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Dynamics of Elasto-Inertial Turbulence in Flows with Polymer Additives

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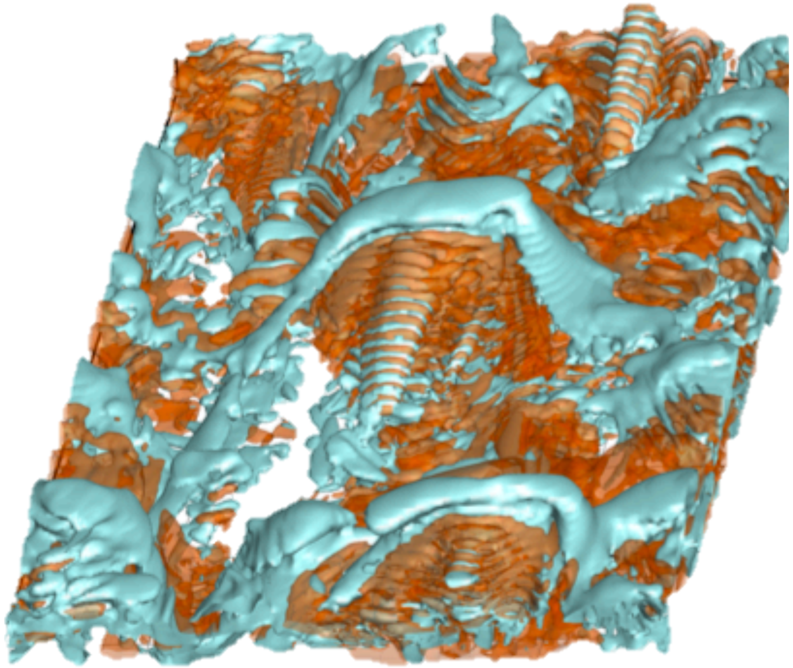

TSFP-8
Poitiers, 30 August 2013

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Acknowledgements

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Collaborators

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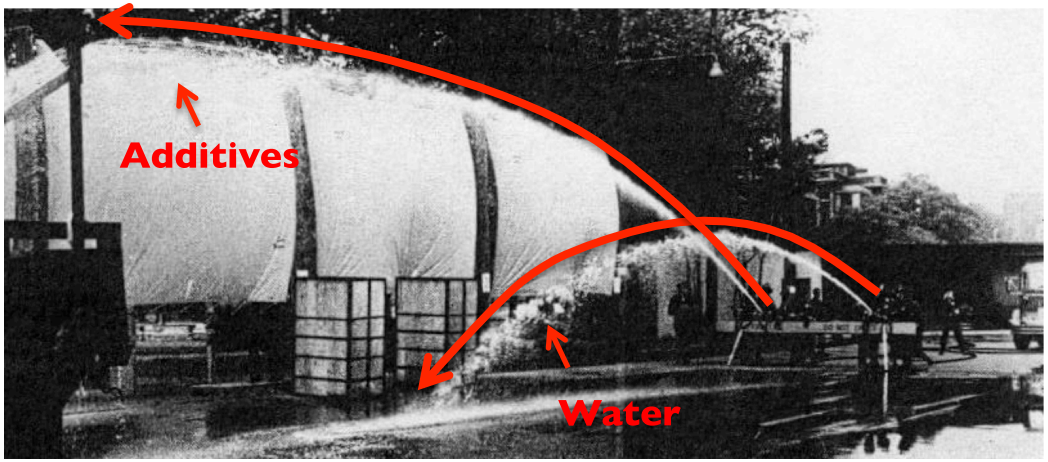
Julio Soria — Monash University, Australia
King Abdulaziz University, Kingdom of Saudi Arabia

Financial support

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

Turbulent drag reduction

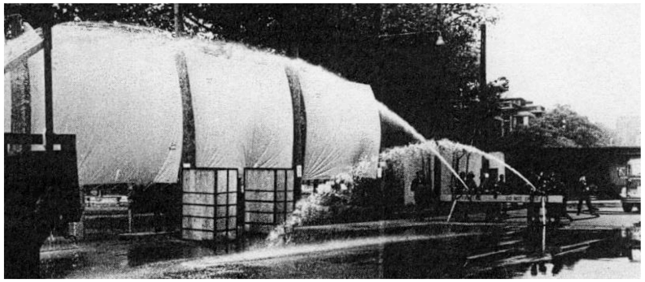


Fire hoses with and without polymer additives

- Up to 80% friction drag reduction, even at low concentration
- No significant effect on drag in laminar flows
- Bounded by Maximum Drag Reduction (MDR) asymptote

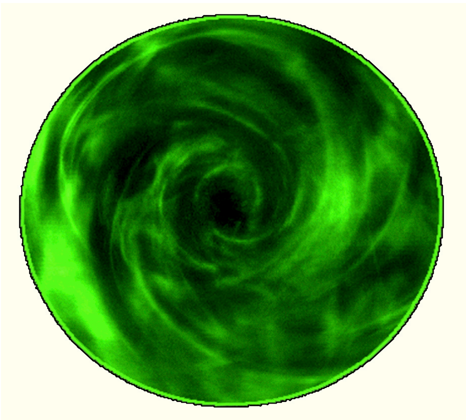
- Pipeline

Turbulent drag reduction



Polymers and turbulence

Elastic turbulence

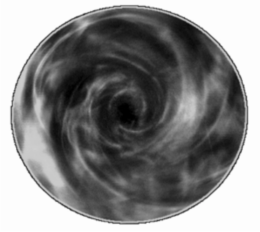


Chaotic motion of a polymer solution in micro-channel
(Groisman & Steinberg, 2000)

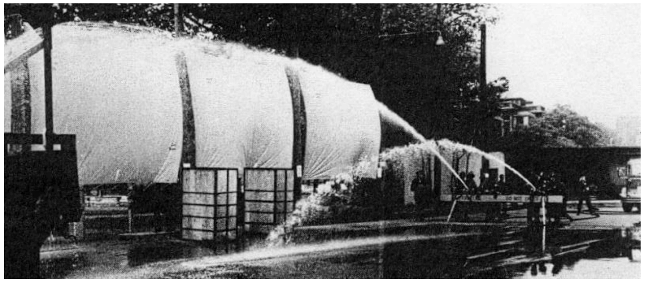
- Existence of elastic turbulence in flows with curved streamlines
- Observed at low Reynolds number
- Strong increase in mixing properties

- Blood flow
- Micro-channel flow

Elastic turbulence



Turbulent drag reduction



Polymers and turbulence

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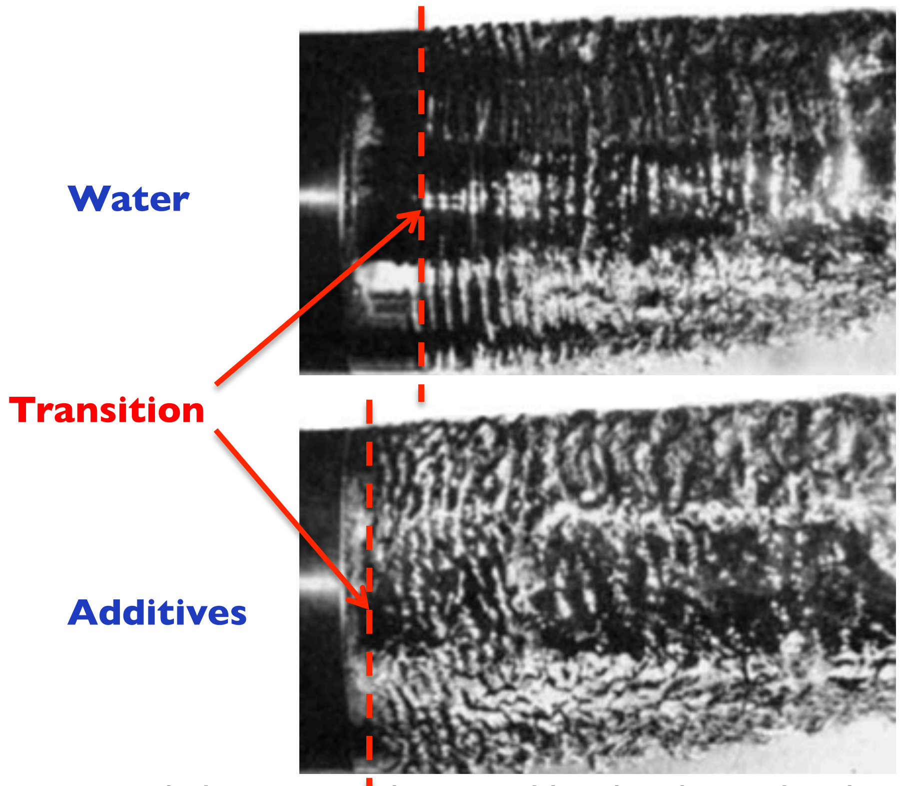
Early turbulence

