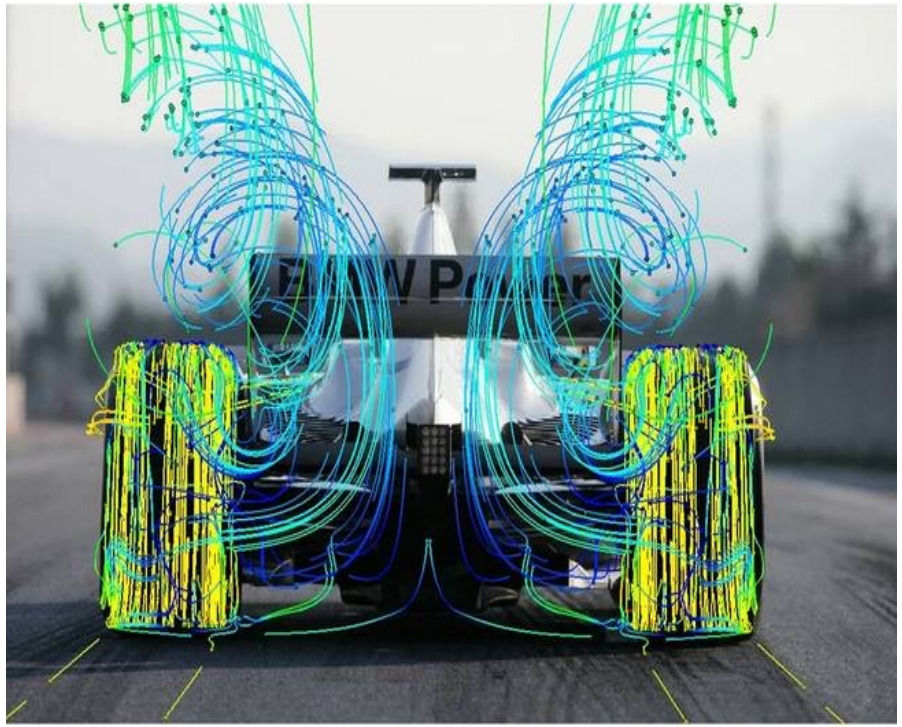
Mystérieuse Turbulence

Bérengère Dubrulle
SPEC
CNRS UMR 3680



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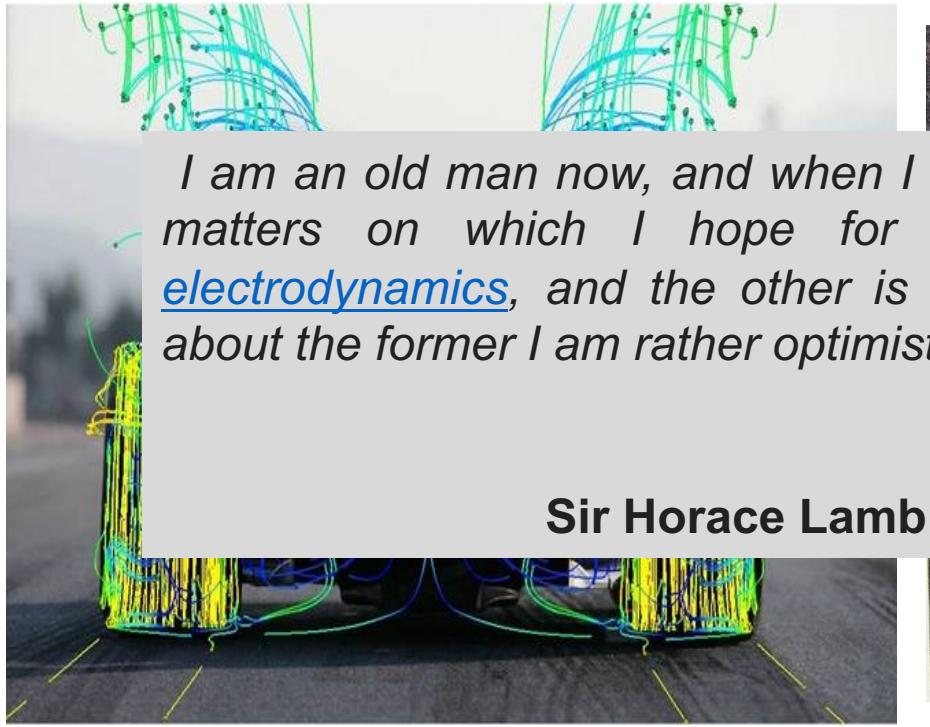
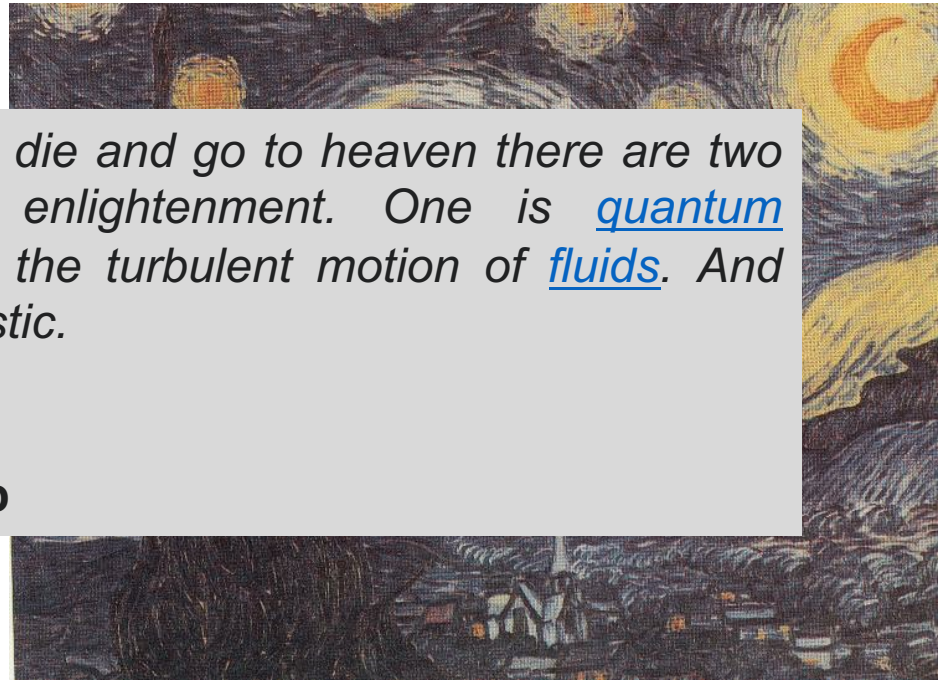
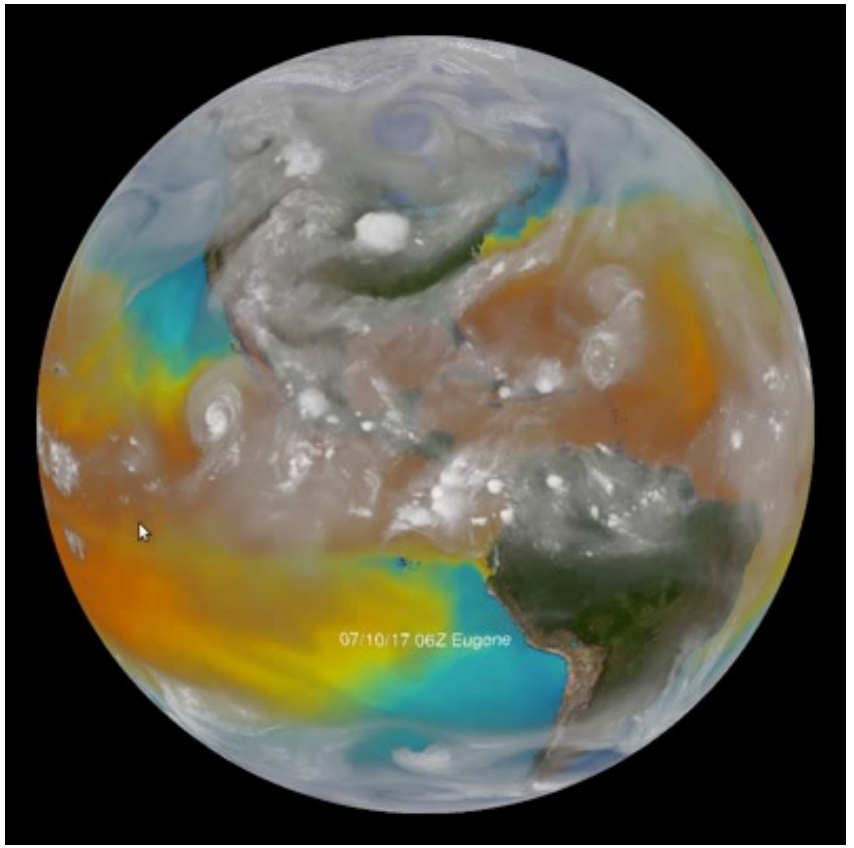




I am an old man now, and when I die and go to heaven there are two matters on which I hope for enlightenment. One is quantum electrodynamics, and the other is the turbulent motion of fluids. And about the former I am rather optimistic.

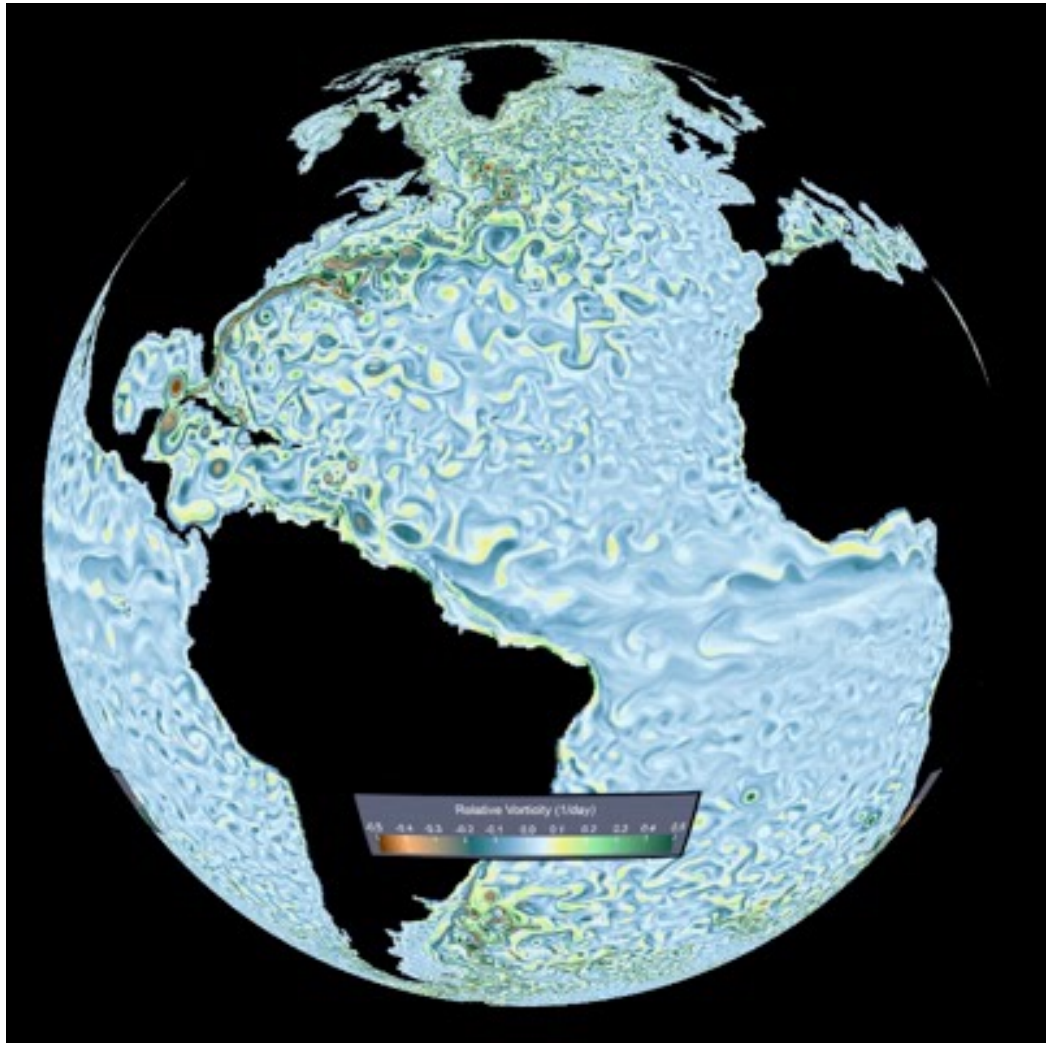
Sir Horace Lamb

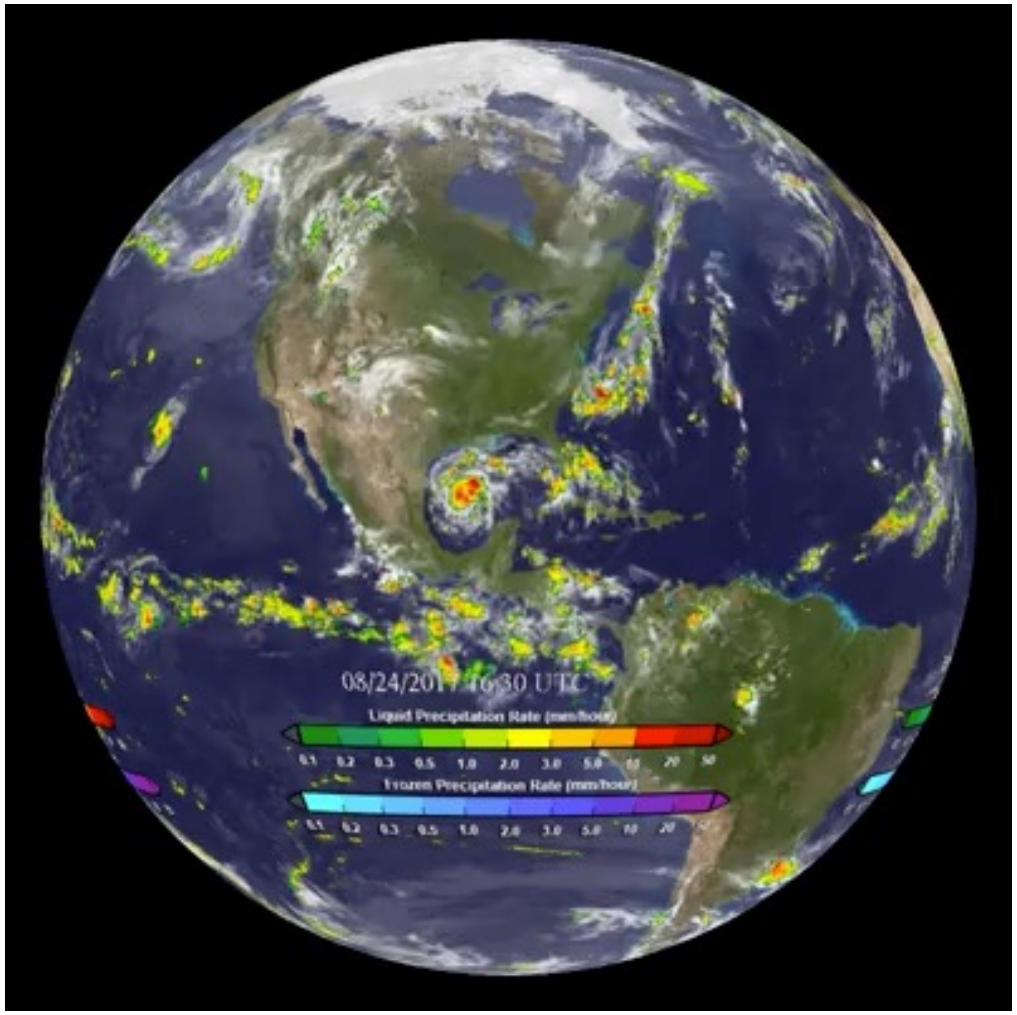
Turbulence….



