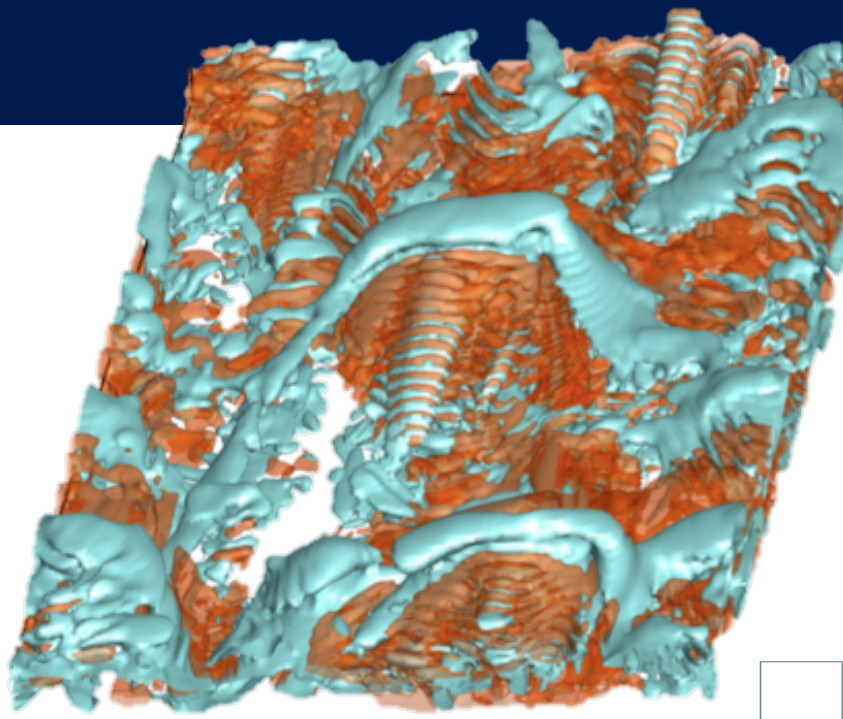
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TOWARDS A BETTER UNDERSTANDING OF POLYMER DRAG REDUCTION IN TURBULENT WALL-BOUNDED FLOWS



Vincent E. Terrapon, Yves Dubief,
Chris M. White & Eric S.G. Shaqfeh

“Polymers in Fluids”
Nice, 14-15 November 2011

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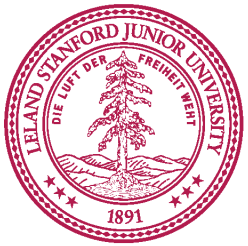
Acknowledgements

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- Prof. Yves Dubief
- Prof. Chris M. White
- Prof. Eric S.G. Shaqfeh
- DARPA Friction Drag Reduction Program at Stanford (2001-2005)





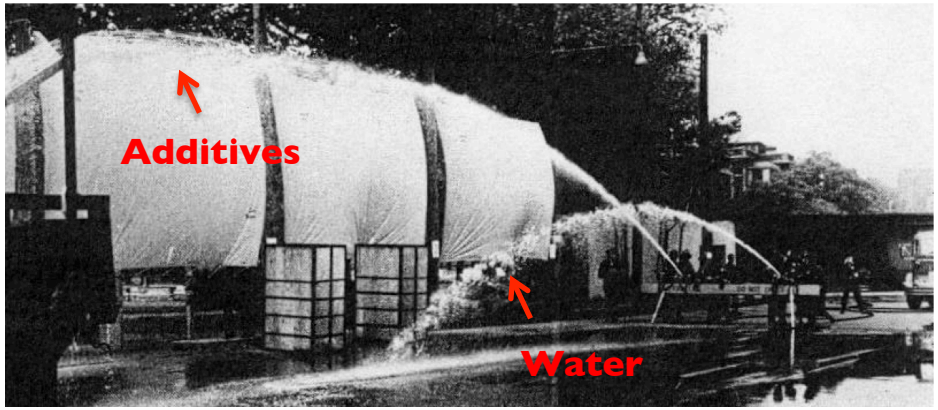




Polymers and turbulence

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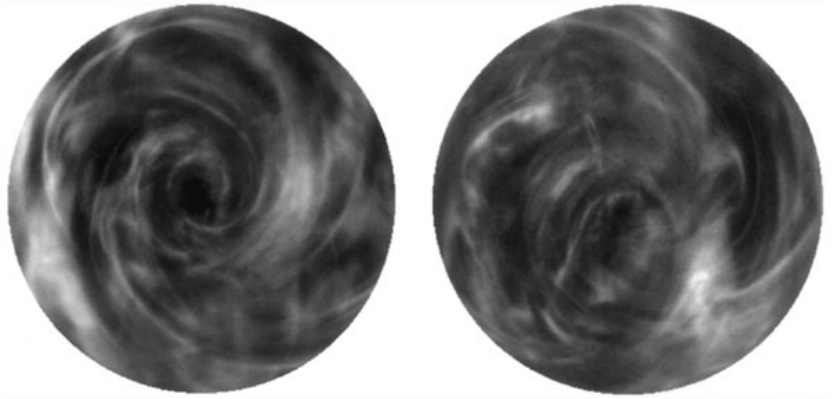
Turbulent drag reduction



Fire hoses with and without polymer additives

- 100 - 1000 ppm of high molecular weight polymers may yield up to 80% friction drag reduction in turbulent wall-bounded flows
- No significant effects on drag in laminar flows
- Drag reduction asymptotes to the Maximum Drag Reduction (MDR)

Elastic turbulence



Chaotic motion of a polymer solution in microchannel (Groisman & Steinberg, 2000)

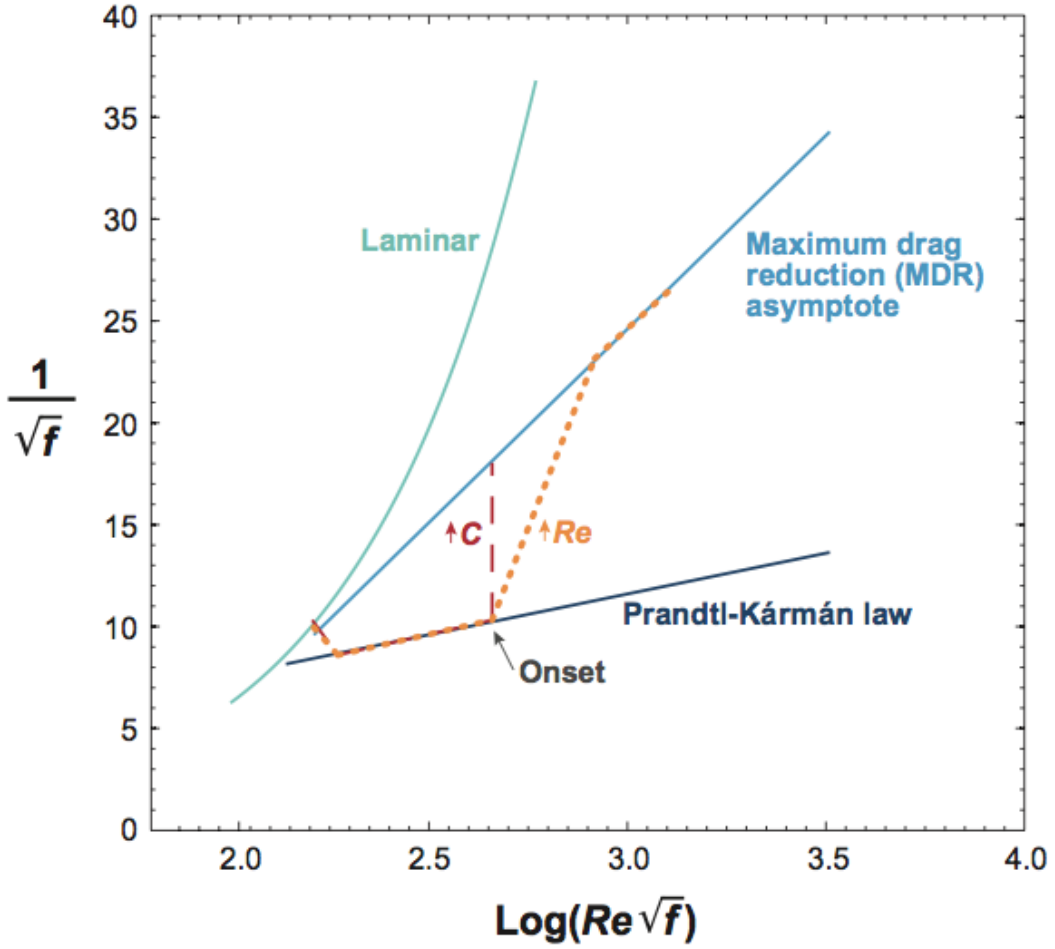
- Elastic instabilities first found in viscometers
- Existence of elastic turbulence in curvilinear flows
- So far only observed for $Re \ll 1$

?

Link

Polymer drag reduction

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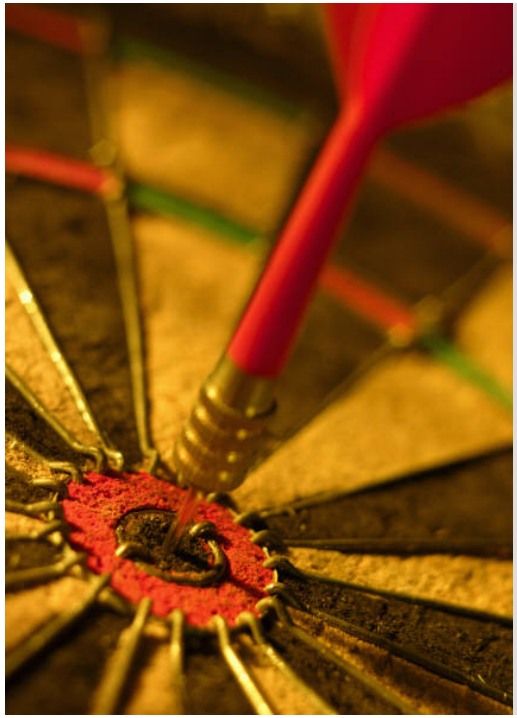
Onset and drag reduction trajectories in Prandtl-Karman coordinates (White & Mungal, 2008)

- After onset, drag reduction (DR) increases with concentration *C* or Reynolds number *Re*
- DR saturates at the maximum drag reduction (MDR) asymptote (also known as Virk's asymptote)
- MDR is universal (independent of polymer, concentration, …)

?

