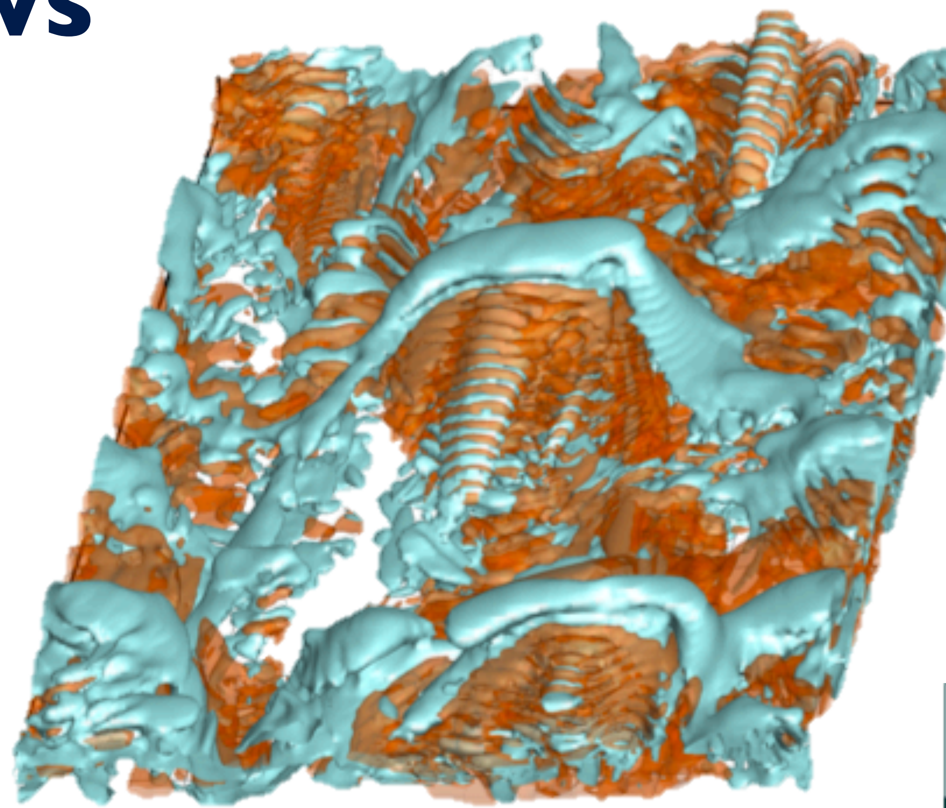
MTFC
RESEARCH GROUP

Elasto-Inertial Turbulence in polymeric flows



V. E. Terrapon
Y. Dubief
J. Soria

APS-DFD 2013
Pittsburgh

Université de Liège

Acknowledgements

Collaborators

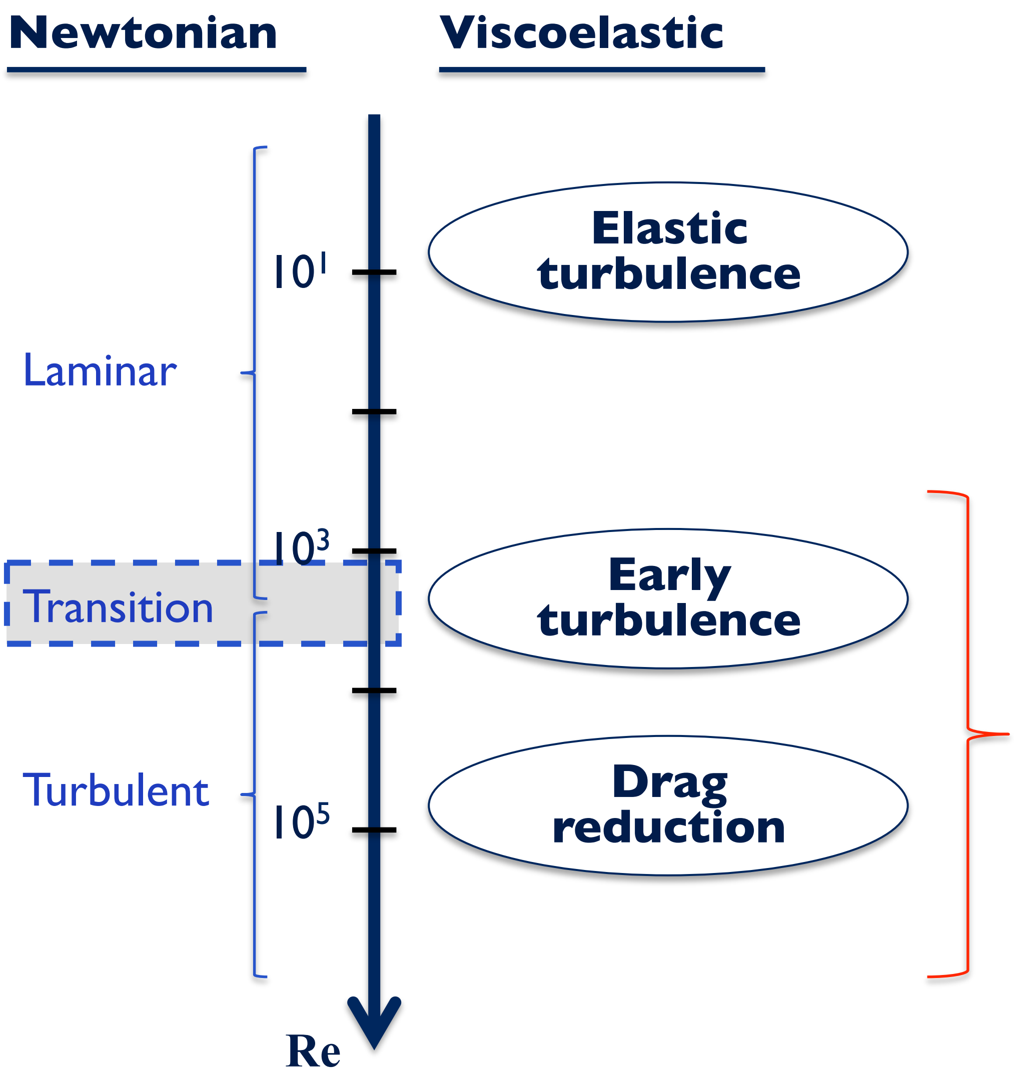
Yves Dubief — University of Vermont, USA

Julio Soria — Monash University, Australia; King Abdulaziz University, Kingdom of Saudi Arabia

Financial support

- Marie Curie FP7 CIG
- Vermont Advanced Computing Center
- US National Institutes of Health
- Australian Research Council
- Center for Turbulence Research Summer Program