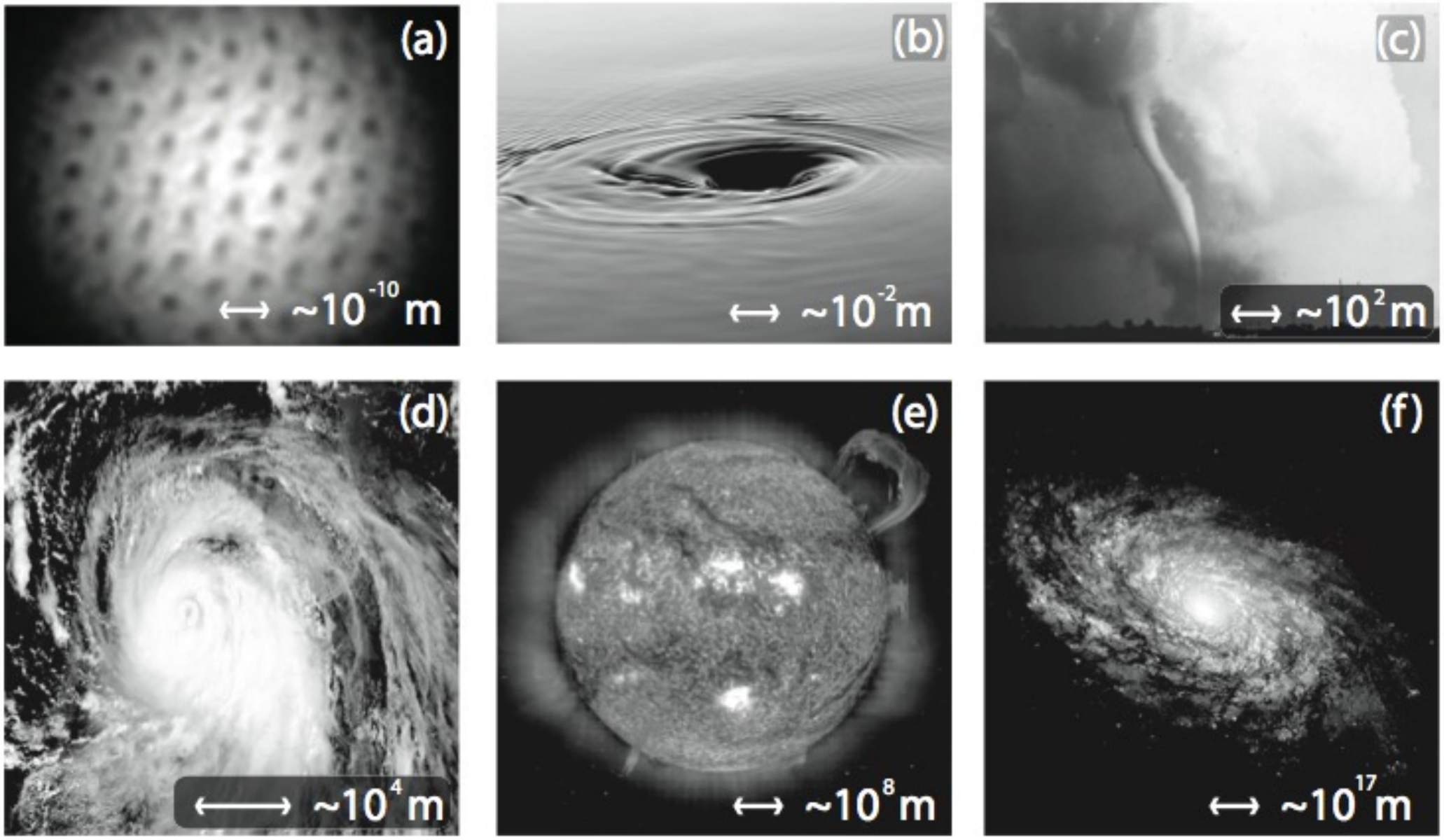
*Définition:La **turbulence** désigne l'état d'un fluide, liquide ou gaz dans laquelle la vitesse présente un caractère désordonné et tourbillonnaire.*

Tourbillons sur la Terre…

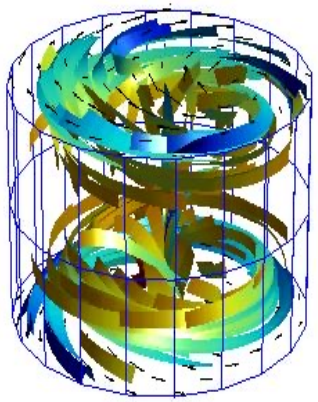




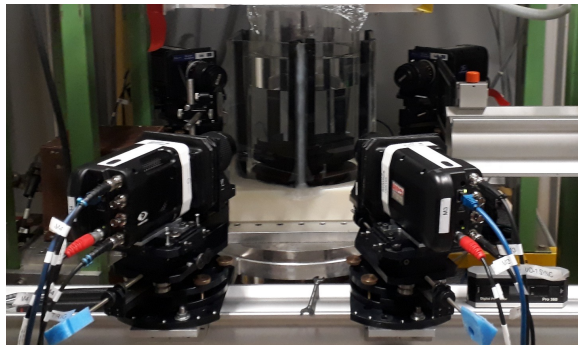
Tourbillons dans l'Univers



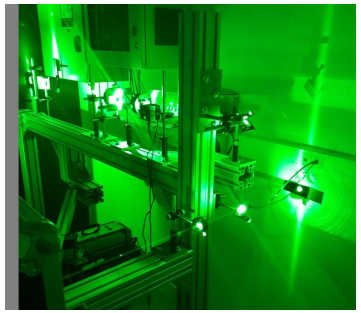
Tourbillons dans le laboratoire



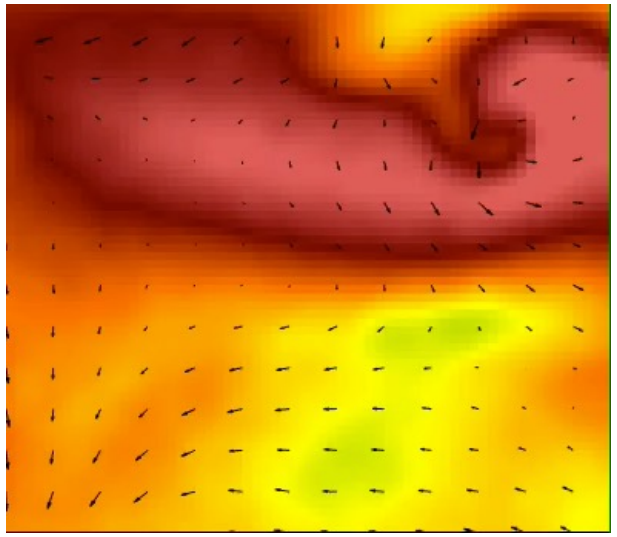
4 Cameras rapides



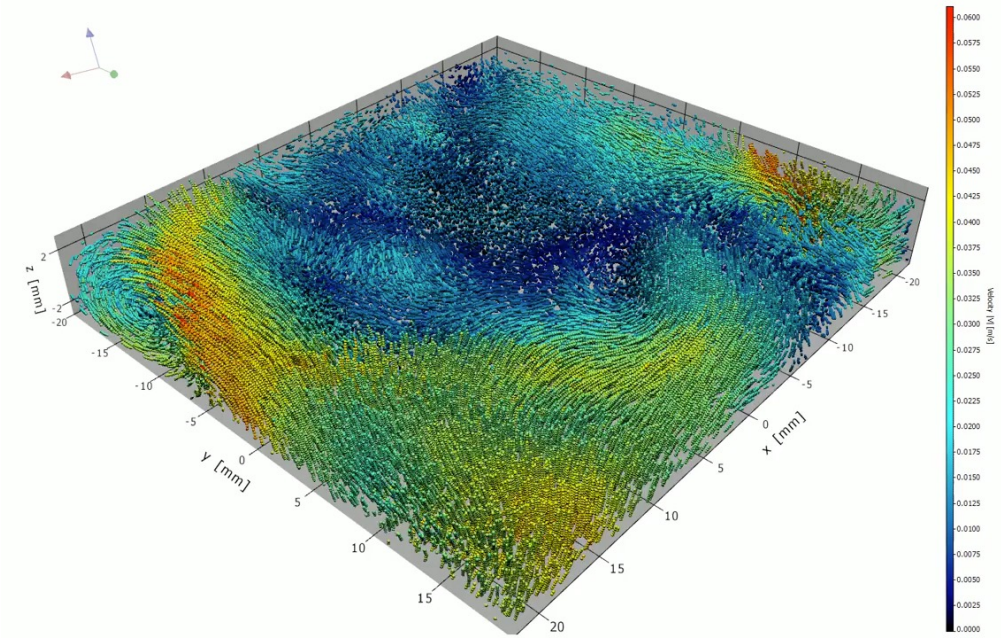
Laser



Mesures SPIV



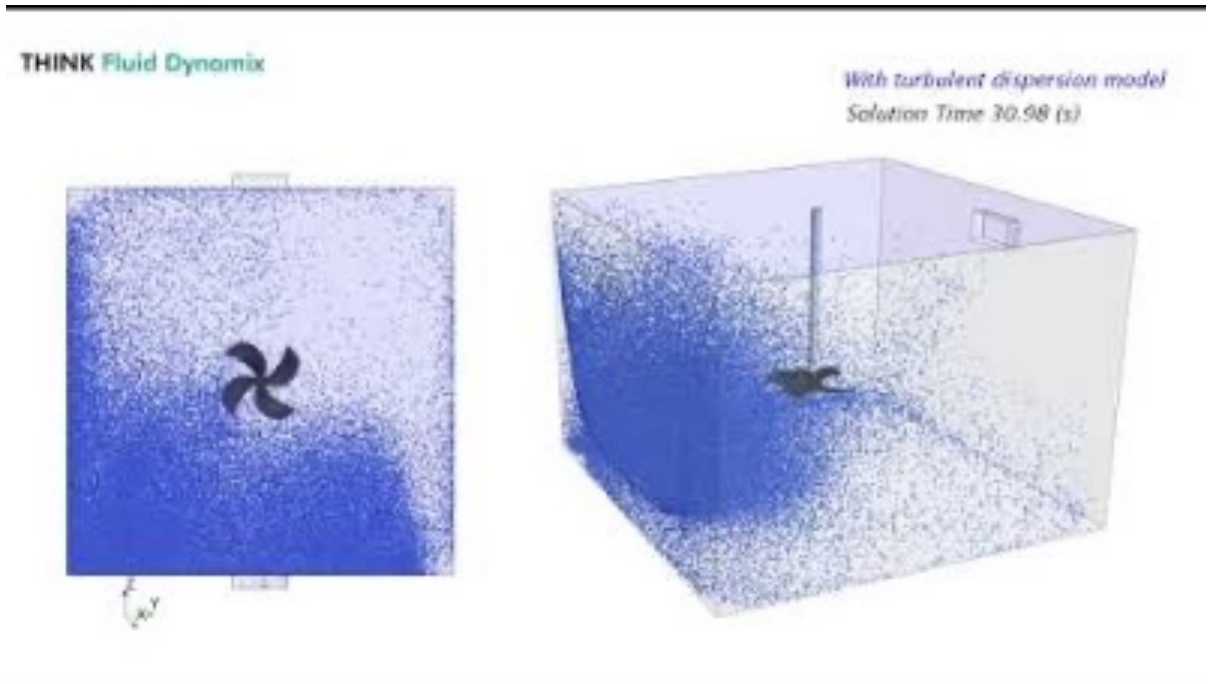
Mesure 4D-PTV

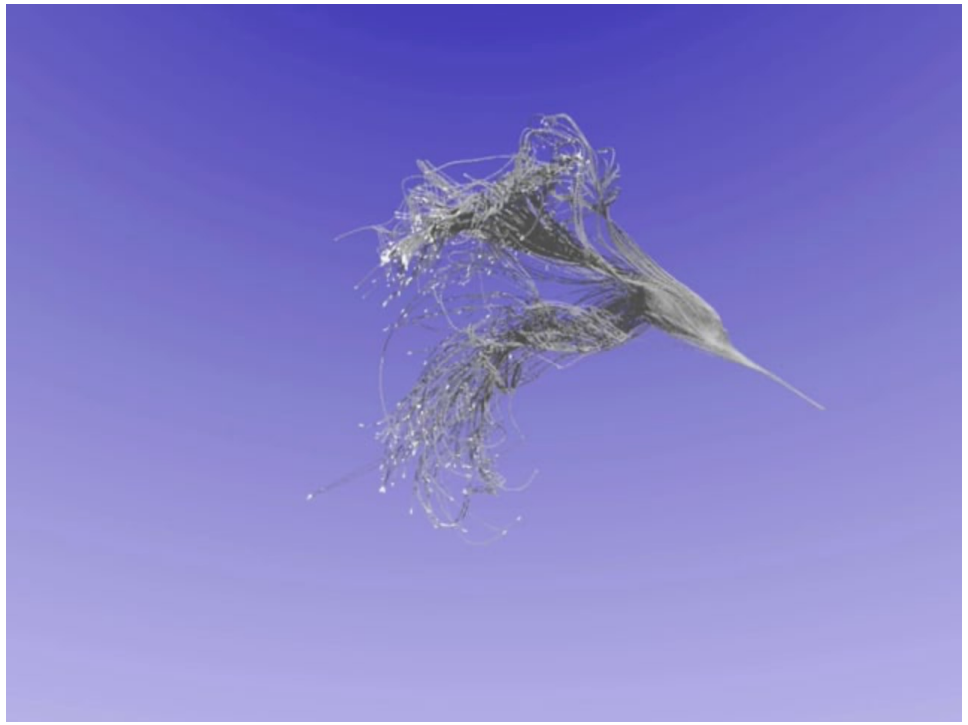


ANR EXPLOIT: F. Daviaud, P. Debue, B. Dubrulle, J-M. Foucault, J-P. Laval, Y. Ostovan, V. Padilla, V. Valori, C. Wiertel

