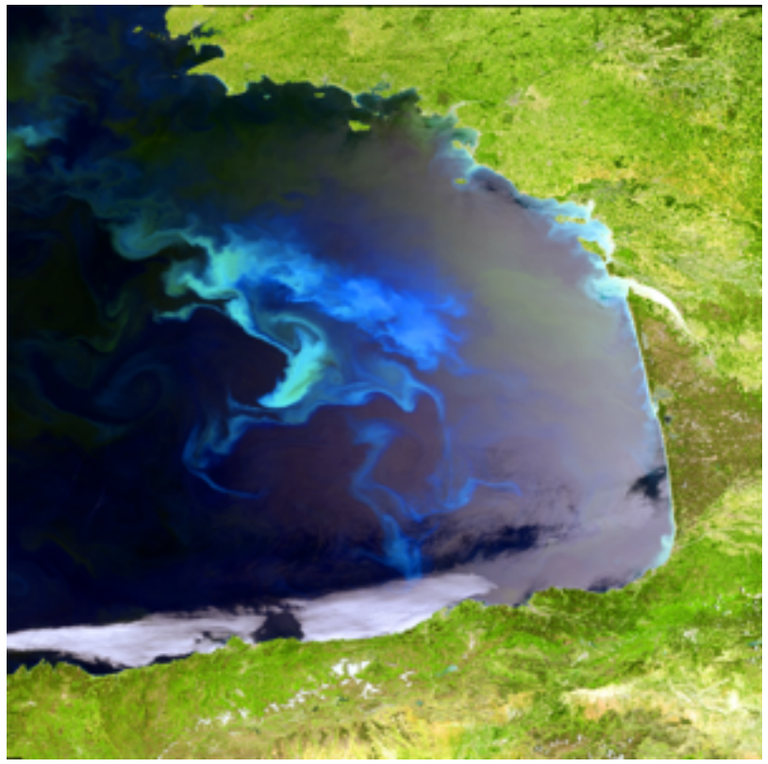
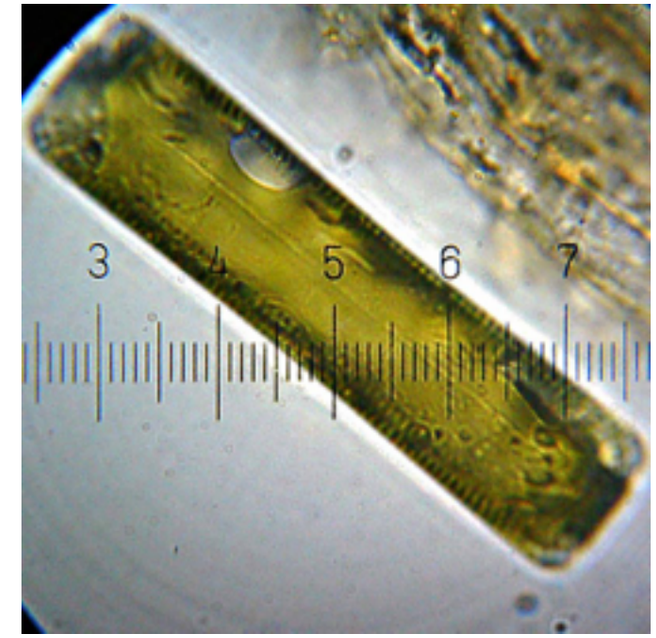
# Fibre flexible en turbulence

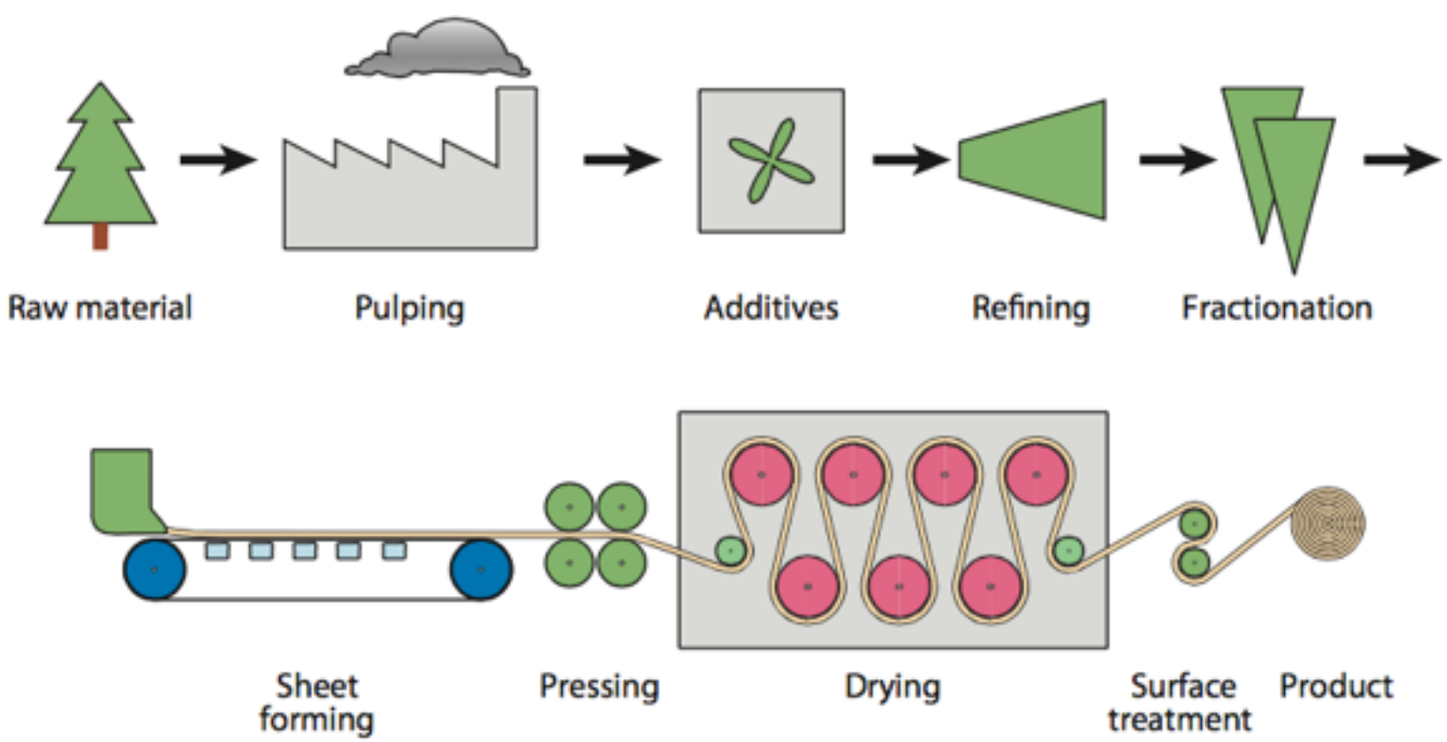
Gautier Verhille, Patrice Le Gal

IRPHE

# Fibres en turbulence



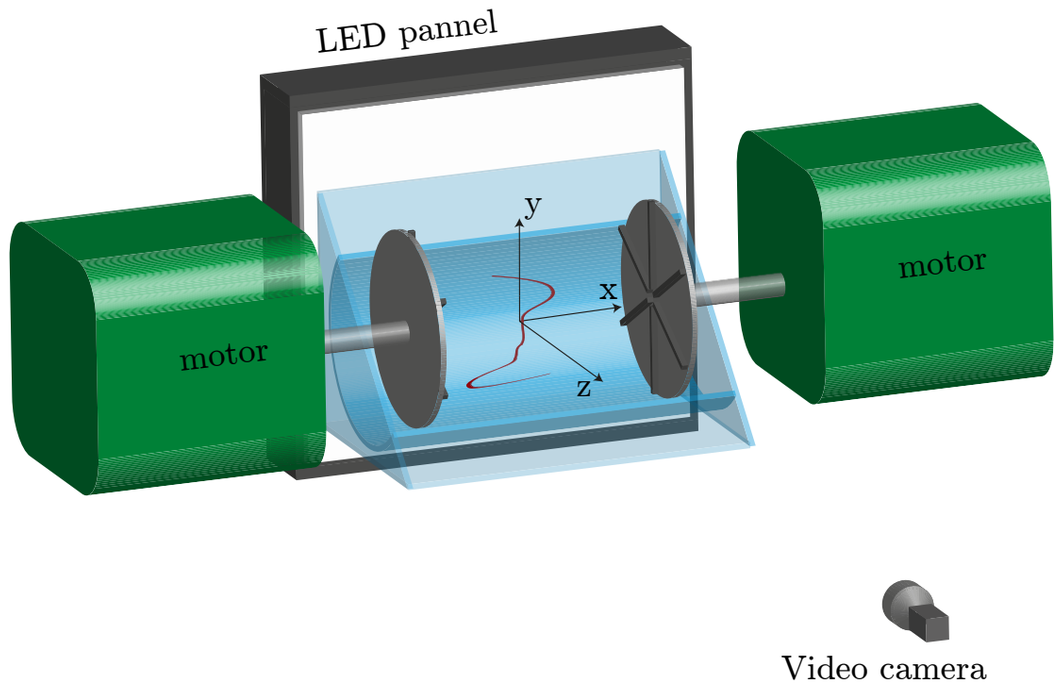


# Questions posées

- Quand doit on prendre en compte la flexibilité d'une particule ?
- Comment se déforment ses particules ?
- Quel est le rôle des déformations sur le transport ?

