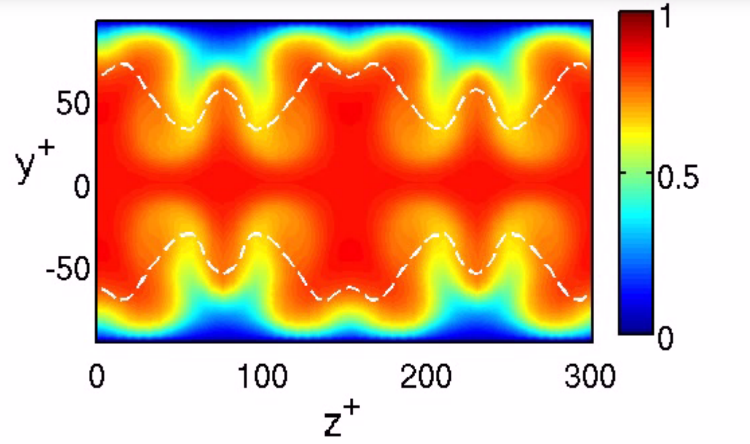
Drag reduction and the dynamics of turbulence in simple and complex fluids



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www.grahamgroup.che.wisc.edu

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- AFOSR
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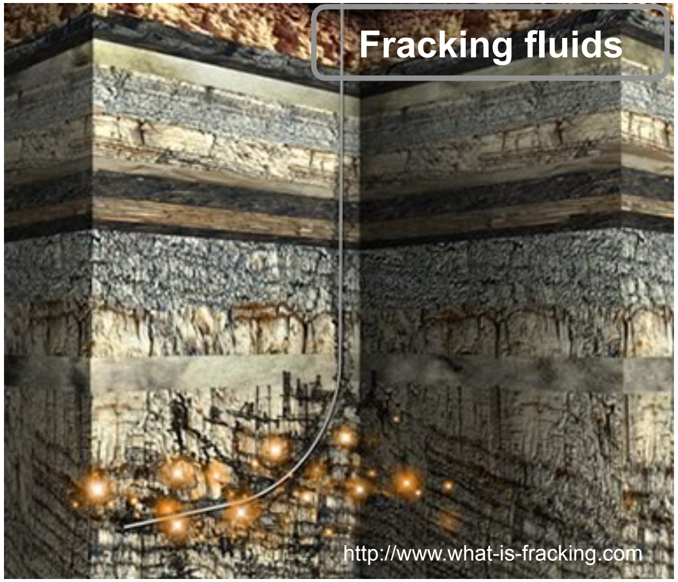
Turbulent flow of complex fluids: drag reduction

- Small amount of long-chain polymer additive reduces friction loss:
  - Increased flow rate/reduced pressure drop.
  - Alaska pipeline: 50% increase in pumping capacity
  - Wormlike micellar surfactant solutions are also effective


Oil Transport

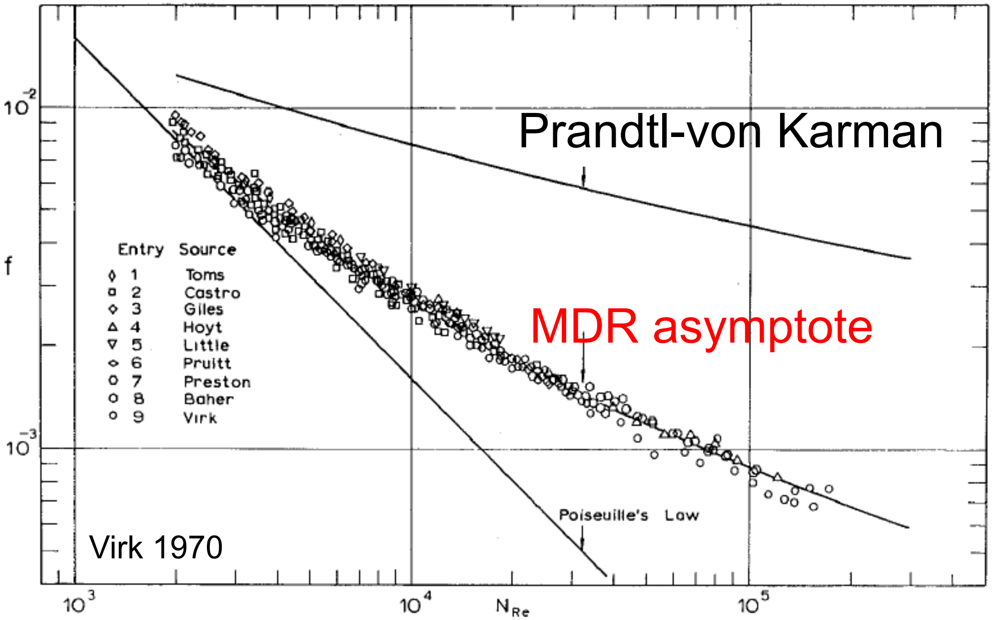
www.alyeska-pipe.com


Fracking fluids

http://www.what-is-fracking.com


District Heating/Cooling

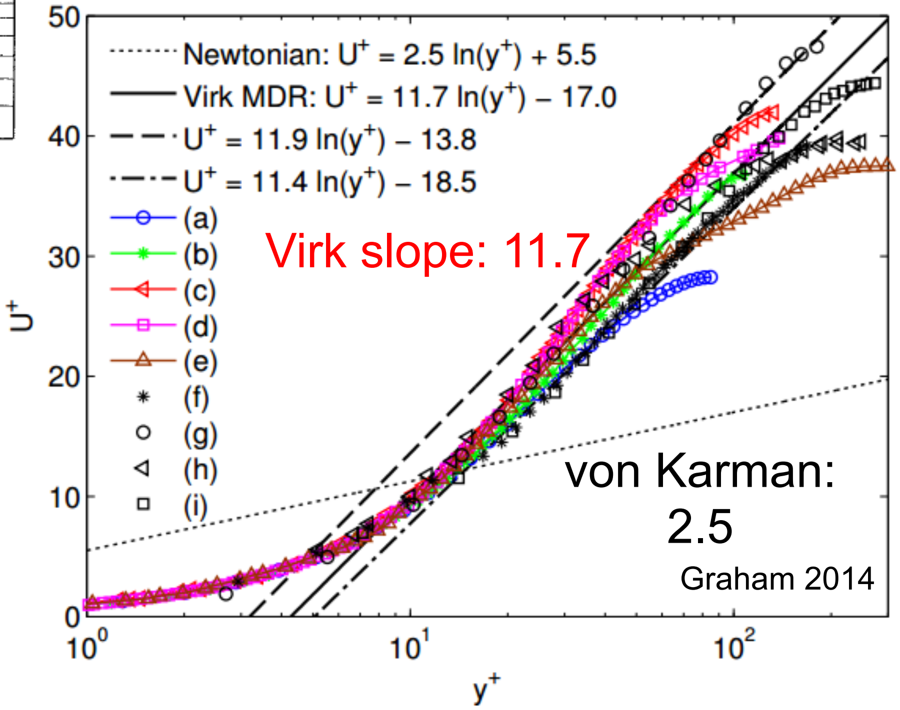
The maximum drag reduction (MDR) asymptote



Virk 1970

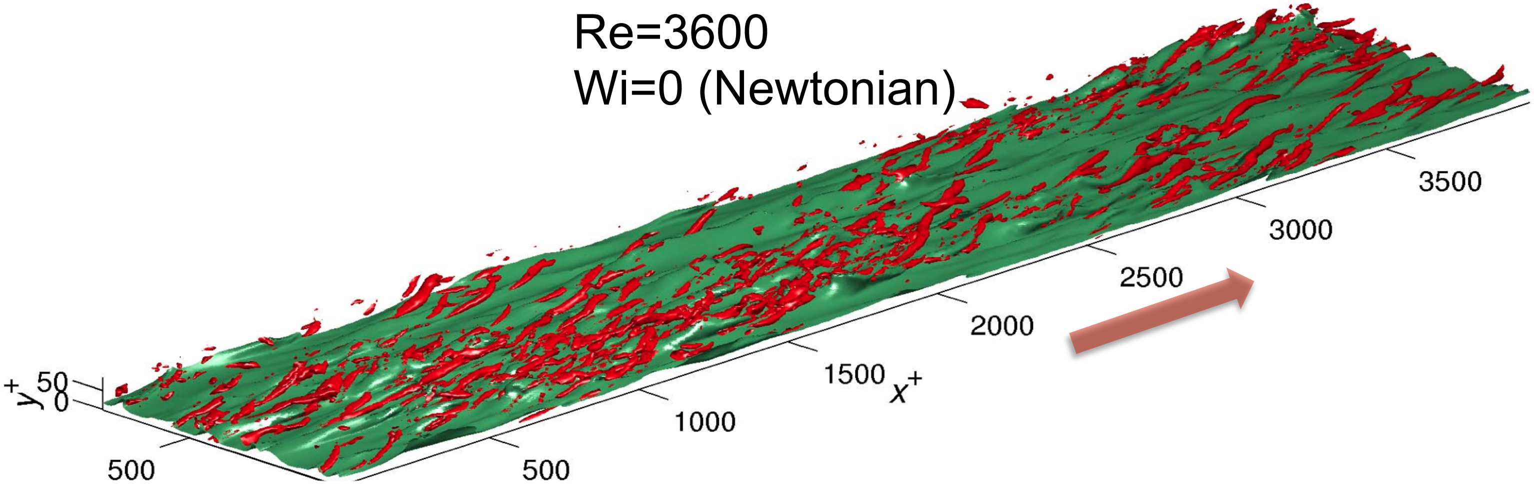
- The upper limit of friction drag reduction that can be achieved in a turbulent flow system by adding polymer
- **High and low Re phenomenon**

