Characterization of Hydrodynamics and Mixing Processes in Obstructed Flows

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Mixing Processes in Pipes, Sewers & the Natural Environment – from Theory to Practice

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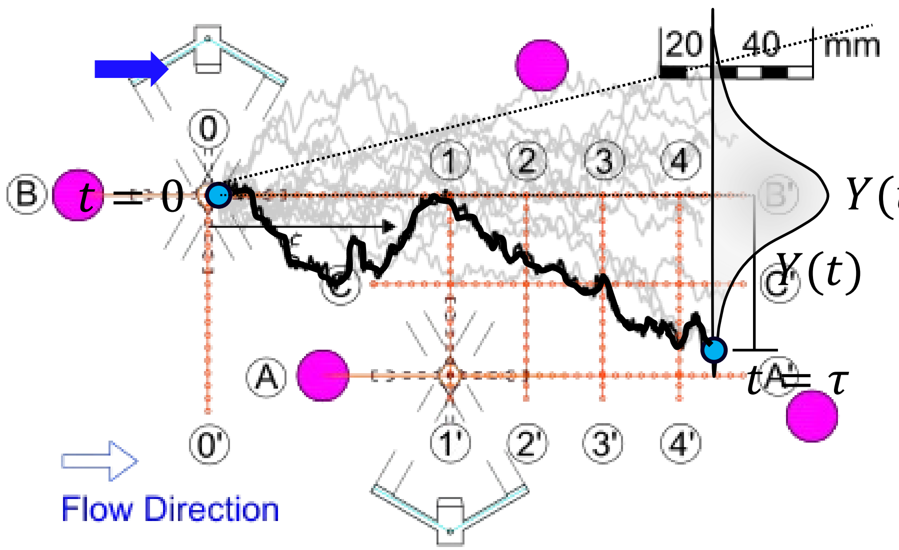
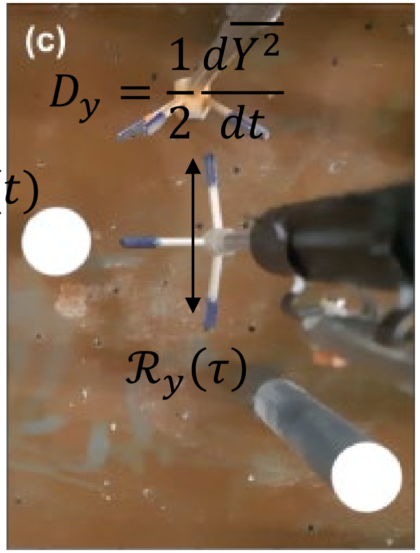
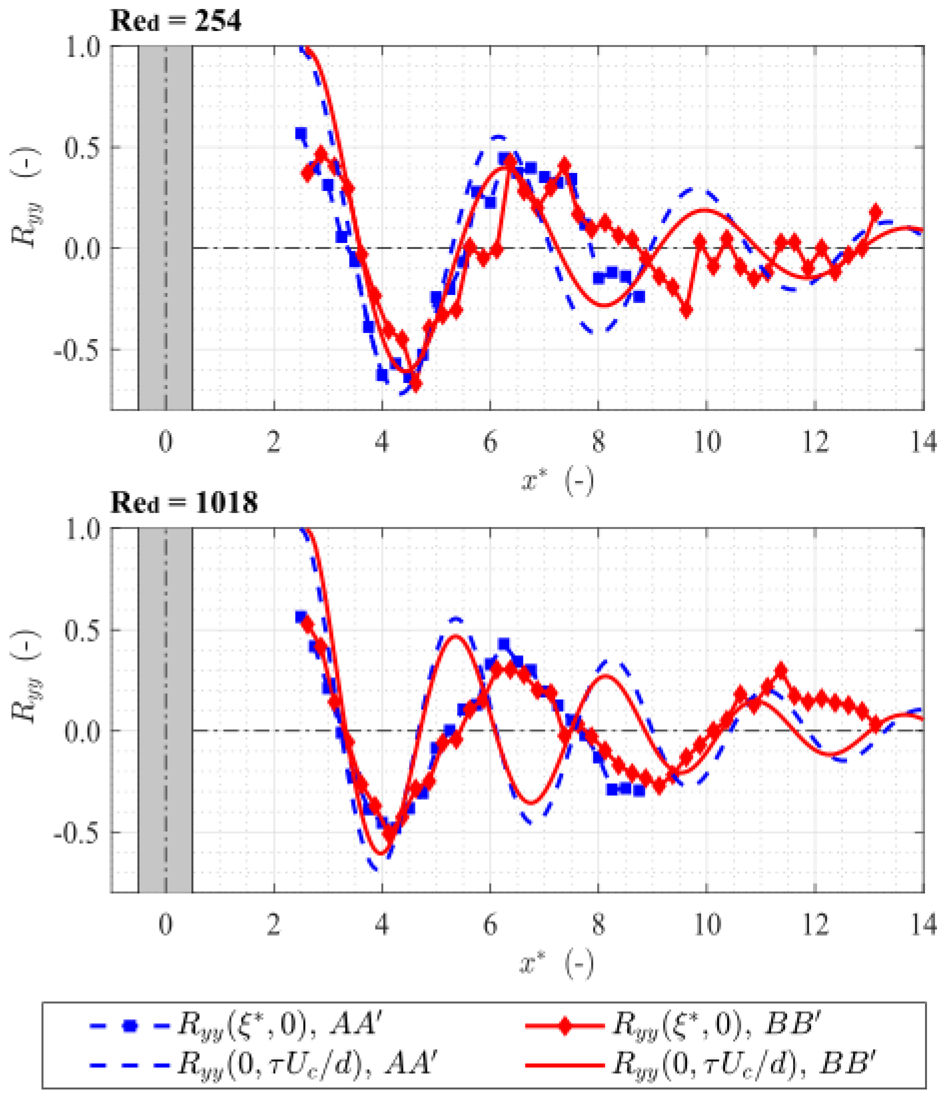
Diffusion in Obstructed Flows

- Diffusion/Dispersion quantifies the increase in spread of a Lagrangian ensemble.
- Experiments designed to measure multi-point velocity statistics (Eulerian FoR) and relate empirically to Lagrangian statistics in obstructed (cylinder) flows.





Eulerian Correlations $R_{yy}(x,t)$



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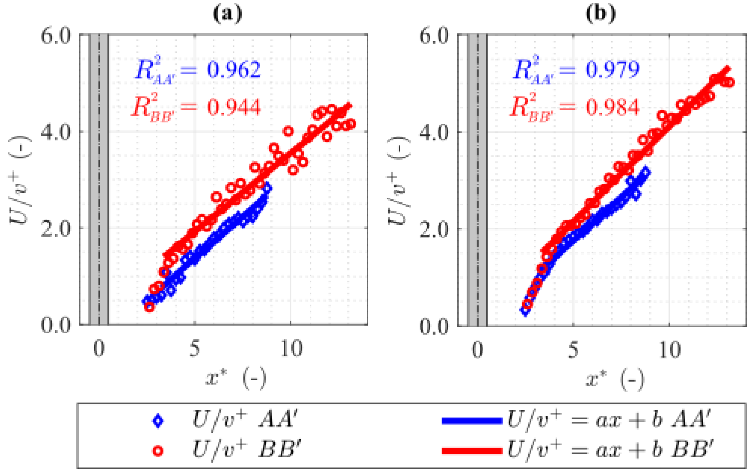
Diffusion in Obstructed Flows

The objective is to obtain the Lagrangian velocity correlation function, $\mathcal{R}_y(t)$, from the measured Eulerian functions $R_{yy}(\xi, 0)$.

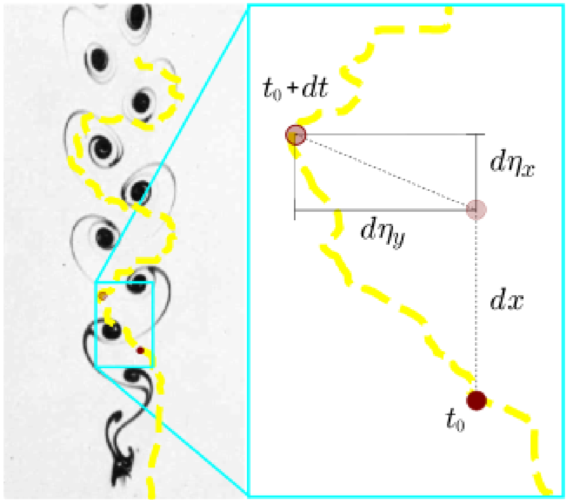
However, this is an undetermined mathematical problem*, so appropriate empirical/theoretical assumptions should be applied. 2 similarity assumptions are applied:

Taylor's rate of diffusion:

$$\frac{dx}{d_{\eta_y}} \sim \frac{U}{v^+} \approx mx + b$$



Similarity between particle trajectories



Measurements show that no momentum transfer occurs between adjacent cylinder wakes.