- **How is the MDR flow characterized?**
- **Why does the flow not relaminarize?**

Objectives



- Identify the **nature of MDR**
- Investigate existence of **small scale** polymer dynamics
- Understand importance of **elasticity**

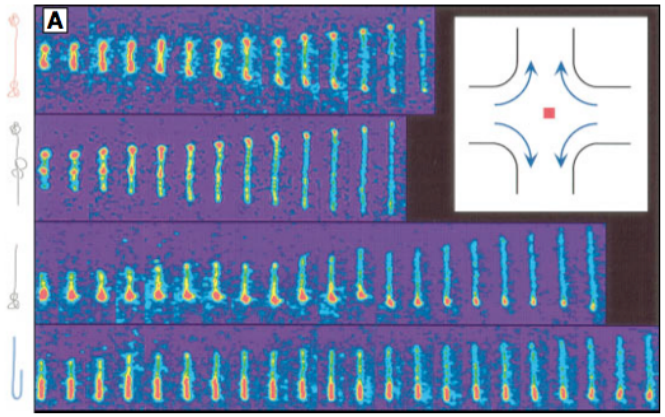
Outline

- **Introduction and background**
- Modeling and numerical implementation
- Maximum drag reduction asymptote
- Elasticity and small scales

A challenging problem

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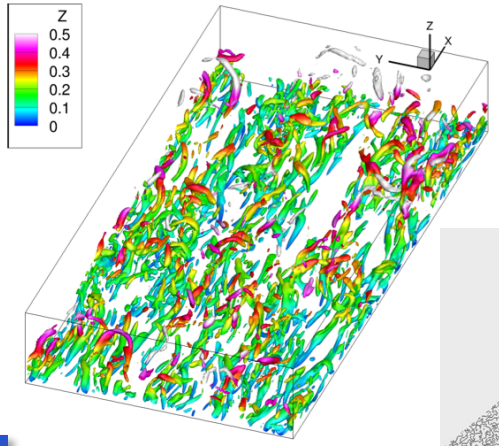
Polymer dynamics in flows



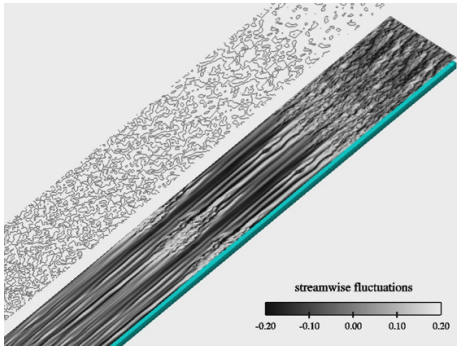
Dynamics of a single DNA molecule in an extensional flow (Perkins *et al.*, 1997)

- Long and flexible macromolecules (e.g., PEO, PAM)
- Tumbling and stretching (coil-stretch transition) dynamics in flows
- Create stress

Wall-bounded turbulent flow



Vortices (colored by distance from wall), and streaks in transitional BL

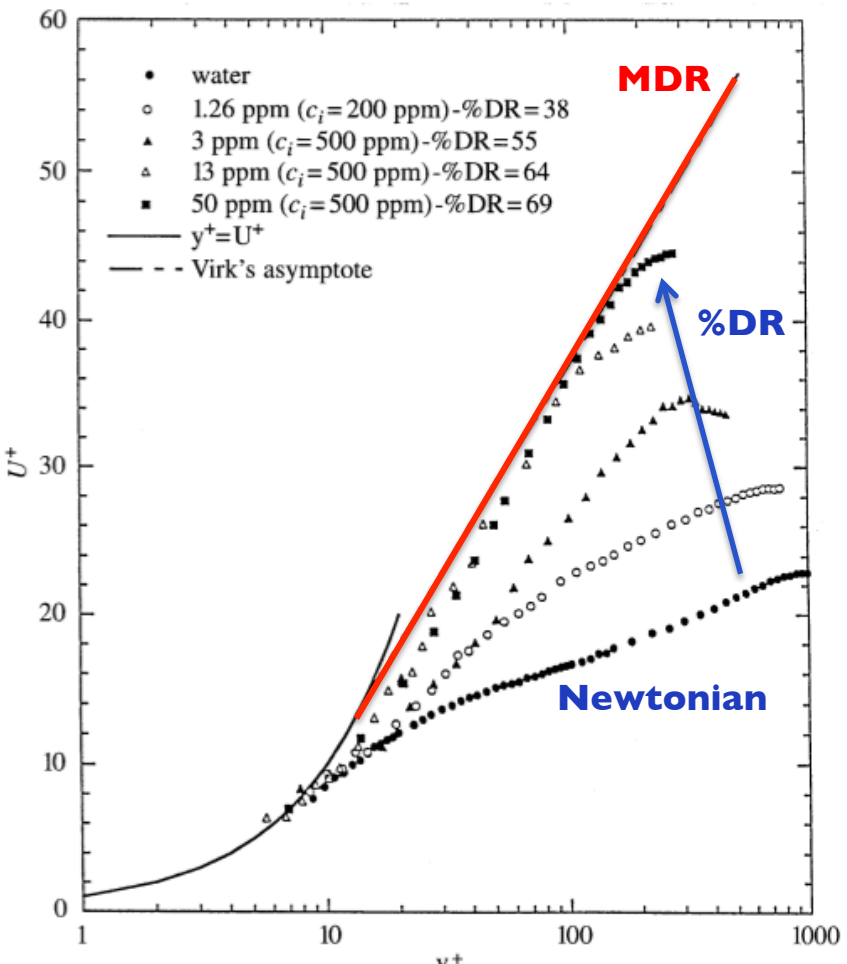


- Streamwise velocity is organized in streaks
- Turbulence is driven by near-wall vortices
- Turbulent friction drag is up to 10× higher than laminar

Agreements and disagreements

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Mean velocity profile



Mean velocity profile in wall units from experimental measurements (Warholic *et al.*, 1999)

- Drag reduction (also for surfactants, fibers)
- Modified log law
  - Newtonian: $U^+ = 0.4 \ln(y^+) + 5.5$
  - Parallel shift at low drag reduction (LDR)
  - Change of slope at high drag reduction (HDR)
  - From buffer layer to edge of boundary layer
- MDR asymptote
  - Universal
  - Not laminar
  - Virk's log-law: $U^+ = 11.7 \ln(y^+) - 17$

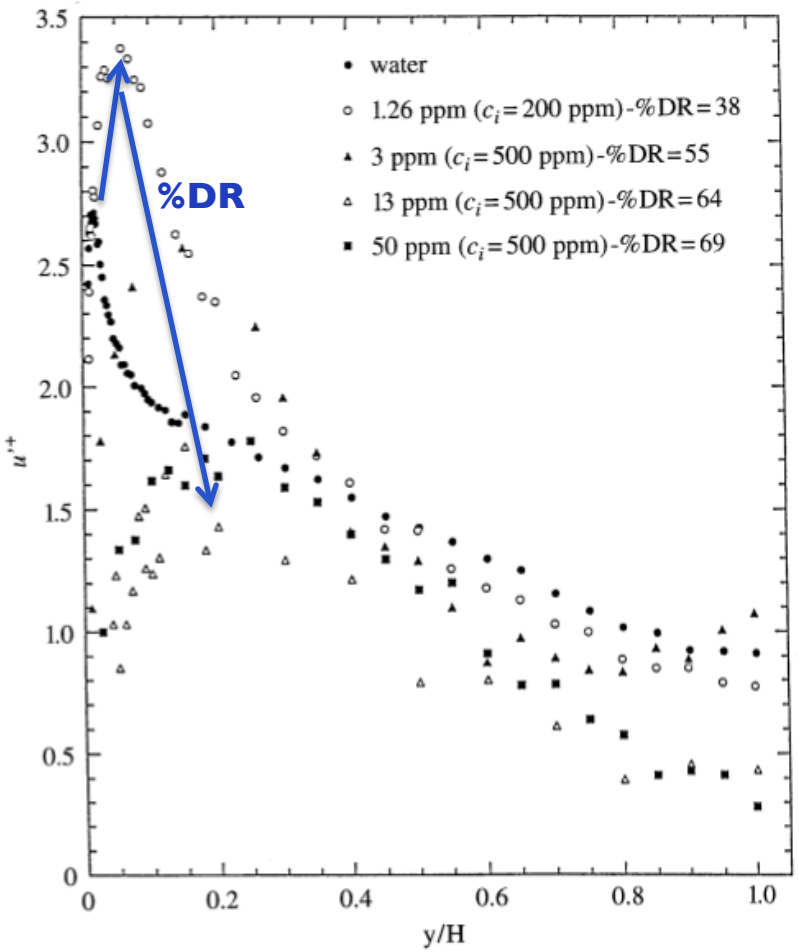
- No changes in DR before MDR asymptote (minimal flow unit)
- Plug flow or change of slope at HDR?
- Only partial MDR asymptote if heterogeneous concentration (e.g., wall injection)

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Agreements and disagreements

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Streamwise velocity fluctuations



Streamwise velocity fluctuations in wall units from experimental measurements (Warholic *et al.*, 1999)

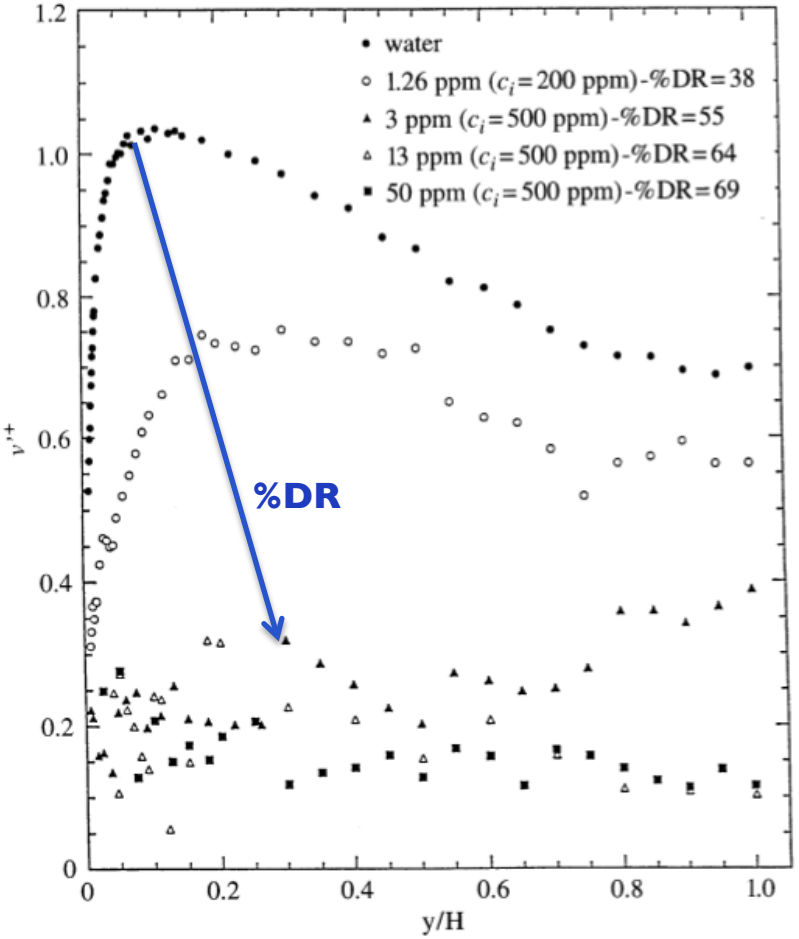
- First, increase in peak value
- Damping of peak value at higher DR
- Displacement of maximum location away from the wall
- Increase in size of buffer layer

- Decrease of maximum streamwise velocity fluctuations not always observed

Agreements and disagreements

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Wall-normal velocity fluctuations



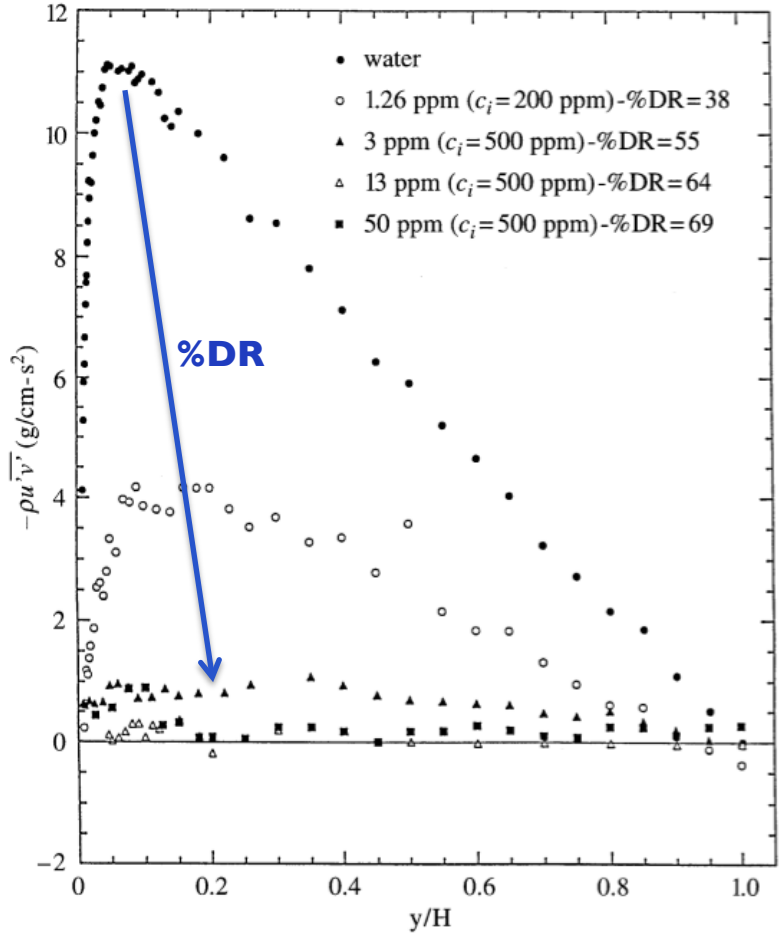
Wall-normal velocity fluctuations in wall units from experimental measurements (Warholic *et al.*, 1999)

