Title: New insights into polymer-induced drag reduction in turbulent flows

Date: May 07, 2014 10:35 AM

URL: http://pirsa.org/14050041

Abstract: Polymer additives are known to cause significant reduction in turbulent friction drag and reduce the energy dissipation rate of fluid transport. This effect is however bounded by a universal upper limit the maximum drag reduction (MDR) asymptote that does not change with polymer properties. Understanding MDR remains an important unsolved problem in the areas of turbulence and non-Newtonian fluid mechanics. Dynamical trajectories on the boundary in state space between laminar and turbulent plane channel flow - edge states - are computed for Newtonian and viscoelastic fluids. Viscoelasticity has a negligible effect on the properties of these solutions and at least at a low Reynolds number their mean velocity profiles correspond closely to experimental observations for polymer solutions in the MDR regime. These results confirm the existence of weak turbulence states that cannot be suppressed by polymer additives explaining the fact that there is an upper limit for polymer-induced drag reduction.

New insights into polymer-induced drag reduction in turbulent flows

Li Xi

Department of Chemical Engineering
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Compute Ontario Research Day
Waterloo, ON, May 7, 2014

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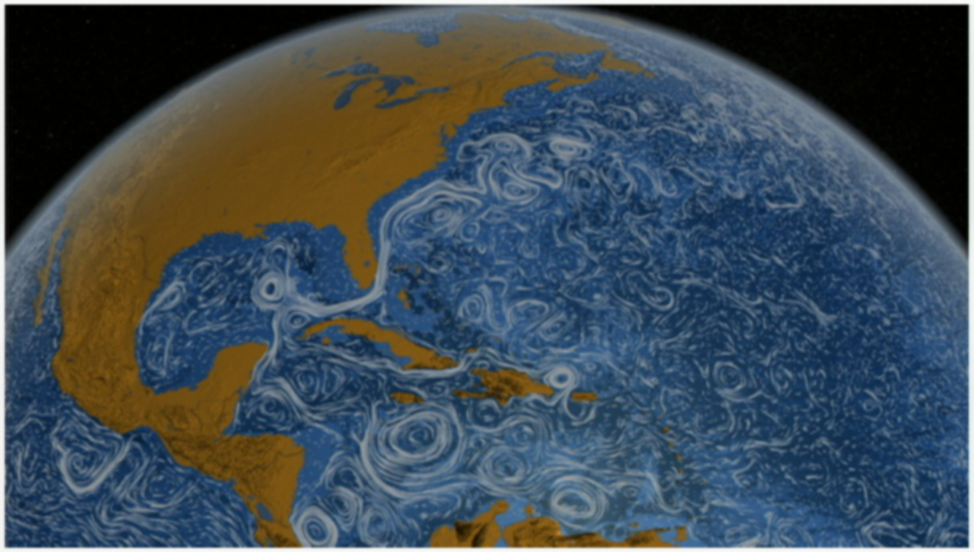
What is turbulence?



nasa.gov

Hu D. L. and Bush J. W. M., *Phys. Fluids*, 2005

Hiuchi H, *Phys. Fluids*, 1993

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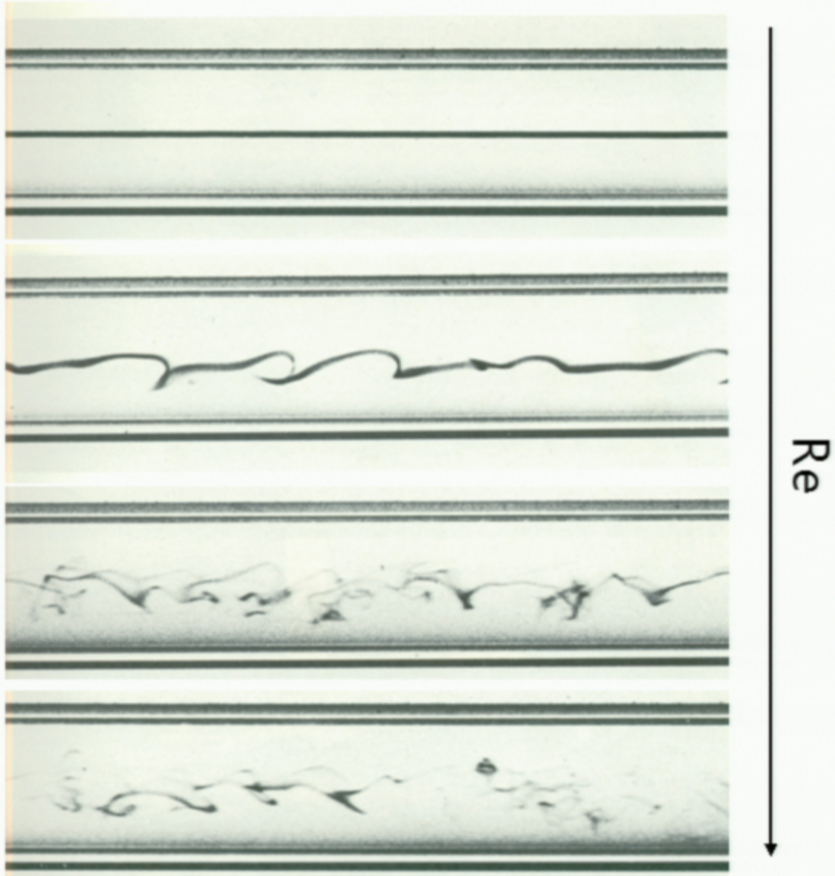
Laminar-Turbulent Transition in Pipe Flow



Reynolds O., *Philos. Trans.*, 1883
http://www.uic.edu/classes/me/me536/gallery.html

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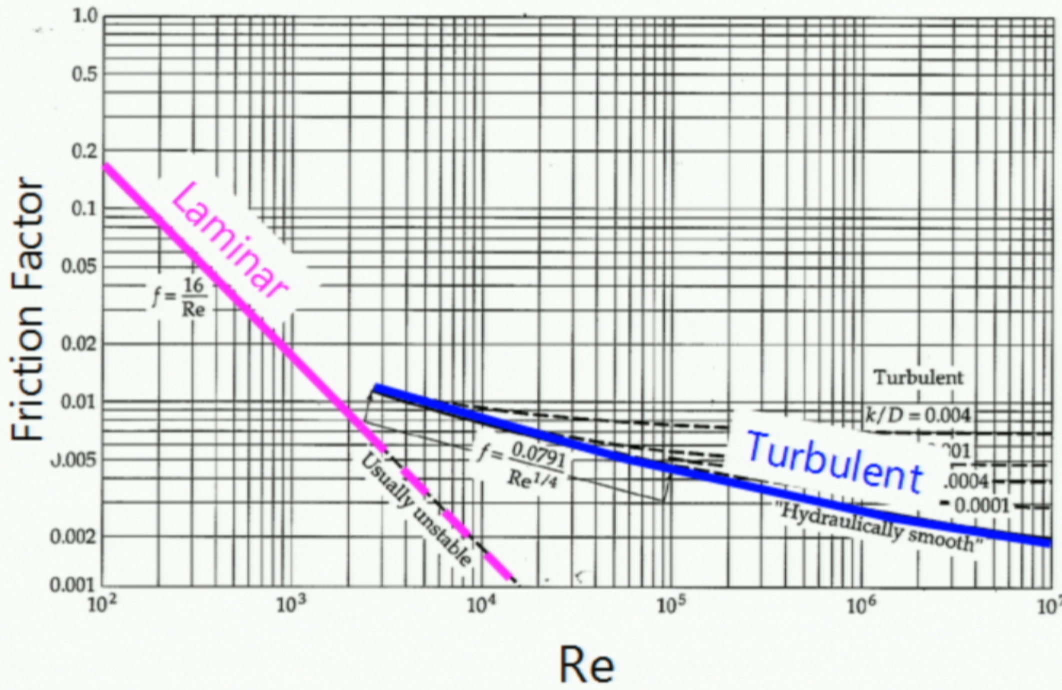
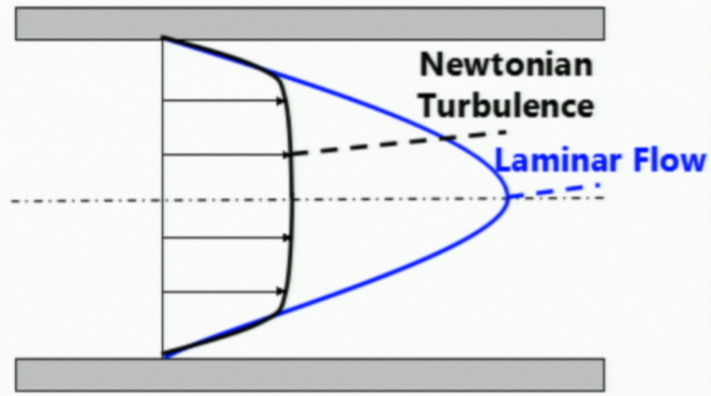
Why do we care?