Le Mauvais côté de la turbulence

Le bon coté de la turbulence: Dispersion de particules

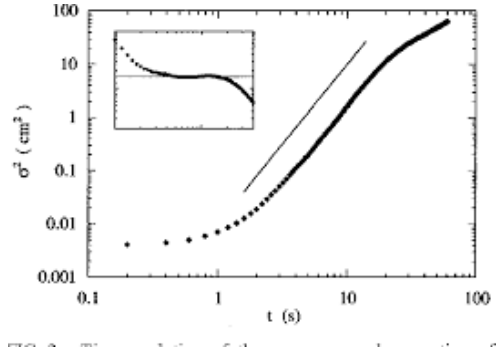




$$< (\Delta x)^2 > (t) \sim < (\Delta x)^2 > (0) e^{\lambda t}$$

Mémoire de la dispersion initiale

Dispersion chaotique

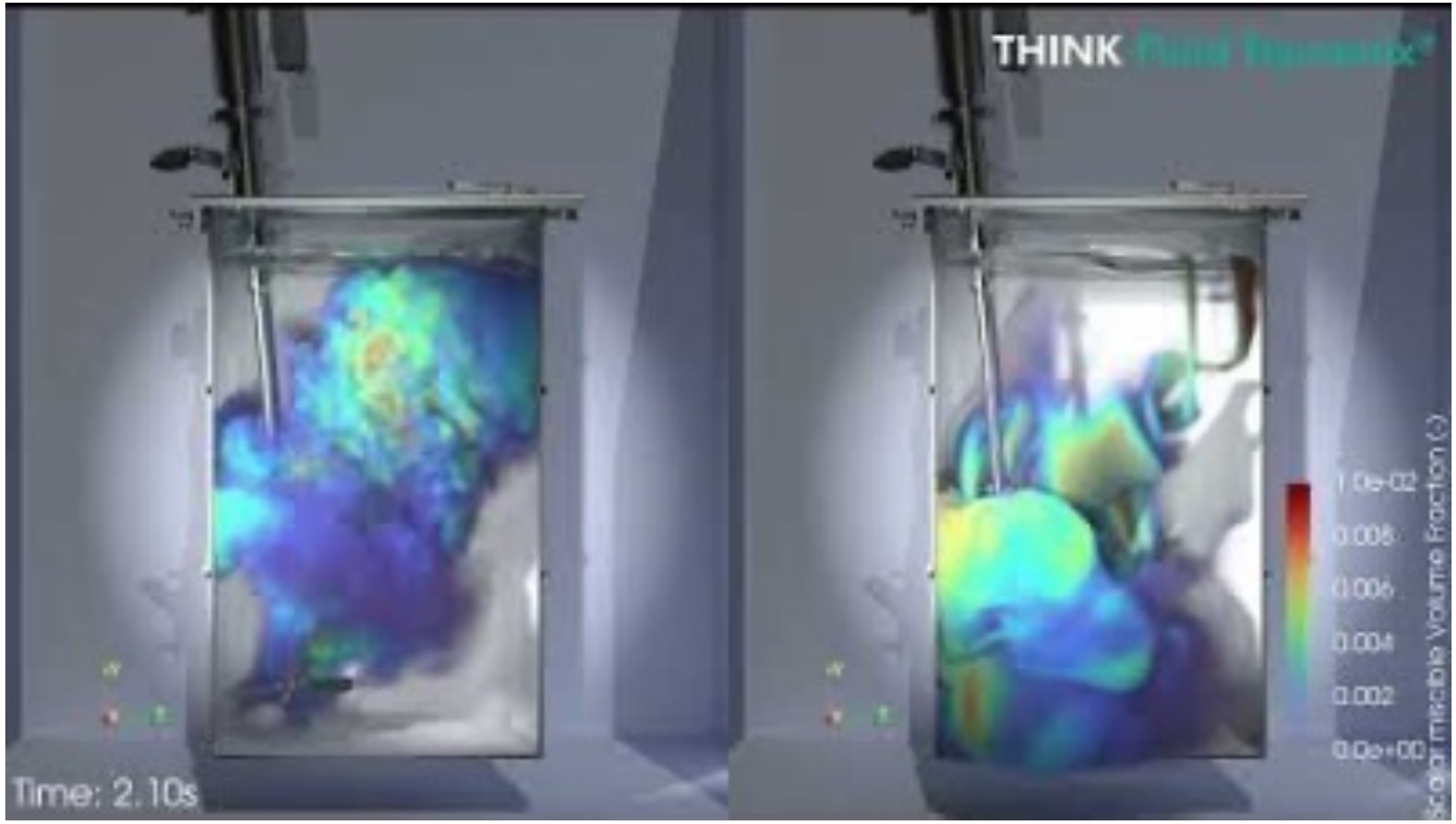


$$< (\Delta x)^2 > (t) \sim \epsilon t^3$$

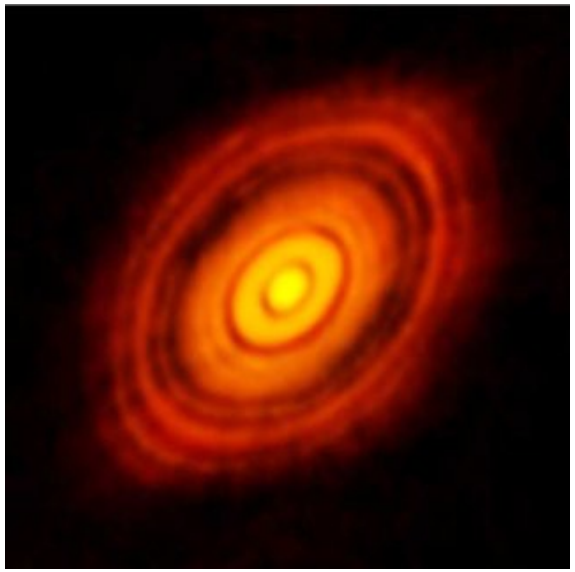
Indépendant de la dispersion initiale

Dispersion turbulente

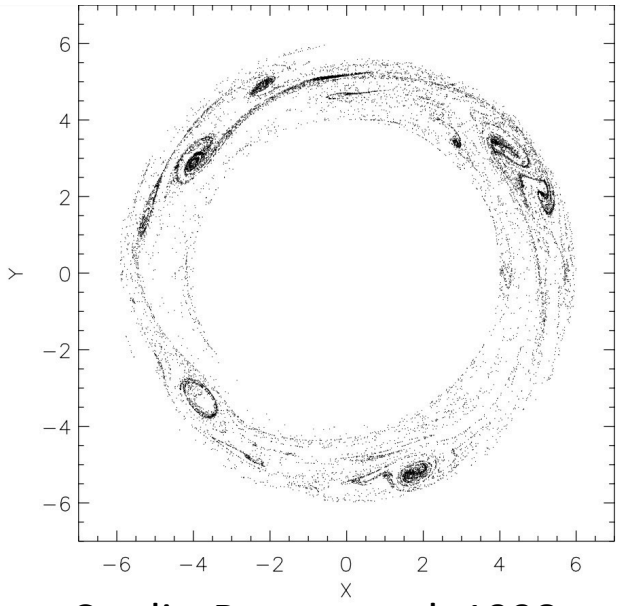
Le bon côté de la turbulence:
Mélange turbulent vs laminaire



Turbulence et formation du système solaire

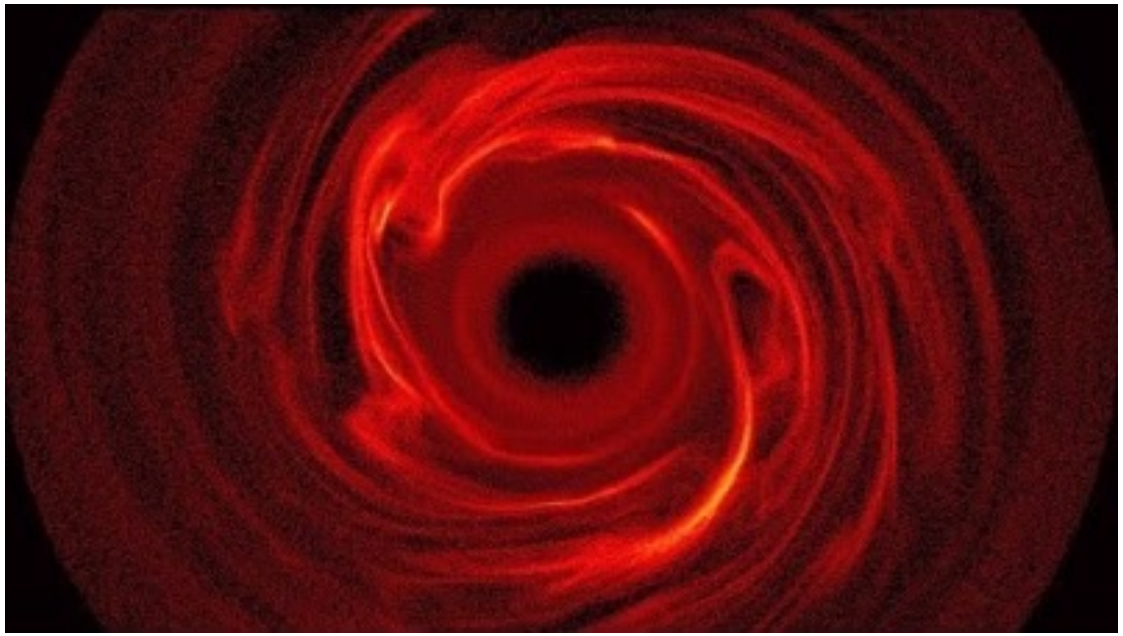


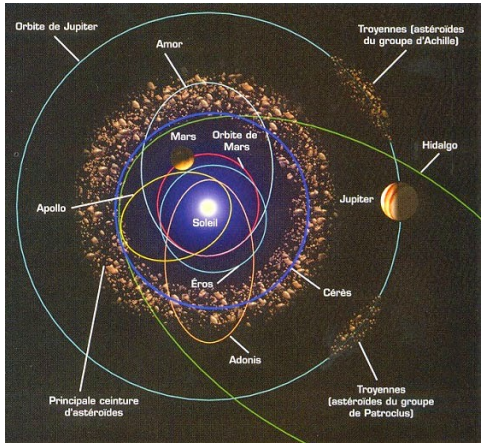
Credit: Alma



Credit: Bracco et al, 1998

Importance de la turbulence pour former les planètes
Importance de la turbulence pour mélanger les éléments





Equations de Navier-Stokes

Dérivées il y a 200 ans par Navier (Ecole des Ponts) et Stokes
À la suite des travaux de Euler

$$\vec{\nabla} \bullet \vec{u} = \vec{0}$$

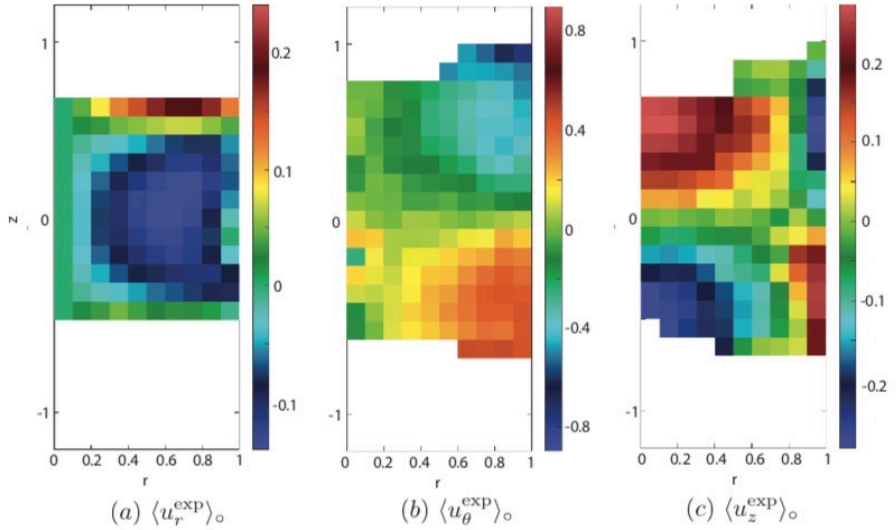
$$\partial_t \vec{u} + (\vec{u} \bullet \vec{\nabla}) \vec{u} = -\frac{1}{\rho} \vec{\nabla} p + \nu \Delta \vec{u}$$

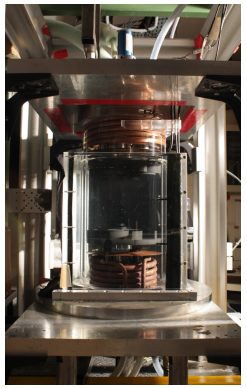
$$\mathrm{Re} = \frac{(u \nabla u)}{\nu \Delta u} = \frac{LU}{\nu}$$

