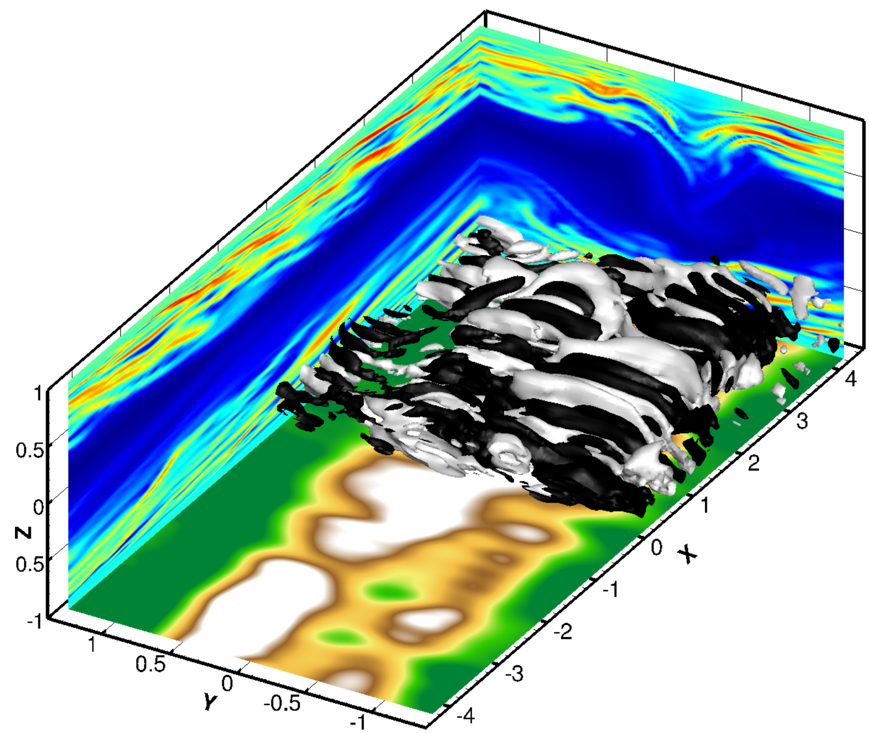
Role of Elasto-Inertial Turbulence on channel flow drag

S. Sid[1], Y. Dubief[2] & **V.E. Terrapon**[1]

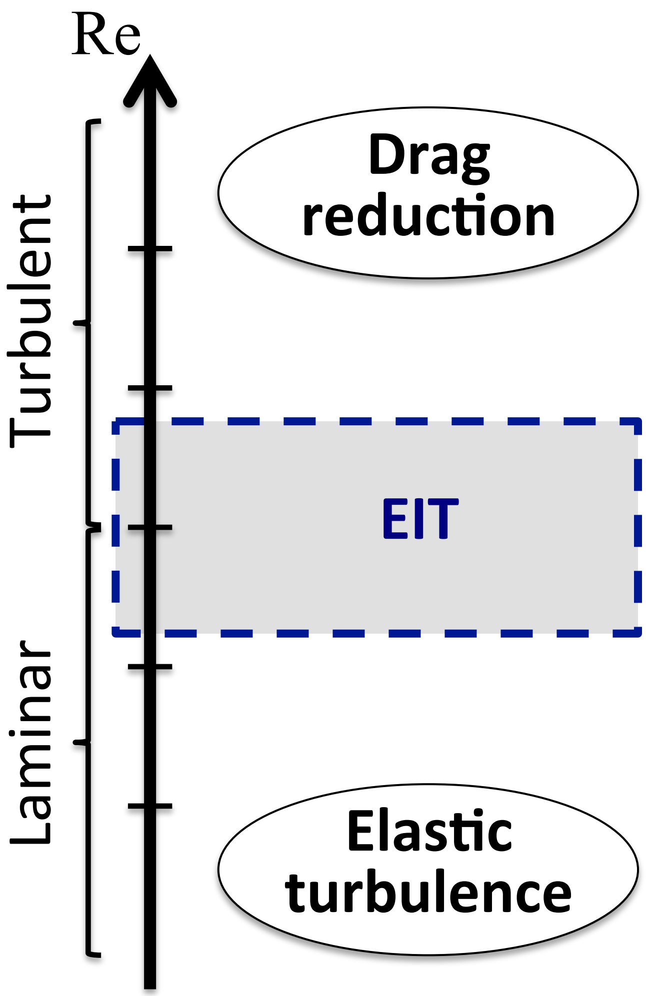
[1] University of Liege (Belgium)

[2] University of Vermont



16th European Turbulence Conference 2017

Polymers and turbulence



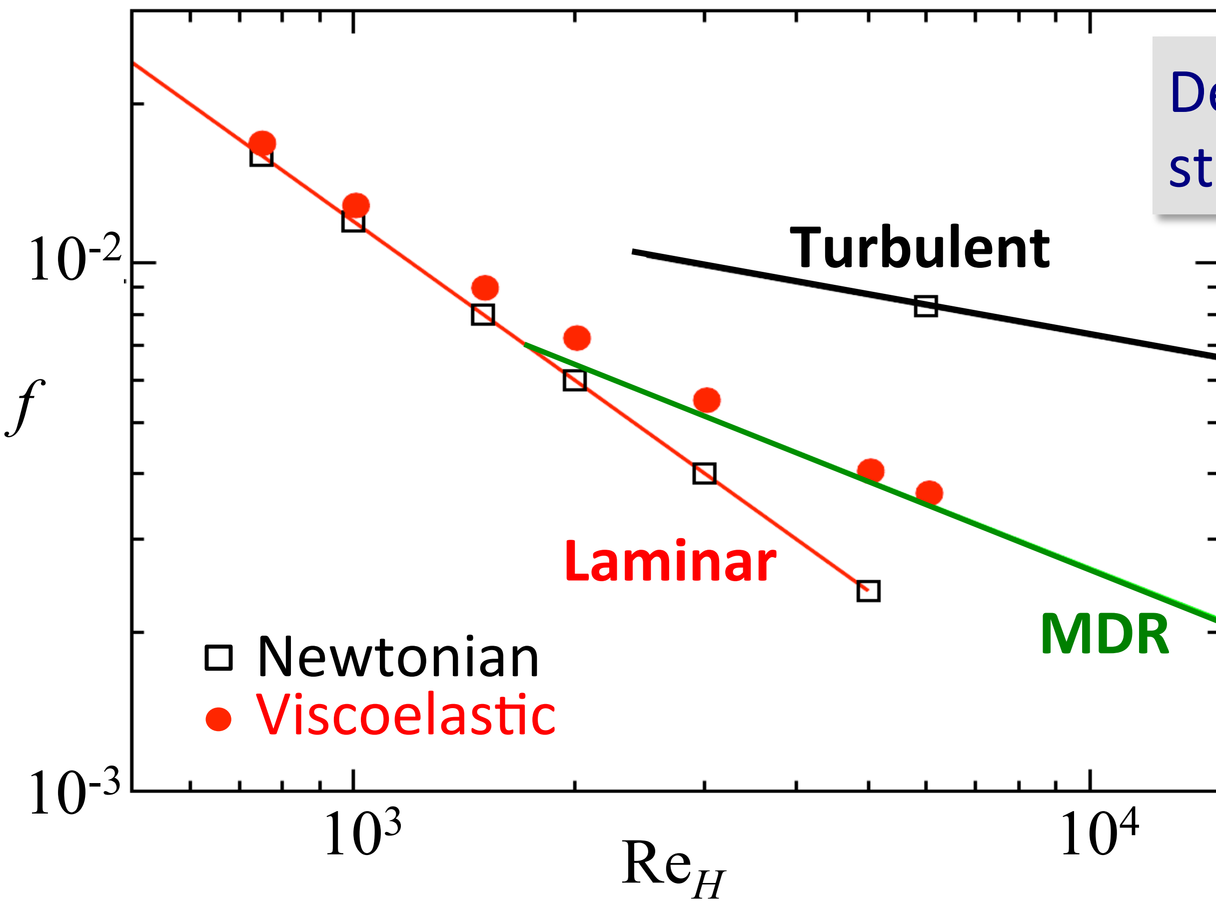
Elasto-Inertial Turbulence

- Non-laminar chaotic state
- **Elastic** and **inertial** instabilities

- **2D**
- **Small-scale critical**

Friction factor – Simulations

Channel flow (FENE-P)

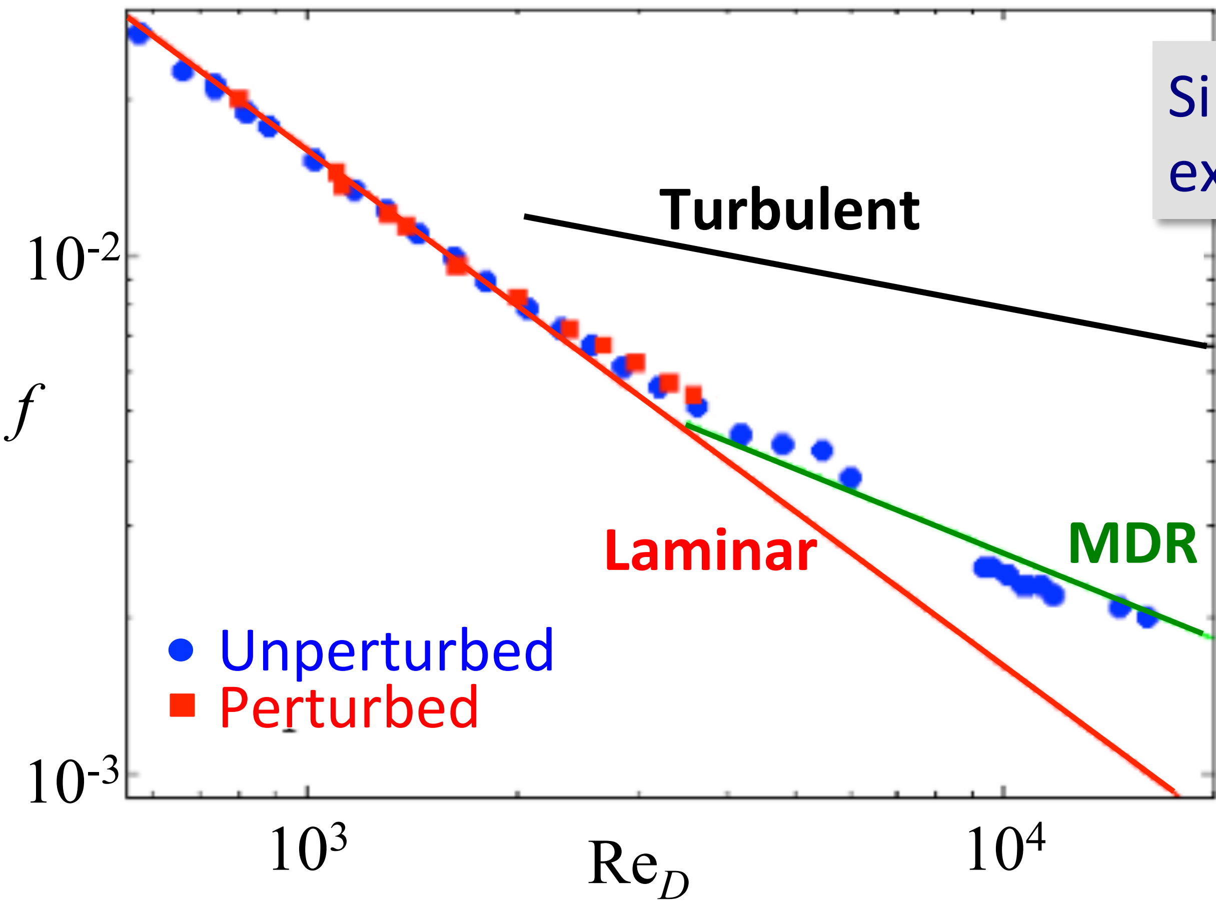


Departure from laminar state at subcritical Re

Dubief *et al.* (Phys. Fluids, 2013)
Terrapon *et al.* (J. Turbul., 2014)

