Low-drag turbulent states in Newtonian and non-Newtonian fluids

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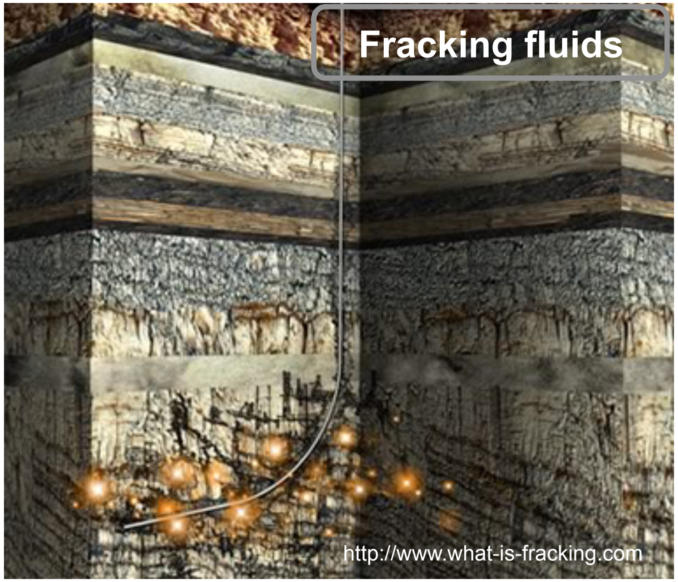
Recurrence, Self-Organization, and the Dynamics Of Turbulence

10th January 2016

Turbulent flow of complex fluids: drag reduction

Oil Transport

www.alyeska-pipe.com



Fracking fluids

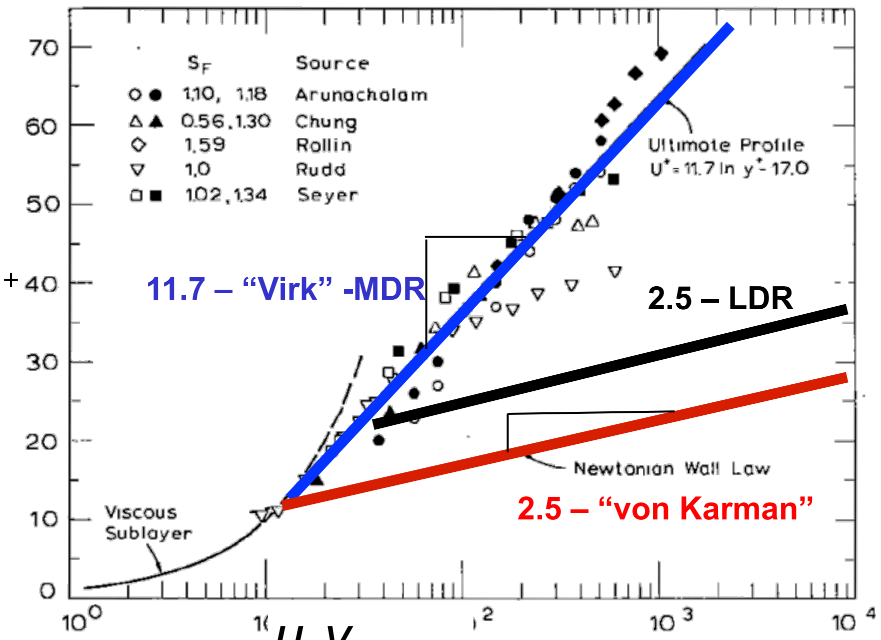
http://www.what-is-fracking.com

- 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

District Heating/Cooling

Drag reduction and the maximum drag reduction (MDR) asymptote

Velocity vs. distance from wall



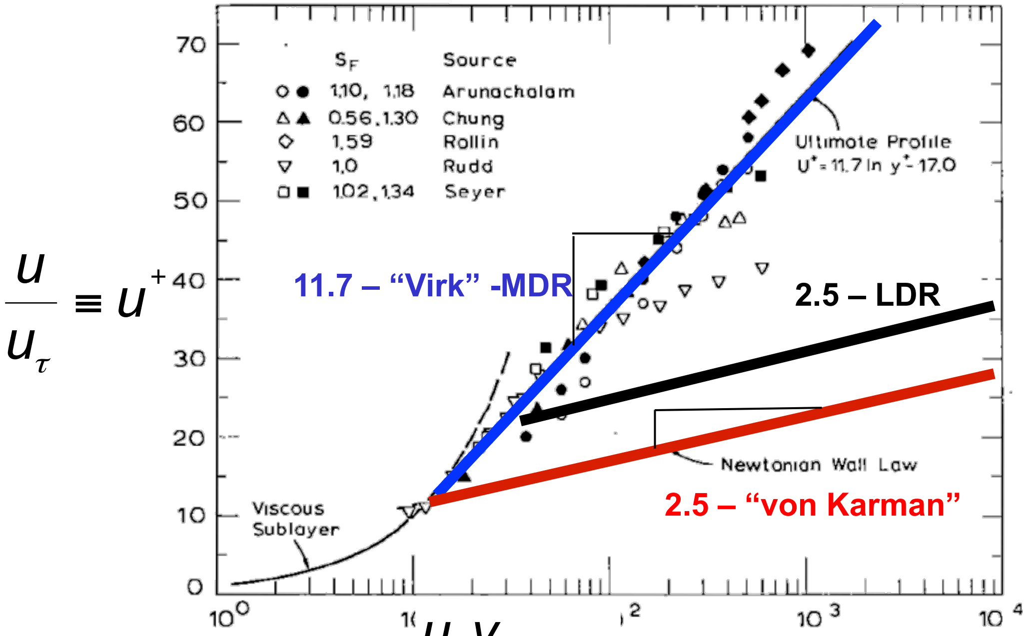
$$\frac{u}{u_\tau} \equiv u^+$$

$$\frac{u_\tau y}{\nu} \equiv y^+ \qquad u_\tau \equiv \sqrt{\tau_s / \rho}$$

Virk, P. S., *AIChE J.* 1975

Drag reduction and the maximum drag reduction (MDR) asymptote

Velocity vs. distance from wall



$$\frac{u}{u_\tau} \equiv u^+$$

$$\frac{u_\tau y}{\nu} \equiv y^+ \qquad u_\tau \equiv \sqrt{\tau_s / \rho}$$

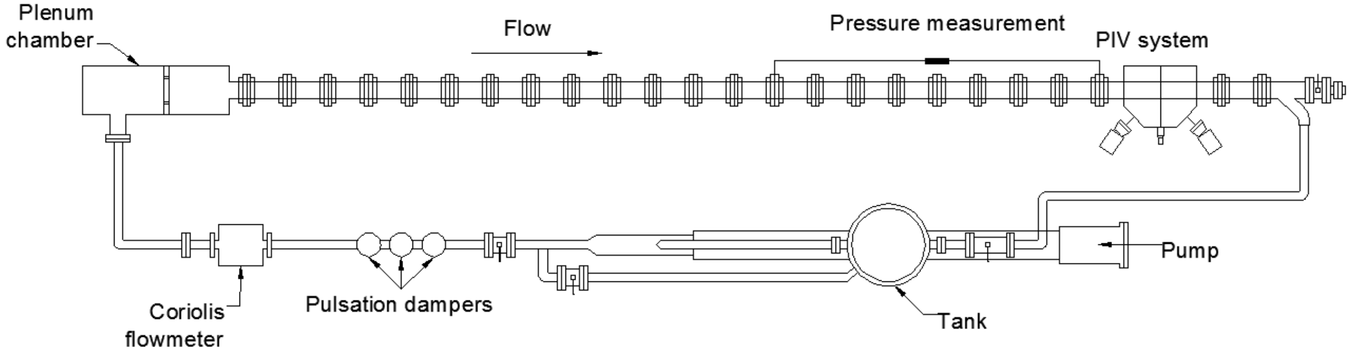
- 1000s of papers…yet never ***quantitatively*** linked to a **measurable fluid property**…. **can we predict *%DR* for a given polymer in a flow?** (1st part of talk)
- **Universal** mean velocity profile: the "Virk" profile – independent of Re, MW, conc., species,… **where might this universality come from?** (2nd part of talk)

Virk, P. S., *AIChE J.* 1975

Low-drag turbulent states in Newtonian and non-Newtonian fluids

Part 1: Polymer solutions (classical time-averaged “global” data)

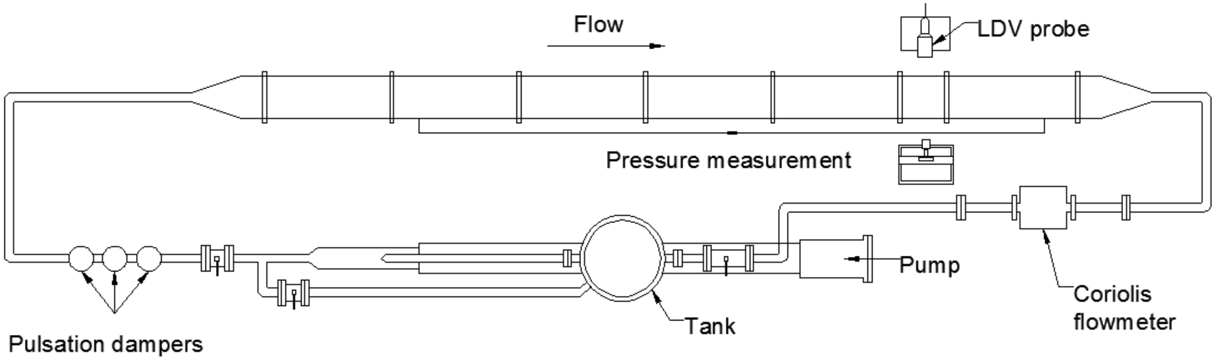
Experimental set-ups (pipe, channel and square duct)



pipe

$R = 50$ mm

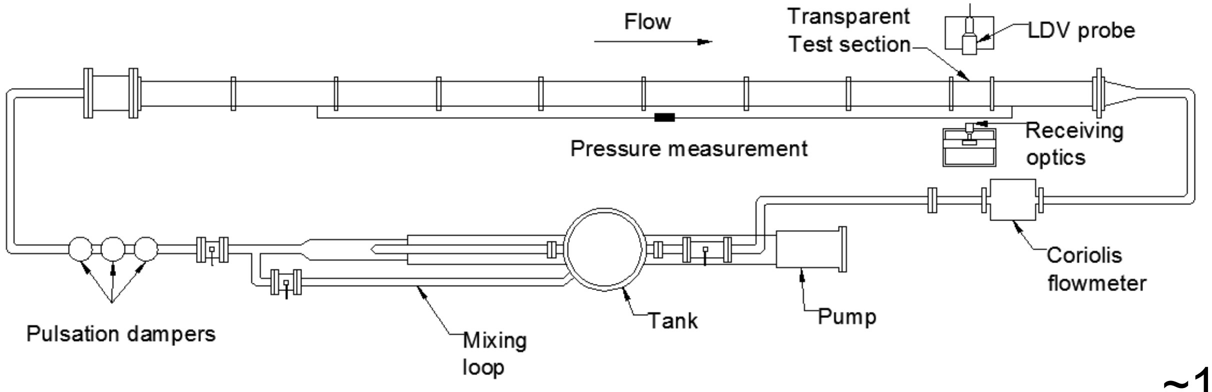
@ ~440 R from inlet



channel

$h = 12.5$ mm ($w = 25\ h$)

@ ~ 500 h from inlet



square-duct

$h = 40.0$ mm ($w = h$)

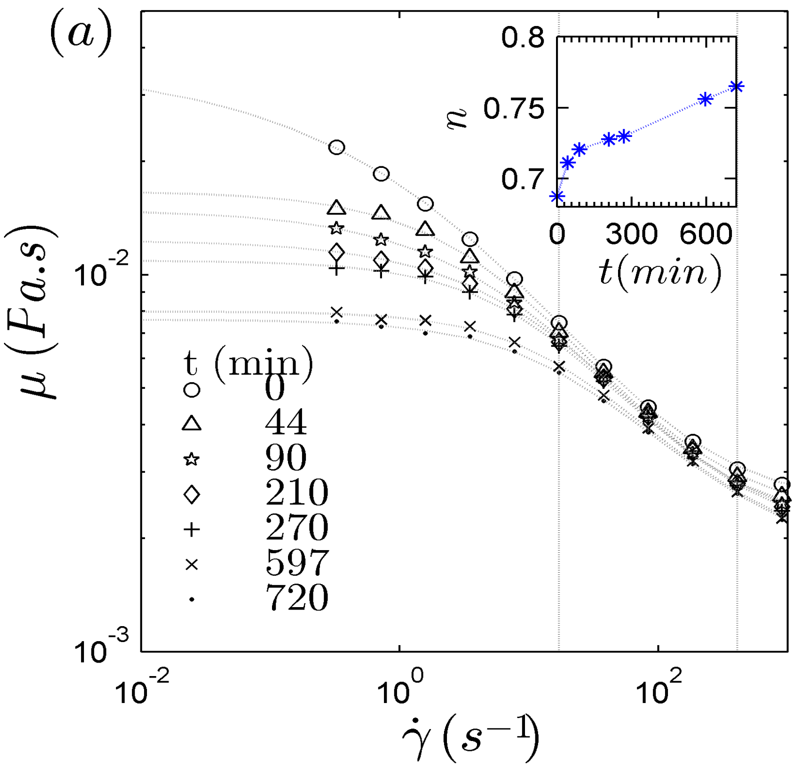
@ ~ 250 h from inlet

~1000 litres vol, up to 28 l/s

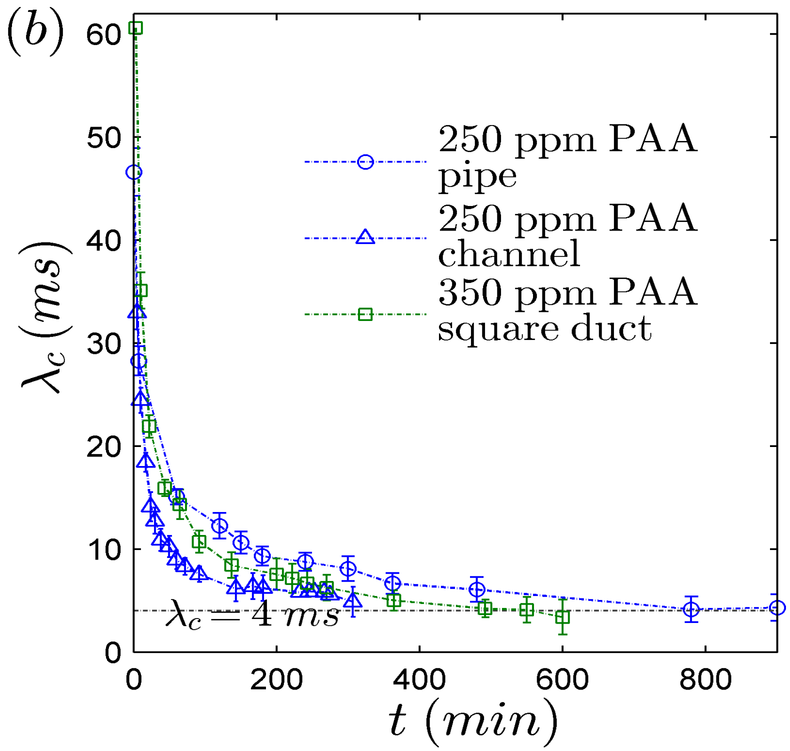
Example working fluid rheology (degrading)