Turbulence: Re>>1

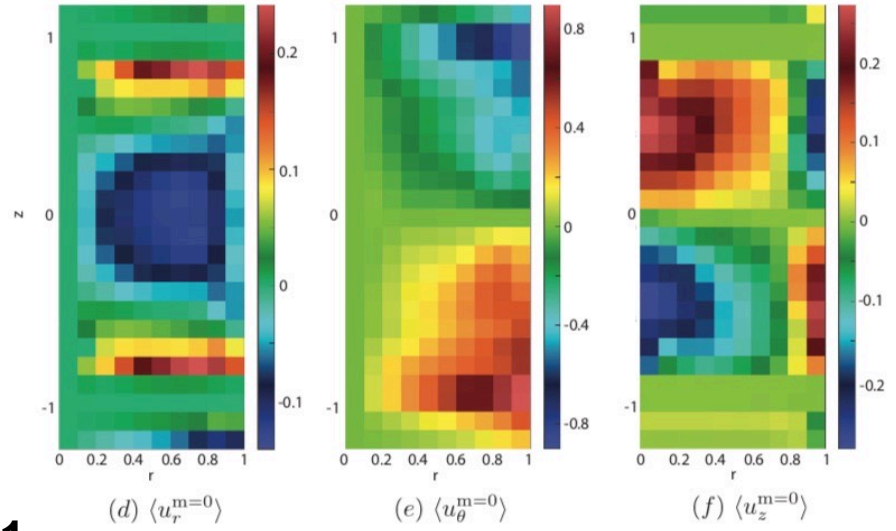
Modèle vs Mesures: vitesse moyenne à $Re=10^3$

Lab





DNS

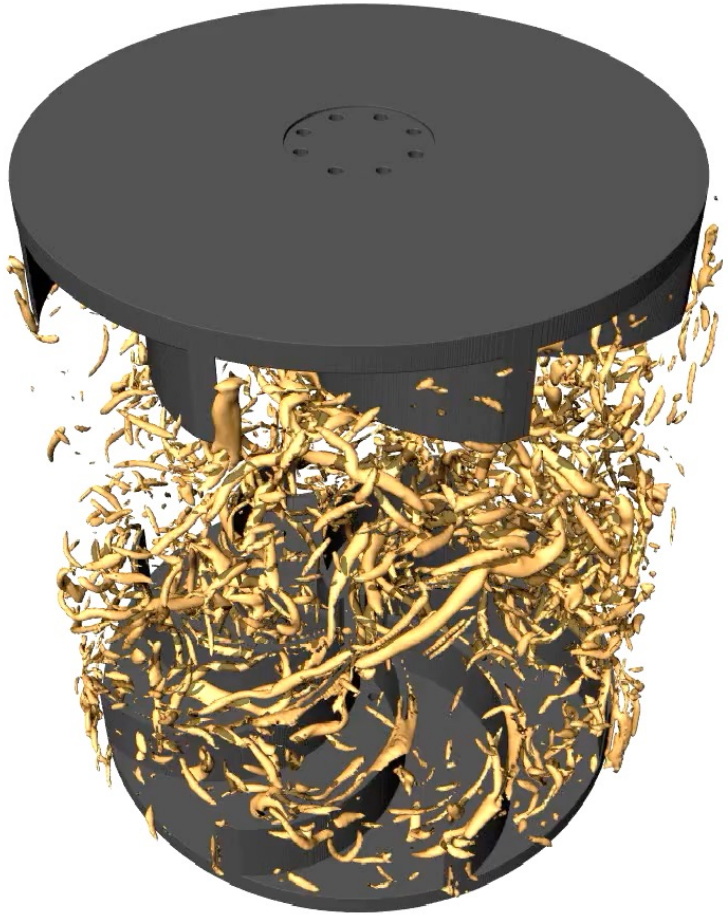


$$\vec{\nabla} \bullet \vec{u} = \vec{0}$$

$$\partial_t \vec{u} + (\vec{u} \bullet \vec{\nabla})\vec{u} = -\frac{1}{\rho}\vec{\nabla} p + \nu \Delta \vec{u}$$

Cappanera et al, 2021

Simulations numériques : tourbillons à $Re=10^3$



Avec les simulations, nous
Pouvons voir des choses difficilement accessibles
aux expériences….

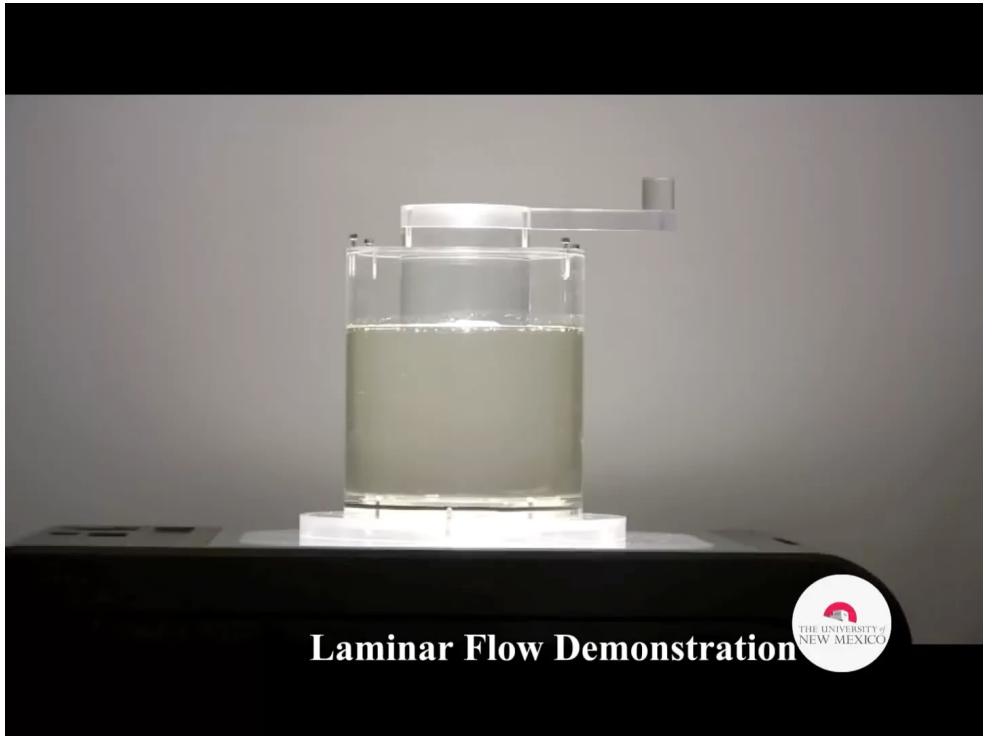
Courtesy H. Faller and A. Harikrishnan

On a les equations… tout est résolu?

Mystère : réversibilité

Ecoulement laminaire

Reversible



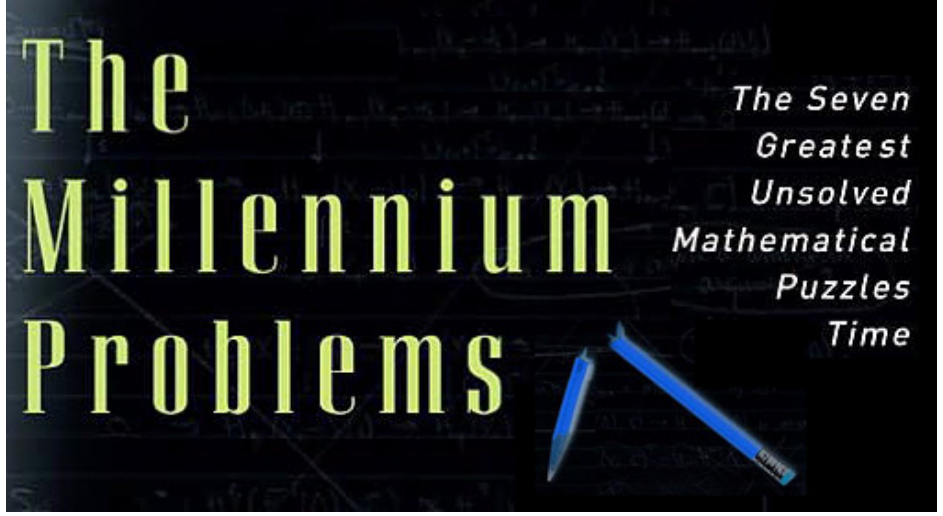
Ecoulement turbulent

Irreversible

D ou vient l'irreversibilité de la turbulence?

Quel est le problème avec la turbulence?

Navier-Stokes et Problème mathématique



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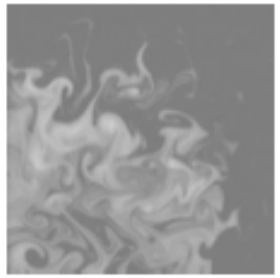
Navier-Stokes Equation

Waves follow our boat as we meander across the lake, and turbulent air currents follow our flight in a modern jet. Mathematicians and physicists believe that an explanation for and the prediction of both the breeze and the turbulence can be found through an understanding of solutions to the Navier-Stokes equations. Although these equations were written down in the 19th Century, our understanding of them remains minimal. The challenge is to make substantial progress toward a mathematical theory which will unlock the secrets hidden in the Navier-Stokes equations.

The Millennium Problems

Official Problem Description — Charles Fefferman

Lecture by Luis Caffarelli (video)



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Theorie:

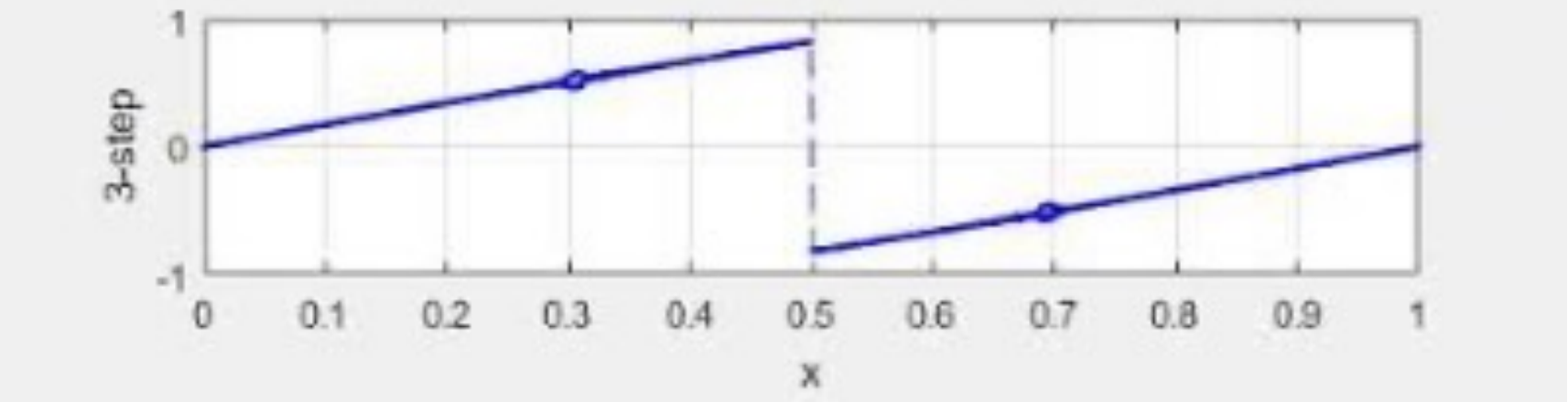
Les equations De Navier-Stokes sont-elles bien posées?
(y a t il des singularites?)

