irphé
Institut de Recherche sur les Phénomènes Hors Equilibre

Aix*Marseille université

CENTRALE MARSEILLE

cnrs dépasser les frontières

Flexible fibers in turbulence

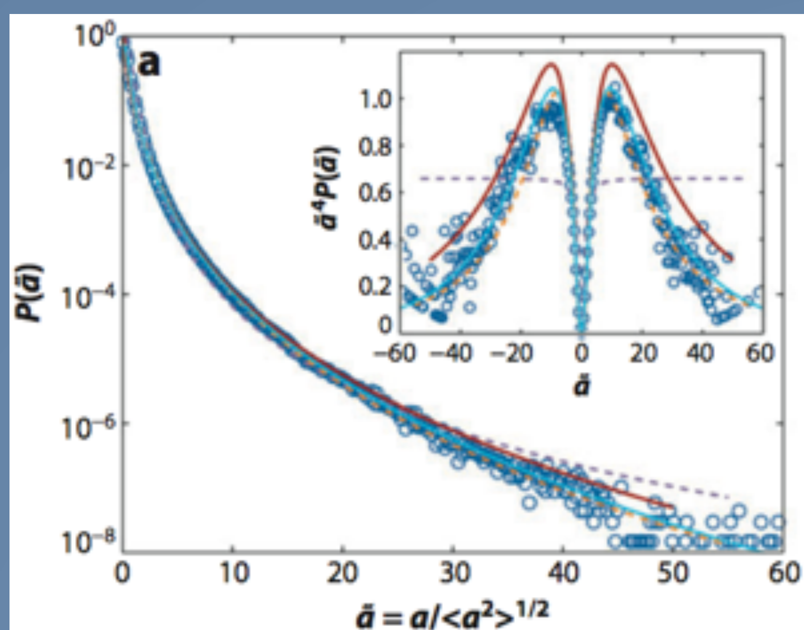
Gautier Verhille

Amélie Gay, Benjamin Favier, Patrice Le Gal
IRPHE - Marseille

Individual particle in turbulence

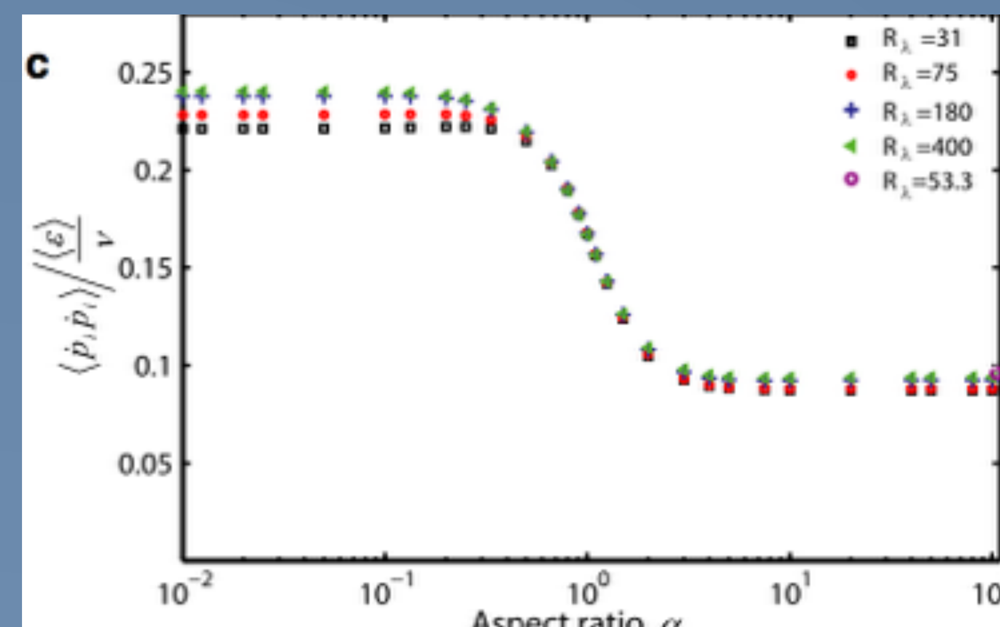
spherical particles anisotropic particles deformable particles

degree of freedom



Toschi, Bodenschatz Annu. Rev. Fluid Mech., 2009

acceleration



Parsa *et al.*, Phys. Rev. Lett., 2012

rotating rate

deformation due to turbulence? Influence on the transport?

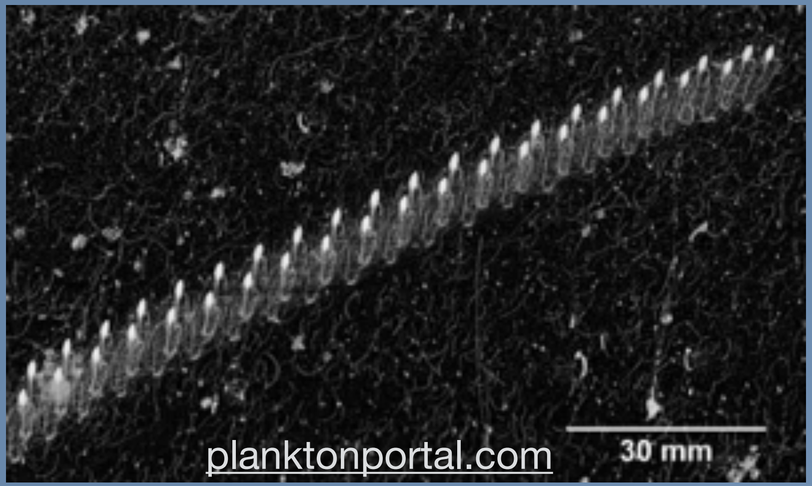
Introduction

Industry

Paper

Non woven textile

Nature



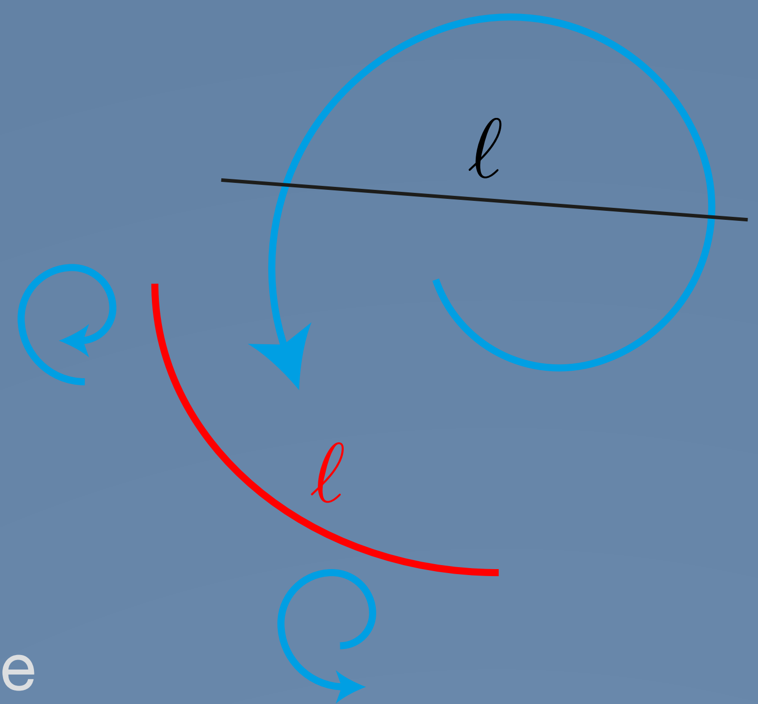
Plankton (here Salps colony)

Algae, pollution…

When does a fiber deform in a turbulent flow?