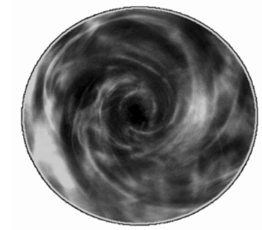


Transition to turbulence around an ogival head with ventilated cavity (Hoyt, 1977)

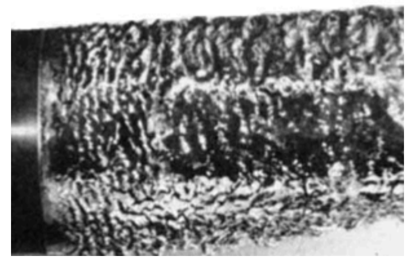
- Transition to turbulence promoted by polymers

- Biofluids

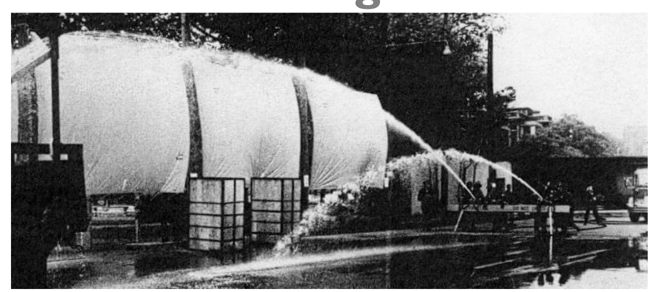
Elastic turbulence



Early turbulence



Turbulent drag reduction



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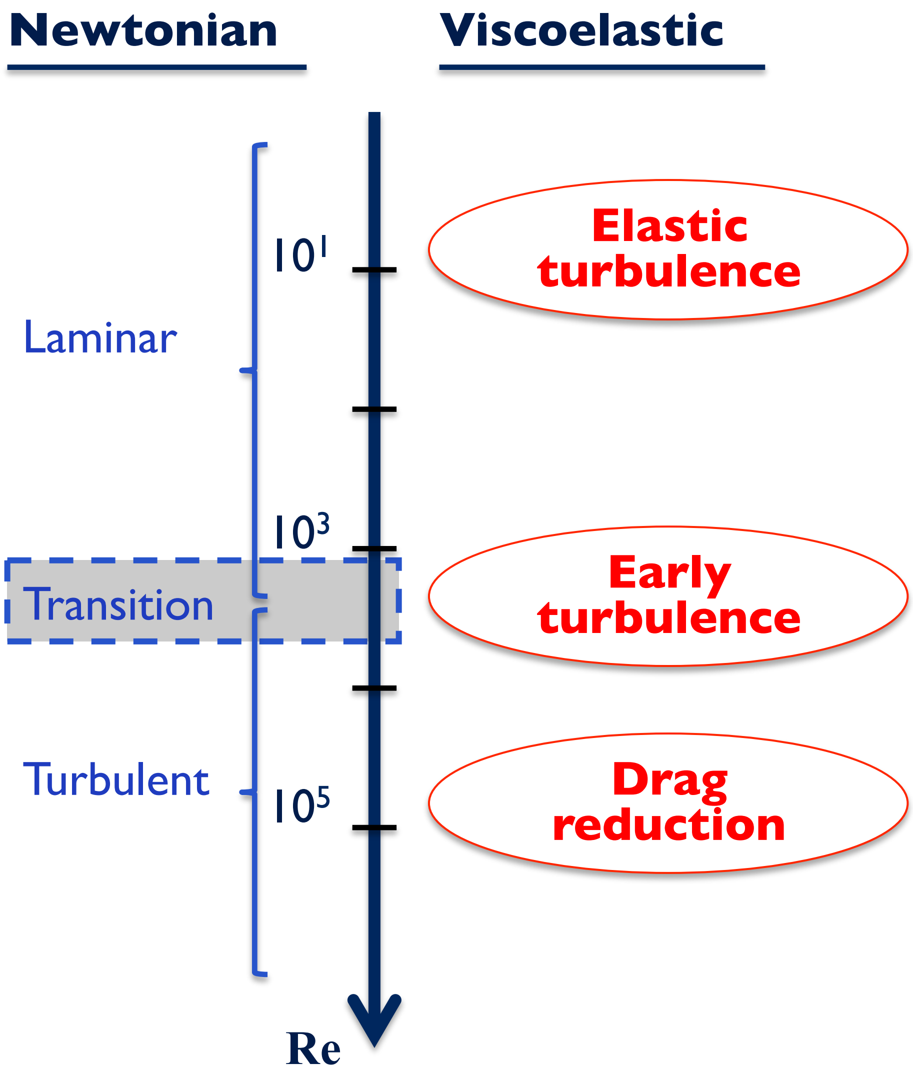
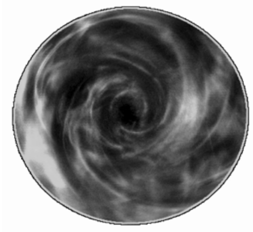
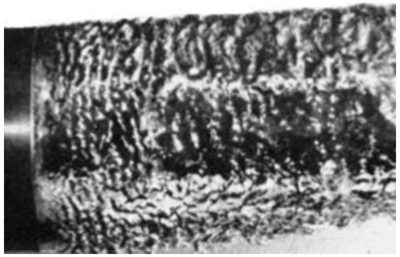


