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Particles and fibres in homogenous isotropic turbulence

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Particles in **turbulent flows**

- Seen in many shapes and sizes in nature and industry

Microplastic dispersal in the ocean

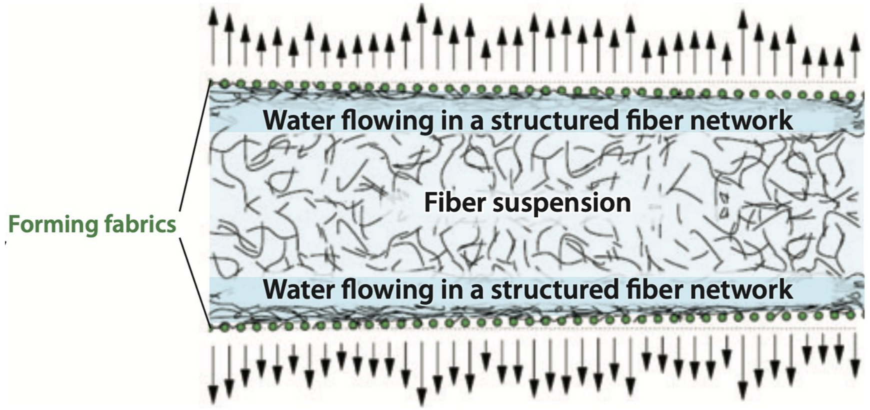
Credit: Carmen Martinez Toron

Pollen dispersal in the atmosphere

Credit: Robert J. Erwin

Pulp processing in papermaking

Credit: Toddmedia/Getty



Lundell *et al*, *Annu. Rev. Fluid Mech.* 2011

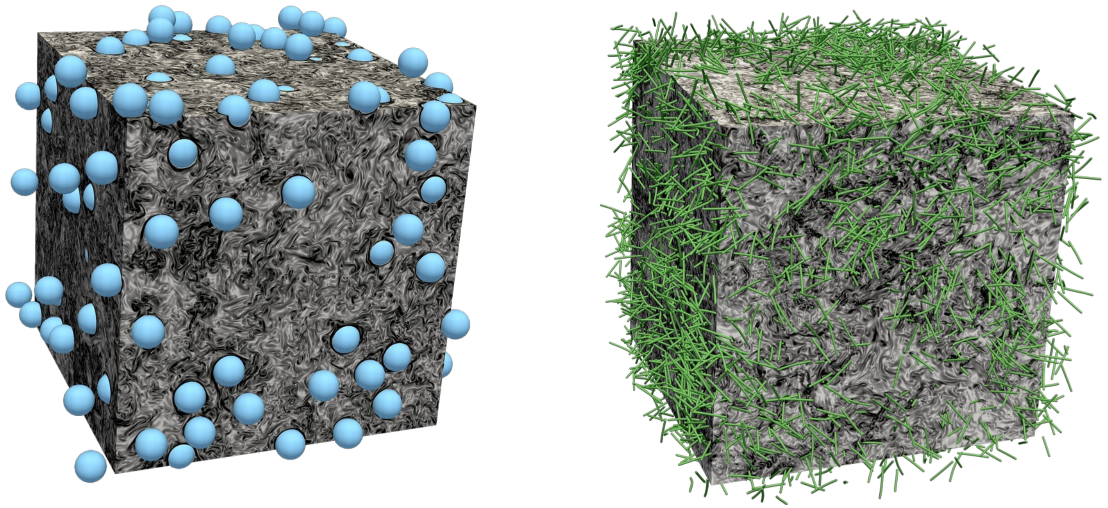
Background

- Previous studies (Voth & Soldati, 2017; Brandt & Coletti, *Annu. Rev. Fluid Mech.* 2021) often use one or more of the following assumptions:
  - small ($c \ll \eta$)
  - isotropic (spherical or point-like)
  - dilute (one-way coupling)

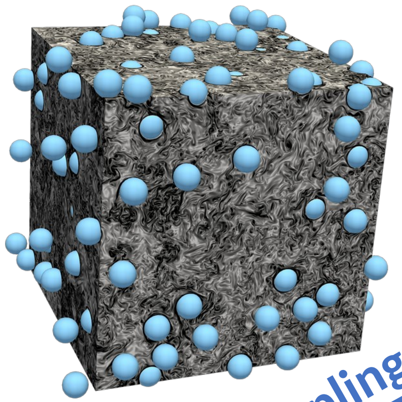
Goal of the work

- We investigate particles which are:
  - finite size ($\eta < c < L$)
  - in non-dilute conditions (two-way coupling)
- We study the **turbulence modulation** by **isotropic** and **anisotropic** particles

How does particle **isotropy** affect the turbulent energy cascade?



