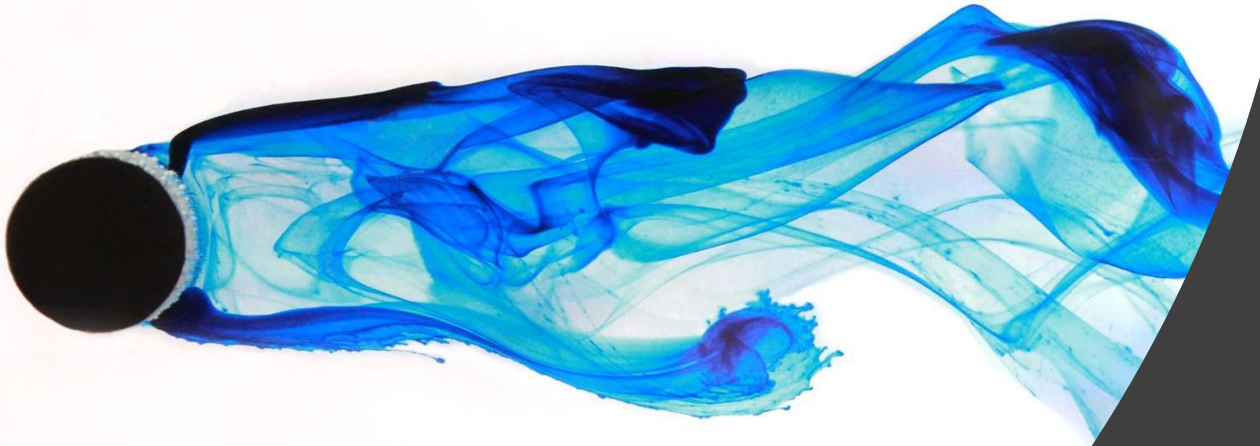


Preliminary Results of Turbulence in Twente Mass and Heat Transfer Water Tunnel

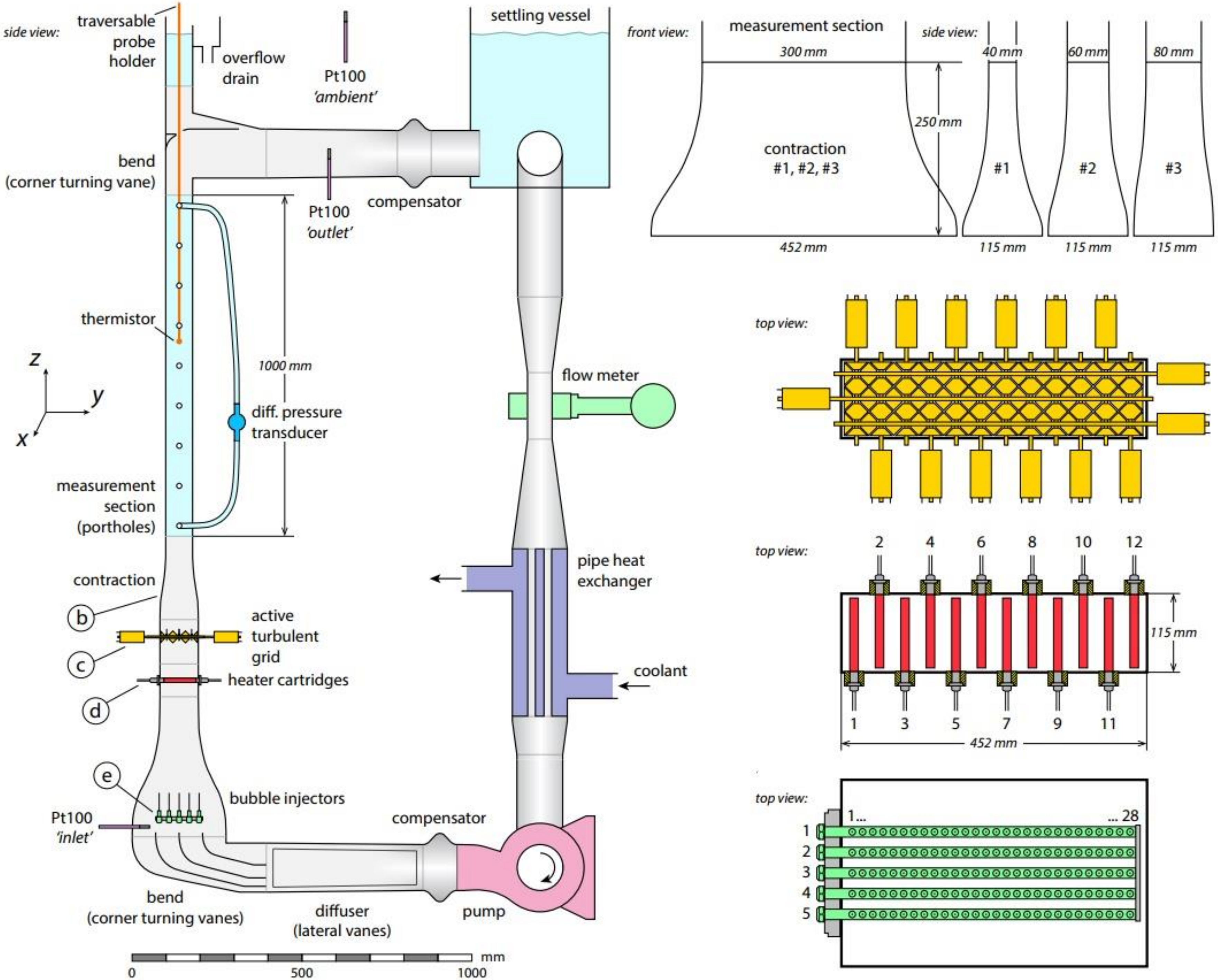
CHEUNG Cheuk Kit

Objective

- Focus on the statistical properties of single-phase turbulent channel flow
    - SD, Skewness, Kurtosis
    - PDF
    - Thermal spectra
    - Structure function
    - Extensive Self-similarity
    - Scaling exponent

Twente Mass and Heat Transfer Water Tunnel

- Design for studying shear-induced multi-phase turbulent channel flow
  - Turbulent Grids
  - Thermistor
  - Measurement section (Glass channel)
  - Water pump
  - Bubble injectors


side view:
traversable probe holder
overflow drain
Pt100 'ambient'
settling vessel
bend (corner turning vane)
Pt100 'outlet'
compensator
thermistor
1000 mm
z
y
x
diff. pressure transducer
flow meter
measurement section (portholes)
contraction
b
active turbulent grid
c
heater cartridges
d
pipe heat exchanger
coolant
e
bubble injectors
Pt100 'inlet'
compensator
bend (corner turning vanes)
diffuser (lateral vanes)
pump
mm
0
500
1000
front view:
measurement section
300 mm
250 mm
contraction #1, #2, #3
452 mm
side view:
40 mm
60 mm
80 mm
#1
#2
#3
115 mm
115 mm
115 mm
top view:
top view:
2
4
6
8
10
12
115 mm
1
3
5
7
9
11
452 mm
top view:
1...
... 28
1
2
3
4
5

Measurement Techniques

- Lock-in Amplifier
  - To amplify the signal
  - Increase signal-to-noise ratio
- Laser Doppler Anemometry (LDA)
  - To measure the flow speed

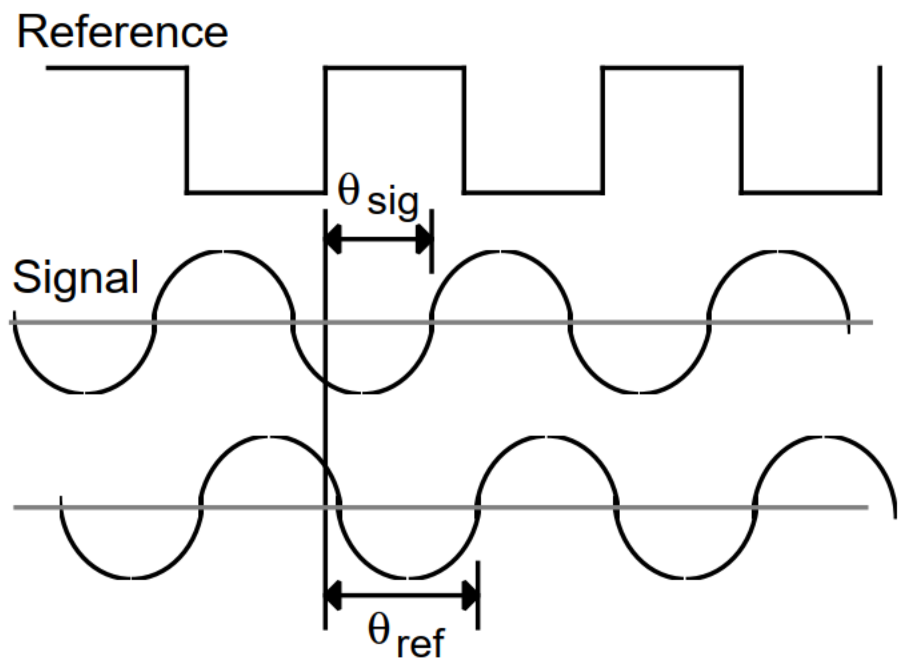
Lock-in Amplifier

$$V_{out} = V_{sig}V_L \sin(\omega_{sig}t + \theta_{sig}) \sin(\omega_L t + \theta_L)$$