The probability distribution of particle trajectories inside the wake is therefore similar to that of a predetermined path along the wake centreline.

v^+: transverse turbulence intensity

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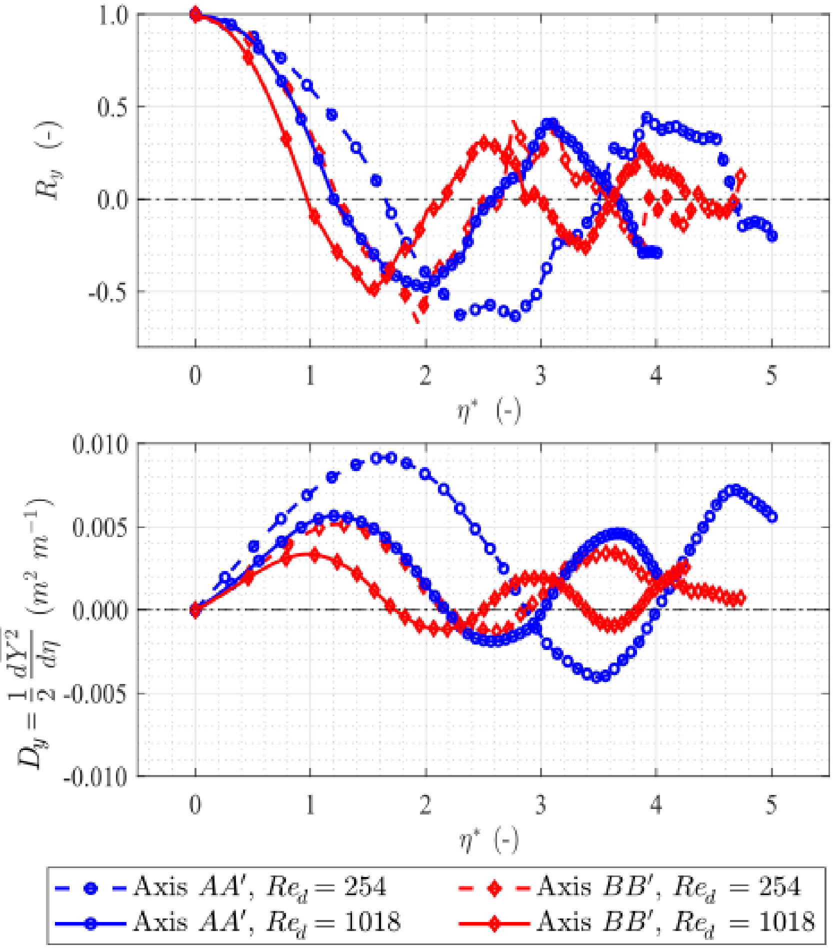
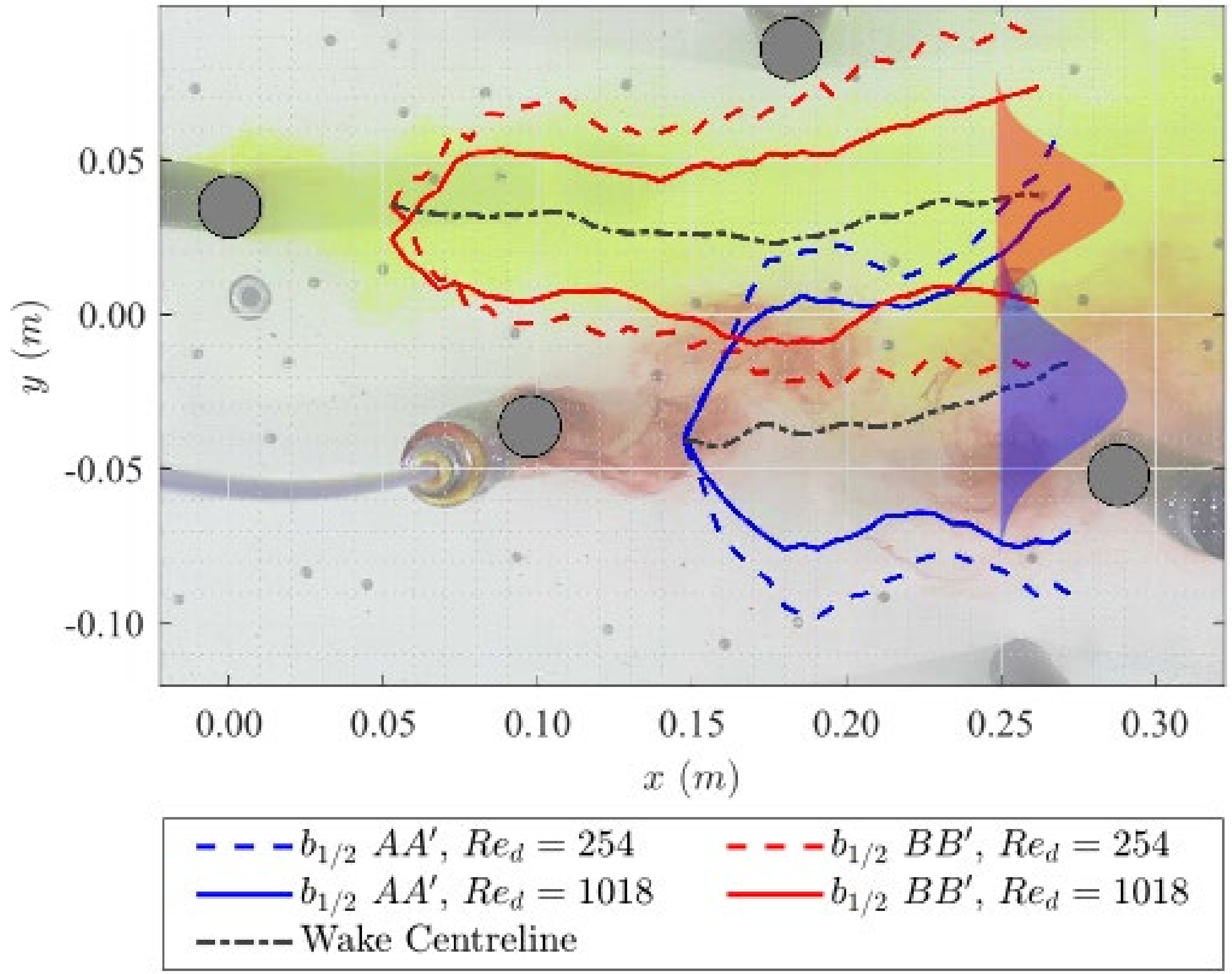
* Lumley, J.L.: The Mathematical Nature of the Problem of Relating Lagrangian and Eulerian Statistical Functions in Turbulence. In: Mecanique de La Turbulence, pp. 17–26. Editions du Centre National de la Recherche Scientifique, Paris (1962).

Diffusion in Obstructed Flows

- $\mathcal{R}_y$ is estimated along a predetermined path.



- Comparing estimations of the cylinder wakes show that it is possible to reproduce the effects of the adjacent flow field, and the diffusive wake downstream of a cylinder.



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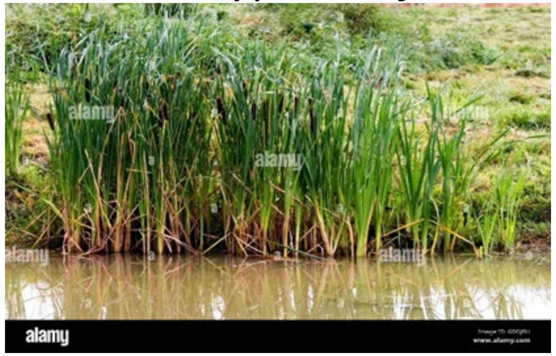
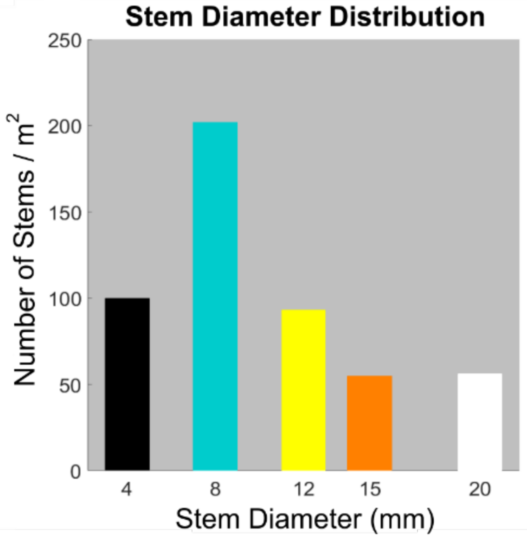
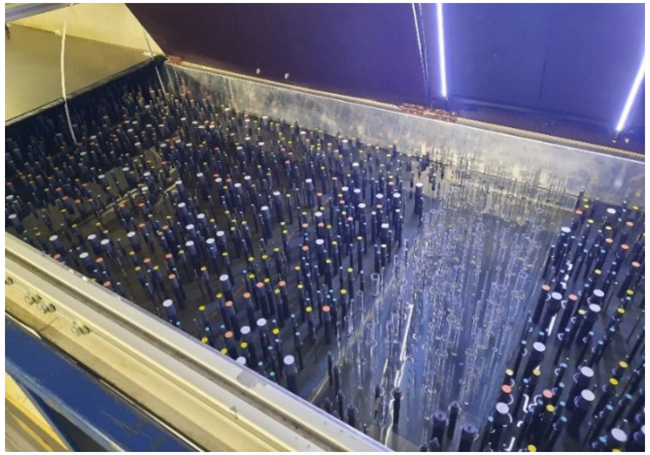
The RandoSticks System

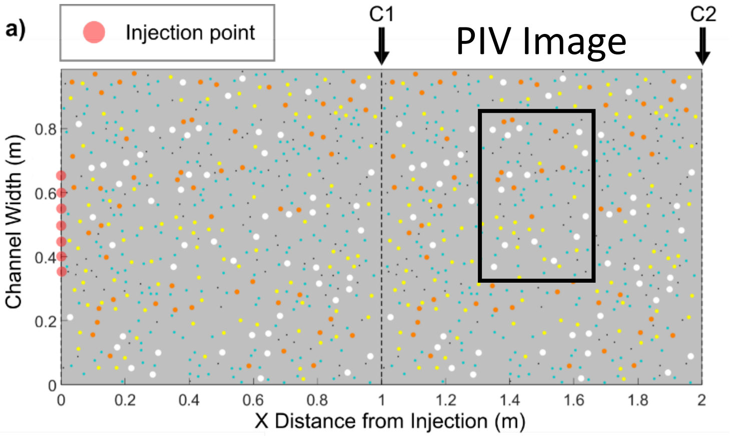
RandoSticks morphology
From characterisation of
Winter *Typha latifolia*



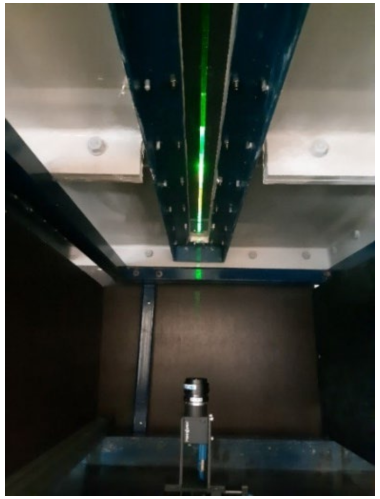


RandoSticks Layout
1.0 m x 1.0 m Repeated
pattern along 9m





Optical System
LIF: 4 lasers
PIV: 1 Laser sheet



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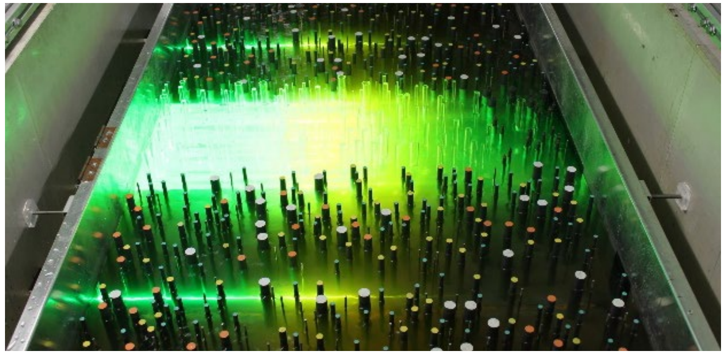
Laser Induced Fluorescence - Calibration

