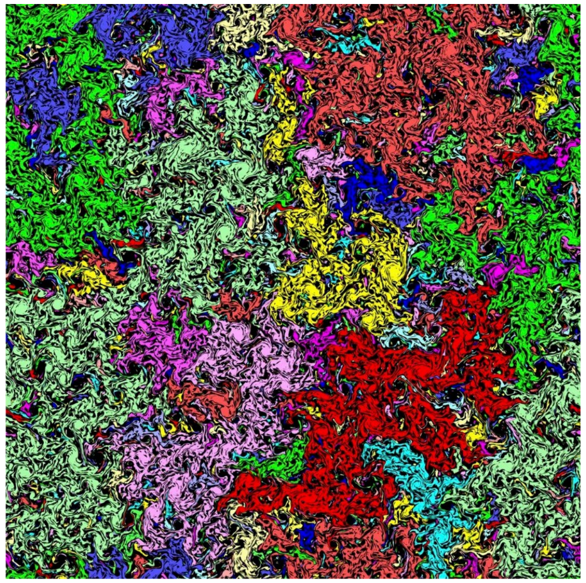
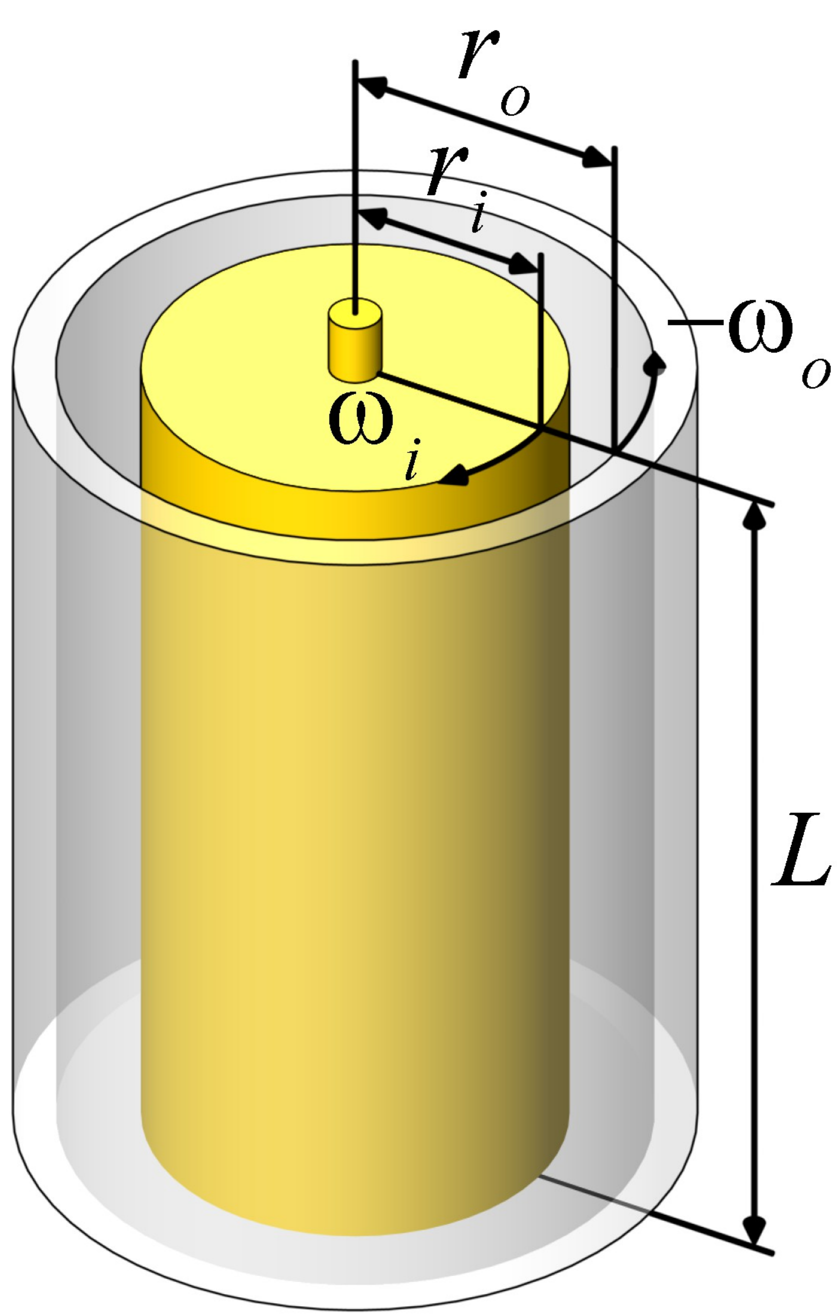
Taylor rolls in high Reynolds number Taylor-Couette flow

Rodolfo Ostilla Mónico
Roberto Verzicco, Siegfried Grossmann, Detlef Lohse

Physics of Fluids
University of Twente





Geometric parameters

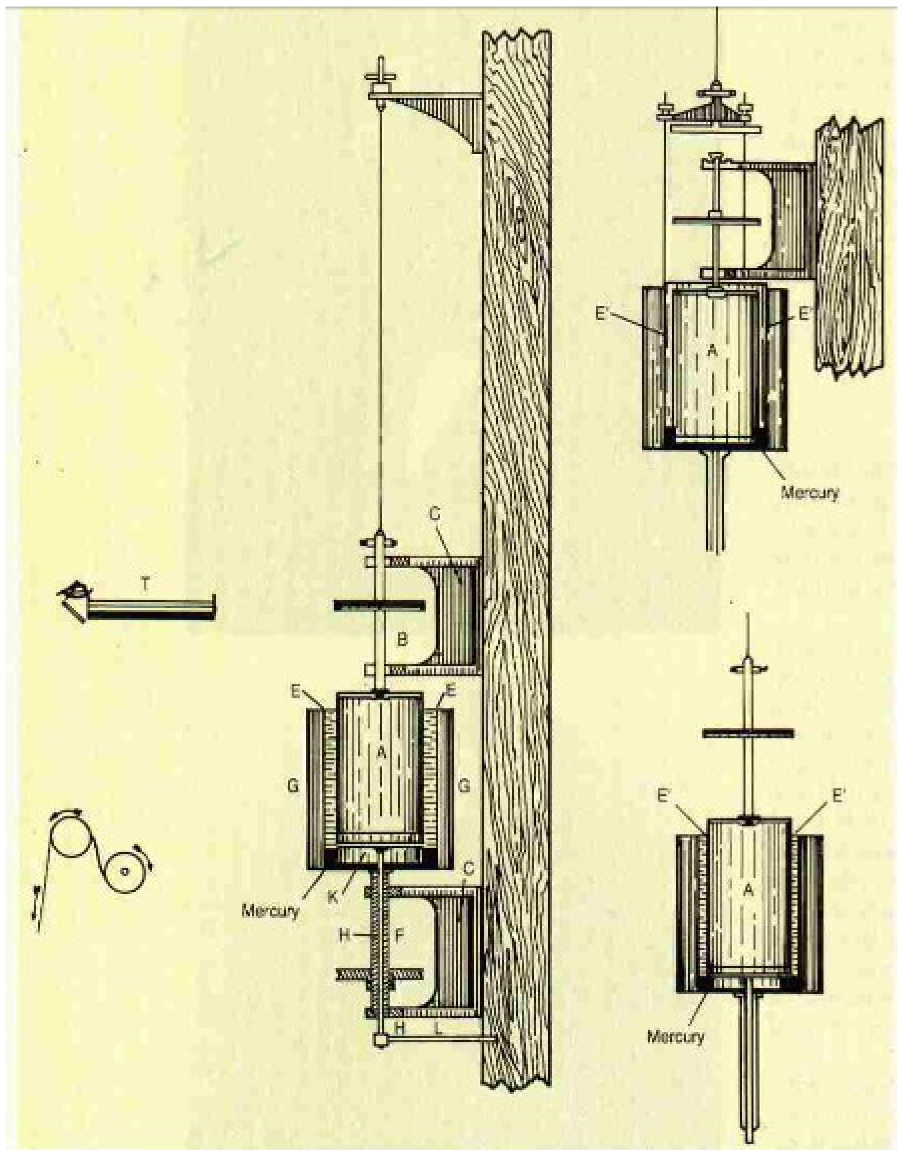
$$\eta = \frac{r_i}{r_o} \qquad \Gamma = \frac{L}{r_o - r_i}$$

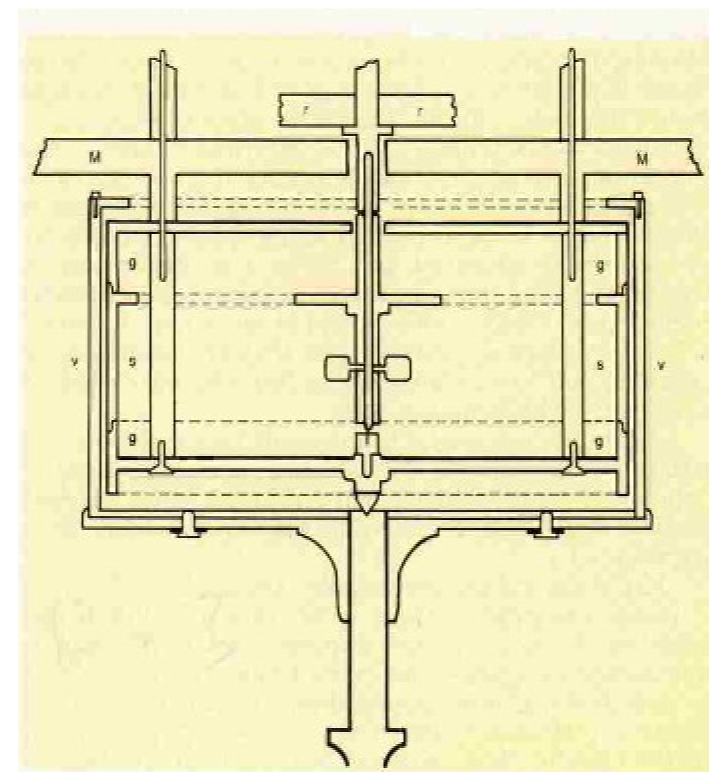
Driving parameters

$$Re_i = \frac{r_i \omega_i (r_o - r_i)}{\nu}$$

$$Re_o = \frac{r_o \omega_o (r_o - r_i)}{\nu}$$

Taylor-Couette experiments from 1890s





R. Donnelly, “Taylor-couette flow: the early days”, Physics Today 1991

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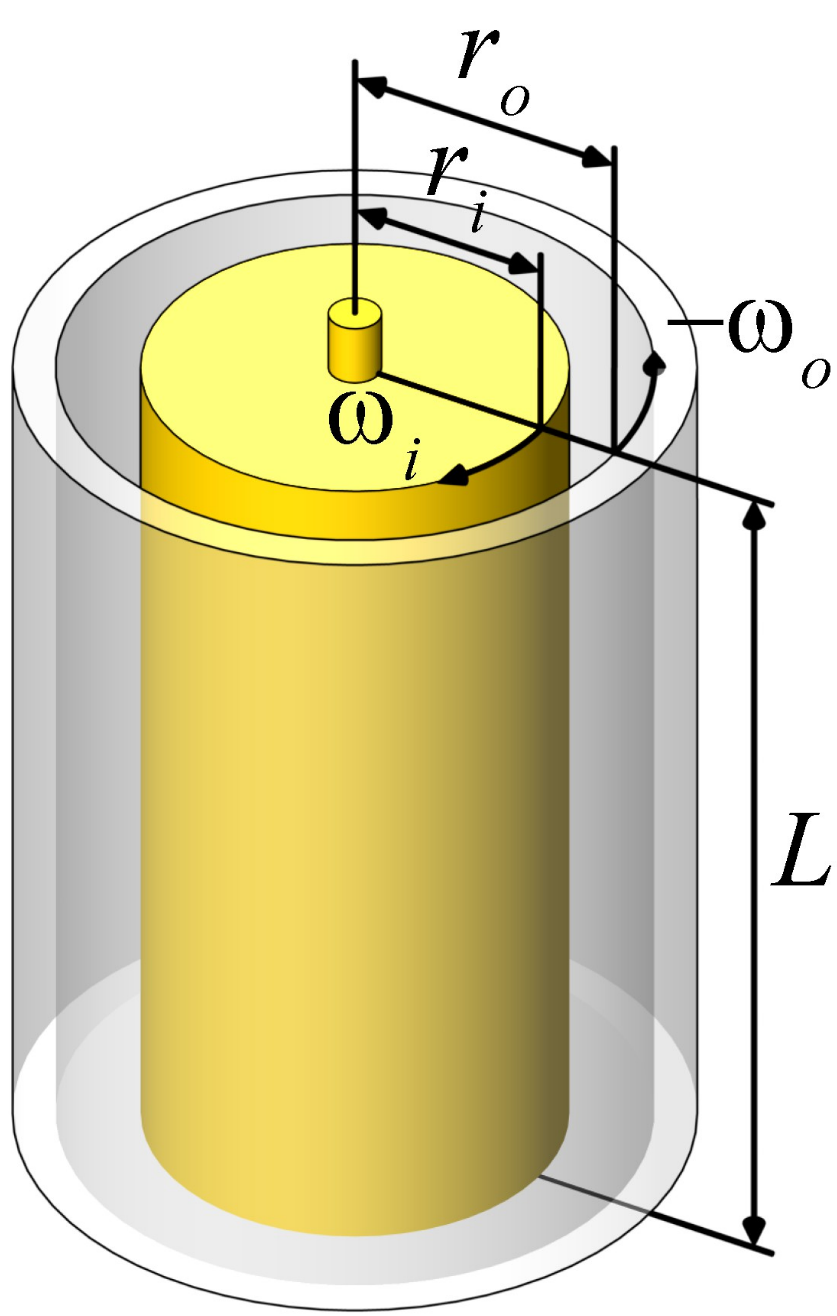
"The hydrogen atom of fluid dynamics" – introduction to the Taylor–Couette flow for soft matter scientists

M. A. Fardin,*[ab] C. Perge[a] and N. Taberlet[ac]

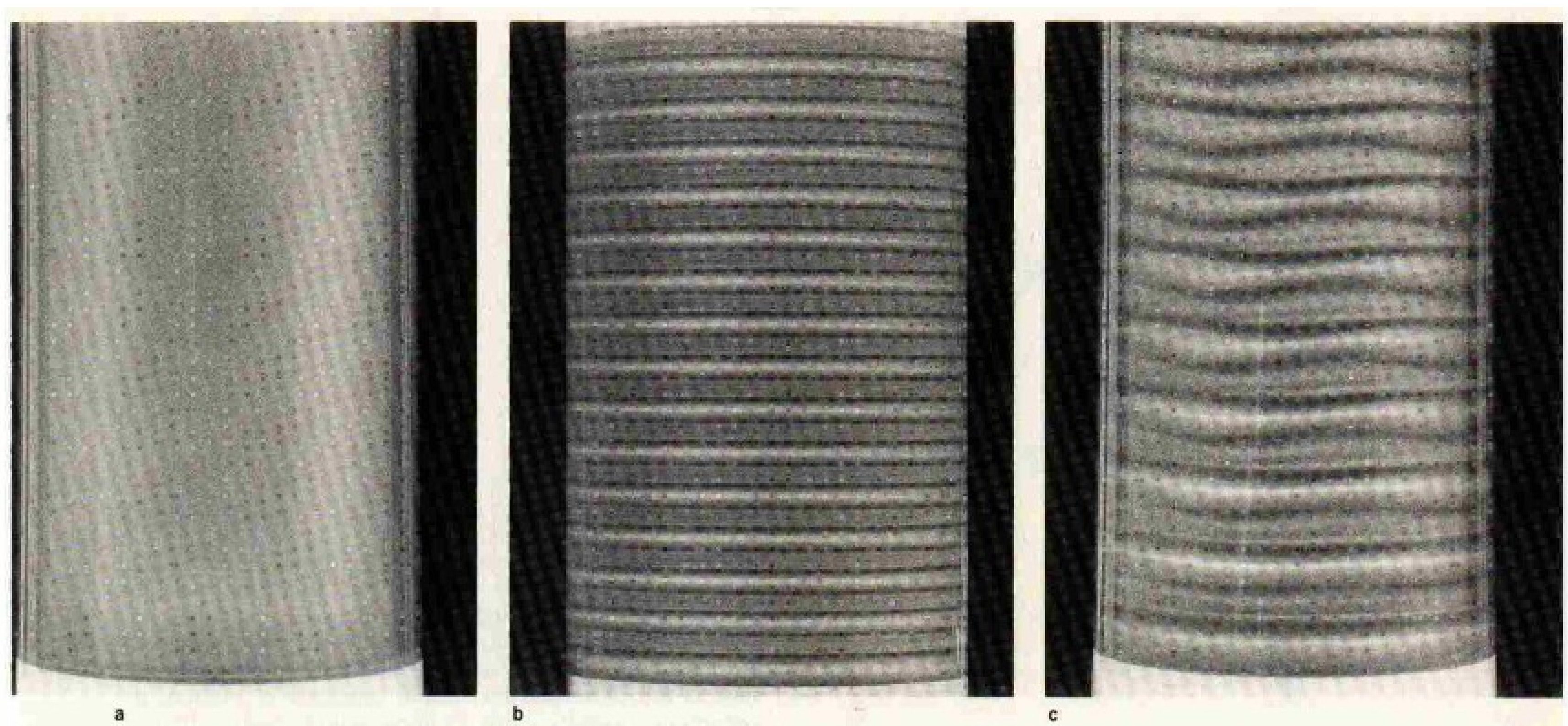


Focus on inner cylinder rotation

$$Re_i = \frac{r_i \omega_i (r_o - r_i)}{\nu}$$

~~$$Re_o = \frac{r_o \omega_o (r_o - r_i)}{\nu}$$~~

The transition to turbulence of TC flow



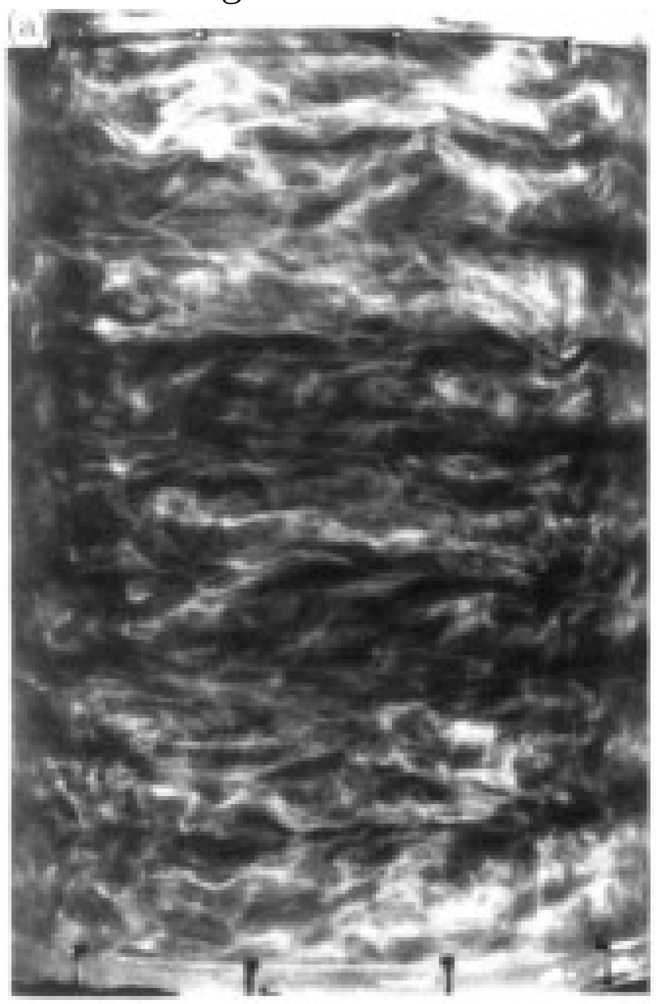
Increasing Reynolds number

R. Donnelly, "Taylor-couette flow: the early days", Physics Today 1991

Do the rolls dissapear at large Re?

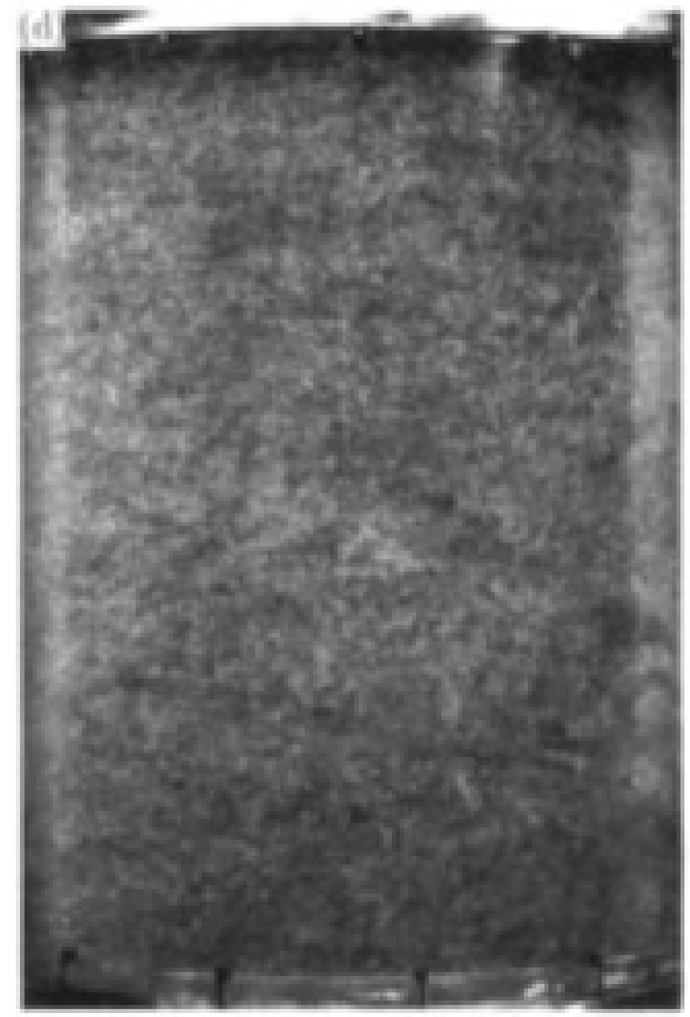
$Re_s \sim 10^4$

(a)



$Re_s \sim 10^5$

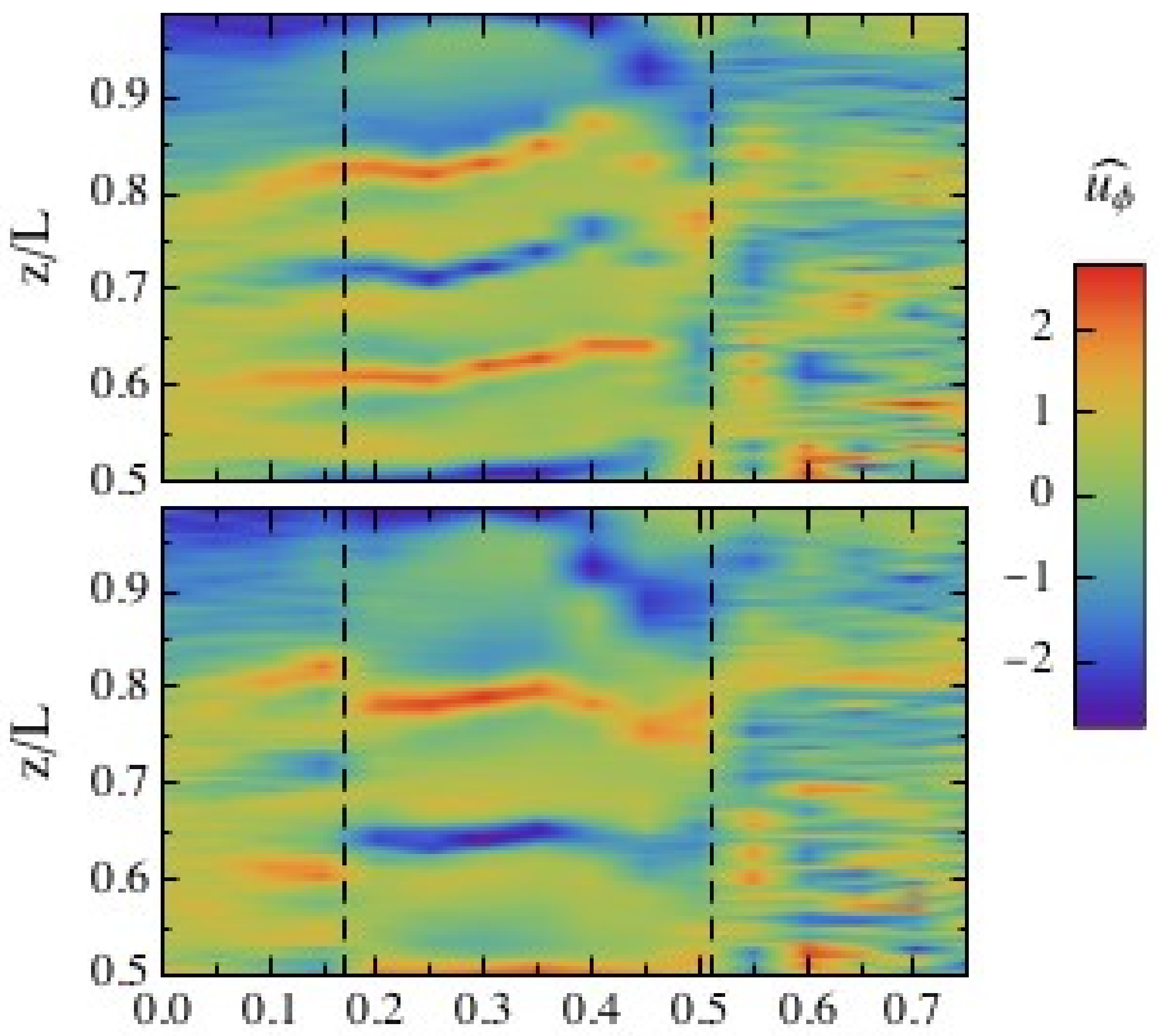
(b)



Increase Reynolds enough

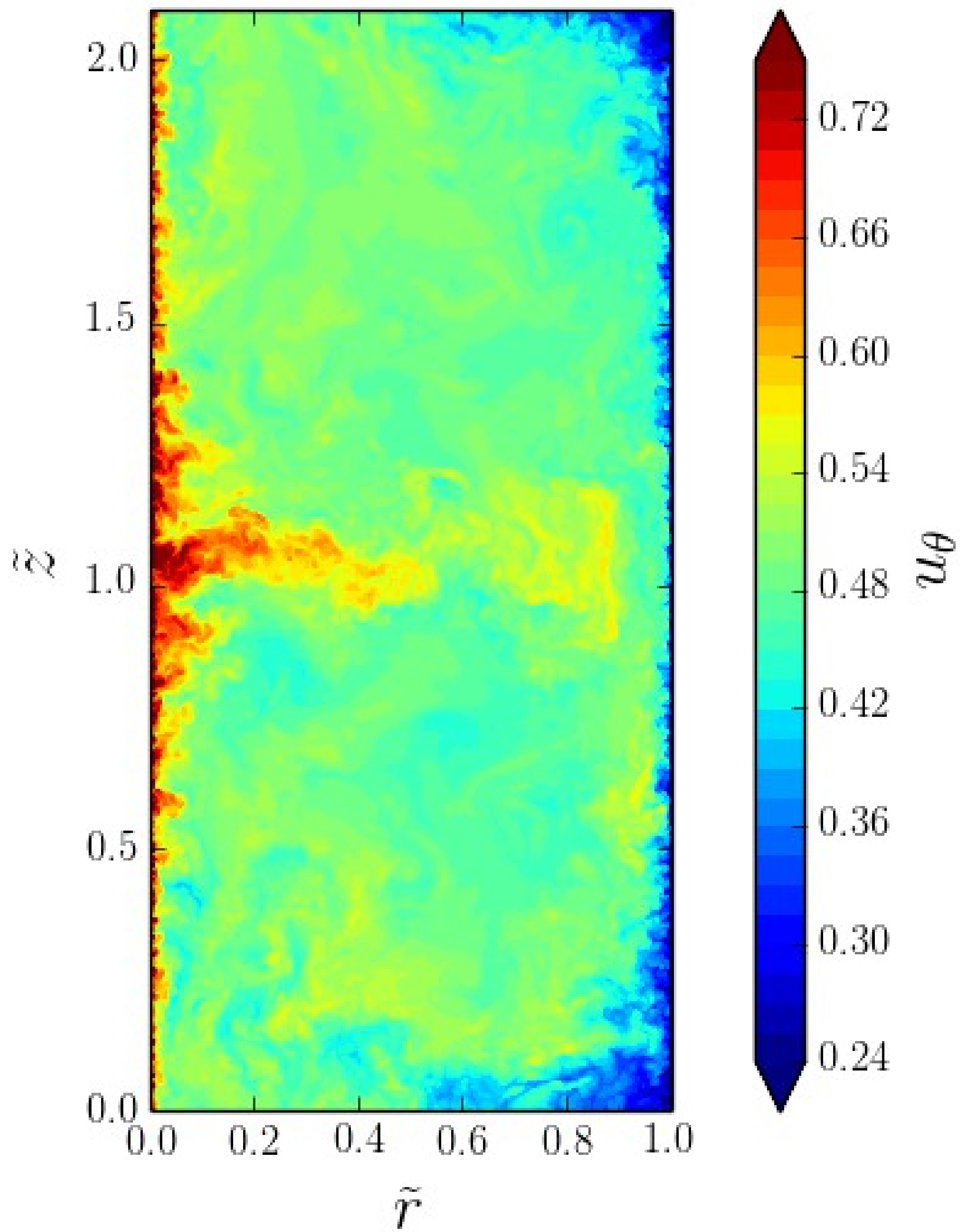
Lathrop DP, Fineberg J, Swinney HS. 1992. Phys. Rev. A 46:6390–6405

Do the rolls dissapear at large Re?



