Small-scale alignment and clustering of heavy inertial fibers in turbulence

AQTIVATE

Cyprus, 28 Sept. – 2 Oct. 2026

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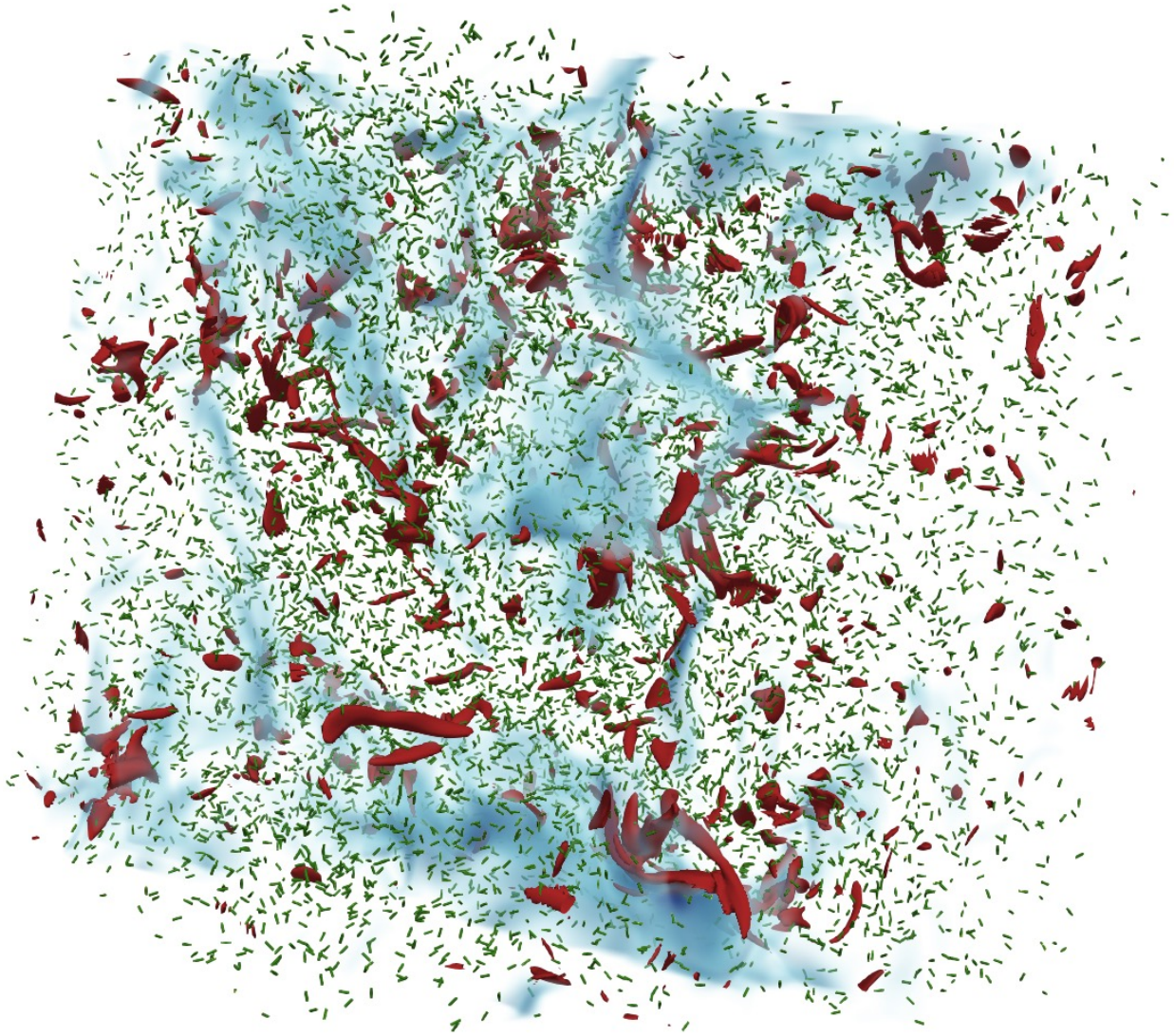
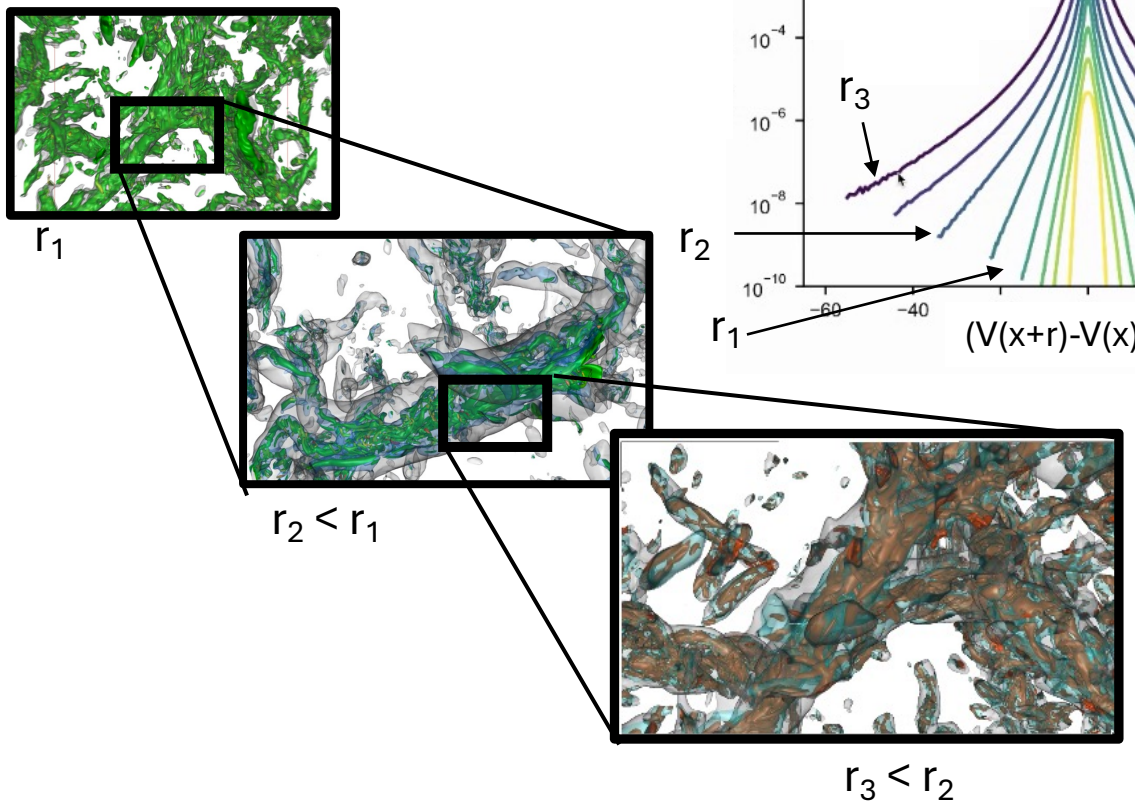
Inria UNIVERSITÉ CÔTE D'AZUR



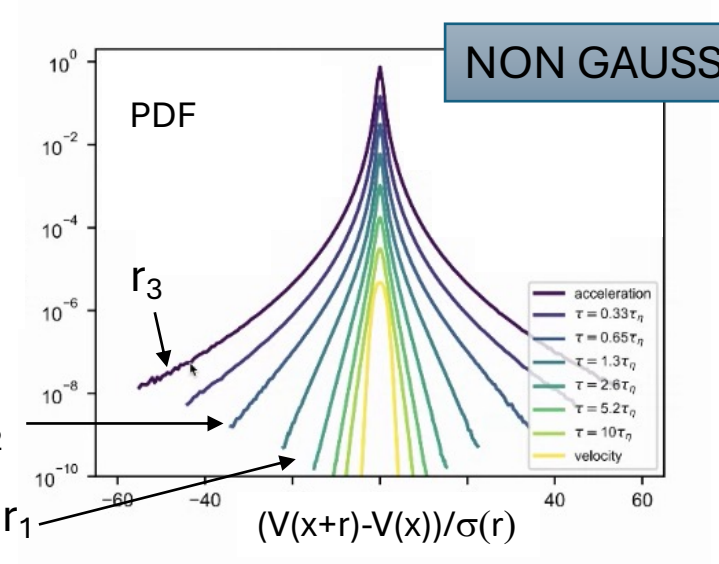
3D turbulent flows

$$\partial_t \boldsymbol{u} + \boldsymbol{u} \cdot \nabla \boldsymbol{u} = -\nabla p + \nu \Delta \boldsymbol{u} + \boldsymbol{F}$$

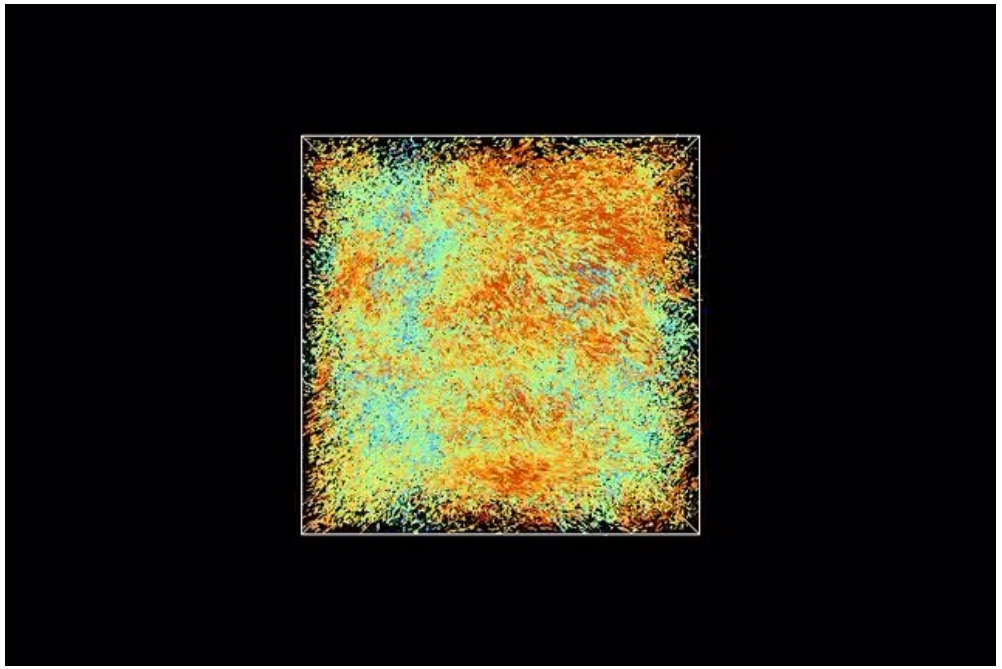
MULTISCALE



NON GAUSSIAN

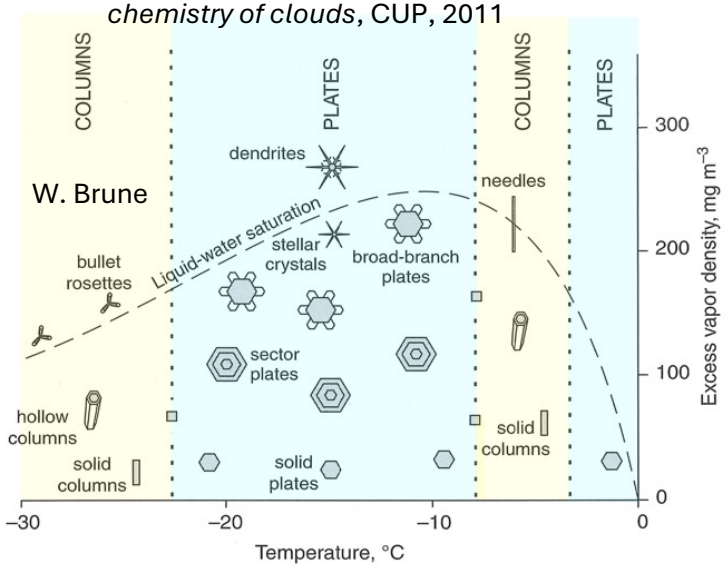


$$\dot{\boldsymbol{X}}(t) = \boldsymbol{V}(t) = \boldsymbol{u}(\boldsymbol{X}(t), t).$$