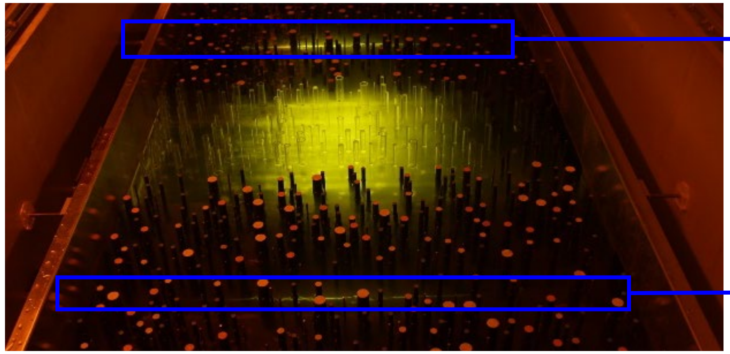
Excitation + Fluorescence



Long-pass

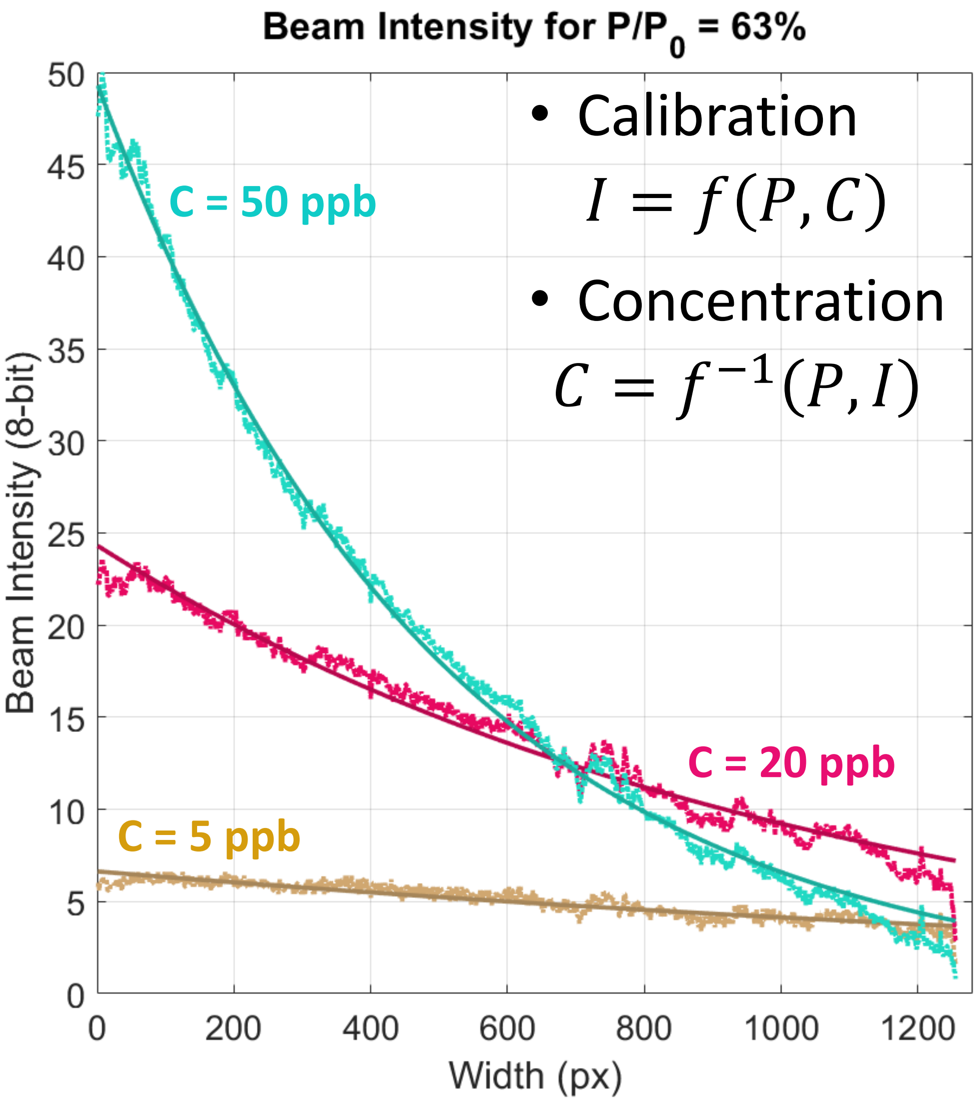
Filter

Isolated fluorescence



Range of: Concentration and

Laser Power



- Calibration

$$I = f(P, C)$$

- Concentration

$$C = f^{-1}(P, I)$$

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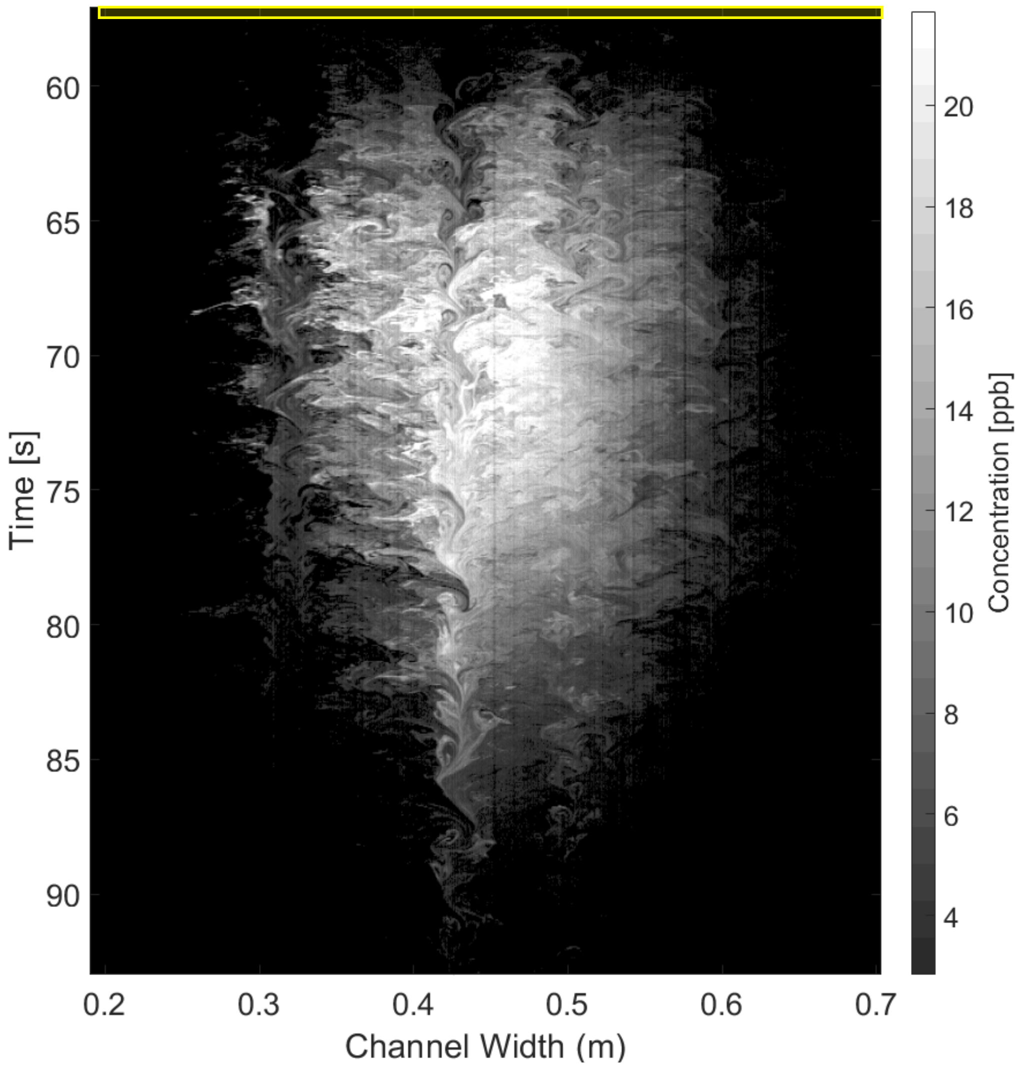
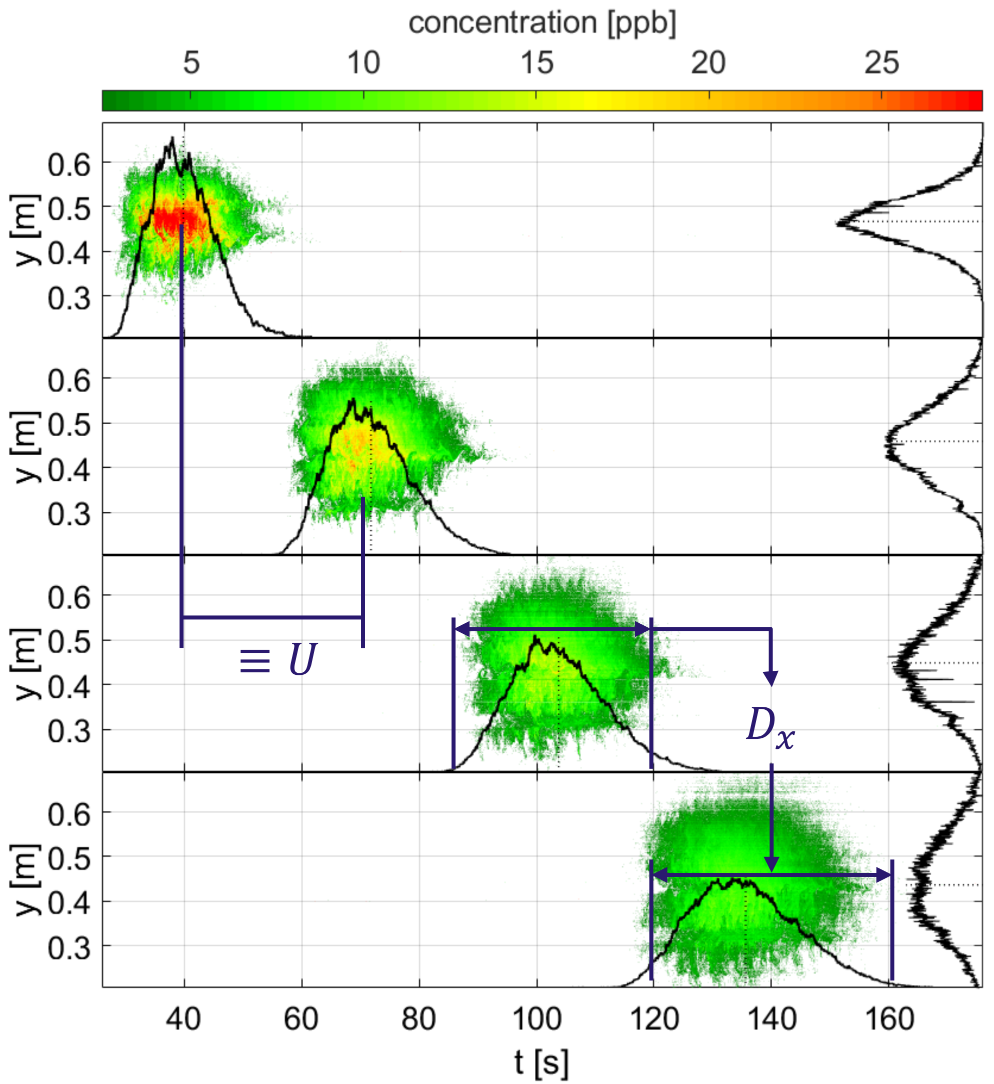
Laser Induced Fluorescence - Experiments