# Déformation d'une fibre dans un écoulement turbulent

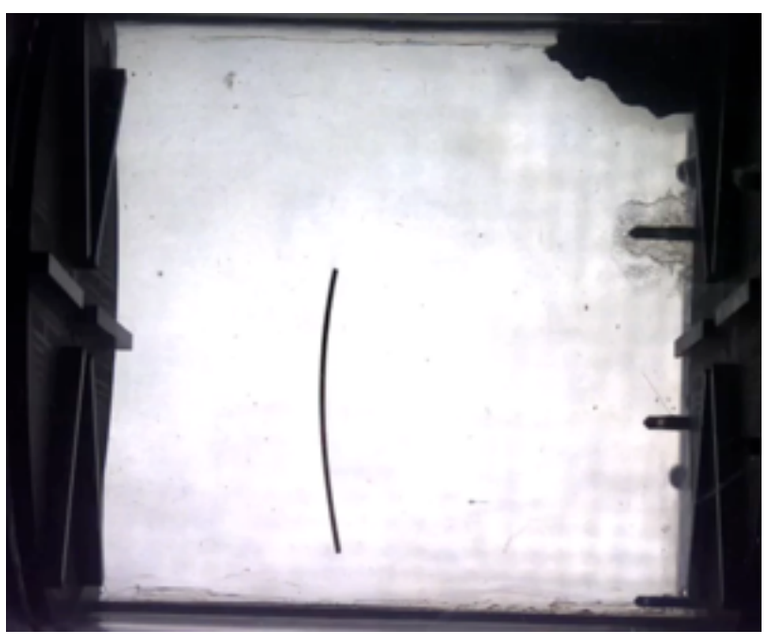



$$R \sim 8.2 \text{ cm}$$

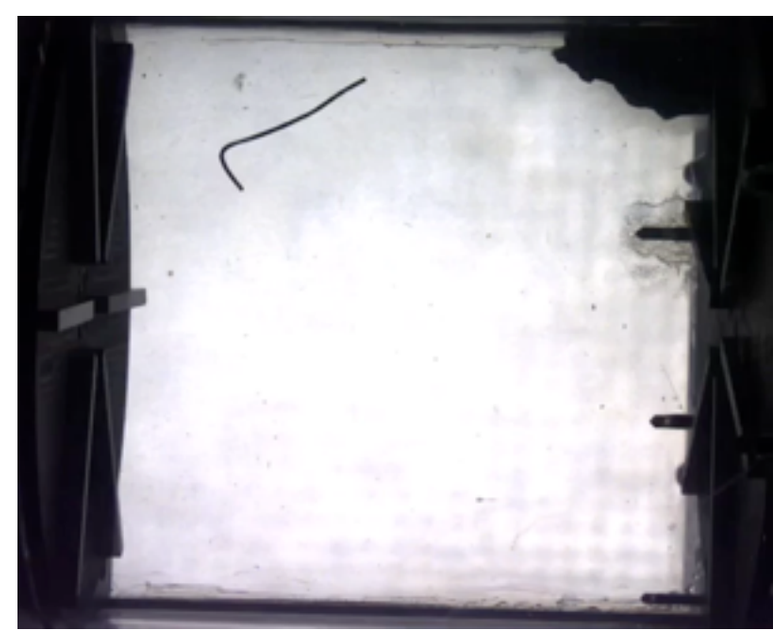
$$Re \in [10^5 \ ; \ 10^6]$$

$$\eta_K \in [12 \ ; \ 91] \ \mu\text{m}$$

$$F \in [2 \ ; \ 30] \text{ Hz}$$



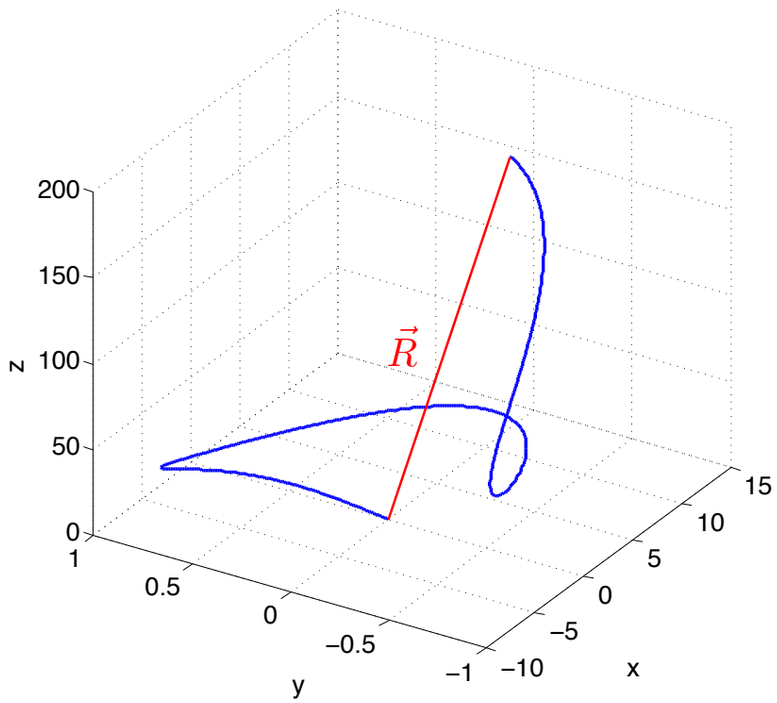
F=2 Hz



F=20 Hz

Travail réalisé avec C. Brouzet

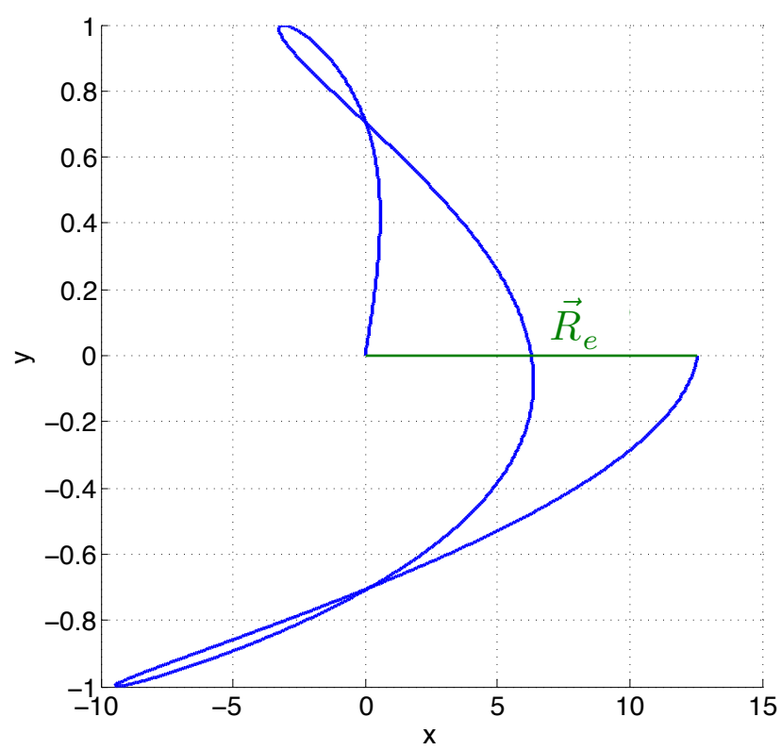
# Evolution du vecteur bout à bout




Correction due à la projection

Norme

$$\langle R_e^2 \rangle = \left\langle \frac{1}{4\pi} \int_{\varphi=0}^{\varphi=2\pi} \int_{\theta=0}^{\theta=\pi} R^2 \sin^2\theta (\cos^2\varphi + \sin^2\varphi) \sin\theta \mathrm{d}\theta \mathrm{d}\varphi \right\rangle$$