Huisman SG, van der Veen RCA, Sun C, Lohse D. 2014. Nat. Commun. 5:3820

Also in DNS with periodic conditions

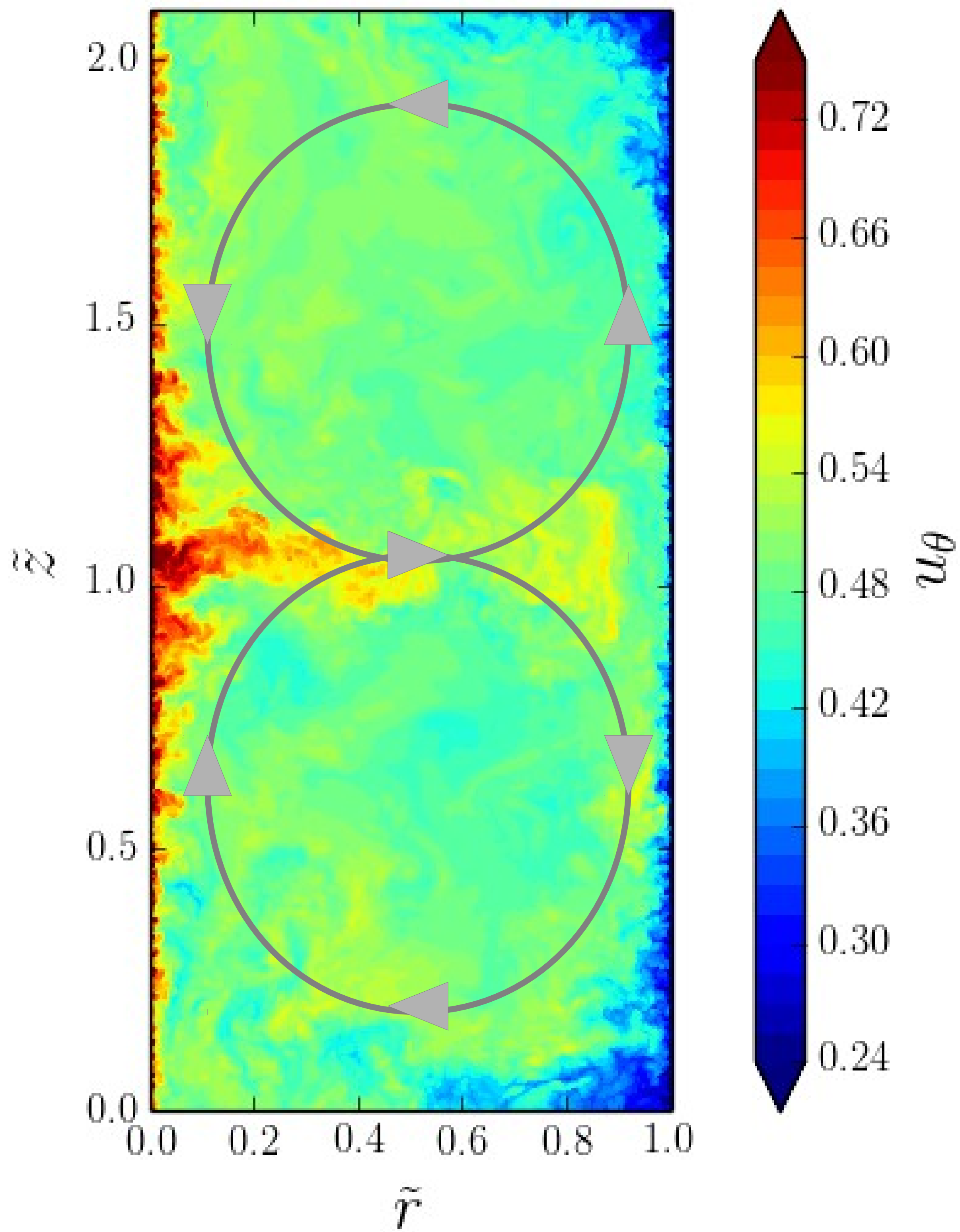


$\eta = 0.909$

$Re_s = 10^5$

$\Gamma = 2$

$\omega_o = 0$



$$\eta = 0.909$$
$$Re_s = 10^5$$
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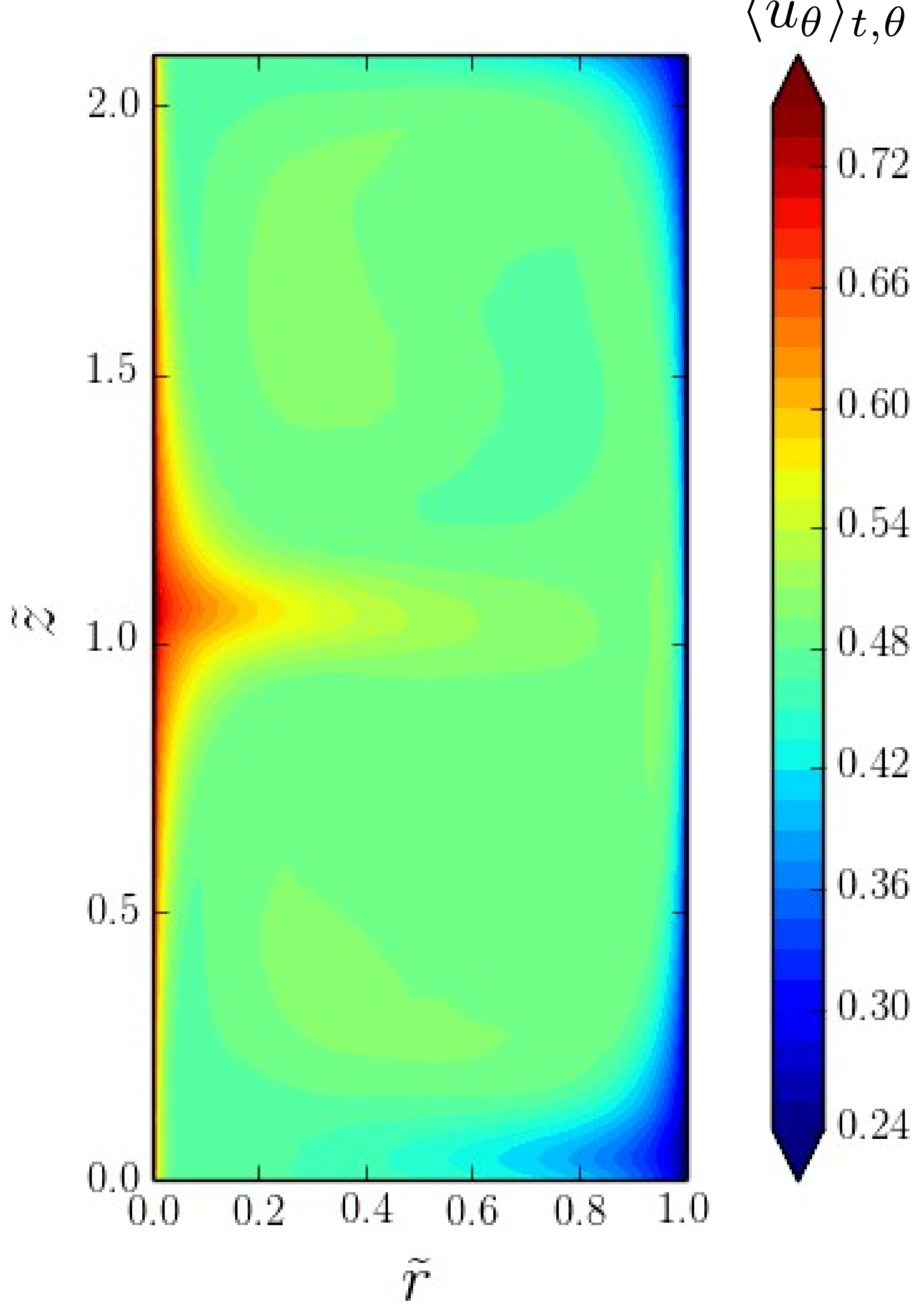
$$\omega_o = 0$$

They are persistent in time



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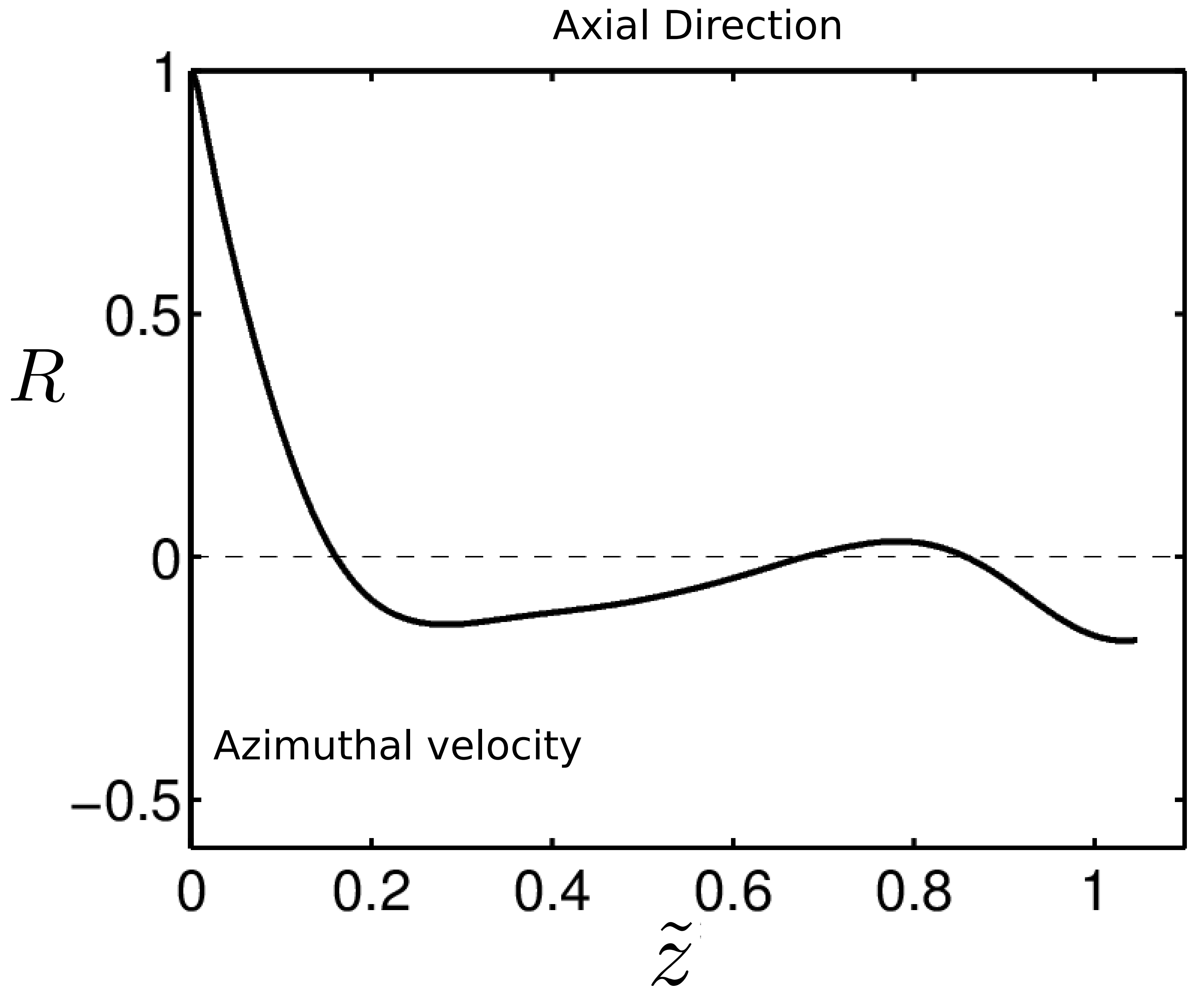
Rolls dominate the axial autocorrelations



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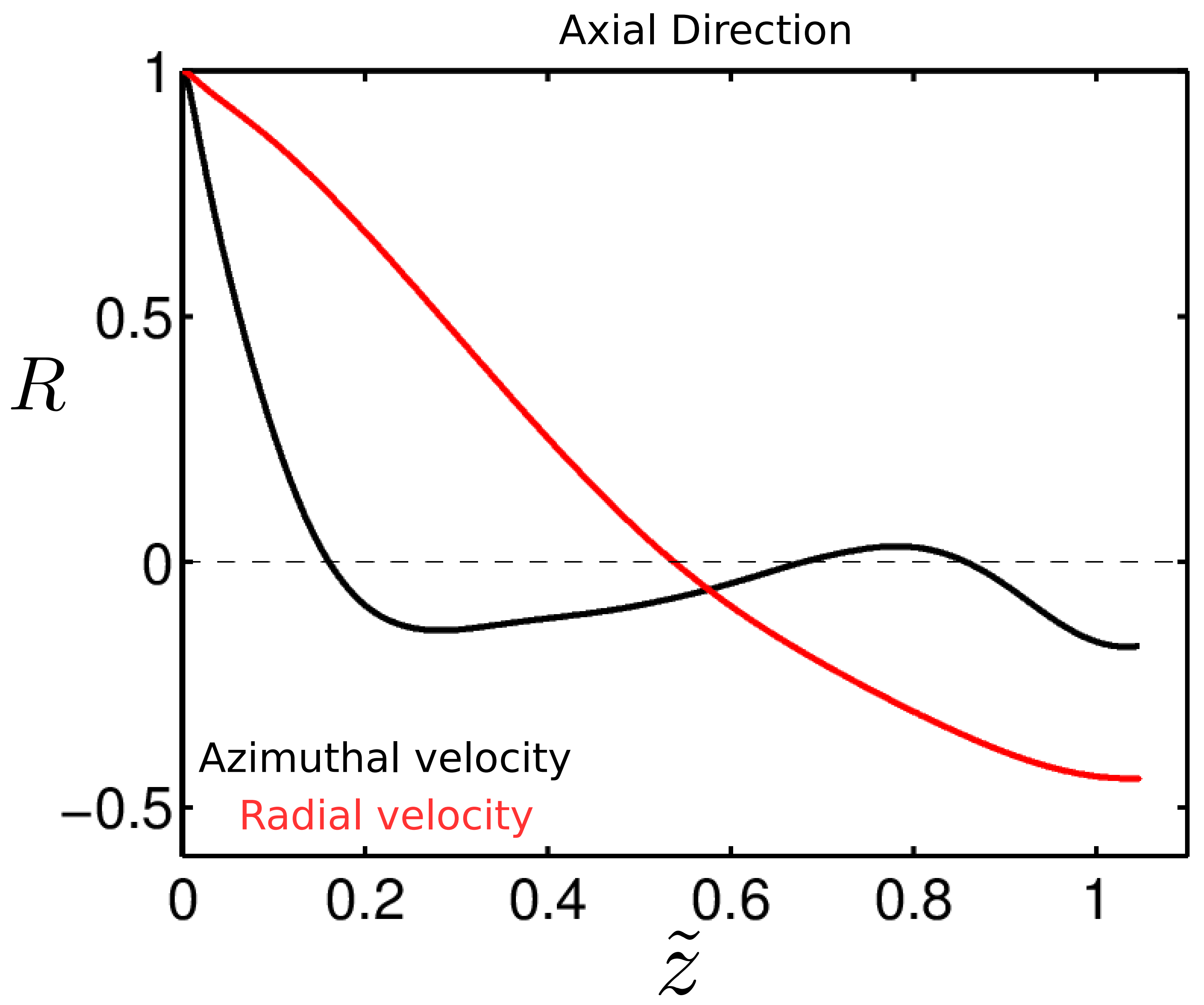
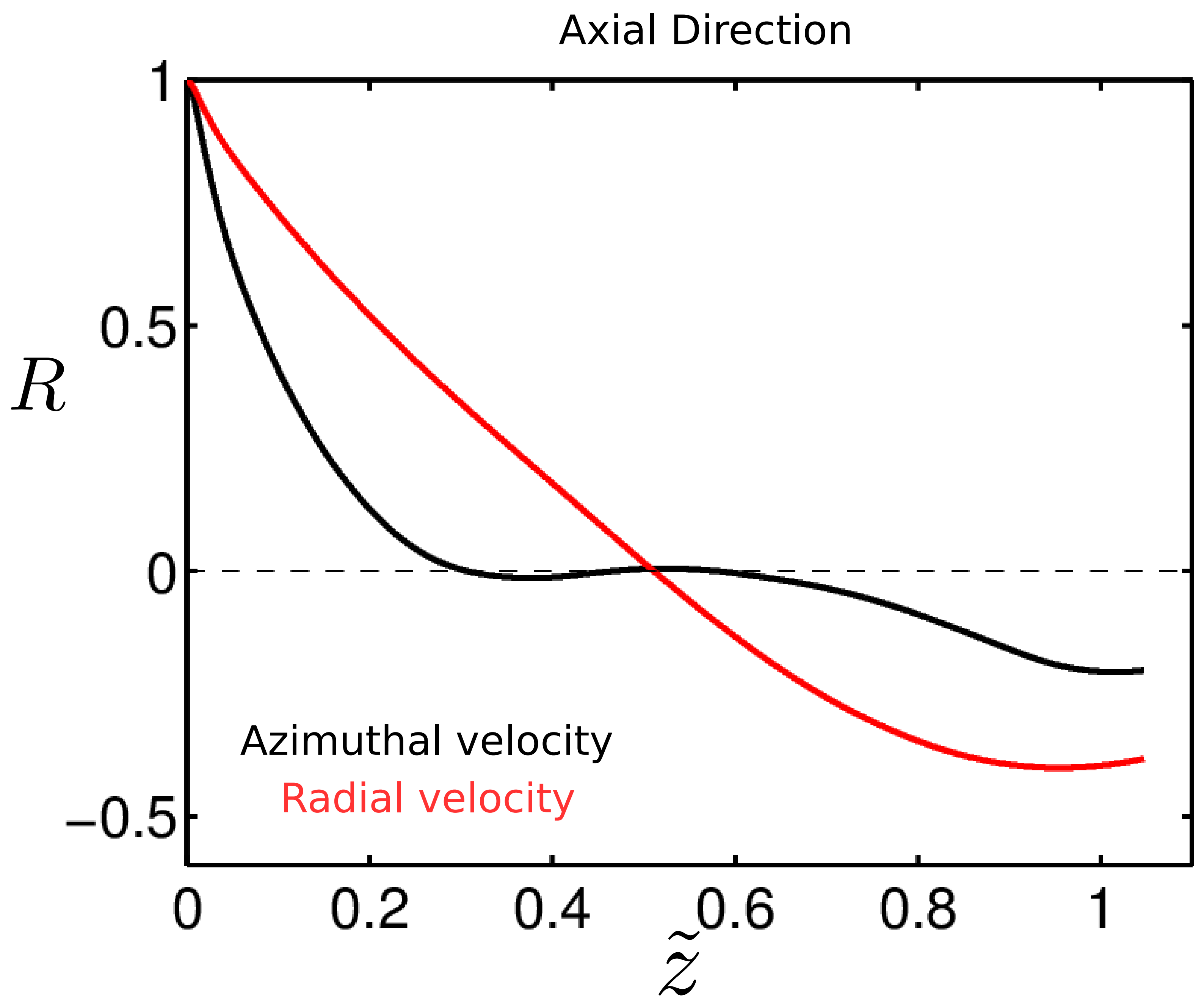


$\eta = 0.909$
$Re_s = 10^5$
$\Gamma = 2$
$\omega_o = 0$

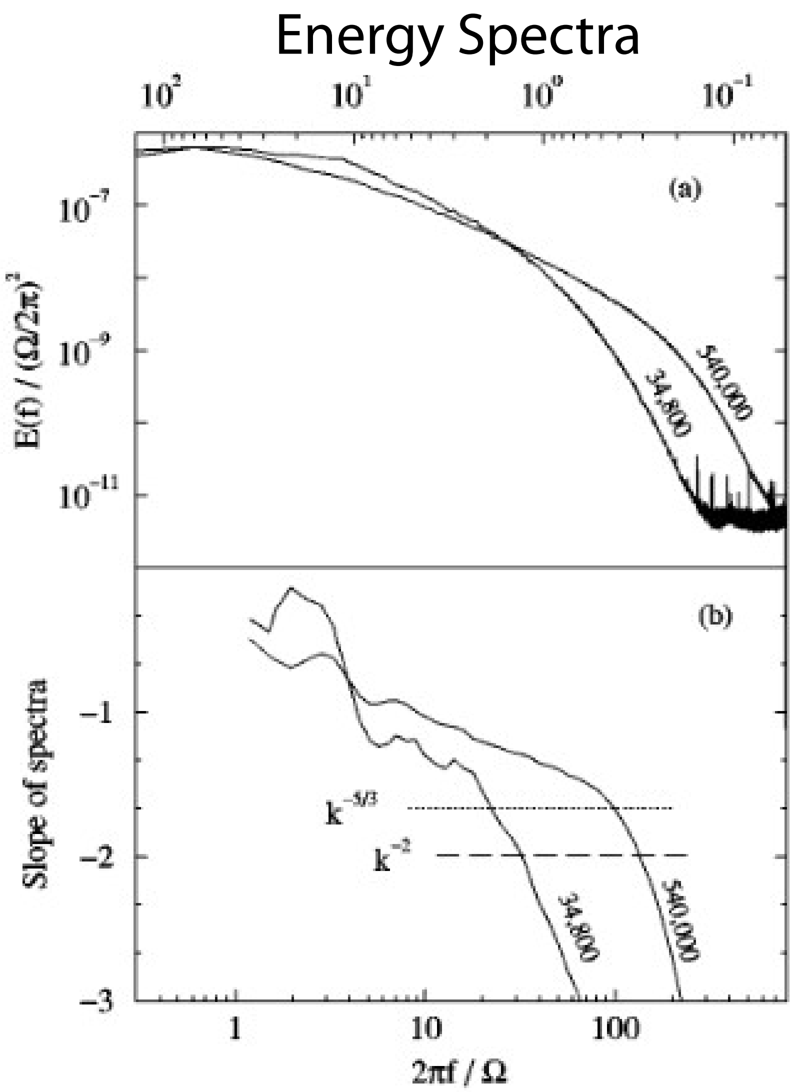
They seem to be resistant to axial flow

Axial autocorrelations with imposed flow



$\eta = 0.909$
$Re_s = 10^5$
$\Gamma = 2$
$\omega_o = 0$

What is the effect of these rolls on the system?

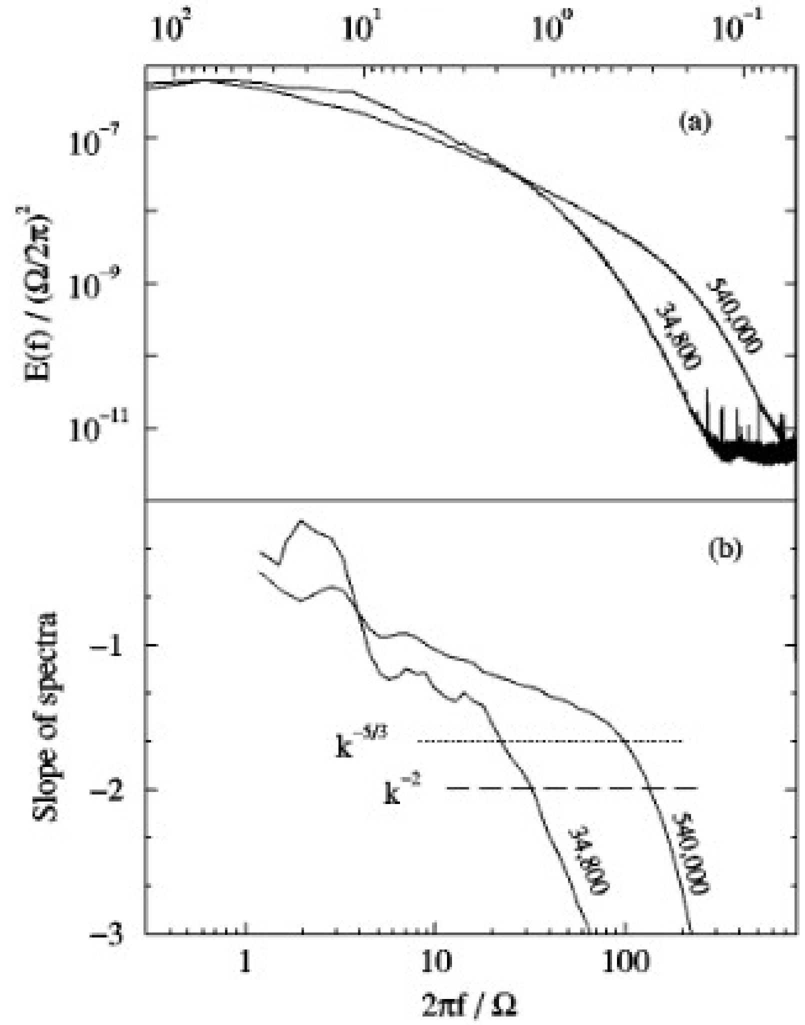


Lewis & Swinney, Phys. Rev. E, 59(5) 5457-5467, (1999)

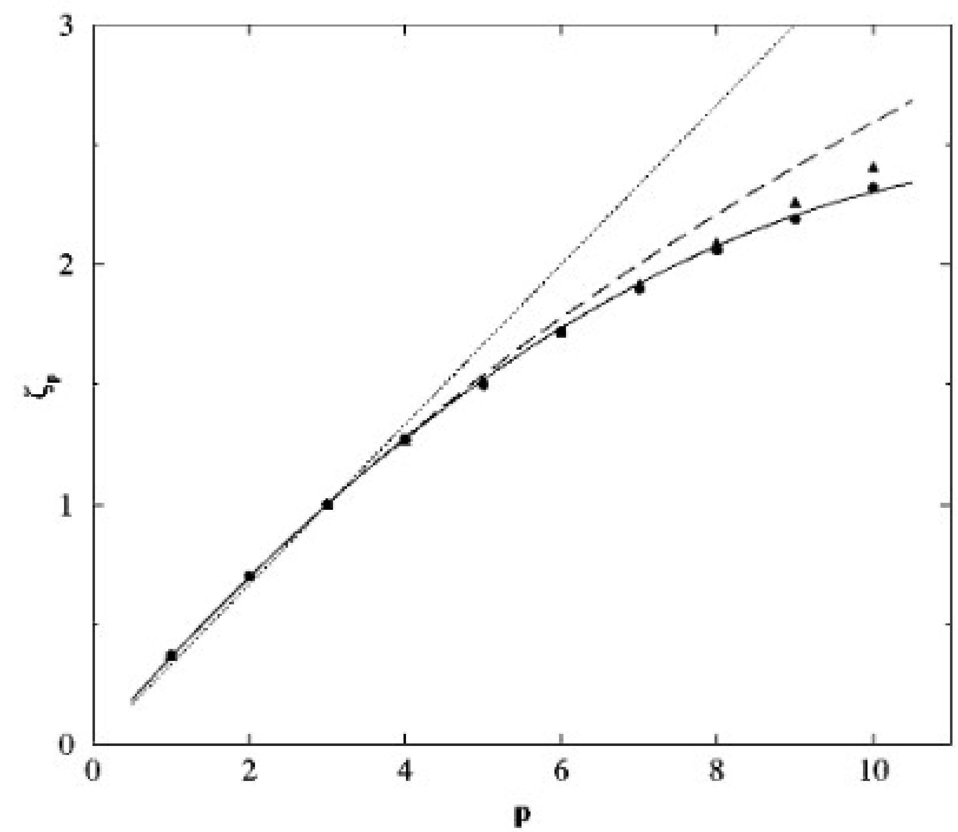
Do the rolls explain the absence of -5/3 energy spectra?

What is the effect of these rolls on the system?

Energy Spectra



Structure function exponent

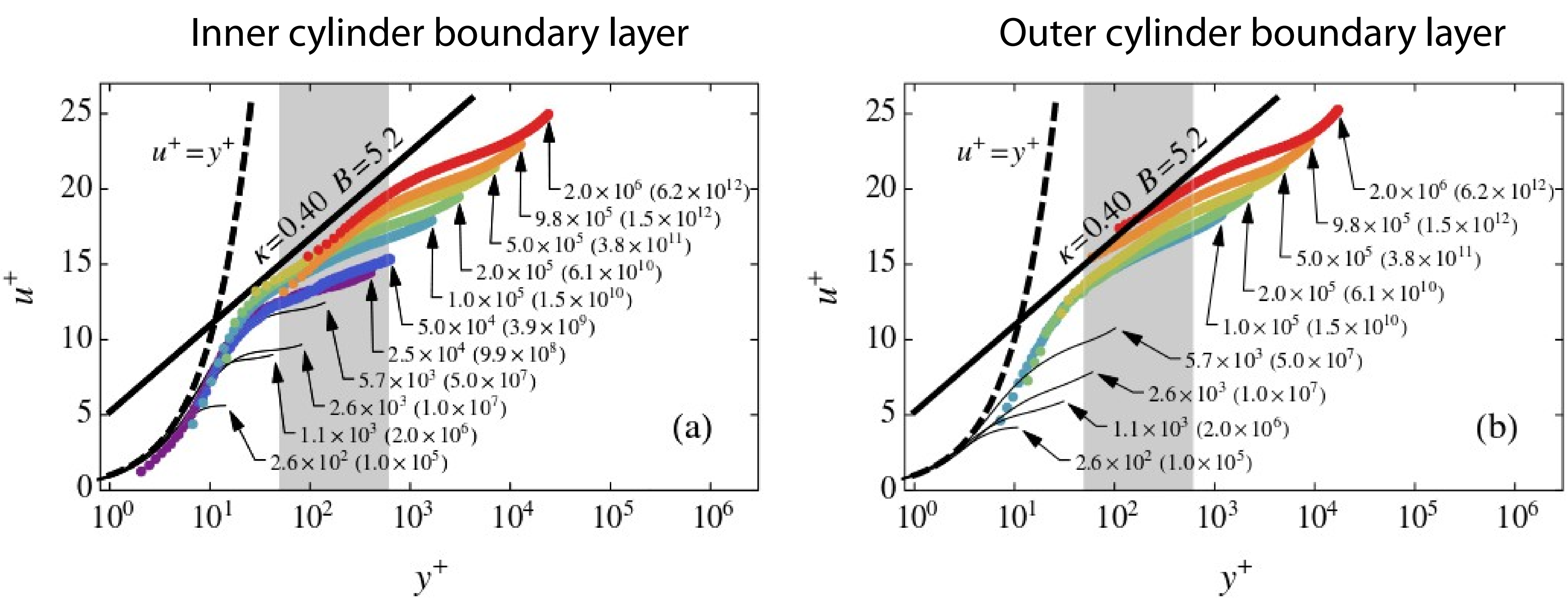


Lewis & Swinney, Phys. Rev. E, 59(5) 5457-5467, (1999)

Do the rolls explain the absence of -5/3 energy spectra?

Structure functions (with ESS) behave similar to other flows

What is the effect of these rolls on the system?



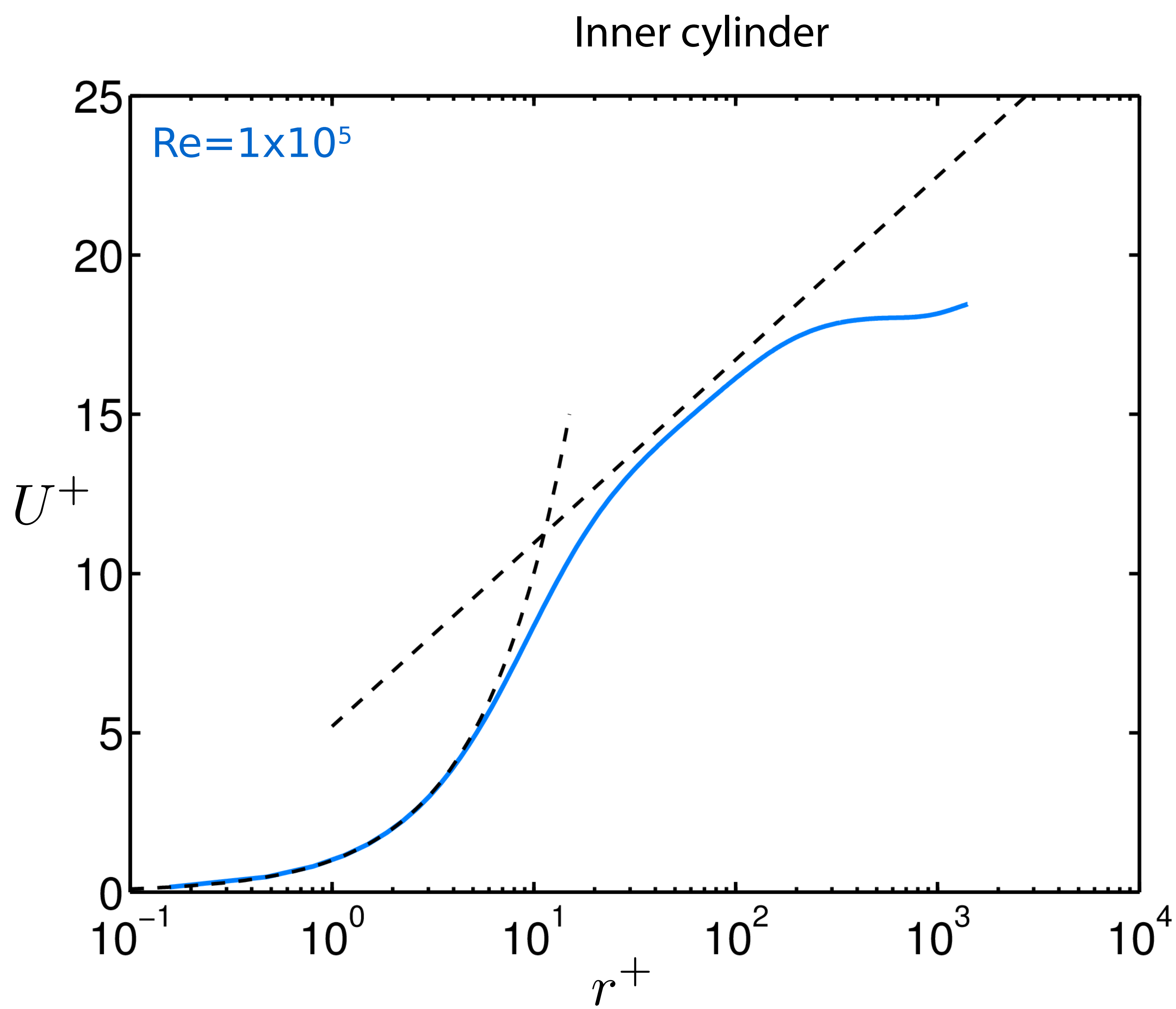
Huisman, Scharnowski, Cierpka, Kaehler, Lohse, Sun, Phys. Rev. Lett, 110 (2013), 264501

Same Prandtl-von Karman velocity profiles as in channels, pipes...

Can we further understand this using DNS?