Bird, Stewart and Lightfoot, *Transport Phenomena*, 2nd ed., 2002

Turbulence of polymer solutions: drag reduction effects

- Very low polymer concentration
  - O(10)-O(100) wppm
- DR% up to 80%.
- Energy saving in fluid transportation.
- Theoretical significance:
  - Turbulence & polymer physics.



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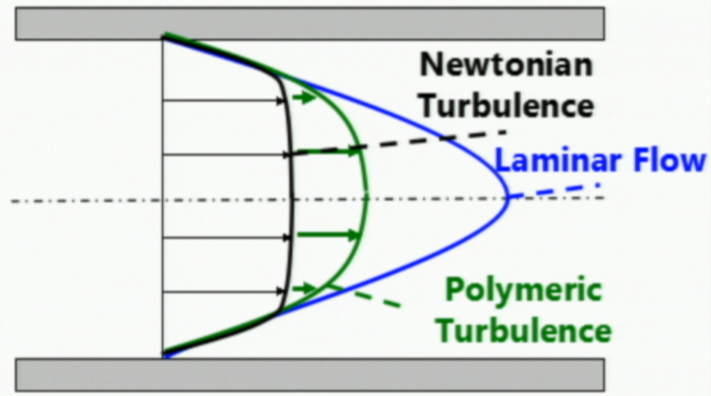

Trans-Alaska Pipeline System

picture credit: http://www.alyeska-pipe.com/

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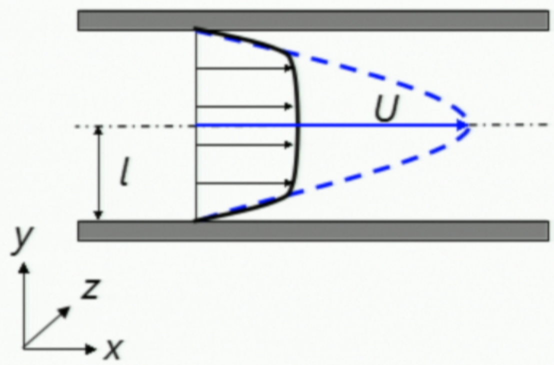
Simulation of viscoelastic turbulence

Physical Systems
PDEs
Fields
Parameters



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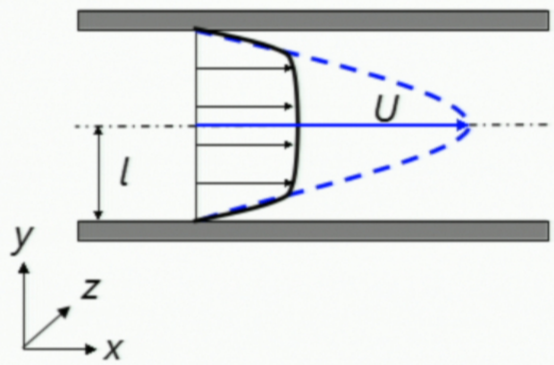

Navier-Stokes Eq.

↓

velocity ($\boldsymbol{v}$) &
pressure (p)

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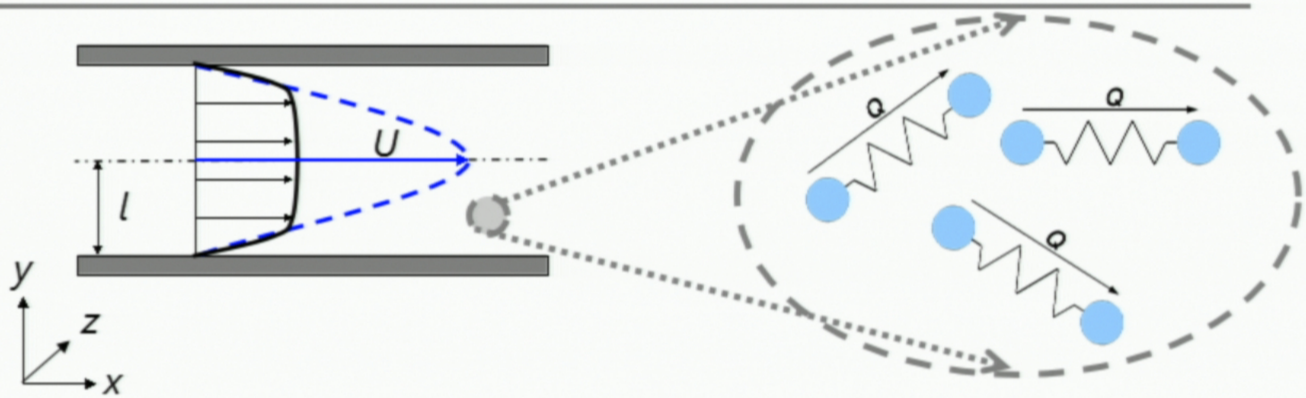
Simulation of viscoelastic turbulence



Navier-Stokes Eq.

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velocity (***v***) &
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FENE-P Constitutive Eq.

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Simulation of viscoelastic turbulence

Physical Systems
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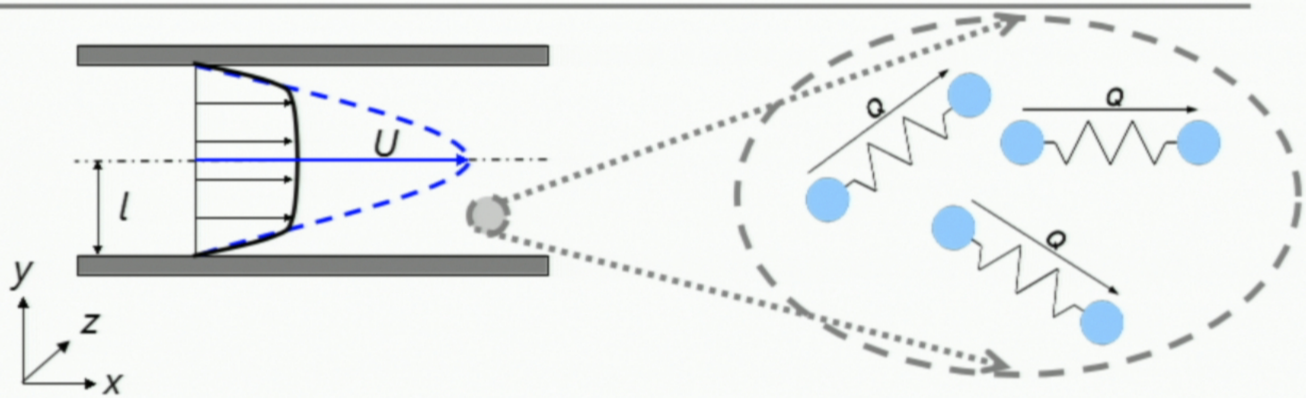

Navier-Stokes Eq. → velocity ($\mathbf{v}$) & pressure (p)

FENE-P Constitutive Eq. → polymer conformation tensor: $\boldsymbol{\alpha} \equiv \frac{H\langle \mathbf{QQ} \rangle}{kT}$

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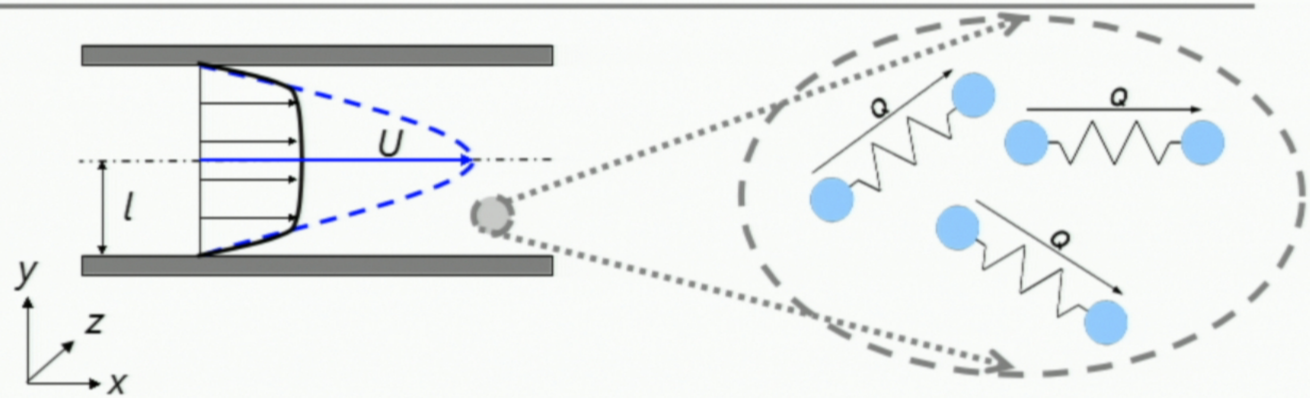
Simulation of viscoelastic turbulence

Physical Systems | PDEs | Fields | Parameters



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$$\mathrm{Re} \equiv \frac{\rho U l}{\eta_s + \eta_p} \qquad \beta \equiv \frac{\eta_s}{\eta_s + \eta_p} \qquad b \equiv \max(\mathrm{tr}(\boldsymbol{\alpha})) \qquad \mathrm{Wi} \equiv \lambda \frac{2U}{l}$$