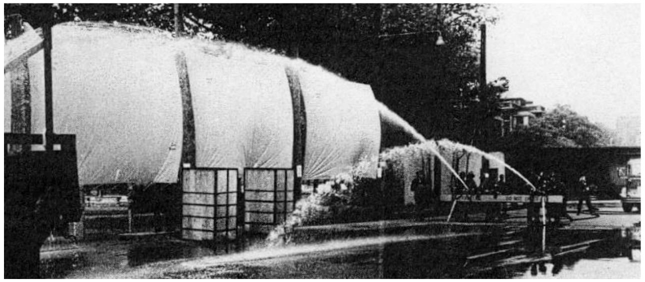
Elastic turbulence



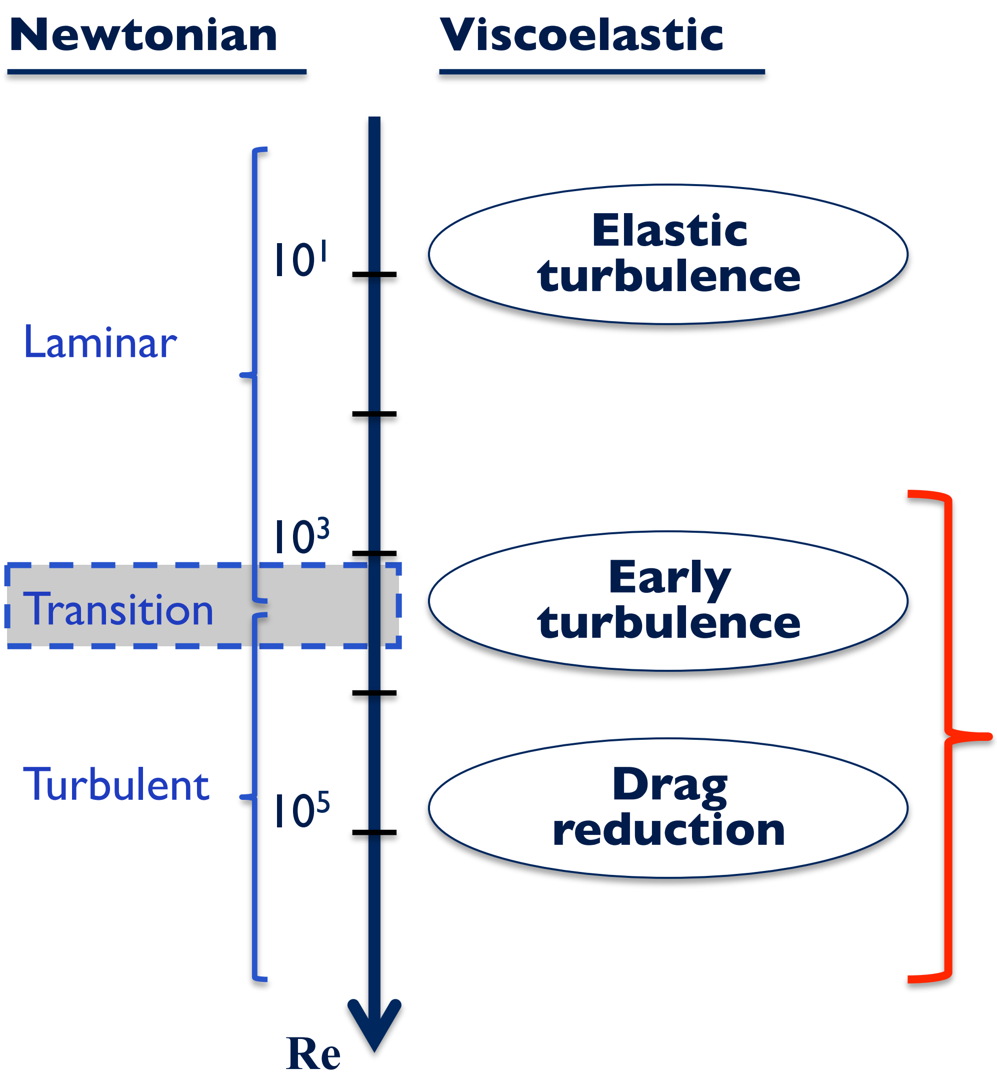
Early turbulence



Turbulent drag reduction



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

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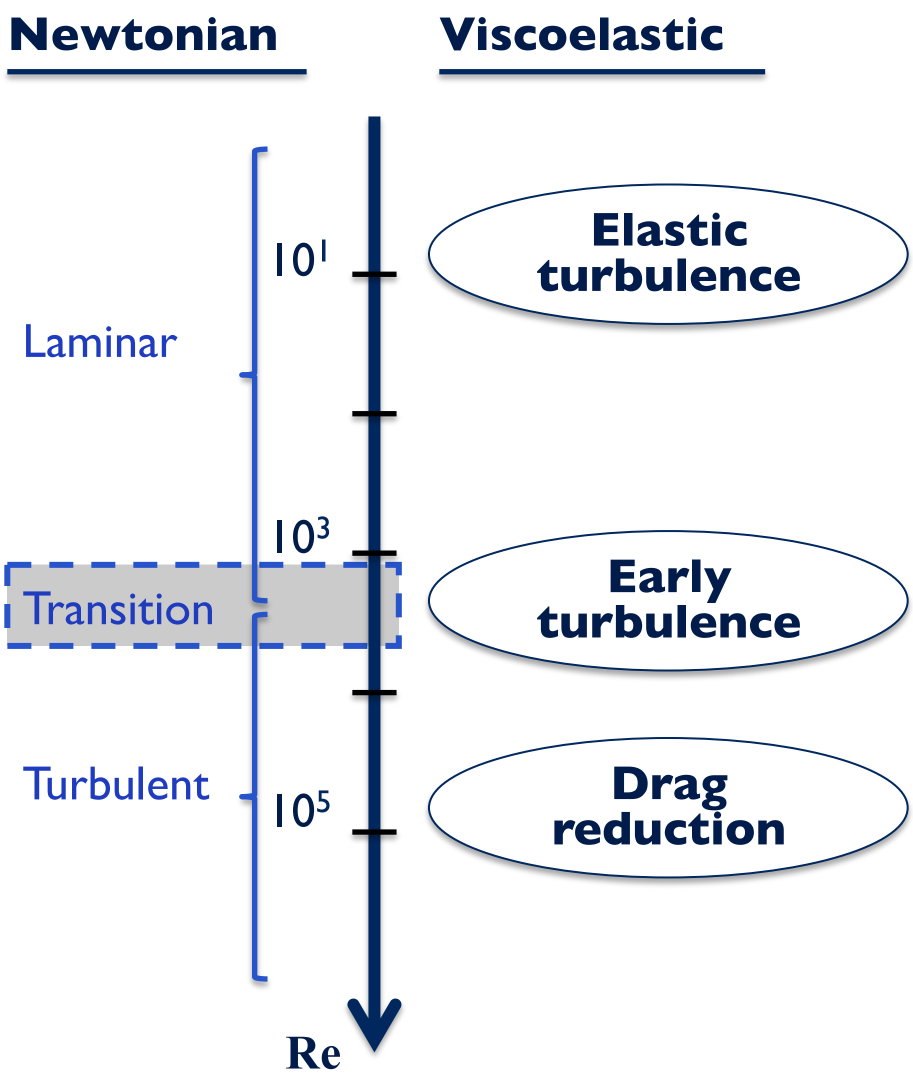

Key questions

- 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?

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Viscoelastic NSE – FENE-P model

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

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

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

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

β Ratio of solvent viscosity to zero-shear viscosity of solution

L Maximum polymer extension

Re Reynolds number

Wi Weissenberg number

$\mathrm{E} = \frac{\mathrm{Wi}}{\mathrm{Re}}$ Elasticity

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Numerical approach

Space
- Structured grid
- 2^{nd} order FD for velocity
- Non-dissipative 4^{th} order compact scheme for polymer stress
- Compact upwind scheme for advection terms of conformation tensor

Time
- Semi-implicit fractional step
- 2^{nd} order Crank-Nicolson/3^{rd} order Runge-Kutta
- Implicit scheme for trace of $\mathbf{C}$ to ensure bounded trace

Artificial dissipation
- Local artificial dissipation (LAD)
- Only used when determinant of tensor $\mathbf{C}$ becomes negative

- Important to rely on accurate numerical method
- Global dissipation ($Sc_{eff} \sim 1$) damps all small scales
- Capturing small polymer scales is critical to represent the correct physics

Min *et al.* (2001), Vaithianathan & Collins (2003), Dubief *et al.* (2005), Dallas *et al.* (2010)

Configuration

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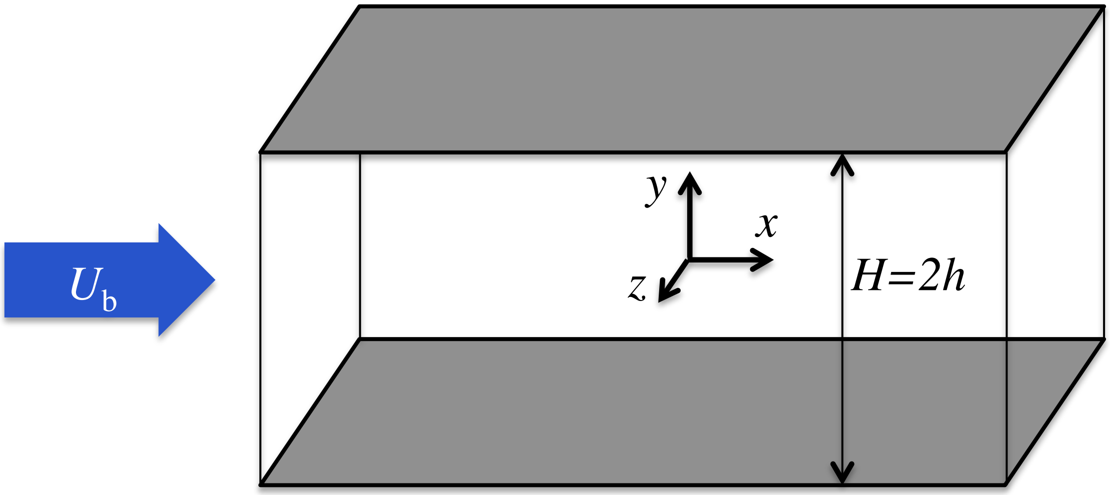
Periodic channel flow



- Mean pressure gradient in x
- Periodic in x and z
- Wall (no-slip) at $y=\pm h$
- Size: $10h \times 2h \times 5h$
- Grid: $256 \times 151 \times 256$

$\text{Re}=\frac{U_b H}{\nu}$	$\text{Wi}=\frac{\lambda U_b}{h}$	$\text{Wi}^+=\lambda\dot{\gamma}$	β	L	h^+	Δx^+	**DM**
▶ 1000	8	24	0.9	200	40	1.5	+7.0%
1000	60	180	0.9	200	40	1.4	+3.5%
▶ 6000	8	96	0.9	200	130	5.0	-56%
6000	60	720	0.9	200	120	4.6	-61%