- Strong damping with increasing DR
- Displacement of location of maximum value away from the wall

Agreements and disagreements

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Reynolds stress



Reynolds stress from experimental measurements (Warholic *et al.*, 1999)

- Strong damping of Reynolds stress with %DR
- Displacement of location of maximum value away from wall
- Contribution of polymer stress growing with %DR

$$\underbrace{-\overline{u'v'}}_{\text{Reynolds stress}} = \underbrace{-\frac{dP}{dx}}_{\text{Pressure gradient}} + \underbrace{\frac{\beta}{Re}\frac{dU}{dy}}_{\text{Viscous shear stress}} + \underbrace{\frac{1-\beta}{Re}\frac{dT_{xy}}{dy}}_{\textbf{Polymer stress (“stress deficit”)}}$$

- Does Reynolds stress vanishes at MDR or is it finite?

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Major contributions

Polymer drag reduction

- Toms (1948): Discovers experimentally the phenomenon
- Virk et al. (1967): Existence of the MDR asymptote
- Lumley (1969): Polymers affect solution viscosity over large scales (viscous effect)
- Voigt (1977): Early turbulence
- De Gennes (1986): Polymer-turbulence interactions are small scale (elastic effect)
- Beris et al. (1996): First DNS of polymer drag reduction in channel
- L'vov et al. (2004), Benzi et al. (2005): Derivation of MDR asymptote
- DARPA Friction drag reduction program (2001-2005)
- …

Elastic turbulence

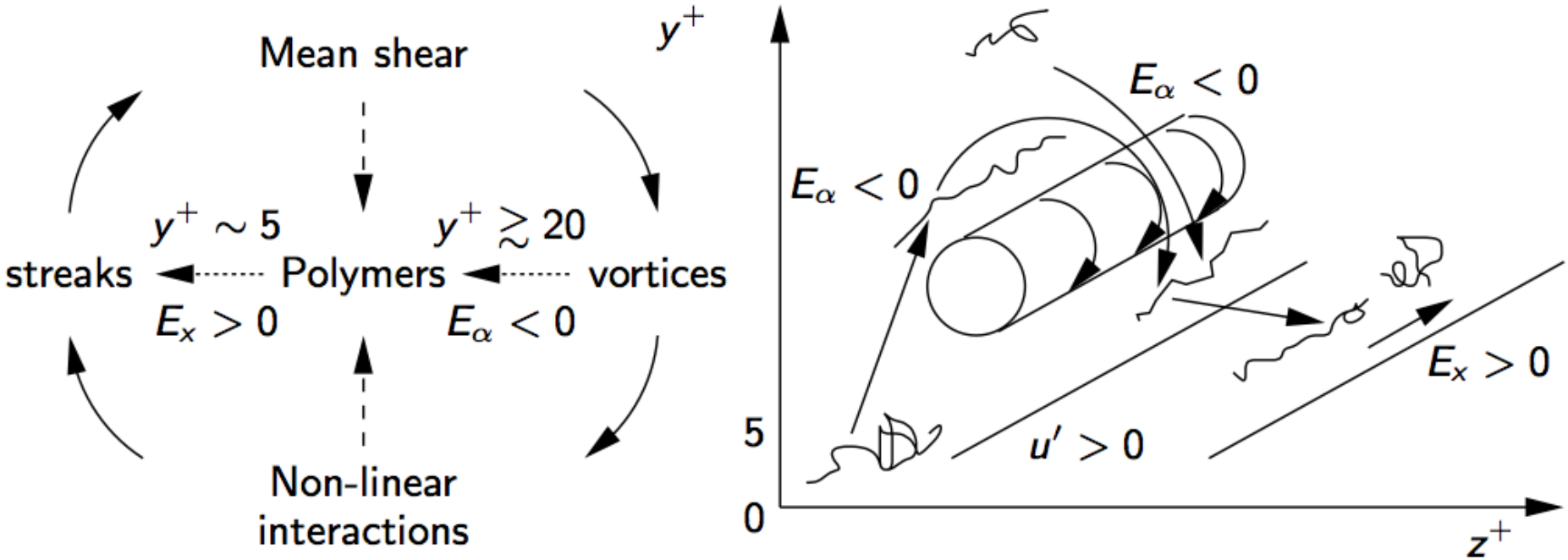
- Larson & Shaqfeh (1990): Elastic instability in inertia-less flow
- Groisman & Steinberg (2000): Elastic turbulence in inertia-less flow

Current understanding of mechanism

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Polymers weaken vortices

- Polymers store turbulent kinetic energy into elastic energy in upwash and downwash flows caused by near-wall vortices, and release it in the high-speed streaks (Dubief *et al.*, 2004)
- The stretch of polymers is caused by the bi-axial extensional nature of these upwash and downwash flows (Terrapon *et al.*, 2004)



Modified wall-turbulence regeneration cycle (Dubief *et al.*, 2004)

Some remaining open questions

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Today

- How can we predict DR onset?
- How do the polymers exactly interact with vortices?
- Where do the polymers really need to act?
- Is DR a viscous / large scale effect or an elastic / small scale effect?
- Do polymers positively contribute to the turbulent kinetic energy?
- What is the nature of MDR?

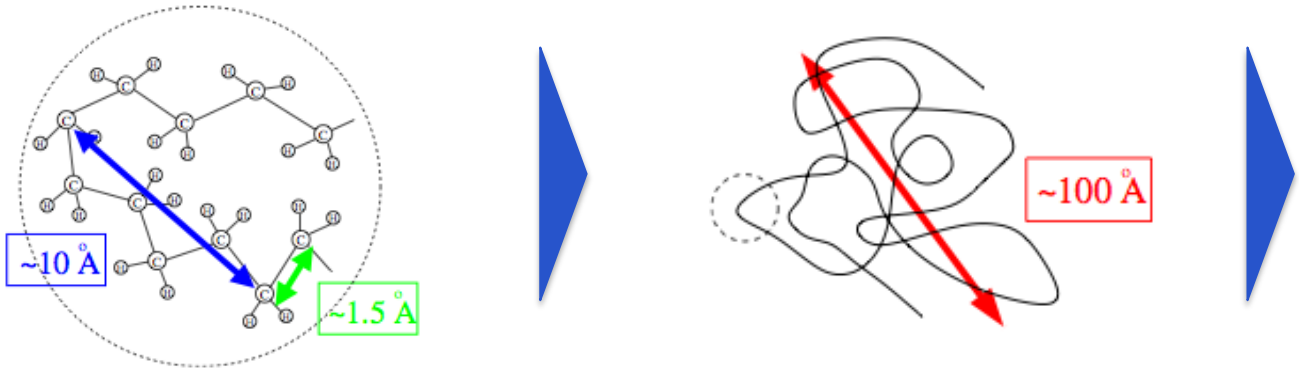
Outline

- Introduction and background
- **Modeling and numerical implementation**
- Maximum drag reduction asymptote
- Elasticity and small scales

Modeling polymer dynamics

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Coarse graining and force balance on beads



Equation for polymer extension vector

$$\frac{d\mathbf{q}}{dt} = \underbrace{\nabla \mathbf{u} \cdot \mathbf{q}}_{\text{Hydro}} \underbrace{- \frac{1}{We} \frac{\mathbf{q}}{2\left(1 - q^2/L^2\right)}}_{\text{Spring}} \underbrace{- \frac{1}{\sqrt{We}} \frac{d\mathbf{n}}{dt}}_{\text{Brownian}}$$

Polymer models

Today

FENE

$$\frac{d\mathbf{q}}{dt} = \nabla\mathbf{u}\cdot\mathbf{q} - \frac{1}{We}\frac{\mathbf{q}}{2\left(1-q^2/L^2\right)} - \frac{1}{\sqrt{We}}\frac{d\mathbf{n}}{dt}$$

$$\mathbf{T}^{poly} = \frac{1}{We}\left\langle\frac{\mathbf{qq}}{1-q^2/L^2} - \mathbf{I}\right\rangle$$

- Stochastic
- Lagrangian
- Particle tracking

FENE-P

$$\frac{d\langle\mathbf{qq}\rangle}{dt} = \nabla\mathbf{u}\cdot\langle\mathbf{qq}\rangle + \langle\mathbf{qq}\rangle\cdot\nabla\mathbf{u}^T - \frac{1}{We}\left(\frac{\langle\mathbf{qq}\rangle}{1-\langle qq\rangle/L^2} - \mathbf{I}\right)$$

$$\mathbf{T}^{poly} = \frac{1}{We}\left(\frac{\langle\mathbf{qq}\rangle}{1-\langle qq\rangle/L^2} - \mathbf{I}\right)$$

- Constitutive
- Eulerian
- Approximation

Viscoelastic NSE

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Continuity

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

Momentum

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

Polymer stress

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

Conformation tensor

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

β — Ratio of solvent viscosity to zero-shear solution viscosity (depends on concentration)

$Re = \frac{U_b h}{\nu}$ — Reynolds number

$We = \frac{\lambda U}{h}$ — Weissenberg number

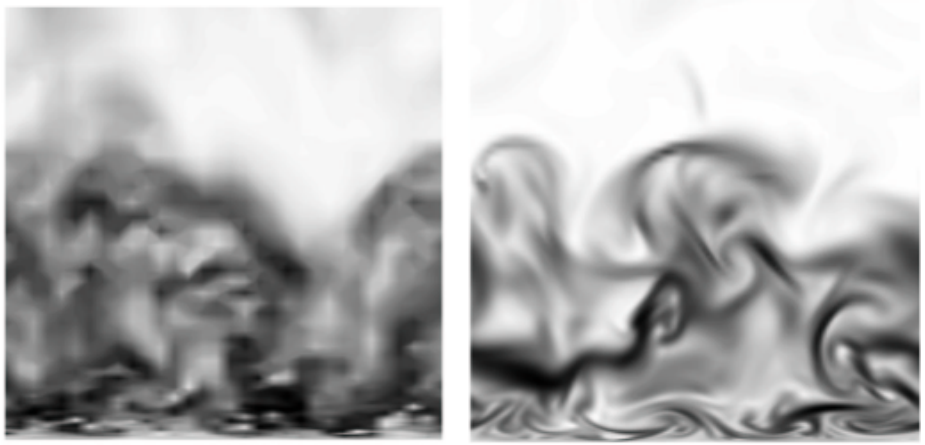
Hyperbolicity of C equation

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Equations for *C* are hyperbolic

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

- Center-of-mass diffusion neglected
- No spatial diffusion term
- Development of very small scales
- Slow decay of energy spectrum
- Instabilities in numerical computations
- Typically, Sc ~ 10^5 - 10^6



Trace of C for different grid resolutions (Dubief, 2002)

Analogy with passive scalar (Batchelor, 1959)