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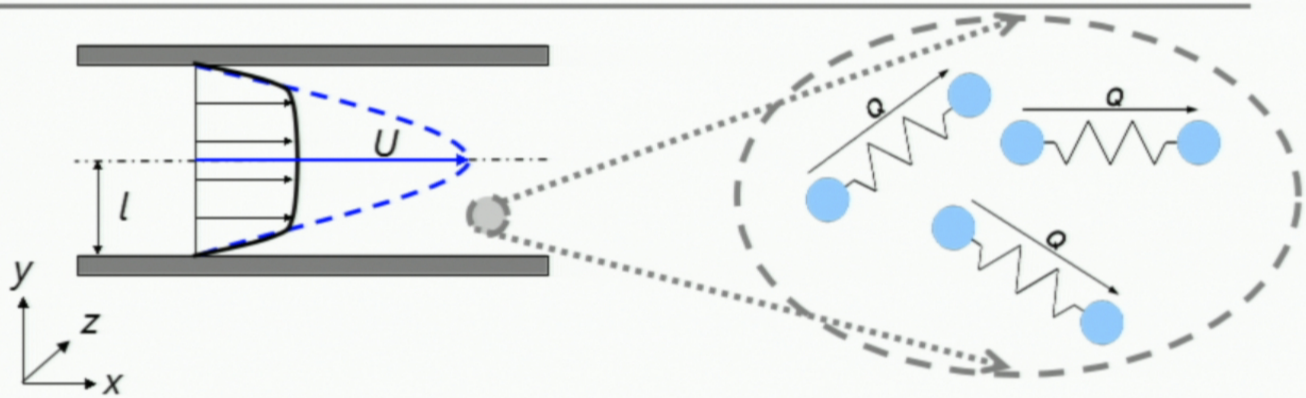
Simulation of viscoelastic turbulence

Physical Systems



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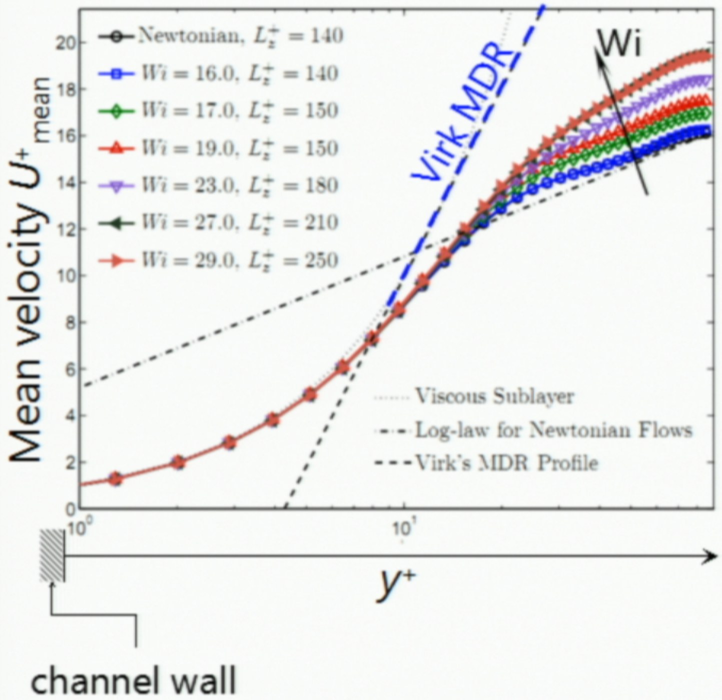
DNS observation of drag reduction



Xi & Graham, *J. Fluid Mech.* 2010

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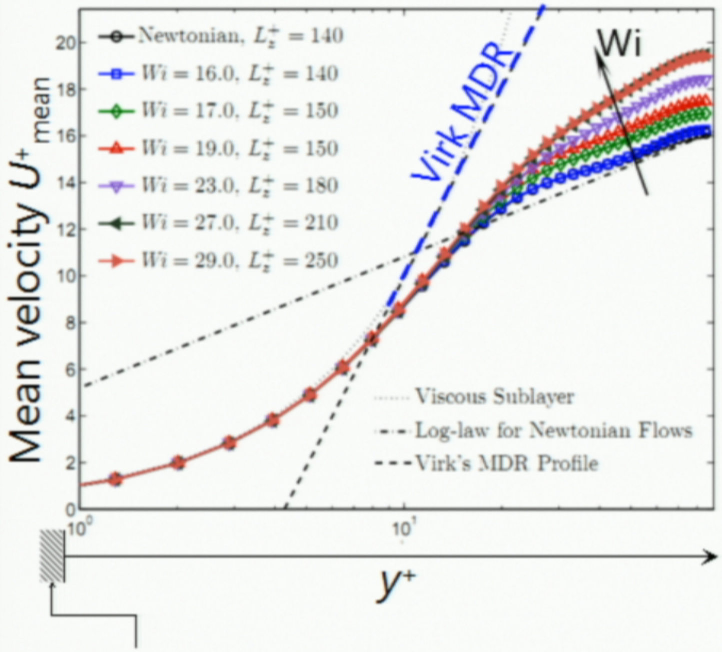

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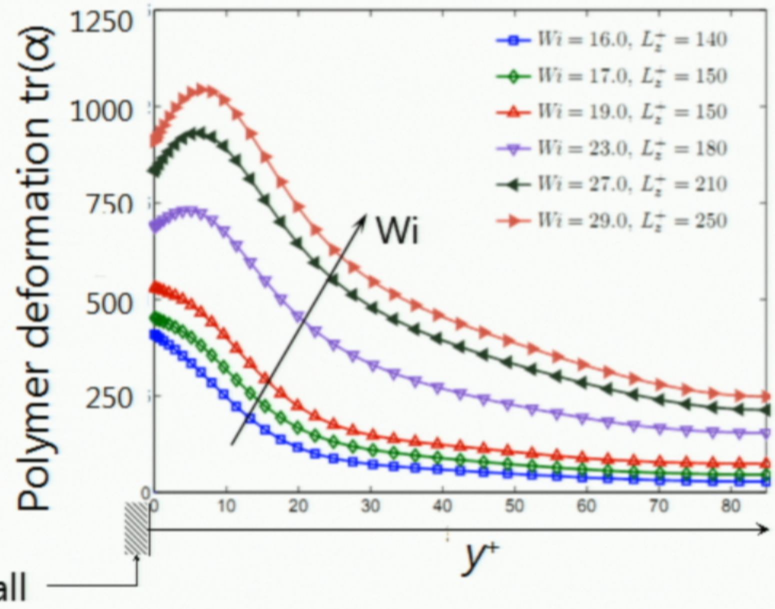

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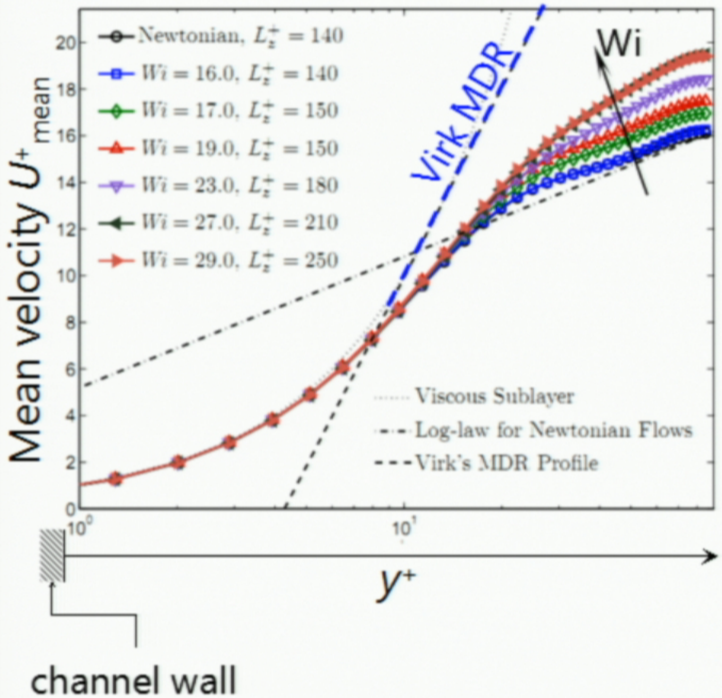
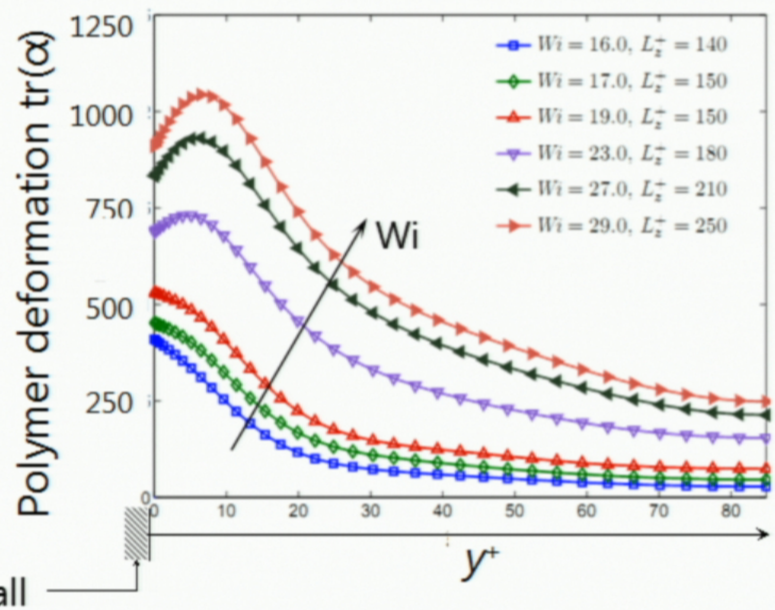
DNS observation of drag reduction



