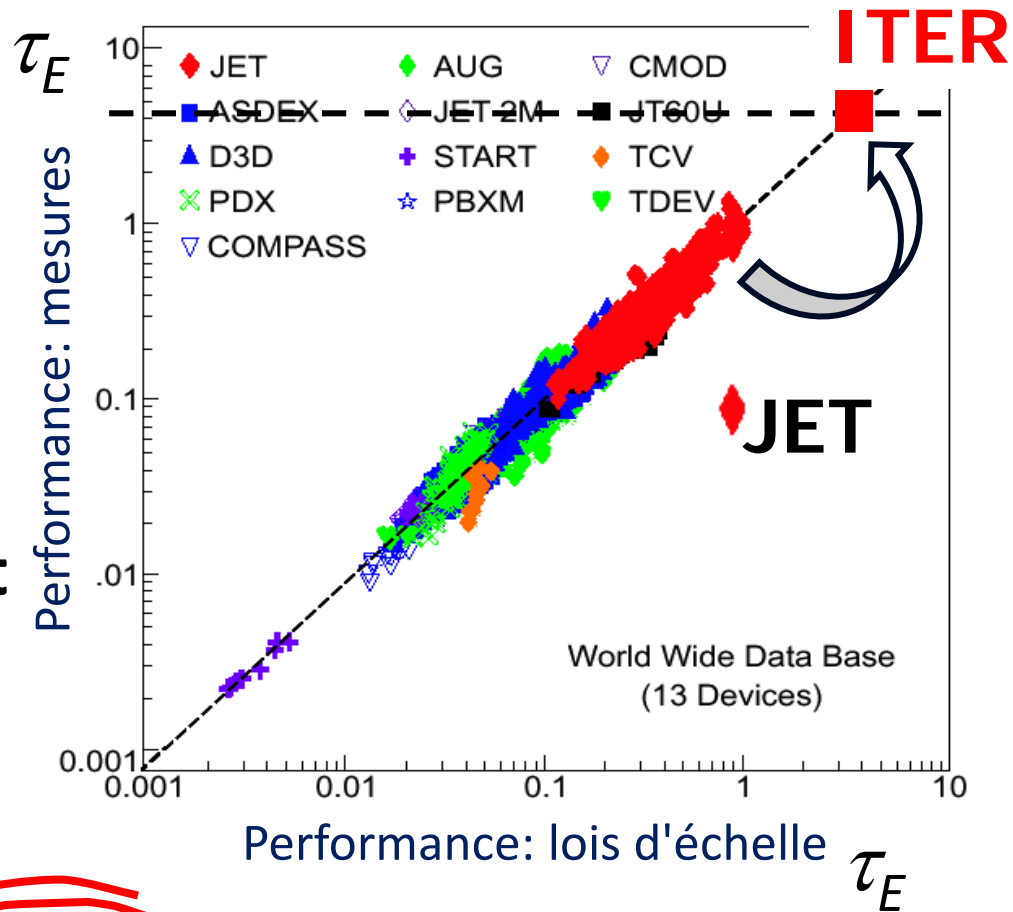
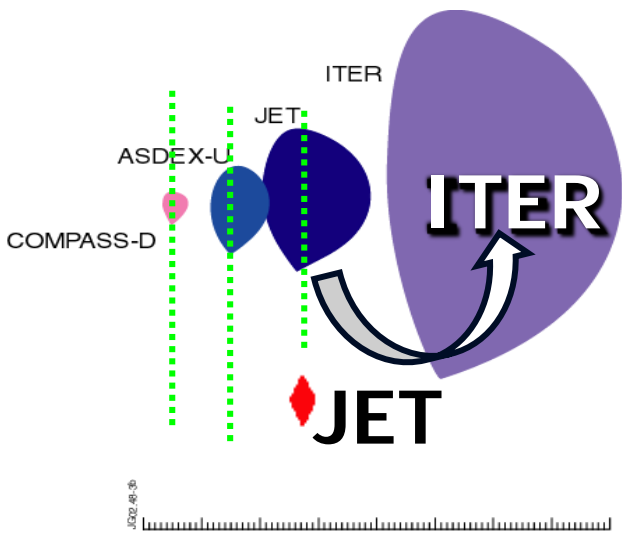
$T_i \approx 10$ keV optimum fusion D, T

$$\tau_E = \frac{6.2 \cdot 10^{20} \text{ s m}^{-3}}{n_e} \frac{Q}{(Q + 5)}$$

$Q \rightarrow +\infty$ ignition

confinement magnétique : n_e faible $\Rightarrow \tau_E$ long

Go big / évidence expérimentale



Performance = taille = coût

Objectif : $\tau_E \approx 5 s$

Loi d'échelle :

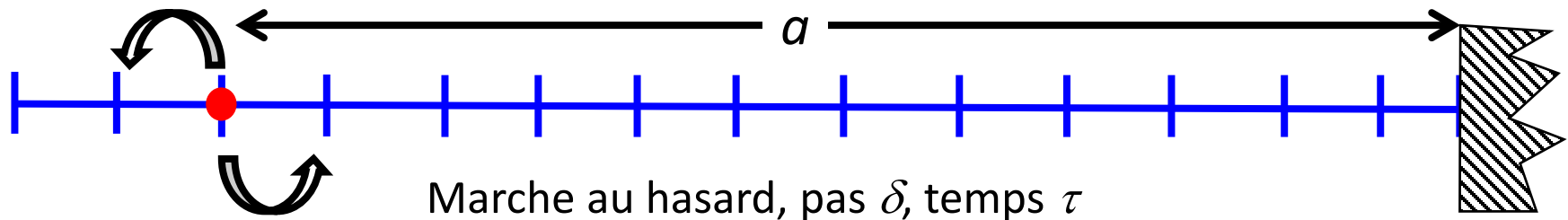
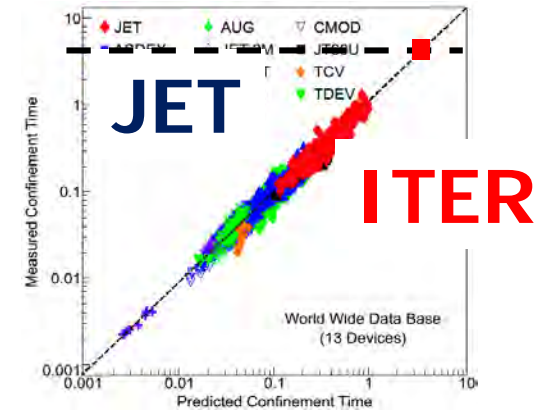
$$\tau_{E,th}^{IPB98(y,2)} = 0.05621 I_p^{0.93} B_T^{0.15} P^{-0.69} t_e^{0.41} M^{0.19} R^{1.97} \Leftrightarrow \text{HORRIBLE !}$$

P = chauffage !

taille

Questions ouvertes sur τ_E

- Incertitudes \Rightarrow risques
- Poids des petits tokamaks ?
- Dispersion des points ?
- Choix des données ?
- Quelle compréhension ?



Transport = diffusion $D = \delta^2 / \tau$

Temps de confinement $\tau_E = a^2 / D$

Pas $\delta \propto$ rayon de Larmor $\rho_L \rightarrow \rho_* = \rho_L / a$

Durée $\tau \propto$ temps parallèle $\tau_{||} \propto a / V_{||}$

$$\tau_E = \frac{a^2}{\rho_L^2} \tau_{||} \approx \rho_*^{-3} \frac{1}{\Omega}$$

Loi d'échelle, paramètres de contrôle (sans dimension)

ρ_* \approx nombre de Reynolds

β : pression plasma

ν_* : collisionnalité

ITER 1998

$$\Omega\tau_E \equiv \rho_*^{-2.7} \beta^{-0.9} \nu_*^{0.0}$$

2.7 -0.9 0.00

Expériences dédiées : JET (EU) & DIII-D (USA)

3.0 0.0 -0.35

$$\Omega\tau_E \equiv \rho_*^{-3.0} \beta^{0.0} \nu_*^{-0.35}$$

Dimension du tokamak / rayon de Larmor $\rho_*^{-1} = \frac{a \Omega}{v_{th}}$

Performance \propto volume = a^3 $\Omega \tau_E \propto \rho_*^{-3}$

Performance \propto champ magnétique = B^3

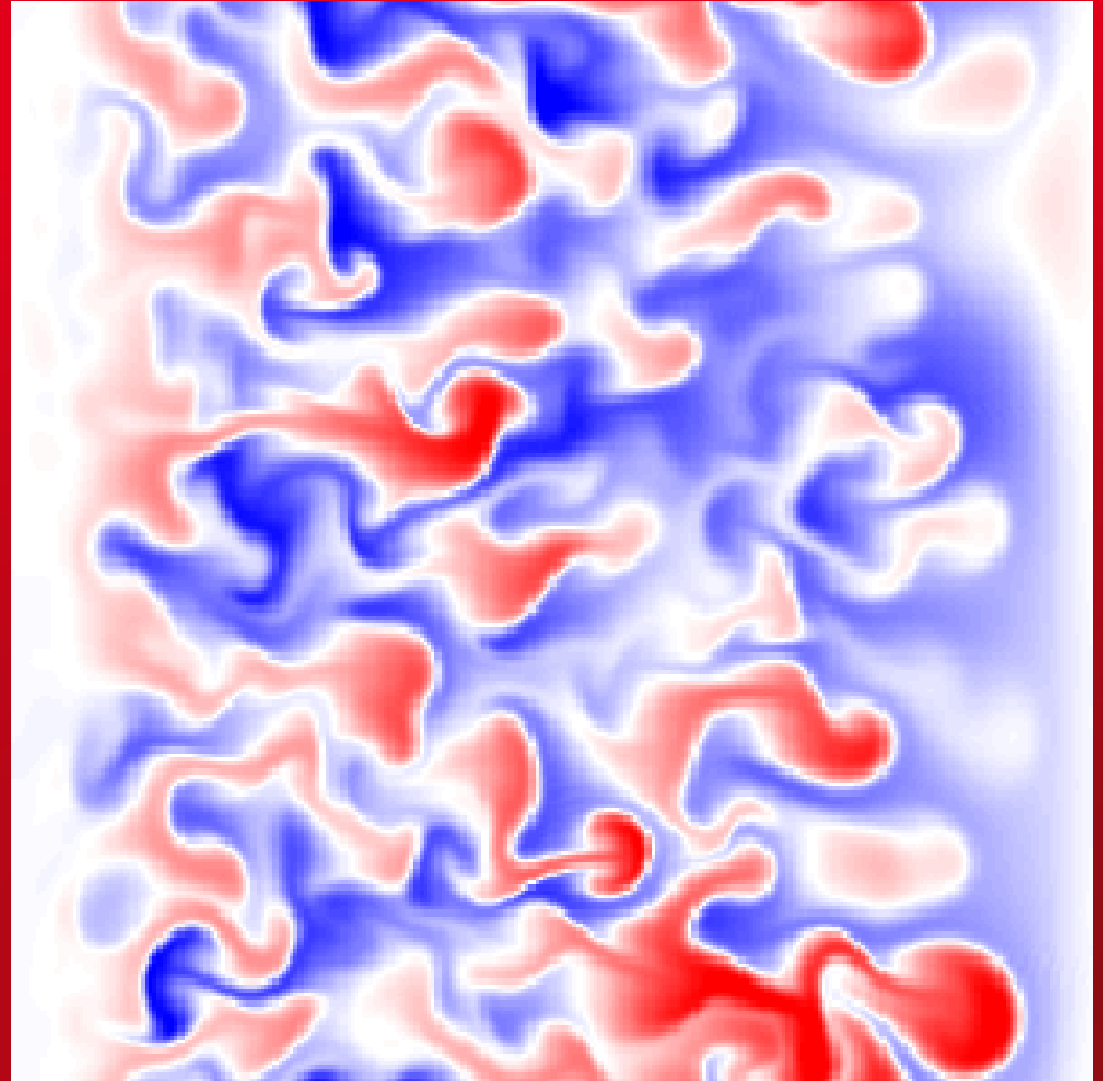
Performance $\propto T^{-3/2} (v_{th}^{-3})$

Chauffage $T \nearrow \Rightarrow$ performance \searrow : Le tokamak rétrécit au chauffage

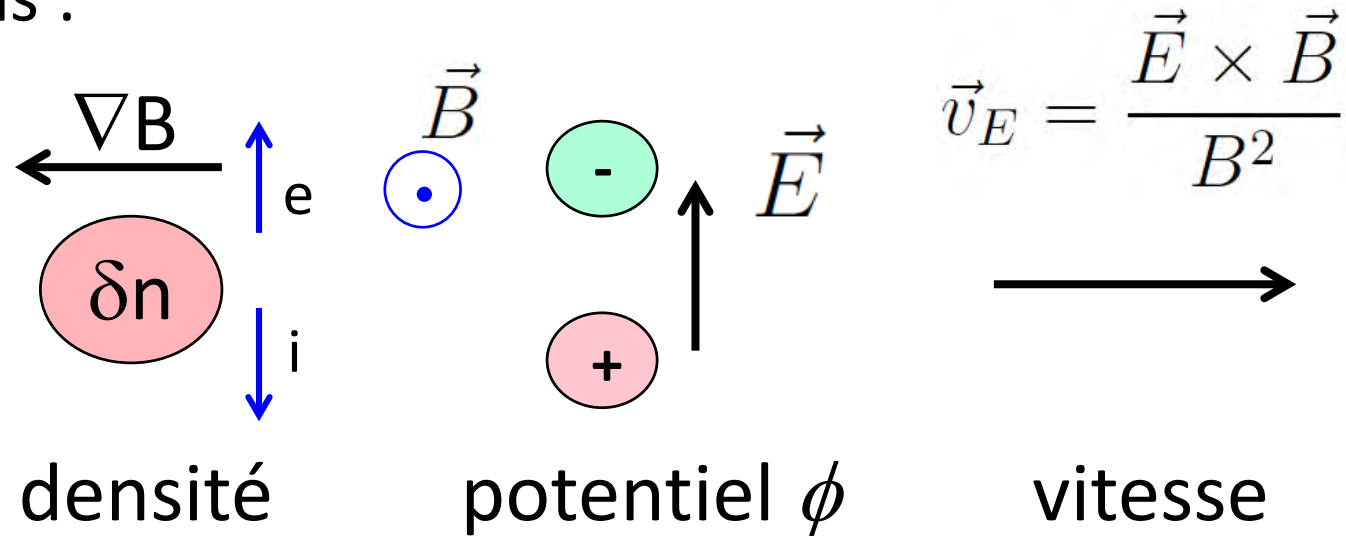
Pourquoi ? rayon de Larmor ρ_L Pourquoi ? $\tau_{//}$

TURBULENCE PLASMA

- *Déterminer le confinement*
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- *Statistiques cinétiques*
How is plasma special?
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Instabilité microscopique = structure potentiel électrique
Fluctuations :