Numerical method



- N **rigid spheres** with diameter c

$$m^p \frac{dU_i^c}{dt} = \oint_{\partial \mathcal{V}^p} \sigma_{ij} n_j \, dA + F_i^{\text{ext}},$$

$$\mathcal{I}^p \frac{d\Omega_i^c}{dt} = \oint_{\partial \mathcal{V}^p} \epsilon_{ijk} r_j \sigma_{kl} n_l \, dA + T_i^{\text{ext}}$$

Hori et al, Comput. & Fluids, 2021

Two-way coupling IBM

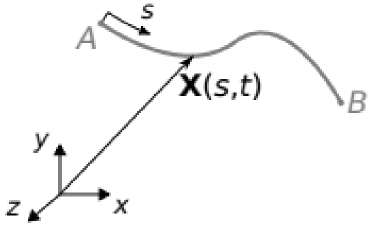
- Homogeneous isotropic turbulence (HIT) with $Re_\lambda \approx 435$

$$\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} = -\frac{1}{\rho_{\mathrm{f}}} \nabla p + \nu \Delta \mathbf{u} + \mathbf{f}_{\mathrm{FOR}} + \mathbf{f}_{\mathrm{FS}}$$

$$\nabla \cdot \mathbf{u} = 0$$

Two-way coupling IBM

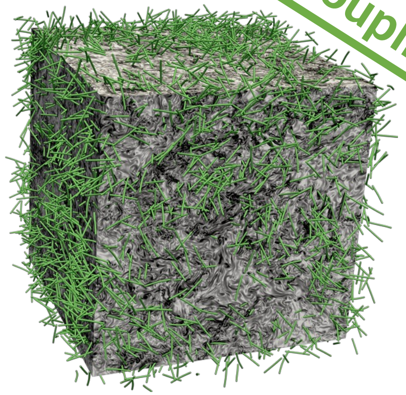
- N **inextensible fibres** with length c



$$\frac{\partial \mathbf{X}}{\partial s} \cdot \frac{\partial \mathbf{X}}{\partial s} = 1$$