polymer extension -> polymer stress -> turbulence suppression



Xi & Graham, *J. Fluid Mech.* 2010

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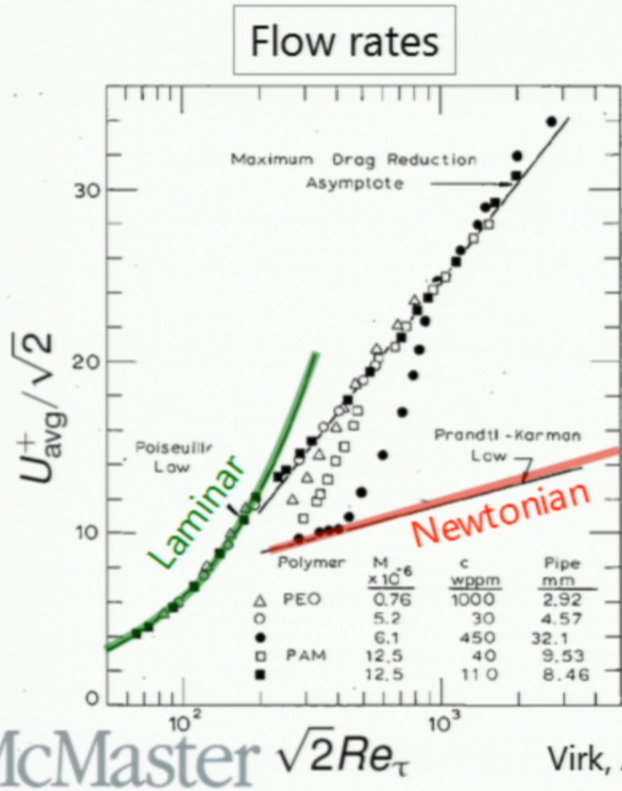
MDR: A universal upper limit of polymer drag reduction



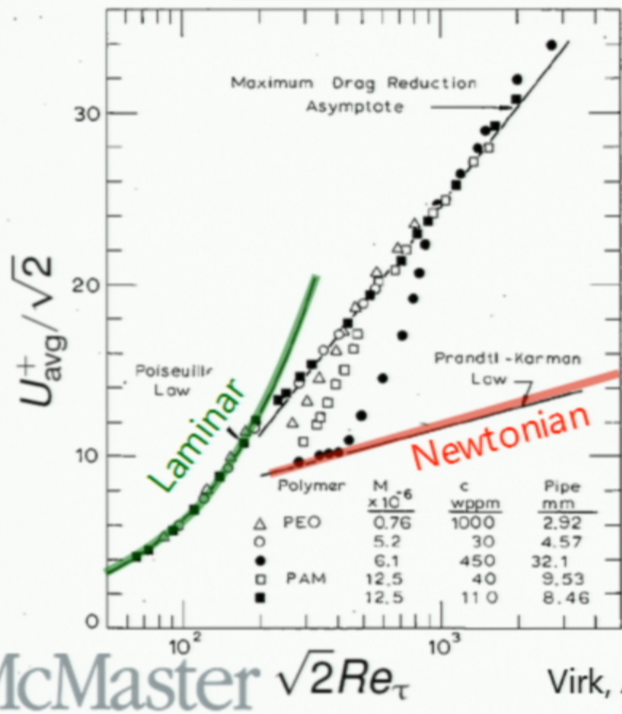
MDR (maximum drag reduction):

- Insensitive to polymer-related properties.
- Universal mean velocity profile.

Virk, *AIChE J.* 1975

MDR: A universal upper limit of polymer drag reduction

Flow rates



Virk, *AIChE J.* 1975

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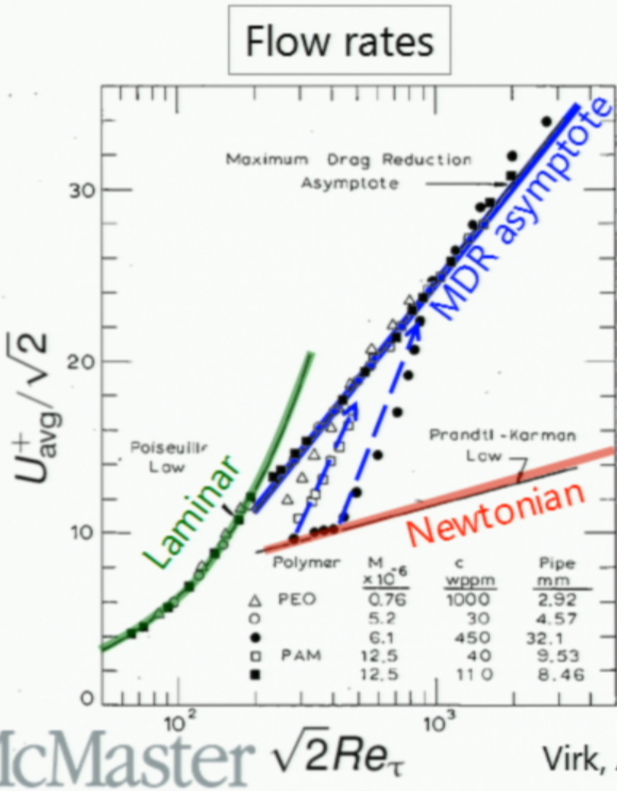

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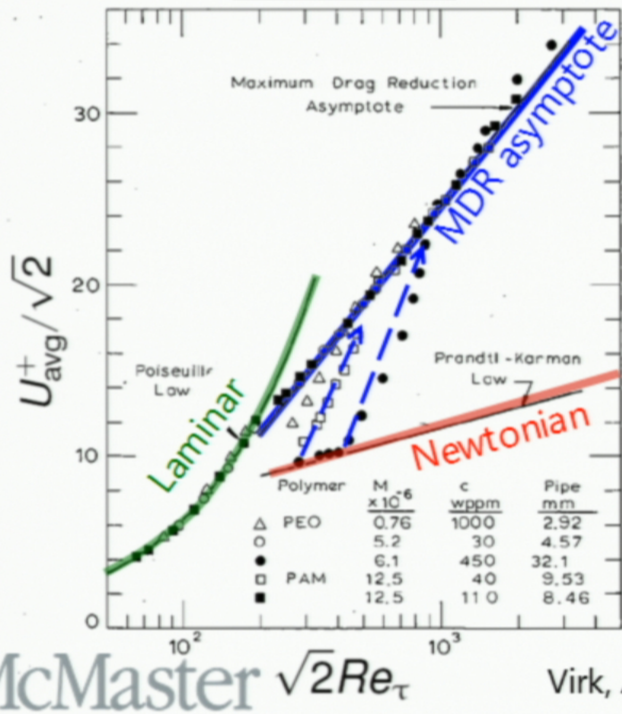
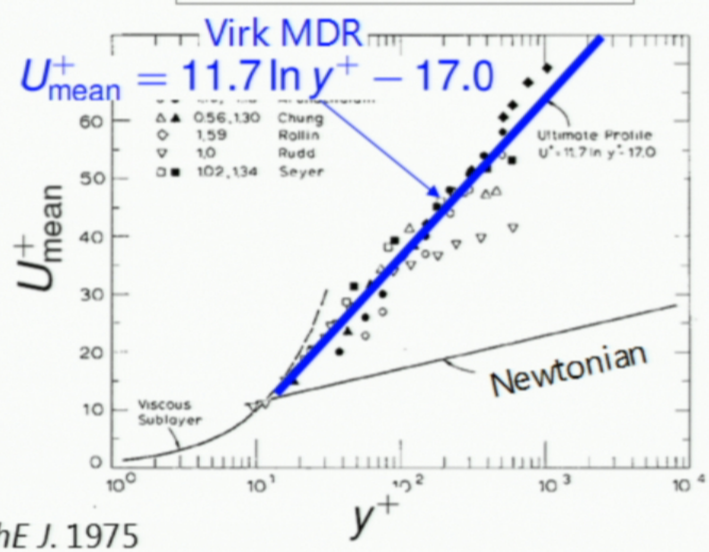