- **Nearly** **universal** **mean velocity profile (log-law slope ~ 11.7)** -- Re, flow geometry, polymer species, MW and concentration
- Much weakened turbulent motions – streaks, streamwise vortices, Reynolds shear stress



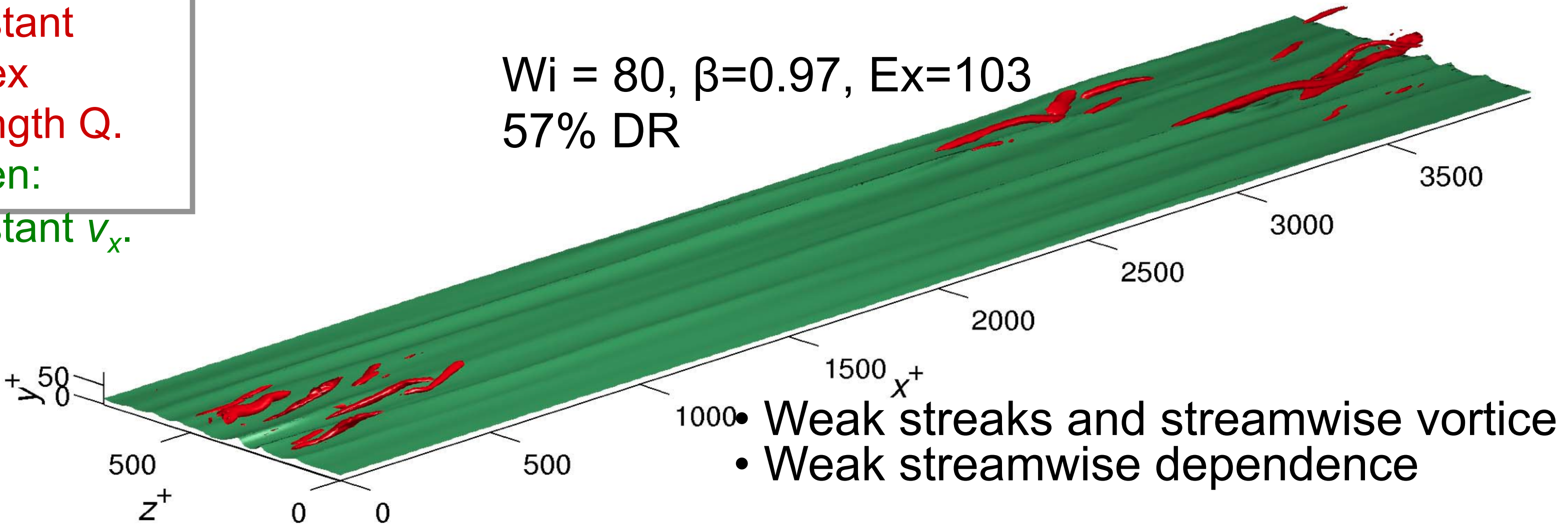
Graham 2014

Turbulence structure: Newtonian and viscoelastic



Re=3600
Wi=0 (Newtonian)

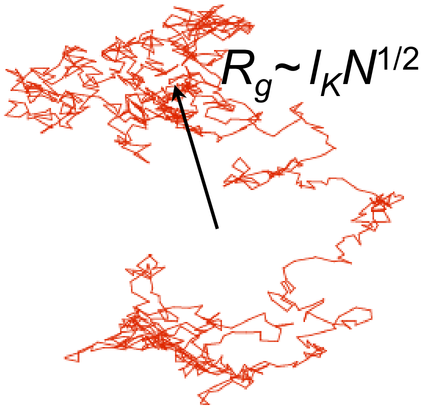
- Red: constant vortex strength Q.
- Green: constant v_x.

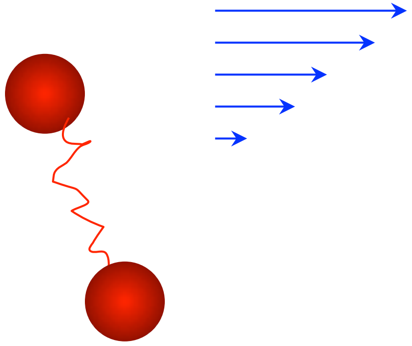


Wi = 80, β=0.97, Ex=103
57% DR

- Weak streaks and streamwise vortices
- Weak streamwise dependence

Dilute polymer solutions





Shear flow: polymer molecules stretch but tumble – weak effect on viscosity:

$$\eta = \eta_s (1 + O(cR_g^3))$$

$$\beta = \frac{\eta_s}{\eta} \qquad 1 - \beta \propto cR_g^3 << 1$$

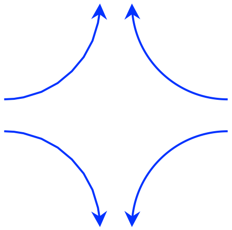
Contour length $L = l_K N >> R_g$

Diffusivity $D \sim \frac{kT}{\eta R_g}$

Relaxation time $\lambda \sim \frac{R_g^2}{D}$

Weissenberg Number $\mathrm{Wi} = \lambda \dot{\gamma}$

Elasticity number $\mathrm{El} = \mathrm{Wi}/\mathrm{Re} = \lambda \nu / H^2$



Extensional flow: polymer molecules stretch exponentially, strongly resisting extension:

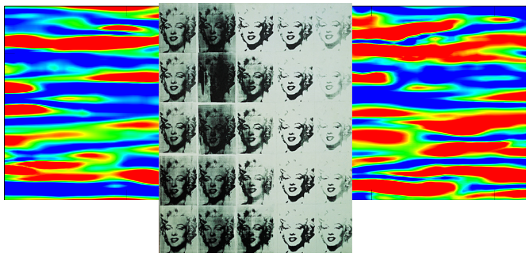
$$\mathrm{Ex} = \max\,(\mathrm{Tr}) = \frac{\eta_p^e}{\eta_s^e} \sim (1 - \beta) \frac{L^2}{R_g^2} >> 1$$

(Lagrangian chaotic velocity fields are extensional.)

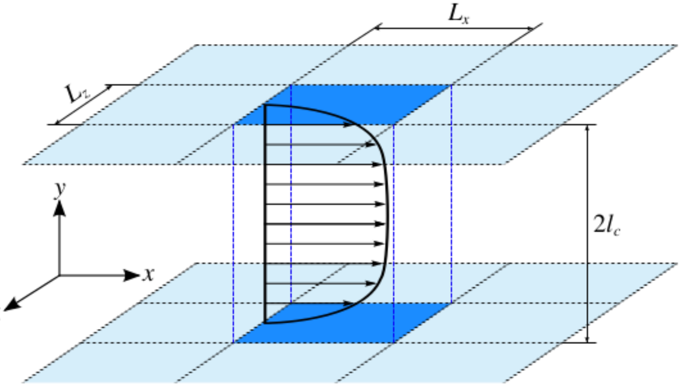
Overview

- Turbulent dynamics of Newtonian and viscoelastic fluids in a minimal channel

  - Intermittency: “active” and “hibernating” intervals
  - A little theory for interaction of polymers and turbulence
  - Hints at an underlying state space structure
- New invariant states in Newtonian minimal channel flow
  - Echoes of real turbulence in simple solutions
  - state space structure of Newtonian (and maybe viscoelastic) minimal channel turbulence
- Toward real turbulence
  - Observations connecting minimal channel results to large domains