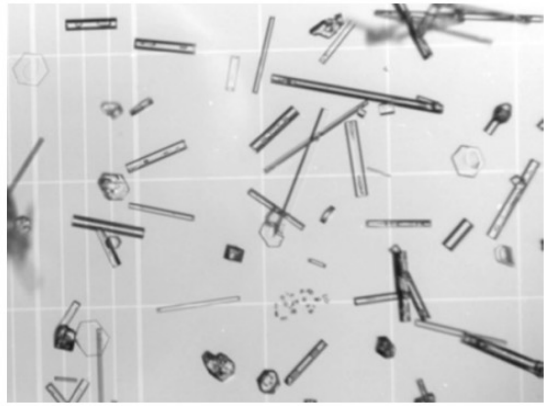


Complex particles in turbulence

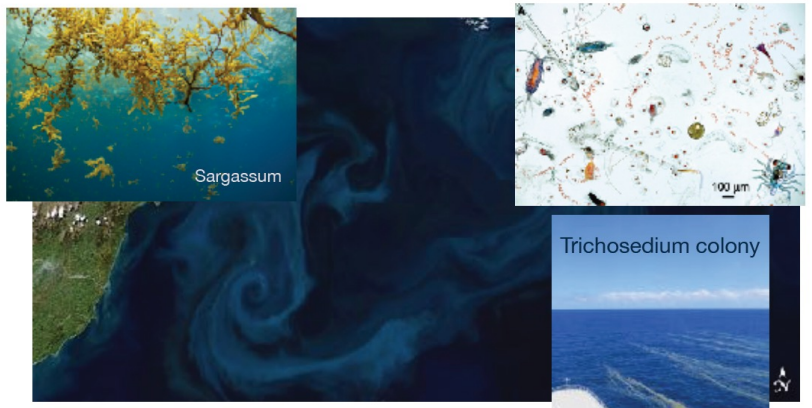
Lamb and Verlinde, *Physics and chemistry of clouds*, CUP, 2011



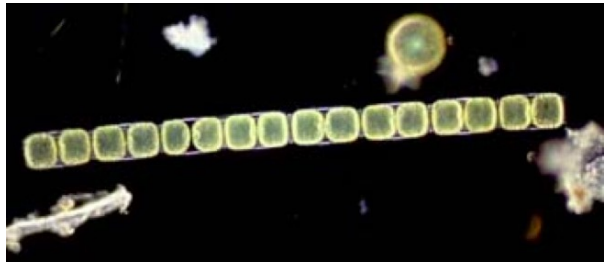
W. Brune



Ice crystals in clouds



Plankton/algae



Diatoms colonies, phytoplankton
(CO2 oceanic pump)



Cellulose fibers (paper industry)

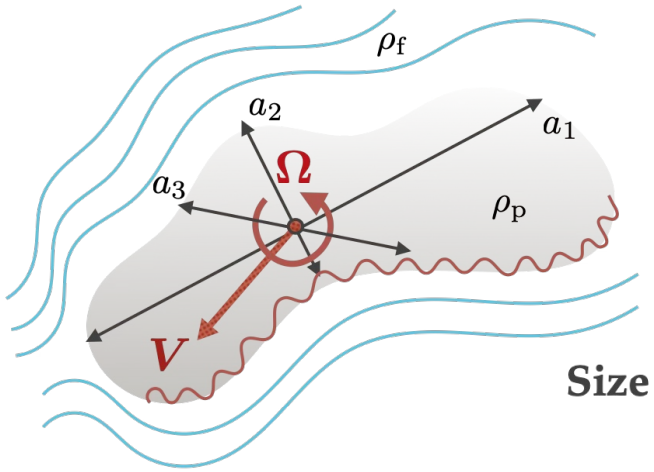
Wang *et al.*, Chemosphere, 329, 2023



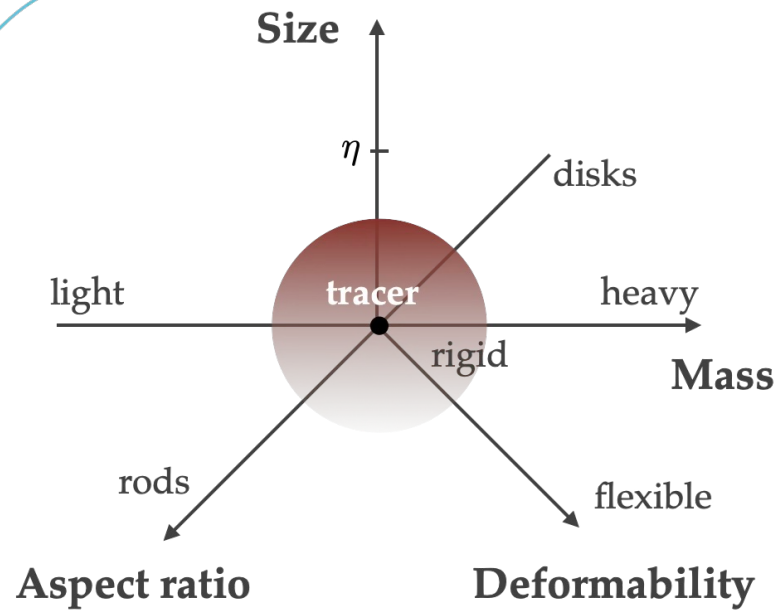
Plastic pollution

Complex particles in turbulence

Intricate dynamics/ parameter space



Possibly large number of internal degrees of freedom



ONE-WAY COUPLING:
how does turbulence affect the particles?

How do they rotate? **Where do they go? (clustering)**

How do they move? **How do they collide?**

Do they align?

How do different shape, length and inertia affect the statistics?

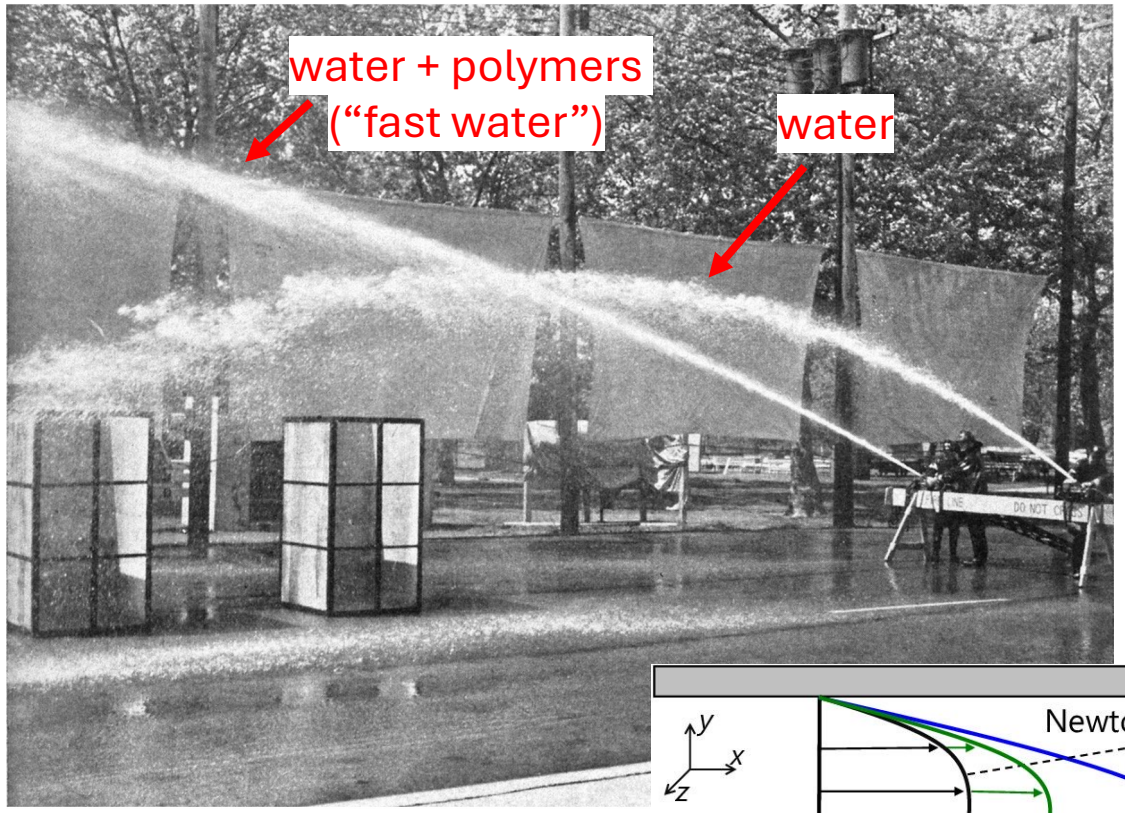
TWO-WAY COUPLING:
+ back-reaction of the particles to the flow

Do particles modify turbulence?

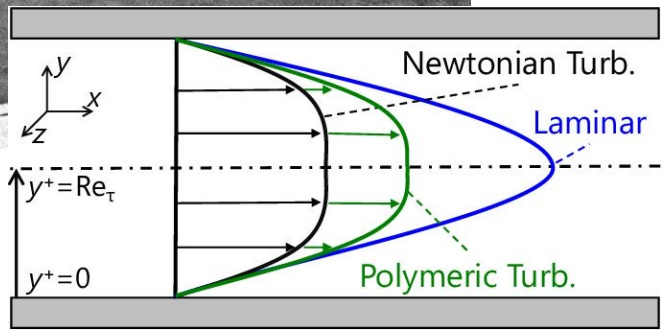
If so, to what extent can their dynamics be exploited to modulate turbulence?

A striking example of two-way coupling: drag reduction

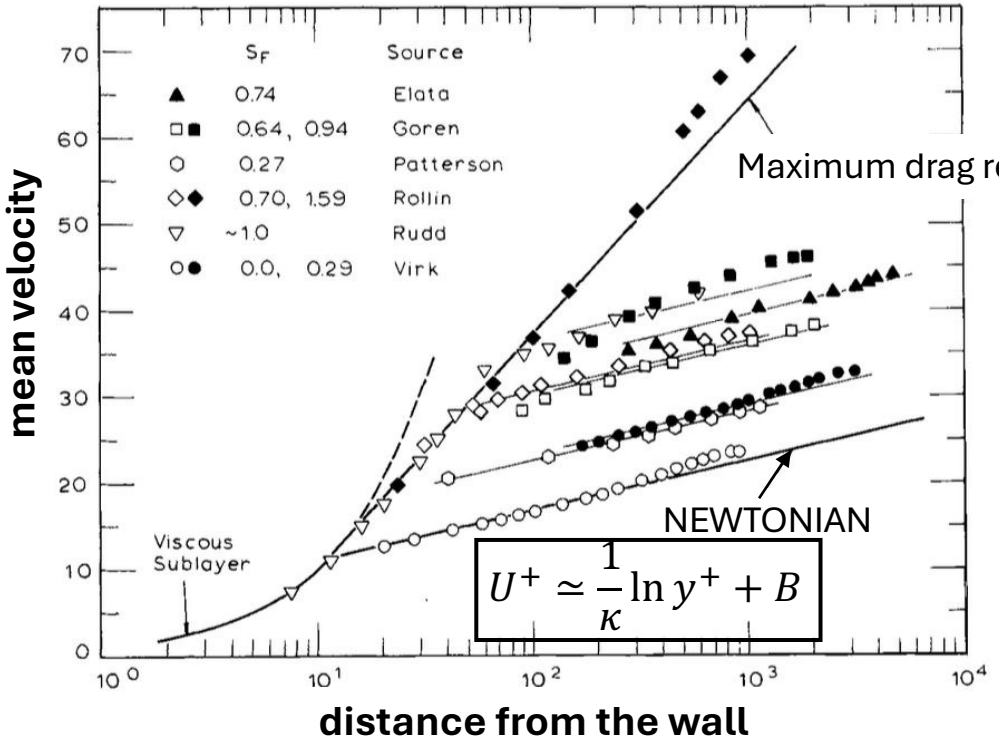
“Slippery water” demonstration, New York, 1969



A. Rajappan, *Polymers and Plastrons: Active and Passive Drag Reduction in Wall-Bounded Turbulent Flows*, Sc.D. thesis, Massachusetts Institute of Technology (2020)

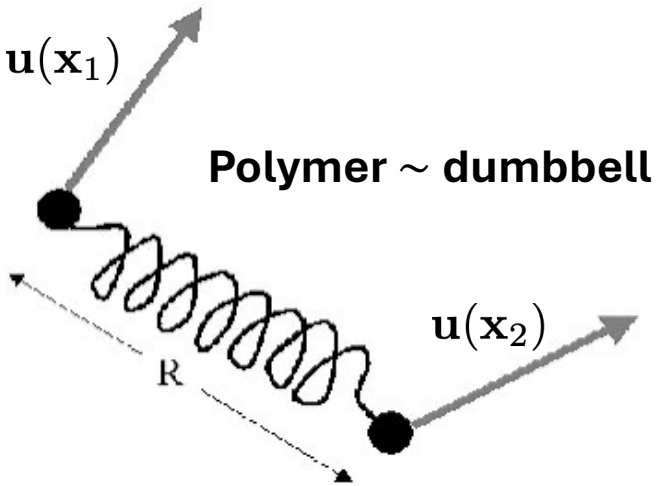


Drag reduction of different polymeric solutions



Virk, Preetinder S. "Drag reduction fundamentals." *AIChE Journal* (1975)

How has the feedback on the flow been modeled?