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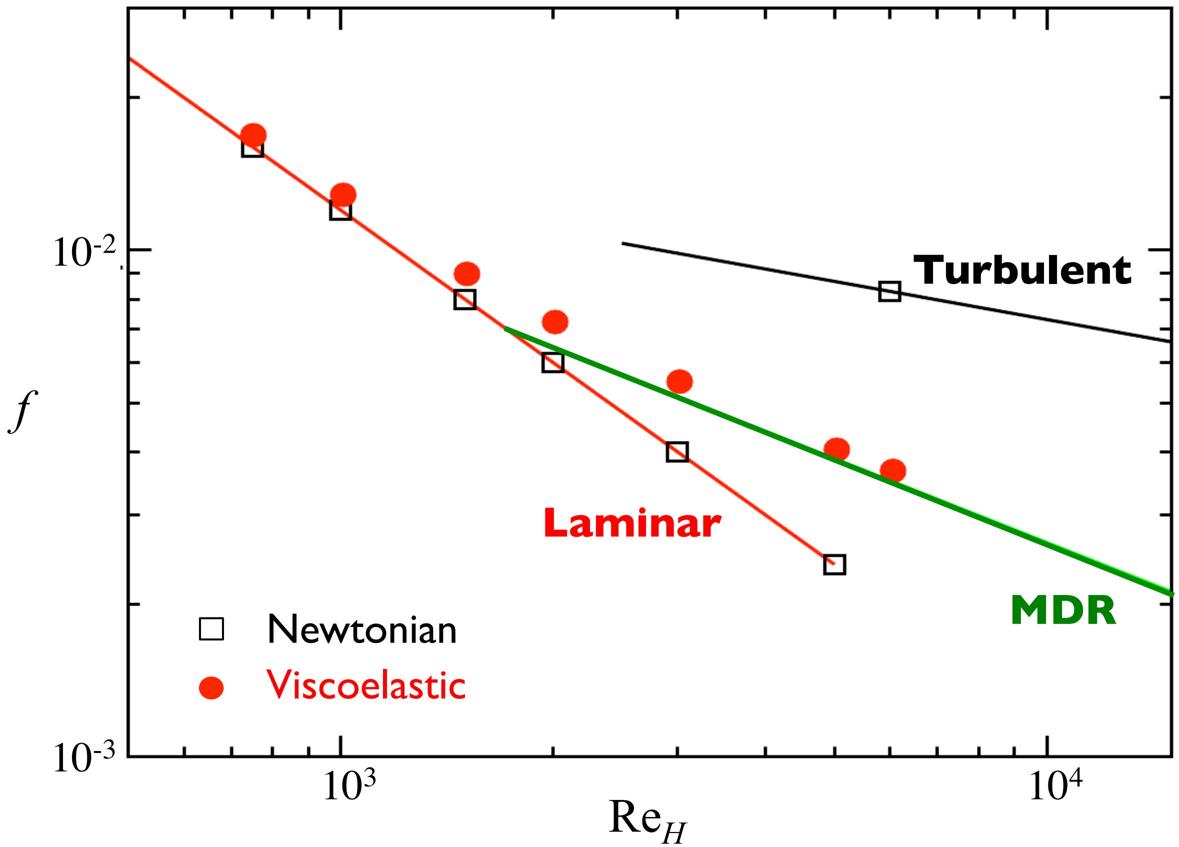
Transitional viscoelastic flows

Channel flow simulations

Friction factor



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

Transitional viscoelastic flows

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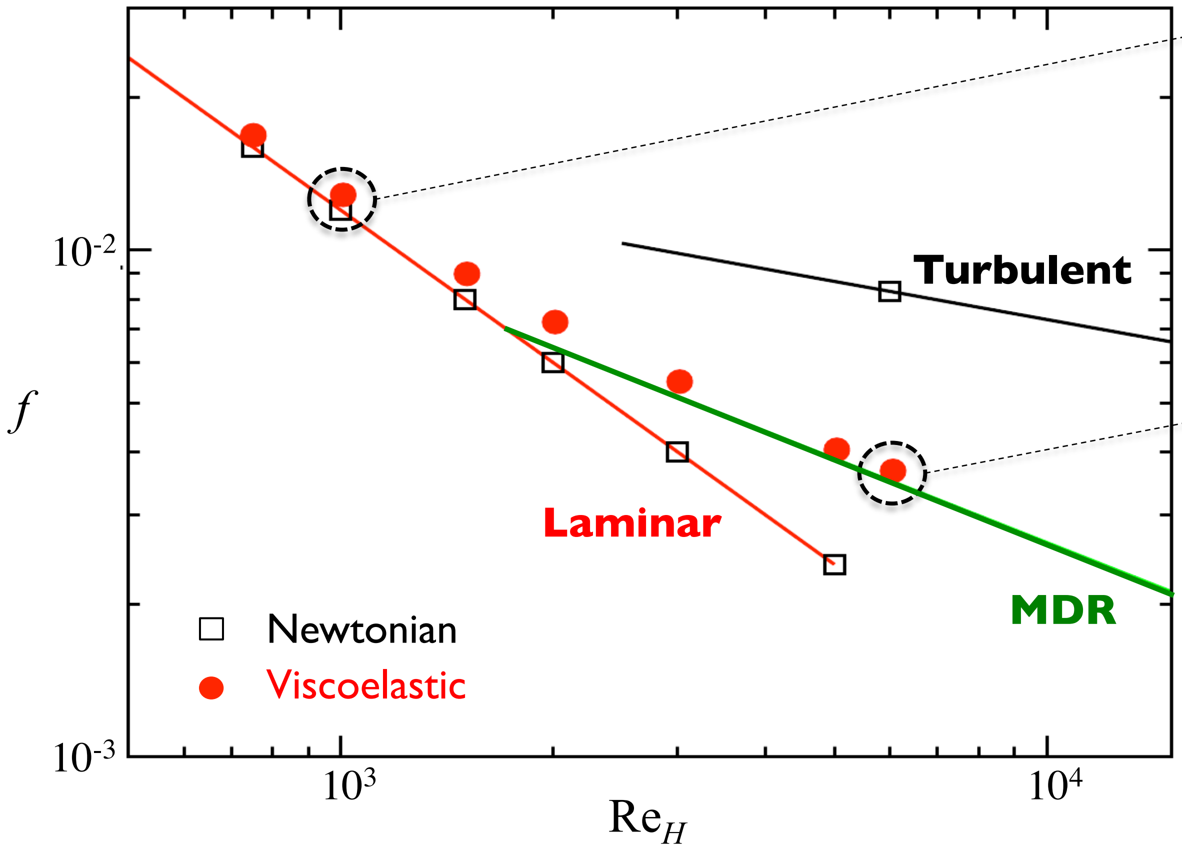
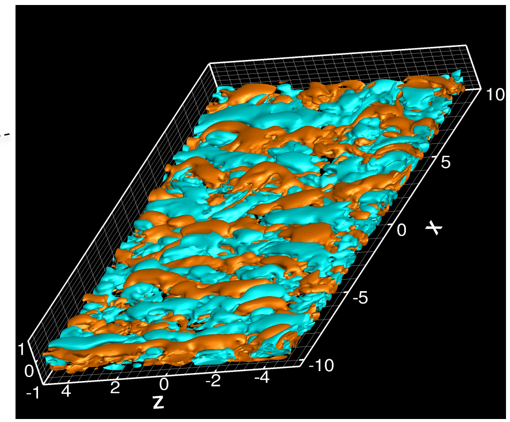
Channel flow simulations

Friction factor

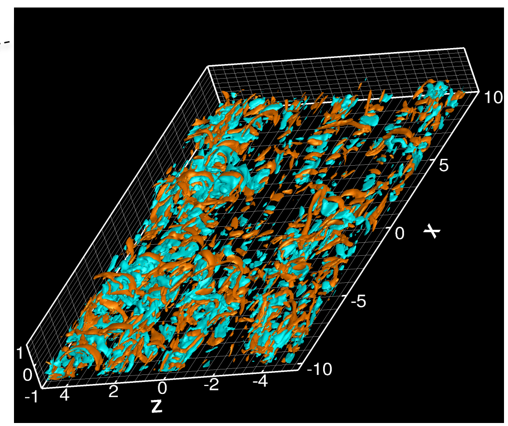




Isosurface of Q_a invariant

Re=1000, Wi⁺=24

- Not laminar
- Elastic contributions



Re=6000, Wi⁺=96

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

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Transitional viscoelastic flows

