Turbulent/non-turbulent interface in boundary layers: scaling and organisation

Kapil Chauhan
(Rio Baidya, Krishna Talluru, Charitha de Silva, Jimmy Philip & Ivan Marusic)

Department of Mechanical Engineering
The University of Melbourne, Australia

Workshop on high Reynolds number boundary layer turbulence
November 20-22, University of New Hampshire, USA

Lee, J. H., Kwon, Y. S., Monty, J. & Hutchins, N. 2012 Tow-tank investigation of the developing zero-pressure-gradient turbulent boundary layer. *Bull. Amer. Phys. Soc.* **57** (17), DFD.R20.8

Visualisation of a boundary layer developing over a flat plate in the tow-tank facility at UoM.

$Re_\tau \approx 0 - 1000$, $\delta = O(10\text{cm})$

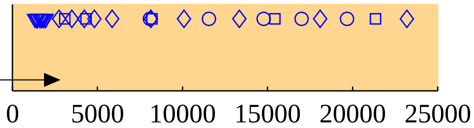
Time-lapse video of smoke over Sydney. Smoke emerging from bushfires in Blue mountains, NSW (October 2013).

$Re_\tau \approx 10^6$, $\delta = O(100\text{m})$

Outline

1. Global characteristics
   - External intermittency (turbulent/non-turbulent interface)
   - Statistical features
   - Organisation
2. Local characteristics of superlayer
   - Scaling of superlayer width and the jump magnitude
   - Implications for the outer flow

1.1 Experiments: hot-wire database



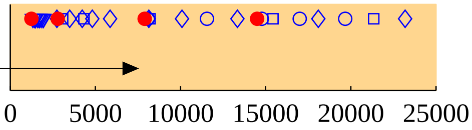
U_∞ (m s^{-1})	δ (m)	u_τ (m s^{-1})	T$_s$ (sec)	T$_s U_\infty/\delta$	F$_s$ (kHz)	dx^+	Re_τ ($\delta u_\tau/\nu$)
10	0.05	0.39	160	32307	50.00	5.37	1330
10	0.05	0.39	160	29298	50.00	5.20	1421
10	0.06	0.39	160	28037	50.00	5.21	1487
10	0.06	0.39	160	25749	50.00	5.23	1626
10	0.07	0.39	160	24159	50.00	5.21	1725
10	0.07	0.38	160	22452	50.00	5.10	1817
10	0.08	0.38	160	20856	50.00	5.09	1951
12	0.11	0.44	120	13373	24.07	14.26	3080
12	0.16	0.43	180	13757	24.07	13.74	4327
10	0.36	0.35	540	15560	24.07	9.83	8207
21	0.36	0.67	240	13856	60.06	14.83	15430
30	0.34	0.96	120	10582	101.01	18.64	21347
20	0.06	0.74	60	20837	65.54	14.55	2745
20	0.08	0.73	60	16091	65.54	14.31	3496
20	0.09	0.71	80	17538	65.54	14.15	4229
20	0.11	0.71	90	17201	65.54	14.07	4823
20	0.13	0.69	100	15224	65.54	13.61	5860
21	0.19	0.69	120	13204	65.54	13.67	8140
20	0.23	0.66	180	15336	65.54	13.12	10092
20	0.32	0.64	180	11162	65.54	12.62	13342
30	0.31	0.94	120	11597	100.00	17.49	18094
41	0.30	1.25	100	13596	100.00	31.52	23186
10	0.38	0.33	300	7964	50.00	4.29	8079
15	0.37	0.48	600	24144	50.00	9.30	11558
20	0.36	0.64	300	16698	50.00	16.44	14771
25	0.35	0.78	300	21755	50.00	24.65	16999
30	0.34	0.92	300	26672	50.00	34.98	19672

▽ - Kulandaivelu, V. & Marusic, I. 2010 Evolution of zero pressure gradient turbulent boundary layers. In *proceedings of 17th Australasian Fluid Mechanics Conference*. 5-9 December, Auckland, New Zealand

◇ - Hutchins, N., Nickels, T. B., Marusic, I. & Chong, M. S. 2009 Hot-wire spatial resolution issues in wall-bounded turbulence. *J. Fluid Mech.* **635**, 103–136

□ - Kulandaivelu, V. 2012 Evolution of zero pressure gradient turbulent boundary layers from different initial conditions. PhD thesis, The University of Melbourne, Melbourne, Australia

○ - Present data

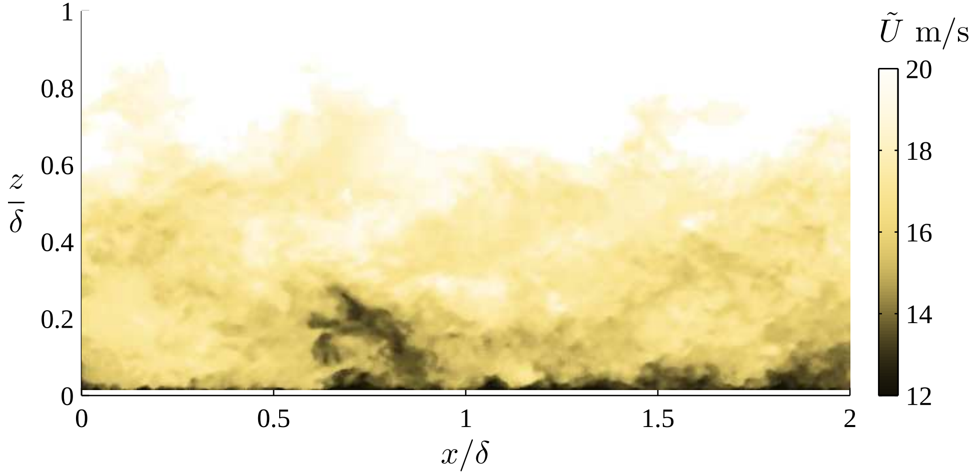


	U_∞ (m s^{-1})	δ (m)	u_τ (m s^{-1})	$L_x \times L_z$	$\Delta x^+ \times \Delta z^+$	N_f	Re_τ ($\delta u_\tau/\nu$)
Hambleton *et al.* (2005)	6	0.08	0.25	$1.5\delta \times 1.34\delta$	32×32	1478	1230
Adrian *et al.* (2000)	11.4	0.1	0.41	$1.4\delta \times 1.4\delta$	36×25	50	2790
Melbourne PIV	10	0.36	0.33	$2\delta \times 1.1\delta$	52×52	1190	7900
Melbourne PIV	20	0.35	0.63	$2\delta \times 1.1\delta$	49×49	1250	14500

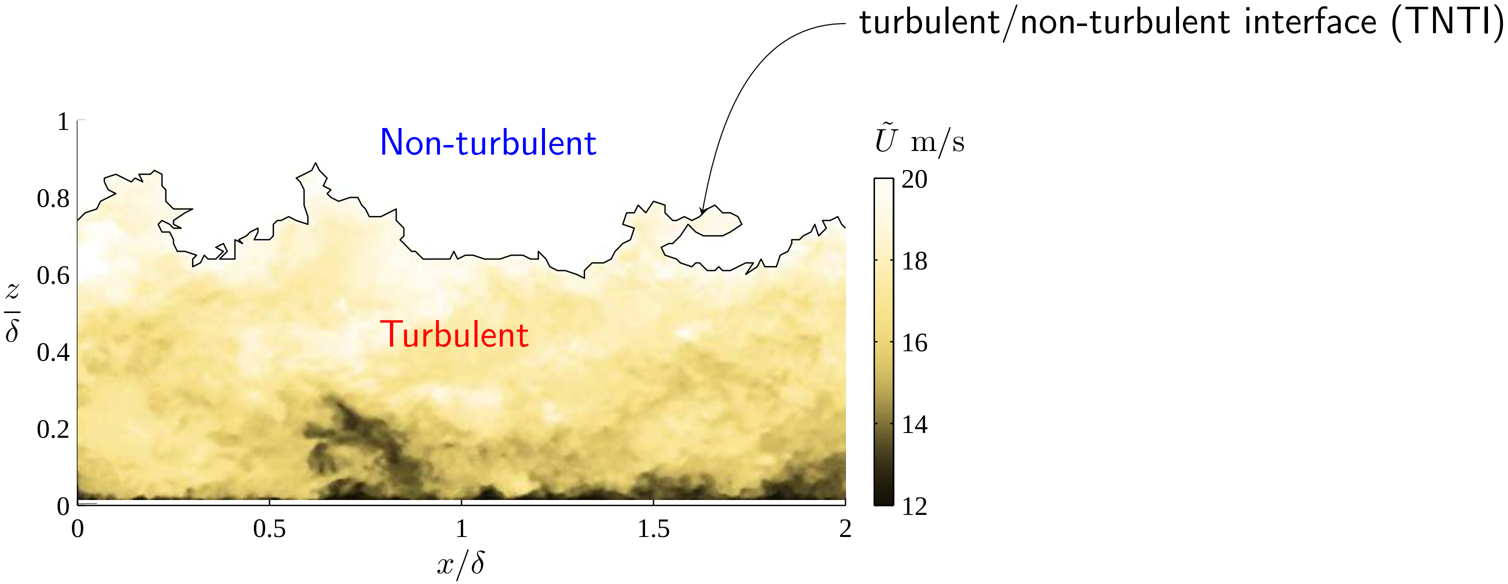
Hambleton, W., Hutchins, N. & Marusic, I. 2005 Simultaneous orthogonal plane PIV measurements in a turbulent boundary layer. *J. Fluid Mech.* **560**, 53–64

Adrian, R. J., Meinhart, C. D. & Tomkins, C. D. 2000 Vortex organization in the outer region of the turbulent boundary layer. *J. Fluid Mech.* **422**, 1–54

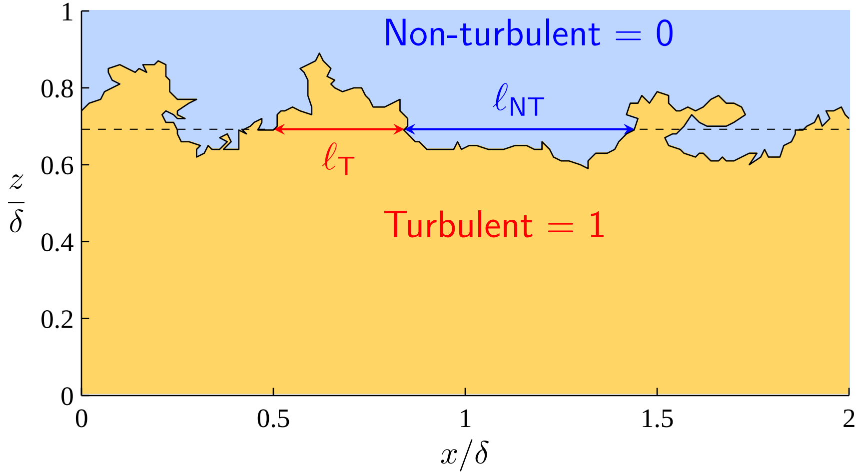
de Silva, C. M., Philip, J., Chauhan, K., Meneveau, C. & Marusic, I. 2013 Multiscale geometry and scaling of the turbulent-nonturbulent interface in high Reynolds number boundary layers. *Phys. Rev. Lett.* **111**, 044501



1.3 External intermittency

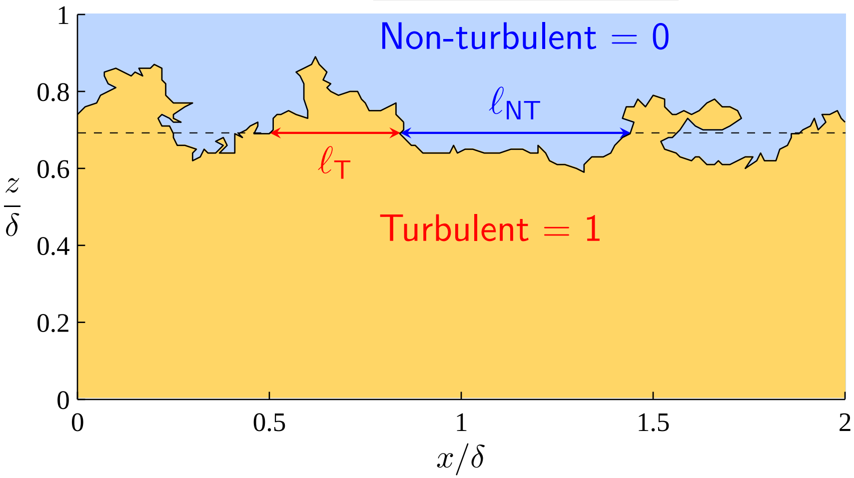


1.3 External intermittency



1.3 External intermittency

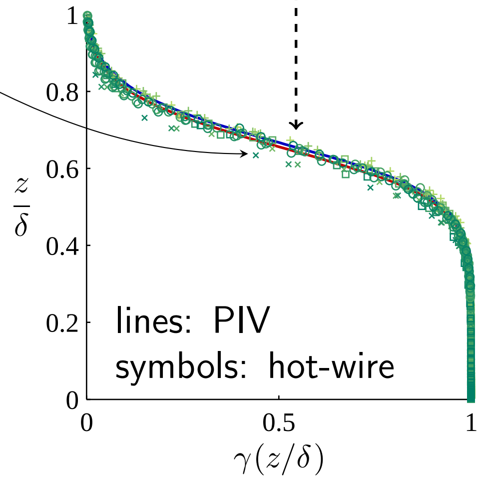
$$\gamma = \frac{\Sigma\, \ell_{\mathsf{T}}}{\Sigma\, \ell_{\mathsf{T}} + \Sigma\, \ell_{\mathsf{NT}}}$$



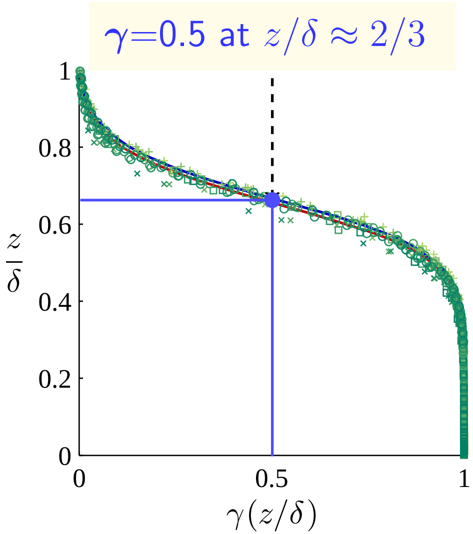
Intermittency function γ

the proportion of time the flow is turbulent at a given point

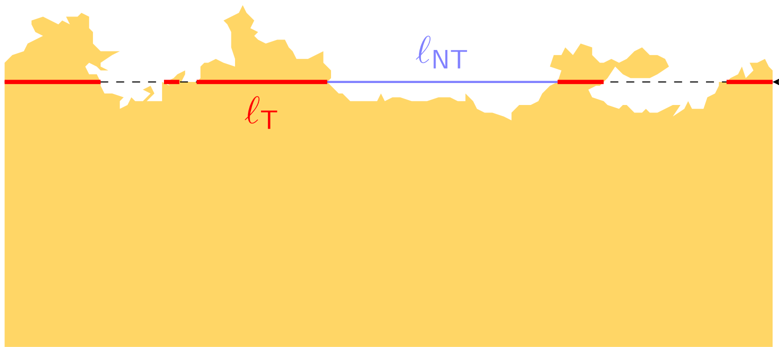
$\gamma \approx$ *error function*

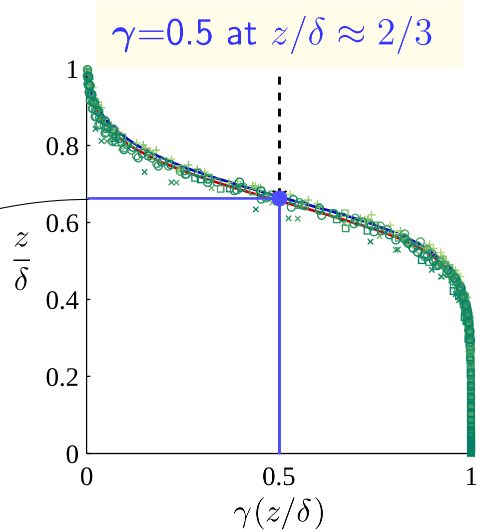


1.4 Characteristics of ℓ at $\gamma = 0.5$, i.e. $(z/\delta = 2/3)$

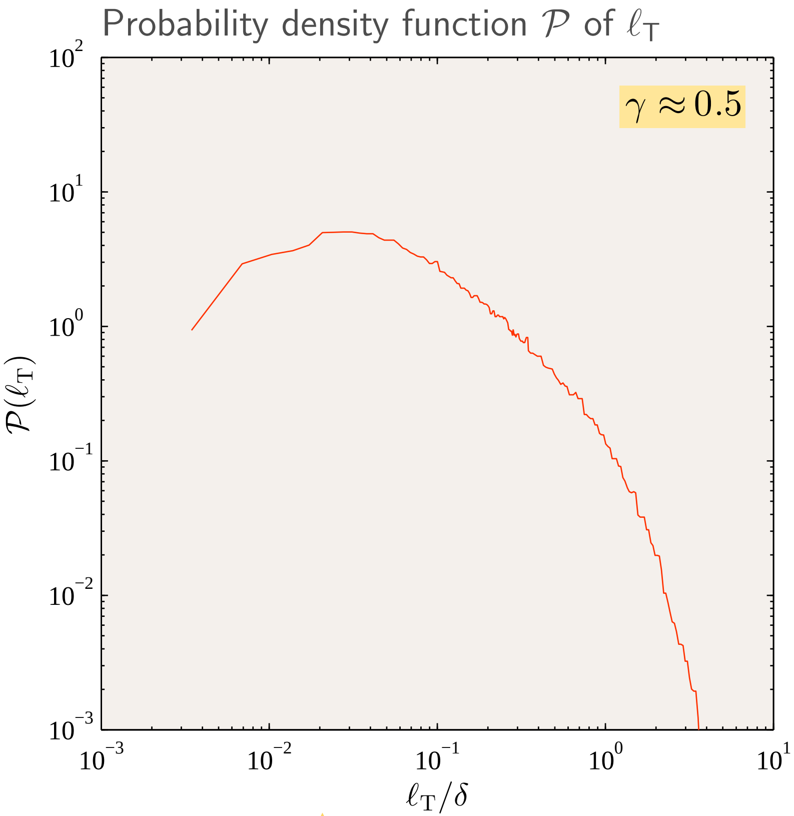


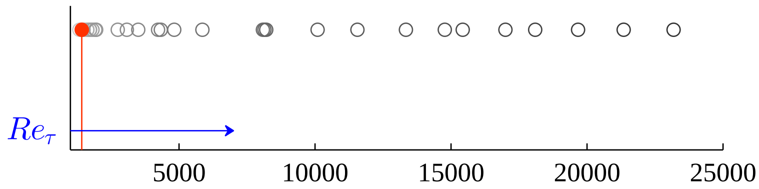
1.4 Characteristics of ℓ at $\gamma = 0.5$, i.e. $(z/\delta = 2/3)$