Elastic energy

$$\mathcal{E}_{el} = \frac{EI}{\ell}$$



Turbulent energy at size ℓ

$$\mathcal{E}_t = \rho \ell^3 u_\ell^2$$

Elastic time

$$\tau_{el} = \frac{\eta \ell^4}{EI}$$

Turbulent time

$$\tau_t = \frac{\ell}{u_\ell}$$

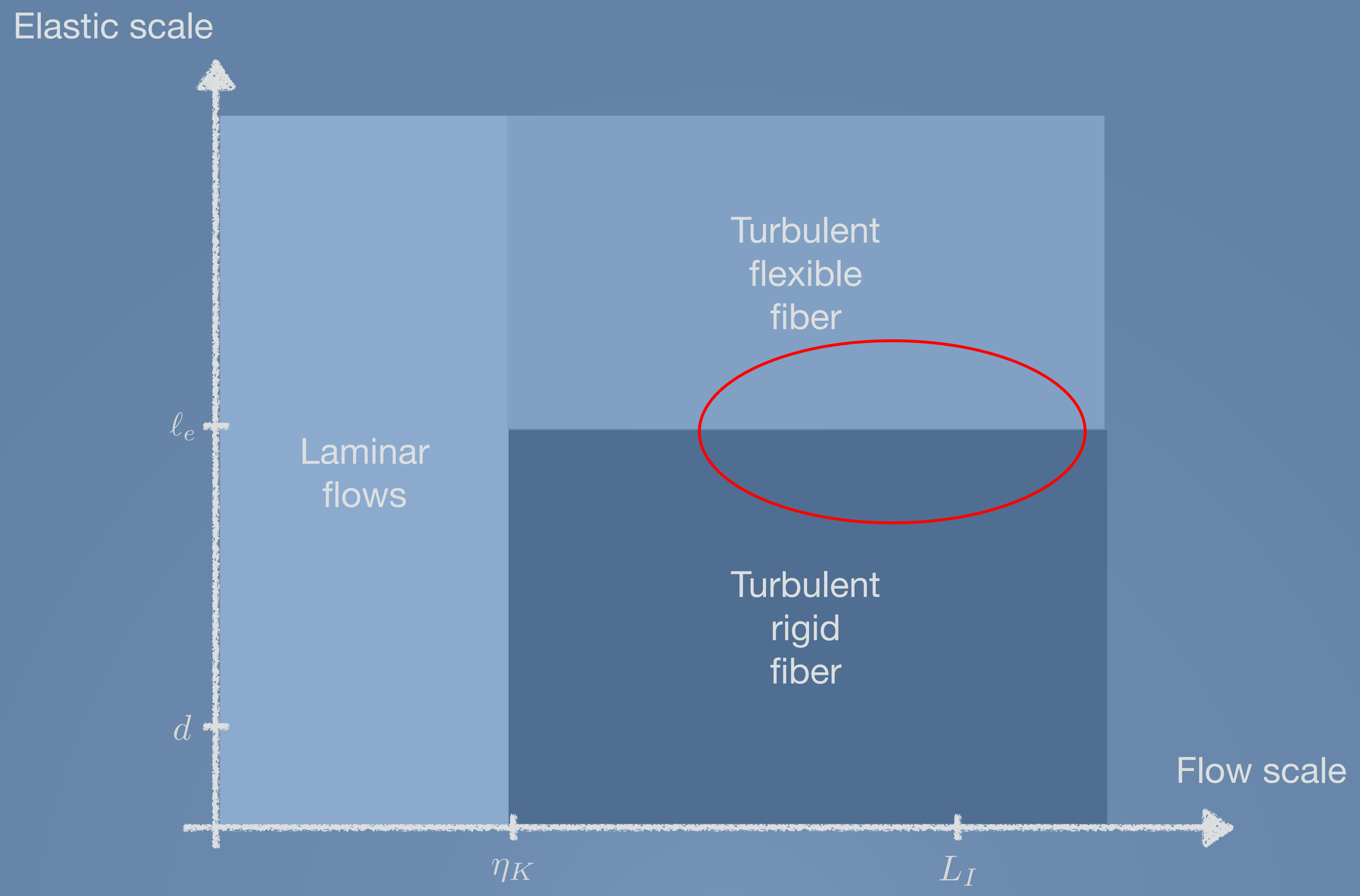
Balance of power

$$\rho \ell^3 \epsilon \simeq \frac{(EI)^2}{\eta \ell^5}$$

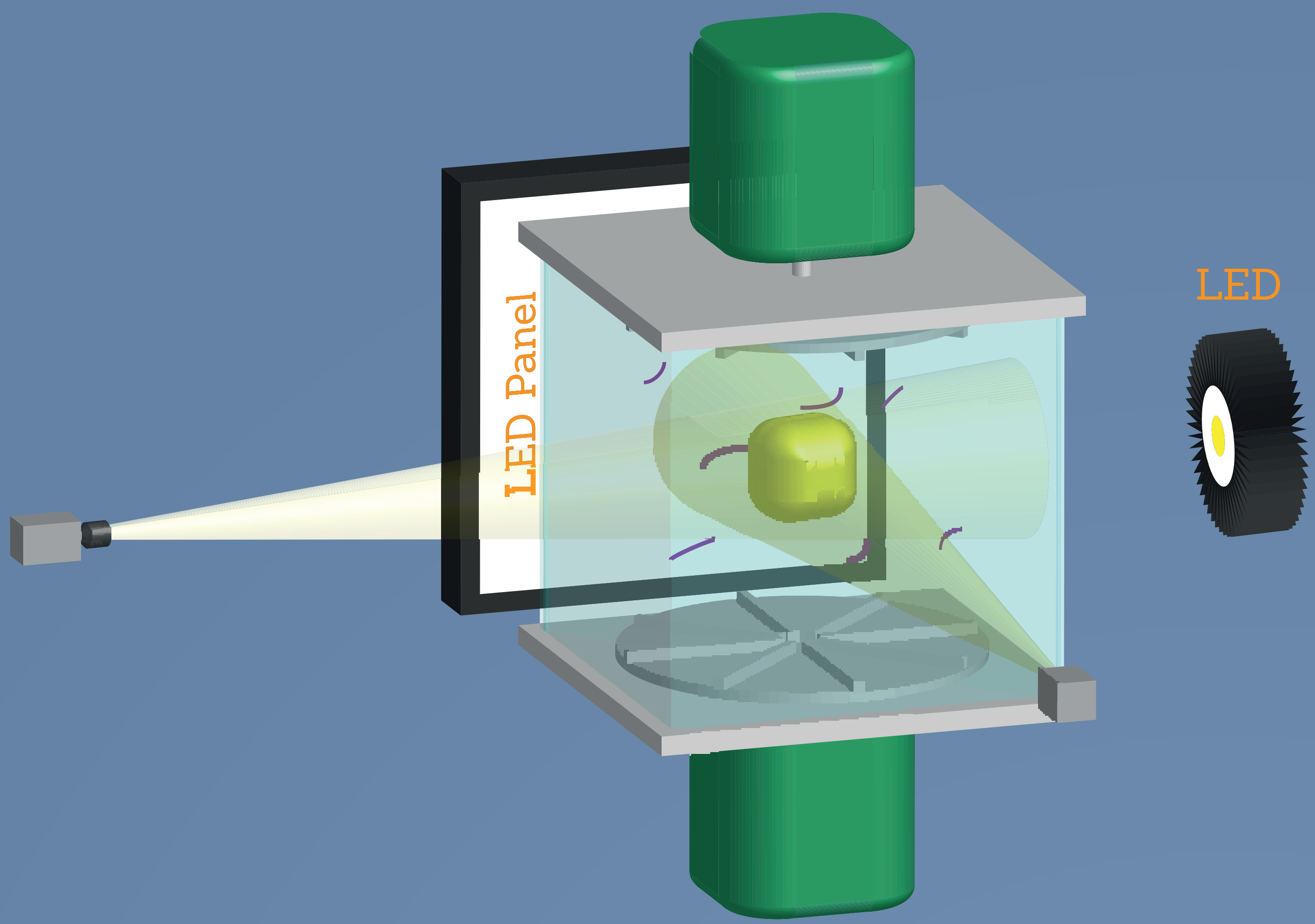
$$\epsilon = \frac{u_\ell^3}{\ell}$$

$$\ell_e = \frac{(EI)^{1/4}}{(\rho \eta \epsilon)^{1/8}}$$

The different length scales



The experimental setup



von Kármán flow

R=8,5 cm
F=15 Hz
ϵ~6 W/kg
$R_\lambda \sim 10^3$

Acquisition

2 cameras 1MPx
5 im/s
reconstructed volume:
cube~6x6x6 cm^3

Fiber mechanical properties: elastic length

$E \simeq 40$ kPa $\quad d = 622 \pm 10\ \mu$m $\quad \rho_f \sim 1.03$ kg.m^{-3} $\quad L \in [1\ ;\ 5]$ cm