Start by looking at the boundary layers…

In DNS we can also see these log-profiles



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$$\Gamma = 2$$
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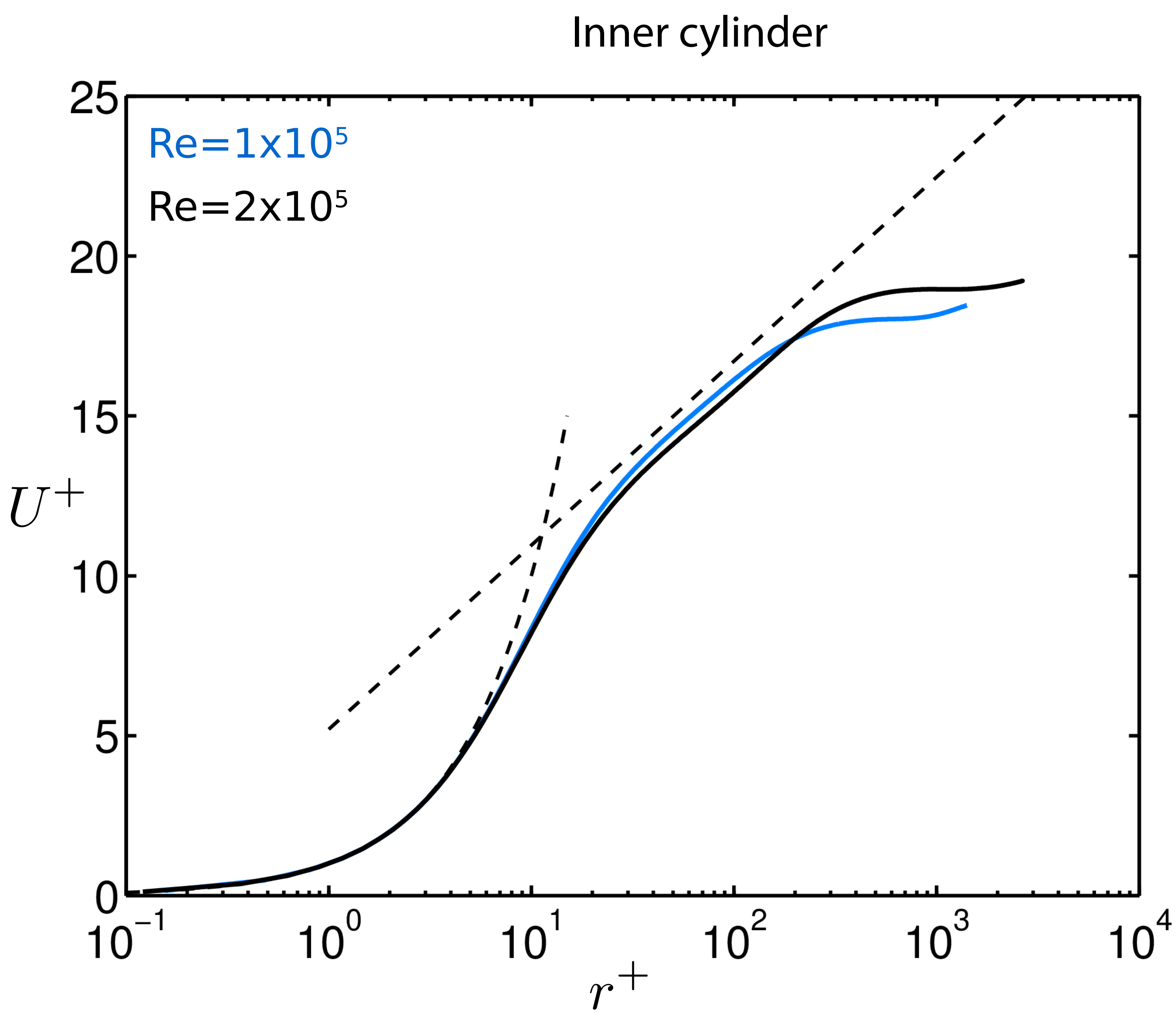

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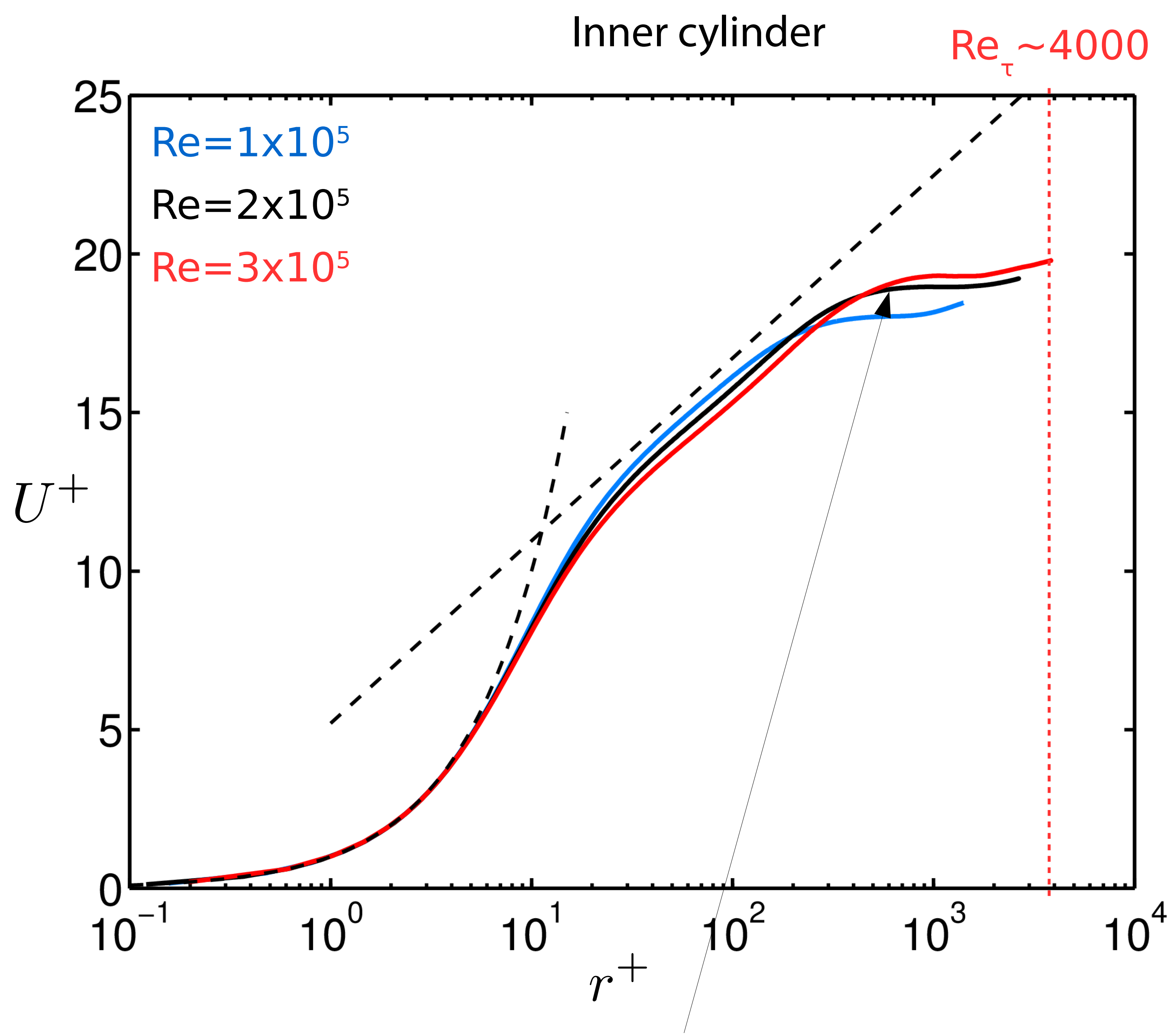
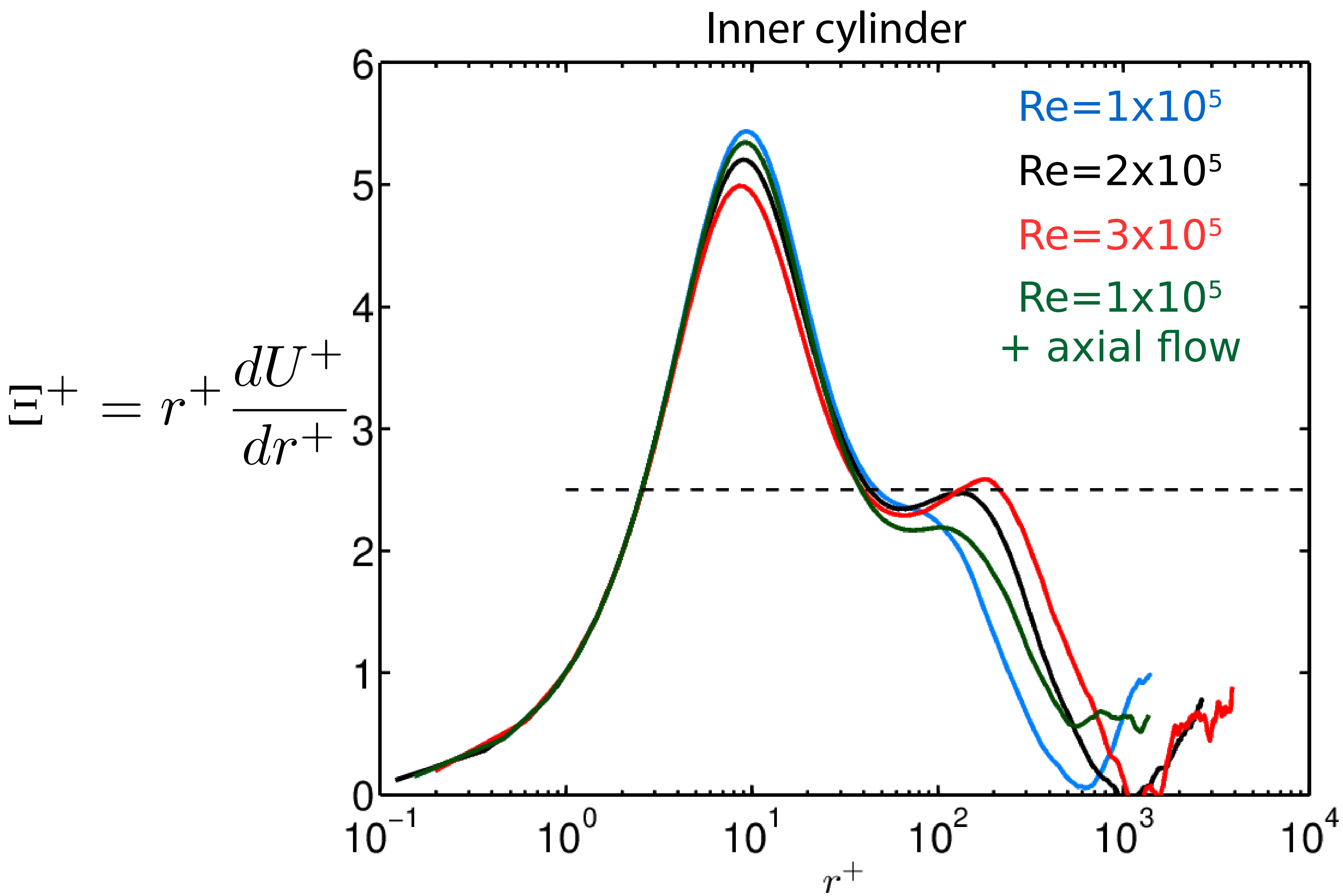


$$\eta = 0.909$$
$$\Gamma = 2$$
$$\omega_o = 0$$

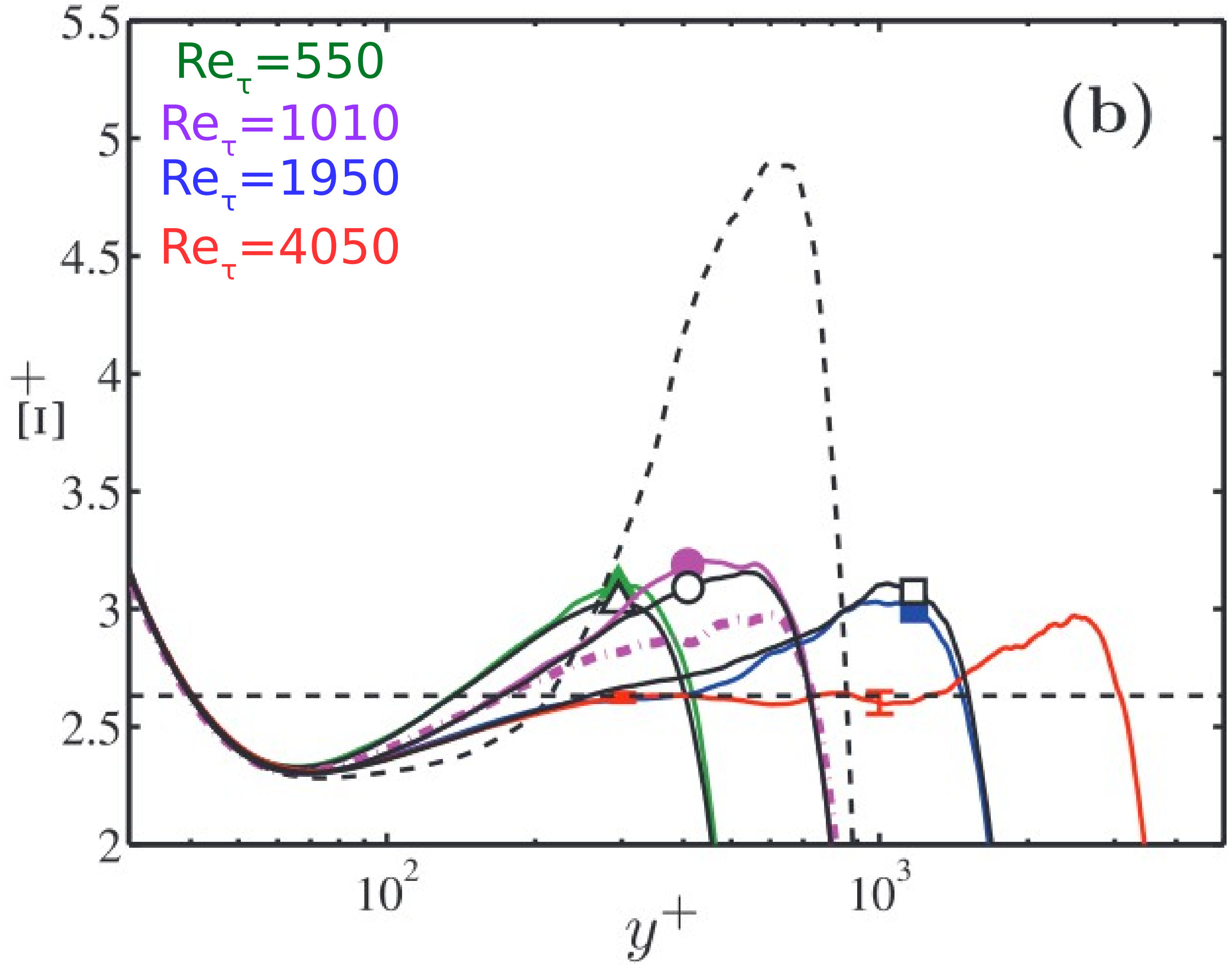
Profiles "bend" around 5% gap width

How logarithmic are the profiles?



$$\eta = 0.909$$
$$\Gamma = 2$$
$$\omega_o = 0$$

S-like behaviour in similar Re_τ channels

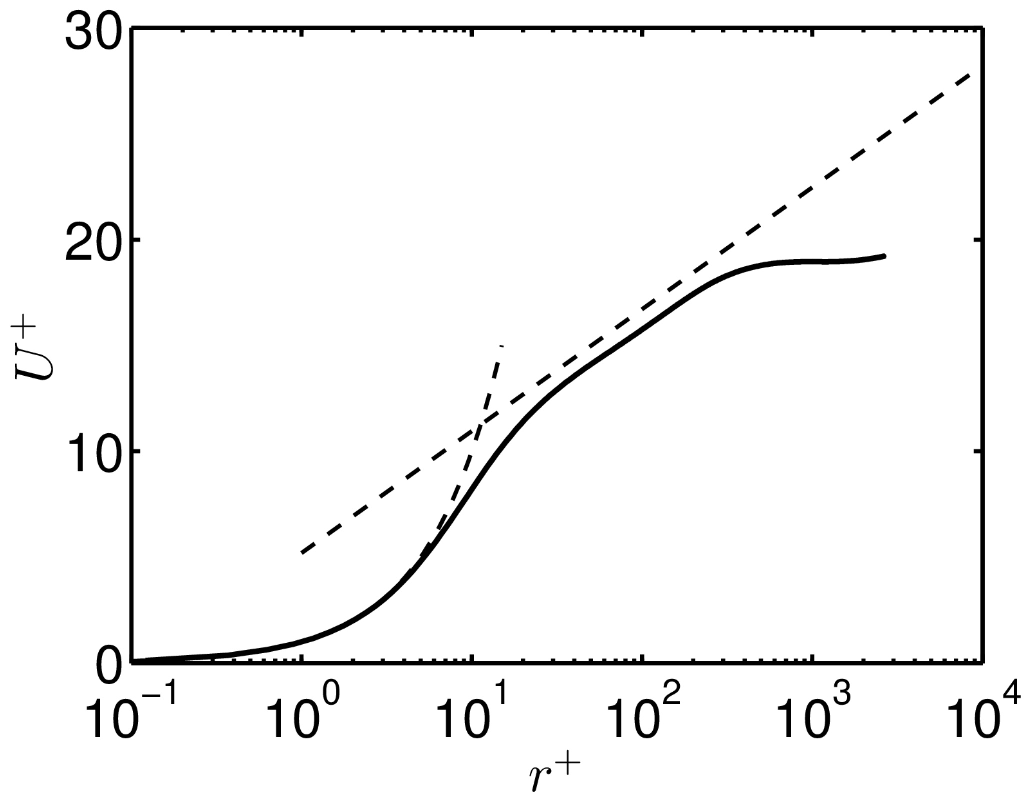


$$\Xi^+ = y^+ \frac{dU^+}{dy^+}$$

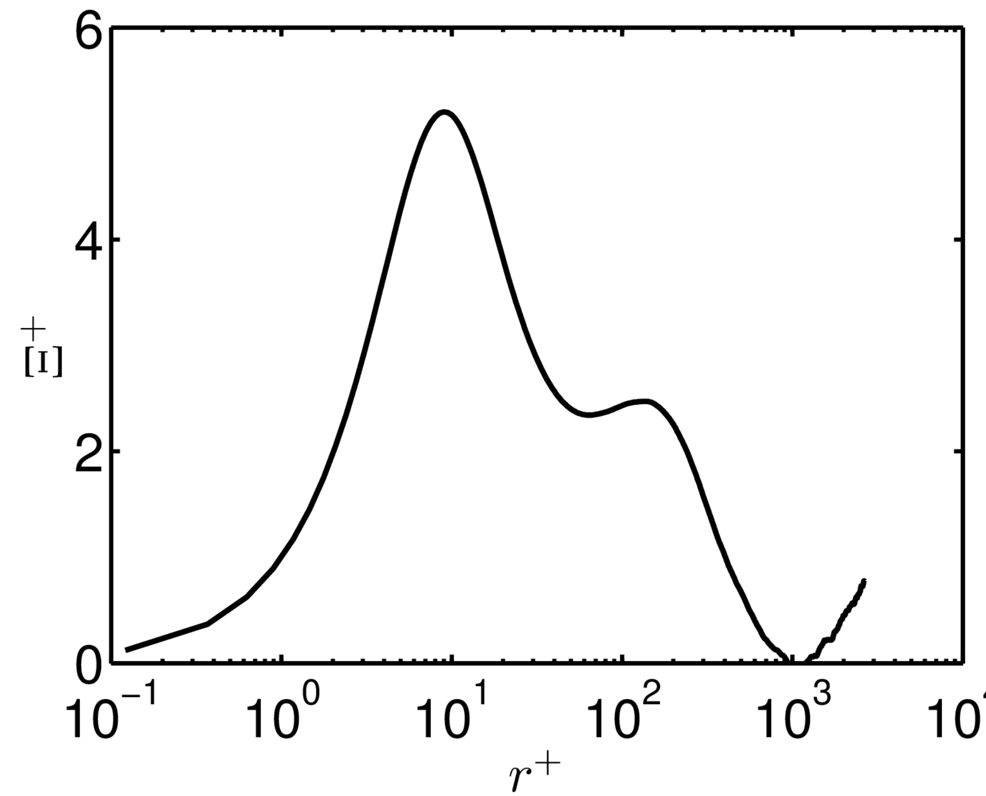
Lozano-Duran, Jimenez, Phys. Fluids , 26 (2014), 011702

Mean profile looks similar to other flows

Streamwise velocity profile for $Re_\tau = 2000$



$$\Xi^+ = r^+ \frac{dU^+}{dr^+}$$



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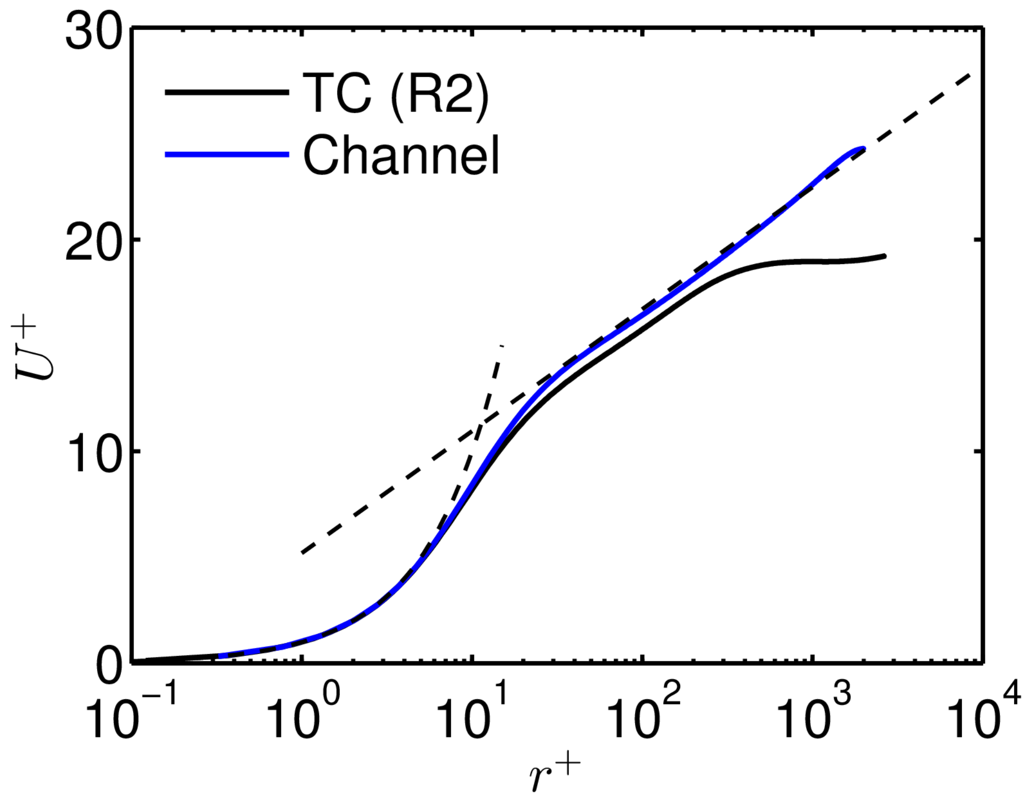

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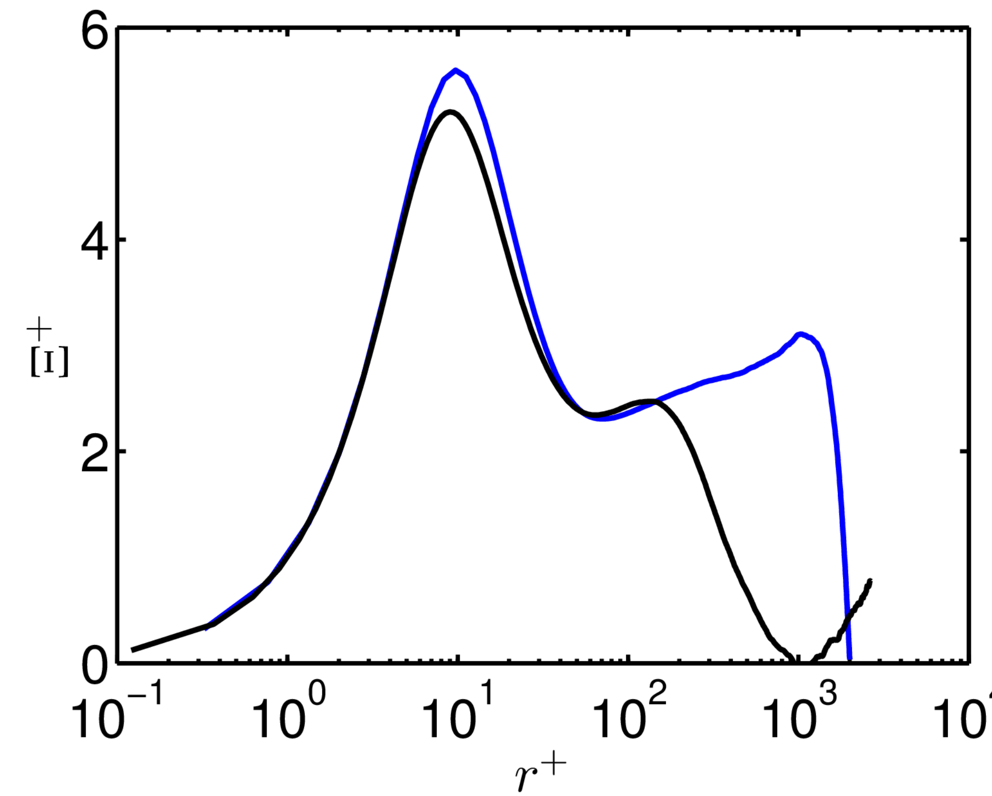

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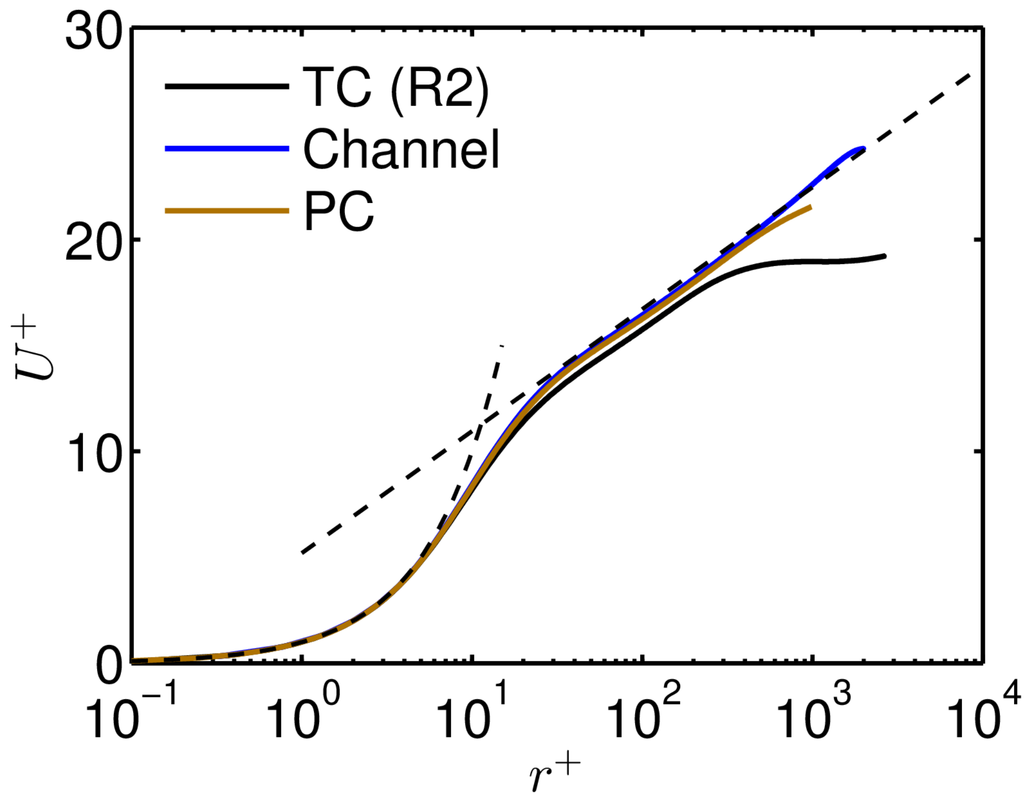

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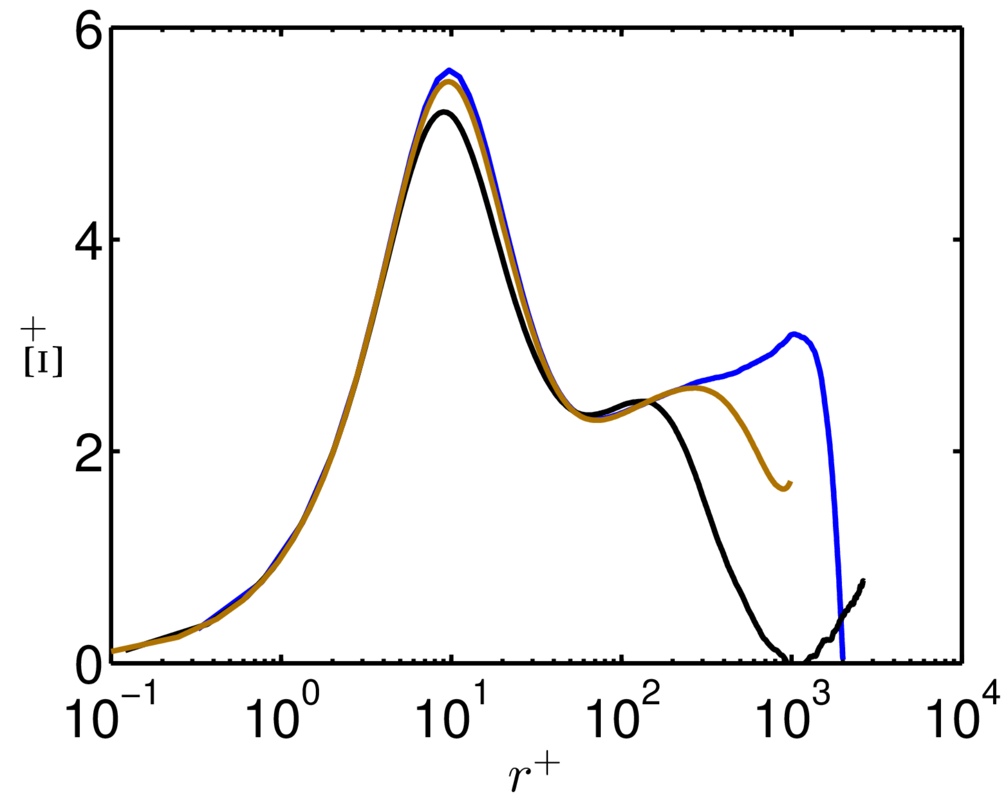

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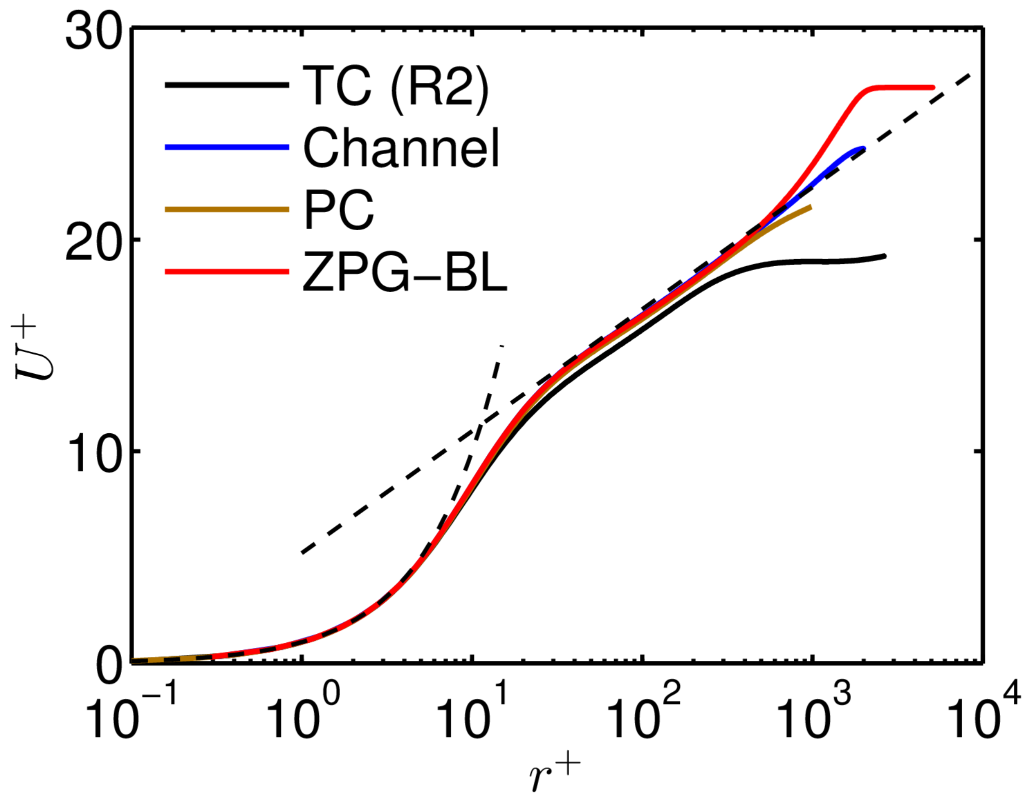
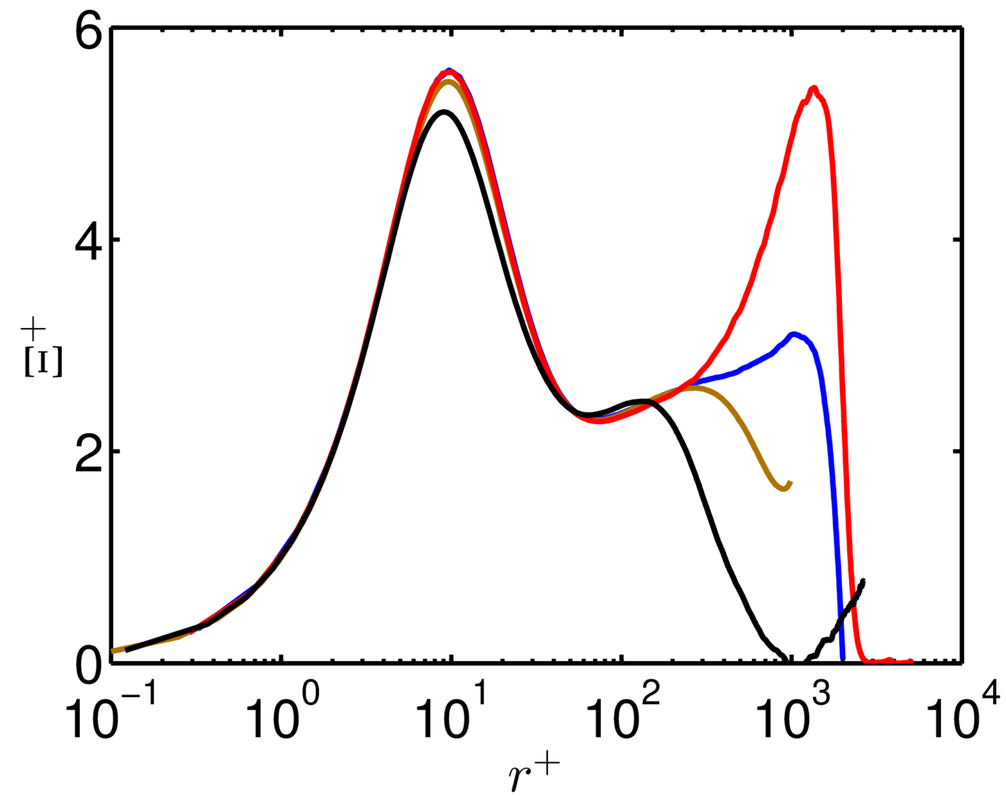


$$\Xi^+ = r^+ \frac{dU^+}{dr^+}$$



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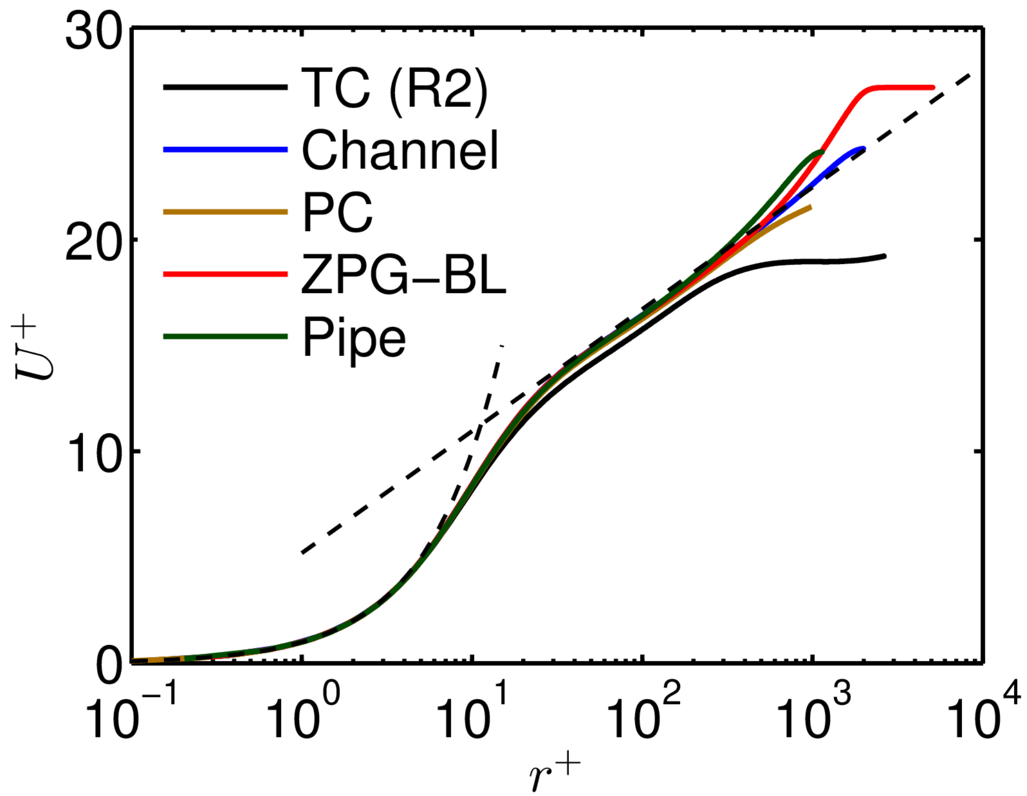