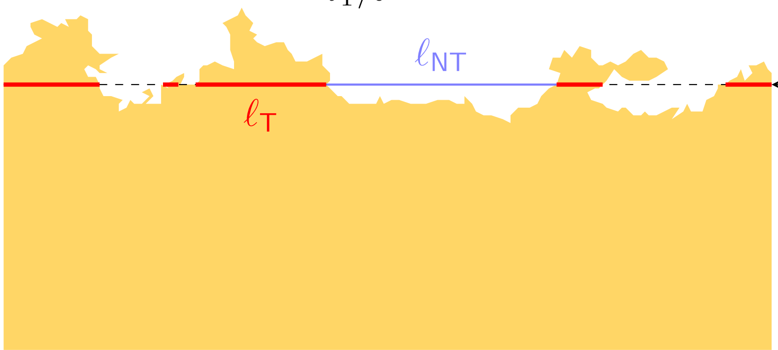


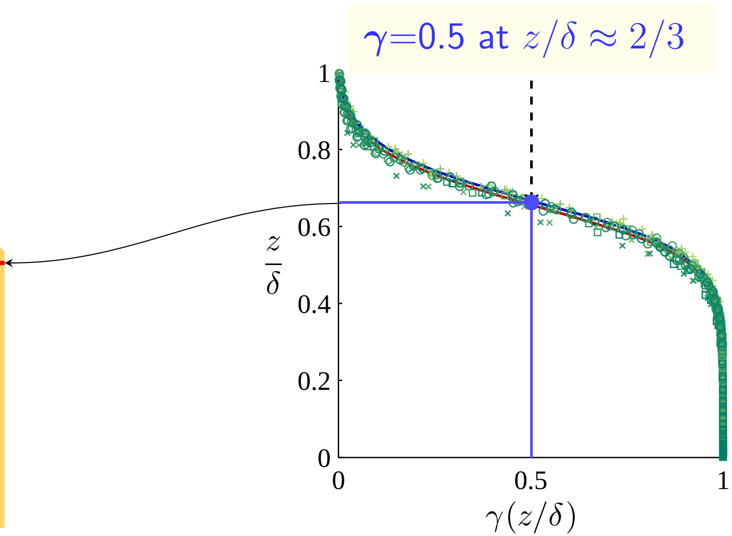


1.4 Characteristics of ℓ at $\gamma = 0.5$, i.e. $(z/\delta = 2/3)$

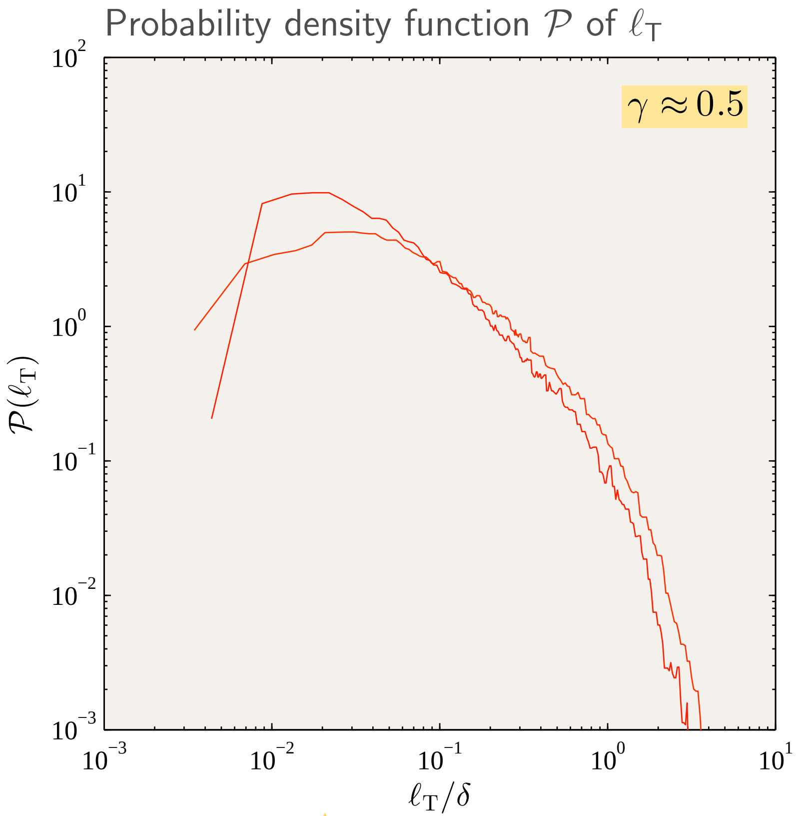


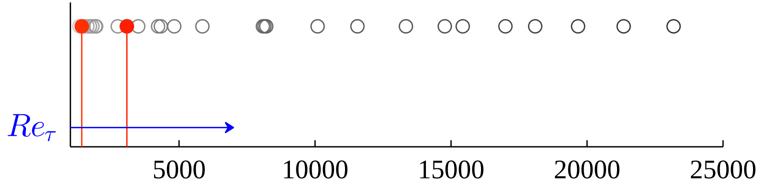


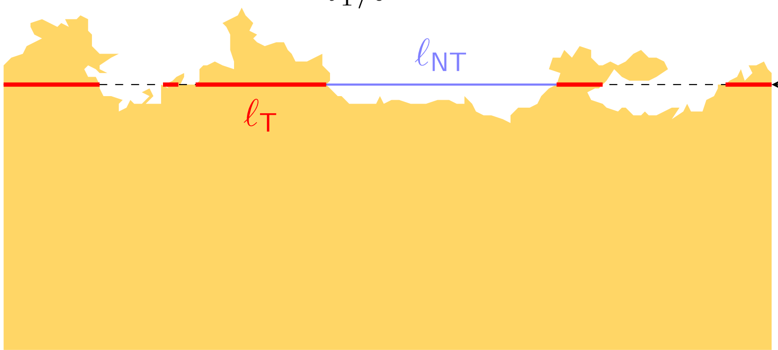


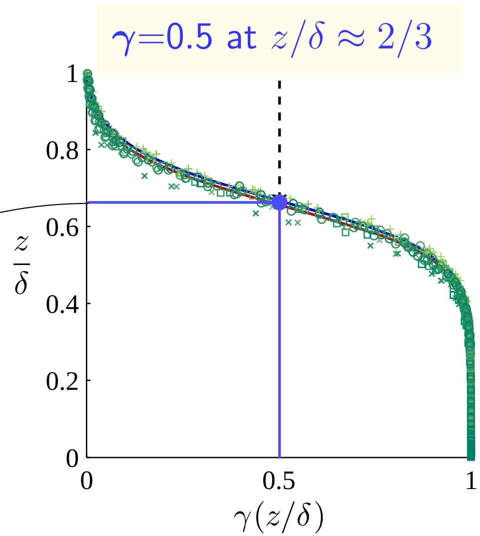


1.4 Characteristics of ℓ at $\gamma = 0.5$, i.e. $(z/\delta = 2/3)$

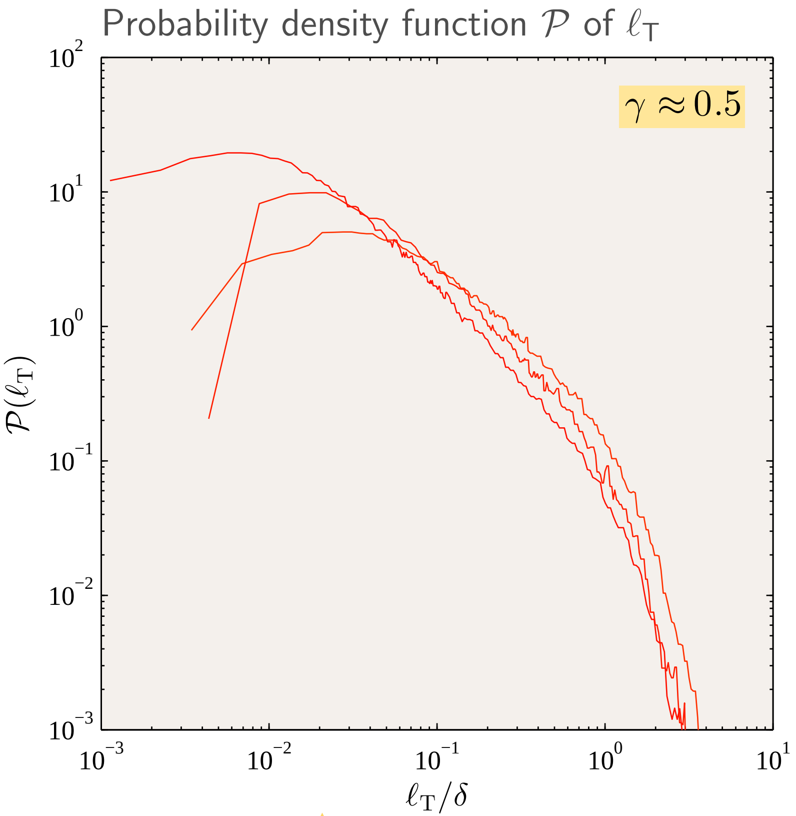


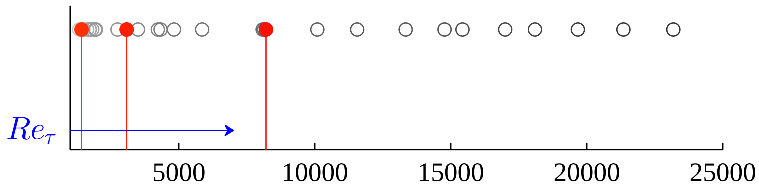


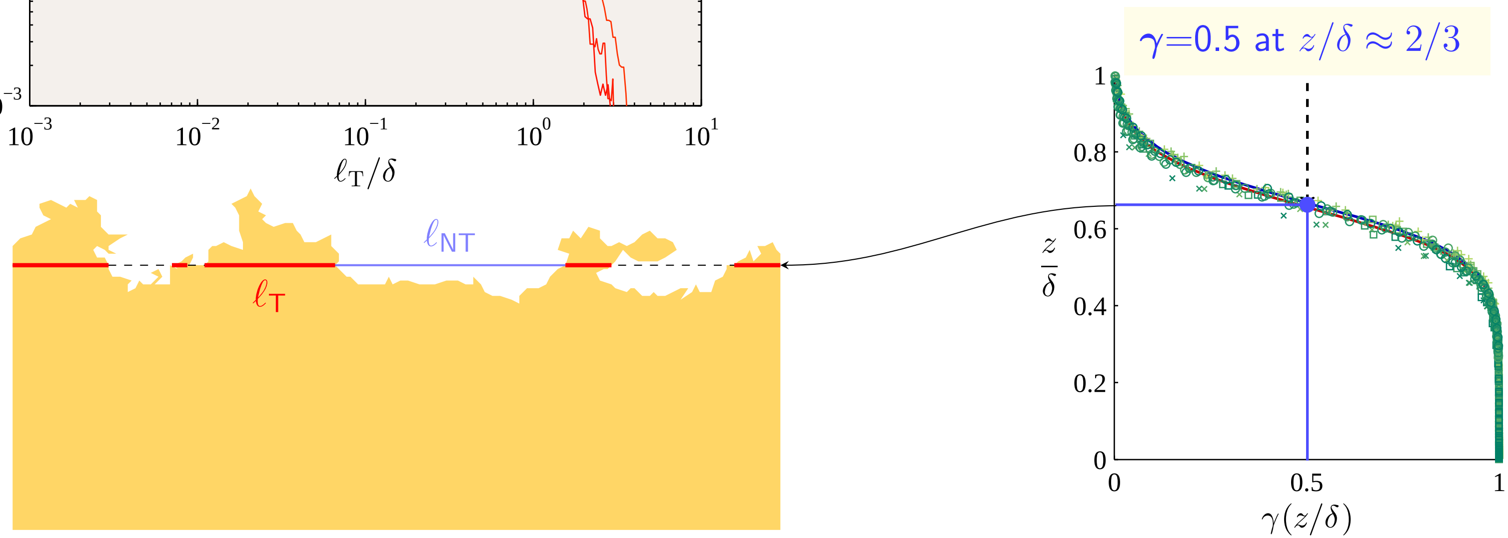




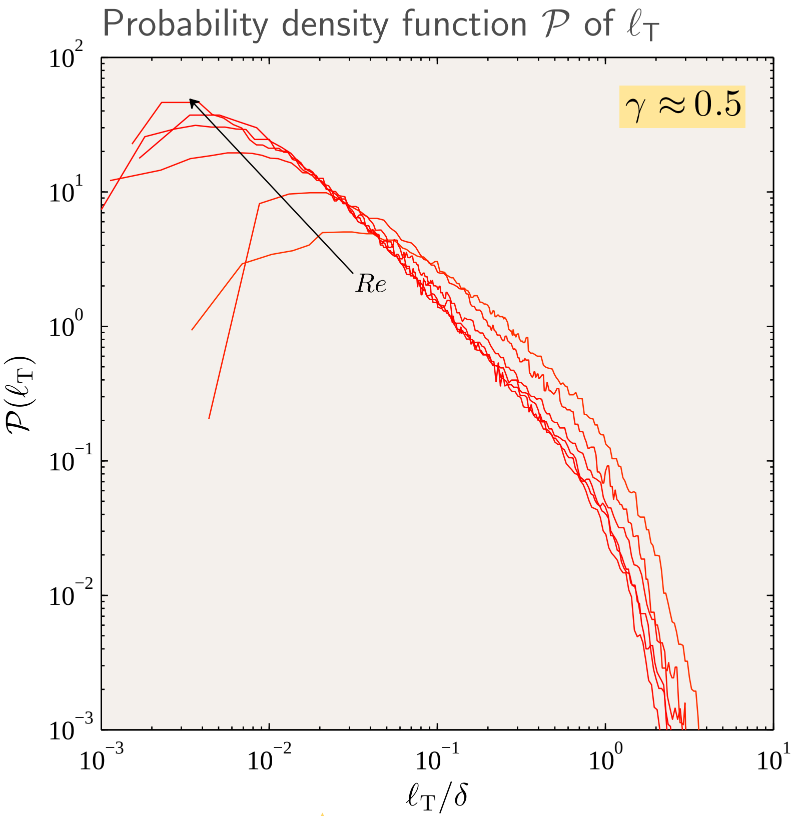
1.4 Characteristics of ℓ at $\gamma = 0.5$, i.e. $(z/\delta = 2/3)$