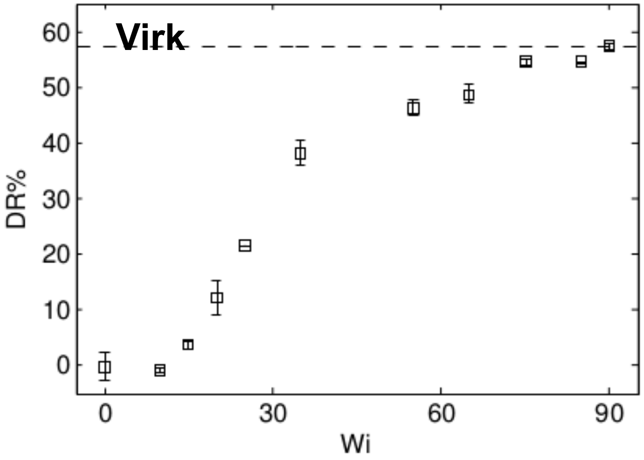


Minimal channel simulations from Newtonian to MDR

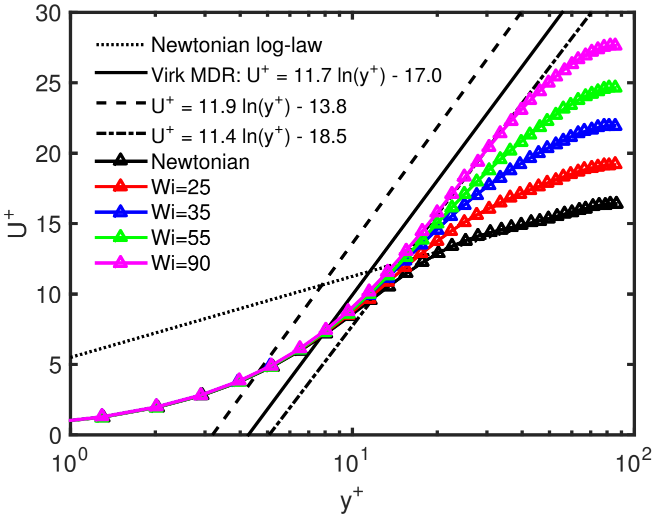


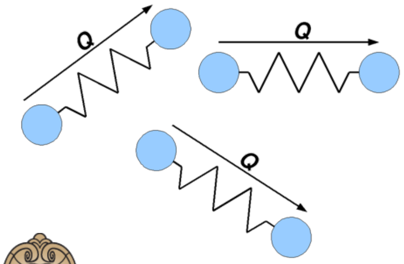
Channel flow geometry

Re=3600 (Re_τ=85), β=0.97, Ex=206, Wi=$\lambda\dot{\gamma}$0-90



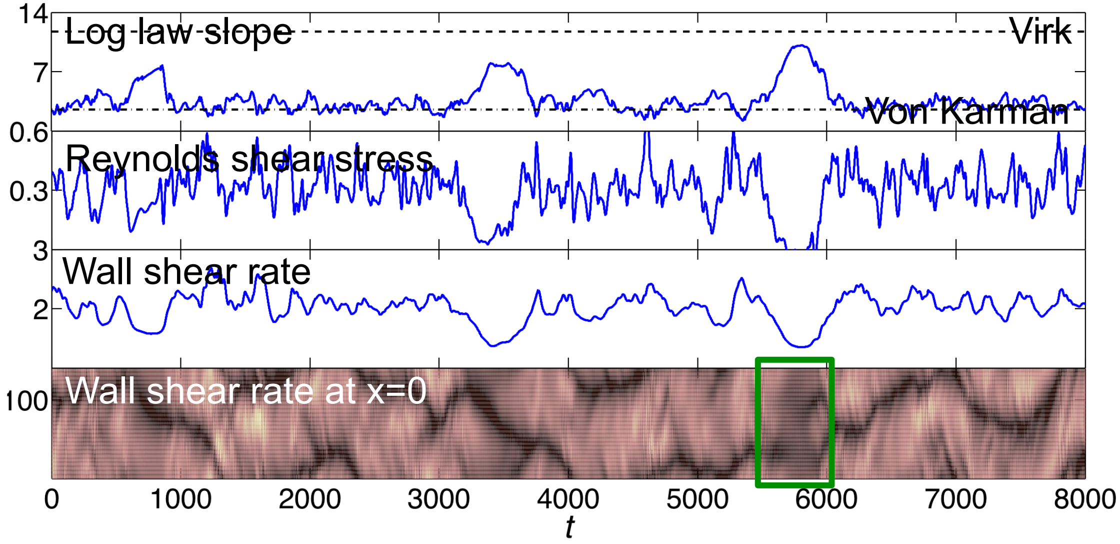
- Simulation in “minimal” domain that isolates the dynamics of individual coherent structures. (cf. Jimenez & Moin JFM 1991)
- Viscoelastic extension of Gibson’s *ChannelFlow* code
- Size of minimal domain increases in both streamwise and spanwise directions as Wi increases.





FENE-P dumbbell model for polymers

Intermittent dynamics for Newtonian and moderate Wi



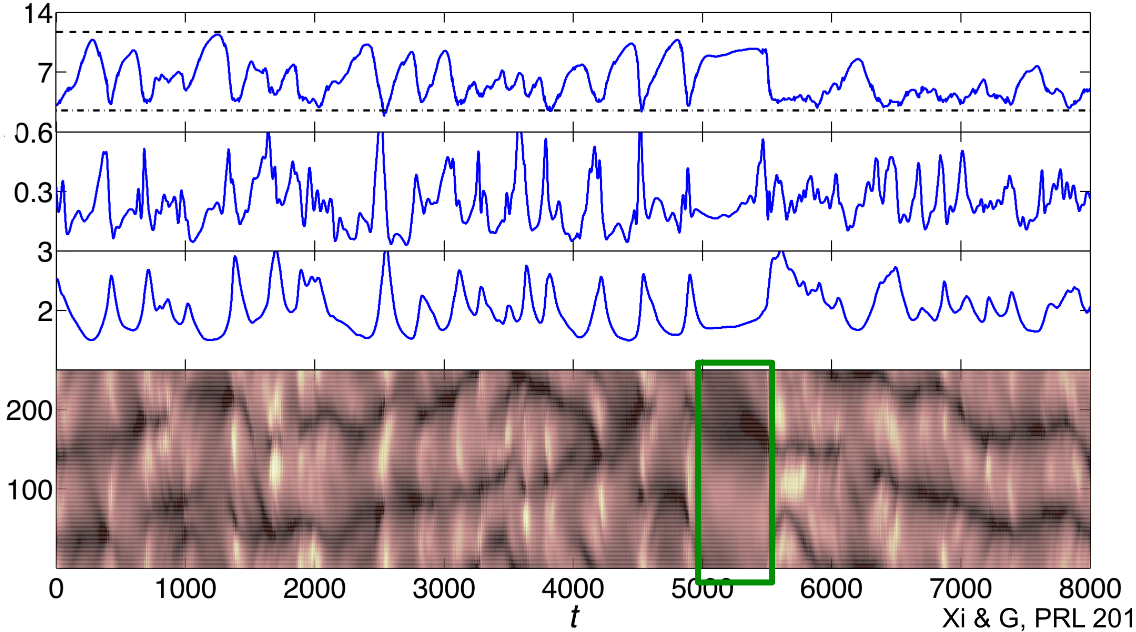
Newtonian

- Re=3600 (Re_τ=85)
- Instantaneous log law slope is usually near von Karman, with infrequent excursions toward Virk
- “quiescent periods” (cf. JM 1991, HKW 1995)

Viscoelastic:

- Wi=29,β=0.97, Ex=103
- 26% DR
- frequent excursions from von Karman to Virk
- Stretching and mean velocity are anticorrelated

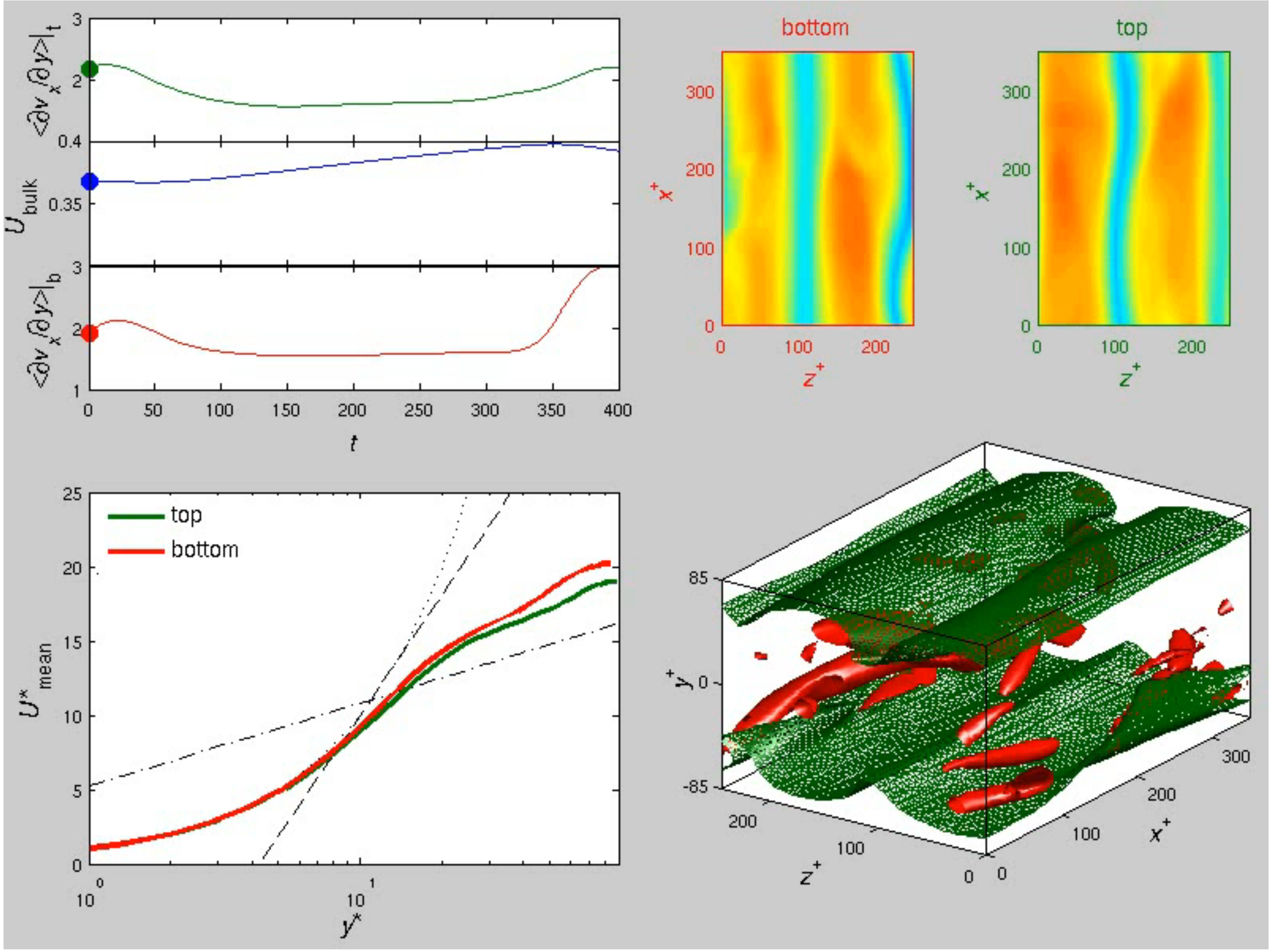
In both cases, intervals of “active” and “hibernating” turbulence are seen



Xi & G, PRL 2010

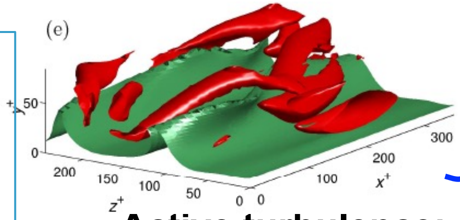
What happens during a hibernation period?