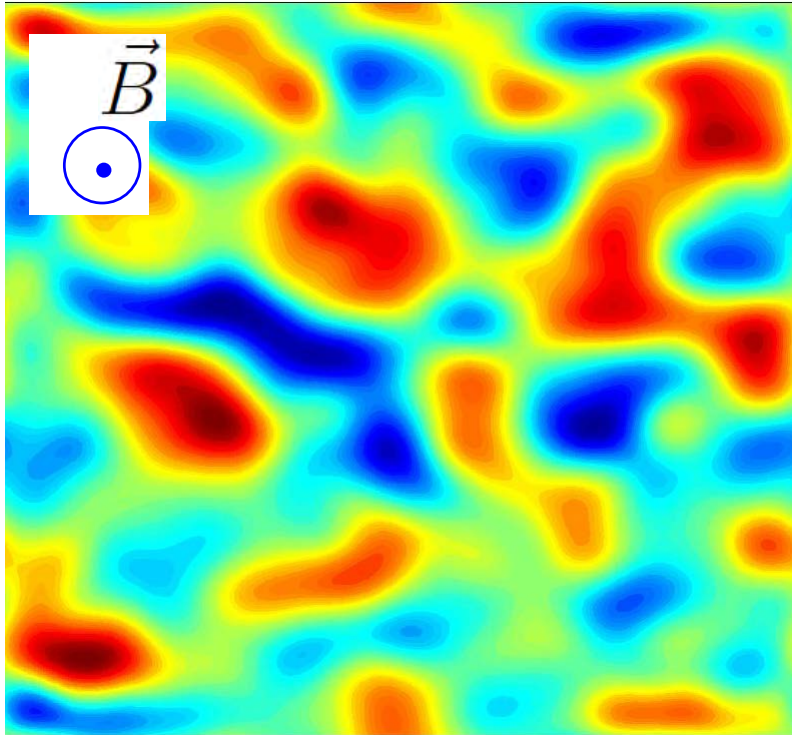


$$|\vec{v}_E| \approx \rho_* v_{th} = \frac{1}{a} \frac{T}{eB} \qquad \vec{v}_E = \frac{\vec{B} \times \vec{\nabla} \phi}{B^2}$$

vitesse

transverse à B

tangente surface $\phi = \text{constante}$



carte du potentiel électrique ϕ
surdensité convection à

$$\phi = \text{constante}$$

B inhomogène

$$\Rightarrow \phi \neq \text{constante}$$

\Rightarrow vitesse turbulente

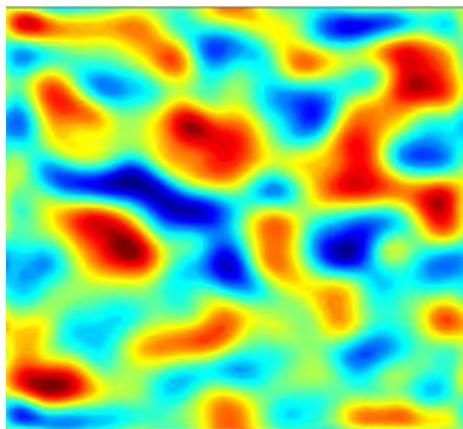
\exists instabilités microscopiques \Rightarrow transport turbulent

Turbulence = problème fondamental

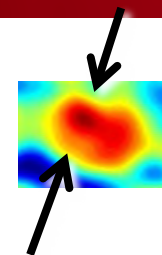
infiniment normal

Turbulence plasma \Leftrightarrow Turbulence atmosphère planétaire

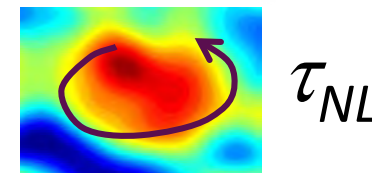
potentiel électrique ϕ



Taille (papillon \neq dépression) δ



Temps caractéristique : τ



Vitesse : $v \approx \delta / \tau = \rho_* v_{th}$

plasma stabilisation : $v_{//} \rightarrow \tau \propto a / v_{th} = \tau_{NL} = \rho / v$

$$\Rightarrow \delta \propto \rho_L$$

Diffusion : $D \propto \rho_* T / (eB) \rightarrow \tau_E \propto 1 s$

Analyse dimensionnelle ? **Constante multiplicative ?**

Chaos et turbulence ?

Etudes linéaires

stabilité/instabilité
relation de dispers

Non linéaires

Simulations
études statistiques

Analogies :

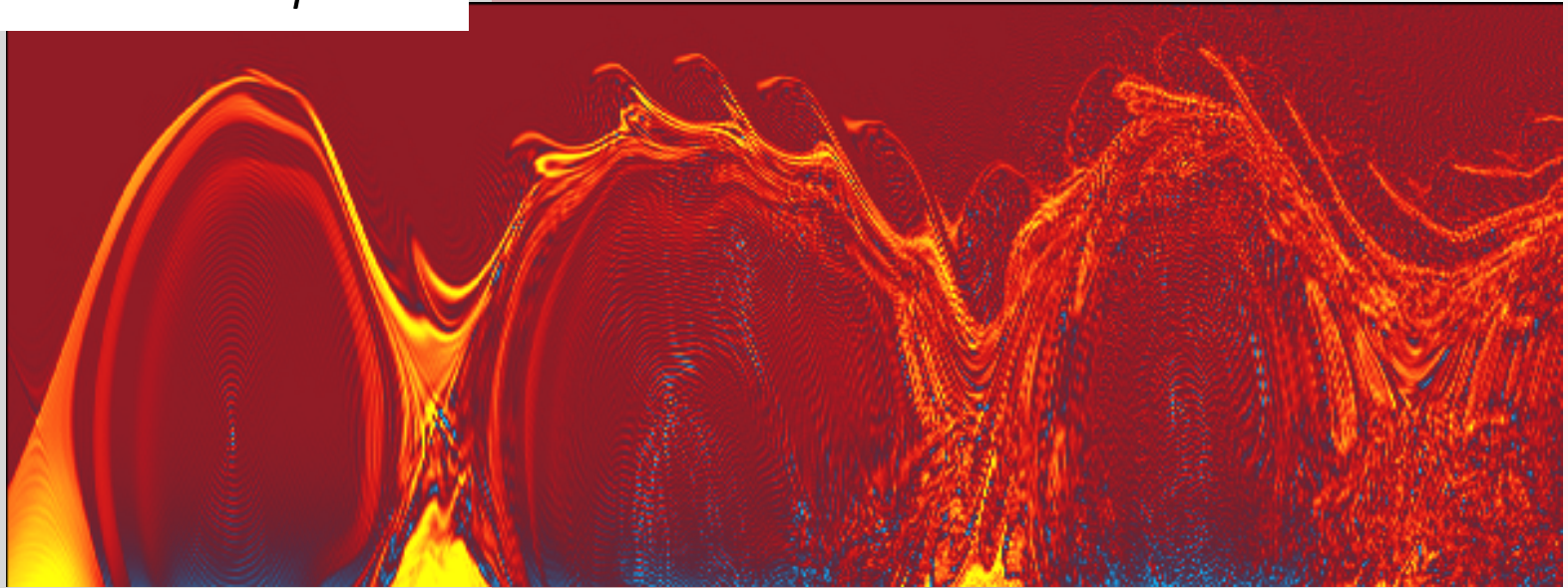
thermo-convection
atmosphères planétaires


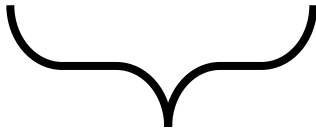


- *Déterminer le confinement*
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- **Statistiques cinétiques**
How is plasma special?
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STATISTIQUES CINÉTIQUES

HOW IS PLASMA SPECIAL?




	liquide	gaz	plasma
densité (m^{-3})	10^{29}	10^{25}	10^{19}
			
	Fluide neutre		Cinétique chargé

Plasma : libre parcours moyen de collision L_{coll}

périphérie : $L_{coll} \geq a$

centre : $L_{coll} \gg a$

Particule caractérisée par position et vitesse
physique statistique = cinétique

	liquide	gaz	plasma
densité (m ⁻³)	10 ²⁹	10 ²⁵	10 ¹⁹
			
	Fluides	Neutres	Cinétique chargé

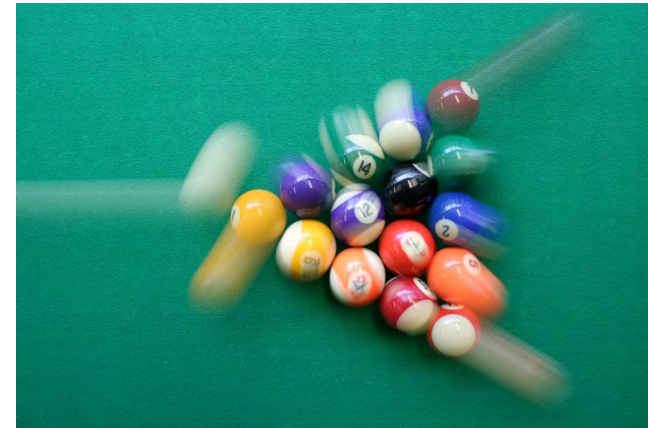
Libre parcours moyen de collision : L_{coll}

Plasma : périphérie : $L_{coll} \geq a$ centre : $L_{coll} \gg a$

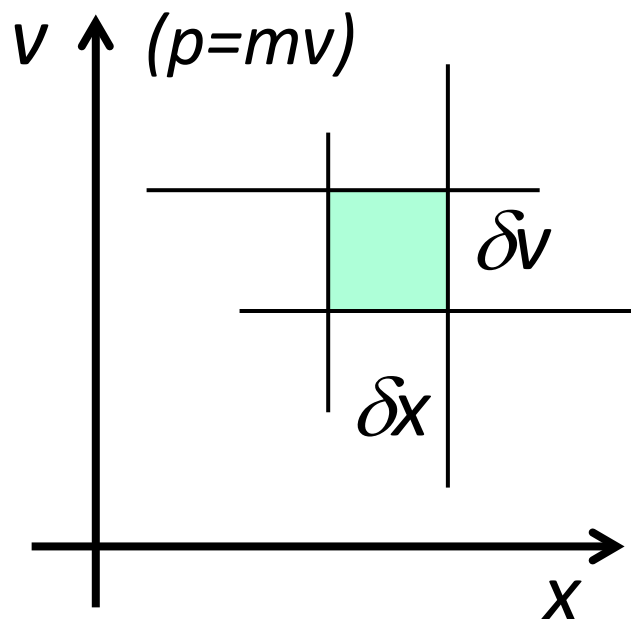
Particules

trajectoire = position & vitesse

physique statistique = cinétique



Statistique : espace des phases



Espace 6 dimensions

Hamilton / Lagrange

Heisenberg : $m \delta v \delta x \geq \hbar$

densité $\rightarrow f(x, v, t)$

fonction de distribution

Flux Γ selon x : $v f$

selon v : $(F/m) f$

Equation cinétique : $\partial_t f + \nabla \cdot \Gamma = source$ 6D

Plasma magnétisé = simplification complexe

Reference species = electrons: $\alpha = e$

1D in position, 1D in velocity = 1D-1V

$$\partial_t f_e + \nabla_x(v f_e) - \nabla_v(E f_e) = 0 \quad \partial_t f_i + \sqrt{\frac{m_e}{m_i}} \left(\nabla_x(v f_i) + \nabla_v(E f_i) \right) = 0$$

$$-\nabla_x E = \nabla_x^2 \phi = n_e - n_i$$

Frozen ion asymptotic limit: $\sqrt{\frac{m_e}{m_i}} \rightarrow 0$

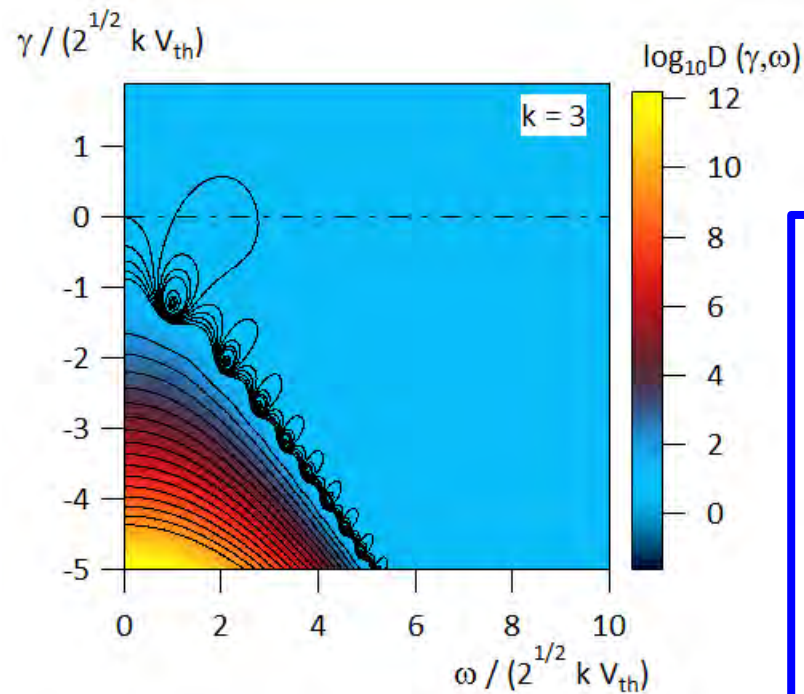
$$\partial_t f_e + \nabla_x(v f_e) - \nabla_v(E f_e) = 0 \quad -\nabla_x E = \nabla_x^2 \phi = n_e - 1$$

Prepared initial state $t = t_0$ conditions:

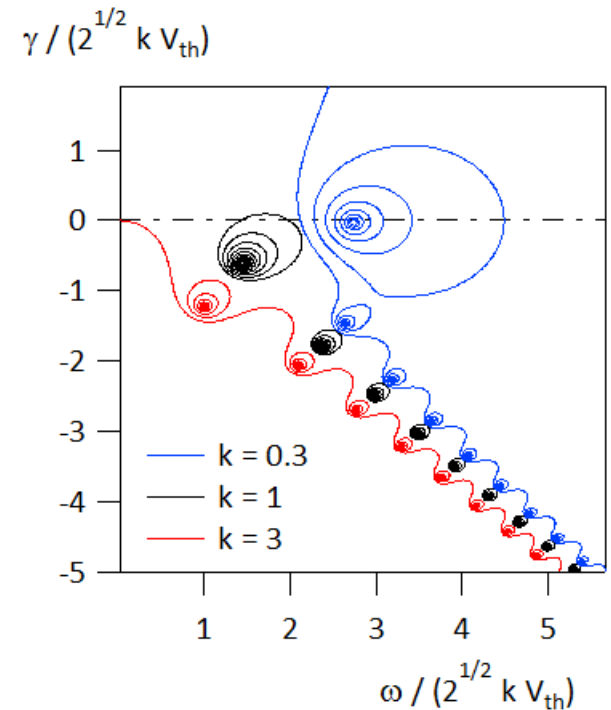
$$f(x, v, t_0) = f_M(v) (1 + \varepsilon_L \cos(kx))$$

Solutions of the dispersion equation $(k^2 + G_{eq}(\Omega/k)) \hat{\phi}(k, \Omega) = 0$

with: $G_M(\Omega/k) = 1 + (\Omega/k) \int_{-\infty}^{+\infty} dv \frac{f_M(v)}{v - \Omega/k}$

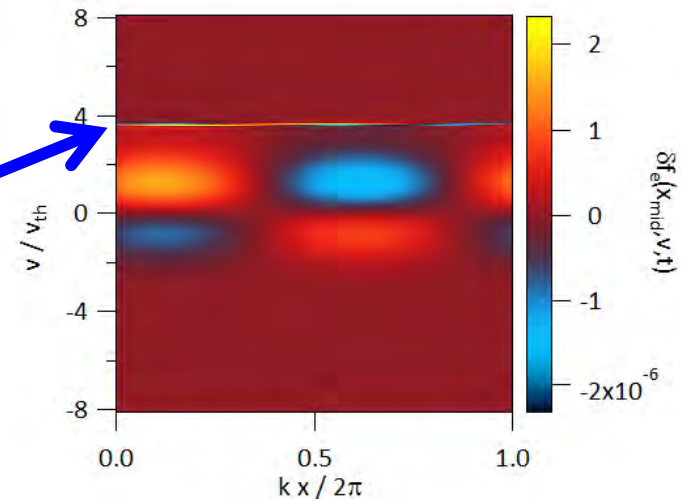


$\gamma < 0$
 $e^{\gamma t} \rightarrow 0$
damping
 ω
 $e^{i\omega t}$
oscillations