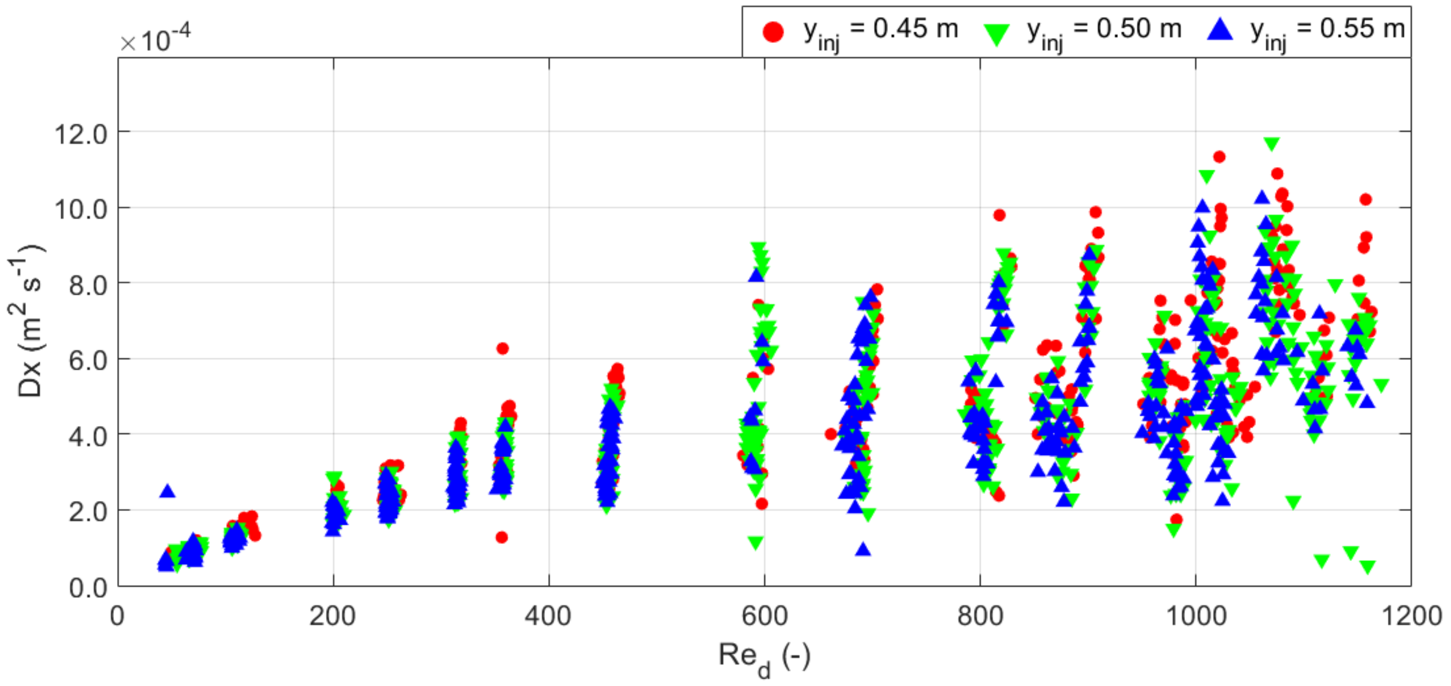
- Concentration profiles show D_x, D_y and U variation

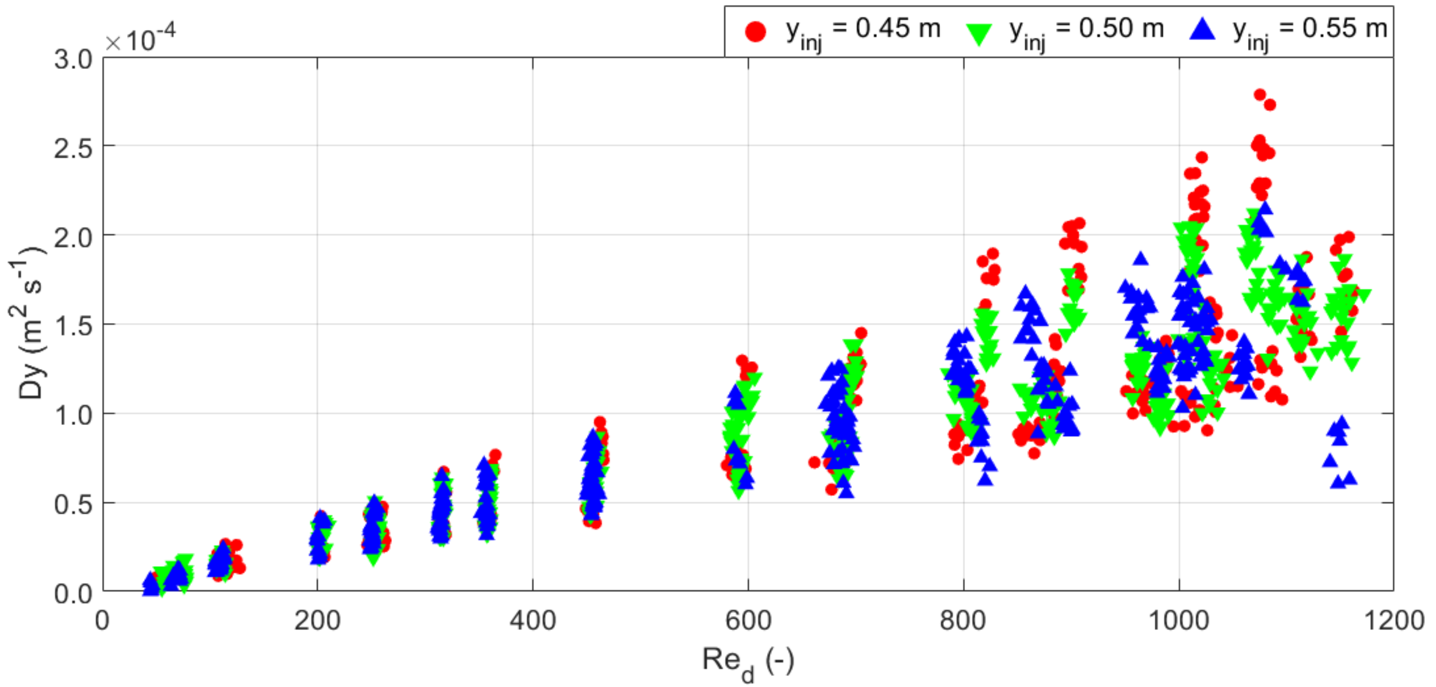
LIF Results

- Comprehensive Re_d range for cylinder flows $40 < Re_d < 1200$
  - Laminar flow (no shedding)
  - Vortex street
  - Transition to turbulence
- Solid volume fraction $\varphi = 0.05$
- 3 reaches
- 3 different injection locations (i.e. initial conditions)

- Results show no effects of initial conditions on long-term dispersion.

- D_x and D_y are proportional to Re_d: increases in advection, turbulence and shear contribute to mixing.