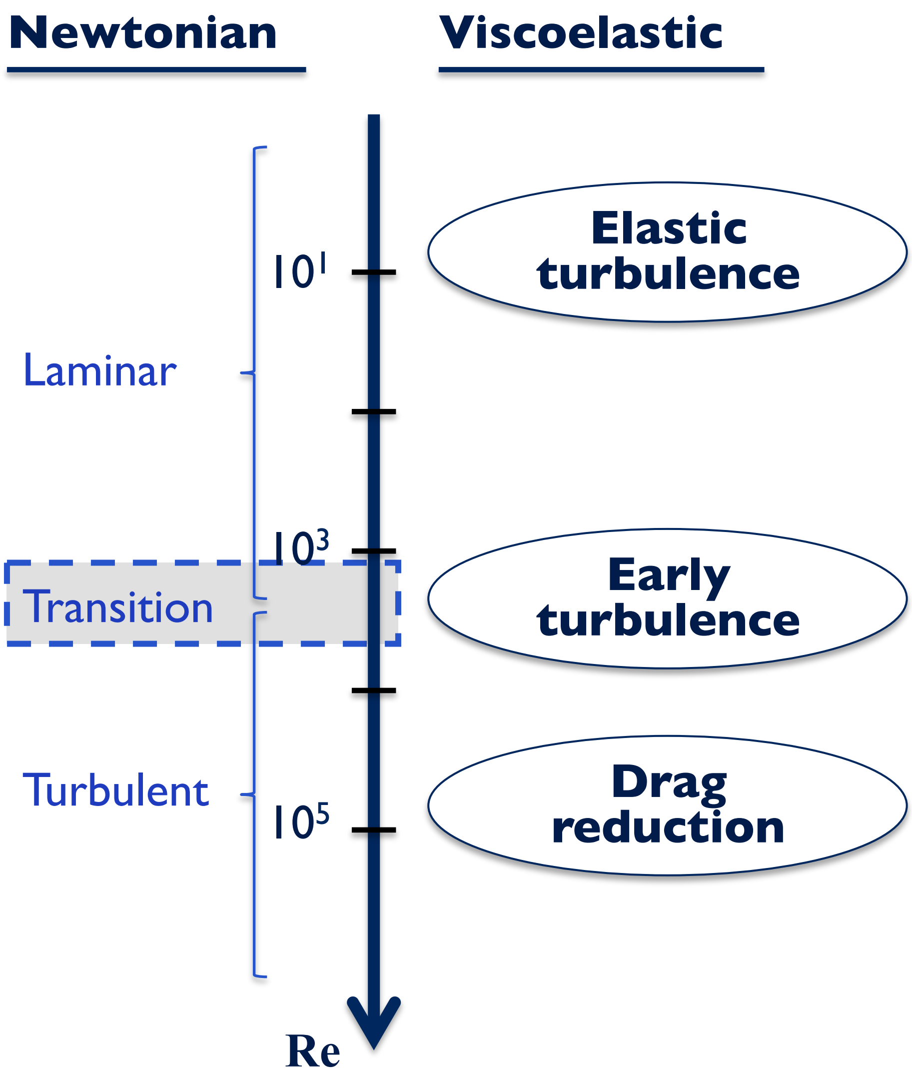
Polymers and turbulence



Elasto-Inertial Turbulence (EIT)

- State of small-scale turbulence
- Contributions from both **elastic** and **inertial** instabilities
- Observed over a wide range of Reynolds numbers
- Possibly state characterizing MDR

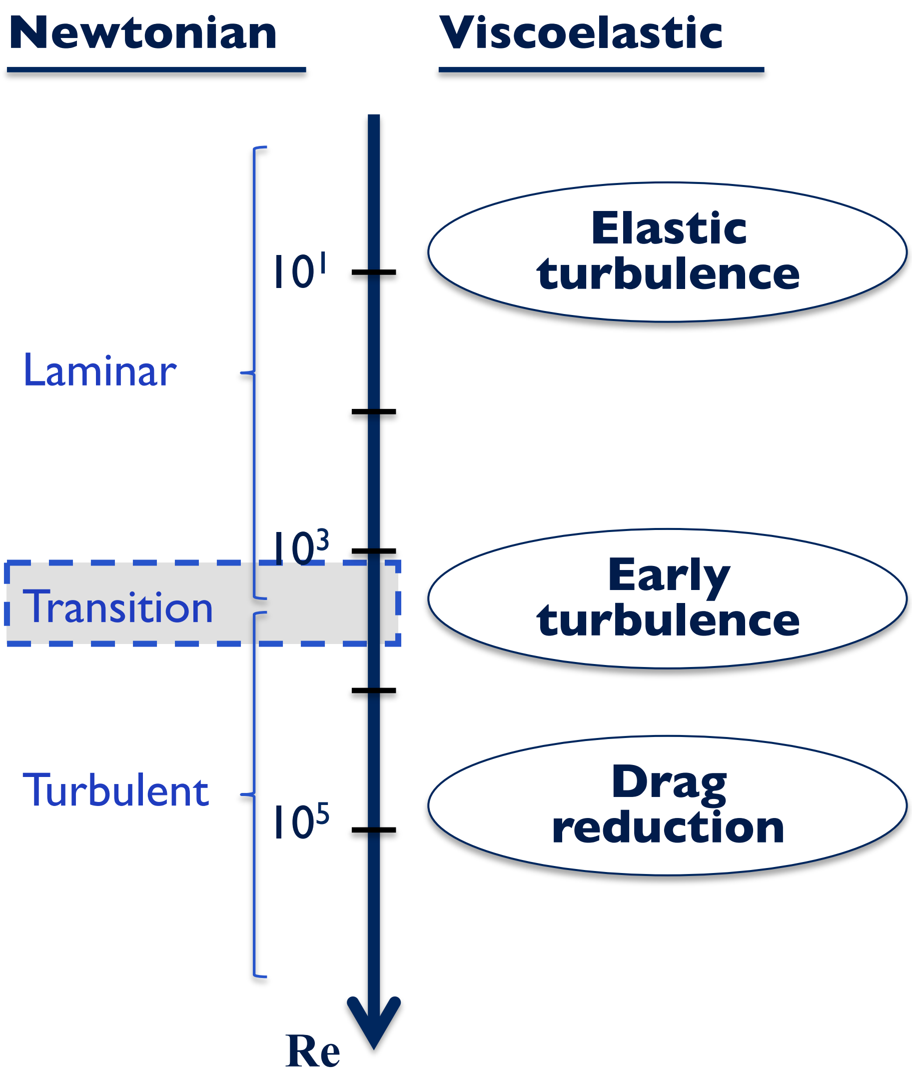
Polymers and turbulence



Key questions

- Is drag reduction
  - a viscous and large-scale effect (Lumley)
  - an elastic and small-scale effect (de Gennes)
- What is the nature of EIT?
  - Relative contributions of elastic and inertial instabilities?
  - Characteristics of MDR?
  - Dynamical interactions between flow and polymers?

Polymers and turbulence



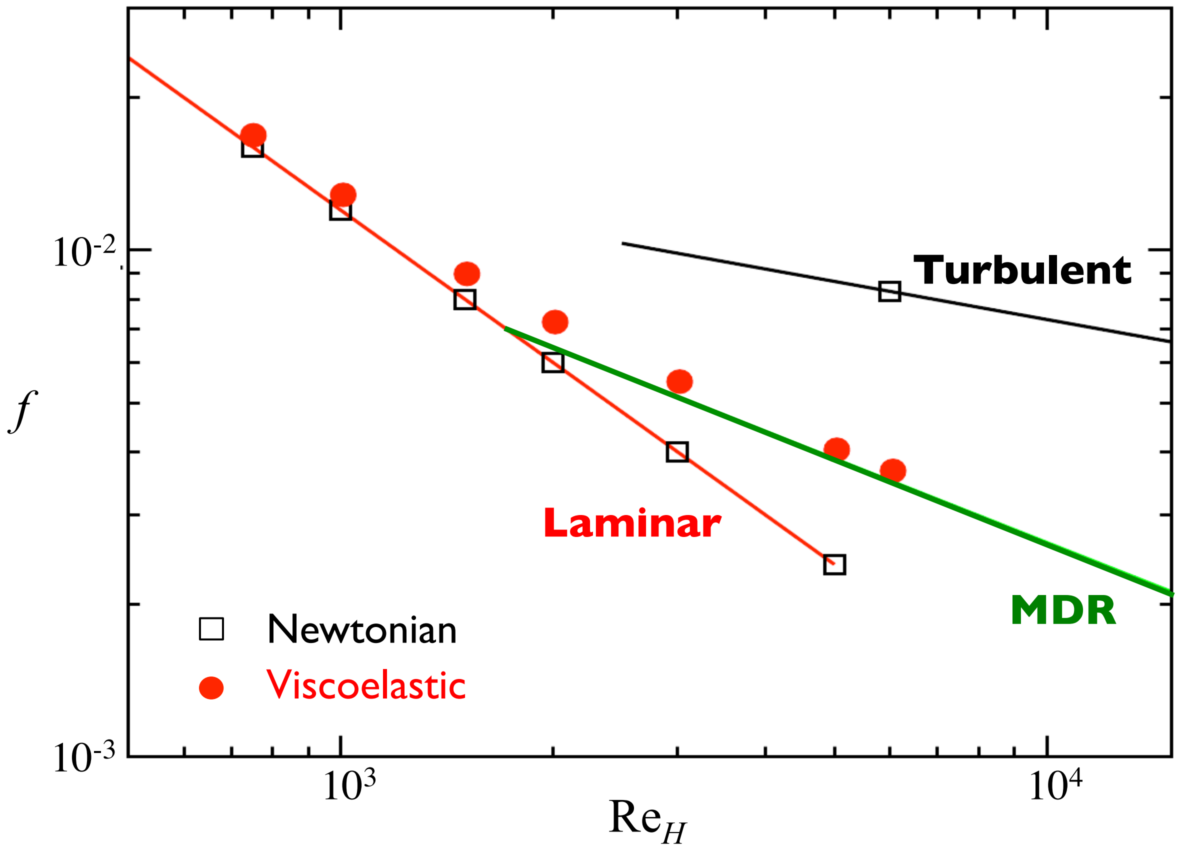
Approach

- Channel flow simulations
- FENE-P model
- Accurate numerics
- Transitional Reynolds numbers