Mean velocity profiles

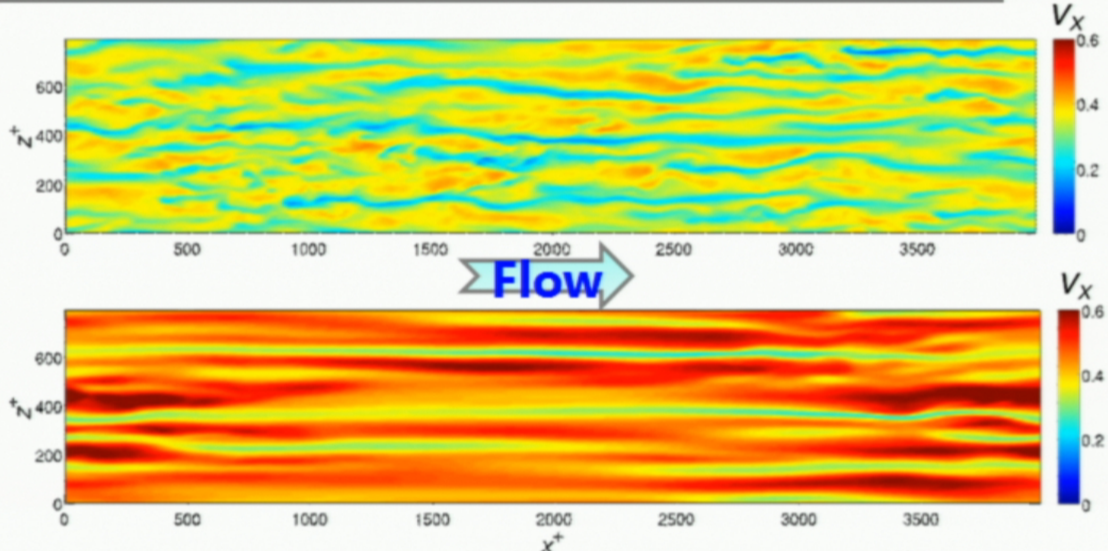


Virk, *AIChE J.* 1975

MDR: A universal upper limit of polymer drag reduction

Newtonian

$DR\% = 57\%$



Xi, *Ph.D. Dissertation*, UW-Madison, 2009

Important questions:

- What sustains turbulence at MDR?
- Why is MDR universal (w.r.t. polymer properties)?
- What is the origin of the flow structures at MDR?

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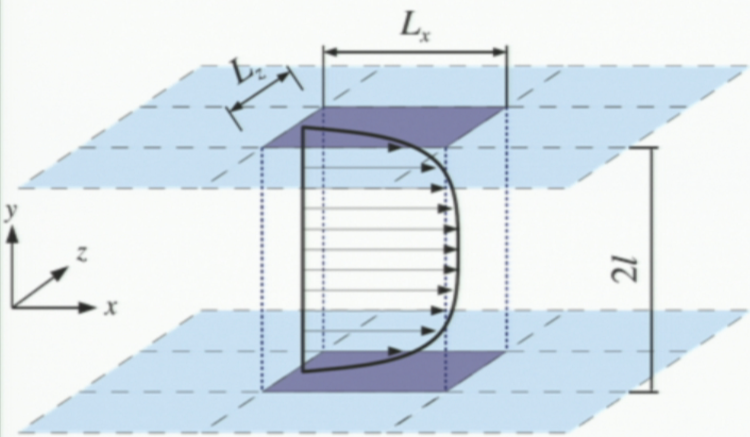
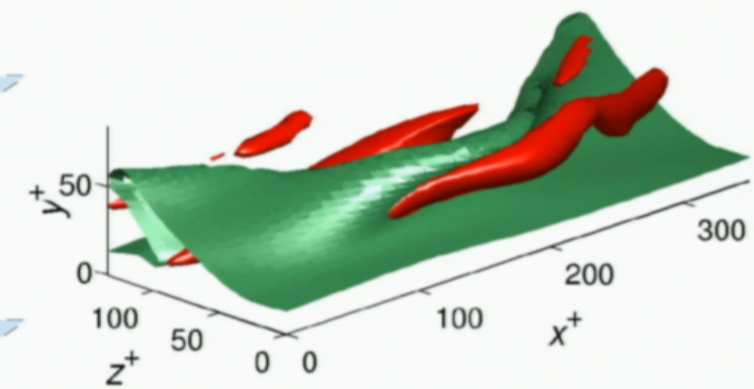
Method: minimal flow units (MFU)

- Isolate the essential flow structure for self-sustaining turbulence.
- Track the time evolution of the most important flow motions.





Red: streamwise vortices
Green: velocity isosurface
(upward pleat: low-speed streak)

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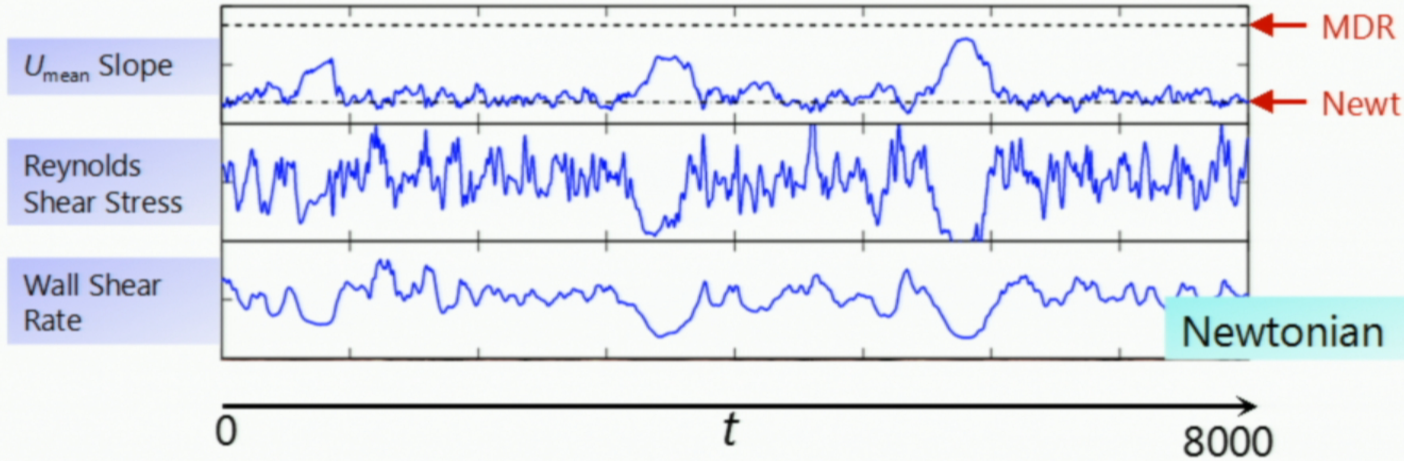
Time series: introducing *active* and *hibernating* turbulence



Xi & Graham, *Phys. Rev. Lett.*, 2010
Xi & Graham, *J. Fluid Mech.*, 2012

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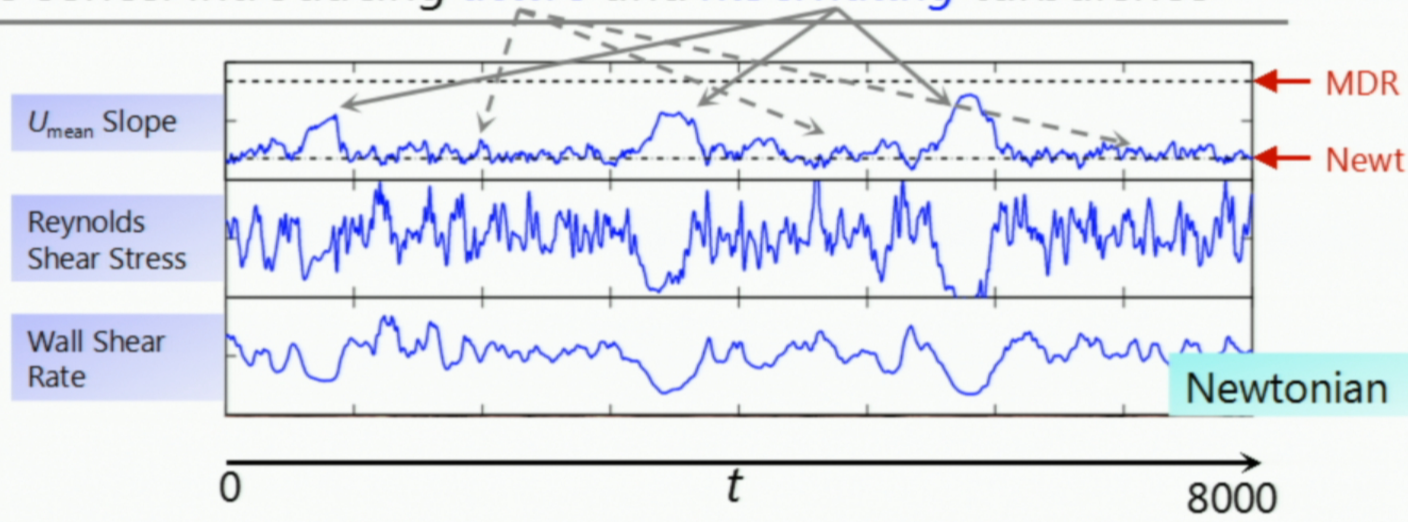