Aqueous solutions of a polyacrylamide (“PAA”)

- various concentrations (*c* = 150, 250, 350 ppm: *c** ~250 ppm)
- two different grades/molecular weights (FlowPAM, Separan)

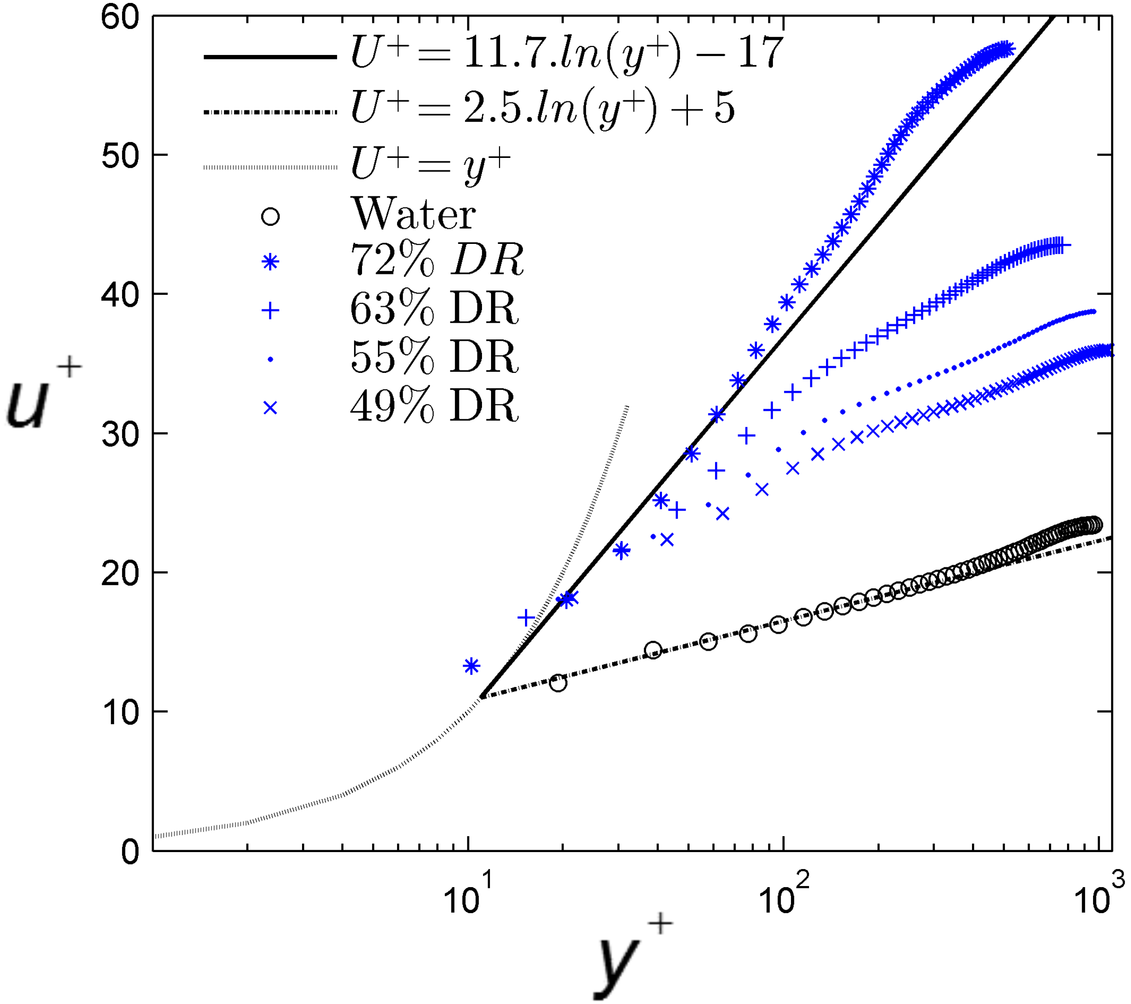


classical shear rheology



extensional rheology (CaBER)

Mean flow field (pipe, SPIV)

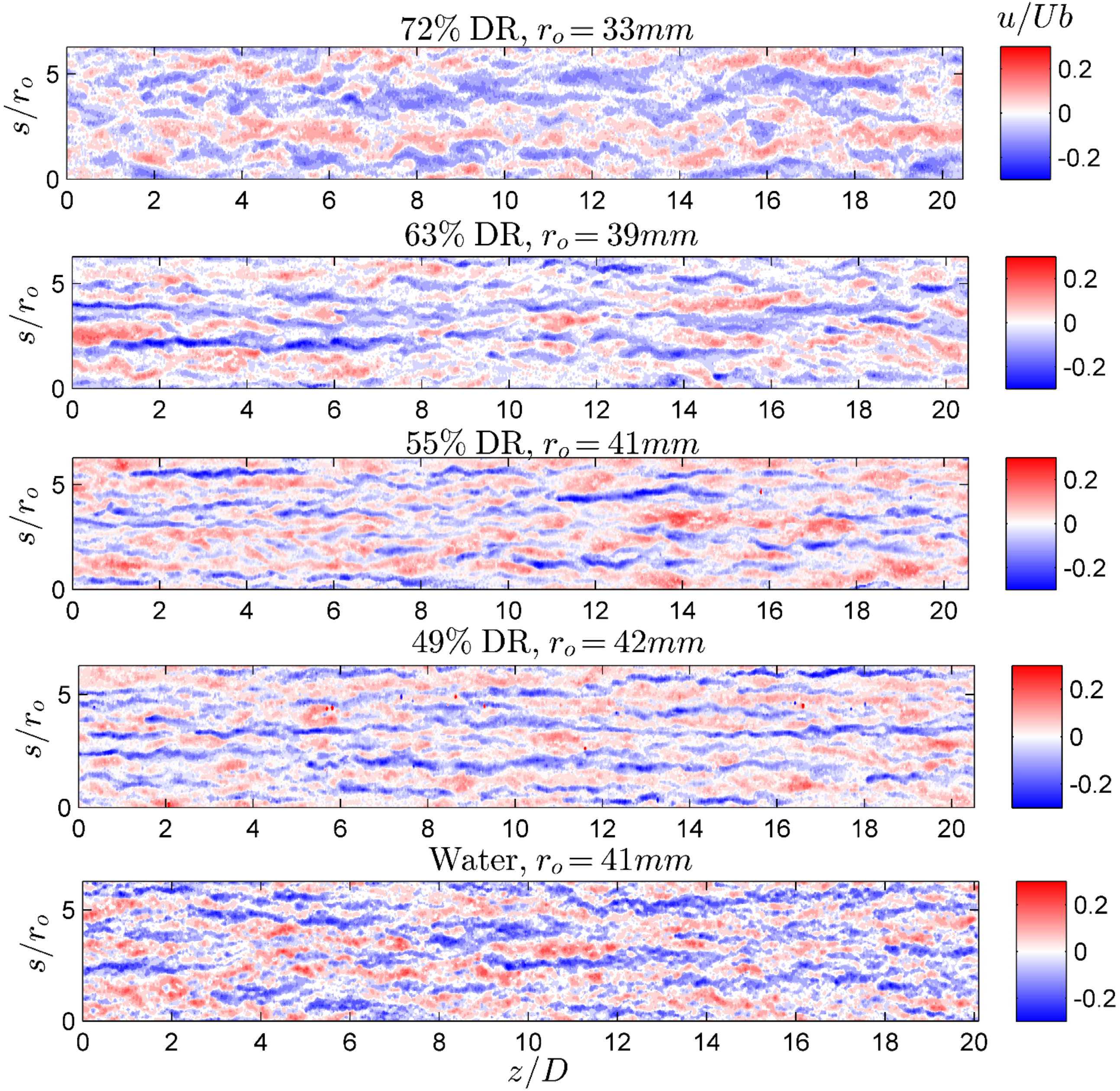


$$u_\tau \equiv \sqrt{\tau_s/\rho}$$

$$\frac{u}{u_\tau} \equiv u^+$$

$$\frac{u_\tau y}{\nu} \equiv y^+$$

Effect of additives on coherent structures in pipe flow (same y^+)



