# Intermittency, Bursting and Dissipation in Stratified Boundary Layer using structure functions and PDF.

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# 2 Motivation and Layout of the talk

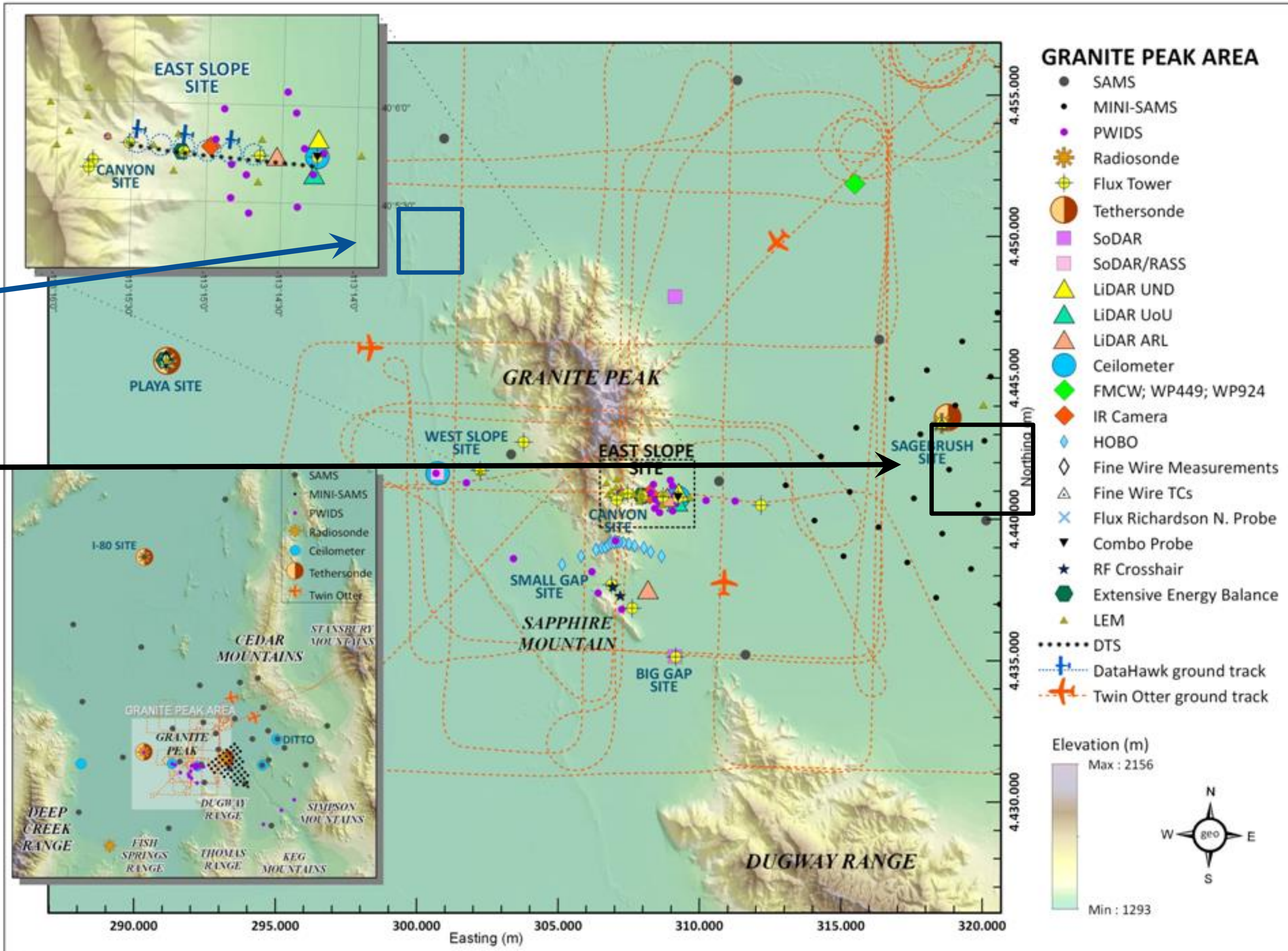
- Fine resolution continuous measurements of nocturnal turbulence, which enable to determine dissipation, velocity derivatives etc. using a combo instrument (multi-sensor hot films embedded within a sonic).
- The use of in-situ calibration by utilizing a low resolution data from Sonic and NN procedure.
- Experimental results on stratified turbulence from fall campaign. Structure functions in stratified turbulence.
- Bursting phenomena. PDF and Extreme dissipation Rates.
- Conclusions

- **DUGWAY FALL RESULTS**
- **NOCTURNAL (STRATIFIED) TURBULENCE**
- **BURSTING**

# 4 Combo Probe Placement

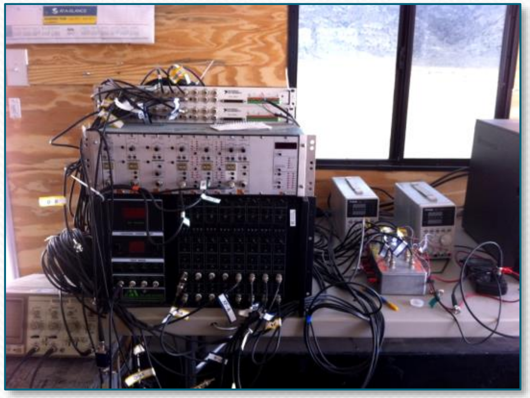
X-1

X-2



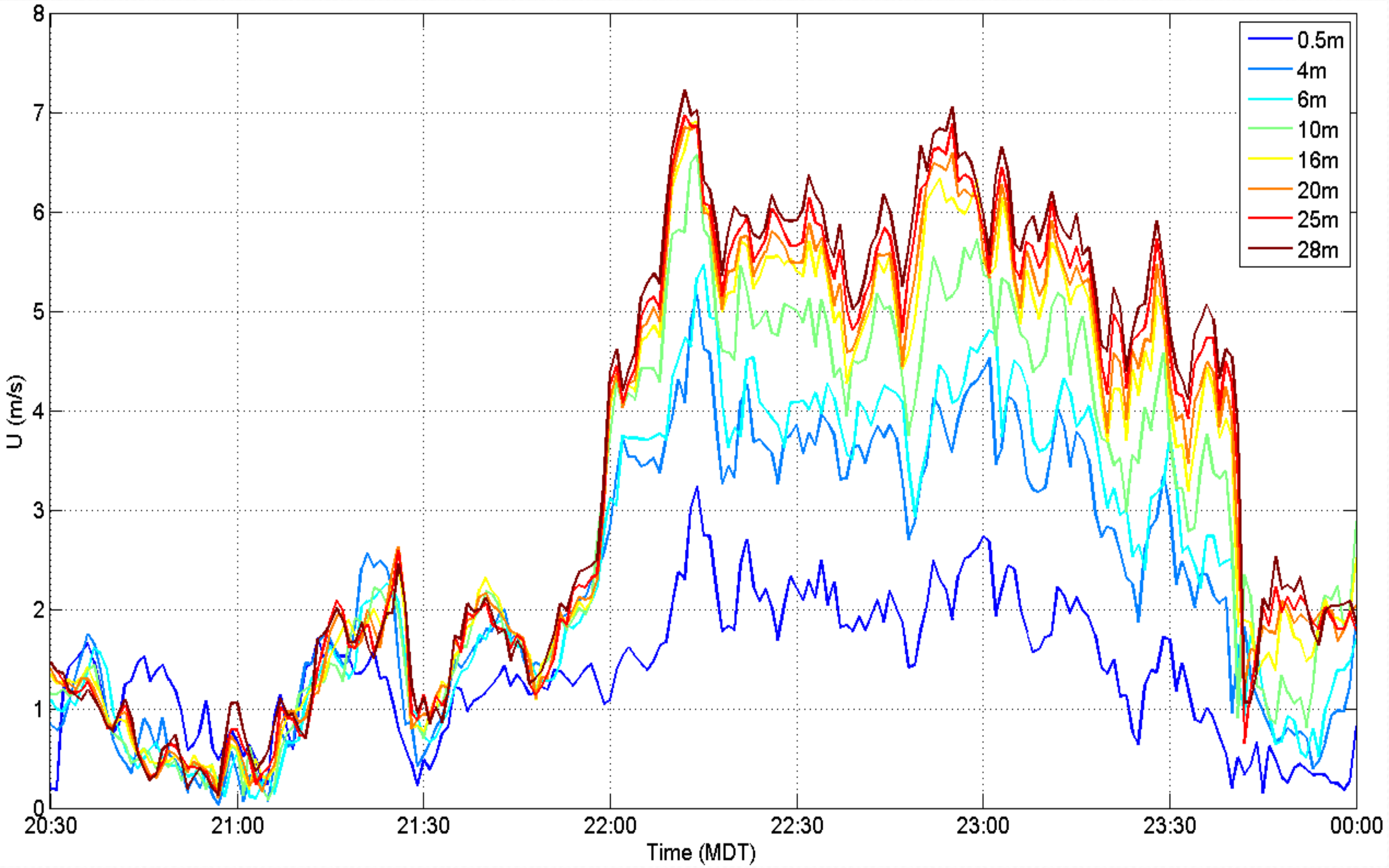
# 5 MATERHORN-X: ES2 tower. Combos at 2 and 6 m