If $\omega_{sig} = \omega_L$,

$$V_{out} = V_{sig}V_L \sin(\theta_{sig} - \theta_L) - V_{sig}V_L \cos[(\omega_{sig} + \omega_L)t + \theta_{sig} + \theta_L]$$

$$V'_{out} = V_{sig}V_L \sin\theta$$



Lock-in Reference

$$V'_{out} = V_{sig}V_L \sin\theta$$ ← Phase Sensitive

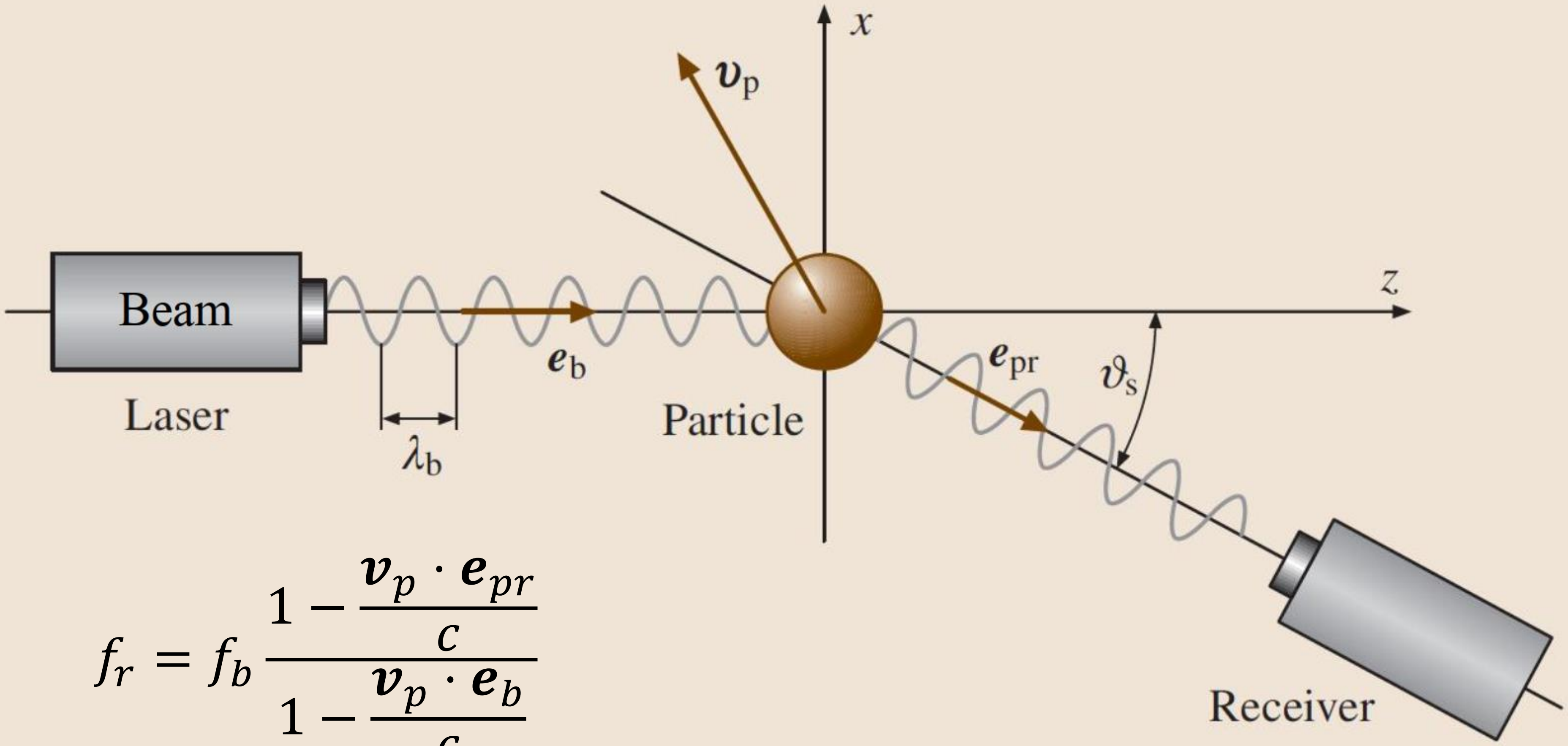
$$X_{out} = V_{sig}V_L \sin\theta$$

$$Y_{out} = V_{sig}V_L \cos\theta$$

$$R_{out} = X_{out}^2 + Y_{out}^2$$

Laser Doppler Anemometry (LDA)

- Direction sensitivity
- High accuracy
- High spatial resolution
- Tracer particles are required



$$f_r = f_b \frac{1 - \dfrac{\boldsymbol{v}_p \cdot \boldsymbol{e}_{pr}}{c}}{1 - \dfrac{\boldsymbol{v}_p \cdot \boldsymbol{e}_b}{c}}$$

$$f_r = f_b \frac{1 - \frac{\boldsymbol{v}_p \cdot \boldsymbol{e}_{pr}}{c}}{1 - \frac{\boldsymbol{v}_p \cdot \boldsymbol{e}_b}{c}}$$

$$\because \left|\boldsymbol{v}_p\right| \ll c,$$

$$f_r \approx f_b + \frac{\boldsymbol{v}_p \cdot \left(\boldsymbol{e}_{pr} - \boldsymbol{e}_b\right)}{\lambda_b}$$

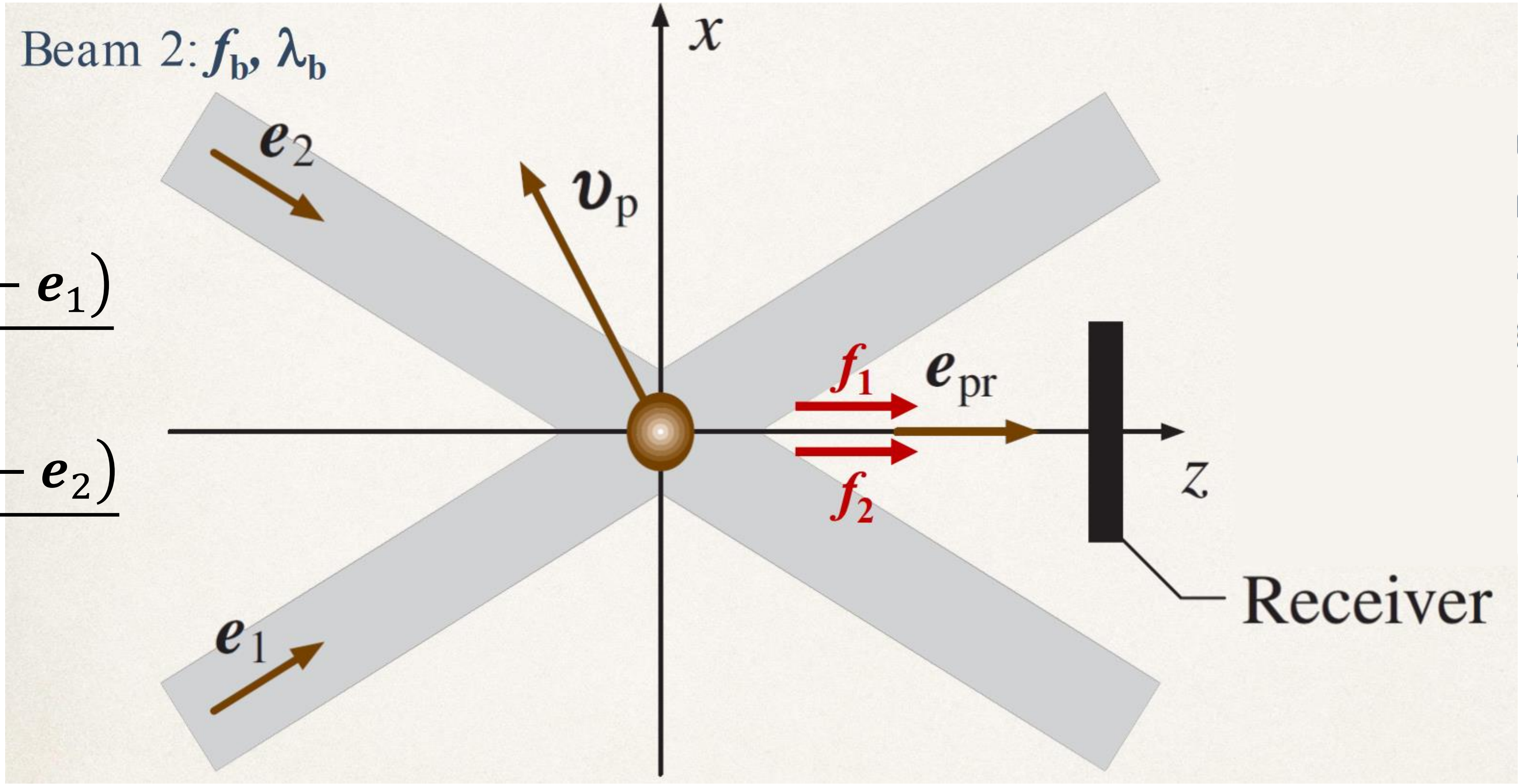
- For $U = 1$ m/s, $\Delta f = 2$ MHz
- For $U = 100$ m/s, $\Delta f = 200$ MHz
- For $\lambda_b = 500$ nm, $f_b \approx 6 \times 10^{10}$ MHz