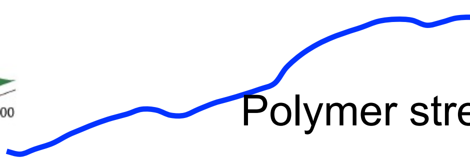
Wi=29



Temporally intermittent dynamics in drag-reduced flow

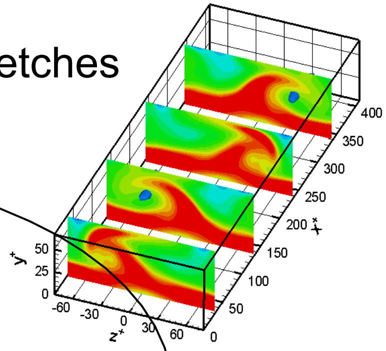
Temporal *anticorrelation* between velocity and stress

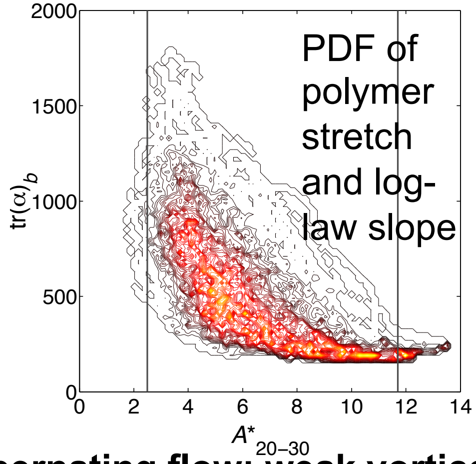




Polymer stretches

Active turbulence: substantial stretching of polymer molecules





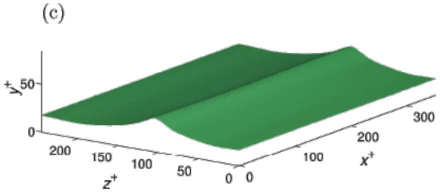
New turbulent fluctuations grow, destabilizing hibernation and generating active turbulence

Polymer stretching suppresses active turbulence (works against streamwise vortices*) and causes hibernation

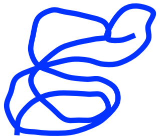
Infrequent hibernation even in Newtonian limit

Hibernating flow: weak vortices, Reynolds stresses and streamwise waviness. Polymers relax.

Shinji Tamano JFM 2011: this anticorrelation is *spatial* in boundary layers



Polymer relaxes



* Dubief; Khomami; Sureshkumar; Adrian; G.

Time scale theory for active intervals

- At the beginning of an active interval polymers are relaxed: hibernation does not strongly stretch chains
- Estimate evolution of polymer stress during an active interval:

$$S \sim \exp\left(\overbrace{2\sigma}^{\text{Active turbulence stretches polymers}} - \underbrace{\frac{1}{\mathrm{Wi}}}_{\text{Polymers relax toward equilibrium}}\right) t$$

- Here σ is the largest Liapunov exponent (stretch rate) for the flow.
- Persistent stretching occurs when $\mathrm{Wi} > \mathrm{Wi}_c = 1/2\sigma$.
- (Transient stretching can occur when $\mathrm{Wi}<\mathrm{Wi}_c$, so $\mathrm{Wi}_{onset}<\mathrm{Wi}_c$.)

- Hypothesize:
  - once $\mathrm{Wi}>\mathrm{Wi}_c$, the duration T_A of an active turbulence interval is simply the time that the polymer stress remains below a threshold value S_T
  - σ during the active interval is independent of Wi, so $\sigma=1/2\mathrm{Wi}_c$

$$T_A = \frac{\ln S_T}{\mathrm{Wi}_c^{-1} - \mathrm{Wi}^{-1}}$$

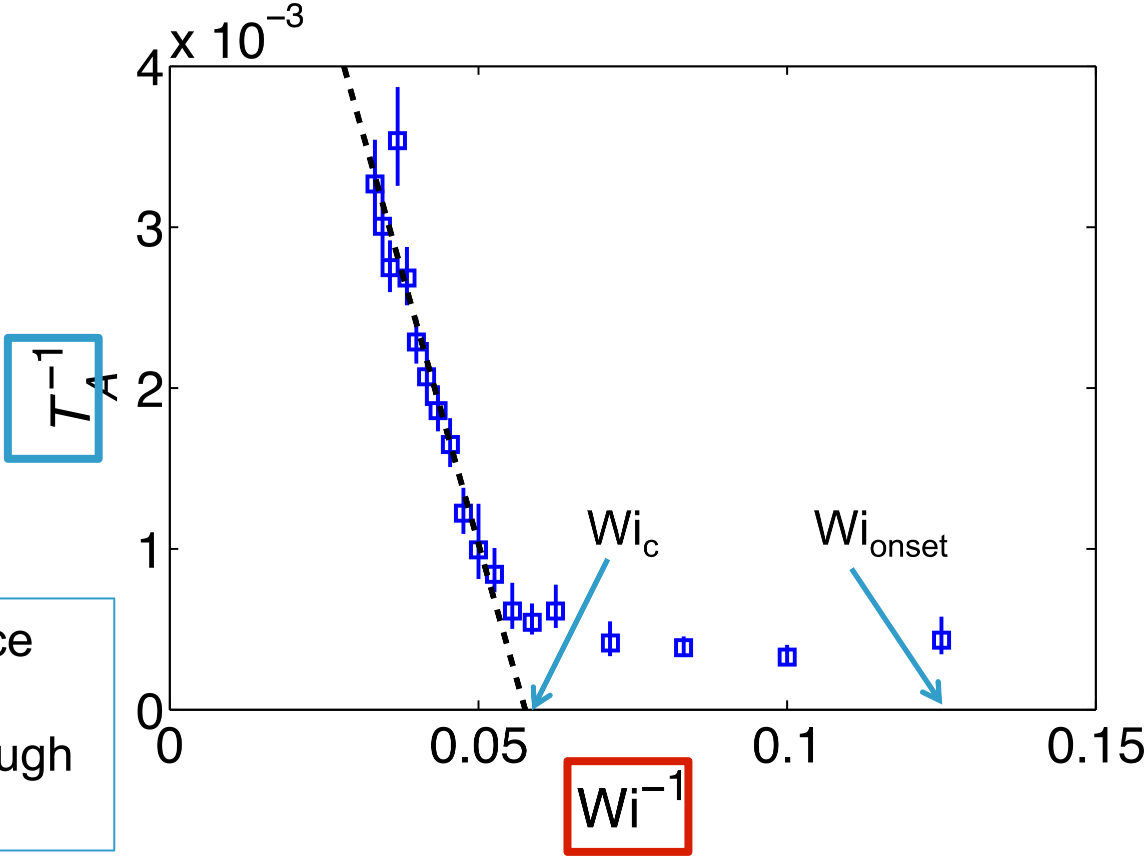
Xi & G, JFM 2012

Time scale theory for active intervals

$$T_A = \frac{\ln S_T}{\mathrm{Wi}_c^{-1} - \mathrm{Wi}^{-1}} \quad \Rightarrow \quad \boxed{T_A^{-1}} = -(\ln S_T)^{-1}\boxed{\mathrm{Wi}^{-1}} + (\ln S_T\,\mathrm{Wi}_c)^{-1}$$

Linear fit of high Wi results:

- $\mathrm{Wi}_c = 17.4$
- $S_T = 1510$



Duration of active turbulence is controlled by how long it takes to stretch chains enough to suppress streamwise vortices

MDR, hibernation and nonlinear dynamics

Viscoelastic MFU turbulence seems to organized around two "states"

- Active: strong vortices/streaks, von Karman slope
- Hibernating: weakly 3D, Virk slope

Some intermittency persists in the Newtonian limit

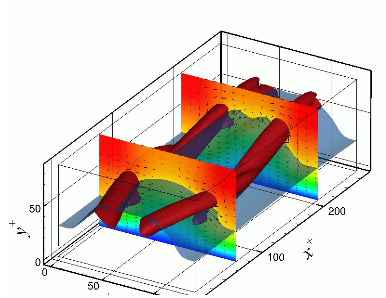
Is there an underlying state space structure that is organizing the dynamics this way? E.g.