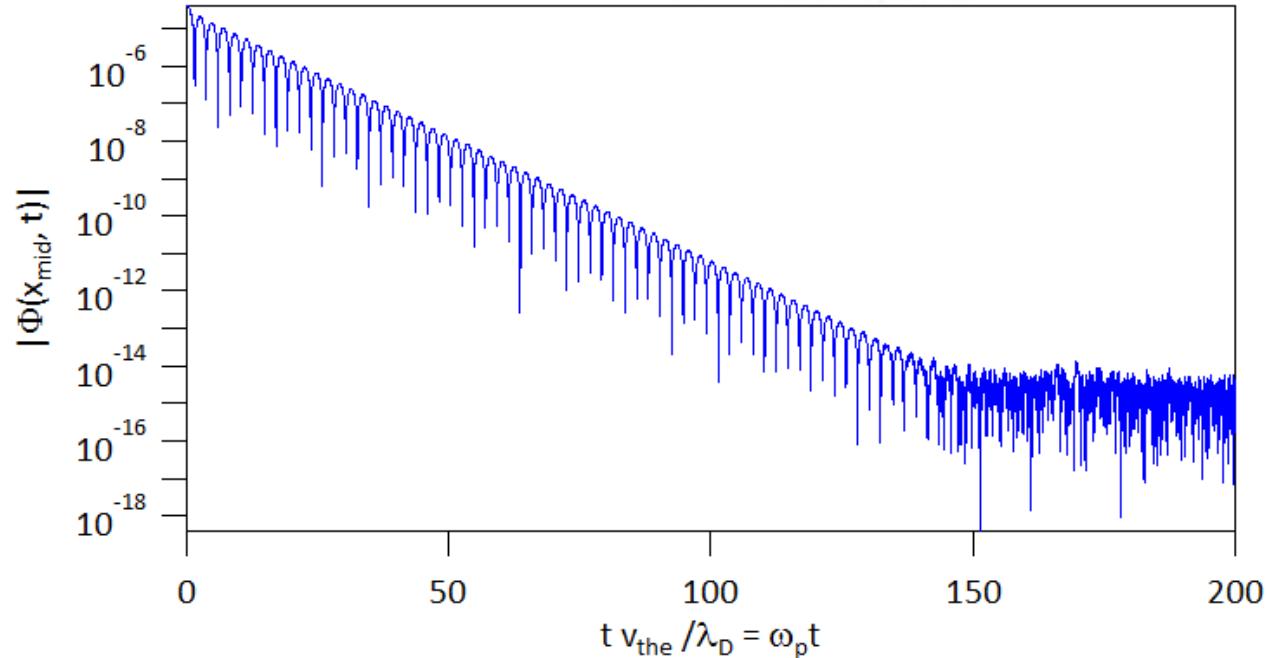


Bulk: frequency of Langmuir waves
Resonance: Ω / k

$$\delta f_e$$



Exponential decay
Electric potential



Amortissement apparent

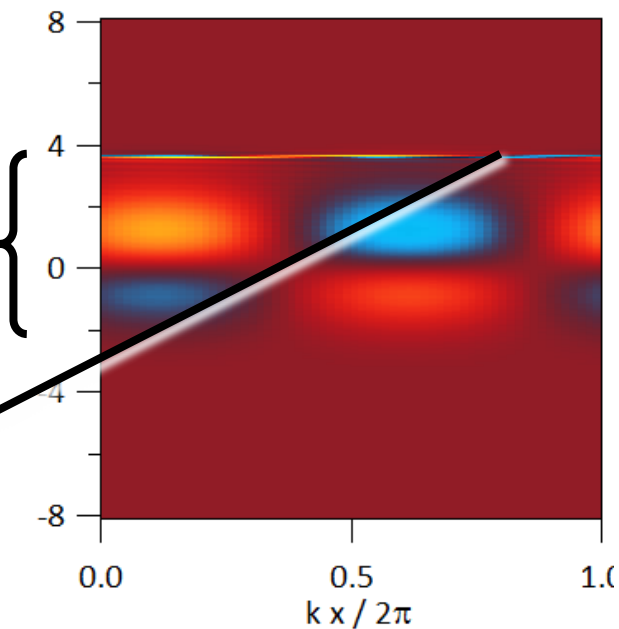
Equation de Vlasov : Entropie conservée

Etat initial :

distribution Maxwellienne
+ structure spatiale

Etat final :

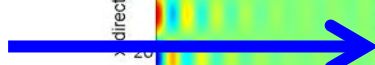
distribution non-Maxwellienne
plus de structure spatiale



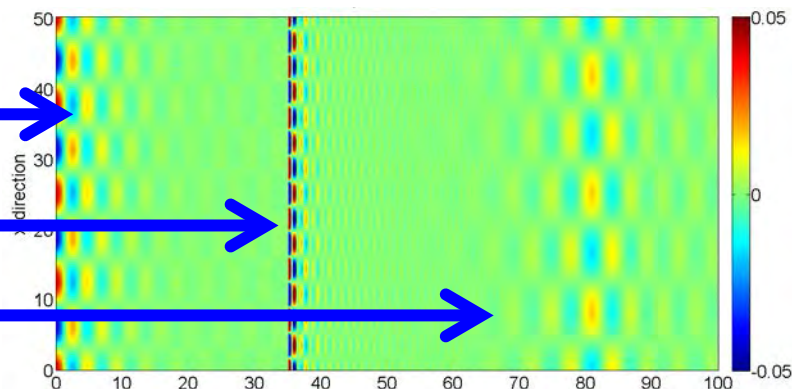
Landau 1



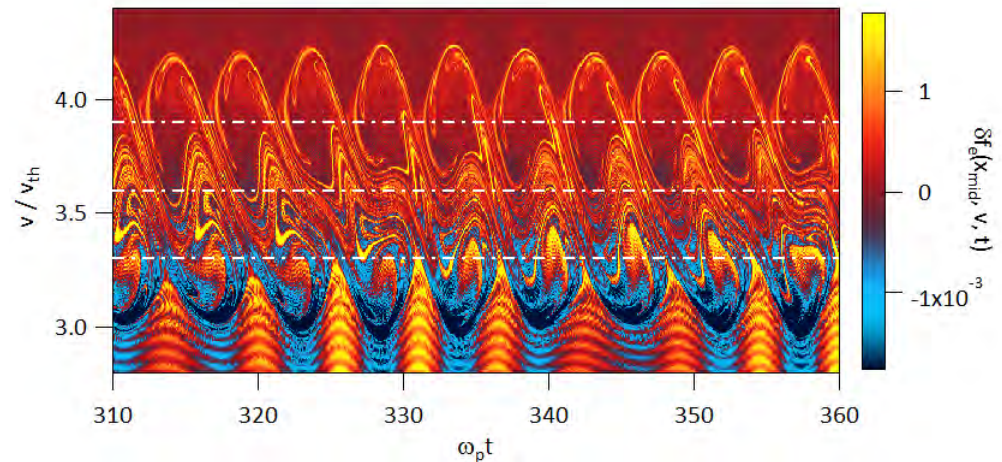
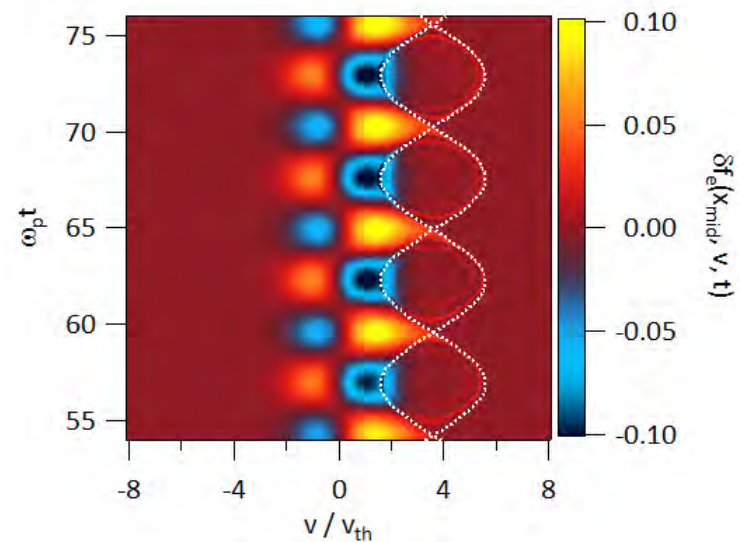
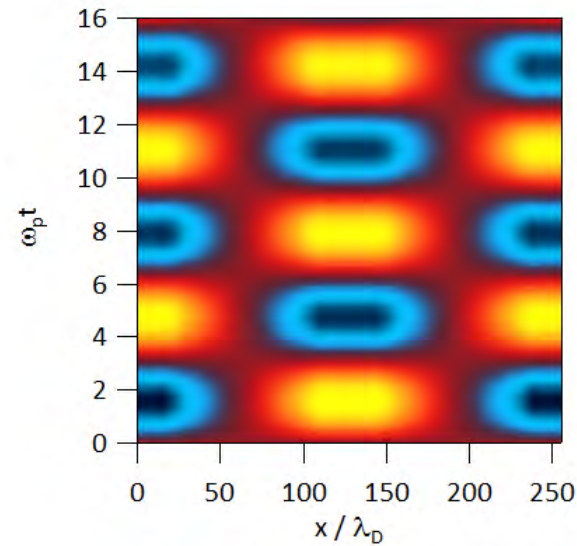
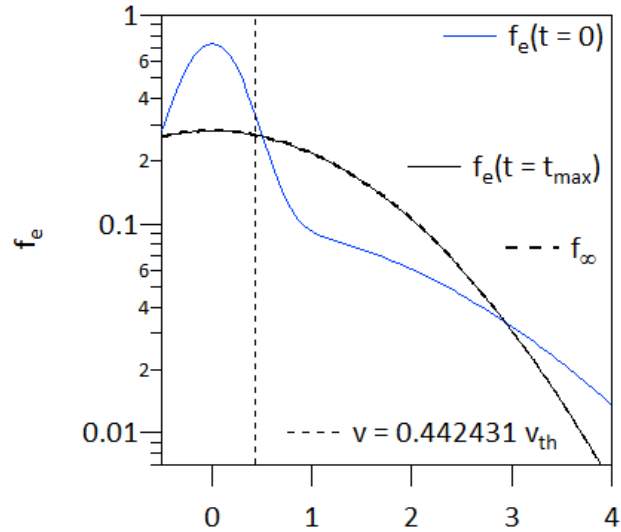
Landau 2



Echo

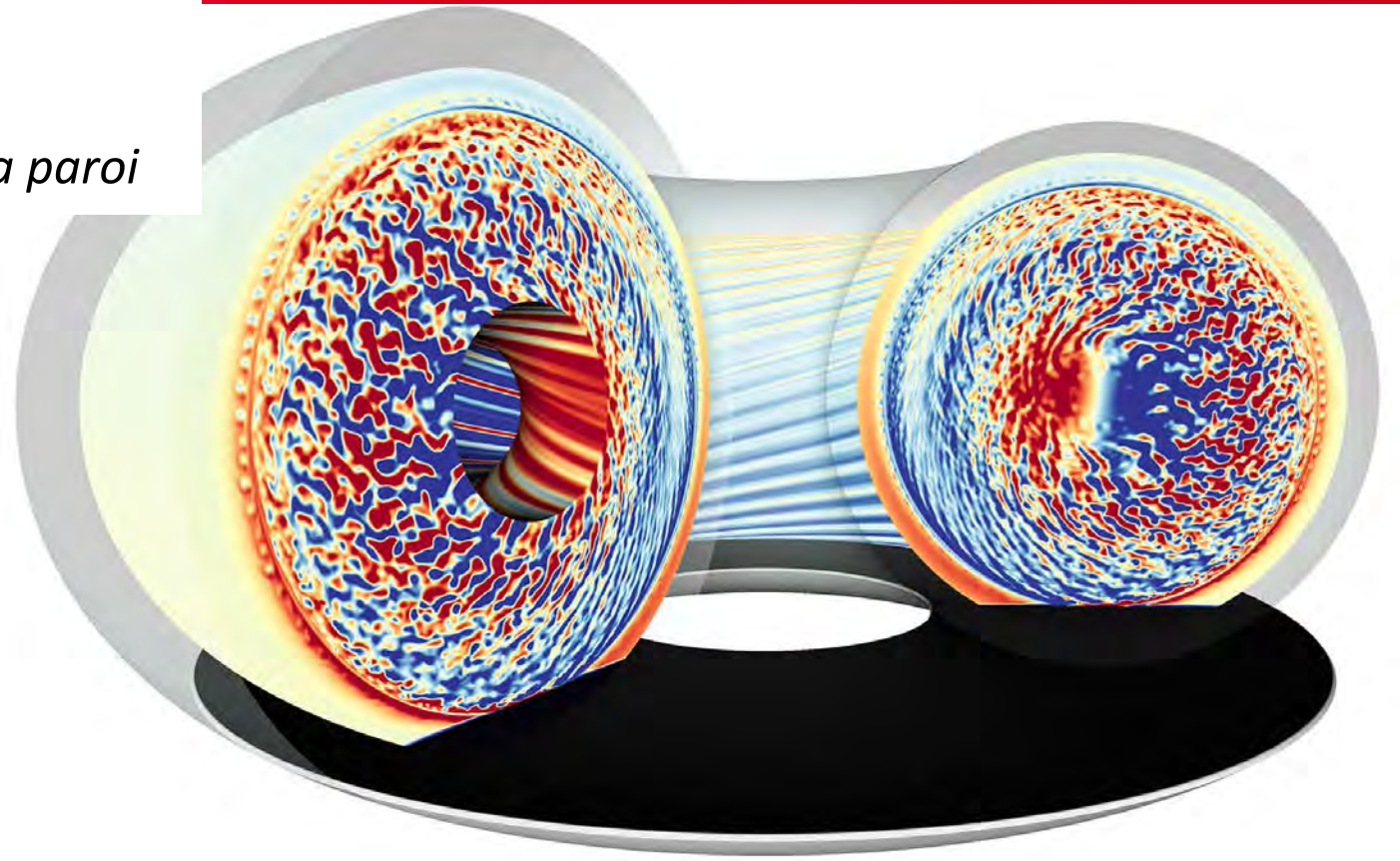


Collisions, heat transfer, sheath physics, quasineutrality...