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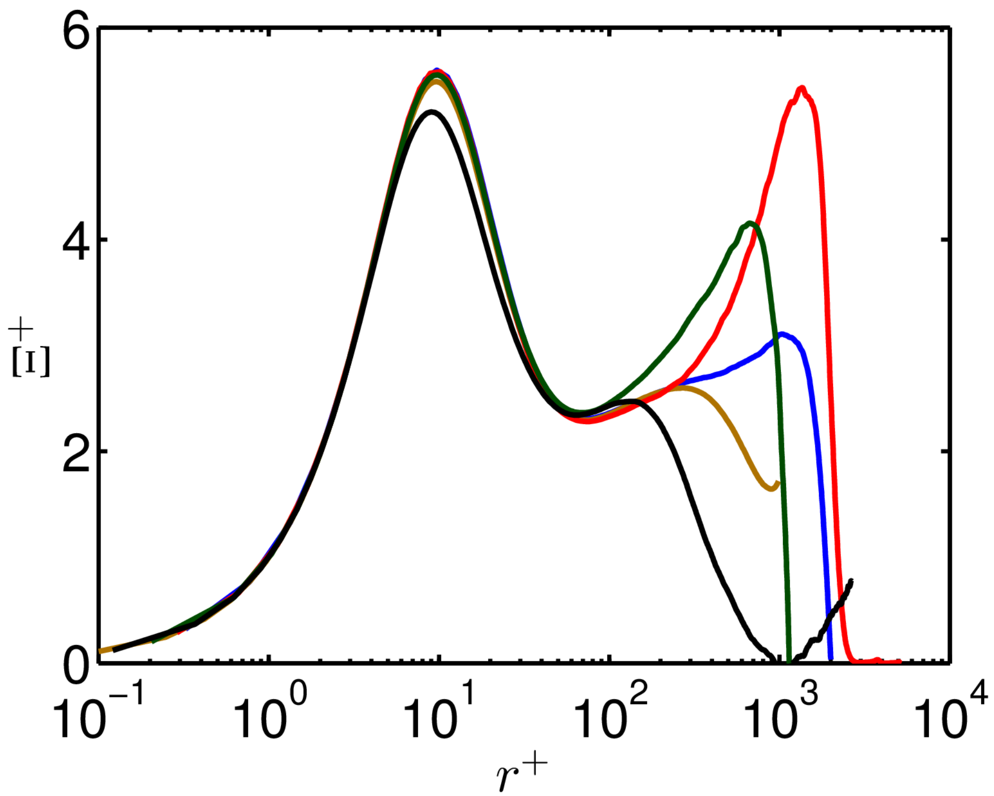

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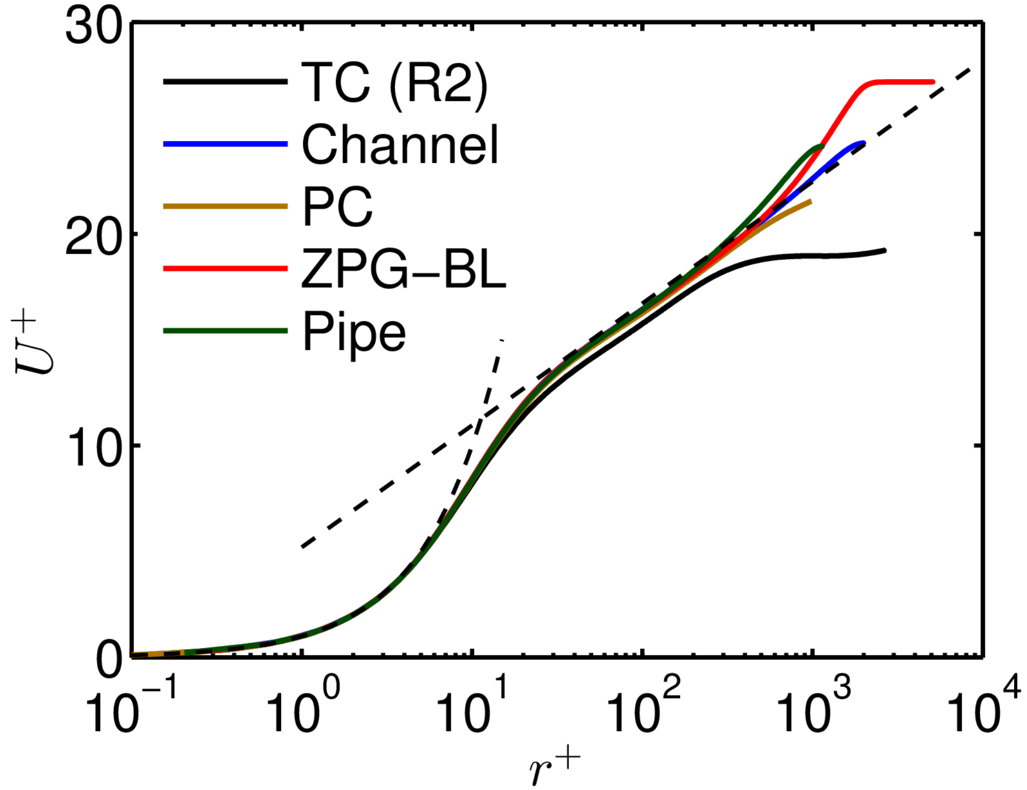
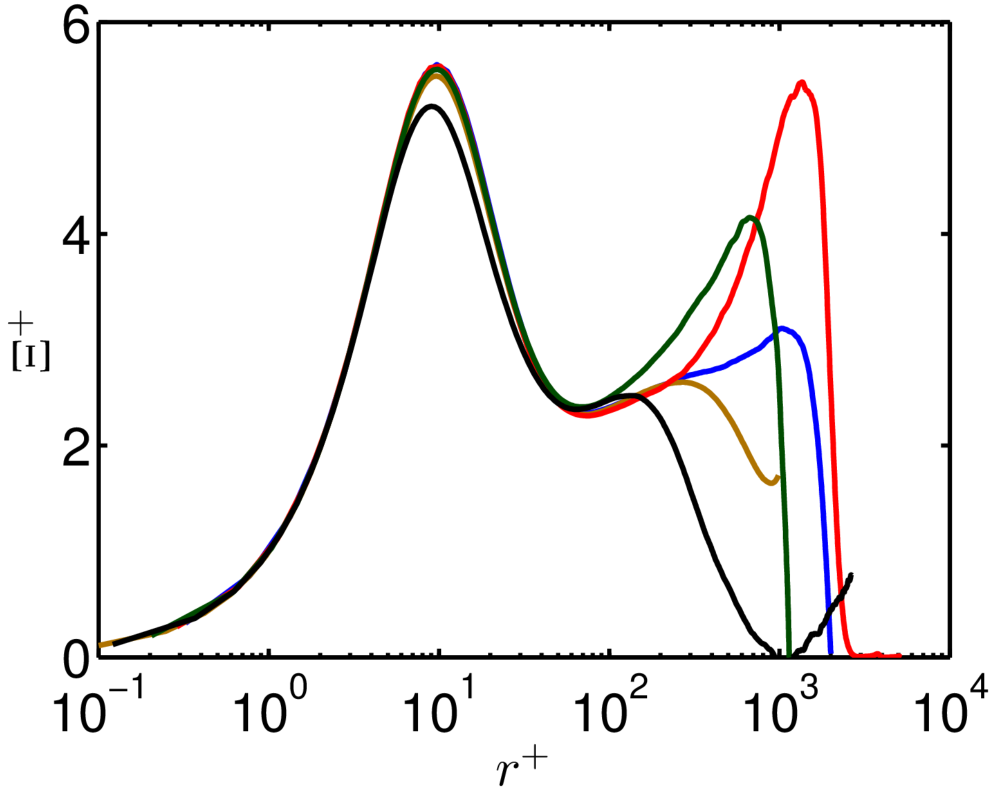
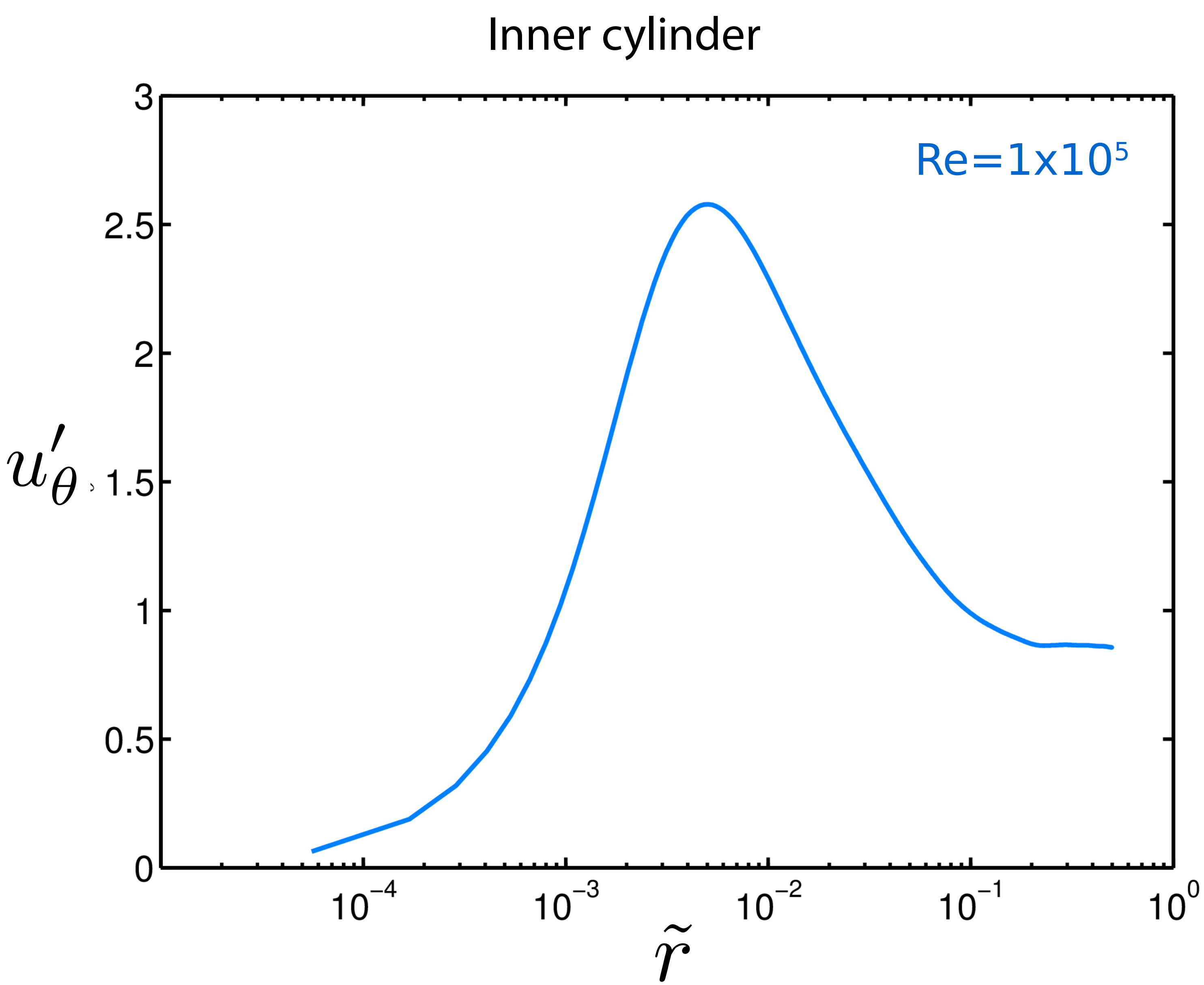


$$\Xi^+ = r^+ \frac{dU^+}{dr^+}$$

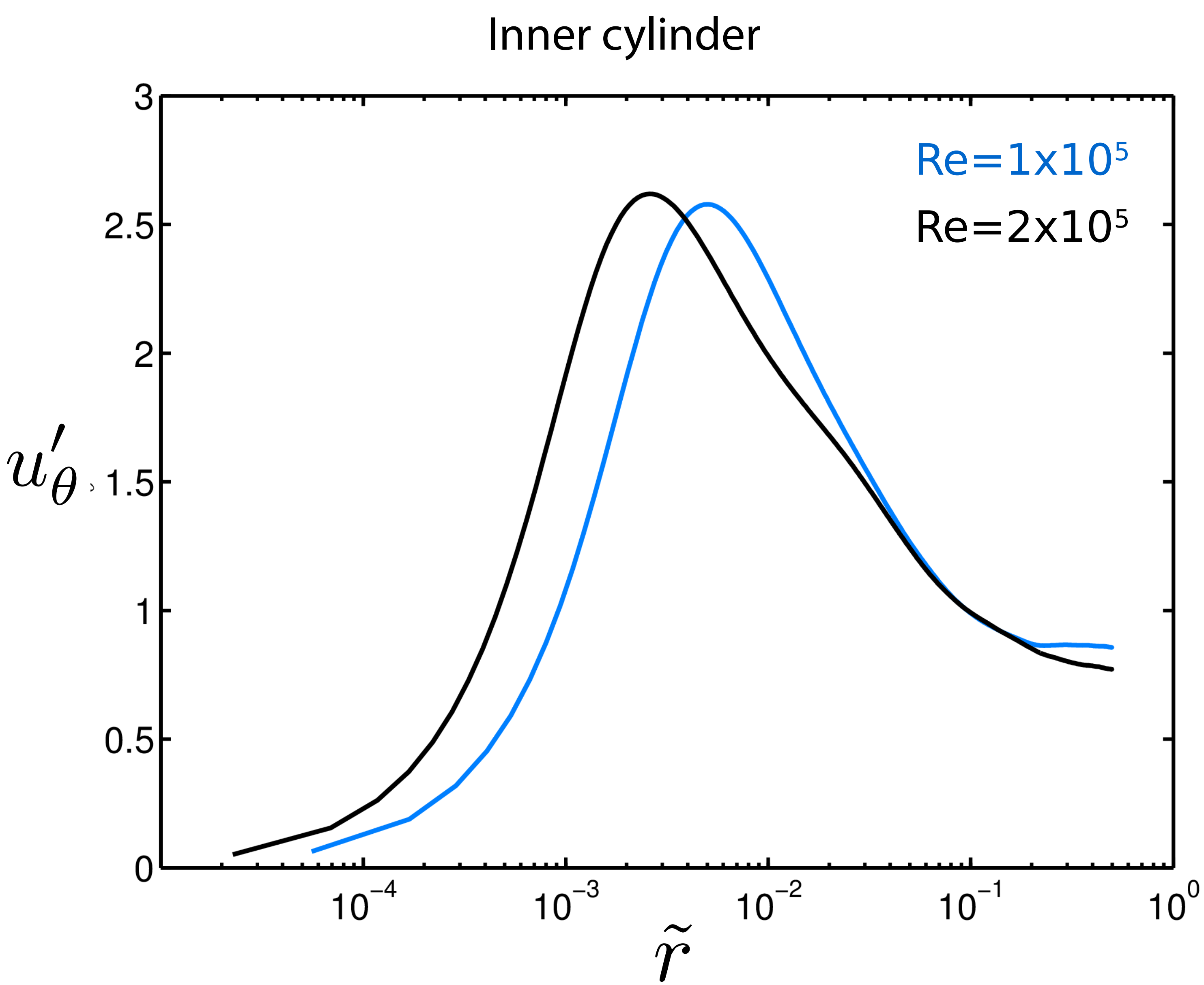


Is this "log-layer" behaviour apparent in other statistics of TC flow?

Overlap layers appear for the fluctuations



Overlap layers appear for the fluctuations



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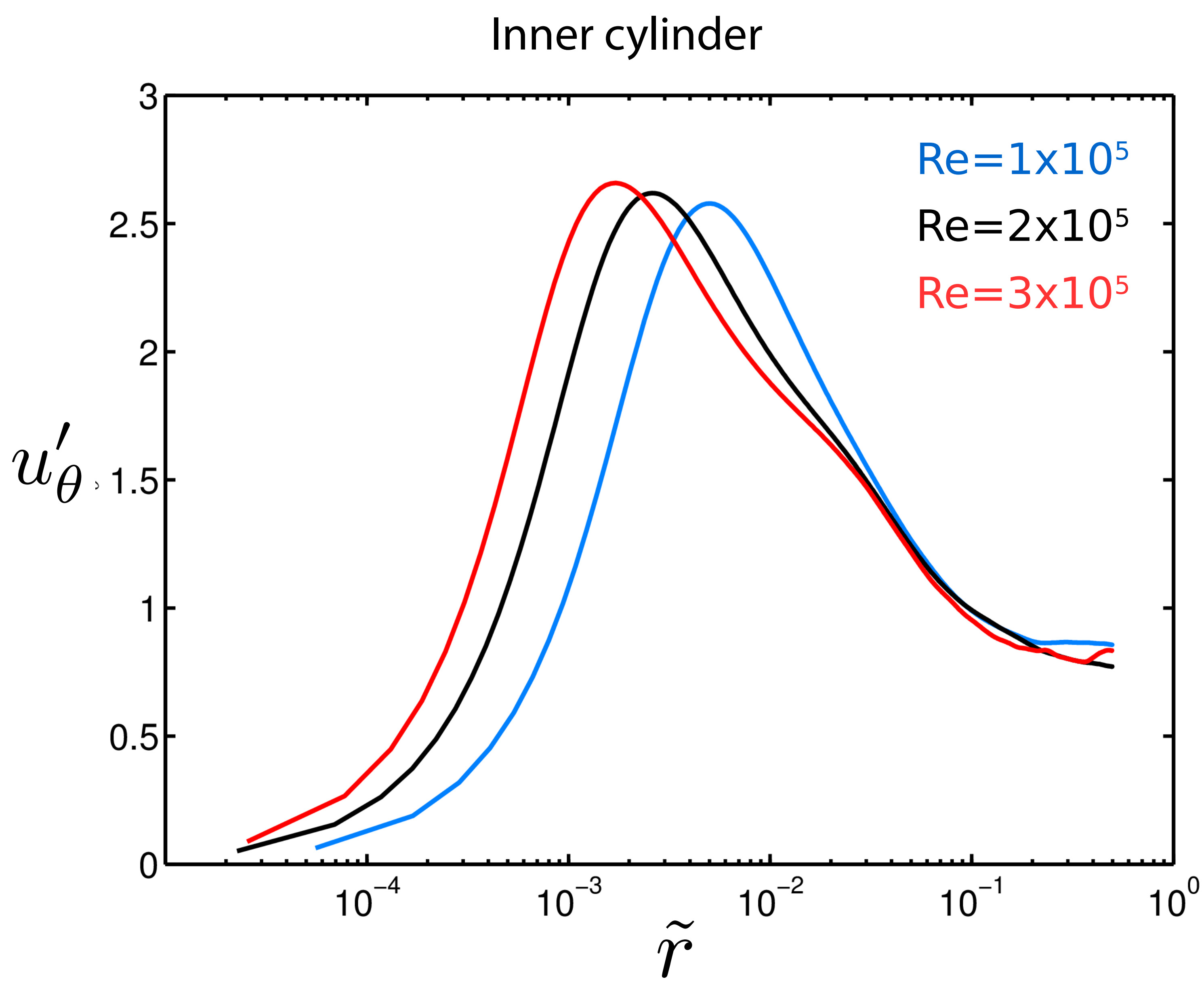
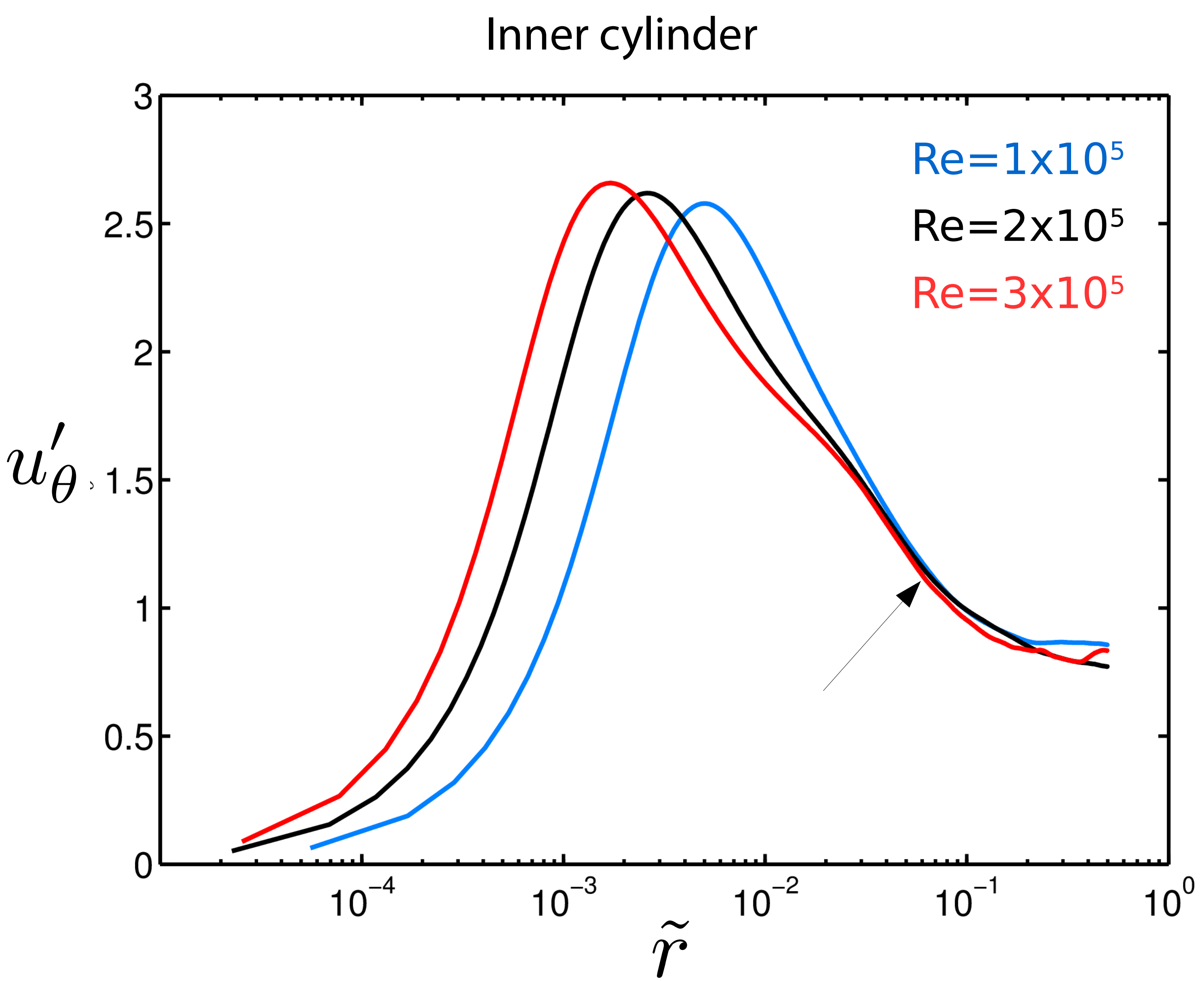
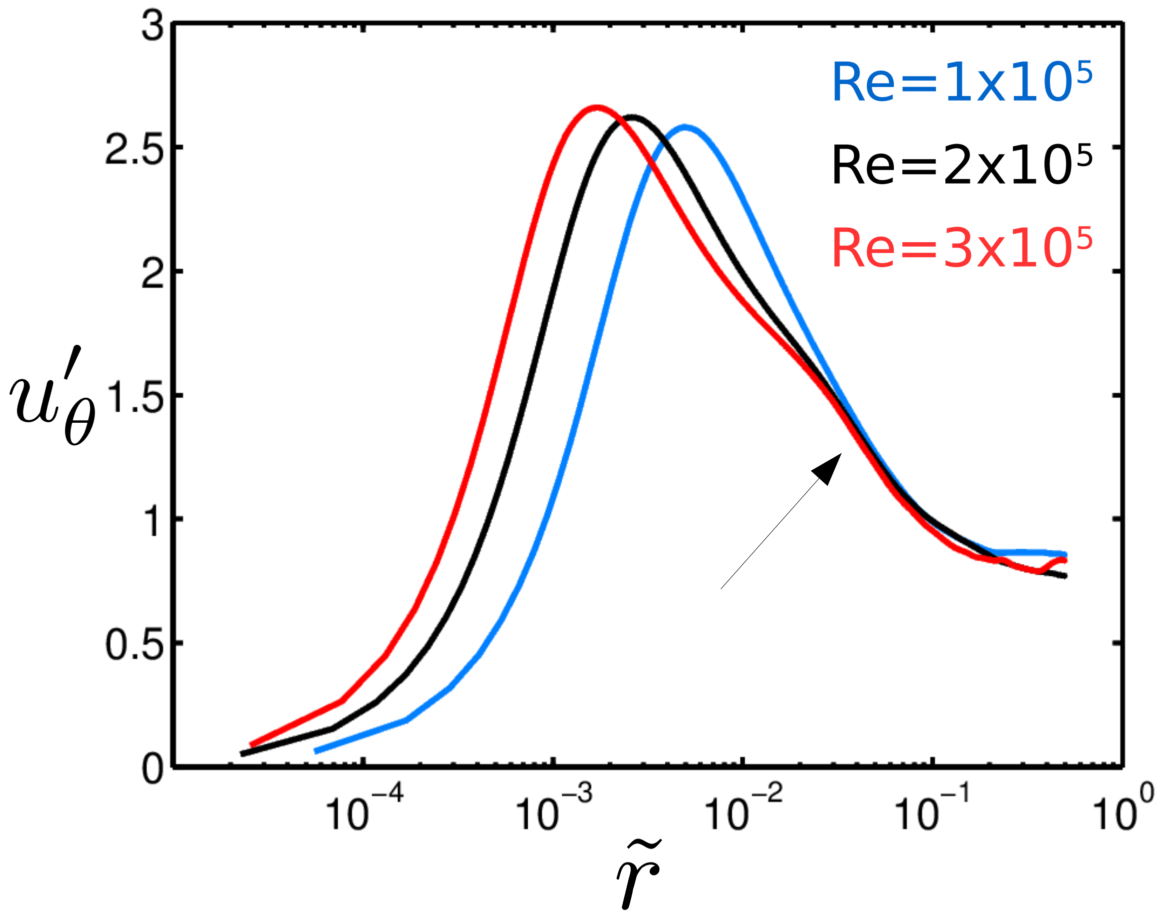


Overlap layers appear for the fluctuations

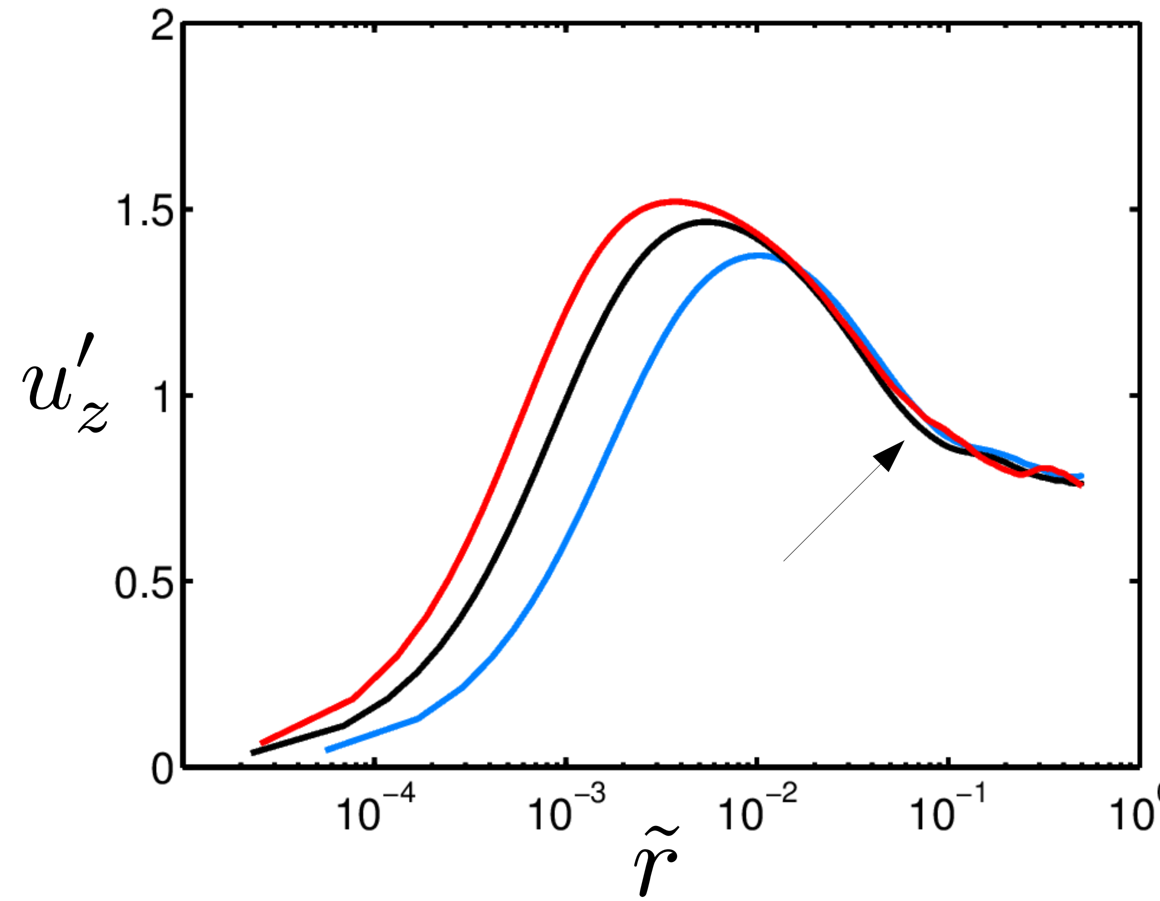


Overlap layer in velocity fluctuations

Streamwise (azimuthal) velocity fluctuations



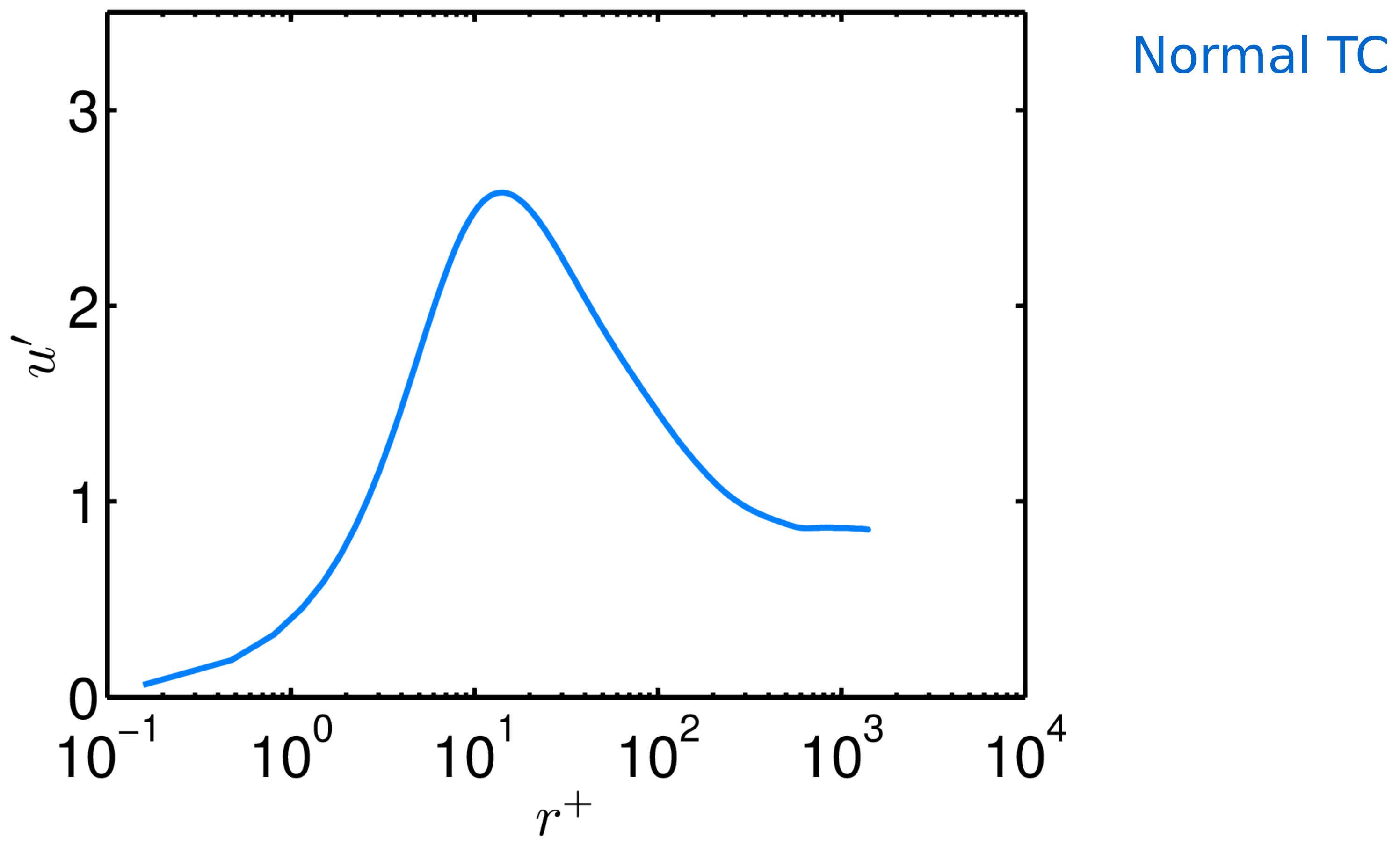
Spanwise (axial) velocity fluctuations



Re_τ is too small to see overlap in u'_r

Is this the full story?

