ENERGY TRANSFER AND ENERGY DISSIPATION IN TURBULENT FLOWS

Παντα ρει (everything flows)

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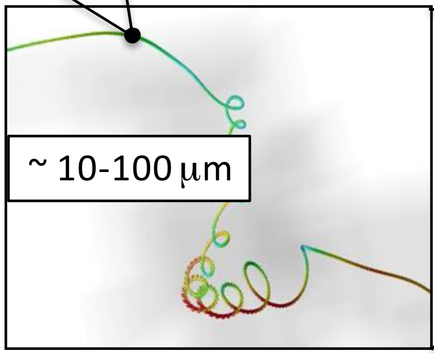
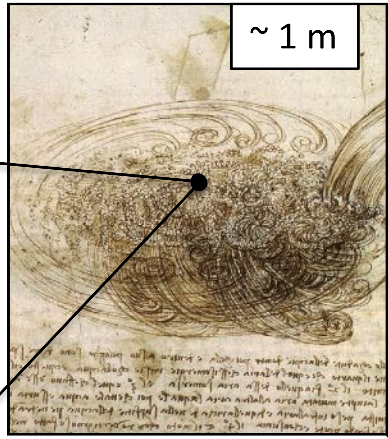
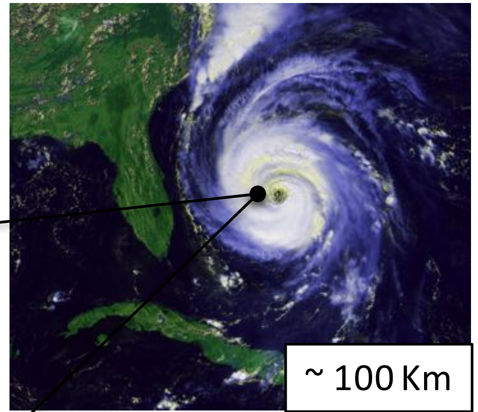






MULTISCALE !

WHERE DOES ENERGY GO ?

WHAT CAN WE SAY ABOUT THE STATISTICAL PROPERTIES OF TURBULENT FLOWS AT LARGE/SMALL SCALES ?

NAVIER-STOKES EQUATIONS:

$$m\vec{a} = \vec{F}$$

$$\partial_t \vec{v} + (\vec{v} \cdot \vec{\partial})\vec{v} = -\vec{\partial}P + \nu \Delta \vec{v} + \vec{f}$$

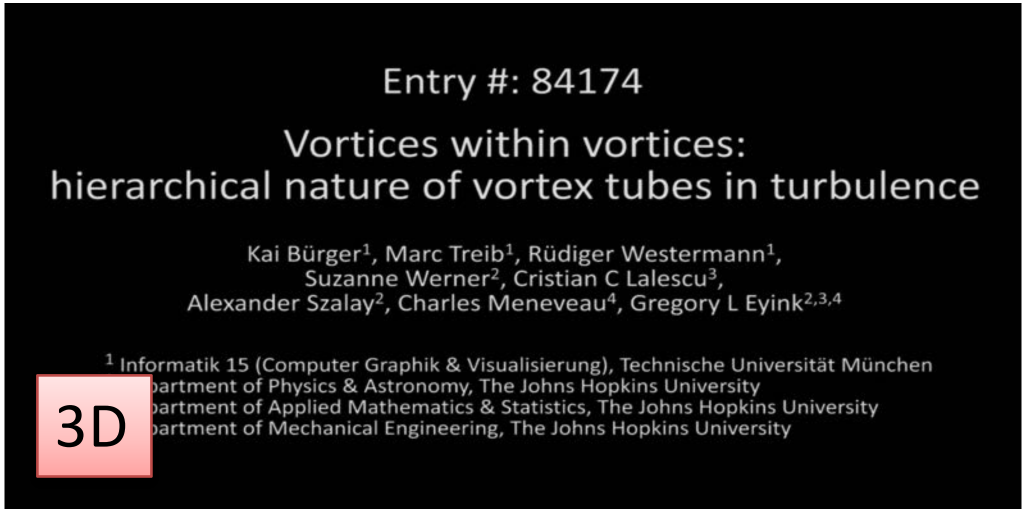
acceleration — pressure — viscosity — external forcing

