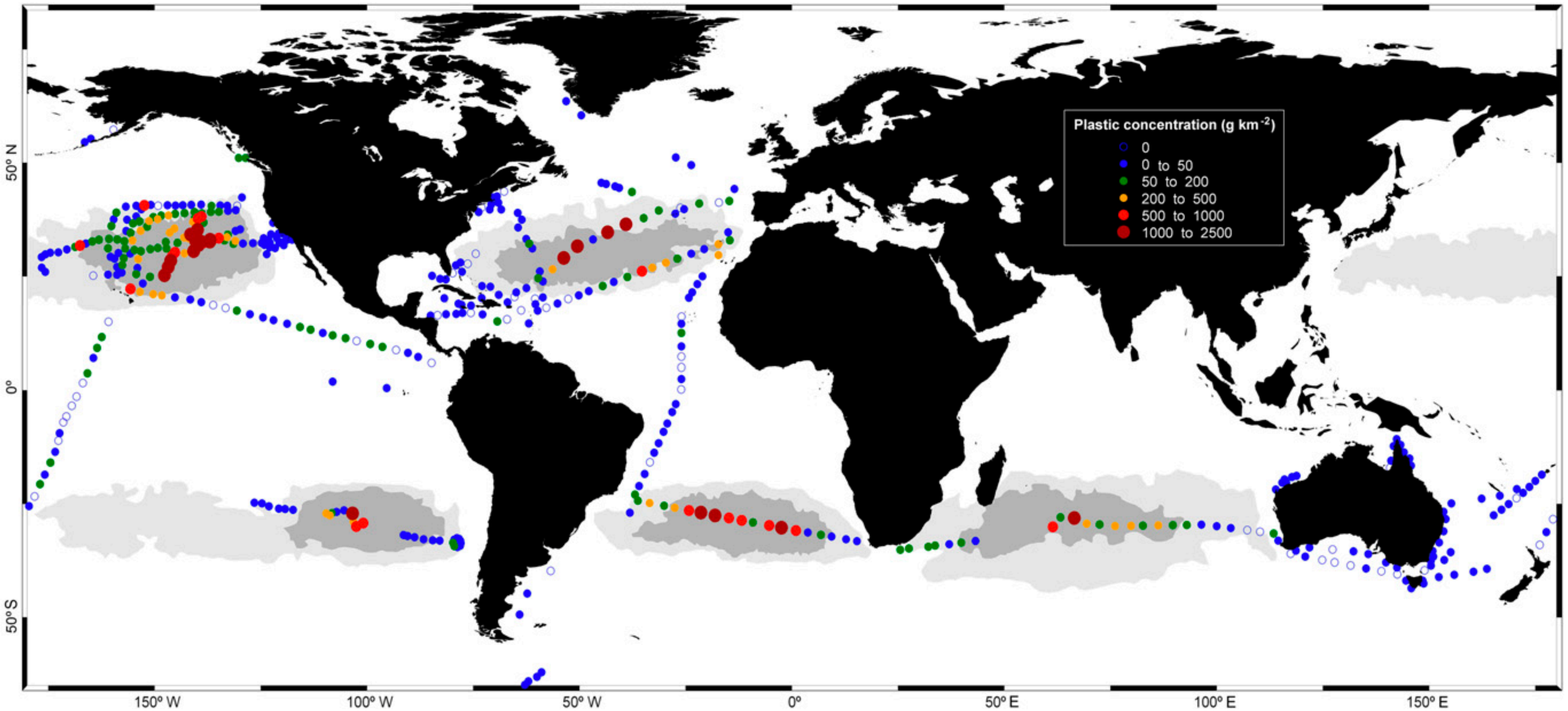
Modeling the deformation and the fragmentation of brittle objects in turbulence

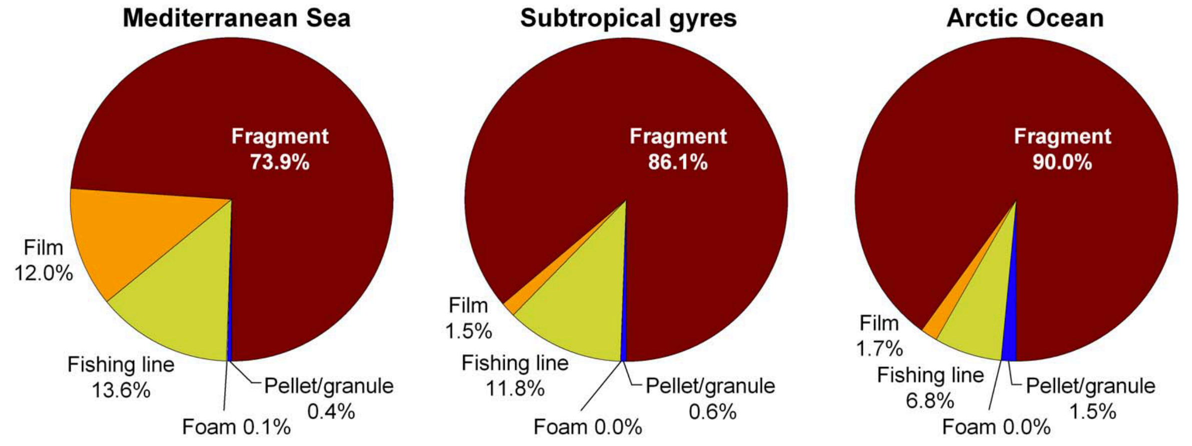
Gautier Verhille

C. Brouzet, M.J. Dalbe, B. Favier, A. Gay, P. Le Gal, N. Vandenberghe, E. Villermaux

Motivation



Cozar *et al.*, PNAS, 2014



Cozar *et al.*, Science Advances, 2017

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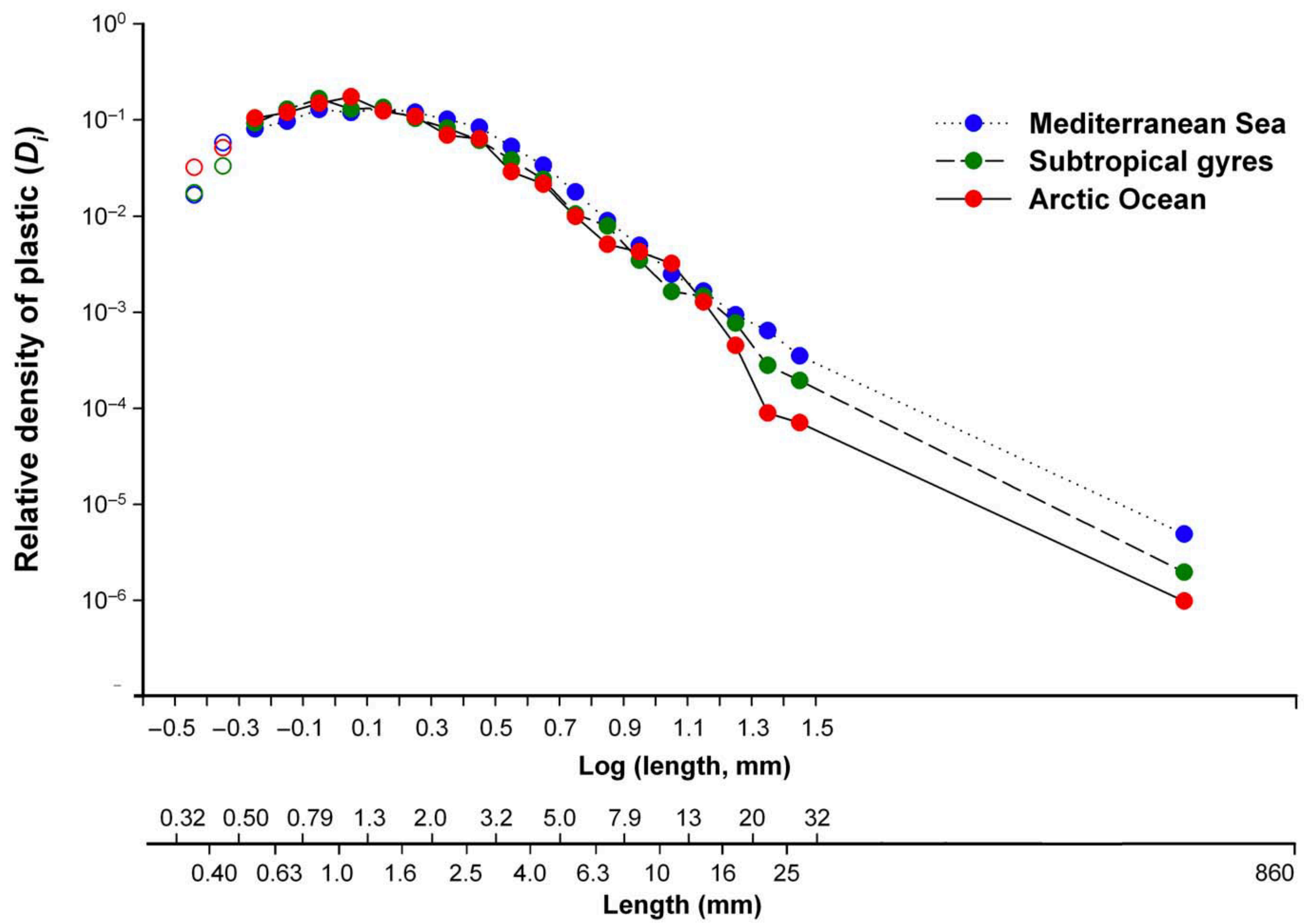

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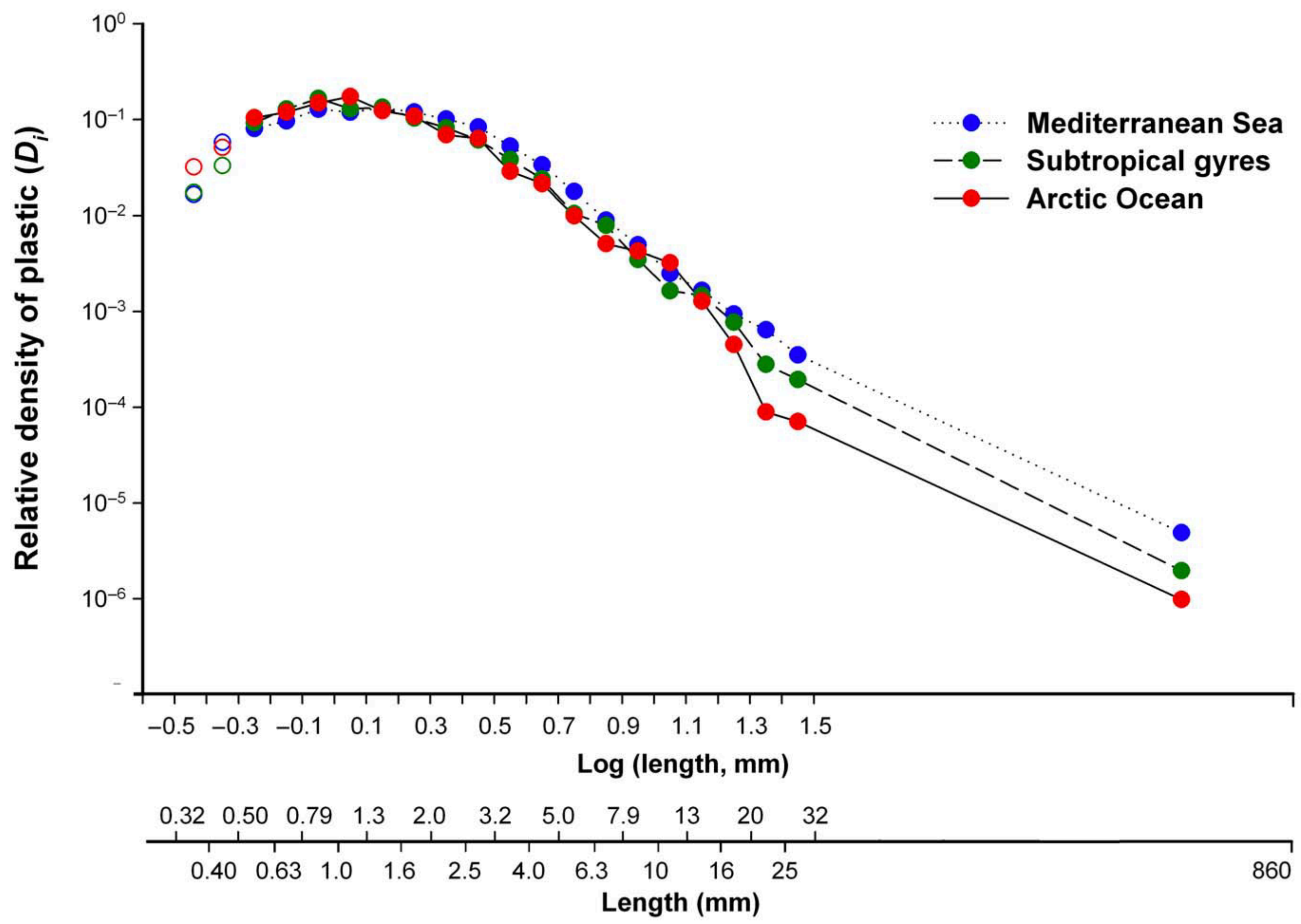
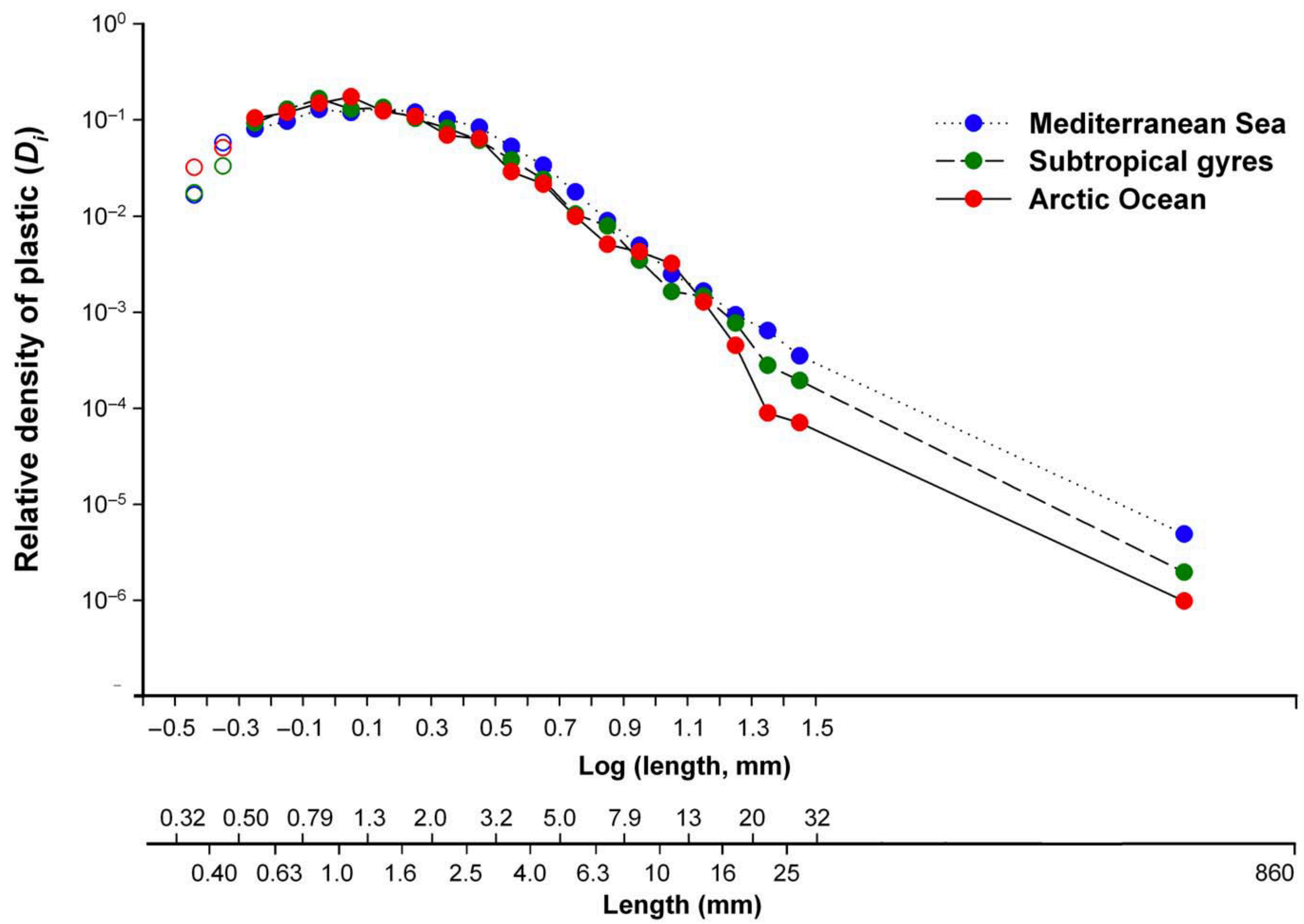


Size distribution independent of the localization

Is there a generic mechanism?

Cozar *et al.*, PNAS, 2014

Motivation



Size distribution independent of the localization

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Two step mechanisms: embrittlement/fragmentation

Cozar *et al.*, PNAS, 2014

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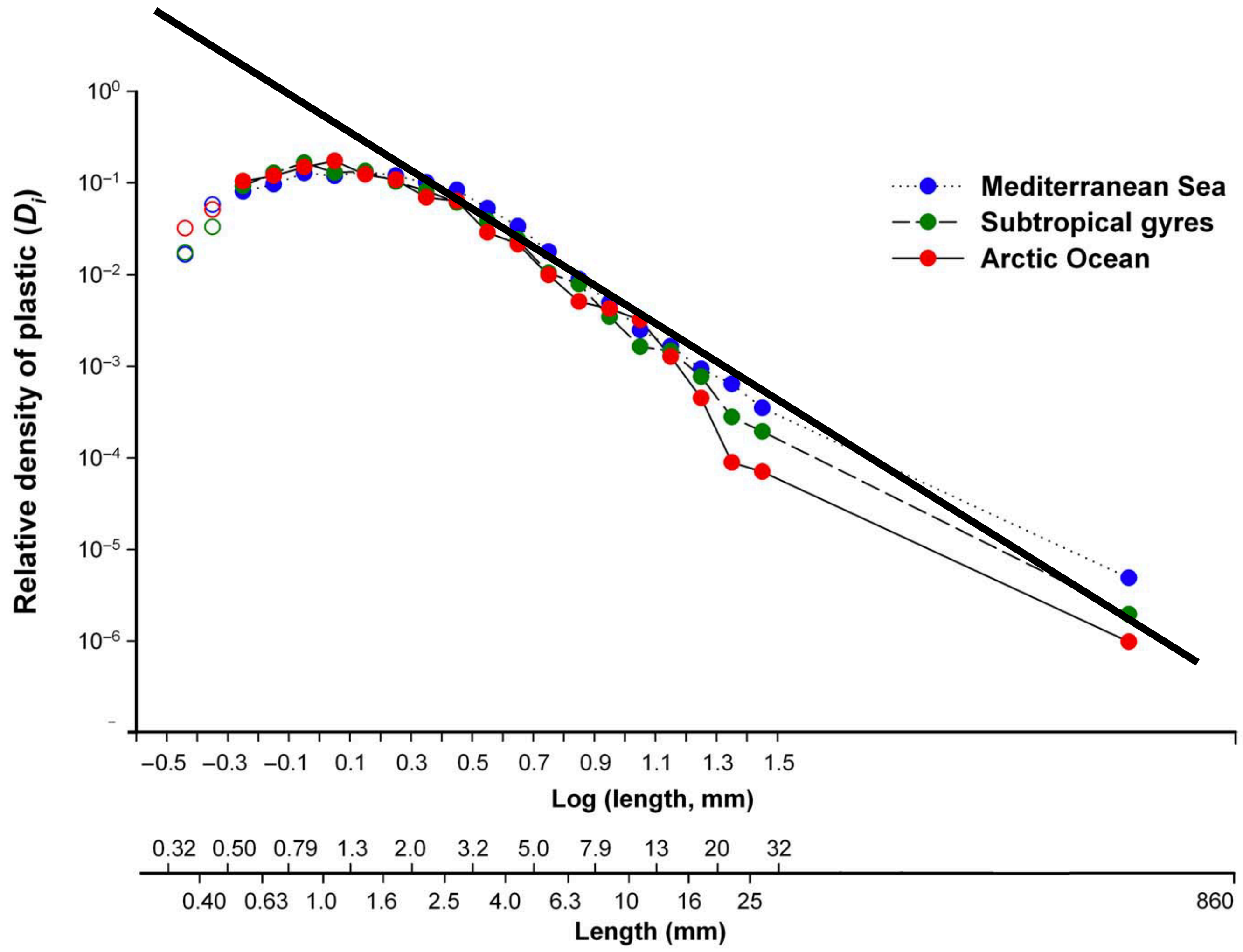


Size distribution independent of the localization

Is there a generic mechanism?

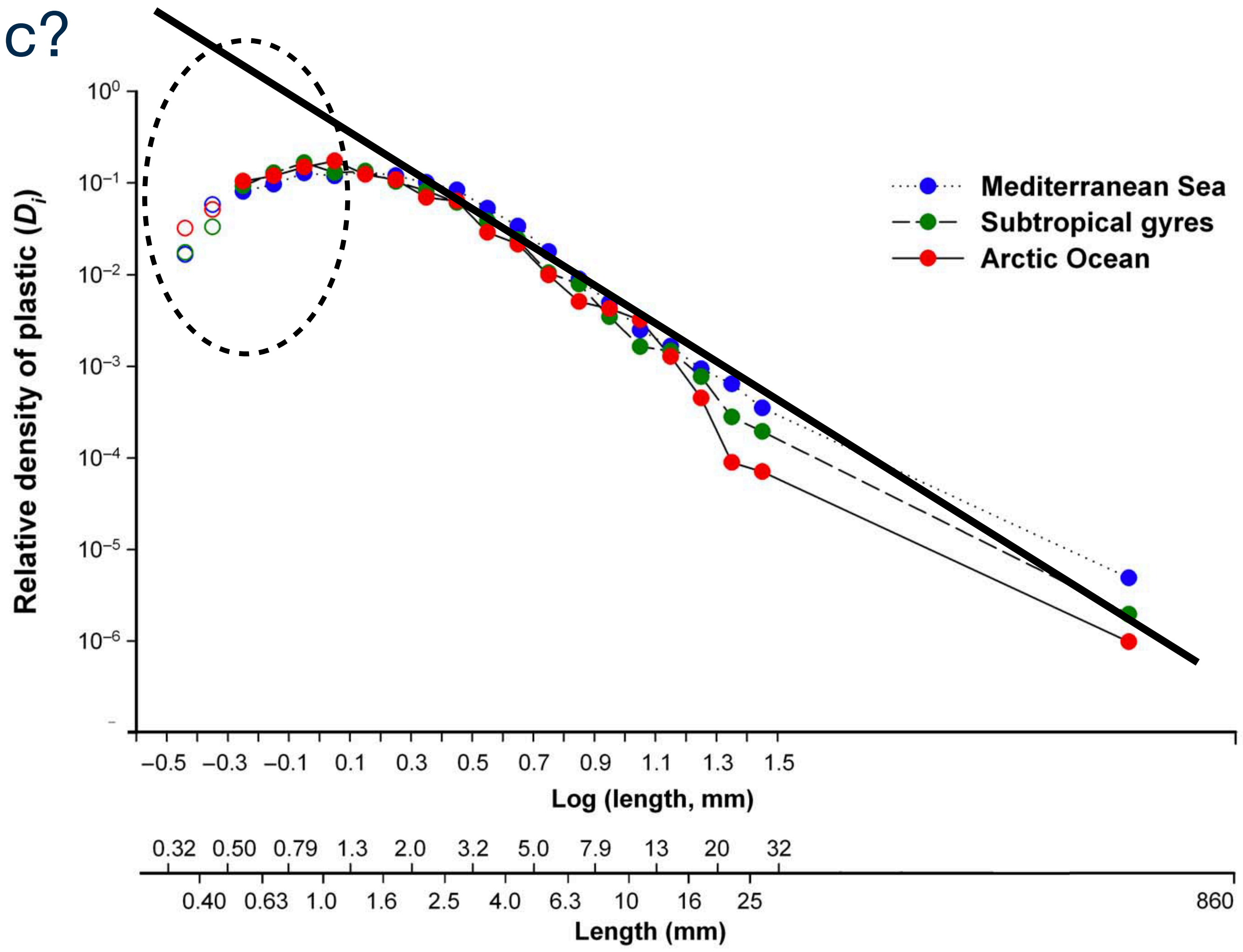
Two step mechanisms: embrittlement/fragmentation

Model for fragmentation proposed by Cozar et al: power law

Cozar *et al.*, PNAS, 2014

Motivation

missing plastic?



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Model for fragmentation proposed by Cozar et al: power law

Cozar *et al.*, PNAS, 2014

Motivation

Cozar's model based on

PRL **104,** 095502 (2010) PHYSICAL REVIEW LETTERS week ending 5 MARCH 2010

New Universality Class for the Fragmentation of Plastic Materials

G. Timár,[1,2] J. Blömer,[3] F. Kun,[1] and H. J. Herrmann[2,4]

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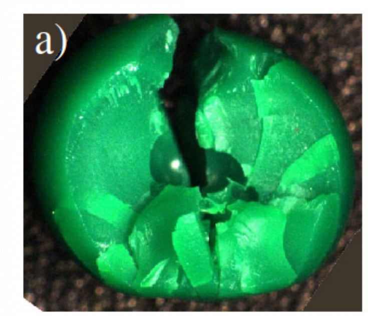
[3]*Spezialwerkstoffe, Fraunhofer Institute UMSICHT, Osterfelder Strasse 3, 46047 Oberhausen, Germany*
[4]*Departamento de Fisica, Universidade Federal do Ceara, 60451-970 Fortaleza, Ceara, Brazil*
(Received 21 December 2009; published 3 March 2010)

We present an experimental and theoretical study of the fragmentation of polymeric materials by impacting polypropylene particles of spherical shape against a hard wall. Experiments reveal a power law mass distribution of fragments with an exponent close to 1.2, which is significantly different from the known exponents of three-dimensional bulk materials. A 3D discrete element model is introduced which reproduces both the large permanent deformation of the polymer during impact and the novel value of the mass distribution exponent. We demonstrate that the dominance of shear in the crack formation and the plastic response of the material are the key features which give rise to the emergence of the novel universality class of fragmentation phenomena.



DOI: 10.1103/PhysRevLett.104.095502 PACS numbers: 62.20.M−, 46.50.+a, 64.60.−i

Mechanism very unlikely in the ocean

Our assumption: plastic breaks due to large deformation during storm

Outline

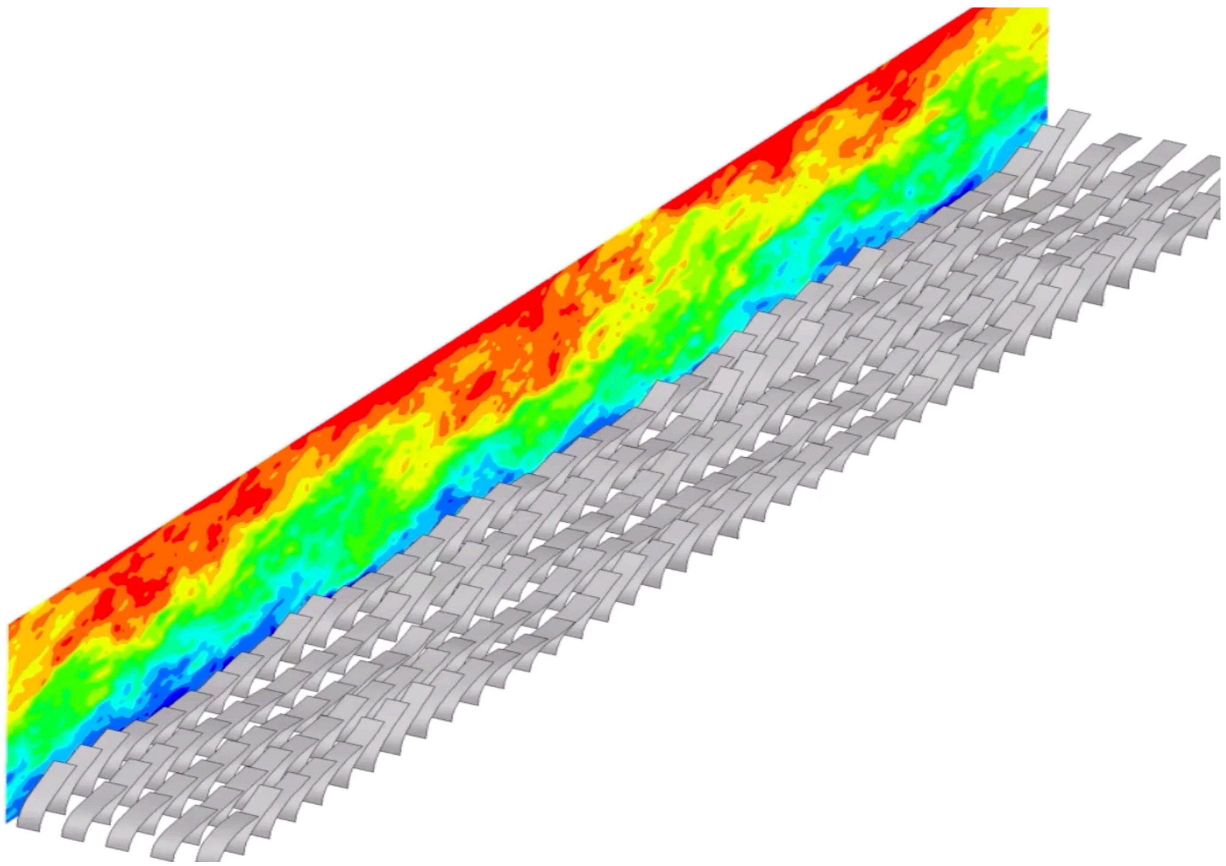
- Particle deformation in turbulence
- Fragmentation: deformation of brittle particles

Particle deformation

Particle deformation

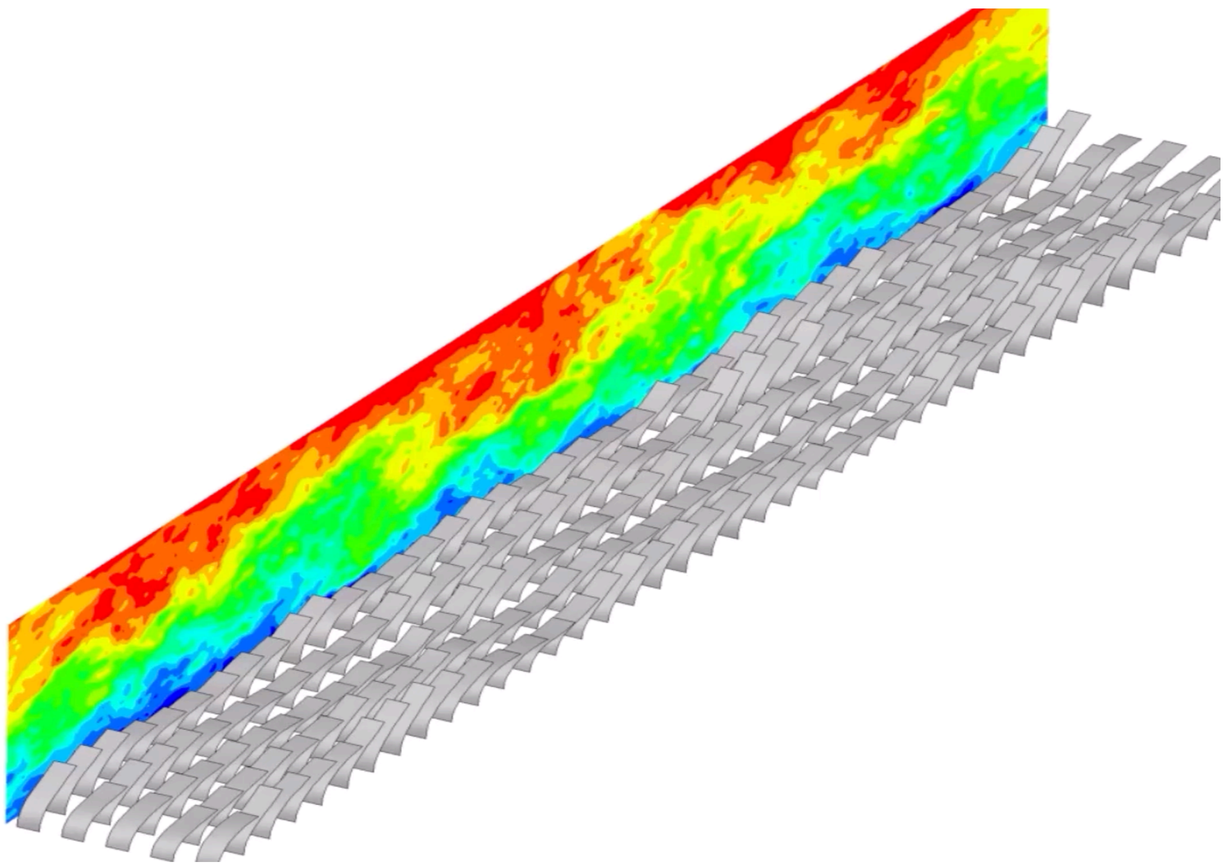
- When does a particle deform in a turbulent flow?
- How does a particle deform in a turbulent flow?