Streamwise velocity fluctuations for $Re_\tau = 1000$



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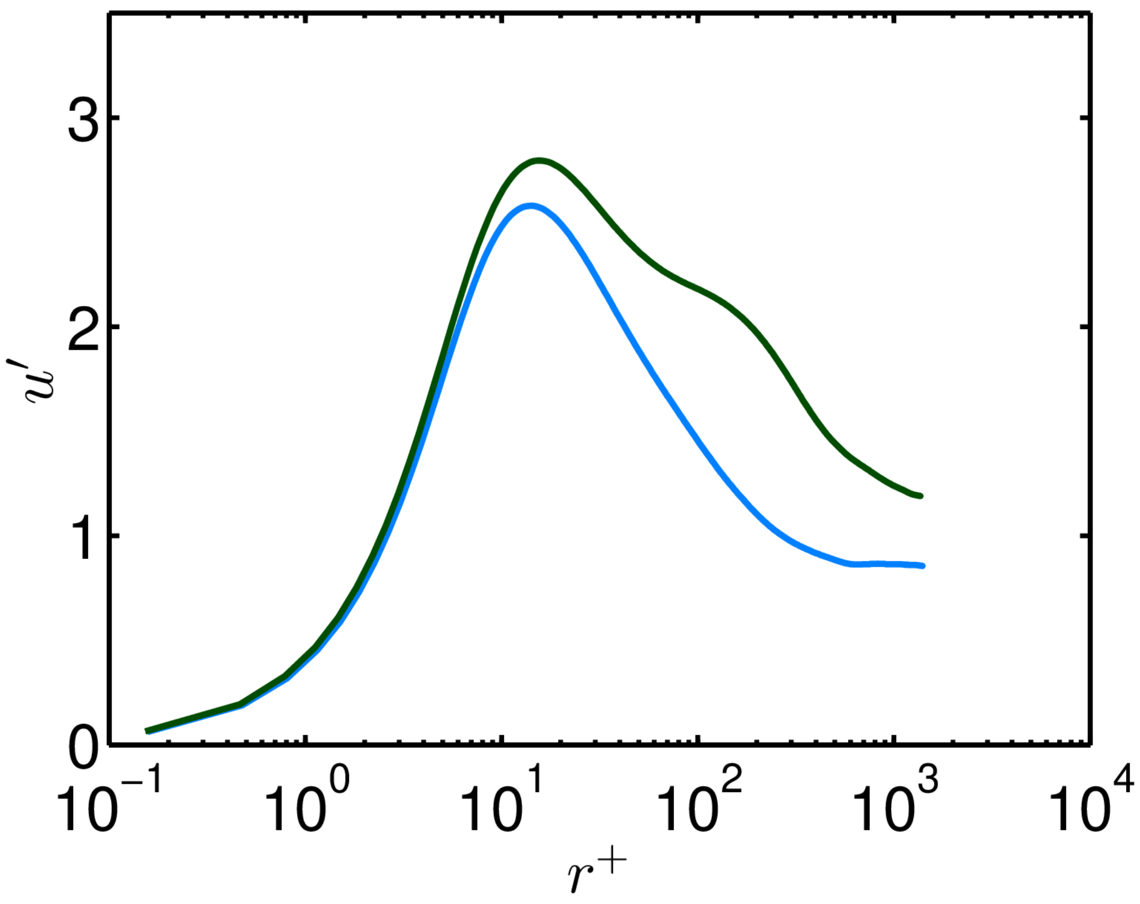
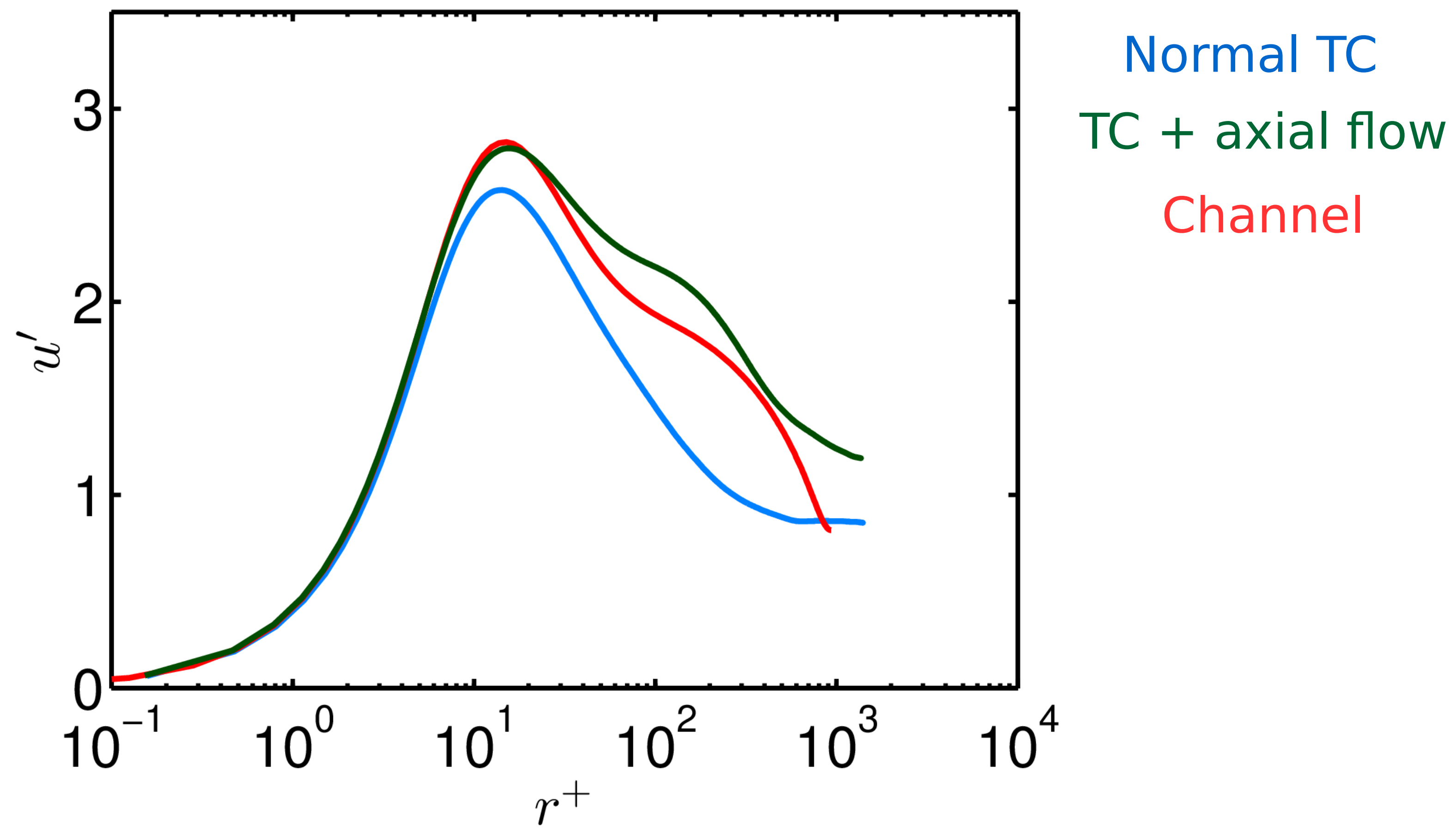


Normal TC

TC + axial flow

Is this the full story?

Streamwise velocity fluctuations for $Re_\tau = 1000$



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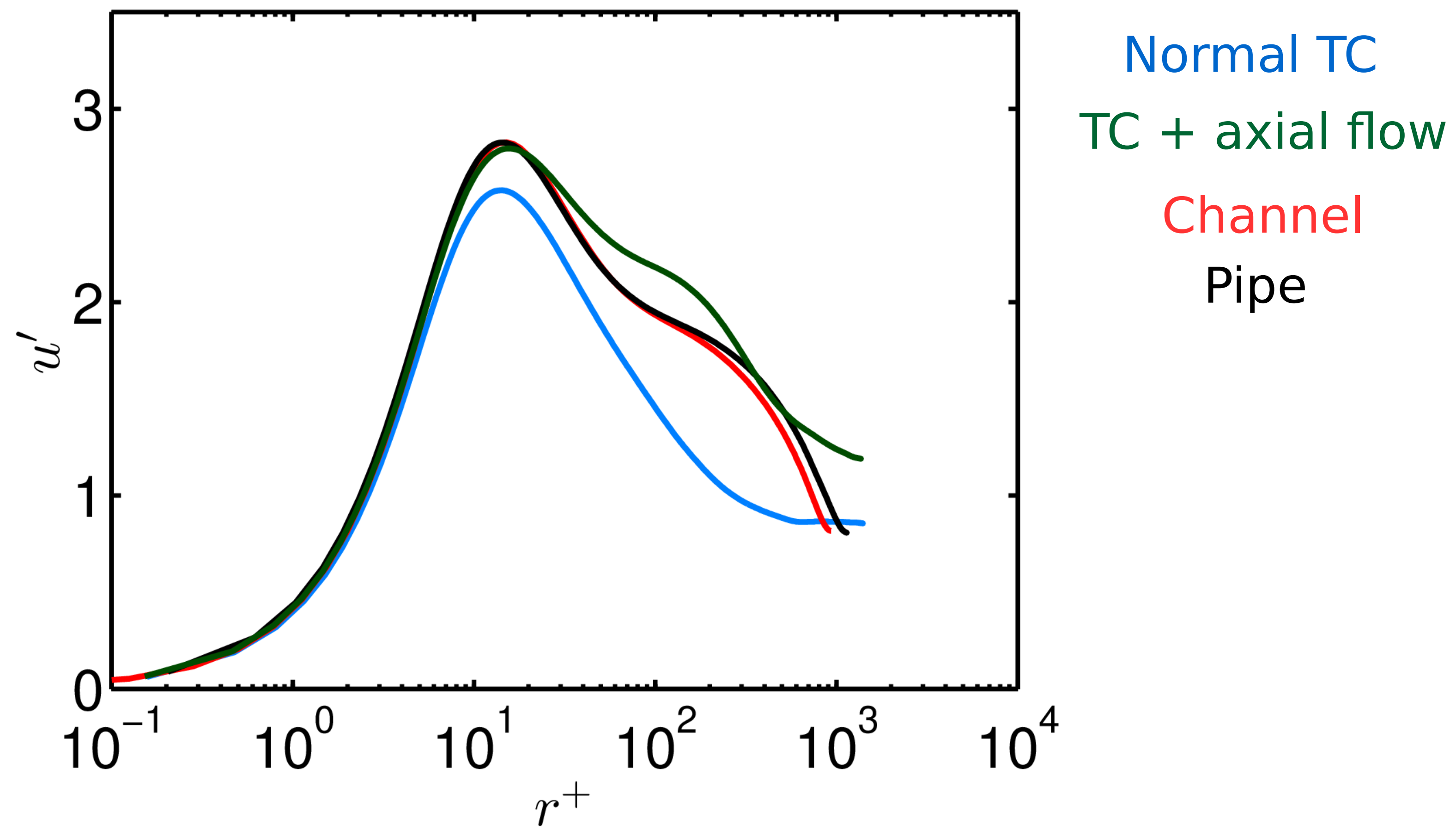

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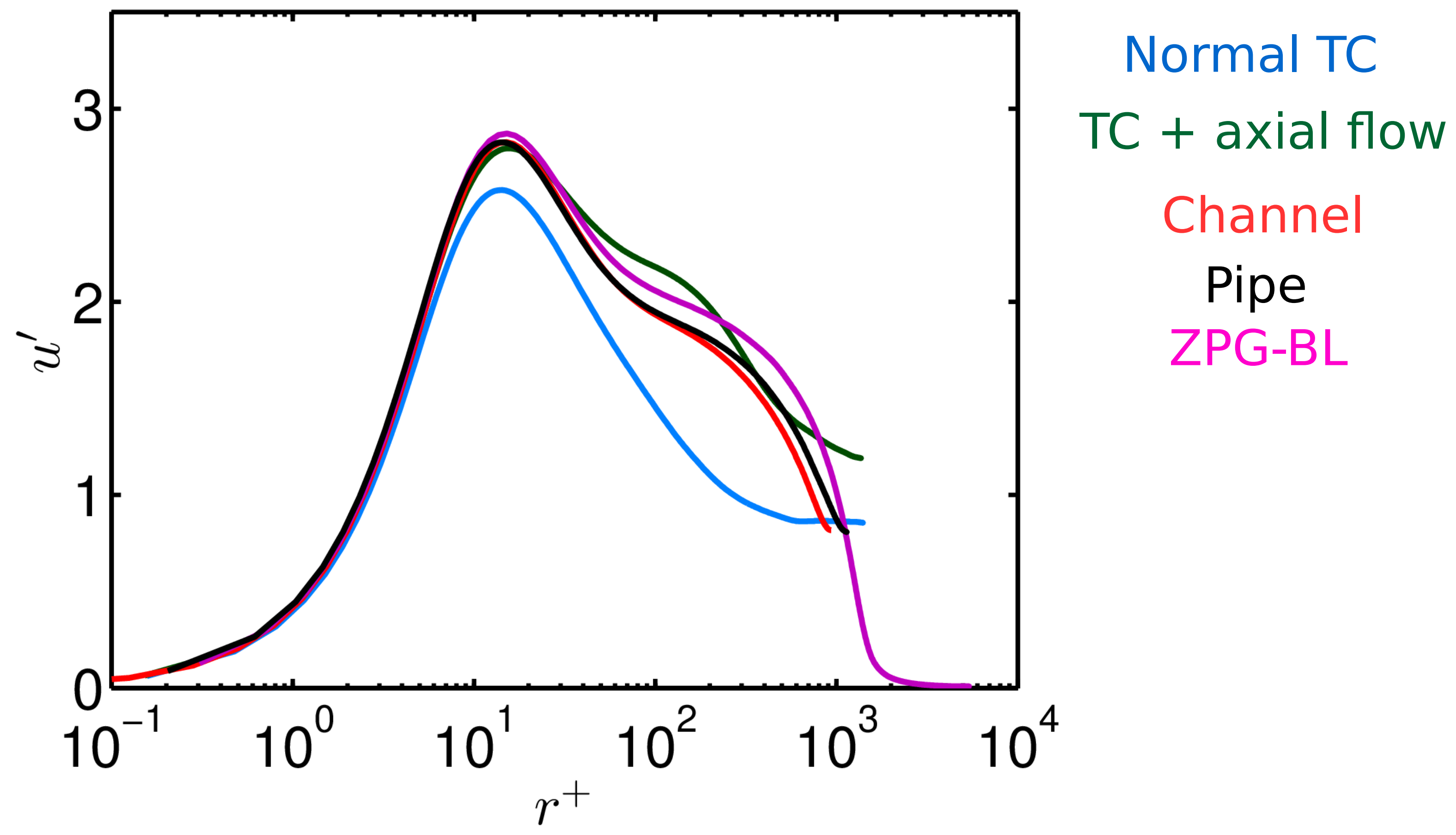

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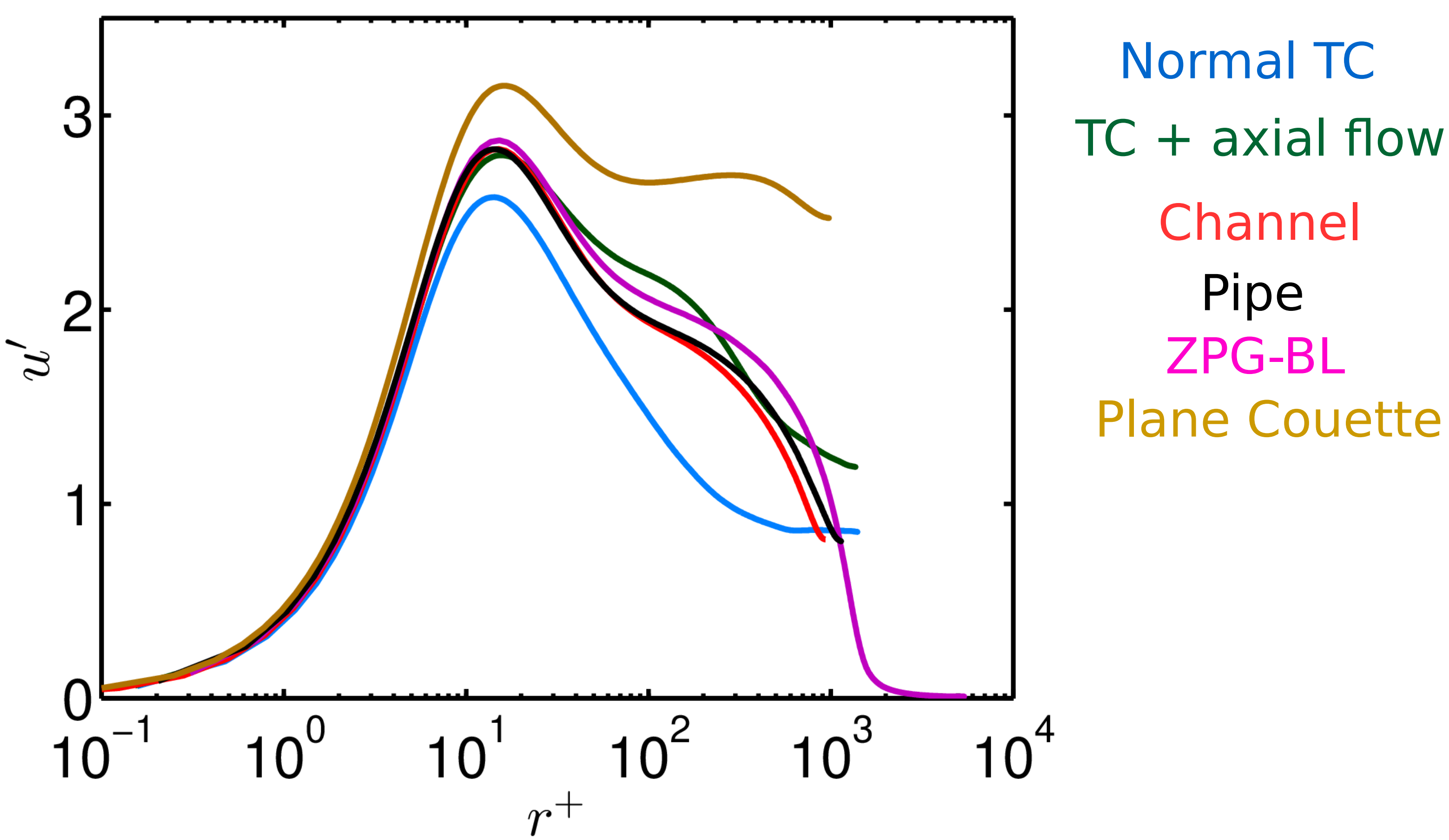

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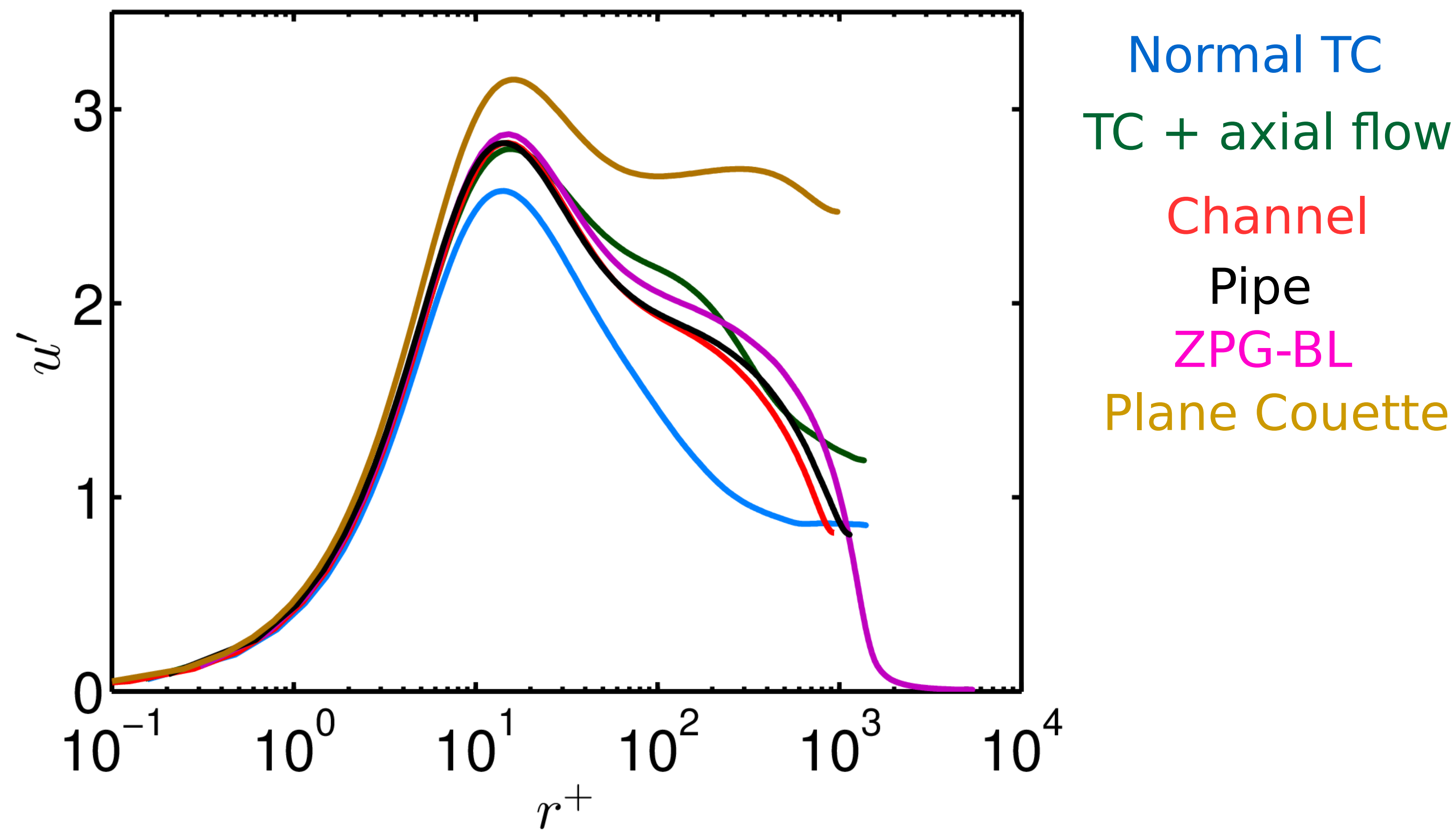
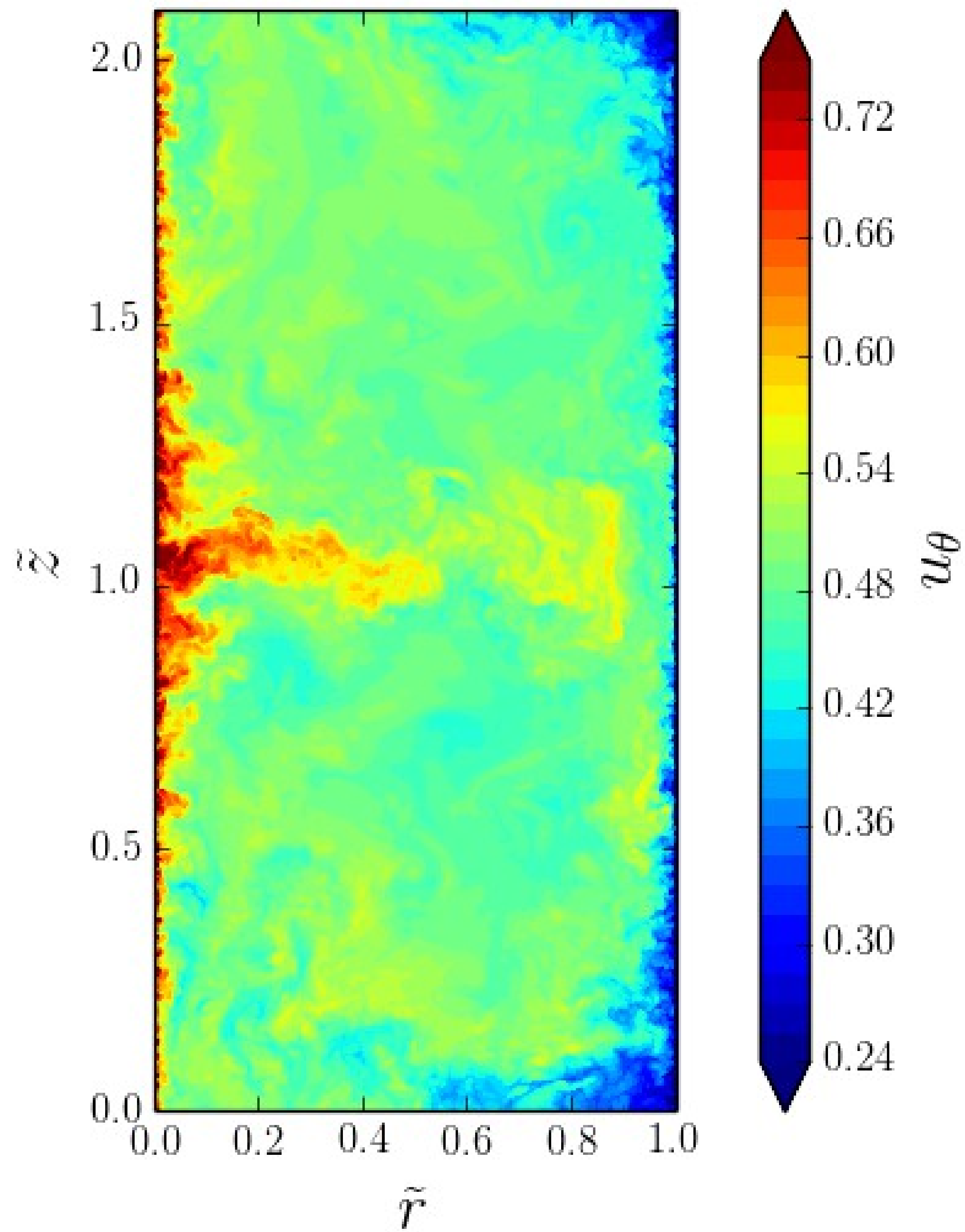
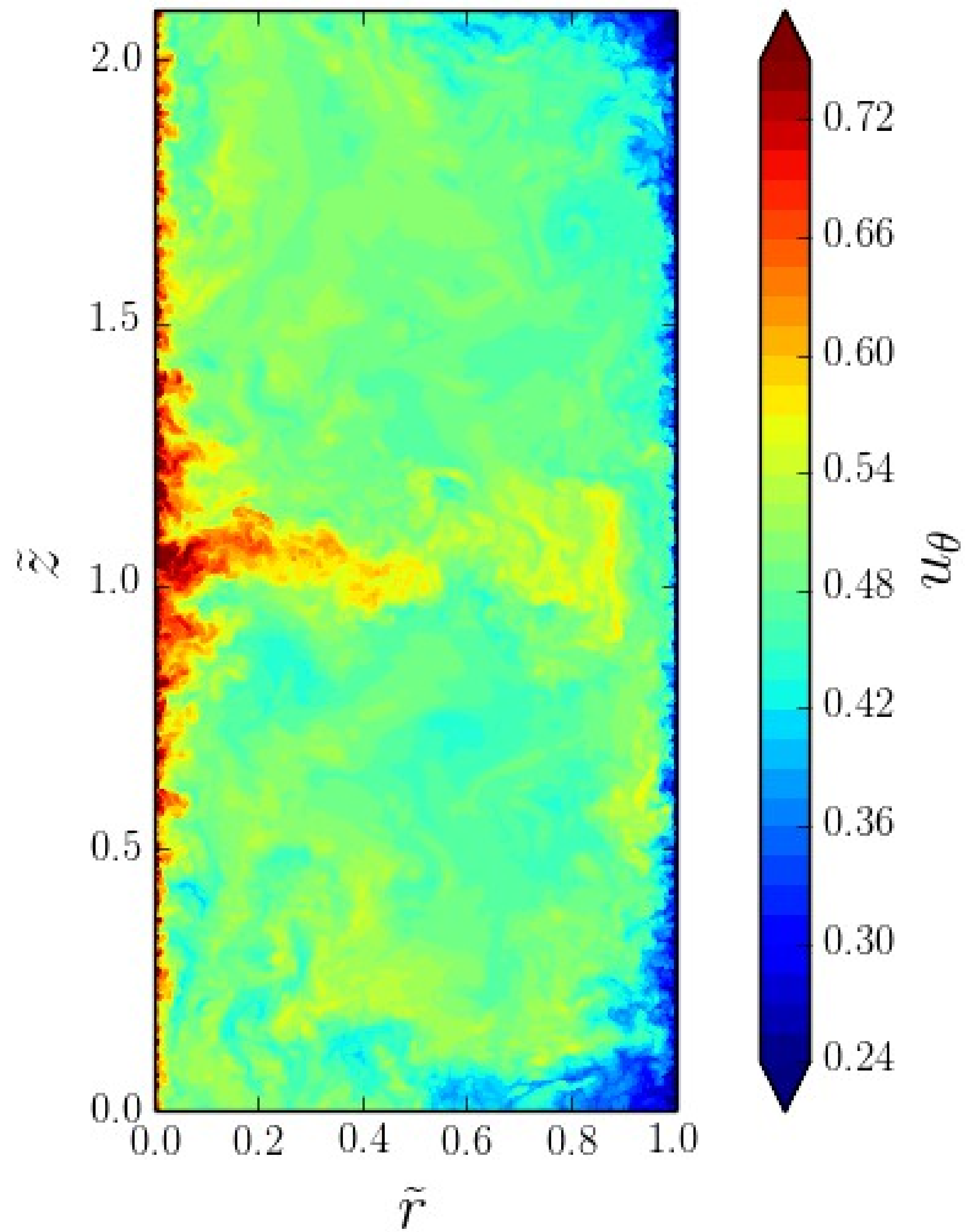