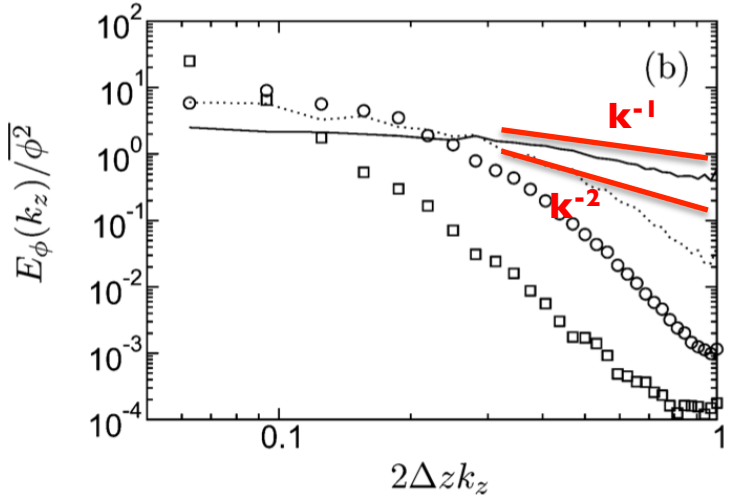
At **Sc>>1**, scalar energy spectrum decreases as

$$\mathbf{E \sim k^{-1}}$$

from Kolmogorov scale η to Batchelor scale

$$\mathbf{k_B \sim Sc^{1/2} / \eta},$$

typically 10^2 - 10^3 smaller than Kolmogorov scale



Spectrum of wall-normal velocity (symbols) and polymer stress (lines) fluctuations for DR=0% and DR=65% (Dubief, 2005)

Numerical approach

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

Time
- Semi-implicit fractional step
- 2nd order Crank-Nicolson/3rd order Runge-Kutta
- Implicit scheme for trace of *C* to ensure trace to be bounded

Artificial dissipation
- Local artificial dissipation (LAD)
- Only used when determinant of tensor *C* becomes negative

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

Min *et al.* (2001)
Dubief (2002)
Vaithianathan & Collins (2003)
Dubief *et al.* (2005)
Dallas *et al.* (2010)

Outline

- Introduction and background
- Modeling and numerical implementation
- **Maximum drag reduction asymptote**
- Elasticity and small scales

Our understanding of MDR

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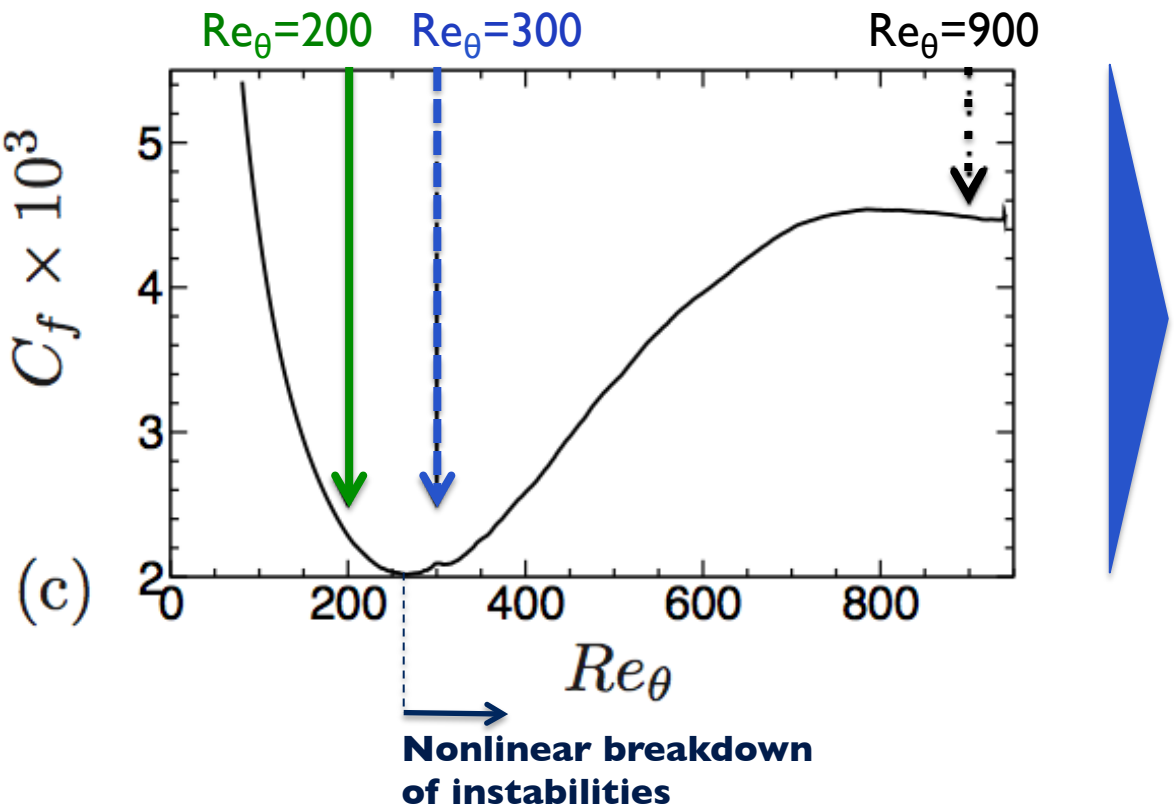
- MDR is the **transitional state** that corresponding to the onset of the **nonlinear breakdown of instabilities**
- MDR flow **oscillates** between pre- and post-breakdown state
  - Polymers disrupt the near-wall autonomous cycle of wall turbulence
  - Vortices are damped out (or sufficiently weakened as to "turn-off" their ability ability to stretch polymers)
  - Stretching mechanism for polymers is limited to wall-shear and spanwise shear layers between streaks (both modest source of polymer stretching compared to biaxial-extensional flow)
  - Polymers recoil, allowing instabilities to grow and new vortices to form
- Oscillation "amplitude" depends on **polymer elasticity**
- There is **no apparent logarithmic scaling** of velocity at MDR or in transitional flows
- There are indications of **elastic instabilities** at small scales that contribute to the regeneration of vortices following the low vortical activity

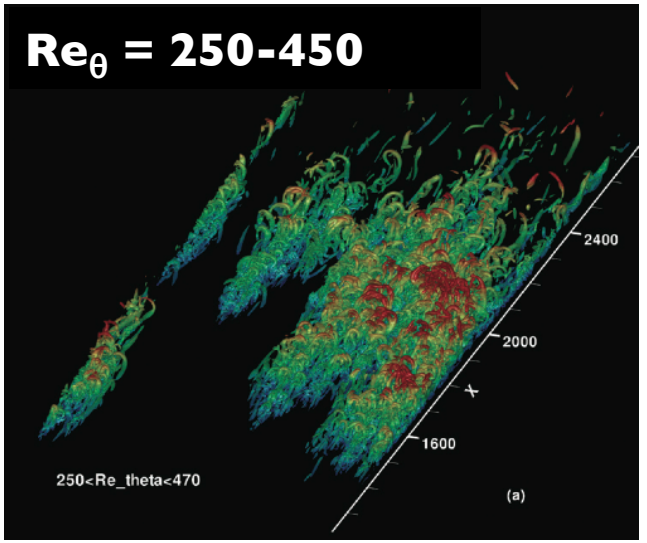
Dubief *et al.* (submitted)
Xi & Graham (2010)
L'vov *et al.* (2004)

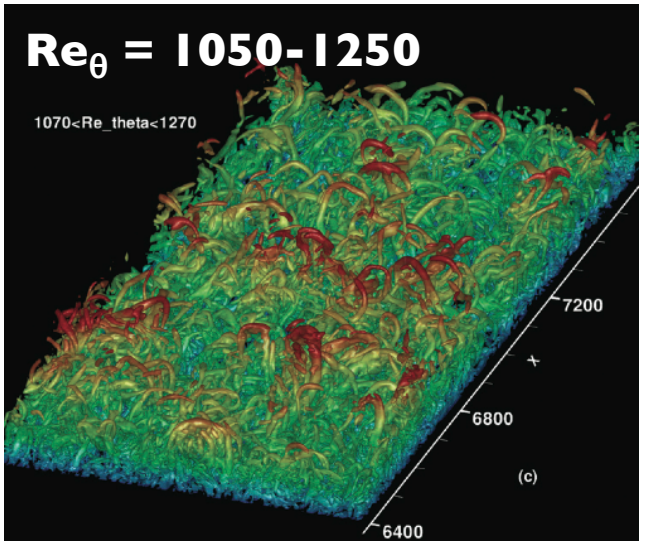
Transition in Newtonian BL

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Skin friction coefficient







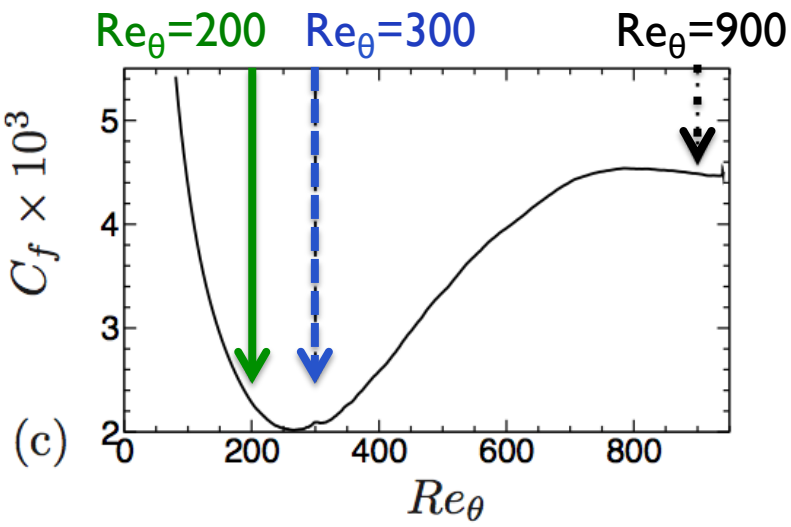
DNS of a zero-pressure gradient flat-plate boundary layer
(Wu & Moin, 2009)

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Transition in Newtonian BL

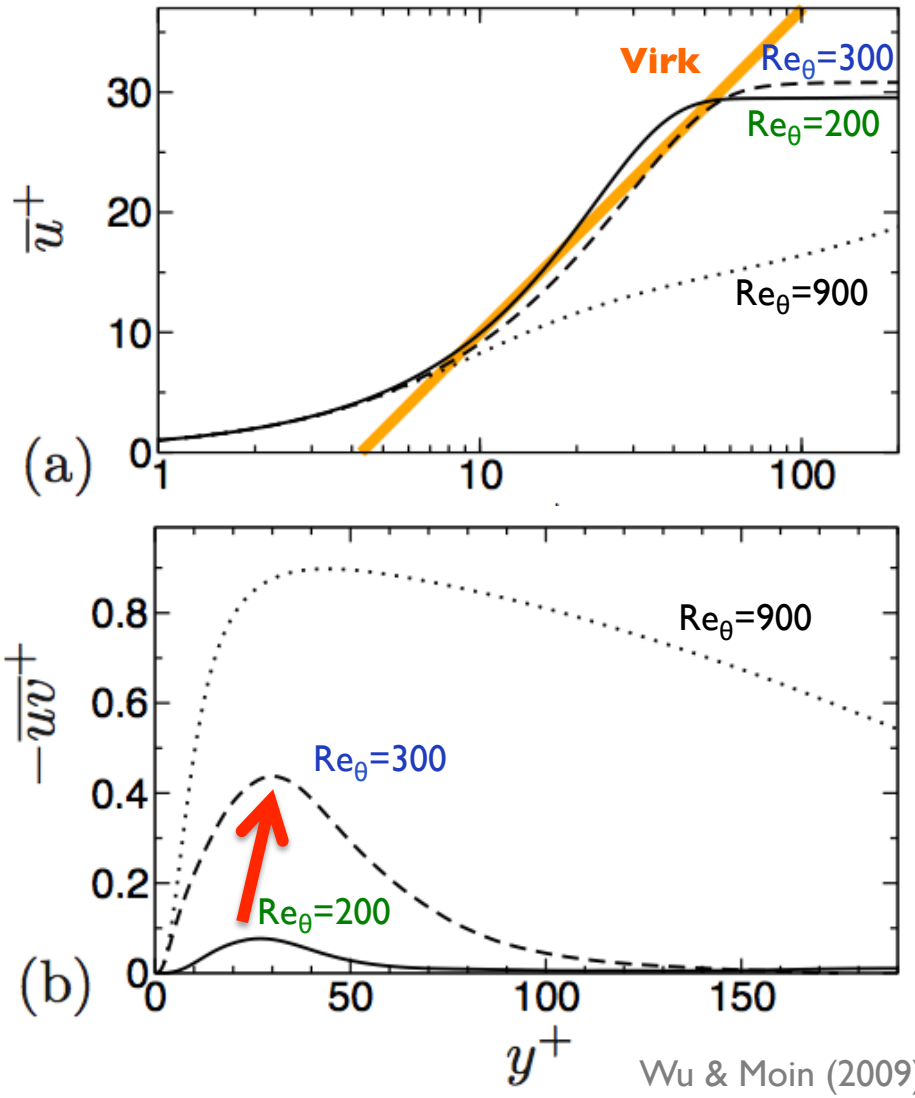
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Skin friction coefficient