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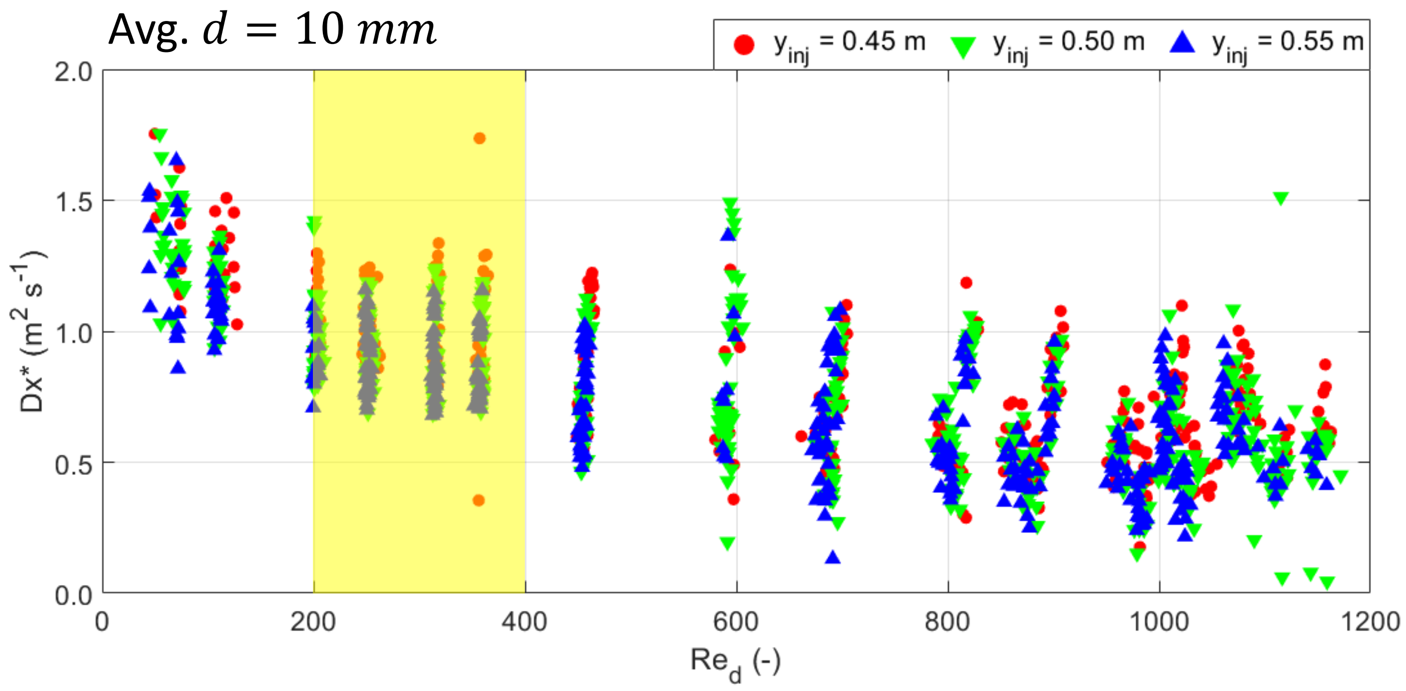
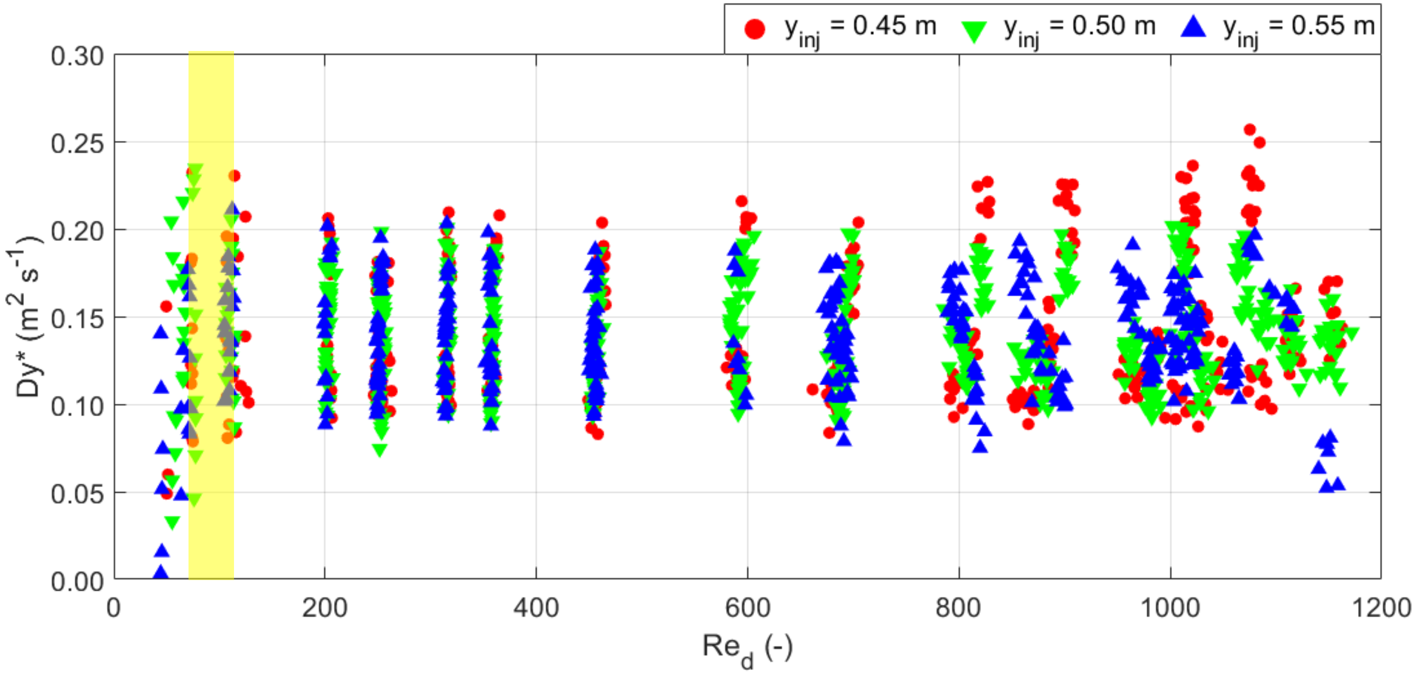
LIF Results

- For D_x^* a transition between trapping-based to advection-based dispersion is identified.
- As turbulence increases, the transfer of mass between zones becomes more efficient.
  - Shear/trapping-based dispersion
  - Transition due to turbulence
  - Advection-based dispersion



- For most Re_d analysed, D_y^* is independent of flow regime. Morphology is the dominant driver of dispersion.
- This asymptotic behaviour is reached after the onset of periodic vortex shedding ($Re_d \approx 100$).



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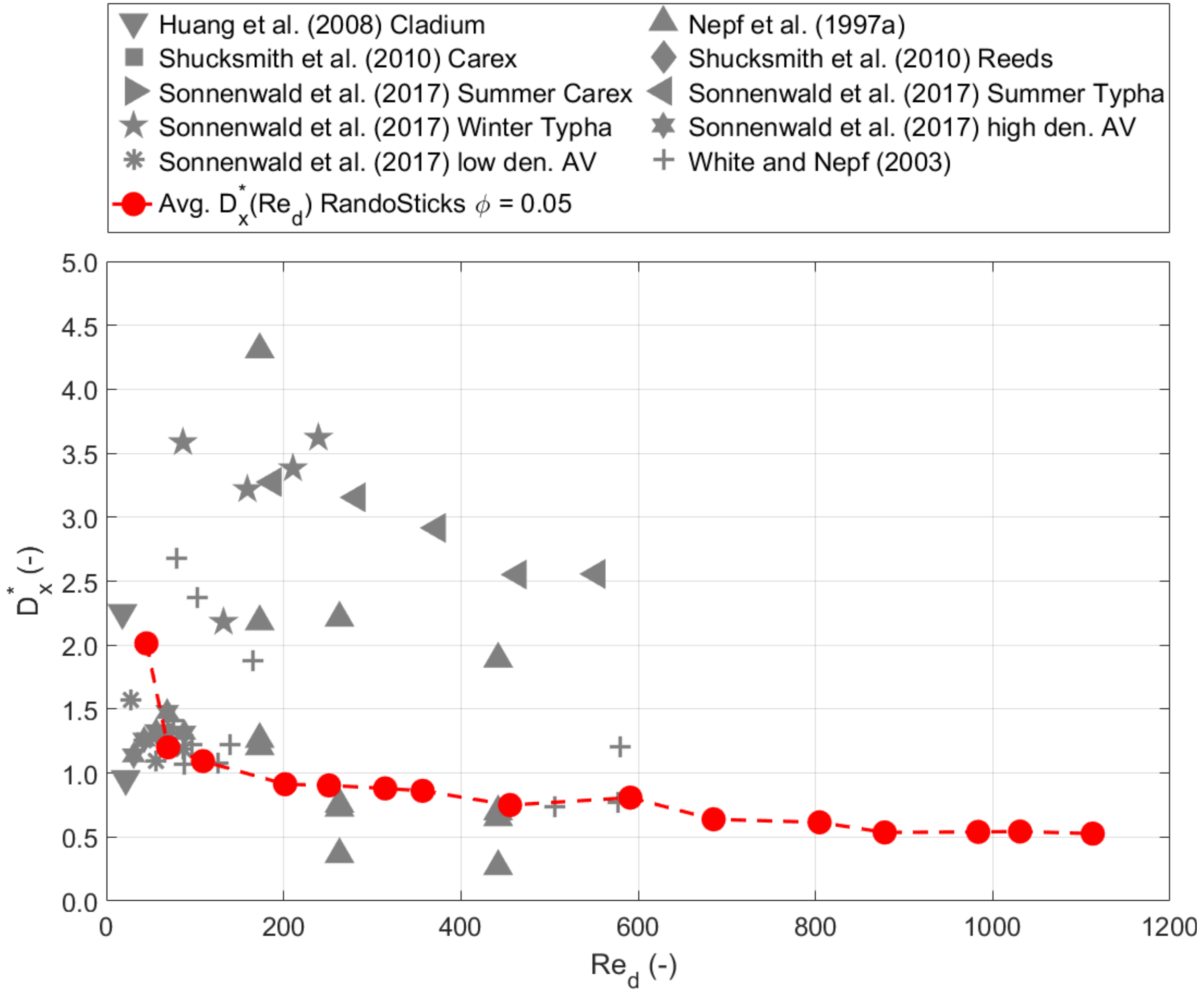
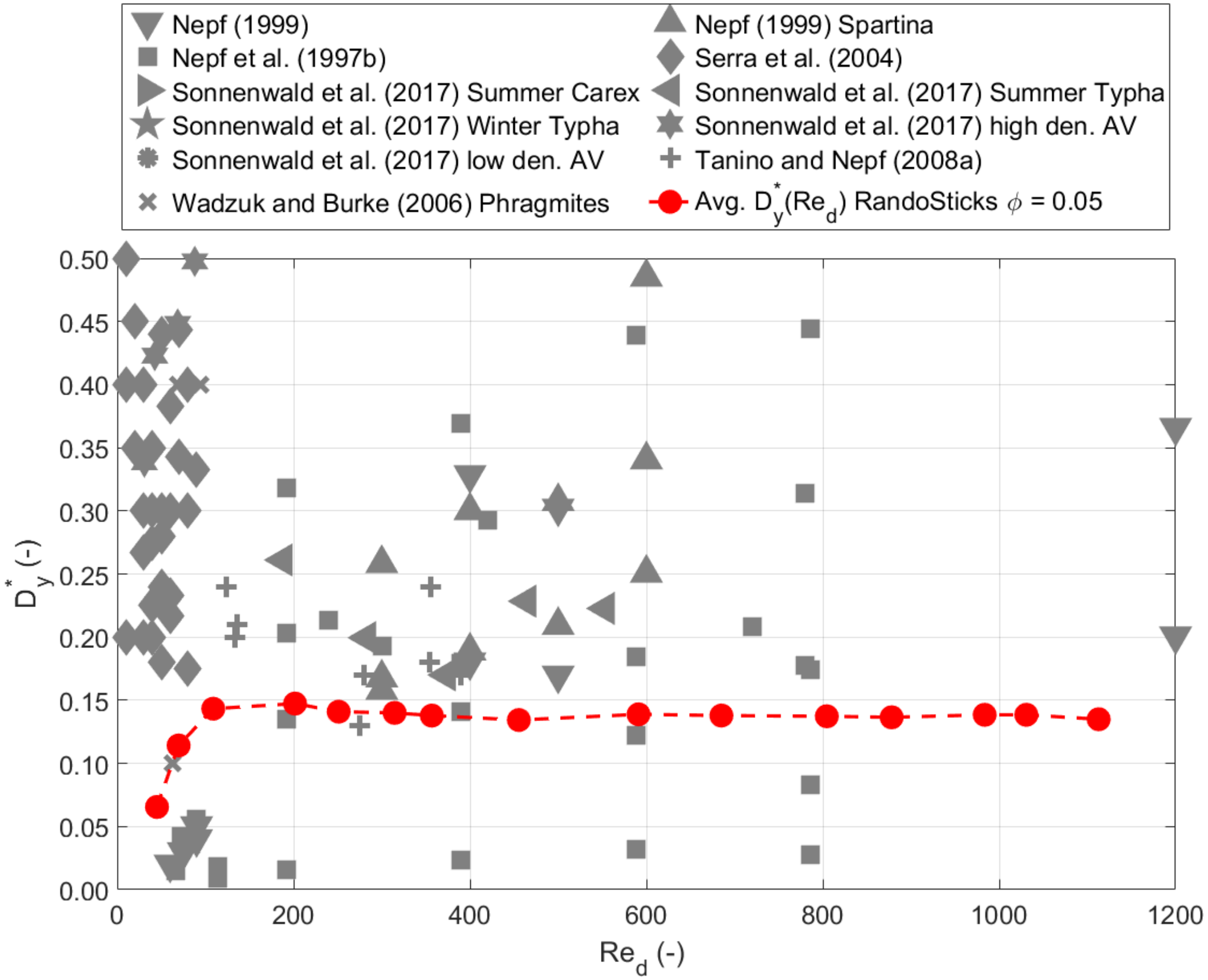
LIF – Previous Results