$$\ell_e = \frac{(EI)^{1/4}}{(\rho\eta\epsilon)^{1/8}} \sim 3.4 \text{ mm}$$

The numerical model

The Cosserat rod model

$$\rho S \partial_{tt} \vec{r} - \partial_s (T \partial_s \vec{r}) + EI \partial_s^4 \vec{r} = \eta (\vec{u} - \partial_t \vec{r})$$

$$|\partial_s \vec{r}|^2 = 1$$

$$St = \frac{\rho S F}{\eta}$$

	Numerics	Experiment
	$St = 0.1$	$St \simeq 5$

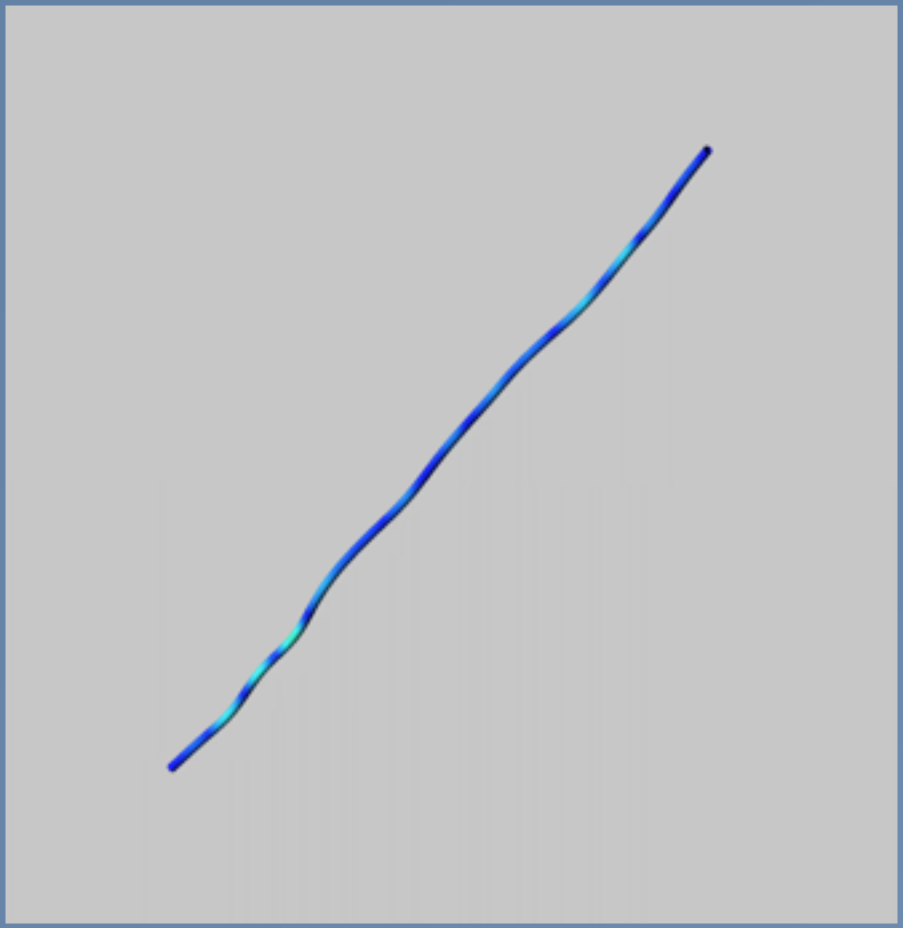
Kinematic simulation

$$\vec{u}(x,t) = \sum_{n=1}^{N} \vec{A}_n \cos(\vec{k}_n \cdot \vec{x} + \omega_n t) + \vec{B}_n \sin(\vec{k}_n \cdot \vec{x} + \omega_n t)$$