Friction factor – Experiments

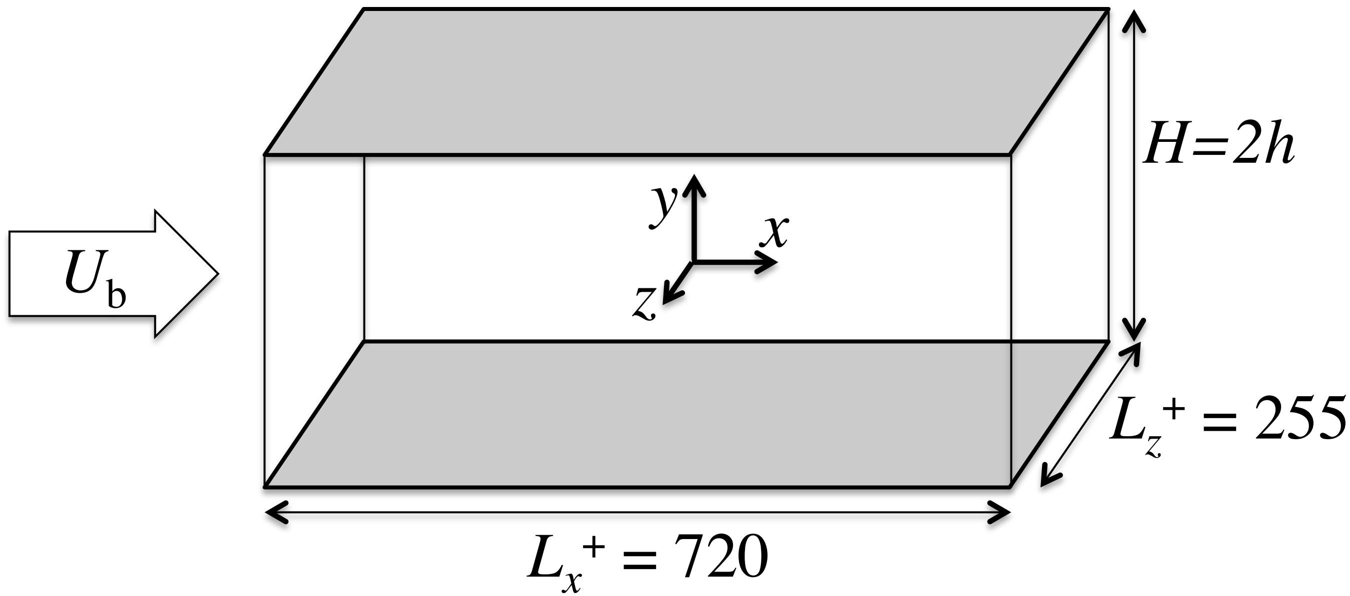
Pipe flow with 500 ppm PAAm solution



Simulations and experiments agree

Samanta *et al.* (PNAS, 2013)

Numerical methodology



- DNS with **FENE-P** model
- Periodic **channel** flow (const. pressure gradient)
- **2D** (512×128) and 3D (256×128×128)
- Initial **perturbation** (blowing and suction at walls)
- 2 different **codes** with different numerics

FENE-P model

Continuity

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

Momentum

$$\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \nabla)\mathbf{u} = -\nabla p + \frac{\boxed{\beta}}{\boxed{\mathrm{Re}}}\nabla^2 \mathbf{u} + \boxed{\frac{1-\beta}{\mathrm{Re}}\nabla \cdot \mathbf{T}} + \frac{\mathrm{d}P}{\mathrm{d}x}\mathbf{e}_x$$

Polymer stress

$$\mathbf{T} = \frac{1}{\boxed{\mathrm{Wi}}}\left(\frac{\mathbf{C}}{1 - \mathrm{tr}C/\boxed{L^2}} - \mathbf{I}\right)$$

Conformation tensor

$$\frac{\partial \mathbf{C}}{\partial t} + (\mathbf{u} \cdot \nabla)\mathbf{C} = \nabla \mathbf{u} \cdot \mathbf{C} + \mathbf{C} \cdot \nabla \mathbf{u}^{\mathrm{T}} - \mathbf{T}$$

Ratio of solvent viscosity to zero-shear viscosity	$\beta = 0.97$
Maximum polymer extension	$L = 70.9$
Reynolds number	$\mathrm{Re}^+ = 85$
Weissenberg number	$\mathrm{Wi}^+ = 40, 100$

Similar results at lower Re^+

Xi & Graham (JFM, 2010)

Advection and small scales

$$\underbrace{\frac{\partial \mathbf{C}}{\partial t} + (\mathbf{u}\cdot\nabla)\mathbf{C}}_{\text{Advection}} = \underbrace{\nabla\mathbf{u}\cdot\mathbf{C} + \mathbf{C}\cdot\nabla\mathbf{u}^{\mathrm{T}} - \mathbf{T}}_{\text{Nonlinear source term}} \quad \underbrace{\left[+\frac{1}{\mathrm{Re\,Sc}}\nabla^2\mathbf{C}\right]}_{\text{GAD}}$$

- No diffusion
- Hyperbolic
- Sub-Kolmogorov scales
- Need stabilization

A **Global artificial diffusion (GAD)**

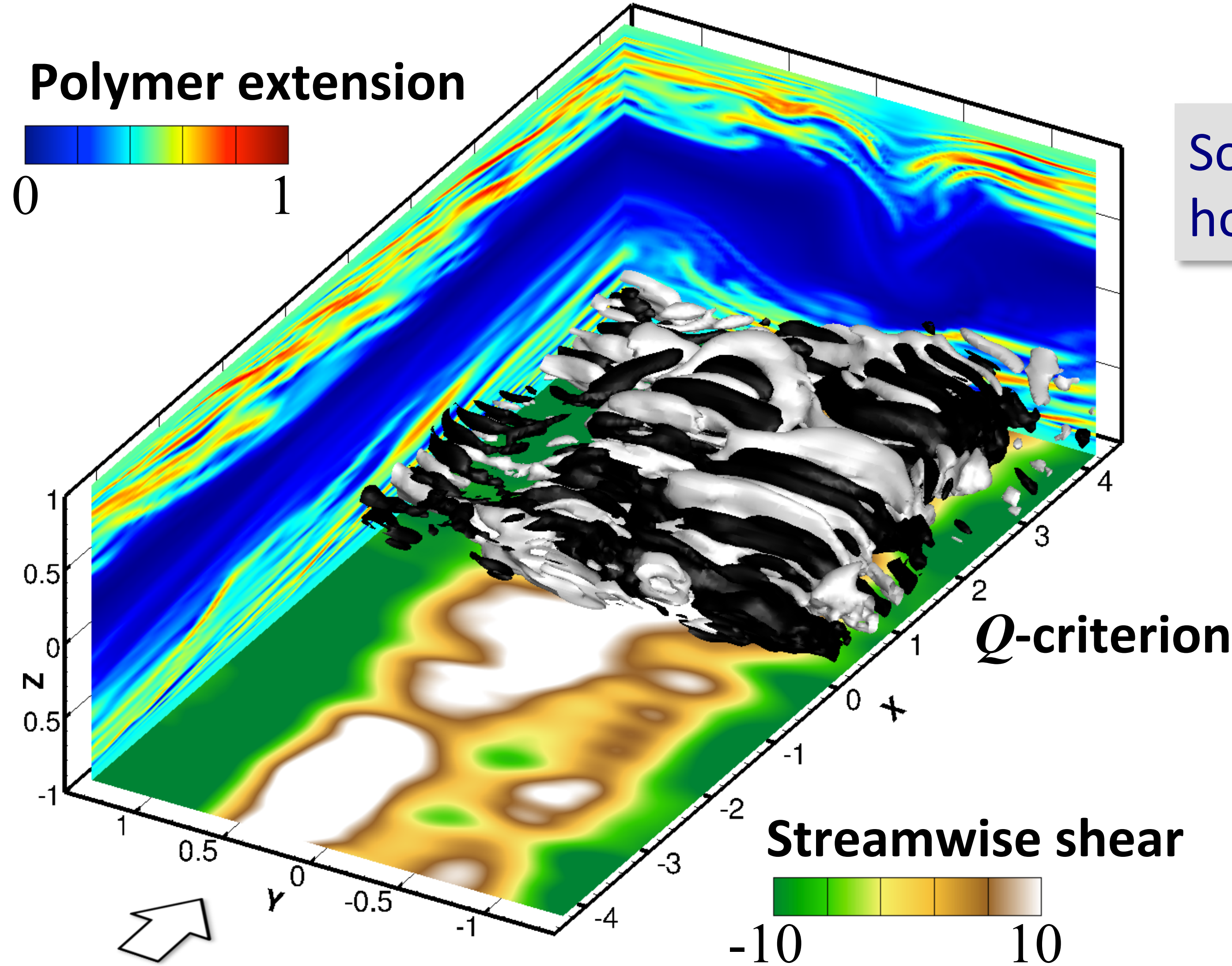
- Used by many with $\mathrm{Sc}_{\mathrm{num}} \sim 1$
- But $\mathrm{Sc}_{\mathrm{polymer}} \sim 10^6$