Example de formation de singularité

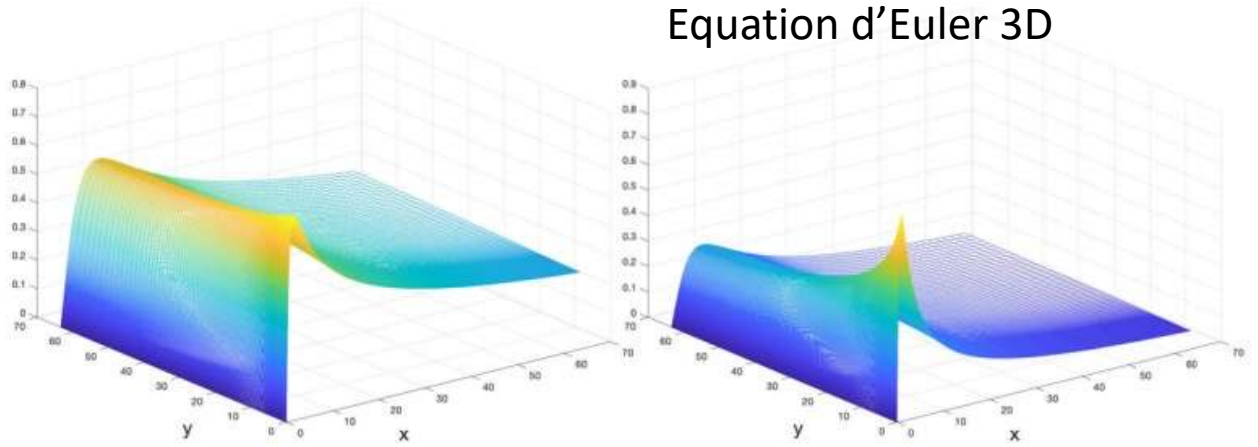
Equation de Burgers 1D

Burgers: $\partial_t \mathrm{u} + u\partial u = \nu \Delta u$

Discontinuité de la vitesse



Equation d'Euler 3D

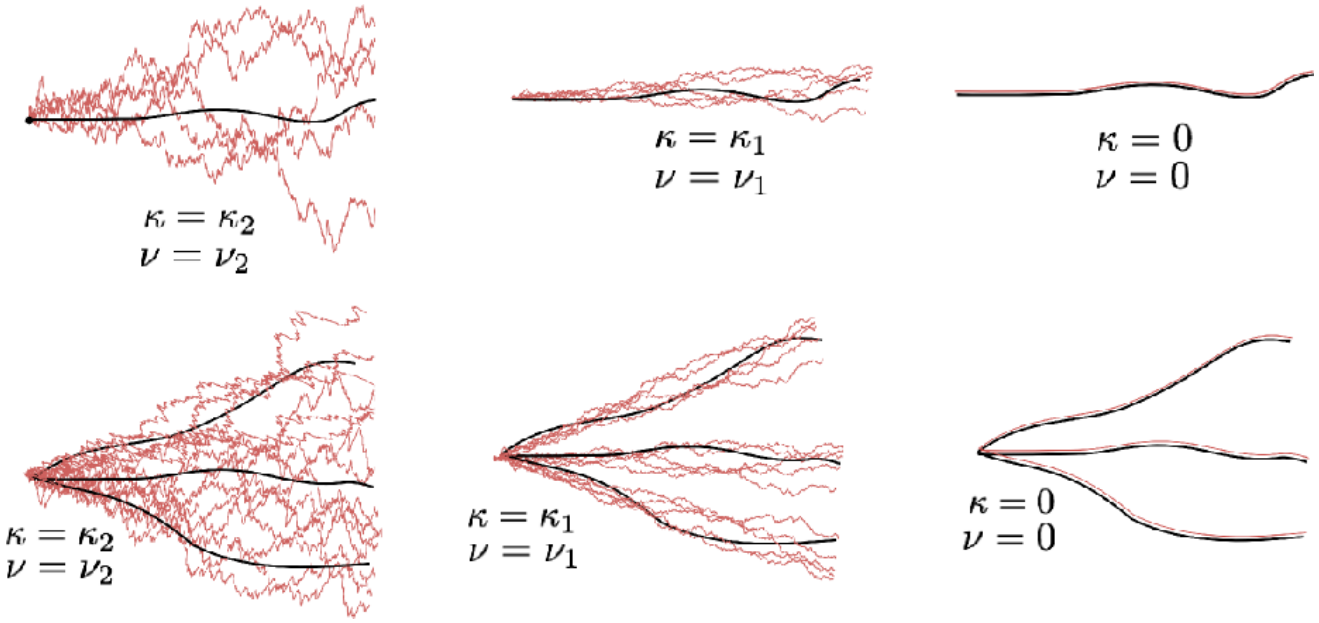


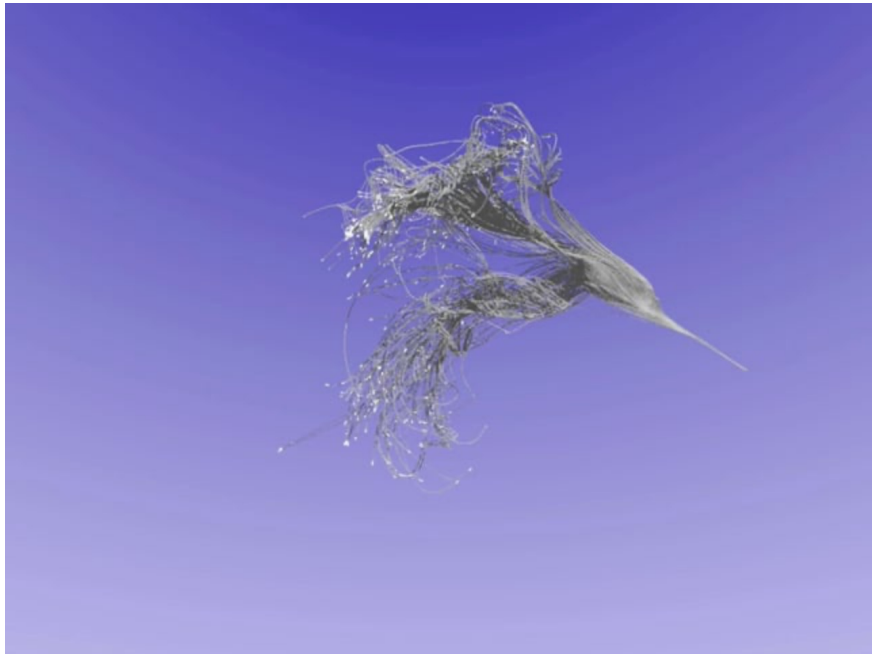
Euler: $\partial_t \mathrm{u} + u\partial u = -\partial p$

Divergence de la dérivée de la vorticité

Problèmes induits par les singularités

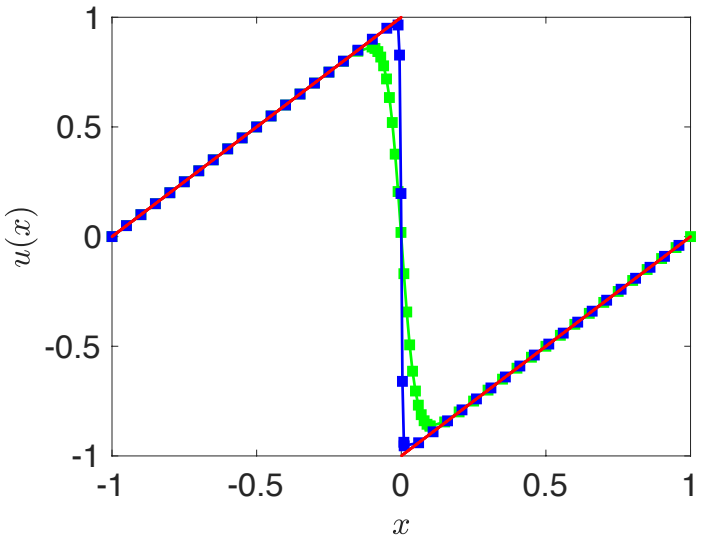
- Elles peuvent briser l'unicité de la solution et induire de la stochasticite spontanée



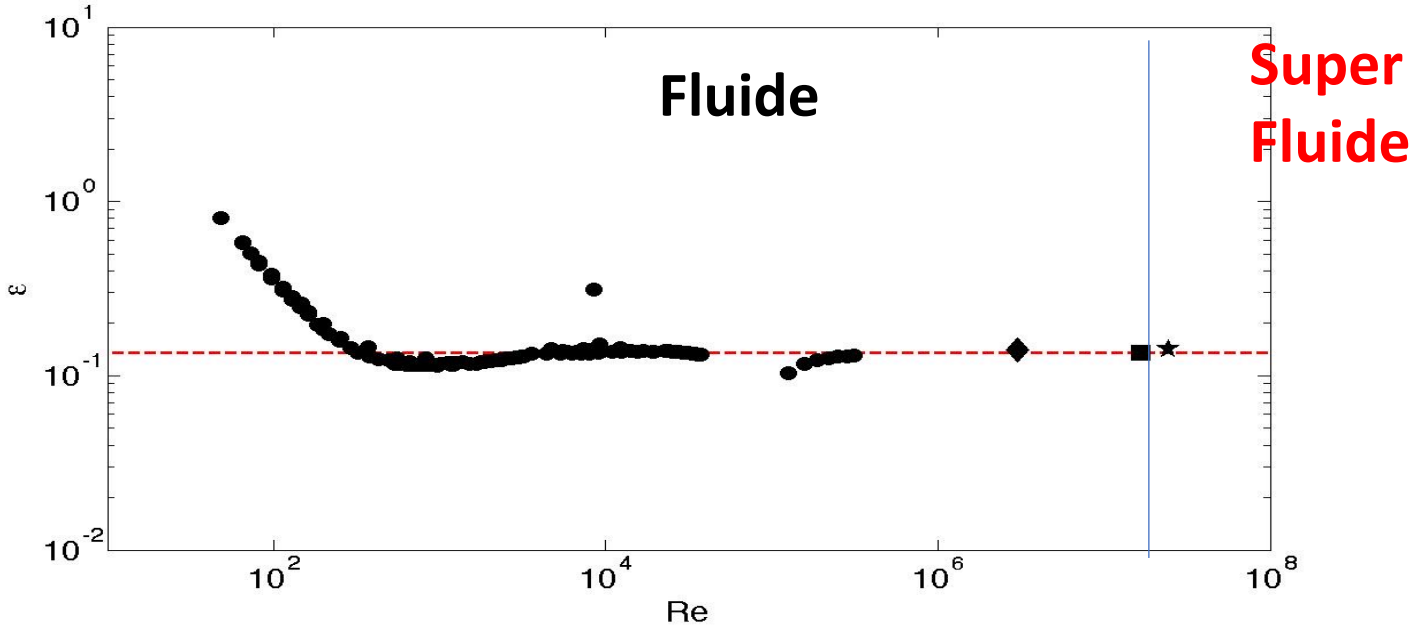


Problèmes induits par les singularités

- Elles provoquent une dissipation et induisent une irréversibilté spontanée



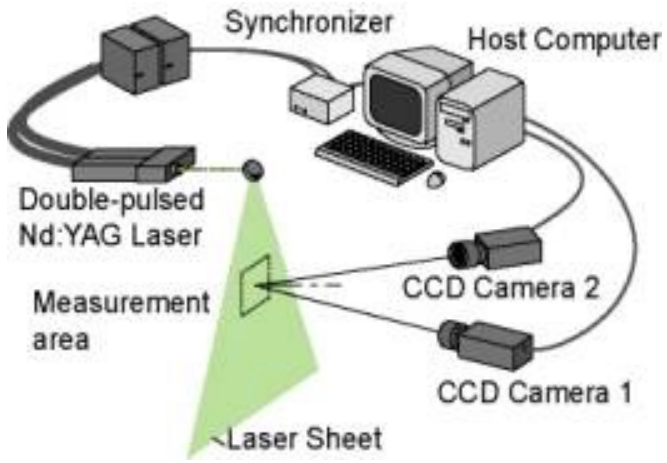
$$D(u) = (\Delta u)^3/12L$$

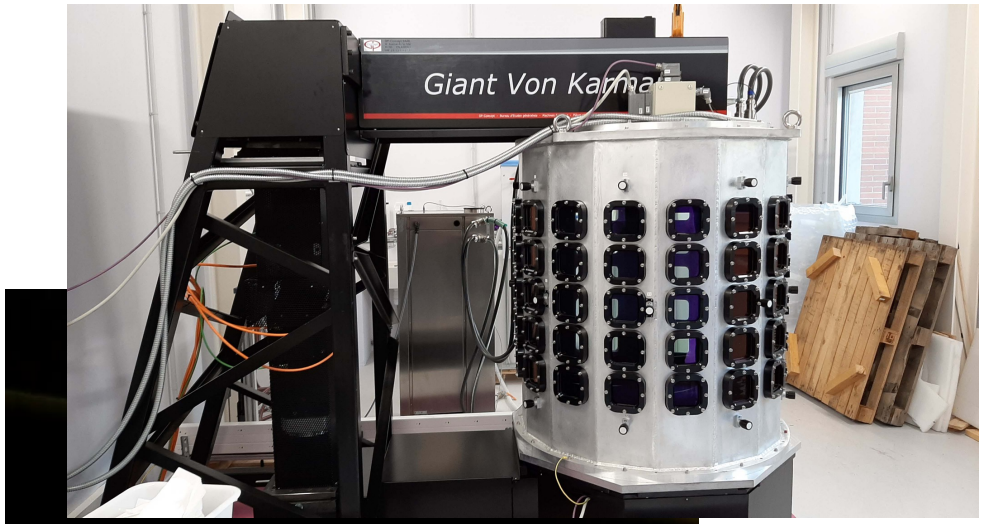


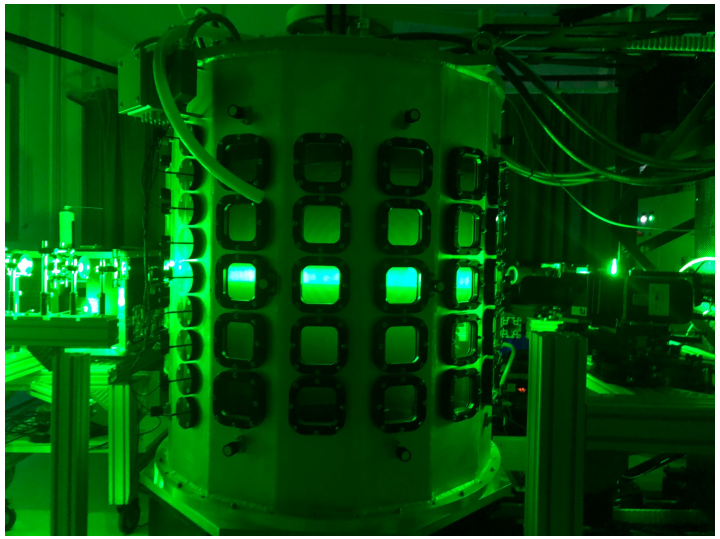
"...in three dimensions a mechanism for complete dissipation of all kinetic energy, even without the aid of viscosity, is available."

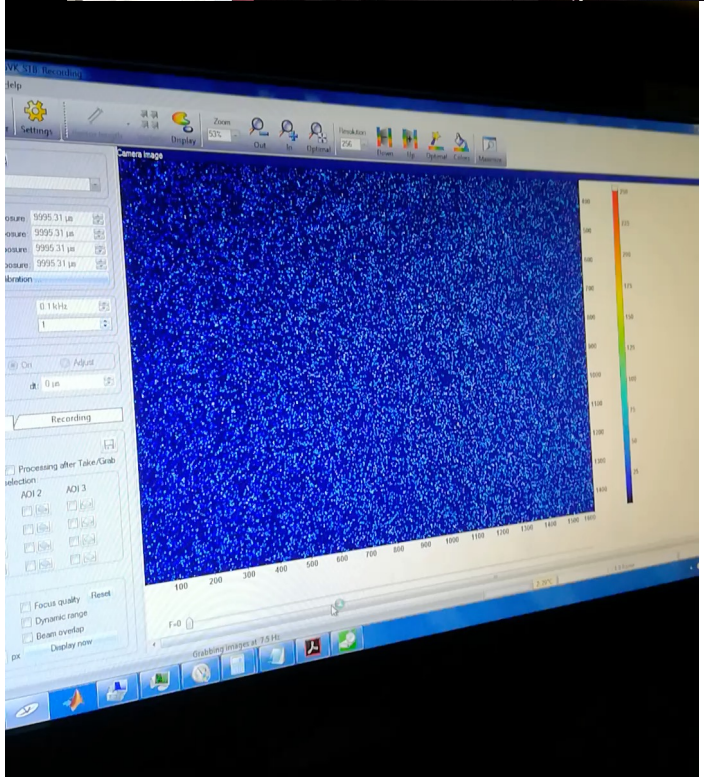
L. Onsager, 1949

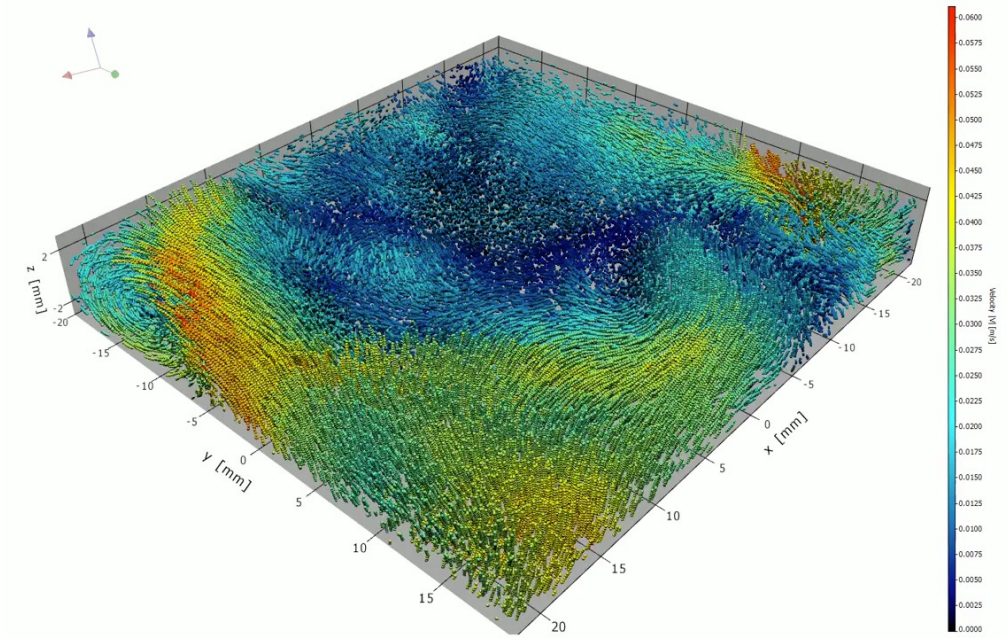
A la recherche des empreintes de singularités…











Saw et al. (2016), Nature-Comm. 7
Cheminet et al, PRL 2022

Quel est le problème avec la turbulence?