GYROKINÉTIQUE IN 5D

- *Déterminer le confinement*
- *Turbulence plasma*
- *Statistiques cinétiques*
How is plasma special?
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Vlasov equation (Boltzmann for plasmas)

Kinetic equation

1-particle distribution function: f_a

$$\frac{df_a(\mathbf{x}, \mathbf{v}, t)}{dt} = \mathcal{C}_a$$

collisions: \mathcal{C}_a

VLASOV operator:

$$\frac{df_a(\mathbf{x}, \mathbf{v}, t)}{dt} = \left(\frac{\partial}{\partial t} + \dot{\mathbf{x}} \cdot \nabla_{\mathbf{x}} + \dot{\mathbf{v}} \cdot \nabla_{\mathbf{v}} \right) f_a(\mathbf{x}, \mathbf{v}, t)$$

$$\frac{df_a(\mathbf{x}, \mathbf{v}, t)}{dt} = \left(\frac{\partial}{\partial t} + \mathbf{v} \cdot \nabla_{\mathbf{x}} + \frac{\mathbf{F}}{m_a} \cdot \nabla_{\mathbf{v}} \right) f_a(\mathbf{x}, \mathbf{v}, t)$$

$$\mathbf{F} = q_a \mathbf{E} + q_a \mathbf{v} \times \mathbf{B}$$

a-dimensional form: $\mathbf{b} = \mathbf{b}_0 + \varepsilon \left((\mathbf{x} - \mathbf{x}_0) \cdot \nabla_{\mathbf{x}} \right) \mathbf{b} \Big|_{\mathbf{x}_0} + \dots$
 $L_0 = R_0$

$$\left(\frac{\partial}{\partial t} + \frac{1}{\sqrt{M_a}} \mathbf{v} \cdot \nabla_{\mathbf{x}} + \frac{Z_a}{\sqrt{M_a}} \mathbf{E} \cdot \nabla_{\mathbf{v}} + \frac{Z_a}{\sqrt{M_a}} \frac{1}{\varepsilon} (\mathbf{v} \times \mathbf{b}) \cdot \nabla_{\mathbf{v}} \right) f_a(\mathbf{x}, \mathbf{v}, t) = \nu_a^* \mathcal{C}_a$$

$$t_0 V_{0,\alpha} = t_0 V_{0,a} \frac{V_{0,\alpha}}{V_{0,a}} = L_0$$

$$\frac{q_a E_0 t_0}{m_a V_{0,a}} = \frac{Z_a}{\sqrt{M_a}}$$

$$\frac{q_a B_0 t_0}{m_a} = Z_a \frac{B_0}{E_0 V_{0,a}} = \frac{Z_a}{M_a} \frac{1}{\varepsilon} \quad t_0 \nu_a = \nu_a^*$$

Large B asymptotic limit of Vlasov

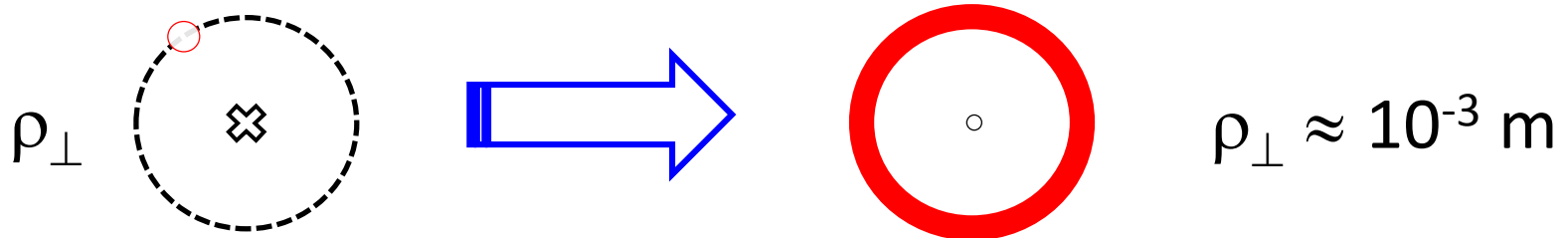
$$\varepsilon \rightarrow 0; \quad b = b_0$$

Asymptotic limit of Vlasov

$$\frac{1}{\varepsilon} \left((\mathbf{v} \times \mathbf{b}_0) \cdot \nabla_{\mathbf{v}} \right) f_a(\mathbf{x}, \mathbf{v}, t) = \frac{1}{\varepsilon} \frac{\partial}{\partial \varphi_c} f_a(\mathbf{x}, v_{\parallel}, v_{\perp}, \varphi_c, t)$$

Gyrokinetic equation: expansion in ε

High frequency (Ω) = \perp particle motion \rightarrow gyroaverage



Gyrokinetics : phase space 6D \rightarrow 5D

- Much better for the code
- Difficult framework

Asymptotic limits in Maxwell equations

- B is given (low β limit)
- electrostatic limit \Rightarrow Poisson equation

$$\nabla_x \cdot \mathbf{E} = -\nabla_x^2 \phi = \frac{1}{\epsilon_0} \sum_{\text{species } a} q_a n_a$$

$$\epsilon_D^2 \nabla_x^2 \phi = - \sum_{\text{species } a} Z_a n_a \quad \epsilon_D^2 = \frac{\epsilon_0 E_0}{n_0 e L_0^2}$$

Asymptotic limit $\epsilon_D^2 \rightarrow 0$

= quasineutrality

$$\sum_{\text{species } a} Z_a n_a = 0$$

**Nonlinear
Gyro-kinetic (5D)**



**simulations
code = GYSELA**

All the confined plasma volume?

Why? Given the cost: mesh size + time steady state ($= \tau_E$)

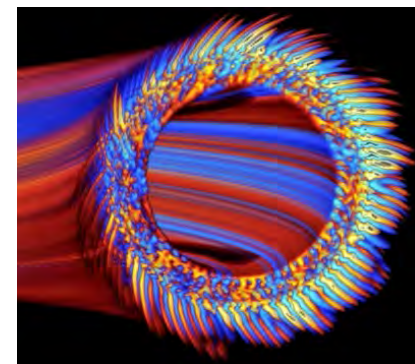
No scale separation

Importance of large scales: barrier physics

Boundaries (no r-periodicity)

No inner radius

outer radius: SOL, heat sink

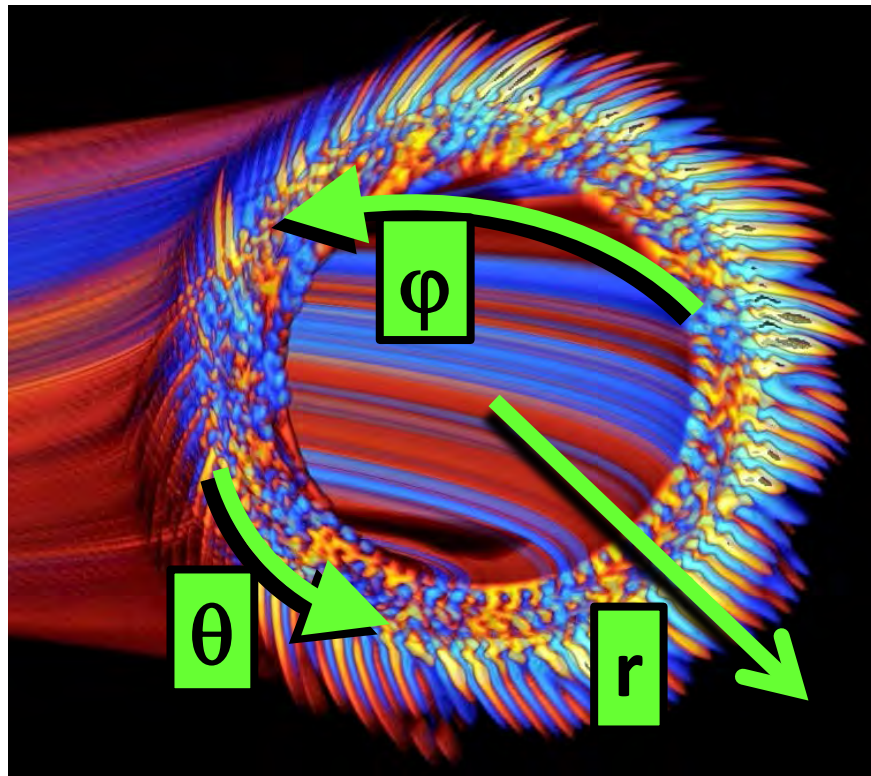


Plasma shaping:

Work in progress

New code version?

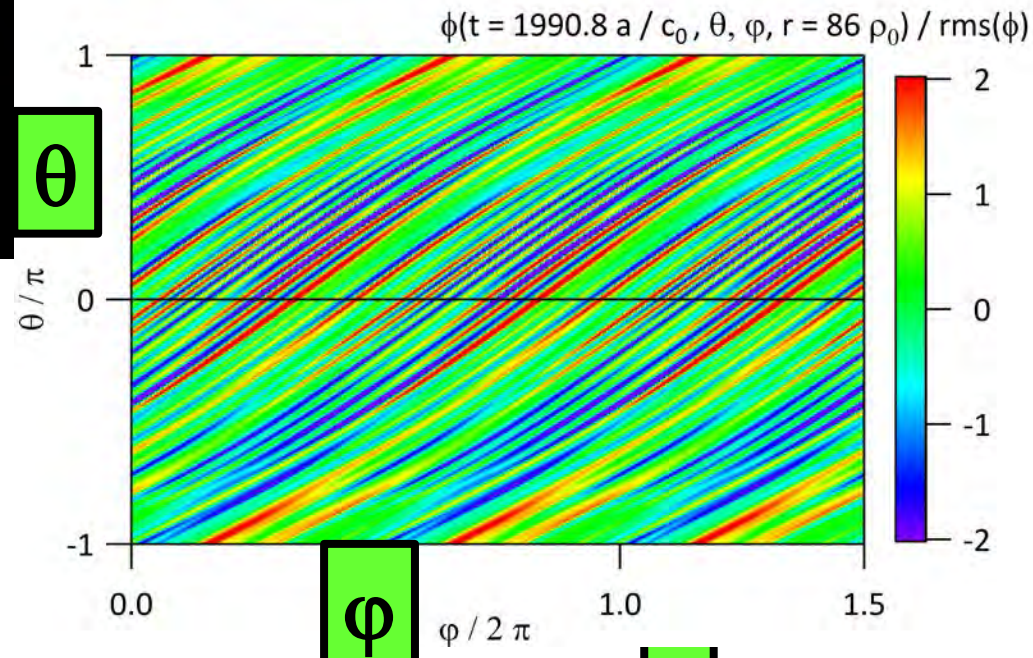
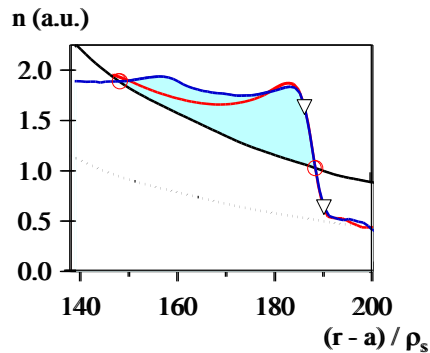
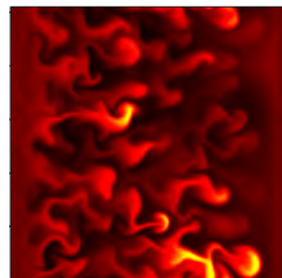




Torus = 2 angles + radial coordinate

unfolding the angles 1-D & 2-D plots

filament structure \approx quasi 2D
 n (a.u.)



Potential fluctuations

CLOCK Time normalised: Omega t = 700 File 1 out of 464 Wall time = 0.000015 s

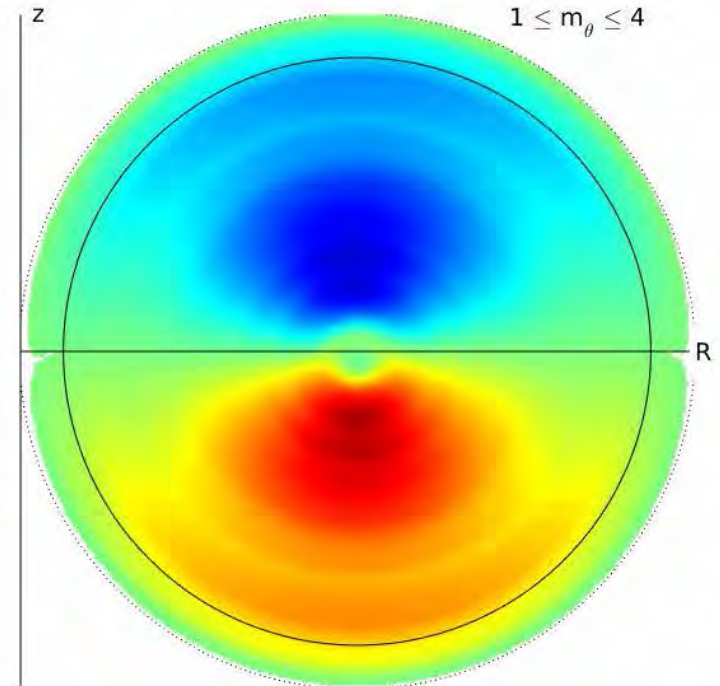
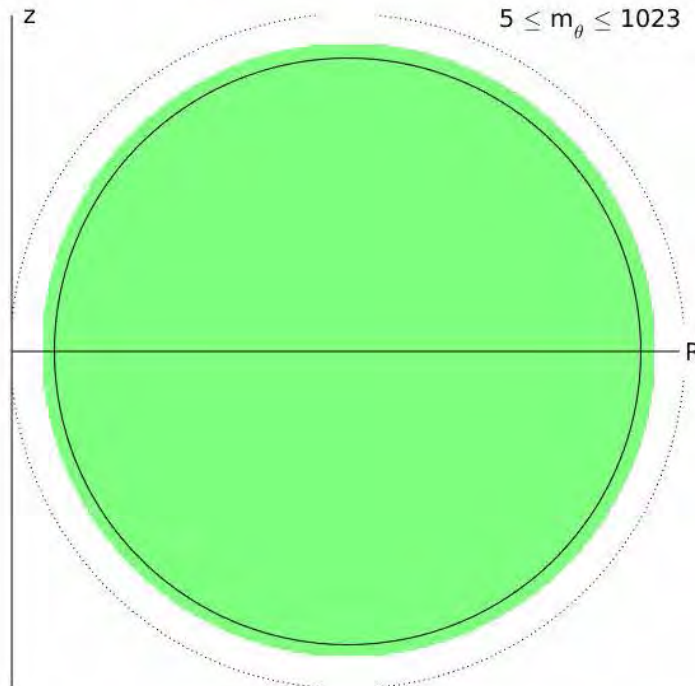
GYSELA
code version = 9

Species: D

Aspect Ratio: A = 6
1 / rho* = 380
nu* = 0.02
Source = 0.00077

Nr = 256
Ntheta = 2048
Nphi = 127
Nv // = 127
Nmu = 15
delta t = 100

Normalisation
left = 0.067
right = 0.008

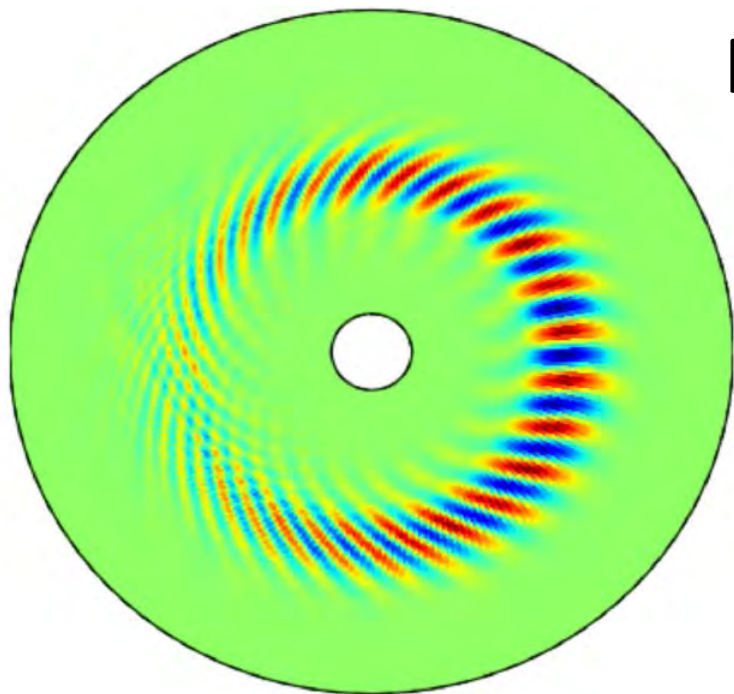


WATT Grand Challenge CINES OCCIGEN2
ENR ESKAPE & Marconi project TraGyK @EUROfusion