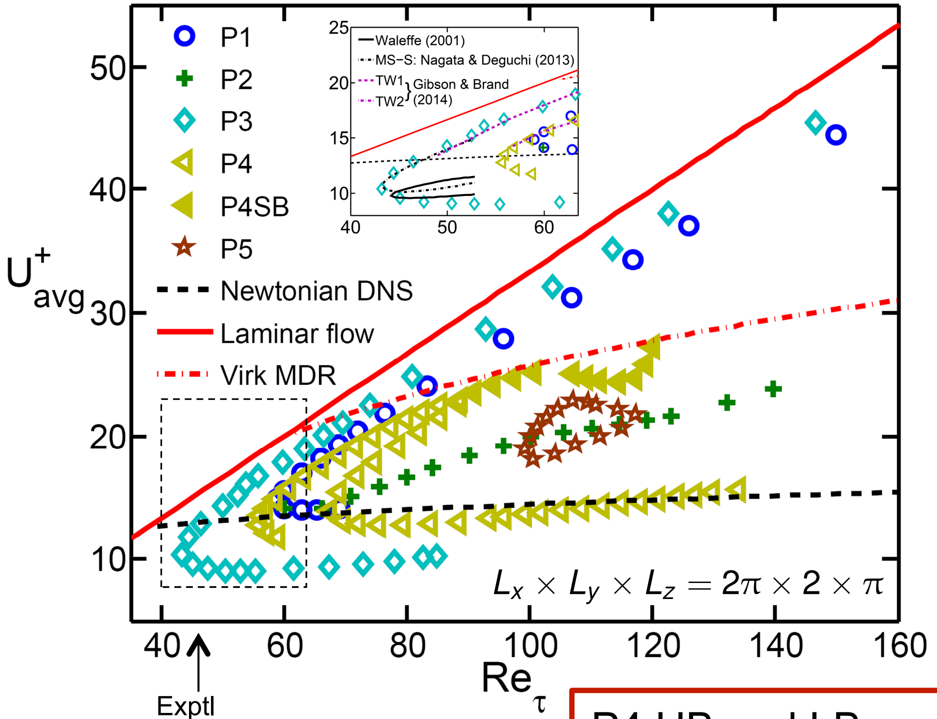
- Nonlinear traveling waves
- Edge states: "marginal" trajectories on the laminar-turbulent basin boundary

If so, to what extent is this present in the Newtonian limit and thus "universal" in some sense with respect to viscoelastic properties?

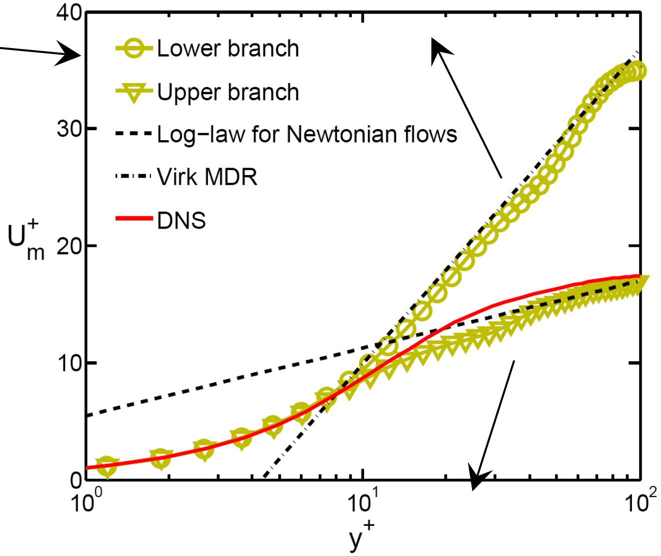
Exact coherent states in *Newtonian* channel flow

- DNS + Newton iteration (*ChannelFlow*) ➔ exact solutions to NSE
  - Nonlinear traveling waves: $\boldsymbol{v}(x,y,z,t)=\boldsymbol{v}(x-ct,y,z)$
  - Initial guesses: velocity fields from DNS
  - Some states are on edge for a range of Re
  - P4 family is interesting:

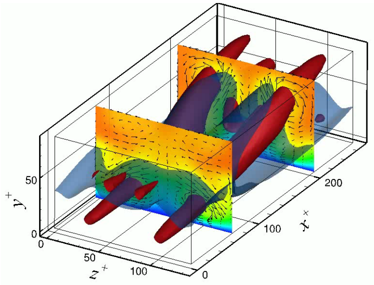




Exptl transition



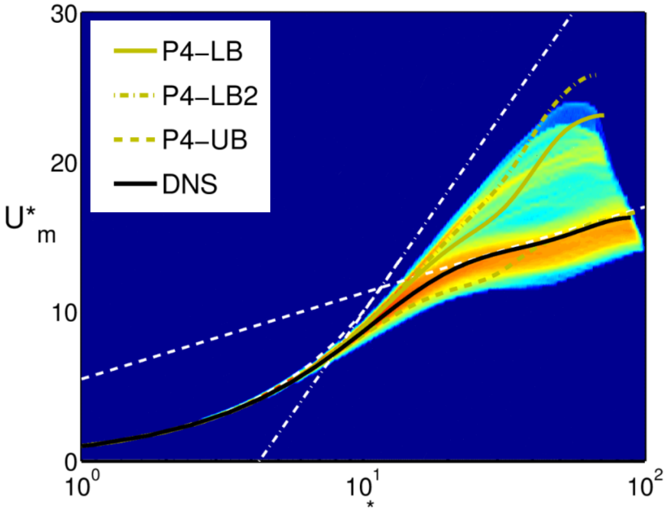
P4 UB and LB are close to von Karman and Virk, respectively!



Park & G. 2015

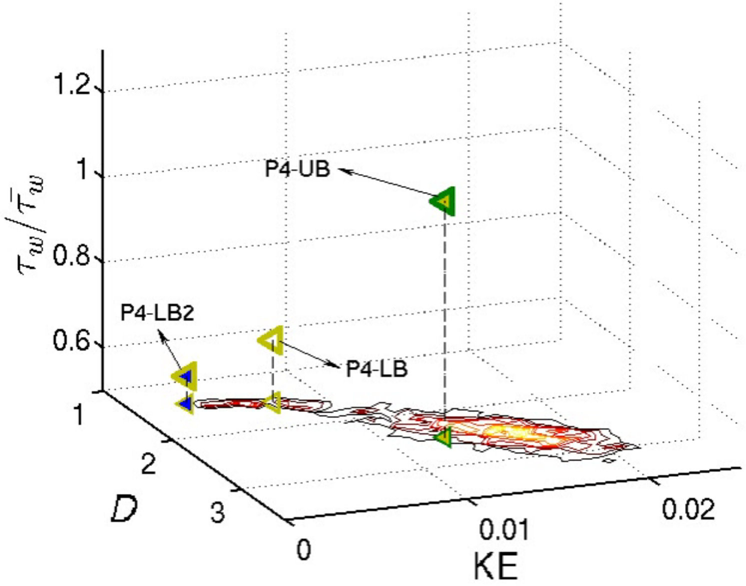
Traveling waves and Newtonian MFU/DNS results

- PDF of instantaneous mean velocity profile (log scale):



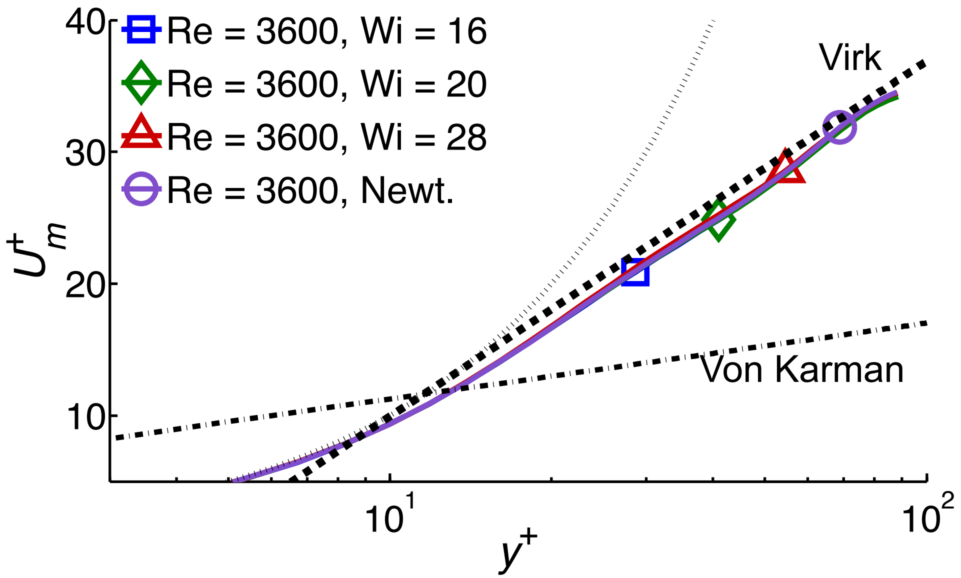
- DNS vs TWs under same conditions (const. Q)
- P4 traveling waves form tight envelope for DNS mean velocity.
- Hibernation is approach to P4 lower branch.

- State-space visualization:
  - By projection using disturbance kinetic energy (KE), energy dissipation rate (D), and wall shear stress (τ_w).
  - There are occasional excursions (hibernation) toward P4 lower branch solutions.
  - Burst phenomenon can be seen as paths escaping from the P4 LB solutions.