Velocity fluctuations are much smaller in TC

“Frozen” rolls reduce the fluctuations



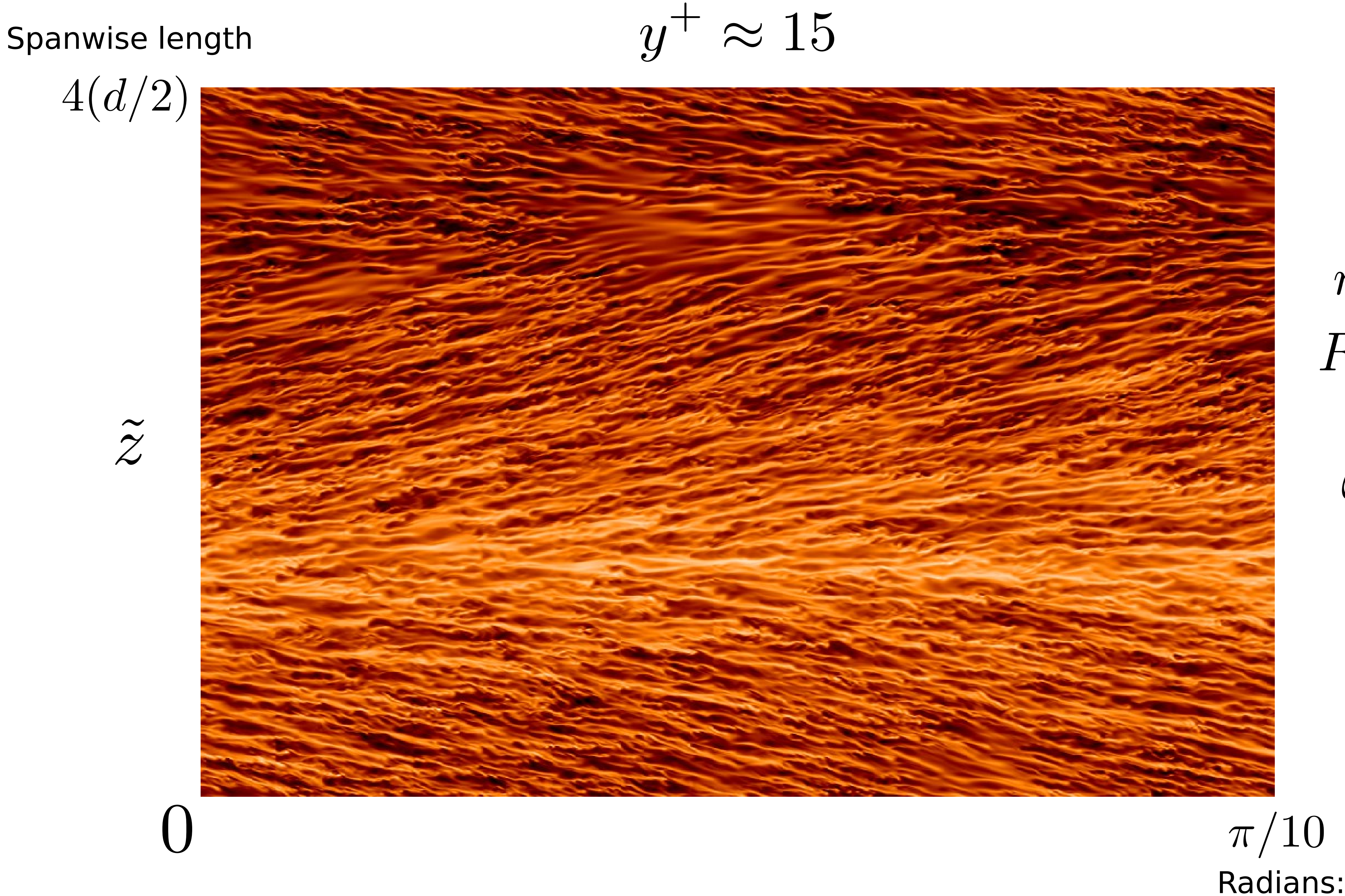
"Frozen" rolls reduce the fluctuations



$4(d/2)$

The rolls affect the boundary layers

$y^+ \approx 15$



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$Re_s = 10^5$

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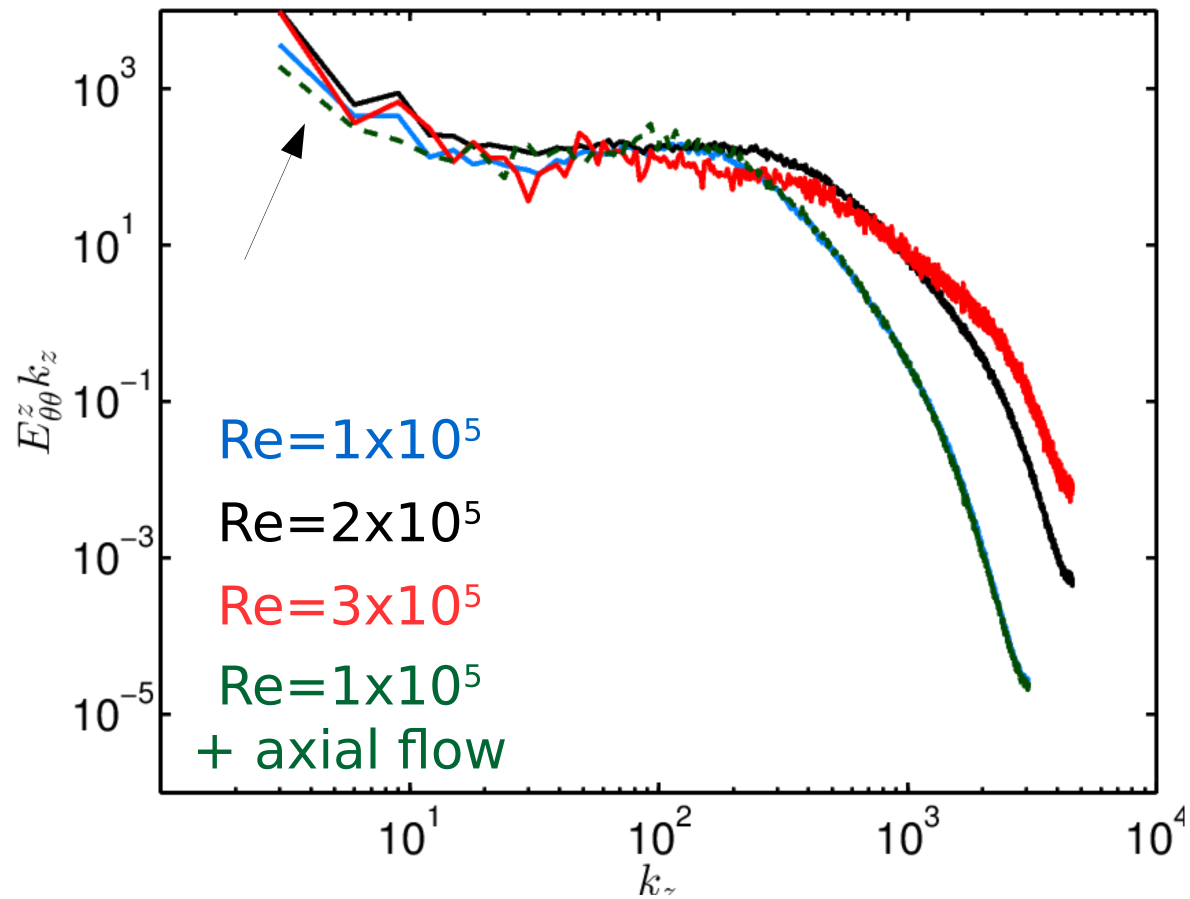
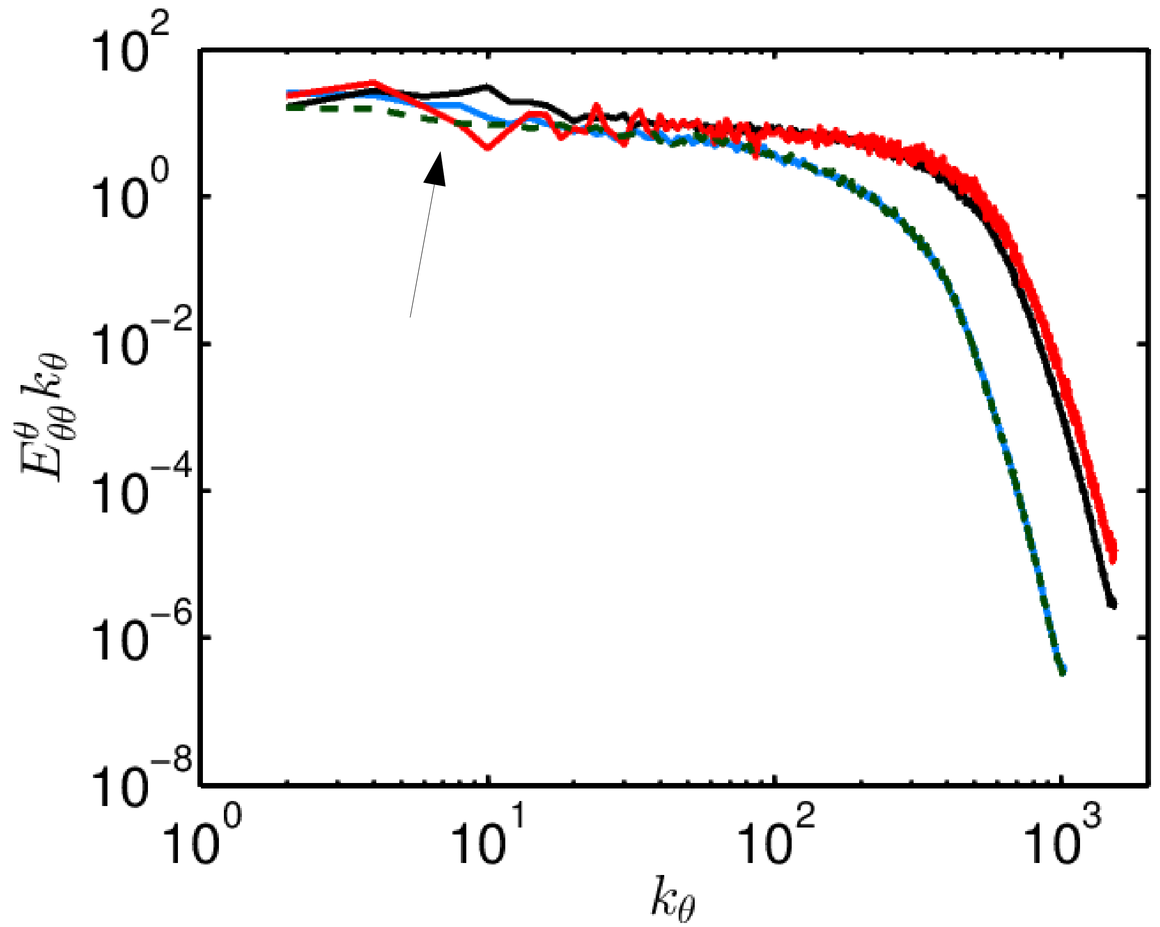
$\omega_o = 0$

Look at the azimuthal velocity spectra

Premultiplied azimuthal spectra at $y^+ \approx 15$



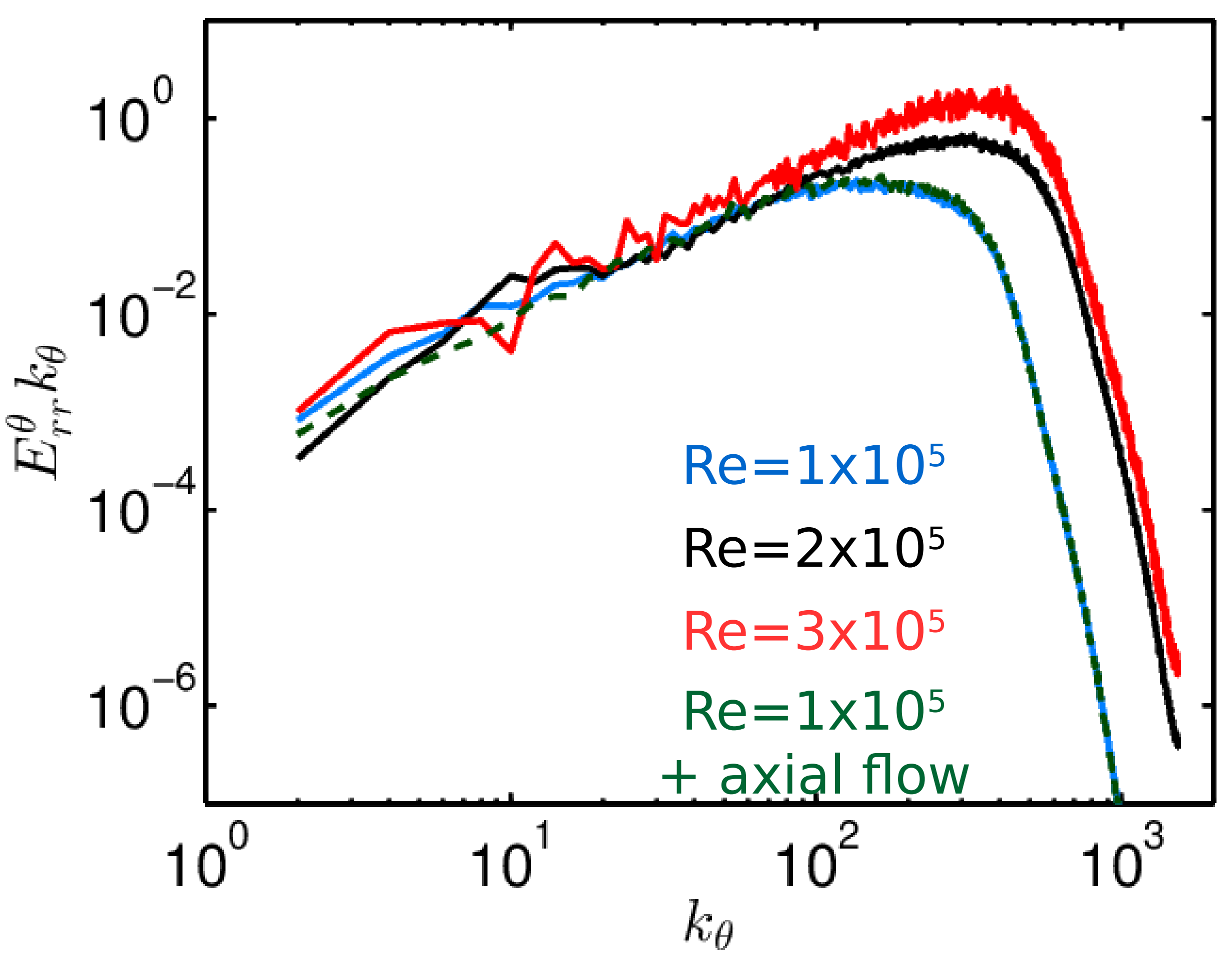
Premultiplied axial spectra at $y^+ \approx 15$



Large-scale rolls are **attached** to the wall

What about the radial velocity?

Premultiplied azimuthal spectra at $y^+ \approx 15$



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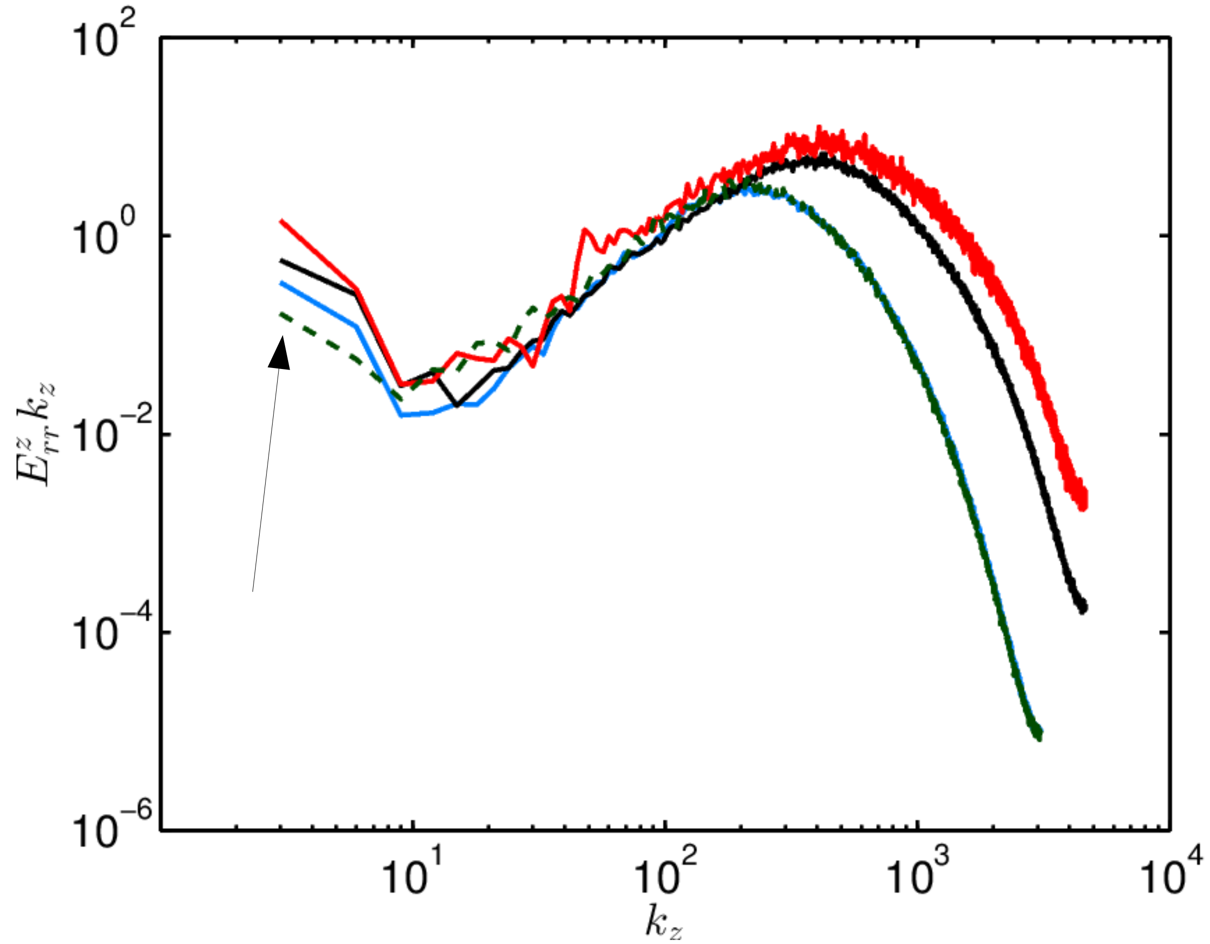
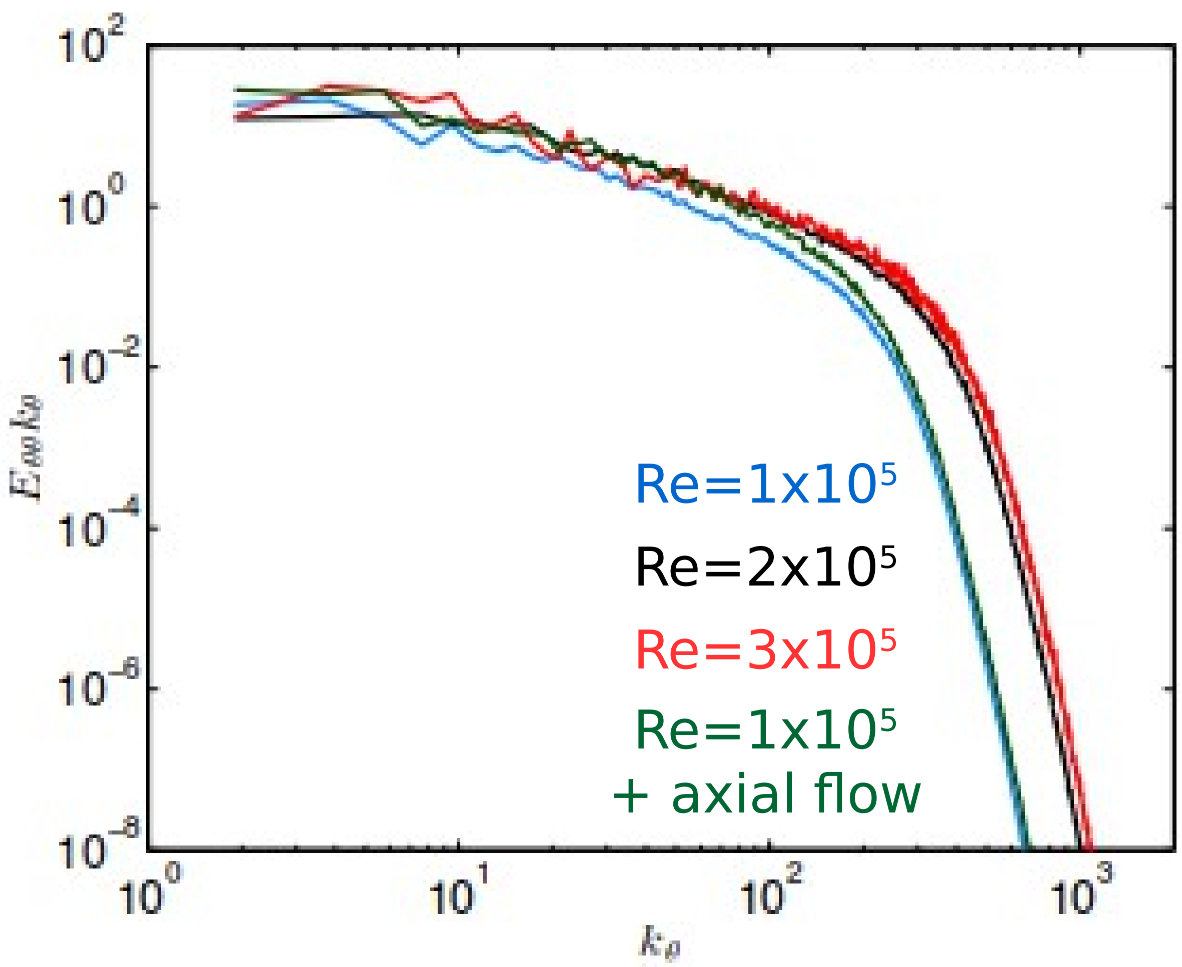


Rolls are **active**, they transport angular velocity near the wall

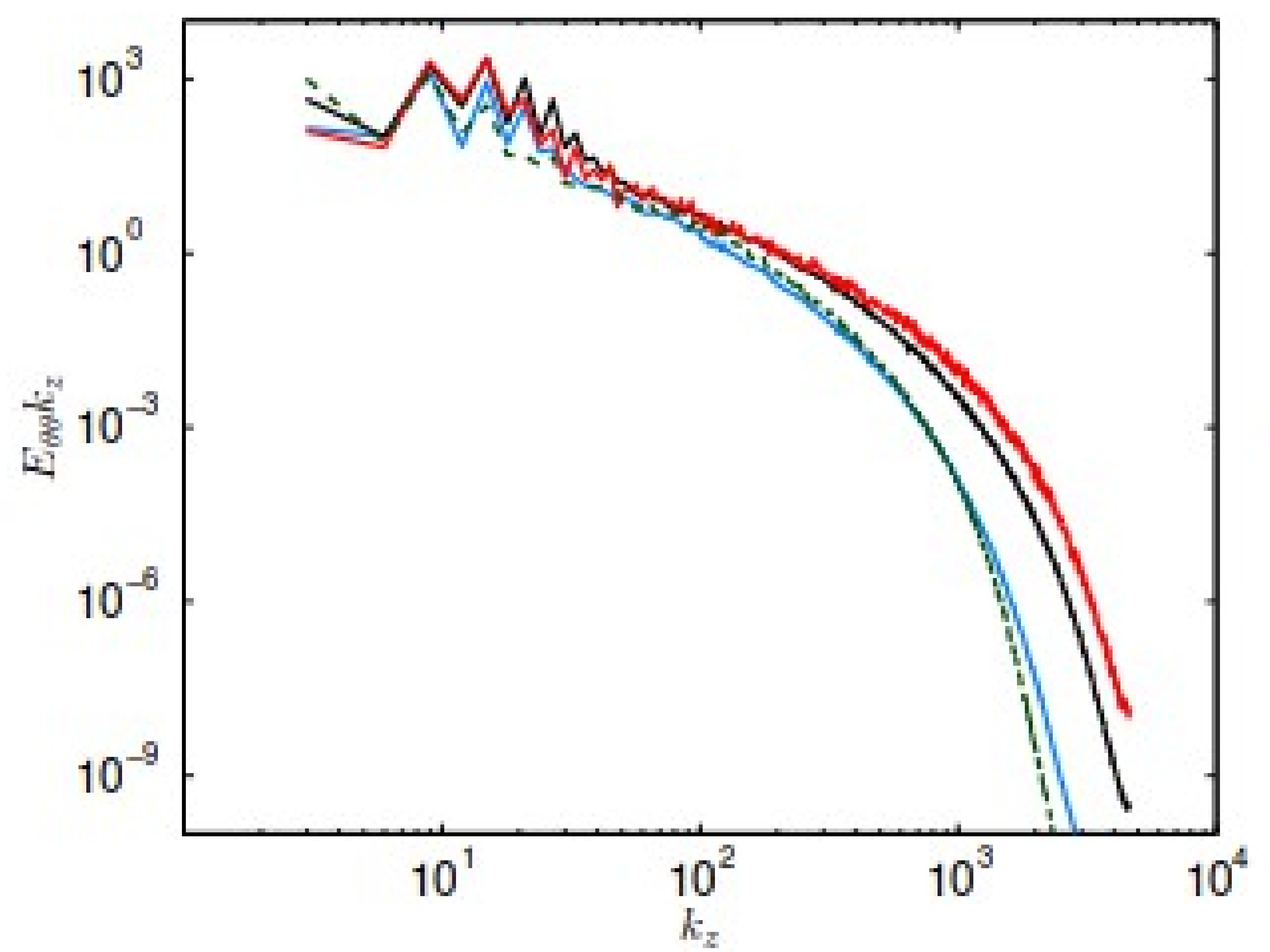
There is a **maxima** in the cospectra for axisymmetric rolls inside the BL

The spectra are similar at the mid-gap

Premultiplied azimuthal spectra



Premultiplied axial spectra

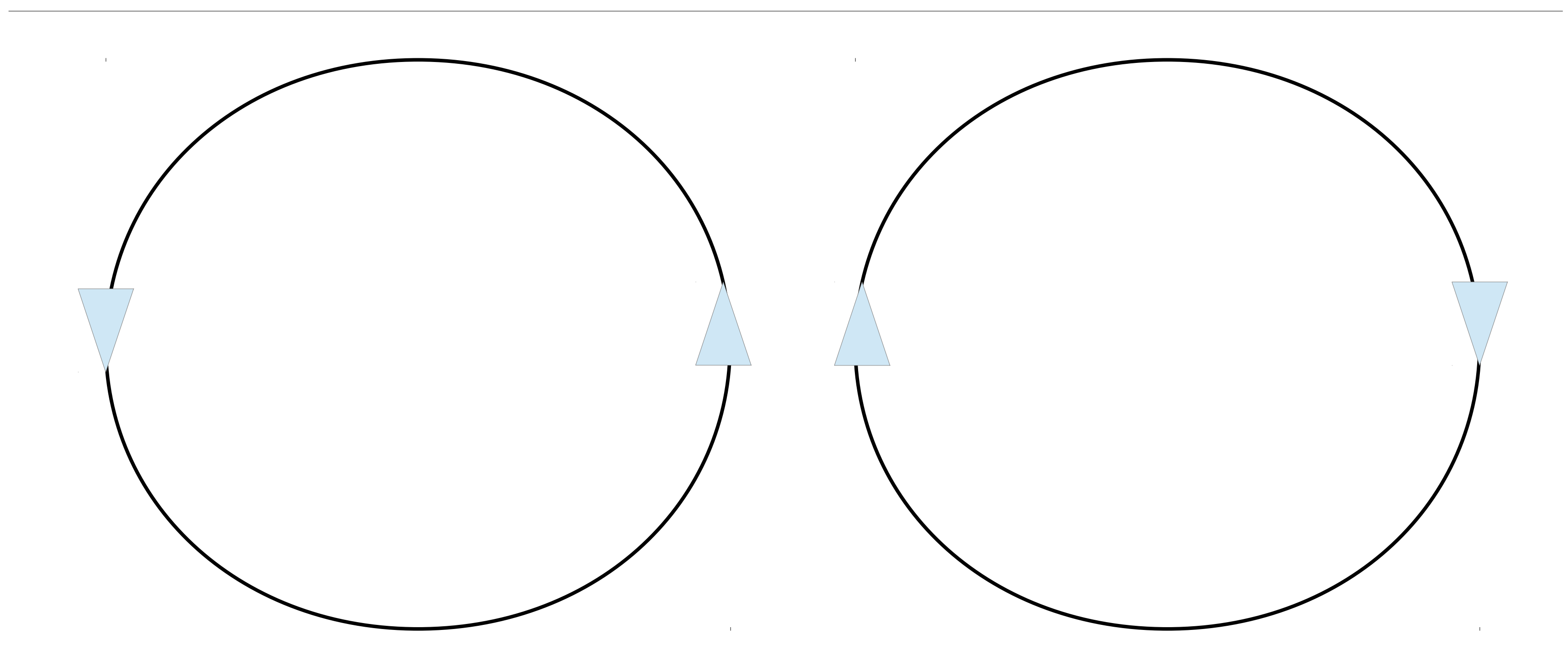


Clear lack of -5/3 energy spectra, without applying Taylor's hypothesis

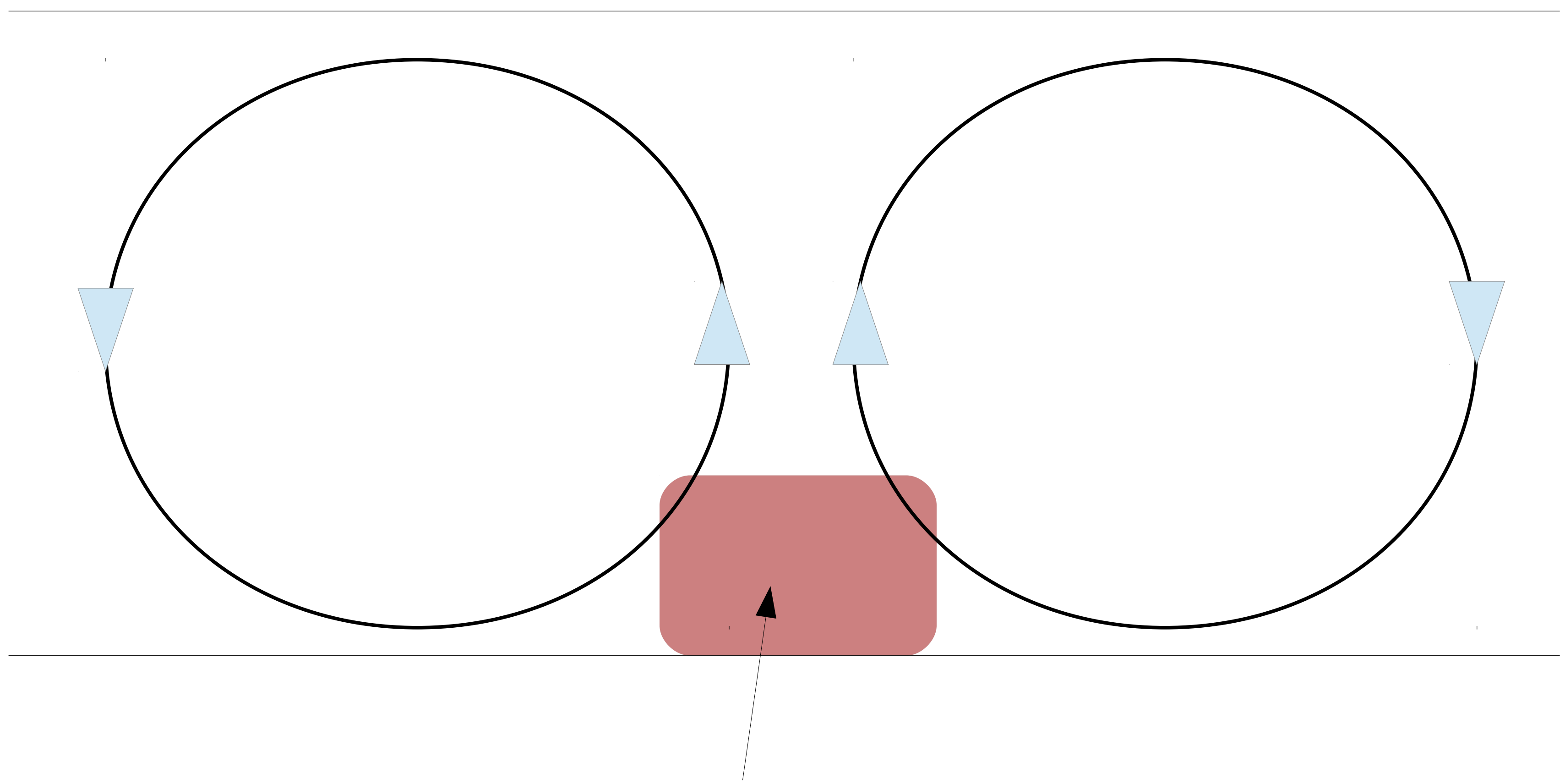
Sawtooth spectra indicates preferential wavelengths

Go back to the drawing board...