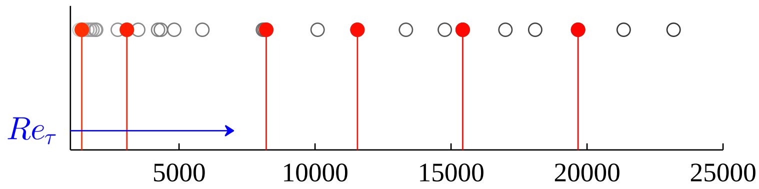


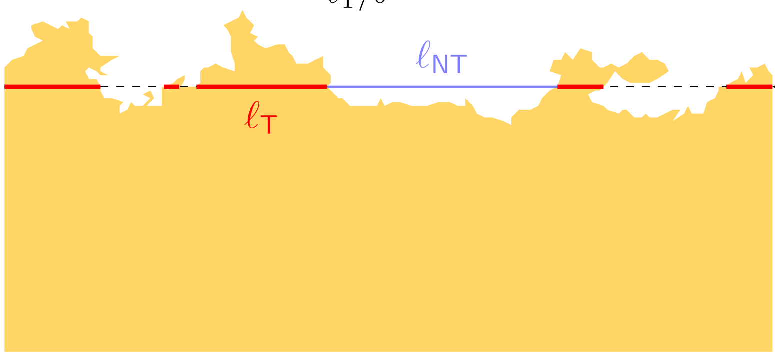


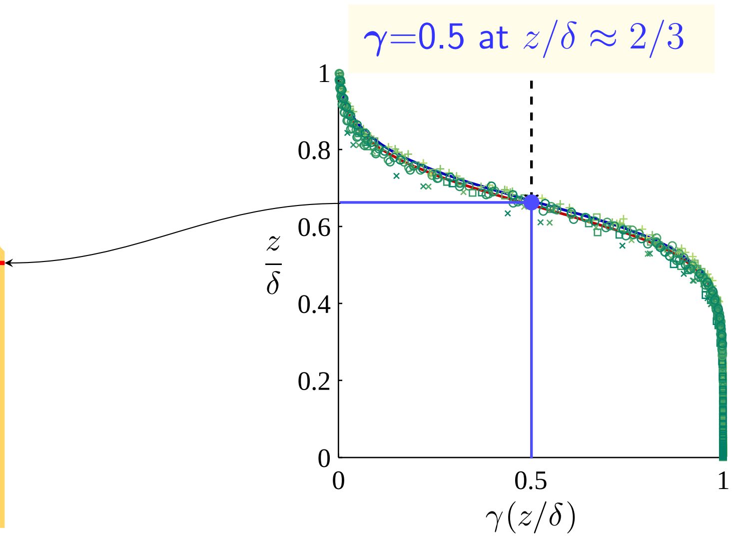


1.4 Characteristics of ℓ at $\gamma = 0.5$, i.e. $(z/\delta = 2/3)$

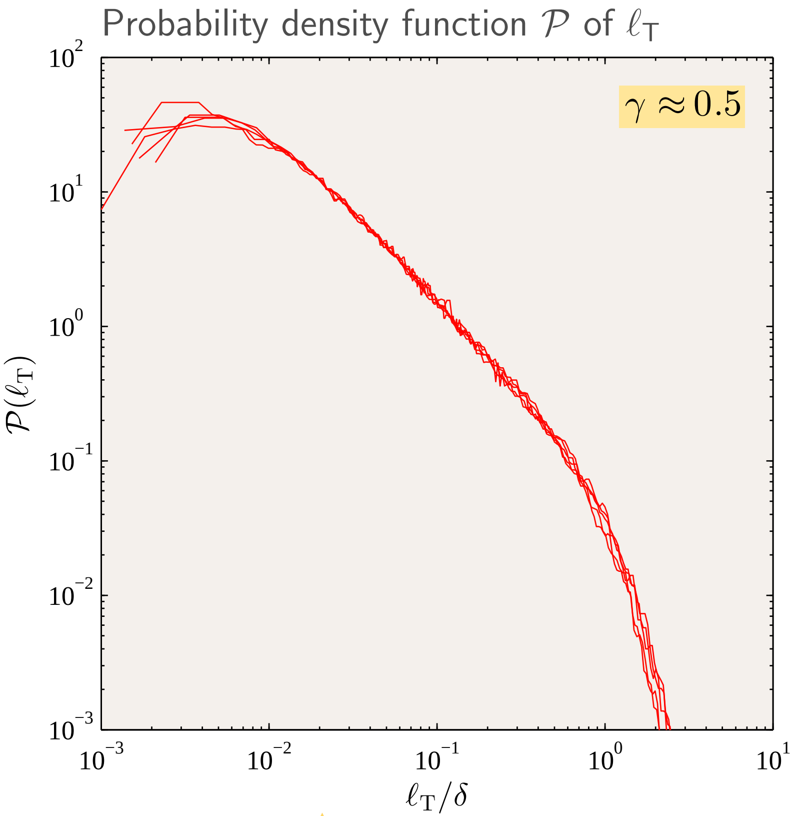


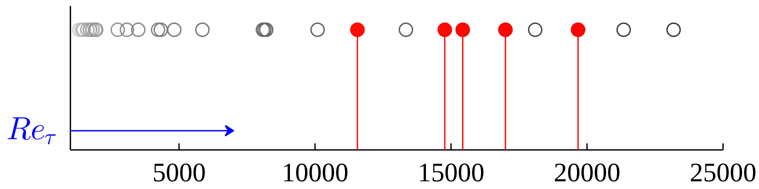


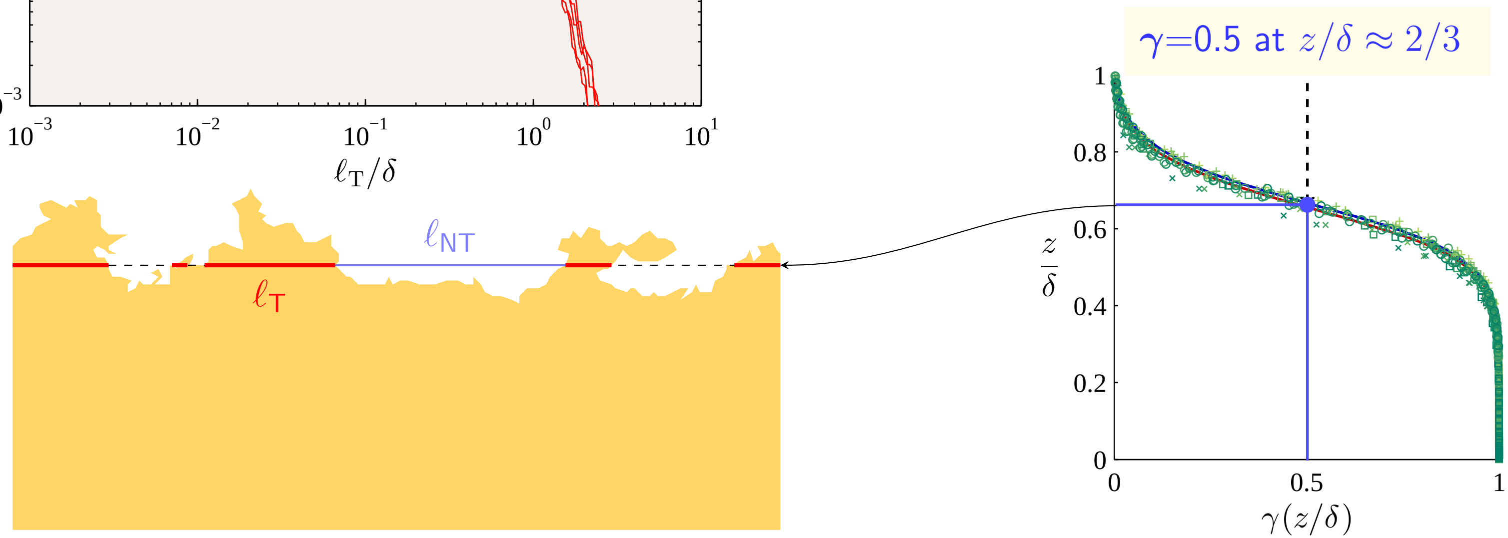


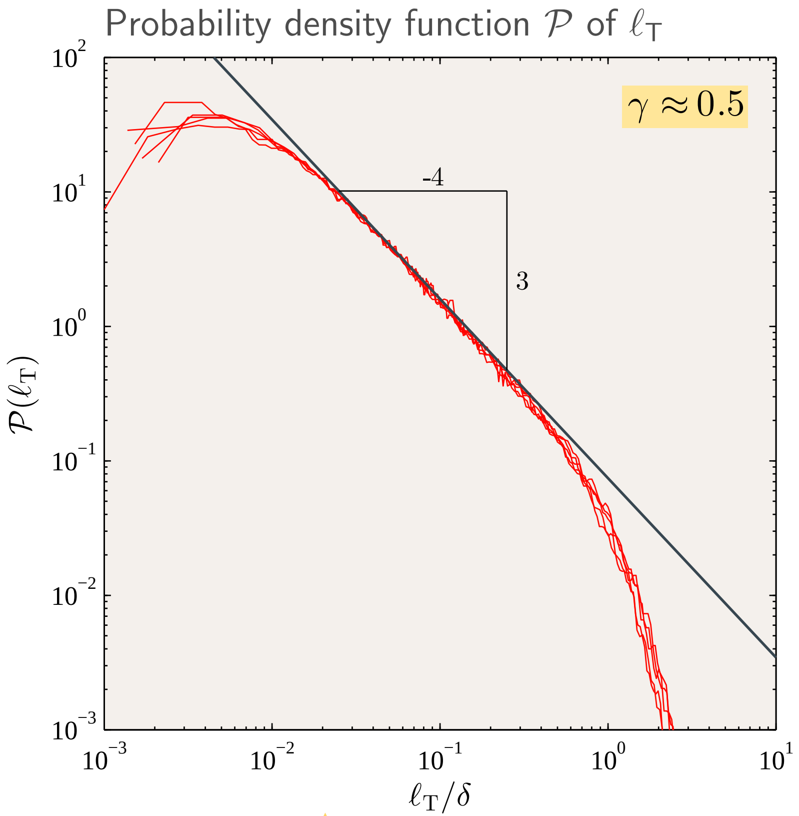


1.4 Characteristics of ℓ at $\gamma = 0.5$, i.e. $(z/\delta = 2/3)$





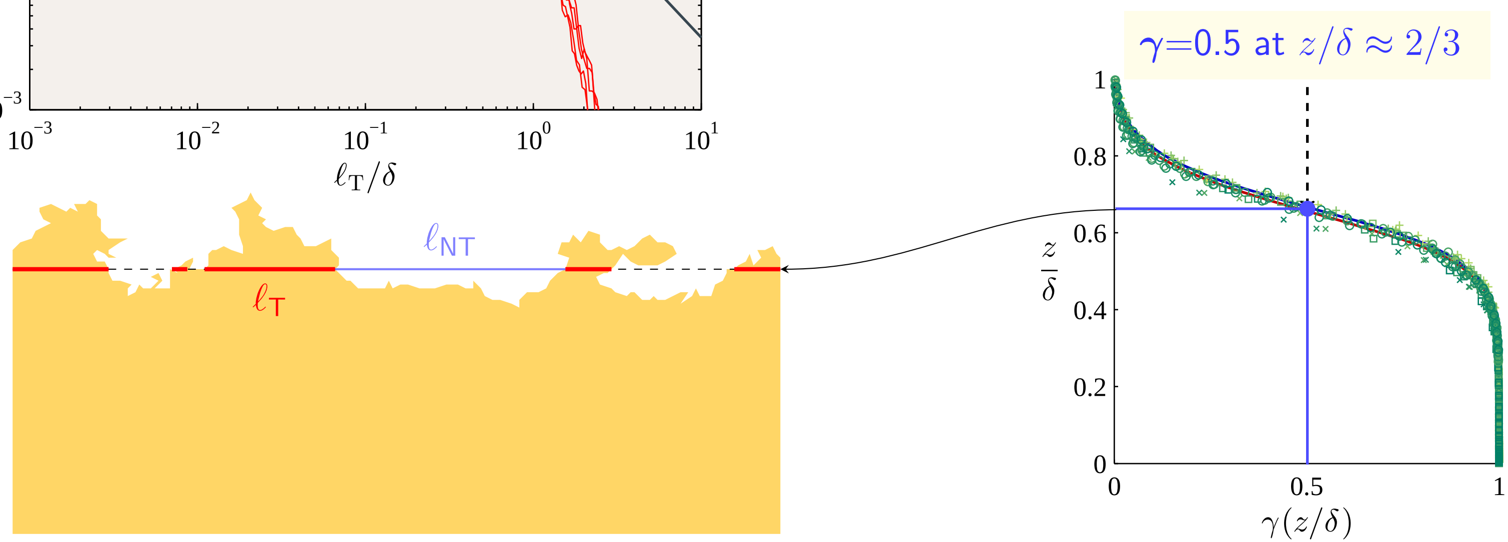


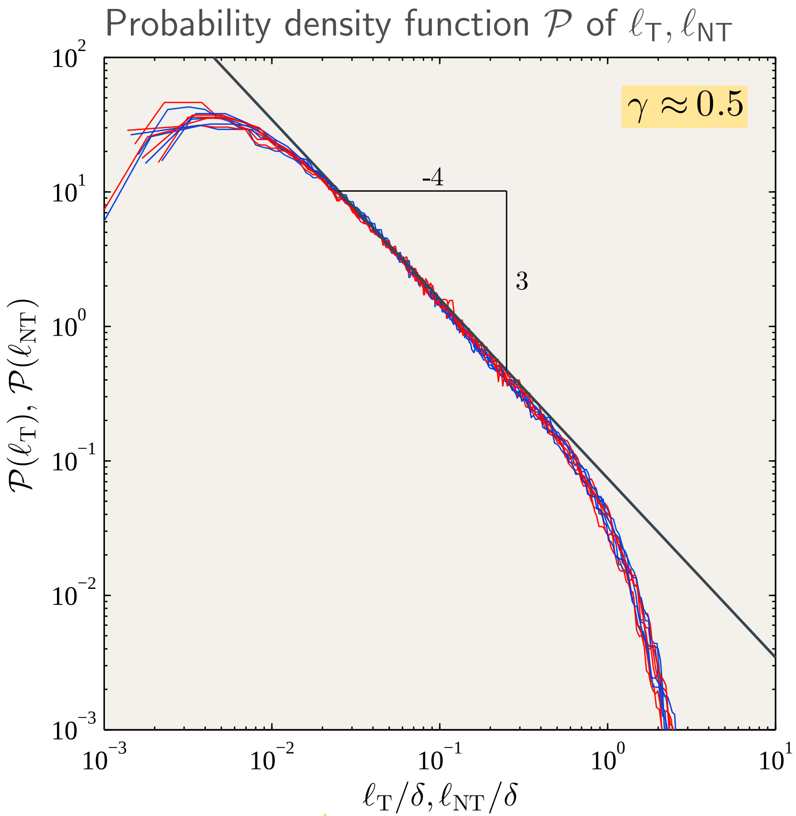


$$\mathcal{P}(\ell) = c\,\ell^{-D_f+1}$$

Segment lengths show fractal behaviour for more than a decade of intermediate scales

Slope = -4/3 (D_f=-7/3) is consistent with previous studies (e.g. Sreenivasan & Meneveau, 1986; Tsuji *et al.*, 1991; de Silva *et al.*, 2013)

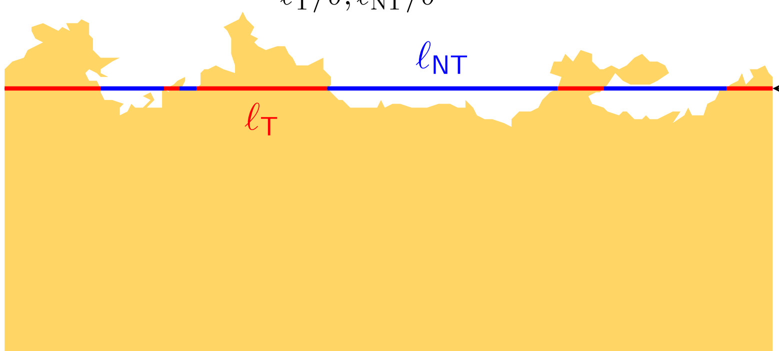


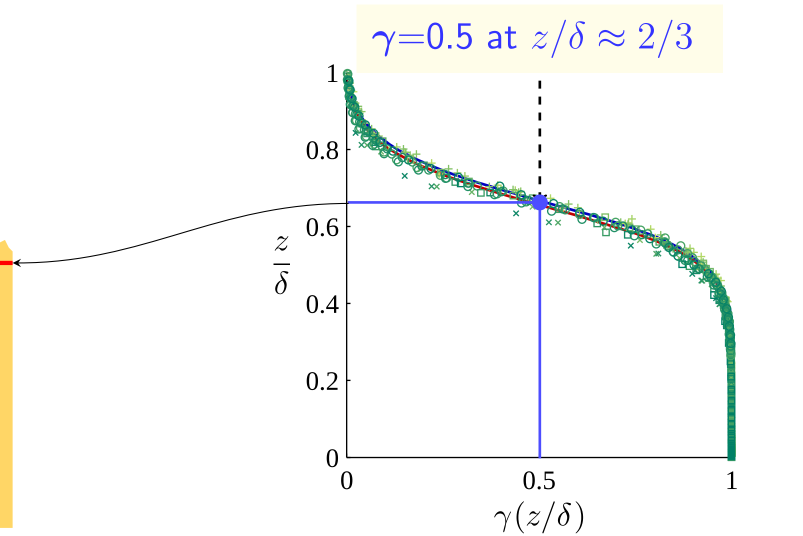


$$\mathcal{P}(\ell) = \mathsf{c}\, \ell^{-D_f+1}$$

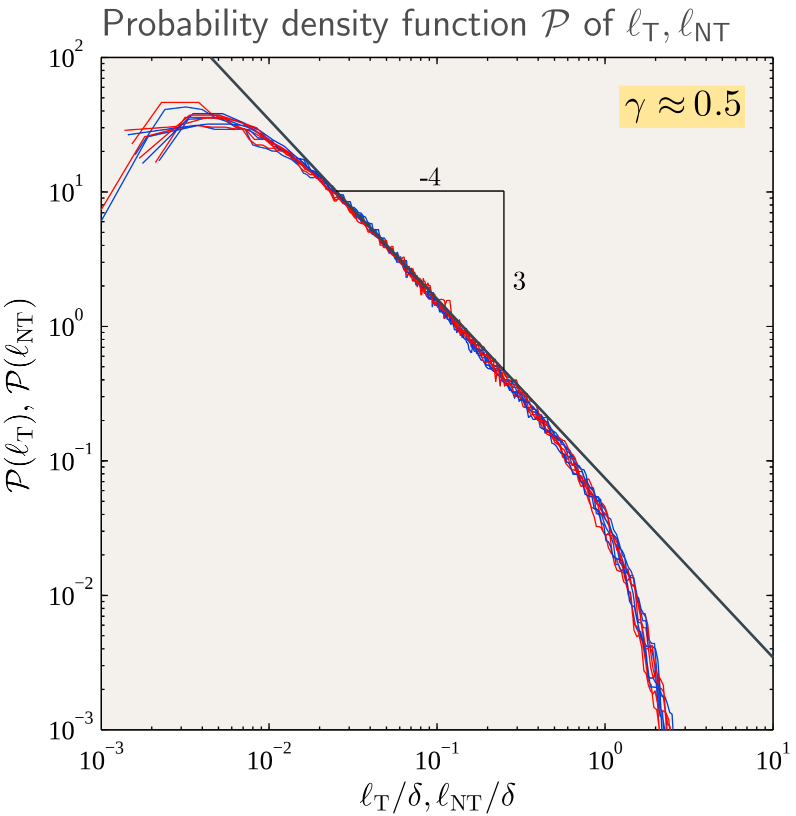
Segment lengths show fractal behaviour for more than a decade of intermediate scales