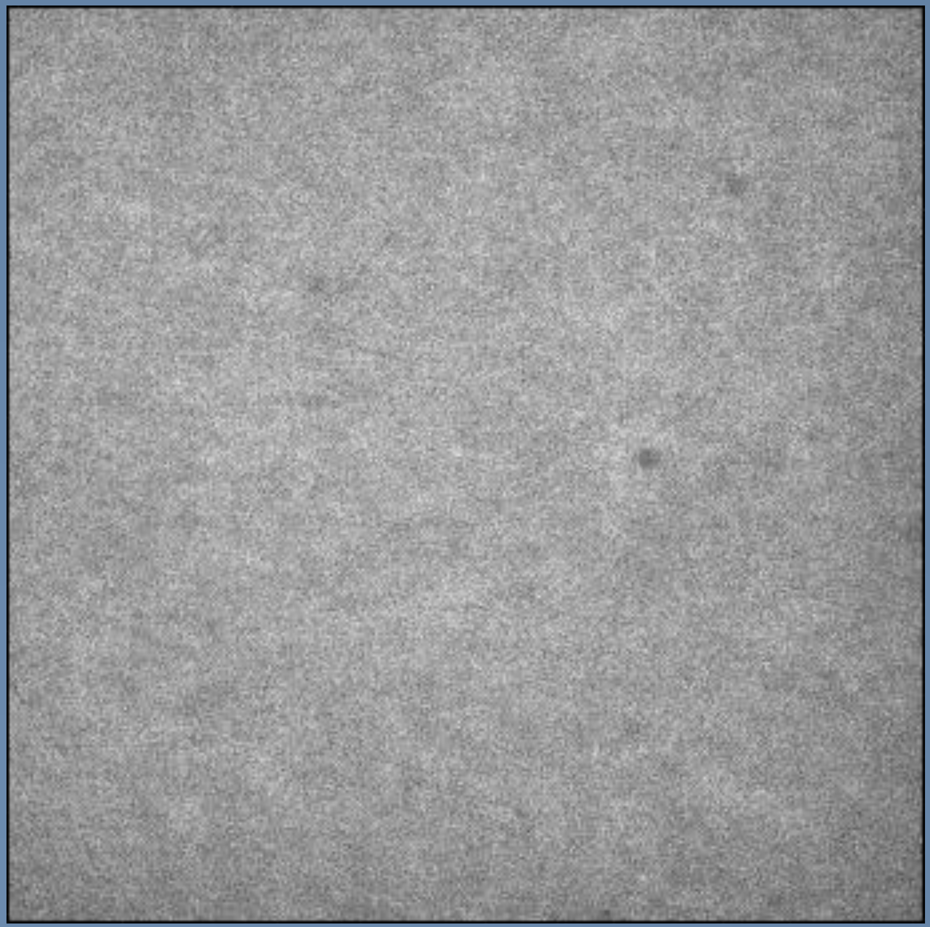
$$\vec{\nabla} \cdot \vec{u} = 0$$

$$E(k) = C_k \epsilon^{2/3} k^{-5/3}$$

Numerics



Experiment

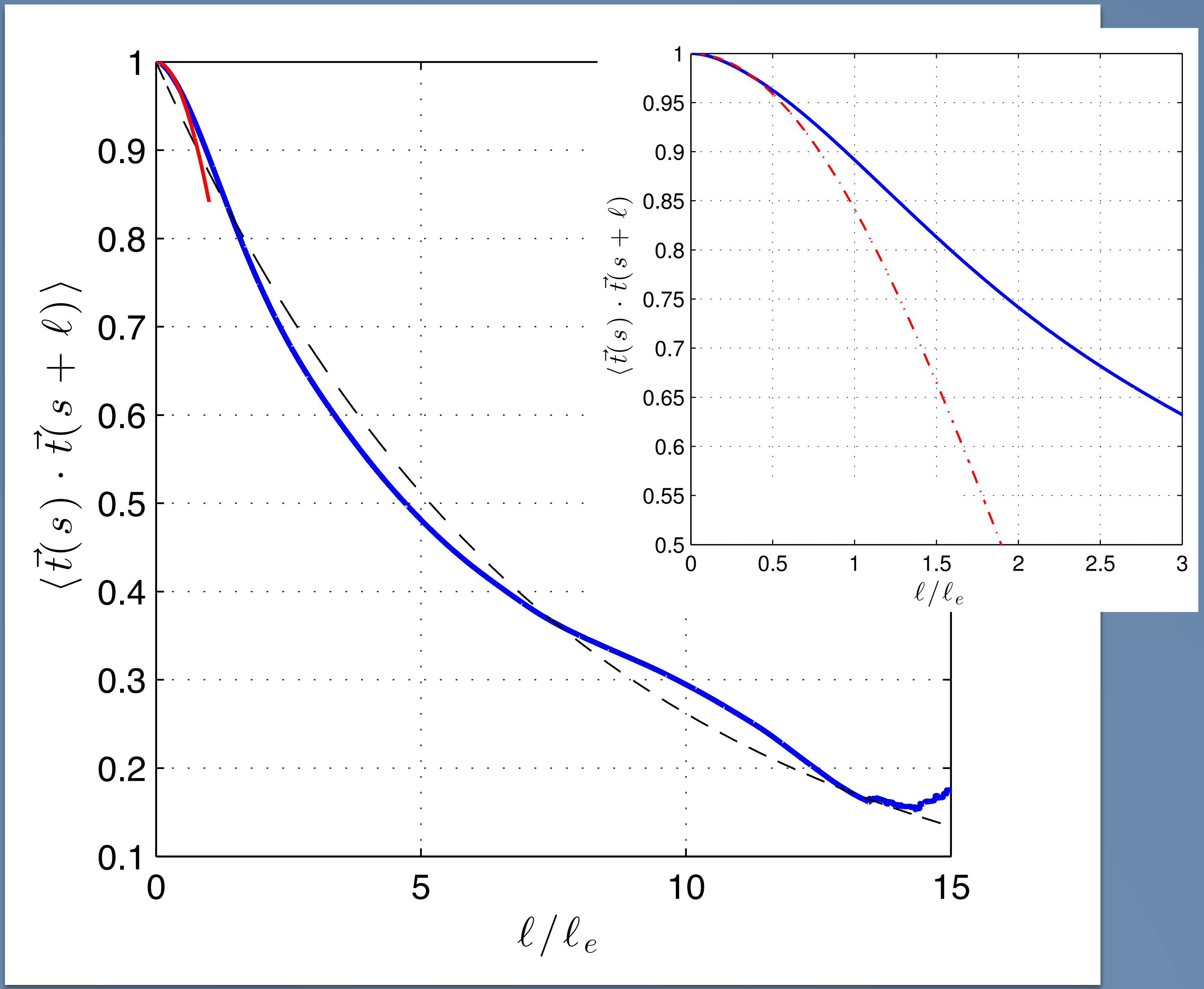


slowed down (x100)

The correlation function: typical evolution

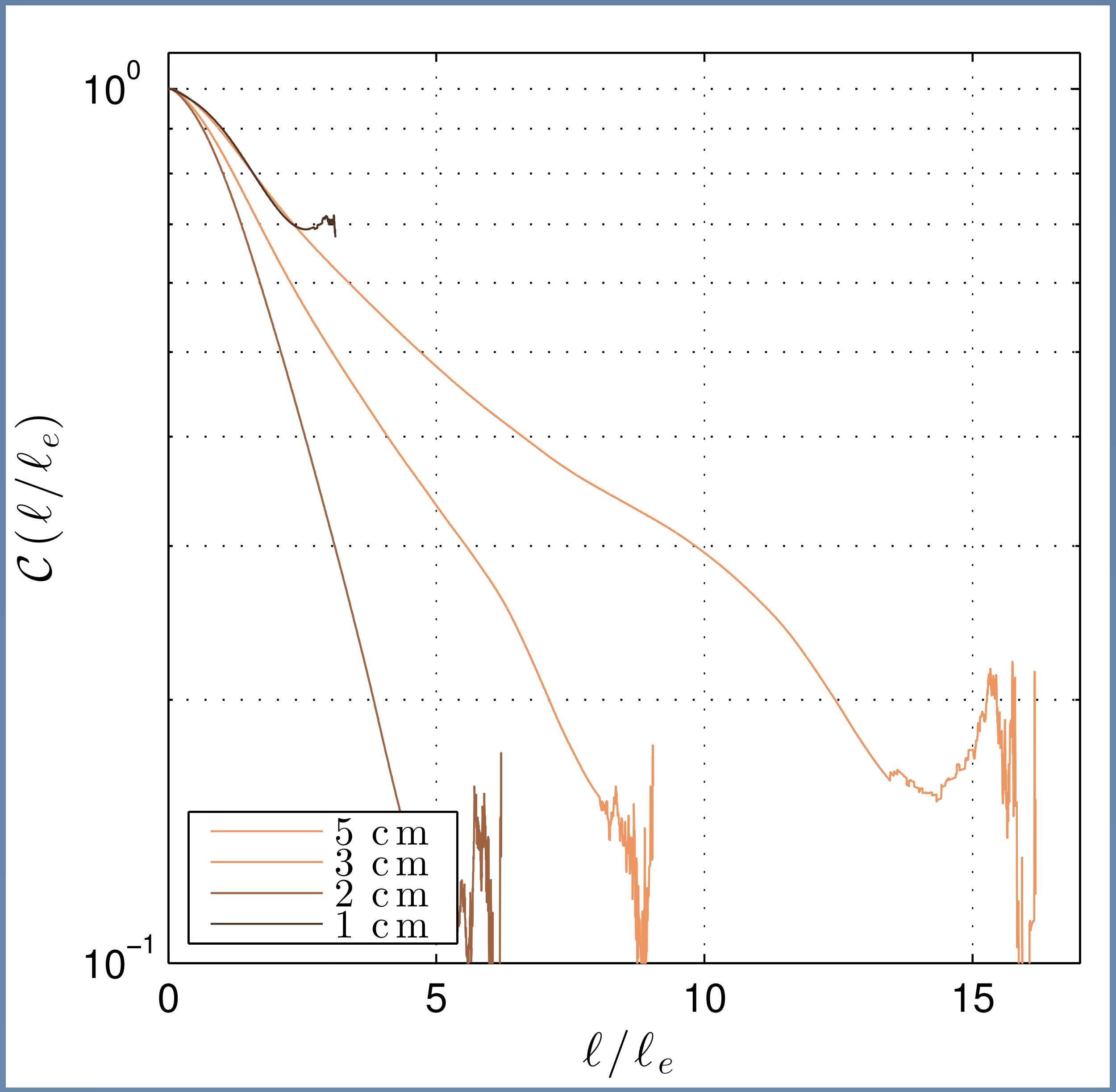
$$\mathcal{C}(\ell) = \langle \vec{t}(s+\ell)\cdot\vec{t}(s)\rangle$$

For wormlike chain polymer $\mathcal{C}(\ell) = \exp(-\ell/l_p)$



$$\langle \vec{t}(s)\cdot\vec{t}(s+\ell)\rangle \simeq 1 - \frac{1}{2}\langle\kappa^2\rangle\ell^2 - \frac{1}{4}\langle\partial_s\kappa^2\rangle\ell^3 + \ldots$$