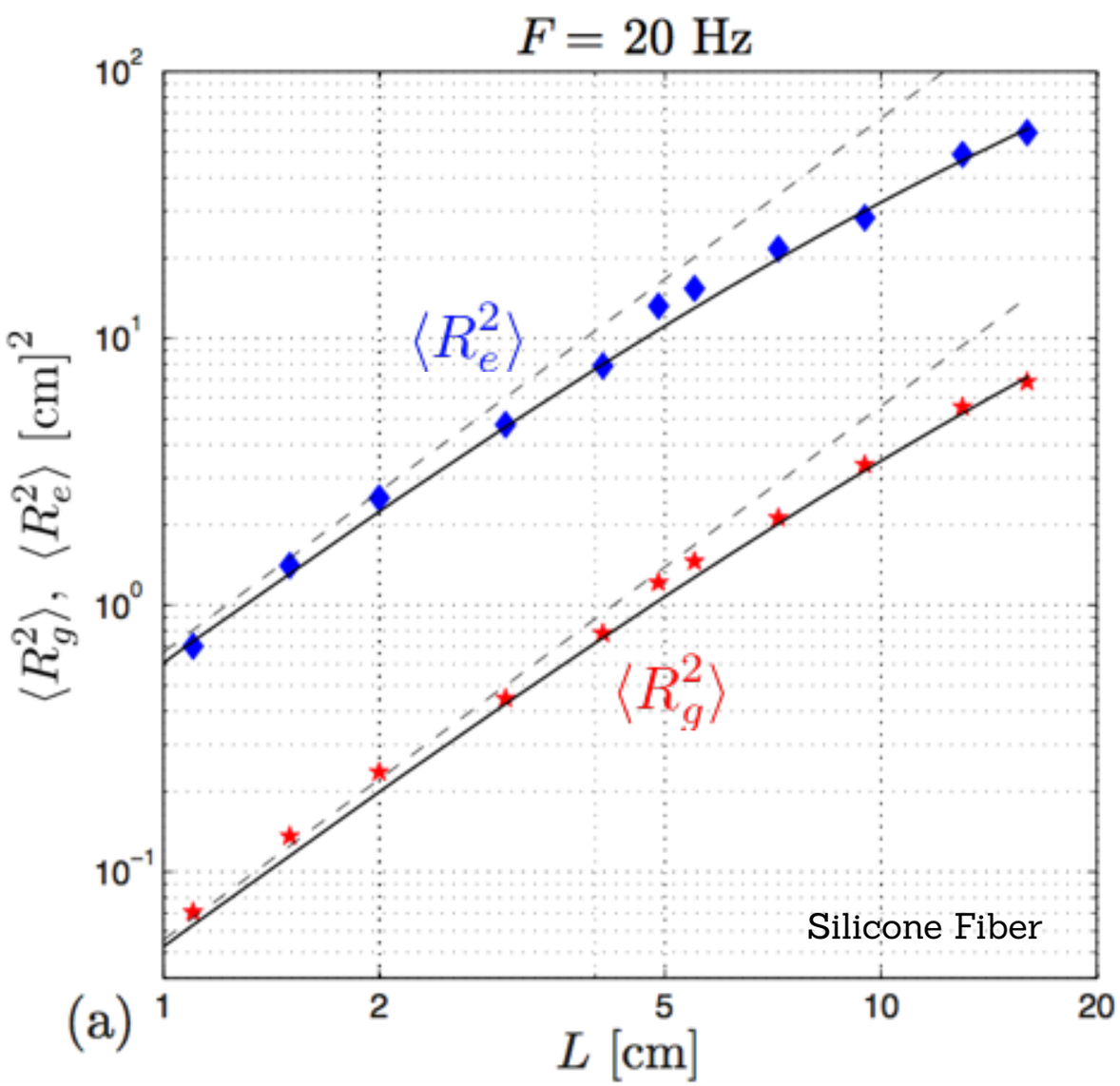



$$\langle R_e^2 \rangle = \frac{2}{3} \langle R^2 \rangle$$

Rayon de gyration

$$R_g^2 = \frac{1}{L} \int_0^L (\vec{r} - \vec{r}_{cm})^2 \mathrm{d}s$$

# Evolution du vecteur bout à bout

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Comment décrire le régime non linéaire ?

# Description de la transition

## Equation d'elastica

$$\underbrace{\rho_f S \partial_{tt} y + \alpha \partial_t y + EI \partial_{ssss} y}_{\text{Elasticité}} = \underbrace{\alpha u + F_H}_{\text{Forçage}} \qquad \alpha \sim \eta$$

## Equation de la dynamique des polymères

Hallatschek *et al.*, PRE 2007

$$\rho S \partial_{tt} y + \eta \partial_t y + EI \partial_{xxxx} y = \xi$$

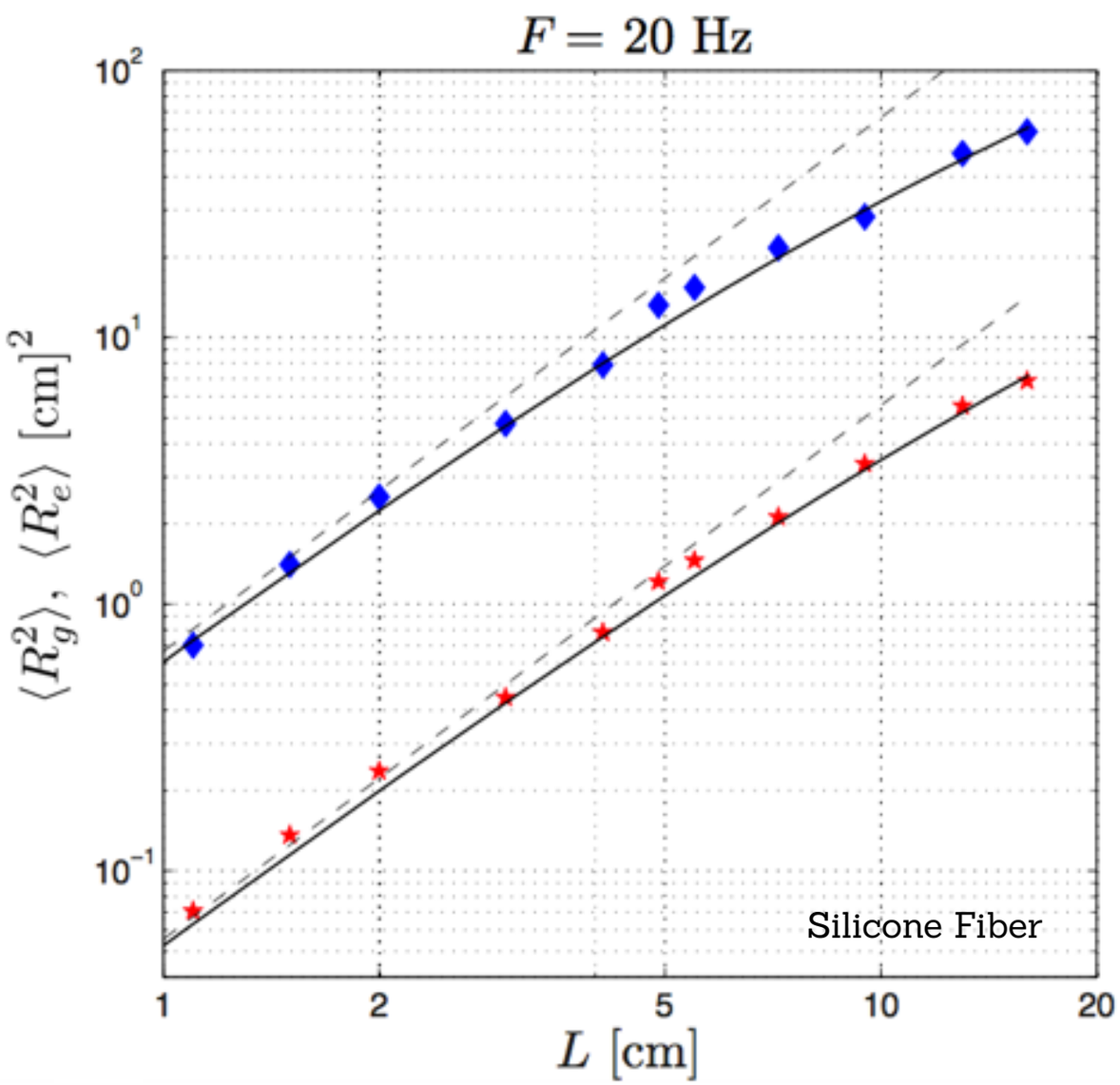
| Turbulence | Polymère |
|---|---|
| forçage = fluctuation turbulente | forçage = fluctuation thermique |