Mean velocity

Reynolds stress



Wu & Moin (2009)

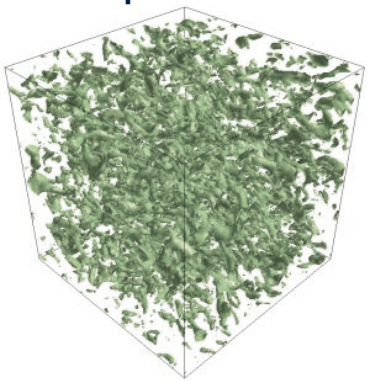
Turbulent states with velocity profiles similar to Virk's profile are confined in a narrow region around the nonlinear breakdown stage, including pre- and post-breakdown stages

Transition in channel flow

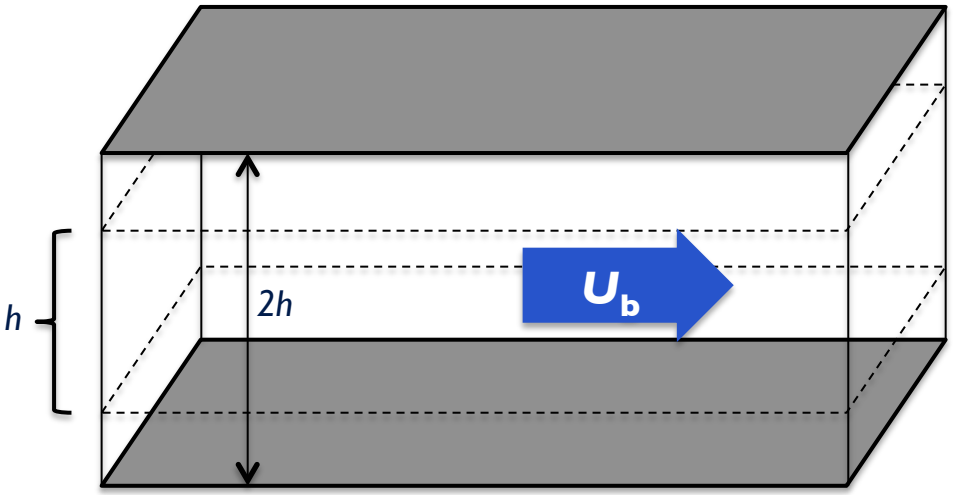
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Simulated "by-pass" transition in channel flow

Forced homogeneous isotropic turbulence



Turbulence intensity
u'/U_b = 0.015, 0.02, 0.025



- $t < 0$:
  - Free-slip
- $t = 0$:
  - No-slip
  - Polymers on (V)
  - Newtonian (N)

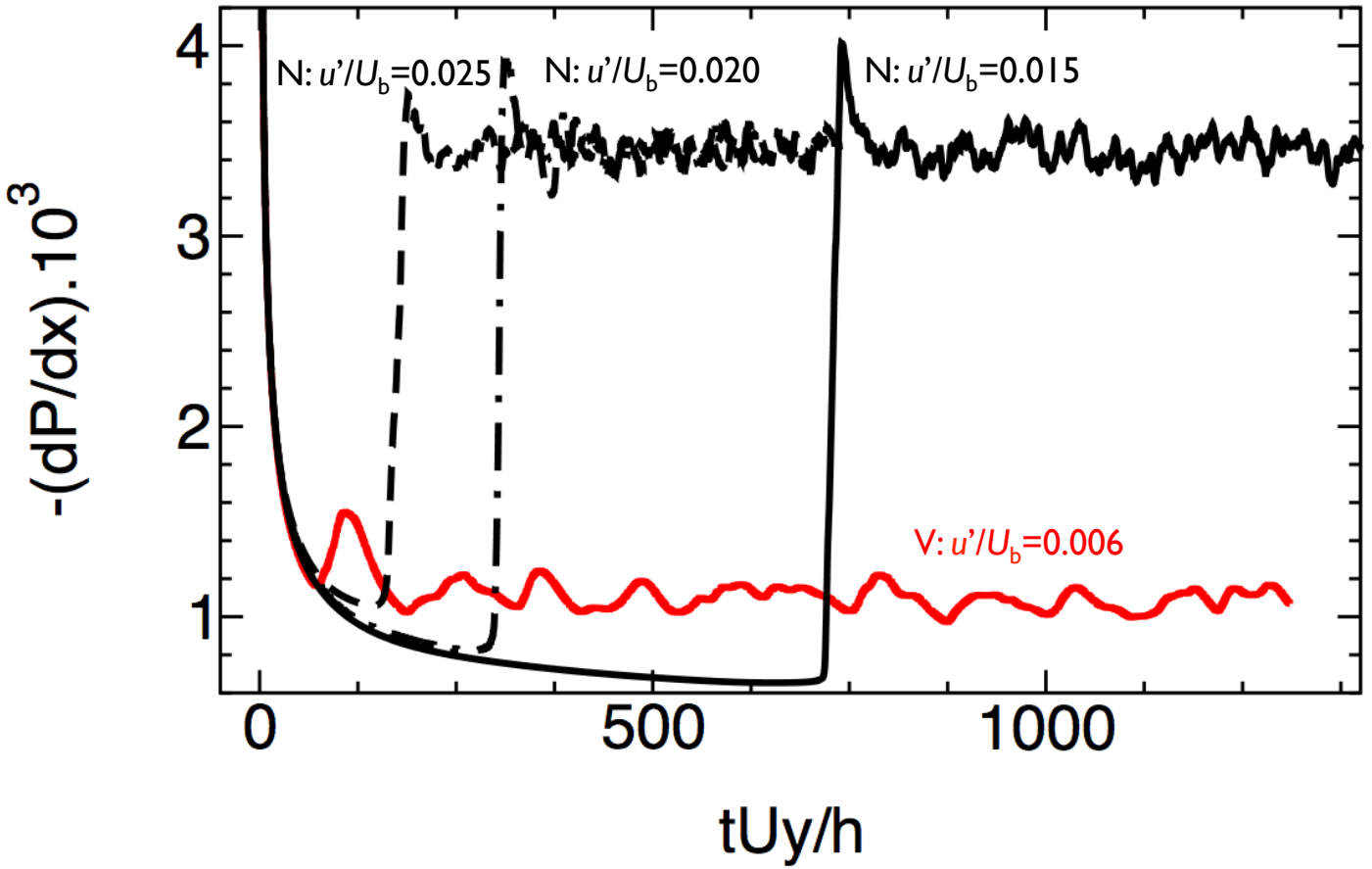
Parameters

• Reynolds numbers:	$Re_\tau = 300, Re_B = 5000$
• Size:	$(20/3)h \times 2h \times (10/3)\pi h$
• Size (wall units):	2000 x 600 x 100
• Grid:	256 x 161 x 256
• Resolution:	$\Delta x^+ = 7.8, \Delta z^+ = 3.9, \Delta y^+_{min} = 0.2$
• Polymers:	$L = 200, We_\tau = 720, \beta = 0.9$
• MDR:	$DR = 65\%, Re_\tau = 180$

Transition in channel flow

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Pressure gradient during transition

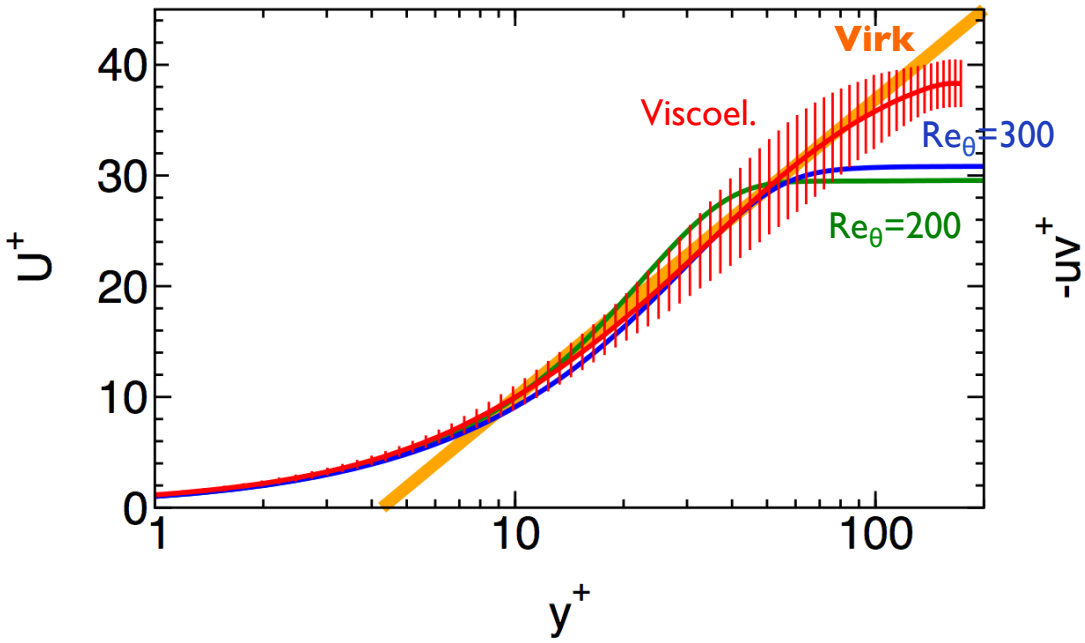


- Newtonian transition takes place earlier for larger fluctuations
- Viscoelastic flow transitions to MDR and stay at MDR
- Viscoelastic flow transitions at lower value of isotropic fluctuations (elastic turbulence?)
- Same fluctuation value would relaminarize a Newtonian flow