- We vary the particle mass fraction

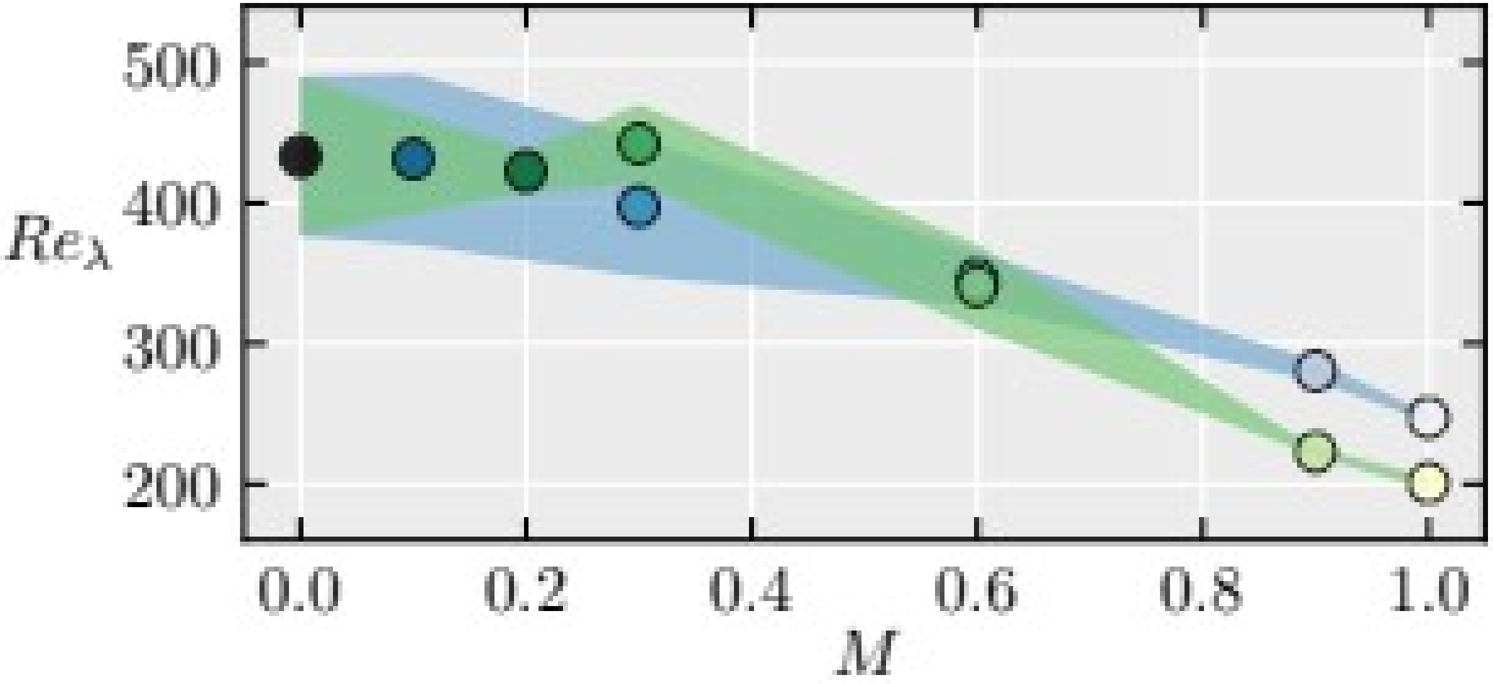
$$M \equiv \frac{m_p}{m_f + m_p}$$



$$\Delta \tilde{\rho} \frac{\partial^2 \mathbf{X}}{\partial t^2} = \frac{\partial}{\partial s}\left(T \frac{\partial \mathbf{X}}{\partial s}\right) - \gamma \frac{\partial^4 \mathbf{X}}{\partial s^4} - \mathbf{F}$$

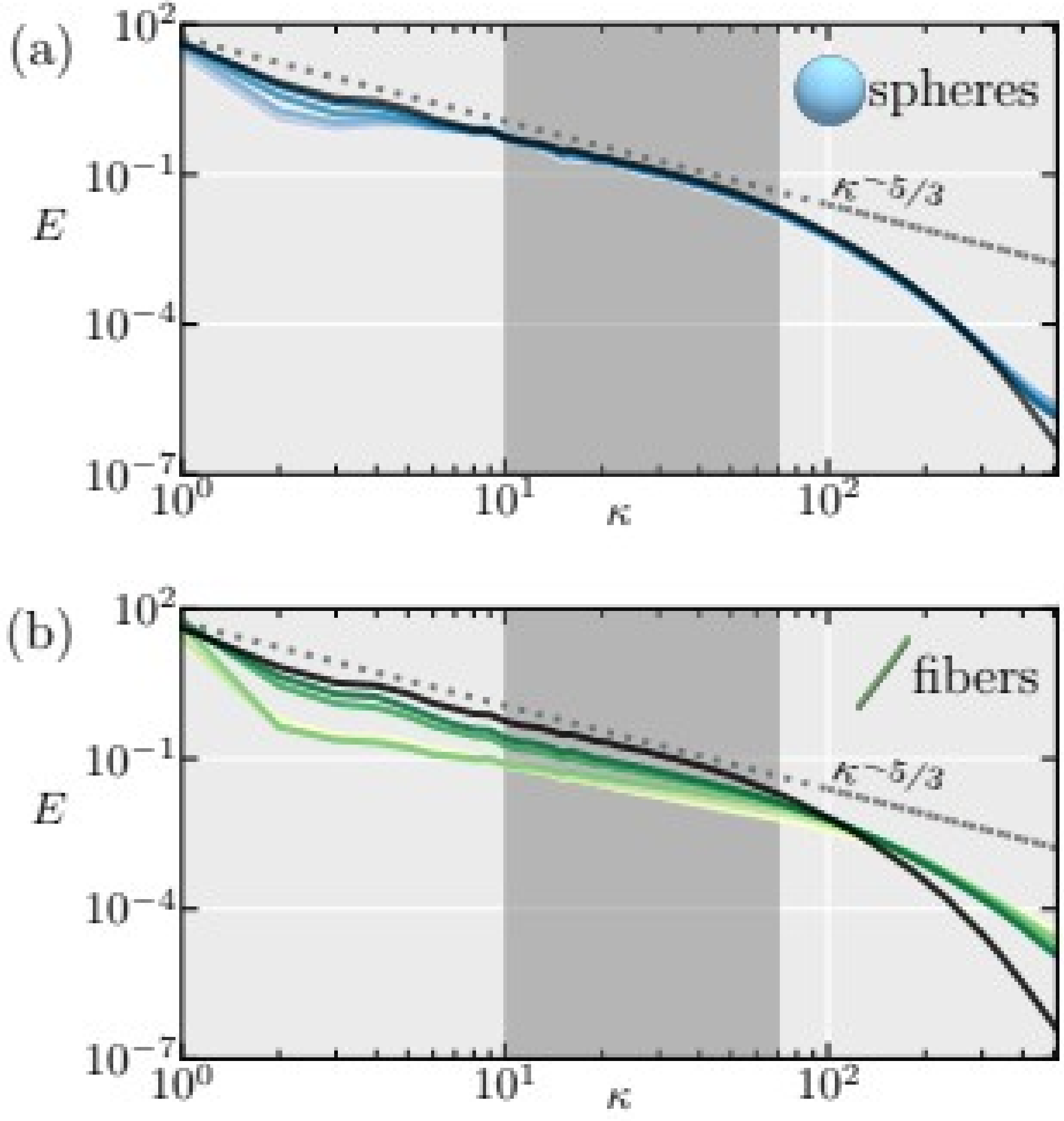
Olivieri et al, Phys. Rev. Lett., 2020
Huang et al, J. Comput. Phys, 2007