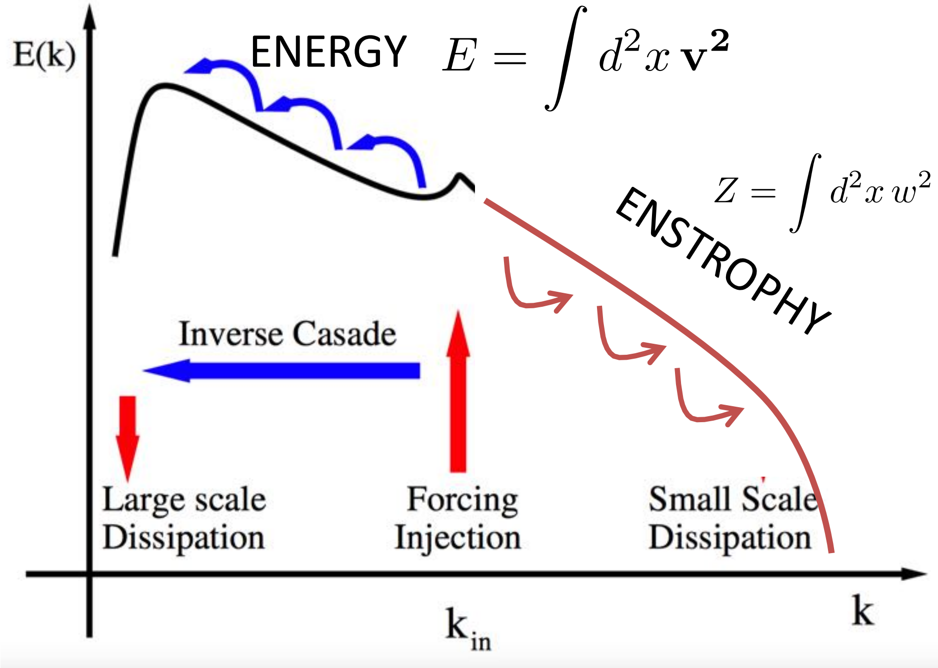
Leonardo da Vinci (~ 1500): "doue la turbolenza de si genera **[injected]**; doue la turbolenza dell aqua si mantiene **[advected]** plugho; doue la turbolenza dell acqua si posa **[dissipated]**"

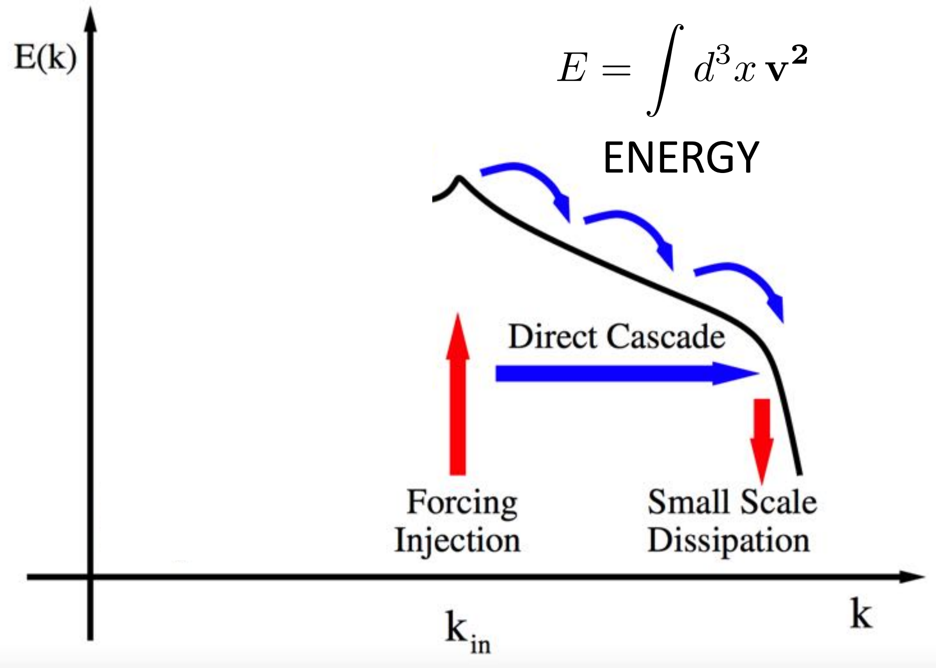
NAVIER-STOKES 3D ←→ 2D

(NASA - Space Flight Center Scientific Visualization Studio)