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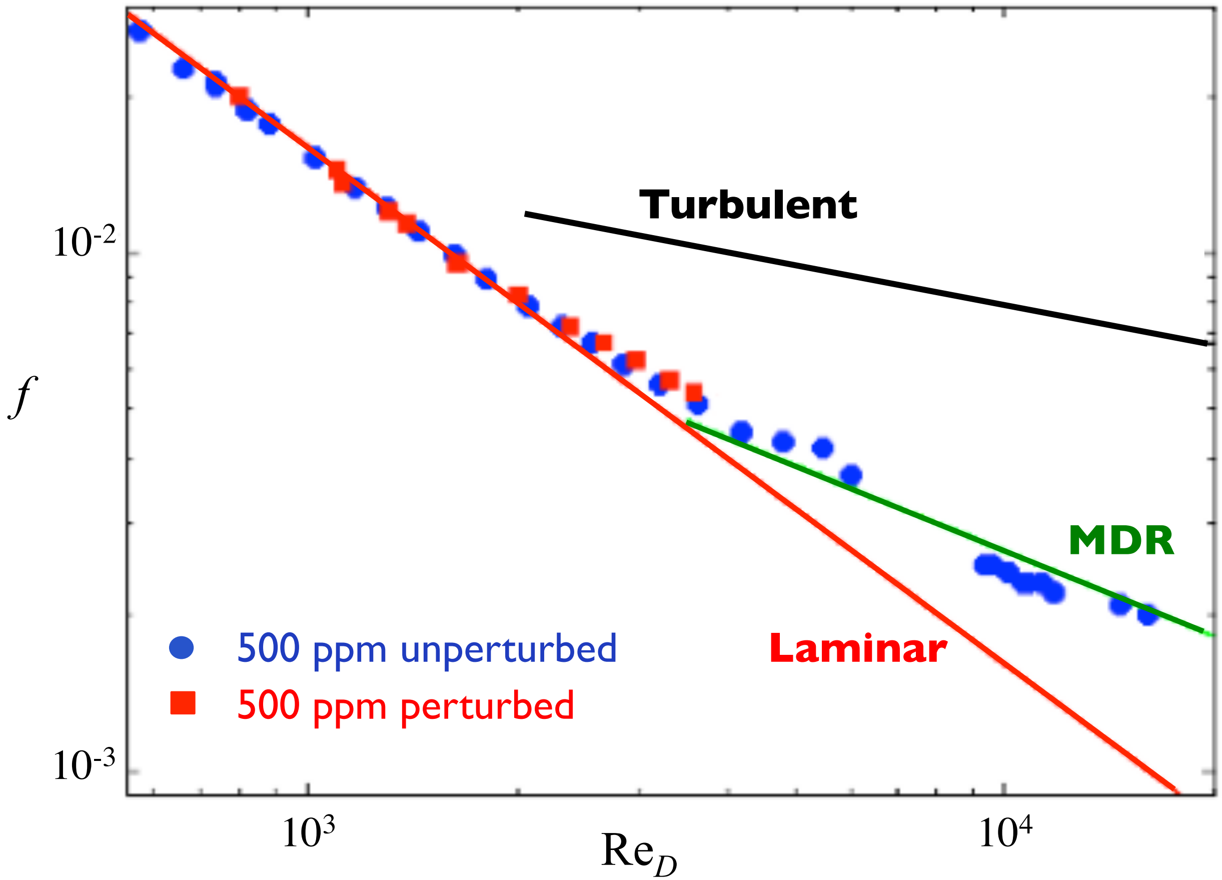
Pipe flow experiment with PAAm solution

Friction factor



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

Results of numerical simulations are confirmed by experimental measurements

Qualitative flow behavior

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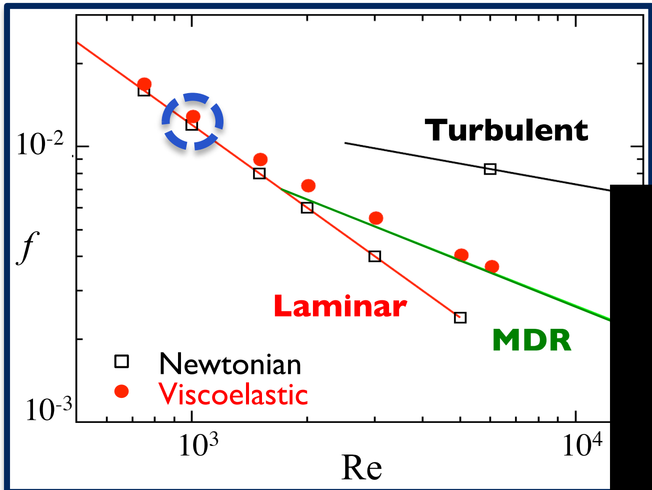
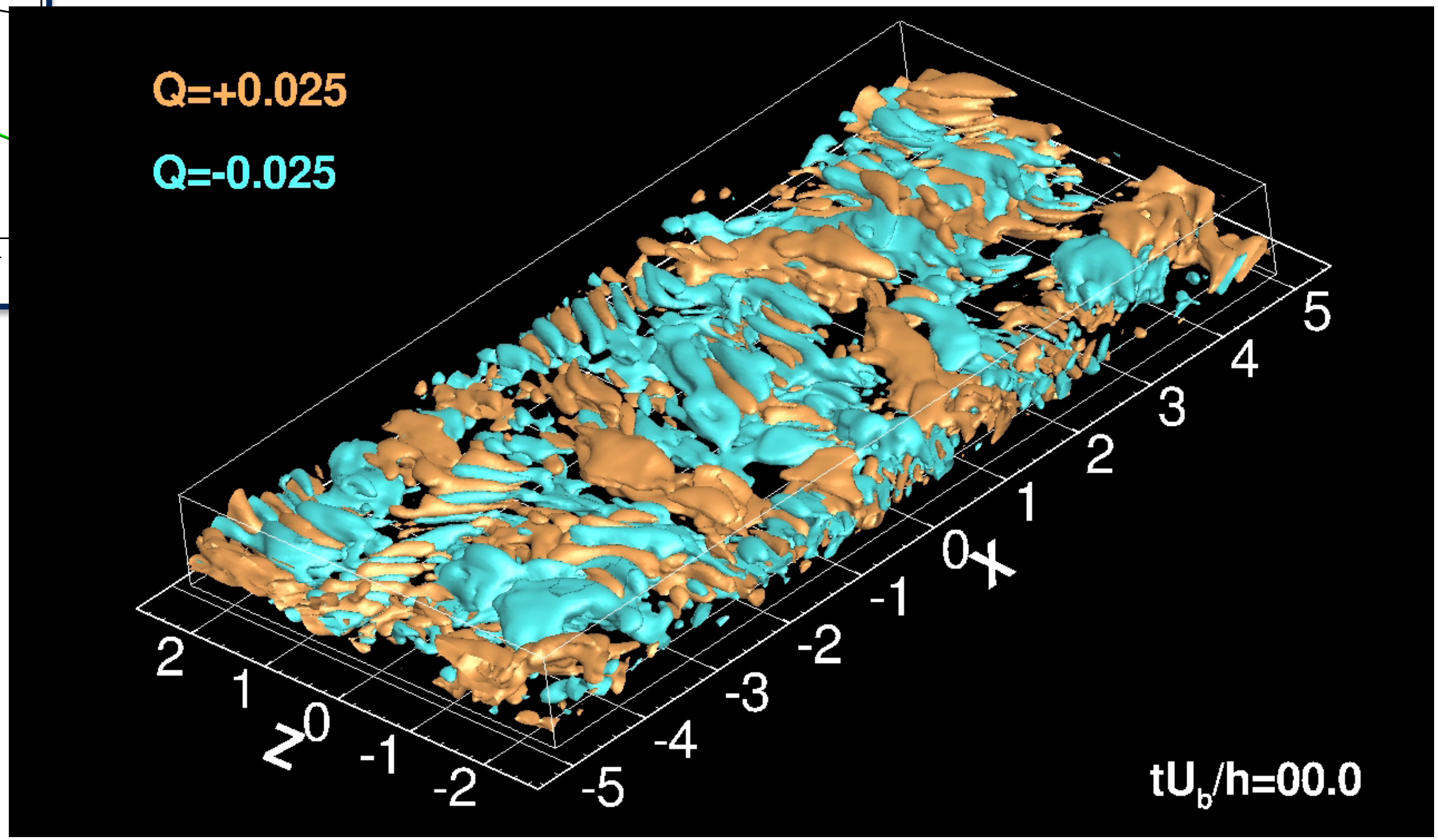
Re = 1000
$Wi^+ = 24$