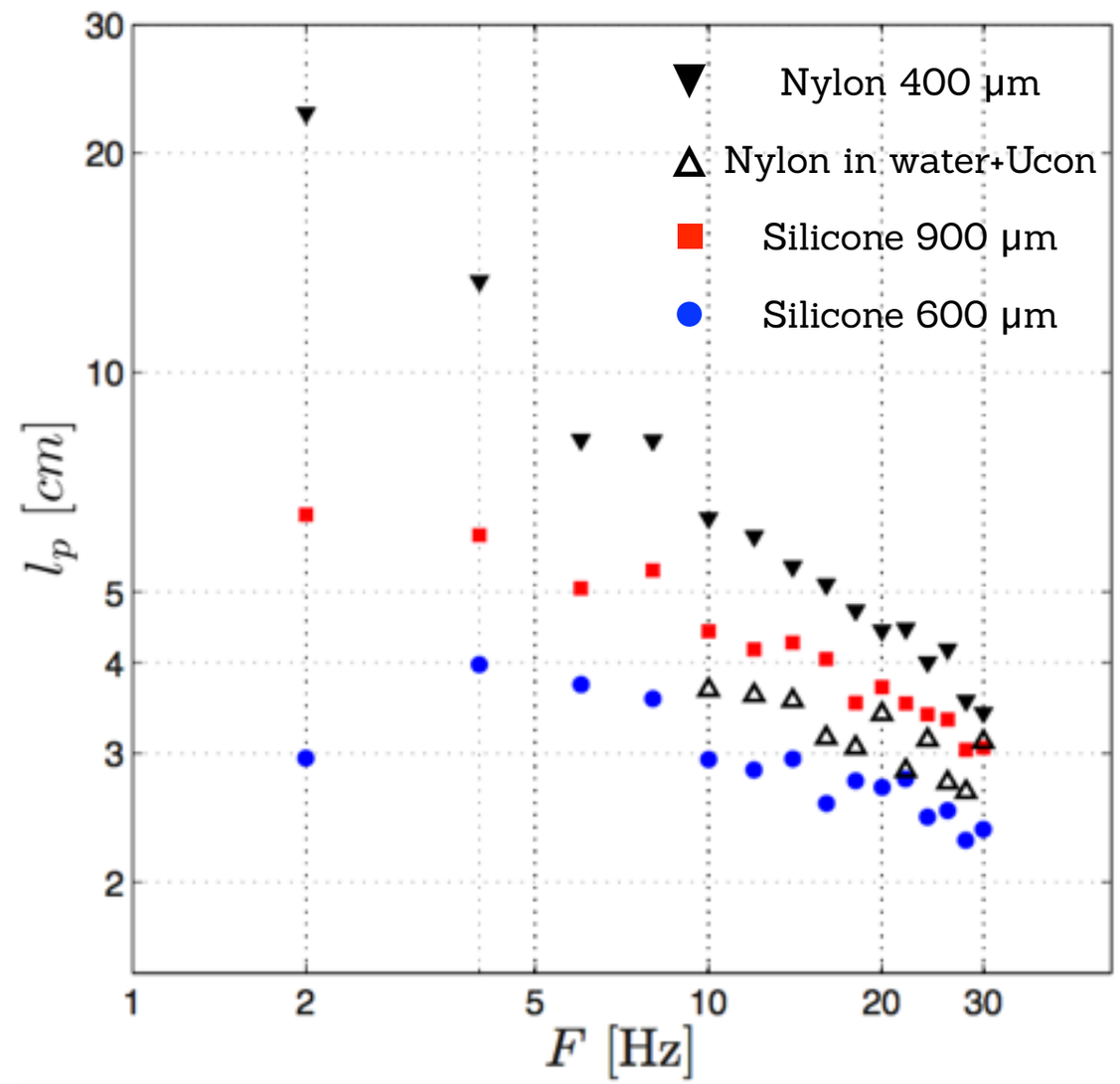
## Modèle des polymères semi-rigides

modèle de polymère court (ADN, ARN, ...) $\langle \vec{r}(s) \cdot \vec{r}(s+\ell) \rangle = e^{-\ell/\ell_p}$

$$\langle R^2 \rangle = 2L\ell_p - 2\ell_p^2 \left(1 - e^{-L/\ell_p}\right)$$

# Evolution de la longueur de persistence




| Fluide | visc. dyn. [mPa.s] | densité | *Re* |
|---|---|---|---|
| eau | 1 | 1 | $10^5$-$1.5 \cdot 10^6$ |
| eau+Ucon | 100±20 | 1,045 | $5 \cdot 10^3$-$1.5 \cdot 10^4$ |

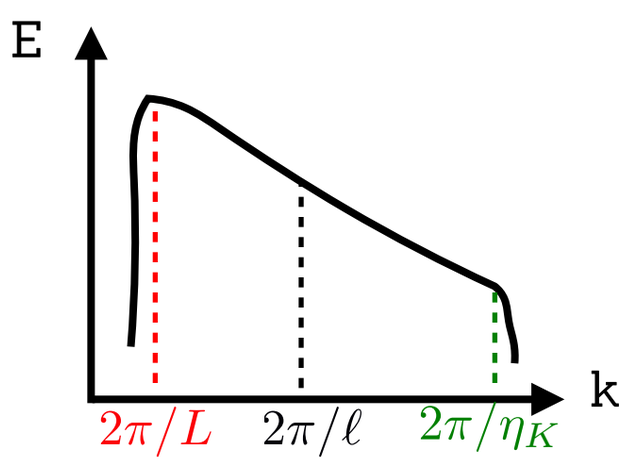
# Modélisation de la longueur de persistence

## Analogie thermique

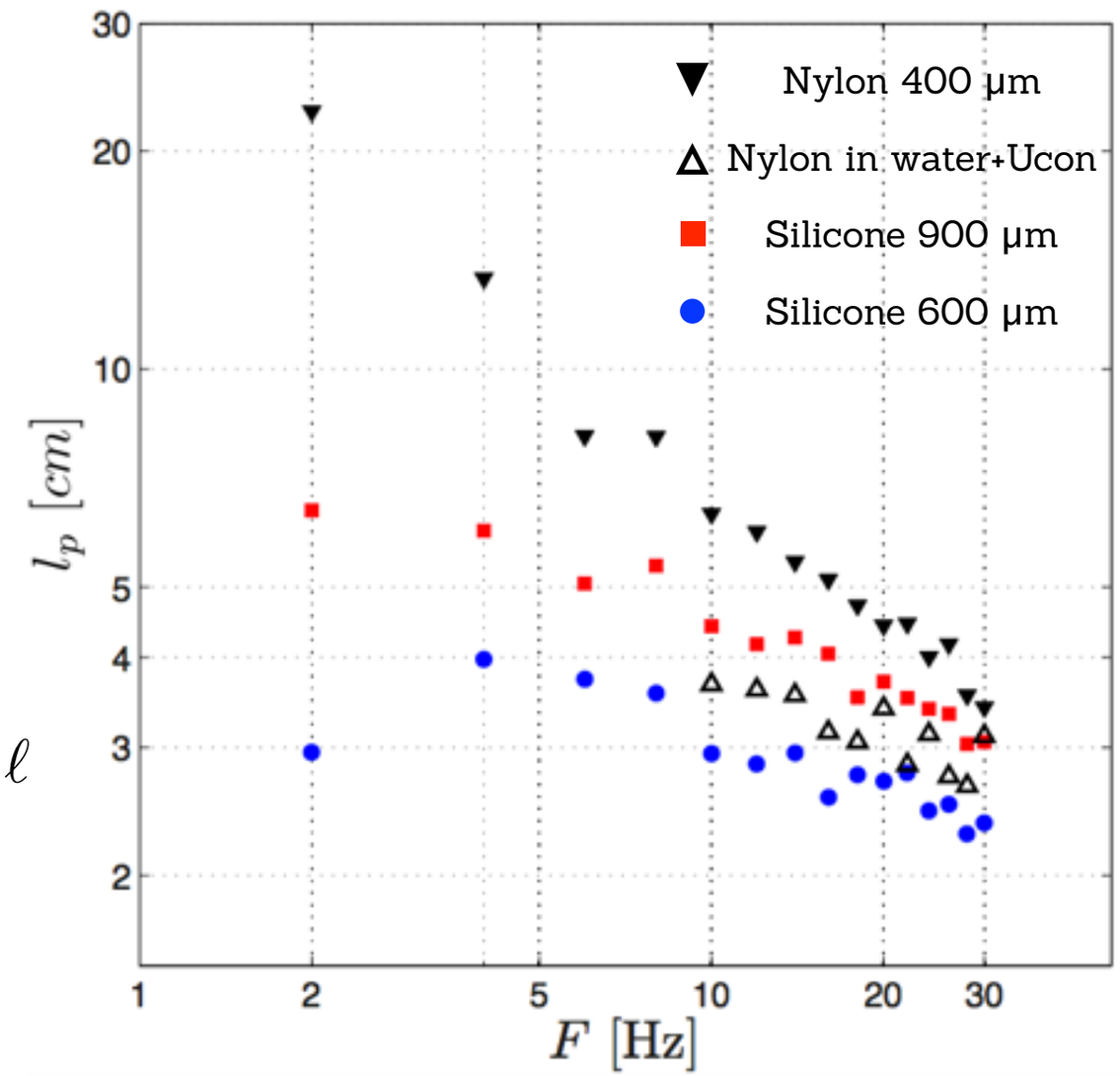
En théorie des polymères :
Energie élastique = Energie thermique