Combo probes located at 2m and 6m

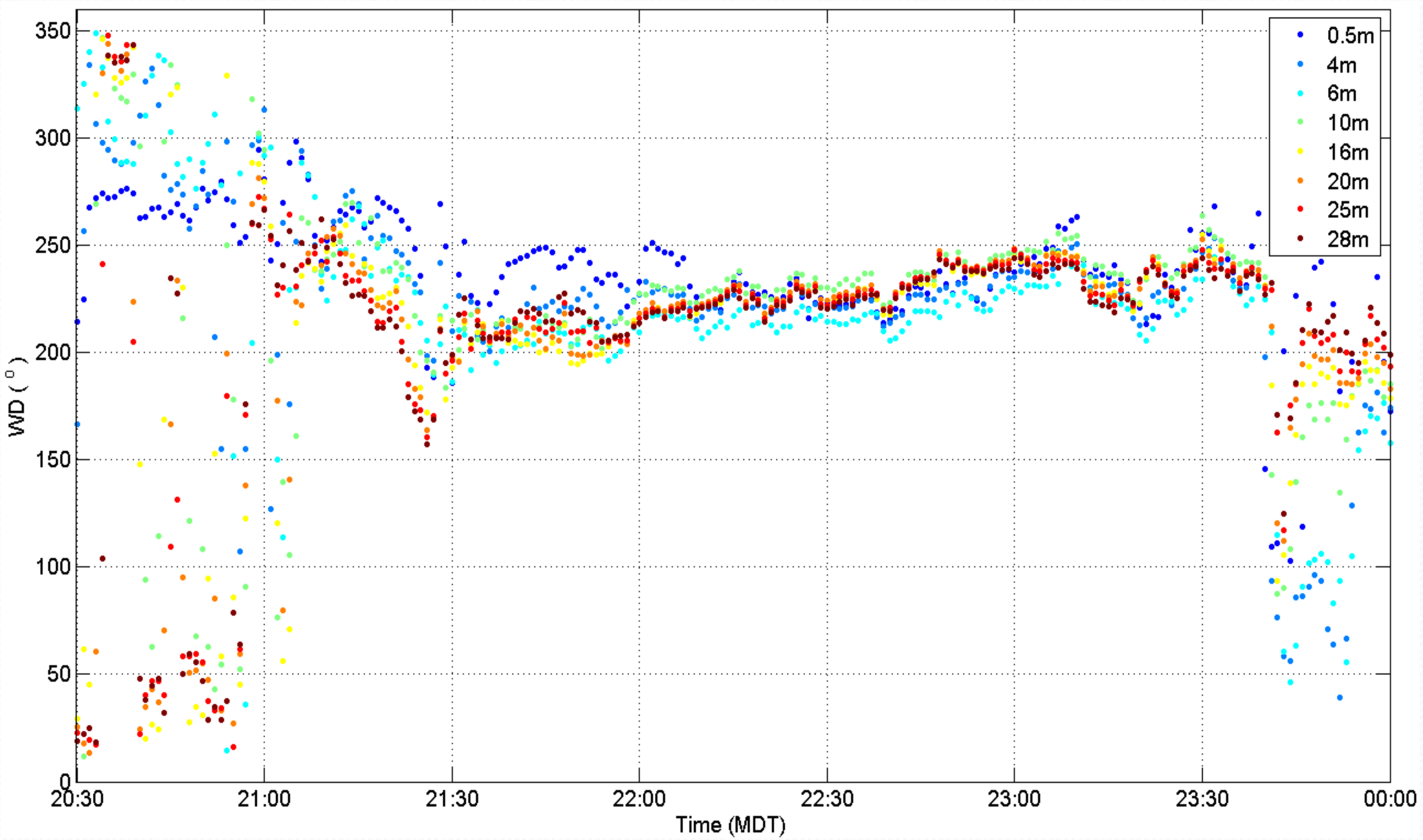


Combo probe electronics

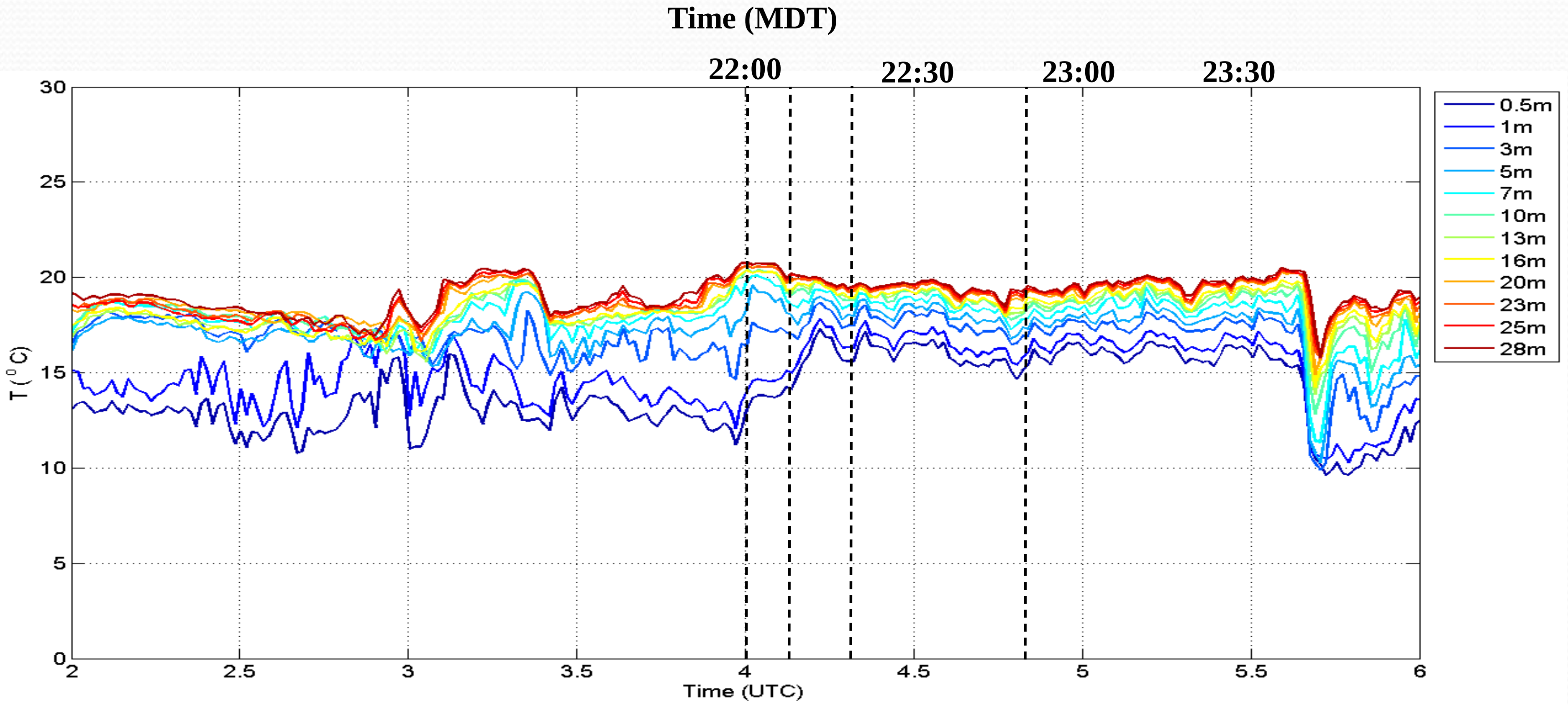
# 6 Wind speed at the ES-2 tower (10/19/2012). At 22:00 MDT, wind speed rapidly increased as the flow developed.



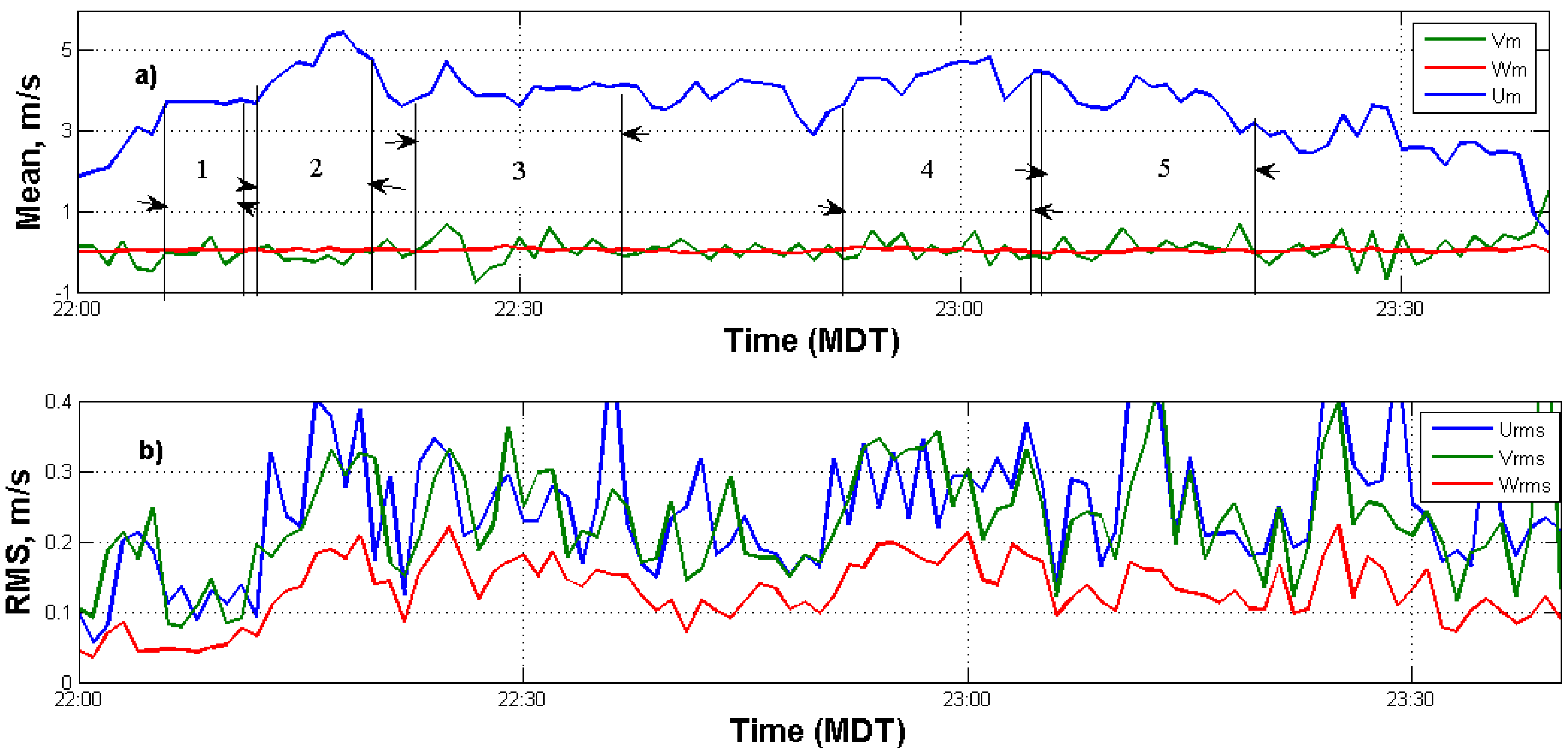
7 Wind direction at the ES-2 tower (10/19/2012). Prior to 21:00 MDT, the wind direction oscillated due to interacting katabatic and downvalley flow. After the flow developed the wind direction was nearly constant during the measurement period (22:00-23:30 MDT) throughout the height of the tower.



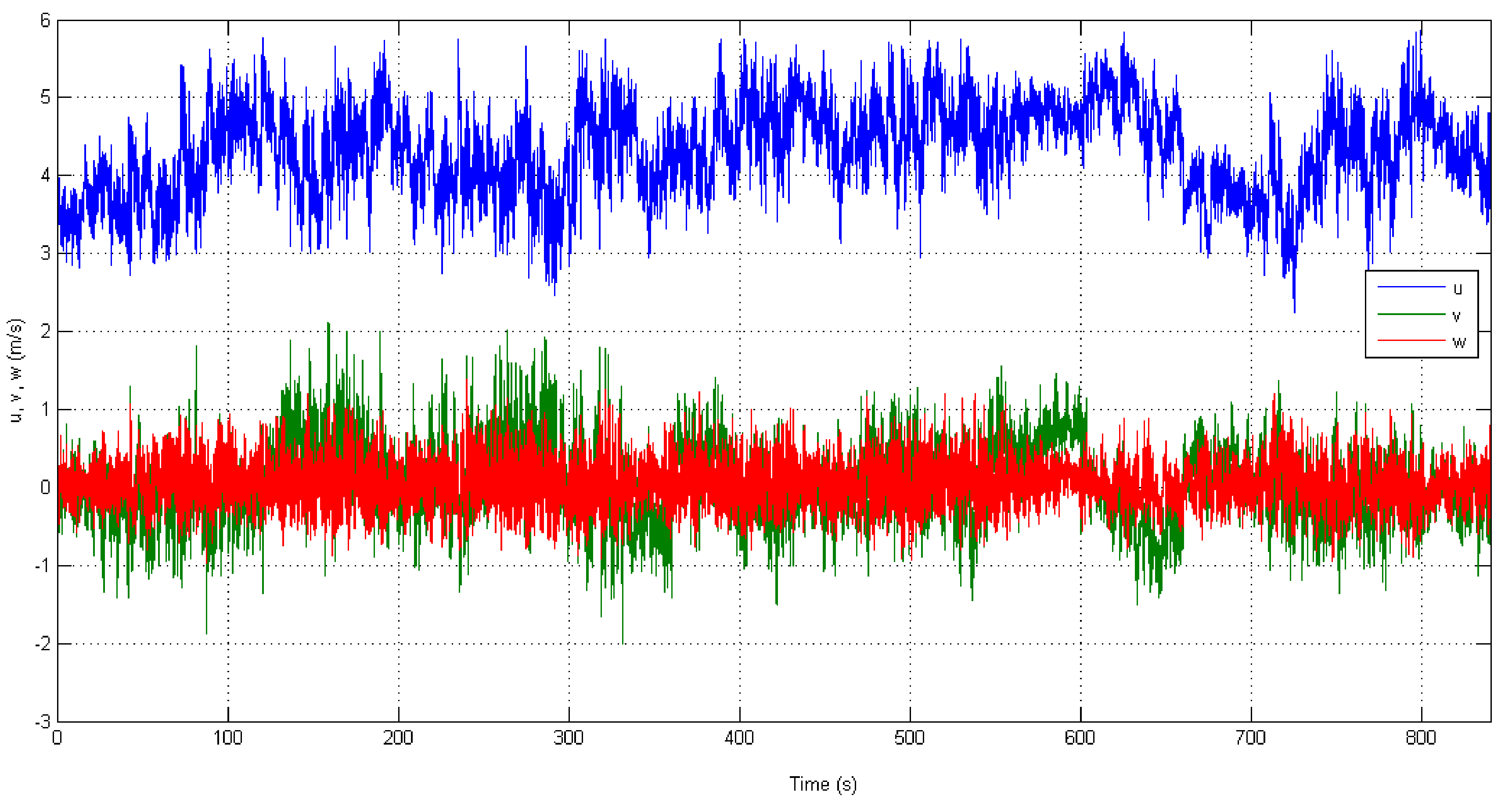
# 8 Temperature at ES2 tower (10/19/2012). (Local Utah time: MDT = UTC-6).