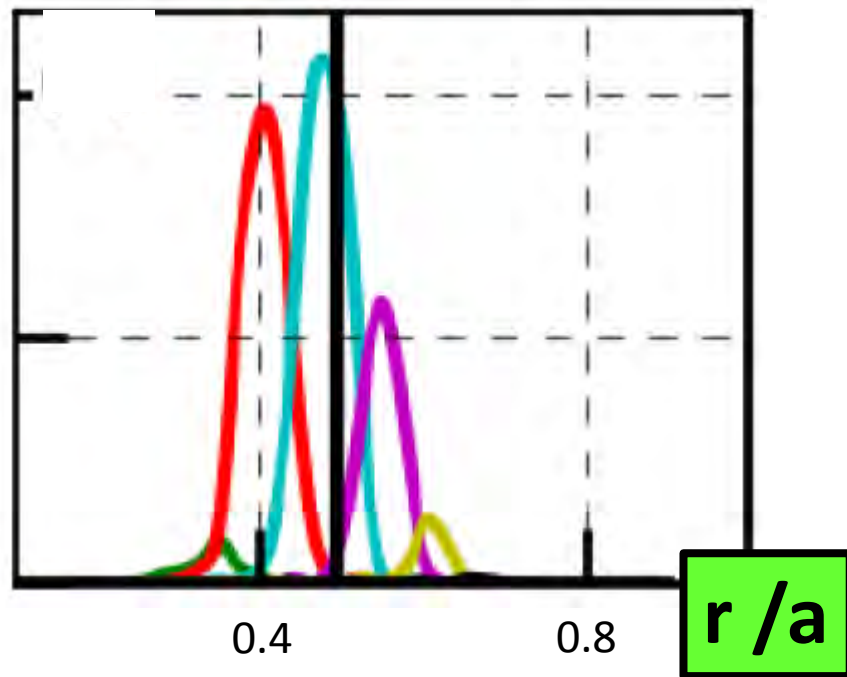
movie making : KFC@AMIDEX

WATT: Grand challenge OCCIGEN2 (8 Million CPU hours)

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



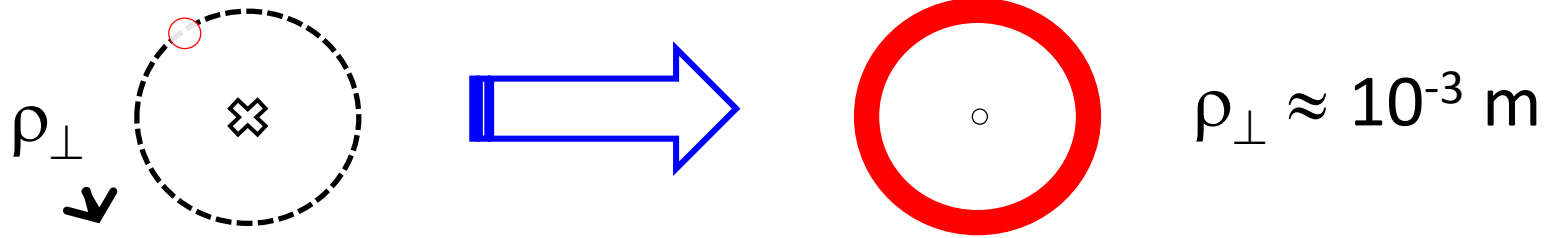
Filtered Eigen mode (r, θ)
ballooned structure



Symmetries

- collisions = isotropic
- gyration = cylindrical
- equilibrium = toroidal axisymmetric
- turbulence/MHD = non-axisymmetric

High frequency (Ω) = \perp particle motion \rightarrow gyroaverage



Particle trapping

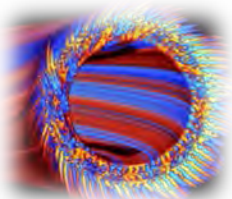
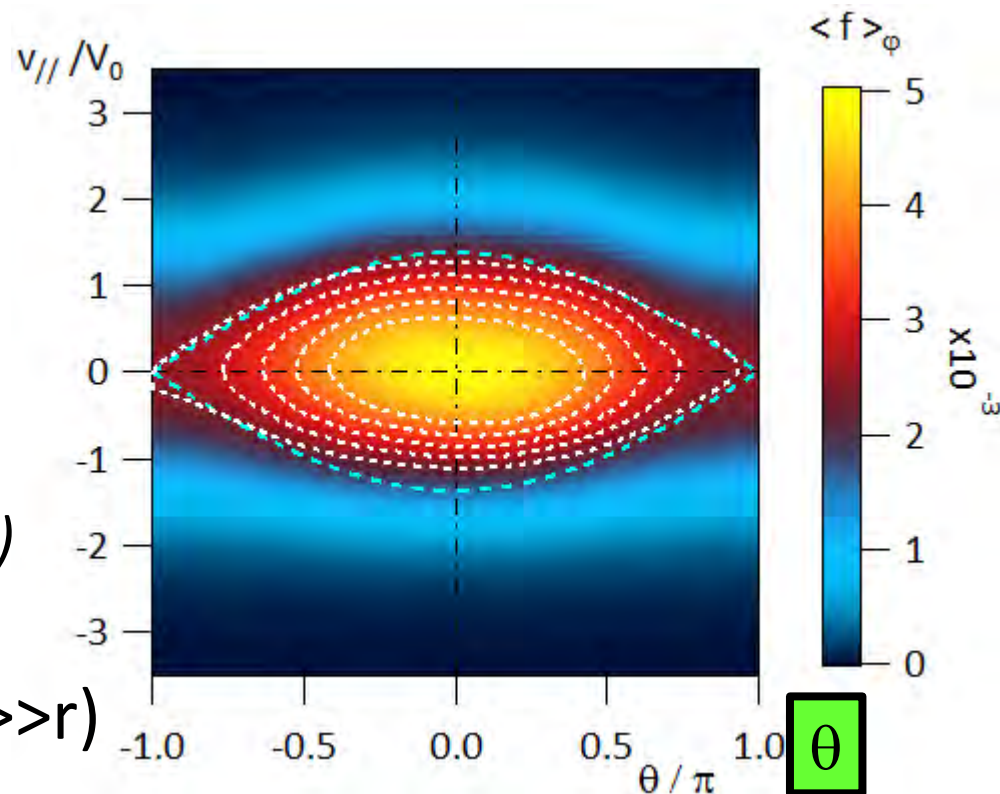
μ magnetic moment

$$H = \frac{1}{2} m_{\alpha} v_{\parallel}^2 + \mu B$$

$B \propto 1 / R$ (Ampère circulation)

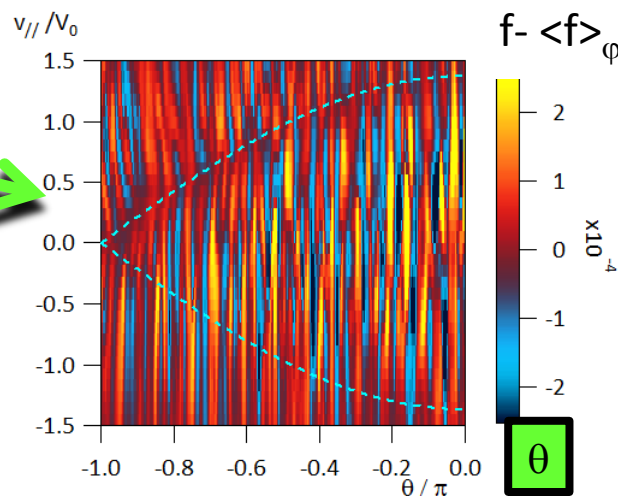
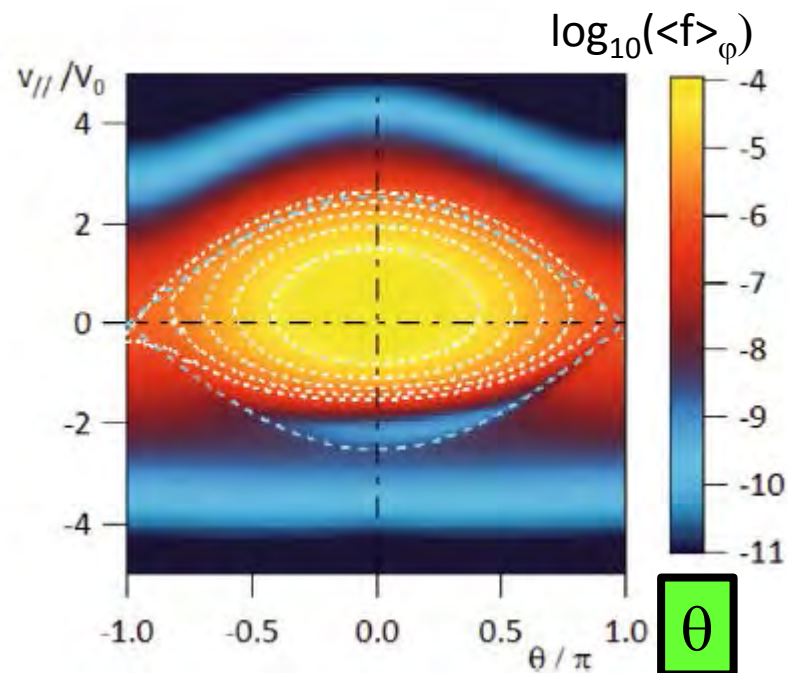
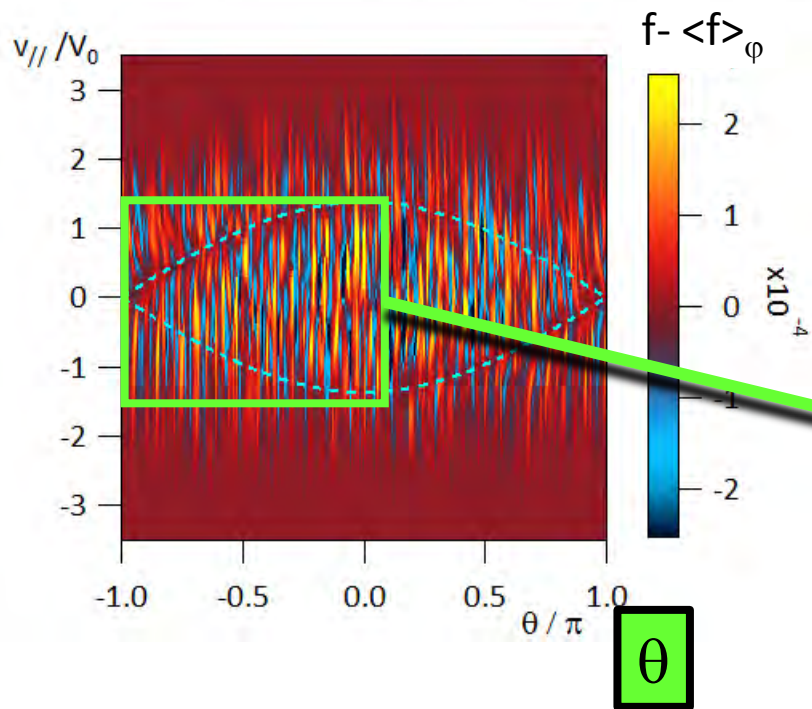
torus: $R = R_0 + r \cos\theta$

\equiv pendulum ($R_0 \gg r$)

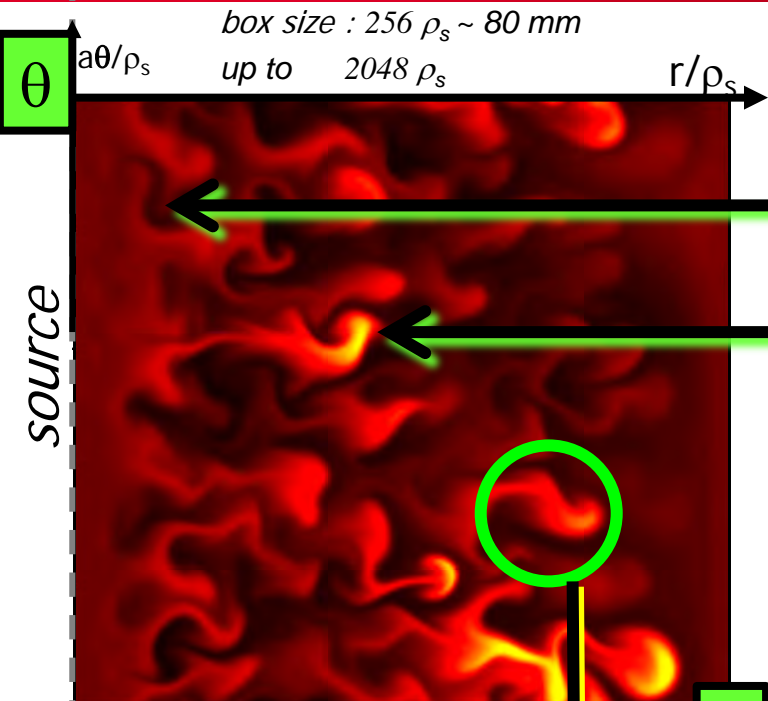


Particle trapping & turbulence

$$H = \frac{1}{2} m_\alpha v_{\parallel}^2 + \mu B + q_\alpha \phi$$



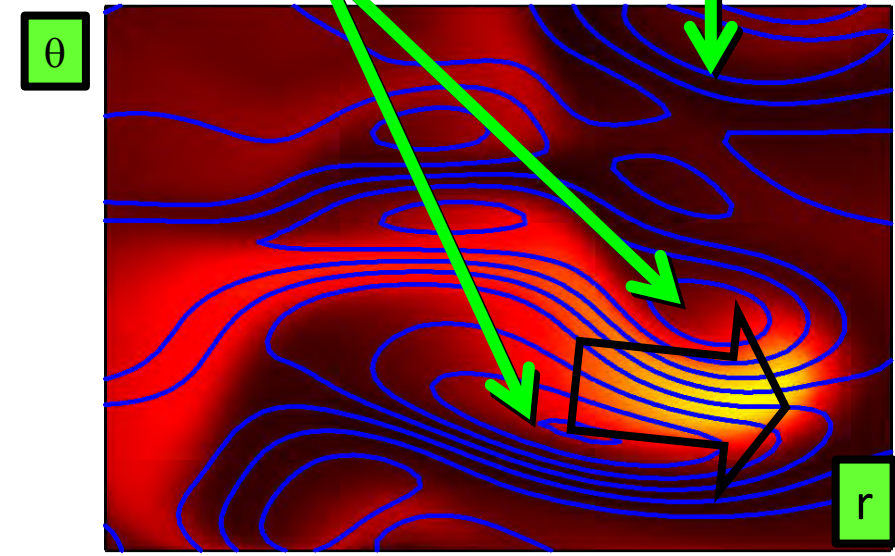
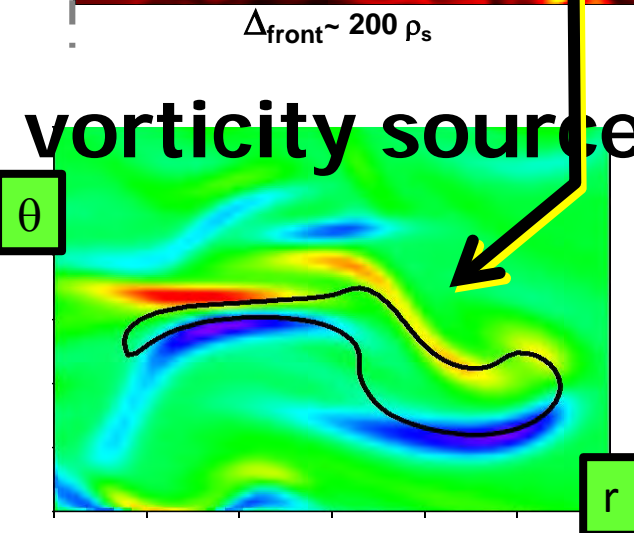
Avalanches: fronts & holes