Second invariant of the velocity gradient tensor: $Q_a = ½ (\Omega^2 - S^2)$

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Qualitative flow behavior

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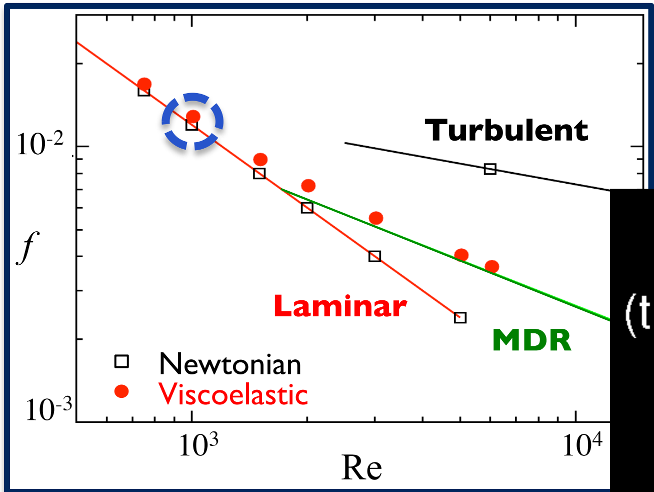
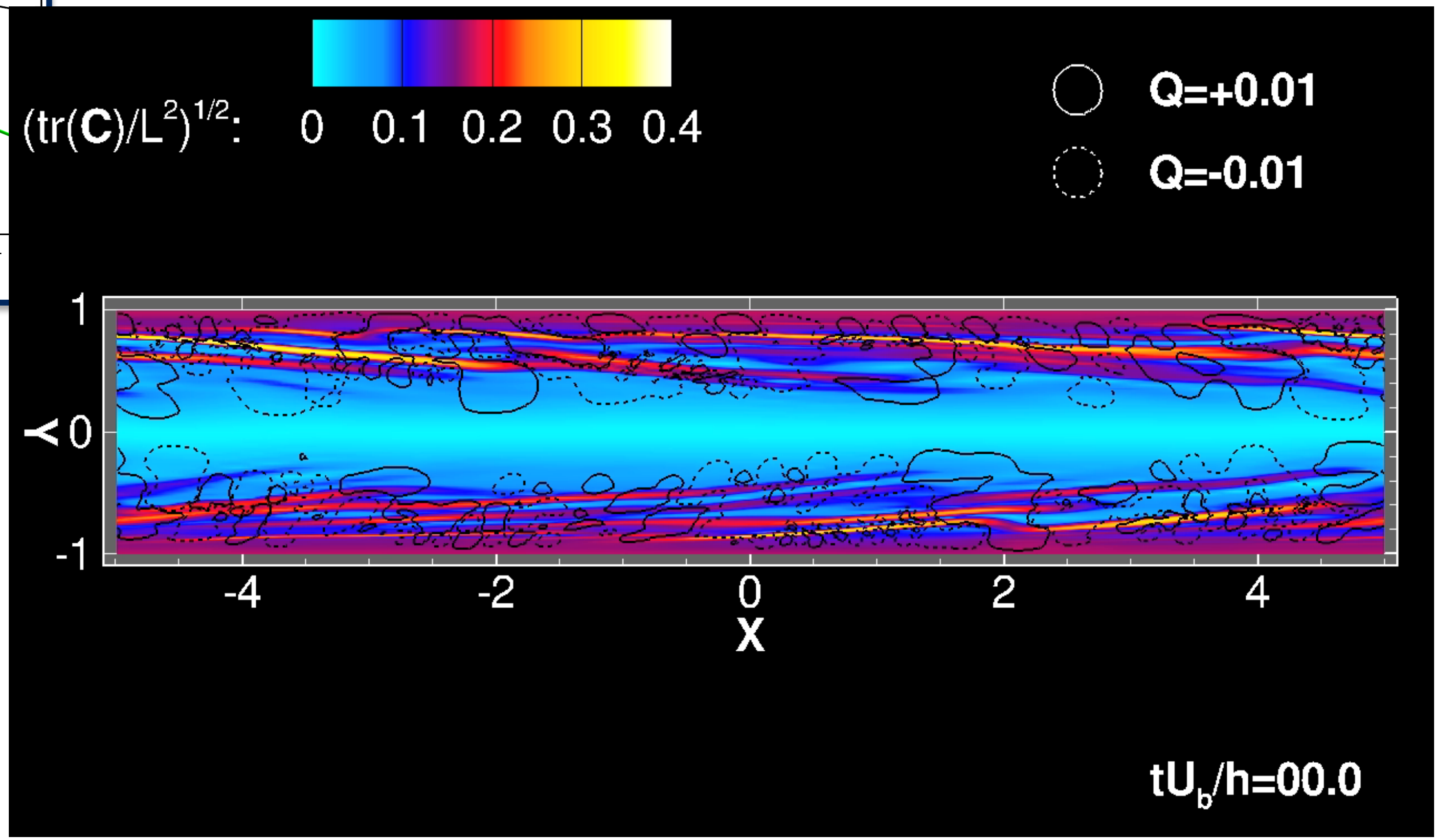


Re = 1000
$Wi^+ = 24$



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

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Qualitative flow behavior

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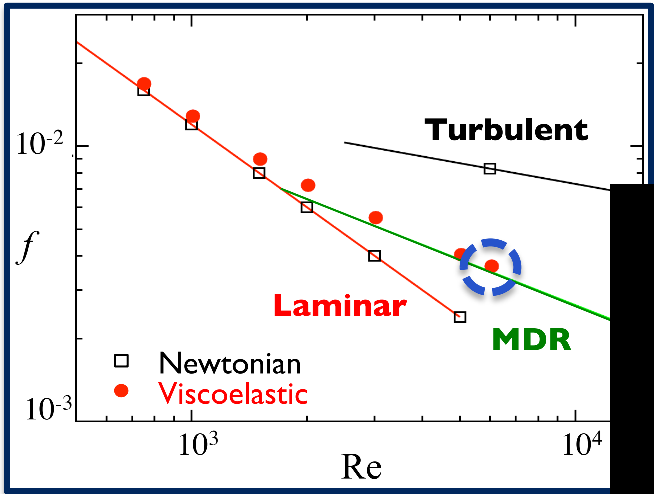
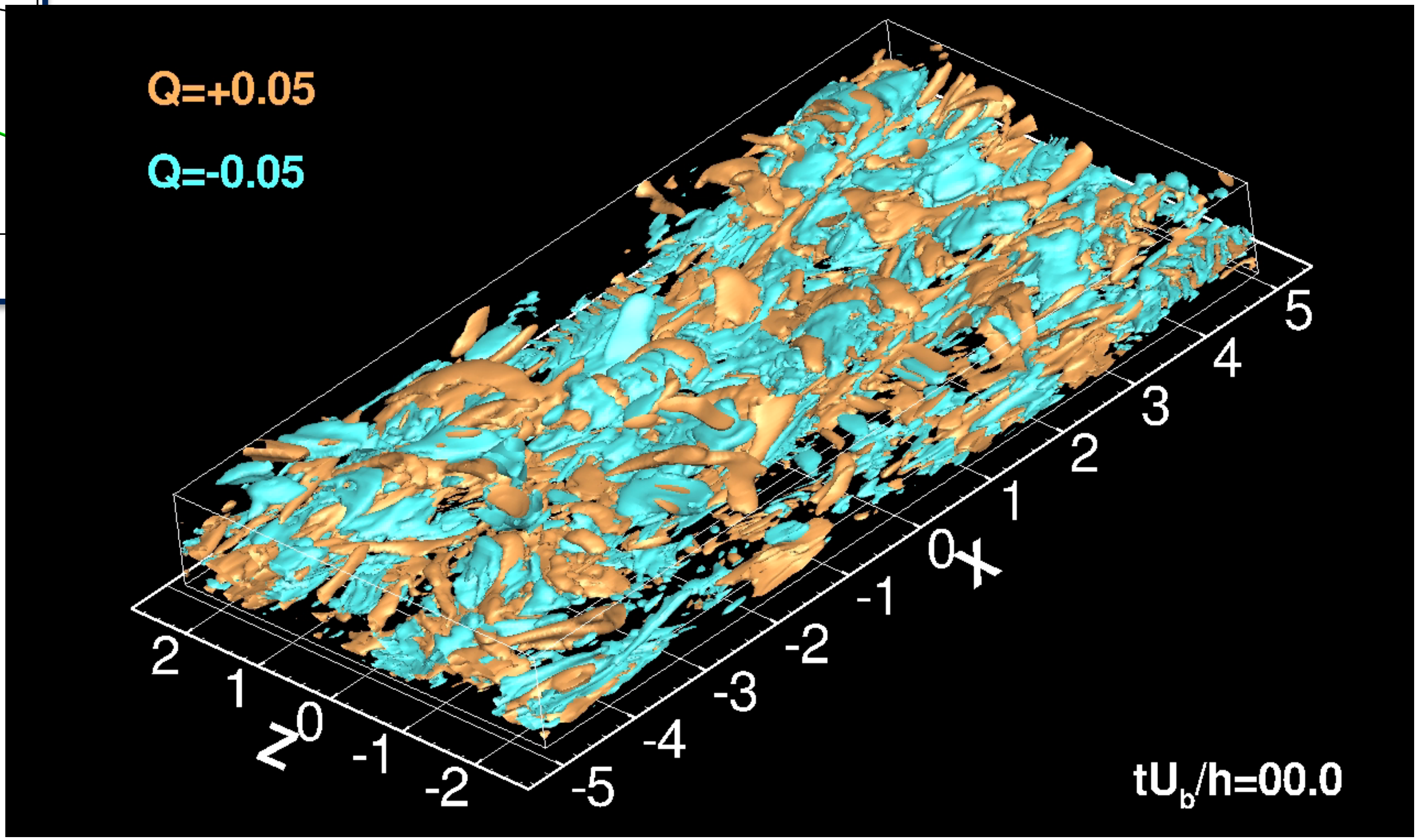
Re = 6000
$Wi^+ = 96$