more coherent

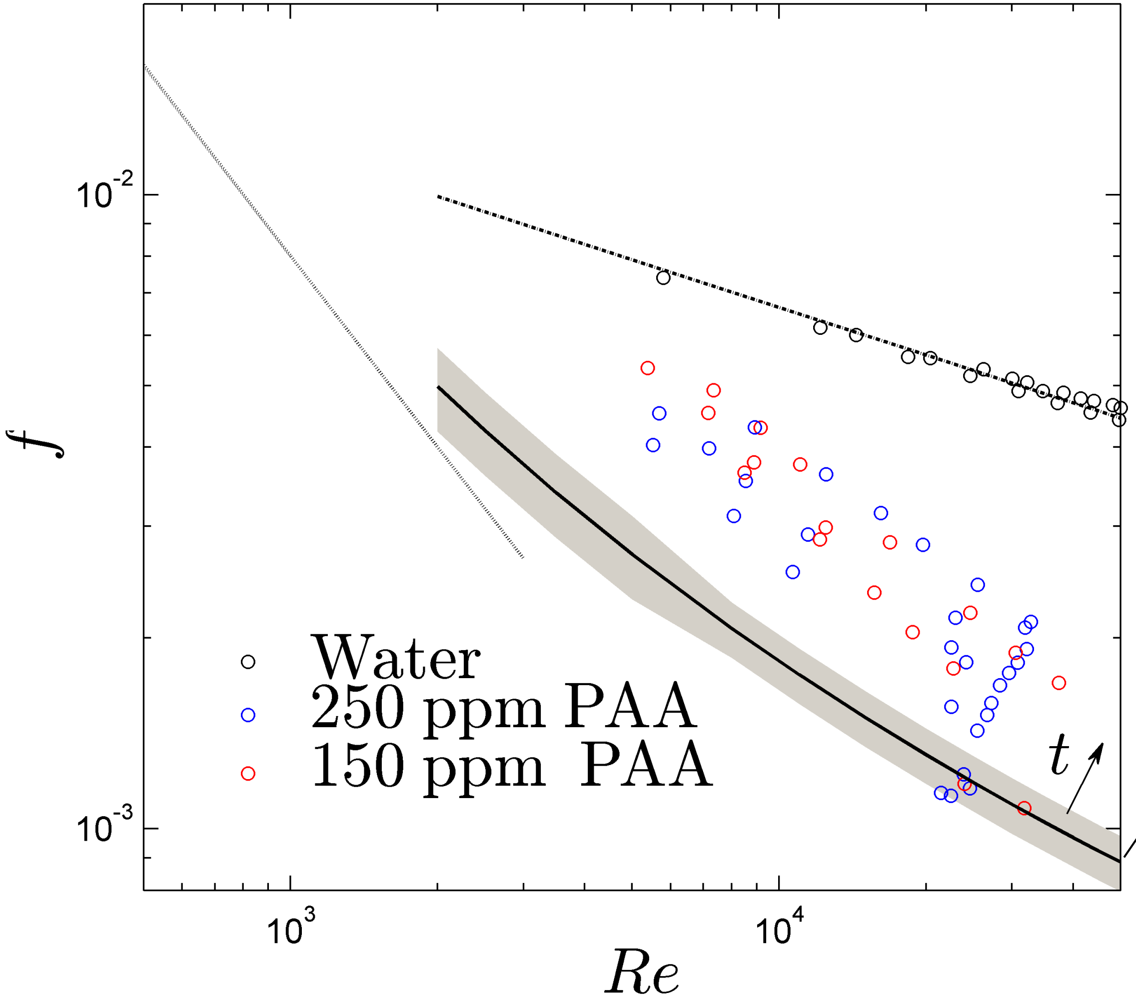
wider/longer

attenuation of small scales

$y^+ = 170$

Friction factor – Reynolds number plots

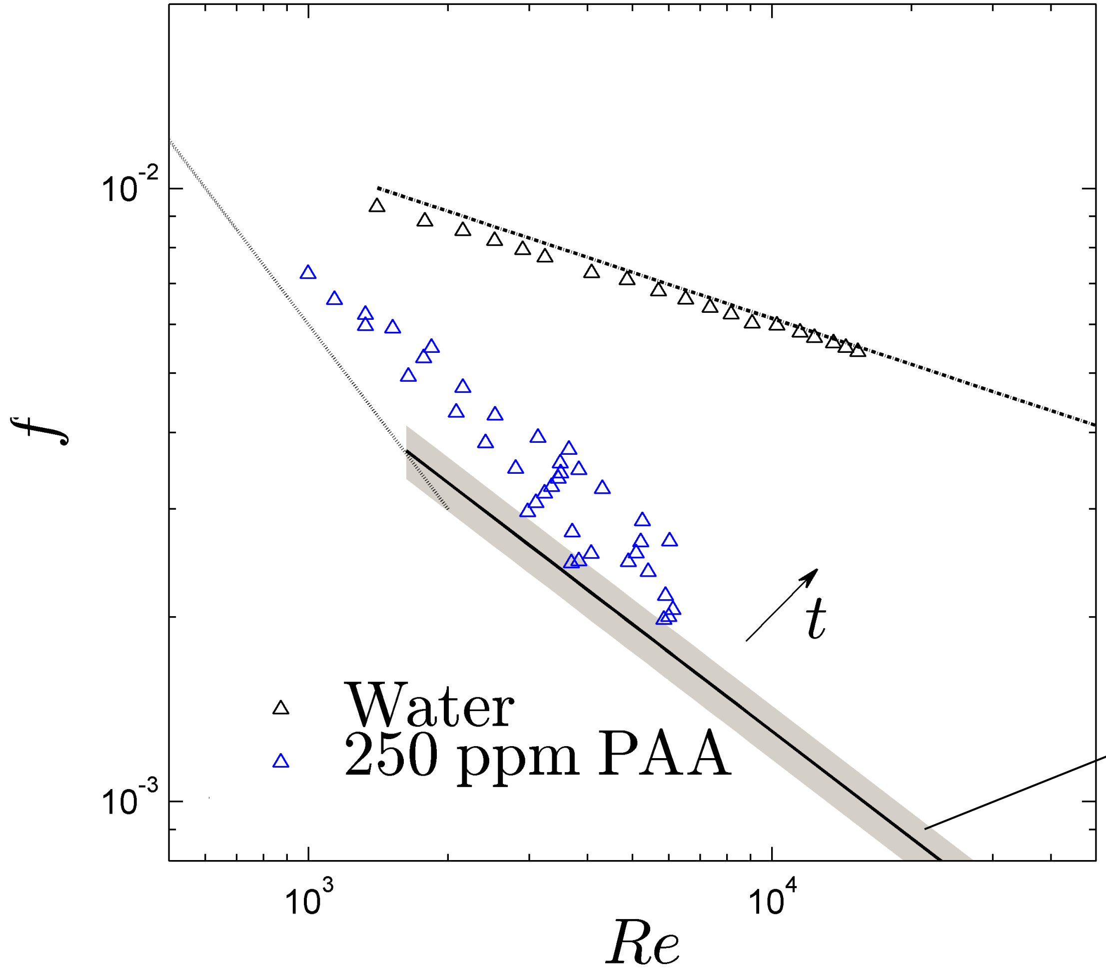
Pipe



VIRK ± 10%

$$Re = \frac{\rho U_B R}{\mu\left(\dot{\gamma}_W, t\right)}$$

Friction factor – Reynolds number plots

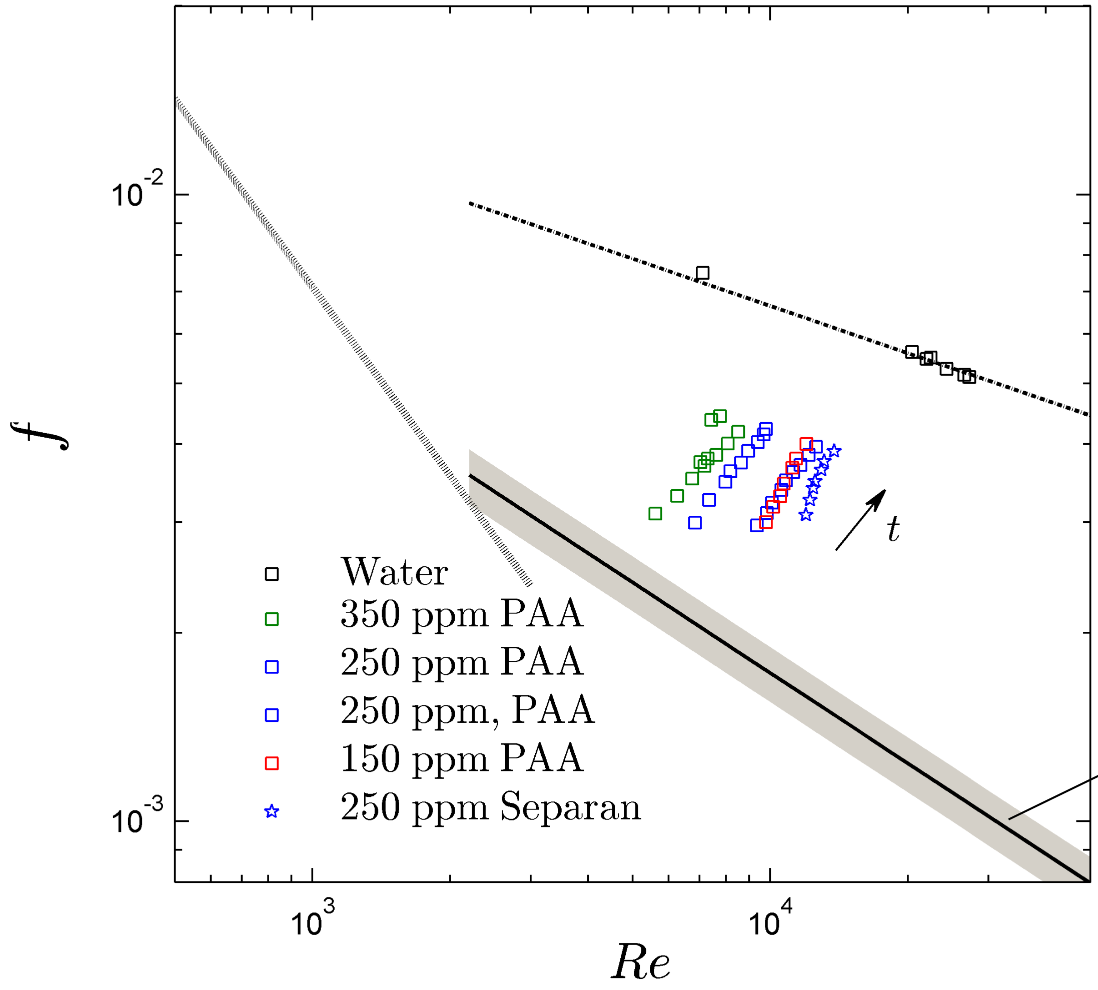


Channel

VIRK ± 10%

$$Re = \frac{\rho U_B h}{\mu\left(\dot{\gamma}_W, t\right)}$$

Friction factor – Reynolds number plots

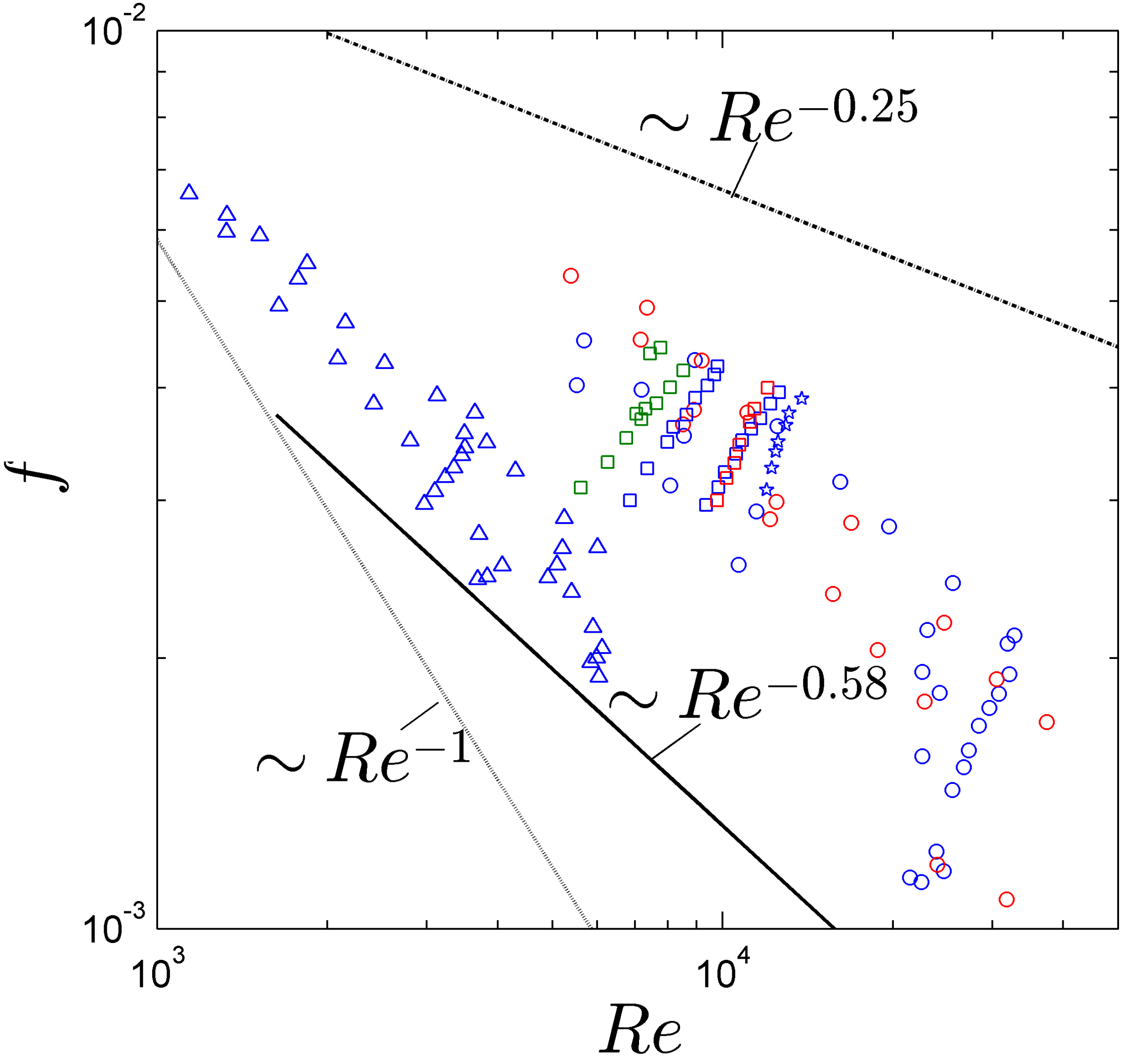


Square duct

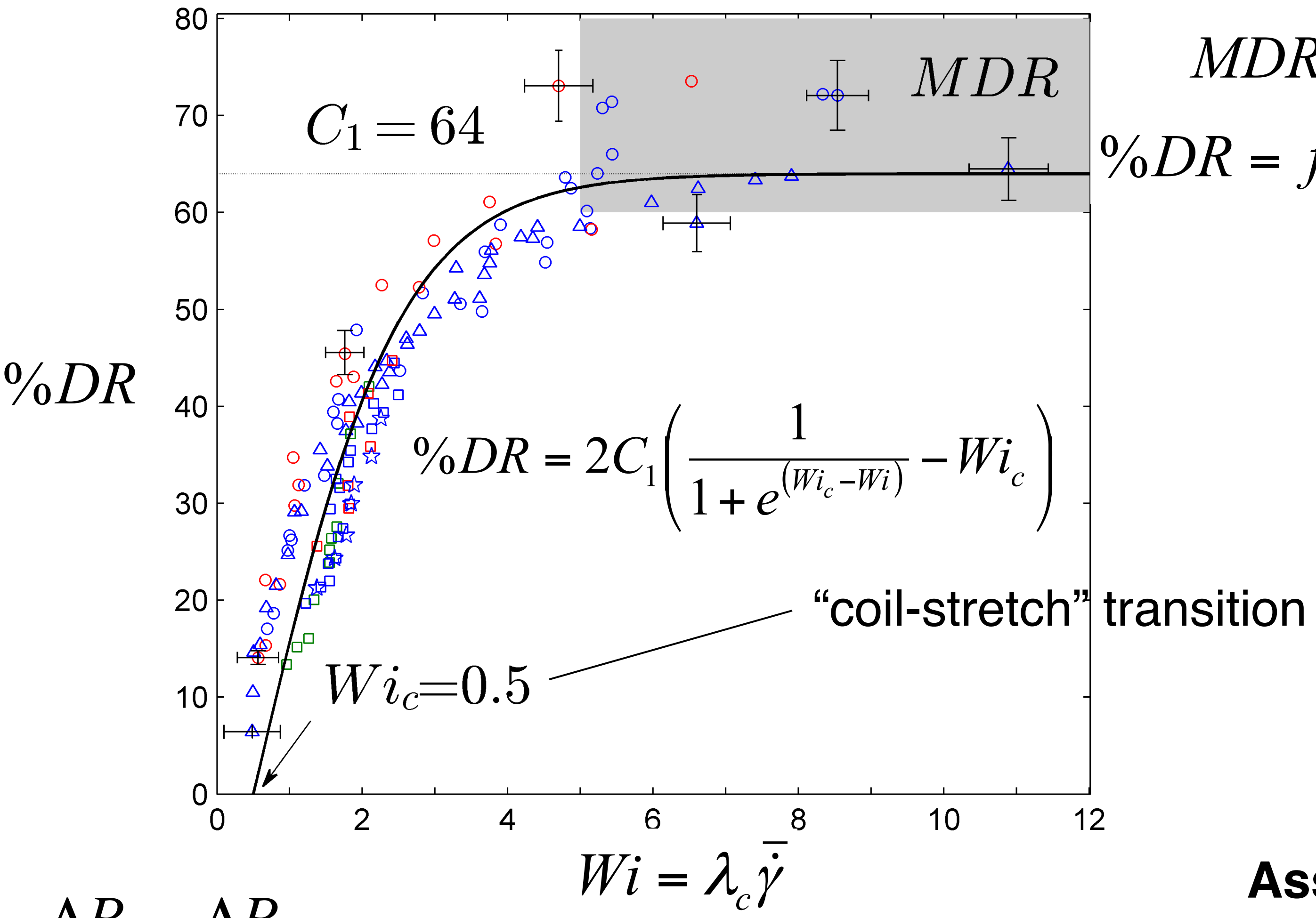
VIRK ± 10%

$$Re = \frac{\rho U_B h}{\mu(\dot{\gamma}_W, t)}$$

Friction factor – Reynolds number combined plot



Master curve Drag-reduction vs Weissenberg number



$$\%DR = 2C_1\left(\frac{1}{1+e^{(Wi_c - Wi)}} - Wi_c\right)$$

$$Wi = \lambda_c \bar{\dot{\gamma}}$$

MDR

$$\%DR = f(Re) \sim Re^{0.1}$$

$$\%DR = \frac{\Delta P_N - \Delta P}{\Delta P_N}$$

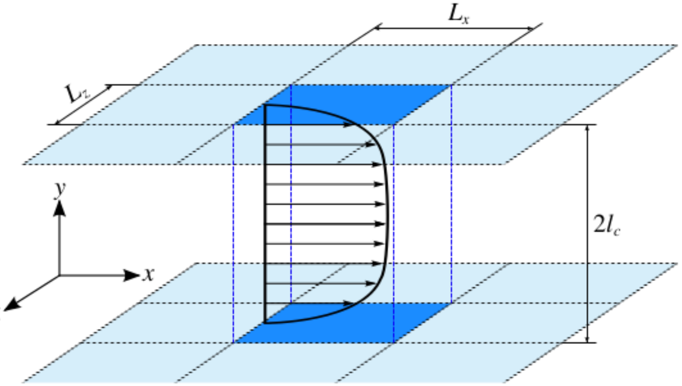
Assumptions

- extensional λ "correct" property
- requires onset stretch(/shear)
- "independent" of *Re*

Low-drag turbulent states in Newtonian and non-Newtonian fluids

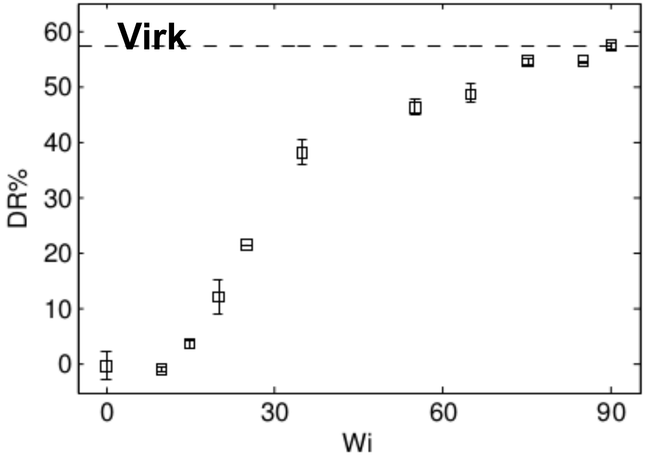
Part 2: Newtonian fluids (conditionally sampled “local” low drag events)

Minimal channel simulations from Newtonian to MDR

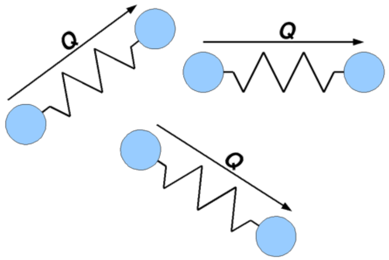


Channel flow geometry

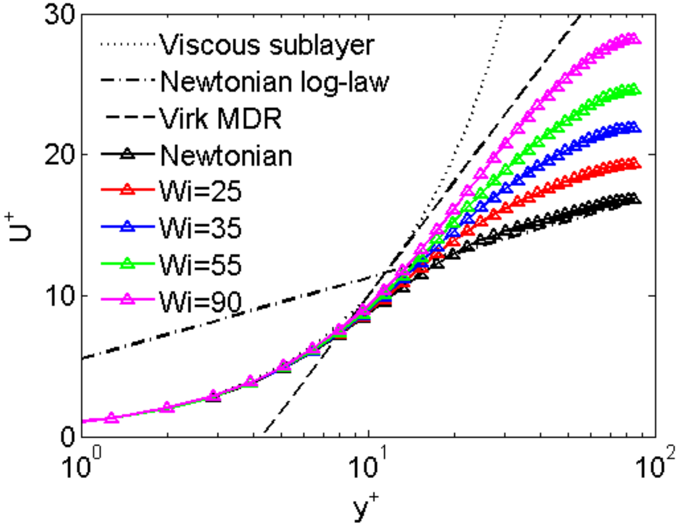
Re=3600 (Re_τ=85), β=0.97, Ex=206, Wi=$\lambda\dot{\gamma}$=0-90



- 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.