Transitional viscoelastic flows

Channel flow simulations

Friction factor

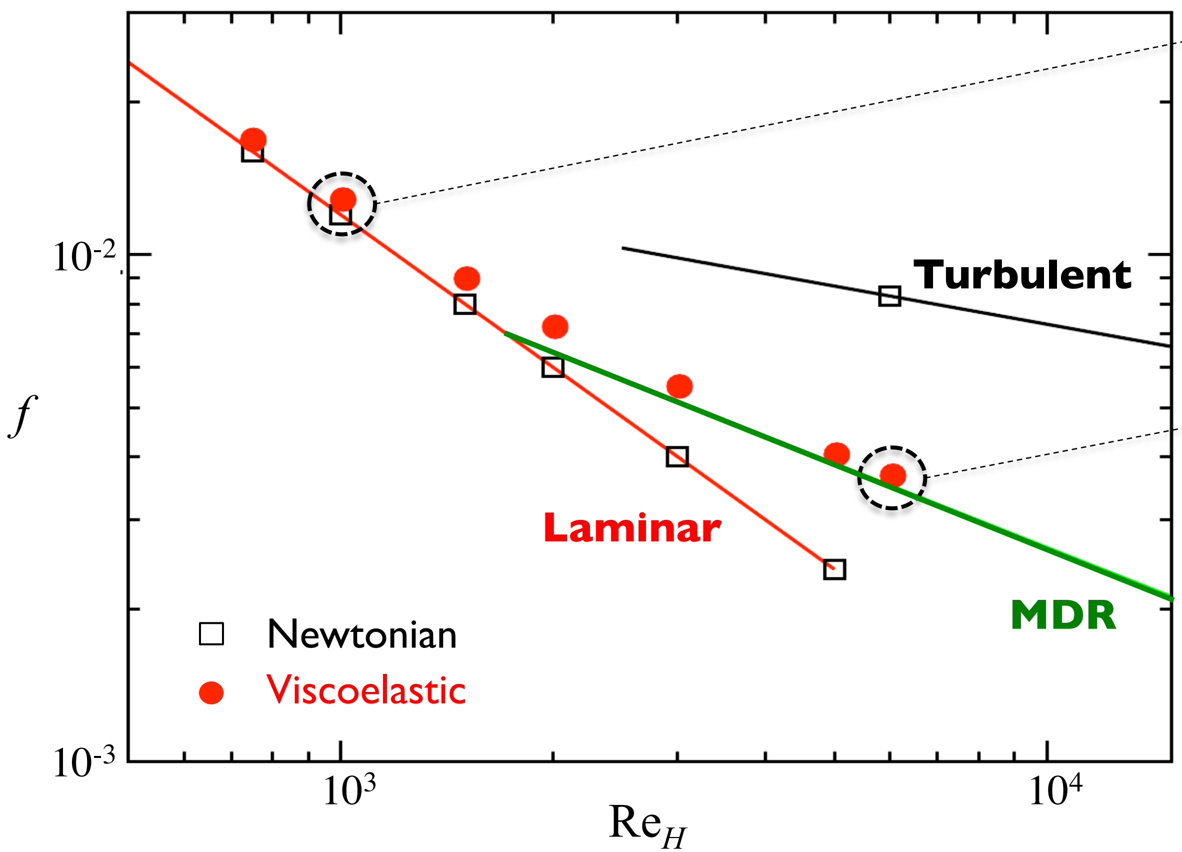


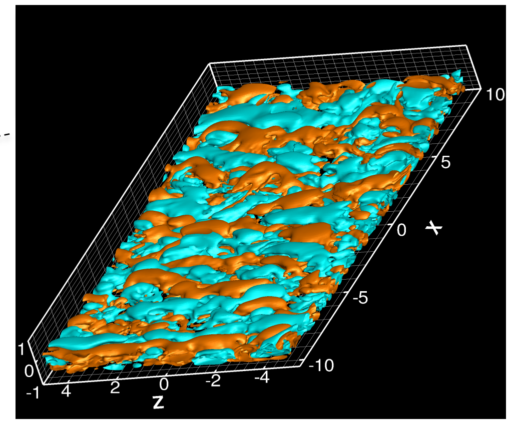
- Departure from laminar state at $\mathrm{Re} \sim 800$
- Smooth transition from laminar to MDR state
- Flow dynamics controlled by elastic and inertial instabilities