Large-scales modulate azimuthal velocity

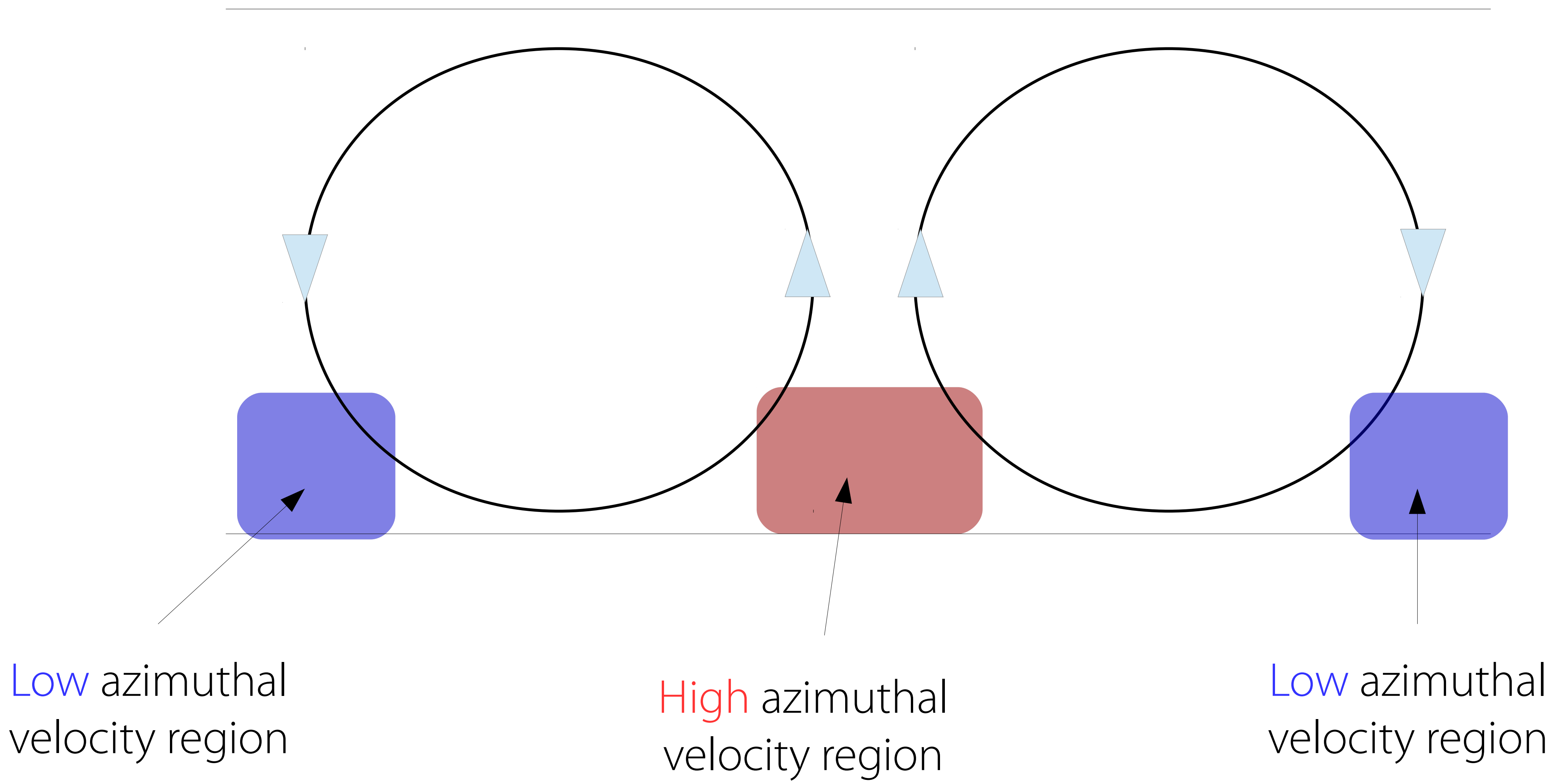


Large-scales modulate azimuthal velocity

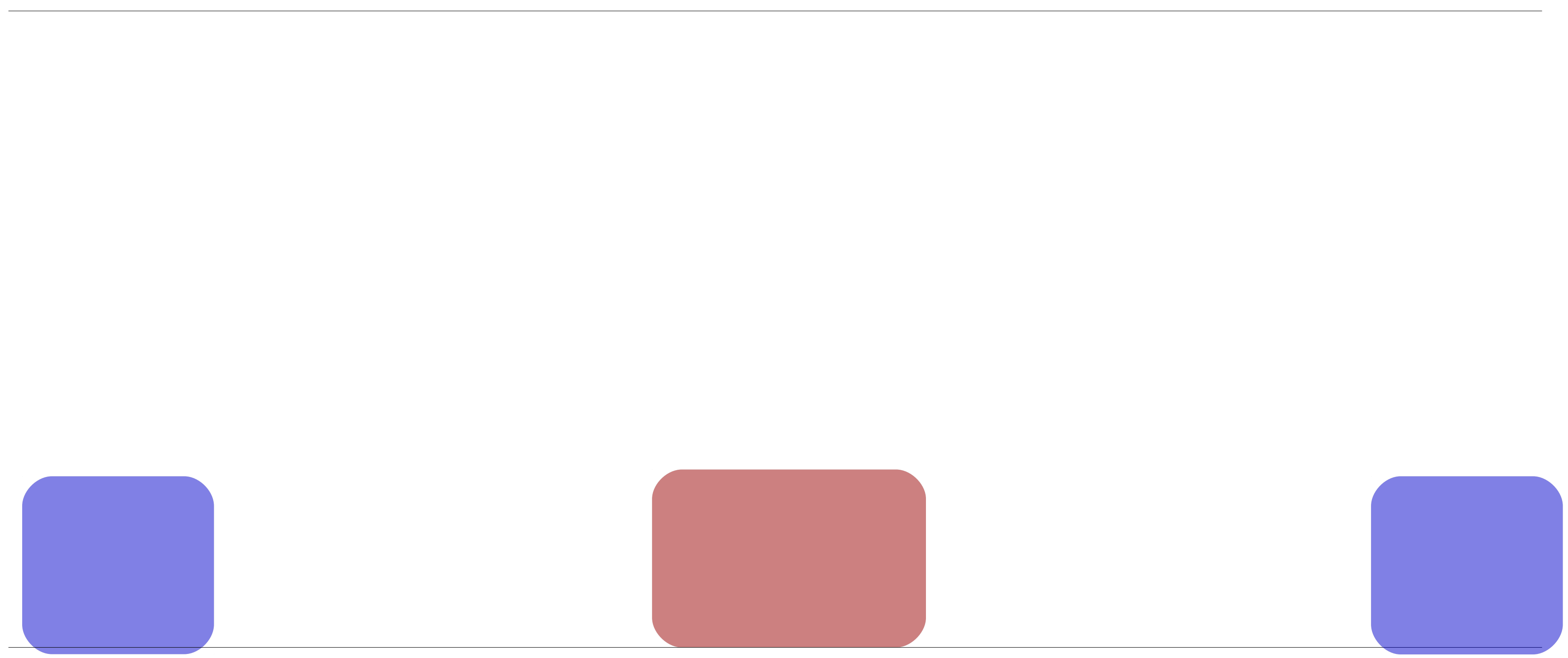


High azimuthal velocity region

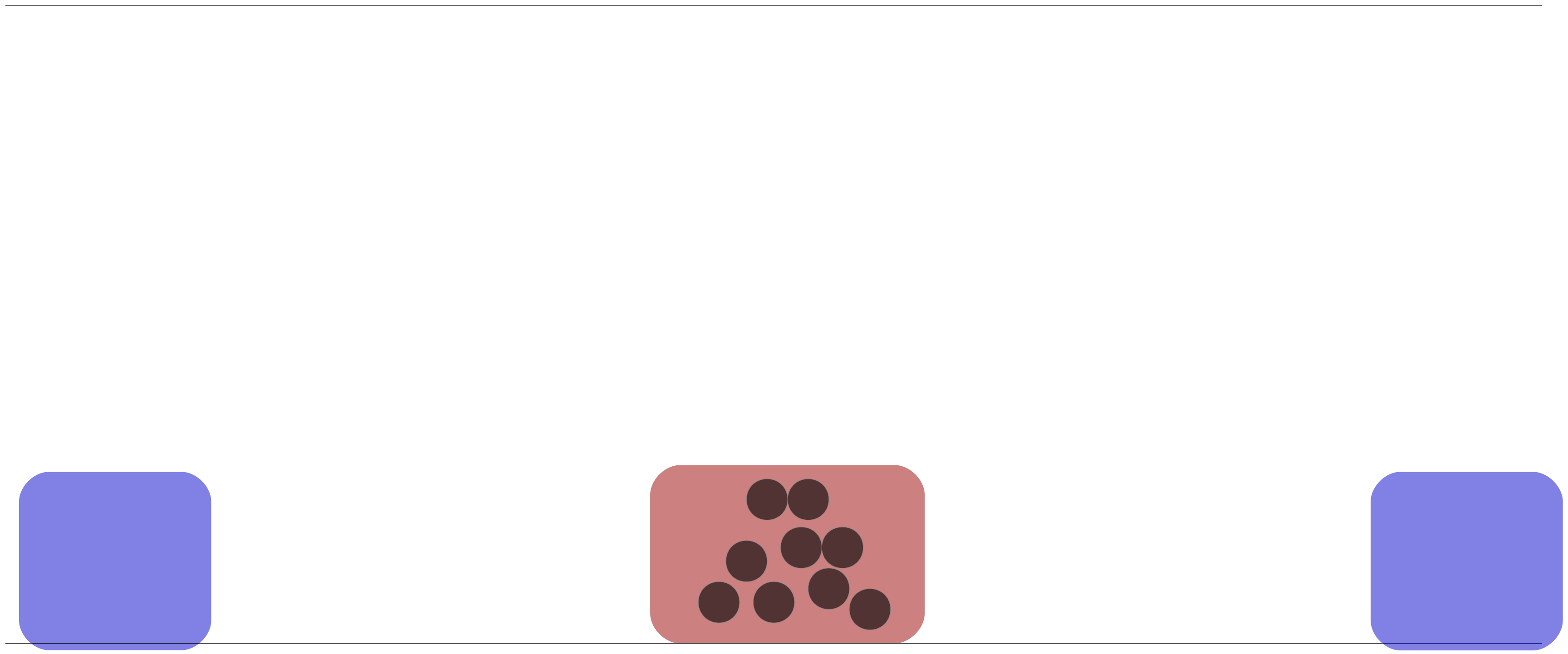
Large-scales modulate azimuthal velocity



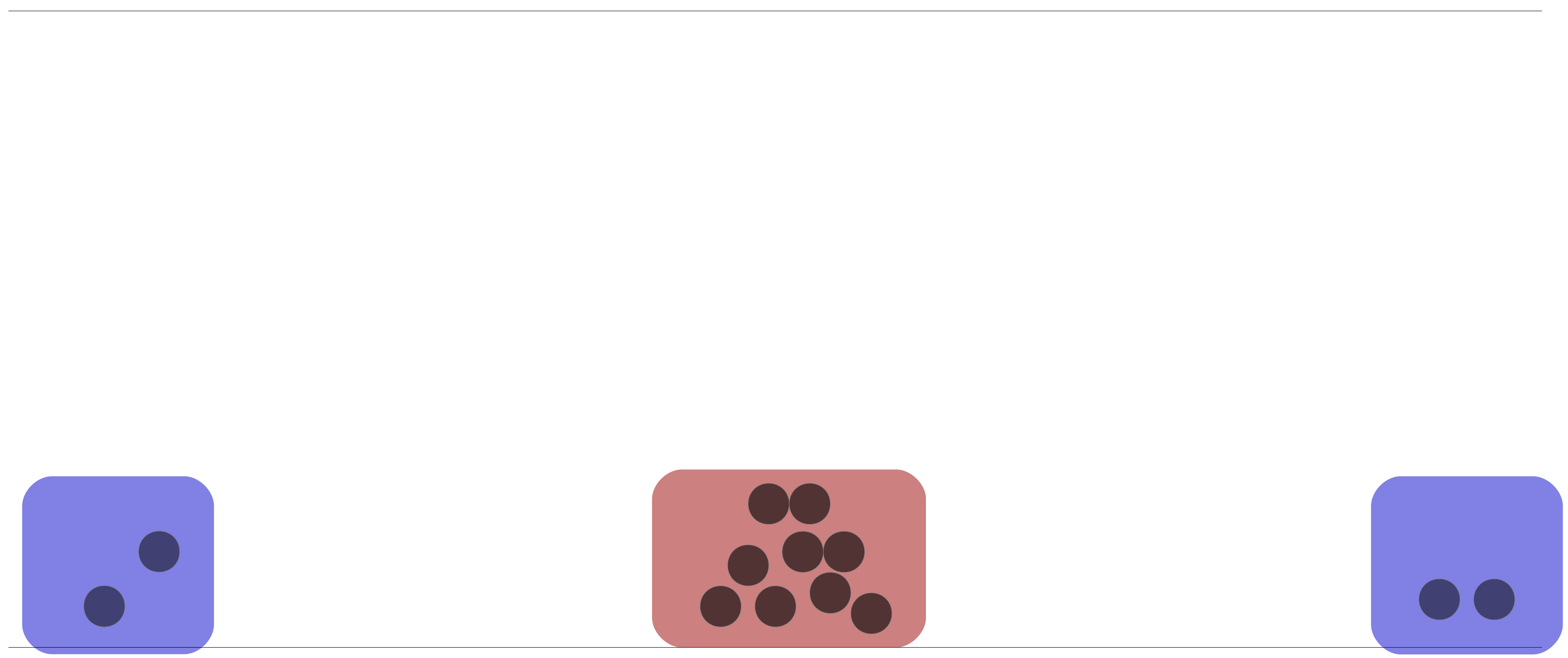
Hairpins generated at certain places



Hairpins generated at certain places



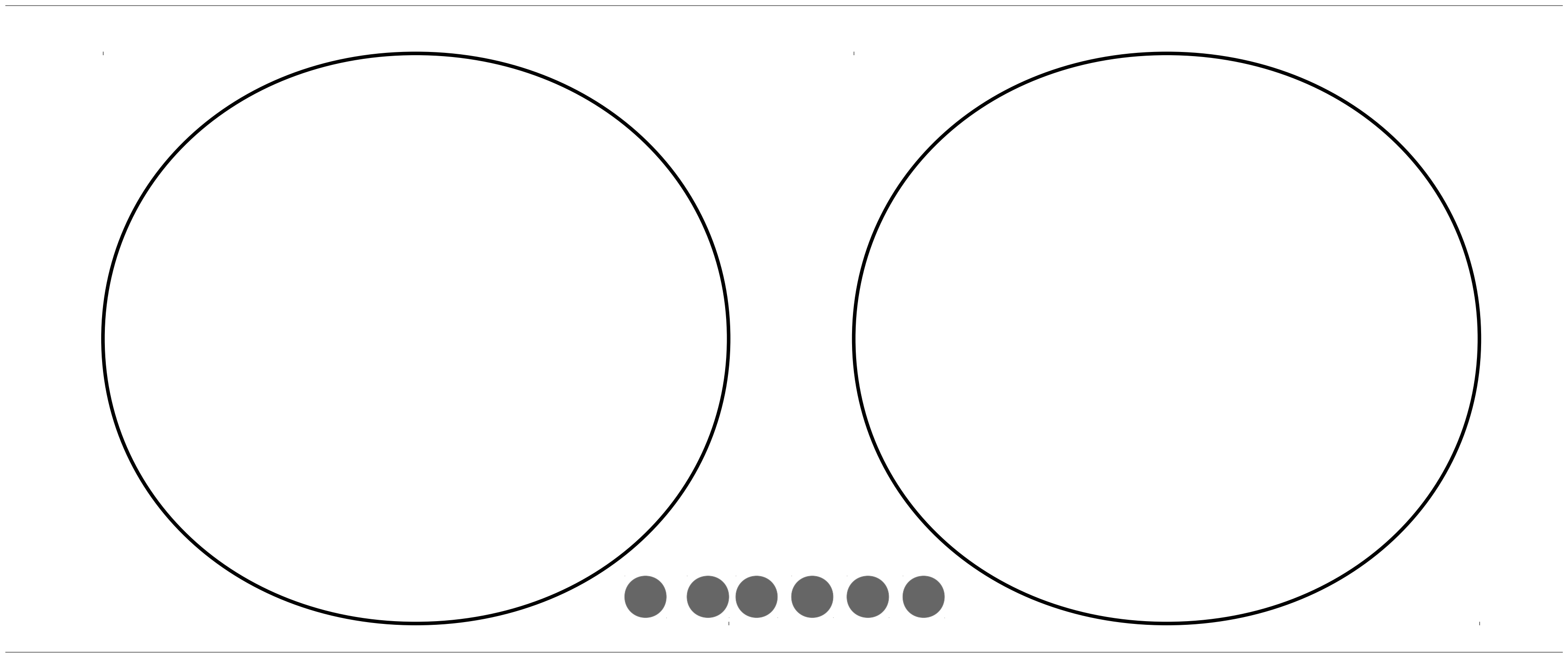
Hairpins generated at certain places



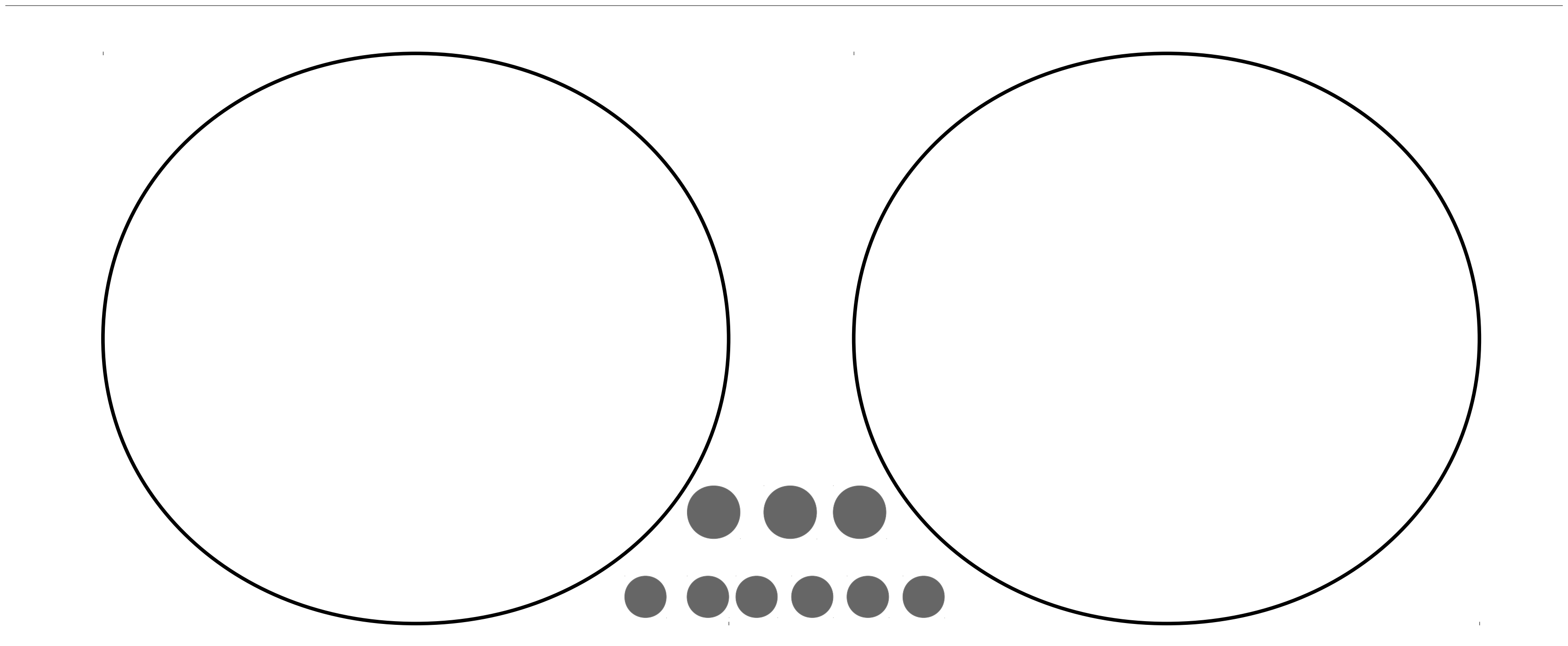
Hairpins transport angular velocity – high u_r & high u_θ

Axially ordered – they cause the maxima in the cospectra

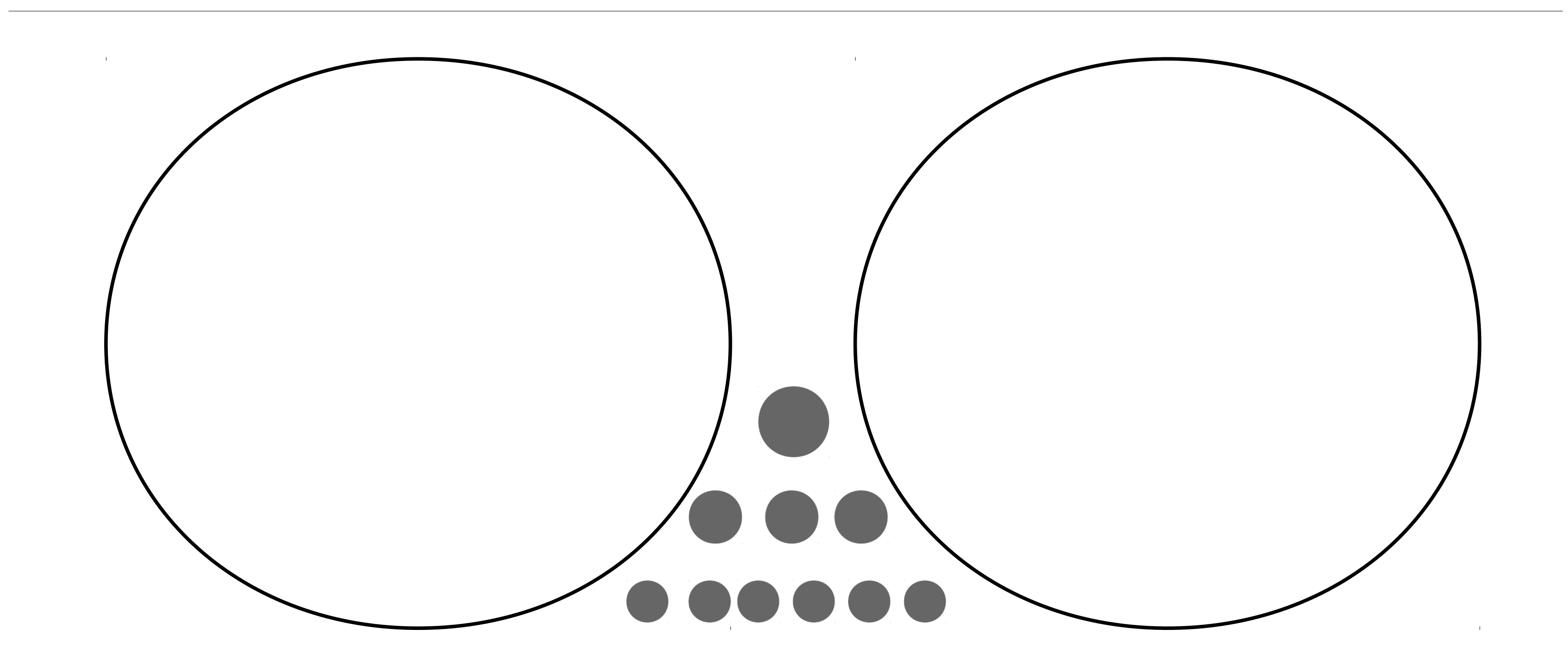
Hairpins merge...



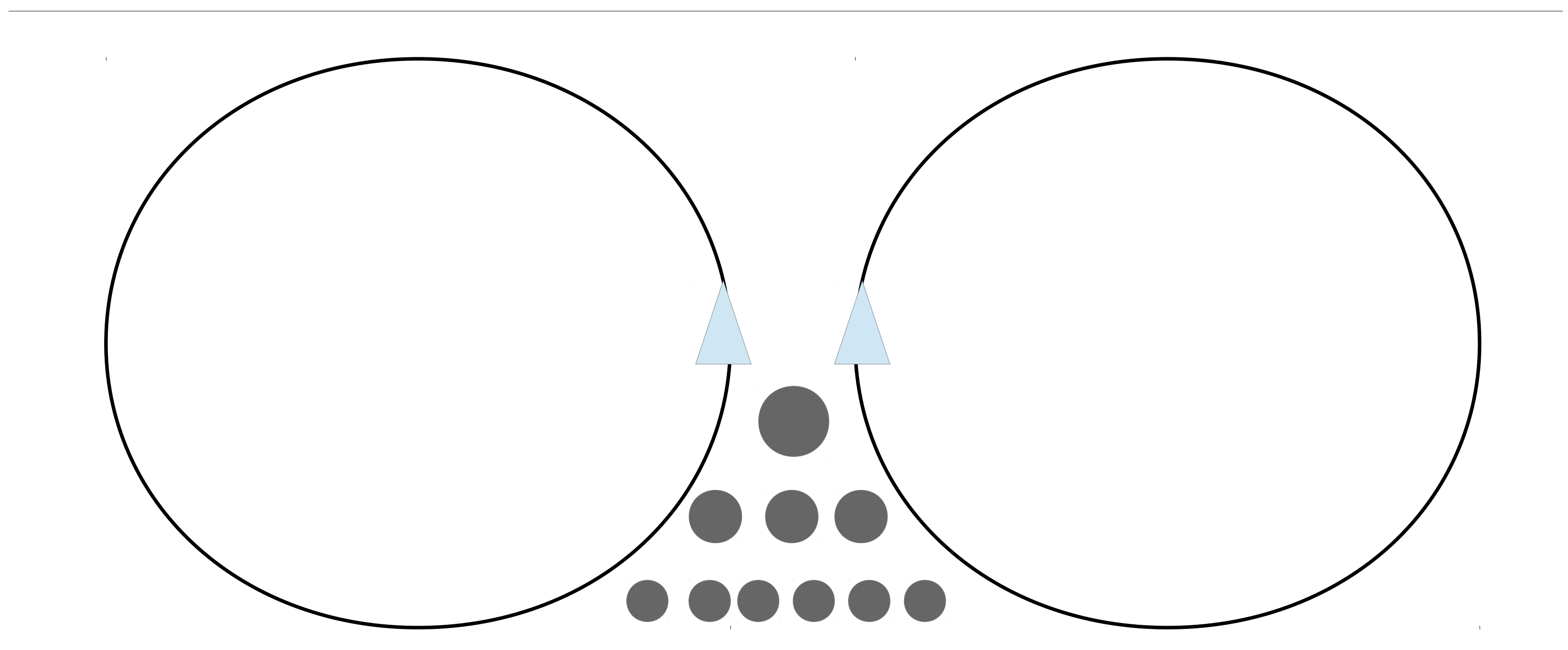
Hairpins merge...



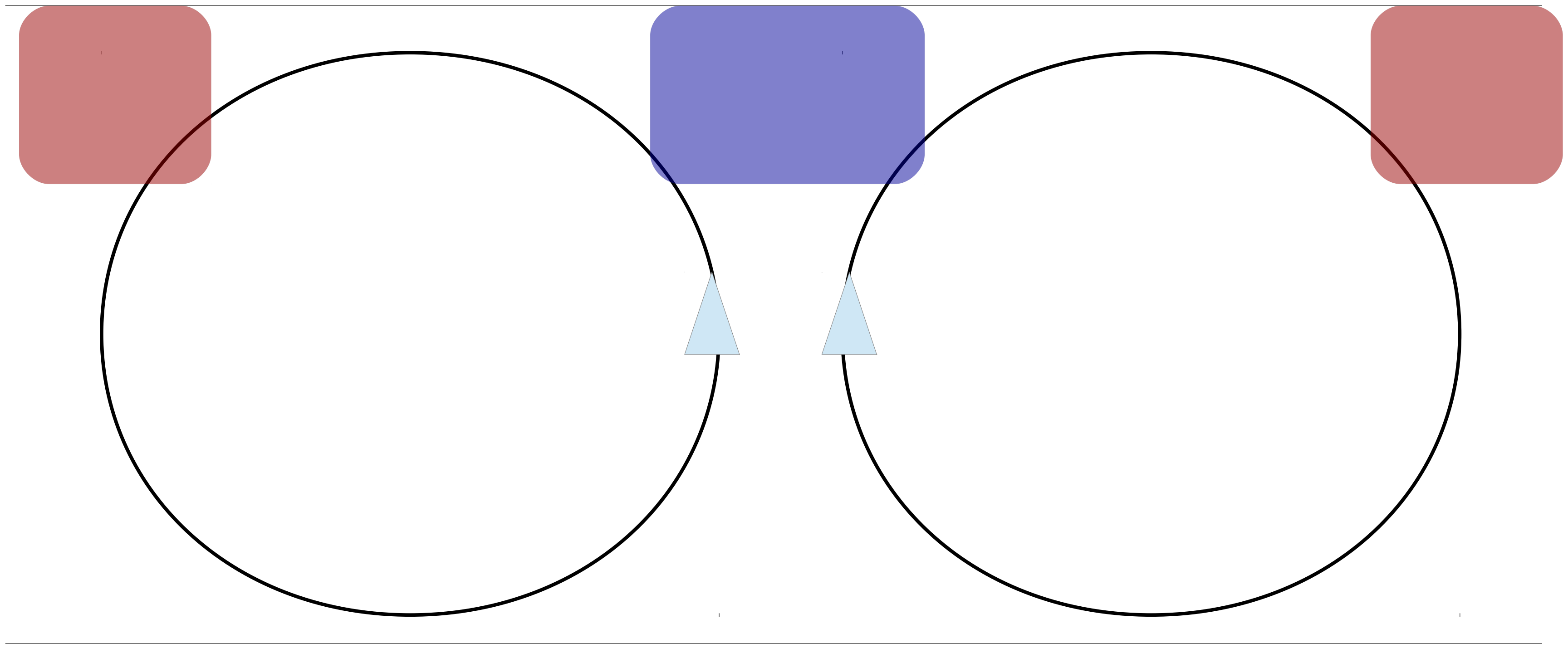
Hairpins merge...

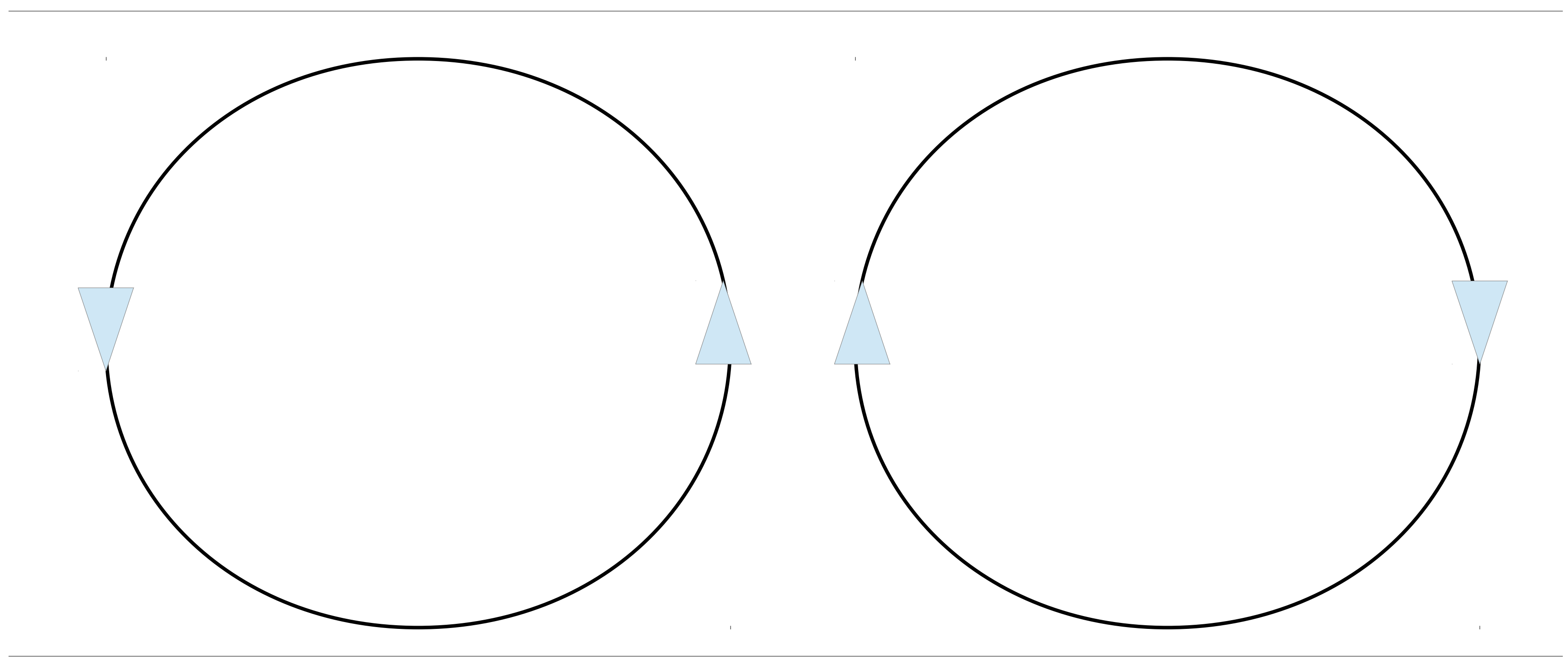


Hairpins merge...



Same process at outer cylinder...

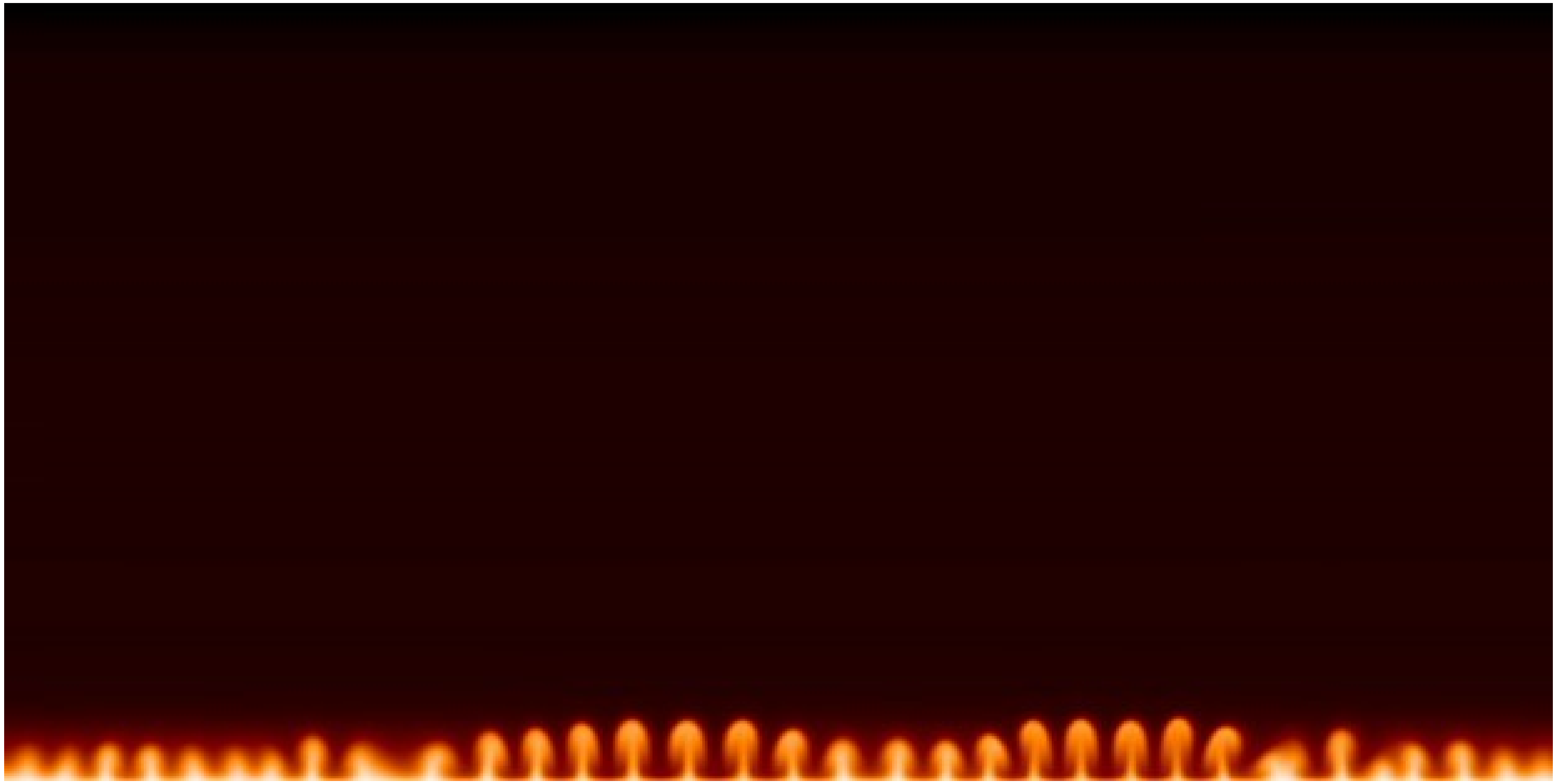




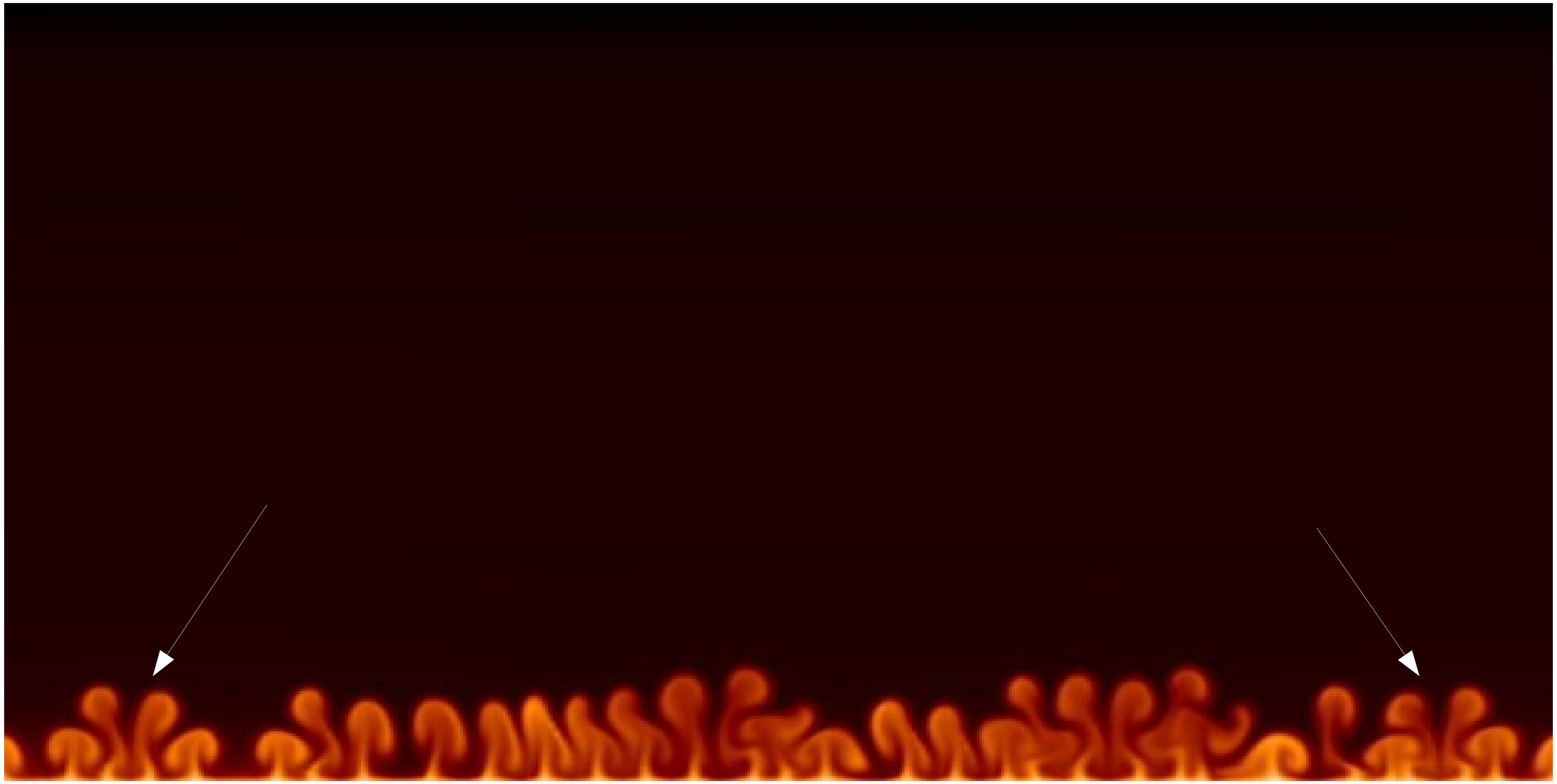
The rolls arise naturally due to linear instability!