B **Local artificial diffusion (LAD)**

- Only locally applied
- Never needed at low Re

3D simulation at supercritical Re

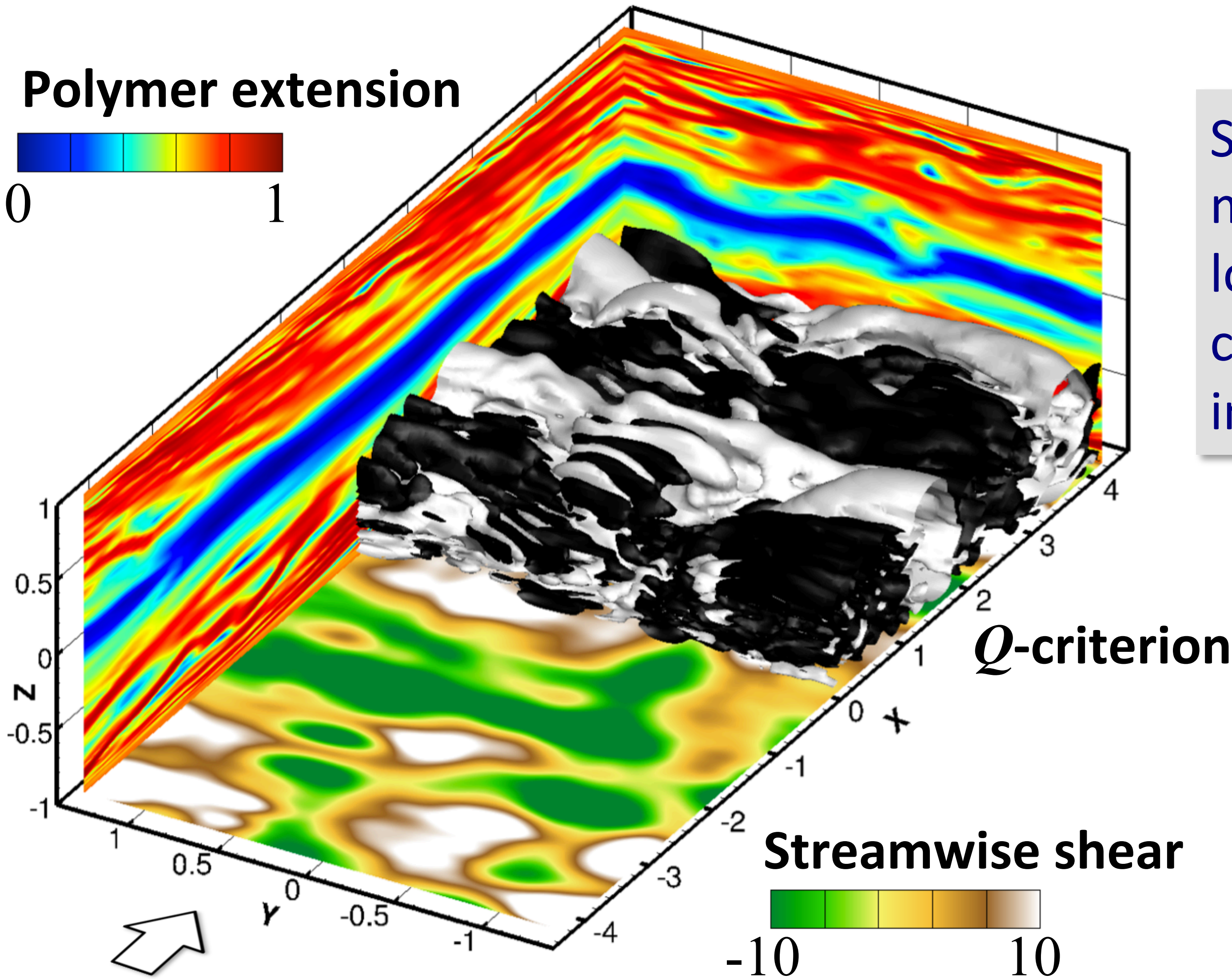
$Wi^{+} = 40$



Some spanwise homogeneity

3D simulation at supercritical Re

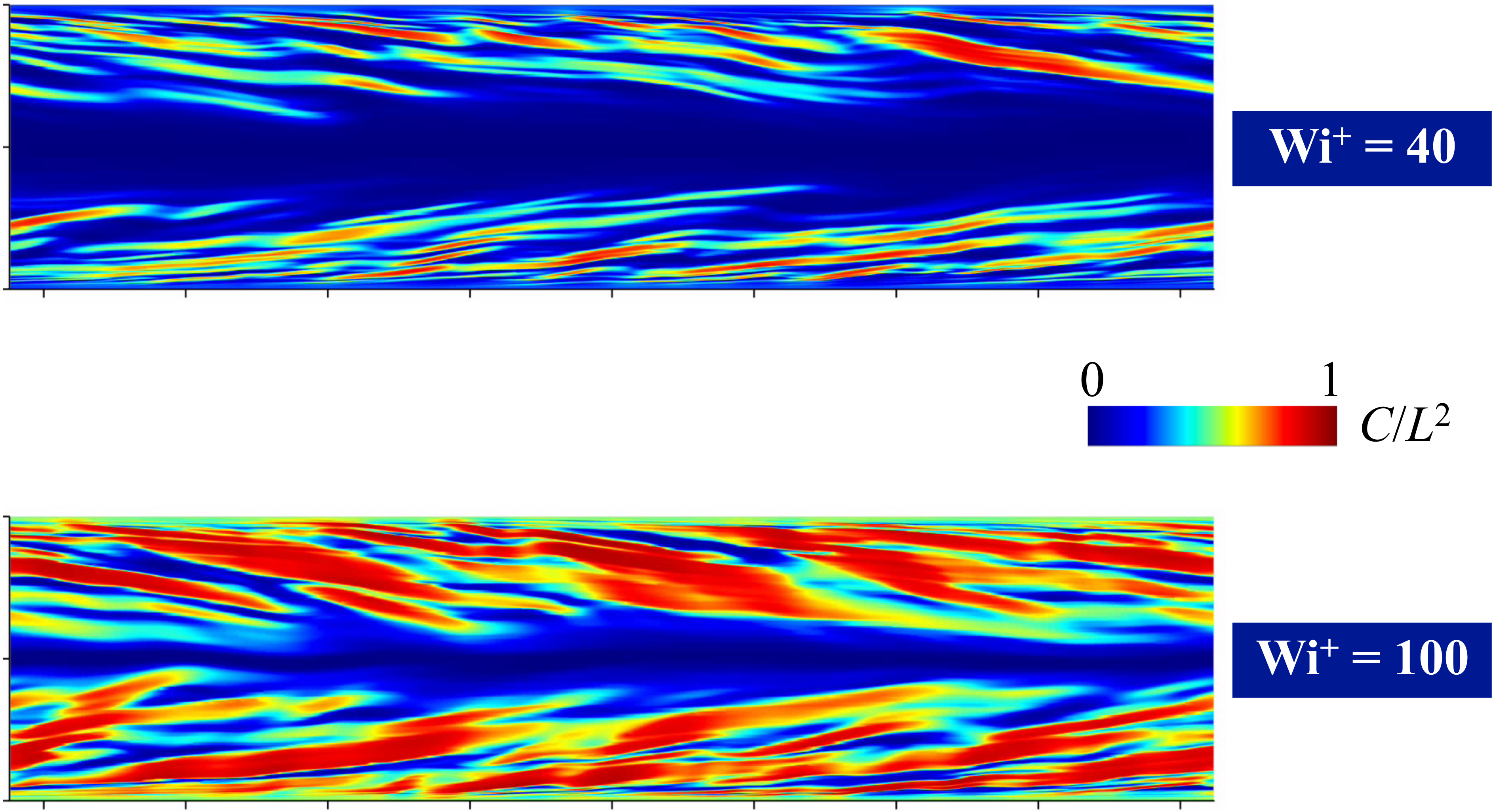
$Wi^+ = 100$



Structures are more 2D due to lower relative contribution of inertia

2D simulation at subcritical Re