# 9 Sonic time series for the nocturnal time period at October 19 (10:00-11:30PM)

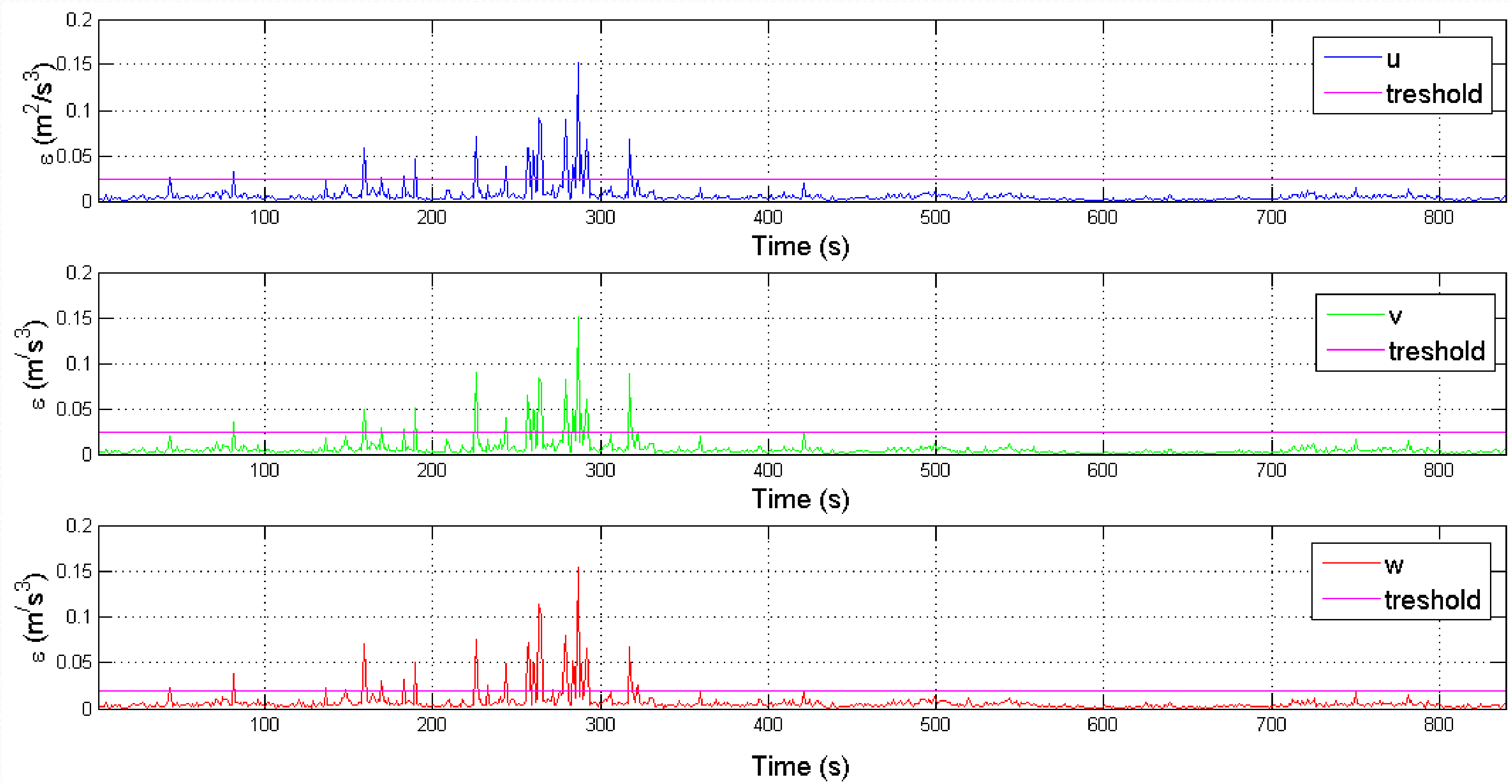


# 10 Fourth sub-interval (SI4). Reconstructed velocity field

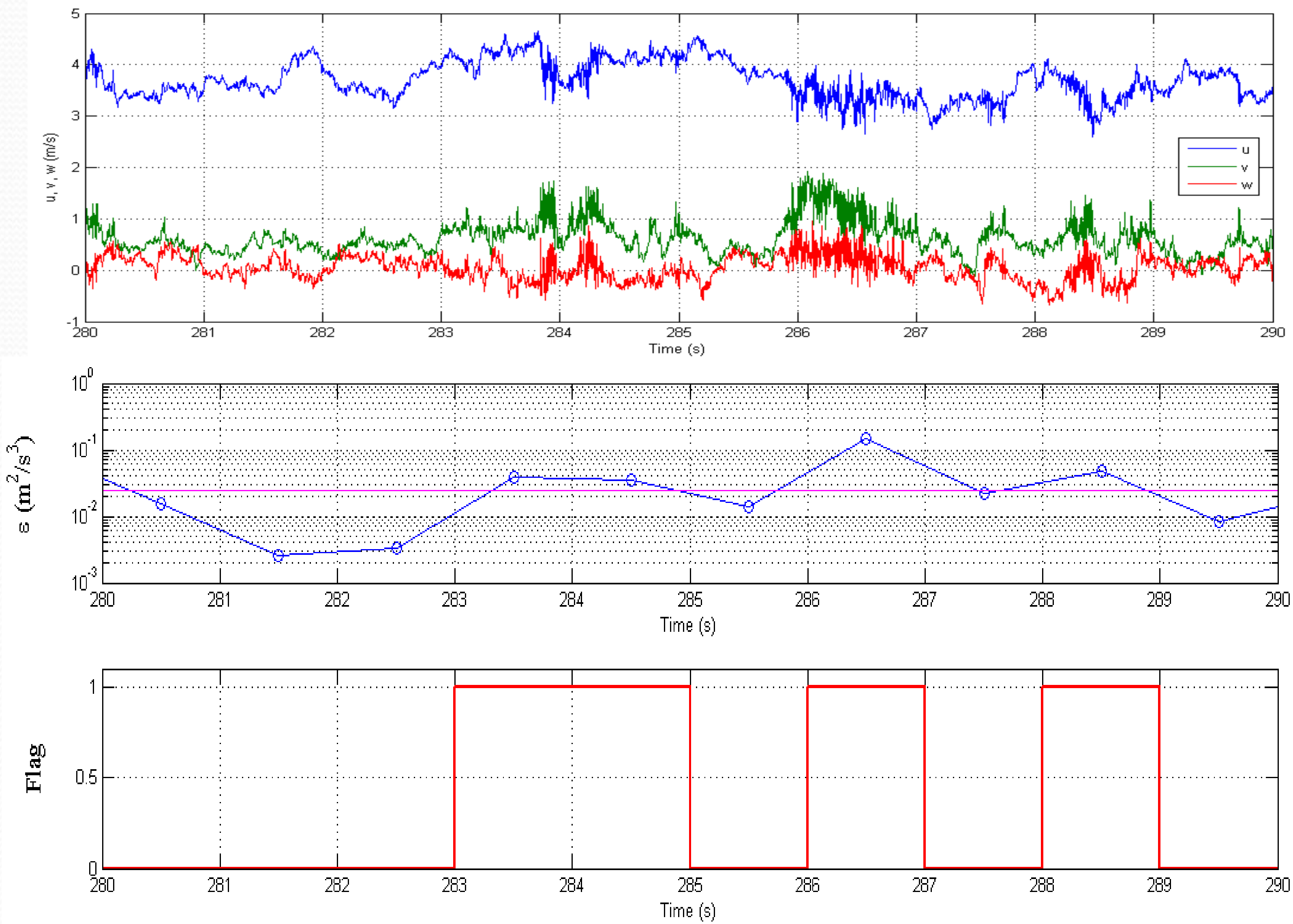


# 11 TKE dissipation in 4th SI

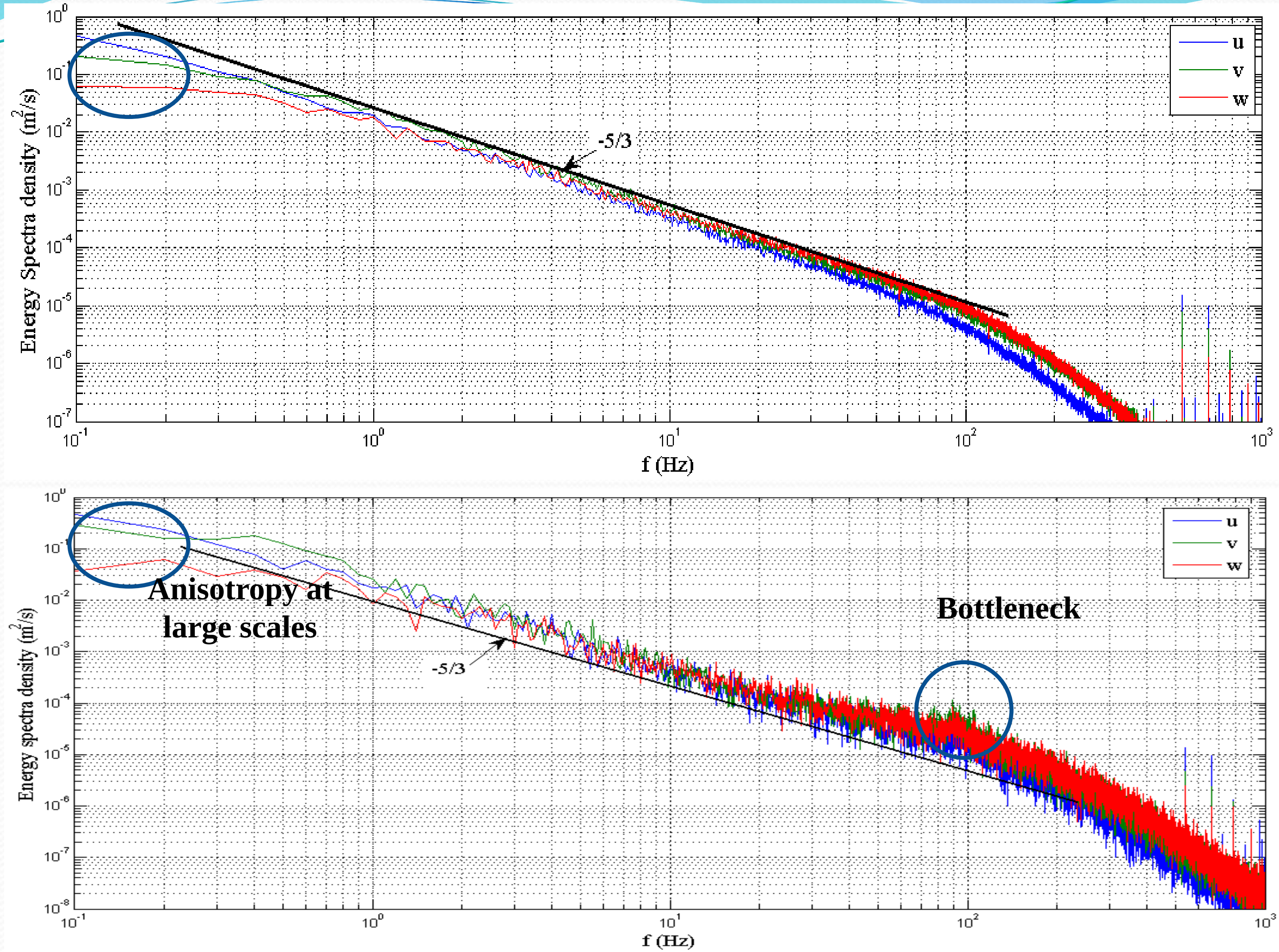
$$\epsilon = 15\nu\overline{\left(\frac{\partial u}{\partial x}\right)^2} \; ; \; \partial x = -U\partial t$$



# 12 Velocity field at bursting events in forth SI. 10 s of the 5th min.



# 13 SPECTRA: upper - no-burst, bottom - burst



# 16 Kolmogorov's Self-Similarity Hypothesis (KSSH) and Postulate of Local Isotropy (PLI)

1. Kolmogorov Self-Similarity Hypothesis (KSSH), which enabled to express, based on dimensionless considerations, the structure function $L_p(r)$ defined as a moment of any order $p$ of the velocity increment $\Delta u$ at a separation $r$ as a function of $\varepsilon$ (mean turbulent kinetic energy TKE dissipation rate) and $r$ as $L_p(r) = (\Delta u)^p \propto (r\varepsilon)^{p/3}$. This is strictly appropriate for Homogeneous Isotropic Turbulence (HIT), a theoretical abstraction that can be made pragmatic by introducing the Postulate of Local Isotropy (PLI) described below.