Transitional viscoelastic flows

Channel flow simulations

Friction factor

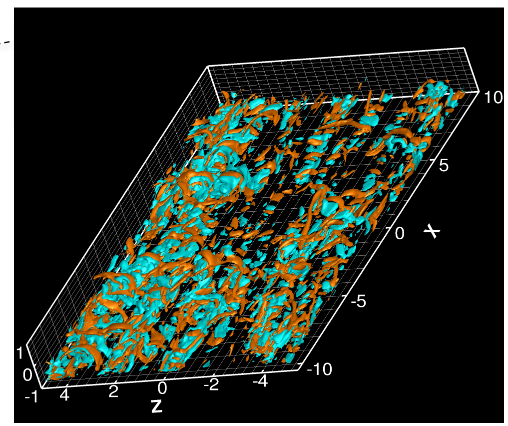




Re=1000, Wi⁺=24

- Not laminar
- Elastic contributions

Isosurface of Q_a invariant



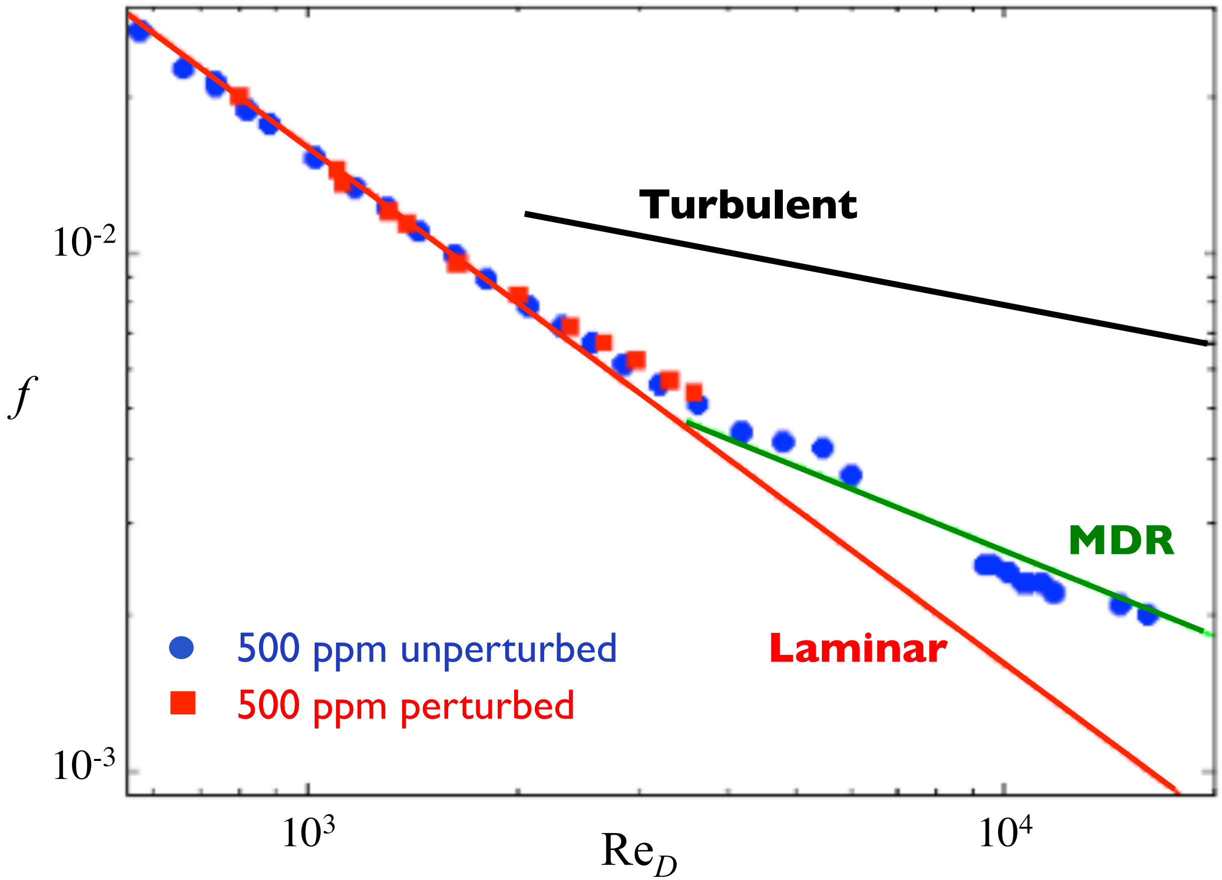
Re=6000, Wi⁺=96

- Inertial & elastic contributions
- Turbulent?
- New state?

Transitional viscoelastic flows

Pipe flow experiment with PAAm solution

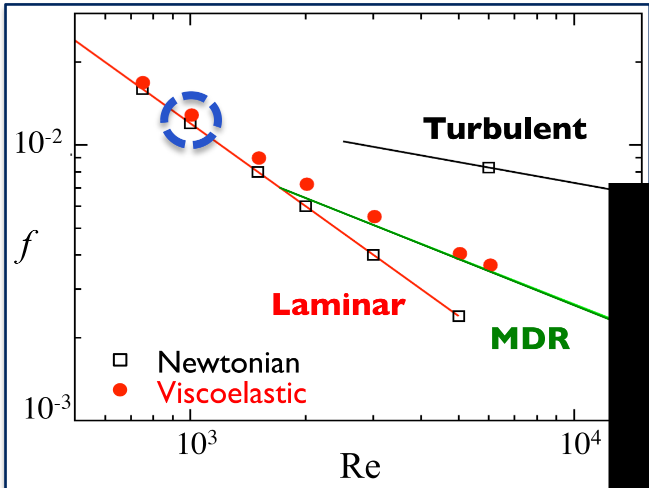
Friction factor



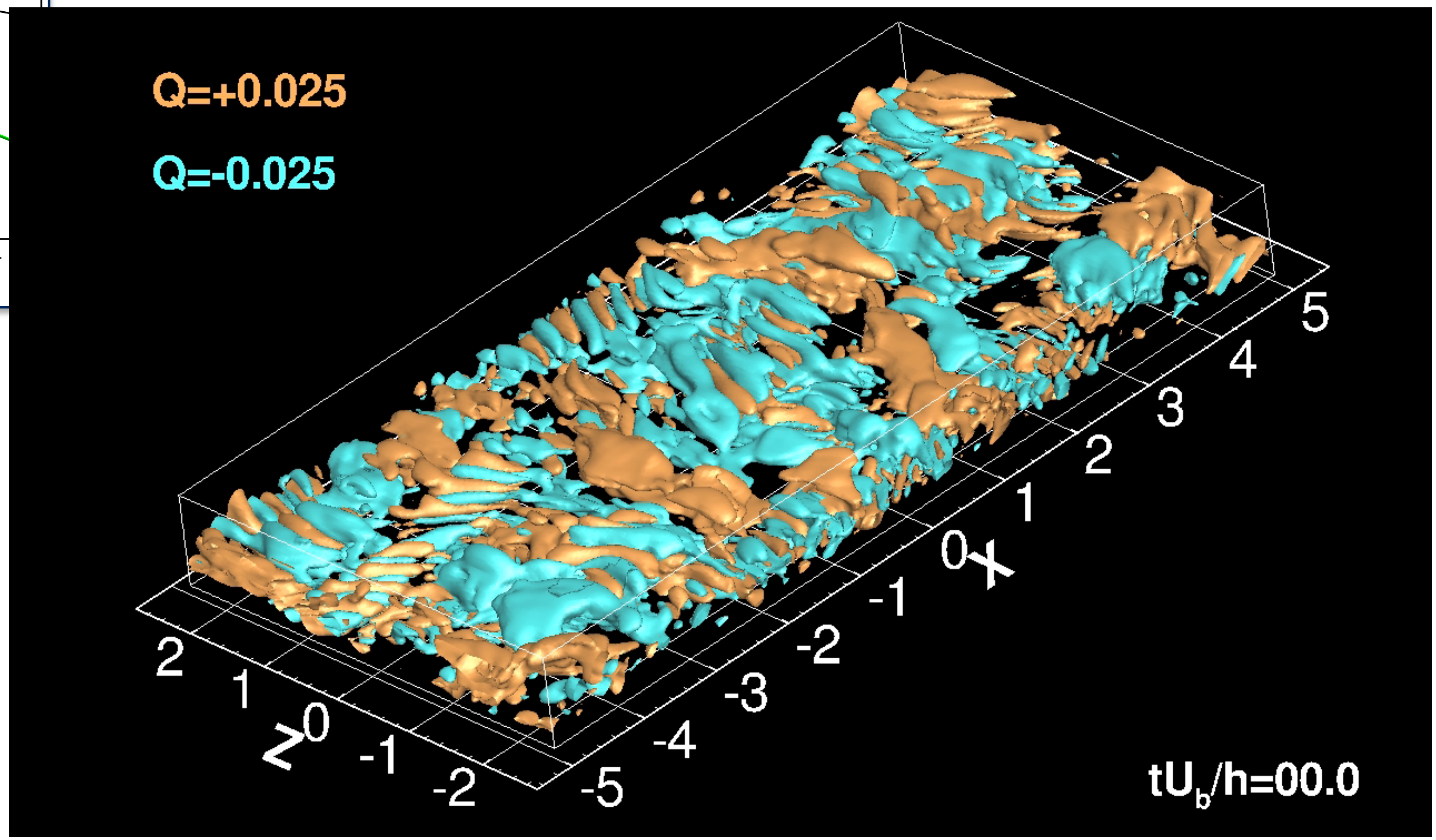
Samanta *et al.*, *PNAS* **110**(26), 2013