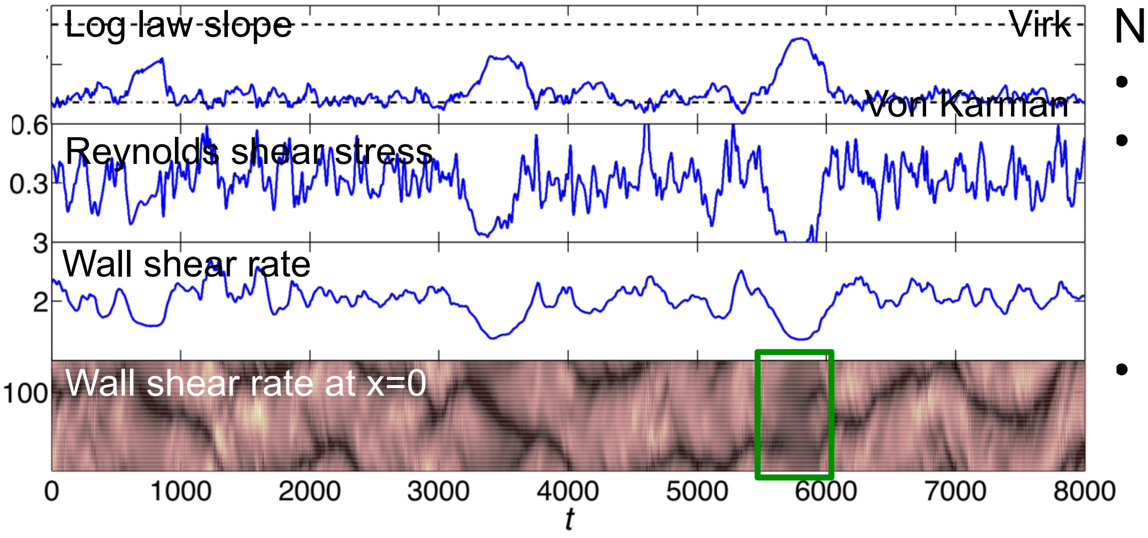


FENE-P dumbbell model for polymers



Graham and co-workers: JFM 2010, 2012, PRL 2010,

Intermittent dynamics for Newtonian and moderate *Wi*



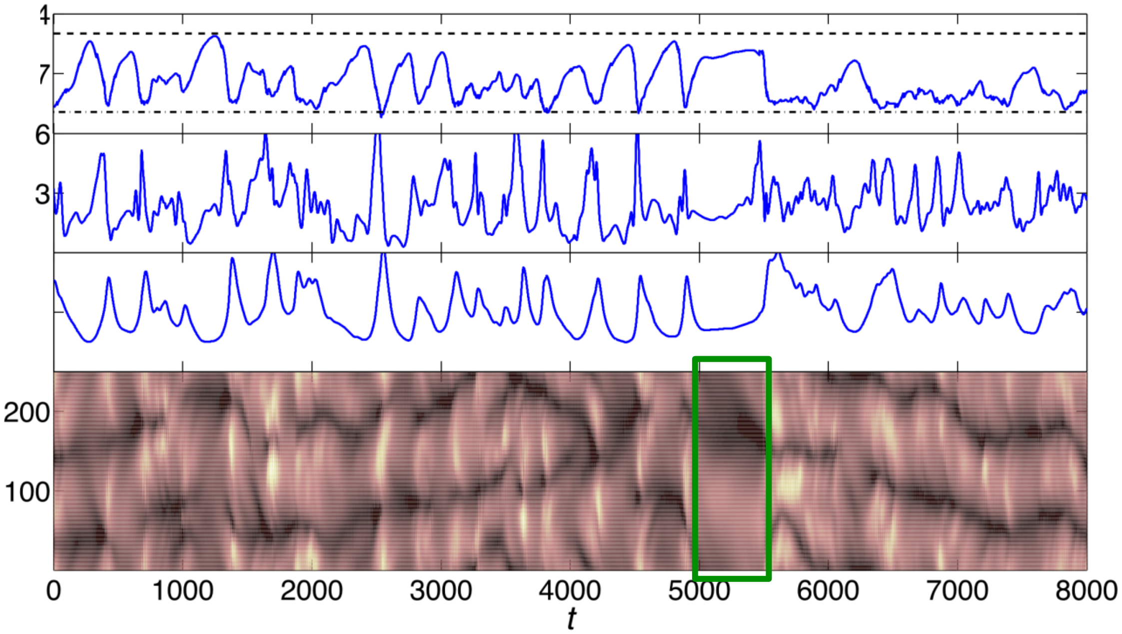
Newtonian (minimal channel)

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

Viscoelastic:

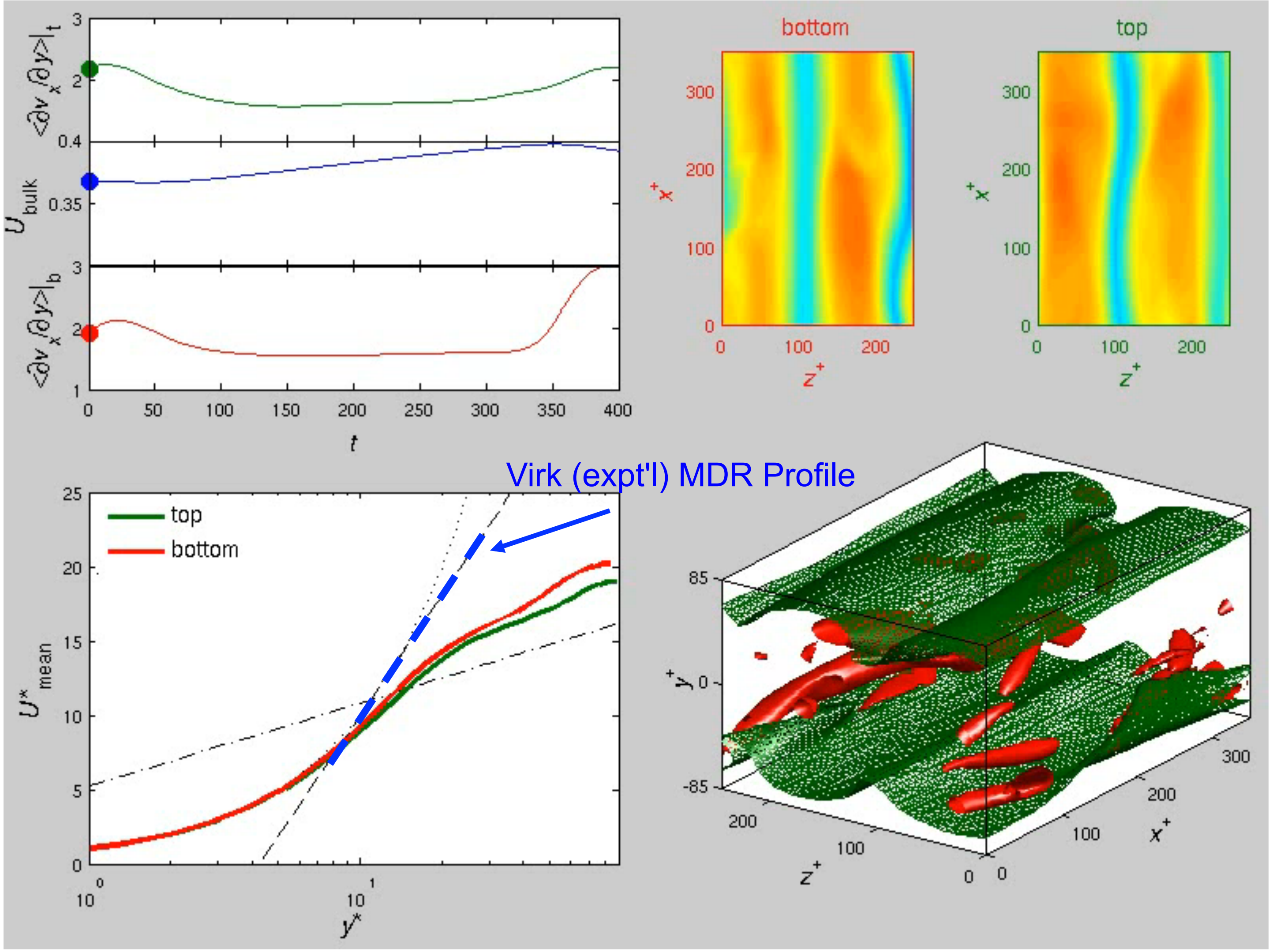
- Wi=29,β=0.97, Ex=103
- 26% DR
- frequent excursions from von Karman to Virk
- Stretching and mean velocity are anticorrelated

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



Graham and co-workers: JFM 2010, 2012, PRL 2010,

What happens during a hibernation period?



Virk (expt'l) MDR Profile

Wi=29

Graham and co-workers: JFM 2010, 2012, PRL 2010,

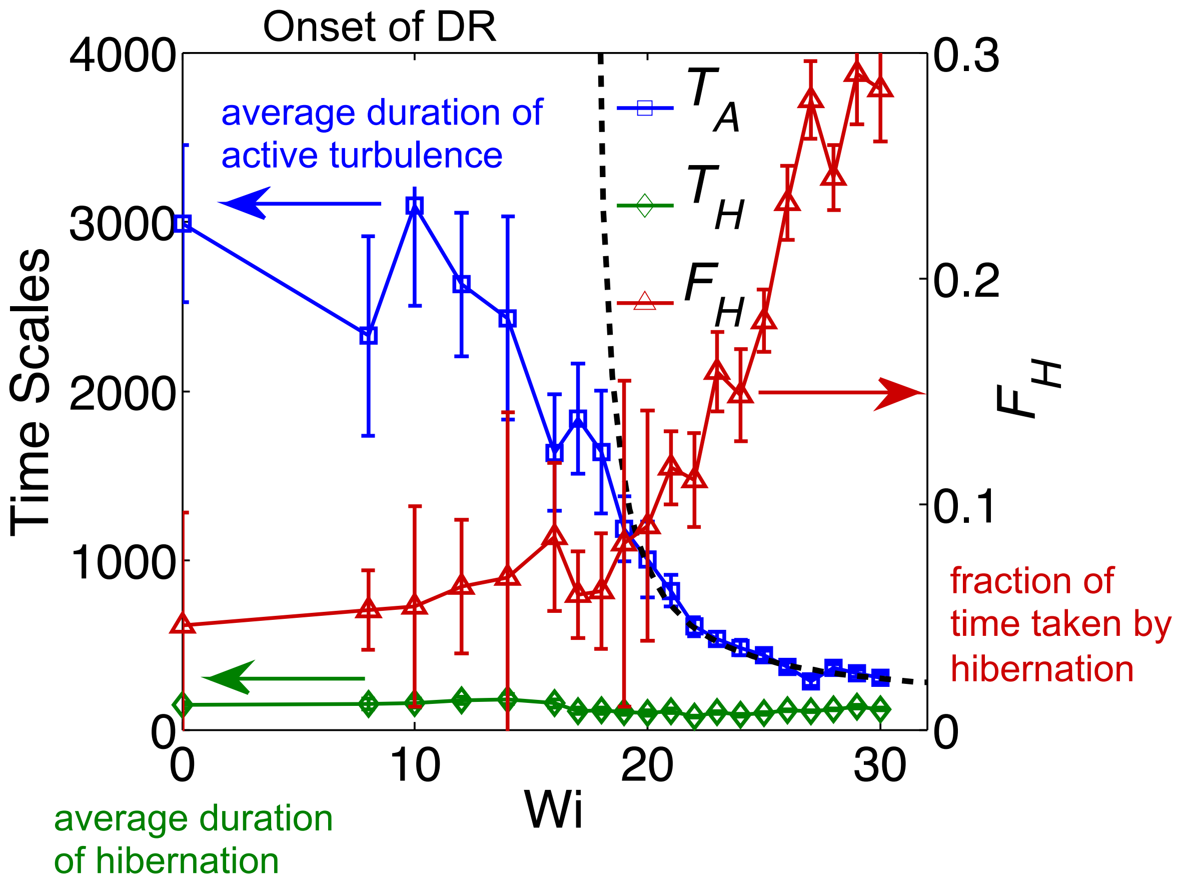
Time scales of hibernating dynamics: low to moderate *Wi*

Criterion:

- Active: log law slope <7
- Hibernating: otherwise

As *Wi* increases:

- Life time of active turbulence is reduced.
- Duration of hibernation is almost invariant.
- Overall, hibernation takes a larger fraction of time.



average duration of active turbulence

fraction of time taken by hibernation

average duration of hibernation

Viscoelasticity compresses the lifetime of an active turbulence interval, facilitating the occurrence of hibernation, while having little effect on hibernation itself. **Hibernating turbulence still present in Newtonian limit.**

Graham and co-workers: JFM 2010, 2012, PRL 2010,

Time scales of hibernating dynamics: low to moderate *Wi*

Initial questions

1. Can hibernating turbulence be observed experimentally in **Newtonian fluids**? (simulations use *minimal* channel and “low” Reynolds number)
2. What are mean flow profiles during hibernation? MDR?
3. What is effect of Reynolds number?
4. Comparison to DNS and travelling wave solutions (Graham group)
5. Flow structures during hibernation (SPIV)