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

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Qualitative flow behavior

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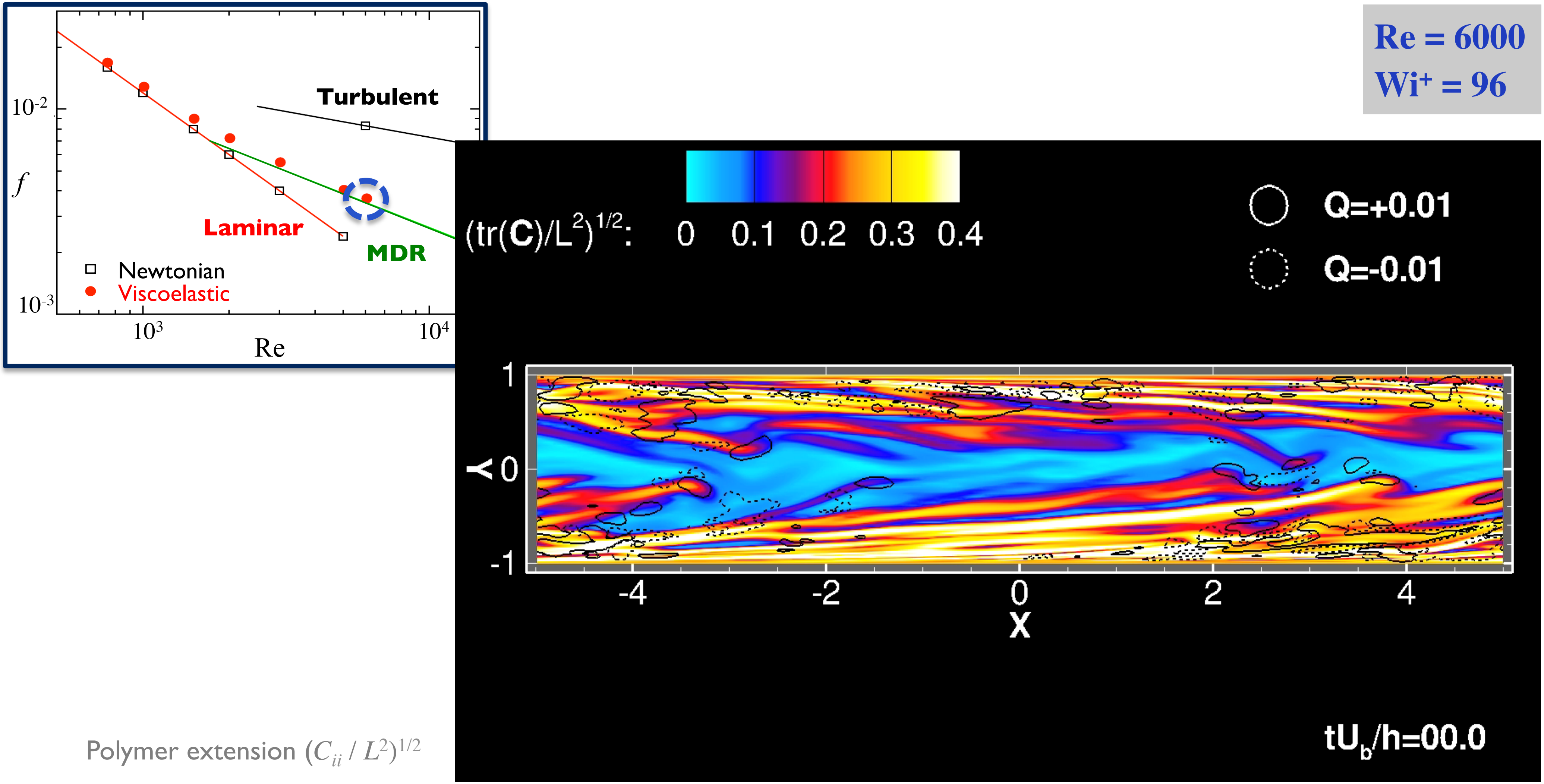
Re = 6000
$Wi^+ = 96$



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

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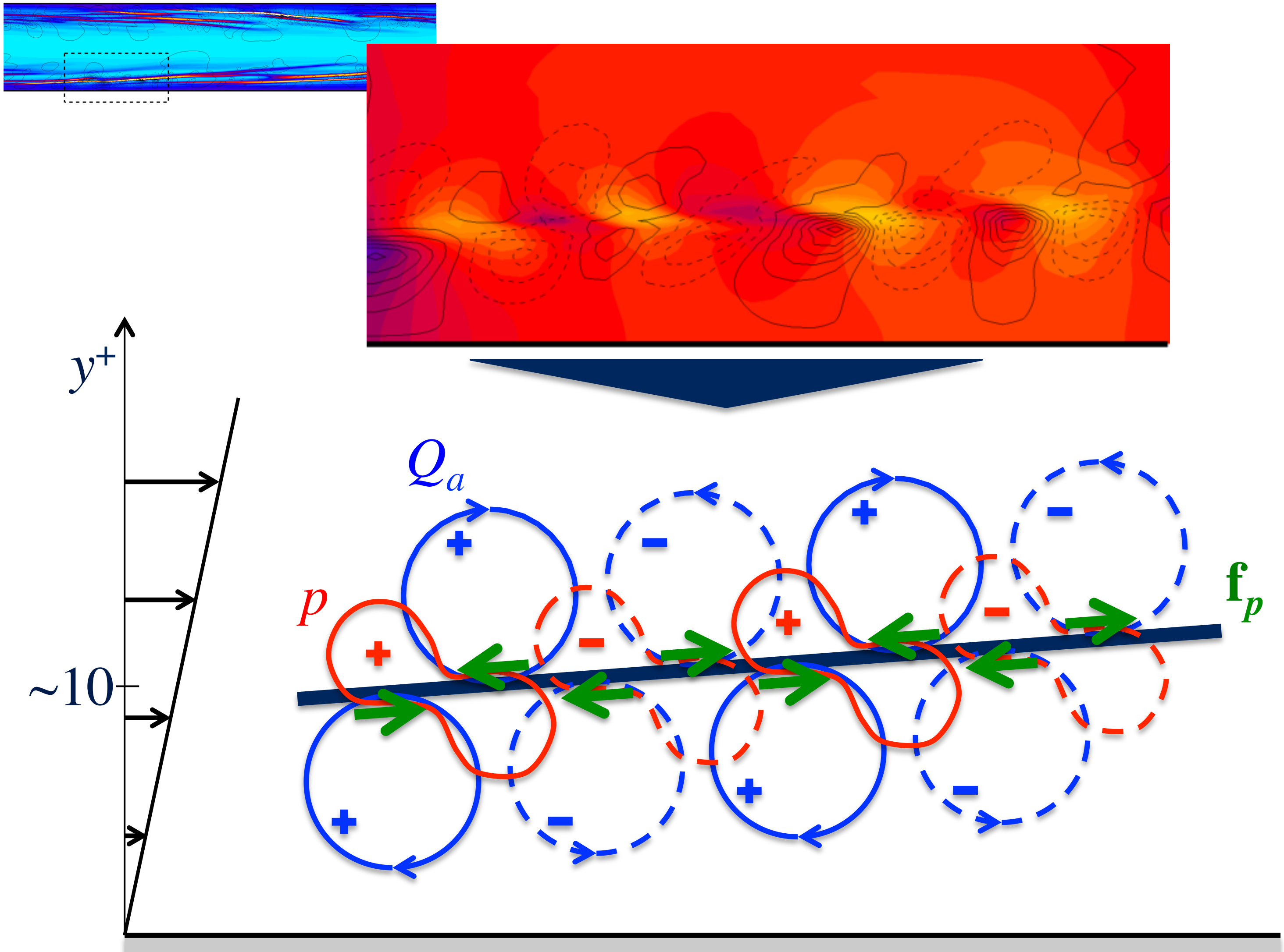
Typical structures