Oscillating behavior

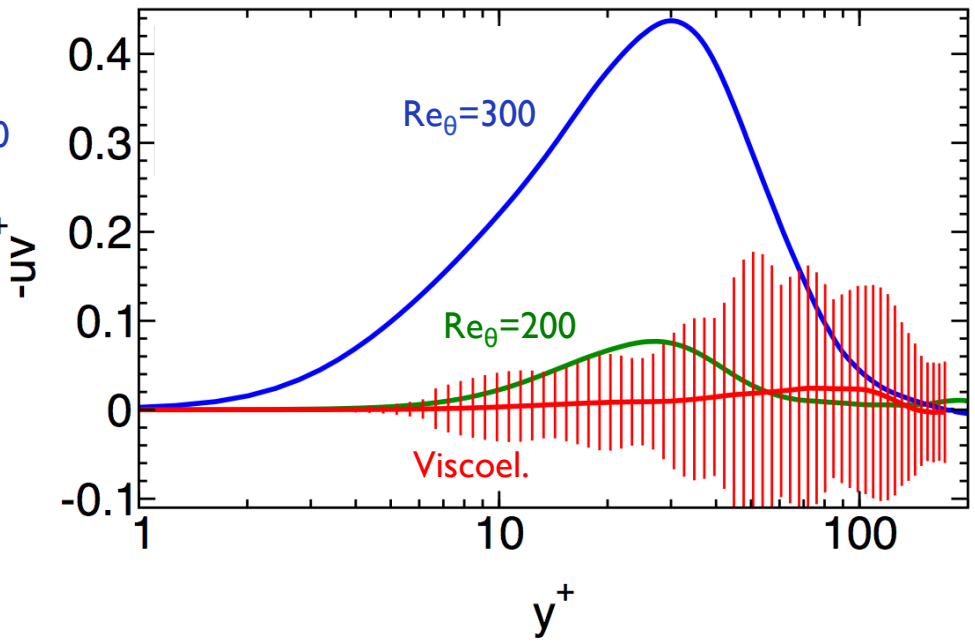
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Mean velocity



- MDR has similar velocity profile as Newtonian transitional flow (i.e.,Virk)
- Time fluctuations at MDR span both pre- and post-breakdown velocity profiles

Reynolds stress

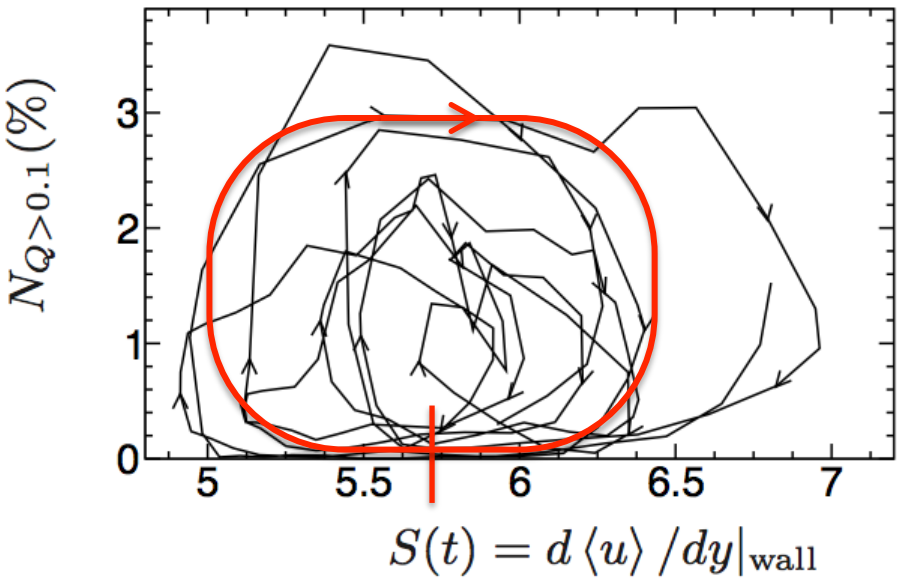


- Average MDR Reynolds stress negligible
- Time fluctuations at MDR larger than pre-breakdown Newtonian case
- Correlation with dP/dx

Oscillating behavior

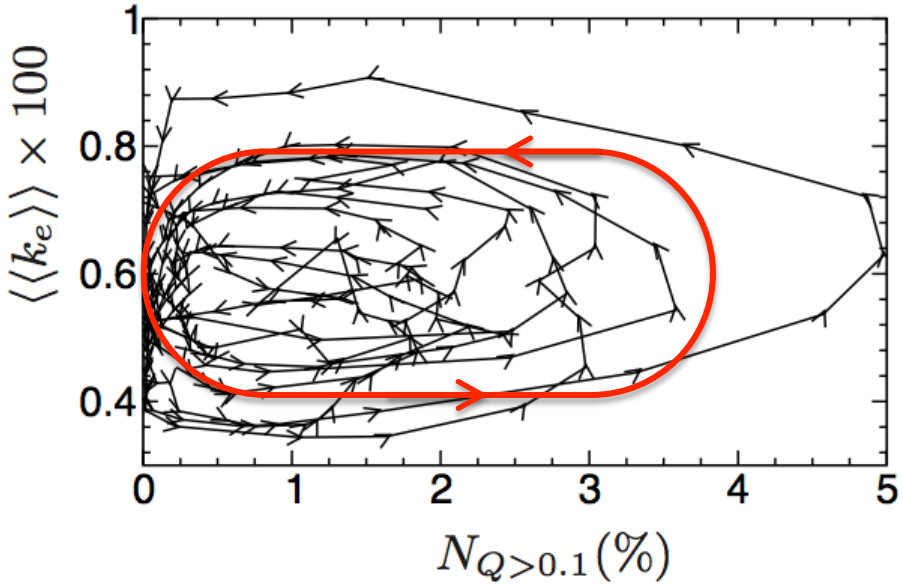
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Vortical activity vs. drag



- Correlation between increase of vortical activity and increasing shear stress
- When vortices are damped, shear stress decreases

Elastic energy vs. vortical activity



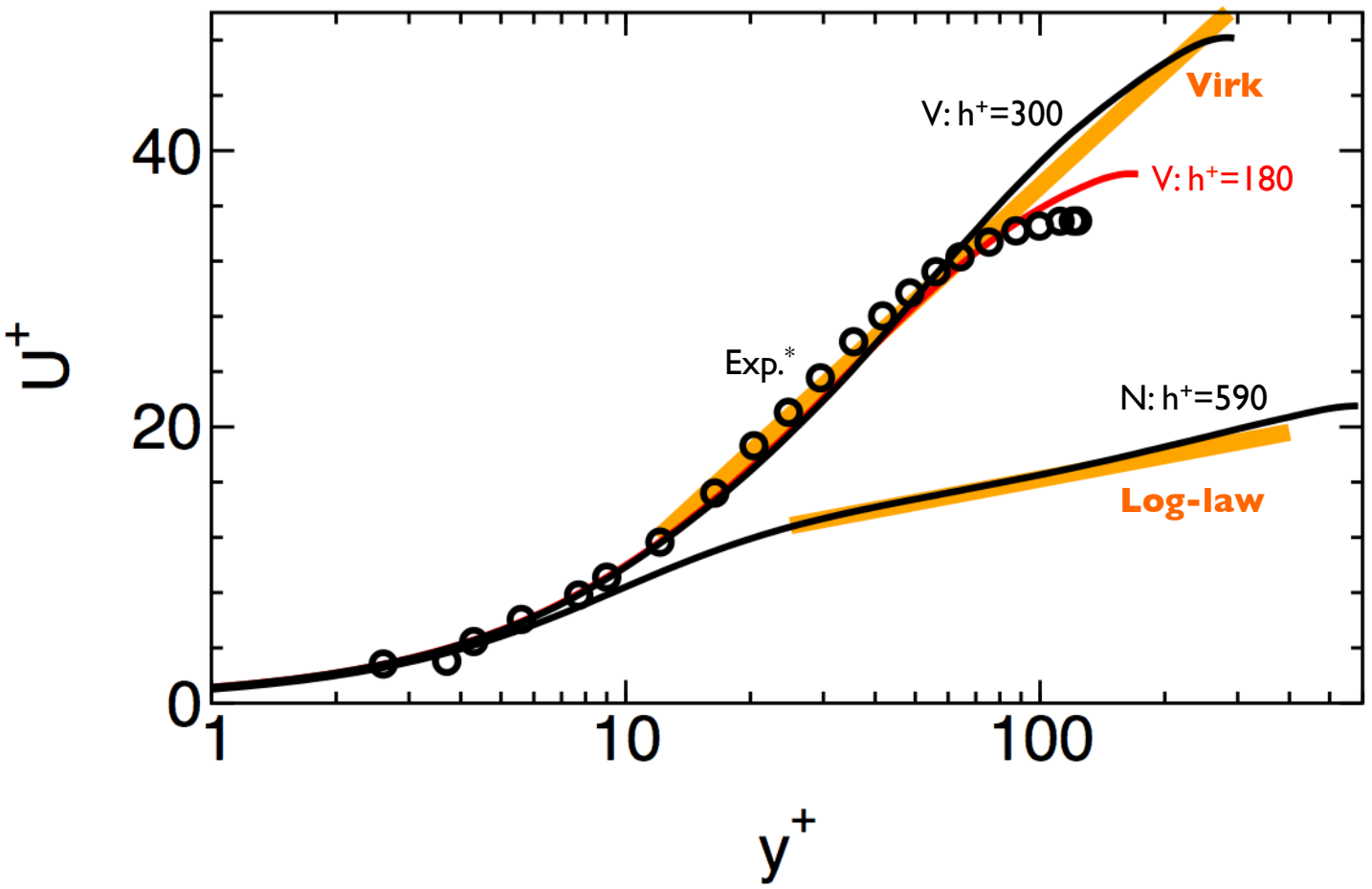
- Elastic energy increases when vortical activity grows
- Elastic energy peaks during decaying portion of vortical activity
- Rapid drop when vortical activity vanishes
- Phase lag depends on elasticity

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Logarithmic MDR behavior?

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Mean velocity profile



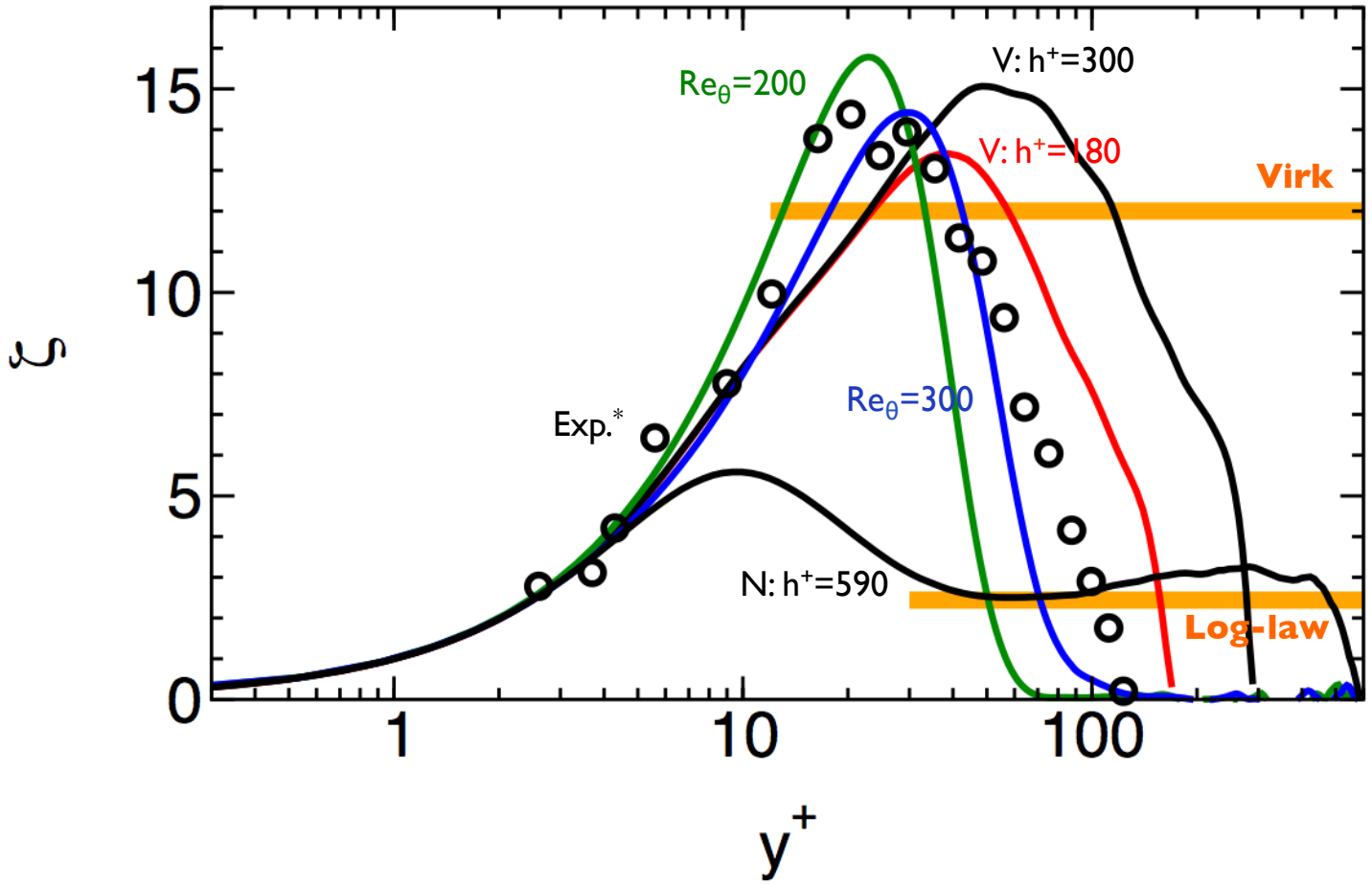
- MDR experiment, BL transitional flow, and MDR simulations straddle Virk's asymptote
- But is it a logarithmic scaling?