Navier-Stokes et Problème pratique

Equations de Navier-Stokes

Peut-on simuler tous les écoulements avec Navier-Stokes?

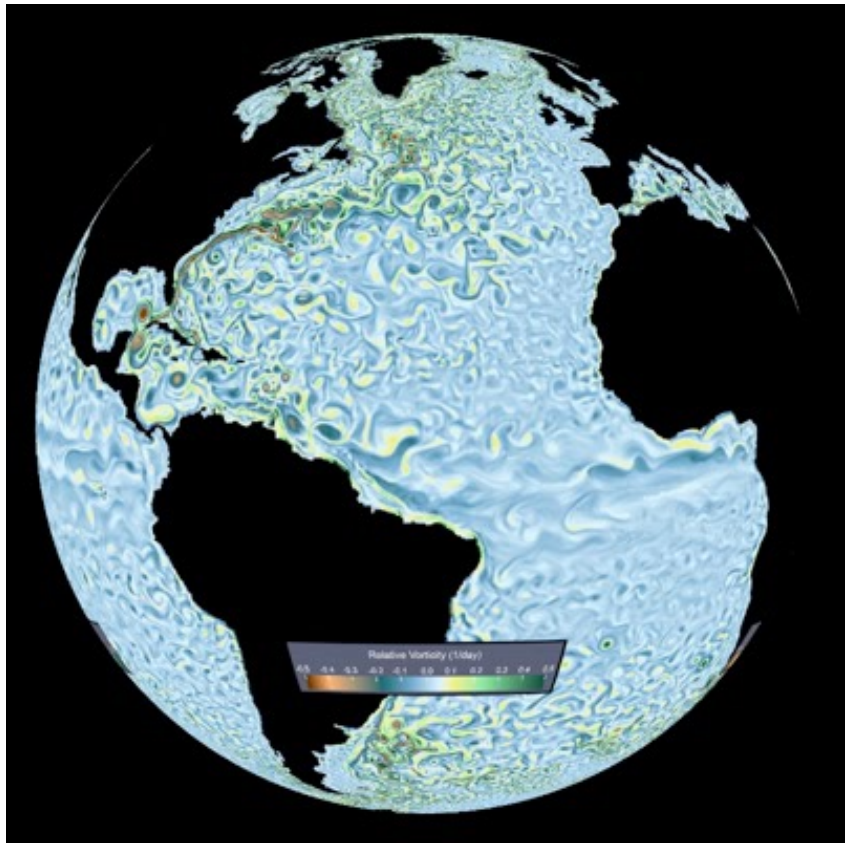
$$\vec{\nabla} \bullet \vec{u} = 0$$

$$\partial_t \vec{u} + (\vec{u} \bullet \vec{\nabla}) \vec{u} = -\frac{1}{\rho} \vec{\nabla} p + \nu \Delta \vec{u}$$

$$\mathrm{Re} = \frac{(u \nabla u)}{\nu \Delta u} = \frac{LU}{\nu}$$

Turbulence: Re>>1

Tourbillons sur la Terre…



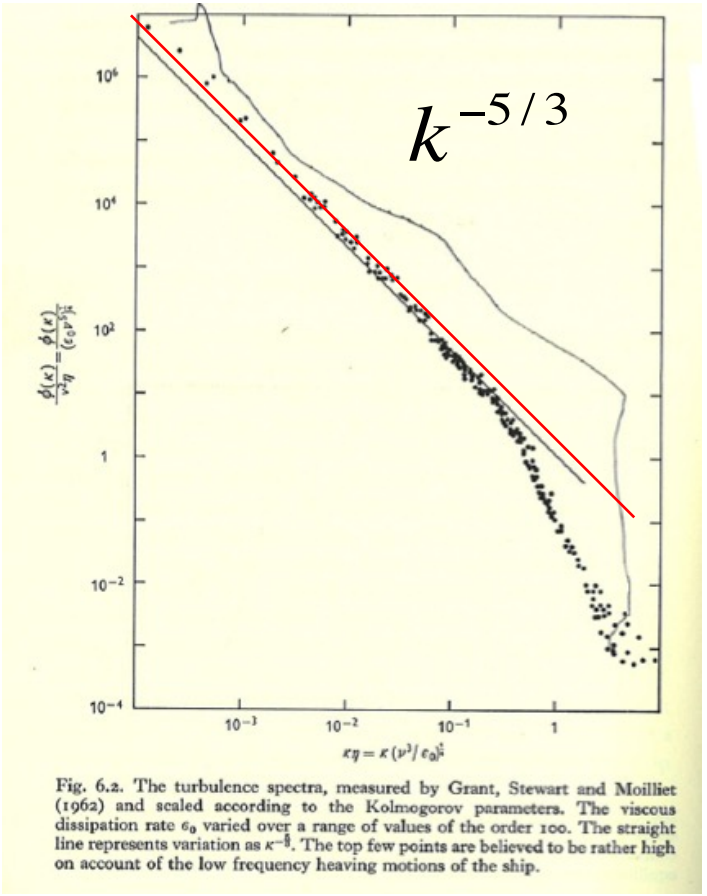
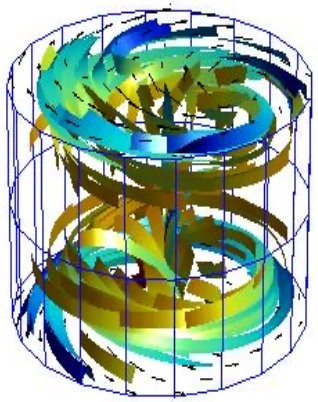


Fig. 6.2. The turbulence spectra, measured by Grant, Stewart and Moilliet (1962) and scaled according to the Kolmogorov parameters. The viscous dissipation rate ϵ_0 varied over a range of values of the order 100. The straight line represents variation as $\kappa^{-\frac{5}{3}}$. The top few points are believed to be rather high on account of the low frequency heaving motions of the ship.

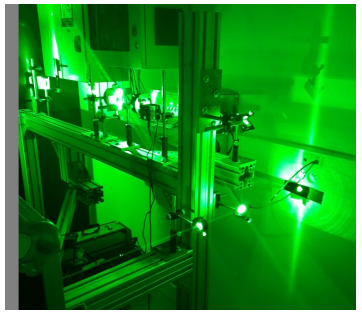
Spectre de Kolmogorov

Mesures:Tourbillons dans le laboratoire

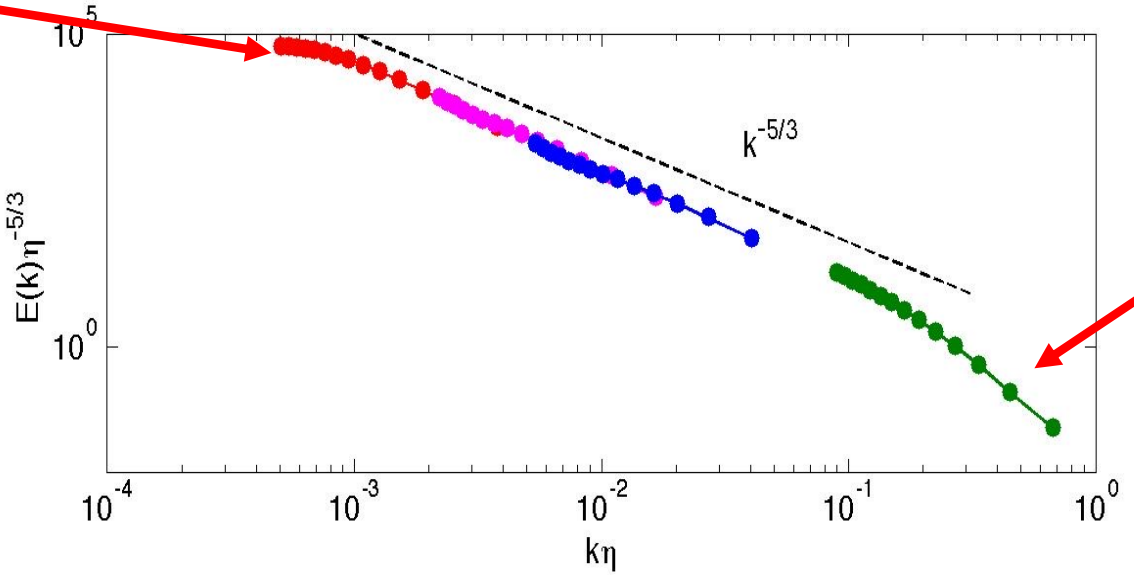


4 Cameras rapides

Laser



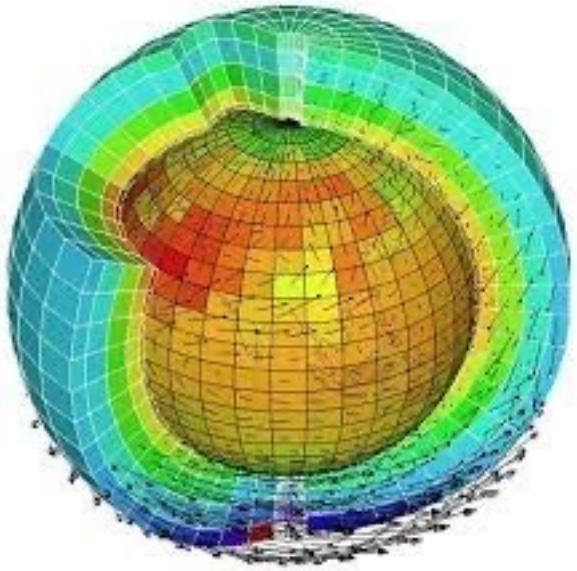
L=Taille du forçage

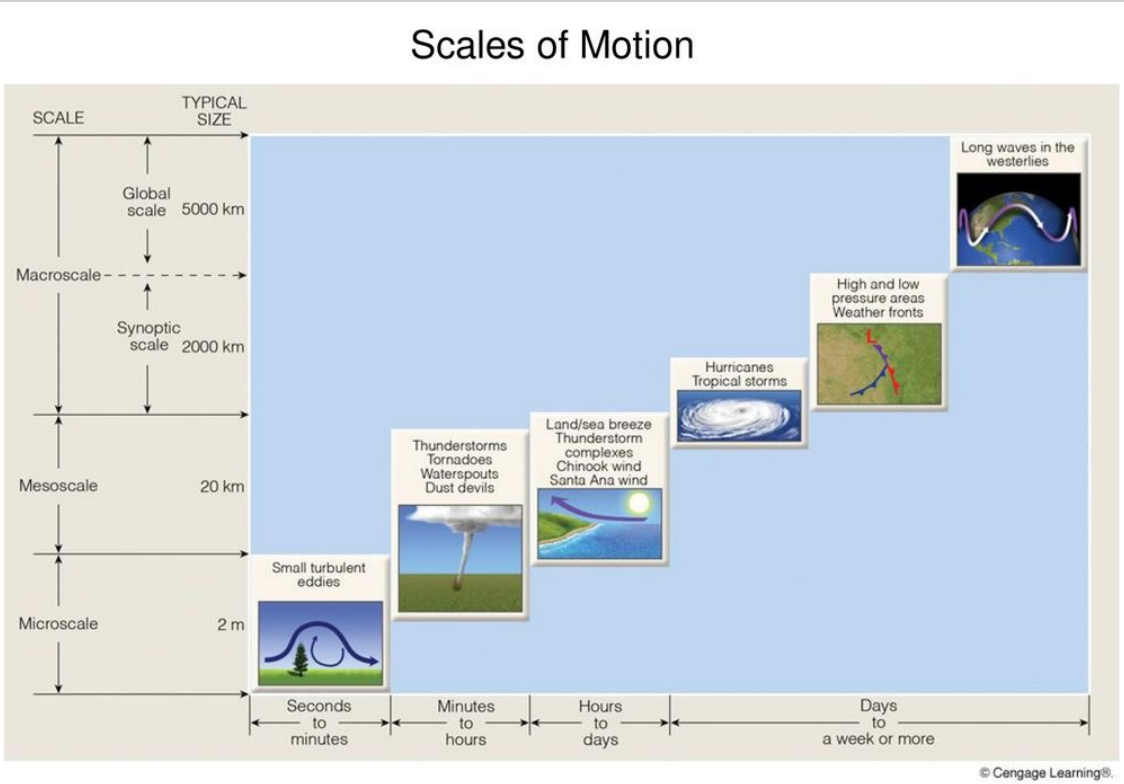


$$\eta \sim \nu^{3/4}$$

Echelle de Kolmogorov

Le problème pratique en turbulence





(pp. 230-231)

Ordres de grandeurs

$L=10^3$ km

η= 1 mm

$(L/\eta)^3=10^{27}$ /pas de temps

1990: 10^8
2023: 10^{13}

Simulations

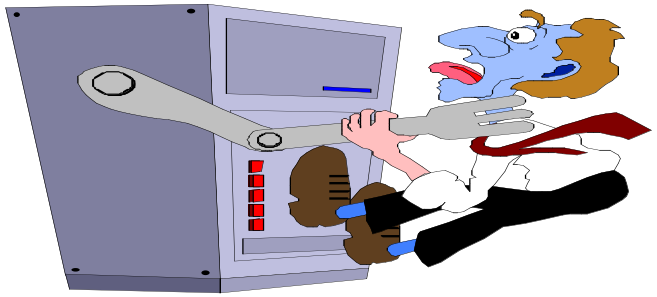
Nombre de points de maille requis $(L/\eta)^3$