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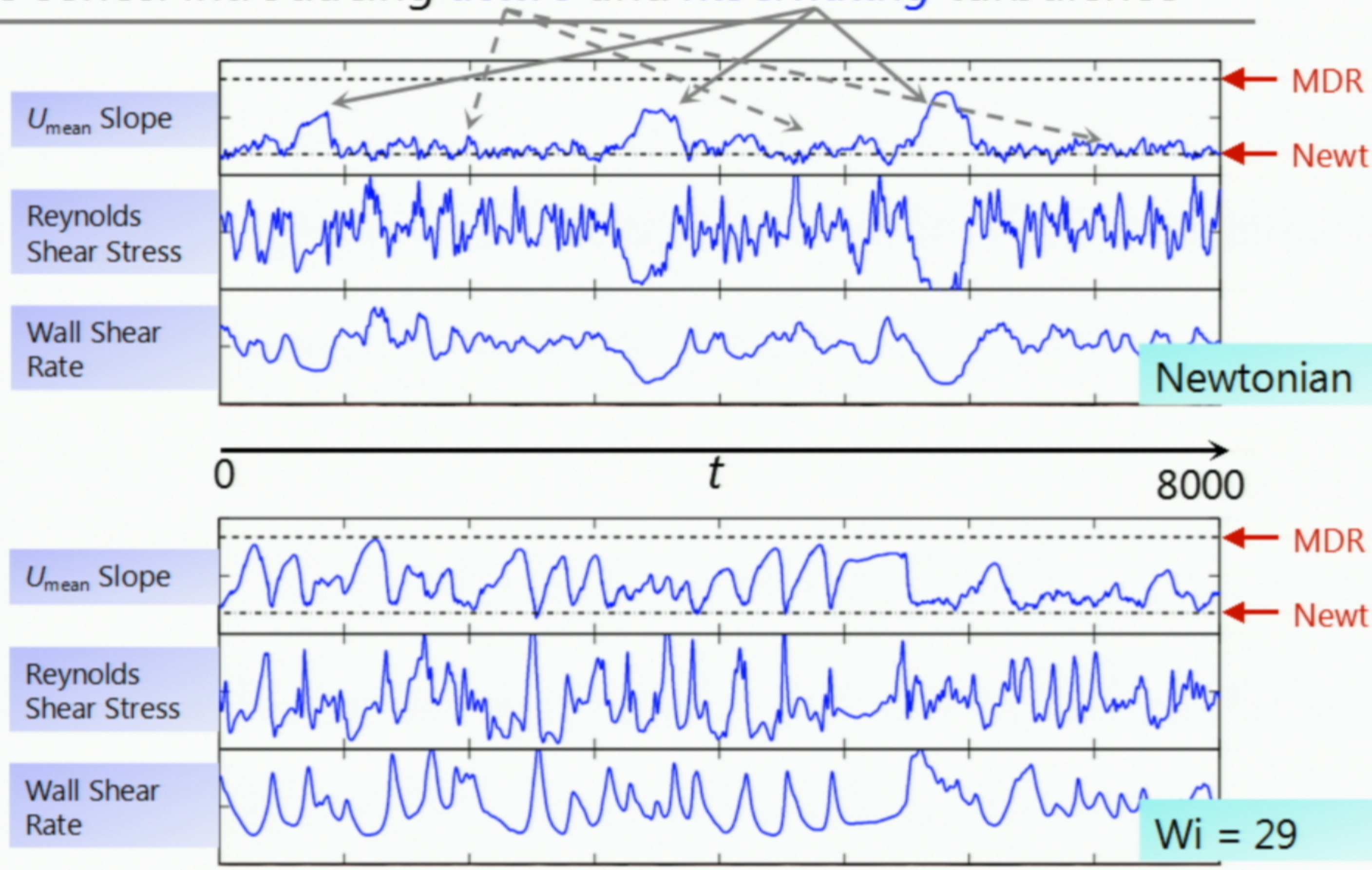

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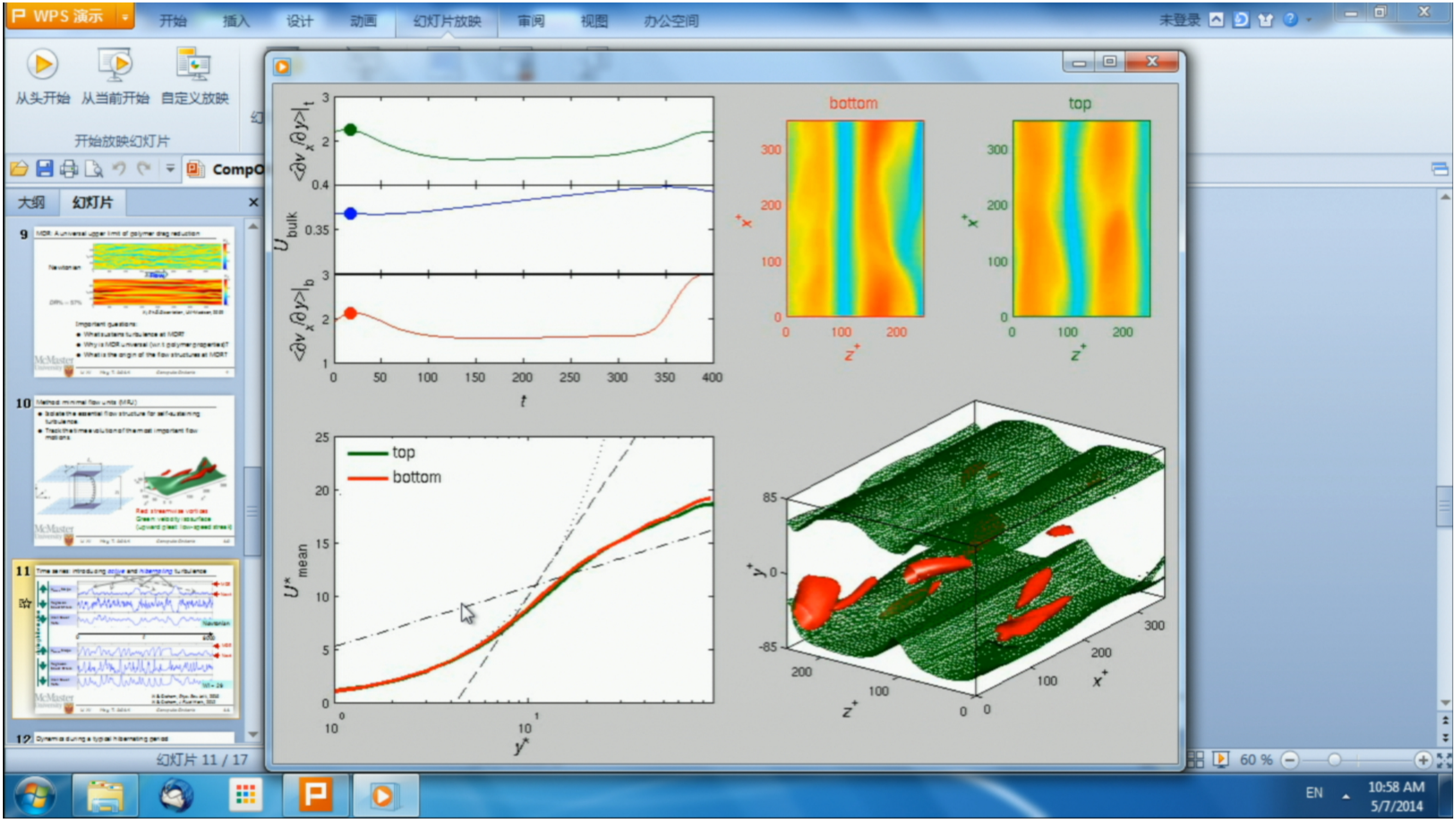