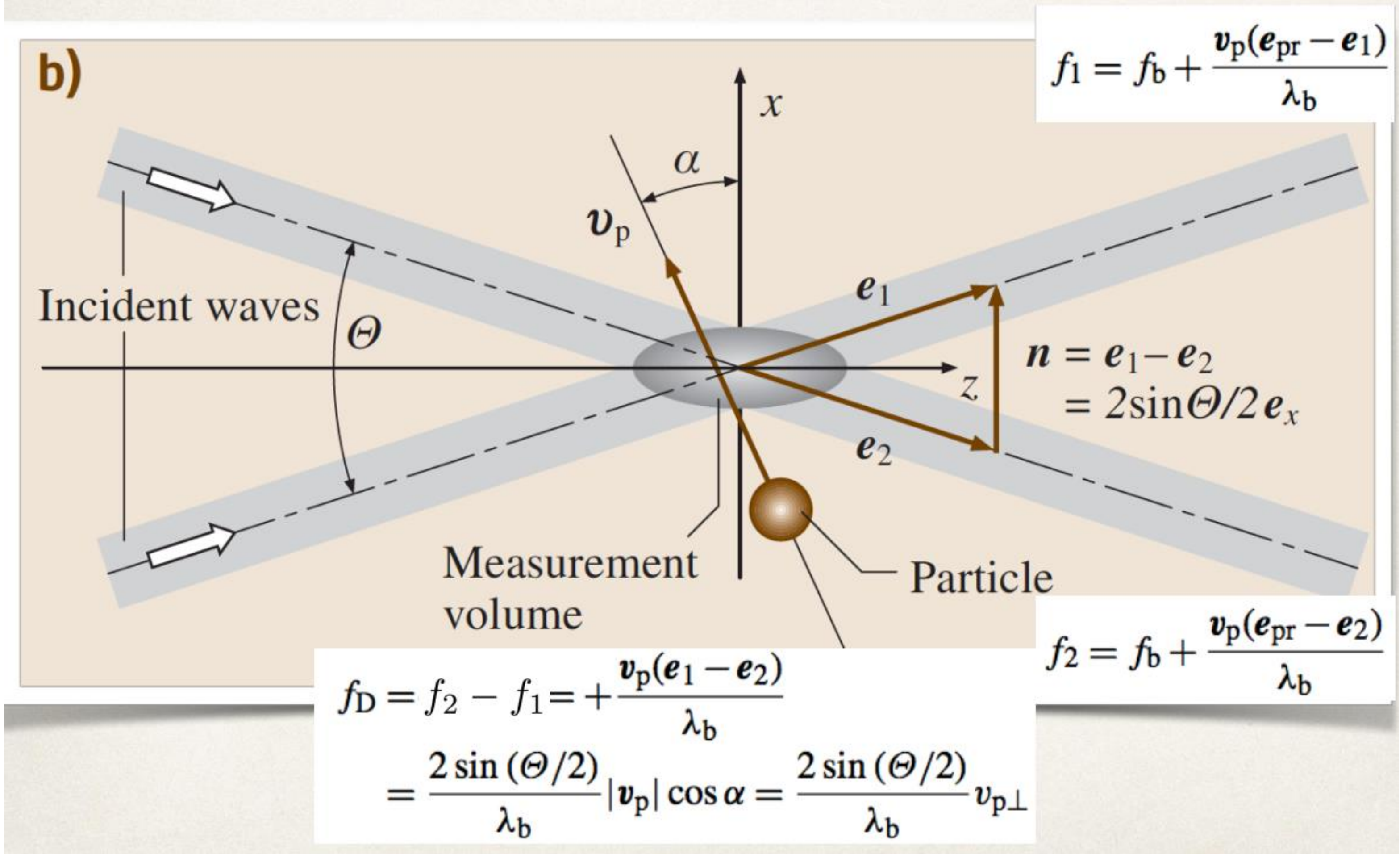
$$f_r \approx f_b + \frac{\boldsymbol{v}_p \cdot (\boldsymbol{e}_{pr} - \boldsymbol{e}_b)}{\lambda_b}$$

$$\Delta f = \frac{|\boldsymbol{v}_p|}{\lambda_b}$$

$$f_1 = f_b + \frac{\boldsymbol{v}_p \cdot (\boldsymbol{e}_{pr} - \boldsymbol{e}_1)}{\lambda_b}$$

$$f_2 = f_b + \frac{\boldsymbol{v}_p \cdot (\boldsymbol{e}_{pr} - \boldsymbol{e}_2)}{\lambda_b}$$





$$f_1 = f_b + \frac{v_p(e_{pr} - e_1)}{\lambda_b}$$

$$f_2 = f_b + \frac{v_p(e_{pr} - e_2)}{\lambda_b}$$

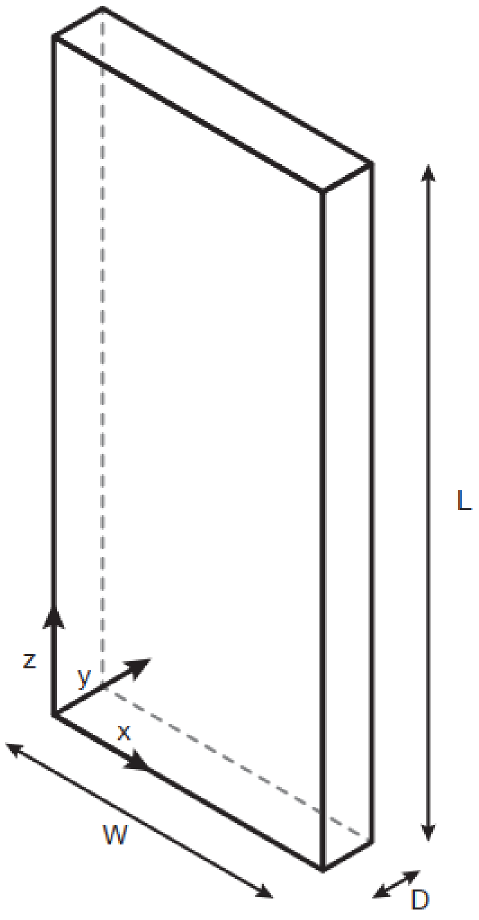
$$f_D = f_2 - f_1 = +\frac{v_p(e_1 - e_2)}{\lambda_b} = \frac{2\sin(\Theta/2)}{\lambda_b}|v_p|\cos\alpha = \frac{2\sin(\Theta/2)}{\lambda_b} v_{p\perp}$$

f_D is the Doppler frequency (beat)

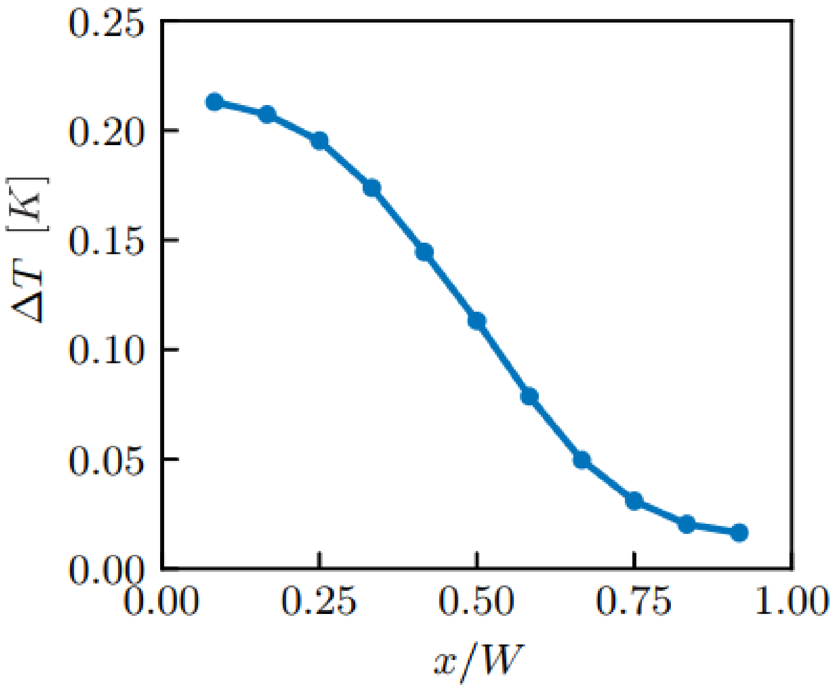
- independent of the receiver position
- linearly proportional to velocity

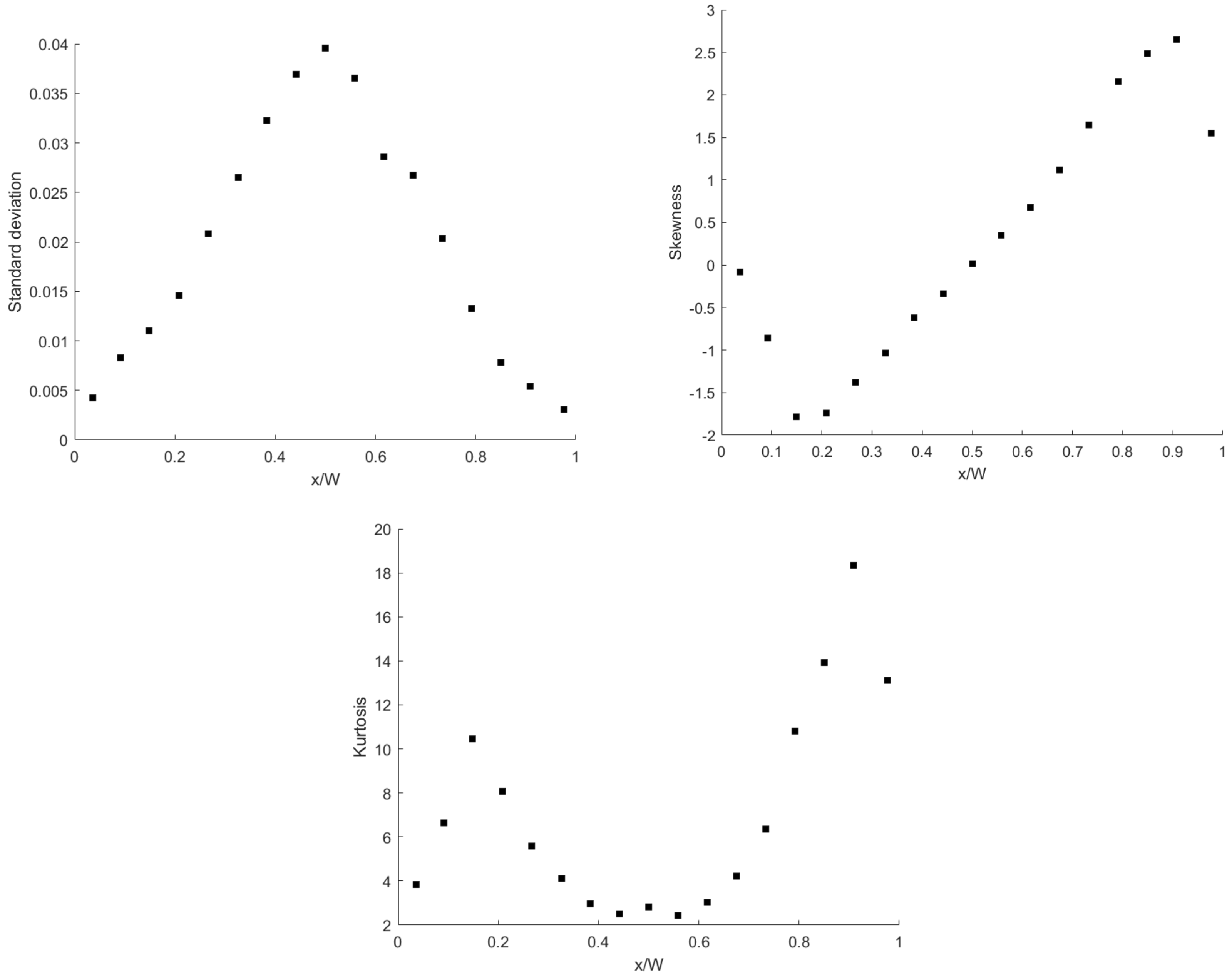
$$f_D = \frac{2\sin(\Theta/2)}{\lambda_b} v_{p,\perp}$$