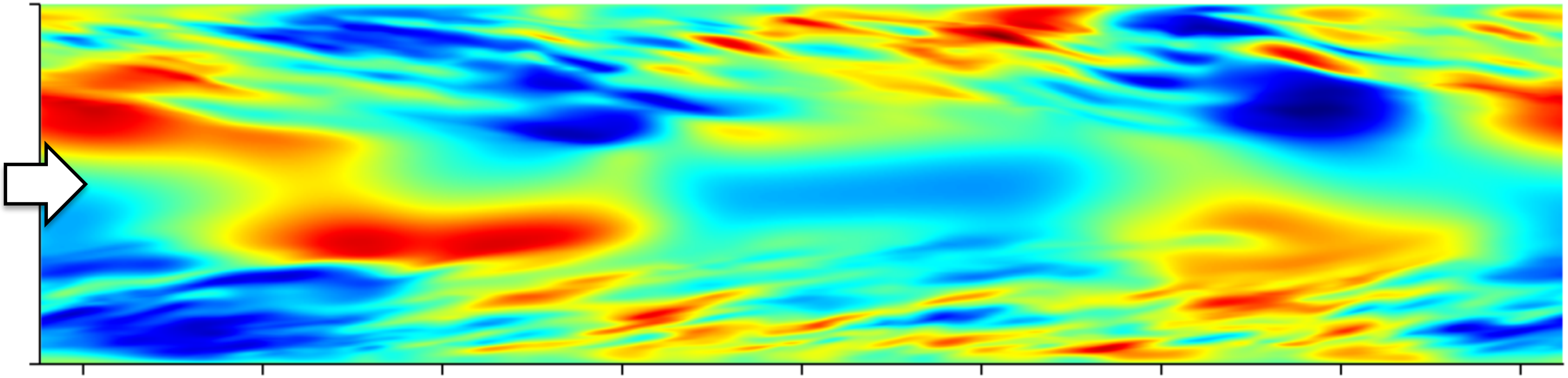
Polymer extension

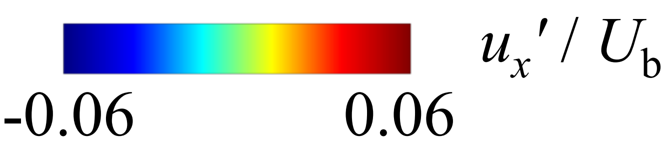


2D simulation at subcritical Re

$Wi^+ = 40$

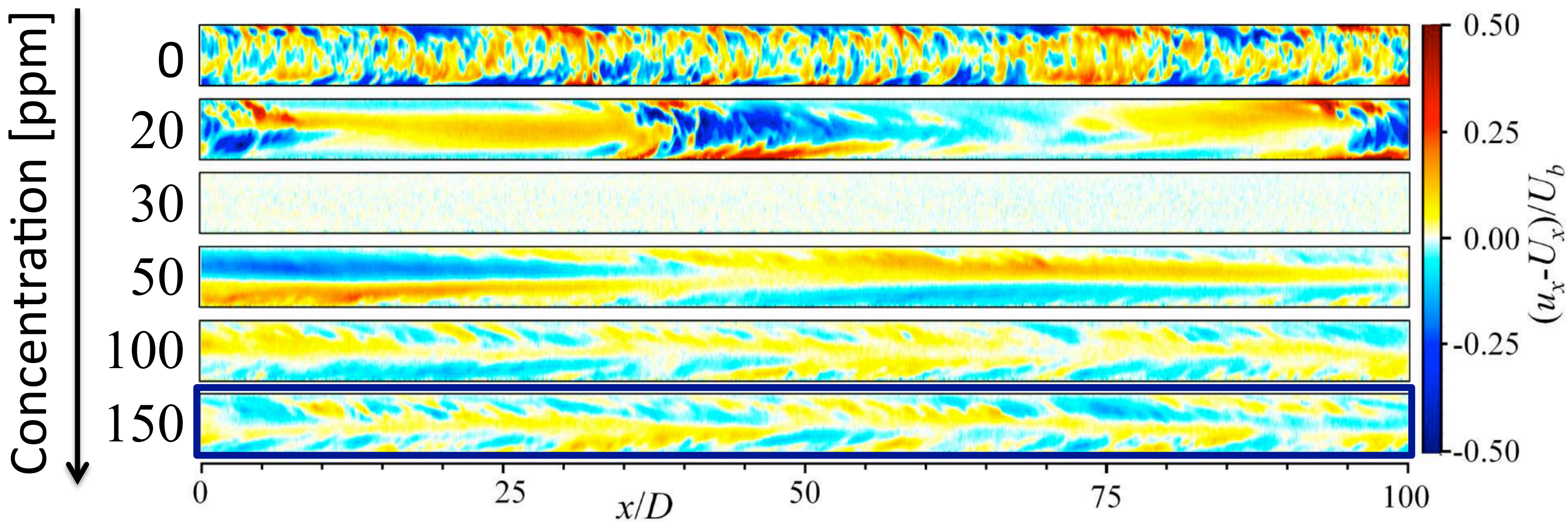
Streamwise velocity fluctuations





PIV measurements in viscoelastic pipe flow

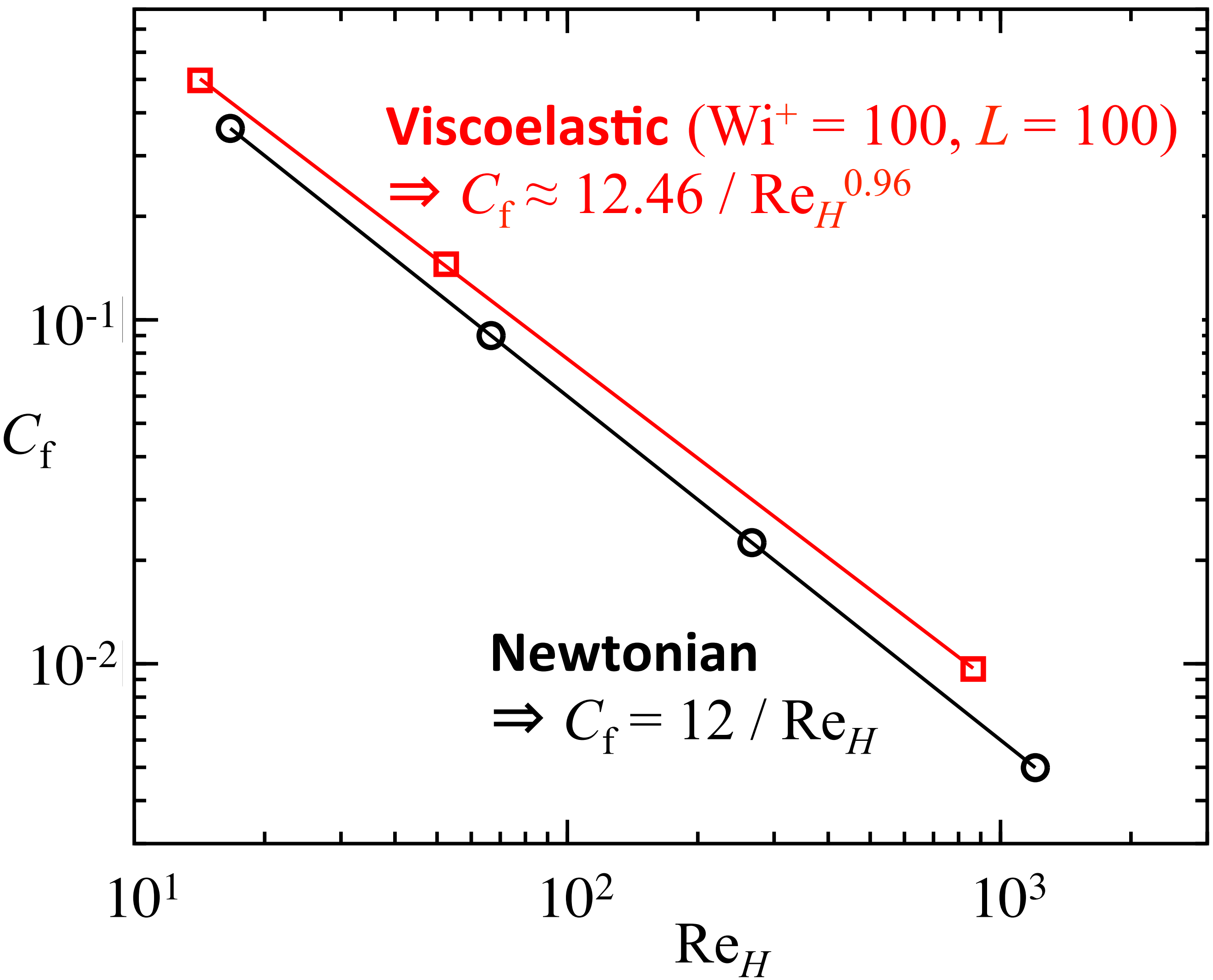
Streamwise velocity fluctuations at $\mathrm{Re}_D = 3150$



Choueiri *et al.* (arXiv, 2017)