Classical fluid-structure approach



Univ. Minnesota

Classical fluid-structure approach



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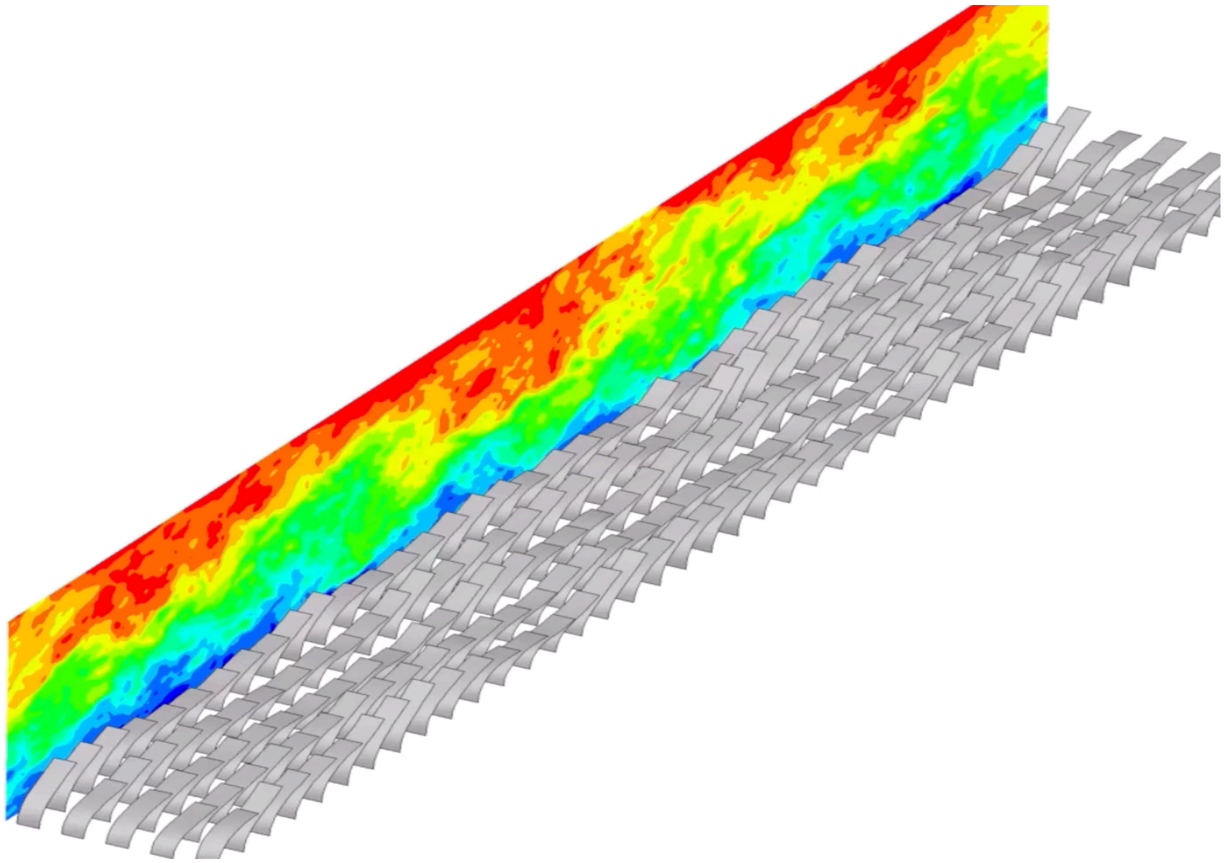

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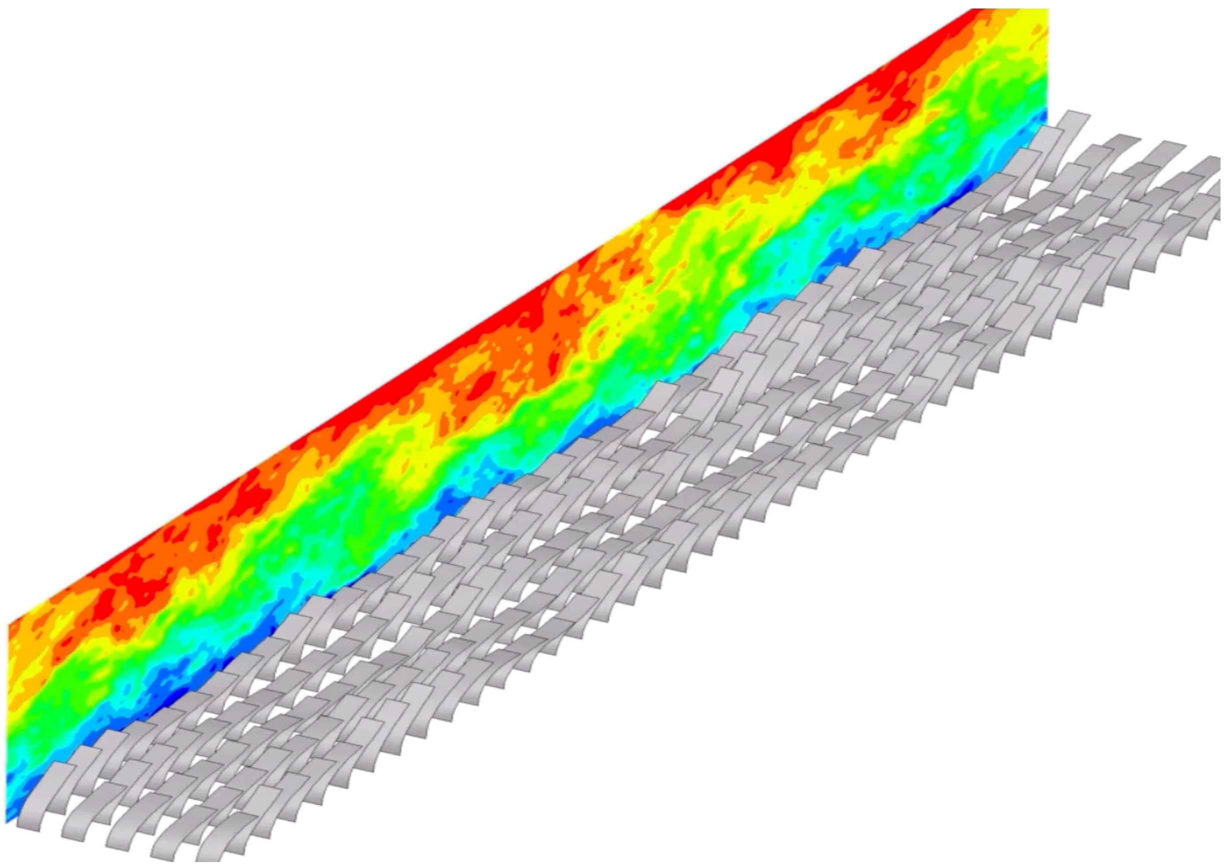
Turbulent flow

Pressure force ~ Bending force

$$\rho S U^2 \sim \frac{EI}{L^2}$$

Classical fluid-structure approach



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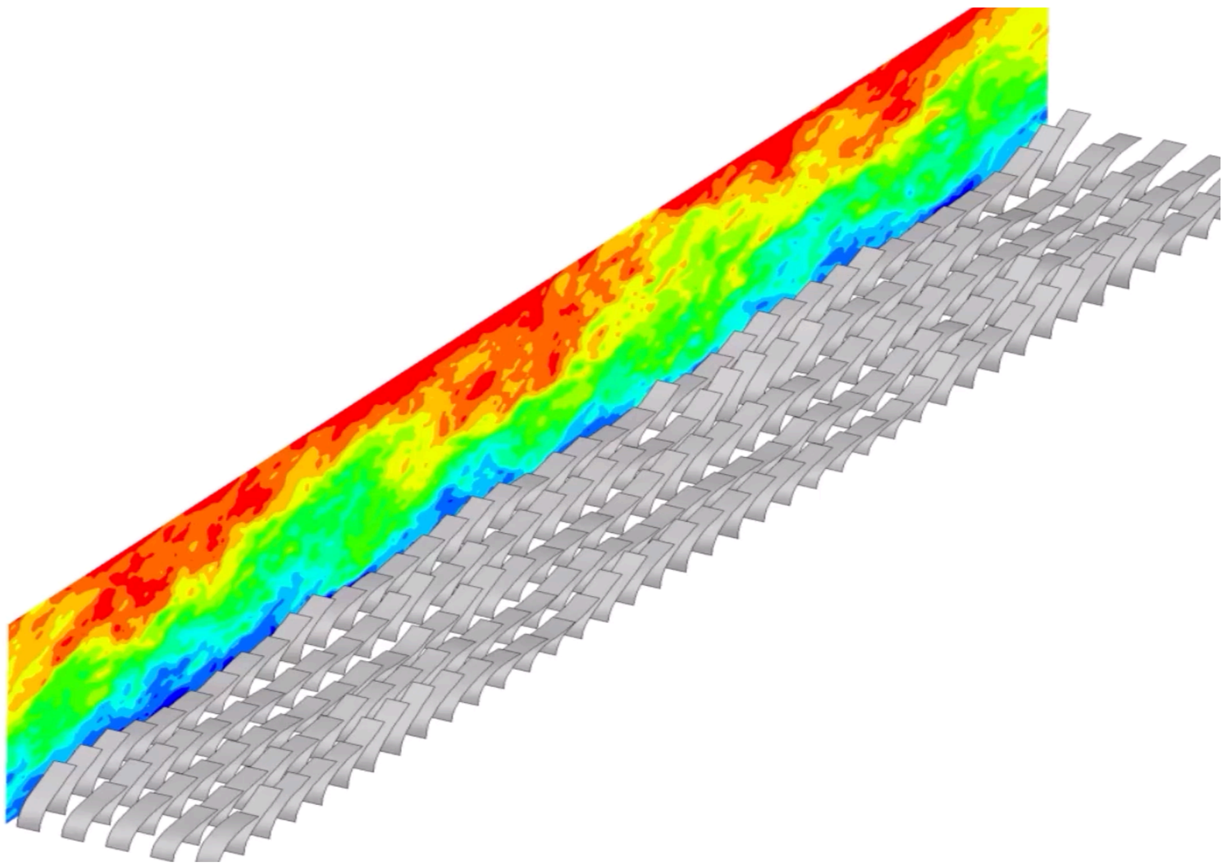

Univ. Minnesota

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Laminar flow

Viscous force ~ Bending force

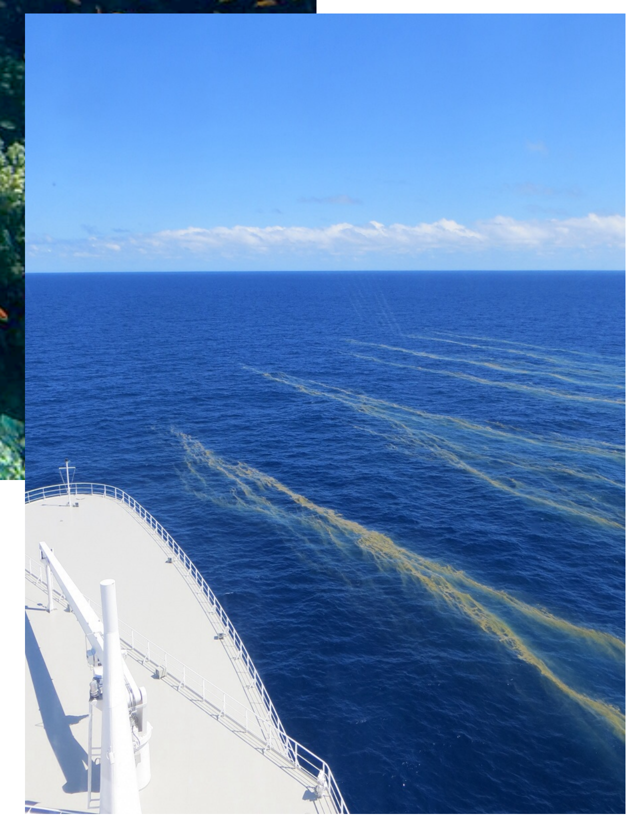
$$\eta L U \sim \frac{EI}{L^2}$$

Here pressure/viscous force also responsible of particle advection.
Which length scale matters for the velocity?

Various shapes in the ocean

Plastic bag, bottle, ...

Fishing line, net, ...



plancton colony
(Trichodesmium)

Various shapes in the ocean

Plastic bag, bottle, ...

Fishing line, net, ...

Here simplest shapes:
Fibers (mainly)
Discs

plancton colony
(Trichodesmium)

The different mode of deformation

$$\sigma\partial_{tt}\boldsymbol{r} - \partial_s(T\partial_s\boldsymbol{r}) + EI\partial_s^4\boldsymbol{r} = \boldsymbol{\xi} \quad , \quad |\partial_s\boldsymbol{r}|^2 = 1 \quad , \quad \boldsymbol{\xi} = \eta(\boldsymbol{u} - \partial_t\boldsymbol{r})$$

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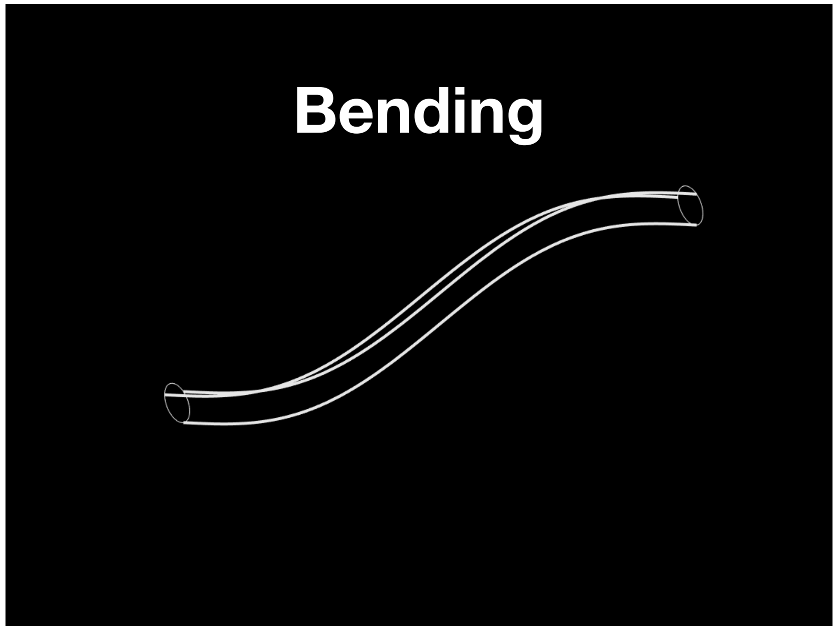
Timescale of the deformation



$$EI \partial_s^4 \boldsymbol{r} \sim \eta \partial_t \boldsymbol{r}$$

$$\tau_b \sim \frac{\eta L^4}{EI}$$

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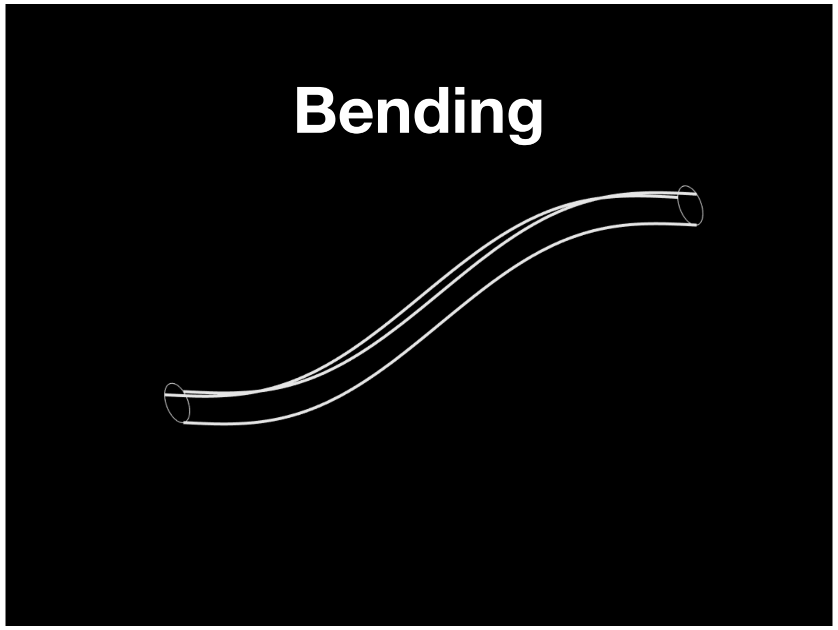

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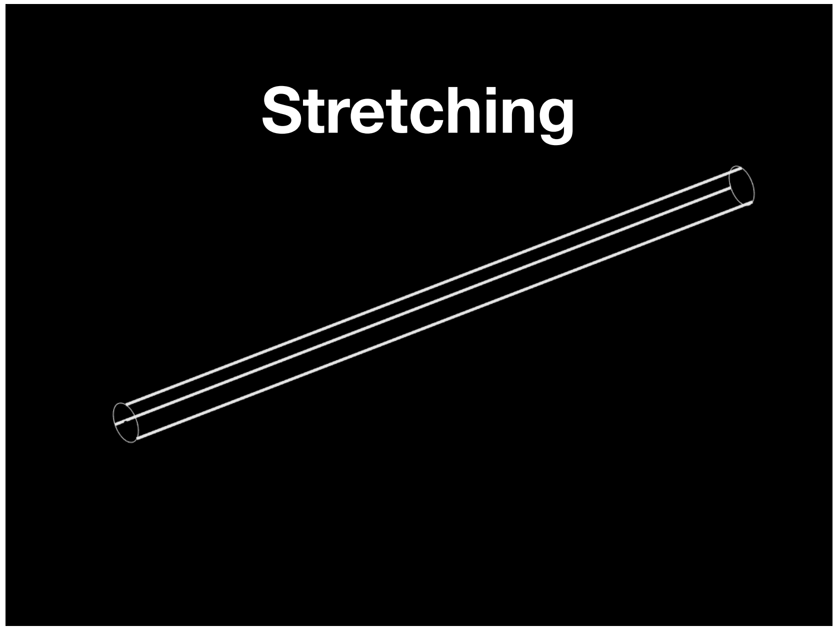


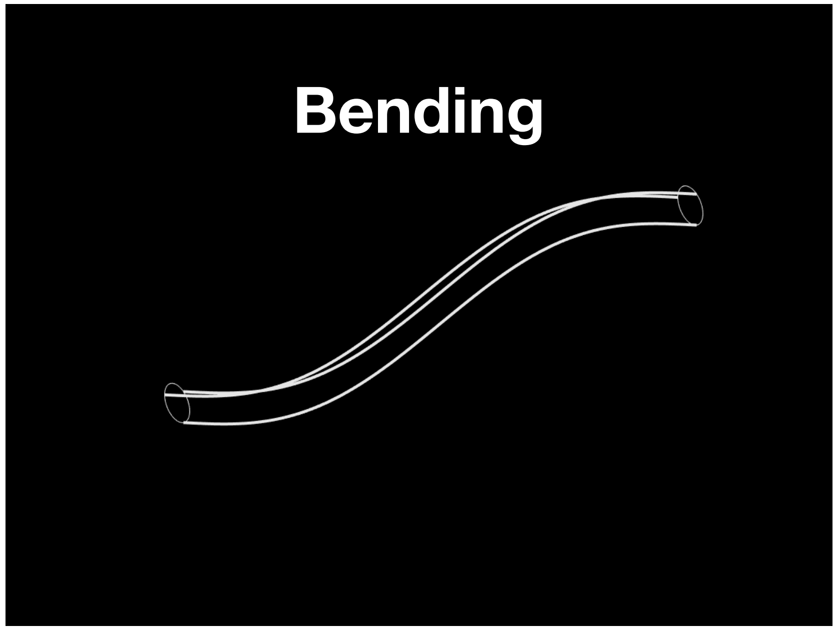
$$Ed^2\partial_{ss}\boldsymbol{r} \sim \eta\partial_t\boldsymbol{r}$$

$$\tau_s \sim \frac{\eta L^2}{Ed^2}$$

The different mode of deformation

$$\sigma \partial_{tt} \boldsymbol{r} - \partial_s (T \partial_s \boldsymbol{r}) + EI \partial_s^4 \boldsymbol{r} = \boldsymbol{\xi} \quad , \quad |\partial_s \boldsymbol{r}|^2 = 1 \quad , \quad \boldsymbol{\xi} = \eta (\boldsymbol{u} - \partial_t \boldsymbol{r})$$

Timescale of the deformation



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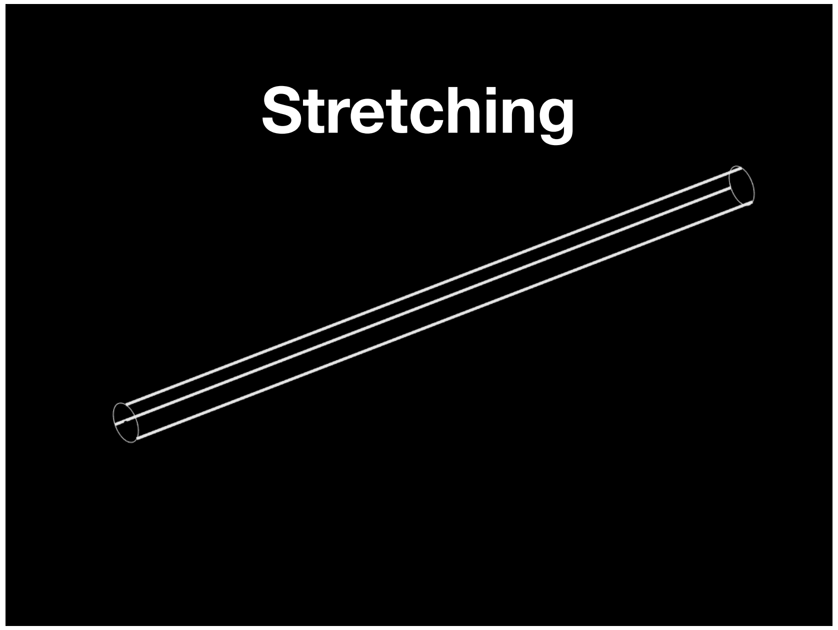
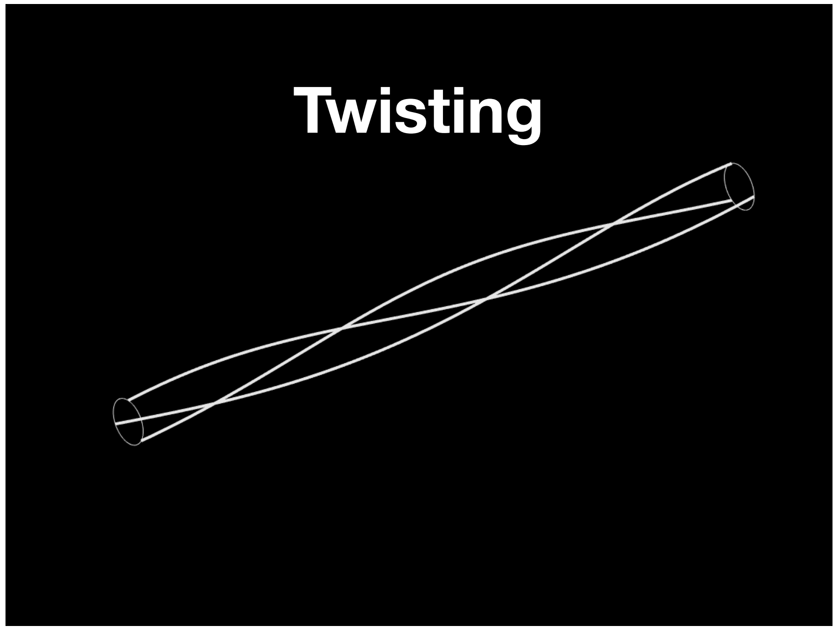


$$E d^2 \partial_{ss} \boldsymbol{r} \sim \eta \partial_t \boldsymbol{r}$$

$$\tau_s \sim \frac{\eta L^2}{E d^2}$$



$$C \partial_{ss} \theta \sim \eta d \partial_t d \theta$$

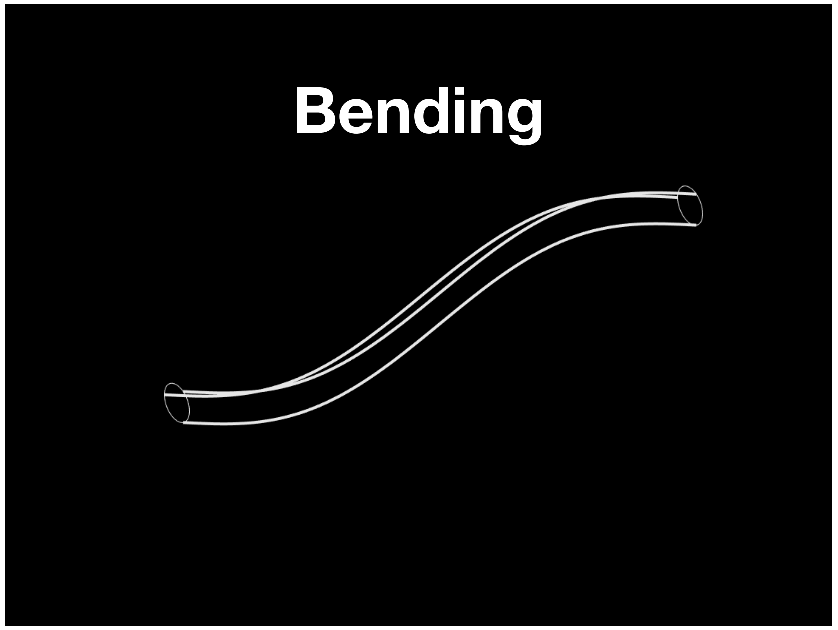
$$\tau_t \sim \frac{\eta d^2 L^2}{C}$$

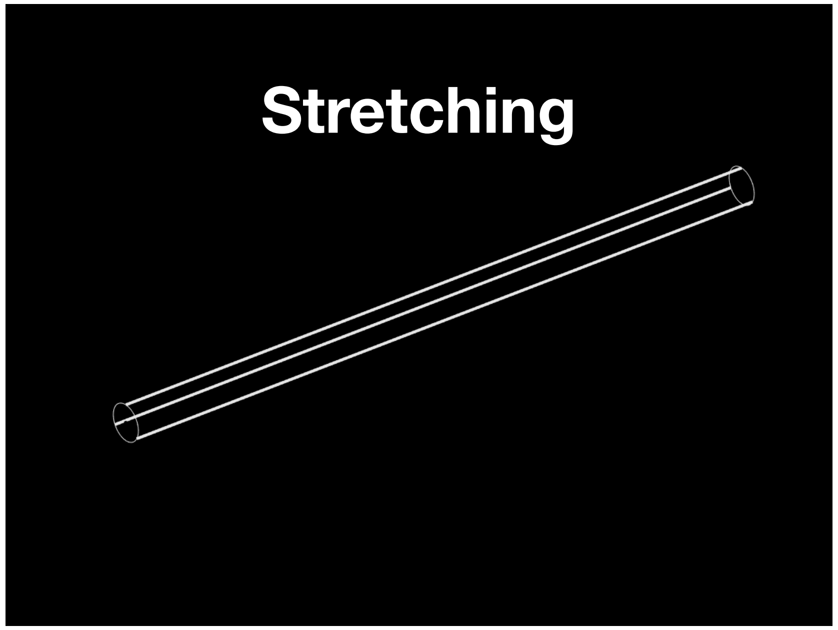
$$C \sim EI$$

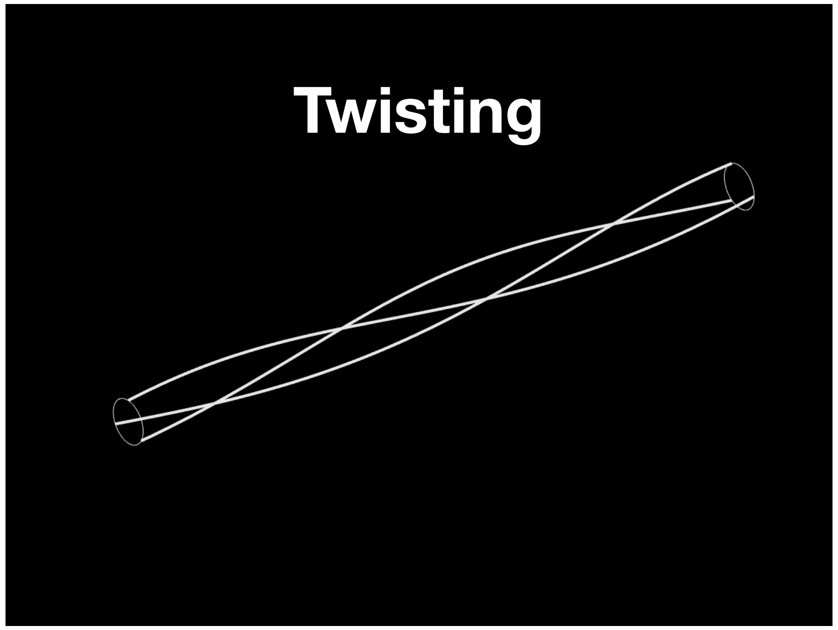
The different mode of deformation

$$\sigma\partial_{tt}\boldsymbol{r} - \partial_s(T\partial_s\boldsymbol{r}) + EI\partial_s^4\boldsymbol{r} = \boldsymbol{\xi} \quad , \quad |\partial_s\boldsymbol{r}|^2 = 1 \quad , \quad \boldsymbol{\xi} = \eta(\boldsymbol{u} - \partial_t\boldsymbol{r})$$

Timescale of the deformation







$$EI\partial_s^4\boldsymbol{r} \sim \eta\partial_t\boldsymbol{r}$$

$$\tau_b \sim \frac{\eta L^4}{EI}$$

$$Ed^2\partial_{ss}\boldsymbol{r} \sim \eta\partial_t\boldsymbol{r}$$

$$\tau_s \sim \frac{\eta L^2}{Ed^2}$$

$$C\partial_{ss}\theta \sim \eta d\partial_t d\theta$$

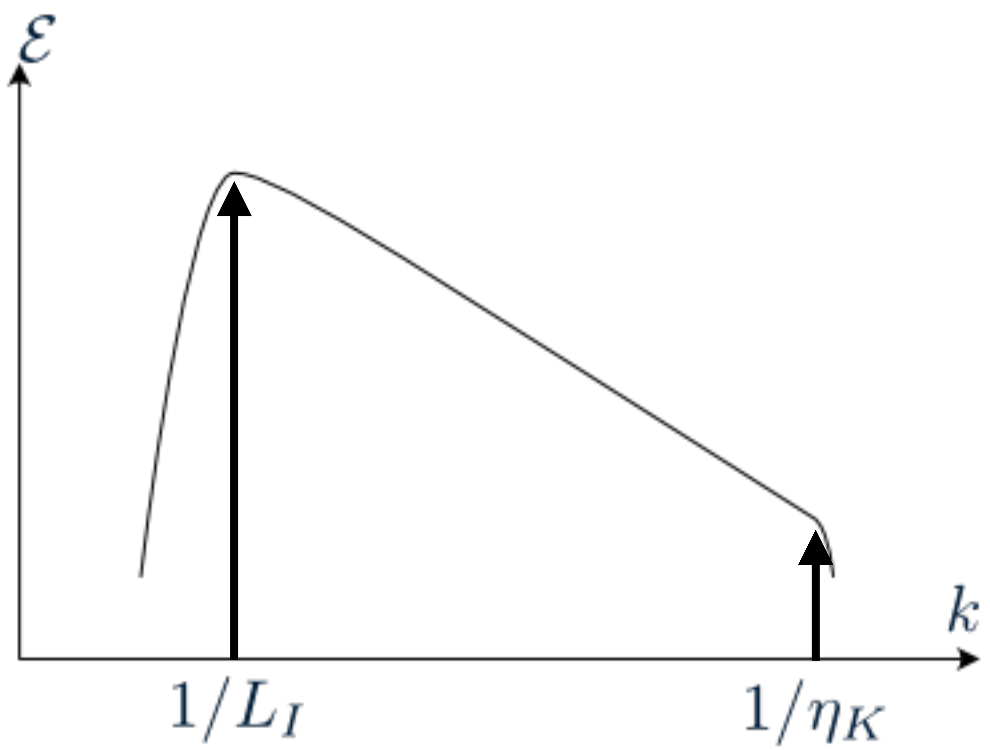
$$\tau_t \sim \frac{\eta d^2 L^2}{C}$$

$$C \sim EI$$

For fibers $L \gg d$ $\qquad \tau_s \sim \tau_t \ll \tau_b$

At first order fibers are inextensible and untwistable

Particle size vs turbulence length scales



$$\eta_K = \left(\frac{\nu^3}{\epsilon}\right)^{1/4} \qquad \tau_K = \left(\frac{\nu}{\epsilon}\right)^{1/2}$$

- Particle smaller than Kolmogorov length
- Particle in the inertial regime
- Particle larger than the integral length

$$\sigma\partial_{tt}\boldsymbol{r} - \partial_s(T\partial_s\boldsymbol{r}) + EI\partial_s^4\boldsymbol{r} = \boldsymbol{\xi} \quad , \quad |\partial_s\boldsymbol{r}|^2 = 1 \quad , \quad \boldsymbol{\xi} = \eta(\boldsymbol{u} - \partial_t\boldsymbol{r})$$

Different correlation for the forcing ξ

Particle smaller than the Kolmogorov length

Smooth flow (at the scale of the fiber)

S. Allende *et al.*, Phys. Rev. Lett., **121**, 154501, 2018.

Particle smaller than the Kolmogorov length

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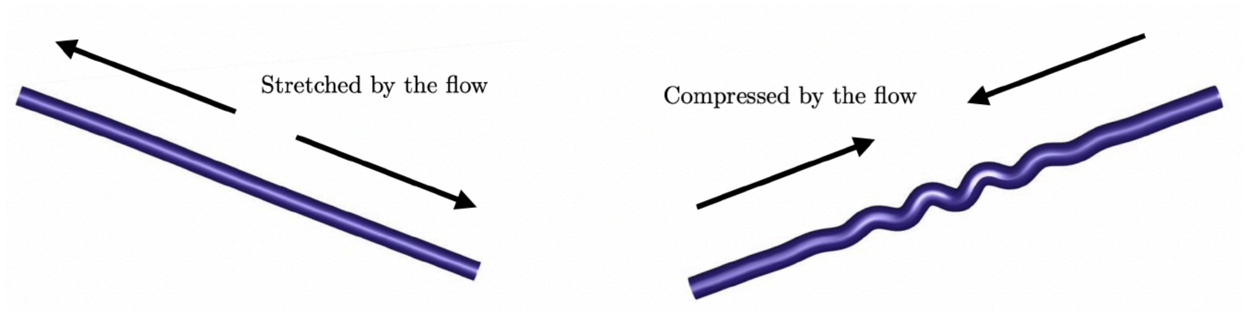

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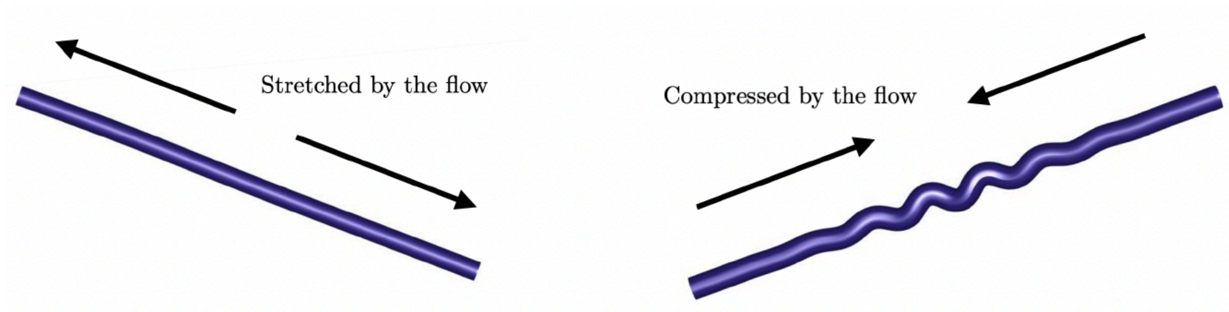

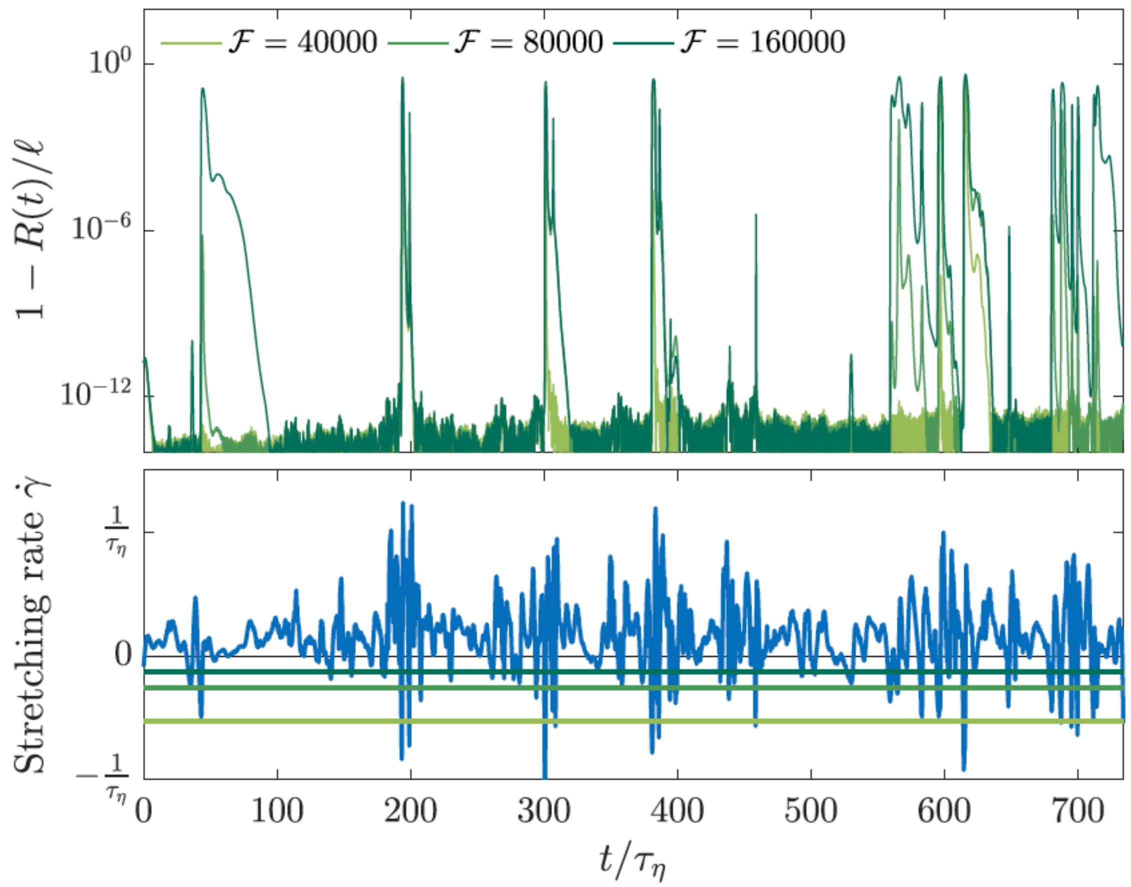

Flexibility parameter

$$\mathcal{F} = \frac{8\pi\rho_f\nu\ell^4}{cE\tau_\eta}$$

Viscous force ~ Bending force

S. Allende *et al.*, Phys. Rev. Lett., **121**, 154501, 2018.

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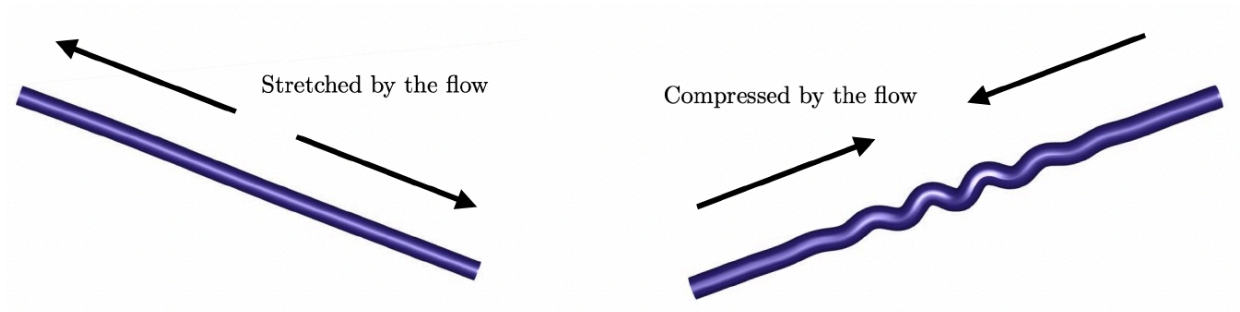