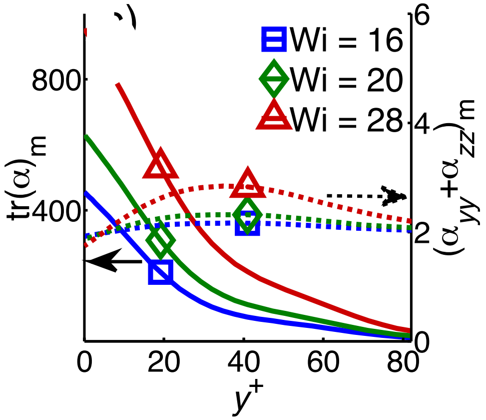


Newtonian and viscoelastic edge states

Mean velocity profiles



Mean polymer stress profiles



- Mean velocity profiles for both Newtonian and viscoelastic edge states collapse onto Virk log law
- Edge state is barely 3D, very weak polymer stretching
- Polymer stretch is dominated by mean shear

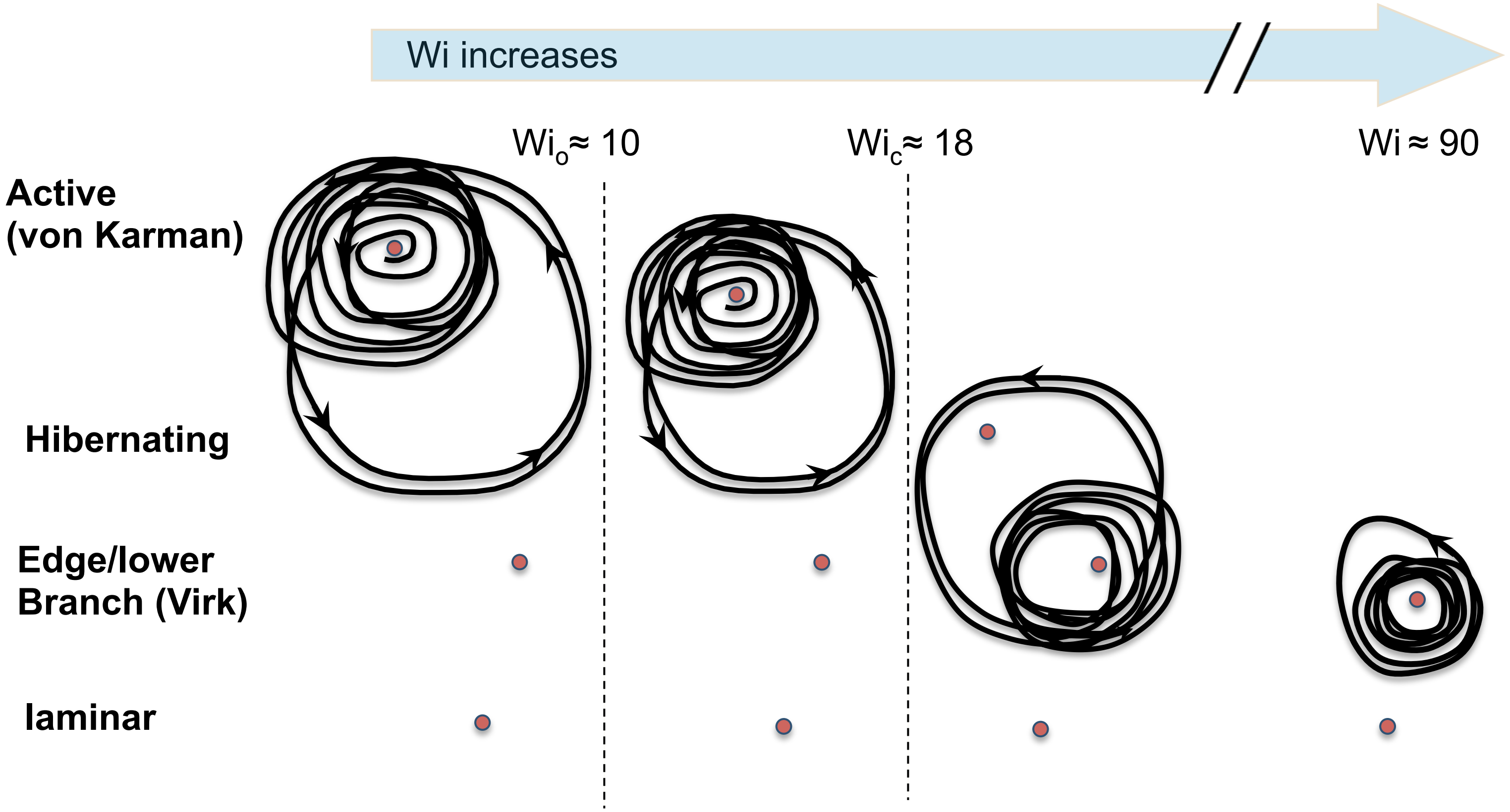
⇒ Edge state does not strongly stretch polymers so is not strongly affected by them

⇒ At this Re, hibernation appears to be an approach to the edge

⇒ Drag reduction in this regime is an approach to the edge.

Xi & G. PRL 2012

Unifying state space picture for drag reduction in MFU



Newtonian
Negligible polymer stretching

Low DR
Transient polymer stretching

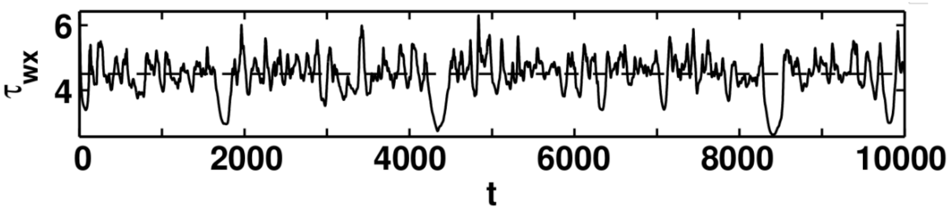
High DR
Persistent stretching in active intervals shortens them

MDR
Hibernation dominates and becomes altered by viscoelasticity

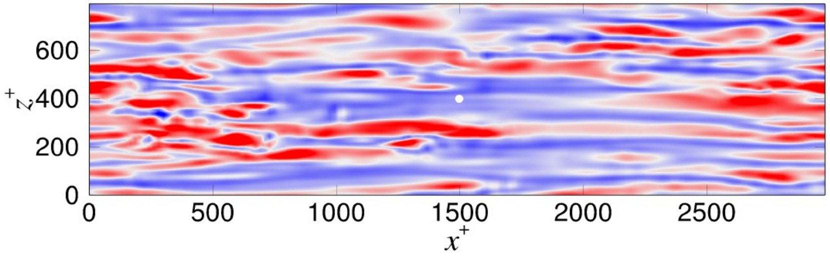
Small to large…

- How is minimal channel turbulence related to the phenomenon of laminar-turbulent intermittency in transitional Reynolds number regime for spatially extended flows?

- How does the temporal intermittency in minimal channels translate to spatiotemporal intermittency in large domains?



Temporal evolution of wall shear stress in a minimal channel. Dashed line represents the mean value.



Spatial variation of wall shear stress in an extended domain. Red: high; blue: low.

- What do the flow statistics and structures look like during high and low drag states in Newtonian flows in large domains?

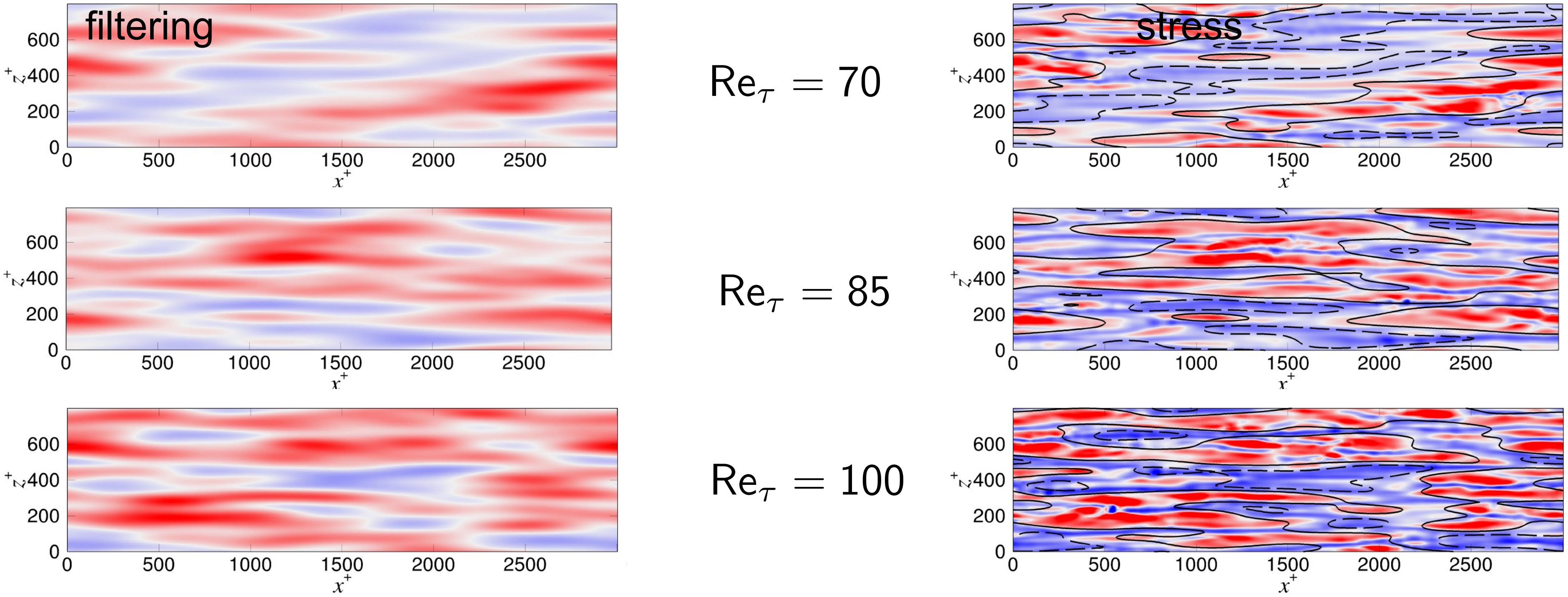
- How are temporal and spatial statistics in large domains related?

- Connections between large-box turbulence and nonlinear travelling waves?