2. PLI assumes that far from boundaries and external forces applied at large scales, turbulence losses memory as it cascades down from large to smaller scales, wherein turbulence becomes locally isotropic and therefore KSSH is applicable. This cascading region (inertial subrange) is suitably separated from the regions of larger TKE containing scales and much smaller viscous dissipation scales. The dissipation subrange is also locally isotropic, but viscous influence therein engenders scaling laws different from those of the inertial subrange.

# Longitudinal structure functions, $L_p(r)$ and $L^*_p(r)$

# 17 *Canonical* and odd *modified* moments

Similar functions based on the longitudinal velocity increment

$\Delta u(x,r) = u(x+r) - u(x)$ and its modulus.

$$L_p(r) = \langle (\Delta u(x,r))^p \rangle; \quad L^*_p(r) = \langle |\Delta u(x,r)|^p \rangle$$

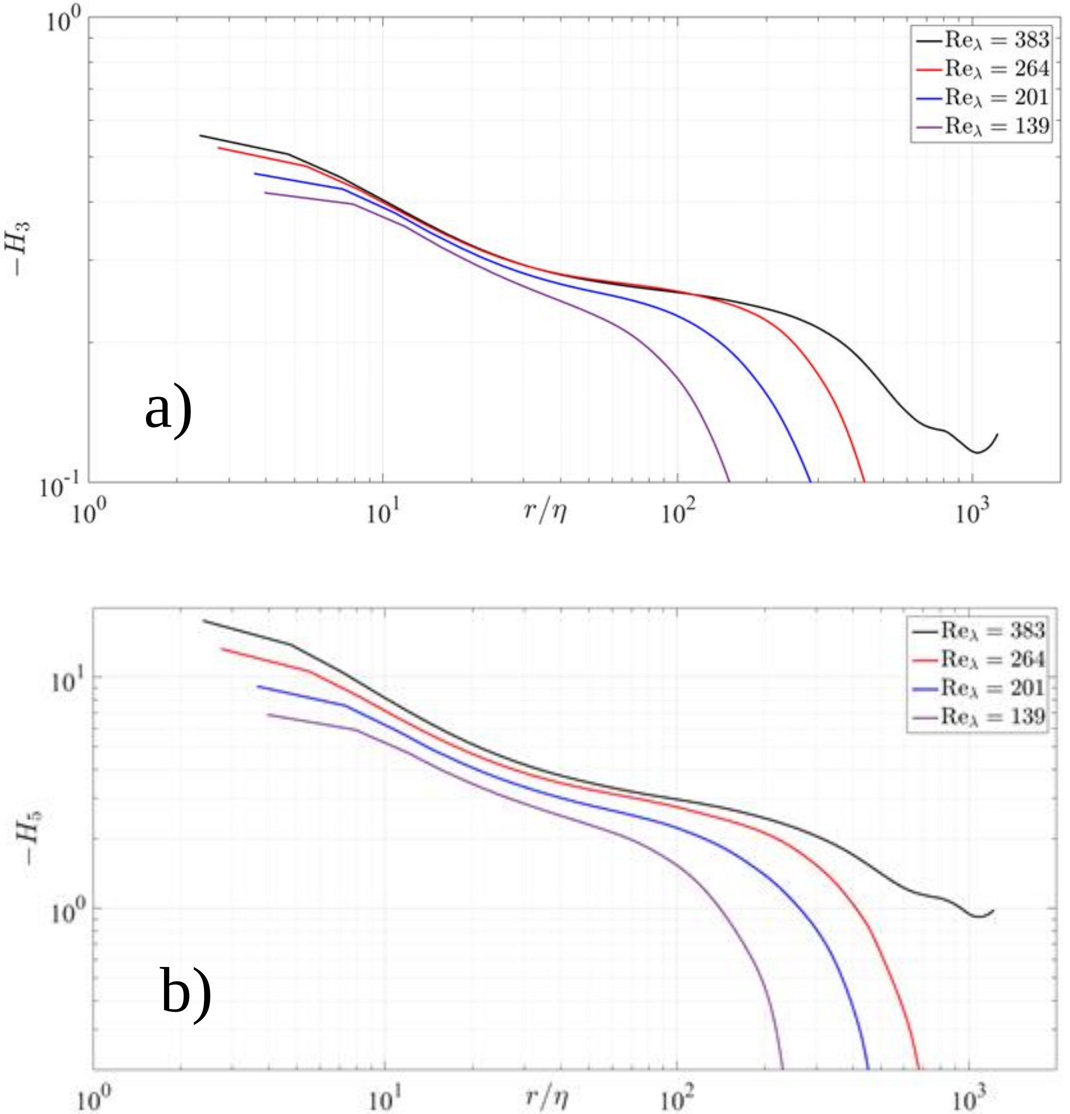
The moments of velocity increment in the *canonica*l form are

$$H_p(r) = L_p(r) \big/ (L_2(r))^{p/2} \qquad H^*_p(r) = L^*_p(r) \big/ (L_2(r))^{p/2}$$

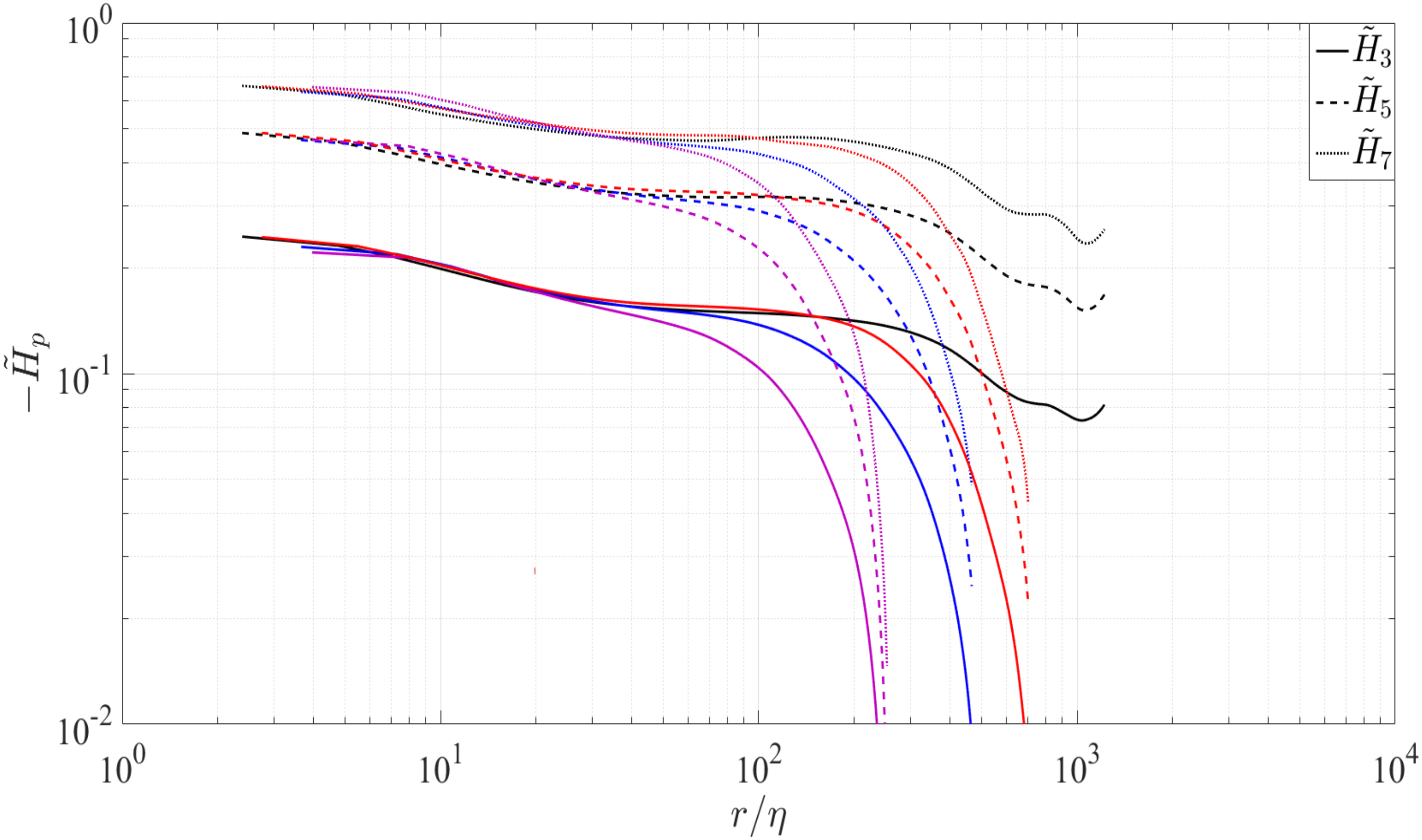
Odd *modified* moments normalized by their modulus:

$$\tilde{H}_p(r) = L_p(r) \big/ L^*_p(r) = H_p(r) / H^*_p(r)$$

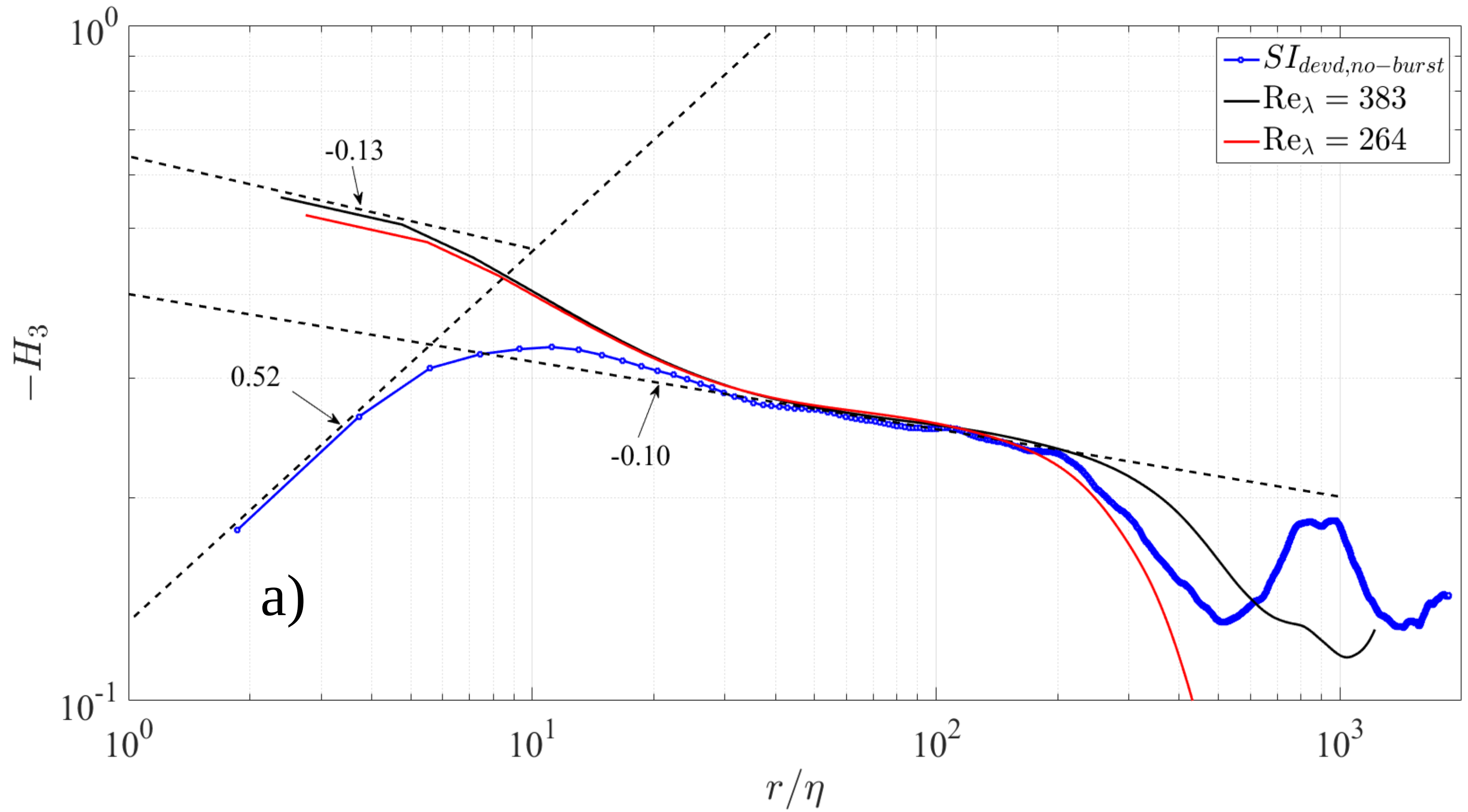
# 18 *Canonical* Moments, 3rd and 5th



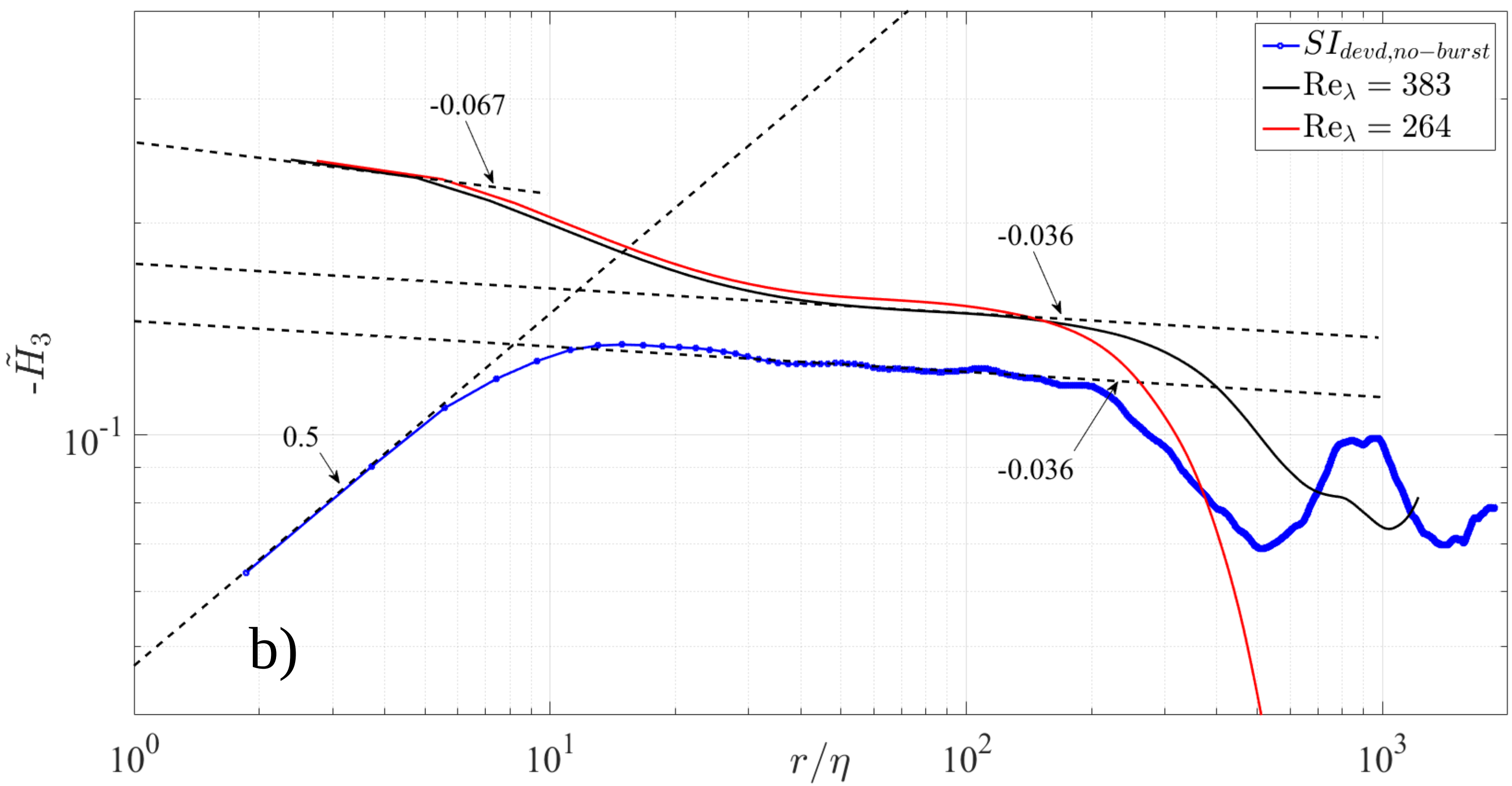
# 19 *Modified* Moments, 3rd, 5th and 7th