2D simulation at subcritical Re

Friction coefficient

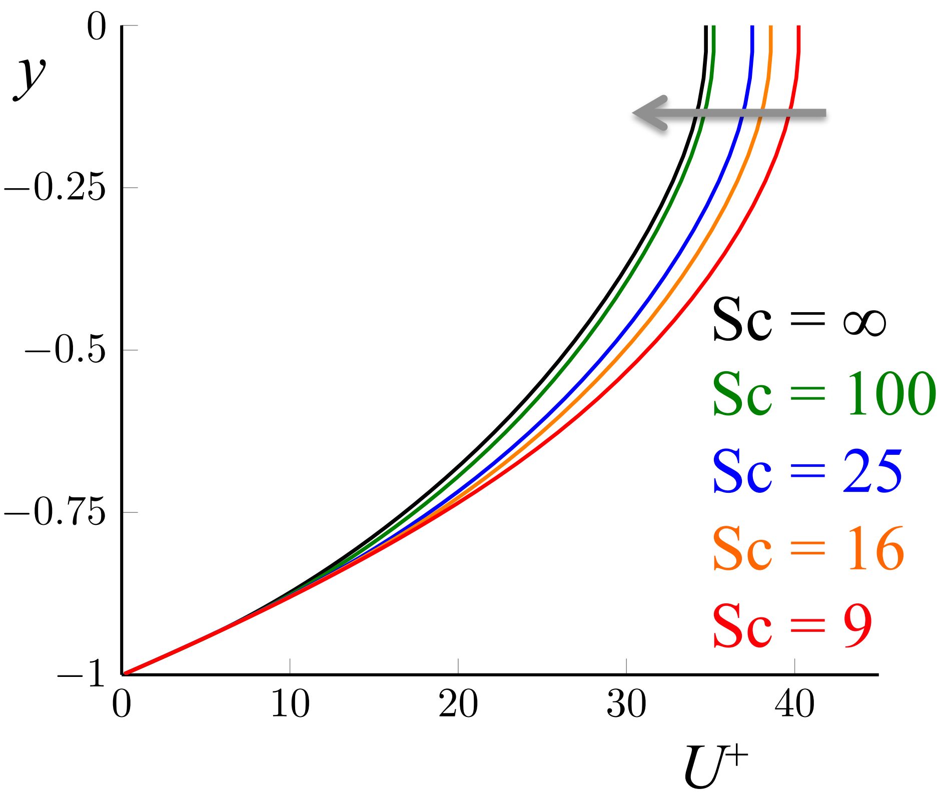


Departure from laminar flow similar to 3D

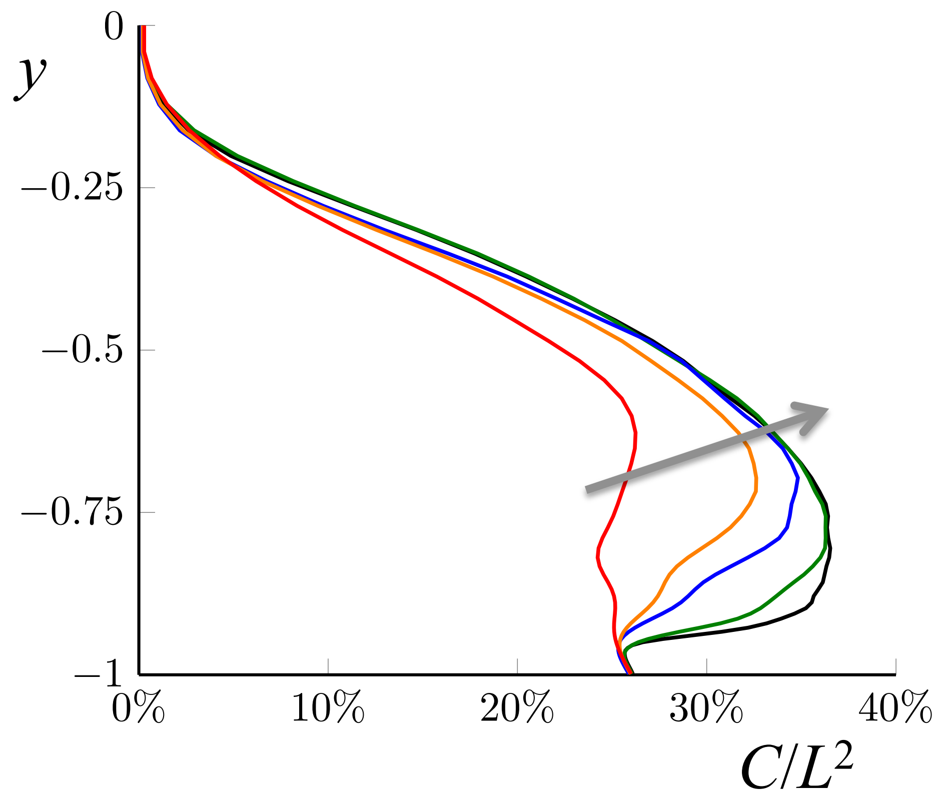
Schmidt number effect

2D, $Wi^+ = 40$

Mean velocity

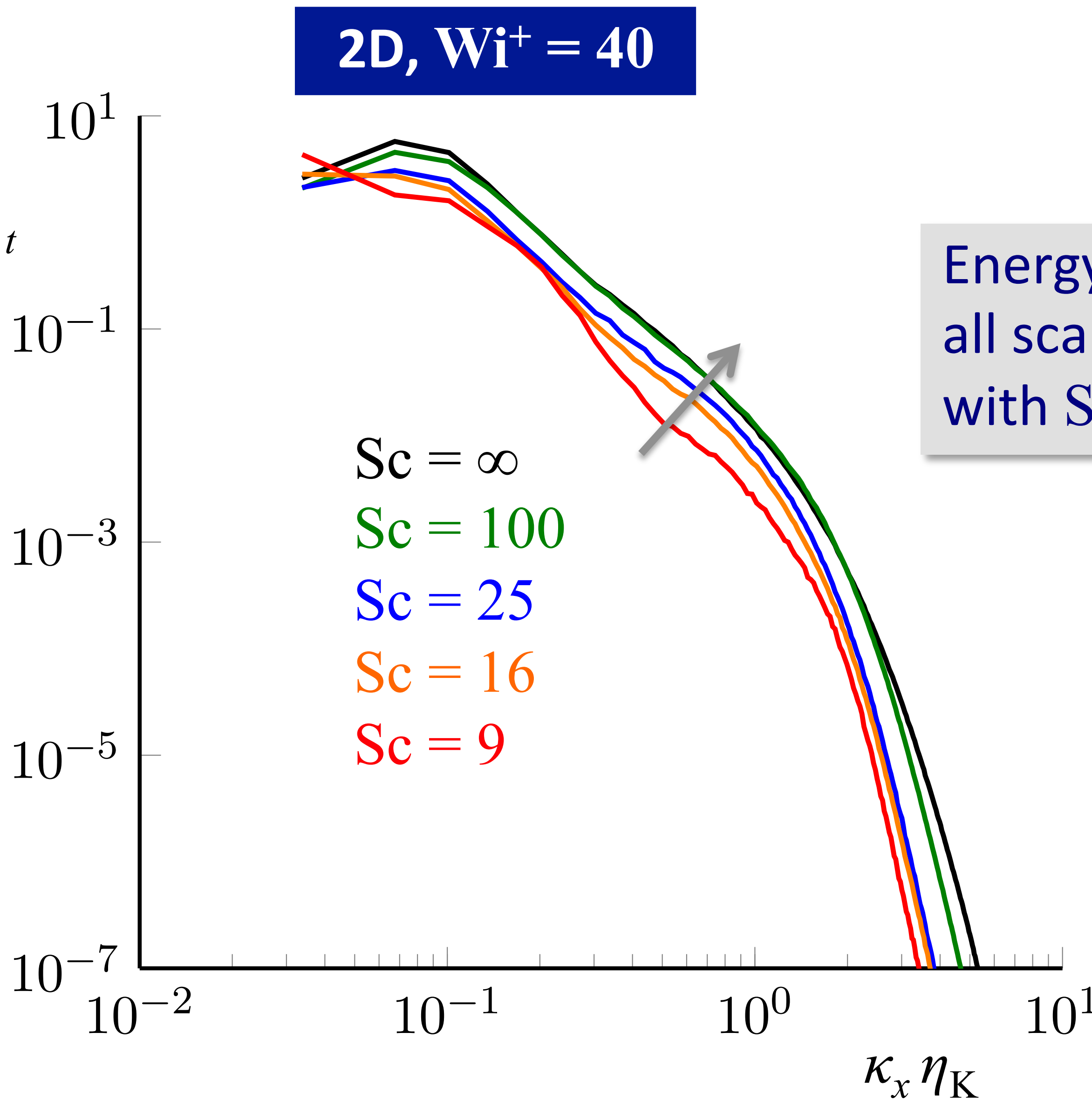


Mean polymer extension



- Sc ~< 9 lead to laminarization!
- Drag and polymer extension increase with Sc

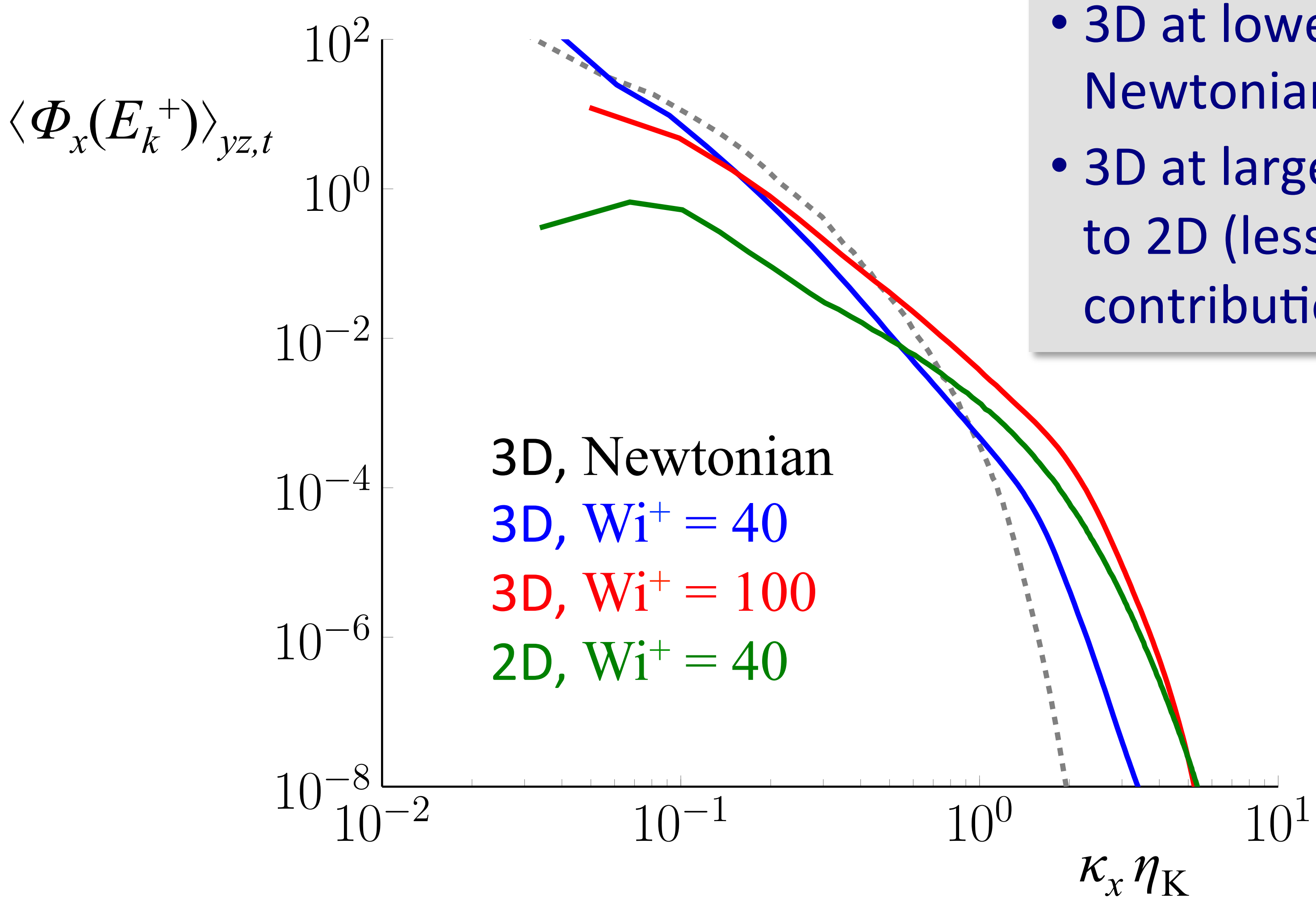
Integrated streamwise spectrum of kinetic energy



Energy content at all scales increases with Sc

Integrated streamwise spectrum of kinetic energy

$Re^+ = 85$, $Sc = \infty$



- 3D at lower Wi shows Newtonian features
- 3D at larger Wi similar to 2D (less inertial contribution)

Conclusions

- EIT is mostly 2D
- Small scales are critical
- Need to respect physics (high Schmidt number)

Open questions

- EIT = elastic turbulence?
- EIT = ultimate MDR state?
- Theory (predictions, shape of spectra, …)