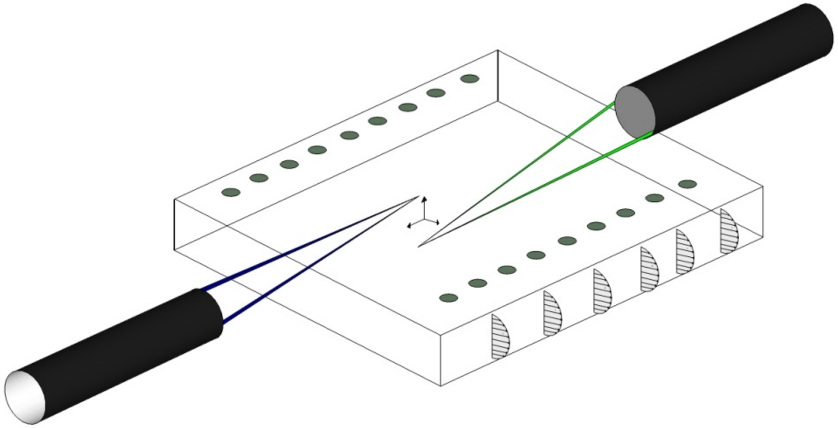
Future questions

1. Effect of additives. 2. Higher *Re*

Ultimate aim

1. Flow control. Can we get maximum drag reduction without recourse to additives?

Laser Doppler Velocimetry and Hot-film probe



Two component LDV (only *u* here)

Incredibly small control volume

100 μm x 25 μm

($x^+ = 0.17$, $z^+ = 0.7$ @ $Re_\tau=85$)

Burst mode: Data rates ~ 100s Hz

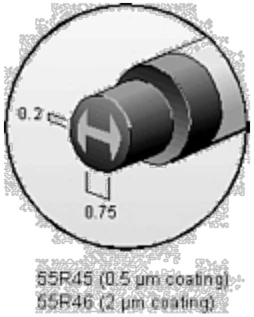
Dantec R46 flush-mounted minaturised hot-film probe

200 μm x 750 μm

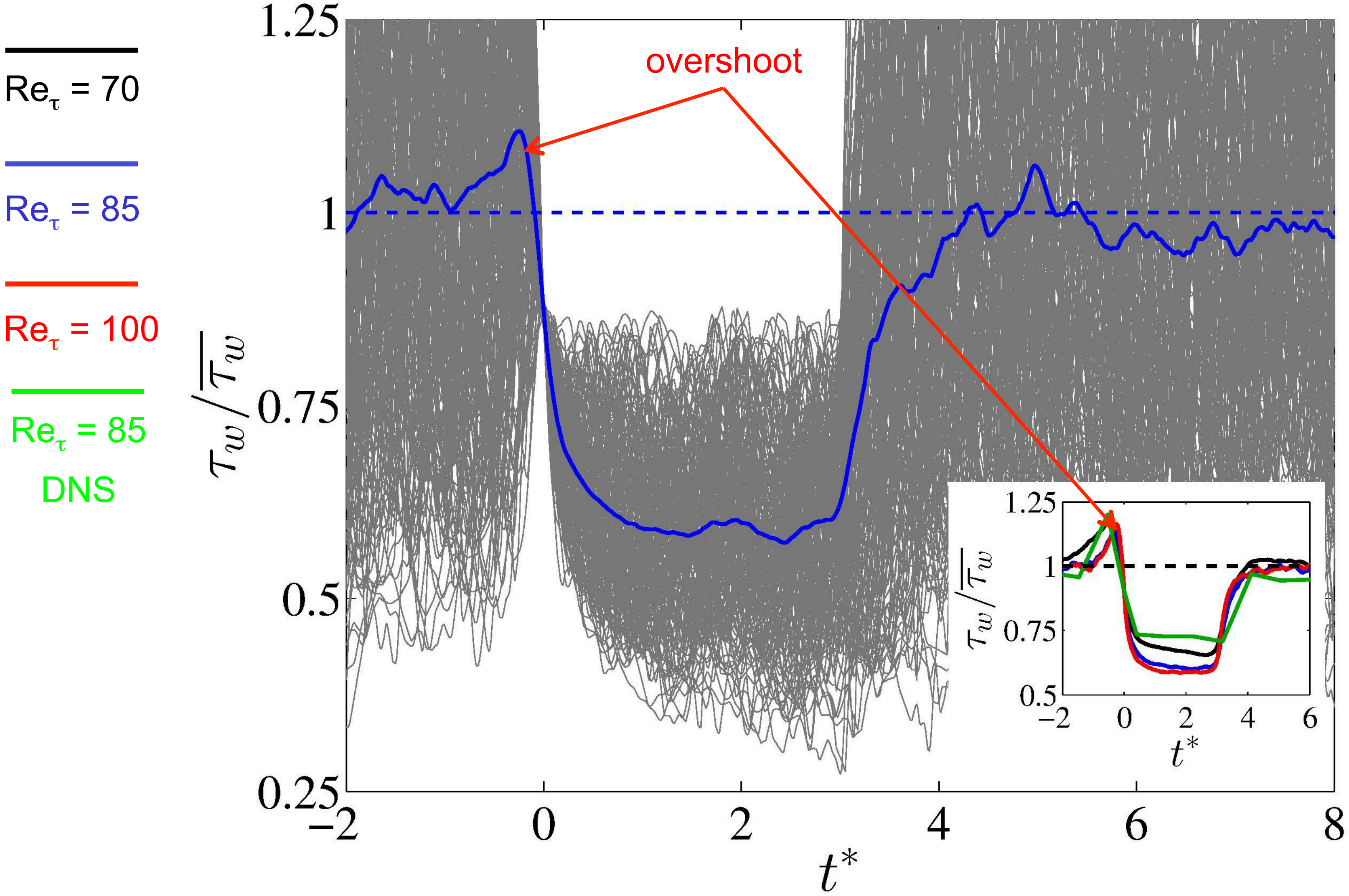
($x^+ = 1.4$, $z^+ = 5.2$ @ $Re_\tau=85$)

Data rates ~ 1000s Hz

use LDV as trigger to get simultaneously (~100s Hz)

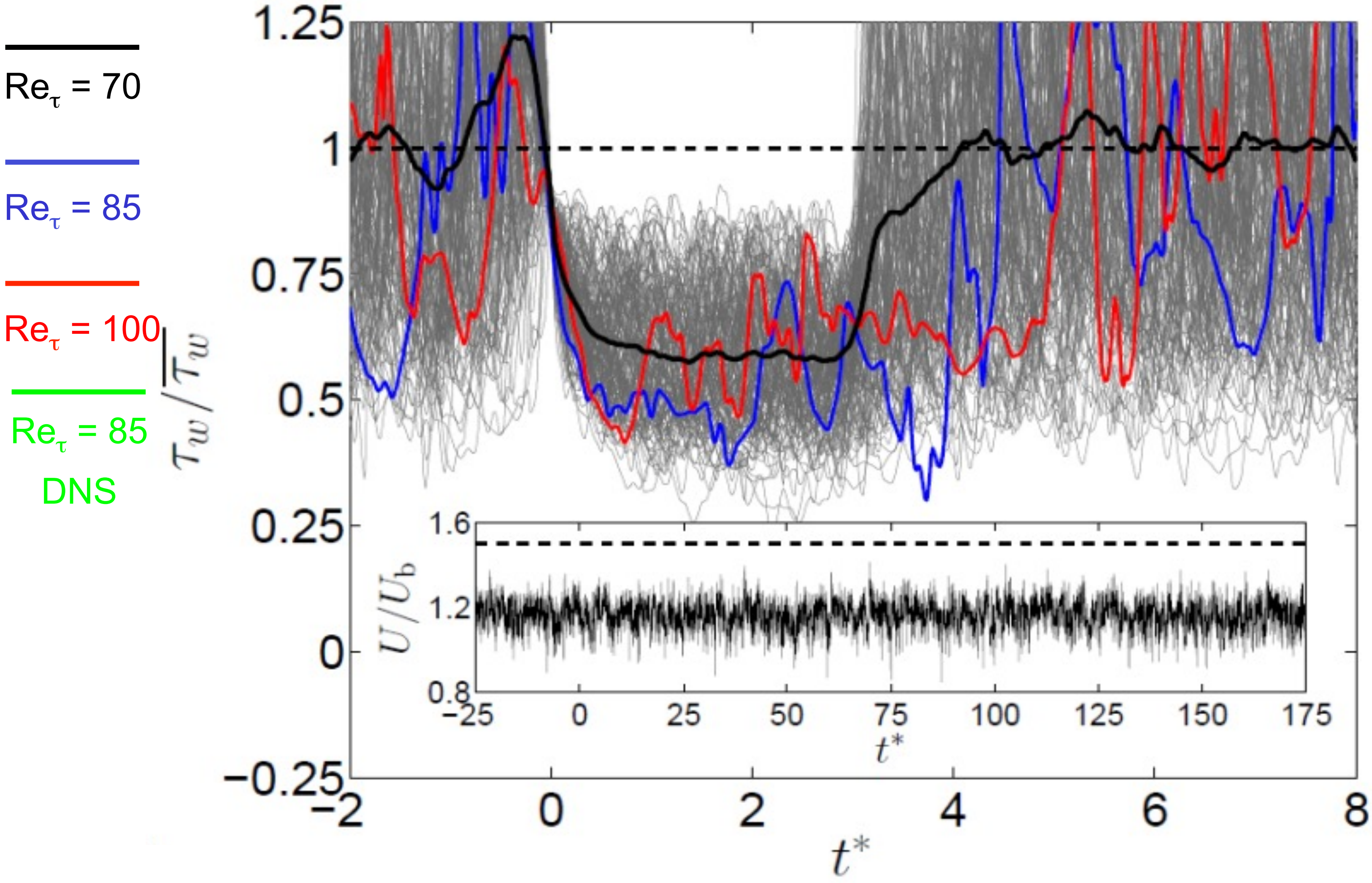


In search of hibernation (criteria 0.9 $\overline{\tau_w}$ for $t^* = t\, u_\tau / h > 3$)



Re_τ = 85 :3 hours sampling simultaneously gives 2,000,000 velocity-wall shear stress data points and approximately 200 hibernating events lasting on the order of 1 sec each

In search of hibernation (criteria 0.9 $\overline{\tau_w}$ for $t^* = t\, u_\tau / h > 3$)

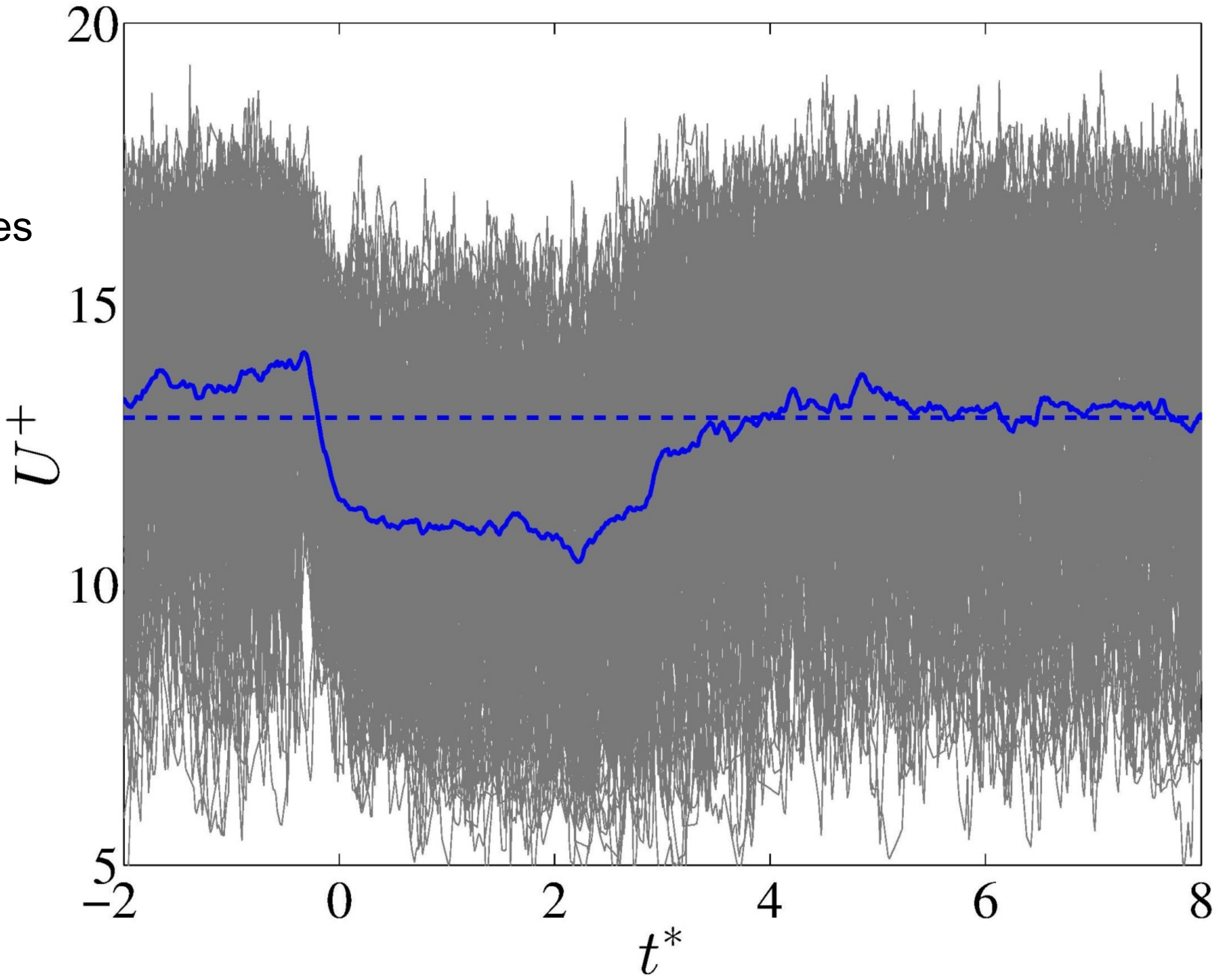


Note strong fluctuations during event

What happens to velocity field during hibernation

$y^+ \sim 26$
(20)

U^+
decreases
(~7%)



Note strong fluctuations during event

What happens to velocity field during hibernation

red = high

(overshoot consistent with exp)