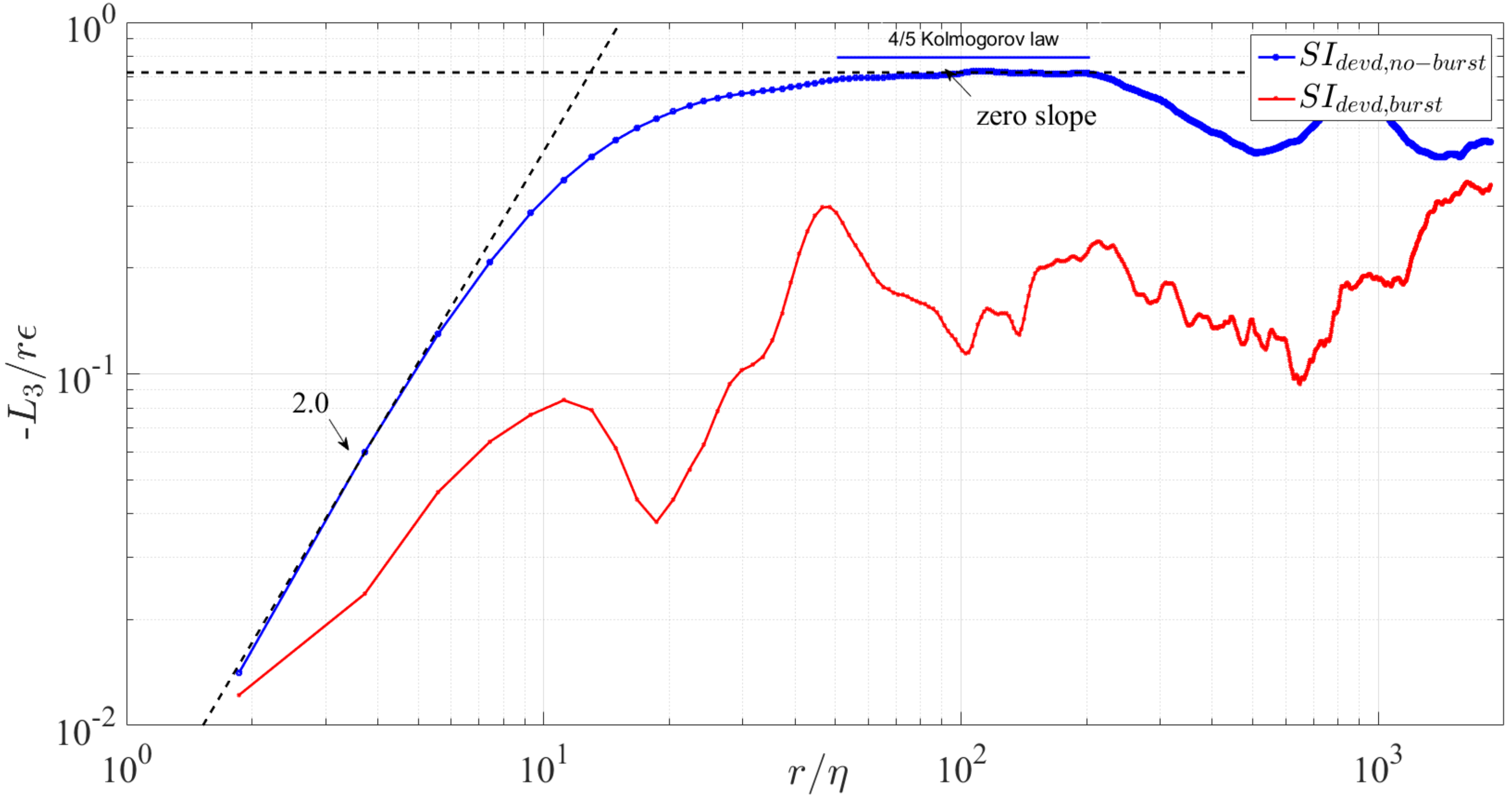
# 3rd *canonical* moment comparison



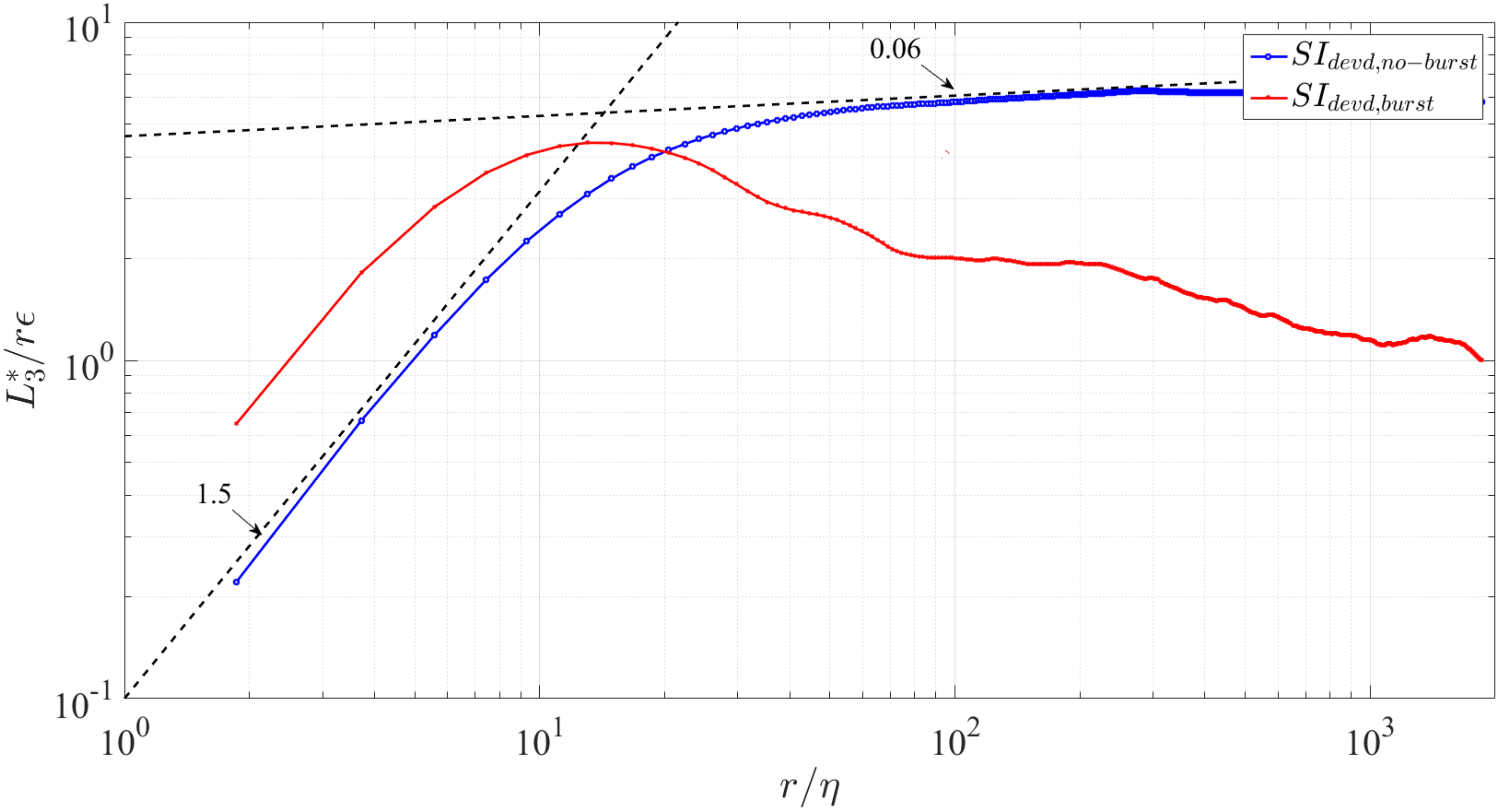
# 3rd *modified* moment comparison



# 24 Normalized according to KSSH 3rd order structure functions

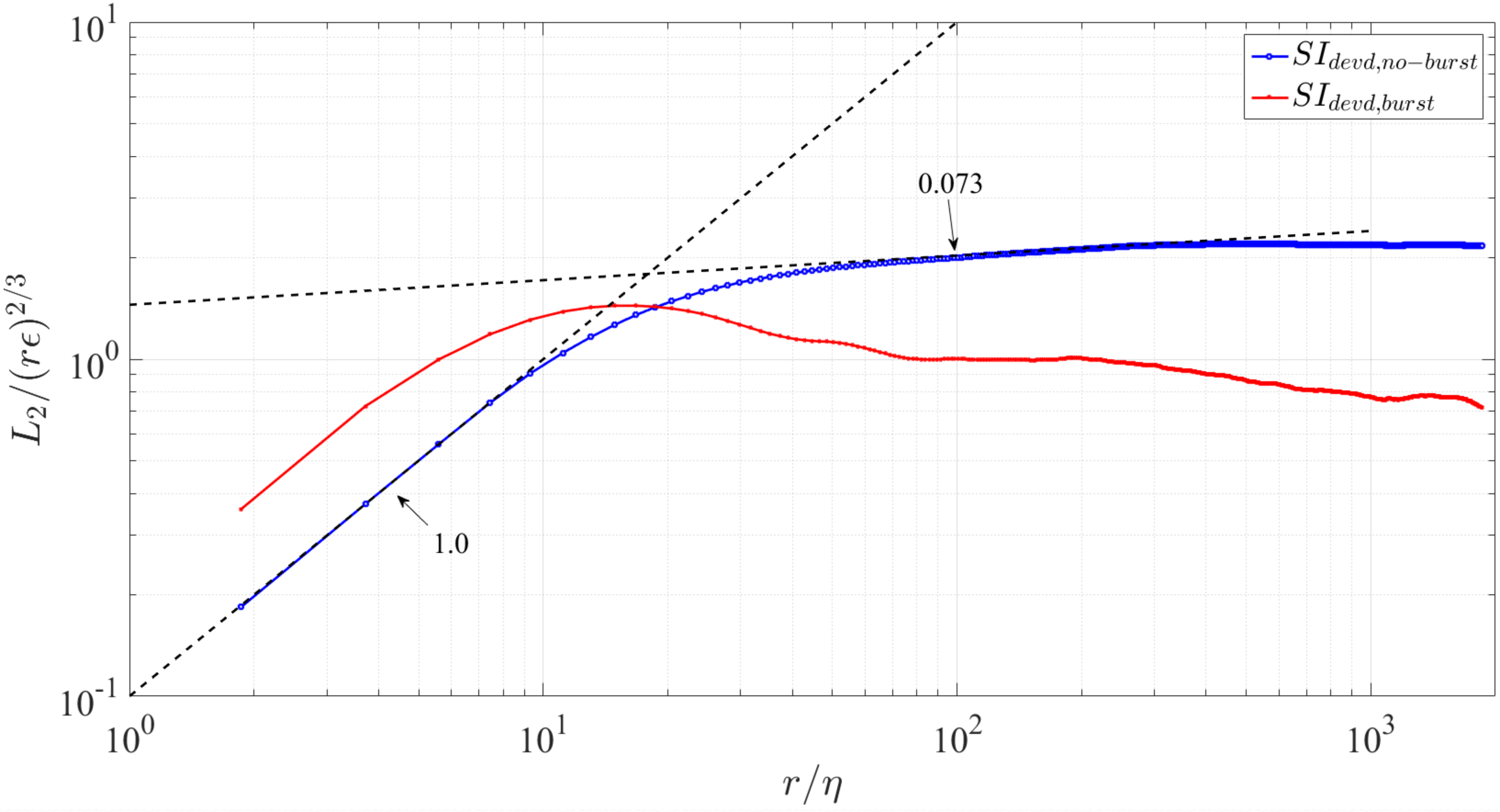


# 25 Normalized according to KSSH 3rd order structure functions for velocity increment modulus

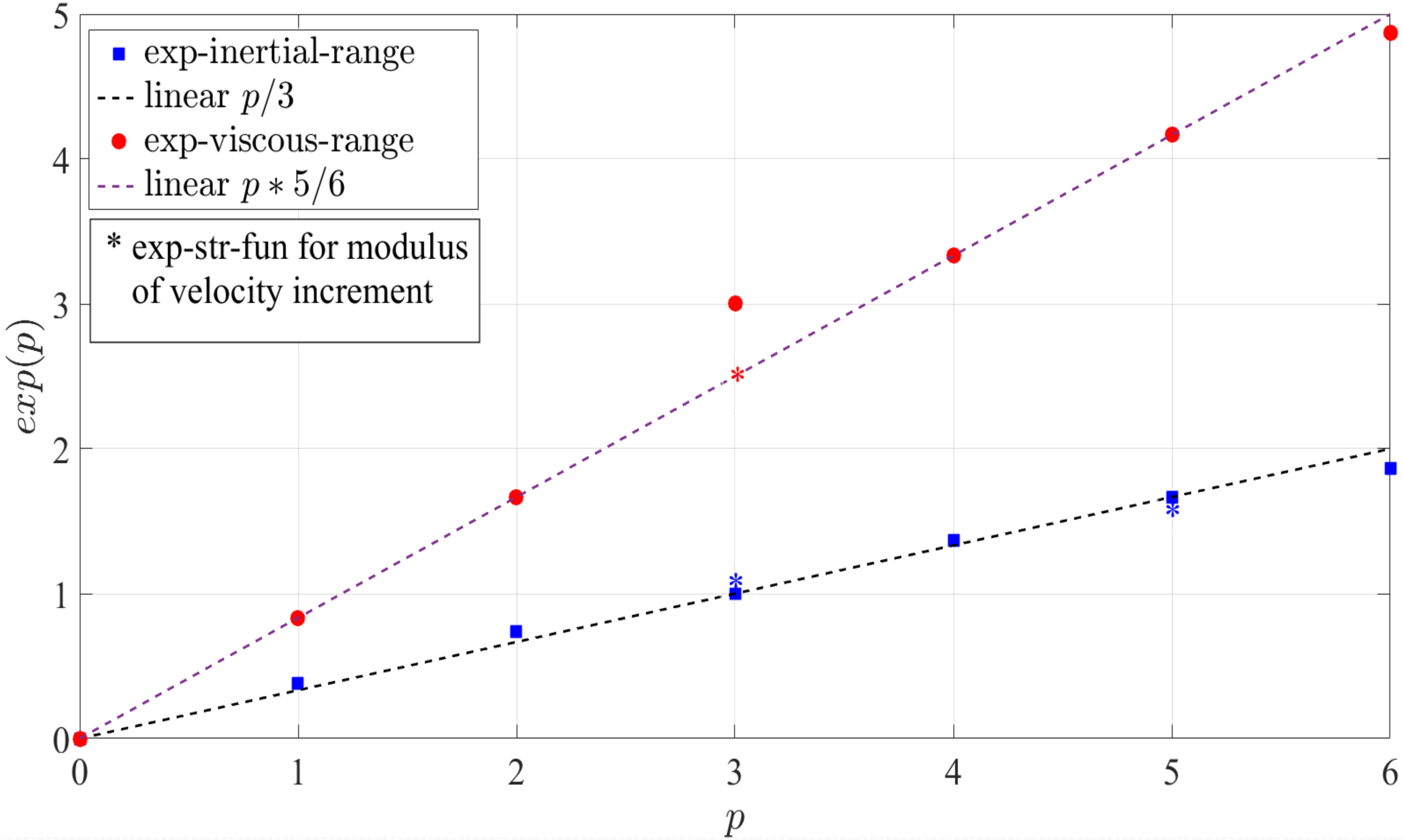


26 **Normalized according to KSSH**

# $2^{nd}$ order structure functions



# 27 Scaling exponents in the *inertial* and *viscous* sub-ranges

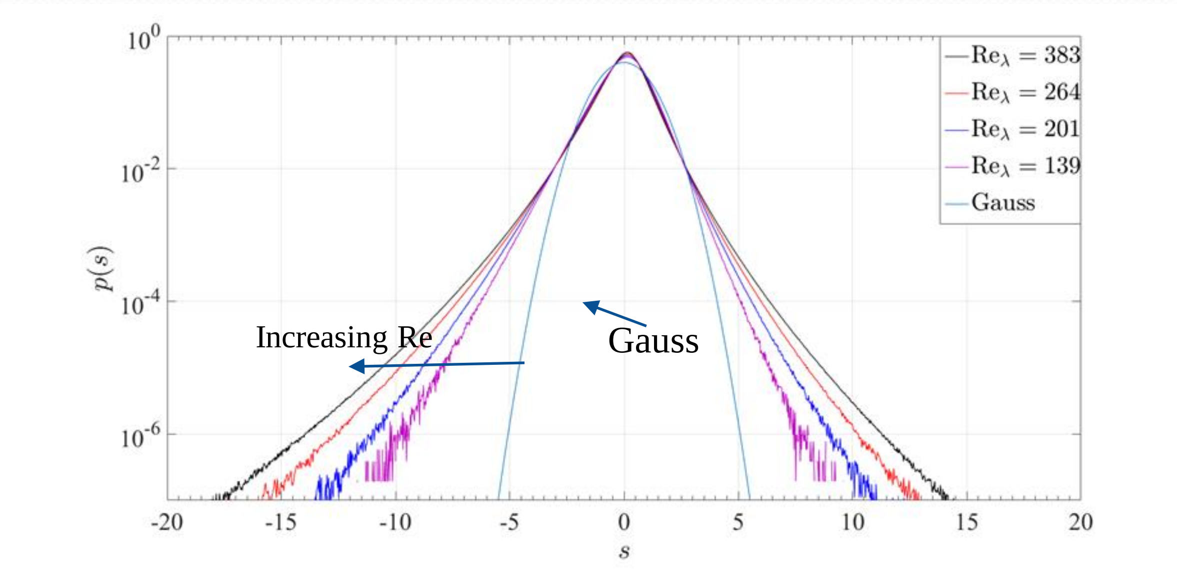


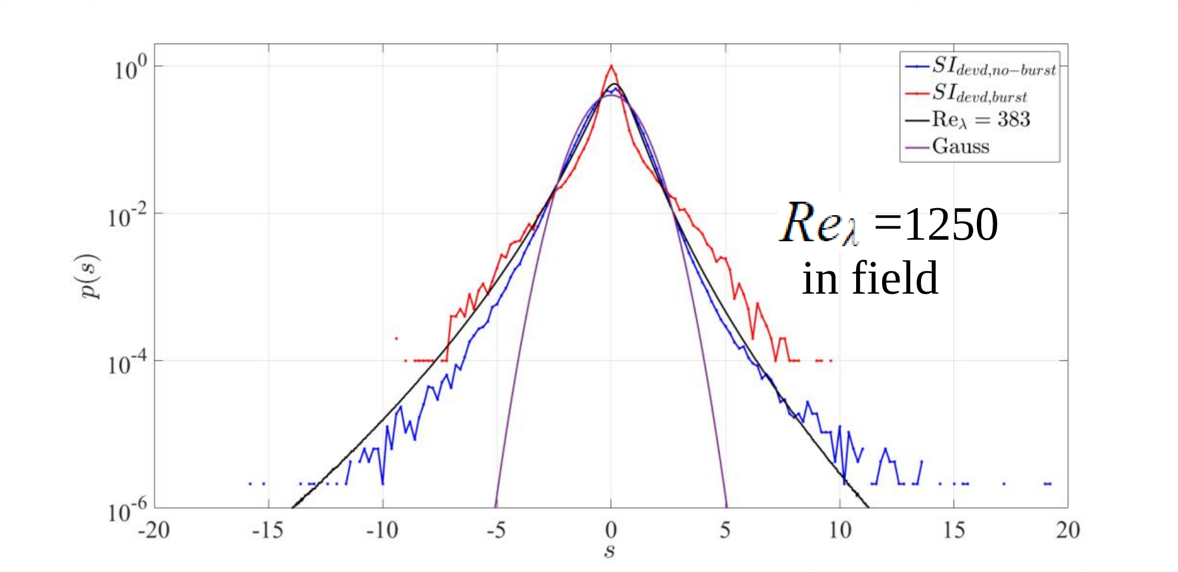
## 28 Scaling exponents of the (structure) functions in the *inertial* and *viscous* sub-ranges for velocity increment and its modulus for datasets without bursts. *kssh* and *lin* – theoretical exponents in *inertial* - *p/3* and *linear* - *p* in *viscous* sub-ranges [18], *hom* and *sh* – experimental and DNS values in HIT (Homogeneous Isotropic) and shear flows [28], *str* –current field data measured under stratified conditions in *nocturnal* ABL. In *viscous* sub-range results for modulus of velocity increment corresponding to 5*p*/6.