Slope = -4/3 (D_f=-7/3) is consistent with previous studies (e.g. Sreenivasan & Meneveau, 1986; Tsuji *et al.*, 1991; de Silva *et al.*, 2013)

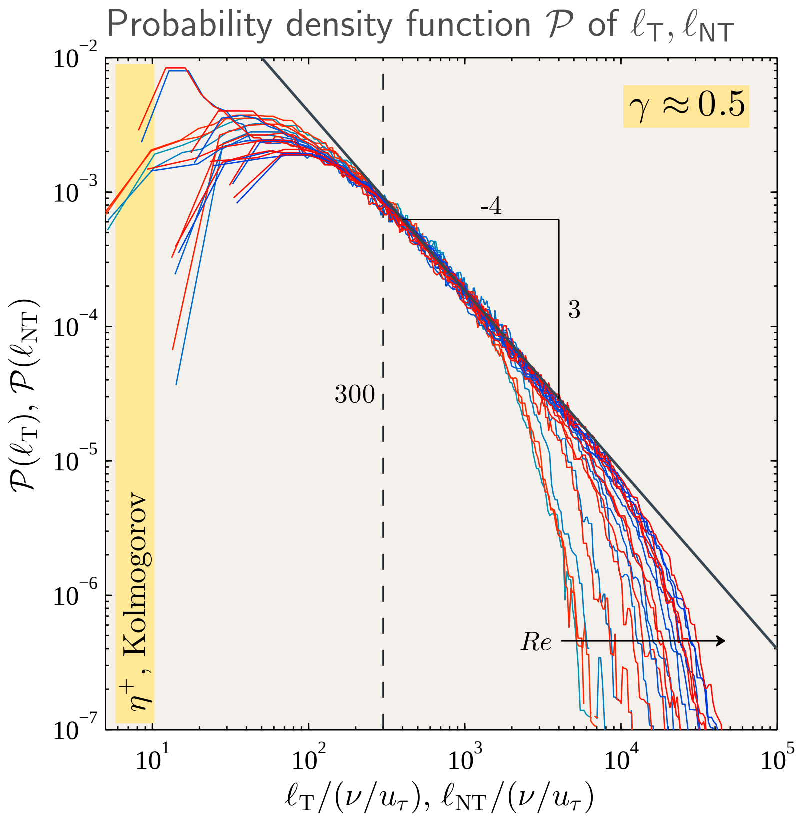




1.4 Characteristics of ℓ at $\gamma = 0.5$, i.e. $(z/\delta = 2/3)$

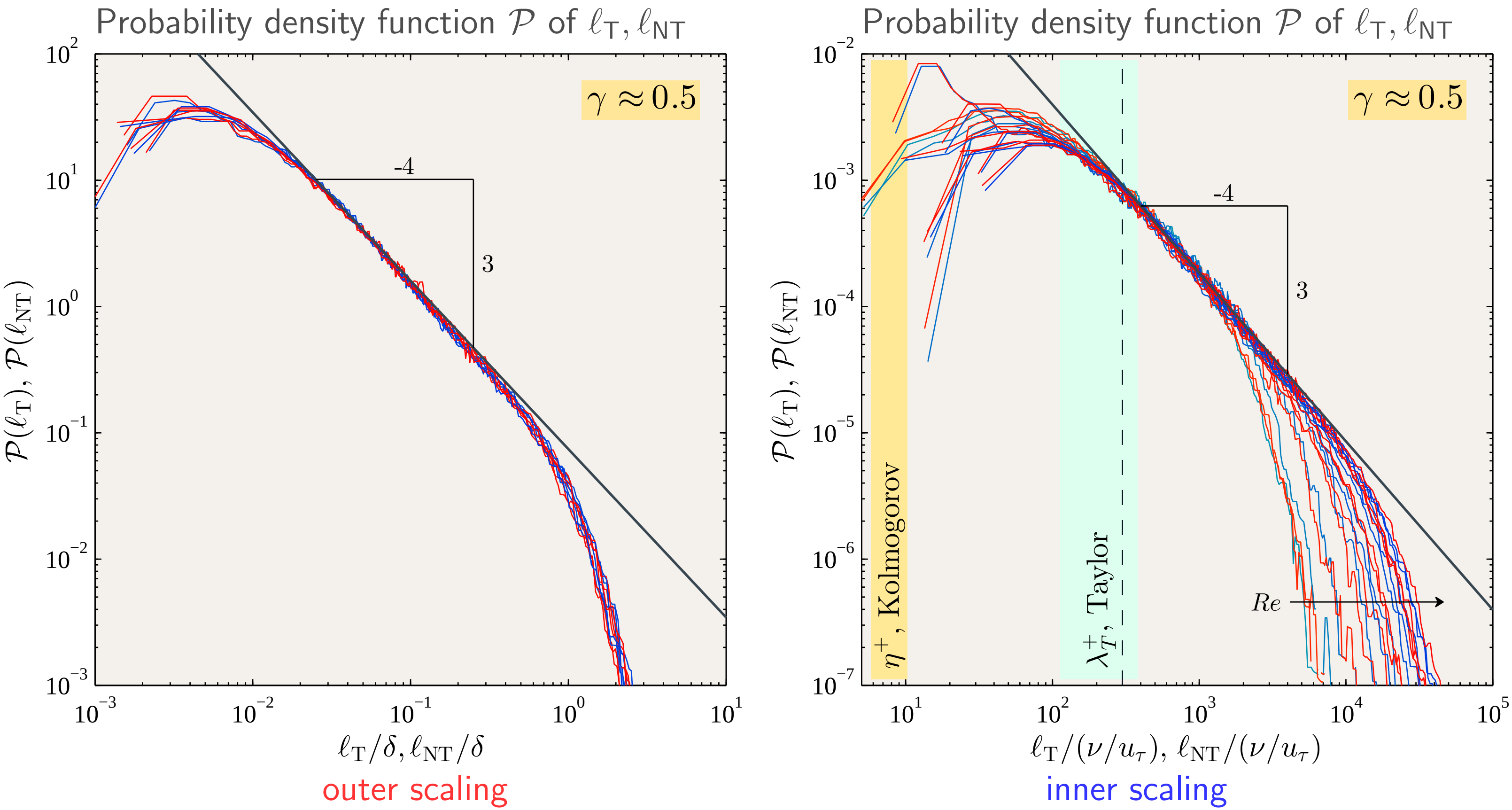


outer scaling

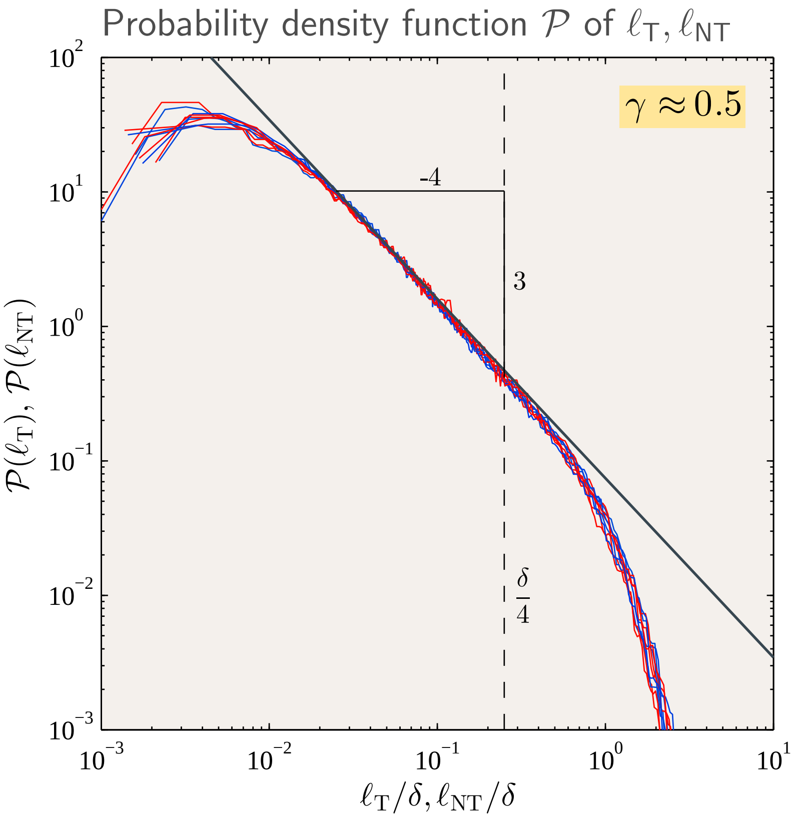


inner scaling

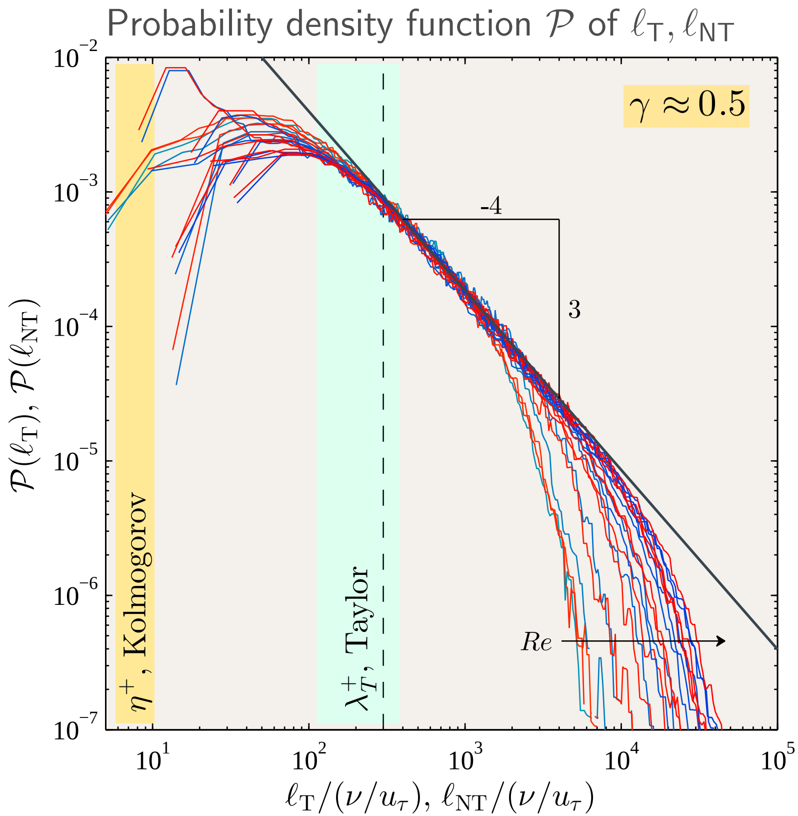
1.4 Characteristics of ℓ at $\gamma = 0.5$, i.e. $(z/\delta = 2/3)$



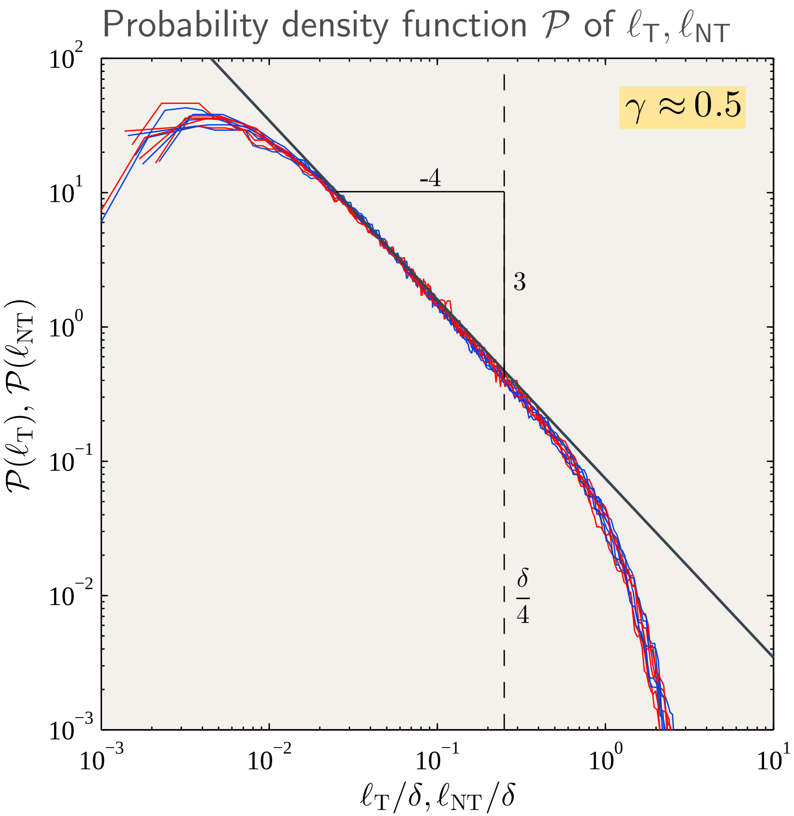
1.4 Characteristics of ℓ at $\gamma = 0.5$, i.e. $(z/\delta = 2/3)$



outer scaling

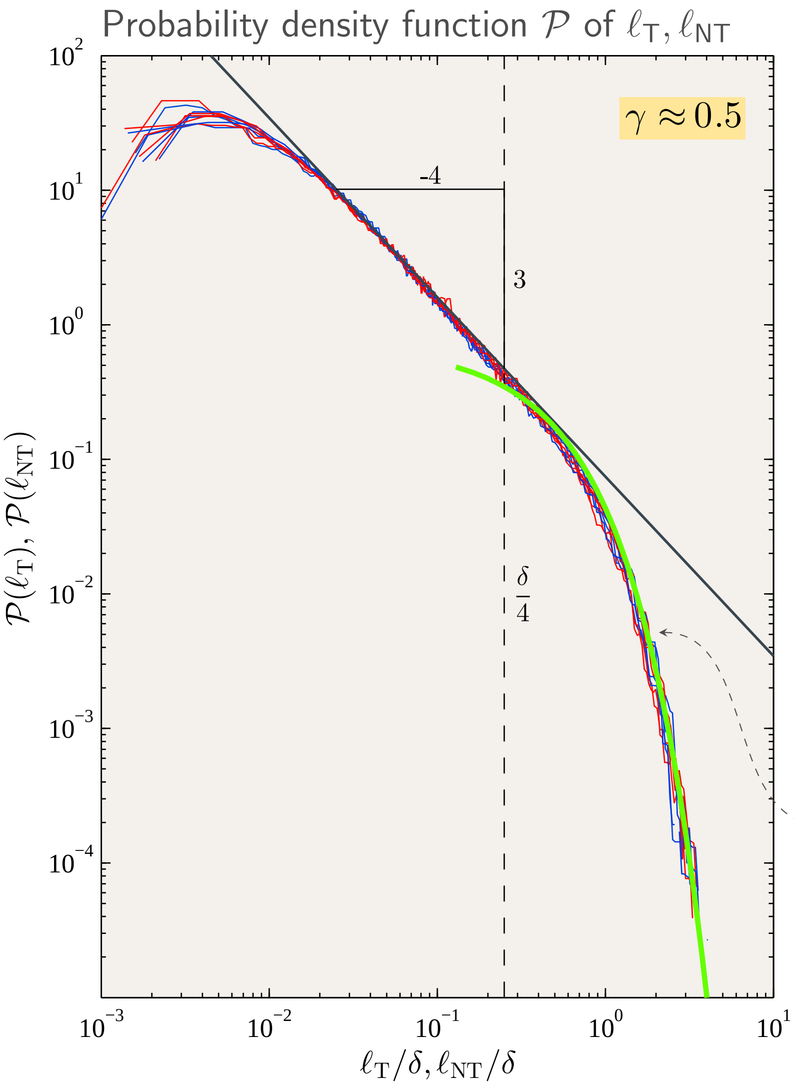


inner scaling



Corrsin, S. & Kistler, A. L. 1955 Free-stream boundaries of turbulent flows. Tech. Rep. TN-1244. NACA, Washington, DC

It would be interesting to know whether p_1 and p_2 approximate exponential distributions for large values of T_1 and T_2. However, the uncertainty of the points in just this range is so great as to render such a quantitative question unanswerable.