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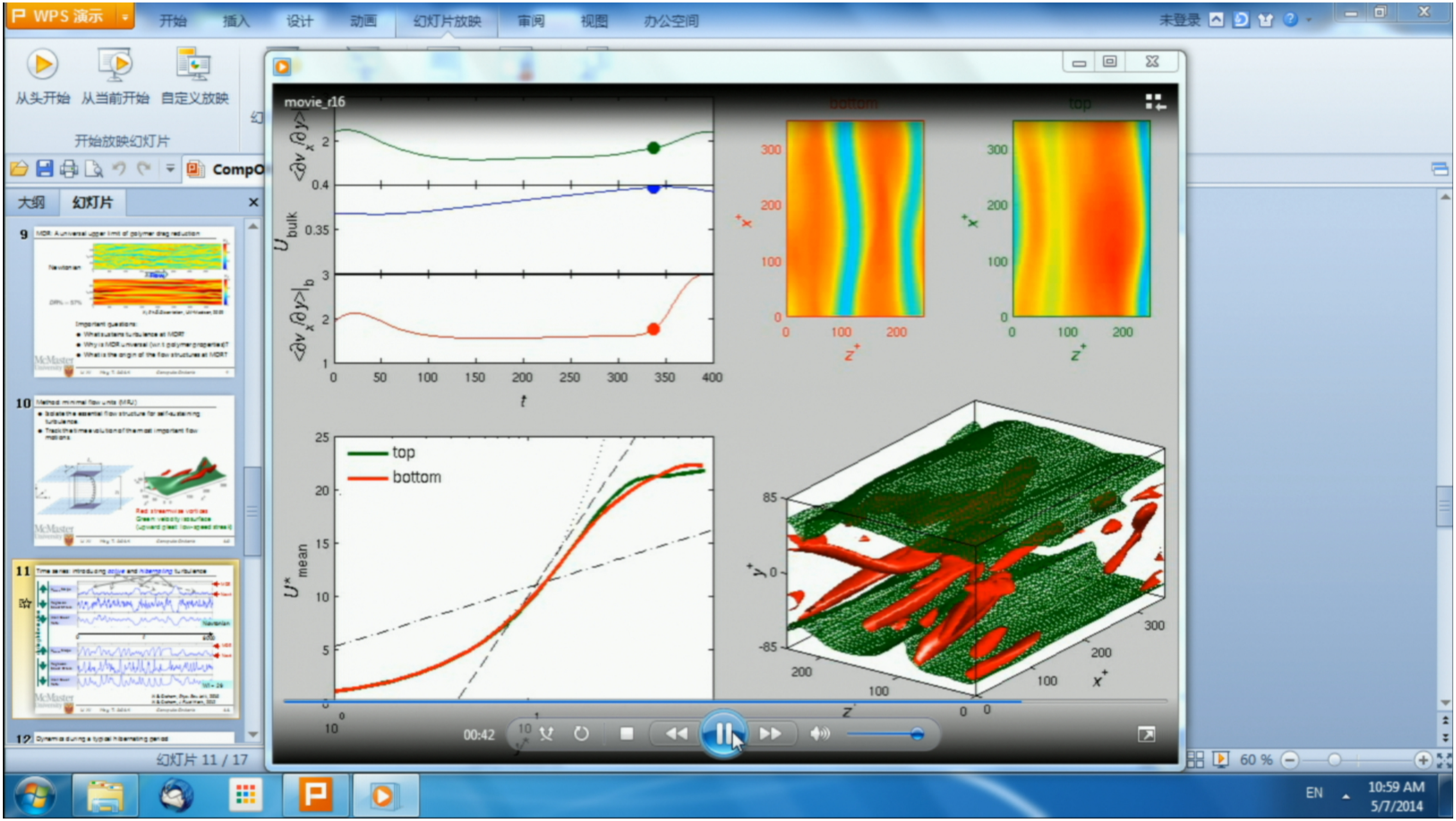
U^{+}_{mean}
U_{bulk}



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U_{bulk}
U^*_{mean}
00:42

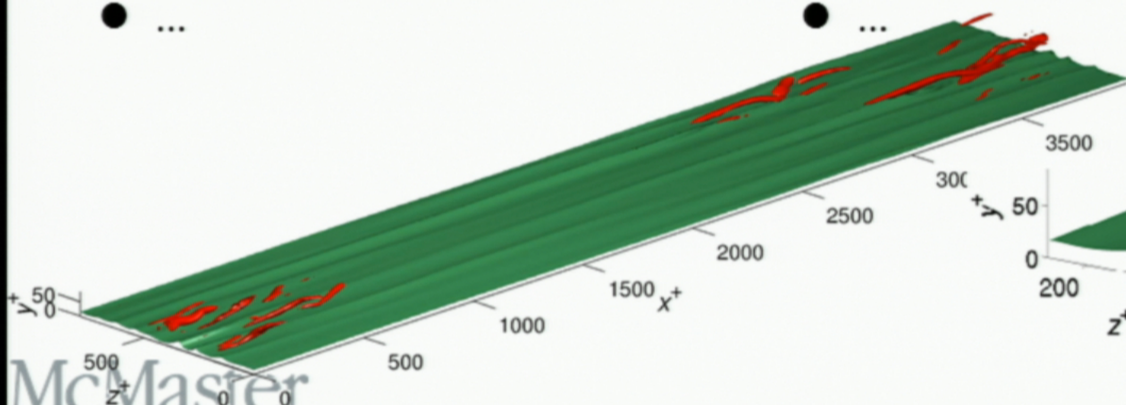
Hibernating turbulence vs. MDR: similarities

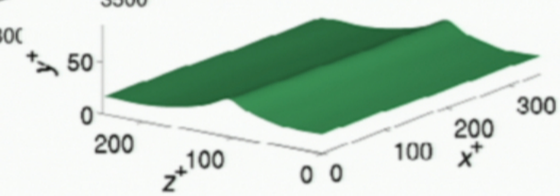
MDR

- Umean slope: A = 11.7.
- Weak streamwise vortices.
- Extended, mostly straight low-speed streaks.
- Lower transverse velocity fluctuations and Reynolds shear stress.
- …

Hibernating Turbulence

- Umean slope: A → 11.7
- Weak streamwise vortices.
- Almost streamwise-independent streaks.
- Lower transverse velocity fluctuations and Reynolds shear stress.
- …





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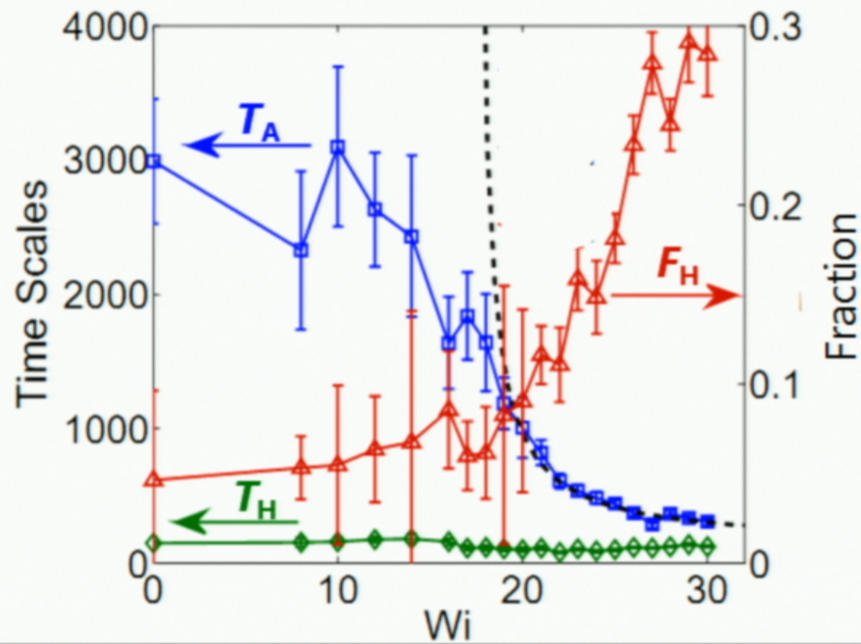
Frequency and duration of hibernating intervals

- T_{Active} decreases with Wi.
- $T_{Hibernating}$ approximately constant.
- Hibernation takes up a larger fraction in statistics at high Wi.



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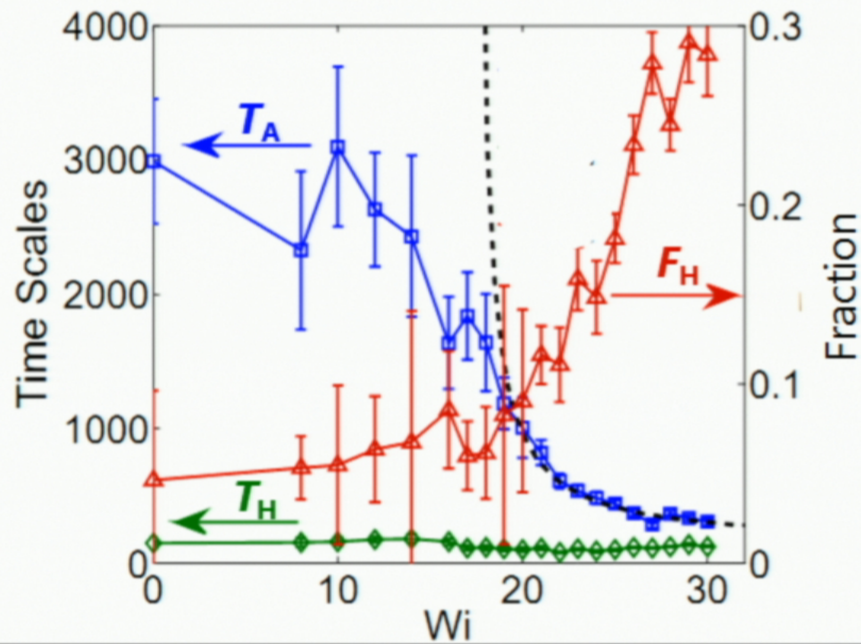
Hibernation is *Newtonian.*