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Particle Image Velocimetry

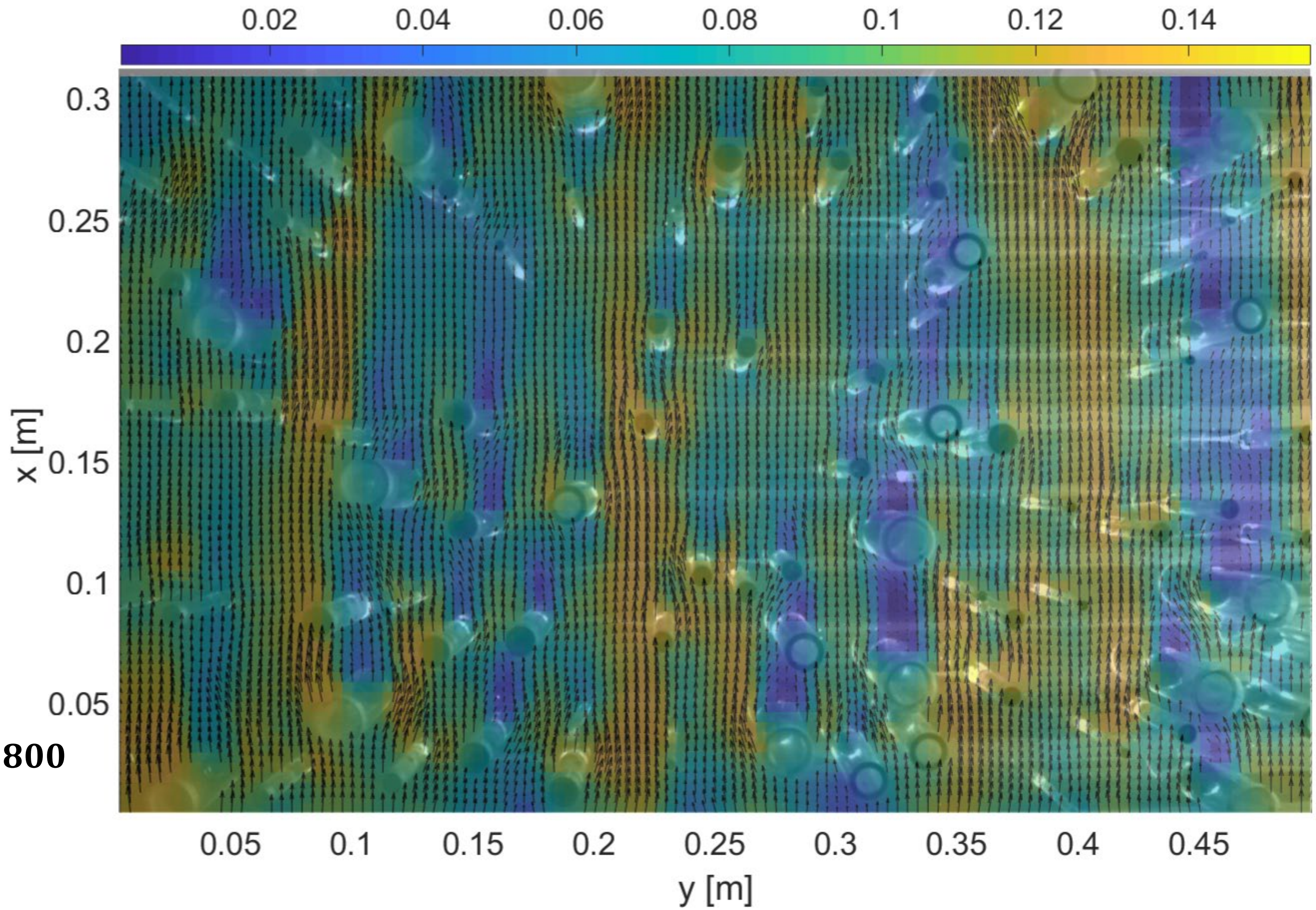
Challenges:

- Light Intensity
- Contrast
- Light uniformity
- Particle Image density

Strategies:

- Subtraction of Light heterogeneities (unseeded images)
- Directional Light Attenuation Correction
- Image Levelization
- Filtering and Signal Improvement