Temps de simulation et énergie

Etat de l'art pour $(L/\eta)^3=10^9$

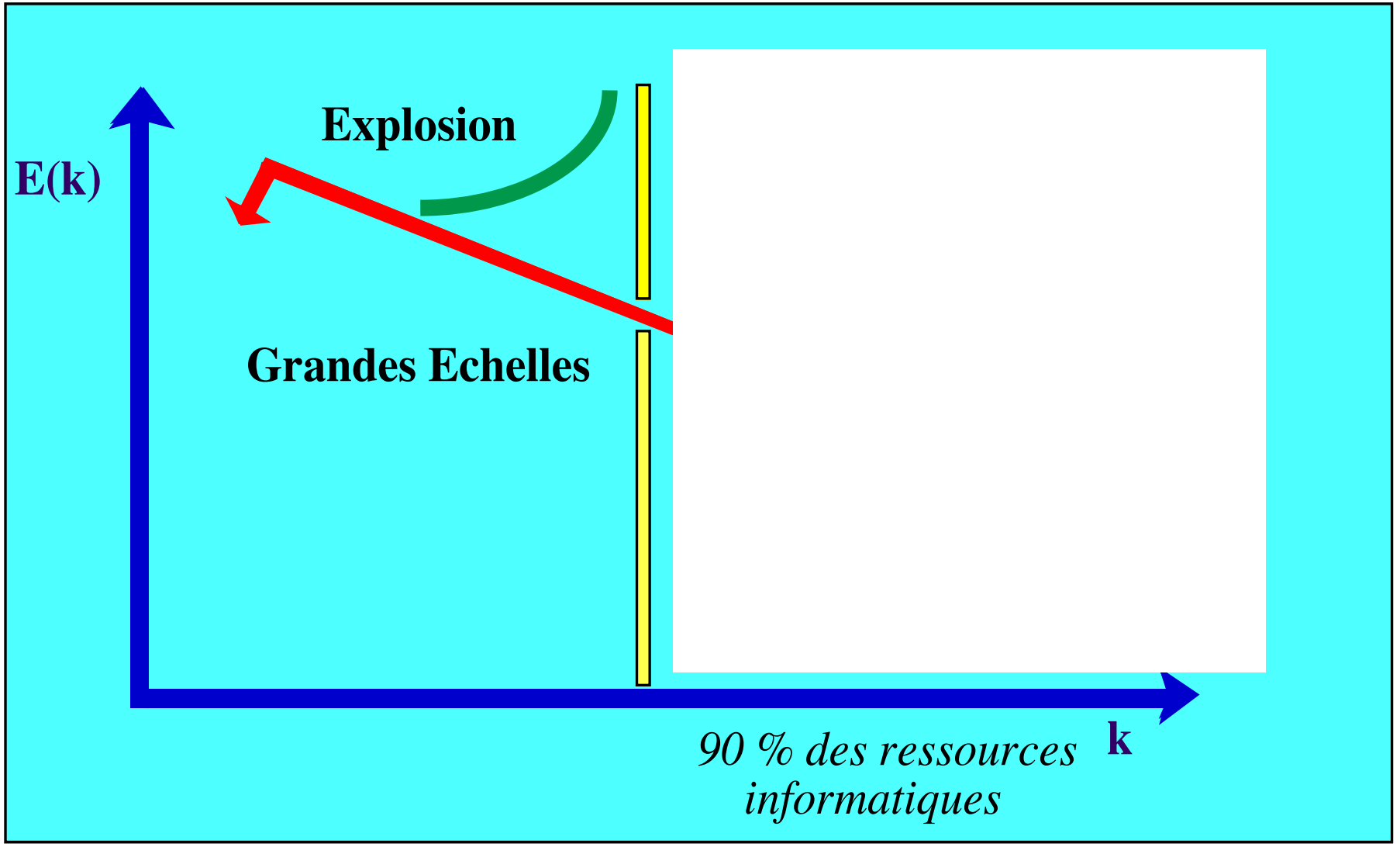
Pour 1 simu resolution 1 km , pendant 100 ans

T_simu=6 ans; P= 60 GWh sur top super-computer avec 4888 GPU

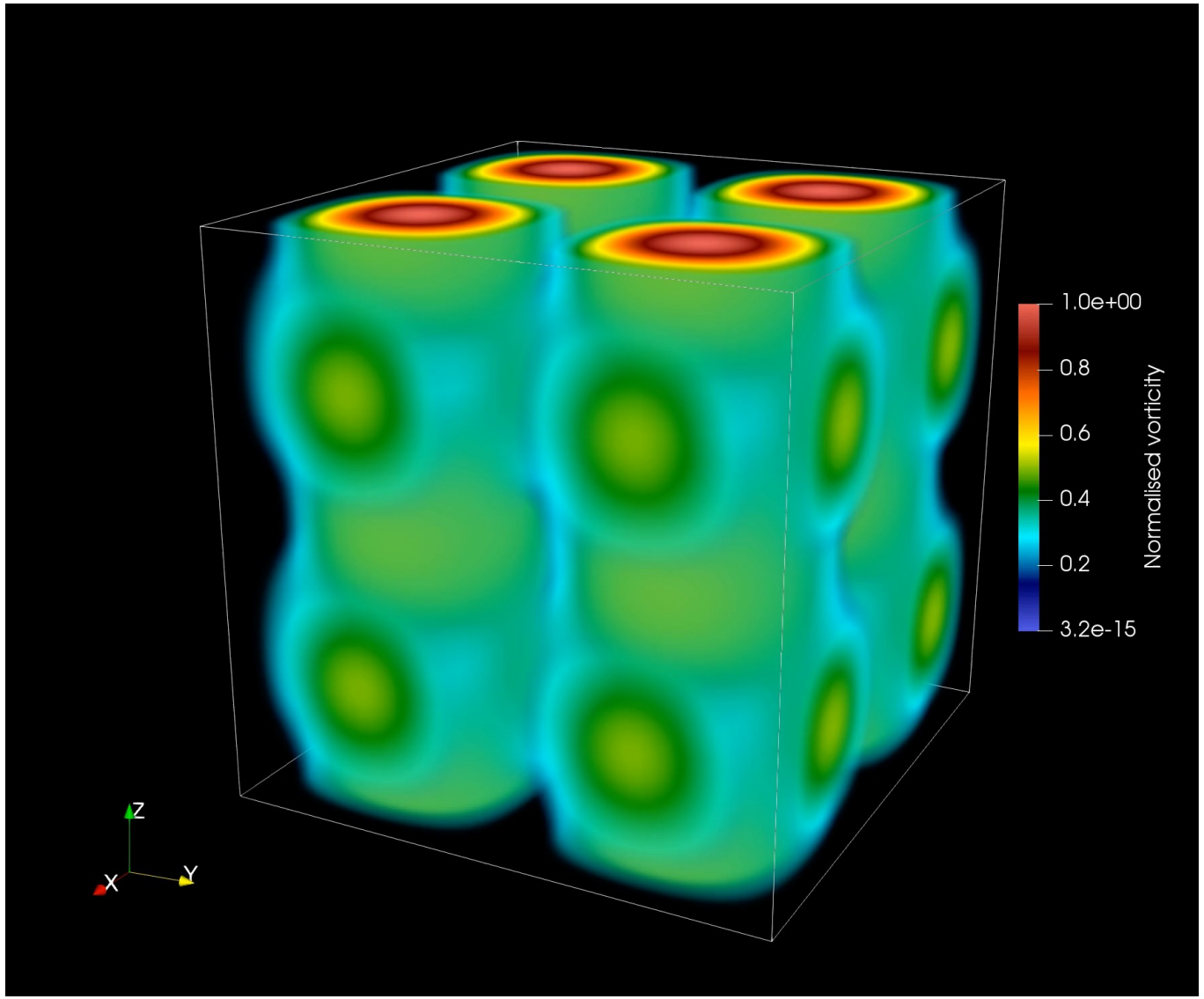


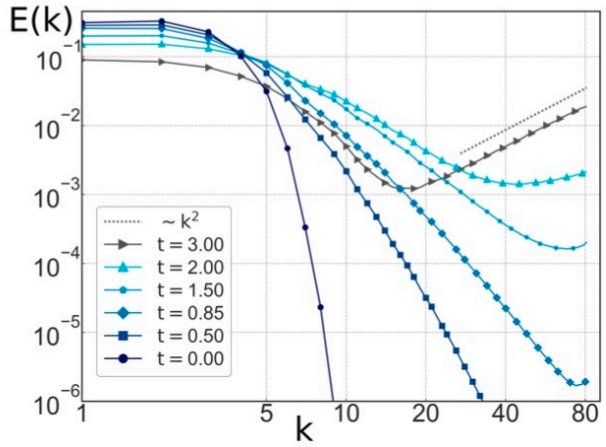
Simuler les effets induits par le changement climatique contribuerait au changement climatique!!

Que peut on faire? Tronquer?



Ce que la troncation simple provoque….



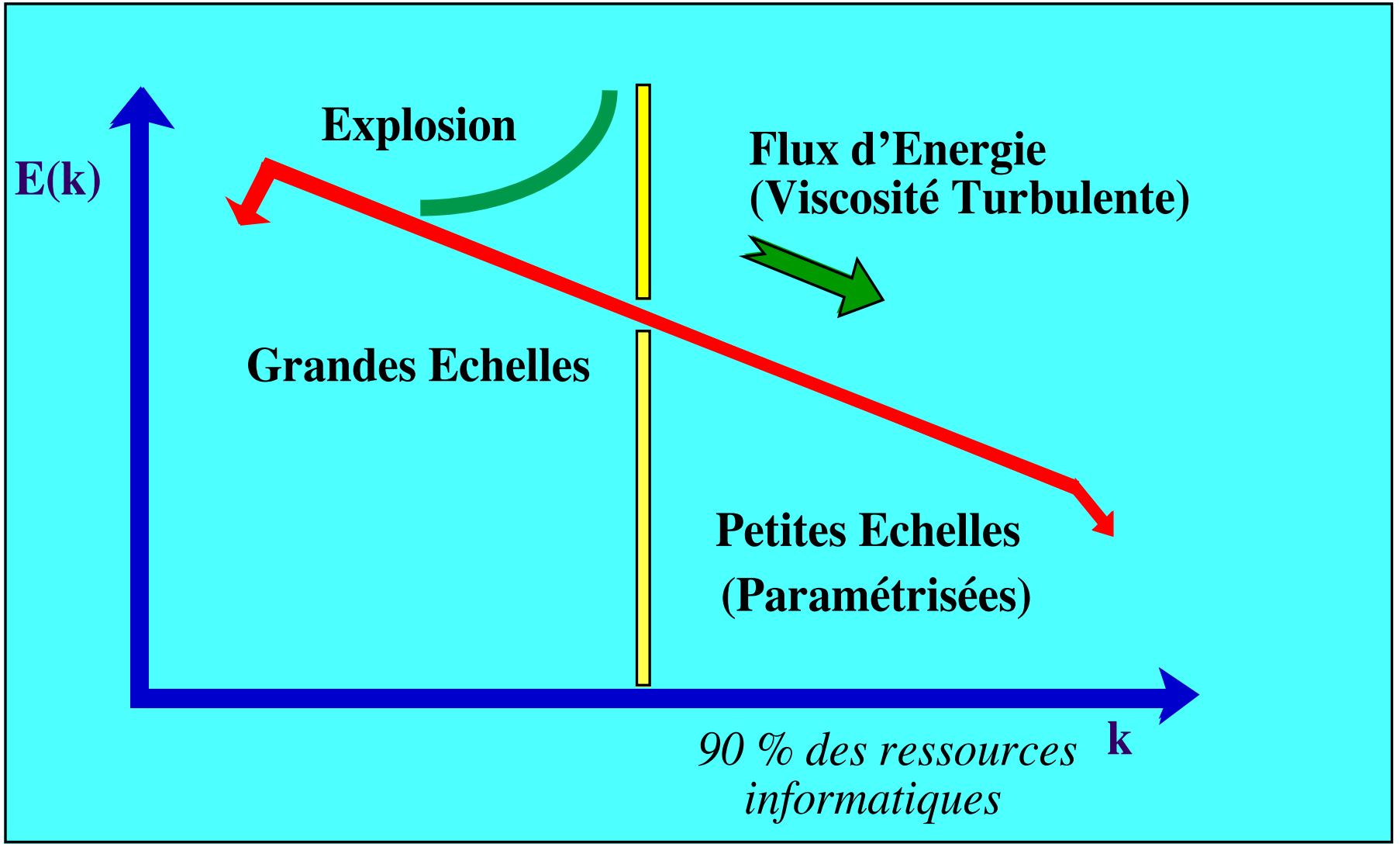


Cichowlas et al, PRL, 2005

A cause de la troncation, toute simulation finit en Bruit à petite échelle

Courtesy J.I. Polanco

Que peut on faire? Paramétrer!