Effect of particles on bulk flow properties



Turbulence modulation

- Both spheres and fibres produce a similar reduction in the Taylor Reynolds number Re_λ.
- The flows with spheres show a reduction in the kinetic energy at the large scales.
- The fibres modulate the flow at all length scales



Kinetic energy scaling

- We fit power law functions $E = A\kappa^{-\beta}$ to the spectra

→ The flows with spheres retain the kolmogorov scaling

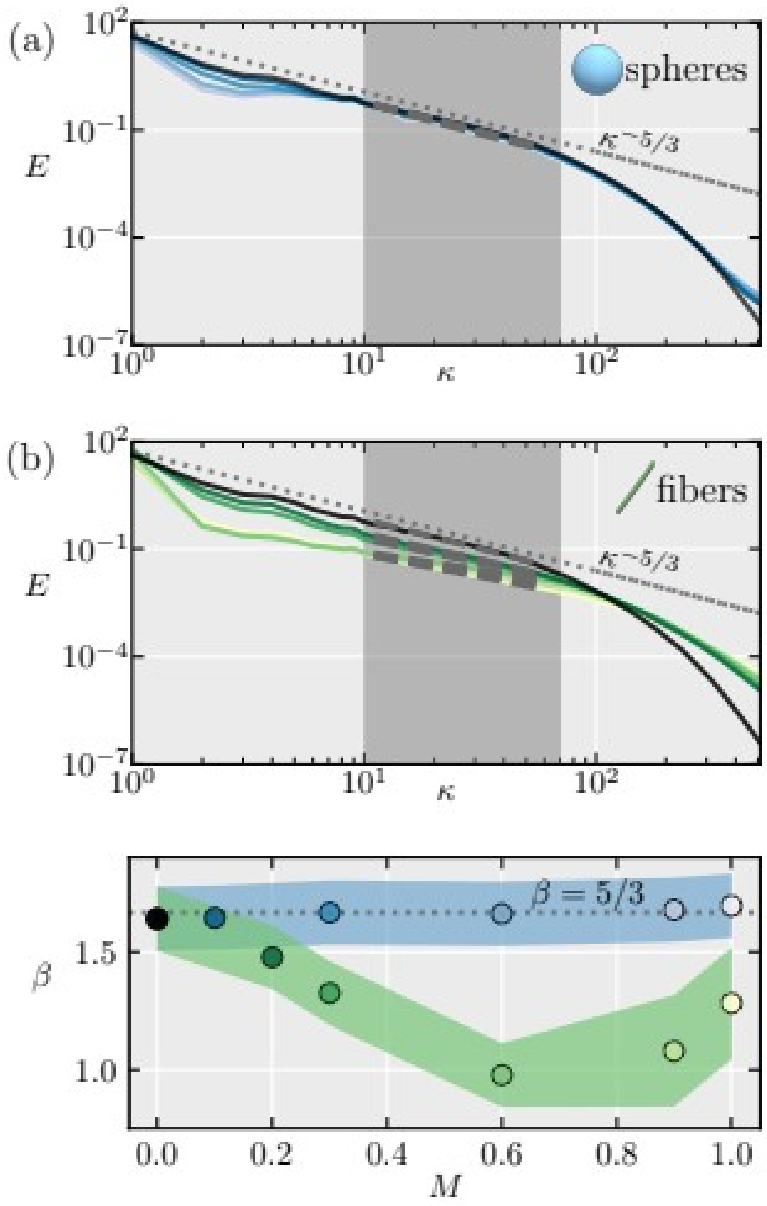
→ As the fibre mass fraction increases, the magnitude of the exponent β reduces