The correlation function: influence of the fiber length

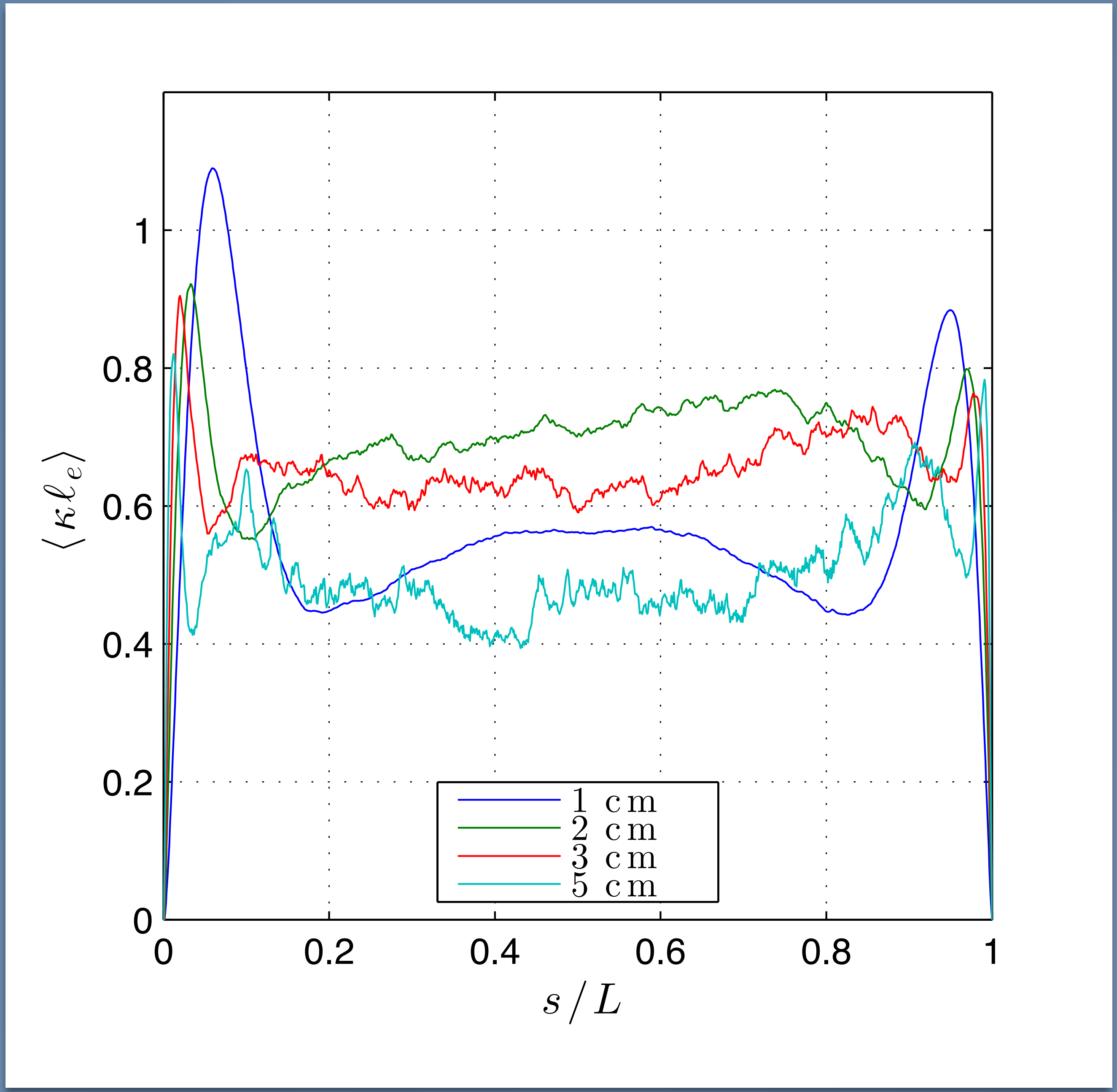


influence of the fiber length related to the flow correlation

$$\langle \vec{t}(s)\cdot\vec{t}(s+\ell)\rangle \simeq 1 - \frac{1}{2}\langle\kappa^2\rangle\ell^2 - \frac{1}{4}\langle\partial_s\kappa^2\rangle\ell^3 + \ldots$$