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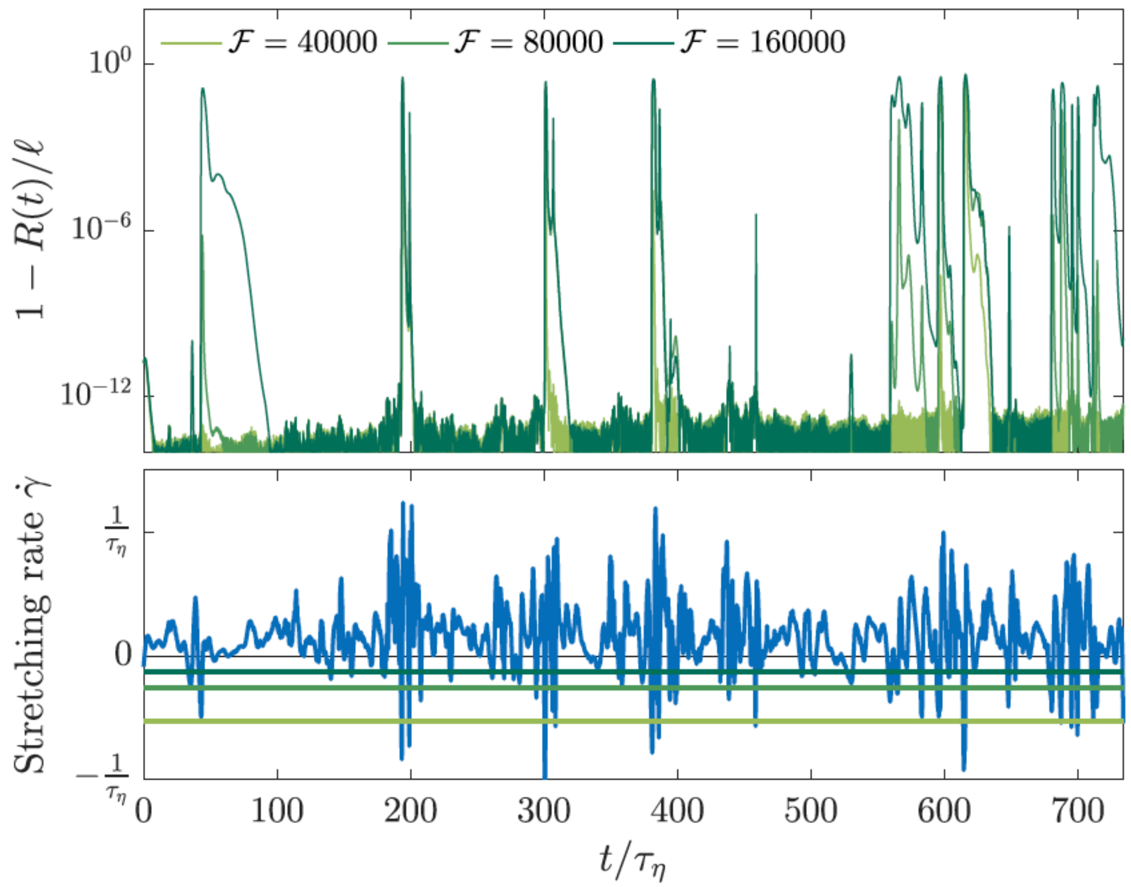

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$$\mathcal{F} = \frac{8\pi\rho_f\nu\ell^4}{cE\tau_\eta}$$

Viscous force ~ Bending force

Strong intermittency of buckling event

Preferential alignment with the strain

Buckling if $\dot\gamma\tau_\eta\mathcal{F} < -\mathcal{F}^\star$

Excited mode depends on $|\dot\gamma|$

S. Allende *et al.*, Phys. Rev. Lett., **121**, 154501, 2018.

Particle larger than the integral length

Correlation depends on the large scale flow

Particle larger than the integral length

Correlation depends on the large scale flow

In homogenenous isotropic turbulence

$\langle u(x+\ell, t+\tau) u(x,t) \rangle \sim \delta(\ell)\delta(\tau)$ for $\ell \gg L_I$ and $\tau \gg T_I$

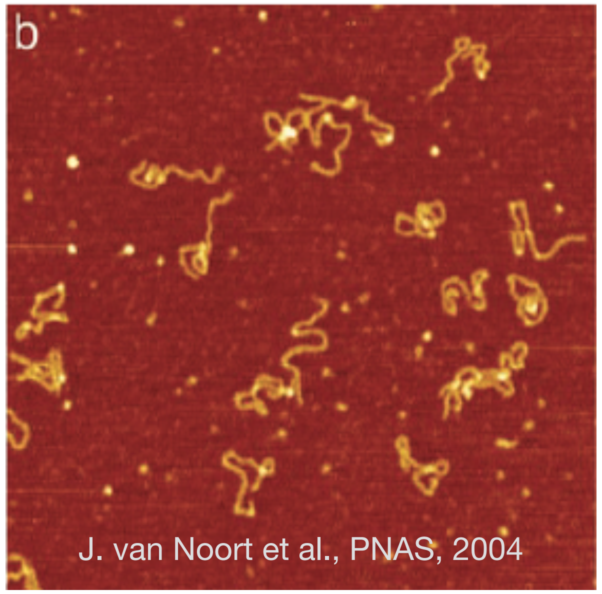
Particle larger than the integral length

Correlation depends on the large scale flow

In homogenenous isotropic turbulence

$\langle u(x+\ell, t+\tau)u(x,t)\rangle \sim \delta(\ell)\delta(\tau)$ for $\ell \gg L_I$ and $\tau \gg T_I$

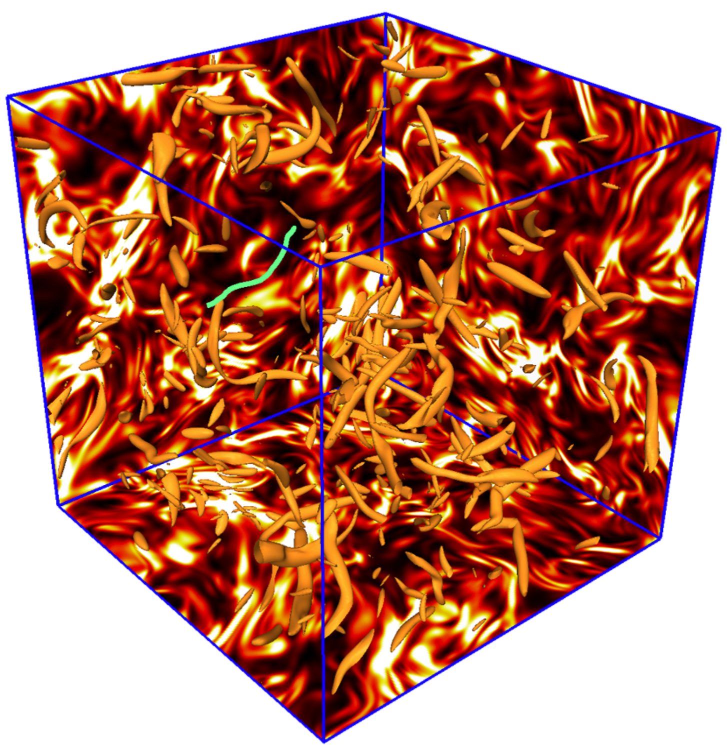
Deformations are expected to be similar to polymer



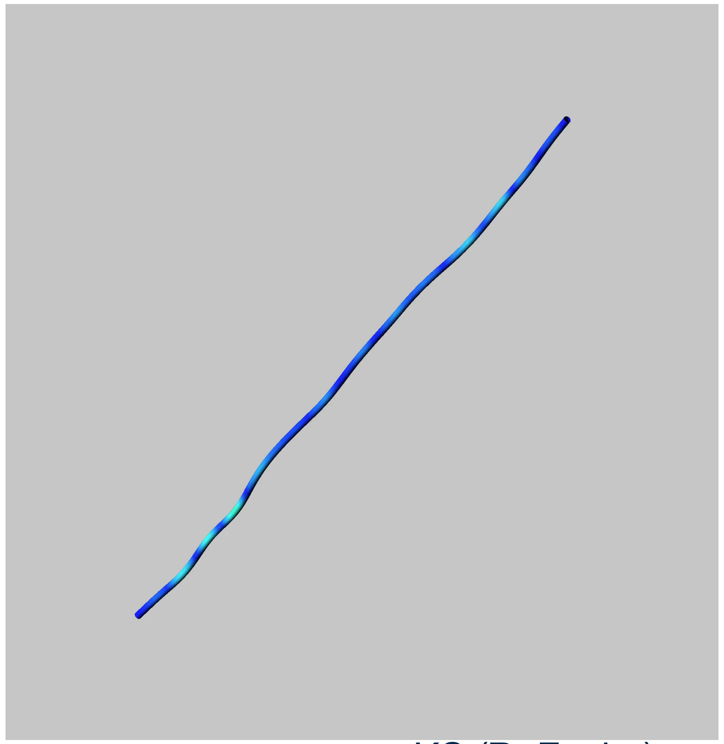
J. van Noort et al., PNAS, 2004

Particle in the inertial range

- Preferential alignment?
- Several length scales and timescales



Rosti *et al.*, Phys. Rev. Lett., **121**(4), 044501, 2018



KS (B. Favier)

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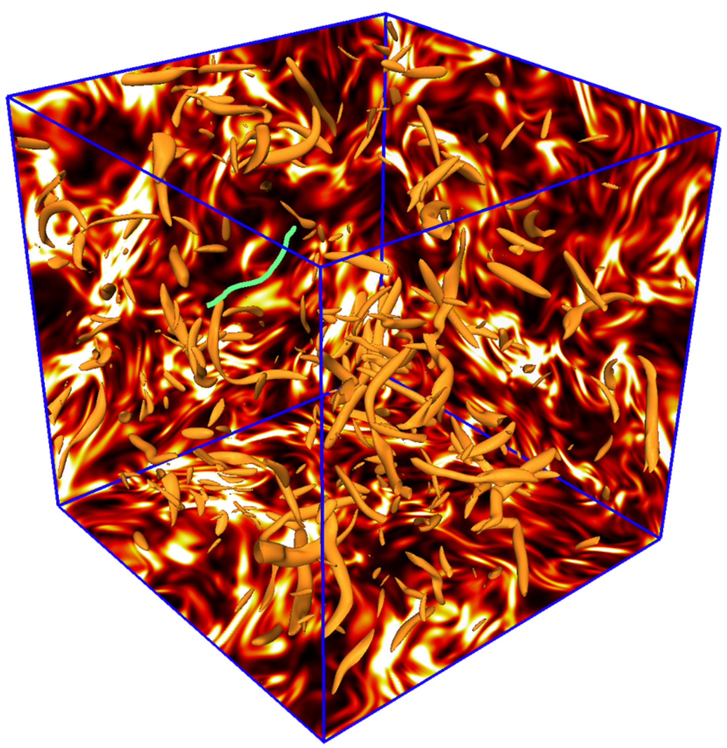

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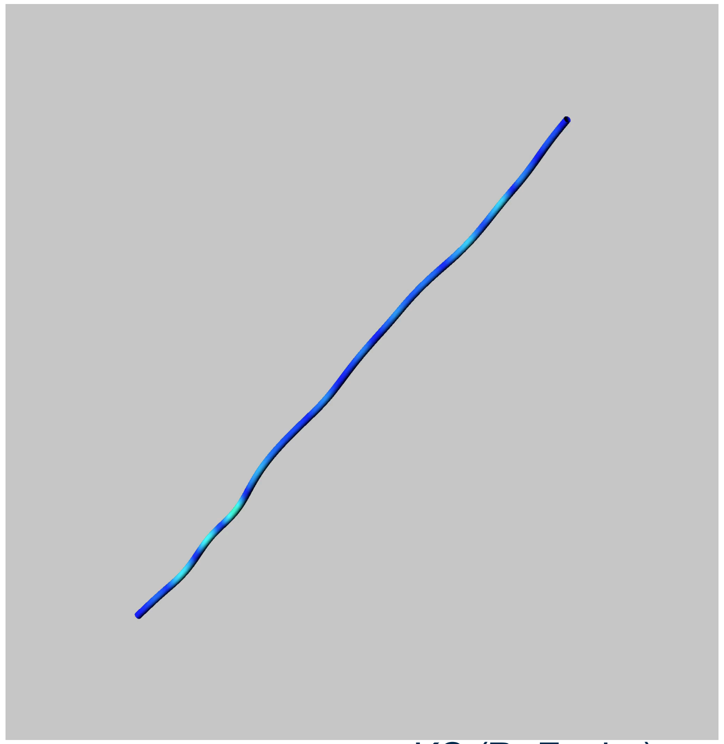
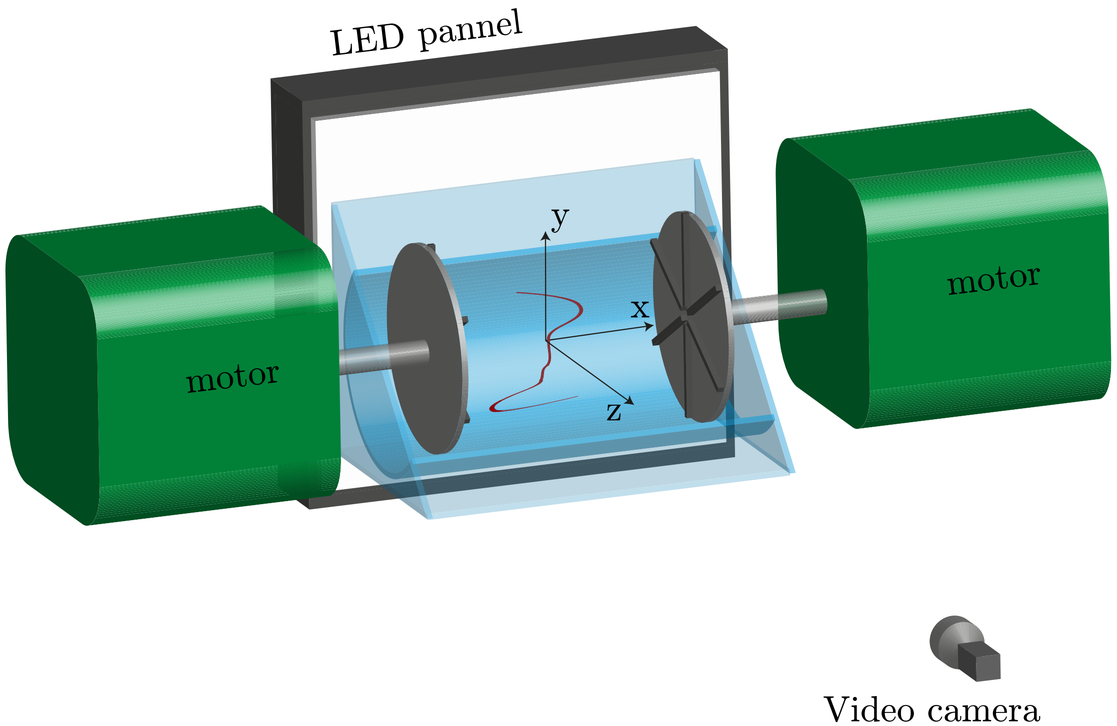


KS (B. Favier)

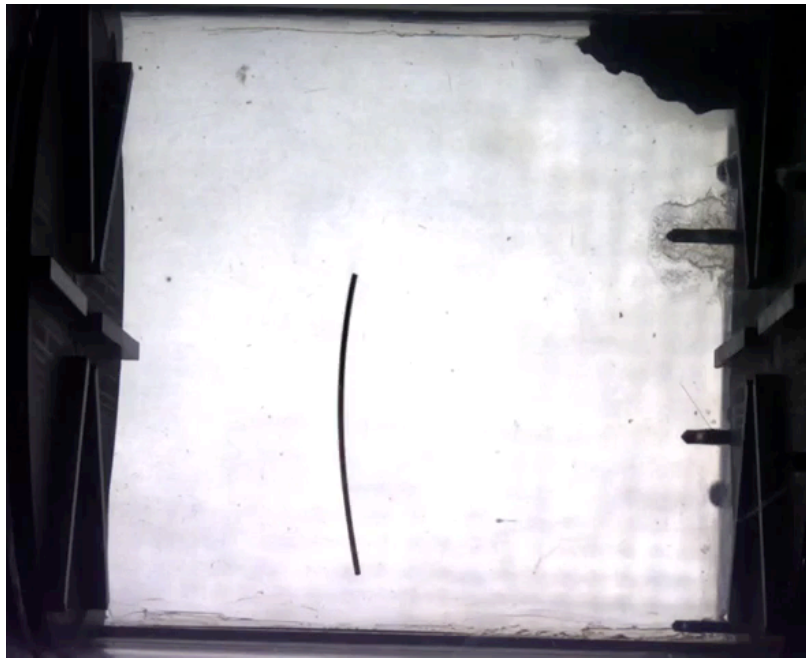
When does it bend?



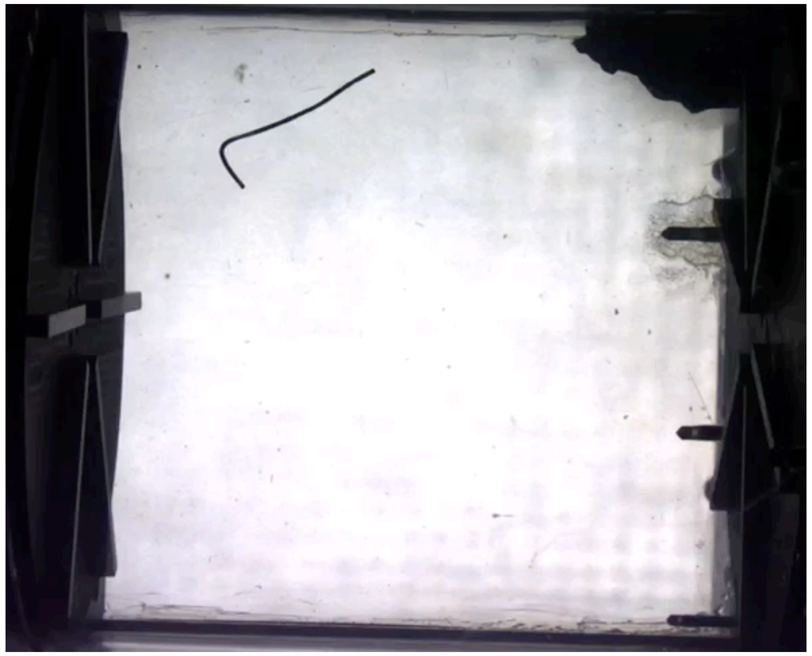
$R \sim 8.2$ cm

$Re \in [10^5\ ;\ 10^6]$

$\eta_K \in [12\ ;\ 91]\ \mu$m



F=2 Hz



F=20 Hz

Brouzet *et al.*, Flexible fiber in a turbulent flow: a macroscopic polymer, *Phys. Rev. Lett.*, 112, 074501, 2014

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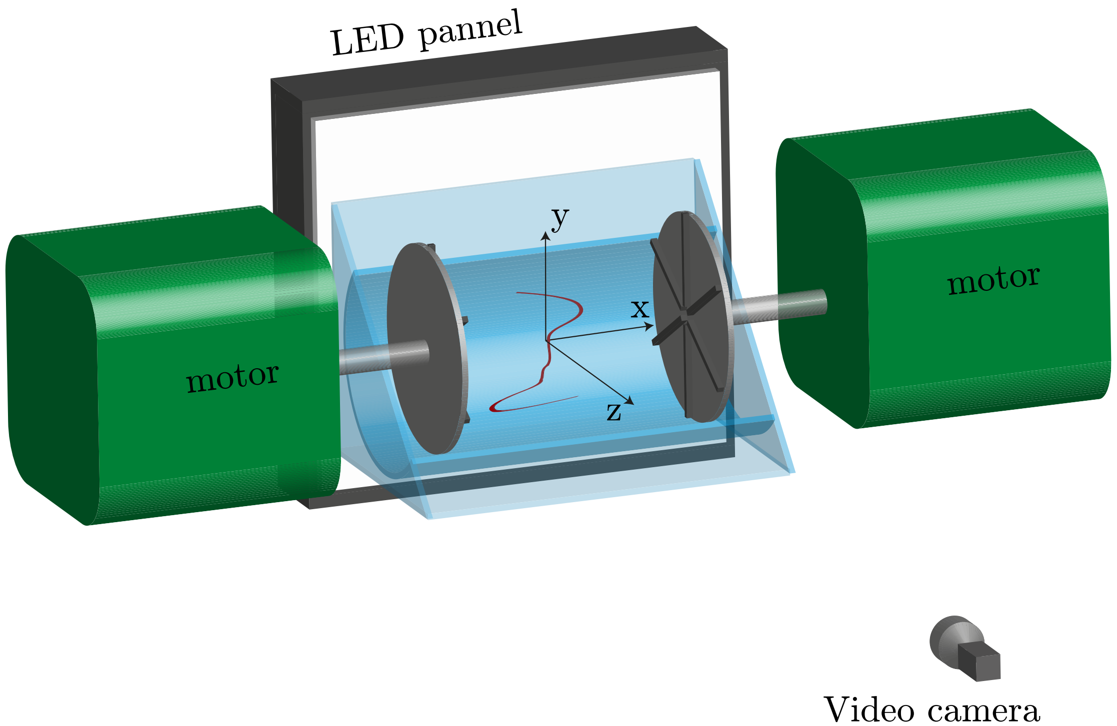

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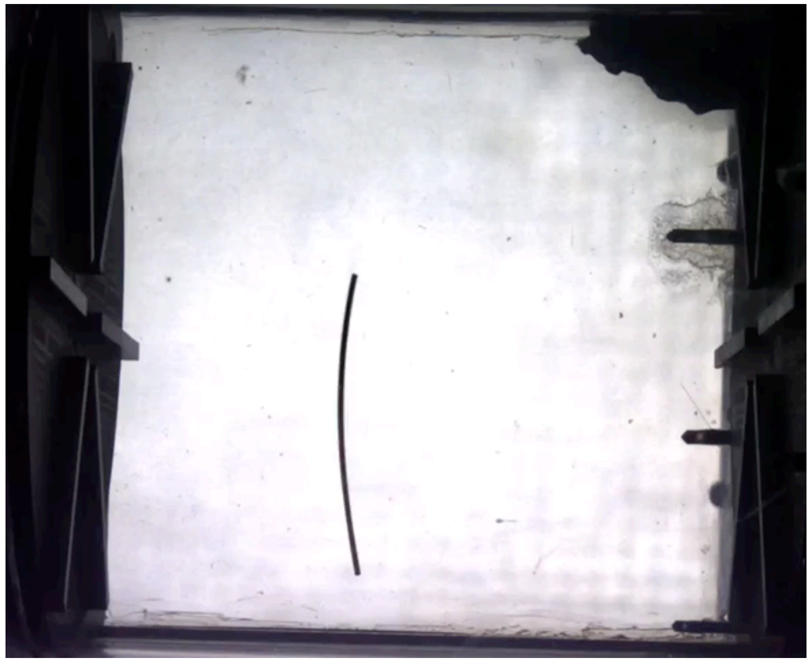

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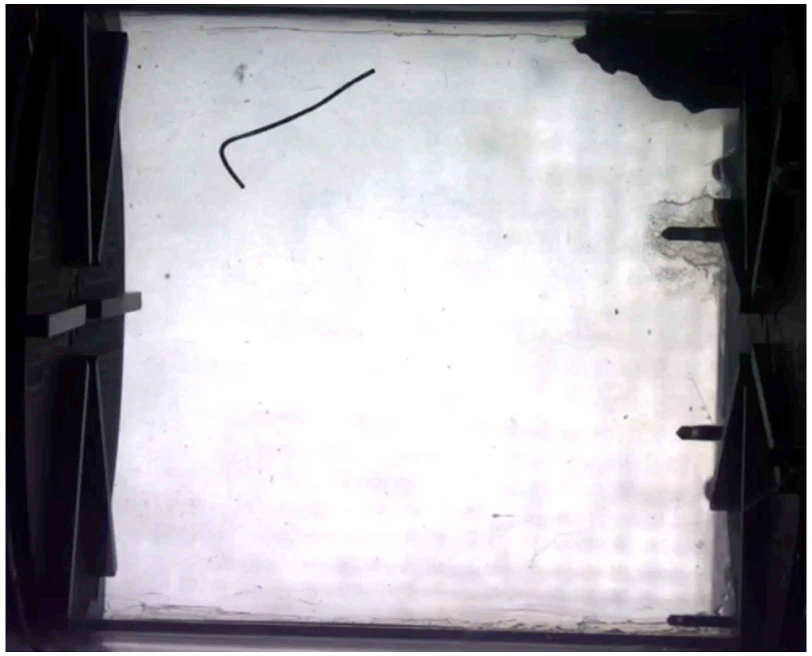

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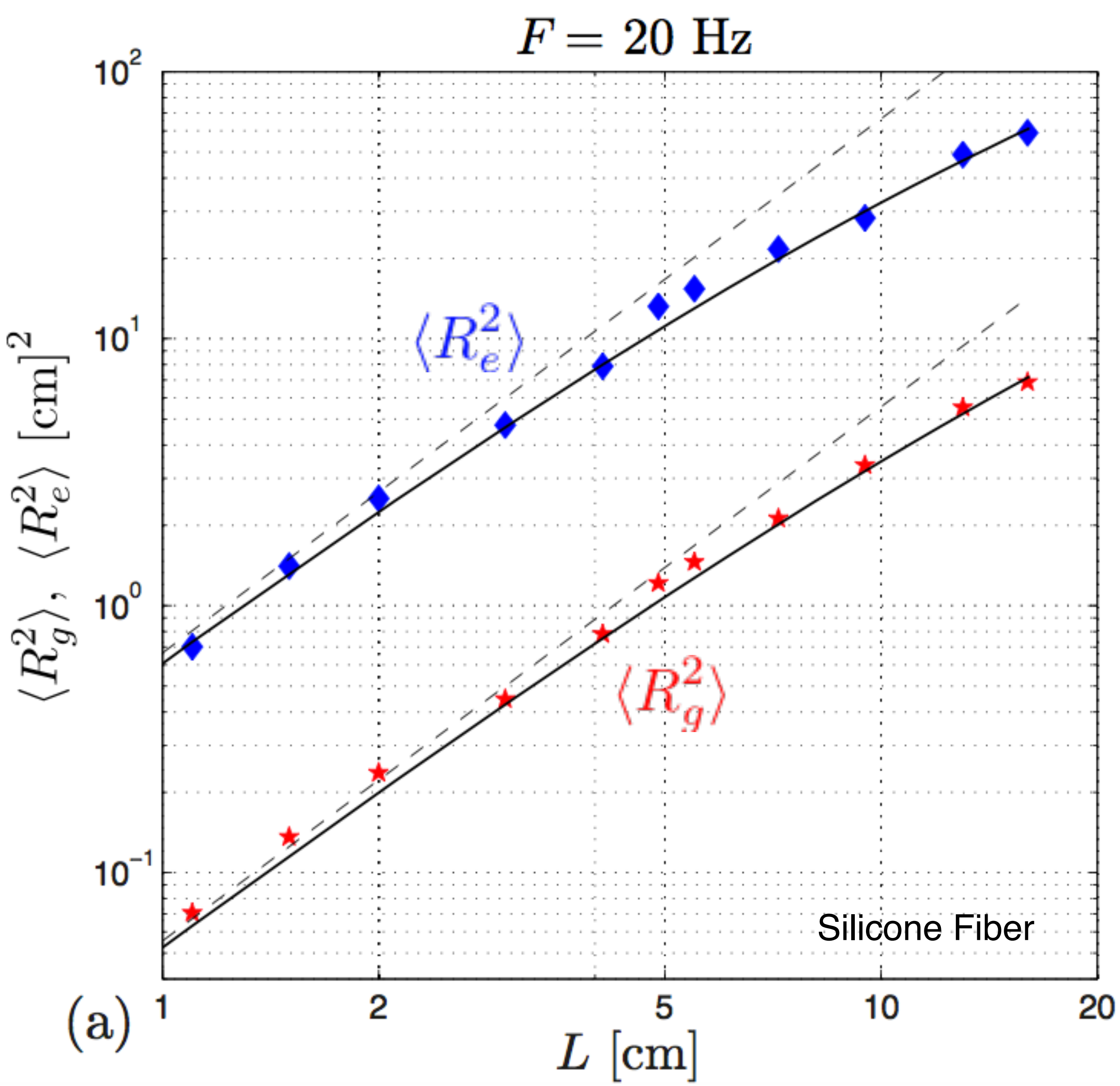
Brouzet *et al.*, Flexible fiber in a turbulent flow: a macroscopic polymer, *Phys. Rev. Lett.*, 112, 074501, 2014

Evolution of the end-to-end vector



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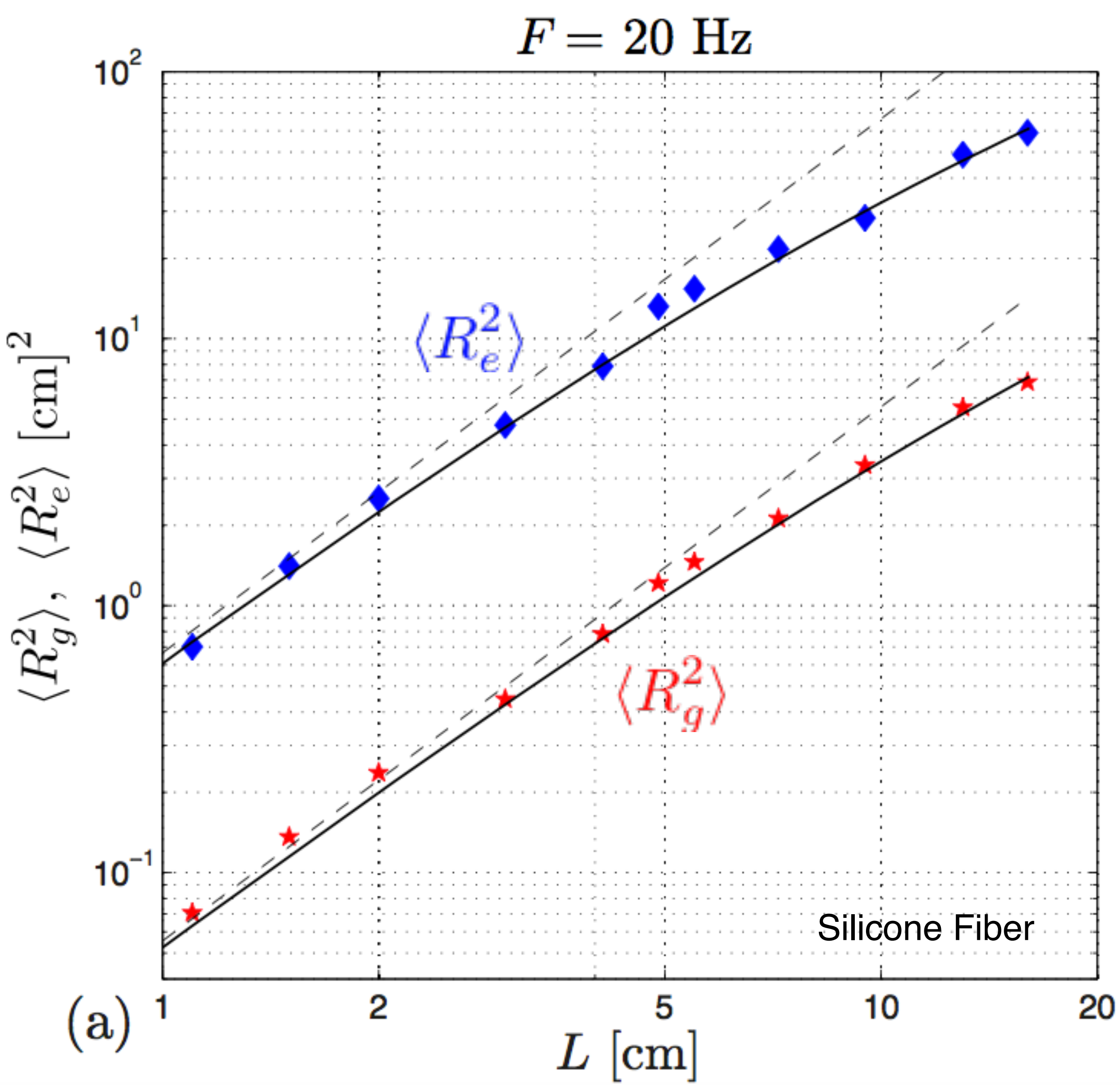
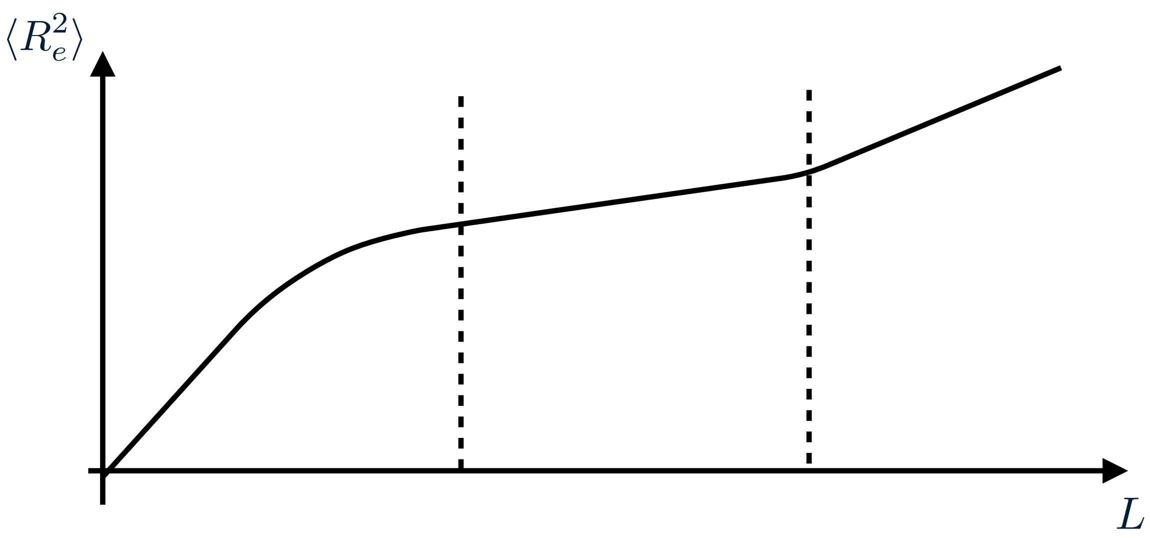


Polymer models



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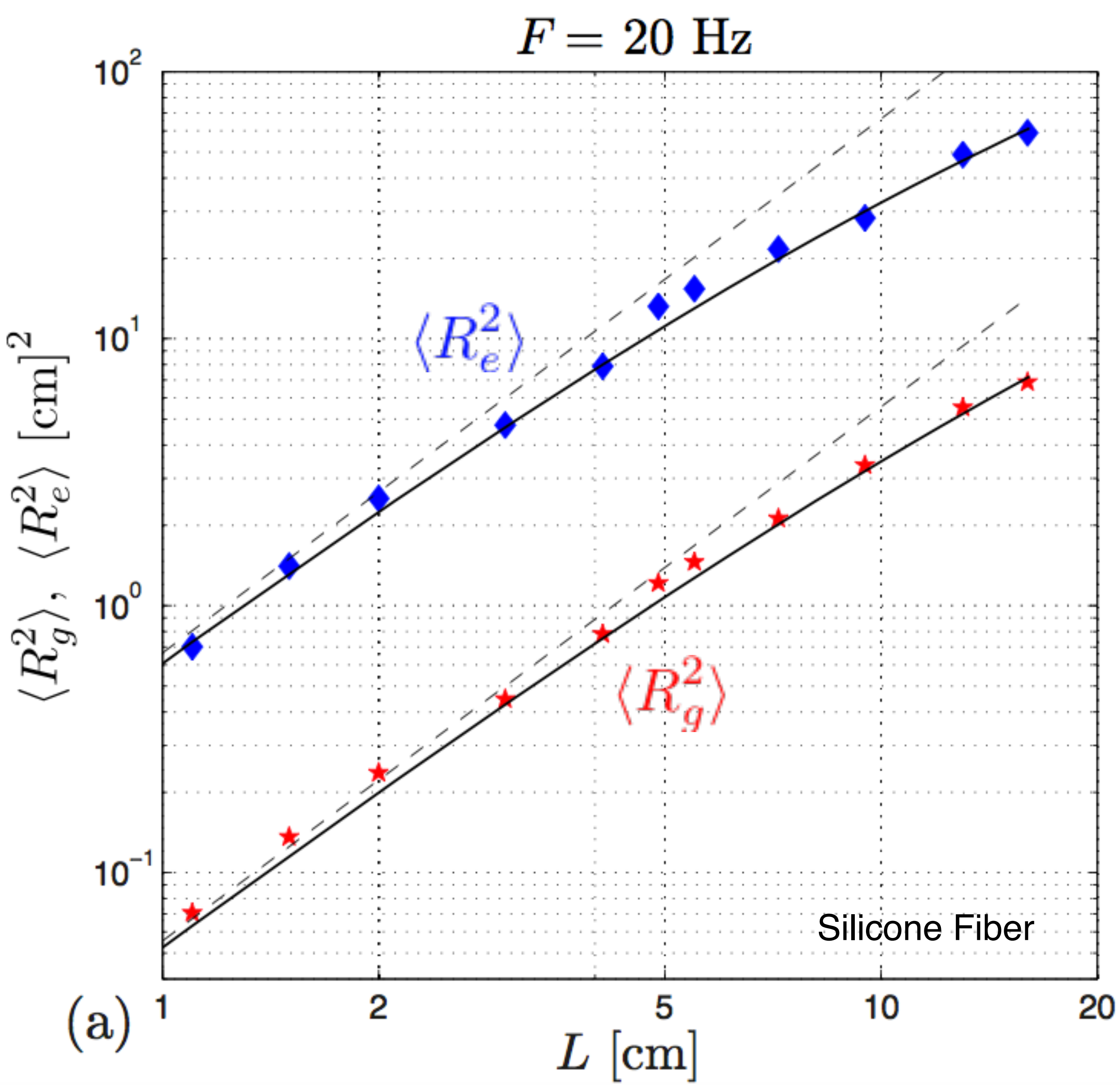