Results of numerical simulations are confirmed by experimental measurements

Qualitative flow behavior

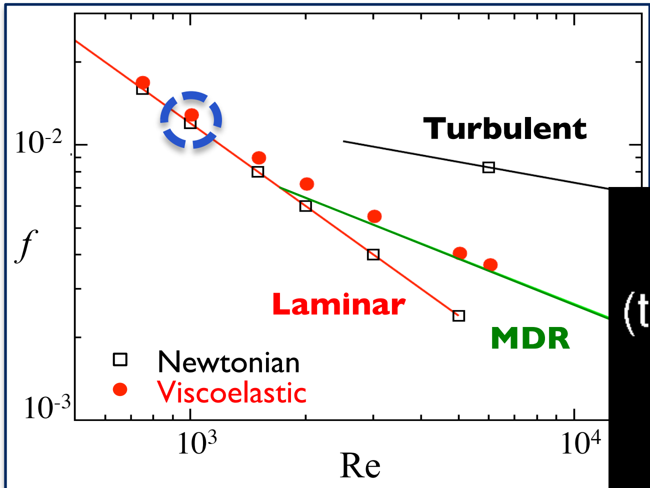


Re = 1000
Wi⁺ = 24

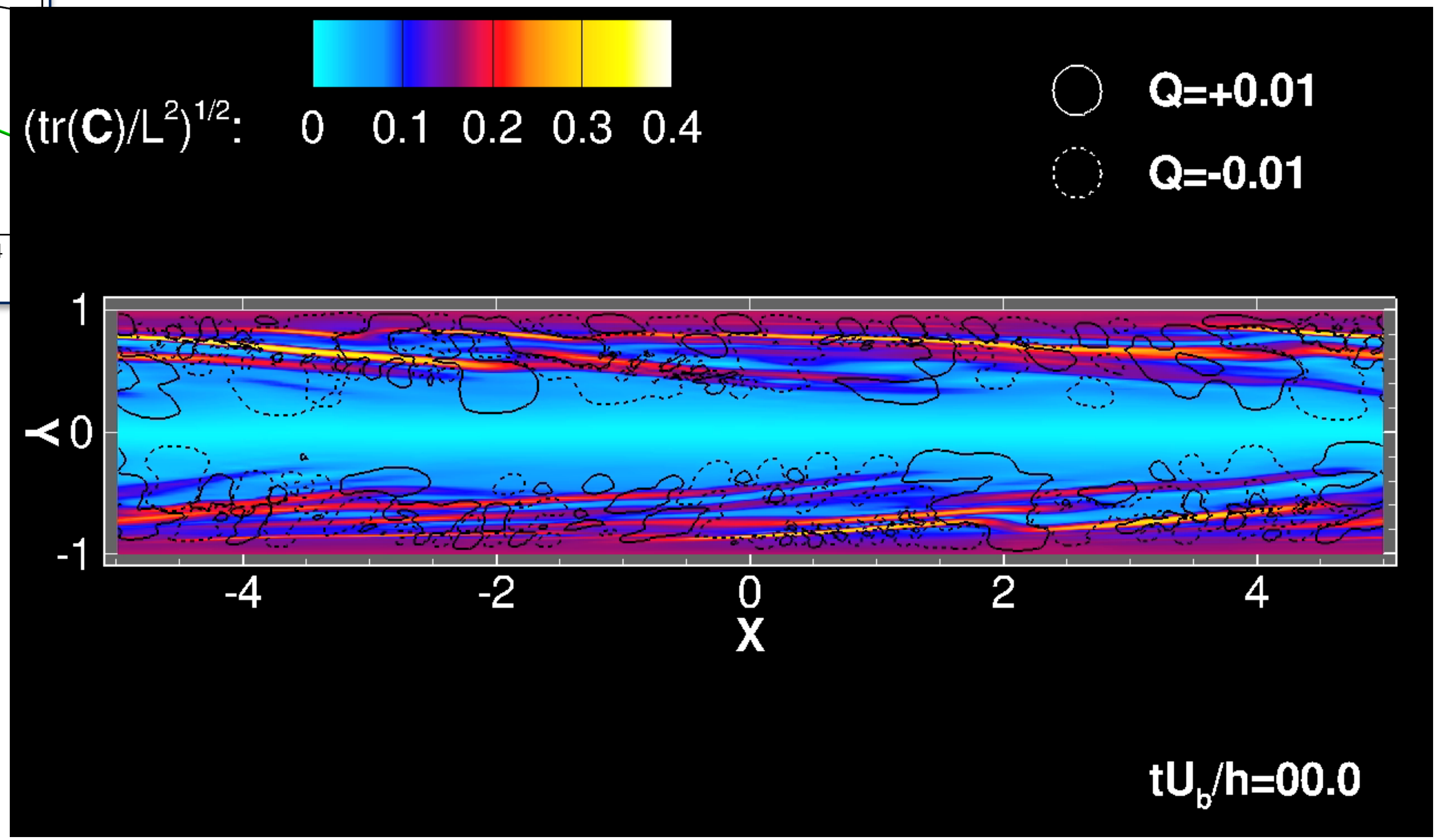


Second invariant of the velocity gradient tensor: $Q_a = \frac{1}{2}(\Omega^2 - S^2)$