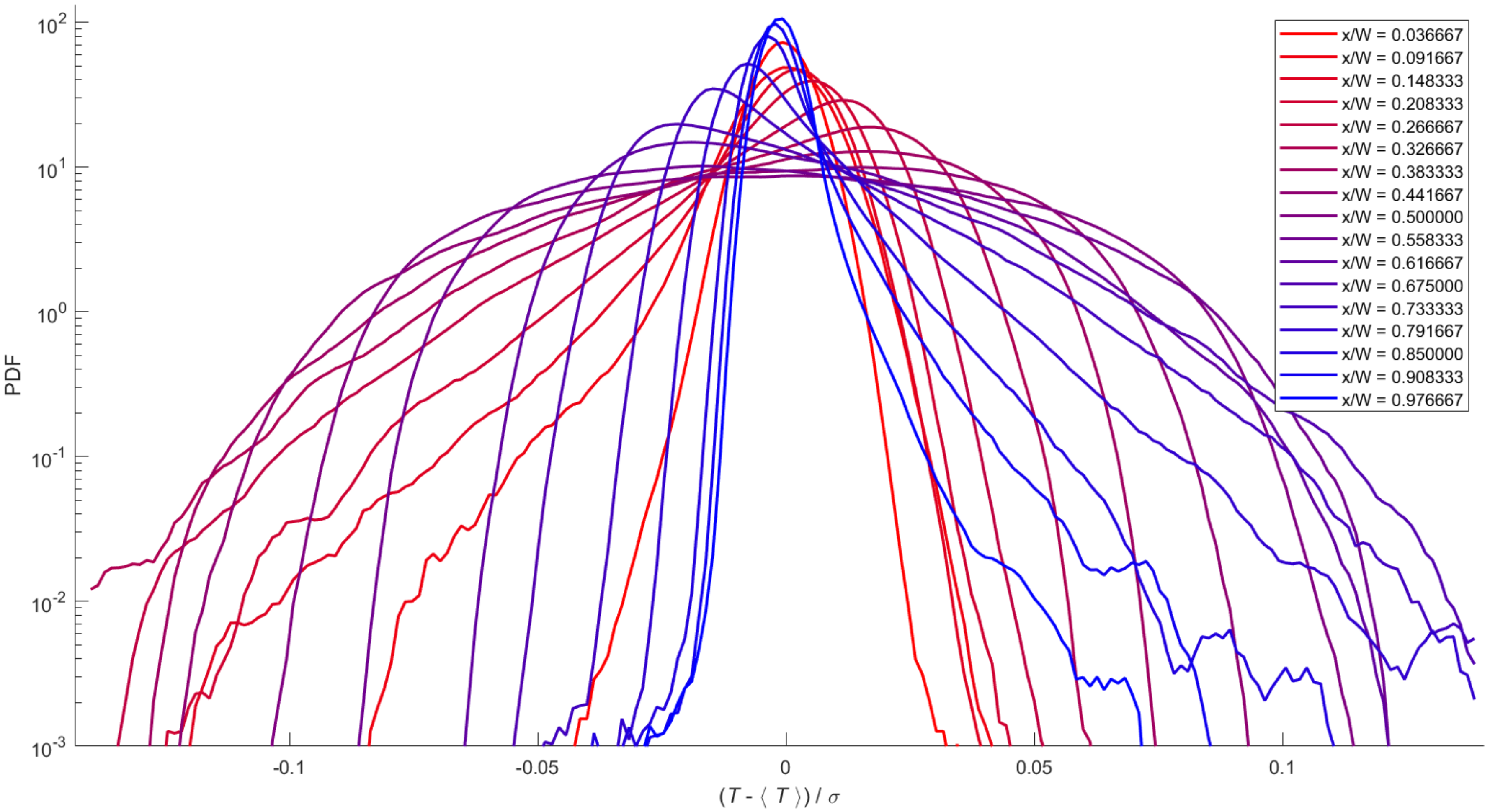
Temperature Measurement



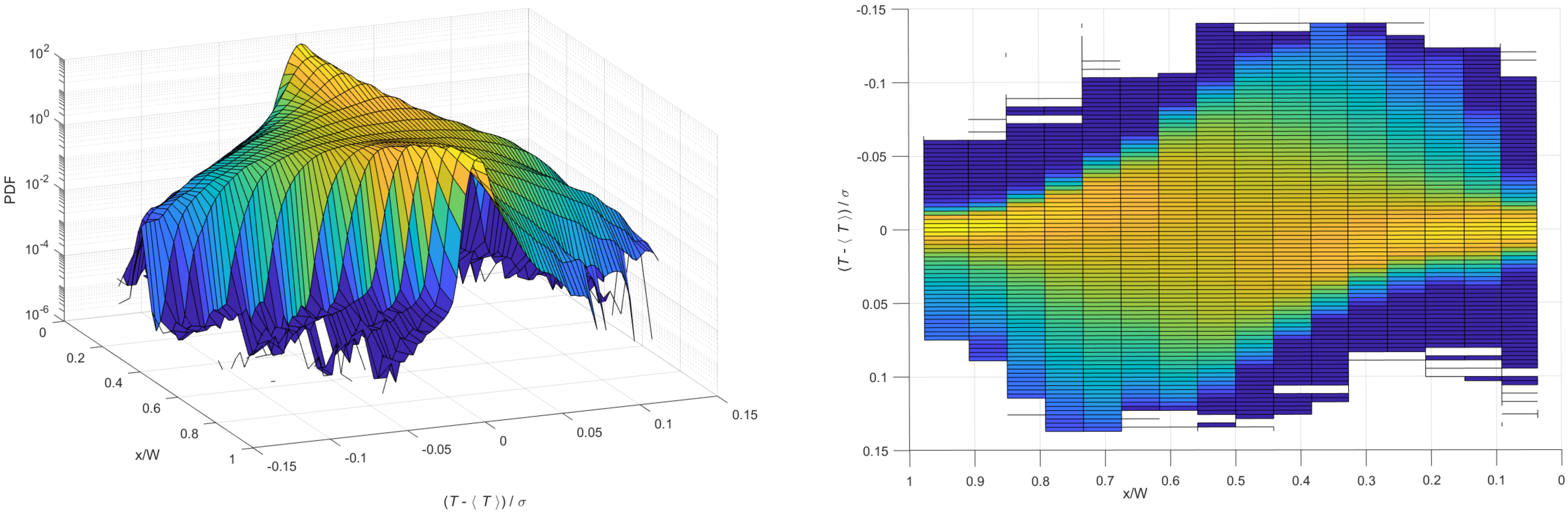
- Only half of the heaters were on
- Measure at $z/L = y/D = 0.5$




Standard deviation
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
0
0.2
0.4
0.6
0.8
1
x/W
Skewness
3
2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
x/W
Kurtosis
20
18
16
14
12
10
8
6
4
2
0
0.2
0.4
0.6
0.8
1
x/W



PDF
(T - ⟨ T ⟩) / σ
x/W = 0.036667
x/W = 0.091667
x/W = 0.148333
x/W = 0.208333
x/W = 0.266667
x/W = 0.326667
x/W = 0.383333
x/W = 0.441667
x/W = 0.500000
x/W = 0.558333
x/W = 0.616667
x/W = 0.675000
x/W = 0.733333
x/W = 0.791667
x/W = 0.850000
x/W = 0.908333
x/W = 0.976667



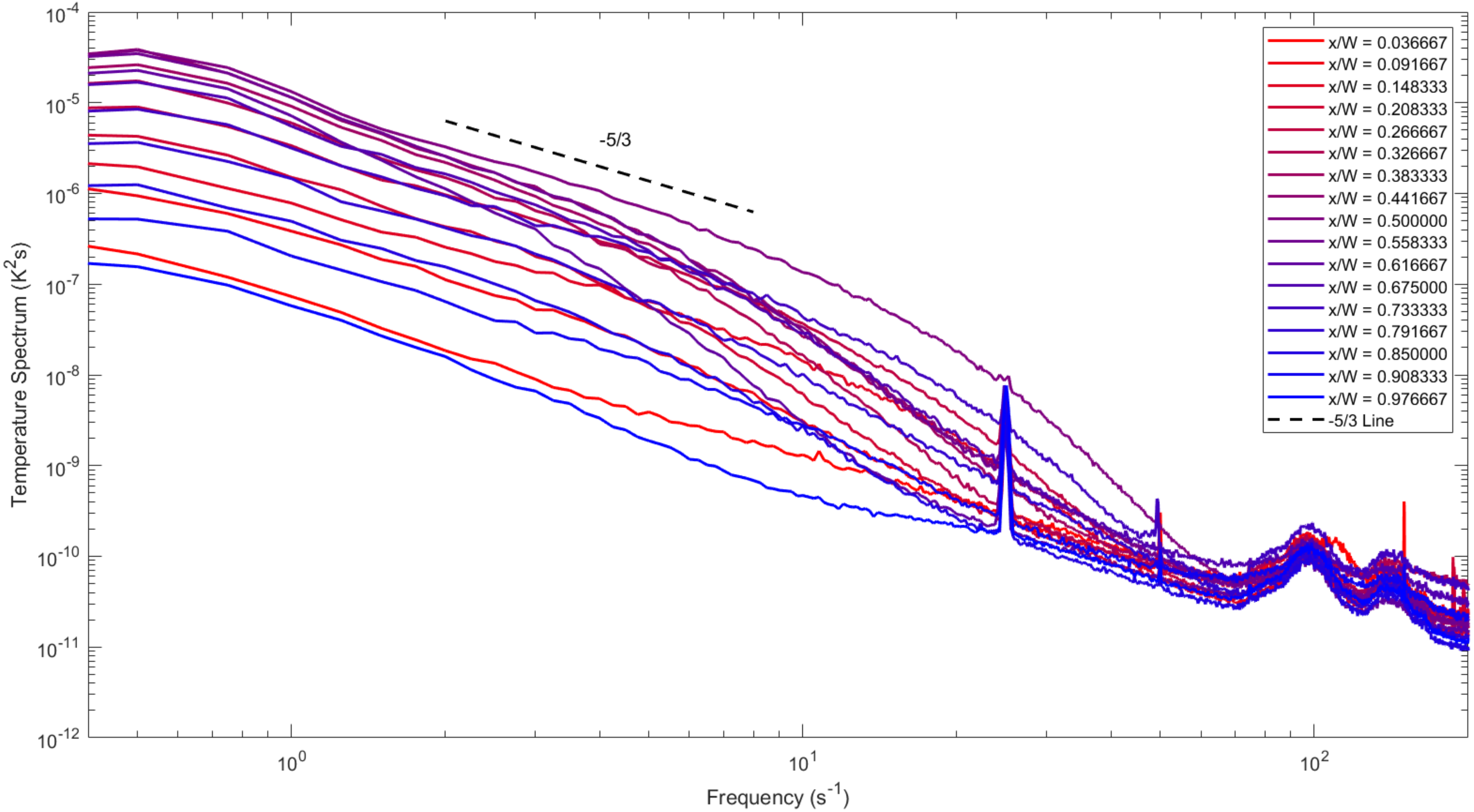
PDF
10^{2}
10^{0}
10^{-2}
10^{-4}
10^{-6}
x/W
(T - ⟨ T ⟩) / σ
-0.15
-0.1
-0.05
0
0.05
0.1
0.15
0.2
0.4
0.6
0.8
1
0.9
0.7
0.5
0.3