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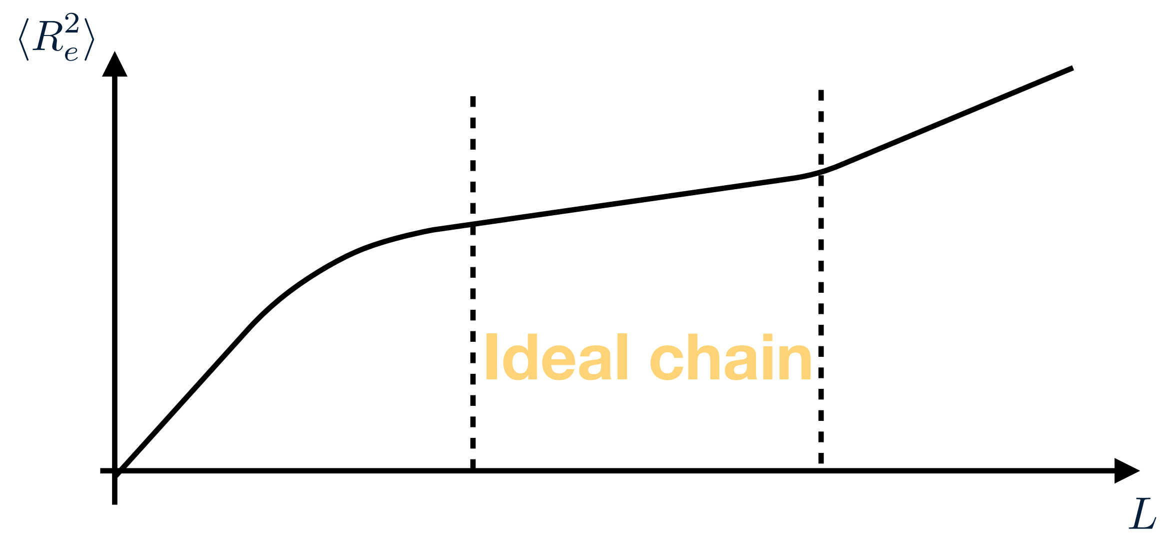

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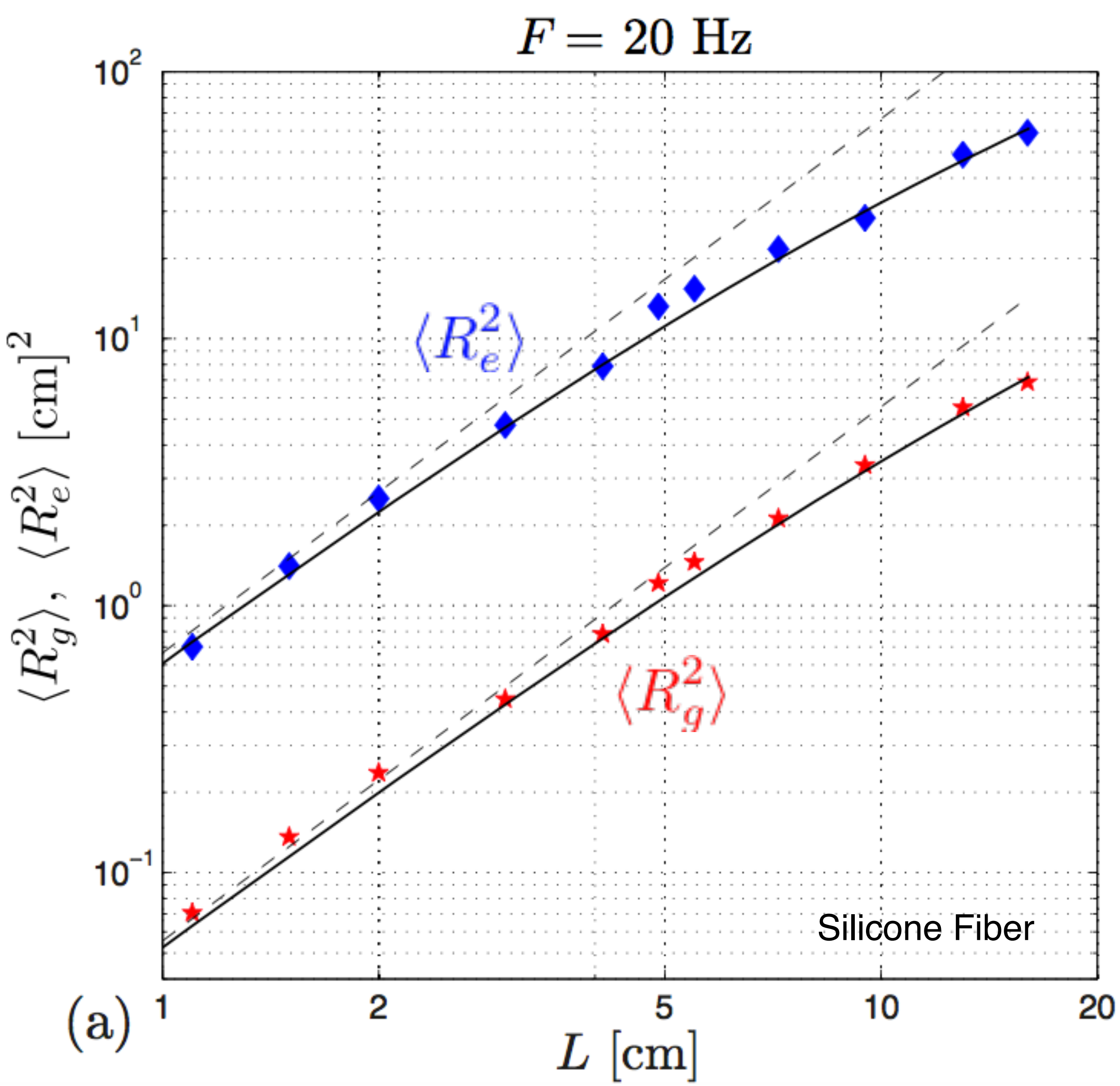
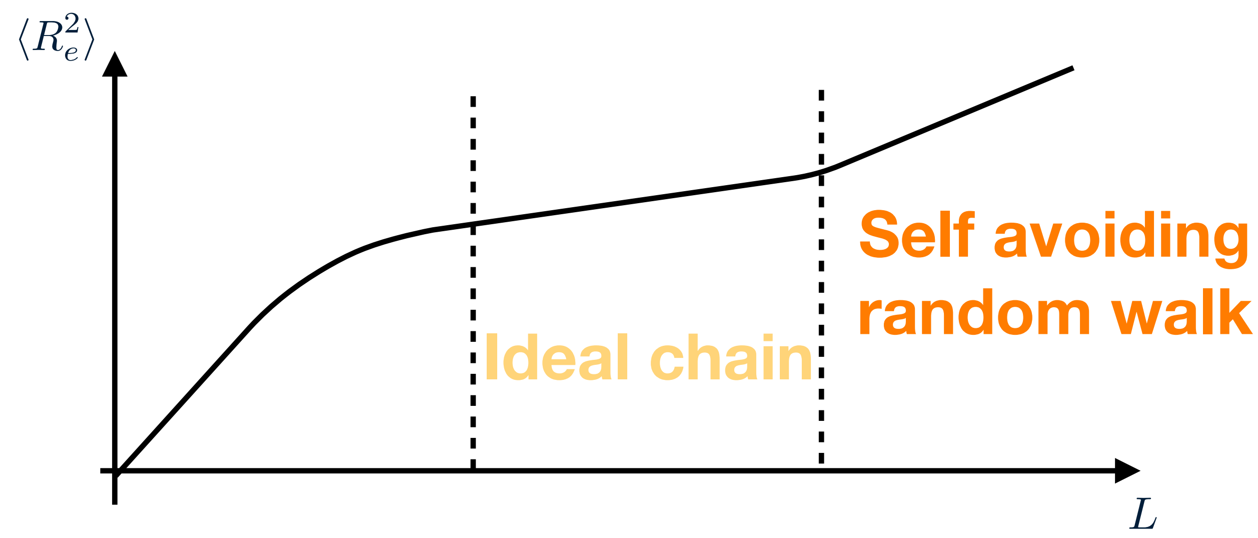


Polymer models



Brouzet *et al.*, Flexible fiber in a turbulent flow: a macroscopic polymer, *Phys. Rev. Lett.*, 112, 074501, 2014

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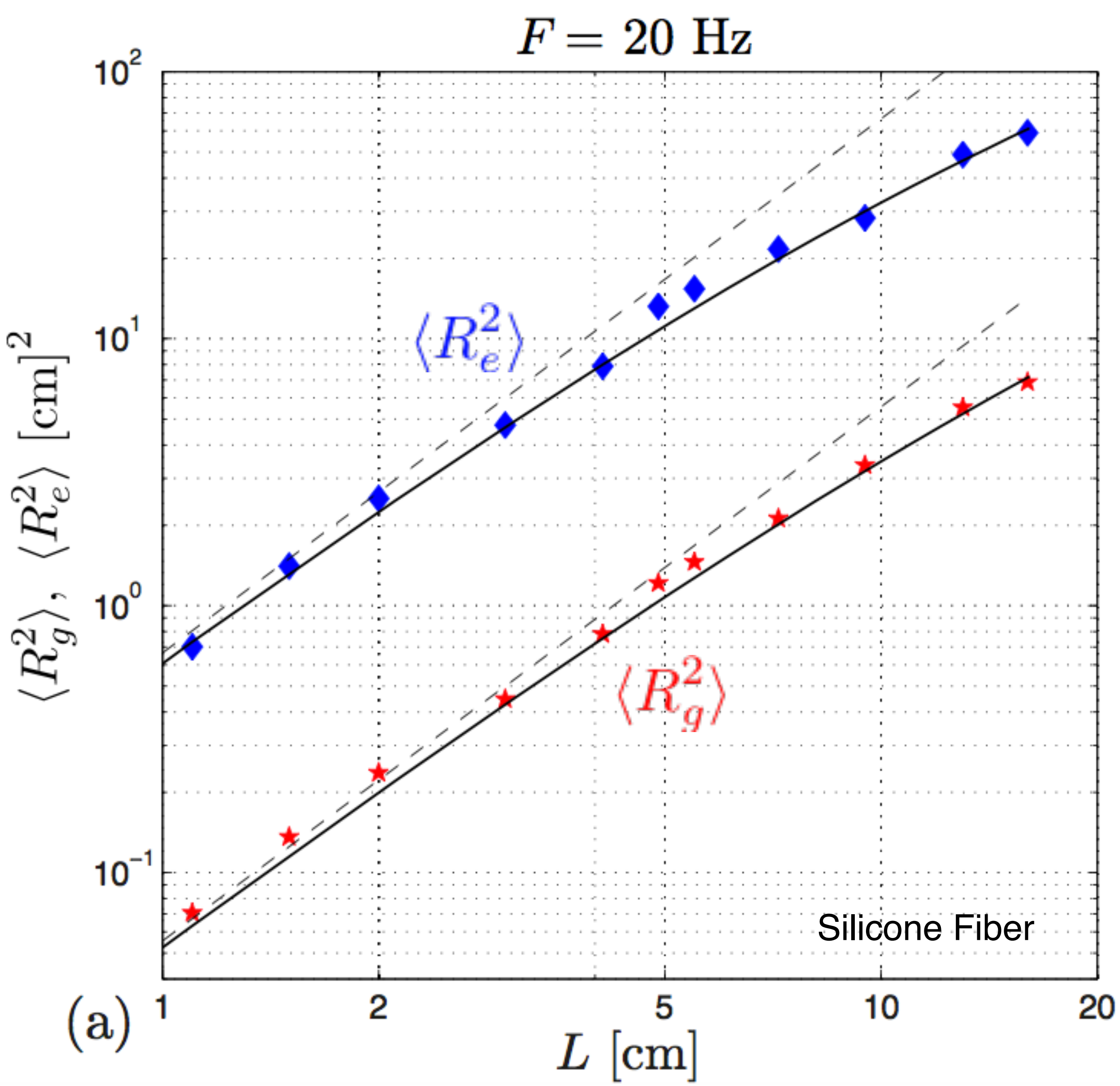

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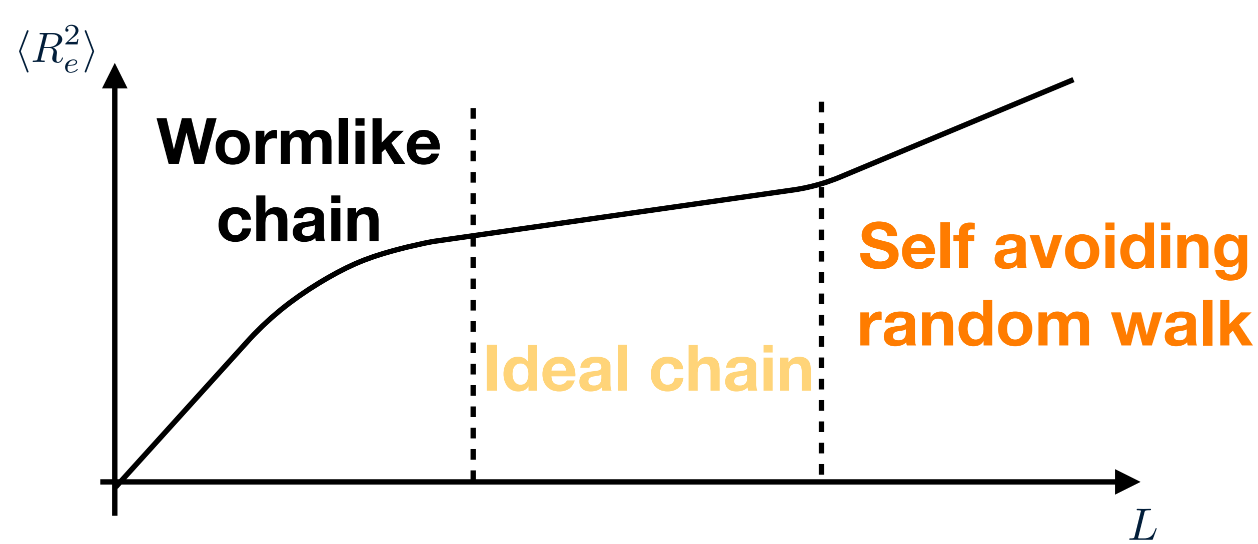

$$\langle t(s+\ell) \cdot t(s) \rangle = e^{-\ell/\ell_P}$$

$$\langle R_e^2 \rangle = 2L\ell_P - 2\ell_P^2 \left(1 - e^{-\ell/\ell_P}\right)$$

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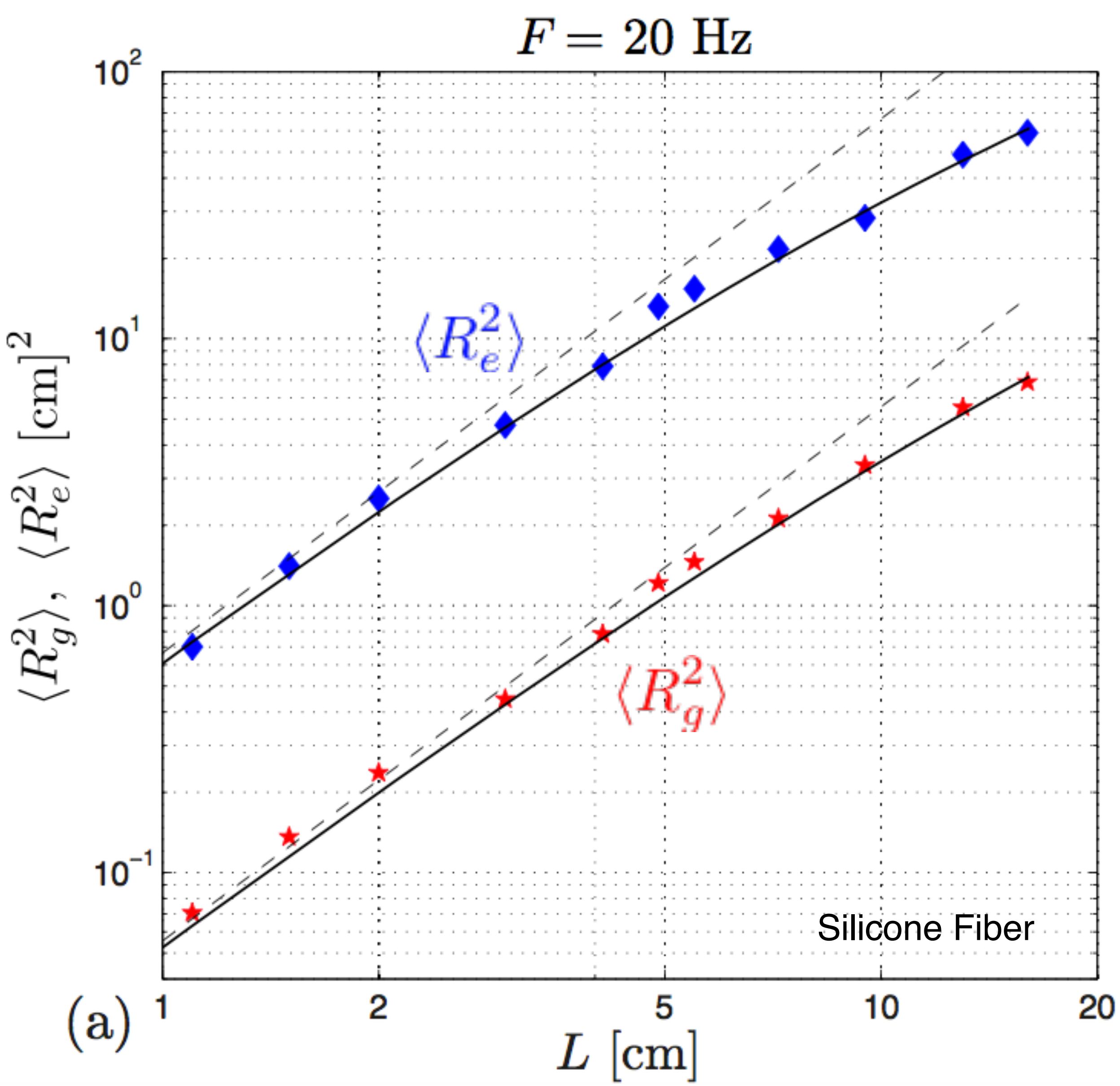

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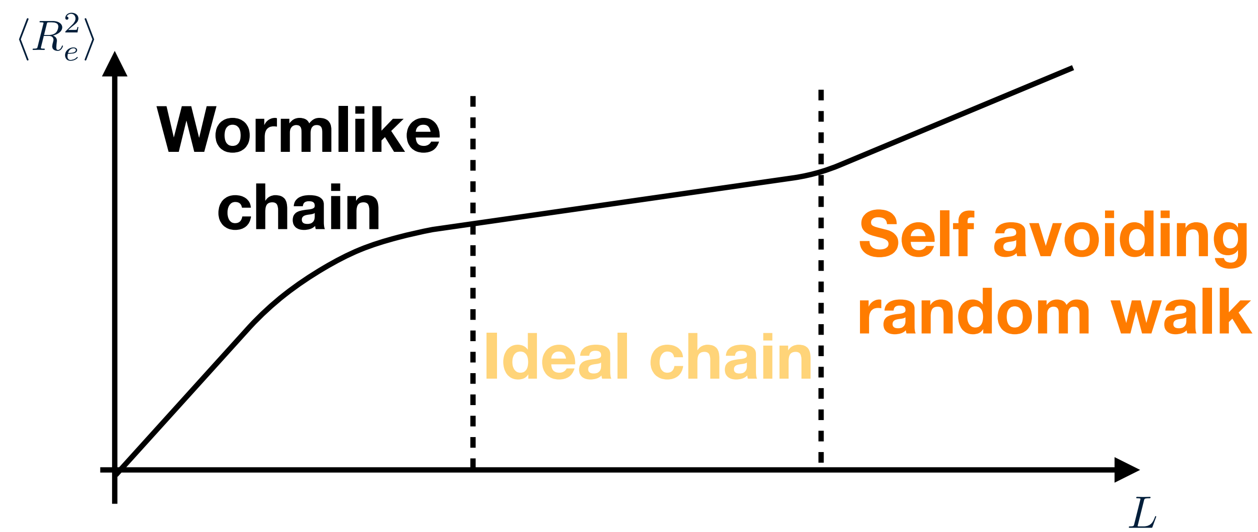

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The physics is hidden in ℓ_P

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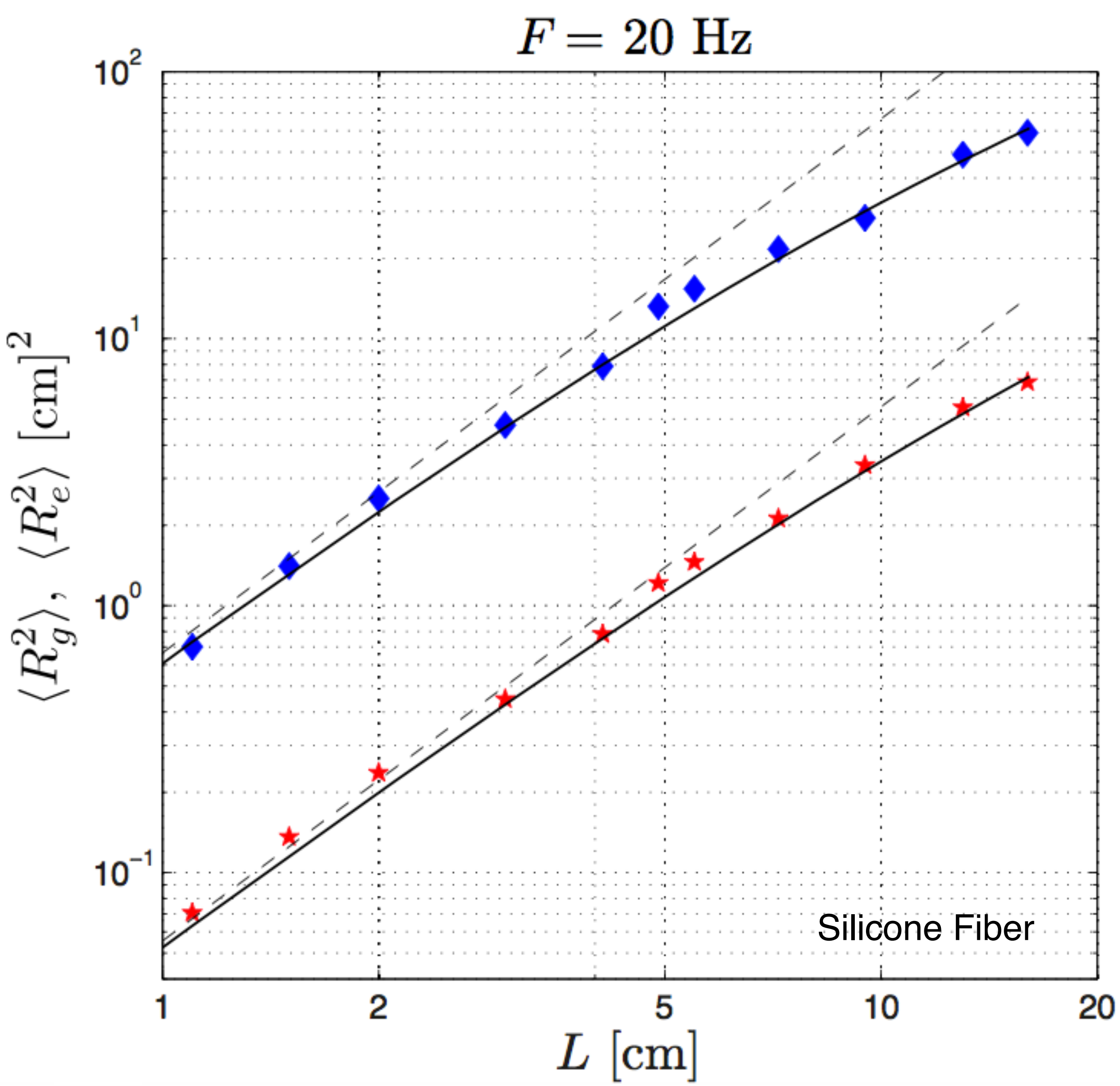
Evolution of the persistence length



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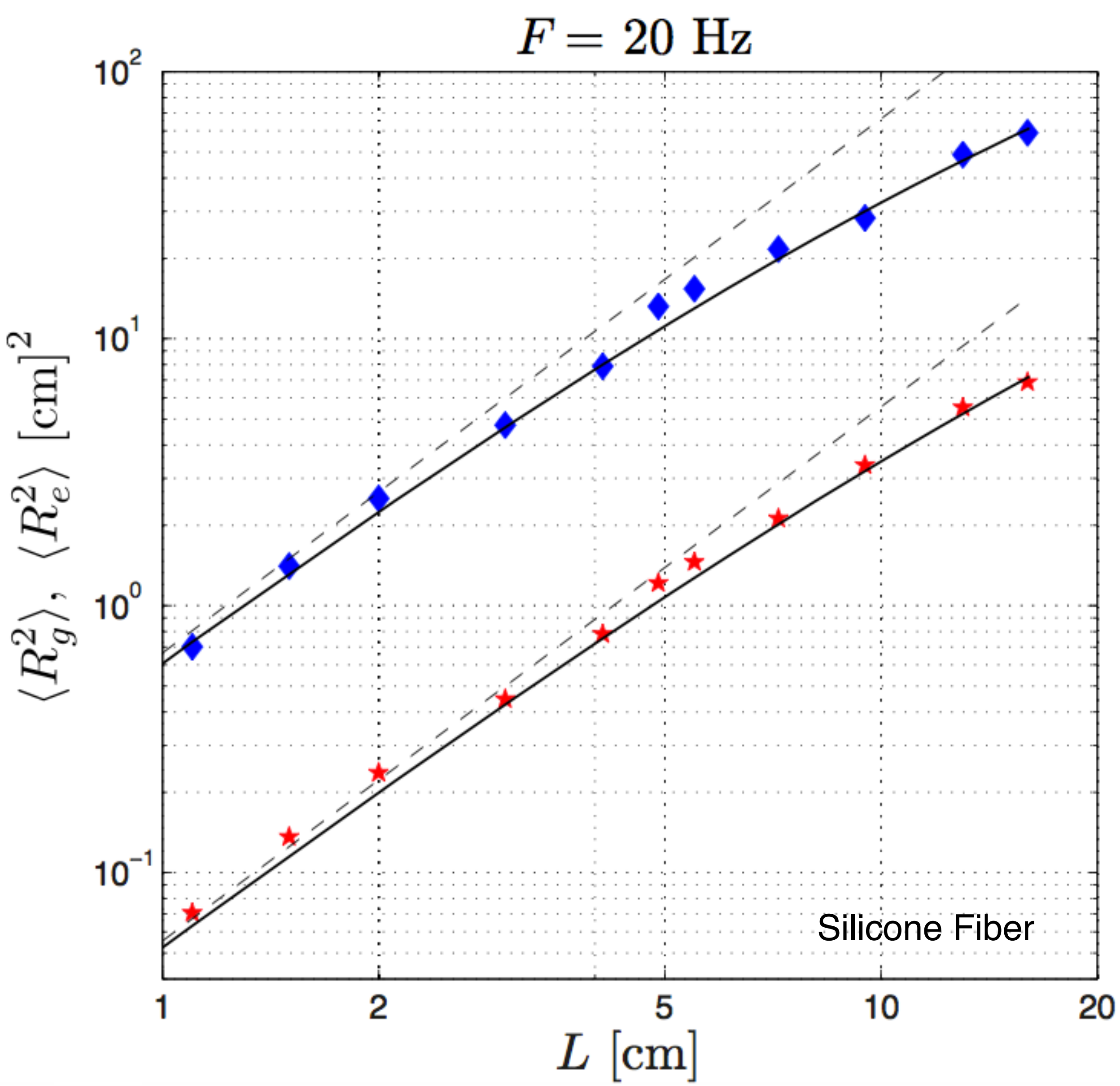

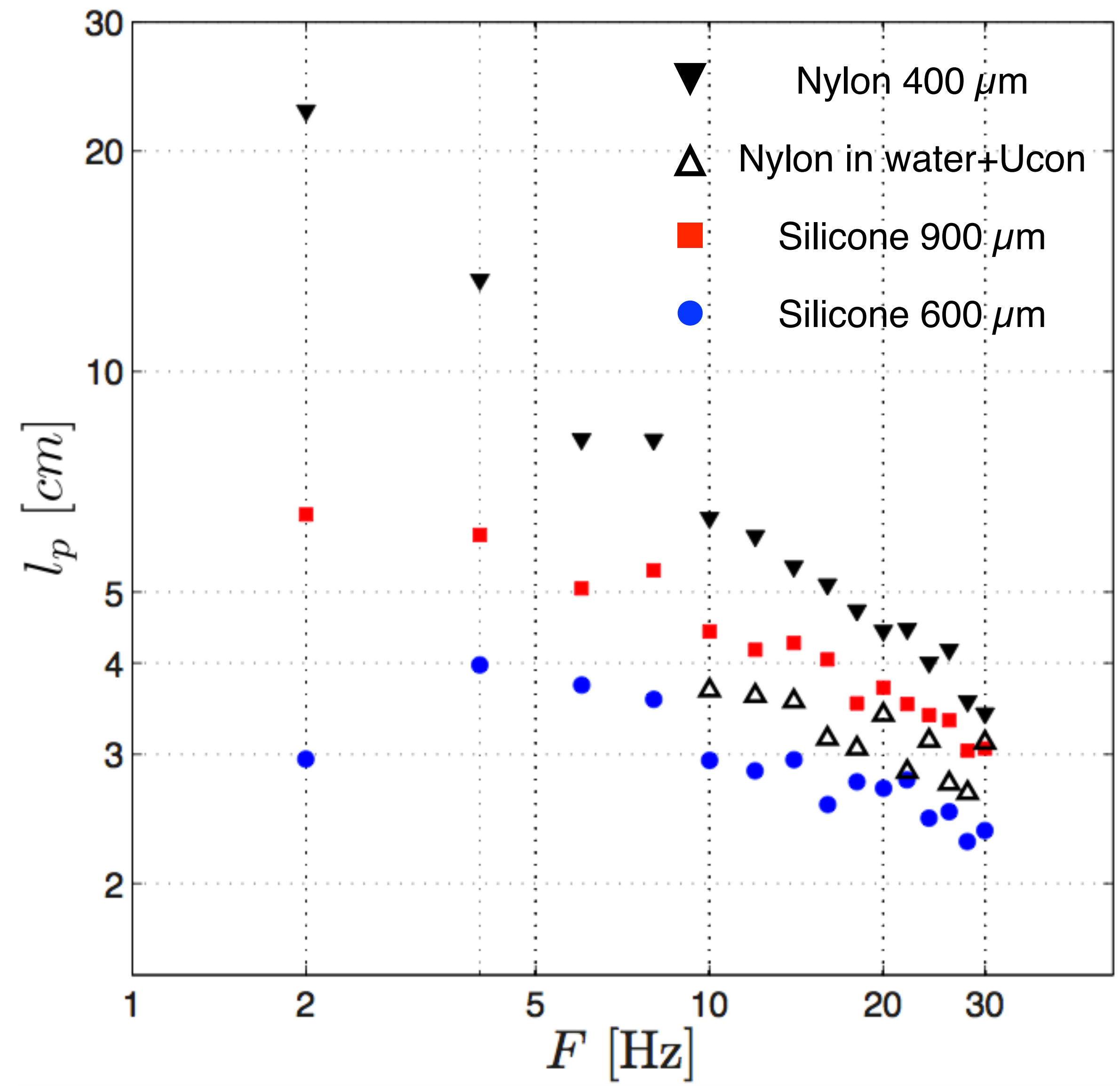

Fluid	dyn. visc. [mPa.s]	density	Re
water	1	1	10^5-1.5•10^6
water+Ucon	100±20	1,045	5•10^3-1.5•10^4

Brouzet *et al.*, Flexible fiber in a turbulent flow: a macroscopic polymer, *Phys. Rev. Lett.*, 112, 074501, 2014

Transition from rigid to flexible particles

Fibers

In polymer theory: $\frac{EI}{\ell_p} = k_B T$

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Analogy in turbulence

$$\ell \sim \left(\frac{EI}{\rho}\right)^{3/14} \varepsilon^{-1/7}$$

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Transition from rigid to flexible particles

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Out of equilibrium stationary process