FENE-P (continuum model for flexible polymers)

$$d\mathbf{R} = \left[(\nabla \mathbf{u}) \cdot \mathbf{R} - \frac{1}{2Wi} f(\mathbf{C})\mathbf{R}\right] dt + \frac{1}{\sqrt{Wi}} d\mathbf{W}_t, \qquad \mathbf{C} = \langle \mathbf{RR} \rangle.$$

- $(\nabla \mathbf{u}) \cdot \mathbf{R}$: stretching by the flow
- $\frac{1}{2Wi} f(\mathbf{C})\mathbf{R}$: elastic relaxation
- $\frac{1}{\sqrt{Wi}} d\mathbf{W}_t$: thermal fluctuations
- $\mathbf{C} = \langle \mathbf{RR} \rangle$: Conformation tensor average over dumbbells

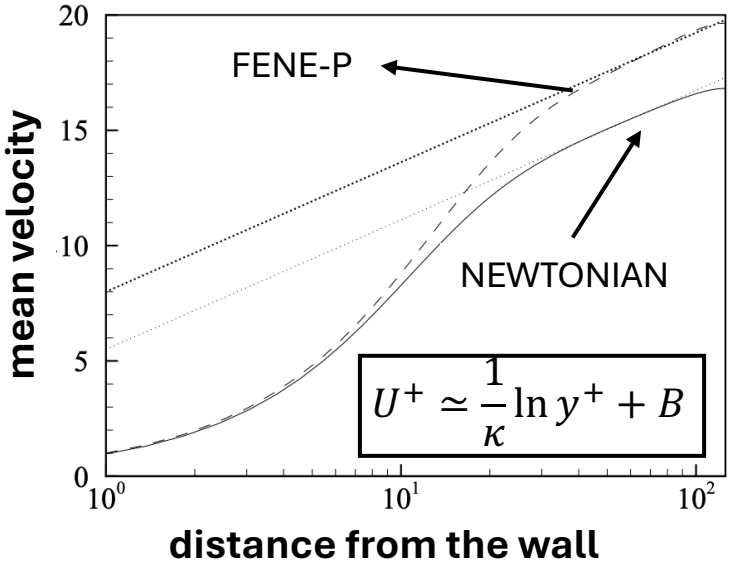
Polymeric stress: $\boldsymbol{\sigma}_p = \frac{1-\beta}{Re\,Wi}\left[f(\mathbf{C})\mathbf{C} - \mathbf{I}\right], \qquad f(\mathbf{C}) = \frac{L_{\max}^2 - 3}{L_{\max}^2 - \operatorname{tr}\mathbf{C}}.$

($1-\beta$: solvent fraction)

EULERIAN - EULERIAN

$$\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} = -\nabla p + \frac{\beta}{Re}\nabla^2 \mathbf{u} + \nabla \cdot \boldsymbol{\sigma}_p + \mathbf{f},$$

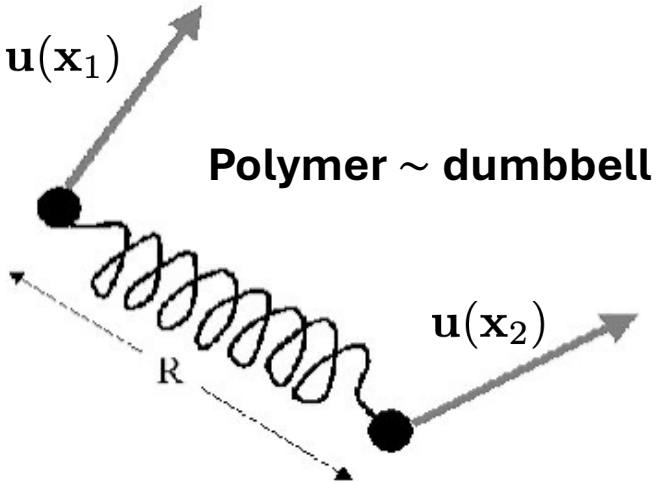
$$\frac{\partial \mathbf{C}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{C} = (\nabla \mathbf{u}) \cdot \mathbf{C} + \mathbf{C} \cdot (\nabla \mathbf{u})^T - \frac{Re}{1-\beta}\boldsymbol{\sigma}_p.$$



Benzi et al., *J. Fluid Mech.* 551, 185–195 (2006)

continuum model: individual polymers are represented statistically

Fully coupled Eulerian-Lagrangian simulations



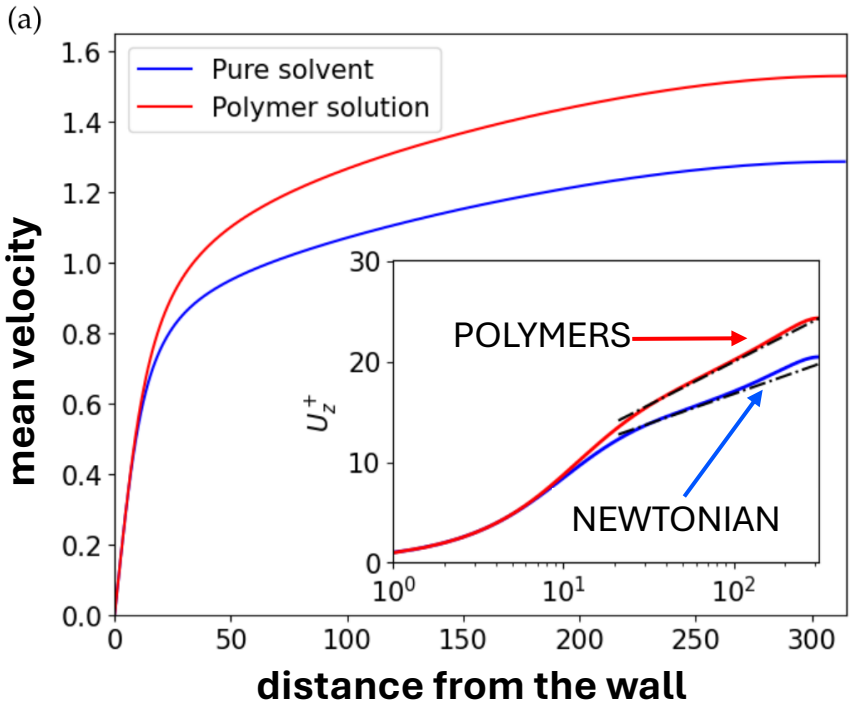
LAGRANGIAN

$$\frac{d\mathbf{R}^{(j)}}{dt} = \mathbf{u}\left(\mathbf{x}_2^{(j)}, t\right) - \mathbf{u}\left(\mathbf{x}_1^{(j)}, t\right) - \underbrace{\frac{1}{Wi}\frac{\mathbf{R}^{(j)}}{1 - |\mathbf{R}^{(j)}|^2/L_{\max}^2}}_{\mathbf{F}_{f\to p}} + \sqrt{\frac{R_{\mathrm{eq}}^2}{3Wi}}\left(\boldsymbol{\xi}_2^{(j)} - \boldsymbol{\xi}_1^{(j)}\right)$$

Fully 2-way coupled simulations **track individual flexible polymers** and their **feedback** on turbulence

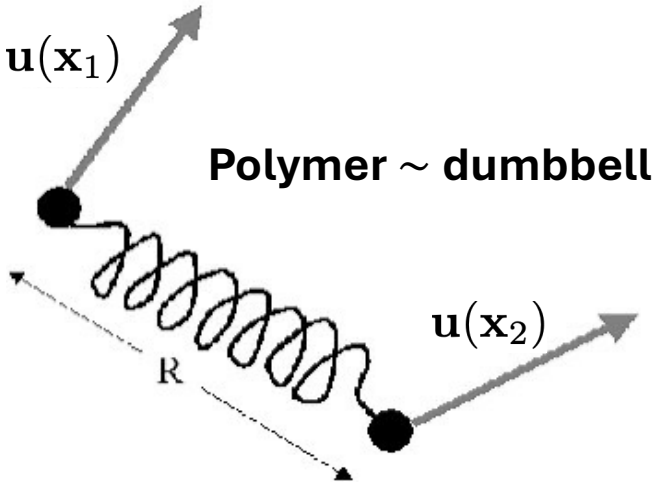
EULERIAN

$$\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u}\cdot\nabla\mathbf{u} = -\nabla p + \frac{1}{Re}\nabla^2\mathbf{u} + \mathbf{F}_{p\to f} + \mathbf{f}, \qquad \mathbf{F}_{p\to f}(\mathbf{x},t) = -\mathbf{F}_{f\to p}(\mathbf{x},t)$$



Serafini, Battista, Gualtieri & Casciola, *Fluids* 7, 355 (2022)

Fully coupled Eulerian-Lagrangian simulations



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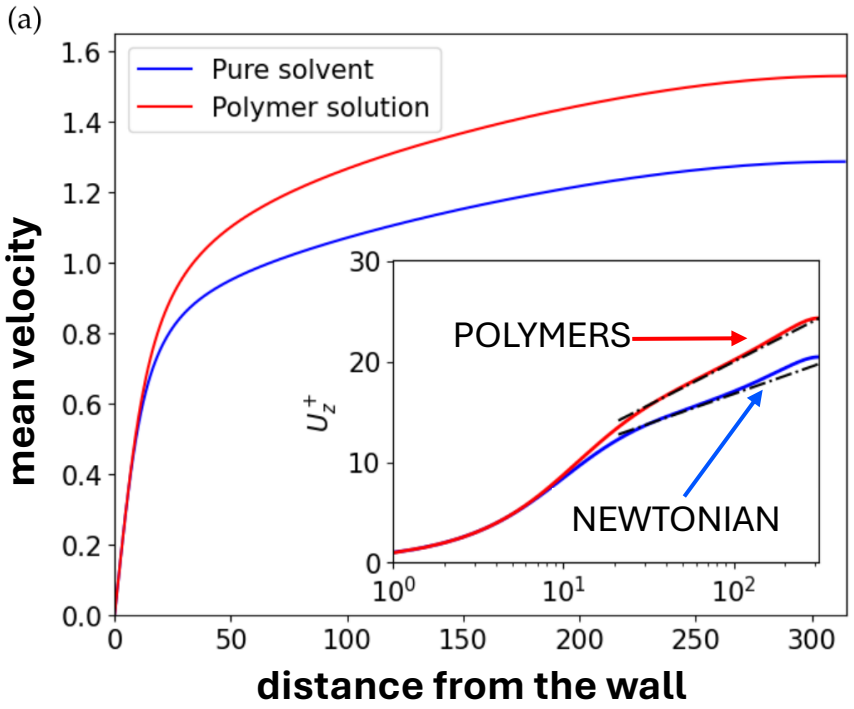