Spatial variation of drag (Newtonian for now)

Detector function after filtering

Wall shear stress

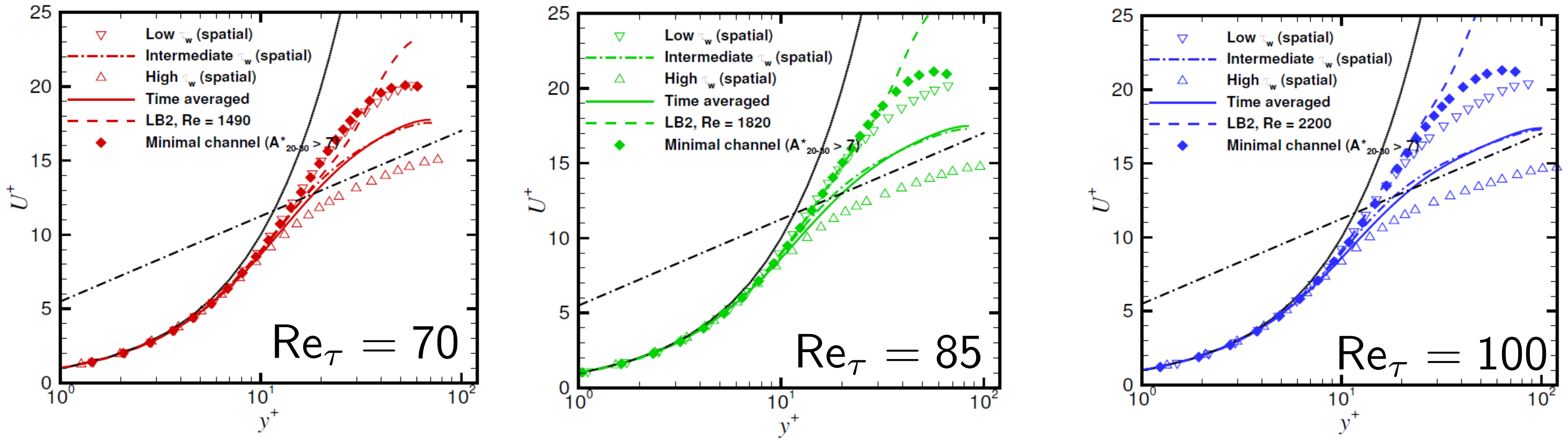


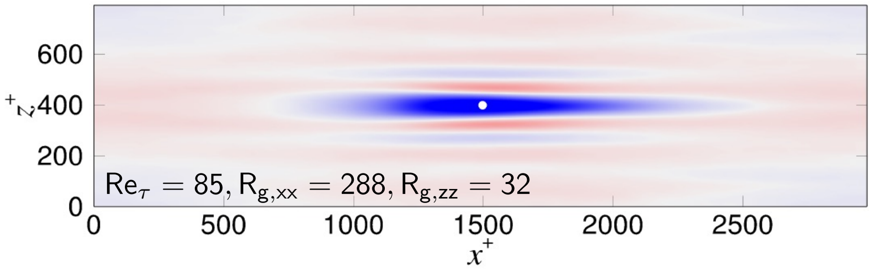
- Edge detection: i.e. finding boundaries between regions of different characteristics: we subdivide signal into 3 classes
- Maximize “interclass” variance: Otsu’s method or k-means clustering
- Signal: Detector function + Gaussian filter (cf. Nolan and Zaki JFM 2013)

$$D = \left|\frac{\partial u}{\partial y}\right|_w + \left|\frac{\partial u}{\partial z}\right|_{y^+=15}$$

Kushwaha, Park and G. PR Fluids 2017

Conditional mean profiles vs lower branch ECS





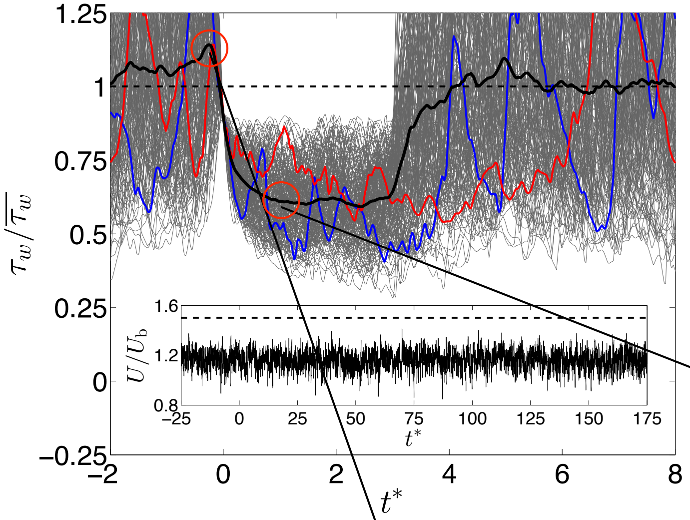
Conditionally averaged wall shear stress of many low-drag patches. White dot represents the centroid.

- Low-stress conditional velocity profiles from both minimal and extended domains are shifted upward and lie close to the lower branch ECS $y^+ \lesssim 30$ for .
- The behavior near the centerline remains distinct.
- Conditional mean profile is independent of Re (over the range studied).

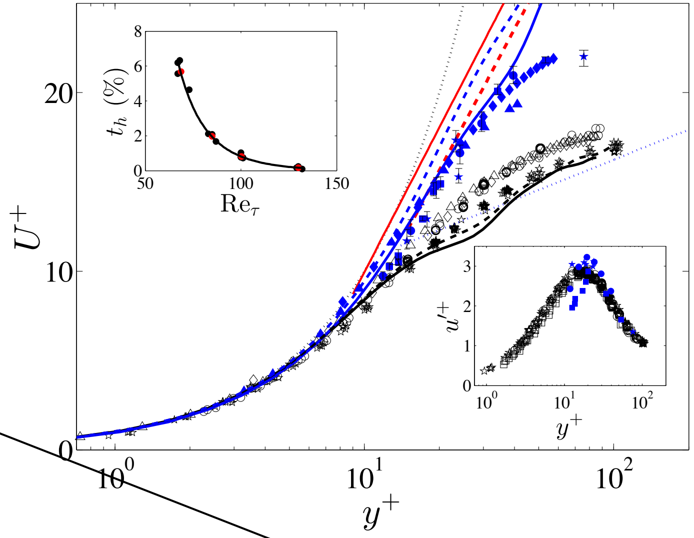
Experiments: low-drag events in channel flow

w/ Rob Poole, Liverpool

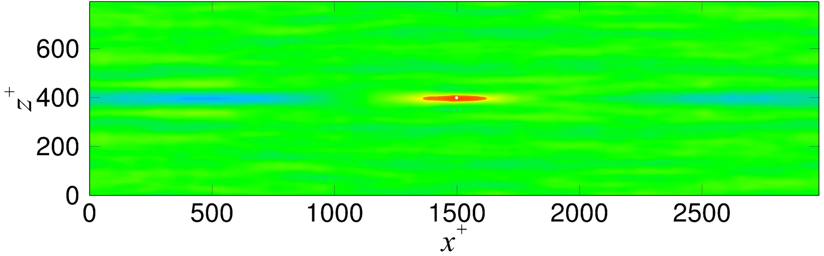
Detect intervals where τ_w drops below 90% for $t^*>3$ at a point on the wall

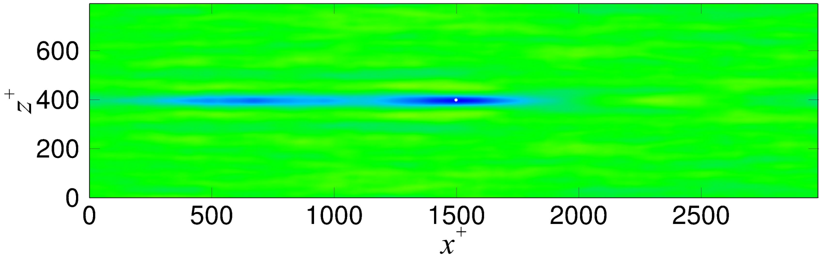


Conditional (upper) and unconditional (lower) velocity profiles+P4LB ECS+Virk



Conditionally averaged wall shear stress, DNS



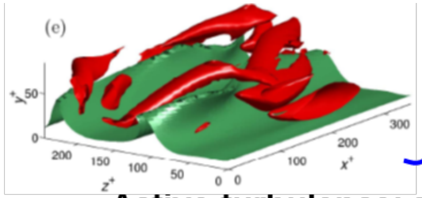


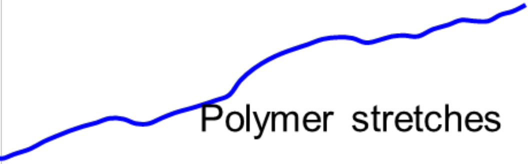
- ➢ Temporal sampling based on shear stress at a point (possible with LDV)
- ➢ Low drag intervals with slope near lower branch appear in experiments

Whalley et al. PR Fluids 2017

Stochastic cycle in drag-reducing flows

Minimal: same structure in whole domain





Polymer stretches

Active turbulence: substantial stretching of polymer molecules

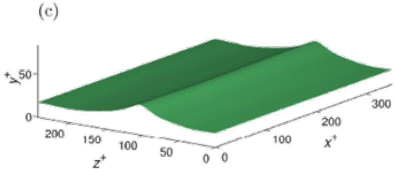
Polymer stretching suppresses active turbulence (works against streamwise vortices) and causes hibernation

Hibernating flow: weak vortices, Reynolds stresses and streamwise waviness. Polymers relax.