$$\frac{EI}{\ell_p} = k_B T$$

En turbulence




Tourbillon de taille $\ell$ doivent avoir assez d'énergie




$$\frac{EI}{\ell} = \frac{1}{2}\rho \ell^3 u_\ell^2 \qquad u_\ell = \epsilon^{1/3}\ell^{1/3} \qquad \ell = \left(\frac{2EI}{\rho}\right)^{3/14} \epsilon^{-1/7}$$

Longueur indépendante de la viscosité

# Modélisation de la longueur de persistence

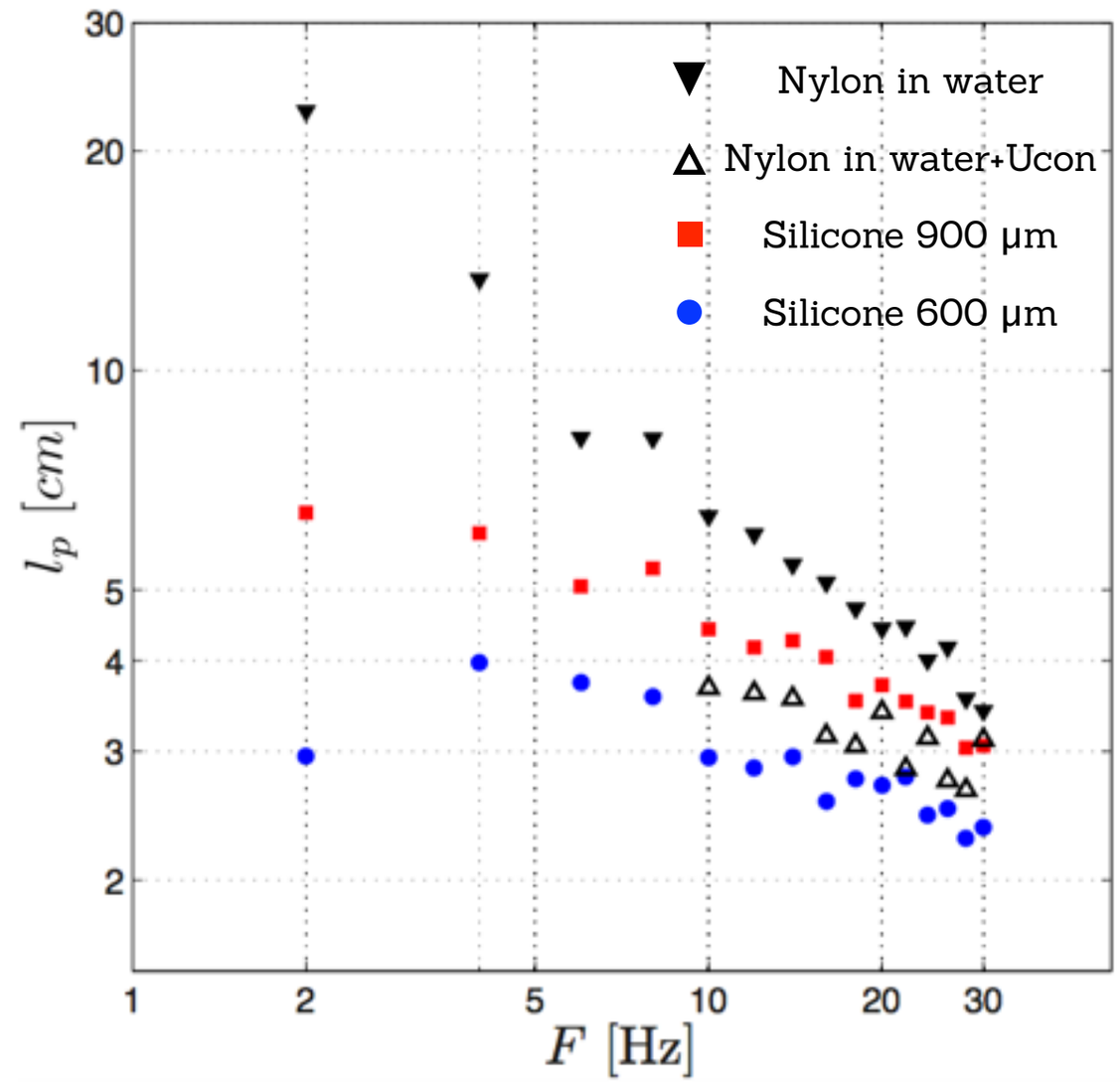
## L'influence du forçage

$$\rho_f S \partial_{tt} y + \alpha \partial_t y + EI \partial_{ssss} y = \alpha u + F_H$$