We can actually see the hairpins merge

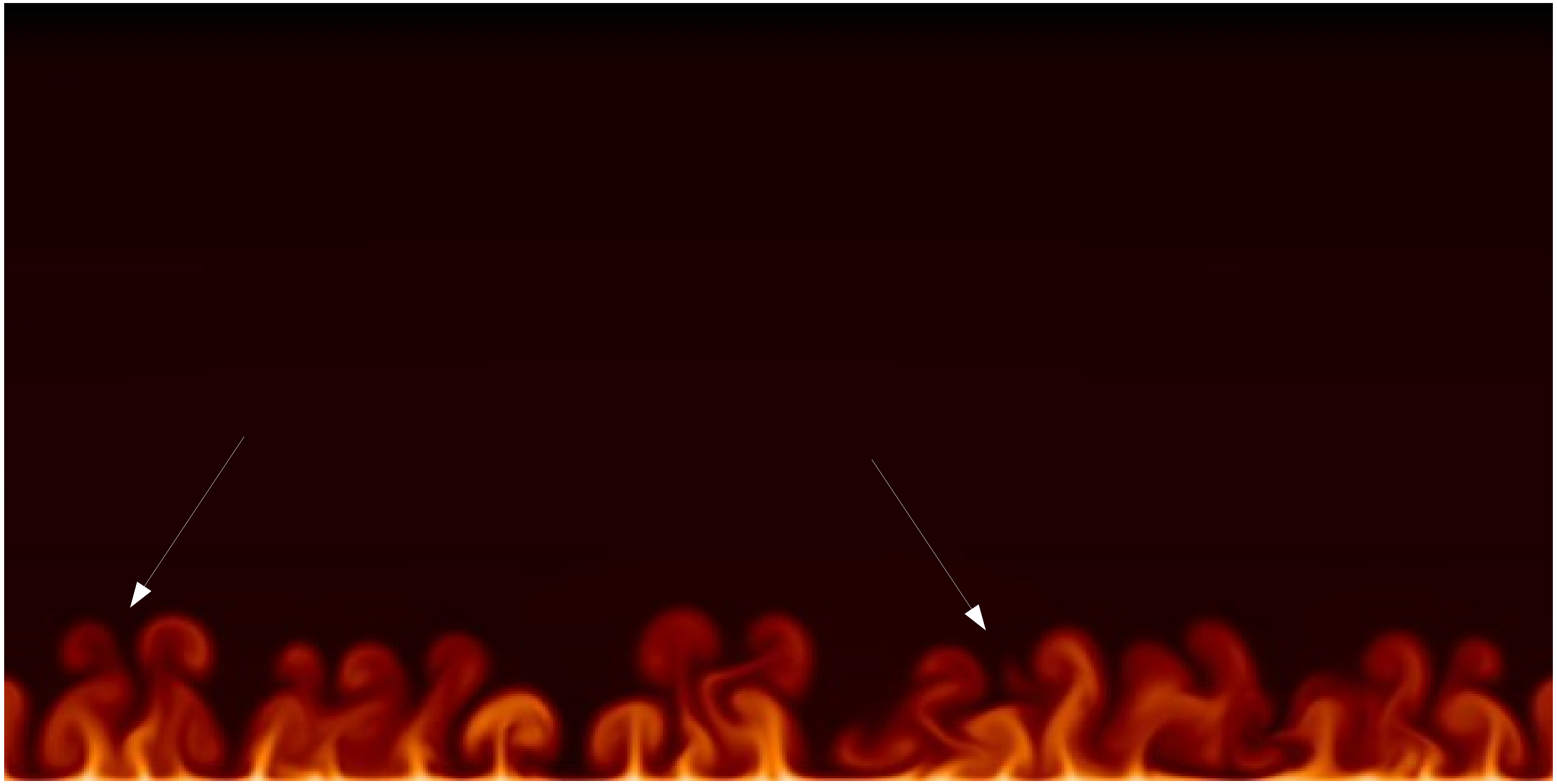
We can actually see the hairpins merge



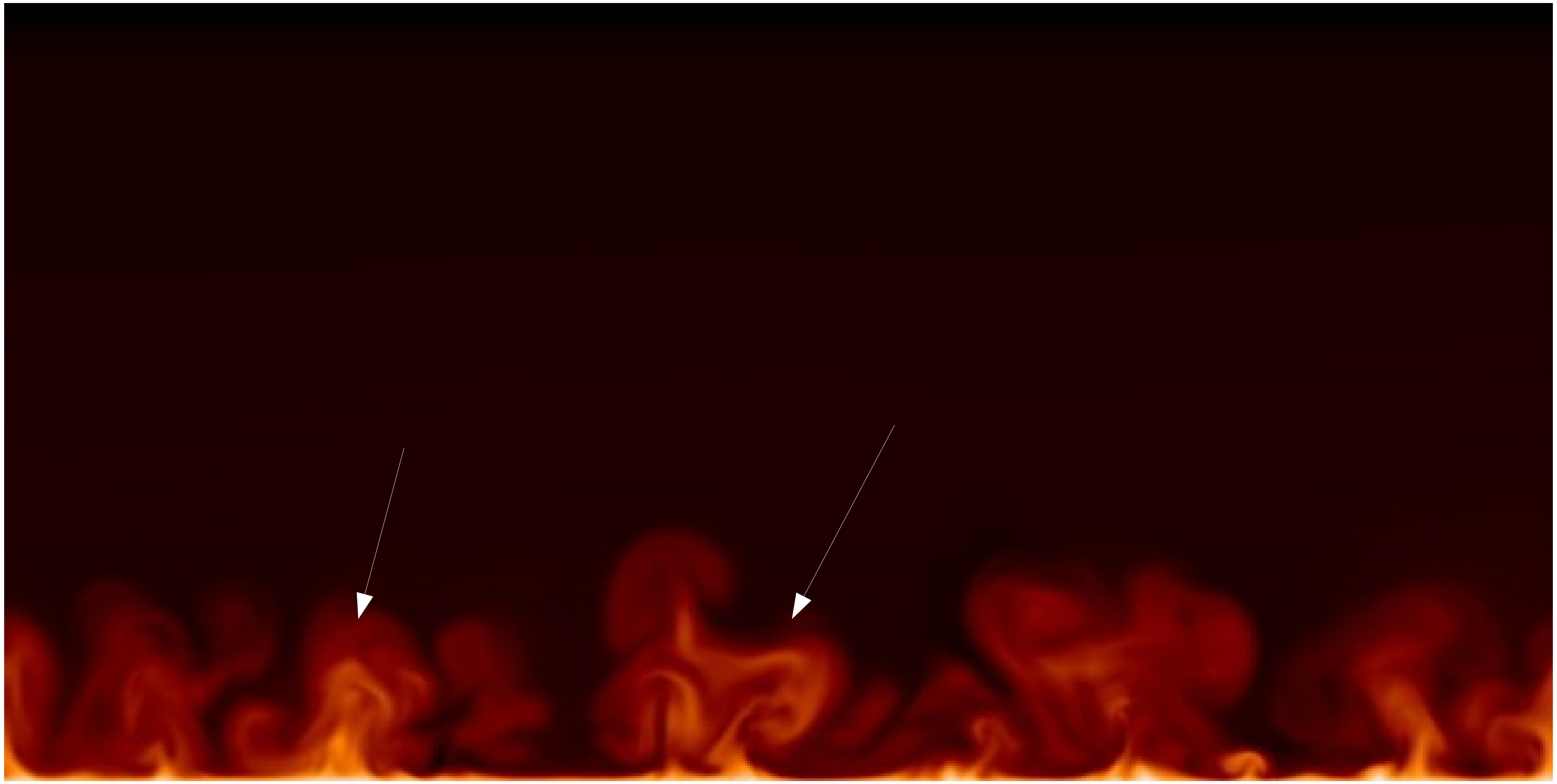
We can actually see the hairpins merge



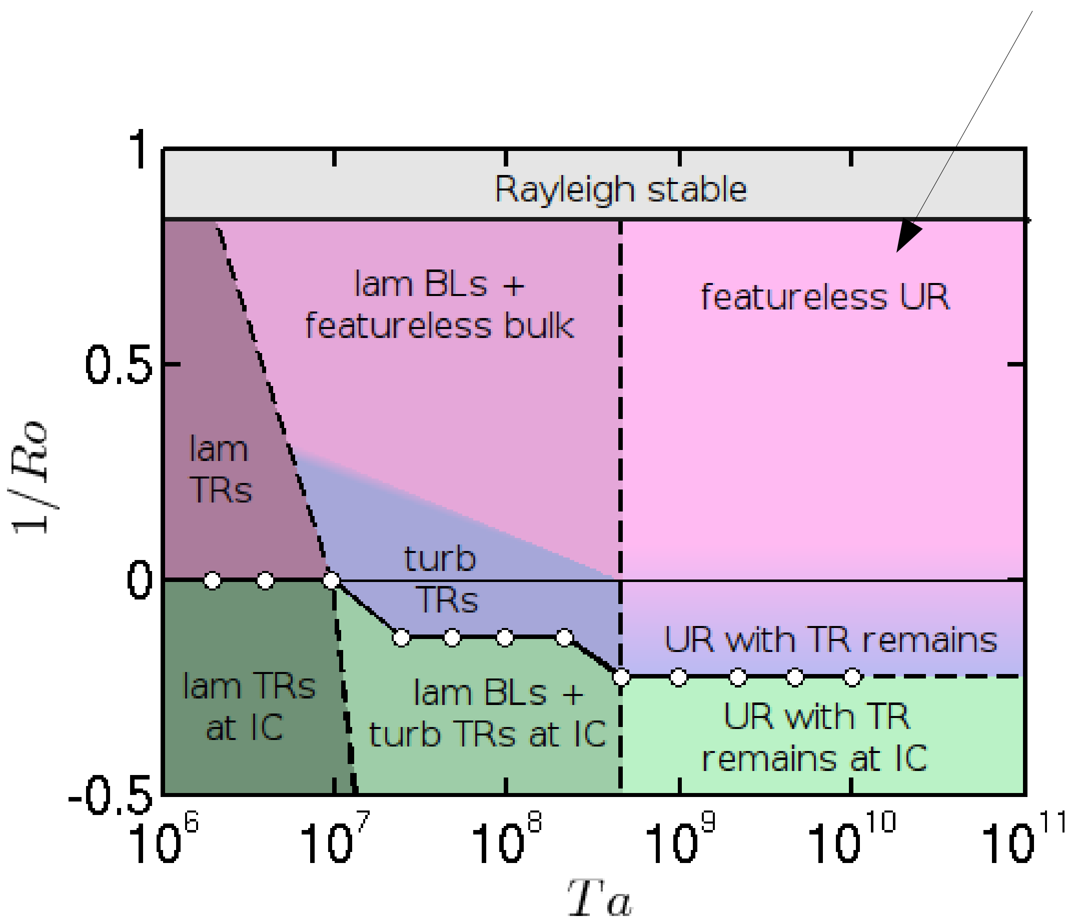
We can actually see the hairpins merge

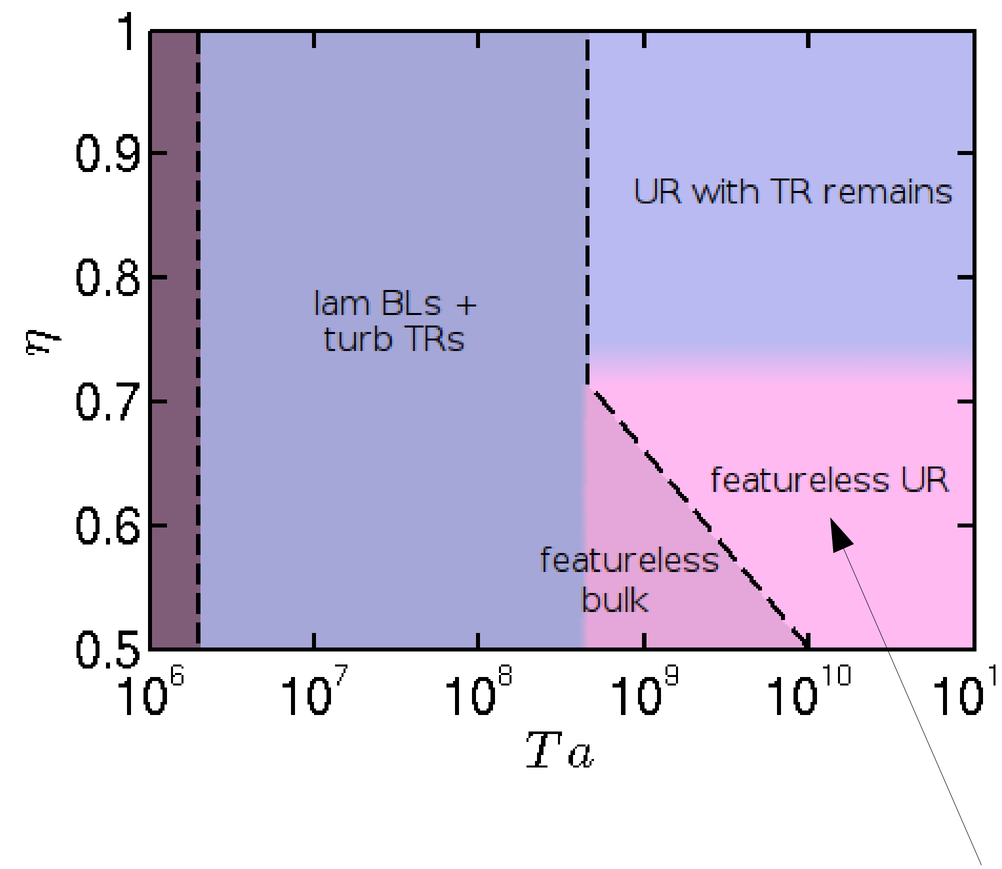


We can actually see the hairpins merge



Can we break the cycle?





Ostilla-Mónico, van der Poel, Verzicco, Grossmann, Lohse. J. Fluid. Mech, in press

Yes – through introducing asymmetry (curvature and solid body rotation)

In summary ...

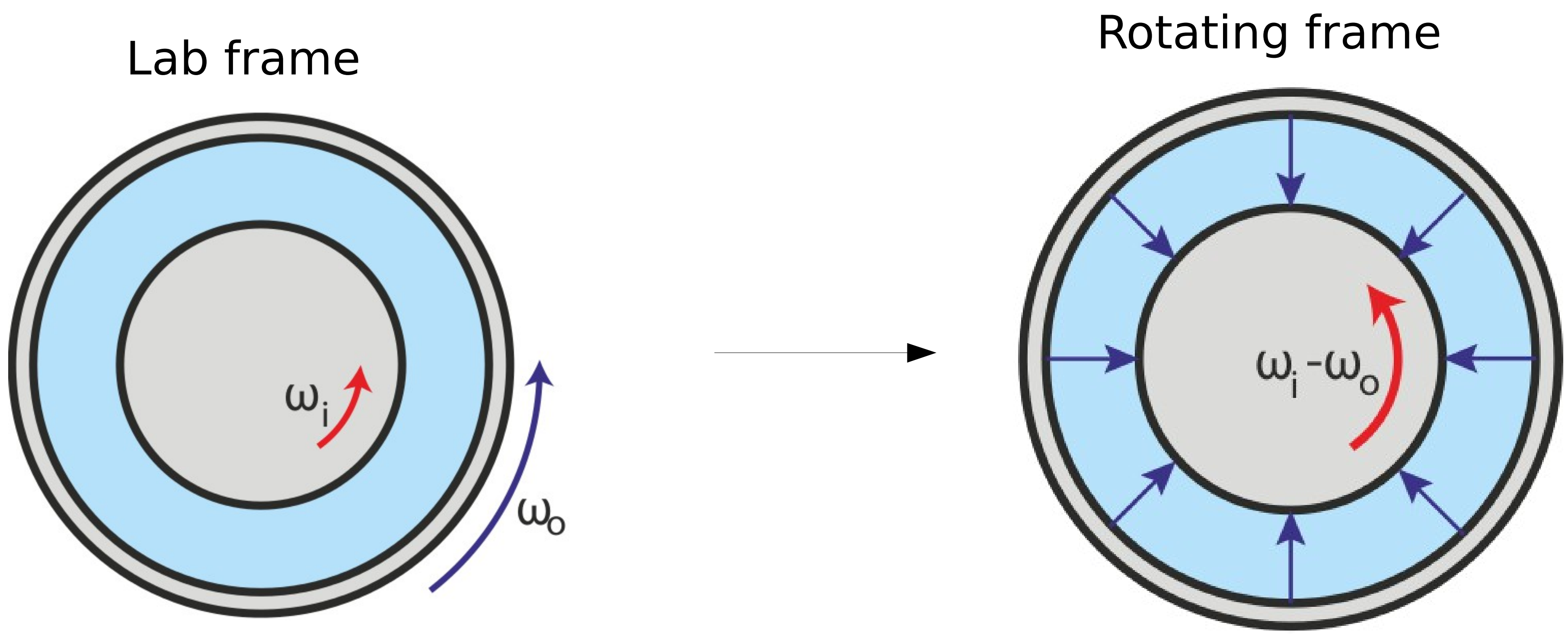
- The boundary layers in TC flow behave in a very similar to those in other canonical flows, with one exception: Taylor rolls.

- Taylor rolls are stationary and are resistant to weak axial flows, but do not form in large curvature or for co-rotating cylinders.

- Taylor rolls are attached to the wall, and actively transport angular velocity through Reynolds stresses.

Questions?

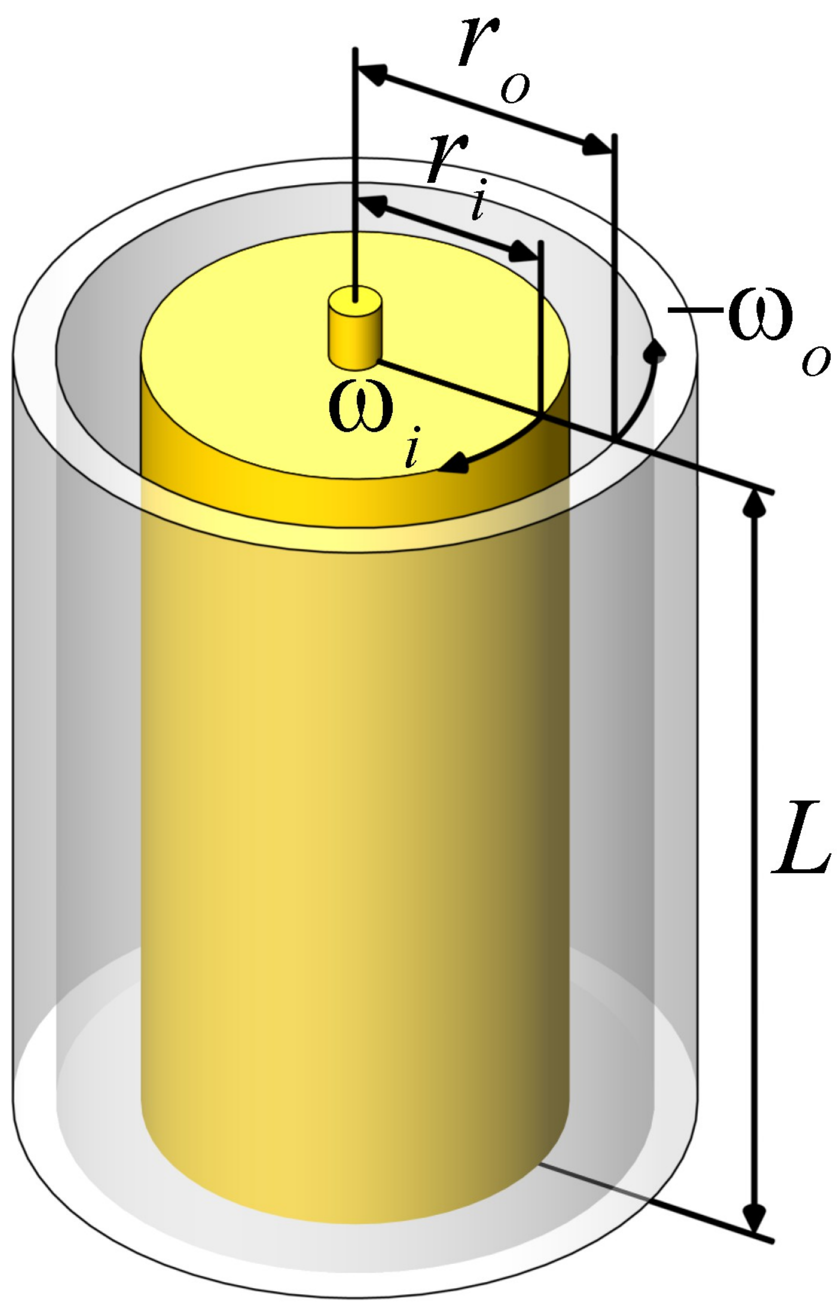
TC in a Rotating frame: outer cylinder rotation as a Coriolis force



$$\partial_t \mathbf{u} + \mathbf{u} \cdot \nabla \mathbf{u} = -\nabla p + \nu \nabla^2 \mathbf{u}$$
$$U_\theta(r_i) = r_i \omega_i$$
$$U_\theta(r_o) = r_o \omega_o$$

$$\partial_t \mathbf{u} + \mathbf{u} \cdot \nabla \mathbf{u} + 2\omega_o \times \mathbf{u} = -\nabla p + \nu \nabla^2 \mathbf{u}$$
$$U_\theta(r_i) = r_i(\omega_i - \omega_o) \equiv U$$
$$U_\theta(r_o) = 0$$

$$Ro^{-1} = \frac{2\omega_o(r_o - r_i)}{r_i(\omega_i - \omega_o)}$$



$$(Re_i, Re_o) \to (Ta, Ro^{-1})$$

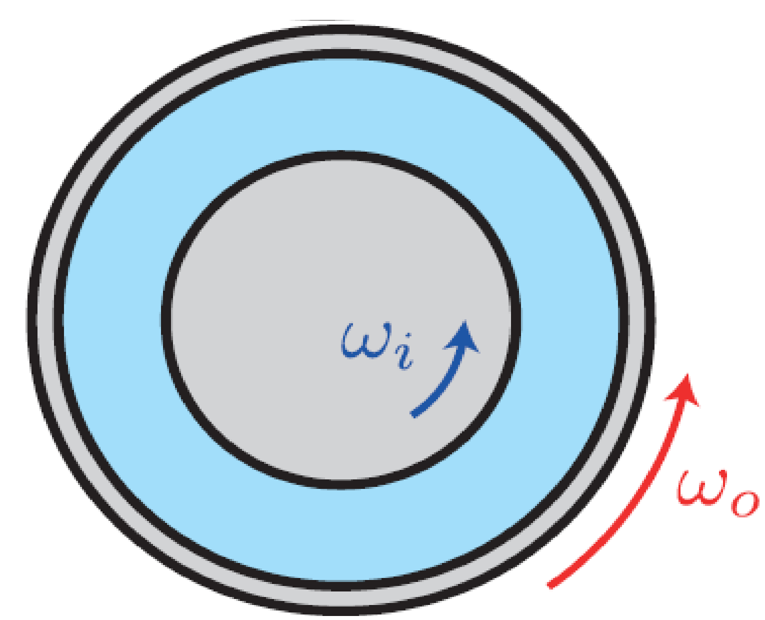
$$Ta = \frac{r_a^6 d^2}{r_g^4} \frac{(\omega_i - \omega_o)^2}{\nu^2} \sim Re_s^2$$

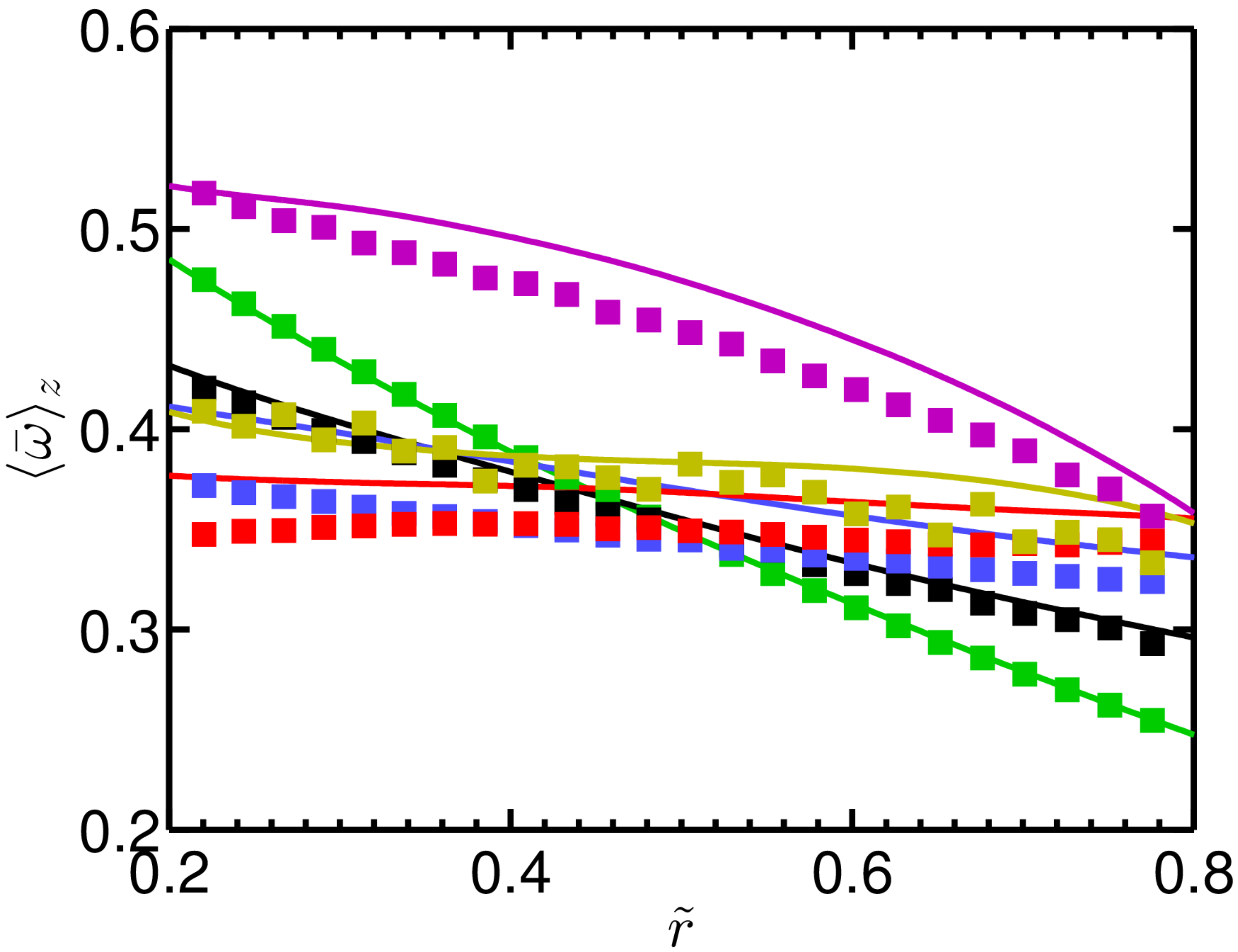
$$Ro^{-1} = \frac{2\omega_o(r_o - r_i)}{r_i(\omega_i - \omega_o)}$$

$Ro^{-1} = 0$ Pure IC rotation

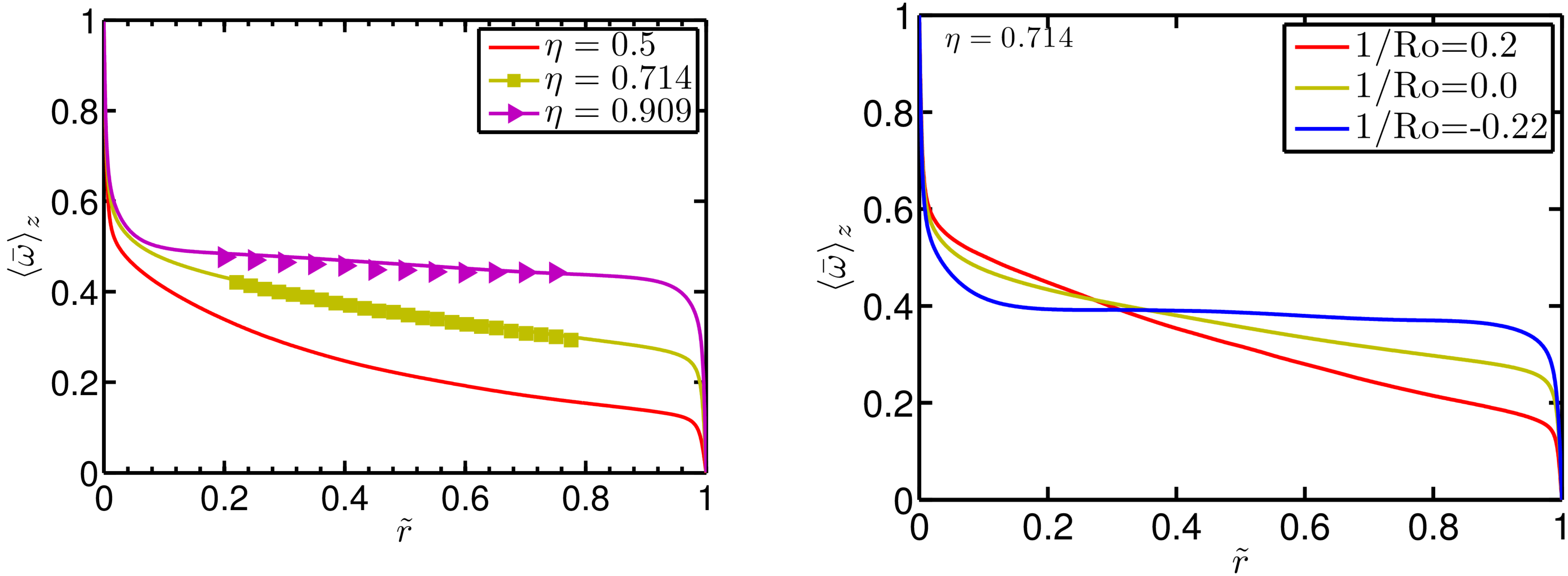
$Ro^{-1} < 0$ Counter-rotation

$Ro^{-1} > 0$ Co-rotation





0.6
0.5
0.4
0.3
0.2
0.2
0.4
0.6
0.8
$\langle\bar{\omega}\rangle_z$
$\tilde{r}$



$\langle\bar{\omega}\rangle_z$
$\tilde{r}$
$\eta = 0.5$
$\eta = 0.714$
$\eta = 0.909$
$\eta = 0.714$
1/Ro=0.2
1/Ro=0.0
1/Ro=-0.22