Xi & Graham, *Phys. Rev. Lett.*, 2010
Xi & Graham, *J. Fluid Mech.*, 2012



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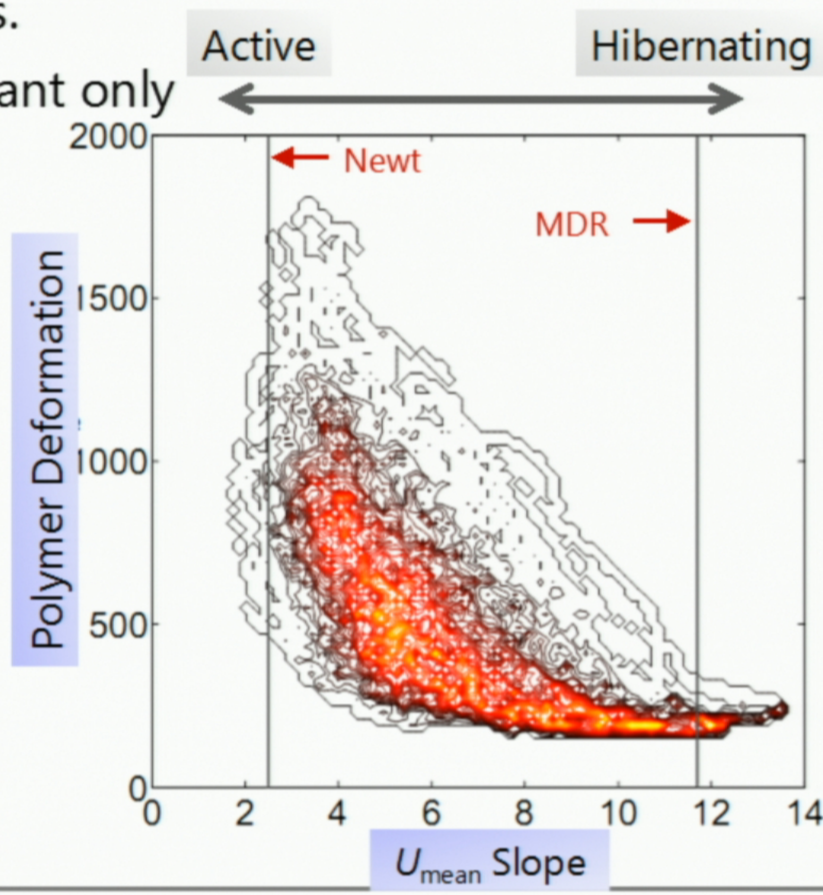
Polymer conformation statistics

- Anti-correlation between the mean velocity and polymer stress.
- Polymer effects are important only within active intervals.



Xi & Graham, *J. Fluid Mech.*, 2012

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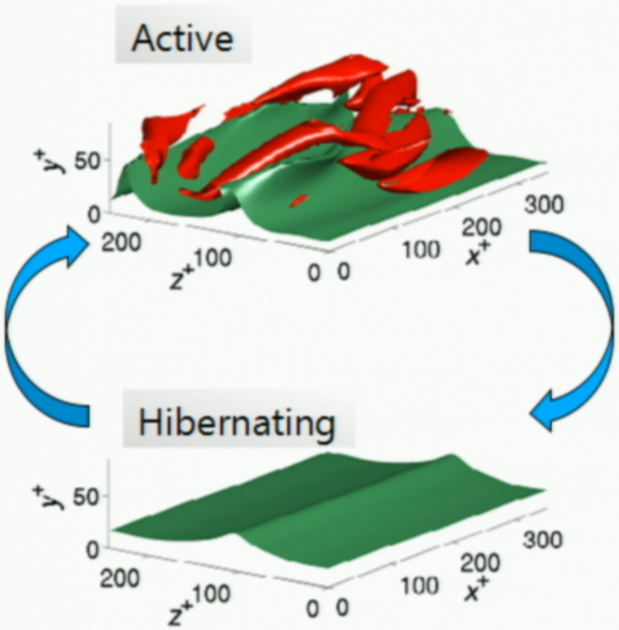
Physical picture and a simple model



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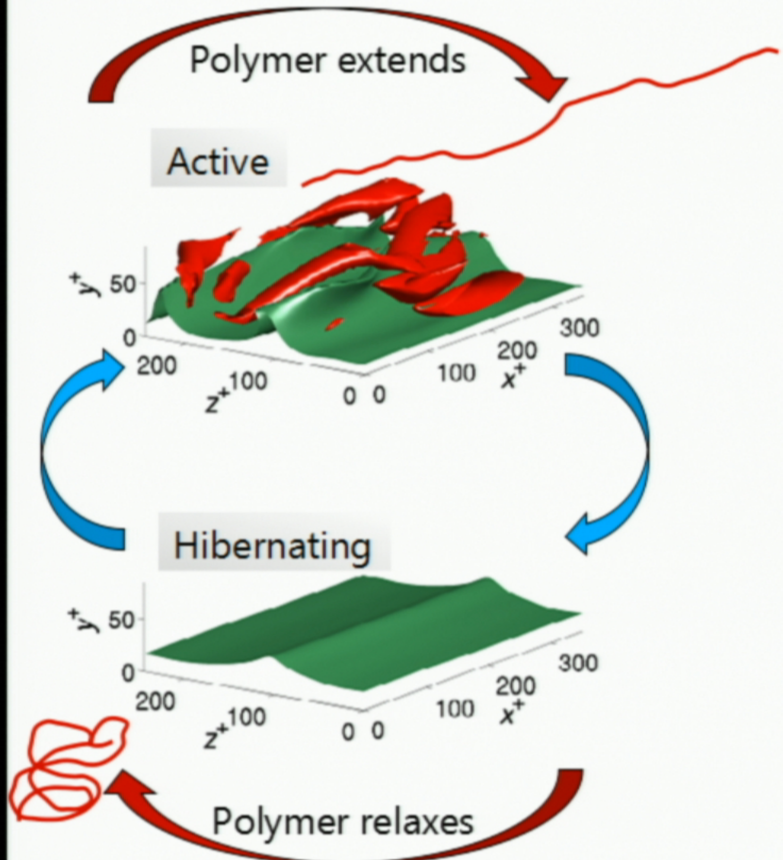

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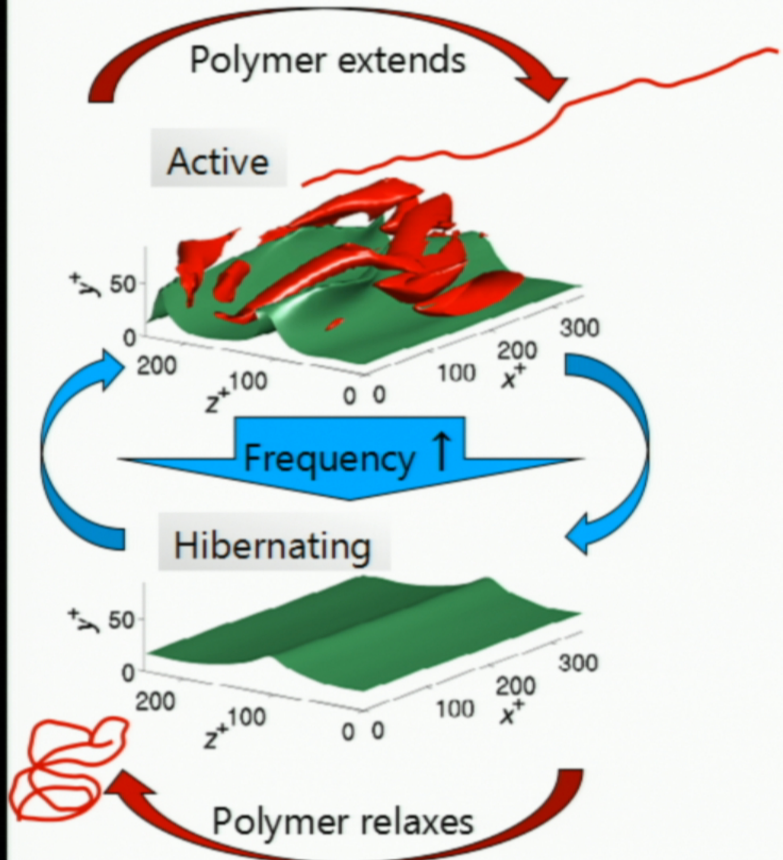

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Summary

- Hibernating turbulence:
  - Newtonian in nature.
  - MDR-like.
- Polymer suppresses active turbulence only.
- As Wi ↑, hibernation becomes more dominant, the flow appears more like MDR.
- A framework consistently explaining all major observations of MDR.

Acknowledgment:

NSF ACS PRF NSERC CRSNG