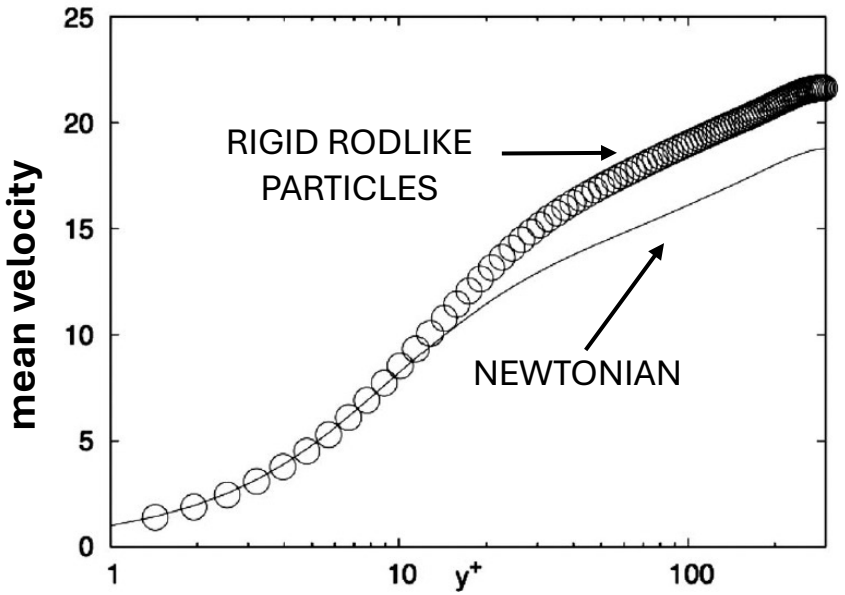
Serafini, Battista, Gualtieri & Casciola, *Fluids* 7, 355 (2022)

polymers still represented as idealized elastic dumbbells…

Another route to drag reduction: rodlike particles

EULERIAN-EULERIAN

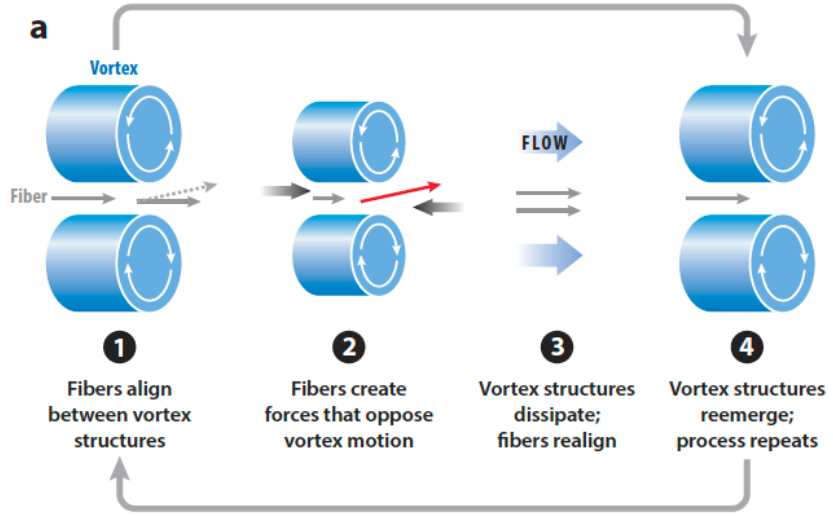
Rigid rodlike additives can enhance the mean flow even without polymer stretching

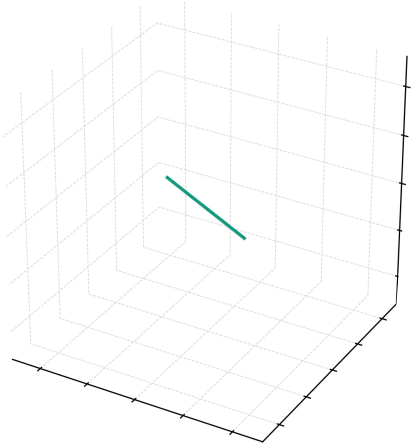


Benzi *et al.*, *Phys. Rev. E* **77**, 046309 (2008)

Continuum model: only for inertialess, small rods, represented by a **orientation-based stress**

Sketch of proposed mechanisms for rigid-fiber induced drag reduction:





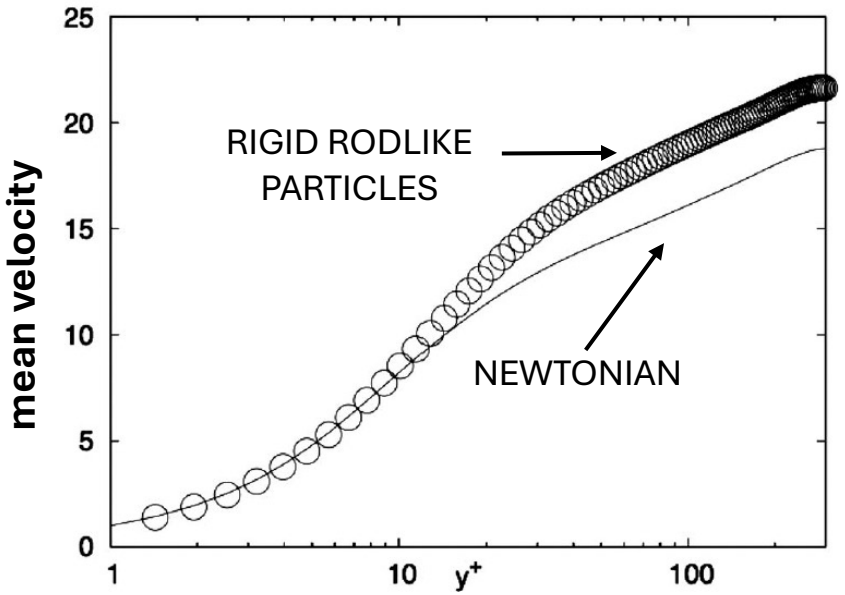
Paschkewitz et al., Journal of Fluid Mechanics 518 (2004)

Flexible polymers:
stretching and elastic relaxation
Rigid fiber:
Orientation, rotation, interaction with vortical structures?

Another route to drag reduction: rodlike particles

EULERIAN-EULERIAN

Rigid rodlike additives can enhance the mean flow even without polymer stretching



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stretching and elastic relaxation
Rigid fiber:

NEED **EULERIAN-LAGRANGIAN** SIMULATIONS TO FULLY RESOLVE RIGID FIBERS DYNAMICS

Some open questions on rigid fibers dynamics

DragREACT
Marie Skłodowska-Curie Postdoctoral Fellowship
Starting 1 October 2026, GA No. 101273291

Funded by the European Union

THIS TALK:
ONE-WAY COUPLING (in HIT):
how does turbulence affect the fibers?

How do they rotate? **Where do they go? (clustering)**

How do they move? **How do they collide?**

Do they align?

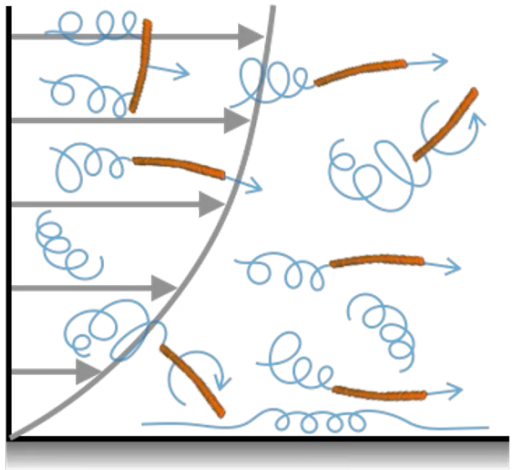
How do different shape, length and inertia affect the statistics?

NEXT (TWO-WAY COUPLING):
back-reaction of the fibers to the flow

How do different fibers feedback on the flow?
(i.e., investigate drag reduction effects, if any)

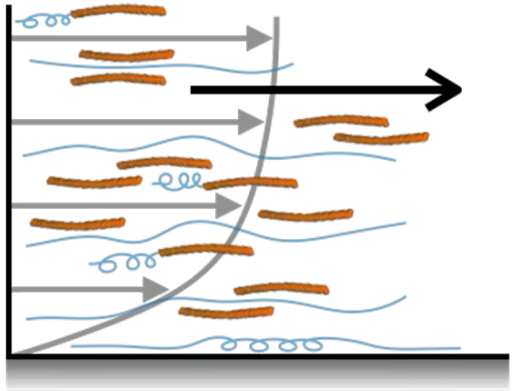
Can we control clustering and alignment?
(i.e., achieving optimal drag reduction)

Fibers (Lagrangian)

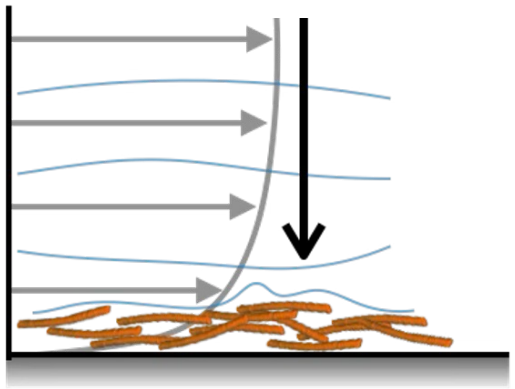


Increased mean flow?

streamwise alignment



Near-wall accumulation



NEED **EULERIAN-LAGRANGIAN** SIMULATIONS TO FULLY RESOLVE RIGID FIBERS DYNAMICS

Models for elongated particles/fibers in turbulence

Assumptions:

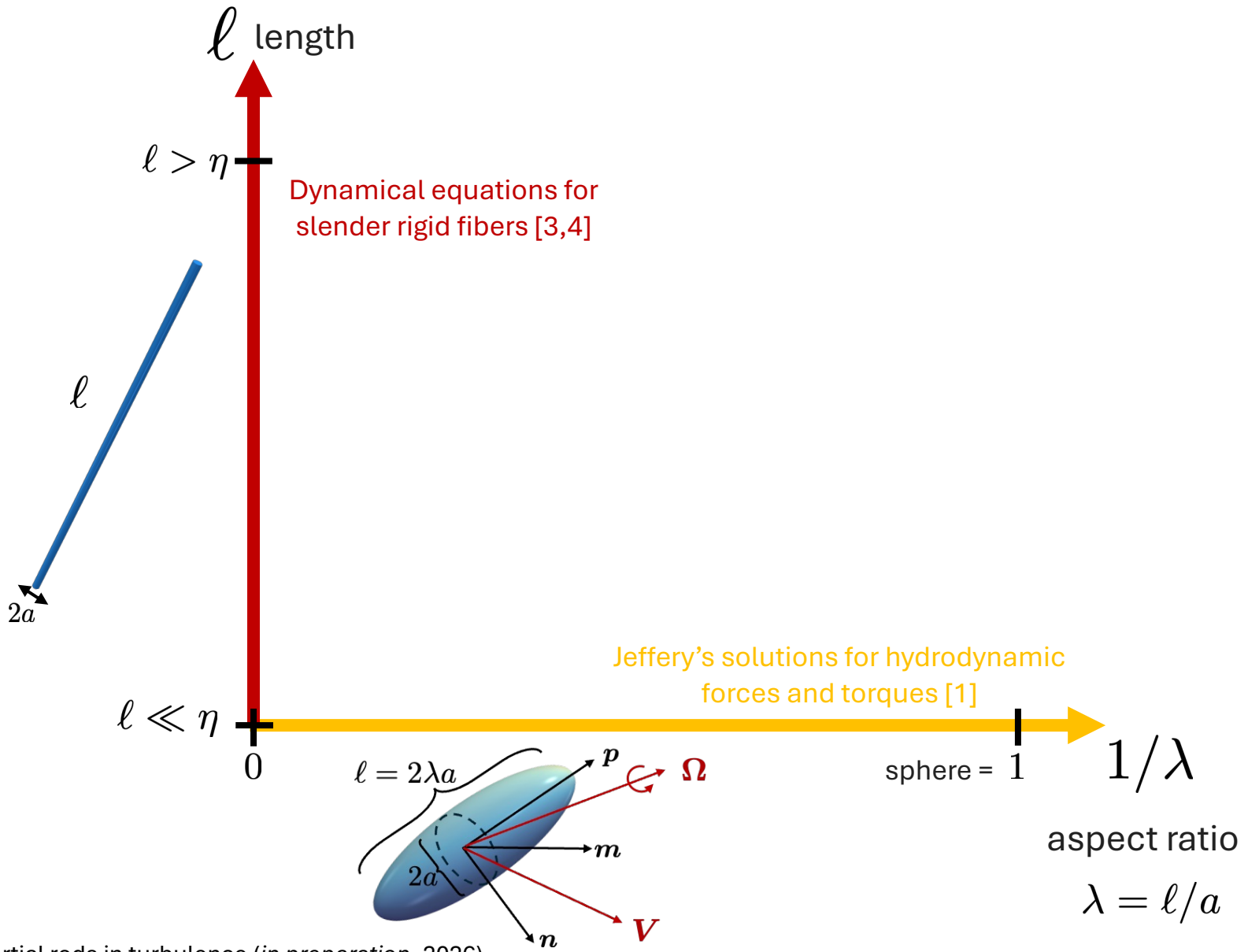
Particles diameter $2a \ll \eta$

Heavy particles $\rho_p \gg \rho_f$

Perturbation = Stokes flow

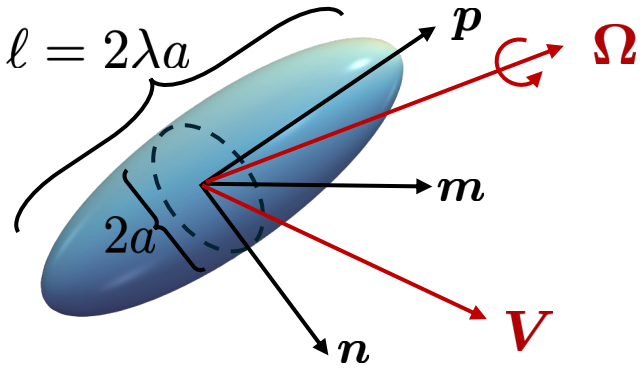
$$\begin{cases} -\nabla p + \mu \nabla^2 \boldsymbol{u} = 0 \\ Re_{\mathrm{p}} = \dfrac{\rho_{\mathrm{p}} |V - u| a}{\mu} \to 0 \end{cases}$$

Analytical solutions for hydrodynamic forces and torques acting on elongated particles [1-4]



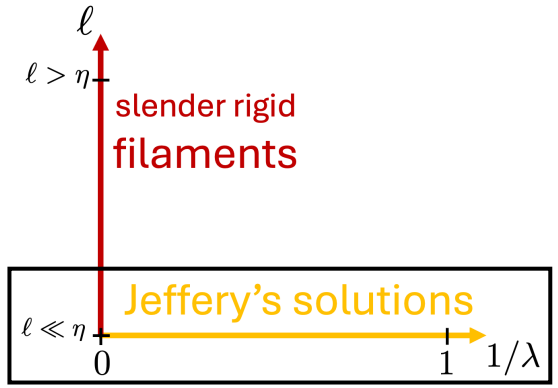
[1] Jeffery. Proc. R. Soc. Lond. A 102:161–79 (1922)
[2] Cox, J. Fluid Mech. 44.4, 791-810 (1970)
[3] Keller & Rubinow, J. Fluid Mech. 75.4, 705-714 (1976)
[4] Calascibetta, Allende, Bec. Alignment and clustering of heavy inertial rods in turbulence (*in preparation*, 2026)

Jeffery's solutions: $\ell \ll \eta$



Particle frame: $\mathbb{Q}^{\mathsf{T}} = [\boldsymbol{m}\,\boldsymbol{n}\,\boldsymbol{p}]$

$$\tilde{\boldsymbol{V}} = \mathbb{Q}\boldsymbol{V}, \quad \tilde{\boldsymbol{\Omega}} = \mathbb{Q}\boldsymbol{\Omega}$$



- **Translational** dynamics: **anisotropic drag**

$$\frac{\mathrm{d}\boldsymbol{V}}{\mathrm{d}t} = -\mathbb{Q}^{\mathsf{T}}\,\mathbb{D}\,\mathbb{Q}\,[\boldsymbol{V} - \boldsymbol{u}(\boldsymbol{X},t)]$$

rotation matrix

drag tensor:
diagonal in particle frame $\mathbb{D} = \mathrm{diag}\left(\frac{1}{\tau_\perp}, \frac{1}{\tau_\perp}, \frac{1}{\tau_\parallel}\right)$

$$\frac{\mathrm{d}\mathbb{Q}_{ij}}{\mathrm{d}t} = -\varepsilon_{ik\ell}\,\tilde{\Omega}_k\,\mathbb{Q}_{\ell j}$$

- **Angular** dynamics: **tumbling vs spinning**

$$\frac{\mathrm{d}\tilde{\boldsymbol{\Omega}}}{\mathrm{d}t} + \mathbb{I}^{-1}\tilde{\boldsymbol{\Omega}} \times (\mathbb{I}\,\tilde{\boldsymbol{\Omega}}) = \begin{pmatrix} -\frac{1}{\tau_{\mathrm{tumb}}}\left(\tilde{\Omega}_1 - \frac{1}{2}\tilde{\omega}_1 + \Lambda\tilde{S}_{32}\right) \\ -\frac{1}{\tau_{\mathrm{tumb}}}\left(\tilde{\Omega}_2 - \frac{1}{2}\tilde{\omega}_2 - \Lambda\tilde{S}_{13}\right) \\ -\frac{1}{\tau_{\mathrm{spin}}}\left(\tilde{\Omega}_3 - \frac{1}{2}\tilde{\omega}_3\right) \end{pmatrix}$$

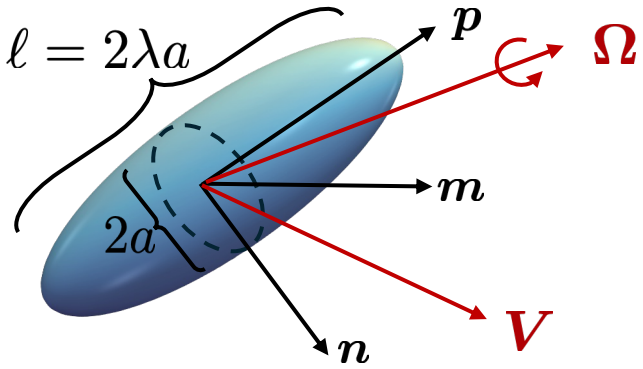
(vorticity and strain tensor)
$\tilde{\omega}_i\,,\ \tilde{S}_{ij}$

$$\Lambda = \frac{\lambda^2 - 1}{\lambda^2 + 1}$$

$\lambda = 1 \rightarrow$ spherical particle

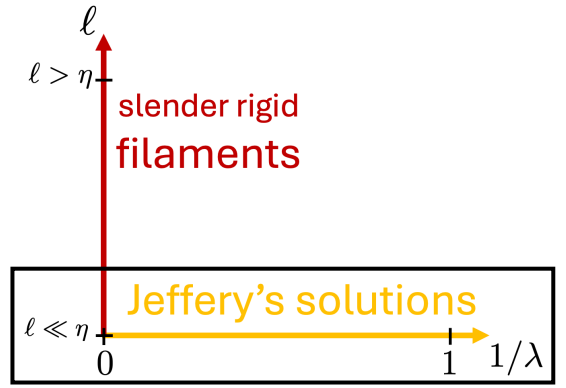
Non-trivial translational-rotational coupled dynamics with different time-scales involved

Jeffery's solutions: $\ell \ll \eta$



Particle frame: $\mathbb{Q}^{\mathsf{T}} = [\boldsymbol{m}\,\boldsymbol{n}\,\boldsymbol{p}]$

$$\tilde{\boldsymbol{V}} = \mathbb{Q}\boldsymbol{V}, \quad \tilde{\boldsymbol{\Omega}} = \mathbb{Q}\boldsymbol{\Omega}$$



- **Translational** dynamics: **anisotropic drag**

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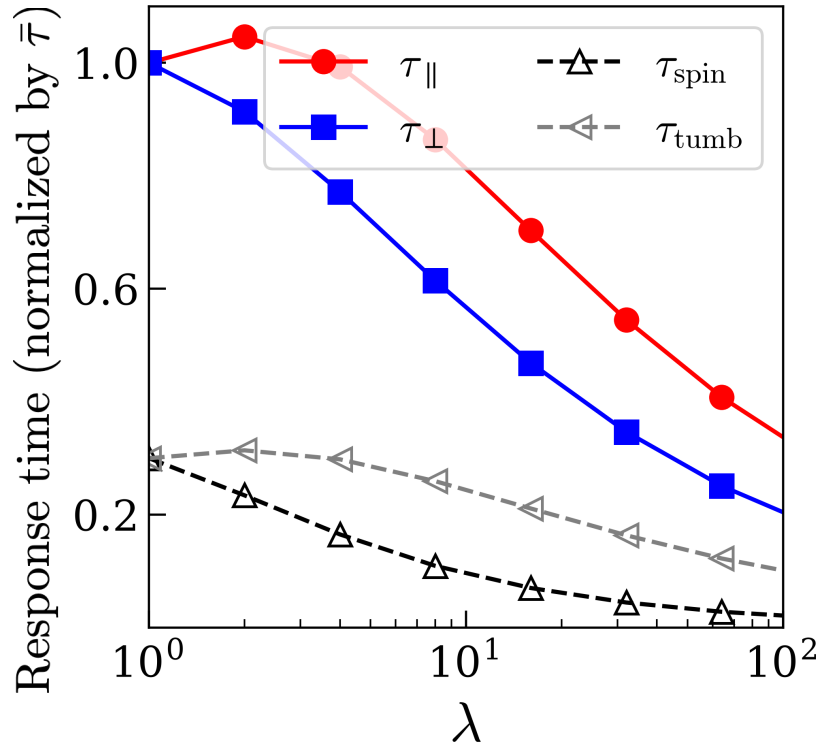
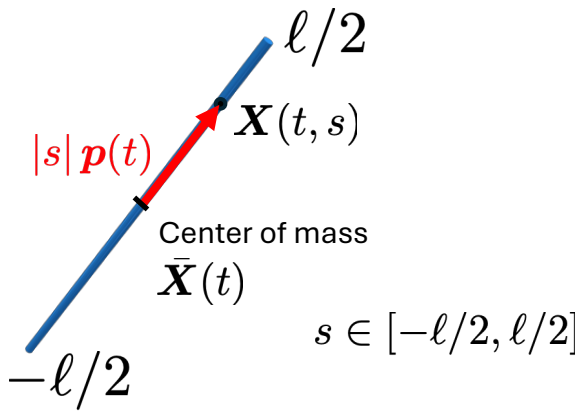


SBT Solutions [*]: thin & rigid fibers of any length

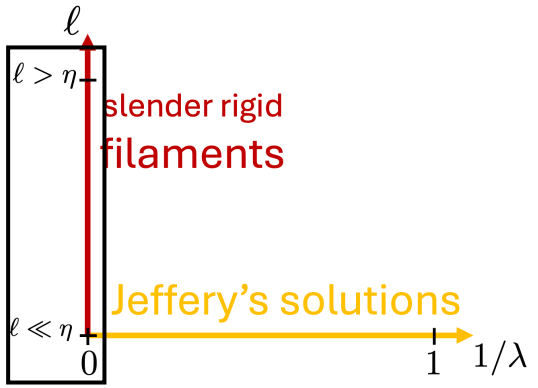


$s \in [-\ell/2, \ell/2]$

(We assume constant density mass)

$$\bar{\boldsymbol{X}}(t) = \frac{1}{\ell}\int \boldsymbol{X}(s,t)ds \qquad \bar{\boldsymbol{V}} = \frac{d\bar{\boldsymbol{X}}(t)}{dt}$$