* Escudier *et al.*(2009)

Logarithmic MDR behavior?

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Indicator function $\zeta = y^+(dU^+/dy^+)$



- If logarithmic behavior, indicator function should be constant
- No apparent logarithmic behavior
  - MDR simulations
  - MDR experiment
  - BL transitional flow
- Possibly due to low Re but other experiments at higher Re show similar velocity profile
- Need more data at higher Re

* Escudier *et al.*(2009)

Outline

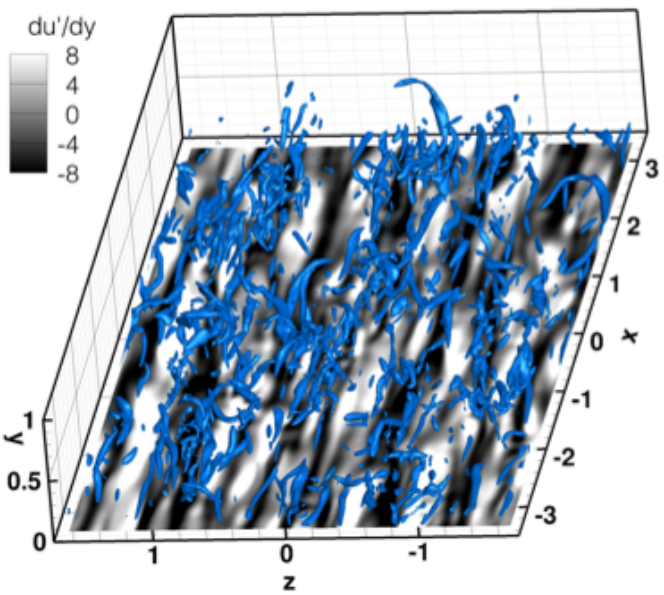
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- Introduction and background
- Modeling and numerical implementation
- Maximum drag reduction asymptote
- **Elasticity and small scales**

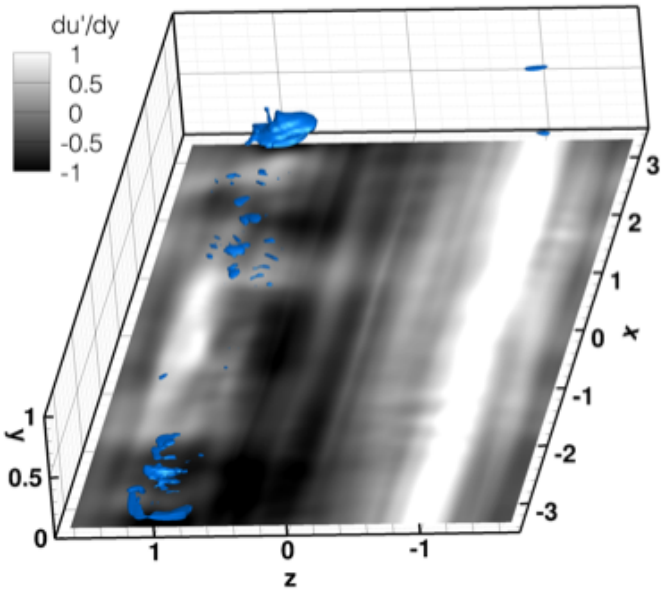
Small scales

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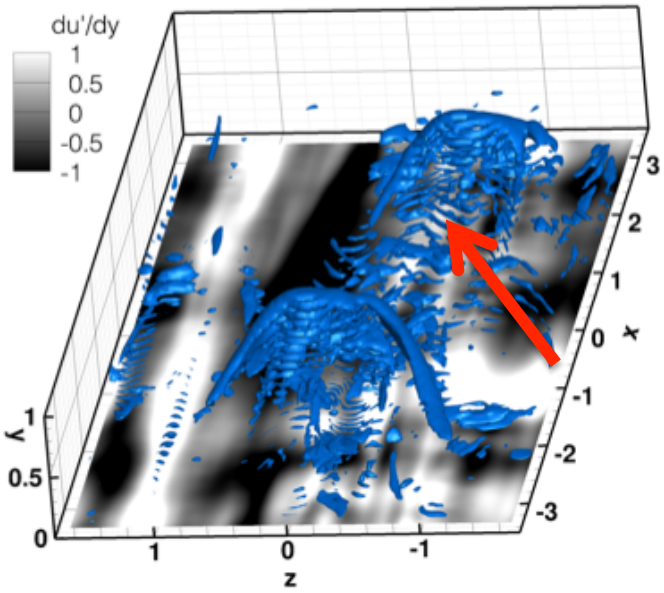
Newtonian



MDR low vortical activity



MDR high vortical activity



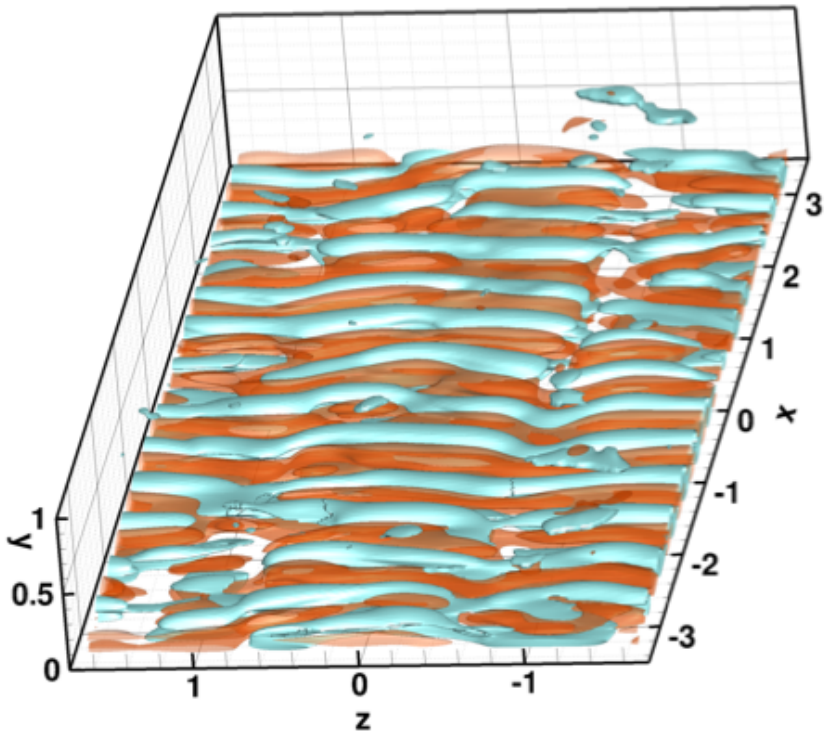
Vortices (blue isosurface $Q > Q_{th} > 0$) and wall shear (B&W contour)

- Polymers damp the vortices
- MDR is a transitional state oscillating between low and high vortical activity
- **But it is more complex than that! What are these small scales?**

Flow structure before transition to MDR

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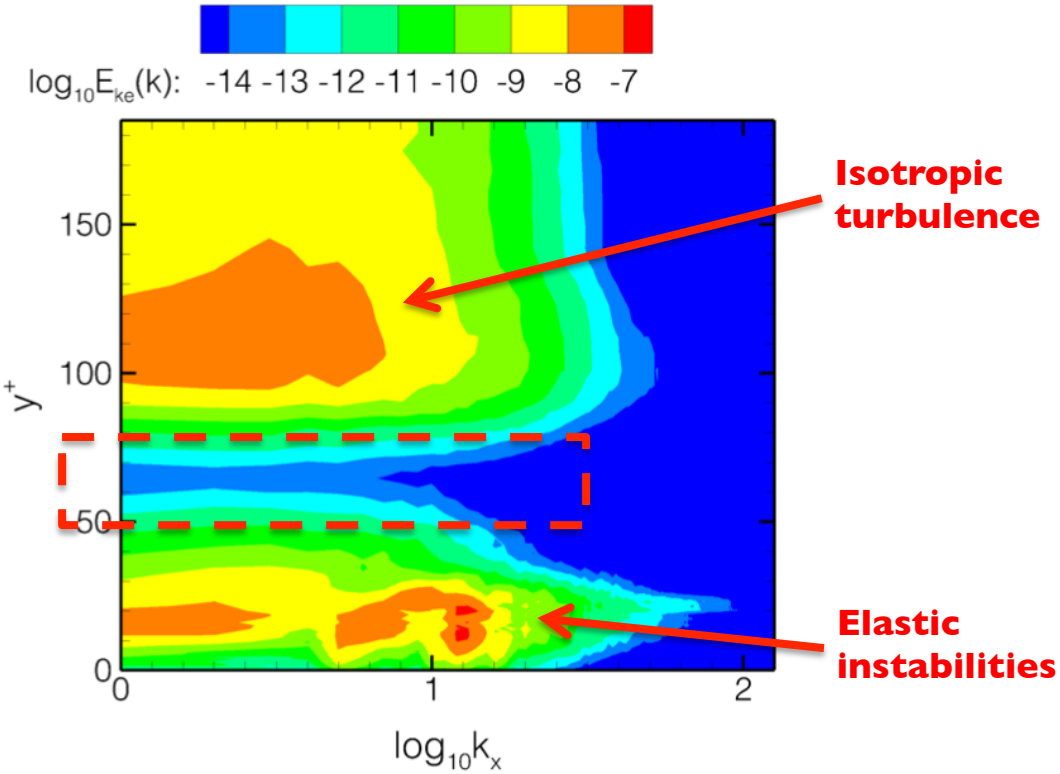
2D elastic instabilities



Isosurfaces of positive (blue) and negative (orange) Q

- Elastic instability (mostly 2D)
- At Kolmogorov scale
- No rotation

Flow spectrum



Flow spectrum map as a function of the distance to the wall

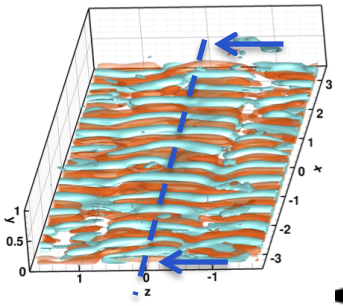
- It is **not** a diffusive process!
- Confirms de Gennes argument