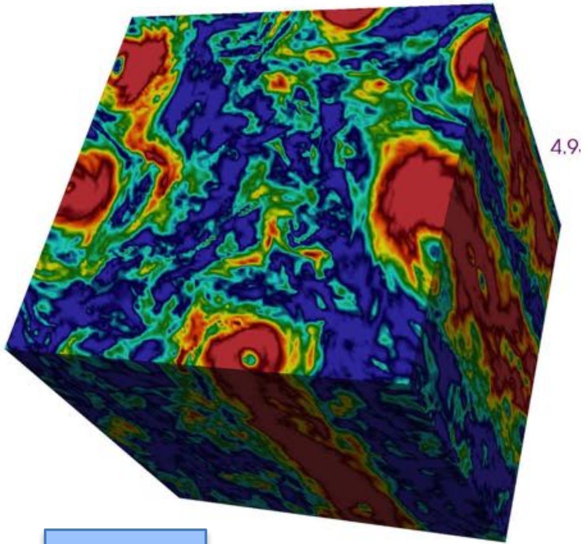
(Vortices within vortices - APS Gallery of Fluid Motions)

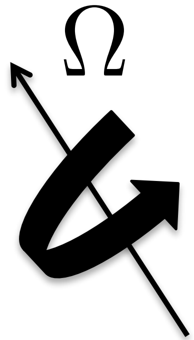


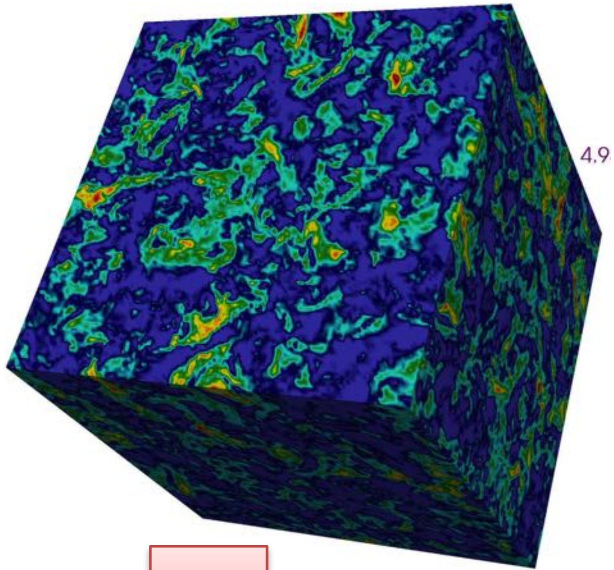




(PHASE) TRANSITIONS IN THE ENERGY TRANSFER: ROTATING FLOWS

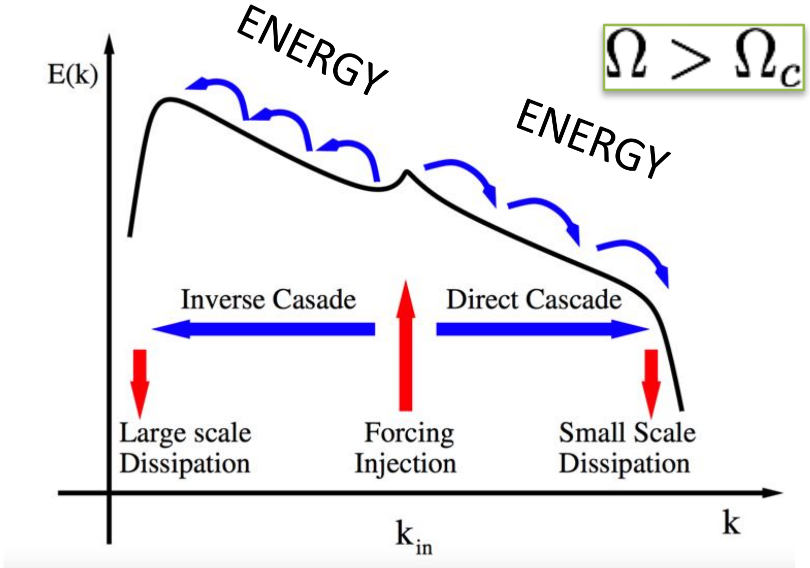


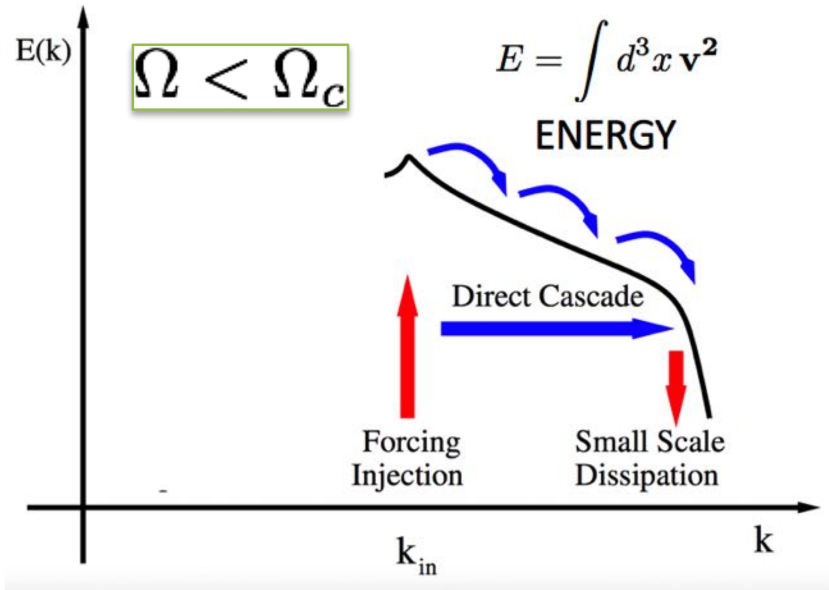




~ 2D

3D





COMPLEX FLUID & COMPLEX FLOWS

$$\begin{cases} \partial_t v + v\partial v = -\partial p + \nu \Delta v \quad + F(B,B) \quad + g\theta \quad + \sum_i c_0(u_i, v)\delta(r - r_i) \; + f \\ \partial_t \theta + v \cdot \partial \theta = \chi \partial^2 \theta \\ \partial_t B + v \cdot \partial B = B \cdot \partial v + \chi \partial^2 B \\ \partial \cdot v = 0 \end{cases}$$

+ boundary conditions

$$\begin{cases} \frac{du_i(r_i,t)}{dt} = -\rho_f |u_i - v| (u_i - v) \\ + \rho_f \left(\frac{Dv}{Dt} - \frac{Du_i}{Dt}\right) + (u_i - v) \times \omega \end{cases}$$

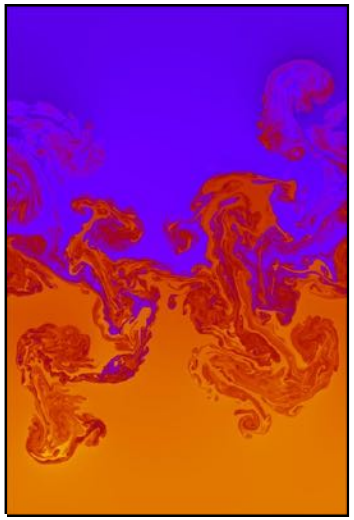
control parameter:

$$Re = \frac{l_0 v_0}{\nu}$$

$$Re \to \infty$$

FULLY NON-LINEAR

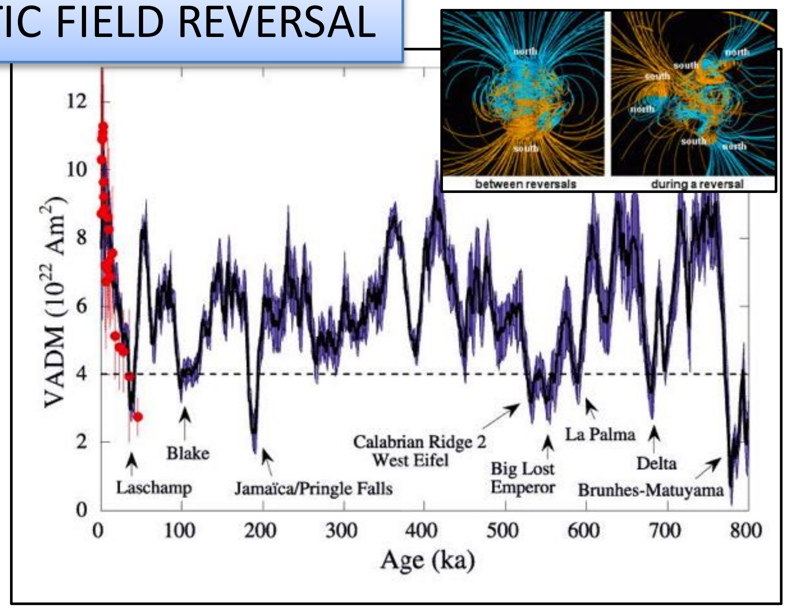
θ_{up} COLD



θ_{down} WARM

CONVECTION

MAGNETIC FIELD REVERSAL



COMPLEX FLUID & COMPLEX FLOWS

$$\partial_t v + v\partial v = -\partial p + \nu\Delta v \quad + F(\boldsymbol{B},\boldsymbol{B}) \quad + g\theta \quad + \sum_i c_0(u_i, v)\delta(r - r_i) \quad + f$$

$$\partial_t \theta + \boldsymbol{v}\cdot\boldsymbol{\partial}\theta = \chi\partial^2\theta$$

$$\partial_t \boldsymbol{B} + \boldsymbol{v}\cdot\boldsymbol{\partial}\boldsymbol{B} = \boldsymbol{B}\cdot\boldsymbol{\partial}\boldsymbol{v} + \chi\partial^2\boldsymbol{B}$$

$$\partial \cdot v = 0$$

+ boundary conditions

$$\frac{du_i(r_i,t)}{dt} = -\rho_f|u_i - v|(u_i - v) + \rho_f\left(\frac{Dv}{Dt} - \frac{Du_i}{Dt}\right) + (u_i - v)\times\omega$$

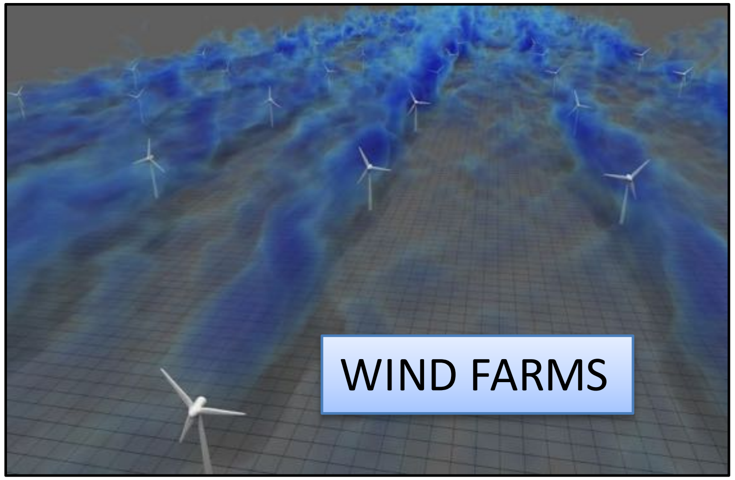
control parameter:

$$Re = \frac{l_0 v_0}{\nu}$$

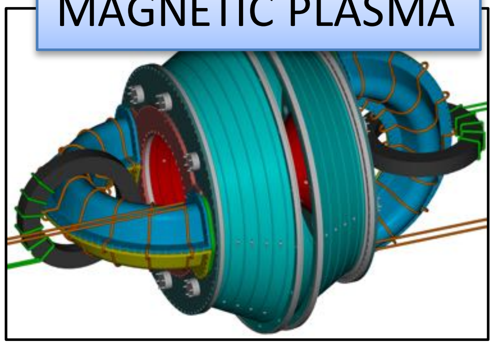
$$Re \to \infty$$

FULLY NON-LINEAR

ROTATING CONVECTION



MAGNETIC PLASMA



COMPLEX FLUID & COMPLEX FLOWS

$$\begin{cases} \partial_t v + v \cdot \partial v = -\partial P + \nu \partial^2 v \; + F(\boldsymbol{B},\boldsymbol{B}) \; + \boldsymbol{g}\theta \; + \sum_i c_0(\boldsymbol{u}_i, \boldsymbol{v})\delta(\boldsymbol{r} - \boldsymbol{r}_i) \; + f \\ \partial_t \theta + \boldsymbol{v} \cdot \boldsymbol{\partial} \theta = \chi \partial^2 \theta \\ \partial_t \boldsymbol{B} + \boldsymbol{v} \cdot \boldsymbol{\partial B} = \boldsymbol{B} \cdot \boldsymbol{\partial v} + \chi \partial^2 \boldsymbol{B} \\ \partial \cdot v = 0 \end{cases}$$