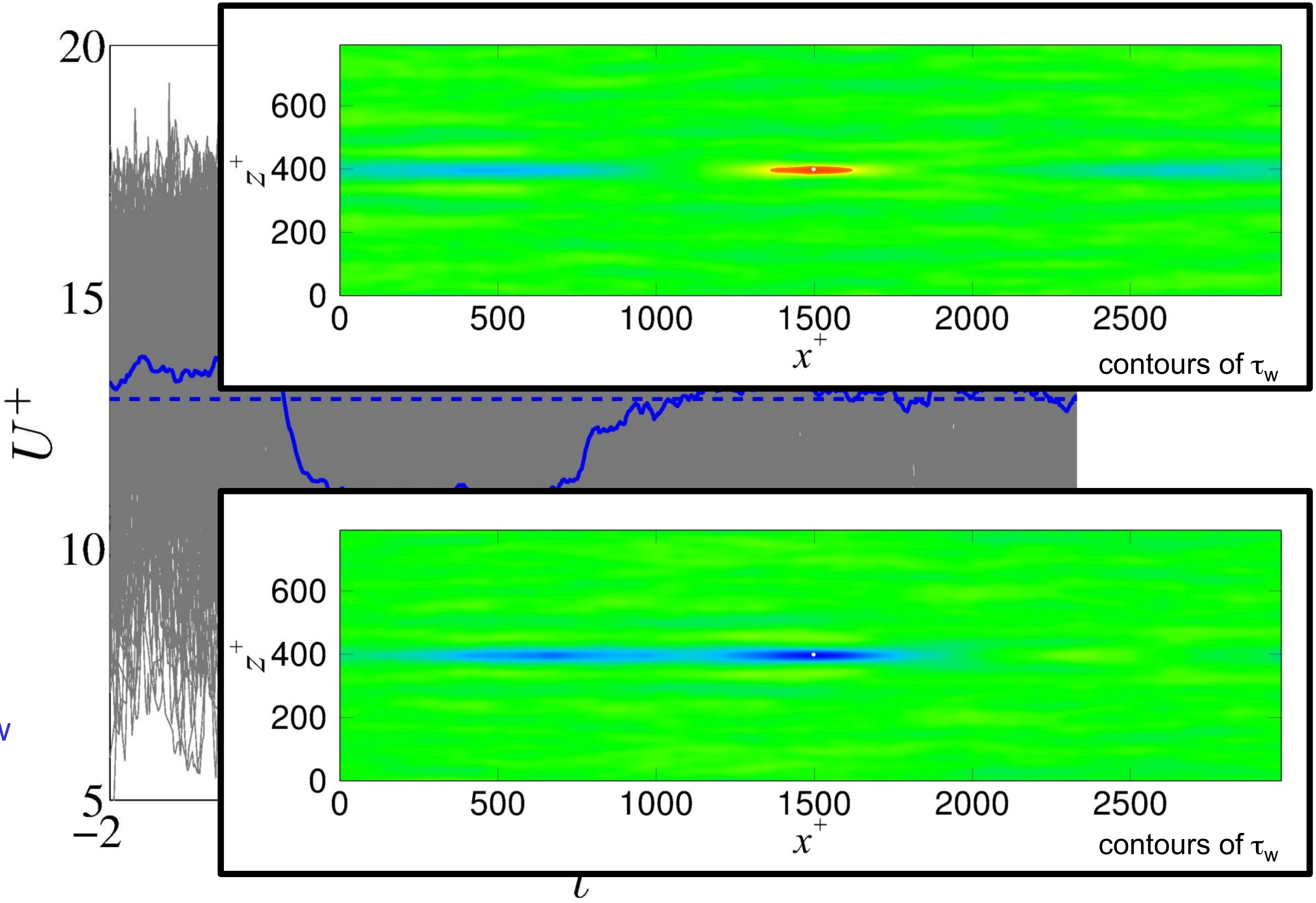
DNS

$t^* = -0.5$

DNS

$t^* = +0.5$

blue = low



low-stress streak $x^+ \sim 1800$, $z^+ \sim 100$

New LDV data at Re_τ = 85: hibernating data

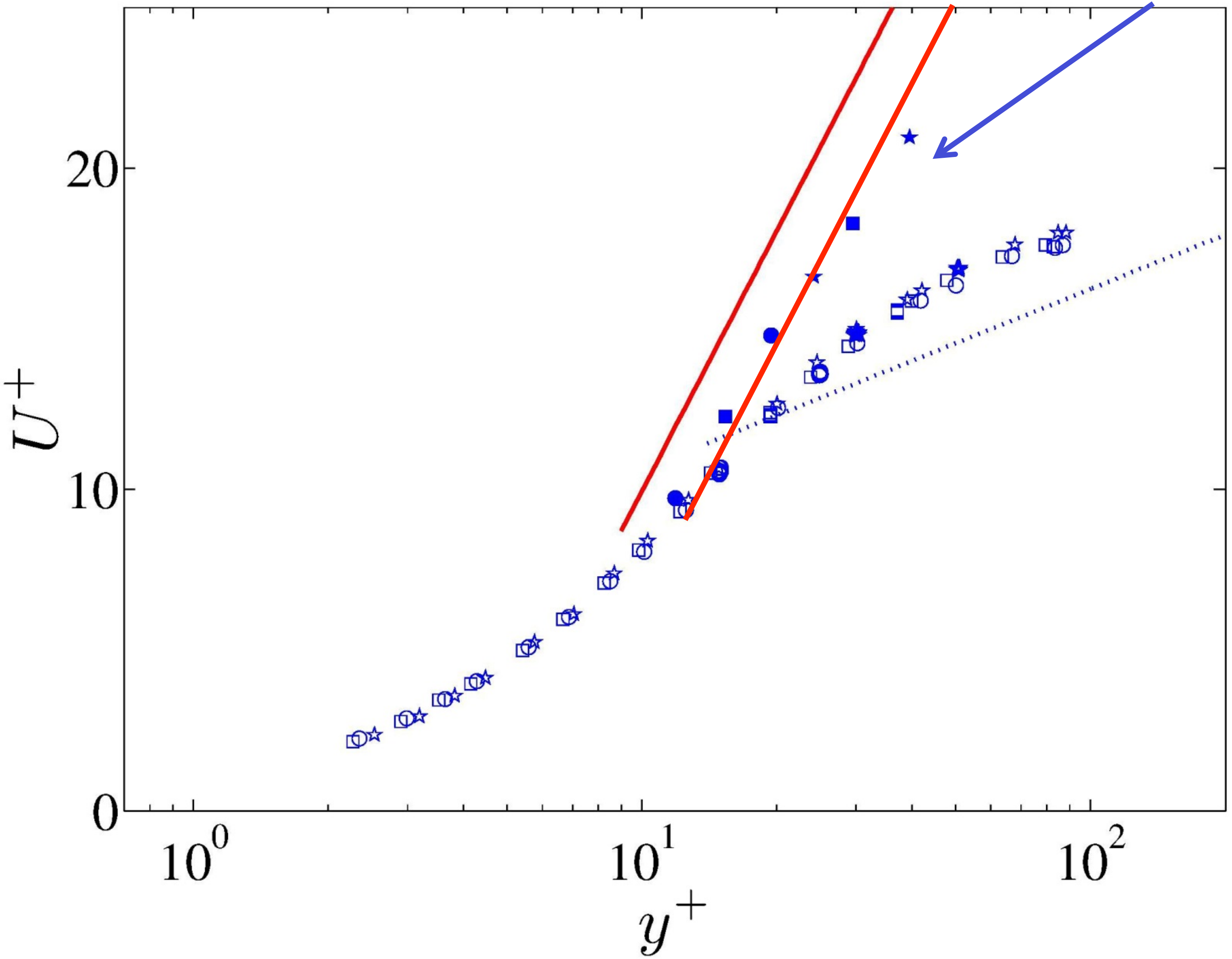
— MDR

- - - log law

— Re_τ = 85

same slope as Virk

u_τ based on average during hibernation

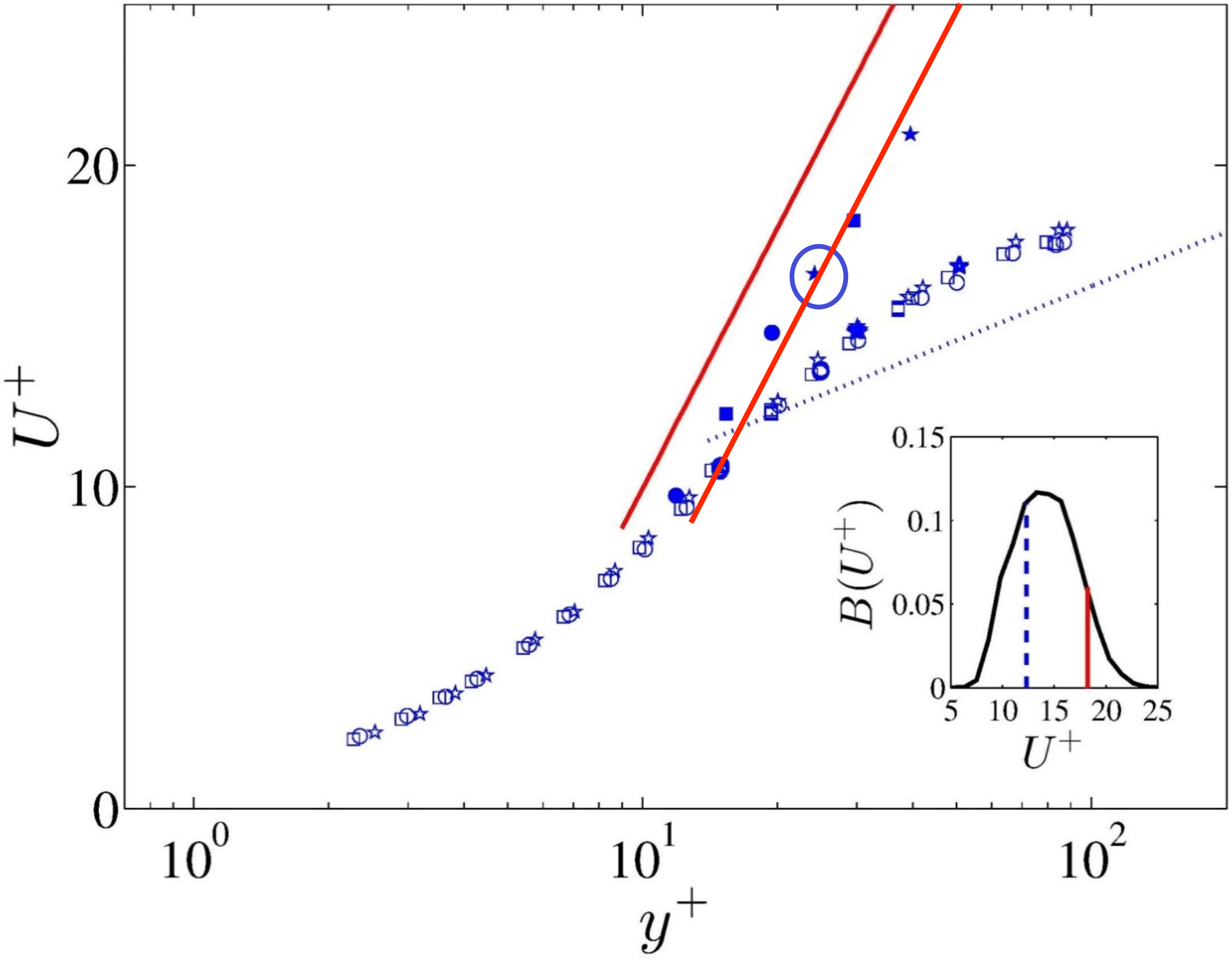


New LDV data at $Re_\tau = 85$: hibernating data

MDR

log law

$Re_\tau = 85$



some events *beyond* MDR

Effect of Reynolds number Re_τ = 70, 85, 100 and 120

MDR

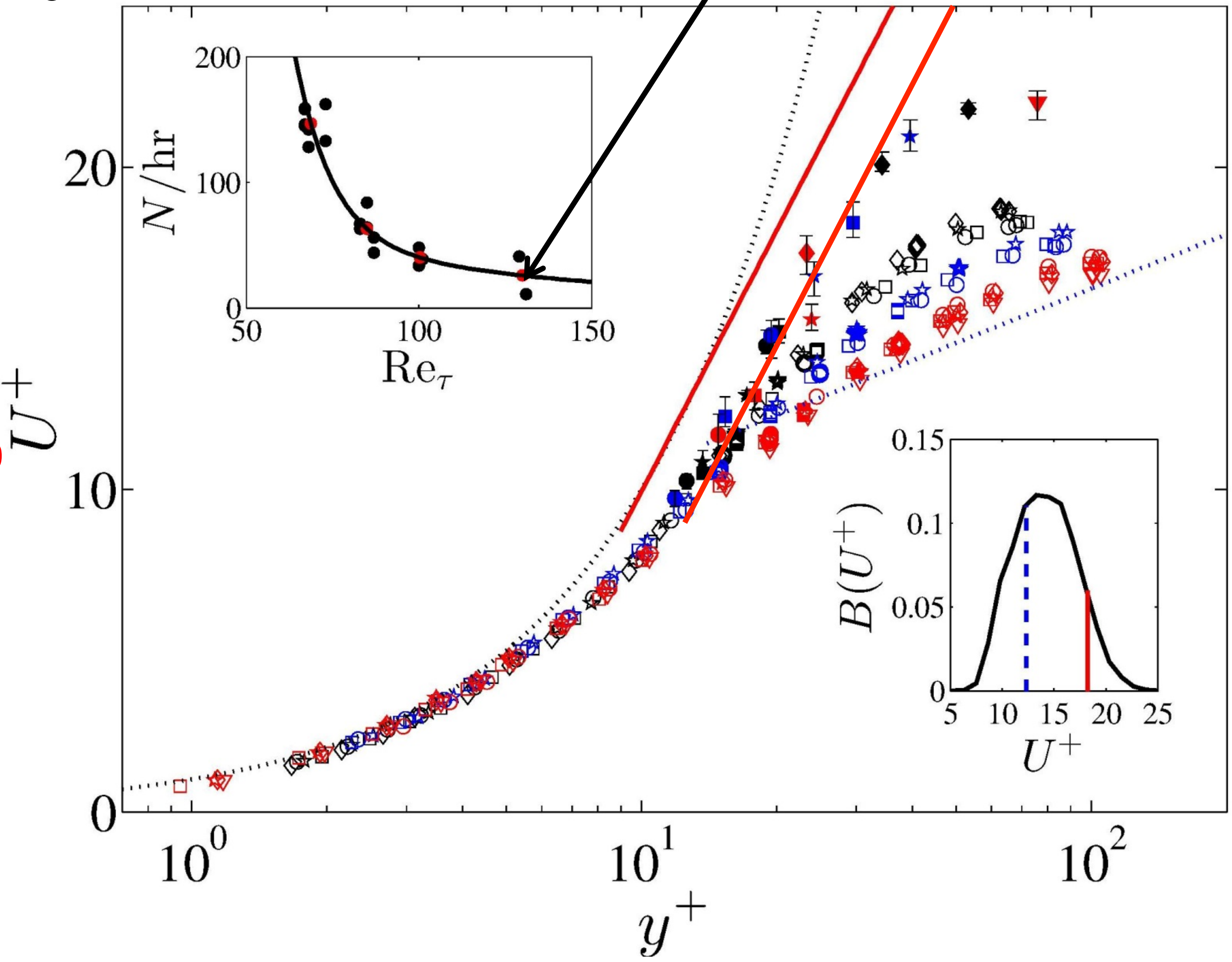
log law

Re_τ = 120: 6 hours sampling gives ~ 100 hibernating events

Re_τ = 70

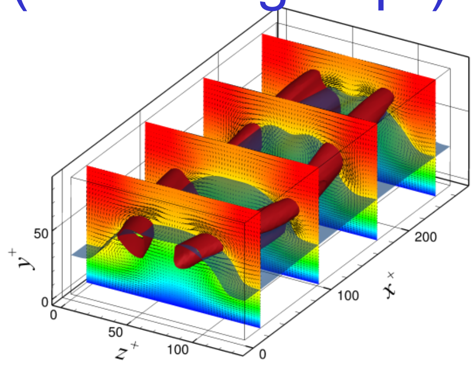
Re_τ = 85

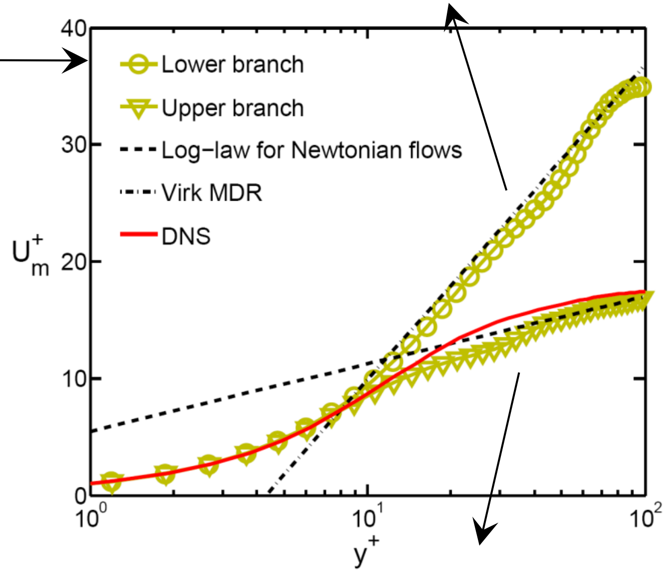
Re_τ = 100

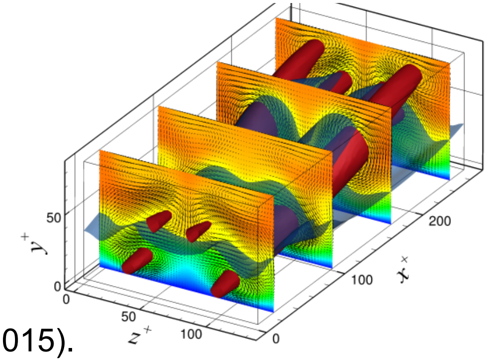


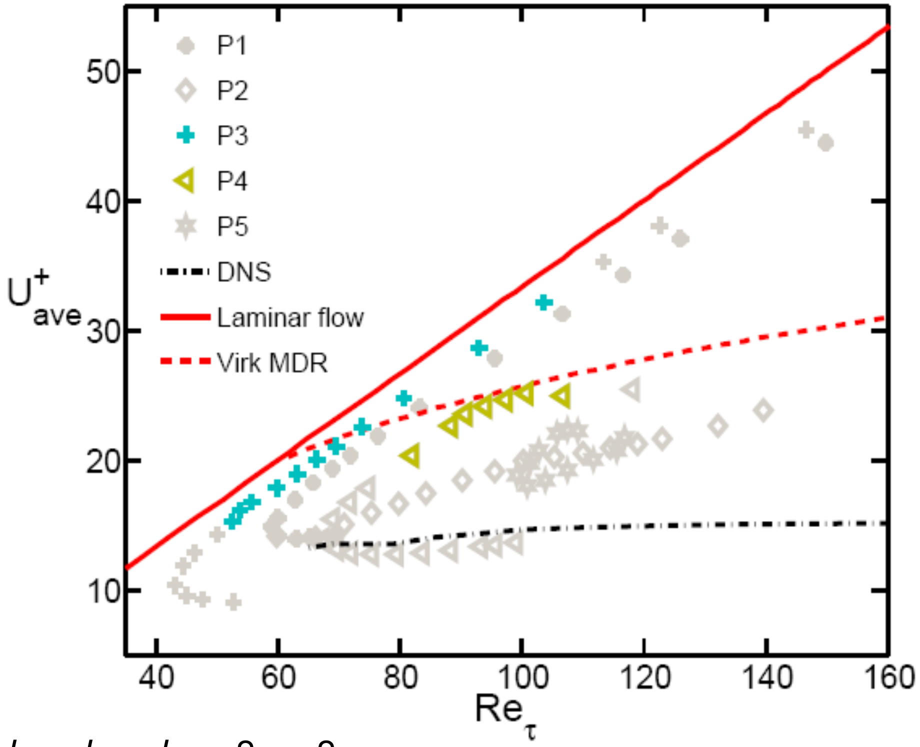