Rigid filament of constant direction ***p***(t)



- **Translational** dynamics:

$$\frac{d\bar{\boldsymbol{V}}}{dt} = -\frac{1}{\tau_F}\left(\mathbb{1} - \frac{1}{2}\boldsymbol{p}\boldsymbol{p}^{\intercal}\right)\left[\bar{\boldsymbol{V}} - \bar{\boldsymbol{u}}(\bar{\boldsymbol{X}},t)\right] \qquad \bar{\boldsymbol{u}}(\bar{\boldsymbol{X}},t) = \frac{1}{\ell}\int \boldsymbol{u}(\boldsymbol{X},t)ds$$

$$\tau_F \approx \frac{m_p \log\lambda}{8\pi\mu\lambda a}$$

[Characteristic time of the fibers]

- **Angular** dynamics:

$$\frac{d}{dt}\boldsymbol{p} = \boldsymbol{\Omega}\times\boldsymbol{p} \qquad \frac{d}{dt}\boldsymbol{\Omega} = -\frac{1}{\tau_F}\left[\boldsymbol{\Omega} - \bar{\boldsymbol{\omega}}\right] \qquad \bar{\boldsymbol{\omega}} = \frac{12}{\ell^3}\int_{-\ell/2}^{\ell/2} s\boldsymbol{p}\times\boldsymbol{u}(\bar{\boldsymbol{X}} + s\boldsymbol{p})ds$$

[*] Cox, J. Fluid Mech. 44.4, 791-810 (1970) ; Keller & Rubinow, J. Fluid Mech. 75.4, 705-714 (1976)
Calascibetta, Allende, Bec. Small-scale alignment and clustering of heavy inertial rods in turbulence (*in preparation*, 2026)

Numerical Results: Validation of the Rotational (Angular) Dynamics

We focus to the **overdamped limit**, $\tau_p = \tau_F \to 0$, for both **Jeffery** and **SBT** solutions:

Jeffery (tumbling):

$$\frac{\mathrm{d}\tilde{\boldsymbol{\Omega}}}{\mathrm{d}t} + \mathbb{I}^{-1}\tilde{\boldsymbol{\Omega}} \times (\mathbb{I}\,\tilde{\boldsymbol{\Omega}}) = \begin{pmatrix} -\frac{1}{\tau_{\text{tumb}}}\left(\tilde{\Omega}_1 - \frac{1}{2}\tilde{\omega}_1 + \Lambda\tilde{S}_{32}\right) \\ -\frac{1}{\tau_{\text{tumb}}}\left(\tilde{\Omega}_2 - \frac{1}{2}\tilde{\omega}_2 - \Lambda\tilde{S}_{13}\right) \\ -\frac{1}{\tau_{\text{spin}}}\left(\tilde{\Omega}_3 - \frac{1}{2}\tilde{\omega}_3\right) \end{pmatrix} \xrightarrow[\text{Tumbling only on 1 \& 2}]{\tilde{\boldsymbol{\Omega}}_{\mathrm{T}} = \tilde{\Omega}_1\boldsymbol{m} + \tilde{\Omega}_2\boldsymbol{n}}$$

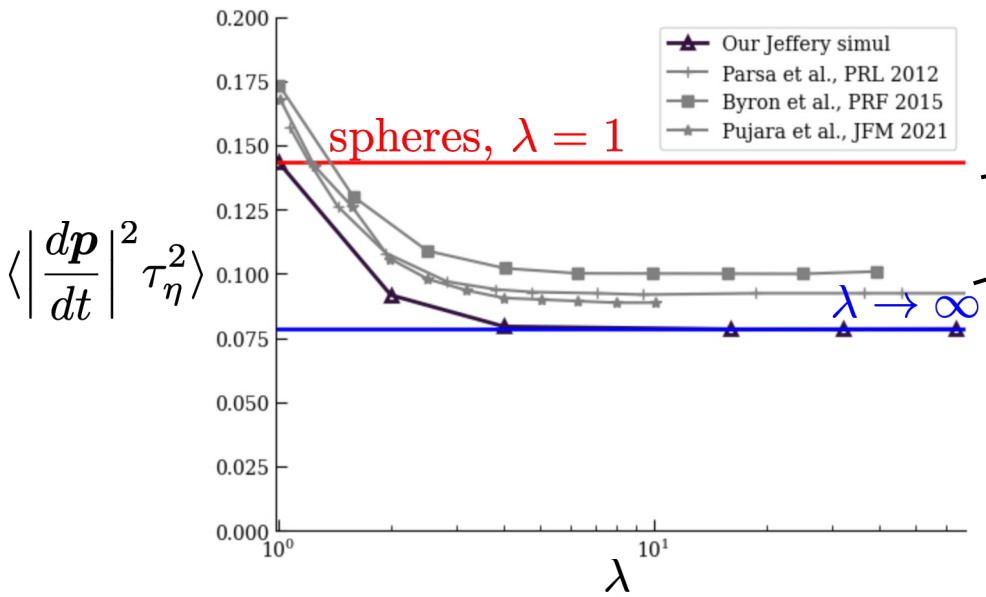
Slender Body Theory:

$$\frac{d}{dt}\boldsymbol{\Omega} = -\frac{1}{\tau_F}[\boldsymbol{\Omega} - \bar{\boldsymbol{\omega}}] \xrightarrow[\text{Tumbling only dynamics}]{} \bar{\boldsymbol{\omega}} = \frac{12}{\ell^3}\int_{-\ell/2}^{\ell/2} s\boldsymbol{p} \times \boldsymbol{u}(\bar{\boldsymbol{X}} + s\boldsymbol{p})ds$$

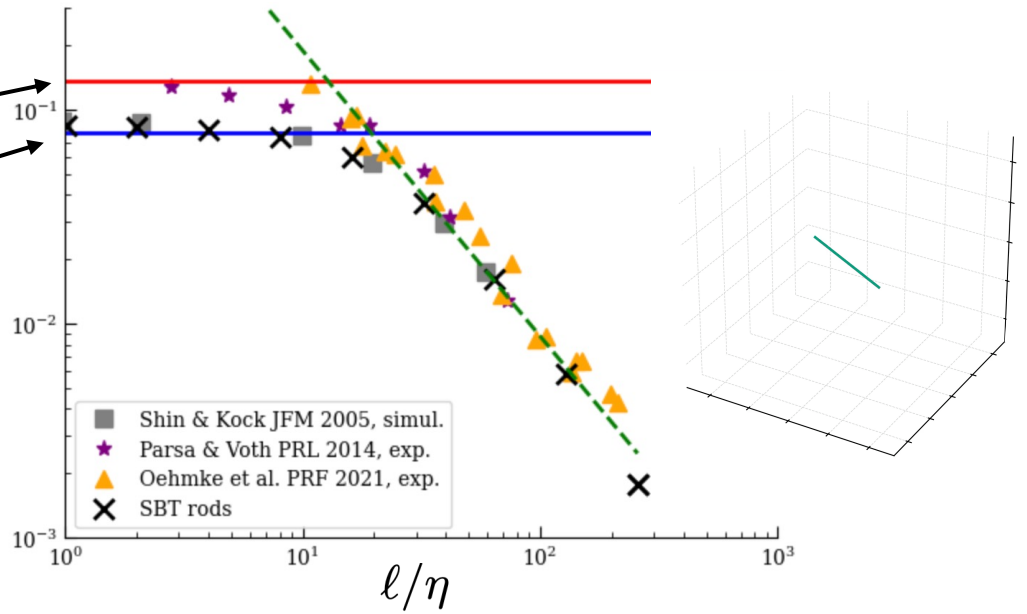
$$\frac{d\boldsymbol{p}}{dt} = \boldsymbol{\Omega}_T \times \boldsymbol{p}$$

$$\left|\frac{d\boldsymbol{p}}{dt}\right|^2 = |\Omega_T|^2$$

Tumbling rate for Jeffery (prolate particles)



Tumbling rate of the rigid fibers (SBT)



Numerical Results: Validation of the Rotational (Angular) Dynamics

We focus to the **overdamped limit:** $\tau_p = \tau_F \to 0$

Slender Body Theory: $\frac{d}{dt}\boldsymbol{\Omega} = -\frac{1}{\tau_F}[\boldsymbol{\Omega} - \bar{\boldsymbol{\omega}}]$ → Tumbling only dynamics → $\bar{\boldsymbol{\omega}} = \frac{12}{\ell^3}\int_{-\ell/2}^{\ell/2} s\boldsymbol{p} \times \boldsymbol{u}(\bar{\boldsymbol{X}} + s\boldsymbol{p})ds$

$$\ell \gg \eta \to \boldsymbol{u} \sim s^{1/3}$$

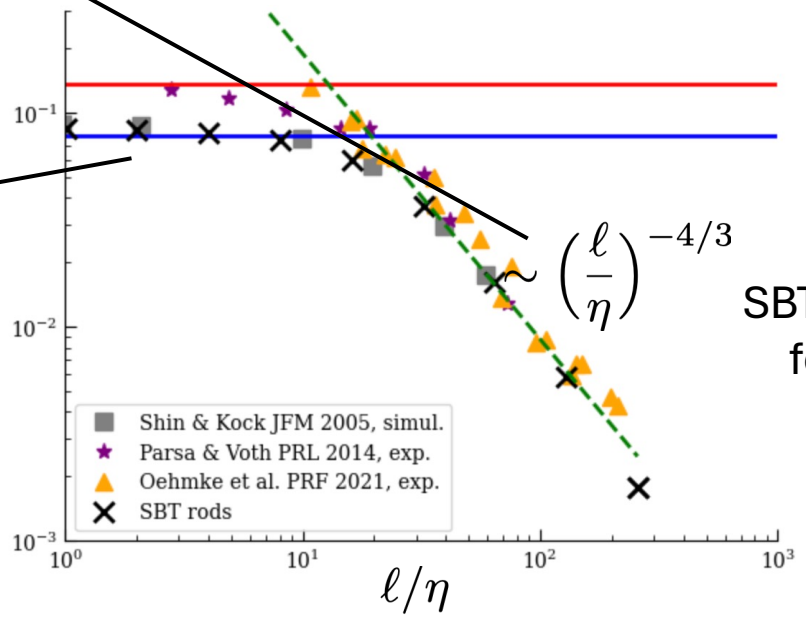
$$\left|\frac{d\boldsymbol{p}}{dt}\right|^2 = |\bar{\boldsymbol{\omega}}|^2 \sim \frac{1}{\ell^6}\left(\int_{-\ell/2}^{\ell/2} s\,\boldsymbol{u}(s)ds\right)^2 \sim \frac{1}{\ell^6}\left(\int_{-\ell/2}^{\ell/2} s\,s^{1/3}ds\right)^2 \sim \frac{1}{\ell^6}\left(\int_{-\ell/2}^{\ell/2} s^{4/3}ds\right)^2 \sim \frac{1}{\ell^6}\,\ell^{14/3} \sim \ell^{-4/3}$$

$$\ell \sim \eta \to \boldsymbol{u} \sim s$$

$$\left|\frac{d\boldsymbol{p}}{dt}\right|^2 = |\bar{\boldsymbol{\omega}}|^2 \sim \frac{1}{\ell^6}\left(\int_{-\ell/2}^{\ell/2} s\,\boldsymbol{u}(s)ds\right)^2 \sim \frac{1}{\ell^6}\left(\int_{-\ell/2}^{\ell/2} s^2 ds\right)^2 \sim const$$

Tumbling rate of the rigid fibers (SBT)

$\left\langle\left|\frac{d\boldsymbol{p}}{dt}\right|^2 \tau_\eta^2\right\rangle$



SBT prediction for $St \to 0$

Numerical Results: Validation of the Rotational (Angular) Dynamics

We focus on the **inertial contribution** , $\tau_p, \tau_F \neq 0$, for both **Jeffery** and **SBT** solutions:

Jeffery (tumbling):

$$\frac{\mathrm{d}\tilde{\boldsymbol{\Omega}}}{\mathrm{d}t} + \mathbb{I}^{-1}\tilde{\boldsymbol{\Omega}} \times (\mathbb{I}\,\tilde{\boldsymbol{\Omega}}) = \begin{pmatrix} -\frac{1}{\tau_{\mathrm{tumb}}}\left(\tilde{\Omega}_1 - \frac{1}{2}\tilde{\omega}_1 + \Lambda\tilde{S}_{32}\right) \\ -\frac{1}{\tau_{\mathrm{tumb}}}\left(\tilde{\Omega}_2 - \frac{1}{2}\tilde{\omega}_2 - \Lambda\tilde{S}_{13}\right) \\ -\frac{1}{\tau_{\mathrm{spin}}}\left(\tilde{\Omega}_3 - \frac{1}{2}\tilde{\omega}_3\right) \end{pmatrix} \xrightarrow[\text{Tumbling only on 1 \& 2}]{\tilde{\boldsymbol{\Omega}}_{\mathrm{T}} = \tilde{\Omega}_1 \boldsymbol{m} + \tilde{\Omega}_2 \boldsymbol{n}}$$

Slender Body Theory:

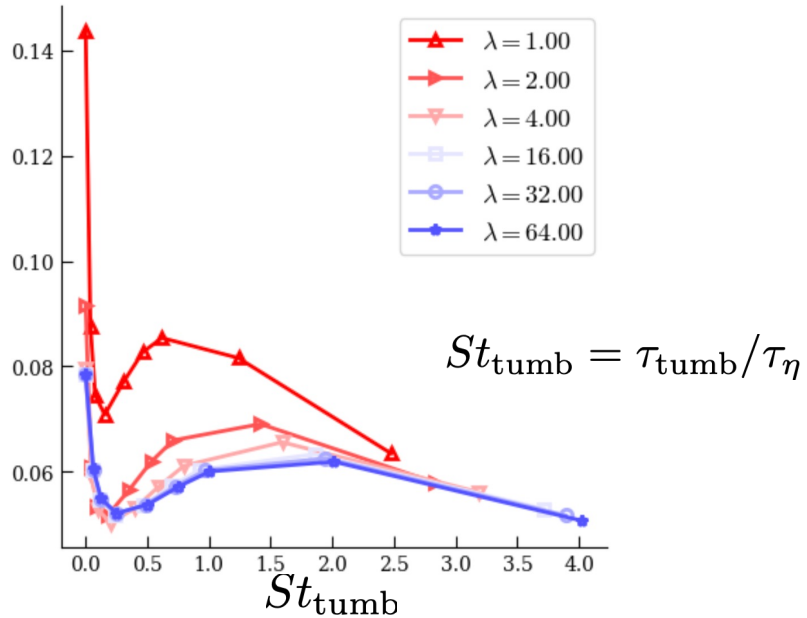
$$\frac{d}{dt}\boldsymbol{\Omega} = -\frac{1}{\tau_F}\left[\boldsymbol{\Omega} - \bar{\boldsymbol{\omega}}\right] \xrightarrow[\text{Tumbling only dynamics}]{} \bar{\boldsymbol{\omega}} = \frac{12}{\ell^3}\int_{-\ell/2}^{\ell/2} s\boldsymbol{p} \times \boldsymbol{u}(\bar{\boldsymbol{X}} + s\boldsymbol{p})ds$$

$$\frac{d\boldsymbol{p}}{dt} = \boldsymbol{\Omega}_T \times \boldsymbol{p}$$

$$\left|\frac{d\boldsymbol{p}}{dt}\right|^2 = |\Omega_T|^2$$

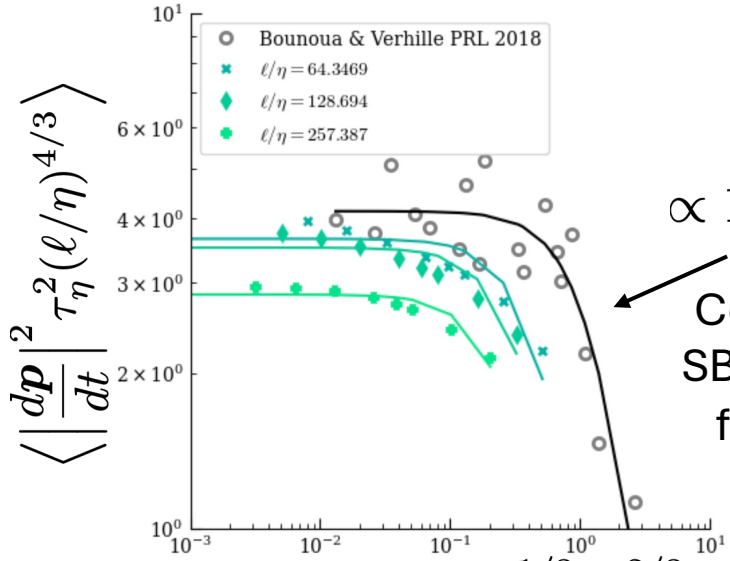
Tumbling rate for Jeffery (prolate particles)

$\left\langle \left|\frac{d\boldsymbol{p}}{dt}\right|^2 \tau_\eta^2 \right\rangle$



$St_{\mathrm{tumb}} = \tau_{\mathrm{tumb}}/\tau_\eta$

Tumbling rate of the rigid fibers (SBT)



$\propto 1/(1 + \beta St^2)$

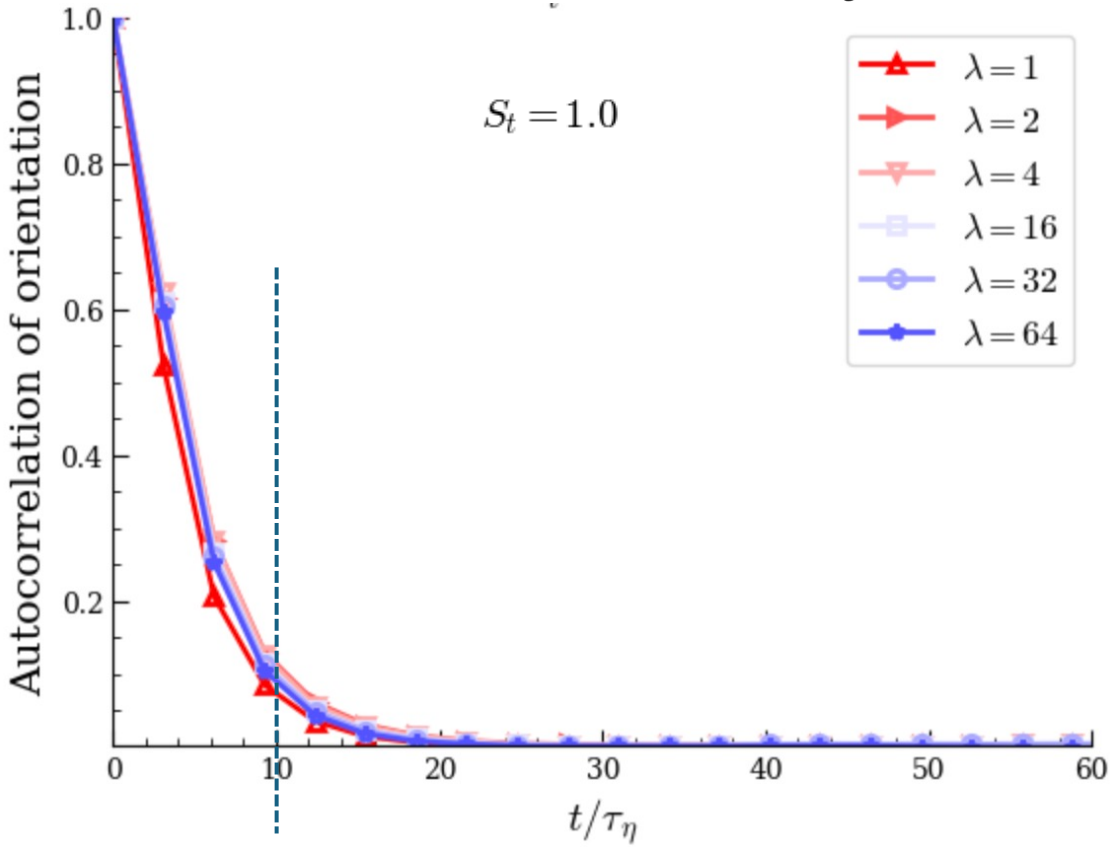
Correction to SBT prediction for $St \rightarrow \infty$

Numerical Results: Preferential Alignment

Is there any preferential Alignment?

We measure **Autocorrelation of filaments orientations**:

$$\left\langle \left(\boldsymbol{p}(t+\tau) \cdot \boldsymbol{p}(t) \right)^2 \right\rangle_c$$

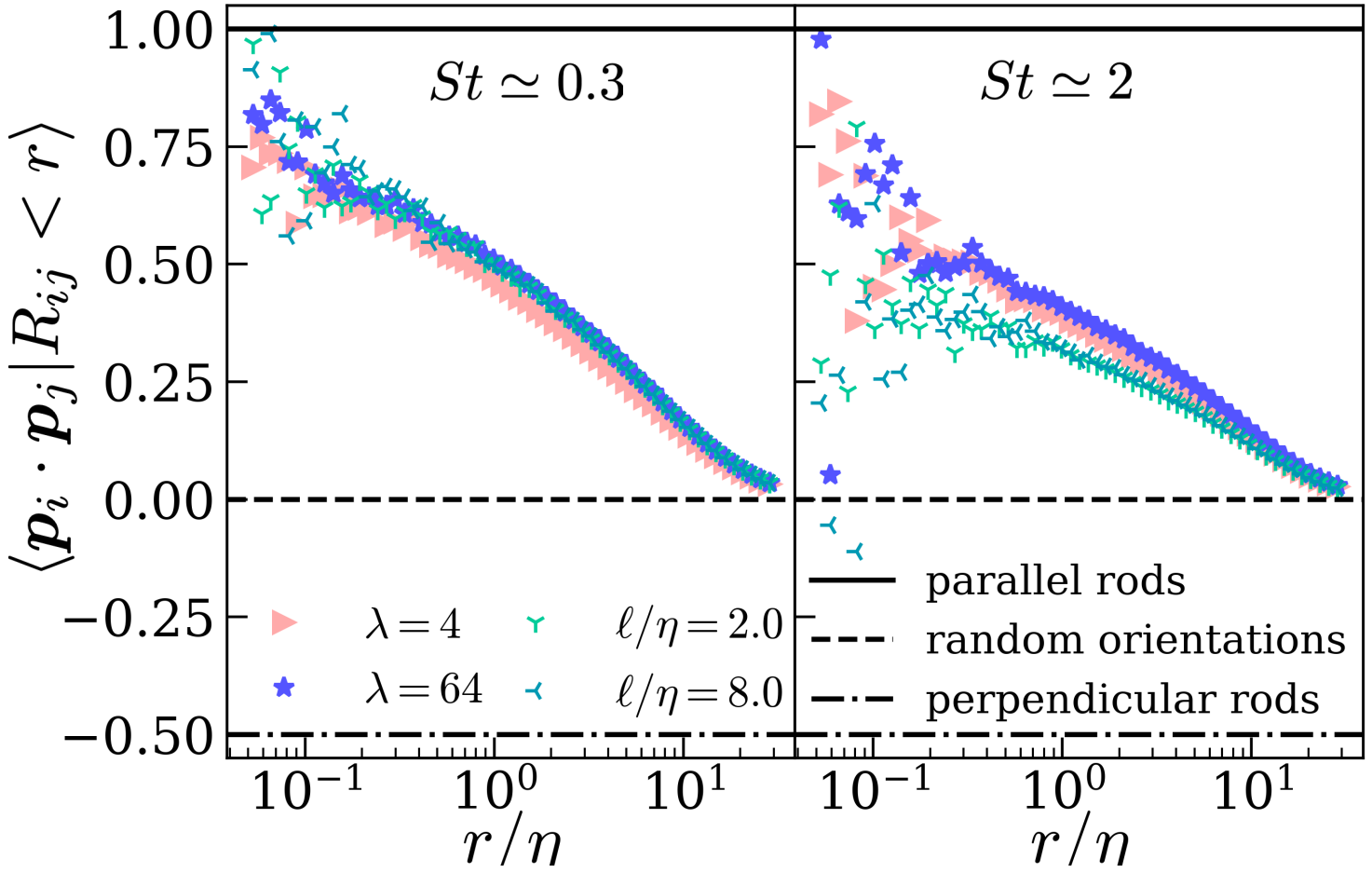


There is a long correlation of orientations before tumbling reorients the filaments

$\sim 10\tau_\eta$ **between tumbling events**

Numerical Results: Preferential Alignment

Is there any preferential Alignment?