The local curvature statistics: mean values

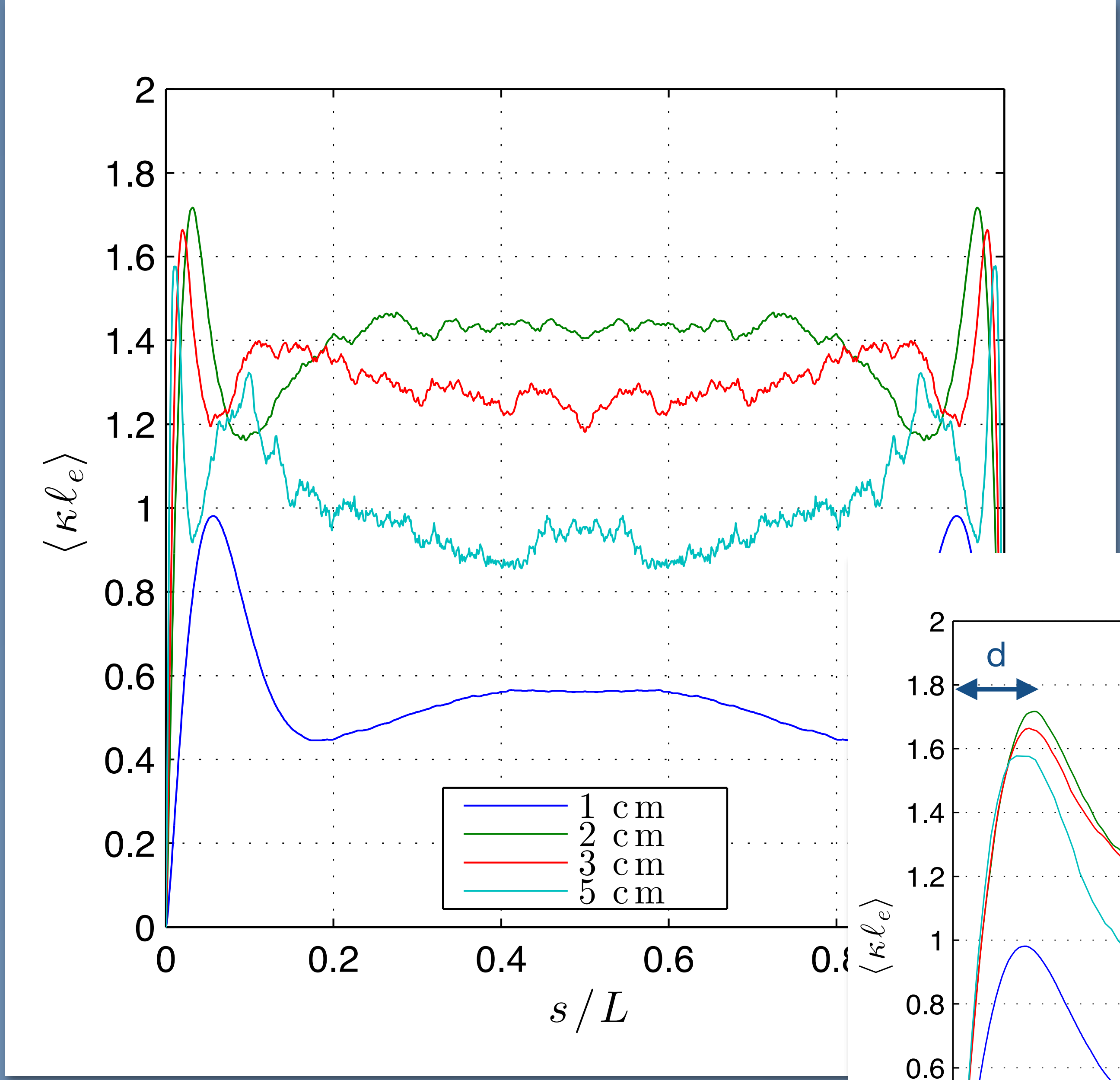
Experiments: raw data

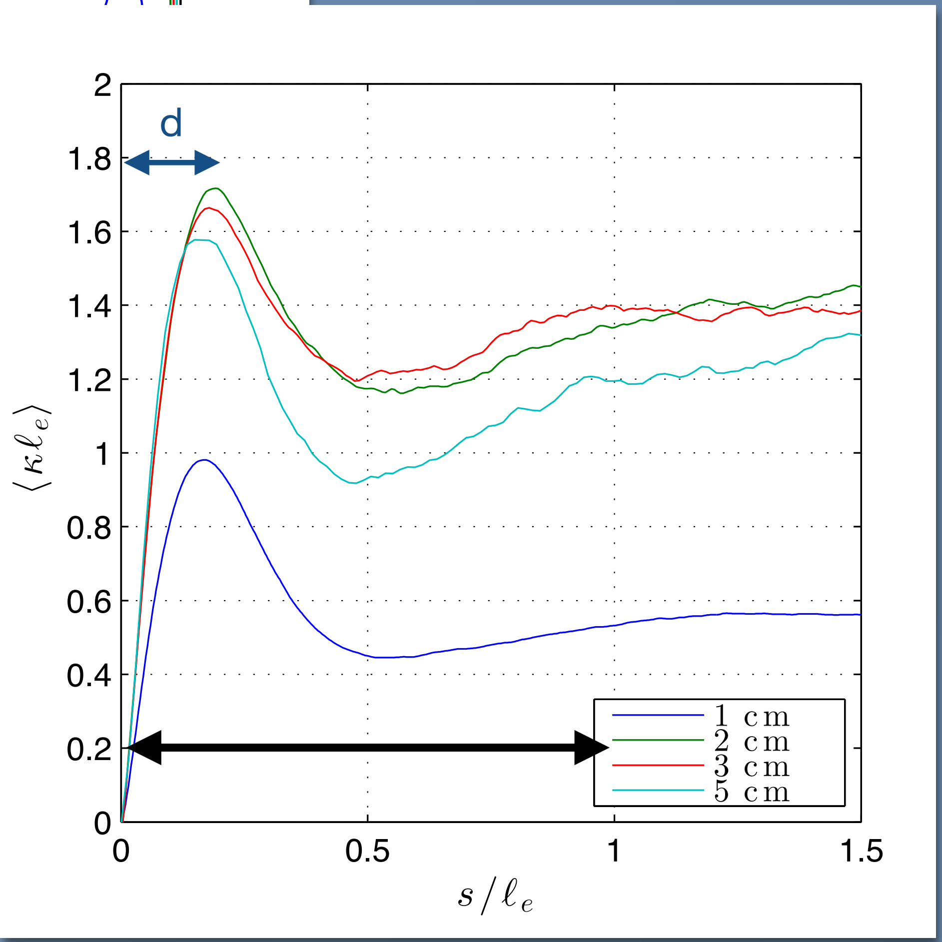


$$\ell_e < L < L_I$$

The local curvature statistics: mean values

Experiments: symmetrized data



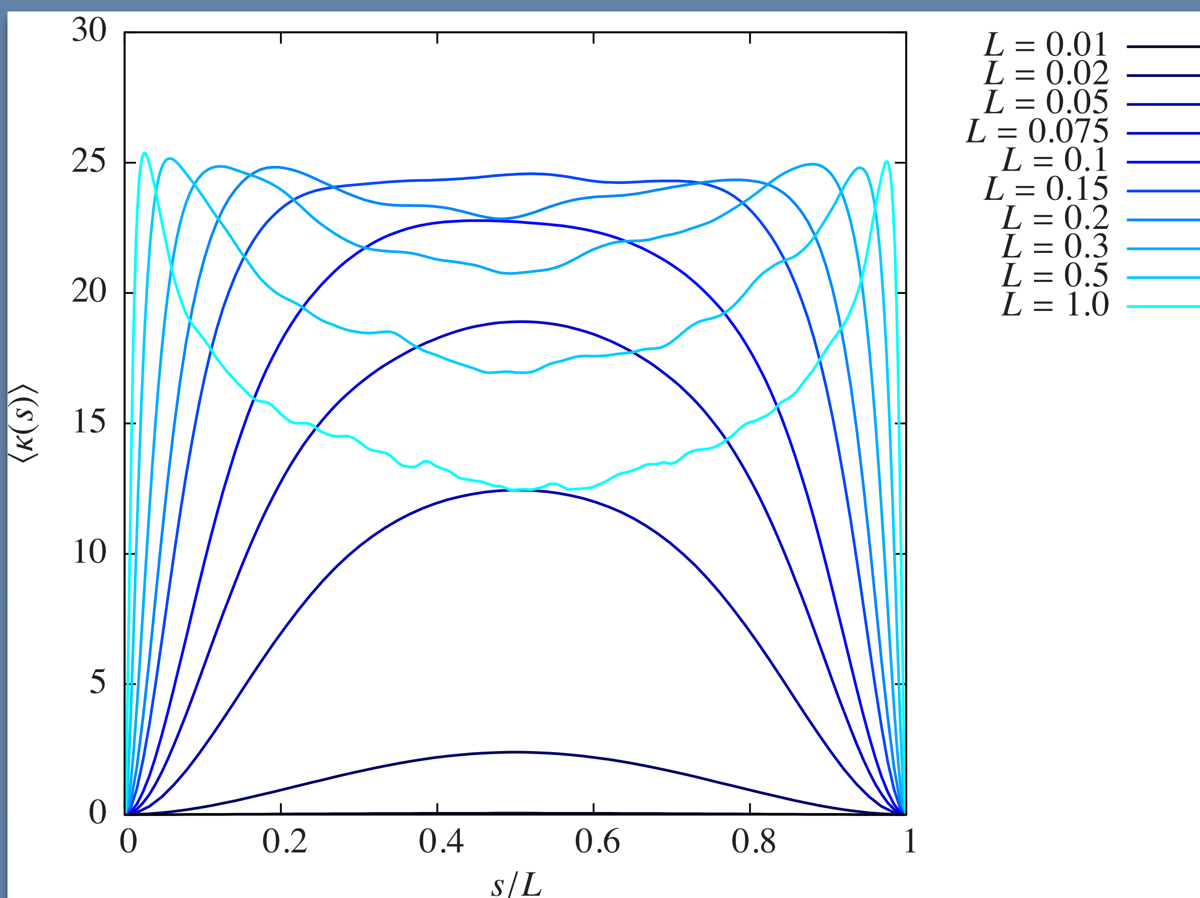


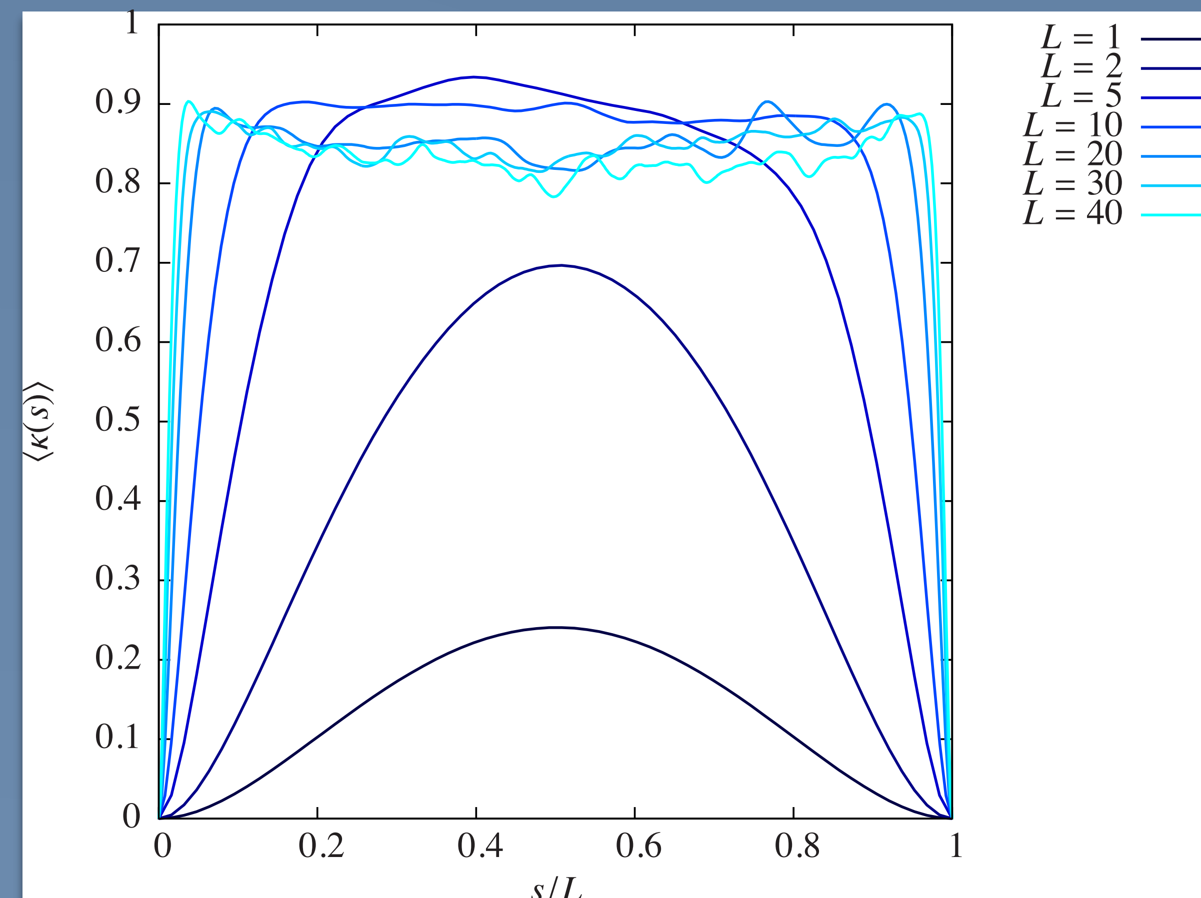
Boundary layer thickness ~ ℓ_e

$\ell_e < L < L_I$

The local curvature statistics: mean values