Acknowledgement

The UNIVERSITY of VERMONT

LIÈGE université

fnrs FREEDOM TO RESEARCH

NSF

SEVENTH FRAMEWORK PROGRAMME

MARIE CURIE ACTIONS

PRACE

C.E.C.I

Questions

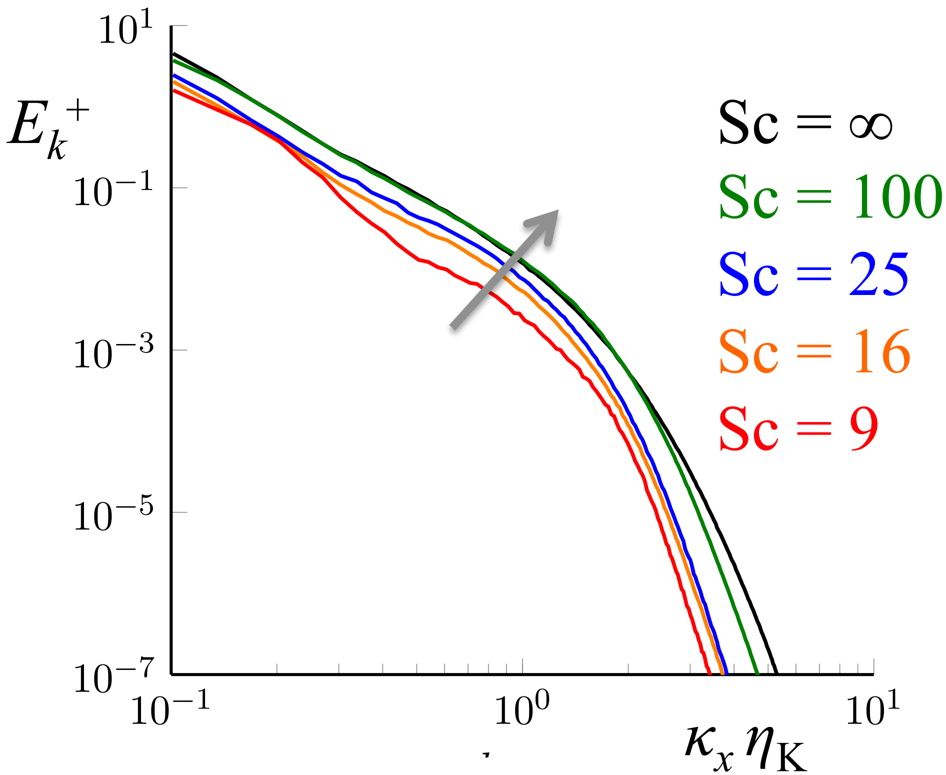
BACKUP

Schmidt number effect

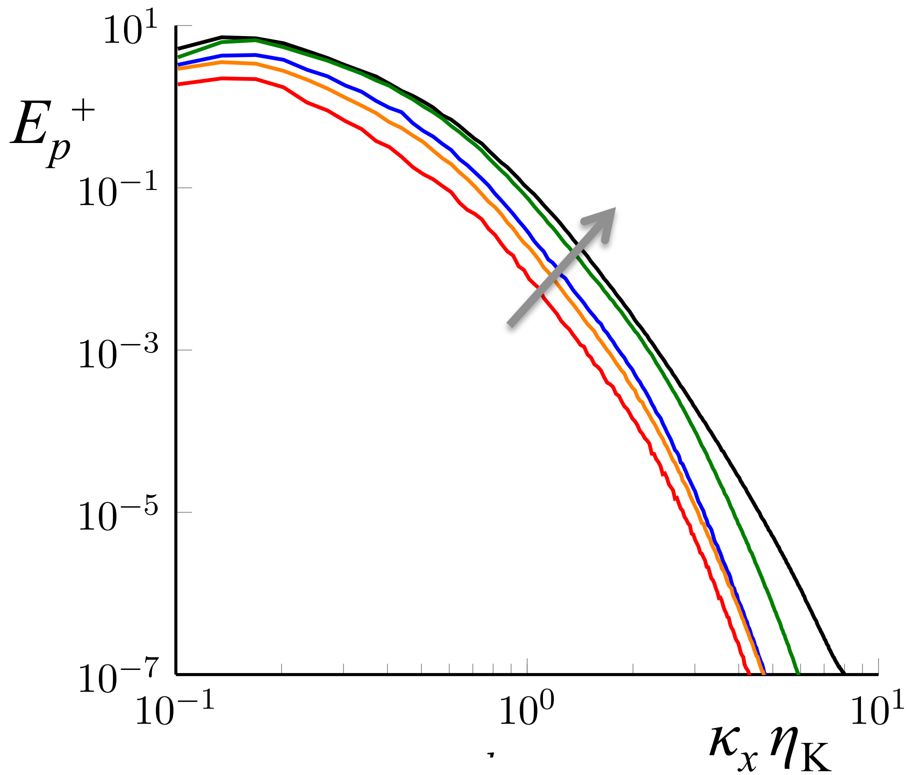
$Wi^+ = 40$

Time-averaged streamwise spectra

Kinetic energy



Elastic energy

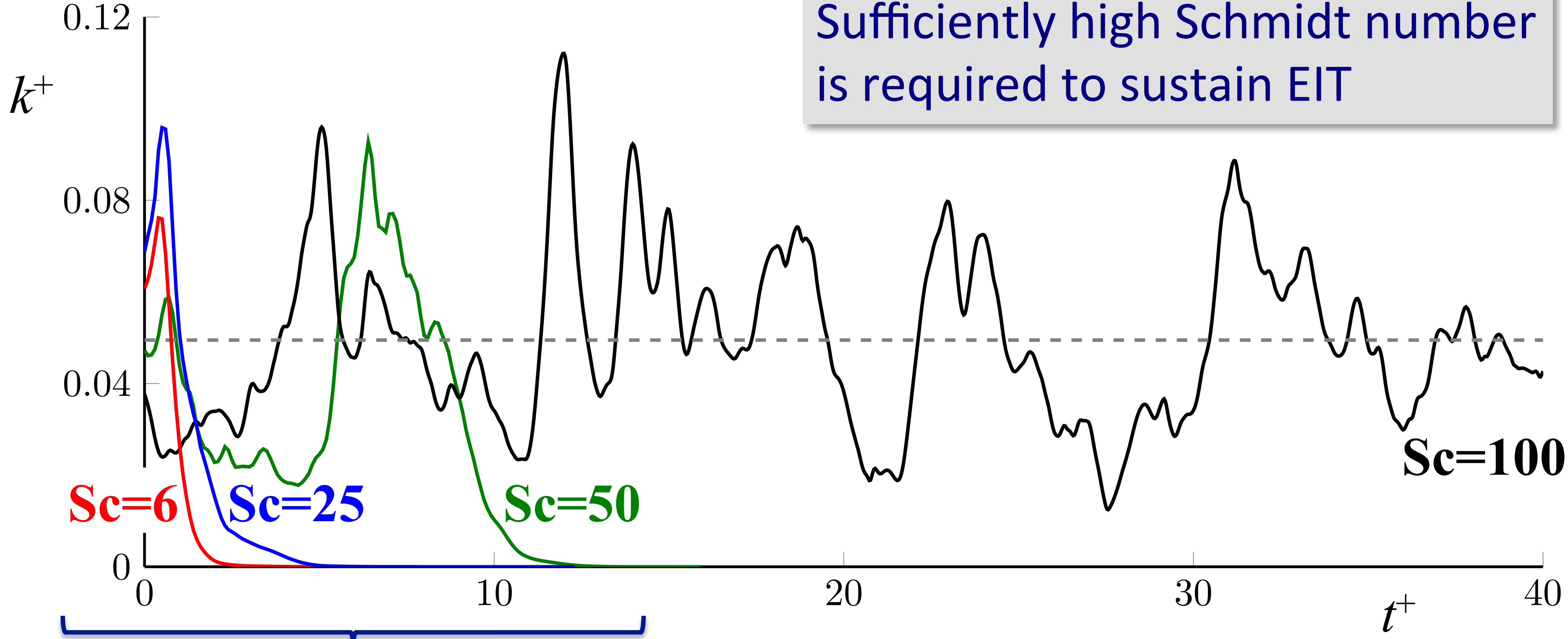


Small scales are critical!