→This is because the fibres reduce the spatial correlation of the two point velocity difference $\delta u \equiv u' - u$.

$$\langle(\delta u)^2\rangle \sim r^{\gamma}$$

→Dimensional analysis gives us a relation between the energy spectrum and the velocity difference (Pope Cambridge University Press, 2000):

$$\gamma = \beta - 1$$

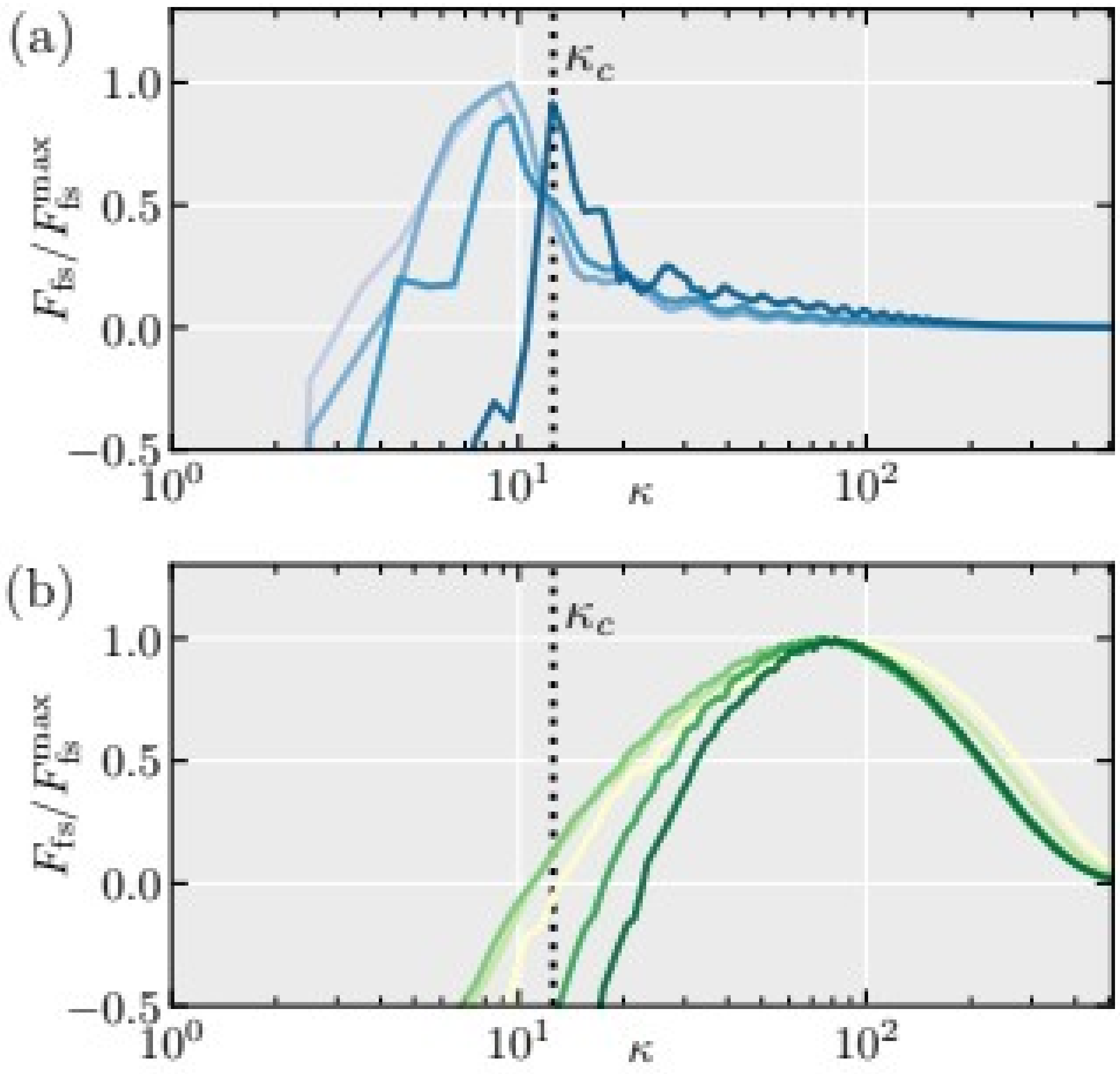


Fluid-solid coupling

- The spectrum of the fluid-solid coupling is

$$F_{\mathrm{fs}}(\boldsymbol{\kappa}) \equiv \frac{1}{2}(\hat{\boldsymbol{u}}^* \cdot \hat{\boldsymbol{f}}_{\mathbf{fs}} + \hat{\boldsymbol{u}} \cdot \hat{\boldsymbol{f}}_{\mathbf{fs}}^*)$$

- We see the spheres act on the fluid at length scales comparable with their diameter c
- Fibres act on the fluid at a broad range of smaller scales



Conclusions

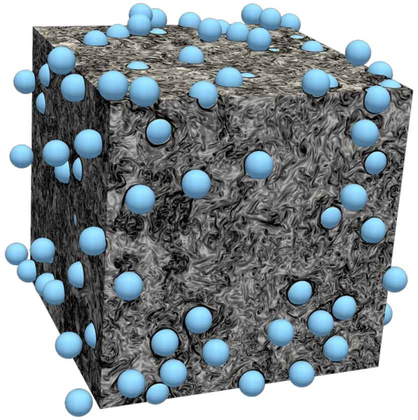
- We have focused on the modulation of turbulence due to *finite-size* particles, and, in particular, on the effect of their isotropy. We found:

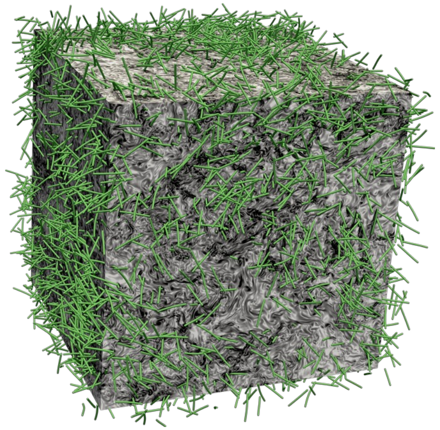
→The isotropic and anisotropic particles have a similar macroscopic effect on the flow (i.e., decrease of Re_λ)

→Isotropic particles act on the fluid at the length scale of their diameter. At smaller scales, the classical Kolmogorov cascade is unperturbed

→Anisotropic particles act on the fluid at a range of lengthscales, decorrelating the flow, and introducing a new scaling behaviour in the inertial range

Thank you!