In polymer theory: $\frac{EI}{\ell_p} = k_B T$

$$\partial_t \mathcal{E} = P_{inj} - P_{dis}$$

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Deformation timescale

$$EI \partial_s^4 \boldsymbol{r} \sim \eta \partial_t \boldsymbol{r}$$

$$\tau_{el} \sim \frac{\eta L^4}{EI}$$

Balance of power

$$\ell_e \sim \frac{(EI)^{1/4}}{(\rho_f \eta \varepsilon)^{1/8}}$$

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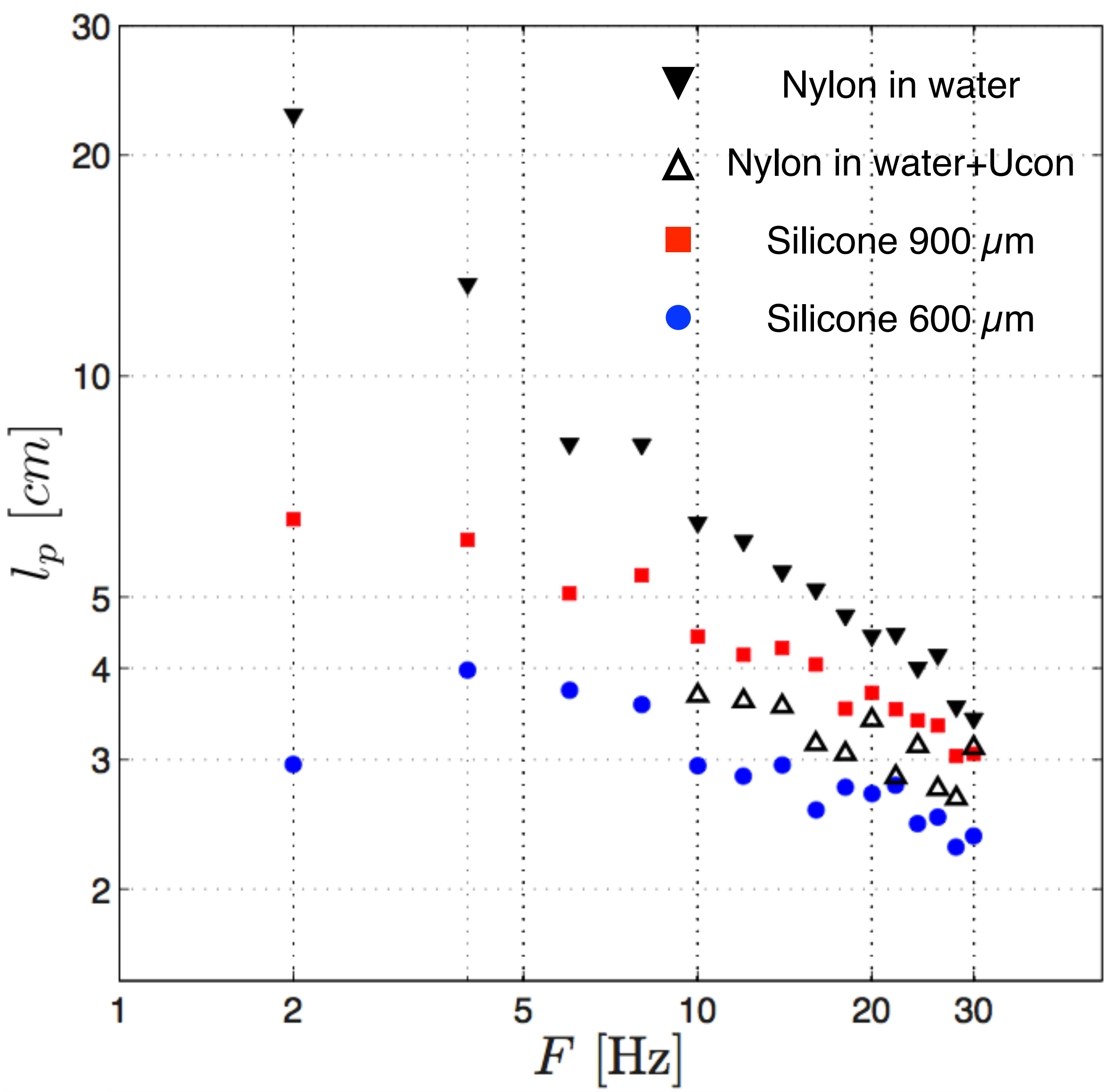
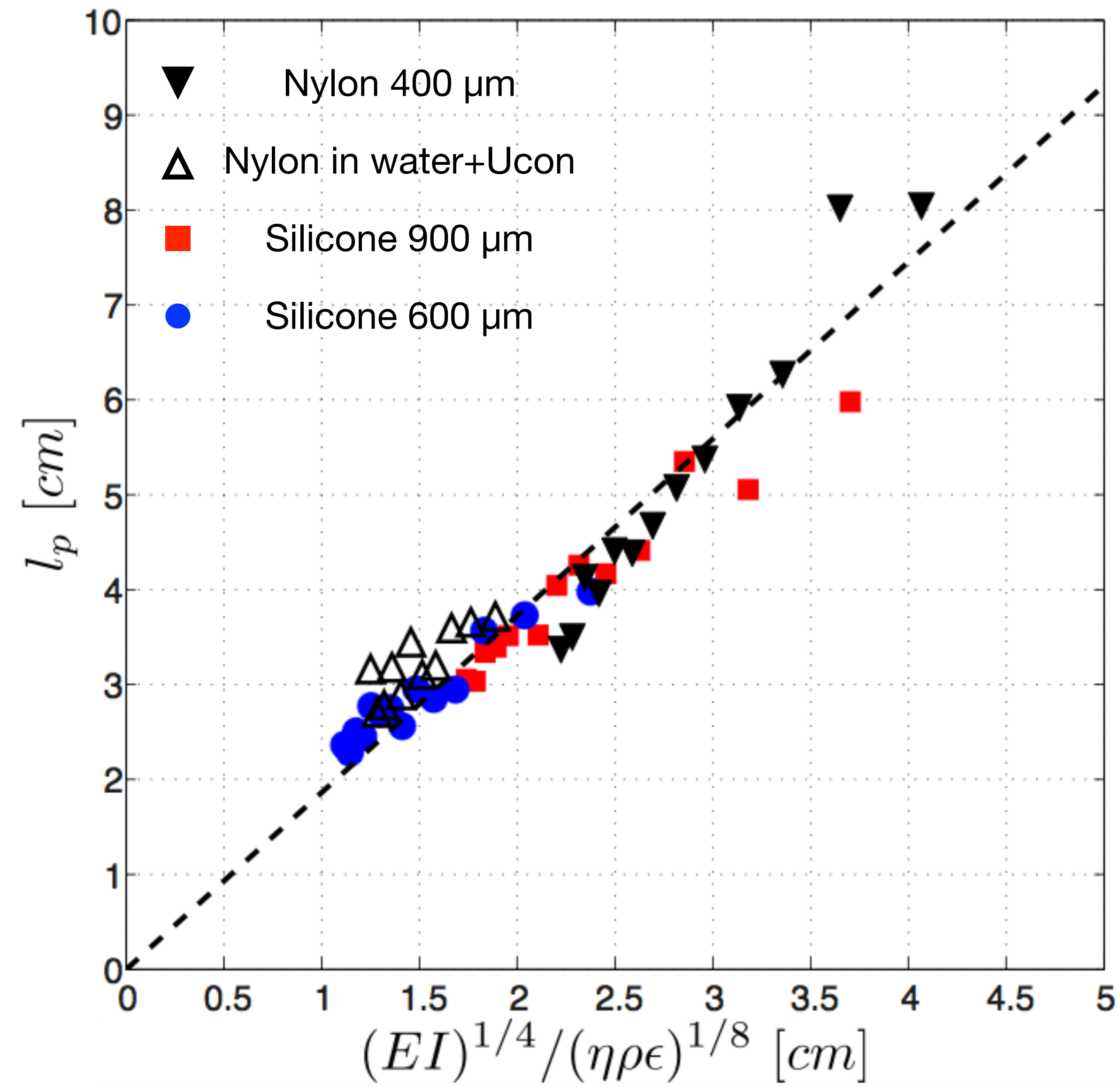
Modeling the persistence length





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Characterization of fiber deformations

Characterization of fiber deformations

Numerical simulation

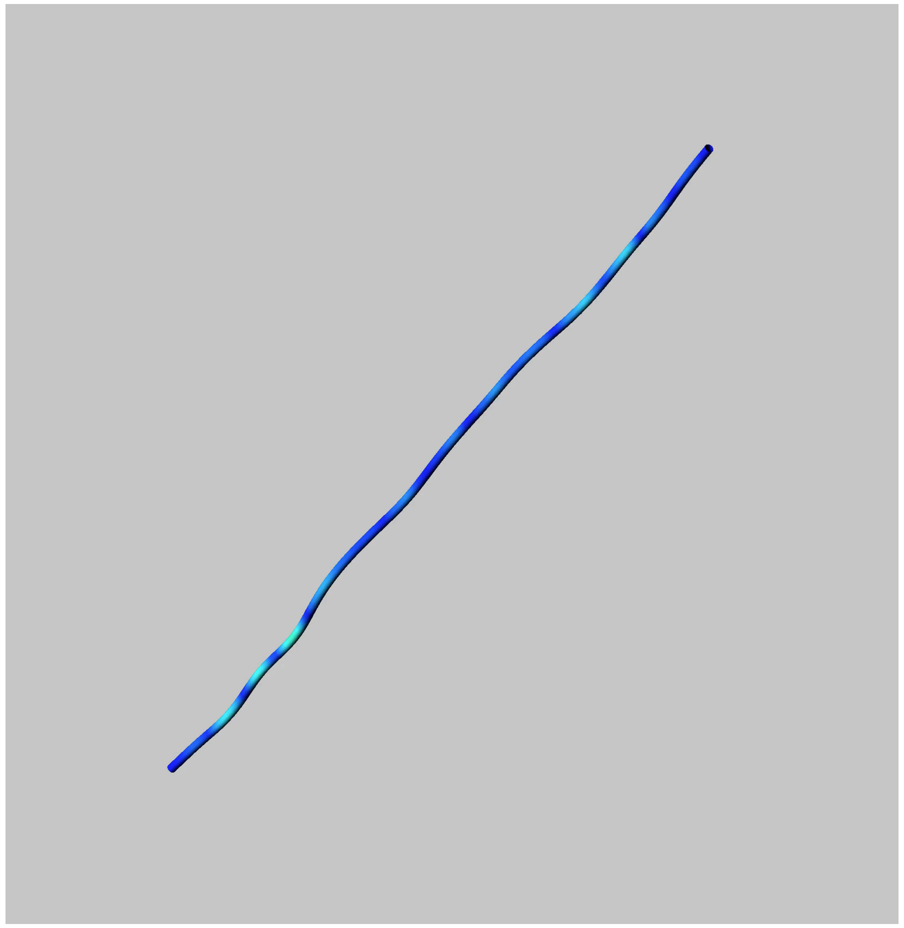
Elasticity

$$\partial_{tt}\boldsymbol{r} - \partial_s(T\partial_s\boldsymbol{r}) + \frac{1}{St}\partial_t\boldsymbol{r} + \gamma\partial_s^4\boldsymbol{r} = \frac{1}{St}\boldsymbol{u}$$

$$|\partial_s\boldsymbol{r}|^2 = 1 \quad \gamma = \frac{EI}{\sigma u^2 L_I^2} \quad St = \frac{\sigma U}{4\pi\eta L_I}$$

Flow: kinematic simulation

Curvature $\kappa^2 = |\partial_{ss}\boldsymbol{r}|^2$



Gay *et al.*, *EPL*, 123(2), 24001, 2018

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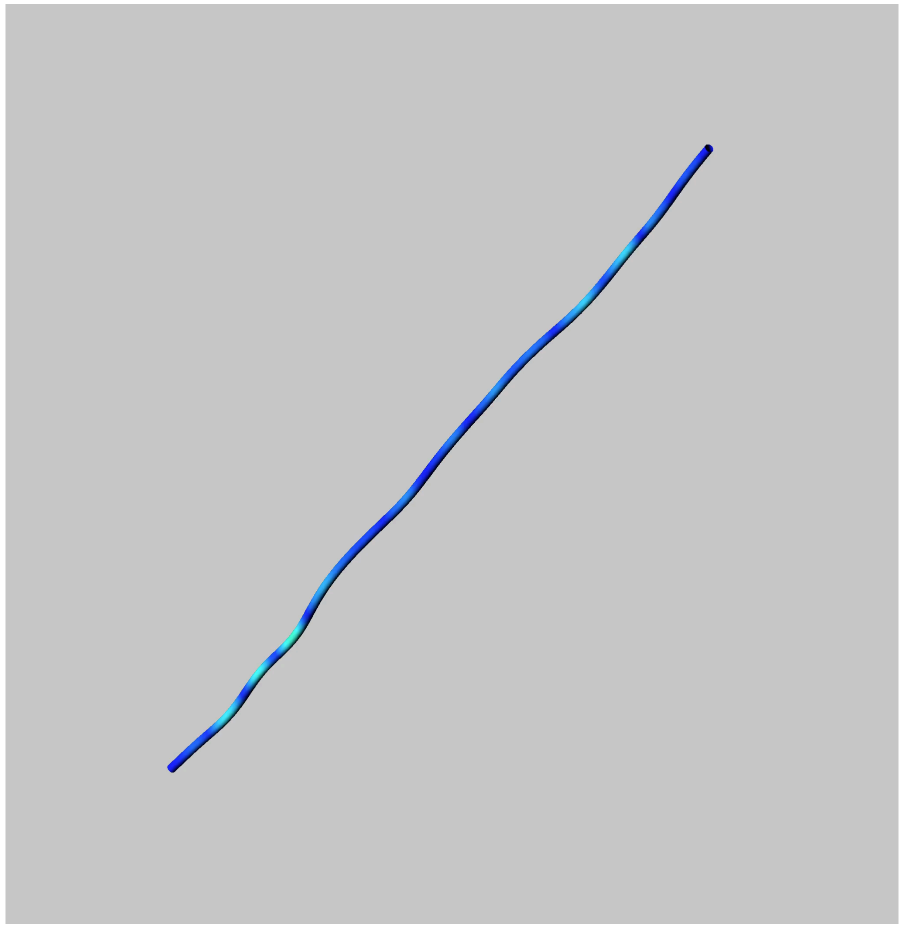

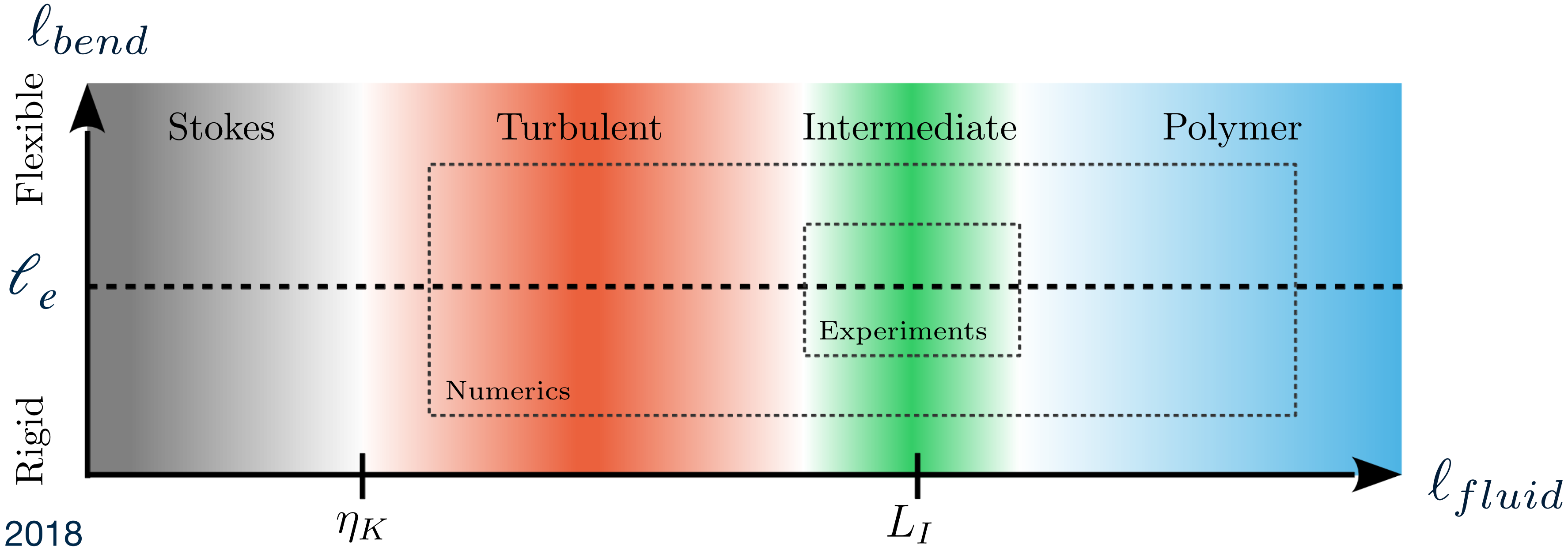

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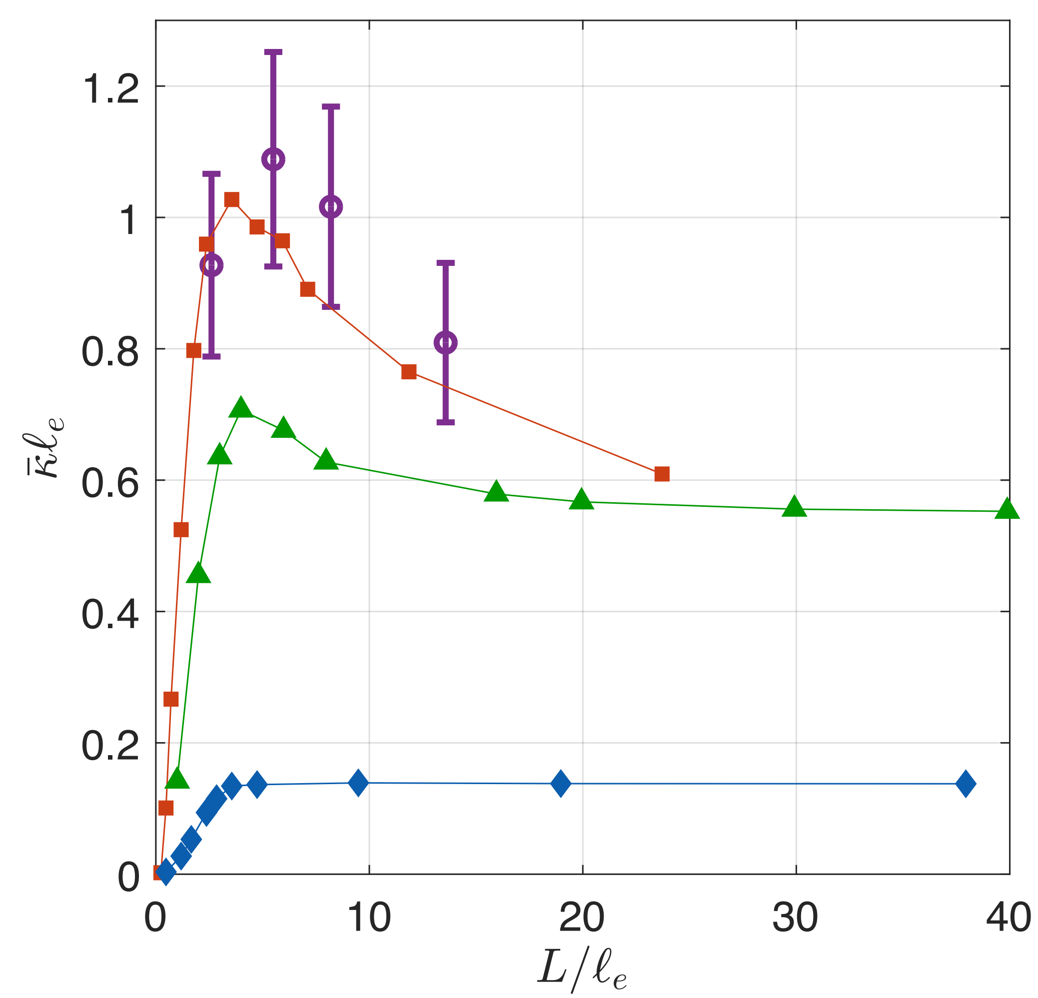

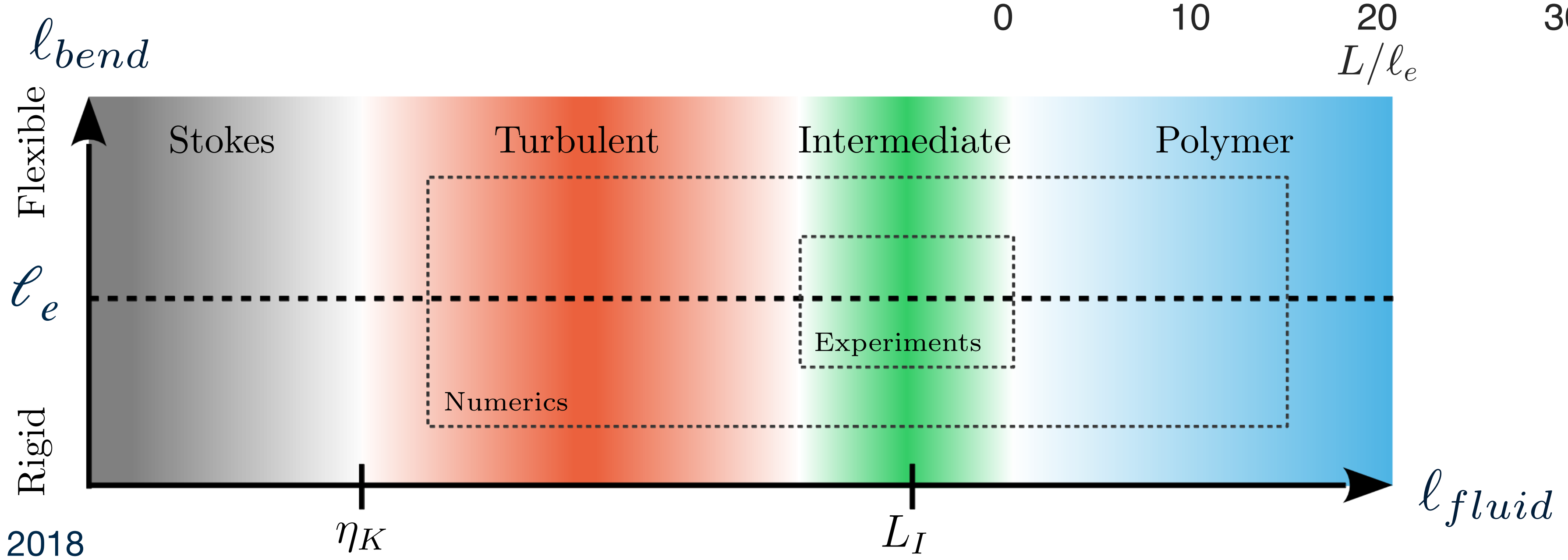

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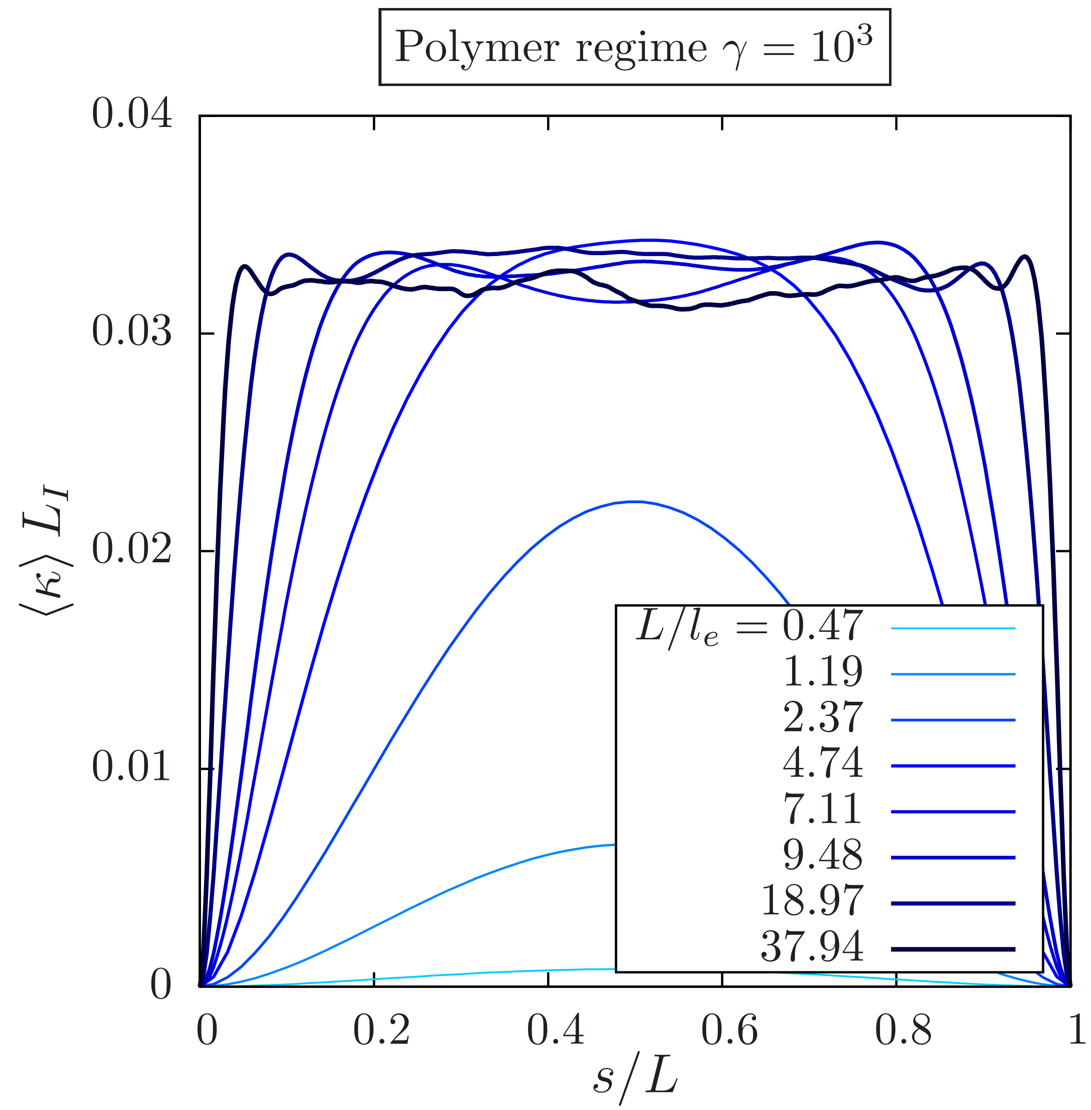
Spatial evolution of the local curvature



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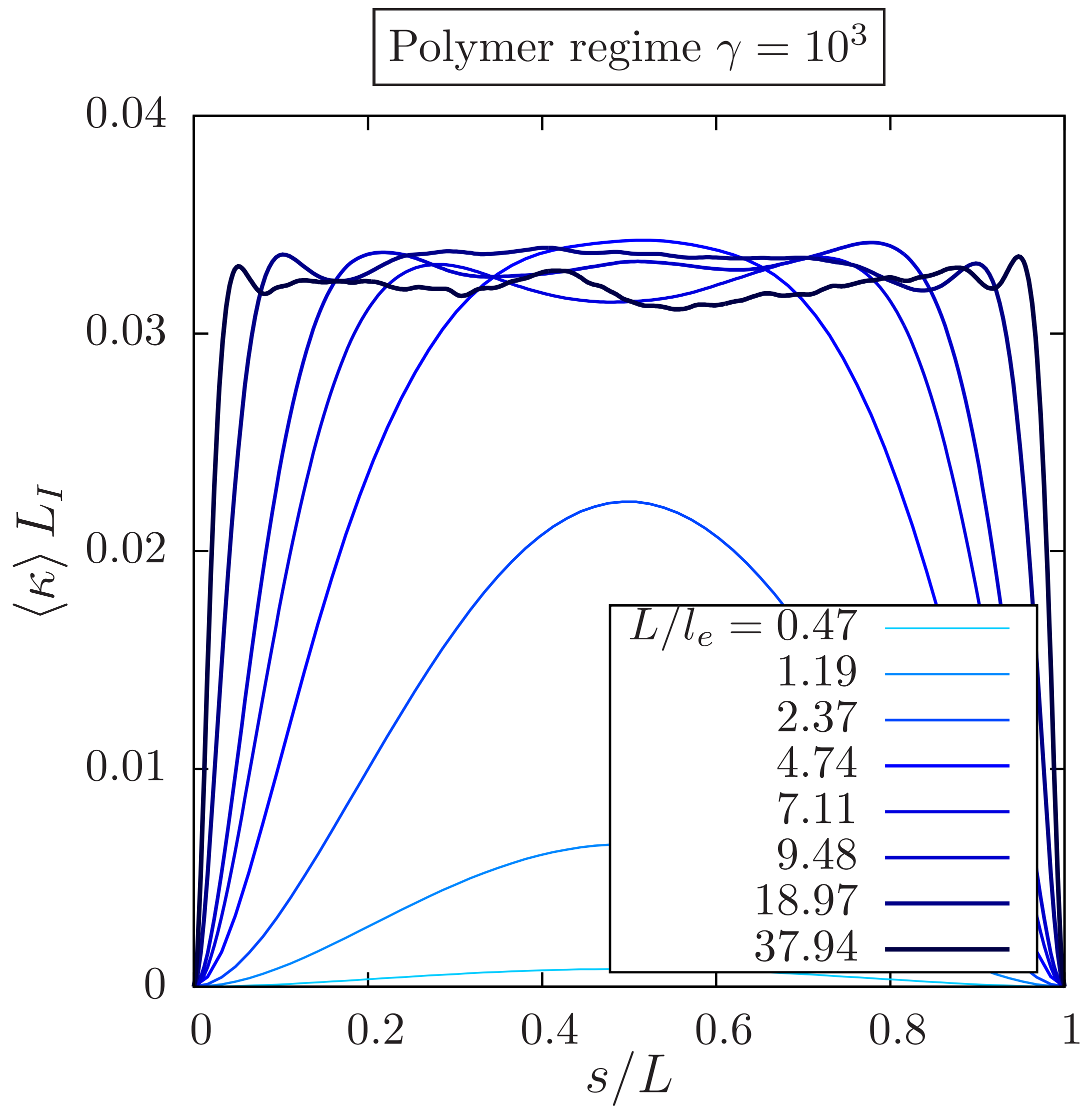

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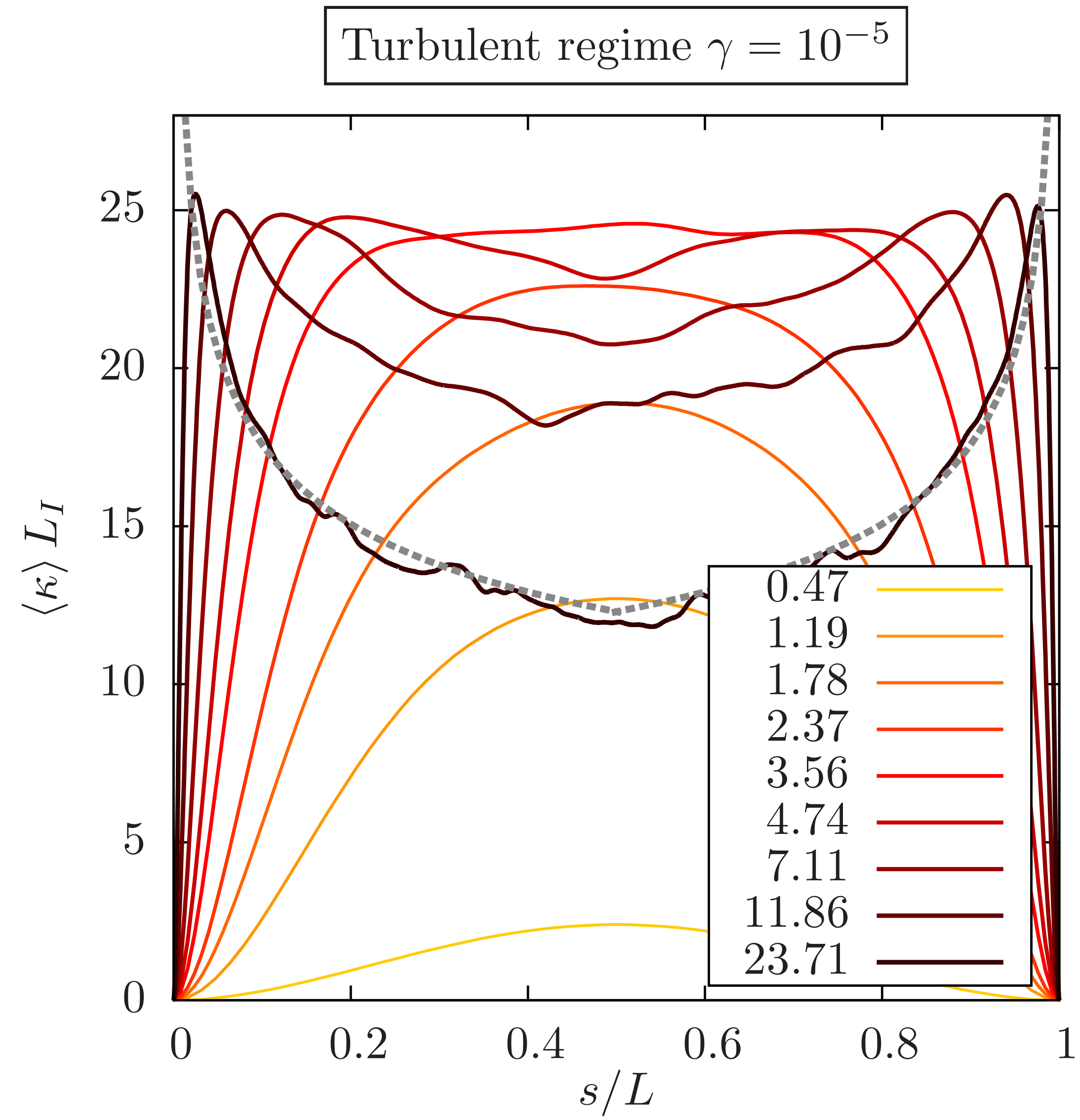

Turbulent regime

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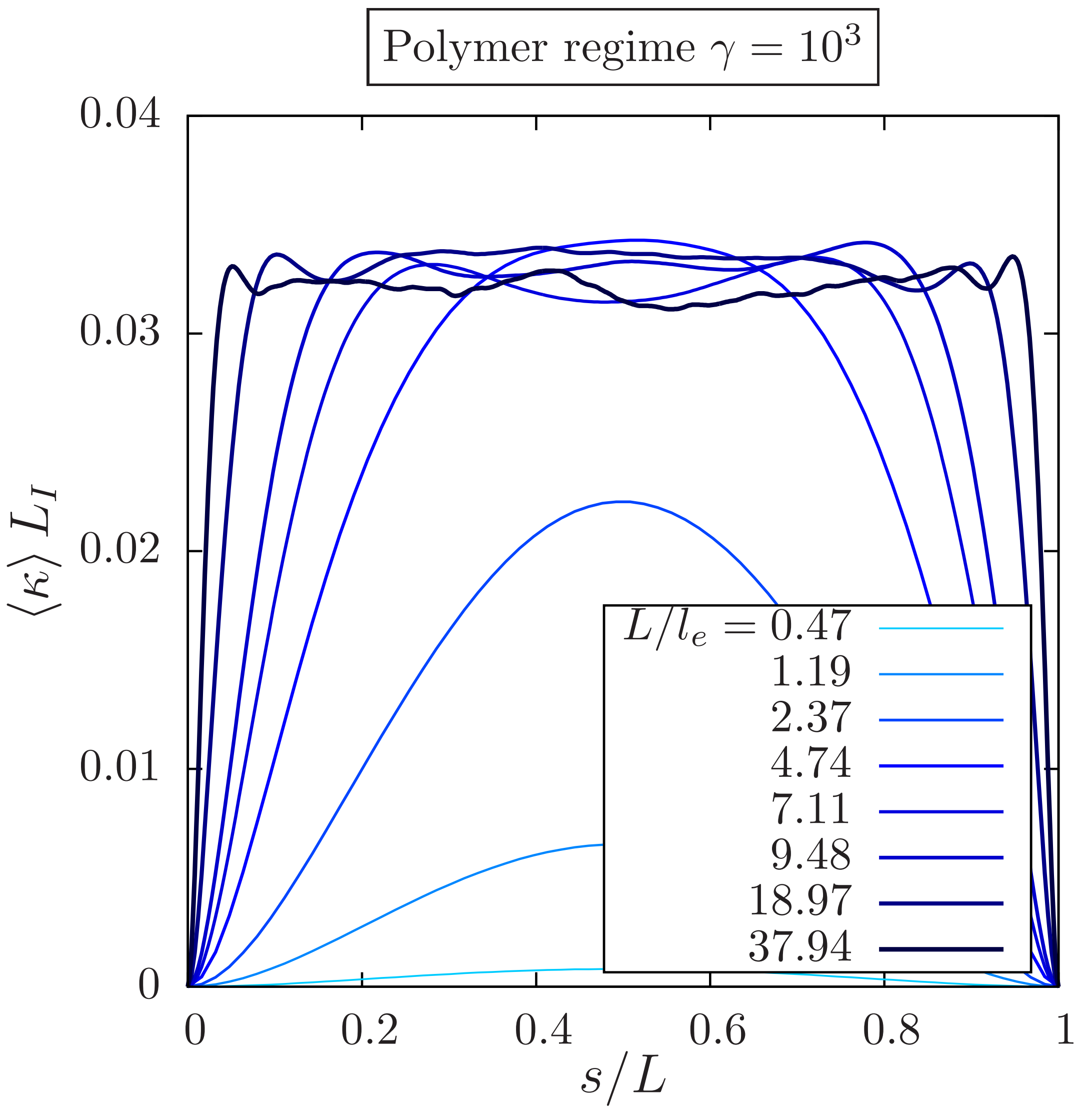

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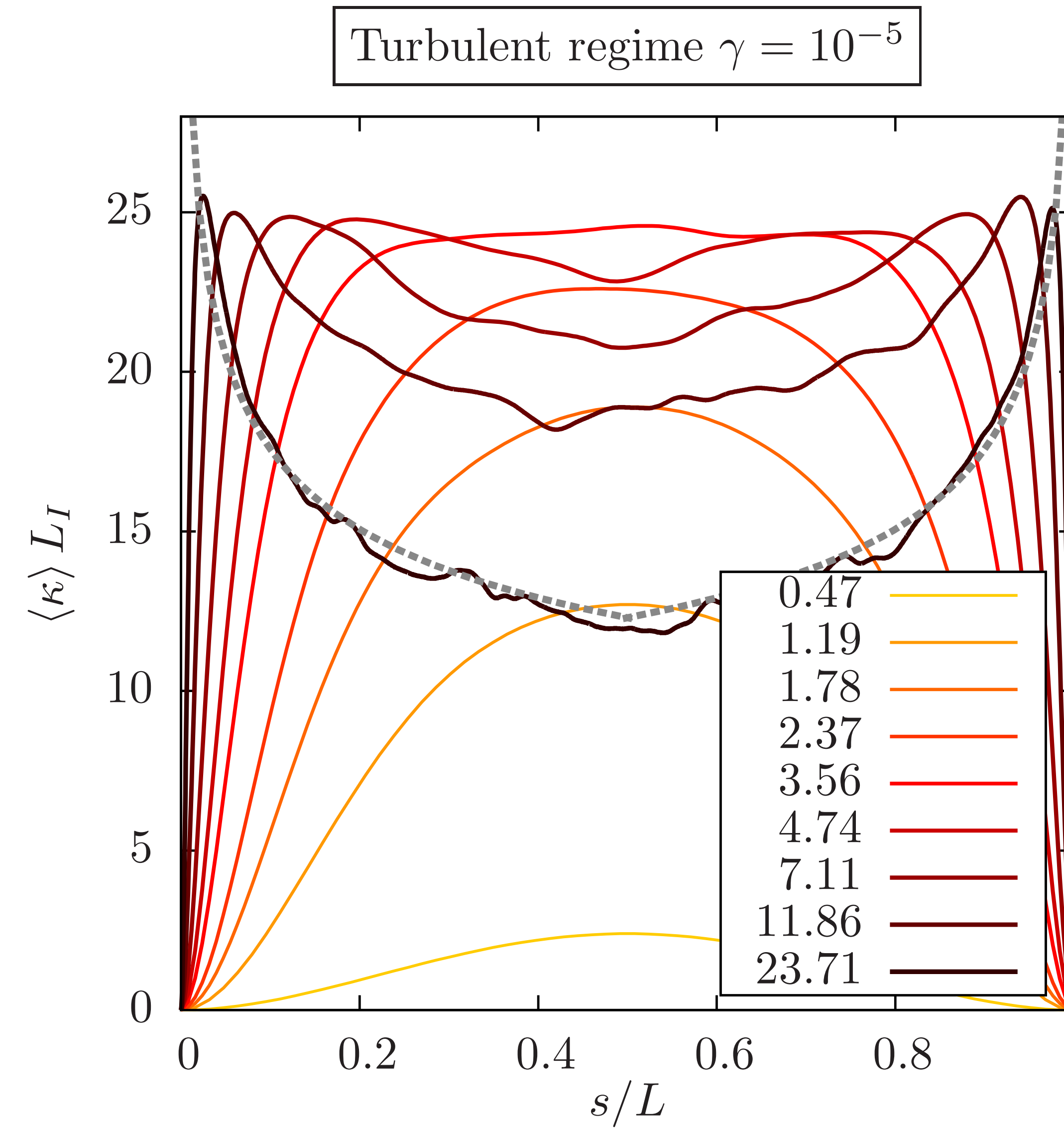