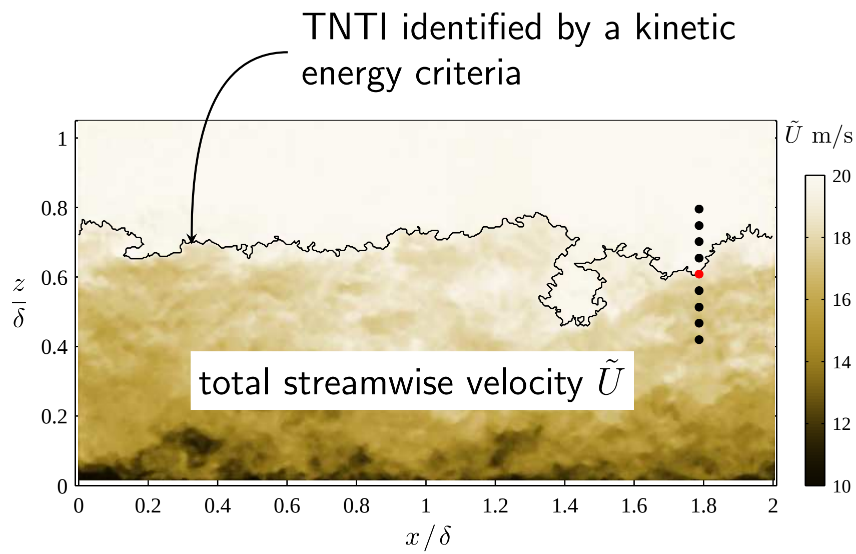
Corrsin, S. & Kistler, A. L. 1955 Free-stream boundaries of turbulent flows. Tech. Rep. TN-1244. NACA, Washington, DC

It would be interesting to know whether p_1 and p_2 approximate exponential distributions for large values of T_1 and T_2. However, the uncertainty of the points in just this range is so great as to render such a quantitative question unanswerable.

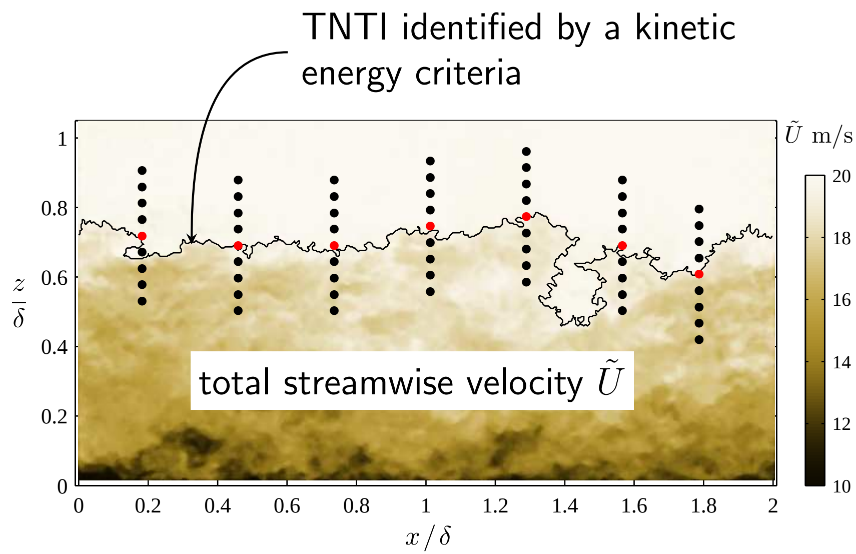
Exponential distribution
$\mathcal{P}(\ell) = \lambda \exp\left[-\lambda\left(\ell/\ell_c\right)\right]$
describes the time between events in a Poisson process, i.e. a process in which events occur continuously and *independently* at a *constant average rate*.
The distribution is memoryless.

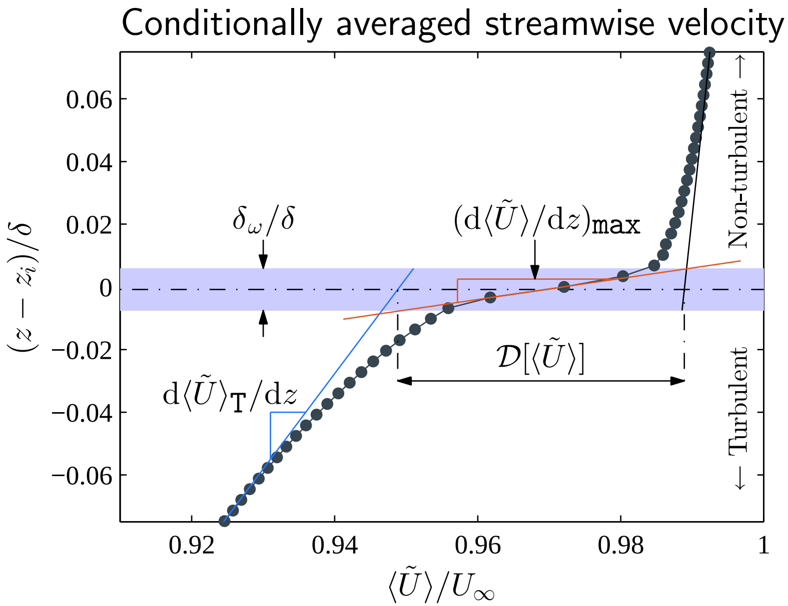
Part 2 - Local characteristics

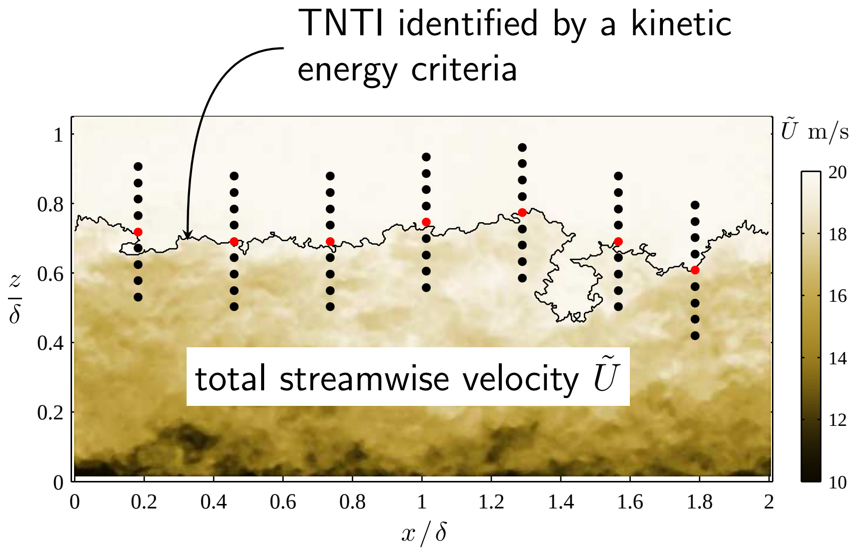
2.1 Conditional averaging relative to the TNTI



2.1 Conditional averaging relative to the TNTI





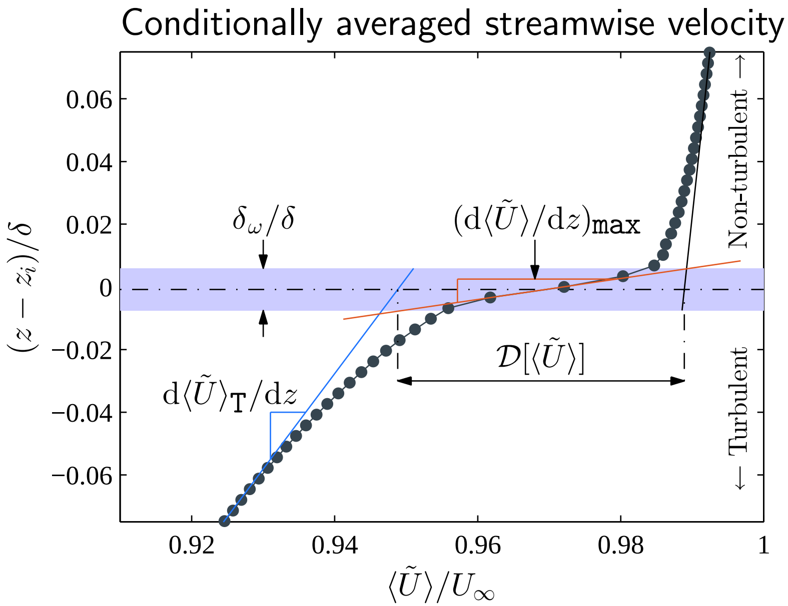


Vorticity thickness $\delta_\omega \equiv \dfrac{\mathcal{D}[\langle\tilde{U}\rangle]}{\mathrm{d}\langle\tilde{U}\rangle/\mathrm{d}z|_{\max}}$

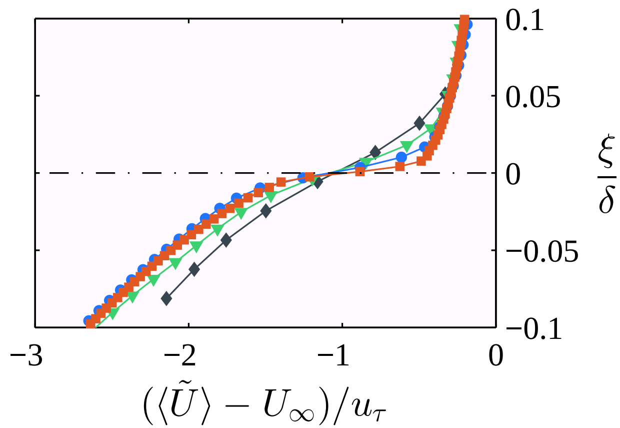
- Linear behaviour of velocity in the turbulent part (e.g. Kovasznay *et al.*, 1970, JFM)
- Sharp change in velocity across the interface (e.g. Chen & Blackwelder, 1978, JFM)
- Similar observations in jets and wakes by Bisset *et al.* (2002); Westerweel *et al.* (2009)

Laminar superlayer as first suggested by Corrsin & Kistler (1955)(NACA TN-1244) exists at the T/NT interface

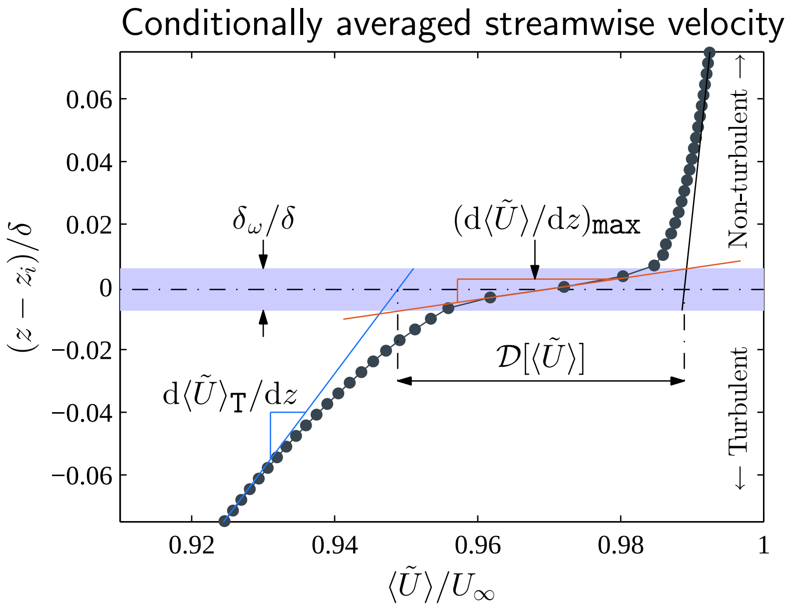
2.2 Scaling - conditional velocity deficit

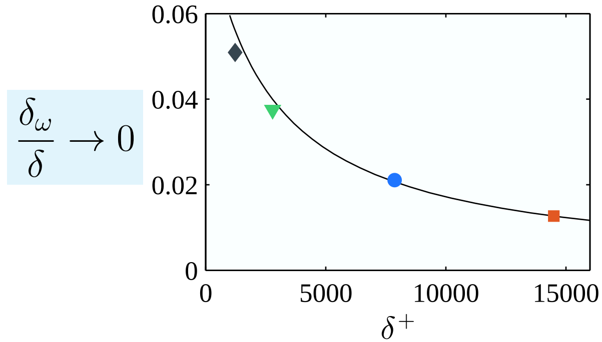


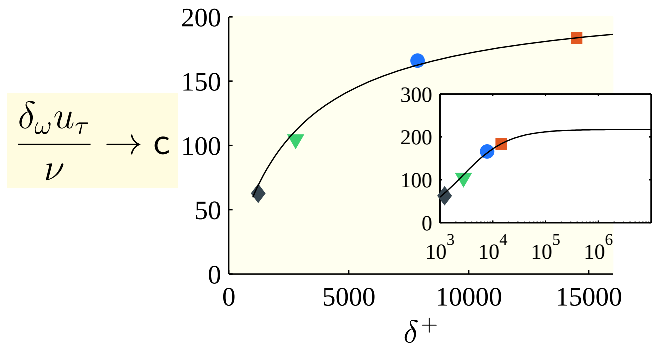
A sharp change in velocity akin to a jump is present at all Re



Experiment	δ^+	U_∞ (m s^{-1})	δ (m)	u_τ (m s^{-1})	$L_x \times L_z$	$\Delta x^+ \times \Delta z^+$	$\tilde{k}$	N_f	Symbol
Hambleton *et al.* (2005)	1230	6	0.08	0.25	$1.5\delta \times 1.34\delta$	32×32	0.15	1478	◆
Adrian *et al.* (2000)	2790	11.4	0.1	0.41	$1.4\delta \times 1.4\delta$	36×25	0.15	50	▼
Melbourne PIV	7870	10	0.36	0.33	$2\delta \times 1.1\delta$	52×52	0.12	1190	●
Melbourne PIV	14500	20	0.35	0.63	$2\delta \times 1.1\delta$	49×49	0.12	1250	■

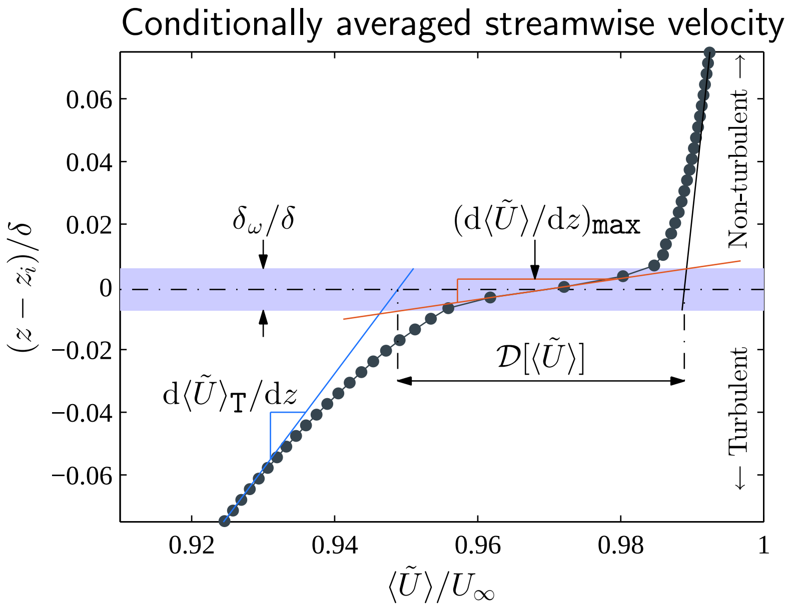


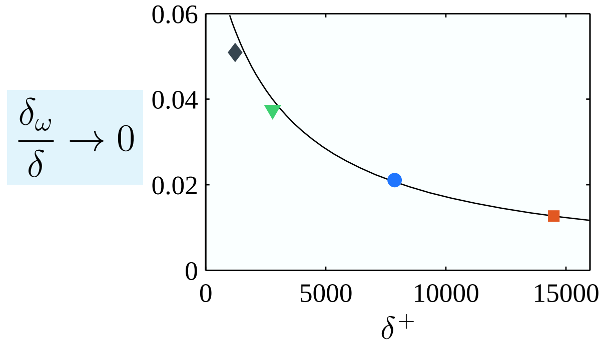


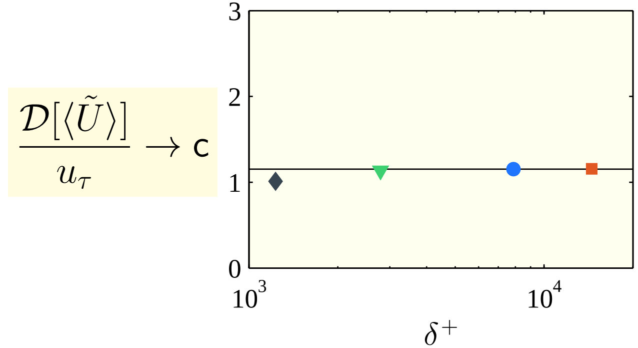


Experiment	δ^+	U_∞ (m s^{-1})	δ (m)	u_τ (m s^{-1})	$L_x \times L_z$	$\Delta x^+ \times \Delta z^+$	$\tilde{k}$	N_f	Symbol
Hambleton *et al.* (2005)	1230	6	0.08	0.25	$1.5\delta \times 1.34\delta$	32×32	0.15	1478	◆
Adrian *et al.* (2000)	2790	11.4	0.1	0.41	$1.4\delta \times 1.4\delta$	36×25	0.15	50	▼
Melbourne PIV	7870	10	0.36	0.33	$2\delta \times 1.1\delta$	52×52	0.12	1190	●
Melbourne PIV	14500	20	0.35	0.63	$2\delta \times 1.1\delta$	49×49	0.12	1250	■