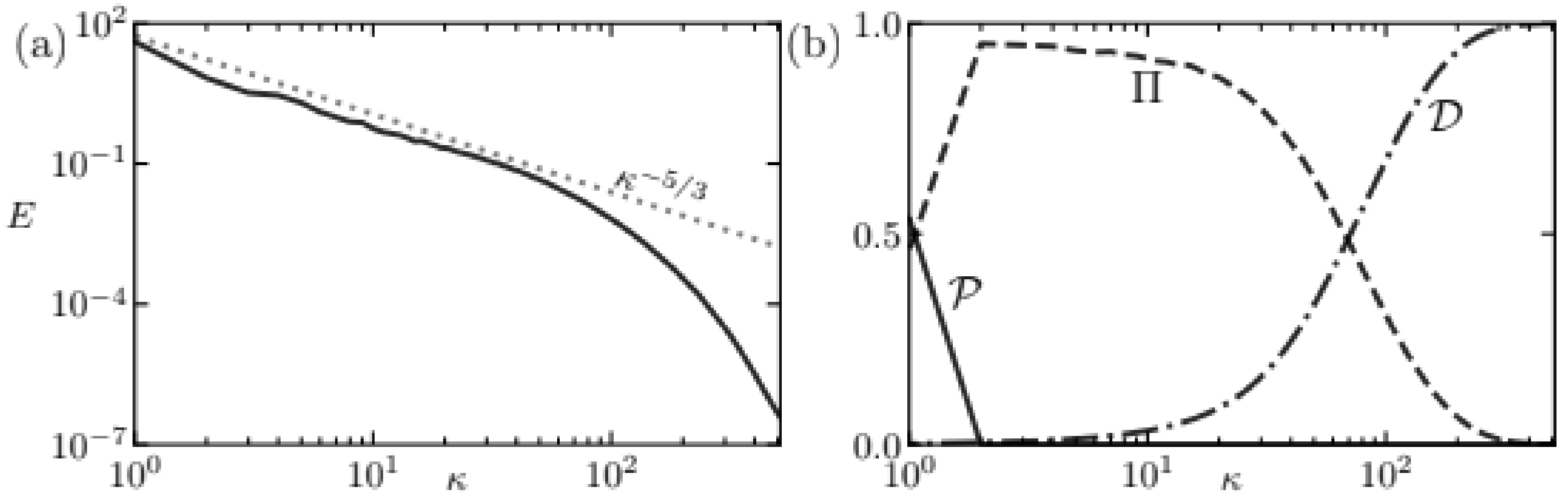


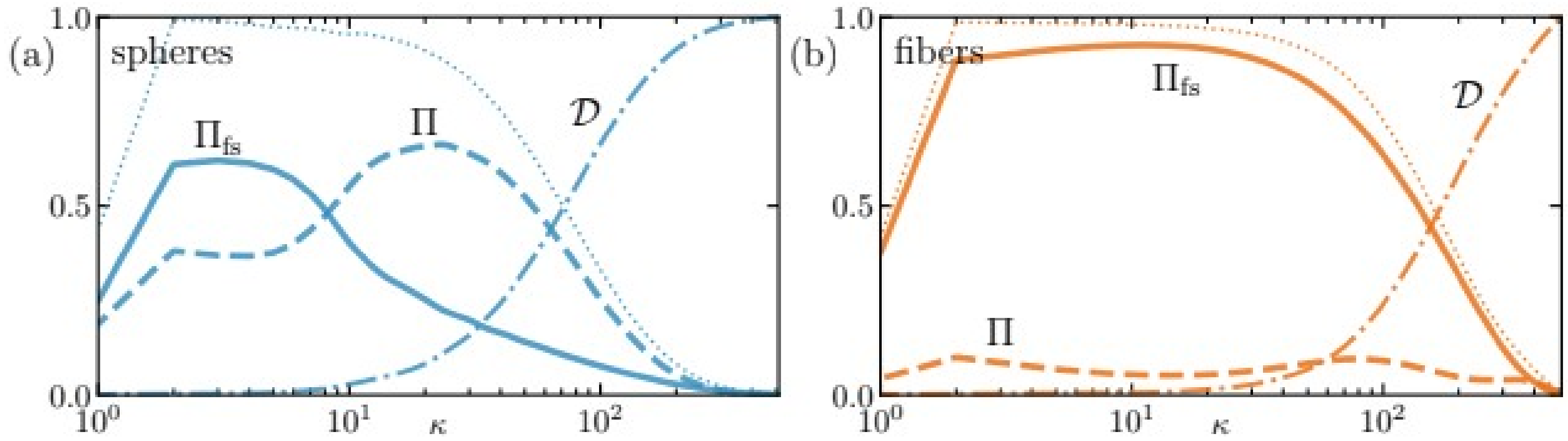


Olivieri, S., Cannon, I. & Rosti, M. E. (2022). The effect of particle anisotropy on the modulation of turbulent flows *(JFM Rapids)*