$$\alpha \sim \eta$$

Temps de relaxation

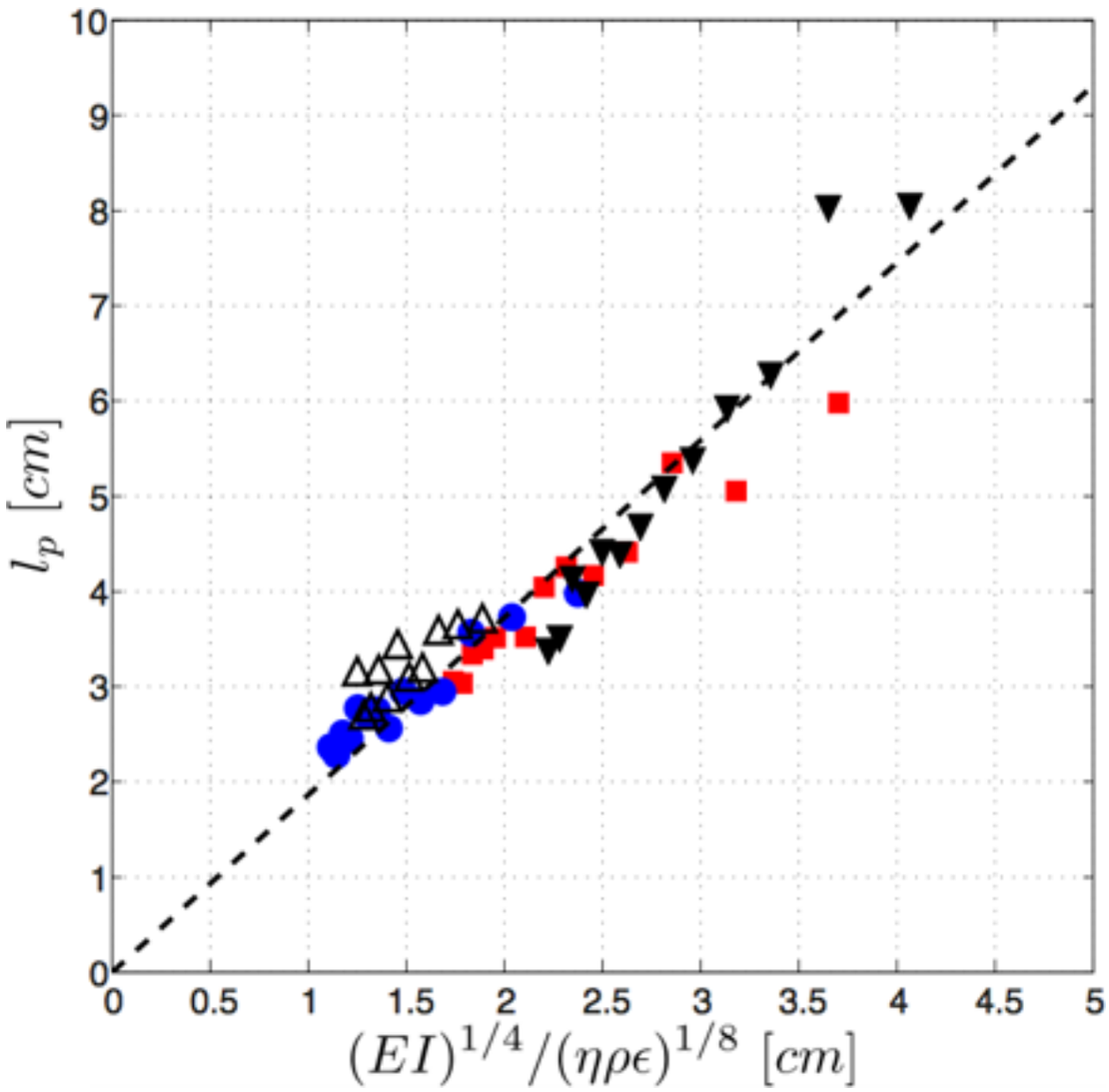
$$\tau_{el} = \alpha \ell^4 / EI$$

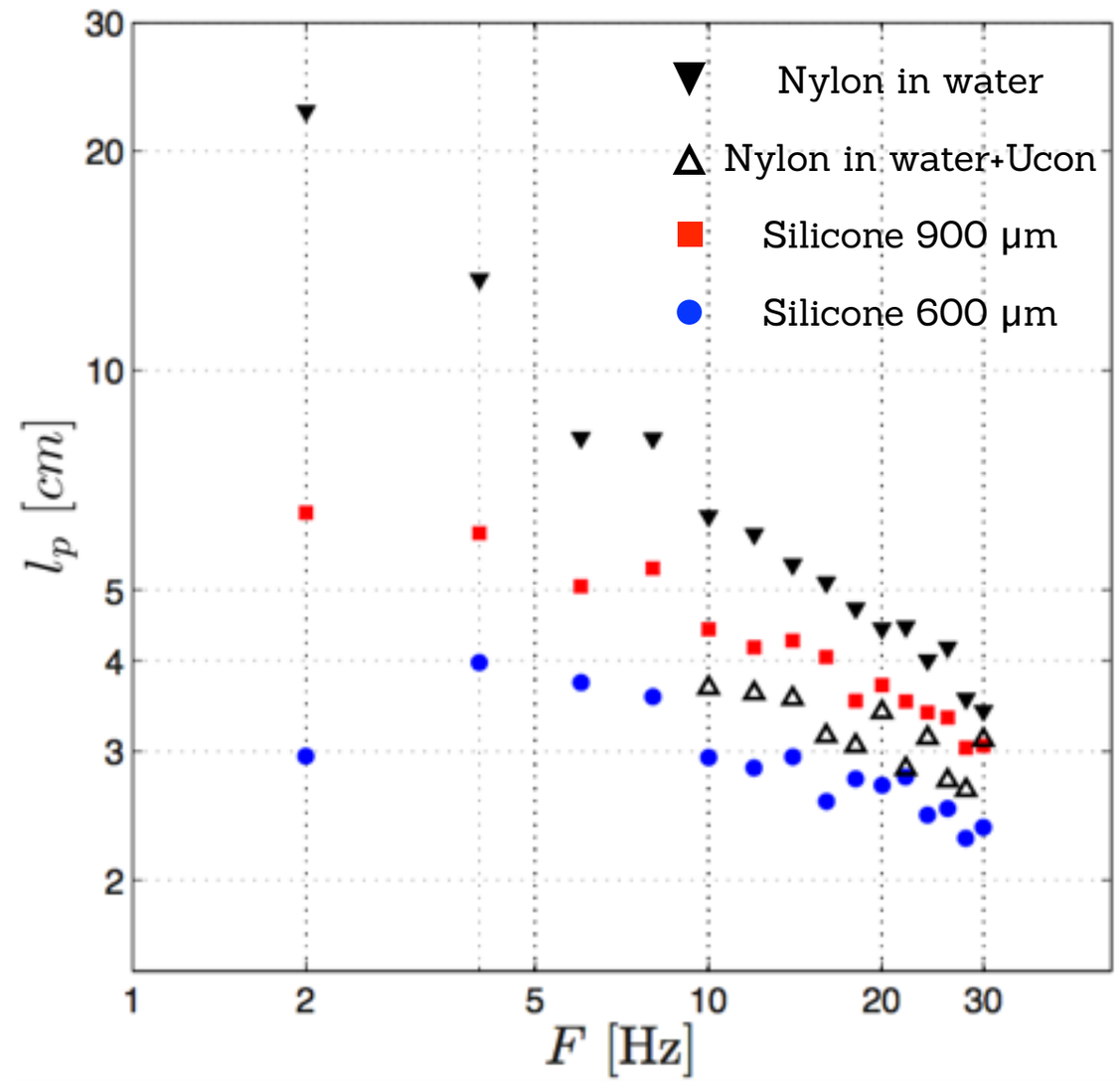



## Equilibre des puissances

$$\rho \ell^3 \epsilon = \frac{(EI)^2}{\alpha \ell^5} \qquad \ell = \frac{(EI)^{1/4}}{(\rho \eta \epsilon)^{1/8}}$$

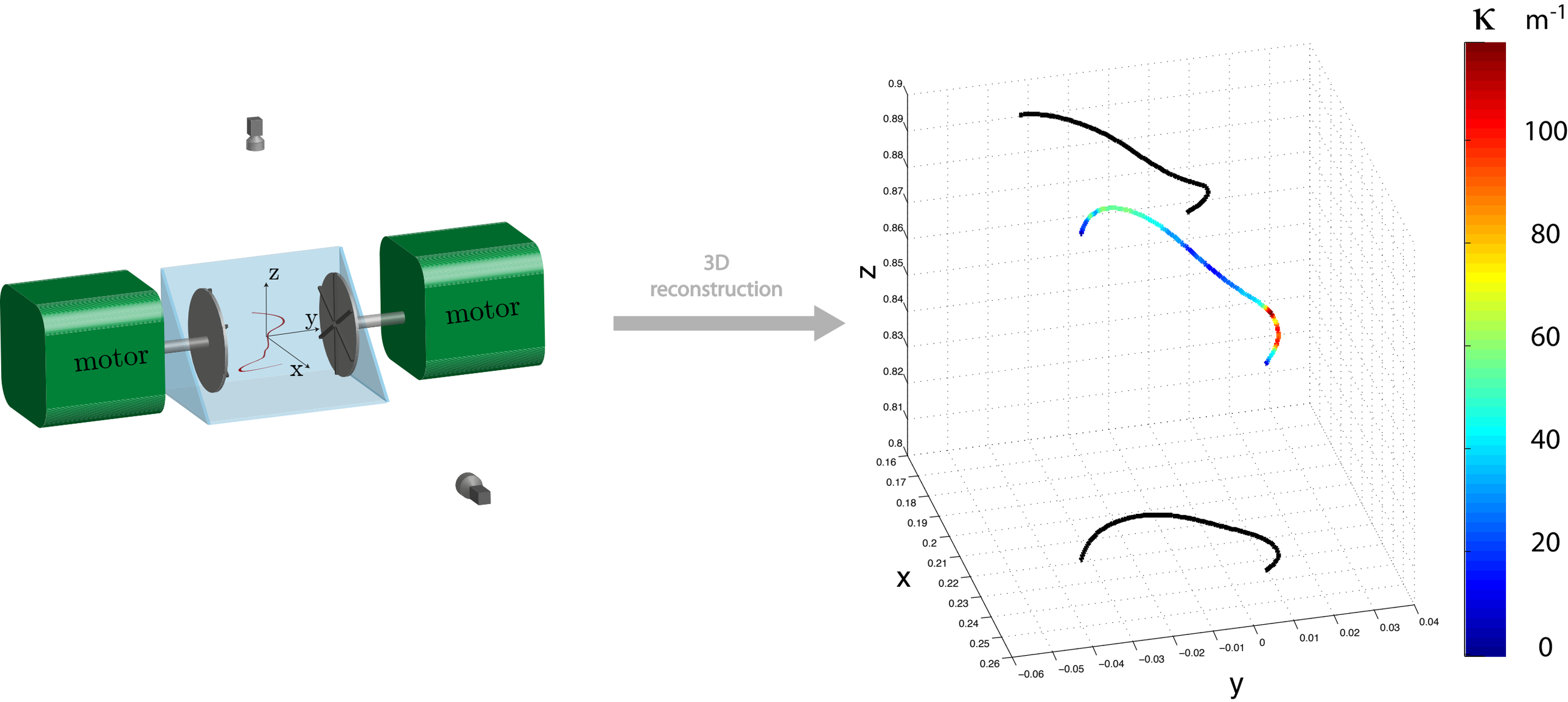
# Modélisation de la longueur de persistence