$$\hat{T}(\boldsymbol{k}) = \mathcal{F}\{T(\boldsymbol{r}, t)\} = \frac{1}{(2\pi)^3} \iiint_{-\infty}^{\infty} T(\boldsymbol{r}, t) e^{-i\boldsymbol{k}\cdot\boldsymbol{r}} d\boldsymbol{r}$$

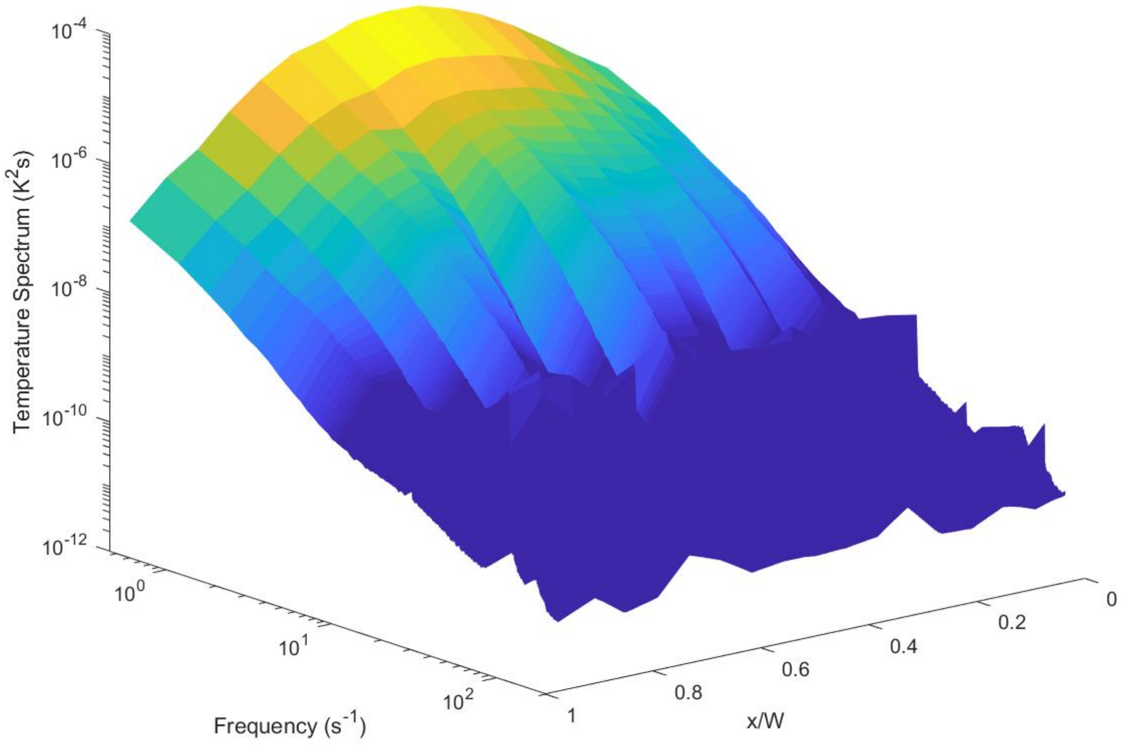
$$\Phi(\boldsymbol{k}) = \hat{T}(\boldsymbol{k}) \cdot \hat{T}^*(\boldsymbol{k})$$

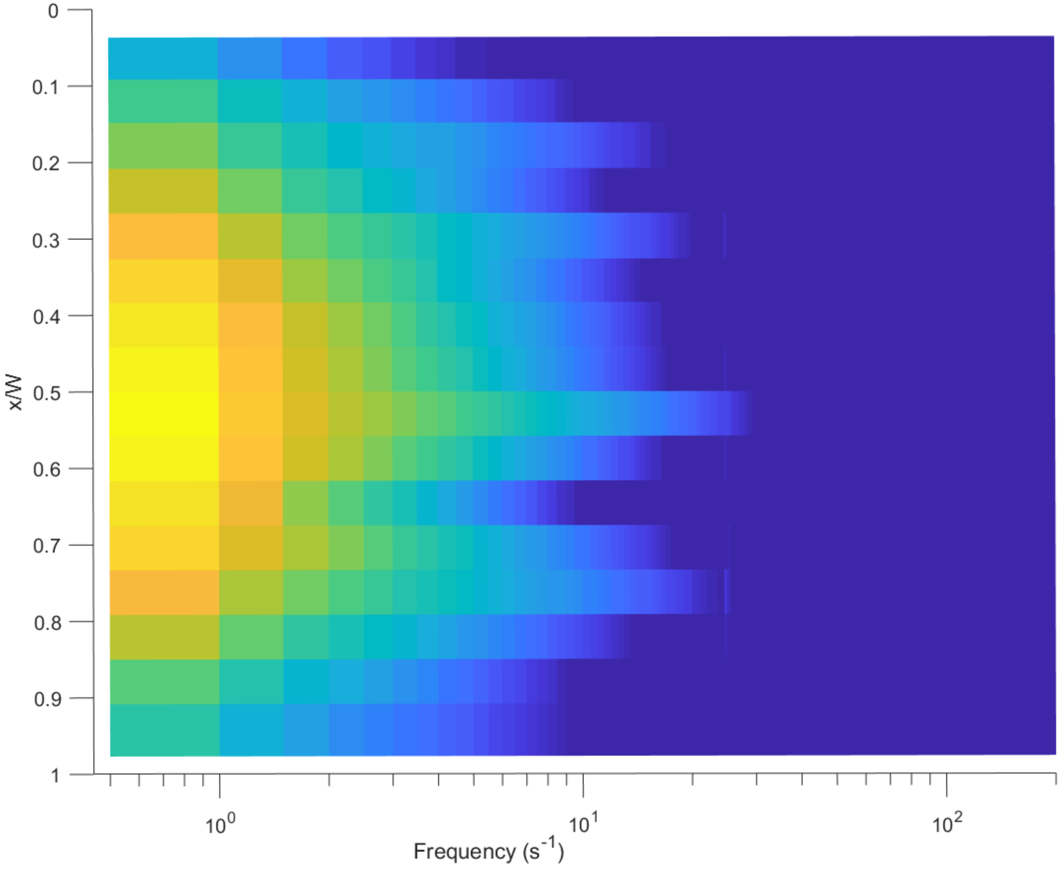
By frozen flow hypophysis,

$$\Phi(\boldsymbol{f}) = \hat{T}(\boldsymbol{f}) \cdot \hat{T}^*(\boldsymbol{f})$$



Temperature Spectrum (K^{2}s)
Frequency (s^{-1})
-5/3
x/W = 0.036667
x/W = 0.091667
x/W = 0.148333
x/W = 0.208333
x/W = 0.266667
x/W = 0.326667
x/W = 0.383333
x/W = 0.441667
x/W = 0.500000
x/W = 0.558333
x/W = 0.616667
x/W = 0.675000
x/W = 0.733333
x/W = 0.791667
x/W = 0.850000
x/W = 0.908333
x/W = 0.976667
-5/3 Line


Temperature Spectrum (K^{2}s)
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^0
10^1
10^2
Frequency (s^{-1})
0
0.2
0.4
0.6
0.8
1
x/W


0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
x/W
10^0
10^1
10^2
Frequency (s^{-1})