Nearby elongated particles are strongly aligned

Numerical Results: Preferential Alignment

How do the particles align between tumbling?

In the overdamped limit, $\tau_p \to 0, \lambda \to \infty$ of Jeffery solution:

$$\boldsymbol{\Omega}_{\mathrm{T}} = \boldsymbol{p} \times \left[\frac{1}{2}\boldsymbol{\omega} \times \boldsymbol{p} + (\mathbb{1} - \boldsymbol{p}\boldsymbol{p}^{\mathsf{T}})\mathbb{S}\boldsymbol{p} \right]$$

$$\frac{d\boldsymbol{p}}{dt} = \boldsymbol{\Omega}_T \times \boldsymbol{p} = \underbrace{\mathbb{A}\boldsymbol{p} - (\boldsymbol{p}^{\mathsf{T}}\mathbb{A}\boldsymbol{p})\boldsymbol{p}}, \text{ where; } \mathbb{A} = \nabla \boldsymbol{u}$$

Infinitesimal separation between two tracers

$$\frac{d\boldsymbol{R}}{dt} = \mathbb{A}\boldsymbol{R}, \quad \boldsymbol{p} = \frac{\boldsymbol{R}}{|\boldsymbol{R}|}$$

p evolves in the **tangent system**

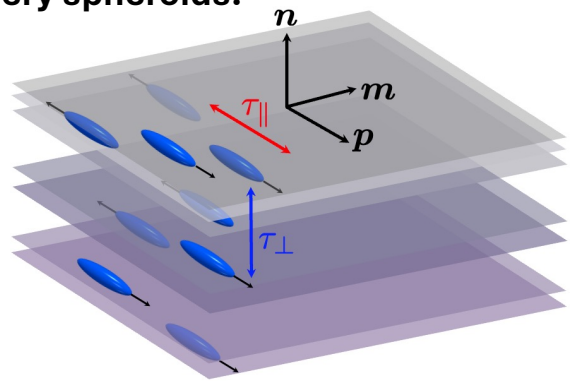
$$\frac{d\boldsymbol{p}}{dt} = \mathbb{A}\boldsymbol{p} - (\boldsymbol{p}^{\mathsf{T}}\mathbb{A}\boldsymbol{p})\boldsymbol{p} = (\mathbb{1} - \boldsymbol{p}\boldsymbol{p}^{\mathsf{T}})\mathbb{A}\boldsymbol{p}$$

Conclusion: for $\tau_p \to 0, \ \lambda \to \infty$

We expect p to align with the most stretching direction of the flow

What happens in the other regimes?

Jeffery spheroids:



Longitudinal and normal Stokes wrt ***p***

$St_{\perp} = \tau_{\perp}/\tau_{\eta}$ $\quad$ $St_{||} = \tau_{||}/\tau_{\eta}$

We expect particles to form fractal set in the ⊥ direction to p

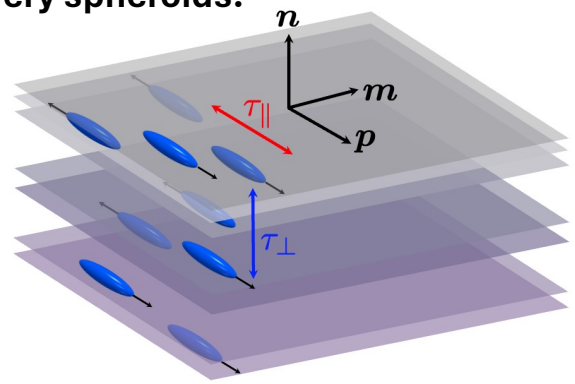
Numerical Results: Clustering

Probability of finding two particles at a distance smaller than *r*

$$P(R_{i,j} < r) \sim Ar^{D_2} + Br^3$$

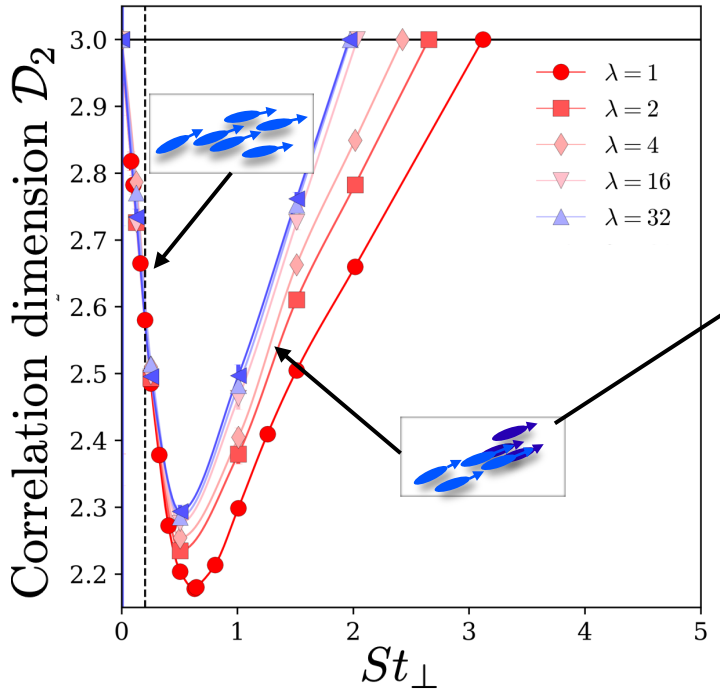
Correlation dimension

Jeffery spheroids:

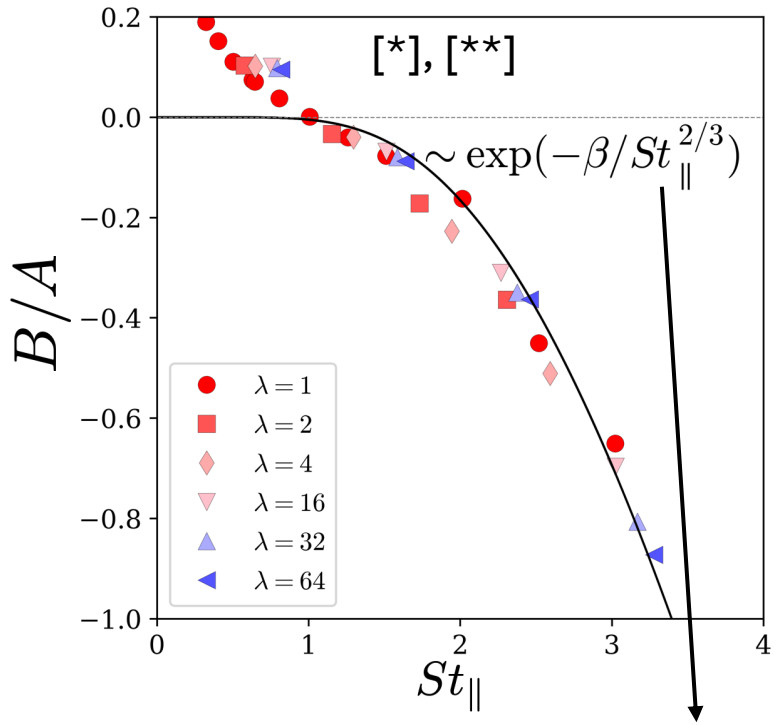


Longitudinal and normal Stokes wrt ***p***

$St_{\perp} = \tau_{\perp}/\tau_{\eta}$ $St_{\parallel} = \tau_{\parallel}/\tau_{\eta}$



Caustics (particle crossing)



St $\gg$ **1**

$$\frac{\mathrm{d}\boldsymbol{V}}{\mathrm{d}t} = -\mathbb{Q}^{\mathsf{T}}\mathbb{D}\,\mathbb{Q}\,[\boldsymbol{V} - \boldsymbol{u}(\boldsymbol{X}, t)]$$

rotation matrix

drag tensor:
diagonal in particle frame $\mathbb{D} = \mathrm{diag}\left(\frac{1}{\tau_{\perp}}, \frac{1}{\tau_{\perp}}, \frac{1}{\tau_{\parallel}}\right)$

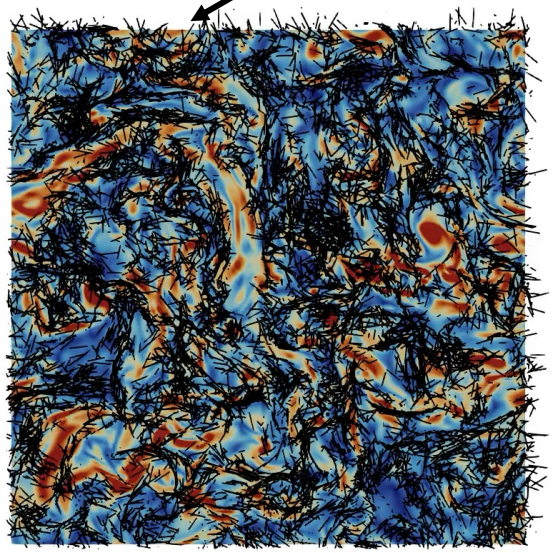
[*] Wilkinson, M., and Bernhard Mehlig. EPL (Europhysics Letters) 71.2 (2005): 186-192.
[**] Falkovich, Gregory, and Alain Pumir. Journal of the Atmospheric Sciences 64.12 (2007): 4497-4505.

Conclusions

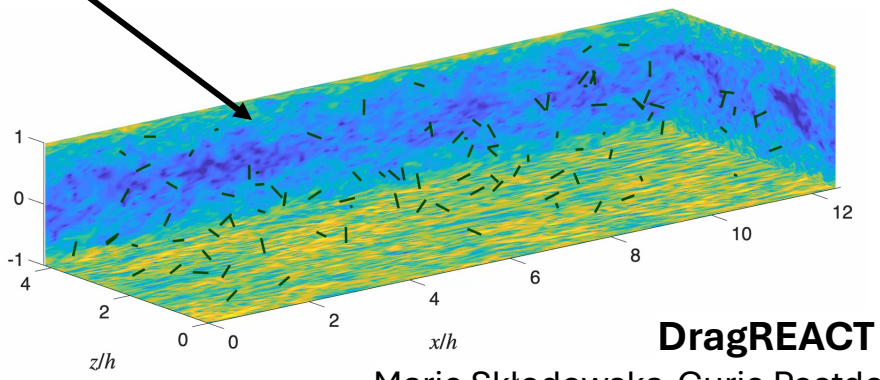
- Unified **asymptotic framework** connecting **Jeffery spheroids** and **rigid fibers**
- Aspect ratio, length and Stokes number strongly affect the rotational dynamics (decreased tumbling rate)
- Elongated particles **preferentially align** with the flow **stretching direction**
- **Clustering (Caustics) mainly controlled by the perpendicular (parallel) Stokes numbers**

Ongoing

Active control: steer fibers and explore control policies with data-driven methods in both **HIT** and **channel flows**

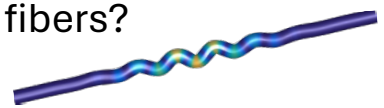


+ Two-way coupling effects on the flow



perspective

Flexible fibers?



perspective

four-way coupling effects
fiber-flow + fiber-fiber

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