Connection to travelling wave solutions (Graham group[1])

- DNS + Newton iteration (*ChannelFlow*)
  - Traveling waves: $\boldsymbol{v}(x, y, z, t) = \boldsymbol{v}(x - ct, y, z)$
  - Initial guesses were velocity fields from DNS
  - Some states are on edge for a range of Re
  - P3 = Waleffe 2003
  - P4 family is interesting:









$L_x \times L_y \times L_z = 2\pi \times 2 \times \pi$

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[1] J. S. Park and M. D. Graham, J. Fluid Mech. 782, 430 (2015).

Connection to travelling wave solutions (Graham group[1])

Re_τ = 70

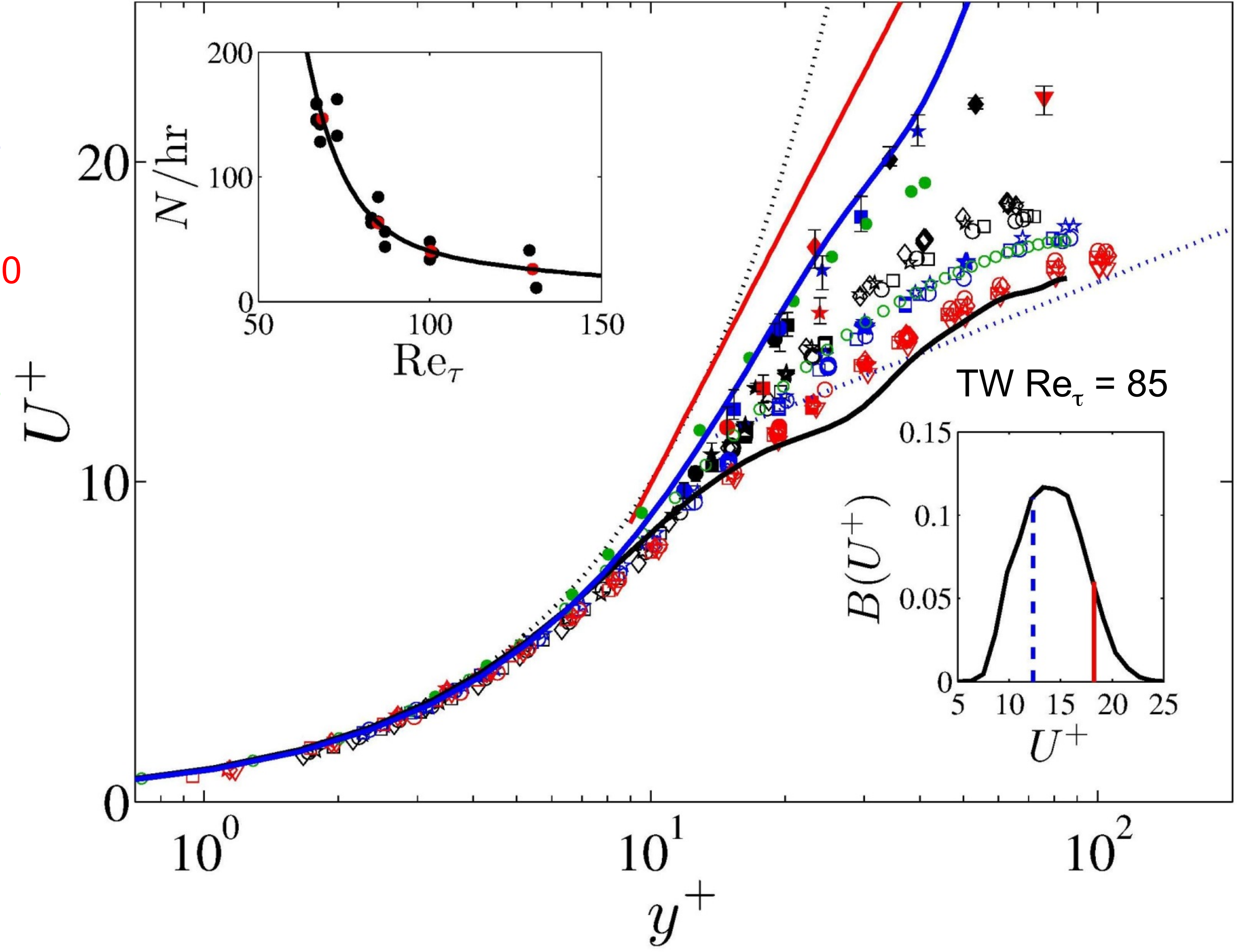
Re_τ = 85

Re_τ = 100

Re_τ = 85

DNS

TW Re_τ = 85



TW Re_τ = 85

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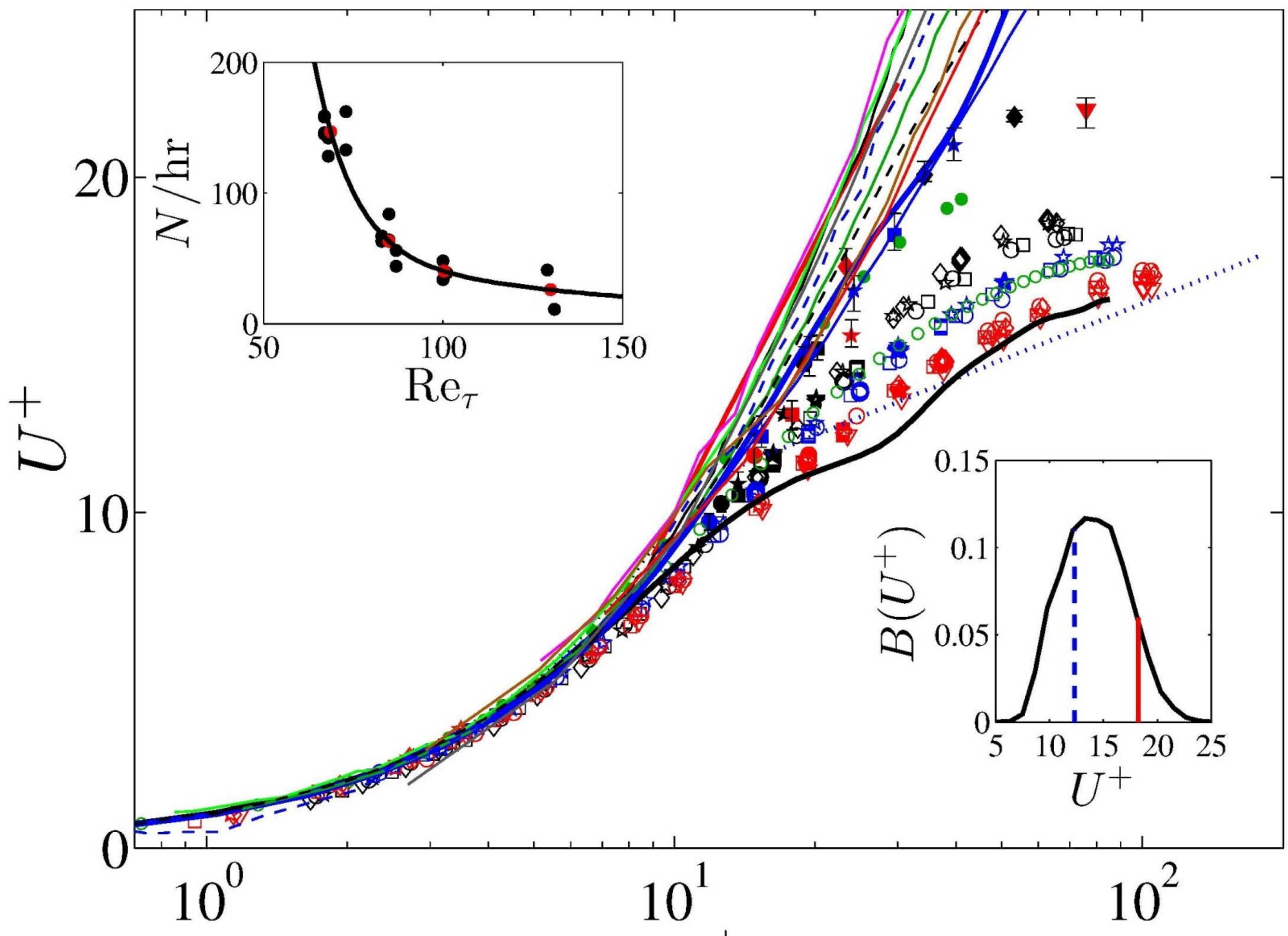
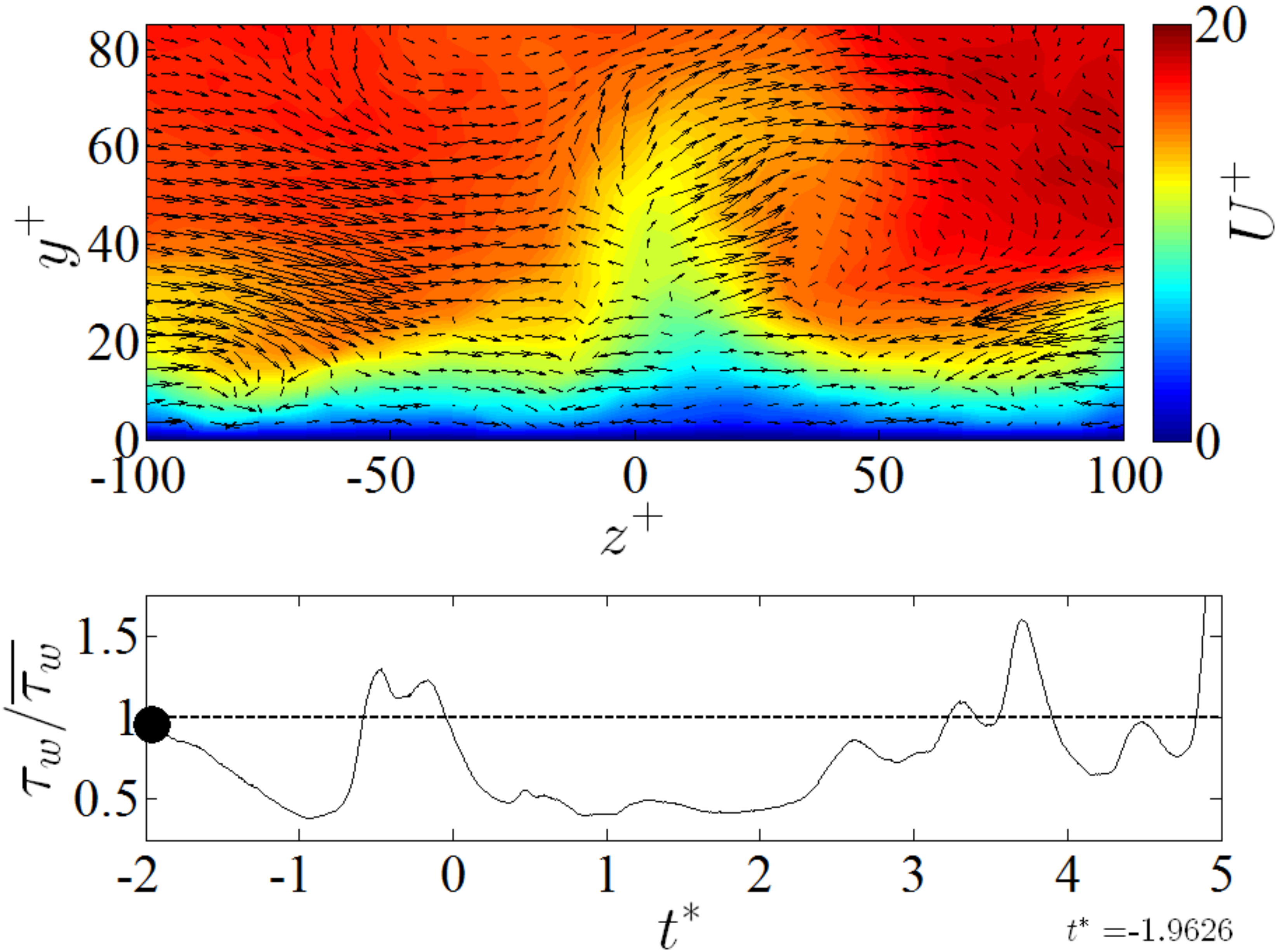
[1] J. S. Park and M. D. Graham, J. Fluid Mech. 782, 430 (2015).