Structure Function

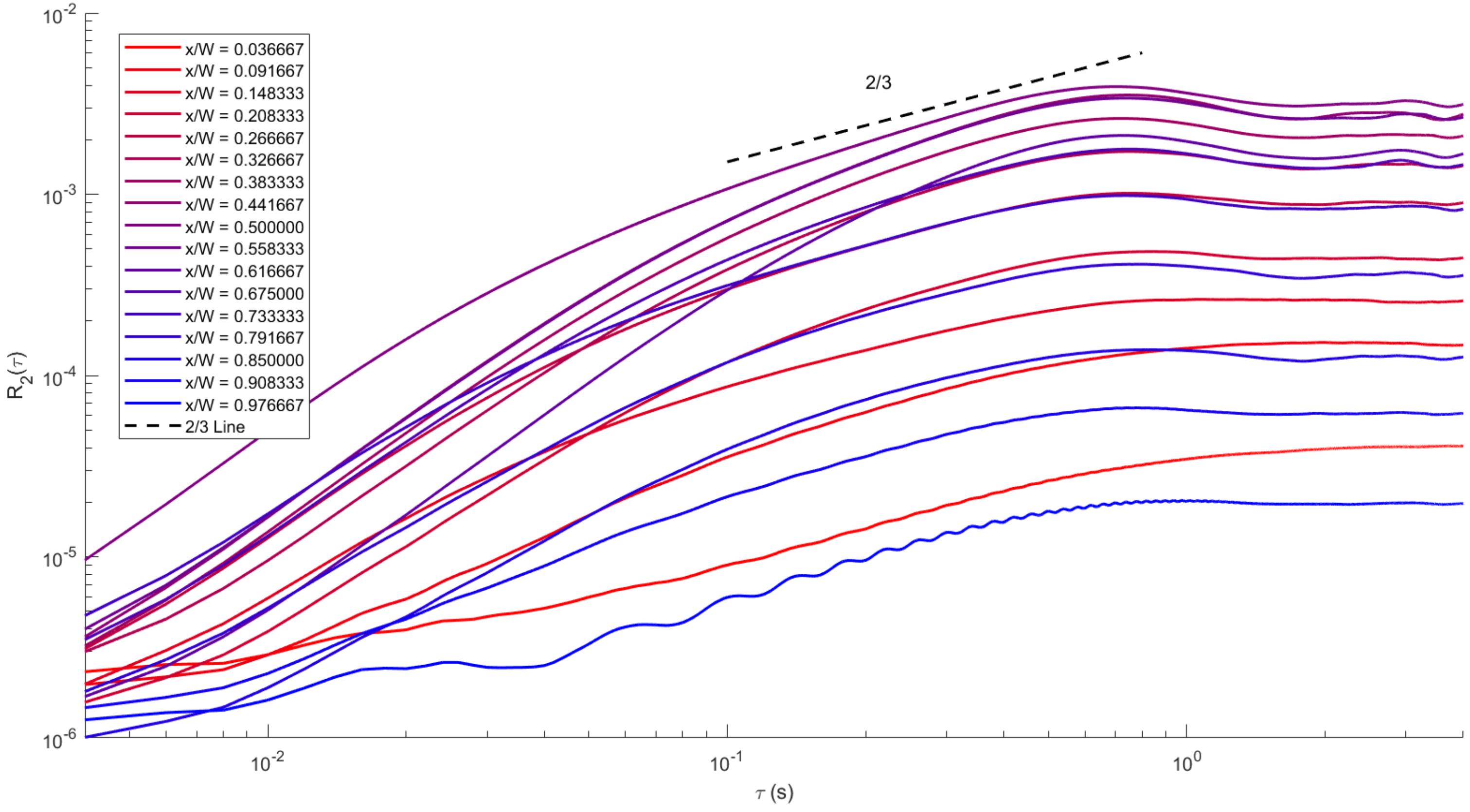
$$\mathbf{D}_n(\mathbf{r}) = \langle |\mathbf{v}(\mathbf{x}+\mathbf{r}) - \mathbf{v}(\mathbf{x})|^n \rangle$$

$$\Downarrow$$

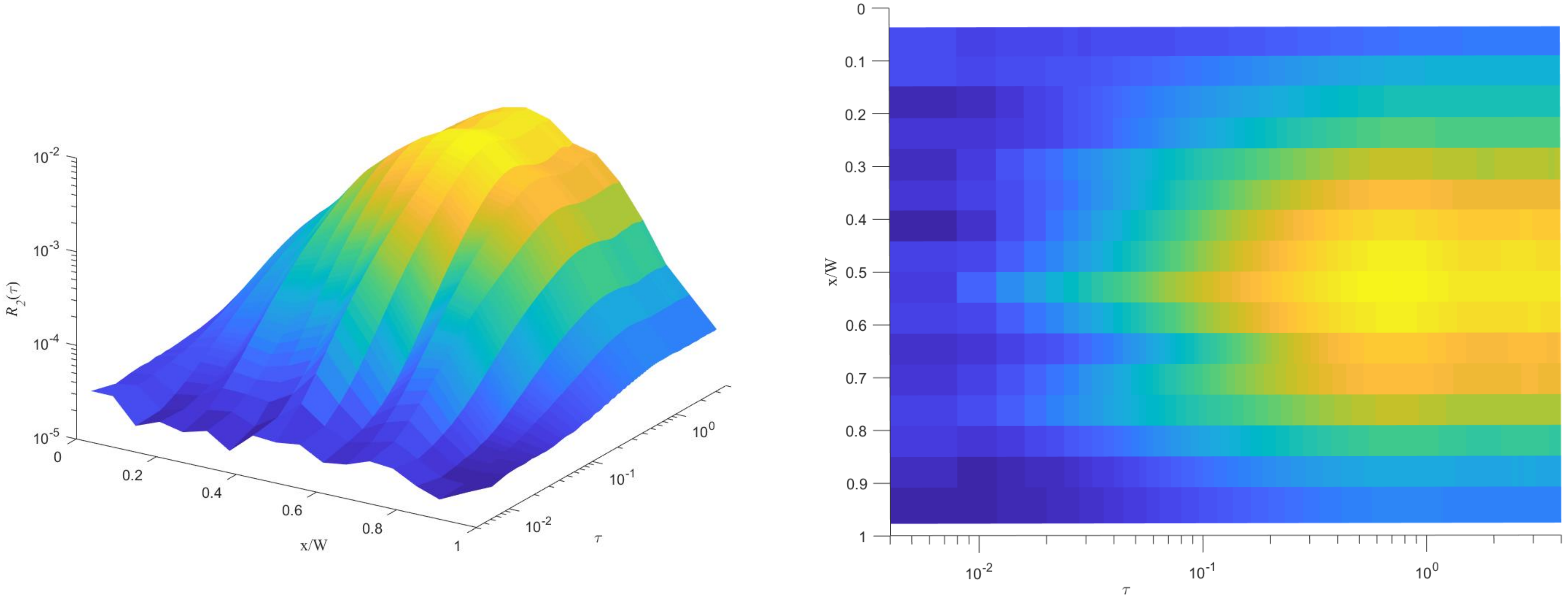
$$R_n(\mathbf{r}) = \langle |T(\mathbf{x}+\mathbf{r}) - T(\mathbf{x})|^n \rangle$$

$$\Downarrow$$

$$R_n(\tau) = \langle |T(t+\tau) - T(t)|^n \rangle$$



x/W = 0.036667
x/W = 0.091667
x/W = 0.148333
x/W = 0.208333
x/W = 0.266667
x/W = 0.326667
x/W = 0.383333
x/W = 0.441667
x/W = 0.500000
x/W = 0.558333
x/W = 0.616667
x/W = 0.675000
x/W = 0.733333
x/W = 0.791667
x/W = 0.850000
x/W = 0.908333
x/W = 0.976667
2/3 Line
2/3
$R_2(\tau)$
τ (s)
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-2}
10^{-1}
10^{0}



$R_2(\tau)$
10^{-2}
10^{-3}
10^{-4}
10^{-5}
0
0.2
0.4
0.6
0.8
1
x/W
10^{-2}
10^{-1}
10^{0}
τ
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
x/W
10^{-2}
10^{-1}
10^{0}
τ

Extensive Self-similarity and Scaling Exponent

$$\Delta v = v(t+\tau) - v(t)$$

Deduced from Navier-Stokes Equation,

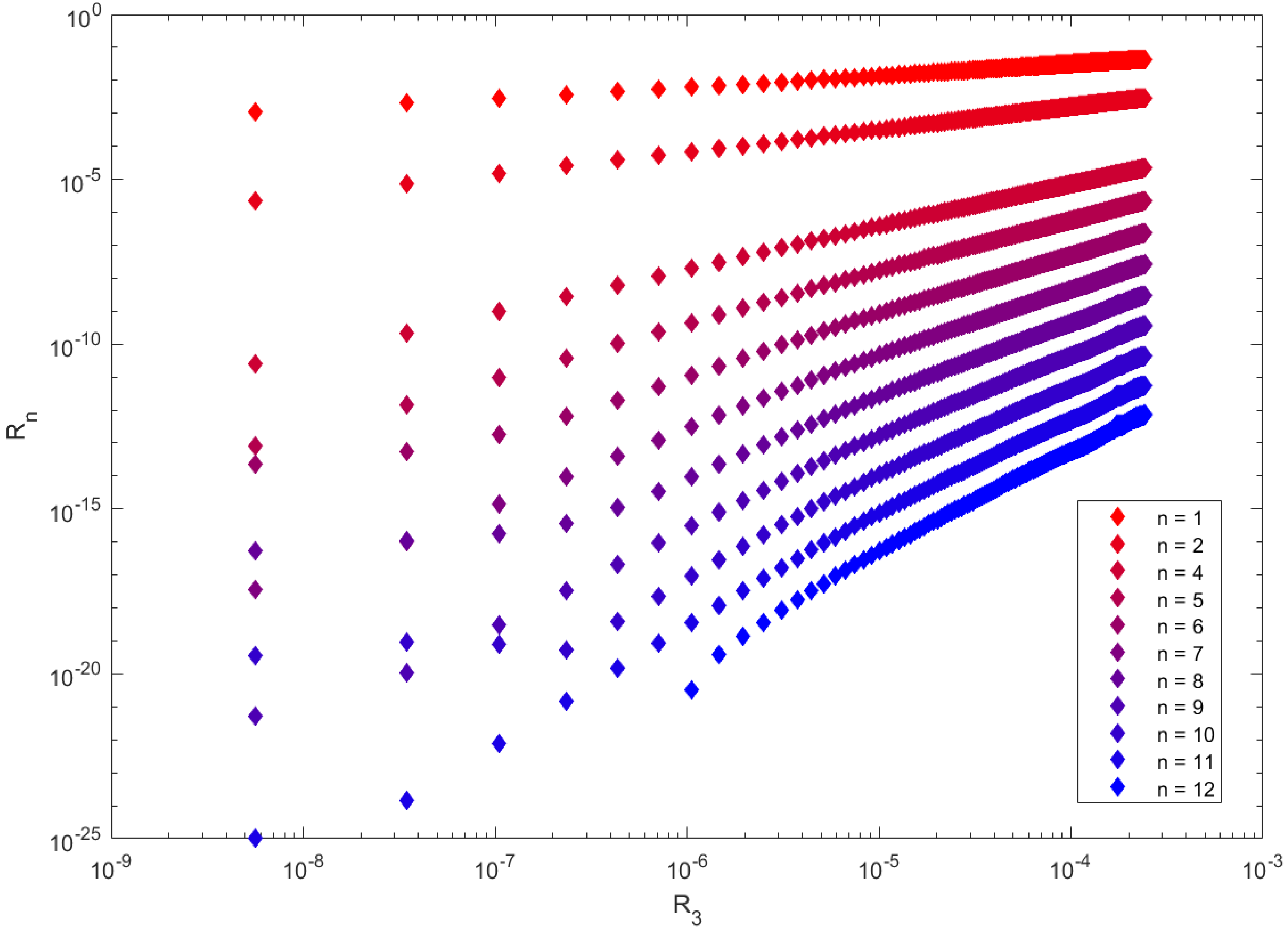
$$\langle \Delta v(r)^3 \rangle = -\frac{4}{5}\varepsilon r + 6\nu \frac{d}{dx}\langle \Delta v(r)^2 \rangle$$

$$\langle |\Delta v|^n \rangle = \alpha |\langle \Delta v^3 \rangle|^{\zeta(n)}$$