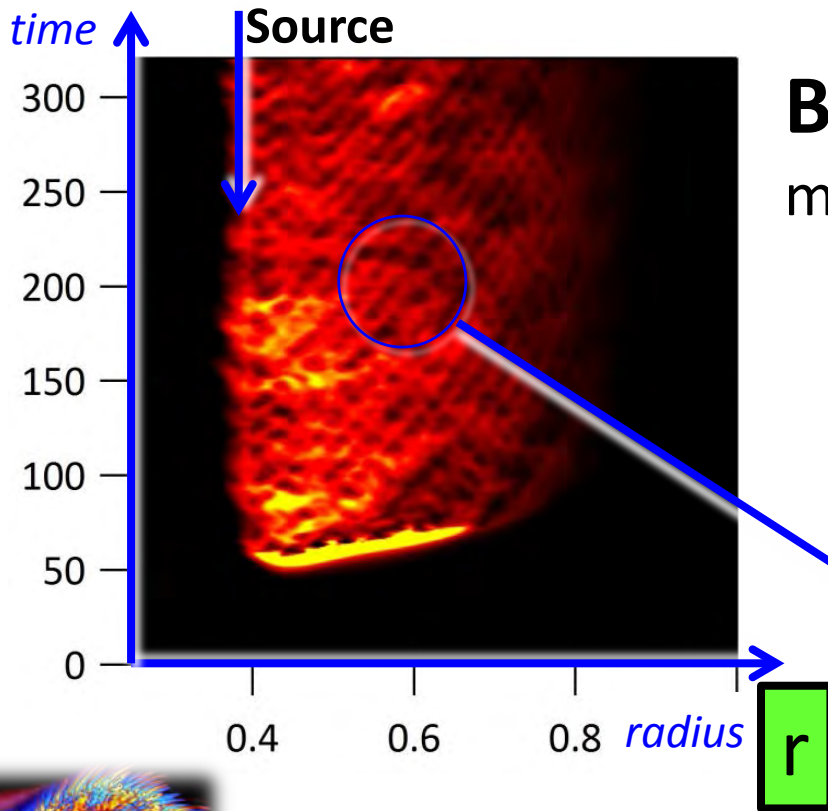
hole (sub-dense)

over-dense front
dipole nested in the
wings of the front

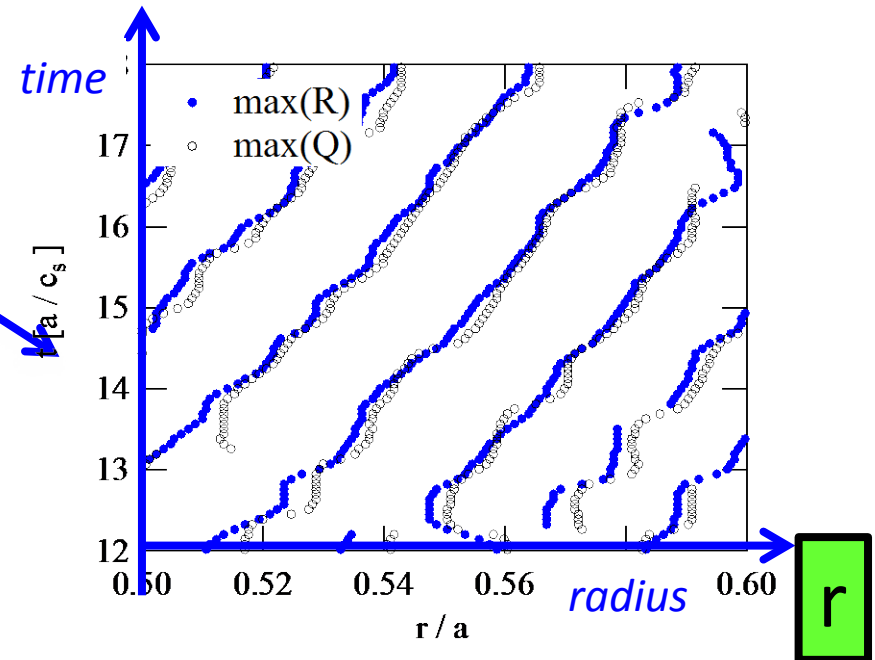
iso stream
function



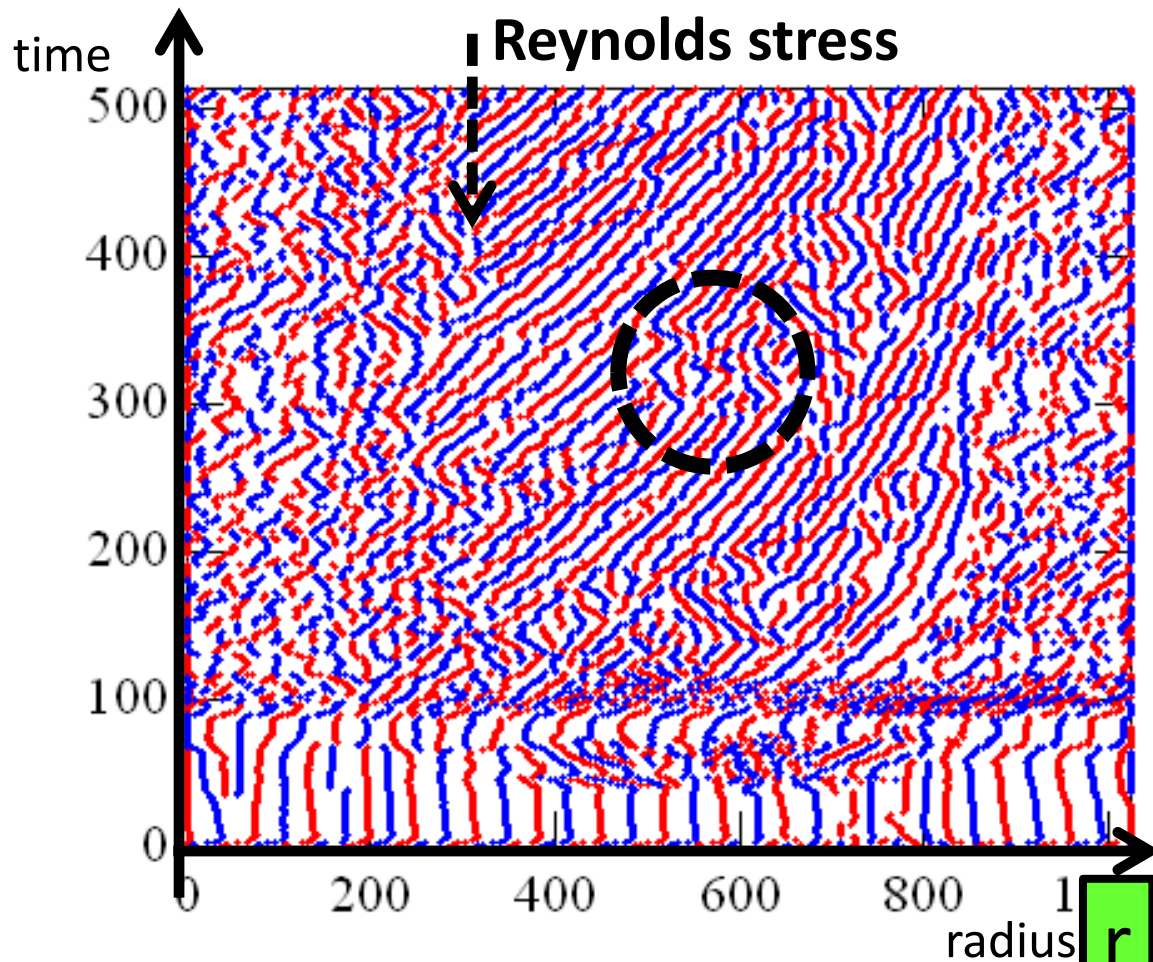
Turbulent electric potential ϕ \Rightarrow Turbulent heat flux
 \Rightarrow Turbulent Reynolds stress



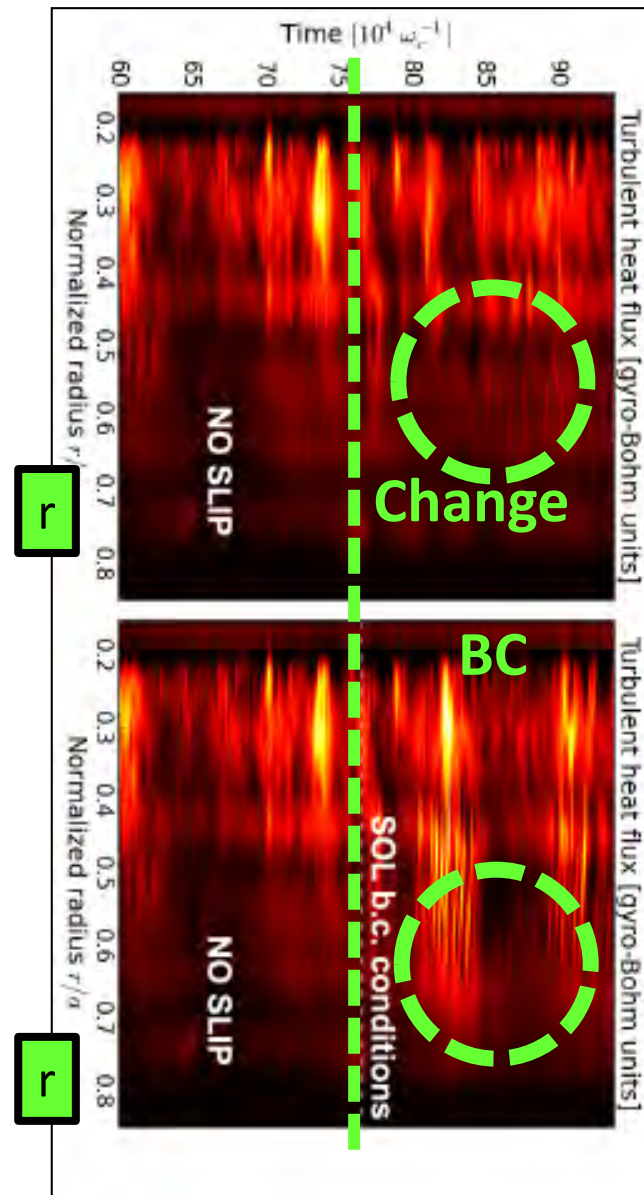
Ballistic transport events
 more avalanche-like (SOC)
 than Fourier-like heat transport