Turbulent regime

Straightening of long fibers in turbulence

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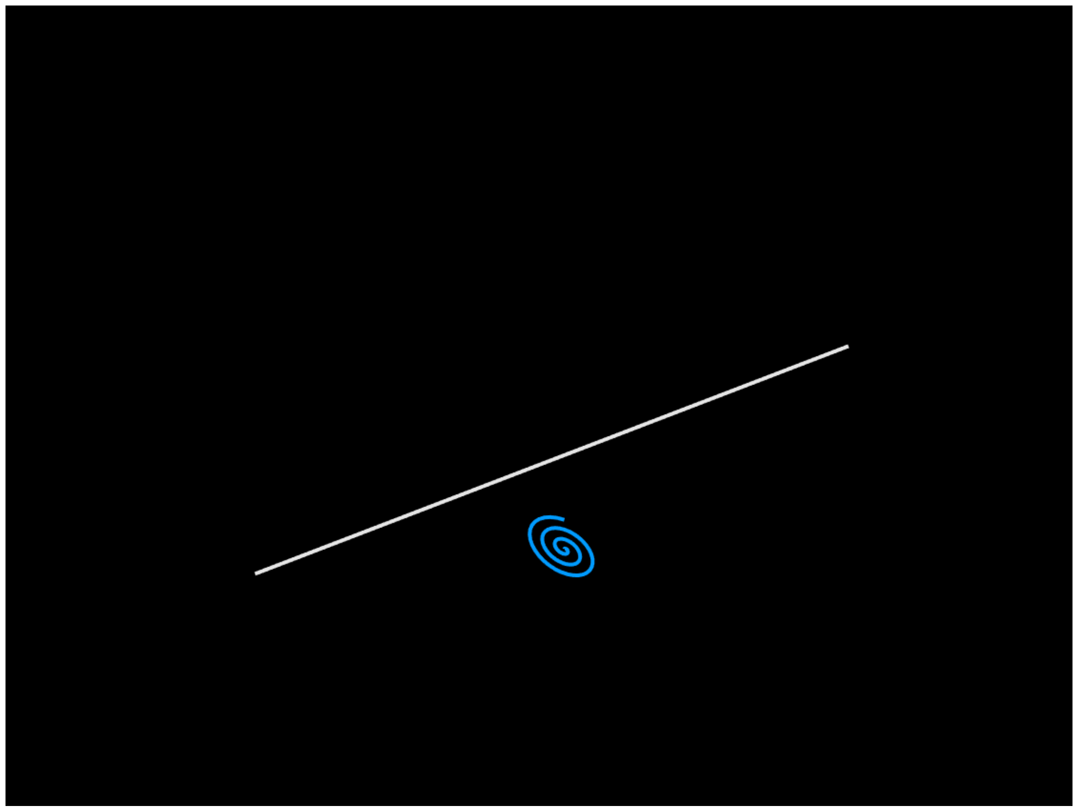

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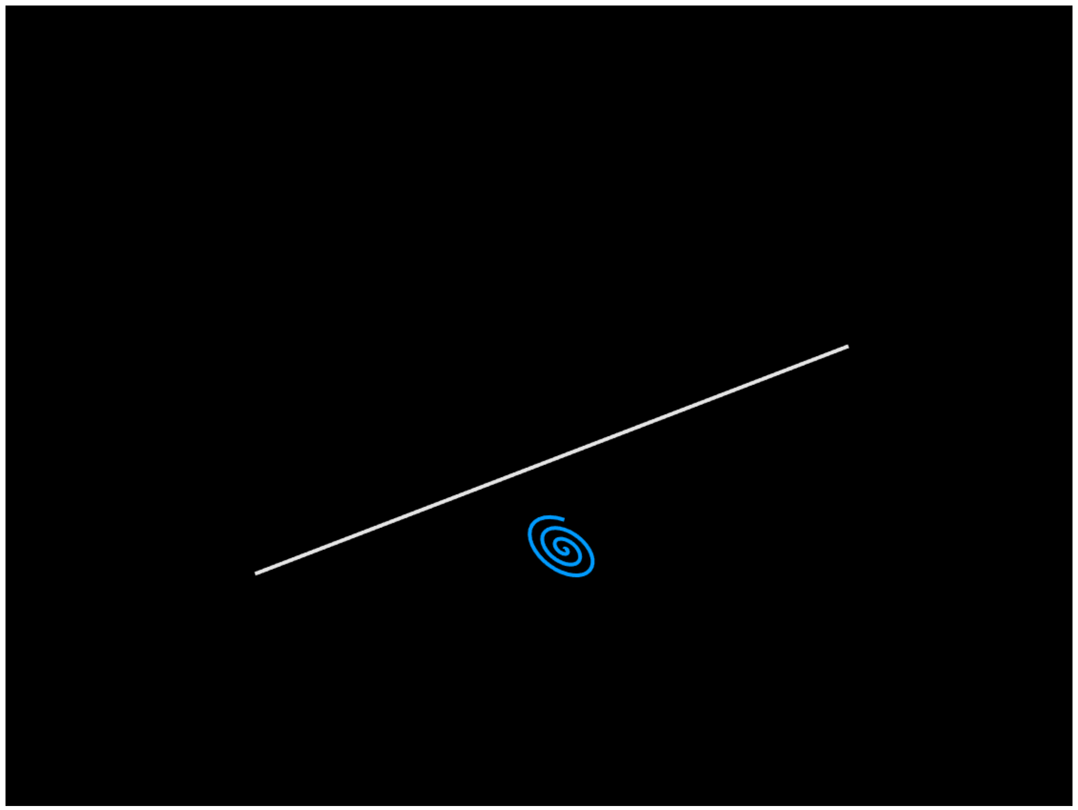

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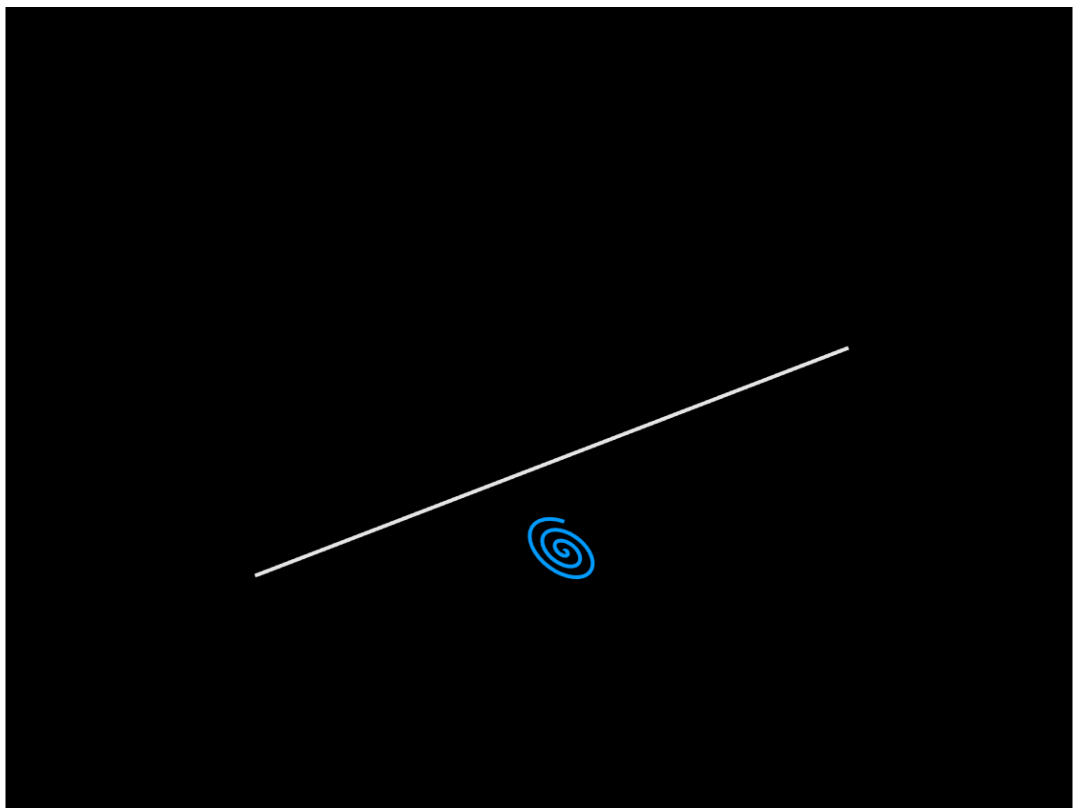

Local deformation => global modification

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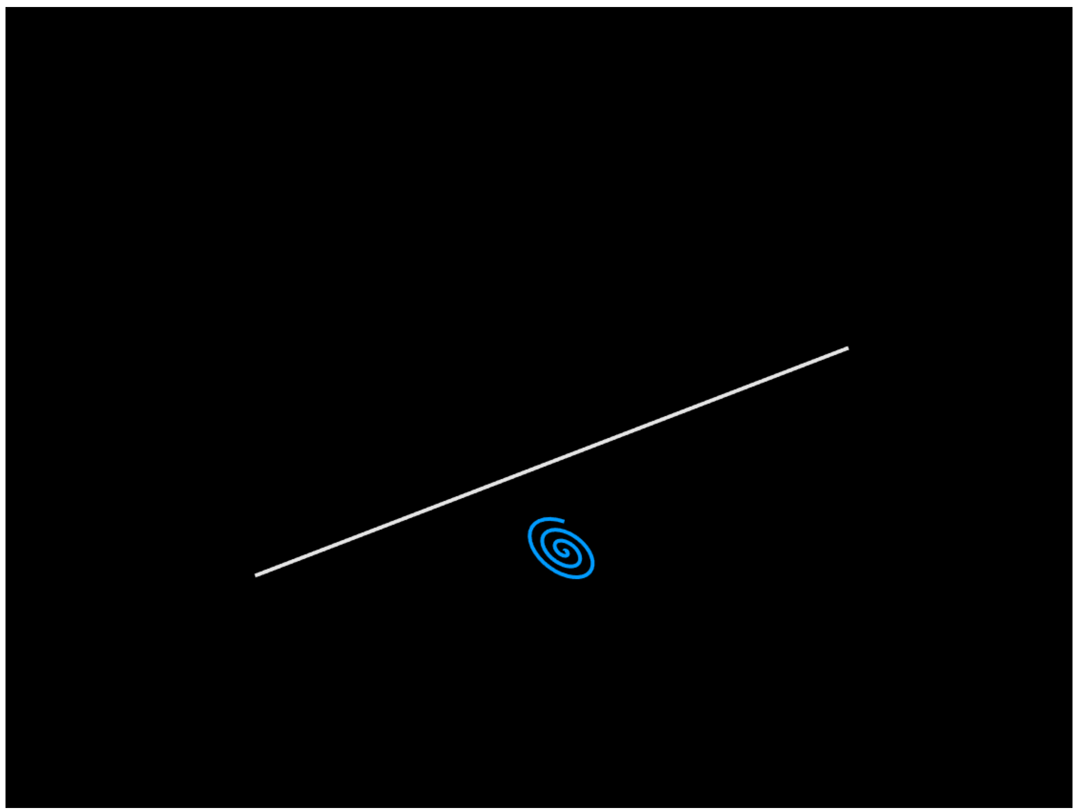

Local deformation => global modification

Additional dissipation term

$$\mathcal{P}_v = \int \eta \partial_t \boldsymbol{r} \cdot \boldsymbol{u} \mathrm{d}s$$

Fiber is inextensible

$$|\partial_t \boldsymbol{r}| \sim \frac{1}{\kappa \tau_\kappa} \qquad \tau_\kappa \sim \frac{\eta}{EI\kappa^4}$$

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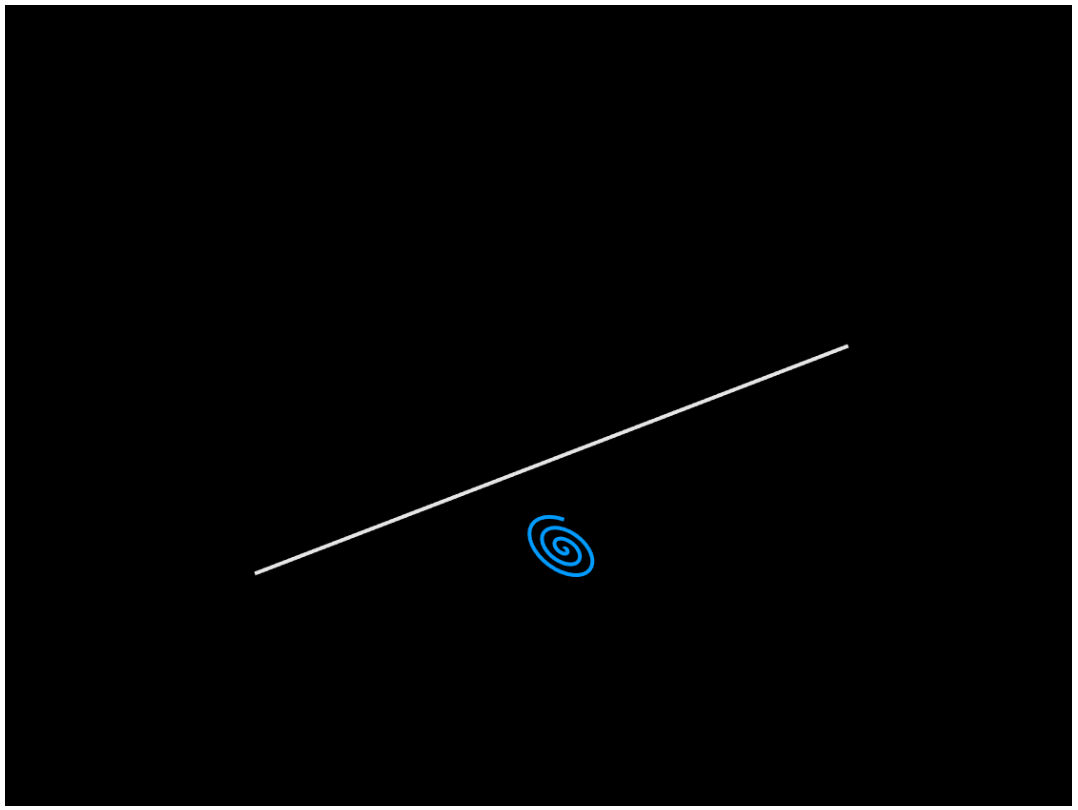

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Spatial correlation

$$\int_0^{s_0} u_{\parallel} \mathrm{d}s \sim s_0 u_{s_0} \sim \epsilon^{1/3} s_0^{4/3}$$

Gay *et al.*, Characterisation of flexible fibre deformations in turbulence, *EPL*, 123(2), 24001, 2018

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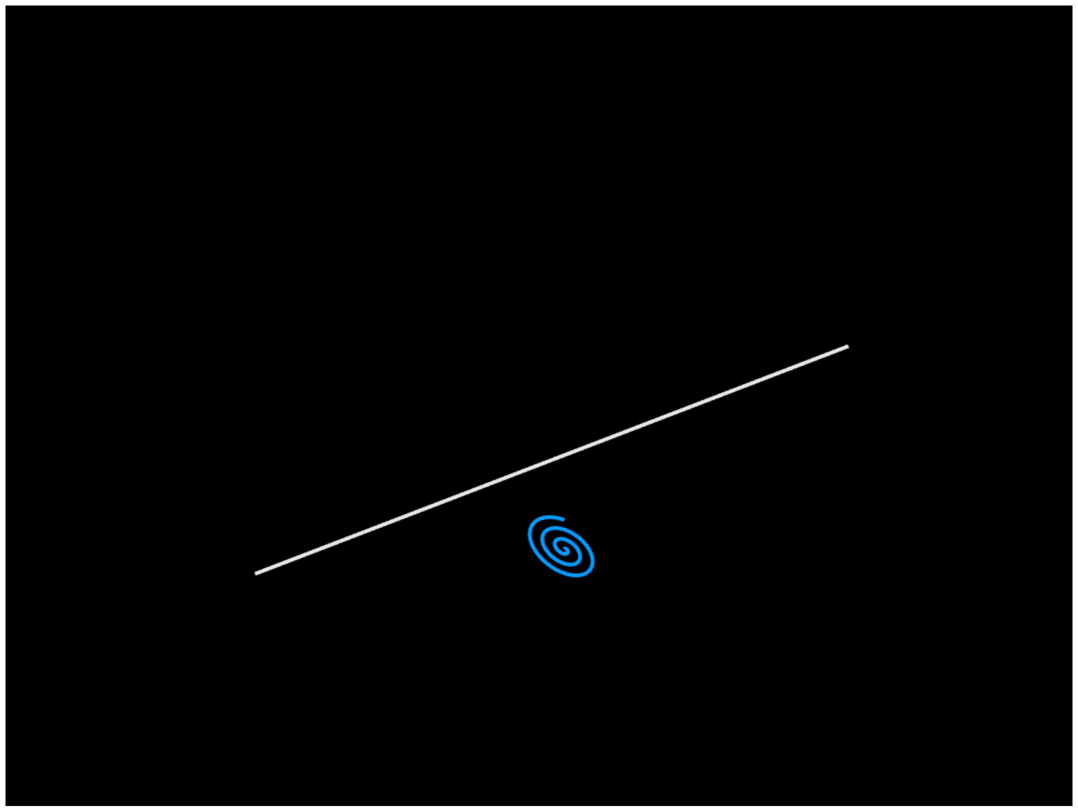

Local deformation => global modification

For long fiber $\mathcal{P}_{turb} = \rho\kappa^{-3}\epsilon \sim \mathcal{P}_v$

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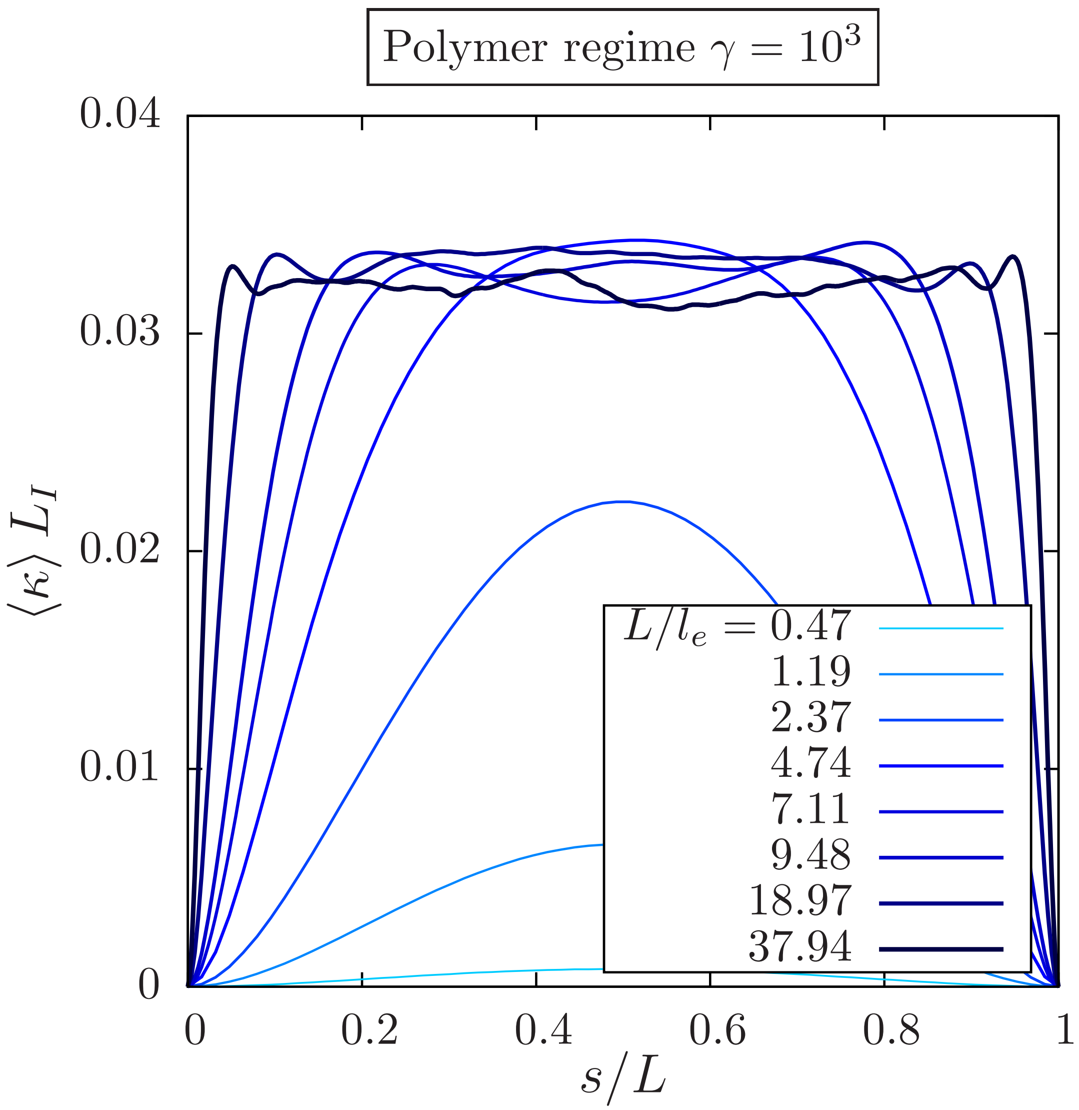

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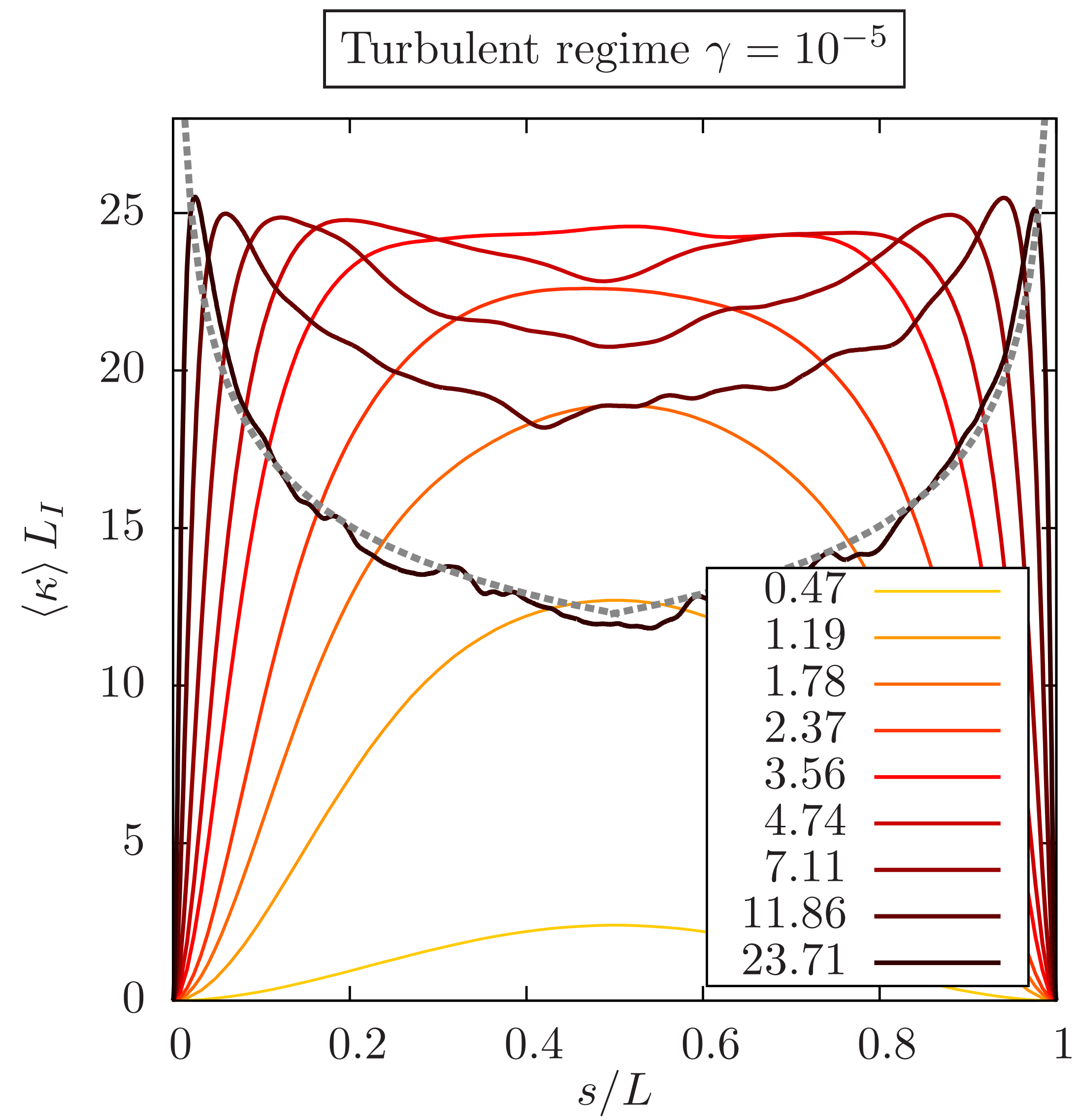

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Conclusion on deformation of fibers

- Fiber longer than $\ell_e = (EI)^{1/4}/(\rho\eta\varepsilon)^{1/8}$ can be bent
- Straightening of the longest fibers due to flow correlation

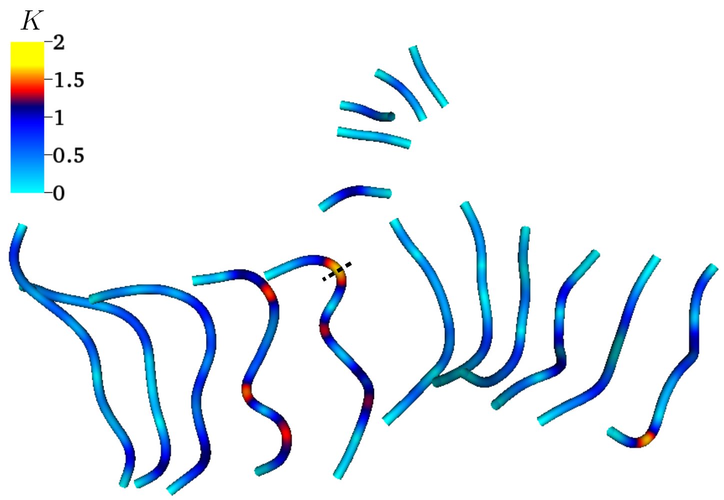
From deformation to fragmentation

Simplest approach: brittle object

No ageing (nor chemical nor mechanical)

Brittle object breaks if $\epsilon_{def} > \epsilon_{max}$

Deformation = strain $\epsilon_{def} = \kappa d$



Independent breaking event

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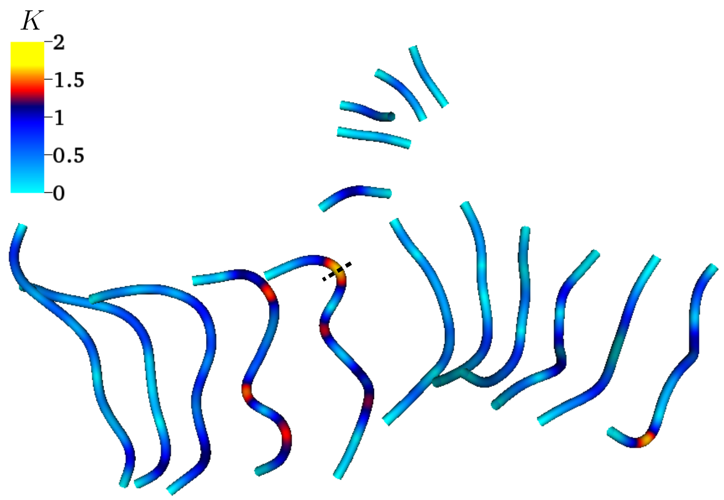


Independent breaking event

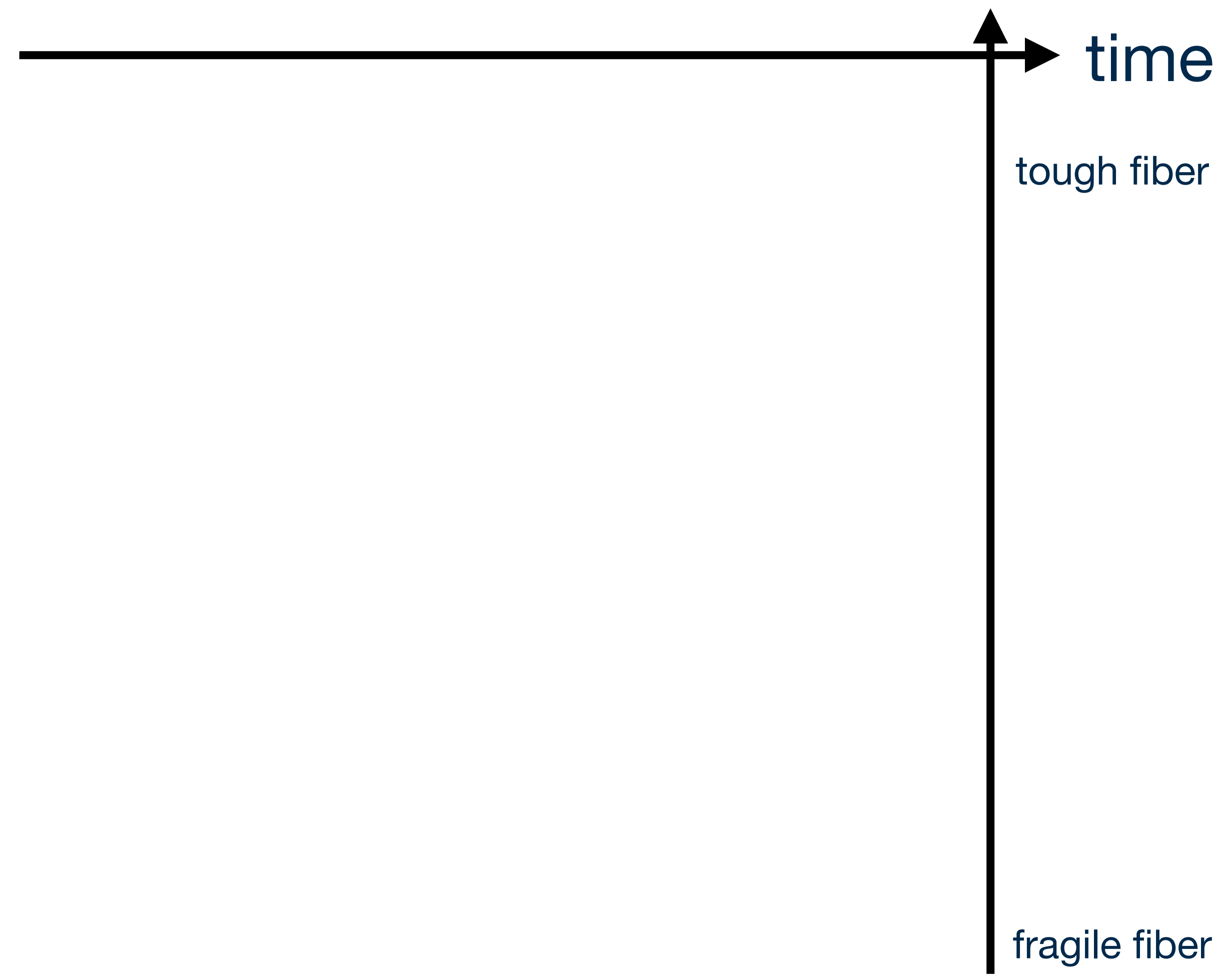
Two parameters : maximum curvature κ_B + duration of the experiments

Brouzet *et al.*, *Phys. Rev. Fluids*, 2021

Simplest approach

Experiment with glass fibers

$$K_B = \kappa_B \ell_e$$



2 different fluids: water / water+Ucon (change viscosity) $\quad \ell_e = \frac{(EI)^{1/4}}{(\rho\eta\varepsilon)^{1/8}}$

raw fiber or heated fiber: modification of κ_B

Brouzet *et al.*, *Phys. Rev. Fluids*, 2021

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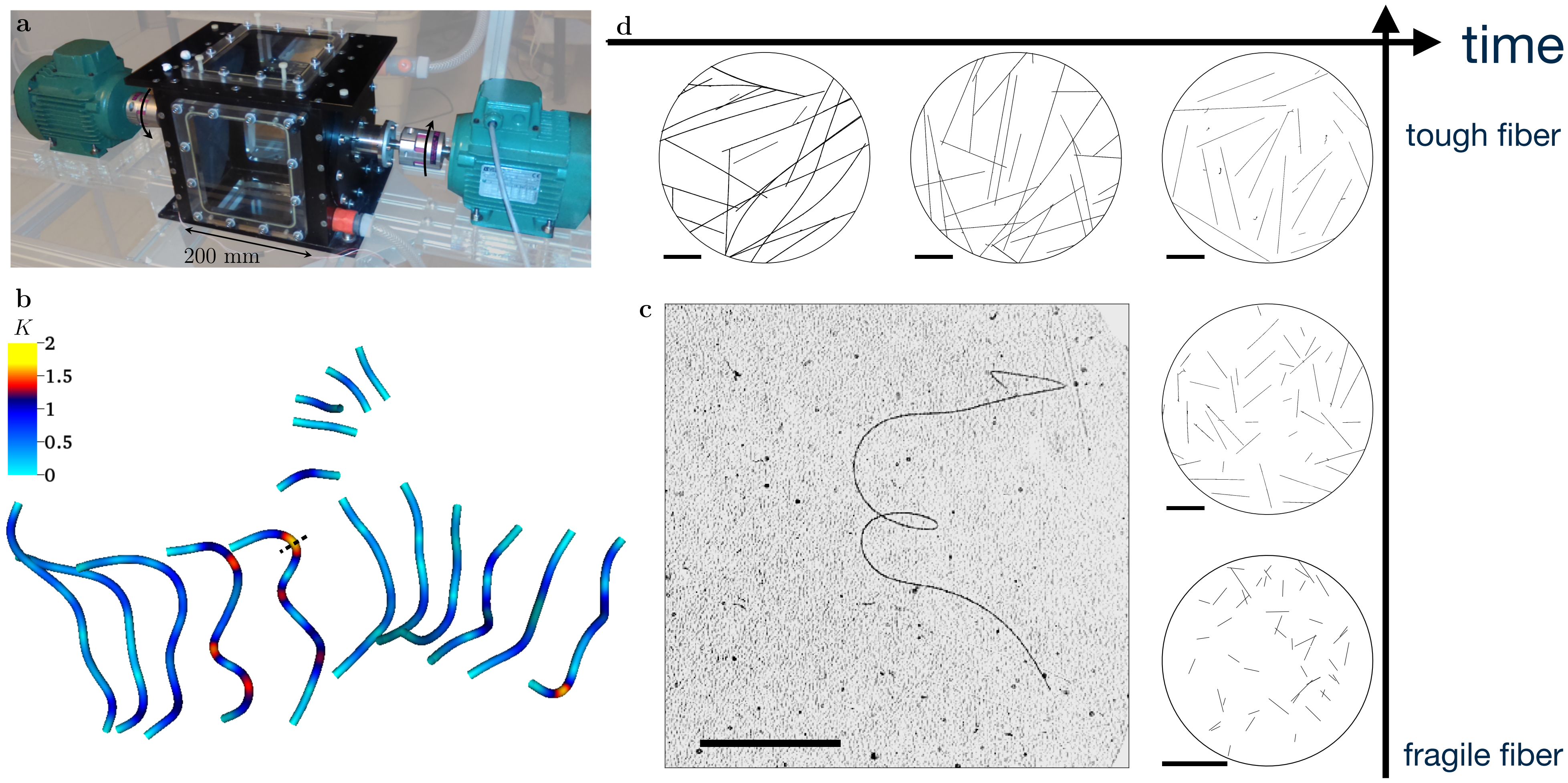