Qualitative flow behavior

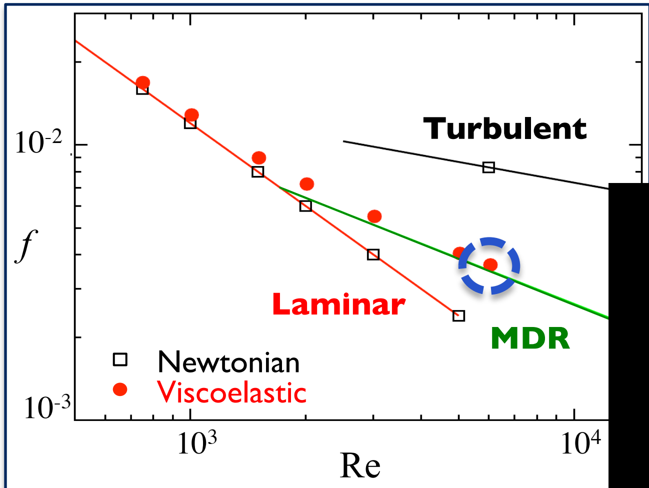


Re = 1000
$Wi^+ = 24$

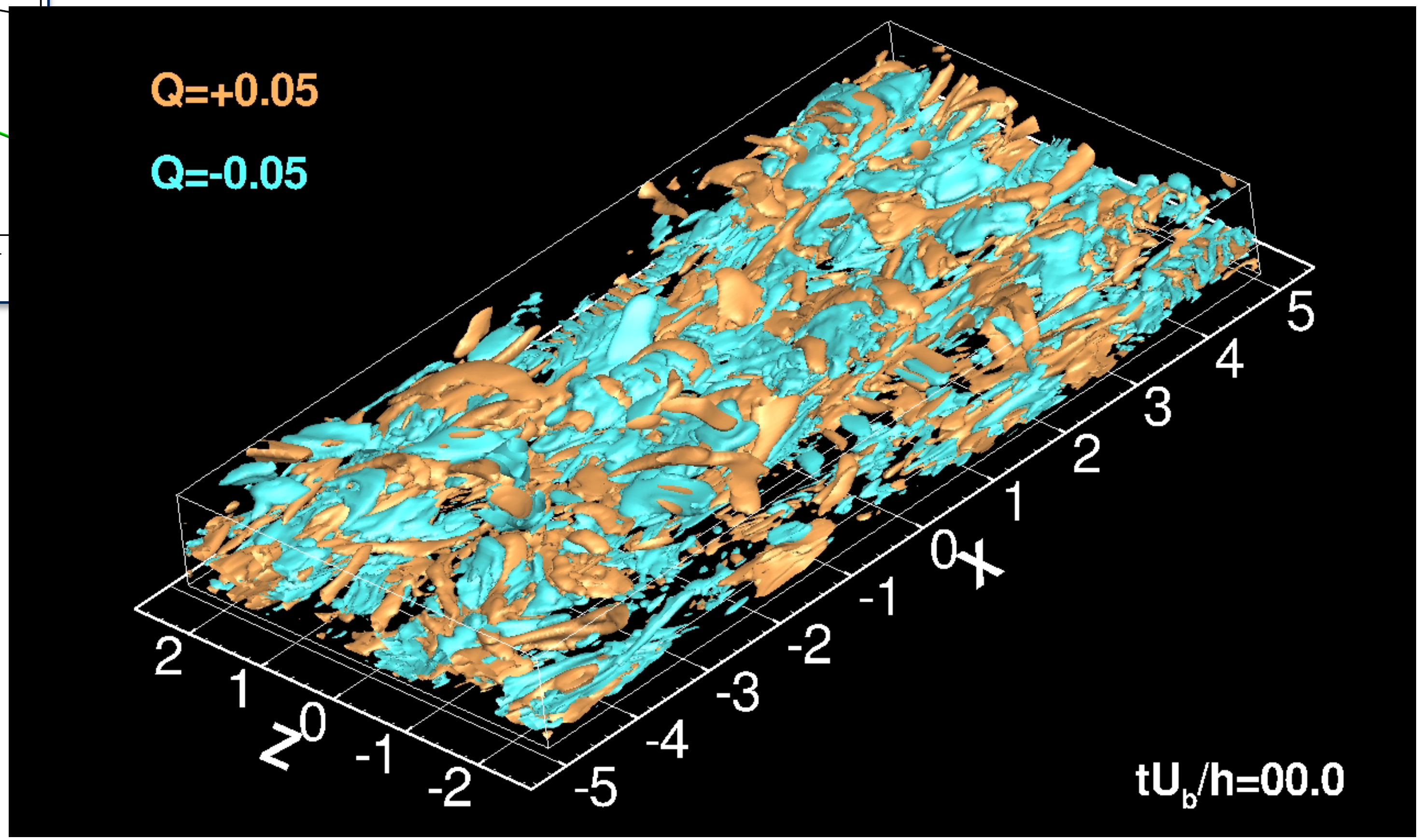


Polymer extension $(C_{ii} / L^2)^{1/2}$

Qualitative flow behavior

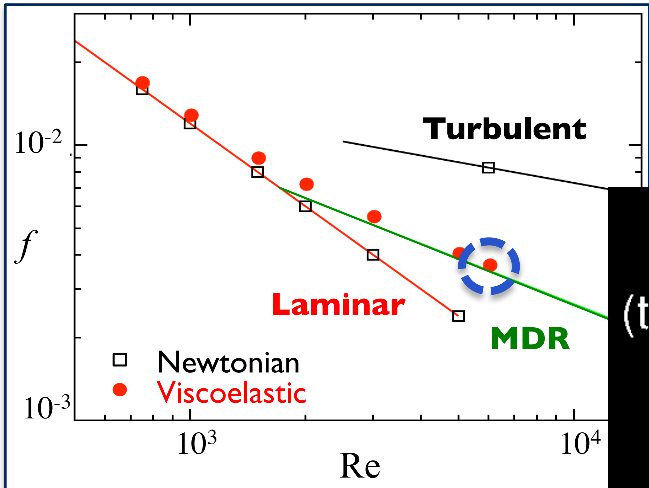


Re = 6000
Wi⁺ = 96

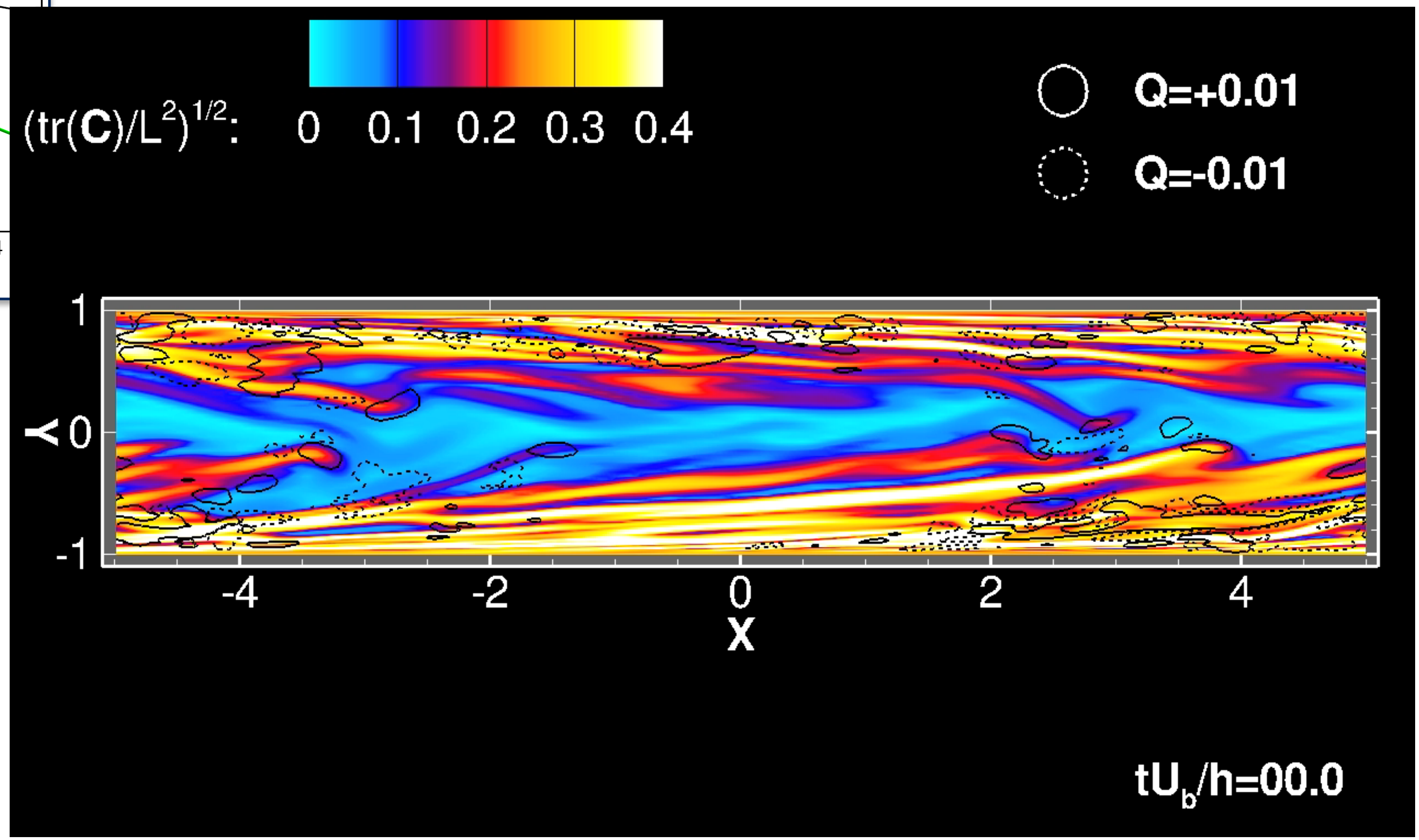


Second invariant of the velocity gradient tensor: $Q_a = \frac{1}{2}(\Omega^2 - S^2)$