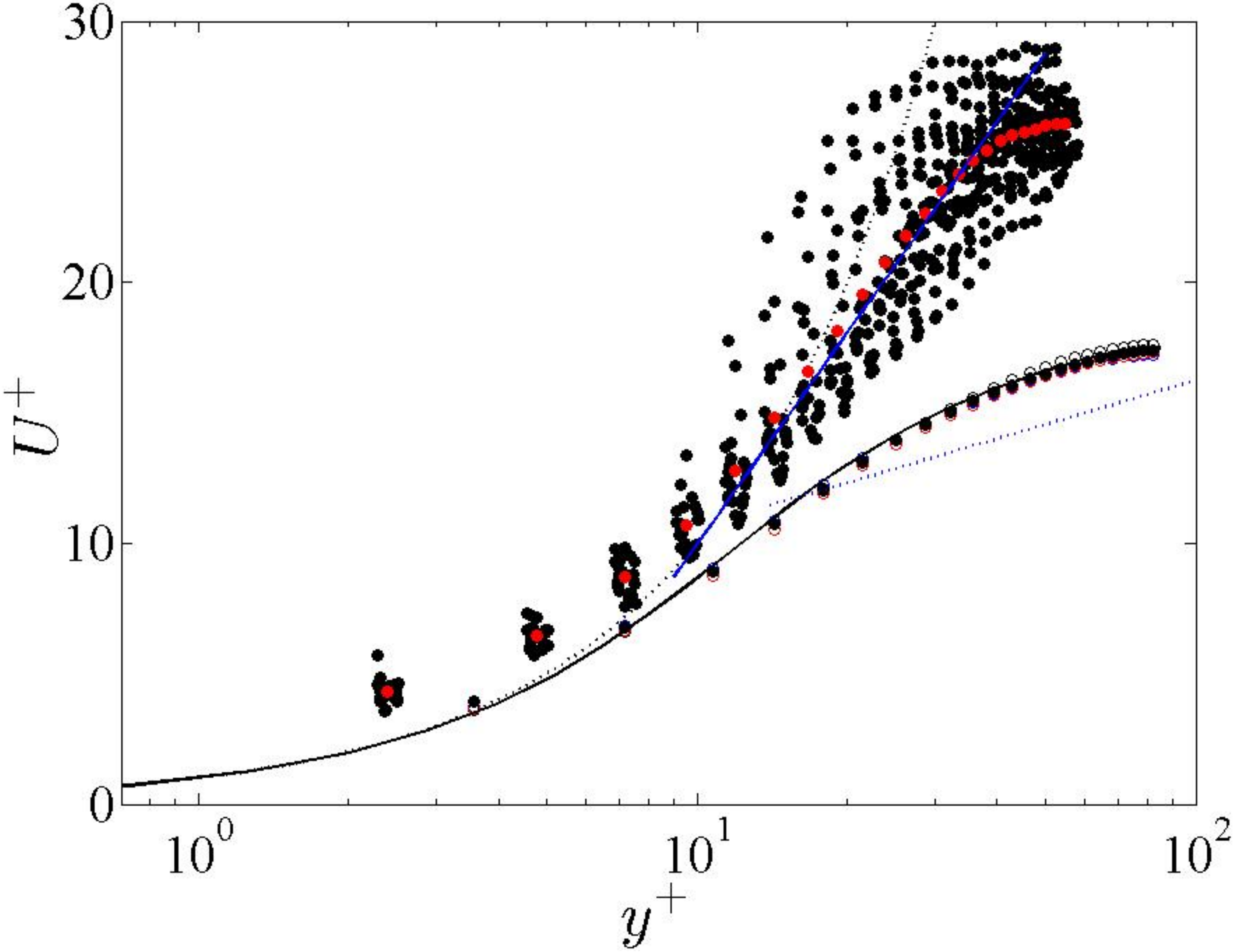
How robust is Virk MDR? Scatter in data sets nominally at MDR



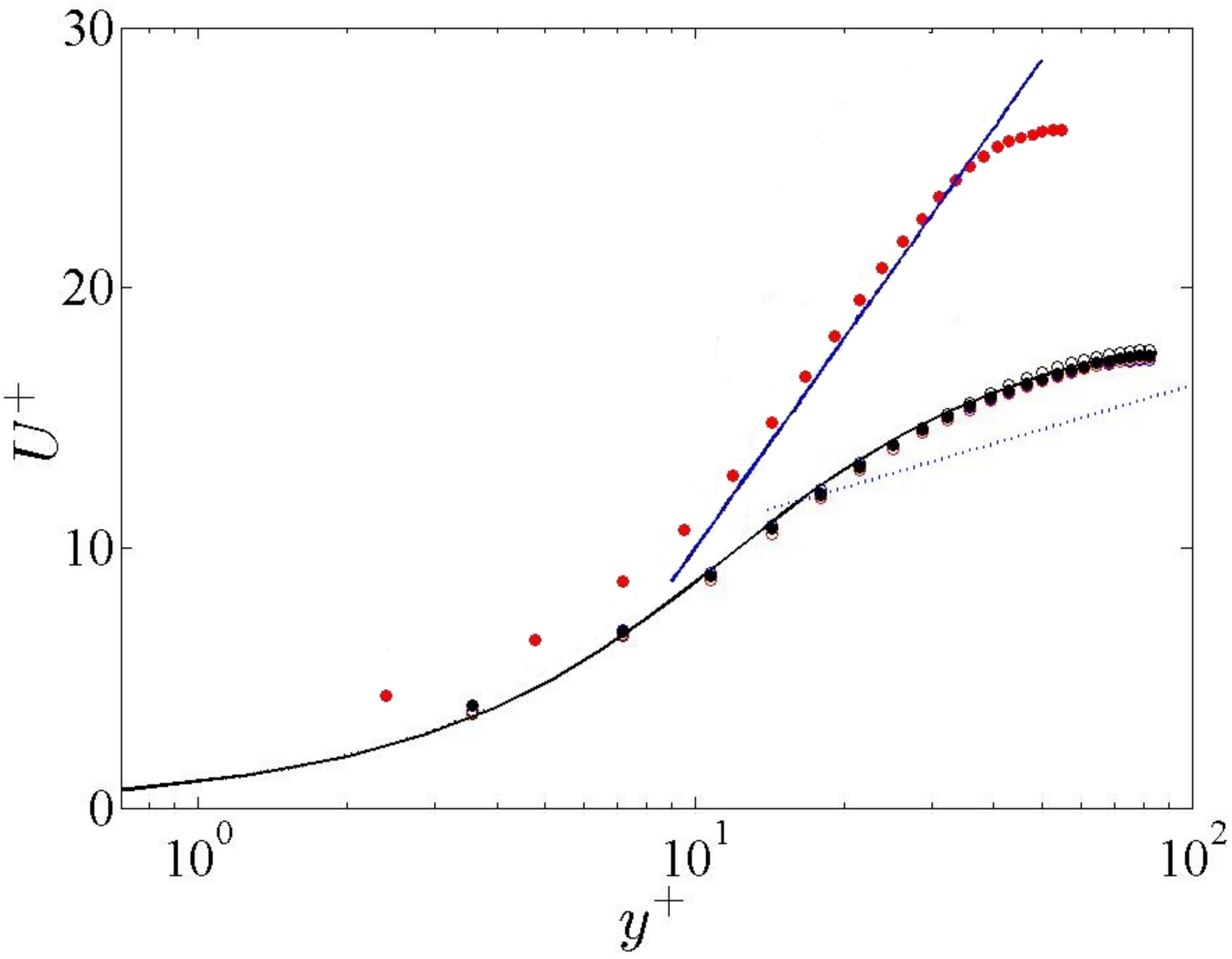
Stereoscopic PIV (2D3C) results



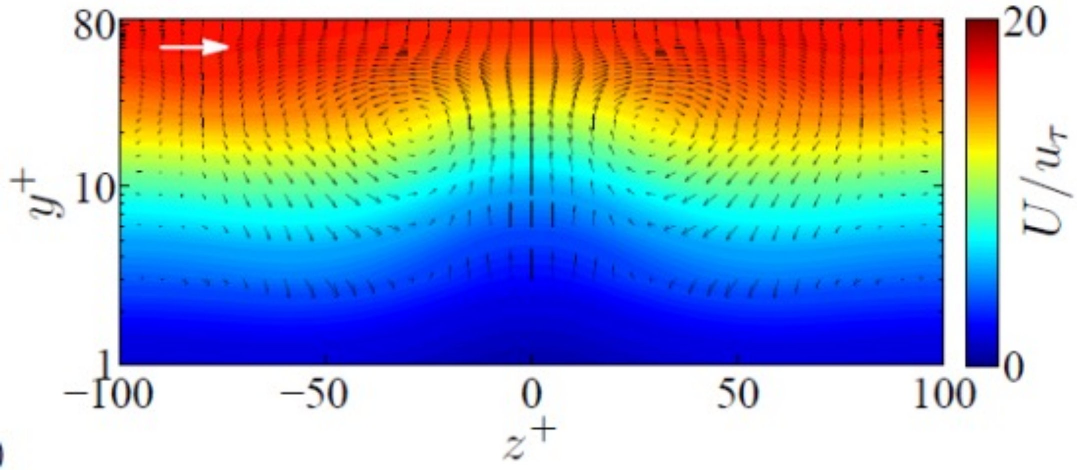
Stereoscopic PIV (2D3C) results



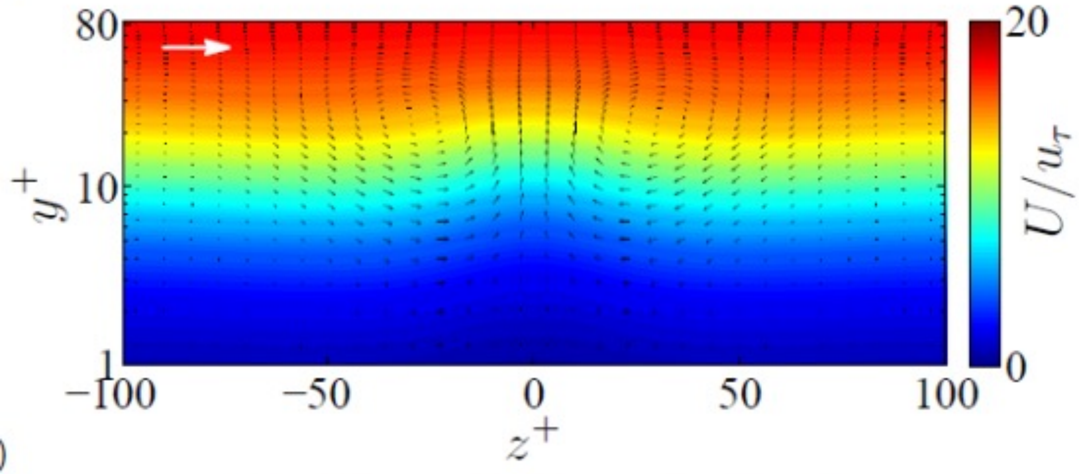
Stereoscopic PIV (2D3C) results



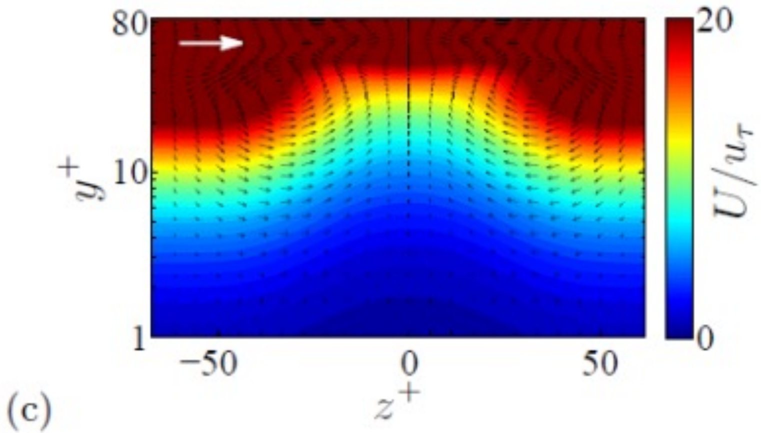
Comparison to travelling wave solutions[1]



SPIV



DNS



TW

- counter-rotating streamwise vortex-pair
- induces a low-speed and low-stress streak in the near-wall region of the flow
- region y^+ <30 good agreement
- far from wall TW remains coherent but DNS/SPIV less so
- vortex cores at (34,33) for DNS/SPIV; (29, 24) for TW (z^+, y^+)

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[1] J. S. Park and M. D. Graham, J. Fluid Mech. 782, 430 (2015).

Tentative conclusions and outlook

Part 1

1. Can now "predict" %DR (at least for PAA) based on CaBER λ
2. Master curve collapse for pipe, channel, square duct ($\neq$ f(Re))

Part 2

1. Spatially and temporarily intermittent "hibernating turbulence" observed experimentally in **Newtonian fluids**.
2. Number of events reduces with increasing Reynolds number
3. Comparison to DNS, travelling wave solutions (Graham group) show good agreement
4. Flow structures during hibernation obtained using PIV

Outlook

1. Higher Reynolds numbers. How does duration scale with Re_τ?
2. Effect of additives: surfactants and high molecular weight polymers

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