Schmidt number effect

Turbulent kinetic energy

Sufficiently high Schmidt number is required to sustain EIT

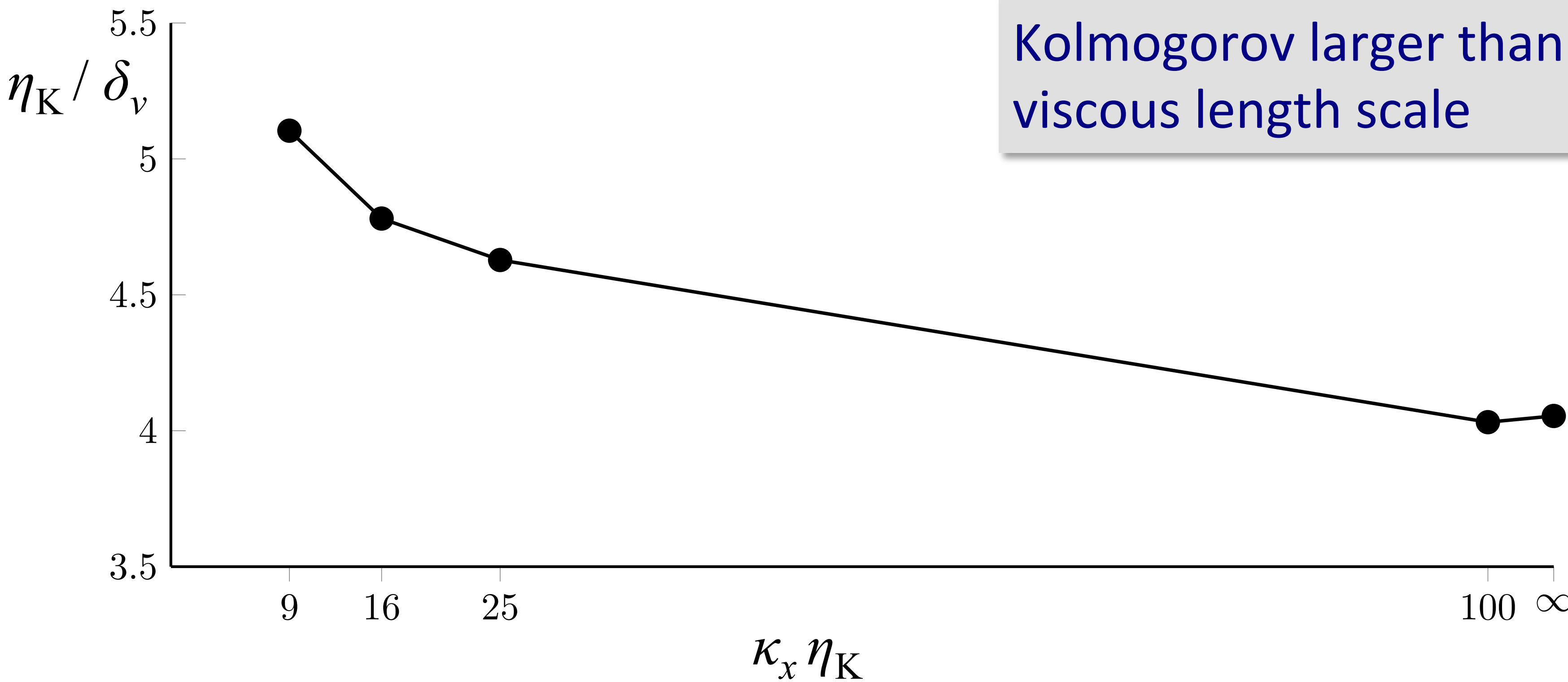


Laminarization

$\mathrm{Wi}^+ = 310$, $\mathrm{Re}^+ = 40$, $\beta = 0.97$, $L = 70.9$, GAD

Schmidt number effect

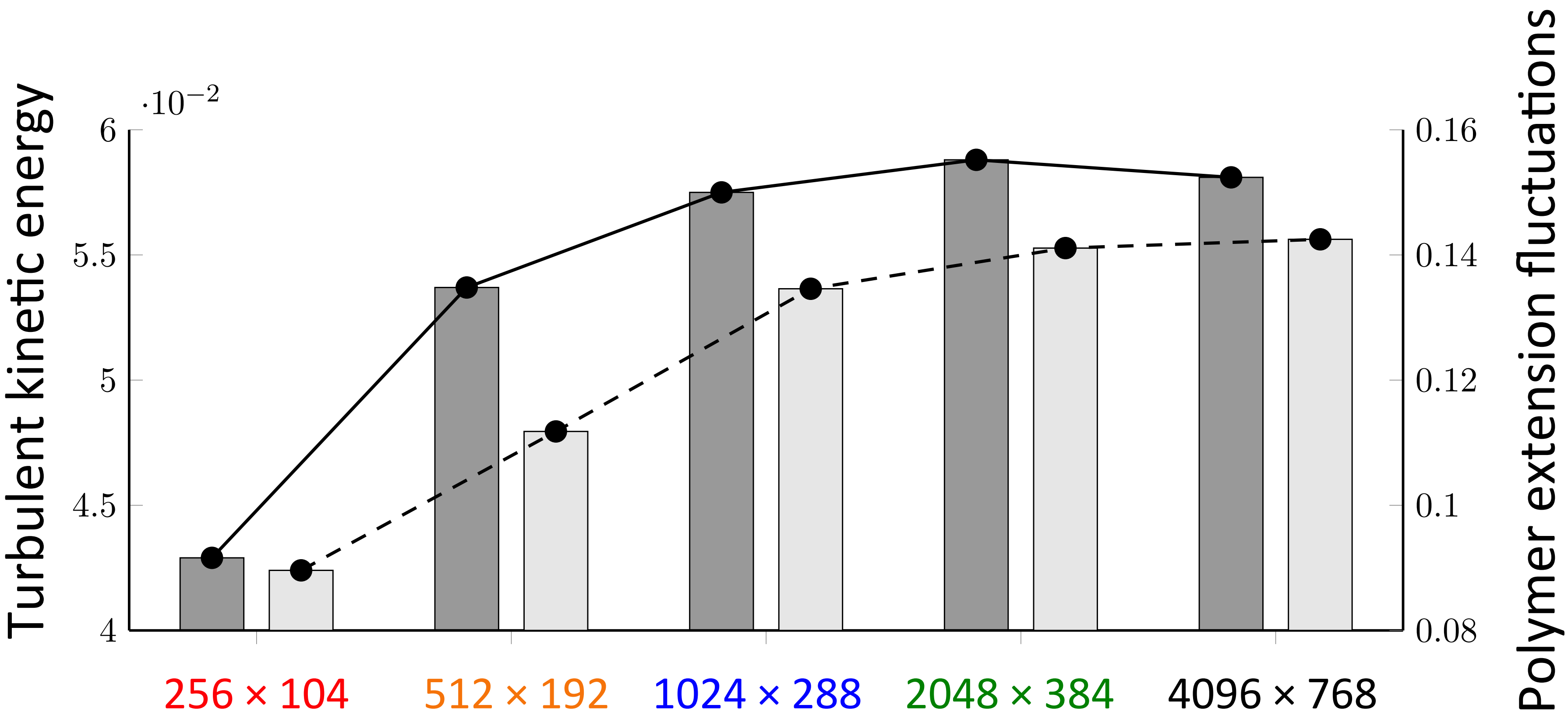
Ratio of Kolmogorov $(\nu^3/\varepsilon)^{1/4}$ to viscous length scale (ν/u_τ)



Kolmogorov larger than viscous length scale

$\mathrm{Wi}^+ = 40$, $\mathrm{Re}^+ = 85$, $\beta = 0.97$, $L = 70.9$, LAD

Sc=100 – Influence of the mesh



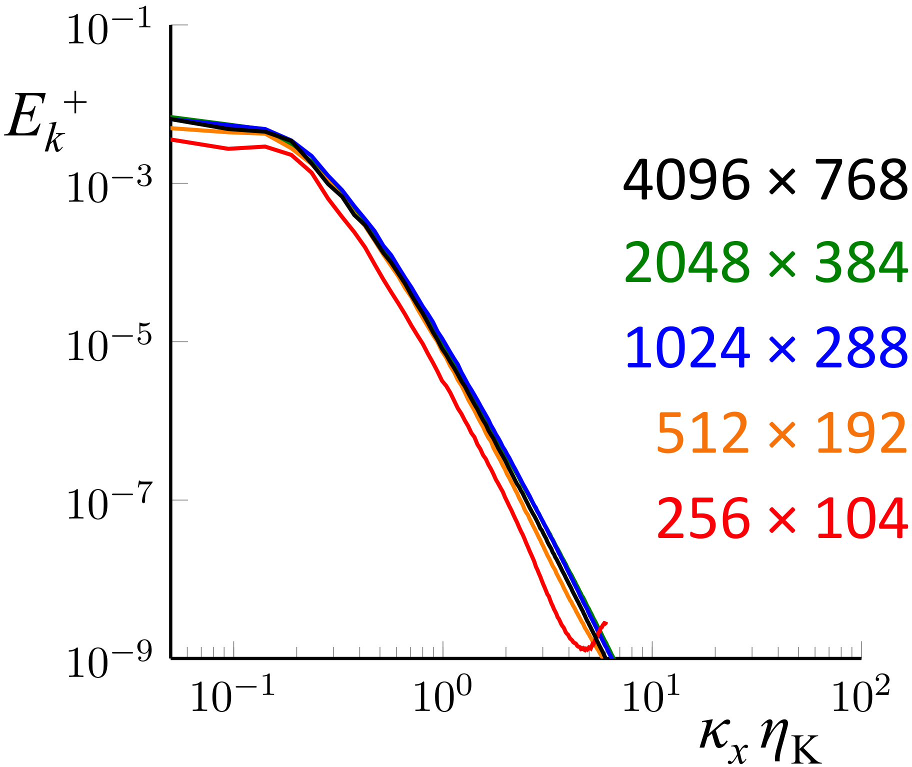
Batchelor scale $\eta_B = (Re^+)^{-1}\ Sc^{-1/2}$ **captured**