6 Experiments: $110 < Re_d < 800$



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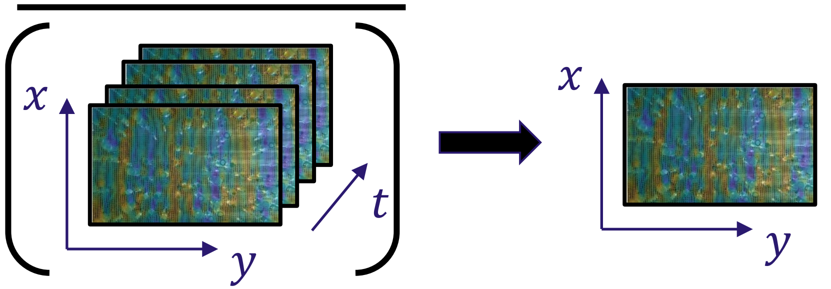
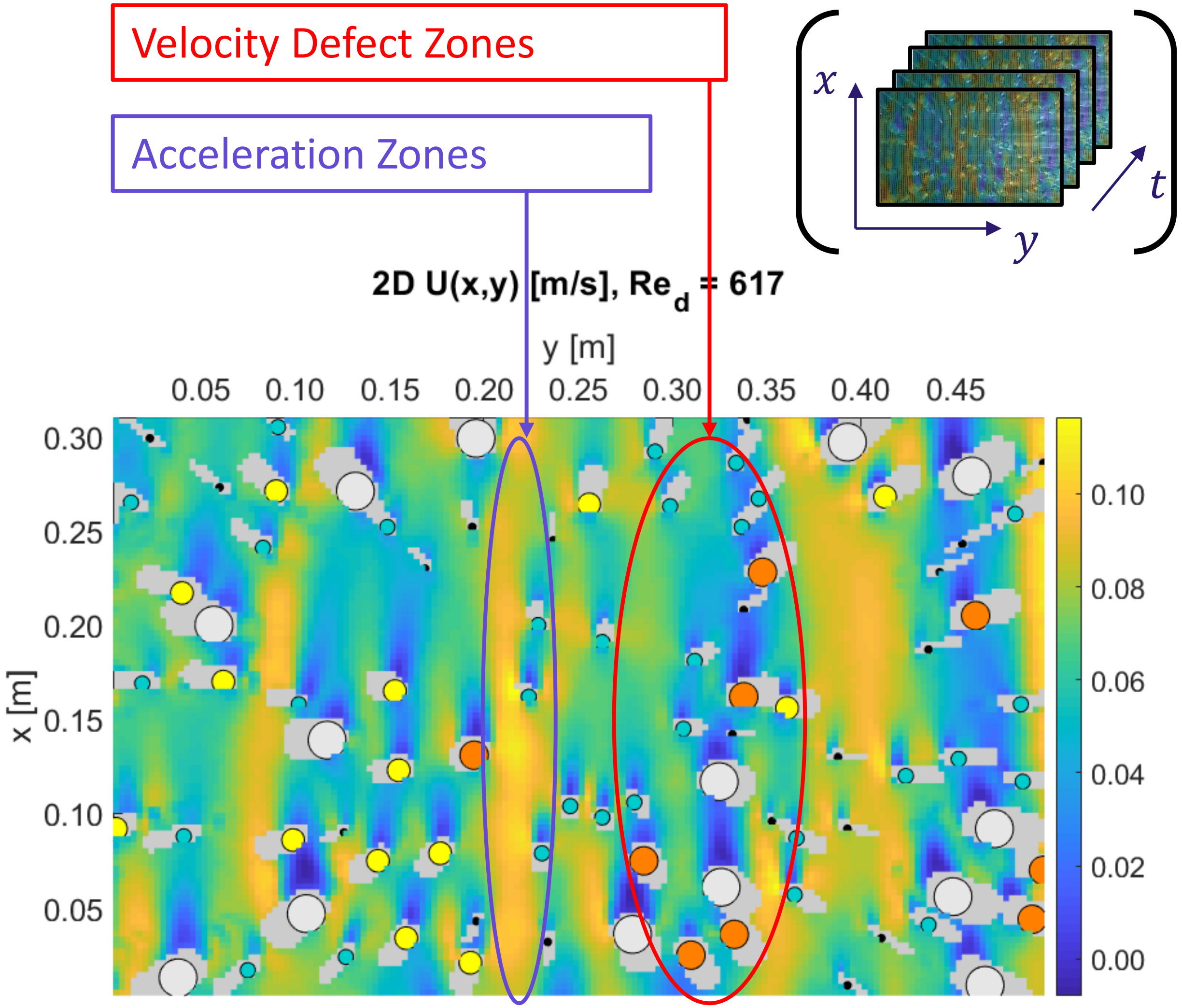
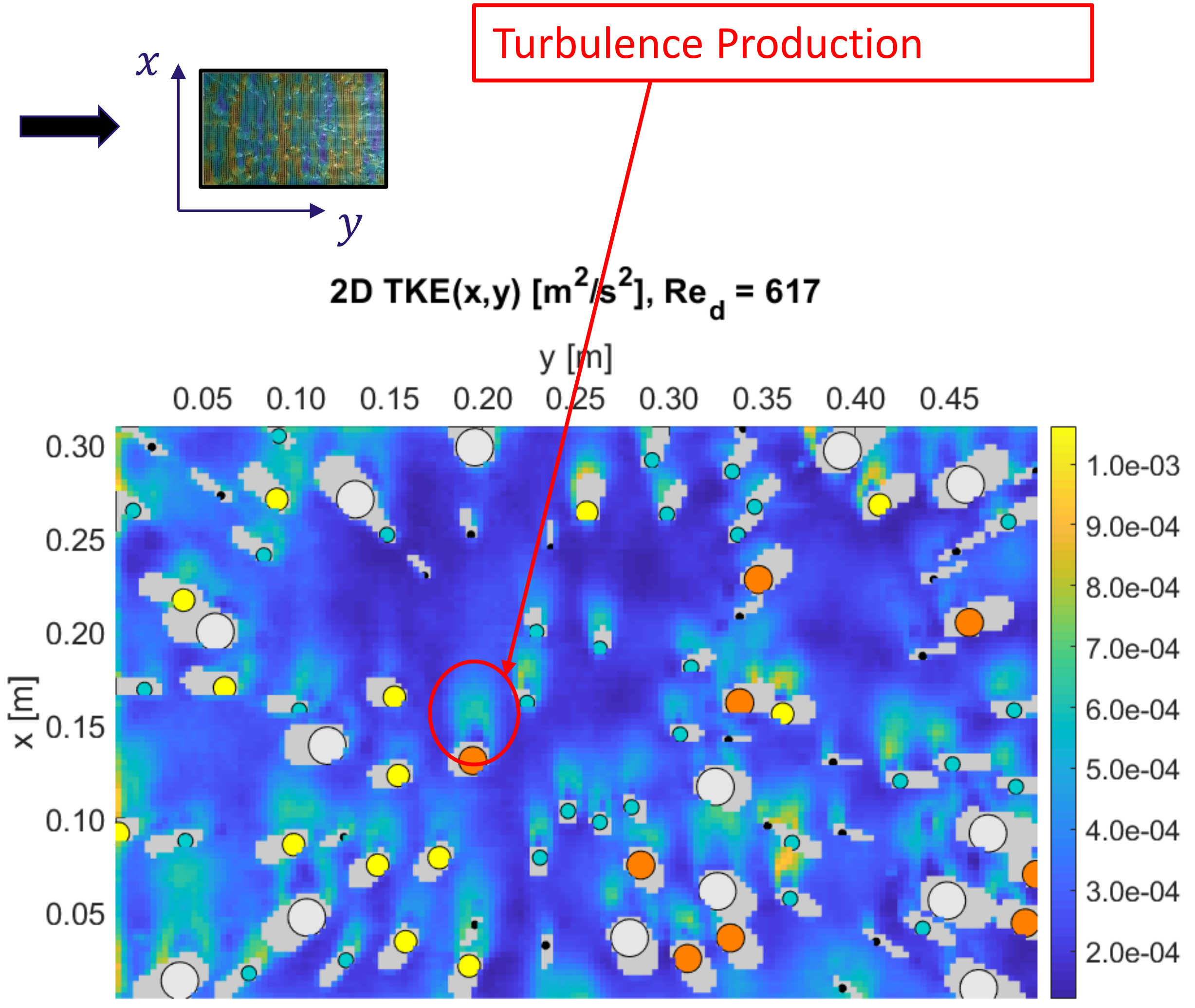
PIV – Mean Velocity Maps







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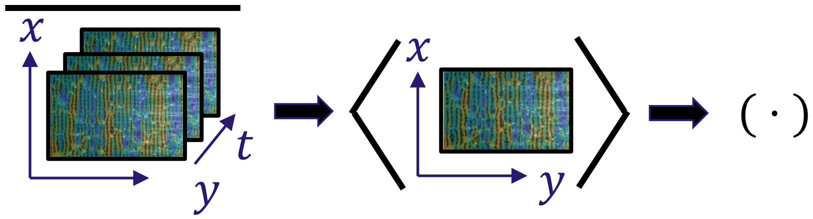
PIV – Virtual Stresses/Fluxes

The Double-Average (DA) framework



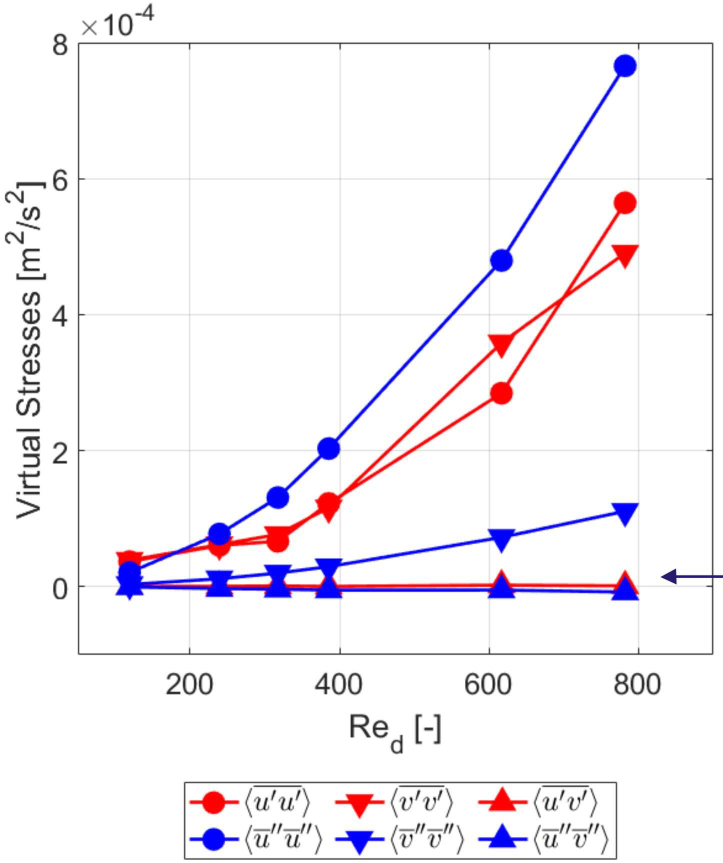
DA decomposition: $u = \langle \overline{u} \rangle + \overline{u}'' + u'$

DA on the Momentum eq. yields the following virtual stresses:

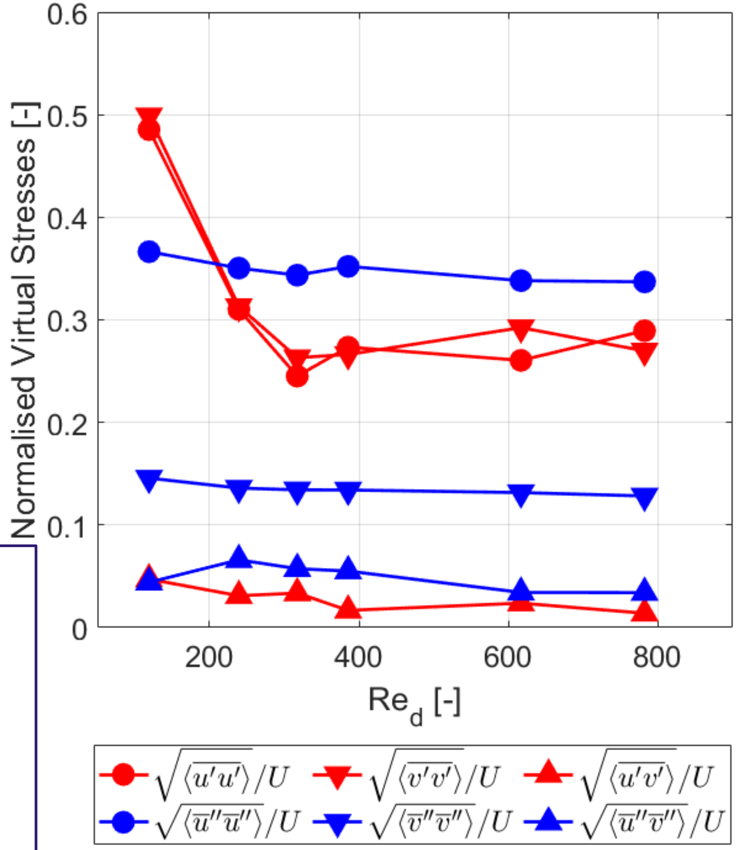
$\langle \overline{u_i' u_j'} \rangle$: Turbulent fluxes, caused by coherence and small-scale velocity fluctuations.

$\langle \overline{u_i}'' \overline{u_j}'' \rangle$: Dispersive fluxes, caused by differential advection.