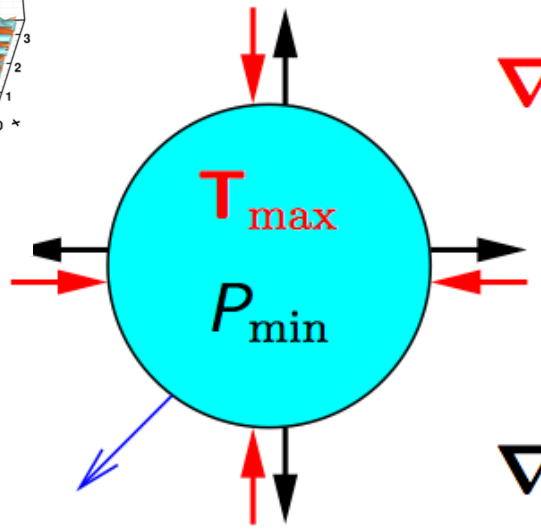
Mechanism of elastic instabilities

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$$\nabla^2 p = \underbrace{2Q + \frac{1-\beta}{Re}\nabla\cdot(\nabla\cdot\mathbf{T})}_{f}$$

$$p(\mathbf{x}) \sim -\frac{1}{4\pi}\int \frac{f(\mathbf{y})}{r} d^3\mathbf{y}$$





- Both hyperbolic polymer equation and elliptic pressure equation are connected
- Small scale perturbations have long range effect (through pressure)
- Maximum stress typically seen at minimum pressure locations

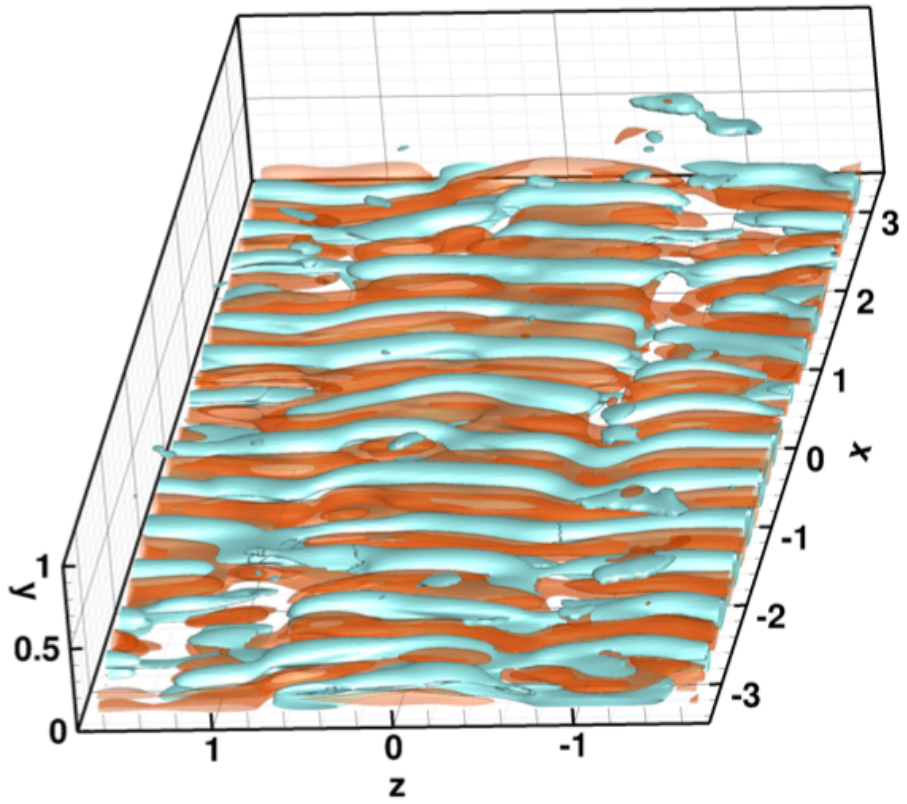
$$Q > 0$$

$$\int_C \nabla p\cdot\mathbf{n}\, dl - \underbrace{\frac{1-\beta}{Re}\int_C \nabla\cdot\mathbf{T}\cdot\mathbf{n}\, dl}_{\text{Polymer stress}} = 2\int_S Q ds$$

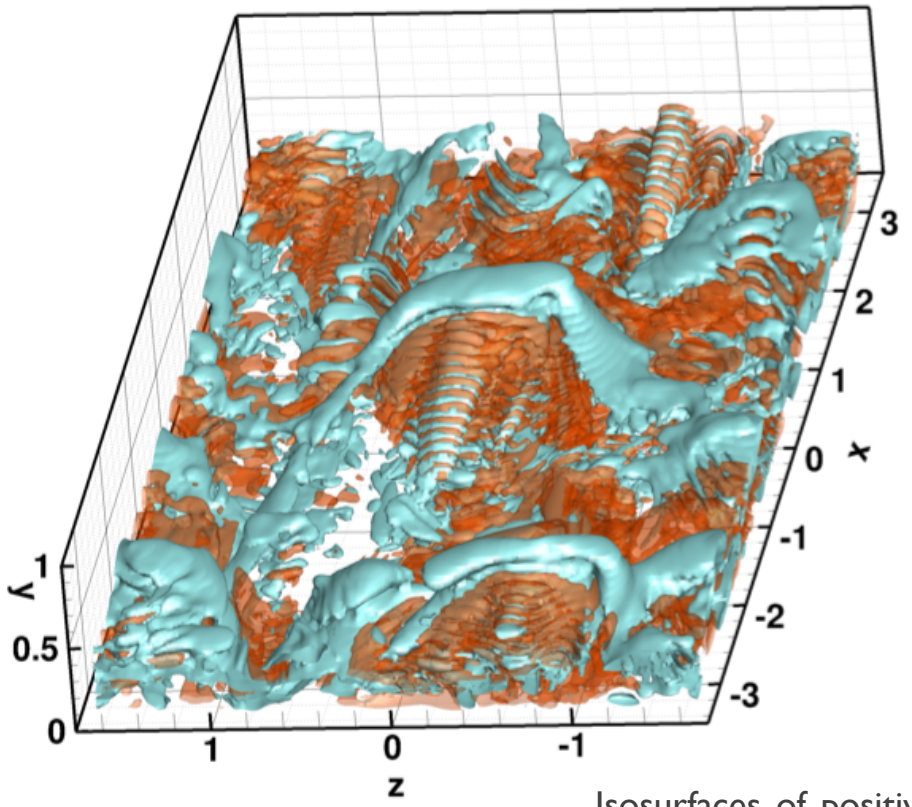
Development of elastic instabilities

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Before transition to MDR



After transition to MDR



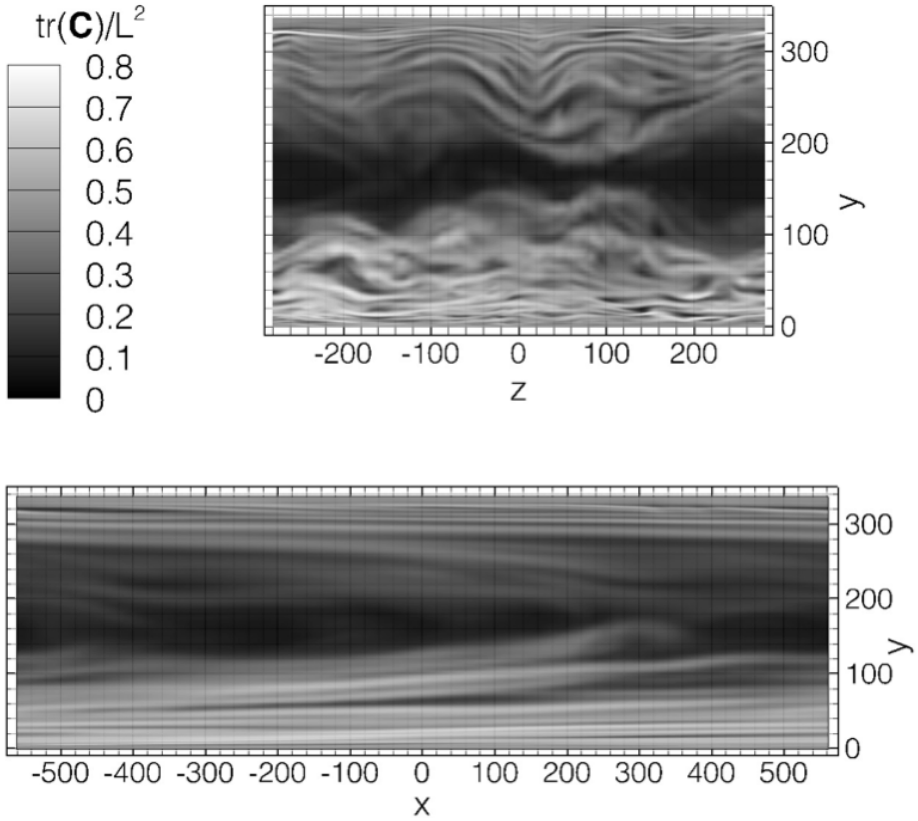
Isosurfaces of positive (blue) and negative (orange) Q

- Similar instabilities but smaller scales after transition to MDR
- Typically in the wake of hairpin vortices
- **Elastic instabilities over large low-Re regions promote transition and oscillating behavior of MDR**

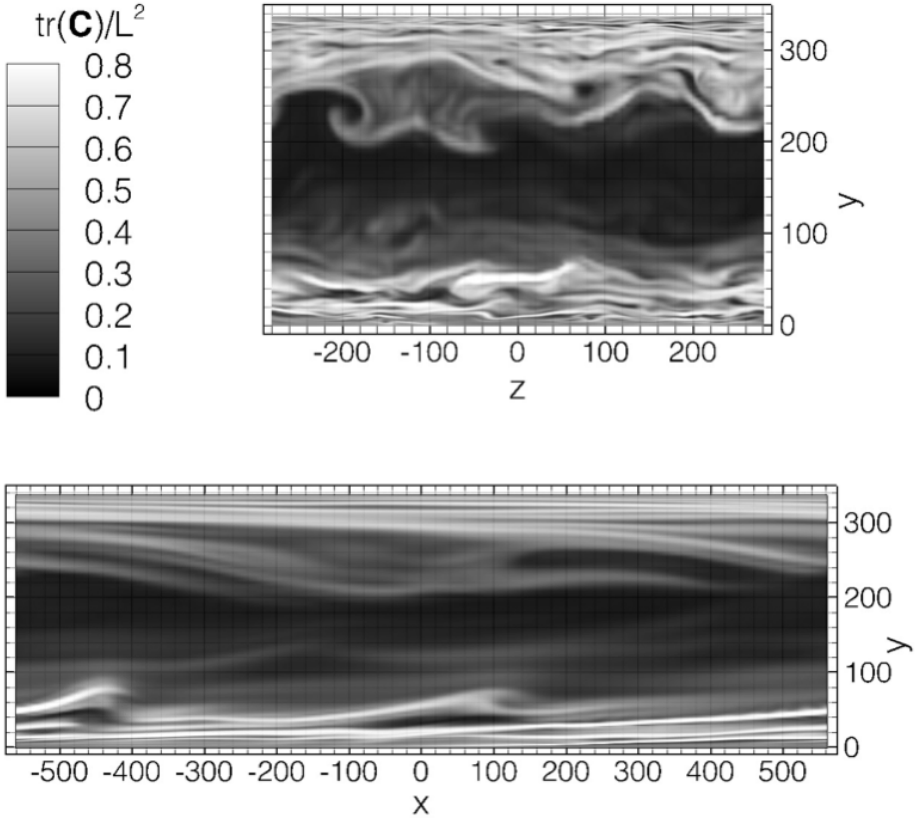
Anisotropy

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Low vortical activity phase



High vortical activity phase



Normalized trace of conformation tensor

- Highly anisotropic (vertical stratification)
- Polymer self-driven turbulence, already seen in **elastic turbulence** and **early turbulence**, might exist in high Re turbulent flows

Conclusions

- MDR is the state of **breakdown of linear instabilities**
- The **fluctuations** of MDR states are governed by the growth rate of vortices and the rate at which polymers can stop that growth
- MDR does not have a **logarithmic** scaling
- Purely **elastic instabilities** promote transition and growth of vortices
- **Small scales** are important to capture
- Need adequate **numerics**