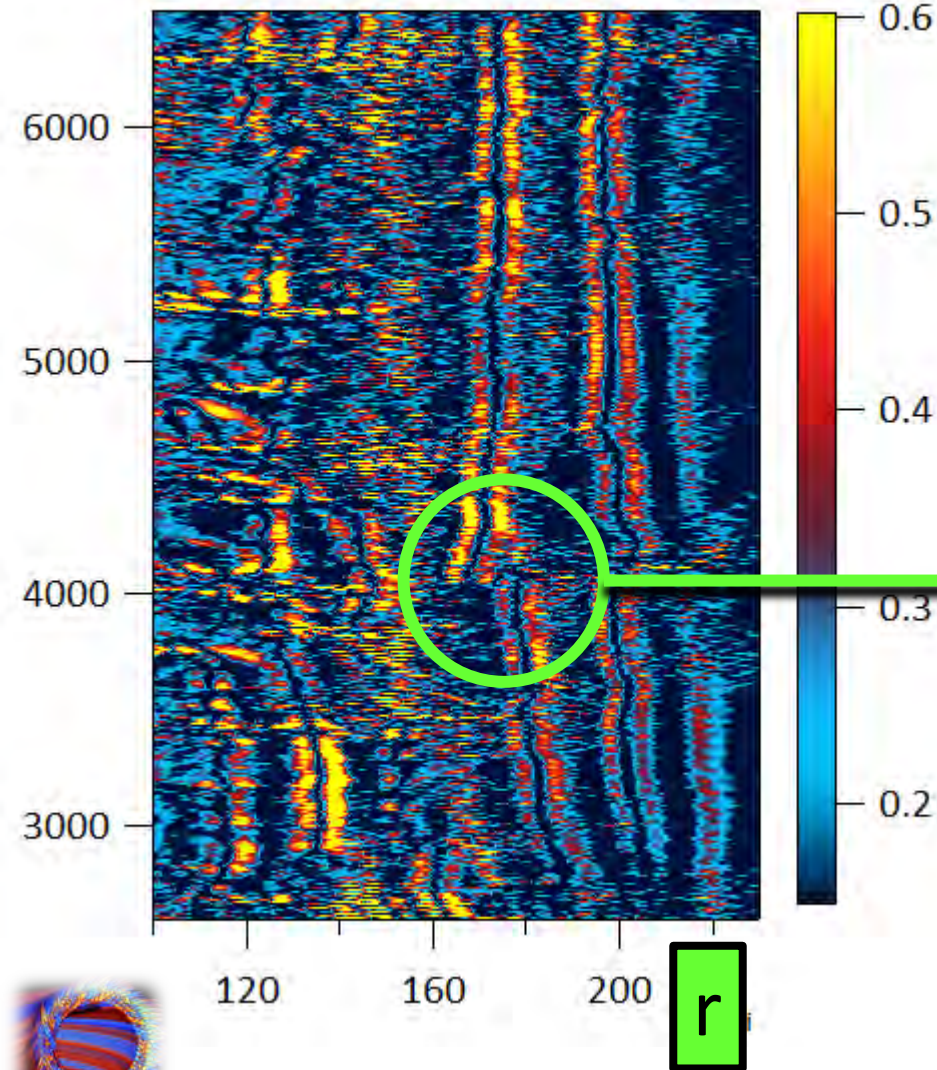
ANR GYPSI



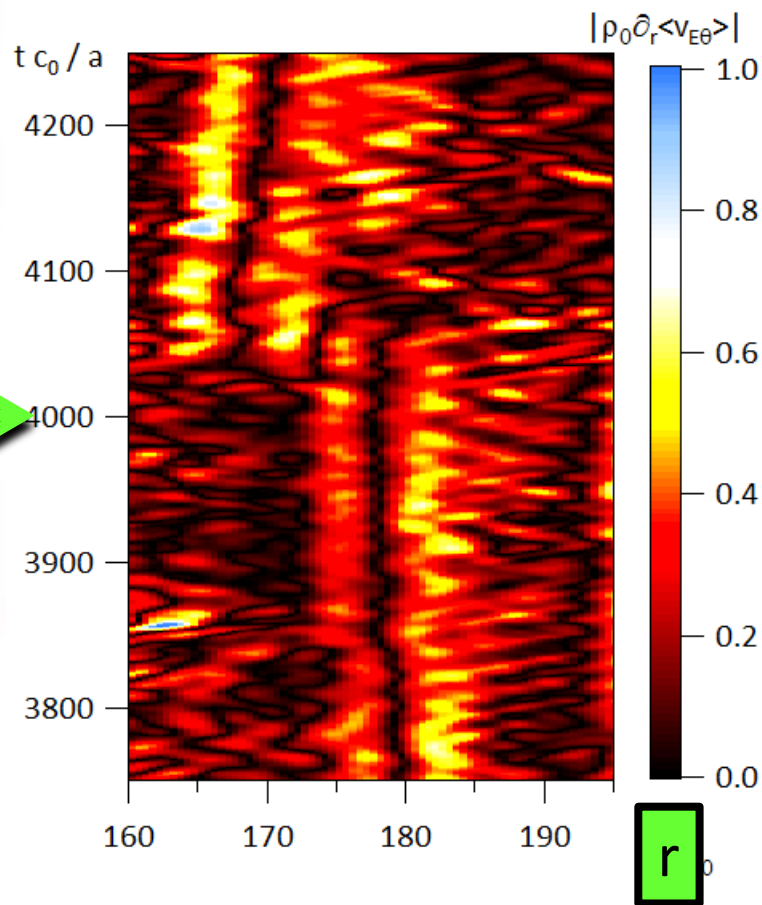
Physics for ITER



$t / (a / c_s)$



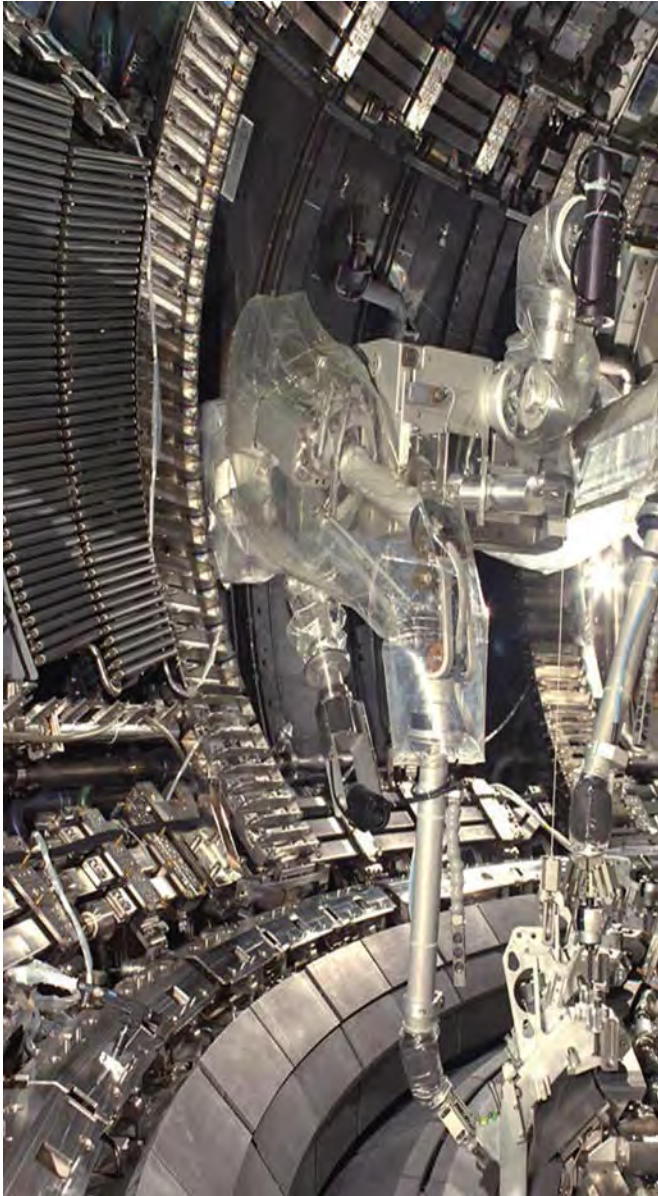
Corrugations = weak barriers



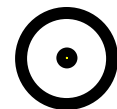
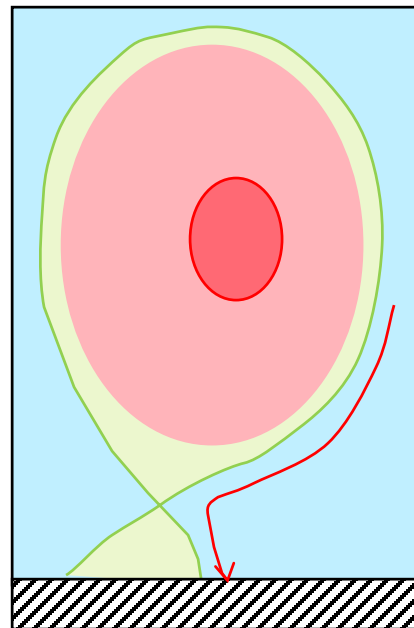
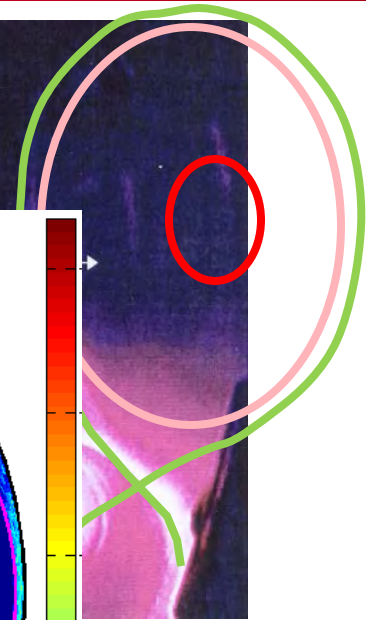
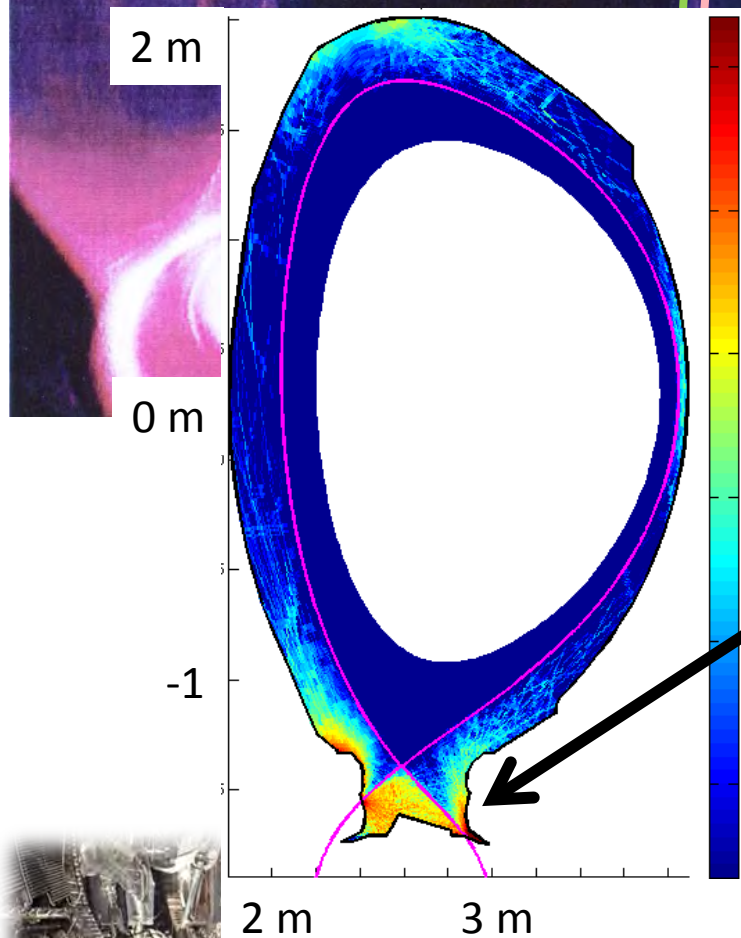
FLUX DE CHALEUR À LA PAROI

Ensuring long life time of
Wall components

- *Déterminer le confinement*
- *Turbulence plasma*
- *Statistiques cinétiques*
How is plasma special?
- *Gyrocinétique 5D*
- **Flux de chaleur à la paroi**



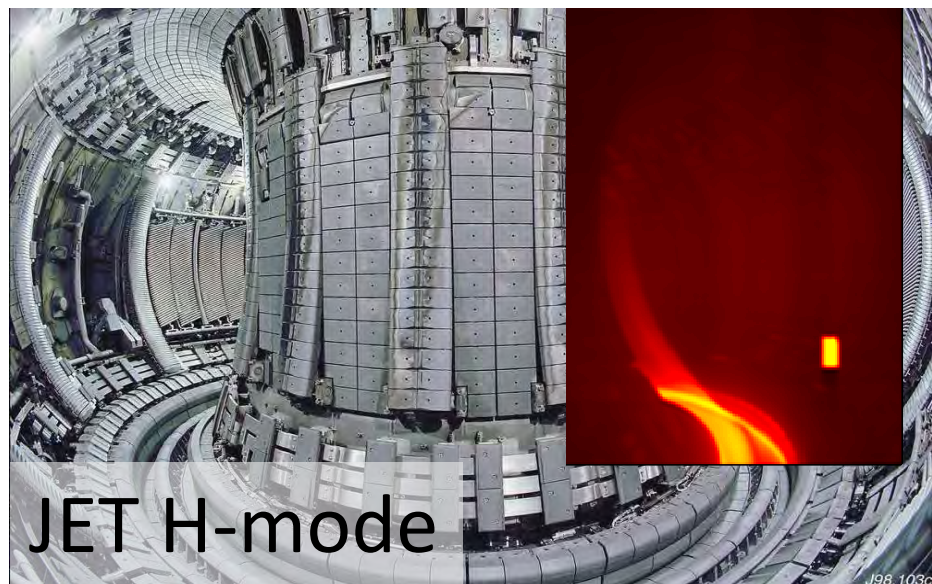
ASDEX-U (Germany)



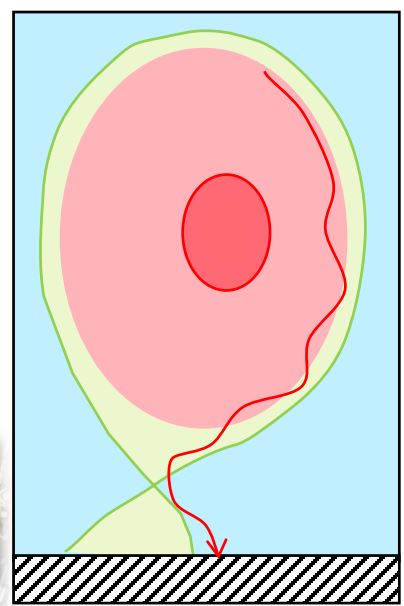
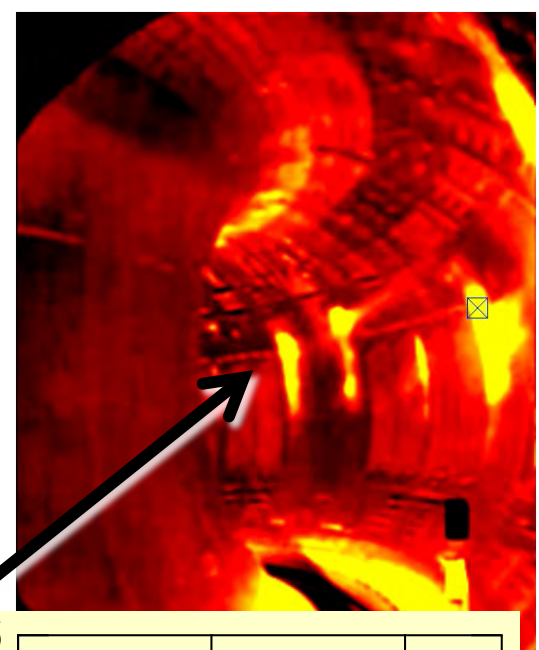
// heat flux
100 MW/m²
to 10 GW/m²

JET experiment (EU)
neutral particle pressure
Divertor volume

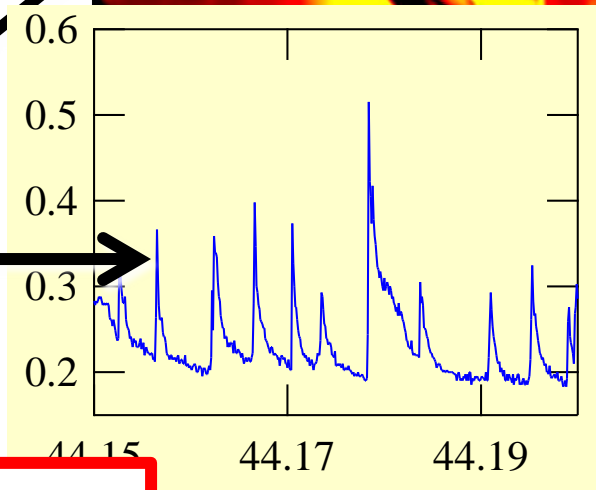
Physics meets Technology
technology limit 10 MW / m²



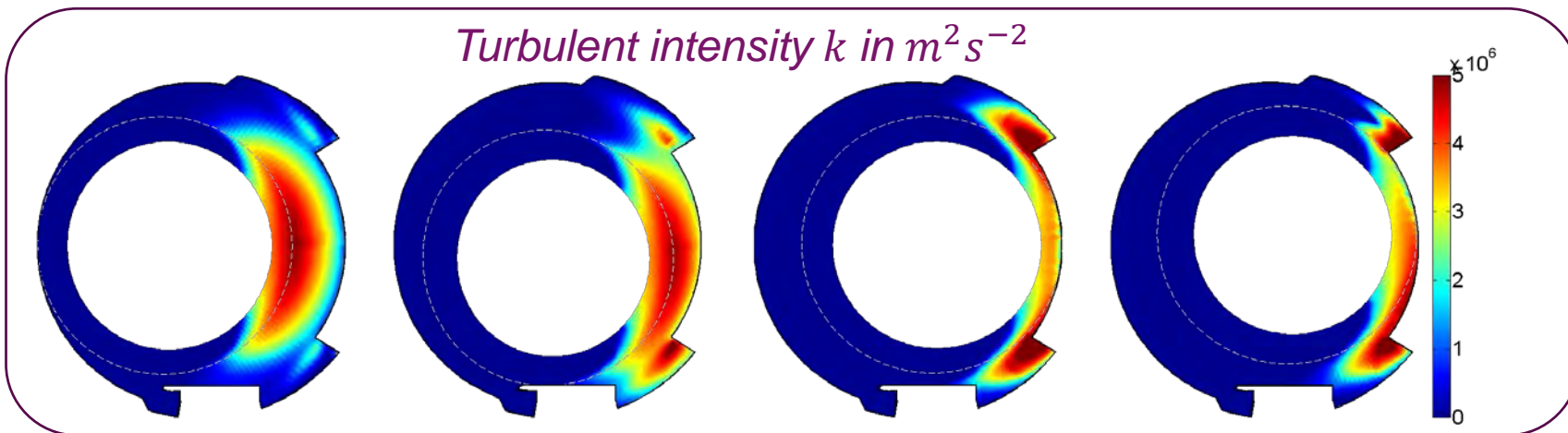
JET H-mode



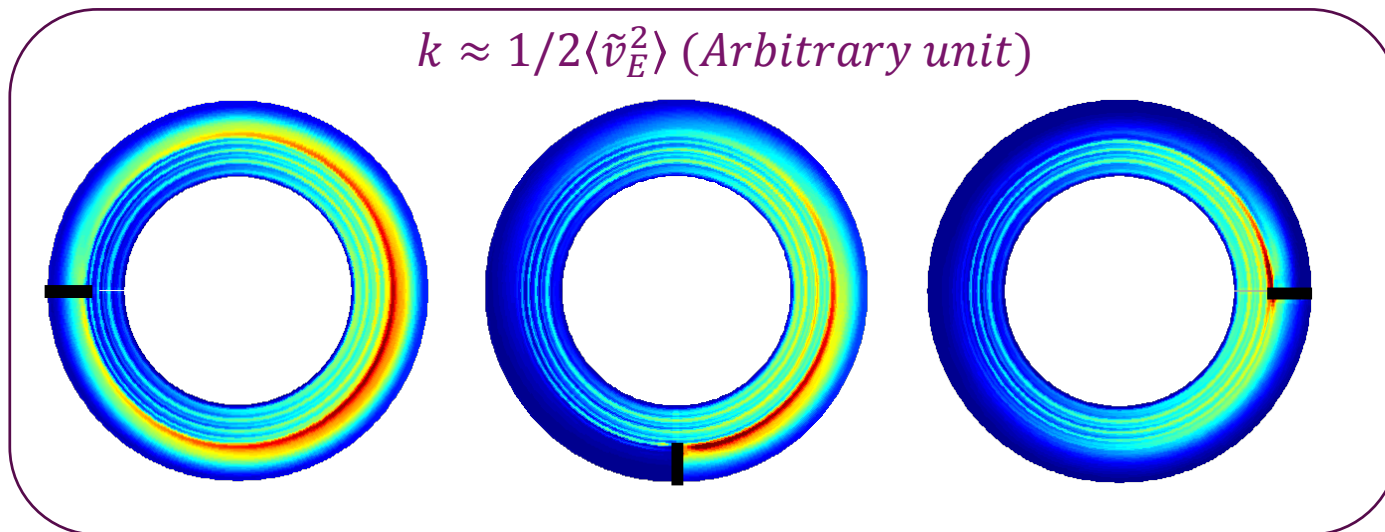
// heat flux
ELM wall impact
relaxation events
quasi-periodic