Qualitative flow behavior

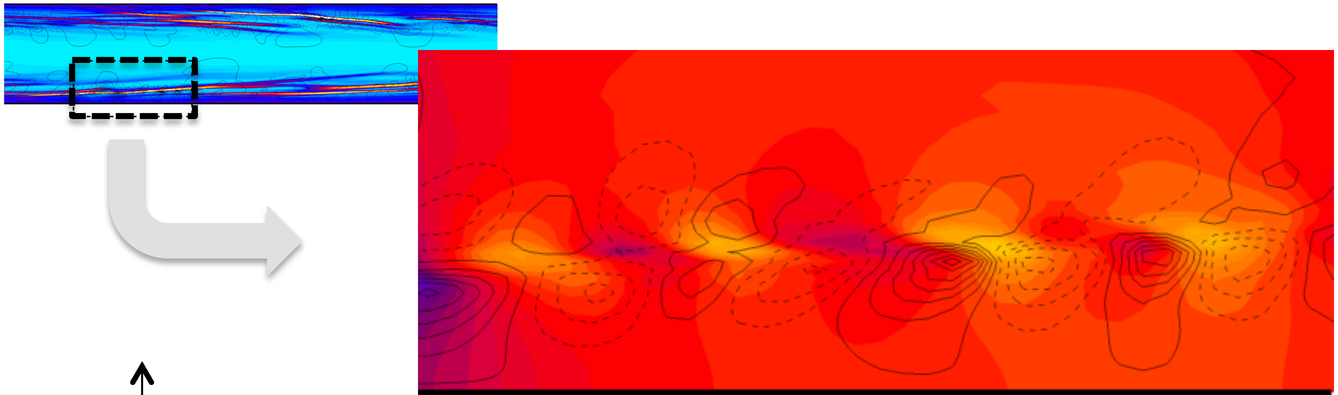


Re = 6000
Wi⁺ = 96

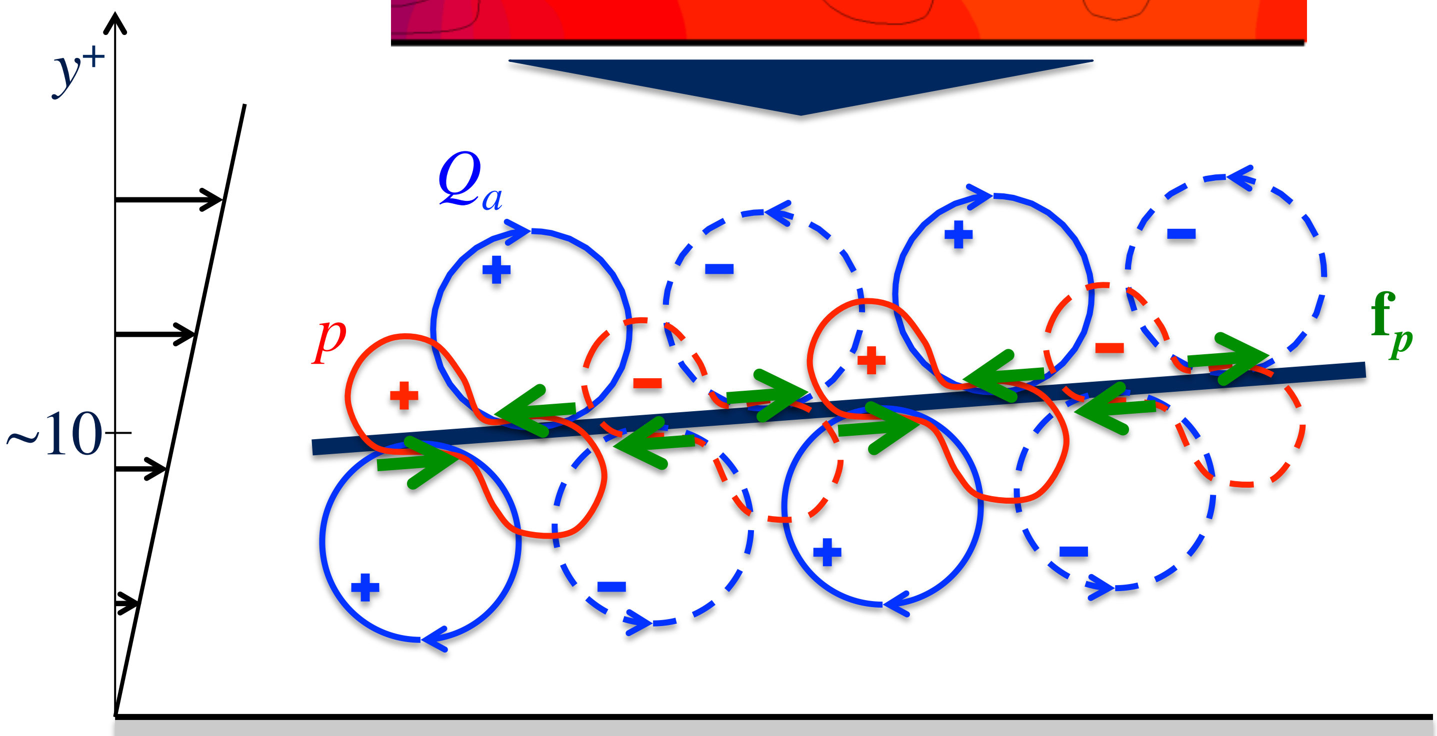


Polymer extension $(C_{ii} / L^2)^{1/2}$

Typical structures



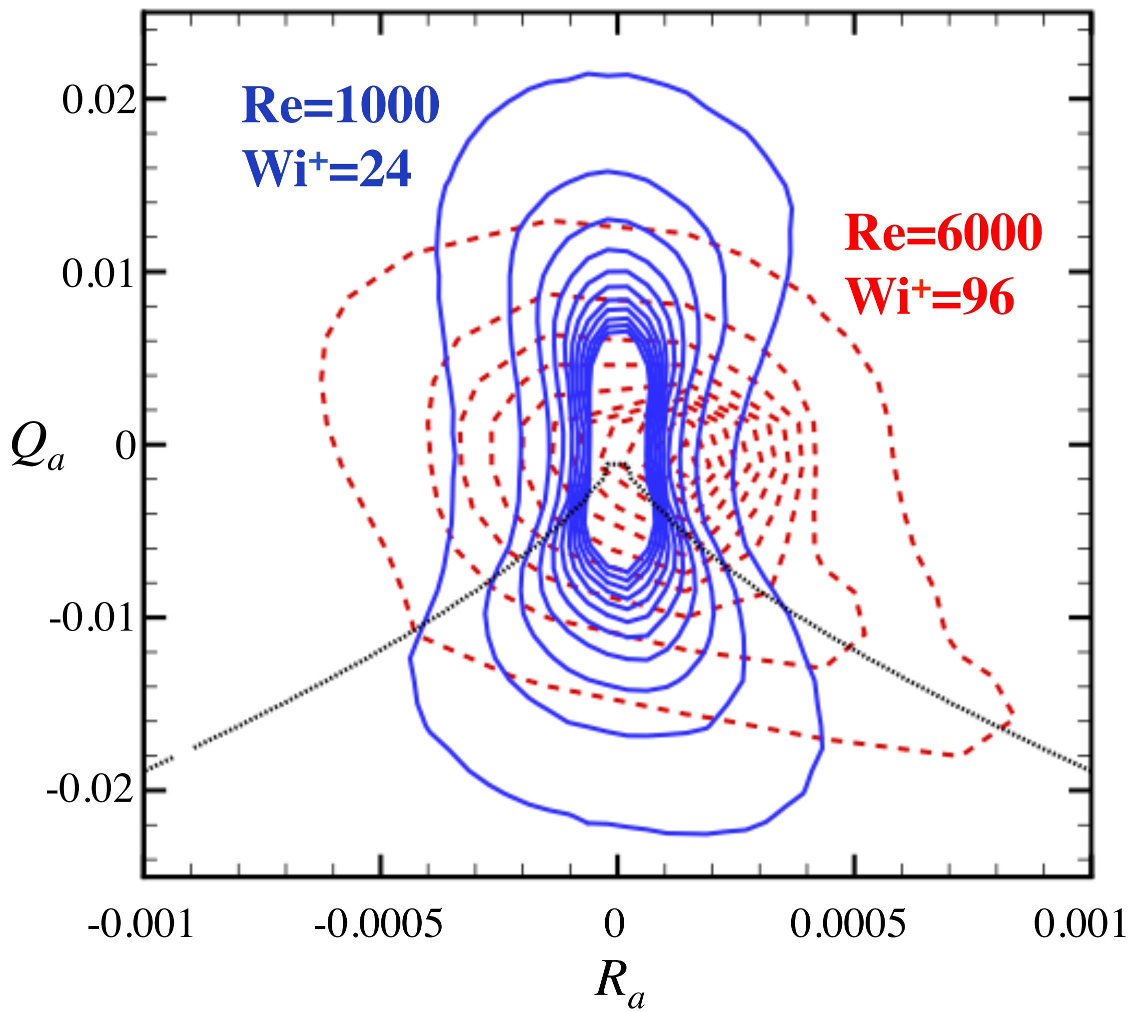
Contour of pressure and isolines of second invariant Q_a



- Train of cylindrical Q_a structures of alternating sign
- On each side of sheet
- Associated with polymeric part of pressure
- Correlated with polymer body force $\mathbf{f}_p$

Flow topology

EIT flow – Joint-PDF



- Change from shear flow ($R_a=Q_a=0$) to mixed flow
- At low Re, symmetric distribution around 2D flow ($R_a=0$)
- At higher Re, "teardrop" shape similar to Newtonian turbulence

Energy transfers

Turbulent kinetic energy budget

$$\int_V P\,\mathrm{d}V - \int_V \varepsilon\,\mathrm{d}V - \int_V \Pi_e\,\mathrm{d}V = 0$$