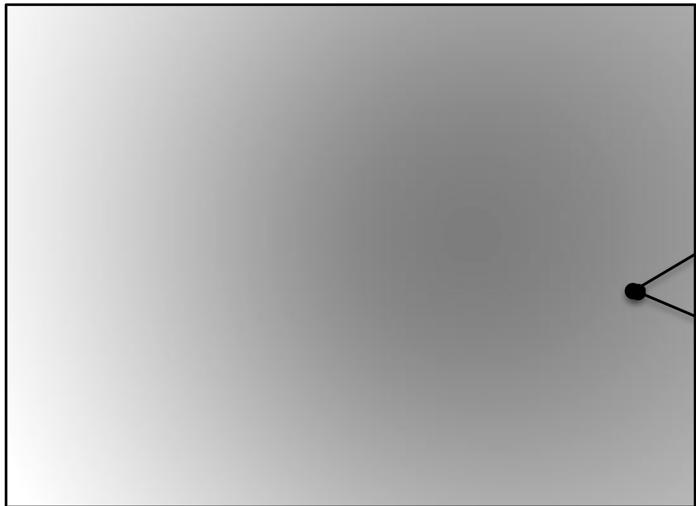
+ boundary conditions

temperature

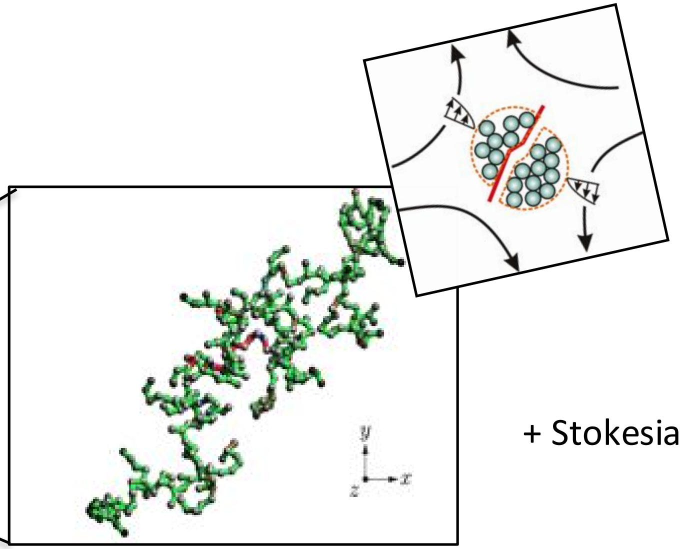
magnetic field

$$\frac{d\boldsymbol{u}_i(\boldsymbol{r}_i, t)}{dt} = -\rho_f |\boldsymbol{u}_i - \boldsymbol{v}|(\boldsymbol{u}_i - \boldsymbol{v}) + \rho_f\left(\frac{D\mathbf{v}}{Dt} - \frac{D\boldsymbol{u}_i}{Dt}\right) + (\boldsymbol{u}_i - \boldsymbol{v}) \times \boldsymbol{\omega}$$

small particles/colloidal aggregates:
Stokes drag, added mass, lift force, etc...