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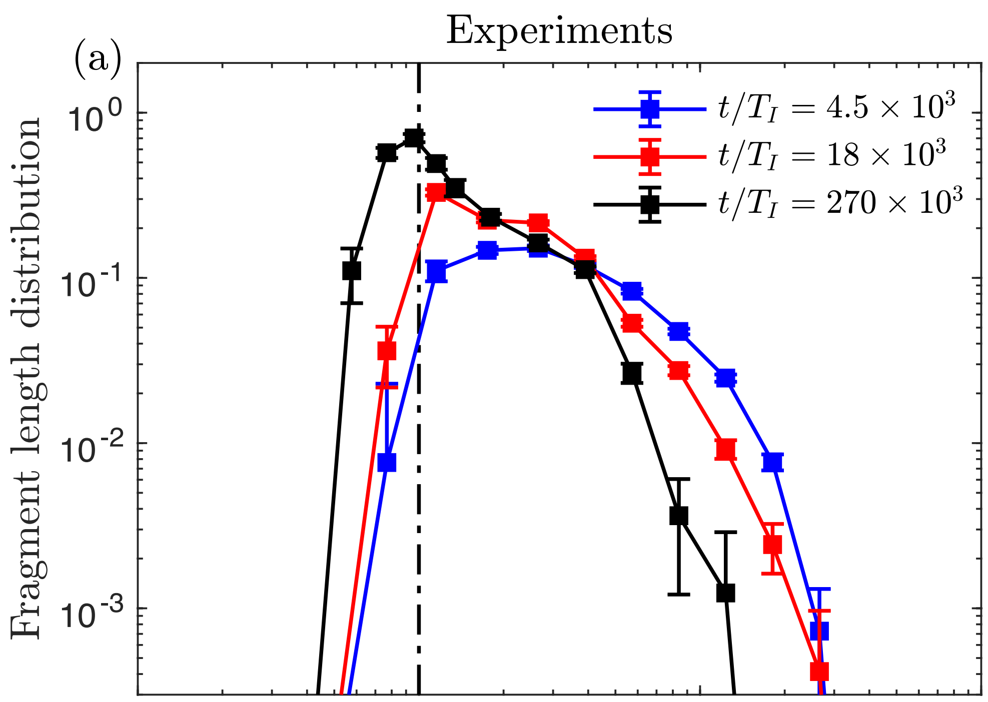
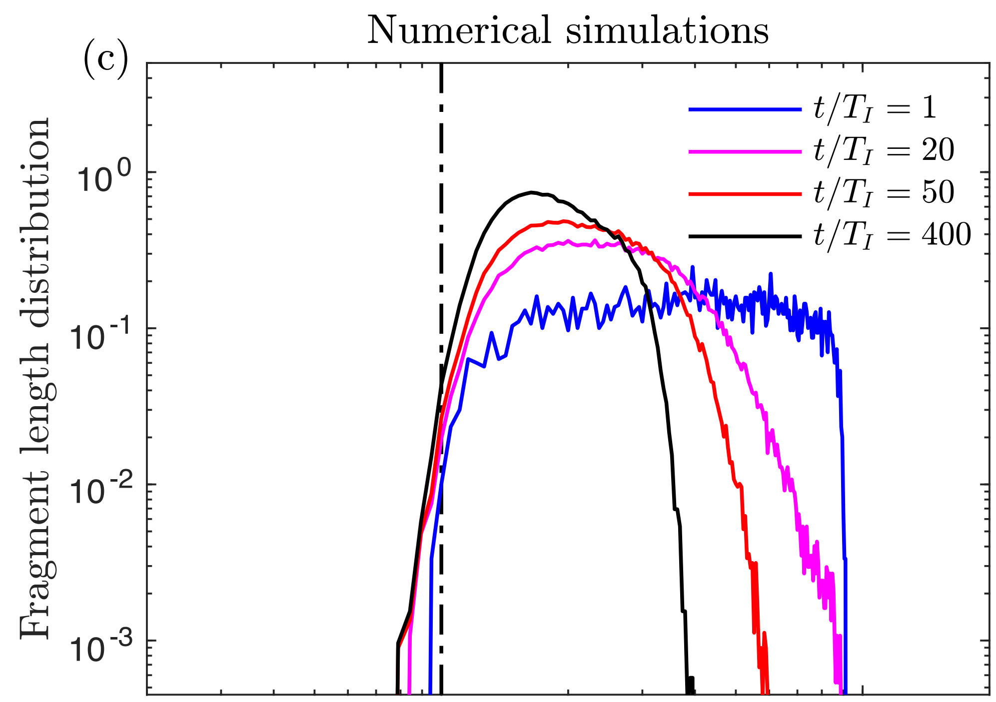
Evolution of the fragment size distirbution

Time dependence





Brouzet *et al.*, *Phys. Rev. Fluids*, 2021

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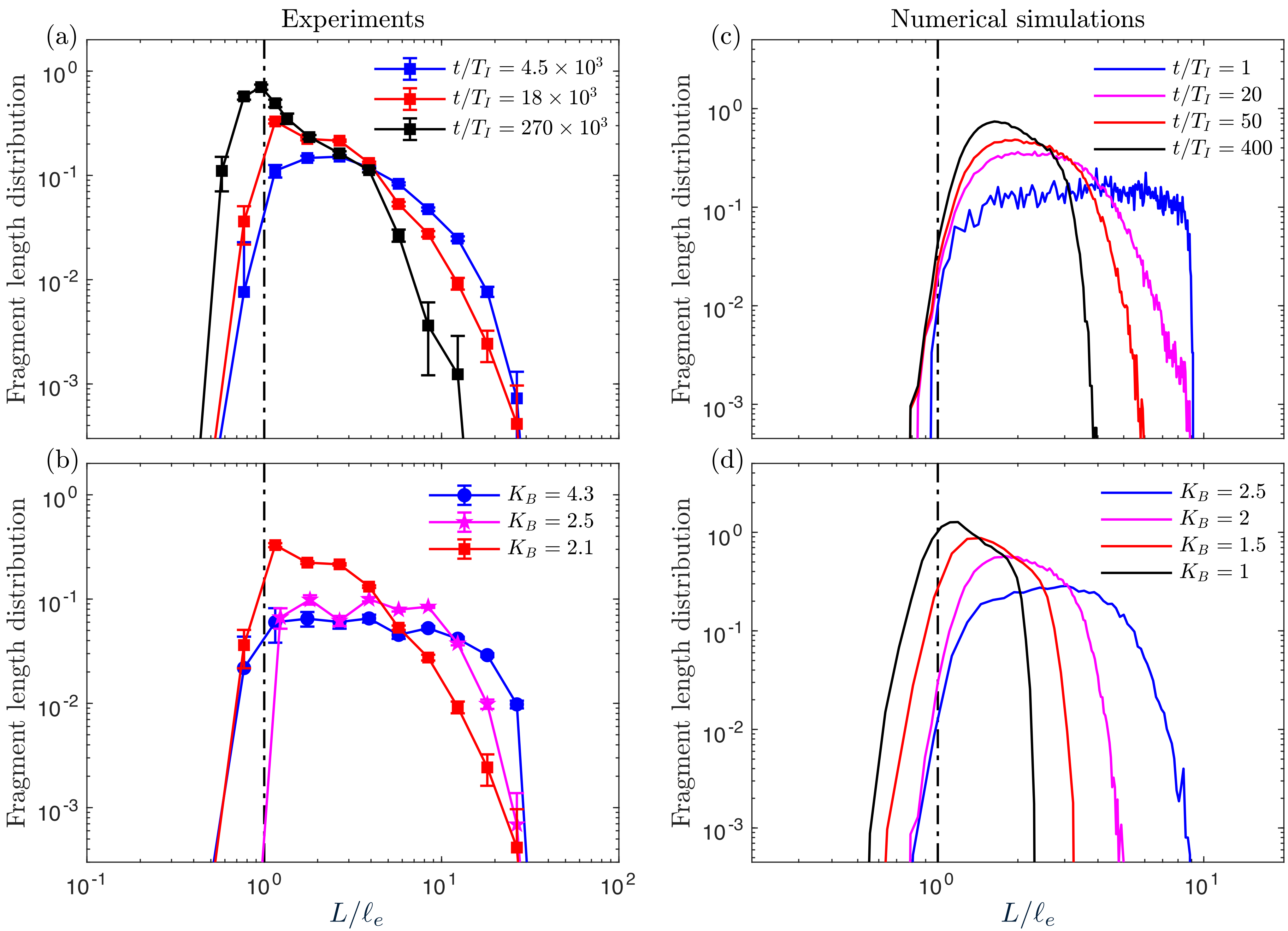
Brittleness



Brouzet *et al.*, *Phys. Rev. Fluids*, 2021

Modeling the evolution of the fragment size distribution

$n_L(t)$ number of fiber of size L at time *t*

$$\partial_t n_L = -n_L p(L) + 2\int_L^\infty n_{L'} p(L')\gamma(L, L')\mathrm{d}L'$$

$p(L)$ probability of breaking per unit time for a fiber of length L

$\gamma(L, L')$ probability that a fiber of length L' breaks into a fragment of size L

Brouzet *et al.*, *Phys. Rev. Fluids*, 2021

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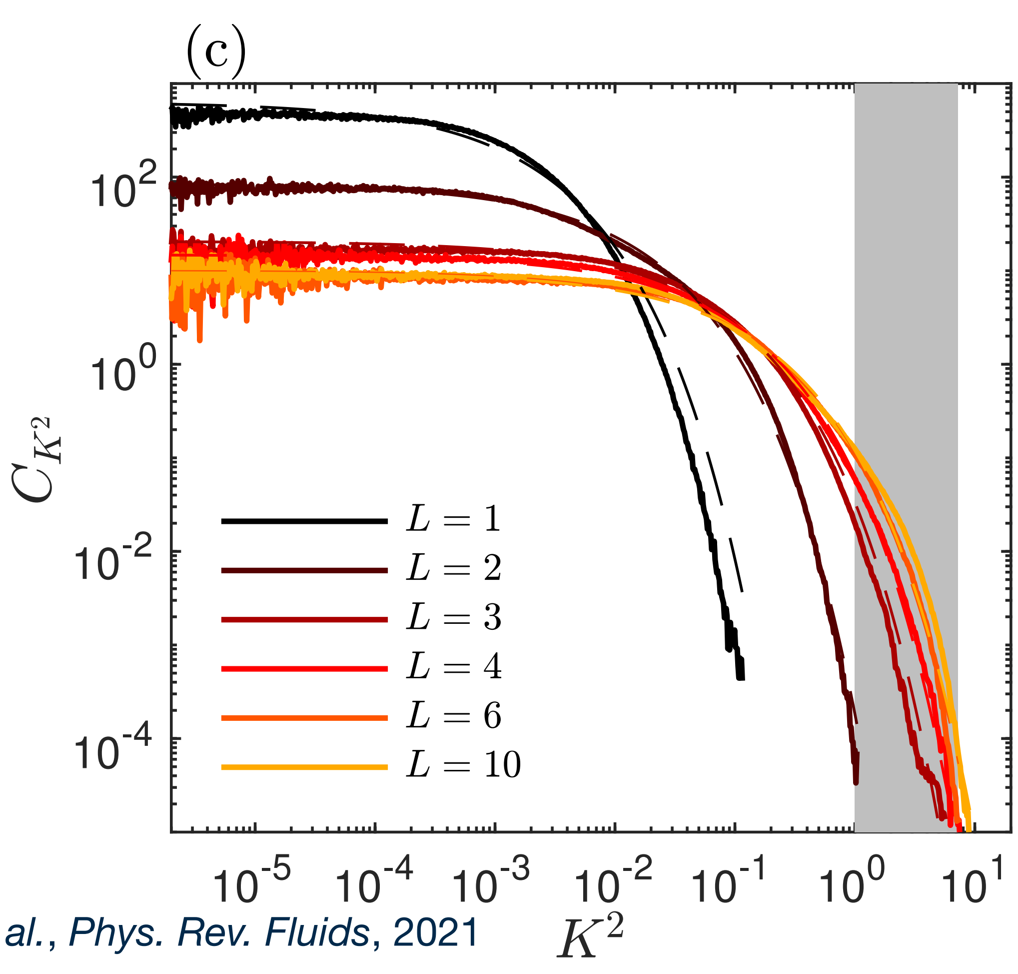

Probability to break locally

$$p_L(K_B) = \int_{K_B^2}^\infty C_{K^2}(x)\mathrm{d}x$$

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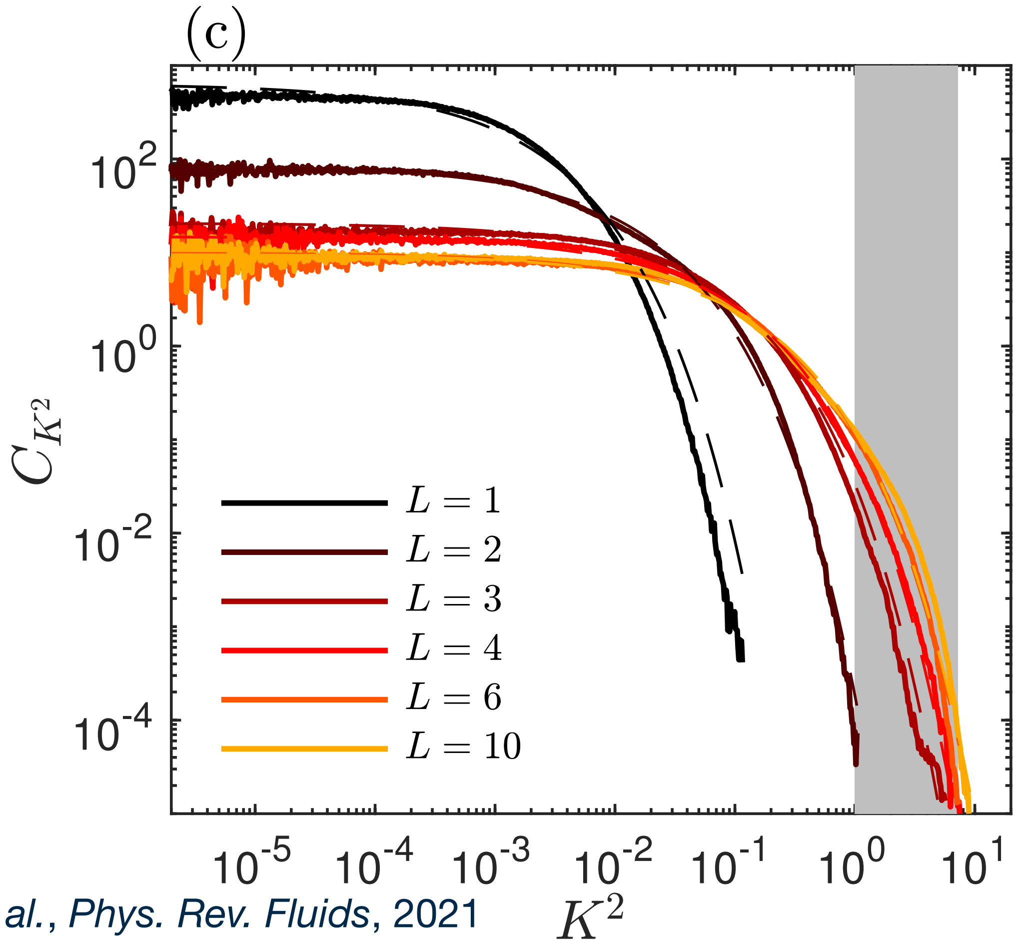

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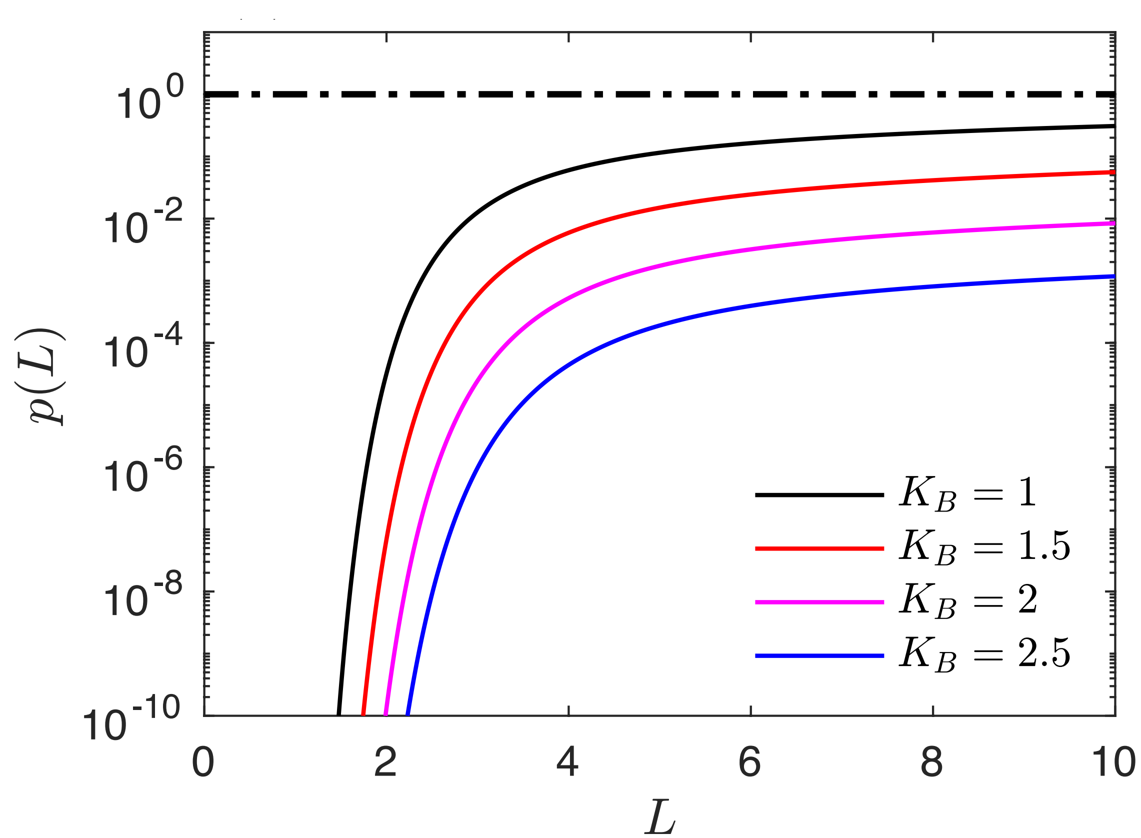

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$\gamma(L, L')$ probability that a fiber of length L' breaks into a fragment of size L

Brouzet *et al.*, *Phys. Rev. Fluids*, 2021

Modeling the evolution of the fragment size distribution

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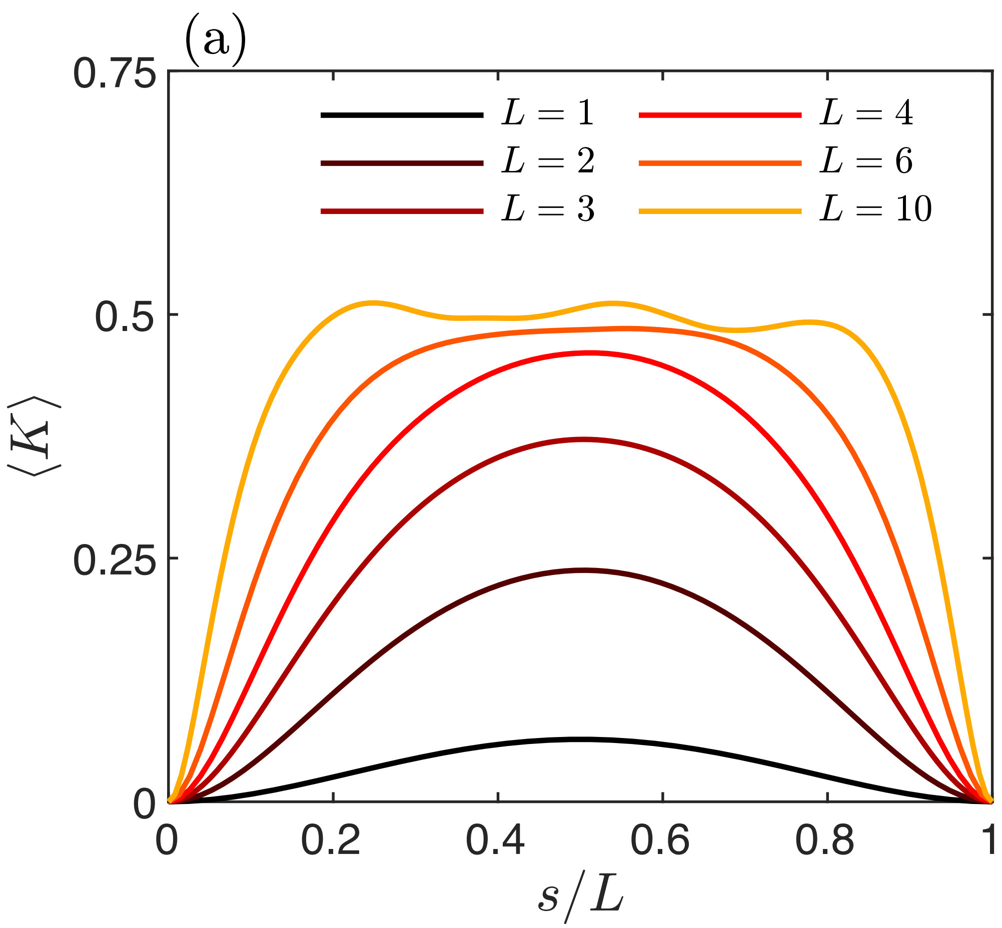
For long fibers: plateau at the center

Boundary condition $\kappa(s=0,L)=0$



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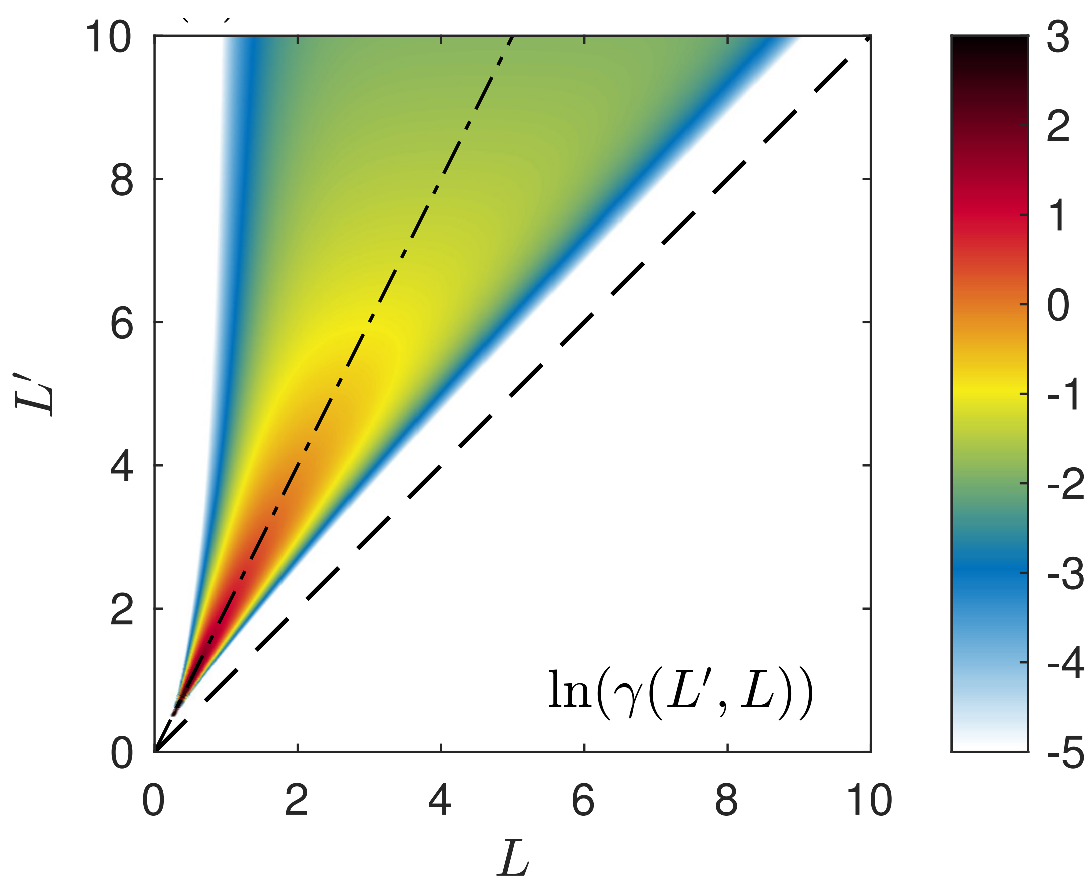
For long fibers: plateau at the center

Boundary condition $\kappa(s=0,L)=0$

short fibers break mainly at the center

Long fibers break uniformly

No breaking at the boundary



Comparison model/numerics

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timescale determined by $\langle L \rangle$

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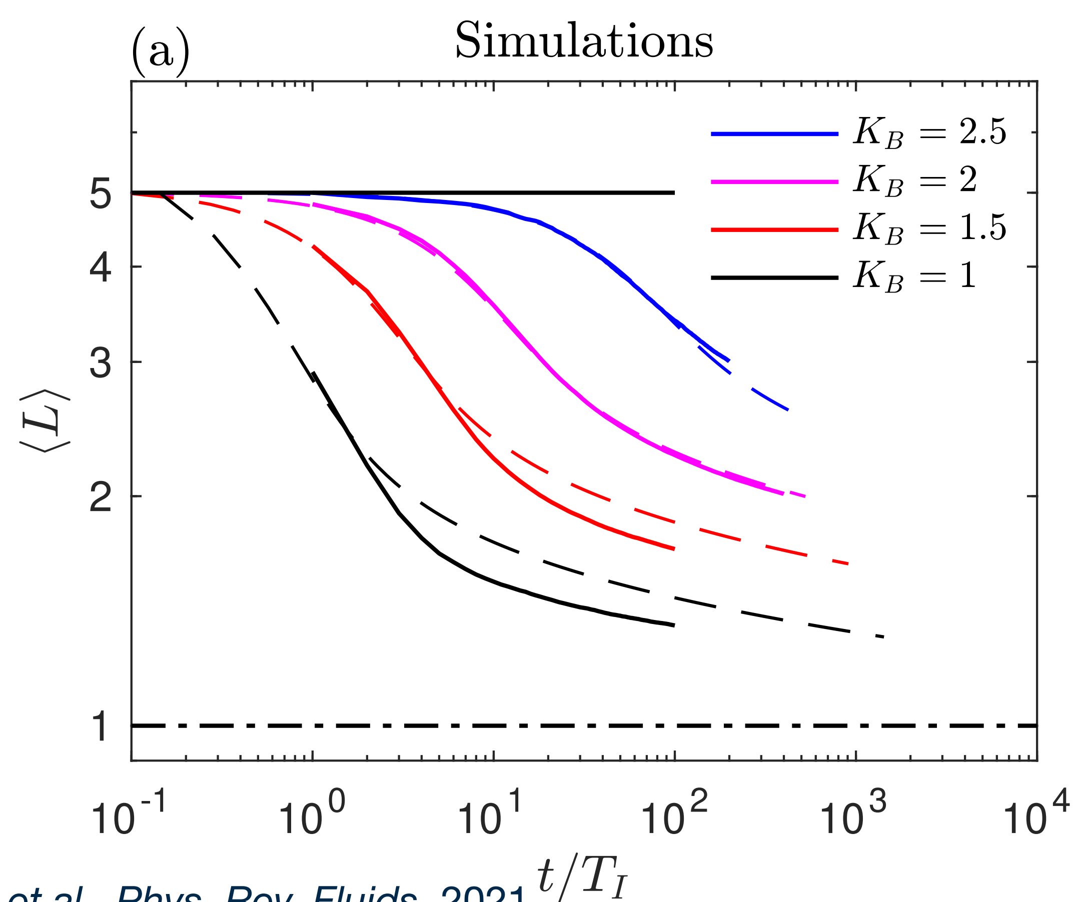

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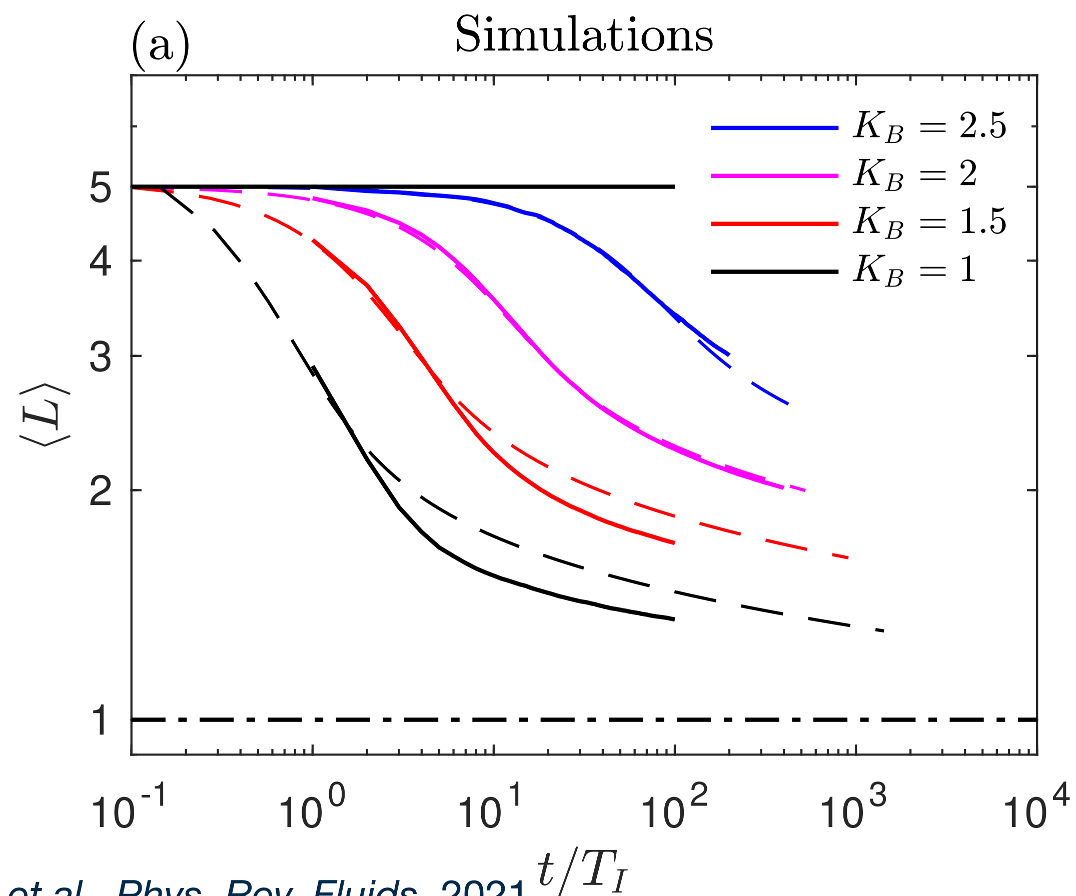
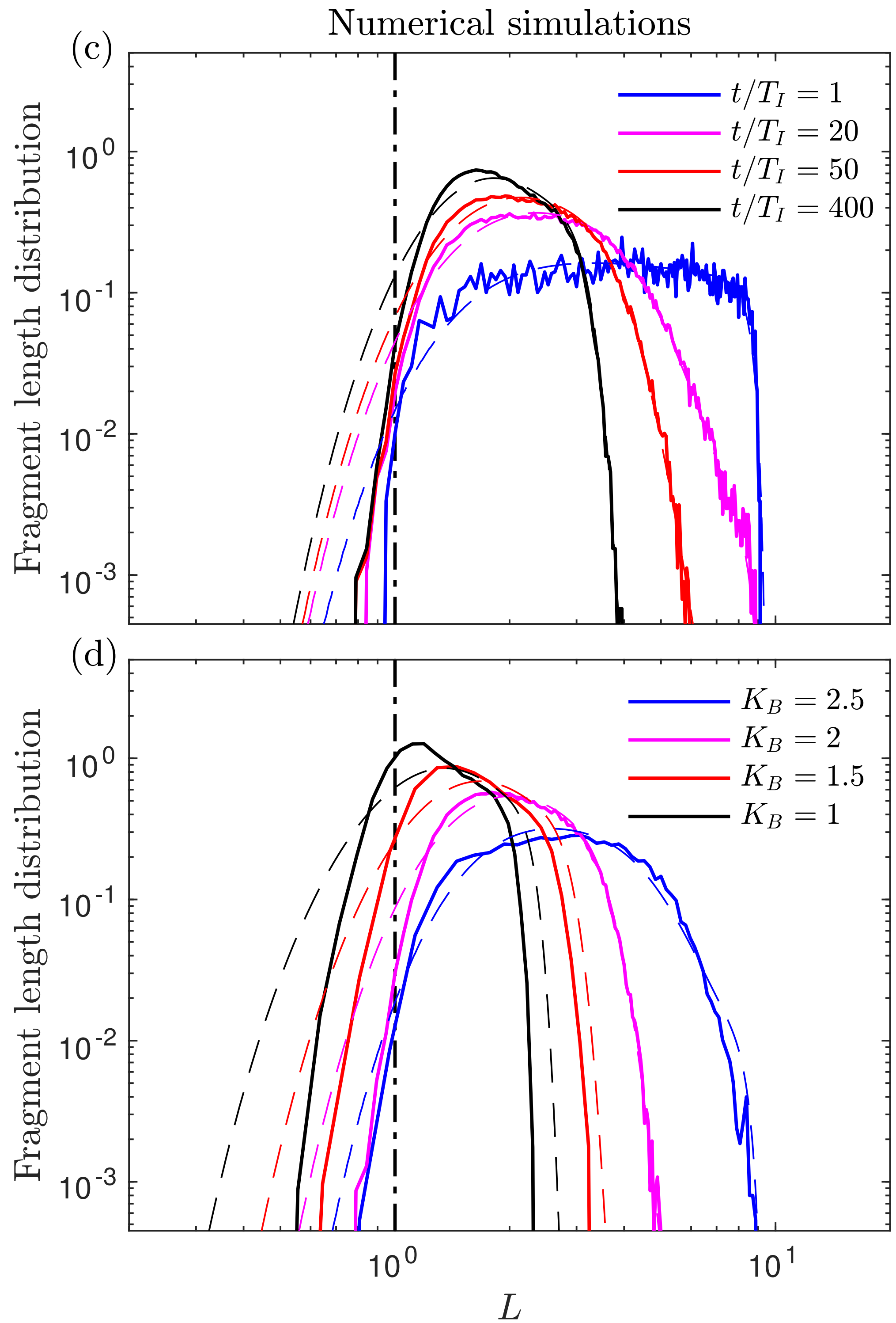




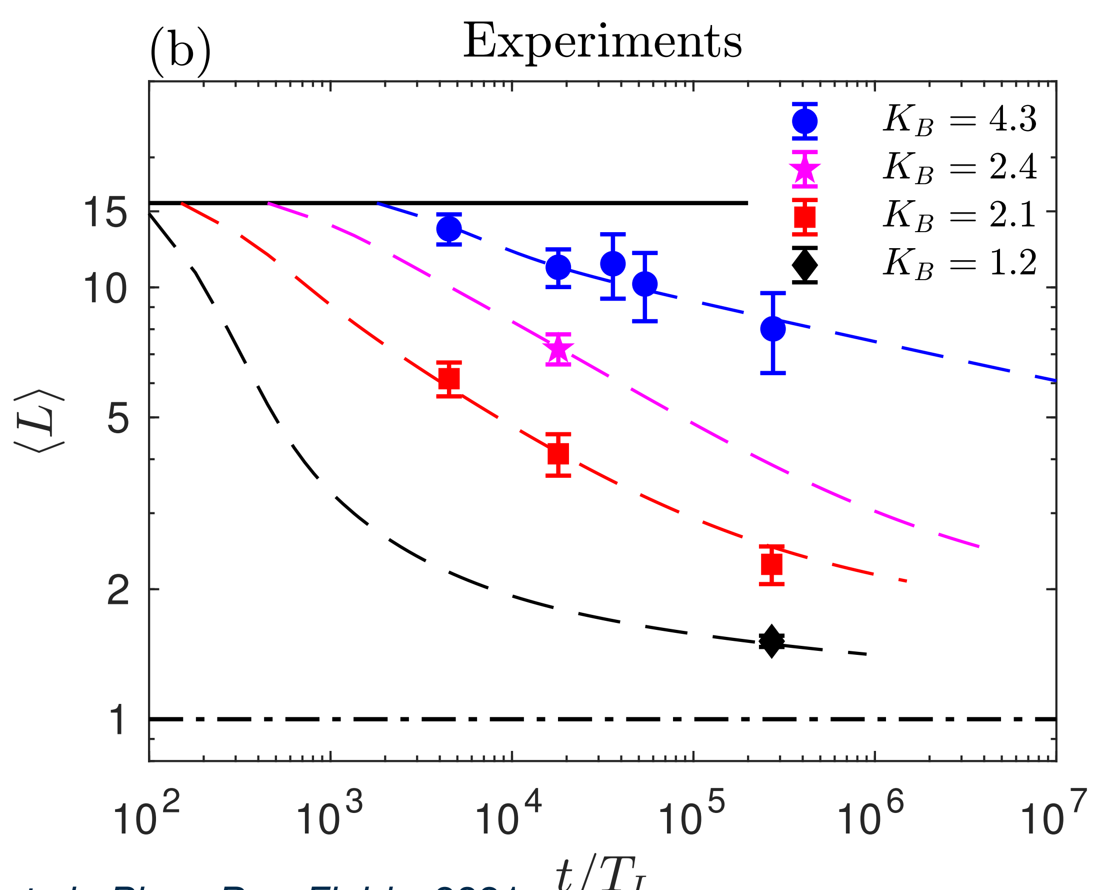
Brouzet *et al.*, *Phys. Rev. Fluids*, 2021