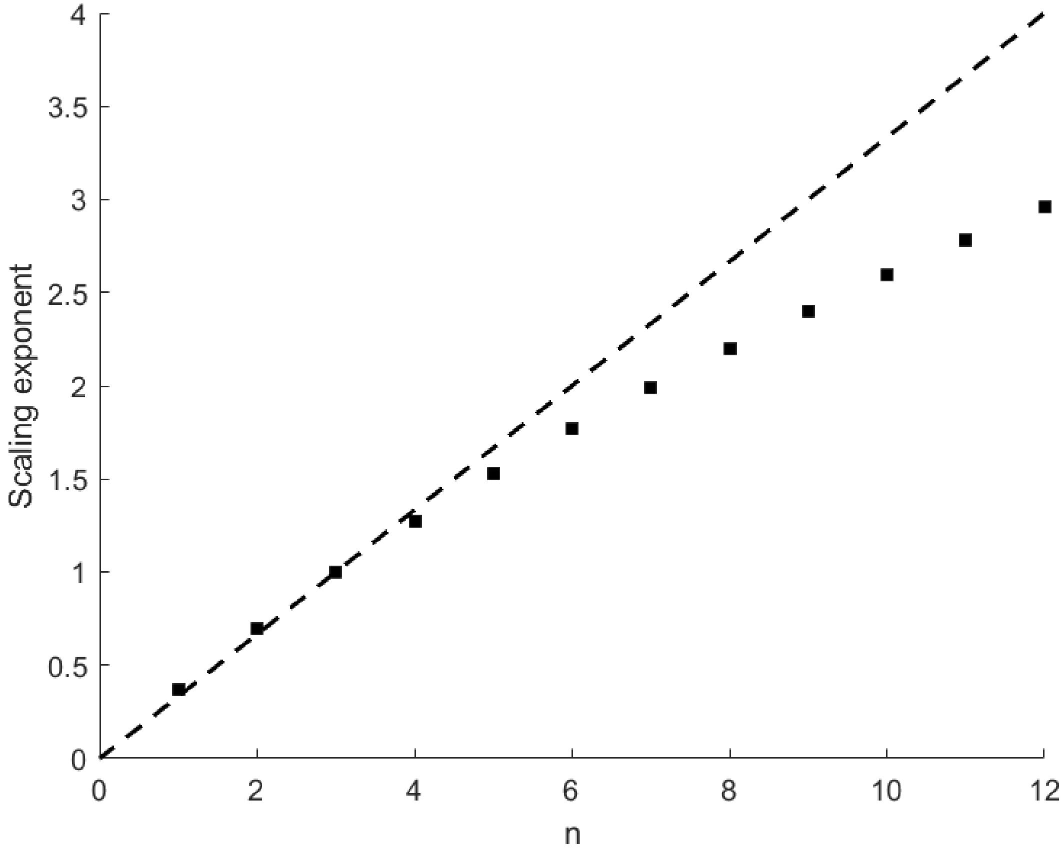
$$\langle |\Delta v|^n \rangle = \beta \langle |\Delta v|^3 \rangle^{\zeta(n)} \quad \text{where } |\langle \Delta v^3 \rangle| = \langle |\Delta v|^3 \rangle$$

$$D_n(\tau) \propto D_3(\tau)^{\zeta(n)}$$

$$R_n(\tau) \propto R_3(\tau)^{\zeta(n)}$$



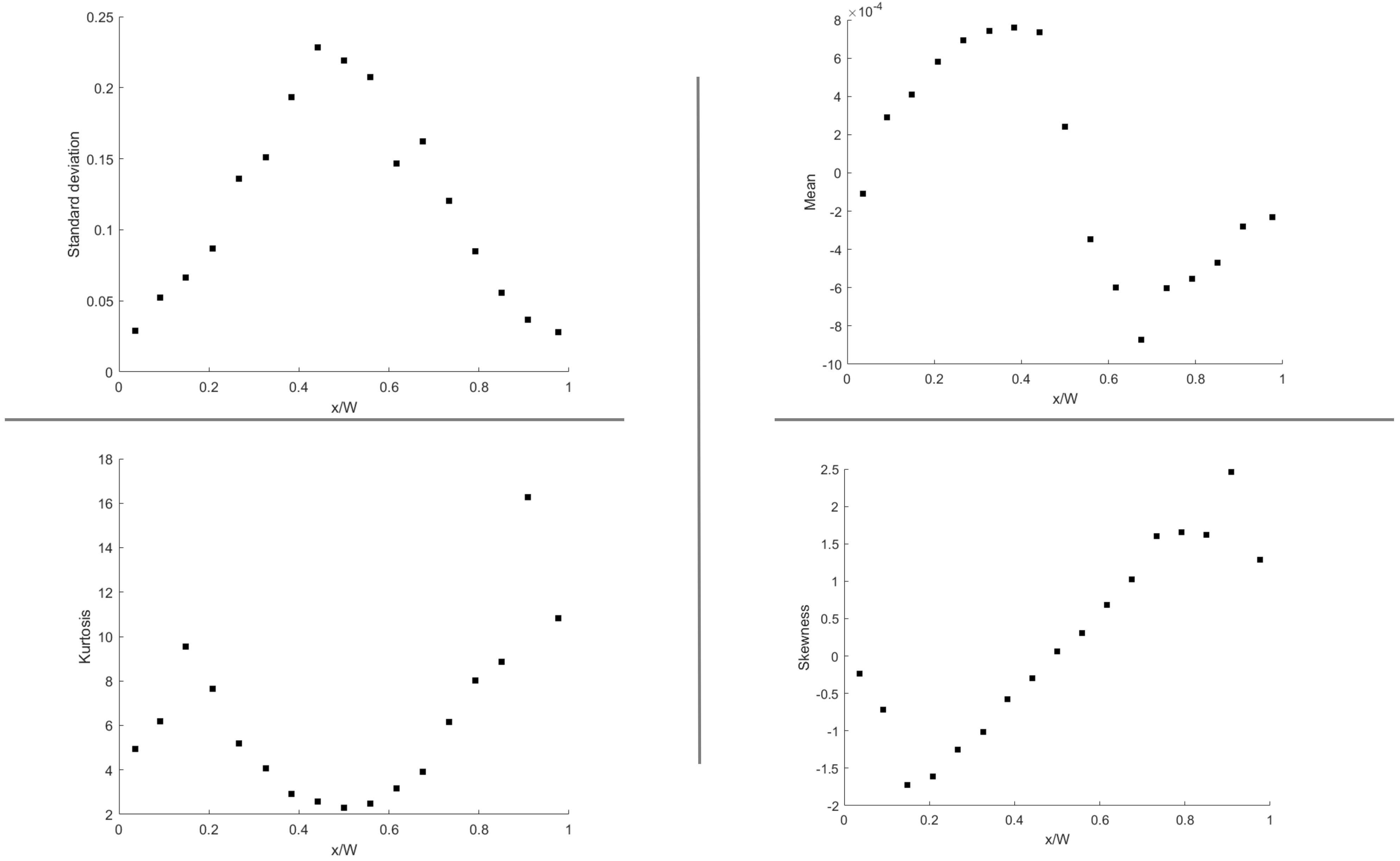
Predicted by Kolmogorov, $\zeta(n) = \frac{n}{3}$