| structure functions of order *p* | $\Delta u(x,r)$ scaling exponents inertial sub-range *kssh, hom*, **str**, *sh* | $\lvert\Delta u(x,r)\rvert$ scaling exponents inertial sub-range *kssh, hom*, **str**, *sh* | $\Delta u(x,r)$ scaling exponents viscous sub-range *lin, hom*, **str**, *sh* | $\lvert\Delta u(x,r)\rvert$ scaling exponents viscous sub-range *lin, hom*, **str**, *sh* |
|---|---|---|---|---|
| 1 | Function identically 0 | 0.333, 0.36, **0.38**, 0.44 | Function identically 0 | 1.0, n/a*, **0.833**, n/a |
| 2 | 0.667, 0.70, **0.74**, 0.77 | 0.667, 0.70, **0.74**, 0.77 | 2.0, n/a, **1.667**, n/a | 2.0, n/a, **1.667**, n/a |
| 3 | 1.0, 1.0, **1.0**, 1.0 | 1.0, n/a, **1.06**, n/a | 3.0, n/a, **3.0**, n/a | 3.0, n/a , **2.50**, n/a |
| 4 | 1.333, 1.28, **1.334**, 1.17 | 1.333, 1.28, **1.334**, 1.17 | 4.0, n/a, **3.333**, n/a | 4.0, n/a, **3.333**, n/a |
| 5 | 1.667, n/a, **1.667**, n/a | 1.667, 1.54, **1.635**, 1.31 | 5.0, n/a , **fluct**, n/a | 5.0, n/a, **4.1667**, n/a |
| 6 | 2.0, 1.78, **1.867**, 1.44 | 2.0, 1.78, **1.867**, 1.44 | 6.0, n/a, **4.87**, n/a | 6.0, n/a, **4.87**, n/a |

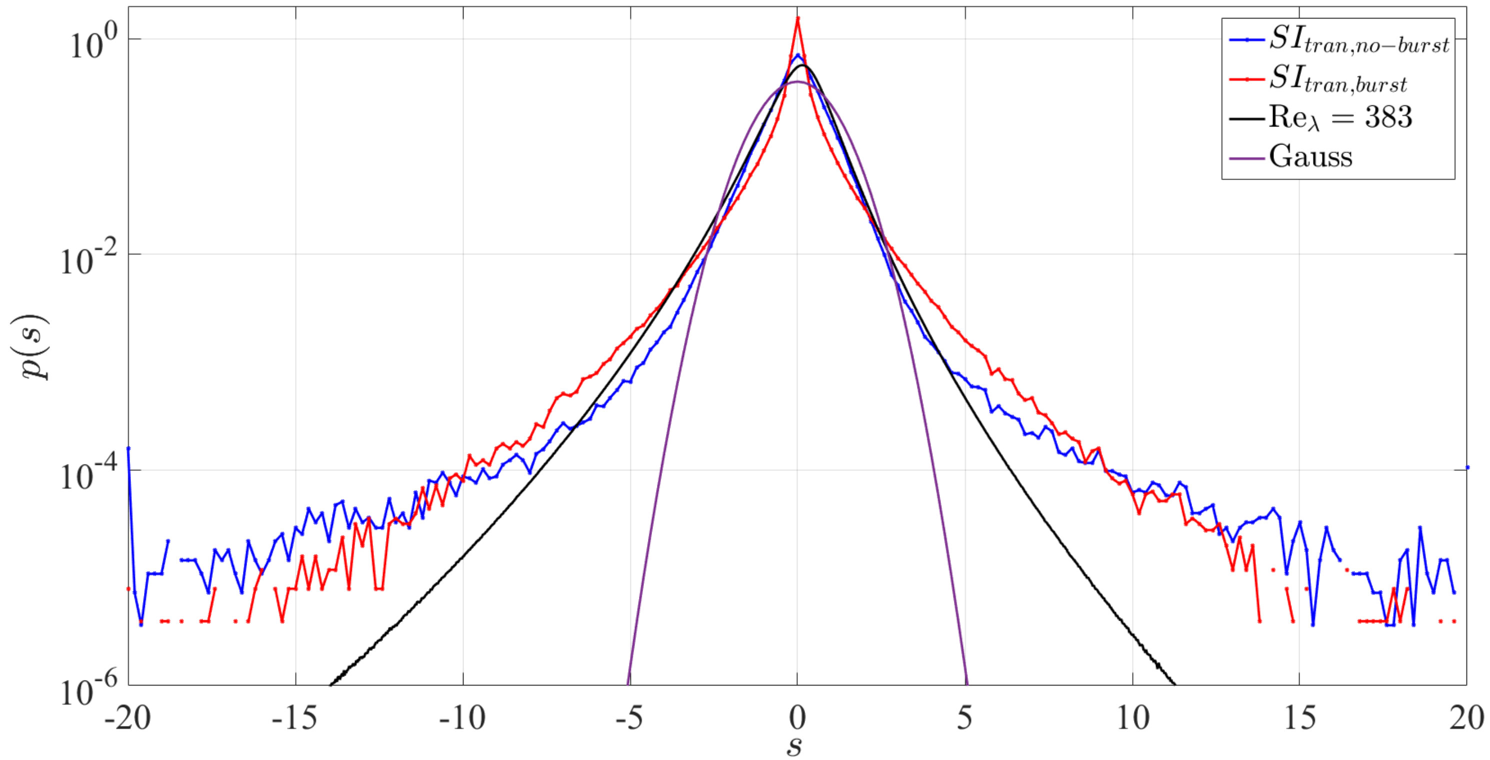
*n/a – not available from experiments or DNS

# 29 PDF of velocity derivatives in HIT of DNS and of nocturnal turbulence in field experiment for $Re_\lambda$ = 1250

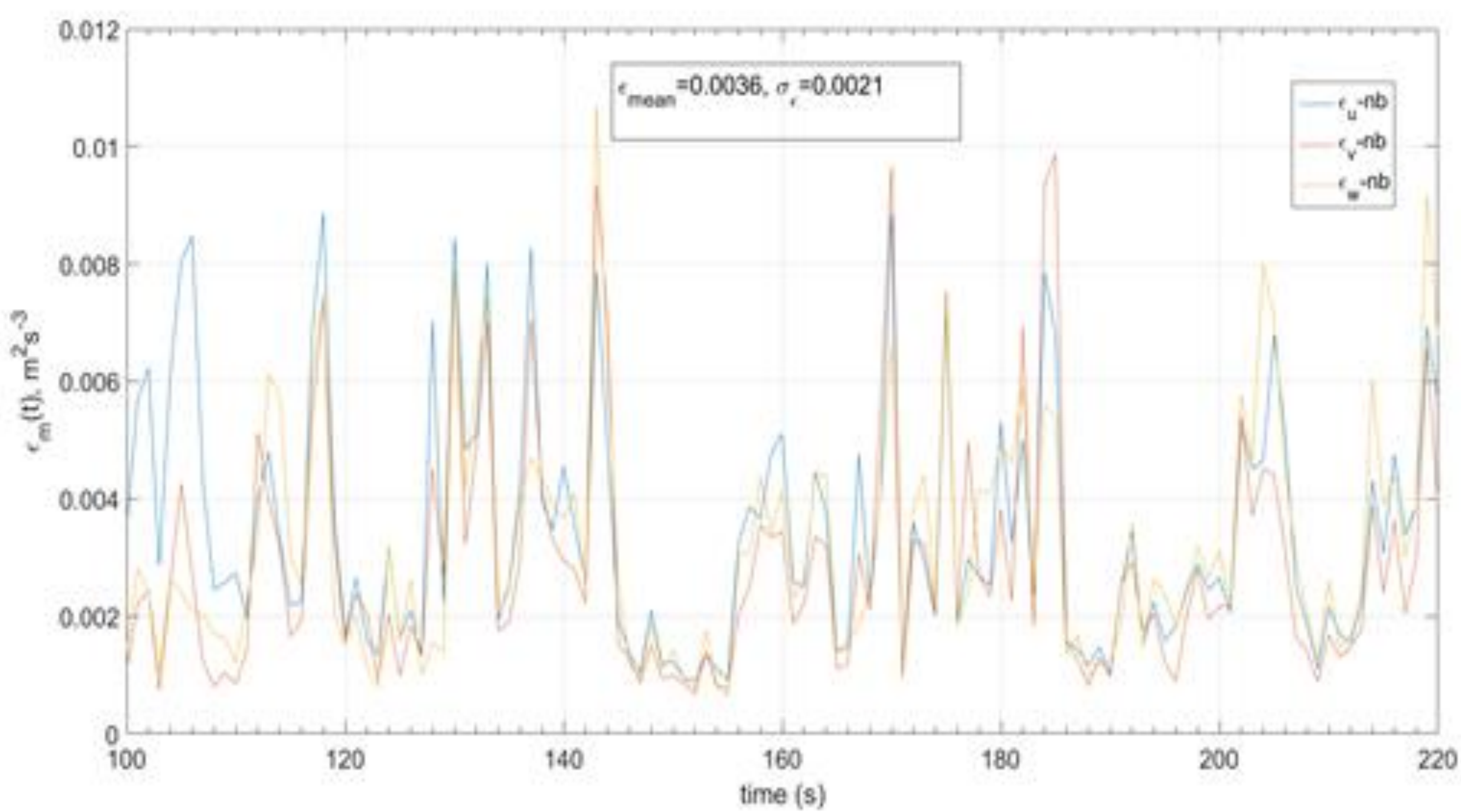


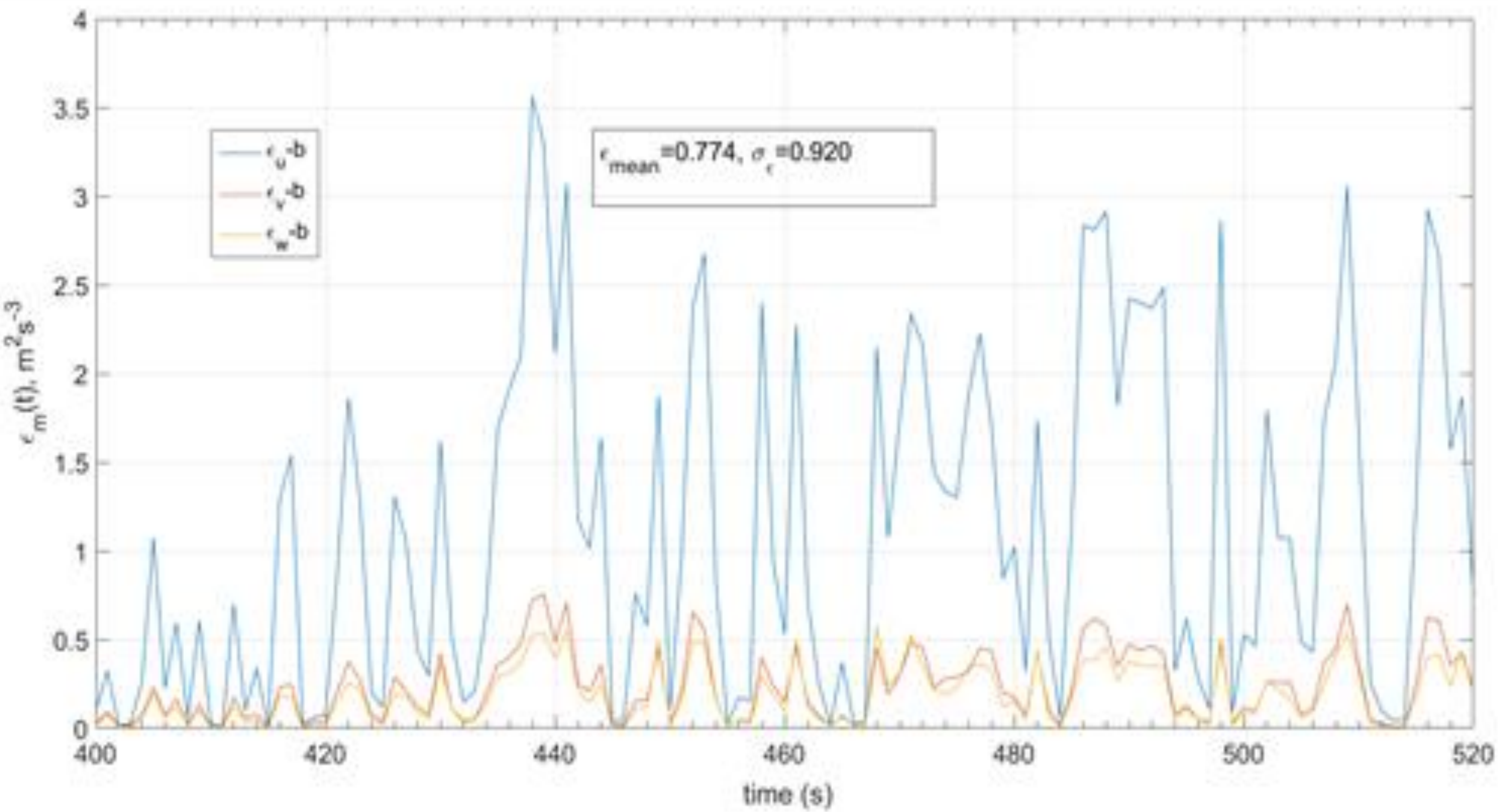
# 31 PDF of the velocity derivative in the transitioning-in sub-interval $SI_{tran}$ for 'burst' and 'no-burst' datasets