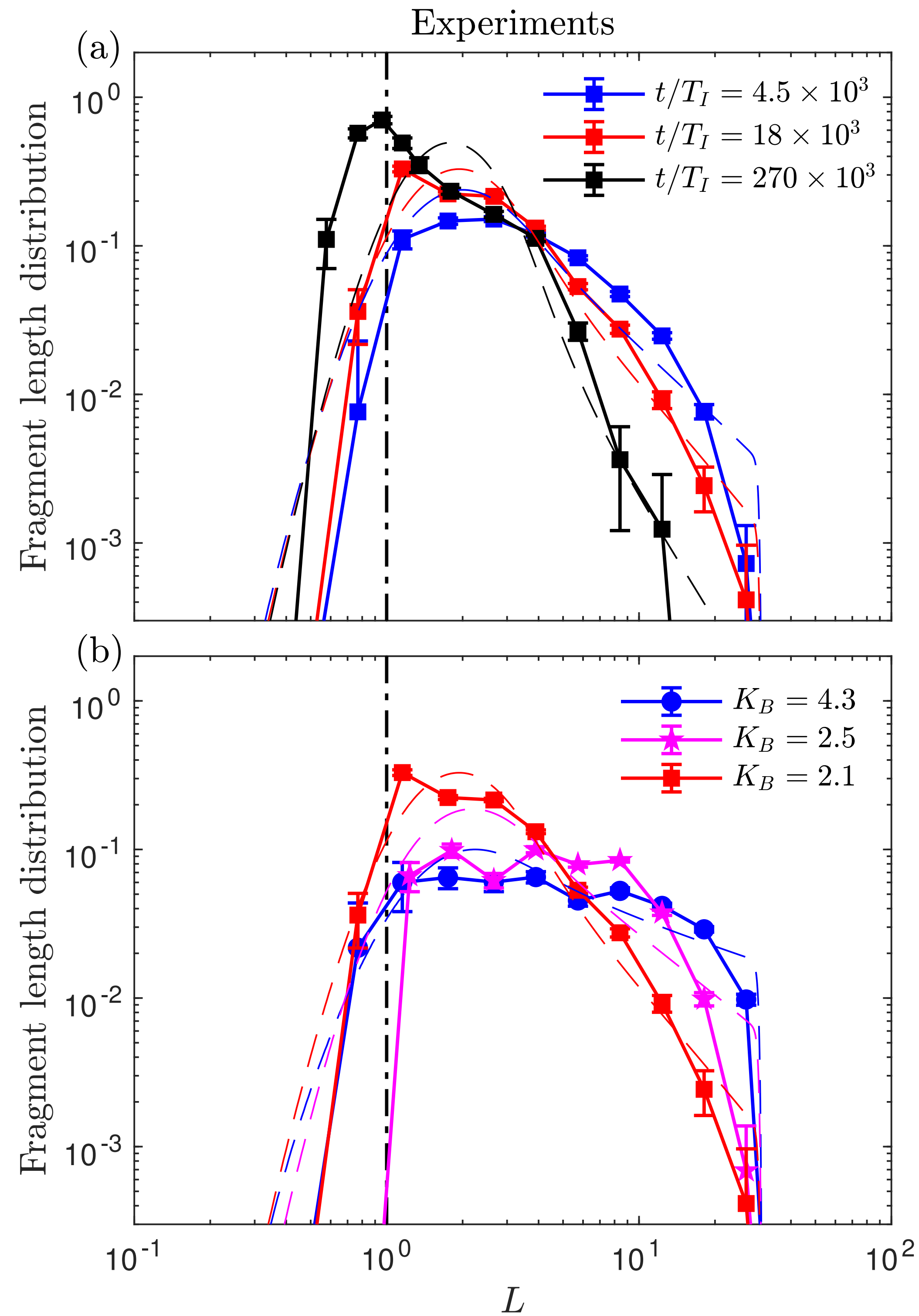
Comparison model/experiments

$$\partial_t n_L = -n_L p(L) + 2\int_L^\infty n_{L'} p(L')\gamma(L,L')\mathrm{d}L'$$

timescale determined by $\langle L \rangle$

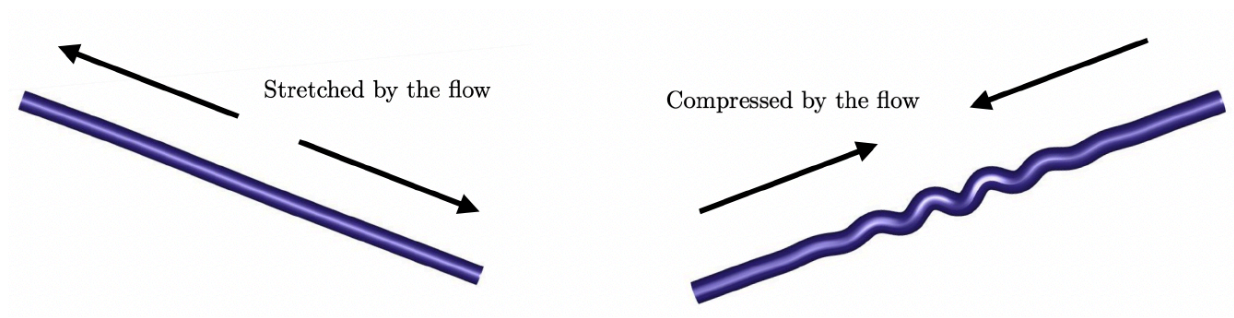
Importance of defects (distribution of κ_B)





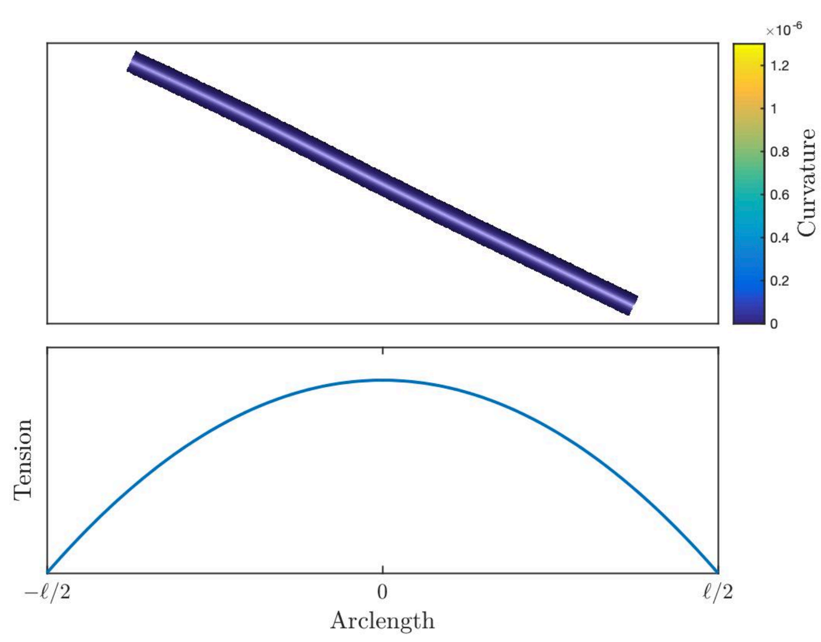
Brouzet *et al.*, *Phys. Rev. Fluids*, 2021

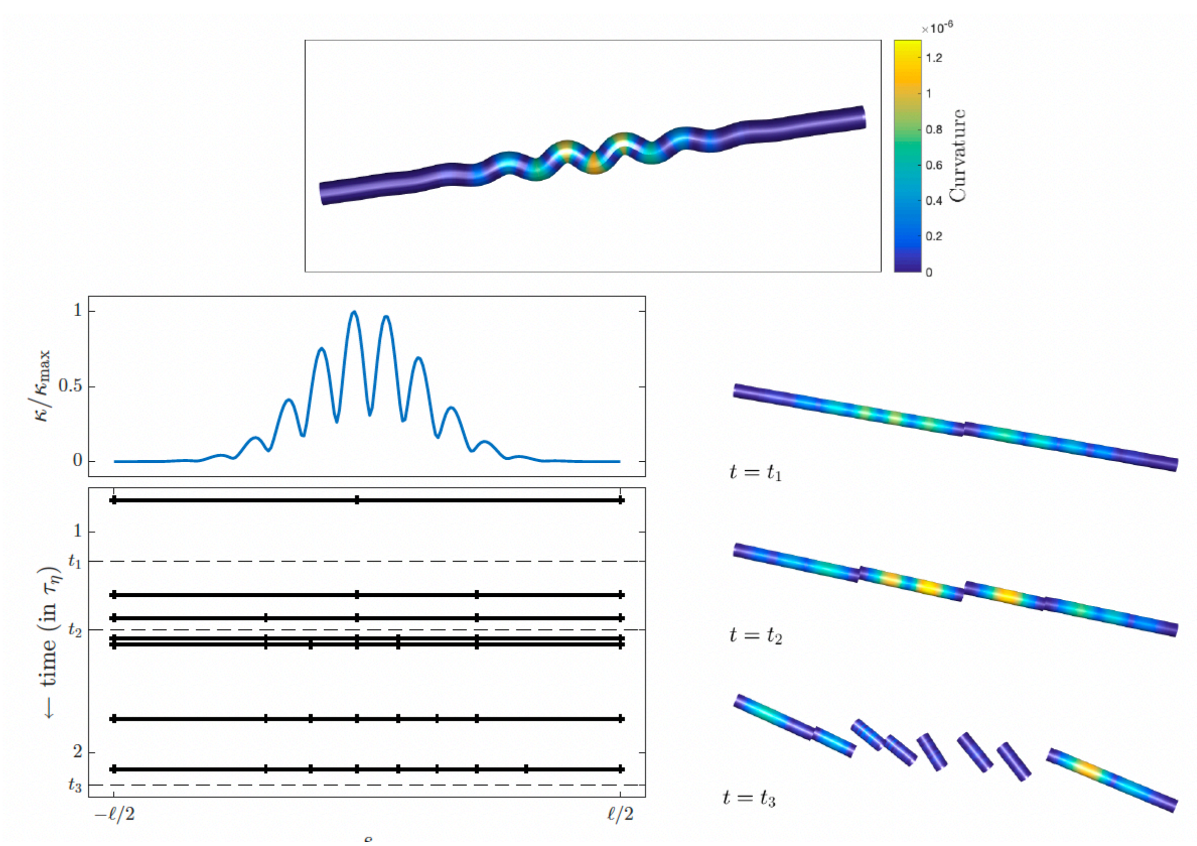
Fragmentation of small fibers



Fragmentation due to tension

Fragmentation due to buckling





Possibility to form very small fragments

Conclusion on the fragmentation of fibers

- No new fragmentation mechanism at small scale are necessary to model the pdf
- Maximum of the pdf is given by the elastic length

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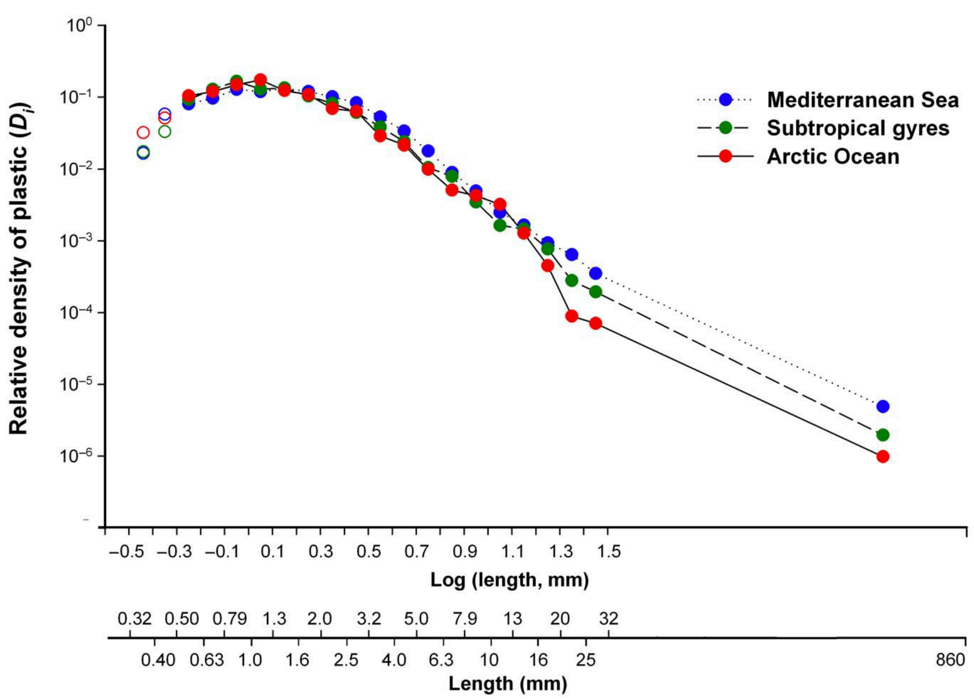


$$\ell_e \sim \frac{(EI)^{1/4}}{(\rho\eta\epsilon)^{1/8}}$$

$$E \sim 1 \text{ GPa} \quad d \sim 50\ \mu\text{m}$$

$$\epsilon \sim 10^{-1} - 10^{2}\ \text{m}^2.\text{s}^{-3}$$

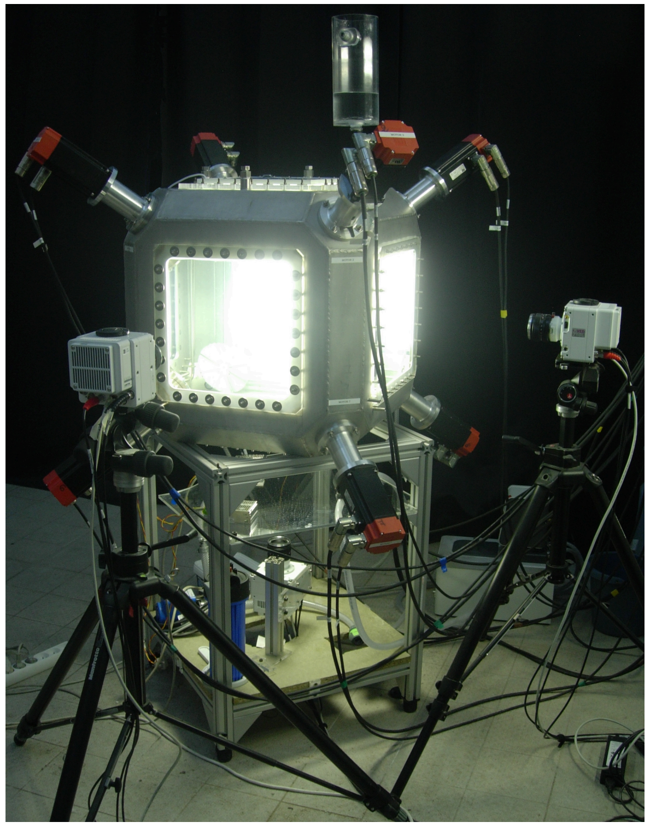
$$\ell_e \sim 2 - 5 \text{ mm}$$

On going and future work

- More complex shapes

Deformability of disc in turbulence

Deformability of disc in turbulence



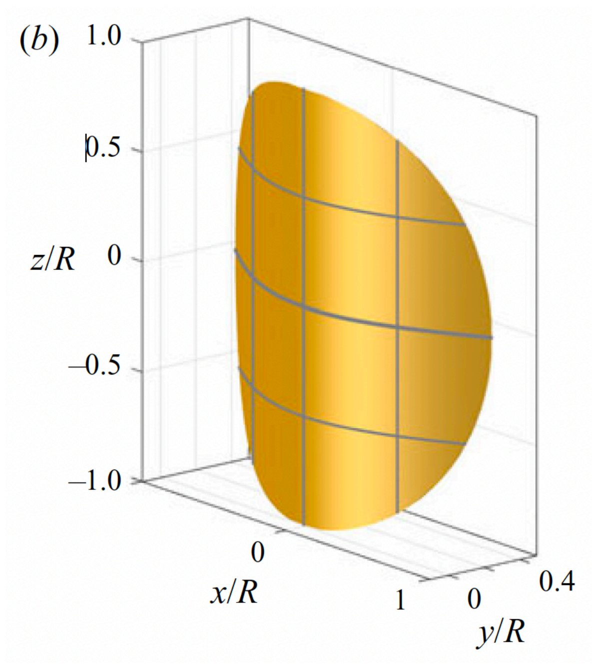
$$R_\lambda \in [300; 710]$$

$$\eta_K \in [30; 70]\ \mu\text{m}$$

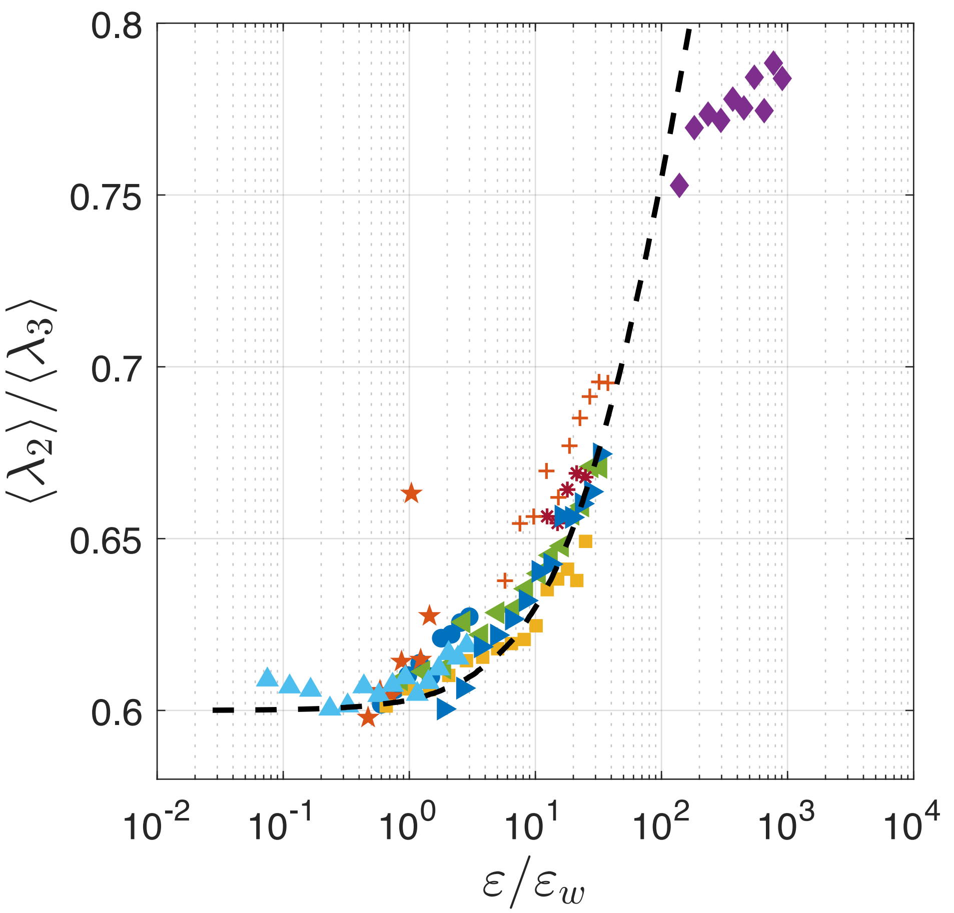
$$L_I \sim 7\ \text{cm}$$

Modeling the threshold of the transition for discs

Main difference with fibers is the timescale of the deformation



λ_i eigenvalues of the moment of the tensor of inertia



$$R_c \sim \frac{B^{3/10}}{(\rho_f \sigma^{1/2} \epsilon)^{1/5}}$$

$E \sim 1$ GPa $\qquad h \sim 80\ \mu$m

$$R_c \sim 5 - 1 \text{ mm}$$

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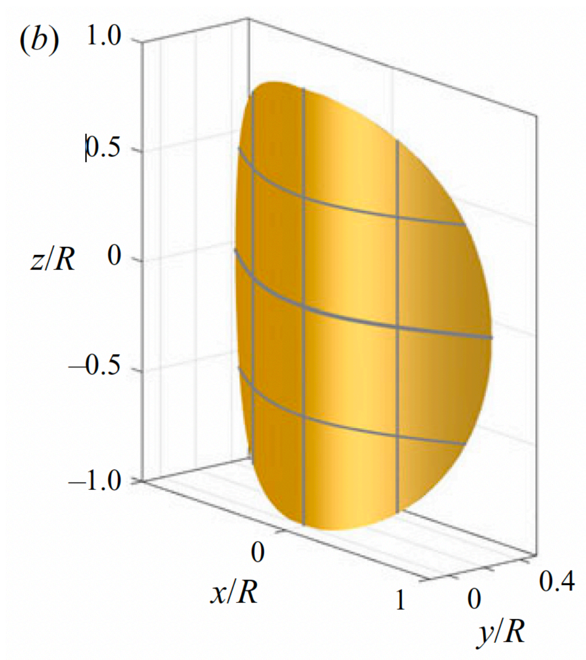

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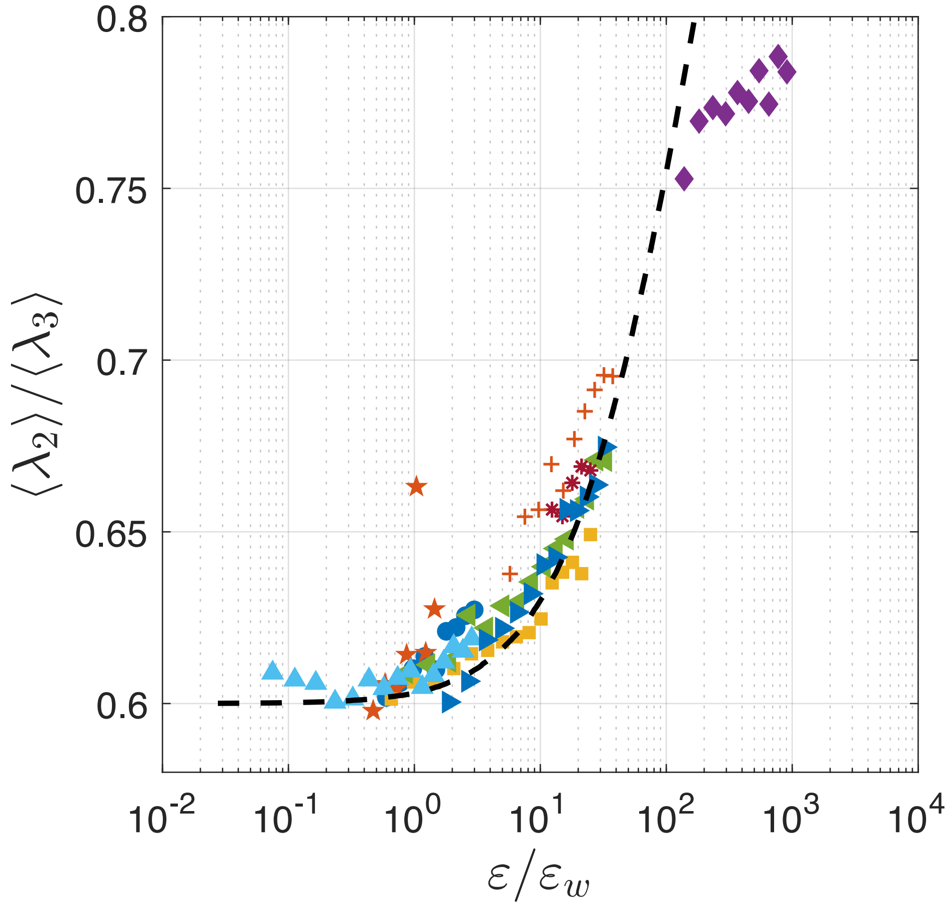

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Verhille, *JFM*, 2022

On going and future work

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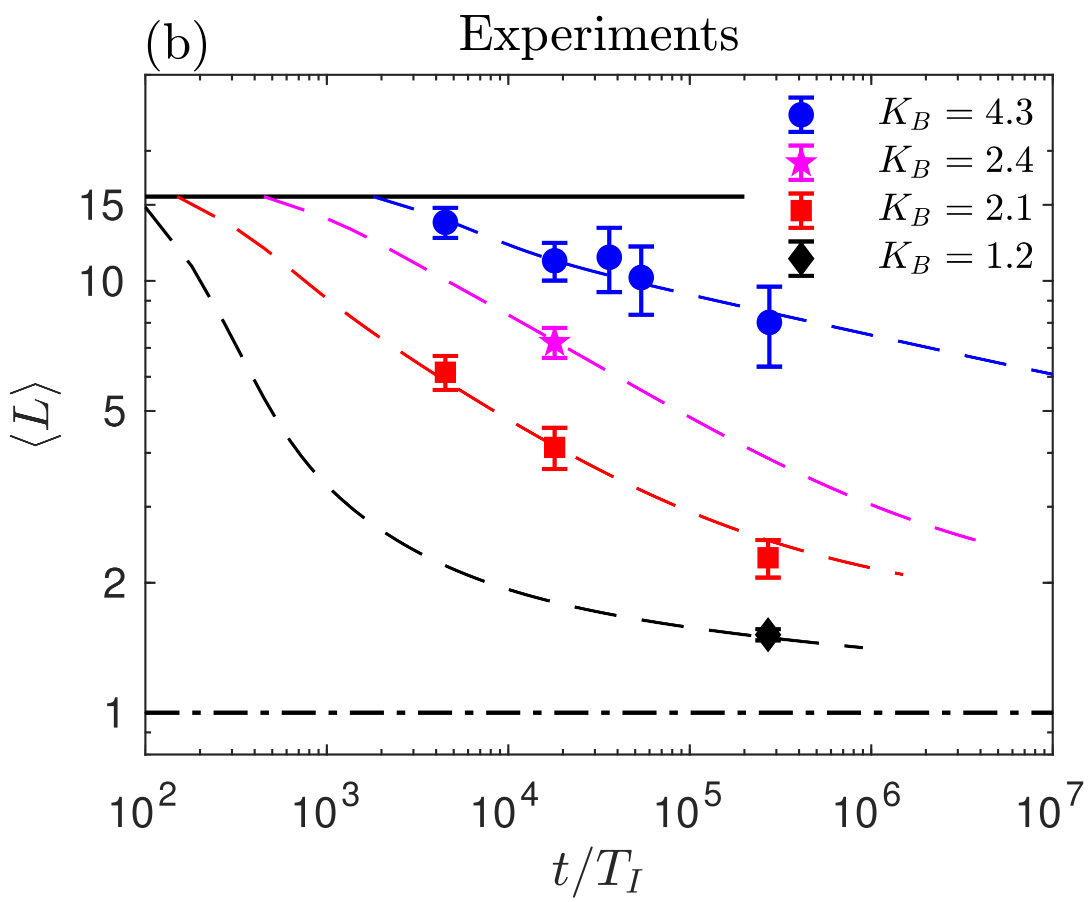
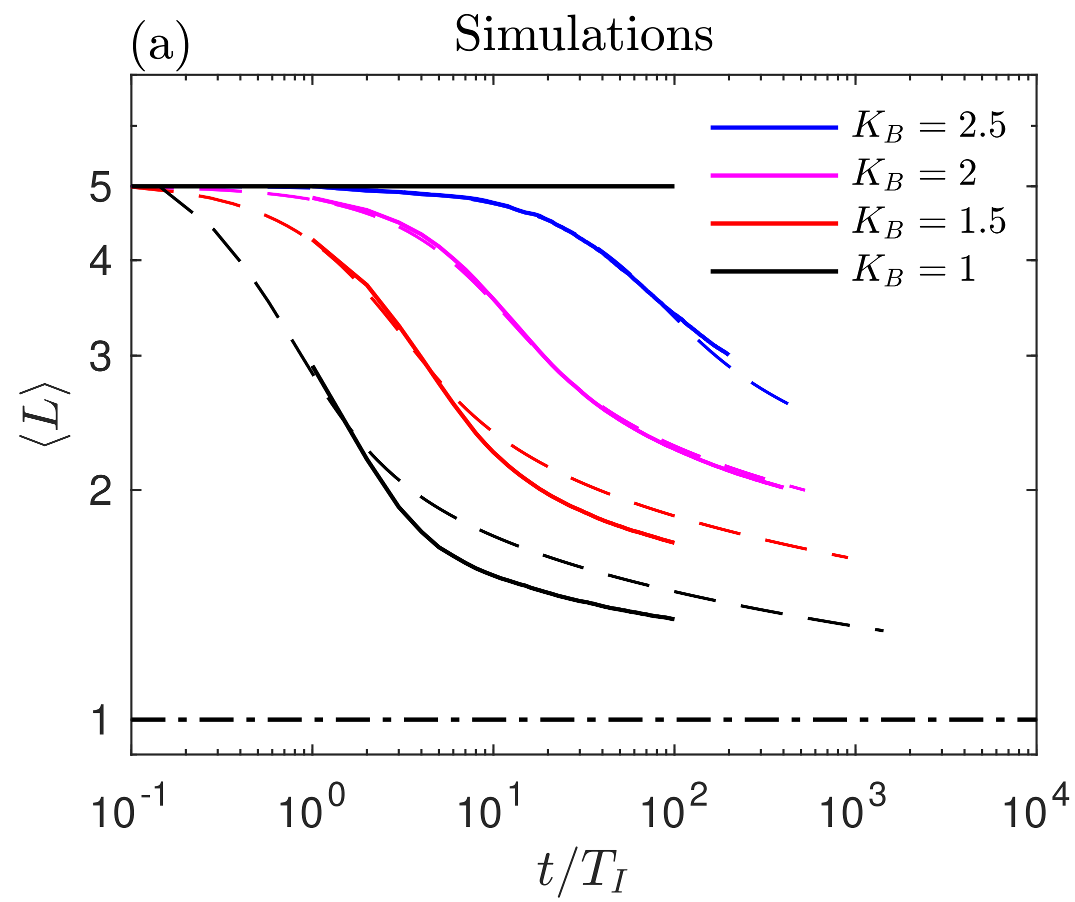
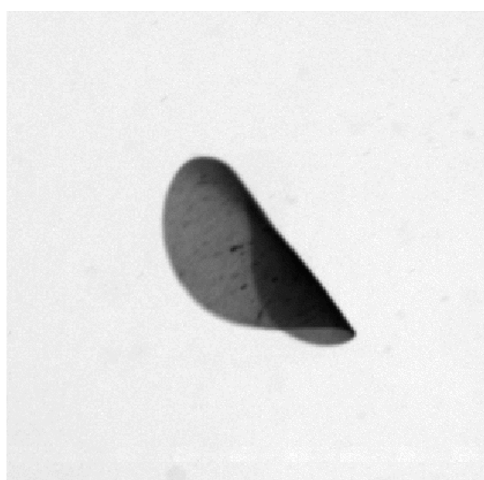
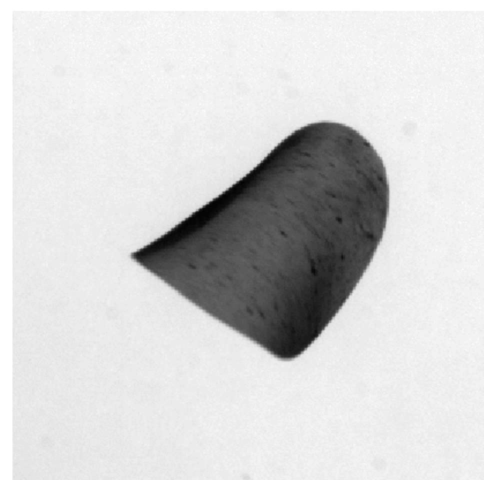
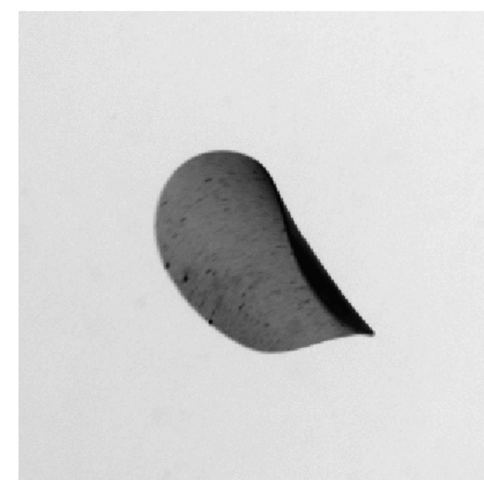
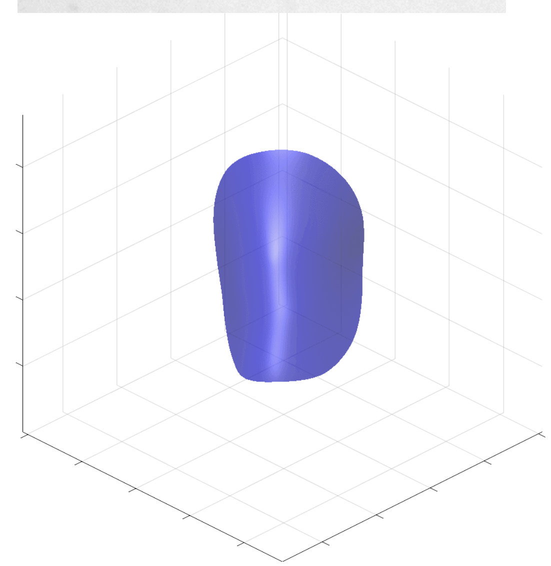
- Dynamics of fragmentation





On going and future work

- More complex shape
- Dynamics of fragmentation
- Influence of deformation on the particle dynamics

E. Ibarra

On going and future work

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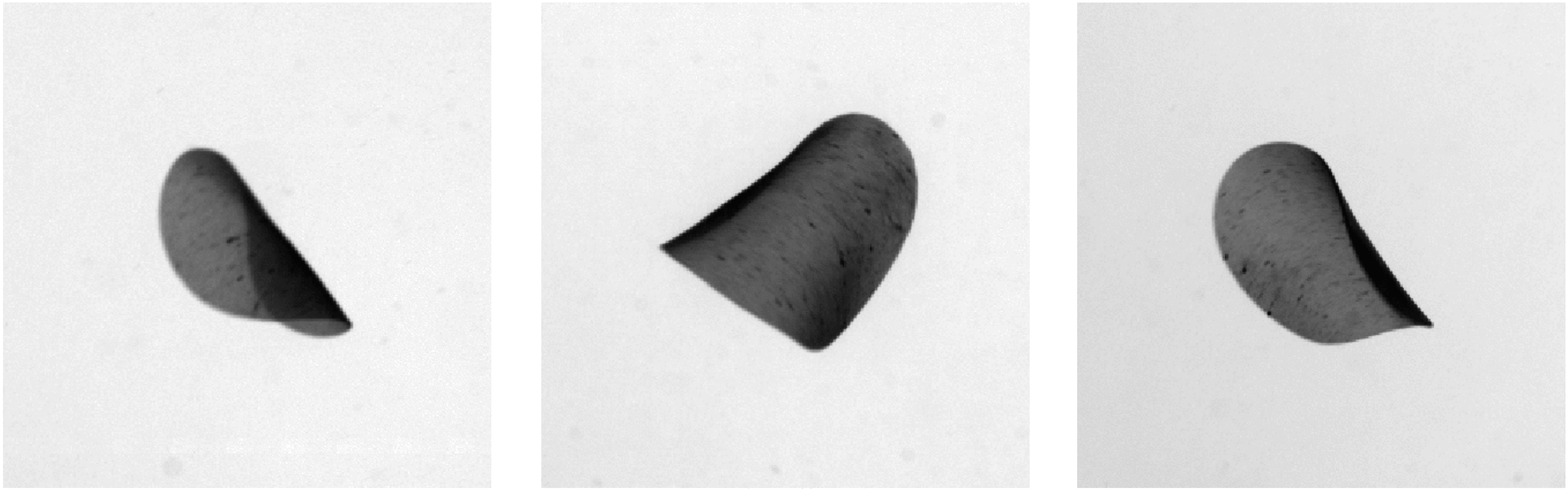

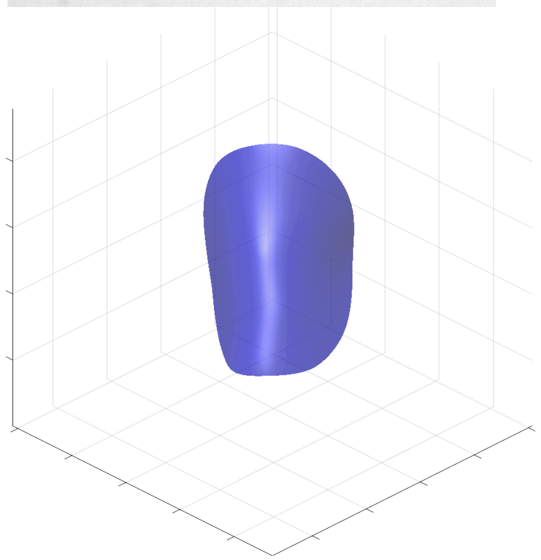

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Thank you for your attention