2.3 Scaling of the superlayer characteristics



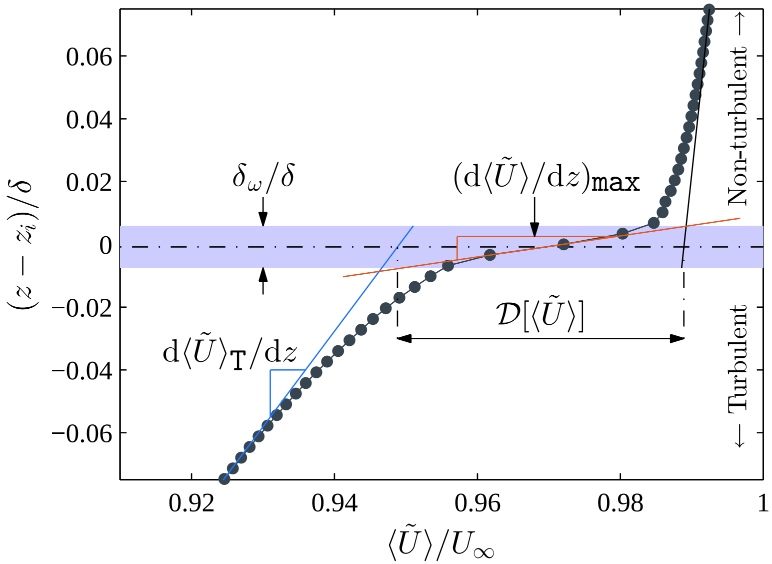




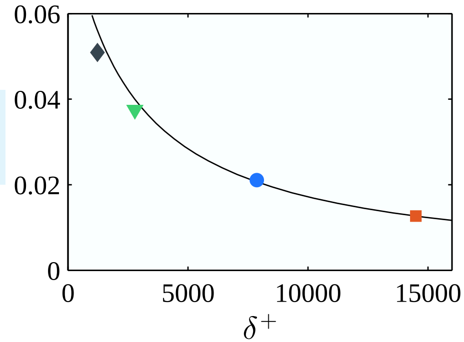
Experiment	δ^+	U_∞ (m s^{-1})	δ (m)	u_τ (m s^{-1})	$L_x \times L_z$	$\Delta x^+ \times \Delta z^+$	$\tilde{k}$	N_f	Symbol
Hambleton *et al.* (2005)	1230	6	0.08	0.25	$1.5\delta \times 1.34\delta$	32×32	0.15	1478	◆
Adrian *et al.* (2000)	2790	11.4	0.1	0.41	$1.4\delta \times 1.4\delta$	36×25	0.15	50	▼
Melbourne PIV	7870	10	0.36	0.33	$2\delta \times 1.1\delta$	52×52	0.12	1190	●
Melbourne PIV	14500	20	0.35	0.63	$2\delta \times 1.1\delta$	49×49	0.12	1250	■

2.3 Scaling of the superlayer characteristics

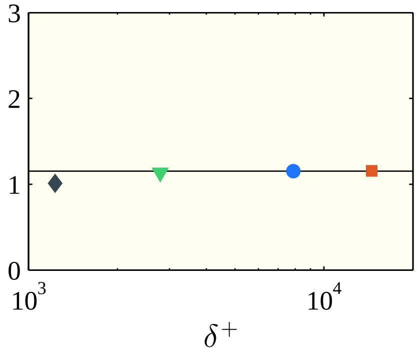
Conditionally averaged streamwise velocity



$$\frac{\delta_\omega}{\delta} \to 0$$

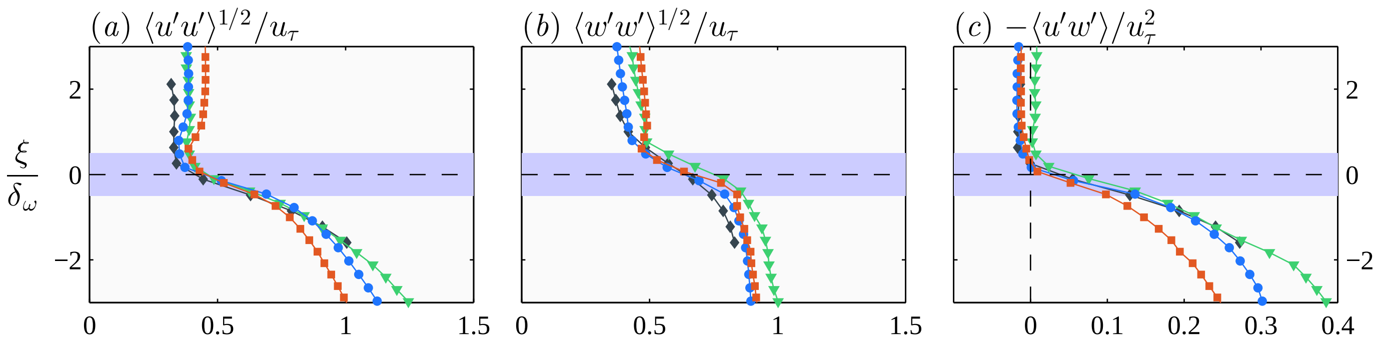


$$\frac{\mathcal{D}[\langle\tilde{U}\rangle]}{u_\tau} \to \mathrm{c}$$

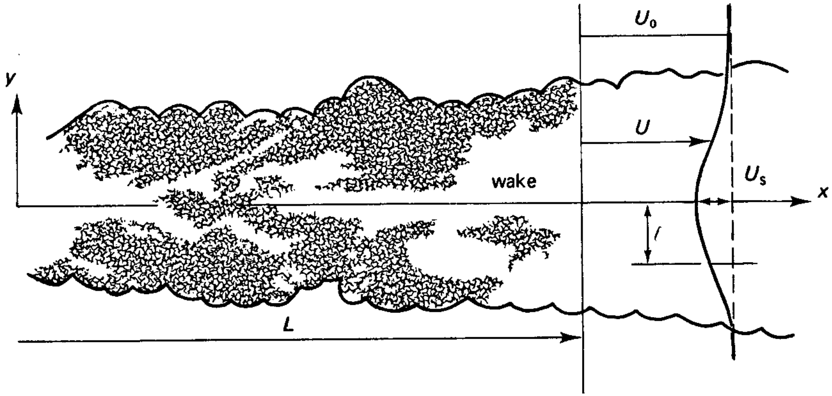


Turbulent stresses, fluctuations relative to the conditional mean

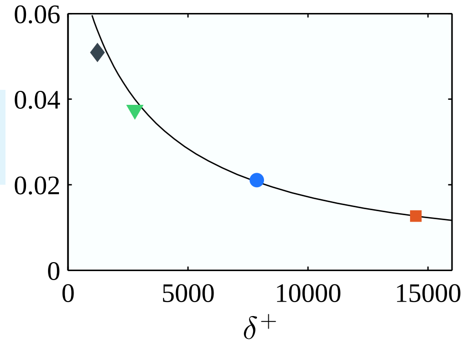
$$\langle u_i' u_j' \rangle \sim u_\tau^2$$



2.3 Scaling of the superlayer characteristics

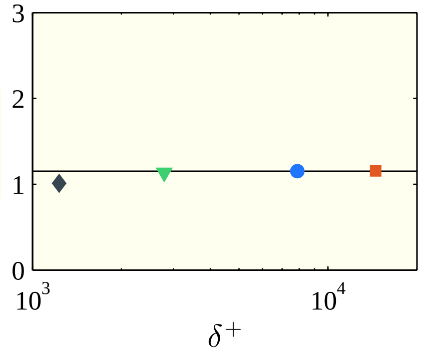


$$\frac{\delta_\omega}{\delta} \to 0$$



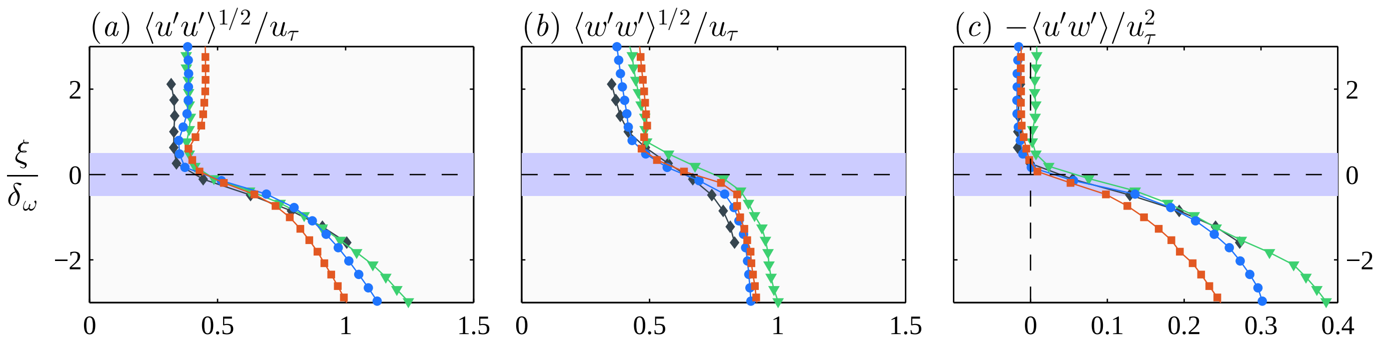
The fluctuations scale according to the mean velocity deficit, *similar to a turbulent wake*

$$\frac{\mathcal{D}[\langle \tilde{U} \rangle]}{u_\tau} \to \text{c}$$

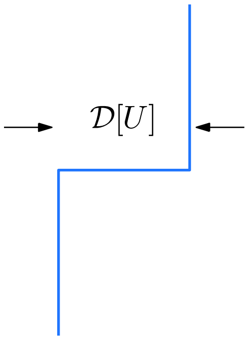


Turbulent stresses, fluctuations relative to the conditional mean

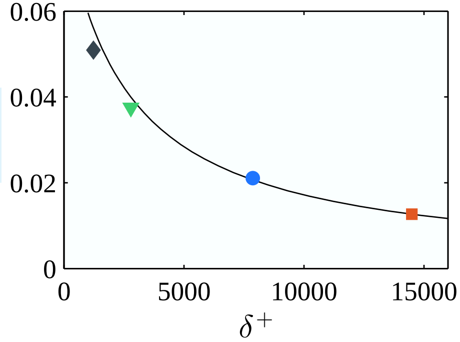
$$\langle u_i' u_j' \rangle \sim u_\tau^2$$



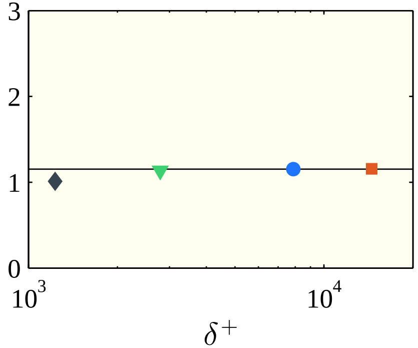
Velocity jump



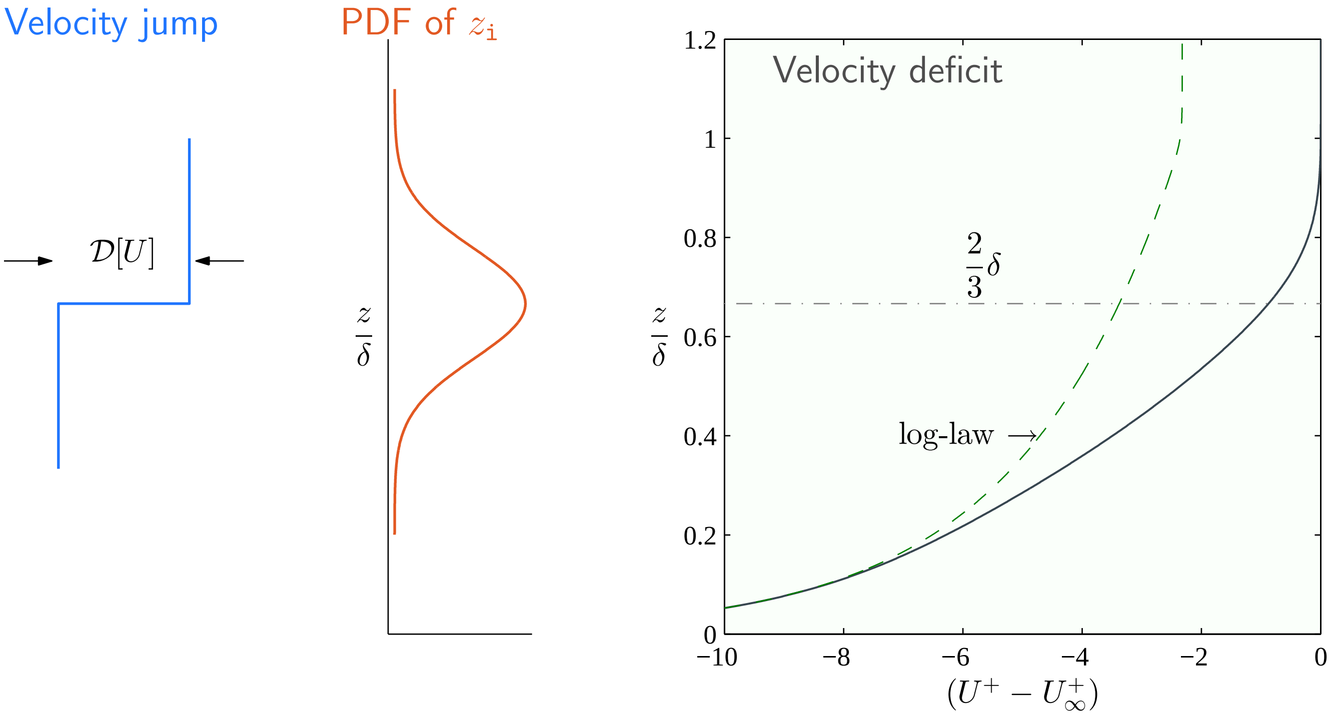
$$\frac{\delta_\omega}{\delta} \rightarrow 0$$



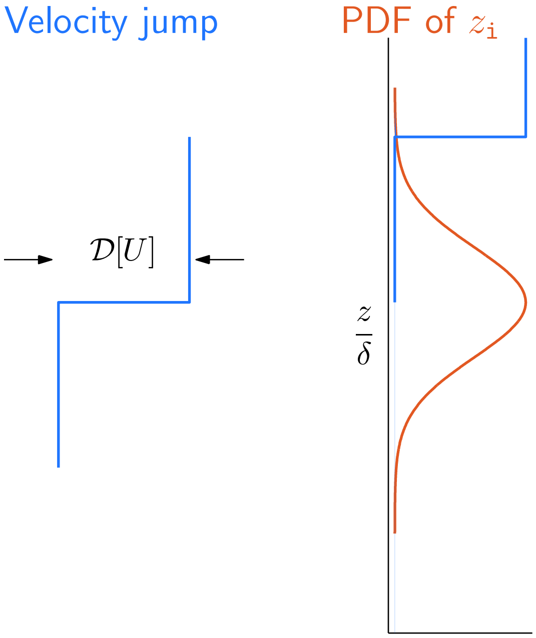
$$\frac{\mathcal{D}[\langle \tilde{U} \rangle]}{u_\tau} \rightarrow \text{c}$$