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

# Reconstruction 3D

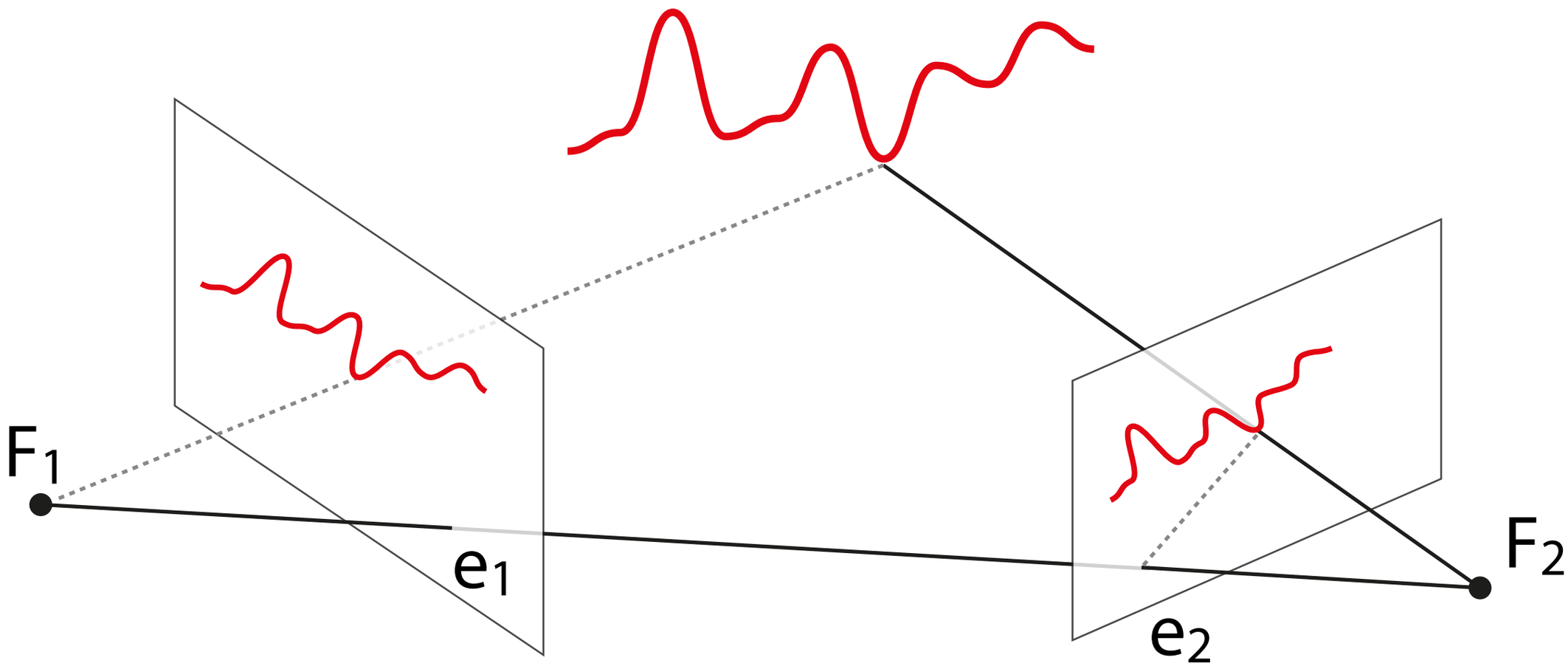



Collaboration avec A. Bartoli

# Reconstruction 3D : principe

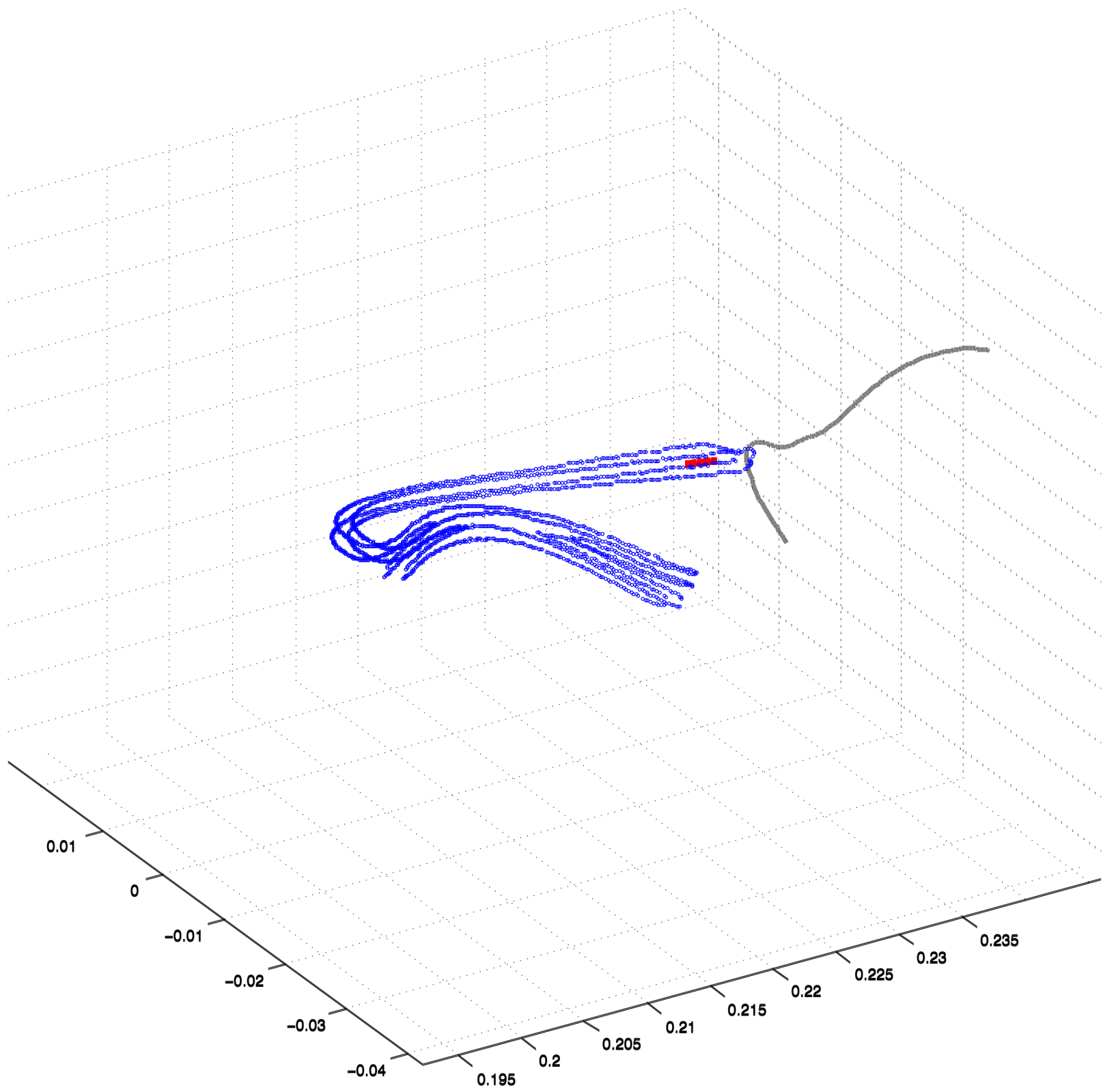
- Calibration des caméras : paramètres de pose et paramètre interne (modélisation pinhole)
- Correction des aberrations géométriques des images + détection des contours
- Triangulation