- 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

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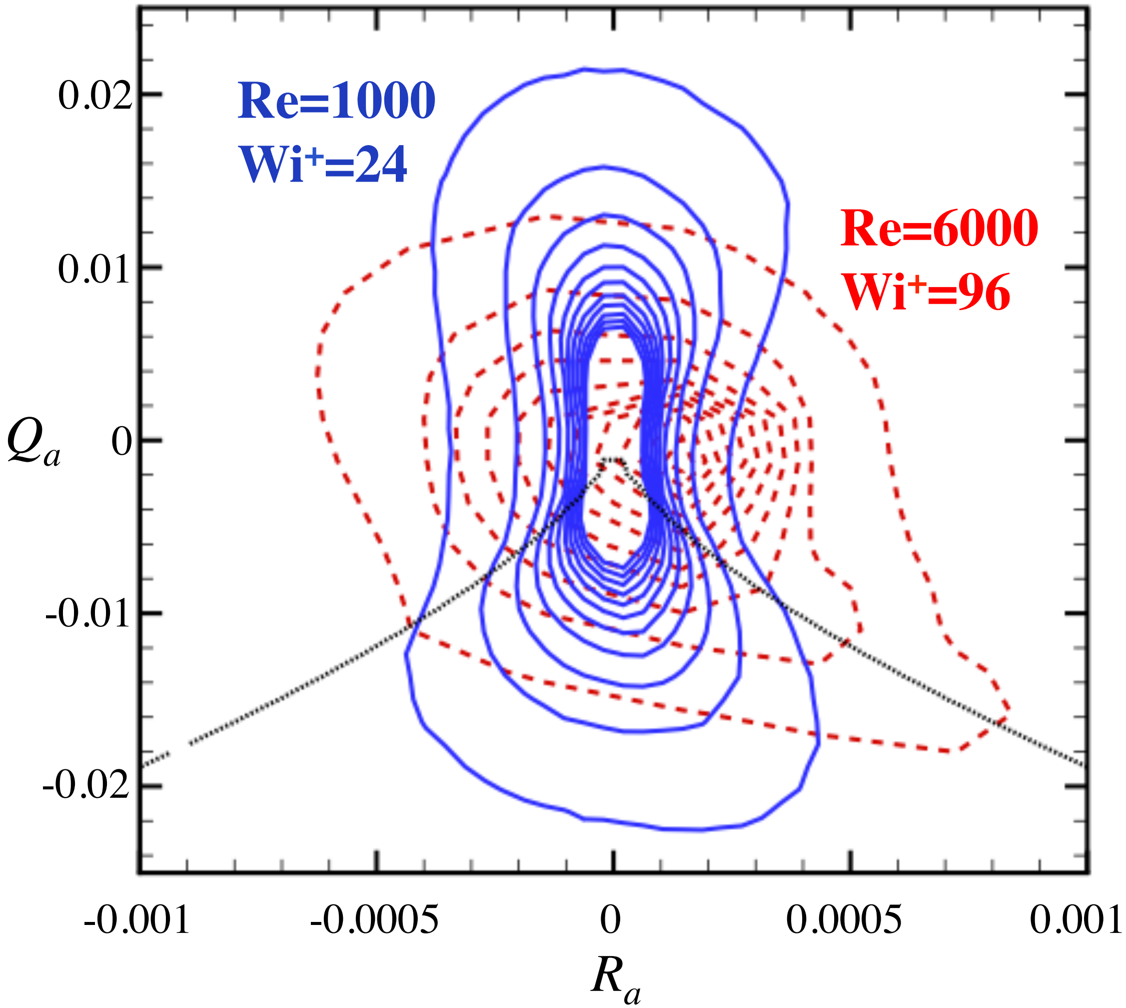
EIT flow: JPDF



- 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

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Energy transfers

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Turbulent kinetic energy budget

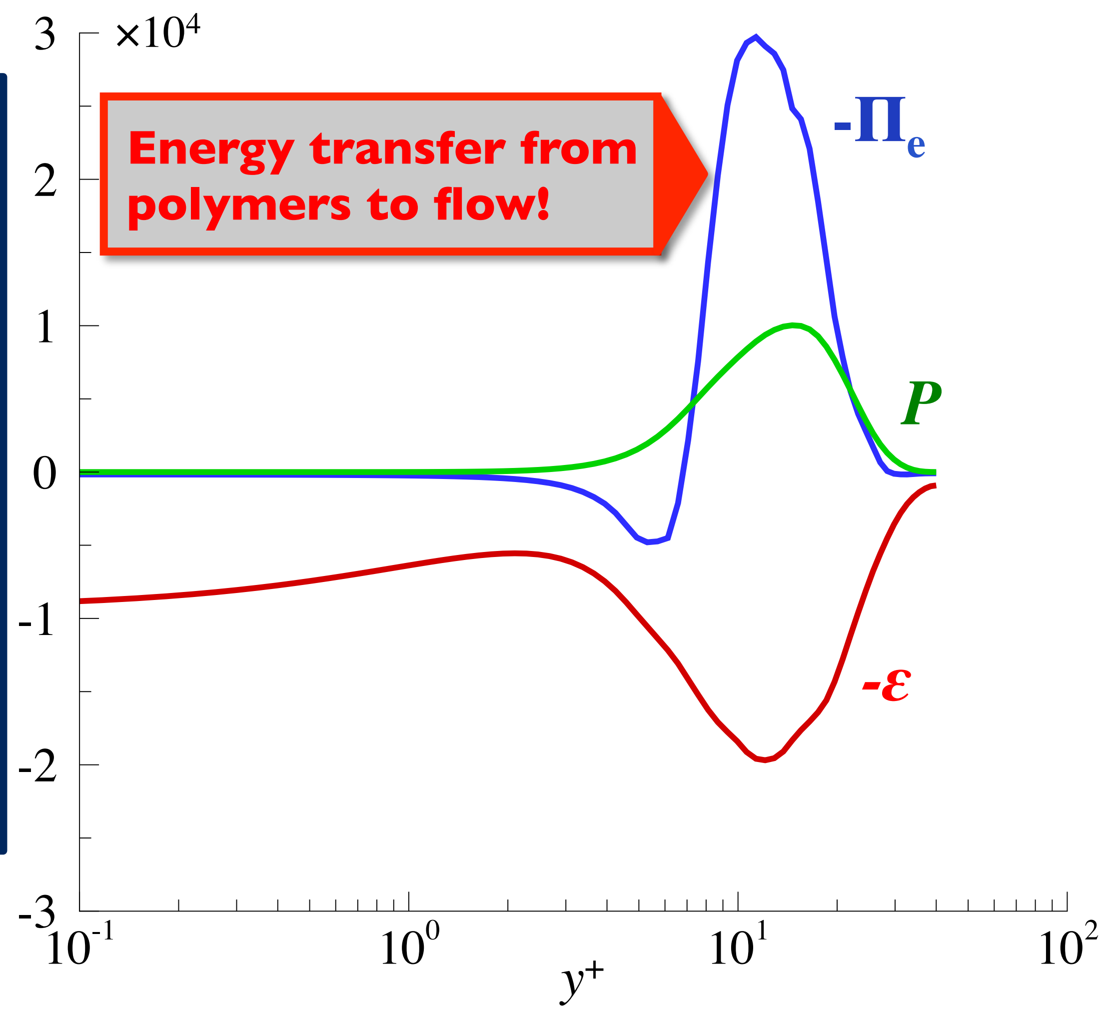
$$\int_V P \,\mathrm{d}V - \int_V \varepsilon \,\mathrm{d}V - \int_V \Pi_e \,\mathrm{d}V = 0$$

Production

Dissipation

Transfer between elastic energy and turbulent kinetic energy

Transfers of turbulent kinetic energy
Re=1000, Wi$^+$=24



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Our current understanding

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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

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

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

Mixed extensional-shear flow

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

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

Conclusion and future work

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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
  - Two-dimensionality
  - Energy transfers and backscatter
- 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