$Wi^+ = 310$, $Re^+ = 40$, $\beta = 0.97$, $L = 70.9$, GAD

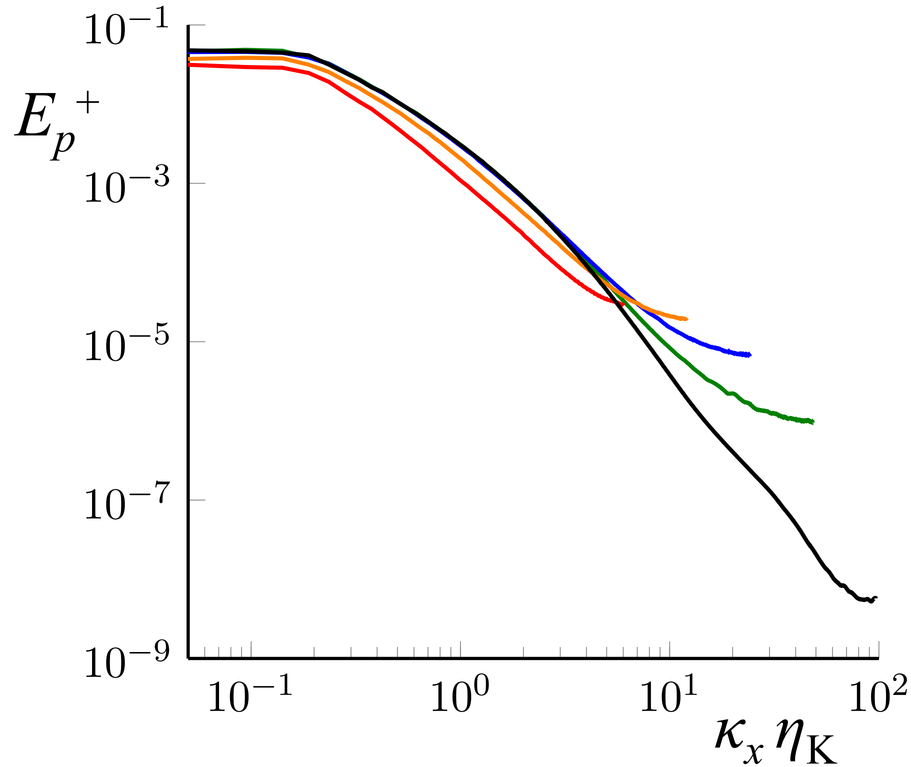
Sc=100 – Influence of the mesh

Time-averaged streamwise spectra

Kinetic energy



Elastic energy

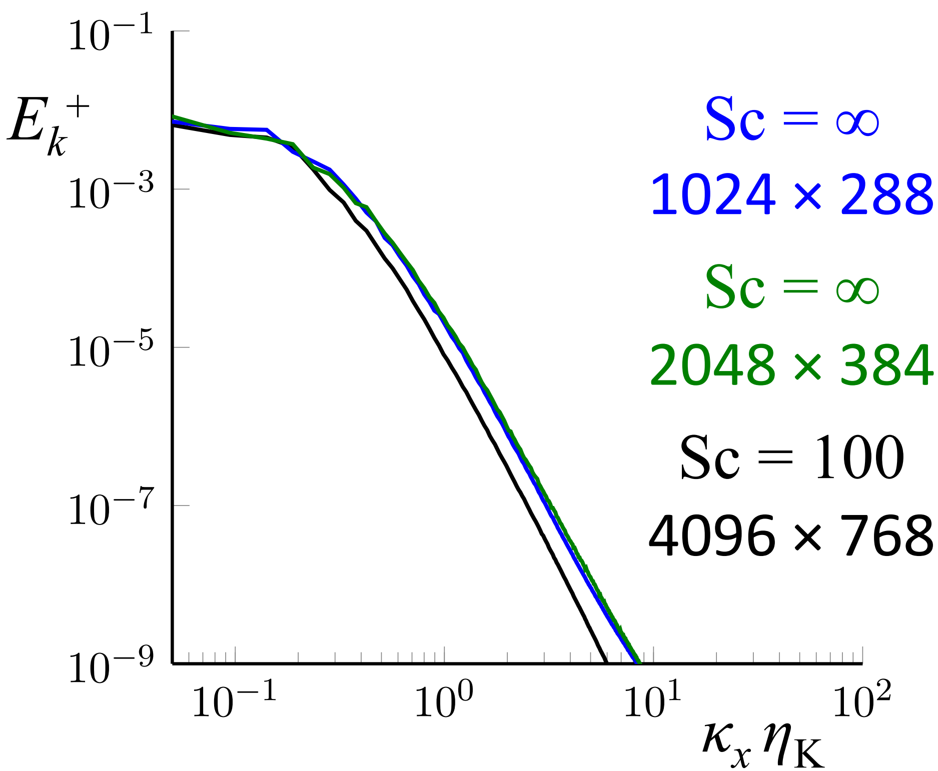


$\mathrm{Wi}^+ = 310$, $\mathrm{Re}^+ = 40$, $\beta = 0.97$, $L = 70.9$, GAD

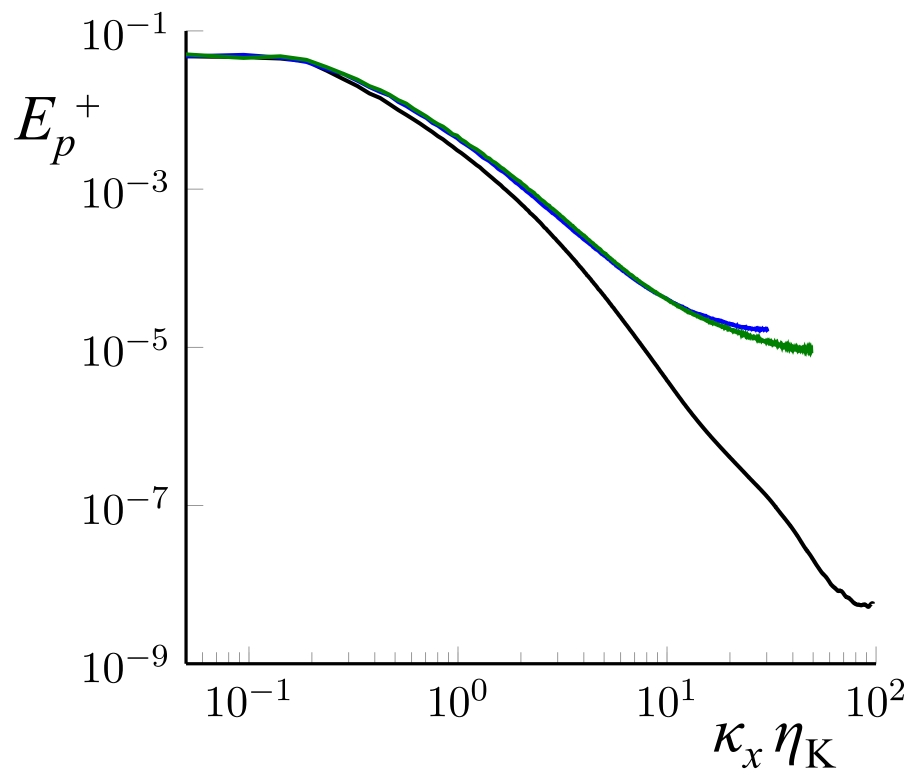
GAD vs. LAD

Time-averaged streamwise spectra

Kinetic energy



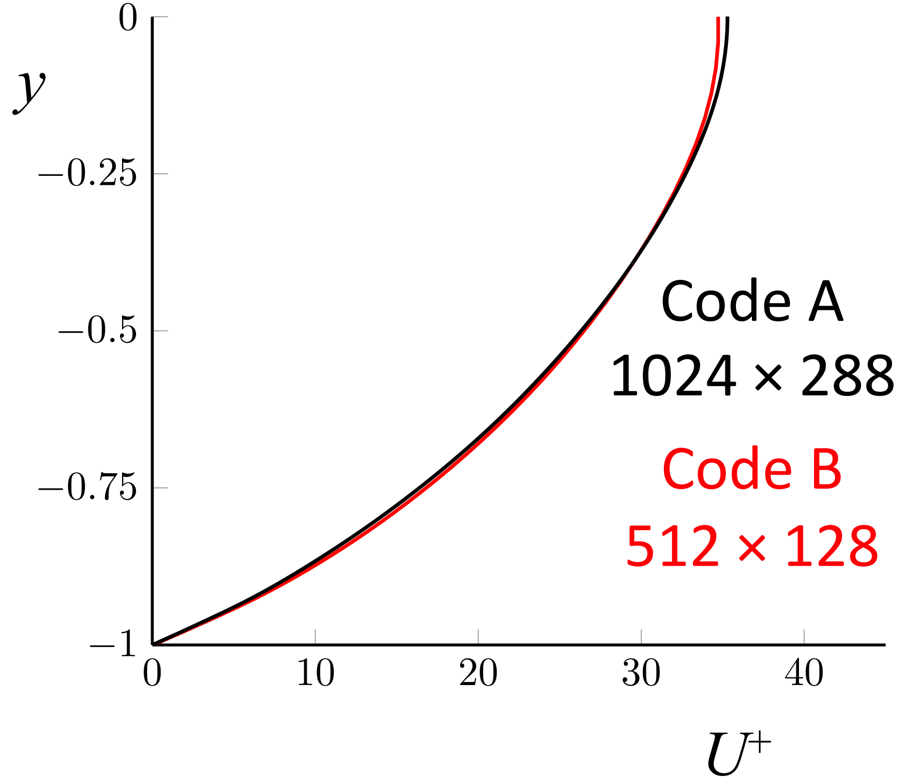
Elastic energy



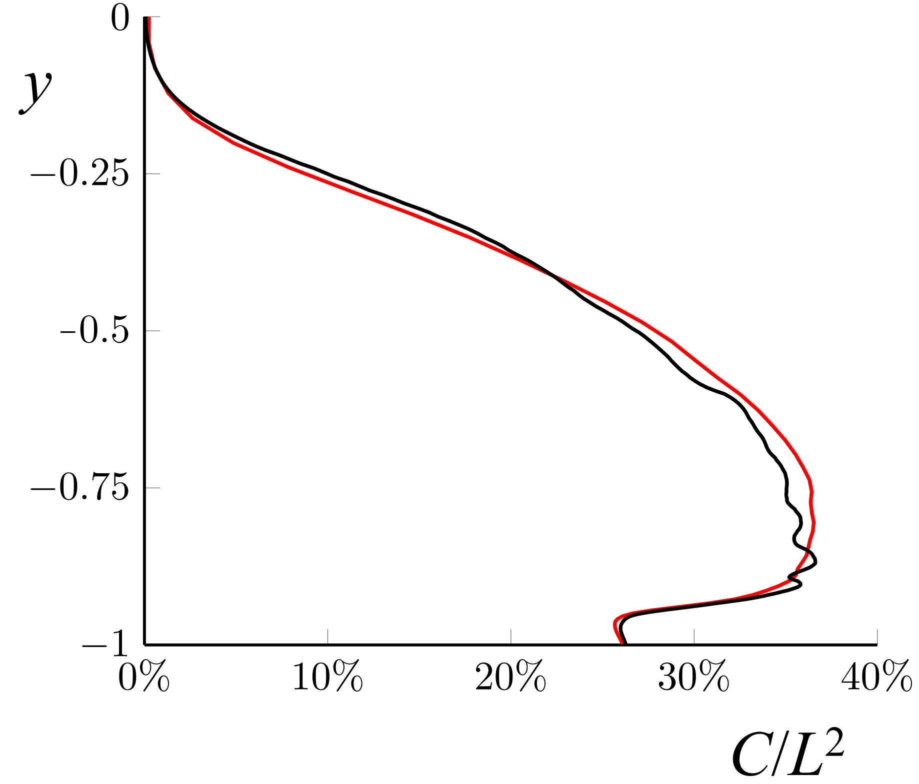
$\mathrm{Wi}^+ = 310$, $\mathrm{Re}^+ = 40$, $\beta = 0.97$, $L = 70.9$, GAD / LAD

Code comparison

Mean velocity

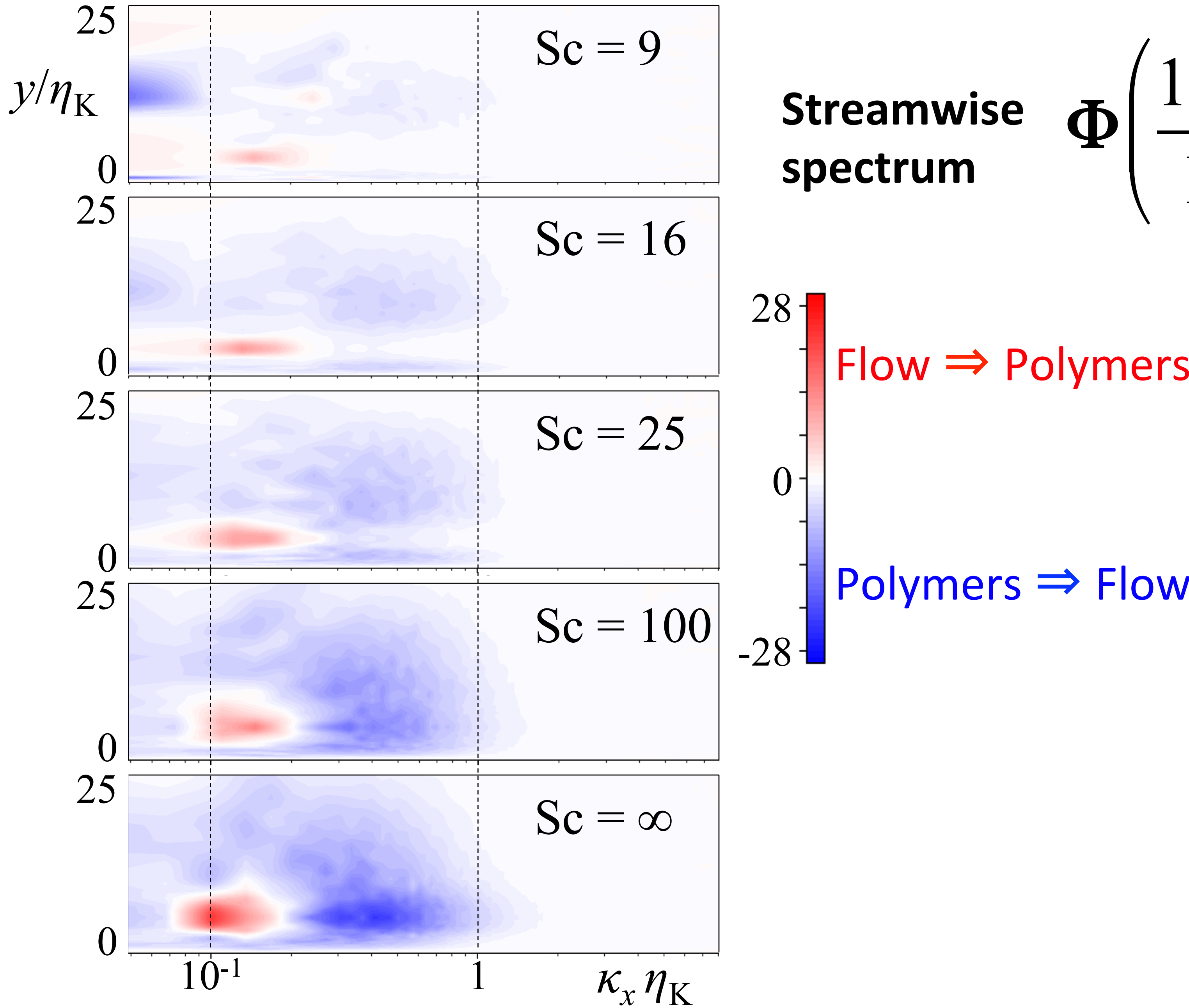


Mean polymer extension



$\mathrm{Wi}^+ = 40$, $\mathrm{Re}^+ = 85$, $\beta = 0.97$, $L = 70.9$, LAD

Transfer from kinetic to elastic energy



Streamwise spectrum $\Phi\left(\frac{1-\beta}{\mathrm{Re}} T_{ij} S_{ij}\right)$

2D simulation at subcritical Re

Polymer extension