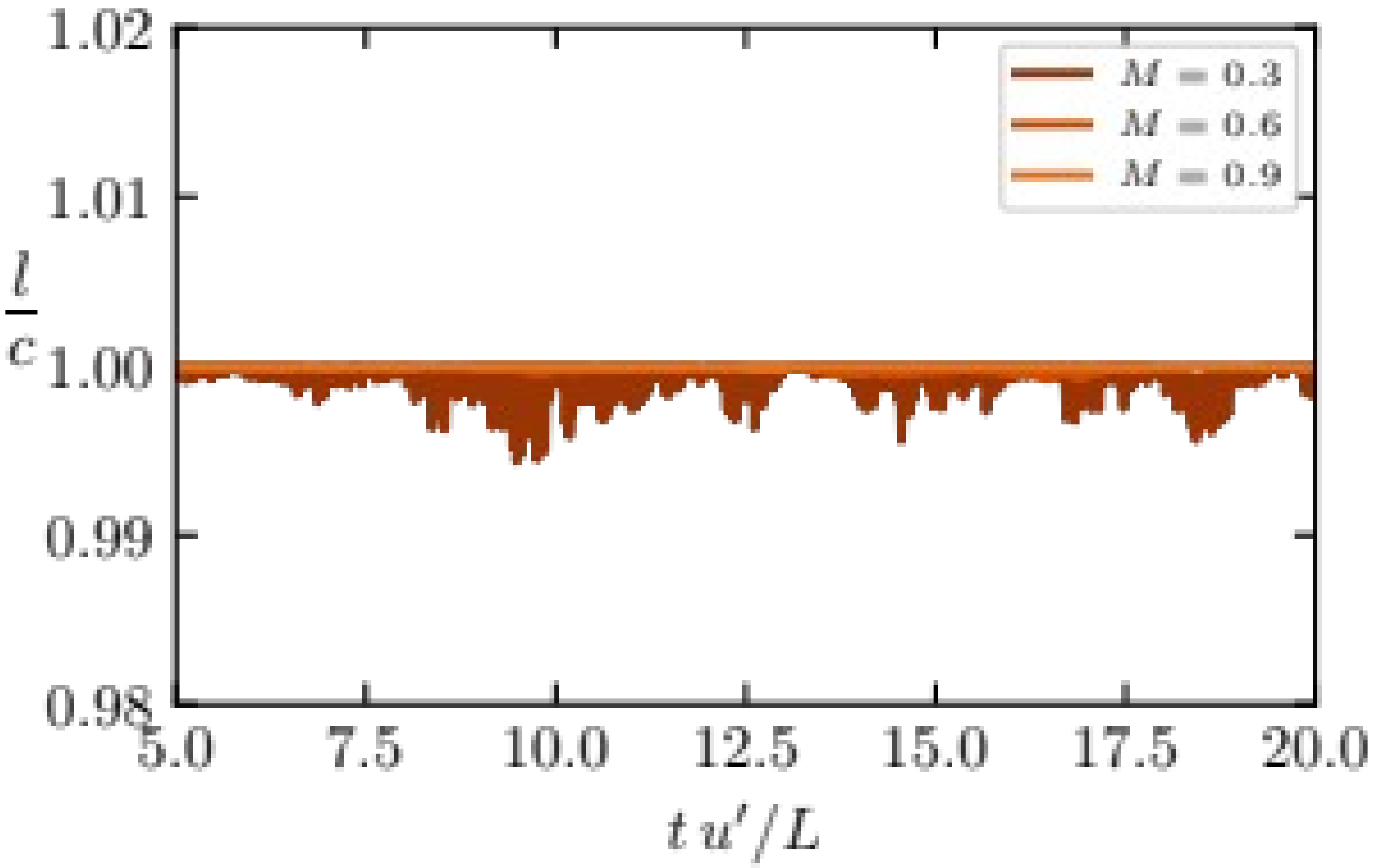
Energy fluxes

$$\mathcal{P}(\kappa) + \Pi(\kappa) + \Pi_{\mathrm{fs}}(\kappa) + \mathcal{D}(\kappa) = \epsilon,$$





Fibre deformation



Fractality of dissipation