Turbulent fluxes are isotropic in a DA sense



Temporal fluctuations of velocity are dominant for $Re_d \lesssim 250$



Cross-fluxes are negligible

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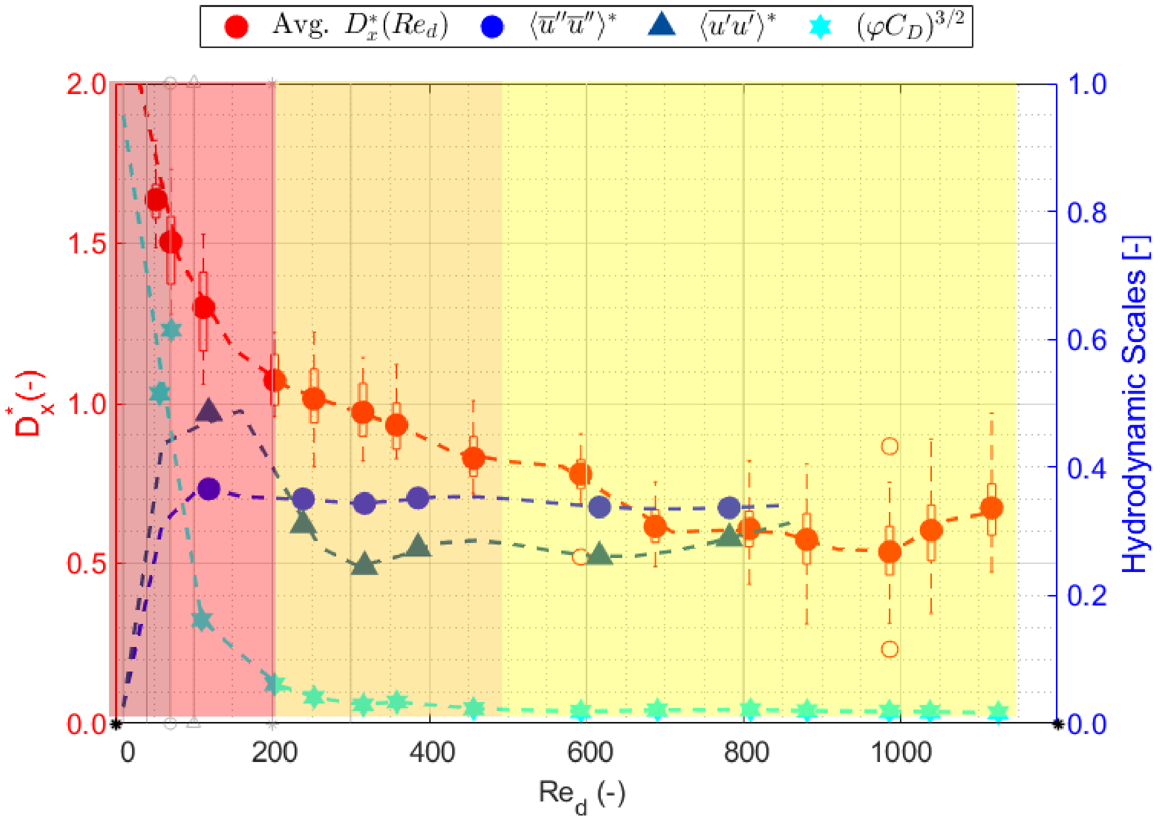
PIV – Dispersion Regimes

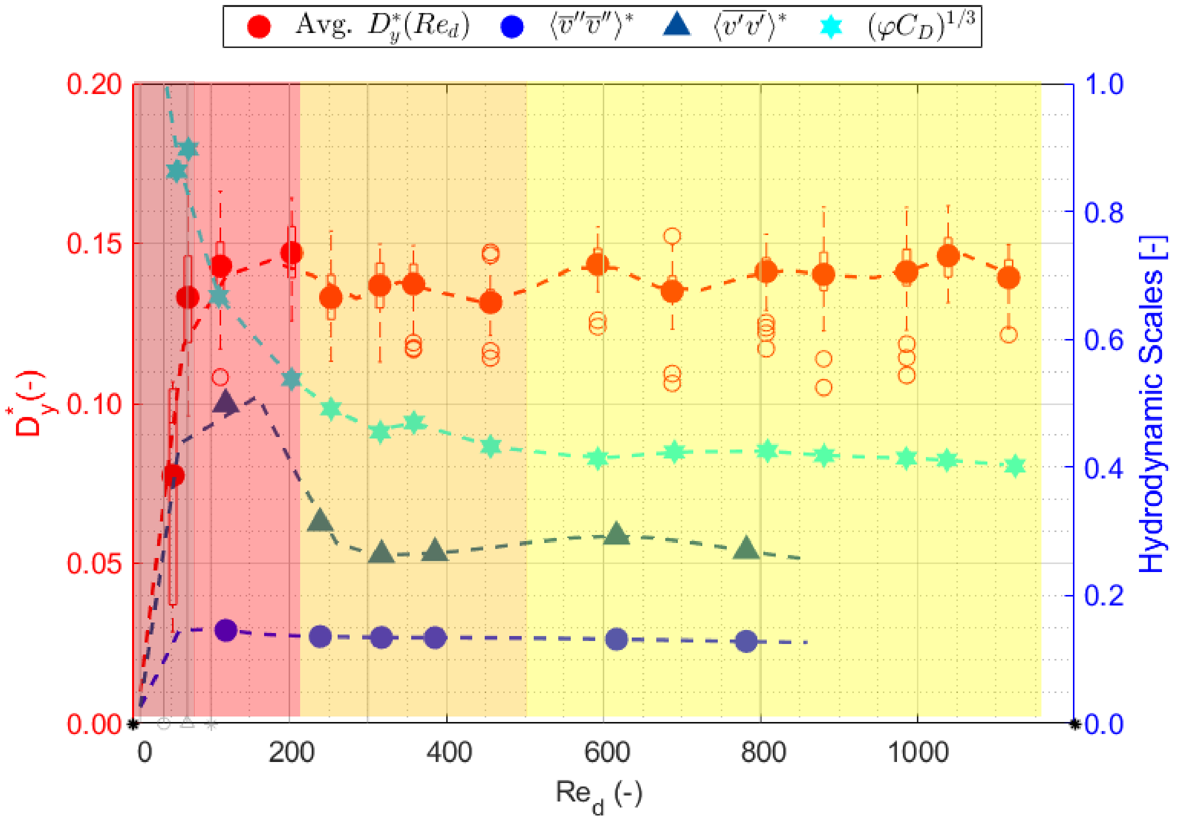
Laminar range: trapping dominates D_x^*. Exchange rates are governed by molecular diff.

Transition range: Small-scale mixing more effective, and predominance of differential advection.

Turbulent range: Dispersion is dominated by shed vortices.

Advective range: Dispersion is purely Fickian.





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* C_D is added to compare with an indicator of flow resistance

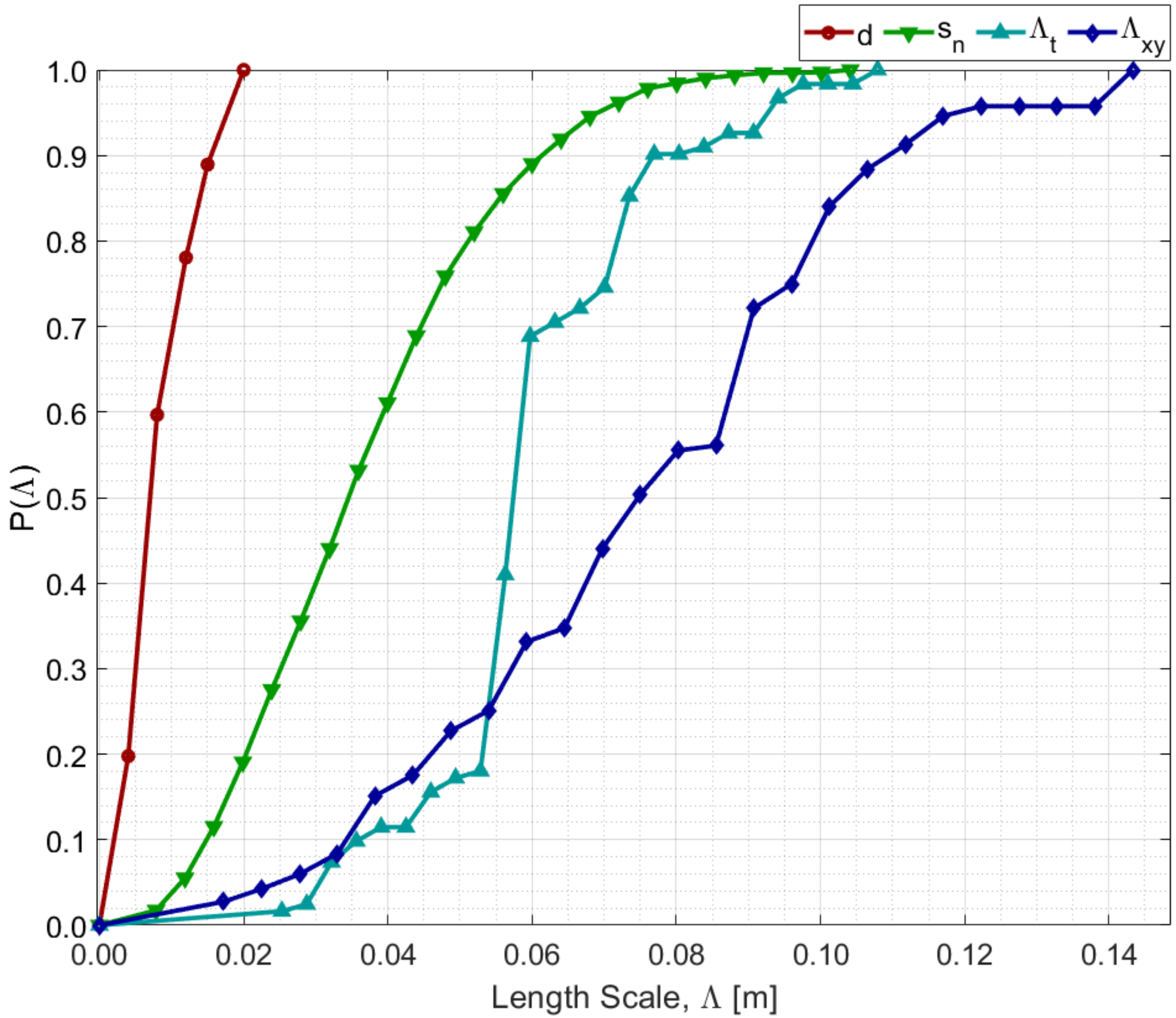
What about the characteristic dispersion scale??

PIV – Flow Scales

The variation of Λ_t and Λ_{xy} reflect the existence of flow structures from non-linear cylinder interactions: clusters.

Steps ahead…

- Simultaneously apply PLIF and PIV to estimate mass flux terms: $\langle \overline{u_i' C'} \rangle$ and $\langle \overline{u_i}'' \overline{C}'' \rangle$. Solve the ADE in a DA framework.
- Evaluate the range of (non-linear) interactions between groups of cylinders to establish what governs the creation of clusters/acceleration gaps.
- Apply Decomposition techniques to evaluate the energy distribution of the range of vegetated flow scales.
- Relate fluxes to morphological parameters.



s_n: edge-to-edge cylinder spacing

Flow scales derived from velocity series at points (Λ_t) and transects (Λ_{xy}).

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