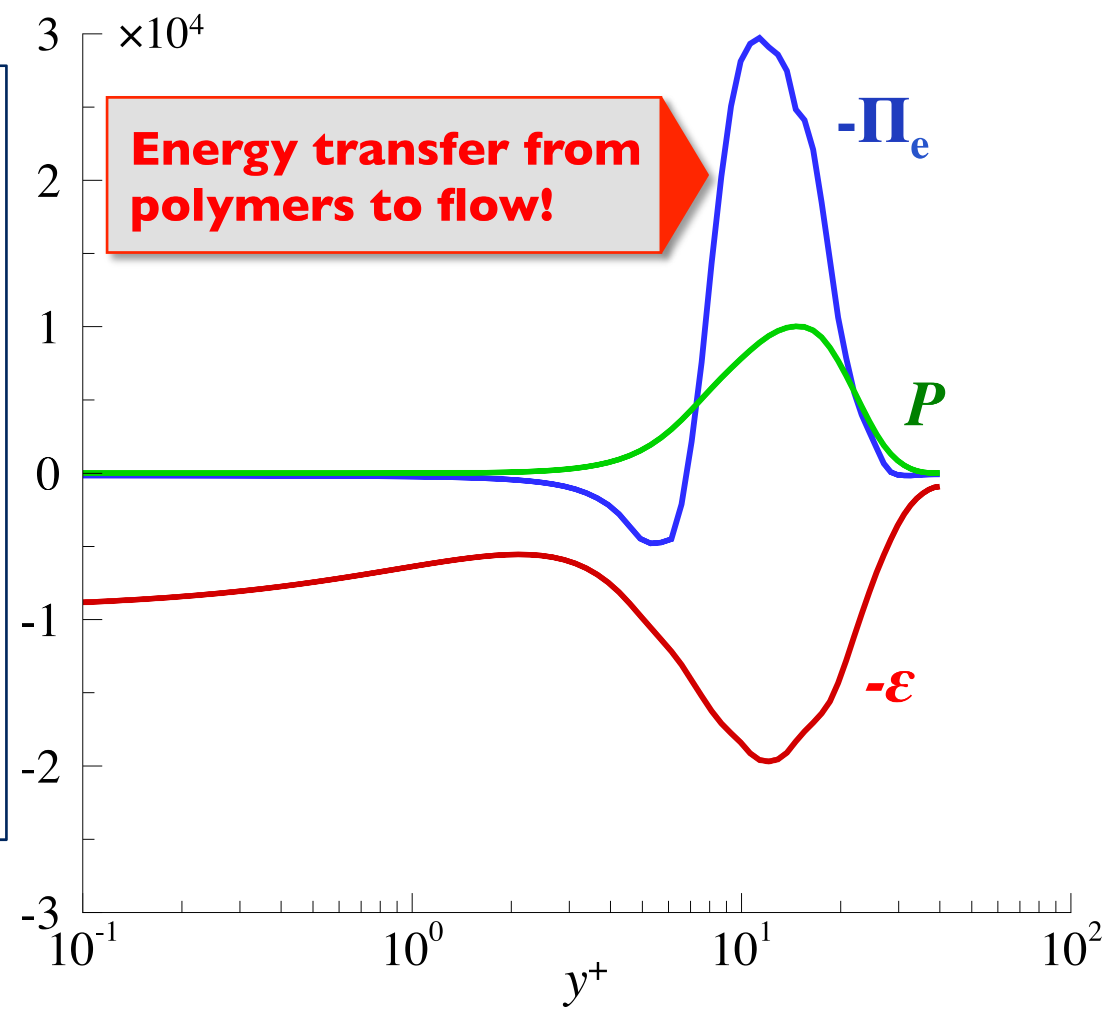
Production

Dissipation

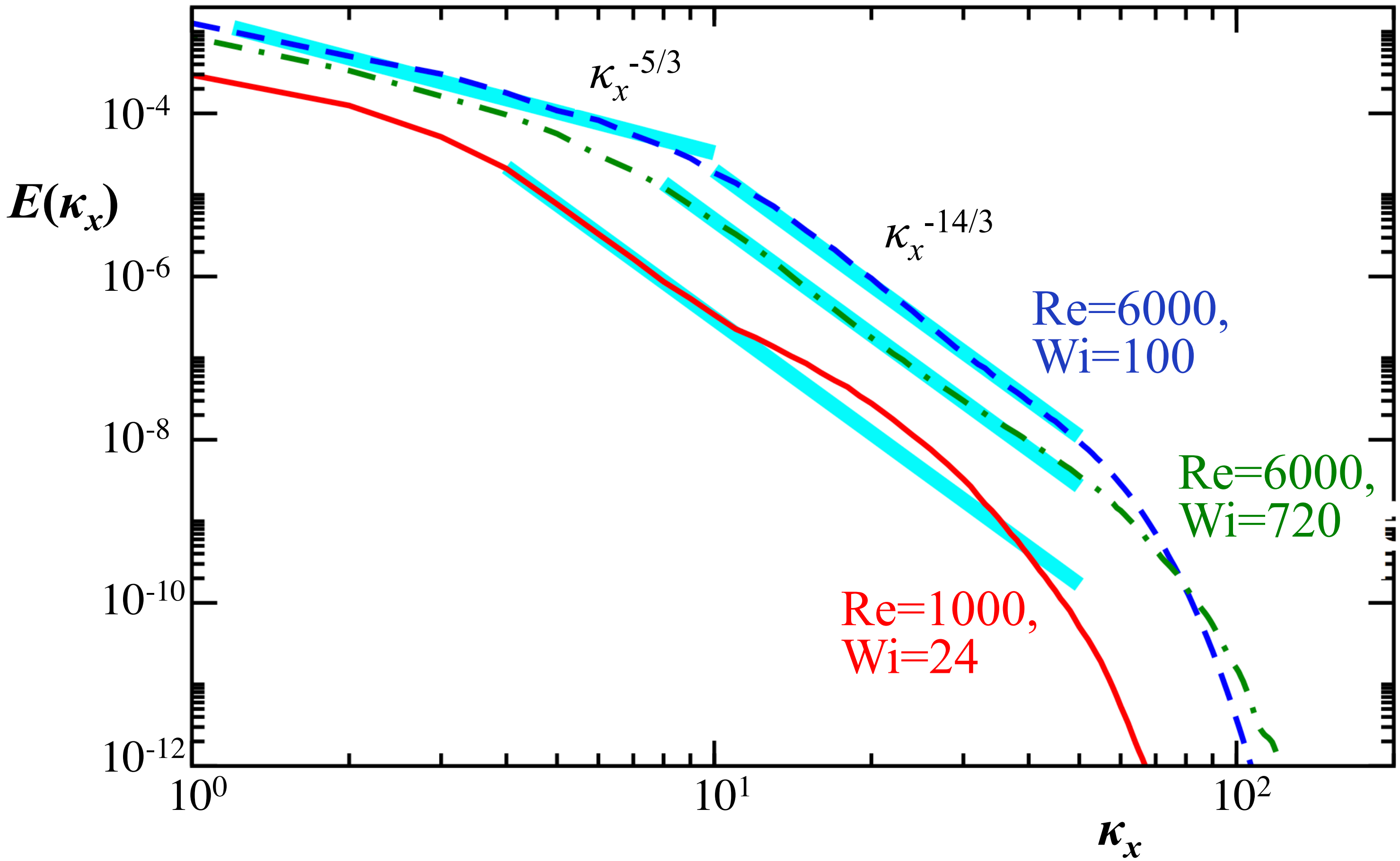
Transfer between elastic energy and turbulent kinetic energy

Transfers of turbulent kinetic energy

Re=1000, Wi$^+$=24



Energy spectrum



-14/3 spectrum agrees well with elastic turbulence and hybrid simulation of Watanabe and Gotoh (JFM 2013)

Our current understanding

Hyperbolic transport equation

$$\partial_t \mathbf{C} + (\mathbf{u}\cdot\nabla)\mathbf{C} = \ldots$$

- Formation of very thin sheets
- Trains of cylindrical structures

Self-sustained

Pressure Poisson equation

$$\nabla^2 p = 2Q_a - \frac{1-\beta}{\mathrm{Re}}\nabla\cdot\left(\nabla\cdot\mathbf{T}\right)$$

- Elliptical pressure redistribution of energy
- Excitation of extensional sheet flow

Mixed extensional-shear flow

$$\ldots = \mathbf{C}\left(\nabla\mathbf{u}\right) + \left(\nabla\mathbf{u}\right)^T \mathbf{C} - \mathbf{T}$$

- Increase of extensional viscosity (anisotropic)
- Anisotropic polymer body force

Conclusion and future work

Key take-away messages

- EIT is a new state of small-scale turbulence driven by both elastic and inertial instabilities
- EIT could characterize MDR regime
- EIT explains seemingly contradictory phenomena in viscoelastic turbulence
- EIT provides support to de Gennes' theory

Next steps

- Further characterize EIT
- Understand the exact mechanisms during transition process

Dubief, Terrapon & Soria, "On the mechanism of Elasto-inertial turbulence", *Phys. Fluids* 2013

Samanta *et al.*, "Elasto-inertial turbulence", *PNAS* **110**(26), 2013

Terrapon, Dubief & Soria, *Proceedings of the TSFP-8*, 2013