New turbulent fluctuations grow, destabilizing hibernation and generating active turbulence

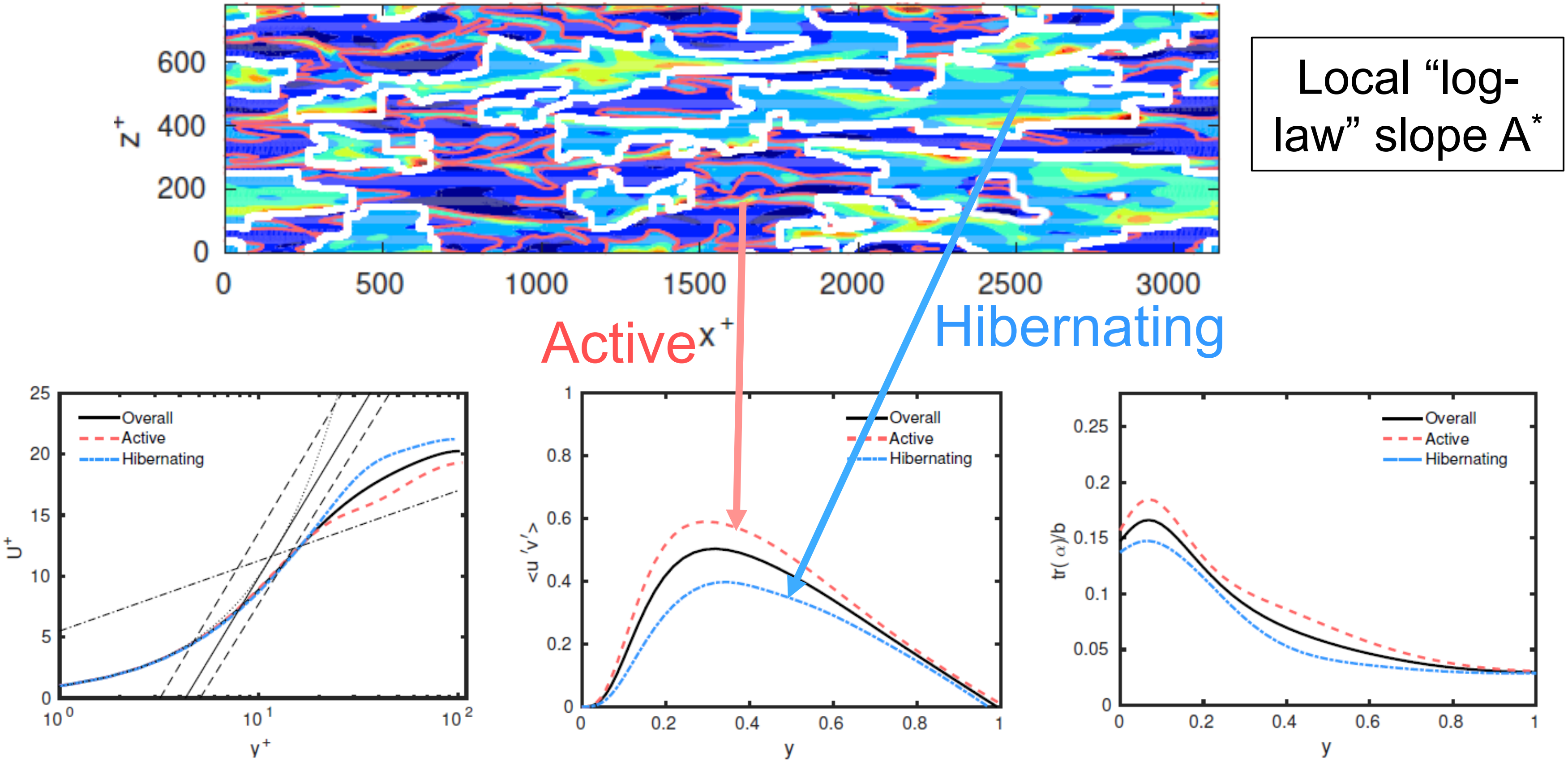
Q: What does the spatiotemporal dynamics look like in non-minimal domains?

Polymer relaxes



Hibernating and active regions in large domains

- $Re_\tau=100$, Wi=24



Local "log-law" slope A^*

Mean velocity profile

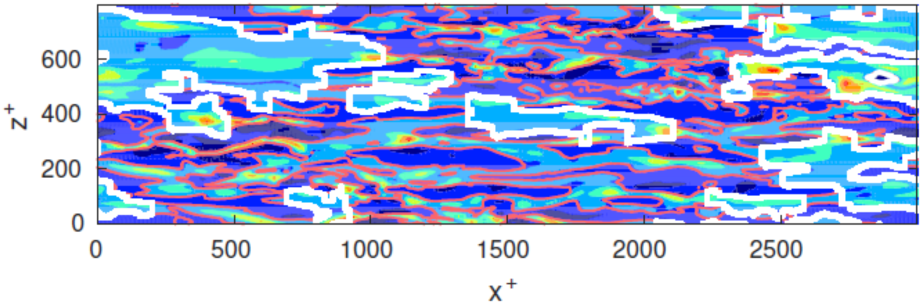
Reynolds shear stress

Polymer stretch

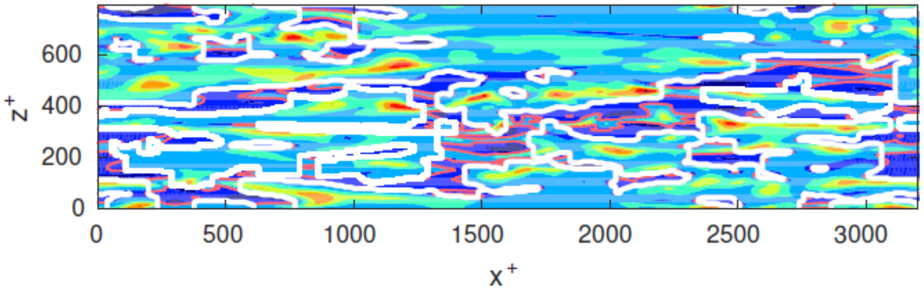
Anticorrelation between stretch and local degree of drag reduction

Dynamics changes with Re_τ and Wi

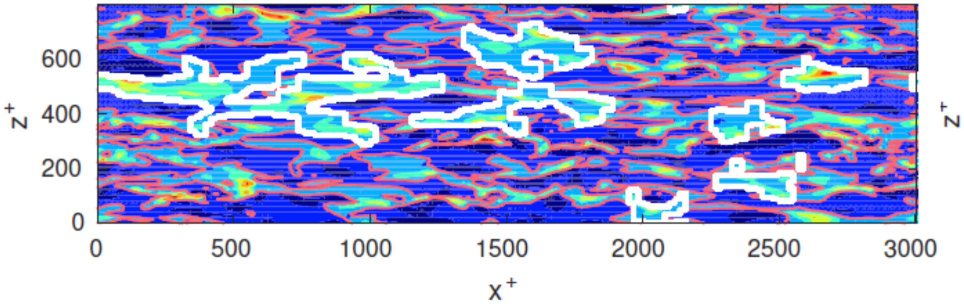
- Re_τ=70,



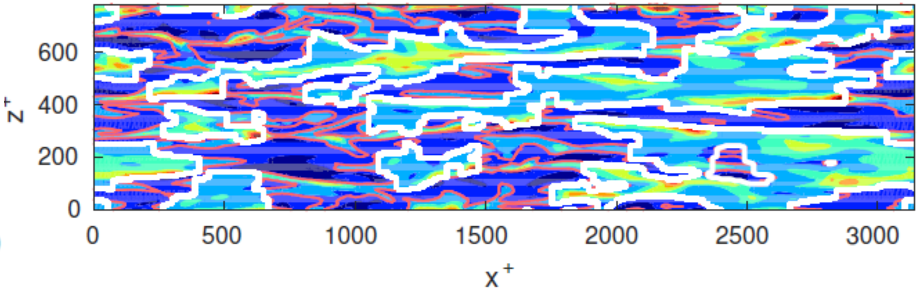
- Re_τ=70,



- Re_τ=100,



- Re_τ=100,



- Hibernating regions ↓ as Re_τ ↑
- Hibernating regions ↑ as Wi ↑

Summary

⇒ Minimal channel studies shed light on the dynamics of turbulent drag reduction in polymer solutions

⇒ Both Newtonian and viscoelastic minimal channel turbulence display intermittent
"hibernating" turbulence:

- ⇒ Long-lived recurrent transient very different from "active" turbulence
- ⇒ Hibernation is present in Newtonian flows but unmasked by viscoelasticity.
- ⇒ Stretch and drag reduction are anticorrelated
- ⇒ Simple theory captures Wi-dependence of lifetimes at low-moderate DR
- ⇒ Mean velocity close to maximum drag reduction (Virk) profile
- ⇒ Close connection to lower branch traveling wave and edge states (and an upper branch TW close to von Karman (active) mean profile)
- ⇒ Near-universality of MDR may arise from Newtonian origin of hibernation

⇒ Large-domain experiments and simulations display *spatiotemporal* intermittency

- ⇒ Low drag intervals/regions display some characteristics of minimal channel ECS
- ⇒ In viscoelastic flow, low drag spatial regions evolve toward MDR at

JFM 2010, 2012, 2015, PRL 2010, 2012, AIChE J 2014, PoF 2014, Phys Rev F 201

What's next?

⇒ Experiments: statistics and structure for polymer solutions near transition (Poole)

⇒ Mechanistic theory for approach to MDR – related to burst instability of ECS?

⇒ Spatiotemporal analysis for large domain viscoelastic flow; viscoelastic ECS (we looked at Waleffe solutions at low Wi a long time ago – better tools now!)

⇒ At high El and Ex, flow transitions directly(?) from laminar to MDR. Connections to elasto-inertial results (Hof, Dubief)

⇒ Spatiotemporal dynamics, larger domains, higher *Re*

⇒ Connections between ECS and McKeon/Sharma resolvent analysis, Newtonian and VE

⇒ Other complex fluids – surfactant solutions, suspensions