Numerics





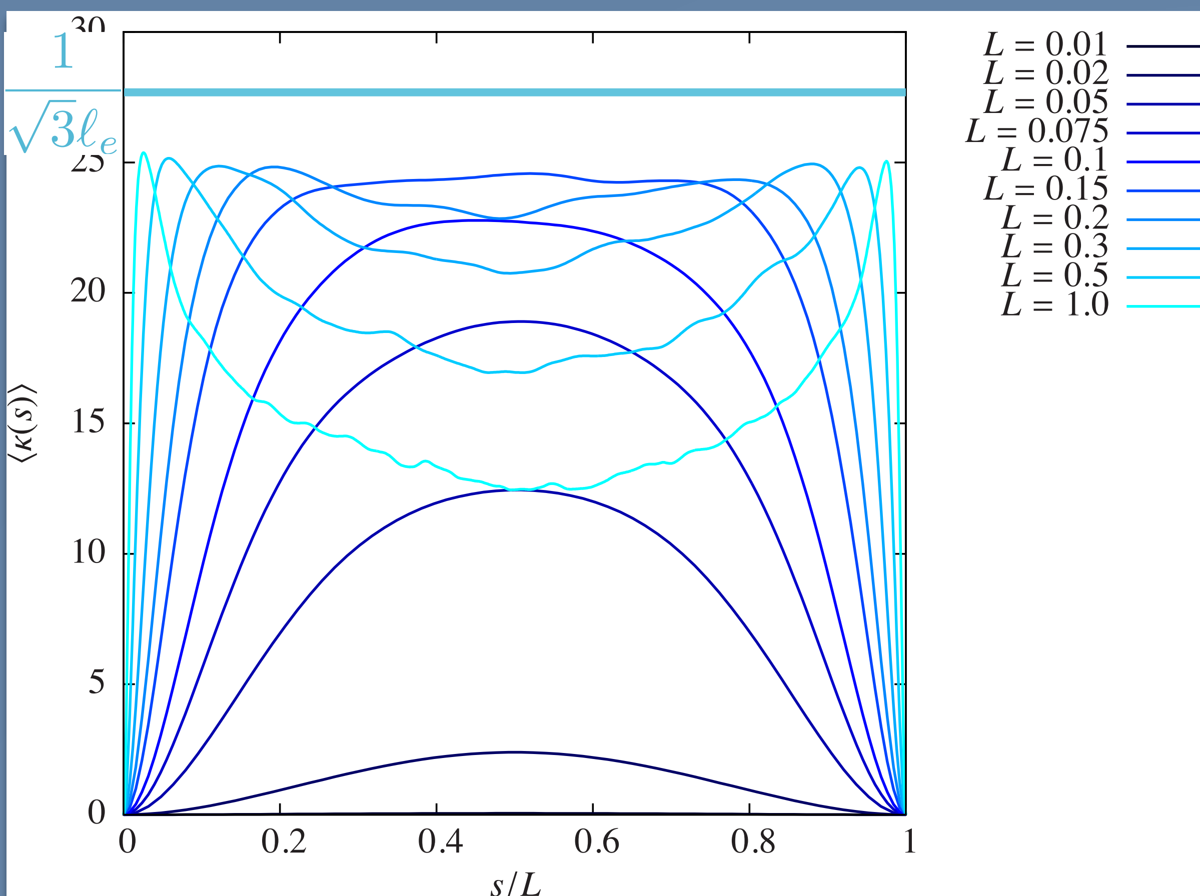
'Turbulent regime'

$$\ell_e \ll L \ll L_I$$

'Polymer regime'

$$L_I \lesssim \ell_e \ll L$$

Interpretation: turbulent regime



$$\ell_e \ll L \ll L_I$$

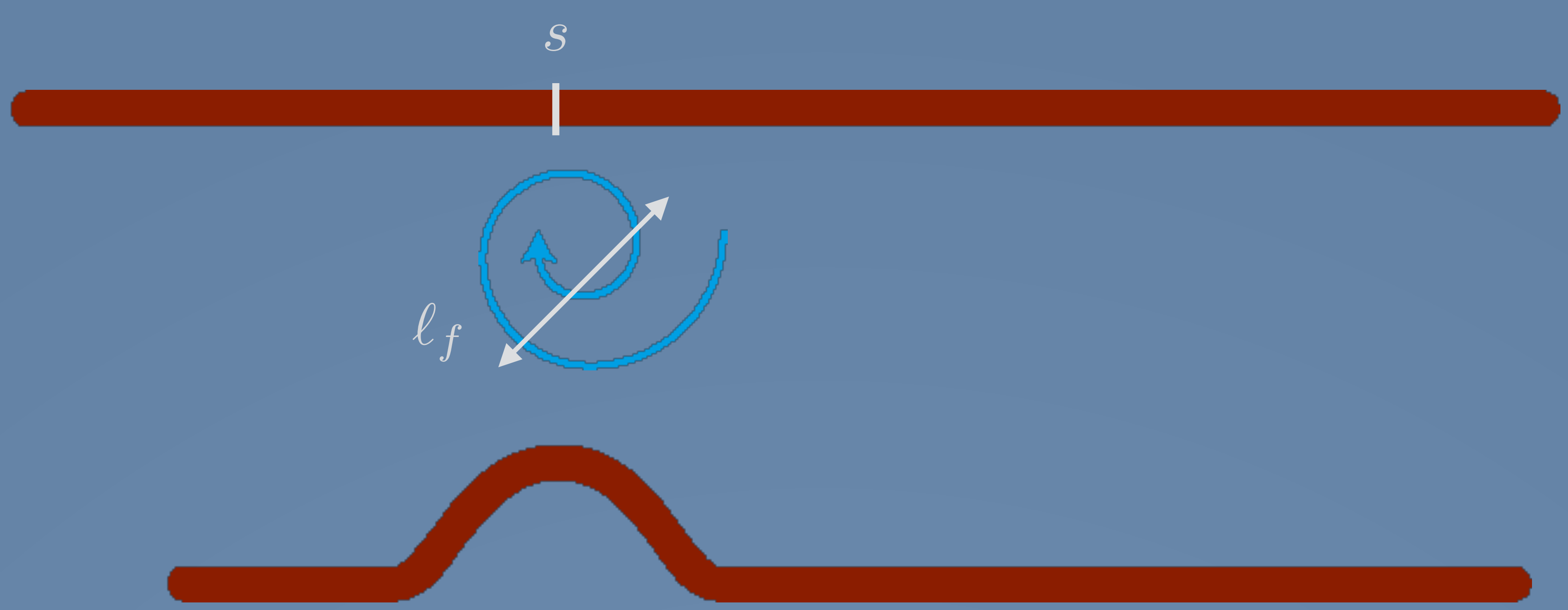
$$\ell_e = cst$$

Maximum of curvature

$$\langle \kappa^2 \rangle = \frac{1}{3\ell_e^2}$$

How to model the evolution for the longest fibers?