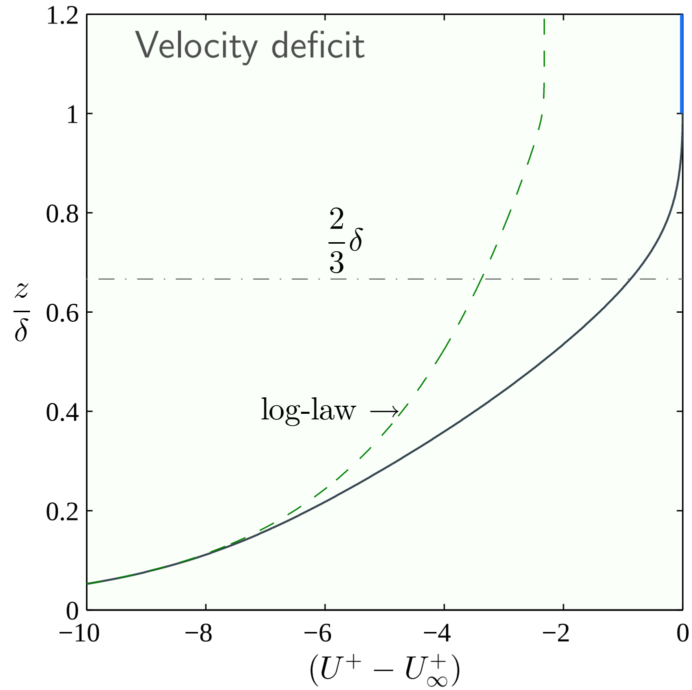


2.4 The superlayer in the outer region

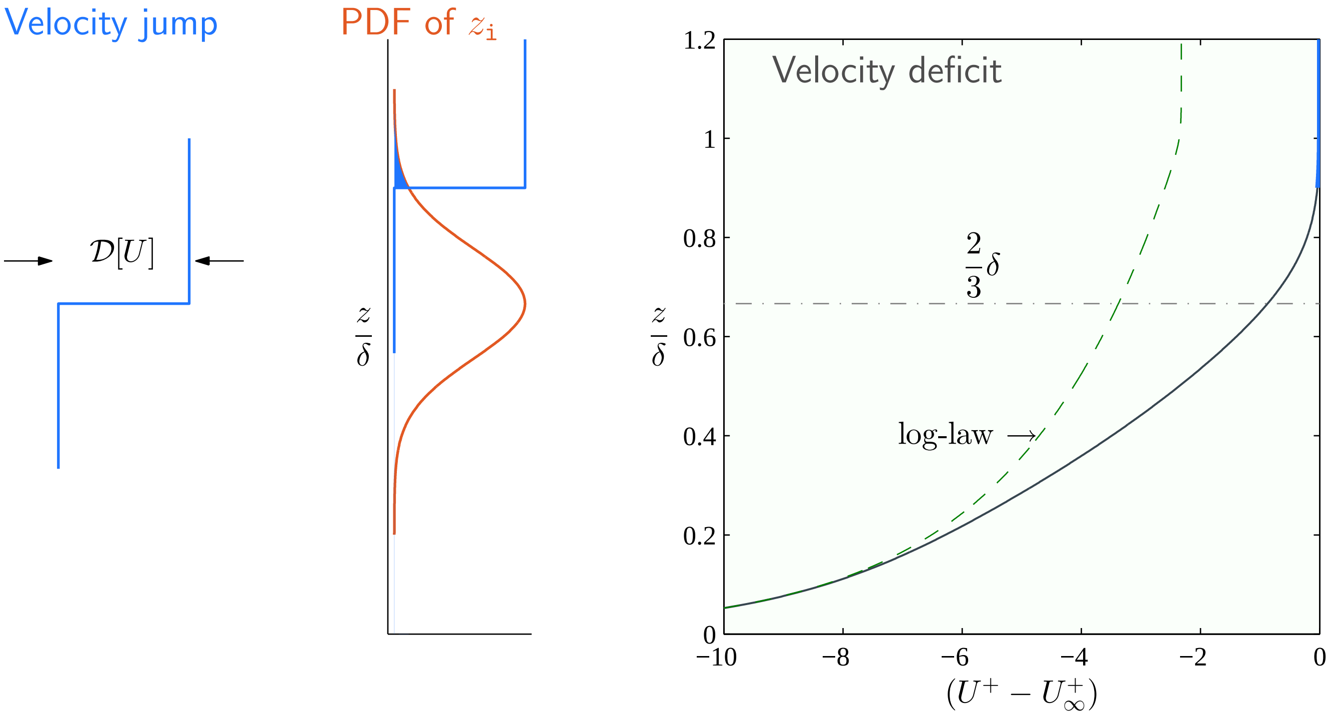


2.4 The superlayer in the outer region

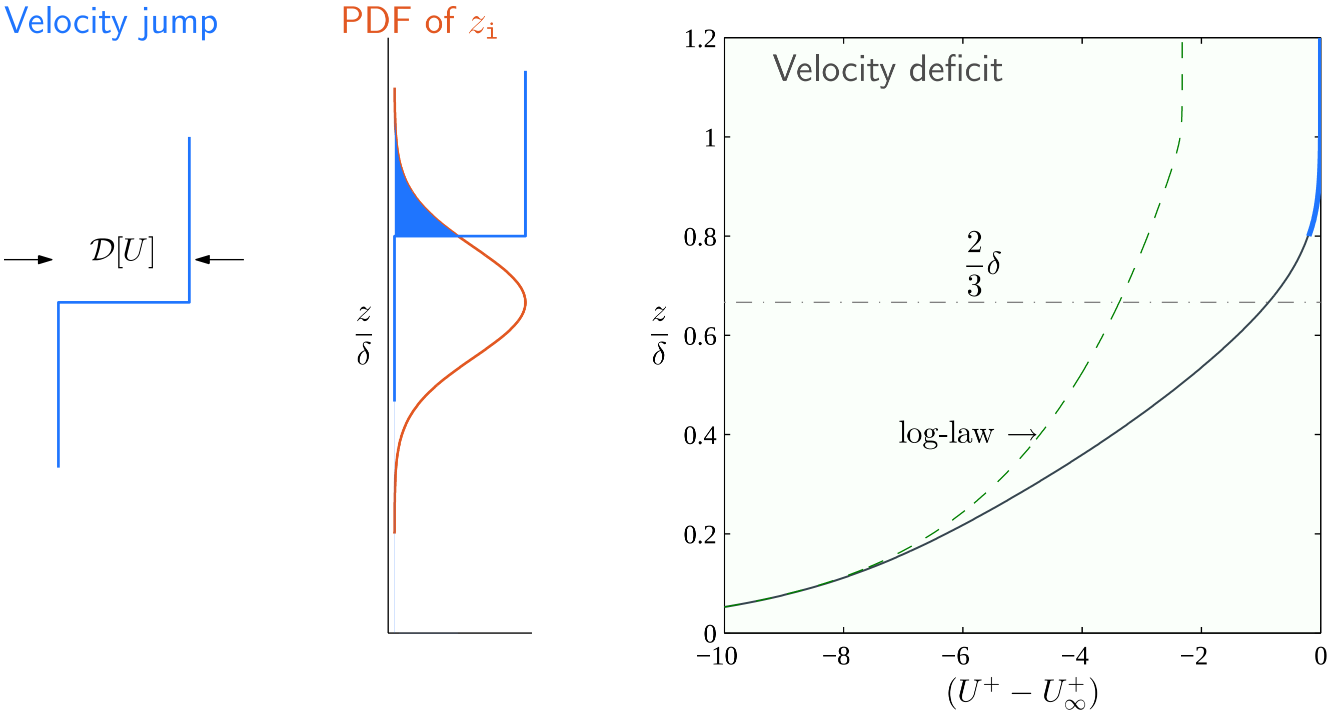




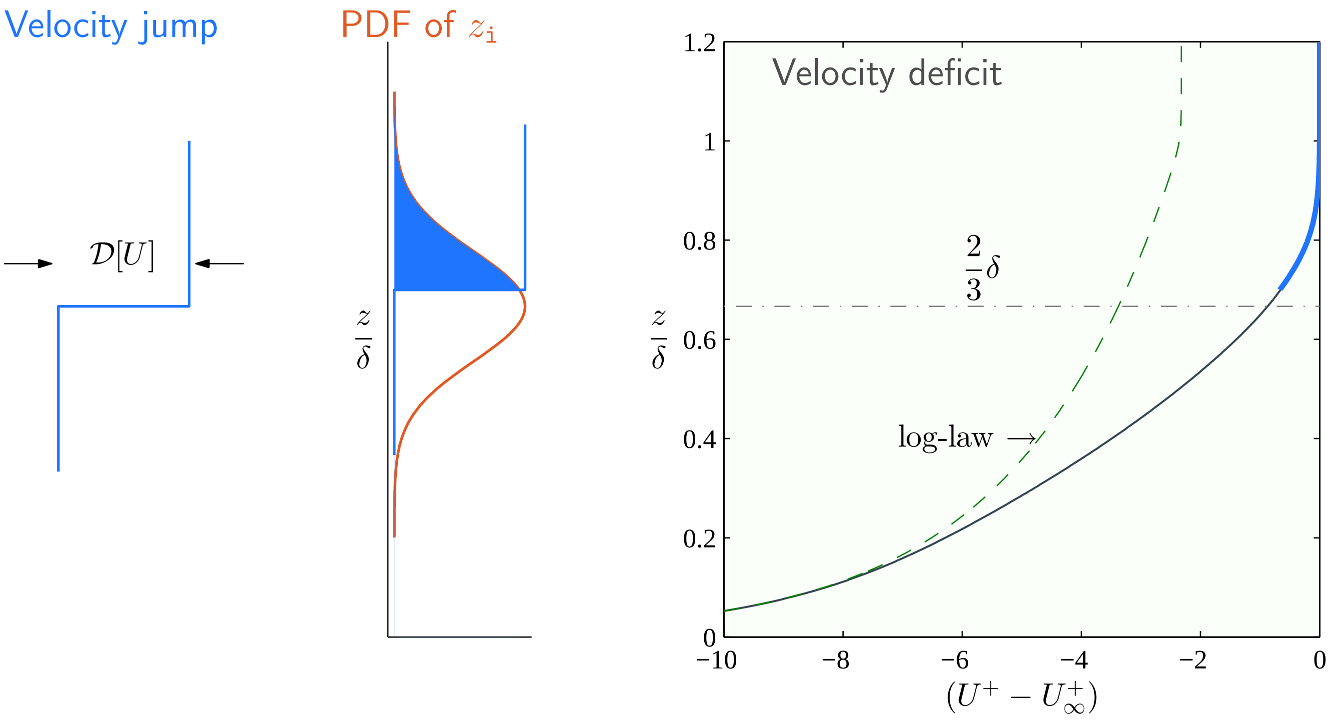
2.4 The superlayer in the outer region



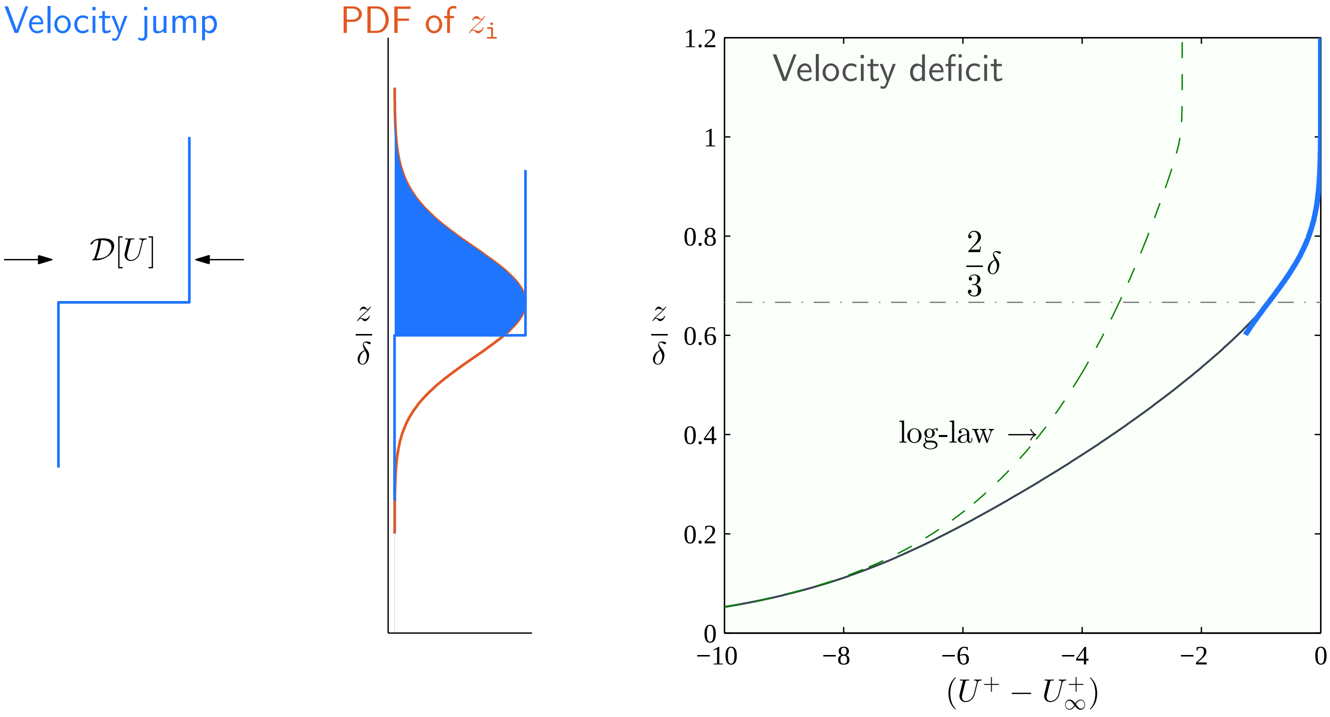
2.4 The superlayer in the outer region



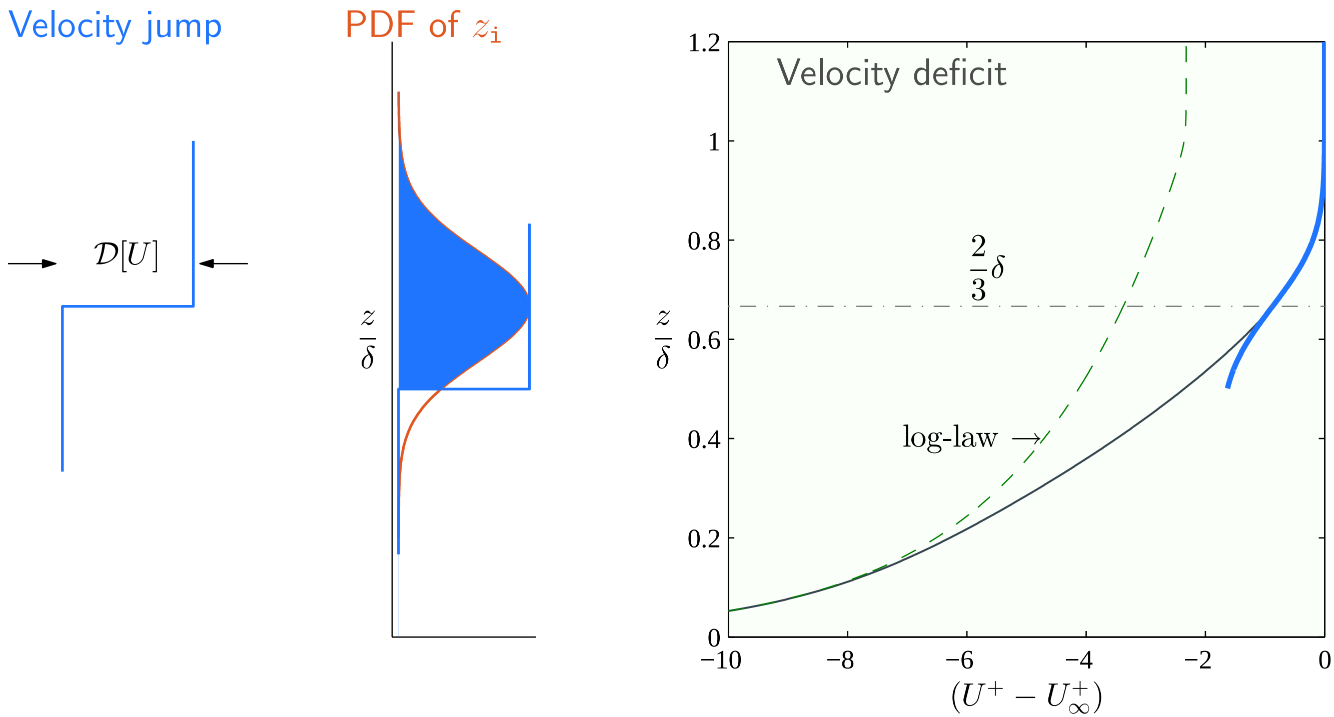
2.4 The superlayer in the outer region



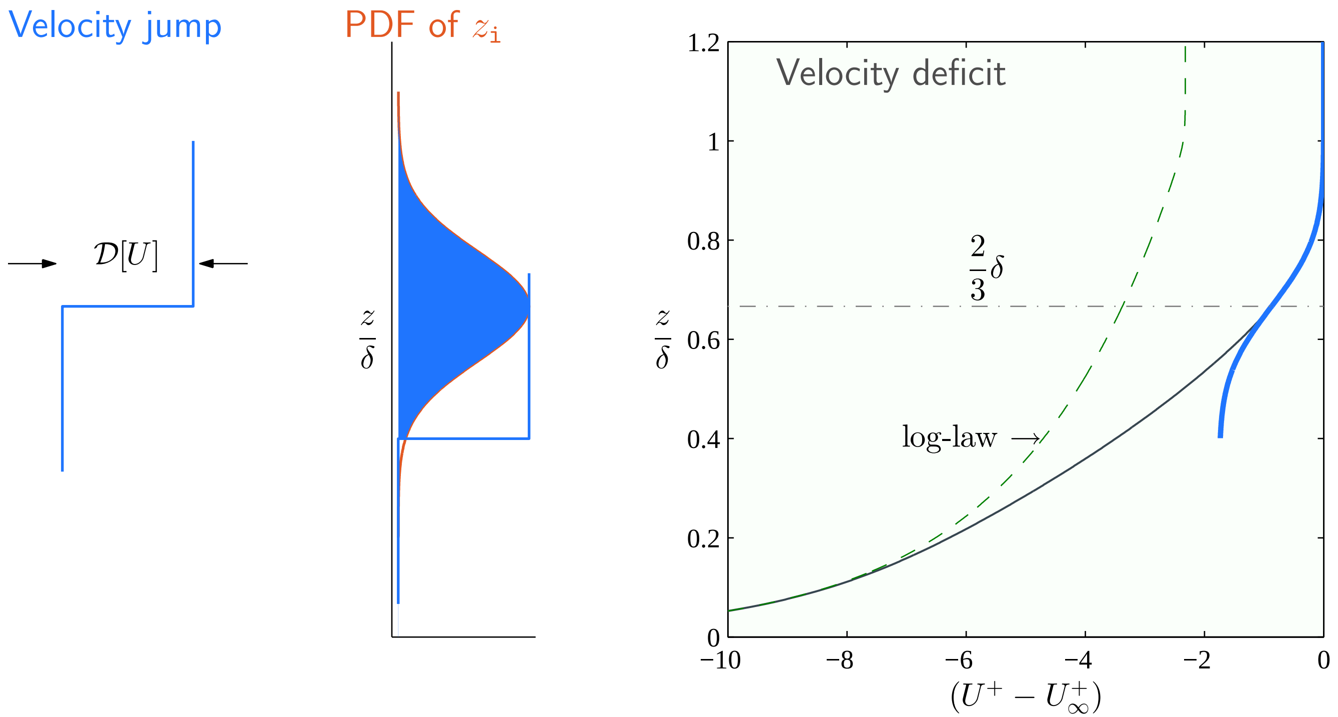
2.4 The superlayer in the outer region



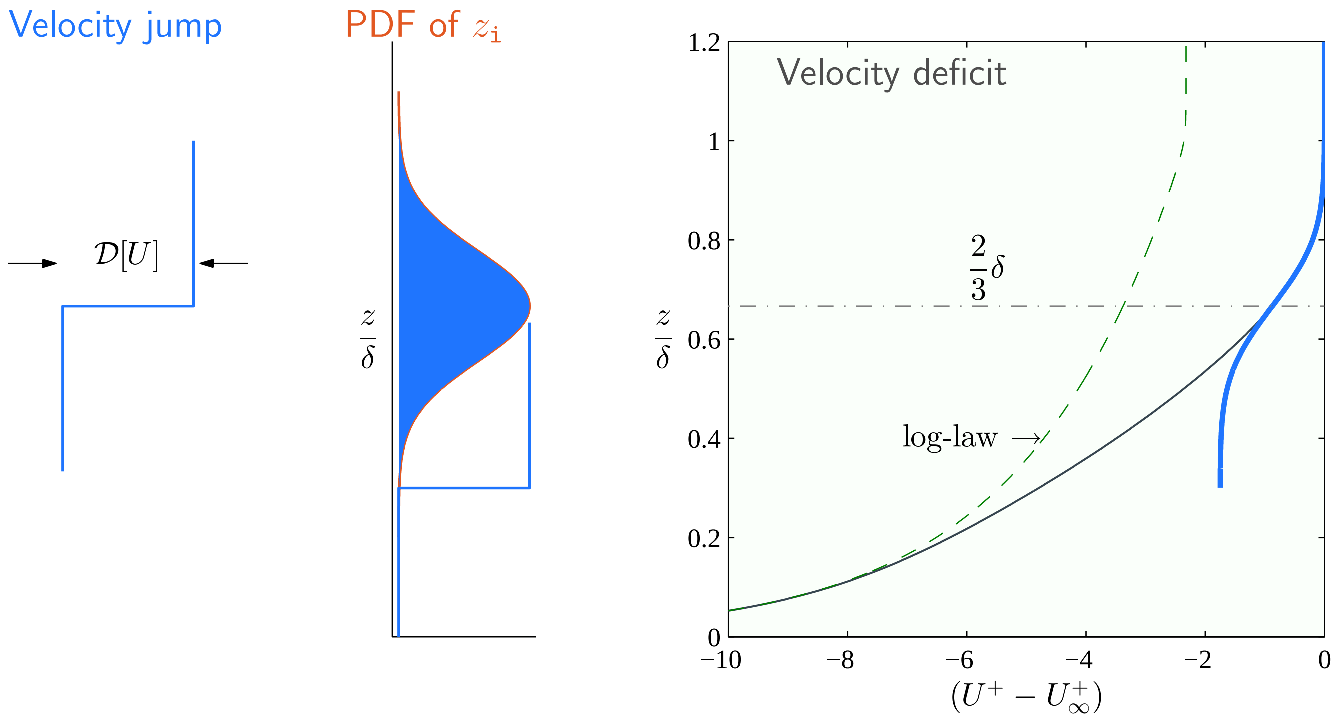
2.4 The superlayer in the outer region

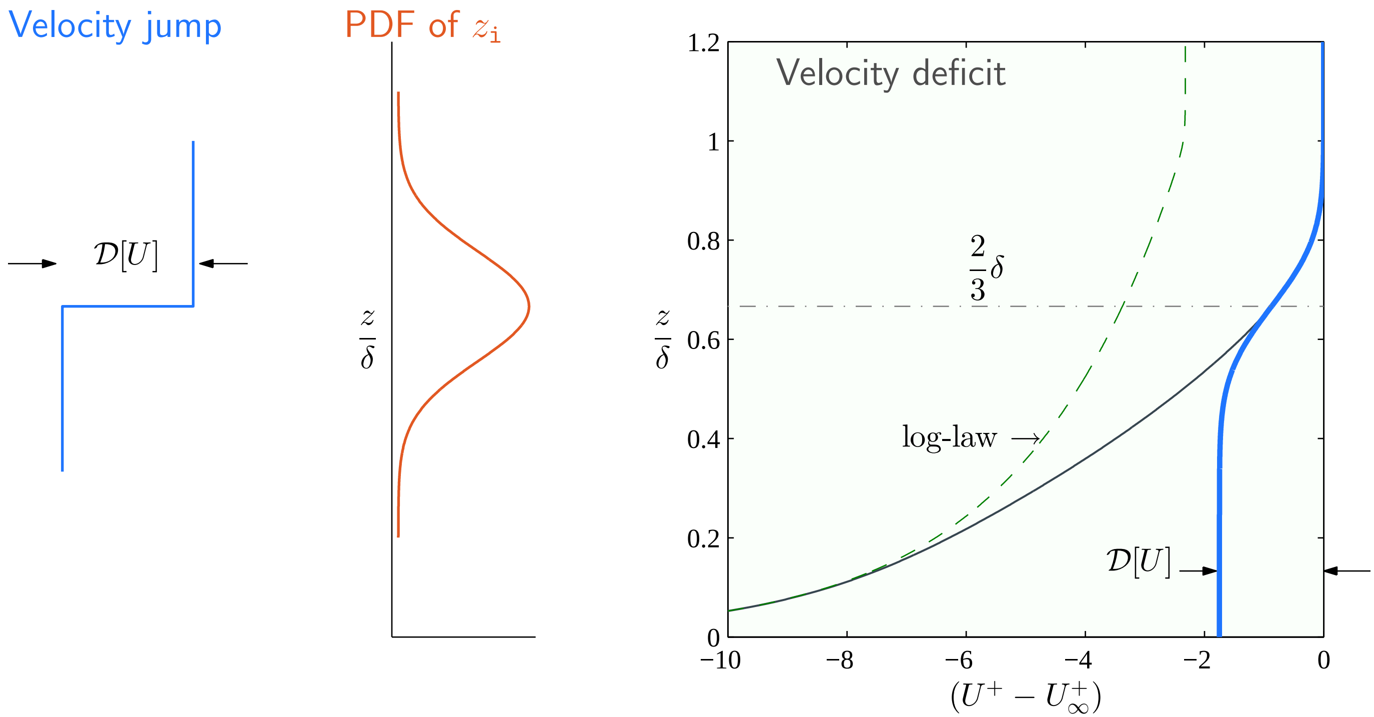


2.4 The superlayer in the outer region



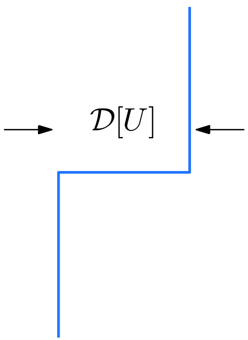
2.4 The superlayer in the outer region



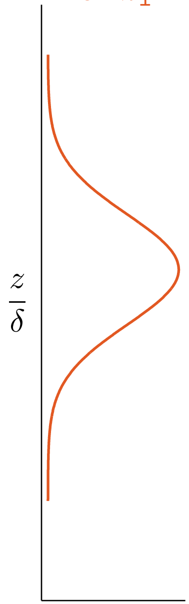

Velocity jump
$\mathcal{D}[U]$
PDF of z_i
$\frac{z}{\delta}$
Velocity deficit
1.2
1
0.8
0.6
0.4
0.2
0
$\frac{2}{3}\delta$
log-law →
$\mathcal{D}[U]$
−10
−8
−6
−4
−2
0
$(U^+ - U^+_\infty)$

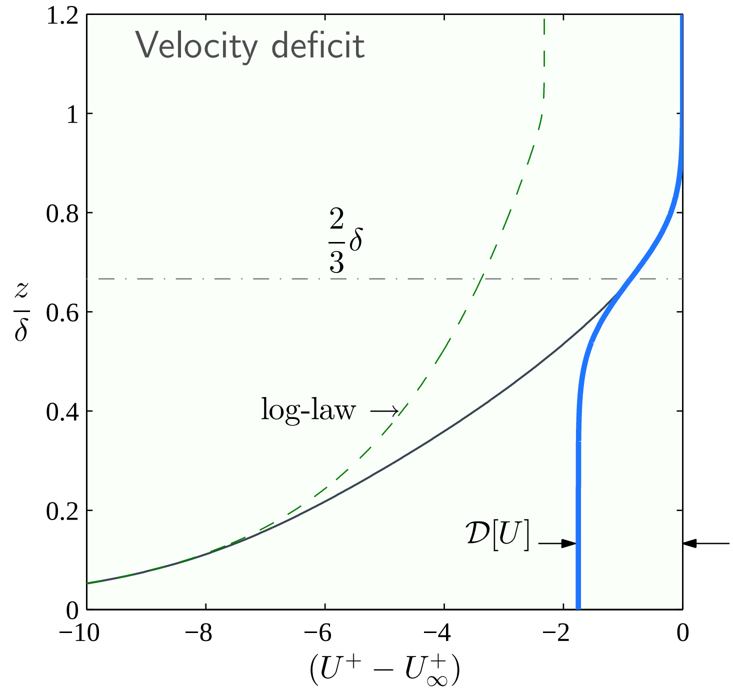
2.4 The superlayer in the outer region

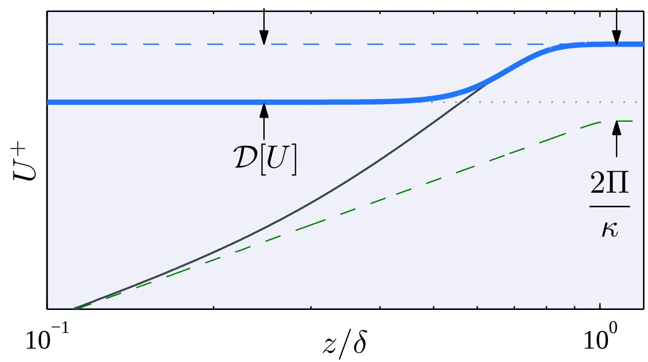
Velocity jump



PDF of z_i

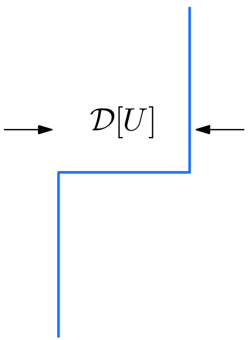




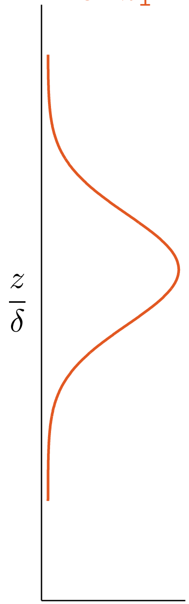


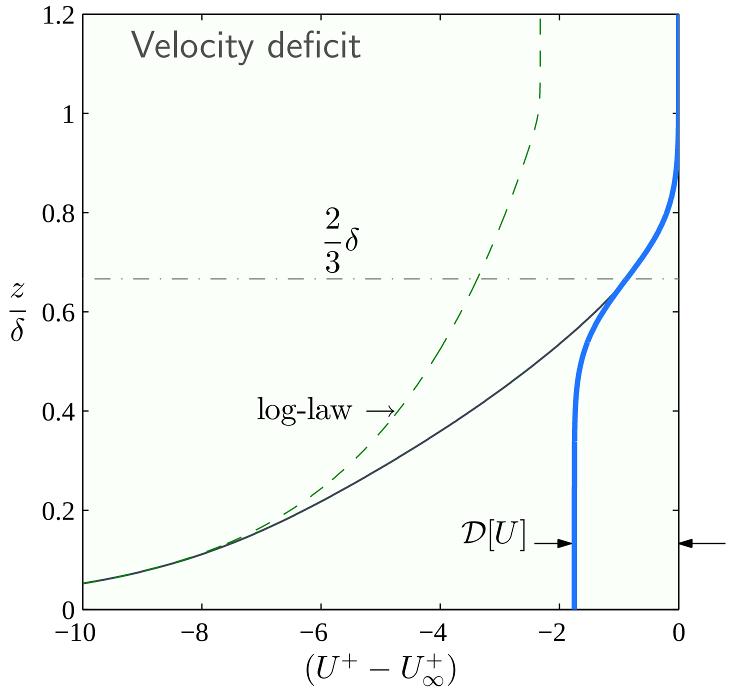
2.4 The superlayer in the outer region

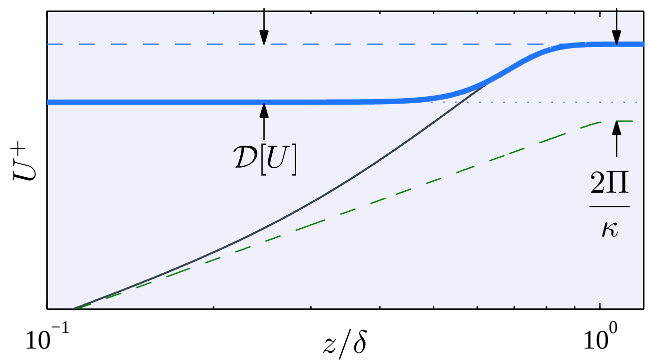
Velocity jump



PDF of z_i







Corrsin's superlayer influences Coles' wake

also Nee & Kovasznay (1969), Huffman & Bradshaw (1972) and Jiménez *et al.* (2010)

1. Global characteristics
   - The turbulent/non-turbulent zone lengths exhibit fractal scaling for the intermediate scales ($\lambda_T \lesssim \ell \lesssim \delta/4$). The fractal dimension is -4/3.