# Reconstruction 3D : triangulation

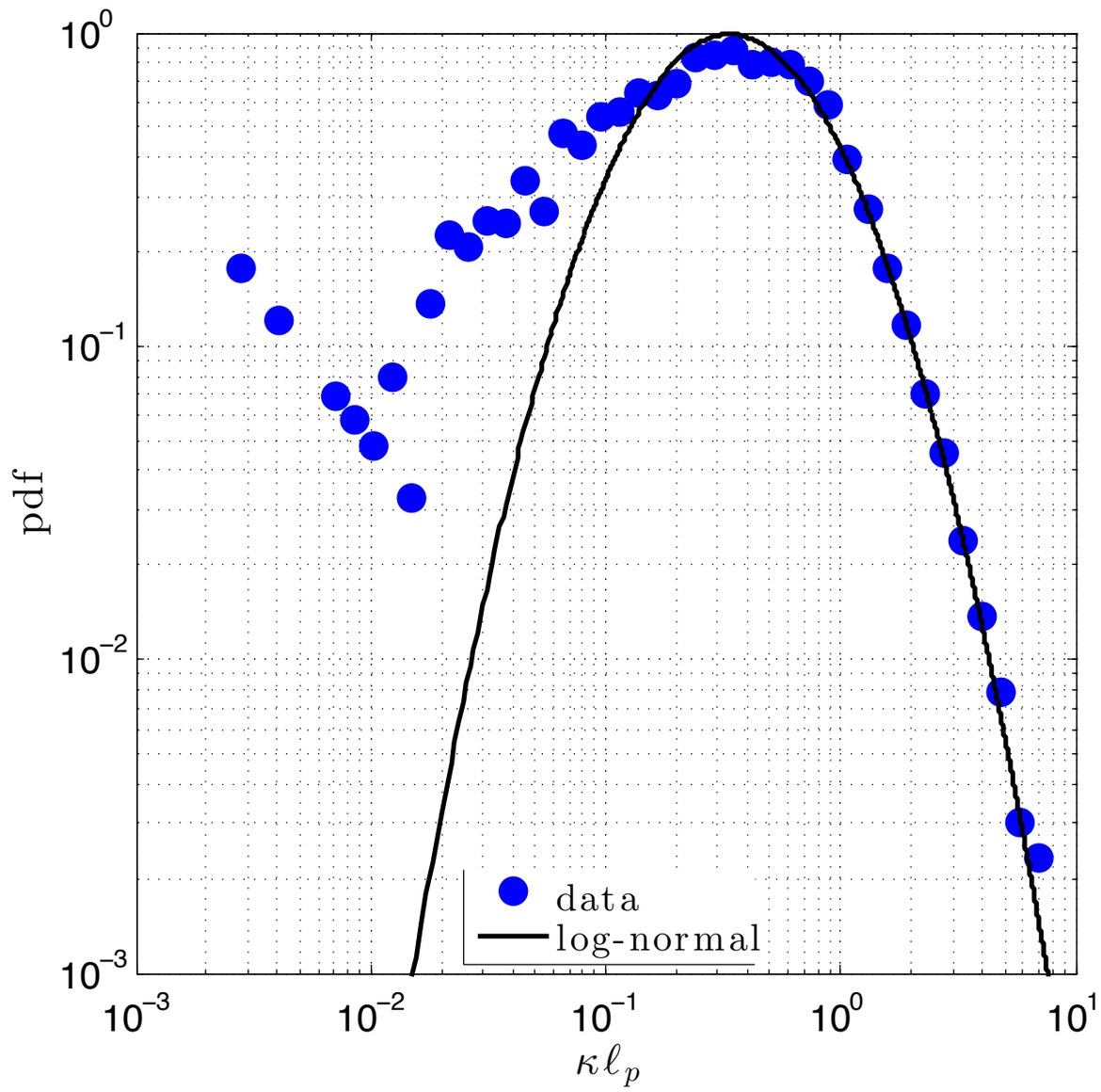


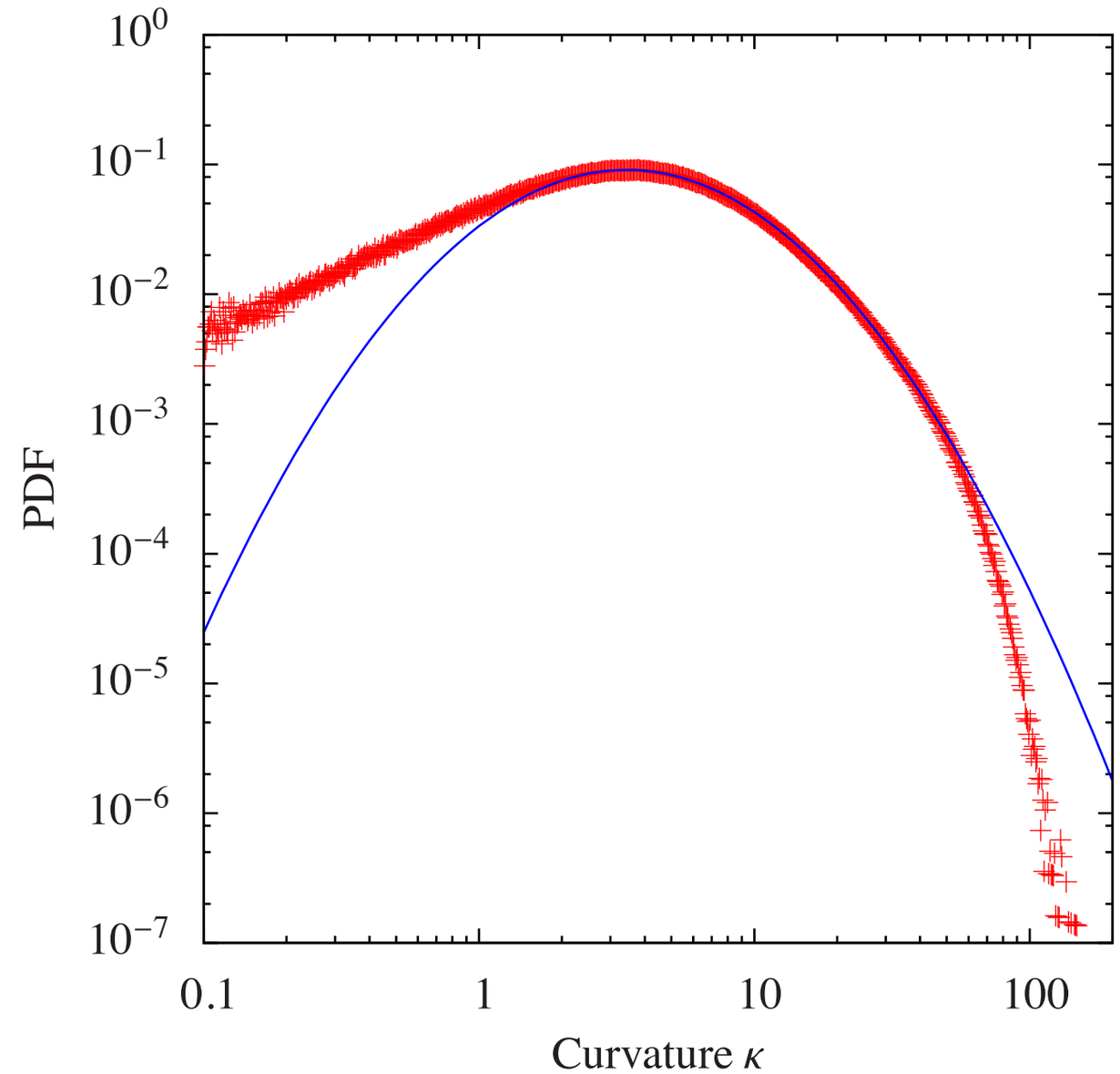

Intersection entre la droite épipolaire et le contour de la fibre

# Reconstruction 3D : identification de la fibre



# Exemple de mesure : distribution de la courbure




Collaboration avec B. Favier

# Conclusion/perspectives

- Mise en évidence d'une transition rigide/flexible
- Reconstruction 3D des fibres

- Interprétation des statistiques mesurées
- Dynamique de relaxation des contraintes
- Influence sur le transport de particules