Interpretation: turbulent regime



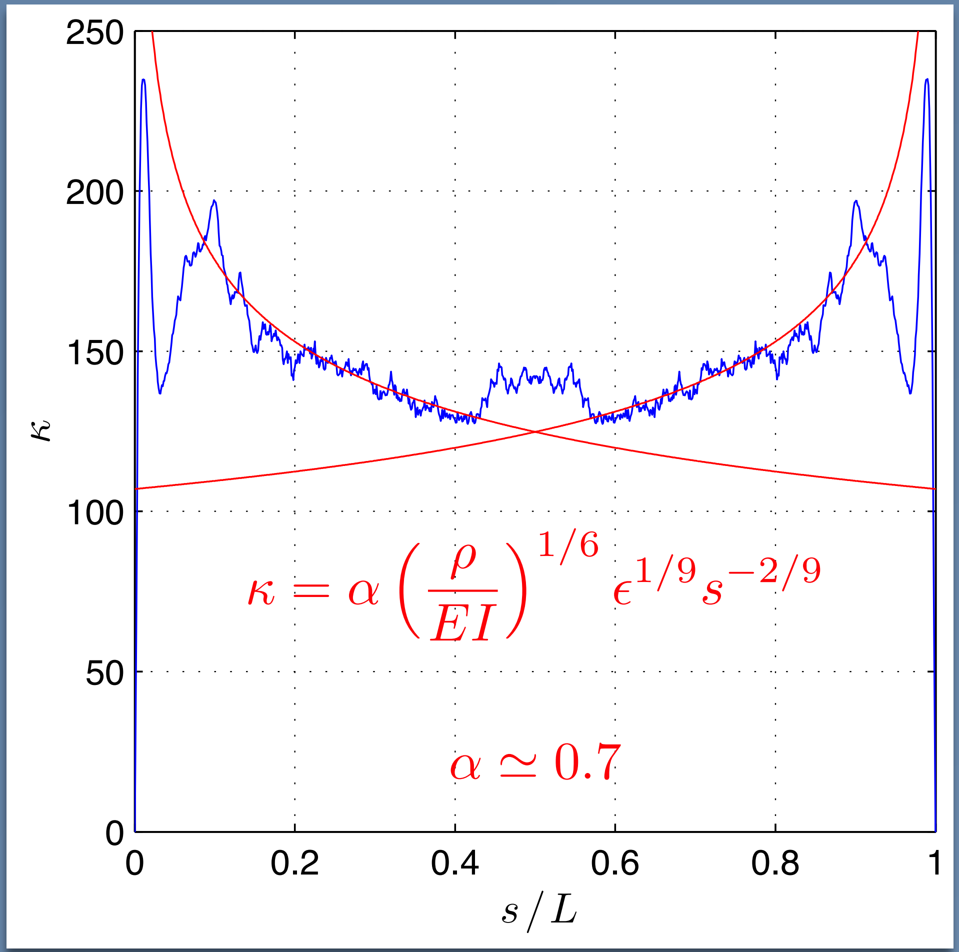
Power budget for semi infinite fiber

$$\rho \ell_f^3 \epsilon = \frac{EI\kappa}{\tau_e} + \eta s u_f v$$

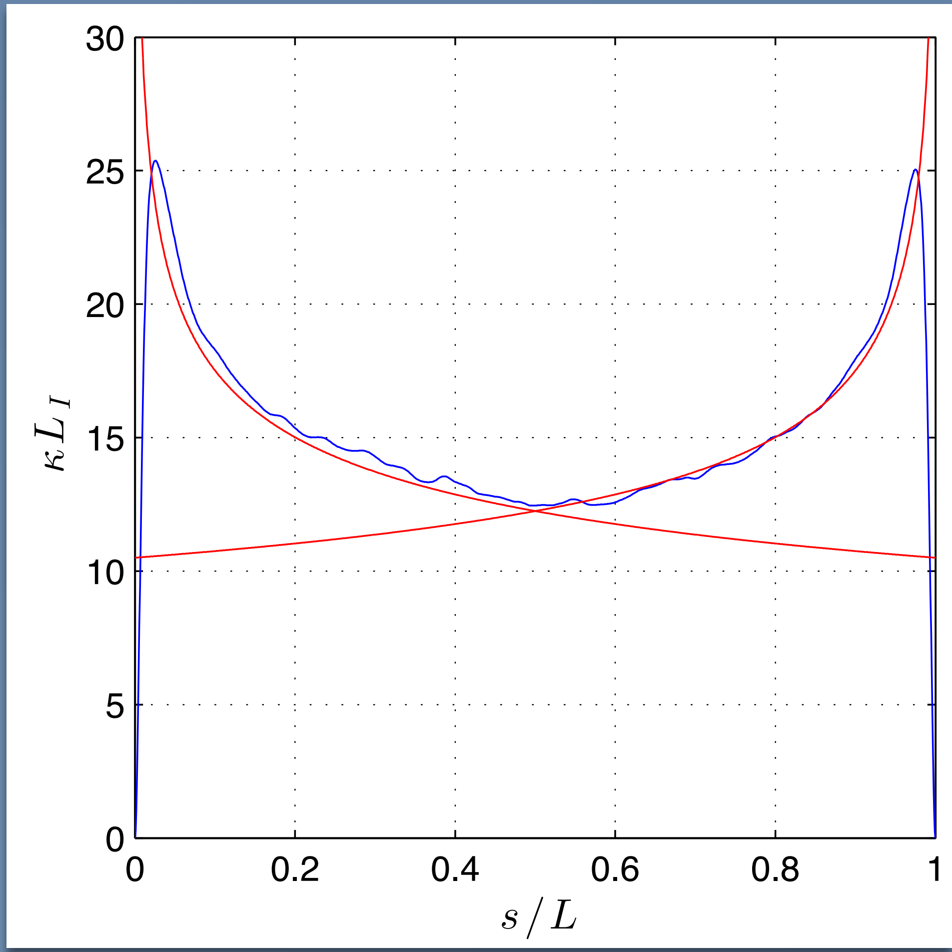
$$\ell_f \sim \frac{1}{\kappa} \qquad \tau_e = \frac{\eta}{EI\kappa^4} \qquad u_f \sim \epsilon^{1/3} s^{1/3} \qquad v \sim \frac{1}{\kappa \tau_e}$$

$$\kappa \sim \left(\frac{\rho}{EI}\right)^{1/6} \epsilon^{1/9} s^{-2/9}$$

Curvature Interpretation: turbulent regime



Experiment

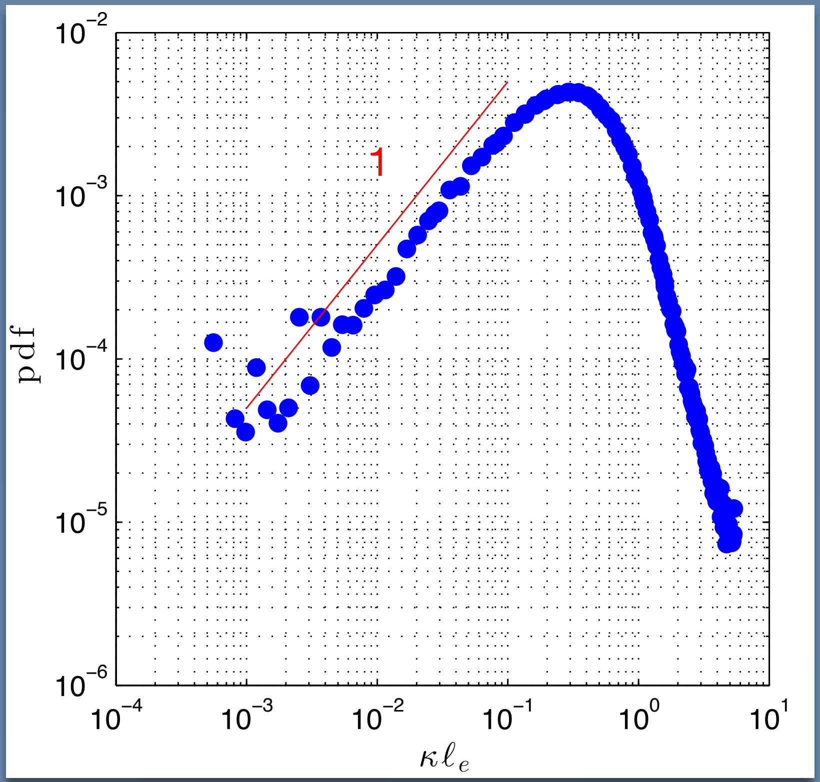


Numerics

Conclusion

- Particle flexibility depends on the ratio : L/ℓ_e $\quad \ell_e = \dfrac{(EI)^{1/4}}{(\rho\eta\epsilon)^{1/8}}$
- Characterization of the deformation by the local curvature
- Modeling with power balance budget

Perspectives



- Curvature statistics

- Dynamics of the deformation
- Influence on the transport

Thank you for your attention