Exemple de paramétrisation: viscosité turbulente

Analyse dimensionnelle

$$\nu_T = KVL$$

Echelle caracteristique

Constante

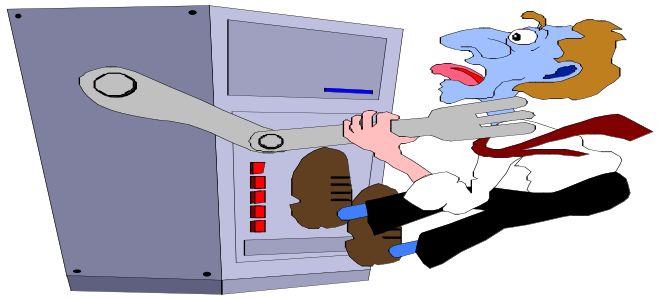
Vitesse caractéristique

Si constant

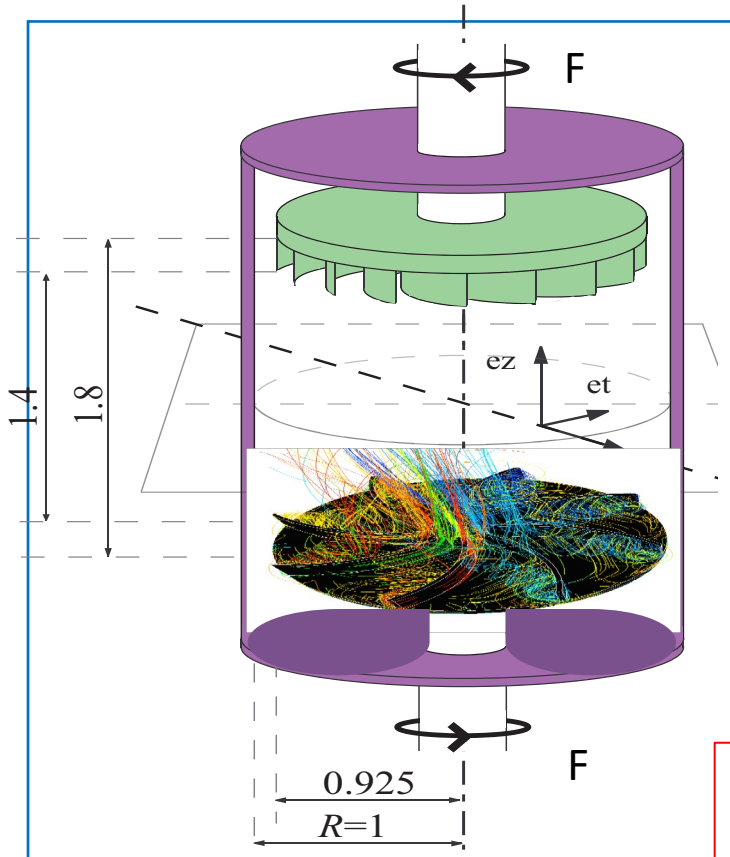
Athmosphère: x6-> goudron
Océan x 5-> miel

$$\vec{\nabla} \bullet \vec{u} = \vec{0}$$

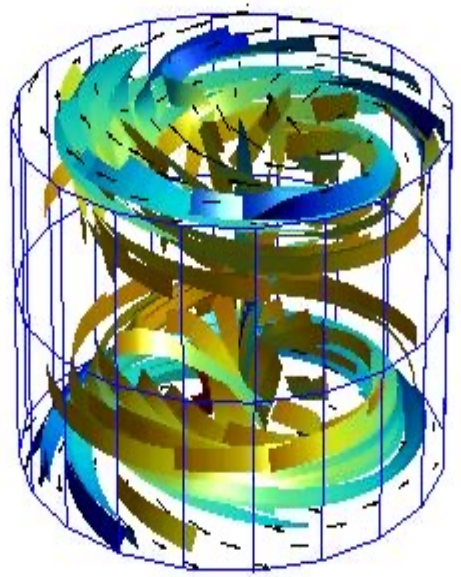
$$\partial_t \vec{u} + (\vec{u} \bullet \vec{\nabla})\vec{u} = -\frac{1}{\rho}\vec{\nabla} p + \nu \Delta \vec{u}$$



Re<10^5



Expérience de **von Karman**



10^2<Re<10^8

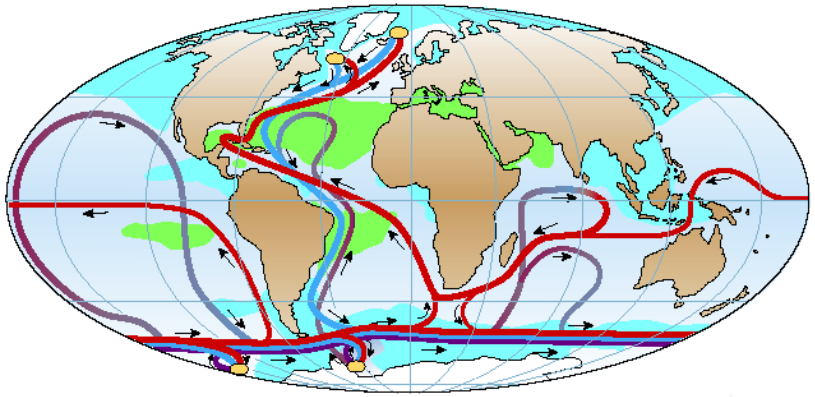
On a (encore) besoin d'expériences pour comprendre la turbulence!

Résultat VKE

Collaboration SPEC/LSCE

Saint-Michel et al, PRL, 2013
Faranda et al, PRL, 2017

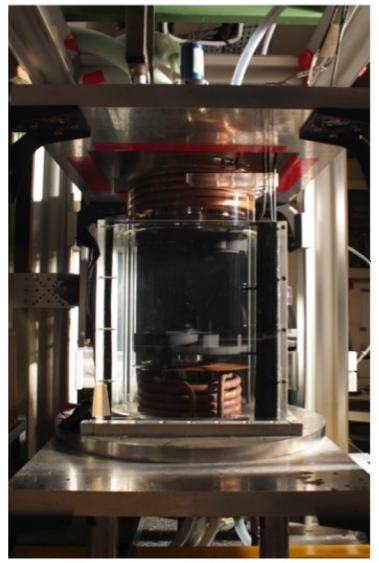
Forçage Solaire
Transport de Chaleur
Circulation Océanique

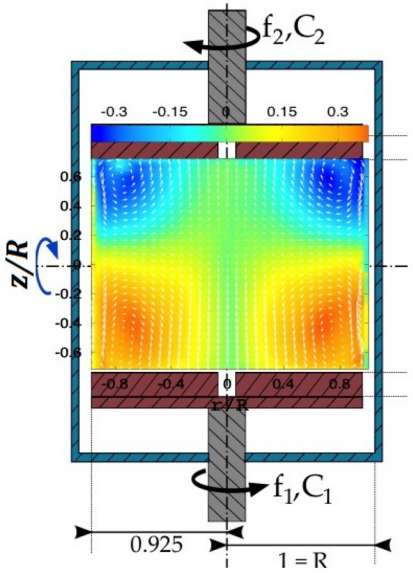


Mesure de Température

Circulation océanique

Forçage par Turbine
Transport Mom. Ciné
Circulation moyenne





Mesure de vitesse

Circulation turbulente

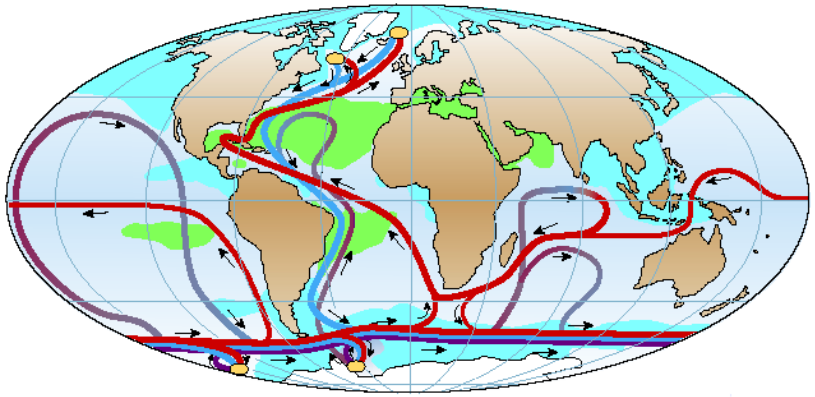
Résultat VKE

Collaboration SPEC/LSCE

Forçage Solaire

Transport de Chaleur

Circulation Océanique



Mesure de Température

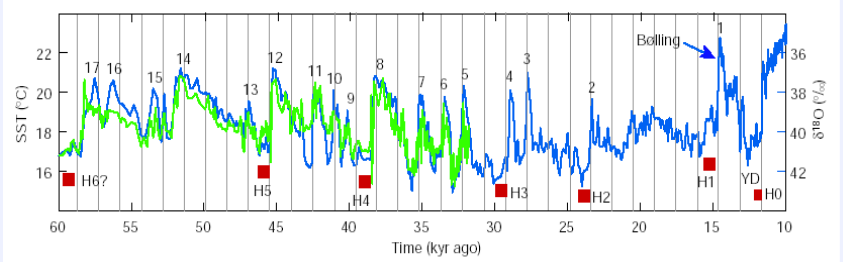


Figure 3 Temperature reconstructions from ocean sediments and Greenland ice. Proxy data from the subtropical Atlantic[86] (green) and from the Greenland ice core GISP2 (ref. 87; blue) show several Dansgaard–Oeschger (D/O) warm events (numbered). The timing of Heinrich events is marked in red. Grey lines at intervals of 1,470 years illustrate the tendency of D/O events to occur with this spacing, or multiples thereof.

Résultat VKE

Collaboration SPEC/LSCE

Saint-Michel et al, PRL, 2013
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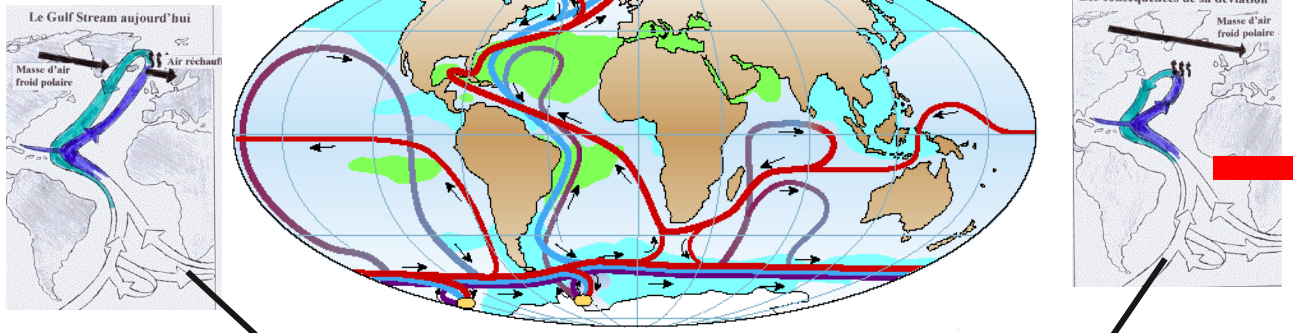
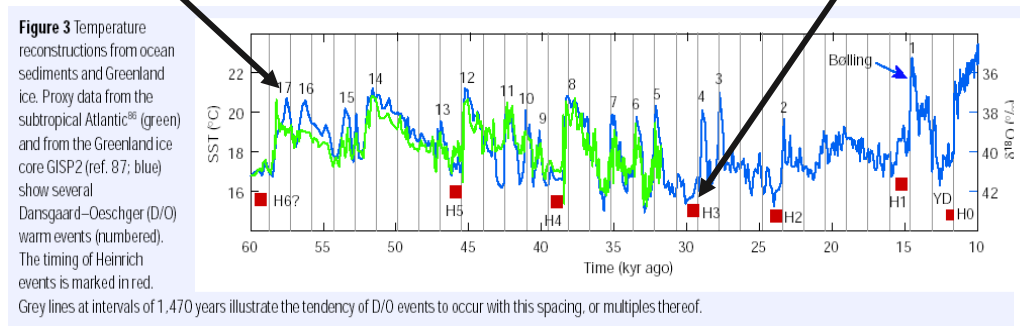
Forçage Solaire
Transport de Chaleur
Circulation Océanique



Mesure de Température



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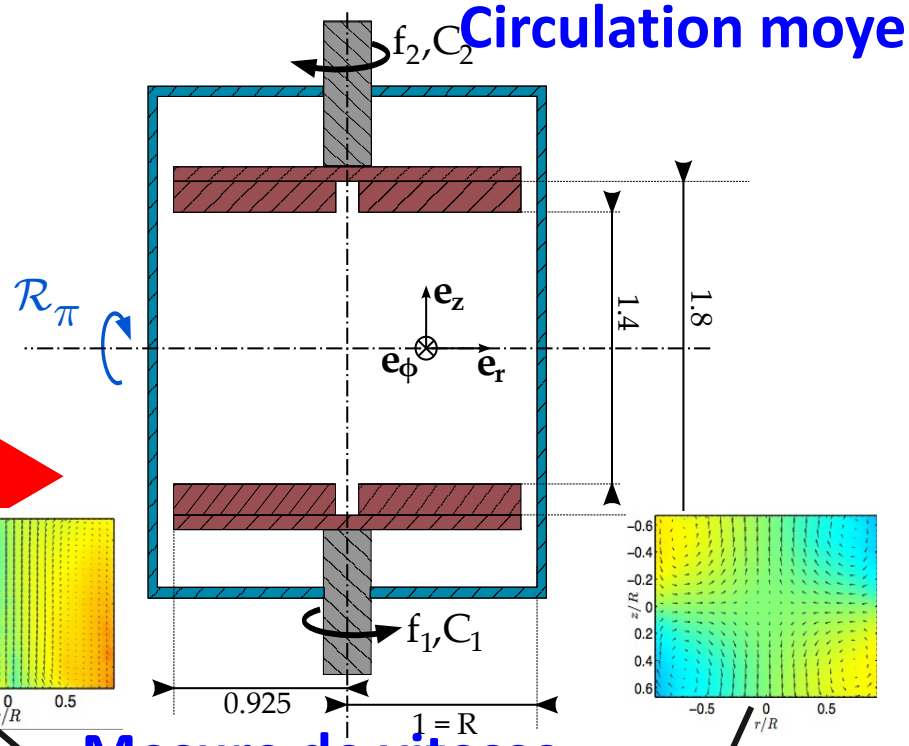
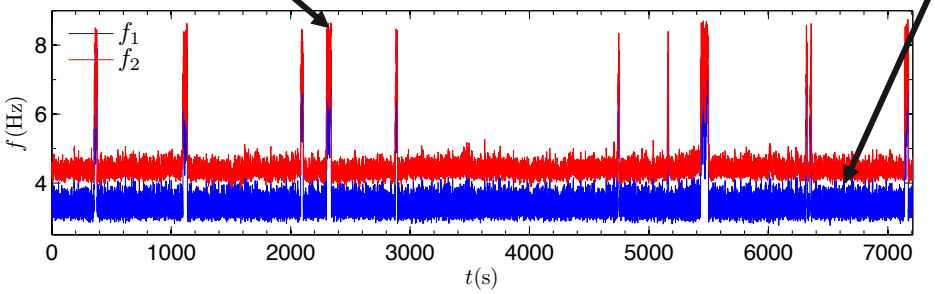


Mesure de vitesse



Conclusion

On a les équations mais ça ne nous aide pas!-> expériences de laboratoire
La paramétrisation est difficile-> travail théorique!

La turbulence restera encore mystérieuse pour longtemps!