   - The tail of the probability density follows an exponential distribution. Large-scale turbulent/non-turbulent zones are appear in a statistically independent manner.

1. Global characteristics
   - The turbulent/non-turbulent zone lengths exhibit fractal scaling for the intermediate scales ($\lambda_T \lesssim \ell \lesssim \delta/4$). The fractal dimension is -4/3.
   - The tail of the probability density follows an exponential distribution. Large-scale turbulent/non-turbulent zones are appear in a statistically independent manner.
2. Local characteristics (of superlayer)
   - Superlayer is shown to exists at the TNTI over a wide Re range.
   - Superlayer jump contributes to the overall wake strength. The presence of superlayer in boundary layers explains the higher wake strength compared to pipe and channels.

APS talk: 'Scaling of the viscous superlayer in zero pressure gradient turbulent boundary layers'
Session R31: Structure of Turbulent/Non-Turbulent Interface
1:00PM Tuesday, 11/26/13, Room: 402

1. Global characteristics
   - The turbulent/non-turbulent zone lengths exhibit fractal scaling for the intermediate scales ($\lambda_T \lesssim \ell \lesssim \delta/4$). The fractal dimension is -4/3.
   - The tail of the probability density follows an exponential distribution. Large-scale turbulent/non-turbulent zones are appear in a statistically independent manner.
2. Local characteristics (of superlayer)
   - Superlayer is shown to exists at the TNTI over a wide Re range.
   - Superlayer jump contributes to the overall wake strength. The presence of superlayer in boundary layers explains the higher wake strength compared to pipe and channels.

APS talk: 'Scaling of the viscous superlayer in zero pressure gradient turbulent boundary layers'
Session R31: Structure of Turbulent/Non-Turbulent Interface
1:00PM Tuesday, 11/26/13, Room: 402

Questions?