DISPERSION OF TWO DIFFERENT SPECIES OF SMALL PARTICLES/AGGREGATES IN A TURBULENT FLOW



+ Stokesian dynamics

COAGULATION/FRAGMENTATION OF COLLOIDAL AGGREGATES IN TURBULENT FLOWS

COMPLEX FLUID & COMPLEX FLOWS

$$\partial_t v + v \cdot \partial v = -\partial P + \nu \partial^2 v \quad + F(B,B) \quad + g\theta \quad + \sum_i c_0(u_i, v)\delta(r - r_i) \quad + f(V_{active})$$

$$\partial_t \theta + v \cdot \partial \theta = \chi \partial^2 \theta$$ ← temperature

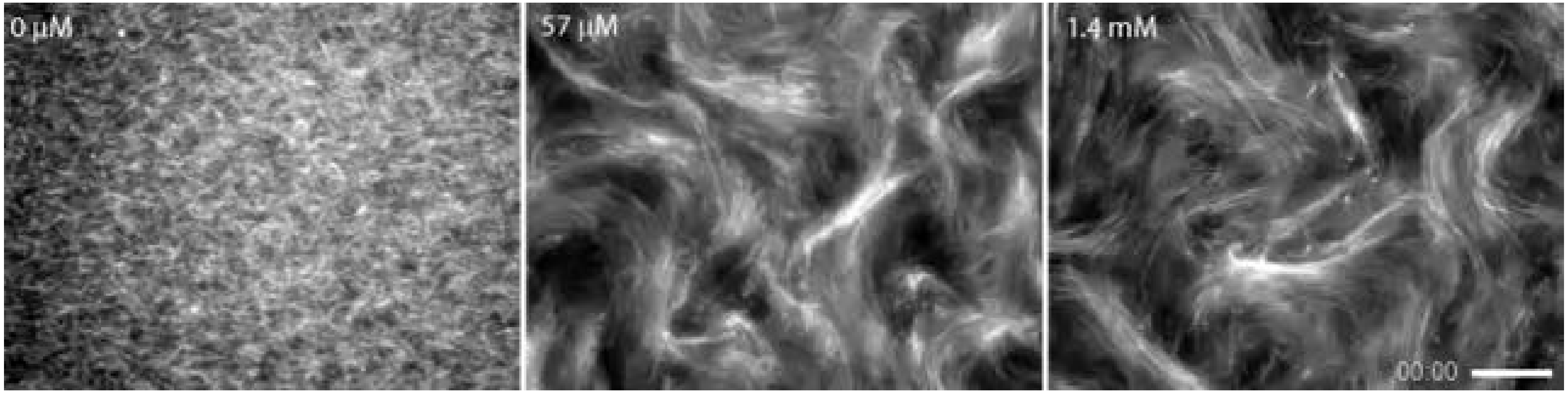
$$\partial_t B + v \cdot \partial B = B \cdot \partial v + \chi \partial^2 B$$ ← magnetic field

$$\partial \cdot v = 0$$

+ boundary conditions

$$\frac{du_i(r_i,t)}{dt} = -\rho_f |u_i - v|(u_i - v) + \rho_f\left(\frac{Dv}{Dt} - \frac{Du_i}{Dt}\right) + (u_i - v) \times \omega$$

ACTIVE MATTER



Sanchez et al Nature 2012 “Microtubules activated by Kinesin Motor Proteins”

$$\begin{cases} \partial_t v + v\partial v = -\partial p + \nu \Delta v \quad +F(B,B) \quad +g\theta \quad +\sum_i c_0(u_i,v)\delta(r-r_i) \quad +f \\ \partial_t \theta + v\cdot\partial\theta = \chi\partial^2\theta \\ \partial_t B + v\cdot\partial B = B\cdot\partial v + \chi\partial^2 B \\ \partial\cdot v = 0 \\ \text{+ boundary conditions} \end{cases}$$

$$\begin{cases} \frac{du_i(r_i,t)}{dt} = -\rho_f|u_i - v|(u_i - v) \\ +\rho_f(\frac{Dv}{Dt} - \frac{Du_i}{Dt}) + (u_i - v)\times\omega \end{cases}$$

control parameter:

$$Re = \frac{l_0 v_0}{\nu}$$

$$\begin{cases} Re \to \infty \\ \nu \to 0 \end{cases}$$

Too many turbulences? NO! -> UNIVERSALITY

ALL TURBULENT FLOWS RECOVER ISOTROPY AND HOMOGENEITY (AT SCALES SMALL ENOUGH)

- Homogeneous & Isotropic Turbulence
- Fully periodic 3D domain
- Gaussian delta-correlated forcing
- Incompressible

Homogeneous and Isotropic turbulence: the (UNSOLVED) hydrogen atom of fluid dynamics

WHY STILL UNSOLVED?
(EQUATIONS ARE KNOWN SINCE 250 YEARS AGO!)