# 35 Two-minute time series of TKE dissipation rate in transitioning-in sub-interval: dataset without bursts (*nb* – no-busts)



# Two-minute time series of TKE dissipation rate in transitioning-in sub-interval: dataset with bursts (*b* – bursts)



# Expressions used for evaluation dissipation 32 and scaling exponents estimates

We have used time interval of 1 s, i.e. more than 1000 Kolmogorov timescales, to conduct initial averaging to obtain the estimate $\varepsilon_m = \bar{\varepsilon}$ by employing the following surrogate isotropic relations for evaluation of dissipation

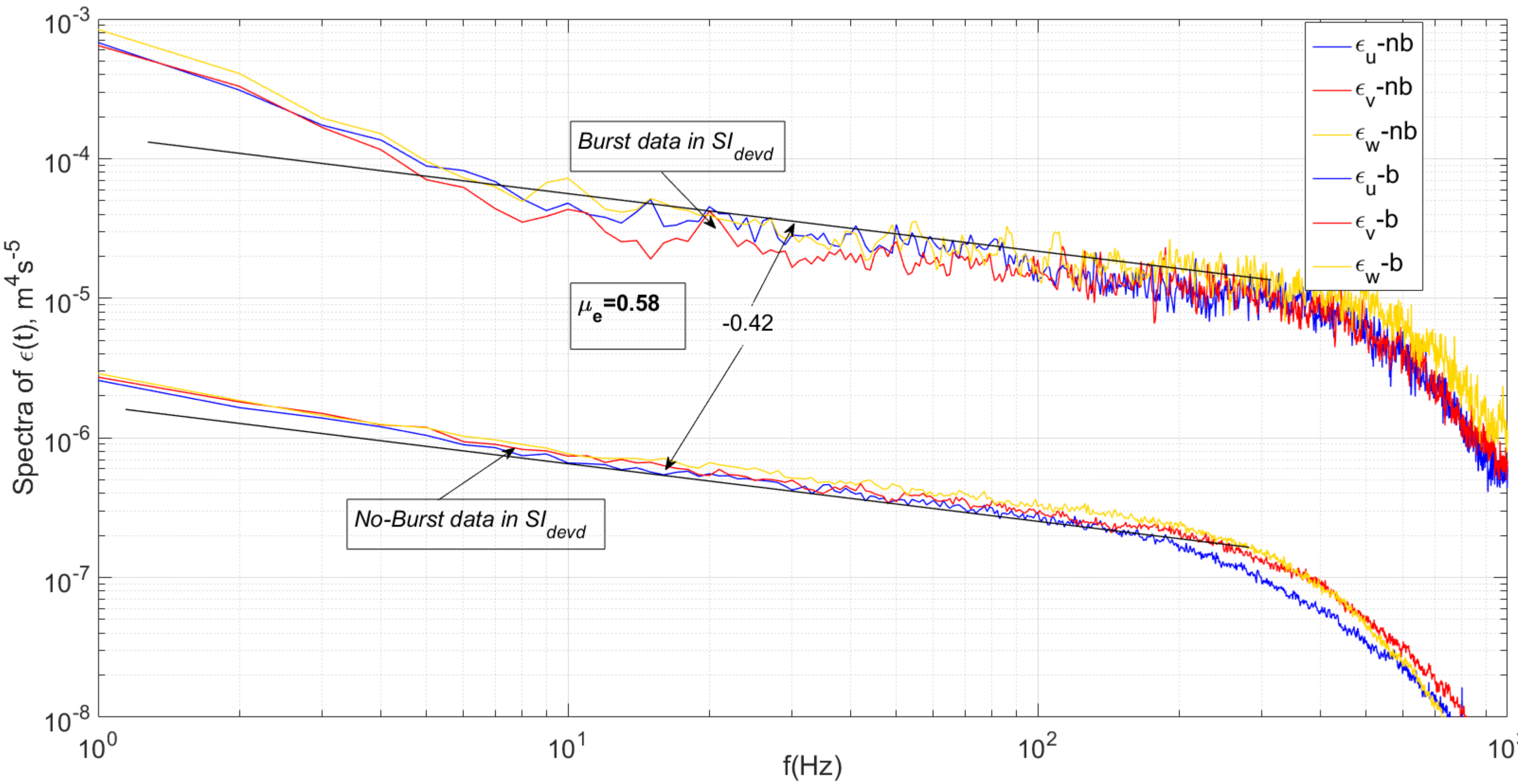
$$\varepsilon = 15\nu(\partial u/\partial x)^2 = 7.5\nu(\partial v/\partial x)^2 = 7.5\nu(\partial w/\partial x)^2$$

The approximate spectral slope of the dissipation spectral density was assessed from the corresponding Figures and the intermittency exponent $\mu_e$ were estimated using the following expression

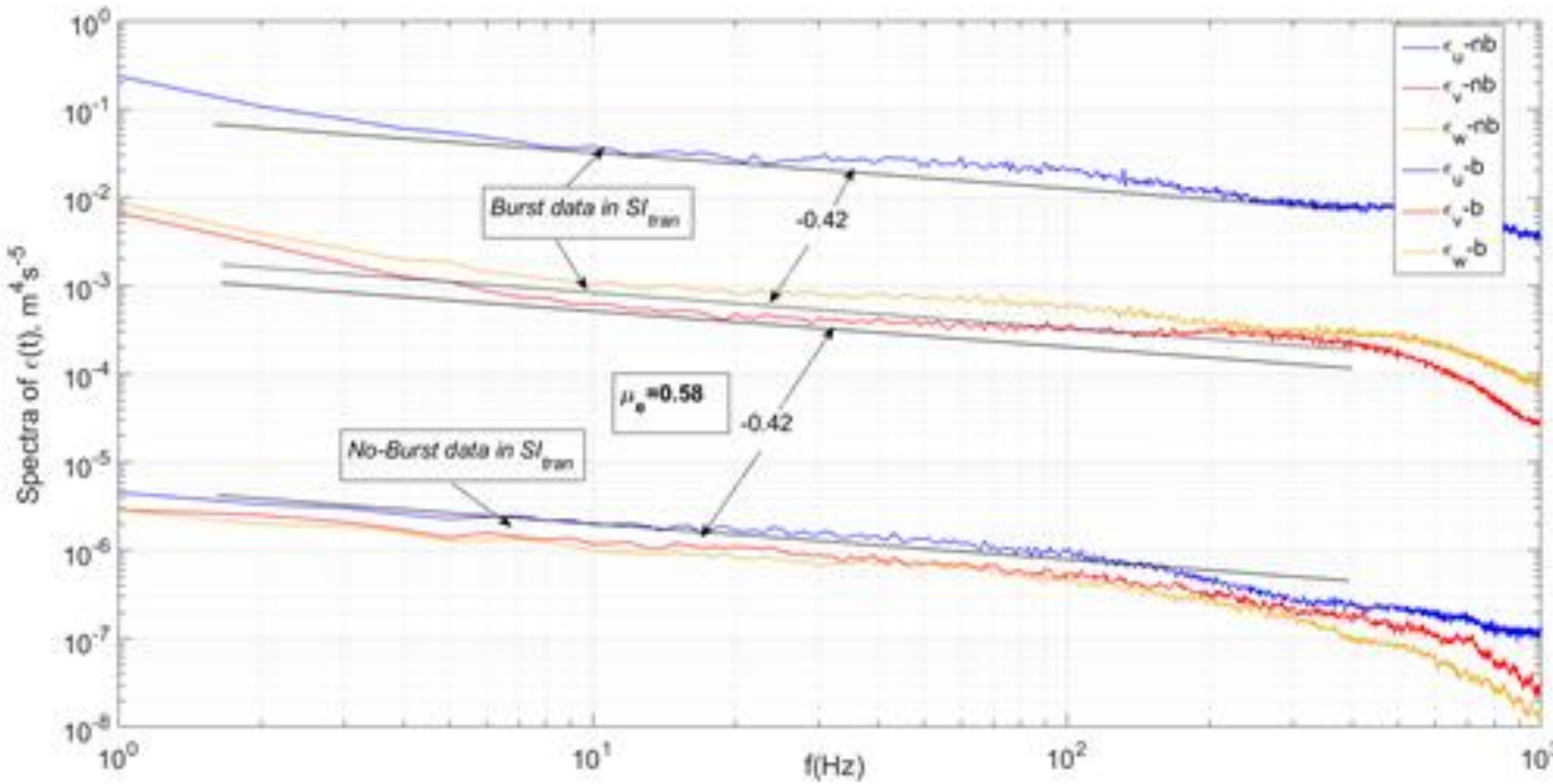
$$E_\varepsilon(k) = 1/\pi \int_0^\infty B_\varepsilon(r)\cos(kr)dr \propto k^{-1+\mu_e}, 1/L \ll k \ll 1/\eta,$$

# 37 Dissipation spectra and scaling exponents in developed sub-interval for datasets with (*b*) and without bursts (*nb*)

$$E_\varepsilon(k) = 1/\pi \int_0^\infty B_\varepsilon(r)\cos(kr)dr \propto k^{-1+\mu_e}, 1/L \ll k \ll 1/\eta$$



# 38 Dissipation spectra and scaling exponents in transitioning-in sub-interval for datasets with (*b*) and without bursts (*nb*)



# Conclusions

- A combo system consisting of hot-film probes and collocated sonic was developed, with a capability of calibrating the hot-films using ***sonic data and a Neural Network (NN).***
- In the present study ***90 minutes of good data*** during an evening transition was measured from an almost laminar flow regime to a fully developed flow regime.
- A new phenomenon was discovered; ***the occurrence of strong bursting of turbulence*** related to the stable stratification.
- The no-burst field dataset as well as DNS datasets of homogeneous isotropic turbulence (HIT) were used to study the structure functions of various order of the velocity increment and its modulus.
- The canonical $p$-moment is obtained by normalizing higher order structure functions of order $p$ by the 2nd order structure function in power $p/2$.

# Conclusions-continuation

- A new (modified) normalization proposed for skewness of longitudinal velocity derivative involves the replacement of the second moment in the denominator of the canonical scaling with the same order 3rd moment of the modulus.
- Detailed comparison of odd $3^{rd}$ and $5^{th}$ order canonical and modified moments evaluated using field data without bursts with their DNS counterparts indicated a very good agreement in the inertial sub-range.
- The 3rd moment yielded the predicted linear dependence of velocity increment with smaller separations in the viscous sub-range. On the contrary, the $2^{nd}$ moment in the viscous sub-range does not support the predicted linear dependence, and instead yielded 5/6 exponent. This explains the surprising scaling exponent of ~0.5 for canonical $3^{rd}$ order structure function in the viscous sub-range.

# Conclusions-continuation

- In the viscous sub-range the above 5/6 exponent for the 2nd moment could be extended for a general *p*-order moment which was supported by our field data for all *p* .
- To isolate stratification effects from the total turbulence field, a simple-minded assumption was made, in that the measured turbulence at a height of 6 m above the ground is contributed by two uncorrelated effects: approximate HIT generated within the katabatic flow arriving from a nearby Granite mountain and motions due to stable temperature stratification at the measurement location. This simple model enabled to qualitatively explain the different scaling exponents obtained in the field data.
- We suggest that the more sophisticated SO(3) formalism developed for decomposition of structure and/or correlation functions to separate contributions of isotropic and anisotropic sectors be attempted in future studies of anisotropy at small scales introduced by large scale stratification.

# Conclusions-continuation

- The spectral magnitude of dissipation rate for strong bursting events observed in transitioning-in sub-intervals are 3-5 orders greater than those in non-bursting ones.
- The scaling exponent in the inertial sub-range of dissipation rate in the presence of moderate burst approximately fits the spectral shapes obtained for non-bursting turbulence, but is less satisfactory with strong bursts.
- The isotropy of dissipation rates computed using surrogate expressions valid in HIT is very poor with strong bursts (the dissipation rate estimated using the longitudinal velocity component provides spectral intensities by more than one order greater than with two lateral components) and the use of isotropic relations for dissipation rate is unjustified.
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# THANK YOU!
# THE END