Must be controlled



SOLEDDGE2D



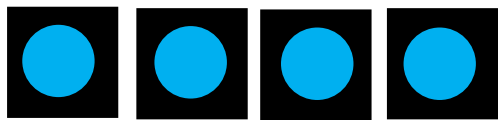
TOKAM3X

**PLANNED: ITER divertor = first actively cooled W divertor
= first divertor to operate 10 years
= first at techno limit 10 MW/m²**

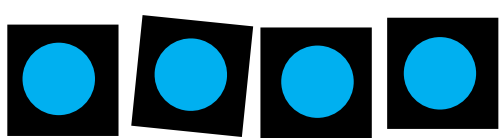
Steady-state

Transients

1 GW / m²



10 MW / m²

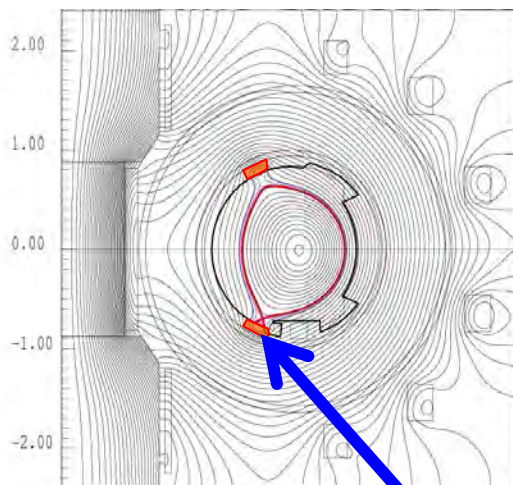
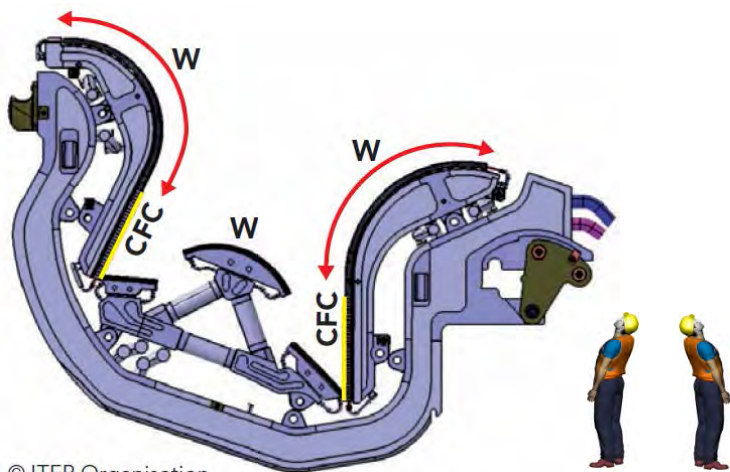


Solution shaping...

300 000 elements to shape

ITER ELM simulator



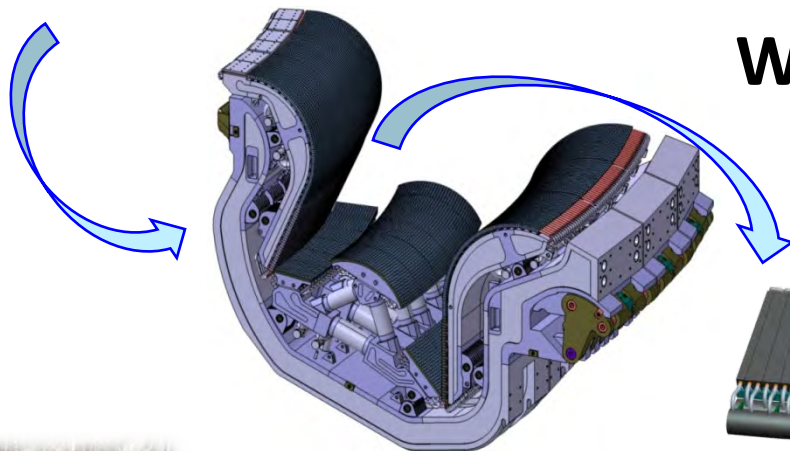


TORE SUPRA 2010-2012

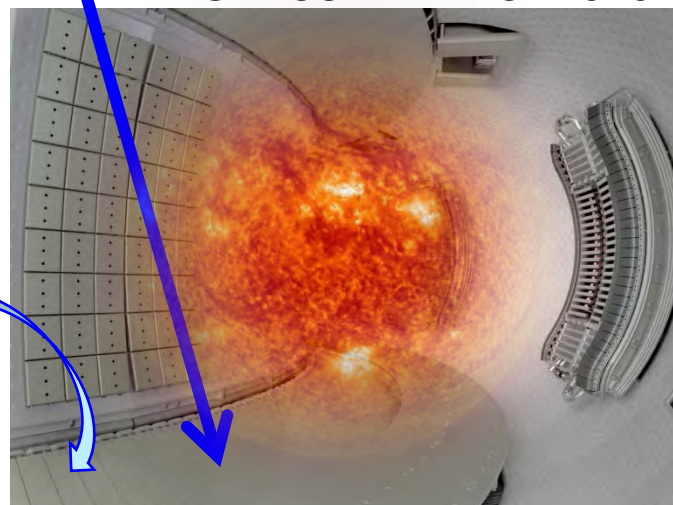
ITER divertor $\leq 10 \text{ MW} / \text{m}^2$

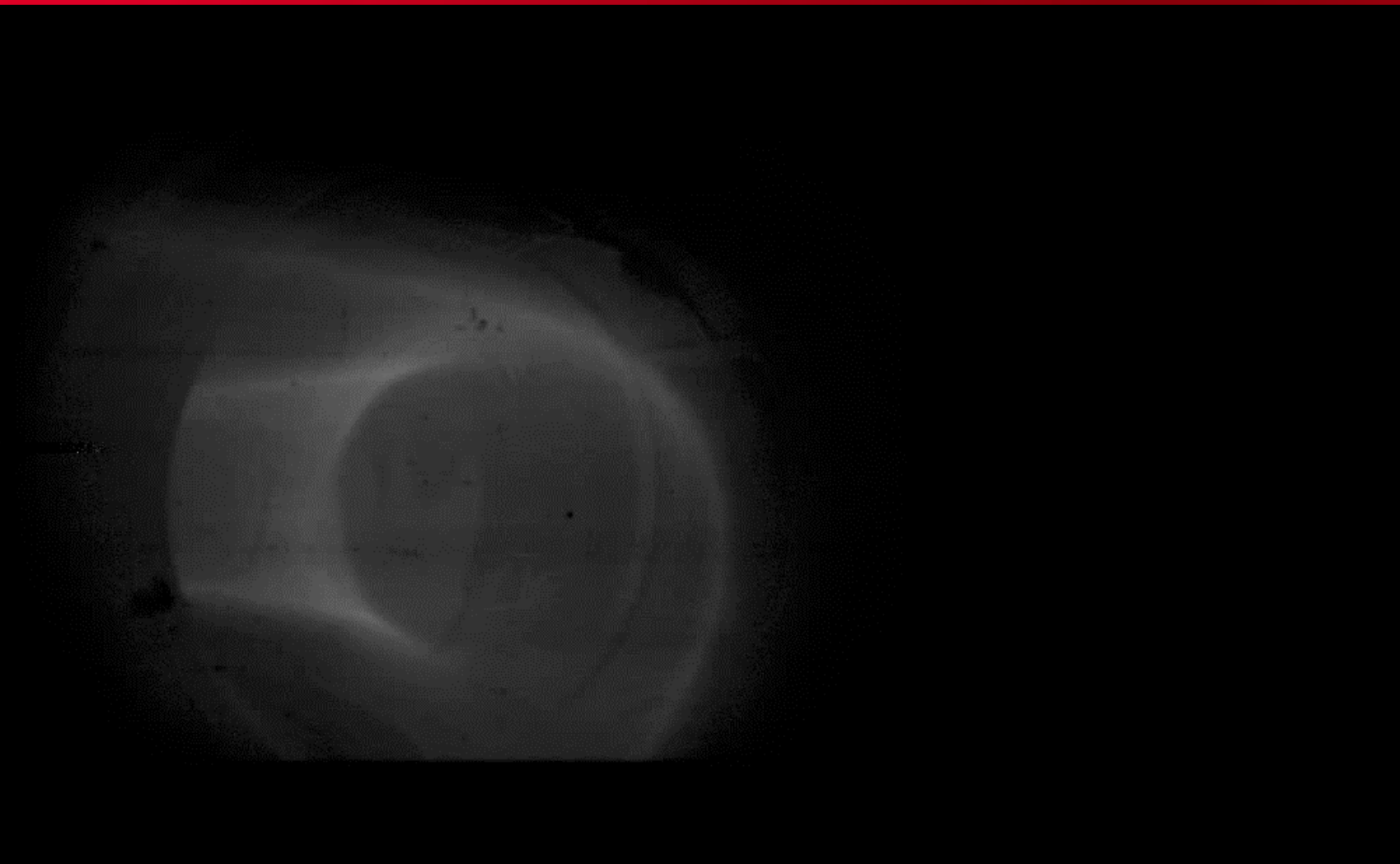
TORE SUPRA
WEST divertor

TORE SUPRA WEST 2016



Tungsten (W) technology





T+ : -15.052 ms

Img# : -31 Cam: Phantom v.7 AcqRes: 800 x 600 Rate: 2000 Exp: 495 μ s EDR: 0 μ s First: -293 Last: 1596 Durat: 0.945 s

Range data:

Description:

Electrons runaways : fin

T+: +403.948 ms

Img#: 807 Cam: Phantom v.7 AcqRes: 800 x 600 Rate: 2000 Exp: 495 μ s EDR: 0 μ s First: -293 Last: 1596 Durat: 0.945 s

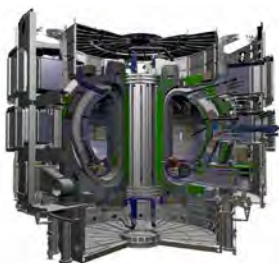
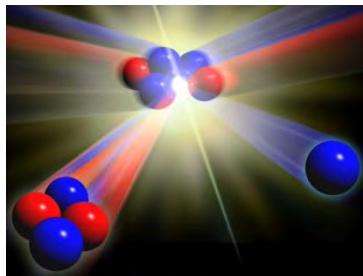
Range data:

Description:

Expérience sur WEST



Long term research in a changing world! (cold war to ITER)

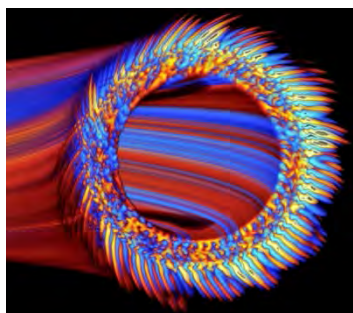
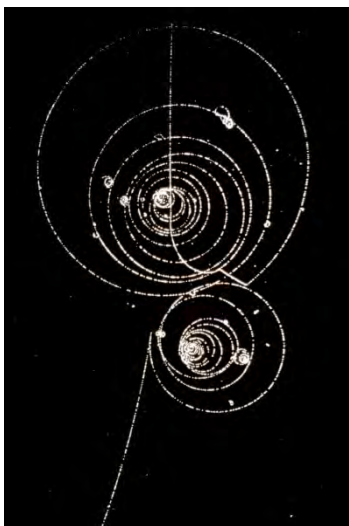


Safe, no waste, inexhaustible...

Complex technology

Tayloring burning plasmas

On the way to material science



Science of complexity

"infinitely normal"

Large scale computing



Big money science

Funding innovation in industry

Stepping Fusion to reactor issues

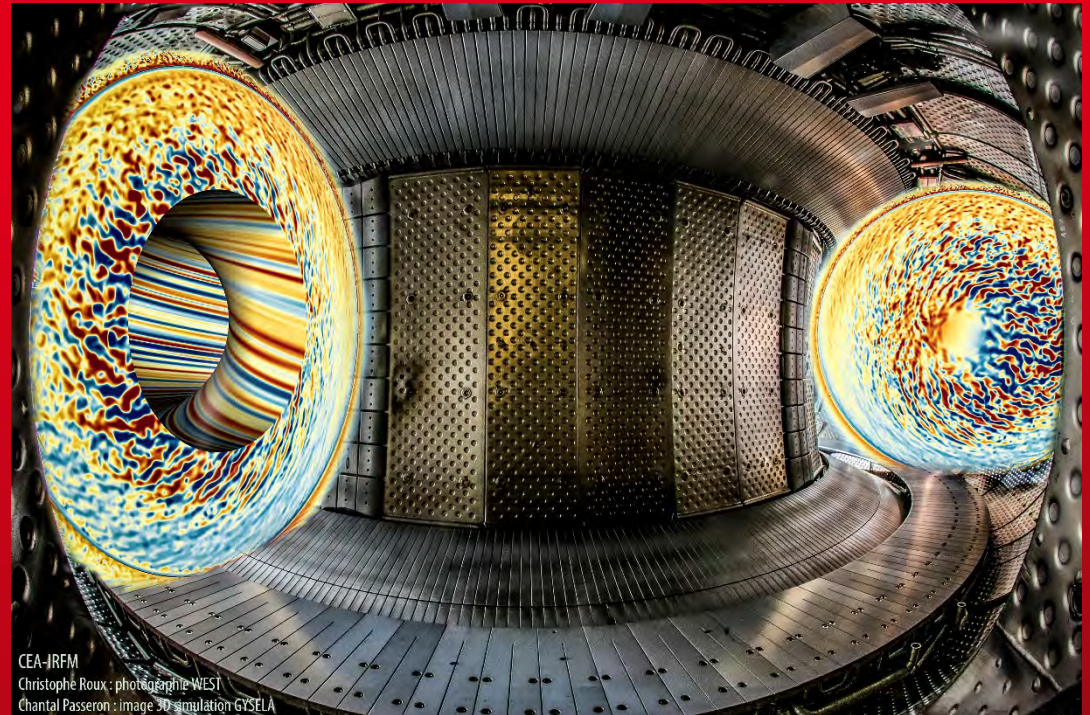
Take away

*Une recherche finalisée
Sur le front de l'énergie
Un rêve pour l'humanité*

*Une collaboration
internationale !
Premier succès d'ITER*

Un prototype aux limites

*Qui va tirer les marrons
du feu ?*



Commissariat à l'énergie atomique et aux énergies alternatives
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