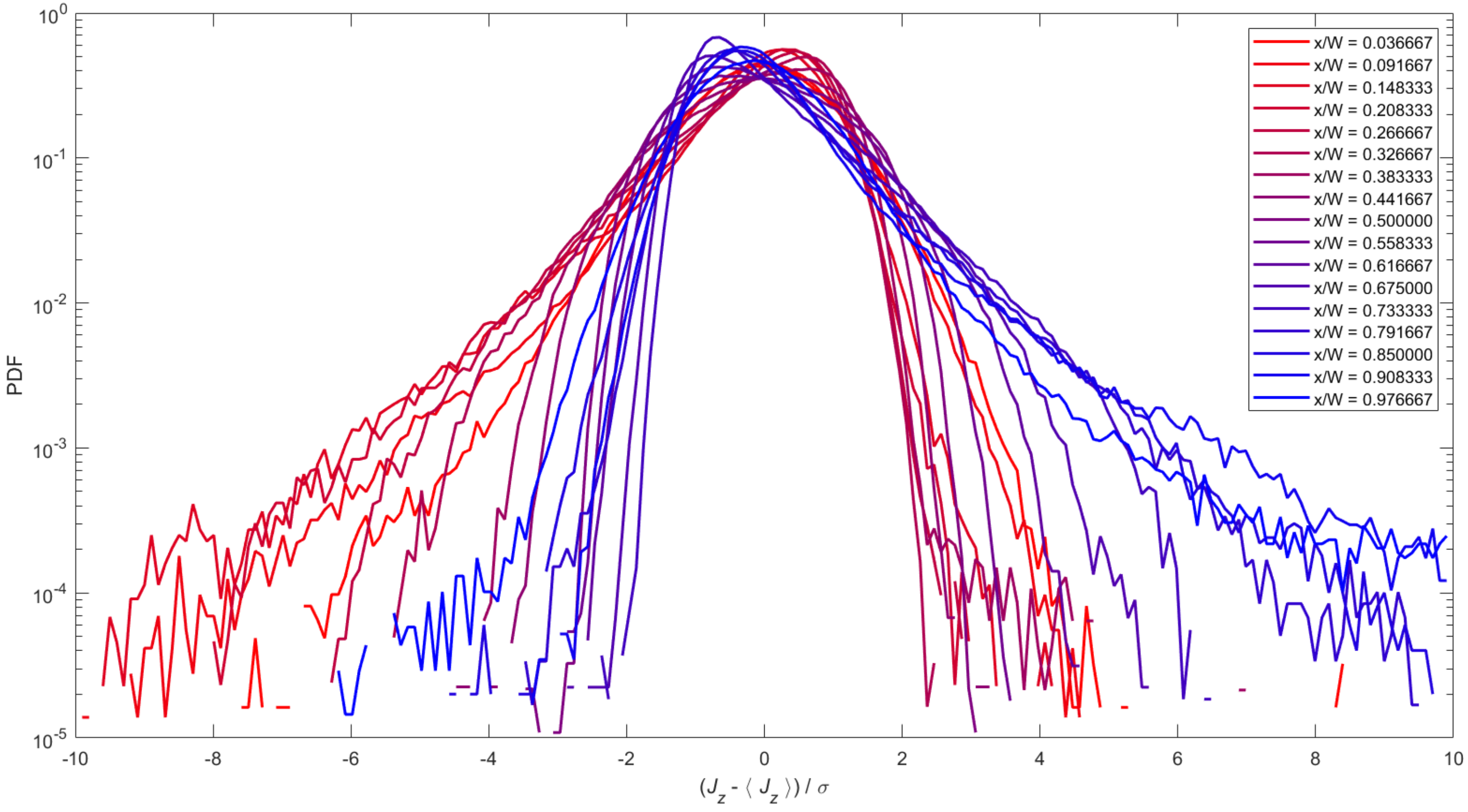
Heat flux Measurement

$$\mathbf{J}(\mathbf{r}) = \frac{\langle \mathbf{v}(\mathbf{r},t)\delta T(\mathbf{r},t)\rangle_{\boldsymbol{t}} H}{\kappa \Delta T}$$

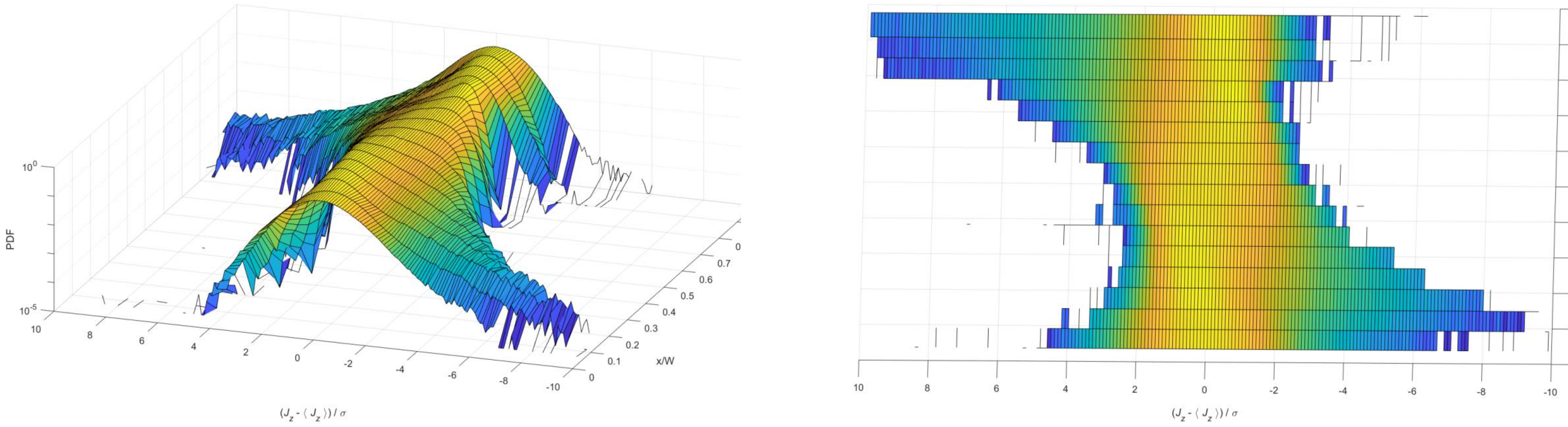
$$J_z(\mathbf{r}_{\mathrm{mid}}) = \frac{\langle v_z(\mathbf{r}_{\mathrm{mid}},t)\delta T(\mathbf{r}_{\mathrm{mid}},t)\rangle_{\boldsymbol{t}} H}{\kappa \Delta T} \qquad \mathbf{r}_{\mathrm{mid}} = \frac{W}{2}\mathbf{i} + \frac{D}{2}\mathbf{j} + \frac{L}{2}\mathbf{k}$$



Standard deviation
Mean
×10^-4
Kurtosis
Skewness
x/W
0 0.2 0.4 0.6 0.8 1
0 0.05 0.1 0.15 0.2 0.25
-10 -8 -6 -4 -2 0 2 4 6 8
2 4 6 8 10 12 14 16 18
-2 -1.5 -1 -0.5 0 0.5 1 1.5 2 2.5



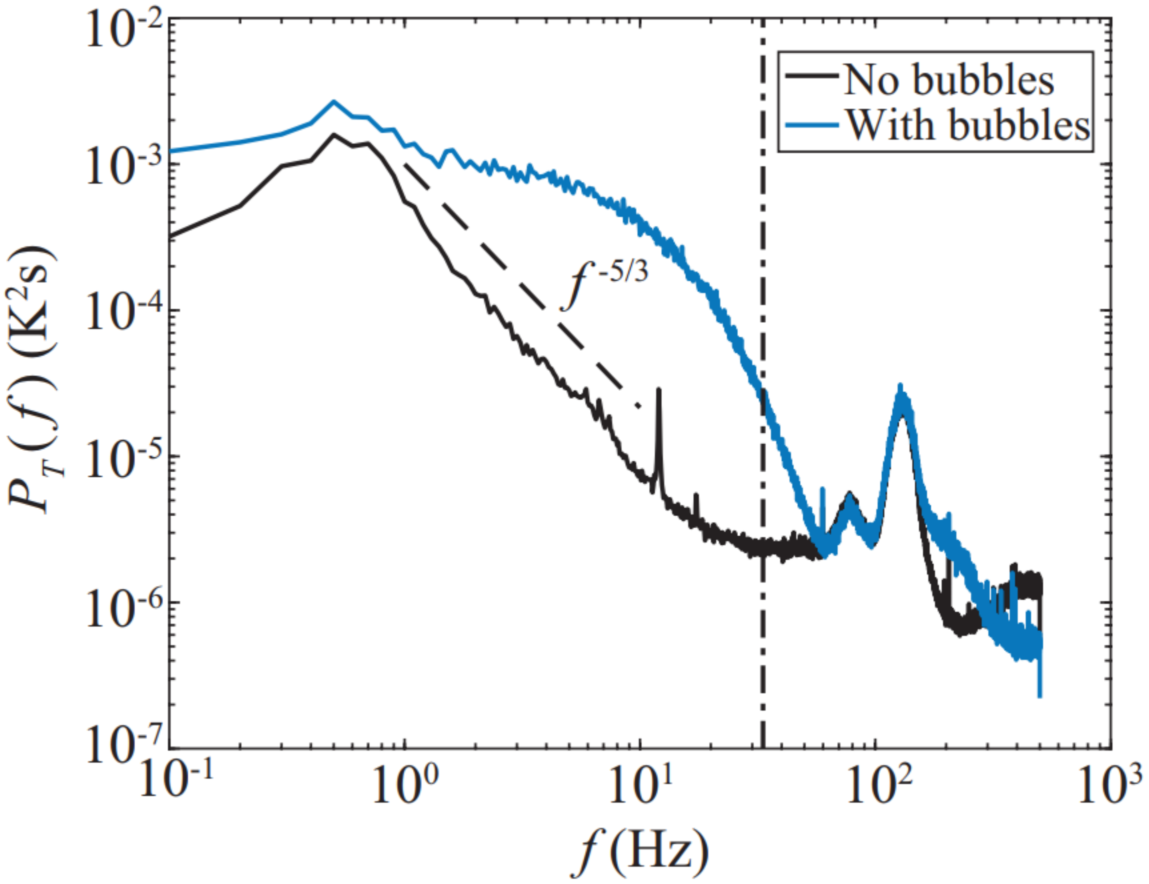
PDF
$(J_z - \langle J_z \rangle) / \sigma$
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
-10
-8
-6
-4
-2
0
2
4
6
8
10
x/W = 0.036667
x/W = 0.091667
x/W = 0.148333
x/W = 0.208333
x/W = 0.266667
x/W = 0.326667
x/W = 0.383333
x/W = 0.441667
x/W = 0.500000
x/W = 0.558333
x/W = 0.616667
x/W = 0.675000
x/W = 0.733333
x/W = 0.791667
x/W = 0.850000
x/W = 0.908333
x/W = 0.976667



PDF
10^0
10^{-5}
10
8
6
4
2
0
-2
-4
-6
-8
-10
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
x/W
$(J_z - \langle J_z \rangle) / \sigma$
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
x/W
10
8
6
4
2
0
-2
-4
-6
-8
-10
$(J_z - \langle J_z \rangle) / \sigma$

Further Study

- Multi-phase
  - Bubble
  - Salt



Reference

1. Gvozdić, B., Dung, O. Y., van Gils, D. P., Bruggert, G. W. H., Alméras, E., Sun, C., ... & Huisman, S. G. (2019). Twente Mass and Heat Transfer Water Tunnel: Temperature controlled turbulent multiphase channel flow with heat and mass transfer. arXiv preprint arXiv:1902.05871.
2. Model SR830 DSP Lock-in Amplifier. Stanford Research System
3. van Gils, D. Laser Doppler Anemometry. Physics of Fluids Group, University of Twente
4. Benzi, R., Ciliberto, S., Tripiccione, R., Baudet, C., Massaioli, F., & Succi, S. (1993). Extended self-similarity in turbulent flows. Physical review E, 48(1), R29.
5. Chan, T. (2019). Preliminary Results of Turbulence in Twente Mass and Heat Transfer Water Tunnel

Thank You